Università degli Studi di Pisa

Facoltà di Scienze Matematiche Fisiche e Naturali

Corso di Dottorato in Fisica

Anno Accademico 2004

Tesi di dottorato

Hadron collider physics with real time trajectory reconstruction

Candidato

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to my family

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1 Introduction

During last century experiments with accelerators have been extensively used to improve our understanding of matter. They are now the most common tool used to search for new phenomena in high energy physics. In the process of probing smaller distances and searching for new particles the center of mass energy has been steadily increased. The need for higher center of mass energy made hadron colliders the natural tool for discovery physics.

Hadron colliders have a major drawback with respect to electron-positron colliders. As shown in fig. 1 the total cross section is several orders of magnitude larger than the cross section of interesting processes such as top or Higgs production. This means that, in order to observe interesting processes, it's necessary to have collisions at very high rates and it becomes necessary to reject on-line most of the “non-interesting” events. The system that performs the on-line selection is usually referred to as *the trigger*.

Figure 1: Cross sections at hadron colliders as a function of the center of mass energy.

The trigger system is playing a major role in hadron collider experiments because it's ability of efficiently selecting different kinds of events dramatically affects the physics reach. This led to the development of several techniques for making faster and smarter triggers. The three basic ingredients of any hadron collider trigger are reconstruction

of calorimetric clusters, tracking in muon systems and tracking in tracking detectors. While several techniques have been developed to make fast reconstruction of calorimeter data and muon system data, the reconstruction of tracker detector data has always been considered a tough problem.

However, in the past, there have been successful approaches to on-line track reconstruction at hadron colliders. Even very precise on-line tracking exploiting the full resolution of the detector has been achieved.

The CDF[1] experiment used a fast on-line track processor since the begin of Run I [2]. It was able to reconstruct tracks at low spatial resolution in the drift chamber down to a P_T threshold of 2.5 GeV in an average time of 2.5 μs . This was a crucial tool used to keep under control the muon and electron trigger rates.

After an upgrade period the CDF II [3] experiment is running. It uses two track processors called XFT [4] and SVT [5].

XFT reconstructs tracks in the drift chamber down to a P_T threshold of 1.5 GeV. The XFT is pipelined and reports the results for a new event every 396ns, with a typical latency of 2 μs . It is suitable for Level-1 trigger decision.

SVT reconstructs tracks in the silicon detector within 20 μs using the full silicon resolution and providing a measurement of transverse impact parameter with spatial resolution comparable to that of the off-line. It is used for the Level-2 trigger decision. Thanks to the SVT processor, the CDF II experiment was the first one to observe fully hadronic decays of the bottom quark at an hadron collider. An interesting example is reported in fig. 2, which shows the peak of the B^0 decaying into 2 hadrons and the result of the fit of the different fractions. This is one of the many samples selected by SVT based triggers that are used for several world best measurements. These events are characterized by two low P_T tracks ($P_T > 2$ GeV) with impact parameters $d_0 > 100 \mu m$ and have to be extracted from a huge background ($\sigma_{tot} \approx 80 mb$) of events full of tracks. Without the impact parameter cut only order of 1 event could have been selected.

The same collaboration that made possible SVT is also working on a second generation processor that could work at Large Hadron Collider (LHC) experiments. This is a general purpose R&D processor called Fast-Track[6] (FTK). The goal of this R&D project is to provide offline-quality tracking for LHC experiments at the level-1 output event rate, which means about 100kHz.

The technique for fast on-line tracking chosen by both SVT and FTK is the “pattern matching” algorithm. A set of precalculated patterns, representing all the possible interesting tracks, is stored in a memory and compared to each event to find tracks. If the comparison is highly parallelized (each pattern is provided with the hardware to compare itself with the event in parallel with all the other patterns) it is possible to build very fast tracking processors. However, to achieve high quality tracking, by this sole method, a too large amount of patterns is required.

In order to perform on-line tracking with off-line quality, the SVT processor divides the track finding problem into two stages [7]. The first stage is a low resolution search for track candidates called roads. This is achieved with a highly parallel Associative Memory (AM) system [8] that solves most of the combinatorial problem using a large

Figure 2: $M_{\pi\pi}$ distribution of the $B \rightarrow h^+ h'^-$ candidates assigning the pion mass to both decay tracks. The resulting fit fractions are overlaid.

pattern bank. Then, the second stage refines the definition of the track down to the detector limit. The key point here is that this second stage can be implemented with more conventional techniques (e.g. a sequential processor) since virtually all of the combinatorial problem that makes track finding so time consuming has already been solved.

This is a general approach that works for every kind of detector. Furthermore, as long as the pattern recognition is implemented without exploiting any symmetry of the detector, as it is in the SVT processor [5], it's unaffected by alignment problems because a single pattern is used for each track^{1 2}. In fact this approach is so general and powerful that it could become the standard way to perform very fast on-line tracking in high energy physics experiments.

This kind of approach subdivides the needed computing power among the two stages. The method is very efficient as long as the first stage is “good enough”, where “good enough” means that the first stage output has a low level-of fakes and high efficiency. The space resolution that achieves this goal should be determined ad hoc for the specific application.

I worked on both SVT and FTK processors.

¹Where tracks differing by less than the device resolution are identified into the same track.

²The SVT has some alignment requirement. This is a different issue. It's due to the fact that it's performing 2D tracking and 2D parameters are meaningful only if the silicon strips are correctly aligned along the z axis.

1.1 My work for competitive heavy flavor physics at hadron colliders

My thesis's work covers different subjects:

- study of the $B^- \rightarrow K^+ \pi^- K^-$ for the measurement of the of the γ angle at CDF;
- study and proposal of possible selections of b-quark rich events at ATLAS such as $Z^0 \rightarrow b \bar{b}$ (with one b decaying into $\mu + X$), $b \bar{b} H/A \rightarrow b \bar{b} b \bar{b}$ and $Z H \rightarrow b \bar{b} b \bar{b}$;
- study and simulation of DAQ and trigger systems that resulted into the approval of two upgrades for the SVT processor.
- advanced trigger hardware techniques for the on-line selection of b-quarks;
- Monte Carlo simulations and comparison with CDF data for the study of QCD events rich of b-quarks.

All these subjects belonging to different fields are strongly motivated and logically connected by the guide line of my thesis, which consists in convincing the scientific community of the importance of a dedicated hardware such as the one now used at CDF, the SVT processor, for extremely fast ($\sim 10\mu s$) and high precision (i.e. off-line quality) pattern recognition at all hadron colliders. The possibility to perform high-quality full on-line tracking is the indispensable ingredient for competitive physics with b-quarks and heavy flavors in general at hadron colliders, which is very high priority for the high energy community and the ultimate aim of my thesis.

The Associative Memory idea [8] is the main, fundamental piece of this picture. This device has been developed in Pisa. The first full-custom VLSI device [9] was produced for CDF. An FPGA Associative Memory was proposed as a device more user friendly and easier to be upgraded [10]. Finally, a standard-cell VLSI chip was proposed [11] as an intermediate solution between full-custom VLSI and FPGA technologies. The standard-cell technology offers densities and timing performances that are comparable to those of the full-custom, but the design can be reliably simulated and realized or upgraded in a reasonably short time. Standard-cell technology has been chosen for the SVT upgrade [12]. I worked at the chip design for the upgrade and I had the responsibility to validate the project, with appropriate simulation of all its functions, and the prototype production, with appropriate tests of the chips and of the new Associative Memory boards. I will be the project leader of the SVT upgrade starting January 2005. I omit the hardware technical details from this thesis in order to concentrate on the Physics issues.

The first part of my thesis is related to my work in CDF. I joined in CDF when SVT was already installed and working to take data. During the 2003 I participated to the SVT trigger study and to the evolution of the data taking devoted to the continuous effort to increase the sample yields. I contributed substantially to the understanding of problems existing in the early CDF data taking and I participated to the proposal of the SVT upgrade. I'm participating to the SVT upgrade, that has been initially approved in September 2003. A larger upgrade program has been approved in July 2004. The upgrade is now under construction and it will be installed during summer 2005.

Chapter 2 describes the SVT triggers as they have been set during the first data taking, their rates and the related expected physics samples: $Z^0 \rightarrow b\bar{b}$, $HZ \rightarrow b\bar{b}\nu\bar{\nu}$, $HW/Z \rightarrow b\bar{b}jj$, techniomuon $\rightarrow \gamma b\bar{b}$, $H \rightarrow \tau\bar{\tau}$ and samples for low P_T B-physics. In particular my work was devoted to the study of the requirements on the CDF's DAQ and trigger systems to be satisfied to realize this physics plan. The work described in chapter 4 shows the incompatibility of this physics plan with the available total rate budget. Very important physics risks to become impossible at CDF II. In particular I report the problem of collecting a sample of $B^\pm$ events sufficient for the measurement of the γ angle, as proposed at CDF [13]. I'm going to show that the proposed upgrades make feasible the γ measurement and the B_s mixing measurement that would be lost if the present SVT were used up to the end of CDF, without upgrading.

Chapter 3 shows the evolution of data-taking during 2003. Every effort is done to increase the samples. I worked in particular to study the SVT efficiency and to extend the SVT role in CDF. The use of tracks reconstructed only in the Silicon detector (SVX-only tracks) can extend on-line tracking to the regions not covered by the Central Outer Tracker (COT). Tracks in the forward regions would extend the coverage of high P_T lepton triggers from $|\eta| < 1$ to $|\eta| < 1.5$. Those triggers are workhorse for most of electroweak, exotic and top analyses based on W, Z decays to leptons. The increased yield will improve W and top mass measurements. In particular I study the case of the forward μ trigger that today in CDF is totally unavailable for physics. This trigger is particularly important for the W, whose signature is based on a single forward isolated track identified also in the muon chambers. I have presented this SVT application to CDF and it has been approved. It becomes also a good motivation for the SVT upgrade that we are building for CDF, since more coverage needs more space in the pattern memory.

Chapter 4 enters in the details of the DAQ problems that reduce dramatically the level-1 trigger bandwidth compared to the design expectation of 50 kHz for the event rate. "Trigger bandwidth" in the following of this thesis means the maximum rate at which events can be collected with a small dead-time (less than 5%). Our impact on the understanding of the problem was essential. Initially, CDF was planning a lot of upgrades for the trigger and DAQ, but nothing was planned for SVT that is the most complex and important part of the system. In fact, poor trigger simulations were consistent with a small impact of the present SVT on DAQ problems. In order to increase data taking efficiency for SVT triggers such as those used for B and $Z^0 \rightarrow b\bar{b}$, I simulated the effect of different SVT improvements on real data. I showed that actually SVT has a great impact on data taking and a good upgrade could increase the level-1 bandwidth by a factor 2. Fig. 3 shows, for one particular trigger, that this increase in bandwidth has an important effect on data taking efficiency, hence on γ and x_s sensitivity. The figure shows that the B_s trigger is strongly prescaled. The prescale factor strictly depends on the instant luminosity and on the level-1 bandwidth. Fast-growing prescale factors, which directly reflect on the efficiency, must be applied to the event flow as the Level-1 rate limit decreases. The situation dramatically worsen as the luminosity increases.

Figure 3: Effect of the Level-1 bandwidth limitation on B_s data taking efficiency for the TTTflow P_T trigger (see sec. 2.5.2). This trigger is the lowest P_T , i.e. highest acceptance, hadronic B trigger. The red arrow refers to mid 2003.

Then the upgrade is described. I will show at the end of chapter 4 that the SVT upgrade will be able to save all the physics channels described in chapter 2.

The second part of my thesis is mainly related to the activity devoted to export the SVT hardware and related trigger ideas to LHC experiments. I was part of the FTK project since the beginning.

Chapter 5 describes the proposed FTK architecture, how it can fit on modern experiments and its performances. I gave a relevant contribution to the definition of the system requirements, that are necessary to use the FTK to efficiently select $b\bar{b}H/A \rightarrow b\bar{b}b\bar{b}$, $Z^0 \rightarrow b\bar{b}$, $H/A \rightarrow \tau\bar{\tau}$ and other b-rich final states. I studied the performances simulating the processor activity on different types of shower Monte Carlo events. I presented and discussed these results with the ATLAS collaboration in many occasions [14, 15, 16, 17, 18]. The proposed system is under examination by the ATLAS collaboration. We proposed new trigger ideas heavily based on the FTK use. I did preliminary simulations for a set of physical channels. These studies are a first step in the process of providing a solid “physics case” in order to support the FTK approval. I studied the trigger rates for the backgrounds of these physics channels rich of b-quarks in the final state, showing that an aggressive b-tagging at level-2 would open new physics reach to the LHC experiments.

Finally we worked to collect in CDF all possible information about b-rich samples studied in the past. They are the typical backgrounds for the “physics cases” we propose and in particular for the channels described in chapter 5. We found that the shower Monte Carlos can give too large rate predictions if applied to exclusive samples such as QCD events with 3 b-quarks inside. I studied the problem with the simulation and I presented the results to the “Matrix Element and Monte Carlo Tuning

Workshop” [19] in 2002. The results are reported in section 5.3.

2 Physics with SVT triggers

The SVT processor operating for the CDF experiment has allowed, for the first time in HEP, to write to tape huge amounts of b-quark decays collected at an hadron collider using on-line impact parameter selection. This has opened the possibility, for the CDF experiment, to extend its physics program to include precision B-physics measurements that, in the past, have been considered impossible at hadron colliders.

The SVT processor allows to select rich samples of b-quarks that have a wide spectrum of applications going from B-physics measurements, to searches for Higgs or exotic signals.

2.1 High- P_T physics with SVT

Tab. 1 lists high- P_T samples that are selected using SVT. The detailed description of level-1 (LVL1) triggers is reported in the following sections. For each trigger the rate is shown for luminosity equal to $20 \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1}$ and $60 \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1}$. The rate for effective triggers is not a linear function of the luminosity. This is equivalent to say that the cross-section of the trigger itself is not a constant, but depends on the luminosity. The effect is due to the experimental definition of the triggers. In fact, each trigger selects a given set of physical processes that of course have constant cross-sections, but in addition to them it also selects non-physical processes such as misidentified signatures. Some examples of misidentified physical signatures are fake tracks, made of noise hits or by mixing up hits from different tracks; muon stubs generated from accelerator background (e.g. protons escaped from the beam); fake missing E_T due to fluctuations in the measurement of the energy in the calorimeters, these fluctuations increase with pile up since the average energy deposition increases. In general, higher instantaneous luminosity generates higher detector occupancy that, combined with a lower resolution of most trigger processors with respect to detector resolution, increases the probability of having fake physical signatures. Throughout the remainder of this thesis, when referring to trigger cross-sections we mean the effective trigger cross-section including both the contributions from selected physical processes and fake signatures.

Physics channel	Level-1 selection name	rate (Hz) @ 2E31	rate (Hz) @ 6E31
$Z^0 \rightarrow b\bar{b}$	L1_TWO_TRK2_&_TWO_CJET5	220	750
Higgs multijet	L1_JET10_&_ΣET90	15	100
Higgs, $Z \rightarrow \nu\nu$	L1_MET15_&_TWO_TRK2	60	600
di τ exotic	L1_TWO_TRK10_DPFI20	100	1800 ³
$\gamma + b$ -jet	L1_EM8	280	840
Total		675	4090

Table 1: List of high P_T triggers using SVT at LVL2

³This trigger is now dynamically prescaled because of its too high Level-1 rate.

Fig. 4, 5, 6 show the dependence of cross-sections from the instant luminosity, as measured on Run II data. For some triggers the cross-section is almost constant for some others it increases steeply, depending on how much the trigger criteria are sensitive to pile-up.

2.1.1 $Z^0 \rightarrow b\bar{b}$

The first data sample from tab. 1 is used for the study of $Z^0 \rightarrow b\bar{b}$ events. The reconstruction of $Z^0 \rightarrow b\bar{b}$ events at CDF will be a very important tool for the determination of the b-jet energy scale, which in Run I was the largest contribution to the top mass systematics.

The selection of $Z^0 \rightarrow b\bar{b}$ events is extremely hard, because of the huge QCD jet background. For this reason the trigger requires a lot of level-1 bandwidth. In fact, the greater is the available bandwidth the better will be the $Z^0 \rightarrow b\bar{b}$ peak reconstruction. One of the difficulties with this analysis is due to the fact that the trigger efficiency on irreducible background must also reach $\sim 100\%$ at masses well below the Z peak in order to allow reliable measurement of the background line shape for the signal extraction [20, 21]. The current level-1 trigger requires two calorimetric towers with energy above 5 GeV (TWO_CJET5) and two tracks with $P_T > 2$ GeV (TWO_TRK2). With this selection the rate is approximately 750 Hz with an instantaneous luminosity of $60 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. The rate increases approximately linearly with luminosity (see fig. 4). The effect of this selection was studied on Run I data [22].

The note in ref. [23] shows the efficiencies for a Higgs signal with a mass of 110 GeV (i.e. slightly higher than the Z^0 mass). It also shows how much it is important to keep track and calorimeter thresholds as low as possible. In fact, the involved b-jets are soft and their fragmentation is such that, thresholds must be placed well below the nominal jet energy in order to get high efficiency and low trigger bias.

The level-2 trigger has been deeply studied in the past and it is based on the use of SVT for the selection of b-quarks. Note [23] shows that a selection using only XFT at level-2 has a background rejection of ~ 3 , while using also SVT the rejection can be as high as 80 (see page. 15 of [23]). In conclusion, b-tagging at level-2 is a difficult selection, but it is the only possible in order to efficiently select $b\bar{b}$ QCD event starting from invariant masses as low as 50 GeV.

However, after $\approx 150 \text{ pb}^{-1}$ of data was collected during Run II, the trigger was shown to be not completely satisfactory since the trigger threshold turn-on was located at masses too close to the Z^0 peak [20]. The trigger has then been changed, and the turn-on moved to lower masses. The Z^0 peak should be visible with this trigger as soon as enough statistic will be collected. All this makes clear the importance of the amount of level-1 bandwidth dedicated to this trigger.

Collecting a high mass resonance such as $Z^0 \rightarrow b\bar{b}$ for the study of energy scale and jet resolution has always been a CDF dream. The Z^0 and W peaks were impossible to collect because of the very high QCD rate reduced by using jet energy thresholds that placed the trigger turn-on at mass even higher than the boson peak. With SVT, for the first time it is possible to realize this dream for b-quarks, since it allows to kill the rate at Level-2 without using high jet energy thresholds.

L1_TWO_TRK2_ & TWO_CJET5_v3 Cross Section vs. Inst. Lum

Figure 4: Level-1 trigger cross-section for $Z^0 \rightarrow b\bar{b}$ as a function of instantaneous luminosity.

This trigger has several applications:

1. Understanding to a 1% precision the energy scale and resolution for b-jets. This would allow to significantly decrease the systematic uncertainty for the top mass measurement. In fact, the top mass systematics is dominated by the jet energy uncertainty [24]. In particular, most of this systematic effect is due to the b-jet energy uncertainty [25].
2. Developing and testing new and better jet energy corrections.
3. Collecting an interesting $b\bar{b}$ inclusive data sample, that can be used for several more exclusive analysis. We will call this sample a minimum bias $b\bar{b}$ sample. Some examples of more exclusive analysis are:
 - (a) SM Higgs + X, with $H \rightarrow b\bar{b}$ and X decaying in any channel (e.g. a vector boson that decays into 2 jets or the Z that decays to $\nu\bar{\nu}$ which is the most promising channel at the Tevatron).
 - (b) SUSY H/A (produced alone or in association with $b\bar{b}$) with H/A that decays to $b\bar{b}$ or $\tau\bar{\tau}$.

Several other triggers overlap with this sample that can offer the possibility of efficiency checks. This was the purpose of [23]. However, this goal is achieved

L1_MET15_&_TWO_TRK2_v2 Cross Section vs. Inst. Lum

Figure 5: Level-1 trigger cross-section for Higgs, $Z \rightarrow \nu\nu$ as a function of instantaneous luminosity.

only partially since, in order to limit the Level-1 and Level-2 bandwidths for this trigger, tighter cuts have been used. The impact parameter cut has been moved to $160 \mu\text{m}$, twice the original proposal.

4. even in the case that none of these discoveries will happen at CDF, this trigger will provide a precious data sample to increase our QCD knowledge in order to tune and correct Monte Carlos, offering an invaluable cultural background for the search of the “new” at the LHC collider, (see sec. 5.3 for an example of the importance of data samples collected during Run I for a better understanding and tuning of Monte Carlos). In addition we should not forget that the complex technology developed and tested at CDF, which is necessary for the selection of b-quarks with low P_T (a lot of high P_T physics has low P_T b-quarks in the final state) at the huge QCD rates, can be applied in future experiments.

2.1.2 Higgs: $HZ \rightarrow b\bar{b}\nu\bar{\nu}$, $HW/Z \rightarrow b\bar{b}jj$

Two other important high P_T triggers using SVT are: “Missing E_T + Higgs” (L1_MET15_&TWO_TRK2) and “Higgs multi-jet” (L1_JET10_&SUMET90). At level-1, as the names themselves suggest, they require missing E_T above 15 GeV and two XFT track with $P_T > 2$ GeV

Figure 6: Level-1 trigger cross-section for $\gamma + b$ -jet (and other exotic analysis) as a function of instantaneous luminosity.

the former, and one calorimetric tower with 10 GeV along with a total energy of 90 GeV the latter. At level-2 they use the SVT impact parameter to reduce the rate. With respect to the $Z^0 \rightarrow b\bar{b}$ trigger they use looser i.p. cuts since the level-1 selection is harder and a smaller rejection factor is acceptable. Those triggers are more exclusive and are more efficient for Higgs selection. In particular they are thought for the $HZ \rightarrow b\bar{b}\nu\bar{\nu}$, which is the most promising channel at CDF (see fig. 7) for the Higgs discovery, and for hadronic Higgs channels such as $HW/Z \rightarrow b\bar{b}jj$. The selection L1-MET15_&-TWO-TRK2 is a nice example of a trigger whose rate increases more than quadratically with luminosity (see fig. 5).

2.1.3 Photon+b-jet: technimega $\rightarrow \gamma b\bar{b}$ and others

The "Photon+b-jet" (L1_EM8) is a trigger dedicated to exotic physics. It has a level-1 rate that is pretty high (see fig. 6 and tab. 1) because it is just the simple requirement of an electromagnetic calorimeter tower of 8 GeV along with the requirement of low energy fraction in the hadronic calorimeter. At level-2 the photon is required to be isolated and the request of a b-jet (here defined as a track with $P_T > 2$ GeV and with i.p. $> 120\mu\text{m}$) is added. This trigger is thought for studies of supersymmetric channels described in

Figure 7: Summary of cross section and mass limits for the Higgs from LEP (yellow area) and CDF (curves).

the "Signatures with high-pt jets" section of [26]. CDF has already published limits for technimega with Run I data from the study of $\gamma b \bar{b}$ events [27].

2.1.4 $H \rightarrow \tau \bar{\tau}$ and others

An interesting trigger for τ dedicated to exotic physics uses SVT at Level-2, with no i.p. cut, to take advantage of the higher purity of SVT tracks with respect to XFT tracks from Level-1. This is an application of SVT as general Level-2 tracker, without using the impact parameter measurement. In SVT silicon hits are added to the XFT track and this improves the measurement of all parameters. The number of fakes is significantly reduced by the addition of SVX information in the pattern recognition, with consequent reduction of the trigger rate.

It would be interesting to increase the SVT efficiency (see sec. 3). In this way SVT could have a more important role as general purpose level-2 tracker. In addition to improving track purity, SVT could extend the coverage in η or P_T with respect to XFT by using tracks measured in the silicon detector only, in such cases where the wire chamber (COT) coverage is insufficient or inexistent, as shown in sec. 3.4.1.

Physics channels	rate (Hz) @ 2E31	rate (Hz) @ 5E31
semileptonic B (electron)	230	630
semileptonic B (muon)	33	83
hadronic B $P_T > 6.5$ (TTTC)	1600	7600
hadronic B $P_T > 5.5$ (TTTA)	5800	19000

Table 2: List of low P_T level-1 triggers using SVT @ LVL2. Please note that the hadronic B $P_T > 6.5$ GeV trigger fully overlaps with the hadronic B $P_T > 5.5$ GeV.

2.2 B-physics with SVT

The most important contribution of SVT up to date is the selection of fully hadronic decays of the B quark. The selection of $B^0 \rightarrow \pi^+\pi^-$ events (see fig. 2), in the hadronic environment characterized by an overwhelming number of charged tracks, is an amazing result.

The importance of the SVT trigger for CDF II is so high that three out of the first four CDF II's published papers used the SVT “hadronic B” trigger.

It should be emphasized that while the B-physics program was originally part only of the CDF Run IIa (the first fraction of the run), now it has been extended and it is part of the flagship Run IIb program. In fact, very important measurements such as those of the B_s mixing and of the γ angle turned out to be more difficult than expected and require a longer data taking period.

Tab. 2 shows the rate of most important B physics triggers. Comparing with tab. 1, we find that the triggers that require most of the level-1 bandwidth are hadronic B triggers. These triggers are providing the data sample for all hadronic B analyses. They belong to the most important improvement of CDF II with respect to Run I and are allowing us to see hadronic B decays for the first time at an hadron collider.

In the next sections I'll discuss in more detail the measurement of the γ angle using $B^\pm$ decays to show, as an example, the importance of the SVT performances for these measurements. In fact the success of this analysis, and of other analysis such as that of B_s mixing, depends on our ability to collect large samples of hadronic B decays.

2.3 The measurement of the γ angle

Different methods are available for the measurement of the γ angle. I'll concentrate on the “Atwood, Duniez and Soni method” (ADS) [28], which is the cleanest from the theoretical point of view and is considered viable at CDF II for a first measurement of the γ angle.

The “Atwood, Duniez and Soni method” has been originally considered at CDF in ref. [13]. We review the original forecasts adding increased knowledge due to available data and measurements of the detector performances.

The system of B mesons is extremely interesting for the study of **CP** violation. In fact, the Bjorken triangle involving B mesons is the one with the highest relative phases among its elements [29].

The presence of a not removable phase in the model Lagrangian leads to **CP** vio-

lation effects. The **CP** effects are divided into two main groups: **CP** violation in the mixing; and direct **CP** violation. In the former case the phase is present in the effective mixing operator. In the latter, the phase is present in the effective decay operator.

- **CP** violation in the mixing. In the case of the mixing the **CP** violation effects are visible through the interference of the following two decay channels with the same final state f :

$$B \rightarrow f \quad \text{and} \quad B \rightarrow \bar{B} \rightarrow f$$

The mixing effects are possible in the systems of neutral mesons.

There are two main experimental difficulties in the study of this kind of effects:

1. the measurable asymmetry is time dependent
2. it's necessary to identify the flavor (B or $\bar{B}$) from which the decay originates. The methods used to identify the flavor are called “tagging” methods.

- Direct **CP** violation. Because absolute amplitude phases cannot be observed, the direct **CP** violation effects are observable only through the interference of two amplitudes. For the B mesons this happens (a) when, in addition to the tree level Feynman diagram, there is an important contribution from penguin diagrams [29] or (b) when, as it is the case of the “Atwood, Duniez and Soni method”, the final state can be obtained through two intermediate states with different weak phases. The important advantage of this second case is that penguin diagrams, that cannot be accurately calculated from the theory, are not involved.

2.3.1 The Atwood, Duniez and Soni method

The Atwood, Duniez and Soni method propose to measure the asymmetry and then extract γ from the decays of charged B mesons. It is a measurement of a direct **CP** violation effect. It has the advantage that the initial state flavor (B^+ or B^-) can be easily determined from the total charge of the final state. This method considers two decay chains that have the same final state but different intermediate states. The interference of the two amplitudes involves the γ angle and allows to extract it from observable quantities.

Let's consider the decay chains:

$$B^+ \rightarrow \bar{D}^0[\rightarrow f]K^+ \quad B^+ \rightarrow D^0[\rightarrow f]K^+ \quad (1)$$

where the final state is $f K^+$ and the two intermediate states are $\bar{D}^0 K^+$ and $D^0 K^+$. In fig. 8 we report the diagrams of the two interfering processes. In order to have a large interference among the two decay chains it's important for the two amplitudes to be similar in modulus.

Because the branching ratios of B^+ to the two intermediate states differ by two order of magnitude, the decay channel f of $\bar{D}^0 / D^0$ must be chosen such that the $\bar{D}^0 / D^0$ branching ratios are different and approximately compensate for the difference in the B^+ branching ratios. This can be achieved by choosing a final state f of the D decay that is a DCS (doubly Cabibbo suppressed) decay of $\bar{D}^0$ and Cabibbo allowed for

Figure 8: Diagrams for the two interfering processes: $B^- \rightarrow K^- D^0$ (color allowed) followed by $D^0 \rightarrow K^+ \pi^-$ (doubly Cabibbo suppressed) and $B^- \rightarrow K^- \bar{D}^0$ (color suppressed) followed by $\bar{D}^0 \rightarrow K^+ \pi^-$ (Cabibbo allowed).

D^0 . With this choice the interference of the two amplitudes is larger and the sensitivity for γ is higher.

The principle of the method is to measure the branching ratios d and $\bar{d}$, respectively from the decay of $B^+ \rightarrow f K^+$ and its charge conjugate $B^- \rightarrow \bar{f} K^-$. In the following equations we define the involved quantities:

$$\begin{aligned} a &= \text{BR}(B^+ \rightarrow K^+ \bar{D}^0) & b &= \text{BR}(B^+ \rightarrow K^+ D^0) \\ c(f) &= \text{BR}(\bar{D}^0 \rightarrow f) & c(\bar{f}) &= \text{BR}(D^0 \rightarrow \bar{f}) \\ d &= \text{BR}(B^+ \rightarrow K^+ [f]) & \bar{d} &= \text{BR}(B^- \rightarrow K^- [\bar{f}]) \end{aligned} \quad (2)$$

The omitted branching ratios ($a, b, \bar{c}(f)$ and $\bar{c}(\bar{f})$) are equal to the corresponding charge conjugates branching ratios. The two observables ($d, \bar{d}$) depend on the branching ratios $a, b, c(f)$ and $c(\bar{f})$, on the γ angle and on the hadronic phase ξ of the decay through the equations:

$$\begin{aligned} d &= a c(f) + b c(\bar{f}) + 2\sqrt{a b c(f) c(\bar{f})} \cos(\xi + \gamma) \\ \bar{d} &= a c(f) + b c(\bar{f}) + 2\sqrt{a b c(f) c(\bar{f})} \cos(\xi - \gamma) \end{aligned} \quad (3)$$

where the phase ξ does not change sign under $\mathbf{CP}$. Should it happen that the strong phase difference ξ is small, then no observable $\mathbf{CP}$ violation would be produced although it would still be possible to extract γ from the absolute number of collected events.

If all branching ratios of equations (2) were known, then equations (3) would be a system of two equations in two unknowns (ξ and γ), hence it would be possible to determine γ apart from a discrete ambiguity.

Unfortunately, the $\text{BR}(\text{B}^+ \rightarrow \text{K}^+ \text{D}^0)$ (b) is very small and it is difficult to be measured. Recent measurements from Babar can be translated into an upper limit for $\frac{b}{a} < 0.068$ [30], which corresponds to $b < 25 \cdot 10^{-6}$. The ratio $\frac{b}{a}$ (also called r_B) determines, in part, the level of interference between the two amplitudes ($\mathcal{M}(\text{B}^+ \rightarrow \text{K}^+ \text{D}^0)$ and $\mathcal{M}(\text{B}^+ \rightarrow \text{K}^+ \bar{\text{D}}^0)$). In most techniques for measuring γ , such as the ‘‘Gronau Wyler and London method’’ (GWL) [31, 32] that relies on **CP** final states for the $\text{D}^0 / \bar{\text{D}}^0$ decays, high values of $\frac{b}{a}$ lead to larger interference and better γ sensitivity. With recent upper limits on $\frac{b}{a}$, the ADS method, that does not suffer from small values of $\frac{b}{a}$ but in contrast turns them into an advantage, is very a promising techniques for the measurement of γ and it also allows to measure the unknown branching ratio b .

Since b is unknown, one set of equations (3) is not enough to determine γ . To avoid this problem, we can look for a second final state f_* for the decay of the $\bar{\text{D}}^0$. The f_* final state will have it’s own hadronic phase ξ_* . Then we can also measure quantities (d_* , $\bar{d}_*$) for this decay, that can be used in a system equivalent to equations (3). In conclusion, by measuring d , d_* and the two conjugate $\bar{d}$, $\bar{d}_*$ we can solve a system of four equations determining the γ angle, the unknown branching ratio b and the two hadronic phases ξ and ξ_* .

When considering two final states for the D^0 decays, there are two hadronic phases ξ and ξ_* involved. They can be written in term of the phases of B and D decay amplitudes as:

$$\xi = \zeta + \delta_f$$

$$\xi_* = \zeta + \delta_{f_*}$$

where ζ is the phase difference among the two B decays ($\text{B}^- \rightarrow \text{D}^0 \text{K}^-$ and $\text{B}^- \rightarrow \bar{\text{D}}^0 \text{K}^-$), δ_f is the phase difference among the decays of D^0 and $\bar{\text{D}}^0$ to f and similarly δ_{f_*} is the phase difference among the decays of D^0 and $\bar{\text{D}}^0$ to f_* . Since the two phase shifts δ_f and δ_{f_*} may be determined [33] from detailed studies of D decays or from data at a $\phi(3770)$ charm factory this relation can be used as an additional constraint to improve our γ sensitivity. As a by product, ζ may also be extracted, providing information about final state interaction effects in B decays.

Even if our final goal is the measurement of γ through the measurement of d , d_* , $\bar{d}$ and $\bar{d}_*$, the measurement of the asymmetries $\mathcal{A}$ and $\mathcal{A}_*$ is important by itself as evidence of **CP** violation in those decays.

For the determination of the asymmetry ($\mathcal{A}$) we can consider only one decay mode f of the $\bar{\text{D}}^0$, and count the number of events for the corresponding final state $f \text{K}^+$ (d) and its charge conjugate ($\bar{d}$), since we don’t need to know the branching ratio b . In fact, the asymmetry $\mathcal{A}$ is defined as:

$$\mathcal{A} = \frac{d - \bar{d}}{d + \bar{d}} \quad (4)$$

The asymmetry can be rewritten as

$$\mathcal{A} = \frac{d - \bar{d}}{d + \bar{d}} = \frac{R \sin \xi \sin \gamma}{1 + R \cos \xi \cos \gamma} \quad (5)$$

R is the ratio between geometric average and arithmetic average of the two BRs, without accounting for **CP** violation:

$$R = \frac{2\sqrt{a c(f) b c(\bar{f})}}{a c(f) + b c(\bar{f})} \quad (6)$$

In the same way an asymmetry $\mathcal{A}_*$ and a ratio R_* can be defined for the f_* channel. The ratio $R \in [0, 1]$ is important because the higher it is, the higher the asymmetry is. When R is equal to 1 the asymmetry is maximum for fixed ξ and γ values. The ratio R is also related to our resolution for the extraction of γ from d, d_* . In fact, R represents the relative importance of the terms proportional to $\cos(\xi \pm \gamma)$ in eq. (3) with respect to the constant term $a c(f) + b c(\bar{f})$. When R is near to one the importance of the term proportional to $\cos(\xi \pm \gamma)$, and then our sensitivity for γ , are maximum.

This ratio is maximum (i.e. approximately 1) when $a c(f)$ and $b c(\bar{f})$ are equal. This is the reason to search the final state f among the suppressed decays of $\bar{D}^0$.

Which are the decay channels of the $\bar{D}^0$ that are doubly Cabibbo suppressed, as it's required by this method? Some of them are: $K^- \pi^+$, $K^- \rho^+$, $K^- \pi^+ \pi^0$ or $K^- \pi^+ \pi^- \pi^+$.

We have to choose two of them that can be effectively observed at CDF. We choose $K^- \pi^+$ and $K^- \pi^+ \pi^- \pi^+$ that do not have π^0 in the final state.

a	$= \text{BR}(\text{B}^+ \rightarrow \text{K}^+ \bar{\text{D}}^0)$	$(3.7 \pm 0.6) \cdot 10^{-4}$	$(\pm 16\%)$	PDG2004
b	$= \text{BR}(\text{B}^+ \rightarrow \text{K}^+ \text{D}^0)$	$2 \cdot 10^{-6}$		estimate [28]
$c(f)$	$= \text{BR}(\bar{\text{D}}^0 \rightarrow \text{K}^- \pi^+)$	$(1.38 \pm 0.11) \cdot 10^{-4}$	$(\pm 8\%)$	PDG2004
$c(\bar{f})$	$= \text{BR}(\bar{\text{D}}^0 \rightarrow \text{K}^+ \pi^-)$	$(3.8 \pm 0.09) \cdot 10^{-2}$	$(\pm 2\%)$	PDG2004
$c(f_*)$	$= \text{BR}(\bar{\text{D}}^0 \rightarrow \text{K}^- \pi^+ \pi^- \pi^+)$	$(3.1 \pm 0.1) \cdot 10^{-4}$	$(\pm 3\%)$	PDG2004
$c(\bar{f}_*)$	$= \text{BR}(\bar{\text{D}}^0 \rightarrow \text{K}^+ \pi^- \pi^+ \pi^-)$	$(7.46 \pm 0.31) \cdot 10^{-2}$	$(\pm 4\%)$	PDG2004
$= \text{BR}(\text{B}^+ \rightarrow \pi^+ \bar{\text{D}}^0)$		$(4.98 \pm 0.29) \cdot 10^{-3}$	$(\pm 6\%)$	PDG2004

Table 3: World averages of involved branching ratios. The table columns show, from left to right, branching ratio symbol, branching ratio description, measurement, relative error and data source.

We can check the values of R and R_* using branching ratios from table (3):

$$\left. \begin{array}{l} ac(f) = (5.1 \pm 0.9) \cdot 10^{-8} \\ bc(f) = 7.6 \cdot 10^{-8} \end{array} \right\} \Rightarrow R \approx 0.98 \quad \left. \begin{array}{l} ac(f_*) = (8.1 \pm 1.3) \cdot 10^{-8} \\ bc(f_*) = 15 \cdot 10^{-8} \end{array} \right\} \Rightarrow R_* \approx 0.95 \quad (7)$$

This means that, with good approximation, R and R_* are 1 and the following equations are valid for $\mathcal{A}$ and $\mathcal{A}_*$:

$$\mathcal{A} = \frac{d - \bar{d}}{d + \bar{d}} \approx \frac{\sin \xi \sin \gamma}{1 + \cos \xi \cos \gamma} \quad , \quad \mathcal{A}_* = \frac{d_* - \bar{d}_*}{d_* + \bar{d}_*} \approx \frac{\sin \xi_* \sin \gamma}{1 + \cos \xi_* \cos \gamma} \quad (8)$$

In conclusion, the two asymmetries are near to the maximum values depending on γ , ξ and ξ_* .

In the following discussion we focus on the final state f , where the D decays to $K^-\pi^+$. It has been shown by studying a similar channel, that both the event yield and the signal to noise ratio (S/N) for $D \rightarrow K^-\pi^+\pi^-\pi^+$ are expected to be similar to those of $D \rightarrow K^-\pi^+$ [34]. The extra efficiency loss due to the reconstruction of two more tracks being compensated by the higher branching ratio.

2.3.2 Summary

The angle γ can in principle be determined through the Atwood, Duniez and Soni method at CDF II.

In order to understand if a sensible measurement is actually possible within CDF Run II, since the branching ratio is very low, we must check the number of events that can be collected. The number of collected events is:

$$\mathcal{N} = \mathcal{N}(B^+ \rightarrow [K^-\pi^+]K^+) + \mathcal{N}(B^- \rightarrow [K^+\pi^-]K^-) \propto d + \bar{d} \quad (9)$$

Since the number of collected events depends on the the asymmetry itself, for the discussion of this measurement it's convenient to factorize $\mathcal{N}$ into an asymmetry dependent part and an asymmetry independent parameter (χ), as shown in the following:

$$\mathcal{N} = 4\chi(1 + \cos\xi \cos\gamma) \quad (10)$$

where χ is the number of expected events $ac(f)$ for the channel $B^+ \rightarrow fK^+$ without accounting for any asymmetry. Equation (10) is valid in the approximation that $ac(f) = bc(\bar{f}) = \chi$, which is approximately valid for the considered decay, as we have verified in equations (7). The parameter χ is a good quantity to be estimated in order to understand the number of events necessary for the measurement.

Even with a small number of events ($\chi \approx 20$) the asymmetry can be measured to be significantly different from 0 for most values of ξ , under the assumption of no background [13].

Of course, we are interested in the extraction of γ and we must take into account the presence of combinatorial and physical backgrounds. The resolution on γ is mainly a function of χ and S/N. In tab. 4 we show some estimates of the achievable resolutions for different values of χ and for different signal to noise ratios [13]. The resolutions are evaluated through pseudo experiments averaging over different ξ and γ values and as a function of S/N. The uncertainty assumed for involved branching ratios is $\pm 10\%$ which, is conservative with respect to current measurement for all branching ratios but one (see tab. 3). In conclusion, a 60° γ angle can be measured even with $\chi \approx 20$ and the worst S/N of 0.2.

As of spring 2004 CDF has collected a data sample of approximately 250pb^{-1} that are available for data analysis. With this sample it is possible to start to evaluate the number of signal events that can be collected during the CDF II data taking period.

χ	S/N		
	0.2	1	2
20	19.5°	14.5°	12°
36	14.5°	11°	9°

Table 4: Resolutions (degrees) for the measurement of γ as a function of χ and signal to noise ratio. The resolutions are evaluated through pseudo experiments averaging over different ξ and γ values.

2.4 Backgrounds

Since the branching ratio for our signal is $\approx 10^{-8}$, it is very important to find a good strategy to reduce the background to an acceptable level. The backgrounds can be divided in two categories: combinatorial background and physical background. The important contribution is from real B decays that will be hard to separate. The combinatorial background can be reduced by requiring a displaced vertex and the D^0 mass constraint.

2.4.1 Physical backgrounds

Tab. 5 summarizes the most important physical backgrounds, identified by **B** in the first column, and relates them to the signal, identified by **S**. On the left part of the table the partial branching ratios for the two decaying steps ($B \rightarrow \bar{D}^0 h$ and $\bar{D}^0 \rightarrow h h'$) are shown. For each channel we show the branching ratios of the signal and the backgrounds. The branching ratios relative to the signal (BR rel.) are also shown. On the right part of the table we show the branching ratios of the combined decay ($B \rightarrow h h' h''$) producing the final state directly from B^+ .

Channel	BR	BR rel.	Channel	BR	BR rel.
S: $B^+ \rightarrow \bar{D}^0 K^+$	$3.7 \cdot 10^{-4}$	1	S: $B^+ \rightarrow [K^- \pi^+] K^+$	$5.1 \cdot 10^{-8}$	1
B: $B^+ \rightarrow \bar{D}^0 \pi^+$	$5.0 \cdot 10^{-3}$	14	B: $B^+ \rightarrow [\pi^- K^+] K^+$	$1.4 \cdot 10^{-5}$	270
S: $\bar{D}^0 \rightarrow K^- \pi^+$	$(1.38 \pm 0.11) \cdot 10^{-4}$	1	B: $B^+ \rightarrow [\pi^- \pi^+] K^+$	$5.1 \cdot 10^{-7}$	10
B: $\bar{D}^0 \rightarrow K^+ \pi^-$	$3.8 \cdot 10^{-2}$	270	B: $B^+ \rightarrow [K^- \pi^+] \pi^+$	$6.9 \cdot 10^{-7}$	14
B: $\bar{D}^0 \rightarrow \pi^+ \pi^-$	$(1.38 \pm 0.05) \cdot 10^{-3}$	10	B: $B^+ \rightarrow [\pi^- K^+] \pi^+$	$1.9 \cdot 10^{-4}$	3700
			B: $B^+ \rightarrow [\pi^- \pi^+] \pi^+$	$6.9 \cdot 10^{-6}$	140

Table 5: Branching ratios for the signal and most important background channels. The channel $B^+ \rightarrow [K^- \pi^+] \pi^+$ has a BR 3700 times higher than the signal!

The most important physical backgrounds are:

- $B^+ \rightarrow \bar{D}^0 K^+$: where the $\bar{D}^0$ decays differently from $K^- \pi^+$. The following backgrounds belong to this category:
 1. $B^+ \rightarrow [\pi^- \pi^+] K^+$
 2. $B^+ \rightarrow [\pi^- K^+] K^+$: this is the doubly allowed Cabibbo decay for the $\bar{D}^0$ with a BR more than two orders of magnitude higher than the signal.

- $B^+ \rightarrow \bar{D}^0 \pi^+$: this channel is kinematically very similar to $B^+ \rightarrow \bar{D}^0 K^+$, but the BR is an order of magnitude higher. It includes the following channels:
 1. $B^+ \rightarrow [K^- \pi^+] \pi^+$
 2. $B^+ \rightarrow [\pi^- \pi^+] \pi^+$
 3. $B^+ \rightarrow [\pi^- K^+] \pi^+$: this is the most serious background. This is the doubly allowed Cabibbo decay for the $\bar{D}^0$ with a BR more than three orders of magnitude higher than the signal.

At this point the ability of separating the signal from the physical backgrounds becomes crucial. In fact, while the combinatorial background reduce our resolution for γ and for the asymmetry, the physical background might alter the measurement itself, introducing an important systematic effect.

The physical backgrounds can be reduced using particle identification (PID) techniques. The most important PID tools at our disposal are time of flight (TOF), dE/dx and mass constraints. Residual background is mainly due to our inability to identify particles.

2.4.2 Reducing the background

We describe a preliminary strategy for background reduction.

As a first step, we can use the decay mass constraints to reject candidates where the final state particle masses are wrongly assigned with high probability. To do this for each candidate we compute the D invariant mass and B invariant mass with all possible (π , K) mass assignments and we reject those candidates for which the best mass assignment does not correspond to our signal. This selection has an efficiency of 90% and a rejection of 110 for the physical background generated with MC simulation accordingly to tab. 5 [13]. After this selection we have $S/N \approx \frac{1}{35}$.

Then we can use PID information provided by the TOF detector and the dE/dx measurement in the wire chamber to further reduce the background. Recently the information from TOF and dE/dx have been combined providing better particle identification performances [35]. The achieved K, π separation as function of P is shown in fig. 9. In order evaluate the available separation power we should consider that two of the three final state tracks come from the trigger and have $P_T > 2\text{GeV}$, while the third one can in principle have P smaller than 2 GeV, in this case we can get advantage from the fact that TOF separation increases at low P.

We assume that all three tracks can be identified with a typical separation of 1.4σ each. The separation power is a measure of our ability to separate tracks (more generally objects or events) into different classes. It is usually expressed in units of σ . In the case of two classes a separation power of $x\sigma$ correspond to the separation that could be obtained using as the discriminating variable a variable that has a gaussian distribution with the same σ for each class, but with the means of the two gaussians differing by $x\sigma$. Instead of cutting on the PID variables we can use statistical separation methods to count the number of signal events. All backgrounds from tab. 5, with the exception of $B^+ \rightarrow [\pi^- \pi^+] K^+$ which is only a minor source of background,

Figure 9: K/ π separation power as function of P obtained combining TOF and dE/dx measurements. *black*: TOF separation. *red*: dE/dx separation. *green*: combined separation. *blue*: theoretical maximum combined separation.

differ from the signal for the mass assignment of at least two final state particles. We conservatively assume to apply PID information to only two tracks to discriminate the signal from the backgrounds. The separation power between signal and background events is $\sim 2\sigma$ and the S/N is $\approx \frac{1}{35}$.

The knowledge of the distribution of PID variables allows us to count the number of events in each class. The error on the number of events is a function of the separation power and of the S/N ratio. For the case of two classes of events, when there is infinite separation (i. e. the discriminating distributions are not overlapping) the error on the number of events in each class is the binomial error: $\sigma_N = \sqrt{f(1-f)N}$ where f is the fraction of events in one class (or the Poisson error if the total number of events is not fixed). Since we have a finite separation power the counting error will be higher. The ratio s of the error with full separation to the one with actual separation is given by the following formula [36]:

$$s = \frac{\sigma_{ideal}}{\sigma_{actual}} = \sqrt{f(1-f) \int \frac{(p_1(x) - p_2(x))^2}{p_{tot}(x|f)} dx}$$

where p_1 and p_2 are the distribution of the discriminating variable x for each class of events. Using two gaussians with a distance of 2σ for p_1 and p_2 , and f equal to our S/N ratio ($\approx \frac{1}{35}$) we get $s = 0.5$. This means that statistical separation methods give a resolution for the number of signal events that is ~ 2 times worse than perfect PID (i.e no background). In other words this result is equivalent, with respect to the resolution for the number of signal events that is the direct observable we want to measure, to have an irreducible background which is only three times larger than the signal.

This result is already very good since the original S/N was $1/3700$. We must also consider that this is a very conservative approach, since important improvements can be obtained everywhere. First of all the information from mass constraints can be used in a more efficient way if combined with the correlation between the charge and the momentum imbalance written as $\alpha = q_1 \cdot (1 - \frac{p_1}{p_2})$ with $p_1(p_2)$ the modulus of the smaller (larger) momentum between the two tracks and q_1 is the charge of the track with smaller momentum⁴. Furthermore, the information from mass constraints can be combined with PID information in a single likelihood fit as already done for the $B \rightarrow h h'$ analysis [37], allowing to extract the fraction of events from different decays using the available information in the best way.

In conclusion, the physical background can be reduced to a level that allows the measurement of γ (see tab. 4).

It is harder to estimate the effect of these selections on the combinatorial background. This can be done only with data. However, at this moment the data is not yet available for this analysis since stripping and reprocessing for this channel is in progress. Furthermore, with currently available statistics the rejection power cannot be determined since the required rejection would leave us with zero background events.

High rejection of combinatorial background will be a primary goal of this analysis when data will be available. We can anticipate that there are several handles to reduce it. In fact, in addition to mass constraints, TOF and dE/dx selections isolation information and 3D vertexing will be decisive for the reduction of combinatorial background.

2.5 The data

The decay chain $B^+ \rightarrow \bar{D}^0 \pi^+$ with $\bar{D}^0 \rightarrow K^+ \pi^-$ is studied to understand the yield of the multi-body sample useful for both difficult measurements of γ and $B_s \rightarrow D_s^- \pi^+$ [38]. It gives information on the large combinatorial and physical backgrounds. The kinematical selection used for $B^+ \rightarrow \bar{D}^0 \pi^+$ with $\bar{D}^0 \rightarrow K^+ \pi^-$ is the same of the selection for the $B^+ \rightarrow [K^- \pi^+] K^+$ analysis. In fact, the only difference is with respect to PID information that is not included yet.

2.5.1 The measurement of χ

Using the sample of events already collected we can estimate our data taking efficiency. We measure the “effective cross-section” including all efficiencies arising from: detector

⁴The alpha variable can be calculated for both the $B \rightarrow \bar{D}^0 h$ and $\bar{D}^0 \rightarrow h h'$ decays.

acceptance, trigger, reconstruction and off-line selection. We use the $B^+ \rightarrow [K^+\pi^-]\pi^+$ signal that has a kinematics very similar to $B^+ \rightarrow [K^-\pi^+]K^+$ and is much easier to extract from the background thanks to the higher BR.

Fig. 10 shows the $K^+\pi^-\pi_B^+$ mass distribution (where π_B^+ is the prompt π from B decay). No PID information is used. The mass assignment is based on the charge and the mass constraint for the $\bar{D}^0$ decay. The trigger and off-line selections are described in sections 2.5.2 and 2.5.4. The high peak on the right is for $B^+ \rightarrow [K^+\pi^-]\pi^+$. The shaded peak is mainly $B^+ \rightarrow [K^+\pi^-]K^+$. Its normalization is fixed to the PDG BR. The two horn structure is due to $B^+ \rightarrow \bar{D}^{0*}\pi^+$ where the $\bar{D}^{0*}$ decays to $\bar{D}^0\pi^0$. In addition there are two continuum background components. One is due to decay of $B^+ \rightarrow \bar{D}^0X$ the other is due to combinatorial background. The signal we are looking for ($B^+ \rightarrow [K^-\pi^+]K^+$) is part of the gray area.

The number of $B^+ \rightarrow [K^+\pi^-]\pi^+$ events in the highest peak is: 4809 ± 88 . From which we get an effective cross section of $\approx 20pb$. To get the effective cross section for $B^+ \rightarrow [K^-\pi^+]K^+$ we can rescale it using the BR from tab. 3. The result is $\sigma_{B^+ \rightarrow [K^-\pi^+]K^+} = \xi \approx 5.3fb$, i.e. approximately 1 event in every $200pb^{-1}$. This number should be compared to a preliminary observation from Babar that does not see significant evidence for the decay $B^\pm \rightarrow [K^\mp\pi^\pm]_D K^\pm$ using an integrated luminosity of $205fb^{-1}$; the result of the fit is $4.7^{+4.0}_{-3.2}$ signal events [30]. In order to compare the event yield at CDF and Babar, we must consider that the Babar number includes the interference of the two intermediate states for both the B^+ and B^- decays and should be compared with $\mathcal{N}$ from eq. 10 that, neglecting the unknown phases ξ and γ , is approximately equal to 4χ . In conclusion the number of signal events collected up to now by CDF and Babar is similar.

The expected Tevatron performances (see fig. 11) up to 2009 should provide an increase of the CDF data sample by a factor 20 (conservatively considering only 50% of the delivered luminosity available for data analysis, see below). The expected PEP-II performances up to 2009 should provide a conservative increase of the Babar data sample by a factor 5 [39]. This means that CDF should have an advantage, from the point of view of collected events, provided that the trigger performances will not deteriorate with higher instantaneous luminosity. To achieve this goal several trigger & DAQ upgrades are in progress, see par. 4.

The meaning of the estimated effective cross section must be carefully considered. First of all this does NOT represent the effective cross-section of the final state we will collect, but it is the “effective cross-section” corresponding to only one decay paths that generates the final state under consideration. So the $\sigma_{B^+ \rightarrow [K^-\pi^+]K^+}$ cross-section does NOT account for interference and corresponds to the parameter χ .

Furthermore we must take into account that this cross-section is an average of the effective data taking cross-section since the begin of Run II. In fact, this cross-section is underestimated because several improvements have been performed to the trigger and DAQ system, see sections 3.3 and 2.6. On the other hand, the effective cross-section to tape could be strongly reduced in the future by the reduction of the available level-1 bandwidth, due to increase of instantaneous luminosity, if SVT is not upgraded (see section 4). In sec. 2.6.2 we show that with the SVT upgrade the loss in

CDF Run II Preliminary

 $L \approx 245 \text{ pb}^{-1}$

Figure 10: Mass distribution for $K^+ \pi^- \pi_B^+$. The high peak on the right is for $B^+ \rightarrow [K^+ \pi^-] \pi^+$. The expected shaded peak is $B^+ \rightarrow [K^+ \pi^-] K^+$, its normalization is fixed to PDG BR. The two-horn structure is due to $B^+ \rightarrow \bar{D}^{0*} \pi^+$ where the $\bar{D}^{0*}$ decays to $\bar{D}^0 \pi^0$. In addition there are two continuum backgrounds. The first one, which is represented by the dashed exponential curve, is the combinatorial background. The second one, which is represented by the other dashed curve that is clearly visible inside the two-horn structure, is due to partially reconstructed B decays ($B^+ \rightarrow \bar{D}^0 X$).

data taking efficiency will be very small. Now the instantaneous luminosity is already

much higher than the average instantaneous luminosity used for the collection of data in fig. 10. When the luminosity increases, the trigger thresholds have to be raised and/or prescale factors have to be increased.

To evaluate the event yield we need to take into account the Tevatron performances. Fig. 11 shows the forecast for the expected performances of the Tevatron up to the end of CDF (2009). The dots represent the expected instantaneous luminosity. The instantaneous luminosity is zero during shutdown periods. After each shutdown, devoted to a particular upgrade of the machine, the instantaneous luminosity is low because the accelerator parameters have to be tuned again, then it increases and eventually reaches a plateau that represents the maximum achievable luminosity for the planned upgrade. The continuous line is the expected integrated luminosity. Actually the Tevatron is performing much better than what has been predicted for 2004 as in fig. 11.

Figure 11: Tevatron luminosity design goals as a function of fiscal year. The “today” arrow stands for summer 2004. It should be underlined that as of summer 2004 the best peak luminosity was above $100 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$.

For the moment, let us just consider that, if in the future we will succeed to maintain the average of the prescale factors applied in the past, assuming an integrated luminosity of $\approx 4 \text{fb}^{-1}$ we get $\chi \approx 20$. The chosen integrated luminosity is the projected delivered luminosity shown in fig. 11 divided by 2 to account for contingency, data taking efficiency etc. The assumed 50% data taking efficiency is reasonable since the fraction of the delivered luminosity that is available on tape, averaged since the beginning of Run II, today is $\approx 80\%$ of the delivered luminosity, while the fraction of luminosity corresponding to good runs with silicon is $\approx 60\%$.

In the following section, we describe the selection of the sample used in the plot

of fig. 10. Then we provide a better estimate of χ in section 2.6. We will show that the SVT upgrade is absolutely necessary for this measurement. To show its impact we compare the yield in the two possible scenarios in which the SVT is or it is not upgraded.

2.5.2 Multi-body trigger

The **B_CHARM** trigger is described in detail in [40]. We report here a simplified description neglecting minor adjustments that have been applied during data taking.

The **B_CHARM** trigger is basically a Two Track Trigger (TTT) optimized for multi-body decays. There are three trigger scenarios known as scenarios “A”, “C” and “Low P_T ”. In the following we will refer to all three level-1 trigger scenarios together as the TTT trigger.

The three scenarios differ in the value of the minimum p_T requirements that are placed on the individual tracks and the track pair. The three triggers are used together during data taking using different prescale factors. Usually the highest p_T trigger scenario “C” (TTTC), also known as **B_CHARM_HIGHPT**, is not prescaled. Recently with instantaneous luminosities as high as $100 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ even the **B_CHARM_HIGHPT** has been prescaled. Scenario “A” (TTTA) known as **B_CHARM** and scenario “Low P_T ” (TTTlow P_T) known as **B_CHARM_LOWPT** have very high prescale factors at the beginning of the store when the luminosity is high. Then the prescale factor is automatically adjusted when the luminosity decreases as necessary to make the best use of the available bandwidth. This technique is called Dynamic PreScale (DPS) and it’s better described in section 3.2.

The **B_CHARM_HIGHPT** selection is described below:

- **level-1**

The level-1 requires at least two XFT tracks reconstructed in the drift chamber (COT, $|\eta| < 1$). In order to have a trigger at least a pair of COT tracks must satisfy the following requirements:

- opposite charge
- $p_T > 2.46 \text{ GeV}/c$ (for both tracks)
- $\Delta\phi < 135^\circ$
- $\sum p_T > 6.5 \text{ GeV}/c$

$\Delta\phi$ is defined as $|\phi_1 - \phi_2|$ and ϕ_1 and ϕ_2 are the two azimuthal angles, in the plane transverse to the beam axis, of the two tracks at the primary vertex. $\sum p_T$ is the scalar sum of the p_T ’s of the two tracks. This selection is in common with the 2-body trigger that uses the same level-1 trigger selection. In particular, the $\Delta\phi$ cut is not optimized for the multi-body decay.

- **level-2**

The level-2 trigger confirms level-1 cuts and adds impact parameter and L_{xy} selection. L_{xy} is the projection of the reconstructed decay length, on the transverse plane, measured with respect to the center of the beam. The selection requires

at least 2 SVT tracks, of which at least a pair must satisfy the following requirements:

- opposite charge
- $p_T > 2.46\text{GeV}/c$ (for both tracks)
- $\sum p_T > 6.5\text{GeV}/c$
- $2^\circ < \Delta\phi < 90^\circ$
- $120\mu m < |d_0| < 1mm$
- $L_{xy} > 200\mu m$

d_0 is the projection of the impact parameter, relative to the center of the beam, on the transverse plane.

With respect to the 2-body trigger level-2, that requires $60^\circ < \Delta\phi < 135^\circ$, the $\Delta\phi$ cut is selecting a different $\Delta\phi$ range that favors more closed pairs of tracks. The rate for the n-body trigger would be higher than for the 2-body trigger, because smaller $\Delta\phi$ angles suffer more from jet background. In order to compensate for the rate increase, the impact parameter cut is set to $120\mu m$ of the n-body trigger, to be compared with the $100\mu m$ cut of the 2-body trigger.

• level-3

At level-3 stereo (i.e. 3D) tracking is performed. Two stereo COT tracks are required to match 2 SVT tracks. The selection requires at least 2 stereo COT tracks, of which at least a pair must satisfy the following requirements:

- opposite charge
- $p_T > 2.0\text{GeV}/c$ (for both tracks)
- $\sum p_T > 5.5\text{GeV}/c$
- $2^\circ < \Delta\phi < 90^\circ$
- $|\eta| < 1.2$ (for both tracks)
- $|\Delta z_0| < 5.0cm$

Δz_0 is the difference of the projection of the impact parameter along the beam axis for the two tracks. This requirement is used to reject pairs of tracks coming from different primary vertexes.

With respect to the TTTC, TTTA lowers the p_T thresholds to $2.04\text{ GeV}/c$ for each track and to $5.5\text{ GeV}/c$ for the pair of tracks. In addition, the TTTlowP_T trigger removes the opposite charge requirement, moves the $\sum p_T$ requirement from level-1 to level-3, reduces the $\sum p_T$ threshold to $4\text{ GeV}/c$, but tightens the level-1 $\Delta\phi$ cut to $\Delta\phi < 90^\circ$.

2.5.3 Trigger rates

In this paragraph, the rates of some of the triggers discussed above are summarized. They will be used in section 2.6 to evaluate what will be the CDF data taking efficiency at instantaneous luminosities up to three times higher than now.

We start considering TTTC and TTTA triggers. Fig. 12 shows the cross-section for the TTTC trigger as a function of luminosity. This trigger uses most of the level-1 bandwidth: at $60 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ it requires more than 10kHz of level-1 bandwidth, out of a total of $\approx 15 \text{kHz}$. The effective cross-section from fig. 12 is fitted with a linear

Figure 12: Effective cross-section for the TTTC trigger as a function of instantaneous luminosity from run 183752.

function. The result is:

$$\sigma_{\text{TTTC}} \approx (60 + 1.85 \cdot \mathcal{L}) \mu b \quad (11)$$

where $\mathcal{L}$ is measured in units of $10^{30} \text{cm}^{-2} \text{s}^{-1}$.

In the same way we determine the dependence of the effective trigger cross-section (see sec. 2.1) with luminosity for the TTTA trigger⁵:

$$\sigma_{\text{TTTA}} \approx (228 + 3 \cdot \mathcal{L}) \mu b \quad (12)$$

⁵The cross-section is a fit of run 185542 data.

with $\mathcal{L}$ measured in units of $10^{30}\text{cm}^{-2}\text{s}^{-1}$.

In fig. 13 we show the effective trigger cross-section for TTTlowP_T. We can see that the cross-section decreases with luminosity because the plot takes into account the effect of dynamic prescale. We will not consider this trigger any more since

Figure 13: Trigger cross-section for TTTlowP_T as function of luminosity. There cross-section is ≈ 0 when the luminosity is greater than $\approx 40 \cdot 10^{30}\text{cm}^{-2}\text{s}^{-1}$, because the dynamic prescale system sets the maximum prescale factor (250).

with peak luminosities as high as $300 \cdot 10^{30}\text{cm}^{-2}\text{s}^{-1}$ only a negligible fraction of the luminosity will be collected at instantaneous luminosity below $40 \cdot 10^{30}\text{cm}^{-2}\text{s}^{-1}$. Above $\approx 40 \cdot 10^{30}\text{cm}^{-2}\text{s}^{-1}$ the cross-section in fig. 13 is shown to drop to zero.

In section 2.6, in order to evaluate the level-1 bandwidth that is not available to dynamically prescaled triggers, we will also need the rate of all not dynamically prescaled triggers. To estimate the cross-section of not dynamically prescaled triggers we use fig. 14, which shows the total level-1 effective cross-section for run 185331 as a function of instantaneous luminosity. Points at luminosity higher than $60 \cdot 10^{30}\text{cm}^{-2}\text{s}^{-1}$ don't include dynamically prescaled triggers that are activated⁶ only when the trigger rate is below 18 kHz⁷ (this happens when the luminosity is approximately below

⁶In fact prescaling is always active, but the prescale factor is not dynamic and it is set to the maximum value: 20 for TTTA and 250 for TTTlowP_T.

⁷18 kHz is the bandwidth now available with the inclusion of the Road Warrior (see sect. 2.6 and 4.5).

Figure 14: Total level-1 effective cross-section for run 185331 as a function of instantaneous luminosity. Points at luminosity higher than $60 \text{E30 cm}^{-2}\text{s}^{-1}$ don't include dynamically prescaled triggers that are activated only when the trigger rate is below 18 kHz. However, they include the TTTC that had a prescale factor fixed to 2.

$60 \cdot 10^{30} \text{cm}^{-2}\text{s}^{-1}$). Those points give us the cross-section (σ_{staticPS}) for all statically prescaled triggers including TTTC. In this run the prescale factor for the TTTC was fixed to 2. This was necessary since June 23rd, 2004 because the Tevatron was delivering instantaneous luminosities in excess of $90 \cdot 10^{30} \text{cm}^{-2}\text{s}^{-1}$ and the dead time was reaching 45%. By fitting those points and subtracting the TTTC contribution, since TTTC will become a DPS trigger, we get the following estimate:

$$\sigma_{\text{staticPS}} \approx (50 + 2.4 \cdot \mathcal{L}) \mu b \quad (13)$$

with $\mathcal{L}$ measured in units of $10^{30} \text{cm}^{-2}\text{s}^{-1}$.

A summary of the corresponding rates is included in tab. 6.

The rates shown in tab. 6 at luminosities higher than approximately $150 \cdot 10^{30} \text{cm}^{-2}\text{s}^{-1}$ are overwhelming. It is impossible to sustain those rates with any foreseen upgrade. The triggers will have to be adjusted in order to reduce the rates. This has been usually done either by improving the trigger selection to increase the trigger purity or by adding a prescale factor, as it recently happened for the TTTC. The assignment of

Trigger rate / $\mathcal{L}$	L1 rates (kHz) @ $\mathcal{L}(\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1})$					
	20	50	100	150	200	300
TTTC	1.6	7.6	24.5	51	86	185
TTTA	5.8	19	52	100	165	340
staticPS	2.0	8.5	29	62	106	230

Table 6: Summary of extrapolated trigger rates for TTTC, TTTA and staticPS triggers. These rates are obtained multiplying the fitted effective cross-sections by the instantaneous luminosity.

bandwidth to different triggers is function of many factors. Some of them are dependent on analysis results that clarify the necessity of future data samples. For example, measurements such as the B_s mixing proven much more difficult than expected and the corresponding triggers have been extended to Run IIb. In the past, when the instantaneous luminosity was low, the level-1 bandwidth was dominated by TTT. We can imagine that in the future, half of the bandwidth will be dedicated to the TTT and half to high- P_T physics. Even with half bandwidth reserved for TTT, the estimated rates are so overwhelming that we should foresee high prescale factors and necessity for more selective trigger strategies.

The main reason for such high rates is the fact that most of those triggers are based on the XFT processor, which was not designed to work at luminosities as high as $300 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ with the current inter-bunch spacing (396ns). In fact the original Tevatron plan was to increase the number of bunches and to reduce the inter-bunch spacing to 132ns, in order to keep the pile up low. Now the plan to increase the number of bunches has been abandoned and we have to cope with pile up much higher than expected. Unfortunately, the XFT processor, which is the core of the level-1 trigger, is very affected by the pile up: the number of fakes and then the trigger rate increase dramatically with the pile up, because of the increasing COT occupancy. To reduce the effect of high pile an upgrade of the XFT processor is in progress. The upgrade will use higher resolution Time to Digital Converters (TDC) that will be able to separate hits from the same bunch crossing into 6 different time bins instead of 2. Those higher resolution TDCs will be used to instrument the stereo layers of the COT, that now are not part of the trigger. The reconstructed track segments in the COT stereo layers will have higher purity thanks to the improved time resolution and will be used in coincidence with the axial track segments to increase the track purity. The upgraded XFT processor is going to be operational starting from the end of 2005. This upgrade should reduce all level-1 trigger rates by a factor of three. However, even with the XFT upgrade, the SVT upgrade will be more than necessary for efficient data taking.

As a starting point for the extrapolation of our data taking efficiency at different luminosities, we use the cross-sections listed above for TTTA and TTTC. In section 2.6.2 we also estimate the effect of the XFT upgrade.

2.5.4 Off-Line signal reconstruction and selection

This paragraph describes the reconstruction and selection of the B candidate. Detailed descriptions of the analysis and Monte Carlo simulations are reported in [41].

This analysis is based on the track reconstruction. Tracks are reconstructed using the SVX and COT detectors.

Candidates are reconstructed from the bottom up. This means that, we start with the $\bar{D}^0 \rightarrow K^+ \pi^-$ decay reconstruction, which is used in the next step to make candidates for the $B^+ \rightarrow \bar{D}^0 \pi^+$ decay.

No PID information is used. The mass is assigned to particles based on the charge and the mass constraint for the $\bar{D}^0$ decay. This means that for two tracks that come from the $\bar{D}^0$ at the positive one is assigned the K mass, while at the negative one the π mass. For the third track the assigned mass is that of the π .

In order to achieve this, we first select only events that come from the TTT trigger paths, then we match off-line track with SVT trigger tracks requiring, for each candidate, that two of the B decay tracks triggered the event. This is the first selection.

For every selected candidate, secondary vertexes are found, then the tracks are refitted with the vertex constraint using the CTVFMT routine [42]. The resulting 2D χ^2 s ($\chi_{r,\phi}^2$) are used to reject low quality candidates. We require a reconstructed vertex with a transverse decay length greater than $400\mu m$ for the B. For the D we require a not negative decay length with respect to the B vertex that, taking into account measurement errors, translates into a $L_{xy}(B \rightarrow D) > -150\mu m$ cut. No requirement on the D decay length with respect to the primary vertex is applied. We require the impact parameter of the reconstructed B to be less than $80\mu m$ to reject events not coming from the primary vertex.

In addition, we require p_T cut for the reconstructed D and B and for the prompt track coming directly from the B decay. Finally we require the prompt track to be near the D in the phase space. We cut on the ΔR variable defined as $\sqrt{(\phi_1 - \phi_2)^2 + (\eta_1 - \eta_2)^2}$.

The selection is summarized below:

1. confirmation of the TTT trigger path on every candidate (see section 2.5.2)
2. $\chi_{r,\phi}^2(D) < 14$
3. $\chi_{r,\phi}^2(B) < 15$
4. $L_{xy}(B) > 400\mu m$
5. $L_{xy}(B \rightarrow D) > -150\mu m$
6. no requirement for $L_{xy}(D)$
7. $|d_0(B)| < 80\mu m$
8. $p_T(D) > 3.5\text{GeV}/c$
9. $p_T(B) > 5.5\text{GeV}/c$
10. $|p_T(\pi_B)| > 1.6\text{GeV}/c$

11. $\Delta R(D, \pi_B) < 1.5$

The mass spectra of the 3-track B-decay has interesting features that are clearly visible in fig. 10 and are described in sec. 2.5.1. There is a shaded peak just below the main $B^+ \rightarrow [\pi^- K^+] \pi^+$ peak, corresponding to the Cabibbo suppressed decay $B^+ \rightarrow [\pi^- K^+] K^+$. The continuum background from partially reconstructed B decays turns on just below the signal and contributes to a minor contamination of the signal itself. The structure with two very pronounced “spikes”, which is on top of the continuum background from partially reconstructed B decays, is the result of a $B \rightarrow D^* \pi$ decay followed by a $D^* \rightarrow D^0 \pi$ decay. The D^* is completely polarized in this decay. As a result, the angle between the momentum of the soft pion in the D^* decay and the D^* flight direction follows a $\cos(\theta)$ distribution; most of the time, the pion will be released either in the same direction as the D^* momentum, or in the opposite direction, while the D momentum will follow the same direction as the D^* did. Depending whether the pion was released parallel or anti-parallel to the D^* flight direction, the missing mass, due to the soft pion that is not included in the reconstruction, will be quantized. Either most of the free energy of the decay will be carried away by the soft pion or very little. These two alternatives explain the two separate “spikes” of the mass distribution.

The fit of the mass distribution is performed in the following way. The signal is composed of two Gaussians; one for the signal peak ($B^+ \rightarrow [\pi^- K^+] \pi^+$) and one for the Cabibbo suppressed reflection. The normalization, average and sigma of the signal’s Gaussian are left free while, for the Cabibbo suppressed reflection, the relative normalization and average with respect to the signal and the absolute sigma are fixed, and taken from Monte Carlo. The two spike structure is modeled with three gaussians: one for each spike and one for the body of the distribution. The continuum background from partially reconstructed B decays is modeled with a linear function, that decays exponentially to represent the physical constraint of invariant mass less than the B mass. The combinatorial background is modeled with a simple exponential.

2.6 The χ estimates for a standard vs upgraded SVT

In order to provide a better estimate of the future data taking efficiency, we have to correct the “effective cross-section” measured in section 2.5.1, to account for the changes in operational conditions (see section 3.3) and for the prescale factor of dynamically prescaled triggers that changes with the instantaneous luminosity profiles.

As already introduced in section 2.5.1, current and future CDF data taking efficiency will be higher than average efficiency up to now, because several improvements have been performed to the trigger and DAQ system, see sections 3.3 and 2.6. The most important changes in the past operational conditions are also discussed in [41], where the increase in data taking efficiency is estimated using data collected with the first delivered luminosity, corresponding to 114pb^{-1} . The estimated correction factor is $R = 1.95 \pm 0.2$. Since we used a more complete data sample of 245pb^{-1} , where the additional data has been collected with the improved operational conditions, we must rescale the correction factor. The updated correction factor is $R = 1.3 \pm 0.13$.

Taking into account this additional effect we get the following effective cross-section:

$$\sigma_{B^+ \rightarrow [K^- \pi^+] K^+} \approx 6.9 \text{fb}$$

corresponding to $\chi \approx 30$.

Accounting for the effect of future prescale factors is more complex. The effective prescale factor (F_{DPS}), for one particular trigger, is calculated with the following formula:

$$F_{DPS} = \frac{1}{\max(0, \min(1, \frac{r_{\max L1} - r_{L1 \text{staticDPS}}}{r_{L1 \text{DPS}}}))} \quad (14)$$

where:

- $r_{L1 \text{staticPS}}$ is the total rate of statically prescaled triggers
- $r_{L1 \text{DPS}}$ is the unprescaled rate of the considered DPS trigger
- $r_{\max L1} - r_{L1 \text{staticDPS}}$ is the bandwidth available for DPS triggers

The fraction $\frac{r_{\max L1} - r_{L1 \text{staticDPS}}}{r_{L1 \text{DPS}}}$ is the inverse prescale factor, since it's obtained dividing the available bandwidth by the unprescaled rate of the considered DPS trigger. The “min(1, ...)” sets the prescale factor to 1 when the available bandwidth is higher then required. The “max(0, ...)” sets the inverse prescale factor to 0 (this means prescale factor *infinity*) when there is no available bandwidth at all.

The involved trigger rates, already described in section 2.5.3, are the following:

1. nonDPS: the sum of all unprescaled triggers
2. TTT scenario C: it will become a dynamically prescaled trigger in the next future
3. TTT scenario A: it has been and will continue to be a dynamically prescaled trigger

Equation 14 must be applied for each dynamically prescaled trigger separately. A priority list of dynamically prescaled trigger is defined. The first triggers for which dynamical prescale is activated are “TTT scenario C” (TTTC) and then “TTT scenario A” (TTTA). This means that to find the prescale factor for TTTC we have to apply equation 14 using the rate of “staticPS” for $r_{L1 \text{staticPS}}$ and the rate of TTTC for $r_{L1 \text{DPS}}$. When the available bandwidth is large enough to set the prescale for TTTC to 1, then we can activate dynamic prescale for TTTA. We can apply equation 14 for TTTA using the rate of “nonDPS” + TTTC for $r_{L1 \text{nonDPS}}$ and the rate of TTTA minus the rate of TTTC for $r_{L1 \text{DPS}}$. We use the difference TTTA-TTTC because there is a 100% overlap among the two triggers and only the extra trigger rate of TTTA uses additional bandwidth.

The combination of maximum level-1 accept rate and trigger rates as functions of instantaneous luminosity gives us the prescale factors as functions of instantaneous luminosity. They can be convoluted with the instantaneous luminosity profile to obtain effective prescale factors. We need the following ingredients:

1. max level-1 accept rate as a function of instantaneous luminosity

2. trigger rates as functions of instantaneous luminosity
3. instantaneous luminosity profiles
1. **maximum level-1 accept rate**

The max level-1 accept rate (r_{maxL1}) and its dependence on luminosity is deeply discussed in section 4. It is the rate at which the dead time is small, operatively defined as less than 5%. We make a raw estimate of the future maximum level-1 accept rate as a function of the luminosity for different level-2 configurations. For the not upgraded SVT system that has been used up to June 2004 we have measured a bandwidth of ≈ 15 kHz at $\mathcal{L} = 50 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$. During June 2004 the first piece of the SVT upgrade, the Road Warrior (RW) (see section 4.5), has been installed and it is already contributing to increase the available level-1 bandwidth. With this configuration we have a bandwidth of ≈ 18 kHz at $\mathcal{L} = 50 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$. These points are included in fig. 15 respectively with labels “SVT” and “SVT+RW”.

A big upgrade, that should be hopefully installed during the shutdown of fall 2004, is the replacement of the level-2 decision system with Pulsar boards [43]. This will contribute to increase the Level-1 available bandwidth. Forecast for the available bandwidth with this partially upgraded configuration (SVT+RW+Pulsar L2), which includes the new level-2 Pulsar system and the Road Warrior in the SVT, is shown in fig. 15. The forecasts for this configuration are available at two luminosities: $50 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ and $300 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$. We can see that the max level-1 accept rate at 5% dead time changes dramatically with instantaneous luminosity. For this configuration, it goes from more than 30kHz at $50 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ to less than 15kHz at $300 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$. With linear interpolation we get:

$$r_{\text{maxL1}} \approx 36000 - 73 \cdot \mathcal{L} \quad (15)$$

with $\mathcal{L}$ measured in units of $10^{30} \text{cm}^{-2} \text{s}^{-1}$.

In the interpretation of these numbers we must remember that, while the two points (SVT, SVT+RW) measured on-line are relative to a mix of different triggers, the forecasts have been done considering only a single type of trigger. The trigger considered (either TTT or $Z^0 \rightarrow b\bar{b}$) requires SVT at Level-2, as a consequence it requires a level-2 processing time longer than average, reducing the Level-1 bandwidth with respect to average conditions. This means that the forecasts for the available bandwidth are conservatively underestimated and CDF will actually have more bandwidth.

In fig. 15 we also show the forecast for the not upgraded SVT with Pulsar level-2 (SVT+Pulsar L2). Finally there is the forecast at $\mathcal{L} = 300 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$, for the fully upgraded configuration (SVT+PL2+RW+TF+AM label) that, in addition to the Pulsar level-2 and the RW upgrades, includes the core of the SVT upgrade: the new Track Fitter(TF) and the new Associative Memory(AM++).

In order to evaluate the effective prescale factors with different configurations, we need to know the available bandwidths as functions of luminosity. For configuration (SVT+RW+Pulsar L2) we have a rough estimate in eq. 15. For the

Figure 15: The curves on plot show the forecast for the dead time as a function of the level-1 trigger rate for different SVT+level-2 configurations and for different luminosity. By choosing a maximum allowed dead time we can find the available bandwidth. For each configuration there is a solid and a dotted line. The former assumes only $Z^0 \rightarrow b\bar{b}$ triggers, while the latter assumes only TTTC. In addition we report two points showing dead time actually measured on-line. (For a complete description see fig. 47 and sect. 4.6.)

other configurations we assume they have the same dependence on luminosity of (SVT+RW+Pulsar L2), then we scale each of them with the appropriate scale factor determined from fig. 15.

Equations 16 summarize the expected level-1 bandwidths for the different config-

urations considered:

$$\begin{aligned}
r_{\text{maxL1}}^{\text{SVT}} &\approx 17000 - 34 \cdot \mathcal{L} \\
r_{\text{maxL1}}^{\text{SVT+RW}} &\approx 20000 - 41 \cdot \mathcal{L} \\
r_{\text{maxL1}}^{\text{SVT+PulsarL2}} &\approx 24500 - 50 \cdot \mathcal{L} \\
r_{\text{maxL1}}^{\text{SVT+RW+PulsarL2}} &\approx 36000 - 73 \cdot \mathcal{L} \\
r_{\text{maxL1}}^{\text{SVT+RW+PulsarL2+TF+AM}} &\approx 61000 - 124 \cdot \mathcal{L}
\end{aligned} \tag{16}$$

2. Trigger rates

The required trigger rates have already been discussed in section 2.5.3.

3. Luminosity profile

The luminosity profiles for the last and best data taking period is shown in fig. 16. Each curve corresponds to a single Tevatron store. For each store, the instantaneous luminosity decreases from a peak luminosity ranging from 60 to 100 $\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ to final luminosities down to 20 $\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$. The corresponding global luminosity distribution is shown in fig. 17. This distribution is obtained histogramming data from fig. 16. Each entry corresponds to a period of 120 seconds of data taking. When the peak luminosity will be 300 $\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$, stores will be shorter in order to exploit the good performances at the beginning. Hence, we expect that luminosities below 40 $\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ will be rare. Therefore the efficiency for the acquisition of the TTTlowP_T trigger, that we are not considering, will be near to zero, see fig. 13. Even with this conservative approach, which neglects the contribution from the TTTlowP_T trigger, we show that we will have $\chi \approx 20$.

2.6.1 Data acquisition efficiency without SVT upgrade

Convoluting the trigger rates from 2.5.3 with the instantaneous luminosity profile from fig. 17 and using eq. 14, it's possible to extract the effective prescale factors. I assume that half of the available bandwidth is used for TTT triggers. To extrapolate to higher luminosity we scale the luminosity distribution given in fig. 17 by factors 2 and 3 to represent respectively peak luminosities of 200 $\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ and 300 $\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$. The effect of this rescale is shown in fig. 18.

Tables 7 and 8 show the efficiency relative to unprescaled rates for different triggers and for different instantaneous luminosities. Tab. 7 refers to the configuration without level-2 and SVT upgrades (SVT), while tab. 8 refers to the upgraded level-2 and partially upgraded SVT system (SVT+RW+Pulsar L2). We see that with the current system even the TTTC trigger would have to be heavily prescaled when the instantaneous luminosity reaches 200 or 300 $\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$. We must remember that most

Figure 16: Luminosity profiles for Tevatron stores from June 1st, 2004 to July 20th, 2004. Each curve represents a single Tevatron store.

of the integrated luminosity will hopefully be delivered with those high instantaneous luminosities, (see fig. 11).

It should be emphasized that the current strategy is to keep the prescale factor for TTTC fixed in order to have at least one trigger for which we know with good accuracy the effective collected luminosity. This means that now the prescale for the TTTC is fixed to the prescale necessary to keep the dead-time low at the maximum luminosity. With current peak luminosity ($100 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$) that prescale factor is 2. However, with higher peak luminosities the prescale factor will be greater. So, in addition to the fixed prescale TTTC, it will be useful to implement also a dynamically prescaled TTTC. The results reported below use dynamical prescale for TTTC.

With the partially upgraded system the efficiency is better but we still lose a factor of 2 even for the TTTC trigger.

2.6.2 Data acquisition efficiency with the SVT upgrade

Tab. 9 shows the expected efficiency with the fully upgraded system (SVT+RW+Pulsar L2+TF+AM). We can see that the efficiency we will have for the TTTC trigger at the

Figure 17: Instantaneous luminosity distribution from June 1st, 2004 to July 20th, 2004. Time without beam is excluded.

Figure 18: Comparison of instantaneous luminosity distribution at three different peak luminosities: 100, 200 and 300 $\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$.

nominal luminosity of $300 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ is $F_{\text{DPS}}=0.7$. This is less than what we had in the past when the TTTC was not prescaled, but it is a great result compared with the present prescale factor of 2 at a nominal luminosity of $100 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$. The introduction of dynamical prescale for the TTTC would allow to recover efficiency even

Trigger name	Efficiency @ peak $\mathcal{L}(\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1})$		
	100	200	300
TTTC	0.91	0.57	0.35
TTTA	0.49	0.11	0.01

Table 7: Forecast for effective prescale factors for the TTTC and TTTA triggers accounting for dynamical prescale with the SVT configuration before the upgrade.

Trigger name	Efficiency @ peak $\mathcal{L}(\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1})$		
	100	200	300
TTTC	0.95	0.78	0.56
TTTA	0.81	0.36	0.14

Table 8: Forecast for effective prescale factors for the TTTC and TTTA triggers accounting for DPS with the partially upgraded configuration (SVT+RW+Pulsar L2)

at present luminosities. Using dynamical prescale for the TTTC we get, from tab. 7, $F_{\text{DPS}}=0.91$ at current luminosity.

In tab. 10 we directly compare the not upgraded system (SVT) with the full upgrade (SVT+RW+Pulsar L2+TF+AM): we see that the upgrade will increase the data taking efficiency by at least a factor of 2. Very conservative assumptions have been used everywhere, even greater efficiencies are expected. This is an extremely important result since it applies to all B physics samples. Furthermore, all high P_{T} samples will benefit from the increase of level-1 trigger bandwidth, even those not directly using SVT.

These results don't include the XFT upgrade yet, that is expected to reduce the trigger effective cross-section by a factor three. In tab. 11 we make the same comparison taking into account the XFT upgrade. We can see that with this configuration we can collect a still larger fraction (0.86, 0.53) of events for the γ measurement, even with the highest luminosity. Considering that all our estimates have been conservative, we can expect to collect a number of events corresponding to at least $\chi \approx 20$.

Trigger name	Efficiency @ peak $\mathcal{L}(\cdot 10^{30} \text{cm}^{-2} \text{s}^{-1})$		
	100	200	300
TTTC	1.0	0.90	0.70
TTTA	0.95	0.55	0.30

Table 9: Forecast for effective prescale factors of the TTTC and TTTA accounting for dynamical prescale with the fully upgraded configuration (SVT+RW+Pulsar L2+TF+AM)

Trigger name	SVT	SVT+RW+PL2+TF+AM
TTTC	0.35	0.70
TTTA	0.01	0.30

Table 10: Comparison of SVT versus SVT+RW+Pulsar L2+TF+AM. Forecasts at $300 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ for the effective prescale factors of the TTTC and TTTA accounting for dynamical prescale.

Trigger name	XFT +SVT+RW+PL2+TF+AM
TTTC	0.86
TTTA	0.53

Table 11: Forecast for effective prescale factors of the TTTC and TTTA triggers at $300 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ taking into account the XFT upgrade and the fully upgraded SVT configuration.

3 Increasing SVT physics reach

This chapter is mainly an introduction to the discussion of chapter 4. It describes the kind of B-trigger and SVT activity that was alive in CDF before the SVT upgrade was approved. We participated to this activity with the main goal of understanding the problems. As a result, we proposed an upgrade of the SVT, which is described in chapter 4. In section 3.4.1 we also describe a new SVT application that will be possible thanks to its upgrade.

Since the beginning of CDF Run II the importance and success of the SVT processor was clear. However, it was also clear that the CDF physics potential at higher luminosity would be limited by the DAQ problems described in chapter 4. In short, the level-2 processing time, which includes the SVT processing time, limits the maximum level-1 accept rate well below its design value of 50kHz.

During 2003 a lot of efforts were devoted to increase the data samples. All possible ideas were implemented to gain bandwidth and to increase data taking efficiency. We will show in this chapter a couple of examples of these smart efforts:

1. Dynamic PreScale (DPS) has been extensively used to optimize resource usage when the luminosity drops. Dynamic prescale allowed to increase the low- P_T B-physics sample by about 30%, see fig. 28. Now, because of the higher instantaneous luminosity, the DPS is used even for the medium P_T trigger (TTTA) and, in the future, it could be used for the highest P_T trigger (TTTC).
2. A single track efficiency increase of about 30% has been obtained implementing the “majority logic” in the track matching criteria. SVT can require 4 fired layers among a total of 5 layers (4/5) instead of the initial criterion requiring 4 fired layers among a total of 4 layers chosen once forever between the 5 detector layers (4/4). Although this came at the price of a longer processing time, as I’ll discuss in section 4, it has been an important achievement because it increases most signal yields by 60%.

The primary goal of these efforts was to improve the trigger efficiency and not to improve the SVT timing. Only minor improvements to the SVT processing time were implemented, namely those not requiring large efforts. In fact, at that time, the trigger bandwidth limits were not an immediate concern, since the Tevatron luminosity still was lower than half the design luminosity. Furthermore, before the introduction of the 4/5 criterion, reducing the SVT timing was not considered as important as reducing the timing of other level-2 subsystems, since with the 4/4 criterion the SVT timing had only a minor impact on the maximum level-1 rate.

However, with the higher processing time of the 4/5 criterion, the level-1 bandwidth limit was reached even at those low luminosities. Other improvements to the SVT configuration started but, although small efficiency losses were allowed in order to reduce the processing time, these less stringent requirements resulted only in minor advantages on the SVT timing. It became clear that a major improvement of the SVT timing was only possible through an upgrade. Of course, going back to the 4/4 criterion

was out of question, since the corresponding bandwidth gain would not compensate for the 60% efficiency loss.

When the 4/5 criterion became the default one, several upgrades were in progress aiming to increase the maximum level-1 rate by reducing the level-2 timing. However these upgrades did not include the SVT. This was the consequence of a strange situation: in order to increase the overall system efficiency, CDF was strongly supporting many trigger and DAQ upgrades since 2000, but nothing was proposed or supported for the SVT processor, which actually is the bottleneck of the system at high luminosity, as we will show in section 4. Probably, the excellent performances of SVT made CDF physicists overlook the problems waiting “beyond the corner”.

In this chapter I will first describe the CDF detector and the trigger system. Then, I will describe a couple of improvements to the SVT. These examples are also important to introduce definitions and subjects necessary to understand chapter 4.

After that, I will describe in section 3.4.1 our first proposal to CDF for increasing the physics capabilities using an upgraded SVT. In fact, the SVT still has tracking capabilities that are unexploited at the moment. For example, silicon-only tracking can be used to increase the geometrical coverage of important triggers beyond the central region ($|\eta| > 1$). We propose a new trigger, made possible by the SVT upgrade, that increases the yield of $W \rightarrow \mu\nu$ by 40% (20% taking into account the trigger efficiency studied in section 3.4.1). This proposal, together with the work described in chapter 4, shows the impact of the approved SVT upgrade.

3.1 The CDF detector and the trigger system

In this section I give an overview of the CDF detector and trigger parts that are relevant for the following discussion.

3.1.1 The CDF detector

Fig. 19 shows an isometric view of the CDF II detector. The inner part of the detector is the tracking system which is contained in a superconducting solenoid providing a magnetic field of 1.4 Tesla. Outside the solenoid there is the calorimeter system, which provides energy measurements for electron, photons and jets. The calorimeters are contained into a shell of steel absorbers that shield the muon chambers, the outermost part of the CDF detector, from non-muon particles generated by $p\bar{p}$ interactions. I’m going to describe the tracking detectors only. A complete description of the CDF detector can be found in [3].

Fig. 20 shows one quadrant of the longitudinal section of the CDF tracking system. The outermost detector is the Central Outer Tracker (COT) drift chamber. The COT provides full coverage for $|\eta| < 1$, with an excellent curvature resolution of $0.15P_T(\text{GeV})\%$. The COT is the core of the integrated CDF tracking system. The COT provides 3-dimensional track reconstruction with 96 detector layers. The 96 layers are organized into 8 superlayers. Four of which are axial, while the others, called stereo, are at small angles. Fig. 21 shows a track as it is seen by the axial COT layers.

Figure 19: An isometric view of the CDF II detector.

Inside the COT there are the silicon detectors: SVX II, ISL and L00. They are complementary to the COT. They provide an excellent transverse impact parameter resolution of $27\mu\text{m}$. The silicon detectors provide 3-dimensional track reconstruction. The achieved longitudinal impact parameter resolution is $70\mu\text{m}$. Fig. 22 shows a cross section of the SVX II. The SVX II is organized into 12 azimuthal wedges. For each wedge there are 5 detector layers each providing one axial measurement on one face of the silicon sensor and a 90° or small angle measurement on the other face. Fig. 23 shows an isometric view of the SVX II. The SVX II is made of three mechanical barrels. Each mechanical barrel is made of two electrical barrels. In fact, within a mechanical barrel each detector element is built of two silicon sensors with independent readout paths. The two sensors are aligned longitudinally to achieve a total length of 29cm, which is the length of each mechanical barrel. Hence, for each wedge and for each layer there are a total of 6 sensors belonging to 3 different mechanical barrels. The L00 and ISL silicon detectors complete the silicon subsystems. The L00 detector, which is directly mounted on the beam pipe, provides best impact parameter resolution. The ISL detector provides up to two additional tracking layers, depending on track pseudo-rapidity, that allow standalone silicon tracking. In particular, ISL allows to extend tracking beyond the COT limit ($|\eta| < 1$), and up to $|\eta| < 2$. The L00 and ISL detectors are not used by the SVT.

Figure 20: Longitudinal section of one quadrant of the CDF tracking systems.

3.1.2 The CDF trigger system

Fig. 24 shows the functional block diagram of the CDF II data flow. The first trigger level is organized as a synchronous pipeline that processes events at the bunch crossing rate and takes trigger decisions within a latency of $5.5\mu\text{s}$. The second trigger level is organized as an asynchronous pipeline of three stages, if we also include the silicon readout, which processes events selected by the level-1 within a nominal latency of $20\mu\text{s}$. As described in chapter 4, the actual decision latency is higher than $20\mu\text{s}$. As a consequence, the maximum level-1 rate is approximately one third of the design value. This problem is mainly due to the fact that there are only 4 level-2 buffers, which are not enough to compensate for the event arrival time and processing time fluctuations. The third trigger level is made of a large CPU farm, which run off-line reconstruction code. A detailed description of the CDF trigger system can be found in [3].

Fig. 25 shows the block diagram of the CDF II trigger system with the level-1 and level-2 subsystems along with their interconnections. The structure of both level-1 and level-2 is similar. Physical objects are reconstructed by the subprocessors, which fed data to the global decision hardware that combines those informations and takes the trigger decision. The eXtremely Fast Tracker (XFT) is part of the level-1. Tracks reconstructed from the XFT are fed to the track eXTRaPolator (XTRP) that extrapolates them to the calorimeters and to the muon detectors. The extrapolated tracks

Figure 21: Two dimensional view of a tracks passing through the COT detector. Units on both axes are cm. The stereo superlayers, which alternate with the axial ones, are omitted.

are used by the global level-1 trigger to identify electron and muon objects.

The SVT is part of the level-2. It receives digitized data from the SVX detector and two dimensional COT tracks reconstructed from the XFT through the track eXTRaP-olator. Tracks reconstructed from SVT are sent to the global level-2 decision hardware. The global level-2 decision hardware is organized a crate containing interface boards for each level-2 subsystem and an alpha CPU. The information collected by the interface boards is transferred to the alpha processor which takes the level-2 decision.

The SVT processor is organized as a set of 12 parallel processor, one for each ϕ wedge of the SVX. Since the each SVX wedge is processed independently, tracks crossing the wedge boundary in the SVX are not reconstructed. In contrast each SVT engine processes data from all six electrical barrels of one wedge, this allows to reconstruct tracks crossing an electrical barrel boundary⁸.

The architecture of one SVT processor is shown in fig. 26. Full resolution data from one SVX wedge and from the XFT is sent to the AM and to the Hit Buffer. The Associative Memory performs the pattern recognition. With the 4/4 criterion a road is found if 4 axial hits in four SVX II layers plus one XFT track are compatible with one of the stored patterns. The four SVX II layers can be chosen independently for

⁸Tracks crossing a mechanical barrel boundary are not reconstructed because of poor alignment between different mechanical barrels.

Figure 22: Cross section of the SVX II detector.

Figure 23: Isometric view of the SVX II detector

each electrical barrel and wedge. The typical choice is the four innermost layers, which provide better impact parameter measurement. However, since few SVX II modules

Figure 24: Functional block diagram of the CDF II data flow.

are broken, for the corresponding barrel and wedge the working layers are used. With the 4/5 criterion, all five layers of the SVX II are used. A road is found if four axial hits and one XFT track are compatible with one of the stored patterns. The Hit Buffer, for each found road, retrieves full resolution SVX hits and XFT track parameters from an internal database built on the fly during detector readout and it sends out these informations as track packets that are processed by the Track Fitter. The list of found tracks is the final output. Fig. 43 shows the physical implementation of one SVT wedge.

3.2 Increasing the heavy flavor yield with Dynamic PreScaling

In the actual RUN II conditions, the use of dynamic prescaling has been shown to be effective for keeping under control the dead-time while exploiting as much as possible the available level-1 bandwidth. A typical “store” at the Tevatron lasts about 20 hours, during which time the luminosity decreases by a factor 2.5 with respect to the

RUN II TRIGGER SYSTEM

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Figure 25: Block diagram of the CDF II trigger system.

initial luminosity. Since the trigger has been tuned for the peak luminosity, a lot of bandwidth is available in the later part of a store. CDF has developed techniques to fill this available bandwidth with the use of dynamic prescales. Essentially, this consists in accepting only a fraction of some level-1 triggers for further processing. The fraction accepted is varied as a function of the available luminosity to keep the rate constant; this feature makes the prescale factor dynamic. This method allows the maximum use of the resources in all luminosity conditions, while keeping the dead-time small.

For example, there are three main level-1 triggers for the hadronic B selection. All of them require 2 tracks with $P_T > 2$ GeV/c and require a $\Sigma P_T > 6.5, 5.5, 4$ GeV/c respectively. The first one ($\Sigma P_T > 6.5$ GeV/c) was never prescaled up to summer 2004. The second one is prescaled, if necessary to keep the total level-1 accept (L1A) rate below 20 kHz accepting a dead-time slightly higher than 5%. The last one, is prescaled

Figure 26: Architecture of the SVT trigger

if necessary to keep the total L1A rate below 16kHz, i.e. allowing for a maximum dead-time of 5%. The difference among the two rate limits is due to the fact that the last trigger has a minor purity and it is convenient to activate it only for smaller dead-times.

Fig. 27 shows on the left the instantaneous luminosity curve during a Tevatron store and on the right the level-1 accept rate for that store. At the beginning of the store the prescales were manually adjusted to avoid dead-time from level-3, until the luminosity decrease is such that level-3 problems disappears. At that point the limit to the level-1 bandwidth necessary to keep dead-time below 5% is caused by the level-2 processing time. The maximum level-1 accept rate is 16kHz, as shown in fig. 27. See section 4 for a better explanation of bandwidth limits.

After the point bandwidth limits come from the level-2 processing time there are 3 sections that correspond to a prescale factor of one for the second trigger and a prescale factor of 4, 2, 1 respectively for the third trigger. The goal is to maintain the L1A rate near to 16 kHz. The prescale of one is enabled when the luminosity reaches

Figure 27: On the left: the instantaneous luminosity as function of time during a Tevatron store. On the right: the L1Accept rate during that store showing the use of dynamical prescale.

$23 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$, which is when half of the instantaneous luminosity is already lost, several hours after the beginning of the store and not much before it's end.

In the first six months that dynamic prescaling was enabled, the low-Pt trigger has been prescaled on average by a factor 0.22, and has given a yield increase of 28% in the $D^+ \rightarrow K^- \pi^+ \pi^+$ channel [44], see fig. 28.

3.3 SVT tracking efficiency and the 4/5 matching criterion

Data was taken by CDF before June 2003 using only four silicon layers with the XFT segment for the on-line pattern recognition and requiring all of them to be fired (4/4).

An important efficiency gain has been recently obtained with the use of “majority logic” in the track match criterion. What is the gain? It is a function of the detector status, which changes even on short timescales. The gain will likely be more significant if the detector signal/noise will decrease, causing higher thresholds and single channel inefficiencies. In fact, during August 2004 the detector thresholds have been increased in order to cope with higher luminosity with a small loss of efficiency thanks to the 4/5. However, there is no gain if inside a wedge a full layer is broken, because in this case the 4/5 criterion will be the same as 4/4 in that wedge.⁹

Fig. 29 shows the SVT track efficiency, measured on data, as a function of the day. The upper plot shows the last 20 SVT working days in June 2003 while the bottom plot shows a longer data taking period, where the 0 correspond to January first. The track efficiency has a slow increment from 60% to 70% due to the SVX detector improvement (larger number of active strips per ladder). This 70% efficiency is the product of different concurrent contributions:

1. the single hit efficiency (95%) contributes as $(0.95)^4 = 81\%$ to the track efficiency;

⁹the 4/5 use offer an advantage even in this case: the pattern set doesn't need to be upgraded as it happens with the 4/4 when ladder is broken or temporary disabled.

Figure 28: Event yield of $D^+ \rightarrow K^- \pi^+ \pi^+$ since the introduction of dynamic prescale. The blue curve is the D^+ yield of the nominal trigger, the green curve is the D^+ total yield including the low- P_T trigger that was effectively prescaled by a factor 4.5 corresponding to an yield increase of 28%.

2. the bank efficiency (95%);
3. the χ^2 cut efficiency after the track fitting (95%);
4. a geometrical acceptance due to the SVX ladder status (95%). This is the improved fraction which resulted in a global efficiency increase from 60% to 70%;

The point 1 is particularly important for the track efficiency improvement.

The 4/5 selection has been implemented in June 2003 and is shown in the lower plot as an additional track efficiency improvement up to 80% ($\approx 15\%$ relative improvement with respect the 4/4). Statistical errors are much larger in the last period since the track efficiency is calculated using a low-statistic sample. Recently, the track P_T acceptance threshold has been increased from 1.5 GeV to 2.0 GeV in order to reduce the level-2 processing time. Moreover, for the same goal, most of the events not used for the impact parameter selection are forbidden to transit through SVT. Only for a few of them it is allowed just to calculate the efficiency shown in fig. 29. This tracking efficiency increment could justify a 30% D^0 yield gain since the D^0 is reconstructed using two tracks [44]. Another 30% comes from the use of the fifth layer (the most external) that allows to recover all tracks lost because they cross two contiguous electrical barrels

Figure 29: The SVT track efficiency as a function of the day. The upper plot shows the last 20 days on which the SVT was working, while the bottom plot shows a longer data taking period. On both plots the 0 of the horizontal scale corresponds to January first 2003.

Figure 30: The SVT track efficiency as a function of the track z coordinate measured at radius 8 cm for the 4/5 (full circles) and 4/4 (empty circles) matching logic.

Signal	4/4	4/5	$R = \frac{\epsilon_{4/5}}{\epsilon_{4/4}}$
D ⁺ yield	11.2 (nb)	17.5 (nb)	1.55 ± 0.06
J/ Φ yield	663 (events)	974 (events)	1.5
B _s MC	N/A	N/A	1.59 ± 0.05

Table 12: Summary of increase in data taking efficiency using 4/5 matching criterion instead of 4/4 for different signals. The last column shows the ratio of efficiency with 4/5 to efficiency with 4/4. For the D⁺ the signal cross-sections with the 4/4 and 4/5 configurations are both measured. For the J/ Φ the number of events with the 4/5 configuration is measured, while the number of events with the 4/4 configuration is evaluated by simulating the 4/4 criterion on the same data.

having a broken ladder. In fact, since with the 4/4 criterion the four SVX layers used by SVT are chosen independently for each wedge and barrel, in the case of a broken ladder the choices of layers for two contiguous barrels, within the same wedge, may be incompatible with tracks crossing the barrel boundary. For example, this happens when for one barrel, the four innermost layers are used, while for the next barrel the innermost layer is broken and the four outermost layers are used. In this case a track, which leaves the interaction point going through the innermost layers of latter barrel and leaving the SVX detector through the outermost layers of the former barrel, will not generate four hits into four SVX layers used by the SVT. Fig. 30 shows the SVT track efficiency as a function of the track z coordinate measured at a radius of 8 cm. Full points show that the majority logic is able to recover the inefficiencies at Z=0 and Z=30 due to electrical barrel boundaries, while the deep at Z=15 remains (physical barrel boundary). However, part of this heavy flavor yield gain is lost when the level-1 trigger dynamic prescale has to be increased to take into account the larger SVT processing time due to the new matching criterion (see fig. 38). The D⁰ yield gain is occasionally less than the expected value and depends on the instant luminosity.

The gain in signal efficiencies are summarized into tab. 12 for some of the most interesting samples.

3.4 Extending the muon trigger coverage using SVT

The SVT could have an important role as a level-2 tracker. Currently the level-2 tracker is limited to $|\eta| < 1$ and $P_T > 2$ GeV. Both the η and P_T coverages of the tracker can be in principle extended to wider ranges with the use of silicon-only tracking.

For sure the most interesting application would be the high P_T lepton triggers. Lepton triggers are very important at CDF. They are used to collect a wide range of physics signals such as W and Z for electroweak measurements (e.g. W mass measurements), semileptonic and dileptonic $t\bar{t}$ decays for top mass and cross-section measurements and several exotic searches that have leptons in the final state and use lepton triggers. In the following we discuss how the SVT upgrade can help also for forward lepton triggers. In particular, we will show a detailed study of SVT application to forward muon selection. Since we concentrate on the forward muon selection we emphasize that improvements to this selection can enlarge the muon data sample. Among important

applications of the muon data sample are the measurements of the W mass and top mass that are fundamental parameters of the SM and can improve the constraints on the expected SM Higgs mass, see fig. 31.

Figure 31: This figure reports m_W and m_{top} measurements. The picture shows the correlation of m_W and m_{top} with the SM Higgs boson mass.

The forward W level-2 trigger is based now on the request of an electromagnetic cluster in the forward calorimeter associated with a missing E_T measurement in the event. The level-1 thresholds are 8 GeV for the electromagnetic cluster and 15 GeV for the missing E_T . The level-2 requires only an electromagnetic cluster of 20 GeV, while the level-3 associate again the cluster of 20 GeV with a missing E_T of 15 GeV. The off-line analysis finally requires 20 GeV for both the EM cluster and the missing E_T . The W efficiency is 70% of which a 10% inefficiency is due to the trigger inefficiency above the nominal thresholds, 20% inefficiency is due to the selection thresholds. This trigger selection can be compared to the central W trigger that uses two different selections. The first one includes a missing E_T request and is similar to the forward W selection. The second one substitutes the 15 GeV missing E_T request with a track of 8 GeV associated with an electromagnetic cluster of 8 GeV at level-1, 16 GeV at level-2 and 18 GeV at level-3. The track requirement in the central electron trigger allows trigger rates (few Hz at level-2) similar to that of the forward electron, but the efficiency on the W is higher. This second central electron trigger is more versatile since it is more inclusive. Two independent samples (“missing E_T + cluster EM” and “track + cluster EM”) are also useful for trigger efficiency studies.

Even more important would be the use of a track for the extension of the inclusive μ trigger to the forward region. It is hopeless to have an inclusive trigger without a track. CDF has a trigger using a forward μ associated with a jet in the central region: this is

good for complex signatures like top, but not for very simple signatures like inclusive W, where the μ is all what you have. An inclusive μ trigger is already done in the region $1 < |\eta| < 1.2$ using a 3-layer XFT track, but it is heavily prescaled. SVT would help even in that region. In conclusion silicon only tracking with SVT can provide a forward trigger for W's and Z^0 s. Increasing the muon trigger coverage from $|\eta| < 1$ to $|\eta| < 1.5$ corresponds to increasing the acceptance by 40% if we take into account the W production differential cross-section simulated with the Pythia [45] Monte Carlo. Taking into account the trigger efficiency, the yield gain for W's is more than 20%.

3.4.1 Silicon only tracking for an inclusive forward muon trigger

I participated in the detailed study of the application of SVX-only tracking for an inclusive forward μ trigger. CDF already has a forward trigger for μ at level-1 but it is heavily prescaled at level-2 and it's used only for calibration.

Figure 32: Half CDF detector: a section through the beam line is shown. The forward muon system is highlighted by colors: the barrel muon chambers (BMU, shown in red), the barrel muon scintillators (BSU-F is the front part in violet and BSU-R is the rear part in blue) and the toroidal scintillators (TSU in green). The silicon vertex detector (SVX) is yellow and the COT is orange.

Fig. 32 shows the detector parts used for this trigger. In the region $1 < |\eta| < 1.25$ the level-1 trigger is the coincidence of an XFT segment found in few layers of the extreme part of the COT, with the barrel muon chamber (BMU) and the barrel front scintillators (BSU-F). Unfortunately the COT coverage in this region is poor and the

XFT efficiency is strongly depended on η . The level-1 rate is 8-16 Hz for an instant luminosity 4×10^{31} and it is simply rate limited at 0.7 Hz at level-2.

In the region $1.25 < |\eta| < 1.5$: the level-1 trigger is the coincidence of the barrel muon chamber (BMU) with the barrel rear scintillators (BSU-R) and the TSU (toroidal scintillators). The efficiency of this trigger is uniform as a function of η , but the rate is much higher (200-400 Hz at level-1 for an instant luminosity of 4×10^{31}). At level-2 this trigger is rate limited to 1.3 Hz.

We propose a single trigger in the region $1. < |\eta| < 1.5$ without the XFT track at level-1, that uses a SVX-only track to reduce the rate at level-2. We plan to use the 4/5 matching criterion and we build a bank for high P_T prompt-leptons ($P_T > 8$ GeV and $d_0 < 500\mu\text{m}$): 30 kpatterns will provide an efficiency of 95% for these leptons and a good efficiency for P_T as low as 4 GeV. The SVT upgrade, which is described in chapter 4, is a necessary ingredient for this application, since additional Associative Memory is required to store patterns for forward muons.

In the following we study the proposed trigger:

- first of all we study the quality of the silicon-only tracks. We use real data to show that the SVX detector alone provides good enough quality.
- as a second step we tune the trigger selection criteria by using a $Z \rightarrow \mu\mu$ sample with the Z decaying with a μ in the central region and a μ in the forward region. We use this sample also to evaluate the trigger efficiency for good energetic muons.
- finally we use the forward muon level-1 sample (the calibration trigger that is simply rate-limited at level-2) to evaluate the level-2 rate of the proposed trigger.

Fig. 33 shows the performance of SVX-only tracking with SVT over a sample of off-line selected $Z^0 \rightarrow \mu\mu$. The ϕ resolution is ~ 6 mrad, the P_T resolution is $\frac{\delta P_T}{P_T} \simeq 8\%$ (P_T in GeV). Fig. 34 shows the performance of SVX-only tracking with SVT for a background sample selected by the level-1 forward muon trigger. The ϕ resolution is ~ 12 mrad, the P_T resolution is $\frac{\delta P_T}{P_T} \approx 15\%$ (P_T in GeV). The P_T and ϕ resolutions measured with the background sample are worse than those measured with the $Z^0 \rightarrow \mu\mu$ sample. This effect is due to higher occupancy in the detector for background events.

As expected the tracking quality is not good for both the signal and the background sample. In fact, we use of only four SVX layers (4/5 matching criterion) that provide a loose constraint, leaving a large fraction of fake tracks, and the limited spatial extension of the SVX detector (up to $R = 10.5\text{cm}$) provides poor curvature resolution. However, the reconstructed tracks have good ϕ resolution and this variable can be used for matching with ϕ hits in the muon chambers. The non-gaussian shape and tails are due to fakes, noise, non-linearities etc.

A 2D matching algorithm between the SVX stub and the muon chamber should be defined. Since we want to implement a trigger for high P_T muons and P_T resolution is poor, extrapolating the SVX stub as a straight line is a good approximation. This algorithm should be applied to all “good tracks”. We define a good track as a SVX track with $\chi^2 < 10$ and $P_T > 4\text{GeV}$. Since the P_T resolution is poor, in order to

Figure 33: Tracking quality for a sample of off-line selected $Z^0 \rightarrow \mu\mu$. The parameters residual are calculated with respect to off-line tracks. *Upper left:* ϕ residual for barrel crossers (dz+). *Upper right:* ϕ residual for non-barrel crossers (dz0). *Lower left:* half curvature residual for barrel crossers (dz+) after $|\phi| < 0.015$ matching cut (w.r.t. off-line tracks) is applied. *Lower right:* half curvature residual for non-barrel crossers (dz0) after $|\phi| < 0.015$ matching cut (w.r.t. off-line tracks) is applied.

have good efficiency for high P_T tracks the threshold must be kept low. We want to evaluate the efficiency of this matching algorithm including all contributions from SVX resolution, multiple scattering, muon chamber resolution and all trigger effects. In order to do that we use the sample of $Z^0 \rightarrow \mu\mu$, where we have muons with high purity, to measure the ϕ matching resolution.

Fig. 35 shows that a good choice for the matching window is $\pm 2.5^\circ$. This defines the trigger selection.

At this point we can evaluate the trigger rate applying this selection over a background sample. We use the sample selected from level-1 for $1.25 < |\eta| < 1.5$ because it does not have the XFT bias. The performances of the proposed SVT selection for forward muons are summarized in tab. 13. A rejection factor of 22 can be obtained

Figure 34: Tracking quality for a background sample selected by the level-1 forward muon trigger. The parameters residual are calculated with respect to off-line tracks. *Upper left:* ϕ residual for barrel crossers (dz+). *Upper right:* ϕ residual for non-barrel crossers (dz0). *Lower left:* half curvature residual for barrel crossers (dz+) after $|\phi| < 0.015$ matching cut (w.r.t. off-line tracks) is applied. *Lower right:* half curvature residual for non-barrel crossers (dz0) after $|\phi| < 0.015$ matching cut (w.r.t. off-line tracks) is applied.

Selection	Z0	background
match $ \Delta\phi < 2.5^\circ$ $P_T > 4$ & $\chi^2 < 10$	126 (events)	213 (events)
efficiency L2 sel.	0.50	
rejection L2 sel.		22

Table 13: Summary of the proposed SVT trigger performances for forward muons.

with a total efficiency of 50%.

Figure 35: *Left:* difference between the ϕ of the muon hit in the muon chamber and the ϕ of the nearest off-line track. *Right:* difference between the ϕ of the muon hit in the muon chamber and the ϕ of the nearest SVT track. The vertical lines represent the chosen trigger cut of $\pm 2.5^\circ$.

4 DAQ limits: SVT upgrade as a solution

CDF has strongly supported trigger and DAQ upgrades to increase the overall system efficiency. They were planned since the Run IIa beginning, thinking to the large luminosity increase expected in the RUN IIb.

The main upgrades planned before 2002 are:

- The level-1 XFT upgrade: the goal is the use of stereo layers for 3-D tracking. The upgrade decreases the fake rates requiring the coincidence of axial hits with the stereo hits.
- level-2 (L2) upgrade: the global level-2 decision, which takes the level-2 decision combining the reconstructed level-2 objects (tracks, jets, leptons), will be replaced with Pulsar boards and newer CPU's for higher processing power (smaller processing time), higher bandwidth communications, more flexibility and better maintenance. The upgraded system is also called Pulsar L2.
- Event Builder (EVB) and level-3 (L3) farm upgrade: the goal is to increase the event builder and level-3 processing rate from 300 Hz to 1kHz.
- TDC upgrade: the goal is to reduce the processing-readout time to allow a level-3 bandwidth of 1 kHz.
- SVT upgrade: just few changes to guarantee the compatibility with the upgraded silicon vertex. The silicon vertex upgrade has been canceled on September 2003 and so were the small SVT rearrangements.

These upgrades are documented at the web pages:

<http://www-cdf.fnal.gov/upgrades/run2b/Documents/Documents.html> Other upgrades have been taken into account in a second time:

- Silicon readout upgrade (SRC upgrade): for a smaller processing time
- Consumer Server Logger (CSL) upgrade: for higher rates to tape
- Off-Line Farm upgrade: in order to reconstruct events accumulated with the new CSL rate.

The technical motivations for new upgrades are the necessity to increase each trigger level-bandwidth and the overall trigger efficiency in order to increase the yield of selected samples.

It is interesting to note that the list of early-planned upgrades do not include any important improvements for the SVT processor that is the most complex piece of the level-2 trigger system. Even the list of the new improvements motivated by actual, unexpected problems of RUN IIa, do not include any SVT improvement. In fact, before my work, the CDF simulation and studies were actually showing that SVT was almost ok (see subsection 4.3). My studies on data and simulation came to the opposite conclusions. I studied the DAQ and trigger bandwidth problems that I will describe in the following (subsection 4.2.2). I showed that SVT processing time is a relevant

contribution to the present DAQ problem (subsections 4.2 and 4.4) and, in order to improve the DAQ performances, the SVT should be upgraded. After understanding the problem, we proposed an upgrade that could substantially reduce it. A first SVT upgrade was approved on 2003 and it will be installed during summer 2005. The effectiveness of the first SVT upgrade triggered a second upgrade that was approved on July 2004, and it will proceed in parallel with the first one.

Summarizing, in the following sections I will describe:

- the trigger bandwidth limits;
- the DAQ main feature that can explain the problems;
- the simulations done before my studies, mistakenly showing that SVT does not influences the data taking;
- my studies and the understanding of the SVT role in the DAQ problems;
- the first SVT upgrade as a good solution for the Run IIa DAQ problems.
- the second SVT upgrade in order to work at Run IIb design luminosity.

4.1 The trigger bandwidth as a limit to physics

The trigger rate for each trigger level has a limit due to the fact that higher rates would produce a too large dead-time. The bottom left plot in fig. 36 shows the dead-time as a function of time for the run 168640 taken during the summer 2003. The time 0 corresponds to the run start. In this case the time 0 also corresponds to the beginning of the store, with maximum instant luminosity. The DAQ is organized in such a way that the dead-time cannot exceed the 5-6% dead-time. The exponential decrease is comes from the instant luminosity decrease due to the store age, while the steps bringing back the dead-time to the maximum level-show the effect of the level-1 dynamic prescales described in section 3.2: when the instant luminosity decreases enough the level-1 prescales are partially released to fill the trigger bandwidth again, at its maximum level.

Fig. 36 shows the level 1, 2 and 3 accept (L1A, L2A, L3A) rates as functions of time, along with total dead-time. The upper limits to the trigger rates are visible in the plots. The L3A rate is limited to 60-65 Hz by the data logging capability (CSL) and the off-line computing power. The limit for the CSL now is 21 Mb/sec. The L2A rate is limited to 300 Hz by the readout time dominated by the TDC data, the Event Building time and the level-3 processing power. The planned TDC, EVB and L3 farm upgrades should improve this limit by at least a factor 3, which is necessary for RUN IIb.

Finally, the L1A rate is limited to less than 16 kHz. Looking carefully at fig. 36, we can see that at the initial time, when the instant luminosity is $\approx 40 \cdot 10^{30} \text{cm}^{-2}\text{s}^{-1}$, the L1A is reduced below the allowed 16 kHz because the L2A and L3A are saturated and dead-time is induced by the readout and logging of too large events. The average size of the event was estimated on RUN I data, taking into account that a large amount of

Figure 36: *top left*: Level-1 accept rate as function of running time. *top right*: Level-2 accept rate as function of running time. *bottom right*: Level-3 accept rate as function of running time. *bottom left*: dead-time as function of running time. All plots refer to store 168640 that started with a luminosity of $42 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$.

B-physics small events would take part of the level-2 and level-3 bandwidth. Since at high luminosity all the bandwidths are saturated by high P_T physics, the B-physics is totally mostly (see below) and the event size is larger than expected.

When the luminosity is not so high and the L2-L3 problems disappear, the L1A is limited to 16 kHz by the use of only 4 buffers to store events processed at level-2 (see section 4.2). In principle, only one buffer is absolutely required, while three buffers are required to take advantage of the fact that the level-2 is organized as a three level pipeline and more buffers are needed to compensate for fluctuations on level-1 accept rate and level-2 processing time. This poor buffering power causes very strong constraints to level-2 processing time (see subsection 4.2.2). The processing time of each stage of the level-2 pipeline is not optimal. While the level-2 and 3 bandwidths correspond to the design bandwidth for the RUN IIa, the level 1 allowed rate (16 kHz) is much smaller than the design value (50 kHz). The planned upgrades were all but one devoted to reduce the level-2 timing. The only exception is the XFT upgrade that will reduce the number of fake tracks at level-1 improving the level-1 purity and reducing the level-1 rate.

As a consequence of this L1A severe limit, large prescale factors have to be applied at level-1, reducing a lot the expected data taking capability. In particular, the high cross section B-physics triggers are heavily prescaled at the beginning of each store. Fig. 3 shows the inverse of the prescale factor for the B_s triggers as a function of the instant luminosity for different L1A rate limits. It is clear that for the 15-16 kHz available in summer 2003, the instant luminosity of $\approx 40 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$ reduces to zero the B_s yield. I will show in the following that the L1A limit is a function of the luminosity itself, and the limit becomes more severe as the instant luminosity increases.

If we go back to tab. 1 and tab. 2, showing the rates of the SVT triggers for the high P_T physics (4 kHz) and low P_T physics (8-19 kHz), we can see that even at luminosity relatively low ($60 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$) the SVT triggers alone would exceed the 16 kHz level-1 bandwidth.

This is a clear problem, since it means that SVT triggers do not have enough bandwidth space for themselves even in the unrealistic hypothesis of using the whole CDF level-1 bandwidth! Going to higher luminosities the trigger rates continue to increase (see table 1 and 2) and the level-1 bandwidth continues to decrease! The level-1 bandwidth, which is not directly affected by event size, is reduced at higher luminosity because of back-pressure due to higher level-2 processing time.

4.2 The level-2 processors and the DAQ constraints

In the SVT [5] trigger stream, three different processors work in pipeline at level-2:

1. the silicon readout system digitizes and reads all data from the silicon detectors and sends them simultaneously to both the level-2 buffer for event building and the SVT system for triggering. The processing time is $\approx 9 \mu\text{s}$ for the digitization and $15 \mu\text{s}$ for the readout.
2. the SVT system starts to work when the event is digitized and it begins to reconstruct tracks while the silicon detector is still being read out. SVT on average ends its processing just before the next event is digitized ($23 \mu\text{s}$ against $24 \mu\text{s}$ of stage 1).
3. the level-2 processors receive the tracks from SVT. The processing time is shorter than the silicon detector readout.

Four level-2 event buffers are available to store the events while the level-2 trigger makes its decision. If a new event arrives at a time when all 4 buffers are full it cannot be accepted thus causing dead-time in the level-2 trigger system. This dead-time increases with higher input rates and longer total processing time.

4.2.1 The slower stage of the pipeline

First of all we should consider the average processing time of each stage in the pipeline. This is an important parameter of the system since. **If enough level-2 buffers were available**, the slower pipeline stage would determine the maximum pipeline input rate.

Figure 37: Both plots show silicon detector readout time distributions. Green is SVX II only, Blue is SVX II+ISL, Cyan is L00+ISL, Red is SVX II+ISL+L00. The left plot include both r - ϕ and stereo layers. The right plot shows only r - ϕ layers.

1. The first stage in the pipeline is the silicon detector digitization and readout. Just after the L1A the SVX digitization starts and takes approximately $9 \mu\text{s}$. During this time the SVT is waiting. After that the silicon readout starts. As soon as the readout starts the SVT begins processing hits. Fig. 37 shows the readout time for all silicon detectors and all layers (left) or only r - ϕ layers (right). All the silicon data are duplicated and sent in parallel to both the DAQ and SVT. Actually, SVT uses only SVX data, whose readout time is shown by the green curve, but a single Silicon Readout Controller (SRC) is doing the whole job, so SVT has to wait the digitization and readout of the whole detector (red curve), before being able to get a new event. In conclusion this pipeline stage takes $9 + 15 = 24 \mu\text{sec}$ and it is the longer processing time in the pipeline. CDF is in the process of upgrading the silicon readout by duplicating the readout path and the readout controllers. One SRC will be dedicated to the SVX only and a second SRC to all other silicon detectors not used by SVT. SVT will then have to wait only for the work of the first SRC. This upgrade will reduce the processing time of this stage by a factor ≈ 2 .
2. The next stage in the pipeline is the SVT processor. Fig. 38 shows measured SVT processing time distributions for the two different matching criteria, 4/4 (green line) and 4/5 (red solid histogram). The figure on the right shows the details of the distribution bodies (0-30 μsec), on linear scale, while the figure on the left shows the same distributions on log scale, to better evaluate the tails up to 250 μsec . For each event the SVT inclusive processing time is calculated from the level-1 accept (L1A) to the time when the last event word leaves SVT, thus it not only include the effective SVT processing time: it also includes the silicon detector digitization and readout. During the readout both the SRC and SVT can work on the same event.

Figure 38: SVT processing time for 4/4 (green) and 4/5 (red) matching logic. The log scale on the left shows the details of the very long tails up to $250 \mu\text{sec}$ while the linear scale on the right shows the details of the main part of the distribution, cut at $30 \mu\text{sec}$. All the distributions are normalized to unit area. Processing time is measured from level-1 accept to the time when the last event word leaves SVT. So it includes the silicon detector digitization and readout.

The average SVT inclusive processing time increases from $23 \mu\text{s}$ for the 4/4 criterion to $32 \mu\text{s}$ for the 4/5 criterion. If we subtract the digitization time we find that SVT has an effective processing time of $14 \mu\text{s}$ (4/4) to $23 \mu\text{s}$ (4/5). The difference between the two matching criteria is discussed in the following sections. It is clear that the 4/5 criterion requires a longer processing time. It is also clear that in the 4/5 case there are larger tails characterized by long processing times (even in excess of $100 \mu\text{s}$). However, we should note that the average processing time is smaller than that of the SRC even in the 4/5 case.

3. The last stage in the pipeline is the global level-2 processor that collects all level-2 detector objects (tracks, jets, leptons) and performs the final decision. This stage has a smaller processing time. It is also going to be upgraded [26].

Fig. 39 summarizes the SRC and SVT timing, showing the case of more than 1 event in the pipeline. Average processing times are shown. During the first event SVT waits for the SRC to finish digitization (red). Then it starts working (green). In the 4/4 configuration it usually ends before the full silicon readout is completed (the SVX, which is used by SVT, is the first detector in the readout process). Even in the 4/5 configuration on average the SVT ends before the next event is fully digitized. In conclusion, the slower stage of the pipeline it is not the SVT but it is the SRC that has a processing time of $24 \mu\text{s}$. In the approximation on which the pipeline event processing rate is the inverse of the slower stage processing time, which would be valid **if enough level-2 buffers were available**, $24 \mu\text{s}$ corresponds to a maximum level-1 bandwidth of 42kHz .

Figure 39: SRC and SVT average processing times for 2 consecutive events. On average the SVT finishes its work before the next event is digitized. The “digitization” (red) time is the time used by the SRC to digitize the SVX hits. During this time the SVT is waiting. The “readout to SVT” (blue) is the time on which the SVX axial hits, which are used by SVT, are sent from the SRC to the SVT. The “additional readout” (black) is the time on which stereo SVX hits, ISL and L00 hits are sent to the DAQ buffers. The SRC cannot start to digitize a new event until the “additional readout” is finished. This is represented from the vertical line connecting the end of SRC processing for the first event to the begin of SRC processing for the second event. The vertical line, which is placed at the end of SVT processing in the 4/5 case and near the end of SRC “digitization” for the second event, shows that even if the SVT finishes its work after the end of the SRC processing for the first event it has to wait for new hits since the SRC starts the “readout to SVT” when SVT is ready.

4.2.2 How the number of level-2 buffers impacts the dead-time

The analysis of the previous paragraph could be interpreted in the sense that the SVT is not the actual limit to the L1A rate, at least before the upgrades of the other stages. However this is not true, because the average values do not tell the full story. There is an up-to-now hidden problem that changes all the conclusions we can make at this point. As we said at the beginning of the previous subsection, **the maximum input rate at level-2 depends only on the average processing time of the slower stage if, and only if, a sufficient number of level-2 buffers is provided to the pipeline**. Since there are only 4 buffers at CDF (really a small number if you consider that the full pipeline needs at least 3 of them regardless of the event arrival time and processing time fluctuations), the actual impact of the three stages on the dead-time is very different from the average case described up to now.

In these conditions we have to face two different contributions.

- The first one involves the average global level-2 latency, to which all the processing times along the pipeline contribute. It is measured to be now $37 \mu\text{s}$ for the 4/4 criterion (9 from SRC digitization, 14 from SVT overlapped on the SRC

readout, 14 from the level-2 processor) and $46 \mu\text{s}$ for the 4/5 criterion (9 from SRC digitization, 23 from SVT overlapped on the SRC readout, 14 from the level-2 processor). An event occupies a buffer for 37 (45) μs , so we should consider which is the probability that 3 other L1As could occur in a shorter time, causing dead-time, since all the level-2 buffers would be full. If the L1A rate is 40 kHz, consecutive L1As will be separated (on average) by 25 μs and the probability of having a fluctuation of 3-4 events in a time of $\approx 40 \mu\text{s}$ (for example) is too high. For this reason the level-1 accept rate has to be lowered. The upgrades will decrease the average processing times, and the average level-2 latency, decreasing the probability of getting clusters of 3-4 L1As during this latency.

- The second contribution comes from long tails in the processing time distributions, which cause tails in the latency distribution. If a level-2 decision is taken every 25 μs , it will free a buffer every 25 μs . However, an event that stays for a longer time inside SVT will cause the level-2 processor to wait. For example an event that takes 100 μs to be processed by SVT causes no buffer release for $\approx 100 \mu\text{s}$. Again, the probability of getting a bunch of L1As and a dead-time during this interval will be too high if the L1A rate is 40 kHz. As a conclusion, even if the SRC average processing time is longer than the SVT average processing time, the SVT has a larger impact on dead-time because of its long tails above 25 μs . This effect is even more important in the case of 4/5 criterion. Finally, we should underline that the impact on dead-time is also due to the relative bandwidth assignment to low- p_T /high- p_T events, since the most complex high- p_T events will generate longer tails.

Reducing the SVT processing time tails would reduce the dead-time. Furthermore, reducing the SVT average processing time helps reducing the level-2 overall latency. The SVT upgrade is important because the number of buffers is really small and it will become absolutely necessary when the new SRC and level-2 processors will reduce their processing time inside the pipeline thanks to their upgrades.

4.3 DAQ simulation: overlooking a detail makes the SVT contribution to dead-time seemingly small

CDF came to the difficult problem of evaluating the level-1 bandwidth gain, which is a real gain of physics, corresponding to a given level-2 processing time improvement. To do this, we need to know how much dead-time is produced by a certain level-2 computing time. The computation of the dead-time in a particular condition is not an easy task. In fact, the CDF DAQ is dead when all 4 level-2 buffers are full. In order to determine the fraction of time on which this condition is true, the queuing of events, with their arrival time and processing time fluctuations must be simulated. A queuing program (ModSim [46]) is used to take into account all the possible effects. It uses timing information for each stage of the trigger and includes the effect of the limited number of level-2 buffers. The processing time distributions for different parts of the trigger and DAQ are given as inputs to the program that simulates events and reproduces quite well the observed dead-time.

Figure 40: Total dead-time as a function of level-1 accept rate for different level-2 configurations and different runs characterized by different initial luminosities. The two curves with triangle markers are generated simulating the 4/4 criterion. The small difference among the two is due to two different timing measurements, from two different runs, given in input to ModSim. The two curves with circle markers are generated simulating the 4/5 criterion. The dark green includes the level-2 improvements and a level-2 accept rate of 300Hz. The light green does not include the level-2 improvements and it has level-2 accept rate of 140Hz. The small red circles are measured during run 164308 that had a peak luminosity of $10 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$. The SVT processing time measured during this run was used to generate the two green simulated curves. The large blue circles are measured during run 168640 with the 4/5 configuration. The peak luminosity was $44 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$.

Fig. 40 shows the total dead-time (%) versus the L1A rate (kHz) in different conditions, which are described in the following paragraphs. When the SVT was still using the 4/4 criterion, Modsim was used to evaluate the importance of some improvements to the level-2 systems. These improvements included the SRC upgrade and other improvements to the level-2 code, which is run by the level-2 processor. They did not include the major level-2 upgrade described at the beginning of this chapter, which is the replacement of the global level-2 decision crate. In order to differentiate these improvements with respect to the major level-2 upgrade I simply call them “level-2 improvements”. The outcome of the simulation was that the available level-1 bandwidth would have increased up to 25kHz with a 5% dead-time, as the blue curve of fig. 40 shows. This result was true assuming the 4/4 criterion and the corresponding SVT processing time. In these conditions, the SVT processing time was small with respect to that of SRC and level-2 processor and improvements to these two subsystems had a large effect on the maximum level-1 rate.

When the 4/5 criterion was activated, Modsim was again used to evaluate the

effect of an SVT upgrade. The two green curves show the results obtained giving in input to ModSim the SVT processing time distribution, measured in run 164308 with 4/5 matching criterion. The simulation has been repeated with and without all the other level-2 improvements and with different level-2 accept rates, producing the small difference between the two green curves. The small advantage due to the level-2 improvements is canceled by the increase of the level-2 accept rate. This means that the effect of the level-2 improvements becomes small when the 4/5 configuration is used with the not upgraded SVT. This can be understood by looking at fig. 39, which shows that in the 4/5 configuration the SVT ends its processing just before the beginning of the SVX readout of the next event. Thus, improvements to the SRC don't help much unless the SVT timing is also improved. The two green lines show that a level-1 rate of 22-23 kHz can be reached with less than 5% dead-time even using the 4/5 matching criterion.

To estimate the effect of an SVT upgrade CDF used the 4/4 criterion time distribution as input to ModSim, in the hypothesis that the upgrade is able to reduce the 4/5 criterion timing to that of the 4/4 criterion. Section 4.5.1 shows that, with the first SVT upgrade, the processing time in the 4/5 configuration will be reduced to that of the not upgraded SVT in the 4/4 configuration. The blue and violet curves show the results obtained in the 4/4 configuration plus level-2 improvements. showing that with a 7% dead-time it is possible to reach the 30 kHz of level-1 rate. It could seem that the advantage of the SVT upgrade is really marginal since the overall gain with respect the green line in fig. 40 is only 5 kHz. For this reason, at first time CDF did not consider an SVT upgrade as important as the other upgrades.

4.4 The SVT timing has a large impact on level-1 bandwidth

However, observing the on-line measurements, in September 2003 we understood that the actual level-1 bandwidth limit was much smaller (≈ 16 kHz) than what shown by the green lines of fig. 40. Thus, we decided to study more this problem and we discovered, as we will see, that the actual gain in level-1 rate, of an SVT upgrade would be much more than 5 kHz.

The blue points shown on the left of fig. 40 are measured points (dead-time and level-1 accept rate) from run 168640. Points corresponding to the initial part of the run are discarded and do not enter the plot, since initially the limit to level-1 accept rate comes from readout, level-3 and data logger (CSL). The blue points show a completely different behavior compared to the green lines, even if apparently they represent the same condition: 4/5 matching criterion. A 5-6% dead-time corresponds to a 16 kHz L1A rate. To understand the difference we put in the plot also the red points from the 164308 run. The SVT timing distribution of this run was used as input to ModSim to produce the green lines: they are the small red points at very low dead-time between 5 and 7 kHz of level-1 accept rate. The difference between the two runs represented by blue and red points is evident. First of all, the initial luminosity of run 164308 is very low ($10 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$), second the maximum L1A rate is 7 kHz, well below the saturation limit, since dead-time is also very low. Run 168640, on the contrary, starts with a luminosity of $44 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$ and the level-1 accept rate as well as the

dead-time saturate to their limits of 16 kHz and 5% respectively.

We made the hypothesis that the higher luminosity produces a significantly longer SVT and level-2 processing times, decreasing the level-1 accept rate limit. My studies showing that the SVT processing time really increases as the instant luminosity increases are reported in [47]. Now the average processing time versus instantaneous luminosity is one of the plots monitored on-line. Fig. 41 shows a recent measurement of average processing time versus instantaneous luminosity¹⁰. Fig. 41 shows that SVT processing time actually increases with higher luminosity. This means that the blue

Figure 41: Average SVT processing time (μs) as a function of instantaneous luminosity ($\cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$), measured during actual data taking.

points in fig. 40 are not the worse we will get. For sure, the points will move on the left with higher instant luminosity reducing even more the available level-1 bandwidth.

Finally, we remove the green lines of fig. 40 that are too much optimistic in order to evaluate the 4/5 case and we show in fig. 42 two new curves, the green points and the light blue line, corresponding to the SVT upgrade effect without any other level-2 improvements, obtained with the same two runs of the blue and violet curves of fig. 40. You can see that the effect of the SVT upgrade is really important.

In conclusion, the SVT upgrade is an important part of the level-2 improvements

¹⁰This recent measurements of the SRC plus SVT processing time cannot be compared with the $32\mu\text{s}$ reported in section 4.2.1, since the SRC and SVT configurations have been adjusted for faster processing sometime at the price of smaller efficiency.

Figure 42: Total dead-time as a function of the level-1 accept rate for different level-2 configurations. The blue points are measured during run 168640, with a peak luminosity of $44 \cdot 10^{30} \text{cm}^{-2} \text{s}^{-1}$. The green and light blue curves are a simulation using the 4/4 criterion processing time. They correspond to the 4/5 criterion with the upgraded SVT. The green and light blue curves are a simulation using the 4/4 criterion processing time including the level-2 improvements. They correspond to the 4/5 criterion with the upgraded SVT and the level-2 improvements.

and its absence would devoid all other improvements of most of their usefulness. We can succeed to double the bandwidth now available and we can probably avoid or substantially reduce the dependence on luminosity. Based on these motivations, INFN approved and funded the first SVT upgrade on September 2003.

4.5 The SVT upgrade as a solution to DAQ problems

I'm going to describe the first SVT upgrade. This upgrade will reduce the processing time of the 4/5 case, bringing it back to the values of the 4/4 criterion.

SVT is divided into 12 azimuthal wedges that are processed in parallel by 12 identical processors, as described in page 2. Fig. 43 shows the structure of the SVT processor for one azimuthal wedge. Going through the data path from the detector we first find

the Hit Finders (HF) that perform clustering of the SVX II signals, then data are merged into a single stream, which includes the XFT tracks, by the Merger. This stream is then sent to both the AM Sequencer (AMS) and the Hit Buffer. The AMS reduces the resolution by logically ORing together a number of silicon strips to obtain the so called Superstrip. Typical Superstrip sizes are about 4 to 8 strips. The AMS sends Superstrips to the AM system¹¹ (32 kPatterns per wedge) that finds roads (see page 2) and sends them back to the Hit Buffer.

The Hit Buffer sends out road data, including all related full resolution hits, to the Track Fitter that performs track fitting. At the end of the data flow there is also one Ghost Buster board (not shown in the picture) that removes track duplicates. Only one track per XFT segment is allowed to be output by the Ghost Buster. When more than one track share the same XFT segment the Ghost Buster chooses the track with the smaller χ^2 .

Figure 43: SVT data flow diagram for one ϕ wedge. The parts in red are the ones changed by the upgrade.

The SVT timing is approximately explained as the sum of two contributions. The first contribution is the time necessary to load the detector hits in the system. This time is proportional to the amount of data to be loaded and does not change much on an event by event basis. The second contribution is the time necessary to process all the roads: that is the time for the Hit Buffer to send road data to the Track Fitter and for the Track Fitter to actually perform track fitting. This time is dominated by the Track Fitter time and it is proportional to the event complexity, i.e. to the number of fits to be performed.

The implementation of 4/5 matching criterion increased the event complexity and,

¹¹see page 2

consequently, the second contribution to processing time. The effect is shown in fig. 38 where the SVT timing distribution of the 4/5 configuration is compared to the one of 4/4 case.

We study the implementation of an upgrade to reduce the 4/5 processing time to values similar to the 4/4 processing time. The first upgrade consists in increasing the AM capability from 32k patterns to 128k patterns per wedge and adding the Road Warrior (RW) board. A larger AM allows the use of thinner roads for pattern recognition, it reduces the number of fakes due to the hit combinations left inside each road after the AM processing. This reduces the workload for Hit Buffer and Track Fitter. The Road Warrior, as we will see, removes duplicated roads before the Track Fitter and saves Track Fitter processing time. This duplication of real tracks is due to the 4/5 matching criterion.

In fact, for each real track it is possible to find only a single 5/5 road (if an hit is found on each layer) and/or a number of 4/5 roads (if an hit is missing on one layer) generated by all the patterns that differ only for a single Superstrip, the empty one. The four non-empty Superstrips are exactly the same for all these roads. If all these 4/5 roads are sent to the Track Fitter, the Track Fitter and Hit Buffer time will be wasted fitting repeatedly the same hit combinations, with no advantage. It is possible to identify and remove these duplicated roads even if the track χ^2 is unavailable.

The Ghost Buster placed after the Track Fitter, see fig. 43, is very efficient to remove all duplicated tracks that are characterized by having the same XFT segment reconstructed in the COT. However, it does not help to reduce the Hit Buffer and Track Fitter processing time.

We plan to anticipate the Ghost Buster function as much as possible. A modified version that can remove duplicates can be placed immediately after the AM in order to remove them before Hit Buffer and Track Fitter. We call it *Road Warrior* (RW). Since it was useful to have the Road Warrior working as soon as possible, it was temporarily installed after the Hit Buffer as it is shown in fig. 43.

The Road Warrior should store the Superstrip combinations (patterns) of found roads in a small Associative Memory built on the fly as roads are sent to the output. Empty Superstrips are identified and flagged. Each road is allowed to proceed to the output only if it differs from all roads previously sent, because of at least one non-empty Superstrip. The necessary information of which Superstrips are empty within a road is now determined looking at the Hit Buffer output stream. For this reason the Road Warrior has been temporarily placed after the Hit Buffer. The new AM will provide, for every found road, a word containing the bitmap of fired Superstrips. Thus, with the new AM, the Road Warrior will receive this information earlier and it will be moved before the Hit Buffer in order to also save its processing time.

4.5.1 SVT simulation

In order to understand the motivations and to prepare an efficient strategy I modified the SVT simulation to simulate the upgraded hardware and I applied it to recent CDF data. These simulations show that with the upgrade, it is possible to reduce the SVT processing time of the 4/5 matching criterion to the processing time of the 4/4 case.

I used data samples selected with the level-1 bias only, since the simulated hardware will work with these events. I used two main data samples:

1. the first one is selected by the level-1 request of two tracks with P_T of at least 2 GeV followed by automatic accept at level-2 and level-3. We refer to this sample using the label *standard (std)*, since it is similar to the main Level-1 triggers used for B physics (TTTC, TTTA, TTTlow P_T of section 2.5.2).
2. the second sample is labeled $Z^0 \rightarrow b\bar{b}$ since it is collected using the $Z^0 \rightarrow b\bar{b}$ level-1 trigger followed by automatic accept at level-2 and level-3. We study the $Z^0 \rightarrow b\bar{b}$ sample to get informations on the SVT behavior when tracking inside soft jets. The $Z^0 \rightarrow b\bar{b}$ level-1 trigger requires two tracks of P_T at least 2 GeV and two separate central calorimeter towers with E_T of at least 5 GeV (see section 2.1.1).

Figure 44: The plot shows the SVT processing time distribution for different SVT configurations running over the *std* sample. *Red*: default 4/5 configuration with 32 kpatterns/wedge. *Green*: 4/5 configuration with 128 kpatterns/wedge. *Blue*: 4/5 configuration with 32 kpatterns/wedge and using the Road Warrior. *Black*: upgraded 4/5 configuration with 128 kpatterns/wedge and using the Road Warrior.

Fig. 44 shows the SVT processing time distribution for different SVT configurations running over the *std* sample. The processing time is estimated in the following way: for

SVT configuration	<i>std</i>		$Z^0 \rightarrow b\bar{b}$	
	< #of fits >	#of fits RMS	< #of fits >	#of fits RMS
4/4 32kpatt	3.9	7.3	9.4	12.1
4/5 32kpatt (now)	39.1	60.6	94	114
4/5 32kpatt + RW	17.6	34.4	42	57.7
4/5 128kpatt + RW	9.3	14.6	23	30.4

Table 14: Average number of fits for different SVT configuration and for both *std* and $Z^0 \rightarrow b\bar{b}$ data samples.

each event the number of fits to be performed is calculated with the SVT simulation; the corresponding processing time is then computed as $time = 19\mu s + 300ns \cdot fits$ plus a gaussian smearing of $1\mu s$ to simulate fluctuations on the arrival time of the last detector hit and other minor effects.

The longest processing time associated with the current 4/5 configuration is represented by the red line in fig. 44. Since the current AM size is fixed, for the 4/5 configuration it was necessary to increase the Superstrips size from 8-4-4-8 (8 strips logically OR-ed together in the inner and outer layers and 4 strips in the intermediate layers) already used for the 4/4 criterion to Superstrips of size 12-8-8-12 (12 strips logically OR-ed together in the inner and outer layers and 8 strips in the intermediate layers). The larger AM will allow to recover the Superstrip sizes of the 4/4 criterion. In fact with 128kPatterns, Superstrips of size 8-4-4-4-8 can be used with the same AM efficiency. The AM efficiency is the geometrical acceptance of the set of patterns stored in the AM. For a fixed number of patterns (i.e. fixed hardware) the efficiency is higher for larger Superstrips, in order to have the same efficiency with smaller Superstrips, more patterns are required to reach the same geometrical acceptance. The gain in the timing distribution due to the smaller road size is shown in green in fig. 44.

I simulated the Road Warrior function that removes ghost roads and applied its effects on CDF data. This reduces the number of fits. The corresponding effect is shown by the blue curve.

Finally, the black curve shows the effect of the full upgrade that combines the larger AM and the Road Warrior.

In tab. 14, I report the average number of fit, with the configurations discussed above, for the *std* as well as the $Z^0 \rightarrow b\bar{b}$ samples. I observe that the $Z^0 \rightarrow b\bar{b}$ sample produces a processing time more than double with respect the standard sample. I can also observe an increase of a factor 10 for the number of fits to be executed in going from the 4/4 to the 4/5 matching criterion at fixed AM size: the standard sample goes up to 39 average combinations and the $Z^0 \rightarrow b\bar{b}$ to 94. The Road Warrior reduces more than a factor two this numbers and the memory extension produces an additional reduction of almost a factor two.

The number of combinations with the first upgrade becomes 2.4 times larger than the not upgraded 4/4 case. Part of this factor comes from the efficiency gain, which can be measured from simulation as the content of real tracks in output from SVT. This number increases from 1.5 tracks per event to 1.9 for the standard sample and

from 2.8 to 3.6 for the $Z^0 \rightarrow b \bar{b}$.

In conclusion, a large part of the complexity increase due to the activation of the 4/5 criterion is recovered by the upgrade. The upgrade restores a configuration similar the 4/4 one. In fact, the SVT will use the Superstrip sizes of the 4/4 configuration and the ghost, which are generated by the 4/5 criterion, are removed. The little additional workload that the 4/5 configuration has, with respect to the 4/4 configuration, is intrinsic to the looser 4/5 matching criterion that is providing the increased efficiency. In order to further reduce the timing we need an SVT upgrade that improves the SVT parameters (Superstrip sizes, fitting time, etc.) beyond that of the original not upgraded system, as the second SVT upgrade does.

4.5.2 Summary

The first upgrade will allow to normally run SVT in the Run IIa design conditions that correspond to a luminosity of up to $80 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. The first SVT upgrade, along with the upgrade of the global level-2 decision system, will increase the available level-1 bandwidth up to 30 kHz. Most of these 30 kHz will be available to high- P_T physics, which will be efficiently collected up at luminosities as higher as $80 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ and even more.

4.6 Second SVT upgrade for very high luminosity

The first upgrade of SVT has been recognized as a necessary improvement to the DAQ system. The first piece, the Road Warrior, has been quickly implemented by using Pulsar boards [43]. It is already working in the experiment and it is providing additional level-1 bandwidth. The success of the first SVT upgrade along with the recent increase of Tevatron instantaneous luminosity and the recently demonstrated need of larger data samples for most important B-physics analysis (see section 2.5.1), pushed CDF to develop a second SVT upgrade. The main purpose of this second upgrade is to improve the SVT timing in order to allow CDF to use SVT up to the Run IIb design luminosity of $300 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$, even if SVT was designed to work only during Run IIa, up to $80 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$.

As luminosity rises, multiple interactions increase the number of hits in the SVX. Thus, the time to process all silicon hits increases (time/hit = ~ 35 ns). However, the more serious problem is the increase in the number of track candidates that have to be fit (time/fit = ~ 300 ns). In each road, the number of fits that has to be done is due to the residual hit combinations produced by more than one hits per silicon layer. As the hit density in the silicon increases, the number of fits can become quite large.

The SVT upgrade aims to both reduce the number of fits and to perform each fit more quickly. The former goal is pursued by reducing the road width through the increase of the total number of patterns per wedge to 512K. The latter, is achieved by increasing the speed of the track fitting board. Replacing the Track Fitter with Pulsar boards that can execute the same logic at a faster clock cycle. Tab. 15 shows the improved DAQ performance in terms of level-1 accept rate. The increase in the amount of data CDF can record is significant.

The existing muon trigger requires a high quality track to match a stub in the muon chambers. At present, the XFT can find tracks that exit the COT before reaching the outer superlayer. However, it is expected that in Run IIb, because of the increase occupancy XFT will require hits in the outer superlayer. This will reduce the efficiency for muons in the rapidity range between 1.0 and 1.5 by $\sim 50\%$. Using silicon tracks instead of COT tracks for muon matching could restore the performance of the muon system.

There is an additional advantage in upgrading the SVT that is more difficult to quantify. The upgrade provides insurance against degradation of the central drift chamber (COT). Without all of the COT superlayers, the XFT has a larger fake rate that increases the burden on the SVT. Such XFT tracks also have worse pointing resolution into the silicon, implying a larger number of patterns for the same overall track efficiency.

In the trigger, the critical parameter is dead-time. At level-2, the dead-time depends on the level-1 trigger rate multiplied by the average time it takes to make a decision at level-2. At current luminosities ($80 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$), both high- P_T and B physics level-1 triggers have to be prescaled because of SVT execution time. In this section, we show the severity of the problem at the Run-IIb design luminosity of $300 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ and how the proposed second SVT upgrade would mitigate the problem.

SVT is divided into 12 azimuthal wedges that are processed in parallel. There are effectively two major SVT stages. The first one reads in the silicon data and does track pattern recognition. To a good approximation, the time for this stage is proportional to the number of silicon hits in the busiest wedge. The second stage fits the track candidates, with an execution time proportional to the number of residual hit combinations to be fit. Data taken with the SVT at different luminosities were used to determine the coefficients for the linear relation $t_{\text{SVT}} = a + b \cdot N_{\text{hits}} + c \cdot N_{\text{comb}}$. Fig. 45 compares the prediction of this model (blue line) with actual timing measurements (solid red histo). The plots also show the fractions of events that are in the distribution tails characterized by a processing time longer than $50 \mu\text{s}$. We expect that these tails are particularly important in reducing the level-1 bandwidth below 20 kHz. Two different data samples are used and shown in the plots: on the left the sample is the trigger mix coming from the output of all level-1 track triggers (TRACK), on the right it is the trigger mix coming from the output of all level-1 triggers not using tracks (NOTRACK). The agreement between the model and the data is good, allowing us to predict the performance of the existing SVT and the proposed upgrade for higher luminosities.

In order to use this model to predict the performance at high luminosity, we need the distribution of the number of SVX hits and track fit combinations as a function of luminosity. Data were taken at three luminosities between $10 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ and $50 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ with a special set of triggers ($Z^0 \rightarrow b\bar{b}$ for high- P_T and the two-track B trigger). Both hit and combination distributions were then extrapolated to $300 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ and used as input in the ModSim program, that has been used in the past to understand the rate limitations of the CDF multi-level trigger system.

Fig. 46 shows three simulations compared to data taken, using the SVT as it ex-

Figure 45: SVT execution time distribution in data (solid histogram) compared to the prediction from the linear model (curve). On the left is a mix of triggers that requires tracks in the level-1 trigger. On the right is a mix that does not require level-1 tracks.

isted in May 2004 i.e. before the installation of the Road Warrior, at a luminosity of $50 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ with a two-track level-1 trigger. The first simulation includes the Road Warrior, which removes duplicate tracks prior to fitting and has recently been implemented with Pulsar boards. The second is with the same system but at a luminosity of $300 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. It is clear that the SVT processing time becomes much longer. The third is with the fully upgraded SVT at the same high luminosity. It shows that the upgrade reduces very well the SVT processing time. The resulting dead-time vs. level-1 rate is shown in fig. 47. The maximum level-1 rates for 5% dead-time are tabulated in tab. 15, showing that CDF will be able to increase its level-1 trigger rate by almost a factor of 2 after the SVT is upgraded. The validity of the results was tested at current luminosities. The rates in the table have uncertainties of approximately $\pm 30\%$ due to the extrapolation of a factor of 6 in luminosity.

not upgraded SVT	SVT after second upgrade
13 kHz	23 kHz

Table 15: The maximum level-1 trigger rate for luminosity of $300 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ and for a level-2 dead-time that does not exceed 5%.

In order to interpret these results, we need the level-1 trigger rates at the Run IIb design luminosity. Again we used data taken at current luminosities to extrapolate up to $300 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. The expected level-1 trigger rates are shown in tab. 16. The uncertainty in these rates is 50% because of the large luminosity extrapolation.

Figure 46: Comparison of SVT timing simulations with data taken with the existing baseline SVT at a luminosity of $50 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. Since the Road Warrior was installed after this study the measured distribution (solid histograms) don't include its effect. The simulation on the left is at the same luminosity but with the Pulsar Road Warrior included. The central figure is with this system but at a luminosity of $300 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. The right figure shows the effect of the proposed SVT upgrade at high luminosity.

trigger	level-1 trigger rate
$Z^0 \rightarrow b\bar{b}$	26 kHz
Two Track Trigger Sc. C (TTTC)	177 kHz

Table 16: The expected level-1 trigger rates at $300 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ from one high- P_T trigger and one B physics trigger.

The comparison of tables 15 and 16 makes it clear that at the design Run IIb luminosity CDF will be dead-time limited. Consequently the SVT upgrade will increase the amount of SVT triggered data CDF can collect by almost a factor of 2. These results are conservative since part of the upgrades are not taken into account (XFT upgrade for example).

4.6.1 The second SVT upgrade

We have shown that the effect of the second upgrade, now we describe it shortly. A full description can be found in [48]. The second SVT upgrade is designed to require a minimum effort to build new hardware. The increase in the number of roads is achieved with a new AM system, the AM++. The second SVT upgrade takes full advantage of the new AMchip that is being designed for the first upgrade. It increases the number of patterns to 512k per wedge, a factor of 16 more than current SVT. In fact new prototype AM chips are under production. The new AM++ boards themselves have been under design for a while based on R&D that was done for LHC experiments. The new Sequencer will use a Pulsar board [43], which was designed for and is now being used in the CDF level-2 upgrade. The Pulsar design is very flexible, with mezzanine cards for various input and output protocols and three powerful FPGAs for data manipulation.

Figure 47: The level-2 dead-time as a function of the level-1 trigger rate for both a high- P_T trigger ($Z^0 \rightarrow b\bar{b}$) and a B physics trigger (two track trigger) for four sets of conditions: in blue, the baseline existing SVT at a luminosity of $50 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$; in red, the same with the addition of the Road Warrior; in green, the same as red except at a luminosity of $300 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$; in magenta, the green conditions but with the upgraded SVT.

A simple mezzanine card containing memory chips and firmware for the Pulsar FPGAs are the major needs for the AM Sequencer. The AM Sequencer will also carry out the Road Warrior function, to remove redundant track candidates prior to track fitting.

The existing Hit Buffer cannot be used with the proposed increase in the number of track patterns. The Hit Buffer functionality will be transferred to a Pulsar board. The additional needed memory will be located on mezzanine cards.

The new Track Fitter will also use the Pulsar board, and will be able to work with a clock three times faster compared to the current Track Fitter. A mezzanine card similar to those used on the other SVT Pulsar boards will be utilized here. The FPGA firmware will be based on the firmware already existing for the current Track Fitter.

The block diagram of the upgraded SVT with the 3 Pulsar boards per wedge is shown in fig. 48.

Figure 48: Block diagram of the upgraded SVT.

In addition to the hardware tasks noted above, we will have to update the on-line, monitoring, and simulation software to reflect the properties of the new boards.

Commissioning the new system will proceed in three steps. New boards will first be tested in the Pulsar test stand. Since Pulsar boards are universal transmitters and receivers, a new board can receive simulated data from one Pulsar and drive its output into another Pulsar. This allows full functionality, full speed testing before a board is brought into the trigger room. When this is complete, the new board can be tested with the rest of CDF without interrupting data taking. An existing SVT splitter board can parasitically feed the real signals into the new board. Its output can be compared to expectation. Finally when these tests are complete, the new boards can replace the old ones in the operating system.

Phased installation is also possible. When the Track Fitters are ready, they can be installed, even if the new AM++ system is not ready. With the new Track Fitters in place, the SVT will operate faster than at present. The AM++ installation requires

the new Hit Buffers and Track Fitters because of the increase in the number of roads.

4.6.2 Summary

The second SVT upgrade has been approved and funded by Fermilab on July 2004. At the design Run IIb luminosity, CDF will be dead-time limited. The SVT upgrade will increase the amount of SVT triggered data CDF can collect by almost a factor of 2. Below design luminosity, it will allow to use lower thresholds for longer periods and to increase the data taking efficiency using DPS triggers at best.

5 SVT evolution: the Fast-Track processor for LHC experiments

The SVT experience would have a natural evolution in a more powerful device to be used in the future LHC experiments. The Fast-Track (FTK) processor has been developed as a R&D project with this purpose. The final goal of the FTK processor is to provide offline-quality tracks reconstructed in the whole detector. This job can be performed efficiently with the dedicated FTK processor. The possibility to have precomputed tracks allows to take full advantage of general purpose CPUs using them for more sophisticated tasks. The outcome of this strategy is a more powerful trigger system able to select more physics to tape.

The performances of FTK have been evaluated by using the ATLAS experiment as a benchmark. My contribution is summarized in the results described in the following sections. In sec. 5.1 I describe a realistic implementation of the FTK processor for the ATLAS experiment. In sec. 5.2 I give a few examples of what could be the physics reach gained with FTK.

5.1 A realistic FTK implementation

In order to consider a realistic application of FTK in terms of number of boards, interface to the experiment etc. it's necessary to decide where and how to insert the processor in the DAQ system and to evaluate the system parameters and a possible system configuration. The main parameters of a FTK processor that must be tailored are the following:

1. the detector layers to be used
2. the FTK input bandwidth
3. the size of the AM bank
4. the workload for the track fitter
5. the track fitting algorithm and quality
6. the detector interface

The first important choice that has been done in the past years is to insert the FTK processor in the ATLAS DAQ system [49] as shown in fig. 49. We propose to place the FTK processor downstream the Read Out Drivers (RODs), which means it will get the tracker data directly from a copy of the RODs outputs. The use of dedicated links allow to feed the FTK processor with event rates up to 100 kHz. The FTK performs track finding and outputs the list of tracks. The FTK output is stored in few Read Out Buffers (ROBs) that can be accessed by the level-2 processors. Data format in these ROBs is identical to that of the other ROBs. One of the great advantages of this scheme is that the size of the output data (the track list) is much smaller than the whole tracker data and can be easily accessed by the level-2 processor at high rate.

Figure 49: Diagram of the ATLAS DAQ system with the insertion of the FTK processor.

In this scheme the insertion of FTK in the DAQ system has a minimal impact. In fact, the only requirement is to send a copy of the data coming from the RODs to the FTK. This can be performed by substituting the ROD output interface called HOLA with a modified version of the HOLA, shown in fig. 50, that provides two identical copies of the output. One is sent to the ROB and the other one to FTK. The modified HOLA has been developed by the University of Chicago and its duplicated output can also be used for debugging purposes. This feature makes the HOLA useful independently of the implementation of FTK, reducing further on the impact of such an implementation on the DAQ. In alternative, since the ROD to ROB connection is an optical S-link [50], optical splitter can be used.

We suppose to use the FTK to perform tracking in the ATLAS Pixels and SCT sub-detectors [51]. The silicon detectors are necessary for a good impact parameter measurement, for this reason they should be used for the FTK on-line pattern recognition. Since the quality of the tracking obtained with silicon detectors is very good (the best impact parameter resolution is $17 \mu\text{m}$ [52] to be compared to $12 \mu\text{m}$, the best value that can be obtained if the whole tracker is exploited), we can plan, at least at the beginning, to use only these sub-detectors.

Figure 50: Picture of the modified HOLA printed circuit board. This HOLA can be used to send a copy of data coming out of RODs to the FTK processor for track finding.

This work proposes the configuration for a possible prototype to be used at the beginning of the LHC[53] run in 2007. The FTK configuration will include 6 barrel layers (Pix0, Pix2, SCT0-3) and, for each end-cap 3 Pixels disks and 6 SCT wheels as shown in fig. 51. SCT's stereo layers are not included.

5.1.1 Prototype description

The first thing to do is to choose and combine the real layers into logical layers that will be used for pattern recognition in the AM. FTK can perform pattern recognition on up to twelve logically defined tracking layers [6]. The chosen configuration of 6 logical layers is shown in fig. 51. In the simplified picture of fig. 51, barrel and disk layers are linked together to guarantee continuous pseudo-rapidity coverage. Detectors with the same patterned lines are logically combined together in order to build a complete layer.

Is it possible to make such a large amount of data available to FTK in time? The input bandwidth sets an upper limit either on the event rate or on the size of the detector connected to it. The FTK processor has an higher data flow rate with respect to the SVT thanks to the parallel readout of the detector on six buses. Nevertheless, in order to sustain very high event rates, it is necessary to organize FTK as a set of independent engines (each with an input bandwidth of 4 Gbit/s), each one working on a different sector of the silicon tracker. Let us divide the detector into azimuthal (ϕ) sectors. This segmentation generates some inefficiency at sector boundaries that can be removed by allowing small overlap regions at the boundaries.

Figure 51: Cross-sectional view (extracted from figure 1-1 in [51]) through the beam axis of one quarter of the ATLAS Semi-Conductor Tracker (SCT) and pixel detectors. The most forward SCT disks (7-9) are not used in this proposal and are not shown in the figure. Each “filling pattern” corresponds to a different logical layer.

Event Size for Different Detector Layers

Pixel Layer	# Cluster /Event	SCT Layer	# Cluster /Event	logical layer	Cluster rate (MHz) 50 kHz LVL1 rate $L=2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$
Barrel 0	1286	Barrel 0	635	Layer 0	64
Barrel 1	854	Barrel 1	652	Layer 1	61
Barrel 2	902	Barrel 2	655	Layer 2	50
Disk 1	216	Barrel 3	665	Layer 3	65
Disk 2	216	Disk 1	430	Layer 4	61
Disk 3	216	Disk 2	323	Layer 5	64
Disk 4	108	Disk 3/4/5/6	430		

Table 17: *Col 1-4*: conservative estimate of the average number of clusters per event per detector layer for the low luminosity occupancy. *Col 5-6*: conservative estimate of the cluster rates per Logical Layer for low luminosity. The level-1 output rate is chosen to be 50 kHz. Cluster rates for disks refer to both end caps.

I performed a conservative estimate of the cluster rates for each logical layer to determine the appropriate number of ϕ sectors for ATLAS. I assumed that, on average detector hits are clusters made of two strips or two pixels. I first evaluate the average number of clusters per event in each detector layer. I use the occupancies described in [51] to evaluate the contribution due to a single minimum bias event. I calculate

the occupancy at low and high luminosity using the overlap of respectively 5 and 25 minimum bias events, and 3 more events to add a conservative estimate of the hard interaction contribution (fig. 2-6 of [51] shows that this is a very conservative estimate for the hard interaction). For the SCT disks we consider the worst-case barrel occupancy. On top of this we add a noise contribution. The number of noise hits per events is a fraction of number of detector channels. We use 10^{-5} for the pixels and 10^{-4} for the SCT [51]. Tab. 17 shows the average number of clusters per event for real layers and the cluster rate for logical layers defined by the patterned lines in fig. 51. We show the rates expected at low luminosity with a reduced level-1 output rate (50 kHz). We use them to define the numbers of needed FTK processors (or ϕ -sectors) for the prototype in the low luminosity scenario.

In conclusion, since each logical layer is loaded in parallel into FTK at a cluster rate of 40 MHz, at the beginning we can segment the ATLAS detector in 2 ϕ -sectors. Since the FTK AM is provided with 6 input busses, these numbers are appropriate for a 6-layer configuration. The addition of extra layers is possible, but they would be serialized on the same existing busses with higher cluster rates. This would require more ϕ -sectors.

A single 9U VME crate would contain the engine core for one detector sector, as described in [6]. The core size is dominated by the large bank of pre-calculated hit patterns used to perform pattern recognition [6]. The required amount of AM, which in fact determines the core size, is evaluated in the next sections. In conclusion the FTK core for a low luminosity prototype will be made of 2 VME crates. The hardware necessary for the FTK connection to the detector is excluded in this computation.

5.1.2 FTK and detector simulation

In order to study the required amount of AM and the workload on the track fitter, we need a simulation of the ATLAS detector. I modified the existing SVT simulation package to prepare a simplified stand-alone simulation program that generates tracks in the ATLAS detector. It takes into account effects such as multiple scattering, ionization energy loss, detector noise, detector inefficiencies, and finite resolution smearing.

I studied the performance of the system using only a part of the silicon ATLAS detector: the ATLAS central detector [51] (barrel). I use only 7 cylindrical layers to find tracks: three pixel layers linked to four R- ϕ silicon layers. Even if the chosen detector layout is different from the one described in section 5.1.1, the simulation results are adequate to show the FTK capability and size.

5.1.3 Associative Memory size

I estimate the AM size for the barrel of the ATLAS experiment in order to show that the necessary system size is modest. I generate tracks in the whole detector. No detector symmetries are exploited, to prevent alignment problems. I store new patterns corresponding to the generated tracks, until the bank reaches the desired efficiency. A reference bank efficiency has been conventionally fixed at 90%.

Figure 52: Bank efficiency as a function of the bank size for P_T thresholds of 1 GeV/c and for different road sizes: large (open diamonds), medium (full triangles) and thin (circles). The bank size is for 1/4 of the whole barrel.

The generated track typology also affects the bank size. It is convenient to restrict the bank to include only tracks we care about. For this purpose I limit the region tracks come from (luminosity region) to that relevant for the physical processes to be studied. I assume a cylindrical luminosity region, with axis on the beam line, with a radius of 1 mm and ± 15 cm long in the longitudinal direction. This restriction is compatible with B-meson decay products, whose impact parameters are a few hundred microns. I include all tracks with $P_T > 1$ GeV. The road size is another critical parameter for both the processor performance and the pattern bank size. I use different values for Silicon and Pixel detectors. Three options, described in tab. 18, have been considered for the road widths. The size of the pre-computed pattern bank has been evaluated for these options. Fig. 52 shows the bank efficiency versus the bank size for the different road options.

In order to choose the optimal road size one must also evaluate the residual computing power needed at the level-2 trigger to complete the full resolution tracking (track fitter workload). Several techniques have been developed in CDF to optimize the use of AM systems. For example, it has been shown that optimizing the shape of the road, i.e. the road size at different layers, the necessary AM size can be reduced for constant

Definition of Road Sizes

Road Type	Pixel Detector	SCT Detector
	Granularity ($R\phi \times z$)	Granularity ($R\phi \times z$)
Large	5 mm x 6.5 cm	10 mm x 12.5 cm
Medium	2 mm x 6.5 cm	5 mm x 12.5 cm
Thin	1 mm x 6.5 cm	3 mm x 12.5 cm

Table 18: Three options considered for the road widths.

track fitter workload [54]. This further optimization has been left for future and more detailed analyses of the LHC applications.

5.1.4 Workload for the track fitter

Beyond the detector simulation a FTK simulation is also required. The simulation program must reconstruct the event in two subsequent steps, in order to reproduce the behavior of the hardware procedure (see [6] for details):

- coarse track (road) finding: all roads are found by simulating the FTK Associative Memory;
- track fitting: all found roads are processed to find the best track parameter values [52, 55] and to reject the fake ones. This is achieved by using linear approximations for the track constraints and the principal component analysis [56].

I wrote a simulation for the first step used to evaluate the track fitter workload. The ATLAS Genova group simulated the second step in order to evaluate the tracking quality [52].

Because of the finite size, a road may contain physical hits belonging to different particles. Also, depending on the road size and on the event hit density, there is a level of combinatorial background consisting of fake roads, i.e. track candidates that will be rejected at full resolution. Therefore, the complexity of the track fitting strictly depends on the following quantities:

- $\langle \#roads/\#track \rangle$: the average number of matching roads per actual tracks in each event;
- $\langle \#combinations/\#road \rangle$: the average number of hit combinations per matching road.

Fig. 53 shows these critical numbers as functions of the road size for the low luminosity run (5 minimum bias events are used as pile-up). The P_T threshold for tracks is fixed at 1 GeV. Results are reported for different QCD samples generated with increasing P_T thresholds of the outgoing partons: $P_T = 10, 40, 100$ and 200 GeV. Detector hits are produced from tracks in events generated with Pythia[45]. The event primary vertex is smeared using a gaussian distribution of $\sigma = 5.6$ cm along z . I allow for one

Fit Rates

Event Type	# fits/track	# tracks/event	# fits/event	level-1 rate(kHz)	Fit rate (MHz)
QCD P_T 200	658	17	11186	0.2	2.2
QCD P_T 100	74	16	1184	2	3
QCD P_T 40	14	10	140	5	0.75
QCD P_T 10	6	8	48	20	1.5

Table 19: Number of fits necessary to reconstruct different QCD events. The table columns show, in order, parton energy threshold, number of fits per real track, number of real tracks per event, a possible level-1 rate budget assigned to the sample at luminosity $L=2 \cdot 10^{33} \text{cm}^{-2}\text{s}^{-1}$, and the fit rate required for each sample.

missing point, requiring 6 fired layers out of 7 to find a track, thus reducing the effect of detector inefficiencies.

Figure 53: *Left plot:* average number of hit combinations per road as a function of the silicon detector road size. The different curves are for various parton thresholds in low luminosity run. The third point of the curve $P_T > 200 \text{ GeV}$ corresponds to 1400 combinations/road. *Right plot:* average number of matching roads per actual track as a function of the silicon detector road size.

We observe that the events with more energetic jets are characterized by larger combinatorial and larger number of fakes, as it is expected because of the jet fragmentation. I also observe that the thinnest road minimizes the differences between the samples. I choose this road size.

In tab. 19 I calculate the average number of fits per real track as the product of the two quantities plotted in fig. 53 for the different QCD samples, together with estimates of the level-1 bandwidths for those events and the corresponding fit rate. The number of fits to be executed is strongly dependent on the jet fragmentation. For the level-1 triggers shown in tab. 19, the total level-2 fit rate is 8 MHz. Since we measured that a Pentium III with an 800 MHz CPU can execute the linear fits at a rate of 1 MHz, eight such CPUs are enough to reconstruct these critical events. We plan to fit these CPUs in the FTK crates. If the detector is divided into two sectors, we can assign 4 CPUs to each sector. Since the fits will be distributed to the 8 CPUs, even the most energetic QCD sample has an average latency of 1-2 ms.

A very interesting alternative is to use a hardware track fitter based on the pulsar board that can perform linear fits as fast as 10MHz, as CDF is doing (see sec. 4.6.1). The use of powerful and cheap FPGAs, containing a lot of parallel hardware multipliers, would make possible to perform a fit each 30 ns, with a fitting rate of at least 33 MHz.

The track fitting algorithm and its quality are described in [52]. The achievable impact parameter resolution is $17 \mu\text{m}$.

In conclusion, a few level-2 processors or hardware fitters can reconstruct the input events.

5.2 FTK physics reach using b -tagging at level-2

In the following section I report few preliminary examples of how the use of FTK can increase the ATLAS physics reach. I participated to all these simulation studies devoted to new trigger selection definitions for the LHC experiments.

One of the major trigger applications of tracks is secondary vertex reconstruction for heavy flavor identification. Since we expect many of the new and exotic particles to be strongly coupled to heavy flavors, the possibility of selecting b -quark events (for both high- P_T physics and low- P_T B -physics) is very desirable. CDF has shown that it is possible to trigger on tracks at both level-1 and level-2. Full resolution and impact parameter selection are provided at level-2. Successful results of the CDF trigger based on on-line impact parameter reconstruction include the study of large samples of D and B hadronic decays and the selection of $Z^0 \rightarrow b\bar{b}$ hadronic events. It is possible to implement similar triggers at the LHC experiments. Preliminary rates and efficiencies have been calculated using the ATLAS software.

We propose new trigger strategies, based on the FTK potential, to collect samples rich in low- P_T b -quarks. We consider two physics cases that will take advantage of these new triggers. First we analyze a high cross section process, $Z^0 \rightarrow b\bar{b}$. Then we consider a rare process, $b\bar{b}H/A \rightarrow b\bar{b}b\bar{b}$.

5.2.1 New trigger strategies for b -quark events

In order to set reference goals for the new triggers, we consider as acceptable the following output rates:

- a few kHz for the level-1 selections. These rates are not too high, since FTK will produce high quality track information for these events allowing a minimum

level-2 computing power to reduce the rates as necessary;

- a few hundred Hz for the level-2 selections;
- a few Hz for the level-3 selections;

At this stage, the precise values of these rates are not critical. To estimate trigger rates we use the physics generator Pythia [45] and the detector simulator ATLASfast [57]. Actual trigger algorithms and threshold turn-on's were not simulated, so the rate estimates should be refined in the future with a detailed trigger simulation in order to be used in the actual experiment.

The jet clustering uses a cone radius $R = 0.4$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, with appropriate P_T -dependent jet corrections applied at each level. More specific corrections are needed because jets produced by b-quarks are reach in soft leptons. While the electron is well measured by the calorimeter, a large fraction of the muon (μ) energy is lost: in ATLASfast the reconstructed μ 4-momentum is added to the jet 4-momentum, if the μ is not isolated and its distance from the jet axis is smaller than $R = 0.2$. A b-jet is defined as a jet containing a b-quark within a cone of radius $R = 0.2$ with respect to the jet axis.

In order to evaluate the contributions to the rate from mistagging and from b-tagging inefficiency, we simulate generic QCD (with all b production mechanisms included). We use two sets of values for the tagging parameters: (a) a b-tagging efficiency of 100% and a mistagging probability of 0% (perfect tagging); (b) a b-tagging efficiency of 60% and a mistagging probability of 1% for u,d-quarks and of 10% for c-quarks (realistic tagging). We define two different level-1 selections for two different categories of events: $\mu 6$ +soft jets and all-jet.

1. Level-1: $\mu 6$ +soft jets

High cross section $b\bar{b}$ processes, in which the b-jet P_T 's are not very large, present problems at level-1. A good example of such a process is $Z^0 \rightarrow b\bar{b}$. At least two jets must be within the tracking acceptance region ($|\eta| < 2.5$) in order to be tagged as b-jets at level-2. However, a two jet requirement at low P_T would give a level-1 rate that is much too high. We thus add a soft-lepton trigger requirement:

- a μ with $P_T > 6$ GeV and $|\eta| < 2.5$;
- a soft jet with $P_T > 25$ GeV (i.e. sharp cut at 25 GeV) and $|\eta| < 2.5$;
- a second soft jet with $P_T > 10$ GeV and $|\eta| < 2.5$.

2. Level-1: all-jet

Events with more than 2 jets in the final state can exploit a pure calorimetric level-1 selection. A good example is final states with four b-jets, making b-tagging at level-2 very efficient. The ability to significantly reduce the trigger rate at level-2 makes an all-jet level-1 trigger with moderate jet P_T thresholds quite plausible. We require at least 3 soft jets and a total transverse energy in the event ($\sum E_t$) above a certain threshold. We consider two alternative sets of P_T thresholds.

The (a) set of cuts is:

Cut (GeV)	$\sigma_{QCD}(\text{nb})$	Rate (kHz)	$\epsilon_{H/A\bar{b}\bar{b}}(\%)$	$\sigma_{H/A\bar{b}\bar{b}}(\text{pb})$
$\mu 6 + \text{soft jets}$	1290	2.6	18.8	20.8
all-jet-a	7500	15	44.5	49.6
all-jet-b	2000	4	24.6	27.1

Table 20: Summary of level-1 selections performances. The table columns show, from left to right, selection name, the cross section for the selected QCD events, and level-1 output rates for an instantaneous luminosity $\mathcal{L} = 2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$, the efficiency for simulated signal events and the cross section for the selected signal events.

- a jet with $P_T > 50 \text{ GeV}$ and $|\eta| < 2.5$
- a jet with $P_T > 20 \text{ GeV}$ and $|\eta| < 2.5$
- a jet with $P_T > 15 \text{ GeV}$ and $|\eta| < 2.5$
- $\sum E_t > 150 \text{ GeV}$

The (b) set of cuts is:

- a jet with $P_T > 70 \text{ GeV}$ and $|\eta| < 2.5$
- a jet with $P_T > 50 \text{ GeV}$ and $|\eta| < 2.5$
- a jet with $P_T > 15 \text{ GeV}$ and $|\eta| < 2.5$
- $\sum E_t > 200 \text{ GeV}$

We used generic QCD events generated with Pythia ($P_T > 10 \text{ GeV}$ for the outgoing partons, $\sigma=6.53 \text{ mb}$) in order to study the $\mu 6 + \text{soft jets}$ selection. To study the all-jet selection we generated a QCD sample characterized by higher P_T threshold (MSEL¹²=1, $P_T > 20 \text{ GeV}$, $\sigma=0.64 \text{ mb}$).

Tab. 20 summarizes the rates. For each case, the table shows the selection requirements, the QCD cross section σ_{QCD} and the rate R for an instantaneous luminosity of $L=2 \cdot 10^{33} \text{cm}^{-2} \text{sec}^{-1}$; the efficiency $\epsilon_{H/A\bar{b}\bar{b}}$ and cross section $\sigma_{H/A\bar{b}\bar{b}}$ are shown for SUSY Higgs ($m_{H/A}=200$) events that, having four b -jets in the final state, can exploit all of these level-1 selections. The signal efficiencies are quite large. The rates are underestimated, since the trigger threshold smooth turn-ons of muons and jets were not simulated.

The natural selection criterion at level-2 is the presence of b -jets inside the tracking acceptance. Again we define two different selections for different level-2 categories: $M_{b\bar{b}}^{\text{cut}}$ and multi- b .

1. Level-2: $M_{b\bar{b}}^{\text{cut}}$

This selection is for events characterized by two b -jets only in the final state. At level-2 we require that both jets are b -tagged. Then we calculate the two b -jet mass and cut on it:

¹²MSEL is a Pythia switch that selects a set of physical processes to be simulated. MSEL=1 selects generic QCD two in two processes.

Level-2 selections and rates

Cut (GeV)	(level-1)	σ (nb)	R(Hz)	ϵZ^0 (%)	σZ^0 (pb)
realistic b-tagging					
$M_{b\bar{b}} > 50$	($\mu 6 + \text{soft-jet}$)	83	165	1.2	87
$M_{b\bar{b}} > 50$	(all-jet-b)	17	35	0.29	22
perfect b-tagging					
3-b	($\mu 6 + \text{soft-jet}$)	4.5	9	8.3	8.9
3-b	(all-jet-a)	9.8	19	27	28
3-b leading	(all-jet-a)	2.8	5.6	18	19
3-b	(all-jet-b)	4.4	9	18	19
3-b leading	(all-jet-b)	0.9	1.7	13	14

Table 21: QCD and signal events passing the level-2 trigger requirements. The table columns show, in order, different selection cuts, the cross section for the selected QCD events, and level-2 output rates for an instantaneous luminosity $\mathcal{L} = 2 \cdot 10^{33} \text{cm}^{-2} \text{s}^{-1}$, the efficiency for simulated signal events and the cross section for the selected signal events.

- at least two b-jets with $|\eta| < 2.5$;
- $M_{b\bar{b}} > M_{\text{cut}}$;

2. Level-2: 3-b

This selection is for events with more than 2 b-jets in the final state. We require at least 3 jets tagged as b-jets and then we require them to be the leading jets (3-b leading).

We can execute each level-2 selection on both level-1 triggers. Tab. 21 shows the resulting rates and signal efficiencies. To study the efficiency of this selection on the Z and Higgs signals, we simulate $10^5 Z^0 \rightarrow b\bar{b}$ with Pythia (MSEL=11, $P_T > 1$ GeV, $s = 7.6$ nb). Higgs signal efficiencies are evaluated with $2 \cdot 10^5$ events ($m_A = 200$ GeV, $\tan\beta = 30$, $\sigma = 111$ pb).

For statistical reasons the b-tagging is taken to be perfect for the 3-b selection (b-tagging efficiency 100% and mistagging probability 0 for all other quarks). This gives a conservative estimate of real trigger rates. Actual rates are roughly half of those produced by the use of perfect tagging. In fact the rate losses due to a realistic b-tagging efficiency (60%) are only partially balanced by the rate increase due to mistagging (1% for light quarks and 10% for c quark). We must also consider that a realistic b-tagging reduces the signal efficiency by roughly a factor $1/4$ ($\sim 0.6^3$) when requiring three real b-jets.

5.2.2 High Cross Section $b\bar{b}$ Processes: $Z^0 \rightarrow b\bar{b}$ (with soft μ @ LVL1)

High cross section $b\bar{b}$ processes, in which the b-jet E_T 's are not very large, present problems at each trigger level. The required low E_T jet threshold at level-1 would saturate the bandwidth, so a new strategy must be used. At level-2, b-jet identification

is mandatory for achieving an acceptable trigger rate. Additional rate reduction must also occur in the Event Filter.

A good example of such a process is $Z^0 \rightarrow b\bar{b}$. In many important ATLAS physics channels, such as Higgs decay into $b\bar{b}$ and Standard Model top decay, accurate mass reconstruction requires that the energy scale and resolution of b jets be well understood. For light quark and gluon jets, there are a number of ways to set the energy scale, *e.g.* $\gamma + \text{jet}$ and $Z + \text{jet}$ P_T balancing. These scales are modified for b -quark jets largely because of the energy lost to neutrinos and unidentified muons in the large fraction of b -jets containing a primary or secondary semileptonic decay, let alone the specific fragmentation function.

In the past, the correction for b -jet response has been derived from simulated events. For precision measurements, this is less than satisfactory; a direct experimental measurement is preferable. The observation of a known $b\bar{b}$ resonance would solve the problem. The obvious candidate is $Z \rightarrow b\bar{b}$. The challenge at a high-energy hadron collider is the large $gg \rightarrow b\bar{b}$ continuum and the even larger gluon and light quark dijet continuum.

To choose the trigger selection, we start considering that at least two jets must be within the tracking acceptance region in order to be tagged as b -jets. However, a two jet requirement at low P_T would give a rate that is too high, even for the level-1. A soft-lepton trigger requirement as in the $\mu 6 + \text{soft jets}$ level-1 trigger reduces the rate and increases the purity of the sample. At level-2 the requirement $M_{b\bar{b}} > 50$ reduces the rate to 165 Hz, see tab. 21.

The significance for an integrated luminosity of 20 fb^{-1} , estimated with just a $M_{b\bar{b}} > 70$ cut, is:

$$S = \frac{\sigma_{Z^0} \times L_{int}}{\sqrt{\sigma_{qcd} \times L_{int}}} = 46.$$

If we look for the Z^0 signal in the optimized window $80 < M_{b\bar{b}} < 100$, the significance increases above 60, with a signal to noise ratio $\frac{S}{N} \approx \frac{1}{250}$.

Of course, the level-2 output rate must be reduced further in the event filter before recording standard size events. However, if level-2 b -tagging is of high quality, then the double-tagged dijet sample will be almost pure $b\bar{b}$.

A possible strategy, that allows to write a larger amount of this events to tape is to use mini-events. The idea is to reduce, for this calibration sample, the event size as much as possible dropping all the informations that will not be required to study b -jet energy scale, resolution and correction. The use of FTK helps also in this direction, since the tracker data can be replaced with reconstructed tracks with a large reduction in size.

If complete events are written out, the level-2 output rate must be further reduced by a factor of 100 in the Event Filter. In principle, the significance is high enough that the events could simply be prescaled, giving a significance of 6 in the 80-100 GeV window for a prescale of 100. However, it is clearly desirable to use quality cuts to select gold events to be written on tape. This will be the subject of future investigations. An other possibility is to dedicate a larger fraction of the available bandwidth to the

collection of $Z^0 \rightarrow b\bar{b}$ sample when the instantaneous luminosity is low, as it could happen during the first period of the LHC run.

In conclusion, a high significance $Z^0 \rightarrow b\bar{b}$ peak can be selected using the FTK processor. The output rate after level-2 is high, but there are several strategies that can be applied to reduce it. We emphasize that this channel is not accessible if b-tagging is not used in the trigger.

5.2.3 Low Cross Section $b\bar{b}$ Processes: $b\bar{b}H/A$

For low cross section processes that contain a distinctive and relatively rare signature, high efficiency trigger strategies can be developed. The SUSY Higgs final state studied here contains four b-jets, making b tagging at level-2 very efficient. The level-1 all-jet-a selection is 45% efficient for the signal (see tab. 20) and produces the highest efficiency also at level-2 (26% in tab. 21). However, the level-1 output rate is 15 kHz. The rate for the all-jet-b is an acceptable 4 kHz and the 18% efficiency at level-2 is greater than that of the μ selection. Of course, if a $\mu 6$ +soft jets level-1 trigger is used for other purposes, the level-2 3-b trigger could be fed by both the all-jet and $\mu 6$ +soft jet level-1 triggers, significantly increasing the overall efficiency for this process.

The analysis for this signal can be found in [58]. It requires the four most energetic jets to be tagged as leading b-jets. However, such a selective cut is unnecessary for trigger purposes.

Tab. 21 shows that for the 3-b leading selection applied to all-jet (b) level-1 criteria the rates are reasonable and the signal efficiency is 13%. This is even better than the optimal one reported in [58] for the supersymmetric Higgs signal. We again note that the signal efficiency would be even larger if in addition to the all-jet trigger we used the $\mu 6$ +soft jet trigger at level-1.

In order to make the physics case clearer, we report fig. 54 from [58], that shows 5σ -discovery contours in the $m_A, \tan\beta$ plane for the $b\bar{b}H/A \rightarrow b\bar{b}b\bar{b}$ analysis and for integrated luminosities of 30 and 300 fb^{-1} . The figure compares the discovery contours due to trigger inefficiencies assumed in 1999 (solid and dashed curves) to those potentially within the detector reach (dotted curves). Trigger inefficiencies basically come from high P_T jet thresholds and, in the up-to-date scenario of budget cuts, have been hardened since 1999, pushing the discovery curves to even higher values of $\tan\beta$ than those shown in fig. 54.

Conversely, the trigger strategy just described here is fully efficient for this analysis, in the sense that it would correspond to the dotted lines in fig. 54. As a result of the rate reduction from b-tagging in the level-2 trigger, we can record on tape events selected with low P_T thresholds (70, 50, and 15 GeV for the first three jets respectively). These thresholds are significantly smaller than those presently set in the jet menus of the LHC experiments.

5.2.4 Low Cross Section $b\bar{b}$ Processes: $ZH \rightarrow b\bar{b}b\bar{b}$

To get a feeling for the efficiency of the cuts just described, we look at $Z^0H \rightarrow b\bar{b}b\bar{b}$. This channel is very similar to the previous one, with the exception that now there are

Figure 54: 5σ -discovery contours curves in the $(m_A, \tan\beta)$ plane for the $b\bar{b}H$, $b\bar{b}A$ with $H/A \rightarrow b\bar{b}$ channels, for integrated luminosities of 30 fb^{-1} and 300 fb^{-1} . The dotted lines show the expected extension in coverage if the LVL1/LVL2 trigger thresholds are not applied.

two heavy bosons, each with a mass constraint.

We generate 10^5 events with Pythia (ISUB¹³ = 24, $\sigma = 0.071 \text{ pb}$). Tab. 22 shows the estimated signal efficiencies. The bottom line is that $Z^0H \rightarrow \bar{b}b\bar{b}b$ events are selected with high efficiency by the same trigger cuts used in the previous section for $\bar{b}bH/A$ events.

Selection	# Z^0H	$\sigma_{Z^0H} \text{ (fb)}$	$\epsilon \text{ (%)}$
L1: 3 jets (2nd set)	40622	29	40.6
L2: 2 leading b-jets	29547	21	29.5
L2: 3 b-jets	34353	24	34.4
L2: 3 leading b-jets	20909	15	20.9

Table 22: $Z^0H \rightarrow \bar{b}b\bar{b}b$ events passing the level-1 and level-2 trigger requirements described in section 5.2.1. The table columns show, in order, level-1 and level-2 criteria, the numbers of selected Z^0H events, cross sections for the selected Z^0H events, and efficiencies for the Z^0H signal.

5.2.5 Conclusions

A hardware track finder for the ATLAS experiment would provide rapid track reconstruction for all events passing the level-1 trigger. By producing high quality tracks

¹³ISUB is a Pythia switch that selects a specific physical process to be simulated.

early in the level-2 processing, FTK would speed up the level-2 algorithms for most objects, reducing the number of necessary CPUs and allowing higher level-1 trigger rates. In particular, the fast track finder would extend the trigger acceptance of interesting events with low P_T objects such as b-quarks or τ 's, by separating them from the huge QCD background.

5.3 Background studies for hadronic final states rich of b-quarks

In this section we report a preliminary study, based on the CDF experience, of backgrounds for hadronic final states rich of b-quarks. These kind of events are the background for all the channels described in section 5.2. Hadronic final states rich of b-quarks are used in several searches such as top quark, Higgs and SUSY. They have been used in CDF Run I, they will be used in Run II and at LHC experiments [59, 60, 61, 22, 58]. Unfortunately, these hadronic channels are affected by a very large and uncertain QCD background. Monte Carlo studies in this sector cannot be conclusive because of the large uncertainties affecting the multi-jet QCD background. Since the most common way to predict the cross-section of such backgrounds at LHC is the use of shower Monte Carlos, it's very interesting to see if they have been reliable to predict cross-sections at the Tevatron.

First of all we collect results from Run I analysis, where b-jets are required in the hadronic final state. No new results are available from Run II data yet. We report indications that rates predicted by shower Monte Carlo Pythia are much larger than rates observed in the data. This result is surprising, since in principle the leading log approximation is expected to underestimate the multi-jet cross sections.

As a second step, we compare Herwig and Pythia predictions to understand if these large cross sections are typical of Pythia. We find that the two Monte Carlos are quite different, if jets are not required to be above a certain P_T threshold. However, the difference is strongly reduced when only jets above 15 GeV are taken into account, as it is usually done in real data analyses.

Finally, we use shower Monte Carlos to find a possible explanation of the CDF results. We show that gluon splitting and flavor excitation are the dominant processes when events with large jet multiplicities are selected. The Monte Carlos are not checked yet against the data for these particular processes in events with large jet multiplicities. In the future they must be carefully tested against the data.

5.3.1 CDF results

Physic study	selected sample	sample name
Search of events $p\bar{p} \rightarrow b\bar{b}\phi \rightarrow b\bar{b}b\bar{b}$ [61]	4 b-jet + X	4B
Search of events $p\bar{p} \rightarrow VH$ [60]	2 b-jet + 2 jet + X	2B2J
All hadronic decay of $t\bar{t}$ pairs [59]	2 b-jet + 4jet + X	2B4J
Search for new particles decaying to $b\bar{b}$ [62]	2 b-jet	2B

Table 23: Physic analysis affected by QCD multi-jet background rich of b-quarks.

CDF Run I		PYTHIA
QCD heavy flavors	QCD fakes	QCD $2 \rightarrow 2$
50.6 ± 11.0	12.1 ± 10.5	1856.2 ± 703.5

Table 24: Expected QCD heavy flavor events in CDF Run II (1 fb^{-1}), calculated from observed Run I data and predicted by PYTHIA.

sub-process	$\sigma(\text{pb})$	$\epsilon_{trig}(\%)$	$\epsilon_{E_T}(\%)$	$\epsilon_{>3b-jet}(\%)$	$\epsilon_{tot}(10^{-2}\%)$	N (events/ fb^{-1})
$q\bar{q}, gg \rightarrow q\bar{q}$	$1.2 \cdot 10^4$	1.23 ± 0.01	63.9 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
$qq, gg \rightarrow qq, gg$	$4.9 \cdot 10^5$	0.98 ± 0.01	60.6 ± 0.3	0.04 ± 0.02	0.02 ± 0.01	972.6 ± 561.5
$gq \rightarrow gq$	$4.4 \cdot 10^5$	1.01 ± 0.01	62.6 ± 0.3	0.02 ± 0.02	0.01 ± 0.01	593.3 ± 419.5
$gb(c) \rightarrow gb(c)$	$3.1 \cdot 10^4$	0.76 ± 0.01	60.3 ± 0.3	0.14 ± 0.04	0.06 ± 0.02	198.3 ± 57.3
$q\bar{q}, gg \rightarrow b\bar{b}, c\bar{c}$	$8.2 \cdot 10^3$	0.94 ± 0.01	62.7 ± 0.2	0.19 ± 0.04	0.11 ± 0.04	91.9 ± 17.7
Total	$9.8 \cdot 10^5$	0.99 ± 0.01	61.6 ± 0.6	0.03 ± 0.01	0.02 ± 0.01	1856.2 ± 703.5

Table 25: Individual and total cross sections and acceptances for the different QCD hard scattering di-jet sub-processes modeled with Pythia. Events are generated with hard scattering $p_T > 40 \text{ GeV}/c$. The E_T thresholds used to calculate ϵ_{E_T} correspond to the selection for $M_{2\text{jets}} = 100 \text{ GeV}/c^2$. Last column shows the expected number of events for 1 fb^{-1} . (More on [61])

The collected analyses, whose observed background is interesting, are summarized in tab. 23. We associate a label to each analysis (last column) that we will use to identify the corresponding selected sample.

The first sample (4B) is the QCD background for $p\bar{p} \rightarrow b\bar{b}\phi \rightarrow b\bar{b}b\bar{b}$ [61], where ϕ is a neutral MSSM Higgs boson. The selection starts requiring at least 3 b -jets (in this section, we define a b -jet as a jet tagged by a secondary vertex) and at least 4 jets above 15 GeV. Tab. 24 shows the number of QCD events expected in the CDF Run II (integrated luminosity of 1 fb^{-1}) extrapolating data observed in Run I, compared to the Pythia prediction for the same integrated luminosity.

These numbers are taken from tables 4 and 5 of reference [61], where the analysis is described in detail. It is interesting to note that the Pythia rate is much higher (a factor 30, although with a large error). Tab. 25 shows the cross sections and acceptances for each simulated sub-process. It is clear that direct production is a small fraction of the background for this analysis.

The second sample (2B2J) is the QCD background for $p\bar{p} \rightarrow HV \rightarrow b\bar{b}qq$ [60] and the third sample (2B4J) is the QCD background for $p\bar{p} \rightarrow t\bar{t} \rightarrow b\bar{b}qqqq$ [59]. In fig. 55 and fig. 56 we see that the QCD multi-jet background is the biggest contribution. Also in these cases Pythia produces good shapes, within the statistical errors, for the studied background distributions. However, since Pythia prediction for the absolute cross-section was exceedingly high, it has been determined from the data [60, 59, 61].

The fourth sample (2B) seems to give very different results. In paper [62] the differential cross section is published as a function of the two b -jet mass. The observed

Figure 55: Invariant mass distribution, $M_{b\bar{b}}$, for 90.6 pb^{-1} of CDF data (points) compared to the fit prediction. The solid line is the sum of the QCD, fakes, $t\bar{t}$, and Z+jets components. The QCD normalization is left free in the fit, while the normalizations of the fakes, $t\bar{t}$, and Z+jets are constrained by Gaussian functions to their expected values and uncertainties.

cross section is compared to Pythia direct production, and the agreement is good. Other $b\bar{b}$ production mechanisms, gluon splitting and flavor excitation, are declared negligible. Fig. 57 shows the results.

In conclusion Pythia is able to reproduce the absolute cross-section for the double b-jet selection, but not for higher multiplicity events with at least 2 b-jets.

5.3.2 Comparing different production mechanisms and Monte Carlos

In order to investigate more deeply the reasons for the Pythia success in the 2B sample and failures in the other samples, we tried to reproduce the results of the 2B sample and after that we studied the multi-jet selections. We use Pythia 6.136 (after switching the multiple interaction OFF) and Herwig 6.1 to generate events at 1.8 TeV with the structure function GRV94L [63].

The generated events are simulated in the detector and reconstructed with a fast and simple software, CMSJET¹⁴, which is not specific for CDF but allows the comparison between different production mechanisms and different Monte Carlos, taking into account a typical hadron collider detector and a typical clustering algorithm (fixed cone with $R=0.6$, pre-clustering seed $E_T = 5$ GeV). In this case we define “b-jet” a jet that has inside its cone (cone radius = 0.6) a particle composed of a b-quark. We require the two leading b-jets to be inside $|\eta| < 2$. We fix a minimum parton $\hat{p}_T$ value in the shower Monte Carlo. To be efficient in event generation the $\hat{p}_T$ threshold was

¹⁴CMSJET was used since a large sample of events was already available.

Figure 56: Reconstructed mass distribution for events with at least one tag (dots). Also shown are the background distribution (shaded) and the contribution from $t\bar{t}$ Monte Carlo events with $M_t=175 \text{ GeV}/c^2$ (hollow). The inset shows the difference in $-\ln(\text{likelihood})$ and the fit used to determine the top mass.

Figure 57: The dijet mass distribution (circles) and double-b-tagged dijet mass spectrum (boxes) compared to a fit to a smooth parametrization (dashed curves). Also shown is a QCD prediction for $b\bar{b}$ production (solid curve)

Figure 58: η distribution for the two final state partons, produced with Herwig (dashed line) and Pythia (solid line). The bias due to the request $\eta < 4$ is negligible.

Figure 59: Differential cross sections (pb/GeV) as functions of $\sum P_T$, produced with Herwig and Pythia, for 3 different parton $\hat{p}_T$ thresholds: 20, 40 and 70 GeV. The plots show that the bias due to the request $\hat{p}_T > 40$ and $\hat{p}_T > 70$ GeV is negligible for $\sum P_T > 150$ and $\sum P_T > 250$ GeV respectively.

progressively increased and a cut on the pseudo-rapidity of the final state partons is applied (before radiation). In tab. 26 the simulated samples are summarized.

Fig. 58 shows the parton η distribution for events that pass our selection. These plots show that the generation cut $|\eta| < 4$ does not bias the sample. The $\hat{p}_T$ cut, instead, introduces a bias, which can be canceled with a cut on the event $\sum P_T$, see fig. 59. Unfortunately, the unbiased sample is much smaller than the generated one. The used cuts are $\sum P_T > 150$ and $\sum P_T > 250$ GeV for the two samples generated with $\hat{p}_T > 40, > 70$ GeV respectively. Maybe the cut on $\sum P_T$ is not the more efficient way to eliminate the bias, but it is a typical selection of all multi-jet analyses at CDF, since all of them use the multi-jet sample, collected with a calorimetric $\sum E_T$ request in the trigger. For this reason we chosen this quantity to remove the bias.

We classify events on the basis of the $2 \rightarrow 2$ hard scattering, independently of the

MC	threshold $ \eta $	threshold $\hat{p}_T$ (GeV/c)	$\sigma(pb)$ ($\times 10^3$)	Number of ev. ($\times 10^3$)	$\int \mathcal{L}$ pb^{-1}	Number of ev. with $b\bar{b}$ ($\times 10^3$)
Pyt	< 4	20	31440	5000	0.16	228 (4.5%)
Her	< 4	20	22633	5000	0.22	161 (3.2%)
Pyt	< 4	40	1289	5000	3.88	290 (5.8%)
Her	< 4	40	936.2	5000	5.34	259 (5.2%)
Pyt	< 4	70	74.49	5000	67.12	316 (6.3%)
Her	< 4	70	54.43	5000	91.86	278 (5.5%)

Table 26: Features of QCD samples generated using Pythia and Herwig: $\hat{p}_T$ and η thresholds, cross section, number of generated QCD events, integrated luminosity and number of events with at least a b -quark in the final state.

following evolution:

1. an event is classified “direct production” if the two partons in the final state are $b\bar{b}$;
2. an event is classified “flavor excitation” if only one parton in the final state is b or $\bar{b}$;
3. an event is classified “gluon splitting” if neither parton in the final state is b or $\bar{b}$.

Fig. 60 shows the Pythia (on the left) and Herwig (on the right) differential cross-sections as functions of the two b -jet mass, for the 2B sample. The total cross section is the solid line, while the dashed line is used for the 3 production mechanisms: gluon splitting at the top, direct production in the middle and flavor excitation at the bottom.

Events are generated as shown in tab. 26. The two dashed lines in each plot correspond to the parton $\hat{p}_T > 40$ GeV threshold and 70 GeV samples, showing the generation bias of the $\hat{p}_T > 70$ GeV sample with respect to that of the $\hat{p}_T > 40$ GeV sample, while the single solid line corresponds to the less biased $\hat{p}_T > 40$ GeV sample. Events are selected requiring at least 2 b -jets inside $|\eta| < 2$.

At energies where the $\hat{p}_T$ generation bias is negligible, direct production is more important than other mechanisms, as stated by the paper [62].

This result shows that both Herwig and Pythia are doing a good job for direct production, which is tested by the CDF measurement [62]. Gluon splitting and flavor excitation are not tested, instead since their contribution is negligible.

In fig. 61 we compare the two Monte Carlos for each production mechanism. The $\hat{p}_T > 40$ GeV sample is shown on the left and the $\hat{p}_T > 70$ GeV sample is shown on the right. We can see that direct production is very similar in Herwig and Pythia, while some differences are present for the other two mechanisms. Pythia has higher cross-sections for flavor excitation and gluon splitting.

Fig. 62 shows the double- b -tagged dijet mass spectrum as shown in fig. 60, but adding the $\sum P_T > 250$ GeV request. The cut on the event $\sum P_T$, usually used on multi-jet analysis to remove the trigger bias, but not used in the 2B sample, decreases the importance of the direct production mechanism in the mass region interesting for

Figure 60: Double-b-tagged dijet mass spectrum produced with Pythia+CMSJET (left) and Herwig+CMSJET (right). The three production mechanisms, gluon-splitting, direct production and flavor excitation, are compared (dashed lines) with the total (solid line). In each plot, a second dashed line, which is below the first one, shows the cross-section of the same production mechanisms but generated with a higher parton p_T threshold. These lines show the effect of the generation bias.

the Higgs search (between 100 and 140 GeV). The effect is clearly visible in fig. 62, where we can see that at invariant mass equal to 120 GeV direct production is a factor 10 below the total cross-section.

Fig. 63 and 64 show the effect of a six jets requirement, similar to the 2B4J sample. The difference between Herwig and Pythia is reduced if all jets are required to be above

Figure 61: Comparison of the double- b -tagged dijet mass spectrum produced with Pythia (solid line) and Herwig (dashed line). The $\hat{p}_T > 40$ GeV sample is on the left and the $\hat{p}_T > 70$ GeV sample is on the right.

a p_T threshold of 15 GeV (see fig. 65). However, there is a residual factor 3-4 between

Figure 62: Double-b-tagged dijet mass spectrum produced with Pythia+CMSJET (left) and Herwig+CMSJET (right). The three production mechanisms, gluon-splitting, direct production and flavor excitation are compared (dashed lines) with the total (solid line). The effect of the $\hat{p}_T > 70$ generation cut is removed by the request $\sum P_T > 250$ GeV.

the Herwig and Pythia cross sections. This is a large number for shower Monte Carlos using the same structure function.

In conclusion, the MC vs data comparison in the 2B sample only tests the direct production mechanism, since flavor excitation and gluon splitting contributions to that sample are negligible. A $\sum E_T$ cut reduces the importance of direct production at invariant masses approximately below the $\sum E_T$ threshold. In this region, the contributions of flavor excitation and gluon splitting are dominant. In this case Herwig

and Pythia show large differences among each other and have not been tested against data. The differences are larger if more jets are required in the event.

Figure 63: Double- b -tagged dijet mass spectrum produced with CMSJET+PYTHIA (on the left) and Herwig+CMSJET (on the right). The three production mechanisms, gluon-splitting, direct production and flavor excitation are compared (dashed lines) with the total (solid line).

5.3.3 Conclusions

The CDF data from RUN I offer an interesting background sample to test Monte Carlos for QCD multijet events, rich of b -quarks. We find indications that Pythia

Figure 64: Comparison of the double-b-tagged dijet mass spectrum produced with Pythia (solid line) and Herwig (dashed line). Only events with at least 6 jets are included.

overestimates the observed cross sections by a large factor.

To understand if the effect is due to Pythia peculiarity or to other characteristic

Figure 65: Double- b -tagged dijet mass spectrum produced with Pythia (on the left) and Herwig (on the right). The three production mechanisms, gluon-splitting, direct production and flavor excitation are compared (dashed lines) with the total (solid line). Only jets with a p^T greater than 15 GeV have been taken into account. Six of these jets are required.

of the shower Monte Carlo approach we perform a comparison between Pythia and Herwig.

We do not find large differences between their cross sections, when only jets above 15 GeV are taken into account, as it is done in all CDF analyses, even those showing the Pythia excess. So, even if it would be nice to understand the Pythia vs Herwig differences, we do not expect that this will help to completely clarify the Pythia vs CDF data differences.

We show that gluon splitting and flavor excitation are the dominant processes contributing to the double b-jet invariant mass, when events with large final state multiplicities and large $\sum E_T$ are selected. These processes must be carefully tested against data.

In these exclusive analyses shower Monte Carlos show discrepancies with respect to the data. In more inclusive analyses such as [62], data are well described by shower Monte Carlos. We succeeded in reproducing these good cases.

Conclusions

The success of the SVT processor was clear since the beginning of CDF Run II. The B-physics program allowed by this device is competitive and complementary with those of B-factories. In particular, the B-physics program was very important, at the beginning or Run II, when the Tevatron luminosity was too low for high- P_T physics. In the meanwhile, CDF has discovered that it needs more integrated luminosity than expected for the most important B-physics measurements, such as those of the B_s mixing and the γ angle. For this reason, the SVT role, which was initially limited to the first part of Run II (Run IIa), has been extended and it will be necessary for the whole CDF life. We have proposed and got approval of the SVT upgrade that will extend the SVT application at very high luminosities.

In this thesis I have described the wide range of SVT applications within CDF. In particular, as an example of challenging measurement with SVT, I discussed that of the γ angle. The SVT upgrade will double the data sample that CDF will collect in the remaining four years of run. Hence, it is very important for all those measurements that will be statistics limited. In fact, for those measurements, the SVT upgrade is effectively providing four additional years of CDF data!

CDF is doing a large effort to improve the trigger and DAQ capabilities. In fact, as it usually happens at hadron colliders, the physics reach can be significantly enlarged with a better trigger system. An example of a recent improvement is the implementation of the 4/5 criterion in the SVT track matching logic, which increased the data taking efficiency by 60%, but at the price of a smaller level-1 bandwidth, which partially cancels the effective gain.

In this scenario, I dedicated myself to investigate how to increase the CDF physics reach through trigger and DAQ improvements. I have found that the level-2 processing time, and in particular the SVT timing, has a significant dependence on luminosity. That meant that the available level-1 bandwidth is decreasing with increasing luminosity. I found that the SVT, after the planned upgrades of the other level-2 subsystems, will be the slower part of the level-2. Hence, the upgrade of the SVT will have a large impact on level-2 performances. My merit was to show that, because of the limited number of level-2 buffers, all those statements hold true, even if the SVT input bandwidth is higher than the design level-1 bandwidth of 50kHz.

The proposed SVT upgrade, beyond improving the SVT timing, will increase its functionality. The SVT trigger for forward muons is an example, but other applications are also possible.

A second generation track processor, namely the FTK, is being developed in Pisa. The fact that such an expertise were available was essential for the proposal and the ongoing realization of the SVT upgrade. The SVT upgrade is a wonderful starting point for applications of this pattern recognition technology at future experiments. The development of a standard-cell associative memory for CDF can be exploited for very powerful applications at future hadron collider experiments.

I joined the FTK project during Summer 2000. I gave a relevant contribution to the definition of a baseline FTK design for the ATLAS experiment and to the FTK hardware development. I have shown examples of the impact of an evolved SVT

tracking processor (FTK) on the trigger and physics program of ATLAS. Whatever is the source of electroweak symmetry breaking, the role of the third generation is likely to be big. The FTK device increases our ability to select b-quarks and τ 's. Having it is a compelling need.

Finally, I have shown that the backgrounds of part of the physics of interest for FTK are overestimated by shower Monte Carlos. As a consequence, the approach to very important physics, such as Higgs physics with multi b-quarks in the final state, could be easier than expected.

Acknowledgments

Preparing a PhD thesis is a long and difficult job, only thanks to the help of many people I was able to complete it.

I wish to thank Paola Giannetti, who guided me in everyday activities and in solving the most puzzling problems. I'm grateful to Mauro Dell'Orso, who encouraged and helped me in studying in depth many scientific aspects.

I also want to thank all colleagues from the CDF experiment and INFN staff, in particular Antonio Bardi, Roberto Carosi, Pierluigi Catastini, Alessandro Cerri, Simone Donati, Ivan Furik, Camille Ginsburg, Paolo Giovacchini, Fabio Morsani, Giovanni Punzi, Michael Schmidt, Mel Shochet, Antonio Sidoti, Franco Spinella.

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