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# CDF - Run II Status and Prospects

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## **Abstract**

After a five year upgrade period, the CDF detector located at the Fermilab Tevatron Collider is back in operation taking high quality data with all subsystems functional. We report on the status of the CDF experiment in Run II and discuss the start-up of the Tevatron accelerator. First physics results from CDF are presented. We also discuss the prospects for  $B$  physics in Run II, in particular the measurements of  $B_s^0$  flavour oscillations and  $CP$  violation in  $B$  decays.



## Introduction

The CDF experiment can look back to a successful  $B$  physics program during the 1992-1996 Run I data taking period. The highlights of Run I  $B$  physics results from CDF include the measurements of the lifetimes of all  $B$  hadrons [1], several measurements of the  $B^0$  flavour oscillation frequency  $\Delta m_d$  [1], the discovery of the  $B_c$  meson [2] and first evidence that the  $CP$  violation parameter  $\sin 2\beta$  is different from zero [3]. Since 1996, the CDF detector has undergone a major upgrade [4] to allow operation at high luminosities and bunch spacings of up to 132 ns, as originally planned for Run II of the Tevatron. The upgraded CDF detector contains several completely new components that took years for successful completion.

Run II officially started in March 2001. Since then much work has gone into commissioning the CDF detector. With the beginning of 2002, the CDF detector is in stable running conditions operating with reliable physics triggers. We report about the first physics results obtained with the upgraded CDF detector from the analysis of the first Run II data collected until the summer of 2002.

## Start-up of Run II

### The Upgraded Tevatron Accelerator

The Fermilab accelerator complex has also undergone a major upgrade since the end of Run I. The centre-of-mass energy has been increased to 1.96 TeV. But most importantly, the Main Injector, a new 150 GeV proton storage ring, has replaced the Main Ring as injector of protons and anti-protons into the Tevatron. The Main Injector also provides higher proton intensity onto the anti-proton production target, allowing for more than an order of magnitude higher luminosities. An additional new storage ring, the Recycler, housed in the same tunnel as the Main Injector, will allow to reuse anti-protons at the end of each store. The design luminosity during the first phase of Run II (Run IIa) is  $5\text{-}8\cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$  for a final integrated luminosity of  $\sim 2 \text{ fb}^{-1}$  by the end of Run IIa. The present bunch crossing time is 396 ns with a  $36 \times 36 \text{ } p\bar{p}$  bunch operation.

Figure 1(a) shows the development of the initial Tevatron luminosity from late 2001 to late 2002. So far, the peak luminosity reached by the Tevatron is  $3.7\cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$  still below expectations. Figure 1(b) is a diagram of the integrated luminosities delivered and recorded by CDF. This graph also includes the amount of data recorded with information from CDF's silicon vertex detector. The total integrated luminosity recorded by CDF in 2002 is about  $100 \text{ pb}^{-1}$  (equivalent to the Run I data set).

### CDF Detector Performance in Run II

The CDF detector improvements for Run II [4] were motivated by the shorter accelerator bunch spacing of up to 132 ns and the increase in luminosity by an order of magnitude. All front-end and trigger electronics has been significantly redesigned and replaced. A DAQ upgrade allows the operation of a pipelined trigger system. CDF's tracking system

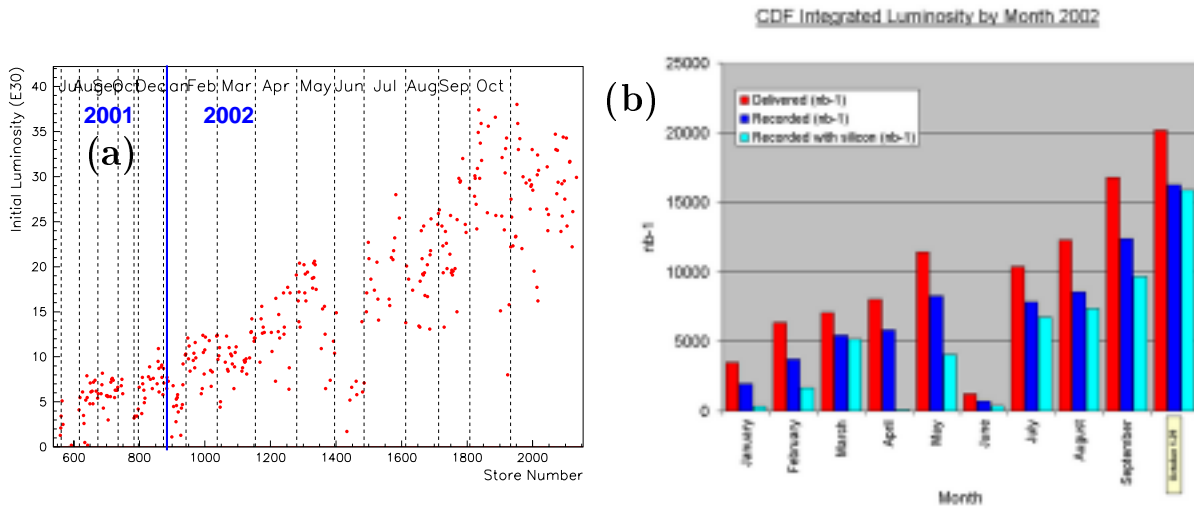


Figure 1: Distribution of (a) the initial luminosity delivered by the Tevatron and (b) the integrated luminosity per month delivered by the Tevatron and recorded by CDF as well as the fraction of data with silicon information.

was completely upgraded. It consists of a new Central Outer Tracker (COT) with 30,200 sense wires arranged in 96 layers combined into four axial and four stereo superlayers. It also provides  $dE/dx$  information for particle identification. The Run II silicon vertex detector consists of seven double sided layers and one single sided layer mounted on the beampipe covering a total radial area from 1.5-28 cm. The silicon vertex detector covers the full Tevatron luminous region which has a RMS spread of about 30 cm along the beamline and allows for standalone silicon tracking up to a pseudo-rapidity  $|\eta|$  of 2. The forward calorimeters have been replaced by a new scintillator tile based plug calorimeter which gives good electron identification up to  $|\eta| = 2$ . The upgrades to the muon system almost double the central muon coverage and extent it up to  $|\eta| \sim 1.5$ .

The most important improvements for  $B$  physics in Run II are a Silicon Vertex Trigger (SVT) and a Time-of-Flight (ToF) system with a resolution of about 100 ps. The later employs 216 three-meter-long scintillator bars located between the outer radius of the COT and the superconducting solenoid. The CDF II Time-of-Flight detector and its performance has been presented by S. Giagu [5] at this conference. As an example of the preliminary performance of the new Time-of-Flight system, Figure 2(a) shows the distribution of reconstructed mass versus momentum for positive and negative tracks showing clear separation of  $\pi$ ,  $K$  and  $p$ . The Time-of-Flight system will be most beneficiary for the identification of kaons with a  $2\sigma$ -separation between  $\pi$  and  $K$  for  $p < 1.6$  GeV/ $c$ . This will enable CDF to make use of opposite side kaon tagging and allows to identify same side fragmentation kaons accompanying  $B_s^0$  mesons [5].

In Run I, all  $B$  physics triggers at CDF were based on leptons including single and dilepton triggers. The newly implemented Silicon Vertex Trigger gives CDF access to purely hadronic  $B$  decays and makes CDF's  $B$  physics program fully competitive with the one at the  $e^+e^-$   $B$  factories. The hadronic track trigger is the first of its kind operating

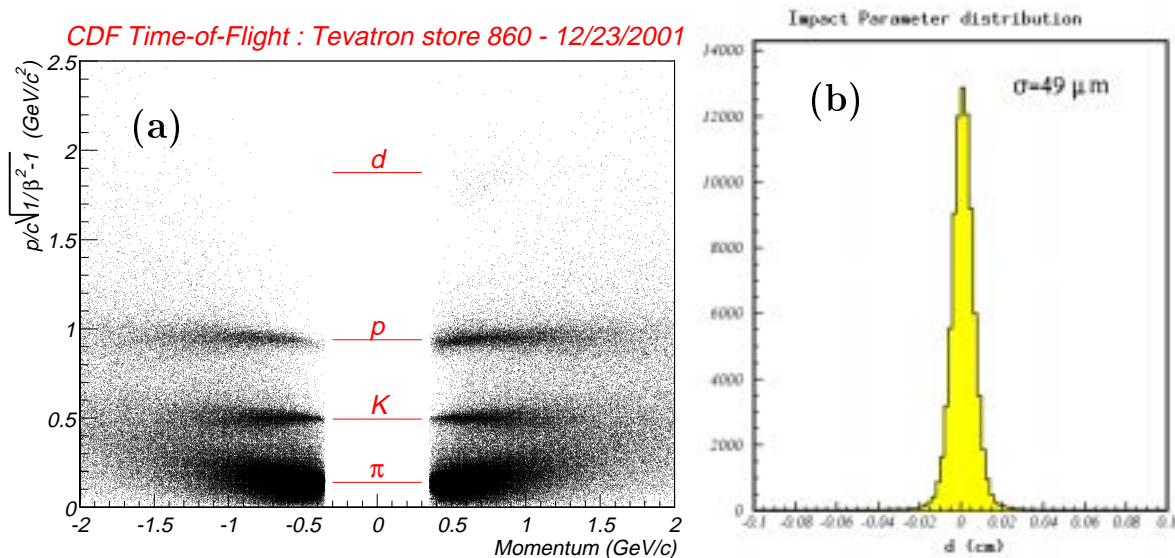


Figure 2: Distribution of (a) the Time-of-Flight reconstructed mass versus momentum for positive and negative tracks and (b) SVT track impact parameter distribution.

successfully at a hadron collider. It works as follows: With a fast track trigger at Level 1, CDF finds track pairs in the COT with  $p_T > 1.5$  GeV/c. At Level 2, these tracks are linked into the silicon vertex detector and cuts on the track impact parameter (e.g.  $d > 100 \mu\text{m}$ ) are applied. The original motivation for CDF's hadronic track trigger was to select the two tracks from the rare decay  $B^0 \rightarrow \pi\pi$ . The Silicon Vertex Trigger was fully operational at the time of this conference. A detailed discussion of CDF's Silicon Vertex Trigger and its initial performance has been presented by D. Lucchesi [6] at this conference. As an example of the performance of this trigger, we show the SVT track impact parameter distribution which behaves as expected. Figure 2(b) indicates a resolution of about  $50 \mu\text{m}$  including a  $33 \mu\text{m}$  contribution from the transverse beam spreading.

## First Run II Physics Results from CDF

At the time of this conference in June 2002, the performance of the CDF detector was already close to what has been achieved in the Run I data taking period and the new devices such as the hadronic track trigger were fully operational. As an example of the capabilities of the SVT two-track trigger, Figure 3(a) shows a  $K\pi$  mass distribution displaying a  $D^0$  signal of  $37,200 \pm 200$  events obtained in a small data sample of only  $5.7 \text{ pb}^{-1}$ . The hadronic track trigger clearly collects large data samples from long-lived charm and beauty decays.

Where does this charm come from? Is it subsequent charm from  $B$  decays or direct charm? Figure 3(b) shows the impact parameter  $d_0$  of the reconstructed  $K\pi$ -pair. In the case of direct charm, the  $D^0$  points back to the primary vertex resulting in  $d_0 \sim 0$  while in the case of the  $D^0$  originating from a  $B \rightarrow D^0$  decay, the  $D^0$  does not necessarily

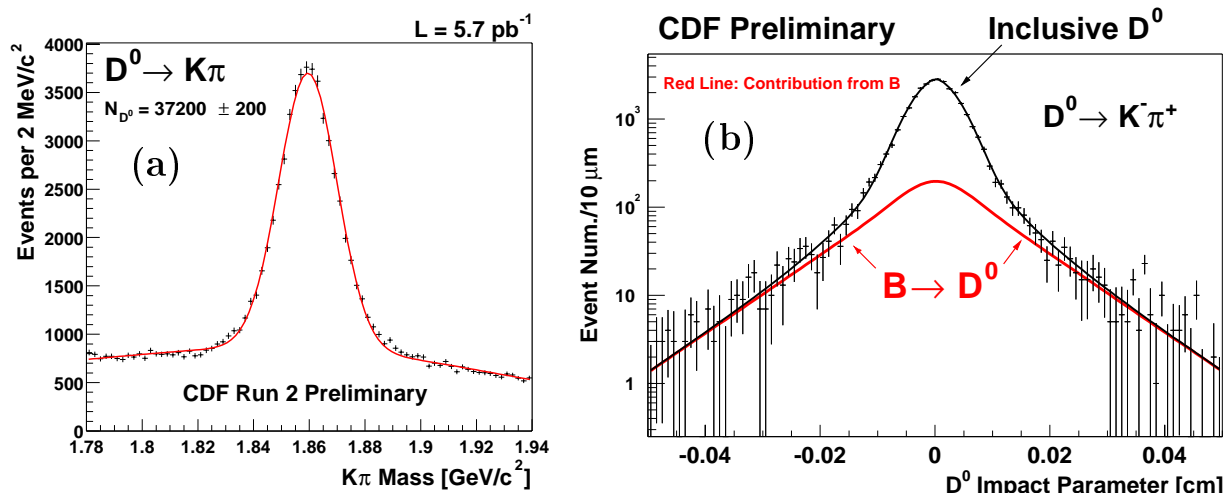


Figure 3: (a)  $K\pi$  invariant mass from data collected with the SVT hadronic track trigger. (b)  $D^0$  impact parameter distribution indicating the contribution from  $B \rightarrow D^0$  and direct charm.

extrapolate to the primary interaction vertex resulting in  $d_0 \neq 0$ . As can be seen from Fig. 3(b), CDF collects large amounts of direct charm with the hadronic track trigger - a new physics opportunity which did not exist in Run I.

The physics results presented by CDF in the summer of 2002 were based on a data sample of  $10\text{-}20 \text{ pb}^{-1}$  and intended to demonstrate that the CDF detector is working and calibrated. They included, for example, first measurements of  $B$  meson masses such as  $m(B^+) = (5280.6 \pm 1.7 \pm 1.1) \text{ MeV}/c^2$ ,  $m(B^0) = (5279.8 \pm 1.9 \pm 1.4) \text{ MeV}/c^2$  and  $m(B_S^0) = (5360.3 \pm 3.8 \pm_{2.9}^{2.1}) \text{ MeV}/c^2$ , or the measurement of the mass difference  $m(D_S^+) - m(D^+) = (99.41 \pm 0.38 \pm 0.21) \text{ MeV}/c^2$  with comparable precision to the current world average  $D_S^+/D^+$  mass difference [7]. For this measurement, the common decay mode  $D_S^+/D^+ \rightarrow \phi\pi^+$  was used. Figure 4(a) show the  $KK\pi$  invariant mass for the  $D_S^+/D^+$  candidate events. Another example of CDF II physics results is the measurement of the inclusive  $B$  lifetime using  $J/\psi \rightarrow \mu\mu$  events demonstrating the good understanding of CDF's new silicon vertex detector. The obtained result  $c\tau_b = (458 \pm 10 \pm 11) \mu\text{m}$  is in good agreement with other measurements [1, 7]. Figure 4(b) shows the decay length distribution from inclusive  $J/\psi$  events with the result of the lifetime fit superimposed.

## Prospects for $B$ Physics in Run II

The highlights of CDF's expected  $B$  physics program in Run IIa include the discovery of  $B_S^0$  flavour oscillations, measurements of  $CP$  violation in  $B$  decays as well as searches for rare  $B$  decays and measurements of  $B$  production and spectroscopy such as  $B_c$  physics. Originally a luminosity of  $2 \text{ fb}^{-1}$  was anticipated to be available in the first two years of Run II. Some of the prospects presented below are based on such a data sample.

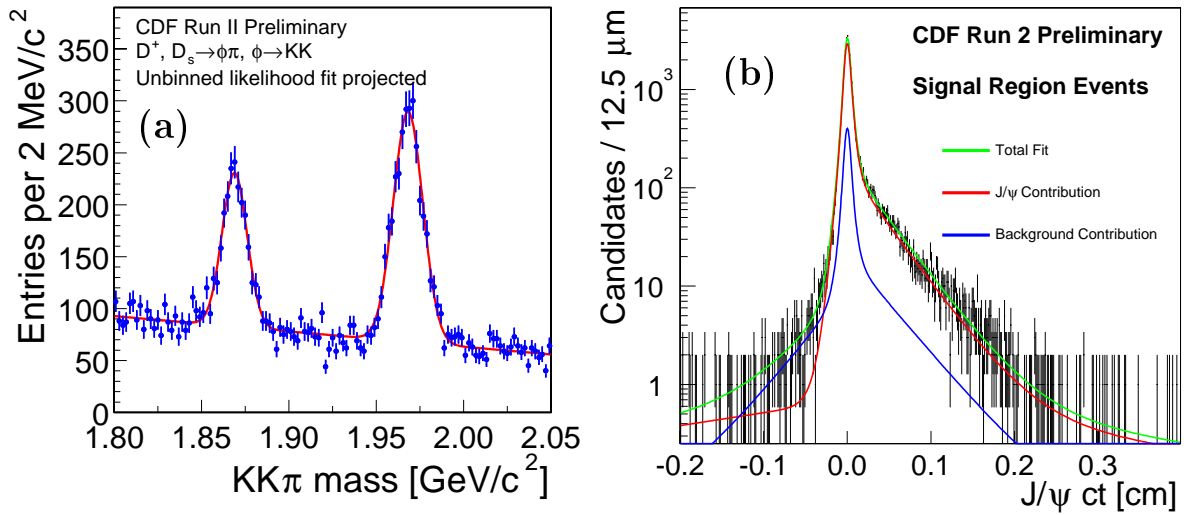


Figure 4: (a)  $KK\pi$  invariant mass for  $D_s^+/D^+ \rightarrow \phi\pi^+$  candidate events. (b) Decay length distribution of inclusive  $J/\psi$  events with the result of the lifetime fit superimposed.

### $B_S^0$ Flavour Oscillations

$B^0\bar{B}^0$  and  $B_S^0\bar{B}_S^0$  flavour oscillations measure the Cabibbo-Kobayashi-Maskawa matrix elements  $|V_{td}|/|V_{ts}|$ . The measurement of the  $B_S^0$  oscillation frequency  $\Delta m_S$  is clearly one of the goals for CDF in Run IIa. Some of the detector upgrades play an important role in CDF's prospects for measuring  $B_S^0$  mixing. The inner layer of silicon mounted on the beampipe improves the time resolution for measuring the  $B_S^0$  decay length to 0.045 ps. This will be important if  $\Delta m_S$  is unexpectedly large. The Time-of-Flight system will enhance the effectiveness of  $B$  flavour tagging, especially through same side tagging with kaons and opposite side kaon tagging, to a total  $\varepsilon\mathcal{D}^2 \sim 11.3\%$  [5]. CDF expects a signal of about 75,000 fully reconstructed  $B_S^0 \rightarrow D_S^+\pi^-, D_S^+\pi^-\pi^+\pi^-$  events in  $2\text{ fb}^{-1}$ .

Figure 5(a) shows the expected sensitivity for a  $5\sigma$ -observation of  $B_S^0$  mixing as a function of the mixing parameter  $x_S = \Delta m_S/\Gamma$  for various event yields. In Fig. 5(b), the integrated luminosity needed for a  $5\sigma$ -observation is plotted versus  $x_S$  for different signal-to-background ratios assuming a sample size of 75k fully reconstructed  $B_S^0$  decays. If the  $B_S^0$  mixing frequency is around the current Standard Model (SM) expectation of  $\Delta m_S \sim 20\text{ ps}^{-1}$  [7], Figure 5(b) indicates that CDF would only need a few hundred  $\text{pb}^{-1}$  to discover  $B_S^0$  flavour oscillations. This assumes all detector components and triggers work as expected. There appear to be indications that the projected event yield might be overestimated. Given this and the small amount of data delivered by the Tevatron at the time of this conference (and even at the end of 2002), it will take some time until CDF can present first results on  $B_S^0$  mixing. A measurement of  $\Delta m_S$  will be the next crucial test of the SM probing whether the obtained result will fit to the current constraints on the CKM triangle which are all in beautiful agreement [7]. It is noteworthy to mention that physics with  $B_S^0$  mesons is unique to the Tevatron until the start of the LHC in 2007.

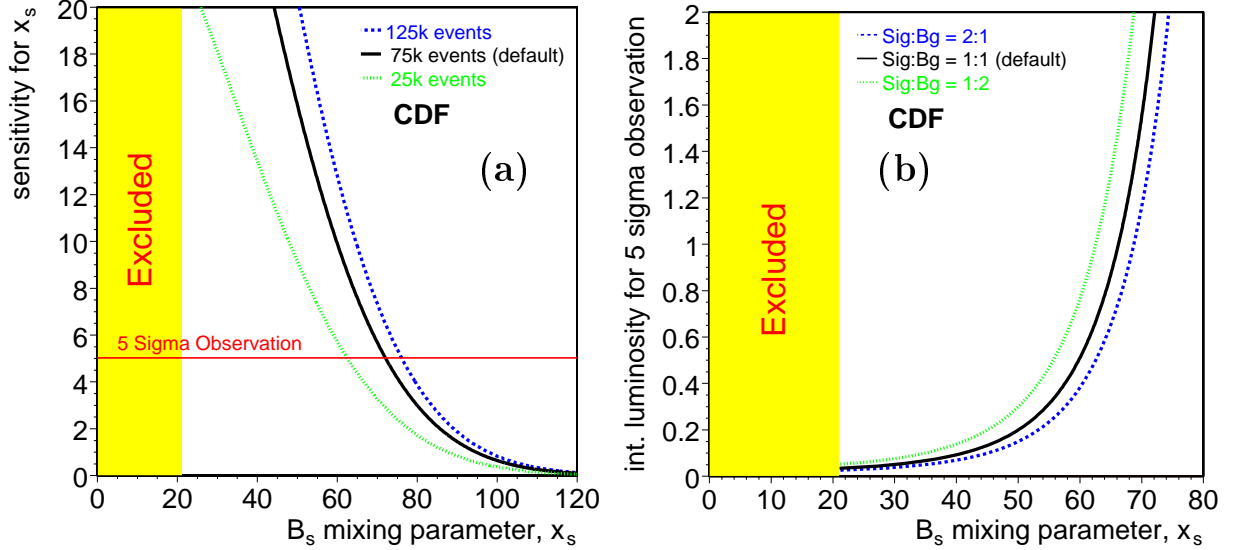


Figure 5: (a) Expected sensitivity for a  $5\sigma$ -observation of  $B_S^0$  mixing as a function of the mixing parameter  $x_S$  for various event yields. (b) Integrated luminosity needed for a  $5\sigma$ -observation versus  $x_S$  for different signal-to-background ratios assuming a default sample size of 75k fully reconstructed  $B_S^0$  decays.

## CP Violation

Several years ago, the most important decay modes for the study of  $CP$  violation in the  $B$  system were believed to be  $B^0 \rightarrow J/\psi K_S^0$  and  $B^0 \rightarrow \pi^+\pi^-$ . The time dependence of  $CP$  violation in the former mode measures  $\sin 2\beta$ , while the decay  $B^0 \rightarrow \pi^+\pi^-$  usually appears in the literature as a tool to determine  $\alpha = 180^\circ - \beta - \gamma$ . However, it has been shown that the so-called penguin pollution in  $B^0 \rightarrow \pi^+\pi^-$  is sufficiently large to make the extraction of fundamental physics parameters from the measured  $CP$  asymmetry rather difficult. An evaluation of measuring  $CP$  violation in  $B^0 \rightarrow \pi^+\pi^-$  does therefore require a strategy to distinguish penguin contributions from tree diagrams. A large number of strategies to disentangle both contributions is discussed in the literature [8, 9]. However, they generally require either very large data sets or involve hard to quantify theoretical uncertainties.

CDF evaluated a strategy of measuring the CKM angle  $\gamma$  as suggested by Fleischer in Ref. [10]. This method is particularly well matched to the capabilities of the Tevatron as it relates  $CP$  violating observables in  $B_S^0 \rightarrow K^+K^-$  and  $B^0 \rightarrow \pi^+\pi^-$ . Both decays are related to each other by interchanging all down and strange quarks, i.e. through the so-called ‘‘U-spin’’ subgroup of the  $SU(3)$  flavour symmetry of strong interactions. The strategy proposed in Ref. [10] uses this symmetry to relate the ratio of hadronic matrix elements for penguins and trees, and thus uses  $B_S^0 \rightarrow K^+K^-$  to correct for the penguin pollution in  $B^0 \rightarrow \pi^+\pi^-$ .

With the hadronic track trigger, CDF expects to reconstruct at least 5000  $B^0 \rightarrow \pi^+\pi^-$



and 20,000  $B^0 \rightarrow K^\pm \pi^\mp$  events in  $2 \text{ fb}^{-1}$  assuming a branching ratio of  $\mathcal{B}(B^0 \rightarrow \pi^+ \pi^-) = 5 \times 10^{-6}$ . The question whether CDF will be able to extract these signals from potentially enormous backgrounds, has been studied. With respect to combinatorial background, a signal-to-background ratio not worse than  $S/B \sim 0.4$  can be expected. Regarding physics backgrounds from  $B \rightarrow K\pi$  and  $B_S^0 \rightarrow KK$  decays, a  $B^0 \rightarrow \pi^+ \pi^-$  signal can be extracted by exploiting the invariant  $\pi\pi$  mass distribution as well as the  $dE/dx$  information provided by CDF's Central Outer Tracker. From this, CDF expects the  $B \rightarrow \pi\pi$ ,  $K\pi$ ,  $KK$  and  $\pi K$  yields to be measured with an uncertainty of only a few percent.

Measurements on the tagged samples determine the time dependent  $CP$  asymmetry for  $B^0 \rightarrow \pi^+ \pi^-$  and  $B_S^0 \rightarrow K^+ K^-$  which is given by:  $\mathcal{A}_{CP} = \mathcal{A}_{CP}^{dir} \cos \Delta mt + \mathcal{A}_{CP}^{mix} \sin \Delta mt$ . With the strategy suggested in Ref. [10], studies at CDF indicate that a measurement of the CKM angle  $\gamma$  to better than  $10^\circ$  could be feasible with  $2 \text{ fb}^{-1}$  of data. The utility of these modes depends on how well the uncertainty from flavour  $SU(3)$  breaking can be controlled. Data for these and other processes should tell us the range of such effects. The resulting Standard Model constraints could be quite stringent. CDF estimates of possible  $SU(3)$  breaking effects show that 20%  $SU(3)$  breaking leads to a systematic error of less than half the statistical precision given above. This encouraging result might allow CDF to make a significant contribution to our understanding of the CKM unitarity triangle within the first  $2 \text{ fb}^{-1}$  of Tevatron data in Run II.

## Rare $B$ Decays

Rare  $B$  decays provide detailed tests of the flavour structure of the Standard Model at the loop level, and as such provide a complementary probe of new physics to that of direct collider searches. As an example, we discuss the decay  $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ . The Forward-Backward asymmetry  $A_{FB}$  in this decay is defined as

$$A_{FB} = \frac{N(\cos \Theta > 0) - N(\cos \Theta < 0)}{N(\cos \Theta > 0) + N(\cos \Theta < 0)} = \frac{N_F - N_B}{N_F + N_B} \quad (1)$$

where  $\Theta$  is the angle between the direction of the  $B^0$  and the direction of the  $\mu^+$  in the rest frame of the  $\mu^+ \mu^-$  system. In general  $A_{FB}$  depends on the decay kinematics. SM calculations predict the distribution of  $A_{FB}$  as a function of the dimuon mass to cross the zero around  $\sqrt{s} = m_{\mu\mu} \sim 2 \text{ GeV}/c^2$  which is stable under various form-factor parameterizations. Figure 6(a) compares the  $A_{FB}$  distributions predicted by the Standard Model with several SUSY models including SUGRA and MIA-SUSY. Some new physics models predict there to be no zero point in the  $A_{FB}$  distribution.

CDF expects about 60  $B^0 \rightarrow K^{*0} \mu\mu$  event in RunIIa which will allow this decay to be seen at the Standard Model level. However, precision studies (particularly of the zero point in the Forward-Backward asymmetry) will require larger integrated luminosity.

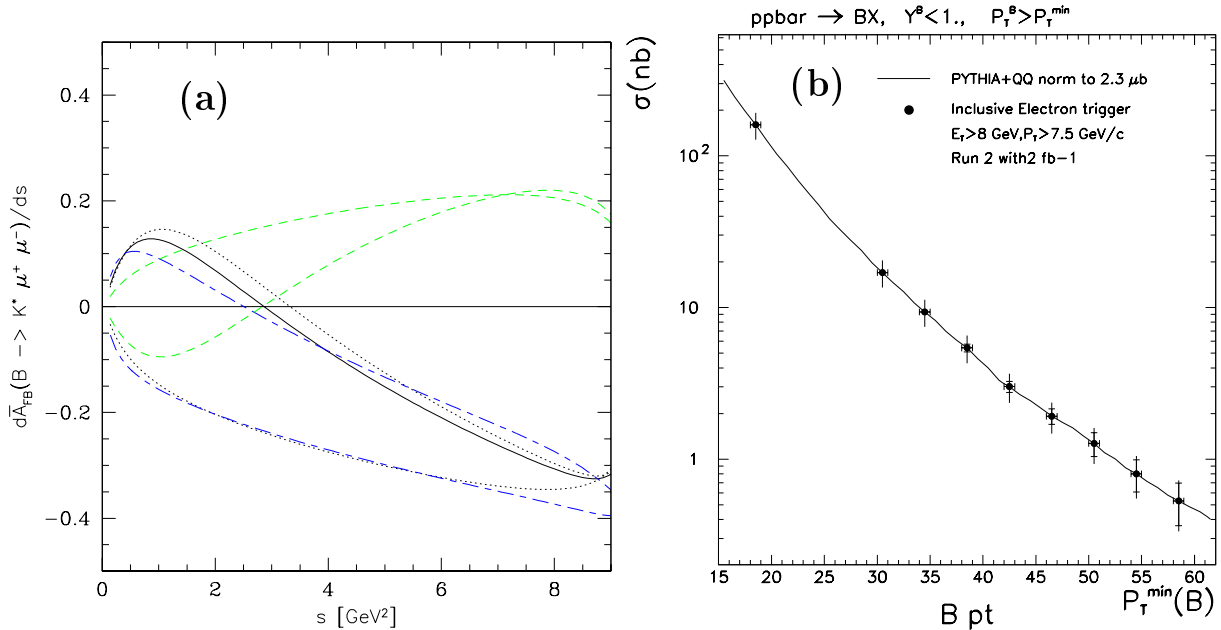


Figure 6: (a) The Forward-Backward asymmetry  $A_{FB}$  in  $B^0 \rightarrow K^{*0} \mu \mu$  decay as a function of  $s = m_{\mu\mu}^2$  predicted with the Standard Model (solid line), SUGRA (dotted) and MIA-SUSY (long-short dashed line). (b) The predicted  $b$  quark production cross section reach as of function of  $B$  meson  $p_T$  for  $B \rightarrow D^0 e X$  assuming  $2 \text{ fb}^{-1}$  of data.

## B Production and Spectroscopy

The discrepancy between the predicted and measured  $b$  quark production cross section at the Tevatron is one of the largest disagreements between Standard Model theory and measurement. A better understand of  $b$  quark production in  $p\bar{p}$  collisions, especially in the high- $p_T$  region as well as  $b\bar{b}$  production correlations is clearly desirable. CDF plans to investigate lepton- $D^0$  events to tag  $b$ -jets in Run II. Figure 6(b) shows the predicted cross section reach as of function of  $B$  meson  $p_T$  for  $B \rightarrow D^0 e X$  with a kinematic cut on the electron of  $E_T > 8 \text{ GeV}$  and  $p_T > 7.5 \text{ GeV}/c$  assuming  $2 \text{ fb}^{-1}$  of luminosity. The statistical errors are predicted from Monte Carlo and scaled by a factor of two to include the effect of background.

## Conclusion

After a five year upgrade period, the CDF detector is back in operation taking high quality data in Run II with all subsystems functional including a new central tacking chamber and silicon vertex detector as well as a hadronic track trigger and a Time-of-Flight system. The understanding of the detector is advanced and first physics results have been presented. We also discussed the prospects for  $B$  physics in Run II, in particular the measurements of  $B_s^0$  flavour oscillations and  $CP$  violation in  $B$  decays. More detailed information about  $B$  physics prospects at the Tevatron in Run II can be found in Ref. [11].

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