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The Tevatron Collider Run 2
Prospects for Discoveries in Particle Physics

Giorgio Bellettini [a*]

[a]Department of Physics of the University of Pisa and INFN-Pisa, Italy
(on behalf of the CDF Collaboration)

The chances of discovering the Standard Model Higgs boson in Run 2 at the Fermilab Tevraton Collider are discussed. The reach of a search for MSSM Higgs boson and for other Susy particles is also mentioned.

1. Foreword

The Run 1 of the Tevatron Collider lasted from fall 1992 to early 1996 and integrated a luminosity of ≈110 pb^{-1} at the energy of 1.8 TeV for both the CDF and D0 . The CDF central tracker comprised a drift chamber and a vertex silicon detector in a solenoid magnetic field. D0 featured a central drift chamber tracker but no field. Run1 was very successful, with great EW, QCD and b physics, and the discovery of the top quark.

For run 2, which started in march 2001, both the Tevatron and the CDF and D0 detectors have been greatly improved. We are now looking forward to a great campaign of physics in run 2 as well, addressing all areas of hard physics accessible at a hadron collider. We will study the dynamics of hadron jets, electro-weak physics through detailed studies of W, Z events, and frontier b-physics including B_s oscillations and mixing. We will also perform studies of the production and decay properties of the top quark.

There is an area extending into the LHC physics domain where we have a chance for new discoveries. This is the search for the Standard Model Higgs boson, if it is light and not much above the LEP lower mass limit, and the low mass sector of new physics that we believe must exist beyond the S.M sector. I will discuss in some detail why these exciting hopes are justified.

*E-mail:giorgiob@fnal.gov.

2. Could we find the Higgs in run 1?

The production cross-sections of the light S.M. Higgs at 2 TeV in the dominant channels are shown in Fig. 1 ([1]).The Higgs decay branching ratios are shown in Fig. 2 ([1]). The main production mechanism is single Higgs production by gluon fusion. For masses below ≈135 GeV a peak in the inclusive mass spectrum of b-jet pairs would signal the boson. CDF has studied these spectra and found no signal, even when the jets in the pair were both b-tagged by a secondary vertex in the jet cone. This is no surprise. The rate of b-pair QCD production at large transverse energies, both by direct heavy flavor excitation and by gluon splitting, is well know theoretically and is many orders of magnitude larger than the expected Higgs rate.

The next largest cross-section is associated production of a W boson and a Higgs. Associated ZH production is further down by only a factor of 3 but is also interesting. In these processes the tag offered by the weak boson in the event is a powerful handle to discriminate against background. Let us estimate whether in run 1 CDF had a chance of discovering the light Higgs by exploiting these production channels and the Higgs decay into $\bar{b} - b$.

For $M_H \approx 110$ GeV the WH cross section is ≈ 0,2 pb. The expected event rate for an integrated luminosity of 110 pb^{-1} is a few dozens. After allowing for the W/Z branching ratios and for trigger and analysis cuts, the overall selection efficiency for these events was ≈1%. Therefore, less than 1 event could be expected. The estimated background rate was many events. Therefore, we expected not to be able to set even a lower limit to the Higgs mass.

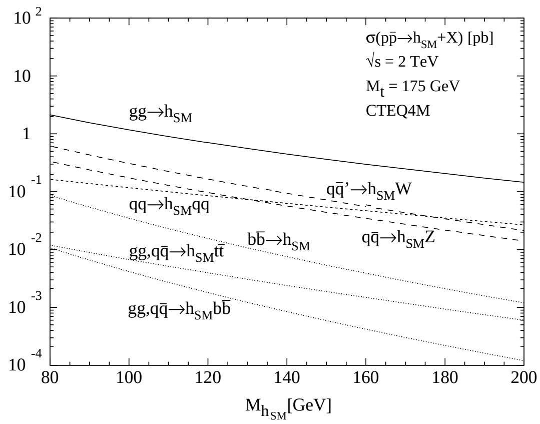

Figure 1. Standard Model Higgs production cross-section at the Tevatron

In run 1 CDF looked for the following channels:
$ZH \rightarrow ll\bar{b}-b$
$WH \rightarrow l\nu\bar{b}-b$
$W/ZH \rightarrow jj\bar{b}-b$
$ZH \rightarrow \nu\nu\bar{b}-b$

The events were selected by requesting large E_t isolated leptons, large missing E_t, large E_t b-tagged jets. Some excess of events over the expected S.M. background was found only in the $\ell\nu\bar{b}-b$ channel, which made this channel not very useful in setting a lower H-mass limit. The channel providing the best limit was $\nu\nu\bar{b}-b$, where the rate matched the S.M. expectations with no Higgs very well. The overall information was combined to get the 95% upper limit on the Hproduction cross section as a function of the mass that is shown in Fig. 3 ([2]).

In the range from the LEP limit to $M_H \sim 130$ GeV, our limit is still a factor of 30 or so higher that the rate expected in the S.M. Indeed, no limit could be set on the Higgs mass.

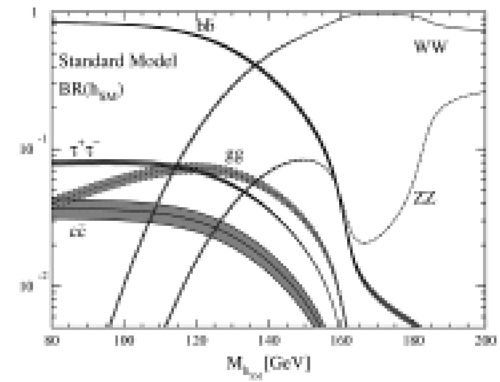

Figure 2. Light S.M Higgs decay branching ratios

3. Run 2 collider upgrades

For run 2, major upgrades have been made to the Tevatron Collider and to the CDF and D0 detectors. A new 150 GeV syncrotron, the "main injector", was built in a new tunnel away from the Tevatron enclosure. The main injector is much faster than the old "main ring" in producing antiprotons to be stored in the debuncher-accumulator-recycler complex. The 8 GeV permanent magnet recycler ring, which is housed in the same tunnel as the main injector, is also new. At the end of a store, the antiprotons rather than being aborted are decelerated in the Tevatron and in the main ring and rescued in the recycler.

While the luminosity at the end of run 1 was around $1{,}5\times10^{31}$cm^{-2} s^{-1} with 6 on 6 proton-antiproton bunches in the collider, a luminosity up to 2×10^{32}cm^{-2} s^{-1} is ultimately planned with the new injector/antiproton source complex. This would be obtained with 36 on 36 bunches. At this point in time this is already the mode of operation of the collider. However, at 2×10^{32}cm^{-2}s^{-1}with these beams the average number of interactions per bunch crossing would be about 5, as one can see in Fig. 4 ([3]). In order to limit this number below about 2 as in run 1 (see Fig. 4 again), one is planning to increase eventually the number of bunches in the antiproton beam to 108,

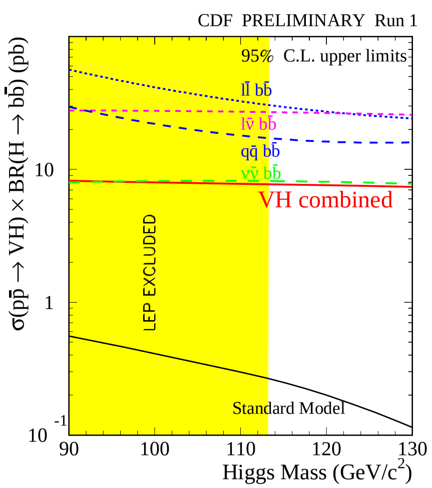

Figure 3. Light Higgs cross-section limits of CDF in run 1

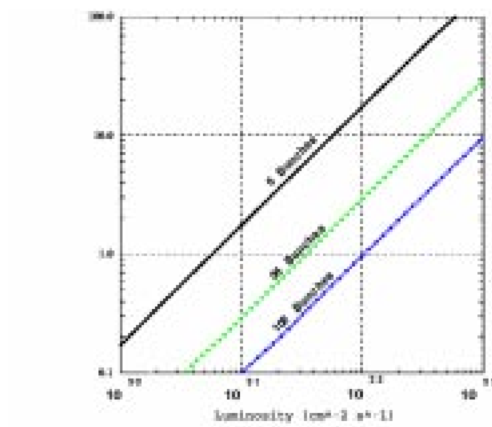

Figure 4. Average number of interactions per bunch crossing as a function of the luminosity. The number is progresively reduced with increasing number of bunches in the beams.The first horizontal line corrisponds to 1 interaction per crossing

with some 140 bunches in the proton beam (leaving some longitudinal space available in the tevatron to allow for beam manipulation). In those conditions the interbunch time will be 132 ns. An average of 5 interactions per crossing would be reached only at a luminosity of $5\times10^{32}\text{cm}^{-2}\text{s}^{-1}$ that is the ultimate reach of the collider.

A possible time profile of the integrated luminosity (for both CDF and D0) in the future years is shown in Fig. 5. Delivering this luminosity is a major goal for the lab. It is unclear how likely it is that it will be achieved. The experimenters are asking for more.

4. Run 2 Detector Upgrades

The CDF2 detector features a new silicon vertex tracker with 7 layers at large angles and 8 layers at $1 <| \eta |< 2$. A central small-gap Central Outer drift Chamber (COT) with 48 axial and 48 small angle stereo wire planes backs the vertex detector at larger radii inside the magnet solenoid. Just outside the COT and still inside the coil a layer of plastic scintillator bars has been installed to measure the time of flight of charged prongs. With about 100 ps resolution, pions can be separated from kaons with 2σ resolution up to a momentum of 1,6 GeV/c. While the central calorimeters have been preserved, the coverage of the calorimeter plug at angles below 30^o has been extended down to 3^o. In the new plug, plastic fast scintillator towers are now employed as sensitive medium. Liquid scintillator "miniplugs" have been added to complete the coverage down to the beam pipes. Also the coverage of the outer drift chamber-plastic scintillator muon detector has been greatly extended.

Finally, all front end, trigger and DAQ electronics has been changed and made able to work with a 132 ns crossing period. At level 1 (within 5 μs), a new tracking trigger has been implemented. At level 2 (20 μs) a Secondary Vertex Trigger SVT signals with $\sim 40\ \mu$m impact parameter resolution, tracks originating away from the primary vertex. SVT is a "first" in hadron collider detectors. CDF relies on it for getting a greatly

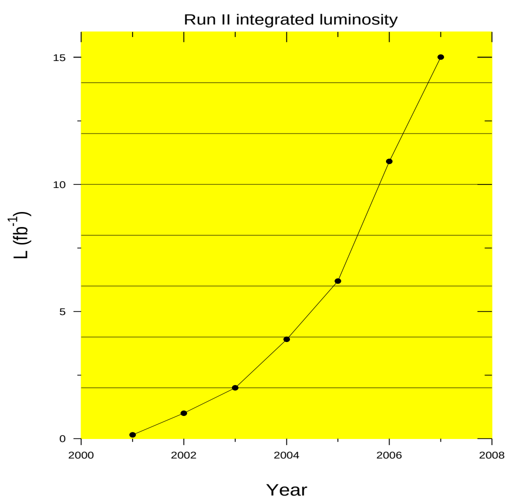

Figure 5. Estimated luminosity to be integrated by CDFand D0 before the start of LHC(tentative)

increased sensitivity in particular on hadronic b-decays.

Except for the liquid argon calorimeter, D0 will employ a new detector. Most noticeably, a solenoid coil has been inserted inside the calorimeter allowing charged particle tracking up to a radius of ~90 cm in a 2 T magnetic field. The tracking detector is new, with a 4-layer double-sided silicon vertex detector followed by a 16-layer scintillating fiber tracker. The outer muon detector has been upgraded with improved coverage at large angles and a new forward system with streamer tubes and scintillator pixels. All electronics is new, and comprises a stand-alone track trigger at level 1.

One may attempt a qualitative comparison of the CDF and D0 run 2 detectors. CDF has a more powerful central tracker, with better pattern recognition and better momentum resolution, some particle ID, and the SVT. D0 has a more complete calorimeter coverage, a better E_{tmiss} resolution and a more complete coverage in the muon detector. The physics reach of the two detectors may not be very different in the new run.

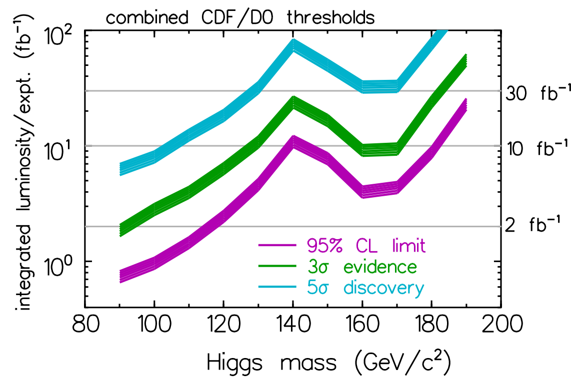

Figure 6. Expected required luminosity for CDF and D0 for light Higgs limits/evidence/discovery in run 2

5. Can CDF and D0 see the Higgs in run 2?

The Tevatron collider energy will be ~ 2TeV. This gives an increased VH cross sections (V=W or Z) by ~30% over run 1. Consider masses around M_H = 120 GeV, where the VH cross-section is ~0,1 pb. Run 2a is defined by a delivered luminosity of ~2fb^{-1} (hopefully by end 2004). By then the produced VH events would be ~200 in each experiment. With a somewhat wider trigger band and better analysis efficiency than in run 1 we might be able to collect ~2% of these. A few VH events would be observed, but the estimated background is more. Therefore we should expect to be able at that point only to set a lower limit to the Higgs mass in this interesting range. Still, we would be getting close to the goal.

The Fermilab Higgs Working Group has made an estimate of the reach of the combined

CDF+D0 experiments for Higgs masses up to ∼190 GeV. This is shown in Fig. 6 ([1]). The three bands indicate as a function of the Higgs mass how much luminosity should be integrated by both experiments in order to reach a 95% exclusion probability, a 3σ evidence, and a 5σ discovery. In computing these figures all VH channels and the two experiments were combined. Information was gathered in the H→ $\bar{b}b$ channel which dominates at M_H <130 GeV and in the H→WW channel which dominates at M_H >140 GeV. Two identical "average" CDF/D0 detectors were simulated. Some reasonable improvements over the run 1 CDF detector in tracking coverage, b-tagging efficiency, jet energy resolution were assumed.

CDF has work in progress in order to make the Run 2 detector appreciably better than simulated by the Higgs Working Group. Since jet energy resolution will play a major role in the H→ $\bar{b}b$ search, we are redesigning our jet reconstruction algorithm. Rather than using calorimetric information only, we are exploiting tracking information whenever possible. We shall also exploit the information provided by the shower max and by the preshower detectors. On comparing the reconstructed jet energy to the well measured photon energy in γ+jet events of Run 1 we have already achieved a better resolution by ∼25%.

In run 1 CDF has been able to isolate a small sample of certified light quark jets by observing a W mass peak in non-b-tagged jet pairs in $\bar{t}t$ events with 2 tagged and 2 non-tagged jets. Similarly, by observing the Z mass peak in the b-tagged inclusive jet pair spectrum we got a small sample of certified b-jets. These processes will provide large samples in run 2 and they will allow both to calibrate the jet energy scale and to optimize the jet energy corrections for light quark and for b quark jets separately.

Within the S.M., there are indirect indications for a very light Higgs from the overall fit to electro-weak observable measured at LEP, SLC and CDF/D0. The Higgs mass is predicted to be with high probability less than ∼ 220 GeV. There are also statistically weak but direct indications from LEP 2 for a Higgs mass of ∼115 GeV. The question is therefore in order: can CDF/D0 find the Higgs if its mass is precisely 115 GeV? Based on the simulations of the Higgs Working Group, a summary answer is as follows.

If the LEP hints are a fluctuation, CDF+D0 will exclude a Higgs of that mass at 95% c.l. with an integrated luminosity per experiment of ∼2 fb^{-1}.

If it is there, we will get a 3σ evidence after ∼5 fb^{-1}(by 2005?) and a 5σ discovery after ∼15 fb^{-1}.

My expectations are that CDF will be able to perform better than what was assumed in those simulations.

6. Non Standard Model Higgs searches

In the MSSM the couplings of two of the neutral Higgs bosons are enhanced at large tanβ. This allows CDF and D0 to claim an increased sensitivity in that region. By interpreting its searches for S.M. Higgs signatures in this framework, CDF has obtained the neutral pseudoscalar MSSM SUSY Higgs limits shown in Fig. 7 ([4]).

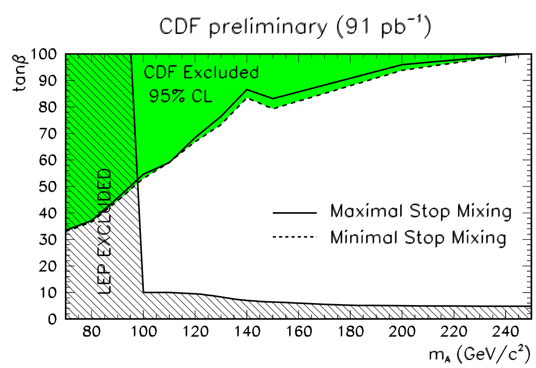

Figure 7. Light MSSM neutral Higgs limits of CDF in run 1

Unfortunately, these limits are in a tanβ region that is unnaturally high (>50 for m_A>115 GeV). However, in run 2 we expect to be able to get down to tanβ ∼25 with ∼5fb^{-1} (Fig. 8 ([1])).

In the MSSM also two charged Higgs bosons are expected. Actually, finding these would be the simplest and most direct way to prove that an observed neutral Higgs is a SUSY one. If the H^+ mass is less than M_{top} - m_b, at large tanβ the decay t $\rightarrow$ H^++ b is a strong competitor of the S.M. decay. The dominant H^+decay would be $H^+ \rightarrow \tau+\nu$ at large positive tanβ. This would originate an anomalous τ lepton rate in the top sample. CDF has put limits on this process by excluding such an anomaly. The dominant H^+ decay would be $H^+ \rightarrow$cs at large negative tanβ. These events would escape b-tagging. This was tested indirectly by checking that the ratio of b-tagged top events in the single and in the double lepton channels is as expected in the S.M.

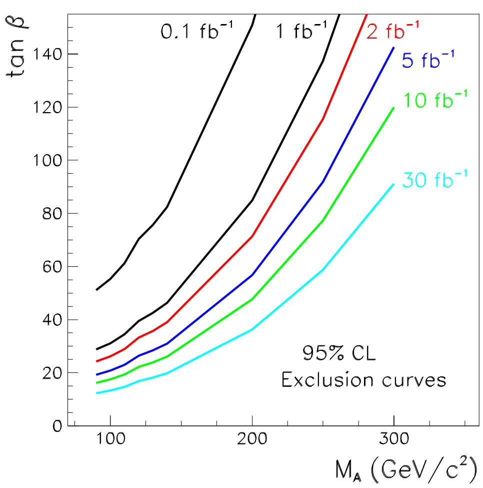

Figure 8. Expected MSSM neutral Higgs reach of CDF and D0 in run 2 ([1])

The CDF M_{H+} run 1 limits, and the much stronger ones expected in run 2 (with 2fb^{-1}) are shown in Fig. 9 ([1]).

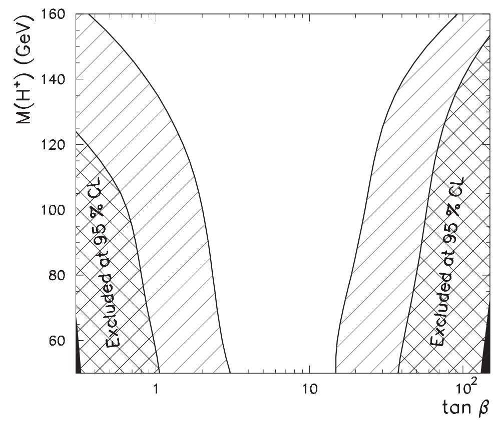

Figure 9. CDF escluded mass regions of MSSM charged Higgs in run 1, and expected reach with 2 fb^{-1} in run 2 ([1])

7. Susy searches

CDF has searched for SUSY particles with null result in the "golden" E_{tmiss} + jet channel, as well as in several other channels suggested by particular models. One may choose to indicate the SUSY discovery potential in run 2 by showing the plot in Fig. 10 ([5]). Here one indicates with the upper line the limit to the mass on a number of SUSY particles beyond which the theory would be unreasonably stretched. This limit ranges from about 800 GeV for squarks and gluinos to about 300 GeV for charginos. The theory most natural values, where the density of expected mass values with varying theory parameters is approximately maximum, is shown at the center of figure. The present experimental limits, although significantly close to the most natural values, are consistently below them. In run 2, already with 2 fb^{-1} and even more with 15 fb^{-1}, we will reach them or go beyond them. Of course, given the flexibility of SUSY there will still be plenty of room left unexplored in parameter space to allow the theory to escape experimental verification.

One might recall a number of anomalies observed in the CDF run 1 data and wonder whether

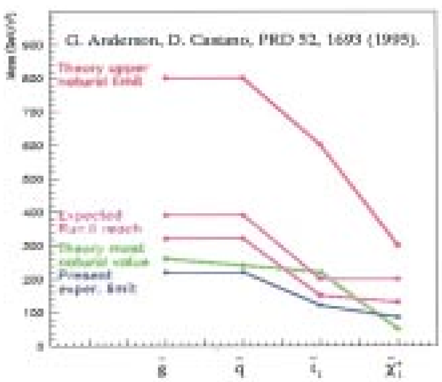

Figure 10. Most natural value, and upper natural mass values of some SUSYparticoles are compared to the CDF reach in run 2 with $2fb^{-1}$ and with $15fb^{-1}$

hints of SUSY have not been already observed. There is a famous $ee\gamma\gamma$ E_{tmiss} event that remains unexplained and has prompted an interpretation in terms of selectron pair production. A moderate excess of rate was observed in the large transverse energy $e\gamma E_{tmiss}$ sample. Very recently, CDF has submitted for publication a paper reporting a puzzling excess of rate at jet multiplicities 2 or 3, of W+jet events containing a large E_t "superjet", i.e. a jet tagged both by a secondary vertex and by a lepton prong. None of these anomalies has sufficient statistical significance and plausible enough interpretation to deserve the credit of a strong hint for new phenomena. Still, it is fair to be puzzled. Needless to say SUSY may not be the real answer. Future will tell.

8. Comparison with LHC

CDF and D0 share much of their physics goals with ATLAS and CMS at the LHC. For Standard Model physics the attainable precision will often be limited by systematic uncertainties in all experiments. For example, the error on top quark mass may be reduced to 2 GeV at the Tevatron and it will be hard to do better than 1 GeV even at LHC. The error on the W mass may be reduced to around 20 MeV at both colliders.

However, the potential of LHC for discovering new phenomena is much larger. At the Tevatron, the reach on S.M Higgs mass cannot possibly go beyond 180 GeV, while at the LHC the reach is up to 1 TeV. At the Tevatron, squarks and gluino masses will be explored up to ~400 GeV, while at the LHC one may reach ~2TeV, well beyond the "reasonable" range shown in Fig. 10 ([5]). Given this, why are we at CDF so excited? Because inspite of its limited reach, the Tevatron does have a chance. The present picture of particle physics is telling us that both the Higgs and some new particle opening the window on physics beyond the S.M. "ought to be light". And also, frankly, because the Tevatron is so many years in front of LHC.

9. Conclusions

The large integrated luminosity potentially offered by the upgraded Tevatron in the years before the start of LHC will make an exciting physics program possible in the next several years. Let aside the luminosity, we can rely now on two much more powerful detectors than in run1. This is a very real point of strength of the run 2 Tevatron program.

The progress of the Tevatron from spring this year has been slow but steady. From this, there is no reason for being pessimistic, but admittedly no particular reason for being optimistic as well.

CDF will be able to produce physics quality data early in 2002. After that, data will flow for years and years. We expect to be able to publish the first papers based on the new data in fall 2002.

Shall we make some discovery later on? Possibly, with luck.

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