PRESENT STATUS OF PHYSICS AT TEVATRON/CDF AND PROSPECT WITH HIGHER LUMINOSITY

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Abstract

The Tevatron Run II program is ongoing at Fermilab with 1.96 TeV $p\bar{p}$ collisions. The upgrade from the Run I system and the present status of the Tevatron and the CDF are presented including some preliminary results obtained in the Run II starting period. The future luminosity prospects and the expected physics sensitivities are also presented.

1 INTRODUCTION

The Tevatron collider has been providing $p\bar{p}$ collisions at the world highest center-of-mass energy since the first collision in 1985. In Run I which was carried out from 1992 through 1996, about 110 pb^{-1} of collision data were collected at $\sqrt{s}$ =1.8 TeV using the CDF detector, and many important results on particle physics were provided including the direct observation of the top quark [1].

After the Run I operation, the Fermilab accelerators were upgraded for Run II toward higher luminosity at the Tevatron [2]. In parallel, the CDF detector was also upgraded in order to allow operation at higher luminosity collisions [3]. The Run IIa operation was started at a center-of-mass energy of 1.96 TeV in March 2001. The CDF II collaboration currently consists of 11 countries, 58 institutes, and about 600 physicists.

2 ACCELERATOR UPGRADE

The goal of the first phase of the Tevatron Run II (Run IIa) is to achieve a peak luminosity of 2×10^{32} cm^{-2}s^{-1} and an integrated luminosity of 2 fb^{-1} at $\sqrt{s}$ = 1.96 TeV. Among a number of upgrades which were made to accomplish the above performance, the important changes are as follows:

- A high-intensity proton synchrotron (Main Injector) was newly built as an injector of the Tevatron. It is also used to produce anti-protons with the fixed-target operation.
- A new storage ring (Recycler) was placed in the same tunnel as the Main Injector to collect anti-protons left over at the end of a store and reuse them in the next store.
- The number of proton and anti-proton bunches in the Tevatron ring was increased from 6 × 6 to 36 × 36.
- The bunch spacing was shortened from 3.5 μs to 396 ns to maintain the number of interactions per bunch crossing properly.

The Recycler ring is currently under final integration, and it will be completed in 2003. In succession to Run IIa, the Run IIb program is planned with minor upgrades toward the accumulation of 15 fb^{-1}.

3 THE CDF DETECTOR UPGRADE

For the Tevatron Run II operation with high luminosity, the substantial upgrades were needed to the CDF Run I detector. We constructed the CDF II detector which is shown in Figure 1. The upgrade was made by replacing the slow components with the fast ones and adding new components to improve the detector capability. The central tracking chamber has been replaced with a new cylindrical drift chamber (Central Outer Tracker, COT) with smaller drift gaps. The silicon vertex detector has been replaced with a new one (SVX II) with faster readout electronics and better radiation resistance. The intermediate silicon layers (ISL) were newly added in the space between SVX II and COT. The plug gas calorimeters have been replaced with new scintillator tile calorimeters which give much faster response. The time-of-flight detector (TOF) was added for better particle identification at low energy. The coverage of the muon detectors has been increased up to $\eta \sim 1.5$. Also all front-end and trigger electronics was re-designed for fast-speed

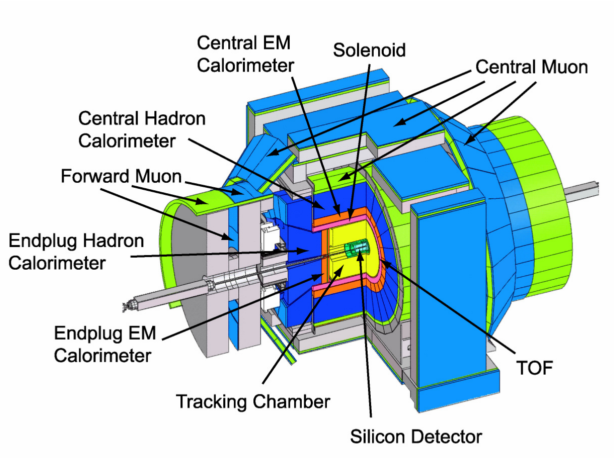

Figure 1 : Schematic view of the CDF II detector

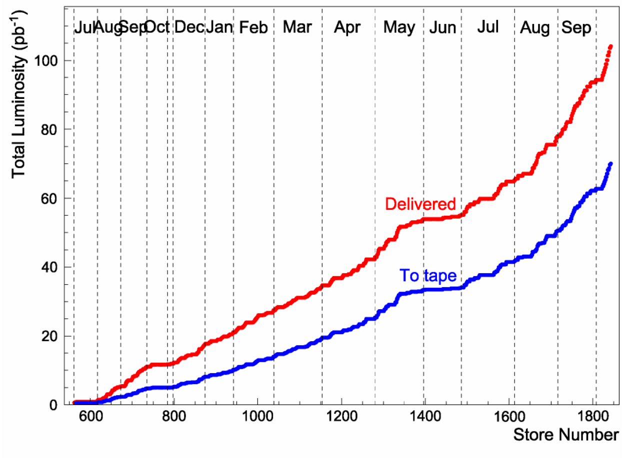

Figure 2 : The integrated luminosity delivered (upper curve) and recorded (lower curve) by the CDF II through October 14th, 2002.

processing. On the construction of the CDF II detector, the large contribution was made by Japanese institutes to the silicon detectors (SVX II and ISL), the end-plug calorimeters, the time-of-flight detector, and the data acquisition system. The installation of all the detector components was successfully completed, and the new CDF II detector was rolled into the collision hall in the fall of 2000.

4 EARLY RESULTS OF RUN IIA

After the half-year commissioning runs, the Run II operation officially started in March 2001. Continuous efforts by the Fermilab accelerator group are keeping the Tevatron luminosity improving. The CDF II detector had been also getting tuned, and it was in stable condition by February 2002. As of October 2002, we are achieving the typical peak luminosity of 2.5 ~ 3.0 × 10^{31} cm^{-2}s^{-1} stably. The integrated luminosity of 100 pb^{-1} has been delivered and 70 pb^{-1} has been recorded so far as presented in Figure 2.

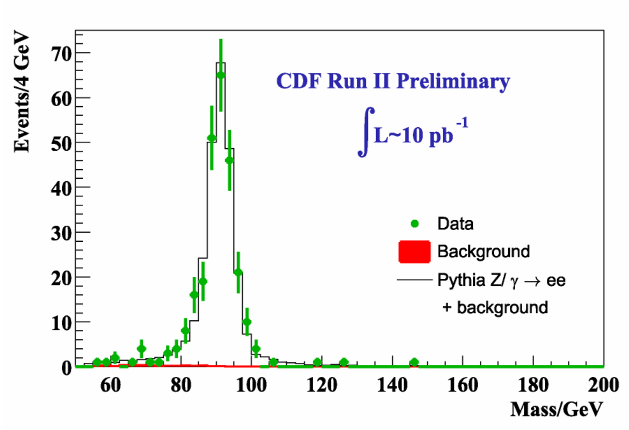

Figure 3 : Invariant mass spectrum of $Z \to e^{+}e^{-}$ candidates.

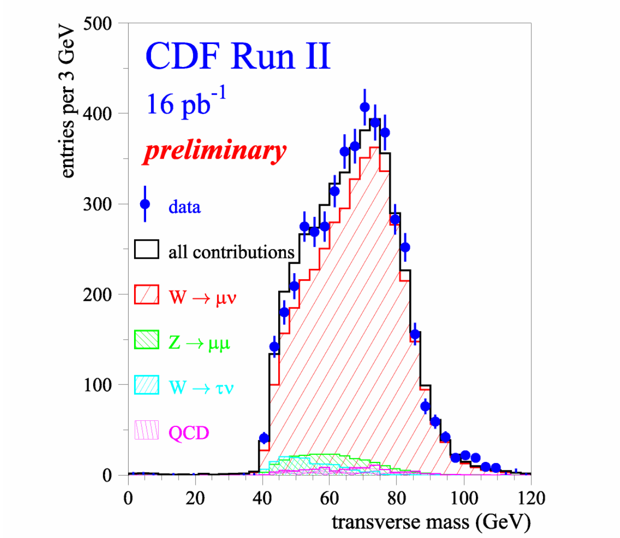

Figure 4 : Transverse mass spectrum of $W \to \mu\nu$ candidates.

Using these data, the physics analysis is currently in progress in parallel with various calibrations. Figure 3 and 4 show the invariant mass spectrum of $Z \to e^{+}e^{-}$ candidates and the transverse mass spectrum of $W \to \mu\nu$ candidates respectively. Both spectra are in good agreement with the Monte Carlo simulations including the expected background spectra. The W mass is extracted from a fit to the transverse mass distribution of $W \to e\nu$ and $\mu\nu$. The mass accuracy is expected to be ~ 30 MeV/c^2 with 2 fb^{-1} in Run IIa, which is competitive to the combined LEP2 result [4].

Figure 5 shows the invariant mass spectrum of $J/\psi \to \mu\mu$ candidates which was obtained by reconstructing low-p_T muon pairs. The spectrum of $\psi(2S) \to \mu\mu$ is also superimposed. By taking advantage of the large statistics of the J/ψ sample, it is used for tracking calibration and momentum-scale adjustment.

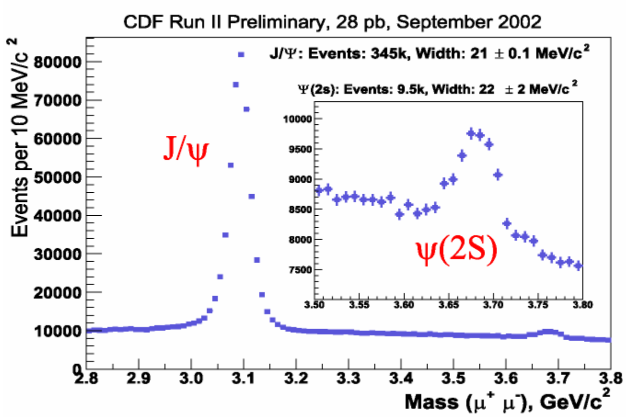

Figure 5 : Invariant mass spectra of $J/\psi \to \mu\mu$ and $\psi(2S) \to \mu\mu$ candidates.

Also, the J/ψ sample is a powerful tool to research B physics. The mass spectrum of B_s^0 obtained from reconstruction of $J/\psi\ \phi(\phi \to K^+K^-)$ is shown in Figure 6. The obtained mass accuracy is starting to be competitive to the world average [5].

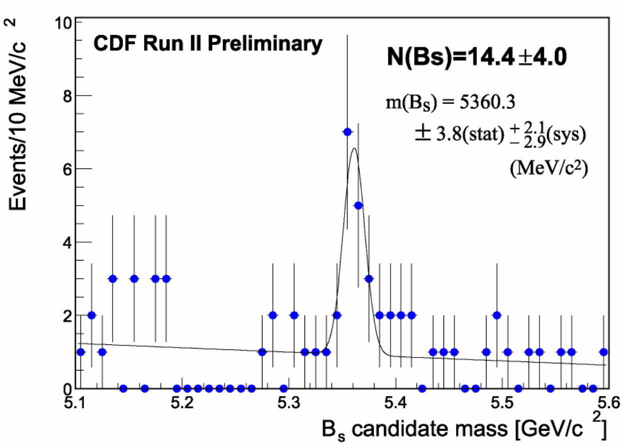

Figure 6 : Reconstructed mass distribution of $B^+ \to J/\psi\ K^+$ candidates.

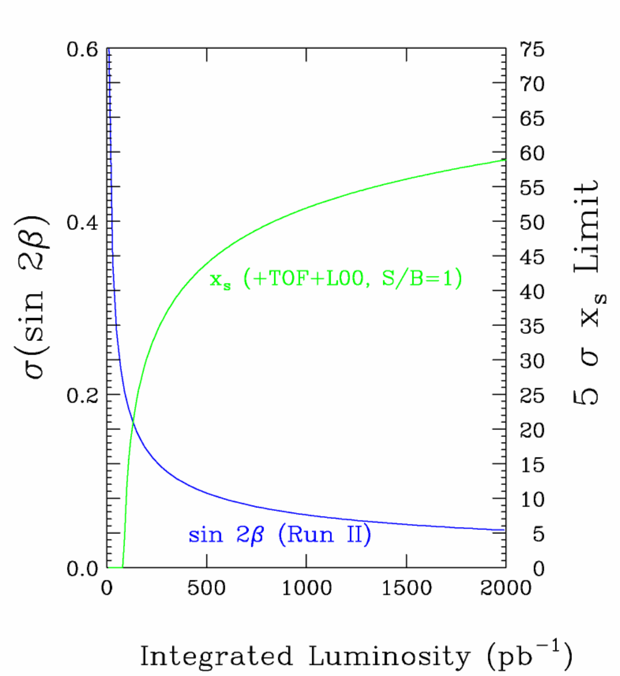

Figure 7 : The expected accuracy of sin2β measurement and the expected sensitivity of x_s for $B_s^0 - \overline{B}_s^0$ mixing as a function of the integrated luminosity.

5 PHYSICS PROJECTIONS TO THE CDF RUN II

As written above, the integrated luminosity will reach 2 fb^{-1} in Run IIa and 15 fb^{-1} in Run IIb. Various physics results are expected assuming the above statistics. One of the most important objectives in Run II is a research on the top quark. By scaling up the yield obtained in Run I, we expect to collect about 800 $t\bar{t}$ events by b-quark tagging with 2 fb^{-1}. The precise measurements of the top quark mass and the production cross section will be made.

The B physics is also expected to give us a great outcome during the Run IIa period [6]. The measurement of $B_s^0 - \overline{B}_s^0$ mixing by means of $B_s^0 \to D_s\pi$ and $D_s\pi\pi\pi$ decay modes is being studied. As presented in Figure 7, the CDF has the sensitivity to the 5σ discovery for x_s (= $\Delta m_s / \Gamma_s$) smaller then 60 with 2 fb^{-1}. This measurement is a unique subject at the Tevatron, and complementary to measurements by other B-factory experiments. Also CP violation in $B^0 \to J/\psi\ K_S^0$ can be observed in terms of the measurement of sin2β with an accuracy of ~0.05.

As for the standard model Higgs search at the Tevatron, the gluon fusion ($gg \to h$) and the vector-boson associated production ($q\bar{q}' \to hW$, $q\bar{q} \to Zh$) are the main production processes. The predicted cross sections are ranging from 1 to 0.1 pb. Concerning the decay mode, $h \to b\bar{b}$ dominates in the low-mass region below 130 GeV/c^2. Based on this prediction, the low-mass Higgs search is being studied in

$$q\bar{q}' \to Wh \to l\nu b\bar{b}$$

$$q\bar{q} \to Zh \to l^+l^- b\bar{b},\ \nu\bar{\nu}b\bar{b}.$$

In order to discriminate the Higgs signal from the large QCD background, we require high-p_T leptons and/or neutrinos (missing energy) for triggering the signal. Studies to improve the b-tagging efficiency and the b-jet reconstruction are in progress. For the high-mass Higgs above 130 GeV/c^2, since the decay $h \to WW$ becomes dominant, we search for

$$gg \to h \to WW^* \to l^+l^-\nu\bar{\nu}$$

$$q\bar{q}' \to Wh \to l^\pm \nu W^* W^* \to l^\pm \nu l^\pm \nu\, jj$$

$$q\bar{q} \to Zh \to l^\pm l^\mp W^* W^* \to l^\pm l^\mp l^\pm \nu\, jj$$

as the Higgs production signal. If the Higgs boson is created via the vector-boson associated production, we can observe a like-sign dilepton which is rare in the standard model background processes. Figure 8 shows the required integrated luminosity either to exclude the standard model Higgs at 95% C.L. limit, or to discover the Higgs at the 3σ or 5σ level of significance as a function of the Higgs mass. For the 120 GeV/c^2 Higgs, it can be excluded with 2 fb^{-1} if it does not exist. However, if it exists, we can achieve the 3σ evidence with 7 fb^{-1} and the 5σ discovery with 15 fb^{-1} [7].

Even if the standard model Higgs is not discovered, the constraint on the Higgs mass can be set through the radiative correction of the top quark mass (M_{top}) and the W boson mass (M_W). The accuracies of M_W and M_{top} are expected to be 30 MeV/c^2 and 3 GeV/c^2 with 2 fb^{-1} in Run IIa, which corresponds to the Higgs mass (M_h) accuracy of $1/2M_h < M_h < 2M_h$ as shown in Figure 9. With 15 fb^{-1} in Run IIb, the Higgs mass will be determined with an accuracy of 30% with improved accuracies of M_W (30 MeV/c^2) and M_{top} (2GeV/c^2).

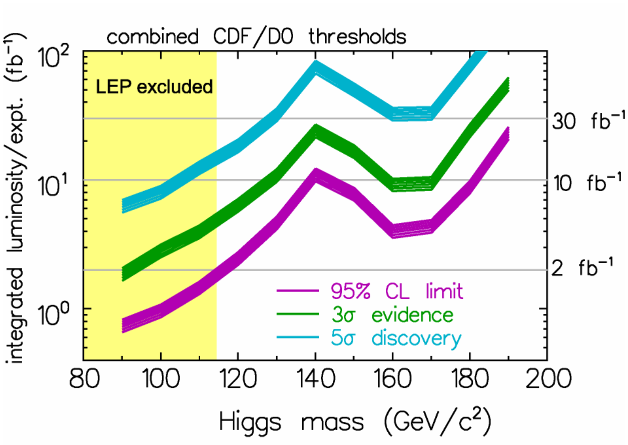

Figure 8 : The required integrated luminosity either to exclude the standard model Higgs at 95% C.L. or to discover it at the 3σ or the 5σ level as a function of the Higgs mass.

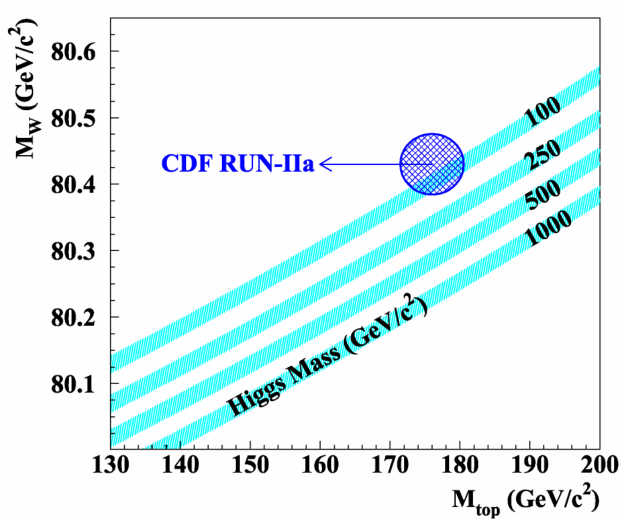

Figure 9 : The standard model prediction of the Higgs mass dependence on the W mass and the top quark mass. The expected accuracy in the CDF Run IIa (2 fb^{-1}) is superimposed.

6 FUTURE PROSPECTS AND SUMMARY

As described in the previous sections, the Fermilab accelerators and the collider detectors were successfully upgraded, and the Tevatron Run IIa operation started in March 2001. The CDF detector is working well, and we are accumulating physics data of $p\bar{p}$ collisions with good quality. Data analyses are also in progress. We expect to maintain the peak luminosity of the Tevatron in the range $2.5 \sim 4 \times 10^{31}$ cm^{-2}s^{-1} in 2002, which will result in the integrated luminosity about 150 pb^{-1}. After the Recycler installation and commissioning in 2003, the peak luminosity is expected to rise up to $4 \sim 6 \times 10^{31}$ cm^{-2}s^{-1}. The integrated luminosity will reach 2 fb^{-1} over 2 ~ 3 years, which is 20 times larger statistics than we accumulated in Run I.

The Run IIb program is planned with higher luminosity after Run IIa. The peak luminosity of 4×10^{32} cm^{-2}s^{-1} is expected. The luminosity gain will be achieved mainly by increasing the anti-proton intensity. The six-month shut-down is scheduled in 2005 to make some minor upgrades of the collider detectors. The silicon detector will be replaced with the radiation-hard ones. The goal of the Run IIb program is the luminosity accumulation of 15 fb^{-1} during 4 year running through 2008.

The Fermilab Tevatron collider will continue to explore the high energy frontier of particle physics until the LHC starts at CERN. It will provide unique opportunities to discover the Higgs boson and to explore the physics beyond the standard model. Also some early results are already competitive to the world best accuracies in spite of the low statistics. It is expected to give us a number of important physics outputs such as the top-quark properties and the CP structure in b mesons using the large statistics through Run IIa and Run IIb.

7 REFERENCES

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