CDF: Run II Physics Projections

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In March 2001, the Fermilab Tevatron will start a new physics run of $p\bar{p}$ collisions at $\sqrt{s} = 2.0$ TeV. The CDF experiments will collect a data sample of 2 fb^{-1} in the first two years. In this paper we describe the B physics prospects at CDF during the upcoming run.

1. Introduction

In this paper we describe the B physics prospects at CDF (Collider Detector at Fermilab). The CDF detector collected a data sample of 110 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV during 1992–96 (Run I). A large number of B physics measurements have been performed with the data sample [1]. The measurement of the CP violation parameter $\sin 2\beta$ [2] is still competitive with the first preliminary results of Babar [3] and Belle [4] experiments. Moreover, it is the unique feature to exploit the B_s^0 and B_c^+ mesons, and b baryons which is not produced at the $\Upsilon(4S)$ machines.

The Tevatron will commence $p\bar{p}$ collisions again in March 2001. The currently named Run II will provide 20 times greater luminosity than Run I, at a center of mass energy of 2 TeV. The goal of the first phase of Run II is the accumulation of 2 fb^{-1} in the first two years. Although a second step will provide a total luminosity higher than 15 fb^{-1} before the turn-on of the LHC. The main goals of the B physics for Run II are a precision measurement of the angles β and γ, and observation of the B_s^0 flavor oscillation as well as the rare B decay searches and studies of the heavier B-hadron states, B_c^+, Λ_b^0, etc.

2. Detector and Trigger Upgrade

The CDF detector has been upgraded [5] to prepare for the high radiation and the high crossing rate under Run II Tevatron environment. There are also several upgrades to improve the sensitivity of the CDF detector to the B physics:

- The acceptances of new silicon vertex detector system and new muon detector system for B decay signals are improved factors by of $\sim$1.4 and $\sim$2, respectively.

- A new silicon layer (L00) located immediately outside of the beam pipe at a radius of 1.6 cm improves the vertex resolution. The typical time resolution for B decays is 45 fs with the L00 and 60 fs without the L00.

- A new time of flight system (TOF) with a 100 ps of the flight time resolution provides a 2σ separation of kaons and pions for charged tracks with momentum less than 1.6 GeV/c.

A new trigger system with a 3-level architecture will be installed. In Run II the Tevatron will be operated with 36 and 121 bunches, and the beam crossing occurs every 396 ns and 132 ns, respectively. The Level-1 system will reduce the rate to 50kHz. Beside the calorimeter and muon triggers, this include a tracking trigger (XFT) for tracks with transverse momentum $p_T > 1.5$ GeV/c. The L1 trigger system will allow us to lower the p_T threshold of the muon trigger from 2.2 GeV/c in Run I to 1.5 GeV/c, and increase the acceptance for the $J/\psi \to \mu^+\mu^-$ trigger by a factor of $\sim$2. The level-2 system will work at a rate of 300 Hz, and include a displaced track trigger (SVT) which uses the silicon detector information and measures the track impact parameter with a 35 μm precision.

In Run I, all the B-physics analyses are based on the data set triggered with on one or two leptons. However, the new trigger system allows

Table 1
Effective tagging efficiency ϵD^2

	$B_d^0 \to J/\psi K_S^0$	$B_s^0 \to D_s^- \pi^+$
Same side	1.9%	4.2%
Lepton	1.7%	1.7%
Jet charge	3.0%	3.0%
Kaon	2.4%	2.4%
Total	9.0%	11.3%
Total (w/o TOF)	6.1%	5.7%

us to recored the hadronic B decay events without requiring any leptons. We designed dedicated triggers for the hadronic B decay events, which required two XFT tracks and two SVT tracks at Level 1 and Level 2, respectively. For example, we expect ~ 20000 and 10000 reconstructed events of the $B_s^0 \to D_s^- n\pi^\pm$ and $B_d^0 \to \pi^+\pi^-$ decays, respectively, in the 2 fb^{-1} of the two track trigger data.

3. Flavor Tagging

The determination of the initial B hadron flavor (B or $\overline{B}$) is important for observing the mixing and CP asymmetries. In Run II, we will employ four flavor tagging methods. One of the methods, same-side tagging, uses charge correlation between a B hadron and its fragmentation tracks. Other three methods, opposite-side taggings use the charge correlation between a B hadron and second $\overline{B}$ hadron: 1) the lepton tagging uses the charged lepton from the semileptonic $b \to \ell^- \bar{\nu} c$ decay; 2) the kaon tagging uses the charged kaon from the sequential $b \to c \to K^-$ decay; 3) the jet charge tagging uses the fact that charge of the b quark to be less than zero.

Table 1 shows prediction of the effective tagging efficiency (ϵD^2). The K-π separation with the TOF detector helps the flavor taggings such as the same side tagging for the B_s^0, and opposite side kaon tagging. For the $B_s^0 \to D_s^- \pi^+$ channel the TOF almost doubles the effective tagging efficiency ($5.7\% \to 11.3\%$).

4. B_s mixing from $B_s^0 \to D_s^- n\pi^\pm$

For measuring the $B_s^0 \bar{B}_s^0$ mixing frequency x_s, Foulier analysis has been usually employed [6], and significance for the analysis is written by

$$Sig(x_s) = \frac{1}{\sqrt{2}} \frac{1}{\sigma x_s} \quad (1)$$

$$= \sqrt{\frac{N}{2} \cdot \epsilon D^2 \cdot \frac{S}{S+B} \cdot e^{-(x_s \frac{\sigma_t}{\tau_{B_s^0}})^2}}, \quad (2)$$

where N is number of the signal events, S/B is signal-to-background ratio, $\tau_{B_s^0}$ is life time of the B_s^0 meson, and σ_t is decay time resolution. It is interesting to note that a 5σ measurement corresponds to $\sigma x_s / x_s = 0.5\%$ with $x_s = 30$. Thus, once we observe the B_s^0 mixing, the statistical uncertainty for the x_s measurement is very small.

The two track trigger will collect a large number of the $B_s^0 \to D_s n\pi$ events, and the new silicon strip detector (L00) significantly improves the decay time resolution. Figure 1 shows the required luminosity for a five sigma observation of the B_s^0 mixing with two different S/B cases. Thus a few hundred pb^{-1} (the first few month) of the Run II data will be enough to observe the B_s mixing with $x_s = 20 \sim 30$. Also the maximum reach of our detector is $x_s \sim 65$

5. $\sin 2\beta$ from $B_d \to J/\psi K_S^0$

In Run I, CDF measures the $\sin 2\beta$ to be $0.79 \pm 0.39 \pm 0.16$ in the 400 events of the $B_d^0 \to J/\psi K_S^0$ sample [2]. The Run II prospect of the statistical uncertainty is obtained by scaling the Run I measurement according to the equation,

$$\sigma(\sin 2\beta) \propto \frac{1}{\sqrt{\epsilon D^2 N}}. \quad (3)$$

The upgraded CDF II detector and the trigger system improve the acceptance for the $B_d^0 \to J/\psi K_S^0$ events by a factor of 2$\sim$3, and we will collect a 20000$\sim$30000 of signal samples in the 2 fb^{-1} of the data. Systematic uncertainty of the $\sin 2\beta$ measurement is mainly caused by the dilution measurement by using $B_d^0 \to J/\psi K^{*0}$ for the same-side tagging and $B_u^+ \to J/\psi K^+$ for the opposite-side taggings.

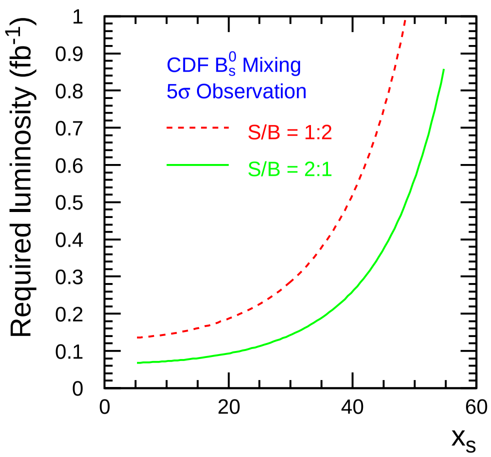

Figure 1. Required luminosity for a five sigma observation of B_s^0 mixing.

With a signal sample of 10000 (30000) reconstructed events, the expected value will be $\sigma(\sin 2\beta) = 0.067$ (0.043).

6. γ from $B_d^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$

To extract the angle γ by fitting on the CP violating observables in the $B_d \to \pi^+\pi^-$, $B_s^0 \to K^+K^-$, and $B_d^0 \to J/\psi K_S^0$ channels is proposed by R. Fleisher [7]. The idea is using U-spin symmetry, a subgroup of flavor SU(3), to relate the CP violation in $B_d^0 \to \pi^+\pi^-$ to the one in $B_s^0 \to K^+K^-$. In the limit of flavor SU(3) symmetry the difference of "penguin pollution" for these two decays is entirely due to CKM matrix elements. Relating the two decays thus allows us to determine a weak phase γ with a small uncertainty due to the penguin pollution.

Figure 2 shows the expected uncertainty for the γ measurement as a function of the γ with 2 fb^{-1}. Each points in the plot show variation of the uncertainty by changing the weak phase β and the strong phase θ within the ranges of 15–35° and 0–360°, respectively. In the plot, we assume to collect 5k $B_d^0 \to \pi^+\pi^-$ events and 10k $B_s^0 \to K^+K^-$ events, and S/B between the $B_d^0 \to \pi^+\pi^-$ signal

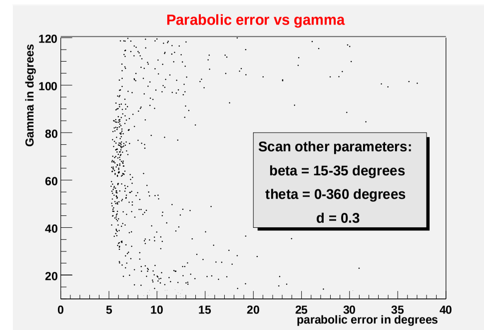

Figure 2. Expected statistical uncertainty for extracting the angle γ as a function of the γ in 2 fb^{-1} of the data.

to combinatorial background to be 1.0. We will measure γ with an error better than 10°

7. Rare $B_d^0 \to K^{*0}\mu\mu$ Decay

The $B_d^0 \to K^{*0}\mu\mu$ decay occur via the quark transition $\bar{b} \to \bar{s}$ that involves loop, "penguin" and "box", diagrams. The Run I CDF set an upper limit on the decay branching fraction to be 4.0×10^{-6} at a 90% confidence level [8].

In Run II we expect ~ 50 events of such decay in the 2 fb^{-1} of the data. Then the Forward-Backward asymmetry (A_{FB}) is an interesting observable. The A_{FB} is defined as follows,

$$A_{FB} = \frac{N(\cos\Theta > 0) - N(\cos\Theta < 0)}{N(\cos\Theta > 0) + N(\cos\Theta < 0)} \qquad (4)$$

where Θ is the angle in the rest frame of the $\mu^+\mu^-$ system between the direction of the B_d and the direction of the μ^+. The Standard Model calculations predicts the A_{FB} distribution to cross the zero around $M_{\mu^+\mu^-} = \sqrt{s} = 2$ GeV/c^2. Although the A_{AB} distribution strongly depends on the $B \to K^*$ form factor, the zero position is stable under various form factor parameterization [9]. However some new physics models predict there is no zero in the A_{FB} distribution [10].

Figure 3 shows the expected A_{FB} distribution and its uncertainty with 50 and 400 signal events.

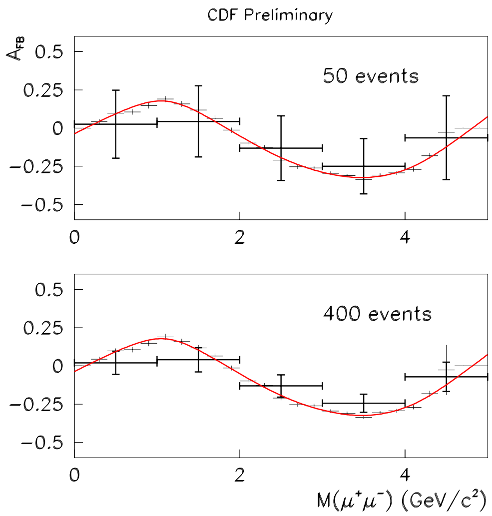

Figure 3. Expected uncertainty for measuring the $A_{FB}(m_{\mu^+\mu^-})$ distribution with 50 events (2 fb^{-1}) and 400 events (15 fb^{-1}) of the data.

The solid lines in the plots correspond to the standard model prediction [11].

8. Other Studies

- The $B_s^0 \to J/\psi\phi$ decays are sum of the CP-even and CP-odd states, and we can extract difference of their width ($\Delta\Gamma$) by fitting the decay time distribution to two exponential components. The Run I CDF experiment observed a 50 events of the $B_s^0 \to J/\psi\phi$ decays and measured the CP-even fraction to be 0.77 ± 0.19 [12]. In Run II, we will obtain 4k events of the $B_s^0 \to J/\psi\phi$ sample per 2 fb^{-1} of data and measure the $\Delta\Gamma$ with a precision of $\pm(0.03$ to $0.08)$ depending on the CP-even fraction.

- The angle γ can be probed the $B_s^0 \to D_s^{\pm}K^{\mp}$ decay [13] which we will collect $\sim$ 850k signals in the 2 fb^{-1} of the data. The expected error for $\sin\gamma$ depends on the signal-to-background ratio and approximately 0.7 and 0.4 for the case with $S/B = 1/6$ and $S/B = 1$, respectively.

- B_c meson was first observed in Run I CDF data with ~ 20 events of the $B_c^+ \to J/\psi\ell^+\nu$ decay [14]. In Run II, we expect $\sim$ 800 $B_c^+ \to J/\psi\ell^+\nu$ events, 360 $B_c^+ \to J/\psi\pi^+$ events, and 30 $B_c^+ \to B_s^0\pi^-$ events per 2 fb^{-1}.

9. Conclusions

CDF has a rich program to exploit the data of Run II Tevatron. The main goals of the B physics in the 2 fb^{-1} of the data are: the measurement of the B_s oscillation with sensitivity up to $x_s \sim 65$; the measurement of the $\sin 2\beta$ with an error of 0.07; the measurement of the γ with an error of $10°$; the studies of the rare B decays and the B_c^+ decays. These are a compatible programs with those at $\Upsilon(4S)$ B factories and CDF will significantly contribute to B physics before the turn-on of B TeV and LHC-b.

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