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Highlights of B Physics at CDF

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HIGHLIGHTS OF B PHYSICS AT CDF §

The CDF Collaboration

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Abstract

The CDF experiment at the Fermilab Tevatron collider has produced many B physics results. Recent measurements on B meson masses, B lifetimes, B branching ratios, limits on rare B decays, and B flavour tagging studies are reviewed.

B Physics at a Hadron Collider

Traditionally B physics has been the domain of e^+e^- machines, but already the UA 1 collaboration has shown that B physics is feasible at a hadron collider [1]. However, the combination of a better mass resolution and vertex detection enables the Collider Detector at Fermilab (CDF) to perform a broader B physics program. At Fermilab's Tevatron proton-antiproton collisions take place at a centre-of-mass energy of 1.8 TeV. In this article we give a brief review of recent highlights of B physics at CDF. These results include measurements from the 1992/93 Run Ia of the Tevatron, where CDF recorded about 20 $p\mathrm{b}^{-1}$, and the ongoing 1994/95 Run Ib, where about 90 $p\mathrm{b}^{-1}$ is written to tape in the period up to July 1995.

The CDF detector is described in detail elsewhere [2]. The detector components relevant for B physics include a muon system with coverage in the central region up to a pseudorapidity of $|\eta| < 1.1$, where $\eta = -\ln[\tan(\theta/2)]$, and electromagnetic and hadronic calorimeters to identify electrons within the same η range. CDF's silicon vertex detector (SVX) [3] provides 2-dimensional tracking with an impact parameter resolution of 13 μm for high p_t tracks. An excellent momentum resolution of $\Delta p_\mathrm{t}/p_\mathrm{t} = [(0.0009 p_\mathrm{t})^2 + (0.0066)^2]^{1/2}$ from CDF's central tracking chamber plus SVX is another important ingredient of B physics at a hadron collider.

The b production cross section $\sigma_\mathrm{tot} \sim 30\mu$b within the central region is quite large at the Tevatron, but the total inelastic cross section is about three orders of magnitude larger. This puts certain requirements on the trigger system in finding B decay products. All B triggers at CDF are based on leptons. Dilepton and single lepton triggers both exist. Because of a steeply falling b production cross section, it is desirable to keep the trigger thresholds as

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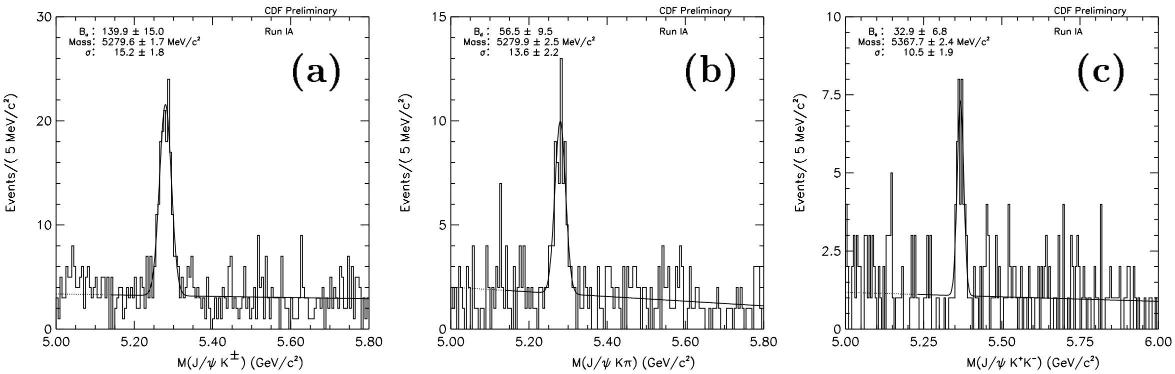

Figure 1: Invariant mass distribution of fully reconstructed B candidates: (a) $B^+ \to J/\psi K^+$, (b) $B^0 \to J/\psi K^{*0}$, and (c) $B_s^0 \to J/\psi \phi$.

B meson	mass $[MeV/\mathrm{c}^2]$	events	fitted width $[MeV/\mathrm{c}^2]$
B^+	$5279.1 \pm 1.7 \pm 1.4$	147 ± 14	14.4 ± 1.6
B^0	$5281.3 \pm 2.2 \pm 1.4$	51 ± 8	11.5 ± 1.9
B_s^0	$5369.9 \pm 2.3 \pm 1.3$	32 ± 6	10.4 ± 2.6

Table 1: Summary of B meson mass measurements.

low as possible. CDF's dilepton triggers consist of a dimuon trigger with $p_{\mathrm{t}} > 2\ GeV/\mathrm{c}$ for both muon legs, and an $e\mu$ trigger with $p_{\mathrm{t}}^{\mu} > 3\ GeV/\mathrm{c}$ and $E_{\mathrm{t}}^{e} > 5\ GeV$. The thresholds for the single lepton triggers are higher with $p_{\mathrm{t}} > 7.5\ GeV/\mathrm{c}$ for muons and $E_{\mathrm{t}} > 8\ GeV$ for electrons.

CDF B Physics Highlights

B Hadron Masses

Using the CDF detector, the masses of the B^+, B^0, and B_s^0 hadrons[‡] have been measured by fully reconstructing the decays $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, and $B_s^0 \to J/\psi \phi$ with the subsequent decays $J/\psi \to \mu^+\mu^-$, $K^{*0} \to K^+\pi^-$, and $\phi \to K^+K^-$. Requiring $p_{\mathrm{t}}(K^-) > 2\ GeV/\mathrm{c}$, $p_{\mathrm{t}}(\phi) > 2\ GeV/\mathrm{c}$ and $p_{\mathrm{t}}(K^{*0}) > 3\ GeV/\mathrm{c}$, as well as $p_{\mathrm{t}}(B^-) > 8\ GeV/\mathrm{c}$, $p_{\mathrm{t}}(B^0) > 8\ GeV/\mathrm{c}$ and $p_{\mathrm{t}}(B_s^0) > 6\ GeV/\mathrm{c}$, one obtains the invariant mass distributions displayed in Fig. 1. An additional cut on $c\tau(B^-) > 100\ \mu\mathrm{m}$ and $c\tau(B^0) > 100\ \mu\mathrm{m}$ was applied, while $c\tau(B_s^0)$ was required to be positive. The obtained fit results are shown in Table 1.

The obtained results are in good agreement with the Particle Data Table values [4], while the precision is competitive with the 2 MeV/c^2 uncertainty of the beam spread governing the CLEO B mass resolution. This result is based on about 20 $p\mathrm{b}^{-1}$ data from Run Ia. At

[‡]Unless otherwise stated references in this paper to a specific charged state are to be interpreted as implying the charge conjugate state as well.

Decay Mode	90% CL Limit on Branching Ratio CDF	CLEO	SM
$B^+ \to \mu\mu K^+$	$1.1 \cdot 10^{-5}$	$0.9 \cdot 10^{-5}$	$4.4 \cdot 10^{-7}$
$B^0 \to \mu\mu K^{*0}$	$2.1 \cdot 10^{-5}$	$2.9 \cdot 10^{-5}$	$2.3 \cdot 10^{-6}$
$B^0 \to \mu^+\mu^-$	$1.6 \cdot 10^{-6}$	$5.9 \cdot 10^{-6}$	$8.0 \cdot 10^{-11}$
$B_S^0 \to \mu^+\mu^-$	$8.4 \cdot 10^{-5}$	–	$1.8 \cdot 10^{-9}$

Table 2: Summary of 90% confidence level upper limits on rare B decays.

the end of Run I we expect to measure B masses with a statistical uncertainty of less than 1 MeV/c^2, while the systematic error will also be around 1 MeV/c^2.

Branching Ratios

These samples of completely reconstructed charged and neutral B mesons can be used to measure B branching ratios. It is advantageous to determine ratios of branching ratios, since many of the systematic errors cancel in a ratio. A preliminary CDF measurement of $BR(B^+ \to J/\psi K^+)/BR(B^0 \to J/\psi K^0) = 0.88 \pm 0.18 \pm 0.06$ is a significant improvement compared to the precision of the corresponding Particle Data Group (PDG) value of 1.36 ± 0.42 [4]. Using the well known branching fraction $BR(B^+ \to J/\psi K^+) = (1.02 \pm 0.14) \cdot 10^{-3}$ from the PDG [4], we obtain $BR(B^0 \to J/\psi K^0) = (1.16 \pm 0.29) \cdot 10^{-3}$. This improves our knowledge about the decay fraction of neutral B mesons into the $J/\psi K_S^0$ decay channel, which is believed to be most relevant for future CP violation measurements in the B system.

CDF has also looked for the Cabibbo suppressed decay $B^+ \to J/\psi\pi^+$ and finds its branching ratio relative to $BR(B^+ \to J/\psi K^+)$ to be $(4.9 \pm 1.8 \pm 1.1)\%$. This preliminary number compares well to the result of $(4.3 \pm 2.3)\%$ given by the CLEO collaboration [5].

Rare B Decays

The large b production cross section makes the Tevatron a favorable place to look for rare B decays. CDF has searched for the rare decay modes $B \to \mu\mu K^{(*)}$ and $B \to \mu^+\mu^-$, which are forbidden at tree level within the Standard Model (SM). The decays $B \to \mu\mu K^{(*)}$ can occur via penguin decays, while higher order loop or box diagrams can be drawn for the decay $B \to \mu^+\mu^-$. The 90% confidence level (CL) upper limits obtained on the branching ratios of these decay modes are compiled in Table 2. They are on the order of 10^{-5} and compare well to the corresponding limits given by the CLEO collaboration [6]. We expect these limits to improve by a factor of about five by the end of Run I, bringing the sensitivity for the decay $B^0 \to \mu\mu K^{*0}$ close to its Standard Model prediction, which is also shown in Table 2.

B Lifetimes

In the B system decay models predict a lifetime difference between the charged and neutral B mesons of about 5% [7]. Reaching this precision would also shed light on the discrepancy

Exclusive lifetime	Semi-exclusive lifetime
$\tau(B^+) = 1.68 \pm 0.09 \pm 0.06$ *ps*	$\tau(B^+) = 1.51 \pm 0.12 \pm 0.08$ *ps*
$\tau(B^0) = 1.64 \pm 0.11 \pm 0.06$ *ps*	$\tau(B^0) = 1.57 \pm 0.08 \pm 0.07$ *ps*
$\tau(B^+)/\tau(B^0) = 1.02 \pm 0.09 \pm 0.01$	$\tau(B^+)/\tau(B^0) = 0.96 \pm 0.10 \pm 0.05$

Table 3: Summary of (left) exclusive and (right) semi-exclusive B lifetime results.

between the theoretical and measured semileptonic branching fraction, which is found to be significantly smaller than predicted from spectator decay models [7]. We report on two lifetime measurements at CDF using fully and semi-exclusive B reconstruction.

Exclusive B Lifetimes

The lifetime measurement using fully reconstructed B mesons represents a Run Ib midrun update using about 70 $p\text{b}^{-1}$. All possible decay modes $B \to \Psi\mathbf{K}$ have been used, where Ψ is mainly a J/ψ but can also be a $\psi(2S)$. $\mathbf{K}$ represents the different kaon states K^+, $K^*(892)^+$, K_S^0, or $K^*(892)^0$. A sample of about 140,000 dimuon candidates with both legs in the SVX, forming a J/ψ peak with a width of about 16 MeV/c^2 on a small background, have been used for this analysis. The vertex and mass constrained J/ψ candidates are vertexed with the $\mathbf{K}$ candidates yielding the two-dimensional decay length L_{xy}. Together with the known B transverse momentum p_{t}, the proper time distributions shown in Fig. 2 are obtained. The bottom $c\tau$ distributions represent the background as obtained by fitting the B sideband regions to a gaussian with exponential tails. An unbinned likelihood fit of this background shape and the signal, which is assumed to be an exponential convolved with a Gaussian, is performed. We obtain the results displayed in Table 3. The main systematic errors result from residual misalignment, trigger bias, and the beam stability during a $p\bar{p}$ store at the Tevatron.

Semi-exclusive B Lifetimes

The exclusive B lifetime measurement is still statistics dominated. One way to increase statistics is to not fully reconstruct the B meson. This is done in the semi-exclusive analysis which uses about 20 $p\text{b}^{-1}$ of Run Ia single lepton trigger events.

The analysis principle is as follows: In a cone around the trigger electron or muon, $D^{(*)}$ meson candidates are reconstructed through their decay modes:

1. $D^0 \to K^-\pi^+$, where the D^0 is not from a D^{*+},
2. $D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+$,
3. $D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+\pi^+\pi^-$,
4. $D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+X$,

where X represents a π^0 which is not reconstructed. The $D^{(*)}$ candidates are intersected with the lepton to find the B decay vertex. Since the B meson is not fully reconstructed, its $c\tau_B$ can't be directly obtained. A correction has to be applied to scale from the $D^{(*)}\ell$ momentum to $p_{\text{t}}(B)$. This $\beta\gamma$ correction is done with the help of a Monte Carlo simulation.

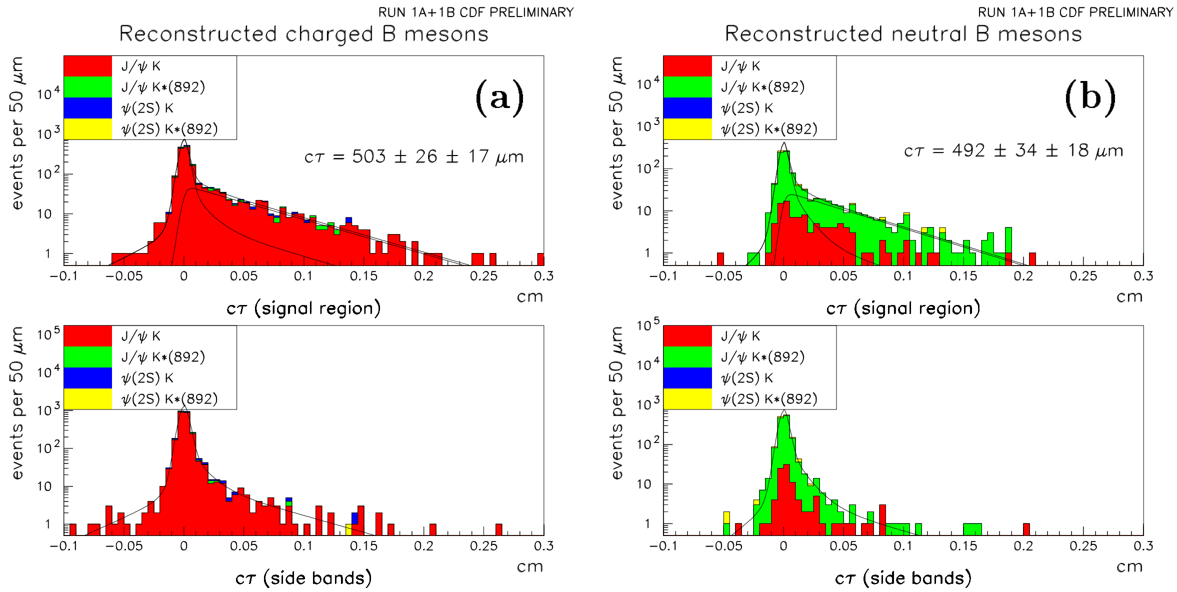

Figure 2: Proper time distributions of (a) charged and (b) neutral B candidates. The bottom plots represent the background $c\tau$ distribution as obtained from the B sidebands.

The final $D^{(*)}$ candidates can be seen in Fig. 3: (a) $D^0 \to K^-\pi^+$, where the D^0 is not from a D^{*+}, (b) $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$, (c) $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, and (d) $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+X$. Although the resolution of the D^{*+} mass peak is worse in case (d) compared to the other channels, it is still good enough to use this mode in this analysis. Note, the charm signals in Fig. 3 are quite clean and rather competitive with $D^{(*)}$ signals found at e^+e^- machines demonstrating the feasibility of B physics in a hadron collider environment without using J/ψ's.

The obtained lifetime distributions from $\ell^+\overline{D}^0$ and ℓ^+D^{*-} are used to determine the individual B^+ and B^0 lifetimes. A $\ell^+\overline{D}^0$ combination usually originates from a charged B meson while ℓ^+D^{*-} comes from a B^0. This simple picture is complicated by the existence of D^{**} states which are the source of $\overline{D}^0$ (D^{*-}) mesons that originate from a decay $B^0 \to D^{**-}\ell^+$, $D^{**-} \to \overline{D}^0X$ ($B^+ \to \overline{D}^{**0}\ell^+$, $\overline{D}^{**0} \to D^{*-}X$). This cross talk from D^{**} resonances has been decomposed using Monte Carlo. A combined lifetime fit yields the B lifetimes given in Table 3. The main systematic errors arise from the background shape, residual misalignment, the $\beta\gamma$ correction, and the D^{**} sample modeling. We expect the statistical error of this measurement to be reduced by a factor of 2.5 at the end of Run I, while the exclusive lifetimes will only improve by a factor $\sqrt{2}$ since this result already represents a midrun update.

The uncertainty of less than 10% on the CDF exclusive and semi-exclusive B lifetime results compares well to individual lifetime measurements by the LEP experiments [8]. Averaging the lifetime ratio results of the exclusive and semi-exclusive analysis yields a mean of $\tau^+/\tau^0 = 1.00 \pm 0.07$ which is very competitive with the lifetime average of 1.08 ± 0.08 given by the LEP B Lifetime Working Group at the 1995 Moriond Conference.

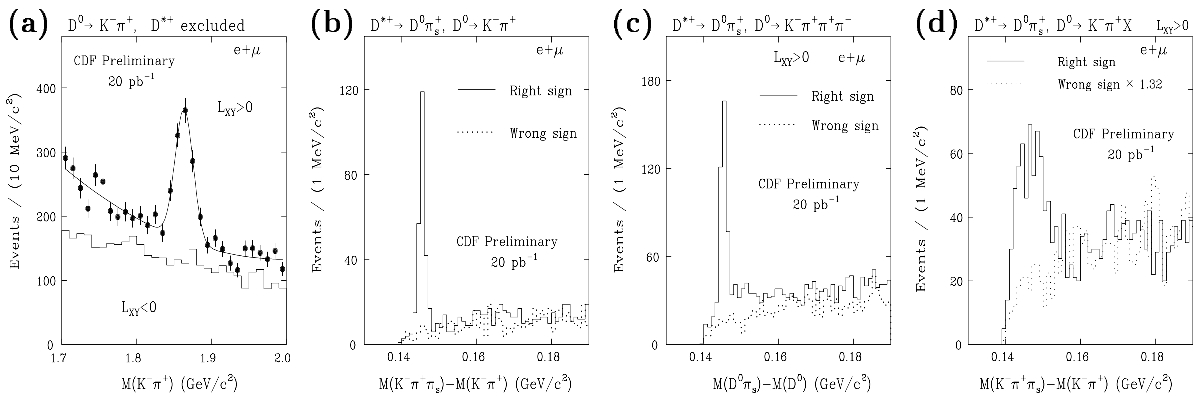

Figure 3: Invariant mass distribution of $D^{(*)}$ candidates from the semi-exclusive liefetime analysis: (a) $D^0 \to K^-\pi^+$, where the D^0 is not from a D^{*+}, (b) $D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+$, (c) $D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+\pi^+\pi^-$, and (d) $D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+X$.

B Flavour Tagging

The knowledge of the flavour of neutral B mesons at their creation is essential for $B\overline{B}$ mixing or future CP violation measurements. In order to compare different flavour tagging methods the figure of merit is the "effective tagging efficiency" εD^2, where ε is the efficiency of how often the tagging algorithm is applicable, and D is the dilution $D = (N_R - N_W)/(N_R + N_W)$, which is the difference of "right tags" N_R to "wrong tags" N_W normalized to the sum of both. Note, a perfect tag yields a dilution of 1, while a random tag results in a dilution of zero. In a CP violation measurement the quantity of interest is the asymmetry $A_{CP} = [N(B^0) - N(\overline{B}^0)]/[N(B^0) + N(\overline{B}^0)]$; e.g. the difference in the number of $J/\psi K^0_S$ events that originate from a B^0 rather than a $\overline{B}^0$. The measured asymmetry $A_{\rm meas}$ is then simply $A_{\rm meas} = D \cdot A_{CP}$, while the uncertainty ΔA_{CP} is given by $(\Delta A_{CP})^2 \simeq [\varepsilon D^2 N]^{-1}$ with N being the number of $J/\psi K^0_S$ events. Thus εD^2 also expresses the statistical power of a tag.

The existing B flavour tagging methods can be seperated into tagging on the *same* side as the B meson of interest or on the *opposite* side, exploiting the decay of the other B hadron in the event. *Same* side tagging (see e.g. [9]) can be achieved utilizing tracks originating from the fragmentation of a b quark into a B hadron or from the decay of higher B resonances (e.g. B^{**}). In both cases the charge of the so-called "bachelor" pion determines the flavour of the B meson. The most common method to perform flavour tagging on the *opposite* side is to exploit the charge of the lepton from a semileptonic decay of the other B hadron in the event. Another way consists of tagging with the charge of the Kaon from the subsequent charm decay, which correlates approximately 80% of the time to the flavour of the B hadron. Finally, using the b jet opposite to the B meson of interest with a jet charge counting method has been successfully applied by the LEP experiments [10].

CDF is studying these different tagging methods with the exception of Kaon tagging, since particle identification via d$E/$dx is poor at CDF. Unfortunately same side tagging is still under study and a result cannot be given at this time. However, CDF has two

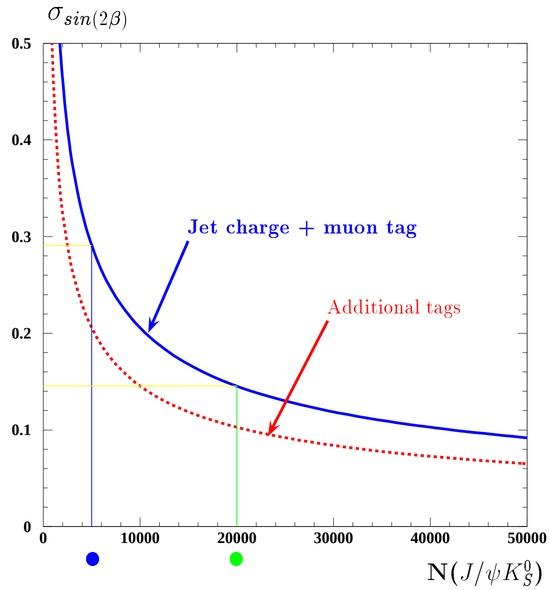

Figure 4: Prospects of the resolution on a measurement of sin(2β) for two flavour tagging scenarios.

preliminary results using lepton and jet charge tagging. From lepton tagging using low p_t muons we obtain $\varepsilon D^2 = (0.71 \pm 0.19)\%$, while jet charge tagging yields $\varepsilon D^2 = (1.01 \pm 0.39)\%$.

In order to estimate CDF's prospects for a CP violation measurement in Run II, the number of expected $B^0 \to J/\psi K_S^0$ has to be known, as well as the sum of effective tagging efficiencies from different flavour tagging methods. Using Run Ia and Ib data CDF finds in 60 pb^{-1} (138 ± 18) $J/\psi K_S^0$ candidates with a signal to background ratio of 1.1. Extrapolating this number to the expected Run II luminosity of 2 fb^{-1} results in about 5000 reconstructed $B^0 \to J/\psi K_S^0$ events. The CP reach with this number of events is illustrated in Fig. 4, where the number of $J/\psi K_S^0$ is plotted versus an expected error on sin(2β). The solid curve represents an εD^2 of 2%, which is given approximately by the sum of the existing results on muon and jet charge tagging. This leads to an error on sin(2β) of about 0.3. However, the CDF detector will undergo major upgrades for Run II. Increasing the lepton coverage out to $|\eta| \simeq 2$, triggering on $J/\psi \to e^+e^-$, and lowering the dimuon trigger thresholds to $p_t^\mu > 1.5$ $GeV/$c will increase the number of expected $J/\psi K_S^0$ events by a factor of 4. Together with an improved εD^2 of 4%, which includes other tagging methods like soft electron and same side tagging, an error on sin(2β) of about 0.1 can be achieved.

Conclusion

There exists a rich B physics program at CDF including results on B meson masses and B lifetimes, B branching ratios, rare B decays, as well as B flavour tagging studies. These measurements are competitive to the ones from e^+e^- collider experiments. Extrapolating towards Run II, which is supposed to start in 1999, a CP violation measurement using $B^0 \to J/\psi K_S^0$ is within reach.

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