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B Physics at the Tevatron

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B PHYSICS AT THE TEVATRON [1]

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Abstract. Precision B-physics results from the CDF and D0 Collaborations based on data collected during the Tevatron 1992-96 run are presented. In particular we discuss the measurement of the B_s meson lifetime, B_c meson observation, and $B^0 - \bar{B}^0$ mixing results obtained using time-evolution analyses. Prospects for the next Tevatron run, starting in 1999, are also reported.

INTRODUCTION

Precision B physics became possible at hadron colliders since the CDF Collaboration installed a silicon vertex detector (SVX) in 1992. The total b production cross section at the Fermilab Tevatron is about 30 μb [1] in the rapidity region $|y| < 1$. For a typical instantaneous luminosity of 10^{31} cm^{-2}·sec^{-1} the corresponding production rate is 300 Hz. However the backgrounds are also large: the b cross section is three orders of magnitude smaller than the total inelastic cross section. Clearly the trigger performance is of vital importance. All B triggers at hadron colliders are based on leptons. The CDF and D0 Collaborations have collected 100 pb^{-1} of data during the 1992-96 run. Currently, all B physics results from the Tevatron are very competitive to the ones from the LEP and SLC experiments [2].

In the following we shall report the latest CDF results on the B_s meson lifetime measurement, B_c meson observation, and time-dependent $B^0 - \bar{B}^0$ mixing.

B_S LIFETIME MEASUREMENT

The B hadron lifetimes are sensitive to the details of the decay mechanism beyond the spectator model. Unlike the D^+/D^0 case, B decay models predict very small differences between the B_u and the B_d lifetimes (5-10%) [3,4]. Although there is some controversy among theorists about the precise size of this effect, there is

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[2] Representing the CDF and D0 Collaborations

agreement that the expected difference between the B^0 and B_s lifetimes is less than about 1%.

CDF has measured the lifetimes of the B^0, B^+, B_s and Λ_b hadrons. In this report, we will discuss a recent update of the semi-exclusive B_s lifetime measurement, using a total of 110 pb^{-1} of data. A summary of other CDF results on B hadron lifetimes can be found in [5–8].

The lifetime of the B_s meson is measured at CDF using the semileptonic decay $B_s \to D_s l \nu X$. D_s mesons are reconstructed in a cone around the lepton using the following channels:

(a) $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$

(b) $D_s^- \to K^{*0}K^-$, $K^{*0} \to K^+\pi^-$

(c) $D_s^- \to K_S^0 K^-$, $K_S^0 \to \pi^+\pi^-$

(d) $D_s^- \to \phi\mu^-\nu$

For the first three decay modes the analysis starts with a single lepton trigger data set, while the semileptonic D_s decay mode is based on a dimuon data sample obtained with a trigger requirement of $M(\mu\mu) < 2.8$ GeV$/c^2$. A secondary vertex is defined at the intersection of the D_s and lepton trajectories in the plane transverse to the beam axis, and a transverse decay distance, L_{xy}, as the projection of the the vector difference of the secondary and primary vertex positions onto the direction of the $D_s l$ system:

$$L_{xy} = \frac{(\vec{x}_{sec} - \vec{x}_{prim}) \cdot \vec{p}_T(D_s l)}{p_T(D_s l)} \tag{1}$$

To extract the proper decay length, $c\tau$, from L_{xy} we need to correct with the appropriate $\beta\gamma$ factor:

$$c\tau = L_{xy} \cdot \frac{M_{B_s}}{p_T(B_s)} \tag{2}$$

where M_{B_s} is the mass of the B_s meson and $p_t(B_s)$ its transverse momentum. However, it is not possible to calculate the $\beta\gamma$ factor exactly: at least a neutrino is missing. $c\tau$ is therefore calculated as follows:

$$c\tau = L_{xy} \cdot \frac{M_{B_s}}{p_T(D_s l)} \cdot K \tag{3}$$

where K is an average correction factor calculated with a Monte Carlo simulation.

About 600 B_s candidates have been reconstructed in the four D_s decay channels, where the $D_s \to \phi\pi$ mode contributes the largest statistics with 220 ± 21 events (Figure 1 (left)). Figure 1 (right) shows the corresponding decay length distributions. From all four D_s decay modes a B_s lifetime of

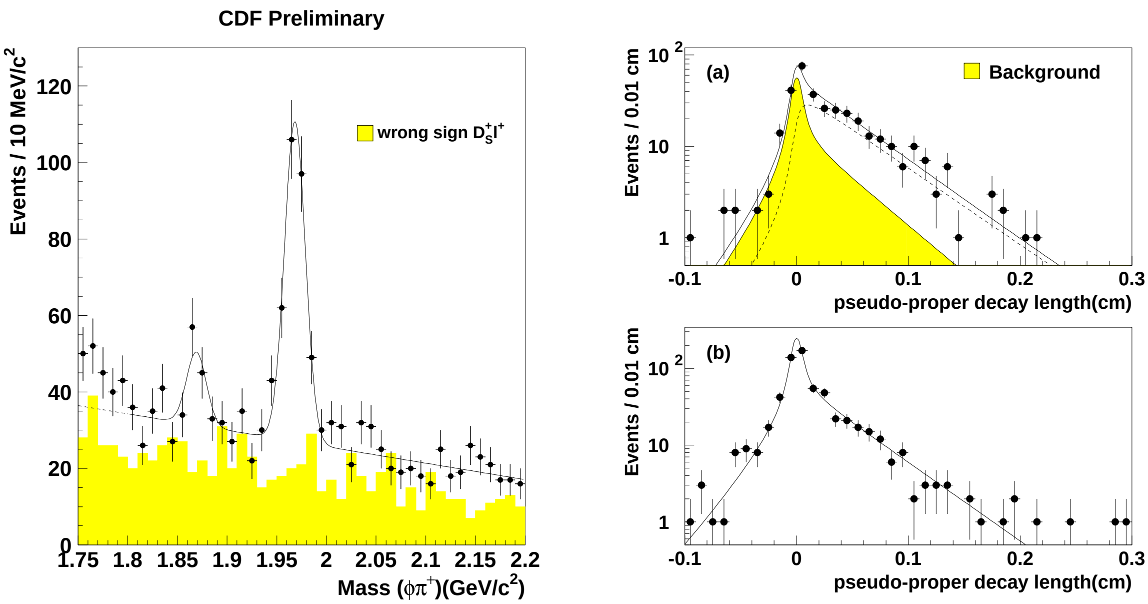

FIGURE 1. (Left) Invariant mass of the $\phi\pi$ system. The points are for right sign $D_s l$ combinations. The shaded histogram shows the wrong sign combination distribution. (Right) Corresponding decay length distributions for the signal (top) and background (bottom) samples.

$$\tau(B_s) = 1.39 \pm 0.09\ (stat.) \pm 0.05\ (syst.)\ \text{ps} \tag{4}$$

has been measured. This measurement is still statistically limited. The main systematic errors arise from the background shape and normalization.

Another possible measurement using the same data sample is to look for a difference in the lifetime of the two B_s mass eigenstates. Theoretical estimates predict $\Delta\Gamma/\Gamma$ to be on the order of $10-20\%$ [9,10]. In the standard model, $\Delta m/\Delta\Gamma$ is related to the ratio of the Kobayashi-Maskawa matrix elements $|V_{cb}V_{cs}|/|V_{tb}V_{ts}|$ which is quite well known, and depends only on the size of QCD corrections. If these QCD corrections can be precisely calculated, a measurement of $\Delta\Gamma$ would imply a determination of Δm, and thus a way to infer the existence of $B_s - \bar{B}_s$ oscillations. We fitted the proper decay length distribution allowing for two different lifetime components (Γ_H and Γ_L), with $\Gamma_{H,L} = \Gamma \pm \Delta\Gamma/2$. Fixing the mean lifetime to its PDG average value [11]

$$\tau_{mean} = \Gamma^{-1}\left(1 - \frac{1}{4}\frac{\Delta\Gamma^2}{\Gamma^2}\right)^{-1} = 1.57 \pm 0.08\ \text{ps} \tag{5}$$

a preliminary fit result is

$$\frac{\Delta\Gamma}{\Gamma} = 0.48\ ^{+0.26}_{-0.48} \tag{6}$$

indicating that the current statistics is not sensitive to a B_s lifetime difference. Based on the fit, a limit on $\Delta\Gamma/\Gamma < 0.81$ (95% CL) can be set. Using the value of

$\Delta\Gamma/\Delta m = (5.6 \pm 2.6) \times 10^{-3}$ [10], an upper limit on the B_s mixing frequency Δm_s can be obtained

$$\Delta m_s < 92 \times (5.6 \cdot 10^{-3})/(\Delta\Gamma/\Delta m) \times (1.57 \text{ ps}/\tau_{B_s}) \quad (95\% \text{ CL}) \tag{7}$$

OBSERVATION OF THE B_C MESON

The B_c^+ meson is the lowest-mass bound state of a family of quarkonium states containing a charm quark and a bottom antiquark. It decays weakly yielding a large branching fraction to final states containing a J/ψ [12–15]. Non-relativistic potential models predict its mass in the range 6.2-6.3 GeV/c^2 [16,17]. In these models, the c and the $\bar{b}$ are tightly bound in a very compact system and have a rich spectroscopy of excited states. There are three major contributions to the B_c decay width: $\bar{b} \to \bar{c}W^+$ leading to final states like $J/\psi\pi$ or $J/\psi l\nu$; $c \to sW^+$ leading to final states like $B_s\pi$ or $B_s l\nu$; and $c\bar{b} \to W^+$ annihilation, leading to final states like DK, $\tau\nu$, or multiple pions. The predicted lifetime is in the range 0.4-1.4 ps [12,18–22]. Because of the wide range of predictions, a B_c lifetime measurement is a test of the different assumptions made in the various calculations.

Limits on B_c production have been placed by various searches at LEP [23–25]. A prior CDF search placed a limit on B_c production in the $B_c^+ \to J/\psi\pi^+$ mode [26].

We report here the observation of B_c mesons produced at the Tevatron using 110 pb^{-1} of data collected by CDF. A more detailed description of this work can be found in Ref. [27]. An online dimuon trigger yielded a sample of about 196,000 $J/\psi \to \mu^+\mu^-$ events. We searched for the B_c using the decays $B_c^\pm \to J/\psi l^\pm \nu$. These decays have a very simple topology: a decay point for $J/\psi \to \mu^+\mu^-$ displaced from the primary interaction point and a third track emerging from the same decay point. A measure of the time between production and decay of a B_c candidate is the quantity

$$ct^* = L_{xy} \cdot \frac{M(J/\psi l)}{p_T(J/\psi l)} \tag{8}$$

where L_{xy} in the distance of the B_c candidate decay vertex to the beam center in the transverse plane. We required $ct^* > 60$ μm.

$B^\pm \to J/\psi K^\pm$ events were identified as a peak in the $\mu^+\mu^-K^\pm$ mass distribution; the fitted peak signal contained 290 ± 19 events. This signal provided a valuable rate calibration, as discussed below. However, for the B_c search, the $B^\pm$ signal events were excluded using a ± 50 MeV/c^2 cut around $M(B^+)$. Finally, the third track had to satisfy a number of electron or muon standard identification cuts.

A Monte Carlo calculation of B_c production and decay to $J/\psi l\nu$ showed that, for an assumed mass of 6.27 GeV/c^2, 93% of the final states would have $J/\psi l$ masses with $4.0 < M(J/\psi l) < 6.0$ GeV/c^2. We refer to this as the signal region,

TABLE 1. B_c Signal and Background Summary

	$3.35 < M(J/\psi l) < 11.0$ GeV/c^2	
	J/ψ e Events	J/ψ μ Events
False Electrons	4.2 ± 0.4	
Undetected Conversions	2.1 ± 1.7	
False Muons		11.4 ± 2.4
$B\bar{B}$ bkg.	2.3 ± 0.9	1.44 ± 0.25
Total Background	8.6 ± 2.0	12.8 ± 2.4
Background (fit)	9.2 ± 2.0	10.6 ± 2.3
Signal (fit)	$12.0\ ^{+3.8}_{-3.2}$	$8.4\ ^{+2.7}_{-2.4}$
Signal + Background	21.2 ± 4.3	19.0 ± 3.5
Candidates	23	14

but candidates with masses in the range 3.35 - 11 GeV/c^2 were accepted. We found 23 $B_c^\pm \to J/\psi\ e^\pm\nu$ candidates of which 19 were in the signal region, and 14 $B_c^\pm \to J/\psi\ \mu^\pm\nu$ candidates of which 12 were in the signal region.

Backgrounds are dominated by fake leptons and by random combinations of real leptons with J/ψ mesons. Table 1 summarizes the results of the background calculation and of a simultaneous fit for the muon and electron channels to the mass spectrum over the region 3.35 - 11 Gev/c^2 [27]. Figure 2 (left) shows the mass spectra for the combined candidate sample, combined backgrounds and fitted B_c contribution. The fitted number of B_c events is $20.4\ ^{+6.2}_{-5.5}$. To test the significance of the result, we generated a number of Monte Carlo trials with the statistical properties of backgrounds, but no B_c contribution. The probability of obtaining a yield of 20.4 or more events is 0.63×10^{-6}, equivalent to a 4.8 sigma effect.

To check the stability of the signal, we generated Monte Carlo signal templates for $5.52 < M(B_c) < 7.52$ GeV/c^2 and repeated the fit. The study showed that the magnitude of the signal is stable over the range of theoretical predictions for $M(B_c)$, and the dependence of the log-likelihood function on mass yielded $M(B_c) = 6.40 \pm 0.39\ (stat.) \pm 0.13\ (syst.)$ GeV/c^2.

We obtained the mean proper decay length $c\tau$ of the B_c meson from the distribution of ct^*, using only events in the mass signal region and after changing the $ct^* > 60\ \mu$m requirement to $ct^* > -100\ \mu$m. This yielded a sample of 42 J/ψ e and 29 J/ψ μ events. We determined a functional form for the shapes in ct^* for each of the backgrounds, and added a resolution- and $\beta\gamma$-smeared exponential decay distribution for the B_c contribution. An unbinned likelihood fit to the data (Figure 2 (right)) yielded the result:

$$c\tau = 137\ ^{+53}_{-49}\ (stat.) \pm 9\ (syst.)\ \mu\text{m} \quad (9)$$

$$\tau = 0.46\ ^{+0.18}_{-0.16}\ (stat.) \pm 0.03\ (syst.)\ \text{ps} \quad (10)$$

From the 20.4 B_c events and the 290 $B^\pm \to J/\psi K^\pm$ events, we calculated the B_c production cross section times the branching fraction $\mathcal{B}(B_c^+ \to J/\psi l^+\nu)$, relative

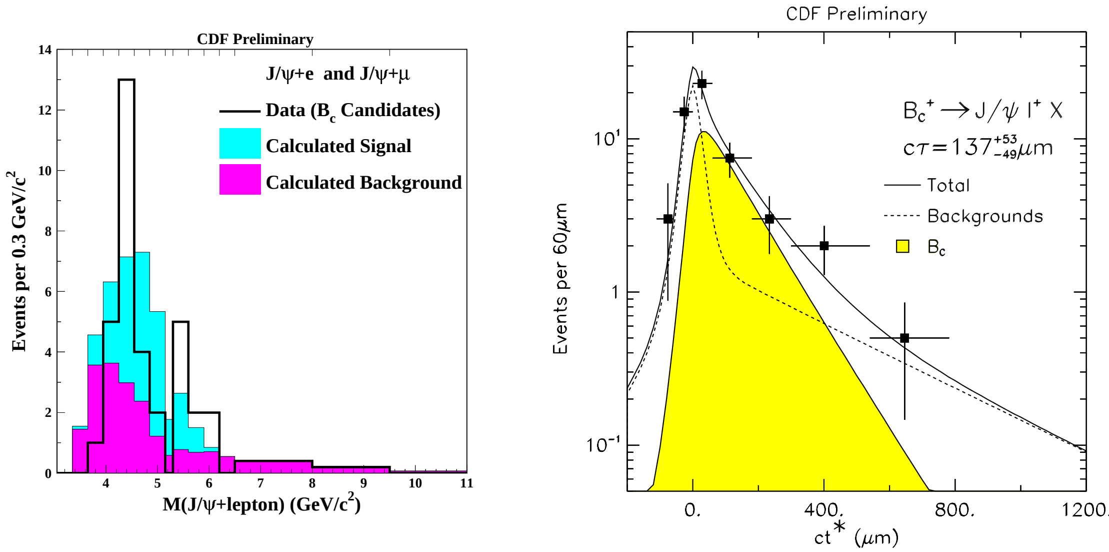

FIGURE 2. (Left) Invariant mass of the $J/\psi l$ system, comparing the data to the signal and background contributions determined in the fit. (Right) Corresponding decay length distributions.

to that for the topologically similar decay $B^+ \to J/\psi K^+$. Several systematic uncertainties cancel in the ratio. Since the detection efficiency for $B_c^+ \to J/\psi l^+\nu$ depends on $c\tau$ because of the ct^* requirement, we quote a separate systematic error because of the lifetime uncertainty. Finally, we multiply the 20.4 events by a factor 0.85 ± 0.15 to correct for other decay channels such as $B_c \to \psi' l\nu$ [27]. The result is

$$\frac{\sigma(B_c)\cdot\mathcal{B}(B_c \to J/\psi l\nu)}{\sigma(B^+)\cdot\mathcal{B}(B \to J/\psi K)} = 0.132\ ^{+0.041}_{-0.037}\ (stat.) \pm 0.031\ (syst.)\ ^{+0.032}_{-0.020}\ (life.) \quad (11)$$

for mesons with $p_T > 6.0$ GeV/c and $|y| < 1.0$. This result is consistent with limits from previous searches [23–25].

$B^0 - \bar{B}^0$ OSCILLATIONS

$B^0-\bar{B}^0$ transitions are allowed in the Standard Model via higher order weak interaction diagrams. Since the flavour eigenstates are not exactly the mass eigentstates, a B^0 produced at time $\tau = 0$ has a certain probability to turn (mix) into a $\bar{B}^0$ at a later time τ. Defining $x = \Delta m\ \tau_B$, where Δm is the mass difference and τ_B the average lifetime of the eigenstates of the mass matrix, the mixing probability is given by

$$\mathcal{P}(B^0(0) \to \bar{B}^0(\tau)) = \frac{e^{-\tau/\tau_B}}{2\tau_B}\cdot(1-\cos(x\frac{\tau}{\tau_B})) \quad (12)$$

The mixing parameters $x_{d,s}$, for the $B^0_{d,s}$ mesons, are related directly to the elements $V_{t(d,s)}$ of the CKM matrix.

In general, a time dependent mixing analysis requires knowledge of the flavour of the B meson at production and decay times. Experimentally, to measure the decay time implies the use of some kind of vertexing algorithm. The flavour at the decay time is determined from the decay products. All the analyses reported here use semileptonic B decays. The B meson decay vertex is measured at the intersection of the lepton and reconstructed charm trajectories. The charm signal "D" can be fully reconstructed or inclusively tagged using a secondary vertex algorithm. In analogy with the semi-exclusive B_s lifetime analysis, the proper decay length is calculated using

$$c\tau = L_{xy} \cdot \frac{M_B}{p_T(''D''l)} \cdot K \tag{13}$$

where K is an average kinematical Monte Carlo correction factor. In all cases, the flavour at decay time is determined using the charge of the lepton.

More challenging is to know the flavour at production time. Several approaches are possible. One possibility is to use the charge correlations of the B meson and other particles produced in the same jet (same-side tagging). These correlations are expected to appear in the fragmentation process or B^{**} decays. The second possibility is to look at the other B meson in the event (opposite-side tagging), that can (for instance) also decay semileptonically, or using a jet charge algorithm.

We present herein three recent measurements of the B_d frequency from CDF.

$B - \bar{B}$ mixing in $D^{(*)}l$ events

In this analysis the charm is reconstructed explicitly using the following channels:

(a) $D^0 \to K^-\pi^+$, where the D^0 is not from a D^{*+}

(b) $D^{*+} \to D^0\pi_s^+,\ D^0 \to K^-\pi^+$

(c) $D^{*+} \to D^0\pi_s^+,\ D^0 \to K^-\pi^+X$

(d) $D^{*+} \to D^0\pi_s^+,\ D^0 \to K^-\pi^+\pi^+\pi^-$

(e) $D^+ \to K^-\pi^+\pi^+$

Tracks with impact parameters significantly displaced from the primary vertex are selected in order to decrease combinatorial backgrounds. The signals are identified as peaks in the invariant mass distributions.

Same-side tagging is used. The momentum of the B meson is approximated by the momentum of its reconstructed portion. Charged tracks within a cone around the reconstructed B meson and consistent with the hypothesis that they originate from the primary vertex of the event are considered. Of the candidate tracks we select as the tag the track with minimum p_T^{rel} relative to the sum of the momenta of the B and that track. The efficiency for finding a tag is about 72%.

Next, the number of right-sign (RS) correlations (*i.e.* $B^0\pi^+$, $B^+\pi^-$) is compared to the number of wrong sign correlations (WS) (*i.e.* $B^0\pi^-$, $B^+\pi^+$) as a function of the proper decay time. For the B^0 meson the following asymmetry is expected:

$$A(\tau) = \frac{N_{RS}(\tau) - N_{WS}(\tau)}{N_{RS}(\tau) + N_{WS}(\tau)} = D \cos(\Delta m_d \, \tau) \tag{14}$$

where D is the so-called dilution of the tagging algorithm. D is related to the mistag fraction w by $D = 1 - 2w$. After correcting for channel cross-talk, the values of D and Δm_d are extracted from a fit to the data. The results are shown in Figure 4 (left):

$$\Delta m_d = 0.471 \ ^{+0.078}_{-0.068} \ (stat.) \pm 0.034 \ (syst.) \ \mathrm{ps}^{-1} \tag{15}$$

and a dilution $D(B^0) = 0.18 \pm 0.03 \pm 0.02$. The systematic error is dominated by the uncertainty in the fraction of D^{**} in semileptonic B decays.

$B - \bar{B}$ mixing in $e - \mu$ events

For this analysis, we trigger on leptons from the semileptonic decay of both B hadrons in an event: $B_1 \to eX$ and $B_2 \to \mu X$. Sequential decays from one B hadron are rejected with the requirement $M(e\mu) > 5$ GeV/c^2. An inclusive secondary vertex is reconstructed in association with one of the leptons. The vertexing algorithm has been tuned for high efficiency near $c\tau = 0$, with the efficiency reaching a plateau of about 40% for $c\tau > 500$ μm. The boost resolution is about 22%. The charge of the lepton associated to the displaced vertex gives the flavour at the decay time. The other lepton provides the flavour tag at the production time.

The challenge of this analysis is to determine the sample composition. It can be estimated from several kinematical quantities, like p_T^{rel} or the invariant mass of the tracks that form the displaced vertex. Here p_T^{rel} is defined as the transverse momentum with respect to the lepton direction of the hardest track in a cone around the lepton. About 86% of the sample is made of $b\bar{b}$ events ($10 - 15\%$ of these events contain sequential leptons), around 11% are events with at least a fake lepton, and the rest comes from $c\bar{c}$ events.

The final sample is formed by 6025 events with a secondary vertex around the electron (electron tags) and 5819 muon tags. Approximately 16% of these events contain both an electron tag and a muon tag. Figure 3 (left) shows the dependence on $c\tau$ of the like-sign fraction of events, defined as $N_{LS}(\tau)/(N_{LS}(\tau)+N_{OS}(\tau))$. A fit to the data is performed including components for direct and sequential b decays, $c\bar{c}$, and fake events. The result is:

$$\Delta m_d = 0.450 \pm 0.045 \ (stat.) \pm 0.051 \ (syst.) \ \mathrm{ps}^{-1} \tag{16}$$

where the dominant systematic error arises from the uncertainties in the sample composition.

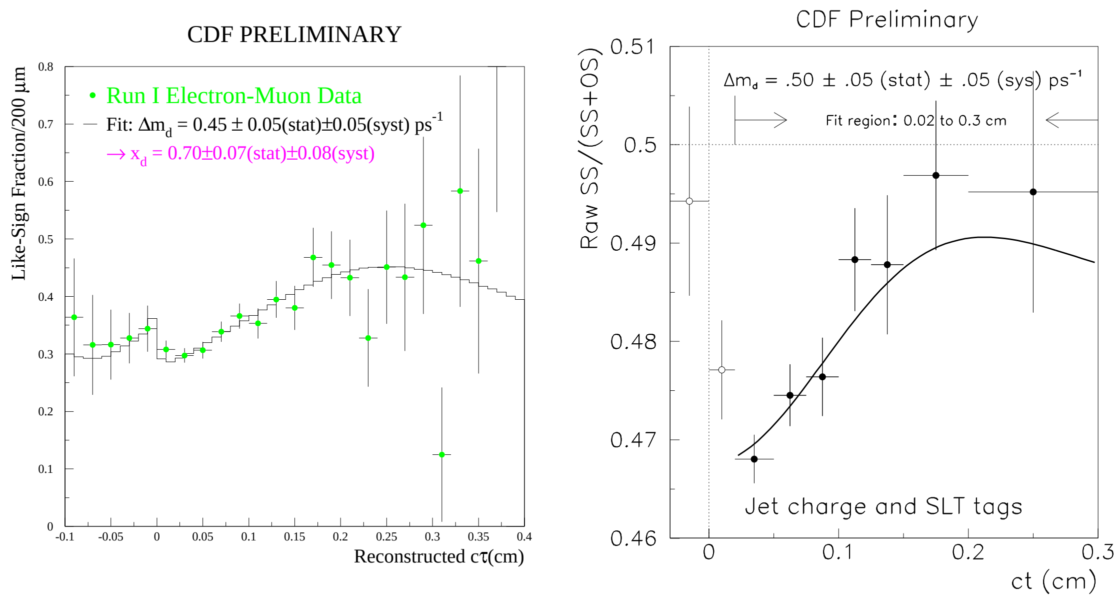

FIGURE 3. Fitted like-sign fraction as a function of the proper decay time for the $e - \mu$ (left), and inclusive lepton (right) mixing analyses.

$B - \bar{B}$ mixing in inclusive lepton events

Starting from events that satisfy an inclusive lepton trigger with $p_T > 8$ GeV/c, opposite-side flavour tagging is implemented using jet charge and soft leptons. The result of this analysis (Figure 3 (right)) is:

$$\Delta m_d = 0.496 \pm 0.052\ (stat.) \pm 0.048\ (syst.)\ \text{ps}^{-1} \tag{17}$$

The effective tagging efficiency of this algorithm has been studied in detail by CDF. Values of $\epsilon D^2 = 1.07 \pm 0.09 \pm 0.10\%$ for lepton tagging, and $0.78 \pm 0.12 \pm 0.09\%$ for the jet charge algorithm are found respectively.

There are still two other CDF opposite-side tagging mixing analyses. The first uses $D^{*+} l^-$ combinations in dilepton events ($\Delta m_d = 0.512\ ^{+0.095}_{-0.093}\ ^{+0.031}_{-0.038}$ ps^{-1}), and the second, dimuon data ($\Delta m_d = 0.503 \pm 0.064 \pm 0.071$ ps^{-1}). After taking into account the statistical overlap between the samples and common systematic errors, the CDF average result is

$$\Delta m_d = 0.481 \pm 0.028\ (stat.) \pm 0.027\ (syst.)\ \text{ps}^{-1} \tag{18}$$

This number is competitive with the LEP determinations [2].

PROSPECTS FOR RUN II

In 1999, the Tevatron together with the Main Injector is supposed to deliver 2 fb^{-1} in two years. By then, the CDF [28] detector will be upgraded with a new

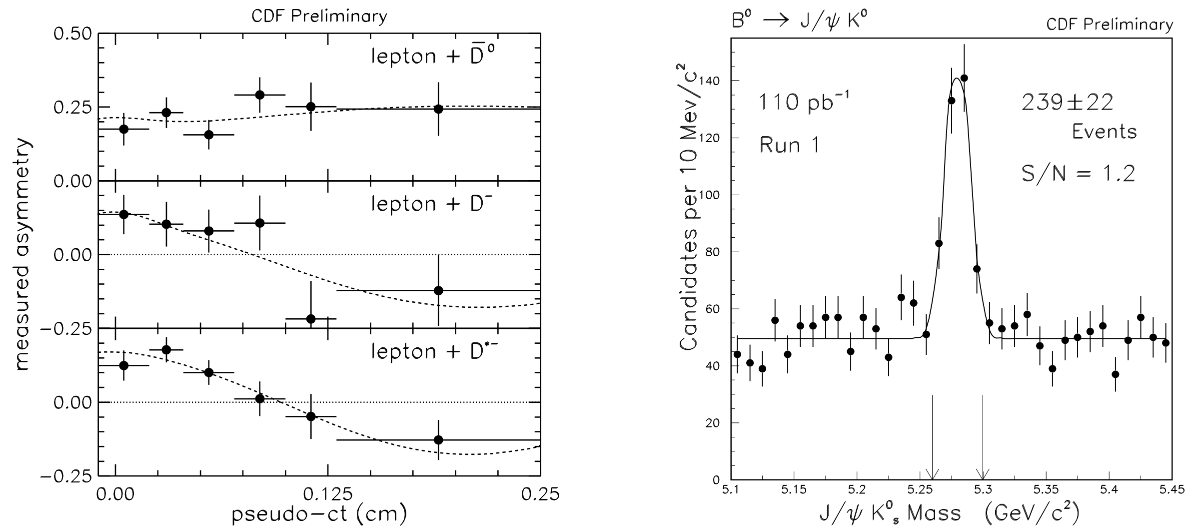

FIGURE 4. (Left) Time dependent asymmetry for B^+ (top) and B^0 mesons in the $D^{(*)}l$ mixing analysis. (Right) $B^0 \to J/\psi K_S^0$ signal collected at CDF during the 1992-96 run.

silicon vertex detector, which doubles the fiducial volume of the current SVX and provides 3-d tracking. A new central tracking system will be in place, designed to handle higher rates and shorter bunch crossing times, while maintaining the excellent momentum resolution and dE/dx capabilities of the Run I detector. With an upgraded trigger and DAQ system CDF plans to operate a fully hadronic trigger for the first time. D0 [29] will enhance considerably its tracking capabilities with an inner silicon vertex detector, surrounded by four superlayers of a scintillating fiber tracker. These detectors will be located inside a 2 Tesla superconducting solenoid.

sin 2β

CP asymmetries in the decay $B^0 \to J/\psi K_S^0$ determine the value of sin 2β. The 1992-96 CDF signal (Figure 4 (right)) is formed by 239±22 events with a signal-to-noise ratio of 1.2. Taking into account the improvements in luminosity, lower trigger thresholds, etc, we expect to collect 15,000 such events. This results in an error of Δsin $2\beta = 0.09$, assuming $\epsilon D^2 = 6\%$.

sin 2α

CP asymmetries in the decay $B^0 \to \pi^+\pi^-$ are related to the value of sin 2α. Here, the challenge is to be able to trigger on this decay. CDF plans to require two charged tracks at L1, and use impact parameter information at L2 (20 Hz). We expect about 10,000 events, that will produce an uncertainty of Δsin $2\alpha = 0.10$ for $\epsilon D^2 = 6\%$.

B_s mixing

Here the reach on Δm_s is limited by the proper time resolution. Monte Carlo studies show that the experiment will be sensitive to values up to 10 ps^{-1}.

CONCLUSIONS

CDF has produced very competitive measurements of the B hadron lifetimes. The B_c meson has been observed with a significance at the 4.8 sigma level. Mixing results are still dominated by statistics. In the frame of these analyses, the feasibility of a number of flavour tagging techniques has been demonstrated for the first time at a hadron collider. For Run II, CDF and D0 will be significantly upgraded. The experiments will focus on the discovery of CP violation in the B sector.

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