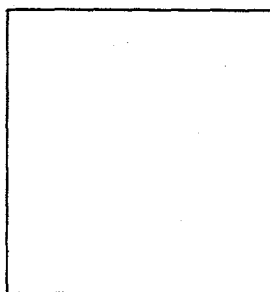


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# $B_d^0$ MIXING AND CP VIOLATION MEASUREMENTS AT THE TEVATRON

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We present six time-dependent  $B_d^0$  mixing measurements of  $\Delta m_d$  from the CDF Run I data. The CDF average is  $\Delta m_d = .494_{\pm .026}^{+ .026} (ps)^{-1}$ . We also present a measurement of the CP-violating asymmetry  $\sin(2\beta)$  using a sample of  $B^0/\bar{B}^0 \rightarrow J/\psi K_s^0$  decays and report  $\sin(2\beta) = .79_{- .44}^{+ .41}$ .

## 1 Introduction

In the context of the standard model, the mixing of  $B_d^0 \leftrightarrow \bar{B}_d^0$  occurs through the charge current coupling between quarks. This can be described in the context of the Cabibbo-Kobayashi-Maskawa (CKM)<sup>1</sup> matrix which transforms the flavor eigenstates of the quarks into their mass eigenstates. The CKM rotation matrix can be completely determined from three angles and a phase. It is useful to write it in the Wolfenstein<sup>2</sup> parameterization as:

$$V_{CKM} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

where  $\lambda = \sin(\theta_C)$  and the three other parameters  $A$ ,  $\rho$ , and  $\eta$  can be described by the remaining two weak rotation angles and the complex phase that introduces CP violation. Unitarity of the CKM matrix can be represented graphically as a triangle in the complex plane. The base of this triangle is scaled to unit length by  $A\lambda^3$ . This leaves three angles  $\alpha$ ,  $\beta$ , and  $\gamma$  and two sides which may be measured.  $B_d^0 \leftrightarrow \bar{B}_d^0$  mixing constrains the element  $V_{td}$  which contributes to one of the triangle sides, while CP violation in the decay  $B^0/\bar{B}^0 \rightarrow J/\psi K_s^0$  determines the angle  $\beta$ .

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### 1.1 $B_d^0 \leftrightarrow \bar{B}_d^0$ Mixing

A neutral  $B_d^0$  meson can oscillate into its anti-particle state,  $\bar{B}_d^0$  through second-order weak processes with a probability equal to:

$$\mathcal{P}(B_d^0(t_0) \rightarrow \bar{B}_d^0(t)) = \frac{e^{-t/\tau_B}}{2\tau_B} (1 - \cos(\Delta m_d t)), \quad (1)$$

where  $\Delta m_d$  is the frequency of the oscillation and is equal to the mass difference ( $\Delta m_d = m_H - m_L$ ) between the heavy and light mass eigenstates,  $\tau_B$  is the mean lifetime of the two mass eigenstates, and  $t$  is the proper decay time of the  $B_d^0$  in its rest frame. The asymmetry between the mixed and unmixed state is

$$A = \frac{P(B_d^0 \rightarrow B_d^0) - P(B_d^0 \rightarrow \bar{B}_d^0)}{P(B_d^0 \rightarrow B_d^0) + P(B_d^0 \rightarrow \bar{B}_d^0)} = \cos(\Delta m_d t) \quad (2)$$

To measure the time-dependent mixing asymmetry, we need three measurements: (1) the flavor of the  $B$  at production, (2) the flavor of the  $B$  at decay, and (3) the proper decay time. At CDF, measuring (2) and (3) are relatively easy. The flavor is known by the  $B$  reconstruction, and the proper time is measured using the CDF silicon vertex detector (SVX) with a 2-D  $r\phi$  resolution of  $\sigma_d \approx (13 + 40/p_T)\mu\text{m}$ . We use three algorithms for determining the  $B$  flavor at production. The soft lepton tagging (SLT) algorithm identifies the flavor of the opposite  $B$  through its decay to a lepton. The jet charge tagging algorithm (JetQ) uses a momentum-weighted charge average of particles in a  $b$  quark jet to infer the charge of the  $b$  quark. These two tagging algorithms are referred to as opposite side taggers (OST) since the production flavor is determined by the  $B$  opposite the  $B$  candidate of interest. The same side tagging algorithm (SST) uses charged tracks surrounding the  $B$  to determine its flavor. The effectiveness of a tagging algorithm is characterized by the efficiency,  $\epsilon$ , which is the fraction of events that can be tagged and the dilution,  $D$ , which dilutes the asymmetry due to an imperfect detector, mistags, etc. The statistical accuracy of a sample of tagged events is proportional to  $N\epsilon D^2$  where  $N$  is the number of events. Figure 1 shows six CDF  $B_d^0$ -oscillation measurements of  $\Delta m_d$ , and the combined average. These measurements exploit all three of the tagging algorithms.

### 1.2 CP-Violation

To measure CP-violation, we use the CP eigenstate  $B_d^0/\bar{B}_d^0 \rightarrow J/\psi K_s^0$ . For the CP-asymmetry to be non-zero, the imaginary phase between the two decay paths leads to a difference in the decay rate. The CP asymmetry is described by

$$A(t) = \frac{P(\bar{B}_d^0 \rightarrow J/\psi K_s^0) - P(B_d^0 \rightarrow J/\psi K_s^0)}{P(\bar{B}_d^0 \rightarrow J/\psi K_s^0) + P(B_d^0 \rightarrow J/\psi K_s^0)} = \sin(2\beta) \sin(\Delta m_d t) \quad (3)$$

The first measurements of  $\sin(2\beta)$  were published by CDF<sup>3</sup> and OPAL<sup>4</sup> in 1998. OPAL measured  $\sin(2\beta) = 3.2_{-2.0}^{+1.8} \pm 0.5$  using  $J/\psi K_s^0$  events. CDF used a sample of  $\approx 200$   $J/\psi K_s^0$  events to measure  $\sin(2\beta) = 1.8 \pm 1.1 \pm 0.3$ . The CDF events required the  $J/\psi$  to be reconstructed in the SVX and used only one tagging method to identify the  $B$  at production.

In the present update, we have expanded the earlier result to include  $\approx 200$  additional events in which the  $J/\psi$  is reconstructed in the central tracker (CTC) thus having large uncertainty on the decay time. We have also allowed for multiple taggers for each event. To measure the time-dependent CP asymmetry, we measure the proper decay time and tag the flavor of the  $B$  at production. Each event can be tagged with either a SST, an OST or both. When multiple taggers are combined the effective dilution ( $D$ ) is:

$$D_{eff} = \frac{D_{OST} \pm D_{SST}}{1 \pm D_{OST} D_{SST}} \quad (4)$$

Table 1: Efficiencies and Dilutions of tagging algorithms used for determining the flavor of  $B_d^0/\bar{B}_d^0 \rightarrow J/\psi K_s^0$

Tag	Efficiency (%)	Dilution (%)
SST <sub>svx</sub>	35.5 ± 3.7	16.6 ± 2.2
SST <sub>non</sub>	38.1 ± 3.9	17.4 ± 3.6
SLT	5.6 ± 1.8	62.5 ± 14.6
JetQ	40.2 ± 3.9	23.5 ± 6.9
Combined	$\epsilon D^2 = 6.3 \pm 1.7$	

To calibrate the OST algorithms, we use the  $B^\pm \rightarrow J/\psi K^\pm$  events which have similar kinematics to the  $J/\psi K_s^0$  signal sample and have a known flavor. For the dilution of the SST, we use the result from our previous measurement of  $\sin(2\beta)^3$ . Table 1 list the efficiencies and dilutions for the different tagging algorithms.

The tagged  $J/\psi K_s^0$  events are fit using a negative log-likelihood function. The fit is described by the signal events, the prompt background and the long-lived background. Each component is broken down into a piece with precision lifetime information and a piece with less precise lifetime information. The probability function includes terms for lifetime, normalized mass ( $M_N$ ) and the tagging efficiency functions. Background asymmetries are constrained by events far from the signal peak at  $M_N = 0$ , and detector asymmetries are accounted for in the fit using a large inclusive  $J/\psi$  sample.

The result for  $\sin(2\beta)$  is shown in Figure 2a including systematic errors due to the dilutions,  $\Delta m_d$ ,  $\tau_{B^0}$ , and  $m_{B^0}$ . The left side of the figure shows the asymmetry versus lifetime using the precision lifetime sample. The solid curve shows the full likelihood fit with  $\Delta m_d$  fixed to the world average and the dashed curve shows the fit with  $\Delta m_d$  floating. The one data point on the right side of the figure is the value of  $\sin 2\beta$  obtained from the CTC sample with low lifetime resolution. This result corresponds to a Feldman-Cousins frequentist limit of  $0.0 < \sin(2\beta) < 1$  at 93% CL. Figure 2b shows the CDF result compared to indirect results in the  $\rho - \eta$  plane<sup>5</sup>. The dotted lines correspond to the central values of  $\beta$  from  $\sin(2\beta) = .79$ . The solid lines represent the  $1\sigma$  regions. The oval shaped region shows the  $1\sigma$  and  $2\sigma$  intervals from indirect measurements of the CKM parameters<sup>5</sup>.

## 2 Conclusion

We present six measurements of the mixing parameter  $\Delta m_d$  from the CDF Run I data and measure  $\Delta m_d = .494_{\pm 0.026}^{\pm 0.026} (ps^{-1})$ . Using the tagging algorithms developed for these mixing measurements, we measure the CP-violating asymmetry  $\sin(2\beta)$  with a sample of  $B^0/\bar{B}^0 \rightarrow J/\psi K_s^0$  decays. We report  $\sin(2\beta) = .79_{-0.44}^{+0.41}$  which corresponds to a Feldman-Cousins frequentist limit of  $0 < \sin(2\beta) < 1$  at 93% CL.

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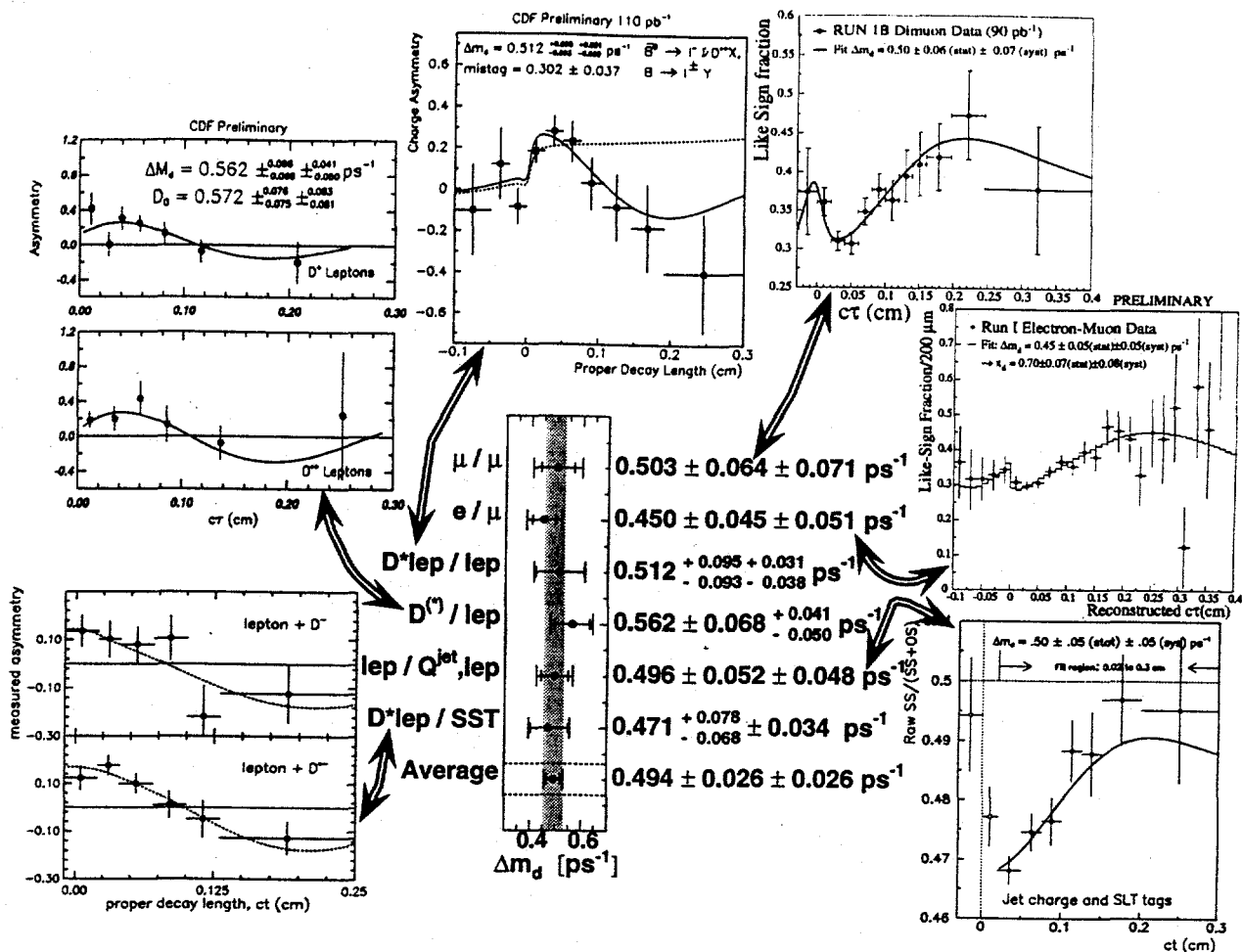


Figure 1: Six measurements of the mixing parameter  $\Delta m_d$  from the CDF Run I data.

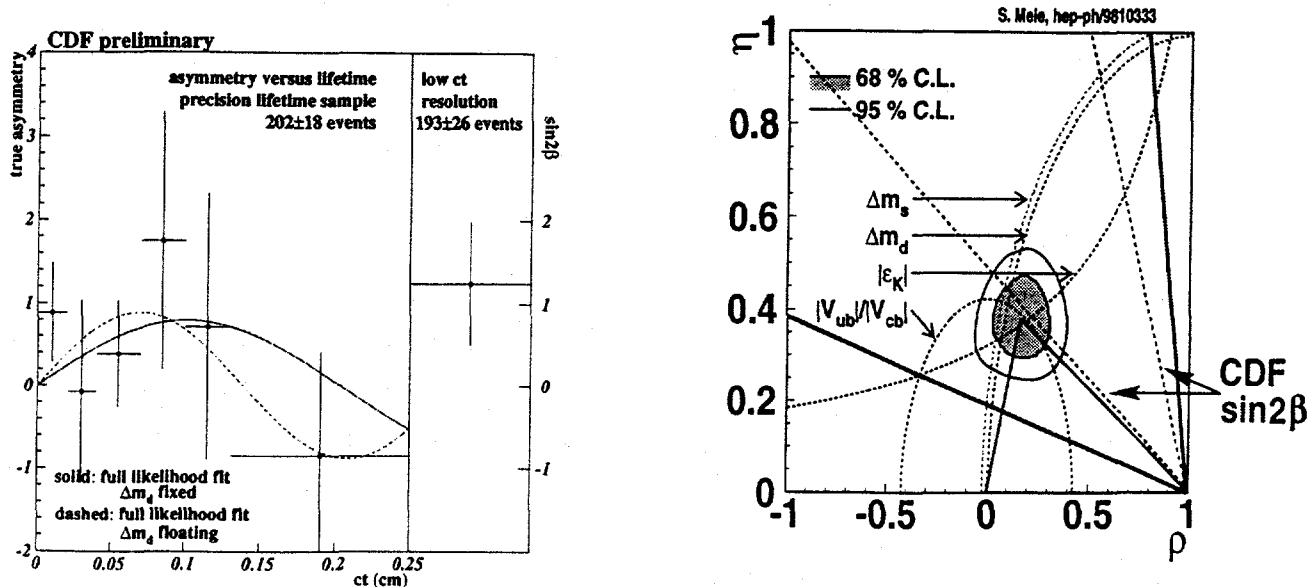


Figure 2: Left figure is the result of  $\sin(2\beta)$  using a negative log-likelihood fit and multiple tags. The right figure shows the CDF result compared to indirect results in the  $\rho - \eta$  plane.