Fermi National Accelerator Laboratory

FERMILAB-Conf-99/207-E
CDF

B_d^0 Mixing and CP Violation Measurements at the Tevatron

K. Byrum

Argonne National Laboratory
9700 S. Cass Avenue, Argonne, Illinois 60439

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

July 1999

Published Proceedings of the *34th Rencontres de Moriond: QCD and Hadronic Interactions,*
Les Arcs, France, March 20-27, 1999

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

CDF/MEMO/ELECTRON/GROUP/4998
V 1.0

B_d^0 MIXING AND CP VIOLATION MEASUREMENTS AT THE TEVATRON

K.Byrum
Argonne National Laboratory, High Energy Physics, Bldg 362, 9700 S. Cass Ave., Argonne, Illinois 60439

Abstract

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

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) [1] matrix which transforms the flavor eigenstates of the quarks into their mass eigenstates. The CKM rotation matrix can be completely determined from the three angles and a phase. It is useful to write it in the Wolfenstein [2] 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, ρ, and η can be described by the remaining two weak rotation angles and the complex phase that introduces CP violation. Unitary 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 α, β, and γ 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 $B^0/\bar{B}^0 \to J/\psi K_s^0$ determines the angle β.

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:

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

where Δm_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, τ_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

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

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 $\sigma_d \approx (13 + 40/p_T)\mu m$. 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, ϵ, 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 Δm_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

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

The first measurements of $\sin(2\beta)$ were published by CDF [3] and OPAL [4] in 1998. OPAL measured $\sin(2\beta) = 3.2^{+1.8}_{-2.0} \pm 0.5$ using $J/\psi K_s^0$ events. CDF used a sample of ≈ 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/ψ 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 ≈ 200 additional events in which the J/ψ 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:

$$D_{eff}=\frac{D_{OST} \pm D_{SST}}{1 \pm D_{OST} D_{SST}} \tag{4}$$

To calibrate the OST algorithms, we use the $B^{\pm} \to J/\psi K^{\pm}$ 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/ψ sample.

The result for $\sin(2\beta)$ is shown in Figure 2a including systematic errors due to the dilutions, Δm_d, τ_{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 Δm_d fixed to the world average and the dashed curve shows the fit with Δm_d floating. The one data point on

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_{svx}	35.5 $\pm$3.7	16.6$\pm$2.2
SST_{non}	38.1 $\pm$3.9	17.4$\pm$3.6
SLT	5.6 $\pm$1.8	62.5$\pm$14.6
JetQ	40.2 $\pm$3.9	23.5$\pm$6.9
Combined	ϵD^2=6.3$\pm$1.7	

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 [5]. The dotted lines correspond to the central values of β from $\sin(2\beta) = .79$. The solid lines represent the 1 σ regions. The oval shaped region shows the 1σ (light shaded region) and 2σ intervals from indirect measurements of the CKM parameters [5].

2 Conclusion

We present six measurements of the mixing parameter Δm_d from the CDF Run I data and measure $\Delta m_d = .494^{\pm.026}_{\pm.026}(ps^{-1})$. Using the tagging algorithms developed for these mixing measurements, we measure the CP-violating asymmetry $\sin(2\beta)$ with a sample of of $B^0/\bar{B}^0 \rightarrow J/\psi K_s^0$ decays. We report $\sin(2\beta) = .79^{+.41}_{-.44}$ which corresponds to a Feldman-Cousins frequentist limit of $0 < \sin(2\beta) < 1$ at 93% CL.

References

[1] N.Cabibbo, *Phys. Rev.* D **10**, 531 (1963);M.Kobayashi and K.Maskawa, PTP **49**, 652 (1973).

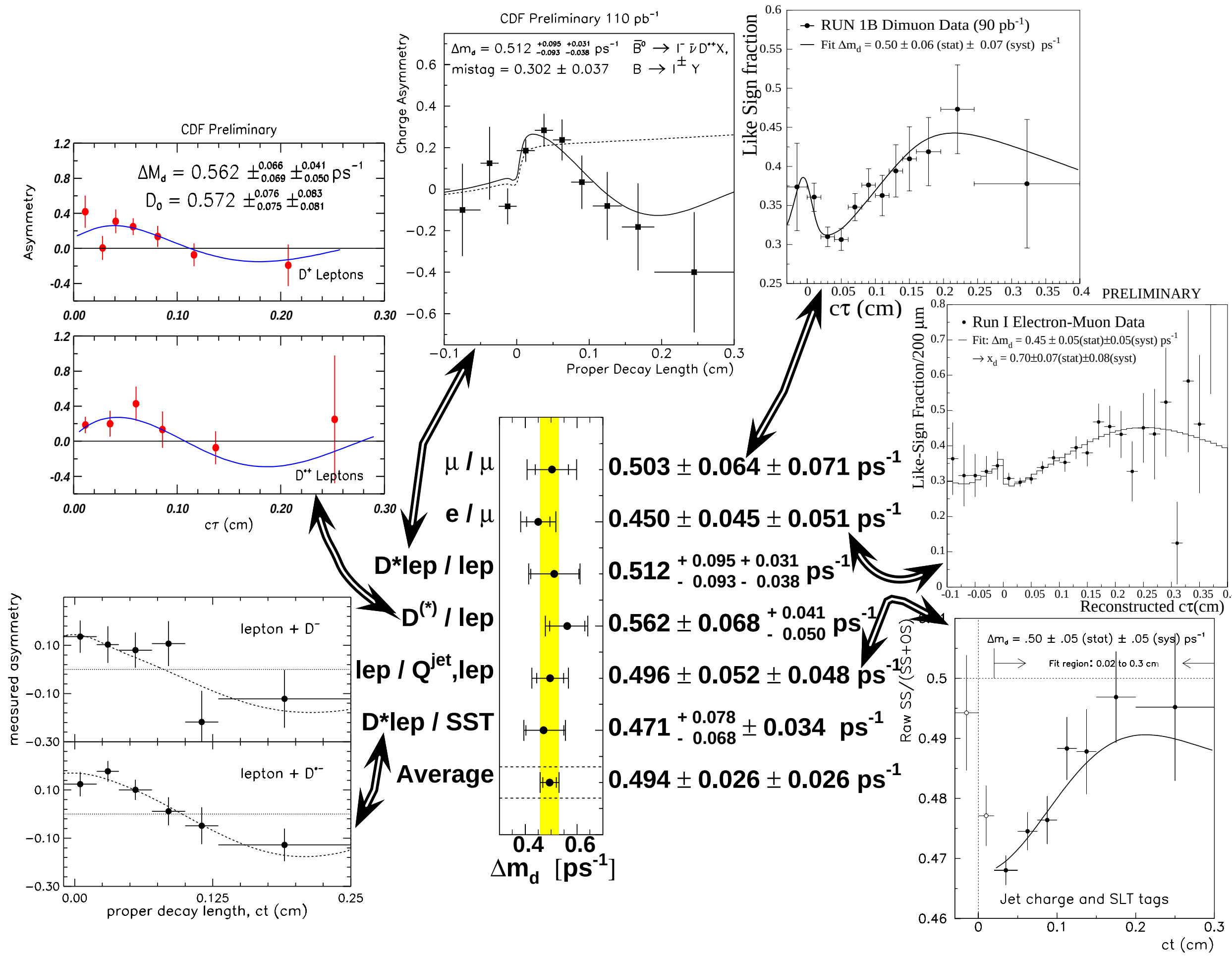

Figure 1: Six measurements of the mixing parameter Δm_d from the CDF Run I data.

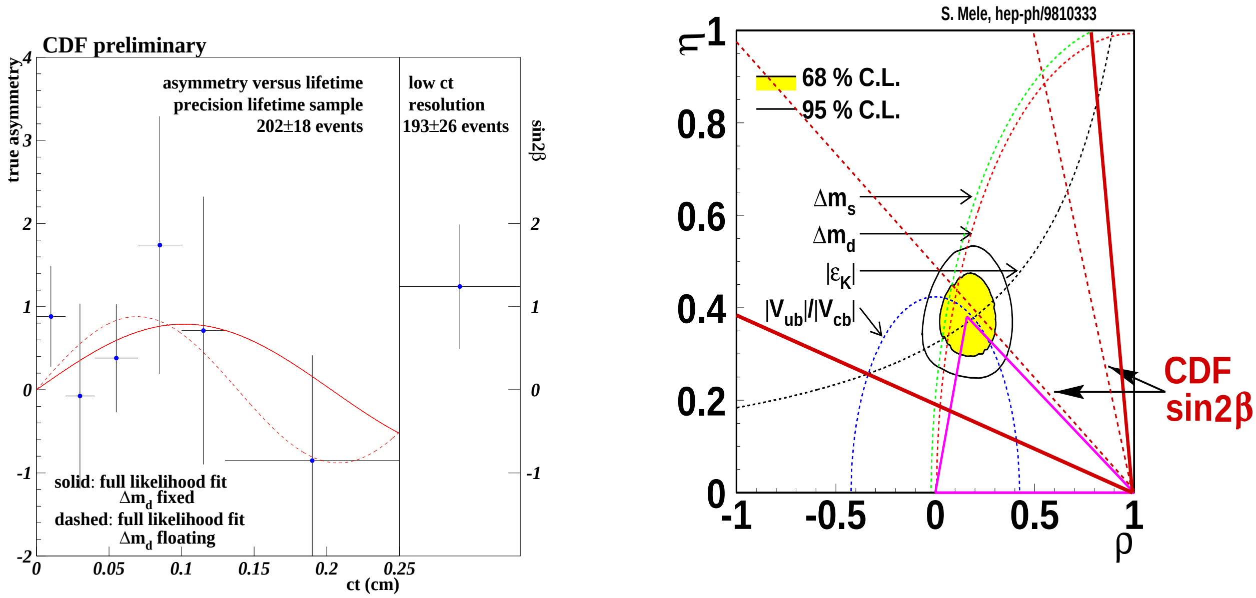

Figure 2: Left figure is the result of $\sin(2\beta)$ using a negative log-likelihood fit and multiple tags. The right figure shows the CDF result compared to indirect results in the $\rho - \eta$ plane.

[2] L.Wolfenstein, *Phys. Rev. Lett.* **51**, 1945 (1983).

[3] F.Abe *et al.*, *Phys. Rev. Lett.* **81**, 5513 (1998).

[4] K.Ackerstaff *et al.*, *Eur. Phys.* J **C3**, 1 (1998)

[5] S.Mele, CERN-EP/98-133, hep-ph/9810333.