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CDF

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B MIXING AND CP VIOLATION AT CDF

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The mixing of the neutral B mesons and the violation of CP symmetry in the B sector can be investigated at the Tevatron proton-antiproton collider. The most severe challenge that these measurements pose is tagging the flavor of a B meson at production. Here we present in detail the method of same side tagging(SST), which is used to obtain a new measurement of the B^0 mass difference $\Delta m_d = 0.446 \pm 0.057(stat) + 0.034 - 0.031(syst)\mathrm{ps}^{-1}$. The significance of SST and other tagging methods for physics during Run II of the Tevatron is discussed.

1 Introduction

1.1 Mixing and CP Violation

In the standard model CP violation[1] and $B^0 - \bar{B}^0$ mixing[2,3] are entirely due to weak transitions between quarks, and depend on the complex elements of the Cabibbo-Kobayasha-Maskowa matrix[4]. The unitarity of this matrix is often represented by the well-known unitarity triangle[5], in which the magnitudes of V_{td} and V_{ub} become the lengths of two sides of a triangle, and their phases become two of the angles. Mixing measurements determine the sides, and CP asymmetries determine the angles.

B^0 mixing is measured by forming the asymmetry in the number of mixed and unmixed B^0's as a function of proper time:

$$A(t) = \frac{N_{B\to B}(t) - N_{B\to\bar{B}}(t)}{N_{B\to B}(t) + N_{B\to\bar{B}}(t)} = \cos(x_d t/\tau) \quad (1)$$

where $x_d = \frac{\Delta m_d}{\Gamma}$ is the mixing parameter and depends on $|V_{td}|$. A measurement of B mixing needs to tag the flavor of the B meson at decay, which is relatively easy, and at production, which is the major experimental challenge.

CP violation at the hadron collider is most easily detected through the decay $B^0 \to J/\psi K^0_s$. Here one can measure the asymmetry:

$$A(t) = \frac{N_{B\to J/\psi K^0_s}(t) - N_{\bar{B}\to J/\psi K^0_s}(t)}{N_{B\to J/\psi K^0_s}(t) + N_{\bar{B}\to J/\psi K^0_s}(t)} \quad (2)$$

which in the standard model is given by $-\sin(2\beta)\sin(x_d t/\tau)$. Here, only the flavor of the B^0 at production needs to be determined.

If the number of correctly tagged events is R and the number of incorrectly tagged is events is W, then the observed asymmetries become:

$$A_{obs}(t) = \frac{R - W}{R + W} A(t) = DA(t) \quad (3)$$

where the constant D is known as the "dilution". For a given dilution D and tagging efficiency ϵ, the error on the asymmetry is given by:

$$\sigma_A^2 = (1 - A^2 D^2)/N\epsilon D^2 \quad (4)$$

The statistical power of a tagging method is ϵD^2.

1.2 Same Side Tagging

Same side tagging (SST), uses the sign of nearby charged tracks to determine the flavor of the b-quark[7]. The principal is illustrated in figure 1: if the $\bar{b}$ quark hadronizes to a B^+ meson, the next particle in the fragmentation chain is either an unobserved neutral pion (or kaon) or a negative pion (or kaon). If it hadronizes to a B^0, the next particle is neutral or positive. Orbitally excited B mesons produce a similar correlation through the decays $B^{**0} \to B^+\pi^-$, and $B^{**+} \to B^0\pi^+$. Correlations between B^0 and nearby tracks depend on the decay time due to mixing, while correlations between B^+ and nearby tracks are time-independent. SST has been demonstrated previously by LEP experiments[6].

2 Investigations of SST at CDF

We search for pion charge correlations with B^0 and B^+ in 110 pb^{-1} of data recorded with the CDF detector[8] at the Fermilab Tevatron Collider in two ways: first, using a large sample of partially reconstructed B's from a high-p_t single-lepton trigger, and second, using a smaller sample of fully reconstructed B's from a J/ψ trigger.

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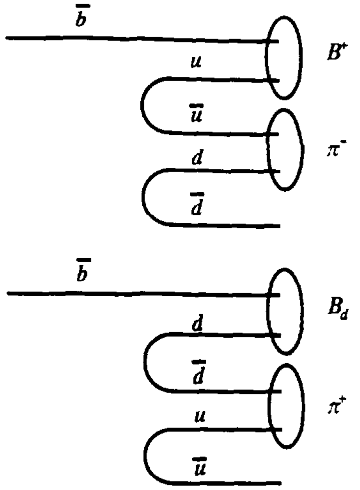

Figure 1: SST principle.

2.1 *Pion correlations in partially reconstructed B mesons*

In the partially reconstructed sample we find a signal of:

- 950 $B^0 \rightarrow D^{*-}\nu l^+$, $D^{*-} \rightarrow \bar{D}^0\pi^-$, $\bar{D}^0 \rightarrow K^+\pi^-$
- 770 $B^0 \rightarrow D^{*-}\nu l^+$, $D^{*-} \rightarrow \bar{D}^0\pi^-$, $\bar{D}^0 \rightarrow K^+\pi^-\pi^+\pi^-$
- 2400 $B^0 \rightarrow D^{*-}\nu l^+$, $D^{*-} \rightarrow \bar{D}^0\pi^-$, $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$
- 1900 $B^0 \rightarrow D^-\nu l^+$, $D^- \rightarrow K^+\pi^-\pi^-$
- 2700 $B^+ \rightarrow \bar{D}^0\nu l^+$, $\bar{D}^0 \rightarrow K^+\pi^-$

In each case the D or D^* is first reconstructed by requiring that tracks come from a common vertex, and then vertexed again with the lepton to form the B-vertex. The proper time of the B at the decay point is estimated from

$$c\tau = L_{xy}^B \frac{m_B}{p_t^B} = L_{xy}^B \frac{m_B}{p_t^{lD}} K \tag{5}$$

where L_{xy}^B is the decay length of the B in the transverse plane, $p_t^{lD} = |\mathbf{p_t}^D + \mathbf{p_t}^l|$, $\mathbf{p_t}^B$, $\mathbf{p_t}^D$, and $\mathbf{p_t^l}$ designate transverse momenta of B, D, and lepton, and K=0.86 is a constant determined from Monte Carlo. The resolution $\sigma_{c\tau}$ is determined from Monte Carlo and can be parameterized by $\sigma_{c\tau}^2 = \sigma_0^2 + \sigma_{3\gamma}^2(c\tau)^2$, with $\sigma_{3\gamma} = 11\%$ and σ_0 varying from $50\mu m$ to 60 μm, depending on the channel. The lepton sign tags the flavor of the B meson at decay. To tag the flavor at production, we choose the track with the lowest momentum transverse to the D candidate, p_t^{rel}. An event is considered taggable if another track can be found with $p_t > 400$ MeV and with separation $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.7$ from the reconstructed B meson. A tagging track is further required to be within 3σ of the primary vertex: this cut rejects pions from D^{**} decays. The efficiency is high (about 72%), and independent of the $c\tau$.

The taggable events are divided into 7 bins in $c\tau$; within each bin the number of events showing the expected correlation with nearby charged tracks ("right sign" events) and the opposite correlation ("wrong sign" events) are determined by fitting a Gaussian plus a background shape. One source of background in each channel is crosstalk from the other channels: eg., if the soft pion is undetected in the decay $B^0 \rightarrow D^{*-}\nu l^+$, $D^{*-} \rightarrow \bar{D}^0\pi^-$, then the event is background to the decay $B^+ \rightarrow \bar{D}^0\nu l^+$, $\bar{D}^0 \rightarrow K^+\pi^-$.

Corrected asymmetries are calculated by estimating the crosstalk from Monte Carlo, then determining two physical asymmetries (B^0 and B^+), from the three observed asymmetries (l^+D^-, l^+D^{*-}, and l^+D^0) for each of the seven bins. The final asymmetries depend on $f^{**} = BR(B \rightarrow \nu l D^{**})/BR(B \rightarrow \nu l X)$, on $f = BR(B \rightarrow \nu l D)/BR(B \rightarrow \nu l X)$, on P_V (the fraction of D^{**} decays to D^*), $\epsilon(\pi_s)$ (the reconstruction efficiency of soft pions from D^*), and $\xi(c\tau)$ (the probability of accidentally tagging on a pion from D^{**}).

Figure 2 shows the final corrected asymmetries. The upper plot is the asymmetry in B^+. It is fit to a flat line yielding a dilution of $D_+ = 0.28 \pm 0.04(stat) + 0.05 - 0.03(syst)$. The lower plot shows the asymmetry for B^0. It shows a clear oscillatory behavior, and is fit to the convolution of a cosine and a resolution function, yielding $D_0 = 0.22 \pm 0.03(stat) + 0.04 - 0.03(syst)$, and $\Delta m_d = 0.446 \pm 0.057(stat) + 0.034 - 0.031(syst)\text{ps}^{-1}$. Table 1 summarizes the systematic errors.

Combining the efficiencies with the dilutions, we obtain: $\epsilon D_+^2 = 5.7 \pm 1.5(stat) + 2.0 - 1.2(syst)\%$, and $\epsilon D_0^2 = 3.4 \pm 1.0(stat) + 1.2 - 0.9(syst)\%$.

Source	Central value	Variation	$\Delta(\Delta m_d)$	ΔD_0	ΔD_+
$\epsilon(\pi_s)$	0.88	+0.12 −0.21	+0.003 −0.005	+0.006 −0.004	+0.039 −0.022
eff. P_V	0.61	+0.39 −0.41	+0.018 −0.005	+0.011 −0.019	+0.001 −0.009
f^*/f	3.7	+4.5 −2.9	+0.000 −0.001	+0.002 −0.000	0.000 −0.001
eff. f^{**}	0.21	±0.08	+0.028 −0.029	+0.034 −0.025	+0.033 −0.025
ξ_{norm}	0.69	±0.17	±0.002	±0.005	±0.004
B^0 Lifetime	450μm	±33μm	+0.002 −0.004	0.0	–
Resolutions	–	–	+0.006 −0.005	±0.001	–
Total	–	–	+0.034 −0.031	+0.04 −0.03	+0.05 −0.03

Table 1: Systematic errors for the partially reconstructed B analysis

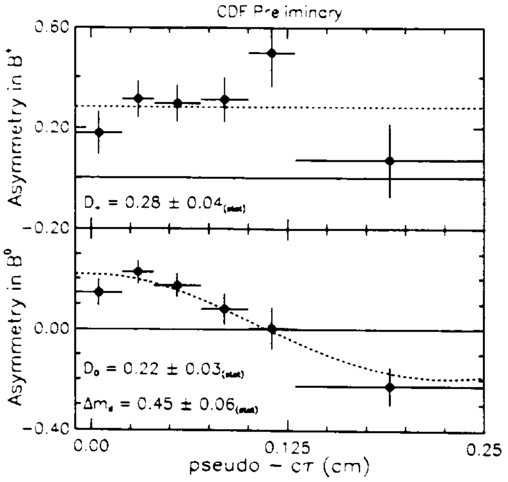

Figure 2: Final corrected asymmetries vs $c\tau$.

2.2 *Pion correlations in Fully Reconstructed B Mesons*

For this study a same-side jet charge technique is used for tagging, rather than the technique described in the previous section. Charged and neutral B mesons are fully reconstructed in the channels $B^+ \rightarrow J/\psi K^+$ and $B^0 \rightarrow J/\psi K^*$. Starting with 420,000 J/ψ's, we obtain 689 B^+ over a background of 290, and 320 B^0 over a background of 116. Tracks within a cone of radius 0.7 are used to compute a jet charge $Q_{SST} = \frac{\Sigma q_i w_i}{\Sigma w_i}$, where the weight w_i of the i^{th} track is a function only of the p_t^{rel}.

$$w_i = e^{-\frac{1}{2}\left(\frac{P_T^{rel} - 0.46}{0.3}\right)^2} \tag{6}$$

and the index i runs over all tracks with $p_t > 700$ MeV. An event is considered taggable if $|Q_{SST}| > 0.4$; the dilutions and efficiencies are measured for each species. Results are shown in table 2. In the case of B^0, these results must be corrected for the mixing; the corrected dilutions are also shown in the table. These dilutions have large errors but are consistent with those of the previous study.

3 CDF Run II

Run II of the Tevatron will begin in 1999 with major improvements to both the accelerator and the detector[9] The design goal of the machine is to deliver $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ for a total integrated luminosity of 2fb^{-1}. Detector upgrades include a 96 cm, 7 layer double-sided silicon tracker. The z-readout will provide CDF with precision 3D tracking. The deadtimeless readout is capable of 50 kHz at level one; at level two this is exploited to trigger on high impact parameter tracks. We now discuss the discovery potential of CDF during Run II.

Three tagging methods are now understood: SST, soft muon and electron tagging, and jet charge tagging; the combined ϵD^2 for these techniques is 4%. With additional effort and detector improvements, such as a time-of-flight counter for kaon tagging, this figure could rise to 8%.

3.1 $\sin 2\beta$

CP asymmetries in the decay $B^0 \rightarrow J/\psi K_s^0$ determine the value of $\sin 2\beta$. The present sample of this decay, collected with a dimuon trigger, is 239 ± 22 events, with a signal-to-noise ratio of 1.2. Taking into account the improvements in luminosity, lower trigger thresholds, a planned dielectron trigger, and a lower signal-to-noise ratio resulting from a 3D precision tracker, we expect to collect about 13,000 of these events, which results in an error $\sigma_{\sin 2\beta} = 0.12$, assuming ϵD^2 of 4.0%.

3.2 $\sin 2\alpha$

CP asymmetries in the decay $B^0 \to \pi^+\pi^-$ determine the value of $\sin 2\alpha$, modulo theoretical uncertainties from penguins. Here, the major challenge is to trigger on the decay. Triggering on pairs of oppositely charged pions with $p_t > 2.0$ GeV results in a level one rate of 16kHz; applying a 100 μm impact parameter cut at level 2 reduces this less than 20 Hz. We expect about 10,000 events. To obtain $\sigma_{\sin 2\alpha} = 0.1$ would require ϵD^2 of 8%.

3.3 $B_s mixing$

The mixing of the neutral B_s meson is of interest because $\frac{x_d}{x_s}$ determines $\frac{|V_{td}|}{|V_{ts}|}$ free from hadronic uncertainties. We have investigated the reconstruction of $B_s \to D_s \nu l$, $D_s \to o\pi$, and also $B_s \to D_s \pi^-\pi^+\pi^-$. 250 decays of the previous type with a signal-to-noise ratio of about 1.8 have been observed at CDF using a single lepton trigger. In extrapolating to Run II we use the improvement in luminosity and trigger, and include additional decay channels of the D_s. We also extrapolate from the single lepton trigger to the dilepton trigger, which is a high-dilution flavor tagged sample. We expect 6,400 tagged B_s events. The Δm_s reach using this sample is limited by the poor $c\tau$ resolution typical of a partially reconstructed decay, to $\Delta m_s \approx 10\text{ps}^{-1}$.

The channel $B_s \to D_s \pi^-\pi^+\pi^-$ is harder to reconstruct but has superior $c\tau$ resolution. It can enter the data sample through the $B^0 \to \pi^+\pi^-$ trigger. Here an ϵD^2 of 8% is needed to obtain 1,600 equivalent tagged events, which would make the experiment sensitive to $\Delta m_s \approx 13\text{ps}^{-1}$.

4 Conclusion

CDF has demonstrated, for the first time in a hadron collider, the feasibility of same side tagging; use of this tagging method yields a measurement of $\Delta m_d = 0.446 \pm 0.057(stat) + 0.034 - 0.031(syst)\text{ps}^{-1}$. The combination of this and other tagging methods currently demonstrated at CDF yields a total ϵD^2 of 4%, which puts the CP violating parameter $\sin 2\beta$ within reach of the Tevatron in Run II. B_s mixing up to $\Delta m_s \approx 10$ ps should be accessible. Measurement of Δm_s up to of 13 ps, and of the CP violating parameter $\sin 2\alpha$ will require improvements in flavor tagging.

Sample	Dil. (%)	Eff. (%)	ϵD^2 (%)
B^+			
Data	33 ± 8	36 ± 2	4.0 ± 1.9
MC	42 ± 1	29.0 ± 0.2	5.2 ± 0.2
MC*	37 ± 1	26.9 ± 0.3	3.6 ± 0.2
Uncorrected B^0			
Data	10 ± 10	41 ± 3	0.4 ± 0.9
MC	13 ± 2	27.1 ± 0.4	0.4 ± 0.1
MC*	12 ± 2	26.5 ± 0.5	0.4 ± 0.1
Corrected B^0			
Data	$19 \pm 19 \pm 2$	41 ± 3	$1.5 \pm 3.0 \pm 0.3$
MC	$25 \pm 4 \pm 2$	27.1 ± 0.4	$1.7 \pm 0.5 \pm 0.3$
MC*	$23 \pm 4 \pm 2$	26.5 ± 0.5	$1.4 \pm 0.5 \pm 0.3$

Table 2: Summary of the fully reconstructed B analysis. Sample labeled MC^* is Pythia Monte Carlo without B^{**}. Below, B^0 dilutions have been corrected for mixing.

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