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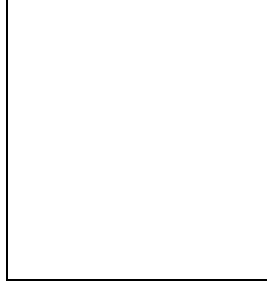
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RARE B DECAYS, MIXING, AND CP VIOLATION AT THE FERMILAB TEVATRON

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We review studies of rare b decays, mixing, and CP violation at the Fermilab Tevatron. With 100 pb^{-1} at $\sqrt{s} = 1.8 \text{ TeV}$, CDF and DØ have searched for lepton number nonconserving and flavor-changing neutral current decays. CDF has also performed multiple time-dependent mixing analyses yielding $\Delta m_d = 0.495 \pm 0.026(stat) \pm 0.025(syst) \text{ ps}^{-1}$ and set a limit on B_s mixing of $\Delta m_s > 5.8 \text{ ps}^{-1}$ at 95% C.L. An analysis of $395 \pm 31 \text{ } B^0 \rightarrow J/\psi K_S^0$ decays has yielded a measurement of the CP violation parameter $\sin 2\beta = 0.79^{+0.41}_{-0.44}(stat + syst)$.

Over two decades since its discovery at Fermilab in 1977, the b quark has become an important laboratory for the exploration of the Standard Model as well as a potential window beyond it. Its kinematic properties, its large mass and long lifetime, and its large production cross section in hadron collisions, make it an excellent subject of study at the Tevatron $\bar{p}p$ collider. In this article, we will review recent results from CDF and DØ in two categories of tests of the Standard Model: the search for rare b decays, and the measurement of asymmetry parameters related to B^0 meson mixing and CP violation. The detectors have been described elsewhere.¹ The data for the results presented here are from the 1992-96 collider run, representing at each experiment. approximately 100 pb^{-1} of integrated luminosity at $\sqrt{s} = 1.8 \text{ TeV}$.

1 Searches for Rare b Decays

The search for rare decay modes is a venerable line of inquiry which has in the past uncovered significant new physics, such as in the 1964 discovery of CP violation by observing $K_L^0 \rightarrow \pi^+\pi^-$ decays.² Table 1 summarizes limits on rare decays of b hadrons set by CDF and DØ. The mode $B_{d,s}^0 \rightarrow e^\pm \mu^\mp$ is sensitive to lepton number-violating physics and has also been used to set a lower limit on Pati-Salam leptoquark mass at $20.4 \text{ TeV}/c^2$ at 95% C.L. The other searches are

Table 1: Limits on rare b decays set by CDF and DØ experiments. “ $\gamma(\text{cnv})$ ” refers to photons identified through $\gamma \rightarrow e^+e^-$ conversions.

Type	Channel	Expt.	90% C.L.	SM Prediction
Lepton number violation	$B_d^0 \rightarrow e^\pm \mu^\mp$	CDF ³	3.5×10^{-6}	0
	$B_s^0 \rightarrow e^\pm \mu^\mp$	CDF ³	6.1×10^{-6}	0
FCNC	$B_d^0 \rightarrow \mu^+ \mu^-$	CDF ⁴	8.6×10^{-7}	1.5×10^{-10}
	$B_s^0 \rightarrow \mu^+ \mu^-$	CDF ⁴	2.0×10^{-6}	3.5×10^{-9}
	$B_{d,s}^0 \rightarrow \mu^+ \mu^-$	DØ ⁵	4.0×10^{-5}	1.1×10^{-9}
	$B^+ \rightarrow K^+ \mu^+ \mu^-$	CDF ⁶	5.2×10^{-6}	0.4×10^{-6}
	$B^0 \rightarrow K^{*0} \mu^+ \mu^-$	CDF ⁶	4.0×10^{-6}	1×10^{-6}
	$b \rightarrow X_s \mu^+ \mu^-$	DØ ⁵	3.2×10^{-4}	6×10^{-6}
	$B_d^0 \rightarrow K^{*0} \gamma$	CDF ⁷	2.2×10^{-4}	$10^{-5} \sim 10^{-4}$
	$B_d^0 \rightarrow K^{*0} \gamma(\text{cnv})$	CDF	1.7×10^{-4}	
	$B_s^0 \rightarrow \phi \gamma$	CDF ⁷	3.9×10^{-4}	
	$B_s^0 \rightarrow \phi \gamma(\text{cnv})$	CDF	3.6×10^{-4}	

for flavor-changing neutral current decays, which proceed through higher-order diagrams in the Standard Model. In the case of $B \rightarrow K \mu \mu$ decays, the sensitivity of the experiments is close to the Standard Model prediction; if the prediction holds true, these decay modes should be observable in the next data run. CDF has also used two techniques to search for the exclusive “penguin” decays $B_d^0 \rightarrow K^{*0} \gamma$ and $B_s^0 \rightarrow \phi \gamma$. One analysis uses a specialized charged track pair + photon trigger, with which $\approx 23 \text{pb}^{-1}$ of data were collected;⁷ a more recent analysis identifies photons through $\gamma \rightarrow e^+e^-$ conversions, a method which has lower efficiency but can be applied to the full dataset. CLEO⁸ has measured $Br(B_d^0 \rightarrow K^{*0} \gamma) = (4.2 \pm 0.8(\text{stat}) \pm 0.6(\text{syst})) \times 10^{-5}$.

2 Time-dependent Analyses of B_d^0 and B_s^0 Mixing

The first evidence of $B^0 \bar{B}^0$ mixing, manifesting itself in an asymmetry between like-sign and opposite-sign lepton pairs, was found by the UA1 collaboration in 1987.⁹ Similar analyses have been performed at CDF and DØ.¹⁰ The addition of a silicon microstrip detector (SVX) to CDF, with its $\sim 50 \mu\text{m}$ impact parameter resolution, has enabled the direct observation at the Tevatron of the state mixture’s time dependence, which can be observed in the asymmetry between the number of decays where the observed decay state is different from the produced state (“mixed”) and where they are the same (“unmixed”): the ratio $(N_{\text{unmixed}}(t) - N_{\text{mixed}}(t))/(N_{\text{unmixed}}(t) + N_{\text{mixed}}(t))$ varies as $\cos \Delta m t$, where t is the proper decay time and Δm is the mass difference between the weak eigenstates.

The interest of such measurements in the context of the Standard Model can be seen from the CKM quark mixing matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

which transforms between the mass and weak eigenstates of the d , s , and b quarks.¹¹ In this model, $\Delta m_d \propto |V_{tb}^* V_{td}|^2$, albeit with considerable hadronic uncertainty in the coefficient. The ratio $\Delta m_s / \Delta m_d$, accessible through the observation of B_s^0 mixing, provides a theoretically cleaner measurement of $|V_{ts} / V_{td}|^2$. In addition, these analyses demonstrate the applicability of tagging techniques, described below, to discern the produced flavor of the neutral B states.

Table 2: Time-dependent measurements of B_d^0 mixing at CDF. The first uncertainties are statistical, the second systematic.

Decay flavor	Decay time	Flavor tag	Δm_d (ps $^{-1}$)	Ref.
$D^{(*)}\ell$	$D^{(*)}\ell$	same side	$0.471^{+0.078}_{-0.068} \pm 0.034$	¹³
ℓ	inclusive vertex	jet, opposite ℓ	$0.500 \pm 0.052 \pm 0.043$	¹⁴
e	inclusive vertex	opposite μ	$0.450 \pm 0.045 \pm 0.051$	¹⁵
μ	inclusive vertex	opposite μ	$0.503 \pm 0.064 \pm 0.071$	¹⁶
$D^*\ell$	$D^*\ell$	opposite ℓ	$0.516 \pm 0.099^{+0.029}_{-0.035}$	¹⁷
$D^{(*)}$	$D^{(*)}$	opposite ℓ	$0.562 \pm 0.068^{+0.041}_{-0.050}$	¹⁸
Average			$0.495 \pm 0.026 \pm 0.025$	
Average with LEP and SLD ¹⁹			$0.481 \pm 0.017(stat + syst)$	

Table 2 summarizes the time-dependent Δm_d measurements performed at CDF, along with how they determine the decay flavor, the proper decay time, and the technique used to infer the produced flavor of the reconstructed B_d . “Same side” tagging relies on charged tracks produced in association with the reconstructed B_d . Sources of charge-correlated tracks include leading fragmentation particles and daughter particles from a common B^{**} parent (recently measured to account for $(28 \pm 7)\%$ of light B production at the Tevatron¹²). The technique used at CDF picks the single lowest p_T^{rel} (relative to the combined B_d +track flight direction) track whose path is consistent with originating from the primary vertex and lies close in $\eta - \phi$ space to the B_d . The efficiency of this method is $\approx 70\%$.

“Opposite side” tagging, on the other hand, relies on the correlation between the produced flavor and information associated with the other b hadron in the event, such as the charge of a lepton, which is most often from the semileptonic decay of that other b , or the momentum-weighted sum of the tracks in a jet (the “jet charge”). The correlation is reduced by such effects as B^0 mixing, sequential c decays, and ambiguities in choosing the opposite jet. The correlation is much stronger in lepton tagging, but the efficiency, $\approx 5\%$, is also much lower than that of jet charge tagging, $\approx 40\%$; for this reason, the analysis which uses both methods searches first for a lepton tag, reserving the jet charge method for events with no such lepton tag. Other analyses^{15,16,17} overcome the low efficiency of the lepton tag by taking advantage of a dilepton trigger sample; in addition to assuring the existence of an opposite-side lepton candidate, these analyses can take advantage of lower energy thresholds than that of single-lepton trigger samples.

CDF has also applied the opposite-side lepton flavor tag to a sample of $1068 \pm 70 B_s^0 \rightarrow \ell \phi h X$ decays found among dilepton triggers, where h signifies an additional charged track consistent with the $\ell \phi$ vertex.²⁰ This sample is $(61^{+4}_{-7})\%$ pure B_s^0 . Using the amplitude fit method,²¹ a lower limit on Δm_s is calculated at 5.8 ps^{-1} at 95% C.L.

3 Measurement of $\sin 2\beta$

The CKM matrix was originally proposed to explain the aforementioned CP violation in neutral K decays: a 3×3 matrix is the smallest unitary matrix with a physical complex phase which can give rise to such effects. As previously mentioned, measurements such as that of $\Delta m_s/\Delta m_d$ are cleanly related to CKM matrix elements. Moreover, such measurements can eventually test the unitarity of the matrix, and hence our understanding of these effects.

It is in this vein that CP violation studies are expanded into the B sector: in particular, the interference between mixed and unmixed B_d^0 decay paths to the CP eigenstate $J/\psi K_S^0$ can produce potentially large, measurable asymmetries between the number of B_d^0 ’s and $\overline{B}_d^0$ ’s

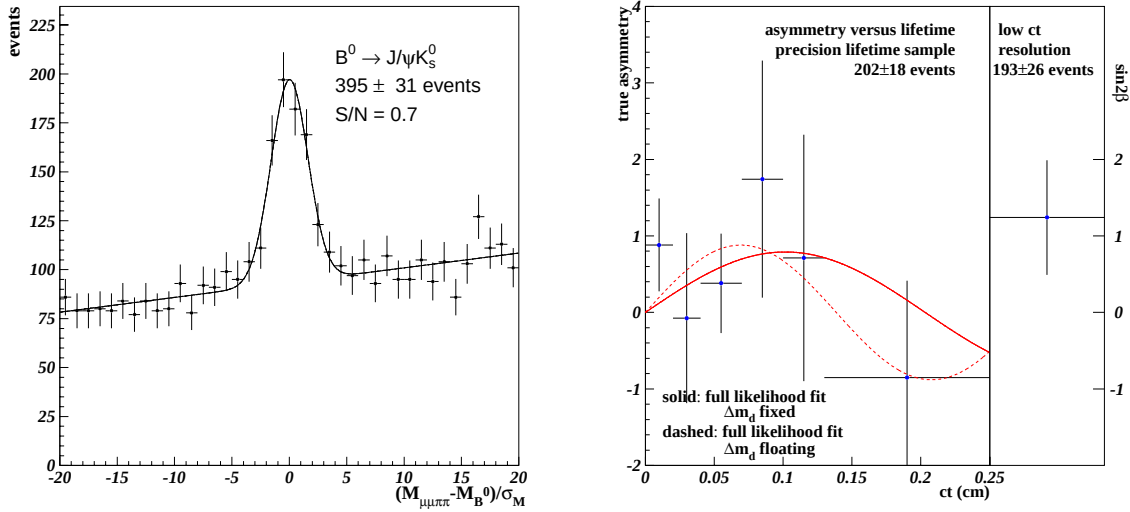


Figure 1: Left: normalized mass distribution of $J/\psi K_S^0$ candidates. Right: time-dependent asymmetry of the precision lifetime sample. The solid and dashed lines are fit results. The point on the right shows the time-integrated asymmetry from the low- ct resolution sample.

decaying into this state at proper time t ,

$$\frac{N(\overline{B}_d^0 \rightarrow J/\psi K_S^0)(t) - N(B_d^0 \rightarrow J/\psi K_S^0)(t)}{N(\overline{B}_d^0 \rightarrow J/\psi K_S^0)(t) + N(B_d^0 \rightarrow J/\psi K_S^0)(t)} = (\sin 2\beta) \sin \Delta m_d t.$$

The parameter β is the function of CKM matrix elements $\arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$.²² We assume for the purposes of the present analysis that physics beyond the Standard Model does not contribute additional phases to $\sin 2\beta$. Indirect evidence, applying the unitarity constraint to data on V_{ub} , B^0 mixing, and CP violation in kaons, suggests a value for $\sin 2\beta$ between 0.5 and 0.9.²³

CDF has reconstructed a sample of 395 ± 31 B_d^0 decays to $J/\psi K_S^0$, where $J/\psi \rightarrow \mu^+\mu^-$ and $K_S^0 \rightarrow \pi^+\pi^-$. The mass distribution is shown in Figure 1(left). Roughly half of the sample takes advantage of the precise t measurements of the SVX, while the other half lies outside the SVX acceptance. For the SVX sample, the signal purity can be seen to improve significantly at larger decay times, which is exactly where the amplitude of $\sin \Delta m_d t$ is best measured.

The three tagging methods—same side, opposite lepton, and opposite jet charge—used in this measurement are similar to those demonstrated in the mixing analyses, and their correct-tag probabilities are calibrated in similar analyses of $\ell D^{(*)}$ and $B^\pm \rightarrow J/\psi K^\pm$ samples. Again, the opposite-side lepton tagging method takes precedence over the jet charge method, but events can have both a same-side and opposite-side tag, in which case the correct-tag probability is adjusted appropriately. The time-dependent asymmetry is plotted in Figure 1(right) along with the results of the unbinned maximum likelihood fit. The non-SVX data essentially contribute a time-integrated measurement to the likelihood fit. The result is $\sin 2\beta = 0.79^{+0.41}_{-0.44}$, where the uncertainty contains both statistical and systematic uncertainties, the latter of which contributes ± 0.16 to the total and is mostly due to uncertainty in the determination of the correct-tag probability. this measurement excludes $\sin 2\beta < 0$ is at 93% C.L.²⁴

4 Conclusion

The physics of the b quark offers rich possibilities for the comparison of experimental measurements with theoretical models. CDF and DØ searches for rare decays have not revealed any

rates that would be unexpectedly large for the Standard Model. Measurements by CDF related to B^0 mixing and CP violation also fall in line with expectations, though at present the uncertainties are large. The upcoming data run, starting in 2000, promises to yield at least 2 fb^{-1} of data. Among other upgrades, DØ will revamp its tracking systems and add a silicon microstrip detector, significantly upgrading its B physics capabilities. CDF will add more layers of silicon at both larger and smaller radii, a time-of-flight system for improved particle identification, and a hadronic displaced-track trigger. If the Standard Model continues its string of successes, the flavor-changing neutral current decay $B \rightarrow K\mu\mu$ should be within reach. Furthermore, in the case of $\sin 2\beta$, both CDF and DØ expect to reduce the statistical uncertainty to levels comparable to that of dedicated B factories,²⁵ and in the area of B_s^0 mixing, CDF should be sensitive to Δm_s values up to about 35 ps^{-1} , which covers the favored Standard Model range.²⁶

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