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Measurement of the CP Violation Parameter $\sin(2\beta)$ in $B^0 \rightarrow J/\psi K_s^0$ Decays

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Abstract
A sample of $\sim$400 $B_d^0/\overline{B}_d^0 \to J/\psi K_s^0$ decays collected in $\bar{p}p$ collisions by the CDF detector is used to directly measure the CP-violation parameter $\sin(2\beta)$. We find $\sin(2\beta) = 0.79^{+0.41}_{-0.44}$, favoring the standard model expectation of a large CP violation in this B^0 decay mode.

1. Introduction

The origin of CP violation has been an outstanding issue since its discovery in $K_L^0 \to \pi^+\pi^-$ decays 35 years ago [1]. In 1972, before charm was discovered, Kobayashi and Maskawa [2] proposed that quark mixing with 3 (or more) generations was the cause. In this case, the CKM matrix relating the mass and weak eigenstates of quarks possesses, in general, a complex physical phase that violates CP. Unfortunately, the K^0 has been the only place to study CP violation. Despite precision K^0-studies, a complete picture of CP violation is still lacking.

CP tests have encompassed B mesons, but the violations in inclusive studies [3] are too small ($\sim 10^{-3}$) to as yet detect. In the '80's it was realized that the *interference* due to mixing of B_d^0 decays to the same CP state could show large violations [4].

$B_d^0/\overline{B}_d^0 \to J/\psi K_s^0$ is the "golden" mode for large effects, with little theoretical uncertainty relating it to the CKM matrix. A B_d^0 may decay directly to $J/\psi K_s^0$, or it may oscillate into a $\overline{B}_d^0$ and then decay to $J/\psi K_s^0$. The two paths have a phase difference, and the interference results in an asymmetry:

$$\mathcal{A}_{CP}(t) \equiv \frac{\overline{B}_d^0(t) - B_d^0(t)}{\overline{B}_d^0(t) + B_d^0(t)} = \sin(2\beta)\sin(\Delta m_d t), \quad (1)$$

where $B_d^0(t)$ $[\overline{B}_d^0(t)]$ is the number of $J/\psi K_s^0$ decays at proper time t from mesons produced as B_d^0 $[\overline{B}_d^0]$. $\mathcal{A}_{CP}$ varies as $\sin(\Delta m_d t)$ because it is shifted by a $\frac{1}{4}$-cycle relative to the $\cos(\Delta m_d t)$ mixing oscillation by the mixed/unmixed decay interference. The amplitude is $\sin(2\beta)$, with $\beta = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ for CKM elements $V_{qq'}$. β is also an angle from the so-called "unitarity triangle" of the CKM matrix.

2. The $B^0/\overline{B}^0 \to J/\psi K_s^0$ sample

We exploit the large B cross section at the Tevatron and obtain a sample of $J/\psi K_s^0$ decays to measure $\sin(2\beta)$. We start from the Run I $J/\psi \to \mu^+\mu^-$ sample ($p_T(\mu)$ above $\sim$1.5 GeV/c) of $\sim\frac{1}{2}$ million events. The $K_s^0 \to \pi^+\pi^-$ reconstruction tries all oppositely charged track combinations (assumed to be pions). The $p_T(K_s^0)$ must be above 0.7 GeV/c, its decay vertex displaced from the J/ψ's by $>5\sigma$, and $p_T(J/\psi K_s^0) > 4.5$ GeV/c. After imposing the J/ψ and K_s^0 masses, the fitted $J/\psi K_s^0$ mass M_{FIT} and error σ_{FIT} are used to construct $M_N \equiv (M_{FIT} - M_0)/\sigma_{FIT}$, where M_0 is the world average B_d^0 mass. The M_N distribution is shown in Fig. 1. A likelihood fit yields 395 ± 31 $B_d^0/\overline{B}_d^0$'s.

The $\bar{p}p$ collisions spread beyond CDF's Si-μvertex tracking detector (SVX), so only about half (202$\pm$18 vs. 193$\pm$26) of the J/ψ's have both muons in the SVX. The precision lifetime information from the SVX allows one to make a time-dependent fit to Eq.1. However, the CP asymmetry remains even when integrated in time; so although lifetime information is basically lost in "non-SVX" data, they are still useful. The statistical power for measuring $\sin(2\beta)$ is only reduced by $\sim 1/3$ for this subsample. The "SVX" subsample was the basis for our previous $\sin(2\beta)$ measurement [5].

3. Flavor tagging

Observing the asymmetry $\mathcal{A}_{CP}(t)$ is predicated upon determining the b "flavor"—whether the B meson is composed of a b or a $\bar{b}$ quark—at the time of production. If the initial flavor is correctly tagged with probability P, then the observed asymmetry

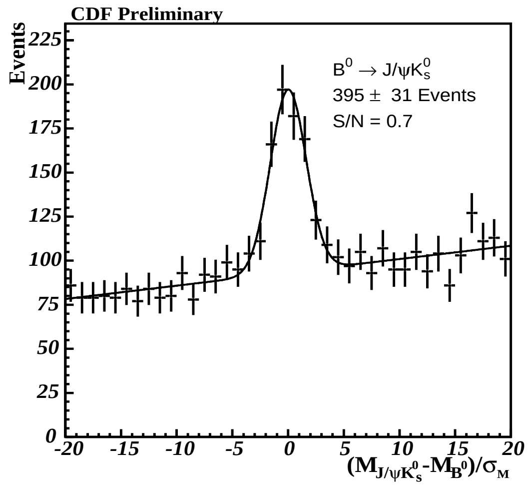

Figure 1. Normalized mass distribution M_N (see text) of the $J/\psi K^0_s$ candidates. A Gaussian signal plus linear background fit to the data is shown by the curve.

is attenuated by the "dilution" $\mathcal{D} = 2P - 1$, *i.e.* $\mathcal{A}_{CP}^{Obs} = \mathcal{D}\sin(2\beta)\sin(\Delta m_q t)$.

A method with tagging efficiency ϵ yields an error on $\sin(2\beta)$ which scales as $1/\sqrt{\epsilon\mathcal{D}^2N}$ for N background-free mesons. Thus, $\epsilon\mathcal{D}^2$ measures the effective tagging power. An analysis can be improved by using several taggers, the combined effect is approximately the sum of the respective $\epsilon\mathcal{D}^2$'s.

The tagging needs for this analysis are similar to those employed in B^0-$\overline{B}^0$ oscillation measurements of Δm. CDF has performed six Δm_d analyses that demonstrate three types of tagging methods. The CDF average Δm_d is $0.495 \pm 0.026 \pm 0.025\,\mathrm{ps}^{-1}$ [6], which is of similar precision to other experiments and agrees well with a world average [7].

We call the first method "same-side tagging" (SST), as it relies on the charge of a particle "near" the B^0 [8]. The idea is simple. A $\bar{b}$ quark forming a B^0_d combines with a d in the hadronization, leaving a $\bar{d}$. To make a charged pion, the $\bar{d}$ combines with a u making a π^+. Conversely, a $\overline{B}^0_d$ will be associated with a π^-. Correlated pions also arise from $B^{**+} \to B^{(*)0}\pi^+$ decays.‡ Both sources have the same correlation, and are not distinguished here.

The SST tag is the candidate track with the smallest momentum transverse to the B+Track momentum. A valid track candidate must be within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 0.7$ of the B, have $p_T > 400$ MeV/c, reconstructed in the SVX, and have its impact parameter within 3σ of the primary vertex.

SST was studied in a Δm_d-analysis [10], and used in our earlier measurement of $\sin(2\beta)$. The SST dilution for the $J/\psi K^0_s$ sample was found to be $16.6 \pm 2.2\%$ [5] for events reconstructed in the SVX. This method has been extended to events outside the SVX coverage (the impact parameter cut is removed); and we find $\mathcal{D}^{SST}_{nonSVX} = 17.4 \pm 3.6\%$.

Two "opposite-side" taggers, where the other b-hadron signals the flavor of the B^0, are also used. The lepton charge from $b \to \ell^-$ decay of the other b-hadron tags the B^0 flavor, *i.e.* ℓ^- (ℓ^+) implies B^0 ($\overline{B}^0$). Lepton (e and μ) identification criteria are applied to all charged tracks§ with p_T thresholds of 1.0 (2.0) GeV/c for electrons (muons). The dilution is measured using a $B^+ \to J/\psi K^+$ sample (~ 1000 events), and we find $\mathcal{D}^{lep} = 62.5 \pm 14.6\%$.

The other opposite-side method is "jet-charge." The tag is a charge average of an opposite-side jet. The jet is formed by a mass-clustering algorithm which starts with "seed" tracks of $p_T > 1.75$ GeV/c, and combines other tracks with $p_T > 0.4$ GeV/c, up to a cluster mass approximating the B mass. The B^0 decay products are explicitly excluded from the jet, as are tracks within $\Delta R < 0.7$ of the B^0. If multiple jet clusters are present, the one most likely to be a b-jet is chosen based on track impact parameters and cluster p_T. The jet-charge for a cluster is:

$$Q_{jet} = \frac{\Sigma_i\, q_i p_{Ti}(2 - T_i)}{\Sigma_i\, p_{Ti}(2 - T_i)}, \tag{2}$$

where q_i and p_{Ti} are the charge and p_T of the i-th track in the jet with $p_T > 0.75$ GeV/c, and T_i is the probability that the track is from the primary vertex. A B^0 ($\overline{B}^0$) is implied if $Q_{jet} < -0.2$ (> 0.2), otherwise it is untagged. The dilution is measured from the $B^+ \to J/\psi K^+$ sample to be $23.5 \pm 6.9\%$.

By coincidence, each tagger has an $\epsilon\mathcal{D}^2$ of $\sim 2\%$. The total $\epsilon\mathcal{D}^2$ is $6.3 \pm 1.7\%$, so our sample of 400 events corresponds to ~ 25 perfectly tagged $J/\psi K^0_s$ decays plus background.

4. Extracting $\sin(2\beta)$

The three taggers are applied to the sample. A lepton tends to dominate the jet-charge if a lepton tag is in the jet. Lepton tagging has low efficiency but high dilution, so the correlation between lepton and jet-charge tags is avoided by dropping the jet-charge tag if there is a lepton tag. This means each B^0 is tagged at most by two methods. If the tag result for an event by method-i is s_i ($s = +1,\ -1,\ 0$ for B^0, $\overline{B}^0$, untagged), then the effective dilution for two tags is $\mathcal{D}_{ij} = |s_i\mathcal{D}_i + s_j\mathcal{D}_i|/(1 + s_i s_j \mathcal{D}_i\mathcal{D}_j)$.

‡ A CDF B^{**} analysis of $\ell D^{(*)}$ data found the fraction of $B_{u,d}$ mesons arising as B^{**} states to be $0.28 \pm 0.06 \pm 0.03$ [9].

§ Lepton identification limits the tracks to $|\eta| < 1.0$. Also, identified conversion electrons are explicitly removed.

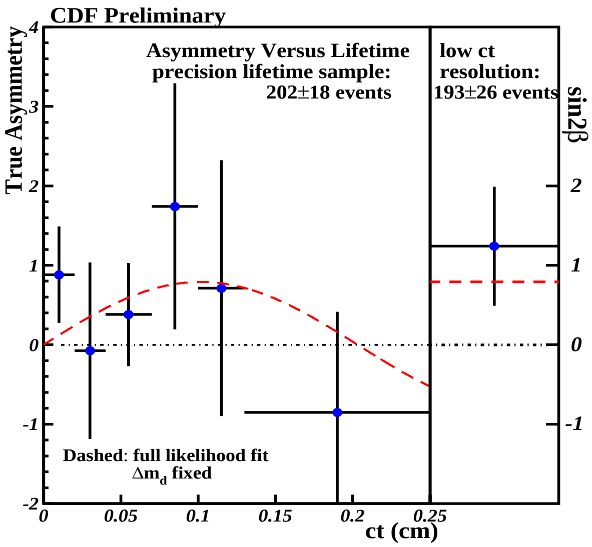

Figure 2. The CP asymmetry of the data with the fit result. The SVX data is shown in proper-time bins on the left, and a single bin for non-SVX data on the right.

An unbinned likelihood fit is performed using the flavor tags (and the effective $\mathcal{D}_{ij}$'s), M_N, and lifetime information from the data; and it computes the likelihood probability that an event is signal or background (either prompt or long-lived). The treatment of the SVX and non-SVX data in the likelihood is different, but both are part of the same fit. The B^0 lifetime and Δm_d values are fixed to world averages (1.54 ± 0.04 ps and $0.464 \pm 0.018\,\mathrm{ps}^{-1}$ [11]). The fit also incorporates allowances for (small) systematic detector biases.

The fit yields $\sin(2\beta) = 0.79^{+0.41}_{-0.44}$ (*stat. + syst.*) for the combined taggers [12]. The fit is shown in Fig. 2 along with a dilution weighted average of the sideband-subtracted data. The result corresponds to $0 < \sin(2\beta)$ for a 93% unified frequentist [13] confidence interval. Although the exclusion of zero has only slightly increased from our previous result [5], the uncertainty on $\sin(2\beta)$ is cut in half.

We applied our taggers and fitting machinery to a sample of ~ 450 $B^0_d \to J/\psi K^{*0}$ decays as a cross check. We find $\Delta m_d = 0.40 \pm 0.18$ ps^{-1}, in accordance with the precision of the $\sin(2\beta)$ analysis.

5. Summary and prospects

We have directly measured $\sin(2\beta)$, and our result provides evidence for large CP asymmetries in B^0 mesons as expected from indirect determinations, *e.g.* $0.52 < \sin(2\beta) < 0.94$ at 95% CL [14].

A critical test, however, requires much greater precision. CDF will attain this in Run II. Starting in 2000, a 2-year run should deliver 20× the luminosity ($\sim 2\,\mathrm{fb}^{-1}$), and be exploited by a greatly enhanced detector [15]. We project $\sim 10^4$ $J/\psi K^0_s$'s from dimuons, for a $\sin(2\beta)$ error of about ± 0.08. Triggering on $J/\psi \to e^+e^-$ may boost the sample by $\sim 50\%$. CDF is also working on a Time-of-Flight system which will aid flavor tagging. We expect to achieve sensitivities in the range projected for the dedicated B factories.

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