$\boldsymbol{CP}$ VIOLATION MEASUREMENTS AT THE TEVATRON*

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The CDF collaboration has adapted several heavy flavor tagging techniques and employed them in analyses of time-dependent flavor asymmetries using data from the Tevatron Run I. The tagging algorithms were calibrated using low-$p_{\rm T}$ inclusive lepton and dilepton trigger data samples. The tagging techniques were applied to a sample of $\sim$ 400 $B_d^0/\overline{B}_d{}^0 \to J/\psi K_{\rm S}^0$ decays and were used to measure the CP violation parameter, $\sin(2\beta)$. Prospects for future improved measurements of the CP violation parameters at the Tevatron are briefly discussed.

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1. Introduction

CP violation was first observed in kaon decays over 30 years ago. In the Standard Model the Cabibbo–Kobayashi–Maskawa (CKM) matrix relates weak and mass eigenstates of quarks. It can also provide a possible mechanism for explanation of the observed CP violation effects. The unitary CKM matrix is described by four physical parameters, one of them being a complex phase.

An analysis of unitarity constraints in which all of the elements are of the same order of magnitude, *e.g.*: $V_{ud}V_{ub}^*+V_{cd}V_{cb}^*+V_{td}V_{tb}^*=0$ and $V_{ud}V_{td}^*+V_{us}V_{ts}^*+V_{ub}V_{tb}^*=0$ provides a rudimentary test of the CKM description of CP violation. The magnitude of the complex elements have been determined from b-hadron lifetimes, branching fractions and — more recently — precise

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flavor oscillation measurements. The relative complex phases of the CKM matrix elements can be studied in measurements of the CP-asymmetries in B-decays. An analysis of the asymmetry in the decay rates of B^0 and $\bar{B}^0$ to a common CP eigenstate $J/\psi K^0_{\rm S}$ provides a measurement of the phase $\beta \equiv \arg(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}})$. The asymmetry, $\mathcal{A}_{CP} \equiv \frac{N(\bar{B}^0)-N(B^0)}{N(\bar{B}^0)+N(B^0)}$, where $N(\bar{B}^0)$ and $N(B^0)$ are numbers of observed decays to $J/\psi K^0_{\rm S}$ given the known flavor of the B meson at production, arises from the interference between the direct decay path, $\bar{B}^0 \to J/\psi K^0_{\rm S}$, and the mixed decay path, $\bar{B}^0 \to B^0 \to J/\psi K^0_{\rm S}$.

The CP-asymmetry $\mathcal{A}_{CP}$ depends on the CP phase difference between the two amplitudes, β and the flavor oscillations term represented by $\sin(\Delta m_d t)$, where Δm_d is the mass difference between the two B^0_d mass eigenstates, and t is proper decay time. In the Standard Model $\mathcal{A}_{CP} \simeq \sin(2\beta)\sin(\Delta m_d t)$ since other contributions are expected to be very small. Values of $\sin(2\beta)$ are constrained to a range of $0.3 \leq \sin(2\beta) \leq 0.9$ from indirect electroweak measurements [1]. In the past, two LEP collaborations reported CP asymmetry values of angle β measured with samples of fully reconstructed $B^0/\bar{B}^0 \to J/\psi K^0_{\rm S}$ decays, $\sin(2\beta) = 4 \pm 2 \pm 1$ (OPAL [2]) and $\sin(2\beta) = 0.84^{+0.82}_{-1.04} \pm 0.16$ (ALEPH [3]). More recently, two new results from the experiments at B factories were published, where $\sin(2\beta) = 0.34 \pm 0.20 \pm 0.05$ (BaBar [4]) and $\sin(2\beta) = 0.58^{+0.32}_{-0.34}(\text{stat.})^{+0.09}_{-0.10}(\text{syst.})$ (BELLE [5]).

In this talk I will describe the flavor tagging techniques adapted by CDF for application in the hadron collider environment and discuss their performance in the flavor oscillation measurements. I will also report on the CP analysis of $B^0_d/\overline{B}_d{}^0 \to J/\psi K^0_{\rm S}$ decays reconstructed in a data sample of 110 pb^{-1} collected by the CDF detector at the Tevatron collider at Fermilab during the 1992–1996 data taking period. The description of the CDF detector can be found in previous publications [6, 7].

2. The sample of $B^0_d/\overline{B}_d{}^0 \to J/\psi K^0_{\rm S}$

The reconstruction of B^0_d mesons was done via the decay $B^0_d/\overline{B}_d{}^0 \to J/\psi K^0_{\rm S}$, with $J/\psi \to \mu^+\mu^-$ and $K^0_{\rm S} \to \pi^+\pi^-$. The selection of the B candidates begins by identifying J/ψ particles that decay into two muons of opposite charge. All pairs of the oppositely charged particle tracks are considered to be candidates for the $K^0_{\rm S}$ decay products. The B candidate mass and momentum are calculated subject to the constraints that the invariant masses of the muon pair and the pion pair are equal to the world average mass of their parent particle, J/ψ and $K^0_{\rm S}$, respectively; come from separate vertices; the reconstructed $K^0_{\rm S}$ candidate points back to the J/ψ vertex; and the $J/\psi K^0_{\rm S}$ system points back to the primary interaction vertex. The silicon micro-vertex detector (SVX) information was used for these constraints when available. For a B candidate with both muons measured in the silicon vertex detector, the typical mass resolution is ~ 10 MeV$/c^2$, and the proper decay length resolution is ~ 50 μm. The normalized mass distributions, $M_{\rm N} = (m_{\mu\mu\pi\pi} - M_{\rm PDG})/\sigma_{\rm fit}$, broken into SVX (left) and non-SVX (right) subsamples, are shown in Fig. 1. The $M_{\rm PDG}$ is the world average B_d^0 mass, $\sigma_{\rm fit}$ is the mass resolution returned from the fit, and $m_{\mu\mu\pi\pi}$ is the invariant mass of the of the two-muon and two-pion combinations. The total number of reconstructed B mesons is 395 ± 31, with a signal-to-noise ratio of 0.7. The sample with both muons reconstructed in SVX contains 202 ± 18 events with a signal-to-noise ratio of 0.9, and the remainder of the sample contains 193 ± 26 events with a signal-to-noise ratio of 0.5. The SVX sample was used to make a time dependent analysis of the CP asymmetry. The preliminary result from the analysis of this data sample was already published [10]. The non-SVX sample with the degraded time resolution, was used to perform the time integrated measurement of the asymmetry.

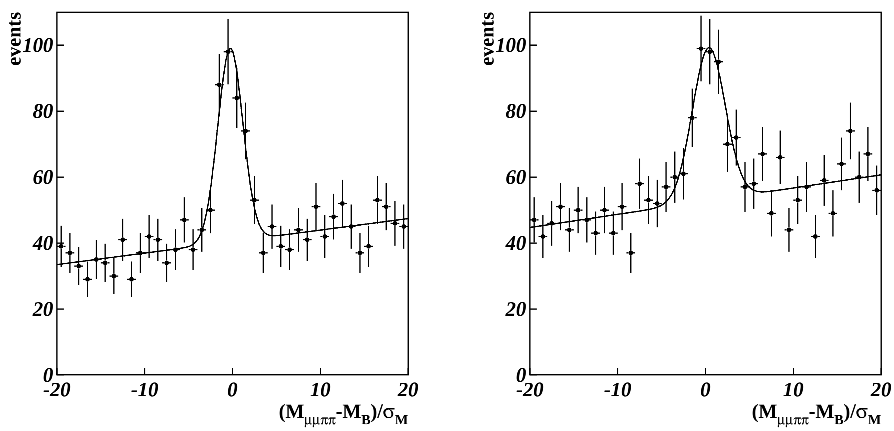

Fig. 1. Normalized mass distributions of the $B_d^0/\overline{B}_d{}^0 \to J/\psi K_{\rm S}^0$ candidates.

3. Identification of B flavor at production and decay

Experimental analysis of the CP asymmetry in the decay mode $B_d^0/\overline{B}_d{}^0 \to J/\psi K_{\rm S}^0$ requires determination of the B_d^0 flavor at the time of production. The fraction of events that are flavor tagged is called tagging efficiency, ε. Among the sample of tagged events the flavor of the B_d^0 meson is determined correctly for $N_{\rm R}$ events, and incorrectly for $N_{\rm W}$ events. The fraction $\mathcal{D}$, defined as $\mathcal{D} = (N_{\rm R} - N_{\rm W})/(N_{\rm R} + N_{\rm W})$ is called "tagging dilution", and is used to describe the observed asymmetry, $\mathcal{A}_{CP}^{\rm obs} = \mathcal{D}\mathcal{A}_{CP}$. The tagging techniques used in this analysis are very similar to the ones used in the $B^0 - \overline{B}^0$ oscillation measurements. The Same Side Tagging (SST) and Soft Lepton Tagging (SLT) algorithms were essentially the same as those used in the $\ell D^{(*)}$ [9] and inclusive lepton [8] analyses. The Jet Charge Tagging (JTQ) algorithm was modified from that in Ref. [8] to increase the efficiency of identifying low-p_{T} jets.

3.1. *Opposite side tagging with soft lepton and jet charge*

The Opposite Side Flavor Tagging techniques use the presence of the other b-hadron in the event on the opposite side of the reconstructed $B_d^0/\overline{B}_d{}^0 \to J/\psi K_{\mathrm{S}}^0$ decay. The flavor of the B meson at the production time is determined either from the charge of the jet on the opposite side or by the presence of the lepton coming from the decay chain $b \to \ell^-$. The Opposite Side Flavor tagging methods were studied using high statistics samples of semileptonic B decays [8, 9], as illustrated in Fig. 2, and they were calibrated using a sample of $\sim 1,000$ $B_u^{\pm} \to J/\psi K^{\pm}$ decays.

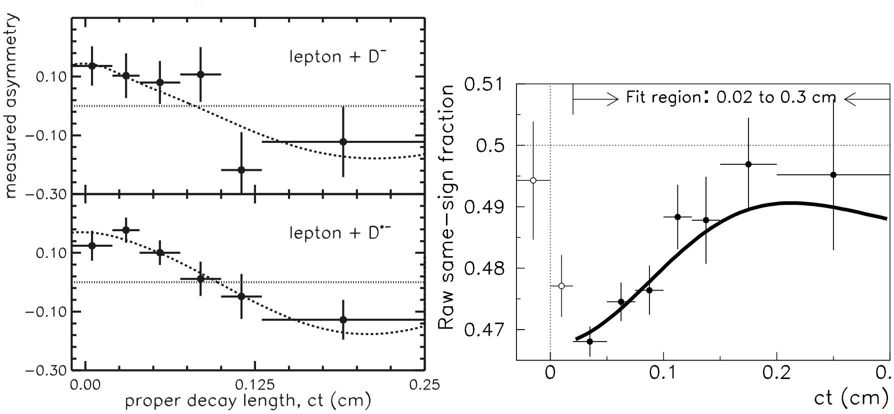

Fig. 2. Flavor oscillation measurements performed as a test of the tagging techniques. Flavor asymmetry as a function of the proper decay length ct. Left: Same Side Tagging algorithm applied to $B \to \ell D^{(*)}$; more details of the analysis are in Ref. [9]. Right: Soft Lepton and Jet Charge flavor tagging algorithms applied to the inclusive lepton data samples. Results from an unbinned likelihood fit are superimposed on the data points. Detailed description of the analysis is published in Ref. [8]. The tagger performance data for all three algorithms are shown in Table I.

The SLT algorithm correlates the charge of the lepton in the event with the flavor of the B^0 at the production time, $\ell^-(\ell^+)$ implies B^0 $(\overline{B}^0)$. Its performance was checked through observation of the $B_d^0 - \overline{B_d^0}$ flavor oscillation

TABLE I

Summary of the statistical power of the taggers from the CDF experiment, measured by εD^2.

Tagging method	Type	Efficiency ε [%]	Dilution D [%]	Eff. dilution εD^2[%]
SST	SVX	35.5±3.7	16.6±2.2	2.1 ± 0.5
	non-SVX	38.1±3.9	17.4±3.6	
SLT	all	5.6±1.8	62.5±14.6	2.2 ± 1.0
JTQ	all	40.2±3.9	23.5±6.1	2.2 ± 1.3
Total				≈ 6.3

using an inclusive lepton trigger sample [8], as shown in Fig. 2. The dilution of the soft lepton tag, as measured using the $J/\psi K^+$ sample, is $\mathcal{D}=63\pm15\%$.

In the JTQ algorithm a momentum weighted charge average of particles in a b-jet on the opposite side, $Q_{\rm jet}$, is used to determine the charge of the b-quark. The event is considered as tagged when $|Q_{\rm jet}| > 0.2$. The performance of the JTQ was also checked with the analysis of the Δm and dilution $\mathcal{D}$ using the inclusive lepton trigger sample (Fig. 2). The dilution of the JTQ method, as measured with the $J/\psi K^+$ sample, is $\mathcal{D} = 24 \pm 7\%$. A summary of the performance of tagging algorithms, described by the value of the dilution and the tagging efficiency, is presented in Table I. The Jet Charge and Soft Lepton tagging algorithms are described in more detail in another CDF publication [8].

3.2. Same Side Tagging

The Same Side Tagging (SST) technique relies on the correlation between the flavor of the B hadron and the charge of a nearby hadron produced either in the fragmentation process that formed a B meson from a b quark or from the decay of B^{**} meson. The charge correlations are the same in both cases: a B_d^0 meson is associated with a positive particle. The SST algorithm selects as a flavor tag, that particle which has the minimum momentum component transverse to the momentum sum of the B and the particle. The particle has to be contained in an η–ϕ cone of 0.7 around the B momentum direction, have $p_{\rm T} > 400$ MeV$/c$, and come from the primary vertex. The performance of this method was calibrated by tagging $B \to \ell D^{(*)}$ decays and observing the time dependence of the $B_d^0\overline{B_d^0}$ oscillation [9], as shown in figure 2. In addition to the usual measurement of the frequency of the oscillation Δm_d, the amplitude of the oscillation, $\mathcal{D}$, called dilution was also determined.

The method has been expanded in scope to be used on the sample of the non-SVX events, which have largely reduced impact parameter information. The performance of the Same Side Tagging algorithm is summarized in Table I.

4. Flavor asymmetry in $B_d^0 \to J/\psi K_S^0$ sample

A combination of three tagging methods was applied to the full sample of ∼400 events, and it improved the results of the previously published analysis [10]. The dilution and efficiencies for the opposite side tagging algorithms were determined using a sample of $B \to J/\psi K^+$ decays, to match the kinematic properties of the two samples. The SLT algorithm is characterized by high dilution but lower efficiency, compared to the performance of the JTQ algorithm. Each event can be tagged by one algorithm on the opposite side and one on the same side. When both SLT and JTQ tags are available, the tagger with higher dilution was selected to avoid introduction of correlations. Therefore, each event in this sample is tagged by a maximum of two algorithms.

Tagged events are simultaneously fitted for a combination of the three tagging methods, using an unbinned likelihood fit with the values of Δm_d and B_d^0 lifetime fixed to the world values. The fitting also takes into account the remaining tag correlations. The asymmetry values for the three tagging methods are shown in Fig. 3. Those events without proper time determina-

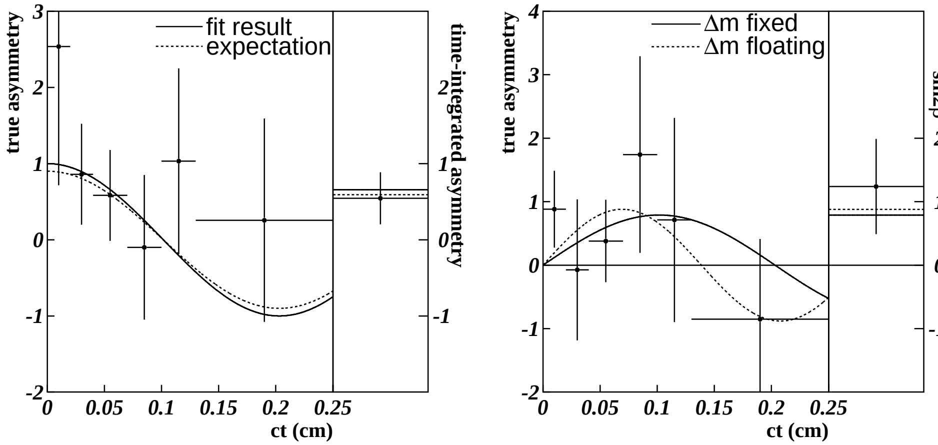

Fig. 3. Results of CP asymmetry studies. Left: Multiple tagging analysis applied to a sample of $B_d^0 \to J/\psi K^{*0}$ decays. A good agreement with expectations is achieved. Right: Multiple tagging analysis results. In addition to the time dependent information the plot displays time-integrated asymmetry for non-SVX events. For comparison the dashed line presents results of the fit with Δm_d left floating in the fit.

tion are presented separately as a single point. We measure $\sin(2\beta) = 0.79^{+0.41}_{-0.44}$(stat.+ syst.). The curves shown in Fig. 3 present the results of the fit. For comparison a fit result is shown with the value of Δm_d floating. As another check of the validity of the applied techniques, the analysis was performed on a sample of ~ 450 $B_d^0 \to J/\psi K^{*0}$ decays. The results of this fit agreed well with expectations and they are shown in Fig. 3.

5. Prospects for Run II

5.1. Detector upgrades

Following a very successful physics program at the Tevatron, the CDF and D0 collaborations, defined their physics expectations and aspirations for the next data collection period, which is beginning in Spring of 2001, and it will last until the turn on of the LHC at CERN. Among the topics related to b-hadron physics, measurements of the CP angles, α, β and γ, and determination of the B_s oscillations parameter $x_s = \Delta m_s/\tau_s$ are of special importance. The Tevatron, after commissioning of the Main Injector, is expected to deliver collisions at luminosities exceeding $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Data samples in excess of 2 fb^{-1} per experiment are expected in the first two years of data taking.

Both collaborations implemented a series of upgrades of their detectors, to eliminate the existing limitations and meet the new set of physics goals. The scope of enhancements included construction of new silicon detectors with larger acceptance and capability of measuring spatial coordinates in 3 dimensions. For the first time silicon vertex track processors are instrumented in the online trigger systems, which will allow for triggering on tracks with the non-zero impact parameter, *e.g.* originated from b-hadron decays. The CDF detector will have an enhanced particle identification capability for lower momentum particles, using the time-of-flight system comprised the long scintillator bars. It is especially important for identification of kaons in the momentum range relevant for tagging the flavor of b-hadrons. The D0 detector will have a superconducting solenoid with the 2 T magnetic field, and a tracking system based on scintillating fibers. The new tracking detectors will significantly improve momentum measurements for charged tracks, and will allow for precision reconstruction of short lived particles during data taking.

5.2. Physics expectations

Many important topics related to B physics will be addressed by CDF and D0 collaborations during the times when two new experiments, BaBar and Belle, are operating at the B-factories at SLAC and KEK. Multiple analyses performed on existing data samples make both CDF and D0 collaborations confident that their physics programs can be successfully realized.

The expected signal size of reconstructed $B_d^0/\overline{B}_d{}^0 \to J/\psi K_S^0$ decays, with $J/\psi \to \mu^+\mu^-$ and $K_S^0 \to \pi^+\pi^-$, should increase from 400 to 10k events. This number can be easily doubled if a lower (1.5 GeV/c instead of 2.0 GeV/c) muon momentum threshold is implemented in the CDF triggering system. Additional 8k $B_d^0/\overline{B}_d{}^0 \to J/\psi K_S^0$ decays followed by $J/\psi \to e^+e^-$ decay are expected. The flavor tagging algorithms will be calibrated using about 40k $B_d^\pm \to J/\psi K^\pm$ events and 20k $B_d^0 \to J/\psi K^{*0}$ events. The combined flavor tagging effectiveness for three algorithms measured with the current dataset is $\varepsilon D^2 = 6.3 \pm 1.7\%$. The expected value increases to $\varepsilon D^2 \sim 7\%$ for the new detector. With such value of the tagging effectiveness the expected error on $\sin(2\beta)$ is equal to $\delta\sin(2\beta) = 0.084$ for 18k reconstructed events, and decreases below 0.04 for a sample of 28k B_d^0 decays. This uncertainty includes systematic errors in the dilution due to the statistics of the calibration samples. The corresponding numbers for the D0 collaboration are summarized in Table III. The time-of-flight subsystem creates a new possibility of tagging flavor of b-hadrons using kaons. Combination of opposite side kaon tagging algorithm with the previously used algorithms will increase the tagging effectiveness to $\varepsilon D^2 = 9.4\%$. The summary of expected tagging performance and the estimated error on the value of $\sin 2\beta$ for both experiments is shown in Table II.

TABLE II

Summary of the expected statistical power of the taggers at both experiments, measured by εD^2.

Tagging method	εD^2 [%]	Detector upgrade	Detector upgrade	εD^2 [%]
	CDF		D0	
SST	2.0	new tracking	same	2.0
SLT	2.0	μ, e ID coverage	μ, e ID coverage	3.1
JTQ	3.0	new tracking	fwd tracking	4.7
Opp.Side K	2.4	TOF		
Total	$\sim \mathbf{9.4}$			$\sim \mathbf{9.8}$

The other very important and unique to the physics program at the Tevatron is the measurement of the mass difference in the B_s^0 meson system. In addition to the studied previously B_s^0 oscillations in the semileptonic decays, the upgraded CDF and D0 detectors will be able to trigger on hadronic B_s^0 decay modes: $B_s^0 \to D_s^-\pi^+$, $D_s^-\pi^+\pi^-\pi^+$, with $D_s^- \to \phi\pi^-, \overline{K}^{*0}K^-$. A large

TABLE III

Precision of $\sin(2\beta)$ measurement expected by the D0 collaboration.

Decay mode	$B^0 \to J/\psi K_s$	
	$J/\psi \to \mu^+\mu^-$	$J/\psi \to e^-e^+$
Trigger Eff. [%]	27	20
Events	40k	30K
$\delta\ \sin(2\beta)$	0.04	0.05
	0.03	

sample, exceeding 20k fully reconstructed events, is expected to be recorded in 2 fb^{-1} of integrated luminosity. The time-of-flight detector will provide an additional tagging method with Kaon identified on the same side as decaying B_s^0 meson. The combined effective tagging efficiency is expected to increase to $\varepsilon D^2 \sim 11.3\%$. The silicon detectors in both experiments will have an excellent impact parameter resolution. For example, in the CDF detector instrumented with an additional layer of silicon directly mounted on the beam pipe, the expected proper lifetime resolution is 45 fs, and in combination with high effective tagging efficiency will result in a measurement of Δm_s up to the value of 63 ps^{-1}.

6. Conclusion

Multiple tagging methods have been validated in the hadron collider environment of the Tevatron. The statistical power of the taggers, measured by the quantity $\varepsilon\mathcal{D}^2$, was determined using data sets accumulated by the CDF collaboration. Using a sample of over $\sim$ 400 events of fully reconstructed $B_d^0/\overline{B}_d{}^0 \to J/\psi K_S^0$ decays and multiple tags, we measured $\sin(2\beta) = 0.79^{+0.41}_{-0.44}$. This result can be translated into the frequentist confidence interval of $0 < \sin(2\beta) < 1$ at 93% confidence level. This year, the Tevatron will begin a new collider run, delivering an expected twenty-fold increase in data over the following two years. With detector and trigger improvements in both experiments, we expect to accumulate a sample of at least $\sim$ 10,000 $B_d^0/\overline{B}_d{}^0 \to J/\psi K_S^0$ events, allowing the uncertainty on $\sin(2\beta)$ to be reduced well below 0.08. All tagging methods will be important tools in the study of CP violation effects in the next run of the Tevatron. The unique to the Tevatron experiments measurement of the Δm_s will have sensitivity up to the expected maximum value.

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