# FLAVOR TAGGING AND 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-$P_t$ inclusive lepton and dilepton trigger data samples. The tagging techniques were applied to a sample of $\sim 400$ $B_d^0/\overline{B}^0{}_d \to J/\psi K_s^0$ 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.

## 1 Introduction

CP violation was first observed in kaon decays over 30 years ago. In the Standard Model the Cabibbo-Kobayashi-Maskawa (CKM) weak and mass eigenstates mixing matrix can 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 flavor oscillations 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 $J/\psi K_s^0$ 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 $J/\psi K_s^0$ given the known flavor of the B meson at production, arises from the interference between the direct decay path, $\bar{B^0} \to J/\psi K_s^0$, and the mixed decay path, $\bar{B^0} \to B^0 \to J/\psi K_s^0$.

The CP asymmetry $\mathcal{A}_{CP}$ depends on the CP phase difference between the two amplitudes, $\beta$ and the flavor oscillations term represented by $\sin(\Delta m_d t)$, where $\Delta m_d$ is the mass difference between the two $B_d^0$ 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] Last year the OPAL collaboration at LEP reported[2] $\sin(2\beta) = 4 \pm 2 \pm 1$, using a sample of 14 $B^0/\bar{B}^0 \to J/\psi K_s^0$ decays.

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 $B_d^0 \to J/\psi K_s^0$ decays reconstructed in a data sample of 110 pb$^{-1}$ collected by the CDF detector at the Tevatron collider at Fermilab. The description of the CDF detector can be found in previous publications[3,4].

## 2 Data Sample

The reconstruction of $B_d^0$ mesons was done via the decay $B_d^0/\overline{B}^0{}_d \to J/\psi K_s^0$, with $J/\psi \to \mu^+\mu^-$ and $K_s^0 \to \pi^+\pi^-$. The selection of the $B$ candidates begins by identifying $J/\psi$ particles that decay into two muons of opposite charge. All

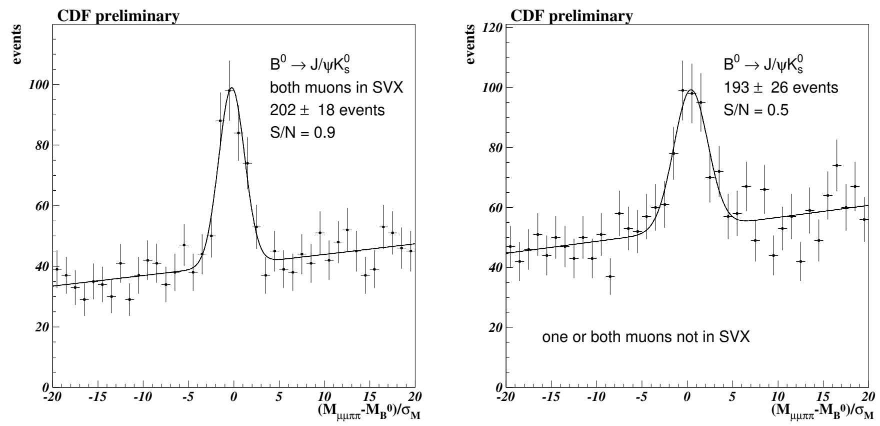


Figure 1: Normalized mass distributions of the $B_d^0 \to J/\psi K_s^0$ candidates.

pairs of the oppositely charged particle tracks are considered to be candidates for the $K_s^0$ 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, $J/\psi$ and $K_s^0$, respectively; come from separate vertices; the reconstructed $K_s^0$ candidate points back to the $J/\psi$ vertex; and the $J/\psi K_s^0$ 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 $\sim 10\ MeV/c^2$, and the proper decay length resolution is $\sim 50\ \mu m$. The normalized mass distribution, $M_N = (m_{\mu\mu\pi\pi} - M_{PDG})/\sigma_{fit}$, is shown in figure 1. The total number of reconstructed B mesons is $395 \pm 31$, with a signal-to-noise ratio of 0.7. The sample with both muons reconstructed in SVX contains $202\pm18$ events with a signal-to-noise ratio of 0.9, and the remainder of the sample contains $193\pm26$ events with a signal-to-noise ratio of 0.5.

## 3 Identification of B Flavor at Production and Decay

### *3.1 Opposite Side Tagging with Soft Lepton and Jet Charge*

The Opposite Side Flavor Tagging techniques use a triggered lepton and a reconstructed secondary vertex to identify the flavor of the B meson at the decay time. The flavor of the B meson at the production time is determined either from the charge of the jet on the side opposite the triggered lepton or by the presence of another lepton in the event. These flavor tagging methods were studied using high statistics samples of semileptonic B decays,[5,6] as illustrated in figure 2. The Opposite Side Flavor tagging algorithms were calibrated using a sample of $\sim 1,000\ B_u^\pm \to J/\psi K^\pm$ decays.

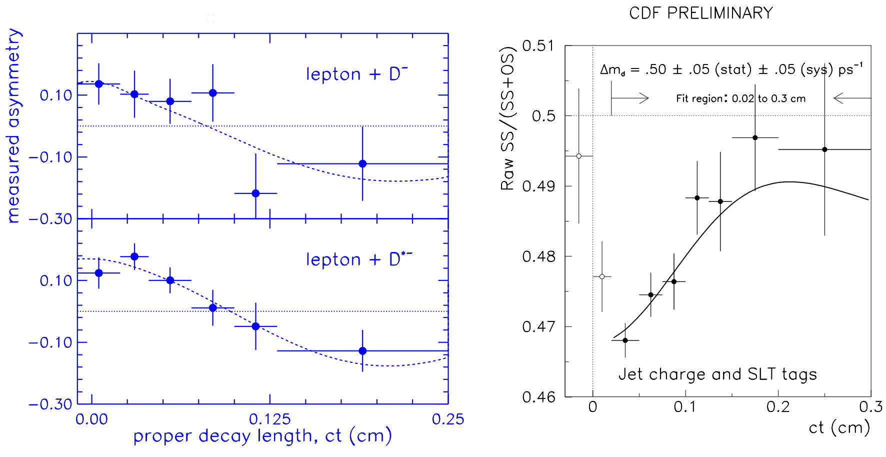


Figure 2: Asymmetry as a function of the proper decay length ct. Left: Same Side tagging applied to $B \to \ell D^*$; Right: Soft lepton and Jet Charge flavor tagging. Results from an unbinned likelihood fit are superimposed on the data points.

The Soft Lepton Tagging (SLT) algorithm correlates the charge of the second lepton in the event with the flavor of the B at the production time. Its performance was checked through observation of the $B_d^0 - \overline{B_d^0}$ flavor oscillation using an inclusive lepton trigger sample,[5] as shown in fig. 2. The dilution of the soft lepton tag, as measured using the $J/\psi K^+$ sample, is $\mathcal{D} = 63 \pm 15$ %.

In the Jet Charge (JTQ) method a momentum weighted charge average of particles in a b-jet, $Q_{jet}$, is used to determine the charge of the b quark. The event is considered as tagged when $|Q_{jet}| > 0.2$. The performance of the JTQ was also checked with the analysis of the $\Delta m$ 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,[a] is presented in table 1. The Jet Charge and Soft Lepton tagging algorithms are described in more detail in another CDF publication.[5]

### *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 $\eta - \phi$ cone of 0.7 around the B momentum direction, have $P_t > 400\ MeV/c$, 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,[6] as shown in fig. 2. In addition to the usual measurement of the frequency of the oscillation $\Delta m_d$, the amplitude of the oscillation, $\mathcal{D}$, called dilution,[b] was also determined.

## 4 Flavor Asymmetry in $B_d^0 \to J/\psi K_s^0$ Sample

Following the conclusion of the Workshop, the CDF collaboration updated the previously published analysis [7] of the $B_d^0 \to J/\psi K_s^0$ decays by employing a combination of three tagging methods to the full sample of $\sim 400$ events. The SST and SLT algorithms were essentially the same as in those used in the $\ell D^{(*)}$[6] and inclusive lepton[5] analyses. The JTQ algorithm was modified from that in ref. 5 to increase the efficiency of identifying low-$P_t$ jets. Each event

[a] The tagging efficiency, $\epsilon$, is the fraction of events that are tagged.
[b] The tagging dilution is defined as $\mathcal{D} = \frac{N_R - N_W}{N_R + N_W}$, where $N_W (N_R)$ are numbers of wrong (right) tagging decisions. The observed asymmetry $\mathcal{A}_{CP}^{obs} = \mathcal{D}\mathcal{A}_{CP}$.

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. In addition, 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.

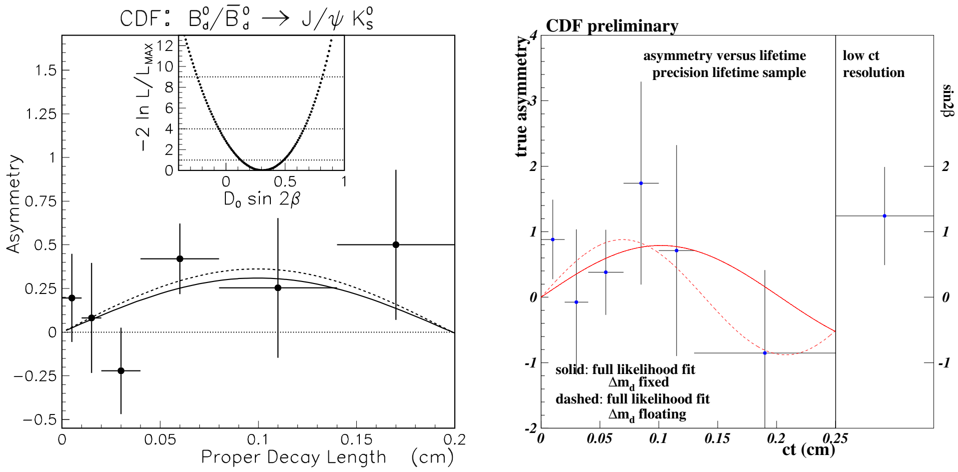


Figure 3: Results of CP asymmetry studies. Left: Time dependent Same Side Tag applied to a sample of $B^0_d \to J/\psi K^0_s$, where two muons are reconstructed in the SVX detector. Right: Multiple tagging analysis results. In addition to the time dependent information the plot displays time-integrated asymmetry for non-SVX events. For comparison the dashed line present results of the fit with $\Delta m_d$ left floating in the fit.

Tagged events are simultaneously fitted for a combination of the three tagging methods, using an unbinned likelihood fit with the value of $\Delta m_d$ fixed to the world value. 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 determination are presented separately as a single point. We measure $\sin(2\beta) = 0.79^{+0.41}_{-0.44}$. The curves shown in fig. 3 present the results of the fit.

## 5 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 $\epsilon\mathcal{D}^2$, was determined using data sets accumulated by the CDF collaboration. Using a sample of over $\sim 400$ events of fully reconstructed $B^0_d/\overline{B}^0{}_d \to$

Table 1: Summary of the statistical power of the taggers, measured by $\epsilon D^2$.

| Tagger | Effective Dilution $\epsilon\mathcal{D}^2$ | Dilution $\mathcal{D}$ | Efficiency $\epsilon$ |
|---|---|---|---|
| SST | $2.1 \pm 0.5$ % | $17 \pm 4\%$ | $38\pm 4\%$ |
| JTQ | $2.2 \pm 1.3$ % | $24 \pm 7\%$ | $40\pm 4\%$ |
| SLT | $2.2 \pm 1.0$ % | $63 \pm 15\%$ | $6 \pm 2\%$ |
| Multiple Tags | $6.3 \pm 1.7$ % | | |

$J/\psi K_s^0$ 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. Next 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, we expect to accumulate a sample of $\sim$ 10,000 $B_d^0/\overline{B}^0{}_d \rightarrow J/\psi K_s^0$ events, allowing the uncertainty on $\sin(2\beta)$ to be reduced to 0.08. All three tagging methods will be important tools in the study of CP violation effects in the next run of the Tevatron.

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