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B Hadron Flavor Tagging Using a Time-of-Flight Detector at CDF

M. Jones, J. Kroll, C. Chen
University of Pennsylvania

Summary of Changes

The following list summarizes the changes incorporated in Version 2 of this note:

- The momentum spectrum of kaons from opposite-side B decays is now shown in Figure 3.
- Results for same-side tagging of $B_s^0 \rightarrow J/\psi\phi$ have been updated using a larger sample of Monte Carlo events.
- Results for same-side tagging of $B_s^0 \rightarrow D_s^- \pi^+$ have been updated using a larger Monte Carlo sample.
- Cuts to simulate the effect of a Level 2 secondary vertex trigger have been applied to $B_s^0 \rightarrow D_s^- \pi^+$ which changes slightly the values of ϵ, D and ϵD^2 shown in Equation 22.
- Section 5 has been added to summarize the projected effectiveness of all flavor tags in Run II, shown in Tables 5-7.

1 Introduction

The weak decays of B hadrons are of great interest, because they probe five of the nine elements in the three-generation Cabibbo-Kobayashi-Maskawa matrix. The unitarity of this matrix leads to nine unitarity relationships, one of which is of particular interest:

$$V_{\mathrm{ud}} V_{\mathrm{td}}^* + V_{\mathrm{us}} V_{\mathrm{ts}}^* + V_{\mathrm{ub}} V_{\mathrm{tb}}^* = 0. \tag{1}$$

In the complex-plane, this sum of three complex numbers can be drawn as a triangle, and this triangle is commonly referred to as *the* Unitary Triangle. The weak decays of B hadrons can be used to measure the magnitudes of the three sides of the Unitarity Triangle, and CP asymmetries in B meson decays can be used to measure the three angles. The goal of B physics in the next decade will be to measure both the sides and angles of this triangle to see if they give a consistent picture.

We can use several approximations to reexpress eq. 1 in a more convenient form:

$$V_{\mathrm{ud}} \approx V_{\mathrm{tb}}^* \approx 1 \tag{2}$$
$$V_{\mathrm{ts}}^* \approx -V_{\mathrm{cb}}; \tag{3}$$
$$\tag{4}$$

V_{us} is $\lambda = \sin\theta_{\mathrm{C}}$. Equation 1 then becomes

$$1 + \frac{V_{\mathrm{td}}^*}{\lambda V_{\mathrm{ts}}^*} - \frac{V_{\mathrm{ub}}}{\lambda V_{\mathrm{cb}}} = 0, \tag{5}$$

which is shown as the sum of three vectors in the complex plane in Figure 1.

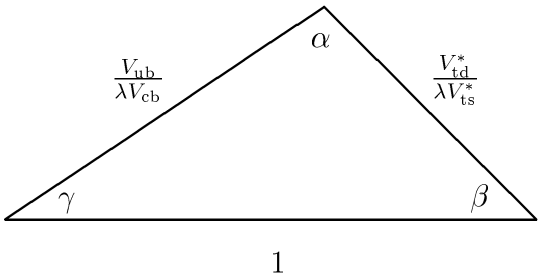

Figure 1: The Unitarity Triangle with the sides renormalized in a convenient way.

The Cabibbo angle is already measured to a precision of 1%: $\lambda = 0.2196 \pm 0.0023$ [1]. The ratio $|V_{\mathrm{ub}}/V_{\mathrm{cb}}| = 0.08 \pm 0.02$ [1], determined from a combination of results from CLEO and LEP, will be measured more precisely by adding data from the asymmetric B factories and CLEO. The angle β will be measured both by experiments on the $\Upsilon(4S)$ and at hadron colliders. The first determination will probably be from measuring $\sin 2\beta$ from the asymmetry in $B^0/\bar{B}^0 \to J/\psi K_{\mathrm{S}}^0$. The ratio $|V_{\mathrm{td}}^*/V_{\mathrm{ts}}^*|$ will probably first be determined by measuring the frequency Δm_s of $B_s^0 \leftrightarrow \bar{B}_s^0$ oscillations, and comparing it to the already well measured frequency Δm_d of $B_d^0 \leftrightarrow \bar{B}_d^0$ oscillations:

$$\frac{|V_{\mathrm{td}}^*|}{|V_{\mathrm{ts}}^*|} = (1.15 \pm 0.05) \cdot \sqrt{\frac{\Delta m_d \cdot m(B_s^0)}{\Delta m_s \cdot m(B^0)}}. \tag{6}$$

The first test of unitarity will be a combination of measurements of $\sin 2\beta$ and $|V^*_{\rm td}/V^*_{\rm ts}|$. The CDF collaboration is in a unique position in that it can do both. Since B^0_s mesons are not produced on the $\Upsilon(4S)$, this physics will be the domain of hadron colliders [1]. Furthermore, in the Standard Model, CP asymmetries induced by mixing in B^0_s decays to CP eigenstates (e.g. $B^0_s/\bar{B}^0_s \to J/\psi\phi$) are expected to be extremely small. A measurement of a significant asymmetry would be indisputable evidence that the Standard Model is incomplete.

1.1 Motivation for a Time-of-Flight Detector at CDF

Measuring flavor oscillations and CP asymmetries requires:

1. reconstructing the B meson in the appropriate final state, *e.g.*, $B^0/\bar{B}^0 \to J/\psi K^0_{\rm S}$ for $\sin 2\beta$, or $B^0_s \to D^-_s\pi^+$, followed by $D^-_s \to \phi\pi^-$, with $\phi \to K^+K^-$ for Δm_s;

2. measuring the proper-time of the B meson decay;

3. determining the flavor of the B meson when it is produced (and in the measurement of flavor oscillations, comparing it to the flavor when it decays). We refer to this determination as "b-flavor tagging." The flavor of the B meson is determined by whether it contains a b quark or $\bar{b}$ antiquark: B^0 ($\bar{b}d$) and B^+ ($\bar{b}u$) have the same flavor, but B^+ and B^- have opposite flavor.

The Time-of-flight detector (TOF) is useful for identifying pions, kaons, and protons. In the context of B physics, particle identification is useful for both reconstructing B decays and for b flavor tagging. The primary motivation for proposing this upgrade is b flavor tagging: we want to use TOF to enhance our b flavor tagging in Run II in order to increase our statistical precision in the measurement of CP violation, as well as our sensitivity to measuring B^0_s oscillations.

The figure of merit for a b flavor tagging method is its "total tagging effectiveness", ϵD^2. Here the efficiency ϵ is how often you can apply the tag given you have a B decay (such as $J/\psi K^0_{\rm S}$) that you want to tag: $0 < \epsilon < 1$. D is known as the "dilution" and is related to the probability $\mathcal{P}$ that the flavor tag is correct: $D = 2\mathcal{P} - 1$. A value of $D = 1$ (or "dilution" = 100%, corresponding to $\mathcal{P} = 1$) describes a perfect flavor tag that is always correct; a value $D = 0$ (or "dilution" = 0%, corresponding to $\mathcal{P} = 0.5$) describes a random tag.

The statistical error on the determination of a CP asymmetry $\mathcal{A}$ determined with N total candidates is approximately

$$\delta\mathcal{A} \approx \frac{1}{\sqrt{\epsilon D^2 N}}. \tag{7}$$

An additional flavor tagging method that increases ϵD^2 by a factor of two leads to a decrease in the statistical error on $\mathcal{A}$ by a factor of $\sqrt{2}$ (and the same decrease on the error of, for example, the CP violation parameter $\sin 2\beta$). A value of ϵD^2 of 1% or more is respectable.

CDF has investigated several b flavor tagging methods:

[1] In the next years, depending on the performance of the SLC collider, the SLD collaboration could achieve a sensitivity of $\Delta m_s = 15\hbar{\rm ps}^{-1}$.

1. the soft-lepton flavor tag or SLT;
2. the jet-charge flavor tag or JCT;
3. the same-side flavor tag or SST.

The SLT and JCT are "opposite-side" flavor tagging methods, that is, they identify the flavor of the other B hadron in the event to infer the flavor of the B hadron of interest. The SLT is based on identifying the semileptonic decay of the B hadron. The charge of the lepton identifies the b flavor of the B hadron: $b \to \ell^-$, but $\bar{b} \to \ell^+$. The JCT is based on the momentum weighted sum of charges of tracks in the jet formed by the b quark. This charge is on average negative for a hadron containing a b quark and positive for a hadron containing a $\bar{b}$ antiquark. The SST is based on the charge correlation of tracks produced in association with the hadronization of a b quark into a B meson. In particular, a π^+ (π^-) is expected to be produced in association with the formation of a B^0 ($\bar{B}^0$).

The performance of these b flavor tagging methods has been quantified by measuring B^0 flavor oscillations, which also requires knowledge of the flavor of the neutral B meson at production. For the SLT we measure $\epsilon D^2 = (1.07 \pm 0.13)\%$ [2]; for the JCT we measure $\epsilon D^2 = (0.78 \pm 0.15)\%$ [2]; and for the SST we measure $\epsilon D^2 = (2.4^{+0.9}_{-0.8})\%$ [3] using a sample of partially reconstructed semileptonic B^0 decays. Based on a combination of Monte Carlo studies and measurements from our data, we estimate $\epsilon D^2 = (1.8 \pm 0.3)\%$ [4] in our $B^0/\bar{B}^0 \to J/\psi K^0_S$ data sample.

The Monte Carlo does not reproduce the predicted tagging efficiencies for SLT and JCT. In the case of SLT, we have problems simulating accurately the identification of soft leptons and the background; in the case of JCT, the Monte Carlo predicts substantially higher tagging effectiveness. This may be due to a combination of deficiencies in the Monte Carlo, including inaccuracies in predicting how often the other B hadron is in the acceptance, and poor modeling of the underlying event and tracking inefficiencies. In contrast, a tuned version of the Pythia Monte Carlo that includes production of B^{**} mesons predicts the performance of the SST remarkably well.

The TOF can be used to enhance both opposite-side and same-side b flavor tagging. The decays of $\overline{B}$ hadrons containing b quarks produce more K^- than K^+ on average. Therefore identifying a charged kaon from B decay can be used as an opposite-side b flavor tag. This is the basis of one of the two flavor tags that will be used by the B factories (the other is the lepton-tag). The TOF can be used for same-side tagging as well. In the case of B^0_s production, the same mechanism described above for B^0 produces a K^+ (K^-) in association with the formation of a B^0_s ($\bar{B}^0_s$). B^0_s physics is especially important, because it will be unique to the Tevatron in Run II. In addition to using kaon identification to enhance SST for $B^0_s/\bar{B}^0_s$, we can also use it to enhance SST for $B^0/\bar{B}^0$. In this case, however, the kaons produced in association with $B^0/\bar{B}^0$ have the opposite charge-b flavor correlation expected for pions. Therefore we will either use the TOF to identify kaons (and protons too, by the way) and reject them, or to switch their charge correlation for the flavor tag.

2 The Time-of-Flight Detector

2.1 Overview

The proposed Time-of-Flight detector, which is described in more detail in [5], would reside in the space formerly occupied by the Central Drift Tubes, which were placed between the outer can of the Central Tracking Chamber and the solenoid. Given the outer radius of the new Central Outer Tracker, there is enough space to allow for scintillator that is 4cm thick. The inner edge of this scintillator will be at a radius of 138cm from the beam axis. The proposed scintillator is Bicron BC408, which, for the geometries under consideration, has a bulk attenuation length of $\sim$ 300 cm and a light propagation speed of about 14 cm/ns. We have considered two geometries. The first geometry, which we refer to as the "long-bar" geometry consists of 216 scintillator bars 3m in length and approximately 4cm $\times$ 4cm in cross-section[2] arranged with the long dimension parallel to the beam axis, so that the bars form a cylinder surrounding the COT. Each scintillator bar will be read out with two photomultiplier tubes (PMT), one at each end. The second geometry is the "short-bar" geometry. It consists of 432 scintillator bars 1.3m in length and 4cm $\times$ 4cm in cross-section. Pairs of bars cover the length in z of the COT with approximately 40cm of space between them centered at $\eta = 0$. Each bar will be read out with a PMT at both ends; the 40cm of dead space in z between the bars provides room for the PMTs and associated base, electronics, and cables. The advantage of the short-bar geometry is that these shorter bars can be installed in the central detector even after the end-cap calorimeters are in place in the collision hall. Other advantages include lower detector occupancy, better time-of-flight resolution, and less sensitivity to radiation damage. The most important disadvantage is cost. The short-bar system has twice as many PMTs and twice as many electronic channels. To operate in our high magnetic field, we need to use special fine-mesh PMTs, which are very expensive.

2.2 Time-of-Flight Simulation

We have written a simulation of TOF that can be used for physics studies. A detailed description of the simulation can be found in reference [5]. The helical trajectories of charged particles in the magnetic field are determined. Particles with $p_T < 330$ MeV/c curve so much in the magnetic field that they never hit the TOF. We approximate the COT tracking efficiency as 100% for charged particles with $p_T > 400$ MeV/c. Particles with $330 < p_T < 400$ MeV/c are not used in physics analyses, but their affect on TOF counter occupancy is taken into account. In addition, the simulation includes:

- The time-of-flight resolution, including the effects of fluctuations in photon statistics in the scintillator.
- The decay in flight of kaons and pions before they enter the TOF.
- Occupancy effects, including shadowing of one track by another (we have not proposed multiple hit electronics), the effect of additional inelastic collisions (minimum bias

[2]The actual cross-section is trapezoidal to fill the available space efficiently.

events), and photon conversions in the scintillator and outer can of the COT.

- The resolution on the time t_0 measured with TOF of the $p\bar{p}$ interaction.

In opposite-side kaon tagging, we are searching for kaons coming from the decay of B hadrons. We must separate these kaons from kaons coming from the underlying event and additional inelastic collisions. We can achieve this separation efficiently by exploiting the relatively long lifetime of B and D hadrons. The kaons from B hadron decay should have significant impact parameters with respect to the primary vertex. The simulation uses a parameterization of the impact parameter resolution of tracks, both for the currently proposed SVXII geometry, and for SVXII plus an additional layer of silicon (Layer 00) with $r\varphi$ readout only, located inside SVXII.

2.3 Kaon Identification with TOF

Particle identification using TOF is performed by comparing the event t_0 with the expected production time of a track, calculated using its momentum, path-length, time-of-flight, and an assumed mass. We also calculate the uncertainty on this difference, and use it to form a χ^2 variable for each mass hypothesis. A small improvement in particle identification power is gained by using the dE/dx information from the COT to form a combined χ^2 variable for each mass hypothesis, i:

$$\chi_i^2 = \chi_i^2(TOF) + \chi_i^2(dE/dx). \tag{8}$$

The probability λ_i that a given track is a particular particle type $i = \pi, K, p, e, \mu$ is calculated using a normalized likelihood:

$$\lambda_i = \frac{f_i L_i}{\sum_j f_j L_j}, \tag{9}$$

where $L_j = \exp(-\chi_j^2/2)$ and f_j are p_T dependent particle fractions, determined from the Monte Carlo. With real data, it will be sufficient to use estimates of these fractions using Monte Carlo, but we can also measure $f_i(p_T)$ directly using TOF.

3 Results on b Flavor Tagging using the TOF

3.1 Flavor Tagging for $B^0/\bar{B}^0 \to J/\psi K_S^0$

To study opposite-side and same-side flavor tagging for the measurement of $\sin 2\beta$, we have generated a sample of $b\bar{b}$-events using the PYTHIA Monte Carlo [6]. The $b\bar{b}$ events were generated with the same parameters used in our published studies [3] on same-side tagging. These parameters were tuned [7] to reproduce the charged multiplicities and p_T distributions observed in the data, but were also found [8] to reproduce several distributions associated with the selection of tracks used for same-side tagging. The B hadrons in these events were decayed using QQ [9] with a modified decay table that forced the decays $\overline{B}^0 \to J/\psi K_S^0$ and $J/\psi \to \mu^+\mu^-$. A sample of 20,000 such events were generated and were used for the studies of both same-side and opposite-side tagging.

To simulate the Run II trigger, we required the two muons from $J/\psi \to \mu^+\mu^-$ to be within $|\eta| < 1$, and each muon was required to have transverse momentum larger than

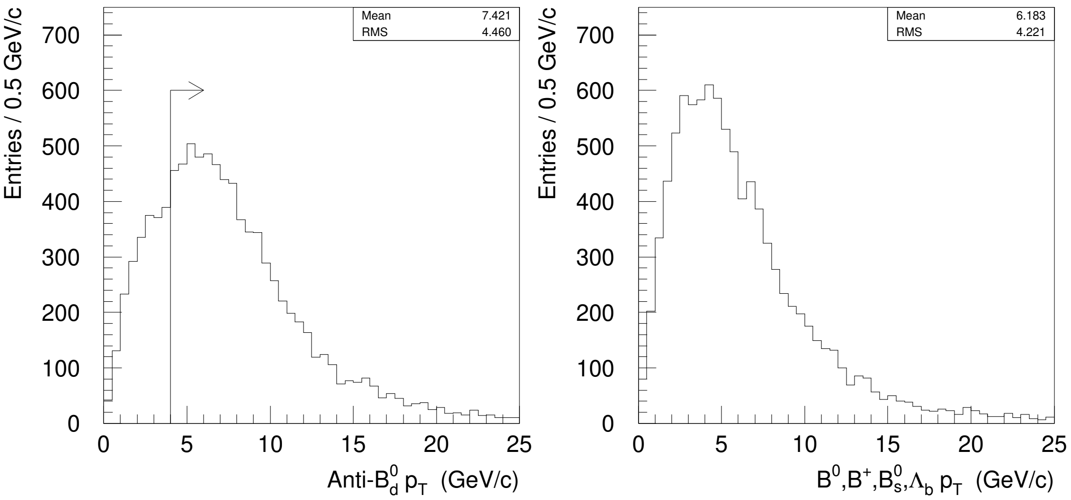

Figure 2: Transverse momentum distributions for the $\overline{B}^0$ that decayed to $J/\psi K^0_S$ (left) and the opposite-side B hadrons (right).

1.5 GeV/c. We also required that the K^0_S have $|\eta| < 1$ and $p_T > 1$ GeV/c. The resulting p_T distributions for the $\overline{B}^0$ and for the opposite-side B hadron are shown in Fig. 2. Finally, when analyzing these data, we require the p_T of the reconstructed $\overline{B}^0$ be greater than 4 GeV/c. This reduces the data sample by 25%, and increases the mean p_T of the $\overline{B}^0$ from 7.3 GeV/c to 8.9 GeV/c.

3.1.1 Opposite-Side Tagging in $B^0/\bar{B}^0 \to J/\psi K^0_S$

The charged kaon multiplicity in flavor tagged B decays has been measured by ARGUS and DELPHI and is summarized in Table 1, along with the multiplicities produced by QQ. The

Experiment	$N(B \to K^+X)$	$N(B \to K^-X)$
ARGUS[12]	0.66 ± 0.05	0.13 ± 0.04
DELPHI[13]	0.605 ± 0.020	0.148 ± 0.019
QQ	0.511 ± 0.007	0.063 ± 0.003

Table 1: Charged kaon multiplicities in B decays. Note that the ARGUS measurements are for B^+/B^0, while the DELPHI numbers are for B^+ only.

inclusive branching fraction $\mathrm{Br}(B \to K^\pm X)$ has not been measured.

The excess of positive kaons in B decays provides a means to tag the flavor of an opposite side B. We construct a flavor tag by selecting tracks identified as kaons that are separated from the $J/\psi K^0_S$ by an isolation cut in η-φ and that have impact parameters inconsistent with production at the primary vertex. A B is tagged if there is exactly one kaon selected in this way according to its charge. No attempt is made to tag the remaining small fraction of the events (14%) in which two or more kaons have been selected.

The acceptance for an opposite side B to have at least one (only one) kaon with $p_T > 0.4$ GeV/c that hits a 3m TOF bar was found to be 0.167 ± 0.004 (0.144 ± 0.004). We did not simulate neutral B meson mixing in the PYTHIA Monte Carlo, but we reverse the charge of the selected kaons if they originated from a B^0 or B_s^0 with probabilities

$$\mathcal{P}(B_s^0 \to \overline{B_s^0}) = \frac{1}{2} \tag{10}$$

$$\mathcal{P}(B^0 \to \overline{B^0}) = \frac{1}{2}(1 - \cos \Delta m_d t) \tag{11}$$

where $m_d = 0.472$ ps^{-1}[14] and t is the decay time of the B^0, generated with an average lifetime of 1.59 ps.

An upper bound on ϵD^2 can be estimated by considering only those kaons that were decay products of the opposite side B hadron. This gives a tagging efficiency of 0.144 ± 0.004 with a dilution of 0.67 ± 0.02 to give a combined effective tagging efficiency of $\epsilon D^2 = 6.5 \pm 0.4\%$. In a real analysis, this will be reduced by the kaon selection efficiency and purity, and by the efficiency with which tracks from the primary vertex are rejected.

The selection of kaons is performed by applying the cut $\lambda_K > 0.25$. The momentum spectrum of kaons from the opposite-side B decay is shown in Figure 3. For an average

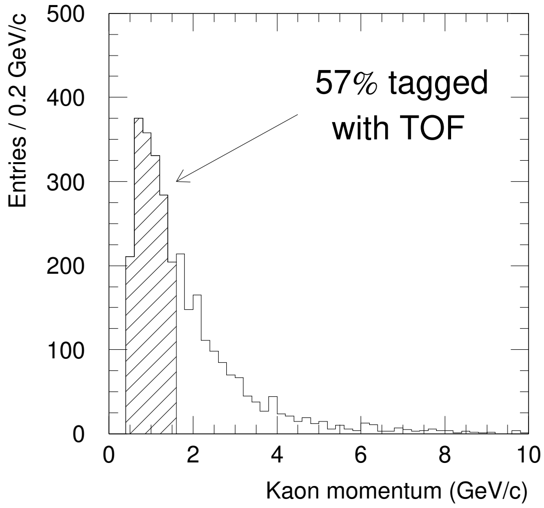

Figure 3: Momentum spectrum of kaons from the B decay opposite the reconstructed $B^0 \to J/\psi K_S^0$ decay. The fraction with $p < 1.6$ GeV/c, for which a 100 ps time resolution yields greater than 2σ K-π separation, is indicated by the hatched region.

time resolution of 100 ps, 2σ K-π separation is achieved for $p < 1.6$ GeV/c. The fraction of the momentum spectrum below this value is 57%. The rejection of tracks from the primary vertex was first performed by requiring that the kaon candidates be separated in η-φ space from the $J/\psi K_S^0$. The $\Delta R_{\eta\varphi}$ distributions of kaons in the Monte Carlo is shown in Fig. 4. The kaons from B decays generally populate the region away from the $J/\psi K_S^0$ jet, while an excess of "same-side" kaons can be seen around the $J/\psi K_S^0$. We select kaons for the tag by requiring $\Delta R_{\eta\varphi} > 1$.

To purify this sample further, the transverse and longitudinal impact parameters and their uncertainties for each track were used to construct a probability weight, $w_{D_0 Z_0}$, under

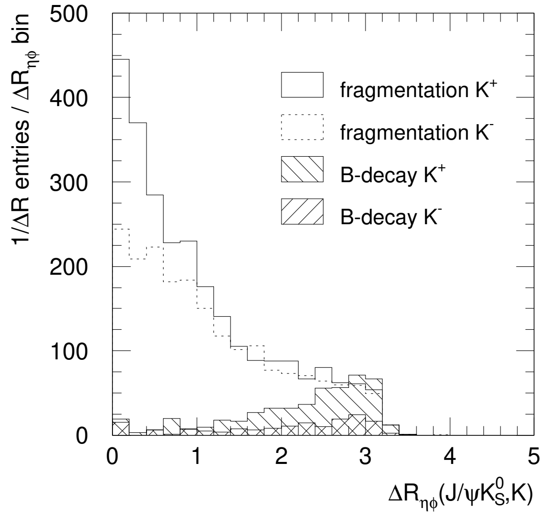

Figure 4: Distributions of $\Delta R_{\eta\varphi}$ for kaons from fragmentation, the underlying event, and from the decay of the opposite-side B. Entries are weighted by $1/\Delta R_{\eta\varphi}$.

the hypothesis that the track originated from the primary vertex. Tracks from the primary vertex have weights distributed uniformly between 0 and 1, while tracks from displaced secondary vertices will generally have weights peaked near zero. The distributions of the weights for these two classes of tracks are shown in Fig. 5. We require kaon candidates to have $w_{D_0 Z_0} < 0.01$ to be considered for the flavor tag.

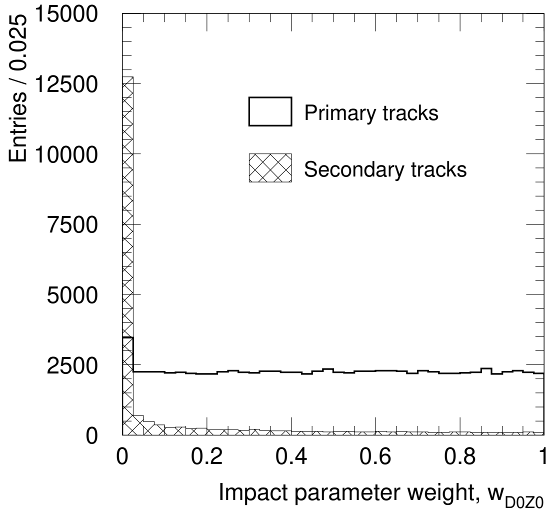

Figure 5: Probability weight distributions for tracks produced at the primary vertex (open histogram) and produced in the decay chain of B-hadrons (hatched histogram).

Applying this algorithm to select opposite-side kaons gave

$$\begin{aligned} \epsilon &= 0.100 \pm 0.003 && (12) \\ D &= 0.44 \pm 0.02 && (13) \\ \epsilon D^2 &= 0.019 \pm 0.001 && (14) \end{aligned}$$

for a TOF system with long bars and no additional minimum bias events. Figure 6 plots the value for the opposite-side tagging ϵD^2 for long and short bar TOF systems for $\langle n_{\rm mb}\rangle = 0, 2, 5$ and 10 additional minimum bias events.

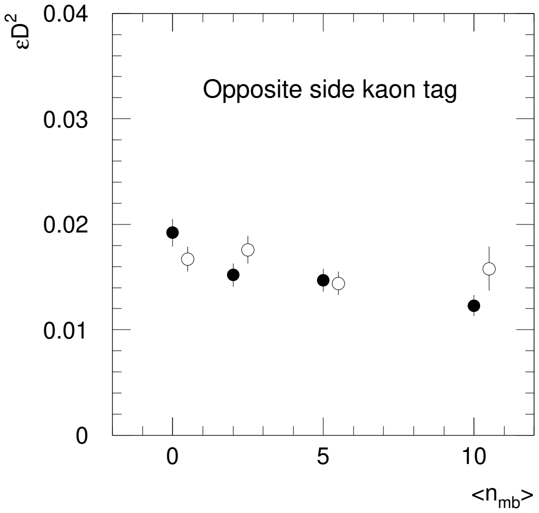

Figure 6: ϵD^2 for opposite-side kaon tagging for an average of 0, 2, 5 and 10 additional minimum bias events. Solid symbols are for a long bar TOF system; open symbols are for short bars.

The tight cut on $w_{D_0 Z_0}$ is necessary to obtain a pure sample of tracks from the decays of the opposite-side B hadron. However, the efficiency for tracks from B decays passing this cut would be increased if their impact parameters were measured more precisely. The proposed "Layer 00" silicon detector would be located very close to the beam pipe and would provide D_0 measurements with a resolution approximately half that of SVXII. We repeated the previous analysis of opposite-side kaon tagging except in this case, the D_0 resolution including Layer 00 [5] was used. This gave

$$\epsilon = 0.112 \pm 0.003 \qquad (15)$$

$$D = 0.461 \pm 0.022 \qquad (16)$$

$$\epsilon D^2 = 0.024 \pm 0.002 \quad \text{(with Layer 00)} \qquad (17)$$

for a system of long bars with no additional minimum bias events. With $\langle n_{\rm mb}\rangle = 2$, we obtained $\epsilon D^2 = 0.020 \pm 0.001$.

The need to reject kaon candidates that have impact parameters consistent with the primary vertex is not necessarily an optimal procedure. Instead, it might be better to apply a high efficiency secondary vertex reconstruction algorithm to the opposite-side tracks from which the kaon candidates would be selected. We could not study this approach since our Monte Carlo did not include a full tracking simulation. Nevertheless, the simplicity of the analysis presented here indicates that opposite-side tagging should be feasible even without sophisticated vertexing algorithms.

Finally, even if the detector simulation is perfect, and the tuned version of PYTHIA is a realistic simulation of the underlying event and B hadron production, there is still the uncertainty associated with QQ, the CLEO Monte Carlo used to simulate the weak decays of the B hadrons. Approximately 40% of the B^0 and B^+ decays in this Monte Carlo are generic $b \to c$ decays with string fragmentation used to dress the charmed quarks to charmed particles. This does not necessarily reproduce reality, so a full simulation will provide a better estimate of ϵD^2, but it could still be wrong by a significant amount, and it could be either too optimistic or too pessimistic.

3.1.2 Same-side Tagging in $B^0/\bar{B}^0 \to J/\psi K^0_{\rm S}$

Figure 7 illustrates the view we have for the fragmentation of a $\overline{b}$ quark into a B^+ or B^0 meson. To form a B^+, a $\overline{b}$ quark combines with a u quark from a $u\overline{u}$ pair, pulled from the vacuum,

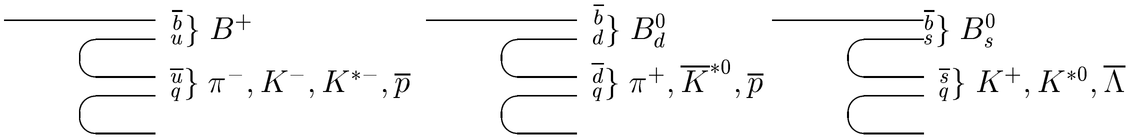

Figure 7: A schematic picture of B^+, B^0, and B^0_s meson formation in $\overline{b}$ quark fragmentation. A B^+ is produced in association with positively charged hadrons only, while a B^0 is produced along with positive pions, negative kaons (*via* $\overline{K}^{*0} \to K^-\pi^+$) and antiprotons. A K^+ is produced in association with a B^0_s.

which leaves a $\overline{u}$ quark available for the formation of the charged hadrons π^-, K^- or $\overline{p}$. For B^+, all charged hadrons formed in this way have the same charge, which is opposite that of the primary $\overline{b}$ quark charge. However, for a B^0 meson, a positive charge correlation occurs only when a π^+ is formed. Same-side tagging methods rely on identifying fragmentation tracks produced in association with a B meson and using their charge to tag the production flavor. The effectiveness of this method for tagging the production flavor of a B^0 is reduced due to the opposite charge correlations of associated pions and kaons/antiprotons. Hence, by restricting the sample of tracks selected as tag candidates to those that are consistent with pions, one can improve the resulting dilution of the flavor tag.

We use the same-side tagging algorithm used in the CDF measurement of $B^0 \leftrightarrow \bar{B}^0$ mixing [3] and in the CDF measurement of $\sin 2\beta$ [4]. This considers all charged particles with $p_T > 400$ MeV/c within an η-φ cone of radius $\Delta R_{\eta\varphi} = 0.7$, centered along the direction of the $J/\psi K^0_{\rm S}$ momentum vector. Since we are considering only fully reconstructed B decays, we do not apply a cut on the impact parameters to select tracks from the primary vertex. For each track considered, the quantity $p_T^{\rm rel}$ is calculated, which is defined as the transverse momentum of the track with respect to the combined momentum vector of the B and the track. If no track can be found in an event that satisfies these criteria, the event is not tagged. If at least one such track is found, the production flavor is tagged according to the charge of the track with the minimum $p_T^{\rm rel}$.

We compare the performance of this algorithm to one that makes use of the particle identification capabilities that would be provided by time-of-flight. In this modified same-

	without TOF	with TOF
ϵ	0.582 ± 0.004	0.539 ± 0.004
D	0.155 ± 0.012	0.187 ± 0.012
ϵD^2	0.014 ± 0.001	0.019 ± 0.001

Table 2: Flavor tagging efficiencies, purities and ϵD^2 for same-side tagging of B^0 using $p_T^{\rm rel}$ with and without TOF used for the identification of associated pions.

side tagging algorithm, we consider tracks with $p_T > 400$ MeV/c within the η-φ cone as before, but also require that they be consistent with being pions *when* they have TOF hits associated with them. This consistency is made based on the the normalized pion likelihood by requiring $\lambda_\pi > 0.1$. If the track has no TOF information, it is still considered as a same-side tagging candidate. The resulting flavor tagging efficiency, dilution, and ϵD^2 are shown in Table 2 for events with no additional minimum bias events. When we use the minimum $p_T^{\rm rel}$ algorithm and no additional information from TOF, our values of efficiency ($\epsilon = 0.582\pm0.004$), dilution ($D = 0.155\pm0.012$), and ϵD^2 agree well with the values obtained by the MIT group that are published in [3]. We considered in addition to $p_T^{\rm rel}$ the track with the maximum p_T and the track with maximum momentum component along the B+track system, $p_L^{\rm rel}$. The comparison of ϵD^2 obtained for the three tags with and without TOF is shown in Table 3. The additional information provided by TOF improves the ϵD^2 obtained for each tag by over 30%.

tag	ϵD^2, w/o TOF	ϵD^2 with TOF
minimum $p_T^{\rm rel}$	0.014 ± 0.001	0.019 ± 0.001
maximum p_T	0.017 ± 0.001	0.023 ± 0.001
maximum $p_L^{\rm rel}$	0.018 ± 0.001	0.024 ± 0.001

Table 3: A comparison of ϵD^2 for three tagging methods with and without the use of TOF to select pions.

These comparisons are for long TOF bars with no additional minimum bias events. Figure 8 shows how ϵD^2 changes depending on the mean number of minimum bias events present. In this analysis, the degradation of ϵD^2 with increasing $\langle n_{\rm mb}\rangle$ is minimal, mainly because the pion identification is only required if a track has associated TOF hits. Thus, the same pion with minimal $p_T^{\rm rel}$ will be chosen as *the* tag even if its TOF information is lost due to occupancy.

3.2 Same-side kaon tagging for B_s^0

The same-side tagging principle also applies when a B_s^0 is formed, except that in this case, an associated kaon is produced in the fragmentation chain, as shown schematically in Fig. 7.

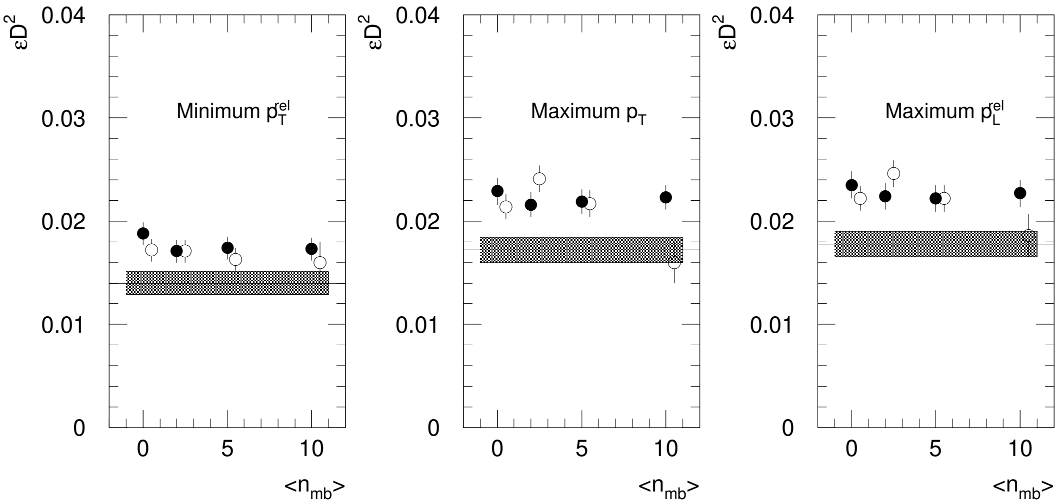

Figure 8: Variation in ϵD^2 with the mean number of minimum bias events present for the three same-side tagging algorithms considered. The solid symbols are for the long-bar TOF system; the open symbols are for the short-bar TOF system; the shaded regions indicate the value of ϵD^2 without TOF.

The ability to identify kaons in a sample of same-side tag candidates can provide a very powerful method for tagging the production flavor of B_s^0 mesons.

To study same-side tagging in B_s^0 decays, we generated approximately 10,000 $\overline{B}_s^0 \to J/\psi\phi$ decays using the PYTHIA Monte Carlo. We imposed the same requirements on the decay products as in the $\bar{B}^0 \to J/\psi K_S^0$ sample, except that we required $p_T(\phi) > 1$ GeV/c, instead of $p_T(K_S^0) > 1$ GeV/c. Again, when analyzing these data, we required the p_T of the reconstructed $\bar{B}_s^0$ be greater than 4 GeV/c.

We apply the same-side tagging algorithm described in section 3.1.2 to the $\overline{B}_s^0 \to J/\psi\phi$ sample, except that in this case we impose a cut on the kaon likelihood, requiring all tag candidates to have $\lambda_K > 0.25$. The charge of the candidate track selected in this way with the smallest $p_T^{\rm rel}$ is used to identify the production flavor. The resulting flavor tagging efficiency, dilution and ϵD^2, for a TOF system with long bars and no minimum bias events are

$$\epsilon = 0.172 \pm 0.004 \quad (18)$$
$$D = 0.385 \pm 0.025 \quad (19)$$
$$\epsilon D^2 = 0.026 \pm 0.002. \quad (20)$$

The other same-side tags have similar performance; maximum p_T and maximum $p_L^{\rm rel}$ both give $\epsilon D^2 = 0.026 \pm 0.002$. The same analysis performed without using TOF to identify kaons gives a higher efficiency of $\epsilon = 0.626 \pm 0.006$ but much lower dilutions of 0.05 ± 0.01, 0.09 ± 0.01 and 0.09 ± 0.01 for the minimum $p_T^{\rm rel}$, maximum p_T and maximum $p_L^{\rm rel}$ tags, respectively. Figure 9 shows ϵD^2 for these three tags for long and short bar TOF systems for $\langle n_{\rm mb}\rangle = 0$, 2, 5, and 10.

These results are strongly dependent on the p_T spectrum of the B_s^0 decays being studied. For the previous results we imposed $p_T(B_s^0) > 4$ GeV/c. If the acceptance is

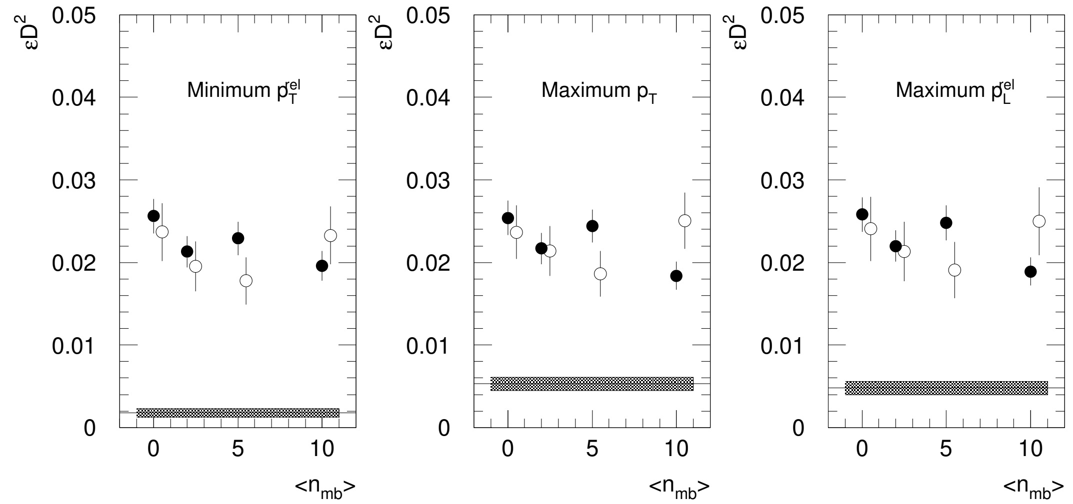

Figure 9: ϵD^2 for the three same-side kaon tags as functions of the mean number of additional minimum bias events. The solid symbols are for the long-bar TOF system; the open symbols are for the short-bar TOF system; the bars are ϵD^2 without TOF.

restricted to $p_T(B_s^0) > 8$ GeV/c, we obtain $\epsilon D^2 = 0.049 \pm 0.006$ for the minimum $p_T^{\rm rel}$ tag. This is particularly interesting since B_s^0 decays tagged with an all-hadronic trigger will have a harder p_T distribution.

To investigate this further, we used PYTHIA to generate a Monte Carlo sample of approximately 11,000 $\overline{B^0}_s \to D_s^+\pi^-$ decays, where $D_s^+ \to \pi^+\phi$ and $\phi \to K^+K^-$. A Level 1 hadronic track trigger was simulated following one of the proposed scenarios for Run II [10]. This trigger requires two oppositely charged tracks with $|\eta| < 1$, each of which has $p_T > 2$ GeV/c. The scalar sum of their p_T was required to be greater than 5.5 GeV/c, and the azimuthal angle between them was required to be $\delta\varphi < 135°$. Since the π^- from the B_s^0 decay has the hardest p_T spectrum, we consider the two oppositely charged tracks to be either $\pi^+\pi^-$ or π^-K^+. The p_T spectrum of the accepted B_s^0 decays is shown in Fig. 10 and has a mean of about 12 GeV/c. Also shown in this Figure is the p_T distribution of the kaons from $\phi \to K^+K^-$, which indicates that about 45% of these kaons have $p_T < 1.7$ GeV/c. A significant fraction of these kaons will then be distinguishable from pions using time-of-flight for particle identification.

In addition, we simulated the effect of a Level 2 secondary vertex trigger by requiring the impact parameter, d, of each track to satisfy

$$120\ \mu\text{m} < |d| < 1\ \text{mm}. \tag{21}$$

These cuts have a minor effect on the p_T spectrum of the selected B_s^0 sample, reducing the mean from 11.8 to 11.6 GeV/c.

Applying the same-side kaon tagging algorithm using $p_T^{\rm rel}$ to this sample gives

$$\begin{aligned} \epsilon &= 0.170 \pm 0.006 \\ D &= 0.496 \pm 0.016 \\ \epsilon D^2 &= 0.042 \pm 0.003, \end{aligned} \tag{22}$$

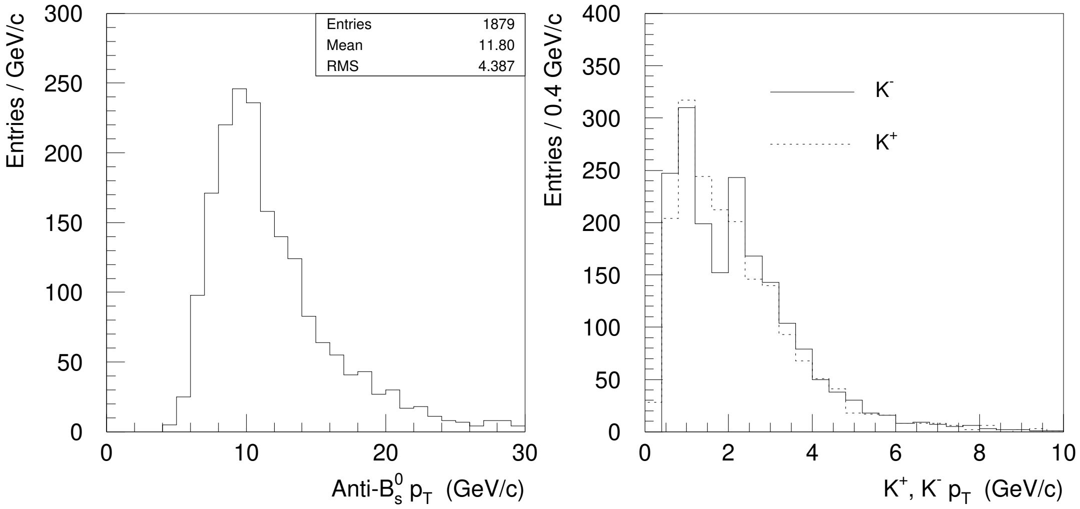

Figure 10: p_T distribution of $B_s^0 \to D_s^- \pi^+$ decays selected with a hadronic track trigger and of the $K^\pm$ from $\phi \to K^+ K^-$.

which is similar to the results obtained with the other tagging variables. Previous studies [11] indicated that we may be sensitive to B_s^0 oscillations in Run II for values of x_s as large as 30. To reach this sensitivity, we need to have as large a value of ϵD^2 as possible. Same-side tagging using kaons in B_s^0 decays promises to add significantly to our overall ϵD^2; indeed it may turn out to be the most powerful single flavor tagging method.

4 Conclusions

B flavor tagging is a crucial experimental component in the measurement of CP asymmetries of the decays of neutral B mesons to CP eigenstates and in the measurement of neutral B mesons flavor oscillations. In particular, the measurement of the asymmetry between the decays $B^0/\bar{B}^0 \to J/\psi K_{\mathrm{S}}^0$, which determines $\sin 2\beta$, the measurement of the asymmetry between the decays $B_s^0/\bar{B}_s^0 \to J/\psi\phi$, which is a sensitive probe of physics beyond the Standard Model, and the search for $B_s^0 \leftrightarrow \bar{B}_s^0$ flavor oscillations, will be among the most important measurements in B physics made during the first years of the next decade. Since B factories running on the $\Upsilon(4S)$ resonance do not produce B_s^0 mesons, CDF is in the unique position to study all three phenomena. We have found that the TOF is particularly important for our studies involving B_s^0 mesons.

Our studies have focused on three methods of flavor tagging:

1. opposite-side kaon tagging;
2. improving same-side tagging in B^0 decays;
3. making same-side tagging possible in B_s^0 decays.

We have quantified the performance of the flavor tags using their effective tagging efficiency, ϵD^2. If we have a sample of N events, then the statistical precision with which we can determine an asymmetry or the statistical significance with which we can measure an oscillation frequency is approximately inversely proportional to $\sqrt{\epsilon D^2 N}$. If we can add a flavor tagging technique or techniques that double the value of ϵD^2, we have effectively doubled the statistics of our data sample.

To determine the additional benefits of adding TOF, we compare to the results we achieved in B flavor tagging without TOF in Run I. We have measured ϵD^2 of three flavor tagging techniques using our Run I data. These are the soft-lepton tag (SLT), the jet-charge tag (JCT), and the same-side tag (SST). The measured values of ϵD^2 are $\epsilon D^2(\mathrm{SLT}) = 1.07 \pm 0.13\%$, $\epsilon D^2(\mathrm{JCT}) = 0.78 \pm 0.15\%$, and $\epsilon D^2(\mathrm{SLT}) = 1.8 \pm 0.4\%$, for at total of $\epsilon D^2(\mathrm{Combined}) = 3.7\%$. This combined number is applicable to tagging B^0 decays only, since SST was measured for B^0 (SLT and JCT are opposite-side tagging techniques so they apply equally to B^0 and B_s^0). The SLT and JCT numbers were measured in a sample with much higher $\langle p_T(B)\rangle$ than anticipated in the samples we will use in Run II, and therefore may be optimistic. On the other hand, recent studies of our exclusive B meson samples indicate that an improved jet-charge algorithm may increase ϵD^2 to 2–3%. To quantify the improvements from TOF, we use our results for ϵD^2 using the long-bar system and no additional minimum bias events (the closest case to the Run I data sample). The results for two additional minimum bias events on average are not significantly worse. We find that for opposite-side kaon tagging (OKT), $\epsilon D^2(\mathrm{OKT}) = 1.9 \pm 0.01\%$ (the error is the statistical error only). Opposite-side kaon tagging can be applied equally to B^0 and B_s^0. If we add Layer 00 to SVXII, then the additional impact parameter resolution improves $\epsilon D^2(\mathrm{OKT})$ to $2.4 \pm 0.02\%$. For SST in B^0, we find that using TOF to help select only pions as SST candidates improves ϵD^2 by 30%. In summary, the TOF could improve our current Run II value of ϵD^2 from 3.7% to 6.2% (6.7% with Layer 00). For SST in B_s^0, we find that using TOF to help select only kaons as SST candidates yields values of ϵD^2 ranging from 3% to 5% depending on $\langle p_T(B)\rangle$ of the data sample. This method alone would more than double ϵD^2 for B_s^0 tagging from the value we achieved so far in Run I (1.9% from SLT and JCT combined), and could end up being the most powerful of all our flavor tagging techniques. Without TOF or some other method to identify charged kaons, SST is essentially ineffective for tagging the flavor of B_s^0 mesons. Combining all our flavor tags, and including those made possible by TOF we could tag B_s^0 mesons with a combined ϵD^2 of 6.8% to 8.8% (add 0.5% to these estimates if Layer 00 is included). The improvements in B flavor tagging are summarized in Table 4.

The summary of our findings is

- TOF would make a dramatic difference in our ability to study B_s^0 system: it could more than triple our flavor tagging effectiveness compared to what we achieved in Run II. This is especially important given the uniqueness of this physics to the Tevatron and the crucial role it plays in the test of closure of the unitarity triangle. Same-side kaon tagging for B_s^0 using TOF may be our most powerful B flavor tag.

- TOF will also improve our tagging of B^0, perhaps by almost a factor of two. This would effectively double the statistical power of our $J/\psi K_S^0$ sample for the measurement of $\sin 2\beta$.

- There is no obvious physics advantage of the short-bar system. Occupancy does not appear to be a limiting issue in neither the long-bar nor the short-bar system, even at luminosities corresponding to 10 extra interactions per crossing (TeV33).

tag	B^0	B_s^0
SLT	1.07 ± 0.13	1.07 ± 0.13
JCT	0.78 ± 0.15	0.78 ± 0.15
SST	1.8 ± 0.4	—
Σ (Run I)	3.7	1.9
OKT	1.9 ± 0.01	1.9 ± 0.01
SST	2.4 ± 0.02	3–5
Σ with TOF	6.2	6.8–8.8
Σ with TOF and L00	6.7	7.3–9.3

Table 4: A summary of the improvements in B flavor tagging provided by a time-of-flight detector (TOF) compared to the performance we achieved with Run I data without TOF. The entries in the table are ϵD^2 in percent.

5 Projections for b Flavor Tagging in Run II

Tables 5, 6, and 7 summarize our expected b flavor tagging effectiveness in Run II with and without the TOF and Layer 00. The flavor tagging effectiveness of the same-side tag depends on whether the neutral B meson is a B^0 or B_s^0, and on $p_T(B)$. As a result the total ϵD^2 for $B^0/\bar{B}^0 \to J/\psi K_S^0$ (summarized in Table 5), $B_s^0/\bar{B}_s^0 \to J/\psi\phi$ (summarized in Table 6), and $B_s^0 \to D_s^- \pi^+$ (summarized in Table 7) are different. The values of ϵD^2 projected for Run II for the soft-lepton tag and the jet-charge tag are taken from the values quoted in the CDF-II Technical Design Report. The values of ϵD^2 for same-side tagging and for opposite-side kaon tagging are the values reported in this note. For opposite-side kaon tagging, we use the value of ϵD^2 that is obtained when both TOF and Layer 00 are used. The potential variation in the effectiveness of the opposite-side flavor tags with the p_T of the B that triggers the event has been neglected, since this variation is expected to be much smaller than in the case of the same-side tag. Studies of applying multiple b flavor tags to our Run I $B^0/\bar{B}^0 \to J/\psi K_S^0$ data sample indicate that adding up the ϵD^2 values of the individual tags is a good approximation of the total tagging efficiency.

6 Acknowledgments

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$B^0/\bar{B}^0 \to J/\psi K^0_{\rm S}$		
	without TOF	with TOF
Same-Side (pion) Tag	1.4	1.9
Soft Lepton Tag (μ)	1.0	1.0
Soft Lepton Tag (e)	0.7	0.7
Jet Charge	3.0	3.0
Opposite-Side Kaon Tag	—	2.4
Total	6.1%	9.0%

Table 5: Projected values for ϵD^2 for Run II without and with TOF. These flavor tagging efficiencies are for $B^0/\bar{B}^0 \to J/\psi K^0_{\rm S}$.

$B^0_s/\bar{B}^0_s \to J/\psi\phi$		
	without TOF	with TOF
Same-Side (Kaon) Tag	0.2	2.6
Soft Lepton Tag (μ)	1.0	1.0
Soft Lepton Tag (e)	0.7	0.7
Jet Charge	3.0	3.0
Opposite-Side Kaon Tag	—	2.4
Total	4.9%	9.7%

Table 6: Projected values for ϵD^2 for Run II without and with TOF. These flavor tagging efficiencies are for $B^0_s/\bar{B}^0_s \to J/\psi\phi$.

$B^0_s \to D^-_s\pi^+$		
	without TOF	with TOF
Same-Side (Kaon) Tag	1.0	4.2
Soft Lepton Tag (μ)	1.0	1.0
Soft Lepton Tag (e)	0.7	0.7
Jet Charge	3.0	3.0
Opposite-Side Kaon Tag	—	2.4
Total	5.7%	11.3%

Table 7: Projected values for ϵD^2 for Run II without and with TOF. These flavor tagging efficiencies are for $B^0_s \to D^-_s\pi^+$

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