



PROSPECTS IN CP VIOLATION MEASUREMENTS AT THE
TEVATRON COLLIDER

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Abstract

The Fermilab Tevatron Collider is currently the most copious source of b -hadrons, thanks to the large $b\bar{b}$ production cross-section in 1.96 TeV $p\bar{p}$ collisions. Recent detector upgrades allow for a wide range of CP violation and flavor-mixing measurements that are fully competitive (*direct* asymmetries in self-tagging modes) or complementary (asymmetries of B_s and b -baryons decays) with B -factories. In this paper we review some recent CP violation results from the DØ and CDF II Collaborations and we discuss the prospects for future measurements.

1 Introduction

Although several substantial improvements have been achieved in understanding the CP violation mechanism, we are left with several open questions, and an experimental effort is necessary to increase our comprehension. The b sector offers many interesting processes in which large CP violating effects are possible, some of which have clean theoretical interpretation. Traditionally, b physics has been the domain of e^+e^- machines operating at the $\Upsilon(4S)$ resonance (B -factories) or at the Z^0 pole. In particular, the recent successful turn on of the Babar and Belle experiments provided an impressive precision in many experimental measurements. Nevertheless, already in 1990 the UA1 Collaboration proved that b physics is accessible in an hadron collider environment ¹⁾, and in 1992 the CDF Collaboration published the first signal of fully reconstructed B meson decays ²⁾. Afterward, the CDF and DØ Collaborations pursued a successful b physics program during the 1992-1996 data taking period (Run I).

Since then the experimental techniques improved significantly, with the development of more precise silicon microvertex detectors and online triggering of tracks from long-lived particles. The Tevatron $p\bar{p}$ Collider, along with the upgraded Collider Detector at Fermilab (CDF II) and the DØ detector, offer today a unique opportunity to study b physics. Tevatron results are fully competitive with B -factories and, in many cases, the Tevatron measurements are complementary to those performed at the B -factories.

We summarize here some of the recent experimental progress in the measurements related to CP violation and flavor-mixing in the *beauty* and *charmed* sectors at the Tevatron. Charge-conjugate modes are implied throughout all this paper unless otherwise specified.

2 The Upgraded Tevatron Accelerator

The Tevatron accelerator complex has undergone an extensive upgrade since the end of Run I. The major improvement is the replacement of the final injection stage with the Main Injector, a new 150 GeV proton ring which provides more efficient injection and higher proton intensity onto the anti-proton production target¹. In Run II (mid-2001 – now) the Tevatron accelerates 36 bunches of protons against 36 bunches of anti-protons producing one collision every 396 ns at 1.96 TeV centre-of-mass energy. The current centre-of-mass energy, higher than in Run I (1.8 → 1.96 TeV), increases by ~ 10 – 30% the production cross-section for heavy flavors. The luminous regions along the beamline are about 30 cm long (RMS), requiring properly designed silicon micro-vertex de-

¹Actually, in \bar{p} production mode, the Main Injector accelerates protons to 120 GeV.

tectors to provide good coverage. The transverse beam-width at the collision points is about $25 - 30 \mu\text{m}$ (RMS). This is sufficiently small compared to the typical transverse decay length² of b -hadrons, $L_{xy} \simeq 450 \mu\text{m}$, to allow a clean separation of secondary from primary vertices. The instantaneous luminosity (\mathcal{L}_{inst}) has been rising steadily since the beginning of Run II. A factor of two increase has been achieved just during the last year (March 2003 – March 2004) up to a record of $\mathcal{L}_{inst} \simeq 6.7 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$. The machine regularly exceeds $\mathcal{L}_{inst} = 5 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$ typically delivering data corresponding to $10 \text{pb}^{-1}/\text{week}$ of integrated luminosity per experiment. At such luminosities on average 1.5 interactions per bunch-crossing occur. The total integrated luminosity delivered is around 400pb^{-1} per experiment but the data taken during the first year were used for machine and detector commissioning. Afterward, about 290pb^{-1} of physics quality data have been recorded on tape by each experiment with typical data-taking efficiencies in excess of 85%. The CDF II results shown in this document used up to 190pb^{-1} of data; the DØ results used up to 250pb^{-1} of data.

3 Overview: b Physics at the Tevatron

The b -hadron phenomenology in $p\bar{p}$ collisions at 1.96 TeV offers several advantages with respect to e^+e^- collisions. The Tevatron $b\bar{b}$ production cross-section is very large, $\mathcal{O}(100 \mu\text{b})$, compared to the typical e^+e^- cross-sections at the $\Upsilon(4S)$ ($\sim 1 \text{nb}$) and Z^0 ($\sim 7 \text{nb}$) resonances. Typical production rate of b quarks at the Tevatron is about 5 kHz and they are produced mainly³ incoherently in $b\bar{b}$ pairs by strong interaction. As a consequence, mixing and CP violation measurements can be performed by reconstructing a single b -hadron in the event, while at B -factories the flavor of one B meson is determined only after observing the decay of the other. Moreover, unlike the B -factories, all species of b hadrons are produced at the Tevatron, including B_s , B_c and b -baryons such as Λ_b and Ξ_b .

However the hadronic environment poses several challenges for the b -physics. The very large $b\bar{b}$ production cross-section is only about $1/500^{\text{th}}$ the total inelastic $p\bar{p}$ cross-section, $\sigma_{inel}(p\bar{p}) \simeq 50 \text{mb}$. Moreover, Tevatron events show high (≈ 50) track multiplicities, due to the fragmentation of the hard interaction products, to the underlying events (*i.e.* hadronized remnants of p and \bar{p}) and to pile-up events (multiple collisions per bunch crossing). One way

² $L_{xy} = \beta_T \gamma c\tau$ where $\beta_T \gamma$ is the Lorentz boost projected onto the plane perpendicular to the beam line ($\simeq 0.5 - 2$ at Tevatron) and $c\tau$ is the proper decay length of the b -hadron ($\simeq 450 \mu\text{m}$).

³The contributions of $p\bar{p} \rightarrow \Upsilon(4S) X$, $\Upsilon(5S) X \rightarrow [\bar{b}b] X$, $p\bar{p} \rightarrow Z^0 X \rightarrow [\bar{b}b] X$, $p\bar{p} \rightarrow W^- X \rightarrow [\bar{c}b] X$ and $p\bar{p} \rightarrow W^- X \rightarrow [\bar{t}b] X$ are neglected.

to identify b -decays in such a complicate environment is to exploit the relatively long lifetime of b -flavors resulting in decay vertices which are separated by hundreds of microns from the primary $p\bar{p}$ interaction vertices. In addition, the distribution of the transverse momentum⁴ (p_T) of b -hadrons at the Tevatron is a steeply falling function. Most of the b -hadrons have very low p_T and decay into particles which are typically quite soft, often having $p_T < 1$ GeV/c. This has two consequences: (1) the need to select tracks as soft as possible conflicts with the limited bandwidth allowed by the data acquisition systems; (2) since the longitudinal component of b -hadrons momentum is frequently very large, they tend to decay into particles boosted along the beam line, thus escaping the detector acceptance. If one b -quark is central (pseudorapidity⁵ $|\eta| < 1$), the other one is central only $\mathcal{O}(10\%)$ of the time.

A key ingredient for an effective b -hadron selection and reconstruction at the Tevatron is, therefore, an excellent tracking system with reconstructing capability extended to low transverse momenta . The tracking system should also provide excellent vertexing performances to select long-lived decays that are likely to contain heavy flavors. Finally, it is necessary a selective trigger and data acquisition system capable to sustain the high rates associated with this physics. In the following section we outline some of the relevant aspects of the CDF II and DØ detectors and triggers.

4 The CDF II and DØ Detectors

The CDF II and DØ detectors are large multipurpose solenoidal magnetic spectrometers surrounded by 4π calorimetry and muon filters. They are axially and azimuthally symmetric around the interaction point and their strengths are somewhat complementary to one another. DØ has a excellent tracking acceptance and very good e and μ identification performance. CDF II features very precise tracking that provides excellent mass resolution and has strong particle identification capabilities. Additional details of the detectors can be found elsewhere 3) 4).

4.1 DØ

The DØ tracking volume consists of an inner silicon detector surrounded by a scintillating fiber tracker both immersed in a 2 T solenoidal field with 52 cm total lever arm. The fiber tracker covers the region $|\eta| < 1.7$, the silicon detector

⁴ p_T is the particle momentum component perpendicular to the beam line: $p_T = p \cdot \sin(\theta)$ where θ is the polar angle with respect to the beam axis ($\theta = 0 \Rightarrow$ particle collinear with the proton direction).

⁵The pseudorapidity η of a particle is defined as $\eta = -\ln \tan(\theta/2)$.

is organized in longitudinal barrels interspersed with azimuthal disks which extend the forward tracking to $|\eta| < 3$. Tracks with transverse momentum as low as 180 MeV/c are reconstructed. The uranium/liquid-argon calorimeter has very good energy resolution for e , γ and hadronic jets and features pre-shower counters to improve e/γ discrimination. The muon system covers $|\eta| < 2$ for muons with $p_T > 2 - 4.5$ GeV/c.

4.2 CDF

The CDF II tracking system consists of an inner silicon system surrounded by a gas-wire drift chamber both immersed in a 1.4 T field with 135 cm total lever arm. Six to seven double-sided silicon layers, plus one single-sided layer, cover the full Tevatron luminous region ($|\eta| < 2$) and extend radially from 1.6 to 28 cm from the beam line. The drift chamber provides 96 (48 axial plus 48 stereo) samplings of track paths within $|\eta| < 1$. Tracking information is integrated with muon (reconstructed at $|\eta| < 1.5$) and calorimeter ($|\eta| < 2$) data for μ and e/γ /hadron identification. Low-momentum particle identification (PID) is performed using a scintillator-based Time-of-Flight detector (TOF) with 110 ps resolution that provides 2σ K/ π separation at $p < 1.5$ GeV/c. The specific ionization information from the drift chamber (dE/dx) complements the PID with 1.4σ K/ π separation for tracks with $p > 2$ GeV/c.

5 The CDF II and DØ Triggers

The trigger system is probably the single most important ingredient to pursue an effective b physics program at the Tevatron. Both CDF II and DØ have a multi-stage trigger system organized in three Levels. CDF II has a data acquisition system faster than DØ, allowing for a higher Level 1 Accept trigger rate, while DØ has Level 2 Accept rate higher than CDF II.

Past experience from Run I suggests that triggering on final states containing single or di-leptons is a successful strategy to select high statistics samples of b -hadron decays. Semi-leptonic $B \rightarrow l\nu_l X$ plus charmonium $B \rightarrow J/\psi X \rightarrow [l^+l^-]X$ decays are $\mathcal{O}(20\%)$ of B meson widths. Both CDF II and DØ adapted such a “conventional” approach to the upgraded detectors. In addition CDF II has a new capability to select events based upon track impact parameter⁶. The following subsections describe the main features of the triggers oriented to b -physics.

⁶The impact parameter of a track $d_0(tr)$ is the minimum distance between the track projection and the primary vertex in the plane transverse to the beam.

5.1 Conventional Triggers

Identification of di-muon events down to very low momentum is possible, allowing for efficient $J/\psi \rightarrow \mu^+\mu^-$ and rare-decays triggers. Both experiments trigger upon J/ψ decays, 15% of which come from b -hadrons, and then fully reconstruct several useful decay modes such as $B_s \rightarrow J/\psi\phi \rightarrow [\mu^+\mu^-][K^+K^-]$. Although CDF II and DØ results shown here use only di-muon modes, future analyses will include data collected through di-electron triggers.

DØ has an inclusive muon trigger with excellent acceptance, that collects very large samples of semileptonic decays. The CDF II semileptonic triggers require an additional displaced track associated with the lepton, providing cleaner samples with smaller yields and are described in the next subsection. Trigger thresholds are summarized in Table 1.

5.2 Triggering on Displaced Tracks

A revolutionary feature of CDF II is the ability to trigger events containing tracks originated in a vertex displaced from the primary. These events are enriched in heavy flavor contents, thanks to the higher mean-valued lifetimes of b -hadrons. The CDF II Silicon Vertex Trigger (SVT)⁵⁾ identifies displaced tracks by measuring their impact parameter with an intrinsic resolution⁷⁾ $\sigma_{SVT}(d_0) \simeq 35 \mu\text{m}$. Such a high accuracy is required to discriminate b -decays from background tracks and can be reached only using the silicon information. The experimental challenge is to read-out the silicon detector and perform pattern recognition while sustaining the high trigger rate. In a typical latency of 25 $\mu\text{s}/\text{event}$, SVT reconstructs with offline-quality two-dimensional tracks (in the plane transverse to the beam) by combining the drift chamber information with the silicon hits.

Two trigger strategies exploit displaced tracks. The “*lepton + displaced track*” trigger requires a displaced track associated to an electron (or muon) to select very clean samples of semileptonic b decays. The “*two track*” trigger requires only two displaced tracks and selects exclusive non-leptonic b -decays for the first time in an hadronic collider. This trigger accumulates large and clean samples of several modes relevant for CP violation and flavor mixing physics such as $B^0 \rightarrow \pi^+\pi^-$, $B_s \rightarrow D_s^-\pi^+ \rightarrow [\phi\pi^-]\pi^+ \rightarrow [[K^+K^-]\pi^-]\pi^+$ and large *charmed* samples as well.

DØ currently employs an impact-parameter-based trigger at Level 3 (software trigger) and is commissioning a hardware silicon-based track trigger at Level 2.

⁷⁾The intrinsic impact parameter resolution combined with the beam-width $\sigma_{beam} \simeq 30 \mu\text{m}$ determines the total impact parameter resolution: $\sigma_{SVT}(d_0) \oplus \sigma_{beam} \simeq 47 \mu\text{m}$.

Table 1: *CDF II and DØ trigger thresholds.*

	CDF ($ \eta < 1$)	DØ ($ \eta < 2$)
inclusive muon		$p_T(\mu) > 3 \text{ GeV}/c$
di-muon	$p_T(\mu) > 1.5 \text{ GeV}/c$	$p_T(\mu) > 2.0 - 4.5 \text{ GeV}/c$
e + displ. track	$p_T(e) > 4 \text{ GeV}/c$ $p_T(tr.) > 2 \text{ GeV}/c, d_0(tr.) > 120 \mu\text{m}$	
μ + displ. track	$p_T(\mu) > 1.5 \text{ GeV}/c$ $p_T(tr.) > 2 \text{ GeV}/c, d_0(tr.) > 120 \mu\text{m}$	
2 displ. tracks	$p_T(tr.) > 2 \text{ GeV}/c$ $\sum p_T(tr.) > 5.5 \text{ GeV}/c, d_0(tr.) > 100 \mu\text{m}$	

6 The Physics Program on CP Violation and Mixing

A broad range of competitive measurements on CP violation and flavor-mixing physics is accessible at the Tevatron with the statistics expected before the start-up of the Large Hadron Collider ($\mathcal{L} \approx 4 \text{ fb}^{-1}$ by the end of 2007). Measurements involving B_s mesons and b -baryons are unique to the Tevatron and play certainly a central role in the physics program of CDF II and DØ. However many measurements in the $B_{d(u)}$ (CDF II, DØ) and *charmed* (mainly CDF II) sector will be competitive with the B -factories results as well. In particular the high yields give some advantage to Tevatron experiments in *direct* CP violation measurements with self-tagging modes.

The exclusive opportunity to collect large samples of B_s mesons gives CDF II and DØ the privileged possibility to study two crucial, and still unknown, parameters of the CKM mechanism: the B_s oscillation frequency Δm_s and the Bjorken angle $\gamma = \text{Arg}[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$. The B_s oscillation frequency allows to determine the ratio $\Delta m_s/\Delta m_d$ which is proportional to the length $|\frac{V_{ts}}{V_{td}}|^2$ of one side of the main CKM unitarity triangle. On the other hand, the simultaneous study of B^0 and B_s decays into two charged hadrons ($B_{d(s)} \rightarrow h^+h'^-$, h being π or K) is a promising strategy to extract information on the γ angle avoiding the uncertainties from hadronic processes.

Many other measurements complement the above benchmark goals. Both experiments will study the V_{ts} weak phase $\beta_s = \text{Arg}[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*]$ using $B_s^0 \rightarrow J/\psi\phi$ samples. The CDF II displaced track trigger provides large hadronic samples where *direct* CP asymmetries can be searched. A few examples are the *charmed* processes $D^0 \rightarrow K^+K^-/\pi^+\pi^-$, the $B^\pm \rightarrow \phi K^\pm$ decays, the $\Lambda_b^0 \rightarrow pK^-, p\pi^-$ modes. In a longer term, CDF II plans also to extract additional information on the CKM angle γ from the $B_{d(s)} \rightarrow D_{(s)}K$ decays. In the following we review the preliminary results of some of the mentioned measurements and we discuss the future perspectives.

6.1 B_s Flavor Mixing

In the K^0 and B^0 systems, particle-antiparticle mixing has been observed and measured. In particular, B -factories experiments have significantly improved the world average of $B^0\overline{B}^0$ mixing frequency up to $\Delta m_d = 0.502 \pm 0.006 \text{ ps}^{-1}$ (in terms of a mass difference between the heavy/light eigenstates)⁶⁾. Mixing proceeds via a second-order weak transition that involves the V_{td} matrix element for $B^0\overline{B}^0$ mixing, which is replaced by V_{ts} in the $B_s\overline{B}_s$ case. Since experimentally $\Re(V_{ts}) \simeq 0.040 > \Re(V_{td}) \simeq 0.007$, we expect the B_s system oscillate at much higher frequency than the B^0 system. To date, in fact, B_s oscillations have not yet been resolved. The current combined world limit sets $\Delta m_s > 14.5 \text{ ps}^{-1}$ (at 95% CL)⁶⁾ *i.e.* a beam of B_s mesons would fully oscillate in less than $1/7^{\text{th}}$ of their lifetime. For the next several years, the Tevatron is the exclusive laboratory for B_s meson studies, including the search for B_s mixing.

CDF II and DØ will measure a differential decay rate between N_{mix} , the number of decays occurred after mixing, and N_{unmix} , those occurred without mixing. The decay asymmetry is a function of the oscillation frequency:

$$A_{mix}(t) = \frac{N_{mix}(t) - N_{unmix}(t)}{N_{mix}(t) + N_{unmix}(t)} = -\cos(\Delta m_s t) \quad (1)$$

Four ingredients are needed to measure B_s mixing:

1. **Flavor at the time of production:** it is necessary to know whether the meson was produced as a B_s or a \overline{B}_s .
2. **Flavor at the time of decay:** it is necessary to know whether the meson was a B_s or a \overline{B}_s when it decayed. This, combined with the flavor at time of production, determines whether the meson had decayed before⁸⁾ or after mixing.
3. **Proper decay time:** it is necessary to know the proper decay time for the B_s since we measure the mixing probability as a function of decay time. Oscillations in the B_s system are too fast to be resolved with time-integrated techniques.
4. **Large B_s samples:** the mixing probability should be sampled for at least part of the decay spectrum. Since fulfilling each of the previous three requirements reduces the initial available statistics, large B_s decays samples are required.

⁸⁾A meson with the same flavor at time of production as at decay could have mixed and mixed back. The time-dependent analysis can not discern “unmixed” meson from those that underwent one or more complete cycles.

6.1.1 Initial and Final-State Flavor Tagging

Two approaches are adopted for initial-state flavor tagging: the *opposite side* algorithms infer the flavor of the B_s from other information in the event, the *same side* algorithms identify the B_s flavor by looking at its own fragmentation.

If a $b\bar{b}$ pair is produced in a Tevatron event, about 11% of the time the $\bar{b}(b)$ -quark fragments into a $B_s(\bar{B}_s)$ meson that can be selected by the trigger. The remaining b -quark (which we refer to as “the *other b*”) hadronizes independently⁹ into another b -hadron. If this *other b*-hadron enters the detector acceptance, its flavor can be measured with several methods and it can be used to infer the flavor of the B_s candidate. The Soft Lepton Tagging (SLT) exploits the correlation between the charge of the lepton from the semileptonic decay of the *other b*-hadron and its flavor ($b \rightarrow l^- X$ while $\bar{b} \rightarrow l^+ X$). The Jet Charge algorithm (JeTQ) measures the momentum-weighted average charge of the *other b*-jet that is correlated with the *other b*-quark charge. The Opposite Kaon Tagging (OKT) exploits the decay chain $b \rightarrow c \rightarrow s$: the charge of the kaon suggests the flavor of the *other b* (K^- comes likely from \bar{B}^0). Such techniques suffer from the limited acceptance for the *other* hadron and are rather inaccurate. SLT tag is wrong if the lepton comes from a sequential decay $b \rightarrow c \rightarrow l^+ X$. In case that the *other b* hadron is a neutral meson, mixing can occur before its decay, producing a wrong tag.

Same Side Tagging (SST) instead looks at tracks nearby the triggered B_s meson. In particular, SST is aimed at exploiting the correlation between the B_s flavor and the charge of a near track produced in the fragmentation. For a \bar{b} quark to become a B_s meson, for instance, it must grab an s quark from the vacuum. An accompanying \bar{s} will be popped from the vacuum which could potentially fragment into a K^+ meson. Alternatively, one could exploit $B^{*++} \rightarrow B^0 \pi^+$ decays, where the pion charge determines the B^0 flavor. Again this technique is inaccurate, since the correlation could be washed out by other fragmentation tracks or the charge information could be lost into neutral particles, like K_S^0 .

The performance of initial-state flavor tagging is quoted in terms of tagging power: ϵD^2 where ϵ is the fraction of times the algorithm converged to a tagging decision, and the dilution D measures the probability of a correct tagging. The dilution is defined as: $D = (N^R - N^W)/(N^R + N^W)$ where $N^R(N^W)$ are the numbers of right (wrong) tags. Experimentally, the asymmetry of Eq. (1) is reduced by the effect of incorrect or inefficient tagging and becomes: $A_{mix}^{exp}(t) = -\sqrt{\epsilon D^2} \cos(\Delta m_s t)$.

Table 2 shows the preliminary tagging performances for CDF II and DØ. DØ tested the performances of SST, JetQ and SLT (with muons) us-

⁹Here one assumes negligible the color correlations between the products of the hard interaction.

Table 2: *CDF II and DØ Performance in Flavor Tagging*

Tagger	CDF II ϵD^2 [%]	DØ ϵD^2 [%]
Soft Muon	0.7 ± 0.1	1.6 ± 1.1
Soft Electron	in progress	in progress
Jet Charge	0.42 ± 0.02	3.3 ± 1.7
Same Side Pion	2.4 ± 1.2	5.5 ± 2.0
Same Side Kaon	in progress	-
Opposite Side Kaon	in progress	-

ing $B^+ \rightarrow J/\psi K^+ \rightarrow [\mu^+ \mu^-] K^+$ decays. CDF II used decays collected by its semi-muonic trigger to measure the SLT performance. The JetQ performance was measured in both semi-leptonic samples. $B^+ \rightarrow J/\psi K^+$ plus $B^+ \rightarrow \overline{D^0} \pi^+$ decays were used to test the Same Side pion algorithm. Although the flavor-tagging optimization is still in progress at both experiments, the high tracking acceptance and the inclusive muon trigger seem to provide DØ an advantage in SLT, JeTQ and pion tagging. However CDF II, thanks to its PID capabilities, will exploit kaon tagging.

The final-state flavor tagging is straightforward: both experiments collect B_s samples with flavor-specific final states such as: $B_s \rightarrow D_s^- \pi^+$ or $B_s \rightarrow D_s^- l^+ \nu_l$.

6.1.2 Proper Decay Time

The mixing frequency is determined by maximizing, with respect to Δm_s , a likelihood function derived from measured and expected asymmetries. The height of the maximum likelihood value, compared with the second highest peak or some asymptotic value at large Δm_s , determines the significance of a mixing observation. To a good approximation, the *average* significance is written as ⁷⁾:

$$\text{SIG}(\Delta m_s) = \sqrt{\frac{S \epsilon D^2}{2}} e^{\frac{1}{2} \cdot (\Delta m_s \cdot \sigma_{c\tau})^2} \sqrt{\frac{S}{S+B}} \quad (2)$$

where S (B) are the signal (background) events and $\sigma_{c\tau}$ is the average resolution on the measurement of the B_s proper decay length. From the exponential dependence in the above equation it is clear the critical role of $\sigma_{c\tau}$ for the oscillation measurement. Since $c\tau = L_{xy} / \beta_T \gamma = L_{xy} \cdot M_B / p_T$, with p_T (M_B) the transverse momentum (mass) of the B_s , the contributions to $\sigma_{c\tau}$ are:

$$\sigma_{c\tau} = \left(\frac{M_B}{p_T} \right) \sigma_{L_{xy}} \oplus \left(\frac{c\tau}{p_T} \right) \sigma_{p_T} \oplus \left(\frac{L_{xy}}{p_T} \right) \sigma_{M_B} \quad (3)$$

The first term $\sigma_{L_{xy}}$, given the topology and kinematics of the decay, depends upon the tracking and vertexing performance of the detector. The second term σ_{p_T} is the uncertainty in the time dilation correction. Its contribution is small for fully reconstructed decays, where the kinematics is closed and p_T is measured precisely from daughter tracks. In partially reconstructed modes (*i.e.* $B_s \rightarrow l^- \nu_l X$), the uncertainty on the B meson momentum contributes significantly ($\mathcal{O}(15\%)$) to the proper time uncertainty. The last term¹⁰ can be neglected in all cases.

CDF II estimated $\sigma_{c\tau} \simeq 67$ fs proper time resolution in a sample of fully reconstructed $B_s \rightarrow D_s^- \pi^+$ decays basing on $\sigma_{L_{xy}} \approx 50 \mu\text{m}$. $D\mathcal{O}$ performance is expected around $\sigma_{c\tau} \simeq 100$ fs (exclusive) and $\sigma_{c\tau} \simeq 150$ fs (semileptonic).

6.1.3 B_s Mixing Samples: Semileptonic Decays

If the true value of Δm_s is close to the current limit ($\Delta m_s \sim 14 - 18 \text{ ps}^{-1}$), semileptonic modes will contribute to the mixing measurement, since the large event yields somewhat offset the poor proper time resolution. Otherwise, if $\Delta m_s > 20 \text{ ps}^{-1}$, $\sigma_{c\tau}$ becomes the limiting factor and semileptonic modes will help mainly for flavor-tagging calibration.

The *left* plot in Figure 1 shows the $KK\pi$ invariant mass from $B_s \rightarrow D_s^- \mu^+ X \rightarrow [\phi\pi^-] \mu^+ X \rightarrow [[K^+ K^-] \pi^-] \mu^+ X$ decays collected by $D\mathcal{O}$. The two peaks correspond to the D^- and D_s^- states, which can both decay to $\phi\pi^-$. The *right* plot in Figure 1 shows the same distribution from CDF II. $D\mathcal{O}$ triggers only on muons and has a specific yield of ~ 38 pb. Even though CDF II triggers on muons and electrons, its specific yield is ~ 5 times smaller. Such a large difference comes from the larger $D\mathcal{O}$ acceptance, however CDF II samples are cleaner (by requiring also a displaced track) with better (a factor of ~ 2) mass resolution.

6.1.4 B_s Mixing Samples: Exclusive Decays

Fully reconstructed modes offer fewer signal events with better proper time resolution and are considered the only useful ones at high values of Δm_s . The CDF II displaced track trigger has accumulated a sample of exclusive $B_s \rightarrow D_s^- \pi^+ \rightarrow [\phi\pi^-] \pi^+ \rightarrow [[K^+ K^-] \pi^-] \pi^+$ as shown in the *left* plot in Figure 2. A clear B_s peak is visible with good purity (S/B ~ 2), the broad shoulder at lower masses is the $B_s \rightarrow D_s^{*-} \pi^+$, where the photon from the D_s^* decay is not reconstructed. The *right* plot shows the expected contributions from a $b\bar{b}$ Monte Carlo simulation. Since the simulation provides a very good description of the sample, signal and sidebands in data are fit using the shapes from the Monte Carlo with floating normalizations. As a result, CDF II performed the

¹⁰ σ_{M_B} is very small compared to other uncertainties.

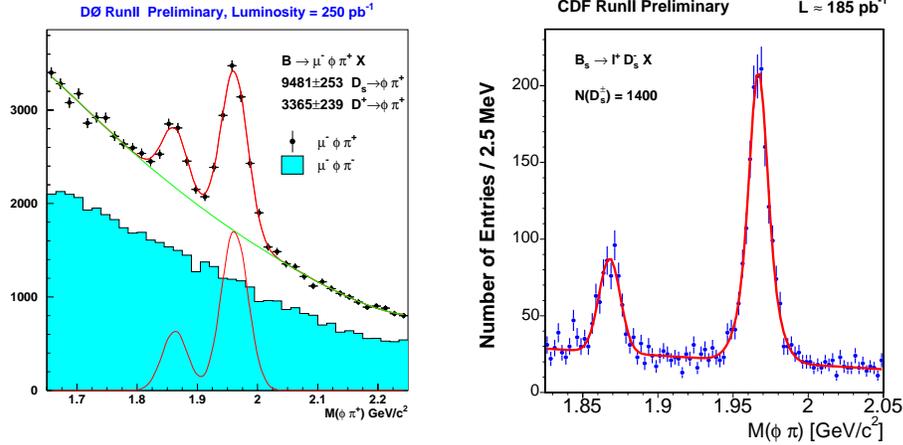


Figure 1: *Left: $KK\pi$ invariant mass from $B_s \rightarrow D_s^- \mu^+ X \rightarrow [\phi \pi^-] \mu^+ X \rightarrow [[K^+ K^-] \pi^-] \mu^+ X$ reconstructed by $D\bar{O}$. Right: $KK\pi$ invariant mass in the same mode reconstructed by CDF II using also electrons.*

first measurement of the branching ratio for this mode:

$$\frac{f_s}{f_d} \cdot \frac{BR(B_s \rightarrow D_s^- \pi^+)}{BR(B^0 \rightarrow D^- \pi^+)} = 0.35 \pm 0.05 \text{ (stat.)} \pm 0.04 \text{ (syst.)} \pm 0.09 \text{ (BR)} \quad (4)$$

where f_s and f_d are the fragmentation functions, and the systematic error deriving from the uncertainty on $BR(D_s^- \rightarrow \phi \pi^-)$ is quoted separately. The result is quoted as a ratio of BRs ' in order to cancel out many common systematics in trigger and reconstruction efficiencies.

6.1.5 B_s Mixing: Prospects

In terms of B_s mixing performance, $D\bar{O}$ takes advantages from the very high semileptonic yields and a total higher tagging power. CDF II has, instead, cleaner samples, better mass resolution and privileged access to larger samples of exclusive decays with better proper time resolution. CDF II and $D\bar{O}$ will extend the search for B_s mixing, however this measurement is very challenging and will take time, effort and a significant data sample.

Assuming the current performance in terms of yield, purity, proper time resolution and flavor tagging, CDF II estimates a 2σ sensitivity for $\Delta m_s = 15 \text{ ps}^{-1}$ with about 500 pb^{-1} of integrated luminosity (year 2005) in the exclusive modes. However, some improvements to the current running configuration are in progress. Additional modes both for the D_s ($D_s^- \rightarrow K^* K^-, K_S^0 K^-$) and

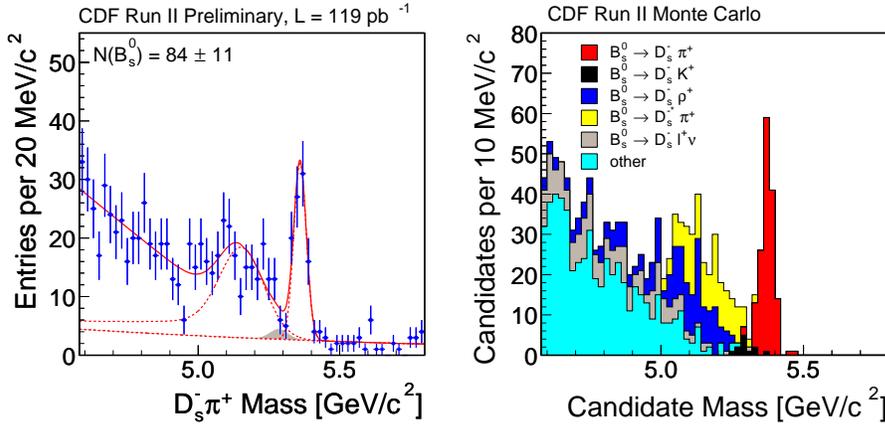


Figure 2: *Left: $KK\pi\pi$ invariant mass from $B_s^0 \rightarrow D_s^- \pi^+$ decays at CDF II. Right: same distribution from Monte Carlo simulation.*

for the B_s ($B_s \rightarrow D_s^- \pi^+ \pi^- \pi^+$) will increase B_s yields by $\sim 20\%$. The proper time resolution is expected to improve soon to $\sigma_{c\tau} \simeq 50$ fs after exploiting the very first silicon layer (1.6 cm from the beam) and an optimized calculation of the beam spot position. After optimization of all flavor tagging algorithms, CDF II expects to reach $\epsilon D^2 = 5\%$ in flavor tagging performance. With these modest improvements, 2 to 3 fb^{-1} of integrated luminosity would be needed for CDF II to scan the region of Δm_s currently preferred by indirect fits ⁸⁾.

DØ instead exploits its large semileptonic yields ($\sim 30\text{K}/\text{fb}^{-1}$ expected) and impressive flavor tagging performance (expected $\epsilon D^2 \simeq 10\%$) and estimates to reach a 1.5σ sensitivity for $\Delta m_s = 15 \text{ ps}^{-1}$ with 500 pb^{-1} .

6.1.6 CDF Run I: Average Time-Integrated Mixing Probability

CDF measured recently the average time-integrated mixing probability on the full Run I data sample ⁹⁾. The ratio $R = LS/OS$ of like-sign (LS) to opposite-sign (OS) di-leptons was measured in $\mathcal{L} \simeq 110 \text{ pb}^{-1}$ of double semileptonic decays of $b\bar{b}$ pairs. A two-dimensional fit of the lepton impact parameters in $e\mu$ and $\mu\mu$ samples selects leptons from b decays. R is related to the average time-integrated mixing parameter:

$$\bar{\chi} = \frac{\Gamma(B_{d,s} \rightarrow \bar{B}_{d,s} \rightarrow l^+ X)}{\Gamma(b \rightarrow l^\pm X)} = f'_d \chi_d + f'_s \chi_s \quad (5)$$

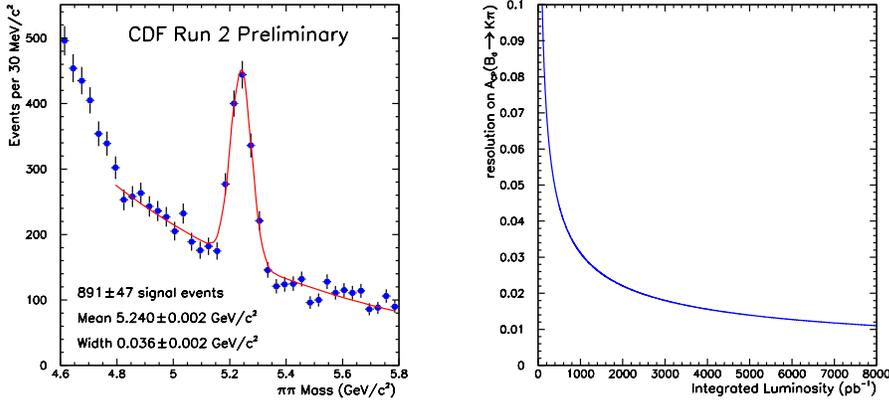


Figure 3: *Left: $\pi\pi$ invariant mass spectrum of $B_{d(s)} \rightarrow h^+h'^-$ candidates. Right: expected statistical resolution versus luminosity for the direct CP asymmetry measurement in $B^0 \rightarrow K^+\pi^-$ at CDF II.*

where the denominator is the semileptonic width of all b -hadrons and f'_d (f'_s) are the fragmentation functions f_s (f_d) weighted with the corresponding semileptonic branching ratio¹¹. $\bar{\chi}$ is a probe for either flavor mixing or B meson fragmentation. The CDF result is: $\bar{\chi} = 0.152 \pm 0.007$ (*stat.*) ± 0.011 (*syst.*). This value is higher than the current world average¹⁰, $\bar{\chi}_{PDG} = 0.118 \pm 0.005$, that is dominated by the measurements at the Z^0 pole.

6.2 CP Violation in $B_{d(s)} \rightarrow h^+h'^-$ Decays

Using the new trigger on displaced tracks, CDF II has collected several hundred events of charmless B^0 and B_s decays in two tracks from $\mathcal{L} \simeq 180 \text{ pb}^{-1}$ integrated luminosity. The invariant mass spectrum of the $B_{d(s)} \rightarrow h^+h'^-$ candidates with pion mass assignment for both tracks is shown in the *left* plot in Fig. 3. A clear peak is seen, and its width ($\sigma \simeq 36 \text{ MeV}/c^2$) is significantly larger than the intrinsic CDF II resolution. This happens because (at least) four different channels overlap under the peak: $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow K^+\pi^-$, $B_s \rightarrow K^+K^-$, $B_s \rightarrow \pi^+K^-$. One of the key physics goals of CDF II is to measure time-dependent decay CP asymmetries in flavor-tagged samples of $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decays. This method was first suggested by

¹¹ $f'_q = f_q / (\Gamma_q \tau_b)$ ($q = s, d$) where Γ_q is the semileptonic width of the B_q meson and τ_b is the average b -hadron lifetime.

Fleischer¹¹⁾ and consists of fitting simultaneously the four CP asymmetries $A_{\text{CP}}^{\text{dir}-\pi\pi}$, $A_{\text{CP}}^{\text{mix}-\pi\pi}$, $A_{\text{CP}}^{\text{dir}-KK}$ and $A_{\text{CP}}^{\text{mix}-KK}$ with:

$$A_{\text{CP}}^{B^0}(t) = A_{\text{CP}}^{\text{dir}-\pi\pi} \cos(\Delta m_d t) + A_{\text{CP}}^{\text{mix}-\pi\pi} \sin(\Delta m_d t) \quad (6)$$

$$A_{\text{CP}}^{B_s}(t) = A_{\text{CP}}^{\text{dir}-KK} \cos(\Delta m_s t) + A_{\text{CP}}^{\text{mix}-KK} \sin(\Delta m_s t) \quad (7)$$

Theoretically, one assumes U-spin symmetry¹² and combines the $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ modes to cancel out the uncertainties coming from hadronic *penguin*¹³ diagrams. This method would allow a reasonably clean determination of the CKM angle γ . First step toward the time-dependent analysis is to disentangle the different contributions to the $B_{d(s)} \rightarrow h^+h'^-$ signal shown in the *left* plot in Fig. 3. Since the TOF K/π separation is marginal in this momentum regime ($p(h) > 2 \text{ GeV}/c$) and the dE/dx separation-power is limited to 1.4σ , an event-by-event separation looks very difficult. Therefore CDF II exploits the statistical separation provided by the combination of kinematics differences between the contributing modes with the PID from dE/dx . An un-binned maximum likelihood fit is performed relying on two discriminating variables. The first one is the dE/dx information calibrated on charged K and π from D^0 in about 300,000 D^{*+} decays¹⁴. The other variable is the kinematic-charge correlation between the invariant mass (with pion assignment) $M_{\pi\pi}$, and the signed momentum imbalance between the two tracks. This quantity is written as $(1 - p_{\text{min}}/p_{\text{max}}) \cdot q_{\text{min}}$ where $p_{\text{min}}(p_{\text{max}})$ is the scalar momentum of the track with the smaller (larger) momentum and q_{min} is the charge of the track with smaller momentum. The distribution from a Monte Carlo simulation of $M_{\pi\pi}$ versus $(1 - p_{\text{min}}/p_{\text{max}}) \cdot q_{\text{min}}$ is shown in Fig. 4. The plots show how the kinematic-charge correlation distinguishes also $K^+\pi^-$ from $K^-\pi^+$ final states providing *direct* CP asymmetry information.

The results from a subsample (65 pb^{-1}) of the events shown in the *left* plot in Fig. 3 are summarized in the second column of Table 3. The measurement presented here is the first observation of the decay $B_s \rightarrow K^+K^-$ with a relative branching fraction of:

$$\frac{BR(B_s \rightarrow K^+K^-)}{BR(B^0 \rightarrow \pi^-K^+)} = 2.71 \pm 0.73 \text{ (stat.)} \pm 0.35 \text{ (}f_s/f_d\text{)} \pm 0.81 \text{ (syst.)} \quad (8)$$

¹²The U-spin symmetry is a subgroup of flavor SU(3) that transforms the d quark into an s quark transforming thus $B^0 \rightarrow \pi^+\pi^-$ into $B_s \rightarrow K^+K^-$.

¹³ $B^0 \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ decay amplitudes receive significant contribution from second-order non-perturbative hadronic diagrams (*i.e.* penguin diagrams). Since they carry weak phases which differ from those of tree-level diagrams, the extraction of CKM parameters from CP asymmetries becomes more complicated.

¹⁴See Section 6.3.1 for the motivation for using $D^{*\pm}$.

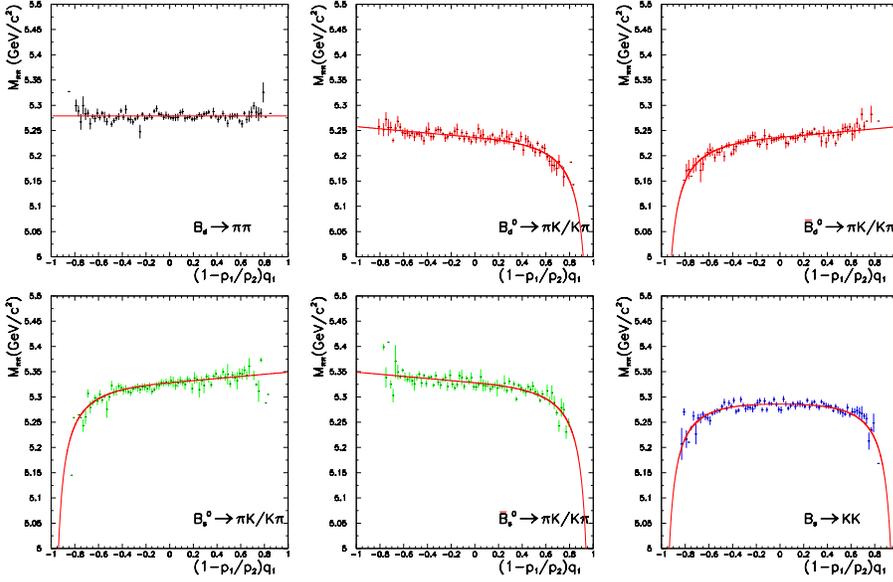


Figure 4: Monte Carlo distributions of the averaged $M_{\pi\pi}$ versus $(1 - p_{min}/p_{max}) \cdot q_{min}$ for each channel. Colored dots are Monte Carlo data, solid red lines are the analytic functions used in the likelihood.

using the world average measurement of the fragmentation fraction $f_s/f_d = 0.27 \pm 0.04$ ¹⁰). The measured *direct* CP asymmetry in the $B^0 \rightarrow \pi^- K^+$ mode is:

$$\frac{N(\bar{B}^0 \rightarrow K^- \pi^+) - N(B^0 \rightarrow \pi^- K^+)}{N(\bar{B}^0 \rightarrow K^- \pi^+) + N(B^0 \rightarrow \pi^- K^+)} = 0.02 \pm 0.15 \text{ (stat.)} \pm 0.02 \text{ (syst.)} \quad (9)$$

Systematic uncertainties in all these results are dominated by the, still preliminary, dE/dx calibrations used. The systematic error on the *direct* CP asymmetry is already comparable to systematics in current B -factories measurements⁶) (Belle: $A_{\text{CP}}^{\text{dir}}(B^0 \rightarrow \pi^- K^+) = -0.088 \pm 0.035 \text{ (stat.)} \pm 0.018 \text{ (syst.)}$). The 15% statistical error of $A_{\text{CP}}^{\text{dir}}(B^0 \rightarrow \pi^- K^+)$ is a promising achievement considering that is obtained in a sample of only 65 pb^{-1} (the current CDF II sample is already three times larger).

The yield projections¹⁵ for $\mathcal{L} = 3.5 \text{ fb}^{-1}$ are summarized in the third column

¹⁵Since the CDF II result is not yet sensitive to the $B_s \rightarrow K^- \pi^+$, the projection for this mode comes from theoretical prediction of the branching fraction.

Table 3: *CDF II results on two-body charmless B decays in 65 pb⁻¹ (second column), projected yields for 3.5 fb⁻¹ (third column).*

Mode	Fitted Yield [events]	Projected Yield/3.5 fb ⁻¹ [evts.]
$B^0 \rightarrow K^+ \pi^-$	148 ± 17 (<i>stat.</i>) ± 17 (<i>syst.</i>)	$\sim 11,700$
$B^0 \rightarrow \pi^+ \pi^-$	39 ± 14 (<i>stat.</i>) ± 17 (<i>syst.</i>)	$\sim 3,100$
$B_s \rightarrow K^+ K^-$	90 ± 17 (<i>stat.</i>) ± 17 (<i>syst.</i>)	$\sim 7,100$
$B_s \rightarrow \pi^+ K^-$	3 ± 11 (<i>stat.</i>) ± 17 (<i>syst.</i>)	$\sim 1,900$

of Tab. 3. The *right* plot in Fig. 3 shows the expected resolution on the *direct* CP asymmetry in the $B^0 \rightarrow \pi^- K^+$ mode basing on the foreseen yields: CDF II will be competitive with current *B*-factories results with less than 1 fb⁻¹ of data. A projection for the time-dependent analysis performed on flavor-tagged samples needs some ingredients that are still being optimized such as the flavor-tagging performance and the proper-time resolution. CDF II estimates that data in excess of 4 fb⁻¹ integrated luminosity are needed to reach $\mathcal{O}(20\%)$ uncertainties. However, an intermediate goal could be to extract information on γ using just the measurements of branching ratios together with some minimal dynamic assumptions, as suggested in ¹²).

6.3 CP Violation in Other Modes

6.3.1 CP Violation with Charm: $D^0 \rightarrow h^+ h'^-$ Decays

The new CDF II trigger on displaced tracks is highly effective in collecting large samples of *charmed* decays. Specific yields in excess of 2 nb were measured for $D^{*+} \rightarrow D^0 \pi^+ \rightarrow [K^- \pi^+] \pi^+$ modes and allowed the best measurement of the *direct* CP violating decay rate asymmetry of $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ to date. Since Standard Model (SM) expectations for *direct* CP violation in such modes are generally small, $\mathcal{O}(10^{-3})$, non-SM CP violation sources could appear if anomalously high asymmetries would be measured. CDF II uses D^0 from D^* decays because (1) the charge of the soft pion from the D^* identifies uniquely the D^0 flavor, (2) a tight cut on $M(D^*) - M(D^0)$ reduces strongly the reflection background. An invariant mass fit in 123 pb⁻¹ of data reconstructs about 7,300 $D^0 \rightarrow \pi^+ \pi^-$ with $\sim 93\%$ purity, and about 16,200 $D^0 \rightarrow K^+ K^-$ with $\sim 75\%$ purity¹⁶. No significant *direct* CP violation in Cabibbo-suppressed D^0 decays is found:

$$A_{\text{CP}}^{\text{dir}}(D^0 \rightarrow K^+ K^-) = [2.0 \pm 1.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)}] \% \quad (10)$$

¹⁶The higher background contamination comes from partially reconstructed $D^0 \rightarrow K^- \pi^+ \pi^0$.

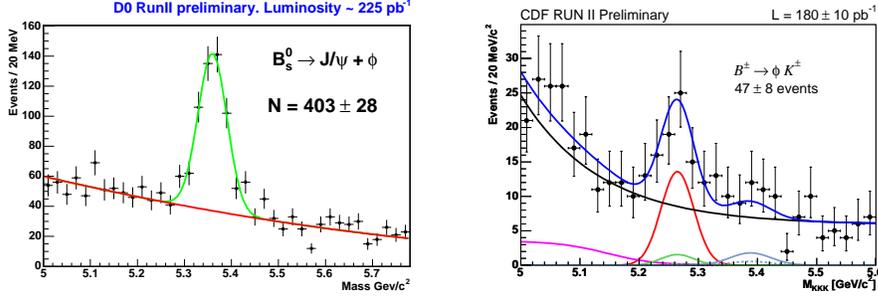


Figure 5: Left: $KK\mu\mu$ invariant mass in $B_s^0 \rightarrow J/\psi\phi$ decays from $D\bar{O}$. Right: KKK invariant mass in $B^+ \rightarrow \phi K^+$ from CDF II.

$$A_{\text{CP}}^{\text{dir}}(D^0 \rightarrow \pi^+ \pi^-) = [1.0 \pm 1.3 (\text{stat.}) \pm 0.6 (\text{syst.})]\% \quad (11)$$

The statistics on the control sample, used to measure residual effects on the intrinsic detector charge asymmetry, dominates the systematics uncertainty.

6.3.2 CP Studies with $B_s^0 \rightarrow J/\psi\phi$ Decays

$B_s \rightarrow J/\psi\phi$ decays will be used to measure the relative lifetime difference $\Delta\Gamma_s/\Gamma_s$ between the two B_s CP eigenstates. Since SM predicts the ratio $\Delta\Gamma_s/\Delta m_s = \mathcal{O}(10^{-3})$, $\Delta\Gamma_s/\Gamma_s$ could be a complementary method for discovering B_s oscillations with large Δm_s values. In addition, once B_s oscillations will be established, the time dependent decay CP asymmetry will provide information about the V_{ts} weak phase β_s . This number is expected small in the SM, so a significantly large asymmetry would hint at New Physics. However, since the final states have two vector mesons, the $B_s^0 \rightarrow J/\psi\phi$ CP-parity depends on their relative angular momentum. Angular analysis is required to separate CP-even from CP-odd decays. Thanks to the di-muon trigger both CDF II and $D\bar{O}$ reconstruct the exclusive mode $B_s^0 \rightarrow J/\psi\phi \rightarrow [\mu^+ \mu^-][K^+ K^-]$. The left plot in Figure 5 shows the $D\bar{O}$ invariant mass plot with 403 ± 28 candidates in $\sim 225 \text{ pb}^{-1}$ of data. $D\bar{O}$ takes advantages of a better muon coverage achieving a larger yield than CDF II (120 ± 13 in about 140 pb^{-1}) although CDF II has higher mass resolution.

6.3.3 Other Direct CP Asymmetries

Samples with flavor-specific final states are used in searches for *direct* CP violation. Several classes of decays are of particular interest. Various $B_{d(u)} \rightarrow \phi X$ decays ($B^+ \rightarrow \phi K^+$, $B^0 \rightarrow \phi K^{*0}$ and $B^+ \rightarrow \phi K^{*+}$) are intriguing because of an apparent $\sim 3.5\sigma$ disagreement between the measurements of $\sin(2\beta)$ in

$B^0 \rightarrow \phi K_s^0$ and $B^0 \rightarrow J/\psi K_s^0$ ¹³). Both CDF II and DØ will be able to reconstruct the above decay modes.

CDF II has reconstructed 47 ± 8 of the *penguin*-dominated $B^+ \rightarrow \phi K^+$ decay in $\sim 180 \text{ pb}^{-1}$ of data (see *right* plot in Figure 5). Using a multi-dimensional likelihood fit that includes invariant mass, ϕ helicity and dE/dx information, CDF II measured the *direct* CP asymmetry in this sample. The SM expectations prescribe zero asymmetry in this channel. The CDF II result is:

$$A_{\text{CP}}^{\text{dir}}(B^+ \rightarrow \phi K^+) = -0.07 \pm 0.17 \text{ (stat.)}_{-0.05}^{+0.06} \text{ (syst.)} \quad (12)$$

This result is already competitive with the current best measurements from B -factories ¹⁴) (see Babar: $A_{\text{CP}}^{\text{dir}}(B^+ \rightarrow \phi K^+) = 0.04 \pm 0.09 \text{ (stat.)} \pm 0.01 \text{ (syst.)}$ for example) despite it was obtained using only 180 pb^{-1} of data. This remarkable achievement is promising and will be improved soon as the statistic increases.

6.3.4 CP Studies with $B_{d(s)} \rightarrow D_{(s)}K$ Decays

Several methods to use $B_{d(s)} \rightarrow D_{(s)}K$ decays for a theoretically clean determination of the CKM angle γ were proposed (see ¹⁵) for example). However these modes need strong particle identification capabilities to identify the small ($\sim 8\%$) contribution of the Cabibbo-suppressed $D_{(s)}K$ final state among the favored $D_{(s)}\pi$. CDF II, thanks to the displaced track trigger, has already reconstructed $B^+ \rightarrow \overline{D}^0 \pi^+$, $B^0 \rightarrow \overline{D}^{(*)-} \pi^+$ and $B_s \rightarrow D_s^- \pi^+$ (shown in the *left* plot in Fig. 2) with fairly good purity. Based on current yields, CDF II expects to collect $\sim 2200 B^+ \rightarrow \overline{D}^0 K^+$ and more than 100 $B_s \rightarrow D_s K^+$ per fb^{-1} of integrated luminosity. The extraction of information on γ is a long term and challenging task that will require a considerable fraction of the expected Run II statistics and fine-tuned particle identification tools.

7 Summary

In the next few years CDF II and DØ will play a key role in CP studies using *charmed* and *beauty* decays. The broad physics program includes both measurements competitive with B -factories and measurements accessible only to the Tevatron such as B_s mixing and b -baryons studies.

The understanding of low-level tools such as tracking and dE/dx is excellent in both experiments. CDF II focused so far on the measurement of *direct* CP asymmetries in self-tagging modes where world-class results have already been achieved. The state of the tools for second generation analyses is advanced and lead already to good performances on flavor-tagging and proper

time resolutions. Both experiments are expected to provide significant contributions in the determination of the mixing parameter Δm_s . DØ will exploit its higher flavor-tagging power and large semileptonic yields. CDF II has larger yields and better time resolution in the exclusive B_s modes. Information on the angle γ will be extracted at CDF II from $B_{d(s)} \rightarrow h^+ h'^-$ decays collected, for the first time in a hadronic collider, by the trigger on displaced tracks.

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