Recent studies of CP violation at the Tevatron

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Abstract. In this paper the most recent Tevatron results concerning CP violation are reviewed. These are the measurements of direct CP asymmetry in the charmless two-body decays of $B^0$, $B^0_s$, and $\Lambda_b$ (performed by CDF), CP asymmetry in $B^+ \rightarrow J/\psi K^+$ (performed by D0), the flavor-tagged measurement of $B^0_s$ semileptonic asymmetry, $a_{1l}$ and the measurement of $b_s$ in the decay $B^0_s \rightarrow J/\psi p\bar{p}$ (performed by CDF and D0).

1. Introduction

One of the challenges for elementary particle physics is to trace all possible sources of the violation of CP symmetry. In the standard model (SM), CP violation is associated with a single irreducible phase in the CKM matrix [1,2] which arises from the charged W transition. Although the standard model picture of CP violation has so far been confirmed by all laboratory measurements, the level of CP violation in the standard model is not sufficient to produce the observed baryon number density in the universe. To search for sources of CP violation beyond the standard model, one can exploit a handful of systems in which the standard model makes a precise prediction of CP violation. Therefore, 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.

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. With the statistics expected before the start-up of the Large Hadron Collider (6 fb$^{-1}$ by the end of 2009, 8 fb$^{-1}$ by the end of 2010) the Fermilab $b$-physics program allows for a wide range of CP violation measurements that are competitive (direct asymmetries in self-tagging modes) or complementary (asymmetries of $B_s$ and $b$-baryons decays) with $B$-factories. We summarize here some of the recent experimental progress in the measurements related to CP violation from the D0 and CDF Collaborations and we discuss the prospects for future upgrades. Precise microvertex detectors and online triggering of tracks from long-lived particles are good examples of the experimental techniques that make all these results possible.

2. The CDF and D0 detectors

The CDF and D0 detectors are large multipurpose solenoidal magnetic spectrometers surrounded by 4\pi calorimetry and muon filters. They are axially and azimuthally symmetric around the interaction point and their strengths are somewhat complementary to one another. D0 has an excellent tracking acceptance and very good $e$ and $\mu$ identification performance. CDF 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].
2.1 D0
The D0 detector consists of a magnetic central-tracking system, comprised of a silicon microstrip tracker and a central fiber tracker, both located within a 2 T superconducting magnet (with weekly reversed polarity). The fiber tracker covers the region $|\eta| < 1.7$, the silicon detector 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 muon system covers $|\eta| < 2$ for muons with $p_t > 2 - 4.5$ GeV/c.

2.2 CDF
The elements of the CDF detector most relevant for B physics analysis are the tracker, the particle identification detectors and the muon system. The CDF tracker is located within a 14.1 kG solenoidal magnetic field and it is composed of silicon detectors [5] surrounded by a drift chamber, COT [6]. The achieved performance of the integrated CDF tracker is a transverse momentum resolution $\sigma(p_t)/p_t = 0.15\%$ (GeV/c)$^{-1}$ and an impact parameter resolution $\sigma(d) = 35 \mu m$ @ 2 GeV/c.

CDF uses two complementary techniques for particle identification, one is the dE/dx measurement in the COT, the other one is the time-of-flight measurement in a dedicated detector, TOF [7]. The CDF central muon detector [8] is located around the outside of the central calorimeter, which is 5.5 interaction lengths thick, at a radius of 347 cm from the beam axis. The pseudorapidity coverage of the muon detector is $|\eta| < 1$.

3. The CDF and D0 Triggers
The trigger system is probably the single most important ingredient to pursue an effective $b$ physics program at the Tevatron. Both CDF and D0 have a multi-stage trigger organized in three levels. Both experiments trigger on final states containing single or di-leptons to select high statistics samples of $b$-hadron decays. Semileptonic $B \rightarrow l\nu X$ plus charmonium $B \rightarrow J/\psi X \rightarrow [h^{-}]X$ decays are of the order of 20% of the $B$ meson widths. In addition CDF has a special trigger (hadronic trigger) to select events based upon track impact parameter (the minimum distance between the track and the beam), called SVT [9]. It is basically a trigger on events containing tracks originated in a vertex displaced from the primary. These events are enriched of heavy flavor contents, thanks to the higher mean-valued lifetimes of $b$-hadrons.

4. The Physics Program on CP Violation
Many measurements form the broad physics program of CDF and D0. Both experiments study the $V_{ub}$ weak phase $\beta_u = \text{Arg}[V_{ub}V_{ub}^*/V_{cb}V_{cb}^*]$ using $B^0_d \rightarrow J/\psi \phi$ samples. The CDF displaced track trigger provides large hadronic samples where direct CP asymmetries can be measured. A few examples are the processes $B^0 \rightarrow K \pi^-$ and the $\Lambda_c \rightarrow p \pi^-$, $pK^-$ modes. In the following, we review the results of the mentioned measurements together with the flavor-tagged measurement of $B^0_s$ semileptonic asymmetry, $a'_s$. Finally, we discuss the future perspectives for $b_s$.

4.1. CP Violation in $B^0_d \rightarrow h^- h^+ X$ decays [10]
CP violation in $B^0 \rightarrow h^- h^+$ decays like $B^0 \rightarrow K \pi^-$ and $\Lambda_c \rightarrow pK^-$ are interesting cases of large direct CP violation predicted under the standard model, which happens when at least two CP-conserving phases and two CP-violating phases participate in a decay. This is the case for charmless two-body B decays (like $B^0 \rightarrow K \pi^+$ ) which proceed through tree diagrams and higher-order (penguin) diagrams. CDF reported the first evidence of the decay and measurement of the direct CP asymmetry in the $B^0 \rightarrow K \pi^+$ and $\Lambda_c \rightarrow pK^-$ decays reconstructed in the data taken by the hadronic trigger (1 fb$^{-1}$).
The invariant mass spectrum of the \(B^0 \rightarrow h^- h^+\) candidates with pion mass assignment for both tracks is shown in Fig. 1 after the selection and optimization procedure. In spite of a good mass resolution (~22 MeV/c²), the various \(B^0 \rightarrow h^- h^+\) modes overlap into an unresolved mass peak. The resolution in invariant mass and in particle identification is not sufficient for separating the individual decay modes on an event by event basis, therefore an unbinned maximum likelihood fit was performed, combining kinematic and particle identification information, to statistically determine both the contribution of each mode, and the relative contributions to the CP asymmetries.

In addition to the improved measurement of branching fractions of the already known modes (\(B^0 \rightarrow \pi^- \pi^+, B^0 \rightarrow K^- \pi^+\) and \(B^0_s \rightarrow K^- \pi^+\) and of the direct CP asymmetry \(A_{CP}(B^0 \rightarrow K^- \pi^+)\), the analysis observes three new rare modes for the first time (\(B^0 \rightarrow h^- h^+\)) candidates passing all selection requirements. The total projection and projections of each signal and background component of the likelihood fit are overlaid on the data distribution. Signals and multi-body \(B\) background components are shown stacked on the combinatorial background component.

The measured CP asymmetry \(A_{CP}(\Lambda_c \rightarrow pK^-) = 0.37 \pm 0.17 \pm 0.03\) is 2.1\(\sigma\) from SM expectation (but still consistent with SM). The measured CP asymmetry \(A_{CP}(\Lambda_c \rightarrow \pi^- \pi^+) = 0.03 \pm 0.17 \pm 0.05\).
4.2. Measurement of direct CP violation in the $B^+ \to J/\psi K^*(\pi^*)$ decays [12]

D0 presents a study of the charge asymmetry in the decay $B^+ \to J/\psi K^*(\pi^*)$. A nonzero value corresponds to direct CP violation in this decay. In the $b \to s cc\bar{b}$ transition, the tree-level and $b \to s$ penguin amplitudes have a small relative weak phase, $\text{Arg}[V_{ts}^* V_{tb}/V_{ub}^* V_{ub}]$. Therefore, the SM predicts a small $A_{CP}(B^+ \to J/\psi K^*) \sim 0.003$ [13]. Thus, the measurement of $A_{CP}(B^+ \to J/\psi K^*)$ is an important way of constraining those new physics models which predict an enhanced value of this asymmetry [13–15].

The invariant mass distribution of the $J/\psi K$ system is shown in Fig. 2 with the result of an unbinned likelihood fit to the sum of contributions from $B^+ \to J/\psi \pi^+$, $B^+ \to J/\psi K^0$ and $B^0 \to J/\psi K^{*0}$ decays, as well as combinatorial background. Around 40000 (1500) $B^+ \to J/\psi K^+$ ($B^0 \to J/\psi K^*$) events are found.

![Figure 2. Result of the unbinned fit of the invariant mass distribution of the $J/\psi K$ system.](image)

To measure the charge asymmetry between the $J/\psi K^+(\pi^+)$ and $J/\psi K^+(\pi^*)$ final states, both physics and detector effects contributing to the possible imbalance of events with positive and negative kaons are taken into account. The main effort was driven to understand the charge asymmetry produced by the difference in the interaction cross section of $K^+$ and $K^-$ with the detector material. The kaon asymmetry is measured directly in data by comparing the exclusive decay $c \to D^* \to D^+ \pi^+$, $D^0 \to \mu^+\nu\bar{\nu}K^-$ and its charge conjugate.

The direct CP-violating asymmetry in the $B^+ \to J/\psi K^+$ decay is measured to be 

$$ A_{CP}(B^+ \to J/\psi K^+) = 0.0075 \pm 0.0061 \pm 0.0030, $$

which is consistent with zero. The world average is $+0.015 \pm 0.017$. This measurement provides the most stringent bounds for new models predicting large values of $A_{CP}(B^+ \to J/\psi K^+)$. The direct CP-violating asymmetry in the $J/\psi \pi^+$ decay is measured to be 

$$ A_{CP}(B^+ \to J/\psi \pi^+) = -0.09 \pm 0.08 \pm 0.03. $$

4.3. Flavor-tagged measurement of $B^0_s$, semileptonic asymmetry, $a_{\mu}^B$[16]

When dealing with a measurement of CP violation in the $B^0_s$, $\bar{b}$ system, the analysis of semileptonic decays, compared to the “golden mode” $B^0 \to J/\psi \phi$, does not involve an angular analysis and is largely independent of the sample composition. Therefore it provides an important contribution to CP violation measurements. D0 has performed a search for CP violation in semileptonic $B^0_s$ decays with a sample corresponding to approximately 2.8 fb$^{-1}$ of integrated luminosity. The flavor of the initial state of the $B^0_s$ meson was determined using the muon charge from the partially reconstructed decay $B^0_s \to D_s^+ \mu^+\nu\bar{\nu}X$, $D_s^- \to \phi\pi\pi^+$, $\phi \to K^0K^*$. The most powerful measurements of CP-violating phases generally involve the use of flavor-tagging, which determines the flavor of the $B$ hadron at production. This task is straightforward for charged particles like the $B_s$, which are self-tagging, but is much more
difficult for neutral mesons, such as the \( B^0_s \). Powerful flavor tags include same-side kaon tags and opposite-side lepton and jet-charge tags. The time-dependent fit to the distributions of \( B^0_s \) candidates yields the CP violation parameter \( \alpha_s = -0.0024 \pm 0.0117 \times 0.0015 -0.0024 \). This is the most precise direct measurement of this asymmetry to date. It can be combined with the result of the inclusive di-muon analysis [17] because the overlap between these samples is small. As the result is statistics limited, an improved measurement will be available as D0 collects additional data.

4.4. CP violation in \( B^0_s \rightarrow J/\psi \phi \) decays

The non-leptonic decays of B mesons are effective probes of CKM matrix and sensitive to potential new physics effects: in the SM, the flavor eigenstates of the \( B^0_s \) system (\( B^0_s \) and \( B^0_s \bar{b} \)) are expected to mix in such a way that the mass and decay width differences between the light (L) and heavy (H) mass eigenstates of the \( B^0_s \) system, \( \Delta m_s \) and \( \Delta \Gamma = \Gamma_L - \Gamma_H = (\Gamma_{\text{even}} - \Gamma_{\text{odd}}) \cos \phi_s \), are sizeable. \( \phi_s \) is the phase \( \text{arg}(-M_2/T_{12}) \), which accounts for CP violation in the mixing (being \( M_2/T_{12} \) the off diagonal elements of the hamiltonian describing the oscillations from particle to antiparticle due to flavor-changing weak interactions). The CP-violating phase \( \phi_s^{\text{SM}} \) is within the SM predicted to be small [18], and thus to a good approximation the two mass eigenstates are expected to be CP eigenstates. New phenomena may introduce a non-vanishing mixing phase \( \phi_s^{\text{NP}} \), leading to a reduction of the observed \( \Delta \Gamma \) compared to the SM prediction: \( \Delta \Gamma = \Delta \Gamma^{\text{SM}} \times |\cos(\phi_s^{\text{SM}} + \phi_s^{\text{NP}})| \) [18].

CP violation in the \( B^0_s \rightarrow J/\psi \phi \) decays occurs through the interference between the decay amplitudes with and without mixing. The relative phase between the decay amplitudes with and without mixing is \( \beta_s^{\text{SM}} = \text{Arg}[-V_{sL}V_{sL}^*/V_{sL}V_{sL}^*] \) and it is expected to be very small [19]. Phenomena beyond the standard model model may alter the mixing phase by a quantity \( \phi_s^{\text{NP}} \) leading to an observed mixing phase \( 2\beta_s^{J/\psi \phi} = 2\beta_s^{\text{SM}} - \phi_s^{\text{NP}} \). Large values of the observed \( 2\beta_s^{J/\psi \phi} \) would be an indication of physics beyond the SM [18]. Assuming that new physics effects dominate over the SM phase, we can approximate \( 2\beta_s^{J/\psi \phi} \approx -\phi_s^{\text{NP}} \approx -\phi_s \).

The decay \( B^0_s \rightarrow J/\psi \phi \rightarrow \mu^+\mu^-K^+K^- \) is a physics rich decay mode as it can be used to measure the \( B^0_s \) lifetime, decay width difference and CP violation phase \( \beta_s^{J/\psi \phi} \). This decay gives rise to both CP-even and CP-odd final states, which can be separated through a study of the time-dependent angular distribution of the \( J/\psi \) and \( \phi \) mesons. There are three angles that completely define the directions of the four particles in the final state. The angles used are \( \rho = \cos \theta_\rho \), \( \varphi_\rho \), \( \cos \psi_\rho \) defined in the transversity basis introduced in [20]. This allows to measure the lifetime difference between the two states as well as the mixing phase through the interference terms between the CP-even and CP-odd waves.

The angular analysis of the \( B^0_s \rightarrow J/\psi \phi \) decays has been performed both by CDF [21] and D0 [22]. The CDF and D0 experiments reconstruct signal samples of \( \sim 3200 \) and \( \sim 2000 \) events with a signal to background ratio of 1.3 and 0.3, respectively. Both experiments reconstruct the decay modes in samples collected by the muon triggers, which require the presence of the muon segments in the muon detectors matched to central tracks. In the offline analysis, \( J/\psi \) and \( \phi \) candidates are required to be consistent with coming from a common vertex and to have an invariant mass compatible with the \( B^0_s \) mass. The proper decay length \( c_t \) is defined by the relation \( c_t = L_{xy} h \cdot M_{B^0_s} / \rho_\mu \). A method combining same-side kaon tags and opposite-side lepton and jet-charge tags was used for the initial-state flavor determination. The figure of merit to quantify the taggers is the tagging power \( \varepsilon D^2 \), \( \varepsilon \) being the tagging efficiency and \( D \) the tagging dilution, \( D = 1 - 2 P_{\text{mistag}} \). \( \varepsilon D^2 \) is found to be 5% for both experiments.

Another important feature of the detector systems used in the analysis is the proper time resolution. In a mixing or CP measurement, proper time resolution further degrades the error on CP asymmetries by the factor \( \exp(-\Delta m_s \sigma_t^2/2) \). Both CDF and D0 now employ low-mass, small-radius silicon called “Layer 00”, mounted directly on the beampipe, to achieve the best possible resolution, under 25 \( \mu \)m in both experiments.
Finally, an unbinned maximum likelihood fit is performed to extract the parameters of interest, \( \beta, \psi \) and \( \Delta \Gamma \), plus additional parameters referred to as “nuisance parameters” which include the signal fraction \( f_s \), the \( B^0_s \) mass, the mean \( B^0_s \) width \( \Gamma = (\Gamma_L + \Gamma_H)/2 \), the magnitudes of the polarization amplitudes in the transversity basis \( |A_0|^2, |A_1|^2, \) and \( |A_2|^2 \), and the strong phases \( \delta_1 = \text{arg}(A_1 A_0^*) \) and \( \delta_2 = \text{arg}(A_2 A_0^*) \). The fit uses information on the reconstructed \( B^0_s \) candidate mass, the \( B^0_s \) candidate proper decay time and its uncertainty, the transversity angles \( \rho \) and tag information \([23,24]\) that involve the event by event tag decision and probability.

An exact symmetry is present in the signal probability distribution, which is invariant under the simultaneous transformation \( (2\beta, -2\beta, \Delta \Gamma, -\Delta \Gamma, \delta_1, 2\pi - \delta_1, \text{ and } \delta_2, 2\pi - \delta_2) \). This causes the likelihood function to have two minima. Confidence regions in the \( \beta, \psi - \Delta \Gamma \) plane are constructed by CDF while similar confidence regions are evaluated by D0 in the \( \phi_s - \Delta \Gamma \) plane. These confidence regions are presented in Fig. 3. Both results show the expected double minimum structure and they are both shifted in the same direction with respect to the SM expectation. Note that the quantities in the horizontal axes are related by \( \phi_s = -2\beta, \psi \). The significances of the deviations are 1.8 standard deviations for CDF and 1.7 for D0.

![Figure 3](image)

**Figure 3.** Confidence regions in the \( \beta, \psi - \Delta \Gamma \) plane from CDF (left) and in the \( \phi_s - \Delta \Gamma \) plane from D0 (right).

A combination of the CDF and D0 results \([25]\) show a 2.2 \( \sigma \) deviation from the SM prediction (see Fig. 4-left). This combination include the D0 analysis with 2.8 fb\(^{-1}\) \([22]\) and a previous CDF result \([26]\) that used only 1.35 fb\(^{-1}\) of data. Although the combined deviation from the SM expectation is not statistically significant, the independent CDF and D0 fluctuations in the same direction are interesting to follow in the future as the analyzes will be updated with improvements and more data. Figure 4 (right) shows the CDF-D0 (assuming CDF+D0 = 2CDF) probability of observing 5\( \sigma \) deviation from the SM as a function of \( \beta, \psi \) assuming \( \Delta \Gamma = 0.1 \) ps\(^{-1}\). The black (red) line assumes 6 fb\(^{-1}\) (8 fb\(^{-1}\)) by the end of run II. The extrapolation assumes no further improvements of the analysis. However improvements in the use of particle identification, tagging power and sample size by using additional triggers are expected from CDF while D0 will optimize the signal selection for better signal to background.
5. Conclusions
In this paper we have reviewed CDF and D0 results concerning CP violation in the $B^0$ sector. Both collaborations are very active in this area. The broad physics program includes both measurements competitive with B-factories and measurements accessible only to the Tevatron such as $b$-baryons and $J/\psi$. CDF has collected $B^0$ $s(J/\psi)$ decays for the first time in a hadronic collider, thanks to the trigger on displaced tracks.

D0 has reached the most precise measurement to date of $B^0_s$ semileptonic asymmetry, $a^d_{sL}$ and on the measured the charge asymmetry between $B^+ \rightarrow J/\psi K^+$ and $B^- \rightarrow J/\psi K^-$. Both CDF and D0 experiments have performed first measurements of CP violation in $B^0_s \rightarrow J/\psi\phi$ decays. Although the accuracy of these measurements is limited, significant regions in the $\hat{\beta}_s^{J/\psi\phi}$ - $\Delta \Gamma$ plane are excluded. Positive values of $\hat{\beta}_s^{J/\psi\phi}$ are preferred by both experiments. The combined CDF and D0 measurement shows a 2.2 standard deviation departure from the SM prediction. Although not significant, it is interesting to see how the $\hat{\beta}_s^{J/\psi\phi}$ measurements evolve as more data is accumulated.

Acknowledgements
I would like to thank the DISCRETE 08 organizers for the opportunity to speak at this Conference and the colleagues from the CDF and D0 Collaborations for assisting me while preparing this talk and this document.

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