B_s MIXING, $\Delta\Gamma_s$ AND CP VIOLATION AT THE TEVATRON

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We discuss the results from the Tevatron experiments on mixing and CP violation in the $B_s^0 - \bar{B}_s^0$ system, with particular emphasis to the updated measurements of the decay-width difference $\Delta\Gamma_s$ and the first measurement of the CP-violating phase β_s using flavor tagging information. We also briefly review the charge asymmetry measurements in semileptonic B_s^0 decays and in $B^\pm \to J/\psi K^\pm$ decays.

1 Introduction

The Tevatron is a $p\bar{p}$ collider operating at the Fermi National Accelerator Laboratory. The protons and anti-protons collide at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV in two interaction points, where the CDF II and DØ detectors are located. The two experiments have collected an integrated luminosity of 3 fb^{-1} and the measurements presented here span from 1.0 fb^{-1} to 2.8 fb^{-1}. The physics of the b quark is a very active research area to challenge the Standard Model predictions. Precise measurements in B^0 and B^+ meson decays, performed at the B factories, improved the understanding of flavor dynamics and proved the Standard Model description very successful. On the other hand, a comparable experimental knowledge of B_s^0 decays has been lacking. The B_s^0 oscillation observation at CDF[1] strongly constrained the magnitude of New Physics contributions in the B_s^0 mixing, while its phase, responsible for CP violating effects, is not precisely determined yet. The B_s^0 sector offers a large variety of interesting processes in which large CP violation effects are still allowed by the current experimental constraints, but are negligible small in the Standard Model. Thus, the Tevatron collider, providing a simultaneous access to large samples of strange and non-strange b-mesons necessary for precision measurements, offers a great opportunity to study the B_s^0 flavor sector, before the start-up of CERN Large Hadronic Collider (LHC).

2 Phenomenology of the B_s^0 System

Flavor oscillation, or mixing, is a very well established phenomenon in particle physics. In the Standard Model the mass and the flavor eigenstates of neutral B mesons differ. This give rise to particle-antiparticle oscillations, which proceed through forth-order flavor changing weak interactions, whose phenomenology depends on the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. The rate at which the neutral $B - \bar{B}$ transitions occur is governed by the mass difference, Δm of the two mass eigenstates, B^L and B^H, where the superscripts L and H stay for "light" and "heavy". The phenomenology of mixing in B_s^0 and $\bar{B}_s^0$ mesons is, then, characterized by the mass difference of the two mass eigenstates, Δm_s, as well as by the decay width-difference $\Delta\Gamma_s \equiv \Gamma_s^L - \Gamma_s^H = 1/\tau_{B_s^L} - 1/\tau_{B_s^H}$. The latter depends on the CP violating phase defined as $\phi_s = \arg(-M_{12}/\Gamma_{12})$, through the relationship $\Delta\Gamma_s = 2|\Gamma_{12}| \times \cos(\phi_s)$. M_{12} and Γ_{12} are the off-diagonal elements of the $B_s^0 - \bar{B}_s^0$ decay matrix from the Schröedinger equation describing the time evolution of B_s^0 mesons [2]. While the Standard Model expectations are small[3], $\phi_s = 4\times10^{-3}$, New Physics could significantly modify the observed phase value contributing with additional processes, $\phi_s = \phi_s^{SM} + \phi_s^{NP}$. The same phase would alter the observed phase between the mixing and the $b \to c\bar{c}s$ transitions, $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP}$, in which the Standard Model contribution is defined as $-2\beta_s^{SM} = -2\arg(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}) \approx \mathcal{O}(0.04)$, where V_{ij} are the elements of the CKM matrix. Since both ϕ_s^{SM} and β_s^{SM} are tiny with respect to the current experimental resolution, we can approximate $\phi_s = -2\beta_s$. A measurement of sizable value of $2\beta_s$ (ϕ_s) would be a clear indication of New Physics.

3 B_s^0 Mixing

While Δm_d was precisely determined at the B factories [4, 5], the B_s^0 mixing frequency has been first measured at CDF experiment[1]. The $B_s^0 - \bar{B}_s^0$ oscillation observation was achieved through a combination of several data-sets of 1 fb^{-1}, in integrated luminosity, which results in:

$$\Delta m_s = 17.77 \pm 0.10 \text{ (stat.)} \pm 0.07 \text{ (syst.) ps}^{-1}, \tag{1}$$

with a significance greater than 5 standard deviations. Two independent types of flavor tags are used to identify the B_s^0 flavor at production: the Opposite Side Tagger (OST) and the Same Side Kaon Tagger (SSKT). The performance of flavor taggers are quantified by the efficiency ϵ and the dilution $\mathcal{D}$, defined as the probability to correctly tag a candidate. The tagging effectiveness, $\epsilon\mathcal{D}^2$ of the OST is 1.8%. The SSKT has $\epsilon\mathcal{D}^2 = 3.5\%$ (hadronic) and 4.8% (semileptonic) and thus contributes most to the sensitivity of the CDF analysis. The accurate measurement of the $B_s^0 - \bar{B}_s^0$ mixing frequency offers a powerful constraint to the ratio $|V_{ts}|^2/|V_{td}|^2$ of CKM matrix elements:

$$\frac{|V_{ts}|^2}{|V_{td}|^2} = 0.2060 \pm 0.0007 \text{ (stat.)}^{+0.0081}_{-0.0060} \text{ (theory)} . \tag{2}$$

DØ recently reported a measurement of the B_s^0 oscillation frequency [6] using a large sample of semileptonic B_s^0 decays and their first hadronic mode, $B_s^0 \to D_s^-[\to \phi(\to K^+K^-)\ \pi^-]\ \pi^+$. DØ combines the tagging algorithms using a likelihood-ratio method, obtaining a total effective tagging power $\epsilon\mathcal{D}^2 = (4.49 \pm 0.88)\%$. With a data-set of approximately 2.4 fb^{-1}, they obtains:

$$\Delta m_s = 18.56 \pm 0.87 \text{ (stat.)ps}^{-1}. \tag{3}$$

The result statistically exceeds the 3σ significance and it is compatible with the CDF measurement. The Δm_s is well consistent with the Standard Model unitarity hypothesis for the CKM matrix.

4 Phase of the Mixing Amplitude and Decay-Width Difference in the B_s^0 System

We present the time-dependent angular analyses of $B_s^0 \to J/\psi(\to \mu^+\mu^-)\ \phi(\to K^+K^-)$ decay mode performed at the Tevatron experiments. The decay $B_s^0 \to J/\psi\phi$ proceeds through the $b \to c\bar{c}s$ transition and gives rise to both CP-even and CP-odd final states. Through the angular distributions of the J/ψ and ϕ mesons, it is possible to statistically separate the two final states

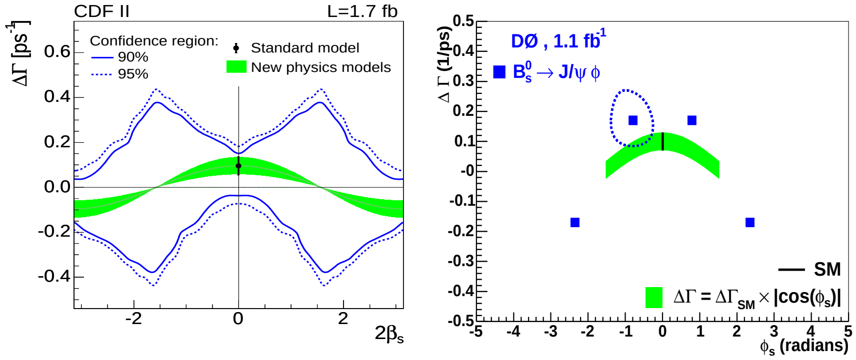

Figure 1: Left: CDF 90% (solid) and 95% (dashed) confidence level contour in the plane $2\beta_s - \Delta\Gamma_s$, compared with the SM prediction and the region allowed in New Physics model given by $\Delta\Gamma_s = 2|\Gamma_{12}|cos(2\beta_s)$, with $\Gamma_{12} = 0.048 \pm 0.018$ ps^1. Right: DØ point estimate in the plane $\Delta\Gamma_s - \phi_s$. The 39% CL contour (error ellipse) is additionally drawn in the plane $\phi_s - \Delta\Gamma_s$. It is also shown the band representing the relation $\Delta\Gamma_s = \Delta\Gamma_{SM} \times cos(\phi_s)$, with $\Delta\Gamma_{SM} = 0.10 \pm 0.03$ ps^1. In DØ nomenclature $\phi_s = -2\beta_s$. The 4-fold ambiguity is discussed in the text.

with different CP eigenvalues, thus allowing to determine the phase β_s and to separate lifetimes for the mass eigenstates, so to measure the decay-width difference $\Delta\Gamma_s$. After the DØ analysis [7] of untagged $B_s^0 \to J/\psi\phi$ decay sample of 1.1 fb^{-1}, and reported at Moriond 2007, the CDF Collaboration presents a similar analysis with a sample of 1.7 fb^{-1} in integrated luminosity [2]. CDF measures $\Delta\Gamma_s = 0.076^{+0.059}_{-0.063}$ (stat.) ± 0.006 (syst.) ps^{-1}, $c\tau_s = 456 \pm 13$ (stat.) ± 7 (syst.) μm, assuming CP conservation ($\beta_s = 0$) results. To date, this is one of the most precise B_s^0 lifetime measurements and it is in excellent agreement with both the DØ results and the theoretical expectations predicting $\tau_s = \tau_d \pm \mathcal{O}(1\%)$. Allowing CP violation, a bias and non-Gaussian fit estimates are observed in pseudo-experiments for statistics similar to the present data-sets. The observed bias originates from the loss of degree of freedom of the likelihood for certain values of the parameters of interest and does not permit a point estimation of $\Delta\Gamma_s$ and β_s . Thus, CDF provides confidence level regions in the $2\beta_s - \Delta\Gamma_s$ plane using the likelihood ratio ordering of Feldman and Cousins [8]. For the Standard Model expectation ($\Delta\Gamma_s \approx 0.096$ ps^{-1} and $2\beta_s = 0.04$ rad [3]), the probability to get equal or greater likelihood ratio than the one observed in data is 22%, which corresponds to 1.2 Gaussian standard deviations. Figure 1 shows the CDF and the DØ results in the $2\beta_s - \Delta\Gamma_s$ plane. Furthermore, the CDF Collaboration performed an angular analysis on the $B^0 \to J/\psi(\to \mu^+\mu^-)K^{*0}(\to K^+\pi^-)$ decay mode for the measurement of the transversity amplitudes and strong phases. Such an analysis plays a key role in the validation of the entire framework used for the $B_s^0 \to J/\psi\phi$ angular analysis. The results obtained for the transverse linear polarization amplitudes at $t = 0$, $A_\parallel$ and $A_\perp$, corresponding to CP even and CP odd final states respectively, as well as the strong phases $\delta_\parallel = \arg(A_\parallel^* A_0)$ and $\delta_\perp = \arg(A_\perp^* A_0)$, are $|A_\parallel|^2 = 0.569 \pm 0.009$ (stat.) ± 0.009 (syst.), $|A_\perp|^2 = 0.211 \pm 0.012$ (stat.) ± 0.006 (syst.), $\delta_\parallel = -2.96 \pm 0.08$ (stat.) ± 0.03 (syst.) and $\delta_\perp = 2.97 \pm 0.06$ (stat.) ± 0.01 (syst.), which are in agreement and competitive with the current B factories results [9].

We present the first Tevatron studies of the $B_s^0 \to J/\psi\phi$ decay mode when the initial state of the B_s^0 meson is identified exploiting the flavor tagging information. In fact, such information allows to separate the time evolution of mesons originally produced as B_s^0 or $\bar{B}_s^0$. The angular analyses which do not use the flavor tagging are sensitive to $|\cos(2\beta_s)|$ and $|\sin(2\beta_s)|$, leading to a 4-fold ambiguity in the likelihood for the determination of $2\beta_s$ (see Figure 1). On the other hand, utilizing flavor tagging algorithms, the analyses gain sensitivity to the sign of $\sin(2\beta_s)$ reducing by half the allowed region for β_s. CDF performed a flavor tagged analysis on a 1.35 fb^{-1} data-set of $B_s^0 \to J/\psi\phi$ reconstructed events, which yields $\simeq 2,000$ signal candidates [10].

The measured efficiencies for OST and SSKT are $\epsilon_{OST} = (96 \pm 1)\%$ and $\epsilon_{OST} = (50 \pm 1)\%$. The dilutions are respectively $\mathcal{D}_{OST} = (11 \pm 2)\%$ for the OST and $\mathcal{D}_{SSKT} = (27 \pm 4)\%$ for the SSKT. The addition of tagging information improves the regularity of the likelihood with respect to the untagged case, but still non-Gaussian uncertainties and biases are observed in simulated experiments with the available statistics. Thus, CDF reports a confidence region constructed according to the Feldman Cousins criterion with rigorous inclusion of systematics uncertainties. In fact, any $\Delta\Gamma_s - \beta_s$ pair is excluded at a given CL only if it can be excluded for any choice of *all* other fit parameters, sampled uniformly within $\pm 5\ \sigma$ of the values determined in their estimate on data. Assuming the Standard Model predicted values of $2\beta_s = 0.04$ rad and $\Delta\Gamma_s = 0.096\ \mathrm{ps}^{-1}$, the probability of a deviation as large as the observed data is 15%, which corresponds to 1.5 Gaussian standard deviations. Moreover, if $\Delta\Gamma_s$ is treated as a nuisance parameter, thus fitting only for $2\beta_s$, CDF finds $2\beta_s \in [0.31, 2.82]$ rad at the 68% confidence level. By exploiting the current experimental and theoretical information, CDF extracts tighter bounds on the CP violation phase β_s. Imposing the constraint on $|\Gamma_{12}| = 0.048 \pm 0.018\ \mathrm{ps}^{-1}$ in $\Delta\Gamma_s = 2|\Gamma_{12}|\cos(2\beta_s)$ [3], $2\beta_s \in [0.24,\ 1.36] \cup [1.78,\ 2.90]$ rad at the 68% CL. Additionally constraining the strong phases $\delta_{\parallel}$ and $\delta_{\perp}$ to the B factories results on $B^0 \to J/\psi K^{*0}$ [9] and the B_s^0 mean width to the world average B^0 width [11], it is found $2\beta_s \in [0.40,\ 1.20]$ rad at the 68% CL. The DØ Collaboration reports an analysis [12] on 2,000 signal $B_s^0 \to J/\psi\phi$ candidates, reconstructed in 2.8 fb^{-1}. DØ combines the tagging algorithms, as done in their B_s^0 mixing analysis. The total tagging power is $\epsilon\mathcal{D}^2 = (4.68 \pm 0.54)\%$ and a tag is defined for 99.7% of the events. To overcome the likelihood pathologies described above, DØ decides to vary the strong phases around the world-averaged values for the $B^0 \to J/\psi K^{*0}$ decay [13], applying a Gaussian constraint. This removes the 2-fold ambiguity, inherent the measurement for arbitrary strong phases. The strong phases in $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$ cannot be exactly related in the $SU(3)$ limit, so the width of the Gaussian is chosen to be $\pi/5$, allowing for some degree of $SU(3)$ symmetry violation. The fit with all floating parameters yields to the measurements

$$
\begin{aligned}
\phi_s &= -0.57^{+0.24}_{-0.30}\ (\text{stat.})^{+0.07}_{-0.02}\ (\text{syst.})\ \text{rad}, \\
\Delta\Gamma_s &= 0.19 \pm 0.07\ (\text{stat.})^{+0.02}_{-0.01}\ (\text{syst.})\ \text{ps}^{-1}, \\
\tau_s &= 1.52 \pm 0.05\ (\text{stat.}) \pm 0.01\ (\text{syst.})\ \text{ps}.
\end{aligned} \tag{4}
$$

The allowed ranges at the 90% CL for the parameters of interest are found to be $\phi_s \in [-1.20, 0.06]$ rad and $\Delta\Gamma_s \in [0.06, 0.30]\ \mathrm{ps}^{-1}$. The expected confidence level contours in the $\phi_s - \beta_s$ plane at 68% and 90% CL are depicted in Figure 2. The level of agreement with the Standard Model corresponds to 6.6%, which is obtained by generating pseudo-experiments with the initial value for ϕ_s set to -0.04 rad and counting the events whose obtained fitted value of the phase is lower than the measured -0.57 rad. The results supersede the previous DØ untagged analysis on a smaller $B_s^0 \to J/\psi\phi$ sample.

5 Charge Asymmetry in B_s^0 Semileptonic Decays

Another way of studying the CP violation induced by the B_s mixing, is to measure the charge asymmetry in semileptonically decaying mesons. The charge asymmetry is connected to the CP violating phase ϕ_s, through the relationship $A_{SL}^s = \Delta\Gamma_s/\Delta m_s \times tan(\phi_s)$. With the underlying assumption of $\phi_s = -2\beta_s$ (see Section 2), an independent measurements on charge asymmetry could be used to constrain the CP violating phase β_s [14]. DØ Collaboration performed two independent analyses to extract A_{SL}^s. The first result is based on the di-muon charge asymmetry measurement [15], defined as

$$
A_{SL}^{\mu\mu} = \frac{N(bb \to \mu^+\mu^+) - N(bb \to \mu^-\mu^-)}{N(bb \to \mu^+\mu^+) + N(bb \to \mu^-\mu^-)}. \tag{5}
$$

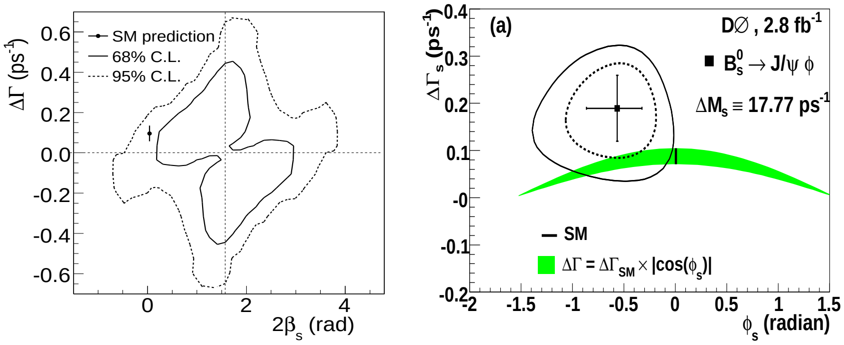

Figure 2: Left: CDF confidence level contour in the plane $2\beta_s - \Delta\Gamma_s$ when using flavor tagging. It quotes the 68% (solid) and 95% (dashed) C.L. The solution with $\Delta\Gamma_s > 0$ corresponds to $\cos(\delta_\perp) < 0$ and $\cos(\delta_\perp - \delta_\parallel) > 0$. The opposite is true for the solution with $\Delta\Gamma_s < 0$. Right: DØ confidence level contours in the $\Delta\Gamma_s - \phi_s$ plane. The curves correspond to the expected 68% (dashed) and 90% (solid) CL. The cross represents the best estimate fit with the one-dimensional uncertainties. According to DØ nomenclature, $\phi_s = -2\beta_s$.

The following asymmetry gets its contributions from both B^0 and B^0_s: by using the world average value for B^0 and B^0_s production fractions and the B^0 charge asymmetry measurements from the B factories, DØ extracts the B^0_s charge asymmetry on a data-set of 1.0 fb^{-1}:

$$A^{\mu\mu,B^0_s}_{SL} = -0.0064 \pm 0.0101 \text{ (stat. + syst.)}. \tag{6}$$

CDF Collaboration also released a similar measurement of the di-muon charge asymmetry [16] on a sample of 1.6 fb^{-1} data. In this analysis, the unbinned likelihood is performed using the impact parameter information of the two muons, in order to separate the $b - \bar{b}$ component of the sample from the others which arise from prompt and charm sources:

$$A^{\mu\mu,B^0_s}_{SL} = 0.020 \pm 0.021 \text{ (stat.) } \pm 0.016 \text{ (syst.) } \pm 0.009 \text{ (inputs) }. \tag{7}$$

Additionally to the statistical and systematic uncertainties, the last uncertainty term comes from the world average value for B^0 and B^0_s production fractions and the B^0 charge asymmetry measurements already discussed in the description of DØ results. Compared to CDF, DØ analysis has strongly reduced systematics uncertainties thanks to a regular flipping of the magnet polarity. Such technique, removing most of the artificial asymmetry in the detector response, is constantly used by DØ to measure all the charge asymmetries described along this paper.

The DØ Collaboration probes the ϕ_s phase also by measuring the charge asymmetry in an untagged sample of $B^0_s \to \mu D_s$ decays, with $D_s \to \phi(\to K^+K^-)\pi$. With a data-set of 1.3 fb^{-1} the charge asymmetry is found to be [17]

$$A^{\mu D_s}_{SL} = 0.0245 \pm 0.0193 \text{ (stat.)} \pm 0.0035 \text{ (syst.)}. \tag{8}$$

6 Charge Asymmetry in $B^+ \to J/\psi K^+$ Decay

We present a search for direct CP violation in $B^+ \to J/\psi K^+$ decays [18]. The event sample is selected from 2.8 fb^{-1} of $p\bar{p}$ collisions recorded by DØ experiment. The charge asymmetry is defined as

$$A_{CP}(B^+ \to J/\psi K^+) = \frac{N(B^- \to J/\psi K^-) - N(B^+ \to J/\psi K^+)}{N(B^- \to J/\psi K^-) + N(B^+ \to J/\psi K^+)}. \tag{9}$$

By using a sample of approximately 40,000 $B^+ \to J/\psi K^+$ decays, the asymmetry is measured to be $A_{CP} = 0.0075 \pm 0.0061$ (stat.) $\pm$ 0.0027 (syst.). The result is consistent with the world average [11] and the Standard Model expectation $A_{CP}(B^+ \to J/\psi K^+) \simeq 0.003$ [19], but has a factor of two improvement in precision, thus representing the most stringent bound for new models which predict large values of $A_{CP}(B^+ \to J/\psi K^+)$. Furthermore, DØ provides the direct CP violating asymmetry measurement in $B^+ \to J/\psi \pi^+$, $A_{CP}(B^+ \to J/\psi \pi^+) = -0.09 \pm 0.08$ (stat.) $\pm\, 0.03$ (syst.). The result agrees with the previous measurements of this asymmetry [11] and has a competitive precision.

7 Conclusions

After the successful B_s^0 oscillation observation, the CDF and DØ Collaboration directed their effort in the exploration of the mixing-induced CP violation effect in the B_s^0 system. We described the first tagged measurement in $B_s^0 \to J/\psi\phi$ performed at the CDF II detector, which improved the sensitivity to the CP violating phase β_s, excluding negative and large values for the phase itself. The DØ Collaboration promptly delivered a similar analysis confirming the results. The agreement of the analyses of $B_s^0 \to J/\psi\phi$ decays, shows an interesting fluctuations in the same direction from CDF and DØ experiments and they will certainly need further investigations to support an evidence, which would be possible exploiting the full Run II data sample, if these first indications are confirmed in the future. We also reviewed the charge asymmetry measurements of B_s^0 semileptonic decays, which provide another independent test for the CP violation in B_s^0 mixing and can be combined with the analyses on $B_s^0 \to J/\psi\phi$ to get a better understanding of the CP violating phenomena. Finally, we presented the world most precise direct CP violating asymmetry in the $B^+ \to J/\psi K^+$ decay mode. The Tevatron experiments are becoming increasingly competitive with B factories results on B^0/B^+ decays and complementary to them in corresponding B_s^0 modes. Since many of the analyses reported do not even use half of the statistics available, significant improvements are expected in the future, as the Tevatron keeps producing data.

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