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CP-violation measurements with $B_s^0 \to J/\psi\phi$ decays at the Tevatron

Isabelle Ripp-Baudot *
IPHC, Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
E-mail: ripp@in2p3.fr

CDF and DØ measurements of the CP-violating phase ϕ_s and the decay width difference $\Delta\Gamma_s$ of the two B_s^0 mass eigenstates using flavour-tagged $B_s^0 \to J/\psi\phi$ decays are presented. The data samples correspond to integrated luminosities of 5.2 and 6.1 fb^{-1} recorded by the CDF and the DØ detectors respectively. This measurement is still statistically limited and adding new decay modes could help reduce its uncertainty. In this perspective, new preliminary measurements of the relative branching fraction of $B_s^0 \to J/\psi f_0(980), f_0(980) \to \pi^+\pi^-$ to $B_s^0 \to J/\psi\phi, \phi \to K^+K^-$ are also presented. They are based on respectively 3.8 and 8 fb^{-1} of CDF and DØ data samples.

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*on behalf of the CDF and the DØ collaborations

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1. Introduction

A CP-violating phase appears in $b \to c\bar{c}s$ decays due to the interference between direct decays and decays occurring through mixing to the identical final state. In the B_s^0 system, this phase is called β_s and is expressed in the standard model in terms of elements of the Cabibbo-Kobayashi-Maskawa matrix [1]:

$$2\beta_s^{SM} = 2\ \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

This phase is experimentally accessible through $B_s^0 \to J/\psi\phi$ decays. However its predicted magnitude within the standard model is very small [2, 3]: $2\beta_s^{SM} = 0.038 \pm 0.002$, so that the current experimental precision does not allow to resolve it.

B_s^0 oscillations are caused by flavour changing weak interaction box diagrams that induce non-zero off-diagonal elements in the B_s^0 meson propagation matrix. The CP-violating weak phase ϕ_s is defined as being the phase between the elements M_{12} and Γ_{12} of this matrix. Its standard model expected value is also very small [4]: $\phi_s^{SM} = 0.0042 \pm 0.0014$. The interesting point here is that the same additional contribution ϕ_s^{NP} due to physics beyond standard model would show up in both $-2\beta_s$ and ϕ_s:

$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

$$-2\beta_s = -2\beta_s^{SM} + \phi_s^{NP}$$

Large new physics effects $\phi_s^{NP} \gg \phi_s^{SM}, 2\beta_s^{SM}$ would lead to an observed phase $\phi_s \simeq \phi_s^{NP} \simeq -2\beta_s$ and in the following we will equally speak of ϕ_s or $-2\beta_s$. Since ϕ_s is negligibly small in the standard model but sizeable in many of its extensions due to new particles participating in the box diagrams, it is a sensitive probe of new physics effects.

Previous experimental constraints on ϕ_s have been obtained at the Tevatron, which favoured larger values than expected from the standard model. A first analysis including flavour tagging has been performed by CDF using a 1.35 fb^{-1} data sample [5] observed a 1.5σ deviation from the standard model expectation. With an increased data set of 2.8 fb^{-1}, the discrepancy raised to 1.8σ [6] and was consistent with the DØ observation with a similar luminosity [7], enabling both results to be merged and bringing the consistency with the standard model to 2.1σ [8]. The results discussed in this report are based on data collected by the CDF and the DØ detectors between February 2002 and June 2009 and correspond respectively to integrated luminosities of 5.2 and 6.1 fb^{-1}.

2. The measurement method

ϕ_s and $\Delta\Gamma_s$ are measured by studying the time evolution of $B_s^0 \to J/\psi\phi$ decays, with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. Enhanced sensitivity is achieved if the evolution is independently studied for mesons produced as B_s^0 or $\bar{B}_s^0$ and decayed in a CP-even or a CP-odd final state. As the final state of the $B_s^0 \to J/\psi\phi$ decay is an admixture of CP eigenstates, angular distributions of the decay products are used in order to statistically disentangle them. To do so, the $\mu^+\mu^-K^+K^-$ final state is described by 3 decay angles, $\cos\psi_T$, $\cos\theta_T$ and ϕ_T, defined in the transversity basis [11].

The decay of the spinless B_s^0 meson into 2 vector mesons is characterized by 3 independent amplitudes A_0, $A_{//}$ and $A_\perp$, corresponding to linear polarization states of the vector mesons. These amplitudes are complex and two independent relative CP-conservating strong phases can be defined, for instance $\delta_{//}$ and $\delta_\perp$ with respect to A_0. Finally the $B_s^0 \to J/\psi\phi$ angular decay rates evolution with time is written as a function of the CP-violating phase ϕ_s, the mass difference Δm_s between the 2 B_s^0 mass eigenstates, their decay width difference $\Delta\Gamma_s$, the B_s^0 lifetime, the 3 transversity amplitudes modules and their 2 relative strong phases. Consequently ϕ_s and $\Delta\Gamma_s$ are obtained from an unbinned maximum likelihood fit to the distributions of the reconstructed $J/\psi\phi$ invariant mass, the reconstructed proper decay time and the 3 transversity decay angles of the selected $B_s^0 \to J/\psi\phi$ candidates. The likelihood function has furthermore to be convoluted with the selection acceptance and to take background contributions into account. The B_s^0 nature at production time information is included as a flavour tagging probability on an event-by-event basis.

3. Data selection

The ϕ_s measurement is still statistically limited and the selection efficiency is a key aspect of this analysis. Both experiments select $B_s^0 \to J/\psi\phi$ decays using the same kind of sequential cuts related to kinematical quantities, reconstructed secondary vertices and constrained kinematic fits. CDF further reduces the background by cutting on a neural network which combines kinematical variables with time-of-flight and energy loss informations in order to identify the 2 kaons coming from the ϕ decay, while in DØ, without particle identification, the selection has to be tighter. The reconstructed invariant mass distributions of $J/\psi\phi$ selected candidates obtained by CDF and DØ are shown in figure 1. The corresponding estimated signal yields are respectively 6504 ± 85 and 3435 ± 84 events.

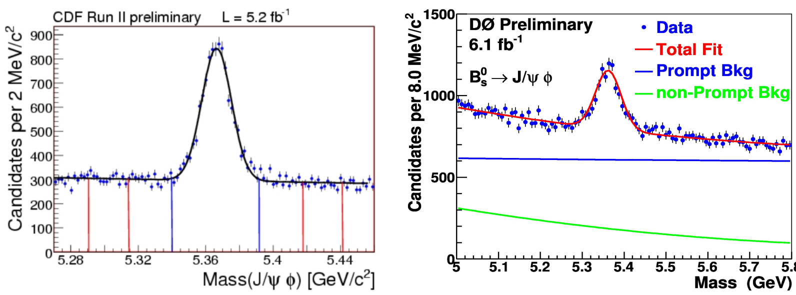

Figure 1: $J/\psi\phi$ invariant mass distribution observed by CDF (left) and DØ (right).

4. Flavour tagging

The nature as B_s^0 or $\bar{B}_s^0$ of the reconstructed meson at production time is inferred from two types of flavour tagging algorithms:

- the reconstructed B_s^0 meson can be directly tagged as it is produced with a so-called same-side tagger, using the sign of the charged kaon produced in association with the B_s^0. CDF takes advantage of its particle identification detectors to improve the selection of the kaon,

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while in DØ, without particle identification, the effect of the even busier environment due to the increasing instantaneous luminosity is more critical, and therefore they have decided not to use it with the latest data.

- besides the same-side tagger a so-called opposite-side tagger is also built, exploiting properties of decay products of the other B hadron produced during the same collision. The algorithm looks for a muon or an electron potentially produced by the semi-leptonic decay of the other B hadron. It also attempts to reconstruct the decay vertex of the other B hadron and computes the vertex charge or the jet charge. All these variables are combined in a tagger using multivariate techniques.

These tagging techniques were initially developed for B mixing measurements, and their performances are calibrated with data. The performances are defined as efficiency times dilution squared, where the dilution is the rate of correct minus wrong tagging: N events tagged by a flavour-tagging algorithm with efficiency ε and dilution D are statistically equivalent to $\varepsilon D^2 N$ events identified with 100 % efficiency and an optimal dilution of 1. As the fragmentation of the other B hadron is independent of the reconstructed meson flavour, the opposite-side tagger is calibrated using inclusive semi-leptonic and exclusive B decays which nature is known. CDF and DØ opposite-side taggers performances are respectively 1.2 % and 2.5 %. The CDF same-side tagger, which performance is 3.2 %, is calibrated by measuring simultaneously the B_s^0 mixing frequency Δm_s and the dilution scale factor.

5. Results

In the CDF analysis an S-wave component is added in the likelihood function, to allow for possible contamination of the ϕ resonance with either f_0 or non-resonant K^+K^- contributions which could bias the result. From a fit to their data they show that the fraction of S-wave is less than 6.7 % at 95 % C.L..

Previously, point estimates have only been possible without flavour tagging and even with the increased dataset it is still not possible to reliably estimate the uncertainties of all the quantities which are extracted from the fit. Therefore CDF assumes no CP-violation (β_s = 0), and doing so they obtain the most precise single measurements to-date of the B_s^0 lifetime, the decay width difference, the transversity amplitudes modules and one of the 2 relative strong phases:

$$\tau_s = 1.53 \pm 0.025 \text{ (stat.) } \pm 0.012 \text{ (syst.) ps}$$

$$\Delta\Gamma_s = 0.075 \pm 0.035 \text{ (stat.) } \pm 0.010 \text{ (syst.) ps}^{-1}$$

$$|A_{//}(0)|^2 = 0.231 \pm 0.014 \text{ (stat.) } \pm 0.015 \text{ (syst.)}$$

$$|A_0(0)|^2 = 0.524 \pm 0.013 \text{ (stat.) } \pm 0.015 \text{ (syst.)}$$

$$\delta_\perp = 2.95 \pm 0.65 \text{ (stat.) } \pm 0.07 \text{ (syst.)}$$

The second relative strong phase is not measured because its central value is near π, which is a symmetric point in the likelihood, leading to non-reliable errors from the likelihood fit.

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In the DØ analysis on the other hand, the K^+K^- system from the B_s^0 decay is assumed to be produced in a pure P-wave. With the S-wave included the differential decay rate has, among others, an additional term proportional to $\cos\psi_T$ which is due to the S and P waves interference. Thus, a significant presence of the S-wave should manifest itself by a forward-backward asymmetry in $\cos\psi_T$, what is not observed in the DØ data and is also consistent with the CDF result. Another difference with the CDF analysis is that DØ places gaussian constraints on Δm_s and on the 2 relative CP-conserving strong phases using world averages [12]. Indeed both $B_s^0 \to J/\psi\phi$ and $B^0 \to J/\psi K^*$ decays are dominated by a colour-suppressed tree diagram that differs only by the substitution of the spectator d- or s-quark. The $B^0 \to J/\psi K^*$ strong phases are measured with a good accuracy and it has been shown theoretically that their strong phases should agree within 10 degrees [13].

The point measurements of the B_s^0 lifetime and decay width difference are obtained in DØ without constraining the CP-violating weak phase, and the uncertainties quoted are the parabolic symmetric one standard deviation estimation from the fit:

$$\tau_s = 1.47 \pm 0.04 \text{ (stat.) } \pm 0.01 \text{ (syst.) ps}$$

$$\Delta\Gamma_s = 0.15 \pm 0.06 \text{ (stat.) } \pm 0.01 \text{ (syst.) ps}^{-1}$$

$$\phi_s = -0.76 \pm 0.37 \text{ (stat.) } \pm 0.02 \text{ (syst.)}$$

All these results are in good agreement with previous determinations of same quantities.

As the uncertainties on the fit parameters show non-gaussian behaviour due to the limited statistics, confidence contours in the ϕ_s-$\Delta\Gamma_s$ plane are preferably quoted. To do so, likelihood values are adjusted to take into account correct statistical coverage of confidence regions by analysing toy Monte-Carlo samples, which also take into account effects of systematic uncertainties. The CDF and the DØ contours in the ϕ_s-$\Delta\Gamma_s$ plane are shown in figure 2 and they are in agreement: $\phi_s \in [-\pi, -1.78] \cup [-1.36, 0.26] \cup [2.88, \pi]$ at 95 % C.L. for CDF, corresponding to a 0.8σ deviation from the standard model central point, and $\phi_s \in [-1.65, 0.24]$, $\Delta\Gamma_s \in [0.014, 0.263]$ and $\phi_s \in [1.14, 2.93]$, $\Delta\Gamma_s \in [-0.235, -0.040]$ at 95 % C.L. for DØ, corresponding to a 1.1σ deviation from the standard model central point. It can be noticed that the consistency with the standard model expectations has improved with respect to previous measurements.

6. $B_s^0 \to J/\psi\phi f_0(980)$ reconstruction

We have seen that current measurements of the CP-violating weak phase in B_s^0 mixing may be larger than predicted by the standard model. However the current errors are still large enough so that it is not significant. Thus adding the $B_s^0 \to J/\psi f_0(980)$ decay channel could help reduce the uncertainty. This decay mode is a CP-eigenstate so that the CP-violating weak phase can be measured without performing an angular analysis.

The first step towards the ϕ_s measurement with this decay mode is to measure its branching ratio. Actually measuring the relative branching ratio with respect to the $J/\psi\phi$ mode allows several systematics cancellation, and only the relative signal yields and the relative reconstruction efficiencies are needed. First measurements of this relative branching ratio have been performed

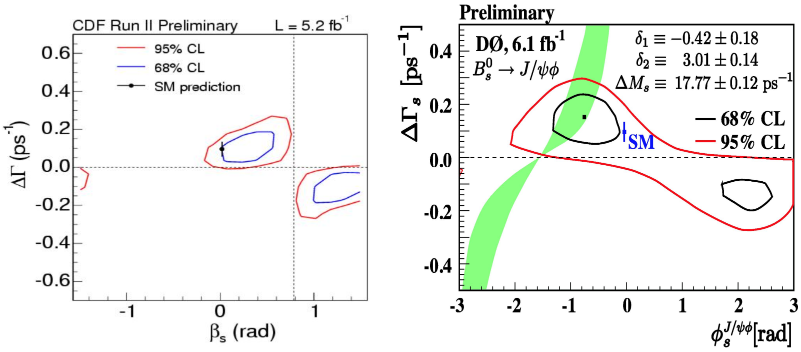

Figure 2: Confidence regions in the ϕ_s-$\Delta\Gamma_s$ plane obtained by CDF (left) and DØ (right). A green band on the DØ plot indicates the region allowed by beyond standard models theories in which new physics effects would arise from a single phase added to the propagation matrix element M_{12} only.

by CDF [14] and DØ [15] using respectively 3.8 and 8 fb^{-1} of their data. The $B_s^0 \to J/\psi f_0(980)$ reconstruction follows exactly the same as the $B_s^0 \to J/\psi\phi$ one. In DØ the selection procedure has been completely reoptimized with the increased dataset and uses two boosted decision tree discriminants trained respectively against prompt J/ψ background and J/ψ background coming from charm and bottom decays. Figure 3 shows the invariant mass distributions observed for the two reconstructed decays by CDF and DØ. They observe respectively 571 $\pm$ 45 (CDF) and 498 $\pm$ 74 (DØ) $B_s^0 \to J/\psi f_0(980)$ signal events, and 2302 $\pm$ 70 (CDF) and 2863 $\pm$ 61 (DØ) $B_s^0 \to J/\psi\phi$ signal events.

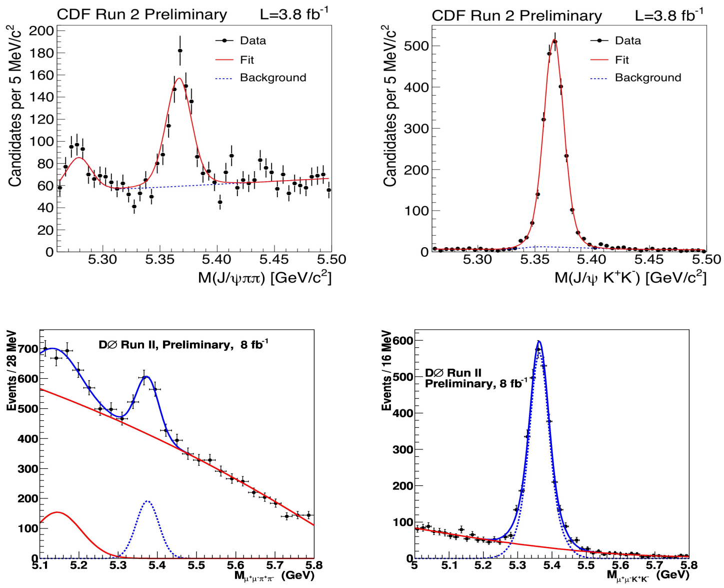

Figure 3: Invariant mass distributions of $B_s^0 \to J/\psi f_0(980)$ (left figures) and $B_s^0 \to J/\psi\phi$ (right figures) decays observed by CDF (top) and DØ (bottom).

The inferred relative branching fractions are $\mathscr{B}(B_s^0 \to J/\psi\phi f_0(980))$ = 0.292 $\pm$ 0.020 (stat.) $\pm$ 0.017 (syst.) for CDF and 0.210 $\pm$ 0.032 (stat.) $\pm$ 0.066 (syst.) for DØ. These results show a good consistency and are also in good agreement with Belle [16] and LHCb [17] measurements.

7. Conclusion

The current most stringent constraints on $\Delta\Gamma_s$ and ϕ_s still come from the Tevatron by studying the time evolution of flavour tagged $B_s^0 \to J/\psi\phi$ decays. Although the discrepancy with the standard model has decreased with respect to previous measurements, the results are now actually also in better agreement with the values of $\Delta\Gamma_s$ and ϕ_s expected from theories beyond the standard model in which Γ_{12} does not receive significant contribution from new physics. They are also consistent with other measurements sensitive to the same CP-violating weak phase, namely the recent observation of an anomalous like-sign dimuon charge asymmetry by DØ [18].

Improved results from the Tevatron have to be expected in a very near future. Indeed the results discussed here use only half of the available statistics. Furthermore, work is going on to improve selection efficiency and signal over noise ratio, and also to increase statistics by adding new channels. In that perspective, first new results by CDF and DØ on the $B_s^0 \to J/\psi f_0(980)$ decay channel have been presented.

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