

## $B_s$ and $CP$ violation at the Tevatron

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**Summary.** — The violation of the  $CP$  symmetry is an important probe for testing the Standard Model of particle physics as well as a missing piece in understanding the history of the universe. While  $CP$  violation in the  $B^0$  and  $B^+$  sector has been precisely measured by the  $B$  factories, the Tevatron with its two experiments CDF and DØ is still the only place to produce and study large samples of  $B_s^0$ -mesons until the startup of the LHC. This article gives an overview of recent results on  $CP$  violation in the  $B_s^0$  sector from both Tevatron experiments.

PACS 11.30.Er – Charge conjugation, parity, time reversal, and other discrete symmetries.

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### 1. – The $B_s$ -meson system

The phenomenology of  $B_s^0$ -mesons can be described in three bases of eigenstates: The *flavour eigenstates* are defined by the quark content:  $|B_s^0\rangle = |\bar{b}s\rangle$ ,  $|\bar{B}_s^0\rangle = |b\bar{s}\rangle$ . Their time evolution is given by the Schrödinger equation

$$(1) \quad i \frac{\partial}{\partial t} \begin{pmatrix} |B_s^0\rangle \\ |\bar{B}_s^0\rangle \end{pmatrix} = \left( \mathbf{M} - \frac{i}{2} \mathbf{\Gamma} \right) \begin{pmatrix} |B_s^0\rangle \\ |\bar{B}_s^0\rangle \end{pmatrix}$$

with the Hermitian  $2 \times 2$  mass and decay matrices  $\mathbf{M}$  and  $\mathbf{\Gamma}$ . Diagonalization of this effective Hamiltonian leads to the heavy and light *mass eigenstates*:

$$(2) \quad |B_s^H\rangle = p |B_s^0\rangle - q |\bar{B}_s^0\rangle,$$

$$(3) \quad |B_s^L\rangle = p |B_s^0\rangle + q |\bar{B}_s^0\rangle.$$

The complex parameters  $p$  and  $q$  are normalized by the relation  $|p|^2 + |q|^2 = 1$ . Mass and width difference between the heavy- and light-mass eigenstates are defined as

$$(4) \quad \Delta m = m_H - m_L = 2 |M_{12}|,$$

$$(5) \quad \Delta \Gamma = \Gamma_L - \Gamma_H = 2 |\Gamma_{12}| \cos(\phi_s),$$

where  $\phi_s$  is a complex phase between  $M_{12}$  and  $\Gamma_{12}$ :

$$(6) \quad \phi_s = \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right).$$

The  $CP$  operator leads to the  $CP$  eigenstates

$$(7) \quad |B_s^{\text{even}}\rangle = \frac{1}{\sqrt{2}}(|B_s^0\rangle - |\bar{B}_s^0\rangle),$$

$$(8) \quad |B_s^{\text{odd}}\rangle = \frac{1}{\sqrt{2}}(|B_s^0\rangle + |\bar{B}_s^0\rangle),$$

where the width difference is defined as  $\Delta\Gamma^{CP} = \Gamma^{\text{even}} - \Gamma^{\text{odd}}$ . The relation between  $\Delta\Gamma^{CP}$  and  $\Delta\Gamma$  contains the phase  $\phi_s$ :

$$(9) \quad \Delta\Gamma = \Delta\Gamma^{CP} \cos(\phi_s).$$

In case of  $CP$  conservation ( $\phi_s = 0$ ), mass and  $CP$  eigenstates coincide. The Standard Model prediction  $\phi_s = 0.004$  is very small [1]. As new physics is expected to have no influence on  $\Gamma_{12}$  but could contribute to  $M_{12}$  [1], the phase  $\phi_s$  between the two elements can be significantly enhanced by new physics effects.

$\Delta m_s$  is the frequency of  $B_s^0 - \bar{B}_s^0$  oscillations and has already been measured by CDF [2] and DØ [3]. The  $B_s^0 \rightarrow D_s D_s$  final state gives access to  $\Delta\Gamma^{CP}$ , while information on  $\phi_s$  can be gained in  $B_s^0$  decays to a flavour specific final state as well as from  $B_s^0 \rightarrow J/\psi \phi$  decays. These measurements will be presented in the following sections.

## 2. – The Decay $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$ and $\Delta\Gamma_s^{CP}$

The CKM favoured  $B_s^0 \rightarrow c\bar{c}s\bar{s}$  transition is the dominant contribution of all  $B_s^0$  decays to  $CP$  eigenstates, with the largest fraction ending in the colour allowed  $D_s^{(*)} D_s^{(*)}$  final state. The  $B_s^0 \rightarrow D_s D_s$  final state is purely  $CP$  even [4]. In the Shifman-Voloshin limit assuming  $m_b - 2m_c \rightarrow 0$  and infinite number of colours [5], also  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$  is dominantly  $CP$  even, neglecting small  $CP$  odd components. Therefore, the observation of that decay indicates a width difference  $\Delta\Gamma_s^{CP}$ , which can be obtained from the branching ratio

$$(10) \quad \frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \approx 2 \cdot \text{Br}[B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}].$$

DØ published an analysis of  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$  on  $2.8 \text{ fb}^{-1}$  of data [6]. The decay was observed with  $3.2\sigma$  significance and the measured branching ratio yields to

$$(11) \quad \Delta\Gamma_s^{CP}/\Gamma_s = 0.072 \pm 0.021(\text{stat}) \pm 0.022(\text{syst}).$$

The CDF analysis of  $B_s^0 \rightarrow D_s D_s$  uses  $360 \text{ pb}^{-1}$  of data [7]. This analysis observed the decay at  $7.5\sigma$ . As the studied  $D_s D_s$  final state is only one out of the final states contributing to the width difference, a limit has been set:

$$(12) \quad \Delta\Gamma_s^{CP}/\Gamma_s \geq 0.012 \text{ at } 95\% \text{ CL.}$$

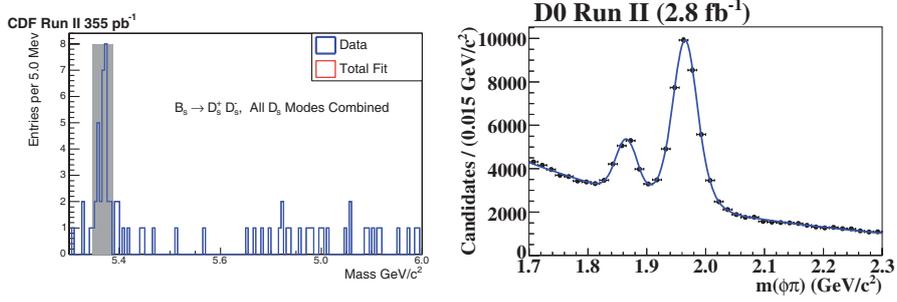


Fig. 1. – The mass spectrum observed in the CDF  $B_s^0 \rightarrow D_s D_s$  analysis is shown in the left plot. In the D0 mass spectrum on the right, the peak at higher mass is from  $D_s$  and the lower peak from  $D^\pm$  candidates.

In fig. 1, the observed mass spectra from the two experiments can be seen. Because D0 reconstructs one of the  $D_s$  candidates in a semileptonic decay missing a neutrino, the mass spectrum for the hadronically reconstructed  $D_s$  candidate is shown.

### 3. – $CP$ asymmetry in semileptonic $B_s^0$ decays

Information on the phase  $\phi_s$  can be gained by measuring the  $CP$  asymmetry,

$$(13) \quad a_{f_s}^s = \frac{\Gamma_{\bar{B}_s^0 \rightarrow f} - \Gamma_{B_s^0 \rightarrow \bar{f}}}{\Gamma_{\bar{B}_s^0 \rightarrow f} + \Gamma_{B_s^0 \rightarrow \bar{f}}} = \frac{|M_{12}|}{|\Gamma_{12}|} \sin(\phi_s),$$

in  $B_s^0$  decays to flavour specific final states. As this is often done in semileptonic  $B_s^0$  decays, it is also called the *semileptonic  $CP$  asymmetry*. In these decays,  $B_s^0 \rightarrow f$  and  $\bar{B}_s^0 \rightarrow \bar{f}$  are allowed, while  $B_s^0 \rightarrow \bar{f}$  and  $\bar{B}_s^0 \rightarrow f$  can only be reached via mixing. The Standard Model expectation is  $a_{f_s}^s = (2.06 \pm 0.57) \cdot 10^{-5}$  [1].

The D0 collaboration performed a time-dependent  $a_{f_s}^s$  analysis on  $5 \text{ fb}^{-1}$  [8] in the decay

$$(14) \quad B_s^0 \rightarrow \mu^+ D_s^- X$$

with subsequent decays of  $D_s^- \rightarrow \phi \pi^-$ ,  $\phi \rightarrow K^+ K^-$  and  $D_s^- \rightarrow K^{*0} K^-$ ,  $K^{*0} \rightarrow K^+ \pi^-$ . Most of the data sample was collected with single muon triggers, although no explicit trigger requirement was made. The resulting  $KK\pi$  mass spectra after a likelihood-based candidate selection can be seen in fig. 2.

The final-state  $b$ -quark flavour is known from the muon of the semileptonic decay. To obtain the initial state flavour, an opposite-side tagging algorithm was used which relies in most cases on the charge of a second muon in the event. Approximately 21% of all events are tagged.

An unbinned maximum-likelihood fit is used to extract the parameters of interest. Contributions from peaking, prompt and long-lived background are modeled in the likelihood function and their parameters are determined from the data sample. To minimize asymmetries caused by detector effects, the polarity of the magnetic field of the D0 detector was reversed regularly during data taking.

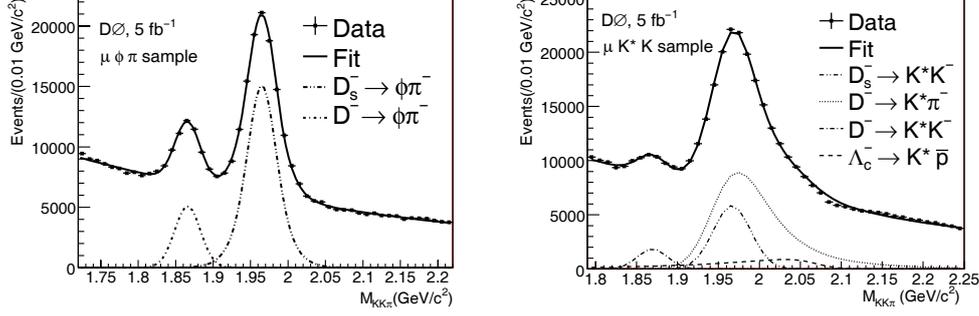


Fig. 2. – Mass distributions observed in the DØ  $a_{fs}^s$  analysis. The  $D_s^- \rightarrow \phi\pi^-$  channel can be seen in the left plot, the  $D_s^- \rightarrow \mu^+ K^{*0} K^-$  on the right.

The resulting measurement

$$(15) \quad a_{fs}^s = [-1.7 \pm 9.1 \text{ (stat)}_{-2.3}^{+1.2} \text{ (syst)}] \cdot 10^{-3}$$

indicates that with increasing statistics this analysis will be close to reaching the sensitivity for constraining models of new physics.

#### 4. – $CP$ violation in $B_s^0 \rightarrow J/\psi \phi$ decays

The decay  $B_s^0 \rightarrow J/\psi \phi$  is one of the most interesting probes of new physics in the entire experimental scenario. In a time dependent measurement of the  $CP$  asymmetry

$$(16) \quad A_{CP}(t) = \frac{\Gamma(\bar{B}_s^0 \rightarrow f_{CP}) - \Gamma(B_s^0 \rightarrow f_{CP})}{\Gamma(\bar{B}_s^0 \rightarrow f_{CP}) + \Gamma(B_s^0 \rightarrow f_{CP})} \approx \pm \sin(2\beta_s) \sin(\Delta m_s t),$$

it gives access to the angle  $\beta_s^{J/\psi \phi}$  of the unitarity triangle given by the second and third column of the CKM matrix:

$$(17) \quad 2\beta_s^{J/\psi \phi} = -\arg[(V_{tb}V_{ts}^*)^2/(V_{cb}V_{cs}^*)^2].$$

The presence of new physics enhancing  $\phi_s$  would affect  $\beta_s^{J/\psi \phi}$  in the same way [9].

The  $J/\psi \phi$  final state can be reached with and without mixing and is a mixture of  $CP$  even and odd states. In the decay of the pseudoscalar  $B_s^0$ -meson into two vector mesons  $J/\psi$  and  $\phi$ , the  $L = 0, 2$  states are  $CP$  even and the  $L = 1$  state is  $CP$  odd. The sensitivity to the phase is increased by studying the time evolution of  $CP$  even and  $CP$  odd states separately, which can be distinguished by the angular distributions of their decay products. Information about mixing is gained by tagging the production flavour of the  $B_s^0$ -meson.

Both Tevatron experiments have performed flavour tagged analyses on  $2.8 \text{ fb}^{-1}$  of data [10,11]. However, they use different conventions: CDF aims for measuring  $\beta_s^{J/\psi \phi}$ , while DØ uses  $\phi_s^{J/\psi \phi} = -2\beta_s^{J/\psi \phi}$ . For easier reading, only  $\beta_s^{J/\psi \phi}$  will be used in the

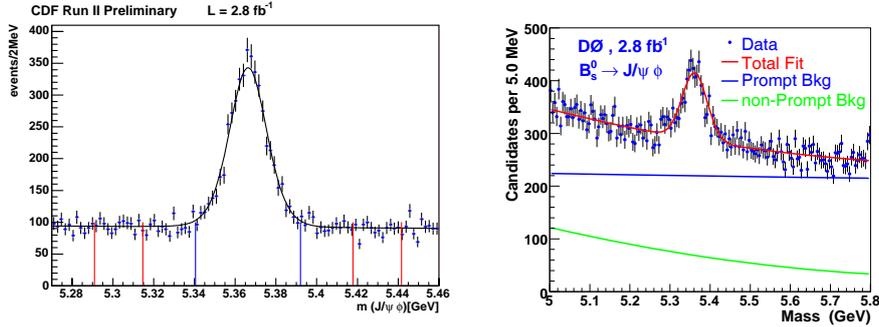


Fig. 3. – Mass distribution of the  $B_s^0 \rightarrow J/\psi \phi$  signal sample for the CDF (left) and the  $D\phi$  analysis (right).

following text. In both cases, the samples of

$$(18) \quad B_s^0 \rightarrow J/\psi \phi, \quad J/\psi \rightarrow \mu^+ \mu^-, \quad \phi \rightarrow K^+ K^-$$

decays have been collected with a di-muon trigger. A selection based on artificial neural networks leads to about 3200 signal events for the CDF analysis, while  $D\phi$  yields approximately 2000 signal events from a cut based selection. The resulting mass spectra can be found in fig. 3.

Information about the  $B_s^0$  production flavour can be gained from various sources. As  $b$ -quarks at the Tevatron are usually produced in form of  $b\bar{b}$  pairs, there are experimental signatures of a second  $B$ -hadron (the so-called *opposite-side B*) besides the  $B_s^0$ -meson (the *same-side B*) that was reconstructed in the decay to  $J/\psi \phi$ .

Same-side tagging makes use of fragmentation tracks: As the  $B_s^0$ -meson contains an  $s$ -quark, the fragmentation partner of that  $s$ -quark must be somewhere in the vicinity. If it ends up in a charged kaon, the charge of this kaon is correlated to the  $B_s^0$  production flavour. Opposite-side tagging evaluates the properties and decay tracks of the other  $B$ -hadron in the event. The inclusive charge of the opposite-side  $B$  decay jet, leptons from semileptonic  $B$  decays as well as kaons from the  $b \rightarrow c \rightarrow s$  decay chain are the main sources of information.

In a binary decision, the chance that a random decision is correct is already 50%. Therefore, the *dilution* of a flavour tagging algorithm

$$(19) \quad \mathcal{D} = \frac{N_{RS} - N_{WS}}{N_{RS} + N_{WS}}$$

is zero if the number of correct decisions  $N_{RS}$  equals the number of incorrect decision  $N_{WS}$ . As most tagging algorithms do not provide a decision for every event, the *efficiency*  $\epsilon$  gives the fraction of tagged events. The effective reduction of statistics due to flavour tagging uncertainties usually scales with  $\epsilon \mathcal{D}^2$  and is called the *tagging effectiveness*.

CDF uses a same-side kaon tagging algorithm with  $\epsilon \mathcal{D}^2 = 3.7\%$  for the first  $1.35 \text{ fb}^{-1}$  of the dataset. For the whole  $2.8 \text{ fb}^{-1}$ , a neural network combination of opposite-side electron, muon and jet charge taggers with  $\epsilon \mathcal{D}^2 = 1.8\%$  is used.  $D\phi$  combined existing same-side and opposite-side tagging with a likelihood method with a tagging effectiveness  $\epsilon \mathcal{D}^2 = 4.7\%$ .

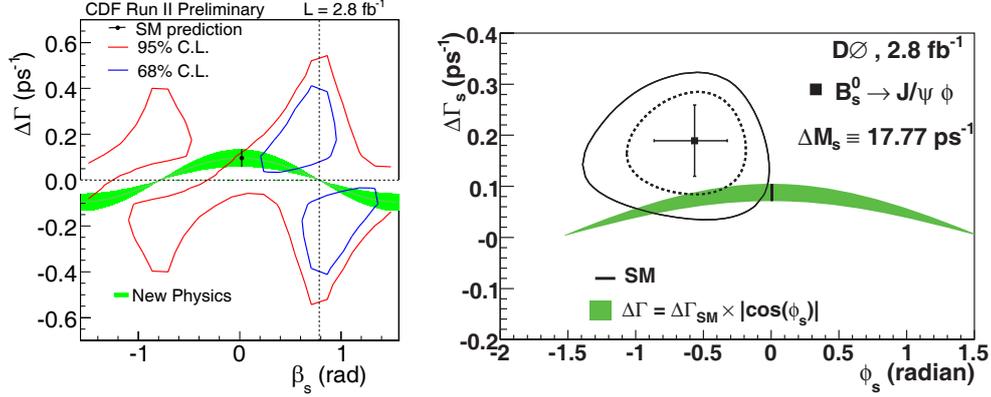


Fig. 4. – (Colour online) Confidence regions of the CDF (left) and DØ (right)  $B_s^0 \rightarrow J/\psi \phi$  analyses.

To extract  $\Delta\Gamma$  and  $\beta_s^{J/\psi \phi}$ , an unbinned maximum-likelihood fit is performed in mass, tagging information, proper decay time and angular distributions. Due to an indeterminacy of the strong phases in the three decay amplitudes of the  $L = 0, 1, 2$  final states, the likelihood function shows two symmetric minima in the  $(\Delta\Gamma_s, \beta_s^{J/\psi \phi})$ -plane. Because the two minima overlap and do not have a Gaussian shape, CDF evaluates confidence regions using the Feldman Cousins method, while DØ decided to constrain the strong phases and remove one of the minima. The resulting contours can be seen in fig. 4. The green band indicates the physical region under the assumption that new physics only affects  $M_{12}$ , but not  $\Gamma_{12}$  [1]. Currently, the compatibility with the Standard Model point is  $1.8\sigma$  for the CDF and  $1.7\sigma$  for the DØ result. Both contours seem to favour a minimum in the same region of the parameter space.

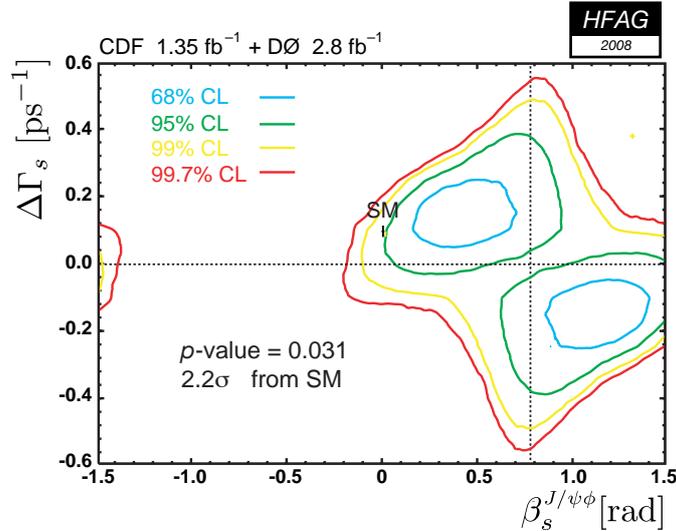


Fig. 5. – HFAG combination of the  $2.8 \text{ fb}^{-1}$  DØ analysis [11] with the  $1.35 \text{ fb}^{-1}$  CDF analysis [13].

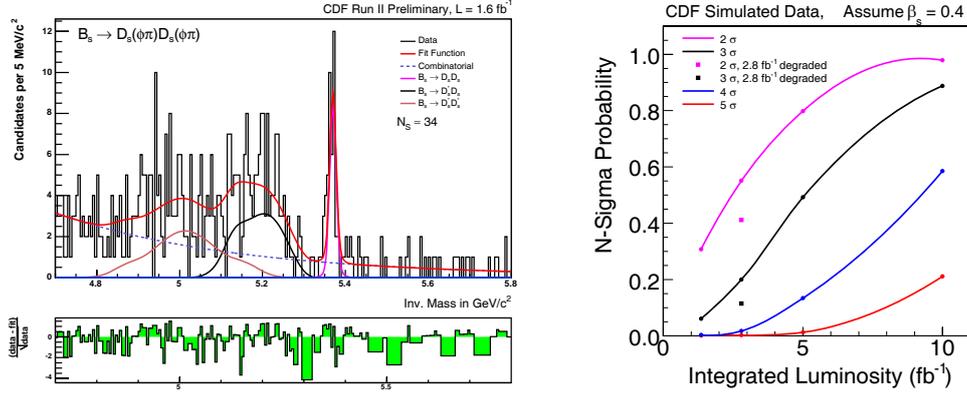


Fig. 6. –  $B_s^0 \rightarrow D_s D_s$  invariant mass spectrum on  $1.6 \text{ fb}^{-1}$  from the update of the CDF  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$  analysis (left) and sensitivity projection for a  $N$ - $\sigma$  observation if  $\beta_s = 0.4$  as a function of integrated luminosity (right).

The Heavy Flavor Averaging Group (HFAG) combined the current  $D\bar{O}$  result on  $2.8 \text{ fb}^{-1}$  with the previous CDF result on  $1.35 \text{ fb}^{-1}$  [13] using the two-dimensional profile likelihoods [12].  $D\bar{O}$  released the strong phase constraint for that combination. The resulting contour can be seen in fig. 5. In the combined result, a discrepancy to the Standard Model prediction of  $2.2\sigma$  is observed.

### 5. – Outlook

Each of the two Tevatron experiments has around  $5 \text{ fb}^{-1}$  data ready for use in the upcoming analysis updates. As the accelerator is performing very well and the initial luminosities are still being improved, even more data can be expected in the remaining time of Tevatron operations.

An updated  $B_s^0 \rightarrow D_s^{(*)} D_s^{(*)}$  analysis including  $D_s^*$  states is in preparation by the CDF collaboration. A preliminary mass spectrum can be seen in fig. 6. Besides more data, other analysis improvements for  $B_s^0 \rightarrow J/\psi \phi$  are in preparation.  $D\bar{O}$  plans to improve the selection of candidates, while improved flavour tagging has been developed at CDF. For future Tevatron results of  $B_s^0 \rightarrow J/\psi \phi$ , a combination group has been installed. Not only a combination of the two-dimensional profile likelihoods, also a simultaneous fit on the full-likelihood functions is planned. In fig. 6, a projection is shown on what could be reached with future Tevatron data. If new physics actually causes a large phase  $\beta_s^{J/\psi \phi} = 0.4$  in  $B_s^0$  mixing, there is a reasonable chance to observe it when combining the power of both Tevatron experiments.

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