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.
PACS `14.40.Nd` – Bottom mesons.

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

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

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

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

$$|B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle. \tag{3}$$

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

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

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

where ϕ_s is a complex phase between M_{12} and Γ_{12}:

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

The CP operator leads to the *CP eigenstates*

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

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

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

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

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 Γ_{12} but could contribute to M_{12} [1], the phase ϕ_s between the two elements can be significantly enhanced by new physics effects.

Δm_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 $B_s^0 \to D_s D_s$ final state gives access to $\Delta\Gamma^{CP}$, while information on ϕ_s can be gained in B_s^0 decays to a flavour specific final state as well as from $B_s^0 \to J/\psi\ \phi$ decays. These measurements will be presented in the following sections.

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

The CKM favoured $B_s^0 \to c\bar{c}s\bar{s}$ 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 $B_s^0 \to D_s D_s$ final state is purely CP even [4]. In the Shifman-Voloshin limit assuming $m_b - 2m_c \to 0$ and infinite number of colours [5], also $B_s^0 \to D_s^{(*)} D_s^{(*)}$ 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:

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \approx 2 \cdot Br[B_s^0 \to D_s^{(*)} D_s^{(*)}] \tag{10}$$

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

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

The CDF analysis of $B_s^0 \to D_s D_s$ uses 360 fb^{-1} of data [7]. This analysis observed the decay at 7.5σ. 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:

$$\Delta\Gamma_s^{CP}/\Gamma_s \geq 0.012 \text{ at } 95\%\ C.L. \tag{12}$$

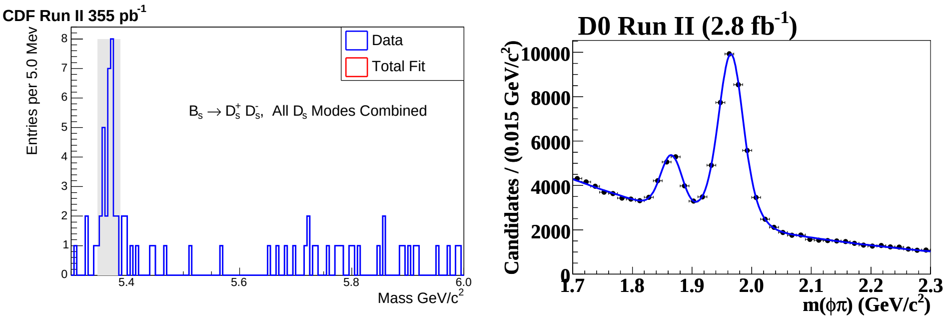

Fig. 1. – The mass spectrum observed in the CDF $B_s^0 \to D_s D_s$ analysis is shown in the left plot. In the DØ mass spectrum on the right, the peak at higher mass is from D_s and the lower peak from $D^{\pm}$ cadidates.

In fig. 1, the observed mass spectra from the two experiments can be seen. Because DØ 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 ϕ_s can be gained by measuring the CP asymmetry

$$a^s_{fs} = \frac{\Gamma_{\bar{B}^0_s \to f} - \Gamma_{B^0_s \to \bar{f}}}{\Gamma_{\bar{B}^0_s \to f} + \Gamma_{B^0_s \to \bar{f}}} = \frac{|M_{12}|}{|\Gamma_{12}|}\sin(\phi_s) \qquad (13)$$

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, $B_s^0 \to f$ and $\bar{B}_s^0 \to \bar{f}$ are allowed, while $B_s^0 \to \bar{f}$ and $\bar{B}_s^0 \to f$ can only be reached via mixing. The Standard Model expectation is $a^s_{fs} = (2.06 \pm 0.57) \cdot 10^{-5}$ [1].

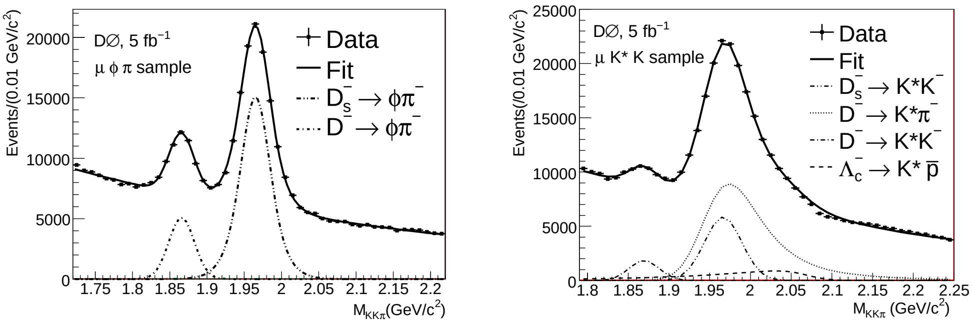

Fig. 2. – Mass distributions observed in the DØ a^s_{fs} analysis. The $D_s^- \to \phi\pi^-$ channel can be seen in the left plot, the $D_s^- \to \mu^+ K^{*0} K^-$ on the right.

The DØ collaboration performed a time dependent a^s_{fs} analysis on 5 fb^{-1} [8] in the decay

$$B_s^0 \rightarrow \mu^+ D_s^- X \tag{14}$$

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 DØ detector was reversed regularly during data taking.

The resulting measurement

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

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

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

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:

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

The presence of new physics enhancing ϕ_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/ψ and ϕ, 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 distiguished 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 fb^{-1} of data [10, 11]. However, they use different conventions: CDF aims for measuring $\beta_s^{J/\psi\ \phi}$,

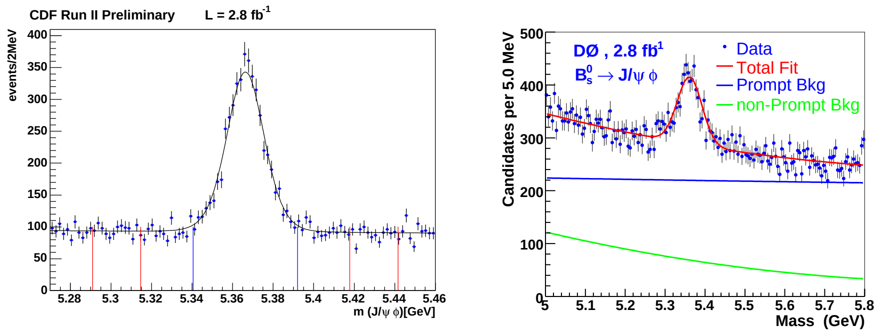

Fig. 3. – Mass distribution of the $B_s^0 \to J/\psi\ \phi$ signal sample for the CDF (left) and the DØ analysis (right).

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 following text. In both cases, the samples of

$$B_s^0 \to J/\psi\ \phi, J/\psi \to \mu^+\mu^-, \phi \to K^+K^- \tag{18}$$

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 DØ 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 $b \to c \to s$ 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

$$\mathcal{D} = \frac{N_{\rm RS} - N_{\rm WS}}{N_{\rm RS} + N_{\rm WS}} \tag{19}$$

is zero if the number of correct decisions $N_{\rm RS}$ equals the number of incorrect decision $N_{\rm WS}$. As most tagging algorithms do not provide a decision for every event, the *efficiency* ϵ 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 $\epsilon\mathcal{D}^2 \approx 4\%$ for the first 1.35 fb^{-1} of the dataset. For the whole 2.8 fb^{-1}, a neural network combination of opposite side electron, muon and jet charge taggers with $\epsilon\mathcal{D}^2 = 1.8\%$ is used. DØ combined existing same side and opposite side tagging with a likelihood method with a tagging effectiveness $\epsilon\mathcal{D}^2 = 4.7\%$.

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 Γ_{12} [1]. Currently, the compatibility with the Standard Model point is 1.8σ for the CDF and 1.7σ for the DØ result. Both contours seem to favour a minimum in the same region of the parameter space.

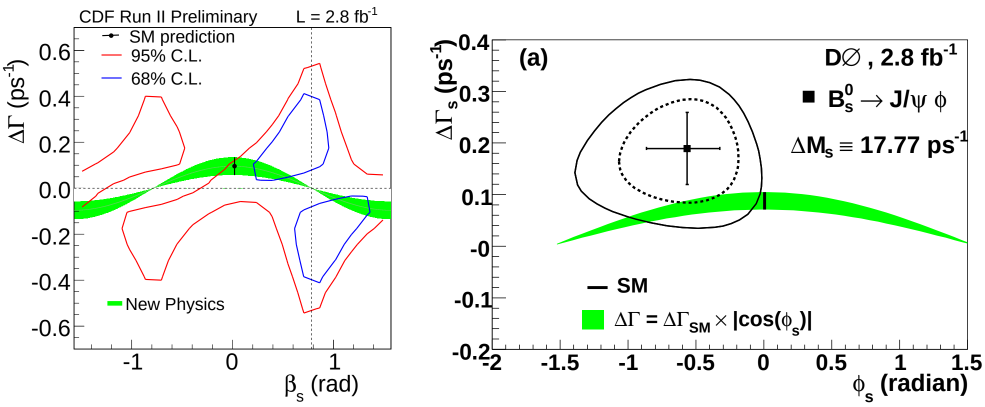

Fig. 4. – Confidence regions of the CDF (left) and DØ (right) $B_s^0 \to J/\psi\ \phi$ analyses.

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

5. – Outlook

Each of the two Tevatron experiments has around 5 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 $B_s^0 \to D_s^{(*)} D_s^{(*)}$ 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 $B_s^0 \to J/\psi\ \phi$ are in preparation. DØ plans to improve the selection of candidates, while improved flavour tagging has been developed at CDF. For future Tevatron results of $B_s^0 \to J/\psi\ \phi$, a combination group has been installed. Not only a combination of the two-dimensional profile likelihoods, also a simultaneous

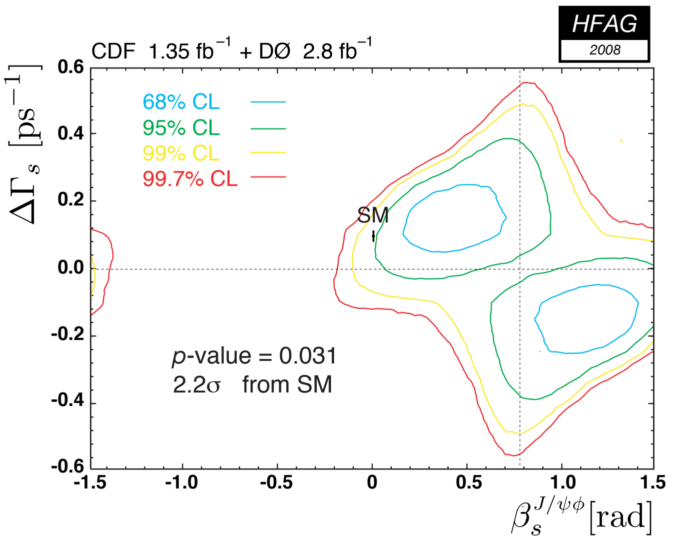

Fig. 5. – HFAG combination of the 2.8 fb^{-1} DØ analysis [11] with the 1.35 fb^{-1} CDF analysis [13].

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.

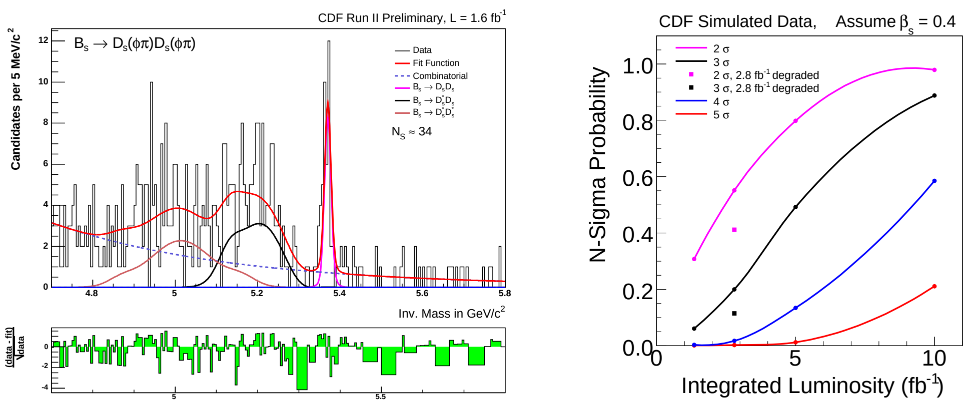

Fig. 6. – $B_s^0 \to D_s D_s$ invariant mass spectrum on 1.6 fb^{-1} from the update of the CDF $B_s^0 \to D_s^{(*)} D_s^{(*)}$ analysis (left) and sensitivity projection for a N-σ observation if $\beta_s = 0.4$ as a function of integrated luminosity (right).

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