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Study of CP violation in $B_s \to J/\psi\ \phi$ decays at CDF

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The first measurement of the CP violation phase β_s in $B_s \to J/\psi\ \phi$ decays in 2007 generated considerable interest. The interest was caused by the small deviation from the SM. While not sufficiently significant, together with other measurements it is suggestive of a possible new physics contribution. In the subsequent update using 2.8 fb^{-1} of data collected by the CDF II detector, the significance of the deviation from the SM further increased. We present latest CDF results on the mean decay width Γ_s and CP violating phase β_s, based on an angular- and time-dependent analysis of the $B_s \to J/\psi\ \phi$ decays, including determination of the flavor of the B_s meson at production time.

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For the search of new physics in quark transitions, the study of oscillating particles is an ideal research field. While the B^0 and the K^0 meson are already well explored, many parameters of the B_s^0 and D^0 meson are still unknown. For the B_s^0, one major milestone in the past was the measurement of its mixing frequency, which was performed in 2006 by both Tevatron experiments CDF and DØ. The following article focusses on the measurement of the CP-violating phase $\beta_s^{J/\psi\phi}$ in $B_s^0 \to J/\psi\phi$ [1].

There are several bases of eigenstates, which are used to describe the neutral B_s^0 meson system. The *flavor eigenstates* are defined by the quark content: $|B_s^0\rangle = |\bar{b}s\rangle$ and $|\bar{B_s^0}\rangle = |b\bar{s}\rangle$. Their time evolution is given by the Schrödinger equation

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

This equation contains the mass matrix M and the decay matrix Γ, which are both hermitian and 2×2 in size. A diagonalization of this effective Hamiltonian leads to the heavy and light *mass eigenstates*:

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

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

In order to preserve normalisation, the complex parameters p and q must fulfill the requirement $|p|^2+|q|^2=1$. Mass and decay 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} defined by

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

The standard model prediction for this phase is $\phi_s = 0.004$ [2].

The CP violating phase β_s is defined by elements of the CKM matrix:

$$\beta_s^{SM} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \tag{7}$$

Its expectation value is $\beta_s^{SM} = 0.02$. For the decay channel used in this analysis, the existence of new physics would affect both phases introduced by the *same* quantity ϕ_s^{NP} [2]:

$$2\beta_s^{J/\psi\phi} = 2\beta_s^{SM} - \phi_s^{NP} \quad \text{and} \quad \phi_s = \phi_s^{SM} + \phi_s^{NP} \tag{8}$$

In case ϕ_s^{NP} dominates over $2\beta_s^{SM}$ and ϕ_s^{SM}, the standard model phases can be neglected. In this way an easy relationship is obtained:

$$2\beta_s^{J/\psi\phi} = -\phi_s^{NP} = -\phi_s \tag{9}$$

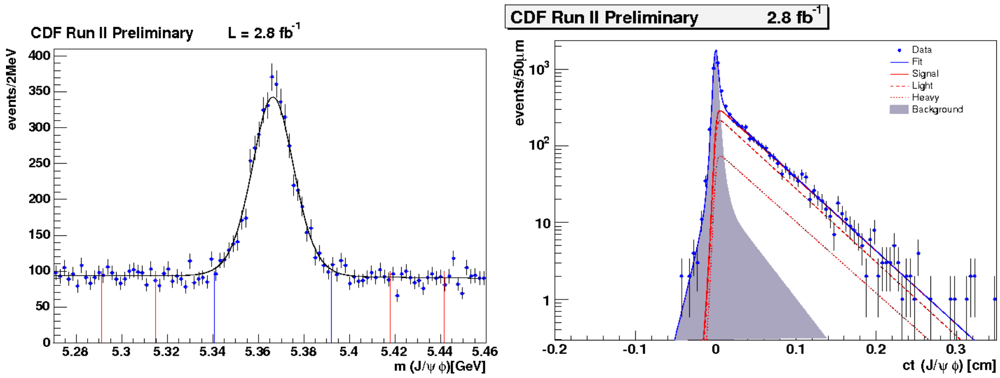

Figure 1: Projections of the result of the unbinned maximum likelihood fit. Mass is shown on the left-hand side, the proper decay time is shown on the right-hand side.

The following B_s^0 decay channel is used for the analysis at hand:

$$B_s \longrightarrow J/\psi(\rightarrow \mu^+\mu^-)\ \phi(\rightarrow K^+K^-) \tag{10}$$

Here the same final state can be reached with and without mixing. The B_s^0 itself is a pseudo-scalar meson while its decay products J/ψ and ϕ are both vector mesons. The final state is a mixture of CP eigenstates, which can be distinguished using the angular quantum number: the $L=0,2$ states are CP even and the $L=1$ state is CP odd.

The data used within this analysis was taken with the CDF detector using proton-antiproton collisions at a center of mass energy of $\sqrt{s}=1.96$ TeV. Those were provided by the Tevatron, a circular particle accelerator at the Fermilab (near Chicago, Illinois). A data amount corresponding to an integrated luminosity of 2.8 fb^{-1} was used. The decays have been collected with a di-muon trigger. The selection was achieved by artificial neural networks and yields about 3200 signal events.

In order to extract the CP violating phase $\beta_s^{J/\psi\phi}$ and the decay width difference $\Delta\Gamma$, an unbinned maximum likelihood fit is used. The fit uses mass, transversity angles, proper decay time and flavor tagging information of each event.

The angular quantities are used to disentangle CP even and CP odd components. This allows for the separate study of those states in proper decay time which increases the sensitivity to the phase $\beta_s^{J/\psi\phi}$.

Flavor tagging refers to the estimation of the production flavor of the B_s^0 candidate. Two different mechanisms are currently used at the CDF experiment: *opposite side tagging* is based on the fact that b quarks at the Tevatron are usually produced in form of $b\bar{b}$ pairs. Here the signatures of the second B hadron are used to reconstruct the production flavor of the signal B_s^0 candidate. *Same side tagging* uses 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 forms a charged kaon, the production flavor of the B_s^0 can be concluded from it.

Projection plots into mass and proper decay time of the unbinned fit can be seen in figure 1. An additional measurement on the mean lifetime assuming no CP violation ($\beta_s^{J/\psi\phi}=0$) gives $\tau(B_s)=(1.53\pm0.04(\text{stat.})\pm0.01(\text{syst.}))$ ps, which is consistent with previous measurements.

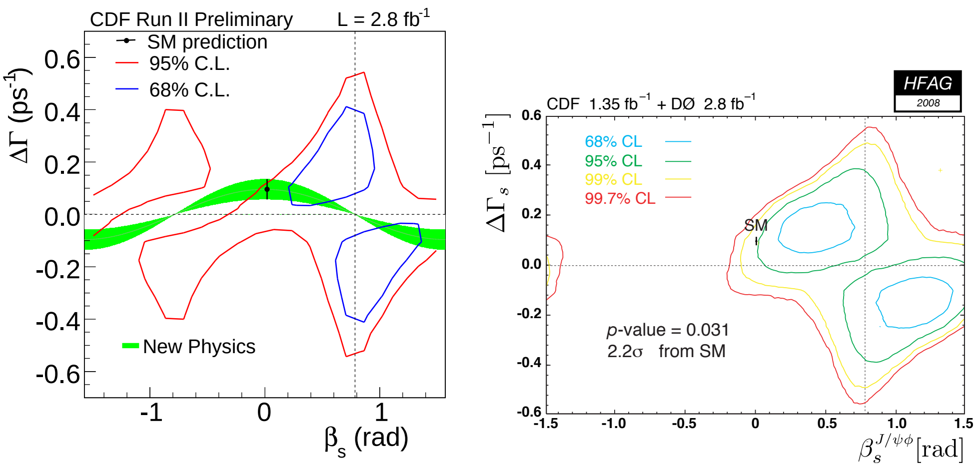

Figure 2: Confidence regions in the $\Delta\Gamma$-β_s-plane. The plot on the left-hand side shows the CDF result. A combination between the DØ and a previous CDF result is shown on the right-hand side.

The uncertainties in the parameter space of β_s and $\Delta\Gamma$ are not Gaussian. Therefore, instead of giving point estimates, a confidence region is studied (figure 2, left). It is determined using a frequentist method and features two distinct, symmetric minima. They are caused by the exact symmetry of the strong phases in the three decay amplitudes of the $L = 0, 1, 2$ final states. The green band indicates the physical region under the assumption that new physics only affects M_{12}, but not Γ_{12} [2]. The deviation from the standard model (black point) amounts 1.8 σ.

DØ, an experiment which is also located at the Tevatron, observes a similar result [3]. The Heavy Flavor Average Group (HFAG) combined it with the previous CDF measurement, which is based on 1.35 fb^{-1} of data [4]. The result of this combination is shown in figure 2 on the right-hand side. Here a deviation from the standard model of 2.2σ is observed.

Altogether, the consistent pattern of those systematic deviation from the standard model is interesting. One possible explanation of those observations is the presence of a t' quark with mass between ~ 300 and ~ 1000 GeV/c^2 [5]. Great efforts are made to update this measurement with more data. Events taken with the two track trigger are studied in order to increase statistics. Furthermore improvements in tagging and particle identification will also be used.

References

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