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CP parameters of the B systems from Tevatron

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Recent results on CP parameters of the B systems obtained by the CDF and DØ collaborations using the data samples collected at the Tevatron Collider in the period 2002 – 2007 were presented at the QCD 2008 conference (Montpellier, France). These results include measurements of the mixing phase $\phi_s^{J/\psi\phi}$, decay width difference $\Delta\Gamma_s$, and CP violation parameters in the B_s and B_u decays.

1. Introduction

The CDF and DØ experiments have successfully collected data since start of the Run II at the Tevatron Collider in 2001. The presented results correspond to an integrated luminosity of up to 2.8 fb^{-1} at each experiment. The large B-meson production cross-section allows enough data to be collected to study the tiny effects of CP-violation in B systems. In particular, the results described in this paper cover measurements of the mixing phase $\phi_s^{J/\psi\phi}$, decay width difference $\Delta\Gamma_s$, semileptonic asymmetry a_s^{sl} in the B_s system and direct CP violation in the B_s and B_u systems.

A theoretical overview of $B_s - \bar{B}_s$ mixing is given in [1,2]. Flavour eigenstates of B_s meson propagate according to the Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix} = \left(M_s - i\frac{\Gamma_s}{2}\right)\begin{pmatrix} |B_s^0(t)\rangle \\ |\bar{B}_s^0(t)\rangle \end{pmatrix} \quad (1)$$

The physical eigenstates $|B_H\rangle$ and $|B_L\rangle$ have different masses and lifetimes:

$$\Delta M_s = M_H^s - M_L^s = 2|M_{12}^s|, \quad (2)$$

$$\Delta\Gamma_s = \Gamma_L^s - \Gamma_H^s = 2|\Gamma_{12}^s| cos\phi_s, \quad (3)$$

where

$$\phi_s = arg(-M_{12}^s/\Gamma_{12}^s) \quad (4)$$

is the CP phase. The CP phase for the B_s system is very small in the Standard Model (SM): $\phi_s^{SM} \approx 0.004$. The review [2] predicts that the CP phase ϕ_s is the most sensitive to the new physics effects. The semileptonic asymmetry defined as

$$a_{sl}^s = \frac{N(\bar{B}_s \to f) - N(B_s \to \bar{f})}{N(\bar{B}_s \to f) + N(B_s \to \bar{f})}, \quad (5)$$

where f corresponds to direct B_s decays $B_s \to f$ (e.g. $D_s^- l^+ \nu_l$), is related to the CP phase:

$$a_{sl}^s = \frac{\Delta\Gamma_s}{\Delta M_s}\tan\phi_s. \quad (6)$$

Measurements of all four parameters in the equation 6 allow testing of the SM predictions with high sensitivity. The mixing phase β_s with the SM prediction $\beta_s^{SM} = arg(-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)) \approx 0.02$ measured in decays $B_s \to J/\psi\phi$ is also related to the phase ϕ_s (see note in [3]). In paper [4] the notation $\phi_s = -2\beta_s$ is used, but to distinguish this phase from the CP phase ϕ_s defined above in equation 4 the notation $\phi_s^{J/\psi\phi} = -2\beta_s^{J/\psi\phi}$ as in [5] is preferable. The new physics contribution could be described by the phase ϕ_s^{NP} which modifies the original mixing phases in the following way: $\phi_s = \phi_s^{SM} + \phi_s^{NP}$ and $\beta_s = \beta_s^{SM} - \phi_s^{NP}/2$.

2. $\phi_s^{J/\psi\phi}$ from $B_s \to J/\psi\phi$ [4,6]

The system $J/\psi + \phi$ from B_s decay represents an admixture of CP-even and CP-odd states. Angular analysis could be used to separate the CP components (see figure 1) and measure the lifetime of each component and phase $\phi_s^{J/\psi\phi}$ [7]. Additional information on the initial state flavor of the B_s meson helps resolve the sign ambiguity on $\phi_s^{J/\psi\phi}$ for a given $\Delta\Gamma_s$ and improves the precision of results. The CDF collaboration used the data

sample corresponding to 1.7 fb^{-1} (this result was updated recently using 2.8 fb^{-1} data sample [8]) and the DØ data sample corresponds to 2.8 fb^{-1}. Constraints on the strong phases δ_i from the B_d system allow the sign ambiguity on $\Delta\Gamma_s$ to be resolved (see recent theoretical work [9]). The CDF and DØ results obtained with different constraints, and compared with the SM prediction are shown in figure 2. The HFAG combination [5] gives two sets of the numerical results obtained with free phases δ_i:

- $\Delta\Gamma_s = 0.154^{+0.054}_{-0.070}$ ps^{-1},
  $\phi_s^{J/\psi\phi} = -2\beta_s^{J/\psi\phi} = -0.77^{+0.29}_{-0.37}$ rad;

- $\Delta\Gamma_s = -0.154^{+0.070}_{-0.054}$ ps^{-1},
  $\phi_s^{J/\psi\phi} = -2\beta_s^{J/\psi\phi} = 2.36^{+0.37}_{-0.29}$ rad.

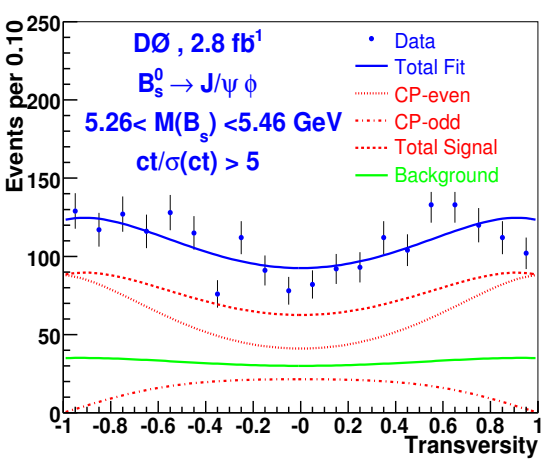

Figure 1. The transversity distribution for the signal-enhanced $J/\psi\phi$ subsample: non-prompt and signal mass region. The curves show: the signal contribution, dotted (red); the background, light solid (green); and total, dark solid (blue).

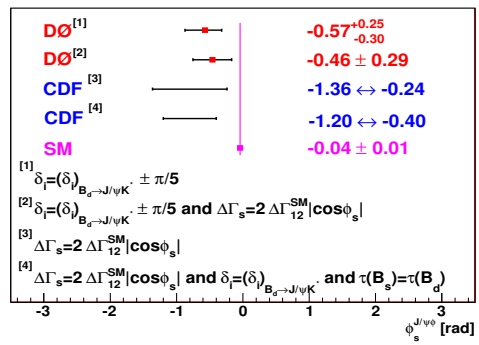

Figure 2. Comparison of the $\phi_s^{J/\psi\phi}$ results from CDF and DØ with the SM prediction.

3. $\Delta\Gamma_s$ from $B_s \to D_s^{(*)} D_s^{(*)}$ [10]

The final state in $B_s \to D_s^{(*)} D_s^{(*)}$ decays is CP-even, although the theoretical uncertainty is not well understood (see for example the discussion in [2]). The branching ratio $Br(B_s \to D_s^{(*)} D_s^{(*)})$ could be used to calculate the decay width difference from the following equation derived in [1]:

$$2 \cdot Br(B_s \to D_s^{(*)} D_s^{(*)}) \approx \Delta\Gamma_s^{CP} \left(\frac{1+\cos\phi_s}{2\Gamma_L} + \frac{1-\cos\phi_s}{2\Gamma_H} \right). \quad (7)$$

The efficient muon triggering system at DØ provides access to these decays through the muons from semileptonic decays of D_s mesons: $B_s \to D_s^{(*)}(\to (\gamma)\phi\pi) D_s^{(*)}(\to (\gamma)\phi\mu\nu)$. Narrow invariant mass peaks from the $\phi \to KK$ decays help to ensure a clean data sample. The number of selected $D_s\phi\mu$ candidates was determined to be $N(D_s\phi\mu) = 31.0 \pm 9.4$ and the resulting branching ratio: $Br(B_s \to D_s^{(*)} D_s^{(*)}) = 0.042 \pm 0.015(stat.) \pm 0.017(syst.)$. Assuming no new physics effects (the SM value of $\phi_s^{SM} \approx 0.004$) one can estimate the decay width difference from equation 7: $\frac{\Delta\Gamma_s}{\Gamma_s} = 0.088 \pm 0.030(stat.) \pm 0.036(syst.)$.

4. CP violation

4.1. B_s semileptonic decays [11,12]

The SM prediction for the semileptonic asymmetry in B_s decays is very small [2]: $a^s_{sl} = (2.06 \pm 0.57) \cdot 10^{-5}$. At the Tevatron the semileptonic asymmetry could be measured either from an inclusive di-muon sample, where $a^s_{sl} \sim \frac{N_{\mu^+\mu^+} - N_{\mu^-\mu^-}}{N_{\mu^+\mu^+} + N_{\mu^-\mu^-}}$, or by using the $XD_s\mu$ sample. The first method has very high statistical accuracy, but requires knowledge of asymmetries of other contributing processes in addition to the detector charge asymmetries. The second method has less statistical power but ensures that the major contribution to the asymmetry comes from the B_s decays. The time-integrated untagged analysis at DØ used the data sample $XD_s(\phi\pi)\mu$ corresponding to 1.3 fb^{-1} to obtain the result $a^s_{sl} = 0.0245 \pm 0.0193 \pm 0.0035$ [13] (this analysis was recently updated using a larger data sample, time dependence and initial-state tagging [14]). The description of the method used to determine the detector asymmetries at DØ is given in [15] where the di-muon asymmetry result is presented. The combination of the two DØ results is published in [12]: $a^s_{sl} = 0.0001 \pm 0.0090$.

The preliminary CDF result obtained using the inclusive di-muon sample is shown in [11]: $a^s_{sl} = 0.020 \pm 0.021 \pm 0.018$.

4.2. $B_s \to K\pi$ [16]

The recent measurements of direct CP violation in the B_u and B_d systems led to the $K\pi$ puzzle (see for example [17]). It is therefore important to measure similar signatures in the B_s system (see discussion in [18]). The impact parameter triggers at CDF are used to collect the hadronic B-decays which are necessary for studies of CP eigenstates. Figure 3 shows the invariant mass distribution for 2 body hadronic decays at CDF assuming pion masses for the tracks. This sample allowed CDF to produce the only measurement of direct CP violation in the B_s system: $A_{CP}^{B_s \to K^-\pi^+} = \frac{N_{\bar{B}_s \to K^+\pi^-} - N_{B_s \to K^-\pi^+}}{N_{\bar{B}_s \to K^+\pi^-} + N_{B_s \to K^-\pi^+}} = 0.39 \pm 0.15(stat.) \pm 0.08(syst.)$. This result is in agreement with the theoretical predictions [19].

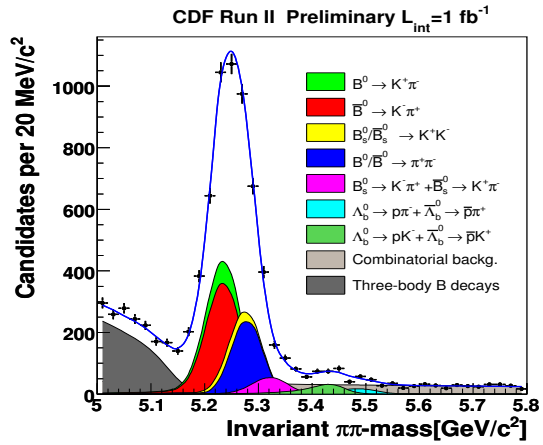

Figure 3. Invariant $\pi\pi$-mass of $B \to h^+h^-$ candidates where h is K or π.

4.3. $B^\pm \to D^0K^\pm$ [22]

CP analysis of the decays $B^\pm \to D^0K^\pm$ represents another example of using the impact parameter triggers at CDF. The CP asymmetry is measured in these decays. This asymmetry is relevant for the determination of the CKM angle γ (see [23,24]). The D^0 meson decays either to CP eigenstates K^+K^- ($\pi^+\pi^-$), or flavour eigenstate $K^-\pi^+$. The different modes were separated using invariant masses, momentum imbalance, total momentum and dE/dx information. The measured asymmetries agree with the B-factory measurements [25,26] and have competitive precision: $A_{CP+} = \frac{Br(B^- \to D^0_{CP+}K^-) - Br(B^+ \to D^0_{CP+}K^+)}{Br(B^- \to D^0_{CP+}K^-) + Br(B^+ \to D^0_{CP+}K^+)} = 0.37 \pm 0.14(stat.) \pm 0.04(syst.)$, $R = \frac{Br(B^- \to D^0K^-) - Br(B^+ \to \bar{D}^0K^+)}{Br(B^- \to D^0K^-) + Br(B^+ \to \bar{D}^0K^+)} = 0.0745 \pm 0.0043(stat.) \pm 0.0045(syst.)$, $R_{CP+} = \frac{Br(B^- \to D^0_{CP+}K^-) + Br(B^+ \to D^0_{CP+}K^+)}{(Br(B^- \to D^0K^-) + Br(B^+ \to \bar{D}^0K^+))/2} = 1.57 \pm 0.24(stat.) \pm 0.12(syst.)$.

4.4. $B^\pm \to J/\psi K^\pm$ [20]

Highly efficient di-muon triggers allow for collection of large J/ψ samples at Tevatron which are competitive with the B-factories in some of the CP violation measurements in B_u and B_d

systems. The SM expectation of the direct CP asymmetry in $B^{\pm} \to J/\psi K^{\pm}$ decays is small: $A_{SM}^{J/\psi K} \sim 0.003$ [21]. However, the new physics effects (for example a fourth generation) may enhance the asymmetry up to 0.01. The DØ experiment measured this asymmetry to be $A^{J/\psi K} = +0.0075 \pm 0.0061(stat.) \pm 0.0027(syst.)$.

5. Conclusion

So far, the Tevatron experiments CDF and DØ have provided the unique sources of the CP parameters in B_s system. The complimentary measurements in $B_{u/d}$ systems are not only supporting the B_s analyses but also providing results competitive with the B-factories. Interestingly though, the CP parameters in the B_s system start showing some deviations from the SM predictions in addition to the $B_{u/d}$ puzzles. All analyses are statistically limited and the precision will improve in the near future.

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