

Measurements of CP violation in the B_s system at D0

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An updated measurement of the CP-violating phase $\phi_s^{J/\psi\phi}$ and measurement of the relative branching ratio of $B_s \rightarrow J/\psi f_0$ to $B_s \rightarrow J/\psi \phi$ using data samples corresponding to an integrated luminosity of 8 fb^{-1} recorded with the D0 detector are reported.

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1. Introduction

One of the most intriguing Tevatron results is related to the charge-conjugation-parity (CP) violation measurements in the B_s system. Both CDF and D0 experiments [1, 2] observed deviations from the Standard Model predictions for the CP-violating phase ($\phi_s^{J/\psi\phi}$) which is measured in the $B_s \rightarrow J/\psi \phi$ decays. Though the deviations are not statistically significant, they agree with each other and with the measurement of the CP violation in the B_s system using same-sign dimuon events [3]. In the Standard Model (SM) the decay $B_s \rightarrow J/\psi \phi$ goes through the decay of the b -quark to $c\bar{c}s$ combination, and the value of $\phi_s^{J/\psi\phi}$ is proportional to the angle β_s of the B_s Unitarity Triangle derived from the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [4] and determined by the interference of the decays with and without $B_s - \bar{B}_s$ mixing: $-2\beta_s^{SM} = \arg(V_{tb}V_{ts}^*)^2 - 2\arg(V_{cb}V_{cs}^*) = -0.038 \pm 0.002$ [5, 6, 7]. New physics contributions to the mixing could change the phase and be observed by measuring strong deviation from the predicted value: $\phi_s^{J/\psi\phi} = -2\beta_s^{SM} + \phi_{NP} \approx \phi_{NP}$. The measurement of $\phi_s^{J/\psi\phi}$ in the $B_s \rightarrow J/\psi \phi$ channel requires disentangling the CP-odd and CP-even final-decay states because both J/ψ and ϕ are vector mesons. The CP eigenstates have different angular distributions, masses ($\Delta M_s = M_H - M_L$) and decay widths ($\Delta\Gamma_s = \Gamma_L - \Gamma_H$) assuming mass eigenstates are pure CP eigenstates. Measurements of the CP-violating phase $\phi_s^{J/\psi\phi}$ depend on $\Delta\Gamma_s$, and the results are often presented as contours in the $(\phi_s^{J/\psi\phi}, \Delta\Gamma_s)$ plot. An additional complication in these measurements appears due to the $\sim 10\%$ non-resonant S -wave contribution under the ϕ peak (Fig. 1) [8] which introduces unknown fraction (F_S) and phase (δ_s) into the analysis.

The $\phi_s^{J/\psi\phi}$ measurement is more straightforward in $B_s \rightarrow J/\psi f_0$ decays due to the presence of the CP-odd final state only (f_0 meson is a scalar) [5] but the branching ratio $\mathcal{B}(B_s \rightarrow J/\psi f_0, f_0 \rightarrow \pi^+\pi^-)$ is approximately four times less than $\mathcal{B}(B_s \rightarrow J/\psi \phi, \phi \rightarrow K^+K^-)$. Precise determination of this ratio is the first step towards CP violation measurements using the $B_s \rightarrow J/\psi f_0$ channel.

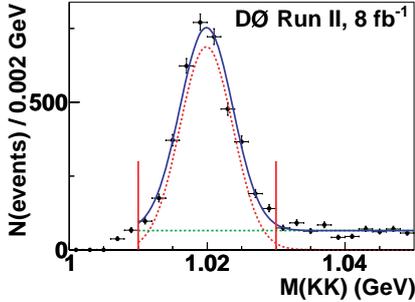


Figure 1: The invariant mass distribution of two kaon candidates when the $J/\psi K^+K^-$ invariant mass is consistent with the B_s mass. The solid line is a fit to a sum of the P -wave $\phi(1020)$ meson decay and a constant term due to S wave.

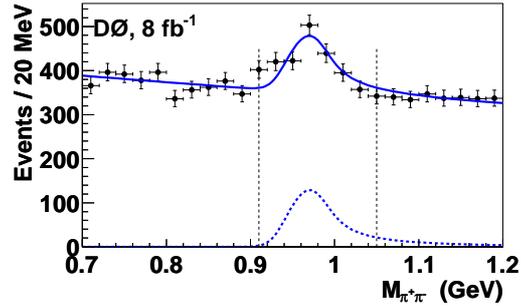


Figure 2: The invariant mass distribution of two pion candidates when the $J/\psi \pi^+\pi^-$ invariant mass is consistent with the B_s mass. The dashed line is the fitted $f_0(980)$ signal.

2. Event Selection

The signal event candidates for the $B_s \rightarrow J/\psi \phi$ and $B_s \rightarrow J/\psi f_0$ channels were selected using

the Boosted Decision Tree (BDT) algorithm. The $J/\psi \rightarrow \mu^+ \mu^-$ decays give a clean sample of J/ψ candidates. The signal candidates are constructed by adding two oppositely charged tracks which create a common vertex with the muons and have an invariant mass consistent with the ϕ (f_0) meson in kaon (pion) hypothesis (Figs. 1, 2). The BDT algorithms were trained on the Monte Carlo (MC) signal and background samples for background events suppression. Two types of background were considered separately: prompt (J/ψ mesons are produced directly) and non-prompt (J/ψ mesons are produced in decays of b -quarks).

The selections of $B_s \rightarrow J/\psi \phi$, $\phi \rightarrow K^+ K^-$ candidates in case of the relative branching ratio measurement of $B_s \rightarrow J/\psi f_0$ were fixed to be the same as for $B_s \rightarrow J/\psi f_0$, $f_0 \rightarrow \pi^+ \pi^-$ candidates except for the $f_0(980)$ mass requirement.

The selections of $B_s \rightarrow J/\psi \phi$, $\phi \rightarrow K^+ K^-$ candidates for the CP violation measurement were tuned to minimize statistical uncertainties on $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$. Simple selection criteria [9] were utilized for a second sample which has been used for consistency checks and systematic effects studies.

3. Measurement of the relative branching ratio of $B_s \rightarrow J/\psi f_0$ to $B_s \rightarrow J/\psi \phi$

The measurement of the relative branching ratio $R_{f_0/\phi} = \frac{N_{B_s \rightarrow J/\psi f_0}}{N_{B_s \rightarrow J/\psi \phi}} \cdot \frac{\epsilon_{reco}^{B_s \rightarrow J/\psi \phi}}{\epsilon_{reco}^{B_s \rightarrow J/\psi f_0}}$ requires knowledge of the corresponding event yields and reconstruction efficiencies. Detailed description of the analysis is given in [10]. The numbers of B_s events determined from the $J/\psi f_0$ and $J/\psi \phi$ mass distributions are 590 ± 84 and 2929 ± 62 respectively. The $B_s \rightarrow J/\psi \phi$ yield should be scaled by the factor 0.88 [2] to take into account the S -wave contribution. The mean relative reconstruction efficiency determined from MC samples and averaged over all the running periods is $\frac{\epsilon_{reco}^{B_s \rightarrow J/\psi \phi}}{\epsilon_{reco}^{B_s \rightarrow J/\psi f_0}} = 1.20 \pm 0.04$.

The resulting relative branching ratio is $R_{f_0/\phi} = 0.275 \pm 0.041(\text{stat}) \pm 0.061(\text{syst})$ with the systematic uncertainties originating from fitting (17.3%), MC efficiency (9.2%), modeling variables in BDT (8.9%), $f_0(980)$ mass window (4.0%) and S -wave contribution (3.5%).

4. CP violation measurements in $B_s \rightarrow J/\psi \phi$

The angular and decay time distributions used in the $B_s \rightarrow J/\psi \phi$ analysis are described in [2]. The following expression illustrates the asymmetry of the B_s/\bar{B}_s decay rates [11]: $\frac{P_{\pm}(t) - \bar{P}_{\pm}(t)}{P_{\pm}(t) + \bar{P}_{\pm}(t)} = \pm \left[\frac{2 \sin(\Delta M_s t) \sin \phi_s^{J/\psi\phi}}{(1 \pm \cos \phi_s^{J/\psi\phi}) e^{+\Delta\Gamma_s t/2} + (1 \mp \cos \phi_s^{J/\psi\phi}) e^{-\Delta\Gamma_s t/2}} \right]$, where $P_{\pm}(t)$ and $\bar{P}_{\pm}(t)$ refer to CP-even (+) and CP-odd (−) final states tagged as B_s or \bar{B}_s at the production time.

Numbers of $B_s \rightarrow J/\psi \phi$ candidates were determined from mass fits to be 5598 ± 113 in case of the BDT selections and 5050 ± 105 in case of the simple selections. The analysis results are following: $\bar{\tau}_s = 1.443_{-0.035}^{+0.038}$ ps, $\Delta\Gamma_s = 0.163_{-0.064}^{+0.065}$ ps⁻¹, $\phi_s^{J/\psi\phi} = -0.55_{-0.36}^{+0.38}$, $|A_0|^2 = 0.558_{-0.019}^{+0.017}$, $|A_{\parallel}|^2 = 0.231_{-0.030}^{+0.024}$, $\delta_{\parallel} = 3.15 \pm 0.22$, $\cos(\delta_{\perp} - \delta_s) = -0.11_{-0.25}^{+0.27}$, $F_S = 0.173 \pm 0.036$. Some parameters are not defined in this report but full description is available in [2]. Systematic uncertainties were determined using Markov Chain Monte Carlo technique and combined with statistical uncertainties. Two-dimensional 68%, 90% and 95% Confidence Level (C.L.) contours are shown in Fig. 3. The p -value for the SM point $(\phi_s^{J/\psi\phi}, \Delta\Gamma_s) = (-0.038, 0.087 \text{ ps}^{-1})$ is 29.8%.

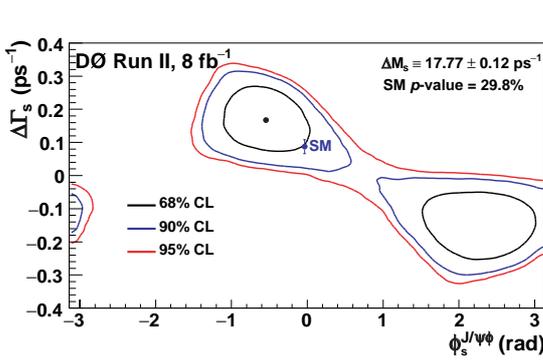


Figure 3: Two-dimensional 68%, 90% and 95% C.L. contours including systematic uncertainties. The standard model expectation is indicated as a point with an error.

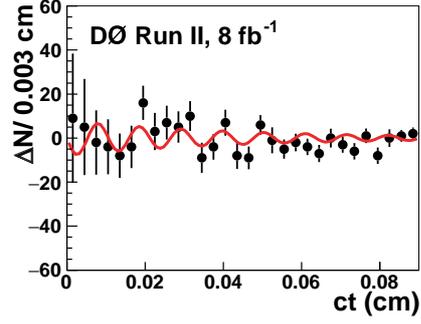


Figure 4: Proper decay length evolution of the difference $\Delta N = N(B_s) - N(\bar{B}_s)$ in the first 0.09 cm (3 ps) for the simple selection sample. The curve represents the best fit to the oscillation with the frequency of $\Delta M_s = 17.77 \text{ ps}^{-1}$.

The asymmetry equation above shows that the time-dependent decay rates for B_s and \bar{B}_s are not equal given non-zero $\phi_s^{J/\psi\phi}$. The time-dependent asymmetry can be represented as $\Delta N \equiv N(B_s) - N(\bar{B}_s) = N_S \cdot C \cdot \sin(\phi_s^{J/\psi\phi}) \cdot \sin(\Delta M_s t) \cdot e^{-t/\tau_s}$, where N_S is number of B_s and \bar{B}_s candidates and $C \approx 0.0025$ is a dilution factor. Fig. 4 shows the proper decay length evolution of ΔN in the first 900 μm ($\sim 2c\bar{\tau}_s$) for the simple selection sample. The fit gives $N_S \cdot C \cdot \sin(\phi_s^{J/\psi\phi}) = -8 \pm 4$ which is consistent with expectations from the $\phi_s^{J/\psi\phi} = -0.55_{-0.36}^{+0.38}$ result.

5. Conclusion

This report presents short description of two D0 analyses: the measurement of the relative branching ratio of $B_s \rightarrow J/\psi f_0$ and CP violation measurements in $B_s \rightarrow J/\psi \phi$. The used data samples correspond to 8 fb^{-1} . The $B_s \rightarrow J/\psi \phi$ results supersede the previous D0 measurements.

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