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Time Dependent Angular Analysis of $B_{s(d)} \to J/\psi\phi(K^{*0})$ and a measurement of $\frac{\Delta\Gamma_s}{\Gamma_s}$

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We present preliminary measurements from a combined analysis of lifetimes and transversity amplitudes for $B_s^0 \to J/\psi\,\phi$ and $B_d^0 \to J/\psi\,K^{*0}$ and present the first direct measurement of the width difference in B_s^0 system using 260 pb^{-1} CDF Run II data. For B_s^0, we obtain $\tau_L = 1.05\ ^{+0.16}_{-0.13} \pm 0.02\,\mathrm{ps}$, $\tau_H = 2.07\ ^{+0.58}_{-0.46} \pm 0.03\,\mathrm{ps}$, $\Delta\Gamma_s/\Gamma_s = 0.65\ ^{+0.25}_{-0.33} \pm 0.01$. The B_d^0 decay amplitudes and lifetime are also measured.

Keywords: B; Mixing; $\Delta\Gamma_s$.

1. Introduction

The mixing between $B_s^0 - \bar{B}_s^0$ and $B_d^0 - \bar{B}_d^0$ leads to the two eigenstates of definite masses (heavy, m_H and light, m_L) and widths (Γ_H and Γ_L). By measuring the mass differences ($\Delta m \equiv m_H - m_L$) in the two systems, one may determine $|V_{td}|/|V_{ts}|$ which has an important impact on our knowledge of unitary triangle and Standard Model. The mass difference Δm_d has been well measured[1]. However no direct measurements of Δm_s have been made because of the high oscillation frequency in B_s^0 system. A large mass difference suggests a large and measurable width difference ($\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$), which can be used to indirectly determine Δm_s[2,3].

In this analysis, we present a time-dependent angular analysis of $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$, pseudo-scalar to vector-vector decays governed by three decay amplitudes. In the B_s^0 system, the mass eigenstates are nearly CP eigenstates and so are the final observed states. A combined analysis based on lifetime and angular information allows for a separation of the heavy (CP odd) and light (CP even) eigenstates and a measurement of the width difference[2]. The channel $B_d^0 \to J/\psi\,K^{*0}$ is related to $B_s^0 \to J/\psi\,\phi$ by SU(3) flavor symmetry, and provides a powerful validation of the fitting technique.

2. Data Sample and Event Selection

The data sample we used for this analysis corresponds to $260\,\mathrm{pb}^{-1}$ of $p\bar{p}$ collisions at 1.96 TeV collected with the upgraded Collider Detector (CDF II) at the Tevatron, from February 2002 to February 2004.

We select events with fully reconstructed B meson candidates where $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ and $B_d \to J/\psi(\mu^+\mu^-)K^{*0}(K^+\pi^-)$. Events were collected using a $J/\psi \to \mu^+\mu^-$ trigger and require all final state particles to be well measured in the silicon detector and the drift chamber[4]. Kinematics requirements including transverse momentum and mass selection are applied to reduce the combinatoric backgrounds. The lifetime is determined from the proper decay length (PDL), by using the information of the transverse distance of the four track vertex from the beamline.

3. Analysis Technique

Considering the final decay products of the B_s^0 (B_d^0), the transversity frame[2] is defined in the J/ψ rest frame. The B meson defines the positive x axis; the K^+K^- ($K\pi$) plane defines the (x, y) plane such that K^+ (K) has positive y momentum; the z axis is defined to make a right handed coordinate system. The transversity angles θ and ϕ are the polar and azimuthal angles of the μ^+; ψ is the helicity angle of the ϕ (K^{*0}) meson. The differential decay rates at time t in the transversity basis for B_s^0 and B_d^0 are given by Eq. (1, 2)[5]:

$$\begin{aligned}\frac{d^4\mathcal{P}_s(\vec{\rho},t)}{d\vec{\rho}\,dt} \propto\, &|A_0|^2 e^{-\Gamma_L t}\cdot f_1(\vec{\rho}) + |A_\parallel|^2 e^{-\Gamma_L t}\cdot f_2(\vec{\rho})\\ &+ |A_\perp|^2 e^{-\Gamma_H t}\cdot f_3(\vec{\rho}) + \mathrm{Re}(A_0^* A_\parallel) e^{-\Gamma_L t}\cdot f_5(\vec{\rho})\end{aligned} \tag{1}$$

$$\begin{aligned}\frac{d^4\mathcal{P}_d(\vec{\rho},t)}{d\vec{\rho}\,dt} \propto\, &\Big[|A_0|^2\cdot f_1(\vec{\rho}) + |A_\parallel|^2\cdot f_2(\vec{\rho})\\ &+ |A_\perp|^2\cdot f_3(\vec{\rho}) \pm \mathrm{Im}(A_\parallel^* A_\perp)\cdot f_4(\vec{\rho})\\ &+ \mathrm{Re}(A_0^* A_\parallel)\cdot f_5(\vec{\rho}) \pm \mathrm{Im}(A_0^* A_\perp)\cdot f_6(\vec{\rho})\Big] e^{-\Gamma_d t}\end{aligned} \tag{2}$$

in which $\vec{\rho} = (\cos\theta, \varphi, \cos\psi)$ and $f_{1,\ldots,6}(\vec{\rho})$ are defined as follows:

$$\begin{aligned}f_1(\vec{\rho}) &= \frac{9}{32\pi} 2\cos^2\psi(1 - \sin^2\theta\cos^2\varphi)\\ f_2(\vec{\rho}) &= \frac{9}{32\pi}\sin^2\psi(1 - \sin^2\theta\sin^2\varphi)\\ f_3(\vec{\rho}) &= \frac{9}{32\pi}\sin^2\psi\sin^2\theta\\ f_4(\vec{\rho}) &= -\frac{9}{32\pi}\sin^2\psi\sin 2\theta\sin\varphi\\ f_5(\vec{\rho}) &= \frac{9}{32\pi}\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi\\ f_6(\vec{\rho}) &= \frac{9}{32\pi}\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi\end{aligned} \tag{3}$$

The three decay amplitudes correspond to linear polarizations states of the vector mesons, where A_0 and $A_{||}$ correspond to the longitudinal and parallel states which are CP (parity) even, while $A_\perp$ corresponds to the perpendicular state which is CP (parity) odd.

In the B_s^0 system, the CP-even angular decay terms evolve in time with $e^{-\Gamma_L t}$, while the CP-odd angular decay terms evolve with $e^{-\Gamma_H t}$. With a flavor unspecified B_s^0 analysis (we don't tag the flavor of B_s^0), the interference between the CP even and odd decays cancels. In the B_d^0 system where the total decay rate is insensitive to first order to any lifetime difference[6], the entire term evolves with a single lifetime $e^{-\Gamma_d t}$. The upper (lower) sign in Eq. (3) is taken for initially produced B_d^0 ($\bar{B}_d$).

An unbinned likelihood fitting method is performed in terms of mass, PDL and the angular variables. The mass distribution is modeled with a Gaussian for the signal and a first order polynomial for the background. The PDL parametrization includes positive exponential(s) for the signal, a δ function for the prompt background and a set of positive and negative exponentials for the mis-measured background, each of which are convoluted with a single gaussian resolution function with widths determined by the event-by-event uncertainty. The angular distributions of the signal are defined according to the decay rate equations above. The background angular distribution is modeled using a similar density functions to allow for S, P and D wave contributions with a different set of amplitudes .

The detector acceptance and efficiency sculpts the angular distribution significantly. We correct for this sculpting by including extra normalization terms in the likelihood function which are determined from Monte Carlo data sample[7]. In the B_d^0 sample, extra terms are included to describe the 10% B_d^0 signals that are reconstructed in a wrong $K-\pi$ assignment. The fitting technique was extensively tested on Monte Carlo experiments and found to be in excellent agreement with expectations.

4. Results and Systematics

The results from the fits are given in Table. 1. The mass, PDL and angular projection plots for the B_d and B_s are shown in Fig. 1 and 2. The observed B_d^0 decay amplitudes and phases agree with the results from BaBar[8] and Belle[9], and the lifetime is in good agreement with the PDG[10] value. A constrained fit for the B_s^0 data is also performed by applying a gaussian constraint of $\Gamma_s = \Gamma_d \equiv 1/\tau_d$. The constraint value is the PDG value for τ_d taking into account of an additional 1% theoretical uncertainty[3]. The fits with and without constraint indicate a non-zero width difference in B_s^0 system and a central value of $\frac{\Delta\Gamma_s}{\Gamma_s}$ much larger than the Standard Model prediction[11], $\frac{\Delta\Gamma_s}{\Gamma_s} = (12 \pm 6)\%$. However, given a sizeable uncertainty, the claim of disagreement with Standard Model can not be made.

Pseudo-experiments with similar statistics have been used to estimate the significance of the measurements. If $\frac{\Delta\Gamma_s}{\Gamma_s} = 0$, one experiment in 315 (718) is expected to give a result larger than what we obtained from the unconstrained (constrained) fit. If $\frac{\Delta\Gamma_s}{\Gamma_s} = 12\%$, one experiment in 84 (204) is expected to give a result larger than what we obtained from the unconstrained (constrained) fit.

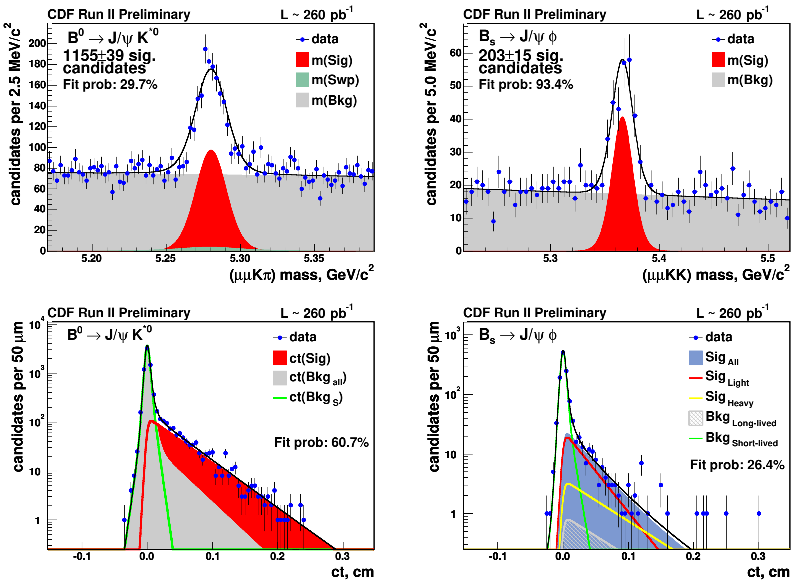

Fig. 1. Fit results projected on data in the mass and PDL sub-spaces: $B_d^0 \to J/\psi\, K^{*0}$ – left column and $B_s^0 \to J/\psi\, \phi$ – right column

Table 1. Summary of the fitting results.

	B_d^0	B_s^0	B_s^0 with $\Gamma_s = \Gamma_d$
N_{sig}	1155 ± 39	203 ± 15	201 ± 15
A_0	$0.750 \pm 0.017 \pm 0.012$	$0.784 \pm 0.039 \pm 0.007$	$0.783 \pm 0.038 \pm 0.007$
$\|A_\parallel\|$	$0.473 \pm 0.034 \pm 0.006$	$0.510 \pm 0.082 \pm 0.013$	$0.539 \pm 0.070 \pm 0.013$
$\|A_\perp\|$	$0.464 \pm 0.035 \pm 0.007$	$0.354 \pm 0.098 \pm 0.003$	$0.308 \pm 0.087 \pm 0.003$
$\arg(A_\parallel)$	$2.86 \pm 0.22 \pm 0.07$	$1.94 \pm 0.36 \pm 0.03$	$1.91 \pm 0.32 \pm 0.03$
$\arg(A_\perp)$	$0.15 \pm 0.15 \pm 0.04$		
$c\tau_{B_d^0}$ (μm)	$462 \pm 15 \pm 6$		
$c\tau_L$ (μm)		$316\ ^{+48}_{-40} \pm 6$	$340\ ^{+40}_{-28} \pm 6$
$c\tau_H$ (μm)		$622\ ^{+175}_{-138} \pm 9$	$713\ ^{+167}_{-129} \pm 9$
$\Delta\Gamma_s/\Gamma_s$ (%)		$65\ ^{+25}_{-33} \pm 1$	$71\ ^{+24}_{-28} \pm 1$
$\Delta\Gamma_s$ (ps^{-1})		$0.47\ ^{+0.19}_{-0.24} \pm 0.01$	$0.46\ ^{+0.17}_{-0.18} \pm 0.01$

The systematics in B_s fitting come from the selection of background angular distribution and the small contamination from B_d^0 decay. The systematics in B_d fitting come from the selection of the background angular distribution, the treatment of $K-\pi$ misidentified events and contamination from B_d non-resonant decays. Other potential sources of systematic uncertainty are found to be negligible.

Several cross checks have been made to confirm the consistency of our results.

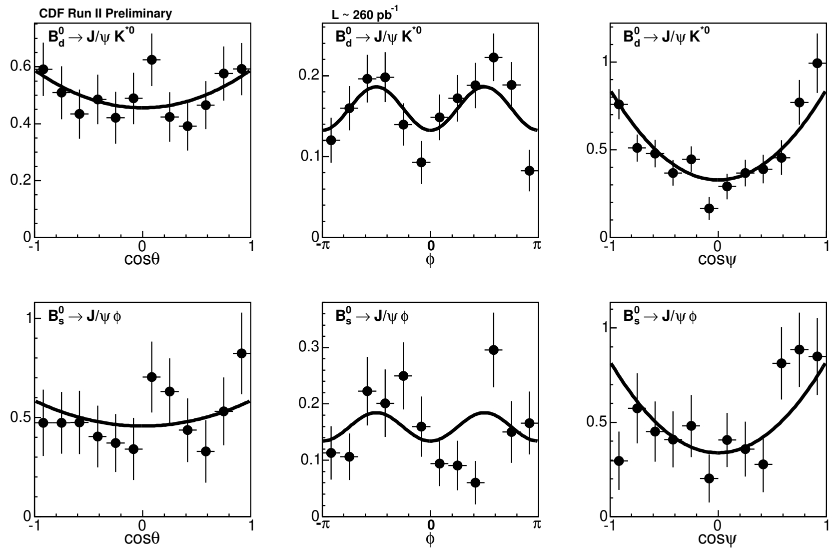

Fig. 2. Projections of the fit results onto the sideband subtracted acceptance corrected signal from data in the transversity sub-space: $B_d^0 \to J/\psi\, K^{*0}$ – top row, $B_s^0 \to J/\psi\, \phi$ – bottom row. A $ct > 0$ cut is applied in the sideband subtraction.

5. Conclusion

We have performed the first time-dependent angular analysis for $B_s^0 \to J/\psi\, \phi$ and $B_d^0 \to J/\psi\, K^{*0}$ decays. The results indicate a nonzero width difference in B_s^0 system and the value observed for $\frac{\Delta\Gamma_s}{\Gamma_s}$ is challenging the Standard Model prediction, $\frac{\Delta\Gamma_s}{\Gamma_s} = (12 \pm 6)\%$. Analysis with more data from CDF is of great interest.

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