Lifetime Difference and CP Asymmetry in the $B_s \to J/\psi\phi$ decay

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Abstract. The B_s meson is an interesting particle to study because a sizable mixing induced CP violation in the $B_s - \bar{B}_s$ system would be an indication for physics beyond the Standard Model. In this paper we present a measurement of the lifetime difference $\Delta\Gamma$ between the B_s mass eigenstates and the CP violating phase in the decay $B_s \to J/\psi\phi$. In 1.7 fb^{-1} of data collected with the CDF II detector at the Tevatron $p\bar{p}$ collider we measure $\Delta\Gamma = 0.076^{+0.059}_{-0.063}$ (stat.) ± 0.006 (syst.) ps^{-1}, well consistent with the Standard Model prediction, and a mean B_s lifetime of $c\tau_s = 456 \pm 13$ (stat.) ± 7 (syst.) μm. We find no evidence for CP violation [1,2].

**PACS.** 13.20.He Decays of bottom mesons – 14.40.Nd Bottom mesons

1 Introduction

In the B_s-$\bar{B}_s$ meson system the flavor eigenstates are not the same as the mass eigenstates. The mass difference between the heavy and light mass eigenstate, B_{sH} and B_{sL}, determines the frequency of the oscillation of the B_s mesons. Two other quantities which affect the time evolution of B_s mesons are the decay rates Γ_H and Γ_L of the two mass eigenstates. The difference $\Delta\Gamma = \Gamma_L - \Gamma_H$ was measured first by CDF[3] and recently with higher precision by DØ[4].

If the difference $\Delta\Gamma$ is larger than a few percent of the mean decay rate $\Gamma = (\Gamma_L + \Gamma_H)/2$ a time dependent analysis of B_s decays without flavor tagging becomes sensitive to a further quantity, the CP violating phase ϕ_s. This phase describes the mixing induced CP violation and is related to the angle β_s in the nearly degenerated unitarity triangle obtained from the multiplication of the second and third column of the CKM matrix. The Standard Model expectation value for ϕ_s is very small[5]. Therefore a measurement of the phase which deviates significantly from zero would indicate new physics.

To determine $\Delta\Gamma$ the lifetime distribution of B_s decays is measured. Because it is very challenging to distinguish the two components of the lifetime distribution additional information is needed to separate the light and heavy mass eigenstates. Therefore we exploit the fact that the two mass eigenstates are related to the CP eigenstates. In case of no CP violation ($\phi_s = 0$) B_{sH} is CP odd and B_{sL} is CP even.

A decay mode that allows to measure both lifetimes is $B_s \to J/\psi\phi$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ which is a composition of CP even and odd states. Because the B_s is a pseudo scalar and J/ψ and ϕ are
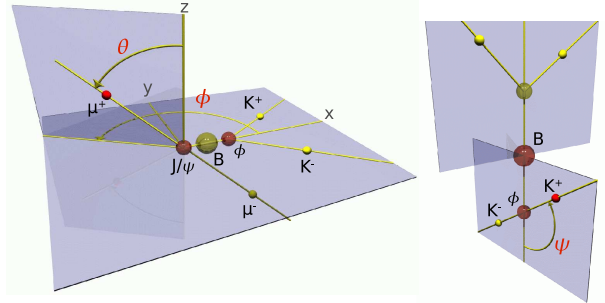
**Fig. 1.** Definition of transversity angles θ, ϕ and ψ.

vector mesons, the orbital angular momentum between the two decay products can have the values 0, 1 or 2. S- and D-wave decays are CP even, P-wave decays are CP odd. Consequently, the two CP eigenstates can be separated by their different angular distributions of the decay products.

The angles $\boldsymbol{\omega} = (\cos\theta, \phi, \cos\psi)$ used in this analysis are defined in the transversity basis illustrated in Figure 1. θ and ϕ are the polar and azimuthal angle of the μ^+ in the rest frame of the J/ψ where the x-axis is defined by the direction of the B_s and the xy-plane by the $\phi \to K^+K^-$ decay plane. ψ is the helicity angle of the K^+ in the ϕ rest frame with respect to the negative B_s flight direction.

2 Data Sample and Selection

The analyzed data sample with an integrated luminosity of 1.7 fb^{-1} was collected by the CDF II detector at the Tevatron which collides $p\bar{p}$ at a centre of mass energy of 1.96 TeV. The detector components essential

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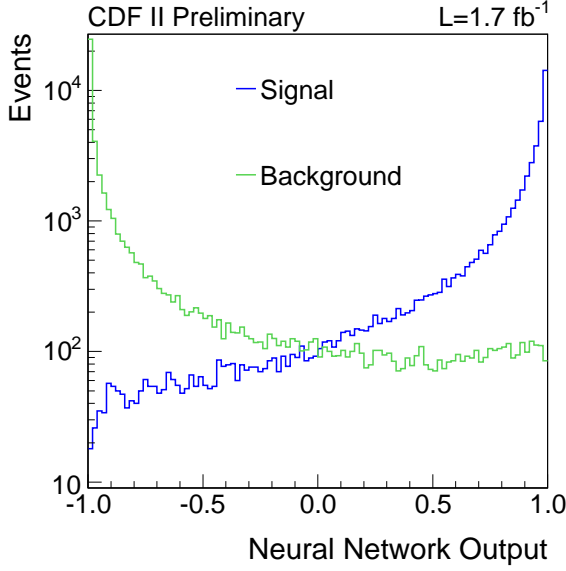
Fig. 2. Network output for B_s signal and background events.

for this analysis are the silicon vertex detector for a precise lifetime measurement, the central drift chamber for good momentum and mass resolution and the central muon chambers for the identification and selection of muons. In addition to the energy loss in the tracker the time of flight detector is used for particle identification. The $B_s \to J/\psi\phi$ events are triggered by a pair of two oppositely charged tracks matched to signals in the muon chambers and having an invariant mass close to the J/ψ mass.

The J/ψ candidates are combined with ϕ candidates built from pairs of oppositely charged tracks assumed to be kaons. The B_s candidate is obtained in a common vertex fit. After applying basic kinematic cuts a neural network is used to improve the selection. The network is trained on simulated B_s signal events and background events from B_s mass sideband data. Kinematic, particle identification and vertex fit quality variables are used as input to the network. Figure 2 illustrates the good separation of signal and combinatorial background events.

With a cut on the network output that optimizes the signal significance 2500 $B_s \to J/\psi\phi$ decays are selected.

3 Mass, Lifetime and Angle Fit

The mean B_s lifetime $c\tau_s = c/\Gamma$, the lifetime difference $\Delta\Gamma$ and the decay amplitudes A_0, $A_{||}$, and $A_\perp$ of the three angular components with relative phases $\delta_\perp$ and $\delta_{||}$ are extracted in a 5-dimensional unbinned maximum likelihood fit in mass, lifetime and angular space. Empirical models are used for the background distribution. The B_s mass signal is described by a sum of two Gaussians. The lifetime and angle distribution

is given by

$$
\begin{aligned}
\frac{d^4 P(\boldsymbol{\omega}, t)}{d\boldsymbol{\omega}dt} \propto & |A_0|^2 f_1(\boldsymbol{\omega})\mathcal{T}_+ + |A_{||}|^2 f_2(\boldsymbol{\omega})\mathcal{T}_+ \\
& + |A_\perp|^2 f_3(\boldsymbol{\omega})\mathcal{T}_- + |A_0||A_{||}|f_5(\boldsymbol{\omega})\cos(\delta_{||})\mathcal{T}_+ \\
& + |A_{||}||A_\perp|f_4(\boldsymbol{\omega})\cos(\delta_\perp - \delta_{||}) \\
& \quad \sin\phi_s(e^{-\Gamma_H t} - e^{-\Gamma_L t})/2 \\
& + |A_0||A_\perp|f_6(\boldsymbol{\omega})\cos(\delta_\perp) \\
& \quad \sin\phi_s(e^{-\Gamma_H t} - e^{-\Gamma_L t})/2
\end{aligned}
\tag{1}
$$

with

$$
\begin{aligned}
\mathcal{T}_\pm &= ((1 \pm \cos\phi_s)e^{-\Gamma_L t} + (1 \mp \cos\phi_s)e^{-\Gamma_H t})/2 \\
f_1(\boldsymbol{\omega}) &= \frac{9}{32\pi}2\cos^2\psi(1 - \sin^2\theta\cos^2\phi) \\
f_2(\boldsymbol{\omega}) &= \frac{9}{32\pi}\sin^2\psi(1 - \sin^2\theta\sin^2\phi) \\
f_3(\boldsymbol{\omega}) &= \frac{9}{32\pi}\sin^2\psi\sin^2\theta \\
f_4(\boldsymbol{\omega}) &= -\frac{9}{32\pi}\sin^2\psi\sin 2\theta\sin\phi \\
f_5(\boldsymbol{\omega}) &= \frac{9}{32\pi}\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\phi \\
f_6(\boldsymbol{\omega}) &= \frac{9}{32\pi}\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\phi.
\end{aligned}
$$

Note that this distribution is invariant under the transformations

$$
\begin{aligned}
\phi_s \to -\phi_s, \ \ \delta_\perp \to \delta_\perp + \pi \quad \text{and} \\
\Delta\Gamma \to -\Delta\Gamma, \ \ \phi_s \to \phi_s + \pi
\end{aligned}
\tag{2}
$$

Because of this four fold ambiguity this measurement is insensitive to the sign of both, ϕ_s and $\Delta\Gamma$.

The finite lifetime resolution and differences of it between signal and background are included in the fit model. The angle dependent acceptance is taken into account by an acceptance function obtained from simulated events. The good description of data by the simulation is exemplarily shown for the selection network output in Figure 3.

The fit projections for mass, lifetime and the angle $\cos\psi$ are shown in Figure 4.

4 Result Assuming no CP Violation

We first consider the case of no CP violation ($\phi_s = 0$). This simplifies the fit model because the last two terms in equation (1) and the fit parameter $\delta_\perp$ vanish.

The result can be affected by several systematic uncertainties which are evaluated using pseudo experiments. The investigated effects are the influence of the angular background, the signal mass and the lifetime resolution model, the contamination of misreconstructed $B^0 \to J/\psi K^*$ decays, the acceptance function and the silicon detector alignment. The largest systematic uncertainty for $\Delta\Gamma$ is the B^0 cross feed and for $c\tau_s$ the lifetime resolution model and the alignment.
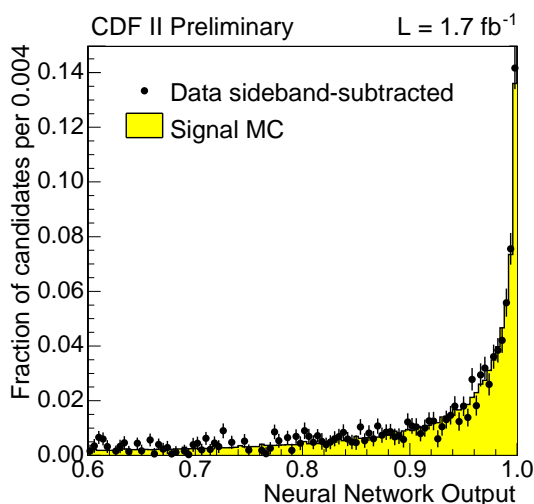
Fig. 3. Distribution of the selection network output for sideband subtracted data and simulation.

Setting $\phi_s = 0$ in the fit we obtain

$$c\tau_s = 456 \pm 13 \pm 7~\mu\text{m}$$
$$\Delta\Gamma = 0.076^{+0.059}_{-0.063} \pm 0.006~\text{ps}^{-1}$$
$$|A_0|^2 = 0.530 \pm 0.021 \pm 0.007$$
$$|A_{||}|^2 = 0.230 \pm 0.027 \pm 0.009$$

The first is the statistical and the second one the systematic uncertainty. Since the likelihood scan for the strong phase $\delta_{||}$, shown in Figure 5, has a non-parabolic shape due to a symmetry at $\delta_{||} = \pi$ we do not quote a point estimate for this quantity.

## 5 Fit with Floating CP Violating Phase ϕ_s

Since a maximum likelihood fit is only guaranteed to be unbiased in case of unlimited statistics we studied the fit in pseudo experiments. In case of free ϕ_s parameter we observe that for low input values of $\Delta\Gamma$ or ϕ_s there is a bias towards higher values. This is illustrated in Figure 6.

The bias can be understood by looking at equation (1). If ϕ_s approaches zero the last two terms vanish and $\delta_\perp$ becomes undetermined. This means that the fit can not improve the description of the data any more by varying ϕ_s. It effectively lost a degree of freedom. The situation is similar when $\Delta\Gamma$ gets zero. Then ϕ_s and $\delta_\perp$ are undetermined.

Because of the biased fit result we do not quote a point estimate for $\Delta\Gamma$ and ϕ_s, but construct a confidence region following the procedure suggested by Feldman and Cousins[6].

For each pair on a grid of assumed true values of $\Delta\Gamma$ and ϕ_s we calculate a p-value, which quantifies the probability to get the fit result observed in data. To determine the p-value we use the likelihood ratio

$$R(\Delta\Gamma, \phi_s) = \log \frac{\mathcal{L}(\hat{\Delta\Gamma}, \hat{\phi}_s, \hat{\theta})}{\mathcal{L}(\Delta\Gamma, \phi_s, \hat{\theta}')} \qquad (3)$$
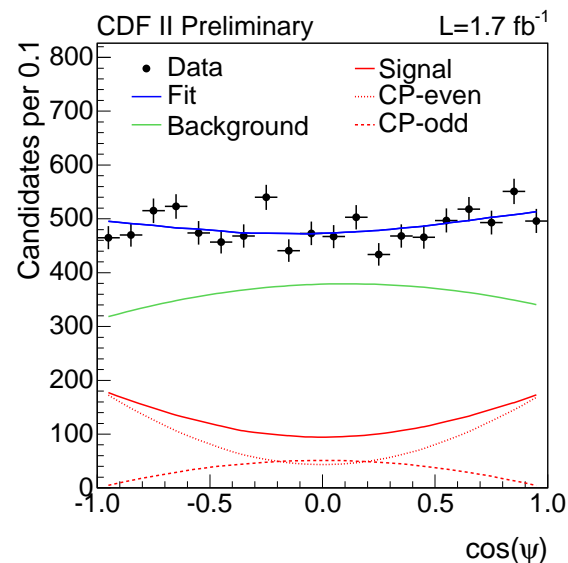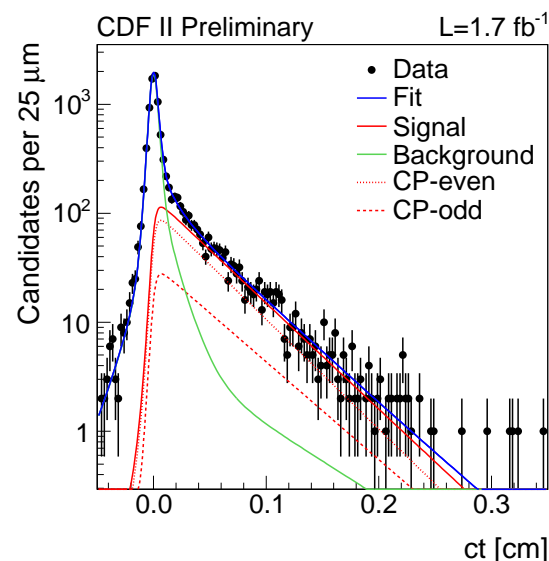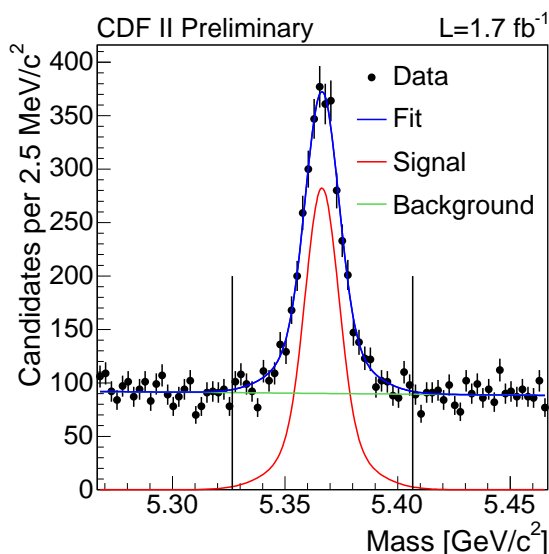
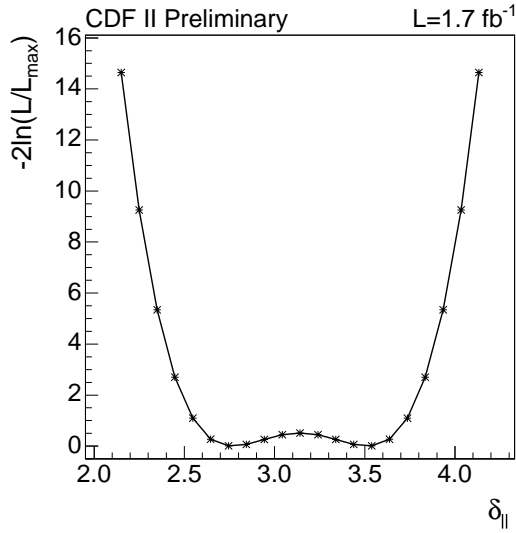**Fig. 4.** Fit projections for mass, lifetime and angle $\cos\psi$.

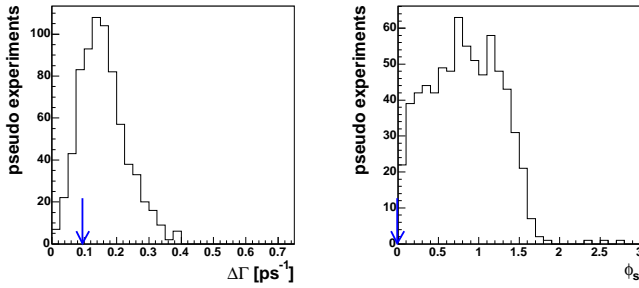**Fig. 5.** Likelihood scan for the strong phase $\delta_{||}$.

Fig. 6. Distribution of fitted $\Delta\Gamma$ (left) and ϕ_s (right) in pseudo experiments. The blue arrow indicates the input value.

where θ are the nuisance parameters and the hat indicates the parameter values which maximize the likelihood $\mathcal{L}$. The R distribution for assumed true values of $\Delta\Gamma$ and ϕ_s is obtained from pseudo experiments. The pseudo experiment input values of the nuisance parameters are taken from a fit to data, a procedure known as plug-in method.

The p-value is the fraction of pseudo experiments with an R value higher than the one in data. The 90% (95%) confidence region is then defined by the $\Delta\Gamma$-ϕ_s points with a p-value above 10% (5%).

The result is presented in Figure 7. Note that only the first quadrant is shown. The other three quadrants can be obtained via the transformations given in equation (2). The p-value for $\Delta\Gamma = 0.1$ ps^{-1} and $\phi_s = 0$, which are approximately the Standard Model predictions, is 22%.

6 Conclusions

Using 2500 $B_s \to J/\psi\phi$ decays selected by a neural network in a data sample of 1.7 fb^{-1} CDF has performed a mass-lifetime-angle fit to measure the lifetime
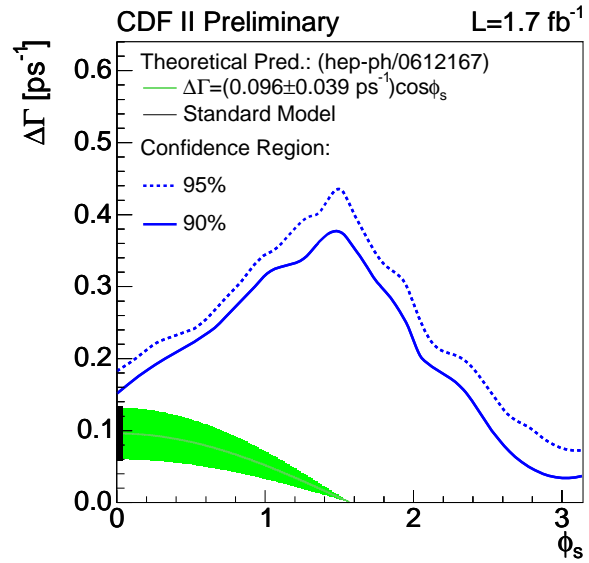

Fig. 7. Confidence region in the $\Delta\Gamma$-ϕ_s plane. Only one out of four possible solutions is shown. The others can be obtained by the transformations $\phi_s \to -\phi_s$ and $\Delta\Gamma \to -\Delta\Gamma$, $\phi_s \to \phi_s + \pi$

difference $\Delta\Gamma$ between the B_s mass eigenstates. The value obtained under the assumption of no CP violation is consistent with the Standard Model expectation[5] and previous measurements[3,4]. The extracted mean B_s lifetime is currently the most precise measurement and agrees well with the world average B^0 lifetime as predicted by theory.

If we allow for CP violation in the fit model we observe a bias away from low $\Delta\Gamma$ and ϕ_s values. It is understood by the structure of the likelihood function and limited statistics. Instead of a point estimate a confidence region is determined in a frequentist way. The result is compatible with the Standard Model and can not rule out any minimal flavor violating new physics scenario which changes the phase ϕ_s, but does not significantly affect $b \to c\bar{c}s$ tree level dominated processes.

References

1. The CP violating phase measurement was presented by CDF briefly after the SUSY07 conference and is therefore included in this article.
2. CDF Collaboration, CDF public note 8950, *www-cdf.fnal.gov/physics/new/bottom/bottom.html*
3. D. Acosta *et al.* [CDF Collaboration], Phys. Rev. Lett. **94** (2005) 101803 [arXiv:hep-ex/0412057].
4. V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **98** (2007) 121801 [arXiv:hep-ex/0701012].
5. A. Lenz and U. Nierste, JHEP **0706** (2007) 072 [arXiv:hep-ph/0612167].
6. G. J. Feldman and R. D. Cousins, Phys. Rev. D **57** (1998) 3873 [arXiv:physics/9711021].