$\mathrm{B_s}$ Lifetime Difference Measurements from the Tevatron

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The two collider experiments at the Tevatron, CDF and DØ, have made a lot of progress in $\mathrm{B_s}$ lifetime difference measurements. Here, we have included 3 different channels of measurements, namely, $\mathrm{B_s} \to \mathrm{J}/\psi + \phi$, $\mathrm{B_s} \to \mathrm{K^+K^-}$ and $\mathrm{B_s} \to \mathrm{D_s^{(*)+}D_s^{(*)-}}$. Combining all the available measurements, we have obtained $\Delta\Gamma_\mathrm{s} = 0.097\ ^{+0.041}_{-0.042}\ \mathrm{ps^{-1}}$ and $\overline{\tau} = \frac{1}{\Gamma_\mathrm{s}} = 1.461 \pm 0.030$ ps. $\Delta\Gamma_\mathrm{s}$ is now 2.3 σ away from zero.

1. $\mathrm{B_s}$ Mixing and $\Delta\Gamma_\mathrm{s}$

In the Standard Model formulation, $\mathrm{B_s}$ mixing exists due to the existence of non-zero non-diagonal elements for the Hamiltonian $< \overline{\mathrm{B}}_\mathrm{s} \mid \mathrm{H} \mid \mathrm{B_s} >$ where the Hamiltonian may be expressed as:

$$\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - i/2 \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix} \quad (1)$$

The matrix element M_{12} is dominated by the top quark contribution whereas the matrix element Γ_{12} is dominated by the $b \to c\bar{c}s$ decay. One consequence is that the two mass eigenstates $\left|B_s^{Heavy}\right\rangle$ and $\left|B_s^{Light}\right\rangle$ are different from their CP eigenstates.

The masses for the two $\mathrm{B_s}$ eigenstates are m_H and m_L and their decay widths are respectively Γ_H and Γ_L. We also have the definitions :

$$\Delta m_s \equiv m_H - m_L \ ; \ \Delta\Gamma_s \equiv \Gamma_L - \Gamma_H \quad (2)$$

where $\Delta\Gamma_s$ is so defined such that $\Delta\Gamma_s > 0$ in the Standard Model.

The CP violation in the Standard Model exists only due to one CP violating weak phase $\delta\phi$ which has the following relationship with the CKM matrix elements:

$$e^{i\delta\phi} = \frac{V_{ts}V_{tb}^*}{V_{ts}^*V_{tb}} \frac{V_{cs}^*V_{cb}}{V_{cs}V_{cb}^*} \quad (3)$$

$\delta\phi$ relates to $\Delta\Gamma_s$ by

$$\Delta\Gamma_s \approx 2|\Gamma_{12}|\ cos(\delta\phi) \quad (4)$$

In the Standard Model, $\delta\phi$ is very small, $\approx 0.005(0.3^\circ)$ [1]. Much larger measurement of $\delta\phi$ and thus (from Eq. 4) a smaller $\Delta\Gamma_s$ would indicate a striking signal of new physics in $\mathrm{B_s} - \overline{\mathrm{B}}_\mathrm{s}$ mixing.

The following relates the $\mathrm{B_s}$ mass eigenstates with their CP eigenstates:

$$|B_L\rangle \approx \frac{1+e^{i\delta\phi}}{2}\left|B_s^{even}\right\rangle + \frac{1-e^{i\delta\phi}}{2}\left|B_s^{odd}\right\rangle \quad (5)$$

$$|B_H\rangle \approx -\frac{1-e^{i\delta\phi}}{2}\left|B_s^{even}\right\rangle + \frac{1+e^{i\delta\phi}}{2}\left|B_s^{odd}\right\rangle \quad (6)$$

2. Untagged $\mathrm{B_s} \to \mathrm{J}/\psi + \phi$ Decay

The $\mathrm{B_s} \to \mathrm{J}/\psi + \phi$ decay is a pseudoscalar to vector-vector decay. The decay amplitude can be decomposed into 3 independent components corresponding to 3 linear polarization states of the vector mesons which are either longitudinal (0), or transverse to their directions of motion and parallel ($\|$) or perpendicular ($\perp$) to one another. The states 0 and $\|$ are CP-even while the state $\perp$ is CP-odd.

As an example, in the DØ analysis, the time-dependent three-angle distribution for the decay of untagged $\mathrm{B_s}$ mesons (i.e., summed over $\mathrm{B_s}$ and $\overline{\mathrm{B}}_\mathrm{s}$), in the above transversity basis is expressed as:

$$\frac{d^3\Gamma(t)}{d\cos\theta\ d\varphi\ d\cos\psi} \propto 2|A_0(0)|^2\, e^{-\Gamma_L t}\, \cos^2\psi(1-\sin^2\theta\cos^2\varphi)$$

*On behalf of the CDF and DØ collaborations.

$$+\sin^2\psi\{|A_\parallel(0)|^2\ e^{-\Gamma_{\rm L}t}\ (1-\sin^2\theta\sin^2\varphi) + |A_\perp(0)|^2\ e^{-\Gamma_{\rm H}t}\ \sin^2\theta\} + \frac{1}{\sqrt{2}}\sin 2\psi|A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)\ e^{-\Gamma_{\rm L}t}\ \sin^2\theta\sin 2\varphi$$

$$+\left\{\frac{1}{\sqrt{2}}|A_0(0)||A_\perp(0)|\cos\delta_2\sin 2\psi\sin 2\theta\cos\varphi -|A_\parallel(0)||A_\perp(0)|\cos\delta_1\sin^2\psi\sin 2\theta\sin\varphi\right\}\frac{1}{2}\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\delta\phi \quad (7)$$

Here, $\delta_1 \equiv \mathrm{Arg}[\mathrm{A}_\parallel(0)^*\mathrm{A}_\perp(0)]$and $\delta_2 \equiv \mathrm{Arg}[\mathrm{A}_0(0)^*\mathrm{A}_\perp(0)]$ are CP-conserving strong phases. As any dependence on $\delta\mathrm{m_s}$ cancels in untagged samples, Eq. 7 contains no $\delta\mathrm{m_s}$ at all.

In the coordinate system of the J/ψ rest frame (where the ϕ meson moves in the x direction, the z axis is perpendicular to the decay plane of $\phi\to K^+K^-$, and $p_y(K^+)\geq 0$), the transversity polar and azimuthal angles (θ,φ) describe the direction of the μ^+, and ψ is the angle between $\vec{p}(K^+)$ and $-\vec{p}(J/\psi)$ in the ϕ rest frame.

The definition of the above three angles can be found in Fig. 1 and Fig. 2.

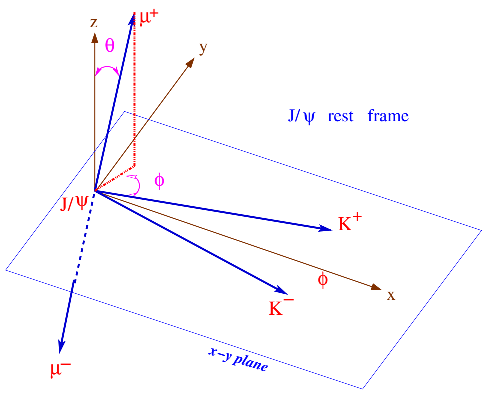

Figure 1. Transversity azimuthal angles (θ, φ).

We perform a simultaneous unbinned maximum likelihood fit to the proper decay length, three decay angles, and mass of $\mathrm{B_s}$ candidates. The likelihood function $\mathcal{L}$ is given by:

$$\mathcal{L} \;=\; \prod_{i=1}^{N}[f_{sig}\mathcal{F}^i_{sig}+(1-f_{sig})\mathcal{F}^i_{bck}], \quad (8)$$

where N is the total number of events and f_{sig}

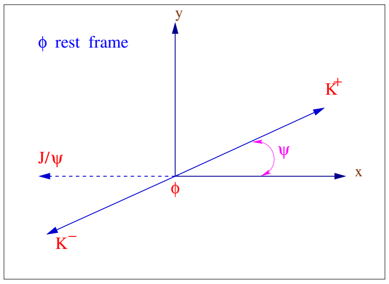

Figure 2. ψ is the angle between $\vec{p}(K^+)$ and $-\vec{p}(J/\psi)$ in the ϕ rest frame.

is the fraction of signal in the sample. $\mathcal{F}^i_{sig}$ is the product of probability distribution functions (PDF's) of the signal mass, proper decay length, and the decay angles, while $\mathcal{F}^i_{bck}$ is for the background. Backgrounds are divided into two categories, based on their origin and lifetime characteristics. "Prompt" background is due to directly produced J/ψ mesons accompanied by random tracks arising from hadronization. This background is distinguished from "non-prompt" background, where the J/ψ meson is a product of a B-hadron decay and the tracks forming the ϕ candidate emanate from a multibody decay of the same B hadron or from hadronization. We allow for independent parameters for the two background components in mass, lifetime, and decay angles. There are about thirty free parameters in the fit.

Eq. (7) is used as the lifetime and decay angle PDF in the fit and we use Gaussian with free mean and width for the B_s signal mass PDF.

Fig. 3 shows the fit projection on the lifetime distribution. This fit assigns 978 ± 45 signal events to the B_s decay and this corresponds to about 0.8 fb^{-1} of data.

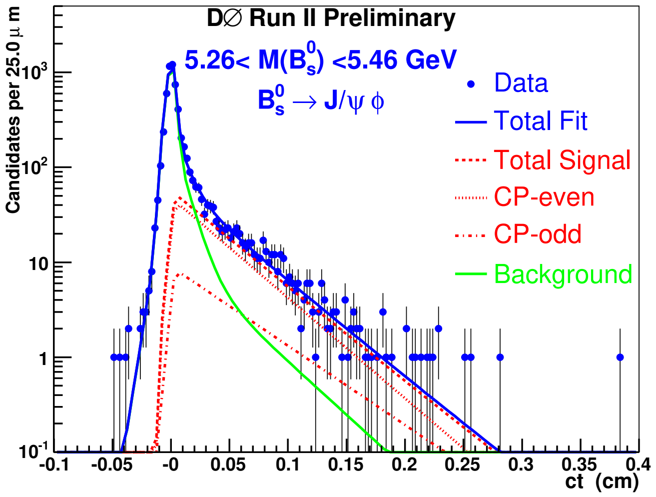

Figure 3. DØ: The proper decay length, ct, of the B_s candidates in the signal mass region. The curves show: the signal contribution, dashed(red); the CP-even (dotted) and CP-odd (dashed-dotted) contributions of the signal, the background, light solid(green); and total, solid(blue).

CDF has also published their results in this channel $B_s \to J/\psi + \phi$ [2]. Fig. 4 shows the CDF fit projection on the lifetime distribution. This result has used about 260 pb^{-1} of data and it contains 203 ± 15 B_s candidates.

For preliminary results of DØ, if $\delta\phi$ is fixed at 0 in the fit, $\delta_1 - \delta_2 = 2.5 \pm 0.4 \pm 0.02$; whereas if $\delta\phi$ is free in the fit, with δ_1 free but $\delta_2 = 0$, $\delta\phi = -0.9 \pm 0.7$. The result is compatible with the Standard Model prediction.

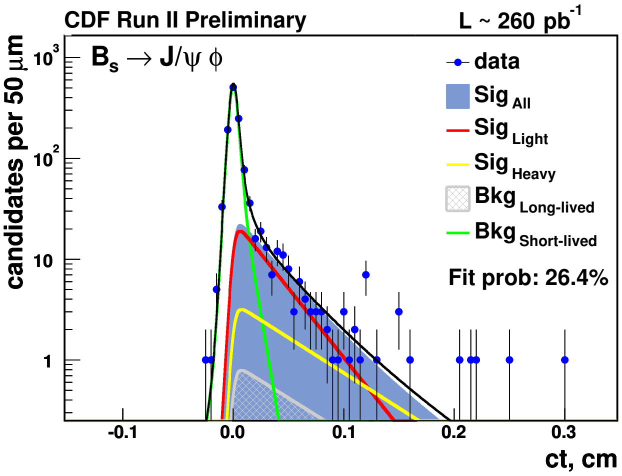

Figure 4. CDF: Projection of the result of the unbinned likelihood fit onto the data for $B_s \to J/\psi + \phi$.

3. $B_s \to K^+K^-$

CDF has made a preliminary measurement [3] of the B_s lifetime in decays $B_s \to K^+K^-$. There has been originally a concern of trigger bias but it has been overcome by detailed simulation. The procedure has been validated in studies of unbiased $B_d \to J/\psi + X$ decays from dimuon triggers. Moreover, the lifetime fits of the same sample with and without applying track trigger cuts have yielded consistent results.

The decay mode $B_s \to K^+K^-$ should be CP-even within 5% uncertainty and it therefore has the lifetime of the "light B_s":

$$\tau_L = 1.53 \pm 0.18(\text{stat.}) \pm 0.02(\text{syst.})\ \text{ps} \quad (9)$$

Combined with the world average on $\Delta\Gamma_s$, this gives:

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} = -0.08 \pm 0.23(\text{stat.}) \pm 0.03(\text{syst.}) \quad (10)$$

4. $B_s \to D_s^{(*)+} D_s^{(*)-}$

$B_s \to D_s^+ D_s^-$ is pure CP even under various theoretical assumptions and the inclusive $B_s \to$

Table 1
Main lifetime difference measurement results from CDF and DØ.

CDF	DØ
$\Delta\Gamma_s = 0.47\ ^{+0.19}_{-0.24} \pm 0.01\ \mathrm{ps}^{-1}$	$\Delta\Gamma_s = 0.15 \pm 0.10\ ^{+0.03}_{-0.04}\ \mathrm{ps}^{-1}$
$\tau_L = 1.05\ ^{+0.16}_{-0.13} \pm 0.02$ ps $\tau_H = 2.07\ ^{+0.58}_{-0.46} \pm 0.03$ ps	$\tau = 1.53 \pm 0.08\ ^{+0.01}_{-0.03}$ ps
$\|A_\perp\| = 0.354 \pm 0.098 \pm 0.003$	$R_\perp = \|A_\perp(0)\|^2 = 0.19 \pm 0.05 \pm 0.01$

$D_s^{(*)+}D_s^{(*)-}$is also CP even within 5% [4]. With this assumption, a measurement of the relevant branching fractions can be used to extract $\Delta\Gamma_s$:

$$\frac{\Delta\Gamma_s}{\Gamma_s} \approx \frac{2\mathrm{Br}(B_s \to D_s^{(*)+}D_s^{(*)-})}{1 - \mathrm{Br}(B_s \to D_s^{(*)+}D_s^{(*)-})/2} \quad (11)$$

With approximately 1 fb^{-1} of data, DØ has made a measurement [5] of the inclusive branching fraction $B_s \to D_s^{(*)+}D_s^{(*)-}$, where one $D_s^{(*)}$ is reconstructed from the hadronic mode $\phi(\to K^+K^-)\pi$ and the other semileptonically into $\phi\mu\nu$.

What DØ has measured is actually the fraction:

$$R = \frac{\mathrm{Br}(B_s \to D_s^{(*)+}D_s^{(*)-}) \cdot \mathrm{Br}(D_s \to \phi\mu\nu)}{\mathrm{Br}(B_s \to D_s^{(*)-}\mu^+\nu} \quad (12)$$

where many systematics uncertainties cancel. Using PDG [6] branching fractions in Eq. (12) and BaBar's new measurement of $\mathrm{Br}(D_s \to \phi\pi)$ [7], the preliminary branching fraction is

$$\mathrm{Br}(B_s \to D_s^{(*)+}D_s^{(*)-}) = 0.071 \pm 0.035(stat.)\ ^{+0.029}_{-0.025}(syst.) \quad (13)$$

Assuming Eq. (11),

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \approx \frac{\Delta\Gamma_s}{\Gamma_s} = 0.142 \pm 0.064(\mathrm{stat.})\ ^{+0.058}_{-0.050}(\mathrm{syst.}) \quad (14)$$

is determined.

CDF has used 355 pb^{-1} of data to fully reconstruct the decay $B_s \to D_s^+D_s^-$ for the first time [8] and has obtained the following branching fraction:

$$\frac{\mathrm{Br}(B_s \to D_s^+D_s^-)}{\mathrm{Br}(B_s \to D_s^+D^-)} = 1.67 \pm 0.41(\mathrm{stat.}) \pm 0.12(\mathrm{syst.}) \pm 0.24(fs/fd) \pm 0.39(Br_{\phi\pi}) \quad (15)$$

CDF continues working to extract $\Delta\Gamma_s$ along this line of analysis and there is good prospect with 1 fb^{-1} of data already taken.

5. Combining $\Delta\Gamma_s$

Combining all the above measurement results and all the inputs of PDG 2004 [9] which include precise measurements of the flavor-specific lifetime of B_s decays, the 1-sigma contour in the space of $\Delta\Gamma_s$ and $\frac{1}{\Gamma_s}$ is obtained and is shown in dashed line in Fig. 5 (originally from [10]). Moreover, the unofficial world average values of $\Delta\Gamma_s$ and $\frac{1}{\Gamma_s}$ are:

$$\Delta\Gamma_s = 0.097\ ^{+0.041}_{-0.042}\ ps^{-1}$$
$$\overline{\tau} = \frac{1}{\Gamma_s} = 1.461 \pm 0.030\ ps \quad (16)$$

This result for $\Delta\Gamma_s$ is currently 2.3 σ from zero. From [1], the Standard Model predicts:

$$\frac{\Delta\Gamma_s}{\Delta m_s} = (47 \pm 8) \times 10^{-4} \quad (17)$$

From Eq. (16) and [11], experimentally we have

$$\frac{\Delta\Gamma_s}{\Delta m_s} = \frac{0.097 \pm 0.042\ ps^{-1}}{17.31\ ^{+0.33}_{-0.18} \pm 0.07\ ps^{-1}} = (56 \pm 24) \times 10^{-4} \quad (18)$$

For new physics searchers, the above experimental result is disappointingly in agreement with the Standard Model prediction.

6. Summary

Experimental results in extracting CP eigenstates mixtures and branching fraction measurements, especially from the Tevatron, have given

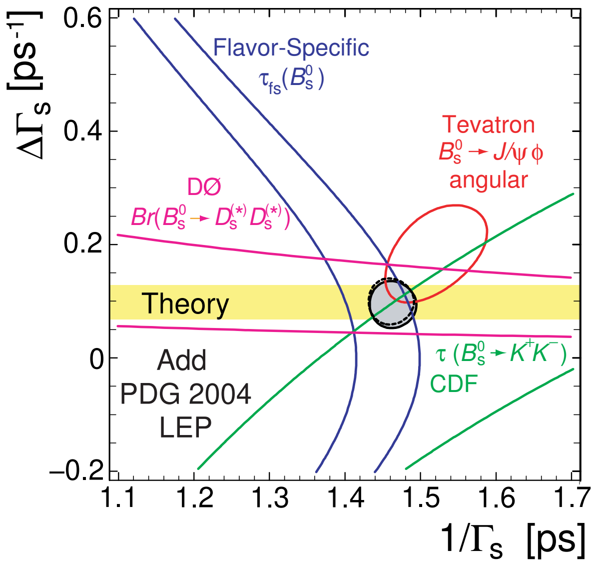

Figure 5. 1-sigma contours ($\Delta(\log L) = 0.5$). The dashed contour is the final result when all prior measurements are included (PDG 2004) [9]. The horizontal band is the Standard Model prediction with f_{B_s} fixed 260 MeV.

a considerable constraint on $\Delta\Gamma_s$. The unofficial average in Eq. (16) is now 2.3 σ away from zero. So far, all results, including CP strong and weak phases, have been consistent with the Standard Model. More results from the Tevatron and elsewhere will certainly pin $\Delta\Gamma_s$ down to greater accuracy in the future.

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REFERENCES

1. Talk given by Ulrich Nierste in Chicago Flavor: http://theory.fnal.gov/people/nierste/cf/degabs2.pdf
2. D. Acosta et al. [CDF collaboration], *Phys. Rev. Lett.* **94** (2005) 101803.
3. D. Tonelli, CDF Hot Topics, FPCP 2006 Proceedings, FPCP06_112, arXiv:hep-ex0605038.
4. R. Aleksan et al., *Phys. Lett.* **B316** (1993) 567.
5. DØ Note 5068-CONF, "Measurement of the Branching Ratio $\mathrm{Br}(B_s \to D_s^{(*)+} D_s^{(*)-})$ with the DØ Experiment, March 21, 2006.
6. S. Eidelman et al., *Phys. Lett.* **B592** (2004) 1 and 2005 partial web update for the edition 2006.
7. B. Aubert et al. [BaBar Collaboration], *Phys. Rev. D* **71** (2005) 091104.
8. CDF Note 7925, "Observation of exclusive $B_s \to D_s^+ D_s^-$, $D_s \to \phi\pi(3\pi, K^*K)$, $D^+ \to K\pi\pi$ with 355 pb^{-1} in Run II, March 29, 2006.
9. Heavy Flavor Averaging Group (HFAG) www.slac.stanford.edu/xorg/hfag/osc/index.html
10. R. Van Kooten, "B_s^0 Decays and B Leptonic Decays", FPCP 2006 Proceedings, FPCP06_342, arXiv:hep-ex0606005.
11. [CDF Collaboration], "Measurement of the B_s - $\overline{B_s}$ Oscillation Frequency", arXiv:hep-ex0606027.