Measurement of the $\bar{B}_s^0$ Meson Lifetime Using Semileptonic Decays with Single Lepton Datasets in CDF Run II

Text for the blessed web page – CDF note 7757

The CDF Collaboration

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Abstract

The lifetime of the $\bar{B}_s^0$ meson is measured in CDF Run II using the partially reconstructed semileptonic decay $\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$, where ℓ^- is a lepton (e^- or μ^-) and the D_s^+ meson is reconstructed in the $\phi\pi^+$ decay mode. The data come from 8 GeV single lepton trigger datasets, corresponding to an integrated luminosity of about 360 pb^{-1}. We find the $\bar{B}_s^0$ meson lifetime to be $c\tau(\bar{B}_s^0) = 414.0 \pm 16.6\ ^{+15.6}_{-13.8}$ μm, or $\tau(\bar{B}_s^0) = 1.381 \pm 0.055\ ^{+0.052}_{-0.046}$ ps, where the first uncertainties are statistical and the second are systematic. We also measure the ratio of the $\bar{B}_s^0$ and $\bar{B}^0$ meson lifetimes to be $\tau(\bar{B}_s^0)/\tau(\bar{B}^0) = 0.938 \pm 0.044\ ^{+0.049}_{-0.046}$, where $\tau(\bar{B}^0)$ is taken from the previous $B^-/\bar{B}^0$ lifetime analysis using the semileptonic decays.

1 Description

The $\bar{B}_s^0$ meson lifetime is measured using the partially reconstructed semileptonic decay $\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$, where ℓ^- is a lepton (e^- or μ^-) and the D_s^+ meson is reconstructed with the $D_s^+ \to \phi\pi^+$, $\phi \to K^+K^-$ decay mode. The data are collected with the CDF detector in Tevatron Run II with 8 GeV single lepton triggers (muons and electrons). The corresponding integrated luminosity used for this analysis is about 360 pb^{-1}, collected through August 2004.

The method is very similar to previous CDF measurements [1]. We reconstruct the D_s^+ meson produced near the lepton candidates. The D_s^+ mass distribution for the combined lepton sample is shown in Figure 1. The event yield and signal fraction are summarized in Section 2.1.

From the $\ell^- D_s^+$ candidates, the $\bar{B}_s^0$ meson decay vertex is reconstructed and the decay length is measured. The reconstruction is performed in the plane perpendicular to the beam axis (z axis). A schematic view of the decay and its reconstruction is displayed in Figure 2. The $\bar{B}_s^0$ meson decay length, L_B, is defined as the distance between the primary vertex and the B_s^0 decay vertex, projected onto the direction of the lepton-D_s^+ system, $\vec{p}_T(\ell^- D_s^+)$:

$$L_B \equiv \vec{V}_B \cdot \frac{\vec{p}_T(\ell^- D_s^+)}{|\vec{p}_T(\ell^- D_s^+)|}.$$

Here $\vec{V}_B$ is the vector connecting the primary vertex and the $\bar{B}_s^0$ decay vertex, and the symbol "$\cdot$" denotes the inner product of the two 2-dimensional vectors.

To measure the lifetime of the B_s^0 meson, we need to know its proper time. The proper decay length $ct(B_s^0)$ is related with the decay length L_B by

$$ct(\bar{B}_s^0) = \frac{L_B}{\beta\gamma} = L_B \frac{M_{\bar{B}_s^0}}{p_T(\bar{B}_s^0)}$$

where $M_{\bar{B}_s^0}$ is the $\bar{B}_s^0$ meson mass, and β and γ are the Lorentz factors. To calculate the proper decay length, we need to know the momentum of the B_s^0 meson for each event. Although we can not reconstruct fully the momentum of the $\bar{B}_s^0$ meson in the semileptonic decays, we can use the momentum of the $\ell^- D_s^+$ system, $p_T(\ell^- D_s^+)$, as a good approximation. We define the "pseudo-proper decay length" ct^* as follows:

$$ct^*(\bar{B}_s^0) \equiv L_B \frac{M_{\bar{B}_s^0}}{p_T(\ell^- D_s^+)}.$$

To relate ct^* and ct, we introduce the factor K, which is the ratio of the transverse momenta of the $\ell^- D_s^+$ system and the $\bar{B}_s^0$ meson:

$$ct^*(\bar{B}_s^0) = ct \frac{p_T(\ell^- D_s^+)}{p_T(\bar{B}_s^0)} \equiv ct \frac{1}{K}, \quad \text{with } K \equiv \frac{p_T(\ell^- D_s^+)}{p_T(\bar{B}_s^0)}.$$

We obtain the distribution of the ratio K using a Monte Carlo simulation of signal events. Figure 3 show the K factor distributions for the muon and electron datasets. They differ slightly because of implicit isolation requirements imposed by electron identification cuts. We use the distributions when we extract the B_s^0 meson lifetime from the observed distribution of ct^*.

We extract the $\bar{B}_s^0$ meson lifetime using the maximum likelihood method. The probability density function of the variable $x \equiv ct^*$ for the signal, the semileptonic $\bar{B}_s^0$ decay, can be expressed as follows:

$$\mathcal{F}_{\bar{B}_s^0}(x; \sigma_{ct^*}; c\tau, s) = \int dk\, H(K)\, \frac{K}{c\tau} \exp\left(-\frac{ct^*}{c\tau/K}\right) \otimes G(s\sigma_{ct^*}),$$

where $H(K)$ denotes the normalized K factor distribution, $G(\sigma)$ is a Gaussian distribution with the width σ. σ_{ct^*} is the calculated resolution in ct^* for the event, and s is the scale factor in the resolution, introduced to account for possible incompleteness in σ_{ct^*} calculation.

The full probability density function, including the background contributions, is given by

$$\mathcal{F}(x) = f_{\rm sig}\, \mathcal{F}_{\rm sig}(x) + (1 - f_{\rm sig})\, \mathcal{F}_{\rm BG}(x),$$

where $\mathcal{F}_{\rm BG}(x)$ represents the combinatorial background events under the D_s^+ meson mass peak, and its shape is determined using events in the sideband of the D_s^+ mass distribution. The term $\mathcal{F}_{\rm sig}(x)$ corresponds to the real D_s^+ meson decays. Among them there are events which are not originating from the semileptonic decays of the B_s^0 meson, such as promptly produced D_s^+ mesons, and $\ell^- D_s^+$ pairs produced in decays of the non-strange B mesons. Therefore, the "signal" function $\mathcal{F}_{\rm sig}$ consists of three terms,

$$\mathcal{F}_{\rm sig}(x) = (1 - f_c)\, [\, (1 - f_b)\, \mathcal{F}_{\bar{B}_s^0} + f_b\, \mathcal{F}_b\,] + f_c\, \mathcal{F}_c,$$

the true signal, the bottom background, and the prompt charm background. The fraction of the prompt charm background is determined using real data, and its ct^* distribution is mostly prompt. The amount and the ct^* distribution of the bottom background are estimated using Monte Carlo calculations, based on measured branching fractions and b-quark fragmentation fractions.

The parameter to be determined by the fit is the B_s^0 meson lifetime $c\tau$. We maximize the joint likelihood, defined for the muon and electron datasets.

$$\mathcal{L}_{\rm combined} \equiv \prod_{\ell} \prod_{i} \mathcal{F}(x_i), \qquad x_i \equiv ct_i^*,$$

where i is the event index, ct_i^* is the pseudo-proper decay length measured for event i, and the product is taken over all events in the signal region in the sample, and ℓ denotes the lepton sample (muon or electron).

The decay length distribution and the fit result are displayed in Figure 4, and the extracted $\bar{B}_s^0$ meson lifetime is given in Section 2.4. The systematic uncertainties in the $\tau(\bar{B}_s^0)$ measurement are summarized in Section 2.2.

We also measure the ratio of the $\bar{B}_s^0$ meson lifetime to the $\bar{B}^0$ meson lifetime. We use a previous CDF measurement of the $\bar{B}^0$ meson lifetime [2], which is obtained also using the semileptonic decays and thus similar final states. The lifetime ratio $\tau(\bar{B}_s^0)/\tau(\bar{B}^0)$ is given in Section 2.4, and its systematic uncertainties are summarized in Section 2.3.

2 Blessed Numbers

This section summarizes the numbers which have been blessed for this analysis.

2.1 Signal yields

Region	$M(K^+K^-\pi^+)$ range (MeV/c^2)	Sample	Events	D_s^+ signal fraction
Signal	1947.5 - 1987.5	$\mu^- D_s^+$	1591	0.503 ± 0.014
		$e^- D_s^+$	706	0.503 ± 0.021
Sideband	1900 - 1930, 2005 -2035	$\mu^- D_s^+$	1181	
		$e^- D_s^+$	535	

2.2 Systematic uncertainties in $\tau(\bar{B}_s^0)$ measurement

Source	Contribution to $c\tau(\bar{B}_s^0)$ (μm)
Prompt charm background	
Prompt charm fraction (f_c)	$^{+10.4}_{-\ 6.8}$
Prompt charm shape ($\mathcal{F}_c$)	$^{+0.0}_{-1.5}$
Bottom background	
Bottom background fraction (f_b)	± 3.6
Bottom background shape ($\mathcal{F}_b$)	$^{+0.0}_{-5.1}$
Missing momentum correction	
$p_T(B)$ spectrum	± 4.9
B decay model	$^{+5.0}_{-0.0}$
Electron cuts	$^{+0.0}_{-1.1}$
D_s^{**+} fraction (f^{**})	± 1.8
Signal fraction (f_{sig})	± 4.7
Resolution scale factor	± 4.0
Decay length cut	$^{+0.0}_{-2.3}$
Combinatorial background shape	± 5.2
Detector alignment	± 2.0
Total	$^{+15.6}_{-13.8}$

2.3 Systematic uncertainties in $\tau(\bar{B}_s^0)/\tau(\bar{B}^0)$

Source	Contribution to $\tau(\bar{B}_s^0)/\tau(\bar{B}^0)$
Prompt charm background	
Prompt charm fraction (f_c)	${}^{+0.025}_{-0.020}$
Prompt charm shape ($\mathcal{F}_c$)	${}^{+0.011}_{-0.012}$
Bottom background	
Bottom background fraction (f_b)	${}^{+0.009}_{-0.008}$
Bottom background shape ($\mathcal{F}_b$)	${}^{+0.003}_{-0.012}$
Sample composition (affects only $\tau(\bar{B}^0)$)	
D^{**} composition (P_V)	${}^{+0.018}_{-0.023}$
π_s^+ reconstruction	${}^{+0.000}_{-0.002}$
Missing momentum correction	
$p_T(B)$ spectrum	${}^{+0.022}_{-0.016}$
Electron cuts	-
B decay model	± 0.012
D_s^{**+} fraction (f^{**})	${}^{+0.017}_{-0.011}$
Signal fraction (f_{sig})	± 0.011
Resolution scale factor	± 0.004
Decay length cut	-
Combinatorial background shape	± 0.012
Detector alignment	-
Total	${}^{+0.049}_{-0.046}$

2.4 Results

The $\bar{B}_s^0$ meson lifetime has been measured using the partially reconstructed semileptonic decays $\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+ X$ to be

$$c\tau(\bar{B}_s^0) = 414.0 \pm 16.6 \ {}^{+15.6}_{-13.8} \ \mu\text{m},$$

or

$$\tau(\bar{B}_s^0) = 1.381 \pm 0.055 \ {}^{+0.052}_{-0.046} \ \text{ps},$$

where the first uncertainties are statistical and the second are systematic. We also find the ratio of the $\bar{B}_s^0$ and $\bar{B}^0$ meson lifetimes to be

$$\tau(\bar{B}_s^0)/\tau(\bar{B}^0) = 0.938 \pm 0.044 \ {}^{+0.049}_{-0.046},$$

where the $\bar{B}^0$ meson lifetime is taken from [2]. They are consistent with other recent measurements. Figures 5 and 6 show comparisons of the results from other measurements [3] and this analysis, for $\tau(\bar{B}_s^0)$ and $\tau(\bar{B}_s^0)/\tau(\bar{B}^0)$.

3 Fit assuming a non-zero $\Delta\Gamma/\Gamma$ value

In the $B_s^0\bar{B}_s^0$ meson system, there should exist two eigenstates of the masses and the lifetimes, $B^0_{s,\mathrm{Heavy}}$ and $B^0_{s,\mathrm{Light}}$. The width difference $\Delta\Gamma$ could be sizable, of order 10% in $\Delta\Gamma/\Gamma$, according to theory. Experimentally, CDF finds $\Delta\Gamma/\Gamma = 0.65^{+0.25}_{-0.33} \pm 0.01$ using $B_s^0 \to J/\psi\phi$ decays, and the 2005 web update version of PDG [4] quotes a world average of

$$\Delta\Gamma/\Gamma = 0.37^{+0.17}_{-0.20}.$$

The results presented thus far have been obtained assuming $\Delta\Gamma/\Gamma = 0$. We could, however, fit for the average decay width Γ assuming a value of $\Delta\Gamma/\Gamma$. The decay time distribution of the signal is modified to be

$$P(t) = \frac{1}{\tau_L + \tau_S}\left[e^{-t/\tau_L} + e^{-t/\tau_S}\right],$$

where τ_L and τ_S are the lifetimes of the long-lived and short-lived mesons, $\Gamma_{S,L} \equiv \Gamma \pm \Delta\Gamma/2 = 1/\tau_{S,L}$, $\Gamma \equiv (\Gamma_S + \Gamma_L)/2$ is the average decay width, and $\Delta\Gamma \equiv \Gamma_S - \Gamma_L$ is the width difference.

We fit for Γ with $\Delta\Gamma/\Gamma$ fixed. For $\Delta\Gamma/\Gamma = 0.37$, we find

$$c/\Gamma = 386.7 \pm 16.0\ \mu\mathrm{m},$$

where the uncertainty is statistical only. From this value and $\Delta\Gamma/\Gamma$, we calculate τ_L and τ_S. The table below summarizes these numbers, including other values of $\Delta\Gamma/\Gamma$ we have assumed.

Figure 7 shows the fit result for $\Delta\Gamma/\Gamma = 0.37$. The data points are identical to those of Figure 4.

$\Delta\Gamma/\Gamma$	$c\tau_S$ (μm)	$c\tau_L$ (μm)	c/Γ (μm)
0.17	376.1 ± 15.2	446.0 ± 18.0	408.1 ± 16.5
0.37	326.3 ± 13.5	474.4 ± 19.6	386.7 ± 16.0
0.54	281.7 ± 11.9	490.1 ± 20.7	357.8 ± 15.1

References

[1] CDF Collaboration,
F. Abe *et al.*, Phys. Rev. D **58**, 092002 (1998);
F. Abe *et al.*, Phys. Rev. D **59**, 032004 (1999).

[2] CDF Collaboration,
`http://www-cdf.fnal.gov/physics/new/bottom/050224.blessed-bsemi-life/`.

[3] Heavy Flavor Averaging Group, hep-ex/0505100 (2005).

[4] Particle Data Group, Review of Particle Physics, 2005 web update version (2005).

4 Blessed Figures

The following figures have been blessed for the measurement of the $\bar{B}_s^0$ meson lifetime using semileptonic decays. More details can be found in CDF note 7683.

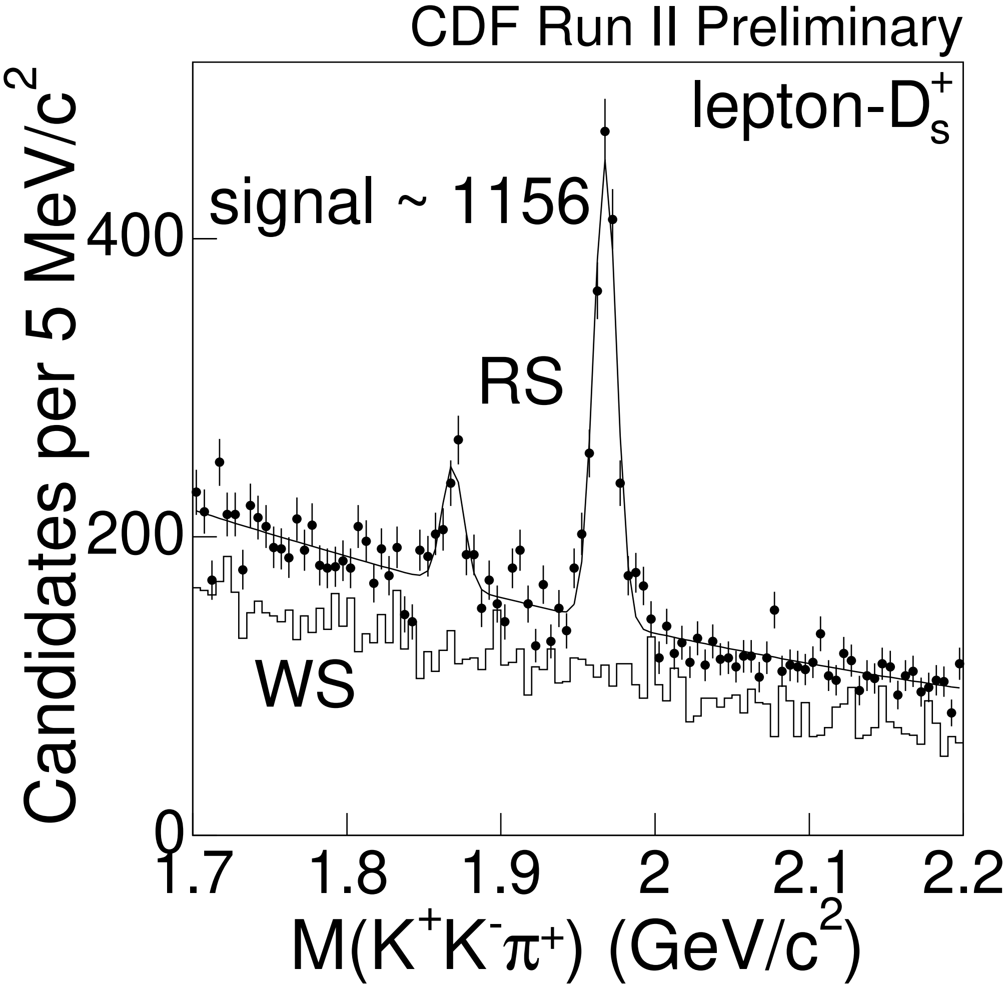

Figure 1: The $\phi\pi^+$ mass distribution reconstructed near the lepton candidates in the combined muon and electron sample. Both right-sign ($\ell^- D_s^+$, RS) and wrong-sign ($\ell^- D_s^-$, WS) charge combinations are shown. The smaller peak near 1870 MeV$/c^2$ is from the Cabibbo-suppressed decay $D^+ \to \phi\pi^+$.

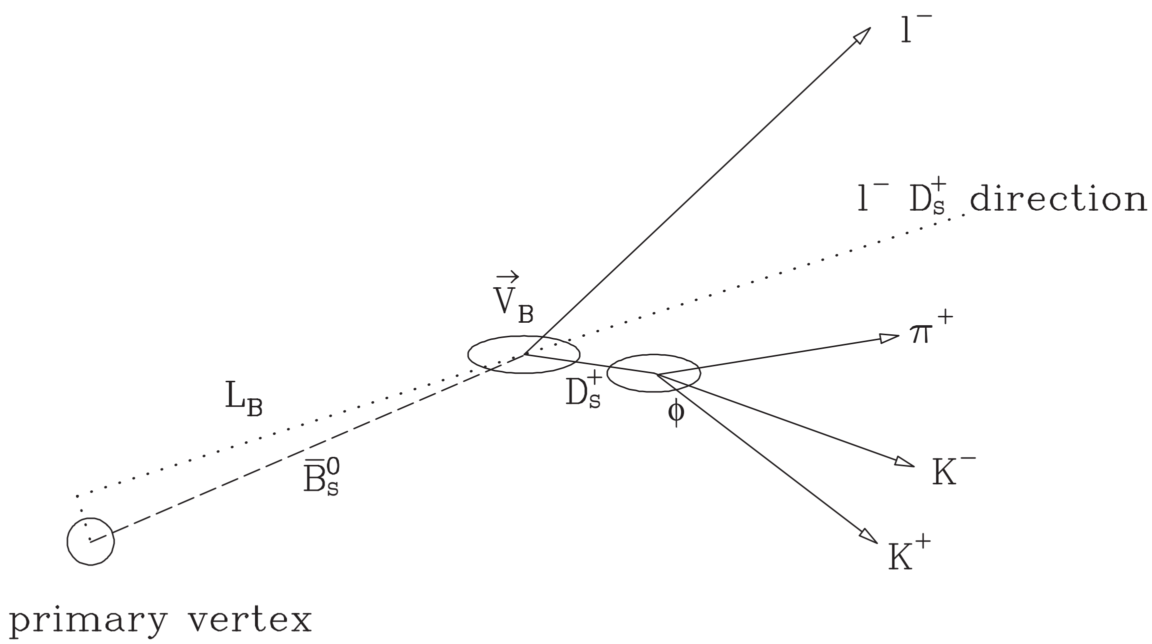

Figure 2: Schematic view of the semileptonic decay $\bar{B}_s^0 \to \ell^- \bar{\nu} D_s^+$, $D_s^+ \to \phi\pi^+, \phi \to K^+K^-$ in the plane perpendicular to the beam axis.

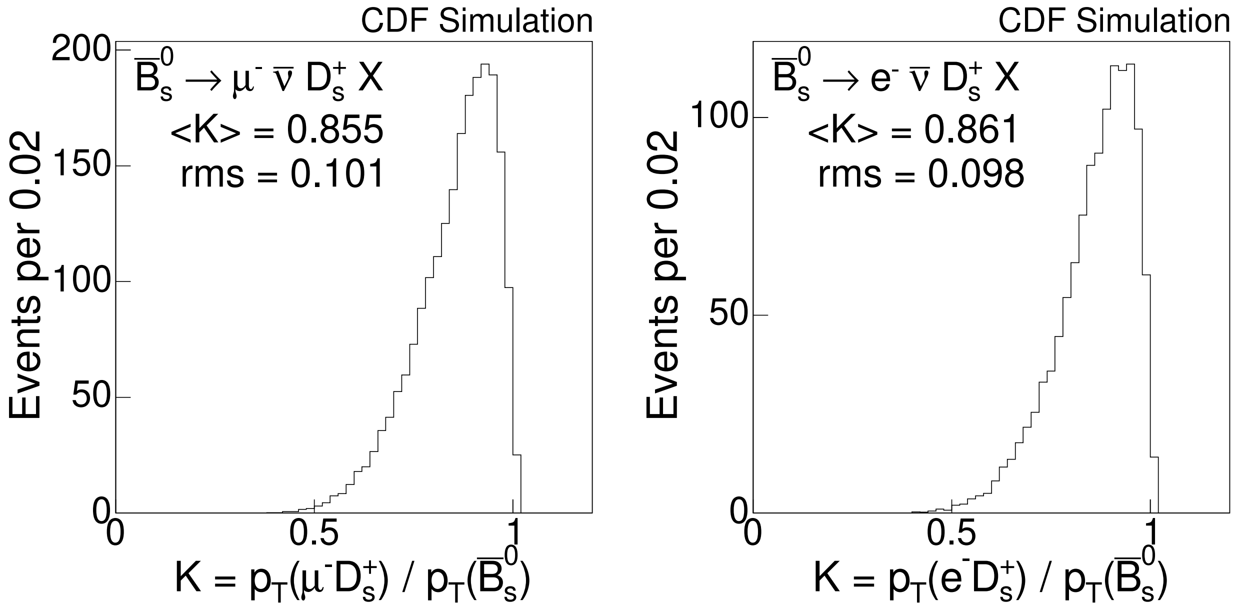

Figure 3: Distributions of the momentum ratio K for the muon and electron datasets.

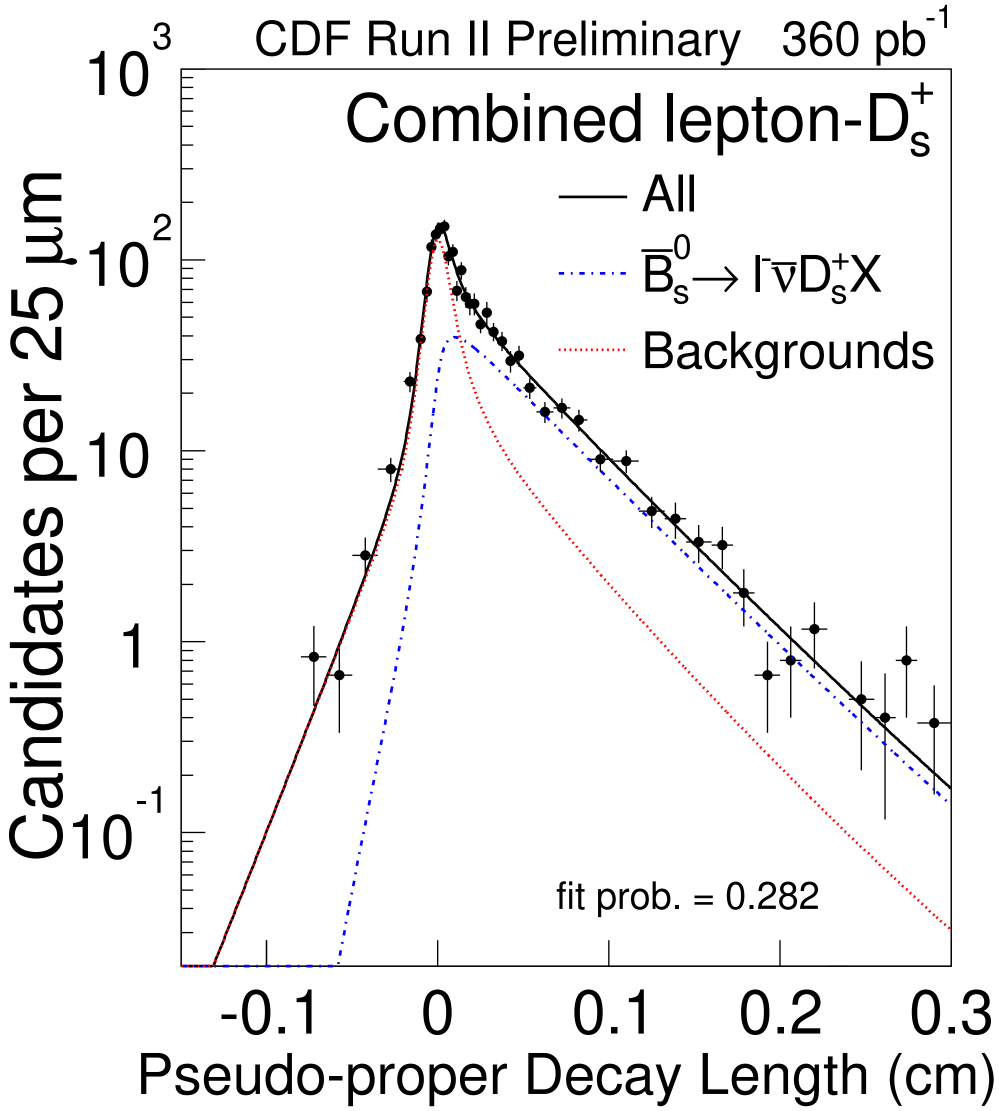

Figure 4: Pseudo-proper decay length distribution for the combined muon and electron sample. The lifetime fit result is superimposed. Points are data, dashed curve shows the sum of all background components (combinatorial and physics backgrounds), while the dot-dashed curve is the signal component. The solid curve is the sum of all components.

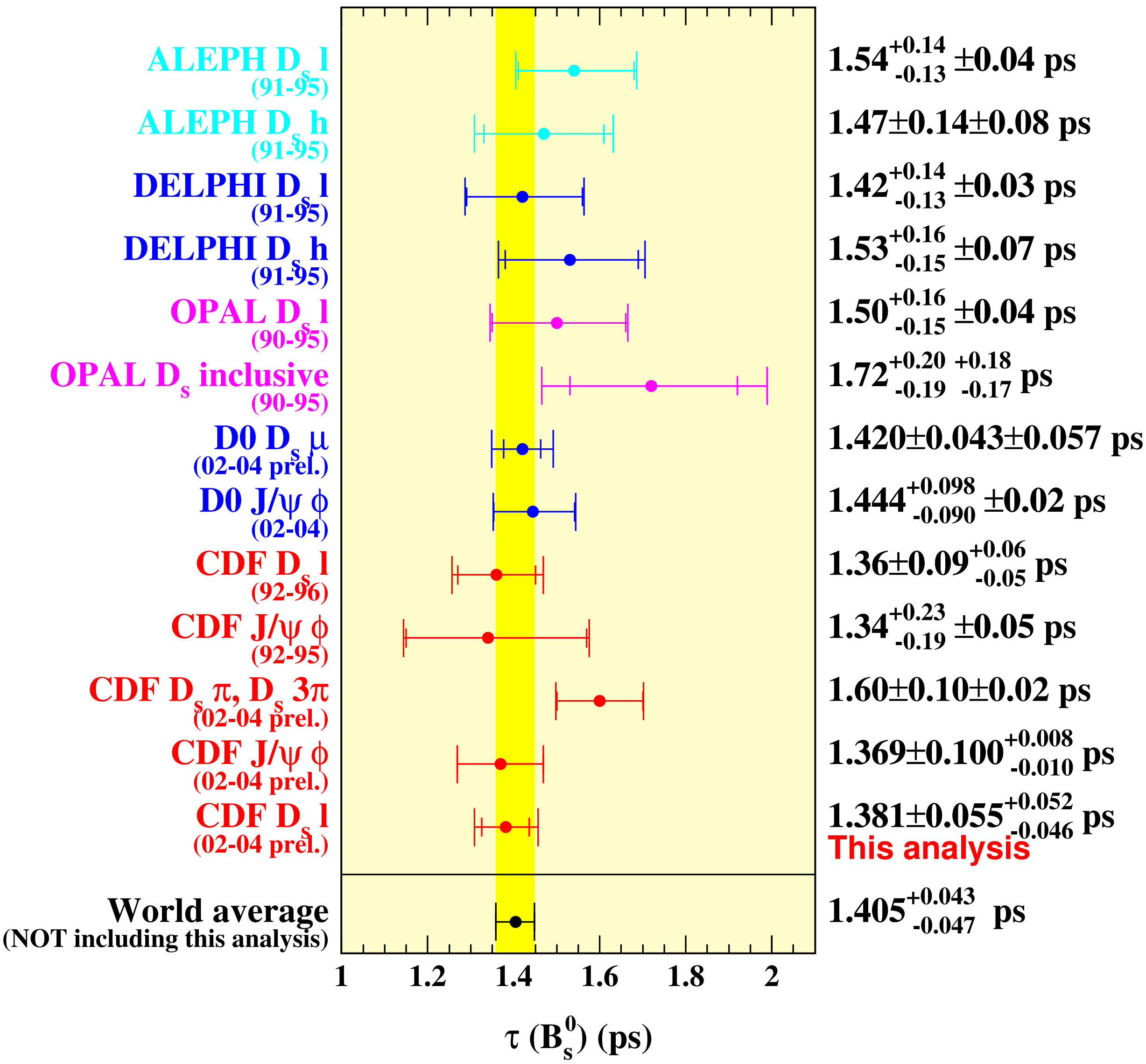

Figure 5: Comparison of the $\bar{B}_s^0$ meson lifetime measured by other experiments and this analysis.

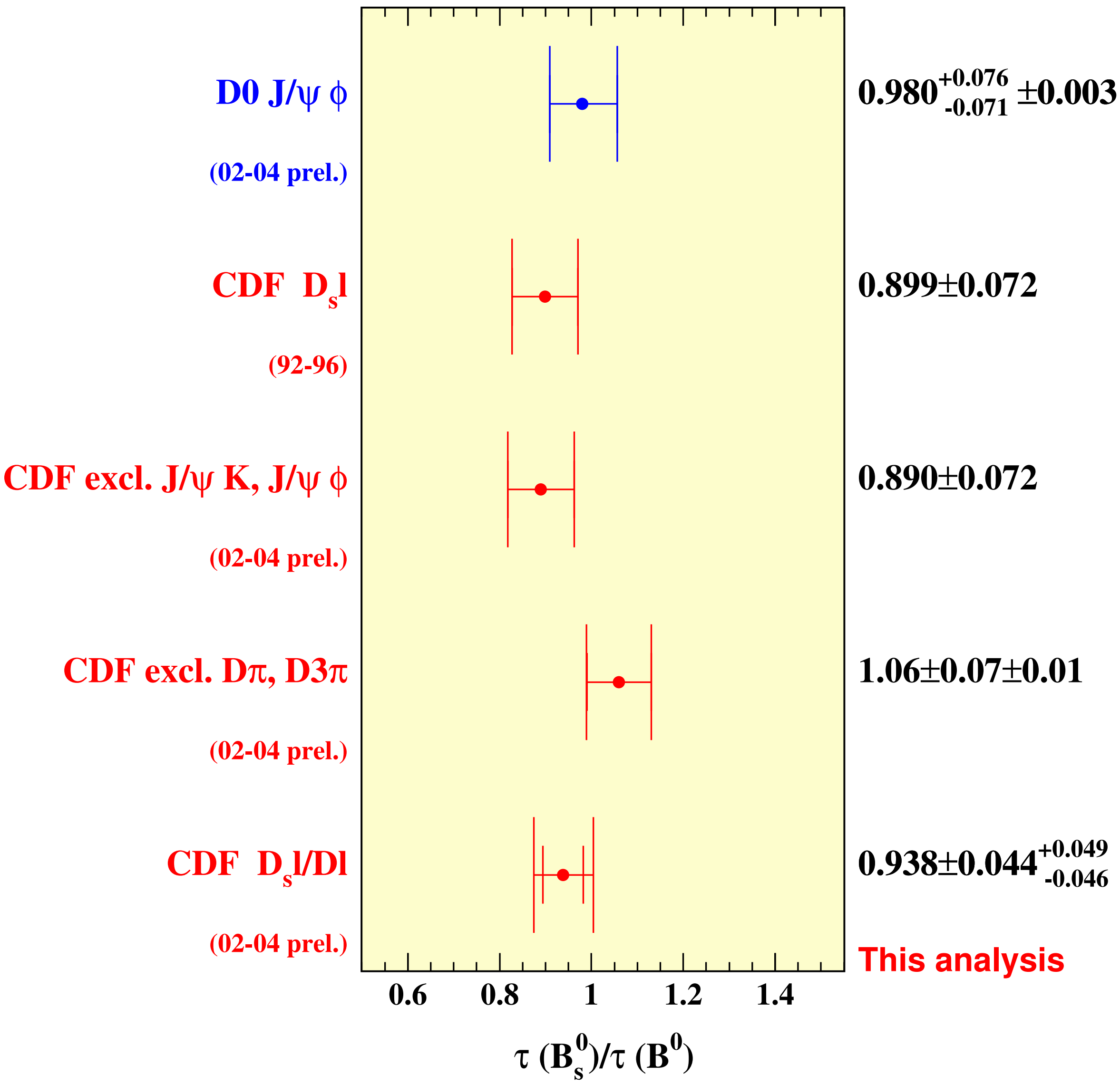

Figure 6: Measurements of the ratio of the $\bar{B}_s^0$ and $\bar{B}^0$ meson lifetimes from other experiments and this analysis. Only those measurements which quote the ratio explicitly are listed.

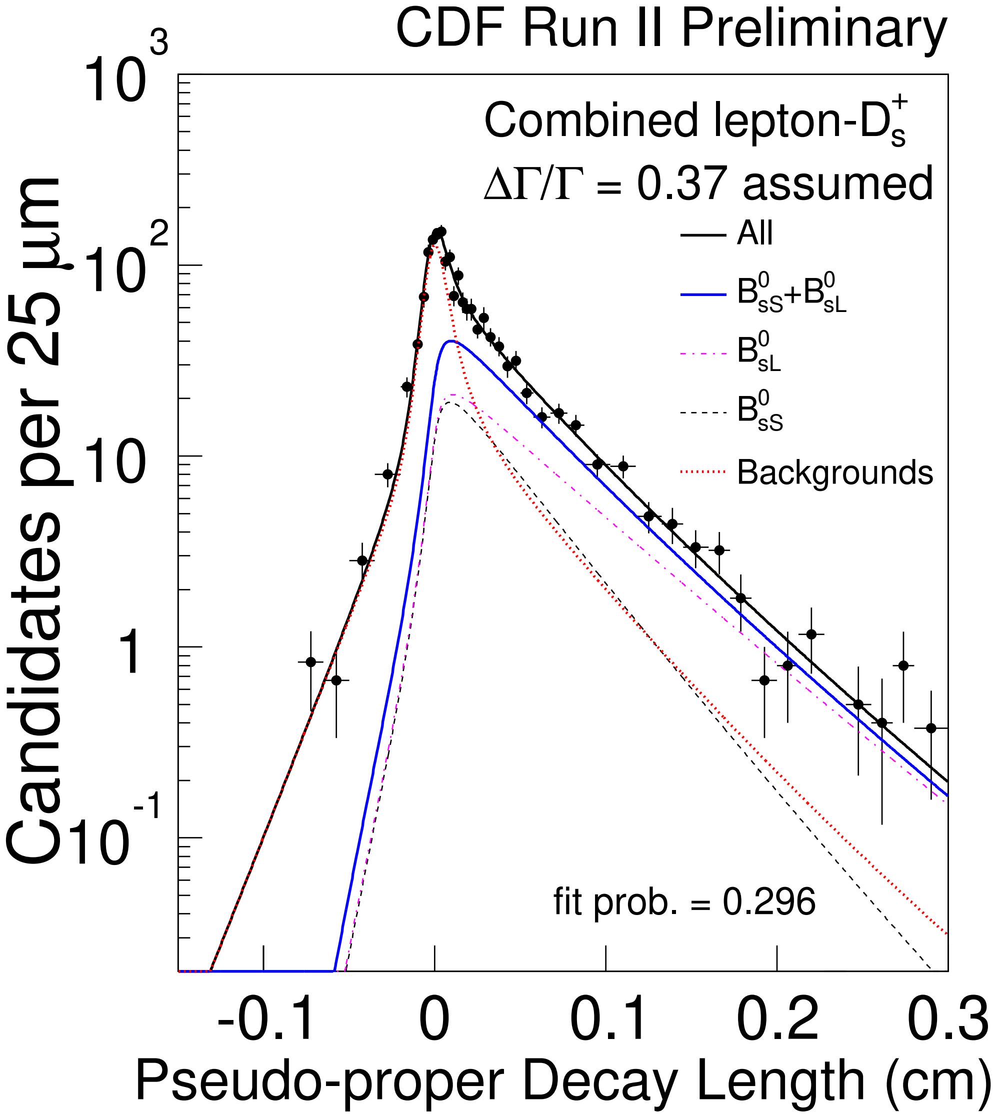

Figure 7: Fit results assuming $\Delta\Gamma/\Gamma = 0.37$. The dashed curve (black) is the short-lifetime component, the dot-dashed curve (magenta) is the long-lifetime component, the inner solid curve (blue) is the sum of the two. The dotted curve (red) corresponds to the total background. The outer solid curve (black) is the sum of all components. The data points are identical to those of Figure 4.