New measurement of lifetimes of B mesons in the exclusively reconstructed decays $B^+ \to J/\psi K^+$ $B^0 \to J/\psi K^{*0}$ $B_s \to J/\psi \phi$

Brief overview of the analysis – CDF note 6551

The CDF Collaboration

May 9, 2004

Abstract

We present a new measurement of B meson lifetimes using the largest CDF data sample. The groundwork has been carried out in year 2003 and is documented in CDF Notes 6266 and 6550 (both are blessed analyses). Since 2003 the analysis is substantially improved by using more data and the data themselves being of better quality. Substantial improvements also come from updated fit models. Other smaller issues not previously discussed are also addressed in the current document.

This analysis is performed using all data collected before February 2004 shutdown, which roughly corresponds to 240pb^{-1}. A total of about 250 high quality B_s signal candidates are observed. For the lifetimes we obtain the following results:

$$\tau_{B^+} = 1.662 \pm 0.033\,(stat.) \pm 0.008(syst.)\,\mathrm{ps}$$

$$\tau_{B^0} = 1.539 \pm 0.051\,(stat.) \pm 0.008(syst.)\,\mathrm{ps}$$

$$\tau_{B_s} = 1.369 \pm 0.100\,(stat.)^{+0.008}_{-0.010}(syst.)\,\mathrm{ps}$$

1 Description

B decays of interest are reconstructed using J/ψ-sample, accumulated via di-muon trigger. The sample size corresponds to exposure of about 240 pb^{-1}. Apart from stringent track quality requirements the following cuts are applied to select B candidates:

Decay	p_T^B	$p_T^{K/\phi}$	$Prob(\chi^2)$	K/ϕ mass window	B mass window
$B^+ \to J/\psi K^+$	5.5GeV/c	1.6GeV/c	10^{-3}	$--$	5170$-$5390MeV/c^2
$B^0 \to J/\psi K^{*0}$	6.0GeV/c	2.6GeV/c	10^{-4}	$M_{PDG}^{K^{*0}} \pm 50.0$MeV/c^2	5170$-$5390MeV/c^2
$B_s \to J/\psi \phi$	5.0GeV/c	1.5GeV/c	10^{-5}	$M_{PDG}^{\phi} \pm$ 6.5MeV/c^2	5220$-$5520MeV/c^2

These cuts are chosen so that the combined (stat.$\oplus$syst.) uncertainty on the extracted lifetime is optimized.

For each B candidate we have the following 4 pieces of information:

1. m_i – measured invariant mass
2. σ_{m_i} – uncertainty on the measured invariant mass
3. ct_i – recontructed proper decay length
4. σ_{ct_i} – uncertainty on recontructed proper decay length

We use unbinned maximum likelihood method to extract the lifetimes. In the past we have used the following 12 parameter model (Figure 1) to the data:

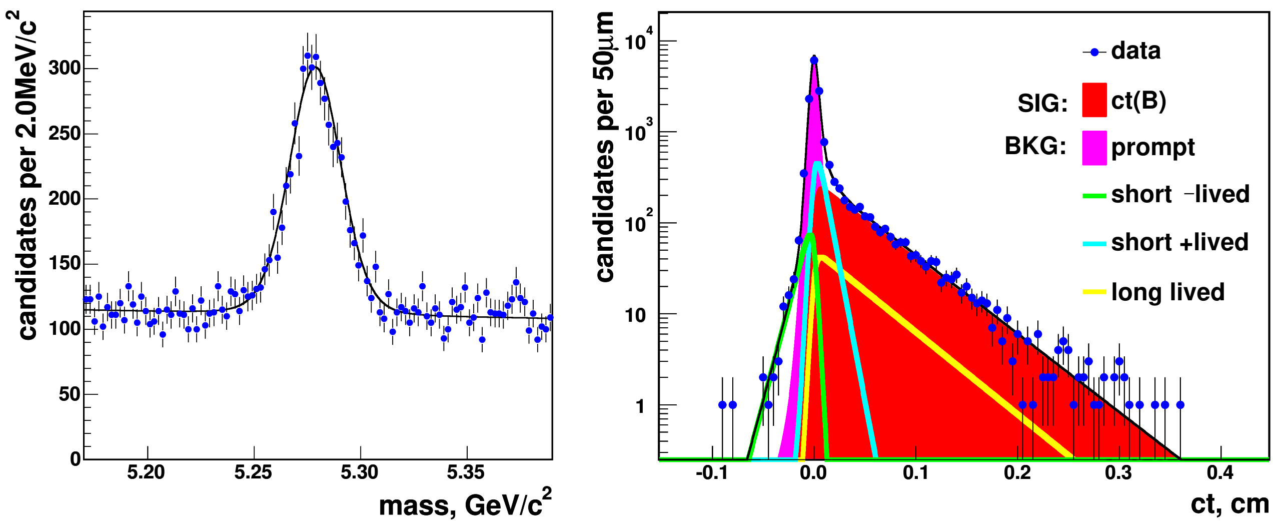

Figure 1: Illustration of the 12 parameter fit model.

- mass (m) – Gaussian for signal, linear background:

$$
\begin{aligned}
F_m^{sig}(m_i, \sigma_{m_i}|M, S_m) &= \frac{1}{\sqrt{2\pi}S_m\sigma_{m_i}} \exp\Big(-\frac{(m_i-M)^2}{2(S_m\sigma_{m_i})^2}\Big), \\
F_m^{bkg}(m_i|A) &= A\cdot m_i + \frac{1}{M_{max}-M_{min}}\Big[1-\frac{A}{2}(M_{max}^2 - M_{min}^2)\Big].
\end{aligned}
$$

1. M – mean of the Gaussian
2. S_m – universal mass error scale factor to correct for consistently underestimated uncertainties
3. A – slope of linear background

- proper decay length (λ) – positively lived exponential for signal, δ-function for prompt background, 3 exponential tails for other sources of background. All of these components are convoluted on event-by-event basis with a resolution function, which is assumed to be a Gaussian of width given by σ_{λ_i}:

$$
\begin{aligned}
F_{ct}^{sig}(ct_i, \sigma_{ct_i}|c\tau_B, S_{ct}) &= E(ct_i|c\tau_B)\otimes G(ct_i, \sigma_{ct_i}|S_{ct}), \\
F_{ct}^{bkg}(ct_i, \sigma_{ct_i}|f_-, f_+, f_{++}, \lambda_-, \lambda_+, \lambda_{++}, S_{ct}) &= (1-f_- - f_+ - f_{++})\cdot G(ct_i, \sigma_{ct_i}|S_{ct}) + \\
&\quad f_-\cdot E(-ct_i|\lambda_-)\otimes G(ct_i, \sigma_{ct_i}|S_{ct}) + \\
&\quad f_+\cdot E(ct_i|\lambda_+)\otimes G(ct_i, \sigma_{ct_i}|S_{ct}) + \\
&\quad f_{++}\cdot E(ct_i|\lambda_{++})\otimes G(ct_i, \sigma_{ct_i}|S_{ct})
\end{aligned}
$$

4. $c\tau_B$ – signal lifetime

5-6. f_-, λ_- – fraction and decay constant of short negatively lived exponential tail

7-8. f_+, λ_+ – fraction and decay constant of short positively lived exponential tail

9-10. f_{++}, λ_{++} – fraction and decay constant of long (positively) lived exponential tail

11. S_{ct} – scale factor to correct consistently underestimated proper decay length uncertainties

The above parameters are combined in a single event PDF:

$$f(m_i, ct_i, \sigma_{ct_i}|\overrightarrow{\text{parameters}}) = f_s\cdot F_m^{sig}\cdot F_{ct}^{sig} + (1-f_s)\cdot F_m^{bkg}\cdot F_{ct}^{bkg}$$

using yet another parameter:

12. f_s – fraction of signal events in the sample

Single event PDFs are then combined in the likelihood function:

$$\mathcal{L} = -2\,log\prod_i f(m_i, ct_i, \sigma_{ct_i}|\overrightarrow{\text{parameters}}),$$

which is then minimized with respect to the vector of 12 parameters.

One of the major improvements in this *new* measurement is that most of the B reflections are either excluded from the samples or are carefully parameterized. In particular we parameterize $B^+ \to J/\psi\pi^+$ reconstructed as $B^+ \to J/\psi K^+$ and B^0 self-reflection due to $K \leftrightarrow \pi$ mass mis-assignment when reconstructing $K^{*0} \to K^+\pi^-$.

A great effort to reduce systematic uncertainties pays off – systematic uncertanties are at all time low. Major improvements come from finalized SXV II alignment as well as from careful candidate selection ensuring well-understood (and thus well-modeled!) sample composition.

2 Blessed Numbers

This section summarizes the numbers which have been blessed as part of this analysis.

2.1 Fit results

Par.	B^+	B^0	B_s	Units
M	5278.67 ± 0.26	5280.11 ± 0.39	5365.51 ± 0.77	MeV/c^2
f_s	0.1223 ± 0.0025	0.1556 ± 0.0052	0.0694 ± 0.0052	
A	-0.85 ± 0.46	-1.37 ± 0.90	-1.96 ± 0.65	(GeV/c^2)$^{-1}$
S_m	1.544 ± 0.028	1.605 ± 0.058	1.862 ± 0.116	
$c\tau$	498.1 ± 9.9	461.3 ± 15.4	410.4 ± 30.0	μm
f_-	0.0373 ± 0.0071	0.0377 ± 0.0138	0.0195 ± 0.0207	
f_+	0.1057 ± 0.0087	0.1387 ± 0.0200	0.1228 ± 0.0192	
f_{++}	0.0135 ± 0.0025	0.0454 ± 0.0067	0.0050 ± 0.0028	
λ_-	52 ± 5	47 ± 9	52 ± 24	μm
λ_+	57 ± 5	44 ± 6	78 ± 12	μm
λ_{++}	397 ± 59	328 ± 40	826 ± 333	μm
S_{ct}	1.249 ± 0.012	1.274 ± 0.024	1.289 ± 0.032	
N_{sig}	3385.6 ± 68.2	1156.3 ± 39.0	255.6 ± 19.0	

2.2 Systematic errors

Systematic effect	Uncertainty on $c\tau_{B^+}\mu$m	Uncertainty on $c\tau_{B^0}\mu$m	Uncertainty on $c\tau_{B_s}\mu$m
SVX Alignment	± 1.0	$\leftarrow$ same	$\leftarrow$ same
Fit Model	± 1.7	$\leftarrow$ same	$\leftarrow$ same
Selection	negligible	$\leftarrow$ same	$\leftarrow$ same
Procedure Bias	± 1.3	$\leftarrow$ same	$\leftarrow$ same
Cross-feed	—	$+0.2\mu$m	-1.7μm
Total	± 2.4	± 2.4	$^{+2.4}_{-2.9}$

2.3 Final results

$$
\begin{aligned}
c\tau_{B^+} &= 498.1 \pm \ 9.9\,(stat.) \pm 2.4(syst.)\,\mu\text{m}, \quad \text{corresponding to} \\
\tau_{B^+} &= 1.662 \pm 0.033\,(stat.) \pm 0.008(syst.)\,\text{ps} \\
c\tau_{B^0} &= 461.3 \pm 15.4\,(stat.) \pm 2.4(syst.)\,\mu\text{m}, \quad \text{corresponding to} \\
\tau_{B^0} &= 1.539 \pm 0.051\,(stat.) \pm 0.008(syst.)\,\text{ps} \\
c\tau_{B_s} &= 410.4 \pm 30.0\,(stat.)^{+2.4}_{-2.9}(syst.)\,\mu\text{m}, \quad \text{corresponding to} \\
\tau_{B_s} &= 1.369 \pm 0.100\,(stat.)^{+0.008}_{-0.010}(syst.)\,\text{ps}
\end{aligned}
$$

These results are compared to the world average and the best single measurements in the table immediately below:

B meson	This, ps	PDG'03, ps	Single best, ps
B^+	$1.662 \pm 0.033 \pm 0.008$	1.671 ± 0.018	$1.695 \pm 0.026 \pm 0.015$
B^0	$1.539 \pm 0.051 \pm 0.008$	1.537 ± 0.015	$1.529 \pm 0.012 \pm 0.029$
B_s	$1.369 \pm 0.100^{+0.008}_{-0.010}$	1.461 ± 0.057	$1.36 \pm 0.09^{+0.06}_{-0.05}$

Measured lifetimes correspond to the following lifetime ratios:

$$
\begin{aligned}
\tau_{B^+}/\tau_{B^0} &= 1.080 \pm 0.042(tot.) \\
\tau_{B_s}/\tau_{B^0} &= 0.890 \pm 0.072(tot.)
\end{aligned}
$$

In calculating the uncertainty on the ratios we account for the fact that most systematic uncertainties are 100% correlated. As a result systematic uncertainties nearly cancel for the ratios, therefore it makes sense to quote a single uncertainty without splitting it into statistical and systematic parts.

3 Blessed Figures

The following figures have been blessed as part of this analysis. More elaborate description can be found in CDF note 6551.

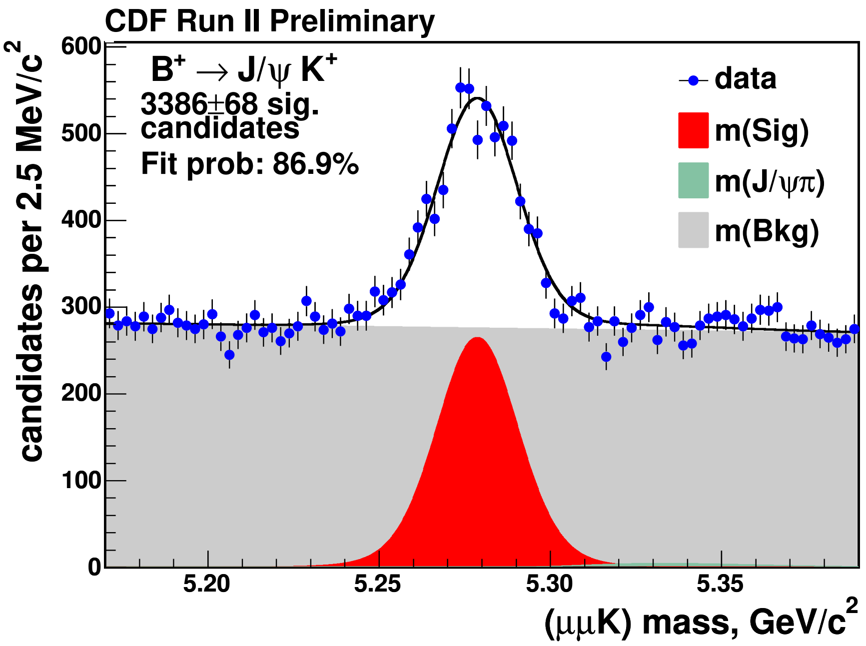

Figure 2: Invariant mass spectrum of the $B^+ \to J/\psi K^+$ candidates. The result of the maximum likelihood fit is overlaid.

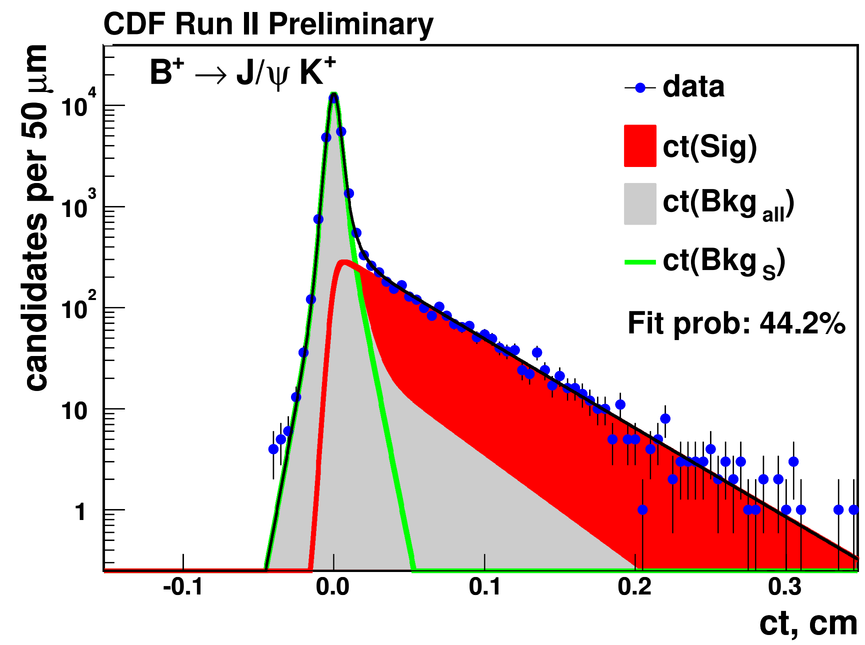

Figure 3: The proper decay length distribution of all $B^+ \to J/\psi K^+$ candidates passing the selection cuts. The result of the maximum likelihood fit is overlaid.

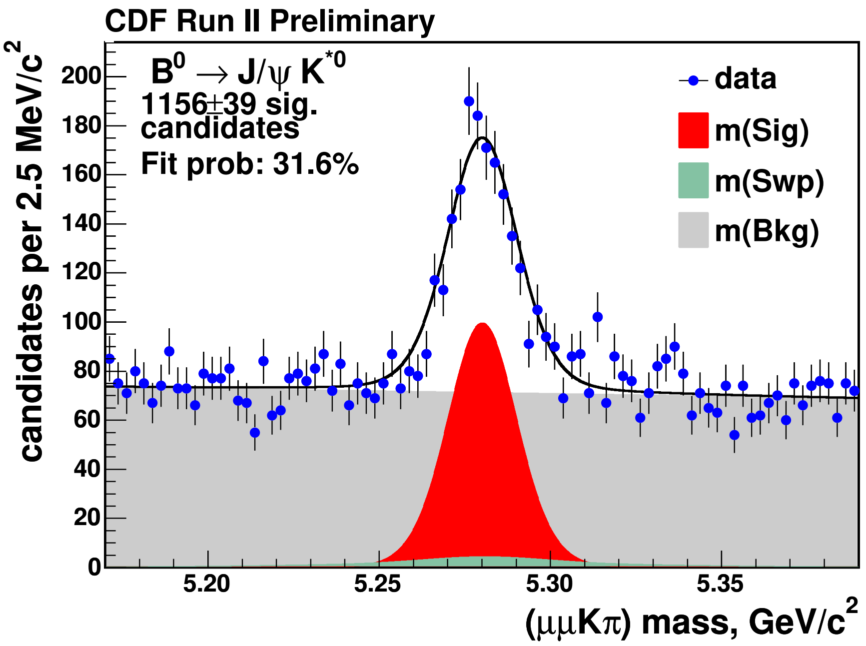

Figure 4: Invariant mass spectrum of the $B^0 \to J/\psi K^{*0}$ candidates. The result of the maximum likelihood fit is overlaid.

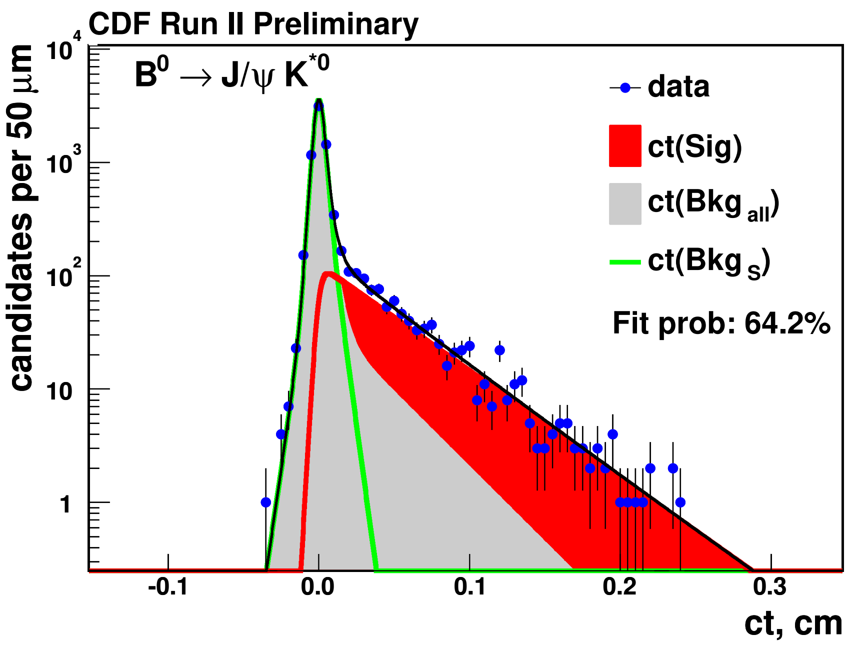

Figure 5: The proper decay length distribution of all $B^0 \to J/\psi K^{*0}$ candidates passing the selection cuts. The result of the maximum likelihood fit is overlaid.

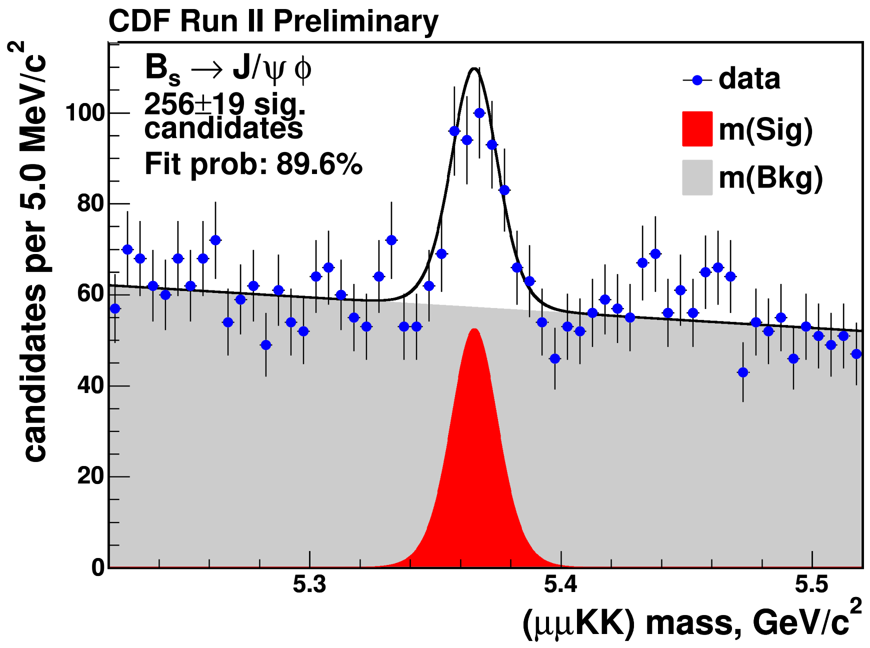

Figure 6: Invariant mass spectrum of the $B_s \to J/\psi\phi$ candidates. The result of the maximum likelihood fit is overlaid.

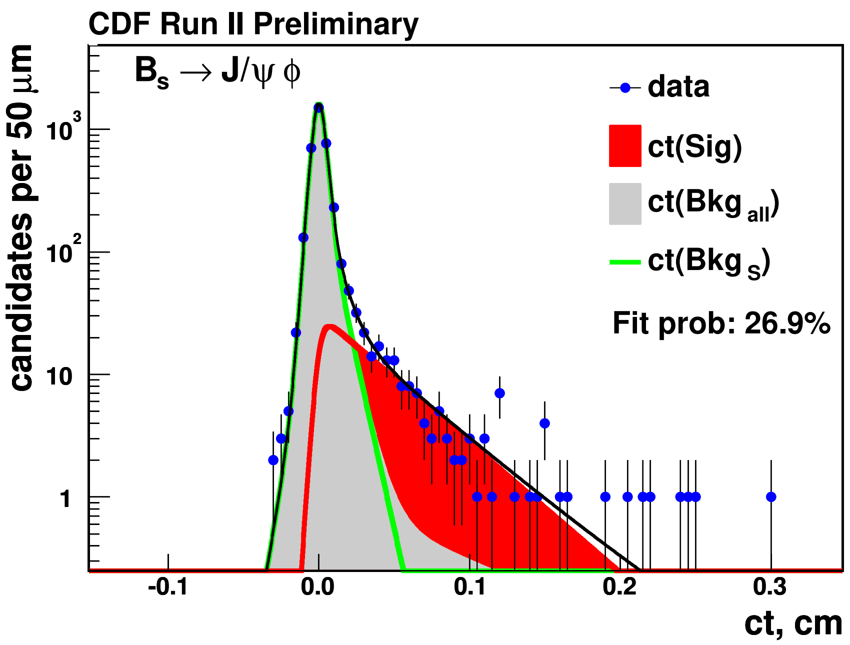

Figure 7: The proper decay length distribution of all $B_s \to J/\psi\phi$ candidates passing the selection cuts. The result of the maximum likelihood fit is overlaid.