Fermi National Accelerator Laboratory

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CDF

Measurement of the B_s Meson Lifetime at CDF

The CDF Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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Abstract

Proton-antiproton collision data corresponding to a total integrated luminosity of ~21 pb^{-1} were collected with the CDF detector at the Fermilab Tevatron collider during 1992-1993. The lifetime of the B_s meson is measured using events from the semileptonic decay $B_s \to \ell^+ \nu D_s^- X$ and from the exclusive decay $B_s \to J/\psi\phi$. For the semileptonic decay channel, 76 $\ell^+ D_s^-$ signal events are selected where the D_s is identified via the decay $D_s^- \to \phi\pi^-$, $\phi \to K^+K^-$. From this sample the B_s meson lifetime is determined to be

$$\tau_s = 1.42\ ^{+0.27}_{-0.23}\ \text{(stat.)}\ ^{+0.11}_{-0.11}\ \text{(syst.) ps.}$$

In the $J/\psi\phi$ channel, 11 events are used and the lifetime is found to be

$$\tau_s = 1.74\ ^{+0.90}_{-0.60}\ \text{(stat.)}\ ^{+0.07}_{-0.07}\ \text{(syst.) ps.}$$

1 Introduction

The lifetime hierarchy of various bottom hadrons can be a probe to the B decay mechanisms beyond the spectator model. In the case of charm mesons, the lifetime of the D^+ is much longer than the D^0 lifetime ($\tau(D^+)/\tau(D^0) \sim 2.5$). This difference, which is not expected in the simple spectator model, can be attributed to the "W exchange" process and final state "Pauli interference" effects. Among the bottom hadrons, however, the lifetimes differences are believed to be much smaller due to the heavier bottom quark mass [1]. Also, theory calculations suggest that $\Delta\Gamma(B_s)$, the difference in widths between the two eigenstates produced by $B_s\overline{B_s}$ mixing, might

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actually be quite large ($\sim 15\%\ \Gamma(B_s)$)[2]. This could mean that the lifetime difference between the so-called 'long' and 'short' B_s mesons is comparable to or even larger than the lifetime difference between the B^+ and B^0 mesons. Such an effect could eventually be observed by measuring the B_s lifetime using semi-leptonic B_s decays and the decay $B_s \rightarrow J/\psi\phi$, where the latter is dominated by a CP even eigenstate. In this paper, we first present a measurement of B_s lifetime using the semi-leptonic decay[3]

$$B_s^0 \rightarrow D_s^- \ell^+ \nu X,$$

where D_s^- is identified via

$$D_s^- \rightarrow \phi\pi^-,\ \phi \rightarrow K^+K^-.$$

We then present a result using an exclusive decay

$$B_s \rightarrow J/\psi\phi$$

with

$$J/\psi \rightarrow \mu^+\mu^-,\ \phi \rightarrow K^+K^-.$$

2 CDF Detector

The CDF detector is described in detail elsewhere [4]. We describe here only the detector features most relevant to this analysis. Two devices inside the 1.4 T solenoid provide tracking of charged particles: the silicon vertex detector(SVX) and the central tracking chamber (CTC). The SVX consists of four layers of silicon micro-strip detectors located at radii between 2.9 and 7.9 cm from the interaction point and provides spatial measurements in the r-ϕ plane[6] with a resolution of 13 μm, providing a track impact parameter resolution of $(13\ +\ 40/p_T)$ μm[5], where p_T is the transverse momentum of a track in GeV/c. The geometric acceptance of the SVX is $\sim$ 60% as it extends to only $\pm$ 25 cm along the beam (z) direction from the nominal interaction point whereas the Tevatron beam is spread with rms width of $\sim$ 30 cm. The CTC is a cylindrical drift chamber containing 84 layers grouped into alternating superlayers of axial and stereo wires. It covers the pseudorapidity interval $|\eta| < 1.1$, where $\eta = -\ln[\tan(\theta/2)]$. The transverse momentum resolution of the CTC combined with the SVX is $\sigma(p_T)/p_T = [(0.0009p_T)^2 + (0.0066)^2]^{1/2}$. Outside the solenoid are electromagnetic (CEM) and hadron (CHA) calorimeters ($|\eta| < 1.1$) which employ a projective tower geometry with a segmentation of $\Delta\eta \times \Delta\phi \sim 0.1 \times 15°$. A layer of proportional wire chambers (CES) is located near shower maximum in the CEM and provides measurement of electromagnetic shower profiles in both the ϕ and z directions. There exist two different muon subsystems in the central region, each of which consists of four layers of drift chambers. The central muon chambers (CMU), located behind 5 interaction lengths of calorimeter material, cover 85% of the azimuthal angle for $|\eta| < 0.6$. Gaps in the ϕ coverage are filled in partly by the central upgrade muon chambers (CMP) with total coverage in ϕ of 80% for $|\eta| \leq 0.6$. These chambers are located behind 8 absorption lengths.

In this analysis, the primary vertex of each event is approximated by the average beam position obtained on a run-by-run basis. The transverse profile of the beam is gaussian distributed with an rms width of $\sim 35\ \mu$m in both x and y directions.

3 B_s Lifetime from Semi-leptonic Decays

3.1 Lepton Identification

Events for this analysis are collected through the inclusive electron and muon triggers. The E_T threshold for the principle single electron trigger is 9 GeV, where E_T is the electromagnetic energy transverse to the beam (z) direction. The muon trigger requires a reconstructed track in the CTC with $P_T > 7.5$ GeV/c matching with track segments in both the CMU and CMP systems.

Offline identification of an electron involves measurements from both the calorimeters and the tracking chamber by requiring (1) small leakage energy into the CHA, (2) good lateral shower profiles measured in the CEM and CES, (3) an association of a charged track based on a position matching with the CES shower and a energy-to-momentum ratio. Photon conversion electrons are removed by searching for an oppositely charged track which has a small opening angle with a primary electron candidate.

A muon candidate is required to have hits in both CMU and CMP chambers to reduce background from hadron punch-throughs. A good position matching is required between track segments in the muon chambers and an extrapolated CTC track.

To ensure a good decay vertex measurement, track quality cuts are imposed on a lepton and any two of the three tracks forming a D_s candidate. We require (1) at least 2 axial superlayers with 4 or more hit wires and at least 2 stereo superlayers with 2 or more hit wires in the CTC, and (2) at least 2 hits in the SVX with a χ^2 contribution to the fit of less than 30.

3.2 D_s reconstruction

D_s reconstruction starts with a search for ϕ candidates. We first define a search cone around the lepton candidate with radius of 0.8. No particle identification is used. Any two oppositely charged tracks with $P_T > 1$ GeV/c within that cone are assigned kaon masses and combined to form a ϕ candidate. A ϕ candidate is accepted when its mass lies in a window of ± 8 MeV/c^2 around 1.019 GeV/c^2, and it has $P_T(K^+K^-) > 2.0$ GeV/c. The ϕ candidate is then combined with another track of $P_T > 0.8$ GeV/c inside that cone which has the opposite charge to the lepton (we call this a 'right sign' combination). This third track is assigned the pion mass. All three tracks (K^+, K^- and π^-) are constrained to come from a common point in space (we call it V_D). The χ^2 probability (with 3 degrees of freedom) of the fit is required to be greater than 1%. In the decay $D_s^- \rightarrow \phi\pi^-$, since the ϕ has spin 1 and both the D_s^- and π^- are spinless, the helicity angle Ψ, the angle between the K^+ and D_s^- directions in the ϕ rest frame, exhibits a distribution $dN/d(\cos\Psi) \sim \cos^2\Psi$. The cut $|\cos\Psi| > 0.4$ is therefore applied to a D_s^- candidate to suppress the combinatorial background which shows a flat $\cos\Psi$ distribution. In addition, the mass of ℓD_s system is required to be between 3 and 6 GeV/c^2 in order to be consistent with coming from a B_s decay. We also apply an isolation cut $E_T^{iso}/P_T(\phi\pi^+) < 1.2$ on a D_s^+ candidate, where E_T^{iso} is a sum of transverse energy over calorimeter towers, excluding the lepton tower, within a cone of radius 0.4 in $\eta - \phi$ space around the lepton candidate. This cut eliminates many of the fake D_s track combinations from high multiplicity background jets. Furthermore, we require that the apparent D_s^- decay vertex V_D is positively displaced from the primary vertex along the direction of the lepton-D_s momentum. Figure 1(a) shows the $\phi\pi^-$ invariant mass distribution for the 'right sign' lepton-D_s combinations. A D_s signal is apparent and a hint of the Cabibbo suppressed $D^- \rightarrow \phi\pi^-$ decay is seen. A binned maximum likelihood fit gives 76 ± 8 events for the D_s^- and 19 ± 7 for the D^-. No enhancement is seen in the corresponding distribution for the 'wrong sign' combinations (see Figure 1(b)).

3.3 Lifetime Samples

To measure the B_s lifetime, we start with a signal plus background sample of 139 events in the mass range between 1.953 and 1.981 GeV/c^2. A combinatorial background of 63 ± 2 events is estimated in this interval.

To model the lifetime distribution of the background underneath the peak, events from the sidebands of the 'right sign' combinations in the interval of 1.885-1.945 GeV/c^2 and 1.990-2.050 GeV/c^2, and also the region 1.885-2.050 GeV/c^2 from the 'wrong sign' combinations, are used.

There are two possible sources of non-strange B meson decays which can lead to the right sign $\ell^+ D_s^-$ combinations. They are

$$B \rightarrow D_s^{(*)-} X_s \ell^+ \nu, \qquad (1)$$

$$B \rightarrow D_s^{(*)-} D, D \rightarrow \ell^+ \nu X. \qquad (2)$$

Because both processes produce softer and less isolated leptons than those from B_s semi-leptonic decay, the acceptances and efficiencies relative to the signal are small (16% and 2.6%, respectively). The first process is yet to be observed experimentally[7]. A theoretical limit of the production is set to be[8]

$$\frac{BR(B_{u,d} \rightarrow D_s^- X_s \ell^+ \nu)}{BR(B_{u,d} \rightarrow X \ell^+ \nu)} < 0.025 \text{ (95\%CL)}.$$

Assuming that 25% of the B_s semi-leptonic decays go through D_s^{**} or non-resonant $D(n\pi)$, and that 20% of them decay to D_s mesons, the fraction of the $\ell^+ D_s^-$ pairs from the first source is limited $< 2.6\%$ of the signal. Here we also used $u : d : s = 3 : 3 : 1$ ratio assumption. For the second source, with the $BR(B \rightarrow D_s X) = 0.10 \pm 0.02 \pm 0.04$ measured by the CLEO experiment and the semi-leptonic branching ratio $BR(D^+ \rightarrow \ell^+ \nu X) = 19.2\%$, $BR(D^0 \rightarrow \ell^+ \nu X) = 7.7\%$ [9], we determine the fraction of $\ell^+ D_s^-$ source to be $\sim 2.6\%$. In summary, the two sources of physics background contribute to the signal sample to a small extent and thus affect the lifetime measurement only slightly. We will consider it as a source of systematic uncertainty, to be described later.

3.4 Lifetime Fitting Method

Only transverse quantities are used in this lifetime measurement. The secondary vertex where the B_s decays to a lepton and a D_s^- (referred to as V_B) is obtained by intersecting the trajectory of a lepton track with the flight path of a D_s^- candidate. The error matrix of the vertex V_B is obtained by combining the error matrix of the D_s decay vertex V_D with the errors of the lepton track parameters. The transverse decay length L_B is defined as the displacement of V_B from the primary vertex projected on the direction of the $P_T(\ell D_s)$, our best estimator of the B_s direction. A factor

$P_t(\ell D_s)/M(B_s)$ (where $M(B_s) = 5.37$ GeV/c^2 [10]) is used to partially correct the decay length for the boost of the B_s meson and leads to a new decay length

$$\ell_B = \frac{L_B \cdot M(B_s)}{P_t(\ell D_s)}, \tag{3}$$

which is referred to as 'pseudo-cτ'. A residual correction between $P_t(\ell D_s)$ and $P_t(B_s)$ is done statistically by convoluting the distribution of $K = P_t(\ell D_s)/P_t(B_s)$ with an exponential decay distribution in the lifetime fit. Figure 2 shows the K distribution estimated from Monte Carlo events.

To determine the B_s lifetime, a maximum likelihood method is used to fit the pseudo-cτ distributions of the signal and background samples simultaneously. The likelihood function $\mathcal{L}$ is written as

$$\mathcal{L} = \prod^{\{S\}}[(1-f_{bg})\mathcal{F}_S(\ell_B, \mathrm{s}\sigma_{\ell_B}) + f_{bg}\mathcal{F}_B(\ell_B, \mathrm{s}\sigma_{\ell_B})] \cdot \prod^{\{B\}} \mathcal{F}_B(\ell_B, \mathrm{s}\sigma_{\ell_B}), \tag{4}$$

where σ_{ℓ_B} is the calculated error on the decay length ℓ_B for each measurement and s is an overall scale factor for the errors. {S} and {B} denote the signal and background samples respectively. The background fraction of the signal sample f_{bg} is estimated from the mass spectra. The l_B distribution of the background sample is parameterized by the function

$$\begin{aligned} \mathcal{F}_B &= (1 - 2\alpha_- - \alpha_+)G + \alpha_+ \exp(x, \lambda_+) \otimes G \\ &+ \alpha_-[\exp(x, -\lambda_-) + \exp(x, \lambda_-)] \otimes G, \end{aligned} \tag{5}$$

where $G(\mathrm{s}\sigma_{\ell_B})$ is a Gaussian distribution which represents a finite resolution of each decay length measurement $\mathrm{s}\sigma_{\ell_B}$. The probability function for the signal is represented by the B_s decay exponential function convoluted with the distribution of the momentum correction factor K and with the Gaussian resolution function.

$$\mathcal{F}_S = \exp(-Kx, c\tau) \otimes K^{dist} \otimes G. \tag{6}$$

Figure 3(a) shows the ℓ_B distribution of the signal sample with the result of the fit superimposed. The solid curve represents the signal plus the combinatorial background under the mass peak and the dashed curve only the background contribution. The ℓ_B distribution of the background samples is shown in Figure 3(b). We find the B_s lifetime to be $c\tau = 425\,^{+80}_{-68}$ μm.

To check the method, we could measure the D_s lifetime using a distribution of the proper decay length of the D_s^-, which is the distance between the secondary vertex V_B and the tertiary vertex V_D and is corrected for the D_s boost by $P_T(D_s)/M(D_s)$. We find $c\tau(D_s) = 135\,^{+40}_{-30}$ μm from the same fit, which is consistent with the world average value [9].

3.5 Systematic Uncertainties

The systematic uncertainties are summarized in Table 1. There are several sources of systematic uncertainties in the measurement. One of them is the treatment of the combinatorial background. We have combined the three background samples to describe the background under the mass peak. When we use them separately, we find a $\pm$ 4% variation in the B_s lifetime, and thus assign this uncertainty due to background variation.

The physics background source, Eq. (2), is treated in the following way. A pseudo-$c\tau$ distribution is generated from a Monte Carlo event sample using an average B lifetime of 450 μm. Here we find an empirical lifetime of $c\tau_{D,D} = 0.206$ cm, which is very long because the lepton arises from the tertiary decay. A term representing this contribution

$$0.026 \cdot \exp(-x, c\tau_{D,D}) \otimes G$$

is added to the signal probability function $\mathcal{F}_S$ and the lifetime fit is redone. We find $c\tau = 408$ μm. Thus a 4% systematic error is assigned. The other source of non-B_s^{0} is treated in a similar way. This mode has less than 1% effect on the B_s lifetime because only the B lifetime is involved here.

The factor K is subject to change from the following sources:

- b quark P_T spectrum (6 μm).
- lepton isolation and trigger effect (4 μm).
- mixture of D_s, D_s^*, and D_s^{**} states in B_s semi-leptonic decays (6 μm).

Adding these in quadrature totals to a 3% systematic uncertainty.

Requiring a positively displaced tertiary vertex can affect the lifetime measurement. A Monte Carlo study shows a shift of at most 2%.

The fitting procedure bias is also studied using a Monte Carlo. The differences of the generated and the fitted lifetime values are plotted. There is no more than 1% shift of the mean.

Finally, the residual mis-alignment of the SVX gives a 2% uncertainty.

All of these systematic uncertainties are summarized in Table 1.

In summary, using 76 ± 8 partially reconstructed B_s semi-leptonic decays, the B_s lifetime is measured to be

$$\tau_{B_s} = 1.42 \,^{+0.27}_{-0.23} \text{ (stat.) } ^{+0.11}_{-0.11} \text{ (syst.) ps.} \tag{7}$$

4 Exclusive Mode

Events for this part of the analysis are collected using the dimuon trigger with a single muon P_T threshold of 2.5 GeV/c. The J/ψ candidates are selected from the $M(\mu^+\mu^-)$ distribution and required to be within $\pm 3\sigma$ of the world average J/ψ mass. The ϕ selection is similar to the semi-leptonic case, but require a ± 10 MeV/c^2 window and $P_T(\phi) > 3.5$ GeV/c cut. The 4 candidate tracks (μ^+, μ^-, K^+, K^-) are vertex constrained and the fit probability is required to be greater than 2%. The combined $J/\psi\phi$ mass plot is shown in Figure 4.

To form the lifetime sample, the following additional requirements are used to select good quality tracks in the SVX.

- At least one of the μ candidate is reconstructed in the SVX with more than two hits and a $\chi^2/dof < 6$.
- At least one more track candidate (not including the muons) is reconstructed in the SVX with more than 2 hits and a $\chi^2/dof < 6$.

The signal mass window is ± 21 MeV/c^2 about the peak value. A total of 11 events are selected with expected signal of 9.5 ± 3.1 from the fit. The sideband events are taken from the mass ranges of 4.8-5.3 GeV/c^2 and 5.5-6.0 GeV/c^2 and contain 32 J/ψ ϕ combinations. The proper decay length can be fully determined by

$$\ell_B = (\vec{V}_{sec} - \vec{V}_{primary}) \cdot \hat{P}_T \frac{M(B_s)}{P_t(B_s)} \tag{8}$$

The lifetime from fitting the proper decay length of the signal sample yields $c\tau$ of 520 $^{+280}_{-190}$ μm. The fit result and the proper decay length distribution are shown in Figure 5. Systematic errors are summarized in Table 2. Using $B_s \to J/\psi\phi$ decays, the final result obtained is:

$$\tau_{B_s} = 1.74 \,^{+0.90}_{-0.60} \text{ (stat.) } \pm 0.07 \text{ (syst.) ps.} \tag{9}$$

5 Summary

The B_s lifetime has been measured in both the semi-leptonic and exclusive decay channels. They are consistent with the results measured using semi-leptonic decays by the DELPHI [11], OPAL [12], and ALEPH [13] experiments at LEP. Within the quoted errors, they are also consistent with the B_u and B_d lifetimes[14] and with the average b hadron lifetime [15] previously measured by CDF.

6 Acknowledgments

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Table 1: Systematic uncertainties using the semi-leptonic mode.

Source	Uncertainty
Resolution function	3%
Background shape	4%
Decay length cut	2%
Fitting method	1%
Boost correction	3%
Misalignment	2%
Non-B_s source	4%
Total	7%

Table 2: Exclusive mode systematic uncertainties

Systematic Source	Uncertainty
Residual misalignment	10 μm
Trigger bias	6 μm
Beam stability	5 μm
Resolution function	6 μm
Background shape	14 μm
Total	20 μm

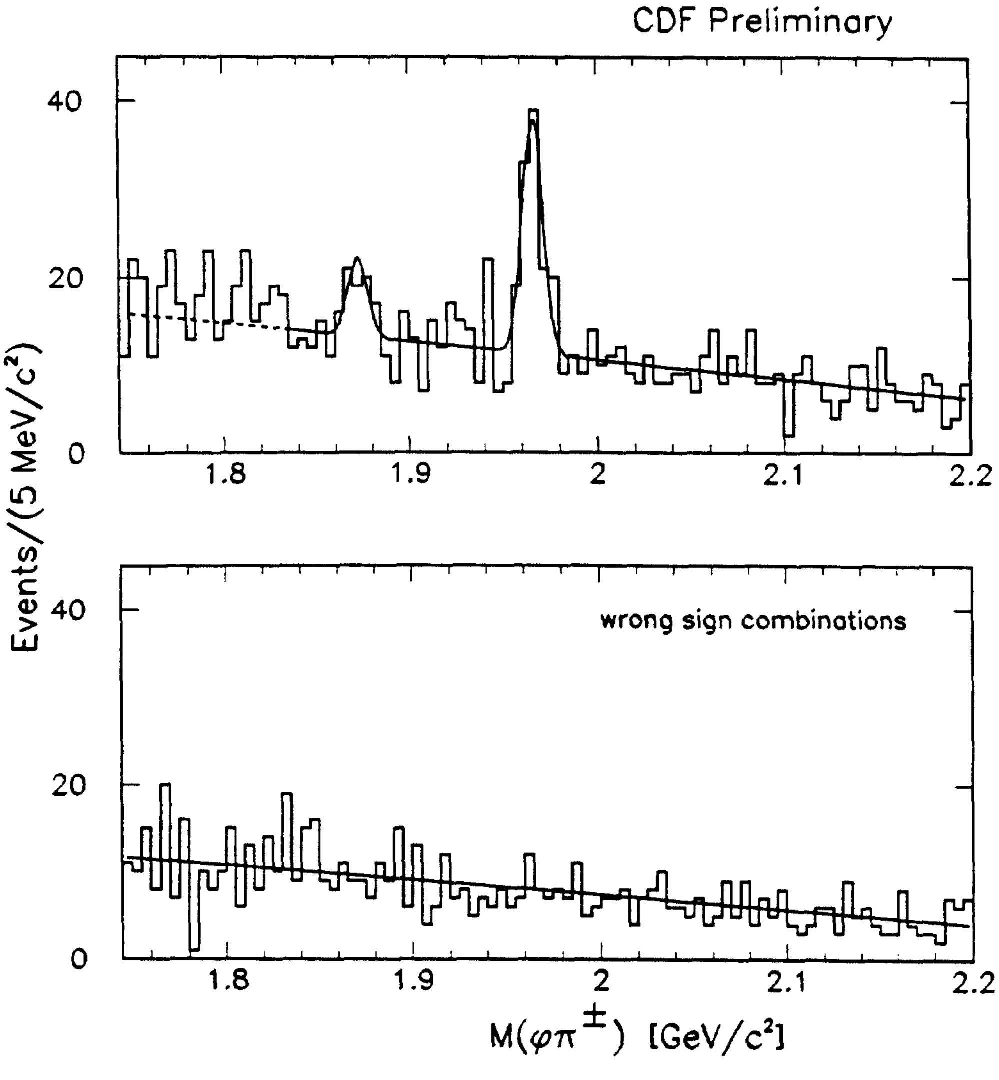

Figure 1: The mass distribution of $\phi\pi^-$ for (a) 'right sign' combination ($\phi\pi^-\ell^+$). (b) 'wrong sign' combination ($\phi\pi^-\ell^-$).

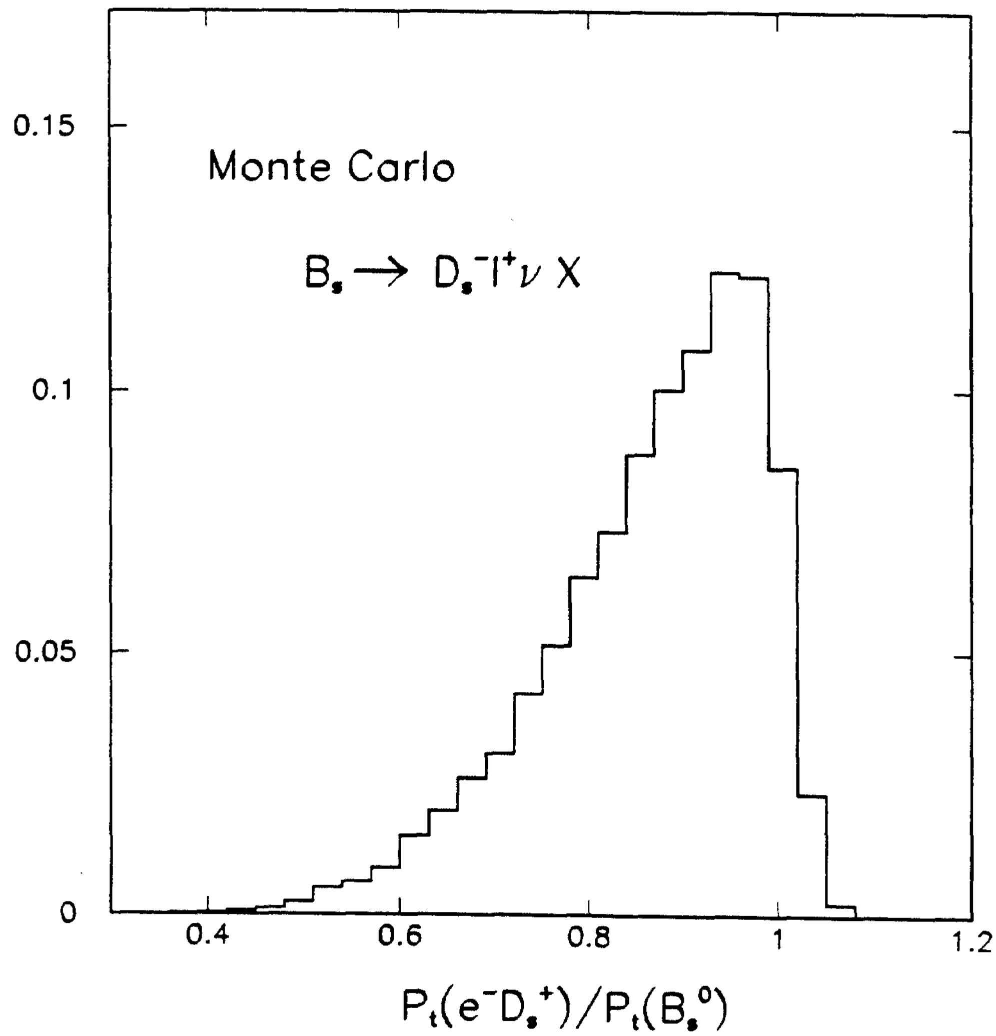

Figure 2: Distribution of the factor K from the Monte Carlo.

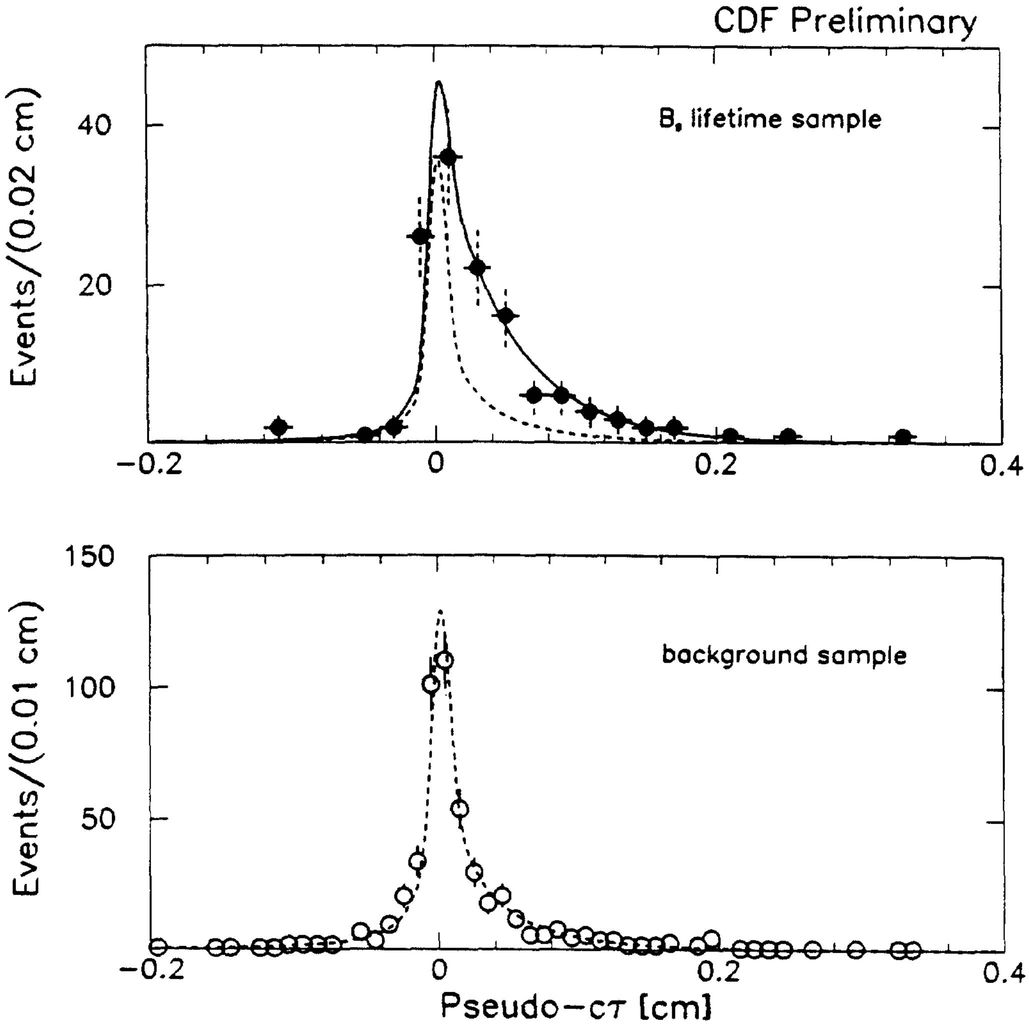

Figure 3: a) Pseudo-$c\tau$ distribution for the $\ell^+ D_s^-$ signal sample with a curve (solid) from unbinned log-likelihood fitting of signal and background. The dashed curve represents the contribution from the combinatorial background. (b) The Pseudo-$c\tau$ distribution for the background sample with a curve representing the background from the fit.

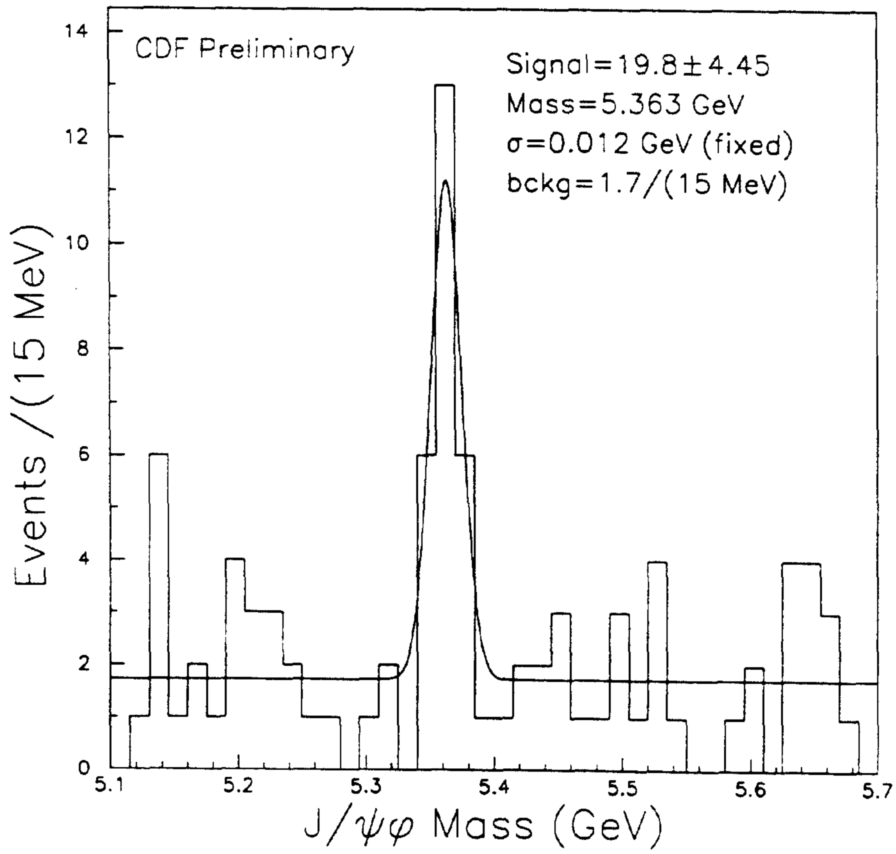

Figure 4: The mass spectrum of $J/\psi K^+K^-$ without the SVX requirement.

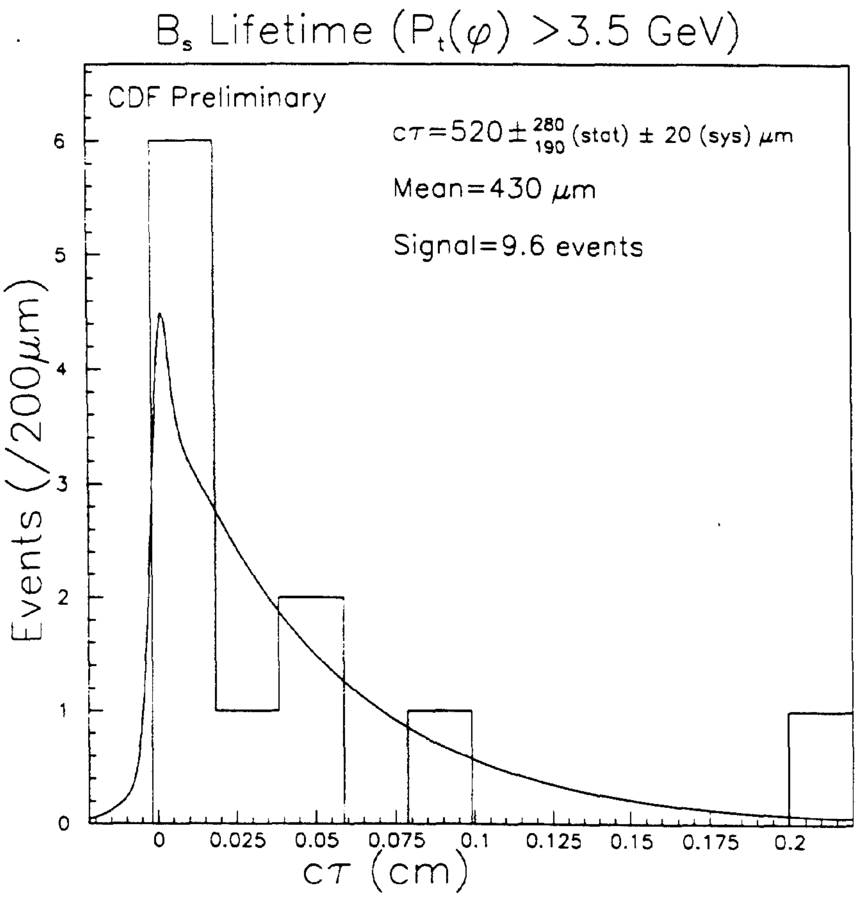

Figure 5: Proper decay length distribution of the lifetime signal sample. The solid curve is the result of the unbinned log-likelihood fit.