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Using Semileptonic Decays**

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Measurement of the B^- and \bar{B}^0 Meson Lifetimes Using Semileptonic Decays

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Abstract

The lifetimes of the B^- and \bar{B}^0 mesons are measured using the partially reconstructed semileptonic decays in the CDF experiment.

Measuring the individual lifetimes of various B hadron species is of importance and interest because it could probe the B hadron decay mechanism beyond the simple spectator decay picture. Possible causes of the lifetime differences include the decays which proceed through the annihilation and the W exchange processes, and the final state Pauli interference effect. These effects obviously play an important role in the charm hadrons, where the difference of a factor of 2.5 is observed between the D^+ and D^0 lifetimes. However, these effects are expected to be smaller in the B hadrons because of the larger mass of the b quark; only differences of order 5-10% are expected [1]. Several direct measurements have been performed by the LEP experiments and the CDF experiment [2]. Also indirect measurements have been performed through the measurement of semileptonic decay branching ratios. The precision of these measurements has begun to approach the expected difference above. Therefore we may actually be able to observe the difference of that magnitude in the near future.

In this Paper we report a measurement of the charged and neutral B meson lifetimes using partially reconstructed semileptonic decays. Events with a lepton (e or μ , denoted by

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ℓ^-) associated with a charm meson D^0 or D^{*+} [3] are isolated from the proton-antiproton collision data at $\sqrt{s} = 1.8$ TeV recorded with the CDF detector at the Fermilab Tevatron collider. About 1500 such decays are reconstructed from the data sample corresponding to an integrated luminosity of 19.3 pb^{-1} recorded during 1992-1993. The D^0 meson is reconstructed using the decay mode $D^0 \rightarrow K^- \pi^+$. The D^{*+} decays are reconstructed using the decay mode $D^{*+} \rightarrow D^0 \pi^+$, followed by $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^+ \pi^-$ and $K^- \pi^+ X$. The lifetimes are measured from their decay length distributions.

The CDF detector is described in detail elsewhere [4]. We describe here only the detector components most relevant to this analysis. Two devices inside the 1.4 T solenoid, the silicon vertex detector (SVX) and the central tracking chamber (CTC), provide the tracking and momentum analysis of charged particles. The SVX consists of four layers of silicon microstrip detectors and provides spatial measurements in the r - φ plane [5], giving a track impact parameter resolution of about $(13 + 40/p_T) \mu\text{m}$ [6], where p_T is the transverse momentum of the track in GeV/c . The transverse profile of the Tevatron beam is circular and has an RMS spread of $\sim 35 \mu\text{m}$. The CTC is a cylindrical drift chamber containing 84 layers grouped into 9 alternating superlayers of axial and stereo wires. It covers the pseudorapidity interval $|\eta| < 1.1$, where $\eta = -\ln[\tan(\theta/2)]$. Outside the solenoid are electromagnetic (CEM) and hadronic (CHA) calorimeters covering the pseudorapidity region $|\eta| < 1.1$. Two muon subsystems in the central region are used, the central muon chambers (CMU) and the central upgrade muon chambers (CMP). The CMP chambers are located behind 8 interaction lengths of material. Events containing semileptonic B decays are collected using inclusive lepton triggers. The E_T threshold for the principal single electron trigger is 9 GeV, where $E_T \equiv E \sin \theta$ and E is the energy measured in the CEM. The single muon trigger requires a $p_T > 7.5 \text{ GeV}/c$ track in the CTC with matched track segments in both the CMU and CMP systems. Offline identification of an electron and muon is described in [7, 8].

In a sample of lepton candidates we look for charm decays near the leptons. The $D^0 \rightarrow K^- \pi^+$ decay is reconstructed as follows. We first form oppositely charged CTC track pairs, and assign kaon and pion masses. In semileptonic B decays the charge of the kaon is identical to that of the lepton. The kaon (pion) candidate is then required to have momentum above

1.5 (0.5) GeV/ c , and to be within a cone of radius 0.6 (0.7) around the electron in the η - ϕ space. We also require that the decay vertex of the D^0 candidate is positively displaced along its flight direction with respect to the primary vertex when measured in the transverse plane. The primary vertex is approximated by the beam position. The $K^-\pi^+$ invariant mass spectrum is shown in Figure 1a, where events qualify as a D^{*+} candidate are removed. To identify the $D^{*+} \rightarrow D^0\pi^+$ decay, an additional track, assuming the pion mass, is combined with a D^0 candidate and the difference between the $D^0\pi^+$ and D^0 invariant masses (Δm) is calculated. In addition to the $D^0 \rightarrow K^-\pi^+$ mode, the $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ mode is used as well. Similar kinematic cuts are applied to kaon and pion candidates. We apply the decay length cut in the latter mode, but no such requirement is made for the former. Figure 1b and c show Δm distributions. The signals are apparent. Shown by the dotted histograms are the spectra from the “wrong sign” ($D^0\pi^-$) combinations, where no significant signals are observed. For the D^{*+} reconstruction we also use the decay mode $D^0 \rightarrow K^-\pi^+\pi^0$ without identifying the π^0 . This mode is dominated by the $K^-\rho^+$ and $K^*(892)^-\pi^+$ modes, and in spite of the missing π^0 it exhibits a (broader) peak in the mass difference in a region of the phase space. We require the $K^-\pi^+$ invariant mass to be between 1.5 and 1.7 GeV/ c^2 , combine the pair with an additional pion candidate and form the mass difference in a similar way. Figure 1d shows the mass difference distribution, and we observe an excess of the “right sign” pairs in the region below 0.155 GeV/ c^2 . For lifetime measurement we define the signal regions as follows. The $D^0 \rightarrow K^-\pi^+$ mode uses the mass range 1.84 - 1.88 GeV/ c^2 . The fully reconstructed D^{*+} modes use the Δm range 0.144 - 0.147 GeV/ c^2 . The D^{*+} with $D^0 \rightarrow K^-\pi^+X$ mode uses the Δm range below 0.155 GeV/ c^2 . The numbers of events in the signal regions are 1213, 202, 364 and 694 in the four modes, with estimated background fractions of 0.54 ± 0.03 , 0.11 ± 0.03 , 0.19 ± 0.03 and 0.40 ± 0.03 , respectively.

The secondary vertex V_B , where the B decays to a lepton and a D , is obtained by intersecting the trajectory of the lepton track with the flight path of the D^0 candidate. The decay length L is defined as the displacement in the transverse plane of V_B from the primary vertex, projected onto the direction of the p_T of the lepton- D^0 system. The effect of the B meson Lorentz boost, which is typically $\beta\gamma = 3 - 4$, is first corrected on an event-by-event basis us-

ing the $p_T(\ell^- D^0)$, and we use a corrected decay length $\xi = LM(B)/p_T(\ell^- D^0)$ which we call the ‘proper decay length’. A residual correction between $p_T(\ell^- D^0)$ and $p_T(B)$ is performed statistically during lifetime fits by using a signal probability distribution function that is a convolution of an exponential decay distribution with a distribution of the momentum ratio $\kappa = p_T(\ell^- D^0)/p_T(B)$ obtained from Monte Carlo events. The κ distribution has an average value of about 0.85 with an RMS width of 0.11, and is approximately independent of the D^0 decay modes and of the $p_T(\ell^- D^0)$. To account for the combinatorial background events under signal mass peaks, we use a probability distribution function which has both signal and background components. Thus the likelihood \mathcal{L} is given by $\mathcal{L} = \prod_i [(1 - f_{bg})\mathcal{F}_{\text{SIG}} + f_{\text{BG}}\mathcal{F}_{\text{BG}}]$, where the product is taken over event i . The signal probability function \mathcal{F}_{SIG} consists of an exponential function with slope $c\tau/\kappa$, defined for only positive decay lengths, convoluted with the κ distribution and a Gaussian distribution with width $s\sigma_i$, where σ_i is an estimated resolution of the proper decay length for event i . The scale factor s accounts for a possible underestimate of the decay length resolution.

We perform the lifetime fit with two steps. We first determine the shape of the background function \mathcal{F}_{BG} and the scale factor s using control samples, and then use them to fit lifetimes with the events in the signal regions. The background sample is defined as the D^0 sideband (1.72-1.80 and 1.92-2.00 GeV/c^2) for the mode $D^0 \rightarrow K^- \pi^+$. For the D^{*+} modes, we use both the right sign sideband ($0.15 < \Delta m < 0.19 \text{ GeV}/c^2$ for $D^0 \rightarrow K^- \pi^+$ and $K^- \pi^+ \pi^+ \pi^-$ modes, and $0.16 < \Delta m < 0.19 \text{ GeV}/c^2$ for $D^0 \rightarrow K^- \pi^+ X$ mode) and the wrong sign sideband ($\Delta m < 0.19 \text{ GeV}/c^2$ for all modes). Proper decay length distributions of the background samples are empirically parameterized by a sum of a Gaussian distribution centered at zero and positive and negative exponential tails. The distributions are shown in Figure 2, where the results of the fit are given by the superimposed curves. Figure 3 shows the corresponding proper decay length distributions of the signal regions.

As a check of the lifetime fitting procedure, we measure the D^0 lifetime using the proper decay length measured from the secondary vertex V_B to the tertiary vertex V_D . The result is $c\tau(D^0) = 144 \pm 12, 132 \pm 13, 132 \pm 12$ and $124 \pm 10 \mu\text{m}$ for the four modes, where the quoted errors are statistical. They are reasonably in good agreement with the world average value

of $124.4 \mu\text{m}$ [9].

The semileptonic decays of the non-strange B mesons can be expressed as $\bar{B} \rightarrow \ell^- \bar{\nu} \mathbf{D}$, where \mathbf{D} is a charm system whose charge is correlated with the B meson charge. If only two lowest lying states, pseudoscalar (D) and vector (D^*), are produced, the $\ell^- D^{*+}$ combination can arise only from the \bar{B}^0 decay. Similarly the $\ell^- D^0$ combination comes only from the B^- , provided that the D^0 from the D^{*+} decay is excluded. However, there exists a room for higher D states, D^{**} (including non-resonant $D^{(*)}\pi$ pairs). Charged D^{**} 's decay to both $D^{(*)+}\pi^0$ and $D^{(*)0}\pi^+$, and neutral D^{**} 's decay to both $D^{(*)+}\pi^-$ and $D^{(*)0}\pi^0$. Hence the $\ell^- D^0$ and $\ell^- D^{*+}$ combinations are no longer pure samples of B^- and \bar{B}^0 decays, rather they are admixture of the two B meson decays. However, as we shall see, they are still nearly orthogonal samples of the two B meson decays and enable us to determine the two lifetimes. To achieve it, we perform a combined fit of the signal samples using a two-component signal distribution function.

To specify the likelihood function of each lepton-charm sample, it is necessary to know its composition in terms of the two B mesons. The composition is estimated as follows. We assume that the charged and neutral B mesons are produced in equal amounts, and also their semileptonic widths are identical. We also assume the D^{**} 's decay exclusively to $D^{(*)}\pi$ via strong interaction, thus fixing their branching ratios by isospin symmetry. The composition depends on the relative branching ratios of semileptonic B decays into D , D^* and D^{**} . It turns out that only the D^{**} fraction (f^{**}) is relevant. A CLEO measurement gives $f^{**} = 0.36 \pm 0.12$ [10]. Secondly it depends on the relative abundance of various D^{**} types, since some of them decays only to $D^*\pi$, and others only to $D\pi$. Changing the abundance is equivalent to changing the branching ratios into $D^*\pi$ and $D\pi$ averaged over various D^{**} types. We define a quantity P_V as the fraction of the former branching ratio relative to the sum of the two, which is assumed to be unity. We assume the abundance of [11], which correspond to $P_V = 0.78$. We consider 0.0 and 1.0 as a bound. Thirdly the composition depends on the lifetime ratio, because the number of $\ell^- D$ events is proportional to a semileptonic branching ratio, which is the product of the lifetime and the partial width. Finally, the sample composition depends on the reconstruction efficiency of the soft pion

in the $D^{*+} \rightarrow D^0 \pi^+$ decay given a reconstructed D^0 . If we miss the pion, the D^{*+} is included in the $\ell^- D^0$ sample and its composition is altered. The efficiency is estimated to be $\epsilon(\pi) = 0.93_{-0.21}^{+0.07}$. Once these parameters are fixed, the sample composition is uniquely determined. The dependence on the lifetime ratio is taken into account in lifetime fits. We find that the $\ell^- D^0$ sample consists of about 85% B^- and 15% \bar{B}^0 decays, and the $\ell^- D^{*+}$ sample consists of about 90% \bar{B}^0 and 10% B^- decays.

The sample composition is a source of systematic uncertainty in the B meson lifetimes. We change the parameters f^{**} , P_V and $\epsilon(\pi)$ in the quoted ranges and fit the B meson lifetimes. We use observed changes as a systematic uncertainty. It is listed in Table I, together with other sources considered in this analysis. A major contribution comes from the treatment of the background events. First the shapes of background decay length distributions, determined using control samples, are subject to statistical fluctuations. We change the shapes within statistical uncertainties and refit signal samples, and use the shifts as a systematic uncertainty. Also our assumed background functional form may not be fully adequate to describe the background shapes. We consider an alternative parametrization, which gives only minimal changes in the result. Also there exists an uncertainty in the amount of background. We change the background fraction by the amount corresponding to one standard deviation, and quote the changes as a systematic uncertainty.

Other sources include the uncertainty in our estimate of decay length resolution and the estimate of the B meson momentum. We have applied a loose decay length cut in some modes, and it introduces a slight bias in the lifetimes. Finally, a residual misalignment of the SVX detector and the stability of the Tevatron beam are considered. Some of these uncertainties are positively correlated between the two B mesons and cancel in the determination of the lifetime ratio.

Our final result is $\tau(B^-) = 1.51 \pm 0.12 \pm 0.08$ ps, $\tau(\bar{B}^0) = 1.57 \pm 0.08 \pm 0.07$ ps and $\tau(B^-)/\tau(\bar{B}^0) = 0.96 \pm 0.10 \pm 0.05$ where the first errors are statistical and the second are systematic. The result is consistent with recent measurements. At present, the two lifetimes are identical to each other within uncertainty, and also to the B_s lifetime [12].

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Source	Uncertainty in		
	$c\tau(B^-)$ (μm)	$c\tau(\overline{B}^0)$ (μm)	$\tau(B^-)/\tau(\overline{B}^0)$
Sample composition			
D^{**} fraction (f^{**})	$^{+5}_{-6}$	$^{+3}_{-2}$	$^{+0.005}_{-0.009}$
D^{**} composition (P_V)	± 1	$^{+1}_{-2}$	$^{+0.005}_{-0.002}$
Soft pion reconstruction	$^{+1}_{-2}$	± 1	$^{+0.001}_{-0.004}$
Background shape	$^{+9}_{-8}$	± 6	± 0.024
Background fraction	± 10	± 11	± 0.033
Decay length resolution	$^{+9}_{-8}$	$^{+6}_{-4}$	$^{+0.007}_{-0.009}$
Momentum estimate			
b -quark p_T spectrum	± 4	± 4	-
Momentum dependence	± 6	± 6	-
Electron cuts	± 9	± 9	-
Decay length cut	-5	-5	± 0.016
Detector alignment	± 10	± 10	-
Beam stability	± 5	± 5	-
Total	± 23	± 22	± 0.046

Table 1: A summary of systematic uncertainties in the B^- and \overline{B}^0 lifetime measurement.

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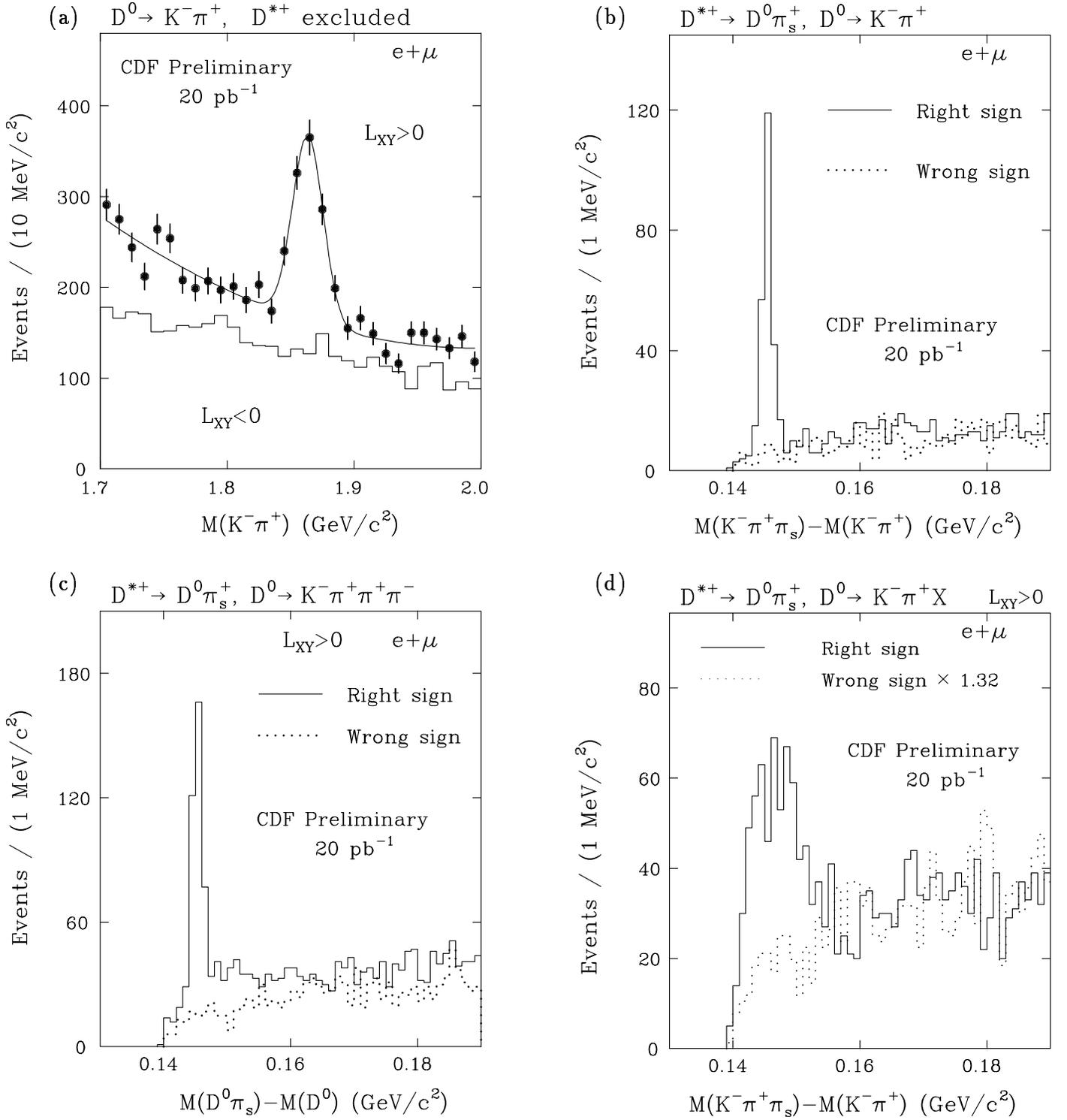


Figure 1: Reconstructed charm signals in lepton events. Four modes are shown: (a) $D^0 \rightarrow K^- \pi^+$ (non- D^{*+}), (b) $D^{*+} \rightarrow D^0 \pi_s^+$, $D^0 \rightarrow K^- \pi^+$, (c) $D^{*+} \rightarrow D^0 \pi_s^+$, $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ and (d) $D^{*+} \rightarrow D^0 \pi_s^+$, $D^0 \rightarrow K^- \pi^+ X$.

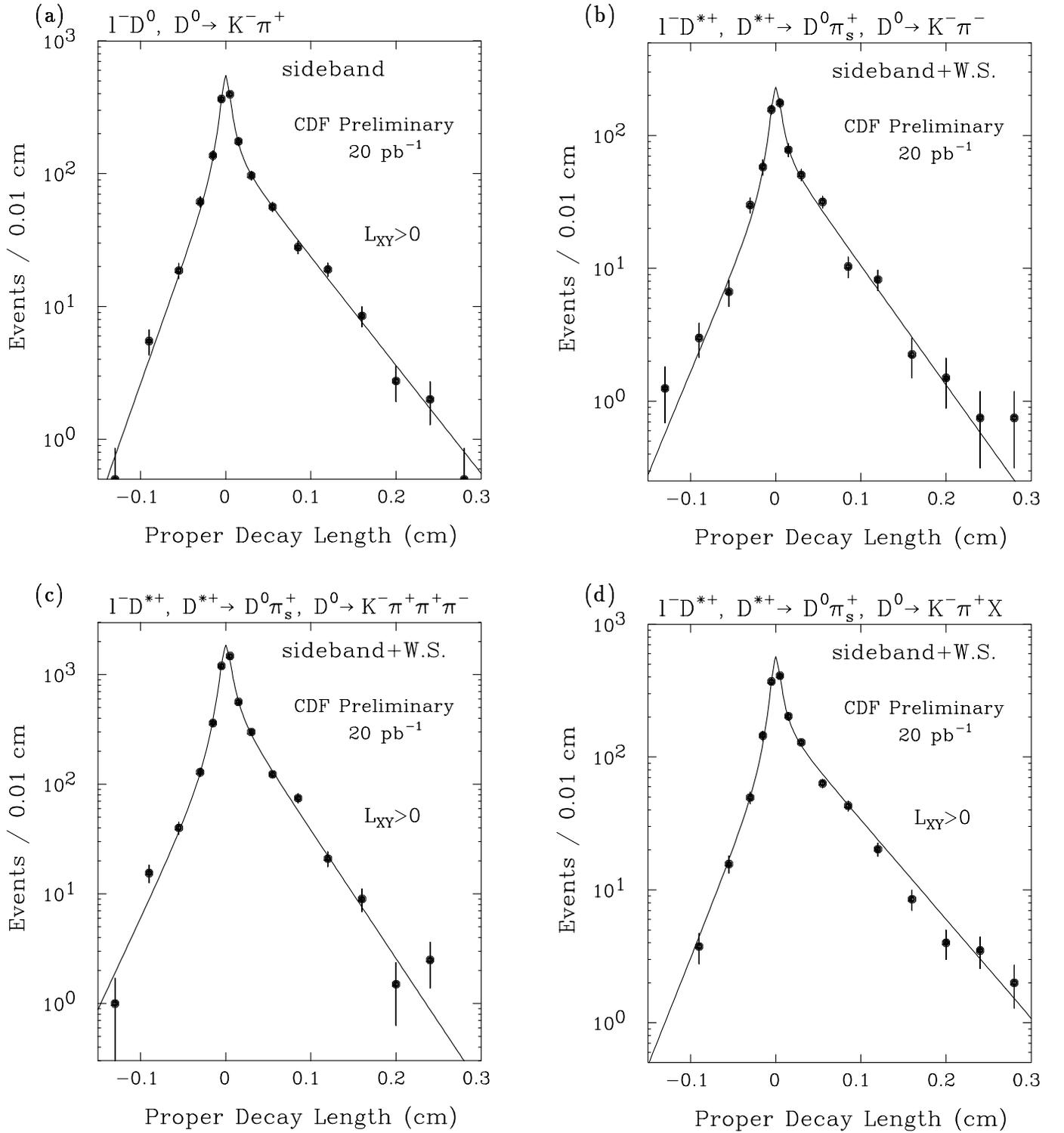


Figure 2: Distributions of proper decay lengths for the lepton- D background samples. Superimposed are the results of lifetime fits to an empirical functional form. The four modes (a-d) are the same as in Figure 1.

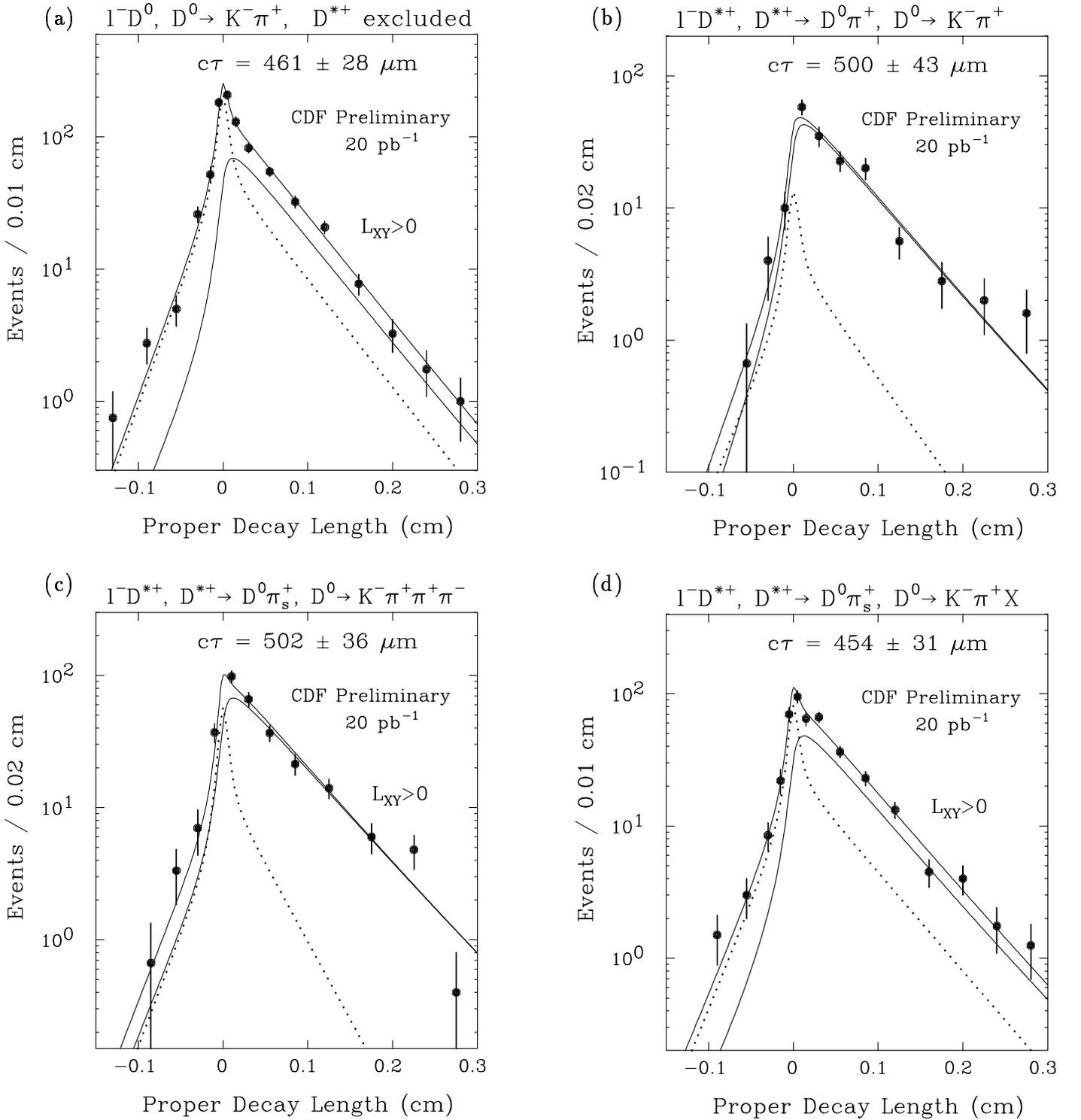


Figure 3: Distributions of proper decay lengths for the lepton- D signal samples. Also shown are the results of lifetime fits, signal and background contributions. The four modes (a-d) are the same as in Figure 1.