Fermi National Accelerator Laboratory

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

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The CDF Collaboration

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Abstract

The lifetimes of the B^- and $\overline{B}^0$ mesons are measured using the partially reconstructed semileptonic decays $\overline{B} \to D\ell^-\overline{\nu}X$, where D is either a D^0 or D^{*+} meson. The data were collected by the CDF detector at the Fermilab Tevatron collider during 1992-1993 and correspond to 19.3 pb^{-1} of $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. We measure the decay length distributions and find the lifetimes to be $\tau(B^-) = 1.56 \pm 0.13 \pm 0.06$ ps and $\tau(\overline{B}^0) = 1.54 \pm 0.08 \pm 0.06$ ps, and the ratio of lifetimes to be $\tau(B^-)/\tau(\overline{B}^0) = 1.01 \pm 0.11 \pm 0.02$, where the first uncertainties are statistical and the second are systematic.

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A measurement of the lifetimes of the different B-hadron species probes their decay mechanism beyond the simple spectator model decay picture. Possible causes of lifetime differences include the strength of the annihilation and the W-exchange graphs, and final state Pauli interference effects. These mechanisms play an important role in the decay of charm hadrons, where the D^+ and D^0 lifetimes differ by a factor of 2.5; however, they are expected to produce smaller lifetime differences, of order 5-10% [1], in the B-hadrons because of the larger mass of the b quark.

Several direct measurements of B^- and $\overline{B}^0$ meson lifetimes have been performed by the e^+e^- experiments and by CDF [2]. Indirect information has been obtained through the measurement of branching ratios [3, 4]. The precision of current measurements now approaches the level where the predicted small differences could be discerned, and improvements in these measurements will provide a strong test of B-hadron decay mechanisms.

In this Letter we report a measurement of the B^- and $\overline{B}^0$ meson lifetimes using partially reconstructed semileptonic decays. The data used in this analysis were collected in 1992-93 with the CDF detector at the Fermilab Tevatron $\overline{p}p$ collider at a center-of-mass energy $\sqrt{s} = 1.8$ TeV, and correspond to an integrated luminosity of 19.3 pb^{-1}. Events with a lepton (e^- or μ^-, denoted by ℓ^-) associated with a D^0 or D^{*+} meson are selected. (Throughout this Letter a reference to a particular charge state also implies its charge conjugate.) The $\ell^- D^{*+}$ candidates consist mostly of $\overline{B}^0$ decays, and the $\ell^- D^0$ candidates consist mostly of B^- decays. The D^0 meson is reconstructed using the decay mode $D^0 \to K^-\pi^+$. The D^{*+}

decays are reconstructed using the decay mode $D^{*+} \rightarrow D^0 \pi^+$, followed by $D^0 \rightarrow K^- \pi^+$, $K^- \pi^+ \pi^+ \pi^-$ or $K^- \pi^+ \pi^0$. The decay length distributions are measured and the lifetimes are extracted after correcting for the relative admixtures of B^- and $\overline{B}^0$ in the samples.

The CDF detector is described in detail elsewhere [5]. We describe here only the detector components most relevant to this analysis. 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 CTC is a cylindrical drift chamber containing 84 readout layers. It covers the pseudorapidity interval $|\eta| < 1.1$, where $\eta = -\ln[\tan(\theta/2)]$ [6]. The SVX consists of four layers of silicon microstrip detectors and provides spatial measurements in the r-φ plane at radii between 2.9 and 7.9 cm, giving a track impact parameter resolution of about $(13 + 40/p_T)$ μm [7], 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 ~ 35 μm. Electromagnetic (CEM) and hadronic (CHA) calorimeters outside the solenoid cover the pseudorapidity region $|\eta| < 1.1$. Two muon subsystems are used, the central muon chambers (CMU) and the central upgrade muon chambers (CMP).

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 track in the CTC with matched track segments in both the CMU and CMP systems corresponding to a p_T threshold of 7.5 GeV/c. The specific criteria used for electron and muon identification are described in Refs. [8, 9].

To identify the $\ell^- D^0$ candidates, we search for $D^0 \rightarrow K^- \pi^+$ decays near the leptons, removing events that are consistent with the $D^{*+} \rightarrow D^0 \pi^+$ decay chain. The $D^0 \rightarrow K^- \pi^+$ decay is reconstructed as follows. We first select oppositely charged pairs of particles using CTC tracks, where the kaon mass is assigned to the particle with the same charge as the lepton (called the "right sign" combination), as is the case in semileptonic B decays. 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 lepton in η-φ space. We require the decay vertex of the D^0 candidate to be positively displaced along its flight direction in the transverse plane

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with respect to the position of the primary vertex. The primary vertex is approximated by the beam position. To remove events consistent with the decay chain $D^{*+} \to D^0 \pi^+$, we combine additional positive tracks with the D^0 candidate and compute the mass difference (Δm) between the $D^0 \pi^+$ and the D^0, assigning the pion mass to the tracks; we remove events with Δm values between 0.142 and 0.148 GeV/c^2. The resulting $K^- \pi^+$ invariant mass spectrum is shown in Figure 1(a). We define the signal region to be in the mass range 1.84 to 1.88 GeV/c^2. The total number of events in the signal region is 1233 with an estimated background fraction of 0.53 ± 0.03. Also shown by the shaded histogram is the mass spectrum for the "wrong sign" ($K^+ \pi^-$ with ℓ^-) combinations, where no significant signal is observed.

To identify $\ell^- D^{*+}$ candidates, we search for $D^{*+} \to D^0 \pi^+$ decays using two fully reconstructed D^0 decay modes, $D^0 \to K^- \pi^+$ and $D^0 \to K^- \pi^+ \pi^+ \pi^-$, and one partially reconstructed mode, $D^0 \to K^- \pi^+ \pi^0$. For the fully reconstructed modes, the D^0 candidate has to be in the mass ranges 1.83 to 1.90 GeV/c^2 and 1.84 to 1.88 GeV/c^2, respectively. For the partially reconstructed mode, we require the mass of a $K^- \pi^+$ pair to be between 1.5 and 1.7 GeV/c^2; we do not reconstruct the π^0 and in the subsequent analysis treat the $K^- \pi^+$ pair as if it were a D^0. We require positive decay lengths in the last two modes. For each mode, we reconstruct the D^{*+} meson by combining an additional track, assumed to have the pion mass, with the D^0 candidate, and computing the mass difference, Δm, between the $D^0 \pi^\pm$ and D^0. Here $D^0 \pi^+$ is the "right sign" combination, and $D^0 \pi^-$ is the "wrong sign". Figures 1(b-d) show the Δm distributions, where the shaded histograms correspond to the "wrong sign" combinations. In Figure 1(d) the peak is broadened because of the missing π^0. We define the signal region as follows. The two fully reconstructed modes use the Δm range 0.144 to 0.147 GeV/c^2, and the $K^- \pi^+ \pi^0$ mode uses the range $\Delta m < 0.155$ GeV/c^2. The numbers of events in the signal regions are 200, 332 and 704, with estimated background fractions of 0.11 ± 0.03, 0.18 ± 0.03 and 0.40 ± 0.03, respectively.

The secondary vertex V_B is obtained by intersecting the trajectory of the lepton track with the flight path of the D^0 candidate. The B decay length L is defined as the displacement in the transverse plane of V_B from the primary vertex, projected onto the transverse

momentum vector of the lepton-D^0 system. In semileptonic decays, the B meson momentum is not completely known due to a missing neutrino and possible other particles. We use the $p_T(\ell^- D^0)$ as an estimator of the B momentum, resulting in a corrected decay length $\xi = Lm(B)/p_T(\ell^- D^0)$ which we call the 'pseudo-proper decay length'. The distribution of the momentum ratio $\kappa = p_T(\ell^- D^0)/p_T(B)$ is obtained from a Monte Carlo calculation and is used in the subsequent lifetime fits. It 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 $p_T(\ell^- D^0)$.

The lifetime is determined from a maximum likelihood fit to the observed pseudo-proper decay length distributions. The signal sample likelihood is given by

$$\mathcal{L}_{\mathrm{SIG}} = \prod_i [(1 - f_{\mathrm{BG}})\mathcal{F}_{\mathrm{SIG}}^i + f_{\mathrm{BG}}\mathcal{F}_{\mathrm{BG}}^i],$$

where the product is taken over the observed events i. The first term represents the probability distribution of a signal event. The second term accounts for combinatorial background events whose fraction in a sample is f_{BG}. The signal probability function $\mathcal{F}_{\mathrm{SIG}}$ consists of an exponential function $\exp(-\kappa\xi/c\tau)$ defined for positive decay lengths, convoluted with the κ distribution and a Gaussian distribution with width $s\sigma_i$. Here σ_i is the estimated resolution of ξ for event i, typically 100 μm, and the scale factor s accounts for a possible underestimate of the decay length resolution.

The ξ distribution of background events, $\mathcal{F}_{\mathrm{BG}}$, is described by a sum of a Gaussian distribution centered at zero, and positive and negative exponential tails. The shape of the background function and the scale factor s are determined from a simultaneous fit of a signal sample and a background sample. We use the combined likelihood $\mathcal{L}_{\mathrm{TOT}}$ defined as $\mathcal{L}_{\mathrm{TOT}} = \mathcal{L}_{\mathrm{SIG}} \mathcal{L}_{\mathrm{BG}}$, where $\mathcal{L}_{\mathrm{BG}} = \prod_j \mathcal{F}_{\mathrm{BG}}^j$ and the product is taken over events j in the background sample. The amount of combinatorial background f_{BG} is also a parameter in the simultaneous fit. This parameter is constrained by adding a term $\frac{1}{2}\chi^2 = \frac{1}{2}(f_{\mathrm{BG}} - \langle f_{\mathrm{BG}}\rangle)^2/\sigma_{\mathrm{BG}}^2$ to the negative log-likelihood $\ell = -\ln\mathcal{L}_{\mathrm{TOT}}$, where the average background fraction $\langle f_{\mathrm{BG}}\rangle$ and its uncertainty σ_{BG} are estimated from the invariant mass distribution. The background sample for the $D^0 \to K^-\pi^+$ mode is formed from the sidebands defined by the mass ranges 1.72 to 1.80 and 1.92 to 2.00 GeV/c^2. For the D^{*+} modes, we use the right sign sideband, $0.15 < \Delta m < 0.19$ GeV/c^2 for the two fully reconstructed modes, $0.16 < \Delta m < 0.19$ GeV/c^2

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for the $D^0 \to K^- \pi^+ \pi^0$ mode, and the wrong sign sideband, $\Delta m < 0.19$ GeV/c^2, for all three modes.

Figure 2 shows the ξ distributions of the events in the signal regions. Also shown by curves are the results of the lifetime fit, with signal and background contributions. We find the lifetimes to be $c\tau(B) = 472 \pm 31, 486 \pm 42, 497 \pm 38$ and 451 ± 31 μm, and the resolution scale factor s to be 1.37 ± 0.05, 1.53 ± 0.11, 1.36 ± 0.04 and 1.32 ± 0.05, in the four samples, where uncertainties are statistical only.

As a check of the procedure, we measure the D^0 lifetime using the proper decay length measured from the secondary vertex V_B to the D decay vertex. The result is $c\tau(D^0) = 144 \pm 12, 132 \pm 13, 132 \pm 12$ and 124 ± 10 μm for the four modes, where the quoted uncertainties are statistical. They are in reasonably good agreement with the world average value of 124.4 ± 1.2 μm [10].

In order to extract the $\overline{B}^0$ and B^- lifetimes, we must take into account the fact that the $\ell^- D^0$ and $\ell^- D^{*+}$ samples are admixtures of the neutral and charged B meson decays. The semileptonic decays can be expressed as $\overline{B} \to \ell^- \overline{\nu} \mathbf{D}$, where $\mathbf{D}$ is a charm system whose charge is correlated with the B meson charge. If only the two lowest lying states, pseudoscalar (D) and vector (D^*), are produced, the $\ell^- D^{*+}$ combination can arise only from the $\overline{B}^0$ decay. Similarly the $\ell^- D^0$ combination comes only from B^- decays, provided that the D^0 from the D^{*+} decay is excluded. However, higher mass D^{**} states (including non-resonant $D^{(*)}\pi$ pairs) are also produced in semileptonic B meson decays and their decays can dilute the charge correlation. For example, the charged D^{**} meson decays to both $D^{(*)+}\pi^0$ and $D^{(*)0}\pi^+$, and the neutral D^{**} meson decays to both $D^{(*)+}\pi^-$ and $D^{(*)0}\pi^0$. Nevertheless, the $\ell^- D^0$ and $\ell^- D^{*+}$ combinations are dominated by B^- and $\overline{B}^0$ meson decays, respectively.

We estimate the fraction g^- of the B^- decays in the $\ell^- D^0$ and $\ell^- D^{*+}$ samples as follows. The production rates of charged and neutral B mesons and their semileptonic decay widths are assumed to be equal. We also assume the D^{**} decays exclusively to $D^{(*)}\pi$ via the strong interaction, thereby allowing us to determine the branching ratios, e.g. $D^{(*)+}\pi^0$ vs $D^{(*)0}\pi^+$, using isospin symmetry. We consider four factors affecting the composition. Firstly, the composition depends on the D^{**} fraction (f^{**}) in semileptonic B decays, which has been

measured to be $f^{**} = 0.36 \pm 0.12$ [4]. Secondly, g^- depends on the relative abundance of four possible spin-parity D^{**} states, some of which decay only to $D^*\pi$ and others to $D\pi$. Changing the abundance is equivalent to changing the branching ratios into $D^*\pi$ and $D\pi$ averaged over various D^{**} states. We define a quantity $P_V = \mathcal{B}(D^{**} \to D^*\pi)/[\mathcal{B}(D^{**} \to D^*\pi) + \mathcal{B}(D^{**} \to D\pi)]$, where $\mathcal{B}$ denotes a branching ratio. We assume the relative abundance found in Ref. [11] with $P_V = 0.78$. We also consider the extreme values $P_V = 0.0$ and 1.0. Thirdly, the composition depends on the lifetime ratio, because the number of $\ell^- D$ events is proportional to the 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 low energy pion in the decay $D^{*+} \to D^0\pi^+$. If we miss the pion and reconstruct the D^0, the D^{*+} is included in the $\ell^- D^0$ sample and the sample composition is altered. The efficiency is measured to be $\epsilon(\pi) = 0.93^{+0.07}_{-0.21}$. We find that $g^- = 0.85^{+0.05}_{-0.12}$ for the $\ell^- D^0$ sample, and $g^- = 0.10^{+0.09}_{-0.10}$ for the $\ell^- D^{*+}$ sample when the two lifetimes are identical. The quoted uncertainties reflect maximum changes in g^- when f^{**}, P_V and $\epsilon(\pi)$ are changed within quoted ranges. We have ignored small contributions to the lepton-$D^{(*)}$ events from physics processes like $\overline{B}^0_s \to \ell^-\overline{\nu}D^{**+}_s$, $D^{**+}_s \to D^{(*)}K$. Therefore the fraction of the $\overline{B}^0$ mesons is given by $g^0 = 1 - g^-$.

We can now determine the B^- and $\overline{B}^0$ lifetimes with a combined fit of the $\ell^- D^0$ and $\ell^- D^{*+}$ samples. We use a two-component signal distribution function given by $\mathcal{F}_{\mathrm{SIG}} = g^-\mathcal{F}^-_{\mathrm{SIG}} + (1 - g^-)\mathcal{F}^0_{\mathrm{SIG}}$, where $\mathcal{F}^-_{\mathrm{SIG}}$ and $\mathcal{F}^0_{\mathrm{SIG}}$ represent the charged and neutral B meson components, respectively. The dependence of g^- on the lifetime ratio is taken into account in the lifetime fits.

The sample composition is a source of systematic uncertainty in the B meson lifetime determination. We change the parameters f^{**}, P_V and $\epsilon(\pi)$ within the quoted ranges, compute the sample composition g^- and fit the B meson lifetimes. We interpret the observed changes as systematic uncertainties; they are listed in Table 1, together with other sources considered in this analysis. The way the background decay length distributions are described is also a source of systematic uncertainties. We have measured them using the sideband regions, thus minimizing model dependence. However, our assumed functional form may

not be fully adequate to describe the true shapes. Thus, we have considered an alternative parameterization including additional exponential terms; this turns out to give only minimal changes in the result.

Other sources of systematic uncertainties include our estimate of decay length resolution and of the B meson momentum. Also we have applied a loose decay length cut in some modes, and it introduces a slight bias in the lifetimes. Finally, a possible residual misalignment of the SVX detector and the stability of the position of the Tevatron beam are considered. Some of these uncertainties are common for the two B mesons and cancel in the determination of the lifetime ratio. All these effects are combined in quadrature to give the total systematic uncertainty.

Our final result is $\tau(B^-) = 1.56 \pm 0.13 \pm 0.06$ ps, $\tau(\overline{B}^0) = 1.54 \pm 0.08 \pm 0.06$ ps, $\tau(B^-)/\tau(\overline{B}^0) = 1.01 \pm 0.11 \pm 0.02$ where the first uncertainties are statistical and the second are systematic. The result is consistent with other recent measurements [2]. At present, the two lifetimes are identical to each other within the uncertainty, consistent with the small difference predicted. They are also identical to the B_s lifetime [12] within the uncertainty.

[a] Visitor

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Source	Systematic uncertainty contributions to		
	$c\tau(B^-)$ (μm)	$c\tau(\overline{B}^0)$ (μm)	$\tau(B^-)/\tau(\overline{B}^0)$
Sample composition			
D^{**} fraction (f^{**})	± 3	± 4	$^{+0.003}_{-0.002}$
D^{**} composition (P_V)	± 1	± 1	$^{+0.001}_{-0.002}$
Soft pion reconstruction	± 1	± 1	± 0.001
Background treatment	± 2	± 2	± 0.006
Decay length resolution	$^{+9}_{-8}$	$^{+6}_{-4}$	$^{+0.007}_{-0.009}$
Momentum estimate	± 12	± 12	-
Decay length cut	$^{+0}_{-5}$	$^{+0}_{-5}$	± 0.016
Detector alignment	± 10	± 10	-
Beam stability	± 5	± 5	-
Total	± 19	± 18	$^{+0.019}_{-0.020}$

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

(1993); P. Abreu et $al.,$ Phys. Lett. B **312**, 253 (1993); D. Buskulic et $al.,$ Phys. Lett. B **307**, 194 (1993), Phys. Lett. B **325**, 537 (1994) (errata); P. D. Acton et $al.,$ Phys. Lett. B **307**, 247 (1993).

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[6] In CDF, φ is the azimuthal angle, θ is the polar angle measured from the proton direction, and r is the radius from the beam axis (z-axis).

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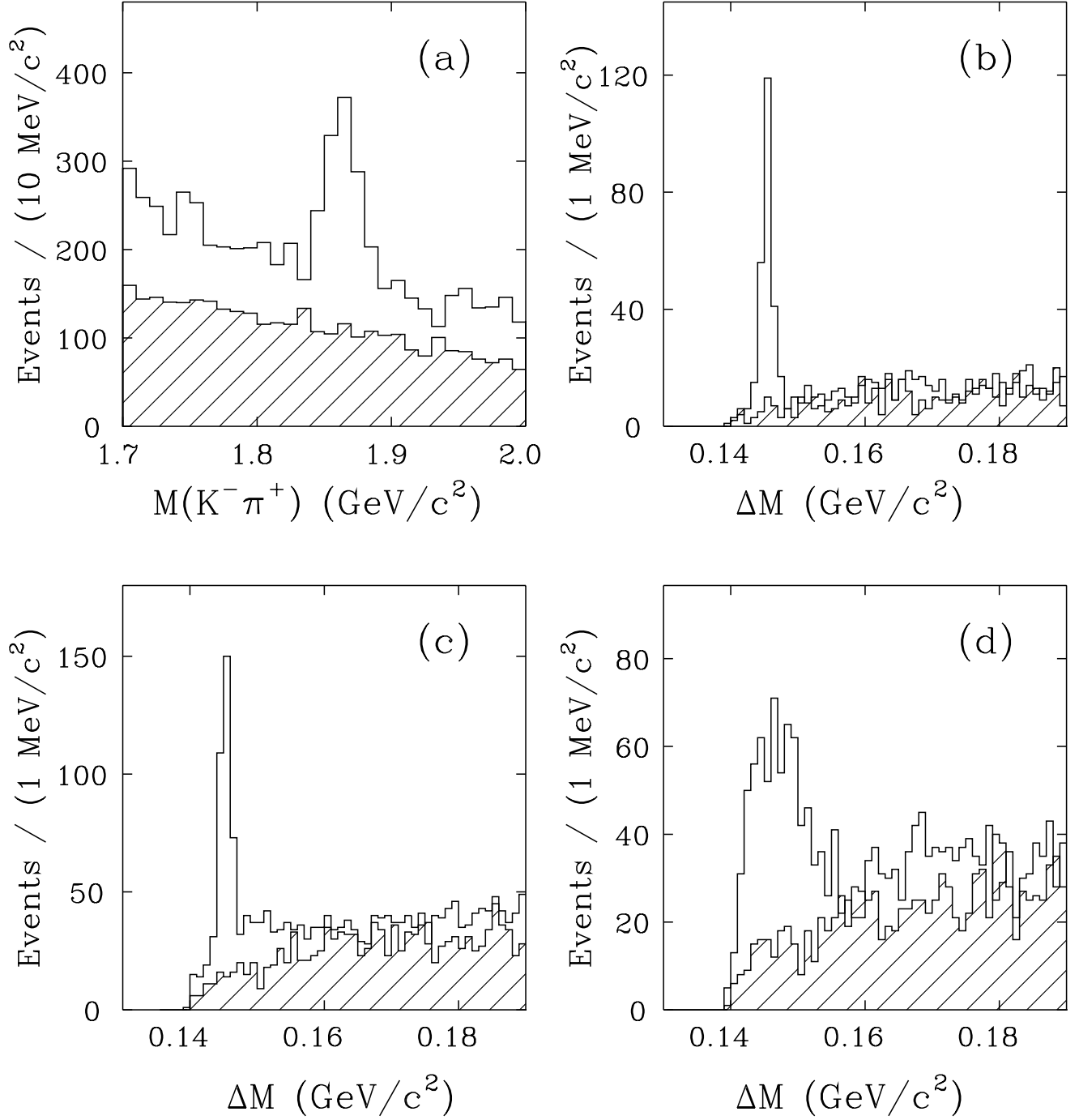
Figure 1: Reconstructed charm signals in lepton events. Four modes are shown: (a) $D^0 \rightarrow K^-\pi^+$ (non-D^{*+}), (b) $D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+$, (c) $D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ and (d) $D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^-\pi^+\pi^0$. Plot (a) shows the $K^-\pi^+$ invariant mass spectra, and (b-d) show the Δm distributions. Shaded histograms show wrong sign combinations, and in (a) they are scaled by 0.5 for display purposes.
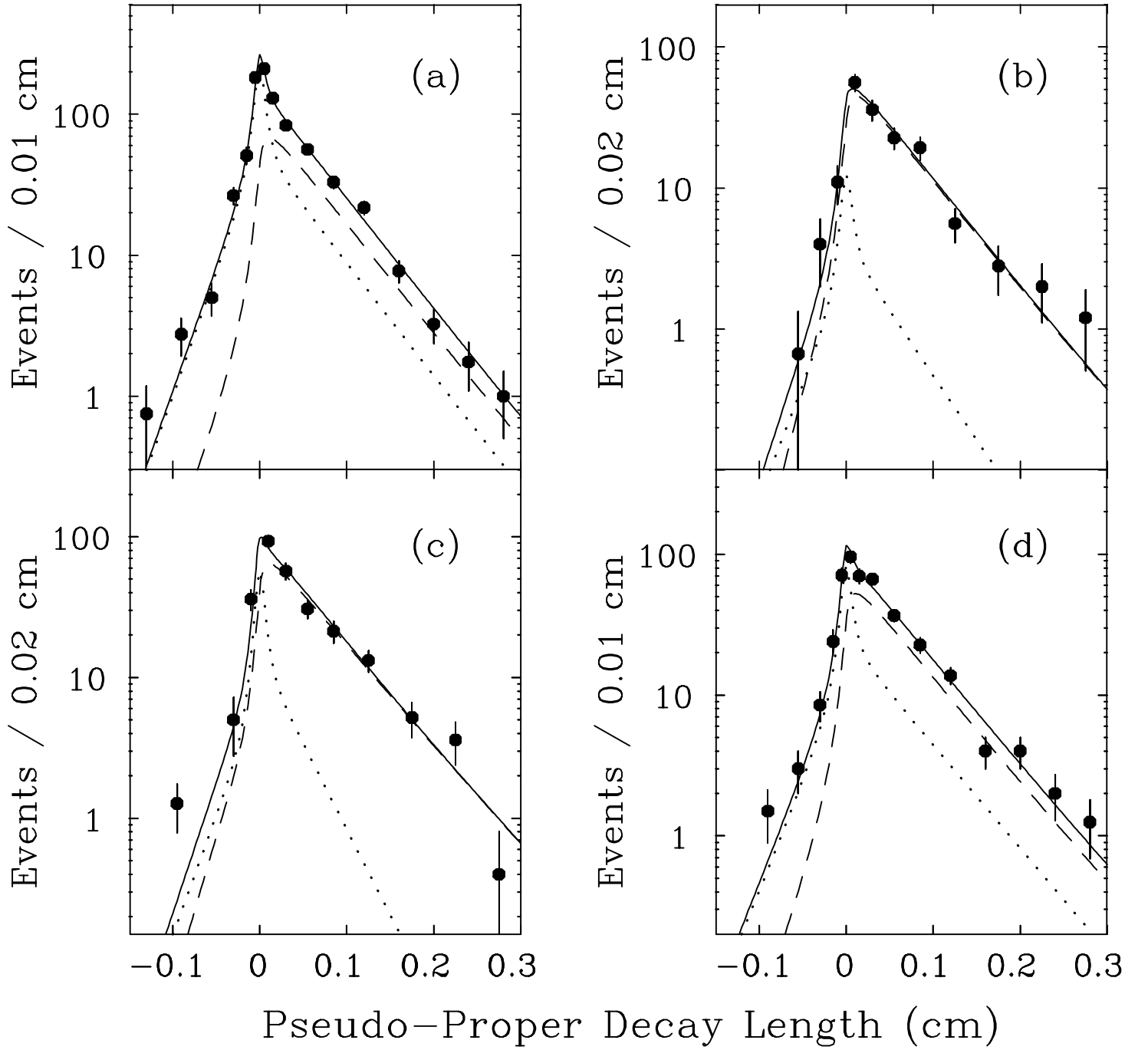
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Figure 2: Distributions of pseudo-proper decay lengths for the lepton-D signal samples (points). Also shown are results of lifetime fits, signal (dashed curve) and background (dotted curve) contributions, and the sum of the two (solid curve). The four decay modes (a-d) are the same as in Figure 1.