Fermi National Accelerator Laboratory

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Measurement of the Average Lifetime of B-hadrons Produced in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

F. Abe et al
The CDF Collaboration

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

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F. Abe,[13] M. Albrow,[7] D. Amidei,[16] C. Anway-Wiese,[4] G. Apollinari,[26] H. Areti,[7] P. Auchincloss,[25] F. Azfar,[21] P. Azzi,[20] N. Bacchetta,[18] W. Badgett,[16] M. W. Bailey,[24] J. Bao,[33] P. de Barbaro,[25] A. Barbaro-Galtieri,[14] V. E. Barnes,[24] B. A. Barnett,[12] G. Bauer,[15] T. Baumann,[9] F. Bedeschi,[23] S. Behrends,[2] S. Belforte,[23] G. Bellettini,[23] J. Bellinger,[32] D. Benjamin,[31] J. Benlloch,[15] A. Beretvas,[7] J. P. Berge,[7] A. Bhatti,[26] K. Biery,[11] M. Binkley,[7] F. Bird,[28] D. Bisello,[20] R. E. Blair,[1] C. Blocker,[28] A. Bodek,[25] V. Bolognesi,[23] C. Boswell,[12] T. Boulos,[14] G. Brandenburg,[9] E. Buckley-Geer,[7] H. S. Budd,[25] K. Burkett,[16] G. Busetto,[20] A. Byon-Wagner,[7] K. L. Byrum,[1] C. Campagnari,[7] M. Campbell,[16] A. Caner,[7] W. Carithers,[14] D. Carlsmith,[32] A. Castro,[20] Y. Cen,[21] F. Cervelli,[23] J. Chapman,[16] G. Chiarelli,[8] T. Chikamatsu,[30] S. Cihangir,[7] A. G. Clark,[23] M. Cobal,[23] M. Contreras,[5] J. Cooper,[7] M. Cordelli,[8] D. P. Coupal,[28] D. Crane,[7] J. D. Cunningham,[2] T. Daniels,[15] F. DeJongh,[7] S. Dell'Agnello,[23] M. Dell'Orso,[23] L. Demortier,[26] B. Denby,[7] M. Deninno,[3] P. F. Derwent,[16] T. Devlin,[27] M. Dickson,[25] J. P. Done,[29] R. B. Drucker,[14] A. Dunn,[16] K. Einsweiler,[14] J. E. Elias,[7] R. Ely,[14] E. Engels, Jr.,[22] S. Eno,[5] D. Errede,[10] S. Errede,[10] A. Etchegoyen,[7a] Q. Fan,[25] B. Farhat,[15] I. Fiori,[3] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[9] M. Frautschi,[18] J. Freeman,[7] J. Friedman,[15] H. Frisch,[5] A. Fry,[28] T. A. Fuess,[28] Y. Fukui,[13] S. Funaki,[30] A. F. Garfinkel,[24] S. Geer,[7] D. W. Gerdes,[16] P. Giannetti,[23] N. Giokaris,[26] P. Giromini,[8] L. Gladney,[21] D. Glenzinski,[12] M. Gold,[18] J. Gonzalez,[21] A. Gordon,[9] A. T. Goshaw,[6] K. Goulianos,[26]

H. Grassmann,[28] A. Grewal,[21] G. Grieco,[23] L. Groer,[27] C. Grosso-Pilcher,[5] C. Haber,[14] S. R. Hahn,[7] R. Hamilton,[9] R. Handler,[32] R. M. Hans,[33] K. Hara,[30] B. Harral,[21] R. M. Harris,[7] S. A. Hauger,[6] J. Hauser,[4] C. Hawk,[27] J. Heinrich,[21] D. Hennessy,[6] R. Hollebeek,[21] L. Holloway,[10] A. Hölscher,[11] S. Hong,[16] G. Houk,[21] P. Hu,[22] B. T. Huffman,[22] R. Hughes,[25] P. Hurst,[9] J. Huth,[7] J. Hylen,[7] M. Incagli,[23] J. Incandela,[7] H. Iso,[30] H. Jensen,[7] C. P. Jessop,[9] U. Joshi,[7] R. W. Kadel,[14] T. Kamon,[29] T. Kaneko,[30] D. A. Kardelis,[10] H. Kasha,[33] Y. Kato,[19] L. Keeble,[29] R. Kennedy,[27] R. Kephart,[7] P. Kesten,[14] D. Kestenbaum,[9] R. M. Keup,[10] H. Keutelian,[7] F. Keyvan,[4] D. H. Kim,[7] S. B. Kim,[16] S. H. Kim,[30] Y. K. Kim,[14] L. Kirsch,[2] P. Koehn,[25] K. Kondo,[30] J. Konigsberg,[9] S. Kopp,[5] K. Kordas,[11] W. Koska,[7] E. Kovacs,[7a] M. Krasberg,[16] S. E. Kuhlmann,[1] E. Kuns,[27] A. T. Laasanen,[24] S. Lammel,[4] J. I. Lamoureux,[32] T. LeCompte,[10] S. Leone,[23] J. D. Lewis,[7] P. Limon,[7] M. Lindgren,[4] T. M. Liss,[10] N. Lockyer,[21] O. Long,[21] M. Loreti,[20] E. H. Low,[21] J. Lu,[29] D. Lucchesi,[23] C. B. Luchini,[10] P. Lukens,[7] P. Maas,[32] K. Maeshima,[7] A. Maghakian,[26] M. Mangano,[23] J. Mansour,[17] M. Mariotti,[23] J. P. Marriner,[7] A. Martin,[10] J. A. J. Matthews,[18] R. Mattingly,[2] P. McIntyre,[29] P. Melese,[26] A. Menzione,[23] E. Meschi,[23] S. Mikamo,[13] M. Miller,[5] T. Mimashi,[30] S. Miscetti,[8] M. Mishina,[13] H. Mitsushio,[30] S. Miyashita,[30] Y. Morita,[13] S. Moulding,[26] J. Mueller,[27] A. Mukherjee,[7] T. Muller,[4] L. F. Nakae,[28] I. Nakano,[30] C. Nelson,[7] D. Neuberger,[4] C. Newman-Holmes,[7] L. Nodulman,[1] S. Ogawa,[30] K. E. Ohl,[33] R. Oishi,[30] T. Okusawa,[19] R. Paoletti,[23] V. Papadimitriou,[7] S. Park,[7] J. Patrick,[7] G. Pauletta,[23] L. Pescara,[20] M. D. Peters,[14] T. J. Phillips,[6] G. Piacentino,[3] M. Pillai,[25] R. Plunkett,[7] L. Pondrom,[32] N. Produit,[14] J. Proudfoot,[1] F. Ptohos,[9] G. Punzi,[23] K. Ragan,[11] F. Rimondi,[3] L. Ristori,[23] M. Roach-Bellino,[31] W. J. Robertson,[6]

T. Rodrigo,[7] J. Romano,[5] L. Rosenson,[15] W. K. Sakumoto,[25] D. Saltzberg,[5] A. Sansoni,[8] V. Scarpine,[29] A. Schindler,[14] P. Schlabach,[9] E. E. Schmidt,[7] M. P. Schmidt,[33] O. Schneider,[14] G. Sciacca,[23] A. Scribano,[23] S. Segler,[7] S. Seidel,[18] Y. Seiya,[30] G. Sganos,[11] M. Shapiro,[14] N. M. Shaw,[24] Q. Shen,[24] P. F. Shepard,[22] M. Shimojima,[30] M. Shochet,[5] J. Siegrist,[28] A. Sill,[7a] P. Sinervo,[11] P. Singh,[22] J. Skarha,[12] K. Sliwa,[31] D. A. Smith,[23] F. D. Snider,[12] L. Song,[7] T. Song,[16] J. Spalding,[7] P. Sphicas,[15] A. Spies,[12] L. Stanco,[20] J. Steele,[32] A. Stefanini,[23] G. Sullivan,[5] K. Sumorok,[15] R. L. Swartz, Jr.,[10] T. Takahashi,[19] K. Takikawa,[30] F. Tartarelli,[23] Y. Teramoto,[19] S. Tether,[15] D. Theriot,[7] J. Thomas,[28] R. Thun,[16] M. Timko,[31] P. Tipton,[25] A. Titov,[26] S. Tkaczyk,[7] A. Tollestrup,[7] J. Tonnison,[24] J. Tseng,[12] M. Turcotte,[28] N. Turini,[3] N. Uemura,[30] F. Ukegawa,[21] S. Vejcik, III,[16] R. Vidal,[7] M. Vondracek,[10] R. G. Wagner,[1] R. L. Wagner,[7] N. Wainer,[7] R. C. Walker,[25] J. Wang,[5] Q. F. Wang,[26] A. Warburton,[11] G. Watts,[25] T. Watts,[27] R. Webb,[29] C. Wendt,[32] H. Wenzel,[7a] W. C. Wester, III,[14] T. Westhusing,[10] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[21] H. H. Williams,[21] B. L. Winer,[25] J. Wolinski,[29] D. Y. Wu,[16] X. Wu,[23] J. Wyss,[20] A. Yagil,[7] W. Yao,[14] K. Yasuoka,[30] Y. Ye,[11] G. P. Yeh,[7] M. Yin,[6] J. Yoh,[7] T. Yoshida,[19] D. Yovanovitch,[7] I. Yu,[33] J. C. Yun,[7] A. Zanetti,[23] F. Zetti,[23] S. Zhang,[15] W. Zhang,[21] and S. Zucchelli[3]

(CDF Collaboration)

[1] *Argonne National Laboratory, Argonne, Illinois 60439*

[2] *Brandeis University, Waltham, Massachusetts 02254*

[3] *Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40126 Bologna, Italy*

[4] *University of California at Los Angeles, Los Angeles, California 90024*

[5] *University of Chicago, Chicago, Illinois 60637*

[6] *Duke University, Durham, North Carolina 27708*

[7] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[8] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*

[9] *Harvard University, Cambridge, Massachusetts 02138*

[10] *University of Illinois, Urbana, Illinois 61801*

[11] *Institute of Particle Physics, McGill University, Montreal H3A 2T8, and University of Toronto, Toronto M5S 1A7, Canada*

[12] *The Johns Hopkins University, Baltimore, Maryland 21218*

[13] *National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan*

[14] *Lawrence Berkeley Laboratory, Berkeley, California 94720*

[15] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*

[16] *University of Michigan, Ann Arbor, Michigan 48109*

[17] *Michigan State University, East Lansing, Michigan 48824*

[18] *University of New Mexico, Albuquerque, New Mexico 87131*

[19] *Osaka City University, Osaka 588, Japan*

[20] *Universita di Padova, Instituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*

[21] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*

[22] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*

[23] *Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*

[24] *Purdue University, West Lafayette, Indiana 47907*

[25] *University of Rochester, Rochester, New York 14627*

[26] *Rockefeller University, New York, New York 10021*

[27] *Rutgers University, Piscataway, New Jersey 08854*

[28] *Superconducting Super Collider Laboratory, Dallas, Texas 75237*

[29] *Texas A&M University, College Station, Texas 77843*

[30] *University of Tsukuba, Tsukuba, Ibaraki 305, Japan*

[31] *Tufts University, Medford, Massachusetts 02155*

[32] *University of Wisconsin, Madison, Wisconsin 53706*

[33] *Yale University, New Haven, Connecticut 06511*

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The average B hadron lifetime has been measured using a high statistics sample of $B \to J/\psi X$ decays recorded with the Collider Detector at Fermilab. The decay vertices of 5344 inclusive $J/\psi \to \mu^+\mu^-$ candidates have been reconstructed using information from a silicon vertex-detector. The measured B lifetime, which is the average over all b-hadrons produced in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV weighted by their branching ratios into J/ψ, is $1.46 \pm 0.06(\text{stat}) \pm 0.06(\text{sys})$ ps.

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Measurements of the B hadron lifetime have improved significantly in the past two years. While earlier experiments at PEP [1] and PETRA [2] were limited both by statistics and by the resolution of their tracking detectors, recent LEP analyses of semileptonic B decays have resulted in smaller statistical uncertainties [3]. Systematic errors associated with the modeling of the semileptonic decays have become the dominant source of uncertainty. Measurement of the decay vertices of $B \to J/\psi X$ candidates provides an alternative method of determining the B lifetime with quite different systematic uncertainties. Until now, however, this technique has suffered from low statistics [4].

We report here a high statistics measurement of the B lifetime determined from a sample of $B \to J/\psi X \to \mu^+\mu^- X$ decays recorded by the Collider Detector at Fermilab (CDF) during the first half of the 1992-93 Tevatron run. The sample corresponds to an integrated luminosity of 10.1 ± 0.7 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. This is the first measurement of the average B lifetime from a hadron collider experiment. Because the B production cross section is large in $p\overline{p}$ collisions [5], it is now possible to obtain statistical uncertainties of $\sim 4\%$ for this mode, which has an effective branching ratio $BR(B \to J/\psi X) \cdot BR(J/\psi \to \mu^+\mu^-) = 7.7 \pm 1.3 \times 10^{-4}$.

The CDF detector has been described in detail elsewhere [6]. For the 1992-93 collider run, a silicon vertex detector (SVX) has been installed [7]. The SVX consists of 4 layers of silicon-strip detectors with r-ϕ readout, that includes pulse height information. The pitch between readout strips is 60 μm, resulting in a spatial resolution of 13 μm. The first measurement plane is located 2.9 cm from the interaction point, leading to an impact parameter resolution of ~ 15 μm for high momentum tracks.

CDF uses a three-level trigger system. At Level 1 the relevant trigger for this analysis requires the presence of 2 charged tracks in the central muon chambers, which cover the pseudorapidity range $|\eta| < 0.6$, where the pseudorapidity

$\eta \equiv -\ln(\tan(\theta/2))$. The efficiency of finding a muon at Level 1 rises from 30% at transverse momentum $p_T = 1.5$ GeV/c to 93% for $p_T > 3$ GeV/c. Level 2 requires that at least one of the muon tracks match a charged track in the Central Tracking Chamber (CTC) found with the Central Fast Track (CFT) processor [8]. The efficiency of finding a track in the CFT rises from 50% at 2.6 GeV/c to 94% for $p_T > 3.1$ GeV/c. The Level 3 software trigger requires the presence of two oppositely charged muon candidates with invariant mass between 2.8 and 3.4 GeV/c^2 [9]. A total of 18451 J/ψ candidates satisfied this trigger and had both tracks reconstructed in the SVX.

To reduce the background in the dimuon sample, the following muon selection cuts were applied: (1) The separation between the track in the muon chamber and the extrapolated CTC track was calculated in both the transverse and longitudinal planes. In each view, the difference was required to be less than 3.0 standard deviations (σ) from zero, where a standard deviation is calculated as the sum in quadrature of the multiple scattering and measurement errors. (2) The energy deposited in the hadronic calorimeter by each muon was required to be greater than 0.5 GeV, the smallest energy expected from a minimum ionizing particle. (3) The p_T of at least one of the muon tracks was required to be > 2.5 GeV/c.

To ensure that the J/ψ decay vertex was well measured, strict track quality cuts were imposed on the sample: (1) both muon tracks were required to be reconstructed in the SVX with hits in at least three layers out of the four possible. (2) All SVX track residuals were required to be less than 4 σ. The χ^2 contribution of these residuals was required to be less than 20. 3) SVX tracks where one or more hits were assigned to more than one track were removed. (4) SVX hits with total charge more than 4 times the average charge deposited by a minimum ionizing particle were removed. (5) The two muons were required to have track parameters consistent with a single decay vertex.

The invariant mass distribution of the final dimuon sample is shown in Figure 1. The grey-hatched area indicates the J/ψ signal region, defined to be ± 50 MeV/c^2 around the J/ψ-mass. This region contains 5667 events. The cross-hatched area shows the two sideband regions, one with mass from 2.9 to 3.0 GeV/c^2, and the other from 3.2 to 3.3 GeV/c^2. The sidebands contain 646 events. These sidebands were used to determine the shape of the lifetime distribution for background events in the J/ψ signal region. After background subtraction is performed, the number of J/ψ's in the signal region is estimated to be 5344 ± 73. The fitted J/ψ mass is $3.0943 \pm 0.0002(\text{stat}) \pm 0.005(\text{sys})$ GeV/c^2 with a mass resolution of 16 ± 0.2 MeV/c^2.

For each J/ψ in the sample, a two dimensional decay distance L_{xy} was calculated. L_{xy} is the projection of the vector $\vec{X}$, pointing from the primary to the secondary vertex, onto the transverse momentum of the J/ψ:

$$L_{xy} \equiv \frac{\vec{X} \cdot \vec{p_t^\psi}}{|\vec{p_T}^\psi|}$$

The position of the secondary vertex is obtained by constraining the two muon tracks to come from a common decay vertex. The primary vertex position is approximated by the mean beam position, determined run-by-run by averaging over many events. The transverse profile of the beam is circular and has an rms of ~ 40 μm.

To convert the transverse decay length into a proper lifetime, the relativistic quantity $(\beta\gamma)_B$ of the B-hadron must be determined. Since the J/ψ's selected by the dimuon trigger typically carry most of the momentum of the B, the $(\beta\gamma)_\psi$ of the J/ψ is a good first approximation to $(\beta\gamma)_B$. Using a Monte Carlo procedure, a $(\beta\gamma)$ correction factor F was calculated as a function of p_T^ψ. F varies only weakly over the p_T range of the J/ψ in our sample and is ~ 0.86. The best estimate of the proper time of the B decay (the "pseudo-$c\tau$") is:

$$\lambda = L_{xy} \frac{M_\psi}{p_T^\psi F(p_T^\psi)}$$

The calculation of $F(p_T^\psi)$ used a b-quark p_T spectrum generated from the next-to-leading order calculation of Nason, Dawson and Ellis (NDE) with a choice of MRSD0 parton distribution functions [10]. To estimate the systematic uncertainties in the shape of this cross section, the NDE production model was compared to a simple power law spectrum, optimized to reproduce the p_T spectrum of our data. The b-quarks were then fragmented using the Peterson fragmentation function [11] where the fragmentation parameter and its uncertainty ($\epsilon = 0.006 \pm 0.002$) have been taken from reference [12]. The B hadrons were then forced to decay into $J/\psi + X$. The J/ψ spectrum in the B rest frame was obtained from the experimental results of ARGUS and CLEO [13]. We also used their results to set bounds on the polarization when modeling the decay $J/\psi \rightarrow \mu^+\mu^-$ [14]. The resulting muons were passed through a computer simulation of the detector and trigger.

In order to obtain the B lifetime from the λ distribution, we fit to 3 sources of dimuon events in the J/ψ invariant mass region:

(i) J/ψ's from B decays: this part is parameterized by a Gaussian function convoluted with an exponential. The fit parameter f_b gives the fraction of J/ψ coming from b-decay.

(ii) J/ψ's directly produced in $p\overline{p}$ collisions, or resulting from the decay of intermediate states which are sufficiently short-lived that their vertex is indistinguishable from the primary vertex (*e.g.* χ_c's): this part is parameterized by a Gaussian function.

(iii) Background coming from processes whose invariant mass falls accidentally in the J/ψ mass window: these events include dimuons from Drell-Yan production, double semileptonic b-decays, meson decays-in-flight and residual hadron punch-through. The shape of this contribution is obtained by fitting the J/ψ sidebands. The fit is parameterized as the sum of a Gaussian function and two exponentials, one above the Gaussian and one below, each with a different slope. Since the dimuon sample contains events from sequential b-decays ($b \to c\mu\nu \to s\mu\nu\mu\nu$), the λ distribution is expected to be asymmetric. The background fraction, f_{BGR}, is determined from the sidebands and is not a free parameter in the fit to the signal region.

Figure 2 shows the λ distribution for the J/ψ sidebands with a fit superimposed. Figure 3 shows the result of an unbinned likelihood fit to the data. The dark-shaded area shows the contribution from the background obtained from the fit of Figure 2. The light-shaded area shows the sum of the background distribution and the Gaussian function convoluted with the exponential from b-decay. The remaining Gaussian centered at 0 (unshaded area) is due to prompt decays. The fit results in:

$$\tau_{\rm B} = 1.46 \pm 0.06\ (\text{stat.})\ \text{ps and } \text{f}_{\rm b} = 15.1 \pm 0.6\%(\text{stat.})$$

The fit parameter f_b obtained in the above procedure does not provide an unbiased measurement of the fraction of J/ψ's coming from b decay. The applied track quality cuts favor isolated muons. These cuts systematically decrease this fraction.

Our estimates of the systematic uncertainties on the above measurement are listed in Table I. Our estimate of the systematic uncertainty in the production and decay kinematics is 3% and comes from studying the parameters of our model, including the b quark production spectrum, J/ψ momentum spectrum in the B rest frame, J/ψ polarization and fragmentation. The uncertainty in the decay vertex resolution has been studied using several independent datasets. Studies of a sample of prompt

$\Upsilon(1S) \rightarrow \mu^+\mu^-$ events and of a high statistics sample of tracks selected from jet events indicate that the resolution function for tracks from the primary vertex is symmetric. A fit to the jet sample results in a mean decay length of $0.2 \pm 0.9\mu$m, consistent with zero. The resolution obtained from this fit agrees to within 5% with the mean of the resolution obtained event-by-event from our vertex-constrained fit.

The uncertainty due to residual misalignment of the SVX has been studied by varying the alignment correction constants. The systematic uncertainty due to misalignment is estimated to be 2%. The variation in the beam position within a run have been measured to be less than 4 μm, which leads to a 1% systematic uncertainty on the $c\tau$ measurement. The effect of impact parameter bias in the CFT and Level 3 trigger gives an estimated uncertainty of 1.4%.

To get the systematics due to the background parameterization we varied the slopes of the two exponentials by one sigma and studied the effect on the lifetime. From this we obtain a systematic error of 0.5% due to the background parameterization. Since the result of the maximum likelihood fit depends on the error on the decay-length which is calculated for each event, we have varied these errors by an overall scale factor and studied the result of this variation on the fit. This study results in an an additional 1.6% uncertainty in the lifetime.

In conclusion, we have measured the average lifetime for b-hadrons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. For events where the b-hadron has decayed to a J/ψ, the lifetime is determined to be:

$$\tau_{\rm B} = 1.46 \pm 0.06 \text{ (stat.) } \pm 0.06 \text{ (syst.) ps}$$

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TABLES

TABLE I. Systematic uncertainties on the average b-hadron lifetime

Description	Contribution in %
Production and decay kinematics	3.0
Residual misalignment	2.0
Beam stability	1.0
Trigger bias	1.4
Background parameterization	0.5
Uncertainty in $c\tau$ resolution	1.6
Total	4.3 %

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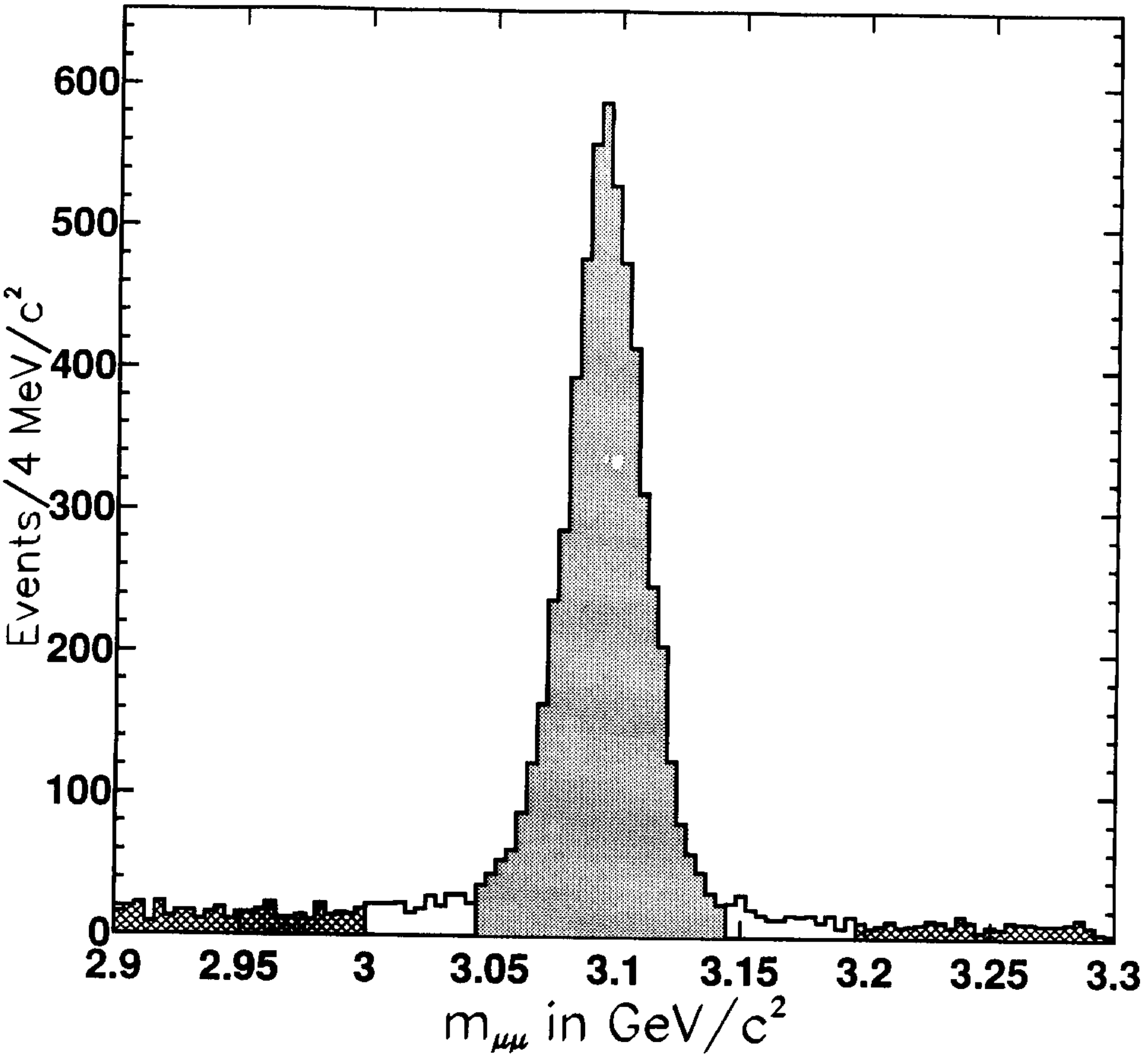
FIGURES

FIG. 1. Invariant mass distribution of two oppositely charged dimuons. The grey-hatched area indicates the J/ψ signal region and the cross-hatched areas show the sideband regions.

FIG. 2. The distribution in λ, the proper decay time, of data from the sideband regions. The solid line shows the results of a maximum likelihood fit.

FIG. 3. The distribution in λ, the proper decay time, of data in the signal region. The curves are the result of the unbinned likelihood fit described in the text.



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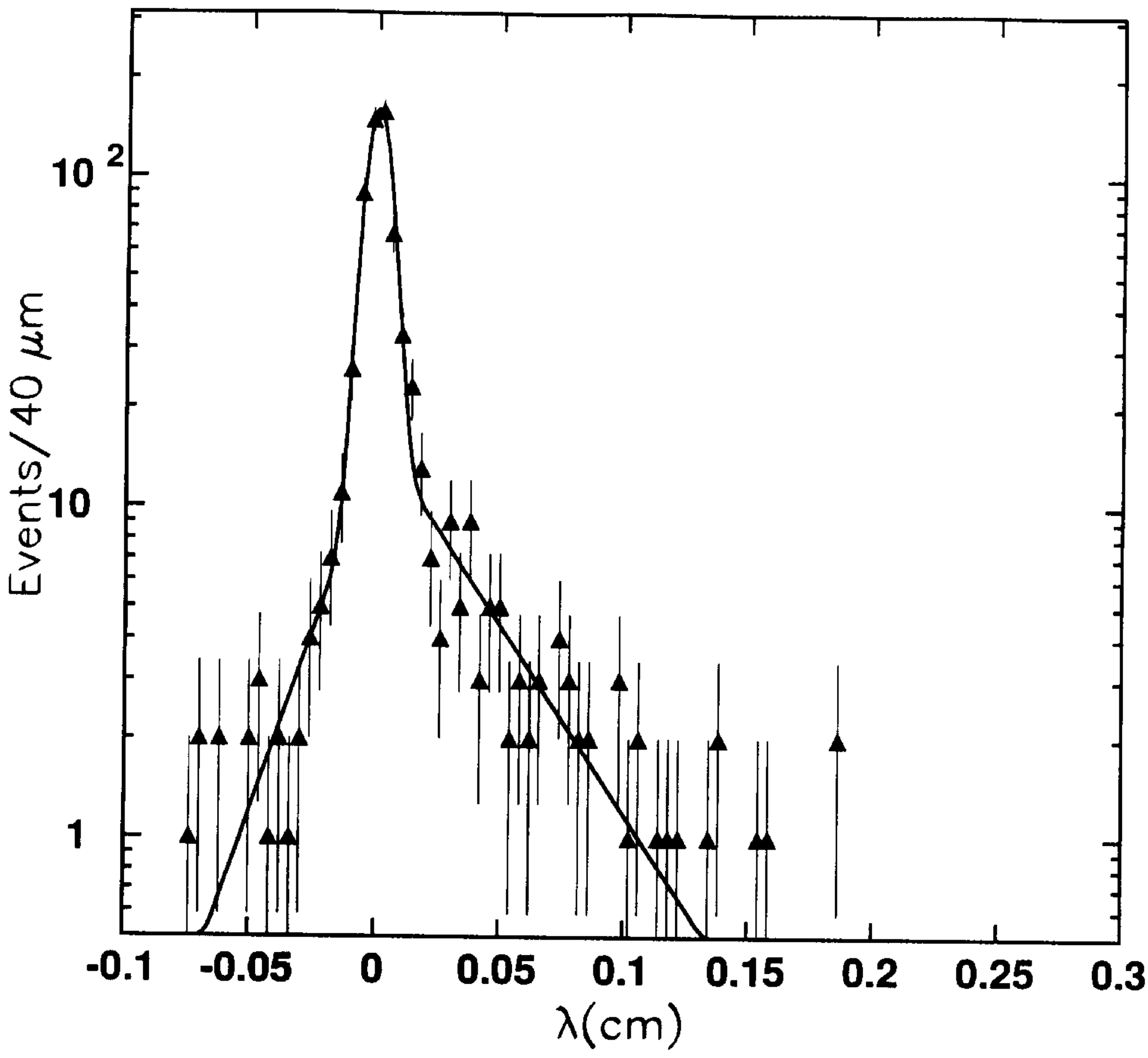
3.3
m_μμ in GeV/c²



Events/40 μm
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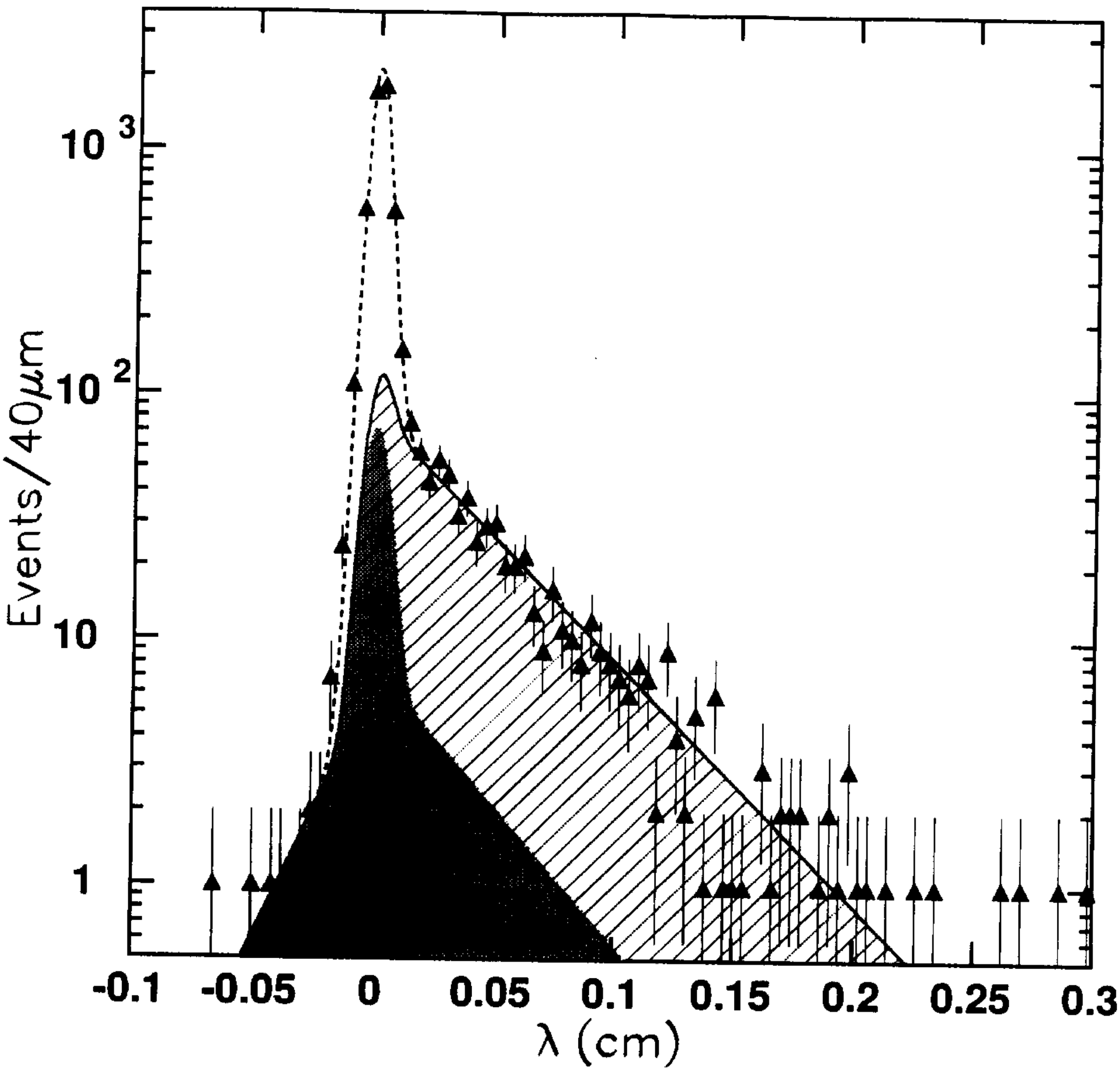
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
λ(cm)



10 ³
10 ²
10
1
Events/40μm
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
λ (cm)