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Measurement of the Lifetime of the B_s^0 Meson Using the Exclusive Decay Mode $\mathbf{B}_s^0 \rightarrow \mathbf{J}/\psi\phi$

F. Abe et al.
The CDF Collaboration

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

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F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[23] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4] S. Aota,[32] G. Apollinari,[27] T. Asakawa,[32] W. Ashmanskas,[15] M. Atac,[7] F. Azfar,[22] P. Azzi-Bacchetta,[21] N. Bacchetta,[21] W. Badgett,[17] S. Bagdasarov,[27] M. W. Bailey,[19] J. Bao,[35] P. de Barbaro,[26] A. Barbaro-Galtieri,[15] V. E. Barnes,[25] B. A. Barnett,[13] E. Barzi,[8] G. Bauer,[16] T. Baumann,[9] F. Bedeschi,[23] S. Behrends,[3] S. Belforte,[23] G. Bellettini,[23] J. Bellinger,[34] D. Benjamin,[31] J. Benlloch,[16] J. Bensinger,[3] D. Benton,[22] A. Beretvas,[7] J. P. Berge,[7] J. Berryhill,[5] S. Bertolucci,[8] A. Bhatti,[27] K. Biery,[12] M. Binkley,[7] D. Bisello,[21] R. E. Blair,[1] C. Blocker,[3] A. Bodek,[26] W. Bokhari,[16] V. Bolognesi,[7] D. Bortoletto,[25] J. Boudreau,[24] L. Breccia,[2] C. Bromberg,[18] N. Bruner,[19] E. Buckley-Geer,[7] H. S. Budd,[26] K. Burkett,[17] G. Busetto,[21] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[13] C. Campagnari,[7] M. Campbell,[17] A. Caner,[7] W. Carithers,[15] D. Carlsmith,[34] A. Castro,[21] D. Cauz,[23] Y. Cen,[26] F. Cervelli,[23] P. S. Chang,[29] P. T. Chang, [29] H. Y. Chao,[29] J. Chapman,[17] M.-T. Cheng,[29] G. Chiarelli,[23] T. Chikamatsu,[32] C. N. Chiou,[29] L. Christofek,[11] S. Cihangir,[7] A. G. Clark,[23] M. Cobal,[23] M. Contreras,[5] J. Conway,[28] J. Cooper,[7] M. Cordelli,[8] C. Couyoumtzelis,[23] D. Crane,[1] D. Cronin-Hennessy,[6] R. Culbertson,[5] J. D. Cunningham,[3] T. Daniels,[16] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[23] M. Dell'Orso,[23] R. Demina,[7] L. Demortier,[27] B. Denby,[23] M. Deninno,[2] P. F. Derwent,[17] T. Devlin,[28] J. R. Dittmann,[6] S. Donati,[23] J. Done,[30] T. Dorigo,[21] A. Dunn,[17] N. Eddy,[17] K. Einsweiler,[15] J. E. Elias,[7] R. Ely,[15] E. Engels, Jr.,[24] D. Errede,[11] S. Errede,[11] Q. Fan,[26] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[9] M. Frautschi,[31] J. Freeman,[7] J. Friedman,[16] T. A. Fuess,[1] Y. Fukui,[14] S. Funaki,[32] G. Gagliardi,[23] S. Galeotti,[23] M. Gallinaro,[21] M. Garcia-Sciveres,[15] A. F. Garfinkel,[25] C. Gay,[9] S. Geer,[7] D. W. Gerdes,[17] P. Giannetti,[23] N. Giokaris,[27] P. Giromini,[8] L. Gladney,[22] D. Glenzinski,[13] M. Gold,[19] J. Gonzalez,[22] A. Gordon,[9] A. T. Goshaw,[6] K. Goulianos,[27] H. Grassmann,[23] L. Groer,[28] C. Grosso-Pilcher,[5] G. Guillian,[17] R. S. Guo,[29] C. Haber,[15] E. Hafen,[16] S. R. Hahn,[7] R. Hamilton,[9] R. Handler,[34] R. M. Hans,[35] K. Hara,[32] A. D. Hardman,[25] B. Harral,[22] R. M. Harris,[7]

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A. Sill,[31] P. Sinervo,[12] P. Singh,[24] J. Skarha,[13] K. Sliwa,[33] F. D. Snider,[13] T. Song,[17] J. Spalding,[7] T. Speer,[23] P. Sphicas,[16] F. Spinella,[23] M. Spiropulu,[9] L. Spiegel,[7] L. Stanco,[21] J. Steele,[34] A. Stefanini,[23] K. Strahl,[12] J. Strait,[7] R. Ströhmer,[9] D. Stuart,[7] G. Sullivan,[5] A. Soumarokov,[29] K. Sumorok,[16] J. Suzuki,[32] T. Takada,[32] T. Takahashi,[20] T. Takano,[32] K. Takikawa,[32] N. Tamura,[10] F. Tartarelli,[23] W. Taylor,[12] P. K. Teng,[29] Y. Teramoto,[20] S. Tether,[16] D. Theriot,[7] T. L. Thomas,[19] R. Thun,[17] M. Timko,[33] P. Tipton,[26] A. Titov,[27] S. Tkaczyk,[7] D. Toback,[5] K. Tollefson,[26] A. Tollestrup,[7] J. Tonnison,[25] J. F. de Troconiz,[9] S. Truitt,[17] J. Tseng,[13] N. Turini,[23] T. Uchida,[32] N. Uemura,[32] F. Ukegawa,[22] G. Unal,[22] S. C. van den Brink,[24] S. Vejcik, III,[17] G. Velev,[23] R. Vidal,[7] M. Vondracek,[11] D. Vucinic,[16] R. G. Wagner,[1] R. L. Wagner,[7] J. Wahl,[5] C. Wang,[6] C. H. Wang,[29] G. Wang,[23] J. Wang,[5] M. J. Wang,[29] Q. F. Wang,[27] A. Warburton,[12] T. Watts,[28] R. Webb,[30] C. Wei,[6] C. Wendt,[34] H. Wenzel,[15] W. C. Wester, III,[7] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[22] H. H. Williams,[22] P. Wilson,[5] B. L. Winer,[26] D. Wolinski,[17] J. Wolinski,[18] X. Wu,[23] J. Wyss,[21] A. Yagil,[7] W. Yao,[15] K. Yasuoka,[32] Y. Ye,[12] G. P. Yeh,[7] P. Yeh,[29] M. Yin,[6] J. Yoh,[7] C. Yosef,[18] T. Yoshida,[20] D. Yovanovitch,[7] I. Yu,[35] L. Yu,[19] J. C. Yun,[7] A. Zanetti,[23] F. Zetti,[23] L. Zhang,[34] W. Zhang,[22] and S. Zucchelli[2]

(CDF Collaboration)

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

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

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

[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] *Hiroshima University, Higashi-Hiroshima 724, Japan*

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

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

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

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

[15] *Ernest Orland Lawrence Berkeley Laboratory, Berkeley, California 94720*

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

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

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

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

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

[21] *Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*

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

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

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

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

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

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

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

[29] *Academia Sinica, Taipei, Taiwan 11529, Republic of China*

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

[31] *Texas Tech University, Lubbock, Texas 79409*

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

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

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

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

Abstract

The lifetime of the B_s^0 meson is measured using the exclusive decay mode $B_s^0 \to J/\psi\phi$, where $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. The data sample consists of 110 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, collected by the CDF detector at the Fermilab Tevatron collider during 1992-1995. We find 58 $\pm$ 12 signal events, and the B_s^0 meson lifetime is determined to be $\tau_{B_s^0} = 1.34\ ^{+0.23}_{-0.19}$ (stat.) $\pm\, 0.05$ (syst.) ps. This result is consistent with previous measurements of the B_s^0, B^+ and B_d^0 meson lifetimes and with theoretical predictions.

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This Letter reports an improved measurement of the B_s^0 meson lifetime using the exclusive decay mode $B_s^0 \to J/\psi\phi$ [1]. The B_s^0 is observed through the decay $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$. This B_s^0 decay mode is cleanly observed in a hadron collider because the $J/\psi \to \mu^+\mu^-$ decay allows an efficient trigger and is reconstructed with good signal-to-background ratio. Furthermore, the decay $\phi \to K^+K^-$ is easily isolated without explicit $K^\pm$ identification because of the narrow natural width of the ϕ. The lifetime measurement is based on our largest sample of exclusive B_s^0 decays and is obtained from $\sim$ 110 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s}$ =1.8 TeV, collected by the Collider Detector at Fermilab (CDF) during the 1992-1995 runs. This result supersedes our previous measurement using this exclusive decay mode [1].

Phenomenological models predict similar B_s^0 and B_d^0 lifetimes and a 5-10% difference between the B^+ and $B_{s,d}^0$ lifetimes [2], and the lifetimes are expected to follow the hierarchy $\tau(B^+) > \tau(B_s^0) \sim \tau(B_d^0)$. These predictions are consistent with measurements of B^+ and B_d^0 meson lifetimes [3], and with recent measurements of the B_s^0 lifetime from CDF [1] and LEP [4]. It has been suggested by recent theoretical calculations [5], in analogy to the $K_S^0 - K_L^0$ system, that the lifetime difference between the two CP eigenstates produced by mixing of the B_s^0 and $\overline{B}_s^0$ may be as much as 15%. Such an effect may manifest itself as a difference in lifetimes measured in semileptonic decay modes of the B_s^0, which are an almost equal mixture of the two CP states, and the decay $B_s^0 \to J/\psi\phi$, which is expected to be dominated by the CP-even state [6]. We have recently reported a low-statistics measurement of the polarization of $B_s^0 \to J/\psi\phi$ consistent with the CP-even hypothesis [7]. The CP-even state is expected to have the shorter lifetime.

The CDF detector has been described in detail elsewhere [8]. We describe here only the detector components most relevant to this analysis. Two devices inside the 1.4 T solenoid are used for the tracking of charged particles: the silicon vertex detector (SVX) and the central tracking chamber (CTC). The SVX consists of four concentric layers of silicon microstrip detectors surrounding the beampipe and located at radii between 3.0 and 7.9 cm from the interaction point. The SVX provides spatial measurements in the r-φ plane [9], giving a track impact parameter resolution of $\sim (13{+}40/P_T)$ μm [10], where P_T is the transverse momentum of the track with respect to the beamline, in GeV/c. The CTC is a cylindrical drift chamber containing 84 sense wire layers grouped into nine alternating superlayers of axial and stereo wires. It covers the pseudorapidity interval $|\eta| < 1.1$, where $\eta = -\ln[\tan(\theta/2)]$. The P_T resolution of the tracks reconstructed in the CTC and SVX detectors is $\delta(P_T)/P_T = ((0.0066)^2 + (0.0009P_T)^2)^{1/2}$. Two muon subsystems in the central pseudorapidity region are used, which together provide coverage in the interval $\mid \eta \mid <1.0$.

The dimuon events used to reconstruct the J/ψ were collected using a three-level trigger system. The first level required two charged tracks in the muon chambers. The efficiency for finding a muon at level one rises from 30% at $P_T = 1.5$ GeV/c to 93% for $P_T > 3$ GeV/c. For most of the data taking period, the second level required that both of the muon tracks match a charged track in the CTC found with the Central Fast Track (CFT) processor. The typical efficiency for finding a CTC track with the CFT at level two rises from 50% for $P_T \sim 1.8$ GeV/c to 94% for $P_T > 2.7$ GeV/c. The third level software trigger requires that two oppositely charged CTC tracks each match track segments in the muon chambers, and that the $\mu^+\mu^-$ invariant mass is between 2.8 and 3.4 GeV/c^2 to select J/ψ candidates.

The reconstruction of the decay mode $B_s^0 \to J/\psi\phi$ begins with the isolation of the J/ψ signal using the decay mode $J/\psi \to \mu^+\mu^-$. To select the muon candidates, CTC tracks are extrapolated to the muon chambers and their positions are required to match track segments in the chambers within errors. The uncertainties are derived from multiple scattering. All four candidate tracks used in the reconstruction of the decay $B_s^0 \to J/\psi\phi$ are required to be well measured by the CTC and the two muon candidate tracks must be measured by at least three of the four SVX layers.

We require the two candidate muon tracks to originate from a single point in space (vertex constraint), after allowing the coordinates of this point and the parameters of the candidate muon tracks to vary in a χ^2 fit. The invariant mass of the vertex-constrained dimuons is formed and required to lie within 80 MeV/c^2 of the world average J/ψ mass of 3.097 GeV/c^2 [11]. All other oppositely charged track pairs are considered ϕ candidates. To improve the mass resolution of the B_s^0, the four tracks are vertex constrained and the muon pair is constrained to have the world average J/ψ mass. To improve the signal-to-background ratio, we require the probability of this vertex constrained fit to be greater than 1%, the invariant mass of the kaon pair to lie within 10 MeV/c^2 of the world average ϕ mass of 1.0194 GeV/c^2 [11], $P_T(\phi) > 2$ GeV/c, and $P_T(B_s^0) > 6$ GeV/c. The four-track vertex is referred to as the secondary vertex. The resulting $J/\psi\phi$ invariant mass spectrum is shown in Fig. 1 fitted with a Gaussian and a second order polynomial. A signal of 58 $\pm$ 12 events is observed.

We determine the lifetime of the B_s^0 meson by measuring the distance traveled by each B_s^0 meson candidate in the transverse plane and applying the appropriate Lorentz boost correction. In addition to the position of the secondary vertex, precise knowledge of the $p\overline{p}$ collision point (primary vertex) is necessary for an accurate determination of distance traveled. The primary vertex is defined to be the run-by-run average beam position, and the typical run duration is several hours. An algorithm using well measured CTC tracks with SVX information determines the average beam position. The beam profile has a RMS of $\sim$35μm in the r-ϕ plane and a RMS of $\sim$30 cm in the z direction. We define the 'signed' transverse decay length $L_T = \vec{x} \cdot \frac{\vec{P}_T}{|\vec{P}_T|}$ where $\vec{x}$ is the vector pointing from the primary to the secondary vertex and $\vec{P}_T$ is the reconstructed transverse momentum of the B_s^0. The proper decay-length of the B_s^0 is then given by $c\tau = L_T \frac{M_{B_s^0}}{P_T}$, where $M_{B_s^0}$ is the reconstructed mass of the B_s^0.

The proper decay-length and invariant mass distributions of the B_s^0 are fit simultaneously using the maximum likelihood method. The likelihood function is given by

$$\mathcal{L} \;=\; \prod_{j=1}^{N} [f_s F^j_{sig} + (1 - f_s) F^j_{bck}],$$

where F_{sig} is the product of the signal mass and proper decay-length probability density functions, F_{bck} is the product of the background mass and proper decay-length probability density functions, f_s is the fraction of signal, and N is the total number of events.

The signal proper decay-length function is a normalized exponential decay function convoluted with a Gaussian of width equal to the calculated event-by-event uncertainty. This uncertainty is derived from the full covariance matrices of the tracks and the uncertainty in the position of the primary vertex. The magnitude of this uncertainty is typically 40 μm. Each uncertainty is multiplied by a scale factor that is allowed to float in the fit. The scale factor accounts for a possible underestimate of the decay length resolution and is consistent with unity.

The signal mass distribution is modeled by a Gaussian distribution of width equal to the calculated event-by-event mass error. The error in mass is derived from the track covariance matrices and is typically of order 0.01 GeV/c^2.

The background proper decay-length distribution function is parameterized as the sum of a zero-lifetime Gaussian, a positive long-lived exponential decay convoluted with a Gaussian and a negative exponential decay function. The background mass distribution is modeled as a second-order polynomial. The normalization of the probability density function is given by the expression:

$$\int\!\!\int [f_s F^j_{sig} + (1 - f_s) F^j_{bck}]\, d\tau_j\, dm_j = 1$$

where τ_j and m_j are the calculated proper decay-time and invariant mass of the jth candidate event respectively. Since a well determined background shape allows us to determine the signal fraction and lifetime with greater accuracy, we select events in a relatively wide mass range, 5.1–5.7 GeV/c^2. The large number of background events included in this range allow for an accurate determination of the parameters describing the background.

The proper decay length and mass spectra are fit to determine the lifetime of the B^0_s, the mass of the B^0_s, the shape of the background proper decay length and mass distributions, and the fraction of signal events. The proper decay length distribution is shown in Fig. 2 after selecting events from $\pm$ 0.05 GeV/c^2 around the fitted B_s^0 mass. This mass range is chosen to display the shape of the $c\tau$ signal distribution more clearly.

Various sources of systematic uncertainty have been studied. The contribution from each source is listed in Table 1.

(1) Variations in the parameterization of the background shape have been studied by fitting alternate shapes to the background $c\tau$ and invariant mass distributions. The fitted lifetime is found to be uncertain by 3.5%.

(2) A possible bias in the fitting procedure has been studied by generating and fitting several thousand mass and lifetime distributions modeled after the data. We assign a 0.5% systematic uncertainty due to a possible bias in the fitting procedure.

(3) We require signals in three or four of the SVX layers for reconstruction of tracks. An uncertainty in the inter-layer separation implies that decay lengths are uncertain by an overall scale factor. A recalculation of the lifetime with these uncertainties taken into account gives a shift of 0.3% in the measured lifetime. We assign a systematic uncertainty of 0.3% to the lifetime due to an uncertainty in the length scale of the SVX. The total systematic uncertainty from all these effects added in quadrature is 3.5%.

The lifetime of the B_s^0 is determined to be

$$\tau_{B_s^0} = 1.34\ ^{+0.23}_{-0.19}\ \text{(stat.)}\ \pm 0.05\ \text{(syst.) ps.}$$

This result is consistent with the world average of [11] $\tau_{B_s^0} = 1.34\ ^{+0.32}_{-0.27}$ ps, from the DELPHI, ALEPH and OPAL experiments [4], and with the recent CDF measurement of [1] $\tau_{B_s^0} = 1.42\ ^{+0.27}_{-0.23}$ (stat) $\pm$ 0.11 (syst) ps.

In conclusion the B_s^0 lifetime has been measured in a hadronic environment in an exclusive decay mode. The significance of this result is comparable to previous measurements in the semileptonic mode $B_s^0 \rightarrow D_s^- \ell^+ \nu_\ell X$ [1, 4]. This is at present the only measurement of the B_s^0 lifetime in an exclusive decay mode. The result is consistent with other measurements of the B_s^0 lifetime and with measurements of the lifetimes of the B^0 and B^+ mesons. With the current level of statistics, a measurement of the lifetime difference between the two CP eigenstates cannot be made to test the Standard Model predictions.

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Table 1: A summary of the sources of systematic uncertainty for the B_s^0 lifetime.

Background parameterization	3.5 %
Fitting procedure bias	0.5 %
SVX Length Scale	0.3 %
Total	3.5 %

[a] Visitor

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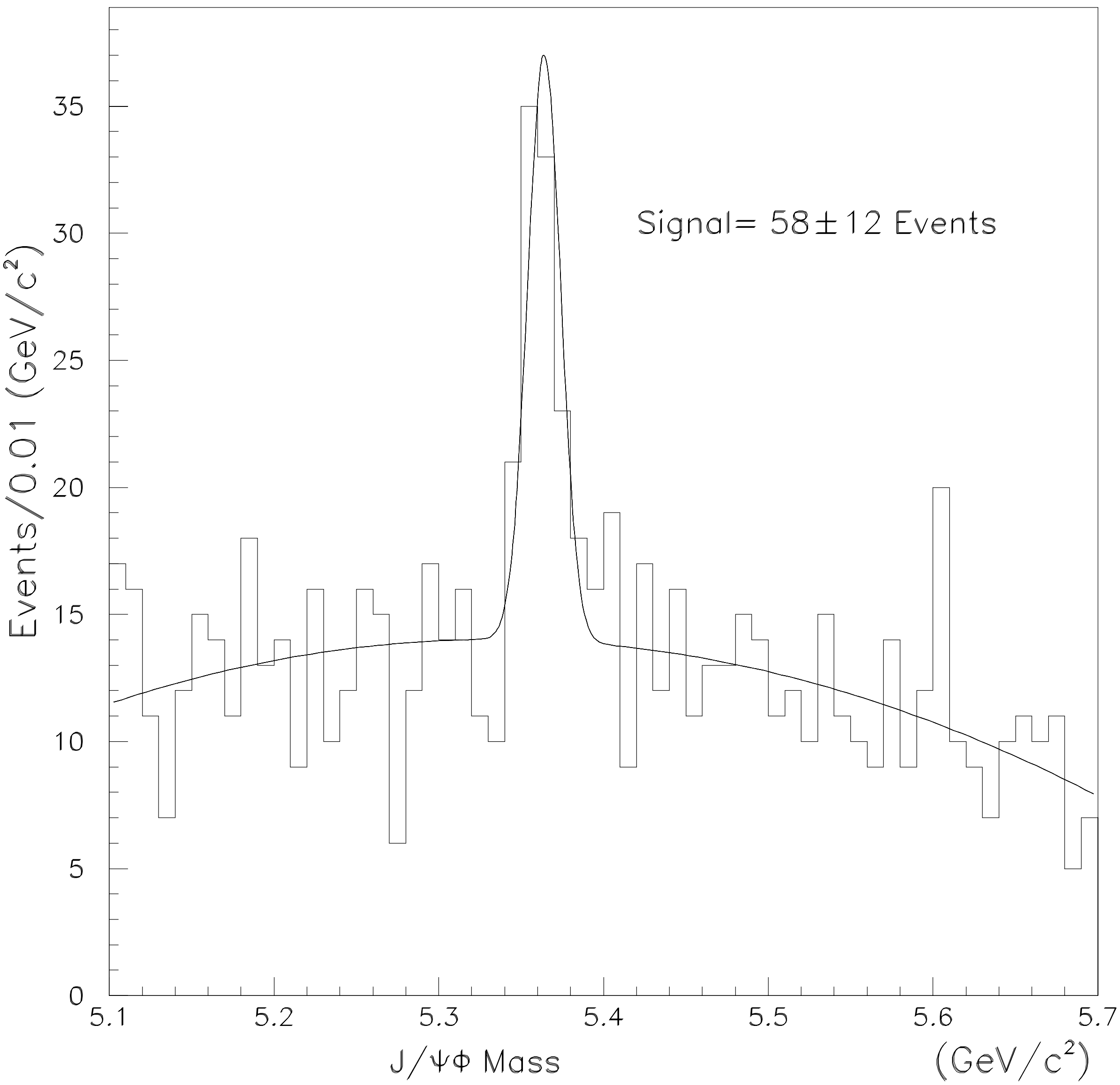

Figure 1: The invariant mass distribution of the B_s^0 candidates is shown fitted to a Gaussian and a second order polynomial.

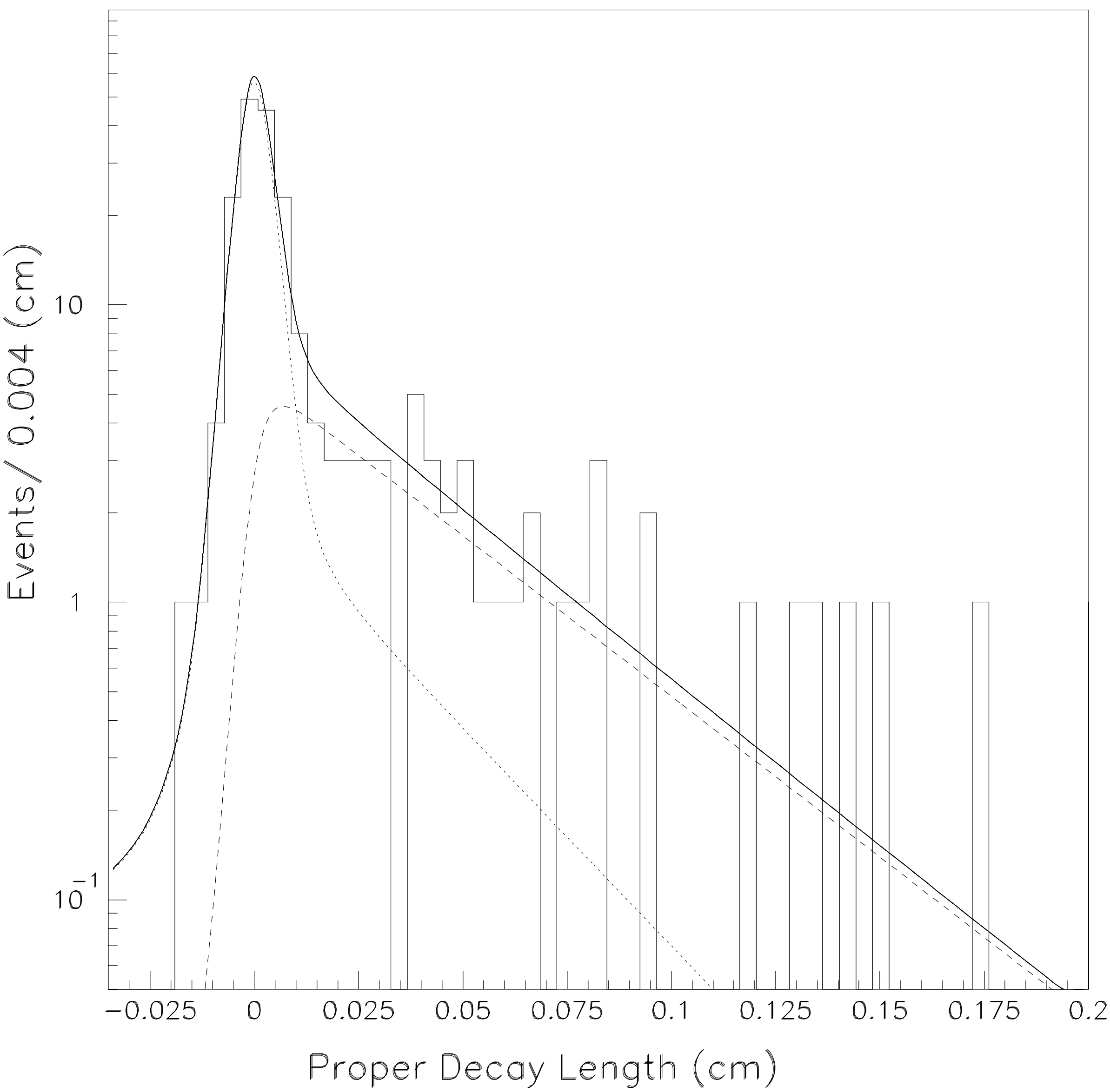

Figure 2: The proper decay length distribution of the B_s^0 is displayed for events selected within $\pm$ 0.05 GeV/c^2 of the B_s^0 fitted mass. The results of the lifetime fit are shown, signal (dashed line), background (dotted line), and the sum of the two (solid line).