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CDF

B Lifetimes at CDF

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Measurements of the average b-hadron lifetime using inclusive $B \to J/\psi X$ events, the individual B_u and B_d lifetimes and their ratio using exclusive $B \to \psi K$ events, and the B_s lifetime using semileptonic $B_s \to l\nu D_s X$ events are presented. These results were obtained from a 21.3 pb^{-1} sample of $\sqrt{s} = 1.8$ TeV $\bar{p}p$ collisions collected in 1992-93 at the Fermilab Tevatron collider and required the precise position measurements of the recently installed CDF silicon vertex detector.

1. Introduction

The Collider Detector at Fermilab (CDF) [1] was upgraded for the 1992-93 Fermilab Tevatron collider run Ia with a silicon vertex detector, the CDF SVX [2]. The SVX consists of 4 concentric layers of silicon microstrip detectors oriented parallel to the beamline. The pitch of the readout strips is 60 μm and for those strips above a preset threshold, the individual strip pulse height (and that of its two nearest neighbors) is recorded for each event. This information, combined with precise construction and track alignment, has resulted in a spatial resolution of 13 μm in the transverse plane. The first and last measurement planes are located at a radius of 3.0 and 7.9 cm from the beamline, respectively. The SVX impact parameter resolution has been measured to be ~ 20 μm for high momentum tracks ($p_T > 8$ GeV/c).

During the 1992-93 Tevatron collider run Ia, CDF collected a data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 21.3 pb^{-1}. This is a five-fold increase over the data sample from the previous run in 1988-89. The larger data sample, in combination with improvements to the data acquisition system, the muon coverage, and most importantly, the installation of a silicon vertex detector, has allowed the first measurements of inclusive and exclusive b-hadron lifetimes at a hadron collider. In this paper we report results on the average b-hadron lifetime using inclusive $B \to J/\psi X$ events, the individual B_u and B_d lifetimes and their ratio using exclusive $B \to \psi K$ events, and the B_s lifetime using semileptonic $B_s \to l\nu D_s X$ events.

2. Average b-hadron Lifetime

In the past several years, experiments at LEP have used semileptonic b decays to obtain statistically precise measurements of the average b-hadron lifetime [3]. As a result of these measurements, the theoretical models of semileptonic decays are now the dominant

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source of uncertainty in the average b-hadron lifetime. The decay $B \to J/\psi X$ provides an alternative determination of this lifetime with different systematic uncertainties. CDF has recently made the first high statistics measurement of the average b-hadron lifetime using the J/ψ decay vertex in $B \to J/\psi X$ events [4]. Implicit in the measurement of the "average b-hadron lifetime" is that the lifetimes of the B mesons and b-baryons are similar and that, when comparing results from different experiments, the various b-hadrons are produced in similar fractions.

To obtain a sample of J/ψ's for measuring the average b-hadron lifetime, the CDF trigger system required that dimuon candidates be reconstructed in the central muon chambers ($|\eta| < 0.6$) [5], that at least one of the muons have a $p_T > 2.6$ GeV/c (corresponding to a trigger efficiency of $\sim 50\%$), and that the opposite sign dimuon invariant mass fall between 2.8 and 3.4 GeV/c^2. In addition, both muons were required to be reconstructed in the SVX, resulting in 18,451 J/ψ candidates in 10.1 pb^{-1}.

After applying muon selection cuts, both muon tracks were required to have hits on at least three out of the four layers in the SVX in order to insure a well-measured vertex. None of these hits could have total charge deposition greater than four times that expected for a minimum ionizing particle and all of them had to have a residual with the fitted track less than 4 times the expected measurement error. Furthermore, the total χ^2 contribution of these residuals had to be less than 20. If any of the SVX hits matched to a muon could be assigned to another track, that muon was eliminated from the sample. Finally, the two muons were refit with a constraint that they come from a common vertex. Only those dimuon pairs consistent with originating from a common vertex were retained, resulting in a total of 5667 J/ψ candidates in a ± 50 MeV/c^2 mass window around the J/ψ mass.

For each J/ψ in the sample, the transverse decay distance (L_{xy}), which is the projection of the vector pointing from the primary to the secondary vertex onto the J/ψ transverse momentum, was calculated. The primary vertex position was approximated by the average beam position for each individual data-taking run. Typically, the beam crossing point has a circular profile and an rms of $\approx 40\mu m$. The transverse decay length was then converted into a proper lifetime (λ) using the $\beta\gamma$ of the J/ψ and a correction factor $F(p_T^{\psi})$ which accounts for the difference in the $\beta\gamma$ of the J/ψ and the b-hadron:

$$\lambda = L_{xy} \frac{M_{\psi}}{p_T^{\psi} F(p_T^{\psi})}, \qquad (1)$$

where $F(p_T^{\psi})$ depends on the b production and decay, including any kinematic requirements of the trigger, and was determined using Monte Carlo.

The λ distribution was fit using curves representing the three sources of dimuon events in the J/ψ region:

- J/ψ from b decays: This is parameterized by an exponential convoluted with a gaussian resolution function. From the fit, the fraction of J/ψ's arising from b-hadron decays (f_b) is also measured, although several of the track quality cuts favor isolated muons and systematically lower this fraction.

- Prompt charmonium production: This includes J/ψ and χ_c mesons which are directly produced in $\bar{p}p$ collisions. This source gives a zero lifetime contribution and is parameterized with a gaussian resolution function.

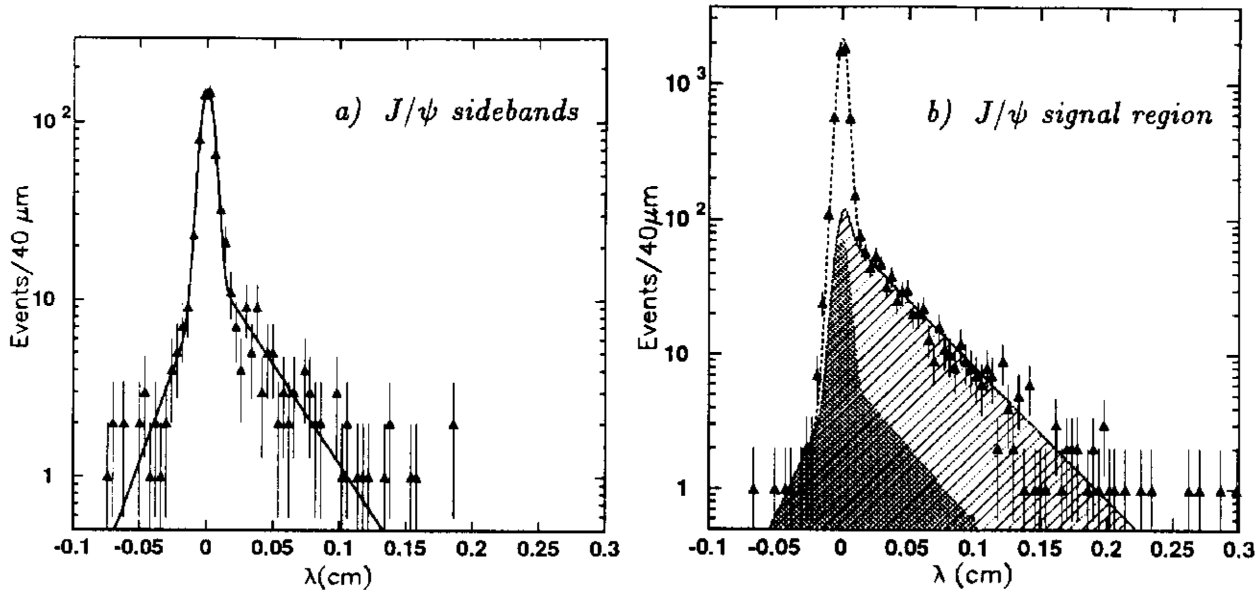

Figure 1: The λ distributions from a) the J/ψ sideband regions and b) the J/ψ signal region. The fits (curves) are described in the text.

- Background processes whose invariant mass happens to fall in the J/ψ mass window: There are many possible background sources, including Drell-Yan production, $b \to c \to s$ cascade semileptonic decays, double semileptonic b decays, meson decays in flight and residual hadron punchthrough. The shape of the lifetime for the background was measured using the J/ψ sidebands. The lifetime distribution of the sideband events was fit to the sum of a gaussian plus a positive and negative exponential, each with a different slope. Both the shape and size of the background are determined from the sidebands and are not free parameters in the fit to the signal region. Due to the presence of cascade and double semileptonic b decays, it was expected that the J/ψ sidebands would have a long-lived positive lifetime component.

Figure 1a shows the λ distribution with the fit for the J/ψ sidebands. Figure 1b shows the results of an unbinned likelihood fit to the data. The dark shaded area is the contribution from the background fit. The light shaded area shows the sum of the background plus the component due to b decays. The remaining unshaded gaussian is due to prompt decays. The fit results in an average b-hadron lifetime of $\tau_b = 1.46 \pm 0.06$ (stat) ps and $f_b = 15.1 \pm 0.6\%$ (stat).

The uncertainty in $F(p_T^{\psi})$ is the dominant source of systematic uncertainty in this measurement (3.0%). This has been estimated by varying the b quark production spectrum and fragmentation, and J/ψ momentum spectrum and polarization in the b-hadron rest frame. Other sources of systematic uncertainty are due to any residual SVX misalignment (2.0%), the uncertainty in the event-by-event calculation of the error on λ (1.6%), possible trigger biases (1.4%), beam instabilities over the course of a Tevatron store (1.0%), and the statistical uncertainty in the determination of the background shape (0.5%). The final result for the average b-hadron lifetime is:

$$\tau_b = 1.46 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})\text{ps}. \quad (2)$$

This measurement already has comparable statistical and systematic uncertainties using only one-half the available data sample and is competitive with previous measurements made at LEP (Table 1 [6]). Gradual progress can be expected towards a more precise measurement as additional data is accumulated and further work is done on reducing the systematic uncertainty.

Experiment	τ_b (ps)	τ_b ref.
Aleph	1.487 ± 0.044	Marseille-93
Delphi	1.612 ± 0.050	DN 93-84
L3	1.518 ± 0.047	Cornell-93
Opal	1.523 ± 0.051	PPE/93-92
CDF	1.460 ± 0.085	PRL 71 (1993) 3421
Average	1.526 ± 0.023	Tsukuba-93

Table 1: Average b-hadron lifetime measurements from CDF and LEP.

3. B_u and B_d Lifetimes

Measurements of the B_u and B_d lifetimes have been made at LEP and PEP using partially reconstructed decays containing a lepton and a D^0 or D^{*+} [7]. Although CDF will also make measurements using this technique, the large b cross section at the Tevatron allows a direct measurement of the charged and neutral B meson lifetimes using fully reconstructed decays involving a J/ψ [8]. The uncertainty in measuring the B^+ and B^0 lifetimes using exclusive modes requiring a J/ψ is at present statistically limited by the number of fully reconstructed B's. In order to increase the sample, some of the track quality cuts applied in the average b-hadron lifetime analysis have been relaxed. Only two SVX hits are required on each track and muons reconstructed in the new CMX chambers ($0.6 <|\eta|< 1.0$) are also included. Charged and neutral B meson are reconstructed in the following eight decay modes (including charge conjugate decays):

$$\begin{array}{lll} B^+ & \to J/\psi K^+ & \to \mu^+\mu^- K^+ \\ B^+ & \to J/\psi K^{*+} & \to \mu^+\mu^- K^0_s\pi^+ \\ B^+ & \to \psi(2S)K^+ & \to \mu^+\mu^-\pi^+\pi^- K^+ \\ B^+ & \to \psi(2S)K^{*+} & \to \mu^+\mu^-\pi^+\pi^- K^0_s\pi^+ \\ B^0 & \to \psi K^0_s & \to \mu^+\mu^- K^0_s \\ B^0 & \to \psi K^{*0} & \to \mu^+\mu^- K^+\pi^- \\ B^0 & \to \psi(2S)K^0_s & \to \mu^+\mu^-\pi^+\pi^- K^0_s \\ B^0 & \to \psi(2S)K^{*0} & \to \mu^+\mu^-\pi^+\pi^- K^+\pi^- \end{array} \quad (3)$$

K^0_S are selected by combining two tracks with impact parameters greater than 2σ, where σ is the measurement error on the impact parameter added in quadrature with the size

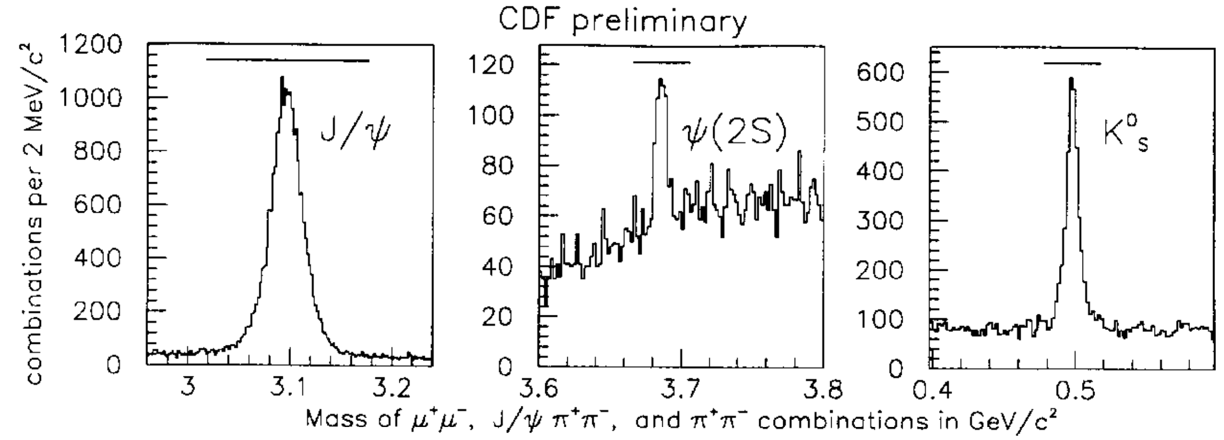

Figure 2: Mass distributions of the J/ψ, $\psi(2S)$, and K_S^0 candidates. The mass cuts are indicated by the horizontal lines above the histograms.

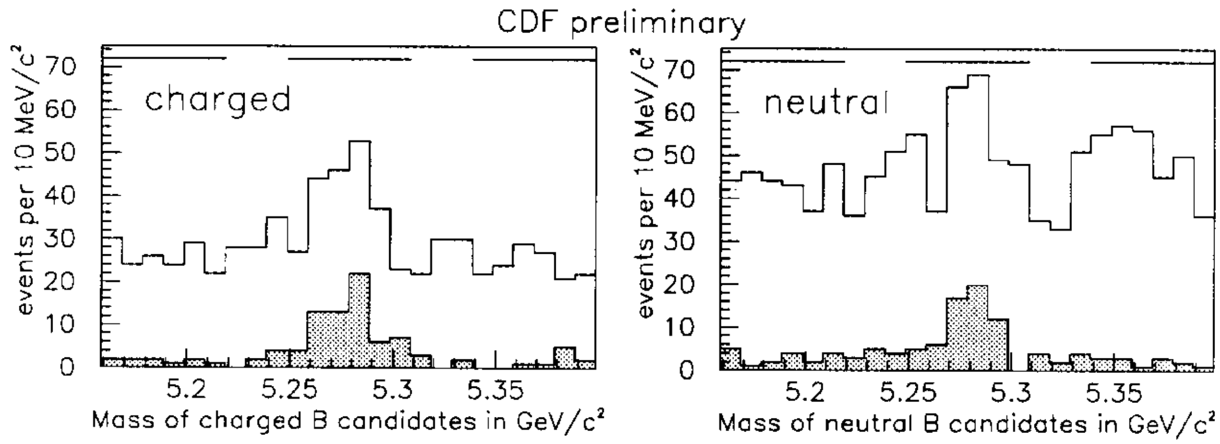

Figure 3: Mass distributions of the fully reconstructed B samples. The shaded histograms are obtained by requiring $c\tau > 100$ μm. The signal and sideband regions are indicated by the horizontal lines above the histograms.

of the beam spot. The K_S^0 itself is required to have a positive decay length and an impact parameter with respect to the J/ψ vertex of less than 2 mm. Since K_S^0's can decay outside the SVX, the tracks used to reconstruct them are not required to have hits in the SVX. The invariant mass distributions of some of the intermediate states are shown in Figure 2. The mass of the $\psi(2S)$ and K_S^0 candidates are required to be within 20 MeV/c^2, while J/ψ and K^* candidates are required to be within 80 MeV/c^2 of their respective world average values [9]. The K^+, K_S^0, or K^* candidates must have a $p_T \geq 1.25$ GeV/c in order to be combined with a J/ψ to reconstruct a B meson.

In the final B reconstruction, all the decay tracks, except those from a K_S^0, are vertex constrained, and the J/ψ and $\psi(2S)$ candidates are mass constrained to their world average values. Any B's with $p_T < 6.0$ GeV/c are rejected. In the case of multiple candidates per event, only the one with the best χ^2 from the constrained fit is kept. The mass distributions for these candidates in the ~ 11 pb^{-1} data sample are shown in Figure 3. The shaded region

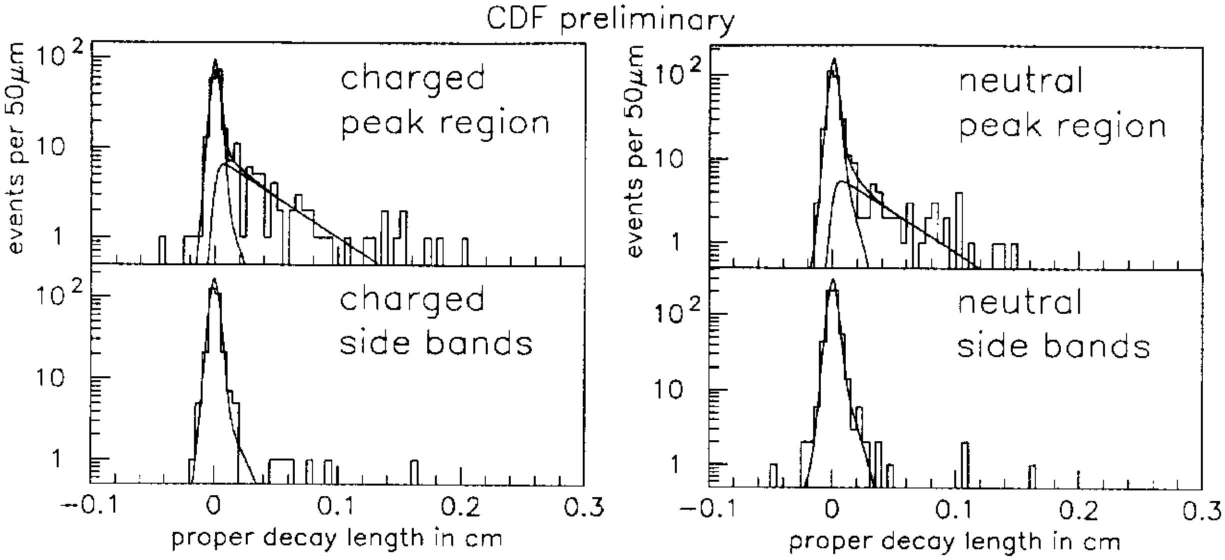

Figure 4: The proper decay length ($c\tau$) distributions of the fully reconstructed B samples. The fits (curves) are described in the text.

shows the same distribution for candidates with proper decay length $c\tau > 100\ \mu m$. There are clear B signals, with a large zero lifetime background. For the lifetime analysis, we define the signal region to be within ± 30 MeV/c^2 of the world average B mass [9]. Sideband regions are defined to be between 60 and 120 MeV/c^2 away from the world average. This region excludes the case where B's with a missing π would be reconstructed.

The proper decay length distributions for charged and neutral B's, for both the signal and sideband regions, are shown in Figure 4. The superimposed curves are the results of separate unbinned likelihood fits for the B^+ and B^0 lifetimes. As for the inclusive analysis, the signal is parameterized as an exponential convoluted with a gaussian resolution function, while the background is a gaussian plus asymmetric exponential tails. However, in this case the signal and background distributions have been fit simultaneously. The fits indicate that there are 75 ± 10 charged and 61 ± 9 neutral B mesons in the signal regions. As can be seen, there still remain a few events at large decay length in the sideband regions. The preliminary measurement of the lifetimes of the B^+ and B^0 mesons is:

$$\begin{aligned} \tau^+ &= 1.63 \pm 0.21(\text{stat}) \pm 0.16(\text{syst})\text{ps}, \\ \tau^0 &= 1.54 \pm 0.22(\text{stat}) \pm 0.10(\text{syst})\text{ps}. \end{aligned} \tag{4}$$

The systematic uncertainty is dominated by the uncertainty in the shape of the positive lifetime tails of the B^+ and B^0 sideband distributions. Assuming that the systematic errors are uncorrelated, we obtain the following charged-to-neutral B meson lifetime ratio:

$$\tau^+/\tau^0 = 1.06 \pm 0.20(\text{stat}) \pm 0.12(\text{syst}). \tag{5}$$

This is consistent with calculations of the B^+/B^0 lifetime ratio, including non-spectator diagrams, that predict τ^+/τ^0 to be equal to 1.0 within 10-20% [10]. As seen in Tables 2 and 3 [6], the precision of the charged and neutral lifetime measurements made by CDF

Experiment	τ^+ (ps)	τ^+ ref.	τ^0 (ps)	τ^0 ref.
Aleph	1.47 ± 0.27	PPE/93-42	1.52 ± 0.24	PPE/93-42
Delphi	1.81 ± 0.22	DN 93-94	1.37 ± 0.26	DN 93-94
Opal	1.66 ± 0.23	OPN-106	1.63 ± 0.18	OPN-106
CDF	1.63 ± 0.26	Marseille-93	1.54 ± 0.24	Marseille-93
Average	1.66 ± 0.12	Tsukuba-93	1.54 ± 0.11	Tsukuba-93

Table 2: Comparison of charged and neutral B meson lifetime measurements.

using fully reconstructed B mesons in the J/ψ sample is similar to that obtained at LEP using other methods. However, the accuracy of lifetime measurements using exclusive decay modes is expected to be better. Work is continuing to add the remaining data to reduce the statistical error of the CDF result and to better understand the shape of the background $c\tau$ distributions.

4. B_s Lifetime

In addition to modes involving a J/ψ, CDF has started to make B lifetime measurements involving a lepton and a reconstructed charm state. The first of these measurements involves an electron or muon with a reconstructed $D_s \to \phi\pi, \phi \to K^+K^-$ decay. Measurement of the B_s lifetime is particularly important for understanding the hierachy of B meson lifetimes and in preparation for time-dependent B_s mixing studies. Measurements of the B_s lifetime, using partially reconstructed semileptonic B_s decays, have been presented previously by several experiments at LEP [11].

The data sample used to perform the preliminary CDF B_s lifetime measurement consists of ~ 13.5 pb^{-1} of single lepton (electron or muon) events triggered with $p_T > 6$ GeV/c. A series of lepton identification cuts were applied offline to these events to obtain a clean sample of electrons and muons with a significant contribution from b-hadron semileptonic decay. For the electron sample, the identification cuts involved good matching between the electron energy measured in the calorimeter and the momentum of the track, small amount of energy leakage into the hadron compartment of the calorimeter ($< 4\%$), good matching in position between the electron track and the cluster centroid in the calorimeter strip chambers and good shower profile in the strip chambers. An algorithm which removes electrons from photon conversion was also applied. For the muon sample, the muon stubs were cleanly identified in the muon chambers and several matching requirements were made between this stub and a tracking chamber track.

The D_s^+ was identified from the decay $D_s^+ \to \phi\pi^+$, followed by $\phi \to K^+K^-$. Any oppositely charged track pair was used to form a ϕ candidate, where each kaon candidate was required to have $p_T > 0.8$ GeV/c and to be in a cone of radius $\Delta R < 0.8$ around the lepton in $\eta - \phi$ space [12]. The ϕ candidate was accepted if it had a mass within ± 8 MeV/c^2 of 1.019 GeV/c^2, and a $p_T > 2.0$ GeV/c.

The ϕ was then combined with another track, which was assigned the pion mass, to form a D_s^+ candidate. This third track (pion candidate) was required to have the opposite

Experiment	τ^+/τ^0 ratio	τ^+/τ^0 ratio ref.	τ_s (ps)	τ_s ref.
Aleph	0.96 ± 0.26	PPE/93-42	1.90 ± 0.46	Marseille-93
Delphi	1.32 ± 0.31	DN 93-94	1.29 ± 0.47	DN 93-87
Opal	1.02 ± 0.21	OPN-106	1.13 ± 0.36	PPE/93-95
CDF	1.06 ± 0.23	Marseille-93	1.54 ± 0.44	Tsukuba-93
Average	1.06 ± 0.12	Tsukuba-93	1.42 ± 0.21	Tsukuba-93

Table 3: The charged-to-neutral B meson lifetime ratio and the B_s lifetime results from CDF and LEP.

charge of the lepton and thus it had the "right sign" to come from a B_s decay. These three tracks were then vertex-constrained to come from a single point and combinations which had a vertex fit $\chi^2 > 15$ for three degrees of freedom were rejected. In addition, to reduce the combinatorial background, $| \cos\psi | > 0.4$ was required, where ψ is the angle between the K^+ and the D_s^+ directions in the ϕ rest frame. This cut removes 40% of the flat background and keeps 93% of the signal.

Additional cuts were applied separately to the electron and muon samples to reduce further the combinatoric background. The electrons have an implicit isolation cut from the trigger requirements. A similar cut was applied to the muons. The sum of the transverse energy observed in the calorimeter towers in a cone of radius 0.4 in $\eta - \phi$ space around the muon, with the muon energy deposition removed, was required to be less than 1.5 times the p_T of the reconstructed D_s^+. This cut removes background jet events which have high multiplicity near the muon and thus cause many track combinations to form near the D_s^+ mass. Finally, for the electron sample, $3.0 < M(e^-, D_s^+) < 6.0$ GeV/c^2 was required to remove combinatoric background from the low mass region. This cut was not necessary for the muon sample.

To measure the B_s lifetime, the tracks of the lepton, the pion, and at least one of the kaon candidates was required to be measured in the SVX. At least 2 hits per track were required in the SVX, the χ^2 for the track fit was required to be less than 20, no shared hits were allowed and the cluster hit size had to be less than four strips.

Finally, the decay length of the D_s^+ meson, L_{xy}, was required to be positive in order to achieve the best signal-to-noise ratio. It is important to have a high signal-to-noise for a good lifetime determination, especially when the sample statistics are low. This cut introduces only a small bias to the B_s lifetime, which will be included in the systematic error.

The $K^+K^-\pi^+$ invariant mass spectrum after all cuts is shown in Figure 5a for the combined electron and muon samples. The signal region is defined as $1.95 < M(D_s^+) < 1.98$ GeV/c^2 and the sideband as $1.99 < M(D_s^+) < 2.2$ GeV/c^2. Only the high mass sideband is used because the low mass sideband can be contaminated from the Cabibbo-suppressed $D^+ \to \phi\pi^+$ decay.

Having isolated a right sign sample of lepton-D_s^+ events, we now turn to the measurement of the B_s lifetime. In addition to the primary vertex, there are two decay vertices in semileptonic B hadron decays due to the finite charm lifetimes. The tertiary vertex (V_D), at which the charm particle decays, is determined by vertex-constraining the tracks coming

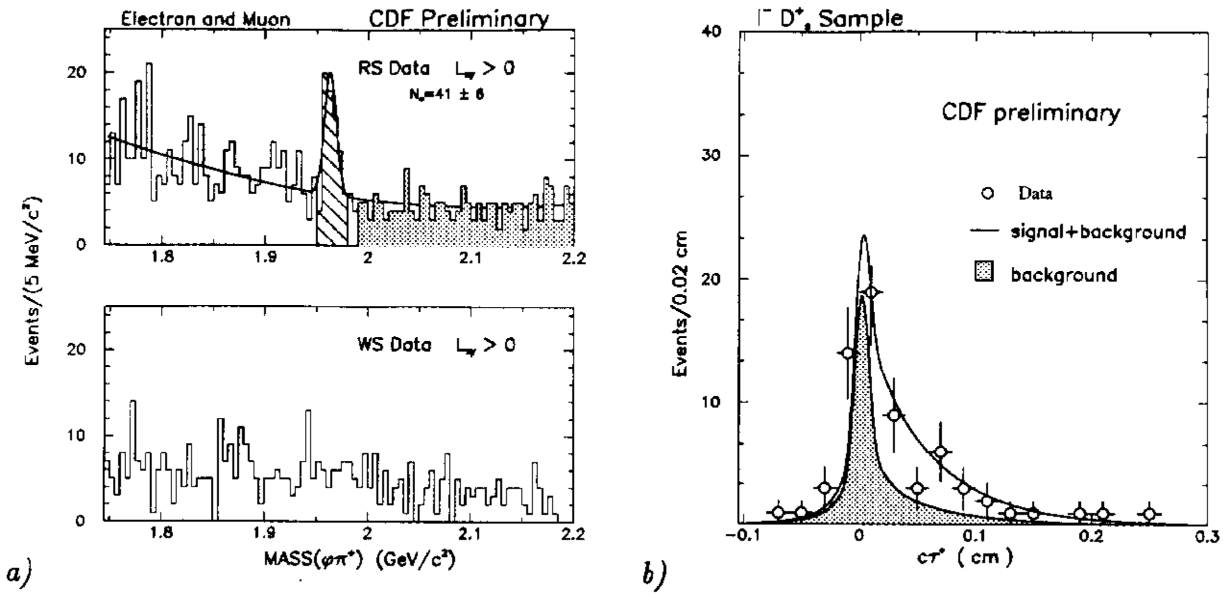

Figure 5: a) $\phi\pi^+$ mass distribution for the combined electron and muon samples, showing a $D_s^+ \to \phi\pi^+$ signal in the right sign (RS) data. The hatched (shaded) area is the signal (sideband) region for the B_s lifetime measurement. b) $c\tau^*$ distribution of the $l^- D_s^+$ signal sample with the lifetime fit.

from the D meson. This vertex is then projected back along the flight direction of the D onto the lepton trajectory to form a secondary vertex (V_B), at which point the B decay occurs. This point is determined in the transverse plane as the intersection of the two straight lines which represent the flight directions of the lepton and the D. The effect of finite lepton and D curvature over the relevent decay lengths are negligible.

As previously, the proper decay length of the B can be defined solely in the transverse plane and is given by:

$$c\tau = \frac{L_B M_B}{p_T(B)}, \tag{6}$$

where L_B is the transverse decay length of the B and p_T is the transverse momentum of the B. Similar to the inclusive B lifetime measurement, $p_T(B)$ is not completely measured in semileptonic decays due to the missing neutrino, so the transverse momentum of the charm-lepton system is used. If we introduce the correction factor K defined by:

$$K \equiv \frac{p_T(Dl^-)}{p_T(B)}, \tag{7}$$

the expression can be rewritten as:

$$c\tau = \frac{L_B M_B}{p_T(Dl^-)} K. \tag{8}$$

However, the partially corrected decay length, $c\tau^*$, is the quantity which is directly measured and we choose to use this variable to make the B_s lifetime measurement:

$$c\tau^* \equiv \frac{L_{B_s} M_{B_s}}{p_T(D_s^+ l^-)}. \tag{9}$$

The distribution of $c\tau^*$ is an exponential function, with its slope representing the lifetime, convoluted with the above momentum ratio K and the resolution function. The B_s lifetime can be determined by fitting this combined function to the observed $c\tau^*$ distribution.

The $l^- D_s^+$ signal sample contains a combinatorial background under the mass peak, as well as the real signal, and the observed $c\tau^*$ distribution is the sum of the two contributions. In order to extract a lifetime from the $c\tau^*$ distribution, we use the high sideband of the $l^- D_s^+$ mass plot and assume that the shape of its $c\tau^*$ distribution is the same as that of the background under the peak.

To determine the B_s meson lifetime, we use the maximum likelihood method and fit the observed $c\tau^*$ distributions of the $l^- D_s^+$ signal and sideband samples simultaneously. In this way we can effectively increase the statistics of the sideband sample.

Performing the lifetime fit on the $l^- D_s^+$ events (Figure 5b), we find $\tau_s = 1.54^{+0.42}_{-0.34}(\text{stat})$. There are several systematic uncertainities in this measurement. The principal ones are due to uncertainties in the resolution function, the background shape, and the momentum correction factor. Contributions from a non-B_s source like $\overline{B}_{u,d} \to D_s^+ \overline{K} l^- X$ are relatively small.

Including the systematic error, the preliminary measurement of the B_s lifetime from CDF is:

$$\tau_s = 1.54^{+0.42}_{-0.34}(\text{stat})^{+0.11}_{-0.12}(\text{syst})\text{ps}. \tag{10}$$

This is consistent with previous measurements made by the LEP experiments (Table 3 [6]). A check of the method was done using lepton-D^0 and lepton-D^{*+}, $D^{*+} \to D^0\pi^+$ events. The B meson lifetime measured in these two samples was found to be consistent with previous measurements. The analysis of the systematic errors of this result will be completed in the near future.

5. Conclusions

With the successful operation of its silicon vertex detector, CDF is now measuring the lifetimes of b-hadrons. The precision of the present measurements will benefit from using the full 21.3 pb^{-1} sample obtained in run Ia and from an additional factor of 3 in statistics expected in the upcoming collider run Ib. Additional measurements, such as the B_s lifetime from exclusive $B_s \to J/\psi\phi$ decays, the Λ_b lifetime from semileptonic and exclusive ($\Lambda_b \to J/\psi\Lambda$) decays could be possible with the run Ib data. All in all, B physics is very *lifely* for CDF!

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12. Separation in the η, ϕ plane is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where ϕ is the azimuthal angle around the beam direction.