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RECENT MEASUREMENTS OF THE B HADRON LIFETIME*

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Abstract

Recent measurements of the B hadron lifetime from PEP and PETRA experiments are presented. These measurements firmly establish that the B lifetime is long ($\sim$ 1 psec), implying that the mixing between the third generation of quarks and the lighter quarks is much weaker that the mixing between the first two generations.

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1. Introduction

In the past few years, the topic of heavy quark lifetimes has been popular. Knowledge of these lifetimes is important in order to understand the flavor-changing transitions between quarks. A scheme to describe quark mixing in the six quark model was first proposed by Kobayashi and Maskawa.[1] An important feature of this scheme is its ability to explain CP violation within the Standard Model.

The B hadrons are composed of bottom (b) quarks and lighter quarks. The spectator decay model for B hadron decay is illustrated in Figure 1. Within this model, B hadron decay is simplified to the free quark decay of a b quark to either an up or charm quark and the emission of a virtual W boson. The b quark decay rate can be calculated in analogy with muon decay where one replaces the muon mass by the b quark mass and accounts for QCD and phase space effects. This calculation is more reliable for semi-leptonic decays. The total decay rate is found from the semi-leptonic rate divided by the *measured* semi-leptonic branching ratio:

$$\frac{1}{\tau_b} \equiv \Gamma_{tot} = \frac{\Gamma(b \to xl\nu)}{\mathrm{BR}(b \to xl\nu)} , \tag{1.1}$$

where the symbol x stands for any hadronic final state. A typical calculation[2] for the semi-leptonic rate gives:

$$\Gamma(b \to xl\nu) = \left(|V_{ub}|^2 + 0.49\,|V_{cb}|^2 \right) \Gamma_0 \;\; (\mathrm{GeV}) , \tag{1.2}$$

where:

$$\Gamma_0 \equiv \frac{G_F^2\, m_b^5}{192\,\pi^3} . \tag{1.3}$$

Here G_F is the Fermi constant, m_b is the b quark mass, and $|V_{ub}|$ and $|V_{cb}|$ are the appropriate terms of the KM matrix for $(b \to u)$ and $(b \to c)$ transitions, respectively. The factor of 0.49 accounts for phase space effects.

From Eqns. 1.1 and 1.2, it is clear that measurement of the B lifetime is able to put constraints on the matrix terms $|V_{ub}|$ and $|V_{cb}|$. These constraints are weakened, however, by uncertainty in the free quark mass m_b. In principle, one would like to consider B hadron decays rather than free quark decays since it is the lifetime of hadrons that we are measuring. In this approach, it is necessary to calculate matrix elements between exclusive hadronic states and then sum the exclusive contributions to find the total decay rate. Two different models on which to base such calculations have been proposed.[3] There is certainly room for more theoretical work in this area.

This talk presents recent B lifetime results that have been reported since the 1986 Berkeley Conference.[4] Measurements from four experiments are summarized: JADE[5] and TASSO[6] at PETRA and HRS[7] and MARK II[8] at PEP. An outline of the experimental problems facing attempts to measure the B lifetime is first given, followed by methods to enrich the B purity of a hadronic event sample. The results from the different experiments are then presented; these results are summarized along with previous measurements made by the DELCO[9] and MAC[10] groups.

2. Outline of Experimental Problems

At PEP/PETRA energies, $b\bar{b}$ events constitute only $\sim 10\,\%$ of the total multihadronic event sample. A schematic view of such an event is shown in Figure 2. This figure illustrates several important experimental considerations relevant to B lifetime measurements. The B hadrons are produced at the e^+e^- collision point; they travel a short distance proportional to their lifetime (and energy) and then decay. Their decay products typically include a charm hadron which then can propagate further and subsequently decay. Approximately 25 % of the time B hadrons decay semi-leptonically. For semi-leptonic (hadronic) decays, the average charged particle multiplicity is 3.8 (6.0). These values are determined from CLEO data[11] and include the secondary charm decay products. In a given

$b\bar{b}$ event, therefore, tracks can originate from B hadron decays or from secondary charm hadron decays. In addition, particles produced after fragmentation can originate from the e^+e^- collision point. The relatively high multiplicities found in B decay plus the propensity of B hadrons to produce neutral particles have made full reconstruction of B decays at PEP/PETRA energies difficult.

As a separate consideration, one must know the B production point to determine its lifetime. This point is typically approximated by the beam centroid determined from Bhabha tracks over many events. As illustrated by the shaded ellipse in Figure 2, the beam spread is approximately 400 μm wide horizontally and 75 μm wide vertically. This spread proves to be a significant contributor to the lifetime measurement error. A method to determine the B production point with better precision on an event by event basis is outlined in Section 4.2.

The major challenges to measuring the B hadron lifetime can therefore be summarized:

1. The $b\bar{b}$ events constitute only $\sim$ 10 % of multihadronic events. How can one improve this fraction?
2. In a given $b\bar{b}$ event, what technique does one employ to estimate the B lifetime?

The four experiments reporting results at this conference use somewhat different approaches to deal with the challenges posed above. These approaches are summarized in Table 1. To date, two techniques have been used to enrich the B fraction or purity. JADE and TASSO employ the boosted sphericity method, while HRS and MARK II rely on the method of high p_t leptons. In addition, TASSO measures the B lifetime using a hadronic event sample with no B enrichment. This method retains the maximum number of $b\bar{b}$ events to determine the B lifetime; however, the lifetime measurement has significant systematic uncertainty resulting from imperfect knowledge of the B fraction and the charm lifetimes and fragmentation.

Table 1. Summary of techniques used by the different experiments.

	JADE	TASSO	HRS	MARK II
Enrichment Technique				
None		√		
Boosted sphericity	√	√		
High p_t lepton		√	√	√
Estimator Used				
Decay distance		√		
Dipole moment	√	√		
Lepton Imp. Par.		√	√	√
Track Imp. Par.		√		

As indicated in Table 1, no less than four different estimators have been used to determine the B lifetime, all which have been employed by TASSO.* The two decay length methods (namely measuring a jet decay distance or a dipole moment) rely on the fact that the average vertex of the tracks in a jet is considerably further displaced from the e^+e^- collision point in $b\bar{b}$ events than in lighter quark events. The two impact parameter methods (namely measuring the impact parameter of high p_t leptons or of all tracks) use the fact that B decays typically produce tracks with a net positive impact parameter measured relative to the e^+e^- collision point. These different estimators are discussed further in Section 4.

* For completeness, all of the different TASSO methods are listed in Table 1. Since these measurements are not statistically independent, only the result with the smallest errors is considered in detail and reported here (namely the measurement using no B enrichment and the jet decay distance). A complete description of all the TASSO measurements can be found in the talk of S.L. Wu in Ref. 6.

3. B Enrichment Methods

3.1 BOOSTED SPHERICITY PRODUCT

The method of the boosted sphericity product was originally developed by TASSO.[12] It achieves B enrichment from the fact the $b\bar{b}$ events are more spherical than *udsc* quark events. The boosted sphericity product is calculated as follows. Each event is divided into two hemispheres by a plane perpendicular to the sphericity axis. In each hemisphere, the observed particles are boosted into the rest frame of a hypothetical particle travelling with $\beta = 0.74$ along the sphericity axis. The β value is chosen from the Monte Carlo to maximize the separation of bottom from *udsc* events. After the boost, the sphericity in each hemisphere is calculated. A cut on the product of the sphericities $S_1 \times S_2$ is used to enrich the sample in $b\bar{b}$ events.

In their analyses that use the boosted sphericity method, the TASSO group employs an algorithm to remove three jet events. They then require $S_1 \times S_2 > 0.18$. With this cut, they find from the Monte Carlo a B fraction of 29 % for an efficiency per event of approximately 12 %. The JADE group does not cut on the boosted sphericity product, but instead prefer to weight their hadronic events by $S_1 \times S_2$. A comparison of $S_1 \times S_2$ for $b\bar{b}$ and *udsc* events is shown in Figure 3.

The advantage of the boosted sphericity method is that it provides some separation between $b\bar{b}$ and *udsc* events with a reasonable efficiency. The amount of separation (and therefore the B fraction) is largely Monte Carlo dependent.

3.2 HIGH p_t LEPTON ENRICHMENT

The method of B enrichment by tagging leptons at high transverse momentum was used by the first measurements of the lifetime by the MAC[13] and MARK II[14] groups. This method relies on the fact that leptons from B decay have significantly higher transverse momentum relative to the hadron direction than do leptons from charm decay or general tracks that are misidentified as leptons. Since B hadrons are not fully reconstructed, their flight direction cannot be perfectly known. The HRS and MARK II groups use the thrust axis as an estimate for this direction. Monte Carlo studies show that this estimate is accurate with an rms error of approximately 8°.

Electrons are identified in the HRS and MARK II by requiring consistency between the momentum of a track as measured in the drift chamber and the corresponding track energy measured in an electromagnetic calorimeter (Pb-scintillator for HRS and Pb-Liquid Argon for Mark II). MARK II also identifies muons in a system of hadron absorbers and proportional tubes.

The HRS group selects a sample of B enriched events by selecting electrons with momenta greater than 2 GeV/c and p_t greater than 1.1 GeV/c. From Monte Carlo studies they estimate this sample to contain $(53 \pm 7)\,\%$ $b\bar{b}$ events. The remaining events are approximately evenly distributed between $c\bar{c}$ events and events in which a hadron is misidentified as an electron.

In the MARK II work the B fraction is determined from an inclusive lepton analysis. The entire lepton (p, p_t) spectrum is fit in terms of its various contributions from bottom decays, charm decays, and background sources. From the fit, one determines the semi-leptonic charm and bottom hadron branching ratios and the average hadron energy ($<z>$ of fragmentation). Measurement of the branching ratios provides a nice consistency check with other experiments, including those at the $\Upsilon(4S)$. Knowledge of the fragmentation $<z>$ is crucial for all experimental determinations of the B lifetime. Since B hadrons are not fully reconstructed at PEP/PETRA, their energies are not known for individual events. The average B hadron energy measured in inclusive lepton analyses is needed to convert estimators such as impact parameter or decay length to lifetime. In their lepton fit, MARK II uses a sample of 2631 electrons and 1230 muons with momentum greater than 2 GeV/c. The results are presented in Table 2. The electron and muon p_t spectra are illustrated in Figures 4a and 4b, respectively.

Table 2. Results from the MARK II inclusive lepton analysis.

Quantity	Electron	Muon
$BR(c \rightarrow l)$	$9.6 \pm 0.7 \pm 1.5$ (%)	$7.8 \pm 0.9 \pm 1.2$ (%)
$BR(b \rightarrow l)$	$11.2 \pm 0.9 \pm 1.1$ (%)	$11.8 \pm 1.2 \pm 1.0$ (%)
$< z_b >$	$0.85 \pm 0.03 \pm 0.05$	$0.82 \pm 0.04 \pm 0.05$

Requiring leptons to have p_t greater than 1 GeV/c, MARK II obtains a B fraction of (65 ± 5) %, with an efficiency per event of 7.5 %. The high p_t lepton tag for B enrichment has a significantly smaller efficiency than the boosted sphericity product; however, its advantages are a higher B purity of the sample, the fact that this purity is determined from the data, and that the mean B hadron energy is measured. We will see later that the lepton impact parameter provides a convenient estimator of the B lifetime.

4. Lifetime Results

We have seen that two different techniques for B enrichment are employed for the measurements presented here. The experimental groups are similarly divided in their choice of lifetime estimator. JADE and TASSO use decay length methods and HRS and MARK II use impact parameter methods to determine the B lifetime.

4.1 Results using decay length methods

Since full reconstruction of B decays at PEP and PETRA is not employed, the lifetime cannot be determined by complete reconstruction of the B decay vertex. It is still possible, however, to get a measure of the lifetime from the position of the average vertex of the tracks in a jet. The general procedure used by JADE and TASSO is as follows. In each hemisphere of an event, one determines the "jet vertex" in the xy plane of tracks that pass quality cuts.* As illustrated in Figure 5, one can determine a decay length by using the sphericity axis as an estimate for the B direction. This length is the distance between the most probable production point and most probable decay point given the sphericity direction and the positions of the beam centroid and jet vertex.[15] The B lifetime is determined from a distribution of such lengths by means of the Monte Carlo simulation. As a variation on the single decay length technique, one can also find the most probable distance between the two jet vertices in an event, constrained to lie parallel to the sphericity axis. This distance, known as the dipole moment, provides an estimate of the B lifetime that is less sensitive to the position of the beam centroid than the single jet decay distance.

The JADE group uses a general sample of approximately 30K multihadronic events taken at $E_{cm} = 35$ and 41.7 GeV. In a given event, the jet vertex in each hemisphere with more than three quality tracks is found. For events having two good vertices, the dipole moment is determined; 15,386 such events remain. By means of Monte Carlo weighting techniques, the dipole moment distribution is separated into a B sample (i.e. one that would be produced if only $b\bar{b}$ events were used) and a non-B ($udsc$) sample. The boosted sphericity product $S_1 \times S_2$ is used as the discriminating quantity in this procedure. The distribution of dipole moments for the B weighted sample is shown in Figure 6. JADE uses a trimmed mean procedure to determine the B lifetime. Monte Carlo events generated at different lifetime values are used to calibrate the dependence of the dipole moment trimmed mean on lifetime. The distribution in Figure 6 has a trimmed mean of 1.01 ± 0.08 mm for a trim value of 0.04. Using this mean, JADE

* The vertex is found in the xy plane only because the detectors have significantly better resolution in this plane than in the z direction. This situation is similarly true for impact parameter measurements.

determines a B lifetime value of:*

$$\tau_b \;=\; 1.46 \pm 0.19 \pm 0.30 \text{ psec} \qquad (\text{JADE})^{\dagger} \; . \tag{4.1}$$

The systematic error comes largely from uncertainty in the charm and bottom fragmentation and from the method of lifetime determination (e.g. cuts made on the tracks and vertices, resolution uncertainties etc.).

In their lifetime measurement, TASSO uses a general sample of 32K multihadronic events taken at $E_{cm} = 35$ GeV; no B enrichment techniques are employed. The good tracks in each event are divided into two jets. The vertex fit is made of all three-track combinations in each jet whose charge sum is ± 1. The combination resulting in the lowest χ^2 of the vertex fit is used, if the probability of the χ^2 is at least 1%. After these cuts, 17,306 jet vertices remain. For each vertex, a decay distance is calculated, as illustrated in Figure 5. A number of cuts are imposed to reject vertices with poorly measured flight directions (e.g. a cut on the decay distance at 1 cm and on its error at 1 mm). After these cuts, a sample of 15,364 decay distances remain. The distribution of these distances, shown in Figure 7, has a mean of $83.7 \pm 5.1\,\mu$m. The most likely B lifetime is determined by a binned χ^2 comparison between the decay distance distribution of Figure 7 with similar ones generated at different lifetimes in the Monte Carlo. This lifetime is found to be:

$$\tau_b \;=\; 1.39 \pm 0.10 \pm 0.25 \text{ psec} \qquad (\text{TASSO})^{\dagger} \; . \tag{4.2}$$

The sources and magnitudes of the various contributions to the systematic error are given in Table 3. The largest contribution is seen to come from uncertainties in the B fraction and fragmentation.

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* In this value and in subsequent ones, the first error is statistical and the second one is systematic.

† Preliminary

Table 3. Systematic errors for the TASSO lifetime measurement (preliminary).

Quantity	Error on Lifetime
Beam spot size and position	± 0.05 psec
Resolution effects	± 0.09 psec
Fitting procedure	± 0.03 psec
Event cuts	± 0.05 psec
Charm fragmentation, lifetimes, D^0/D^+ ratio	± 0.09 psec
B fragmentation	$^{+0.10}_{-0.11}$ psec
B fraction	± 0.17 psec
Total	± 0.25 psec

4.2 Results using impact parameter methods

We have previously seen that B enrichment at the 60 % level can be obtained with moderate efficiency by tagging high p_t leptons. These leptons can be used to estimate the B lifetime by the calculation of a signed impact parameter. The impact parameter is measured in the xy plane with respect to the presumed B production point (*à priori* taken to be the beam centroid). The thrust axis of the event serves to estimate the B flight direction and to determine the sign of the impact parameter. The impact parameter is given a positive sign if the intersection point of the lepton trajectory and the assumed B trajectory corresponds to a positive decay length and a negative sign otherwise. The lifetime is determined from the lepton impact parameter distribution with the aid of the Monte Carlo.

The requirement of a high p_t lepton reduces the statistical power of the impact parameter method relative to decay length techniques. Nevertheless, the impact parameter method does have a number of advantages in terms of smaller systematic errors. Because of scaling, the impact parameter is less sensitive to the mean B hadron energy than the decay length. The lepton impact parameter technique is also less dependent on the charm fragmentation and lifetime values and on general properties of events that determine the B fraction (e.g. multiplicities).

The HRS group uses 200 pb^{-1} of data collected at $E_{cm} = 29$ GeV at PEP. From this data, they obtain a sample of 312 high p_t electrons with a B purity of $53 \pm 7\,\%$. The electron impact parameter distribution measured relative to the beam position is shown in Figure 8; it has a mean of $80 \pm 27\,\mu$m. The impact parameter distribution is fit by means of maximum likelihood techniques. In this fit, a parameter is used to allow the width of the Gaussian describing the experimental resolution to be scaled. The result of the fit is:

$$\tau_b \;=\; 1.02\,^{+0.42}_{-0.39}\ \text{psec} \qquad \text{(HRS)}\ . \tag{4.3}$$

The error in this measurement represents the combined statistical and systematic errors. The dominant systematic errors come from B fraction and fragmentation uncertainty.

The MARK II group uses 204 pb^{-1} of data taken at $E_{cm} = 29$ GeV. They isolate a sample of 386 electron and 231 muons at high p_t with a B purity of $65 \pm 5\,\%$. In each event, a vertex method is used to determine the B production point. This method is illustrated in Figure 9. The event is divided into two jets on the basis of a plane perpendicular to the thrust axis. A vertex is made of the quality tracks in each jet. Using this vertex, the thrust direction, and the beam position as inputs to the decay length method, an estimate is made of the B production point. In this procedure, the effects of uncertainty in the thrust direction are taken into account. The lepton impact parameter is subsequently measured relative to the estimated production point. Through a variety of checks in the data and the Monte Carlo, it can be shown that this procedure produces an unbiased estimate of the B production point. A factor of two gain in impact parameter precision is obtained by using the estimated production point over the beam centroid. This gain results from the reduction in the error due to the horizontal beam size.

The MARK II group has done a systematic study of their detector resolution. The resolution function has been determined from the impact parameter/error distribution for tracks in hadronic events. The tracks selected are those having a small fraction of their transverse momentum in the xy plane, thereby reducing the effects of lifetime. The resolution function determined in this manner is used in the fit to the lepton impact parameters.

The impact parameter distribution for the 617 leptons in the MARK II sample is shown in Figure 10; it has a mean of $114.1 \pm 12.5\,\mu$m. A maximum likelihood fit to this distribution yields:

$$\tau_b \;=\; 0.98 \pm 0.12 \pm 0.13 \text{ psec} \qquad \text{(MARK II)} \ . \tag{4.4}$$

A summary of the relevant systematic errors for the MARK II lifetime measurement is given in Table 4. The MARK II analysis uses a value of fragmentation $< z >$ determined from their inclusive lepton analysis. The overall systematic error is largely determined by uncertainties in resolution, fragmentation, and the B fraction.

Table 4. Systematic errors for the MARK II lifetime measurement.

Quantity	Error on Lifetime
Resolution uncertainty	± 0.07 psec
Lepton (B) fractions	± 0.08 psec
B fragmentation, $< z > = 0.83 \pm 0.07$	± 0.05 psec
Other	± 0.04 psec
Total	± 0.13 psec

4.3 SUMMARY OF LIFETIME RESULTS

The lifetime results presented in this talk are summarized in Figure 11, along with previously reported measurements from DELCO and MAC. In this figure, the statistical and systematic errors for each measurement have been combined in quadrature. The lifetime measurements cluster in the 1 to 1.5 psec range and are in good agreement with one another. A weighted average of the measurements shown in Figure 11 is 1.18 ± 0.14 psec.[6] Using this average and Eqn. 1.2, one can place limits on the Kobayashi-Maskawa matrix terms describing B decay. These constraints are illustrated in Figure 12. They reflect uncertainty in the measured B semi-leptonic branching ratio (here taken to be $12.1 \pm 0.8\,\%$); however, theoretical uncertainties in the calculation of Eqn. 1.2 are not considered.

Also indicated in Figure 12 are the constraints imposed by the ratio:

$$R = \frac{|V_{ub}|}{|V_{cb}|} = 0.07 - 0.23 \ . \qquad (4.5)$$

The lower bound on this ratio comes from a preliminary ARGUS measurement of $(b \to u)$ transitions, while the upper bound comes from a CLEO study of the endpoint spectrum for leptons from B decay.[16] Together the constraints limit the value of V_{cb} to lie in the neighborhood of 0.05. That this number is significantly smaller than the Cabibbo angle indicates that the coupling between the third generation of quarks and the lighter quarks is much weaker than that between the first and second generations.

5. Conclusions

In this talk, four new measurements of the B hadron lifetime from experiments at PEP and PETRA are presented. These measurements employ two different B enrichment techniques and estimate the lifetime by decay length and impact parameter techniques. The average lifetime from all experiments is 1.18 ± 0.14 psec. With this value, considerable constraints are imposed on the terms of the KM matrix describing B decay. At this point, we have probably reached the limit of possible accuracy obtainable by the methods presented here. New goals in B physics include the measurement of the charged and neutral lifetimes and the reconstruction of exclusive decays at SLC/LEP energies.

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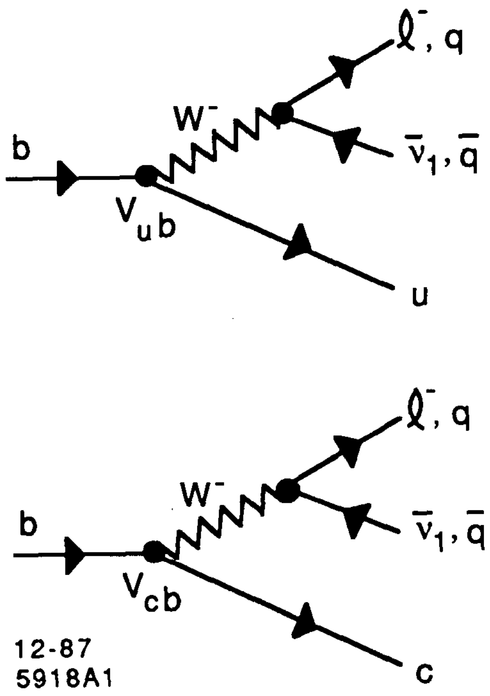

Figure 1: B hadron decay in the spectator model. The figure illustrates the relevant terms of the KM matrix for each amplitude.

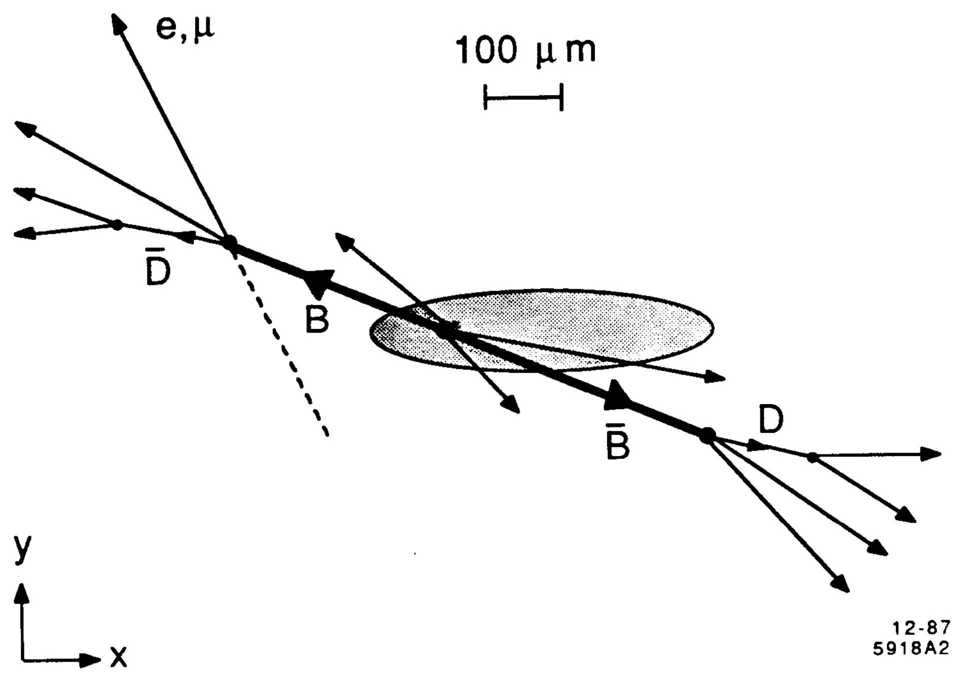

Figure 2: Schematic view of a $b\bar{b}$ event at PEP/PETRA. The shaded ellipse represents the e^+e^- collision region. Semi-leptonic and hadronic decays are illustrated.

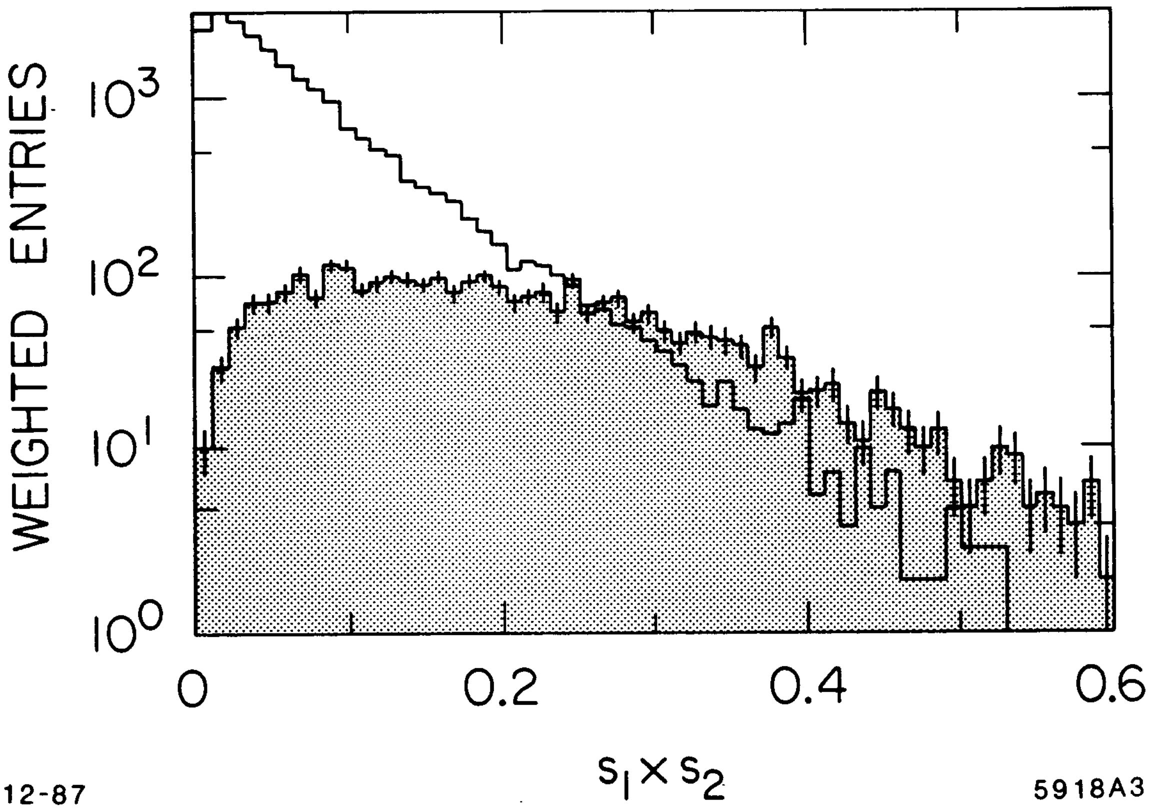

Figure 3: Comparison of the boosted sphericity product, $S_1 \times S_2$, for $b\bar{b}$ events (dotted) and *udsc* events (clear). This figure is determined from Monte Carlo studies (JADE).

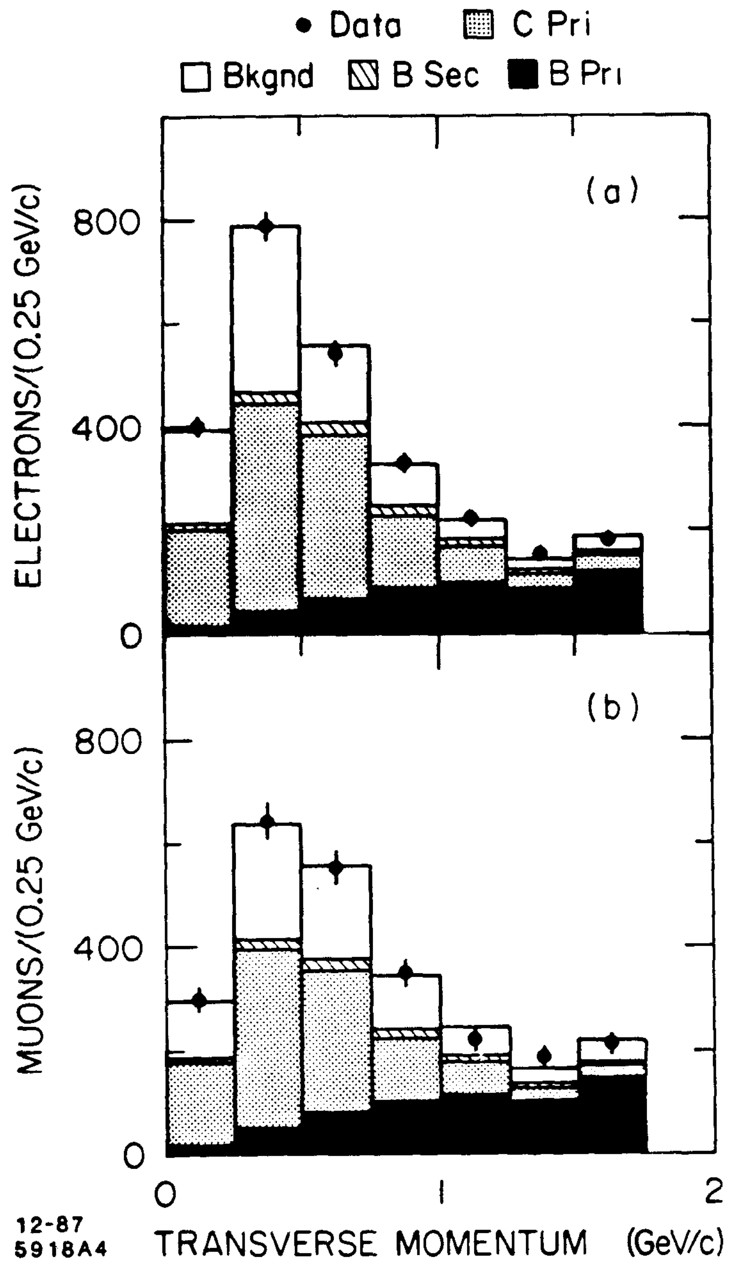

Figure 4: Results from the MARK II inclusive lepton analysis. Transverse momentum spectra for (a) electrons and (b) muons. The data is represented by points with error bars; the various components of the fit are represented by bargraphs.

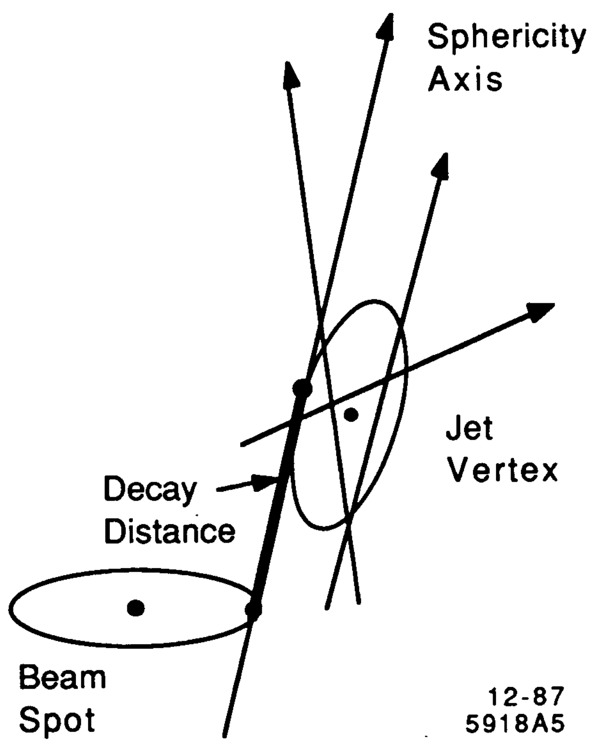

Figure 5: Schematic diagram of decay distance calculation. The decay distance is the line segment parallel to the sphericity axis whose one endpoint is consistent with the beam position (given the beam errors) and whose other endpoint is consistent with the jet vertex (given the vertex errors).

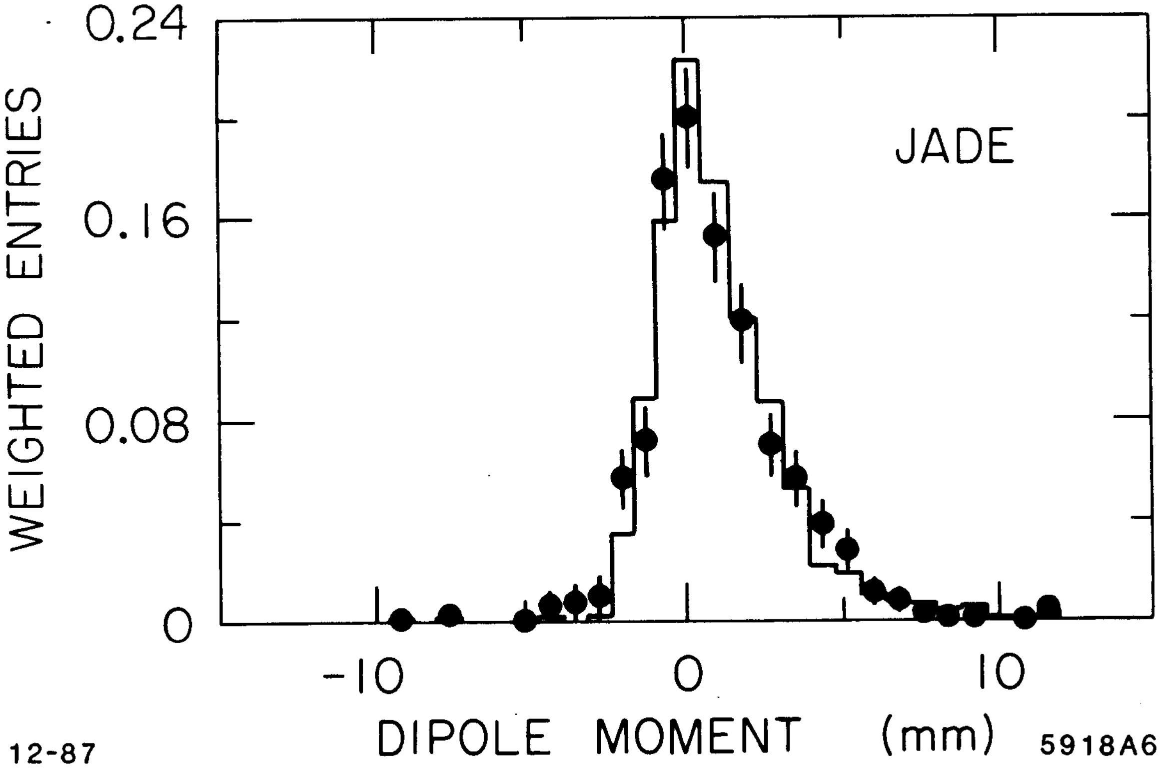

Figure 6: JADE results (preliminary). Distribution of dipole moments for the B weighted sample. The histogram corresponds to the Monte Carlo prediction for a lifetime of 1.5 psec.

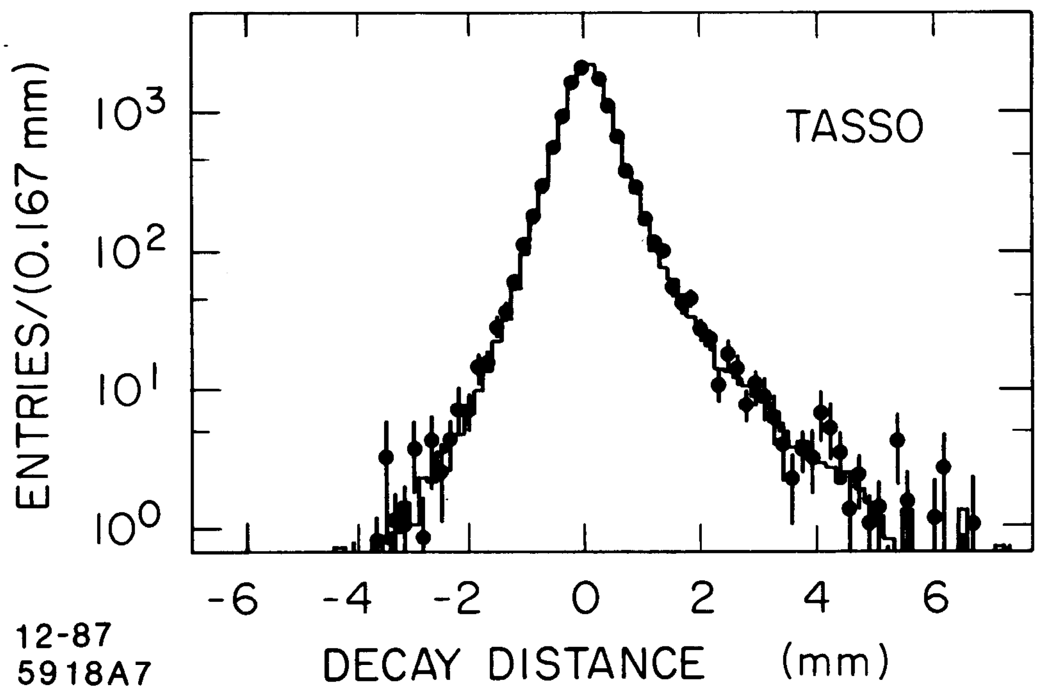

Figure 7: TASSO results (preliminary). Decay distance distribution for a sample of general multihadronic events. The histogram corresponds to the Monte Carlo prediction for the measured lifetime.

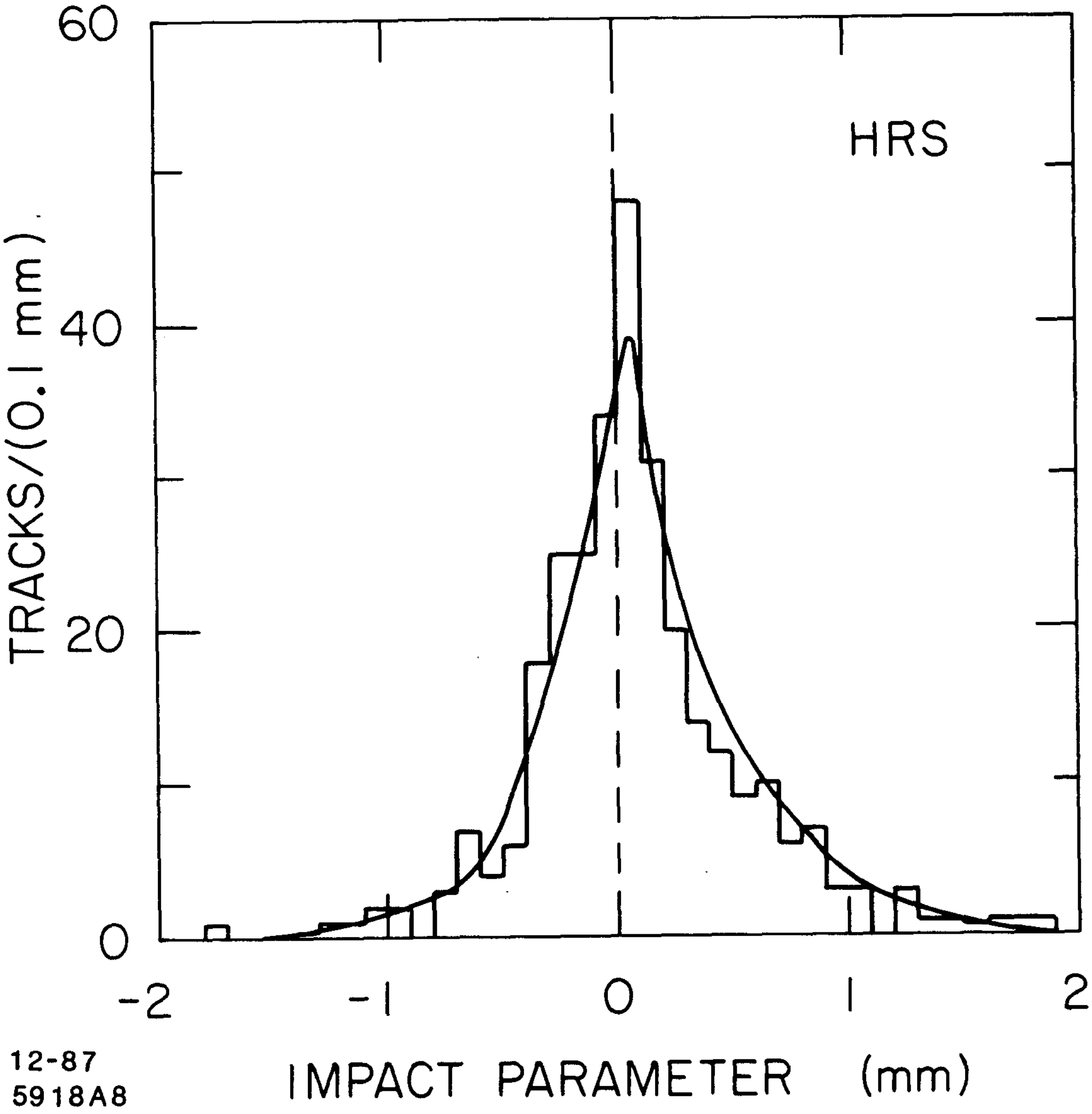

Figure 8: HRS results. Impact parameter distribution for a sample of high p_t electrons. The curve corresponds to the maximum likelihood fit for the measured lifetime.

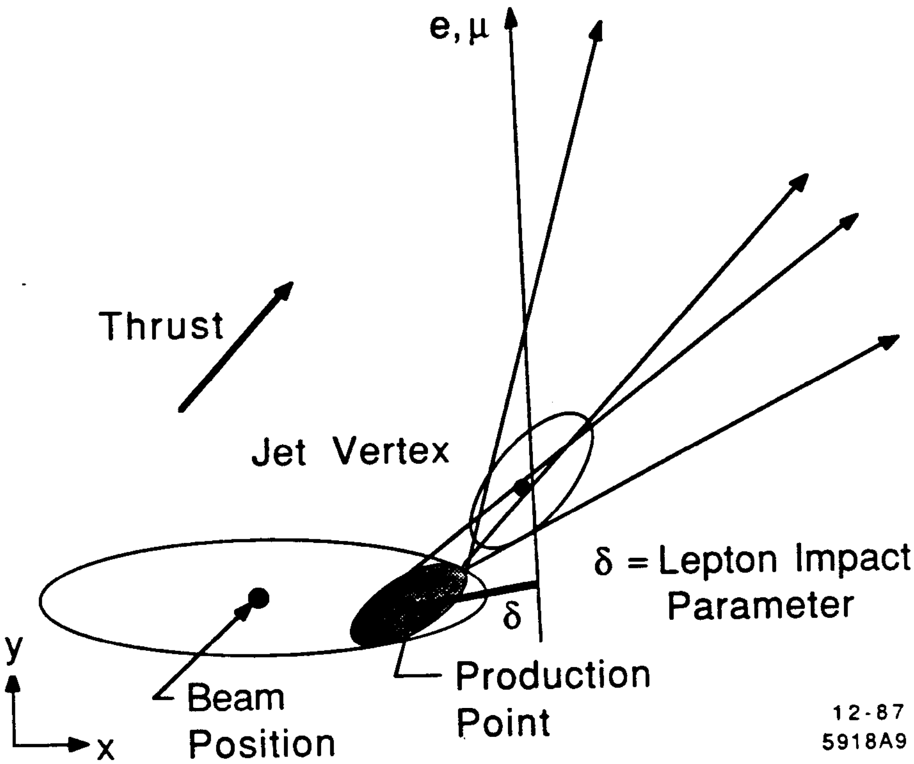

Figure 9: Vertex method to estimate the B production point (MARK II). The measured impact parameter is indicated by the symbol δ.

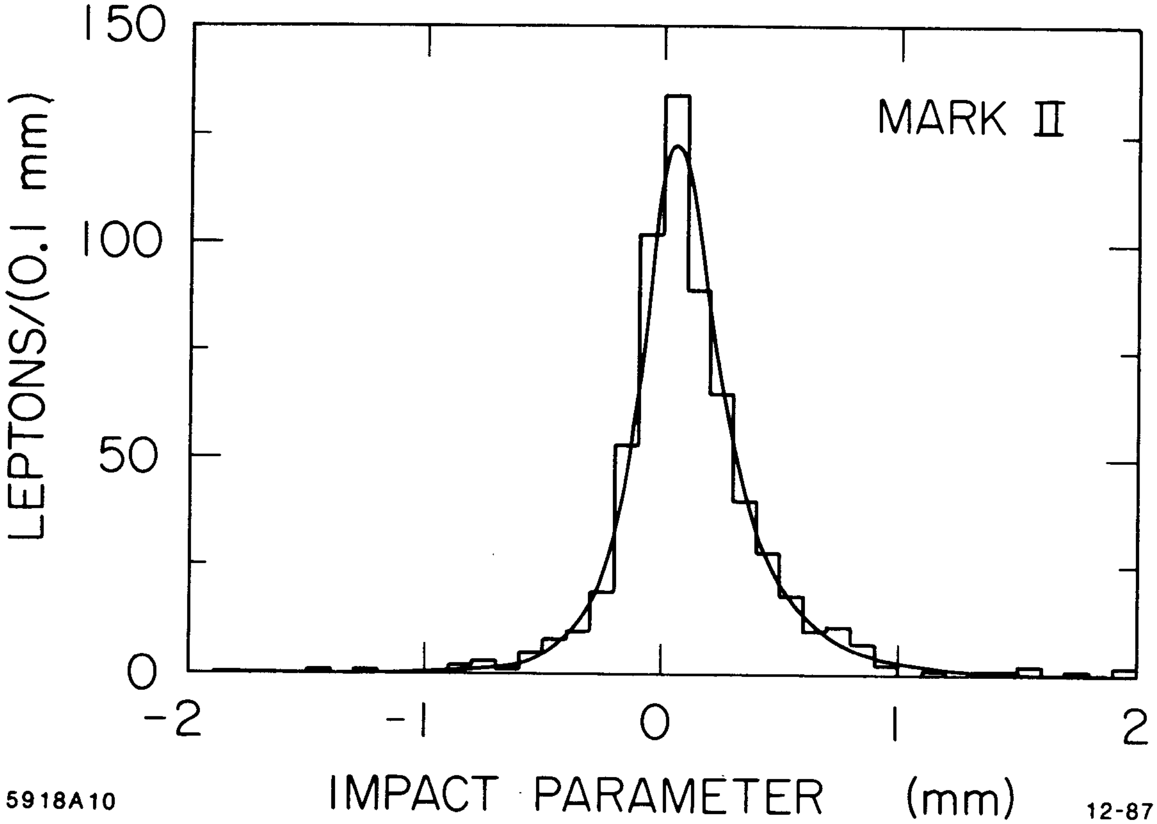

Figure 10: MARK II results. Impact parameter distribution for a sample of high p_t leptons. The curve corresponds to the maximum likelihood fit for the measured lifetime.

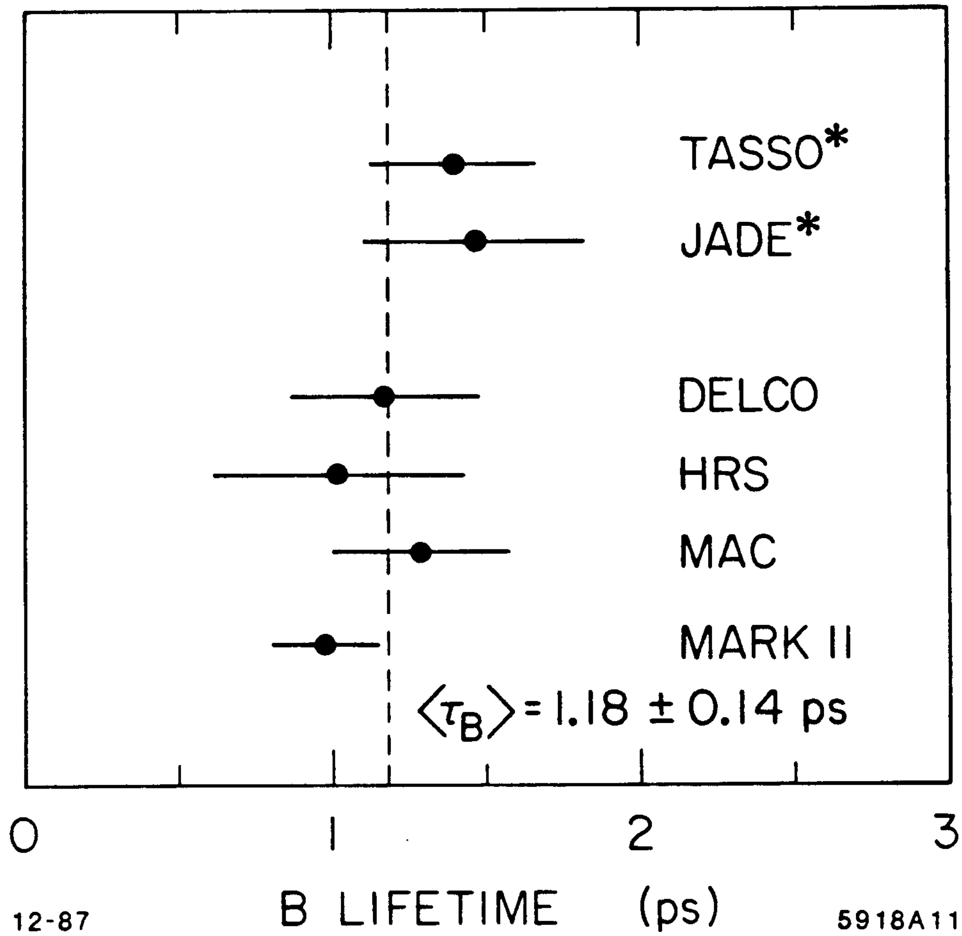

Figure 11: Summary of B lifetime results. The average lifetime is determined in Ref. 6.

* Preliminary

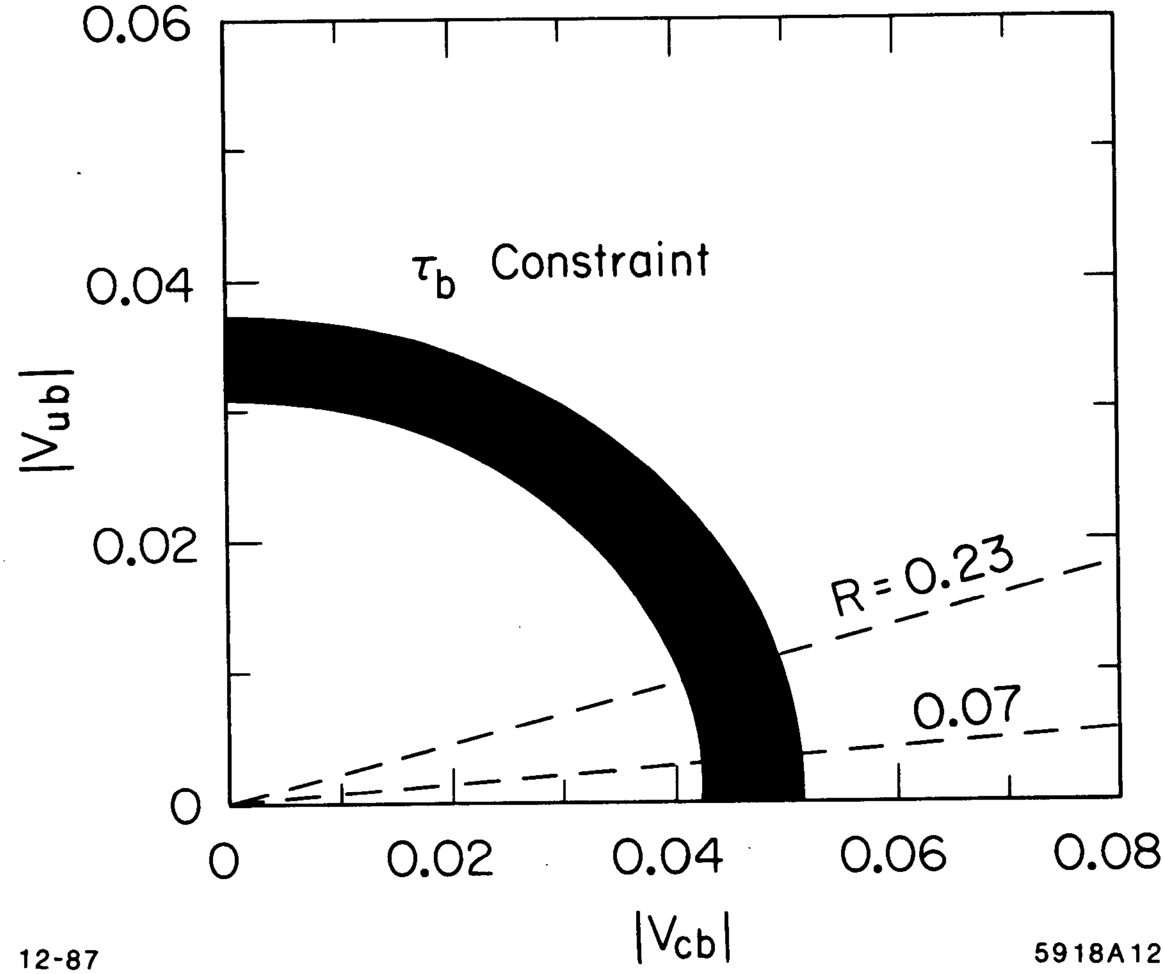

Figure 12: Constraints on the KM matrix elements for B decay. The dark band corresponds to the constraint imposed by the B lifetime measurements. The dotted lines reflect the constraints imposed by the ratio $R \equiv |V_{ub}/V_{cb}|$.