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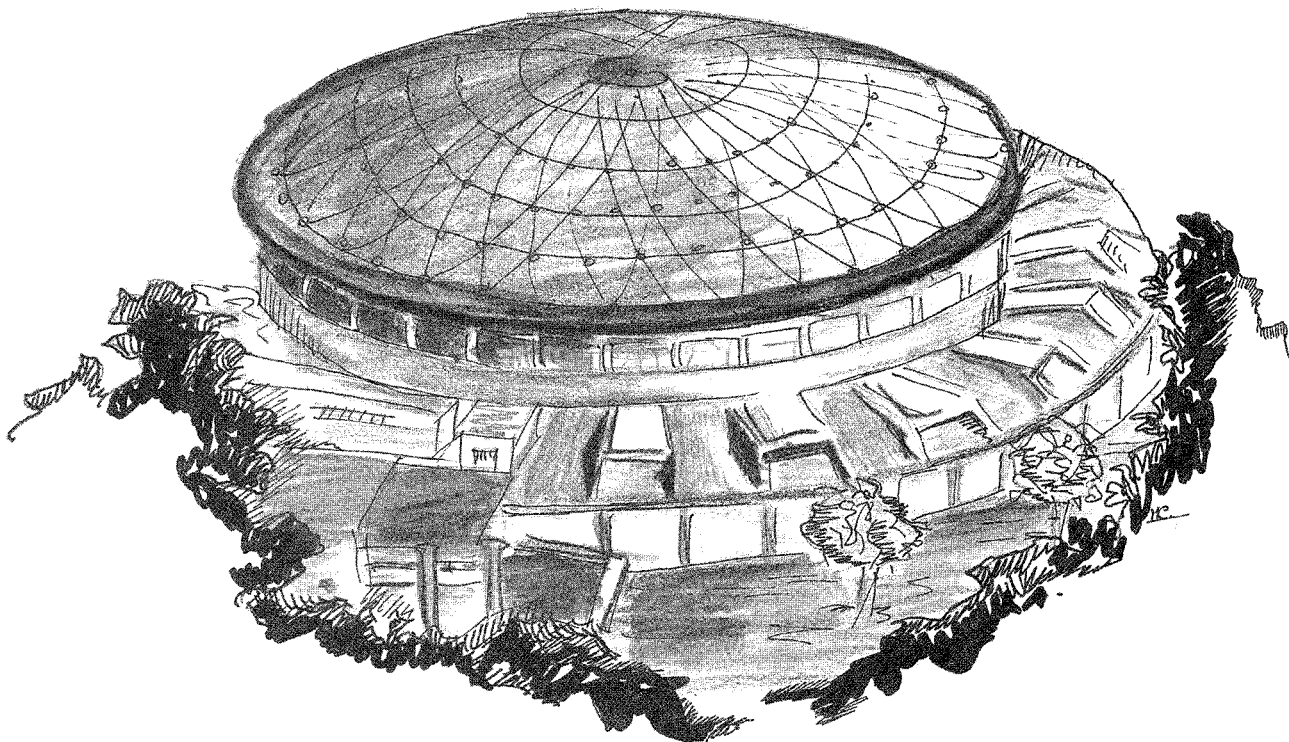
M. Piccolo:

B MESON LIFETIME MEASUREMENT

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B MESON LIFETIME MEASUREMENT

M. Piccolo
INFN - Laboratori Nazionali di Frascati, P.O. Box 13, 00044 Frascati - Italy

1. Introduction

The lifetime of hadrons containing b-quark has been the subject of extensive experimental work and theoretical speculation; its importance is due to implications on some of the fundamental parameters of the Standard Model, such as the top quark mass and the mixing angles.

Since the pioneer measurements of the MAC and MARK II collaborations at PEP in 1983[1] [2] the progress has been impressive; but many issues still remain open and await further study.

In this paper we will discuss the field's present status; we will start with an overview of the theoretical motivations for this measurement in the Standard Model framework; we will then review the experimental techniques used, emphasizing the most recent measurements. The following section will be devoted to the results comparison and to the systematic errors discussion; we will conclude with some remarks on the further developments foreseen in the near future.

2. The theoretical implications

In the framework of the Standard Model, the b quark plays a very important role: the study of the B mesons properties can enable us to obtain the values for three out of the four free parameters of the Cabibbo-Kobayashi-Maskawa[3] matrix, which alone determines the structure of the weak charged currents. Two of the three mixing angles are infact linked to the decay properties of the b hadron; the phase which appears in the imaginary part of the matrix elements, and is thought to be responsible for the CP violation, is presently constrained only by K mesons data, but is at least just as sensitive to B physics phenomena.

A brief reminder : the weak charged current quark transitions

$$q_i \longrightarrow q_j \; W$$

proceed with a width proportional to $|V_{ij}|^2$, where V_{ij} is an element of the CKM matrix:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Several parametrizations have been suggested for this matrix, a particularly convenient one by Maiani[4] :

$$\begin{pmatrix} cos\beta cos\theta & cos\beta sin\theta & sin\beta \\ -sin\gamma cos\theta sin\beta e^{i\delta} - sin\theta cos\gamma & cos\gamma cos\theta - sin\gamma sin\beta sin\theta e^{i\delta} & sin\gamma cos\beta e^{i\delta} \\ -sin\beta cos\gamma cos\theta + sin\gamma sin\theta e^{-i\delta} & -cos\gamma sin\beta sin\theta - sin\gamma cos\theta e^{-i\delta} & cos\gamma cos\beta \end{pmatrix}$$

where, in first approximation, θ is the well known Cabibbo angle, γ and β are the equivalent *mixing* angles between the second and the third, the first and the third generations, respectively.

The b quark lifetime, ignoring phase space factors and in the crude approximation where the B semielectronic branching ratio is 1/9, is given by:

$$\frac{1}{\tau_b} = 9(\frac{m_b}{m_\mu})^5 \; \frac{1}{\tau_\mu} \; (|V_{cb}|^2 + |V_{ub}|^2) =$$

$$= 9 \; \frac{G_F^2 m_b^5}{192\pi^3} \; (|V_{cb}|^2 + |V_{ub}|^2) = 9 \times 10^{14} \; (\frac{m_b}{4.9 GeV})^5 \; (|V_{cb}|^2 + |V_{ub}|^2) sec^{-1}$$

and is a measurement of $|V_{bc}|$, since $|V_{bu}|$ is much smaller, as known from the fact that the B mesons decay almost entirely into charmed particles.

In the *naive* spectator model, the B hadron lifetime is the same as the free b quark's, since the light quark doesn't play a significant role in the decay mechanism: all B particles are therefore expected to have the same lifetime. This is of course an oversimplified picture and even if the *spectator* approximation is a valid one, the fact that we must deal with particles, not free quarks, both in the initial and in the final state, must be considered.

Due to the complications deriving from the hadronization, the study of the B-mesons lifetime, which is a measure of the global strength of the decay, is an important probe not only for the weak charged currents, but also for QCD effects. As we consider the various phenomena which may contribute to the real particles total widths, the picture gets increasingly complicated. A partial list of effects to be considered, includes:

a) Mass effects [5] : mostly of a purely kinematics nature, but still important, especially for the B decays into heavy lepton τ and charmed particles.

b) Radiative QCD corrections [6] .

c) Short distance [7] [8] gluon emission, which leaves the semileptonic widths unchanged, while enhancing the hadronic channels.

More effects could lead to deviations from the *naive* picture: additional non spectator diagrams may contribute to the B_d 's and B_u 's width ; interference effects, when the final state can be reached through different paths, could reduce the partial width into a given channel. These and other contributions could in principle be disentangled, provided that separate branching ratios and lifetimes for the various B mesons species can be measured.

Overall, the spectator model should be a better approximation for the B

system than for the D, since the b quark is much heavier than the charm, and the lifetime measurement can be quite reliably translated into determinations of the quantity $|V_{bc}|^2 + |V_{bu}|^2$. The branching ratios measurements would constrain the $|V_{bu}|/|V_{bc}|$ ratio; this is crucial, since the CP violation phenomena can only be explained as a by-product of the quarks mixing in the charged current interaction, if $|V_{bu}|$ is not zero, but we don't yet have any hard evidence to sustain this.

3. The b-lifetime measurement in e^+e^-

All of the experimental data now available on the B lifetime come from e^+e^- annihilation experiments, except one beautiful event with two B decay vertices observed by WA75 at the CERN SPS[9] . The situation is likely to change in the next few years as more fixed target experiments are about to start taking data, with sophisticated solid state vertex detectors.

The b flavored particles *average* lifetime has been measured by several PEP and PETRA experiments ; the first non-zero results were announced in 1983 by MAC and MARK II at PEP and came as a big surprise, since a much shorter value was expected, on the basis that the mixing angle γ was roughly the same as the Cabibbo angle. If in the expression for the b lifetime we enter the value $|V_{bc}| \approx sin\gamma \approx sin\theta_c = 0.22$, we get a value for τ_b of the order of $10^{-14} sec$.

MAC and MARK II quoted values over 1 *psec* for τ_b , thus fixing $sin\gamma$ at a much lower value than $sin\theta_c$, and establishing that the third generation *mixing* with the second is not as strong as the second to the first. This explains why the Cabibbo theory worked so well in describing the weak interactions between the first and second generation particles, and a third generation was not required to explain the data available at the time of the Υ 's discovery. For this reason, the extension to a 3 x 3 matrix introduced by Kobayashi and Maskawa in 1973 went largely ignored until the discovery of the Υ particles.

Even if the B lifetime is *long* for a weak decay, it's still short enough to make the experimental determination difficult for present e^+e^- experiments. Measurements have been performed at PEP and PETRA where B particles travel an average length of 700 to 1000 μm before decaying; no exclusive decay mode has

been reconstructed yet at these energies, because of the high background level (b production accounts for only 1/11 of hadronic events), the high decay multiplicity and the low detector acceptance.

B mesons have been completely *reconstructed* up to now only at threshold, at the $\Upsilon(4S)$ mass, where the production mechanism is two-body and the signal to background ratio is much more favorable ; on the other hand, these events are not useful for lifetime measurements since the B's are produced almost at rest.

In order to produce B mesons with a decay path long enough to be measured, the experiment must be performed at a higher energy, in the so called *continuum* region; since B 's cannot be reconstructed, their momentum and velocity can't be determined; this has forced the development of new, unconventional, experimental techniques for measuring the lifetime.

The methods used are based on the following approach: first a sample of *b enriched* events is selected, with a background contamination determined by Montecarlo simulations; then an estimator of the decay length is found, to a good extent independent from the details of B production for the selected events. The lifetime extracted in this way , is clearly an average quantity which refers to the various species of b particles present in the sample, each one entering in the average with a weight proportional to the production cross-section.

The most widely used technique to obtain a *b enriched* sample consists in selecting multihadronic events containing a lepton with high transverse momentum respect to the thrust axis. About 25 % of the B's decay semileptonically producing leptons with a harder transverse momentum distribution than any competing process; by requiring the presence of a lepton with $p_\perp > 1 \ GeV/c$ the b-events percentage in the hadronic sample increases from 9 % to as much as 60 - 70 % , while $\approx 10\%$ of the signal is kept.

The $b\bar{b}$ events produced at PEP/PETRA energies , i.e. at $\approx 30 \ GeV$ c.m. total energy , have a rather complex topology: the primary quark-antiquark pair produced in the e^+e^- annihilation, will hadronize as a B mesons pair, plus a few other light mesons, pulling more quarks from the *sea:* following this rather poorly understood process, the energy available is redistributed to the final state particles. The B mesons (b-baryons will be produced in only a few cases, therefore for simplicity we will refer to b-particles as B mesons) will typically carry $\approx 80\%$ of the beam energy, while the remainder is divided into an average of five charged and three neutral light hadrons.

The B mesons travel an average of 0.7 mm before decaying; $\approx 25\%$ of the time a lepton will be produced, together with a charmed particle, with a typical multiplicity of 4 charged prongs; the charmed particle decay will result into a separate vertex and possibly an additional lepton. The B momentum can't be measured, because of the neutrinos which escape detections and the secondary and tertiary vertices cannot be resolved with the available experimental resolution.

The primary vertex is not known a priori: the interaction can occur anywhere within the region of beam crossing; in e^+e^- storage rings the beams are gaussian shaped with r.m.s. of ≈ 500 μm in the horizontal direction and ≈ 50 μm vertically. The beam envelope centroid can be determined with good precision, 10 - 20 μm , by measuring the closest approach distance between Bhabha scattering tracks; This can be monitored on a run by run basis :it is usually stable, and just drifts slowly with time.

Measuring the b-lifetime in e^+e^- annihilation is quite a challenge for the experimentalist : as pointed out before, the interaction point is not known, as well as the B direction and momentum; all these quantities can be determined statistically, not on an event-by-event basis. The available information include the position of the beam spot center, which can substitute the primary vertex, the thrust direction ,*i.e.* the direction which maximizes the projected momenta of the particles in the event; the lepton track which is likely to come directly from the B decay. The method used for extracting the lifetime uses the fact that the B tracks will have an impact parameter distribution not centered at zero respect to the beam centroid, and the shift's value is related to the B lifetime.

4. The detectors

The b-particles lifetime has been studied by several e^+e^- experiments: MAC, MARK II, DELCO and HRS at PEP, TASSO and JADE at PETRA ; most of these collaborations have performed more measurements, based on different data samples and/or different analysis; Following the earlier b-lifetime measurements, several of these detectors have been upgraded with the addition of more precise tracking devices near the interaction region, in order to improve their vertex finding capability.

I will now quickly review the main features of each apparatus, emphasizing the characteristics which are more relevant in the b-lifetime measurement.

MAC is a compact calorimetric apparatus which is designed with emphasis on lepton identification, especially muons, whose tracking and momentum measurement is done twice independently in the central and in the outer regions. The central drift chamber is relatively small, covering the radial region from 10 to 100 cm , and is immersed in a solenoidal magnetic field of $\approx$ .7 T. In 1984 the vacuum pipe radius was reduced to 3.5 cm and a sophisticated smaller chamber was added, to improve the track extrapolation to the origin. The complete calorimetric coverage, unique to this detector, is important for the precise determination of the thrust axis, through the energy flow measurement.

MARK II is a general purpose apparatus with good electron identification capabilities and reasonably good momentum resolution. The tracking system includes a large drift chamber and a smaller high precision vertex detector, which allows a precise measurement of the distance of minimum approach.The thrust axis direction is obtained from the measured momenta of the charged particles only. Electrons are measured in a large acceptance Liquid Argon Calorimeter, while muons are identified over $\approx$ 55% of the solid angle by chambers preceded by 1 m thick iron absorber.

DELCO is a detector specialized in electron identification; this is achieved by using Cerenkov counters instead of calorimetric techniques. This implies the possibility of identifying electrons over a much wider momentum range, in particular below 1 GeV/c ; since lower momentum tracks have on the average a larger impact parameter, Delco gains noticeably by being able to lower the cut on the electron momentum, and this compensates for the moderate momentum and vertex resolution of the central tracking.

HRS is by far the best detector for what momentum resolution is concerned, thanks to the very large volume dedicated to tracking and to the high field (1.6 T) provided by a superconducting magnet. Part of the data was collected after installing a dedicated vertex detector which further improved the track extrapolation to the origin. The electron identification is obtained with *standard* sampling shower counters.

TASSO is an other general purpose apparatus, with characteristics and performances similar to MARK II ; the electromagnetic calorimeter also uses the liquid argon technique, but its solid angle coverage is not complete since in 2

octants it has been replaced by a hadron identification system. The more recent data has been collected by using a dedicated vertex detector.

JADE is also a general purpose detector; its main feature is a sophisticated jet chamber tracking system, which also provides particle identification using combined dE/dx and momentum measurements. The chamber is inserted in a conventional solenoidal magnet and is followed by a lead glass e.m. calorimeter. This detector provides very good lepton identification over a large solid angle and good momentum resolution for charged tracks.

5. The measurement techniques

I will now discuss the main features of the experimental methods used to extract the b-quark lifetime from the PEP or PETRA data. The *standard* method for measuring a lifetime consists in identifying the decay products, measure their total momentum and the distance of their *vertex* from the interaction point. For the b-particles in PEP/PETRA hadronic events it's not possible to identify all the decay products, so a different approach is needed to convert the measured distances to the proper decay time.

The production of a $b\bar{b}$ pair from the e^+e^- annihilation results in hadronic events with peculiar characteristics, which can be exploited to obtain a sample of events *enriched* in B mesons; such a statistical identification can be a substitute for a direct positive one, provided that the background contamination in the sample is known. The B direction can be substituted by the thrust axis, using the fact that the fragmentation is hard and the b-particle follows the b-quark direction quite closely , which in turn is approximated by the thrust axis.

Such a method is clearly somehow dependent on the details of the experiment, on the Montecarlo simulation used to reproduce the data and on the knowledge of the various components present in the selected event sample. It has, however, one clear advantage over the traditional technique used in bubble chamber or emulsion experiments, where in order to sift the interesting events from a very large sample, a cut is made on the distance between the secondary and the primary vertex, thus biasing the lifetime measurement.

B-*enrichment* is obtained with either one of two basic methods that I would

classify as **semileptonic tag** and **event shape tag** , respectively; each experiment tailors one or both of these techniques to the characteristics of its own apparatus, so the analysis may differ; I will now briefly describe the general features which apply to all measurements.

The semileptonic tag is widely used to select heavy mesons : the presence of a lepton in a multiprong event is itself a good indicator for the weak decay of a heavy quark object being produced. Other lepton sources in e^+e^- hadronic events include J/ψ decays, Dalitz pairs, τ decays , pions and kaons decays in flight. Since the b-particles are much heavier than any other lepton source, the leptons produced in B semileptonic decays have, on the average, an higher transverse momentum, with respect to the original parent direction. A lower cut on the lepton transverse momentum with respect to the thrust direction is therefore a possible *b-enrichment* tool.

To quantitatively determine such an enrichment, a Montecarlo simulation, reproducing both the characteristics of the collected events and the detector details, is needed. As an example I will describe how this method is implemented in the MAC experiment: both muons and electrons are selected among all tracks having at least a 2 GeV momentum. The transverse momentum distribution of muons, measured respect to the thrust axis, is shown in fig. 1 with the breakdown in the different sources: for higher $p_\perp$ values, most of the muons come from direct b decay.

The b event fraction in the final event sample, where the b-lifetime is measured, depends on the cut on $p_\perp$ which is used, as shown in fig. 2 . MAC chooses a cut of 1.5 GeV/c in $p_\perp$, obtaining a purity of (60.3 ± 2.6) % for the muon sample, (59 ± 5) % for the electrons.[10]

Once the b-enriched sample has been selected , the next step is to find an estimator representative of the b quark lifetime. One is given simply by the average value of the leptonic tracks impact parameter; this is basically the technique used for the earlier measurements. Each experiment tried to improve the accuracy by considering the error in the impact parameter measurement for each event,and by using a more accurate statistical procedure than the straight average, to evaluate the distribution center value.

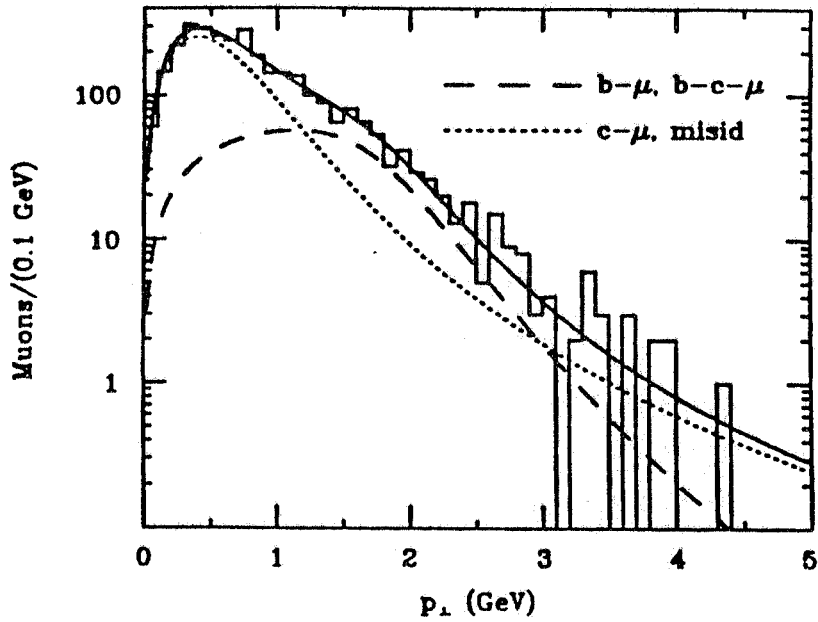In measuring the impact parameter, it's obviously important to define the

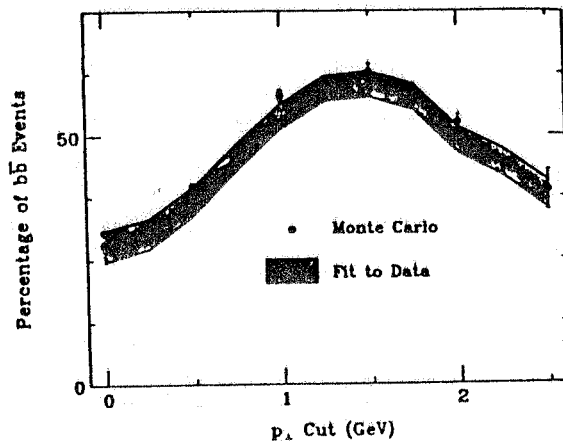*fig 1: MAC $p_\perp$ distribution of muons*

fig. 2 : MAC Percentage of bottom events as a function of of the $p_\perp$ cut. The band shows the $\pm 1\ \sigma$ of the fit to the data .

zero of the scale and a convention for the sign. The origin is usually taken as the centroid of the beam spot , a precisely known quantity, stable over a time span which exceeds the run duration. The b-lifetime measurement requires a large sample of events, collected over periods of at least several months, in some cases even a few years. The position of the beam centroid can slowly shift with time, but it's continuously monitored, on a run by run basis, using Bhabha scattering events. Shown in fig. 3 is the jitter of the interaction point position over a period of about nine months, as determined by the MAC experiment at PEP. While the

size of the beam profile is quite large, $\sigma_x \approx 400\mu$, $\sigma_y \approx 50\mu$, its center can be determined with high precision using collinear pairs, the r.m.s. being only 10μ. A good control of the systematic effects is clearly of fundamental importance in order to measure lifetimes in the picosecond range, which result in an average lepton impact parameter of $\approx 100\mu$.
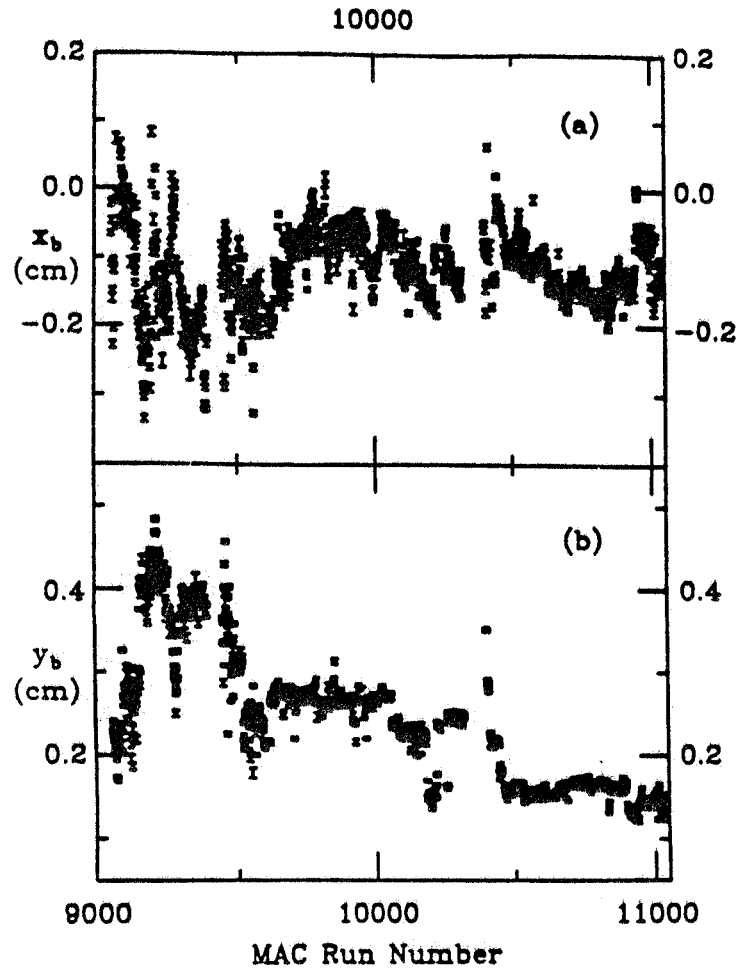

fig. 3 : MAC jitter of the beam spot centroid over a period of nine months. the x_b coordinate is the radial one , y_b the vertical.
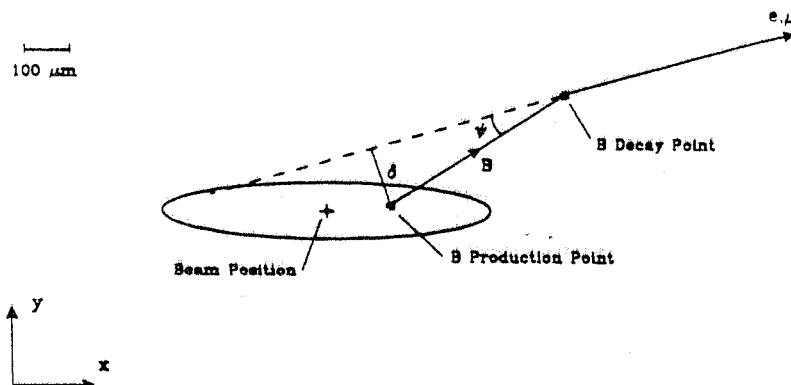

fig. 4 : Definition of the impact parameter and related quantities .

A *signed* impact parameter must be defined, so that a zero lifetime would correspond to a zero mean value for the distribution: the sign is defined positive if the lepton track appears to be emitted forward by a decaying particle travelling along the thrust axis, as shown in fig. 4 . A small fraction of B decays (less than 10%) will produce a *backward* lepton and contribute to the negative side of the impact parameter distribution; this effect can be taken into account when translating the impact parameter measurement into the lifetime determination.

The average impact parameter is a good lifetime estimator[11] : it can be shown that for massless daughter particles and complete phase space integration, the average value of the tracks impact parameter is independent from the momentum spectrum of the parent particle and is proportional to the lifetime. This is not exactly the case for the typical measurement of b (or c) semileptonic decays, but it's still true in first approximation; using the notation in fig. 4 , we have:

$$< \delta > \; = \; < l \sin \psi > \; = \; < \beta \gamma \sin \psi > \;\; \tau$$

the product $\beta \gamma \sin \psi$ is almost a relativistic invariant and can be treated as a constant. This approximation will, however, result into a systematic error, since the constant's value is evaluated by MonteCarlo and is slightly dependent on the momentum distribution of the b particles produced , which in turn is determined by the fragmentation mechanism of the primary quarks.

Another source of systematic error is the less than perfect knowledge of the sample's composition, since the impact parameter's measured average value depends on the sample purity:

$$< \delta_{meas} > \; = \; f_b \; < \delta_b > \; + \; f_c \; < \delta_c > \; + \; f_{bkg} \; < \delta_{bkg} >$$

where f_b , f_c and f_{bkg} indicate the fractions of leptons from b decays and c decays, and background, respectively. These fractions, and the average impact parameters for both charm decays and background , are all evaluated using a MonteCarlo simulation, and are cause of systematic errors when δ_b is derived from δ_{meas} ; these contributions to the systematic uncertainty should be carefully evaluated.

The impact parameter distribution is the convolution of a gaussian whose σ is equal to the experimental resolution, with an exponential whose slope is determined by the lifetime. Several different approaches have been used to disentangle these contributions: maximum likelihood , distribution mean , trimmed mean and median.[12] As an example, I will show the performance of a very simple, yet robust, estimator: the mean value. This is infact an effective quantity to use when determining the slope of an exponential distribution convoluted with a gaussian. The two extreme cases in which the distribution mean retains the complete information coming from the maximum likelihood analysis are:

$$\sigma \gg \lambda \quad , \quad \sigma \ll \lambda$$

where λ and σ are the slope of the exponential distribution and the width of the convoluting gaussian respectively.

In these two limits, the lower bound on the statistical error is not appreciably different if a maximum likelihood fit is performed or the standard deviation of the mean is calculated . When $\lambda \approx \sigma$, the lower bound on the maximum likelihood fit gains in significance over the error on the mean; the maximum effect is 11 % for $\lambda \approx \frac{\sigma}{2}$. On the other hand, in the region where $\lambda \sim \sigma$ the correlation beetween λ and σ causes a non negligible systematic error in the fit, due to the less than perfect knowledge of the experimental resolution. The mean value instead is not affected by this uncertainty, since the error on this quantity can be evaluated in first approximation, as the ratio of the width of the distribution to the square root of the number of entries.

The experimental resolutions however, are not truly gaussian functions, since they all have long non-gaussian tails. This is the main reason why the ability of the simple mean value to reproduce λ is somehow impaired. Other statistical tools, like the median or the trimmed mean, are less sensitive to the distribution's tails and can be used as robust estimators of the lifetime, having a reduced sensitivity to the systematic effects.

The first determinations of the b-flavored particles lifetimes were performed using the technique described above and yielded results around 1-2 psec. (1983-1985) The second generation experiments were carried out during the next couple of years and included improvements both in hardware and software, as more precise tracking chambers and new more sofisticated analysis techniques were employed .

After the first MAC and MARK II results in 1983 proved that the b-lifetime was much longer than anticipated and its measurement was possible in e^+e^- interaction at c.m. energy around 30 GeV, most of the apparata running at PEP and PETRA were equipped with a *vertex detector* and new ideas in data handling started to emerge. The most important improvement on the older analysis was the possibility of attributing a *primary vertex* to each event in the selected sample.

A more precise estimate than the beam centroid as the interaction point was the most important factor in achieving improved lifetime measurements by most experiments. Although the identification of the 4 secondary vertices typically present in a $b\bar{b}$ event was still out of the detectors reach, a significant improvement was obtained by using most of the tracks in each event to determine an *average* vertex; this was then defined as the interaction point in the impact parameter measurement. How this new technique allows a better resolution in the MAC data is shown in fig. 5 . On the negative side, this method might introduce biases that must be carefully studied in order to understand the systematic errors.
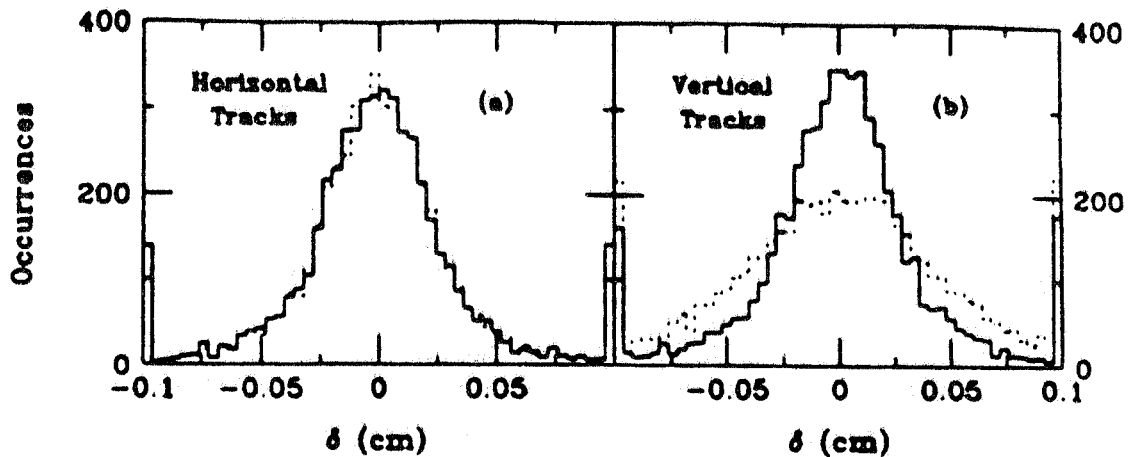

fig. 5 : MAC Impact parameter distribution using the beam centroid (dotted) or the event by event vertex estimate (full)

The different groups use several variations of the basic analysis technique; in each case a detailed work is necessary , using both real and simulated data, to assess the reliability of the method, its biases and the sources of the systematic uncertainties. MAC, for instance, defines a primary vertex as the one obtained

using all tracks in each event , provided that they are well measured, are away from the thrust axis by more than 12 degrees, and the momentum is larger than 0.5 GeV/c.

The average charged multiplicity is larger for B hadronic decays than for the semileptonic modes; a possible concern is that when all tracks are used to determine an *average vertex*, it would not be in the middle of the two B vertices (average interaction point) but shifted toward the side where the B decays hadronically. A detailed Montecarlo study has however proved that this is not an important effect since the bias due to this particular definition of the primary vertex does not exceed 5 microns. Similar conclusions have been reached by other groups when studying their own vertex definition.

The final results of the four experiments running at PEP[13] [14] [15] [16] are shown in fig. 6 ; all the distributions look clearly asymmetric and the b-lifetime values obtained from the analysis of these data are in good agreement .
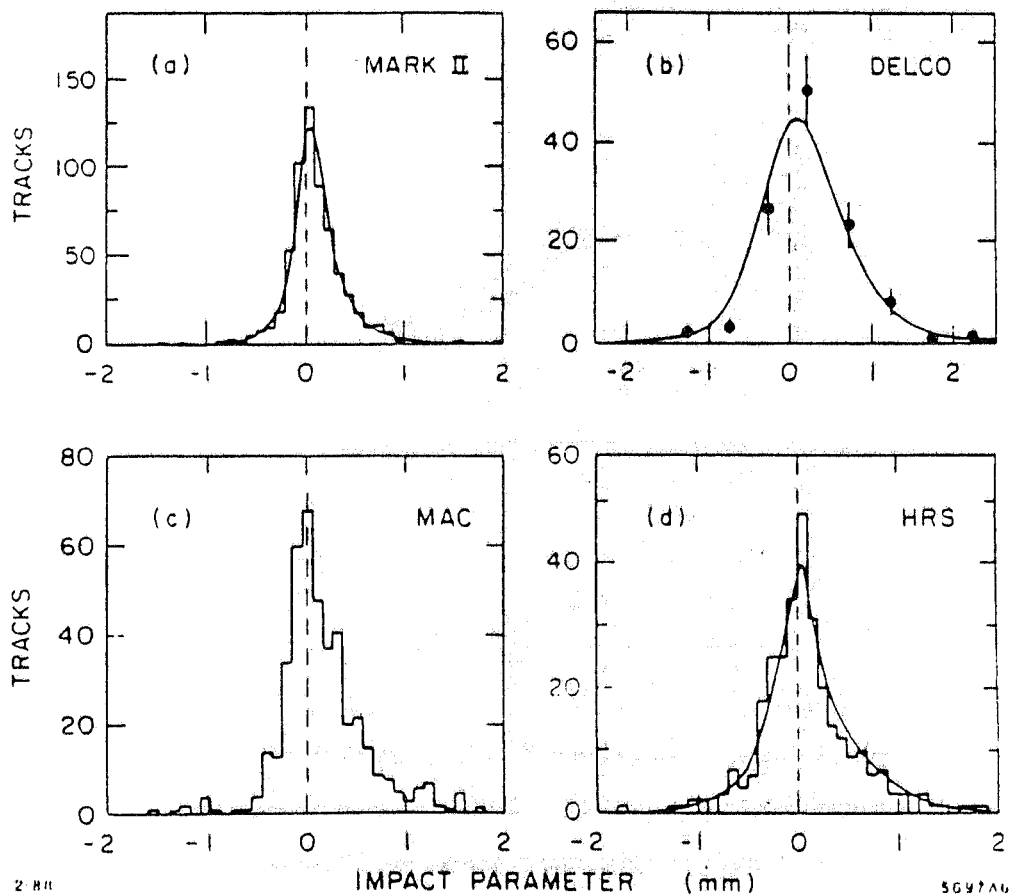

fig. 6 : Impact parameter distributions for the PEP experiments

TASSO[17] and JADE[18] the two PETRA groups which have published re-sults on b-lifetime have each performed several measurements , some using the usual techniques, some with a completely different method, for both the $b\bar{b}$ event enrichment and the lifetime determination. TASSO starts from all its multi-hadronic events, and selects the b-enriched sample on the basis of a new variable called "boosted sphericity" . The procedure is the following: each multihadronic event is divided into 2 jets by a plane perpendicular to the usual sphericity axis: each jet is then *boosted* to its own center of mass. The β for this transformation is calculated assuming that the jet is from a b quark and that its momentum is the average value obtained from the b fragmentation function. The sphericity for each jet is then computed again in the new reference frame.

The distribution of the product $s_1 \times s_2$ of the two sphericity values is shown in fig. 7 ; a quite clean separation is observed between the lighter quarks and the bottom quark. The major drawback for this technique is that the evaluation of the sample composition, in terms of quark content, is heavily dependent on the Montecarlo assumptions.
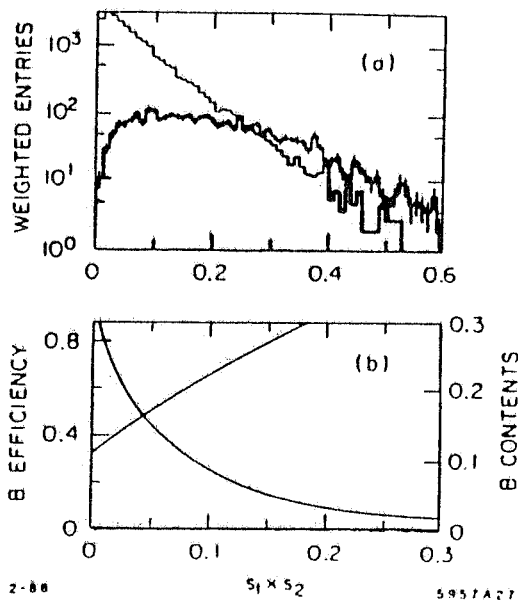

fig. 7 Tasso : Distribution of the product of the
boosted sphericity for each jet : a) weighted entries
for hadronic events: light quarks and b quarks.
b) b-events fraction and b-efficiency as a function of $s_1 \times s_2$.

The average B lifetime is then determined from the impact parameter distribution, where entries are from all the well measured tracks, after unfolding the background contribution.

The Tasso collaboration also follows a completely different approach: no attempt is made in enriching the sample of b events; all 2-jets events are considered and the decay length of the best 3-prongs vertex in each hemispheres is measured. The b-lifetime is then extracted from this distribution, using the Montecarlo results for lighter quarks. Of course the Montecarlo assumptions play an important role in this method also and this makes it this algorithm prone to systematic uncertainties.

Another TASSO analysis uses a combination of these two methods: the events are first selected on the basis of the boosted sphericity and then the decay length of the best 3 prongs vertex in each jet is measured. One more method that TASSO uses is the so called *dipole method*, based on the measurement of the average vertex separation of the two jets in multihadronic events. The results obtained by each of these analysis, on the same data sample but with rather different biases and other systematic effects,agree completely.

The JADE collaboration has measured the b-particles lifetimes using similar techniques; for example in one analysis the dipole moment is measured for a sample of 30000 multihadronic events : the boosted sphericity is then calculated to assign to each event a probability of being a true $b\bar{b}$, $c\bar{c}$ or light quark event. Their result is shown in fig. 8 .
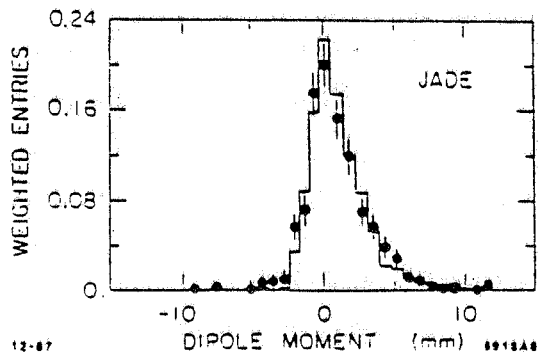

fig 8. JADE : Boosted sphericity weighted distribution
of the dipole moments of hadronic events

6. Summary of results and discussion of the systematic errors

All but one result on the b-lifetime come from e^+e^- experiments; only one fixed target experiment has two B decays, although they are very well reconstructed. In table 6.1 the results from the best measurements performed by each e^+e^- collaboration are summarized, together with information on the analysis technique used and the experimental resolution.

Table 6.1

	MAC	MARK II	DELCO	HRS	JADE	TASSO
L (pb^{-1})	220	200	214	200	70	75
R_{min} Vtx Chamber	4.5	10	12	9	10	8
$b\bar{b}$ Events (%)	60	65	79	53		
Point res.(μm)	< 50	90	150	100	160	120
Measured λ (μm)	114 ± 13	129 ± 14	249 ± 49	80 ± 27	1080 ± 80	84 ± 5
Lifetime (psec)	1.24 $\pm .2 \pm .17$	0.98 $\pm 12 \pm 13$	1.17 $^{+27}_{-22} \pm .17$	1.02 $^{+0.42}_{-0.42}$	1.46 $\pm .19 \pm .30$	1.39 $\pm .10 \pm .25$

The weighted average of the results gives :

$$\tau_B = (1.18 \pm 0.14) \times 10^{-12} sec$$

Results can be more easily compared using the plot in fig. 9 .

All available data point to a lifetime between 1 and 1.5 psec , consistent both with each other and with the pioneer MAC and MARK II results; in comparing the data, or when trying to combine the results for quoting a *comprehensive* result, great care should be devoted to the treatment of the systematic errors.

I have already mentioned the fact that systematic errors arise from both the imperfect knowledge of the detector performances (e.g. tails of the spatial resolution function) and the uncertainties in the Physics parameters used in the analysis as a substitute of unknown quantities. Some of these effects are the same in all experiments, some are peculiar to the combination detector - analysis technique.

In a lifetime measurement the systematic errors are the limiting factor, in

achieving a good precision rather than statistics. This applies in particular to the experiments we have described, where the impact parameters or the decay distances to be measured are often smaller, or at best of the same order, as the experimental resolution. The presence of unforeseen or not well under control systematic effects could substantially change the measured quantities or even wipe out the effect of a non zero b-lifetime.
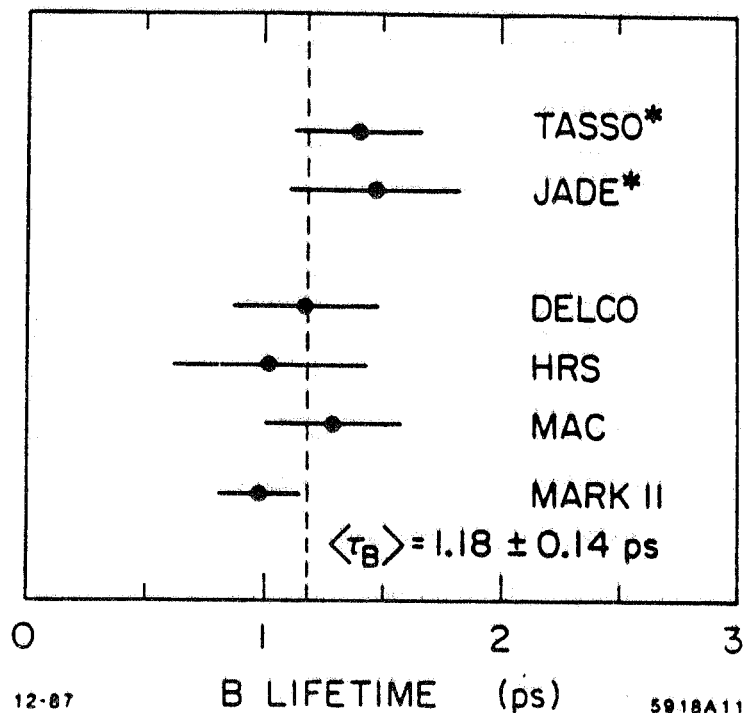
fig. 9 : Summary of the b-lifetime measurements :
for each collaboration only the most accurate result is plotted.
The errors are statistical only.

Given the large number of detectors involved and the variety of the analysis techniques used, the discussion of the systematic effects should be done separately for each experiment. Even for uncertainties shared by everybody, the resulting systematic effect must be carefully evaluated in each case; consider as an example the b fragmentation function. This influences the lifetime value in more than one respect: the more primary b quark energy goes to the B meson, the fewer tracks from the primary vertex, which all have zero impact parameter. The quantitative dependence of the final result from the uncertainty in the Peterson variable (world data[19] permit $\epsilon_b = 0.012^{+0.019}_{-0.009}$ which correspond to a beam energy fraction of 0.78 ± 0.05 for the B) depends however on the analysis technique (the tracks

whose impact parameter has been measured, for example) and on the statistical procedure used in extracting the lifetime from the measured distribution.

As a typical example, I will report here the breakdown of the MARK II measurement's systematic error, which is evaluated to be 13 % overall .[20]

The main instrumental effects are the uncertainties in the impact parameter resolution and in the thrust axis direction, whose contributions are 6 % and 3 % respectively. The resolution function is empirically determined, and affects the lifetime value as the parameters are changed from the minimum value of the likelihood function. The error in the determination of the direction of the parent b quark , approximated with the thrust axis, also results in a systematic uncertainty in the lifetime.

Many parameters used in the analysis are unknown and have to be obtained from the Montecarlo simulation: a detailed work is then necessary to understand how much the results vary when the Montecarlo inputs are changed. In the MARK II analysis the uncertainty on the background subtraction contributes a 3 % error to the lifetime measurement, 5 % is due to the b and c fragmentation functions while the biggest effect is due to the uncertainty in the lepton fraction, 9 %.

Effect	$\Delta\tau/\tau$
Lepton fraction	9 %
b and c Fragmentation	5 %
Background (i.e. 2 γ 's)	3 %
Resolution function	6 %
Thrust vs B direction	3 %
Total	$\approx 13\%$

fig. 10 shows how much the b-lifetime determination is affected by systematic uncertainties as the sample purity and the b-quark fragmentation function, which determines the average B meson momentum.
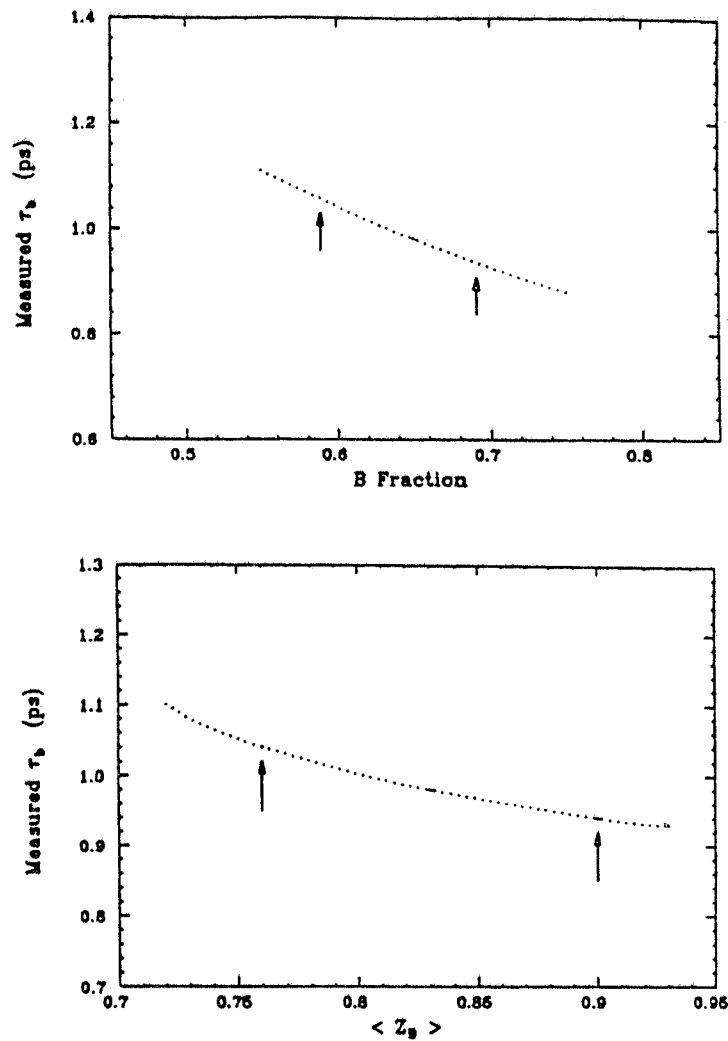

fig. 10 : Dependence of the b-lifetime measurement from :

a) the fraction of b decays in the final sample

b) the $< z_b >$ value of the b quark fragmentation

(Mark II analysis of systematic effects)

7. Determination of $|V_{cb}|$

We have already pointed out how important the b-quark lifetime is , in the the Standard Model framework, since it's strictly related to the mixing angle between the second and the third quark families,one of the free parameters in the theory to be determined experimentally.

Several assumptions, however, are involved in extracting $|V_{bc}|$ from measured value of B mesons average lifetime; in order to quote a *honest* result from the available data , theoretical uncertainties have to be taken into account as well as experimental ones.

The coefficients of the C-K-M matrix elements in the lifetime formula are somehow dependent on the model used in the calculation : different kind of approaches give quite consistent results for the $|V_{bc}|$ coefficient but they differ up to 50% for the $|V_{bu}|$.

Using the limits available on the ratio $\frac{|V_{ub}|}{|V_{cb}|}$ [21] [22] , and assuming the *free quark* model to evaluate the functional relation between the measured lifetime and the mixing matrix elements :

$$\tau_b \approx \frac{2.35 \times 10^{-14} \, Br(b \rightarrow l\bar{\nu}X)}{2.04|V_{ub}|^2 + |V_{cb}|^2} \, (sec)$$

the value obtained for $|V_{cb}|$ using $Br_{b \rightarrow l\bar{\nu}X} = 12.1\%$ is :

$$|V_{cb}| = 0.047 \pm 0.003 \pm 0.005$$

where the first error refers essentially to experimental uncertainties and the second to the theoretical modeling of the $\tau_b \, V_{cb}$ relation.

The b lifetime measurement ,together with the $\frac{|V_{ub}|}{|V_{bc}|}$ ratio and unitarity determine or severely constrain all the absolute values of the C-K-M matrix elements in the hypothesys of three generations : as a matter of fact the matrix becomes almost diagonal and the mixing between the second and third generation of quarks is extremely small . This in turn bears consequences on the mass of the top quark , on the ratio $\frac{\epsilon'}{\epsilon}$ and on the size of CP violation effects expected in beauty Physics

8. Conclusions

Five years have gone by since the first rough measurements which proved the b-quark lifetime to be much longer than anticipated . A lot of effort by six large collaborations using powerful apparata at PEP and Petra have gone into improving the original measurements . The overall picture which is emerging now shows a high degree of consistency between the various measurements , but the techniques used up to now seem to be limited by systematic effects. Hadro and/or photoproduction experiments are likely to give their contribution in the near future so that a completely new data base of experimental results will be added to the existing ones.

New machines and new apparata will come into operation in the near future, Lep and in particular SLC with its extremely small luminous spot will help understanding many unsolved problems regarding the decay of beauty particles : eventual differences in lifetime between charged and neutral B's , lifetime of the B_s , of the B-baryons and so on. On a longer time scale the *long* b lifetime will be used as a tool to identify and flag b-flavoured particles in order to perform more sophisticated measurements and solve one of the most fascinating problems of our universe : the CP violation phenomemena.

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