RECENT RESULTS FROM THE MARK II EXPERIMENT†

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1. Introduction and Short History of the Mark II Experiment

The Mark II experiment first started taking data in 1978 at the SLAC SPEAR storage ring. It was the first e^+e^- detector with a large, many layer cylindrical drift chamber (CDC) and a large liquid argon calorimeter.[1] After two years at SPEAR, it was moved to the PEP storage ring, where it was upgraded a year later with a seven layer precision vertex drift chamber,[2] located between the CDC and the beampipe, for the study of particle lifetimes. In this configuration (hereafter referred to as PEP5), it took 205 pb^{-1} of data at $\sqrt{s} = 29$ GeV over three years. Among the many Mark II contributions to particle physics at PEP were the study of inclusive lepton production and measurements of the lifetimes of heavy particles (D mesons, B hadrons, and the τ lepton).

For its last run at PEP in 1985/86, the Mark II was upgraded[3] with a new, 72 layer CDC, a new endcap calorimeter, and a new solenoid magnet, in anticipation of moving the experiment to the interaction region of the SLC. In 1987, the detector was again moved, and took data in the first two SLC runs, in 1989 and 1990. After making the first measurements of Z^0 properties in e^+e^- collisions and the first searches for the Z^0 decaying into new particles in 1989, the Mark II was again upgraded with a new precision vertex detection system. This system consisted of a

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three layer silicon strip vertex detector (SSVD) surrounded by a 38 layer precision drift chamber vertex detector (DCVD), situated between a new, small radius beam pipe (2.5 cm) and the CDC.

The Mark II experiment recorded its last Z^0 on November 21, 1990, and the detector is now in retirement. In 1991, two major studies were undertaken with data taken at various points in the Mark II lifetime, and these analyses will be the subject of this talk. The first analysis, performed on the 1990 Z^0 data sample taken with the precision vertex detectors, established the technique for identifying Z^0 decays into $b\bar{b}$ pairs by selecting events where several tracks have large impact parameters with respect to the Z^0 production point.

The second analysis involved a search for $\tau^+\tau^- f\bar{f}$ events in the PEP5 data sample. An anomalously large cross section for events of this type was reported in 1991 by the ALEPH collaboration.[4] While the Mark II data sample at the Z^0 is too small to see a signal of the size reported by ALEPH, one consistent explanation of the ALEPH observation is the final state radiation of virtual photons in the reaction $e^+e^- \rightarrow \tau^+\tau^-$ at a rate higher than expected by QED. These virtual photons then decay into low mass e^+e^-, $\mu^+\mu^-$, or $\pi^+\pi^-$ pairs. If this explanation is correct, it shouldn't matter whether the $\tau^+\tau^-$ final state is produced by Z^0 decay or by e^+e^- annihilation at lower energies, as long as there is enough phase space to produce the $f\bar{f}$ pairs. There are $\sim$ 21,000 $\tau^+\tau^-$ events in the Mark II PEP5 data sample, with $\sim$ 9000 events in the fiducial region where the probability of missing a track in an event is small ($|\cos\theta_T| < 0.74$). This compares well to the ALEPH data sample on which the observation was based, which contains $\sim$ 8400 $\tau^+\tau^-$ pairs. While the non-observation of an excess of $\tau^+\tau^- f\bar{f}$ events in the PEP5 data sample can not by itself refute the ALEPH observation, it can constrain the possible explanations of the phenomenon, in particular the above mentioned one.

2. Impact Parameter Tagging and Measurement of the $b\bar{b}$ Fraction in Hadronic Z^0 Decays

Decays of the Z^0 into $b\bar{b}$ pairs are the easiest of the d-type quark decays to isolate, as the produced B hadrons retain much of the energy of the initial b quarks and have quite unique decays. In addition to being interesting just as an individual measurement of the $Zq\bar{q}$ coupling, a precise measurement of the $b\bar{b}$ fraction ($R_{b\bar{b}} = \Gamma(Z^0 \rightarrow b\bar{b})/\Gamma(Z^0 \rightarrow hadrons)$) is sensitive to the top quark mass because of the large coupling of the b quark to the t quark.[5] The most accurate measurements of $R_{b\bar{b}}$ so far use the large semi-leptonic BRs of b quarks ($\sim$ 10% each for e and μ) to tag B decays,[6] but these measure $\mathrm{BR}(b \rightarrow \ell X) \cdot R_{b\bar{b}}$, and $\mathrm{BR}(b \rightarrow \ell X)$ is only known to $\sim$ 8%.

We can also tag $b\bar{b}$ events by using the fact that B hadrons travel on the average $\sim$ 2 mm from the Z^0 production point before decaying. This and the large $< p_T >$ in B decays results in events which often have several tracks with large impact parameters (b) with respect to the Z^0 production point. Badly measured tracks and low momentum tracks which heavily multiple scatter also produce tracks with large b. To reduce the effect of these backgrounds, it's better to use impact parameter *significance* ($\equiv \mathrm{b}/\sigma_\mathrm{b}$) rather than b. Here $\sigma_\mathrm{b} = \sqrt{\sigma_{TR}^2 + \sigma_{PV}^2 + \sigma_{COR}^2}$, where σ_{TR} is the calculated track extrapolation error, which has contributions from detector resolution and multiple scattering, σ_{PV} is the uncertainty in the determination of the Z^0 primary vertex (production point), and σ_{COR} is a correction factor, ideally zero.

The critical parts of a detector for an impact parameter tagging analysis are the tracking chambers. For the Mark II, the 72-layer CDC[7] was used to find the charged tracks in the events and to measure their momenta and dip angles. These tracks were then projected in towards the SLC interaction point (IP) through the 38 layer DCVD,[8] which consisted of 10 tilted jet cells in 2 atm of 92:8 CO_2:Ethane gas. The first and last measurement points in the DCVD were at 5.1 and 16.6 cm, respectively. The diffusion-limited single hit resolution of the DCVD was typically

$\sigma^2(\mu m^2) = 28^2 + 43^2 \cdot d(cm)$ for tracks in hadronic events. There was almost full efficiency for finding hits from tracks as closely spaced as 500 μm, corresponding to an angular separation of about 5 mrad at the mean chamber radius.

After the tracks were fit to their measurements in the CDC and the DCVD, they were projected into the SSVD. The SSVD[9] consisted of three cylindrical layers of silicon strip detectors located at 29, 34, and 38 mm from the beam axis, just outside of the 25 mm radius beam pipe. Each SSVD layer consisted of 12 modules of 512 strips each, with strip pitches of 25, 29, and 33 μm, respectively. The modules in the different layers were staggered to eliminate gaps and to facilitate the internal alignment of the silicon system. The average SSVD single hit resolution was measured to be 7.1 μm. The SSVD could distinguish hits from tracks separated by as little as 100 μm, corresponding to an angular separation of about 3 mrad.

Since both the SSVD strips and the DCVD wires were parallel to the beam axis, impact parameters were precisely measured only in the plane transverse to the beam axis. For this reason, all impact parameters and associated errors used in this analysis were for the tracks projected into the transverse plane. To estimate the location of the Z^0 primary vertex (PV), we took the four tracks in the event with the smallest b with respect to the average beam IP and tried fitting them to a common vertex three at a time. If the vertex fit had a probability of > 1% then this was taken as the seed for the PV search. The remaining track in the event which gave the highest vertex probability was then added to the seed and the vertex fit probability was recalculated. This was repeated as long as the vertex fit probability remained above 1%. When there were no more tracks in the event which satisfied this requirement, the PV search was finished. The typical size of the PV error ellipse was 15 $\times$ 75 μm, and since both tracks and the major axis of the PV error ellipse tend to line up with the event thrust axis, a typical value for σ_{PV} was 20 μm. Typical measured resolution values were $\sigma_b = 28$ μm for the highest momentum tracks, and $\sigma_b = 77$ μm for tracks with $p_\perp\sqrt{\sin\theta} = 1$ GeV/c. We found that we needed $\sigma_{COR} = 15$ μm to account for remaining detector misalignment and effects not included in the PV fit error ellipse.

The Mark II recorded 10.1 ± 0.7 nb^{-1} of data on or near the Z^0 peak in 1990 with the vertex detector system in place. The hadronic event selection cuts were 7 or more charged tracks and a visible energy greater than half the center-of-mass energy. After these cuts, 220 events were left ($\varepsilon_{HAD} = 80\%$).

If there are tails on the detector resolution function in the data that are not properly represented in the Monte Carlo (MC), the efficiencies for tagging events will be underestimated, resulting in a systematic error. For this reason, we studied our resolution function in detail.[10] Since poorly measured tracks are hard to model, we put stringent requirements on the tracks used in the analysis. Tracks were required to have ≥ 25 position measurements in the CDC, ≥ 15 in the DCVD, and ≥ 1 in the SSVD. Tracks were also required to have $p_\perp \geq 150$ MeV/c, $|b| < 2$ mm, $|\Delta_z| < 15$ mm, $|\cos\theta| < 0.8$, and $\sigma_{TR} < 200$ μm. The requirement that the track have $|b| < 2$ mm is efficient for removing tracks from K^0 and hyperon decays, as well as grossly mismeasured tracks. From the 220 events, 2640 tracks passed these cuts.

The impact parameter significance distributions for the selected tracks are shown in Fig. 1. The distribution for high precision tracks (those with $\sigma_{TR} <$ 25μm) is shown in Fig. 1a, and the distribution for low precision tracks ($\sigma_{TR} >$ 25μm) is shown in Fig. 1b. For these distributions only, the track being histogrammed was first removed from the PV fit. The impact parameter was signed relative to the event thrust axis in the usual way. The sign of the b is positive if the track crosses the thrust axis corresponding to a positive decay length from the PV, otherwise b is negative. The points with errors are the data, and the dashed line histograms are the MC expectations. We used the Lund JETSET 6.3 MC[11] Z^0 decays, and then these events were passed through the complete Mark II detector simulation program. Detailed studies were performed to make sure that resolutions, efficiencies, multiple scattering, nuclear scattering, beam related backgrounds, and realistic alignment errors were all properly represented in the MC.[10] The exact values of critical physics parameters in the MC, such as the B hadron lifetime, were set to world averages.[12] We adjusted the amount of material in the

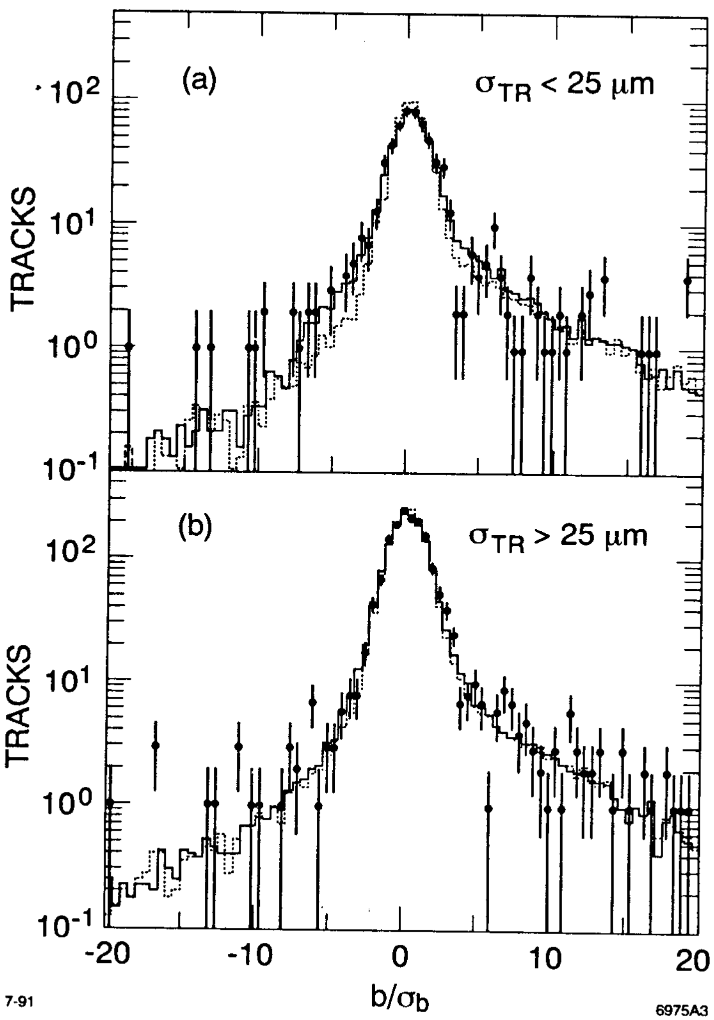

Fig. 1

detector MC (within reasonable limits) to get the "core" of the b/σ_b distribution for low precision tracks to agree between data and MC.

There are asymmetric non-Gaussian tails in both distributions. The asymmetry is due in most part to the signal we are looking for, the decay products of B hadrons at large positive values of b/σ_b. The MC does not as closely reproduce the data in the "far tails" ($|b/\sigma_b| > 3$) for the high precision tracks as it does for the low precision tracks. To correct for this, we added additional Gaussian-distributed smearing to a randomly chosen subset of all tracks in the MC to simulate a tail on the resolution function. We varied the size and fraction of tracks affected by this tail until the MC agreed with the data on the negative side of Fig. 1a, as these tracks contain a much smaller fraction of tracks from the signal we are looking for than those with positive b/σ_b. The low precision tracks are not very sensitive to this tail, as they have much larger errors due to multiple scattering. We needed to add $75 \pm 25\mu$m of smearing to $15 \pm 5\%$ of the tracks in the MC to get it to agree with the data (the solid histograms in Fig. 1).

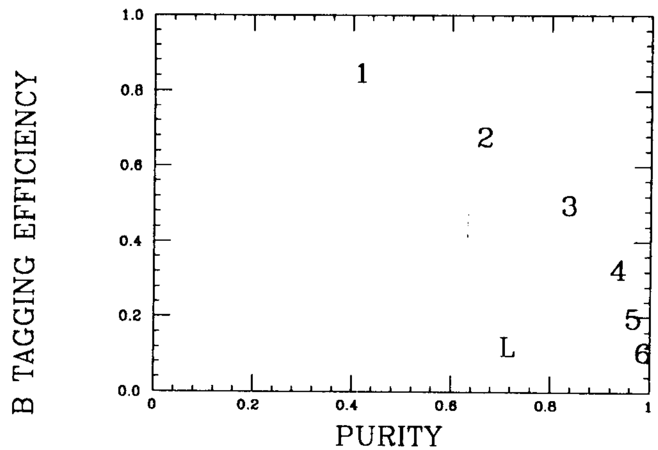

Figure 2.

There are many possible algorithms for tagging $b\bar{b}$ events using track with large

b/σ_b. The one we found to be optimal for our detector and data sample required three or more tracks with $b/\sigma_b > 3.0$. The tagging efficiency versus sample purity, as measured in the MC, is shown in Fig. 2 for various different values of N, the minimum number of tracks with $b/\sigma_b > 3.0$ required for an event to be tagged as a $b\bar{b}$ event.* The numerical symbols are the N values of the various tags. We used the Lund JETSET 6.3 MC and the full detector simulation plus 75μm of additional smearing added to 15% of the tracks to calculate the efficiencies. Also shown (the L symbol in Fig. 2) is the efficiency and purity of a *typical* high p_T lepton tag.[13] For our tag ($N = 3$), we calculate an efficiency $\varepsilon_b = 0.50$ at a purity $P = 0.85$.

We tagged 32 events with ≥ 3 tracks with $b/\sigma_b > 3.0$, corresponding to a value of $R_{b\bar{b}} = 0.251$ with a 19.5% statistical error. The significant contributions to the systematic error estimate on this measurement are shown in Table 1. Their quadrature sum is 12%. However, it should be noted that the systematic errors can be substantially reduced on similar measurements in the near future. With a larger data sample, the first three errors could have been substantially reduced. LEP measurements will reduce systematic errors due to fragmentation models and B hadron lifetimes, and CLEO, ARGUS, and LEP measurements will reduce those due to B decay properties and the charm fraction. With larger data samples, dividing the tracks into jets and using tagging algorithms similar to the one we used ($\geq N$ tracks with $b/\sigma_b \geq M$) to tag individual jets will allow interesting cross-checks. Double tagged events give a direct measure of the tagging efficiency, and one can also include addition information from the event, such as high p_T leptons. Methods have also been investigated[14] for reducing certain of the systematic uncertainties by fitting the

$$S \equiv \frac{1}{\sqrt{N}} \sum b/\sigma_b$$

distribution for additional parameters, such as resolution scale factors and lifetime-like parameters. With very high statistics, this may be the best way to minimize the systematic error on the lifetime-tagged B fraction.

Source of Systematic Error	Contribution
Resolution Function	$\pm 9\%$
Tracking Efficiency	$\pm 2\%$
Material and Multiple Scattering	$\pm 4\%$
Fragmentation Model	$\pm 4\%$
B Hadron Lifetime	$\pm 4\%$
B Decay Properties	$\pm 3\%$
Charm Fraction	$\pm 2\%$

Table 1. Sources of systematic error and their estimated magnitude.

We have also studied whether the measured $R_{b\bar{b}}$ was sensitive to the exact number of tracks required in the tag, the exact value of the b/σ_b cut, or the method of determining the PV. Within the statistical errors of the measurements, we see no systematic effects from these parts of the analysis. A MC without the additional 75μm of smearing added to 15% of the tracks, while not consistent with the data, would have resulted in a measured value of $R_{b\bar{b}}$ which was 7% larger, well within the 9% error attributed to our uncertainty in the resolution function.

In conclusion, we have investigated methods for tagging $Z^0 \to b\bar{b}$ decays using track impact parameters. Requiring ≥ 3 tracks with $b/\sigma_b > 3.0$ results in a tagging efficiency of 50% with an 85% purity. We have measured $R_{b\bar{b}} = 0.251 \pm 0.049 \pm 0.030$, in good agreement with other measurements and with the standard model expectation of $R_{b\bar{b}} = 0.22$.

3. Search for $\tau^+\tau^- f\bar{f}$ Production at PEP Energies

In order to search for a $\tau^+\tau^- f\bar{f}$ signal in our $\sqrt{s} = 29$ GeV data, we needed to develop techniques for rejecting the copious sources of background to the possible signal which exist in the lower energy data. The Berends-Daverveldt-Kleiss MC[15] was used to generate a sample of $\tau^+\tau^-\mu^+\mu^-$ events with $m_{\tau\tau} > 9$ GeV/c^2 and $0.3 < m_{\mu\mu} < 5$ GeV/c^2, and we tuned our selection cuts to find this signal. This

MC was also used to model other 4 lepton final states which might be background to the signal. The Lund JETSET 6.3 MC[11] was used to model the multihadronic background, and the KORALZ3 MC[16] was used to generate samples of $\tau^+\tau^-$ and $\tau^+\tau^-\gamma$ events.

First we assembled the set of quality charged tracks and photons from an event. For the charged tracks, we required $p_\perp \geq 80$ MeV/c, $|b| < 1$ cm, and $|\Delta_z| < 3$ cm. If the track was identified as an electron in the liquid argon calorimeter, and its measured energy in the calorimeter was greater than that measured in the drift chamber, we rescaled the track's $\vec{p}$ by E_{LA}/E_{DC}. We required the photons be isolated clusters in the calorimeter with $E > 200$ MeV.

We then placed constraints on the event as a whole to make sure it had the topology we were looking for. Events were required to have only four or six charged tracks, a total charge of zero, a total number of charged and neutral tracks less than ten, $|\cos\theta_{TH}| < 0.74$, and between 9 and 27 GeV of visible energy. Events were rejected if there were any pairs of tracks consistent with being a photon conversion.

The next step was to identify $V \to f\bar{f}$ candidates in the events. V candidates were taken as all oppositely charged pairs with $m_{ee} < 5$ GeV/c^2, an opening angle of $< 118^o$, and a mass recoiling against the V candidate of > 14 GeV/c^2. If a pair of tracks in an event passed these cuts, all remaining tracks were boosted into the frame recoiling against the V candidate and a thrust analysis was performed on these boosted tracks. The contents of each thrust axis formed a τ candidate, and each τ candidate was required to have a charge of $+1$ or -1. The combined mass of the V and all charged tracks (assigned pion masses) in a hemisphere was required to be > 1.8 GeV/c^2. This cut suppressed $\tau^+\tau^-\gamma$ final state radiation events. We required that the angle between the two τ candidates be $> 90^o$ in the lab frame, and that the combined mass of the V and the closest τ candidate be > 3 GeV/c^2. These cuts helped in rejecting $\tau^+\tau^-$ and hadronic events.

We also put maximum mass limits on each τ candidate depending on the hemisphere topology. An 1 (charged) prong, < 2 neutral τ candidate was required to have a mass < 1.2 GeV/c^2, an 1 prong, 2 neutral needed $m < 1.4$ GeV/c^2, an 1 prong, > 2 neutral needed $m < 1.9$ GeV/c^2, a 2 prong, 0 neutral needed $m < 1.8$ GeV/c^2, and a 2 prong, ≥ 1 neutral needed $m < 1.7$ GeV/c^2.

We divided the remaining τ candidates into two classes. The *leptonic* τ candidates were those with 1 charged track, and if there were neutrals present, a combined mass < 150 MeV/c^2 (though called leptonic, this category will also include $\tau \to \pi\nu$ decays). All other τ candidates were classified as *hadronic* decays. Then, following the ALEPH analysis, we defined $\eta_i = E_i/E_\tau$, where E_i is the observed energy of the τ candidate in the recoil frame, and $E_\tau = E_{RECOIL}/2$. If a τ candidate was classified as a leptonic decay, we required $0.16 < \eta_i < 0.77$, if a decay was hadronic, $\eta_i > 0.22$, and if both τ candidates were leptonic, $\eta_1 + \eta_2 < 1.4$. These cuts reject $e^+e^-f\bar{f}$ and $\mu^+\mu^-f\bar{f}$, and junk. At this point, our MC studies predicted we should see 3.1 ± 0.1 $\tau^+\tau^-f\bar{f}$ events, 0.3 $\tau^+\tau^-$, $e^+e^-f\bar{f}$, and $\mu^+\mu^-f\bar{f}$ events, and 28 $e^+e^- \to q\bar{q}$ events with at least one valid $\tau^+\tau^-f\bar{f}$ configuration.

We then implemented another technique for rejecting the still large $e^+e^- \to q\bar{q}$ background.[17] For this we used the fact that the missing mass squared (MM^2) is ~ 0 for τ *hadronic* decays, and the mean of the MM^2 distribution is slightly positive for *leptonic* decays, while no such constraints hold for the hadronic backgrounds. We then used the MC MM^2 distributions for *hadronic* and *leptonic* τ decays as probability density distributions. Figure 3 shows the MM^2 distributions from the $\tau^+\tau^-f\bar{f}$ MC, with full detector simulation except for the fact that the true τ direction is used.

We then normalized the peaks of the distributions in Fig. 3 (denoted f_H and f_L) to 1. If we knew the direction of the τ candidates, we could calculate the MM^2 for each τ and multiply the appropriate values of $f_i(MM^2)$ together to form a joint probability to use as a separation variable. However, we do not have a good measure of the directions of the τ's in the data, so we varied that direction in the recoil frame over all possible values and calculated:

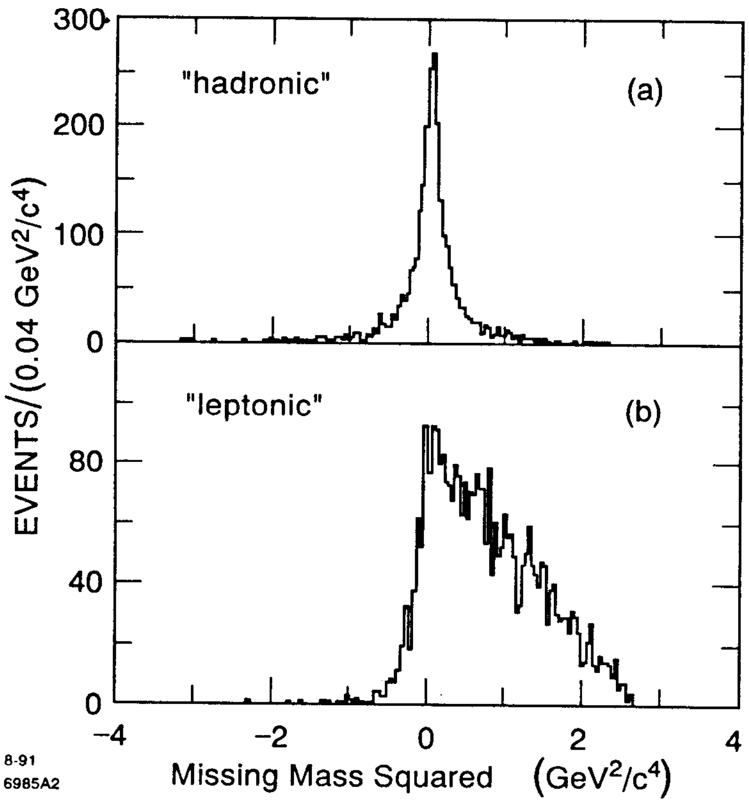

Fig. 3

$$\psi \equiv \max_{\substack{0\leq\theta\leq\pi \\ 0\leq\phi\leq 2\pi}} f_1(M^2_{\nu 1}(\theta,\phi)) f_2(M^2_{\nu 2}(\theta,\phi)).$$

We then defined Ψ as the largest value of ψ for all possible $\tau^+\tau^- V$ configurations in an event, and cut on Ψ to reject hadronic backgrounds.

Figure 4 shows the Ψ distributions for the $\tau^+\tau^-\mu^+\mu^-$ MC, the $q\overline{q}$ MC, and the data, respectively. While some of the $\tau^+\tau^-\mu^+\mu^-$ events are distributed from 0 to 1, most of them have values very close to 1, while the maximum value of Ψ for the $q\overline{q}$ MC is < 0.20. We then applied a final requirement on the data that $\Psi > 0.30$. This left 1 event which passed all our cuts, whereas the $\tau^+\tau^- f\overline{f}$ MC's predict 2.33 events.

We performed several checks to make sure our efficiency estimates were correct. We removed the conversion rejection cut, and observed 3 events in the data. The MC's said we should observe 5.3 events, with 2 of these events from $\tau^+\tau^-\gamma$. We then changed the cuts on the event and the V to allow a γ in place of the V. The KORALZ3 $\tau^+\tau^-\gamma$ MC predicted that we should observe 145 ± 7 $\tau^+\tau^-\gamma$ events, and we observed 152. This gives confidence in the $\tau^+\tau^-$ part of the $\tau^+\tau^- f\overline{f}$ efficiency. We then looked for $e^+e^- f\overline{f}$ and $\mu^+\mu^- f\overline{f}$ events. The $\tau^+\tau^- f\overline{f}$ analysis was used, except that we required both hemispheres be classified as *leptonic* decays, $\eta_i > 0.78$, and $\eta_1 + \eta_2 > 1.64$. We expected 62.2 events to pass these cuts, and we observed 65 events in the data sample. This gives confidence in the $f\overline{f}$ part of the $\tau^+\tau^- f\overline{f}$ efficiency.

In conclusion, we observed 1 event which satisfied the analysis requirements for $\tau^+\tau^- f\overline{f}$ events in our $\sqrt{s} = 29$ GeV data sample, where we expected to see 2.33 ± 0.11 events. This allows us to put a limit of $N_{OBS}/N_{EXP} < 2$ at the 95% confidence level. The ALEPH collaboration observed 15 events where they expected 3.2 in their 1990 data sample. If the ALEPH result of observing 4.7 times the number of expected $\tau^+\tau^- f\overline{f}$ events were a universal enhancement factor for e^+e^- interactions well above $\tau^+\tau^- f\overline{f}$ threshold, we would expect to see 11 events passing our $\tau^+\tau^- f\overline{f}$ selection cuts in our data sample. The probability of seeing 0 or 1 event when one should see 11 is 2×10^{-4}. For a summary of the recent searches by the LEP experiments for events of this type, see the talk of Francois Richard in these proceedings.

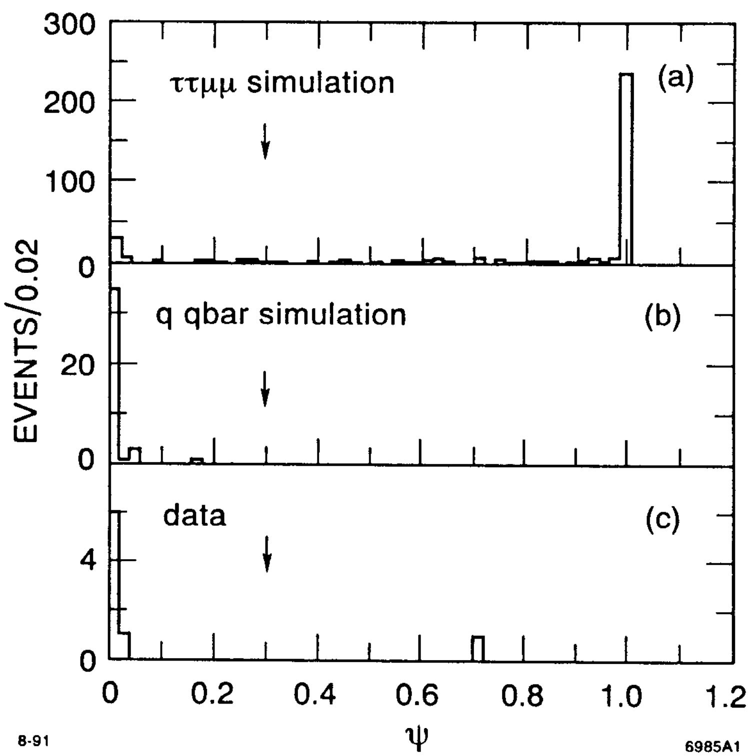

Fig. 4

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