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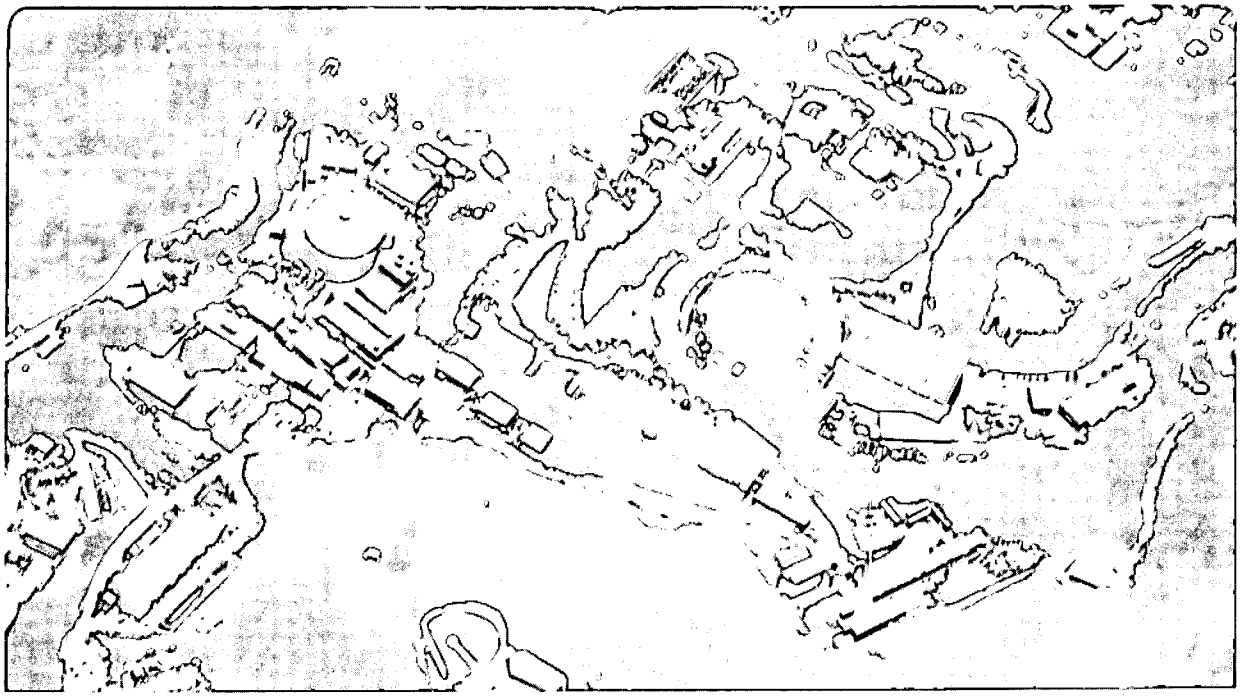
July 1991



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MEASUREMENT OF THE $b\bar{b}$ FRACTION IN HADRONIC Z^0 DECAYS WITH PRECISION VERTEX DETECTORS*

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ABSTRACT

We have measured the fraction of $b\bar{b}$ events in hadronic Z^0 decays, $R_{b\bar{b}}$, using the vertex detector system of the Mark II detector at the SLC. We tag $b\bar{b}$ events by requiring the coincidence of three or more tracks with significant impact parameters. This tag is 50% efficient and results in a sample of 85% purity. We find $R_{b\bar{b}} = 0.251 \pm 0.049 \pm 0.030$, in good agreement with other measurements and the Standard Model prediction.

The fraction of $b\bar{b}$ events in hadronic Z^0 decays, $R_{b\bar{b}} = \Gamma(Z^0 \to b\bar{b})/\Gamma(Z^0 \to hadrons)$, provides a clean measurement of the $Zb\bar{b}$ coupling strength, and is of considerable theoretical interest due to its sensitivity to the top quark mass through higher order corrections to the $Zb\bar{b}$ vertex.[1] In this paper we report a measurement of $R_{b\bar{b}}$ which differs from other measurements[2-6] in that $b\bar{b}$ final states are identified by selecting events in which several tracks have significant impact parameters with respect to the Z^0 production point. This method is based on the fact that B hadrons produced in Z^0 decays travel on average about 2 mm before decaying, and it relies on the precise reconstruction of charged particle trajectories.

The data reported here were taken with the Mark II detector at the SLAC Linear Collider (SLC) during 1990. For this measurement, the Mark II detector[7] was augmented with high precision vertex detectors which permitted the accurate reconstruction of particle trajectories near the Z^0 production point. Charged particle tracking was accomplished with three detector systems: the central drift chamber (CDC), the drift chamber vertex detector (DCVD), and the silicon strip vertex detector (SSVD). The 72-layer CDC[8] was used to find charged tracks in the events and to measure their momenta. Located directly inside the CDC was the 38 layer DCVD,[9,10] which consisted of 10 tilted jet cells. The first and last measurement points in the DCVD were at 5.1 and 16.6 cm from the beam axis, respectively. The single hit resolution of the DCVD was measured with hadronic data to be typically $\sigma^2(\mu\mathrm{m}^2) = (28)^2 + (43)^2 \cdot \mathrm{d(cm)}$, where d is the drift distance to the sense wire plane. The efficiency for finding hits from closely spaced tracks was nearly one for tracks as close as 500 μm, corresponding to an angular separation of about 5 mrad at the mean chamber radius. The SSVD[11] 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 with 512 strips each, and strip pitches of 25, 29, and 33 μm, respectively. Averaged over all tracks, the 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, particle trajectories were most accurately determined in the plane perpendicular to the beam axis. All impact parameters used in this analysis were for tracks projected into this plane.

The integrated luminosity was 10.1 ± 0.7 nb^{-1}, taken near the peak of the Z^0 resonance. Hadronic Z^0 decays were selected[12] by requiring that there be at least seven charged tracks in the fiducial tracking volume and that the sum of the energy of charged and neutral tracks exceed half the center of mass energy. These criteria select 80.0% of Z^0 hadronic decays. A total of 220 events passed these cuts.

An event was tagged as a $Z^0 \rightarrow b\bar{b}$ decay if there were three or more tracks in the event with $\mathrm{b}/\sigma_{\mathrm{b}} > +3.0$, where the impact parameter b was measured with respect to the Z^0 primary decay vertex (PV) and σ_{b} was the calculated error in b. The impact parameter is a signed quantity. A positive sign indicates that the vector from the PV to the point where the track intersects the thrust axis makes an acute angle with respect to the track direction.

The position of the PV in each event was determined in the plane perpendicular to the beam by fitting a subset of the tracks in the event to a single vertex. The tracks to be included in the fit were chosen as follows. The four tracks in the event that came closest to the average interaction point were fit to a common vertex three at a time. A three-track combination for which the probability of the fit exceeded 1% was chosen as the seed for the PV search. Each of the remaining tracks in the event was then added to the seed in turn, and the vertex fit probability recalculated. The track associated with the most probable vertex fit was retained if the vertex fit probability remained above 1%. This process was repeated until there were no more tracks in the event satisfying this requirement. Monte Carlo (MC) studies confirmed that tracks which did not originate from the primary interaction point but from heavy quark decays did not strongly influence the PV determination.

In order to eliminate poorly measured tracks from the analysis, all tracks were required to satisfy a number of criteria. Each track was required to have an angle with respect to the beam axis (θ) such that $|\cos\theta| < 0.8$. The transverse momen-

tum of each track with respect to the beam axis ($p_\perp$) was required to be larger than 150 MeV/c. The point-of-closest-approach of the track to the PV was required to be less than 15 mm along the beam direction and less than 2 mm transverse to the beam direction. Each track was required to have at least 25 position measurements in the CDC, at least 15 measurements in the DCVD, and at least one measurement in the SSVD. The calculated error in the track position at the point of closest approach to the PV (σ_{TR}) was required to be less than 200 μm. This error included the contribution from multiple Coulomb scattering in the beam pipe and detector.

The impact parameter error is calculated according to the expression $\sigma_{\rm b} \equiv \sqrt{\sigma_{TR}^2 + \sigma_{PV}^2 + (15\mu{\rm m})^2}$, where σ_{TR} is defined above, σ_{PV} is the projection of the error ellipse from the PV fit onto the track, and the extra 15 μm is included primarily to account for detector misalignment.[13] The error ellipse from the PV fit was typically about 15 μm x 75 μm, oriented with its semi-major axis nearly parallel to the thrust direction. The average impact parameter error approaches 28 μm for high momentum tracks, and is 77 μm at $p_\perp\sqrt{\sin\theta} = 1$ GeV/c.

In order to estimate the tagging efficiencies reliably, impact parameter resolution and tracking efficiency must be accurately simulated by the MC. The detector simulation included the effects of detector resolution, layer by layer efficiencies, multiple Coulomb scattering, and elastic and inelastic nuclear scattering. The multiple scattering contribution to the impact parameter resolution was sensitive to the amount of scattering material in the detector. The amount of material in the simulation was therefore adjusted to account for the observed impact parameter resolution of low momentum tracks. The residual alignment errors resulting from the statistical limitations of the alignment procedure were also included in the simulation. Beam associated backgrounds were simulated by the careful mixing of MC events with randomly triggered beam-on data recorded close in time with the Z^0 events in our sample.

We checked the accuracy of the simulation by comparing the predicted distribution of b/$\sigma_{\rm b}$ to that observed in the data. Figure 1a shows this distribution for

high resolution tracks ($\sigma_{TR} < 25\mu$m) which pass the selection criteria. The track being histogrammed was excluded from the subset of tracks used to determine the PV. Tracks from bottom and charm decays preferentially populate the positive tail. The negative half of the b/σ_b distribution is therefore a good measure of the detector resolution function and is relatively insensitive to the value of $R_{b\bar{b}}$. The MC simulation, which is shown as the dotted histogram in the figure, approximates the data, but underestimates both the width of the core and the amount of the negative tail. Accordingly, we adjusted the resolution function that was used in the simulation until it agreed with the negative half of the measured distribution. This was accomplished by adding a Gaussian-distributed tracking error with a mean of zero and an r.m.s. width of 75 μm to the simulated impact parameter of 15% of the MC tracks, selected at random. The improved simulation is shown as the solid histogram in Figure 1. The fraction of tracks affected by this tail distribution can be varied by $\pm 5\%$, and the r.m.s. width can be varied by $\pm 25\mu$m before the MC distribution becomes inconsistent with the measured distribution. This adjustment has very little effect on the simulation of the b/σ_b distribution for lower resolution tracks, shown in Figure 1b. The simulation describes these data adequately.

$R_{b\bar{b}}$ was calculated from the observed fraction of tagged events after determining tagging efficiencies for $b\bar{b}$ and non-$b\bar{b}$ events. We used the Lund 6.3 MC[14] with the parton shower option to simulate Z^0 decays. The values of several important MC parameters were taken from measurements performed at the LEP storage ring and from lower energy experiments where appropriate. The B hadron lifetime was set to 1.24 psec,[15] the mean fragmentation variable $< x_E >_b$ was set to 0.68,[3][4] and $R_{c\bar{c}}$ was set to 0.17.[16] The multiplicity and momentum spectra of the B decay products were tuned to agree with the measurements of the CLEO[17] and ARGUS[18] collaborations. For those events passing the hadronic selection cuts, the tagging efficiency was 0.500 for $Z^0 \rightarrow b\bar{b}$ decays and 0.023 for Z^0 decays into other quark flavors.

The application of the $b\bar{b}$ tagging requirement to the sample of 220 hadronic events resulted in a sample of 32 events. After correcting for the fact that the event

selection criteria were 3.0% more efficient for selecting $b\bar{b}$ events, we calculate that $R_{b\bar{b}} = 0.251 \pm 0.049$, where the error is statistical only.

We have checked this result by varying the $b\bar{b}$ tagging requirements and re-evaluating $R_{b\bar{b}}$ after accounting for changes in the tagging efficiencies. Requiring 2 (4) or more tracks with $\mathrm{b}/\sigma_{\mathrm{b}} > +3.0$, instead of 3, changed the $b\bar{b}$ tagging efficiency by +33% (−31%), but led to values of $R_{b\bar{b}}$ which differed from the nominal value by only +1.6% (+5.9%). Requiring 3 or more tracks with $\mathrm{b}/\sigma_{\mathrm{b}} > +2.0$ (+4.0) changed the $b\bar{b}$ tagging efficiency by +16% (−12%), and led to changes in $R_{b\bar{b}}$ of +1.7% (+10.0%). All these values of $R_{b\bar{b}}$ are consistent with the value cited above.

The significant contributions to the systematic error in $R_{b\bar{b}}$ are listed in Table 1. Several of these errors arose from uncertainties in the performance of the detector. To study the effects of uncertainties in the detector resolution function, we varied the amount of additional tracking error in the MC within the ranges discussed above. The effect of attributing the additional tracking errors to particular azimuthal regions in the detector was also investigated, as were the effects of adding a small additional tracking error to all tracks in the simulation and adding a large, nearly uniformly distributed error to a small fraction of the simulated tracks. From these studies, the estimated systematic error due to uncertainty in the detector resolution function was ±9%. If we had not adjusted the resolution function in the simulation to include additional tracking errors, the value of $R_{b\bar{b}}$ would be 7% larger. The uncertainty in the tracking efficiency was due to imperfect knowledge of the CDC performance, uncertainties in the efficiency of associating vertex information with CDC tracks, and uncertainties in the double track resolution. The net uncertainty was ±2%, and this resulted in an uncertainty in $R_{b\bar{b}}$ of ±2%. The determination of the amount of scattering material in the detector was uncertain by ±2%, which resulted in a ±4% uncertainty in $R_{b\bar{b}}$. Neither elastic nor inelastic nuclear interactions, which were modelled in the MC, had a significant effect on the determination of $R_{b\bar{b}}$.

In addition to detector related effects, systematic errors associated with im-

precise knowledge of Z^0 event properties and heavy quark production and decay have been explored. The B hadron lifetime was varied by ± 0.12 psec, $< x_E >_b$ was varied by ± 0.03, and $R_{c\bar{c}}$ was varied by ± 0.04. The multiplicity and momentum spectra of the B decay products were allowed to vary within the errors of the CLEO and ARGUS measurements. The effects of uncertainties in the charmed hadron lifetimes and in the relative populations of the various charmed particle types were found to be $< 1\%$. The total systematic error from all sources listed in Table 1, added in quadrature, is $\pm 12\%$ of the measured $R_{b\bar{b}}$.

In conclusion, we have presented a method for tagging $Z^0 \rightarrow b\bar{b}$ events based on the precise measurement of track impact parameters. This method, which tags $Z^0 \rightarrow b\bar{b}$ decays efficiently (50%) and cleanly (85% purity), holds considerable promise for future precision measurements of $R_{b\bar{b}}$. We have measured $R_{b\bar{b}}$ to be $0.251 \pm 0.049 \pm 0.030$, where the quoted errors are statistical and systematic, respectively. This measurement is consistent with previous measurements and with the prediction of the Standard Model, $R_{b\bar{b}}$=0.22.[16]

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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. Contributions to estimated systematic error.

Figure Caption

1. Distribution of b/σ_b for tracks with $\sigma_{TR} < 25\mu m$ (a) and $\sigma_{TR} > 25\mu m$ (b). The data are shown as points with error bars. The dotted histogram is the Monte Carlo prediction before additional tracking error is added to the simulation; the solid histogram includes the effects of the additional tracking error discussed in the text.

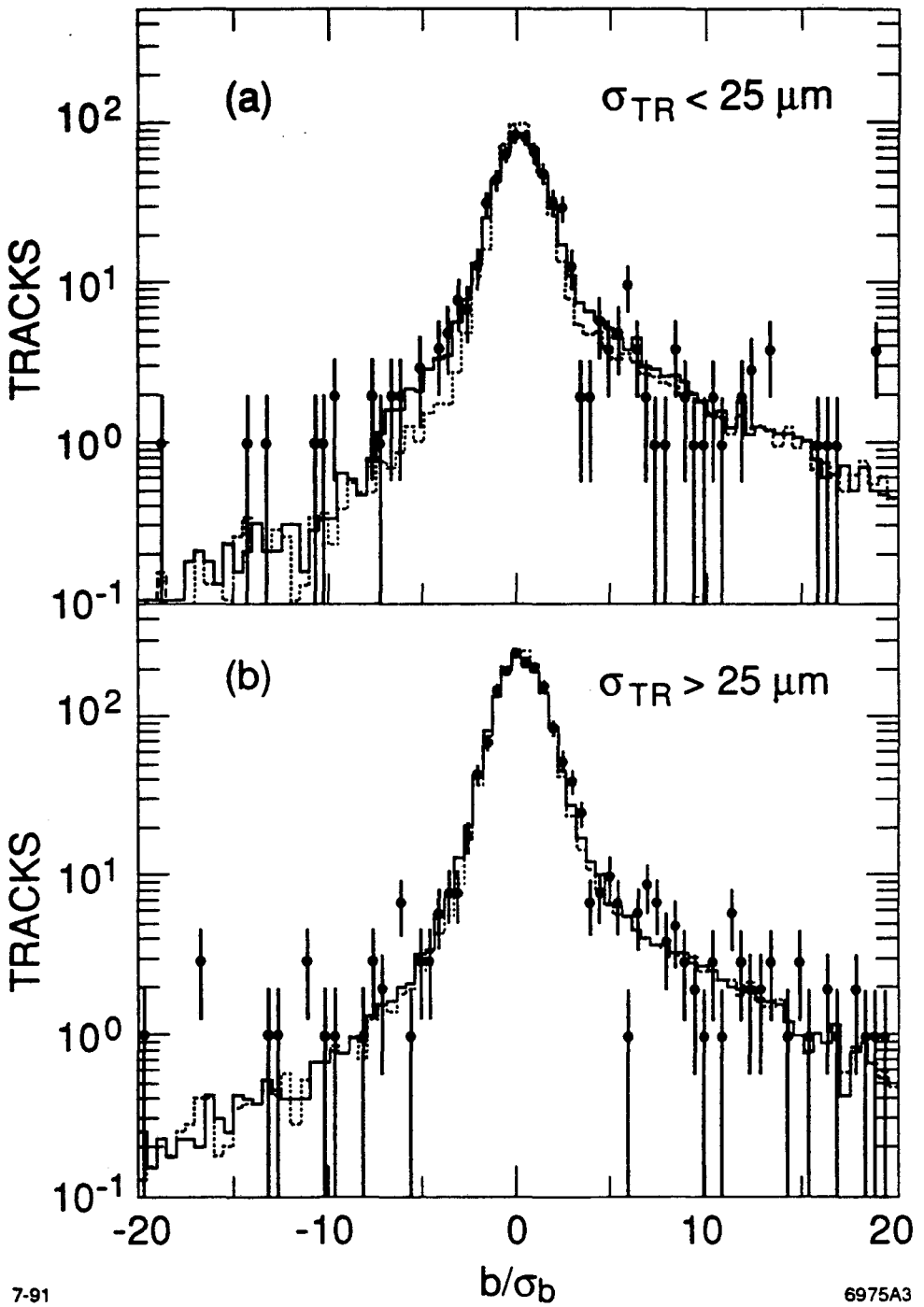
(a)
$\sigma_{TR} < 25\ \mu m$
(b)
$\sigma_{TR} > 25\ \mu m$
TRACKS
TRACKS
10^2
10^1
10^0
10^{-1}
-20
-10
0
10
20
b/σ_b
7-91
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Fig. 1

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