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## Measurements of $R_b$ with Impact Parameters and Displaced Vertices

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### ABSTRACT

We present measurements of  $R_b$  using the SLD at the SLC. The analyses use 2-D and 3-D impact parameter tags and a displaced 3-D vertex tag which all exploit the small size and stability of the  $e^+e^-$  interaction point and the precision 3-D CCD pixel vertex detector to achieve high  $b\bar{b}$ -tagging efficiencies and purities. The combined measurement yields  $R_b = 0.229 \pm 0.011$  and is consistent with Standard Model predictions.

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# 1 Introduction

Measurements of the  $Z^0 \rightarrow b\bar{b}$  coupling provide an interesting means for testing the Standard Model. In contrast to those for light flavors, the  $Z^0 \rightarrow b\bar{b}$  vertex is expected to be subject to relatively large radiative corrections resulting from  $|V_{tb}| \sim 1$  and the large top quark mass[1]. The quantity  $R_b = \frac{\Gamma(Z^0 \rightarrow b\bar{b})}{\Gamma(Z^0 \rightarrow \text{hadrons})}$  isolates the  $Z^0 \rightarrow b\bar{b}$  vertex corrections as it is insensitive to QCD effects and oblique corrections which affect all quark flavors equally. Using  $R_b$ , vertex corrections directly resulting from the presence of the  $t$  quark may be observed. Recent evidence from CDF and D0 for a top mass of  $\sim 180 \text{ GeV}/c^2$  [2] suggests that a deviation in  $R_b$  from the tree level coupling of  $\sim -1.5\%$  should be observed. Furthermore, proposed extensions of the Standard Model would imply additional potentially measurable deviations in  $R_b$  from the Minimal Standard Model value[3]. Currently, the LEP average  $R_b$  measurement is  $\sim 2\sigma$  high[4] compared to the Standard Model value. These measurements include lepton tags[5], event shape tags[6], lifetime double tags[7], or a mixture of different tags[8]. The measurements presented here use simple event lifetime tags with relatively transparent systematics and are performed under the unique experimental environment with the CCD pixel vertex detector of the SLAC Large Detector(SLD)[9] and the small interaction point of the SLAC Linear Collider.

The SLD with its precision vertex detector has excellent resolution for measuring decay lengths and separating secondary vertices from primary vertices. The SLAC Linear Collider(SLC)  $e^+e^-$  beams collide at the SLD interaction point with center of mass energy equal to the  $Z^0$  peak. The small and stable  $Z^0$  production point provided by the SLC combined with the precision of the detector enhances the use of methods which directly exploit the  $B$ -hadron lifetime to tag  $b\bar{b}$  events with high efficiency and low contamination.

The large mass and long lifetime( $\sim 1.5 \text{ ps}$ ) of  $B$ -hadrons results in the production of many secondary vertices of high multiplicity displaced far from the primary vertex in  $Z^0 \rightarrow b\bar{b}$  decays. A significant number of tracks from these secondary vertices will have large impact parameters with respect to the primary vertex. Methods to tag  $b\bar{b}$  events initially developed by the TASSO[10] and MARK II[11] experiments used cuts on either the number of tracks with large impact parameters or the number of secondary vertices for their  $b\bar{b}$  tags. Here, using similar techniques, we present  $R_b$  results obtained from three variations of  $b\bar{b}$  event lifetime tagging methods.

The content of this paper is organized as follows: The SLD and the performance of its components used in this analysis are introduced. The means of determining the event production point is presented. The Monte Carlo (MC) simulation used in determining the tagging efficiencies is outlined. The details of the event and track selection are then described. Finally,  $R_b$  results along with systematics and verification checks are given.

## 2 The SLAC Large Detector

During the 1992 and 1993 runs over 60k  $Z^0$  events produced by the SLC were recorded by the SLD. A subset of these events constitute the fiducial sample for the analyses presented here. Details of all SLD components are described elsewhere[9]. Here we

describe only the detector elements used for this analysis, namely the Vertex Detector (VXD), the Central Drift Chamber (CDC) and the Liquid Argon Calorimeter (LAC) operating in a 0.6T magnetic field.

## 2.1 Vertex Detector

The close proximity of the VXD[12] to the beam line and the precise 3-D hit locations it provides allow clear distinction of secondary vertices from the primary vertex. The VXD consists of 480 charge coupled devices (CCDs) as the basic detector elements. Each CCD consists of 20  $\mu\text{m}$  thick active epitaxial silicon residing on a 180  $\mu\text{m}$   $p^+$  silicon substrate and contains  $375 \times 578$  22  $\mu\text{m}$  square pixels. Eight CCDs mounted on an alumina mother board with printed electrical connections comprise a ladder. Each ladder has 4 CCDs on the top face and 4 on the bottom face, spaced so as to leave no gaps in the CCD coverage along the length of the ladder. There are 60 ladders arranged in 4 concentric layers with each ladder having an active length of 92 mm. The innermost ladders are located 29 mm from the beam line and the outermost ones at 41 mm. The geometry of the VXD is shown in a cross-section transverse to the beamline in Figure 1. The innermost (outermost) layer subtends a range of  $|\cos\theta| < 0.85$  ( $< 0.75$ ). The spacing of the ladders in  $\phi$  is such that there are no gaps in the  $\phi$  coverage of the CCDs between the first and last pairs of layers. A track coming from the interaction point is guaranteed to pass through two CCDs, with the average being 2.3. Dark current in the detector is reduced to a negligible level by operating at a temperature of 195K using cold nitrogen gas flowing throughout the VXD. A low mass cryostat surrounding the VXD insulates it from the rest of the detector. The ladder support system is made of beryllium to reduce multiple scattering and provide maximal mechanical stability. A 1 mm thick Be beam pipe with a 100  $\mu\text{m}$  Ti liner is located at a radius of 25 mm. Including a 0.5 mm Be gas shell, the total material before the first CCD layer is 0.71% radiation length (rl); for each CCD-layer traversed at normal incidence a particle will see  $\sim 1.1\%$  rl. (See Table 1.) Approximately 4% of the CCD channels were found to be faulty immediately after installation mostly due to inaccessible connection problems. No further degradation in the performance of the CCDs, their connections, or the front end electronics was observed during the 1992 or 1993 runs.

## 2.2 Central Drift Chamber

Charged track momentum measurements are made using the CDC[13] which is 1.8m long and extends radially from 0.2m to 1.0m. It consists of 10 superlayers, four coaxial to the beam with each of these separated from the next by two with stereo angles of  $\pm 41$  mrad. Each superlayer consists of cells 50 mm along the radius and  $\sim 59$  mm wide in azimuth at the midpoint. Each of the 640 cells contains eight 25  $\mu\text{m}$  diameter gold plated tungsten sense wires separated radially by 5 mm. Eighteen 150  $\mu\text{m}$  diameter gold plated aluminum field shaping wires are placed 3.5 mm from either side of the sense wire plane. Two additional field shaping wires at the top and bottom of the cell plus twenty-five 150  $\mu\text{m}$  diameter gold plated aluminum field wires surrounding the cell complete the field shaping. The geometry of the CDC as seen from one

end of the detector is shown in Figure 2. The sense and field shaping wires of a cell are strung as a unit to a Lexan block so that the relative positions of the wires within a cell are fixed and well known. Readout for pulse heights and times of hits is implemented on both ends of the wires. This information is used to derive the drift times and charge division of the hits. An average spatial resolution of  $70 \mu\text{m}$  is obtained with a cool gas of  $\text{CO}_2$ :Argon:Isobutane in the ratio of 75% : 21% : 4% respectively. In addition,  $\sim 0.3\%$  of water is added to help retard wire aging. The chamber is operated at atmospheric pressure. The chamber pressure, temperature and gas mixture is monitored and controlled precisely. The radiation lengths of material seen by a track passing through the central tracking volume are listed in Table 1.

### 2.3 Liquid Argon Calorimeter

The LAC[14] is used in the hadronic event trigger and in determining the thrust axis direction for event acceptance cuts. The LAC barrel inner radius is 1.77m and extends to 2.91 m. The barrel and endcaps consist of lead plates separated by liquid argon. The barrel covers  $|\cos\theta| < 0.84$  and endcaps cover  $0.82 < |\cos\theta| < 0.98$  for the full azimuthal range. Each has a 21 radiation length thick electromagnetic (EM) section before a 2.0 absorption length hadronic (HAD) section. In the barrel the azimuthal segmentation( $\Delta\phi$ ) for the EM section is 33 mrad and the polar segmentation( $\Delta\theta$ ) is given by  $\frac{\Delta\theta}{\sin\theta}=36$  mrad. In both the polar and azimuthal dimensions the HAD towers are twice the size of the EM towers. The projective area of the towers in the endcaps is approximately the same as the barrel. The energy resolution of the calorimeter barrel for electromagnetic showers of energy E is measured to be  $\frac{\sigma}{E} = \frac{15\%}{\sqrt{E(\text{GeV})}}$  and  $\frac{60\%}{\sqrt{E(\text{GeV})}}$  for hadronic showers.

## 3 Tracking Performance

The analyses in this paper rely critically on the performance of the tracking systems. The first stage of track reconstruction is done in the CDC with pattern recognition followed by track fitting. The second stage leading to a combined CDC and VXD track is then performed by extrapolating the CDC track into the VXD and linking to the best set of VXD hit pixel clusters. A combined track fit is performed using the Billoir[15] method to take into account the track multiple scattering through detector material.

The CDC track pattern recognition is aided by the charge division with a resolution of  $\sim 6$  cm along the wire, while the final track fit only uses the drift time information from axial and stereo wires. The CDC gas drift velocity constants are determined on a run by run basis and checked against values obtained from slow monitoring information of gas temperature, pressure and water concentration. The cell by cell wire block position alignment is determined from tracks[16] with constraints provided by the known mechanical construction tolerances. Isolated tracks in hadronic  $Z^0$  decay events are used to determine the local cell offsets and tilts, while  $Z^0 \rightarrow \mu^+ \mu^-$  and cosmic ray events are used to remove long range global misalignment

features. The CDC spatial resolution achieved is 50-100  $\mu\text{m}$  for most parts of a cell and  $\sim 200 \mu\text{m}$  near the sense and field wires. The azimuthal angle and polar angle resolution on the track direction at the inner radius of the CDC are 0.45 mrad and 3.7 mrad respectively for high momentum tracks.

The VXD hit cluster linking includes a final pass to allow linking to just one VXD hit with a loose beam constraint during pattern recognition. This results in a uniform track VXD linking efficiency around the full azimuth without degradation for regions with malfunctioning ladders. Each VXD hit cluster is only allowed to be associated to one track. This mainly removes tracks produced in particle interactions with detector material which linked to wrong VXD hits. Correctly linked tracks very rarely lose hits in this arbitration process due to the fine granularity of the 3-D pixels. For all good CDC tracks within the VXD acceptance, with transverse momentum  $P_{\perp} > 300 \text{ MeV}/c$  and which extrapolate to the proximity of the interaction point, 93% link to VXD hits in the data. This agrees with the MC simulation to within 1%. Of these CDC tracks there are still tracks resulting from long lived particle decays and products of interactions with detector material which should not have VXD links. MC studies indicate that for CDC tracks from primary vertex and heavy hadron decays, 96.2% are correctly linked with VXD hits. Of the remaining tracks 2.3% have no VXD link and 1.5% linked with at least one wrong VXD hit.

The VXD ladders and barrel structures were optically surveyed before installation [12][17]. The individual ladder survey provides relative locations of CCDs on the same ladder while the barrel structure survey supplies the ladder locations for an initial VXD geometry. The VXD internal ladder to ladder alignment is then performed using tracks in  $Z^0$  decay events allowing each ladder to shift, rotate and bow while relative locations of CCDs on each ladder are fixed according to optical survey measurements. The tracks in all  $Z^0$  decay events which have hits in three or more VXD layers are used to provide local constraints between layers, while the  $Z^0 \rightarrow \mu^+\mu^-$  and  $Z^0 \rightarrow e^+e^-$  events are used to provide global constraints. Special attention is paid to the matching of CDC tracks and VXD hit vectors globally and as a function of  $\phi$  in both the CDC and VXD alignment procedures. The VXD internal alignment parameters show very good consistency between 1992 and 1993 data, indicating that the beryllium support structure has indeed ensured the integrity and stability of the VXD internal geometry over a long period of time against thermal cycling. As a last step of the alignment procedure, the VXD is treated as a rigid body and its rotation and shift with respect to the CDC are determined using tracks in hadronic  $Z^0$  events. The overall VXD spatial resolutions achieved, including intrinsic and remaining alignment errors, are estimated from tracks with hits in 3 layers (see Figure 3) and from the miss distance for  $Z^0 \rightarrow \mu^+\mu^-$  and  $Z^0 \rightarrow e^+e^-$  tracks fitted to VXD hits alone with a momentum constraint. The two methods obtained very similar results corresponding to a single hit  $r\phi$  resolution of 5.5  $\mu\text{m}$  over all  $\cos\theta$  and effective  $z$  resolution of 5.5  $\mu\text{m}$  at  $\cos\theta = 0$  and 9  $\mu\text{m}$  averaging over tracks at  $|\cos\theta| > 0.55$ . The deterioration of effective  $z$  resolution at high  $|\cos\theta|$  is primarily due to alignment errors in the ladder radial position and shape.

The impact parameter resolution obtained from combining the CDC and VXD hits for high momentum tracks is determined from the two track miss distance using  $Z^0 \rightarrow \mu^+\mu^-$  events. The single track impact parameter resolution is found to be 11  $\mu\text{m}$  in the  $r\phi$  view and 38  $\mu\text{m}$  in the  $rz$  view. The significantly better resolution in the  $r\phi$  view is due to the much more accurate CDC track  $\phi$  angle resolution compared to polar angle resolution used in the combined fit. The impact parameter resolution

for lower momentum tracks is determined from hadronic  $Z^0$  data and using the MC to correct for contributions from heavy hadron decay and uncertainty in the interaction point position. The impact parameter resolution obtained for 1 GeV tracks at  $\cos\theta = 0$  is  $76 \mu\text{m}$  in the  $r\phi$  view and  $80 \mu\text{m}$  in the  $rz$  view. The momentum resolution for the combined CDC and VXD track fit is  $\frac{\delta p_{\perp}}{p_{\perp}} = 0.01 \oplus 0.0026 p_{\perp}$ . The combined track fit also improves the track momentum direction resolution near the interaction point by 30% in  $\phi$  and 40% in  $\theta$  compared to the CDC-alone track.

## 4 Primary Vertex Determination

An accurate knowledge of the individual event Primary Vertex position (PV) is necessary as a reference location to distinguish secondary vertices in  $b\bar{b}$  events. The best estimate of the PV in the transverse plane is the average SLC Interaction Point ( $\langle IP \rangle^1$ ). The size of the SLC luminous region is much smaller in the transverse dimensions ( $\sigma \sim 2 - 3 \mu\text{m}$  in  $x$  and  $0.5 - 1 \mu\text{m}$  in  $y$ ) than in the beam direction ( $\sigma_z \sim 700 \mu\text{m}$ ). For this reason, the  $\langle IP \rangle$   $r\phi$  position is determined with track parameters and errors from many sequential hadronic events. Due to the large spread of the luminous region in the beam direction the longitudinal position of the PV is determined for each event individually.

### 4.1 Transverse Position

If tracks consistent with coming from the  $Z^0$  PV in a single hadronic event are fit to a common vertex in the  $r\phi$  plane, the PV fit error ellipse is typically  $\sim 100 \mu\text{m}$  along the major axis and  $\sim 15 \mu\text{m}$  along the minor axis. This  $\sim 15 \mu\text{m}$  would be the PV contribution to the impact parameter error of a track in the direction of the major axis, which is approximately the direction of the thrust axis. Tracks at large angles to the thrust axis have significantly larger errors.

The motion of the SLC IP for the time period over which events are averaged is estimated to be  $\sim 6 \mu\text{m}$  determined by monitoring the corrector magnets which keep the SLC beams in collision. This means the  $\langle IP \rangle$   $r\phi$  position is a better estimate of the PV position in an event than the one found with tracks from only that event. Using the  $\langle IP \rangle$  as the PV position substantially reduces the uncertainty in the PV location due to single track resolution, and removes the elongation of the PV error ellipse in the direction of the thrust axis, as the  $\phi$  distribution of thrust axes is isotropic. In addition, by averaging over many events to determine the IP position, systematic errors due to the difficulty of finding the correct PV in events with many secondary decay vertices are greatly reduced.

The SLD data sample is divided into sets of 30 sequential hadronic  $Z^0$  decays, except when a run ended after more than 20 events into a set, at which point the set is ended. An  $\langle IP \rangle$  is then determined for each set. All tracks which have VXD hits and which come within  $3\sigma$  of a trial  $\langle IP \rangle$  are fit to a common vertex. Typically 330 tracks are used in a fit. The fit  $\langle IP \rangle$  is then used as a new trial  $\langle IP \rangle$ , and the

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<sup>1</sup>The IP position is the center of the luminous interaction region within which the PV is located.

process is iterated until it converges. The  $\chi^2/dof$  and the fraction of tracks within  $3\sigma$  of the fit  $\langle IP \rangle$  are checked for each set, along with the time history of the  $x$  and  $y$   $\langle IP \rangle$  positions, to identify sets which might span a major shift in  $IP$  position. The  $\chi^2/dof$  is required to be  $< 1.3$ , and the number of tracks used in the fit is required to be more than eight times the number of events in the set. Information from the SLC correctors is used to help determine exactly when a major shift occurs. When a major shift is found within a set, the boundaries of the set are changed to coincide with where the IP shift occurs while still maintaining  $\sim 30$  events per set whenever possible, and the fitting procedure is repeated.

The fit  $\langle IP \rangle$  position for the set in which an event resides is then used as the best estimate of the PV  $r\phi$  position for that event. For a hadronic  $Z^0$  decay, some tracks from that event are most likely used in the fit, but typically any one event contributes only a few percent of the tracks used in the fit. The uncertainty in the  $\langle IP \rangle$  ( $\sigma_{IP}$ ) is the convolution of the statistical error from the fit ( $\sim 3 \mu\text{m}$ ), the extent of the SLC luminous region ( $\sim 1 \mu\text{m}$ ), and the motion of the IP within a set ( $\sim 6 \mu\text{m}$ ), giving a total of  $\sim 7 \mu\text{m}$  when added in quadrature. Several methods are used to estimate  $\sigma_{IP}$  from the data. The distribution of track impact parameters with respect to  $\langle IP \rangle$  in  $\mu^+\mu^-$  events (shown in Figure 4 for the 1993 data) is a good independent measure, as  $\mu^+\mu^-$  and  $e^+e^-$  events are not used in any way for the determination of  $\langle IP \rangle$ . The  $\sigma$  of the distribution is  $12.7 \mu\text{m}$ ; when the track extrapolation error, measured from  $\mu^+\mu^-$  miss distance, is subtracted in quadrature, this gives  $\sigma_{IP} = 6.7 \mu\text{m}$ . In hadronic events where most tracks fit to a common vertex, the distance ( $y_T$ ) between the  $\langle IP \rangle$  and the fit vertex, projected onto the minor axis of the fit vertex error ellipse, also contains information on  $\sigma_{IP}$ . This  $y_T$  distribution, while having high statistics, includes some contamination from  $Z^0 \rightarrow b\bar{b}$  and  $c\bar{c}$  events. A second sample where all tracks fit to a common vertex is a very pure sample of light quark events but are significantly lower in statistics. The  $y_T$  distributions for both these samples were studied, along with the  $\mu^+\mu^-$  and  $e^+e^-$  track impact parameter distributions, and all distributions agree with  $\sigma_{IP} = 7 \mu\text{m} \pm 2 \mu\text{m}$  ( $9 \mu\text{m} \pm 2 \mu\text{m}$ ) for the 1993 (1992) data.

Even though the procedure for finding the  $\langle IP \rangle$  is set up to minimize large beam motion in each set, it is still possible that a few sets contain events which occur far from the  $\langle IP \rangle$ . The same distributions which are used to estimate  $\sigma_{IP}$  are searched for evidence of non-Gaussian tails. The cleanest of the checks, the  $\mu^+\mu^-$  impact parameter distribution, shows no evidence for non-Gaussian tails, but because  $\Gamma_{Z^0 \rightarrow \mu^+\mu^-} \ll \Gamma_{Z^0 \rightarrow \text{hadrons}}$ , this in itself can not conclusively rule out non-Gaussian tails on  $\langle IP \rangle$ . The highest statistics check, the  $y_T$  distribution in hadronic events where most tracks fit to a common vertex, shows that the MC and data have similar non-Gaussian tails. The MC indicates this tail is due to the occasional inclusion of  $B$  or  $D$  decay tracks in the vertex fit. All other distributions show smaller non-Gaussian tails than this one. The non-Gaussian tails in all the distributions are conservatively represented by a second IP spread ( $\sigma'_{IP}$ ) of  $100 \mu\text{m}$  in  $< 0.25\%$  ( $< 0.5\%$ ) of the events collected in 1993 (1992).

## 4.2 Longitudinal Position

In contrast to the  $r\phi$  view, the approach of combining many events to determine  $\langle IP \rangle$  cannot provide an adequate estimate of the event PV  $z$  position due to the rather large beam interaction region  $z$  spread of  $\sigma_z \sim 700 \mu\text{m}$ . The best estimate of the PV  $z$  position for an event comes from a technique using only the median  $z$  of tracks in the event itself. Each track with associated VXD hits is extrapolated to the point of closest approach to the  $\langle IP \rangle$  in the  $r\phi$  view and the  $z$  coordinate of the track at this point is denoted as  $z_{doca}$ . A selection of tracks is then made to require the track  $r\phi$  impact parameter to the  $\langle IP \rangle$  to be less than  $500 \mu\text{m}$  and consistent with originating from the  $r\phi \langle IP \rangle$  within  $3\sigma$  based on the estimated track impact parameter error and  $\langle IP \rangle$  error. The event IP  $z$  location is simply defined as the *median* of the  $z_{doca}$  values from the selected tracks. For the small fraction of events with no tracks passing this selection, all tracks with VXD hits are used. The choice of the median  $z$  method instead of the more common approach involving vertexing is based on the result of a MC study showing that the median  $z$  is more robust against the effect of inclusion of tracks not originating from the PV. The typical resolution of locating the PV  $z$  as derived from MC using RMS of the residual  $z_{estimate} - z_{true}$  are (32,36,52)  $\mu\text{m}$  for ( $uds, c, b$ ) events respectively. The tails of the PV  $z$  residual distributions can be characterized by the fraction of events with residual  $> 100 \mu\text{m}$ . The fraction of such events are (0.8%,1.6%,7.5%) for ( $uds, c, b$ ) events respectively according to the MC.

## 5 Monte Carlo Simulation

The analyses use the flavor tagging efficiencies, estimated from the MC, to determine  $R_b$  from the rate at which events are tagged in the data. It is therefore necessary to have an accurate simulation of  $Z^0$  event properties and detector response.

### 5.1 Monte Carlo Physics Modelling

The  $Z^0 \rightarrow hadrons$  MC events are simulated using the JETSET 6.3[18] generator framework. The QCD parton shower and LUND string fragmentation parameters used are the same as those determined by TASSO at  $\sqrt{s} = 35 \text{ GeV}$ [19], and have been found to be in good agreement with data at the  $Z^0$  energy[20]. The heavy flavor fragmentation functions used for the  $b$  and  $c$  quarks are according to Peterson *et.al.*[21] with  $\epsilon_b = 0.006$  and  $\epsilon_c = 0.06$  respectively. The resulting average energy of  $\langle x_E \rangle = 0.695$  for  $B$  hadrons in  $b\bar{b}$  events and  $\langle x_E \rangle = 0.501$  for  $D^*$  mesons in  $c\bar{c}$  events are in good agreement with the existing measurements[22]. The mean event total charged particle multiplicity of  $\langle n_{ch} \rangle = 21.1$  from this MC is also consistent with the experimental measurements[23].

The decays of  $D^0, D^+, D_s$  mesons and  $\Lambda_c$  baryons are simulated with exclusively tabulated branching ratios based on measurement results listed in the particle data group review[24]. Some unmeasured decay modes are also included with branching ratios according to expectations from isospin symmetry in comparison with measured decay modes. Decay modes with large measurement errors are adjusted within



tolerance to reproduce the observed inclusive production rates of leptons, kaons[24] and the  $D$  meson decay charged multiplicity distributions from Mark-III[25]. The charm meson 3-body semileptonic decay simulation uses the WSB[26] form factor model, while all remaining decay modes are simulated by phase space distribution. The decays of weakly decaying charm baryons other than  $\Lambda_c$  are simulated using the JETSET 6.3[18] heavy flavor decay package. The  $D^{*+}$  and  $D^{*0}$  decay branching ratios in the MC are updated to the recent measurements from CLEO[27].

$B$  hadron decays are simulated via a hybrid heavy hadron decay model. The  $B$  baryon decay simulation uses the unmodified LUND 6.3 heavy hadron decay package[18], while the  $B$  meson decay simulation involves several parts as follows:

- A total of 25.0% of the simulated  $B$  meson decays are semileptonic. The ISGW[28] form factor model is used with the inclusion of  $D^{**}$  production. The fractions of decays producing charmed spectator mesons  $D$ ,  $D^*$ , and  $D^{**}$  are chosen to be 0.33, 0.58, and 0.09, respectively in our MC. The semileptonic branching fractions to electrons, muons and taus are set to (11.0%,11.0%,3.0%) respectively. The resulting MC lepton momentum spectrum from  $B_u, B_d$  decays in the  $B$  rest frame, including the leptons from  $b \rightarrow c \rightarrow \ell$ , is in reasonable agreement with the recent CLEO data[29].
- A total of 12.5% of the branching fraction for each  $B$  meson is simulated with exclusively tabulated branching ratios based on various observed two body hadronic decays[24].
- A total of 6% of the  $B$  meson branching fractions in the MC are produced containing charm baryons in the decay. Baryon production in  $B$  meson decay simulation is controlled explicitly to only occur in association with charm baryon production based on the conclusion from CLEO[30]. The charm baryons are produced by means of internal  $W$ -emission diagrams with diquark popping in the fragmentation involving the charm quark.
- The remaining 56.5% of the branching fraction is simulated via the LUND 6.3 heavy hadron decay package[18], extensively tuned so that the average  $B_u, B_d$  decays in the full model provide a good representation of inclusive particle production for  $B$  meson decays measured at the  $\Upsilon(4s)$ . In this model, the weak decay matrix element is used to specify the four momenta of the quark-level decay products of  $b$  quark decay. Two separate  $q\bar{q}'$  systems are formed from the  $b$  quark decay product and the spectator antiquark. The system involving the spectator is then collapsed into a single particle, while the other system is allowed to fragment according the standard LUND scheme for particle branching and flavor assignment with fragmentation product distributed kinematically according to a phase-space distribution. The fractions of  $D^{**}$  production and internal  $W$  emission are tuned to provide a good description of the charm hadron momentum spectrum in  $B$  meson decays as measured by CLEO[31]. Adjustments are also made to the vector/pseudoscalar particle production ratios and strange quark yield in the fragmentation to achieve a good description of various measured particle production fractions and momentum spectra.

The resulting MC inclusive production rates for various particles averaged between  $B_u$  and  $B_d$  meson decays are listed in Table 2 together with the current measurement

values for comparison. Besides the lepton and charm meson momentum spectra in the  $B$  decay rest frame, the momentum spectra of  $\pi^\pm, K^\pm, K^0$  and protons for average  $B_u, B_d$  decays in the MC are also checked and found to be in good agreement with the ARGUS measurements[35]. The charged track multiplicity for average  $B_u\overline{B}_u$  and  $B_d\overline{B}_d$  decays also gives a good description of the measured  $\Upsilon(4s)$  decay charged multiplicity distribution[33][34].

All mean decay lifetimes of charm hadrons used in the MC are from the 1992 Particle Data Group review[24]. The mean decay lifetime of  $B$  hadrons in the MC are set to 1.55 ps for  $B$  mesons and 1.10 ps for  $B$  baryons, which are in good agreement with current measurements[36]. The  $B$  baryon production in the MC amounts to 8.9% of  $B$  hadron production which in turn translates to an average MC  $B$  hadron lifetime of 1.51 ps.

## 5.2 Detector Simulation

The MC detector simulation is based on GEANT 3.15[37], with a detailed geometric description of the SLD, and produces data that models the detector's response to charged and neutral particles. Simulated  $Z^0$  events are overlaid with signals from events taken on random beam crossings in close time-proximity to each recorded real  $Z^0$  and then processed using standard reconstruction as for data. Information about dead detector channels and the high voltage status of CDC layers from the random beam crossing events are used to simulate detector performance. These random beam crossing events also assist in simulating precisely the geometric and time dependent pattern of beam backgrounds, detector readout noise and trigger conditions. The detector geometry is smeared to reflect uncertainties remaining after the detector alignments have been performed. The simulation elements mentioned here result in a MC with a properly luminosity weighted overall detector response and machine background with the same time dependence as in the data.

# 6 Event and Track Selection

## 6.1 The Event Trigger

The trigger for events used in this analysis employs a simple and efficient algorithm which combines tracking and calorimeter information. The algorithm requires at least 15 GeV of energy in LAC towers passing a high threshold cut (240 MeV for EM towers, 1.2 GeV for HAD towers). At least 10 towers must have contributed to the energy sums with at least one being in the forward and one being in the backward sections of the barrel. Additionally, a track must have been found in the CDC. A track is identified, in the acquisition system, by constructing a map of cells which have hits on at least 4 wires. Then the list of these cells versus superlayer is compared against a lookup table for combinations which are consistent with nearly straight tracks. Any matching combination indicates a track. To avoid triggering on beam background

bursts the trigger is vetoed if the number of CDC cells with at least 6 of the 8 wires hit is  $> 275$ .

## 6.2 Event Selection

To further decrease contamination from non-hadronic interactions and to ensure the relevant detector components are fully operational on a given event the following criteria are placed on events passing the event trigger. The visible energy in events as measured from charged tracks must exceed 18 GeV. The thrust axis, determined from calorimeter clusters, is required to be in  $|\cos\theta| < 0.71$  which is well within the VXD acceptance. At least 7 CDC tracks are required to be present to assist in eliminating  $\gamma\gamma$  and  $\tau^+\tau^-$  events. At least one CDC track must have hits from the first or second CDC layer to ensure that the high voltage to these layers is on. At least three tracks with two or more VXD hits must be found. A fiducial set of 16K(5K)  $Z^0$  events is obtained from 1993(1992) data. The corresponding samples of MC events is 84K(22K) for 1993(1992). The non-hadronic background (primarily  $\tau^+\tau^-$ ) is  $< 0.2\%$ , as determined from the MC. The flavor bias potentially introduced by trigger and event selection for  $b$ -quarks relative to light flavor  $Z^0$  events is determined from the MC. No bias was observed within Monte Carlo statistical errors.

## 6.3 Track Selection

Poorly measured tracks and tracks resulting both from interactions with the detector material and from long lived particle decays often have large impact parameters that can lead to contamination of the  $b$ -tagging signal. These tracks can be efficiently removed by requirements on the measured production point of the tracks and by identifying and removing long lived neutral particles that decay into a pair of tracks ( $V^0$ ) before leaving the track detection region.

Well measured tracks are selected by requiring that the CDC track start at radius  $< 39.0$  cm, and has  $> 40$  hits. The CDC track is required to extrapolate to within 1 cm of the  $\langle IP \rangle$  in  $xy$ , and within 1.5 cm of the PV in  $z$  to eliminate tracks from interaction with the detector material and poorly measured tracks. The fit of the CDC track must also satisfy  $\chi^2/d.o.f. < 5$ . At least one VXD hit is required, and the combined CDC/VXD fit must satisfy  $\chi^2/d.o.f. < 5$ . Tracks with  $xy$  impact parameter errors  $> 250 \mu\text{m}$ , or with  $xy$  impact parameters  $> 3.0$  mm with respect to the  $\langle IP \rangle$  are removed. The impact parameter error cut acts both as a quality cut and an effective minimum momentum cut. The impact parameter cut assists in removing poorly measured tracks and long-lived strange particle decay products, gamma conversion and nuclear interaction products. Tracks passing all criteria mentioned above will be referred to as quality tracks.

$V^0$ s from  $K_s^0$  decays and  $\Lambda$  decays are identified by searching for pairs of charged tracks forming a neutral vertex significantly displaced from the  $\langle IP \rangle$  with a mass consistent with a  $K_s^0$  or  $\Lambda$ . Gamma conversions are identified by searching for track pairs of opposite charge which, when the tracks are assigned the mass of an electron are consistent with a near zero parent mass at the point where the tracks are parallel to each other in the  $r\phi$  view. Loose requirements on the separation of the

tracks at the vertex position and the opening angle of the tracks are applied. Any track found to belong to a  $V^0$  is eliminated.

### 6.3.1 Tracking Efficiency Corrections

The fraction of tracks passing the quality cuts is different between data and MC. This is primarily due to a simplified simulation of the dependence of the CDC hit efficiency and resolution on the position within a CDC cell. The hit efficiency and resolution near the field wires are too optimistic in the MC. The MC is corrected to yield the proper fraction of quality tracks by systematically removing tracks according to the discrepancy between data and MC on the fraction of CDC tracks classified as good and on the CDC to VXD linking rate for the good CDC tracks. The correction is performed by determining the difference between data and MC on the quality track multiplicity fraction in ranges of  $p_{\perp}$ ,  $\cos\theta$ ,  $\phi$ , and the angle with respect to jet direction for CDC tracks and in the difference in fraction of good CDC tracks that link to VXD hits in ranges of  $p$ ,  $\cos\theta$ , and  $\phi$ . About 6% of the MC tracks are removed to correct for both the good CDC and linking fractions. The dependence of the corrections on the various variables is found to be small which reflects the random nature of the CDC track misreconstruction despite the correlated local hit loss within a cell. This is an expected result of the geometry having a large number of staggered small cells.

### 6.3.2 Tracking Resolution Corrections

The distribution of track impact parameters after suppression of the track population from long lived particle decays is used to check the MC impact parameter resolution. This distribution is generated by using only tracks that appear to originate behind the primary vertex with respect to the jet axis with which the track is associated. Details of the method are given in section 7.1.1. These lifetime depleted impact parameter distributions from the data and MC are compared in the  $r\phi$  and  $rz$  projections for different  $p_{\perp}$  and  $\cos\theta$  regions to examine the quality of MC simulation for impact parameter resolution. The non-Gaussian tail of the impact parameter distribution in the data is found to be well described by the MC in both  $r\phi$  and  $rz$  projections. The core of the MC  $r\phi$  impact parameter distribution is observed to be broader than the data by  $\sim 8\%$ . This is caused by a slightly pessimistic alignment error used for the VXD CCD position smear in the MC. Corrections for this effect are applied to the reconstructed MC track  $r\phi$  impact parameters using the MC information of the true origin of the tracks. The core of the MC  $rz$  impact parameter distribution on the other hand is observed to be narrower than the data. This is the result of some remaining systematic misalignment effects mainly in the VXD ladder bowing shape and the  $\phi$  dependent CDC and VXD track polar angle matching, which have little effect in the VXD spatial resolution estimate but become more significant for the combined CDC and VXD track fit. The MC track  $z$  coordinates at the  $xy$  point of closest approach ( $z_{doca}$ ) are adjusted to mimic the effects in the data. A Gaussian smear of  $\frac{16}{\sin\theta} \mu\text{m}$  is applied to the MC track  $z_{doca}$  in addition to a systematic  $\phi$  dependent shift of  $z_{doca}$  with magnitude typically around  $\pm 20 \mu\text{m}$ . The corrections mentioned here are used in the analyses but the distributions of Figure 5 referred to in Section 7.1, 7.2, and

7.3 are shown without tracking resolution corrections.

## 7 $R_b$ Measurements

$R_b$  is measured by isolating  $b\bar{b}$  events using tags on the lifetime information from the quality tracks in the fiducial sets of events from the MC and the data. For each  $b$ -tag the rate at which events are tagged in data and the efficiencies for tagging each flavor ( $b\bar{b}$ ,  $c\bar{c}$  and  $u\bar{u} + d\bar{d} + s\bar{s}$ ), estimated from MC, are used to calculate  $R_b$ :

$$R_b = \frac{f_{tag} - \epsilon_{uds} - (\epsilon_c - \epsilon_{uds})R_c}{\epsilon_b - \epsilon_{uds}} \quad (1)$$

where  $\epsilon_i = N_{tagged}^i / N_{input}^i$ ,  $i=(b, c \text{ or } uds)$  from the MC and  $f_{tag} = N_{tagged}^{data} / N_{input}^{data}$  from the data. The denominators,  $N_{input}^i$  and  $N_{input}^{data}$ , are the number of data and MC events which passed the selection cuts. The Standard Model value for the  $c$  fraction  $R_c = \frac{\Gamma(Z^0 \rightarrow c\bar{c})}{\Gamma(Z^0 \rightarrow \text{hadrons})} = 0.171$  is used for determining  $R_b$ . The purity of the  $b$ -tagged sample,  $\Pi_b$ , is used as a monitor of the quality of the  $b$ -tag. It is defined as the fraction of  $b\bar{b}$  events in the tagged MC sample using Standard Model values for  $R_b$  and  $R_c$ . The MC generates an  $R_b$  of 0.215.

Three tag methods have been used which take advantage of different abilities of the tracking systems to obtain a high  $\epsilon_b$  while minimizing systematics resulting from modelling of light quarks by having a high purity for the  $b$ -tagged sample. The mechanics of the tags and the results obtained are given below.

### 7.1 2-D Impact Parameter Tag Method

The 2-D impact parameter method utilizes the excellent  $r\phi$  resolution of the tracking systems, the accurate  $\langle IP \rangle$  knowledge in the  $r\phi$  plane and the simplified detector resolution systematics in this plane.

#### 7.1.1 Impact Parameter Signing

The track 2-D impact parameters are signed to indicate whether the track originates in front or behind the PV with respect to the jet axis. The JADE jet finding algorithm[38] with  $y_{cut} = 0.02$  is used on tracks in the event to determine the jet axes and to obtain the track to jet associations. The  $y_{cut}$  is chosen to minimize misassignments of tracks to jets while maintaining an accurate estimate of the  $b$ -hadron flight direction. An average of 2.6 jets per  $Z^0$  event are found. Each track is assigned a positive(negative) impact if it crosses its jet axis in front(back) of the  $\langle IP \rangle$ . This is determined from the sign of the 2-D dot product of a vector from the  $\langle IP \rangle$  to the tracks  $xy$  point of closest approach to the  $\langle IP \rangle$  with the jet axis direction. Secondary decay tracks preferentially populate positive impact parameters due to the lifetime of the parent particle. Negative impact parameter tracks are most often the result of tracking resolution, poorly measured tracks, products of interactions in the detector

material and IP position resolution. Some lifetime information does appear in the negative impact parameter distribution, as negative impact parameters can naturally occur for tertiary decays and as a result of errors in jet assignment and direction.

The significance of the track impact parameter is used as the tagging variable for the tracks. The significance is given by the signed and normalized impact parameter,  $\delta_{norm} = \frac{\delta}{\sigma_\delta}$ , which is formed from the signed impact parameter divided by the error on the track extrapolation combined with the beam position error. The negative normalized impact parameter distribution is used to test the MC resolution simulation by comparing MC and data. The  $\delta_{norm}$  distribution of the data and MC are shown in Figure 5.

### 7.1.2 Tag Requirements and Results

Events are tagged as  $b\bar{b}$ 's by requiring at least three quality tracks in the event to have a significance of  $\delta_{norm} > 3.0$ . These cuts are selected to minimize the overall uncertainty in  $R_b$ . Figure 6 shows the  $b$ -tagging efficiencies and purities for various normalized impact parameter cuts. The number of events versus the number of quality tracks with  $\delta_{norm} > 3.0$  is shown in Figure 7a. In the 1993(1992) data 2617(815) events are tagged. The results are:

|             | $\epsilon_b(\%)$ | $\epsilon_c(\%)$ | $\epsilon_{uds}(\%)$ | $\Pi_b(\%)$ | $R_b \pm (\text{statistical error})$ |
|-------------|------------------|------------------|----------------------|-------------|--------------------------------------|
| <b>1993</b> | 62.7             | 8.9              | 0.3                  | 89          | $0.230 \pm 0.005$                    |
| <b>1992</b> | 61.7             | 9.1              | 0.2                  | 89          | $0.230 \pm 0.009$                    |

## 7.2 The 3-D Impact Parameter Method

The 3-D impact parameter method explores the full capability of the SLD high precision vertex detector. By using the full 3-D information from each track in an event this method is more efficient in tagging  $b$ -events for the same  $b$ -purity.

### 7.2.1 Differences from 2-D Impact Parameter Tag Method

The implementation of the 3-D impact parameter method differs in only a few respects from that of the 2-D impact parameter method. The major difference is that a true 3-D impact parameter is calculated for each track from the point on the extrapolated track which minimizes the distance between the track and the PV. This point on the track is referred to as the 3-D point of closest approach ( $POCA_{3D}$ ). The impact parameter is then signed as described in section 7.1.1, but using a 3-D dot product between the jet direction and the direction of the vector from the PV to the  $POCA_{3D}$ . This signed impact parameter is then normalized by the error on the extrapolated track at  $POCA_{3D}$  combined with the beam position error to form  $\delta_{3D}^{norm}$ . The distribution of  $\delta_{3D}^{norm}$  compared between data and uncorrected MC is shown in Figure 5. It should be noted that  $\delta_{3D}^{norm}$  unlike its 2-D counterpart ( $\delta_{norm}$ ) has zero

phase space at  $\delta_{3D}^{norm} = 0$  leading to the dip visible in Figure 5. The criteria used for track selection differ from the standard cuts only in that the 3-D impact parameter errors and 3-D impact parameters are used rather than the  $xy$  projection.

### 7.2.2 Tag Requirements and Results

Events are tagged as  $b\bar{b}$ 's by requiring at least three quality tracks in the event to have a significance of  $\delta_{3D}^{norm} > 3.0$ . Figure 6 shows the  $b$ -tagging efficiencies and purities for various normalized impact parameter cuts. The number of events versus number of quality tracks with  $\delta_{3D}^{norm} > 3.0$  is shown in Figure 7b. In the 1993(1992) data 3314(1051) events are tagged. The results are:

|             | $\epsilon_b(\%)$ | $\epsilon_c(\%)$ | $\epsilon_{uds}(\%)$ | $\Pi_b(\%)$ | $R_b \pm (\text{statistical error})$ |
|-------------|------------------|------------------|----------------------|-------------|--------------------------------------|
| <b>1993</b> | 76.7             | 14.8             | 0.7                  | 85          | $0.227 \pm 0.004$                    |
| <b>1992</b> | 73.6             | 14.1             | 0.6                  | 85          | $0.240 \pm 0.008$                    |

## 7.3 The 3-D Displaced Vertex Method

The 3-D displaced vertex method exploits the fact that most  $B$  decay tracks should form good secondary vertices in 3-D to reduce contamination from poorly measured tracks. The large separation of the secondary vertices from the  $PV$  reduces sensitivities on errors in the  $PV$  position and sensitivities to uncertainties in  $B$ -lifetimes. The vertex momentum vector provides an estimate of the  $B$  momentum direction without relying on an accurate knowledge of the jet direction.

### 7.3.1 Vertex Identification and Normalized Decay Length Determination

All combinations of quality track pairs in the same jet are tested for a 3-D geometrical vertex fit. The same jet finding algorithm as that for the impact parameter tag methods is used. The quality track selection differs from the standard cuts only in that the  $V^0$  track rejection is not applied in this analysis. To qualify as an 'analysis vertex', the 3-D vertex fit  $\chi^2$  must be less than 10, the two track momentum vector opening angle is required to be  $< 90^\circ$  in 3-D and  $< 160^\circ$  in the  $r\phi$  projection. The vertex position  $r\phi$  radius is required to be  $< 2.2$  cm to avoid vertices from interactions occurring at the beam pipe and detector material. There are on average  $\sim 23$  such 2-prong analysis vertices per event passing the vertex selection cuts. The MC average event vertex multiplicity with tracking efficiency corrections agree with the data to  $\pm 0.5$  vertices. These 2 prong vertices are subsequently analysed individually and no attempt is made to merge them into unique multi-prong vertices; hence each track may appear in more than one vertex.

The 2-prong vertex decay length ( $L$ ) is defined as  $L = (\vec{r}_v - \vec{r}_0) \cdot \vec{P}_v / |\vec{P}_v|$  where  $\vec{r}_v$  is the vertex 3-D position vector and  $\vec{r}_0$  is the PV position.  $\vec{P}_v$  is the summed momentum vector of the 2-prong vertex. The projection of the apparent

vertex displacement vector to the summed momentum direction helps to suppress effect of spurious track combinations and the effect of a shift in the estimated PV from its true location. This also naturally defines the sign of the decay length as positive if the vertex displacement direction is in the same direction as the vertex momentum vector. The significance is given by the normalized decay length ( $L_{norm}$ ) which is formed by dividing  $L$  by the vertex decay length error,  $\sigma_L$ , where  $\sigma_L$  is obtained from the vertex position error and the PV position error projected along the vertex momentum direction then added in quadrature. The distribution of the normalized decay length compared between data and uncorrected MC is shown in Figure 5.

### 7.3.2 Tag Requirements and Results

Events are tagged as  $b\bar{b}$ 's by requiring at least 4 analysis vertices with  $L_{norm} > 3.0$ . Efficiencies and purities obtained with the  $b$ -tag for various normalized decay length and vertex multiplicity cuts are shown in Figure 6. In the 1993 (1992) data 3218 (971) events are tagged. The distribution of the number of analysis vertices with  $L_{norm} > 3.0$  in an event is shown in Figure 7c for data and MC. The results are:

|             | $\epsilon_b(\%)$ | $\epsilon_c(\%)$ | $\epsilon_{uds}(\%)$ | $\Pi_b(\%)$ | $R_b \pm (\text{statistical error})$ |
|-------------|------------------|------------------|----------------------|-------------|--------------------------------------|
| <b>1993</b> | 71.6             | 17.6             | 1.8                  | 79          | $0.221 \pm 0.005$                    |
| <b>1992</b> | 69.1             | 14.9             | 1.4                  | 81          | $0.228 \pm 0.009$                    |

## 8 Systematics

### 8.1 Detector Systematics

The tracking efficiency systematic reflects the uncertainty in the corrections applied to the MC to obtain the correct yield of quality tracks. To estimate the systematic error associated with the  $p_{\perp}$ ,  $\phi$  and  $\cos\theta$  dependence of the track efficiency corrections, the change in  $R_b$  when it is remeasured with these dependencies averaged out relative to the nominal  $R_b$  result is used. The observed change is  $\sim 1\%$ , for all methods, and is taken as the systematic contribution. In addition, a variation of 0.3 tracks per event between different periods of the data is unexplained by the known deficiencies in the MC simulation. Changes in  $R_b$  due to a  $\pm 0.3$  quality track event multiplicity variation in the MC is included as a systematic error.

The tracking resolution systematic comes from the various corrections to the impact parameters in the MC. These include the  $r\phi$  impact parameter modifications to correct for the MC VXD CCD position oversmearing and the  $rz$  smearing and shift corrections, as explained in section 6.3.2, which predominantly affect only the core of the impact parameter and decay length distributions. The uncertainty is taken as the changes in  $R_b$  that result from not applying these corrections in turn then added in quadrature.

The uncertainty of the primary vertex  $xy$  location simulation is represented



by adding an  $\langle IP \rangle$  tail with IP extent of  $100 \mu\text{m}$  for  $< 0.25\%$  ( $< 0.5\%$ ) of the 1993 (1992) MC events. The change in  $R_b$  that results by adding this tail to the  $\langle IP \rangle$  position is taken as the systematic from the modelling of the precision to which the  $\langle IP \rangle$  is tracked. In both the 3-D impact parameter tag and the 3-D displaced vertex tag the MC events with PV  $z$  greater than  $100 \mu\text{m}$  from the true MC event PV  $z$  have their weights increased by 50% to conservatively estimate the contribution from unmodeled PV  $z$  tails.

The MC statistical error on the trigger and event selection flavor bias is also taken as a systematic error. The combined detector and IP modelling uncertainties for each method is shown in Table 3.

## 8.2 Physics Systematics

Systematics due to the uncertainty of physics quantities in the MC are estimated using a MC event weighting technique. The MC event weights are assigned according to the probability ratio between the nominal MC distribution and an alternative distribution which represents the uncertainty for a physics variable. Using the event weighting scheme the following physics systematics are studied.

The average  $B$ -hadron lifetime is varied by  $\pm 0.10$  ps for  $B$  mesons and  $\pm 0.30$  ps for  $B$  baryons. These variations are based on the current exclusive  $B$  lifetime measurement errors which are generous given the constraint of the more precisely known average  $B$  hadron lifetime [36]. The effect of uncertainty in heavy flavor fragmentation is determined by varying the  $\epsilon$  parameter of Peterson fragmentation function to correspond to  $\delta\langle x_E \rangle = \pm 0.025$  and  $\pm 0.021$  for  $c$  and  $b$  quarks respectively. These variations are conservative choices, larger than the error on some of the individual measurements [22], chosen because of our rather indirect knowledge of the complex fragmentation process. In addition, results derived from the modified Bowler fragmentation function [39] for  $c$  and  $b$  quarks, with a significantly different fragmentation function shape, are compared with the results obtained using the Peterson function for the same  $\langle x_E \rangle$ . The mean charged multiplicity per  $B$ -hadron decay is varied by  $\pm 0.25$  tracks. This corresponds to a  $\sim 2\sigma$  error on  $B$  meson decay average charged multiplicity measured at the  $\Upsilon(4s)$  [33][34]. The choice of this large variation is aimed at covering the lack of knowledge on  $B_s$  and  $B$ -baryon decay multiplicities. A 6% absolute variation is applied to the  $B$  decay  $D^+$  production ratio  $\frac{\Gamma(B \rightarrow D^+ X)}{\Gamma(B \rightarrow \text{all})}$  due to the distinctly long lifetime of the  $D^+$  compared to other charm hadrons. The generous variation on this ratio compared to present experimental uncertainty of  $\pm 4\%$  [36] is taken as a representative estimate covering uncertainties in the production of all charmed hadron species in  $B$ -hadron decays. The effect of varying the  $B$ -baryon production rate in  $b\bar{b}$  events by 3% is also examined in view of its different lifetime compared to the  $B$  mesons. To estimate the effect of the details of the kinematics in the  $B$  decay model, an MC  $b\bar{b}$  event sample with an alternative  $B$  decay model is used. This alternative model is also tuned to the various measurements at  $\Upsilon(4s)$  but the decay product momenta for hadronic  $B$  decay modes are distributed by pure phase space. The charm hadron decay mean charged multiplicities are varied by  $\pm 0.06, \pm 0.10, \pm 0.31$  and  $\pm 0.40$  for  $D^0, D^+, D_s$  and  $\Lambda_c$  respectively. The uncertainties assigned to the  $D^0$  and  $D_s$  decay charged multiplicities are according to the MARK-III measurement [25] while the uncertainty for  $D^+$  is taken as the discrepancy between

the MC and MARK-III measurement mainly due a deficit of 1-prong  $D^+$  decay modes in the MC. These charmed hadron decay multiplicity variations are applied to  $b\bar{b}$  as well as  $c\bar{c}$  events in the determination of  $R_b$  variations. A variation of  $\pm 5\%$  in the  $D^+$  production rate in  $c\bar{c}$  events is used as a representative systematic of the production rate uncertainties of various charmed hadron species. The production of long lived strange particles in the fragmentation process can be a significant cause of tagging the light flavor events. This effect is studied from the event fragmentation  $K^0$  and  $\Lambda$  production multiplicity by varying the MC fragmentation  $s\bar{s}$  popping suppression factor relative to  $u\bar{u}$  and  $d\bar{d}$  popping in the range  $0.30 \pm 0.03$ . The influence due to the uncertainty associated with the fragmentation of  $uds$  events is checked further by a variation of the average event charged multiplicity by  $\pm 0.3$  tracks for  $uds$  events corresponding to the typical measurement error of the event mean charged multiplicity for all  $Z^0 \rightarrow \text{hadrons}$  events [23]. Finally, a crude estimate is made for the effect of heavy quark pair production due to gluon splitting. This is done by simply varying the  $g \rightarrow b\bar{b}$  and  $g \rightarrow c\bar{c}$  rates by 50% from that predicted by JETSET.

In addition, the effect of the present experimental uncertainty in the  $Z^0 \rightarrow c\bar{c}$  branching fraction of  $\delta R_c = \pm 0.017$  is also included as a systematic error as it is used directly in the  $R_b$  calculation. The uncertainty introduced by MC jet axis modelling is determined by varying the JADE jet finding algorithm parameter  $y_{cut}$  from 0.01 to 0.10. The resulting effect of each physics systematic on  $R_b$  for each  $b\bar{b}$  tagging method is given in Table 3 where the subtotal is obtained from summing the contributions in quadrature.

The different tagging methods clearly have different sensitivities to different systematics despite all being lifetime tags. It can be seen from Table 3 that the 2-D impact parameter tag is more sensitive to the  $B$  lifetime uncertainty due to the less distinctive decay lifetime information in a projective view. The displaced vertex tag is on the other hand more sensitive to decay multiplicity uncertainties and tracking inefficiencies, an understood feature due to the amplified track pair combinatorial fluctuation with track multiplicity. The 3-D impact parameter tag with a more evenly distributed systematics is giving the lowest overall systematic error. A common feature between the 3 methods is that the bulk of the systematics on  $R_b$  come from the uncertainty on the  $b$ -tagging efficiency  $\epsilon_b$  with origins in both physics and detector simulation.

### 8.3 Verifications

The stability of the  $R_b$  results are checked for consistency within the estimated errors. All results are checked against variations with the  $b$  tagging cuts. The variations of measured  $R_b$  versus track or vertex multiplicity with different significance cuts are shown in Figure 8. The low multiplicity and low significance regions are more sensitive to  $udsc$  background and detector resolution effects while the high multiplicity and high significance regions are more sensitive to  $b$  physics systematics and tracking efficiency. The variations of the measured  $R_b$  values for the different tagging cuts can be seen to be generally within the total errors at the nominal cuts where the total errors are expected to be smallest.

Variations of the  $R_b$  results versus orientation of the events is studied by measuring  $R_b$  for events with thrust axis direction in different  $\phi$  regions separately. The

ambiguity in the thrust direction is removed by taking the thrust axis to always point along the positron beam direction. The result for each method in each  $\phi$  region is given in Table 4 and the results in different  $\phi$  regions can be seen to be statistically consistent with each other for each method.

The variations of measured  $R_b$  can also be checked versus the time periods the data were taken. The results from the 1993 data and 1992 data are statistically consistent with each other for each of the methods as seen from section 7. When the 1993 data is divided into two periods for early and late 1993, the results are again consistent for each of the three methods.

## 9 Summary

$R_b$  has been measured at the SLD using three methods with high  $b$ -tagging efficiency and purity utilizing the precision vertex detector combined with the small stable SLC interaction point. These measurements yield values of:

- The 2-D impact parameter method:  

$$R_b = 0.230 \pm 0.004(\textit{statistical}) \pm 0.012(\textit{systematic})$$
- The 3-D impact parameter method:  

$$R_b = 0.230 \pm 0.004(\textit{statistical}) \pm 0.010(\textit{systematic})$$
- The 3-D displaced vertex method:  

$$R_b = 0.223 \pm 0.004(\textit{statistical}) \pm 0.015(\textit{systematic})$$

A combined result is made using correlations estimated from the MC according to the method of Lyons et. al.[40]. The correlation between the 2-D impact parameter and 3-D impact parameter methods, the 3-D impact parameter and 3-D displaced vertex methods, and the 2-D impact parameter and 3-D displaced vertex methods were found to be (78%,59%,68%) respectively. The result is:

$$R_b = 0.229 \pm 0.011(\textit{combined statistical and systematic error})$$

In conclusion, we have used 3 different variations of lifetime  $b$ -tags to measure  $R_b$ , and all give results consistent with the Standard Model. Currently, our measurement precision has not yet reached the level of being able to probe the details of the  $Z^0 \rightarrow b\bar{b}$  vertex corrections and discriminate between different models. We have demonstrated that the crucial issue of the precision vertex detector resolution, especially the tails of distributions relevant to the lifetime tagging technique in general, can indeed be brought to a good level of understanding through dedicated detector calibration and detailed MC simulation. Uncertainties due to modelling the detector response are expected to decrease further as tracking inefficiencies are better understood. The physics modelling systematics are not expected to significantly decrease using these techniques in the near future. However, the simple approach of the event tag analyses with tagging efficiencies from MC has yielded much detailed knowledge of the physics

modelling and detector simulation issues associated with the lifetime  $b$ -tagging techniques through a direct confrontation with these sensitive issues. This provides a solid foundation for development of techniques with lower systematic errors, leading to higher precision  $R_b$  measurements.

We thank the staff of the SLC for their efforts in the challenging task of bringing sub-micron sized stable colliding beams to the SLD for a unique physics program. We thank the technical staff at the collaborating institutions for their valiant support in the construction and maintenance of the SLD.

## References

- [1] A. Akhundov, D. Bardin, and T. Riemann, *Nucl. Phys.* **B276**, 1 (1986);  
W. Beenakker, and W. Hollik, *Z. Phys.* **C40**, 141 (1988);  
B. W. Lynn, and R. G. Stuart, *Phys. Lett.* **B252**, 676 (1990);  
J. Bernabéu, A. Pich, A. Santamaria, *Phys. Lett.* **B363**, 326 (1991).
- [2] CDF Collaboration: F. Abe *et. al.*, **FERMILAB-PUB-95-022-E** (1995);  
D0 Collaboration: S. Abachi *et. al.*, **FERMILAB-PUB-95-028-E** (1995).
- [3] W. Hollik, *Mod. Phys. Lett.* **A5**, 1909 (1990);  
F. Boudjema, A. Djouadi, and C. Verzegnassi, *Phys. Lett.* **B238**, 423 (1990);  
A. Djouadi *et. al.*, *Nucl. Phys.* **B349**, 48 (1991);  
M. Boulware and D. Finnel, *Phys. Rev.* **D44**, 2054 (1991);  
R. S. Chivukula, E. H. Simmons, and J. Terning, *Phys. Lett.* **B331**, 383 (1994).
- [4] T. Liu, and D. Ng, *Phys. Lett.* **B342**, 262 (1995).
- [5] ALEPH Collaboration: D. Buskulic *et. al.*, *Z. Phys.* **C62**, 179 (1994);  
DELPHI Collaboration: P. Abreu *et. al.*, *Z. Phys.* **C56**, 63 (1992);  
L3 Collaboration: B. Adeva *et. al.*, *Phys. Lett.* **B259**, 199 (1991);  
OPAL Collaboration: P. D. Acton *et. al.*, *Z. Phys.* **C58**, 523 (1993).
- [6] DELPHI Collaboration: P. Abreu *et. al.*, *Phys. Lett.* **B281**, 383 (1992).
- [7] ALEPH Collaboration: D. Buskulic *et. al.*, *Phys. Lett.* **B313**, 535 (1993);  
OPAL Collaboration: P. D. Acton *et. al.*, *Z. Phys.* **C60**, 579 (1993);  
OPAL Collaboration: D. Akers *et. al.*, *Z. Phys.* **C65**, 17 (1994);  
DELPHI Collaboration: P. Abreu *et. al.*, *Z. Phys.* **C65**, 555 (1995).
- [8] ALEPH Collaboration: D. Buskulic *et. al.*, *Phys. Lett.* **B313**, 549 (1993);  
DELPHI Collaboration: P. Abreu *et. al.*, *Phys. Lett.* **B295**, 383 (1992);  
L3 Collaboration: O. Adriani *et. al.*, *Phys. Lett.* **B307**, 237 (1993);  
OPAL Collaboration: R. Akers *et. al.*, *Z. Phys.* **C61**, 357 (1994).
- [9] SLD Collaboration: G. Agnew *et. al.*, *SLD Design Report* **SLAC-0273** (1984).
- [10] TASSO Collaboration: W. Braunschweig *et. al.*, *Z. Phys.* **C38**, 543 (1988).
- [11] MARK-II Collaboration: R. Jacobsen *et. al.*, *Phys. Rev. Lett.* **67**, 3347 (1991).
- [12] G. Agnew *et. al.*, **SLAC-PUB-5906** *Proceedings of the 26th International Conference on High Energy Physics, Dallas, Texas, USA, Aug 1992.*
- [13] M. Hildreth *et. al.*, **SLAC-PUB-6656** *Submitted to IEEE Trans. on Nucl. Sci.* (1994).
- [14] D. Axen *et. al.*, *Nucl. Instr. & Meth.* **A328**, 472 (1993).
- [15] P. Billoir, *Nucl. Instr. & Meth.* **225**, 352 (1984).
- [16] D. Williams, Ph.D. Thesis, MIT **SLAC-REPORT 445** (1994).
- [17] R. Cotton, Ph.D. Thesis, Brunel University (1993).

- [18] T. Sjöstrand, and M. Bengtsson, *Comp. Phys. Comm.* **43**, 367 (1987),  
T. Sjöstrand, *Comp. Phys. Comm.* **39**, 347 (1986).
- [19] TASSO Collaboration: W. Braunschweig *et. al.*, *Z. Phys.* **C41**, 359 (1988);  
P. N. Burrows, *Z. Phys.* **C41**, 375 (1988).
- [20] OPAL Collaboration: M. Z. Akrawy *et. al.*, *Z. Phys.* **C47**, 505 (1990).
- [21] C. Peterson *et. al.*, *Phys. Rev.* **D27**, 105 (1983).
- [22] ALEPH Collaboration: D. Buskulic *et. al.*, *Z. Phys.* **C62**, 179 (1994);  
L3 Collaboration: B. Adeva *et. al.*, *Phys.Lett.* **B261**, 177 (1991);  
OPAL Collaboration: R. Akers *et. al.*, *Z. Phys.* **C60**, 199 (1993);  
OPAL Collaboration: R. Akers *et. al.*, *Z. Phys.* **C61**, 209 (1994);  
ALEPH Collaboration: D. Buskulic *et.al.*, *Z. Phys.* **C62**, 1 (1994);  
DELPHI Collaboration: P. Abreu *et. al.*, *Z. Phys.* **C59**, 533 (1993);  
OPAL Collaboration: R. Akers *et. al.*, *Z. Phys.* **C60**, 601 (1993).
- [23] ALEPH Collaboration: D. Decamp *et. al.*, *Phys. Lett.* **B273**, 181 (1991);  
DELPHI Collaboration: P. Abreu *et. al.*, *Z. Phys.* **C50**, 185 (1991);  
L3 Collaboration: B. Adeva *et. al.*, *Phys. Lett.* **B259**, 199 (1991);  
OPAL Collaboration: P. D. Acton *et. al.*, *Z. Phys.* **C53**, 539 (1992).
- [24] The Particle Data Group, *Phys. Rev.* **D45**, Part II (1992).
- [25] MARK-III Collaboration: D. Coffman *et. al.*, *Phys. Lett.* **B263**, 135 (1991).
- [26] M. Wirbel, B. Stech, and M. Bauer, *Z. Phys.* **C29**, 637 (1985).
- [27] CLEO Collaboration: F. Butler *et. al.*, *Phys. Rev. Lett.* **69**, 2041 (1992).
- [28] N. Isgur, D. Scora, B. Grinstein, and M. B. Wise, *Phys. Rev.* **D39**, 799 (1989);  
Code provided by P. Kim and CLEO Collaboration.
- [29] M. Artuso (CLEO Collab.), HEPSY-7-93, talk presented at Workshop on *b*  
Physics at Hadron Accelerators, July 1993.
- [30] CLEO Collaboration: G. Crawford *et. al.*, *Phys. Rev.* **D45**, 752 (1992).
- [31] M. Thulasidas, Ph.D thesis, Syracuse University (1993).
- [32] F. Muheim (CLEO Collaboration), talk presented at the 8th DPF Meeting,  
Albuquerque, New Mexico, Aug 1994.
- [33] ARGUS Collaboration: H. Albrecht *et. al.*, *Z. Phys.* **C54**, 13 (1992).
- [34] CLEO Collaboration: R. Giles *et. al.*, *Phys. Rev.* **D30**, 2279 (1984).
- [35] ARGUS Collaboration: H. Albrecht *et. al.*, *Z. Phys.* **C58**, 191 (1993);  
ARGUS Collaboration: H. Albrecht *et. al.*, *Z. Phys.* **C62**, 371 (1994).
- [36] The Particle Data Group, *Phys. Rev.* **D50**, Part I (1994).
- [37] GEANT 3.15 Program, *CERN Application Software Group*, **CERN Program  
Library** (1993).

- [38] JADE Collaboration: S. Bethke *et. al.*, *Phys. Lett.* **B213**, 235 (1988).
- [39] M. G. Bowler, *Z. Phys.* **C11**, 169 (1981);  
T. Sjöstrand, *Comp. Phys. Comm.* **82**, 74 (1994).
- [40] L. Lyons *et. al.*, *NIM* **A270**, 110 (1988).

|                    | Mean Radius<br>( mm) | $L/L_R$<br>(%) |
|--------------------|----------------------|----------------|
| Ti Liner           | 25.0                 | 0.28           |
| Be Beam Pipe       | 25.5                 | 0.28           |
| Be Inner Shell     | 27.0                 | 0.14           |
| Layer 1 Ladder     | 29.5                 | 1.15           |
| Layer 2 Ladder     | 33.5                 | 1.15           |
| Layer 3 Ladder     | 37.5                 | 1.15           |
| Layer 4 Ladder     | 41.5                 | 1.15           |
| Be Outer Shell     | 45.5                 | 0.20           |
| N <sub>2</sub> Gas | 80.0                 | 0.06           |
| Cryostat           | 165.5                | 0.98           |
| CDC Inner Wall     | 200.0                | 1.80           |
| CDC Gas            | 600.0                | 0.50           |
| CDC Wires          | 600.0                | 0.20           |

Table 1: Radiation lengths seen by a track passing through the central tracking volume at  $\theta = 90^\circ$ . It should be noted that on average a track will only pass through 2.3 ladders.



| Decay type                                     | MC $\langle B_u \& B_d \rangle$ |       | Measurements |           |
|--|---------------------------------|-------|--------------|-----------|
| $B \rightarrow e$                              | 0.110                           | 0.104 | $\pm$ 0.004  | [36]      |
| $B \rightarrow \mu$                            | 0.110                           | 0.103 | $\pm$ 0.005  | [36]      |
| $B \rightarrow \tau$                           | 0.030                           | 0.041 | $\pm$ 0.010  | [36]      |
| $B \rightarrow D^0$                            | 0.629                           | 0.621 | $\pm$ 0.026  | [32]      |
| $B \rightarrow D^+$                            | 0.259                           | 0.239 | $\pm$ 0.037  | [32]      |
| $B \rightarrow D_s$                            | 0.099                           | 0.100 | $\pm$ 0.025  | [32]      |
| $B \rightarrow D^{*+}$                         | 0.236                           | 0.230 | $\pm$ 0.040  | [36]      |
| $B \rightarrow \text{Charmed Baryons}$         | 0.060                           | 0.064 | $\pm$ 0.011  | [36]      |
| $B \rightarrow J/\psi$                         | 0.014                           | 0.013 | $\pm$ 0.002  | [36]      |
| $B \rightarrow D^{(*)} D_s^{(*)}$              | 0.065                           | 0.050 | $\pm$ 0.009  | [36]      |
| $B \rightarrow \pi^\pm$ (Direct)               | 3.564                           | 3.59  | $\pm$ 0.11   | [35]      |
| $B \rightarrow K^\pm$                          | 0.765                           | 0.78  | $\pm$ 0.04   | [35]      |
| $B \rightarrow K^0$                            | 0.692                           | 0.64  | $\pm$ 0.04   | [35]      |
| $B \rightarrow \text{Proton}$                  | 0.092                           | 0.080 | $\pm$ 0.005  | [36]      |
| $B \rightarrow \Lambda$                        | 0.023                           | 0.040 | $\pm$ 0.005  | [36]      |
| $B \rightarrow \text{Charged Tracks} \times 2$ | 10.95                           | 10.81 | $\pm$ 0.24   | ARGUS[33] |
|  |                                 | 10.99 | $\pm$ 0.30   | CLEO [34] |

Table 2: MC average  $B_u, B_d$  meson decay inclusive particle yield compared to experimental measurements.

| DETECTOR<br>MODELLING   | 2-D Impact<br>ERROR (%) | 3-D Impact<br>ERROR (%) | 3-D Vertex<br>ERROR (%) |
|---|-------------------------|-------------------------|-------------------------|
| Tracking/Linking Efficiency   | 2.9                     | 2.5                     | 4.9                     |
| Tracking Resolution   | 0.5                     | 1.5                     | 1.3                     |
| Beam Position Tails   | 0.5                     | 0.5                     | 0.3                     |
| Trigger/Event Selection   | 0.5                     | 0.5                     | 0.5                     |
| Subtotal  | 3.1                     | 3.1                     | 5.1                     |
| PHYSICS<br>MODELLING  | 2-D Impact<br>ERROR (%) | 3-D Impact<br>ERROR (%) | 3-D Vertex<br>ERROR (%) |
| <b>B-lifetimes</b><br>( $\tau_{Bmeson} = 1.55 \pm 0.10$ ps,<br>$\tau_{Bbaryon} = 1.10 \pm 0.30$ ps) | 2.6                     | 1.4                     | 1.2                     |
| <b>b-fragmentation</b><br>(Peterson $\langle x_e \rangle = 0.695 \pm 0.021$ )                       | 2.2                     | 1.2                     | 0.8                     |
| <b>b-fragmentation</b><br>(Bowler vs. Peterson w/ $\langle x_e \rangle = 0.695$ )                   | 0.2                     | 0.8                     | 0.6                     |
| <b>b-baryon production</b><br>( $8.9 \pm 3.0\%$ )   | 0.6                     | 0.5                     | 0.7                     |
| <b>B-decay to <math>D^+</math></b><br>( $\pm 6\%$ absolute)   | 0.3                     | 0.3                     | 0.4                     |
| <b>B-decay multiplicity</b><br>( $\pm 0.25$ tracks per $B$ decay)                                   | 2.2                     | 1.5                     | 3.6                     |
| <b>B-model</b><br>(exclusive phase space vs.<br>tuned LUND 6.3)                                     | 0.7                     | 1.0                     | 1.0                     |
| <b>c-fragmentation</b><br>(Peterson $\langle x_e \rangle$ for $D^* = 0.501 \pm 0.025$ )             | 0.5                     | 0.4                     | 0.2                     |
| <b>c-fragmentation</b><br>(Bowler vs. Peterson w/ $\langle x_e \rangle = 0.501$ )                   | 0.1                     | 0.1                     | 0.2                     |
| <b>c-decay to <math>D^+</math></b><br>( $\pm 5\%$ absolute)   | <0.1                    | 0.7                     | 0.6                     |
| <b>c decay multiplicity</b>   | 0.9                     | 0.8                     | 1.5                     |
| <b>s production</b><br>( $s\bar{s}$ popping varied by 10%)  | 0.3                     | 0.1                     | 0.2                     |
| <b>uds decay multiplicity</b> ( $\pm 0.3$ tracks)   | 0.1                     | 0.1                     | 0.2                     |
| <b><math>g \rightarrow b\bar{b}</math> splitting</b> ( $\pm 50\%$ )                                 | 0.5                     | 0.5                     | 0.2                     |
| <b><math>g \rightarrow c\bar{c}</math> splitting</b> ( $\pm 50\%$ )                                 | 0.3                     | 0.3                     | 0.2                     |
| $\Gamma(Z^0 \rightarrow c\bar{c})$<br>( $R_c = 0.171 \pm 0.017$ )                                   | 1.0                     | 1.4                     | 1.7                     |
| <b>Jet Axis Modelling</b><br>(JADE $y_{cut}$ varied from 0.01 to 0.10)                              | 0.8                     | 0.8                     | 0.8                     |
| Subtotal  | 4.4                     | 3.3                     | 4.8                     |
| <b>TOTAL</b>  | <b>5.4</b>              | <b>4.6</b>              | <b>6.9</b>              |

Table 3: Summary of detector and physics systematics for each  $b\bar{b}$  tagging method.

| SLD $\phi$       |   |        | 2-D Impact | 3-D Impact       | 3-D Vertex        |                   |                   |
|------------------|---|--------|------------|------------------|-------------------|-------------------|-------------------|
| Quadrant         |   |        | $R_b$      | $R_b$            | $R_b$             |                   |                   |
| $\frac{-\pi}{4}$ | < | $\phi$ | <          | $\frac{\pi}{4}$  | $0.234 \pm 0.009$ | $0.232 \pm 0.008$ | $0.226 \pm 0.009$ |
| $\frac{\pi}{4}$  | < | $\phi$ | <          | $\frac{3\pi}{4}$ | $0.231 \pm 0.009$ | $0.236 \pm 0.008$ | $0.230 \pm 0.009$ |
| $\frac{3\pi}{4}$ | < | $\phi$ | <          | $\frac{5\pi}{4}$ | $0.230 \pm 0.009$ | $0.225 \pm 0.008$ | $0.228 \pm 0.009$ |
| $\frac{5\pi}{4}$ | < | $\phi$ | <          | $\frac{-\pi}{4}$ | $0.225 \pm 0.009$ | $0.216 \pm 0.008$ | $0.212 \pm 0.009$ |

Table 4:  $R_b$  results versus axial quadrants of the SLD. The errors are statistical only.

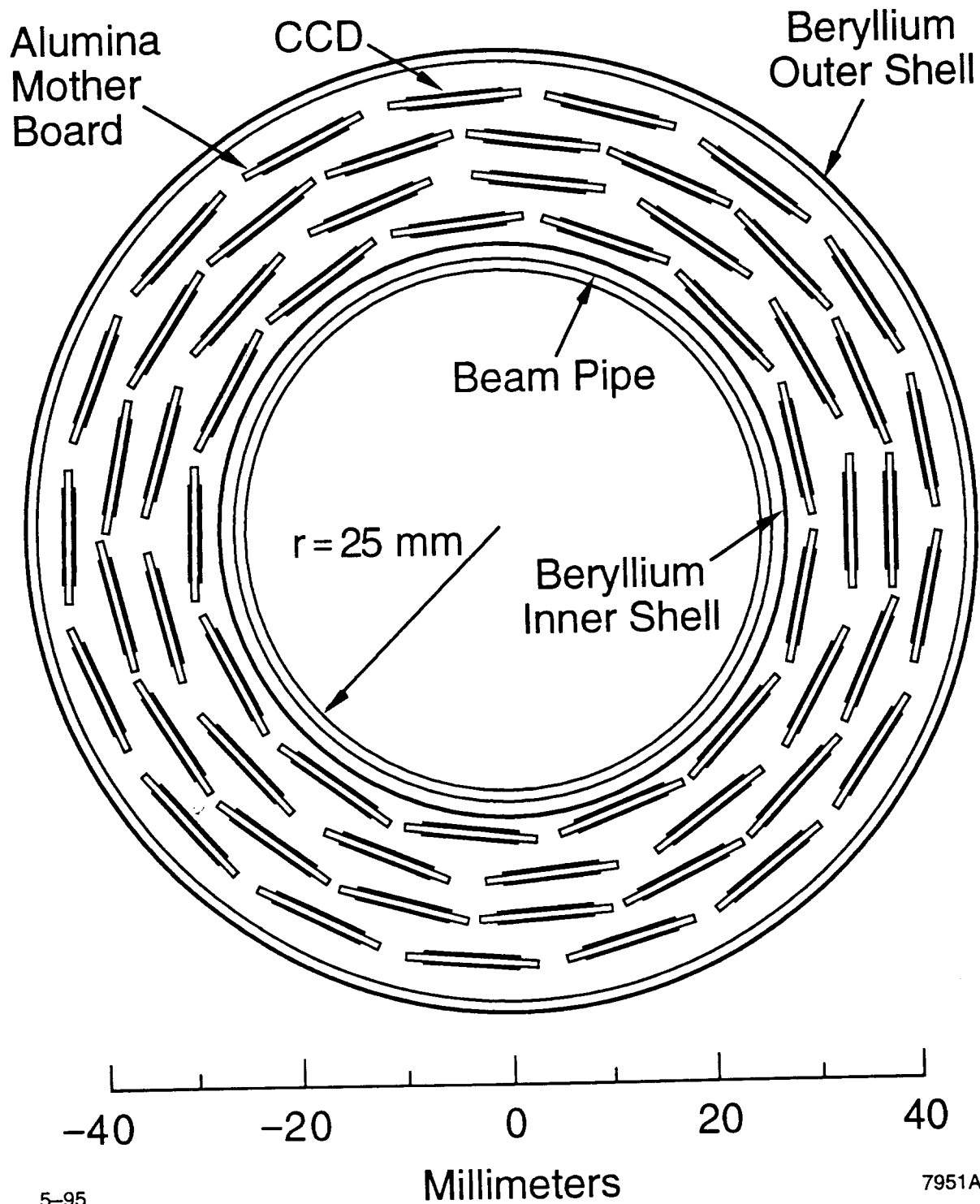


Figure 1:  $xy$  cross-section of the VXD geometry. There are 60 ladders with 4 CCDs on the top face and 4 CCDs on the bottom face of each ladder.

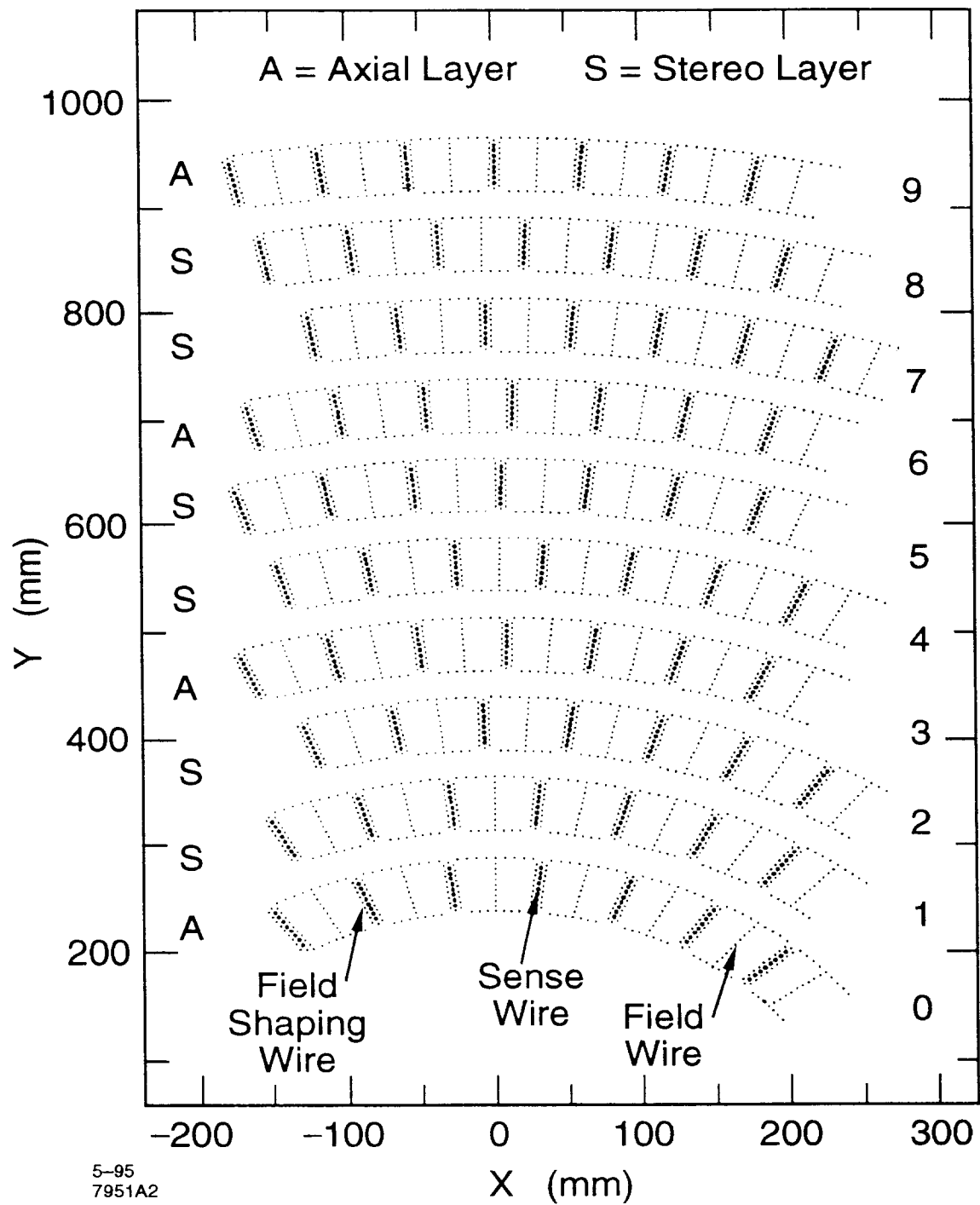
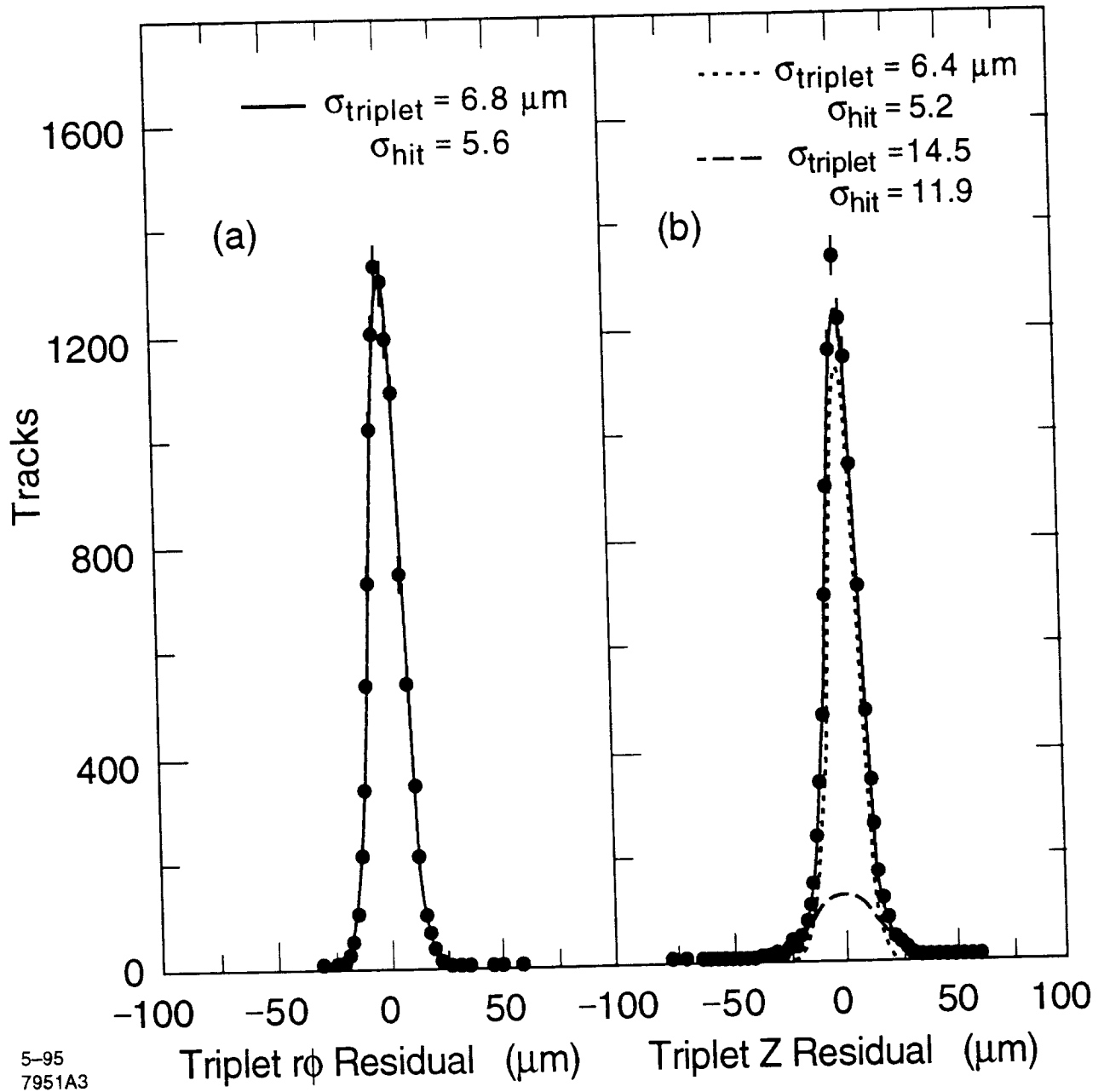


Figure 2:  $xy$  cross-section of a portion of the CDC endplate showing the relative location of sense and field wires.



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Figure 3: Plot of the residual of the middle hit in a triplet of VXD hits from the same track on three separate layers relative to track which is forced to go through the first and last hit of the triplet. All tracks with momentum greater than 1 GeV/c for all  $\cos\theta$  in hadronic  $Z^0$  events are used. The single hit resolution ( $\sigma_{\text{hit}}$ ) is obtained from the triplet miss distance by dividing by 1.22 to account for broadening due to the finite resolution of the other two hits at an average lever arm ratio.

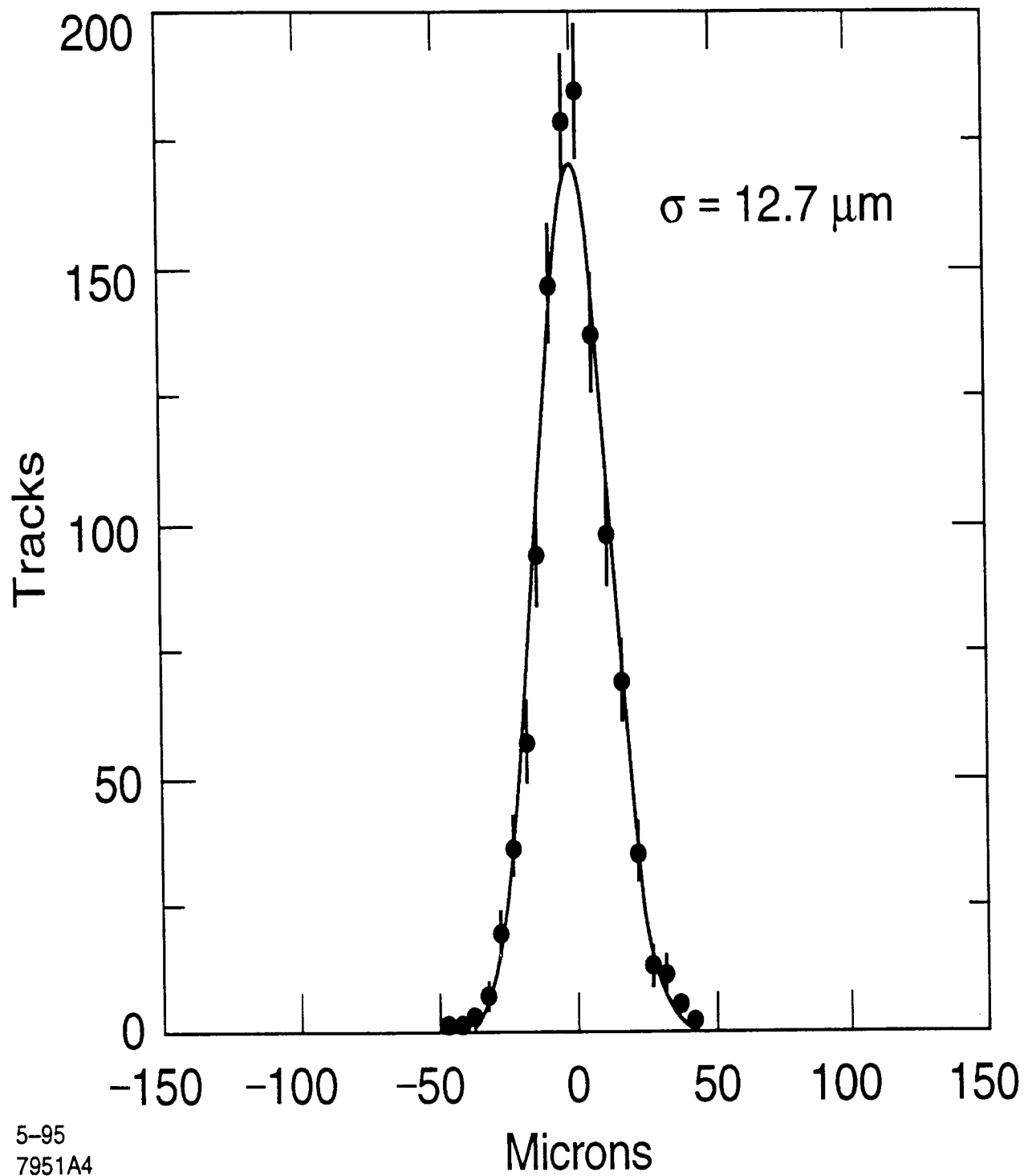


Figure 4: Distribution of track impact parameters in  $\mu^+\mu^-$  events with respect to the  $\langle IP \rangle$  determined from hadronic events.

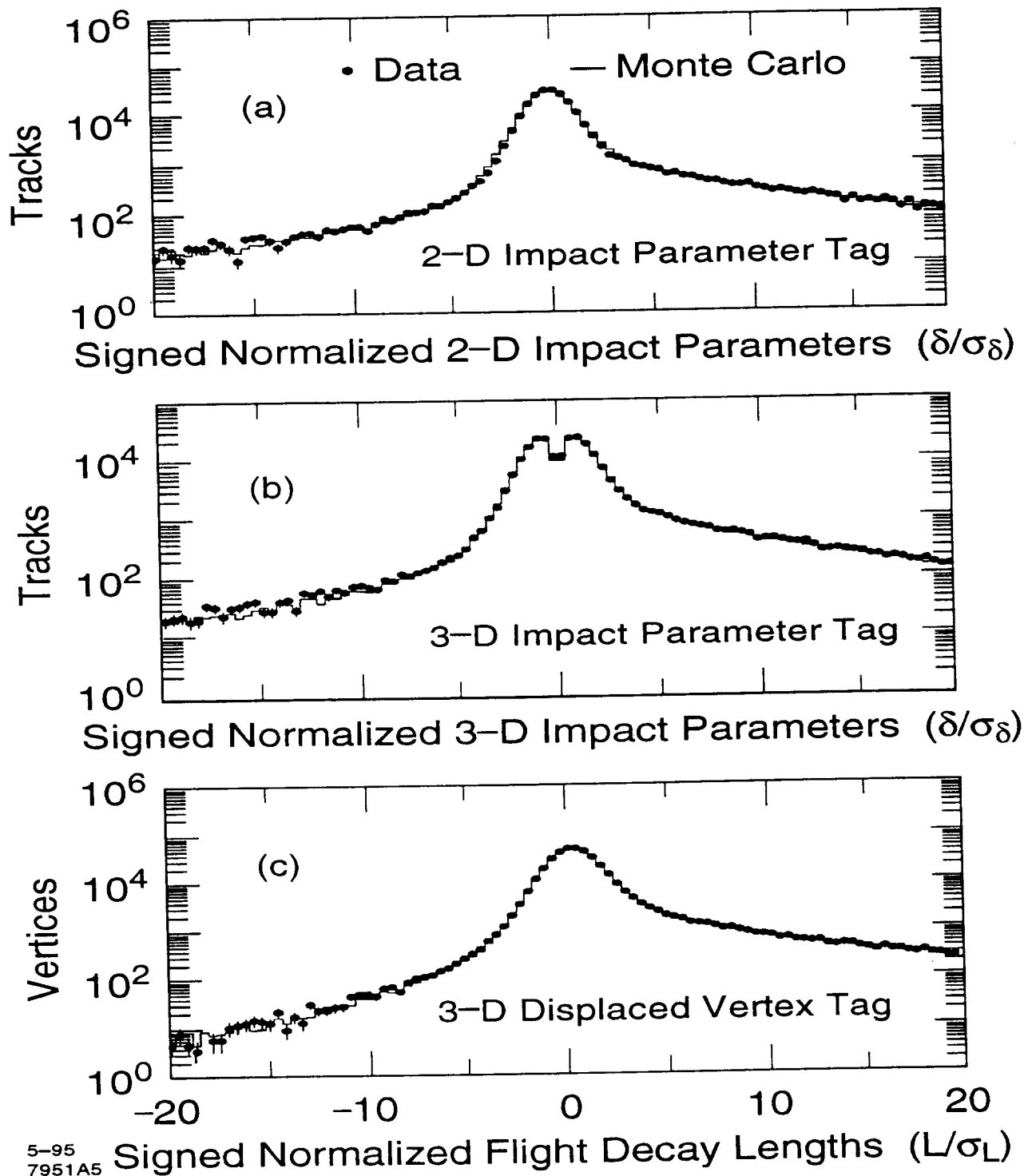


Figure 5: Data and Monte Carlo Signed Normalized 2-D and 3-D Impact Distributions, and Signed Normalized Flight Decay Length Distributions without tracking resolution corrections for the MC.



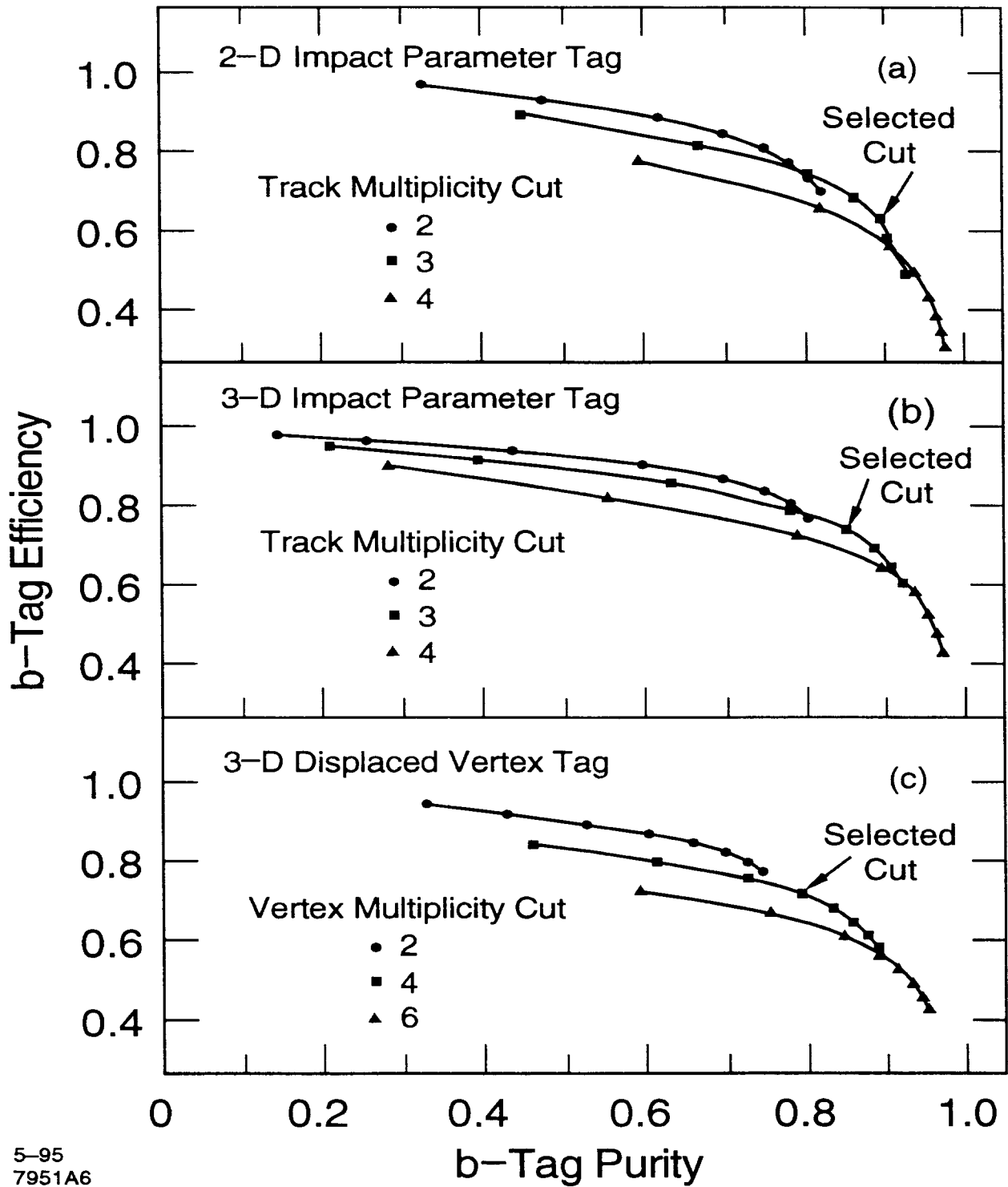
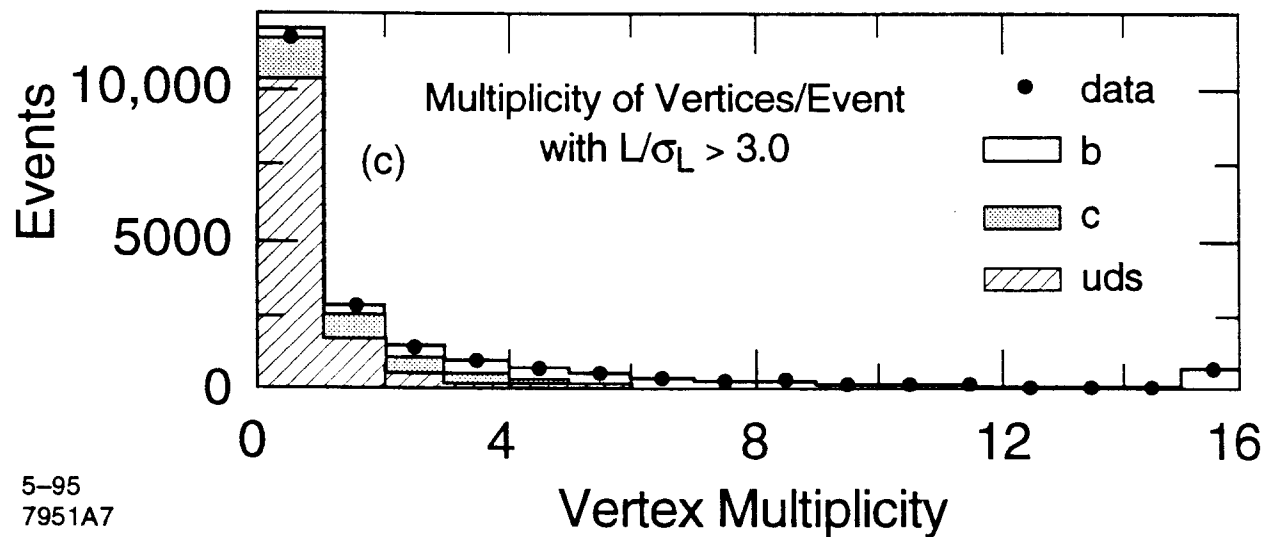
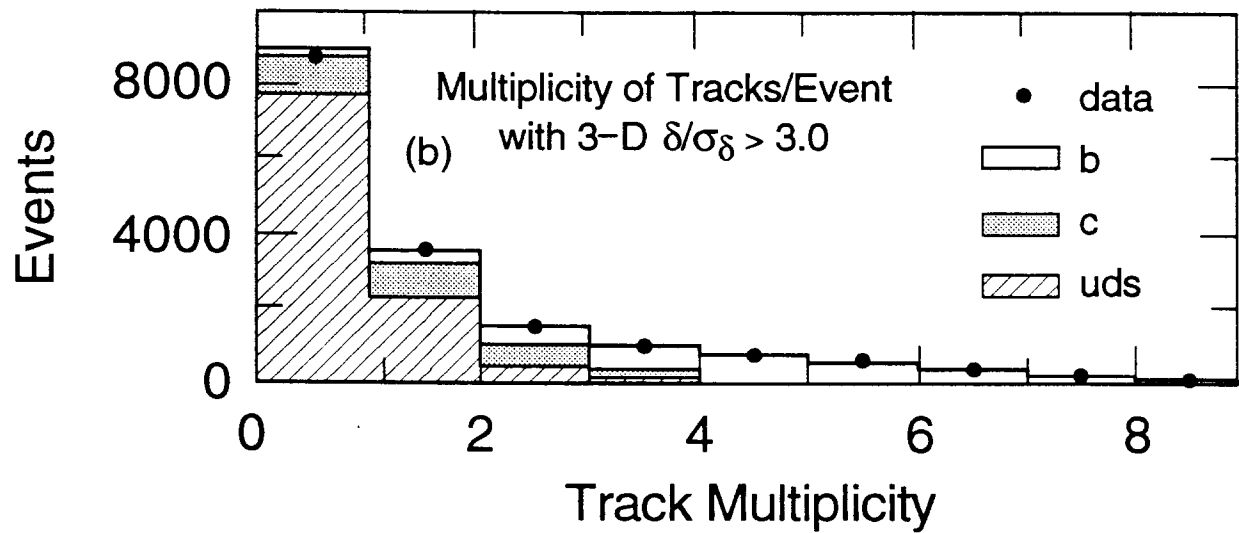
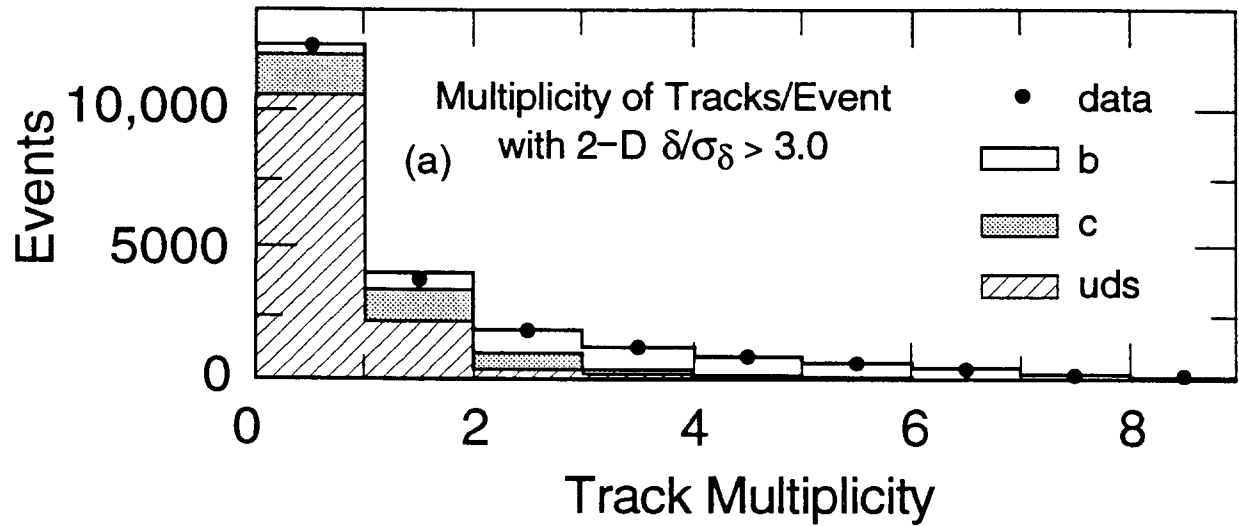
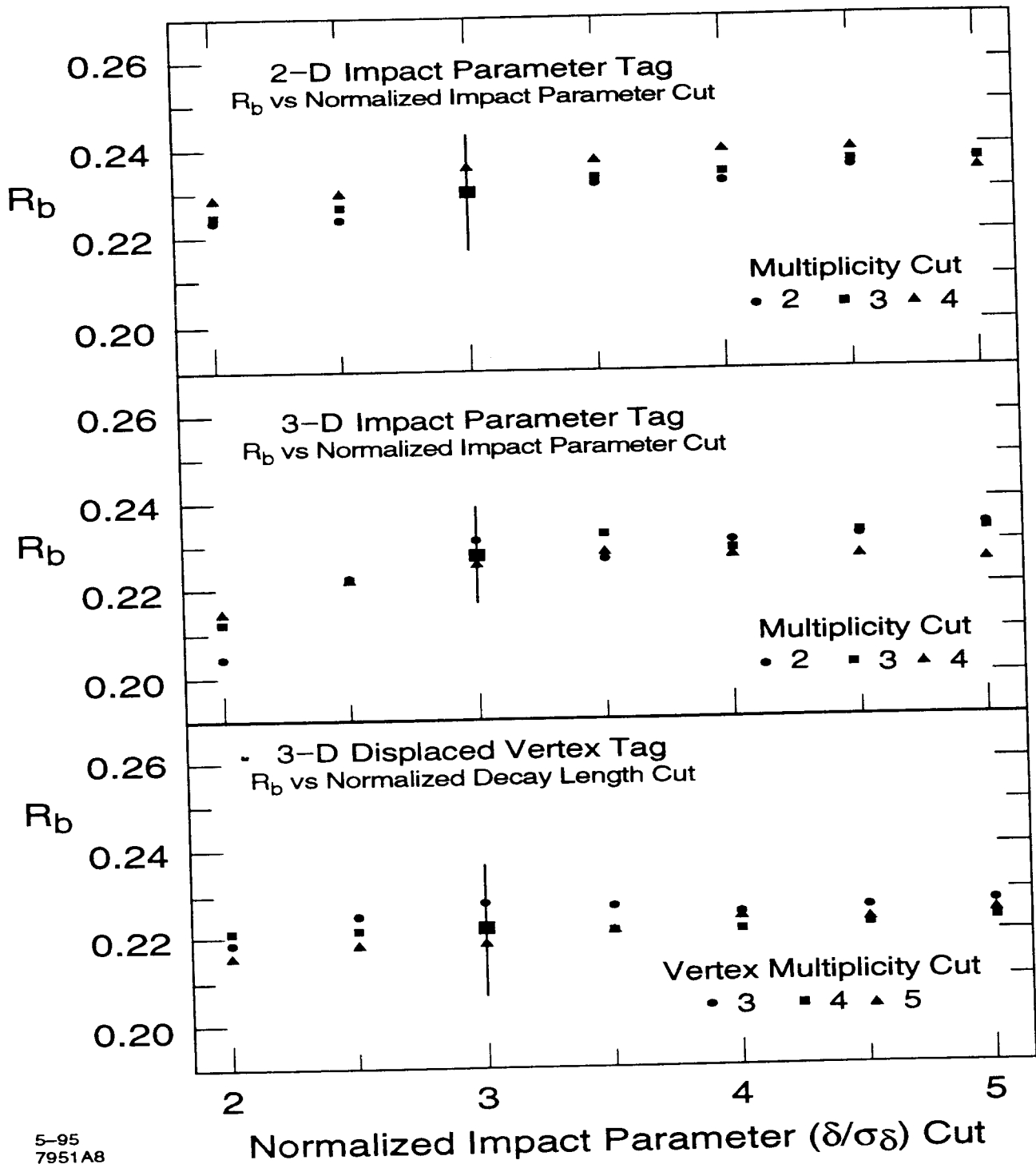


Figure 6:  $b\bar{b}$  event tagging efficiencies versus purities for each  $b\bar{b}$  event tagging method with different multiplicity and significance cuts, derived from the Monte Carlo. Each curve represents the estimated efficiencies and purities as the significance cut is varied from 1.5 to 5.0, in steps of 0.5, while the multiplicity cut is fixed.



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Figure 7: Data and Monte Carlo event counts vs. number of significant tracks and vertices in the events. The Monte Carlo total event count has been normalized to data.



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Figure 8:  $R_b$  versus tagging cuts in the 2-D and 3-D Impact Tag and the 3-D Displaced Vertex Tag. The result at nominal cuts for each method is shown as large square together with the estimated total error bar at the nominal cuts.

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