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A Measurement of $R_b = \dfrac{\Gamma(Z^0 \to b\bar{b})}{\Gamma(Z^0 \to hadrons)}$ at SLD*

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ABSTRACT

A measurement of the ratio $R_b = \Gamma(Z^0 \to b\bar{b})/\Gamma(Z^0 \to hadrons)$ is reported. This measurement is made using the CCD-based vertex detector of the SLD detector at the SLAC Linear Collider. Efficient tagging of $b\bar{b}$ events is performed with an impact parameter technique that takes advantage of the small and stable interaction point of the SLC and *all* charged tracks in Z^0 decays. In a sample of 27K Z^0 events, a value R_b=0.235±0.006±0.018 is obtained.

The branching ratio $R_b = \Gamma(Z^0 \to b\bar{b})/\Gamma(Z^0 \to hadrons)$ measures the coupling of the *b*-quark to the Z^0 gauge boson. In the absence of non-standard model contributions to Z^0 decays, the radiative vertex corrections are dominated by a heavy ($m_t \gg m_Z$) *t*- quark.[1] Of all fermions, only $Z^0 \to b\bar{b}$ receives a large vertex radiative correction. Measuring the ratio R_b rather than $\Gamma(Z^0 \to b\bar{b})$ isolates the vertex corrections, since the oblique corrections, common to all fermions, largely cancel in the ratio.[1] Similarly, large QCD corrections also cancel in the ratio.[2] The insensitivity of R_b to conventional radiative and QCD corrections makes it sensitive to the presence of new physics, once m_t is known. We present herein a measurement of R_b from a sample of 27K Z^0 events collected in 1992 and 1993 at $\sqrt{s} \approx 91$ GeV (near the peak of the Z^0 resonance) in the SLD detector at the SLC. The *b*-tagging technique employed, or a variant thereof, may lead to future measurements of R_b at the 1% level, providing sensitivity to physics outside the standard model.

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Due to the long *B*-hadron lifetime and large boost, $Z^0 \rightarrow b\bar{b}$ events produce tracks with large displacements (δ) from the interaction point.[3] In addition, because of the large *b*-quark mass, tracks from *b*-decays have large transverse momenta relative to the initial quark direction, making a 2D impact parameter analysis appropriate. The process $Z^0 \rightarrow b\bar{b}$ can be identified by requiring a large number of charged tracks, each having a large positive δ with respect to the e^+e^- interaction point (IP).[4] A precise measurement of δ for both hadron and lepton tracks, and an independent determination of the IP position for each event, allows a high *b*-tagging efficiency and high purity to be obtained. Exploiting the SLC beam size and stability in the transverse dimensions and choosing a 2D tagging technique, rather than a 3D one, allows full decoupling of the *b* production point in each event from the *b* fragmentation and decay processes in that event. Biases introduced at the extrema of fragmentation and decay may lead to systematics which are difficult or impossible to measure.

For this analysis, a subset of the elements of the SLD are utilized: the vertex detector (VXD),[5] covering 76% of 4π sr, the drift chamber (CDC),[6] covering 85% of 4π sr, and the calorimeter (LAC),[7] covering 95% of 4π sr. The VXD contains 480 CCD chips of 20μm thick EPI silicon, organized in four concentric ~9.2cm long cylindrical layers, starting at 29mm and extending to 41mm from the beam line. Each CCD contains 375x578, 22μm square pixels. To reduce dark current, the VXD operates at 195°K. A 100μm *Ti*-liner and a 1mm thick *Be* beam pipe are located at a radius of 25 mm. Including a 0.5mm *Be* gas shell, the total material before the first CCD layer is 0.71% rl ; each CCD-layer adds ~1% rl.

The 2.1m long cylindrical CDC extends radially from 0.2m to 1.0m. The central tracking detectors lie in a 0.6T axial B-field. The CDC contains 80 sense wire planes (48 2.5° stereo, 32 coaxial to the beam) arranged in a jet-cell geometry of 10 superlayers of 8 wires each. An average spatial resolution of ~70μm is obtained with a cool gas of CO_2-Ar-Isobutane.

Charged tracks found in the CDC are linked with pixel-clusters in the VXD. For regions where there exists a dead or inefficient CCD, tracks can be reliably linked with single clusters by using the SLC beam position as a weak constraint in pattern recognition. Within the VXD solid angle, a track intersects 2.3 CCDs on average, and 96% of all well measured CDC tracks have ≥1 linked pixel-clusters. A combined fit using the Billoir method[8] is performed to properly account for multiple scattering as the track is extrapolated through the VXD material and the beam pipe. The angular errors of the CDC combined with local $<\delta\phi>$ and $<\delta z>$ of the VXD clusters of 6μm and

7μm, respectively, lead to xy (othogonal to the e⁻ beam) and rz (plane containing the beam axis) impact resolutions of $(\alpha,\beta)_{xy}$ = (15μm, 70μm) and $(\alpha,\beta)_{rz}$ = (43μm, 70μm), respectively.[9]

The SLD trigger [7] is based on loose calorimetric and tracking criteria, and is fully efficient for hadronic Z^0 decays in the solid angle of the VXD. Hadronic Z^0 events are reconstructed and selected for analysis by requiring a large visible energy in ≥ 7 charged tracks (E_{vis}>18 GeV). The thrust axis, reconstructed from charged tracks, is required to lie well within the VXD acceptance ($|\cos\theta_T|<0.71$). The track multiplicity requirement eliminates 2γ and $\tau\bar{\tau}$ events. We also require events to come from periods where the VXD was fully operational, and we require at least three tracks with two or more VXD links. From 13.5 K (13.4K) triggers in 1992 (1993) data, 5641 (6147) Z^0 events are retained. The non-hadronic background (primarily $\tau\bar{\tau}$) is <0.2%. The flavor bias potentially introduced by this selection for *b*-quarks relative to all hadronic Z^0 events is found from Monte Carlo to be less than 0.7%.

To tag $b\bar{b}$ events with minimal bias, a knowledge of the IP position with precision comparable to the best track impact resolution (in the plane transverse to the beam) is required in each candidate event. The <rms> transverse profile of SLC beams is 2.2 ⊗ 2.2 μm^2 in 1992 and was reduced to 2.4 ⊗ 0.8 μm^2 in 1993, implying a negligible contribution from the extent of the luminous region. However, the spatial stability of the crossing point (σ^{IP}) must be established. SLC utilizes beam-beam deflection scans and feedback on one beam to maintain e^-e^+ collisions and stabilize the IP in space. The IP position is *tracked* using hadronic Z^0 events. To find the average IP x and y positions and errors (σ_x^{IP} and σ_y^{IP}), a fit to a common vertex is performed using tracks of small impact parameter from ~20 consecutive Z^0 events (~240 tracks). Samples of events typically span no more than 3hrs. The 1992 (1993) data are divided into 323 (313) sets of IP positions. The IP position can be tested in hadronic Z^0 decays by comparing the primary vertex position found in each event to the IP position. By projecting this displacement along the direction transverse to the thrust axis, and unfolding the expected resolution from tracking itself, a value $\sigma_{xy}^{IP} \approx 10\mu m$, is obtained (Figure 1b). An independent test of the IP position determination can be made with muon pairs which are not used in the IP detrmination itself. The impact parameter of each track from a $\mu^+\mu^-$ event relative to the other track in the event, and relative to the previously determined average IP positions, gives $\sigma_x^{IP} \approx \sigma_y^{IP} \approx 8\mu m$. (see Figure 1a). Finally, the variation of the currents in the corrector magnets used to keep the SLC beams in collision confirms that the motion of the IP within an averaging period is ≤10μm *independent* of the tracking.

The b-tagging algorithm proceeds as follows. CDC tracks are selected which start at r<0.4m, have >40 hits, extrapolate to the IP within 1.0cm in xy, and within 1.5cm in z, and have good fit quality (χ^2/df <5). At least one good VXD link is required, and the combined CDC/VXD fit must satisfy χ^2/df <10. The xy impact parameter (δ) of the track relative to the IP, and its error (σ_δ) are calculated. Poorly measured tracks (those with $\sigma_\delta > 250$ μm), or tracks with $|\delta|>0.003$m, are removed. The latter result largely from long-lived strange particles, gamma conversions and longnuclear interactions. Track impact parameters are signed using the following technique. The JADE jet finding algorithm[10] with y_{cut}=0.02 is used to determine the jet axes in the event from the set of all good tracks. We find an average of 2.5 jets per Z^0 event. For each track, $|\delta|$ is signed +(-) if it crosses its jet axis in front (back) of the IP. A signed and normalized impact parameter (δ_{norm}) is formed from $\pm|\delta|$ divided by σ_δ added in quadrature with σ^{IP}. Secondary decay tracks preferentially populate $+|\delta_{norm}|$, while $-|\delta_{norm}|$ tracks largely reflect errors in the jet assignment and direction, tracking resolution, and IP position. Fig. 2 shows δ_{norm} for the data, and for Monte Carlo (MC) events with simulation of the detector.

An event is b-tagged by requiring a minimum number of tracks (N_{track}) with large normalized impact parameter ($\delta_{norm} > N_{sig}$), where N_{sig} is the number of standard deviations. Figure 3 shows the b-tagging purity (Π_b) vs. efficiency (ε_b) as the N_{sig} cut is varied.[11] Contours for a number of multiplicity cuts are also shown in Fig. 3. For this analysis we choose N_{sig}= 3 and require at least three tracks passing the δ_{norm} cut. This tag selects 1056 of 5641 events from 1992 data and 1114 of 6147 events from 1993 data. The MC and standard model cross-sections for $Z^0 \to q\bar{q}$ are used to estimate the purity of the sample, Π_b=0.80. Using MC efficiency estimates of ε_b = 0.64, ε_c=0.13, and ε_{uds}=0.02, we obtain a value of R_b = 0.235±0.006 (stat. error only), after averaging the two sets of data.

The MC detector simulation is based on *GEANT* and produces raw data that models the detector's average response to charged and neutral particles. Simulated data is overlaid with random background events taken in close time-proximity to each recorded Z^0 then reconstructed with standard pattern recognition and tracking codes. This technique closely reproduces the time dependent backgrounds and the detailed changes in detector performance. The MC does not exactly reproduce the δ_{norm} distribution observed in the data. Some MC tracks are adjusted after reconstruction to make the impact parameter distribution in the MC agree more closely with the data over a range of δ_{norm} from -15.0 to 0.0. A fit is performed, to make the corrections. While no degradation of resolution is required to get the cores ($|\delta_{norm}| < 2$) of the distributions to match, we find about 4% of all linked tracks require position smearing as large as 500μm. This reflects a non-

Gaussian component of the resolution which is primarily due to mis-linked tracks. A difference in track finding efficiency between the data and the MC is also observed and corrected for. This correction is performed as a function of momentum, $\cos\theta$, φ, and ξ (angle to jet direction), by randomly removing MC tracks. About 10% of the MC tracks passing CDC and VXD cuts are removed. After these corrections, good agreement between the MC and the data in both shape and normalization is seen in Fig. 2 over the entire distribution.

Table I summarizes the fractional systematic errors in the R_b measurement; they are divided into detector and physics modeling sources. The uncertainty from tracking efficiency is estimated by averaging out the dependencies on each of the tracking correction variables. The uncertainty from tracking resolution is estimated by examining the variation of R_b with reasonable variations of the impact parameter tail smearing parameters. An upper limit on the amount of non-Gaussian tail which could be present in the σ^{IP} distribution is derived from the hadronic and leptonic Z^0 decays and used as an estimator for the effect of the IP position systematics on R_b. The combined detector and IP modeling error is 5.9%.

The physics modeling systematics are dominated by uncertainties in heavy quark fragmentation, lifetimes, and multiplicities. The average *B*-hadron lifetime is varied about the world average of 1.45±0.10ps. The effect of fragmentation has been studied with the LUND MC, using Peterson functions with $(\langle x_e \rangle, \varepsilon)=(0.494\pm0.025, 0.06)$ and $(0.700\pm0.021, 0.006)$ for *c* and *b* quarks, respectively. The total charged multiplicity in *B*-hadron decays has been allowed to vary by ±0.5 tracks to assign an error which properly reflects present experimental uncertainties on B-multiplicities. Exclusive models of the hadronic and semileptonic decays of B- and c-hadrons have been incorporated into LUND and adjusted to reflect present knowledge of their decays. Whenever possible, exclusive semileptonic decays incorporate proper form factors and matrix elements, while exclusive hadronic decays have been studied with a pure phase space model. A second model attempting to preserve the weak matrix elements using the factorization hypothesis, provides a test of the sensitivity to induced momentum and charge correlations. A ±20% variation of both the ratios $\Gamma(B\rightarrow D^+X)/\Gamma(B\rightarrow all)$ and $\Gamma(c\rightarrow D^+X)/\Gamma(c\rightarrow all)$ were found to contribute less than 1% each to the systematic error on R_b. The present uncertainty in the charm branching fraction of the Z^0, $\Gamma(Z^0\rightarrow c\bar{c})/\Gamma(Z^0\rightarrow \text{hadrons})=0.170\pm0.017$,[12] contributes about 1.6%. The jet axis algorithm has been studied by varying the JADE algorithm parameter y_{cut} from 0.02-0.1. Finally, the MC models have been modified to more properly reflect the present expectations for the distribution of

Table I. Systematic Errors on R_b

DETECTOR MODELING	ERROR (%)	PHYSICS MODELING	ERROR (%)
Tracking Resolution	3.5	Jet Axis Modeling	<1.0
Tracking/Linking Efficiency	4.5	B-Lifetimes	2.2
IP Position Tails	1.6	b-Fragmentation	2.4
Subtotal	5.9	B-Decay To D^+	<1.0
		B-Multiplicity	2.9
		B-Model	1.0
		$\Gamma(Z^0 \rightarrow c\bar{c})$	1.6
		c-Fragmentation	<1.0
		c-Decay To D^+	0.9
		Subtotal	5.0
		TOTAL	7.7

strongly and weakly decaying hyperons carrying heavy flavors. The overall physics modeling systematic error is estimated to be 5.0%.

In conclusion, we have measured R_b using a technique which relies on the counting of all charged tracks with large 2D normalized impact parameters relative to the beam interaction point. Tagged b-samples with high efficiency (64%) and purity (80%) are obtained. The result relies strongly on the detailed understanding of the vertex detector and the IP position. Combining our 1992 data with our preliminary data from 1993, we find

$$R_b = 0.235 \pm 0.006_{stat} \pm 0.014_{detector} \pm 0.012_{physics} .$$

This result is consistent with the prediction of $R_b \approx 0.22$ in the standard model.[13]

Already, with a sample of 27K Z^0 events, this technique is no longer statistics limited and is now approaching precision in detector and physics-modeling systematics similar to other measurements which employ high p_T lepton flavor tags and have physics systematics which are substantially different. We anticipate that the error from the detector modeling will decline further, while the error on physics uncertainties will only decline as new measurements of fragmentation and the underlying decay processes become available.

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3) For $b\bar{b}$- events at the Z^0, $<\gamma\beta c\tau> \approx 2.7$mm and $< \delta> \approx 240\mu$m.

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FIGURES

Fig. 1) a) The distribution of impact parameters relative to the average IP for tracks in $\mu^+\mu^-$ events, and b) The distribution of the difference between the event-by-event primary vertex and the average IP, projected onto the axis perpendicular to the thrust axis.

Fig. 2) The δ_{norm} distribution for all tracks passing the cuts described in the text. The points are the data, the dotted line the MC corrected for efficiencies but uncorrected for track smearing, and the solid line the MC corrected for both efficiency and smearing.

Fig. 3) The tagging purity versus efficiency from the corrected MC for different values of N_{track} and N_{sig} cuts.

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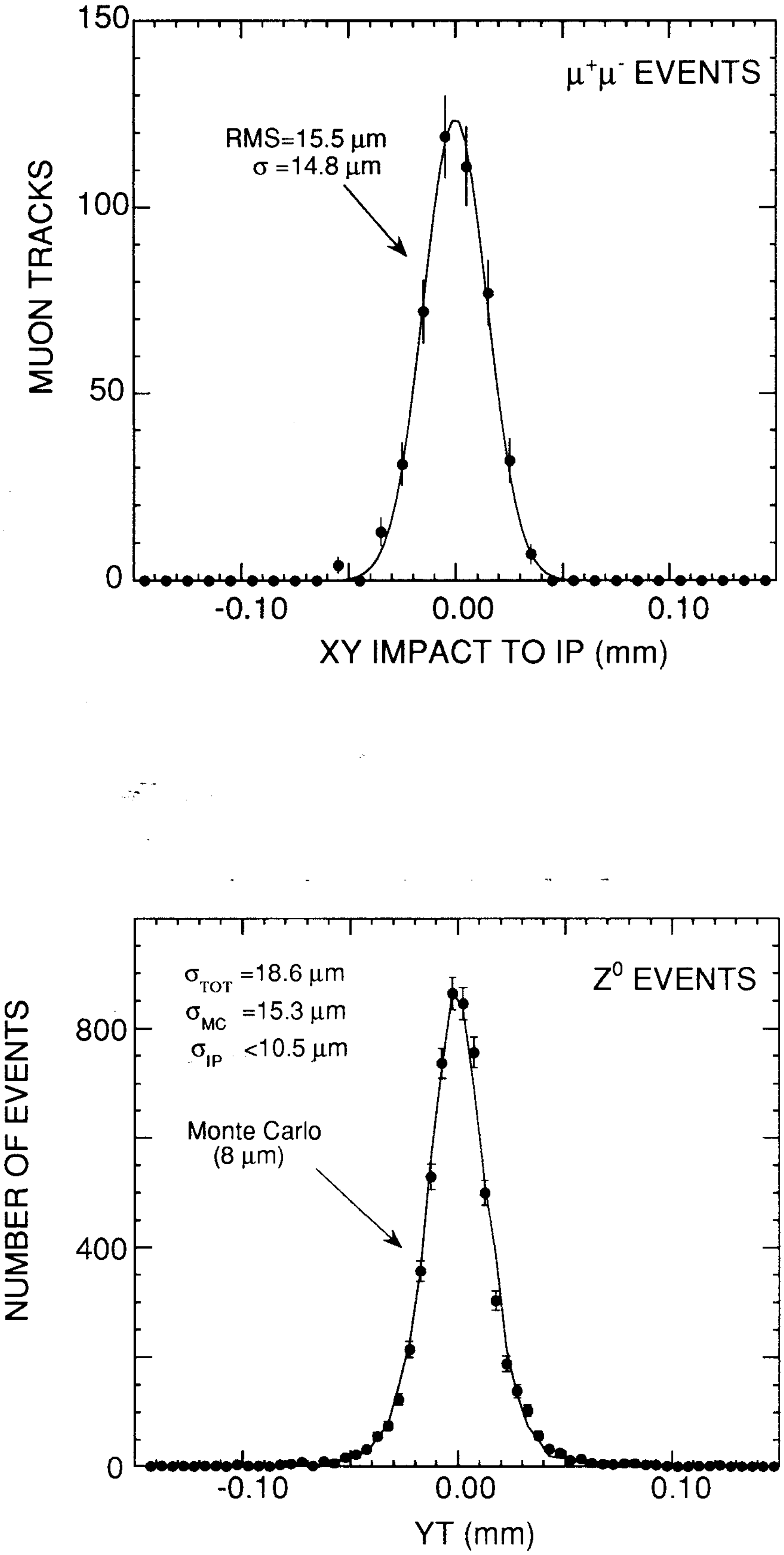
(33)*Vanderbilt University*
(34)*University of Victoria*
(35)*Yale University*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μ+μ- EVENTS
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σ =14.8 μm
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NUMBER OF EVENTS
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σTOT =18.6 μm
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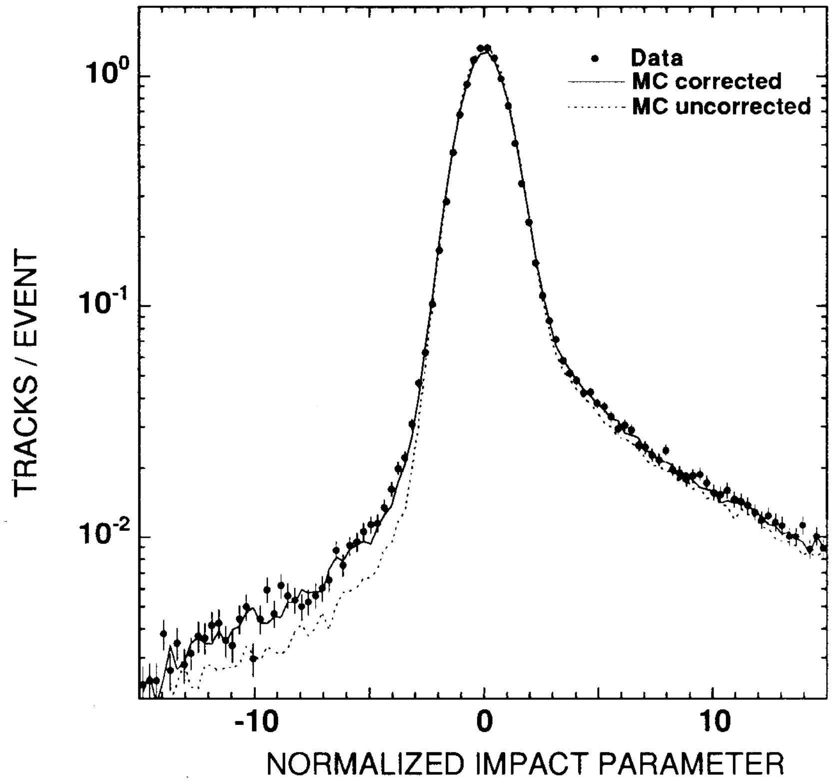
YT (mm)

Fig. 1



Data
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MC uncorrected
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10^{-2}
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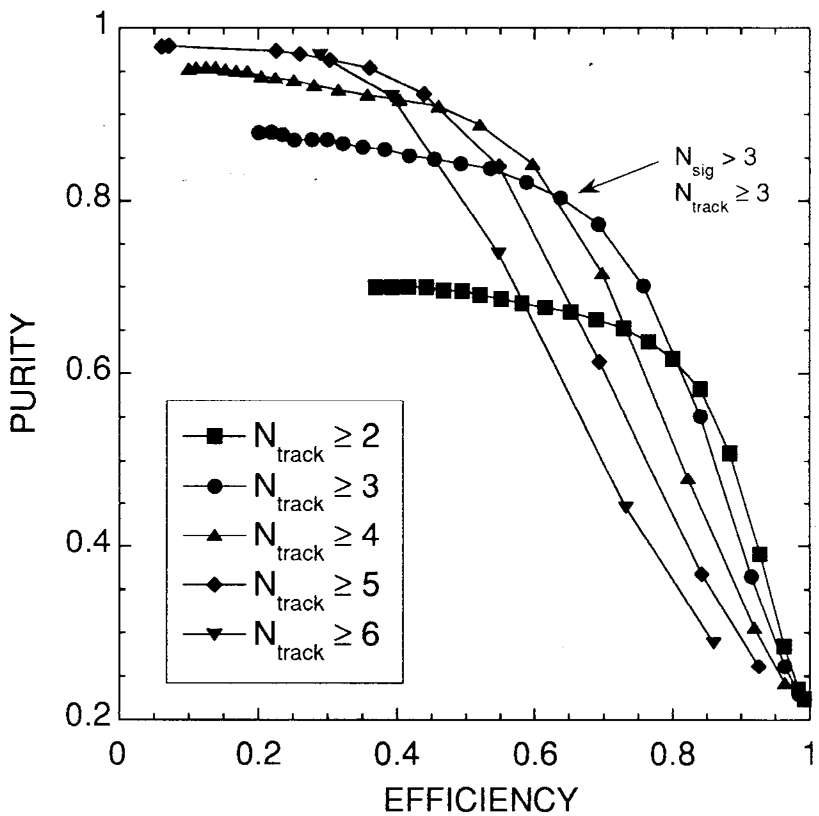
10
NORMALIZED IMPACT PARAMETER

Fig. 2



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PURITY
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EFFICIENCY
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$N_{track} \geq 3$
$N_{track} \geq 2$
$N_{track} \geq 3$
$N_{track} \geq 4$
$N_{track} \geq 5$
$N_{track} \geq 6$

Fig. 3