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QVSRCH
A Tool for Inclusive Secondary Vertex Finding

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Abstract

QVSRCH analyzes events for the presence of secondary vertices. It finds a primary vertex, two jet directions, the coordinates of a secondary vertex candidate in each jet direction, and a variable for tagging jets with significant secondary vertices. The B purity is over 90% at 60% efficiency for an event tag applied to Monte Carlo events in the VDET acceptance. A routine QVSTVA is also provided for assigning tracks to the three vertices. The track assignment efficiency is over 80% for Monte Carlo B decays with significant flight distances, with an average of 0.5 primary tracks background per jet.

1 Introduction

The B hadrons produced by Z^0 decay typically travel 2 mm before decaying to about 5 charged hadrons, including the decay products of tertiary charmed hadrons. With the ALEPH VDET, the error on the reconstructed decay distance can be as small as 200μ, providing a 10σ signal. However, there are typically 5 other charged hadrons from the primary vertex in the same hemisphere of the event, making over 1000 possible combinations of tracks. If the hemisphere multiplicity fluctuates to 15, which is not uncommon, there are over 32000 combinations. The brute-force approach of forming a vertex from all combinations of tracks becomes exponentially impractical at high multiplicity.

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QVSRCH uses a different approach to find secondary vertices. The problems of the determining the coordinates of secondary vertices and of dividing tracks between the primary and secondary vertices are solved simultaneously. The algorithm is based on a search in coordinate space, rather than a search among track combinations.

For given primary and secondary vertex coordinates, we define $\Delta\chi^2$ as the difference between the χ^2 when all tracks are assigned to the primary vertex, and the sum of the primary and secondary vertex χ^2 values when some tracks are transferred from the primary to the secondary vertex. The maximum $\Delta\chi^2$ for fixed vertex coordinates is obtained simply by assigning each track to the closest vertex. The central idea in QVSRCH is to calculate this $\Delta\chi^2$ for a grid in secondary vertex coordinate space, and call the point of maximum $\Delta\chi^2$ the secondary vertex. As long as there are any usable tracks in the hemisphere, a secondary vertex candidate is always produced, although the significance of the vertex obviously varies.

The improvement in the χ^2 when the secondary vertex is introduced can be used as a measure of the vertex significance. Large values can be used to tag B decays. A routine called QVSTVA (for track-vertex-association) is also provided in the QVSRCH package to determine which vertex is closest to a given track, after the vertices have been found.

QVSRCH is not intended to be a substitute for routines that fit the vertex of an explicit combination of tracks selected on some independent basis, *e.g.*, their invariant mass. It is more appropriate to consider QVSRCH as a pattern recognition routine than a fitting routine. In fact, due to some approximations and assumptions internal to QVSRCH, if the tracks selected by QVSTVA as belonging to a given vertex are given to a conventional vertex fitting routine, they will normally produce a somewhat different vertex than the one found by QVSRCH.

2 How to use QVSRCH

QVSRCH is available in the UPHY area. Read the comments at the beginning of the code which explain the arguments. The calling routine must have DIMENSION statements for the arguments.

The only input arguments are BPOS(3) and BSIZ(3), which are arrays the user must load with the beam position and size. The UPHY routine GET_BP is probably the best way to do this, but filling BPOS from ALPHA variables QVXNOM, QVYNOM, QVZNOM, and filling BSIZ with fixed values of .0200, .0020, 2.0 gives adequate performance. QVSRCH will then find its own primary vertex, 2 jet directions, and a secondary vertex in each jet.

The primary vertex and errors are returned in arrays PVTX(3) and EPVTX(3). The jet directions are returned as normalized vectors in a single array DJET(3,2). The secondary vertices are returned in array AVTX(3,2) in ALEPH coordinates, with covariance matrices in CAVTX(3,3,2). In DJET, AVTX, and CAVTX, the last subscript is the jet number, either 1 or 2, and the other subscripts refer to (x, y, z) in the ALEPH coordinate system. Note that the correlations in the covariance matrix CAVTX are quite large, because the vertex error along the jet direction is normally much larger than the errors normal to the jet direction.

The secondary vertices are also returned in coordinates based on the primary vertex and jet directions in array SVTX(3,2). The vertex errors in these coordinates are in array ESVTX(3,2). In these coordinates, the primary vertex is at $(0, 0, 0)$ and the jet direction vector is $(0, 0, 1)$. The first coordinate contains mostly r-ϕ information, and the second contains mostly r-z information. The jet coordinate system is convenient because lifetime information appears as a positive value for the third coordinate, and the correlations are much smaller (and neglected).

The array BTAG(2) contains $\Delta\chi^2$ for the secondary vertices in the jets, divided by 2 for historical reasons.

Normal completion is indicated by JERR=0, with values of 1, 2, or 3 indicating results were obtained but there were problems with the secondary vertex error calculations. The unreliable errors are flagged by being set negative. Larger JERR values indicate some output information is missing, and has been set to large negative values.

QVSRCH uses ALPHA charged tracks with at least 4 TPC hits and χ^2 per degree of freedom of less than 4. There are no explicit momentum or $\cos\theta$ cuts, but there are cuts on r-ϕ, r-z, and 3-dimensional impact parameters of tracks that become more stringent as more is known about the location of the vertices. There is no requirement of VDET hits, and no jet angle cut, although performance obviously is poorer when few tracks are inside the VDET acceptance.

It is possible to prevent QVSRCH from using specified tracks by the LOCK feature of ALPHA. It is possible to suppress the primary vertex finding part of QVSRCH by setting any element of BSIZ to a negative value. It is then necessary for the user to provide his own primary vertex and errors in the arrays PVTX and EPVTX. The default is for QVSRCH to find its own jet directions using PCPA objects and selected charged tracks. If your ALPHA cards specify other energy flow objects, including pre-clustered jets, QVSRCH will try to interpret your cards appropriately. It is possible to suppress the jet finding in QVSRCH with a 'NQVJ' card. It is then necessary to provide your own two normalized jet direction vectors in the array DJET(3,2). In any case, a message will be printed specifying which jet option has been taken.

QVSRCH will work with POT, DST, and MINI data, but the lack of d_0 and z_0 error information makes it impossible to run on NANO data. Since QVSRCH requires about 0.035 seconds real time on CERNVM per event as measured by TIMED, (0.7 'CERN-unit' seconds measured by ALPHA routine QTIMED) little would be gained by running on the NANO in any case.

3 How to use QVSTVA

The input arguments of QVSTVA are the ALPHA track number ITK, the primary vertex coordinates PVTX, the two jet direction vectors DJET, and the two secondary vertices in the jet coordinate systems SVTX. These have exactly the same meaning as in QVSRCH. The outputs are JET, the jet which QVSRCH considers the track to be in, and IVX, information about which vertex in that jet which QVSRCH considers the track to be in. JET is not an ALPHA jet number, but simply 1 or 2. IVX=-1 means the track failed the track cuts, IVX=0 means the track passed the cuts but is far from any vertex, IVX=1 means the track is closer to the primary vertex, and IVX=2 means the track is closer to the secondary vertex. Note that a LOCKed track will fail the track cuts and will return IVX=-1.

4 Primary Vertex Algorithm

QVSRCH calls QVSPVX to find the primary vertex. QVSPVX uses the beam coordinates and size as input arrays BPOS and BSIZ, and returns the primary vertex and errors in arrays PVTX and EPVTX. The input argument TSMR is the amount to add in quadrature to the track fit errors to make the vertex errors more realistic in B events. The output argument IERR=0 means successful termination, with IERR=1 meaning the vertex errors are questionable, and IERR=2 means there were not enough good tracks to find a vertex.

Tracks passing within 3 mm of the beam axis are used to find a coarse z vertex coordinate. Tracks passing within 3 mm in space (or 3 mm in r-ϕ if the z_0 error is more than 1 mm) of this point on the beam axis are extrapolated to the plane defined by the y coordinate of the beam. The track impact points and errors are used to calculate the χ^2 of candidate primary vertices at points 20μ apart in a 1 mm square grid. If the error in the track impact point is less than 20μ in either x or z, that error is increased to 20μ, to prevent tracks between the grid points from being ignored. Tracks only contribute to the χ^2 of points out to 3σ. The beam coordinate and size in x are also included in the χ^2. The grid point with the minimum χ^2 is found, and a paraboloid surface is fit to the region around it to interpolate between grid points, with the curvature of the surface giving the vertex error. Negative curvature or failure of this interpolation fit cause IERR=1. The result of this grid-search procedure is the point with the minimum χ^2 when considering all tracks within 3σ of that point, with no need for iteration.

For *uds* events more than 45° from the beam direction, the core resolution is about 30μ in x, z, and along the jet direction, although there are tails that make the RMS closer to 50μ. For B events, many tracks miss the primary vertex. Since the tracks actually from the primary vertex are fewer and of lower momentum with larger scattering errors, the resolution would be degraded even if it were possible to eliminate all tracks from secondary vertices. In fact, there are many tracks from B decay which miss the primary vertex by more than their error but less than the

3σ cutoff. This degrades the resolution further, and also causes the vertex error to be an underestimate. The RMS vertex resolution is about 90μ in B events, and the error is underestimated by about a factor of 2.

The input argument TSMR can be used to compensate for the additional track smearing due to lifetimes in B events, with a value of 0.0100 (100μ) making the error approximately correct at little cost in the resolution for B events. However, the performance of the rest of the QVSRCH package for finding vertices and tagging B events is best with TSMR=0.

It is possible to use QVSPVX as a stand-alone primary vertex routine requiring no jet directions. The average time required by QVSPVX is 0.006 seconds as measured by TIMED on CERNVM (0.120 'CERN-unit' seconds measured by ALPHA routine QTIMED)

5 Jet Finding

QVSRCH calls QVSJET to find the jet directions. QVSJET is an interface to the ALPHA routines QJMMCL and QJOPTR. The output array DJET contains normalized direction vectors for jet 1 and jet 2. Jet 1 is the one with the highest energy, and jet 2 is the one forming the highest invariant mass with jet 1. The output argument NJETS is the number of jets that were found. Jet clustering is done with YCUT=.02 and EVIS=91.173. Note that these are different from the standard heavy-flavor-lepton jet finding. QVSRCH returns JERR=64 and does not attempt to find secondary vertices if QVSJET returns NJETS<2.

If the user supplies a 'NQVJ' card, QVSJET sets NJETS=2 and returns, assuming the user has already filled DJET with his own jet directions. If there is an 'ENFJ' card, QJOPTR is called with the 'EJ' option, so pre-clustered jets will be clustered farther. If there is an 'ENFW' card, QJOPTR is called with the 'EF' option, so stored energy flow objects will be clustered. If none of the above cards exist, the default is to call QJOPTR with the 'PC' option, so PCPA objects and selected charged tracks will be clustered. In this last case, a 'NOPC' card will cause only charged tracks to be clustered (not recommended). In the other cases, 'NOPC' will be ignored by QVSJET. Users should be aware that not all data sets have all the above objects stored, and that occasionally the ALPHA and the MINI packages change in ways that may require changes to QVSJET.

6 Secondary Vertex Algorithm

QVSRCH calls QVSVTX to find the secondary vertices in the jets. QVSVTX uses as input the primary vertex and error PVTX and EPVTX, and two jet directions DJET. These input arguments are in the regular ALEPH coordinate system. It returns the secondary vertex coordinates in SVTX, and the errors in ESVTX. These output arrays are in the jet coordinate systems, where the primary vertex is at

$(0,0,0)$ and the jet directions are $(0,0,1)$. The array BTAG contains $\Delta\chi^2$ for the secondary vertices in the jets, divided by 2. (The factor of 2 is because internally, the calculations are treated as log-likelihood rather than χ^2, to allow a sophisticated treatment of tails, although this has not proven to be necessary). The output argument IERR=0 means successful termination, with IERR=1 meaning the vertex errors in jet 1 is questionable, IERR=2 meaning the same for jet 2, and IERR=3 the same for both jets. IERR=4 means not enough tracks for jet 1, IERR=8 the same for jet 2, and IERR=12 means not enough tracks in either jet.

A track must pass within 3 mm in space (or 3 mm in r-ϕ if the z_0 error is more than 1 mm) of the primary vertex to be used by QVSVTX. Each track is considered to be a member of exactly one jet, the one that gives the more positive dot product with the ALPHA track momentum direction. Note this does not correspond exactly to 'hemispheres,' since the jet directions are not exactly back to back in most cases. It also may not correspond exactly to jet cluster membership.

The position, direction, and curvature of a track at the point closest to the ALEPH z axis are calculated. These are rotated to the jet coordinate system, along with the matrix describing the d_0 and z_0 errors. The quadratic polynomials describing the track coordinates in the jet system as a function of distance along the jet direction are calculated. The track errors are also expressed as errors transverse to the jet direction. These transformations need be done only once for each track and allow the subsequent calculations of $\Delta\chi^2$ to be very efficient.

The χ^2 of the 3-dimensional distance between the track and the primary vertex is calculated, including the primary vertex errors. This is the maximum possible contribution to $\Delta\chi^2$ that the track can make, even if the secondary vertex lies exactly on the track. Note that this implies that tracks very close to the primary vertex have very little influence on the secondary vertex finding process. To reduce sensitivity to hit assignment errors, scattering, kinks, *etc.*, this contribution is never allowed to be greater than the equivalent of 3σ for any single track.

The calculation of $\Delta\chi^2$ is done for a region extending ±1 cm along the jet direction in 200μ steps and extending $\pm500\mu$ in the two orthogonal directions in 20μ steps. Track errors are increased to the grid size if necessary to avoid missing tracks. The calculation is actually done in two 2-dimensional projections rather than in 3 dimensions, to save time and storage space. This undoubtedly throws out some information on good tracks, but also reduces the confusion from tracks with good impact parameter information in one projection and bad information in the orthogonal projection.

A 'jet-track' defined by the primary vertex and its errors, and parallel to the jet direction, is also included in the $\Delta\chi^2$ grids. However, the 'jet-track' is treated as having an angle error of 50 milliradians, appropriate to the jet angle resolution. (The angle error is ignored for real tracks, since it is implicit in the d_0 and z_0 errors, although this assumption becomes invalid for flight distances approaching the beam pipe radius.)

After the contribution of each track in the jet has been accumulated, the grids are scanned for the points of maximum $\Delta\chi^2$ in each orthogonal projection at a consistent distance along the jet. A local paraboloid is fit around these points, combining the information from the two projections. This is used to interpolate between grid points, to estimate the secondary vertex errors, and to estimate the value of $\Delta\chi^2$ at the peak. If this paraboloid fit produces anomalous results, IERR is set to the appropriate non-zero value, and the corresponding ESVTX element is set negative. This is rare in B events with well-separated vertices, but less rare in *uds* events.

There are some properties of QVSVTX vertices that may be surprising. In some cases, the paraboloid fit will extrapolate to a vertex outside the grid. (In the Monte Carlo, many of these vertices are 'correct.') It is possible for QVSVTX to find a vertex that contains only a single track, because of the 'jet-track.' There is a dip at zero in the distribution of SVTX(3,J), the vertex coordinate along the jet direction in jet J, because a secondary vertex very close to the primary vertex necessarily has a very small $\Delta\chi^2$ value. There is also structure in the distribution related to the 200μ grid spacing. The truncation of the maximum $\Delta\chi^2$ contribution of a single track at the equivalent of 3σ results in structure in the BTAG distribution with bumps at multiples of $3^2/2 = 4.5$.

7 Track-Vertex Association Algorithm

QVSTVA first checks which jet track ITK belongs to by comparing the ALPHA momentum vector direction to the two directions in DJET. It then checks if a track has at least 4 TPC hits, χ^2 per degree of freedom less than 4, and $|d_0|$ *or* $|z_0|$ with respect to the primary vertex less than the greater of 3 mm or the absolute value of flight distance of the secondary vertex along the jet direction. These cuts are intentionally very loose to keep the efficiency high. Nevertheless about 10% of all B decay tracks fail to satisfy them, even for jets with $|\cos\theta| < 0.7$. Tracks with the LOCK bit set by ALPHA are also rejected. IVX=-1 is returned for rejected tracks.

The normalized impact parameters of the track in the jet coordinate system in both the r-ϕ-like and r-z-like directions are calculated with respect to both the primary and secondary vertices. For this purpose, the primary vertex is assumed to have errors of 50μ in ALEPH x and z, and 20μ in ALEPH y, and the secondary vertex is assumed to have errors of 50μ transverse to the jet direction and 350μ along the jet direction. The vertex errors are assumed to be uncorrelated to the track errors. The complications of the more statistically rigorous procedure of using the full vertex covariance matrices and removing the correlation to the track errors have not been found to make a significant improvement in the results, probably because the vertex errors have large contributions from mistaken track assignment that are not reflected in the covariance matrices.

If the track is more than 3σ away from both the primary vertex and the secondary vertex in its jet, in both projections in the jet coordinate system, it is declared to belong to neither vertex by returning IVX=0.

If the track is less than 3σ away from either of the two vertices (not necessarily the same one) in both projections, information from both projections is used to calculate the χ^2 of its miss distance from both vertices. If the χ^2 is less for the primary vertex, IVX=1 is returned. If the χ^2 is less for the secondary vertex in the same jet, IVX=2 is returned.

A small fraction of the tracks are less than 3σ away from at least one vertex in one projection but more than 3σ from both vertices in the other projection. In this case, it is assumed that the track was improperly reconstructed in the projection where the track is far from both vertices. In this case, the bad projection is ignored, and the assignment is made on the basis of the other.

8 Performance as a B-Tag

One simple application of QVSRCH is to tag B jets or events. The signal is simply a large value of the BTAG variable, indicating the χ^2 can be improved by a large amount if a secondary vertex is introduced along with the primary vertex. Figure 1a shows the BTAG distribution for B jets with $|\cos\theta| < 0.7$ in 1991 HVFL02 Monte Carlo, and figure 1c shows BTAG for *udsc* jets. The means are 12.6 for B jets and 3.2 for *udsc* jets. Figure 1b shows the increase in B purity from the initial value of 22% to nearly 100%, and the decrease in efficiency, as the cut on BTAG is increased from zero to large values. Figure 1d shows the purity as a function of efficiency. For a cut BTAG > 10, the B efficiency is about 55% and the purity is about 80%.

Figure 2 shows QVSRCH as an event tag, where both jets were required to satisfy $|\cos\theta| < 0.7$. The last bin contains the large number of overflows. With a cut BTAG(1)+BTAG(2) > 20, the efficiency is greater than 60% and the B purity is greater than 90%.

Figure 3 shows the distribution of the BTAG variable for 1991 and 1992 ALEPH Class 16 data, and for 1991 HVFL02 Monte Carlo data. The left column is the raw distributions. The agreement between the two data sets is rather good. The Monte Carlo has a somewhat smaller mean, but not a smaller RMS. This probably indicates that compared to data, *udsc* events have smaller BTAG values and B events have larger BTAG values in the Monte Carlo, consistent with better tracking in the Monte Carlo than the data. The right column is the distributions after requiring BTAG in the *opposite jet* to be greater than 10. The means all increase dramatically, indicating that lifetime information in one hemisphere is correlated to lifetime information in the other hemisphere. However, the agreement between data and Monte Carlo is not greatly improved.

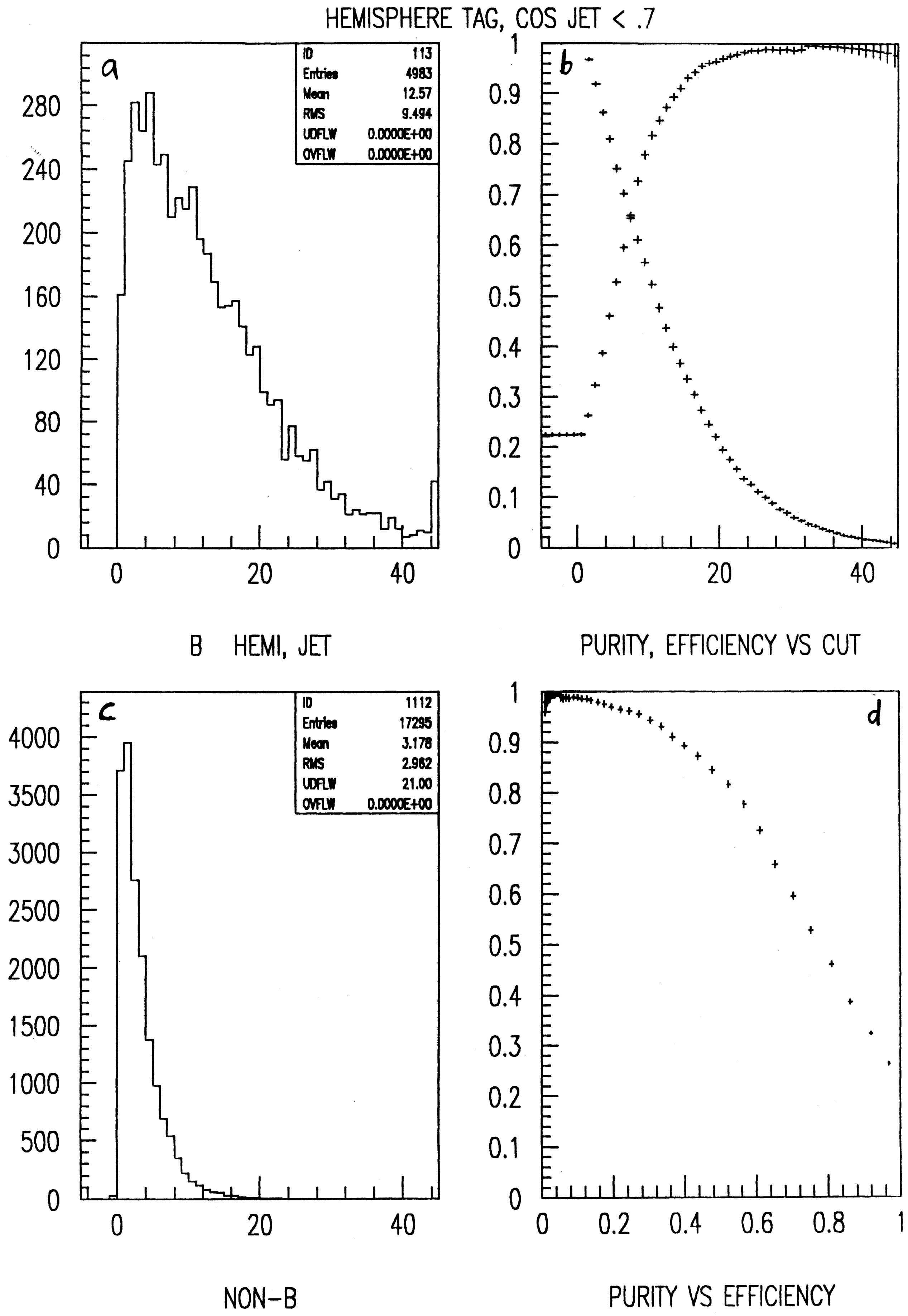


Figure 1: Hemisphere B-tag performance.

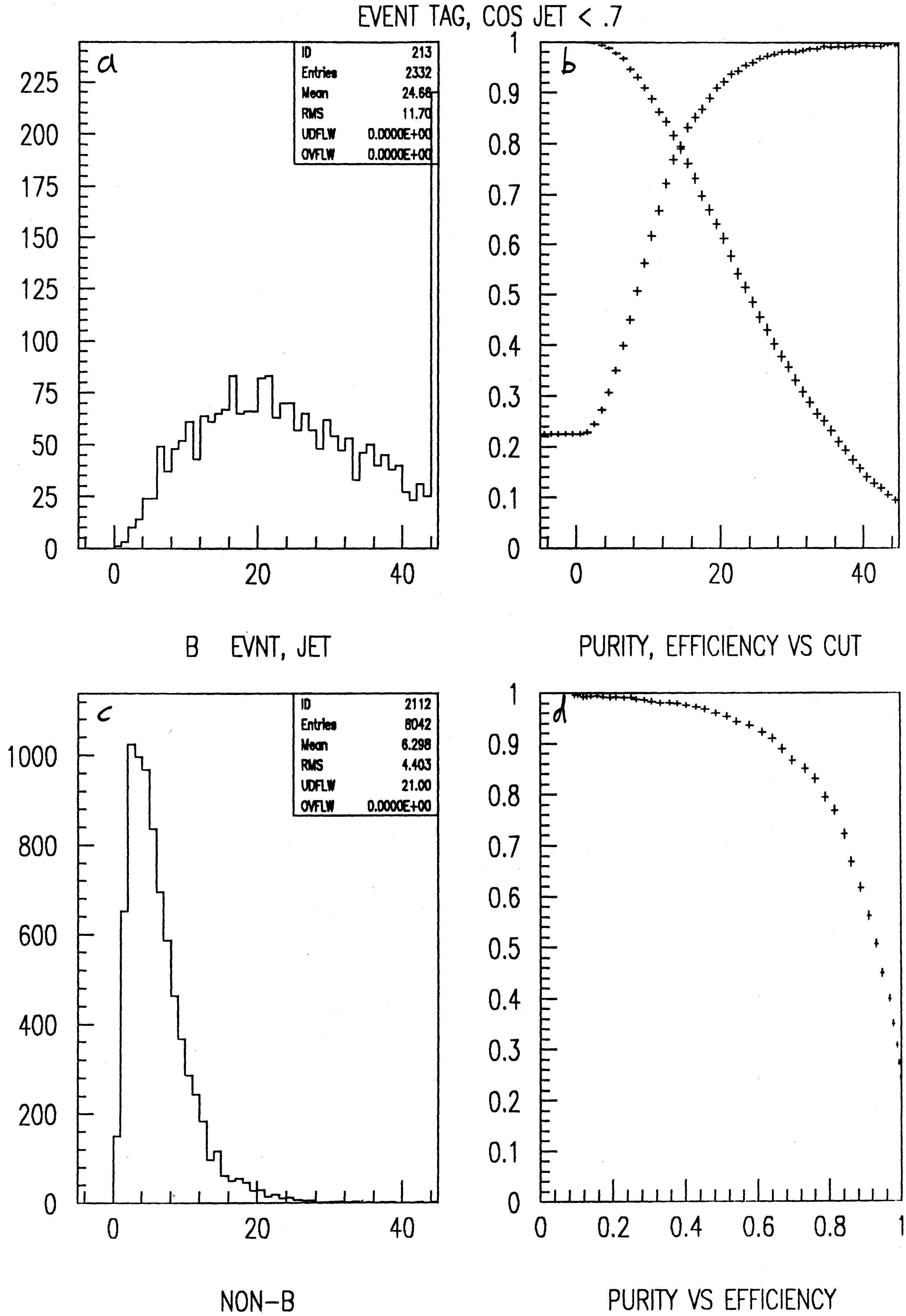


Figure 2: Event B-tag performance.

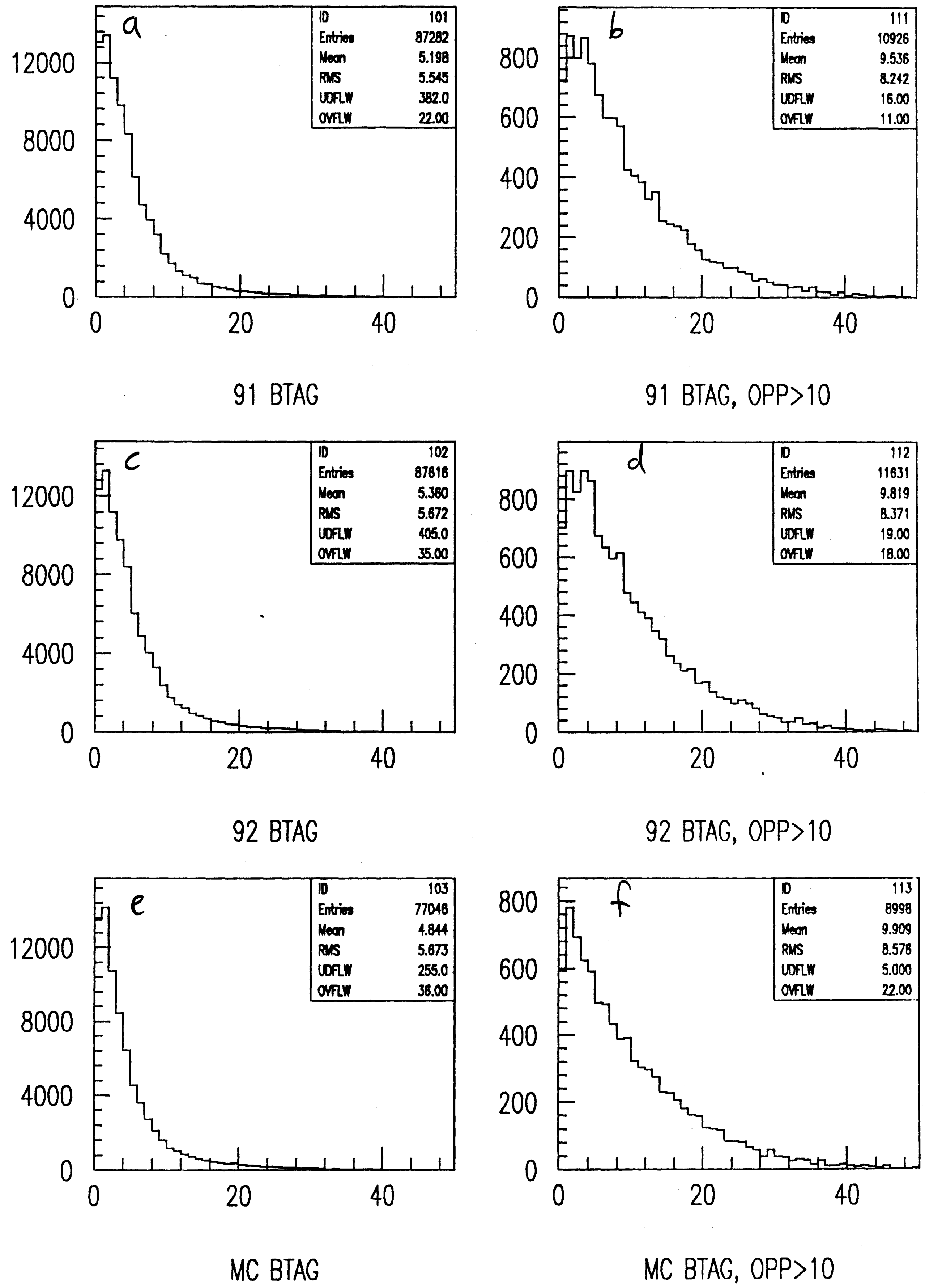


Figure 3: Data and Monte Carlo BTAG distributions

9 Performance as a Secondary Vertex Finder

By construction, QVSRCH always finds a secondary vertex candidate, even in *uds* events. Figure 4a shows the distribution of the 'decay distance' SVTX(3,J) for *uds* jets in 1991 HVFL02 Monte Carlo. (All jets in figure 4 were required to have $|\cos\theta| < 0.7$.) The distribution in nearly symmetrical, with most secondary vertices within 1 mm of the primary, but with a tail extending the full ±1 cm of the scan range.

Figure 4b shows the reconstructed decay distance as a function of the generated decay distance in Monte Carlo charm events. The plot has been allowed to saturate near $(0,0)$ to show that QVSRCH has some efficiency to find charm decays, as indicated by the clustering of events along the diagonal. The efficiency to find a vertex within 1 mm of the generated decay distance is about 40%.

Figure 4c is the reconstructed decay distance for charm jets, with a negative side similar to the *uds* distribution above it, but a substantial positive tail. Also plotted is the distance distribution for events with generated decay distance more than 3 mm.

Figure 4d is the difference between the reconstructed and generated decay distances, with and without requiring the generated decay distance to be > 3 mm. A gaussian fit to the core of the distribution with the decay distance cut gives a resolution of 500μ.

Figure 5a shows the distribution of the 'decay distance' SVTX(3,J) as a function of the generated decay distance in B jets with $\cos\theta < 0.7$ in 1991 HVFL02 Monte Carlo. The correlation is rather striking, especially since the plot has been allowed to saturate badly. Careful observation shows the region above the diagonal contains more events than the region below the diagonal. This is due to tertiary charm vertices pulling the QVSRCH vertex to longer decay distance.

Figure 5b shows difference between the reconstructed and generated B decay distances as a function of the difference between the charm and B decay distances, all projected on the jet direction. The plot has been allowed to saturate to show the diagonal band from events where QVSRCH has found the tertiary charm vertex rather than the secondary B vertex.

Figure 5c shows the reconstructed decay distance for B jets. A negative tail is present but proportionately much smaller than for *uds* or charm events. (The small fraction of B events with very short decay lengths have the same appearance as *uds* events, including the negative tail.) Superimposed in 5c is the distribution of reconstructed decay distances requiring the generated B decay vertex to be 2 mm from the primary. The edge of the smeared exponential is now at larger distance, but there are also some events improperly reconstructed in a broad region around the primary vertex.

Figure 5d shows the vertex resolution along the jet direction. The upper distribution has a gaussian core with $\sigma = 370\mu$, but with substantial tails. If the generated B decay distance is greater than 2 mm, the middle distribution (which

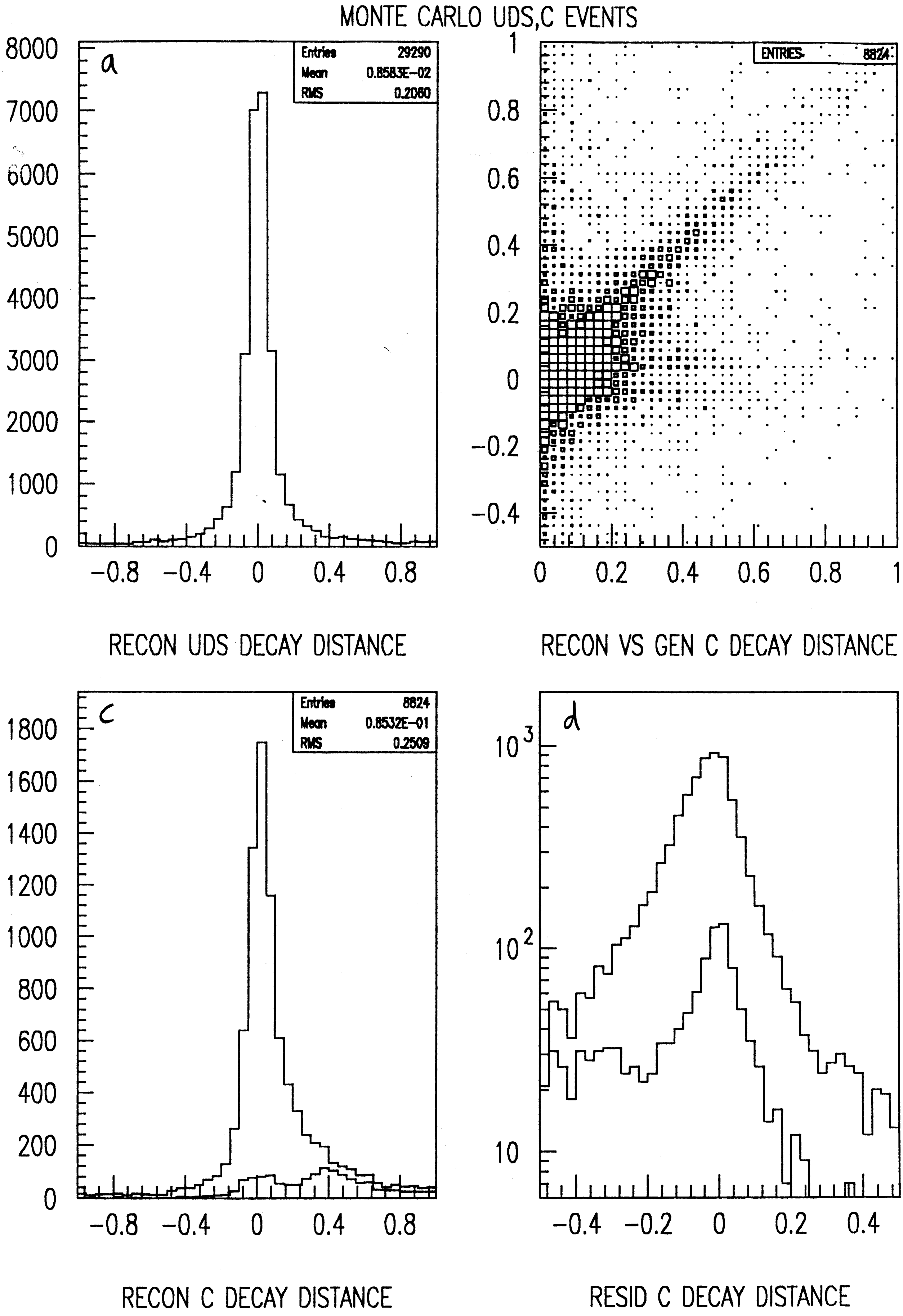


Figure 4: Monte Carlo *uds* and charm secondary vertex reconstruction.

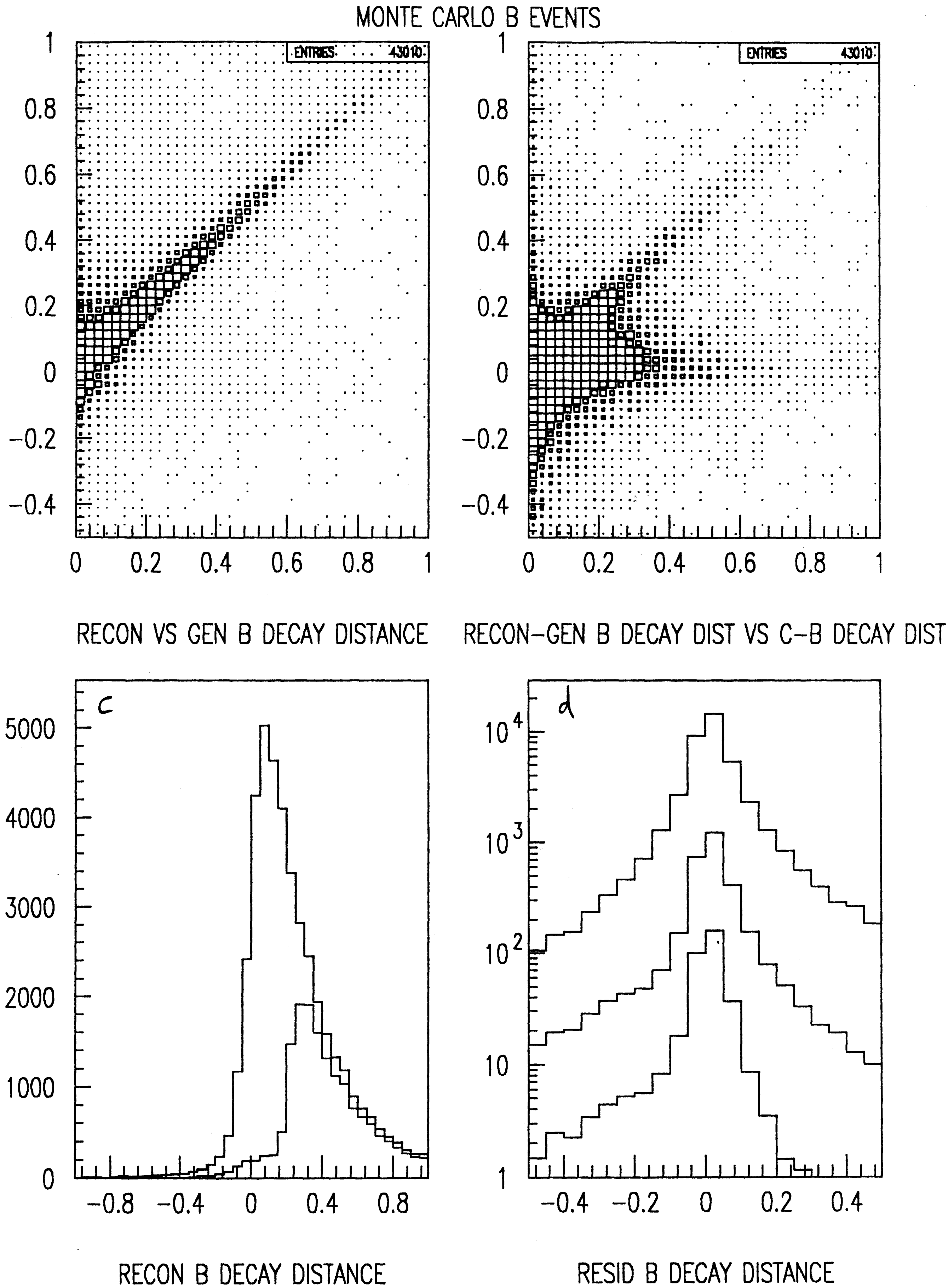
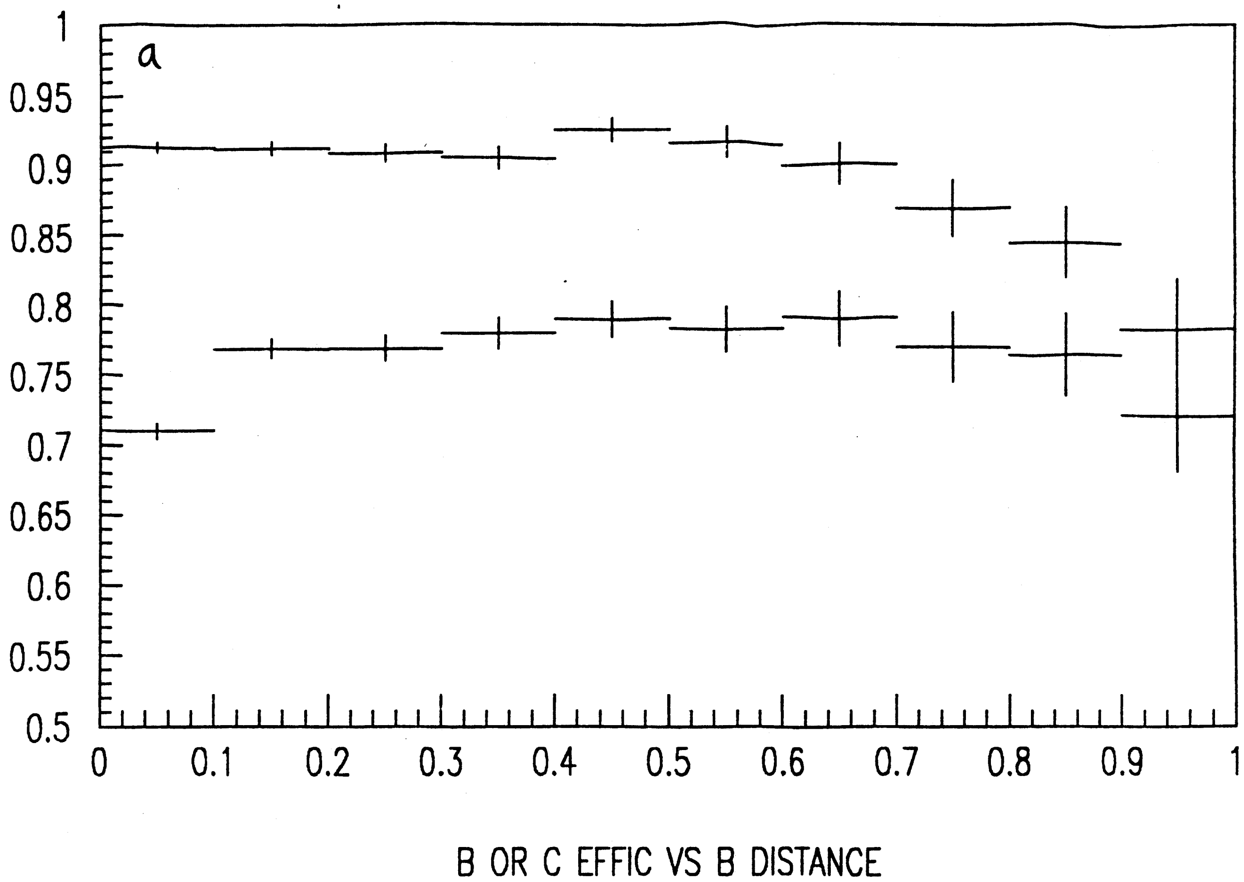


Figure 5: Monte Carlo B vertex reconstruction



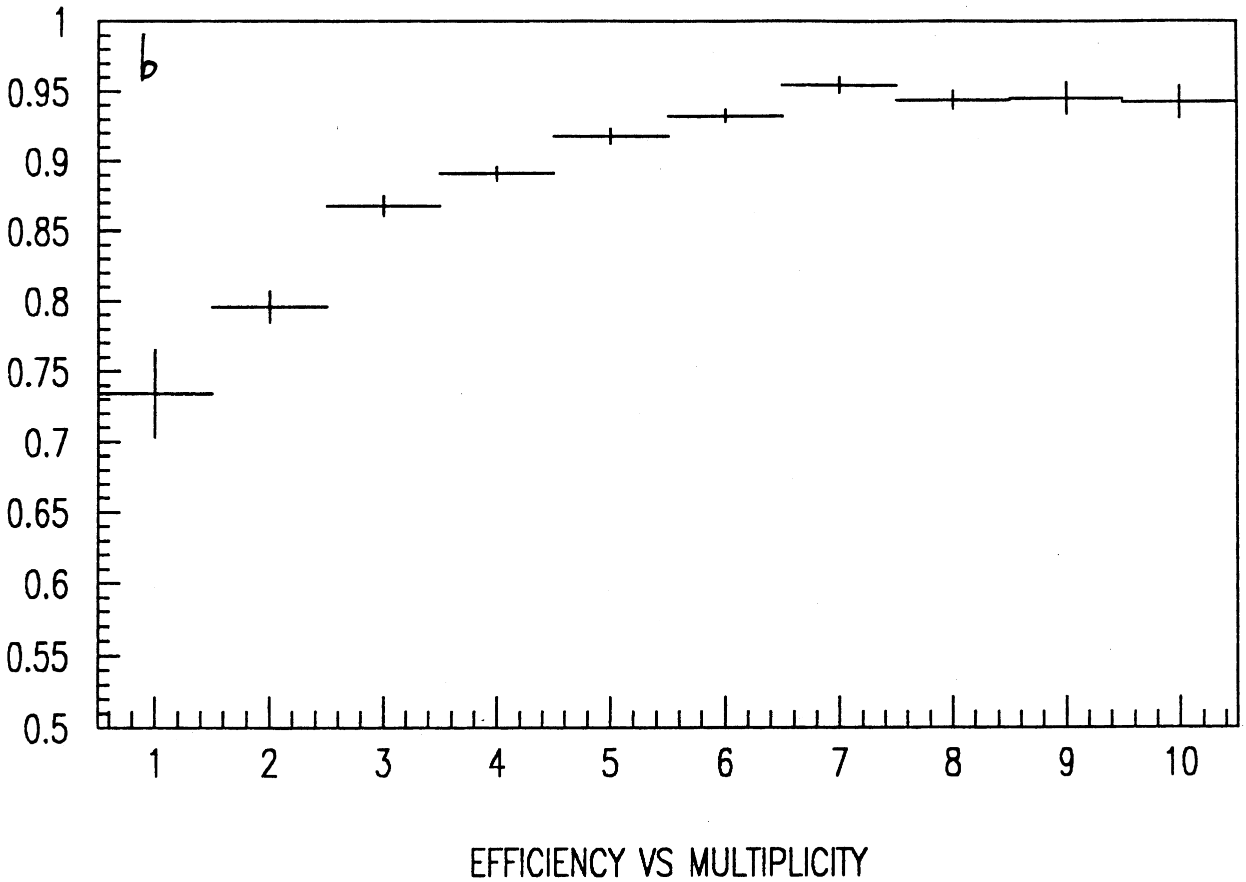


Figure 6: Monte Carlo B vertex efficiency

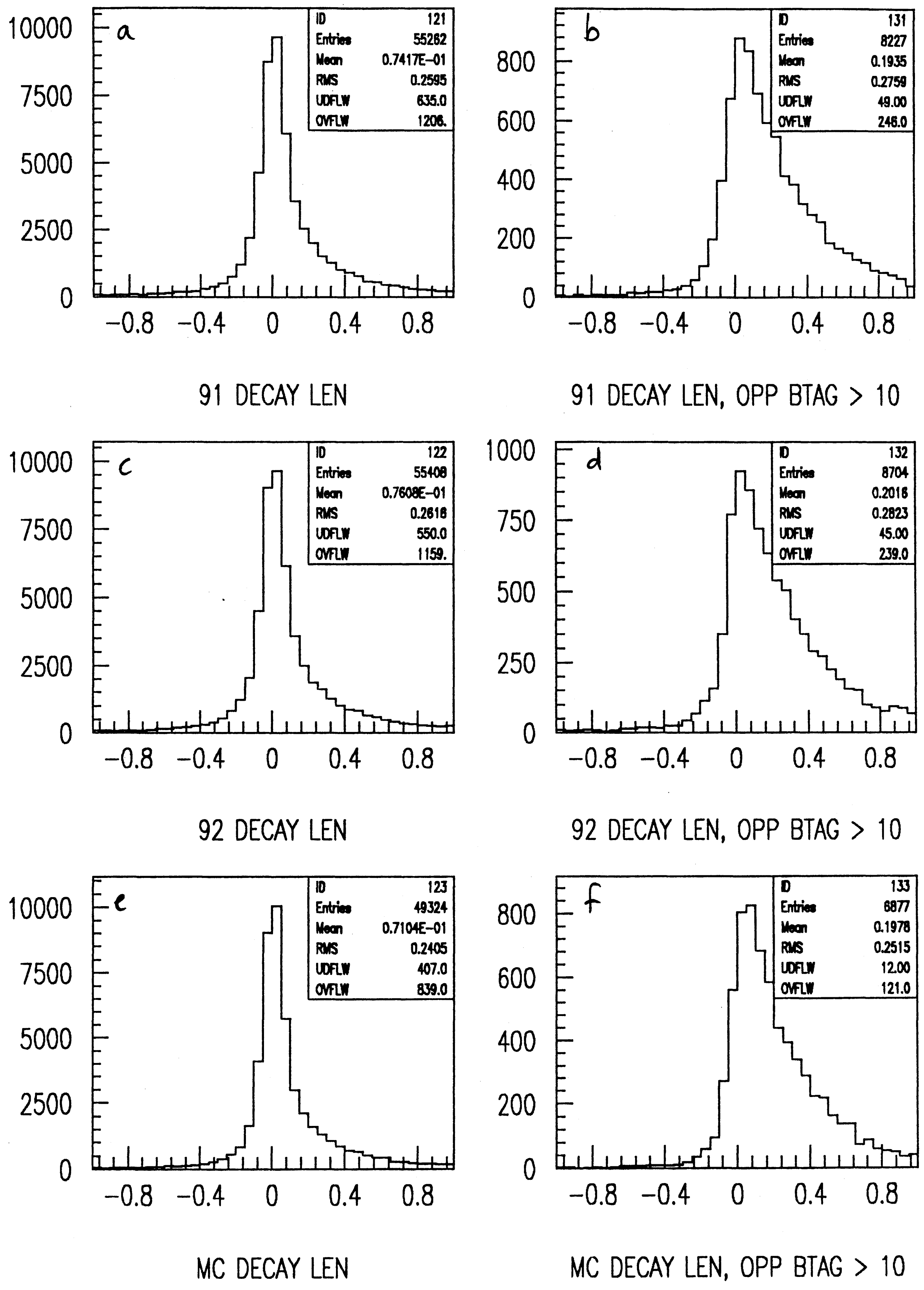


Figure 7: Data and Monte Carlo decay distance distributions

has been shifted downward for clarity) is obtained, showing some improvement in the tails. If in addition the distance between the generated tertiary charm decay and the generated B decay is required to be less than 1 mm, the lower distribution (which has also been shifted downwards for clarity) results. Since events where the charm vertex was far from the B vertex are removed by this cut, the long positive tail is dramatically reduced. The negative tail is also reduced, presumably because QVSRCH is more efficient at finding B decays if all the charm decay tracks are also consistent with the B vertex than if they are not. The core resolution in this case is 320μ.

Figure 6a shows the efficiency for QVSRCH to 'find' B vertices in jets with $|\cos\theta| < 0.7$ in 1991 HVFL02 Monte Carlo, as a function of the generated B decay distance. The lower points are the probability that the reconstructed decay distance was within 1 mm of the generated distance, equivalent to 3σ of the gaussian core resolution. The efficiency exceeds 75% except at large distance, where jet angle errors cause some vertices to be outside the transverse scan region of QVSRCH, and at short distances where the B vertex is difficult to distinguish from the primary vertex, and QVSRCH has a higher probability of finding the tertiary charm vertex instead. The upper points are the probability that the reconstructed vertex is no more than 1 mm upstream of the generated B vertex, *i.e.*, that QVSRCH has found either the B vertex, the charm vertex, or an average of the two. In this case the efficiency exceeds 90% for most of the scan range.

Figure 6b shows the efficiency with this second definition as a function of the sum of the generated charged multiplicities of the B and charm decays in a jet (the average value in the Monte Carlo is about 5). The efficiency falls off somewhat at lower multiplicity.

Figure 7 shows the distribution of SVTX(3,J), the decay distance along the jet, for 1991 and 1992 ALEPH Class 16 data, and for 1991 HVFL02 Monte Carlo data. The jets were required to satisfy $|\cos\theta| < 0.7$. The means are displaced by more than 700μ toward positive decay distance. The tail at negative decay distance is much larger in the data. If the opposite jet is required to have BTAG>10, the means become about 2 mm positive, and the distributions become reasonably exponential.

10 Track-Vertex Association Performance

Figure 8a shows the efficiency for the combination of QVSRCH and QVSTVA to assign tracks to the secondary vertex as a function of generated decay distance for 1991 HVFL02 Monte Carlo B jets with $|\cos\theta| < 0.7$. To be precise, generator level decay tracks from the B vertex or a tertiary charm or τ vertex (with no other cuts) formed the denominator, and the numerator was the reconstructed tracks matched by the ALPHA function KBESTM to the generated tracks (or their decay muons) that passed all the cuts that QVSTVA imposes and were assigned to whatever sec-

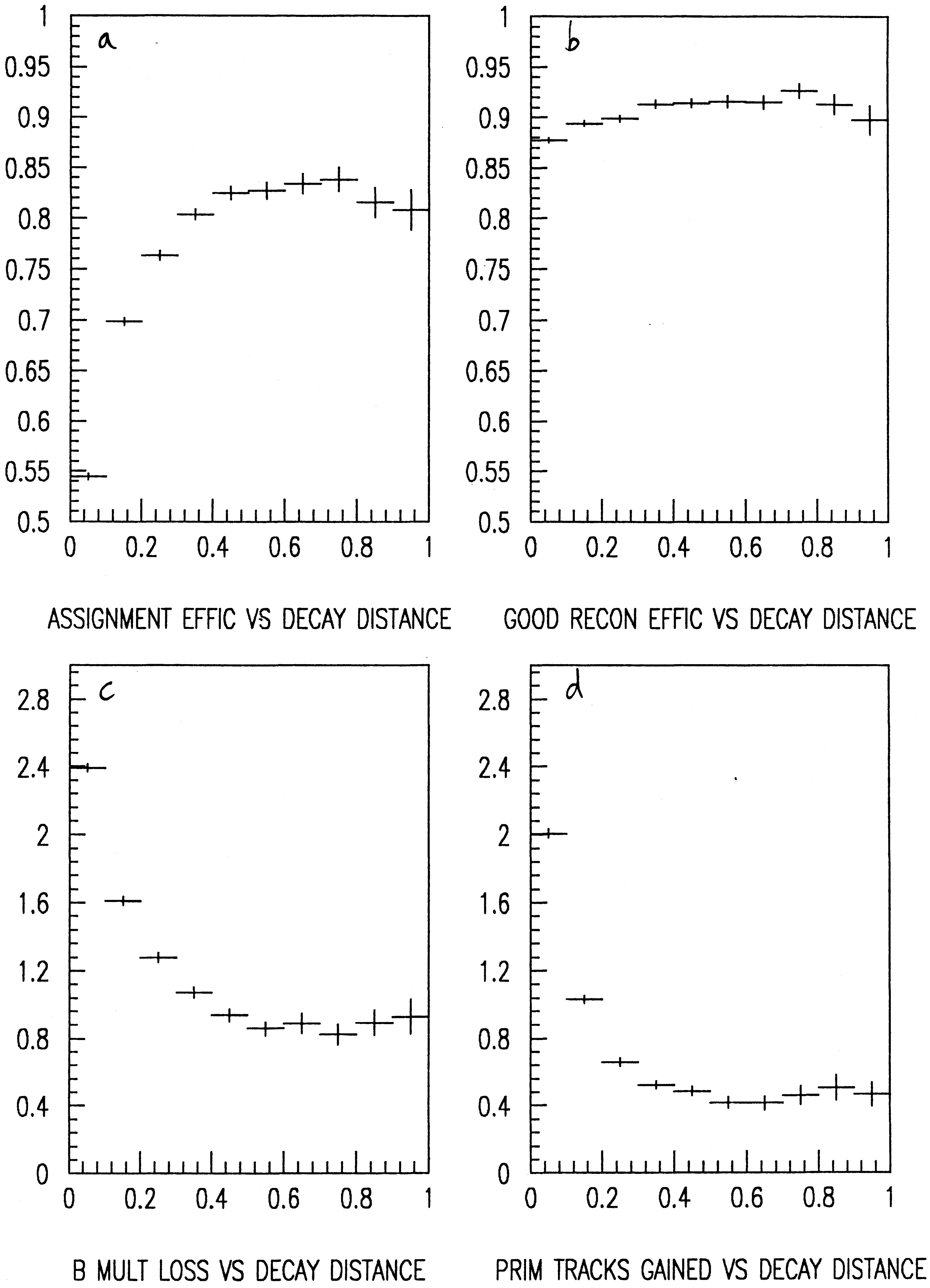


Figure 8: Track-vertex-association in Monte Carlo B jets

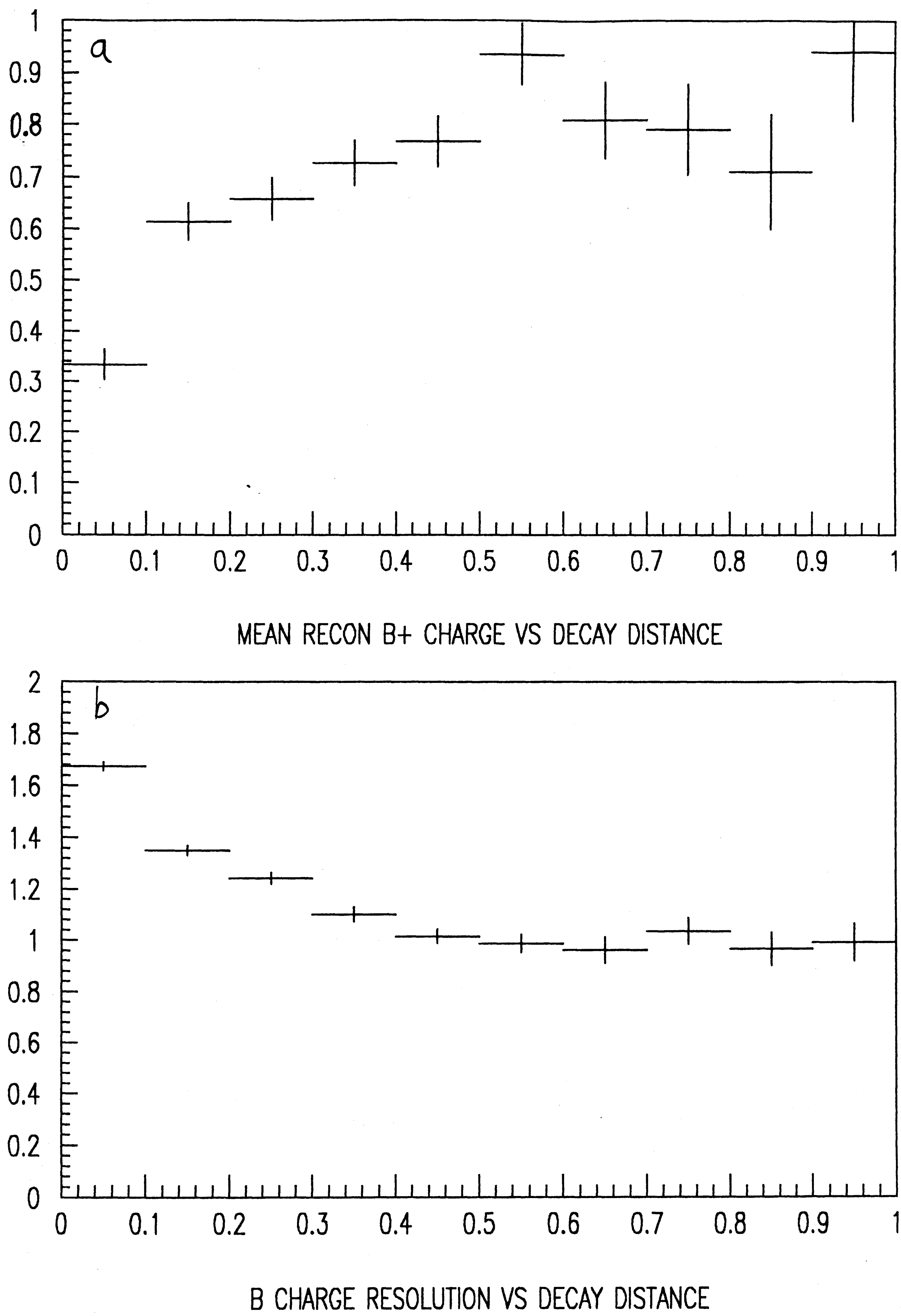


Figure 9: Vertex charge measurement in Monte Carlo B jets

ondary vertex was found by QVSRCH. This ratio has some multiplicity dependence which has been averaged over. At very short decay distances, a track has a roughly equal chance to be assigned to the secondary vertex or the primary vertex. The efficiency is about 70% for decay distances of 1 mm, and about 80% for decay distances of 3 mm or more.

Figure 8b shows the efficiency for the above tracks to pass the loose cuts in QVSTVA imposed before the vertex impact parameter cuts: at least 4 TPC hits, χ^2 per degree of freedom less than 4, and either $|d_0|$ **OR** $|z_0|$ with respect to the primary vertex less than the greater of 3 mm or the absolute value of the secondary vertex decay distance. Thus, of the 20% of the tracks not assigned to well-separated secondary vertices, roughly half are quite poorly reconstructed or missing, even though the jet angle is inside the VDET acceptance.

Figure 8d shows the difference between the total multiplicity reconstructed by QVSTVA, and the correctly assigned B multiplicity as defined above. The excess is tracks from the primary vertex (or other vertices) mistakenly assigned to the secondary vertex. Figure 8c shows information analogous to figure 8a, but in terms of lost tracks rather than efficiency, for comparison. For well-separated vertices, on the average about .5 decay track is lost because it is not reconstructed or fails the loose cuts, another .5 track is incorrectly assigned to the primary vertex, and .5 background tracks are included in the secondary vertex.

Figure 9a shows the mean charge of B^+ decays reconstructed by QVSRCH and QVSTVA in the Monte Carlo as a function of decay distance. As one might expect, it resembles the track assignment efficiency as a function of distance.

Figure 9b shows the charge resolution of Monte Carlo charged and neutral B decays reconstructed by QVSRCH and QVSTVA as a function of decay distance. The resolution is about 1 unit for distances of a few millimeters, degrading somewhat at shorter distances. The resolution is about the level expected given the losses of real B decay tracks and background of primary tracks. A charge resolution of 1 unit is not sufficient to distinguish charged and neutral B decays on an event by event basis, but it is sufficient to do so on a statistical basis, with high statistics given the inclusive nature of QVSRCH.

11 Pictures

Figure 10a-d shows one jet of a Monte Carlo B event in the jet coordinate system used by QVSRCH. The left plots show distance from the primary vertex along the jet as a function of the r-ϕ-like transverse position, and the right plots show distance along the jet as a function of the r-z-like transverse position. Note that the distance along the jet extends ± 1 cm, while the orthogonal distance extends only $\pm 500\mu$. The upper two plots show the contours of $\Delta\chi^2$ found by QVSRCH, along with the reconstructed vertex and its errors. The inner contour corresponds to 1σ, and the outer contour to 3σ. The lower two plots show the tracks considered to be in the jet.

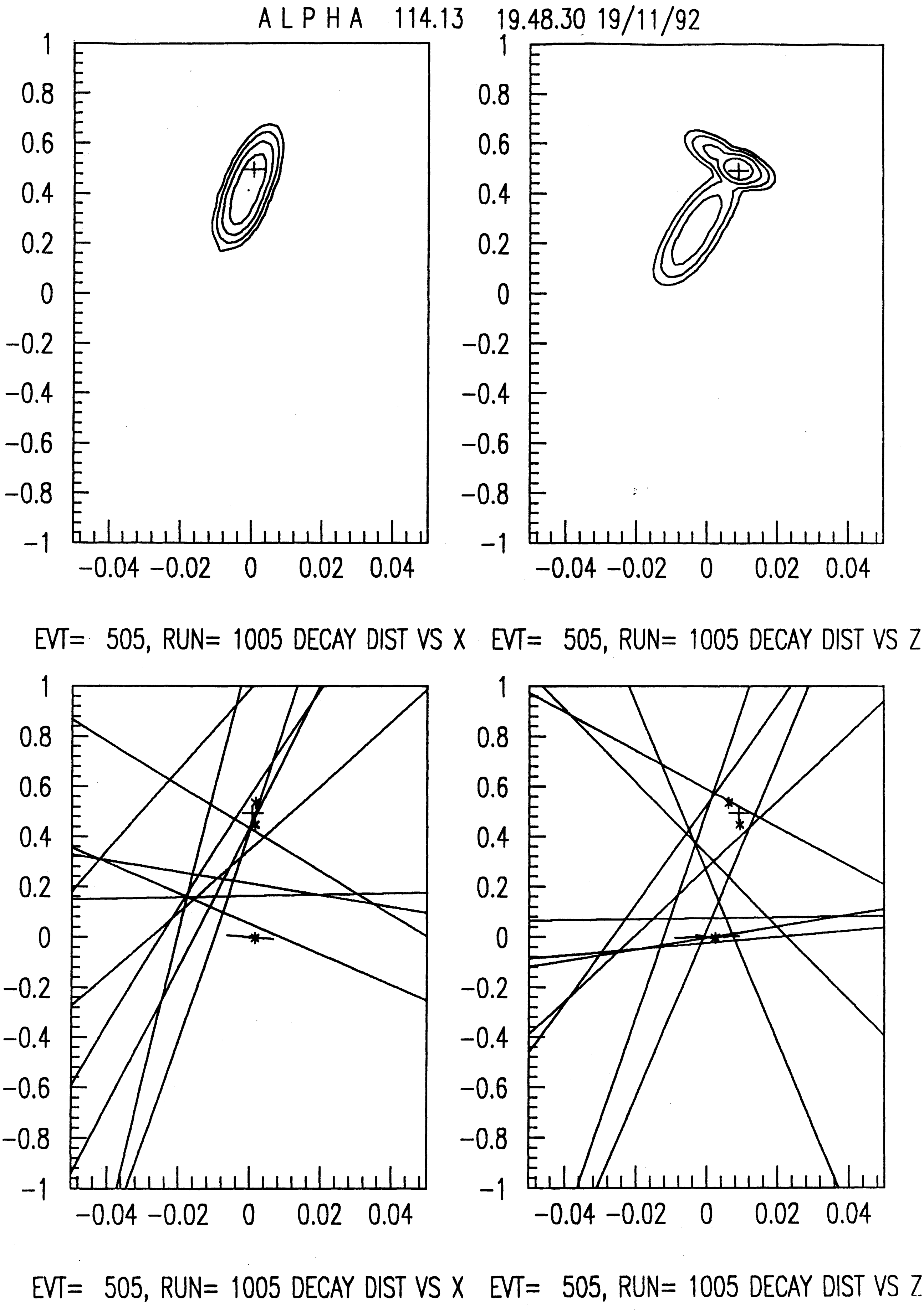


Figure 10: B Monte Carlo secondary vertex reconstruction

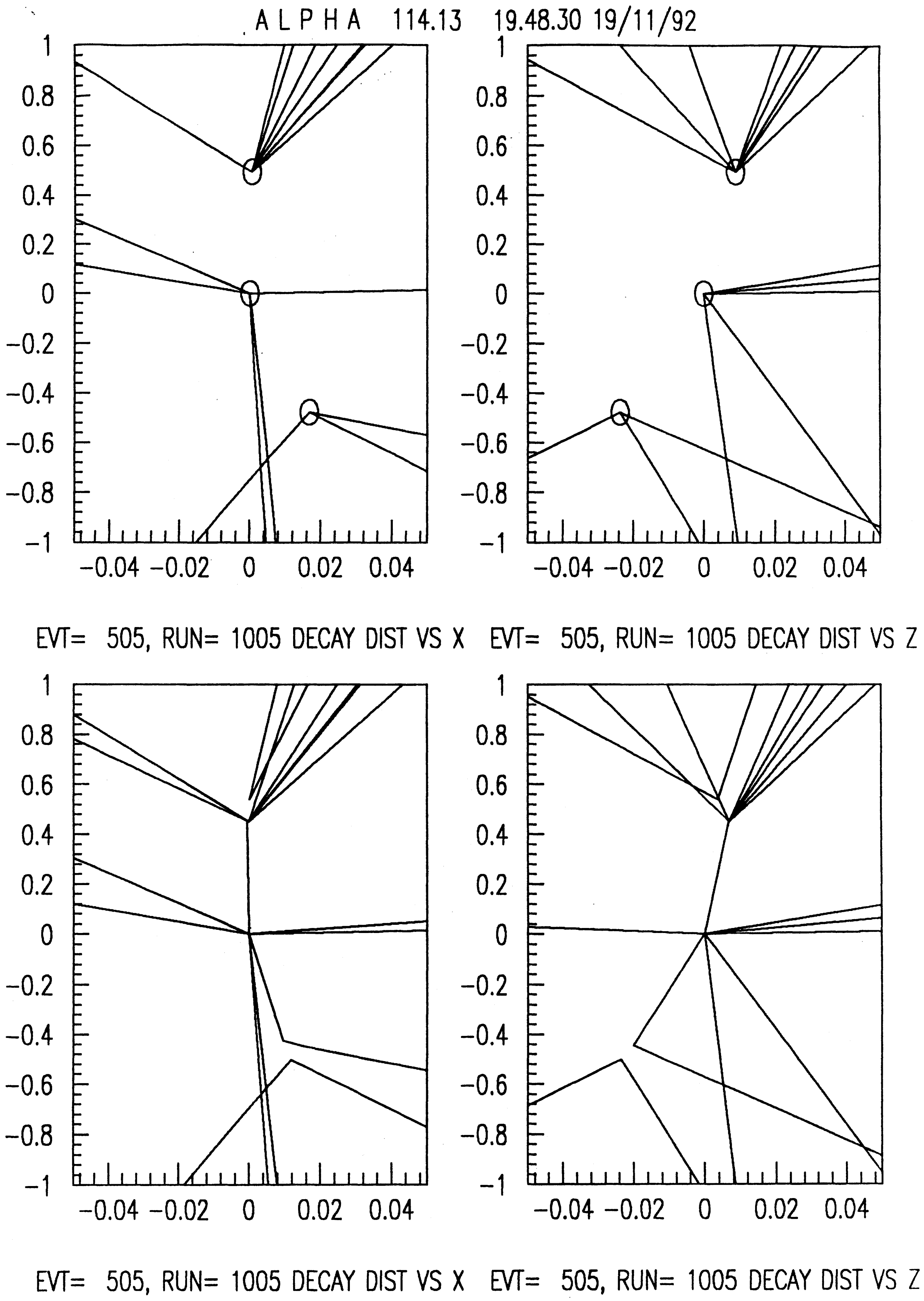


Figure 11: B Monte Carlo track-vertex reconstruction

The asterisk symbols are the generated primary, secondary, and tertiary coordinates. The reconstructed primary and secondary vertices and their errors are also shown.

Figure 11a-d shows both jets of the same Monte Carlo B event as reconstructed by QVSRCH and QVSTVA. The upper two plots are the reconstruction and the lower two plots are the generator information. As before, the left plots show the r-ϕ-like projection, and the right plots show the r-z-like projection. The upper half of each plot is jet 1, and the lower half is jet 2. The tracks and vertices have been plotted in coordinates with the origin at the generated primary vertex and rotated using the reconstructed jet directions. The coordinates of the reconstructed vertices are indicated by the (distorted) circles. The reconstructed tracks have been shifted transversely and drawn as emerging from the vertex to which they have been assigned. (This is only a graphical device, and does not imply that QVSRCH or QVSTVA have done any kind of constrained re-fit.) In jet 1, there is a charged B decay to 7 charged tracks followed by a neutral charm decay to 2 tracks. One of the B decay tracks does not pass the track cuts, but all the other tracks are correctly assigned. In jet 2, there is a charged B decay to a single charged track and a neutral charm decay to 2 tracks. All tracks are correctly assigned.

12 Conclusion

QVSRCH is intended to be an easy-to-use pattern recognition routine for finding inclusive secondary vertices, but not a substitute for conventional vertex-fitting routines. It works by finding the point at which a secondary vertex would give the largest improvement in the sum of the χ^2 of the primary and secondary vertices, compared to the χ^2 when all tracks are assigned to the primary vertex. In the Monte Carlo, for jets with $|\cos\theta| < 0.7$, the hemisphere B tagging purity is over 80% at 50% purity, and the event tagging purity is over 90% at 60% efficiency, but the agreement in the tag variable distribution between data and Monte Carlo is not particularly good. The efficiency to find a vertex within 1 mm of the correct flight distance for a B decay is nearly 80% in the Monte Carlo, with the efficiency to find either the B decay or a point between the B decay and the subsequent charm decay nearly 90%. At flight distances of more than 3 mm, the track assignment efficiency is over 80% for B decays, and the number of primary tracks incorrectly assigned to the secondary vertex is less than 0.5.