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Changes in the track reconstruction to recover from the TPC sector 6 failure

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Abstract

During the 2000 running, DELPHI has suffered from a short in one sector of the TPC. On September 1st the chamber died completely leaving only 11/12 of the detector acceptance. This note details the changes made to the reconstruction code to recover tracking efficiency. The so called "IDVD" tracking code is used to reconstruct the tracks from the remaining detector information. The DELPHI Barrel RICH was used for the first time as a tracking device to further improve the efficiency. An account will be given of the changes in the track reconstruction code, the reconstruction of Barrel RICH track elements and the improved tracking performance.

1 Introduction

The TPC with its 3 dimensional tracking capability is the primary DELPHI barrel tracking detector. During this year's data taking, one out of the 12 sectors (6 on each side of the detector) suffered from a developing short between an anode and a ground wire. On September 1st sector 6 died completely. Almost at the same time first signs of a possible Higgs signal were reported by the LEP experiments at the LEPC [1] resulting in a one month extension of the running in 2000. Because the 4 jet channel of $e^+e^- \rightarrow HZ \rightarrow b\bar{b}q\bar{q}$ is the dominant decay channel, it was important to recover from the efficiency loss due to the failure of TPC sector 6.

The so called "IDVD" tracking is used to recover the tracks lost in the dead TPC sector. The reconstruction is based on the Inner Detector (ID) and Vertex Detector (VD) information. The code was originally written to find single tracks in jets from particles which had reinteracted in the material of the detector before reaching the TPC [2]. Its efficiency to reconstruct a track in $R\phi$ is high because of the high efficiency of the ID jet chamber, where the left-right ambiguities are easily solved by the association to the precise VD $R\phi$ points. The problem for the IDVD tracking is to find the correct z and θ of the tracks. Here many combinations of 2 VD Rz points might point to the primary vertex region. The VD multiplexing pattern [3] adds additional ambiguities, because depending on the VD layer one hit leads to 1-3 mirror hits at different Rz positions. Therefore changes to the IDVD tracking were needed in order to solve the problems due to the increased complexity of the event reconstruction without the TPC. For an intermediate processing (DELANA-S) of the new data for the November LEPC a version of a tracking code without sector 6 was used which included a first set of modifications.

In preparation for a final processing of this years data further changes to the reconstruction code were made, including for the first time the use of Barrel RICH (RIB) track elements. A track passing the Barrel RICH leads to huge pulses in the form of a train of hits along the drift direction. The new pattern recognition exploits this signature and uses additional information from the gas ring photons to validate the track points. Using the Barrel RICH track points significantly improves the track reconstruction efficiencies in the sector 6 region.

The note is structured as follows. Firstly, the DELANA-S reprocessing and changes to the track reconstruction are discussed in sections 2 and 3. Secondly, the reconstruction and simulation of Barrel RICH track elements are discussed in section 4. Finally, the performance of the new tracking in sector 6 including the RICH track elements is shown in section 5.

2 Changes for the 2000 DELANA-S reprocessing for the September LEPC

Hits in the Outer Detector (OD) have an approximate precision of 5 cm in Rz at a radius of 202 cm. The association of Outer Detector hits to track candidates allows for a good θ estimate assuming the primary vertex. These hits can therefore be used to guide the association of VD Rz hits in a later stage of the reconstruction. The first change to the DELANA [4] reconstruction was to allow for the association of OD hits to all IDVD track candidates in the region of sector 6. The sector was treated as a "TPC crack" in the barrel track search (TKSB [5]). The "IDVD pivot" track search in TKSB is the first reconstruction code used to find the IDVD tracks in the $R\phi$ projection. Unfortunately the efficiency of the OD association to low energy tracks was found to be rather low since the code was foreseen to search for OD hits on high energy tracks essentially contained in the TPC cracks . The poor track quality of low energy IDVD candidates extrapolated to the radius of the OD leads to large χ^2 values when comparing the track parameters to the OD hits. Therefore a second attempt was introduced in the IDVD tracking to reassociate missed hits by trying to fit all possible IDVD+OD combinations in a region of ± 0.15 rad around the extrapolation.

If a track candidate has no OD hit associated, then the only other detector measuring Rz in the region of sector 6 are the Straws. Based on the present calibration the detector provides a Rz measurement from the stereo angle with a precision of only 15 cm corresponding to a $R\phi$ resolution of 330μm (~ 100 % correlation). Hence it gives only limited information about the track Rz position. As a consequence, in jets a track candidate without OD hits has a high change of matching with more than 50 combinations of Rz hits from the different VD layers. The only handle is to use only those combinations which lead to small impact parameters at the primary vertex (less than 1.5 cm and 2 cm in $R\phi$ and Rz, respectively). For identical hit combinations but different multiplexings only the solution with the smallest impact parameter in Rz is retained. Nevertheless the number of possible combinations causes a problem to the event ambiguity processing, because swapping of hits between adjacent tracks quickly increases the combinatorial problem. A protection against too many combinations was introduced. If there are between 10 and 20 combinations, then single (double) Rz hits are not considered if there are 2 (3) hit combinations. In case of more than 20 combinations only those with 3 or more VD Rz hits (forward or overlapping regions) are considered. The other possible combinations are rejected.

Before the death of sector 6 ordinary IDVD tracks in the barrel region should arise only from particles which reinteract in the detector material and hence do not reach the calorimeters, Barrel RICH and muon chambers. Therefore the association of energy deposits, RICH information or muon chamber hits to IDVD tracks was prohibited. The only exception were tracks in the TPC ϕ and θ cracks having OD hits associated. Another important technical change is that for the region of sector 6 this protection was removed, and hence the association of the additional detector information to the tracks was allowed reducing double counting of energy from charged tracks and from calorimeter deposits.

2.1 Data quality in the DELANA-S processing

High and low multiplicity tracking situations have to be distinguished.

Low multiplicity events, for which no primary vertex is found using tracks outside sector 6, have a problem in finding the correct multiplexing for the VD Rz hits used in the IDVD tracks. In Figure 1 the reconstructed θ is plotted against the true value for a dedicated single track simulation [7]. The off-diagonal bands are due to wrong multiplexing solutions and amount to about 20 % of tracks.

In high multiplicity events the primary vertex is determined before reconstructing the IDVD tracks, hence the multiplexing solution is not the main problem. However, the swapping of Rz hits between tracks results in a rate of only 1.26 correct VD Rz hits per track together with 0.46 wrong hits. This disturbs the determination of the jet axis in θ

compared to the usual situation with the TPC.

The track reconstruction efficiency drops slightly in the region of sector 6. As can be seen in Figure 2 for Z^0 events [6], the track multiplicity per jets drops from 8.8 to 7.9 leading to a loss in the reconstructed charged jet energy of $\sim$4 GeV. The loss is partially recovered ($\sim$3 GeV) using the calorimeter information. These losses are taken into account in the individual physics analyses.

The b tagging also suffers from loosing the TPC information from sector 6. In Figure 3 the efficiency-purity curves [8] are shown. A separate calibration was performed [8] for IDVD tracks in sector 6. For the same purity the efficiency in sector 6 drops by about a factor 2, but the b signal is still clearly visible in the data and b tagging is possible in that region.

In summary for the data taken after the death of sector 6 no fiducial cut was needed to obtain results in the Higgs searches for the DELPHI presentation at the LEPC [9].

3 Further improvements to reconstruction code

After the start of the DELANA-S processing further improvements have been added to the reconstruction code. This new code will be used for the final reprocessing of the 2000 data. Besides other code changes, the RIB track points (which will be discussed later) have been introduced to the reconstruction for the first time.

For low multiplicity events the reconstruction of the primary vertex z position has been improved to ease the multiplexing solution of isolated tracks. In the vertex finder a fall back is now introduced, which uses the average z position w.r.t. the beam spot from tracks found outside sector 6. This fall back is used if the vertex finder fails because of bad χ^2 or because only one additional track is found outside sector 6.

It is necessary to veto IDVD like track candidates reconstructed using only poor detector information, which therefore have a high risk of being fake. The IDVD tracking had a list of explicit cuts against bad detector combinations. This list has been replaced by a new table of good combinations which also eases the inclusion of the RIB into the tracking. The new list shown in Table 1 consists of detector combinations used to reconstruct the track together with the minimum number of VD $R\phi$ and Rz hits required. The principle is to ensure good reconstruction in both the $R\phi$ and Rz projection. The VFT counts as a part of the VD. Since the VFT is providing space points, its hits are added to both the number of $R\phi$ and Rz hits. The ID jet chamber has calibration problems close to the wire planes. In such cases an additional VD $R\phi$ hit is required to validate the track. If an IDVD track matches with a secondary vertex the requirements on the number of VD $R\phi$ and Rz hits are reduced by one. A special case are VFT only tracks. Here the number of $R\phi$ hits required is only 2 and not 3 like for the VD only tracks, taking into account the reduced number of possible layers.

The ambiguity solution of full jets reconstructed without the TPC poses a combinatorial problem, because the low redundancy in the reconstruction leads to a large number of possible candidate combinations. To reduce the combinatorial problem the reconstruction is split into two stages. In the first stage only those IDVD tracks are considered in the ambiguity solution which have at least 3 Rz measurements and therefore not only don't assume the primary vertex, but also have an additional internal constraint. Then the complete IDVD reconstruction is iterated using only the left over detector hits and all

detector combination	minimum # of VD $R\phi$ hits	minimum # of VD Rz hits
VD	3	1
VD+ID	2	1
VD+STW	2	1
VD+RIB	3	1
VD+OD	3	1
VD+ID+STW	1	0
VD+ID+RIB	2	0
VD+ID+OD	2	0
VD+ID+STW+RIB	1	0
VD+ID+STW+OD	1	0
VD+ID+RIB+OD	1	0
VD+ID+STW+RIB+OD	1	0
VD+STW+RIB	2	0
VD+STW+OD	2	0
VD+STW+RIB+OD	1	0
VD+RIB+OD	2	0
ID+STW+RIB	0	0
ID+STW+OD	0	0
ID+STW+RIB+OD	0	0

Table 1: *New list of good IDVD like track candidates. For each detector combination the minimum number of VD hits required in $R\phi$ and Rz are listed. See text for further details.*

newly found possible candidates are considered. This 2nd call to the IDVD tracking is done after the 2nd stage of the tracking detector local pattern recognitions, because at this stage all possible hit information from the OD and the Straws is available. The Rz information from the 2nd stage OD and Straw hits are used to improve the association of VD Rz hits to IDVD candidates.

4 The DELPHI Barrel Rich as a tracking device

The efficiency to reconstruct an IDVD track using the OD is limited by the amount of material in front of the detector. Therefore track elements reconstructed in the Barrel RICH drift tubes provide complementary information. Because the Barrel RICH is a device to measure single converted Cherenkov photons and not track ionisation, the resolution of the track element is expected to be limited to about 1cm in $R\phi$ and 1 cm in Rz. The Rz resolution is sufficient though to resolve the VD Rz association problem. Therefore an algorithm was developed for a stand alone Barrel RICH track element. An existing algorithm [10] was evaluated and served as a starting point for the new pattern recognition.

4.1 Description of the algorithm

In Figures 4 and 5 a display of a hadronic event and a muon pair event with all the hits in the Barrel RICH is given. On the display the track extrapolation, the RICH track element and a 100 mrad band around the liquid ring are shown. The track can be recognised by a train of successive hits in Rz confined to a region in $R\phi$ of 8 cm. These hits are caused by after pulsing of the chamber due to the large pulse of electrons from the track ionisation in the drift gas. This situation differs from photons from the liquid radiator which are converted to single electrons giving thus a much smaller signal.

The basic idea for the pattern recognition and the reconstruction of a track element is to find a large train of successive hits in Rz. On the contrary, for the reconstruction of the Cherenkov ring single photo-electrons are selected.

The Barrel RICH consist of 2 half cylinders with in total 2 times 24 sectors each covering a 15 degree azimuthal angle, situated at a radius of about 150 cm. Photo-electrons drift towards the multi wire proportional chambers (MWPC), which are located at $z = \pm 155$ cm. The hits, that are used in the pattern reconstruction, have three basic coordinates $R\phi$, Rz and R. The latter being the depth from the pad readout of the chambers. First they are ordered in drift time, i.e. Rz. A short drift time means that the hit is close to the MWPC. Per sector one looks for a train of more than 10 hits within a distance in $R\phi$ of 4 cm and a Rz length difference w.r.t. the last hit of 5 cm. The start and end position in Rz are stored. This train of hits is called a cluster. The $R\phi$ position of this cluster is determined by averaging over the hits. The position in Rz is taken from the coordinate of the first hit, because it is closest to the track.

In order to reduce the rate of fake clusters (i.e. clusters that are not due to a track) a probability is calculated using as input parameters:

- the number of hits,
- the length in Rz of the train of hits,
- the r.m.s. in R (depth) and the r.m.s. in $R\phi$.

In Figure 6 this probability P_{cl} is shown for associated and unassociated clusters using hadronic events. Clusters with a probability P_{cl} of less than 10% are rejected.

In a second step a search for a Cherenkov ring in the liquid radiator is performed using the position of a reconstructed cluster. Hits associated to any cluster in a given sector as well as hits at large radii ($R > 149$ cm, i.e. far from the liquid radiator) are removed. Additional cuts remove background hits. Afterwards the Cherenkov angle is determined selecting single photons taking into account the refraction of light in the detector materials. The number of photons in the ring is determined selecting photons within a 100 mrad window around the saturated Cherenkov angle of 0.67 rad. The mean Cherenkov angle is determined averaging over the angles of the selected photons. Other quantities like the distribution of photons in Rz along the ring are calculated. The number of photons in the ring and the distribution in Rz are used to confirm the reconstructed cluster by defining an additional probability. This probability is combined with the cluster probability P_{cl}. In Figure 7 this combined probability P_{co} is shown for associated and unassociated track elements using hadronic events. Clusters with a probability P_{co} of less than 20% are rejected.

Finally, close-by clusters are examined to further reduce the rate of fakes. Only one of the clusters is chosen if clusters lie within a distance in $R\phi$ of ± 10 cm and in Rz of ± 20 cm. In order to make the best choice, a probability is calculated using the probability for the cluster P_{cl}, the Rz position of the cluster, the mean Cherenkov angle and the number of photons in the ring. For the remaining clusters track elements are created which will be used in the track search and fit.

4.2 Performance of the algorithm

The performance of the algorithm for the reconstruction of the Cherenkov angle was evaluated. Using the track extrapolation as an input to the ring algorithm, the Cherenkov angle distribution for signal and background single photo-electrons are shown in Figure 8 for muon pairs. A clear signal around a Cherenkov angle of 0.67 rad can be observed.

The resolution of the Barrel RICH track element can be determined from Figure 9. Here the difference between the track extrapolation and the RICH track element are shown in $R\phi$ and signed Rz (for negative Rz values the difference gets an additional minus sign) for hadronic events. It can be described by a Gaussian plus a background term. The width of the Gaussian distribution in $R\phi$ is 1 cm and in Rz 0.7 cm. The asymmetry of the tails in signed z arises from cases where the first photon was not selected.

The overall performance of the algorithm is shown in Figure 10. The efficiency to find a RICH track element for tracks with momenta above 1 GeV/c is 69% if the outer detector (OD) is in the track and 55% if only the TPC (not the OD) is in the track. The average efficiency is 59% in hadronic events and 71% in muon pair events. One can observe that the efficiency for high momentum tracks is lower (62% if the OD is in the track) than for low momentum tracks. This is due to the fact that low momentum tracks are more isolated in hadronic events. Isolated clusters are more efficiently reconstructed, because they suffer less from overlaps. Furthermore there is a cut (as described in the previous section) to protect against fake clusters which lie within a distance of ± 10 cm in $R\phi$ and ± 20 cm in Rz. Thus if two tracks cross the RICH within this range only one track element will be created. This results in an efficiency loss for close-by i.e. high momentum tracks.

Figure 11 shows an efficiency loss of about 10% which is observed at the sector boundaries due to edge effects.

Another important parameter is the fraction of unassociated (or fake) clusters in hadronic events, shown in Figure 11. For a cut on the probability P_{co} at 20% it is only 33%. In muon pairs it is less than 15%. In 40% of the cases the unassociated track element is more than 50 cm away from the closest track.

4.3 RICH information in the simulation

The effect of after pulsing due to the enormous track ionisation is not correctly modelled in the simulation. Therefore the track clusters were explicitly introduced at the stage of the reconstruction.

Starting from a simulated truth track at the inner radius of the Barrel RICH it was check whether the track crosses fully the drift tube and lies inside the sensitive volume. If it does, a track element is lifted with an efficiency of 95%. The $R\phi$ resolution is modelled using a Gaussian distribution with a r.m.s. of 1 cm. For the Rz coordinate the r.m.s.

of 0.7 cm is used and the tail in Rz which can be seen in Figure 9 is added. The loss of efficiency at the edge of the sectors as introduced to obtain the agreement which can be seen in Figure 11. Fake track elements are created at a rate of 33% within a distance of 20 to 70 cm of the simulated tracks. Finally, close by clusters are removed within a distance of ± 10 cm in $R\phi$ and ± 20 cm in Rz. This causes an inefficiency inside narrow jets, similar to the observed effect in the data.

4.4 Inclusion of the RIB track points into the global tracking

Several changes to the DELANA tracking were made to include the RIB clusters in the global reconstruction. The track fit (TKFB [11]) outlier logic was modified to take into account the RIB hits. As in the case of the hits from the Forward RICH (RIF), the RIB point will be removed first from the fit if the track χ^2 probability is bad. In the ambiguity solution (FXSOLV [12]) the RIB hit is now taken into account. For each track including the RIB the score is increased by 3, giving it again the same weight as the RIF. The list of bad detector combinations has been extended to account for RIB hits. These combinations are vetoed in the ambiguity solution of normal tracks and are therefore left over for the IDVD reconstruction code. Table 2 shows the list of additional bad combinations.

without VD	with VD
RIB only	VD+RIB
RIB+ID	VD+RIB+ID
RIB+STW	VD+RIB+STW
RIB+OD	VD+RIB+OD
RIB+ID+STW	VD+RIB+ID+STW
RIB+ID+OD	VD+RIB+ID+OD
RIB+STW+OD	VD+RIB+STW+OD
RIB+ID+STW+OD	VD+RIB+ID+STW+OD

Table 2: *List of detector combinations vetoed in the ambiguity processing of normal tracks. The combinations are subject to the later IDVD reconstruction.*

Finally, the track searches were modified to include the RIB hits in the tracks. Like for any other ordinary tracking detector the RIB pattern recognition creates track elements before the track searches are run. The RIB hits are associated to normal barrel tracks outside sector 6 using the former Straw association search in the ”forward” tracking package TKSF. This was done because the inflexible software design of the ”barrel” track searches (TKSB) make it technically more difficult to modify the code for the inclusion of a new detector. In the IDVD tracking the RIB is treated like the OD. The hits inside the region of sector 6 are considered in this search. The association of the RIB points to the IDVD track candidates is done together with the OD and Straw hits before the VD Rz hits are associated. Hence the RIB hits are used as an additional constraint to guide the selection of possible Rz hits in the different VD layers. This significantly reduces the number of possible ambiguities in the reconstruction.

5 Performance of the track reconstruction code without sector 6

In Figure 12 a graphic is shown for an example event with one jet in the dead sector 6 region. Most of the tracks are reconstructed using the Barrel RICH and OD information.

The performance of the IDVD tracking in the region of sector 6 can be studied on simulation by removing the TPC information in hadronic WW events. To correctly reproduce the situation where situation where sector 6 is off the primary vertex position is artificially introduced in the IDVD tracking. In the real data the primary vertex can in hadronic events can be found form the tracks outside sector 6.

The reconstruction efficiency for primary tracks is shown in Table 3 for tracks above 0.5 GeV/c using simulated data. The number of correctly reconstructed tracks is compared to the number of tracks which contain information from more than one track and to the number of fakes. The results based on 200 WW events are shown for the three DELANA versions removing the TPC information from the events. A clear gain in efficiency is visible using DELANA-S compared to DELANA-C. The difference between DELANA-S and the final version is less striking. It is more visible in the next table.

package	simulated	correct rec.	badly rec.	fakes	efficiency
final version	3989	2106	1181	140	82.7 %
DELANA-S	3989	2051	1143	164	80.1 %
DELANA-C	3989	1752	937	175	67.4 %

Table 3: *The number of reconstructed primary tracks for the different reconstruction packages. The TPC information is removed from the simulated hadronic WW events. Shown are results using the final package and using the DELANA-S version. The reference is given by the old DELANA-C tracking package.*

Table 4 shows the association efficiency for the different detectors to reconstructed tracks. Again the new tracking is compared to the result using the old reconstruction package and using the intermediate DELANA-S version. The main difference between the old package and DELANA-S is the increased efficiency in the OD which reflects in the increased tracking efficiency. The reduction in VD Rz and in the Straw efficiency for DELANA-S is due to additional tracks which were lost completely using the old version of DELANA-C. The inclusion of the RIB points and the additional changes to the IDVD tracking improved the efficiency for these detectors as can be seen from columns 2-5.

The Barrel RICH hit information will also be used for the data before the sector 6 failure. The association efficiency of RIB hits to hadronic tracks is 88.5 % in simulation, leaving the rest of the event essentially unchanged.

6 Summary

A first version of a new track reconstruction code was used successfully for the DELANA-S processing to recover from the failure of the TPC sector 6. The data was then used to prepare the DELPHI Higgs search results for the November LEPC and for a fast DELPHI paper [13] published in time with the other LEP collaborations.

detector	correct	wrong	noise	efficiency	DELANA-S	DELANA-C
VD $R\phi$	10369	164	11	99.3 %	98.8 %	97.9 %
VD Rz	4976	1342	74	72.9 %	64.1 %	71.4 %
ID jet	3131	73	5	97.9 %	97.7 %	98.9 %
Straws	1982	94	12	88.5 %	75.6 %	80.7 %
B.RICH	849	337	215	80.6 %	-	-
OD	994	267	45	86.7 %	84.4 %	12.7 %

Table 4: *The association efficiency of different detectors to tracks in reconstructed WW events without TPC information on the simulation. Shown are results using the final package (columns 2-5) and using the DELANA-S version. The reference is given by the old DELANA-C tracking package.*

To further improve the data quality a new pattern recognition package was developed to reconstruct the track point in the Barrel RICH drift tubes. The inclusion of the additional point in the IDVD track reconstruction further increases the tracking efficiency for the final reprocessing of the LEP-2 data set.

Acknowledgements

We would like to thank M.E.Pol for her help in testing different versions of the new tracking code.

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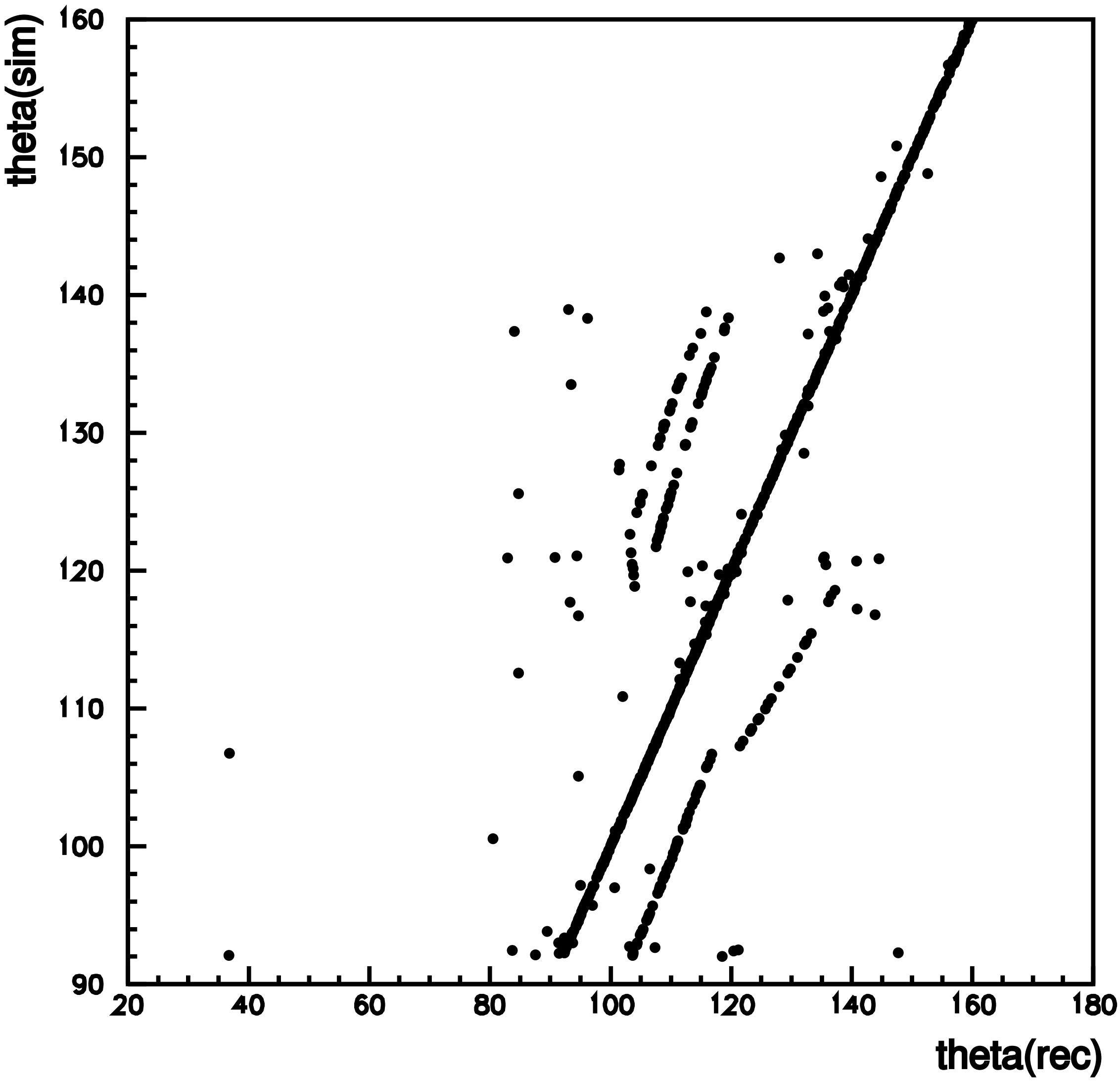

Figure 1: *The reconstructed track θ compared to the true value for a sample of dedicated single track simulation events [7]. The off-diagonal bands are due to wrong multiplexing solutions.*

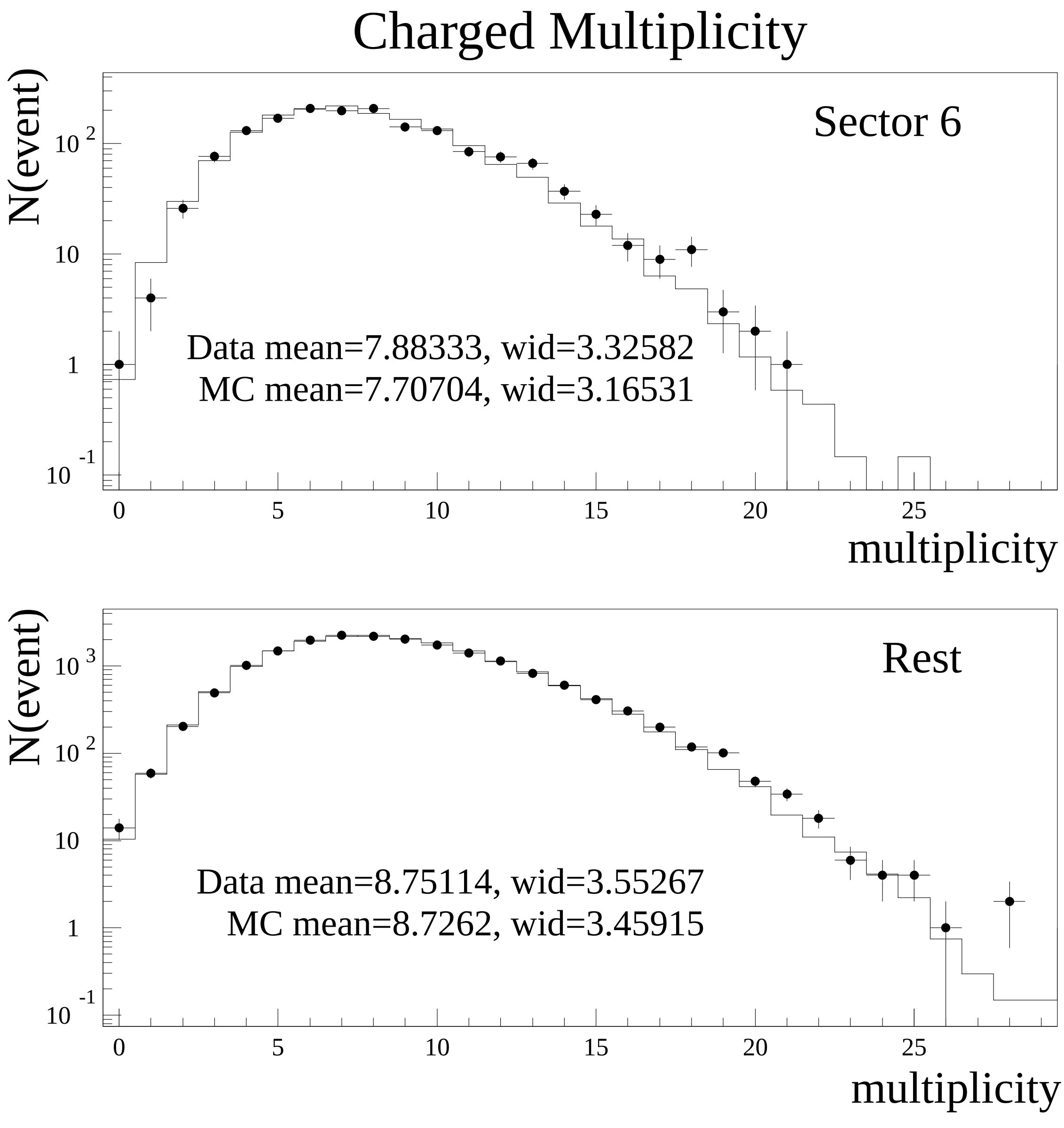

Figure 2: *Charged multiplicity of jets in hadronic* Z^0 *decays in the region of sector 6 and with the TPC [6].*

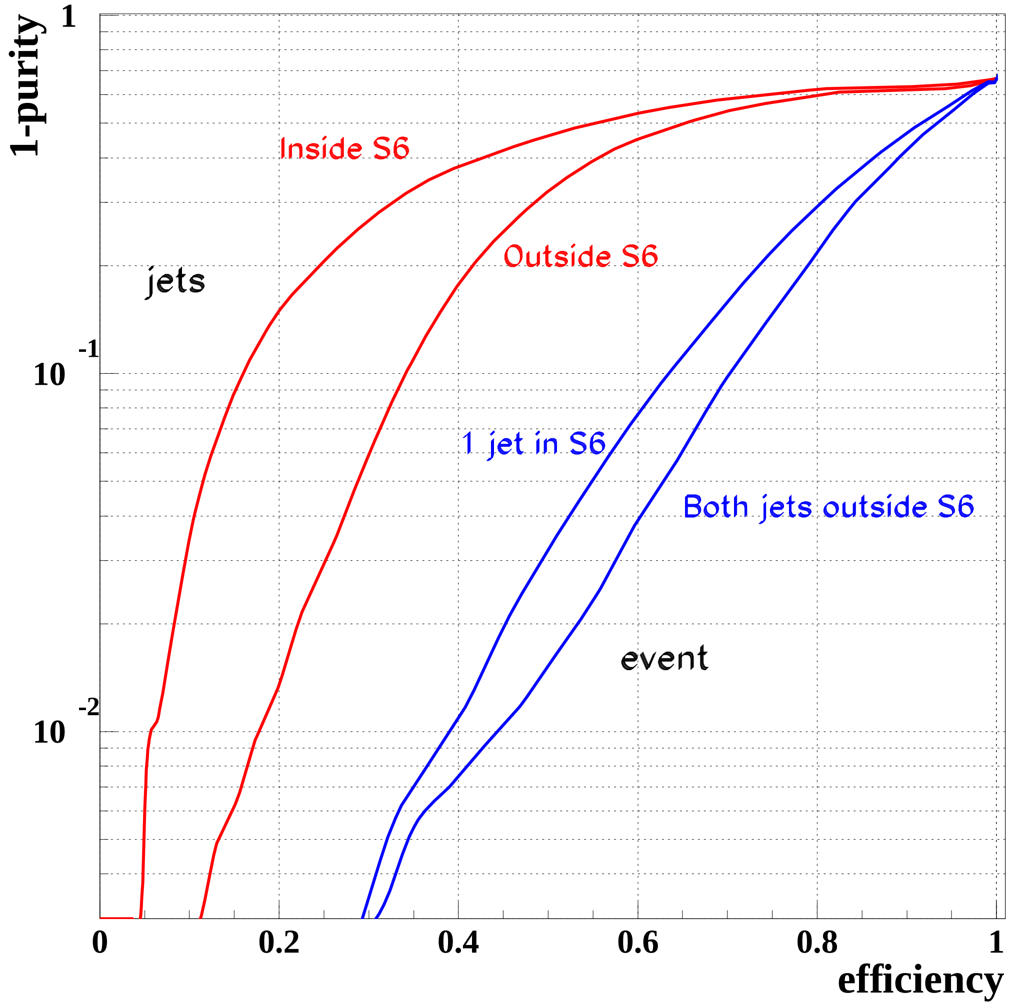

Figure 3: *The 1-purity of the b-tagging as a function of the efficiency for jets and events. Compared are the situations for jets inside and outside sector 6 for the DELANA-S processing. [8].*

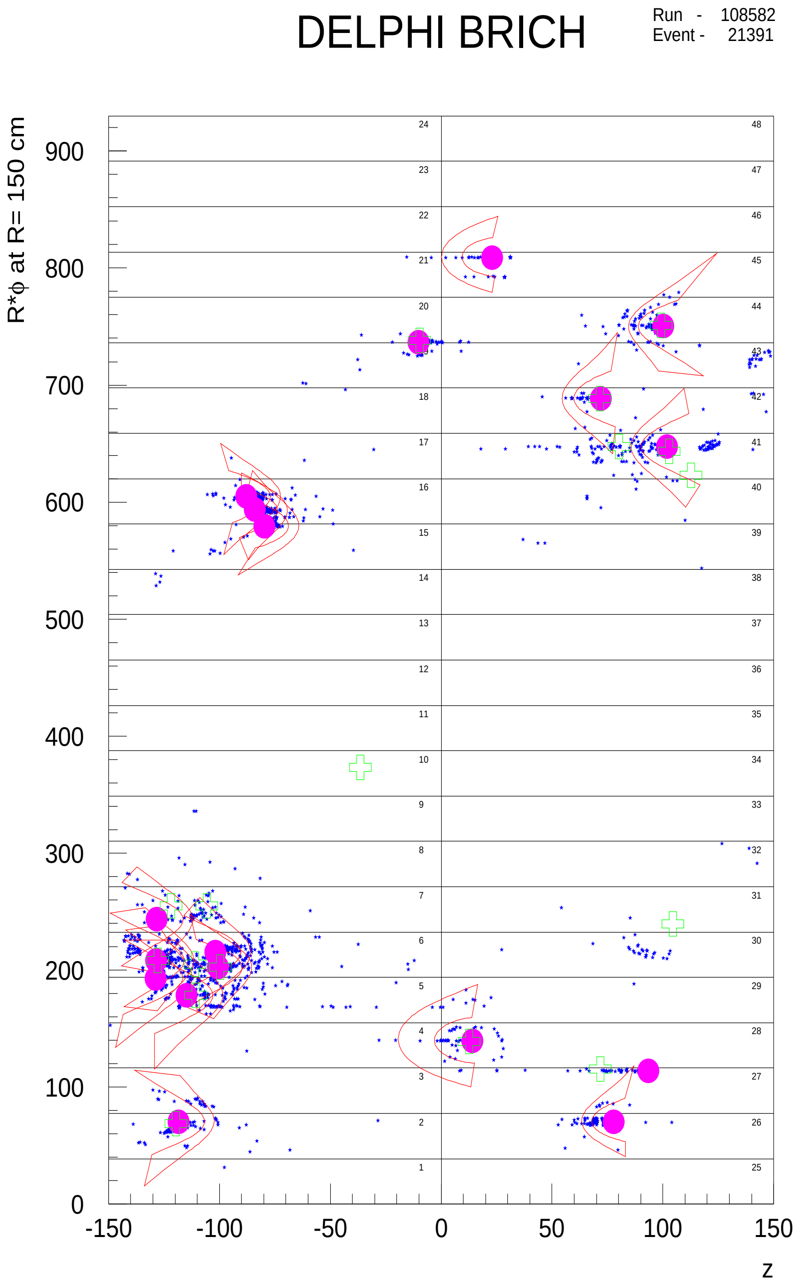

Figure 4: *Display of a hadronic event. Stars are the hits in the Barrel RICH, the open crosses are the track extrapolation, in dot is reconstructed RICH track element. The curves indicate the ± 100 mrad band around the saturated Cherenkov angle of 0.67 rad.*

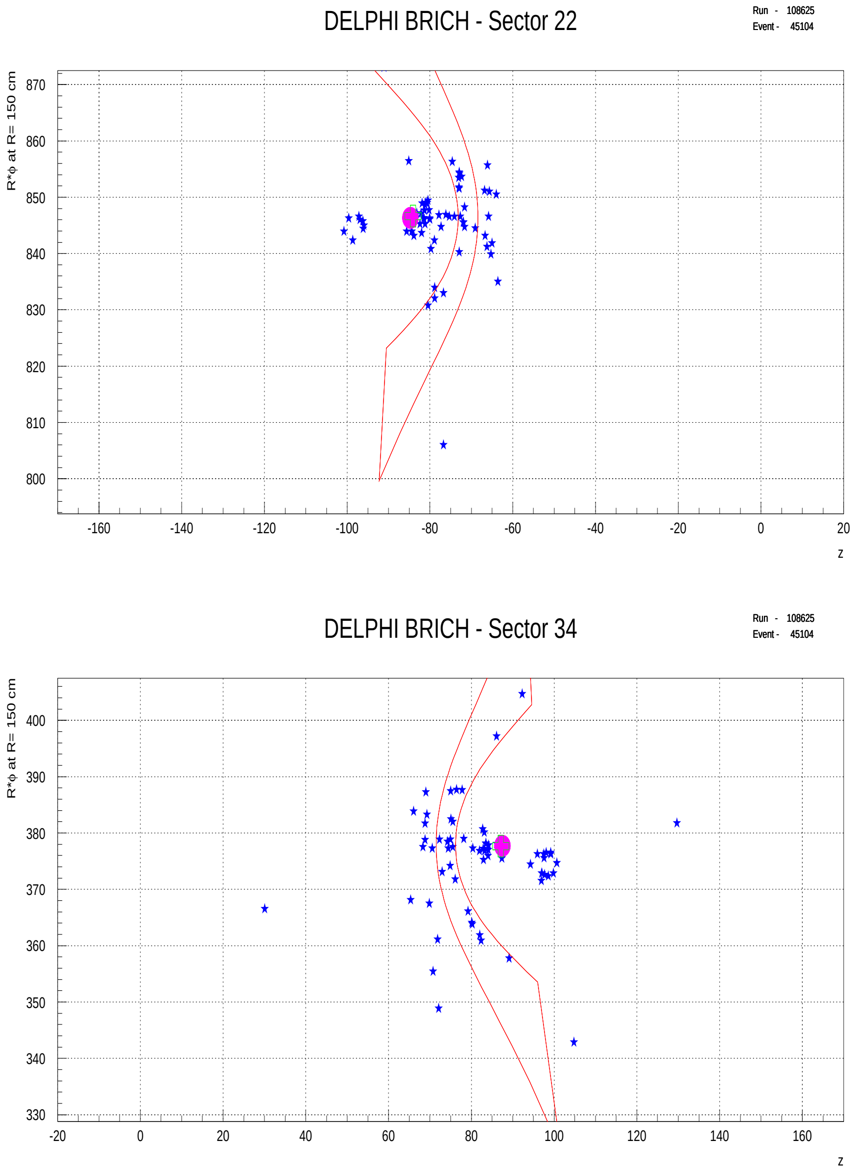

Figure 5: *Sector displays of a muon pair event (see also Figure 4).*

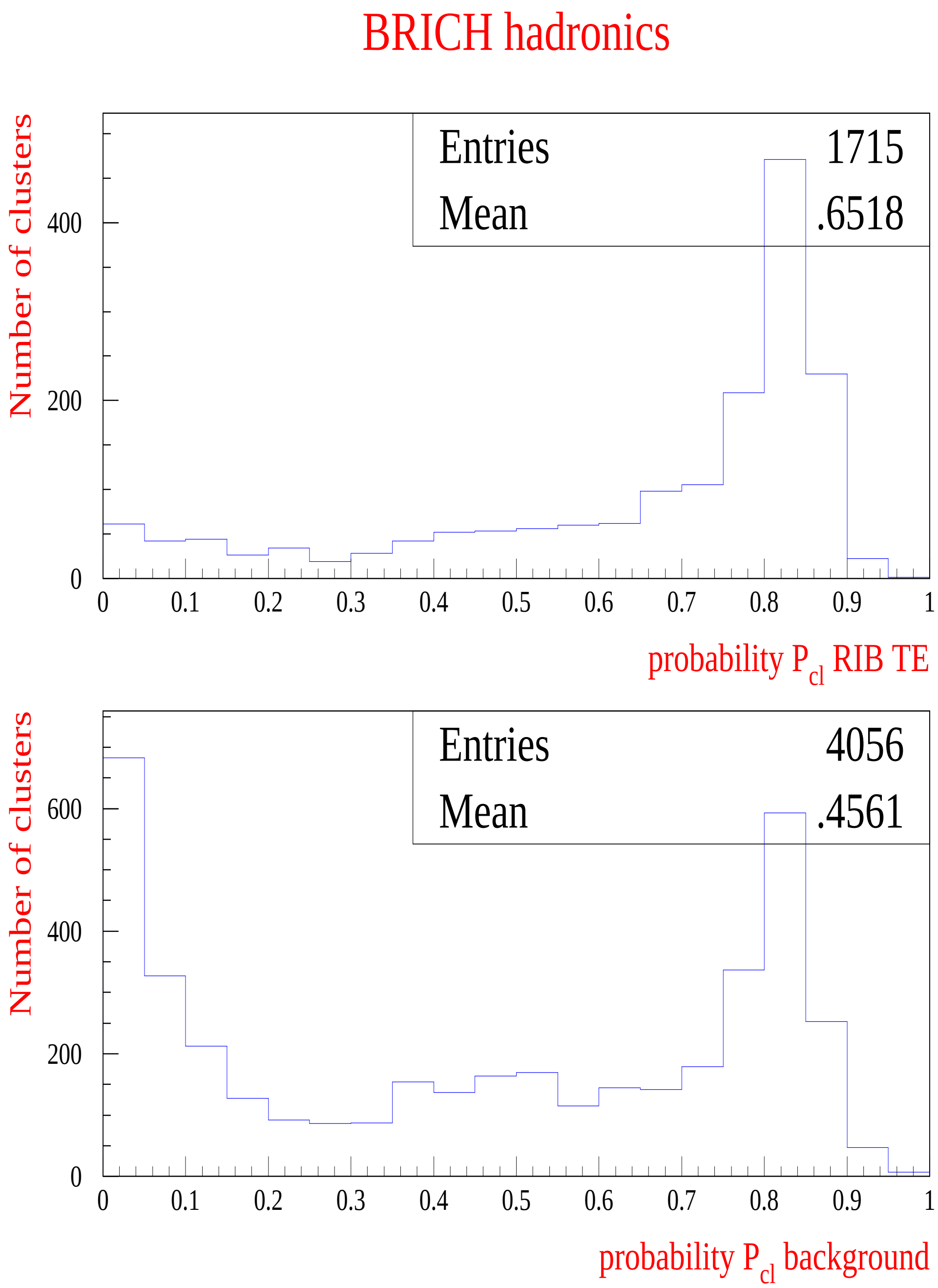

Figure 6: *Probability P_{cl} for associated (top) and unassociated (bottom) clusters in hadronic events. A cut is placed at 10% to reduce the rate of fake clusters.*

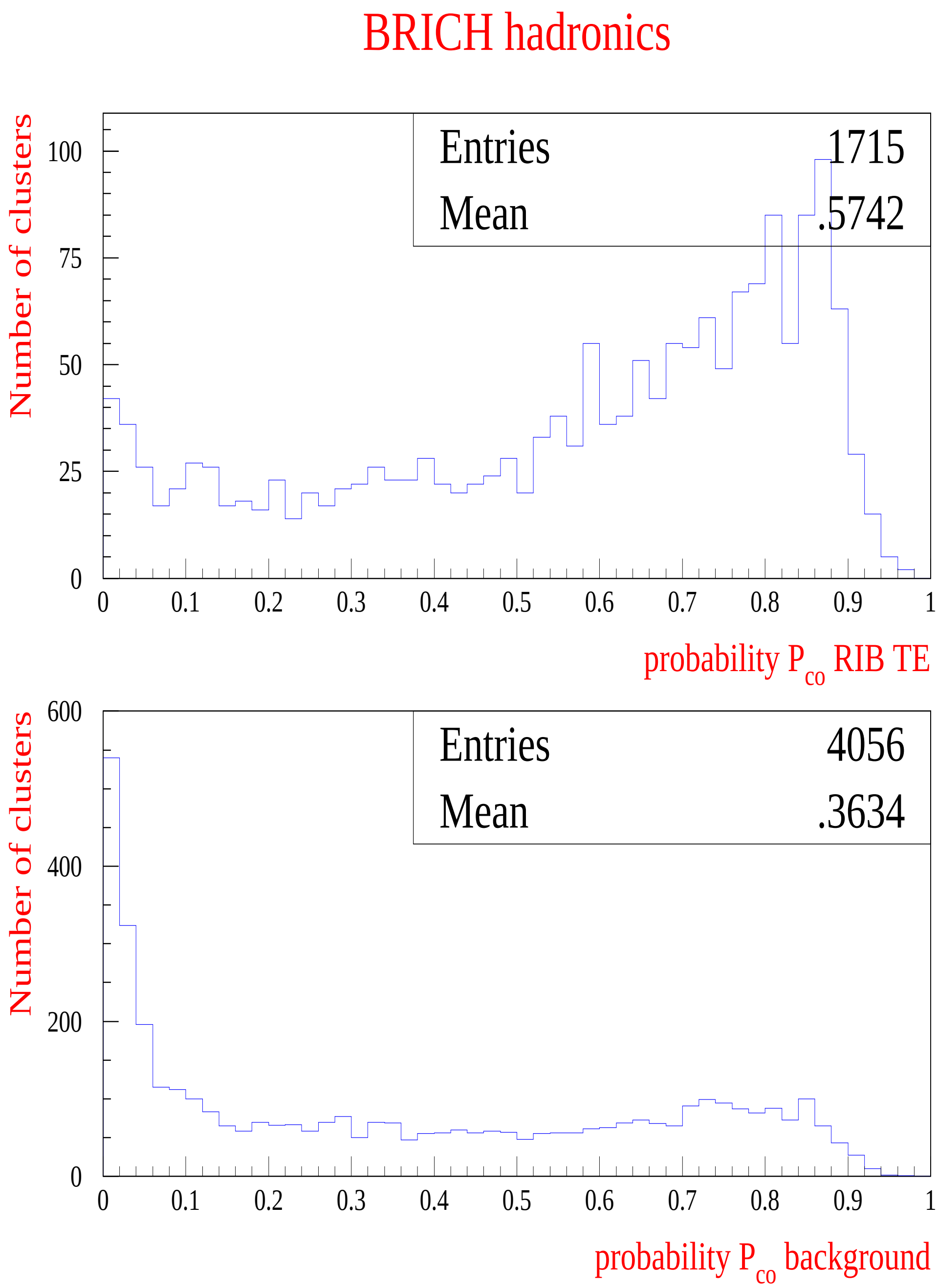

Figure 7: *Probability P_{co} for associated (top) and unassociated (bottom) clusters in hadronic events. A cut is placed at 20% to reduce the rate of fake clusters.*

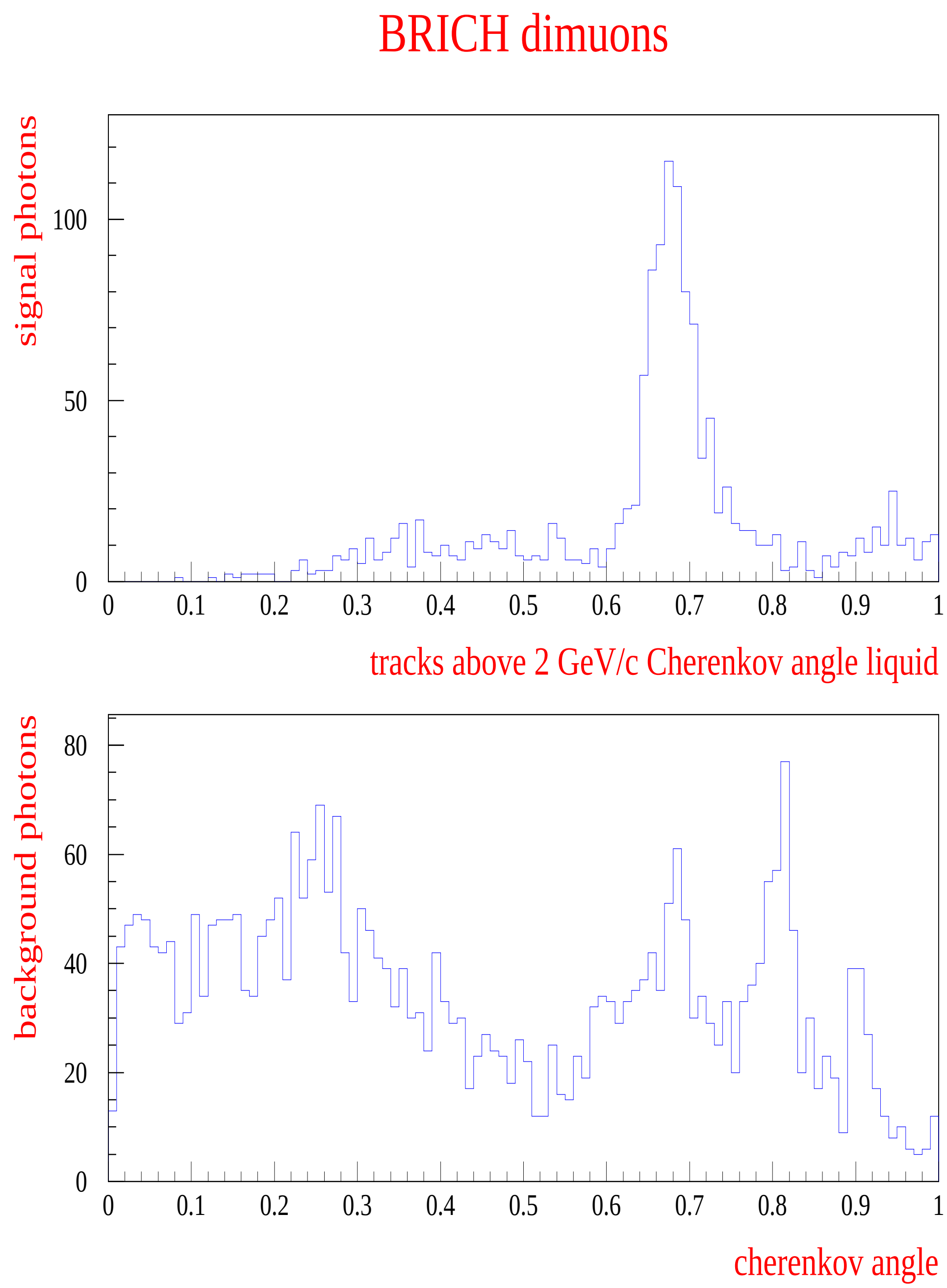

Figure 8: *The Cherenkov angle distribution for signal (top) and background for single photons in muon pair events.*

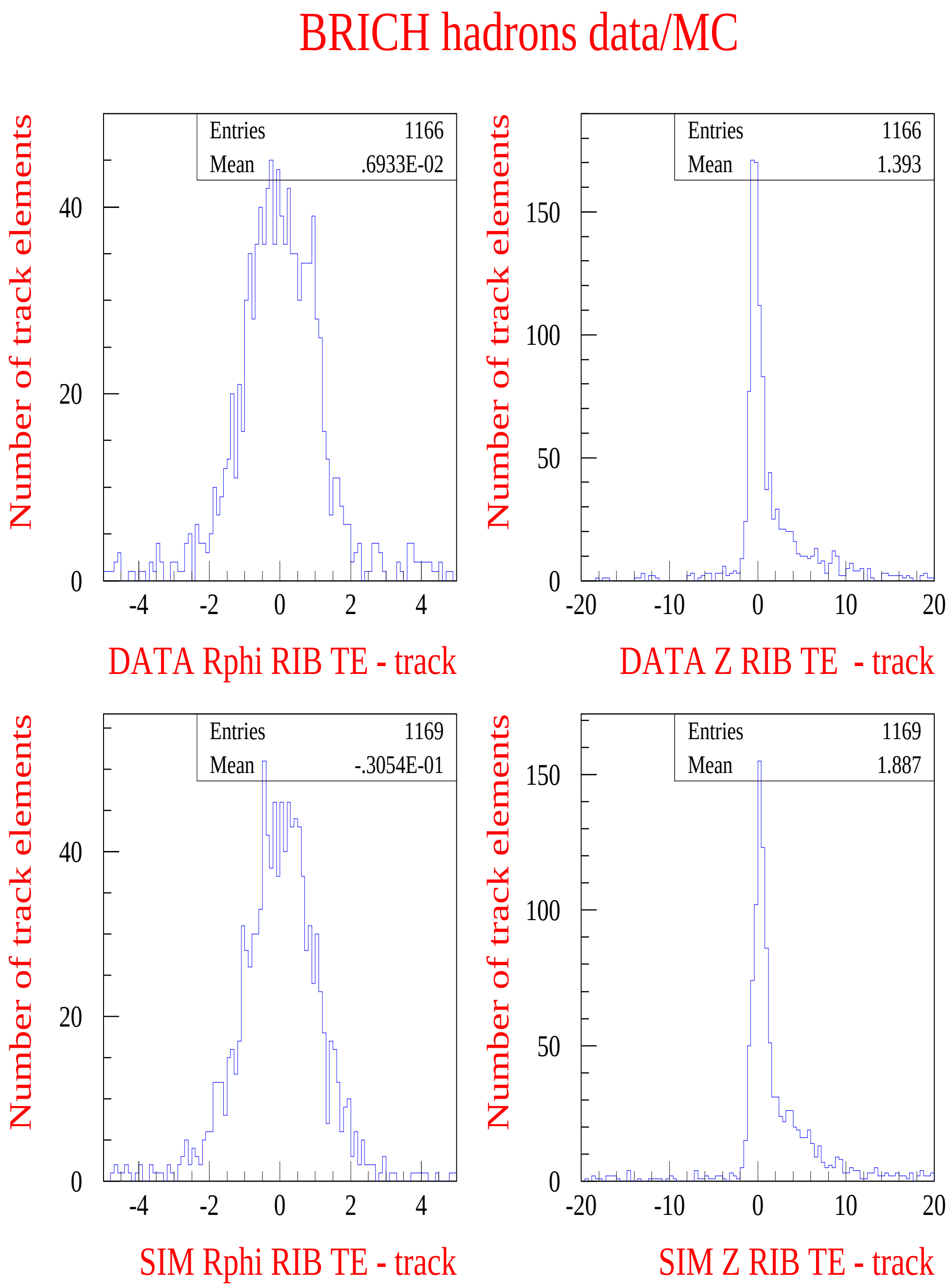

Figure 9: *The distance between the track extrapolation and the RICH track element in $R\phi$ and Rz in hadronic events for data and simulation.*

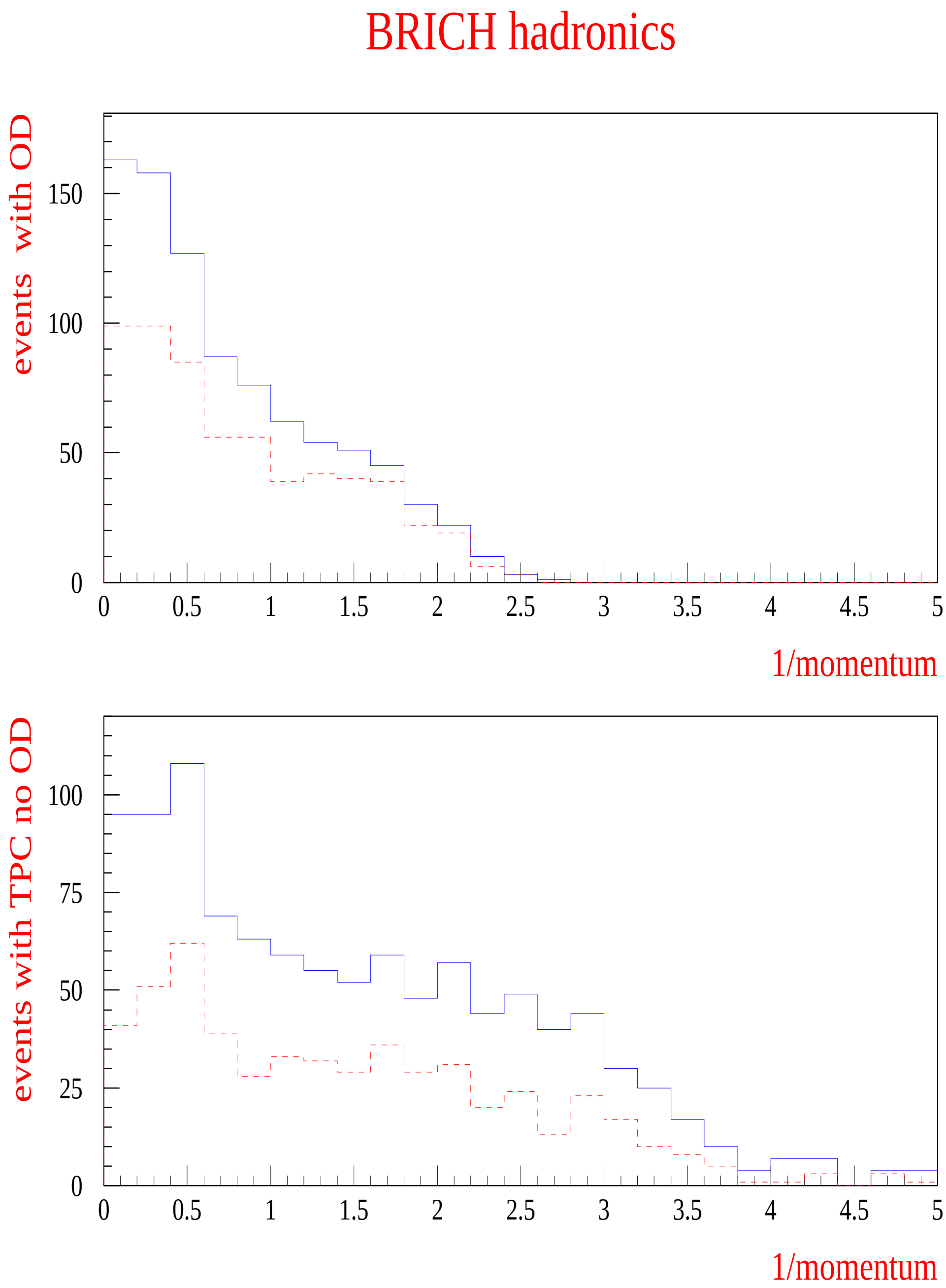

Figure 10: *The number of tracks with (top) and without (bottom) the outer detector in the track as a function of the inverse momentum. The dotted line shows the number of tracks with an associated RICH track element.*

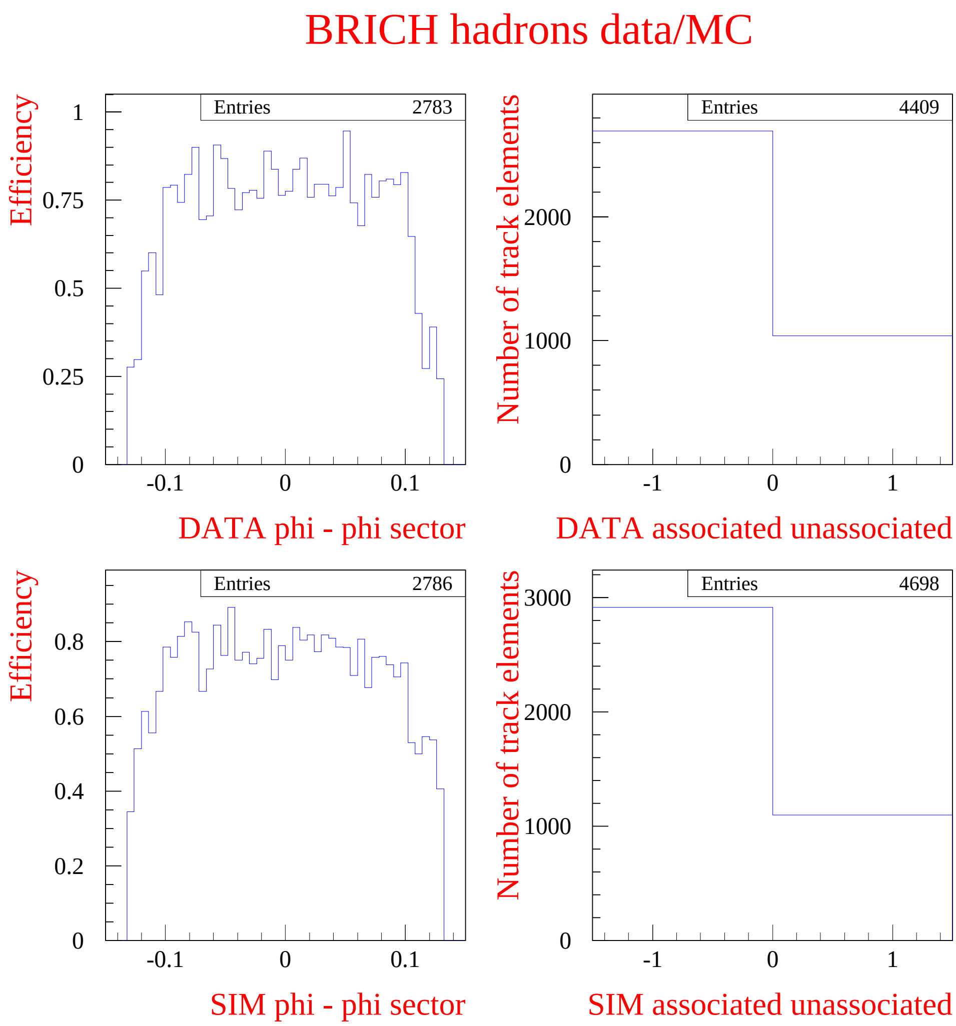

Figure 11: *The efficiency as a function of ϕ of the track over a RICH sector for data and simulation. The number of associated and unassociated track elements for data and simulation.*

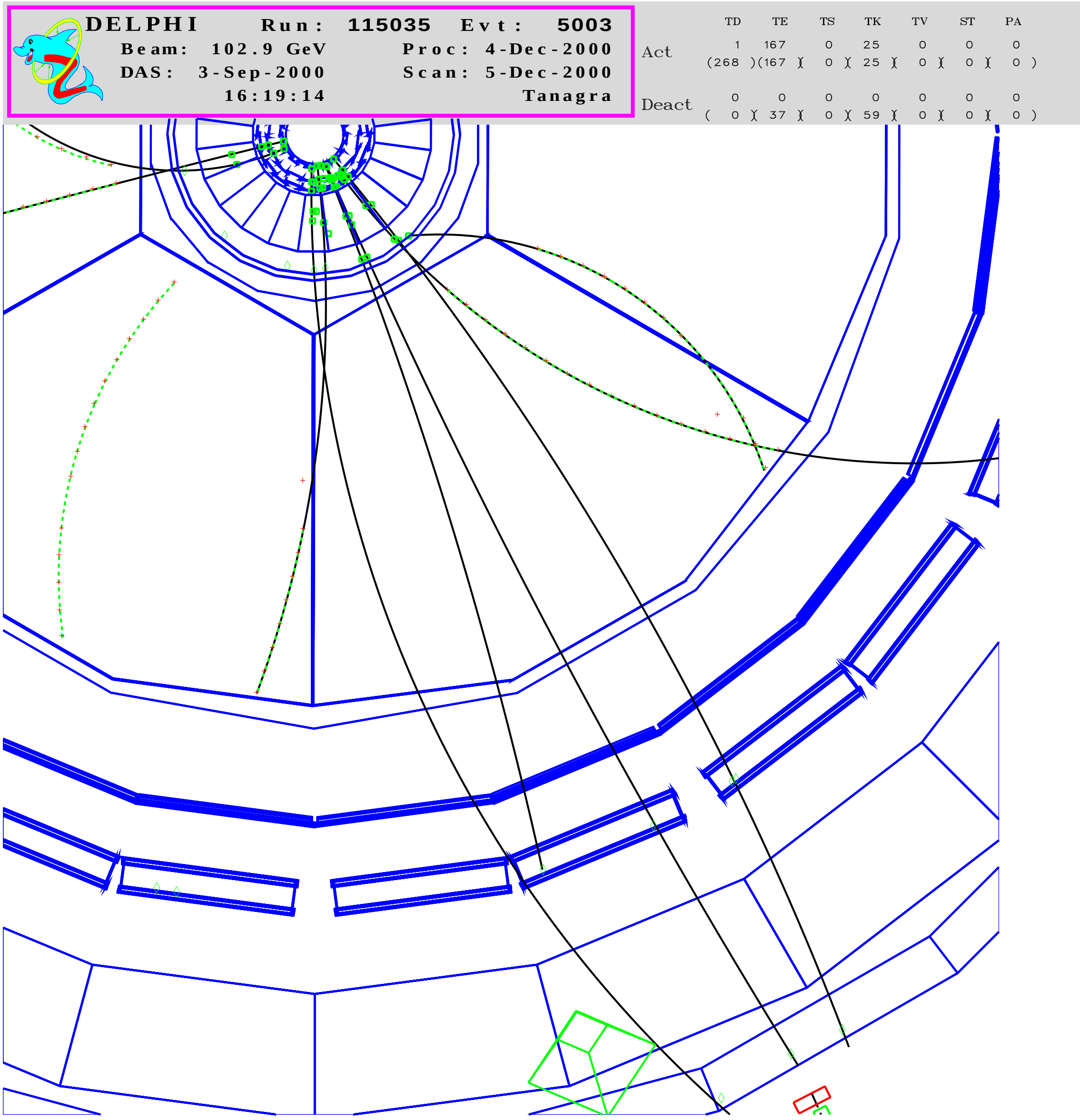

Figure 12: *An example event with a jet in the dead sector 6. Shown is an $R\phi$ view of the barrel detector. Most tracks in the sector are reconstructed using the OD and/or RIB hit information as can be seen in the lower right of the graphic.*