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The new "ID+VD" track search in DELANA

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Abstract

Hermiticity is crucial for most of the physics analyses at LEP 2. Hadronic interactions of charged particles in the DELPHI detector material and acceptance problems in the forward region are possible causes of detection inefficiency. Reconstruction algorithms based only on the Silicon Tracker, including the VFT, and the Inner Detector information are important to detect those particles. In this note the new reconstruction software, its inclusion into to global track reconstruction package and its performance are described.

1 Introduction

At LEP 2 the hermiticity and jet energy resolution is important to most of the physics analyses. A possible cause of detection inefficiencies for charged particles in DELPHI are hadronic interactions in the detector material. Especially in the forward region most of the tracking detectors operate behind the material of the end caps of the barrel detectors. High momentum tracks can escape from detection in the ϕ boundaries of the TPC sectors and in the TPC middle wall. Dedicated track reconstruction algorithms are needed to reconstruct those tracks before the interaction using the barrel VD, the VFT and the Inner (and Outer) Detector information.

A first algorithm to reconstruct tracks using the information from the Inner Detector (ID) jet chamber and the silicon micro strip vertex detector (VD) has been implemented in the DELANA [1] tracking package for the full reprocessing of the LEP 1 data set [2]. A post DELANA package was used to reconstruct tracks based only on the VD hits [3]. Both of these packages were written especially for the 1994 Silicon Tracker [4].

The Silicon Tracker [5] and the Inner Detector have been upgraded for LEP 2. The polar coverage of the VD has been enlarged down to 22°. Half of the Inner layer and the full Closer and Outer layers have been equipped with $R\phi$ and z detectors. The Very Forward Tracker (VFT), which is composed of 2 layers of pixel detectors and 2 layers of double sided mini strip modules, extends the polar coverage down to 11°. The ID jet chamber as been replaced by a longer chamber extending the polar coverage down to 13°. The trigger layers are replaced by five layers of straw tubes (STRAWs) providing an additional precise track point before the TPC. An update to the track reconstruction code has been done to exploit the detector improvements [6]. Also the old "ID+VD" tracking has been changed to include the VFT and the STRAW information. A post DELANA package was added to reconstruct tracks based only on the VFT hit information in the forward direction [7].

The three reconstruction packages, the "ID+VD" tracking and the two post DELANA packages to reconstruct "VD only" and "VFT only" tracks, are replaced by a single new "ID+VD" track search which is fully integrated into the DELANA software environment. Technically it is now a part of the forward track seach (TKSF) [6].

This note describes the new algorithms and the code changes to correctly integrate the "ID+VD" tracking into the global track reconstruction in DELANA. The results of the new package and its interplay with the post DELANA analysis code to reconstruct the hadronic interaction vertex structure are also discussed. The new code will be used for the final 2 years of DELPHI data taking, starting from the LEP startup of 1999, as well as for the final reprocessing of the full LEP 2 data set.

2 Aspects of the DELANA tracking code

In this section only those aspects of the DELANA tracking code are discussed which are relevant to the new "ID+VD" track search. See elsewhere for a more detailed description of the DELANA tracking [1, 6, 8].

At the beginning of the barrel track search (TKSB) three vertexing packages are used to reconstruct V0 decays (K^0_s, Λ) [9], photon conversions into an electron-positron pair [10] and hadronic interactions [11]. These packages use only the TPC track elements (TE).

The hadronic vertex and the photon conversion positions are stored in a common block for later use in the "ID+VD" track search. The secondary track elements associated to the reconstructed vertices are flagged for the track reconstruction. This prevents (false) association of ID or VD hits, which originate from other tracks.

One of the search algorithms in TKSB is the so called "ID+VD pivot" search. In this search the ID jet chamber TEs are extrapolated to the VD plaquettes to find possible combinations of 2 or more VD $R\phi$ hits in different layers. Each combination of $R\phi$ VD hits and an ID jet chamber TE is fitted. The track candidate is extrapolated to the TPC and the Outer Detector (OD) to find the corresponding hits in these detectors. Apart from the ordinary tracks, which include the TPC, track candidates are also created for combinations including only the ID and the VD. Possible OD hits are assocuated to the candidate, if the track is in the dead region of the TPC in the sector ϕ boundaries or the middle wall. In addition a search for ID plus OD combinations is done is these regions.

In TKSF three different search algorithms are used to reconstruct tracks measured (at least) in the ID and in the VFT or in the VD and VFT overlap. One algorithm is starting from "VFT multipoint" TEs, which include combinations of hits in different layers found by the VFT standalone pattern recognition [12], to search for the track. The average beam spot position is used in this search to constrain the direction of the track candidate. The second algorithm uses the ID jet chamber TEs in a similar way as done in TKSB to search for additional combinations of VFT hits in $R\phi$. Again the beam spot position is used to constrain the track direction to search for hits in the rest of the detector. The third algorithm starts directly from the ID plus VD combinations found in TKSB to search for VFT hits in the overlap region between the VD and the VFT. In addition the STRAW TEs are associated to all barrel and forward track candidates.

After the barrel and forward track searches all track candidates are refitted [13] and the event ambiguity solution is carried out [14]. At this stage all "ID+VD" combinations are removed from the sample of candidates to avoid track splitting in the ambiguity solution. The VD Rz hits are associated to the resolved tracks after the event solution. Then the "ID+VD" track search is called to fully reconstruct the "ID+VD" tracks and to associate the left over VD Rz hits to those tracks.

3 The task of the "ID+VD" track search

The "ID+VD" track search is called after the first stage track searches and works on the remaining unassociated TEs in the event. The task of the "ID+VD" track search is to reconstruct short tracks measured only in the tracking detectors close to the interaction region, namely the VD, the VFT, the ID jet chamber and the STRAWs. A special case are high momentum tracks in the TPC cracks for which also the Outer Detector hits are used.

The detectors used to find the short tracks provide different tracking information. The ID jet chamber and the STRAWs provide good $R\phi$ information, while only the STRAWs give a rough z estimate with a precision of $15cm$ from the stereo angle of the outermost two layers of straw tubes. The VD measures hits separately in both projections $R\phi$ and Rz. The main track reconstruction problem in the barrel region is to resolve the Rz associations to the tracks. The VFT in the forward region provides three dimensional track points and is the basis to reconstruct the tracks.

4 Problems with the old "ID+VD" track searches

The old "ID+VD" track search was developed on the DST and later used inside DELANA. Therefore it was not designed as a search, but as a tagging routine to identify the correct Rz hits in the VD instead of allowing for ambiguous associations in an early stage of the reconstruction. The code was also specially adapted to the 1994 detector and hence it was very inflexible with respect to changes in the detector setup, especially in the Silicon Tracker. Therefore the efficiency and purity of the track finding was not optimal after the major detector updates for LEP 2. Some code changes were done in a first update [6] to allow for the VFT in the forward direction. But the basic principles were unchanged and hence the efficiency of the code was not satisfactory. In order to fully benefit from the detector improvements a true track search algorithm was needed, which is flexible, allows for ambiguities and makes full use of standard DELANA tracking packages.

As mentioned above, two post DELANA packages were used to reconstruct tracks using only VD or VFT hits. It has been found for the LEP 1 data, that the "VD only" tracking inside MAMMOTH was recovering inefficiencies in the "ID+VD search" [11], but leaving the ID unused for the reconstructed track.

The old "VD only" track reconstruction was written (in the same way like the old "ID+VD" track search) for the 1994 detector layout of the VD. Therefore it was not adapted to the new VD detector and its data structure. The "VFT only" tracking inside DSTANA was never used for a processing of a complete data set.

5 Updates to the first stage track searches

The first step to implement the new "ID+VD" track search algorithm in DELANA was to check and update the reconstruction code related to the "ID+VD" track reconstruction. The following corrections and changes have been done :

- One region of special interest for the "ID+VD" tracking are the TPC sector boundaries in ϕ as well as the middle wall at $\theta = 90°$. In the ϕ cracks of the TPC pattern recognition is insufficient to reconstruct a track element from only the wire timing information. Also no attempt is made to reconstruct only the z and θ for an approximate $R\phi$ position in the boundary region. Therefore high momentum tracks escape from reconstruction. At $\theta = 90^0$ particles pass through the TPC wall and hence are not detected in the TPC. To study and improve the track finding efficiency in the ϕ and θ cracks a set of special simulation events containing muon tracks in these regions was generated. Figure 1 shows the a typical reconstructed event after corrections to the "ID+VD pivot" track search in TKSB to improve the efficiency for picking up the Outer Detector hit. In addition the "ID+VD pivot" track search now also associates the Outer Detector hits to the track candidates at $\theta = 90^0$.

- The reconstruction of the hadronic vertices at the beginning of the track searches is very important for protecting these tracks from false associations of VD hits. The vertex positions are important input for the reconstruction of the "ID+VD" tracks before the interactions, because they can be used to define θ and z of the tracks. In figure 2 a reconstructed hadronic interaction is shown. In many cases the photon conversion finder would classify 2 out of the secondary tracks, which have a small opening angle, as being from a converted photon. This is due to a very loose cut tuning in this package. Therefore the calling order of the vertexing packages has been changed such that the hadronic interaction finder is running first.

- The new "ID+VD" track search is called before the 2nd stage of the ID jet chamber and the STRAWs. A correction to the extrapolation package EXX [1] was done in order to create extrapolation banks for the reconstructed "ID+VD" tracks for all detectors. These extrapolations are used to improve the first stage TEs found in the ID jet chamber and the STRAWs. The predictions from the extrapolated tracks are also used to find additional TEs which improve the track finding efficiency of these detectors. A similar approach was tried using the "ID+VD" tracks to obtain predictions for the 2nd stage of FCA. The purity of the newly created FCA 2nd stage TEs (found on the basis of these extrapolations) was poor and hence this method is not used for FCA.

6 The new "ID+VD" track search

The new "ID+VD" track search uses four different starting points to reconstruct the tracks. Combinations of the ID jet chamber and STRAW TEs with either the VD $R\phi$ or the VFT hits are found by the barrel and forward track searches. Therefore these two classes (as the "ID+OD" tracks) are filtered from all track candidates which are not selected by the first event ambiguity processing. In addition a search in $R\phi$ is done to reconstruct tracks seen only in the VD. In the forward the result of the VFT standalone pattern [12] is used to reconstruct tracks seen only in the VFT. In the "ID+VD" search the primary vertex and the positions of hadronic vertices are used to reconstruct the tracks. Also the elastic scattering vertices are reconstructed in case the secondary tracks were seen in the TPC. In the following the reconstruction algorithms and the structure of the code are discussed.

6.1 Primary and secondary vertex information

At the beginning of the "ID+VD" track search the DELANA vertex reconstruction package [1] is called to reconstruct the primary vertex position on the basis of the reconstructed first stage tracks. All tracks which are not associated to the primary vertex are candidates for tracks from secondary interactions. Tracks, which are not associated to reconstructed hadronic interactions, photon conversions or V0 decays are kept for the search of elastic scatterings, if the first measured point of the track is outside the ID jet chamber. The vertex positions of the reconstructed hadronic interactions (and of the tagged photon conversions) are converted into "measured track hits" or "pseudo-TEs". These "pseudo-TEs" are later used to reconstruct the track in front of the interaction.

6.2 The "VD only" search algorithm

The first step in the reconstruction is the search for tracks in $R\phi$ using the VD hits. The algorithm is based on the DST package [3].

The reconstruction of the "VD only" tracks starts from the $R\phi$ hits in the Outer layer. Each of $R\phi$ hits has to pass a signal-over-noise cut. All hits in modules with high occupancy are also rejected. From the good Outer layer hits a straight line is drawn to the primary vertex. All hits in the Closer layer which are near these lines are considered as candidates in the following. Also the Closer layer hits have to pass the signal-over-noise cut as well as a cut on the module occupancy. Circles in $R\phi$ are drawn through each of the Outer plus Closer layer hit combinations using the primary vertex to define the radius. The radius of the circle is required to correspond to a minimum p_t of 0.03 GeV. The circles in $R\phi$ are used to search for additional hits in the Inner layer as well as in the overlaps of the Outer and Closer layers. Again, hits with low signal-over-noise or hits from modules with high occupancy are rejected.

For each circle all combinations are considered which include at least one hit in all three layers. Combinations including additional hits in an overlap are preferred. A candidate track is reconstructed in $R\phi$ using the DELANA track fit [13] and assuming $\theta = \pi/2$. Bad combinations fail the χ^2 cut in the fit and single hits could be rejected by the outlier logic. All combinations passing the track fit are kept as "VD only" candidates.

6.3 The "VD pivot" track search

The reconstructed "VD only" candidates are used as a starting point to search for additional TEs in the ID jet chamber or the STRAWs. Technically the search is done using the forward track search algorithm [6]. I.e., the "VD only" candidates are extrapolated to both detectors and candidate lists of possible TE combinations are created. From these lists the "ID+VD" track candidates are reconstructed using the track fit.

6.4 Input from the barrel and forward searches

"ID+VD" tracks with VD $R\phi$ hits in only two layers are not reconstructed by the "VD pivot" track search. Such combinations are reconstructed by TKSB in the "ID+VD pivot" track search. Also track candidates in the TPC cracks which include the OD are found by this search. In the forward region "ID+VFT" track candidates are reconstructed by TKSF. Therefore all track candidates from the first stage track searches which were not selected by the event ambiguity processor are scanned for combinations of ID jet chamber, STRAW or OD TEs with VD and VFT hits. These combinations are used as candidate tracks in the "ID+VD" track search.

6.5 Association of hadronic vertices to the track candidates

Estimates of the z position and the polar angle θ are only present for a small part of the barrel track candidates. The STRAW detector gives a rough z measurement with a resolution of only 15 cm. The OD is used for the small fraction of high energy tracks in the TPC cracks. The VD is providing a very precise Rz measurement in the full outer and closer and in the external half of the Inner layer. The double metal Rz readout leads to up to 4 multiplexing ambiguities for a single hit. Therefore it is beneficial to use additional z information provided by the reconstructed hadronic interaction vertex and the primary vertex to select the right multiplexing ambiguity when associating the VD Rz hits.

A dedicated search is done to find the "ID+VD" track candidates which can be associated to a reconstructed hadronic vertex. For each possible combination of a track candidate and a reconstructed hadronic interaction it is required that the VD $R\phi$ hits which are used in the track are on the same z side as the vertex. For such a combination it is required that the extrapolated track matches with the $R\phi$ position of the vertex. Afterwards z and θ of the track is determined by refitting the track through the Rz positions of the primary and the hadronic vertex. In case of a forward track, which is measured in the VFT, the z of the primary vertex is not used in the fit, but it is required that the track after refitting through the hadronic vertex is pointing towards the primary vertex position to remove fake associations.

6.6 The association of Rz hits in the VD

The association of VD Rz hits to the track candidates is done using a new algorithm which is embedded inside the standard framework of the VDANA [15] hit association routine. Only the Rz hits, which are not associated to first stage tracks, are left over at this stage of the reconstruction and hence the level of ambiguity is largely reduced. But the multiplexing of the Rz readout in the vertex detector leads to multiple ambiguities which need to be resolved.

The search for Rz hit combinations is done in the modules crossed by the "ID+VD" track in $R\phi$. Most of the two layer combinations of mirror images from the multiplexing do not point to the primary vertex. Therefore any combinations found when scanning all θ directions starting from from the primary vertex are considered as candidates. The z or θ of the tracks are taken into account if they were measured from an external TE or if they were determined from hadronic vertices. In the forward three layer combinations are searched for which include an Inner layer Rz hit. Single hits are considered in case no two or three layer combination is found. For single hits all multiplexing ambiguities in agreement with the $R\phi$ hits associated to the track are taken into account. The primary vertex position is used as an additional constraint in case no other z information is available apart from the single Rz hit.

The result of the association routine is a set of possible ambiguous Rz hit combinations. For each combination the track fit is used as an additional filter. A complication in the treatment of the Rz hits is the bookkeeping of the multiplexing for each hit. It is necessary to change the multiplexing position inside the VDANA common blocks each time a hit is used in the track fit until the final resolution of the ambiguity is done at the end of the reconstruction.

6.7 The "VFT only" reconstruction

At this point the tracks measured only in the VFT are reconstructed. The starting point of the reconstruction are the so called "VFT multipoints". These TEs are combinations of two or three VFT hits in different layers which are found by the VFT local pattern recognition. For each of the combinations the track fit is called assuming the primary vertex position as an additional track point. Candidates are rejected if they fail the fit onto the primary vertex.

6.8 Association of missing VFT hits

The overlap of the VD and the VFT is a crucial region. Therefore each track candidate is extrapolated to all VFT layers and a search is done for unassociated hits. This search also improves the hit finding efficiency for the "VFT only" tracks found using the result of the VFT local pattern recognition. The association of an additional hit is verified using the track fit.

6.9 Search for elastic scatterings

Before the final resolution of the track (z) ambiguities an attempt is made to reconstruct vertices from elastic scatterings. This search is done for those tracks which have no other z information than a single VD Rz hit. The secondary tracks were selected at the beginning of the event processing of the "ID+VD" track search. First the intersections in $R\phi$ of an "ID+VD" track and a secondary track are calculated. Combinations are selected if the radial position of an intersection is outside the VD and inside the TPC first rows. Furthermore it is required that the angle between the "ID+VD" track and the secondary track at the intersection is small and that the extrapolated "ID+VD" track matches with the z position of the secondary track. The "ID+VD" track is refitted using the R and z position of the intersection as an additional track point if the combination passes the cuts.

6.10 First multiplexing solution

A problem for the event ambiguity processing are track candidates which only differ in the choice of the Rz multiplexing solutions of one or two associated hits in the VD. These tracks have the same TE content and are therefore treated as identical in the ambiguity processor. Therefore such ambiguities are resolved before. In these cases only the candidate with the smaller z impact parameter is retained in the event.

6.11 Selection of good "ID+VD" track candidates

It is beneficial to remove badly measured "ID+VD" track candidates from the event, because they have a high risk of being fakes. The ID jet chamber has calibration problems for short drift times if tracks are close to the wire planes. Therefore the measurement errors of the ID jet chamber TEs in these regions are 2 mm. Because of this large error the "ID+VD" tracks close to the wire planes can get unphysical high momentum which is a problem for the reconstruction of the energy flow in the event. Additional quality cuts are applied for the "ID+VD" track candidates. Table 1 gives an overview of the rejection criteria.

For all tracks passing the selection the software module identifier is modified to classify the track content. A summary of software module identifiers is given in table 2. This table replaces the table given in reference [6] for all processings after DELANA 99 A. See reference [6] for the definition of the other digits in the identifier. All candidates are written as TS banks into TANAGRA [16] to prepare the ambiguity solution.

6.12 Processing of track ambiguities

At the end of the "ID+VD" reconstruction all left over track ambiguities need to be resolved. This is done using the event ambiguity processor [14] of DELANA. The task of the ambiguity processor is to select the largest possible set of "ID+VD" tracks from the set of candidates, which includs the largest number of TEs and has the best χ^2 probability. Two modifications of the algorithm are made. The fit χ^2 probability of an "ID+VD" candidate with large $R\phi$ or z impact parameters to the primary vertex is scaled and no sub-tracks are created by the ambiguity processor. The first change is needed because of the Rz multiplexing ambiguity in the VD, the second change reflects the low redundancy of "ID+VD" tracks.

The result of the ambiguity processing is the final set of reconstructed "ID+VD" tracks. These tracks are then extrapolated to all detectors to prepare the 2nd stage processing of the local pattern recognition. The χ^2 and the number of degrees of freedom of the "ID+VD" tracks should not be used in a physics analysis. Their values are set to zero at the end of the reconstruction.

7 Results of the new "ID+VD" track search

The rate of "ID+VD" tracks in real data and in simulation have been studied on a test processing of the '98 Z0 data. Table 3 gives an overview of the results. On average 2.28 "ID+VD" tracks per hadronic Z^0 are found by the new reconstruction software. Good agreement of real data and simulation is found. Figure 3 shows as an example the reconstruction efficiency for primary tracks as a function of the polar angle in the forward region. A clear gain in the polar region below 15 degree is visible after the inclusion of the "VFT only" tracks.

A new tuning of the reconstruction package for secondary interaction MAMMOTH [11] has been done to fully exploit the new "ID+VD" track search results. An example of a reconstructed secondary interaction event is shown in figure 2. Table 4 shows the rates of "ID+VD" tracks which are linked to secondary vertices. The study was also done on the sample of '98 Z^0 hadronic events and compared to the simulation.

To transfer the improvements in the reconstruction to the physics analysis level the DELPHI analysis skeleton SKELANA was modified. The new version includes an improved selection of "ID+VD" tracks and a better treatment of reconstructed secondary interactions. See reference [17] for details. In the forward region a new electron identification package REMCLU [18] was written which is tagging electrons based on "VFT only" tracks and the electromagnetic showers in the FEMC.

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all	tracks with bad impact parameters: $\Delta z > 2$ cm, $\Delta R\phi > 1.5$ cm "ID+VD" and "VD only" tracks without any z measurement (or hadronic vertex) "ID+VD" tracks with only 1 associated hit in the VD or VFT (and no OD or STRAWs)
ID wire planes	ID plus OD combinations, if no VD or STRAWs on the track ID plus only 1 or 2 VD $R\phi$ hits and no STRAWs or OD
VFT only	VFT only which fail the primary vertex fit combinations of Pixel layers 1 and 2 (safety because of hot pixel map errors)
VD only	less than 3 layers in $R\phi$ less than 2 layers in Rz

Table 1: Table of "ID+VD" track categories which are rejected.

soft. module identifier	VD z layers or VFT hits	hadronic interaction or elastic scattering	z of primary vertex used
x1xxx	1	yes	if needed
x2xxx	2	yes	no
x3xxx	0	yes	yes
x4xxx	1 (or STW)	no	if needed
x5xxx	2	no	no
x6xxx	"ID-OD" like		if needed
x7xxx	like 3xxx, but only 2 $R\Phi$ hits		yes
x8xxx	like 4xxx, but only 2 $R\Phi$ hits		if needed

Table 2: Software module identifier of tracks created by the "ID+VD" track search. See reference [6] for definition of the other digits. No difference is made between VD and VFT hits. Tracks with or without ID jet chamber get the same identifier.

detector combination	real data	simulation
ID+VD, > 1 Rz hit	0.86	0.92
ID+VD, 1 Rz hit	0.21	0.18
VD only	0.49	0.34
ID+VFT	0.26	0.17
VFT only	0.40	0.35
ID(+VD)+OD	0.06	0.05
total	2.28	2.01

Table 3: Rate of reconstructed "ID+VD" tracks per hadronic Z^0 in real data '98 and in simulation.

detector combination	real data	simulation
ID+VD	42 %	48 %
VD only	21 %	25 %
ID+VFT	18 %	24 %
VFT only	18 %	13 %

Table 4: Rate of "ID+VD" tracks which are linked to reconstructed secondary vertices using the MAMMOTH package. See reference [11] for details.

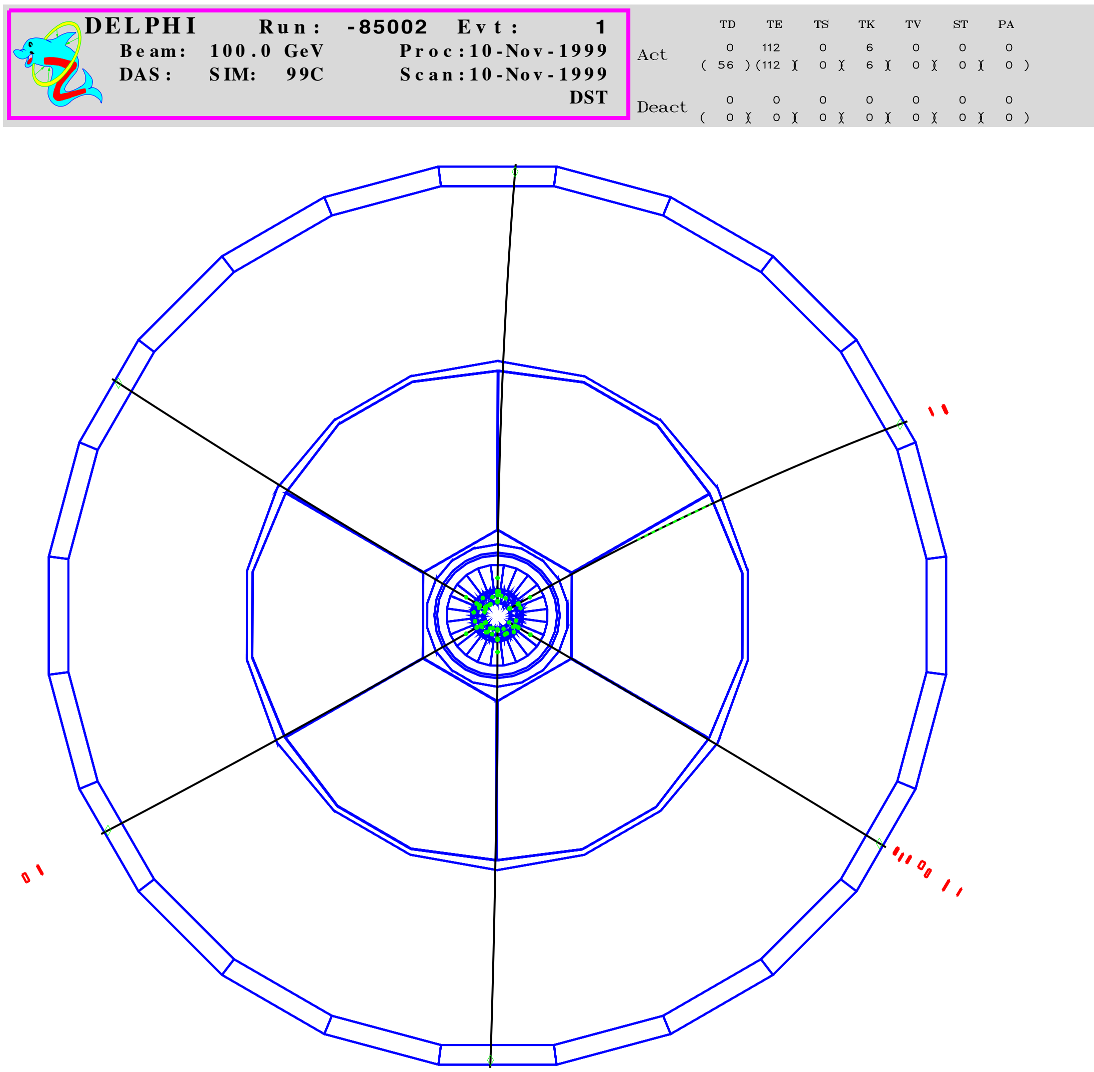

Figure 1: *Typical reconstructed toy event with 6 simulated muons in the TPC ϕ cracks. Shown is an $R\phi$ view of the barrel tracking detectors. The muon momenta are 5, 10, 15, 20, 25 and 30 GeV/c (anti-clockwise).*

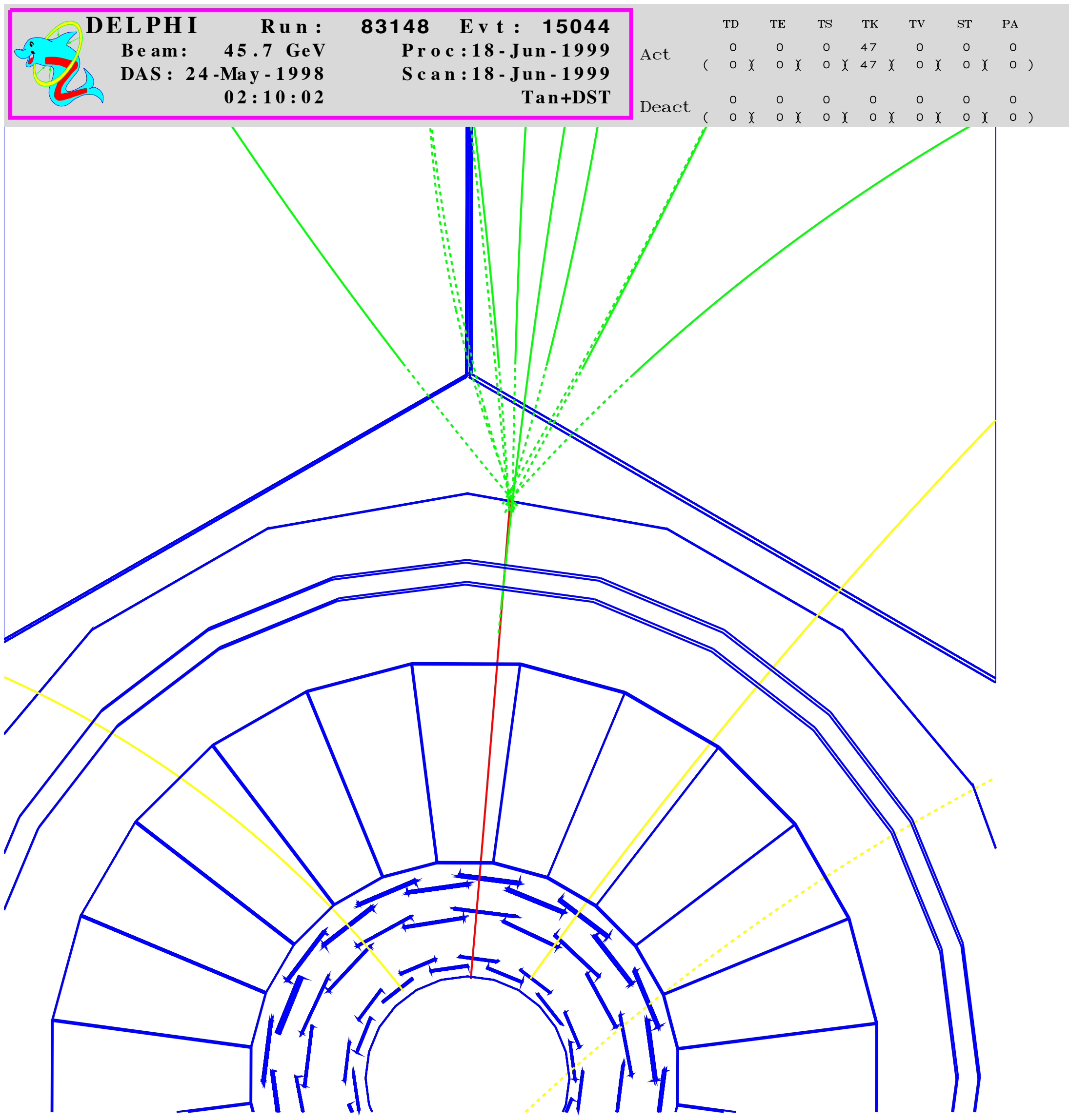

Figure 2: *An reconstructed hadronic interaction. The photon conversion finder would classify 2 out of the 11 secondary tracks as being from a converted photon.*

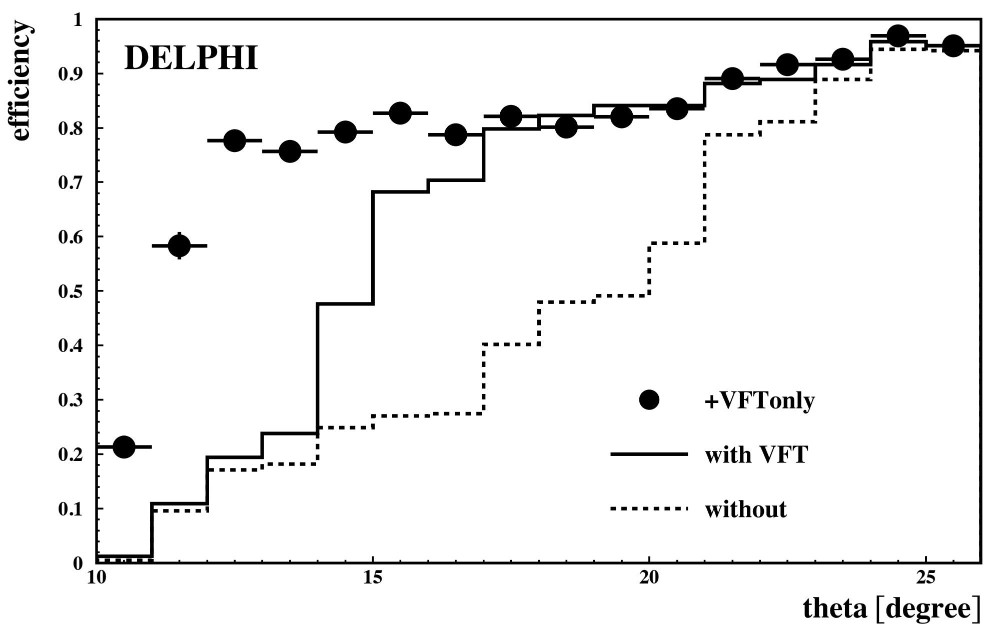

Figure 3: The efficiency to reconstruct primary tracks in simulated hadronic Z^0 events as a function of the polar angle. Shown are the results with and without the VFT in the track reconstruction as well as the additional gain due to the tracks reconstructed only in the VFT.