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Alignment of the ALEPH Tracking Devices

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Abstract

The techniques and the requirements on the accuracy for the alignment of the three ALEPH tracking devices, a large Time Projection Chamber (TPC), a cylindrical drift chamber (ITC) and a double sided silicon vertex detector (VDET), are presented. This includes internal VDET and TPC alignment techniques, relative global positioning of the three tracking detectors and calibration of residual distortions. Starting from survey measurements, real data were used to improve on the internal and global positioning of the detectors. The final alignment was done with a sample of 20000 hadronic Z^0 decays and 4000 $Z^0 \rightarrow \mu^+\mu^-$ events taken in the 1991 LEP running period.
After all corrections a momentum resolution of $\Delta p/p^2 = 0.6 \times 10^{-3}\,(\mathrm{GeV/c})^{-1}$ and impact parameter resolutions of 25 and 29 μm in the $R\phi$ and Rz directions were achieved for tracks measured in all three tracking devices.

1 Introduction

Charged particle tracking in the 4π solid angle detector ALEPH [1] is provided by a Time Projection Chamber (TPC), a conventional cylindrical drift chamber called the Inner Tracking Chamber (ITC) and a silicon vertex detector (VDET). At radii between 30 and 180 cm the TPC measures 21 three dimensional coordinates on fully contained tracks. The ionisation charge is recorded at two end-plates by a system of proportional wire chambers with segmented cathode pad readout. Eighteen wire chambers (sectors), in three different shapes, are mounted on each end-plate and are arranged in two concentric circles, the inner one having six and the outer one twelve sectors. The $R\phi$ position of a coordinate is measured with a resolution of 180 μm and the z position with 740 μm respectively [2]. Between 12 and 30 cm the ITC measures on eight concentric circular rows of wires the $R\phi$ position of a coordinate with a resolution of 150 μm . The ALEPH double sided silicon vertex detector consists of 96 silicon wafers, arranged in two concentric cylinders with 6.4 and 11.5 cm average radius respectively. 36 wafers are mounted on the inner layer, 60 on the outer one. The wafers, with a 5% overlap between each other in $R\phi$, are staggered in azimuth between the inner and outer layers to ensure full angular coverage. Each wafer is read out in two perpendicular directions, with a resolution of $\sim$ 10 μm in each.

The alignment problem consists in the determination of the global positions of TPC, ITC and VDET relative to a given reference system treating each detector as a single rigid body, and the determination of the local positions of TPC sectors and VDET wafers relative to each other. Usually global position parameters are redundant with the local alignment parameters and are mainly used to keep the local parameters small.

2 Precision Requirements

One important application of the ALEPH tracking system is the measurement of track impact parameters. This example was used to quantify the required alignment accuracy for TPC and ITC relative to the VDET. The precision requirements were estimated with a simple model, where the outer tracking was reduced to a single measurement, whose precision was the statistical combination of all the separate measurements. This effective point was placed at the average measurement radius of the points, weighted by their precision. Misalignment of the outer tracking was modeled by moving this point perpendicular to the track direction and looking to the impact parameter resolution, given a fit with this effective outer point and two VDET hits. The allowed tolerances for the alignment were defined as the ones, where the impact parameter resolution was degraded by at most 5%. This tolerances are listed in table 1.

To estimate for example the required alignment precision for individual VDET wafers, a full Monte Carlo simulation of the ALEPH tracking was used. The Monte Carlo data were reconstructed with wafers randomly displaced from their design positions. The study was made with high momentum ($\sim$ 45 GeV/c) tracks from $Z^0 \rightarrow \mu^+\mu^-$ decays, in order to remove multiple scattering effects. The parameters considered were the six degrees of freedom for a rigid body, expressed in a cylindrical coordinate system. Again the acceptable misalignment was defined as the one, which degrades the impact parameter resolution by at most 5%. The results are listed in table 2.

Because of their large lever arm, the outer tracking devices are important for measuring the track angle, and hence contribute significantly to the impact parameter measurement. The TPC contributes effectively in the Rz direction a measurement point with $\sim$ 200 μm accuracy at an effective radius of about one meter. The expected impact parameter resolution for high momentum tracks in the Rz plane is about 32 μm using only the VDET, and 20 μm using the VDET and TPC measurement. It is therefore important to have also an accurate alignment in the Rz plane for the TPC sectors and to know, due to the long drift length of 220 cm in the TPC, the longitudinal drift velocity to better than one part in 10^4.

3 Alignment Techniques

The final global and local positions of all tracking detector components were determined in place with real data from Z^0 decays. It was however important to have also alignment data from survey measurements as start values for a data driven alignment and as unbiased references, which are immune to many detector systematics, for consistency checks. Especially important for the calibration of residual systematic effects in the Rz direction in the TPC was a measurement of the VDET wafer positions relative to each other in the laboratory (optical alignment). This was made before the insertion of the VDET into ALEPH and after its assembly. The relative positions of all the wafers were measured in three dimensions, using a microscope. The $R\phi$ and z positions were measured directly with an estimated resolution of 2 μm , whereas the radial positions were determined, with an estimated resolution of 10 μm , by adjusting the focus of the microscope. The direct measurement was verified by comparing the positions of measured reference points in the wafer planes, which were known to less than 1 μm from the mask, used to create the wafers.

With the aid of this optical VDET alignment the absolute scale of the TPC longitudinal drift velocity was verified by comparing the reconstructed track polar angle in the TPC with the one in the VDET [3]. This calibration with VDET was accurate to one part in 10^4, one order of magnitude below the systematic accuracy of the Laser calibration system [2, 4]. The systematic uncertainty in the Laser calibration system is mainly due to the uncertainty in the deflection angles of the Laser beams into the TPC.

Also the time dependence of the drift velocity was monitored on a run by run basis with data, to minimize systematic biases in the Rz direction due to a variation of the longitudinal drift velocity on short time scales. Laser runs for the drift velocity measurement could only be made in LEP filling periods. The Laser calibration data covered therefore periods of several data runs. The new calibration was done by measuring the difference Δz_0 of the average z vertex in each TPC half of tracks originating from hadronic Z^0 decays. This difference is a function of the longitudinal drift velocity and t_0, the measured time difference in starting the digitization in the two TPC halves. It is known that t_0 is constant in time, therefore Δz_0 per run could be used to adjust the drift velocity on a run by run basis. The tracks, which were used to calculate the mean z vertices were only fit to TPC and ITC points. This method of calibrating the drift velocity was very important for a period after a repair work on the TPC. The drift velocity had changed by more than 2% and approached, exponentially changing, the stable long term average again. The new drift velocity calibration improved the impact parameter resolution in the Rz direction by 34%.
After this adjustments the data driven alignment procedures were started.

3.1 Global Alignment of VDET and ITC relative to the TPC

In a first step the position of the TPC was taken from the survey measurements and the ITC was aligned globally to the TPC. In the TPC track distortions due to field inhomogeneities were already corrected (the methods for determining these corrections are described in [2]). Starting from global alignment constants, determined with cosmics [5], the three translational alignment parameters and the three Euler angles relative to the TPC were determined with tracks from the processes $Z^0 \rightarrow \mu^+\mu^-$ and $Z^0 \rightarrow q\bar{q}$, by minimizing the residuals $\Delta_{R\phi}$ between the expected hit positions of tracks extrapolated from the TPC into the ITC and the actually measured $R\phi$ hit positions in the ITC. In first order depends

$$\Delta_{R\phi} \simeq R_{ITC}\psi - z(\delta \sin\Phi + \theta\cos\Phi) - (\Delta x \sin\Phi - \Delta y \cos\Phi)$$

for high momentum tracks on five alignment parameters, the rotation angle of the ITC relative to the TPC (ψ), the angle between the ITC axis and the TPC axis in the $x-z$ plane (δ), the analog angle in the $y-z$ plane (θ), and the translational offsets of the ITC center relative to the TPC center (Δx and Δy) in the $x-y$ plane. R_{ITC} is the average ITC radius, Φ the azimuthal track angle and z the longitudinal coordinate of the measured point. The offset Δz of the ITC center relative to the TPC center in the z

direction was taken from the survey measurements. In an analog way the VDET was positioned relative to the combined ITC-TPC tracking system.

3.2 TPC Sector Alignment

The next step was the relative alignment of TPC sectors in the $R\phi$ plane. The position of each wire chamber in the TPC end-plate is mechanically determined by pins located with high precision on the end-plate frame. The positions of these sectors were determined in two independent optical survey measurements to an accuracy of about 100 μm [6, 7]. The position in the $R\phi$ plane of the pads relative to the reference points of the sector is known by construction with a precision of the order of 60 μm .

The relative alignment of the 18 sectors in each end-plate has also been determined with $Z^0 \rightarrow \mu^+\mu^-$ events, where the radially outgoing muons have a momentum equal to the beam energy (neglecting higher order QED effects). Each muon track was fitted with three helix segments, one measured by the ITC, one measured in an inner sector and one in an outer sector of the TPC. The track fit was made with a common radius of curvature and dip angle for all three helix pieces, but allowing for offsets in the azimuthal plane at the boundaries between ITC and TPC and between inner and outer TPC sectors. The dip angle was only determined by the TPC longitudinal coordinate measurement and the momentum of each track was fixed to beam energy. The radial and azimuthal positions of each sector and its rotation about its center were determined by minimizing the azimuthal deviations between the TPC and ITC helix segment.

First all inner sectors were aligned to reference helices fitted to ITC points only, then the outer TPC sectors were aligned to reference helices fitted together with ITC and TPC points from the aligned inner sectors. In this way, the sectors in each TPC end-plate were aligned relative to each other and the complete end-plate was aligned globally to the ITC. As a consequence, the two TPC end-plates are also aligned relative to each other.

After aligning in $R\phi$ TPC and ITC, the VDET was aligned with data for the first time internally in $R\phi$ relative to these two detectors. The methods for this alignment are described in section 3.3.

TPC sectors were then aligned in the longitudinal direction to the VDET with the following approach: A single helix was fit to the two tracks of $Z^0 \rightarrow \mu^+\mu^-$ events, with the momentum constrained to the beam energy. Only VDET and ITC coordinates were used in the fit. The position of this helix in $R\phi$ was therefore determined by the VDET and ITC measurement, whereas the track dip angle was only measured by the VDET. In $R\phi$ all up to now determined alignment constants for VDET, ITC and TPC were used, in Rz however the global VDET z position from the survey measurement and the internal alignment from the optical survey of the VDET was used. For each TPC sector s two effective alignment constants were determined, a longitudinal shift Δz_s of the sector center relative to its nominal z position and a rotation κ_s of the sector in the Rz plane around the sector center in order to align its symmetry axis with the radial line. Δz_s and κ_s were determined by minimizing in the sector reference frame (for a definition see Ref [1]) the measured z residuals

$$\delta z \simeq \Delta z_s + (r\cos\phi - r_s)\tan\kappa_s$$

of TPC points with respect to the single helix. r and ϕ are the radius and the azimuthal angle of the measured TPC coordinates. Fig. 1 shows δz as function of the radius before and after applying these alignment corrections in the two TPC halves.

3.3 VDET Alignment Techniques

Because of the high measurement accuracy of the VDET is the internal VDET alignment with data strongly sensitive to any residual systematic effects in the outer tracking devices, like e.g. small residual misalignments or small field inhomogeneities. In order to become as much as possible independent of such effects and to provide a self consistent, mainly VDET internal alignment the concept of a constrained residual was used. This is a residual where only some of the track information comes from the outer

tracking devices, while the rest is determined with VDET hits. Two types of constrained residuals were minimized in the alignment procedure: single constraints, where the outer track is displaced to go through a VDET hit, and double constraints where both the track direction and position are determined from the VDET. All constrained residuals work equally well in the $R\phi$ and Rz projections.
Three different types of single constrained residuals were used:

- A constrained residual (overlap constraint), which measures the relative positions of two adjacent wafers and exploits therefore the overlap between wafers in the $R\phi$ plane, through which 5% of all tracks pass. Taking the track direction and curvature from the outer tracking, the track is constrained to pass through one of the VDET hits and the residual with the other hit is measured. This removes largely possible angular misalignment effects in the outer tracking from the residual, since the distance between the wafers is only a few mm.
- A constrained residual (two-layer constraint), which measures the relative positions of wafers in different layers at the same ϕ. The same principle as above is applied to tracks which traverse both layers of the VDET. Here in principle all tracks can be used, but the dependence on the outer tracking angular measure is larger due to the larger distance between layers ($\sim$ 5 cm).
- A constrained residual (muon constraint), which measures the relative positions of wafers on opposite sides of the detector. This uses $Z^0 \rightarrow \mu^+\mu^-$ events exclusively. Neglecting higher order QED effects, the two muons are emitted with opposite momentum from the Z^0 , which is produced at rest. Thus, both tracks can be fit to a single helix. This averages the outer tracking systematics on opposite sides of the detector, and greatly increases the statistical precision of the fit. The accuracy can be further increased by constraining the momentum of the single-fit track to the LEP beam energy. If the single-fit track is constrained to one VDET hit, the constrained muon residual with respect to the VDET hit on the opposite side of the detector can be constructed.

The most powerful constraints used in the alignment are the so called double constrained residuals:

- A double constrained residual, which is the combination of the overlap and two-layer single constraints, where only the curvature is taken from the outer tracking. The track angle is defined by the two hits in the two VDET layers.
- A double constrained residual, which is an extension of the single muon constraint. With a single-helix fit to both muons, there are four VDET hits on a single track. Taking two on opposite sides of the detector, and constraining the momentum to the beam energy, one can solve for all five track parameters using only the VDET hits. Projecting this track to the other layer forms a residual analogous to the two-layer constraint, but with no dependence on the outer tracking.

For tracks which pass through the overlap region a third type of constrained residual can be defined, the so-called three-layer constraint. Here triplets of VDET hits which have been associated to an ITC-TPC track are considered and a helix is then fit through two of the VDET hits (one hit from each layer), without using any of the coordinates in the ITC or TPC. Only the value of the track curvature is copied from the ITC-TPC measurement. The feed-through of a systematic error on the curvature is very small. This track is then propagated to the third VDET layer (this only works in the overlap region) where its position can be compared to that of the remaining hit in the triplet. The method is thus very similar to the overlap method except that the track angle is now measured with the VDET alone. This method has also a better statistical precision on the dip angle than the TPC for large dip angles.

3.4 Alignment Iteration

The procedures, described above, were iterated one more time, using the previously determined constants as input. Combinations of two tracking detectors were used to check and update the alignment parameters of the third. In a first step the internal TPC sector alignment was updated using muon pairs. A single helix, with momentum constrained to beam energy, was fit to the track segments of the two muons reconstructed in the VDET and the ITC. Then the positions of all inner sectors were measured relative to these helices. Analogous the position of outer sectors was checked to helices were now not only VDET and ITC points, but also the coordinates of the updated inner sectors were used in the fit. With tracks originating from $Z^0 \rightarrow q\bar{q}$ decays and fit only to VDET and TPC points, precision adjustments to the positions of individual wires in the ITC were made, by minimizing the $R\phi$ residuals on ITC wires. Finally the full VDET alignment was repeated with the updated outer tracking detector parameters.

4 Results from Data

The final alignment was produced with a sample of selected 20000 $Z^0 \rightarrow q\bar{q}$ events and 4000 $Z^0 \rightarrow \mu^+\mu^-$ events.

The systematic alignment errors were estimated by comparing the different constraint techniques. With the final alignment the constrained residuals for each VDET wafer were determined separately for each technique. The data imply a VDET internal bias of 4 (8) μm in the $R\phi$ (Rz) direction and overall tracking errors of $\sim$ 15 (20) μm in the $R\phi$ (Rz) direction [8].

Using the double constrained overlap residuals, the effective VDET $R\phi$ (Rz) point resolution was determined, which is a combination of the intrinsic detector resolution and the alignment accuracy. A point resolution of 12 μm at normal incidence for both $R\phi$ and Rz directions was found in the data, compared to 10 (8) μm in $R\phi$ (Rz) for the Monte Carlo.

A measure for the overall alignment are the momentum resolution and the impact parameter resolution. The momentum resolution was studied with tracks from $Z^0 \rightarrow \mu^+\mu^-$ decays. For tracks reconstructed in TPC, ITC and VDET a momentum resolution of $\Delta p/p^2 = 0.6 \times 10^{-3}\,(\mathrm{GeV/c})^{-1}$ was achieved in agreement with the Monte Carlo prediction. The ratio of the beam energy over the momentum as it is measured by the three tracking detectors for dimuon events is shown separately for positive and negative muons in figure 2.

The impact parameter resolution has been studied with the 'miss distance' of the two tracks from dimuon events. In the $R\phi$ direction this distance is given by the sum of the impact parameters d_0 of the two muons, where d_0 is defined by the distance of closest approach of a track to the beam axis, with the sign of the z-component of the angular momentum with respect to this axis. The sum Σd_0 of the d_0 parameters of the positive and negative muon vanishes on average. The z coordinate of the point, where d_0 is evaluated, is called z_0. In the Rz direction the miss distance is measured by the projection of the difference Δz_0 of the two z_0 values onto a direction perpendicular to the track direction. The distributions for Σd_0 and Δz_0 are shown in figure 3 and 4. The width of these distributions is $\sqrt{2}$ times the impact parameter resolution in the respective direction. From a gaussian fit one obtains a impact parameter resolution of 25 μm in the $R\phi$ and 29 μm in the Rz direction for tracks measured in all three tracking detectors. With the momentum constrained to beam energy the data show impact parameter resolutions of 17 μm and 29 μm respectively for the $R\phi$ and Rz directions to be compared with 13 and 20 μm in the Monte Carlo. The larger value in z is due to the lack of z information in the ITC. For tracks, which are only measured by ITC and TPC, the impact parameter resolutions are 107 μm in $R\phi$ and 820 μm in Rz and the momentum resolution is $\Delta p/p^2 = 0.8 \times 10^{-3}\,(\mathrm{GeV/c})^{-1}$.

5 Conclusion

The ALEPH tracking detectors were aligned internally and globally with tracks from $Z^0 \rightarrow q\bar{q}$ and $Z^0 \rightarrow \mu^+\mu^-$ decays. A momentum resolution of $\Delta p/p^2 = 0.6 \cdot 10^{-3}$ $(\mathrm{GeV/c})^{-1}$, and impact parameter resolutions of 25 μm in the $R\phi$ and 29 μm in the Rz direction were achieved for tracks reconstructed in VDET, ITC and TPC. The resulting performance is near to the design estimates of the detector.

References

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[7] E. Milotti, ALEPH Internal Note 87-63, 1987;
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Tables

Table 1: Tolerances on the alignment for an effective outer tracking

View	Radius	Resolution	Accuracy
$R\phi$	77 cm	34 μm	40 μm
Rz	105 cm	220 μm	85 μm

Table 2: Tolerances (1 σ) on VDET alignment parameters

Movement	Radial	$R\phi$	z
Shift	15 μm	7 μm	7 μm
Rotation	0.5 mrad	0.8 mrad	0.8 mrad

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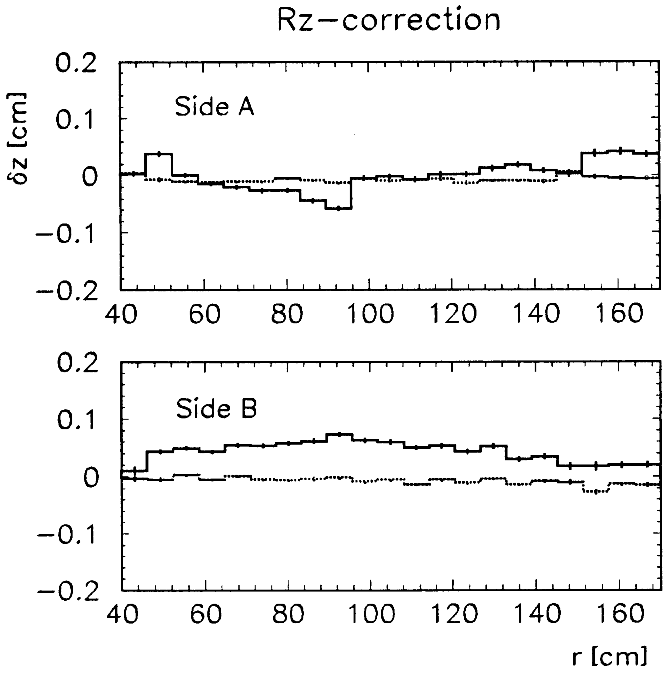

Figure 1: *Residual δz in the Rz direction as a function of the radius for TPC coordinates in the two TPC halves relative to a single helix fit, made with VDET and ITC points only, before (solid line) and after (dashed line) aligning TPC sectors in the Rz direction.*

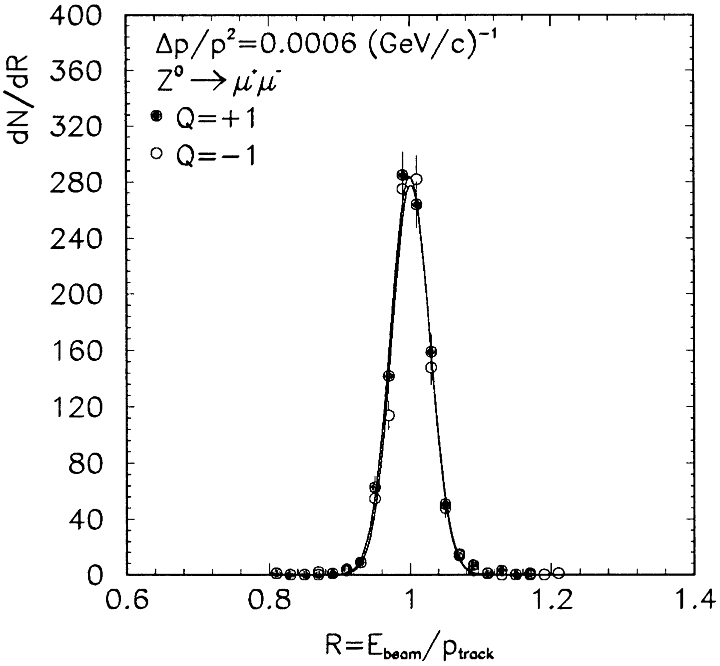

Figure 2: *The ratio beam energy over track momentum measured in the ALEPH tracking system for muons (charge Q) from $Z^0 \to \mu^+\mu^-$ decays.*

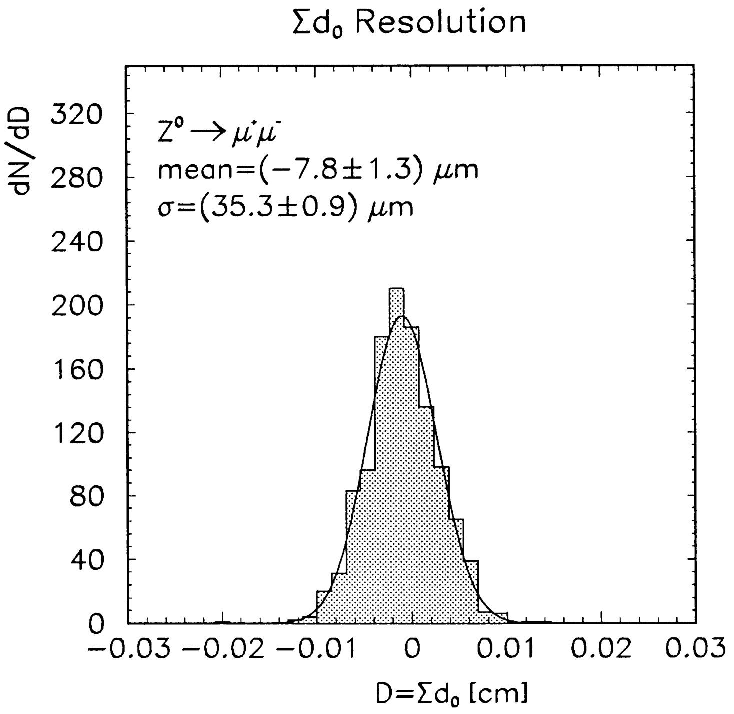

Figure 3: *Signed distance Σd_0 for $Z^0 \to \mu^+\mu^-$ decays.*

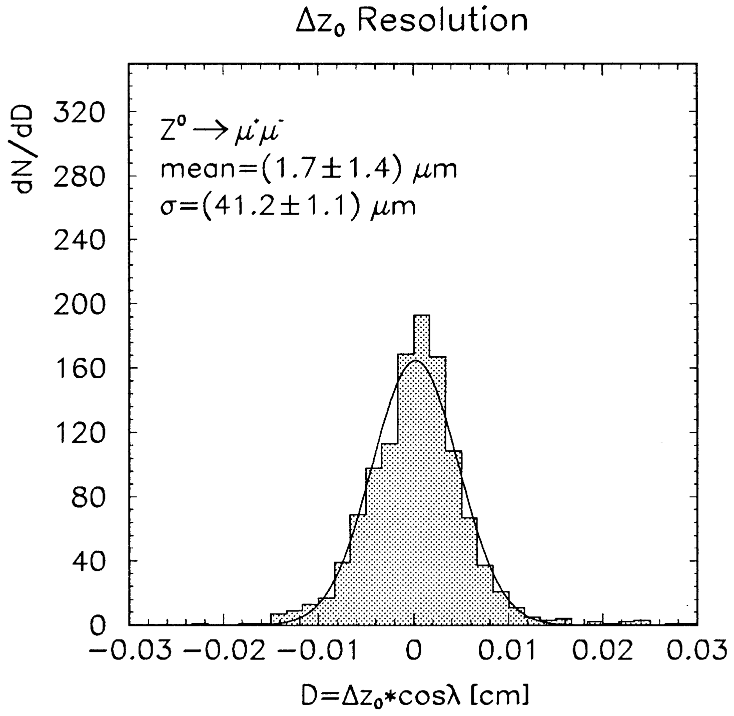

Figure 4: *Miss distance perpendicular to track direction in the Rz plane ($\Delta z_0 \cos\lambda$) for $Z^0 \to \mu^+\mu^-$ decays.*