# Distortion Corrections for the ALEPH TPC 

```
Werner did this
during }10\mathrm{ years
of LEP running
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## Overview

- Brief overview of the detector
- Historical development
- Distortion corrections for the TPC
- Tour through some problems and their correction
- Detector performances
- Summary


## The ALEPH Detector



## TPC



- $\mathrm{r} \varphi$ from pad position
- z from drift time (pads + wires)
- dE/dx from wires and pads
- Length $=4.7 \mathrm{~m}$
- Outer radius $=1.8 \mathrm{~m}$
- Total weight $=3.6 \mathrm{t}$
- Drift length $2 \times 2.2 \mathrm{~m}$
- Up to 21 space points / track
- 18 wire chambers / endplate
- 47340 channels in total
- $\mathrm{B}=15 \mathrm{kG}$
- HV (Membrane) $=-27.5 \mathrm{kV}$
- Gas
- Volume $43 m^{3}$
- Argon/Methan (91:9) at atmospheric pressure
- Angular coverage
- $2 \pi$ in $\varphi$
- 21 pad rows hit for $|\cos \Theta| \leq 0.8$
- At least 3 pad rows for $|\cos \Theta| \leq 0.97$

- r $\varphi$-resolution : $180 \mu \mathrm{~m}$
- z-resolution (pads + wires) : $500 \mu \mathrm{~m}$
- $\mathrm{dE} / \mathrm{dx}: 4.5 \%$ for Bhabha electrons

Pad size: $\delta r \varphi \times \delta r=6.2[\mathrm{~mm}] \times 30[\mathrm{~mm}]$


## Historical Development

## LEP startup 1989-1990

- Failure of magnet compensating power supplies in 1989 requires development of field correction methods
- Derived from 2 special Laser runs (B on/off)
- Correction methods described in NIM A306(1991)446
- High statics Muon pairs from Z-decay is main calibration sample


## 1991-1994 (LEP 1)

- Silicon Vertex Detector 1 becomes operational in 1991
- Development of common alignment procedures for all three tracking detectors
- Incidents affect large portions of collected statistics and require correction methods based directly on data
- 1991-1993 7 shorts on field cage affect $24 \%$ of collected data. 1994 disconnected gating grids make $20 \%$ of data unusable
- All data finally recuperated with data-based correction models


## 1994-1996 (LEP 1/2)

- Aleph Tracking Upgrade Program (Reprocessing of LEP 1 data)
- Improved coordinate determination requires better understanding of systematic effects.
- Combined calculations for field and alignment distortions in TPC. Reevaluation of B-field map.
- All methods for distortion corrections are based now directly on data
- Development of "few" parameter correction models to cope with drastically reduced calibration samples at LEP 2.
- Use high statistics LEP 1 muon pairs to make improved maps also for LEP 2


## 1995-2000 (LEP 2)

- New VDET 2 with larger acceptance (end 1995)
- Z pairs are only available in special calibration runs at begin of running period and on request from experiments after incidents. Very limited statistics compared to LEP 1.
- More frequent beam losses cause time dependent "charge up" effects in the TPC and new shorts. Both distortions are superimposed.
- For short corrections LEP delivers small amount of $Z$ pairs (~700 muon pairs) on experiment's request.
- Time dependent effects are usually present throughout the year and have to be tracked with hadrons.


## Distortion Corrections for the TPC

- Use real data : Muon pairs from Z-decays
- Prerequisite: preliminary calibration of inner tracking detectors exists already
- Global alignment e.g. from survey measurements or from previous data alignments
- Internal calibration for VDET and ITC (Can be done without TPC)
- Fit the 2 tracks of each muon pair with a common single helix
- Momentum is constrained to beam energy
- Helix parameters are determined with 4 hits from VDET and up to 16 hits from ITC. TPC is not in the track fit.

- Measure coordinate residuals in TPC respective to extrapolated single helix on 3 dimensional grid $(\Delta r \varphi, \Delta z)_{\text {obs. }}\left(r_{n}, \varphi_{n}, z_{n}\right)$

$$
\begin{aligned}
& \Delta r \varphi_{\text {observed }}=\Delta r \varphi_{\text {Fields, Aligmment }}-\frac{d_{0}}{\sqrt{r^{2}-d_{0}^{2}}} \Delta r_{\text {Fields, Alignment }} ; \\
& \Delta z_{\text {observed }}=\Delta z_{\text {Fields, Alignment }}-\frac{r}{\sqrt{r^{2}-d_{0}^{2}}} \tan \lambda \Delta r_{\text {Fields, Alignment }}
\end{aligned}
$$

$$
d_{0}=\text { Signed distance of closest approach to origin }
$$

- Compute for fields and alignment $(\Delta r \varphi, \Delta r, \Delta z)_{\text {Fiedss, Alignment }}$ from
- Potential for fields
- Coordinate transformation equations for alignment

$$
\Rightarrow \Delta r \varphi_{\text {Fields, Alignment }}(r, \varphi, z)=\sum_{i} \Delta \widehat{r \varphi}_{i}(r, \varphi, z) \cdot A_{i}
$$

- Solve (overdetermined) system of linear equations for unknown parameters $A_{i}$

$$
\|\left(\begin{array}{c}
\Delta r \varphi_{\text {obs }}\left(r_{1}, \varphi_{1}, z_{1}\right) \\
\Delta z_{\text {obs }}\left(r_{1}, \varphi_{1}, z_{1}\right) \\
\vdots \\
\Delta r \varphi_{\text {obs }}\left(r_{N}, \varphi_{N}, z_{N}\right) \\
\Delta z_{\text {obs }}\left(r_{N}, \varphi_{N}, z_{N}\right)
\end{array}\right)-\left(\begin{array}{ccc}
\Delta \widehat{r \varphi}_{1}\left(r_{1}, \varphi_{1}, z_{1}\right) & \cdots & \Delta \widehat{r \varphi}_{M}\left(r_{1}, \varphi_{1}, z_{1}\right) \\
\Delta \hat{z}_{1}\left(r_{1}, \varphi_{1}, z_{1}\right) & \cdots & \Delta \hat{z}_{M}\left(r_{1}, \varphi_{1}, z_{1}\right) \\
\vdots & & \vdots \\
\Delta \widehat{r \varphi}_{1}\left(r_{N}, \varphi_{N}, z_{N}\right) & \cdots & \Delta \widehat{r \varphi}_{M}\left(r_{N}, \varphi_{N}, z_{N}\right) \\
\Delta \hat{z}_{1}\left(r_{N}, \varphi_{N}, z_{N}\right) & \cdots & \Delta \hat{z}_{M}\left(r_{N}, \varphi_{N}, z_{N}\right)
\end{array}\right) \cdot\left(\begin{array}{c}
A_{1} \\
\vdots \\
\left.A_{M}\right)
\end{array} \|=\boldsymbol{M i n}\right.
$$

- Solve system of linear equations with Singular Value Decomposition (SVD) (e.g. Numerical Recipes, Cambridge University Press)
- SVD can cope with linear dependencies in function matrix. Solution has from all possibilities the smallest length.

$$
\|\vec{A}\|=\text { Min }
$$

SVD provides for each parameter a weight which allows to identify insignificant parameters to the problem (i.e. remove all parameters with weight < threshold)

## Ansatz for $(\Delta \widehat{\boldsymbol{r} \varphi}, \Delta \hat{r}, \Delta \hat{z})_{\text {Fields }}$

- Start with Potential

$$
\begin{gathered}
\Phi_{E}=U_{0}\left(1-\frac{|z|}{z_{M}}\right)-U_{0} \tilde{\Phi}_{E}(r, \varphi, z) ; \quad U_{0} \simeq-27 k V ;\left|\tilde{\Phi}_{E}(r, \varphi, z)\right| \ll 1 ; \quad \text { E-Field } \\
\Phi_{B}=-B_{z}^{0} z-B_{z}^{0} z_{M} \tilde{\Phi}_{B}(r, \varphi, z) ; B_{z}^{0} \simeq 15 k G ;\left|\tilde{\Phi}_{B}(r, \varphi, z)\right| \ll 1 ; \quad B-\text { Field }
\end{gathered}
$$

- Calculate solutions for Laplace equation for double cylinder

$$
\Delta \Phi=0 ; \rightarrow \Phi=\sum_{i j} a_{i j} \Phi_{i j}(r, \varphi, z) ;
$$

- Compute

$$
\vec{E}=-\nabla \Phi_{E} \quad ; \quad \vec{B}=-\nabla \Phi_{B}
$$

- Compute distortions from Langevin equation

$$
\begin{aligned}
& \vec{v}=\frac{\mu}{1+(\omega \tau)^{2}}\left(\vec{E}+(\omega \tau) \frac{\vec{E} \times \vec{B}}{|\vec{B}|}+(\omega \tau)^{2} \frac{\vec{B}(\vec{E} \cdot \vec{B})}{\vec{B}^{2}}\right) \\
& \Delta \widehat{r \varphi}_{E}=\frac{1}{1+(\omega \tau)^{2}} \int_{z}^{z_{\mu}}\left(\frac{E_{\varphi}}{E_{z}}-(\omega \tau) \operatorname{sign}\left(B_{z}\right) \frac{E_{r}}{E_{z}}\right) d z ; \quad \Delta \hat{r}_{E}=\frac{1}{1+(\omega \tau)^{2}} \int_{z}^{z_{\mu}}\left(\frac{E_{r}}{E_{z}}-(\omega \tau) \operatorname{sign}\left(B_{z}\right) \frac{E_{\varphi}}{E_{z}}\right) d z ; \\
& \Delta \widehat{r \varphi}_{B}=\frac{(\omega \tau)}{1+(\omega \tau)^{2}} \int_{z}^{z_{\mu}}\left((\omega \tau) \frac{B_{\varphi}}{B_{z}}-\frac{B_{r}}{\left|B_{z}\right|}\right) d z ; \quad \Delta \hat{r}_{B}=\frac{(\omega \tau)}{1+(\omega \tau)^{2}} \int_{z}^{z_{\mu}}\left((\omega \tau) \frac{B_{r}}{B_{z}}-\frac{B_{\varphi}}{\left|B_{z}\right|}\right) ; \\
& r(z) \simeq r+\frac{\partial r}{\partial z} \delta z ; \varphi(z) \simeq \varphi+\frac{\partial \varphi}{\partial z} \delta z ;\left|\frac{\partial r}{\partial z},\left|\frac{\partial \varphi}{\partial z}\right| \ll 1\right.
\end{aligned}
$$

$$
E_{z}(r, \varphi, z) \simeq E_{z}^{0}= \pm \frac{U_{0}}{z_{M}} ; \quad B_{z}(r, \varphi, z) \simeq B_{z}^{0}
$$

## Characteristics of Solutions

- Solution by separation of variables. 3 classes of solutions corresponding to choice of separation variable $k^{2}$
- $k^{2}=0$

$\tilde{\Phi}_{0}=\ln \left(\frac{r}{r_{o}}\right)\left(A_{0}\left(\frac{z}{z_{M}}\right)+B_{0}\right)$;
$\tilde{\Phi}_{v}=\left(\frac{r}{r_{o}}\right)^{v} \sin (v \varphi)\left(A_{v}\left(\frac{z}{z_{M}}\right)+B_{v}\right)+\left(\frac{r}{r_{o}}\right)^{v} \cos (v \varphi)\left(C_{v}\left(\frac{z}{z_{M}}\right)+D_{v}\right) ; v= \pm 1 \ldots \pm \infty ;$
- $k^{2}>0$


$$
\begin{gathered}
\Psi_{v m}\left(\lambda_{v m} r\right)=\left|\begin{array}{cc}
J_{v}\left(\lambda_{v m} r_{i}\right) & N_{v}\left(\lambda_{v m} r_{i}\right) \\
J_{v}\left(\lambda_{v m} r\right) & N_{v}\left(\lambda_{v m} r\right)
\end{array}\right| ; \Psi_{v m}\left(\lambda_{v m} r_{i}\right)=\Psi_{v m}\left(\lambda_{v m} r_{o}\right)=0 ; \\
v=0 \ldots \infty ; m=1 \ldots \infty ;
\end{gathered}
$$

- $k^{2}<0$

$$
\begin{aligned}
& \tilde{\Phi}_{v m}=\binom{P_{v m, F C o u t}\left(\lambda_{m} r\right)}{P_{v m, F C i n}\left(\lambda_{m} r\right)}\left(A_{v m} \sin (\nu \varphi)+B_{v m} \cos (\nu \varphi)\right) \sin \left(\lambda_{m} z\right) ; \\
& P_{v m, F C o u t}\left(\lambda_{m} r\right)=\frac{\left|\begin{array}{ll}
I_{v}\left(\lambda_{m} r\right) & I_{v}\left(\lambda_{m} r_{i}\right) \\
K_{v}\left(\lambda_{m} r\right) & K_{v}\left(\lambda_{m} r_{i}\right)
\end{array}\right|}{\left|\begin{array}{ll}
I_{v}\left(\lambda_{m} r_{o}\right) & I_{v}\left(\lambda_{m} r_{i}\right) \\
K_{v}\left(\lambda_{m} r_{o}\right) & K_{v}\left(\lambda_{m} r_{i}\right)
\end{array}\right|} ; P_{v m, F C i n}\left(\lambda_{m} r\right)=\frac{\left|\begin{array}{ll}
I_{v}\left(\lambda_{m} r\right) & I_{v}\left(\lambda_{m} r_{o}\right) \\
K_{v}\left(\lambda_{m} r\right) & K_{v}\left(\lambda_{m} r_{o}\right)
\end{array}\right|}{\left|\begin{array}{ll}
I_{v}\left(\lambda_{m} r_{i}\right) & I_{v}\left(\lambda_{m} r_{o}\right) \\
K_{v}\left(\lambda_{m} r_{i}\right) & K_{v}\left(\lambda_{m} r_{o}\right)
\end{array}\right|} ; \\
& \lambda_{m}=\frac{m \pi}{z_{M}} ; v=0 \ldots \infty ; m=1 \ldots \infty ;
\end{aligned}
$$

## Greensfunction

$$
\Delta_{\vec{x}} G(\vec{x}, \hat{\vec{x}})=-4 \pi \delta(\vec{x}-\hat{\vec{x}}) ; \quad G(\vec{x}, \hat{\vec{x}})=0 ; \vec{x}, \hat{\vec{x}} \in \text { Boundary }
$$

Solution with Ansatz: $\quad G(\vec{x}, \hat{\vec{x}})=\sum_{\Lambda} a_{A}(\hat{\vec{x}}) U_{\Lambda}(\vec{x})$;

$$
\Rightarrow \quad G(\vec{x}, \hat{x})=4 \pi \sum_{\Lambda} \frac{1}{\Lambda^{2}} U_{\Lambda}(\hat{\vec{x}}) U_{\Lambda}(\vec{x}) ;
$$

$U$ fulfills Helmholtz equation :

$$
\begin{gathered}
\Delta U_{\Lambda}+\Lambda^{2} U_{\Lambda}=0 ; \quad U_{\Lambda}(\vec{x})=0 ; \quad \vec{x} \in \text { Boundary } \\
U_{\Lambda_{v m}}(r, \varphi, z)=\frac{1}{N_{v m n}} \Psi_{v m}\left(\lambda_{v m} r\right)\binom{\sin (v \varphi)}{\cos (v \varphi)} \sin \left(\frac{n \pi}{z_{M}} z\right) ; \quad \Lambda_{v m n}^{2}=\lambda_{v m}^{2}+\left(\frac{n \pi}{z_{M}}\right)^{2} ;
\end{gathered}
$$

## Ansatz for $(\Delta \widehat{\boldsymbol{r} \varphi}, \Delta \hat{r}, \Delta \hat{z})_{\text {Alignment }}$

- Transformation from measured TPC coordinate to global ALEPH coordinate

$$
\overrightarrow{\mathcal{X}}_{\aleph}=A_{3}\left(A_{2}\left(A_{1} \vec{x}_{T P C}+\vec{t}_{1}\right)+\vec{t}_{2}\right)+\vec{t}_{3} \quad \begin{aligned}
& \text { 1. TPC sector frame } \rightarrow \text { TPC endplate frame } \\
& \text { 2. TPC endplate frame } \rightarrow \text { TPC frame } \\
& \text { 3. TPC frame } \rightarrow \text { Aleph global coordinate system }
\end{aligned}
$$

- Compute $\Delta \vec{x}_{\aleph}$ as function of small variations of $\left(A_{i}, \vec{t}_{i}\right)$

$$
\begin{aligned}
\text { e.g. } A_{2} & =R_{x} R_{y} R_{z} ; \Rightarrow \Delta A_{2}=9 T_{x} R_{x} R_{y} R_{z}+\delta R_{x} T_{y} R_{y} R_{z}+\phi R_{x} R_{y} T_{z} R_{z} ; \\
R_{x, y, z} & =\text { Rotations of } \operatorname{SO}(3), T_{x, y, z}=\text { Generators of Lie Algebra of } S O(3)
\end{aligned}
$$

- Apply boundary conditions to alignment parameters, e.g endplate alignment should not move complete TPC

- Alignment and field corrections are not independent
- e.g tilt of "perfect TPC" relative to B-field axis causes transverse drift velocities

- e.g bowing of the TPC endplate requires alignment and E-field



## Remarks

- There are other corrections (e.g. timing shifts in hardware) which may interfere with the above corrections.
- With the single helix fit residuals can only be measured in a limited acceptance region, i.e.
- Field and alignment corrections can not always be distinguished. The solution may be not unique.
- Fit matrix can be therefore almost degenerate ( $\rightarrow$ SVD).
- "External" information helps in guiding the fit.


- Direct fitting of Fourierseries for field distortions is avoided
- Slow convergence = many coefficients needed
- Practical problems for numerical solutions
- Does not allow to identify the contributing distortions
- Normally a simple parameterised potential on the boundary is constructed and transformed via the Greensfunction in a parameterised distortion map (see examples later)
- The calibration is done iteratively (typically 2 iterations)

- Inner detector movements over time are monitored externally and are corrected for the final calibration

VDET movements recorded by the VDET laser system for the years 1998 to 2000






Fourieranalysis

- Powerspectrum from measured residuals
- No corrections applied to data
- $v=0$ : fields ( $\mathrm{E}-$ and B-map needed)
- $v=1$ : mainly global alignment
- $v>1$ : mainly internal alignment (e.g. sector alignment)

Data without corrections



## Tour through some problems and their correction

- Static problems (always there)
- TPC tilt
- Endplate bowing
- Nonlinear potential on fieldcage
- Single incidents
- Disconnected gating grids (space charge)
- Shorts on field cage
- Time dependent effects
- "Charge up" effects


## Tilt of TPC

$\Delta r \varphi(r, \varphi, z)=r \phi_{G}-(\delta x)_{G} \sin \varphi+(\delta y)_{G} \cos \varphi-\operatorname{sign}(z) z_{M}\left(\delta_{G} \sin \varphi+\vartheta_{G} \cos \varphi\right)$

- Example for coupling of field and alignment corrections
- Tilt already seen in survey measurements
- Confirmed with cosmic run (low statistics)
- Data were used to improve the previous measurements and to monitor time dependence



## Bowing of TPC endpaltes

$$
\Delta z_{\text {obs }}=\Delta z_{\text {Alignment }}-\left(\Delta r_{\text {Field }}+\Delta r_{\text {Alignment }}\right) \tan \lambda
$$

- Discovered after installation of VDET 1
- Endplate bows outward (TPC has slight overpressure)
- Main effect
$\sim 1 \mathrm{~mm}$ bowing
- Small variation with time
- Coupling of alignment and field corrections (phi dependence from sectors)



## Alignment

$$
\Delta z(r, \varphi)=\sum_{S}\left(\vartheta_{S} r \sin \left(\varphi-\bar{\Phi}_{S}\right)+\delta_{S}\left(R_{S}-r \cos \left(\varphi-\bar{\Phi}_{S}\right)\right)+(\delta z)_{s}\right) ;
$$

Endplate is equipotential surface

$$
\Phi\left(r, \varphi, z_{M}+\Delta z(r, \varphi)\right)=0 ; \Rightarrow \tilde{\Phi}\left(r, \varphi, z_{M}\right) \simeq-\frac{\Delta z(r, \varphi)}{z_{M}}
$$

Distortionpotential

$$
\begin{array}{r}
\tilde{\Phi}(r, \varphi, z)=-\sum_{v m} \frac{1}{2 N_{v m}^{2}}\left(A_{v m} \sin v \varphi+B_{v m} \cos v \varphi\right) \Psi_{v m}\left(\lambda_{v m} r\right) \frac{\sinh \left(\lambda_{v m} z\right)}{\sinh \left(\lambda_{v m} z_{M}\right)} \\
\binom{A_{v m}}{B_{v m}}=\int_{r_{i}}^{r_{0}} \int_{0}^{2 \pi} \Delta z(r, \varphi) \Psi_{v m}\left(\lambda_{v m} r\right)\binom{\sin v \varphi}{\cos v \varphi} r d r d \varphi ;
\end{array}
$$

## Nonlinear Potential on Field Cage

Possible sources

- Manufacturing errors on electrodes
- Nonlinear resistor chain
- Finite resistivity of FC insulator


Insulator

- Helically wound Mylar $75 \mu \mathrm{~m}$ thick
- 100 mm pitch inner FC, 200 mm pitch outer FC
- Foils glued with Hexel 6103 ( $20 \mu \mathrm{~m}$ thick)


## Finite Field Cage Resistivity

Potential on Field Cage Surface

$$
\Phi\left(r_{F C}, \varphi, z\right)=U_{0} \frac{\sinh \left(\sqrt{\frac{R_{t o t}}{R_{B}}}\left(1-\frac{|z|}{z_{M}}\right)\right)}{\sinh \left(\sqrt{\frac{R_{t o t}}{R_{B}}}\right)} ;
$$



Distortionpotential

$$
\tilde{\Phi}\left(r_{F C}, \varphi, z\right)=\left(1-\frac{|z|}{z_{M}}\right)-\frac{\sinh \left(\sqrt{\left.\frac{R_{t o t}}{R_{B}}\left(1-\frac{|z|}{z_{M}}\right)\right)}\right.}{\sinh \left(\sqrt{\frac{R_{t o t}}{R_{B}}}\right)} ;
$$

$$
\tilde{\Phi}(r, \varphi, z) \simeq-\operatorname{sign}(z) \frac{R_{\text {Tot }}}{R_{B}} \sum_{n} \frac{1}{(n \pi)^{3}} \sin \left(\frac{n \pi}{z_{M}} z\right) P_{0,(\text { FCout, } F C \text { Cin })}\left(\frac{n \pi}{z_{M}} r\right) ;
$$

- Results from fit can be interpreted as potential deviation or axial shift of electrodes
- Fit prefers $\rho \simeq 10^{16}[\Omega \mathrm{~cm}]$





## Correction for nonlinear potential + endplate bowing






## Disconnected Gating Grids

- In 1994 the gating grids of 2 sectors got disconnected
- $\sim 10 \%$ of collected statistics affected
- Endplate potential changes
- Ions escape into TPC volume (spacecharge)
- Distortions depend on azimuthal angle and on current



Correction: Fit directly Fourier expansion of Poisson equation :


$$
\Lambda_{v m m}^{2}=\lambda_{v m}^{2}+\left(\frac{n \pi}{z_{m}}\right)^{2} ;
$$

$U_{\Lambda_{v m n}}(r, \varphi, z)=\frac{1}{N_{v m n}} \Psi_{v m}\left(\lambda_{\nu m} r\right)\binom{\sin (\nu \varphi)}{\cos (\nu \varphi)} \sin \left(\frac{n \pi}{z_{M}} z\right) ; \sum_{z[c m]}^{-200}$

## Data 1994



## Short on Field Cage

- History
- First one end of 1991 ( $\sim 13 \%$ of collected data affected)
- Sharp edge on electrode damaged FC insulator
- During repair carbon fibres were introduced in the TPC volume
- 1992: series of 5 shorts ( $\sim 41 \%$ of collected data affected)
- 1993: 1 short ( $\sim 10 \%$ of collected data affected)
- July 1999: short after beam loss (~58\% of collected data affected)
- Appears just before LEP ramps CM energy to 200 GeV
- August-September 2000: short appears after beam loss and disappears after a second one ( $\sim 15 \%$ of collected data affected)
- Higgshunt
- Appear typically after beam loss
- $R \varphi$ - residuals in TPC $\sim 1$ [mm] $\Rightarrow$ severe impact on tracking
- Except for the 1991 short all shorts are due to introduced carbon fibres
- Short may disappear again $(1992,2000)$
- Position of fibre may change after a new beam loss (e.g. 1992)
- Fibre may be not found or at a different place during a TPC opening = short position not necessarily known from intervention $\Rightarrow$ corrections from data are essential
- At LEP2 shorts were always accompanied by time dependent "charge up effects" on inner FC
$\Rightarrow$ need for parameterised model to disentangle both effects in data



Fibre found at $\mathrm{z}=36 \mathrm{~cm}$

## Intervention during 1999 shutdown



$$
\tilde{\Phi}(r, \varphi, z) \simeq \operatorname{sign}\left(z_{S}\right)\left(\frac{\Delta U_{0}}{U_{0}}\right) \sum_{n} \frac{\cos \left(\frac{n \pi}{z_{M}} z_{S}\right)}{n \pi} \sin \left(\frac{n \pi}{z_{M}} z^{n}\right) P_{\text {On, } F F C i n}\left(\frac{n \pi}{z_{M}} r\right)
$$



Short 1999 : Fit with all tracking detectors


## "Charge up" effects on Field Cage

- History
- First observed 1992 after a beamloss which caused also a short
- At LEP2 observed every year (beam losses were more frequent)
- Characteristics
- Effect on inner FC, near interaction point , $\Delta \mathrm{r} \varphi \sim 200$ [ $\mu \mathrm{m}$ ] at inner padrows
- Residuals depend on time, decaytime ~ month
- No convincing azimuthal dependence observed
- Impact on physics: mainly bias on impact parameter
- Source: unknown
- Corrections can not be done with $\mu$-pairs at LEP2 $\rightarrow$ not enough statistics to follow time evolution




- Model parameters
- Position $z_{0}\left(\varphi_{0}\right)$
- Width $z_{w,}\left(\hat{\varphi}_{w}\right)$
- $\Delta V$
- Data are binned in time intervals and fitted with model


Distortionpotential (independent of $\varphi$ )

$$
\tilde{\Phi}(r, \varphi, z) \simeq \sum_{i, n}\left(\frac{\Delta V_{i}}{U_{0}}\right) \frac{-2 \sin \left(\frac{n \pi}{z_{M}} z_{0, i}\right) \sin \left(\frac{n \pi}{z_{M}} z_{w, i}\right)}{n \pi} \sin \left(\frac{n \pi}{z_{M}} z\right) P_{0 n, F C i n}\left(\frac{n \pi}{z_{M}} r\right) ;
$$

## TPC Lasersystem


inner field cage


Data 1997: $R \phi$ residuals 4 inner TPC padrows






- Corrections fitted with Hadrons in time slices
- Result tested with muon pairs



## Tracking Spectrometer Resolutions

- All data are from 1997 to 2000
- Calibration data
- Muon pairs taken at Z with no known detector problem
- High statistics
- Represent optimal resolutions
- Calibration data for corrections of TPC problems are shown separately
- High energy muon pairs
- Include also all periods with detector problems (e.g. shorts)
- Low statistics
- Test corrections obtained at Z or with Hadrons


## Impact Parameter Resolution

Calibration Data


## Impact Parameter Resolution

High Energy Data



## Momentum Resolution

## Calibration Data



High Energy Data


## Momentum Resolution



Resolutions for different beam energies (high energy data)




## Calibration Data for TPC Problems

Impact Parameter


Calibration data for TPC problems after correction $=$ most pessimistic case


| $\begin{array}{ll} \frac{x}{0}_{1}^{1200} \\ z_{0}^{1200} \end{array}$ | Constant <br> Mean <br> Sigma | $\mathbf{5 2 6 . 6} \pm$ $-0.4903 \mathrm{E}-04 \pm$ $\mathbf{0 . 5 2 6 0 E - 0 3} \pm$ | 12.09 $0.8936 \mathrm{E}-05$ $0.8030 \mathrm{E}-05$ |
| :---: | :---: | :---: | :---: |
| 1000 800 | $\begin{aligned} & \mathbf{Z}^{0} \rightarrow \mu^{+} \mu^{-} \\ & <\mathbf{E}_{\text {Beam }}>=45.6 \mathrm{GeV} \\ & \bullet \mathbf{Q}=+1 \\ & Q=-1 \end{aligned}$ | $5.3$ | $0^{-4}$ |


$23.6 \mu \mathrm{~m}$


Momentum

## Summary

- Mathematical distortion correction models with only a small number of free parameters and mainly data driven correction methods allowed
- to understand the different distortion contributions
- to cope with limited calibration samples (e.g. at LEP 2)
- to recuperate large portions of data which were affected by incidents
- to follow time dependent effects
- to maintain the spectrometer resolutions throughout the running periods
- Muon pairs from $Z$ decays with its kinematic constraints provided a unique reaction to measure residual distributions in the TPC directly with data
- no a priori assumptions about TPC distortions (>< "Hadron fit")
- limits the application of some of the correction methods in other environments besides unbiased residual distributions can be obtained with other methods

