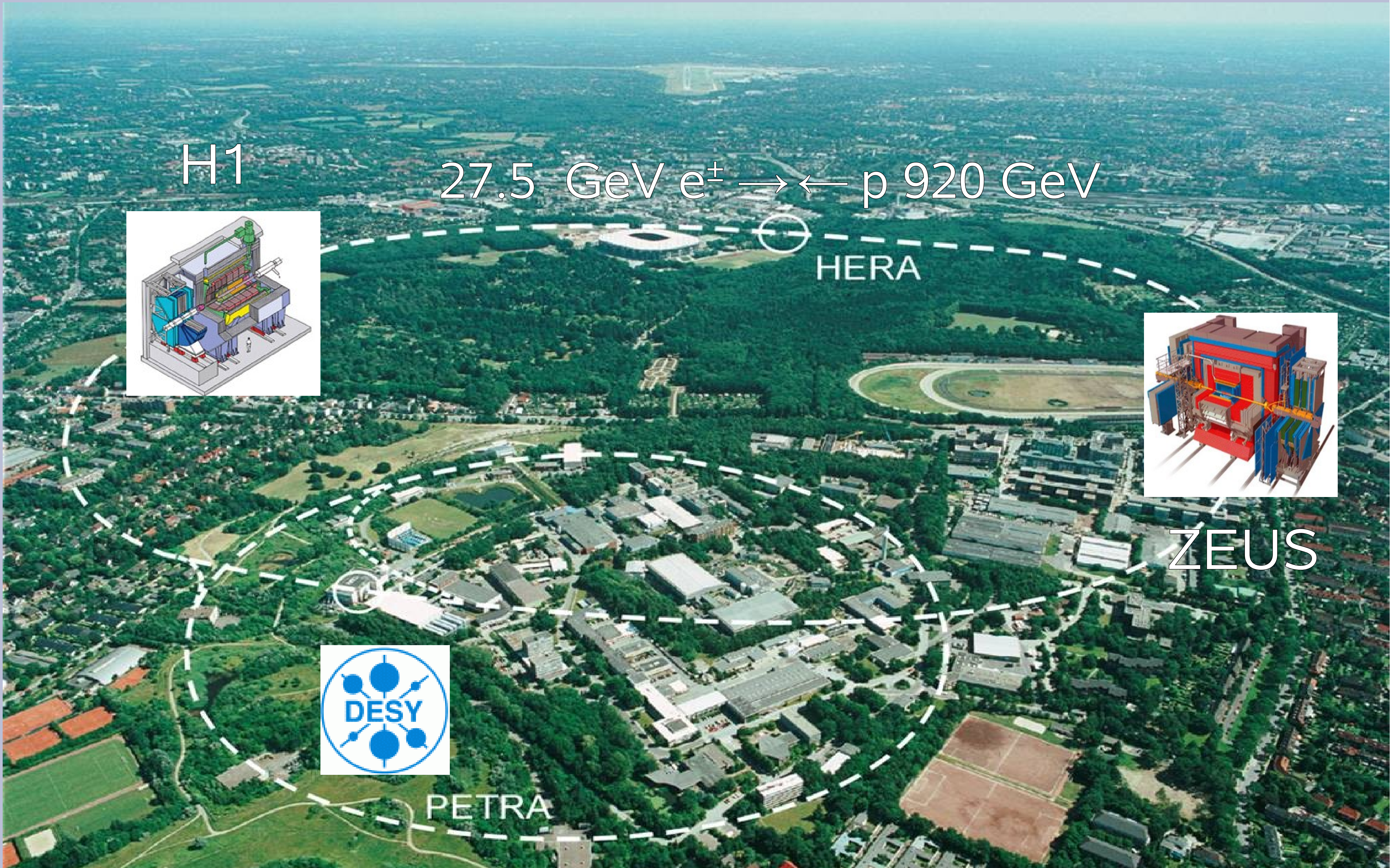
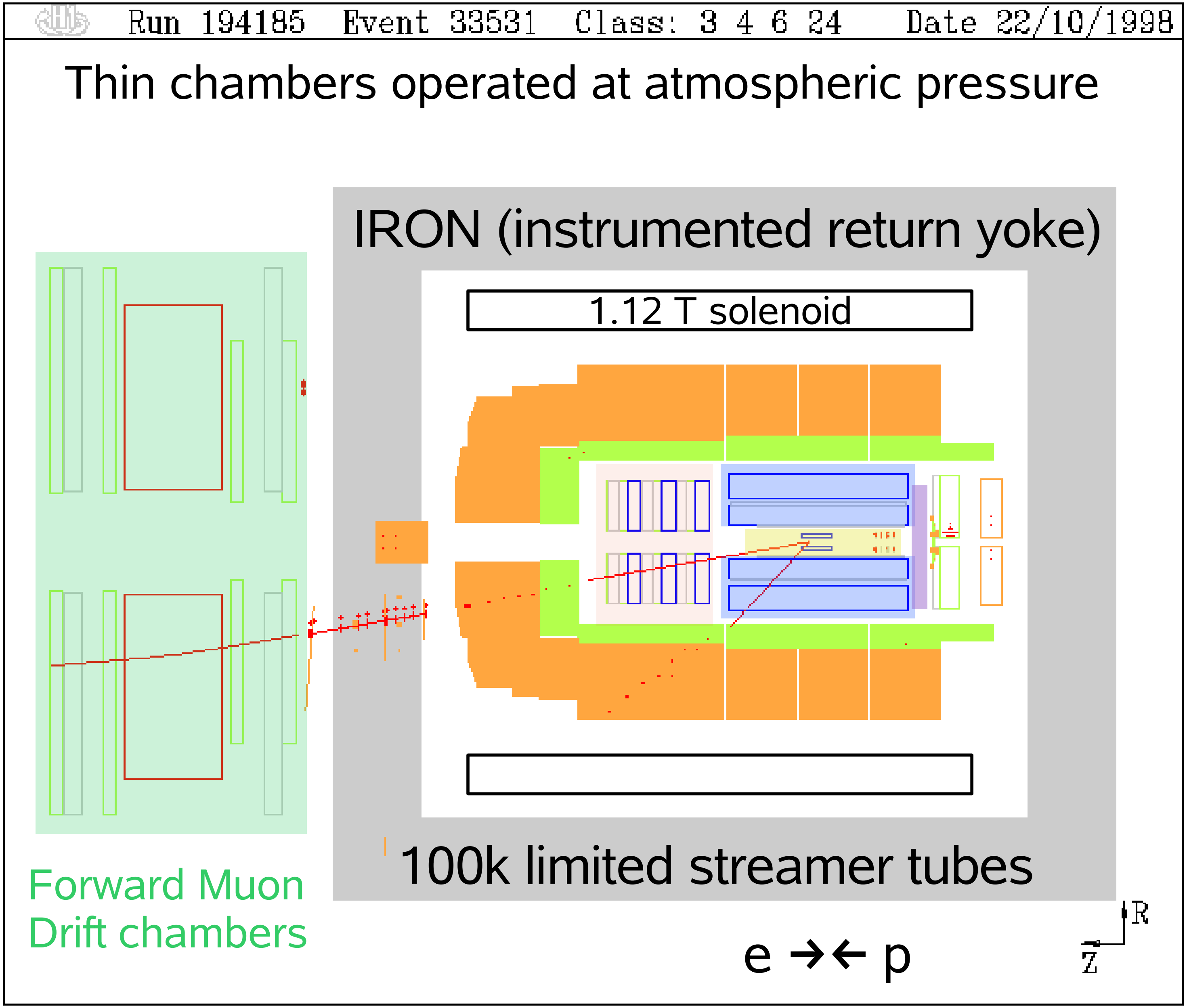
ZEUS/H1 Alignment Experiences



Overview

- H1 (C. K.)
  - H1 Trackers
  - History
  - Alignment Overview
  - Repro2k
    - HERA I Central tracker alignment and calibration
  - Constants management
- ZEUS (R. Mankel)
  - ZEUS tracking system
  - Micro Vertex Detector
    - Laser Alignment
    - Cosmic muon alignment
    - ep collision alignment
  - Physics application $\tau(D^+)$
- Summary

H1 Trackers



Thin chambers operated at atmospheric pressure

IRON (instrumented return yoke)

1.12 T solenoid

100k limited streamer tubes

Forward Muon
Drift chambers

e → ← p

Forward Tracker
Drift chambers

Central Tracker
Drift chambers
(Jet, Z)

Silicon Tracker
Strips
forward, central, backward

Backward Tracker
Drift, prop. chamb.

History

- Designed, built 15-20 years ago,
  mainly drift chambers ("analog") ⇒ tracking optimization
  = alignment (geometry) ⊕ calibration (time to distance)
- Later Silicon Strips added ("digital")
- Usually small group of people per tracker for installation, operation, maintenance, online software and calibration, offline software and calibration and alignment ⇒ priorities in this (decreasing) order
- At end of HERA-I coordinated (al.+cal.) effort (99-01) for reprocessing of HERA-I data, concentration on central trackers ("Repro2k")

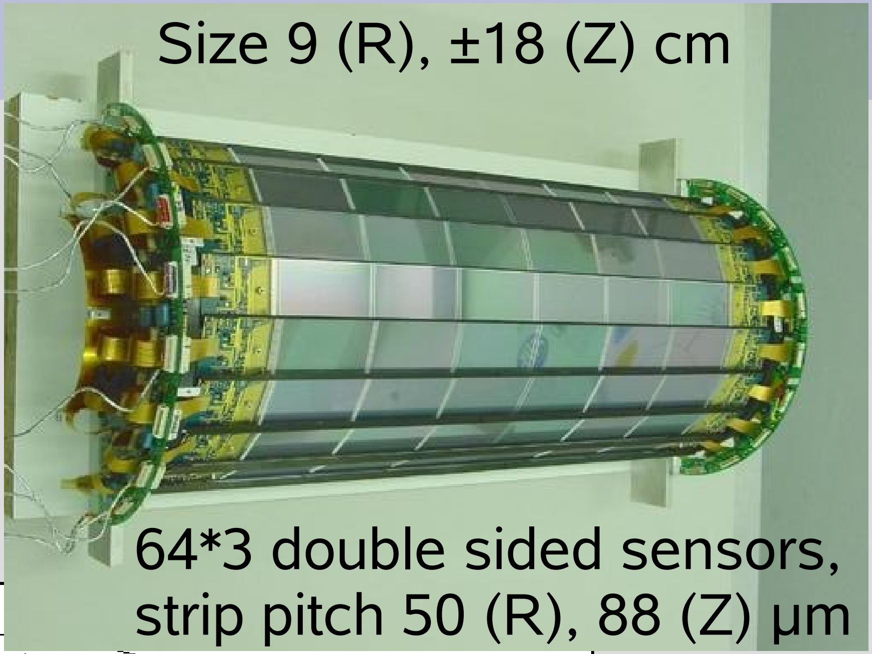
Alignment Overview – Data sets

- Survey from construction, installation
- Tracks from ep interaction
- Tracks from cosmic ray muons ("cosmics")
  - Dominant source for high p_t (several GeV) tracks, 10-20 Hz in central tracker
  - Easy possible to vary detector parameter (B, E, ..)
  - Different phase space (ϕ, θ, z_0, dca, flight (time) direction)
    - At begin: difficult, problematic
    - At end: opportunity for cross checks

Alignment Overview - Methods

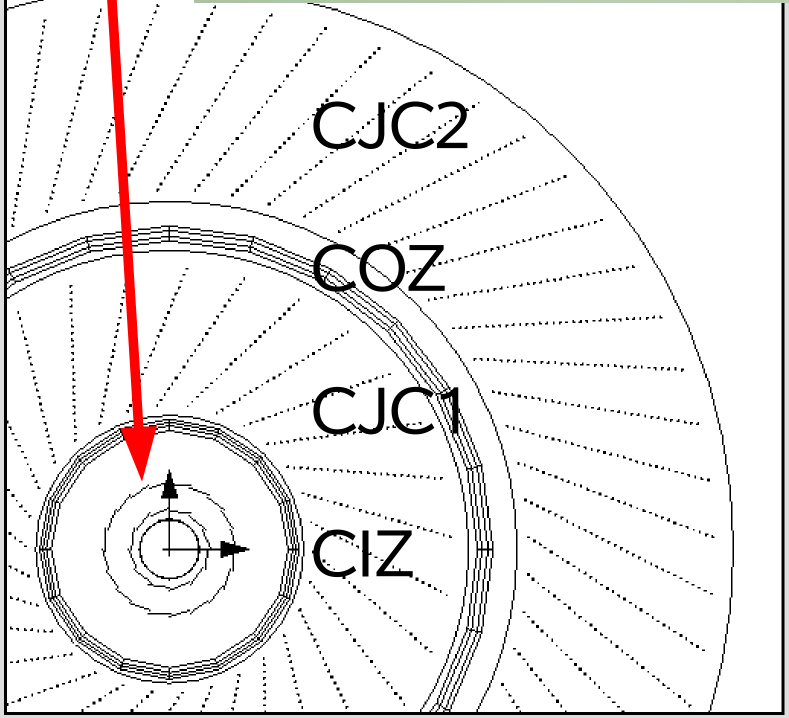
- Internal
  - Cosmics at B=0, relative alignment of detector parts: forward muon, forward tracker, IRON
- External (to central tracker)
  - Cosmics, use extrapolated central tracks: IRON
  - Scattered e, use event vertex, central tracks: backward tracker cross check with kinematic constraints (E/p, ..)
  - ep tracks, compare track parameter: forward tracker
  - Any track, Kalman filter with vertex, central space points: forward/backward silicon
- Combined
  - Any track, millepede, alignment and calibration: central silicon tracker (CST), Jet (CJC), Z chambers (CIZ/COZ)

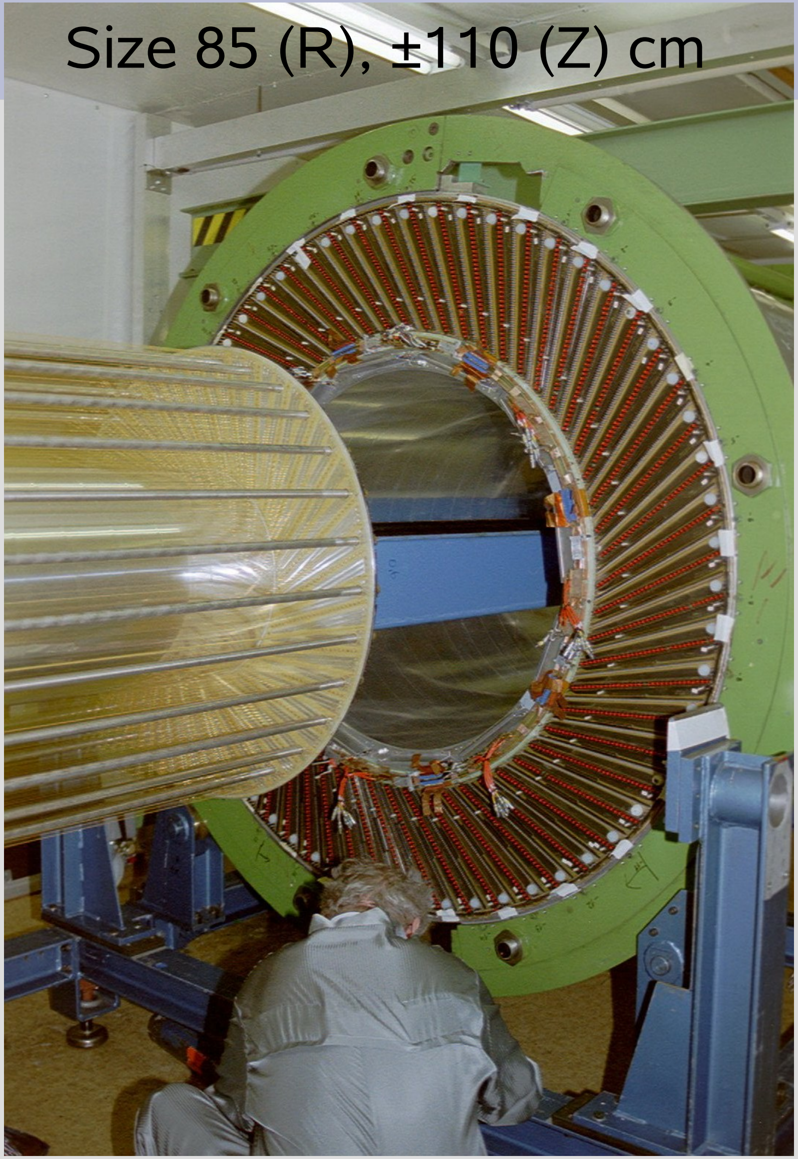
Central Trackers



Size 9 (R), ±18 (Z) cm

64*3 double sided sensors, strip pitch 50 (R), 88 (Z) µm





Size 85 (R), ±110 (Z) cm

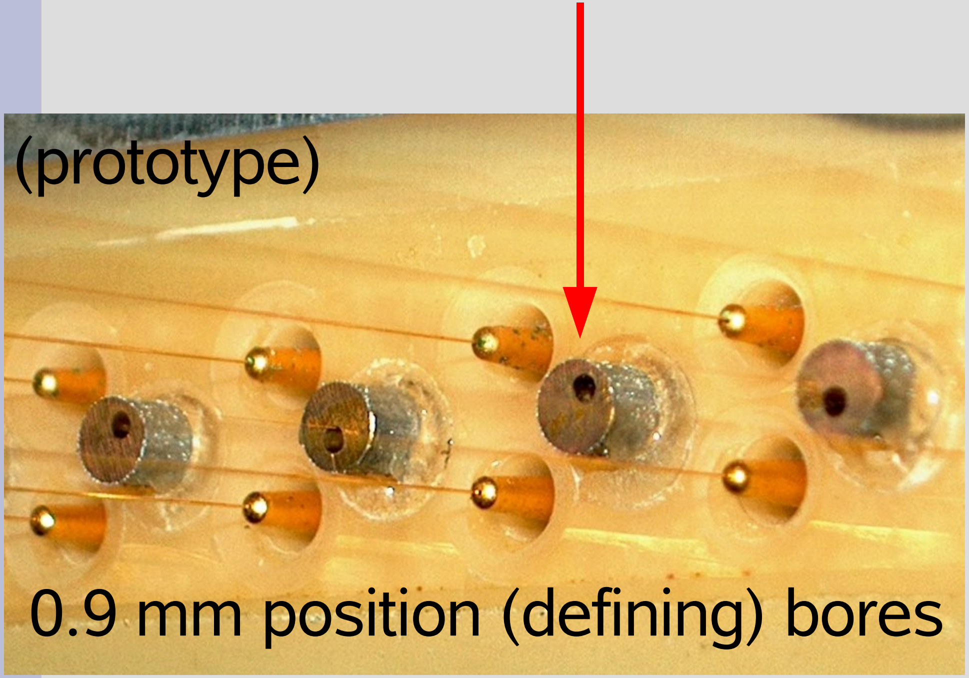
2640+160 double ended wires, resolution few 100 µm (drift) ⊗ several cm (charge division)

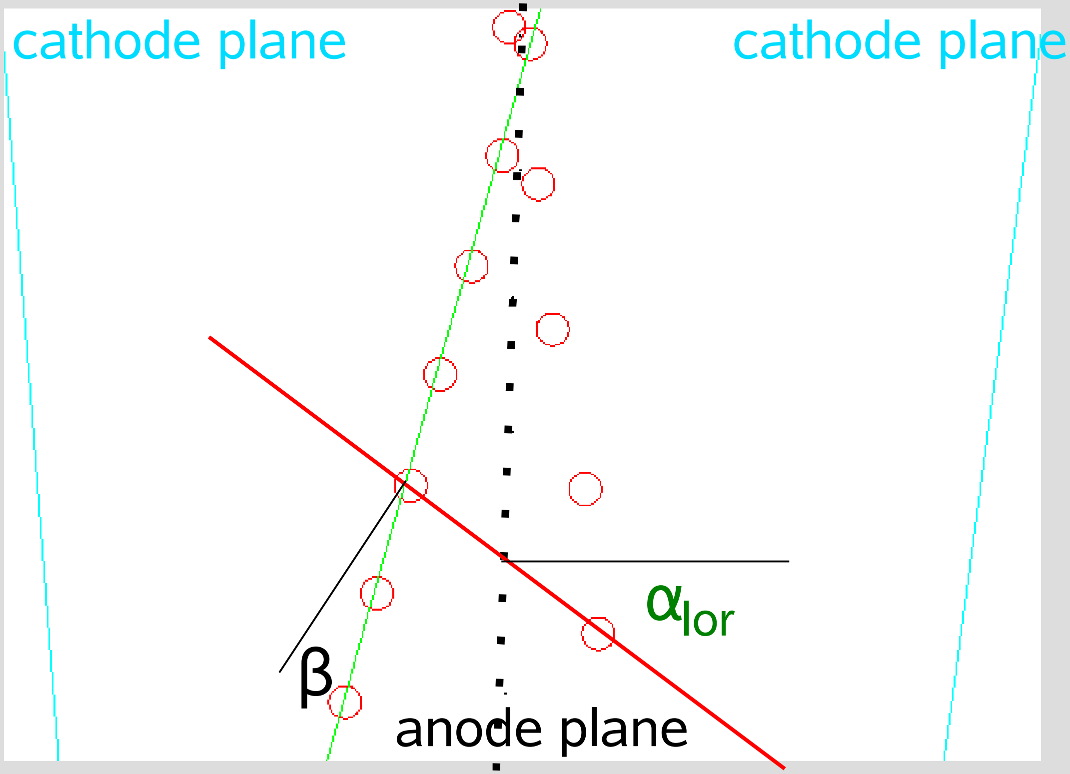
Repro2k

- Calibration and alignment directions: subdetector
  - In details: local corrections, stable
  - As whole: stability (temperature, pressure, ..)
- Rϕ calibration and alignment: CJC/CST
  - Rϕ measurement in CJC, CST
  - Millepede setup
  - Millepede operation
- ZS calibration and alignment: CIZ/COZ/CST
- CJC charge calibration: ZS, dE/dx
- Conclusion
- Refinements

CJC Rϕ measurement (1)

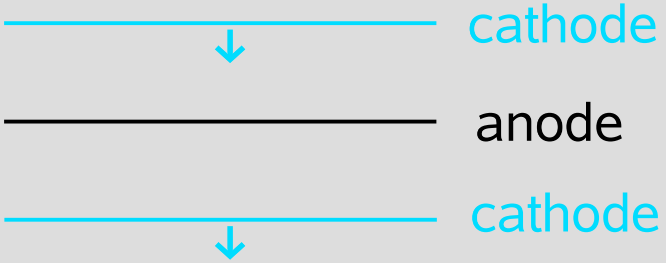
- Drift distance from time
  - $d = (t-t_0)\, v_d + R_{iso}\, (1-1/\cos\beta),\ \beta = \phi_{track} - \alpha_{lor} + \pi/2$
- Point(s) in Rϕ from drift distance and direction, wire pos.
  - $(x,y) = (x_{wire},y_{wire}) \pm d\, (\cos\alpha_{lor},\sin\alpha_{lor})$, sign by pattern recognition





CJC Rϕ measurement (2)

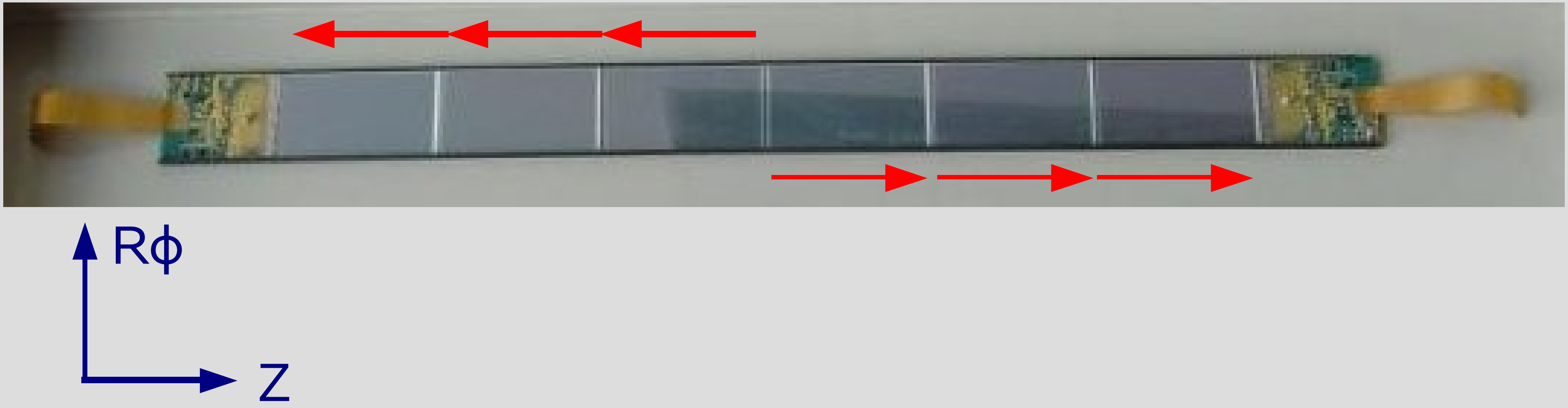
- Drift velocity and lorentz angle depend on
  - Electrical, magnetic field ⇒ spatial variations
  - Gas composition and density ⇒ variations with time (P_{atm}, T)
- Calibration, alignment correlation: complex example
  - Gravitational sagging of cathode wires larger than for anodes ⇒ as function of ϕ and Z for the 2 drift directions differences in
    - Distance D anode to cathode
    - Electrical field E=U/D
    - Drift velocity $v_d(E)$



  - Calibration with common v_d give different t_0 for drift sides ⇒ equivalent to wire displacement in drift direction (up to 100 µm)
  - Due to different ϕ, Z distribution different for cosmics, ep tracks

CST Rϕ measurement

- Position on ladder (2*3 daisy-chained sensors)
  - COG of (p-side) strips above noise
  - 3fold ambiguity resolved by external Z measurement (track)
  - sensor position (on half ladder) from microscope survey
- Half ladders positions (rigid bodies) in space



CJC/CST Rϕ millepede setup (1)

- Local track model
  - Residuals to initial track fit as measurements
  - Cosmic track halves together (reverse flight time for upper)
  - B>0: Parabola + 1%X_0 scattering (angle) between CJC/CST
  - B=0: Straight line
- Global (alignment) parameter
  - CJCs
    - rigid body (except Δz) + twist of end walls (≙ curvature offset)
    - anode wire staggering, electrostatic deflection, gravitational sagging
    - corrections to anode wire position per layer (112)
  - CST
    - rigid body (except Δz) per half ladder (320)

CJC/CST Rϕ millepede setup (2)

- Global (calibration) parameter
  - v_d, α_{lor}, t_0 per CJC (⇒ online calibration)
  - v_d correction per cell half, t_0 per cell (180+90): E(ϕ), HV problems, temperature gradient
  - v_d correction per layer half, t_0 per layer (112+56), E(R)
  - t_0 correction per Flash ADC (330): cable length, electronics
- Additional parameter for special studies
  - Isochrone radius, non linearities, ..
- Constraints for local corrections
  - Average (weighted) is zero
  - Easy to switch on/off set of parameters

CJC/CST Rϕ millepede operation (1)

- Iteration loop: 3fold
  - Internal millepede iterations
  - Rerun millepede with last corrections
  - Rerun track reconstruction with last corrections
- Samples used
  - Several 10k tracks
  - Initially cosmics
    - Large distance to ep interaction point (dca, Z_0)
    - Small curvature
  - As cross check ep
    - Small distance to IP
    - Large curvature
    - Full ϕ coverage !
  - Finally cosmics+ep

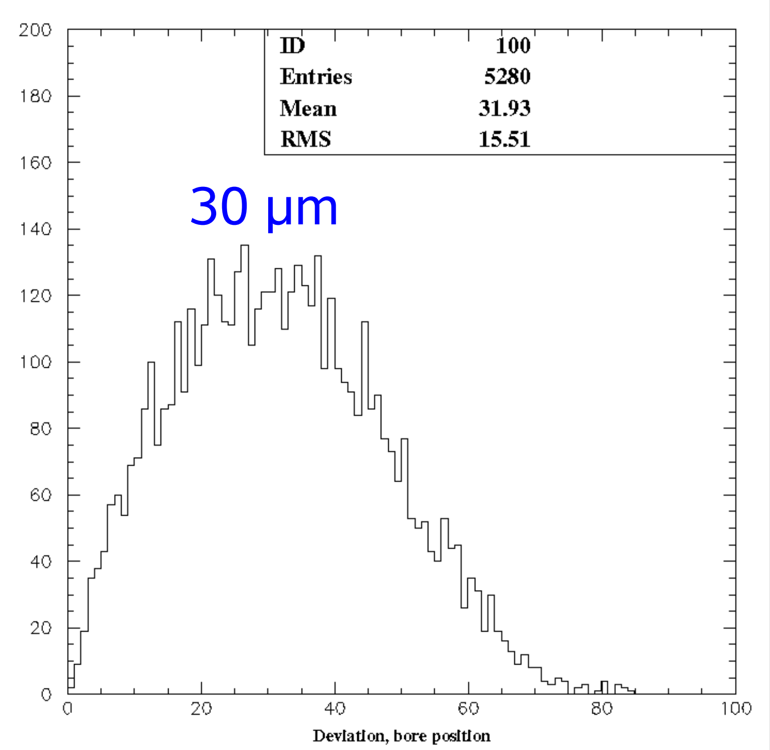
CJC/CST $R\phi$ millepede operation (2)

- Lesson 1: CST as (absolute) reference
  - Large tilt of wire planes due to bad initial CST alignment ⇒ allow global CJC/CST misalignment
  - End wall twists incompatible with installation survey ⇒ give up

⇨ Use CJC2 and end wall survey of position bores ('89)

⇨ Get twists from B=0 cosmics

⇨ Realign CST half ladders
⇒ 40-60 µm 'shrinkage',
radial COG ?



30 µm

deviation bore position

CJC/CST Rϕ millepede operation (3)

- Lesson 2: B=0 vs B>0 cosmics
  - Twists from B=0 compatible with installation survey, wire positions with end wall survey
  - Inconsistent alignment with B>0 cosmics

⇨Include magnetic field inhomogeneities (few %) in track model

- Lesson 3: ep vs cosmics tracks
  - Low p_t tracks need different t_0 than cosmics (have different β distribution: curvature*R vs dca/R)

⇨Fit isochrone radius in addition

- CJC track parameter resolution improved by factor 1.5 (at high momenta)

CIZ/COZ/CST ZS millepede setup

- Local track model
  - Straight line
  - ZS space points, need Rφ track parameters for corrections (arc length vs radius, polygon correction)
- Global (alignment) parameter
  - CIZ, COZ as rigid body (except $\Delta\phi$)
  - Wire position in z (160)
- Global (calibration) parameter
  - v_d, t_0 per wire (320)
- CST
  - As reference in overlap region, else fixed COZ
  - Internally aligned with cosmics

CIZ/COZ/CST ZS millepede operation

- Space points
  - Some effort to get all the corrections right: isochrone, polygon, flight time (cosmics vs ep)
- Reference: CST vs COZ
  - Convergence for both cases
  - Inconsistent results, CST likes to stretch chambers by 0.5‰
  - Fine with “CST shrinkage” from Rϕ alignment
- CIZ/COZ single hit resolution improved by factor 2

CJC charge calibration: ZS, dE/dx

- From charges $Q_{\pm}$ measured on both wire ends
  - $Z = L\,(Q_+ - gQ_-)/(Q_+ + gQ_-)$, $\Delta x\, dE/dx = G(Q_+ + gQ_-)$
- Calibration algorithm (V. Blobel)
  - Simultaneous fit of wire length (L), relative (g) and absolute gain (G) for 2640 wires
  - Nonlinear in relative gain ⇒ constrained parabola
  - Central silicon tracker, Z chambers as reference
- Surprise
  - Wire length varies with total charge

⇨ Traced back to wrong FADC response function in online code

Conclusion

- Should have
  - defined first a robust scale
  - aligned, calibrated all involved subdetectors simultaneously
  - done both projections (Rϕ, ZS) together

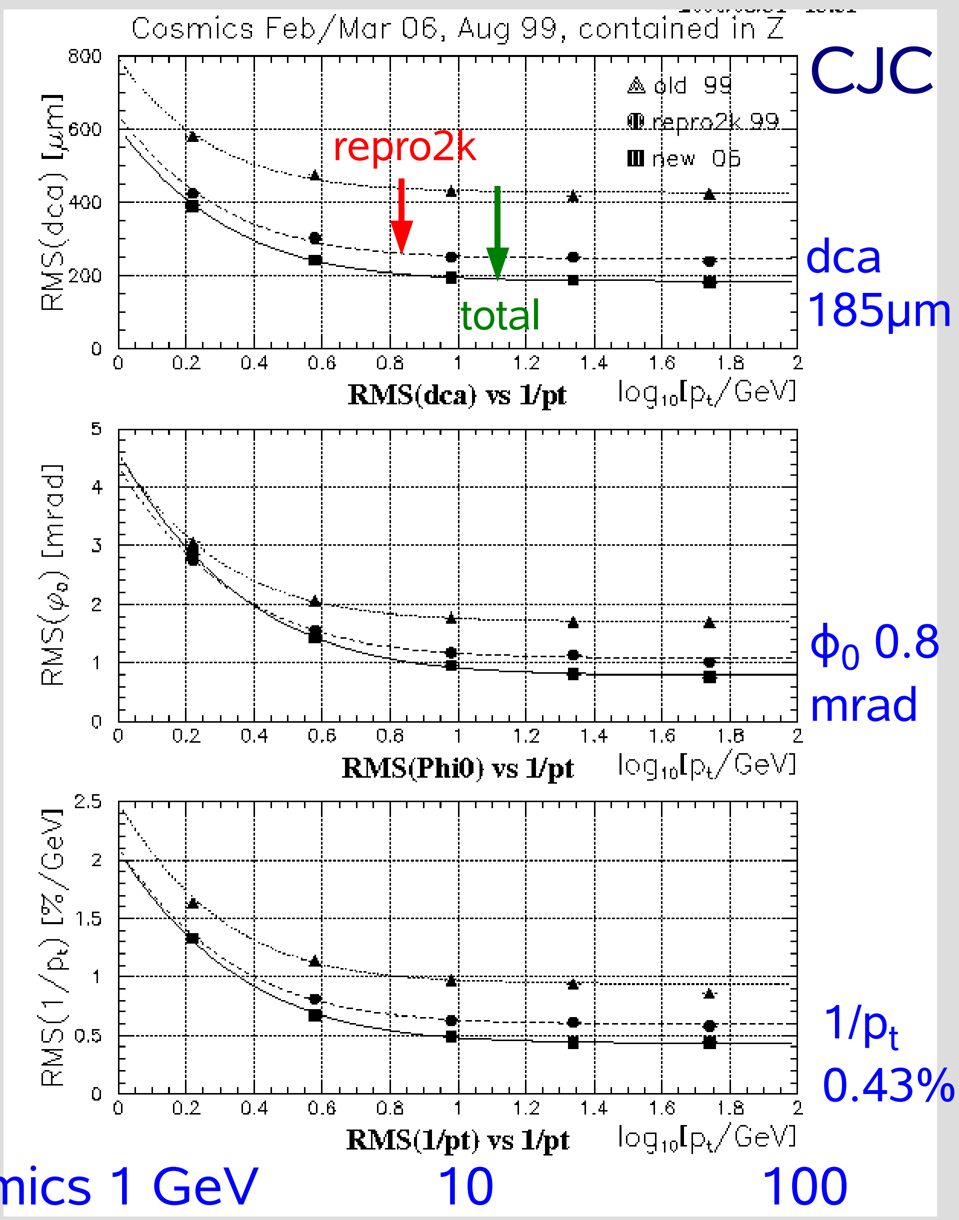
Refinements (Rϕ) 2006

- CJC
  - Calibration: account for B(R,Z) ⇒ $\alpha_{lor}(R,Z)$, $v_d(R,Z)$
  - Improved isochrone model inspired by simulation (GARFIELD) $R_{iso}(\beta,B)$

⇨ Factor 2 improvement in total

- CST
  - Replace microscope sensor survey by alignment with data

⇨ 11 µm single hit resolution



cosmics 1 GeV 10 100

Constants management

- Database
  - Design
  - Implementation
  - Statistics
- Online calibration

Database

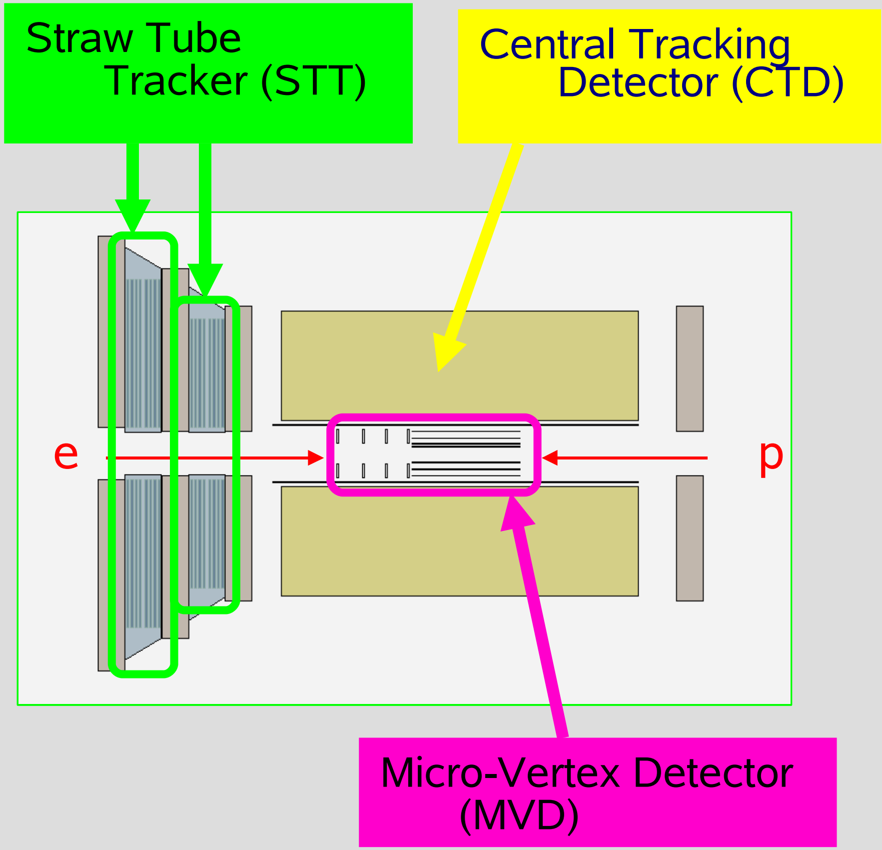
- Design
  - Records can't be changed or deleted, only new versions added
    ⇒ possible to go back to snapshot at any point in time
  - Meta information in 'data dictionary', some mandatory
  - 1 master for writing, read only satellites (external sites, ..)
  - No write restrictions, but detailed bookkeeping
- Implementation
  - Selfmade middleware (Fortran, C, SQL, PL/SQL)
  - User gives command (string), gets pointer into (BOS) memory
  - Master in Oracle (7,8,9) RDB, satellites in flat (FPACK) files
- Statistics (master) for last 9 years
  - 14M user job connections, 0.5M writing 3.5M records (2.3GB)

Online calibration

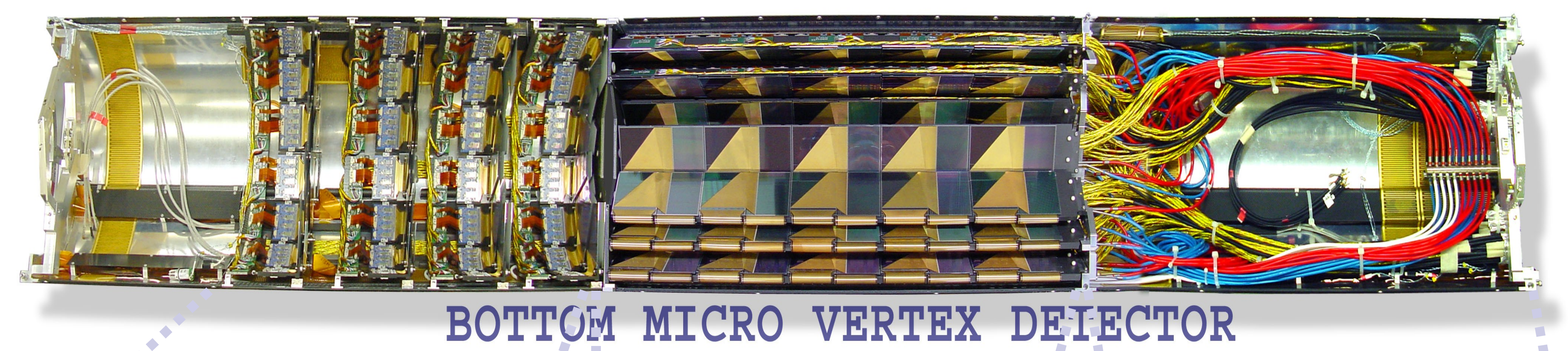
- Constants defined per run (up to 1h)
- Online processing of data
  - On many nodes in parallel
  - Using offline code
  - Putting special monitor records into data stream (selected tracks, .., millepede matrix/vector)
- Monitor records
  - Collected by special job
  - Used to calculate new calibration constants after run end
- Database records
  - Updated for significant changes
  - Fed back to online processing

The ZEUS Tracking System

- ZEUS tracking system was significantly extended during HERA luminosity upgrade (2000/01)
  - ☐ Micro-Vertex Detector (MVD)
  - ☐ forward Straw Tube Tracker (STT)
- Initial HERA-II running suffered from unstable machine operation & harsh background conditions
  - ☐ no real commissioning possible
- After introduction of additional experiment shielding in 2003, the first "serious" HERA-II data-taking proceeded from Nov 2003 (start of "2004 run")
- 2005 dataset (142 pb^{-1}) recently reprocessed with improved MVD alignment



The Micro-Vertex Detector (MVD)



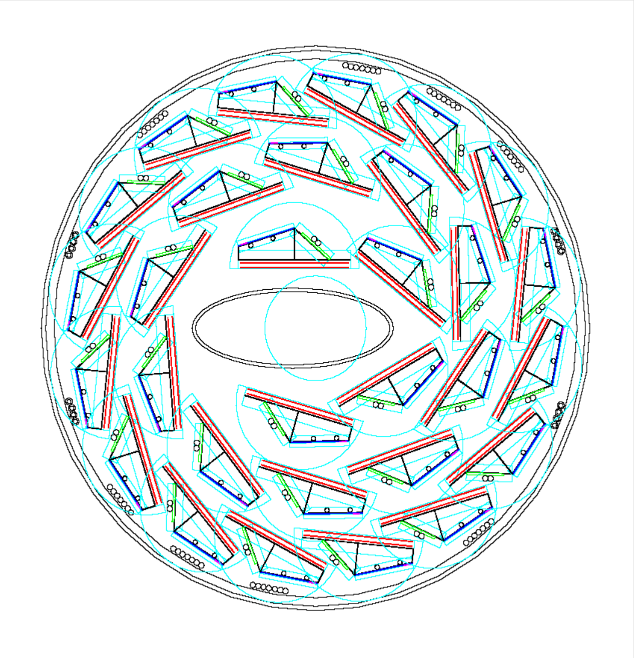
The forward section:
- 4 wheels
- each composed of 2 layers of 14 Si detectors
- in total 112 hybrids, 50k channels

The barrel section:
- 30 ladders
- each composed of 5 modules of 4 Si detectors
- in total 300 hybrids, >150k channels

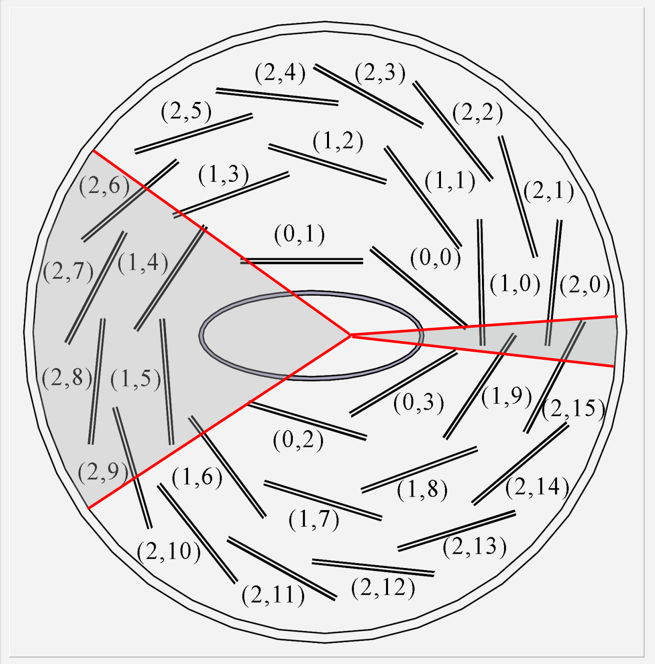
The rear section:
- Cooling pipes and manifolds
- Distribution of FE, slow control and alignment cables

The Layout of the MVD Barrel

Mechanical view



Tracking view

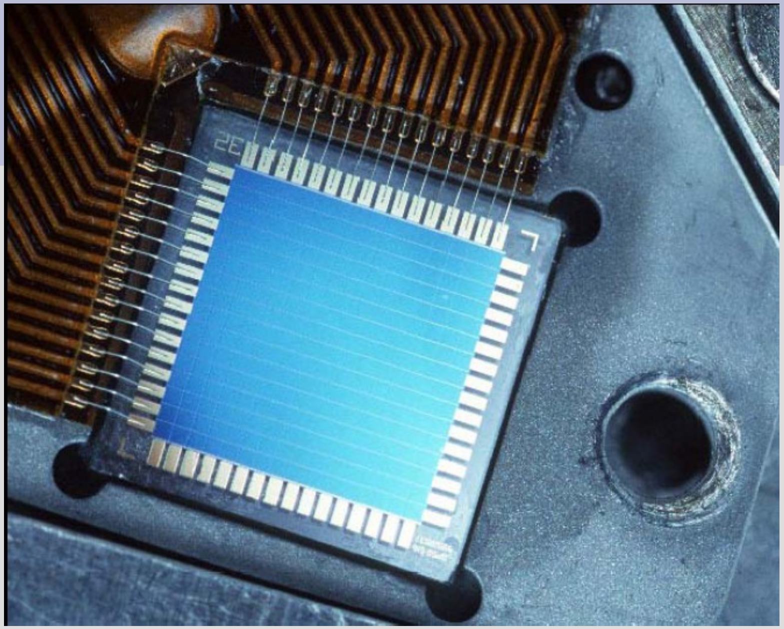


- Major part of azimuthal acceptance covered by three cylinders of ladders (→ six measurements per track)
- Optimal use of available space between beam pipe & CTD

Alignment of the ZEUS MVD

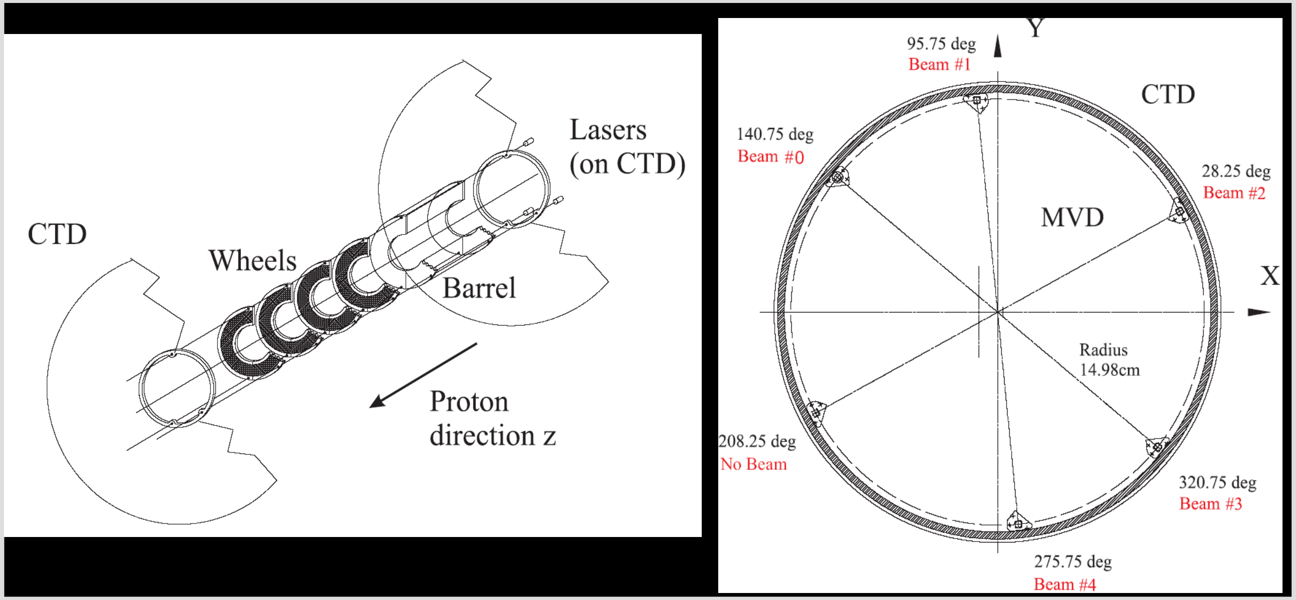
- Main drift chamber (CTD) is a homogeneous, well-understood tracking medium → focus on MVD
- From survey, positions of sensors within ladders are expected to be known within 5 μm. Absolute positions & orientations of ladders & wheels, however, are less well known.
- Main sources of in-situ MVD alignment are
  - MVD laser alignment
  - alignment with cosmic muons
  - alignment with tracks from ep collisions

Laser Alignment



- 5 laser beams (780 nm, 5 mW), 7 sensors per beam
- Double-sided sensors measure position to ~10 µm

- Purpose:
  - monitor global alignment and possibly distortions of MVD
  - identify unstable conditions

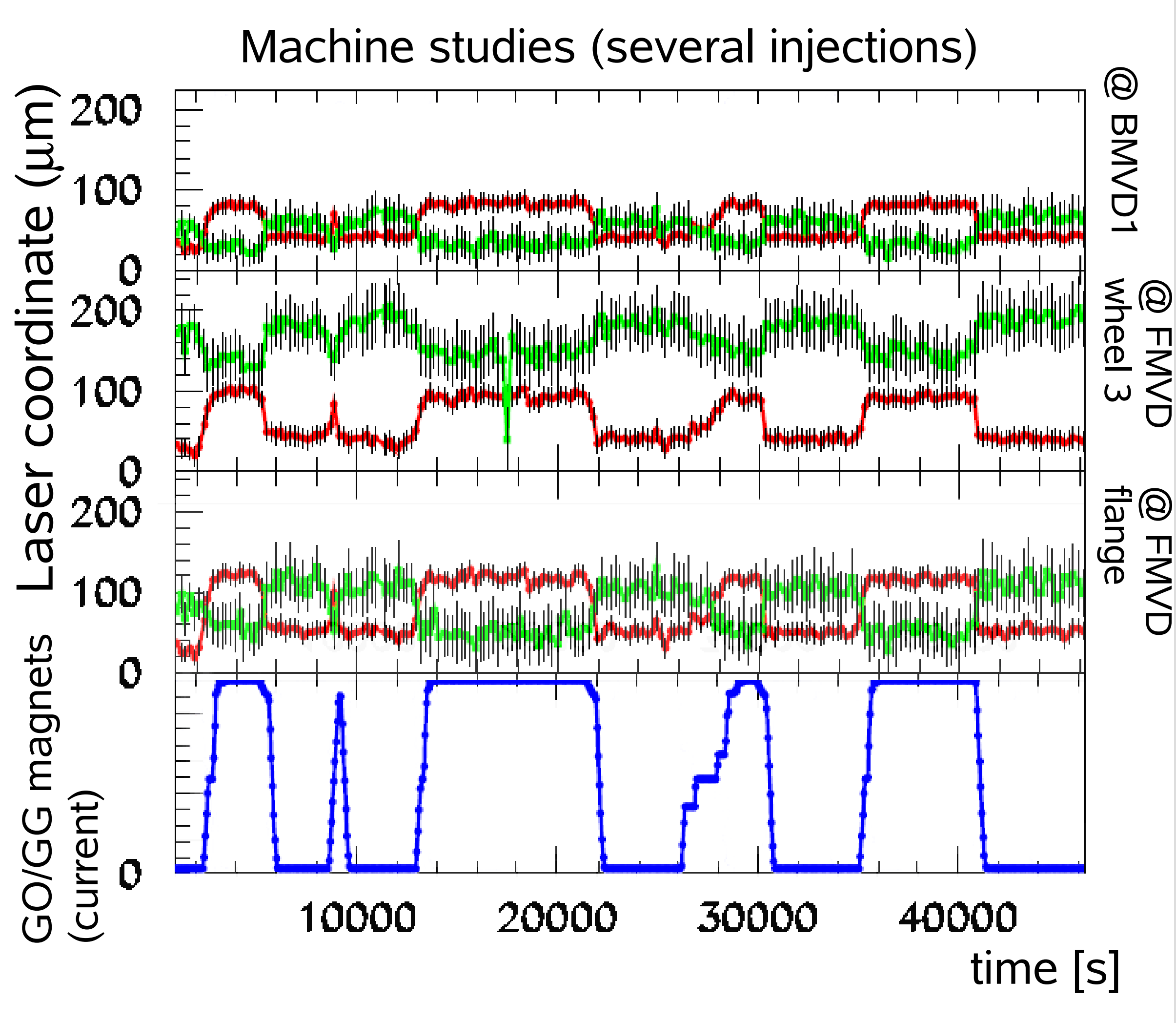


MVD Laser Alignment (cont’d)

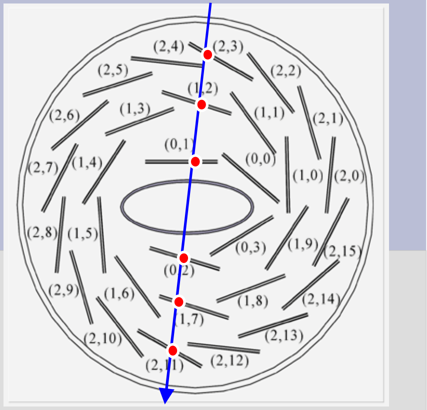
- Due to its sensitivity, laser alignment records effects from ramping of HERA magnets during injection

- During data-taking conditions, laser alignment shows high stability of MVD/CTD geometry

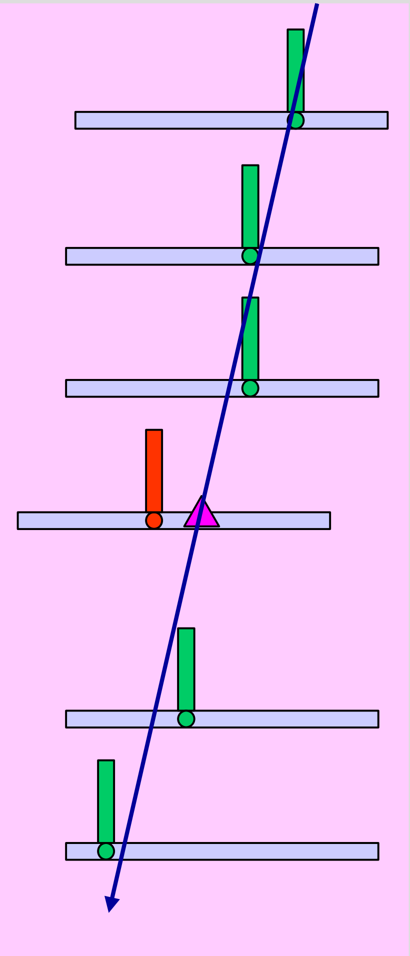
➔ Important warning system



Alignment with Cosmic Muons

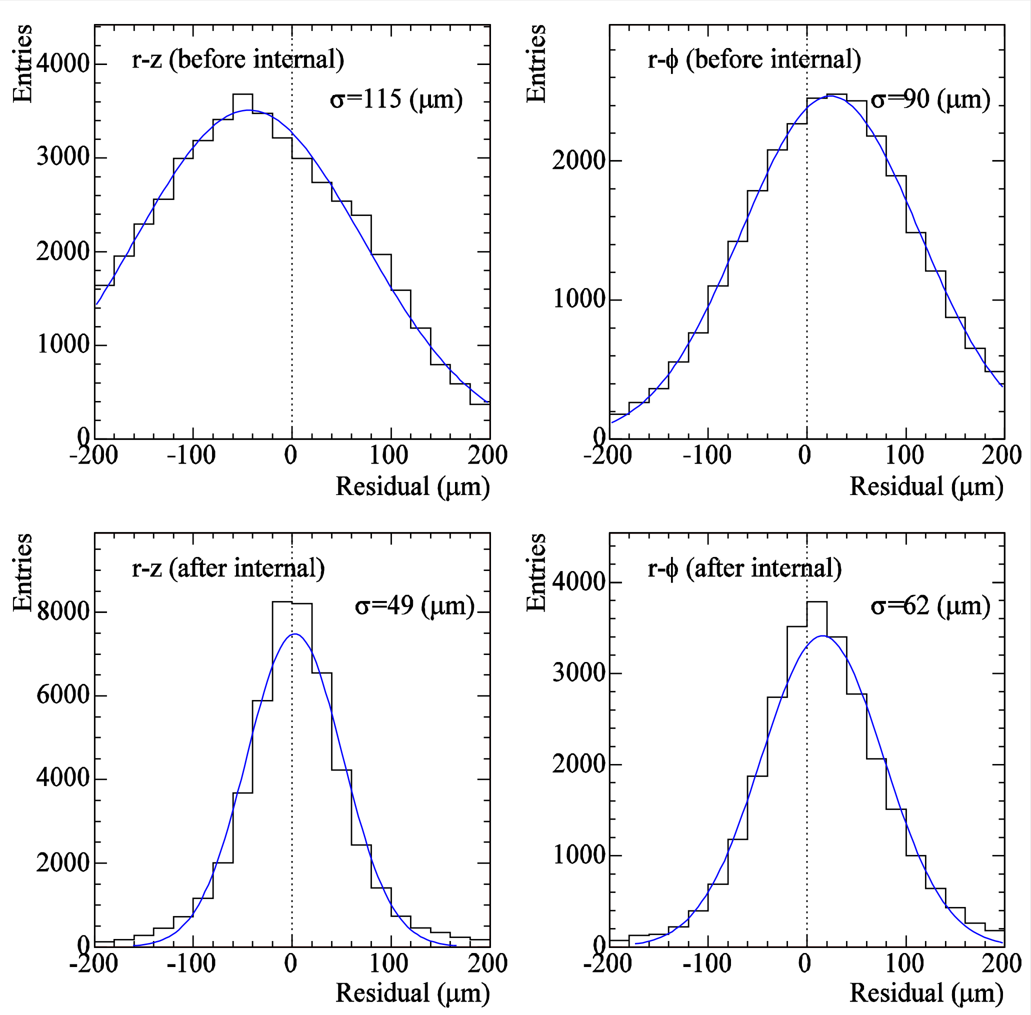


- Advantages:
  - clean signature. Achievable samples ~100k events (1-2 weeks of dedicated running)
  - tracks passing through whole height of detector → typically 6 hits (rφ)+6 hits (z) on track
- Method:
  - for each ladder in barrel, determine residuals of hits with tracks (fitted under exclusion of the very hits of this particular ladder)
  - local least squares fit determining 6 alignment parameters (3 shifts + 3 rotations) for ladder
  - apply for all ladders, iterate, combine with global alignment



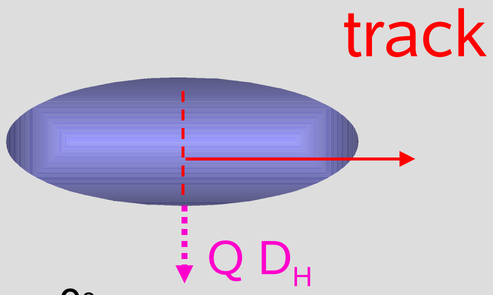
Alignment with Cosmic Muons (cont'd)

- Based on ~100k good cosmic tracks
- Considerable reduction of residual widths, down to ~50 µm
- Principal limitation:
  - ladders on sides of barrel are not well covered
  - forward wheels cannot be aligned at all



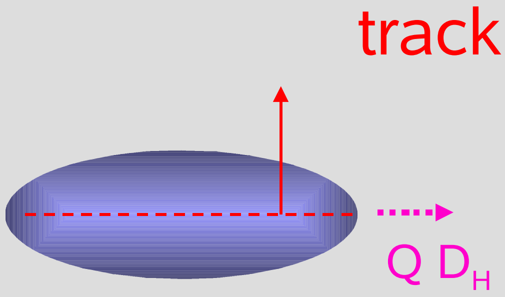
Using Inclusive Impact Parameter Distributions to Check Alignment

- Study impact parameter with respect to beam spot → independent of vertex reconstruction
- Typical beam size at HERA 110 x 30 μm
  - run-by-run beam spot to compensate movements
  - at LHC this may work even better (round beams)
- Inclusive selection of tracks (p_T>3 GeV) gives very clean impact parameter distributions
- Expectation (if perfect alignment):
  - narrow distributions for horizontal tracks
  - wider distributions for vertical tracks



φ=0°

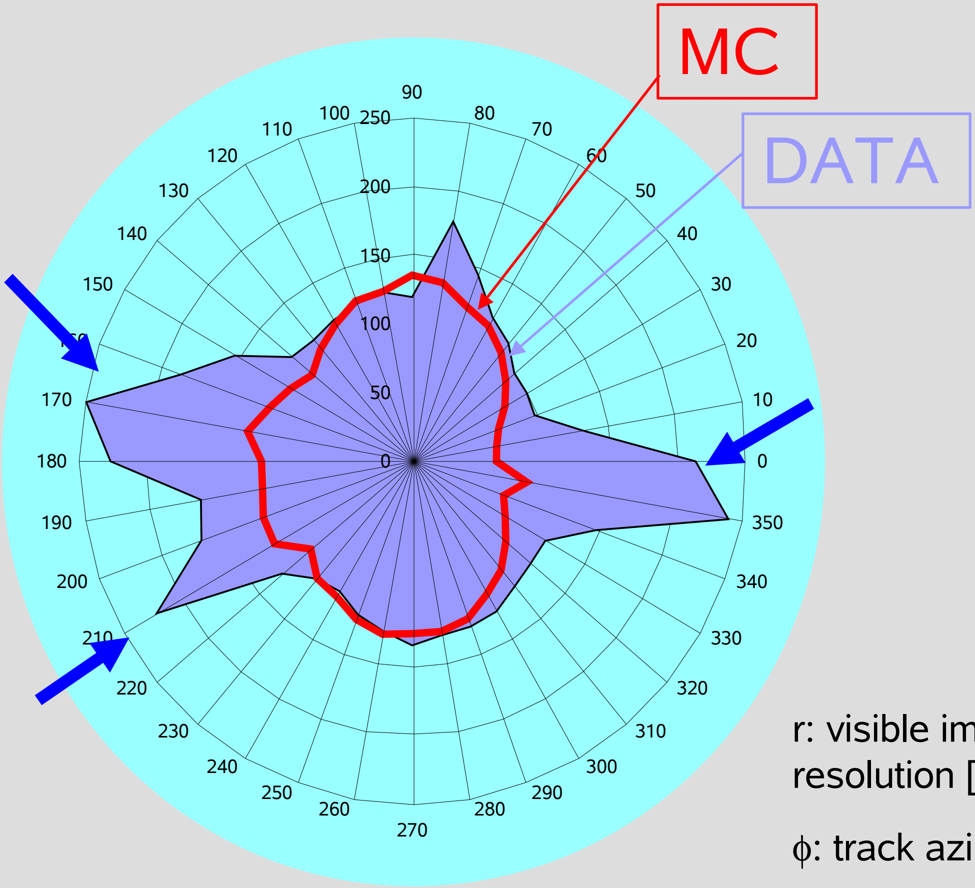
Beam spot projection narrow



φ=90°

Beam spot projection wide

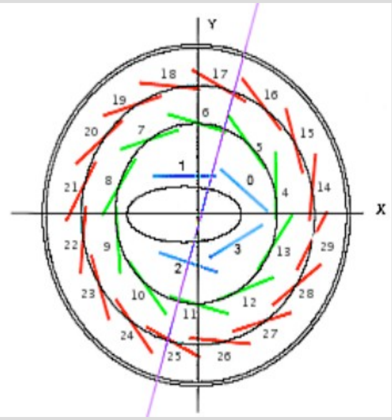
Impact Parameter “Radar Map”



- ➔ significant excess in impact parameter resolutions in certain azimuth ranges
- ➔ correlation with ladders that are least accessible to cosmics alignment
- ➔ need alignment method that covers whole detector

r: visible impact parameter resolution [μm]

ϕ: track azimuth

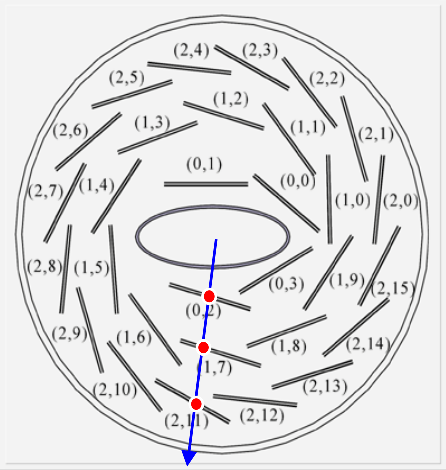


at level of cosmic alignment

Alignment with ep Collisions

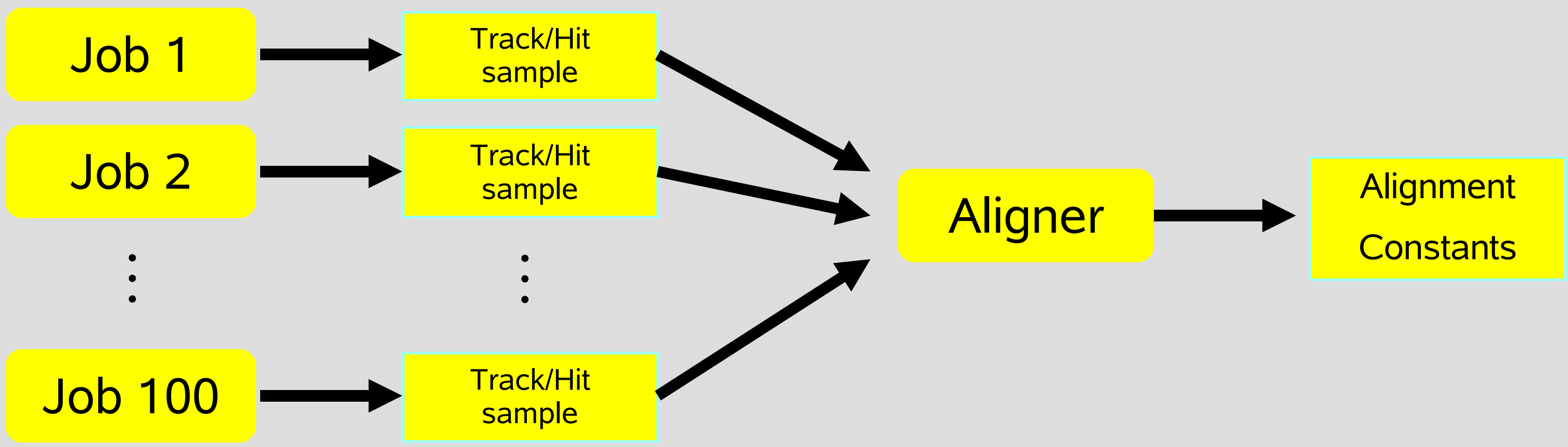
- Tracks from ep collisions form the largest quantitative basis for alignment
  - select about 1 M tracks per ~10 M ep events
- Compared to cosmic muon alignment, far less redundancy at MVD level (only ~6 hits instead of ~12 per track)
  - ➔ compensate this by using beam spot and CTD segment as additional constraint
  - ➔ not feasible to use unbiased residuals. Must take correlations into account

- ■ High granularity of alignment parameters
  - ➔ 2 shifts + 3 rotations per individual sensor
  - ➔ about 3000 alignment parameters
- ■ Simultaneous global fit of all track and alignment parameters
  - ☐ millions of free parameters
  - ☐ use fitting engine “millepede” (by V. Blobel)



Thanks to Volker Blobel for access to his program & his advice

The ZEUS ep Alignment Factory

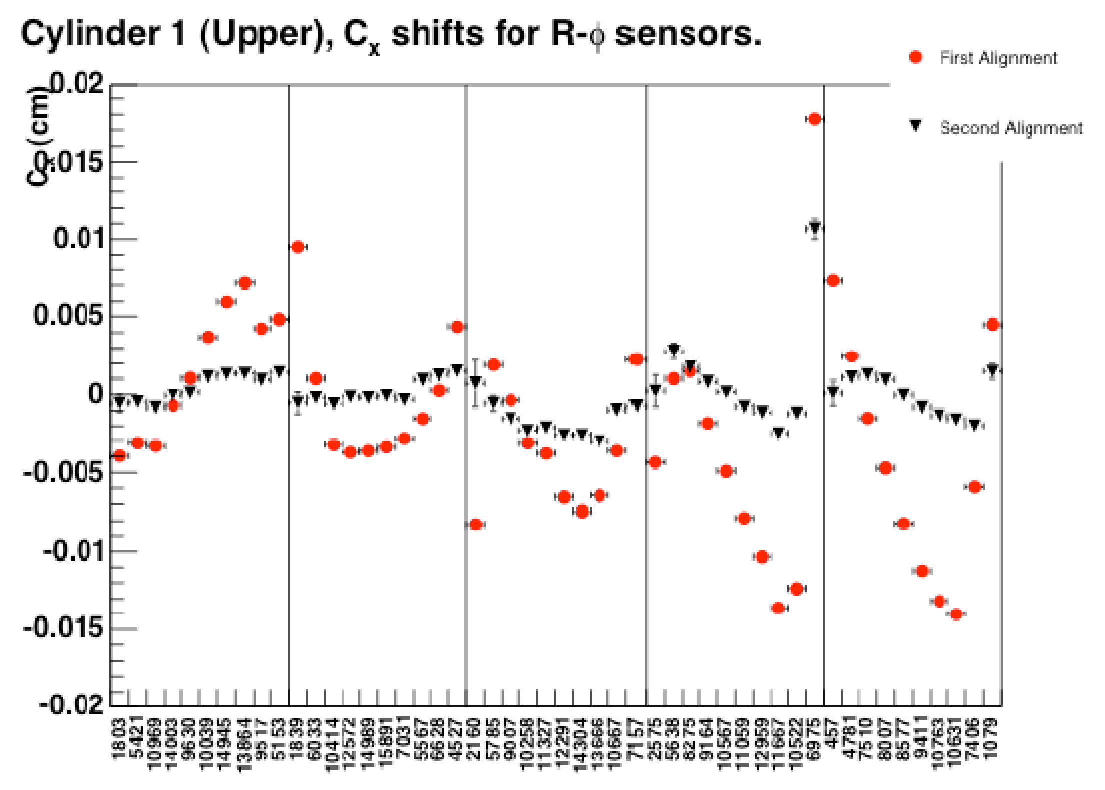


ROOT
format

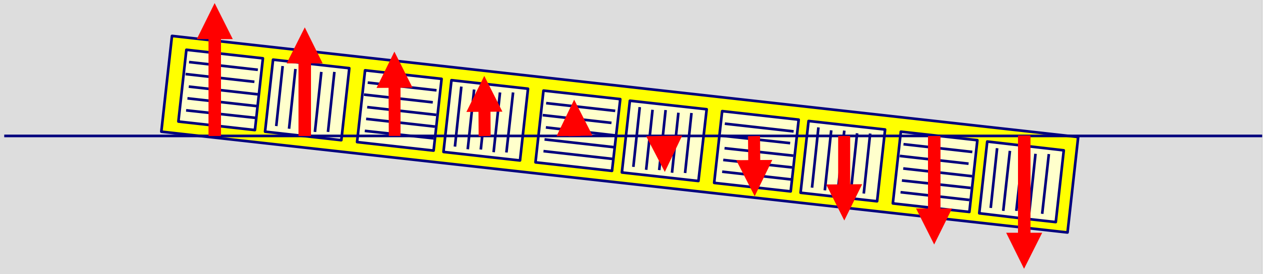
- Track selection parallelized on farm (1-2 days, 1M tracks)
- Actual fit (“aligner”) takes 10-20 minutes

Alignment Constants: Snapshot

- Clear correlations of modules within ladder
  - no evidence for significant shifts within ladder
  - high precision of construction & survey
- rφ: indications for ladder-level rotations (sub-mrad)
  - possibly some indications of sag, twist or warp effects?
- Typical alignment accuracy ~20 µm

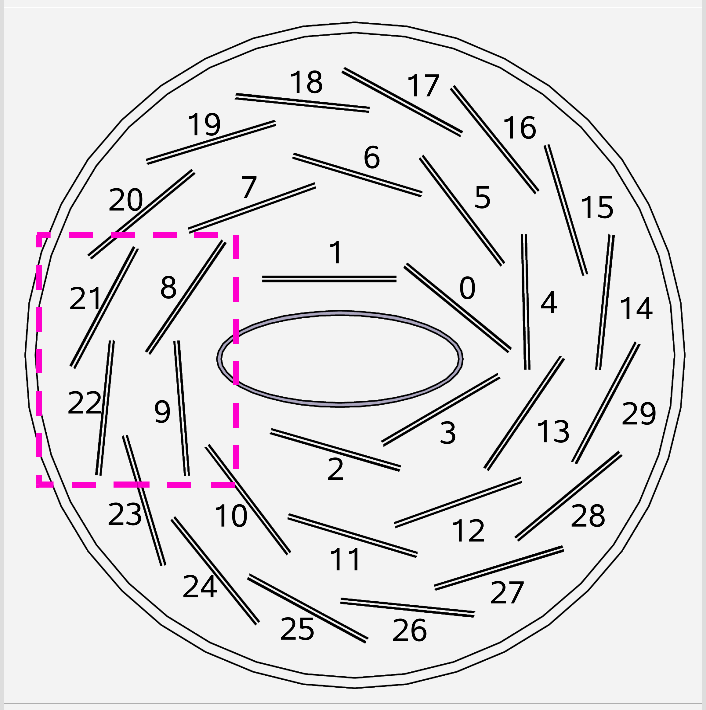


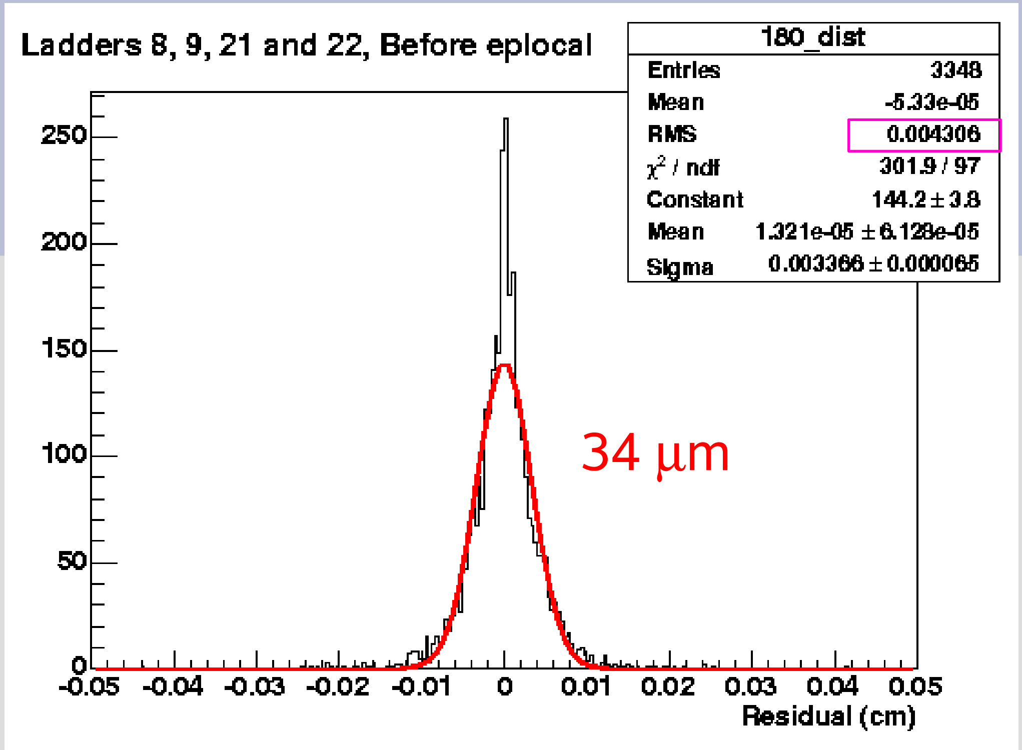
Note: error bars exclude multiple scattering

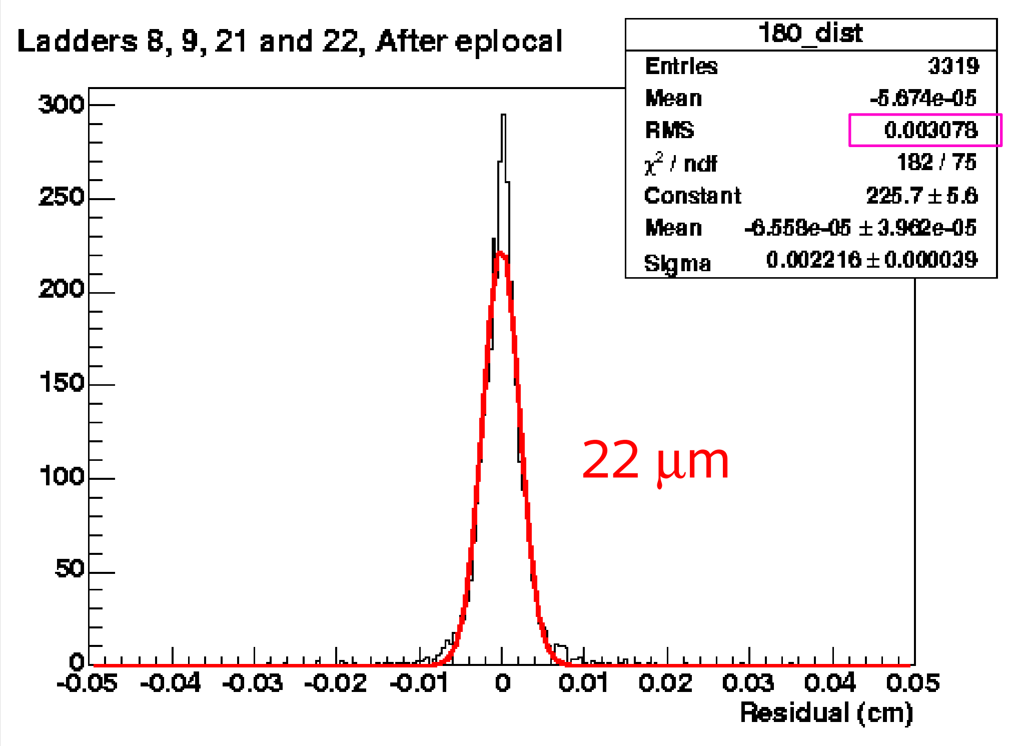


Hit Residuals

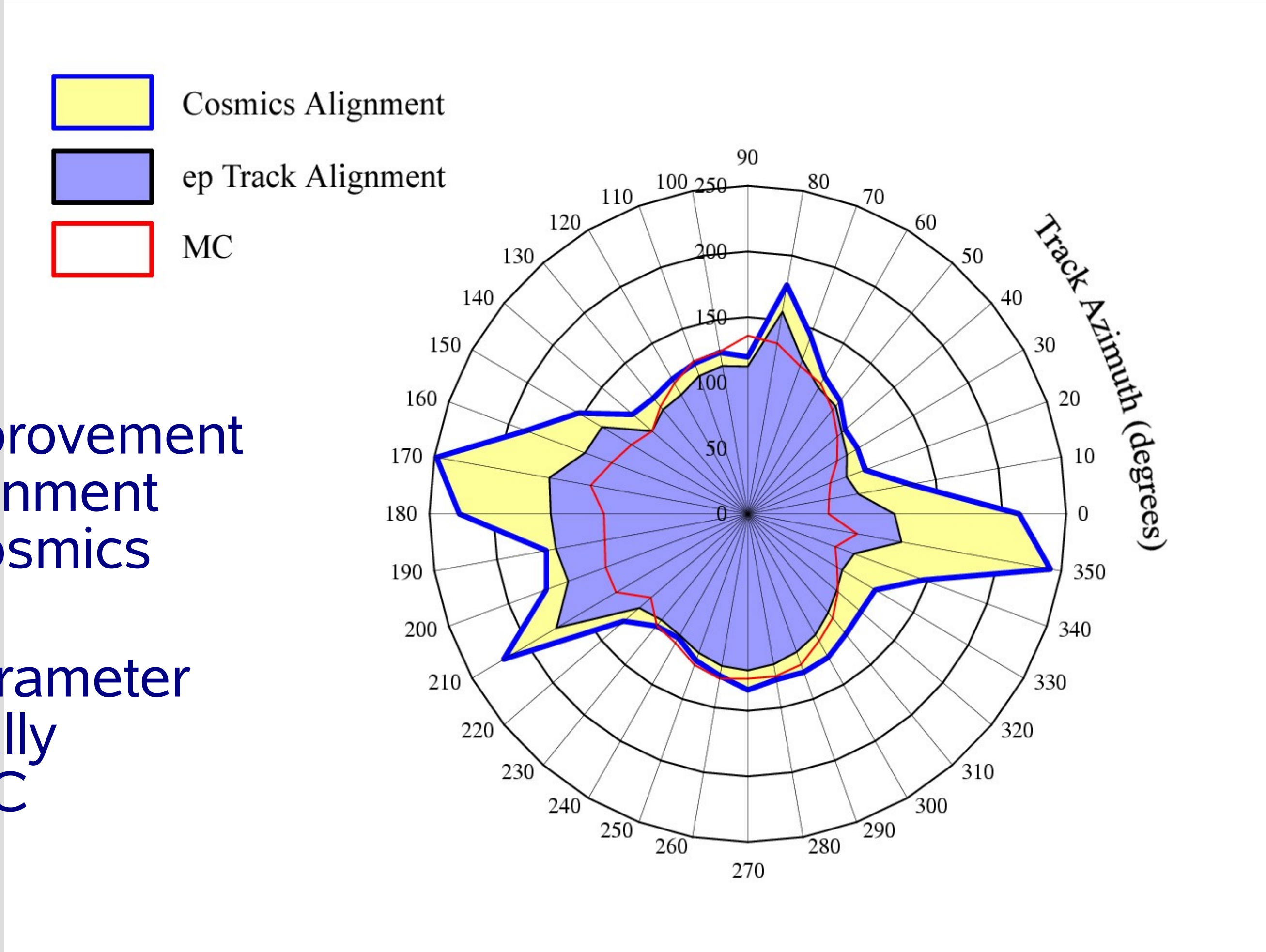
- Significant improvement from ep track alignment in critical areas







Impact Parameter Resolution After ep Track Alignment

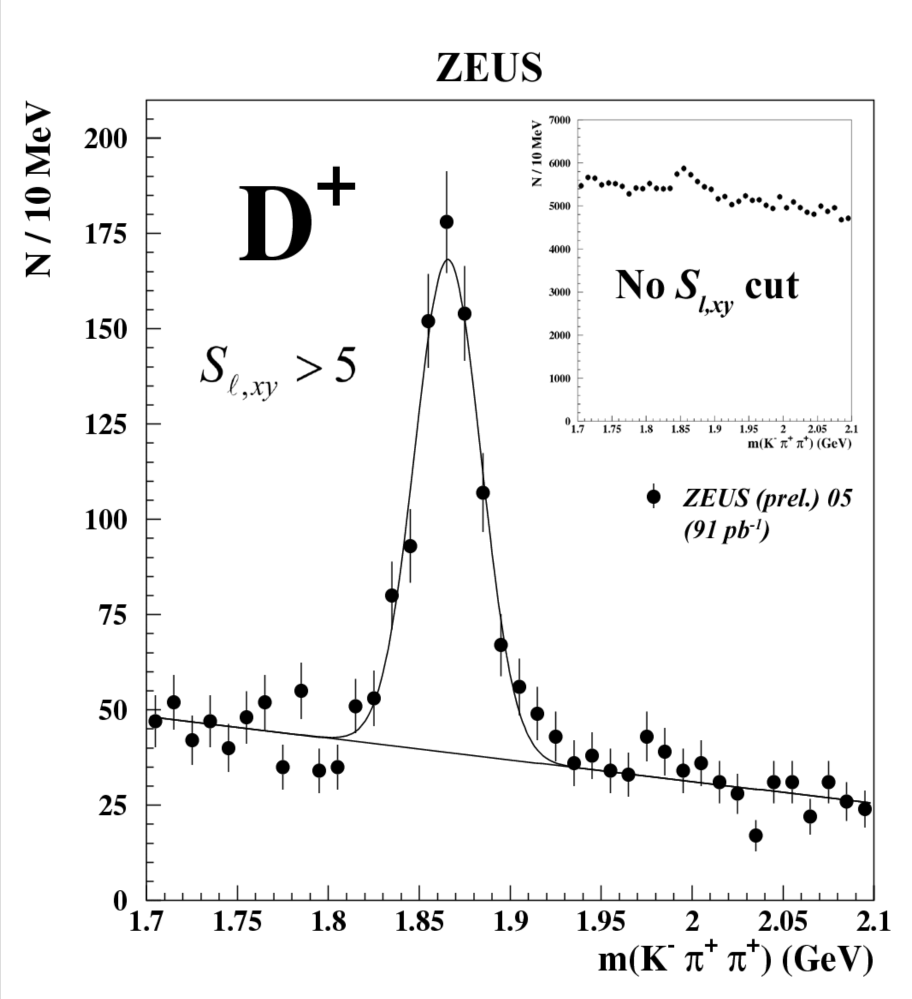


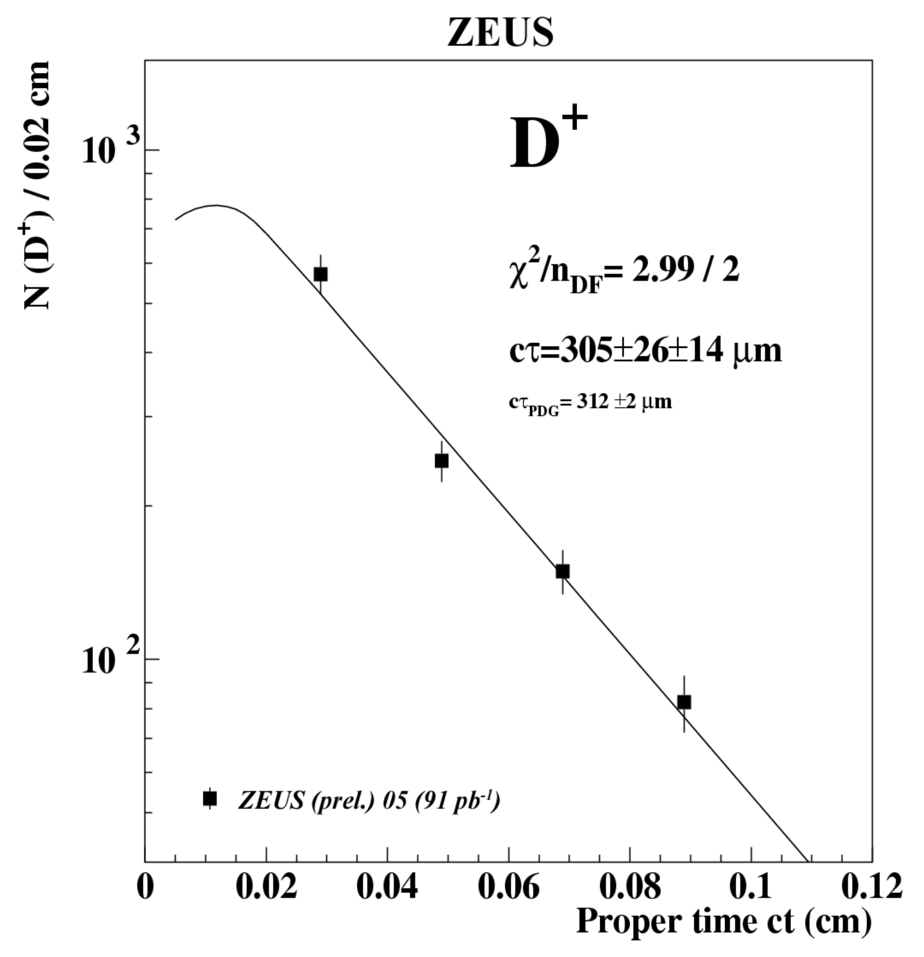
- Considerable improvement from ep track alignment with respect to cosmics alignment
- Visible impact parameter resolution generally comparable to MC

$D^+ \rightarrow K^- \pi^+ \pi^+$

ZEUS 2005 reprocessed with ep alignment.

Submitted to ICHEP06 conference.





Summary

- H1, millepede
  - Need scale, reference
    Robustness more important than nominal resolution
  - Be as global (subdetectors, projections together) as possible
    Explore the different systematics (more but uncorrelated)
- ZEUS, MVD
  - Laser alignment to monitor stability
  - Initial alignment with cosmics
  - Final accuracy from ep collision tracks and global fit
  - Beam spot and impact parameter important to constrain and monitor alignment