Track-based Alignment Paper

Jim Pivarski

Texas A&M University

Gervasio Gomez

Instituto de Fisica de Cantabria

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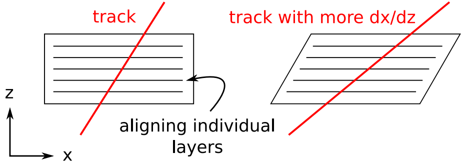
Contents and structure

- Two independent sections on local alignments
- One section on global alignment with both procedures
  - algorithms are described separately
  - MC studies and results are shown together
- 24 pages, 12 figures

Local DT alignment

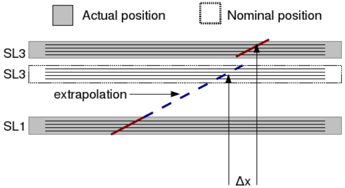
Alignment of layers and superlayers in chambers

- Two alignments described:
  1. layer alignment, including information from tracks, quality control measurements, and photogrammetry
  2. superlayer alignment, using tracks and photogrammetry independently, then cross-checked
- Tracks alone are not sufficient to align layers and fit tracks simultaneously: consider shear distortion

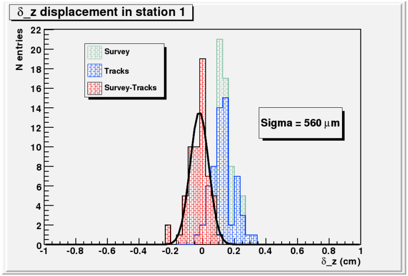


- Because (1) uses all of the available data sources, no cross-checks are possible
- Alignment (2) uses 2-D segment from each superlayer to determine x, ϕ_z, and especially z (width of glue layer)

Local DT alignment



(a) Interpretation of $\Delta x^{\text{geom}} = \frac{dx}{dz}\delta_z$.

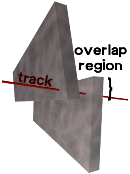


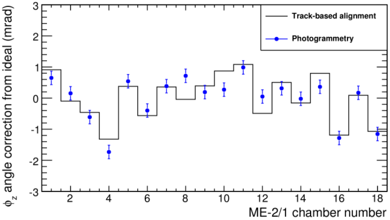
- Superlayer alignment can be performed purely with tracks because each superlayer defines a line with slope $(\frac{dx}{dz})$
  - discrepancies between segments $\longrightarrow$ x corrections
  - …as a function of $y \longrightarrow \phi_z$ corrections
  - …as a function of $\frac{dx}{dz} \longrightarrow z$ corrections
- Good agreement with photogrammetry for all 3 parameters
- Only z was significant (due to glue layer)

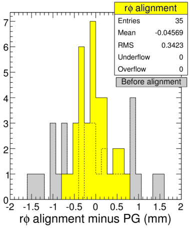
Local CSC alignment

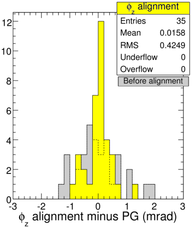
Alignment of chambers in rings

- Uses overlap of neighboring chambers for precise relative alignments
- Relative corrections propagated around the ring (full mathematical detail given in note)
- Tracks-only measurement compares favorably with photogrammetry ($\vec{B} = 0$ beam-halo)









- Includes a Monte Carlo study
- Extension to layer alignment mentioned, but not developed (would require more beam-halo to demonstrate)

Global alignment: algorithms

- 2 sections: HIP and MillePede
- Complete description of Muon-HIP, how it differs from standard HIP:
  - tracks fixed by tracker
  - treatment of segment residuals: Δx, Δy, $\Delta \frac{dx}{dz}$, $\Delta \frac{dy}{dz}$ including CSC case
  - fit function: convolution of misalignment and propagation errors
  - sample fits (data only)
- Complete description of MillePede:
  - how it differs from the general case (fixed tracks)
  - list of potential systematic errors

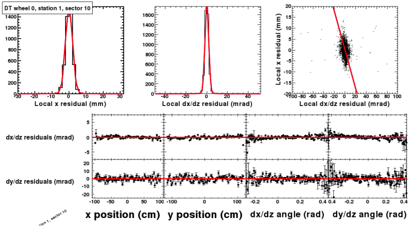
$$\begin{pmatrix} \Delta x^{\mathrm{geom}} \\ \Delta y^{\mathrm{geom}} \\ \Delta \frac{dx}{dz}^{\mathrm{geom}} \\ \Delta \frac{dy}{dz}^{\mathrm{geom}} \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\frac{dx}{dz} & -y\frac{dx}{dz} & x\frac{dx}{dz} & -y \\ 0 & 1 & -\frac{dy}{dz} & -y\frac{dy}{dz} & x\frac{dy}{dz} & x \\ 0 & 0 & 0 & -\frac{dx}{dz}\frac{dy}{dz} & 1+\left(\frac{dx}{dz}\right)^2 & -\frac{dy}{dz} \\ 0 & 0 & 0 & -1-\left(\frac{dy}{dz}\right)^2 & \frac{dx}{dz}\frac{dy}{dz} & \frac{dx}{dz} \end{pmatrix} \begin{pmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \delta_{\phi_x} \\ \delta_{\phi_y} \\ \delta_{\phi_z} \end{pmatrix}. \quad (22)$$

(The above matrix is an extension of Equation 17 in [8]). For CSCs, the curvilinear residuals $\Delta r\phi^{\mathrm{geom}}$ and $\Delta d(r\phi)/dz^{\mathrm{geom}}$ introduce corrections suppressed by r, the radial distance to the beamline:

$$\begin{pmatrix} \Delta r\phi^{\mathrm{geom}} \\ \Delta \frac{dr\phi}{dz}^{\mathrm{geom}} \end{pmatrix} = \begin{pmatrix} 1 & \left[-\frac{x}{r}+3\left(\frac{x}{r}\right)^3\right] & -\frac{dx}{dz} & -y\frac{dx}{dz} & x\frac{dx}{dz} & -y \\ 0 & -\frac{dx}{dz}\left(\frac{1}{2r}\right) & 0 & \left[\frac{x}{r}-\frac{dx}{dz}\frac{dy}{dz}\right] & 1+\left(\frac{dx}{dz}\right)^2 & -\frac{dy}{dz} \end{pmatrix} \begin{pmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \delta_{\phi_x} \\ \delta_{\phi_y} \\ \delta_{\phi_z} \end{pmatrix} \quad (23)$$

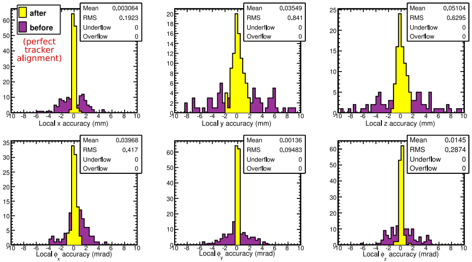
To extract geometric residuals from the measurements, we construct an ansatz describing all effects and fit it to the data. Each of the four observables is represented by a convolution of a Gaussian and a Lorentzian (to model the power-law scattering tails),

$$f(t;\, t_0, \sigma, \gamma) = \int_{-\infty}^{\infty} \frac{1}{\pi}\frac{\gamma}{(t-s-t_0)^2+(\gamma)^2} \times \frac{1}{\sqrt{2\pi}\sigma}\exp\left(\frac{-s^2}{2\sigma^2}\right)\, ds. \quad (24)$$

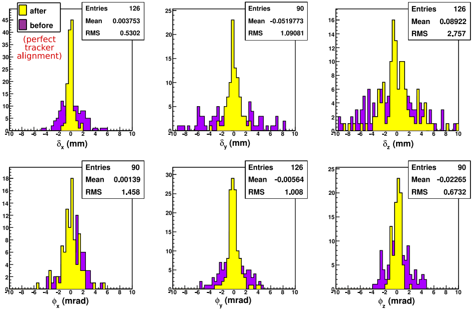


Parallel MC studies

HIP:



Millepede:

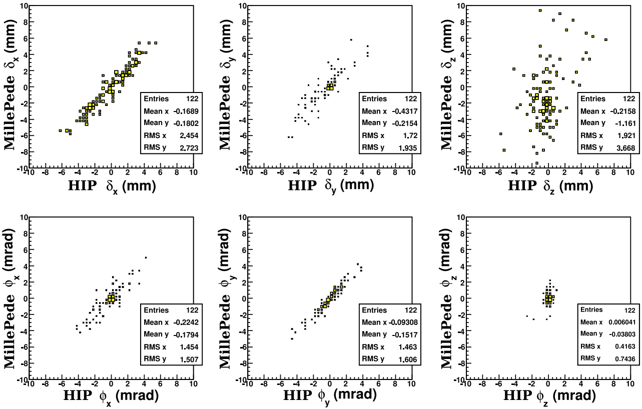


- Cosmic ray Monte Carlo
- Everything the same as data except no tracker misalignment, $\vec{B}(\vec{x})$ errors, or internal DT misalignment
- Width of difference between aligned and true:

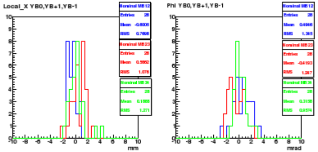
	HIP	MP	
δ_x	0.19	0.53	mm
δ_y	0.84	1.09	mm
δ_z	0.63	2.76	mm
δ_{ϕ_x}	0.42	1.46	mrad
δ_{ϕ_y}	0.09	1.01	mrad
δ_{ϕ_z}	0.29	0.67	mrad

Results (cross-checks)

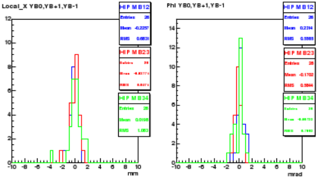
- Since the output of alignment is a many-parameter geometry which doesn't mean much to an outside reader, what we show in the Results section are cross-checks
- First check (internal consistency): residuals minimized
- Second: algorithms agree (within uncertainties set by MC)



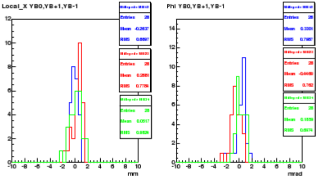
Results (cross-checks)



(a) Before global alignment



(b) Results from the HIP algorithm



(c) Results from the MillePede algorithm

- Third check: local and global agree
  - local track fits are partly independent of global track fits
  - higher precision from shorter propagation through only one layer of iron
  - can only quantify relative positions
- Local differences maintained (and slightly improved) despite few-mm scale global corrections

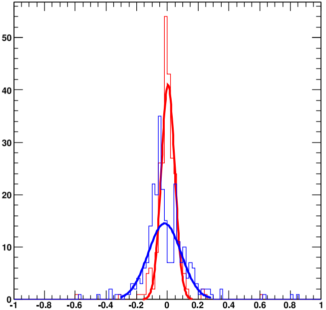
	x (mm)	ϕ_y (mrad)
before align 1 — 2	0.77	1.35
before align 2 — 3	1.08	1.25
before align 3 — 4	1.27	0.96
HIP 1 — 2	0.68	0.56
HIP 2 — 3	0.69	0.56
HIP 3 — 4	1.09	0.71
Millepede 1 — 2	0.67	0.80
Millepede 2 — 3	0.78	0.76
Millepede 3 — 4	0.98	0.70

Results (cross-checks)

- Fourth: split each cosmic ray into two LHC-like halves, fit top and bottom independently
  - any mismatch in $1/p_T$ is purely instrumental
  - select $p_T \gtrsim 200$ GeV to emphasize contribution of the muon alignment (long lever arm for resolution of small sagitta

Before muon alignment

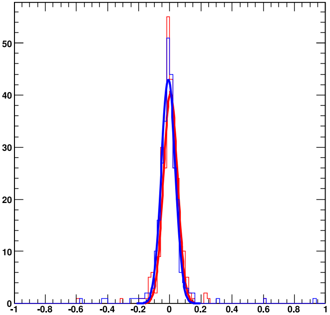
	mean	sigma
Tracker-only:	0.0040	0.044
With first muon station:	−0.0180	0.108



$$\frac{(1/p_T)_{\text{upper}} - (1/p_T)_{\text{lower}}}{\sqrt{2}\,(1/p_T)_{\text{lower}}}$$

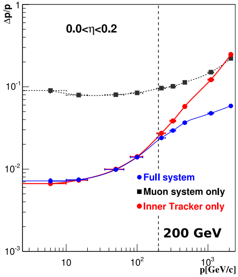
After muon alignment

	mean	sigma
Tracker-only:	0.0042	0.045
With first muon station:	−0.0097	0.045



$$\frac{(1/p_T)_{\text{upper}} - (1/p_T)_{\text{lower}}}{\sqrt{2}\,(1/p_T)_{\text{lower}}}$$

Plot from Technical Design Report (no misalignment)



sigma ~ 0.025 at 200 GeV for a perfect detector

Conclusions

- This paper contains many mature analyses, demonstrating the quality of our detectors and tracking, and should be published
- Later than nominal CRAFT paper schedule (our apologies!):

DPG/POG reading/review/Pre-approval	July 1
ARC Review	July 15–Aug 15
Collaboration-wide review	Aug 20–Sep 6
Final Tar Ball of Paper to Editors	Sep 20
48 Hour notice for final urgent comments	Sep 24
Submission to J.INST	Sept 30