CRAFT Paper: Muon Track-based Alignment

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21 July, 2009

A talk about the paper

- This talk is to present the scope and the contents of CMS CFT 09-016: *Alignment of the CMS Muon System with Cosmic Ray and Beam-Halo Tracks*
  - with a focus on new results (since the LHC Alignment Workshop)
- You are welcome to read the note on

  https://twiki.cern.ch/twiki/bin/view/CMS/CFT-09-016-TrackBasedMuonAlignmentNote

  and send comments!
- Status: currently under internal review by most closely-related communities: muon alignment, DT-DPG, CSC-DPG, and AlCa
- If approved by DT-DPG, it will be submitted to an ARC on Thursday

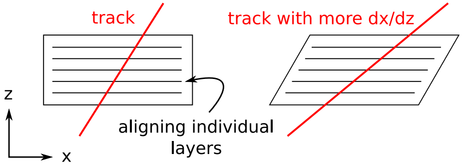
Structure and contents

- 24 pages (with blanks), 13 figures

- Local alignments are alignments using “short” tracks that do not propagate through any layers of iron
- Global alignment is chamber alignment relative to the tracker
  - both HIP and MillePede are represented, with MC studies and real-data cross-checks

Two local DT alignments

1. Description of general layer alignment, combining tracks and survey data (quality control measurements and photogrammetry)
   - complete description of algorithm (good reference)
   - tracks-only alignment is degenerate: e.g. chambers can shear

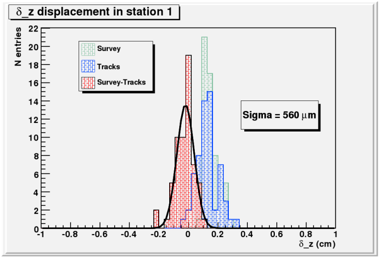


   - no results to show because independent measurements are needed in the alignment procedure: no available cross-checks

2. Separate alignment of superlayers with tracks and photogrammetry independently, with cross-check

   See Pablo's talk:

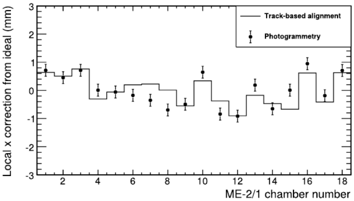
   http://indico.cern.ch/conferenceDisplay.py?confId=59273

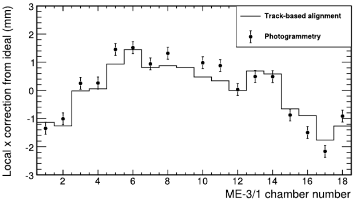


- This is the "CSC Overlaps method" (ring alignment from pairs of chambers using beam-halo or collisions):

  http://indico.cern.ch/conferenceDisplay.py?confId=46769

  - complete description of the method: propagation around ring
  - Monte Carlo studies
  - cross-check with photogrammetry (all 3 parameters $\times$ 2 rings)





- Does not include discussion of layer alignment (only a brief comment)
  - demonstration would require higher statistics than 2008 beam-halo

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)
    - detailed list of potential systematic errors

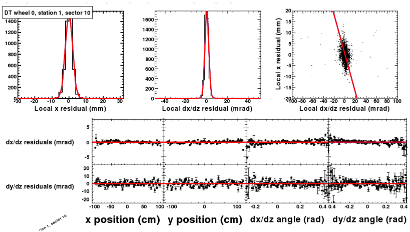
$$\begin{pmatrix} \Delta x^{\mathrm{geom}} \\ \Delta y^{\mathrm{geom}} \\ \Delta \frac{dx}{dz}^{\mathrm{geom}} \\ \Delta \frac{dy}{dz}^{\mathrm{geom}} \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\frac{dx}{dz} & -y\frac{dx}{dz} & x\frac{dx}{dz} & -y \\ 0 & 1 & -\frac{dy}{dz} & -y\frac{dy}{dz} & x\frac{dy}{dz}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

(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:

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

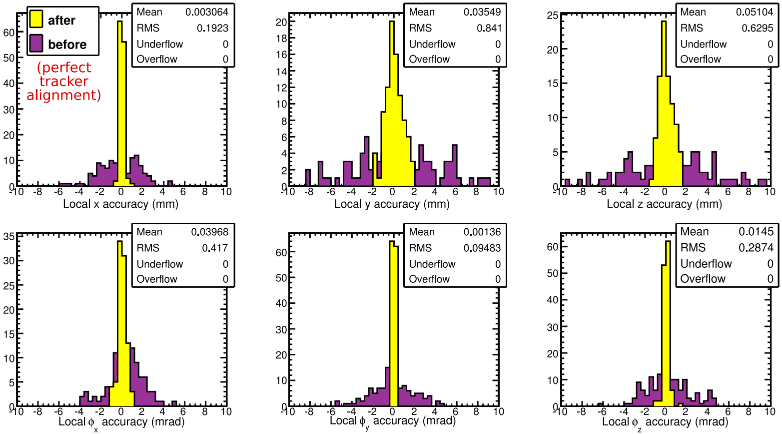
To extract geometric residuals from the measurements, we construct an ansatz describing all effects and fit it to the data. Each of the four observables is represented by a convolution of a Gaussian and a Lorentzian (to model the power-law scattering tails),

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



Monte Carlo section

- Both algorithms studied in Monte Carlo, MillePede plot is new
- This is the HIP plot (old)



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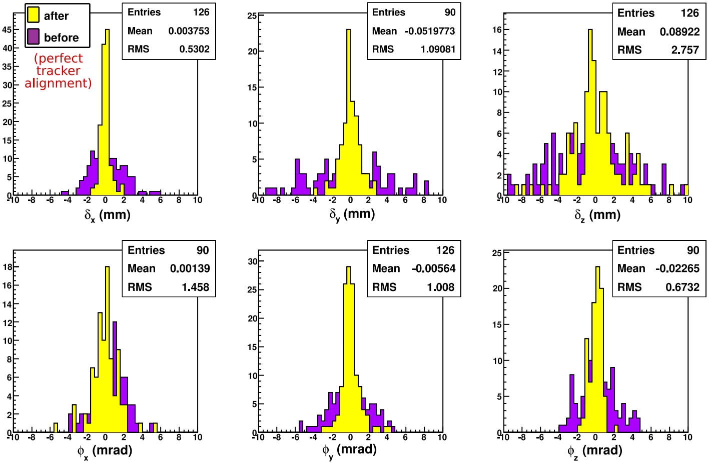
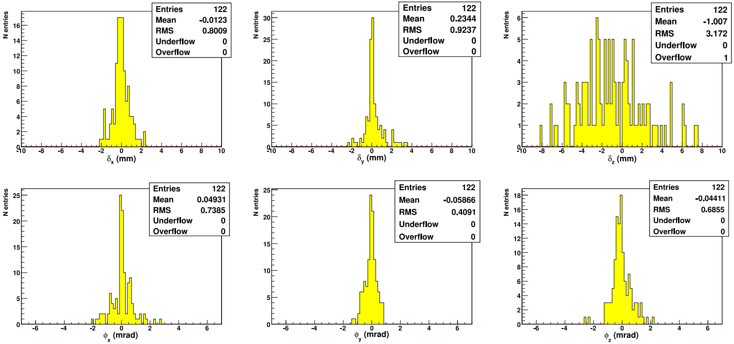


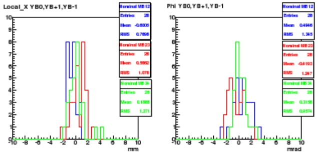
Results: cross-checks

- The only "results" that make sense to show in an alignment paper are cross-checks
  - baselines like IDEAL and "before CRAFT" don't mean anything to an outside reader
- First check: procedures converged (comment in words)
- Second: comparison of the two algorithms

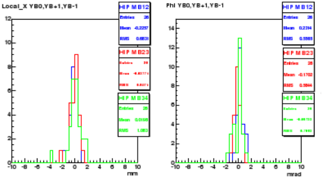


- Scale of differences can be understood from Monte Carlo

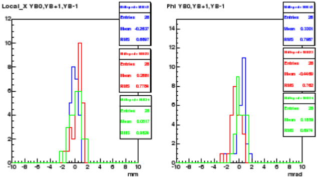
Results: cross-checks



(a) Before global alignment



(b) Results from the HIP algorithm

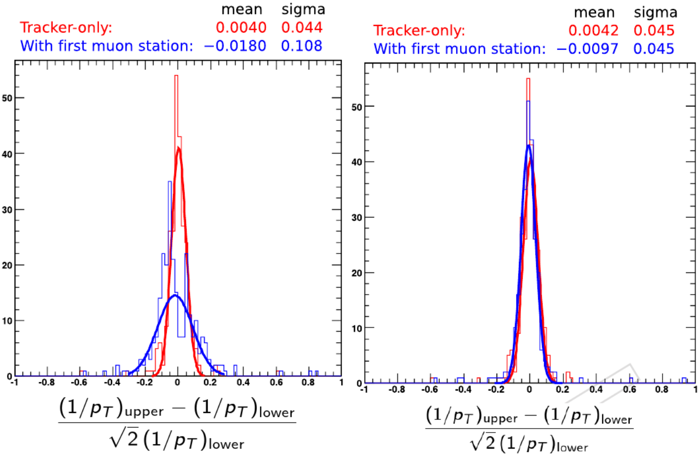


(c) Results from the MillePede algorithm

- Third check: extrapolation of segments between neighboring chambers
  - local track data is partly independent of global track data
- Procedure:
  1. group chambers into pairs in neighboring stations, same sector
  2. select $p_T > 50$ GeV segments
  3. collect differences in extrapolated $r\phi$ positions and angles
  4. correct for non-linearity of tracks by averaging μ^+ and μ^- results
  5. peak of each chamber-pair distribution is an entry in the histograms

Results: cross-checks

- Fourth check: momentum resultion from cosmic track splitting



(a) Before global muon alignment (b) Results from the HIP algorithm

Figure 13: Top vs. bottom $1/p_T$ comparison for $p_T \gtrsim 200$ GeV split cosmic rays.

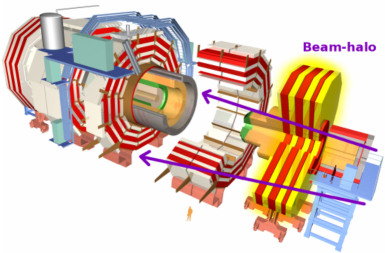
Conclusions (of this talk)

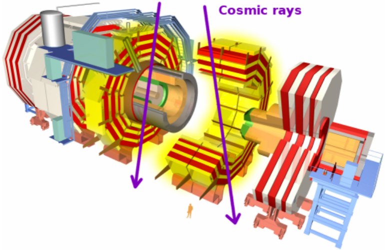
- I hope I've given you a good overview of what is in the paper and a chance to ask questions/raise issues about it in person
- To answer questions about the content of the paper itself, I've attached a set of slides on the content, to use as backup

Backup

Outline

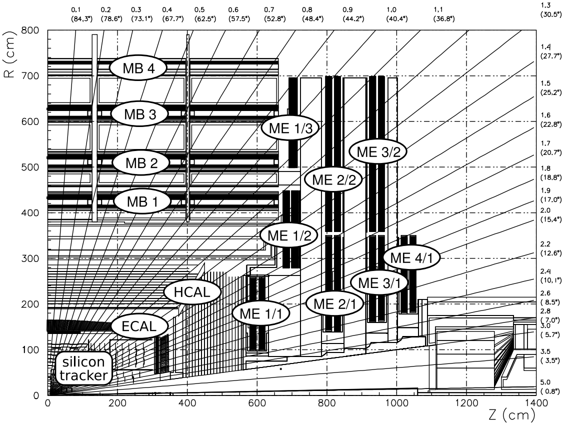
- Quick overview of the CMS muon system
- Alignment strategies
- Endcap results with 2008 LHC beam-halo
- Barrel results with CRAFT cosmic rays





CMS muon system

- Tracking in modular chambers: 6 to 12 layers each
- Global track formed from chambers' segments and the silicon tracker



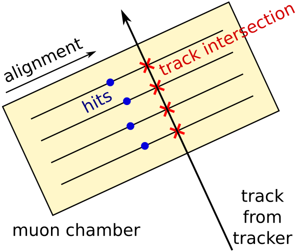
- Barrel (drift tube) chambers grouped into 4 radial stations, 5 longitudinal wheels
- Endcap (cathode strip) chambers grouped into 8 rings per endcap

- This talk will be about aligning the individual chambers
- Target for alignment is scale of $r\phi$ hit resolutions: $\mathcal{O}(100\text{–}300\ \mu\text{m})$

Alignment Strategy

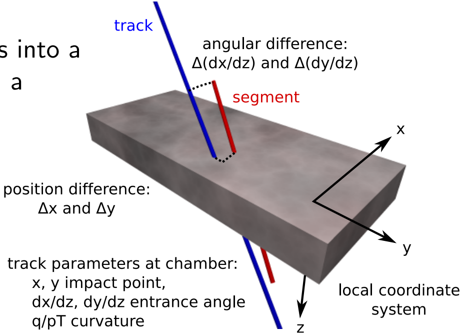
- Consideration: Tracks measured with high precision in the silicon tracker, then pass through thick layers of iron (solenoid return yoke)
  - resolution of global tracks is dominated by tracker data (for $p_T \lesssim 200$ GeV in barrel, $p_T \lesssim 500$ GeV in endcap)
  - scattering in iron can be confused for misalignment with a single track, but scattering is random; misalignment is systematic

- Strategy: fit tracks to the tracker only, then propagate to the muon system
  - misalignment given by the *peak* of the residuals distribution (residual = track − hit)
  - control for propagation effects: material budget, $\vec{B}(\vec{x})$, etc. have different dependencies on momentum and charge



- Consideration: no obstacles to track-fits inside the chambers
  - gas volume with negligible scattering
  - low magnetic field: field lines follow iron yoke between chambers

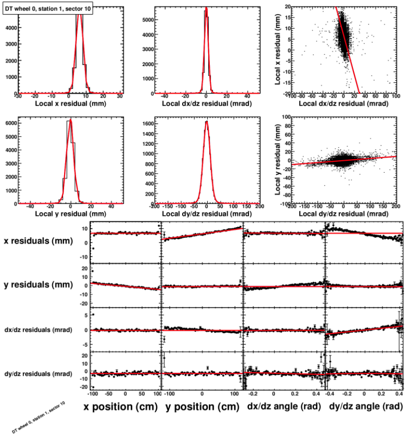
- Strategy: combine residuals into a 2-D position difference and a 2-D angle difference (4-component "residuals")



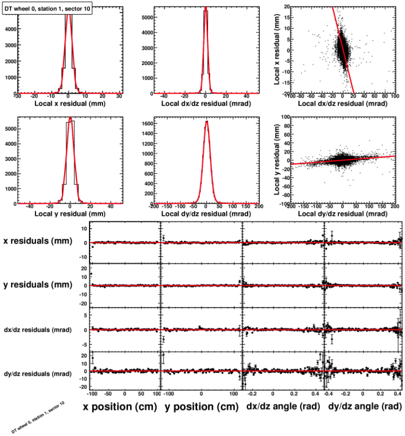
  - more highly constrained than traditional approach
  - compute 6 rigid-body degrees of freedom (3 translations and 3 rotations) from inversion of 6×4 matrix, rather than 6×2

Sample fits: Monte Carlo

Before alignment



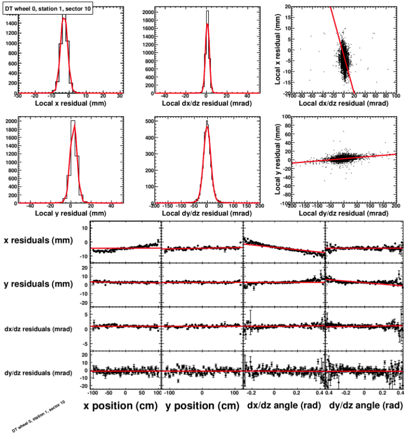
After alignment



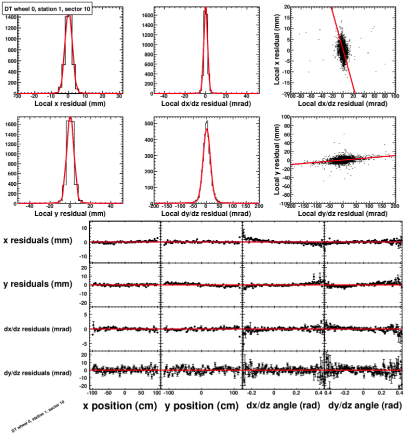
- Projection of fits (all parameters = 0 other than the one shown) overlaid on *simulated* data for one chamber
- Method works well in Monte Carlo

Sample fits: real cosmic rays

Before alignment



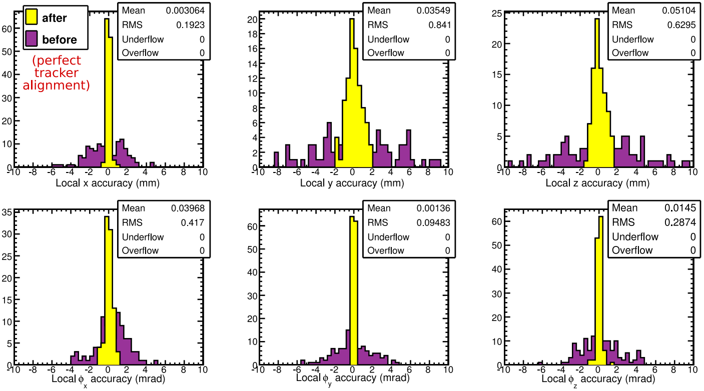
After alignment



- Projection of fits (all parameters = 0 other than the one shown) overlaid on *real* data for the same chamber
- Largely the same behavior in data; studying small discrepancies

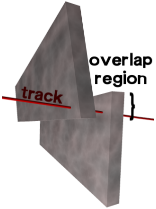
Monte Carlo accuracy

- Plot aligned-minus-true value of each of the 6 parameters for every chamber (histogram entries are chambers)
  - achieved 100–300 μm goal in $r\phi$ (local x coordinate: top-left)
  - systematics-dominated event sample

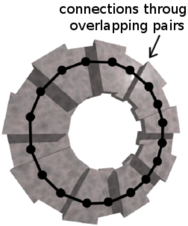


Note: this is a study of the muon alignment only, given a perfectly-aligned silicon tracker for input tracks.

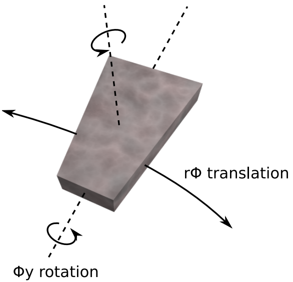
- Consideration: Complimentary information available from global and local track propagations
  - propagation from the silicon tracker conveys information about the global CMS coordinate system
  - propagation from one chamber to its neighbor is less susceptible to scattering
  - partially-independent datasets from the same muons!
- Strategy: Develop alignment methods for both and cross-check
  - in the endcap, Cathode Strip Chambers (CSCs) overlap along their edges
  - propagate relative alignment information through all overlapping CSC pairs
  - provides a complete alignment within a consistent local coordinate system



Alignment from CSC Overlaps

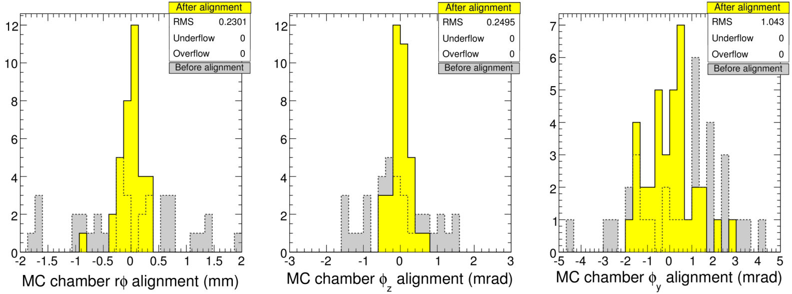


- Align a ring of CSCs with only local tracks by solving a system of 18 or 36 equations (for 18, 36 chambers per ring)
- Apply to 3 degrees of freedom



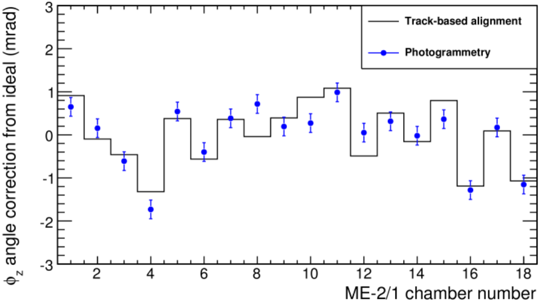
Monte Carlo accuracy

(statistics limited, similar sample size as data)

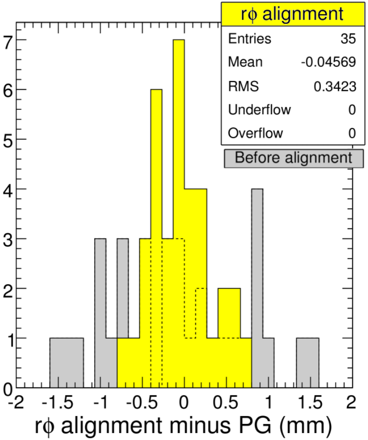


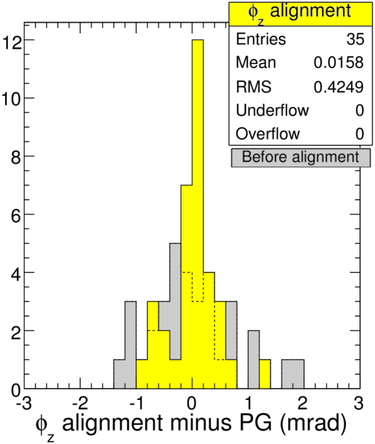
- Captured a total of 12 minutes of LHC muons, Sept 10–19, 2008
- Enough to align CSC rings closest to the beamline (33,000 events in overlapping edges)
- Local alignment cross-checked by photogrammetry: measurements from a literal photograph of the detector

Both methods observed (expected) differences with respect to the design geometry, with high correlation



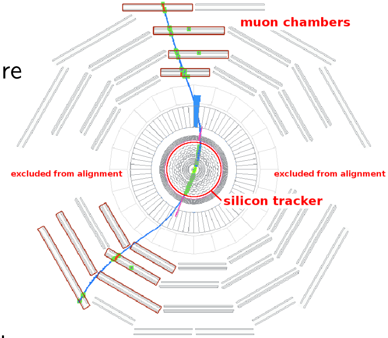
- Chamber-by-chamber comparisons with photogrammetry (PG):
  - agreement with 270 μm position and 0.35 mrad angular accuracy
  - for these chambers, intrinsic hit uncertainty is 166 μm
  - statistics-limited: reach $\sigma_{\text{align}} \lesssim \sigma_{\text{hits}}$ with an hour of beam





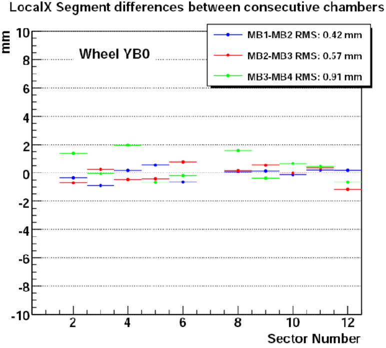
- Cosmic Rays At Four Tesla (CRAFT): 1 month of cosmic rays
  - all systems taking data concurrently: can align major subsystems relative to one another
  - solenoid at full field (3.8 T): can select high-momentum tracks

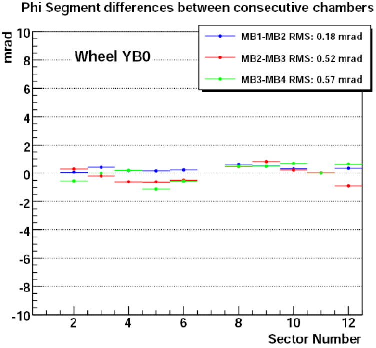
- Applied global alignment procedure to top and bottom of barrel (central 3 wheels, 10/12 sectors, due to vertical distribution of cosmic rays)



- Data and MC are both systematics-limited in most chambers

- Cross-check of global alignment with local data
  - propagate chamber segments through only one layer of iron with aligned geometry, check for consistency
  - RMS of differences: 0.42 mm, 0.18 mrad for innermost chambers



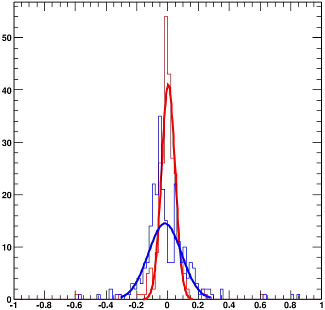


CRAFT cosmic ray data

- High-level test: 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

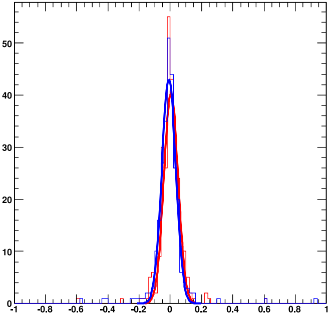
	mean	sigma
Tracker-only:	0.0040	0.044
With first muon station:	−0.0180	0.108



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

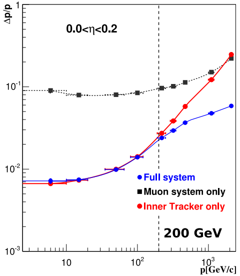
After muon alignment

	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

- Alignment strategy tailored to unique characteristics of the CMS muon system
- Procedures are well-understood in Monte Carlo, with reasonably good agreement with data
- Different methods based on global and local data for cross-checks
- Demonstrated excellent performance in beam-halo and cosmic rays: a good sign for alignment with first collisions!