Alignment of the CMS muon system with tracks

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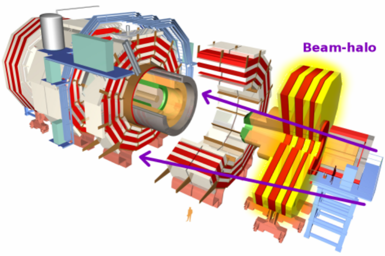
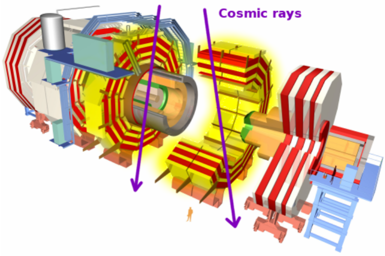
on behalf of the CMS Collaboration

30 July, 2009

Outline

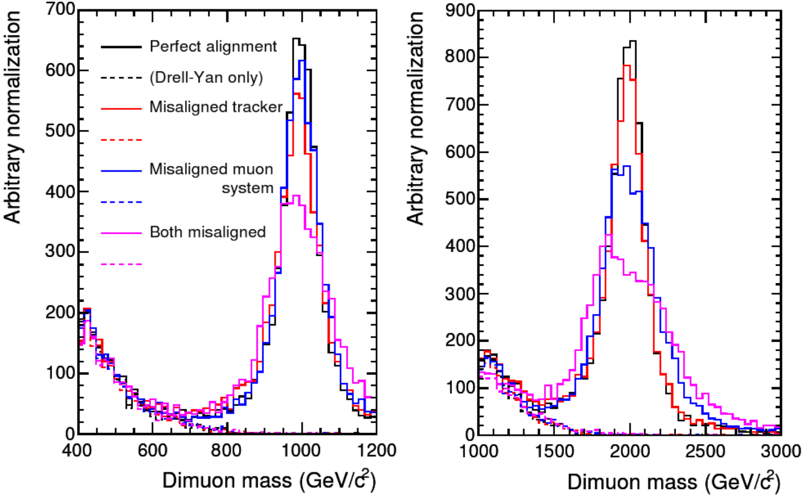
- Motivation for muon alignment
- Quick overview of the CMS muon system
- Alignment strategies
- Endcap results with 2008 LHC beam-halo
- Barrel results with CRAFT cosmic rays





Example physics case

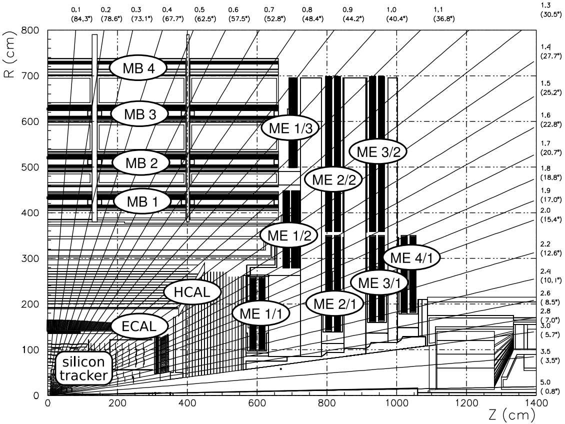
$Z' \to \mu\mu$ peak significance depends on resolution, and hence alignment



Importance of muon alignment (blue) increases with muon energy

CMS muon system

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



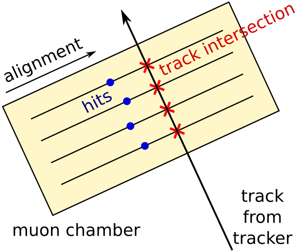
- Barrel (drift tube) chambers grouped into 4 radial stations, 5 longitudinal wheels
- Endcap (cathode strip) chambers grouped into 8 rings per endcap

- 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

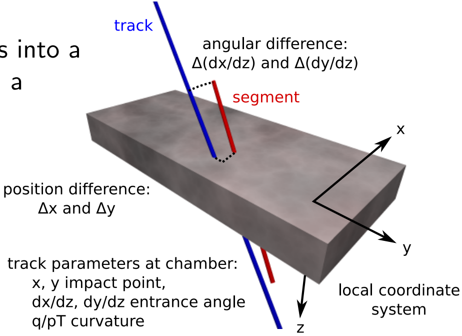
- Consideration: Tracks measured with high precision in the silicon tracker, then pass through thick layers of iron (solenoid return yoke)
  - resolution of global tracks is dominated by tracker data (for $p_T \lesssim 200$ GeV in barrel, $p_T \lesssim 500$ GeV in endcap)
  - scattering in iron can be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



Alignment Strategy

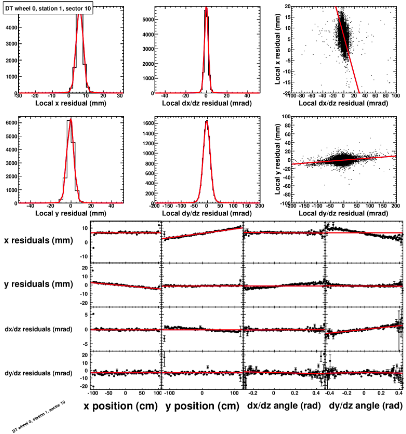
- **Consideration:** no obstacles to track-fits inside the chambers
  - gas volume with negligible scattering
  - low magnetic field: field lines follow iron yoke between chambers
- **Strategy:** combine residuals into a 2-D position difference and a 2-D angle difference (4-component "residuals")



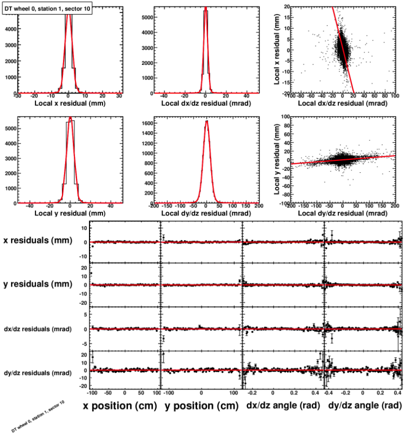
  - more highly constrained than traditional approach
  - compute 6 rigid-body degrees of freedom (3 translations and 3 rotations) from inversion of 6×4 matrix, rather than 6×2

Sample fits: Monte Carlo

Before alignment



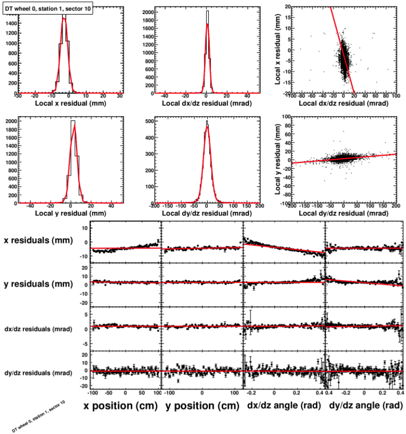
After alignment



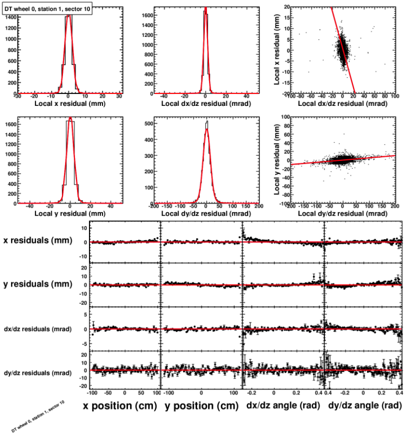
- Projection of fits (all parameters = 0 other than the one shown) overlaid on *simulated* data for one chamber
- Method works well in Monte Carlo

Sample fits: real cosmic rays

Before alignment



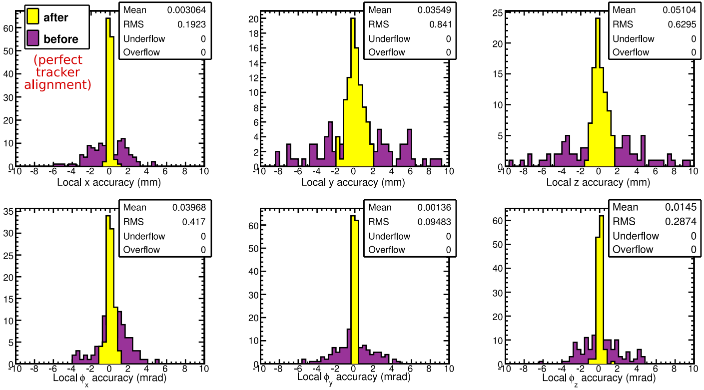
After alignment



- 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

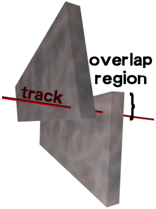
- Plot aligned-minus-true value of each of the 6 parameters for every chamber (histogram entries are chambers)
  - achieved 100–300 μm goal in $r\phi$ (local x coordinate: top-left)
  - systematics-dominated event sample



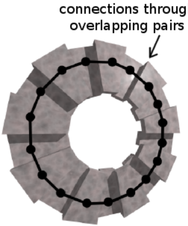
Note: this is a study of the muon alignment only, given a perfectly-aligned silicon tracker for input tracks.

Alignment Strategy

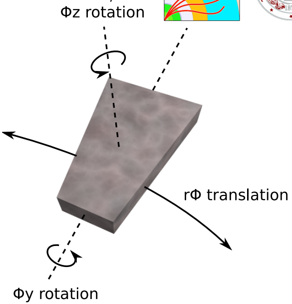
- Consideration: Complimentary information available from global and local track propagations
  - propagation from the silicon tracker conveys information about the global CMS coordinate system
  - propagation from one chamber to its neighbor is less susceptible to scattering
  - partially-independent 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

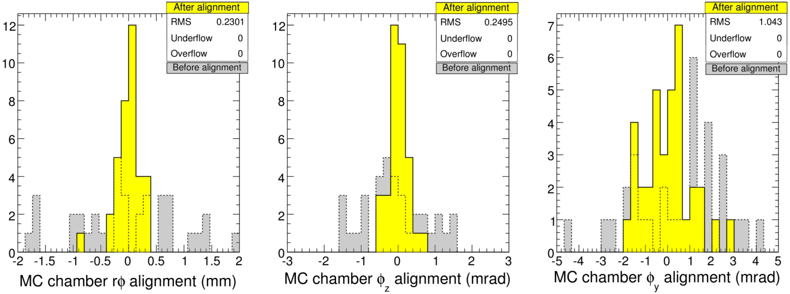


- Align a ring of CSCs with only local tracks by solving a system of 18 or 36 equations (for 18, 36 chambers per ring)
- Apply to 3 degrees of freedom



Monte Carlo accuracy

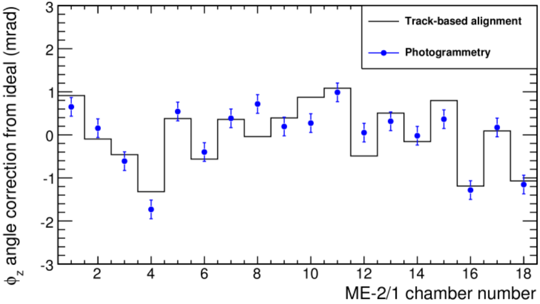
(statistics limited, similar sample size as data)



2008 LHC beam-halo data

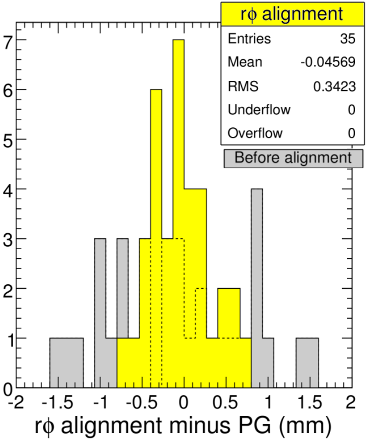
- Captured a total of 12 minutes of LHC muons, Sept 10–19, 2008
- Enough to align CSC rings closest to the beamline (33,000 events in overlapping edges)
- Local alignment cross-checked by photogrammetry: measurements from a literal photograph of the detector

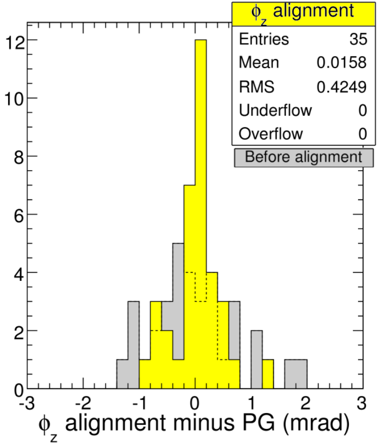
Both methods observed (expected) differences with respect to the design geometry, with high correlation



2008 LHC beam-halo data

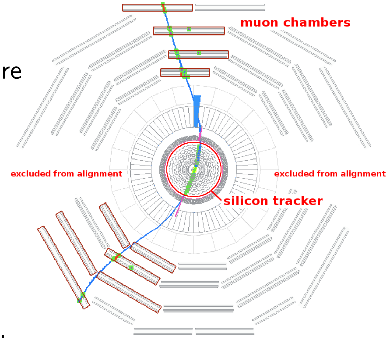
- Chamber-by-chamber comparisons with photogrammetry (PG):
  - agreement with 270 μm position and 0.35 mrad angular accuracy
  - for these chambers, intrinsic hit uncertainty is 166 μm
  - statistics-limited: reach $\sigma_{\text{align}} \lesssim \sigma_{\text{hits}}$ with an hour of beam





- 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

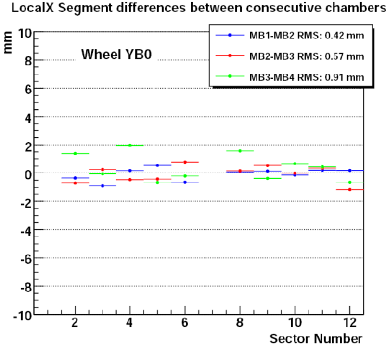
- Applied global alignment procedure to top and bottom of barrel (central 3 wheels, 10/12 sectors, due to vertical distribution of cosmic rays)

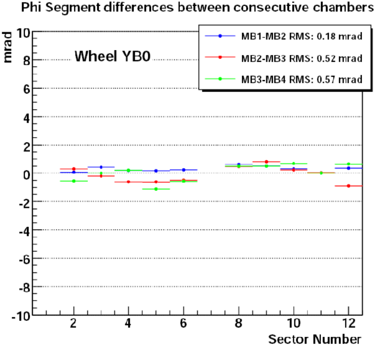


- Data and MC are both systematics-limited in most chambers

CRAFT cosmic ray data

- 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



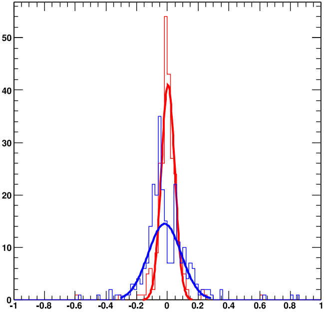


CRAFT cosmic ray data

- 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

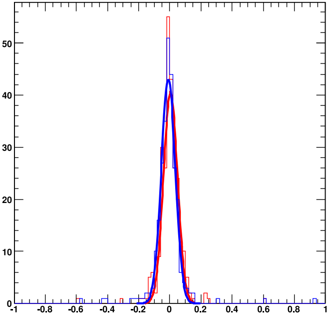
	mean	sigma
Tracker-only:	0.0040	0.044
With first muon station:	−0.0180	0.108



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

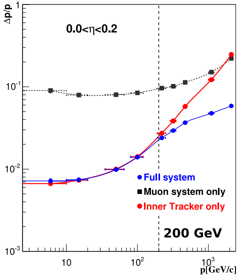
After muon alignment

	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!