Alignment of the CMS muon system with beam halo and cosmic muon tracks

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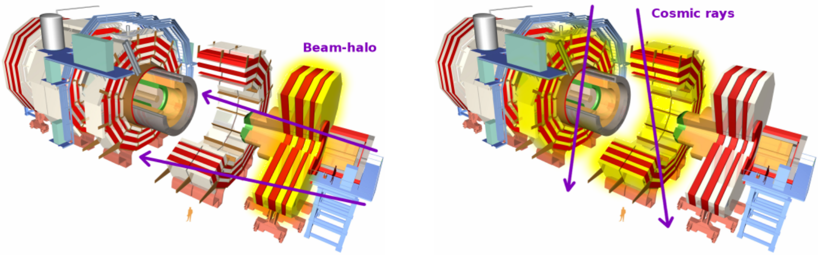
on behalf of the CMS Collaboration

15 June, 2009

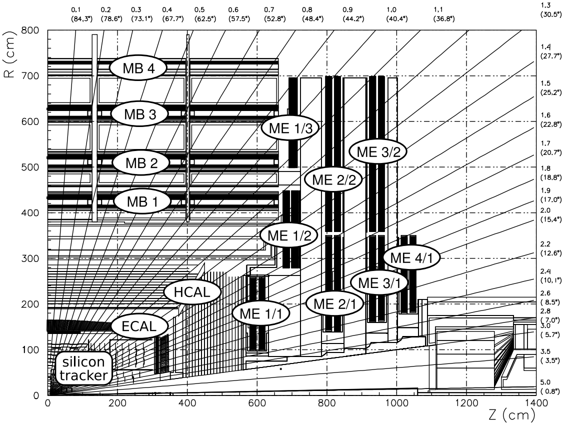
Outline

- Quick overview of the CMS muon system
- Alignment of endcap chambers with LHC beam-halo tracks
- Alignment of barrel chambers 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

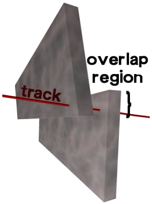


- Barrel (drift tube) chambers grouped into 4 radial stations, 5 longitudinal wheels
- Endcap (cathode strip) chambers grouped into 8 rings per endcap

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

Beam-halo alignment method

- Endcap muon chambers were designed with a small overlap region for alignment
- Tracks passing through overlap region connect chambers without any intervening scattering material or long-distance propagation
- High-precision relative alignment of chamber pairs



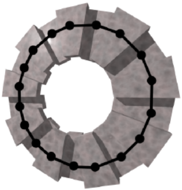
- Propagate pair corrections around each ring with a simultaneous solution of 18 (36) equations $\times$ 3 parameters (1 translation, 2 angles)

pair-wise residuals

alignment corrections

$$\chi^2 = (\alpha_{12} - A_1 + A_2)^2 + (\alpha_{23} - A_2 + A_3)^2 + \ldots$$

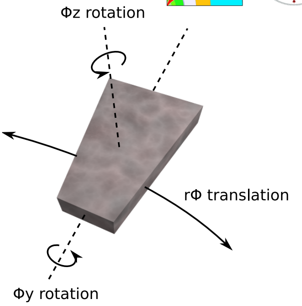
$$\frac{1}{2}\frac{\partial \chi^2}{\partial A_2} = (\alpha_{12} - A_1 + A_2) - (\alpha_{23} - A_2 + A_3) = 0$$

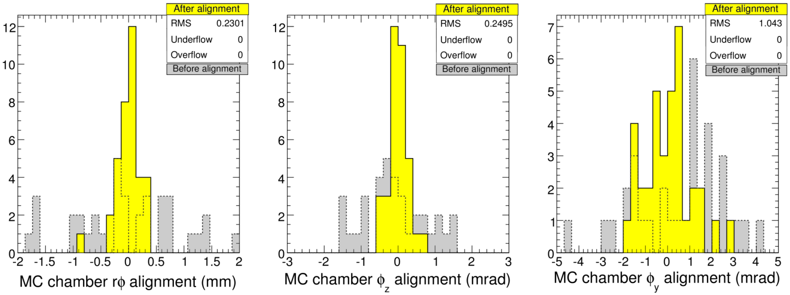


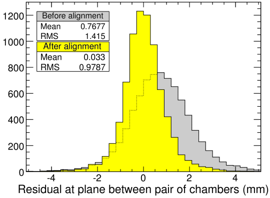
- Followed by rigid-body alignment of internally-aligned ring with global tracks, to connect ring's coordinate system to silicon tracker

Test of method in Monte Carlo

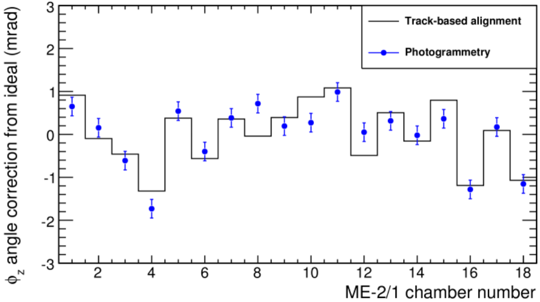
- Procedure applied to Monte Carlo sample with statistics comparable to 2008 LHC single-beam run
- Plot aligned-minus-true value for each of the 3 parameters, for every chamber (histogram entries are chambers)
  - RMS is the accuracy predicted by MC





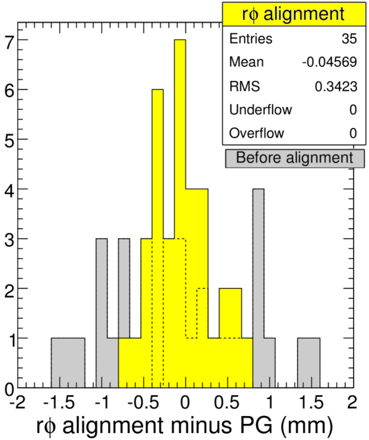


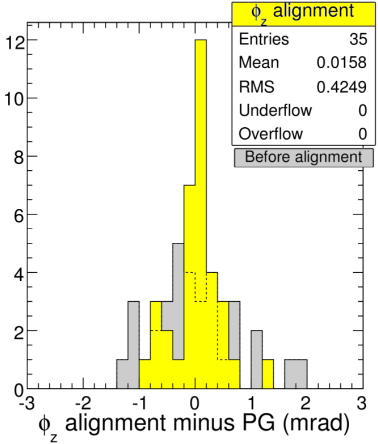
- Procedure applied to September 2008 LHC beam-halo dataset
- ME−2/1 and ME−3/1 only (highest statistics from beam-2)
- Narrows and centers residuals distribution (left)
- Verified by independent photogrammetry: alignment from a literal photograph of the detector
- Both saw corrections relative to the design description, with high correlation



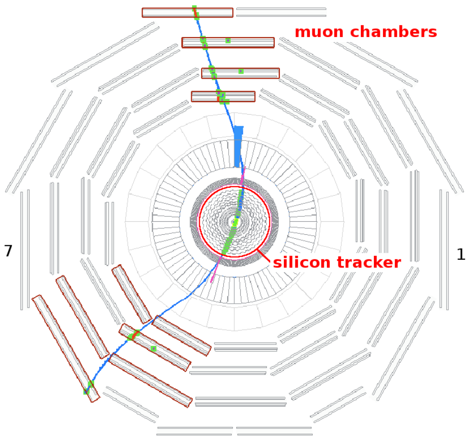
2008 LHC beam-halo data

- Chamber-by-chamber comparisons with photogrammetry (PG):
  - agreement with 270 μm position and 0.35 mrad angular accuracy
  - close to the 166 μm intrinsic hit uncertainty (for these chambers)
  - 33,000 events from a 9-minute long run ($\frac{3}{4}$ of 2008 beam data)





Global muon alignment



Goal

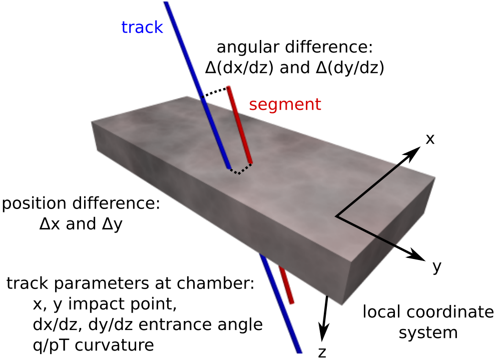
- Obtain consistent, CMS-wide coordinate system in one step

Method

- Select tracks that pass through muon chambers and tracker
- Fit track using tracker information only
- Align chamber to optimize residuals

- Can be applied to all chambers using collisions muons, and most barrel chambers with CRAFT cosmic rays (central wheels −1, 0, +1, all sectors except the horizontal ones: 1 and 7)

Chamber residuals



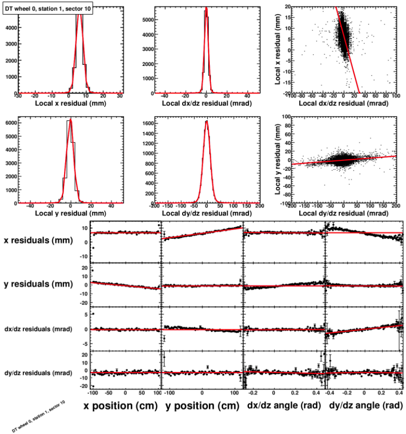
- Chamber measures 2-D position and direction: 4-component residuals
- Access to 6 rigid-body alignment parameters (3 translation, 3 rotation) through a 6×4 derivatives matrix

Alignment fit

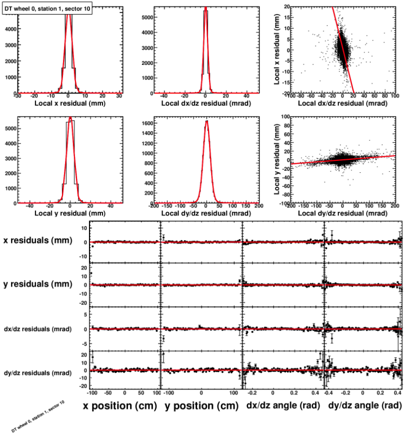
- Single fit function for each chamber, including all geometric and propagation effects
- Project 8-dimensional, 16-parameter fit onto all coordinates for validation

Sample fit results: MC

Before alignment



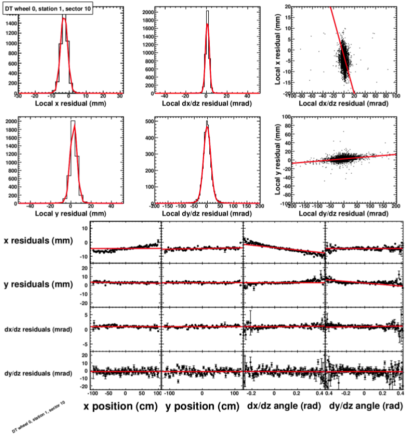
After alignment



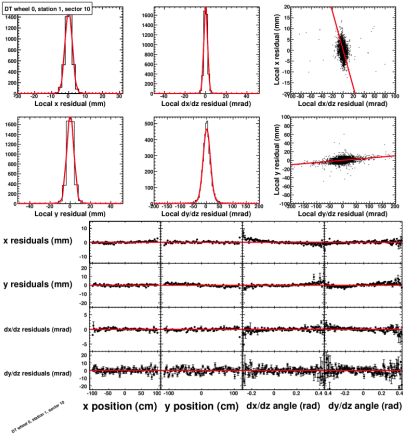
- Projection of fits (all parameters = 0 other than the one shown) overlaid on *simulated* data (profile plots) for one chamber
- Method works well in Monte Carlo

Sample fit results: CRAFT data

Before alignment



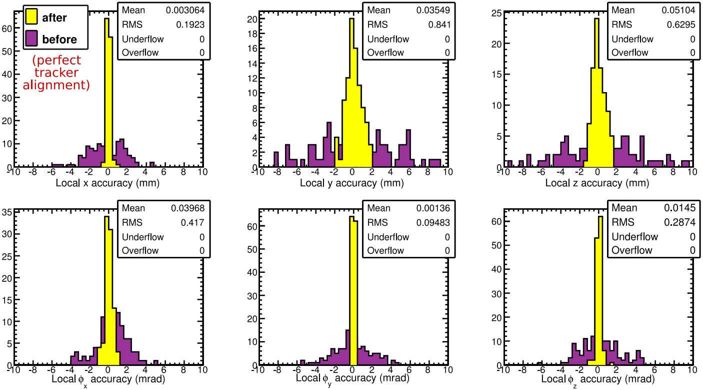
After alignment



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

MC cosmic ray results

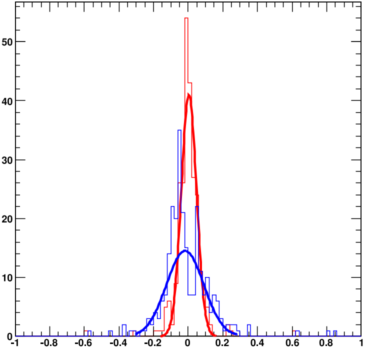
- Plot aligned-minus-true value of each of the 6 parameters for every chamber (histogram entries are chambers)
  - predicted resolution for local x (global $r\phi$) is 200 μm
  - CRAFT and MC are both systematics dominated
- MC tracker geometry is ideal: this demonstrates the reach of the muon alignment method, given a well-aligned tracker



- Split $p_T \gtrsim 200$ GeV cosmic rays into upper and lower halves, refit each half independently and compare the results
- Two track-fits for each cosmic ray: any mismatch is instrumental

Before muon alignment

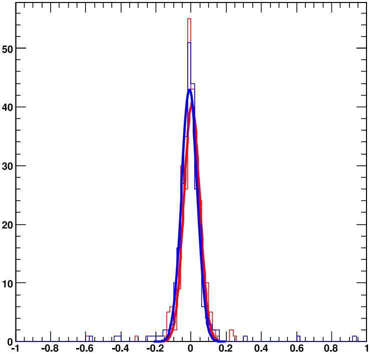
	mean	sigma
Tracker-only:	0.0040	0.044
With first muon station:	−0.0180	0.108



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

After muon alignment

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

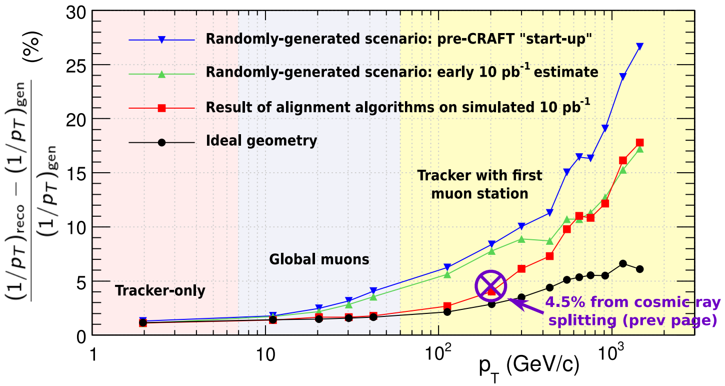


$$\frac{(1/p_T)_{\text{upper}} - (1/p_T)_{\text{lower}}}{\sqrt{2}\,(1/p_T)_{\text{lower}}}$$

Comparison with expectations

- MC resolution vs. p_T with different alignment scenarios
- Track reconstruction method optimized by p_T

  (at high p_T, use only first muon station to avoid hit confusion from muon showering)



- MC simulations yield much better results than early estimates
- Cosmic ray splitting is close to MC simulations at 200 GeV

Conclusions

- Track-based alignment methods were successfully applied to 2008 LHC beam-halo and CRAFT cosmic ray muons
- High resolution predicted by Monte Carlo, supported by data-driven measurements
- Pre-collisions alignments offer significantly improved tracking for the 2009 start-up
- They also demonstrate that tools and procedures are ready for alignment with collisions muons