Muon Alignment with Tracks

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Summary/Outline

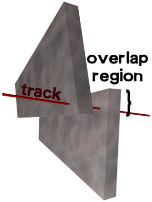
- CSC Overlaps procedure in beam-halo data
  - Reached 300 μm accuracy!
  - Verified with photogrammetry
  - Everything makes sense in MC
  - Led to the discovery of a 10 μm (compounded) error in the geometry description
- A first look at layer alignment with CSC Overlaps
- Wheel/disk alignment in CRAFT
  - Delivered a working system on time
  - Diagnostic of results: dependence on tracker, $\vec{B}$ error
  - Using muon residuals to measure bulk tracker misalignment
- Update on database comparison tool and photogrammetry database

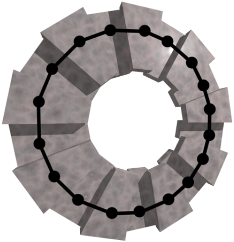
CSC Overlaps Alignment

- Baseline alignment procedure shown to require 10–100 pb^{-1} for a few hundred micron precision
- Quicker alternative:
  1. relative alignment of chambers in each ring (CSC Overlaps)
  2. align whole ring relative to tracker with a small number of quality globalMuon tracks
- Particularly good for layer alignment

Overlaps chamber alignment:

1. select tracks that pass through overlap of chambers in a ring
2. require consistency in pair of segments: slope and intercept
3. solve system



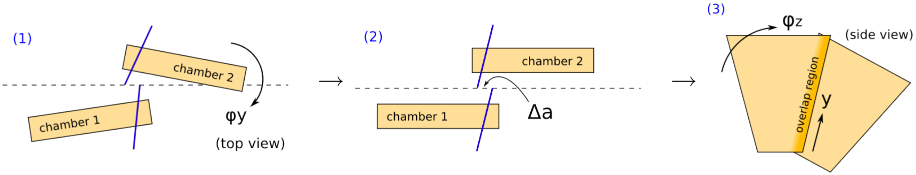


System is over-constrained: must be consistent with a circle ("closure")

Three-step procedure

Interdependencies between alignment parameters are unidirectional

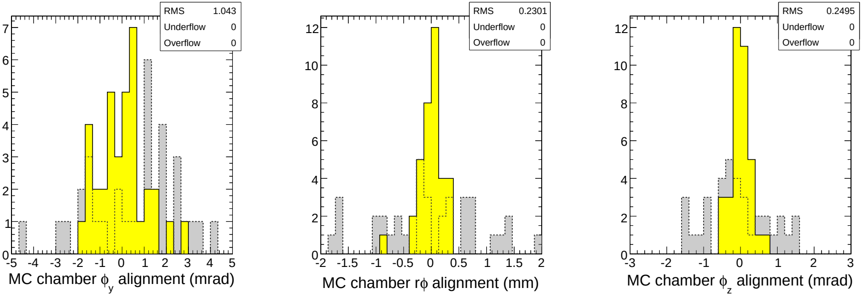
0. Fit segment of track in each chamber to $\phi(z) = a + bz$
1. Align φ_y angles (rotation around vertical axis) $\Delta b \to 0$
2. Align $r\phi$ positions (rotation around beamline) $\Delta a \to 0$
3. Align φ_z angles (rotation in the detector plane) $d(\Delta a)/dy \to 0$



- Parameters decouple when aligned in this order (for example, φ_y depends only on Δb, but $r\phi$ depends on Δa and Δb)
- These are all of the rigid-body parameters accessible to overlaps tracks

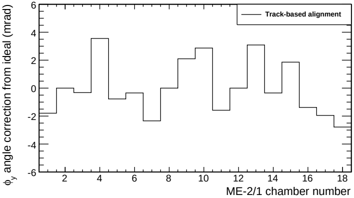
Demonstration in Monte Carlo

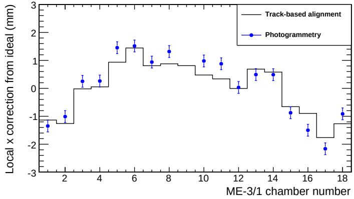
- Randomly misalign chambers and apply procedure using beam-halo Monte Carlo
  - statistics are roughly the same as September beam-halo
  - some chambers have more tracks, others less because ϕ distribution not perfectly modeled
- Plot aligned position minus true position in simulation (resolution)
- Unaligned is grey, aligned is yellow; one histogram entry per chamber
  - $\delta\varphi_y \sim 1$ mrad, $\delta r\phi \sim 230$ μm, $\delta\varphi_z \sim 0.25$ mrad

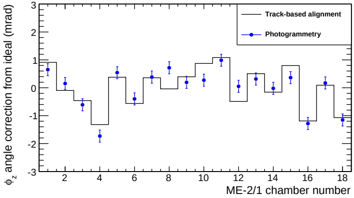


Alignment in real data

- Aligned ME$-2/1$ and ME$-3/1$ using beam-halo data
- Compared with photogrammetry
  - only track-based alignment sensitive to φ_y (only two alignment pins)
- Plot corrections relative to ideal geometry for each chamber
  - track-based: solid histogram
  - photogrammetry: blue points
- Physical misalignments are $\sim$2 mrad in φ_y, 1 mm in $r\phi$, and 1 mrad in φ_z
- Corrections from independent methods follow each other closely

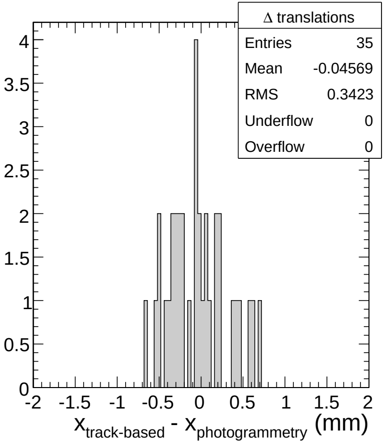


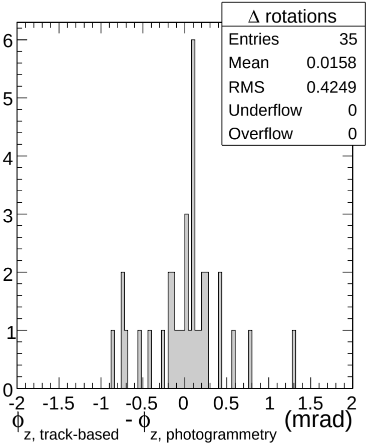




Determine accuracy from PG

- RMS difference between track-based and PG: 340 μm, 0.42 mrad
- Photogrammetry $r\phi$ uncertainty is $(300/\sqrt{2})\ \mu\text{m} = 210\ \mu\text{m}$
- $r\phi$ errors in track-based method alone $= \sqrt{340^2 - 210^2} = 270\ \mu$m
- φ_z errors $= \sqrt{0.42^2 - (0.3 \cdot \sqrt{2}\ \text{mm}/1.85\ \text{m})^2} = 0.35$ mrad





Ring consistency (closure)

- Each residual distribution represents the difference in alignment between two chambers
- Must sum to zero: $(x_1 - x_2) + (x_2 - x_3) + \ldots + (x_N - x_1) = 0$
- φ_y and φ_z residuals have always summed to zero ("closed")
- $r\phi$ residuals closed in MC, but not in data
- Agreement with photogrammetry ruled out possibility of alignment mistake; pointed to error in CMSSW chamber description
  - active volume of chambers is 2.5 mm closer to beamline, *or*
  - active volume is 800 μm wider than in description
- Oleg found 10 μm rounding error in strip width description
  - multiplied by $\sim$80 strips $\approx$ 800 μm wider active volume
- Implemented correction; ME$-$2/1, $-$3/1 closure is now perfect!

$$\sum_{\text{chamber } i} (r\phi_i - r\phi_{i+1})$$

	before (mm)	after (mm)
ME$-$2/1	+14.30	-0.72 $\pm$ 0.42
ME$-$3/1	+15.90	-0.36 $\pm$ 0.51

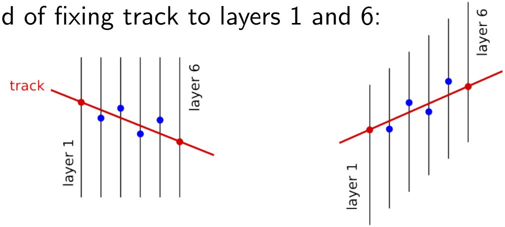
CSC Overlaps conclusions

- Reached goal for ME2,3,4/1 accuracy in real data
- Routine algorithm can align any ring except ME3/1 (no overlaps)
  - requested new CSCOverlapsAlignmentAlgorithm package in CVS
  - important for rings to be complete (no missing chambers): possible to work around a missing chamber by applying external constraints (e.g. straight line monitors)
- Triggers and AlCa paths defined to collect overlaps events from beam-halo and first collisions
  - Collisions muons will provide more uniform ϕ and R coverage
  - Very little data needed: this 300 μm resolution comes from 9 minutes of beam-halo!

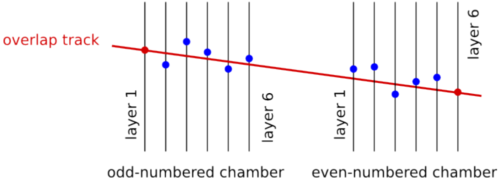
Early Look at CSC Layers

CSC layer alignment

- *First* first look at layer alignment by Karoly in MTCC
- Internal chamber data can only simultaneously determine four layers and a straight track, insensitive to shear
  - method of fixing track to layers 1 and 6:



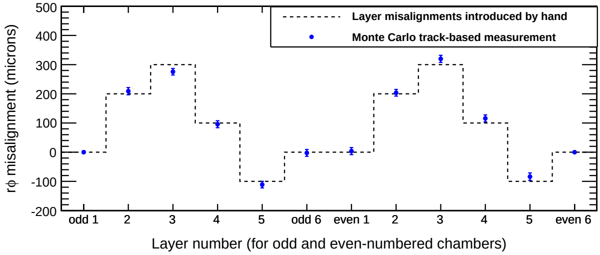
- Overlap events allow us to add one degree of freedom per chamber
  - five layers is enough to describe complete internal alignment



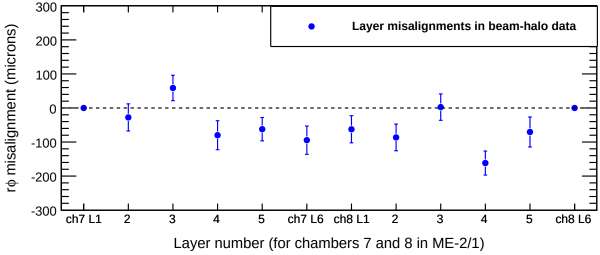
Plots of layer residuals

Test in Monte Carlo with 36× statistics (folded all pairs)

- residuals (blue points) reproduce misalignment pattern (histogram)

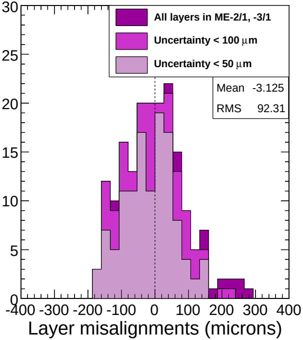


Example in data: chamber 7, layer 1 and chamber 8, layer 6 are fixed



Typical scale and resolution

- Observed ∼100 μm layer misalignments in ME−2/1 and −3/1
  - technique requires chambers to be previously aligned
  - (and must be followed by a chamber re-alignment)
- About half as large as misalignments observed in MTCC (which was ME+)
- Resolution with full beam-halo run is 40–100 μm, hard to see misalignments



- I have not cross-checked these with FAST measurements yet

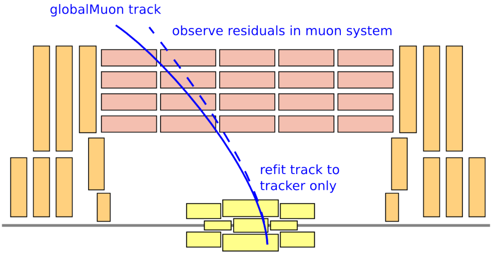
Status and conclusions

- Not yet integrated into an alignment routine: just illustrative plots
- Layers only need to be aligned once
- Definitive CSC layer alignment will probably be done with early collisions

Global Alignment in CRAFT

We have globalMuons!

- First real-data tests of full baseline HIP procedure:
  - select globalMuon tracks
  - refit, ignoring muon hits
  - use unbiased residuals to align wheels/disks/chambers

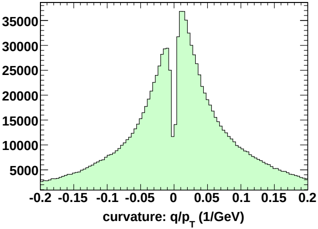


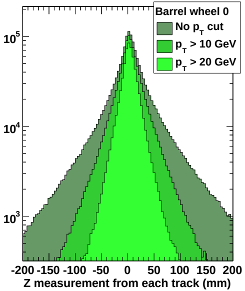
- Features of CRAFT
  - 10s–100s of thousands of globalMuons in barrel
  - thousands in endcap
  - magnetic field to select high momentum, minimize alignment errors due to $\vec{B}$-field error and multiple scattering

- Delivered a functional workflow and constants in time for CRAFT re-reco
  - but constants not fully understood, not used in this re-reco

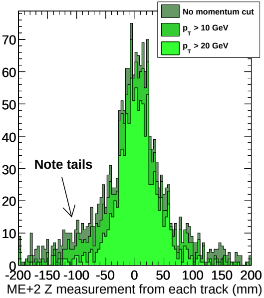
Momentum cut/extrapolation

- $\vec{B}$-field errors and multiple scattering affect low-momentum tracks
- Alignment error $\to 0$ as $|p| \to \infty$
- Plot vs. curvature (q/p_T), fit around 0
  - constant = misalignment
  - antisymmetric in q = $\vec{B}$ errors
  - symmetric in q = scattering

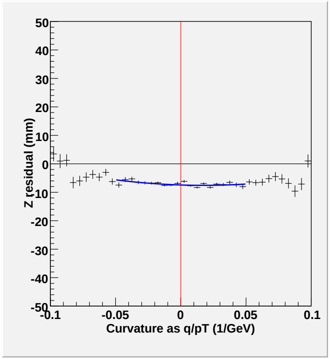




Barrel wheel 0



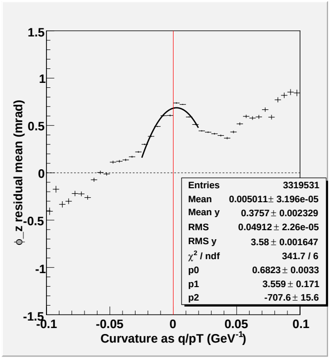
Endcap disk +2



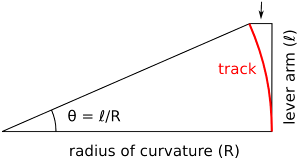
Barrel wheel −2

Measuring the $\vec{B}$-field (aside)

- A method like this can also be used to measure the CMS $\vec{B}$-field
- "ϕ_z residual" ($\approx$ local x residual divided by R) is most influenced by $\vec{B}$-field error at $\eta = 0$
- Can derive $\approx$ 0.0035 T (0.1%) error from slope of wheel 0 alignment plot
  - average scale correction through all stations
  - demonstration of statistical power
- 10% $\vec{B}$-error observed between stations 3 and 4 in a more focused study (Ugo Gasparini)



diff between B(on) and B(off) = gap = R(1 - cosθ) = Rθ² = ℓ²/R



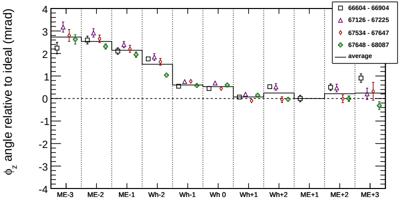
R = (3.3 m) pT/qB

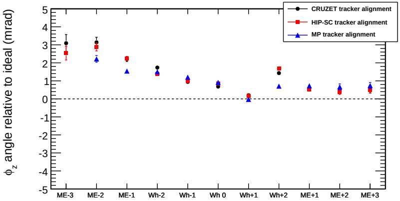
ℓ (p_1) = (gap) pT/q

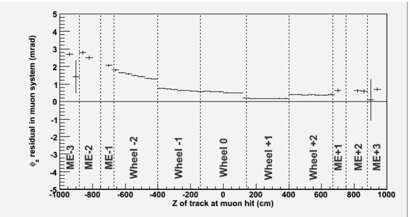
$\boxed{B = (p_1)\ (3.3\ \text{m})/\ell}$

- (Large $\vec{B}$-error in a small region is suppressed by ℓ in the alignment plot)

ϕ_z alignment results

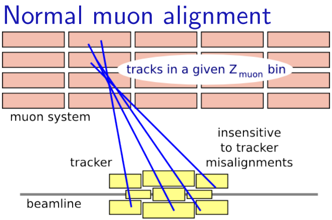


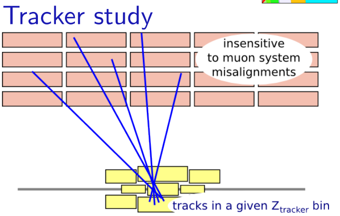




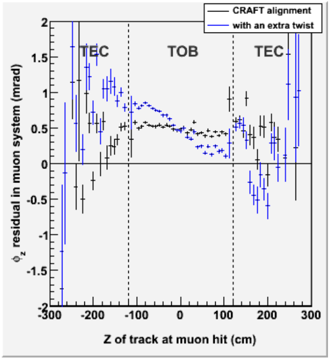
- Aligned ϕ_z for all wheels/disks with the $q/p_T \to 0$ method
- Observed a large (2.5 mrad) twist in the minus endcap
- Reproducible in all
  - stable 3.8 T runs (top plot)
  - tracker alignments (middle) (CRUZET, CRAFT-HIP, CRAFT-MillePede)
  - Muon-MillePede: same effect
- Divide into smaller bins: replace wheel number with z position (bottom plot)
  - real misalignment indicated by discontinuities
  - external bias indicated by variation inside wheels

Check for bias from the tracker

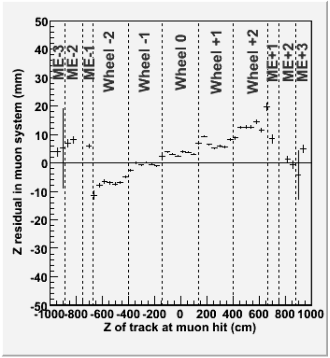




- Broad distribution of cosmic rays averages over the detector at the unconstrained part of the track
- Plot muon ϕ_z residuals vs. Z_{PCA} (black)
- Slope (0.2 mrad across TOB) may indicate a twist in the tracker which gets extrapolated to muon system
- Zijin Guo added a tracker twist by hand (0.6 mrad, blue points): easily observed
- Need to resolve muon and tracker twists simultaneously

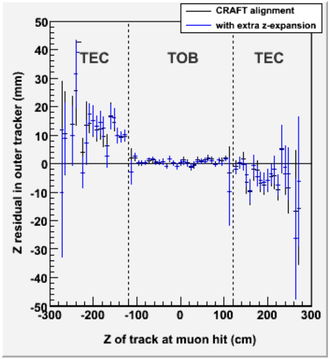


z alignment results



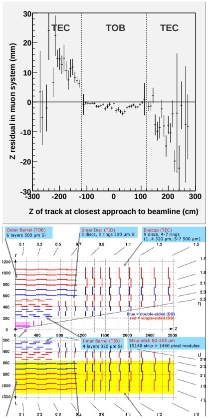
- Effect is large and negative: globalMuons think that the real CMS is *wider* than ideal geometry by 14 mm across barrel (0.2%)

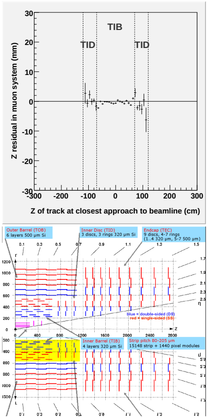
- z-expansion is a weak mode of the tracker, hard to determine with tracks
- Unfortunately, muon residuals can't resolve a plausible z-expansion (black vs. blue: 0.1% tracker stretch)
- But we can see large displacements of TEC relative to TOB (discontinuity)

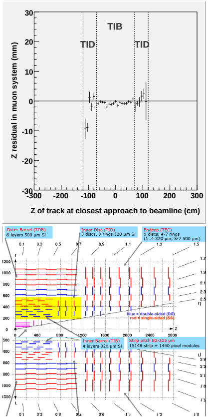


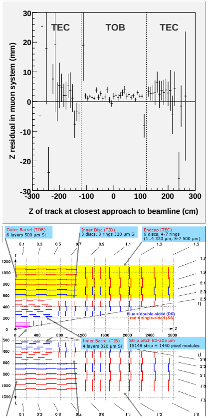
Tracker z alignment study

- Tracker displacements are a scale multiple of muon z residual discontinuities, about 10 times smaller (lever arm of propagation)
- Select parts of the tracker by cutting on R_{PCA} and by removing tracker hits from refit



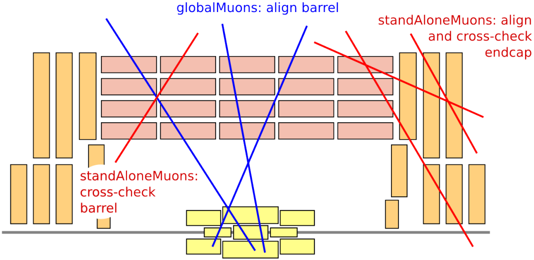






CRAFT conclusions

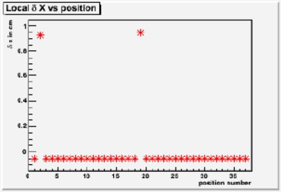
- We have the machinery to produce constants (works in MC, see CSA08)
- Now that we have a large collection of tracks with magnetic field, we can diagnose real-data effects:
  - momentum dependent ($\vec{B}$ error, multiple scattering)
  - dependence on tracker alignment
  - propagator/refitter errors? (not ruled out)
- Comparison with hardware alignment is not the only validation
  - many cross-checks are available in track dataset
- Optimal CRAFT alignment would include standAloneMuons:

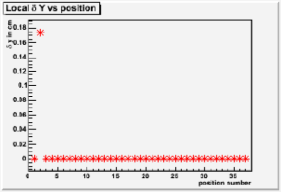


- Awaiting cosmic ray-aware standAloneMuon refitter from tracking group

Updates on Tools

- Database comparison tool (Jim Bellinger)
  - performs *local* comparisons of geometry descriptions: i.e. matches ME2/1 in geometry A to ME2/1 in geometry B, removing overall translation/rotation, showing only chamber-by-chamber differences
  - complete and in CVS (MuonGeometryArrange)





- Conversion of photogrammetry results into CSCAlignmentRcd (Karoly and Oleg)
  - for easier comparison with track-based/hardware alignments (via Jim's tool)
  - for long-term archival
  - most issues resolved: working on z heights of PG targets and sign conventions

Whole-talk conclusions

- The CSC Overlaps procedure really works!
  - we *will* be able to align complete rings in 3 d.o.f. with desired precision
  - built-in consistency check revealed a geometry error that was quickly fixed
- Overlaps provide a path to CSC layer alignment
- Baseline alignment workflow is functional, but produces puzzling results
  - muon alignment, $\vec{B}$-field commissioning, and tracker alignment, are interrelated but seperable
  - track dataset is rich enough to contain many cross-checks; standAloneMuons will reveal more
- Database comparison tool is ready for use (and is being used)
- Photogrammetry results will be uploaded to the offline database