Track-based Alignment of the Muon System

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- The big, big picture: two groups studying alignment of the muon system, following complementary approaches of HIP and MillePede algorithms (just as in tracker alignment)

- Traditionally associated with DT and CSC, but as we integrate CMS, we'll need to be more clearly associated with our approaches and ability to cross-check each other, rather than our subdetectors

- At this stage, we have both learned a lot about our respective subdetectors with CRUZET and beam-halo data; that's what I'd like to present to you, but focusing on the work I know best

- Overview
  - DT intra- and inter-wheel alignment with cosmic rays
  - Alignment of muon chambers, CSC disks to a fixed reference
  - Precision interalignment of CSC chambers with beam-halo

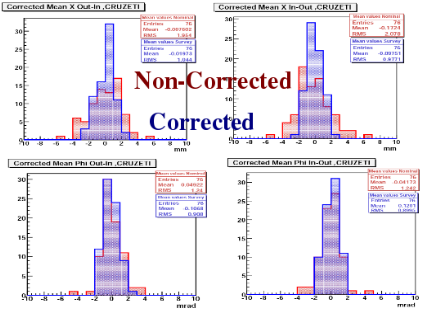
Barrel Alignment in CRUZET

DT Muon Alignment

P. Martínez, F. Matorras (IFCA), A. Calderón (INFN)

- Three levels of alignment:
  - Included in the current DB's
    - Internal geometry of chambers
    - Chambers inside the wheels
  - Being validated
    - Wheel-To-Wheel alignment (next page)

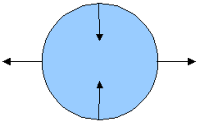
Local X displacement

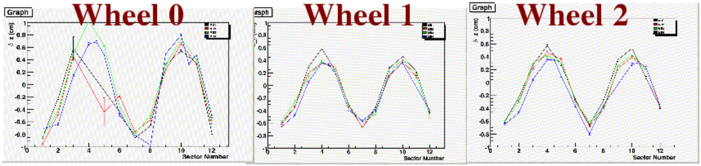


Rotation w.r.t. Local y axis

From 2 mm to 1 mm improvement

Shape of the misalignment



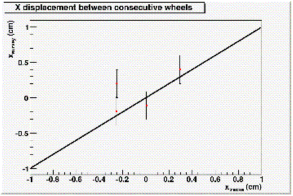


The correlation of local delta_Z with sector number indicates a gravitational sag

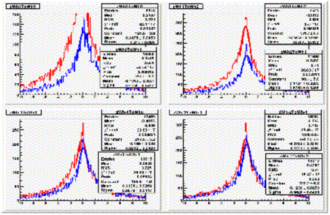
DT Muon Alignment

P. Martínez, F. Matorras (IFCA), A. Calderón (INFN)

- Wheel to wheel alignment:
  - **Geometry produced using Survey measurements**
  - **Geometry produced using only tracks**



Comparison with survey: agreement within the errors except for YB-2 (under investigation)



Calculation of relative Z displacement between consecutive wheels Wn to Wn+1 and Wn+1 to Wn. Agreement to the 400 microns level.

Repeating wheel to wheel aligment with B field

- Software status:
  - **The Millepede-like algorithm (MuonStandaloneAlgorithm package) is being ported to the common alignment framework**
  - **Classes integrated in the common framework has been created to deal with 4DSegments: Derivatives, AlignmentParameters**
  - **Final step (to do): rewrite the algorithm using these new tools**

HIP and Endcap Alignments

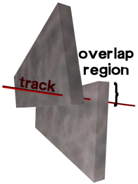
HIP-based program

- Long-term plan is to fit muon track parameters to the tracker only and align muon chambers relative to fixed tracks
  - uncorrelates objects on the same wheels, disks
  - yields tracker-muon interalignment
- However,
  - depends on tracker alignment unless tracking volume sufficiently averaged over (e.g. with cosmic rays: see CSA08 results)
  - we should not wait for a large collisions sample to start!
- Short-term plan:
  - Take advantage of overlapping edges of CSCs to align rings (this talk)
  - Align rings to tracker or muon barrel as rigid bodies with HIP

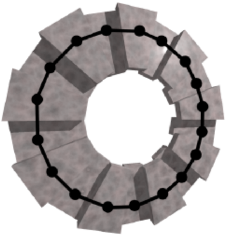
    Demonstrated last CMS Week, we have since followed the movement of CSC disks through all opening and closing and published result in the database for CRUZET reprocessing
- Medium-term plan:
  - Align chambers to tracker in CRUZET-3/4 or CRAFT (better)

CSC overlaps alignment

- Locally reconstruct tracks through overlapping CSC edges
- Essentially no multiple scattering, but sensitive to small effects (no averaging over a large volume)
- Need to reconstruct whole ring of alignment corrections A_i from pairwise residuals $\alpha_{i,i+1}$



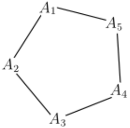
- Methods:
    - Propagate one at a time: simple diagnostic, but error is cumulative
    - Iterate many times: generates 1-D waves (can be dampened)
    - Solve for global best-fit: only an 18×18 or 36×36 matrix



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

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

$$\begin{pmatrix} 0 \\ \alpha_{23} - \alpha_{12} \\ \alpha_{34} - \alpha_{23} \\ \alpha_{45} - \alpha_{34} \\ \alpha_{51} - \alpha_{45} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ -1 & 2 & -1 & & \\ & -1 & 2 & -1 & \\ & & -1 & 2 & -1 \\ -1 & & & -1 & 2 \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \end{pmatrix} \quad \text{for}$$

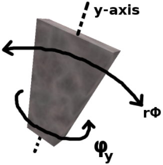


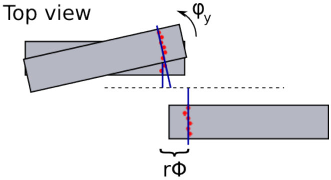
- Plan in February: HIP iterations, alternating even and odd chambers
- Given few observables, reduced to 1D (local x) for better control
- Switched from full tracker to linear fits, again for better control
- Discovered a weak mode due to cancellation between left and right side of chamber; dropped hits from one side (used other side as cross-check)
- Removed discretization effects from wire granularity by parameterizing alignment in global $r\phi$, rather than local x
- Solve whole-ring alignment in one step to speed up convergence
- Algorithm works very well in Monte Carlo! (accurate, ring closes)
- But in data, there were still some effects
  - Misalignment angles are significant, switched from a track fit on one side to track fits on both sides to be sensitive to relative angles
  - Observe system with as many different data-driven methods as possible for confidence

- On September 12, dataops delivered an AlCaReco sample of 110,000 overlaps events and 825,000 generic beam-halo, reduced to tracks and hits for optimized reading
- Armed with a working procedure in Monte Carlo, we went to work on the data immediately
- The rest of this talk will show a snapshot of alignment status and current best results

Parameters

- φ_y angles first, then $r\phi$ positions
- ME−2/1 & ME−3/1 (highest statistics)
- Run 62232: 2/3 of full statistics in short time

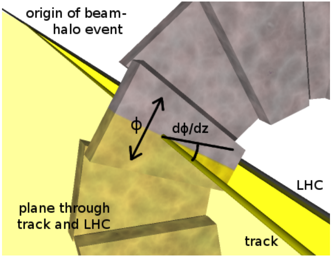




Determining φ_y angles

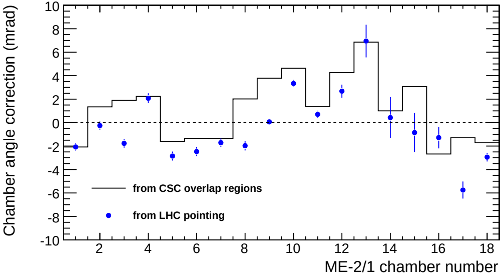
Three independent methods (for cross-checks):

1. Pure overlaps: $d\phi/dz$ slope must agree in pairs
2. Generic beam-halo: $d\phi/dz$ must agree on a track from ME$-2/1$ to ME$-3/1$
3. $d\phi/dz$ must be on average zero, because beam-halo tracks come from the LHC (absolute, not pairwise)



Corrections from (1) and (3):

Completely different methods, disjoint sets of tracks, reproduces some trends



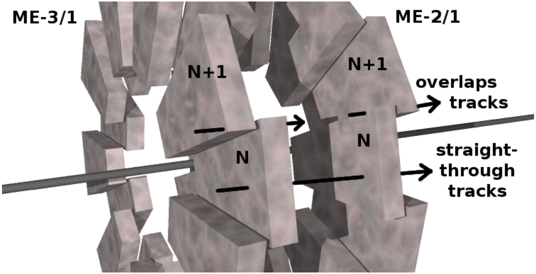
Determining $r\phi$ positions

Taking φ_y from LHC pointing for now, we can attempt $r\phi$ alignment

(one needs a 10 mrad φ_y misalignment to make a 1.25 mm mistake in $r\phi$, and we saw at most 4 mrad disagreements)

Two independent methods:

1. Overlaps: track intercepts must match between N and $N+1$
2. Straight-through: track must match between $N_{ME-2/1}$ and $N_{ME-3/1}$

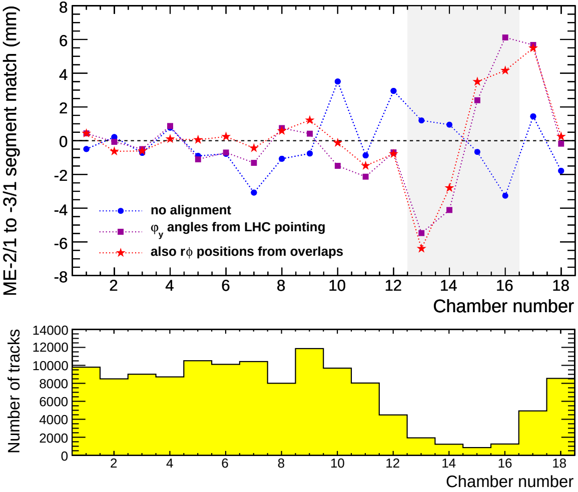


Align with (1) and look at a plot of (2) for each N (data-driven estimate of alignment quality)

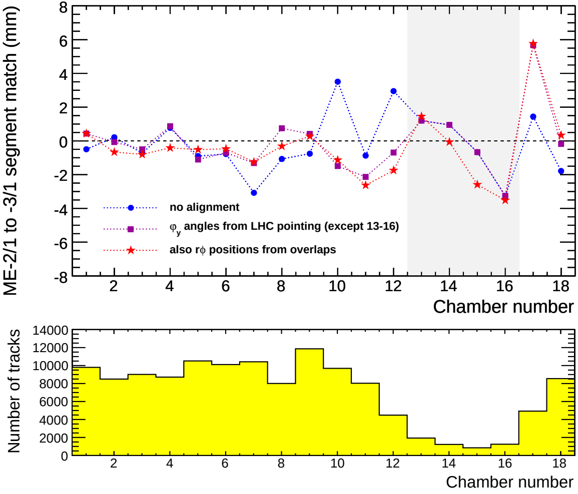
- straight-through tracks pass through more material
- but there are more of them

Cross-checking $r\phi$ positions

- As we apply corrections, we improve alignment (as seen by straight-through tracks) in chambers 1–12 & 18
- Chambers 13–16 are unreliable due to poor statistics on φ_y



- Don't attempt to align φ_y on chambers 13–16 (leave at default value) and repeat

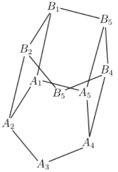


Another tool: combined fit

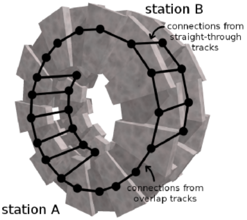
- Overlaps and straight-through tracks form a rigid frame: if errors are not correlated between the rings, a combined fit would isolate errors to one chamber (single-ring fit tries to distribute error uniformly)
- Two benefits:
  - diagnostic tool for identifying which chambers don't fit
  - yields the best set of constants with our present knowledge (excluding outliers)
- But lose an independent cross-check

$$\begin{aligned}\chi^2 = {} & (\alpha_{12} - A_1 + A_2)^2 + (\alpha_{23} - A_2 + A_3)^2 + \ldots \\ & (\beta_{12} - B_1 + B_2)^2 + (\beta_{23} - B_2 + B_3)^2 + \ldots \\ & (T_1 - A_1 + B_1)^2 + (T_2 - A_2 + B_2)^2 + \ldots\end{aligned}$$

$$\begin{aligned}\frac{1}{2}\frac{\partial\chi^2}{\partial A_2} = {} & (\alpha_{12} - A_1 + A_2) \\ & - (\alpha_{23} - A_2 + A_3) - (T_2 - A_2 + B_2) = 0\end{aligned}$$

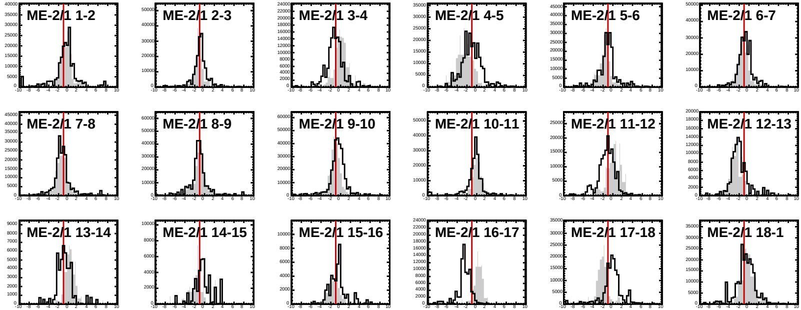


$$\begin{pmatrix} 0 \\ \alpha_{23} - \alpha_{12} + T_2 \\ \alpha_{34} - \alpha_{23} + T_3 \\ \alpha_{45} - \alpha_{34} + T_4 \\ \alpha_{51} - \alpha_{45} + T_5 \\ \beta_{12} - \beta_{51} - T_1 \\ \beta_{23} - \beta_{12} - T_2 \\ \beta_{34} - \beta_{23} - T_3 \\ \beta_{45} - \beta_{34} - T_4 \\ \beta_{51} - \beta_{45} - T_5 \end{pmatrix} = \left(\begin{array}{rrrrr|rrrrr} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 3 & -1 & & & & -1 & & & \\ & -1 & 3 & -1 & & & & -1 & & \\ & & -1 & 3 & -1 & & & & -1 & \\ -1 & & & -1 & 3 & & & & & -1 \\ \hline -1 & & & & & 3 & -1 & & & -1 \\ & -1 & & & & -1 & 3 & -1 & & \\ & & -1 & & & & -1 & 3 & -1 & \\ & & & -1 & & & & -1 & 3 & -1 \\ & & & & -1 & -1 & & & -1 & 3 \end{array}\right) \begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{pmatrix}$$



Example diagnostic

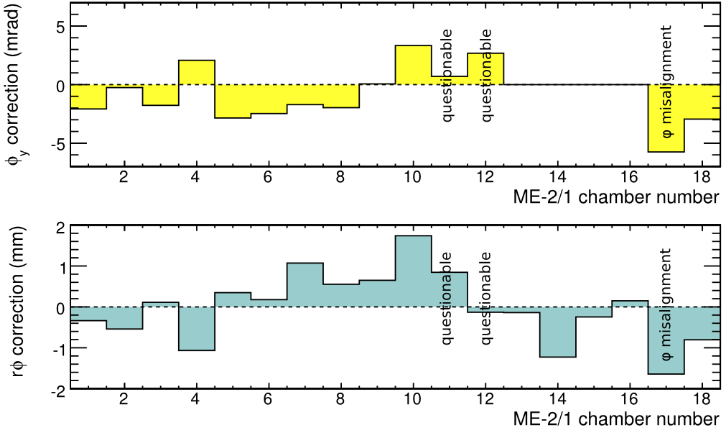
Overlap residuals from combined fit (red line is single-ring fit, grey is unaligned)



- Chamber 17 is clearly wrong (as we could have guessed from slide 14), also in ME−3/1, likely also a bad φ_y angle
- Also relevant to look at wide residuals vs. y (for φ_z rotation effects)

Current best results

- Constants from combined fit with chambers 13–16 unrotated
- Chamber 17 has the wrong angle in either ME$-2/1$ or ME$-3/1$
- Chambers marked "questionable" also don't fit well
- ∞-stats Monte Carlo resolution is 2.2 mrad in φ_y, 370 μm in $r\phi$



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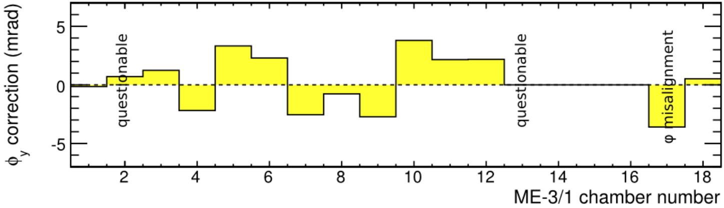

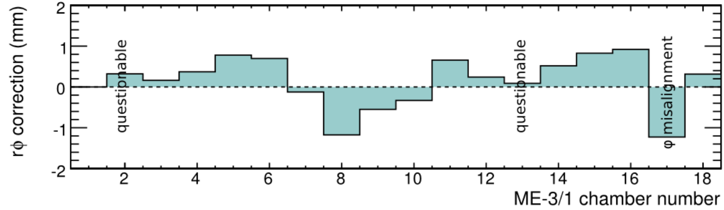

Conclusions

- RMS of $r\phi$ constants is 750 μm, suggesting that the random error in both physical CSC placement and track-based alignment are small (RMS of φ_y is 2.5 mrad)
- Beam-halo events provide several different cross-checks on alignment (all with different systematics), in addition to comparison with hardware alignment
- Part of a two-step process in which internally-aligned rings can be set relative to a reference (barrel or tracker)
- Rings must be complete (only ME$+$2/1, ME$+$3/2, ME$-$2/1, ME$-$2/2, ME$-$3/1) or augmented with hardware measurement
- Still trying to get a deeper understanding of these residuals (the overconstrained systems are not perfectly satisfied)