Alignment of the DT chambers with a HIP-based algorithm

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Overview

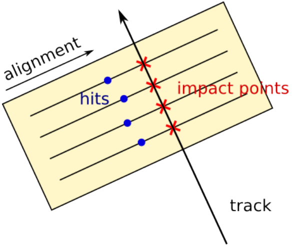
How does DT alignment fit into our plans?

Goal: align the whole muon system with a consistent HIP-based procedure in the same coordinate system used by the tracker

- Limitation of cosmic rays: distribution doesn't illuminate sides of the detector well, and statistics for tracks that link the tracker and the muon endcap are especially poor
- CRAFT plan:
  1. align well-illuminated DT chambers relative to the tracker with globalMuons
  2. align remaining DT chambers relative to aligned DT chambers with standAloneMuons
  3. align CSCs relative to aligned barrel with standAloneMuons
- Step 1 is complete, with supporting evidence demonstrating that this is a true alignment, not simply a minimization of residuals
- We are ready to submit these constants for CRAFT re-processing

Outline for this talk

- Basic description of the procedure
- Detailed study of residuals, controlling for systematic effects
  - effect of $\vec{B}$-field mismodelling
  - effect of multiple scattering
  - effect of biases in the track source
  - effect of non-uniform illumination of the chambers
- Validation plots
  - comparison with old constants (CRAFT_ALL_V4) and MillePede Group's constants
- Conclusion: summary of proposed HIP constants
- Epilogue: discovered a chamber description error; early investigations



HIP algorithm: “Hits and Impact Points”

- Using a track as reference, alignment correction is the peak of the residuals distribution
- Our residual ≡ (impact point) − (hit)

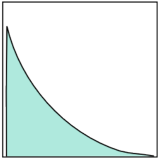
Implementation is not exactly the same as that in the tracker

Important differences:

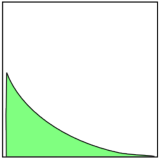
- Muon hits excluded from refitted tracks: tracker is external reference
  - breaks the circularity between fitting tracks and aligning chambers
  - no need to iterate: convergence in one step
- Only hits within a chamber on one track are averaged with weights
  - handles statistics of correlated hits properly
- Muon chambers are much bigger than silicon wafers: study residuals as a function of position throughout each chamber

Effect of $\vec{B}$-field mismodelling

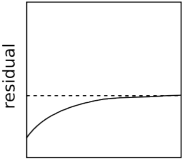
- Magnetic field is known to be mismodelled at the level of 30%
- Track propagation is sensitive to integral of $\vec{B}$-field error along its path
- How can we get reliable residuals?



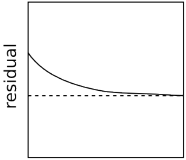
momentum spectrum of positively-charged tracks



momentum spectrum of negatively-charged tracks



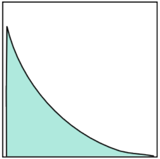
momentum of positively-charged tracks



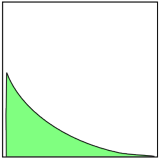
momentum of positively-charged tracks

- Number of positively-charged and negatively-charged muons is not equal, but the momentum spectra are identical (fact used in charge ratio analysis)
- Small deviations of reconstructed track from average muon trajectory is antisymmetric with charge

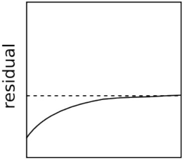
Effect of $\vec{B}$-field mismodelling



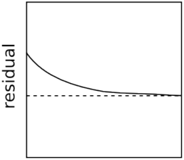
momentum spectrum of positively-charged tracks



momentum spectrum of negatively-charged tracks



momentum of positively-charged tracks



momentum of positively-charged tracks

- Measure residuals peak in two bins, one for each charge
- Non-weighted average is insensitive to $\vec{B}$-field errors

$$\text{alignment} = \frac{R_+ + R_-}{2}$$

- Difference is maximally sensitive

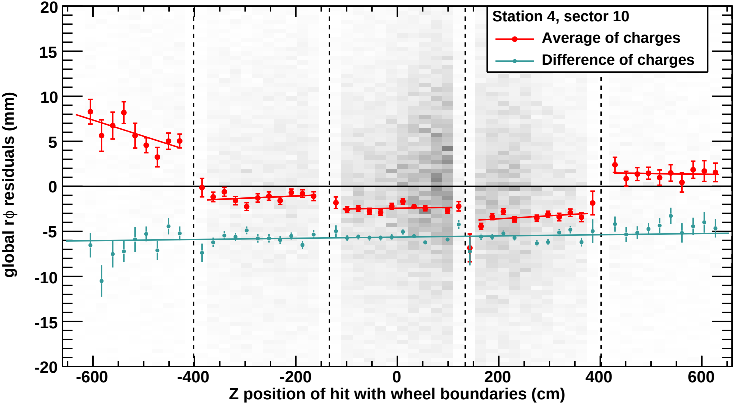
$$\text{error tracer} = \frac{R_+ - R_-}{2}$$

- Effectively scales up negatively-charged muon statistics such that the two curves cancel
- Systematic error $= (\text{error tracer}) \times (\text{charge mismeasurement}) \times \dfrac{0.3}{2.3}$

$$\sim (\text{error tracer}) \times (\text{a few percent or less})$$

- Demonstration in station 4 (largest $\vec{B}$-field errors):
  - despite large $(R_+ - R_-)/2$ difference ("error tracer"),

    the $(R_+ + R_-)/2$ average cleanly breaks at chamber boundaries



grey background is the raw 2-D residuals distribution

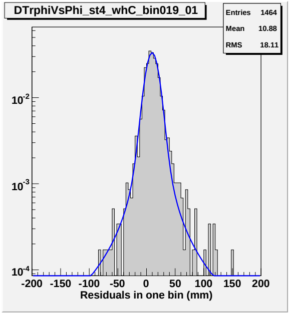
linear fits are only a guide for the eye: not used in alignment!

Effect of multiple scattering

- Alignment correction is the peak of the residuals distribution because
  - good tracks agree about the alignment correction
  - bad tracks (which scatter) disagree in different ways

Scattering processes follow power-law distributions, while experimental resolution is Gaussian

$$f(x) = \int_{-\infty}^{\infty} \frac{1}{\pi} \frac{\Gamma/2}{(x-\xi)^2 + (\Gamma/2)^2} \times \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-\xi^2}{2\sigma^2}\right) \, d\xi$$

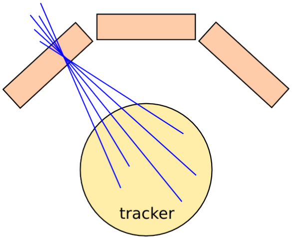


The peak of every subset of residuals is determined from an unbinned fit

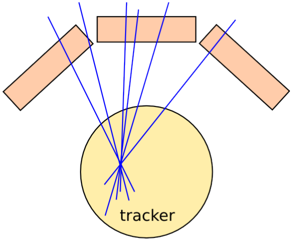
- regular mean $(\sum x_i/N)$ is mathematically equal to the center of an unbinned Gaussian fit
- this is a small generalization: only added tails
- tails de-emphasize outliers because power-law contributes far less to log likelihood than exponential

Effect of biases in track source

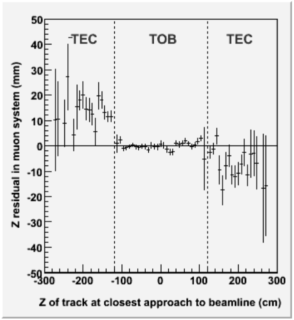
- Track source is treated as an absolute reference; any biases would be communicated to the muon geometry
- Virtue of cosmic rays: wide distribution of entrance angles effectively averages over tracking volume
  - distribution of biases must be "low multipoles" e.g. $\sin\phi$, $\sin 2\phi$, z, z^2, z^3 etc.
- Extenal biases cannot know anything about the chamber boundaries
- Opportunity to X-ray tracker and identify sources:



instead of plotting this...

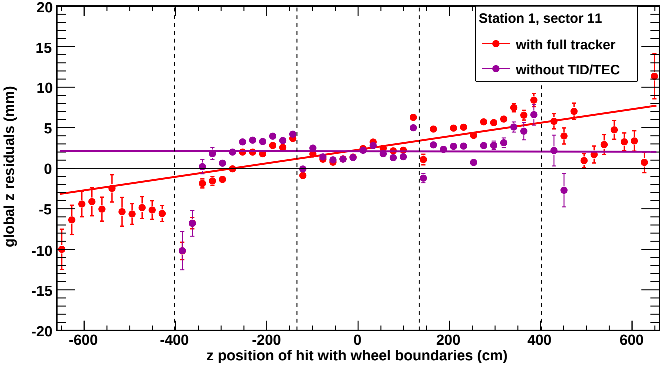


...plot this



Effect of biases in track source

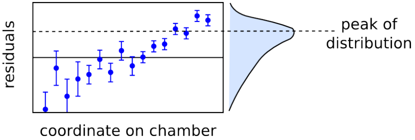
- Dropping all tracks with TID and TEC hits reduces a $z_{\text{residuals}} \propto \left(\sin 2\phi\right)\left(z\right)$ trend in track source
- Wheels ± 2 most affected by TEC; excluding these tracks limits our alignment to inner wheels
  - follow-up with standAloneMuon alignment of wheels ± 2 using inner wheels as a reference (part of plan on page 2)



Effect of non-uniform distribution

- Muon chambers are large and cosmic ray distribution is not uniform

- Chambers with angular misalignments can legitimately have linear trends in the residuals



- Chamber offset should be calculated by the intersection of this trend at the center of the chamber, not the center of mass of the source of tracks

- Divide each chamber into four bins, perform simple average

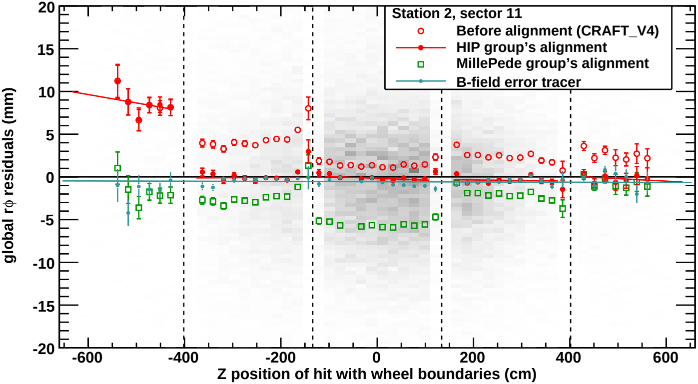
local $x < 0$ local $y > 0$	local $x > 0$ local $y > 0$
local $x < 0$ local $y < 0$	local $x > 0$ local $y < 0$

- Similar to charge-binning for $\vec{B}$-field control (total of 8 bins)
- However, this relies on approximation that distribution of tracks is linear

Alignment presented here

- Align individual chambers, rather than wheels
- Three degrees of freedom: local x, y, ϕ_z
  - local x: offset in global $r\phi$ residuals
  - local y: offset in global z residuals (first test)
  - local z: linear trend in $R_{r\phi}$ vs. ϕ and R_z vs. z (because globalMuons are constrained to originate in tracker)
  - ϕ_x: trend in R_z vs. z only, but second-order
  - ϕ_y: trend in $R_{r\phi}$ vs. ϕ only, but second-order
  - ϕ_z: linear trend in $R_{r\phi}$ vs. z and R_z vs. ϕ
- Only accept chambers in which all 8 bins were successfully fitted with at least 30 "hits" each (averages of 1-D residuals in a chamber on a track)
- Input muon alignment/calibration: from CRAFT_ALL_V4 (first re-processing, includes layer and superlayer corrections)
- Input tracker alignment/calibration: new version for second re-processing, including layer-by-layer Lorentz angle corrections

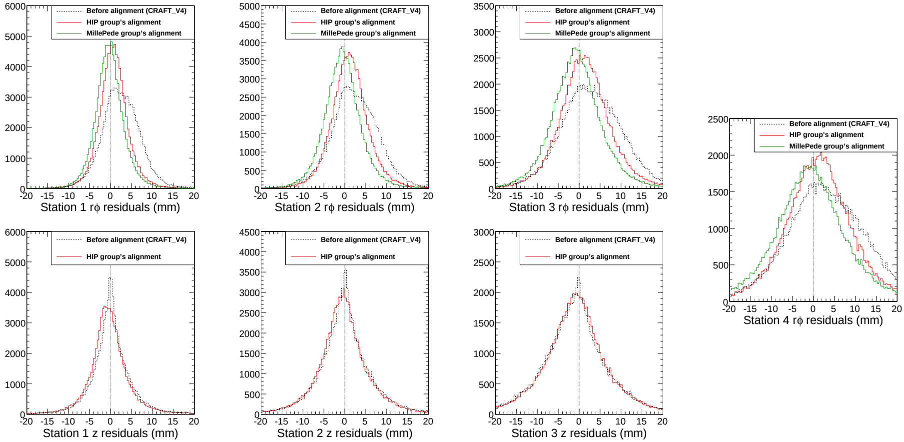
- See "more information" for 152 pages of plots like this one
  - dataset is divided such that you're only ever looking at one chamber at a time
  - grey background is the raw 2-D residuals distribution
  - linear fits are only a guide for the eye, not used in alignment



- Wheel −2, station 2, sector 11 didn't have enough tracks for alignment

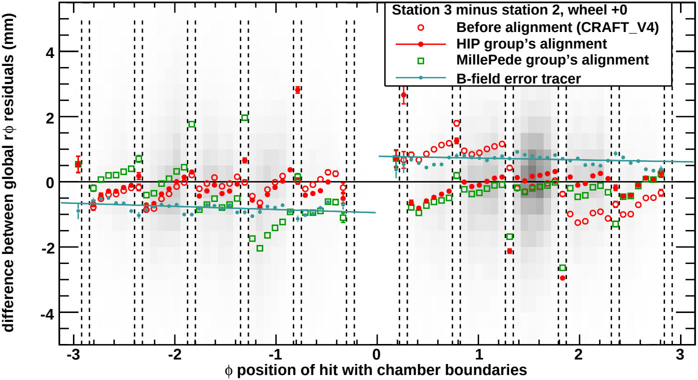
Summary of residuals

- To summarize, project all residuals ($p_T > 80$ GeV, all chambers)
  - like the tracker's χ^2/N_{dof} plot, but unweighted
  - less sensitive measure of alignment, but convenient

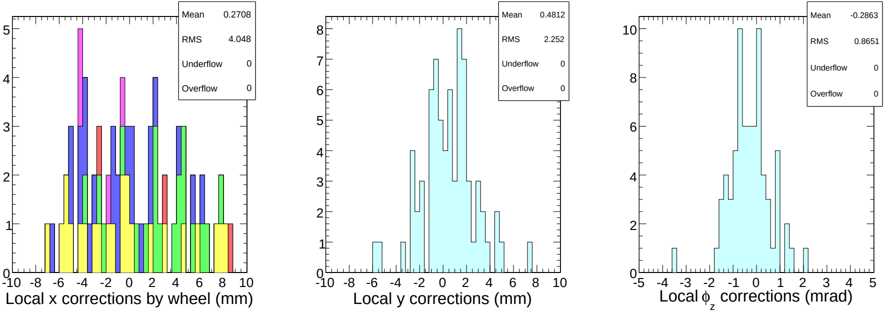


Linearly-independent validation

- Residuals in plots are calculated the same way as residuals in alignment
- Linearly-independent test: residuals differences between pairs of stations
  difference $= (\text{st. 3 track} - \text{st. 3 hit}) - (\text{st. 2 track} - \text{st. 2 hit})$
  - shows *relative* positions of chambers; globalMuon is just a ruler
  - note zoomed vertical scale: accuracy is 1–2 mm
  - also shows $\vec{B}$-field error between the stations, not integrated



Values of the corrections



- 5–10 mm changes in $r\phi$ positions, but they don't correspond to an overall rotation of the wheels
- A scan of residuals differences plots suggests that remaining misalignment is on the order of 1–2 mm
- Also important: apparent stretching of DT chambers (see epilogue)

Conclusions

- Proposal for CRAFT:

  upload these constants with optional minor updates:

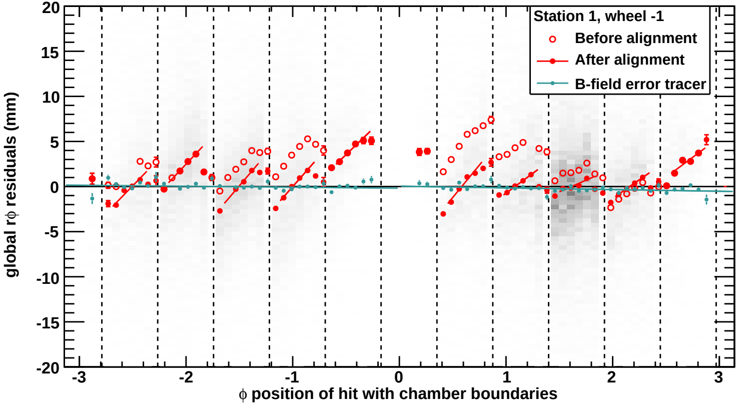
  - we could drop local y corrections at this stage
  - if so, we could take advantage of the tracker TEC (bias was in z direction, not $r\phi$)
  - lower threshold for chamber alignment (fewer unaligned chambers, more consistent system)

- Constants-generation takes about 2–3 hours, validation suite takes 10–20 minutes on an empty CAF

  - available on demand

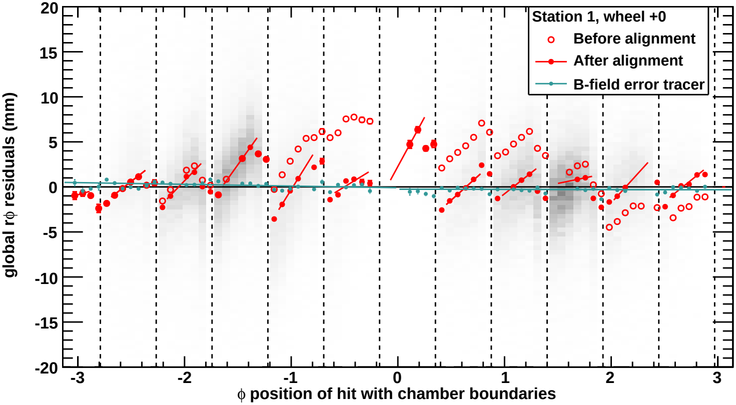
Epilogue: DT chamber stretching

The clue (1/3)



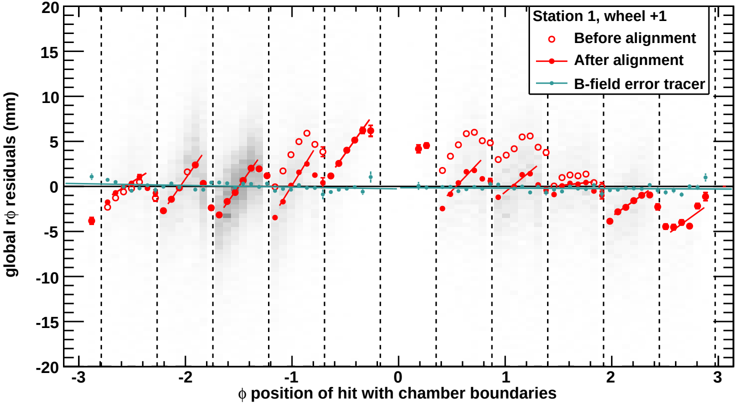
- Linear trends in unbiased $r\phi$ residual vs. ϕ inside each chamber
- Unaffected by local x alignment (as expected)
- Curious thing: they all seem to have the same slope

The clue (2/3)



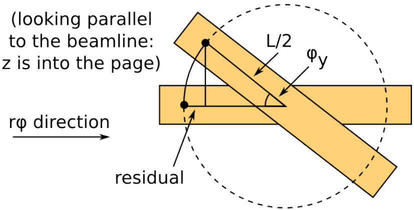
- What if it's a linear bias in the distribution from the track source, partly absorbed by the alignment?
  - impossible: ϕ must have periodic boundary conditions
  - if we realigned chambers to make a continuous line, it could not match at $\pm\pi$ (it would fail a "closure condition")

The clue (3/3)



- So it's a real effect related to the chambers, not the track source
  - not fixing it would smear chamber resolution by 5 mm!
- What rigid body misalignments can cause it?
  - ϕ_y (rotation around axis parallel to the beamline)
  - ΔR (radial displacements)

The ϕ_y possibility

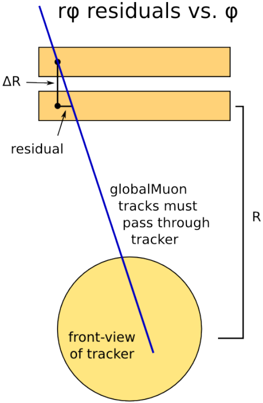


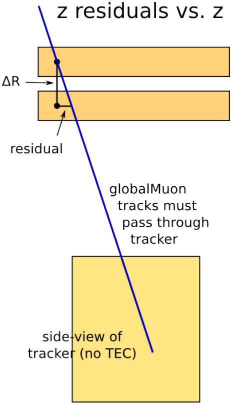
- ϕ_y rotation can make a chamber appear narrower
- but it's a second-order effect:

$$\begin{aligned} \text{residual} &= (L/2)\,(1 - \cos\phi_y) \\ \phi_y &\approx 70 \text{ mrad} \end{aligned}$$

- Could *all* the chambers be independently misaligned by about 70 mrad?
- Same effect observed in IDEAL and CRAFT_ALL_V4 constants: it would have to be a physical misalignment of real chambers
- I think we can safely say that this is not what's happening
  - the magnitude is too big, and
  - the pattern is too regular

The ΔR possibility





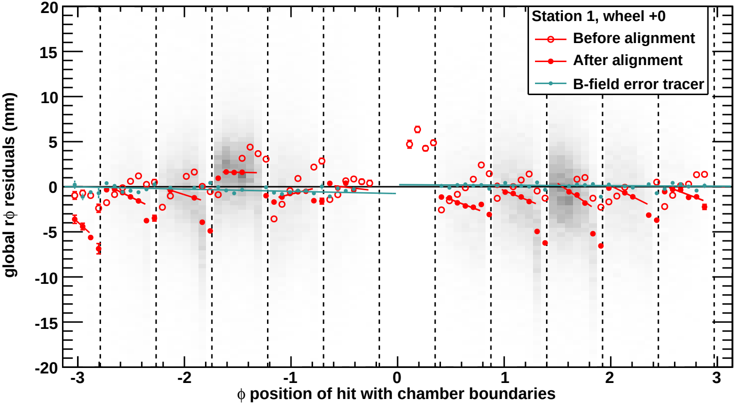
- A track sample constrained to pass through the tracker can introduce effects of this sort

$$\Delta R = \frac{R}{(L/2)} \text{(residual)}$$

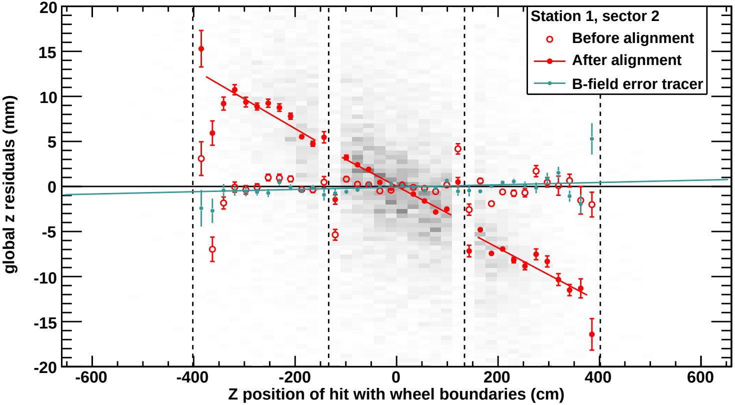
- But it has to appear in both types of residuals

Trial ΔR alignment (1/2)

- To see if this is plausible, I expanded the radius of all DT stations by 15 mm in a private test
  - seems to cancel the $r\phi$ residual vs. ϕ trend in the $-\pi < \phi < 0$ range, but overshoot slightly in the $0 < \phi < +\pi$ range



- However, look what happens to the z residual vs. z: clearly both types of residuals can't be satisfied!
- The open circles are the case of no ΔR shift



So, what could it be?

- Process of elimination for all rigid body degrees of freedom
  - ~~ϕ_y: implausible~~
  - ~~ΔR (a local z translation): can't reconcile both $r\phi$ and z residuals~~
  - local x, y translations: can't introduce any linear trends in residuals, only offsets
  - ϕ_z rotation: introduces a linear trend in $r\phi$ residuals vs. z and z residuals vs. ϕ, but not what we're looking for
  - ϕ_x rotation: also would have to be implausibly large, and only affects z residuals (the opposite of what we're looking for)

- Non-rigid degree of freedom
  - *some kind* of stretching would easily explain it
  - an error in the geometry description, duplicated by CMSSW, would account for its regularity (with outliers due to small individual ΔR misalignments)

Analogy with CSC case

- Last year, a similar track-based technique uncovered a 0.8 mm error in CSC widths
- For the same reasons, chamber stretching was degenerate with increasing the distance from the beamline
- Degeneracy was resolved with photogrammetry of alignment pins
  - track-based procedure reproduced $r\phi$ positions of alignment pins with 270 μm accuracy
  - R positions of pins were therefore directly comparable, and constrained distance from the beamline
- CSC geometry experts investigated and quickly found a 10 μm strip pitch angle error, which, compounded over 80 strips, changed the width by 0.8 mm, explaining the observation with tracks
- DTs have an advantage over CSCs in that they precisely measure z residuals in addition to $r\phi$ residuals, so we can already break degeneracy between ΔR and stretching
- In the CSC case, we predicted the magnitude but made a mistake in guessing the sign: we'd follow up on any effect of this magnitude

Conclusions: what to do?

- I would like to ask DT geometry experts to look for a chamber description error on the order of 5 mm across the local x dimension
- We have shown that it is a real chamber-level effect and ruled out the possibility of it being caused by any rigid chamber misalignment
- "Stretching/squashing" can be interpreted loosely
  - only distortions which affect active elements matter
  - a bulging layer can look narrow (though that's a second-order effect, like ϕ_y)
  - a $\phi_y \sim 70$ mrad rotation built into the chamber?
  - a ΔR misalignment for superlayers 1 and 3 and not superlayer 2 could explain the incompatibility of $r\phi$ and z residuals
  - it's hard to imagine timing effects playing a role, since left- and right-hand sides of each wire would be affected oppositely
  - ...
- Since it's causing ± 2.5 mm unbiased residuals errors at the ends of the chambers, it's as important for resolution as alignment