Alignment with Tracks

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Outline for this talk

- Reminder of pre-collisions goals, status of procedures and constants
- What we learned from beam-halo/CRAFT and how it applies to collisions data
- Timeline of what needs to be done when the beam arrives

Goals for pre-collisions

- Primary: test and improve all parts of the alignment system, with a strong preference for procedures that will be useful in the colliding-beams era
- Secondary: develop new procedures that are better optimized for cosmic rays, to improve constants more now

	Procedure	collisions	beam-halo	cosmics	Status
			*Applicable to...		
1.	CSC Overlaps	yes	yes	no	validated with data (ME−2/1, −3/1)
2.	Tracker-to-muon chambers ("Baseline")	yes	no	DT wheels −1, 0, +1	validated with data, provided constants, sub-mm precision
3.	Tracker-to-CSC disk	yes	no	seems to be possible, but rough	observing first results, provided constants, needs more work
4.	Barrel-to-endcap	no	no	yes	in development

*Depends on track distributions: beamspot-pointing, longitudinal, and mostly vertical

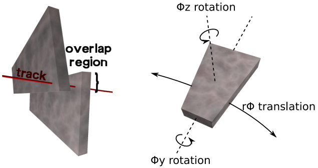
1. CSC Overlaps

1. CSC Overlaps

- Extend pairwise chamber alignment around ring; three DOF: $r\phi$, ϕ_y, ϕ_z
- Demonstrated 270 μm $r\phi$, 0.35 mrad ϕ_z accuracy by photogrammetry cross-check, in 9 minutes of beam-halo

Implications

- This means that we have resolved all *local* issues (with ME2/1, 3/1); remaining issues are track-source and propagation through material
- We can use Overlaps to diagnose Baseline by applying both procedures to the same set of tracks (in collisions)

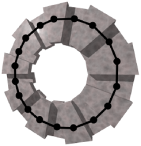


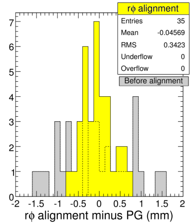
pair-wise residuals

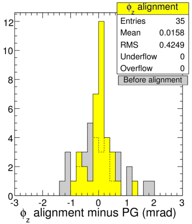
alignment corrections

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

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







Why not upload the constants?

Since beam-halo constants are good, why not use them in reconstruction?

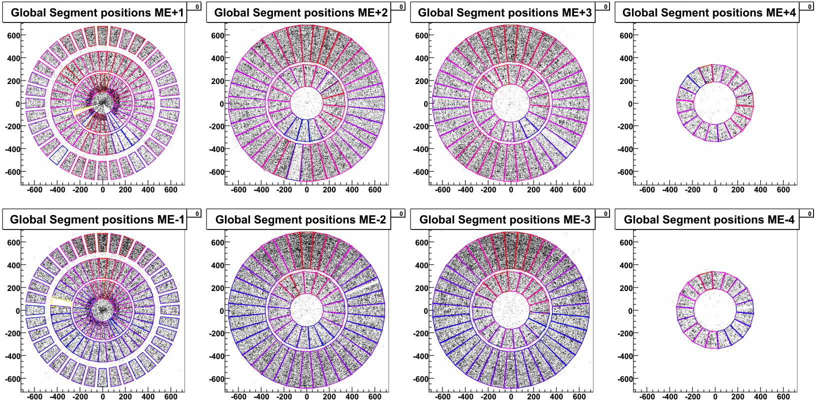
- Method requires complete rings
  - only ME$-2/1$ and $-3/1$ were available: combination of high statistics due to being close to the beamline and status of chambers during those 9 minutes in 2008
  - to benefit from alignment, track would need to pass through exactly these two rings: very rare for CRAFT cosmic rays
- Measurement performed with $\vec{B} = 0$, unclear how much physical motion occured between beam-halo era and CRAFT

And yet. . .

- In a sense, we did: one can think of the beam-halo/photogrammetry comparison as validating the *photogrammetry*
- We uploaded all of the CSC photogrammetry chamber positions: they are being used in reconstruction now

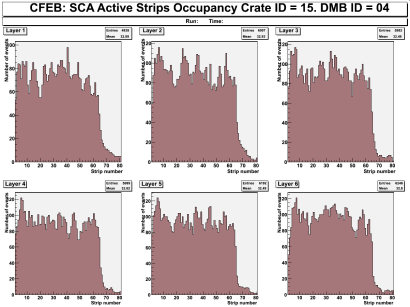
Completeness of rings (1/2)

- Most rings are reliably complete, thanks to 6 months of work
- Snapshot from June 11 (99322):



A. Kubik

Completeness of rings (2/2)



- Something to be careful about: CFEB inefficiencies
  - since overlaps procedure only requires hits along the edges of CSCs, this is only a problem when first or last CFEB (1 or 5) is inefficient/dead

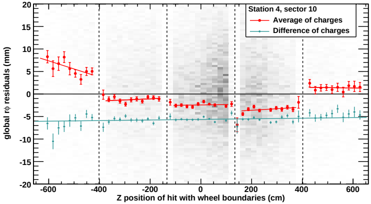
- Armando's list of bad CFEBs includes 3 bad edge CFEBs, all in different rings (+1/2/15.1, +2/2/15.5, +3/2/19.5)
- Overlaps procedure can be modified to fill-in missing information by assuming perfect closure (sum of residuals around ring = 0)
- This is different from a dead chamber, which would remove two overlaps measurements, one from each side

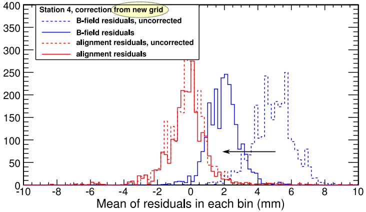
2. Baseline procedure (tracker-to-muon chambers)

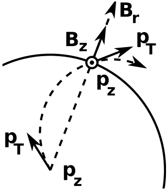
2. Baseline procedure

- Method: (1) fit track in tracker, (2) propagate it to muon chamber, (3) align chamber to agree with track
- In the long run ($\gtrsim 50$ pb^{-1}), all chambers can be aligned like this
- Cosmic rays illuminate many DT chambers (wheels -1, 0, $+1$, except stations 1 and 7)
- Aligning the barrel in CRAFT improved our understanding about the following:
  - how can we disentangle alignment from magnetic field effects when we propagate tracks from the tracker? (resolved)
  - how can we be sure that the tracker is not globally distorted? (we have some techniques, but not completely resolved)
  - also developed much more robust fitting procedures, less sensitive to single-scattering tails
- These are the “non-local” issues, complimentary to what we learned with beam-halo; most carries over from DT to CSC

Magnetic field effects





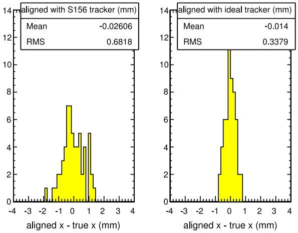


$\vec{B_z} \cdot \vec{p_T}$ and $\vec{B_r} \cdot \vec{p_z}$ both cause $r\phi$ residuals that are antisymmetric in charge

- Residuals have seperable components when viewed as a function of charge
  - alignment is independent of the tracks' charge
  - $\vec{B}$ (and dE/dx) errors are antisymmetric in charge
- Alignment residuals (red) have discontinuities at chamber boundaries before alignment and are unaffected by changing the $\vec{B}(\vec{x})$ map
- Charge antisymmetric residuals (blue) are insensitive to chamber geometry and change dramatically with new maps (example from February)

Track-source distortion

- Alignment information is propagated from the tracker: if the tracker is misaligned, the muon system will be too
- Two classes of distortions:
  - small-scale: all collisions muons for a chamber point back to the same misaligned region of the tracker (right, from CSA08)

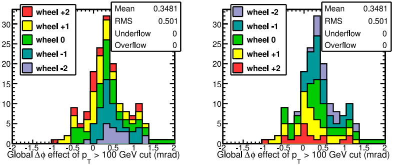


  - global: tracker weak mode gets imprinted onto the muon system, something $\propto \sin\phi$, $\sin 2\phi$, z, z^2, etc., or combinations
- Muon alignment is much less sensitive to errors in track direction (ϕ and η) than errors in track curvature (p_T)
  - curvature errors grow quadratically as track propagates
- In cosmic ray alignments, small-scale distortions are "washed out" by the fact that cosmics don't all point to the same spot

Observed global distortion

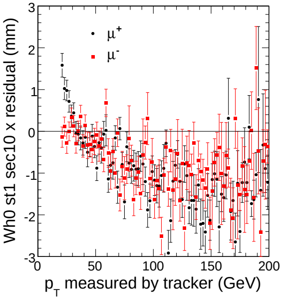
- $20 < p_T < 100$ GeV tracks and $100 < p_T < 200$ GeV tracks yield different alignments, with a different overall shape (right)
  - rotation and twist of the barrel *that depends on* p_T

Differences in chamber ϕ positions between alignments

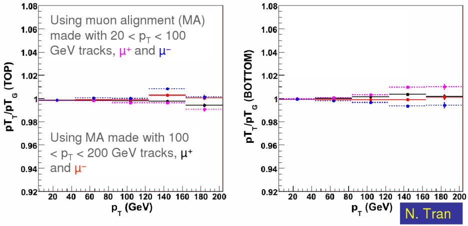


same chambers, opposite stacking order

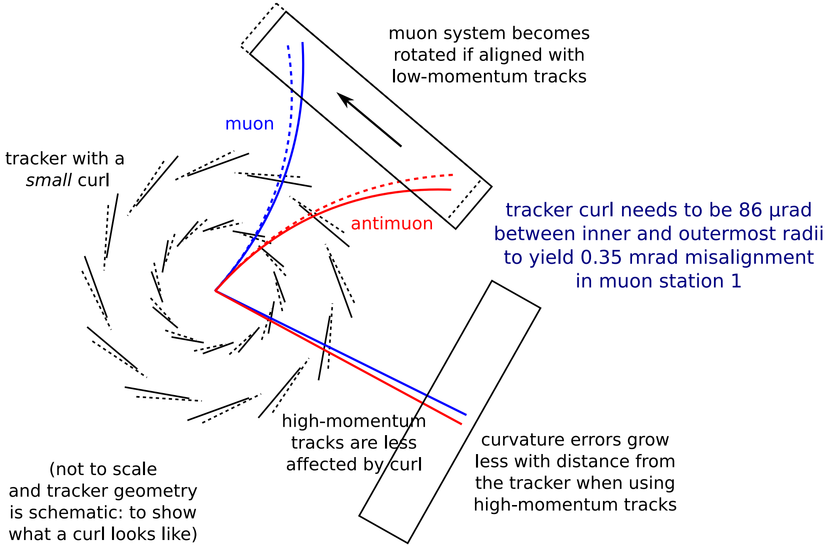
- Magnetic field/material corrections have been applied— this effect in residuals is independent of charge, not a $\vec{B}$, dE/dx issue (bottom-left)



- High-p_T alignment yields more consistent momentum measurements at all momenta



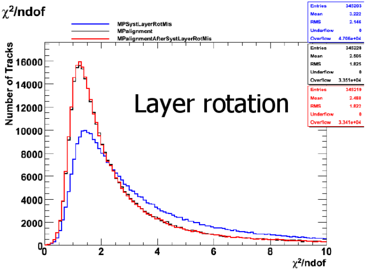
Tracker curl *hypothesis*

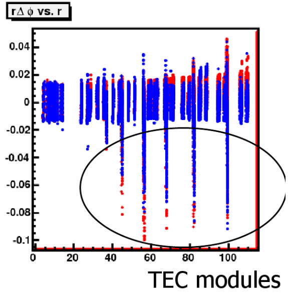


Tracker curl *constraints*

Black= MP starting object

Blue= misaligned Red= aligned on top of misalignment



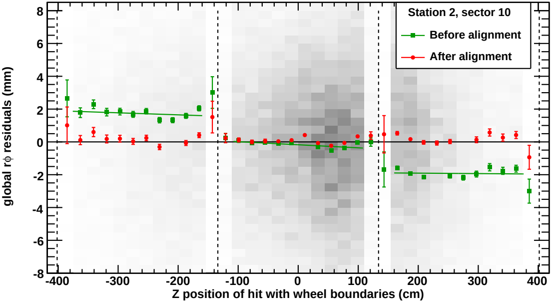


- Studies performed in CRAFT data Zijin Guo, Roberto Castello
- Left: tracker tracks are sensitive to 300 μrad curl (blue: adding curl worsens χ^2 and red: re-aligning restores it)
- Right: also restores wafer positions within 150 μrad except TEC
  - TEC not used in muon alignment; not relevant here
  - restored chamber positions randomly distributed around zero: no *systematic* trend on the scale of 86 μrad
- Source of distortion has not been explained: ongoing work...

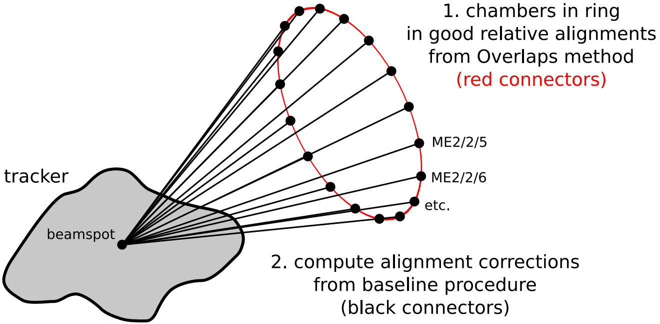
Redundant binning

- To partially distinguish track biases from real misalignments, plot residuals in finer bins than the chamber size
  - global chamber distortions and propagation errors have a smooth effect on residuals
  - misalignments introduce sharp discontinuities at the chamber boundaries (dotted lines) because they are large rigid bodies

(I'll use this again later in the talk, for the endcap)

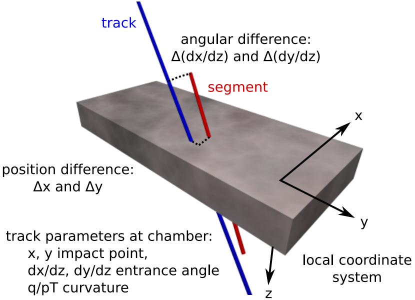


- In the endcap, we can run the Baseline and Overlaps procedures with the same tracks
- Orthogonal sets of connectors (relative alignments):
  - chamber positions measured relative to tracker with Baseline
  - relative to next-door ring neighbors from Overlaps
  - should observe nothing more than whole-ring misalignment
- Sensitive to elliptical distortions of the tracker or endcap track-propagation



Improved alignment fits

- Based on CRAFT experience, we revised our fit model in two ways:
  - expanded residuals to include angular components, to improve resolution on angular alignments
  - one many-parameter fit for alignment and instrumental effects

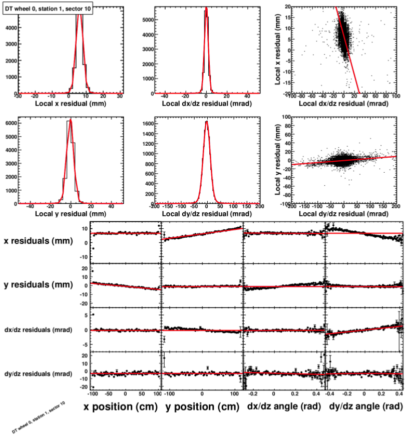


- DT chamber measures 2-D position and direction: 4-component residuals
- Access to 6 rigid-body alignment parameters (3 translation, 3 rotation) through a 6×4 matrix instead of the usual 6×2

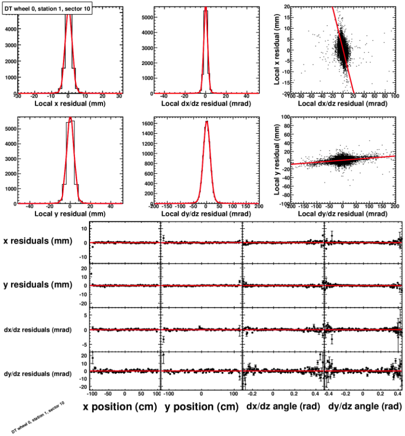
- CSC wire groups are too granular for alignment: $\mathcal{O}$(cm) non-Gaussian
- Strips measure 1-D position and direction: 2-component residuals
- Access to 6-DOF through a 6×2 matrix (instead of 6×1), though in practice only 3 DOF can be resolved with precision

Sample fit results: DT MC

Before alignment



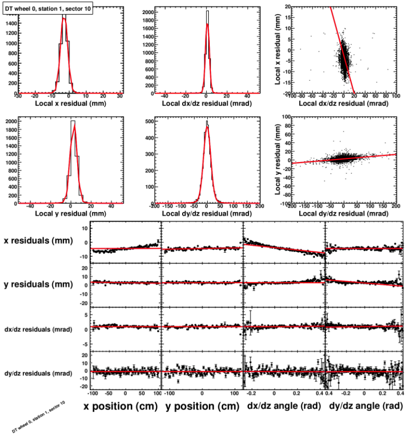
After alignment



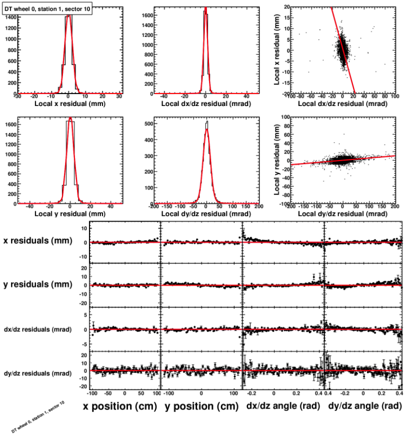
- Projection of fits (all parameters = 0 other than the one shown) overlaid on *simulated* cosmic rays (profile plots) for one chamber
- Method works well in Monte Carlo

Sample fit results: DT data

Before alignment

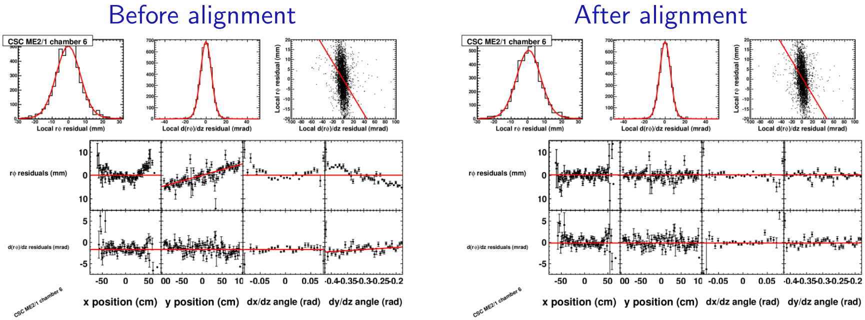


After alignment



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

Sample fit results: CSC MC



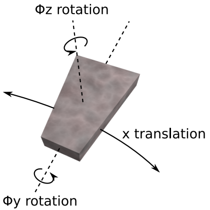
- Projection of fits (all parameters = 0 other than the one shown) overlaid on simulated *collisions* (profile plots)
- Given the level of DT agreement, we don't expect show-stoppers

Why only 3 parameters?

- Only the red terms are significant; the rest are small because
  - $\frac{dx}{dz}$ is the non-radial, non-longitudinal component of track direction: only very low p_T tracks would have non-negligible $\frac{dx}{dz}$
  - R is the distance from the hit to the beamline, large compared to x coordinates in the chamber

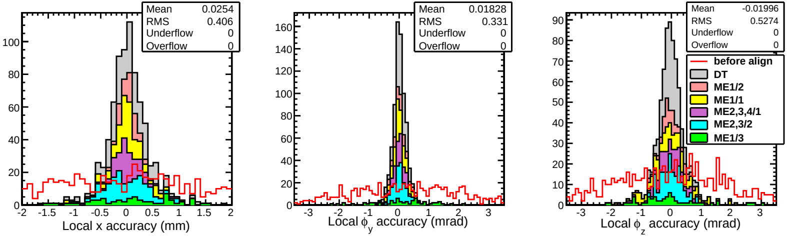
(residuals) = (matrix) · (alignment parameters)

$$\begin{pmatrix} \Delta r\phi \\ \\ \Delta \dfrac{dr\phi}{dz} \end{pmatrix} = \begin{pmatrix} \color{red}{1} & -\dfrac{x}{R} & -\dfrac{dx}{dz} & -y\dfrac{dx}{dz} & x\dfrac{dx}{dz} & \color{red}{-y} \\ \\ 0 & -\dfrac{dx}{dz}\dfrac{1}{2R} & 0 & \dfrac{x}{R} - \dfrac{dx}{dz}\dfrac{dy}{dz} & \color{red}{1+\left(\dfrac{dx}{dz}\right)^2} & \color{red}{-\dfrac{dy}{dz}} \end{pmatrix} \begin{pmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \delta_{\phi_x} \\ \delta_{\phi_y} \\ \delta_{\phi_z} \end{pmatrix}$$



- In-practice accessible parameters are δ_x, δ_{ϕ_y}, and δ_{ϕ_z}, the same as in the Overlaps procedure
- Attempts to align others in MC yield poor resolution (but with the right dependence on R)
- Complimentary to hardware's best parameters

- Putting together all of the updated algorithms, MC alignment accuracy is (for 50 pb^{-1}, no tracker misalignment):



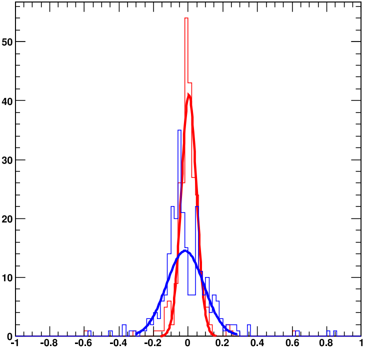
	x (μm)	ϕ_y (mrad)	ϕ_z (mrad)
DT	430	0.21	0.31
ME1/1	350	0.22	0.70
ME1/2	180	0.24	0.37
ME1/3	740	0.93	1.07
ME2,3,4/1	250	0.17	0.47
ME2,3/2	380	0.20	0.35
everything	400	0.33	0.53

Data-driven test of CRAFT p_T

- 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

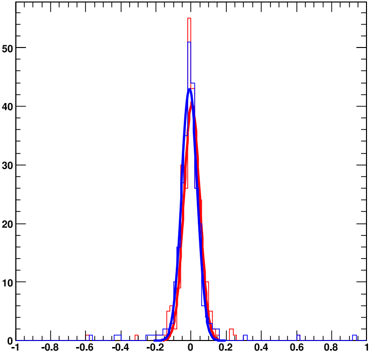
	mean	sigma
Tracker-only:	0.0040	0.044
With first muon station:	−0.0180	0.108



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

After muon alignment

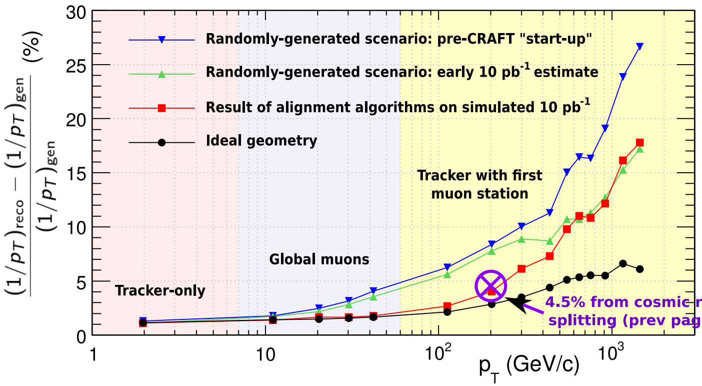
	mean	sigma
Tracker-only:	0.0042	0.045
With first muon station:	−0.0097	0.045



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

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

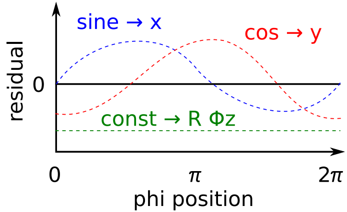
  (at high p_T, use only first muon station to avoid hit confusion from muon showering)

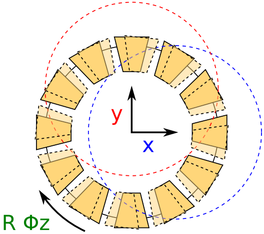


- MC simulations yield much better results than early estimates
- Cosmic ray splitting is close to MC simulations at 200 GeV

3. Tracker to CSC disks

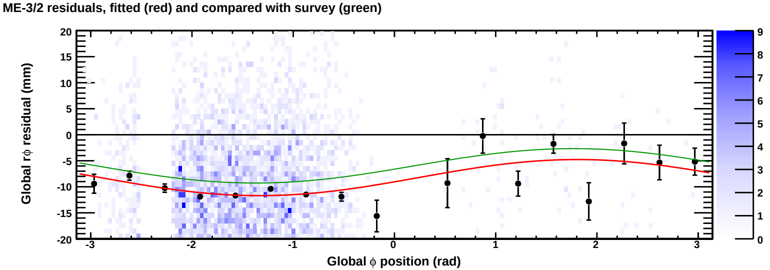
- Method: same tracker-to-muon propagation, but plot versus phi position and fit {const, sine, cosine} to get $\{R\phi_z, x, y\}$ of the disk





- Fewer tracks are needed to align whole disks than individual chambers
- Necessary as final step after Overlaps (internal ring alignment)
- The following are first investigations; there are unsolved issues

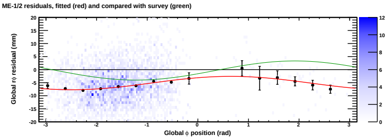
- Strip-only residuals versus phi position
- Blue scale is the 2-D histogram, black points are bin-by-bin averages
- Red line is a fit to the residuals, green line is *adjusted* survey
- Important: residuals are relative to tracker and original survey is relative to cavern, so we adjust survey to fit cavern to tracker
  - $\{YE-2, -1, +1, +2\} \times 3$ DOF is reduced to 3×3 parameters
  - only meaningful to compare relative differences between rings (next page), rather than one ring alone, because of the fit



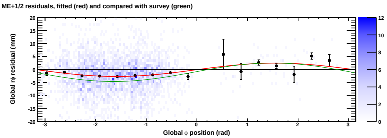
(pre-adjustment) survey data from R. Goudard

Comparison with survey (2/2)

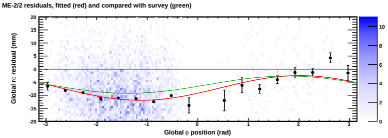
ME−1/2



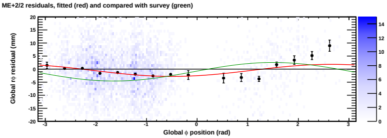
ME+1/2



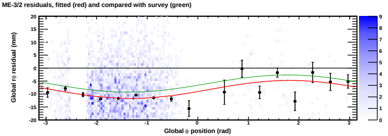
ME−2/2



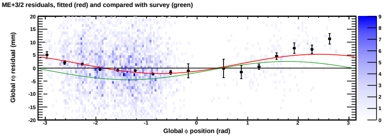
ME+2/2



ME−3/2



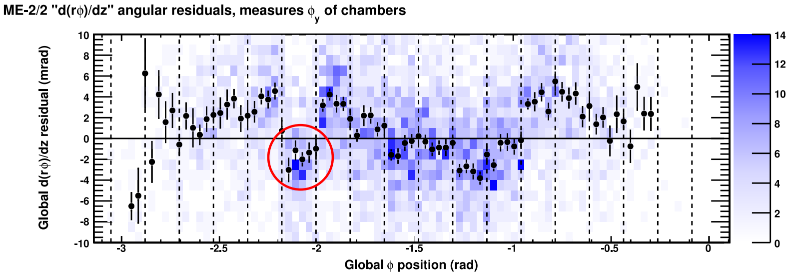
ME+3/2



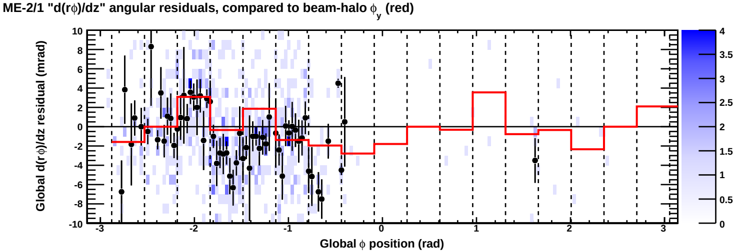
- Millimeter-level disagreement between residuals and survey
- But ME−2, −3 and +2, +3 residuals agree with each other: good!

Redundant binning

- We also have $d(r\phi)/dz$ angle residuals
- Bin them more finely than the chambers (dashed lines are boundaries)
- We do observe some discontinuities, indicating real ϕ_y misalignments between chambers
- Few-mrad is the same misalignment scale that was observed by beam-halo



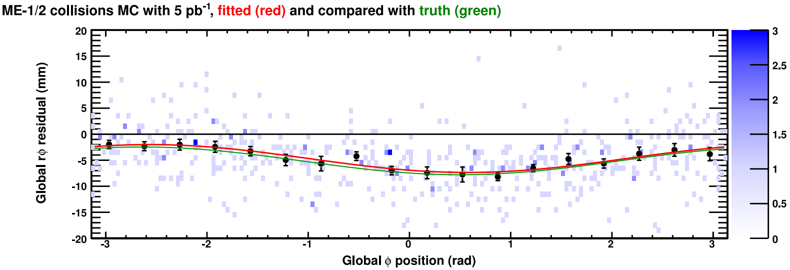
- Difficult to actually compare tracker-to-disk and beam-halo directly, because very few cosmic rays connect ME$-2/1$ with the tracker
- Nevertheless, we can try: these are ϕ_y with beam-halo overlaid



- To allow for tracker distortions and propagator errors, we can focus on the discontinuities at the chamber boundaries
- The discontinuities do not agree in detail with beam-halo: can form an argument that chambers have rotated between $\vec{B} = 0$ and CRAFT

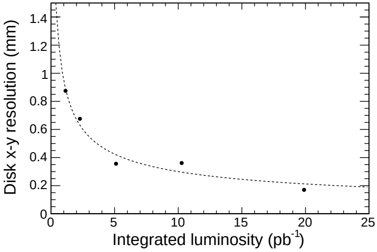
How does it look in MC?

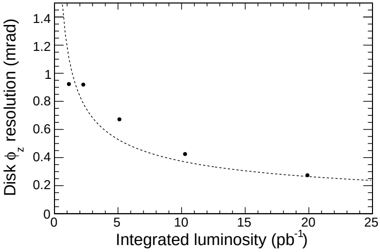
- Collisions MC (5 pb^{-1}): tracks uniform in ϕ but not more numerous
- Much easier to fit const + sine + cosine, accurate results
- Roughly the same widths
- Cosmic-ray MC (full sample): zero tracks (probably a generator-level cut)



MC disk-fitting study

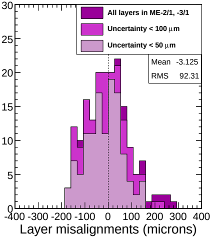
- With ϕ-symmetric collisions, how much data do we need to align the disks?
- Includes residual misalignments after CSC Overlaps alignment (assuming same resolution as 2008)
- Independent samples scale with $\sqrt{N}$





Timeline for beam

- Now and CRAFT-2009
  - validate cosmic ray tracker-to-disk procedures with CRAFT-2008 and -2009
  - automate all procedures and monitoring for CRAFT-2009, then simply run them
- Month of beam-halo only
  - re-run beam-halo procedure on new samples
  - kludge incomplete rings if necessary
  - any corrections needed for $\vec{B} \neq 0$?
  - one-time layer alignment with full dataset (low-statistics 2008 pilot study on right)



- First collisions: 5 pb^{-1}
  - run Overlaps procedure on collisions data, compare with beam-halo result
  - use tracker-to-disk method to connect internally-aligned rings to tracker
- Later collisions: 50 pb^{-1}
  - run Baseline procedure with same tracks: do they agree? If not, do track-by-track comparisons to diagnose the problem
  - do collisions alignments agree with cosmic rays in the barrel?
  - when all of these are resolved, we will have a physics-quality alignment!

- We have used 2008 beam-halo and CRAFT samples to be as prepared as possible for aligning with collisions
- Beam-halo demonstration vetted our knowledge of local aspects of alignment (such as CSC strip pitch angle); CRAFT wheel -1, 0, $+1$ alignment tests propagation of tracks over long distances through iron and imperfect magnetic fields
- We have produced and uploaded track-based constants for most barrel chambers, and for endcap disk positions, though our understanding of the latter can be significantly improved
- We know what issues we'll need to work on, at what time, in the LHC start-up process