Muon Alignment for Reprocessing

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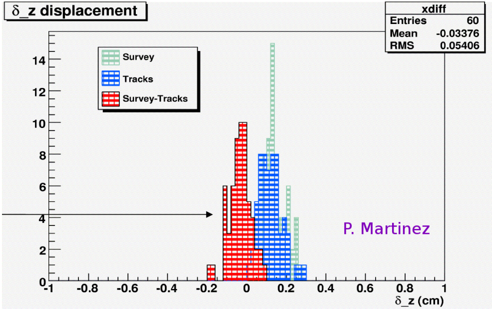
- The muon alignment community has agreed upon an alignment update for the next reprocessing, to be proposed for sign-off tomorrow

- It has three parts:
  - internal DT alignment
  - hardware + photogrammetry CSC alignment
  - global chamber alignment for DT wheels -1, 0, $+1$

- Global chamber alignment will need to be re-created with final tracker geometry and APEs
  - internal sign-off plots were all made with the nearly-final alignment
  - we do not expect large differences with the final tracker (geometry needs to be centered and APEs need to be updated)
  - we'll need to verify that the differences are small by HyperNews

Internal DT alignment

- Physically-motivated correction (glue layer)
- Track-based alignment method agrees with survey (540 μm in δ_z)
- Track-based constants proposed for sign-off



Hardware + photogrammetry CSC alignment

- Photogrammetry describes every chamber with $\vec{B} = 0$ T
- Hardware constants on top of PG describe disk-bending in $\vec{B} = 3.8$ T
- All sign issues have been resolved; tracks have been re-fitted with the new constants

Both of these were described in detail by Pablo on May 12; they haven't changed

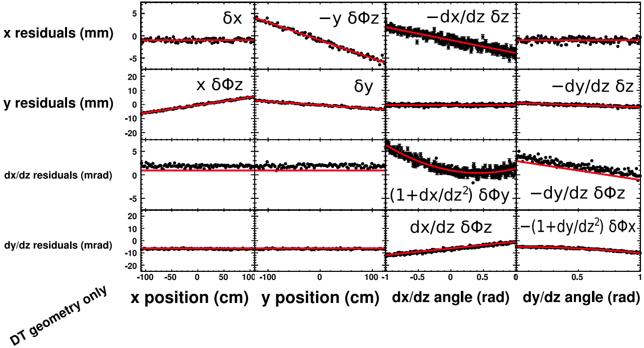
Global chamber alignment

- New since last alignment (CRAFT_ALL_V5–12, Jan 29):
  - combined fit to all 6 DOF, rather than independent x, y, ϕ_z
  - well-defined region for alignment: wheels -1, 0, $+1$, all sectors except 1 and 7 (highest statistics)
  - high p_T cut: 100–200 GeV, rather than 20–100 GeV
- Studied in Monte Carlo (geometry-only, collisions, and cosmic rays)
- Verification by different methods/groups:
  - tracker/globalMuon momentum ratio (N. Tran)
  - cosmic ray splitting (J. Tucker and N. Tran)
  - segment extrapolation (A. Calderon)

Combined 6-DOF fit

- Segment angle residuals ($\Delta\frac{dx}{dz}$ and $\Delta\frac{dy}{dz}$) give us more constraints

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



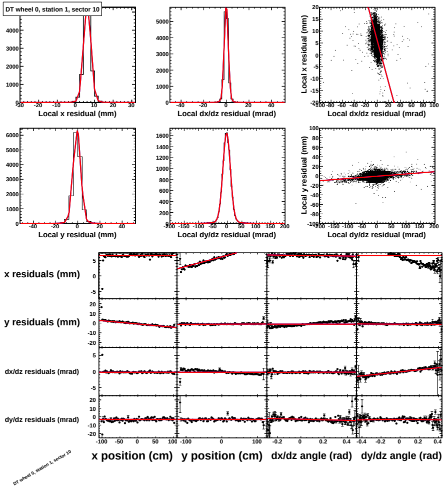
"Geometry-only MC": concoction of CMSSW alignment tools and propagator to simulate alignment with no detector effects

Validates our extension of the Karimaki derivative matrix (including signs)

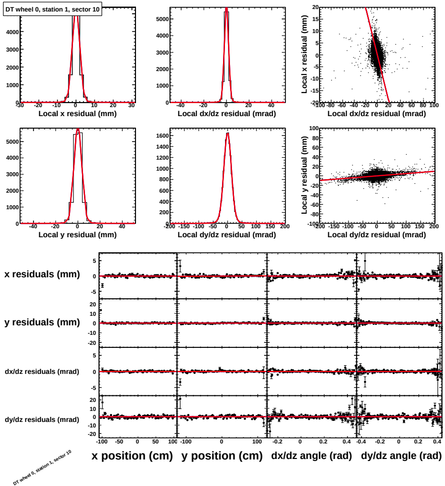
Example in full cosmics MC

- Fit 4-D residuals distribution with all propagation effects included
- 3-way convolution of alignment matrix, Gaussian errors, and Lorentzian scattering (8-D space, 16 parameters, check projections)

Before (misaligned)



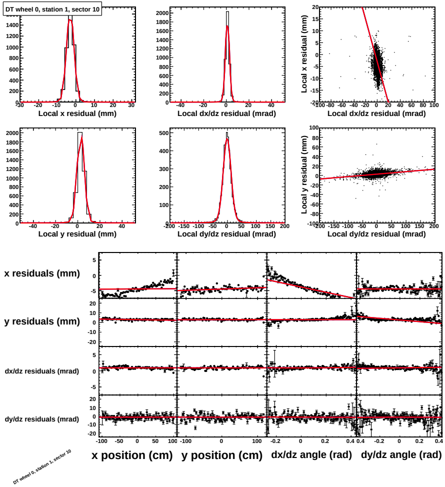
After (aligned)



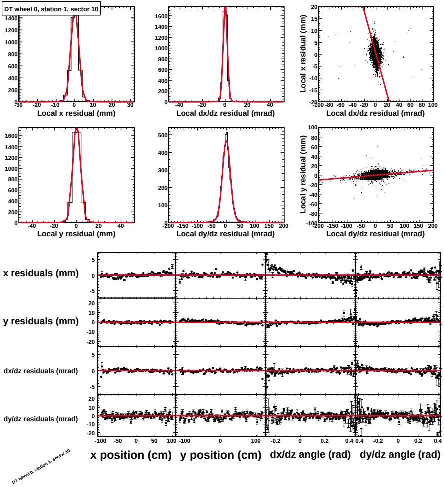
Same example in real data

- Wheel 0, station 1, sector 10 (largest statistics, bottom of CMS)

Before (misaligned)

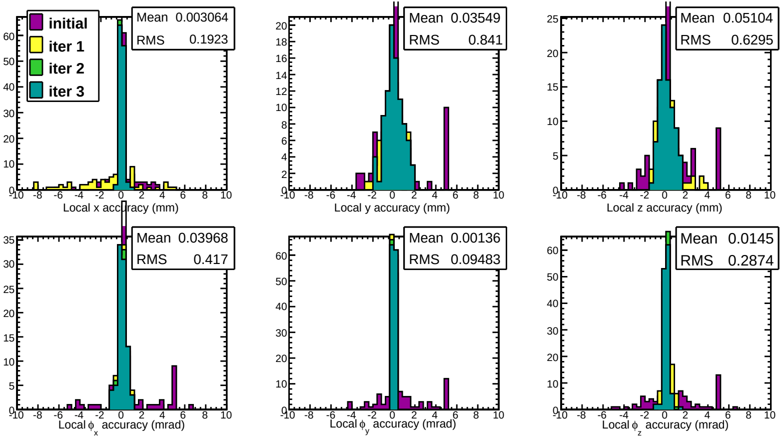


After (aligned)



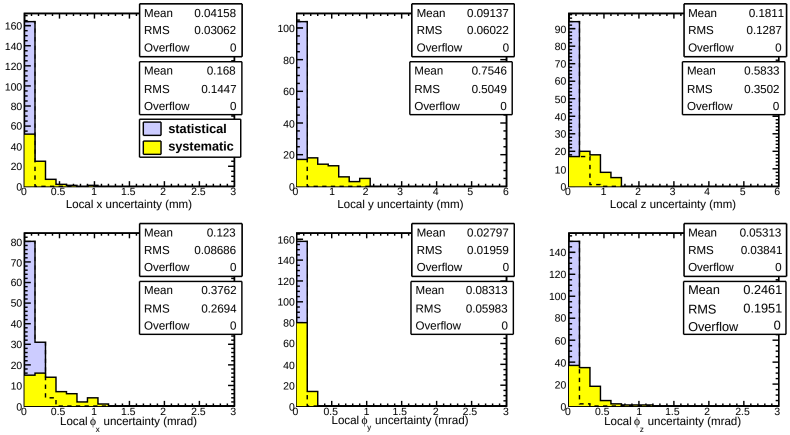
Accuracy in cosmics MC

- All aspects of the MC alignment same as CRAFT except:
    - ideal tracker, ideal $\vec{B}(\vec{x})$ map, ideal internal DT alignment
    - about 4 times the sample size
- After 2 iterations, attain $r\phi$ accuracy of 200 μm

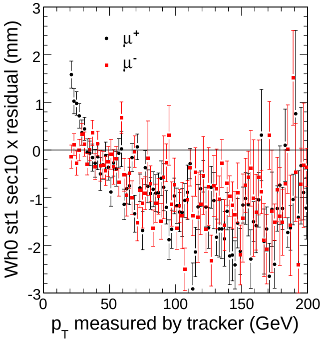


Error analysis in MC

- Statistical uncertainty from alignment fit is about 3–4 times smaller than differences between alignment and MC-truth
- Define systematic error $= \sqrt{(\text{absolute error})^2 - (\text{statistical})^2}$
  - this "systematic" doesn't include unsimulated effects



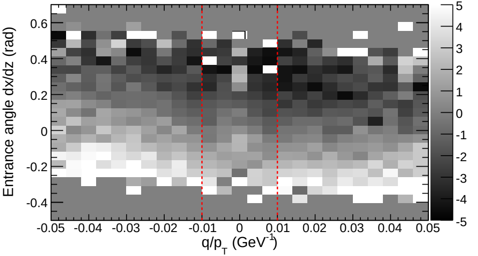
Dependence on p_T cut



- Expected and observed: splitting in residuals between μ^+ and μ^- at low momentum ($\vec{B}$ and dE/dx effects)
- Unexpected and observed: charge-independent variation in residuals at very high p_T
- Dependence on p_T and $\frac{dx}{dz}$ (sawtooth) are both unexplained and may be related

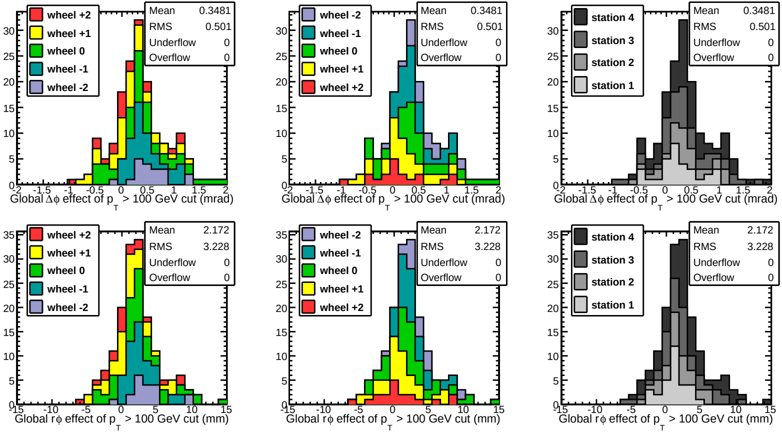
- Neither effect is present in Monte Carlo
- Could be explained by tracker curl, but tracker studies already rule out the required magnitude (backup slides)

Color scale: residuals (mm)



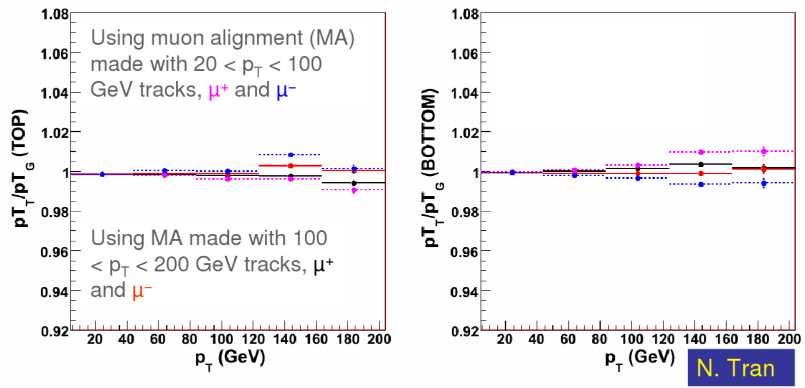
Effect of p_T cut on alignment

- These plots show the difference between alignments produced with low p_T (20–100 GeV) and high p_T (100–200 GeV)
  - global coordinates: $\Delta\phi$ (top row) is rotation around beamline, $r\phi$ (bottom row) is the same orientation for all chambers
- 0.35 mrad rotation, 0.04 mrad/m twist, and 3.2 mm spread



Alignments from low and high p_T differ: how do we know which is right?

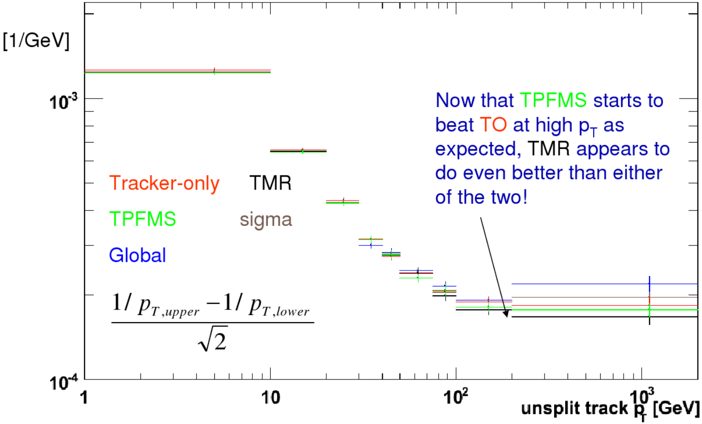
- Ratio of tracker p_T and globalMuon p_T vs. momentum in CRAFT
- Study repeated with low and high p_T alignments (from prev page)
- Alignment made with high p_T (solid red and black) yields more correct ratios (1.0) at all momenta



Studies of p_T effect

Alignments from low and high p_T differ: how do we know which is right?

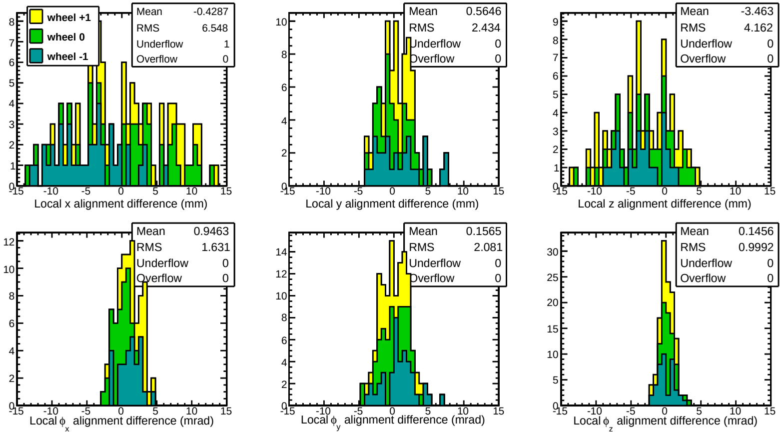
- Cosmic track splitting: difference between top and bottom half of cosmic ray
- Using high-p_T alignment, tracks with station 1 muon hits (TPFMS and TMR) yield better resolution than tracker only (TO) for the first time!
  - this was not the case for the low-p_T alignment or any previous alignments
- Highest-p_T bin in this study is statistically independent of 100–200 GeV alignment



J. Tucker

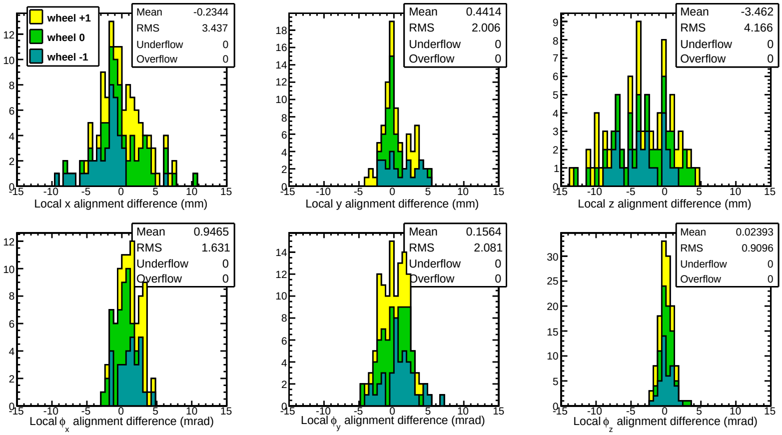
DB comparisons

- CRAFT_ALL_V4 (before global alignment) minus new constants
- Large spread is seen in absolute positions only; relative motion within sectors is much smaller



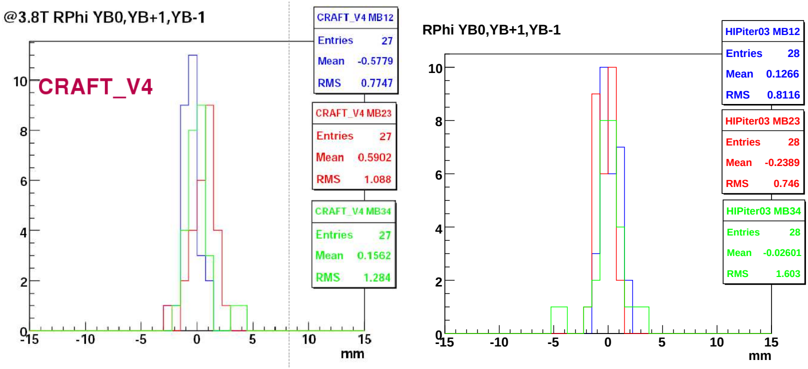
DB comparisons

- CRAFT_ALL_V5–12 (first global alignment) minus new constants
- Wheel-by-wheel dependence is the p_T effect (new constants were produced with high-p_T)



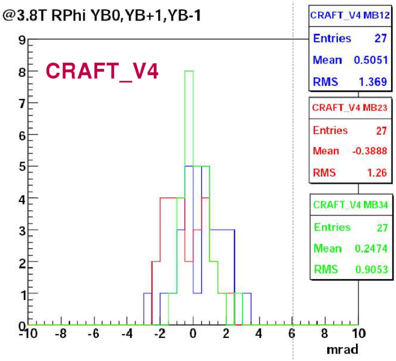
Verification with segments

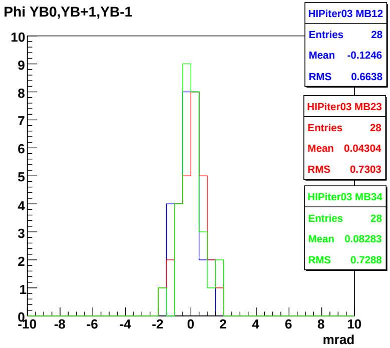
- Test internal consistency of muon alignment by extrapolating segments from one station to the next
- Relative local x position mostly unchanged: sectors move together
- $\sim$800 μm in stations 1–3
- Outlier station 4 (green) chambers: possible internal misalignment



A. Calderon

- Relative local $\frac{dx}{dz}$ angle improved by almost a factor of 2
- $\sim$0.7 mrad





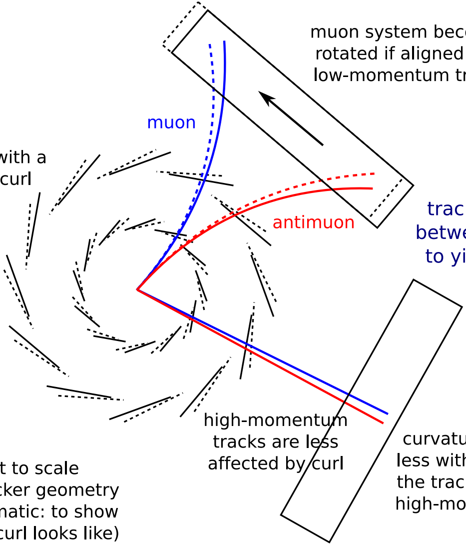
A. Calderon

Conclusions

- New muon alignment constants are ready to be signed-off
  - internal DT alignment
  - hardware + photogrammetry CSC alignment
  - global chamber alignment for DT wheels -1, 0, $+1$
    (pending final tracker alignment and APEs)
- New techniques allow for a more complete alignment: 6 DOF
- Behavior studied in Monte Carlo: technique is sound and capable of 200 μm resolution
- Real results verified by several independent techniques
- Dependence of residuals on p_T and $\frac{dx}{dz}$ (sawtooth) is still unexplained and exhibits global patterns (p_T-dependent rotation and twist)

Tracker curl hypothesis

p_T-dependent rotation could be curl in tracker, if large enough

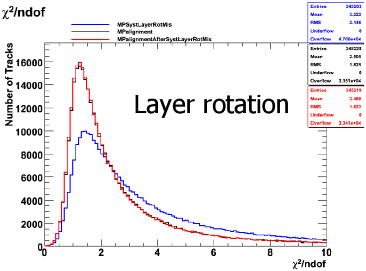


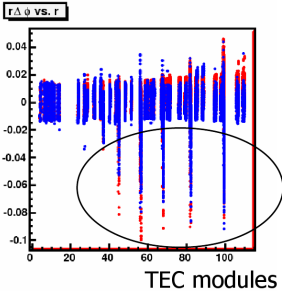
tracker curl needs to be 86 μrad
between inner and outermost radii
to yield 0.35 mrad misalignment
in muon station 1

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