Update on global alignment of the muon system

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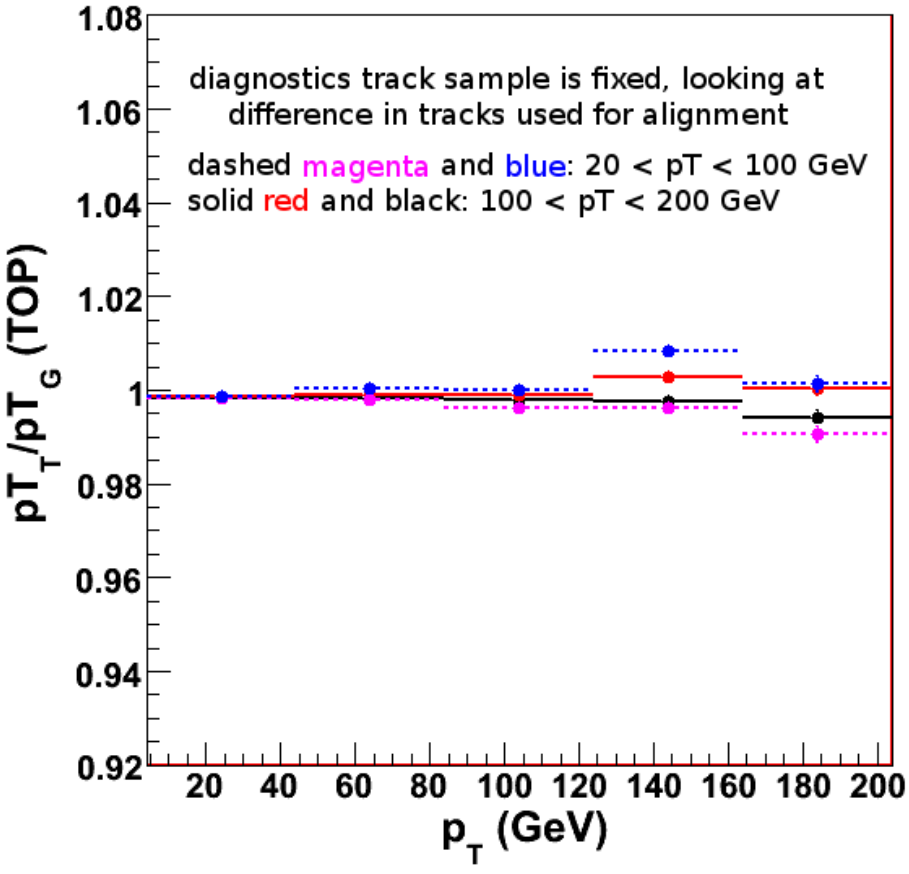
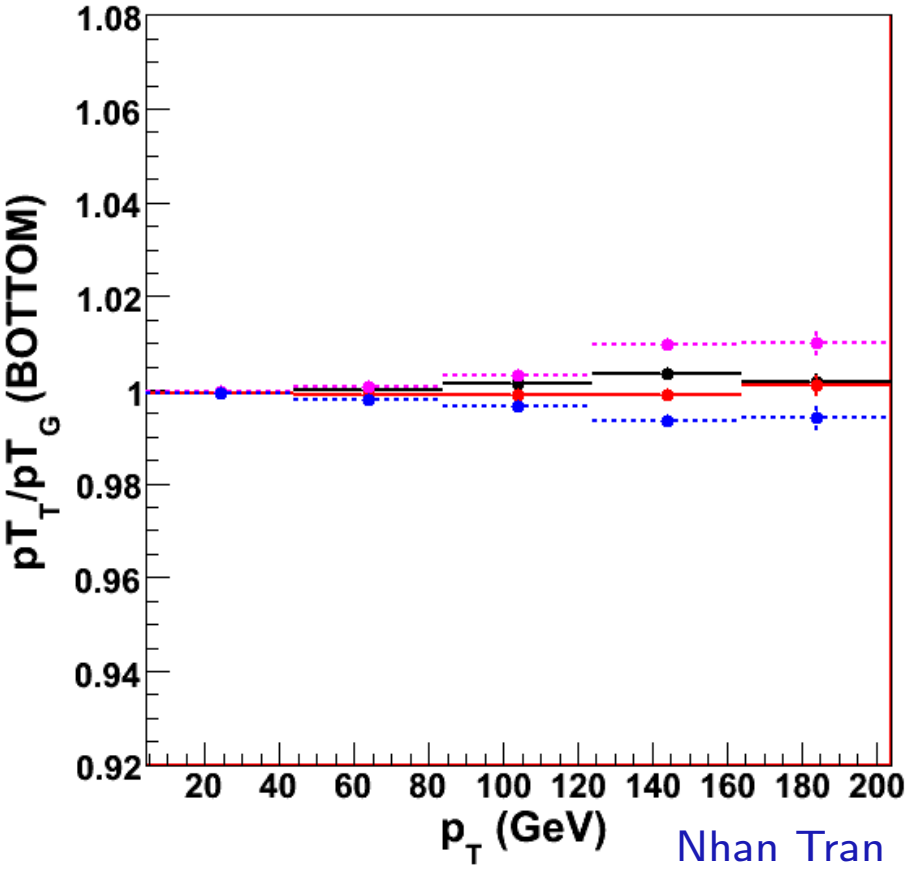
Global alignment with tracks

- Status: demonstrated high precision with collisions MC and produced CRAFT barrel alignment with $20 < p_T < 100$ GeV tracks (under review)
- Goal: move on to endcap alignment soon, where disk misalignments are known to be large
- Meanwhile: Jordan and Nhan performed their resolution diagnostics and provided very useful feedback
  - new DT alignment did not improve momentum-matching at all
  - what's the difference between alignment and diagnostics? diagnostics have a higher p_T cut
  - produced a muon alignment with $100 < p_T < 200$ GeV:
    1. muon system seen to rotate 0.35 mrad
    2. big improvement in diagnostics plots (Jordan's talk)
- This talk: to determine what this means/find the underlying cause of the improvement

The difference p_T makes

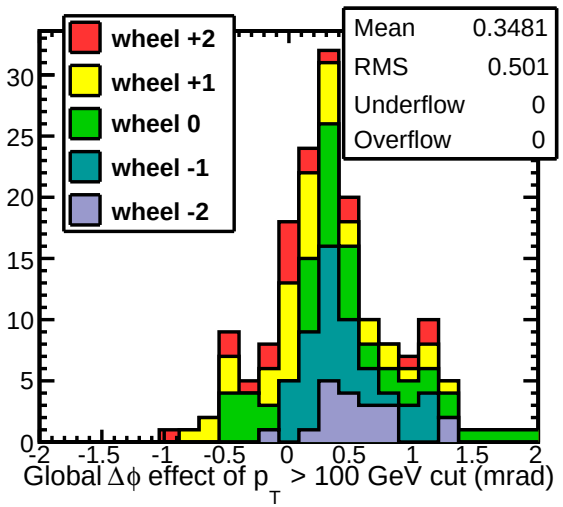


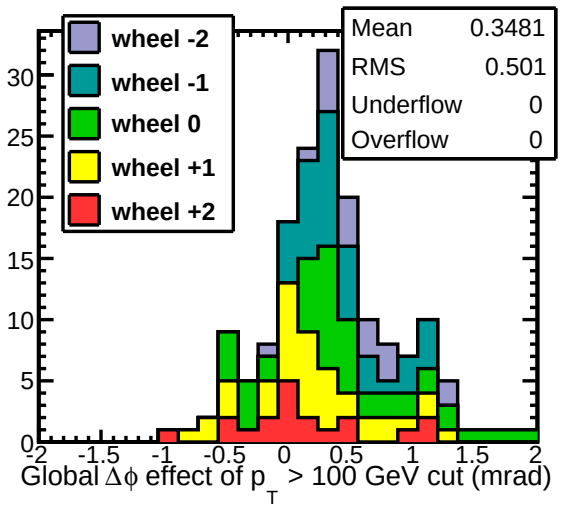


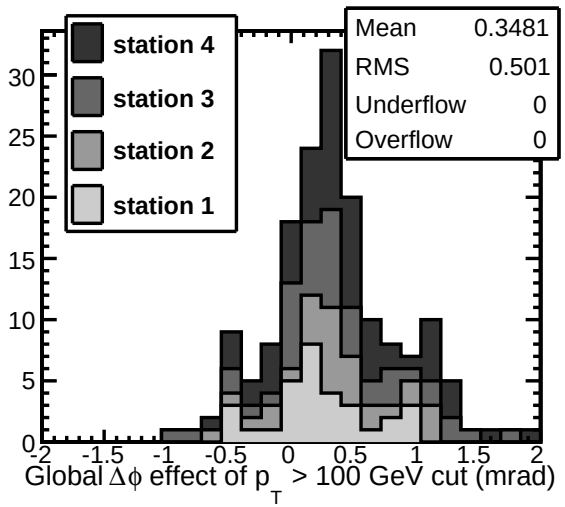
- February and "new" $20 < p_T < 100$ GeV alignments lead to split track and tracker-muon discrepancy at high energies
- Nhan tried adding 0.4 mrad rotation which empirically fixed things
- Re-aligning using only $100 < p_T < 200$ GeV tracks yields a 0.35 mrad rotation and also improves resolution

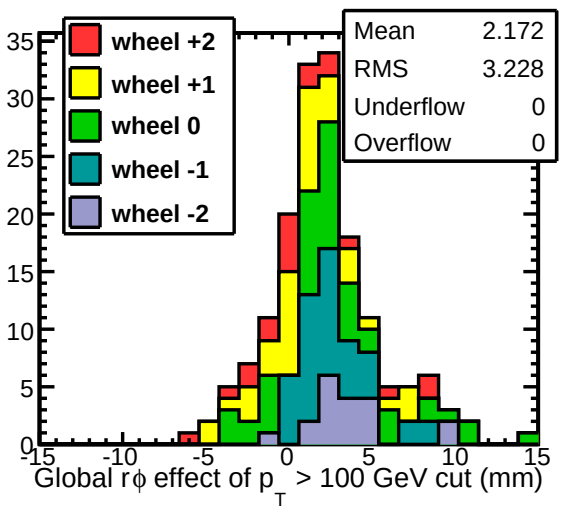
How did the chambers move?

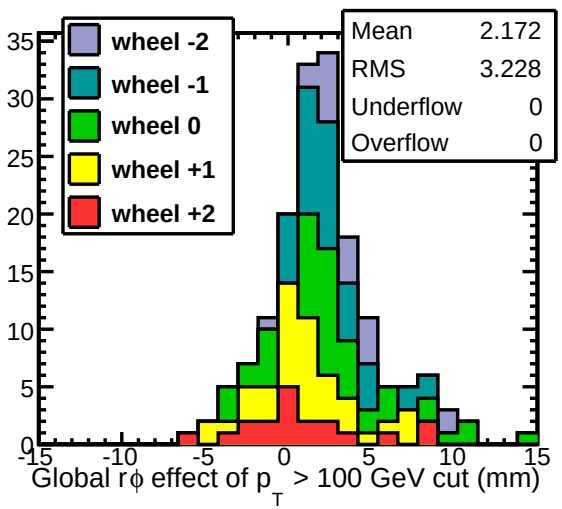
- $\Delta\phi$ rotation around beamline (top row) and $r\phi$ position difference (bottom row) between high-p_T and low-p_T, presented three ways
- 0.35 mrad rotation, 0.04 mrad/m twist, and 3.2 mm spread

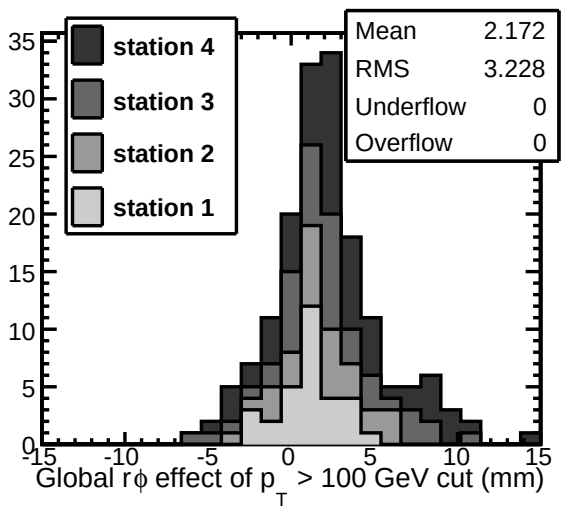






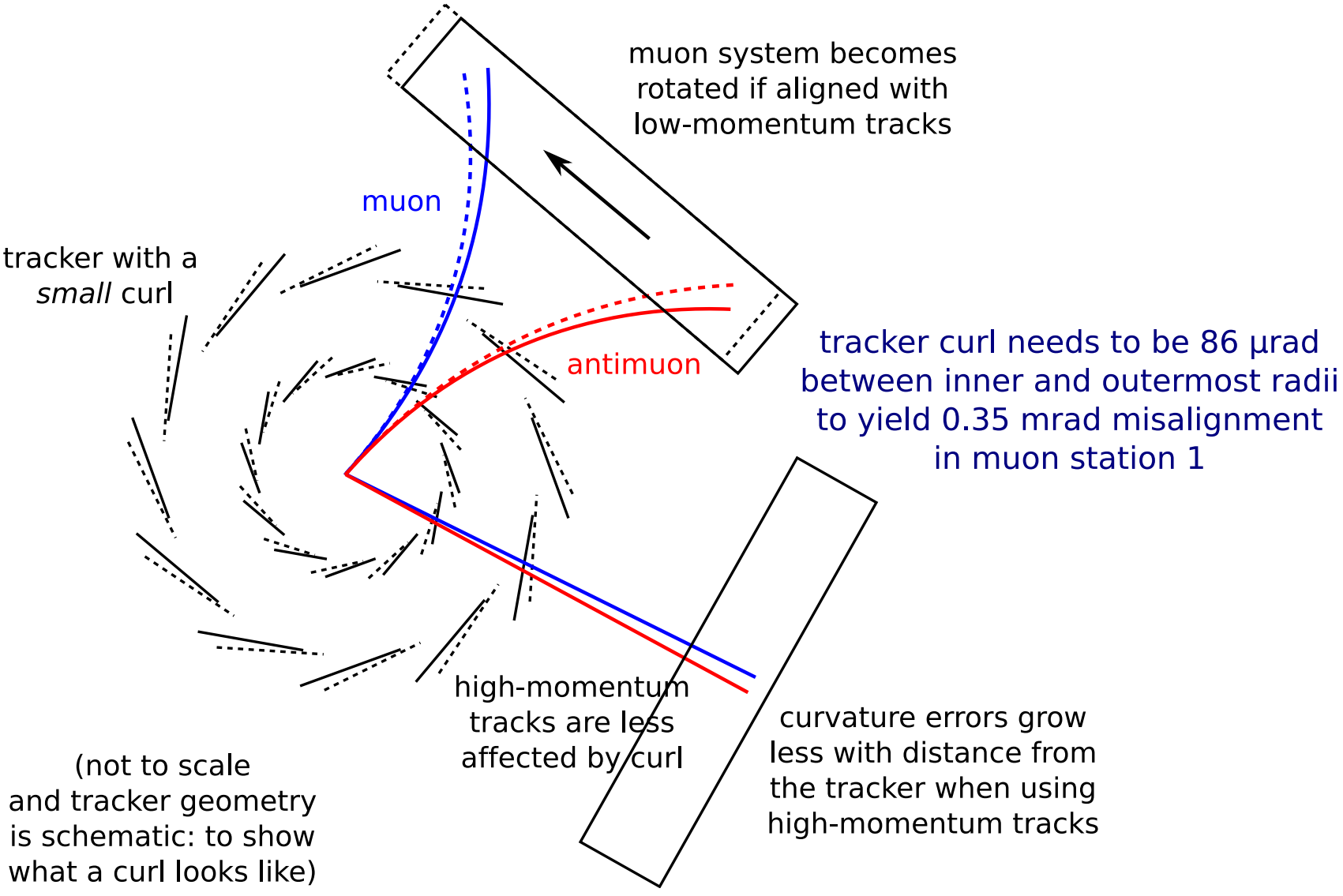






- Fact: Low-p_T alignment is systematically rotated relative to high-p_T alignment
- Reminder: each chamber is aligned to the tracker independently; chambers are *not* collectively aligned as a group
  - nothing in the procedure correlates neighboring chambers with each other with higher precision than they are positioned in global coordinates
- Mystery: how could either alignment acquire a systematic offset?
  - Reminder: all charge-antisymmetric effects like $\vec{B}(\vec{x})$ and dE/dx are explicitly cancelled: must be charge-independent
  - Hypothesis #1: tracker "curl" weak mode projected onto muon system? (tracker curl has tighter constraints than this)
  - Hypothesis #2: related to distribution of cosmic rays and "sawtooth effect" (open possibility, but it's complicated)

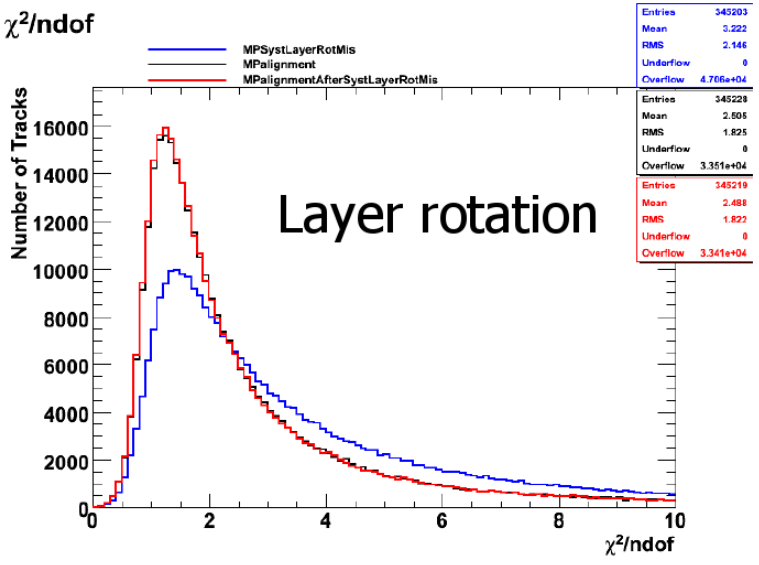
Tracker curl hypothesis

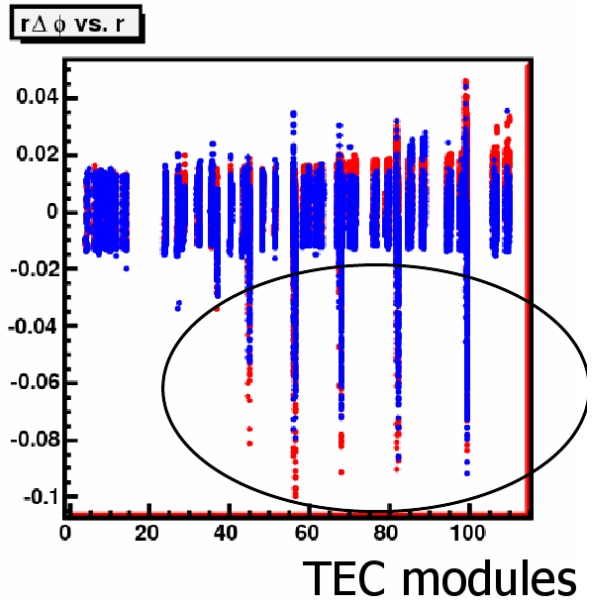


Tracker curl constraints

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

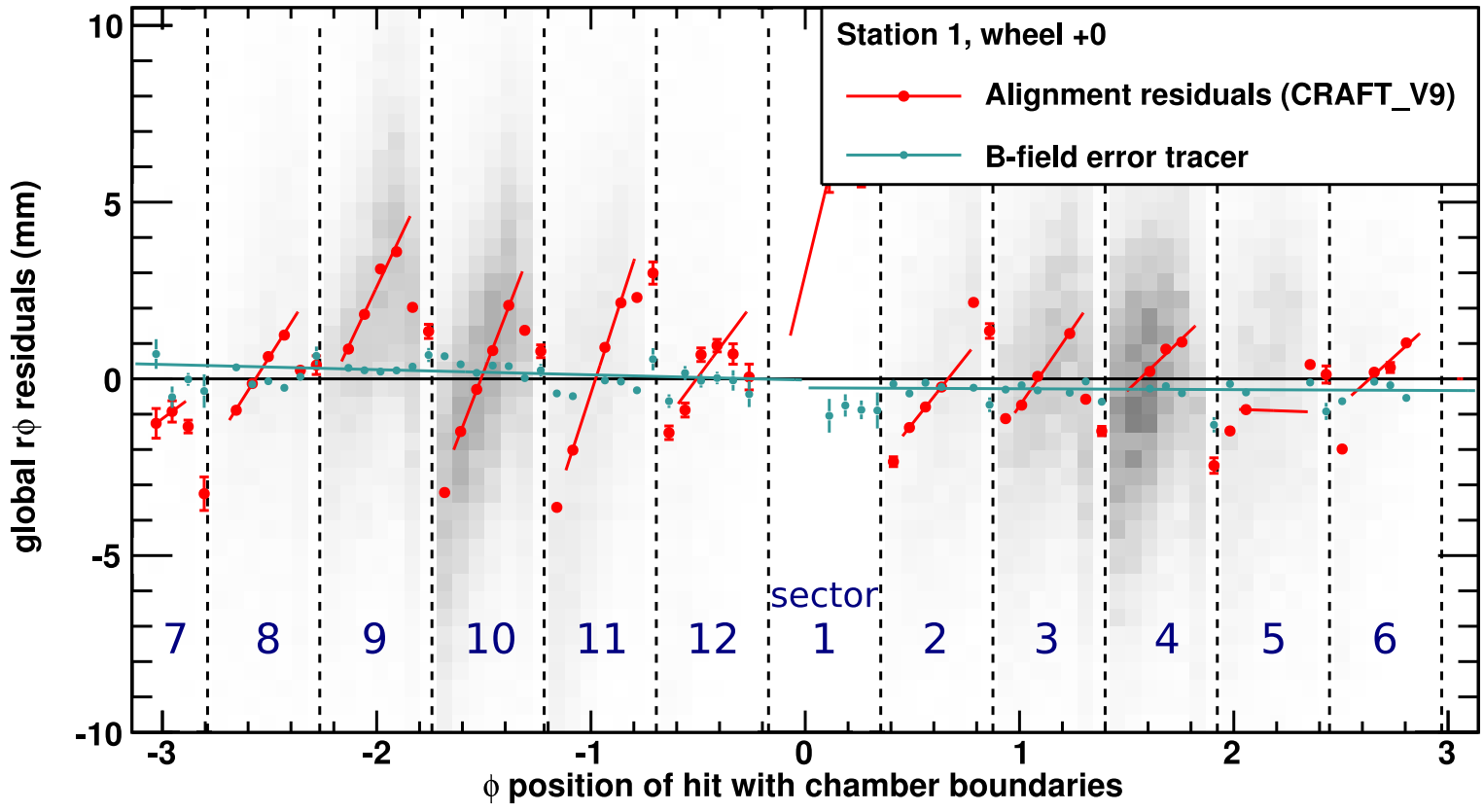
Tracker curl conclusion

- Tracker curl hypothesis requires a larger systematic trend than dedicated systematics studies allow
- *Might* account for the spread, but not the systematic rotation

Muon residuals studies: outline

1. Reminder: "sawtooth effect" in DTs still unexplained
2. We see low-p_T/high-p_T rotation in raw residuals
3. Sawtooth effect is related to p_T effect, but not in a simple way

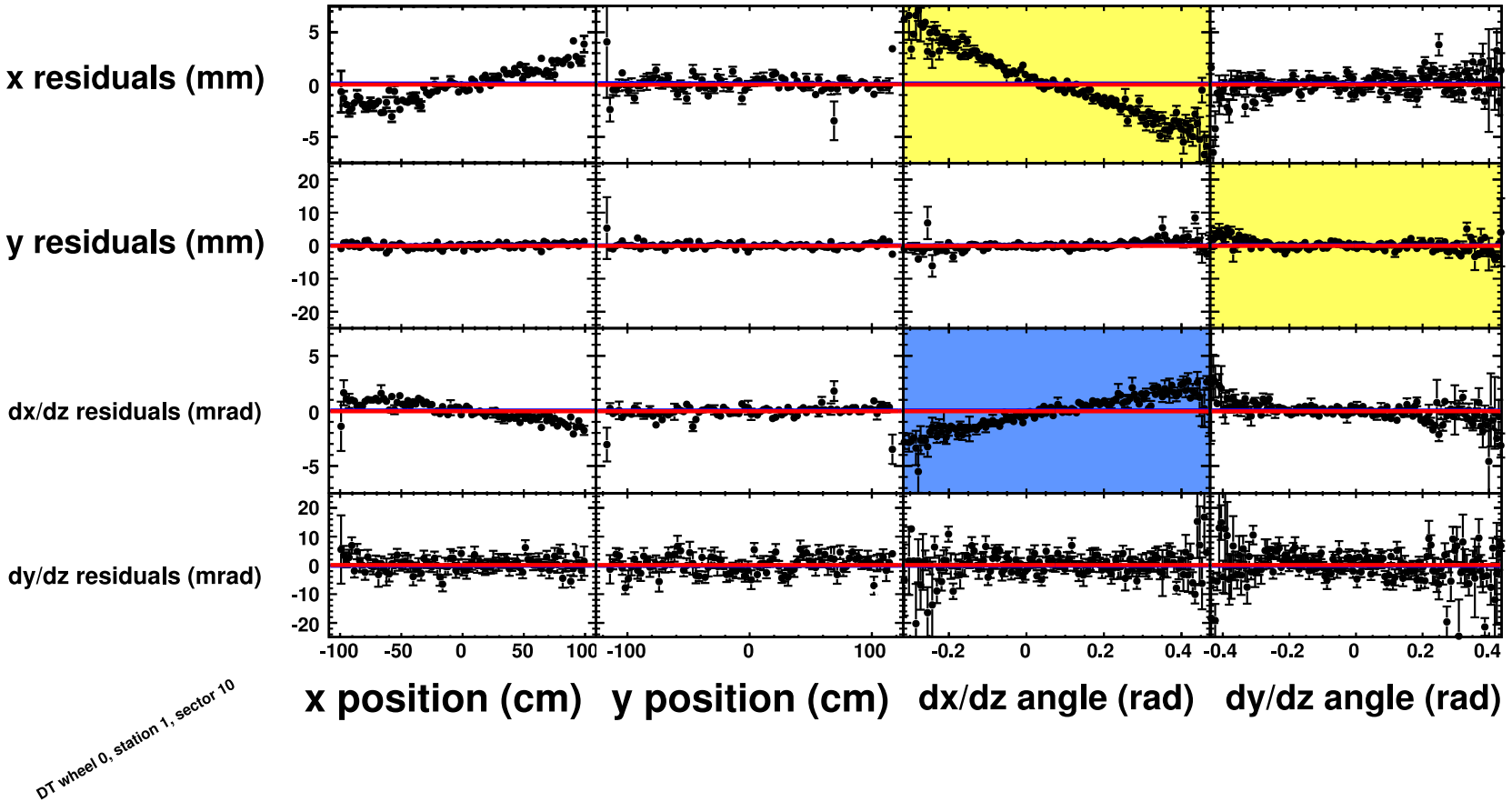
Sawtooth effect



old plot, shown in Torino

- Global $r\phi$ (Δx) residual vs. ϕ trends, unrelated to rigid-body alignment
  - ϕ is equivalent to local x position and $\frac{dx}{dz}$ entrance angle
  - Δx residuals correlated with $\Delta\frac{dx}{dz}$ angular residuals (understood)

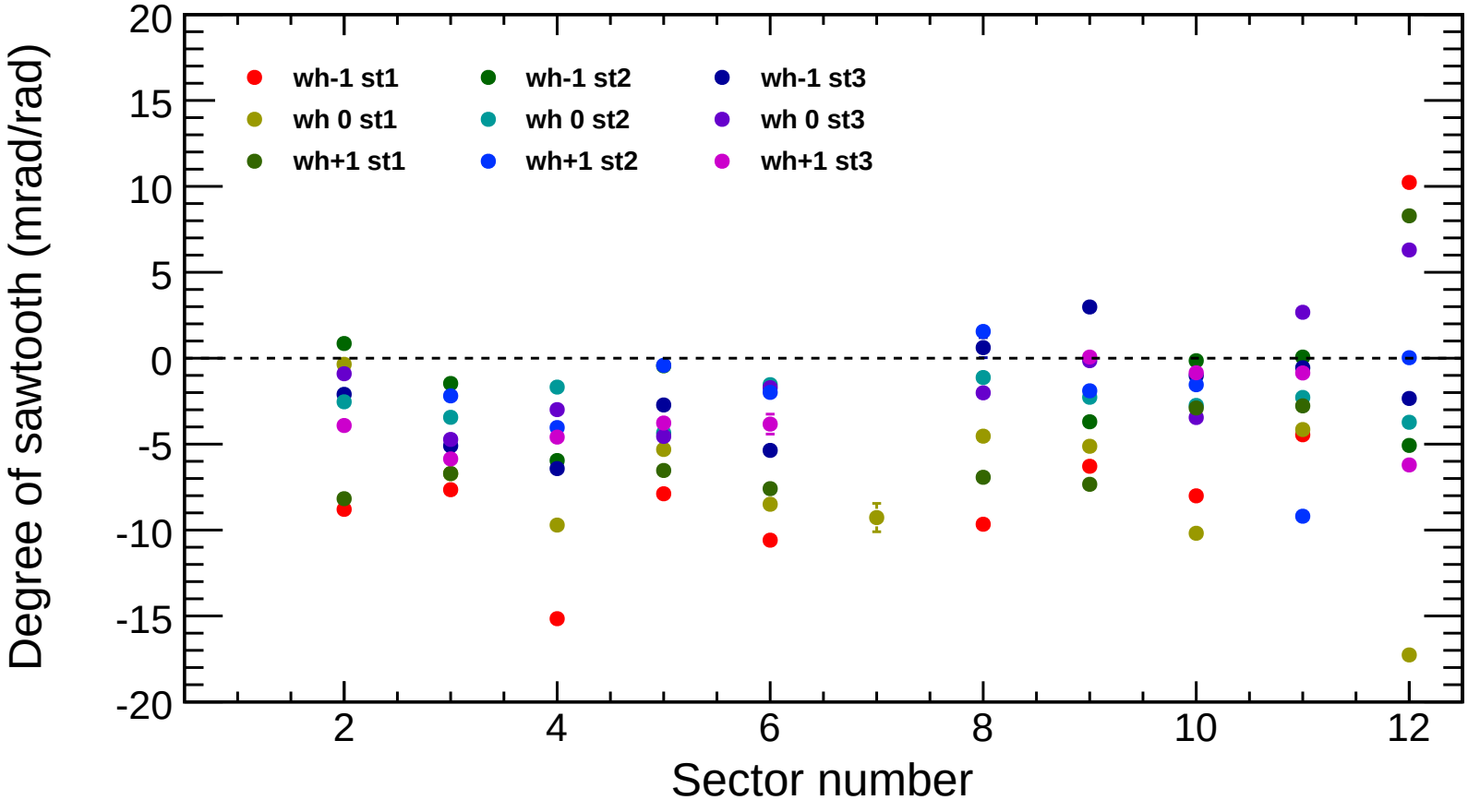
Sawtooth in one chamber



- These are all of the constraints on a single chamber alignment fit
  - sawtooth seen in correlated x and $\frac{dx}{dz}$, but more strongly in latter
  - yellow boxes: *both* must be sloped for radial (z) misalignment
  - blue/grey box: must be $(1 + (\frac{dx}{dz})^2)$ for ϕ_y angle misalignment
  - 6-DOF alignment cannot eliminate sawtooth trend

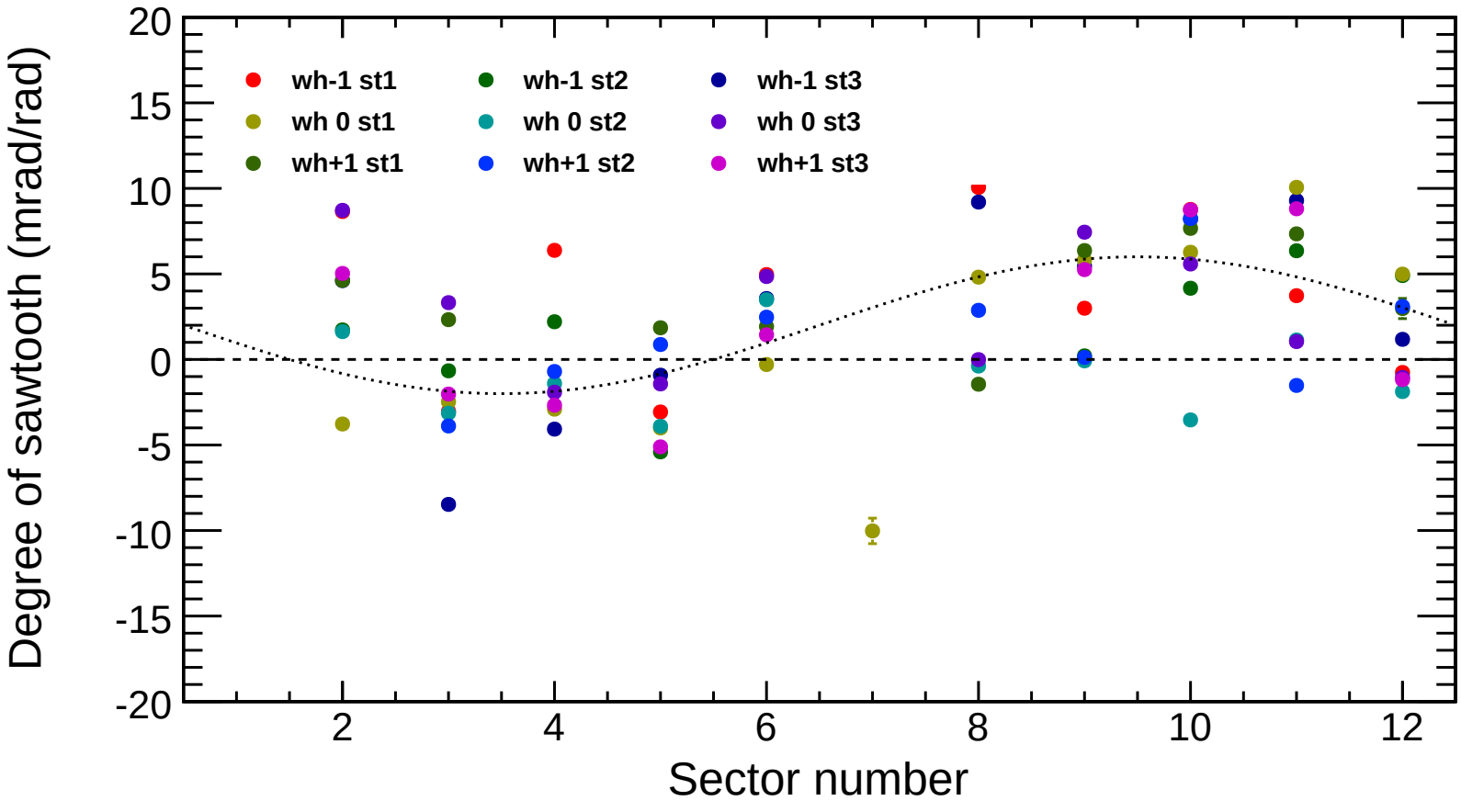
Sawtooth distribution: low-p_T

- Distribution of the effect (from separate linear fits to $\Delta\frac{dx}{dz}$ vs. $\frac{dx}{dz}$)
  - mostly depends on station number (largest in station 1)

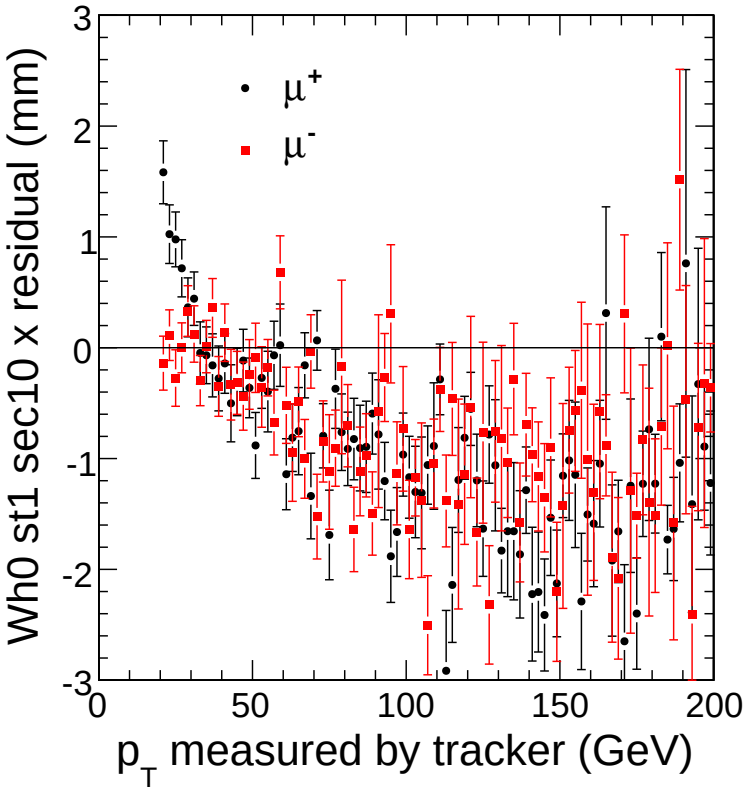


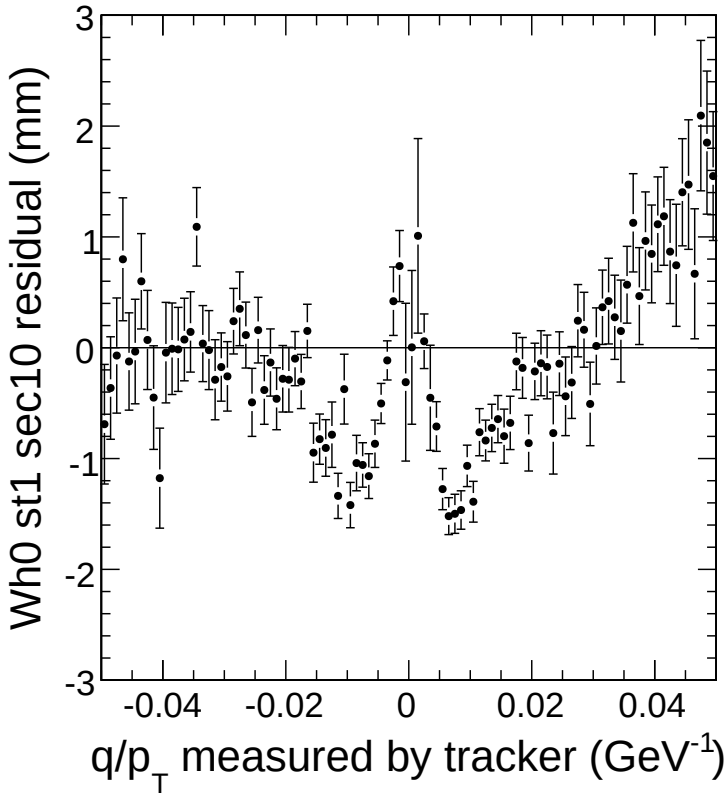
Sawtooth distribution: high-p_T

- Same thing with $100 < p_T < 200$ GeV tracks
  - distribution more centered
  - $2 + 4 \sin \phi$ curve is vaguely suggested... a clue?



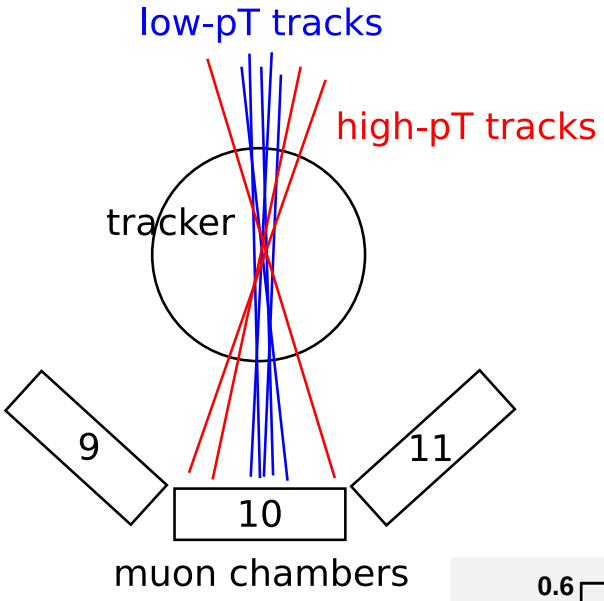
p_T effect in raw residuals





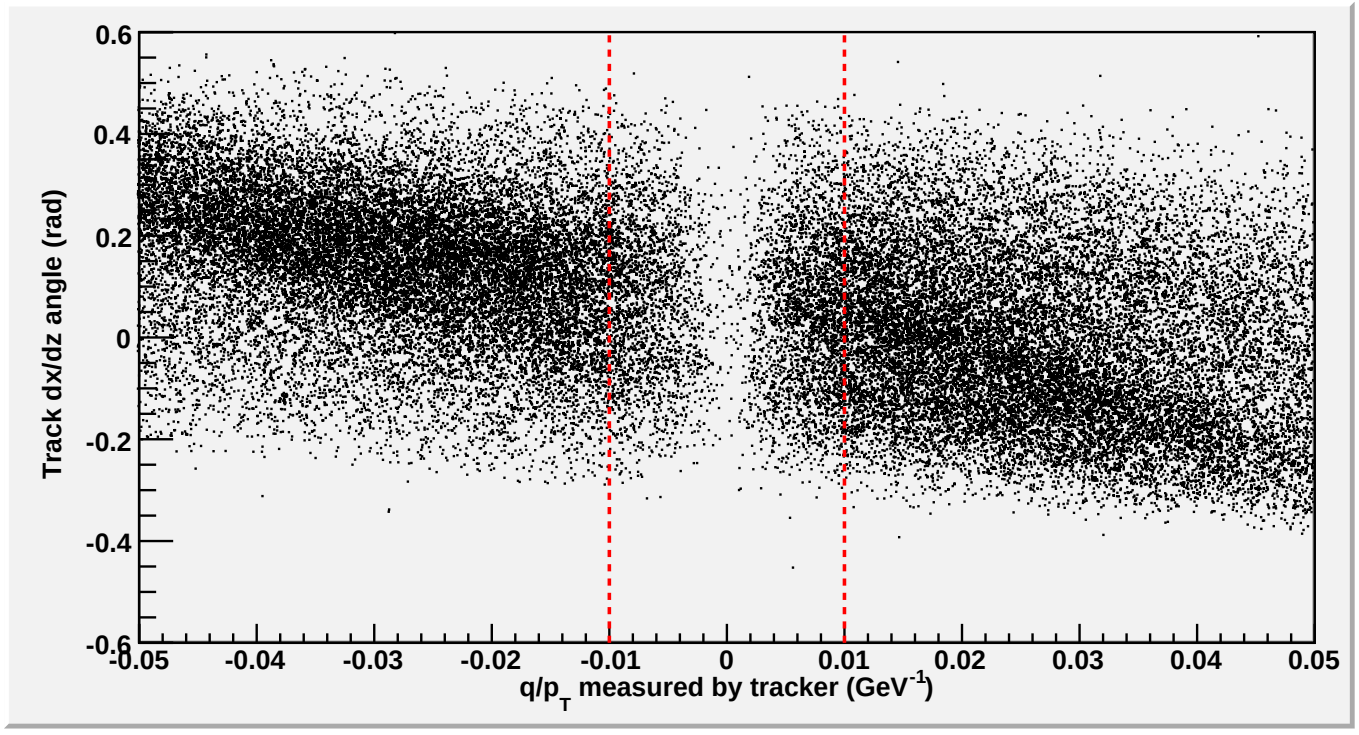
- Same chamber as page 10 (wheel 0, station 1, sector 10, bottom of barrel)
- μ^+/μ^- splitting at low-p_T can be due to $\vec{B}(\vec{x})$ or dE/dx errors
- Drifts to lower residual at high-p_T, independent of charge
  - high-p_T alignment: $100 < p_T < 200$ GeV
  - returns at very high-p_T??? not seen in all chambers...

$\frac{dx}{dz}$ (sawtooth variable) and p_T



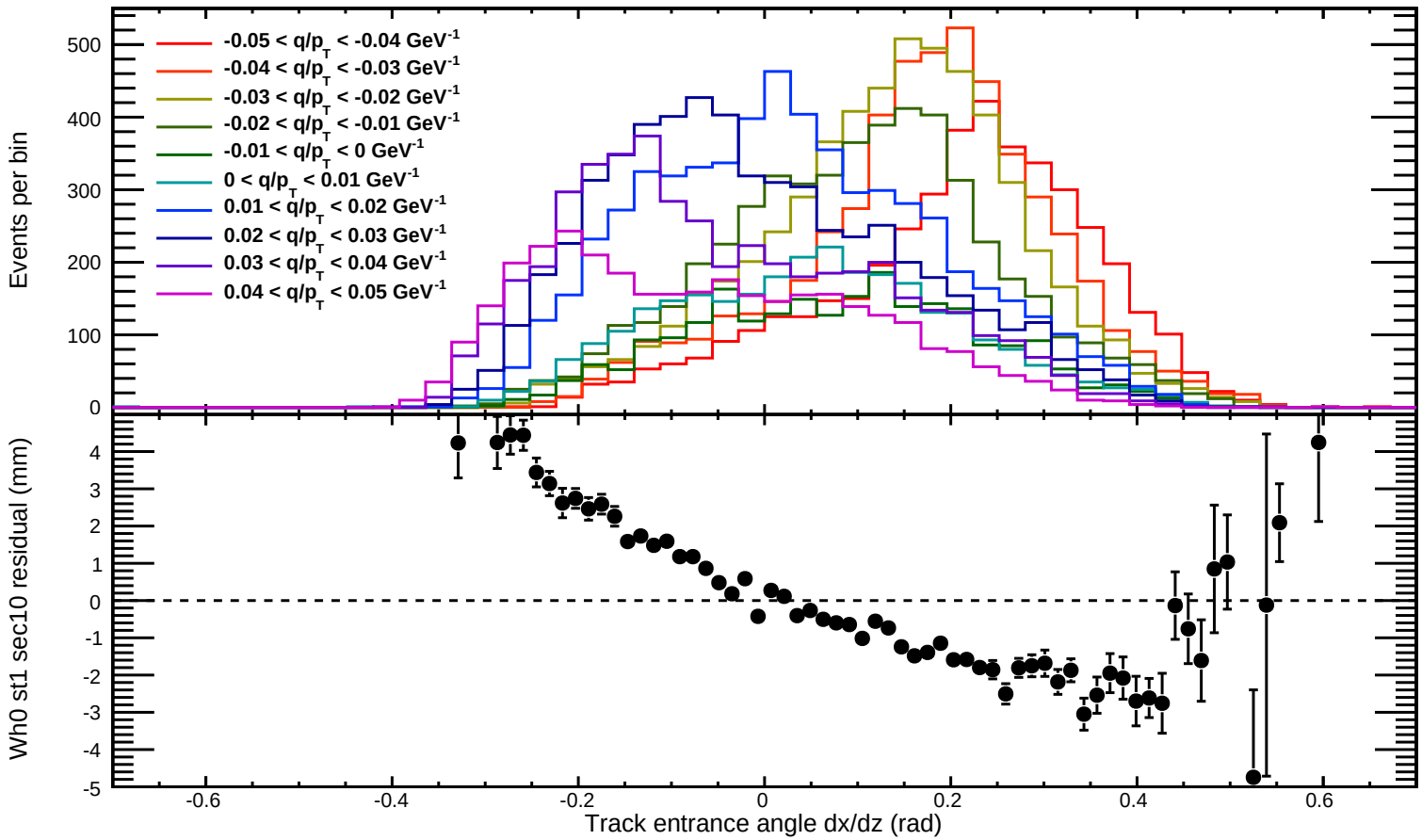
- Still looking at only one chamber, note that $\frac{dx}{dz}$ and p_T are related
- Expected because low-p_T muons are more vertically collimated by the Earth
- Unique to cosmic rays: in ϕ-symmetric collisions, p_T and $\frac{dx}{dz}$ will be independent

- Low-p_T band is sloped because of $\vec{B}$



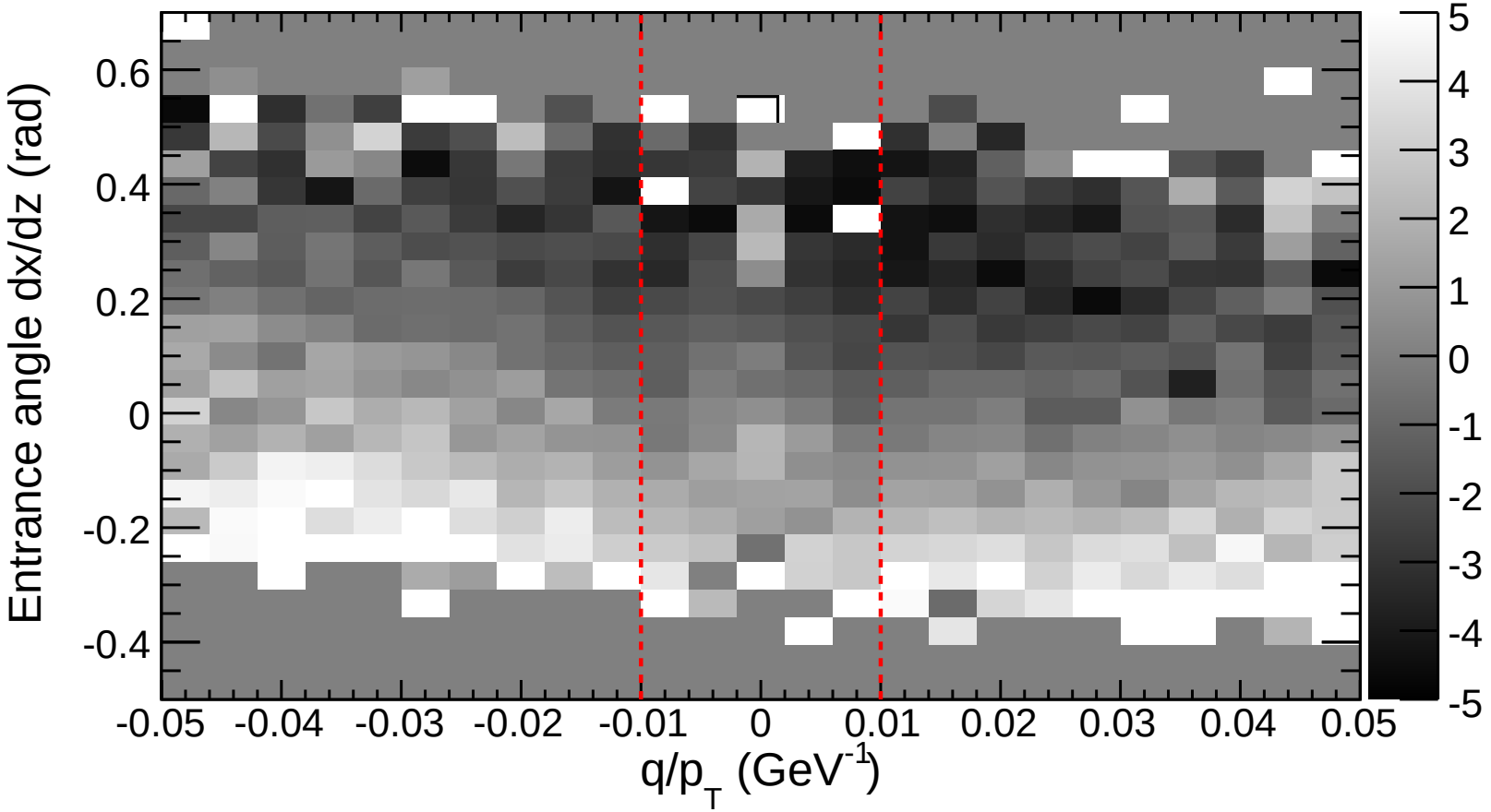
Is it just integration?

- Muons in different q/p_T slices are sensitive to different parts of the sawtooth line
- But if this were the only effect, $-0.05 < q/p_T < -0.04$ GeV^{-1} and $0.04 < q/p_T < 0.05$ GeV^{-1} would have opposite-signed residuals
- They don't: we saw that the p_T effect is charge-independent

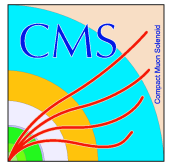


Dependence on both p_T and $\frac{dx}{dz}$

- Residuals (greyscale, mm) are a function of both p_T and $\frac{dx}{dz}$
  - sawtooth effect is vertical trend from dark to light
  - p_T effect is horizontal darkening in center
  - still one chamber only: different for each chamber, due to geometry



Conclusions



- Alignment performed with $100 < p_T < 200$ GeV cut clearly improves resolution (see Jordan's talk)
  - for the first time, tracker + muon outperforms tracker alone at high p_T
- High-p_T alignment results in a systematic 0.35 mrad rotation, consistent with Nhan's empirical study
- A p_T-dependent rotation could be caused by tracker curl
  - we would need 86 μrad in the tracker to explain 0.35 mrad in the muon system
  - tracker studies rule out systematic trends on this scale
  - *might* account for the spread
- Sawtooth effect is still unexplained (volunteers appreciated!)
- Sawtooth and p_T effects intermingle because cosmic ray distribution is a function of both entrance angle and p_T
- One effect is not derived from the other simply by integration