Summary of Current Global-Distortion Knowledge and Tools for Resolving them in General

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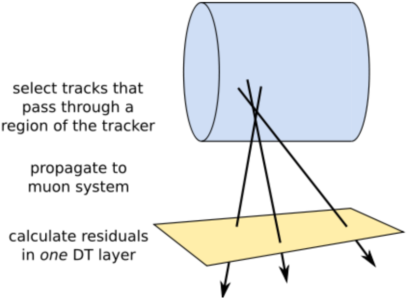
Summary

- There is evidence that a persistent effect in muon residuals is due to a global distortion of the tracker
  - it is probably a tracker-χ^2-invariant weak mode, resolved by the external information— the muon chamber hits
- Strongest indication is that a true tracker weak mode, generated intentionally with Millepede, reproduces/cancels some of the features of the bias
- The effect is not fully understood, but is too important to ignore
  - shape of the apparent bias:

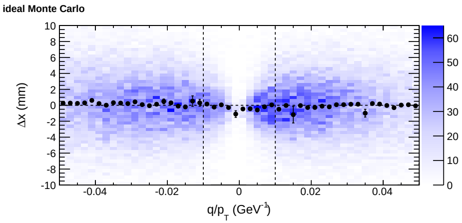
$$\Delta\kappa(p_T, \phi, \theta) - \Delta\kappa(p_T \to 0, \phi, \theta) = (0.0005\ \mathrm{GeV}^{-1}) \sin(\phi - 0.7) \exp\left(-\frac{(100\ \mathrm{GeV})^2}{2\, {p_T}^2} \right)$$

  - implies *either* 2.5% modulation of Z mass in ϕ *or* complete washing-out of Z' mass, or a little of both
- This "unpleasant discovery" could be turned into a technique for correcting the bias and even providing definite uncertainty estimates on curvature bias: systematic errors for physics analyses

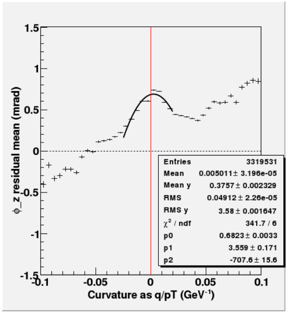
Diagnostic method

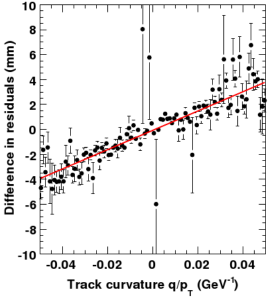


- Tracker-only track fit
- Propagate to only one muon layer (single rigid-body alignable)
- Dependence of residuals (Δx) on tracker-track curvature (q/p_T) cannot be attributed to muon misalignment

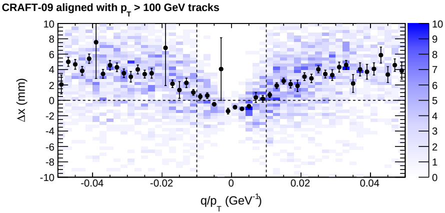


The Δx vs q/p_T plot

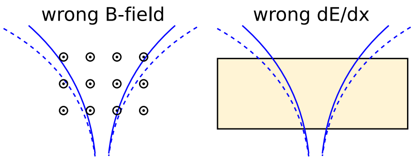


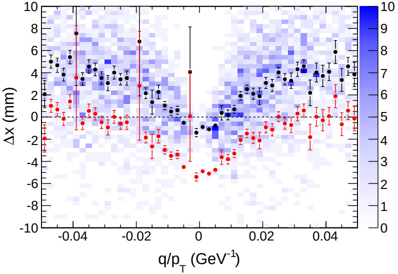


- Originally made to distinguish alignment errors from magnetic field map errors
- Top: first plot, Dec 2008, rough because all chambers combined (not yet aligned), shows the high-momentum feature
- Bottom-left: a more focused plot, single sector, $\Delta x_1 - \Delta x_2$ for two stations, shows antisymmetric magnetic field effect but no high-momentum feature
- Feature only present in residuals on tracks from the tracker, in both CRAFTs



Interpretation of this plot

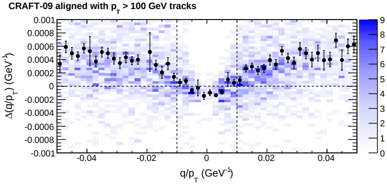




- Both magnetic field and material budget errors lead to antisymmetric effects on Δx
  - high-momentum feature effect is therefore neither
- When it is made with a single muon layer, layer misalignment (in $r\phi$) corresponds to vertical translation
  - ignore vertical offsets

- Transform $\Delta(q/p_T) = \dfrac{\epsilon}{x(q/p_T) - x(q/p_T + \epsilon)} \Delta x$, numerical derivative calculated by running propagator twice (purely mathematical); $\Delta(q/p_T)$ vs q/p_T quantifies tracker only

What we can constrain



- $\frac{\partial x}{\partial(q/p_T)}$ is nearly constant vs q/p_T (within a ϕ region), so $\Delta(q/p_T)$ has the same behavior as Δx
  - needs to be studied as a function of ϕ!
- Therefore, vertical offsets in $\Delta(q/p_T)$ vs q/p_T should be ignored, because they are equivalent to muon alignment
- We constrain only curvature bias differences:

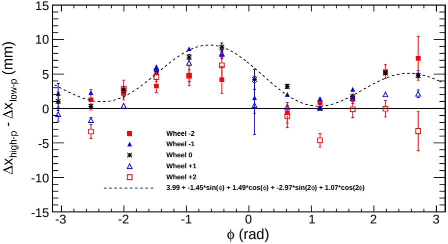
$$\Delta\kappa(\kappa, \phi, \theta) - \Delta\kappa(\kappa \to \infty, \phi, \theta)$$

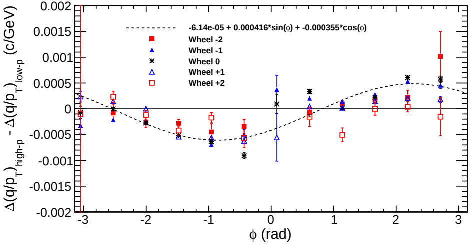
in 12 ϕ bins (sectors) and 5 $\cot\theta$ bins (wheels), $\kappa = q/p_T$

- Observed form is

$$\Delta\kappa(\kappa, \phi, \theta) - \Delta\kappa(\infty, \phi, \theta) = (0.0005\ \mathrm{GeV}^{-1}) \sin(\phi - 0.7) \exp\left(-\frac{(100\ \mathrm{GeV})^2}{2\, {p_T}^2}\right)$$

What led to the empirical form





- In these plots, we show how the differences between the tops and bottoms of the Gaussians vary in ϕ, θ
- Top is from raw residuals Δx
- Bottom is from curvatures $\Delta(q/p_T)$
- $\sin(2\phi) \to \sin(\phi)$ in the transformation is not understood, but consistent (when considering different tracker geometries and differences of geometries)

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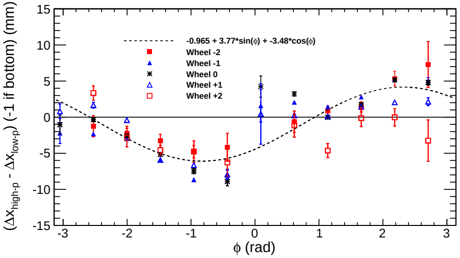

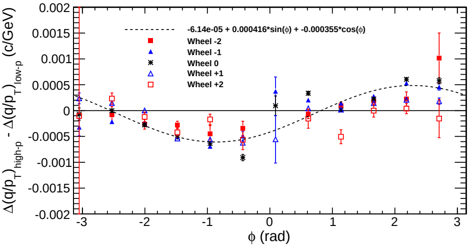

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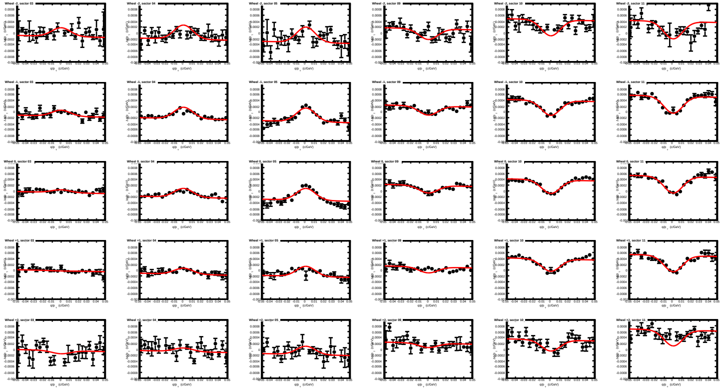
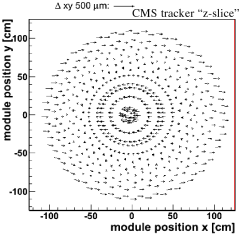
Parameterization and combined fit

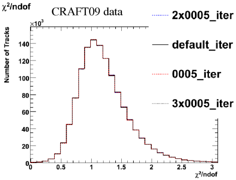
using the $\Delta(q/p_T)$ plots and expanding the expression to include wheels

$$(A)\kappa + \Big[(F + F_\theta \cot\theta) + (S + S_\theta \cot\theta)\sin(\phi) + (C + C_\theta \cot\theta)\cos(\phi)\Big]\exp(-\kappa^2 W^2/2)$$

$$\chi^2/N_{dof} = 2194/1066 = 2.06$$







- Coherent distortion of tracker with no tracker χ^2 sensitivity
- We can see its effect with muon reisduals

$$(A)\kappa + \left[(F + F_\theta \cot\theta) + (S + S_\theta \cot\theta)\sin(\phi) + (C + C_\theta \cot\theta)\cos(\phi)\right] \exp(-\kappa^2 W^2/2)$$

	χ^2/N_{dof}	A	F (GeV^{-1})	F_θ (GeV^{-1})
mode×0	2194/1066	−0.000 70	−0.000 082	−0.000 039
mode×1	2171/1068	−0.000 63	0.000 098	−0.000 063
mode×3	1991/942	−0.000 68	0.000 277	−0.000 070
uncertainty		0.000 09	0.000 005	0.000 009

	S (GeV^{-1})	S_θ (GeV^{-1})	C (GeV^{-1})	C_θ (GeV^{-1})	W (GeV)
mode×0	0.000 3533	−0.000 113	−0.000 345	−0.000 057	95.0
mode×1	0.000 3892	−0.000 156	−0.000 335	−0.000 063	93.1
mode×3	0.000 4310	−0.000 170	−0.000 386	−0.000 096	84.1
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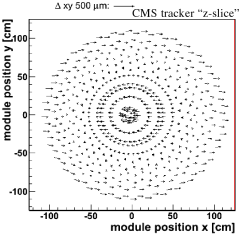

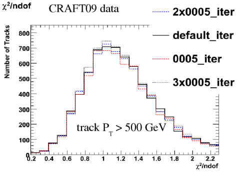

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Graphical presentation

$$(A)\kappa + \left[(F + F_\theta \cot\theta) + (S + S_\theta \cot\theta)\sin(\phi) + (C + C_\theta \cot\theta)\cos(\phi)\right] \exp(-\kappa^2 W^2/2)$$

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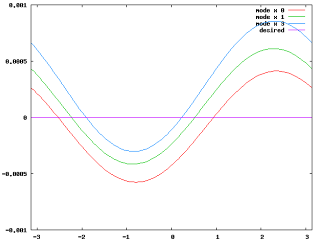


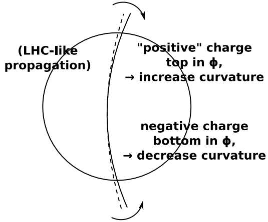
How it can be used

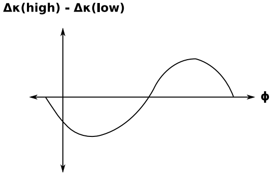
- The observed bias must be corrected in the geometry, *even* if only to verify that the diagnostic is being correctly interpreted
- However, *uncertainties* on fitted parameters quantify systematic errors in momentum for physics analyses
- Covariance matrix for fit on previous page:

$$(A)\kappa + \left[(F + F_\theta \cot\theta) + (S + S_\theta \cot\theta)\sin(\phi) + (C + C_\theta \cot\theta)\cos(\phi)\right] \exp(-\kappa^2 W^2/2)$$

$$\begin{array}{rrrrrrrr}
7.2 \cdot 10^{-9} & 1.9 \cdot 10^{-11} & 5.1 \cdot 10^{-12} & -8.3 \cdot 10^{-12} & -1.7 \cdot 10^{-11} & -6.4 \cdot 10^{-11} & 4.5 \cdot 10^{-11} & -1.2 \cdot 10^{-6} \\
 & 2.9 \cdot 10^{-11} & -1.2 \cdot 10^{-12} & 3.2 \cdot 10^{-12} & 4 \cdot 10^{-12} & 1.4 \cdot 10^{-13} & 1.8 \cdot 10^{-12} & 1 \cdot 10^{-8} \\
 & & 8.2 \cdot 10^{-11} & 3.8 \cdot 10^{-12} & 1 \cdot 10^{-11} & 2.2 \cdot 10^{-12} & -4.9 \cdot 10^{-12} & -2.4 \cdot 10^{-7} \\
 & & & 4.1 \cdot 10^{-11} & -2.9 \cdot 10^{-12} & 1.9 \cdot 10^{-12} & 6.6 \cdot 10^{-12} & 1.8 \cdot 10^{-6} \\
 & & & & 1.2 \cdot 10^{-10} & 6.2 \cdot 10^{-12} & -1 \cdot 10^{-11} & -1.7 \cdot 10^{-6} \\
 & & & & & 9.7 \cdot 10^{-11} & -4.6 \cdot 10^{-12} & 8.2 \cdot 10^{-7} \\
 & & & & & & 2.6 \cdot 10^{-10} & 2.5 \cdot 10^{-6} \\
 & & & & & & & 4.4
\end{array}$$

- Regardless of any remaining global distortions of the tracker, we would have measured limits on how wrong the momenta might be
- Precision with CRAFT-09: a few percent momentum uncertainty at 1 TeV (depending on parameterization; 0.5% for simple constant)





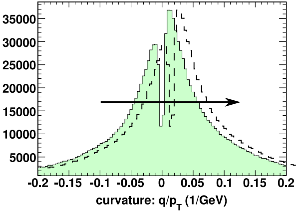
- Shape of the effect has maximum effect on cosmic rays and resonances decaying at rest

- Top and bottom are both affected by 0.000 5 GeV^{-1} $\rightarrow$ 50% at 1 TeV or 0.05% at 1 GeV
- But there's a fundamental uncertainty here: we measure $\Delta\kappa(\text{high}) - \Delta\kappa(\text{low})$ where "high" momentum tracks have $p_T \gg 100$ GeV, and "low" have $p_T \ll 100$ GeV
- From what we know now, either the Z will be unaffected and the Z' completely smeared, or vice-versa, or a little of each
- If we assume that CRAFT-08, CRAFT-09, and the current alignment have the same weak modes (not guaranteed), then it seems that the Z' will be okay: effect on charge ratio and cosmics endpoint are $\sim 0.000\,05$ GeV^{-1}

Absolute curvature bias

- If we could know the absolute curvature bias of either high or low momentum tracks, we could use the muon residuals to predict to the other

- Cosmics endpoint: assuming ∼flat efficiency for high-momentum muons, cosmic ray spectrum in q/p_T must point at zero (they trail off to infinite momentum)



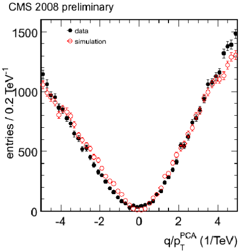
  - identifies high-momentum constant offset in $\Delta(q/p_T)$ vs q/p_T (next slide)

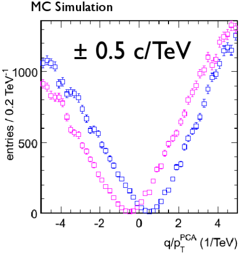
- Known resonance masses: identify linear slope in low-momentum $\Delta(q/p_T)$ vs q/p_T

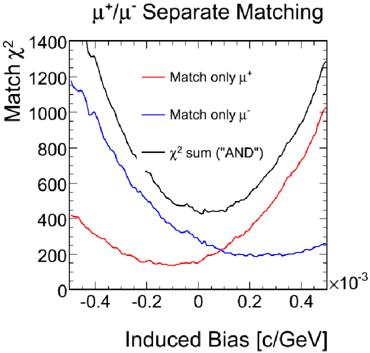
- Curvature of tracks in zero magnetic field: identify constant offset in low-momentum $\Delta(q/p_T)$ vs q/p_T

- $K_S \to \pi^+\pi^-$ decay direction constraint: identify constant offset in low-momentum $\Delta(q/p_T)$ vs q/p_T (following slides)

Cosmics endpoint (I. Furić)

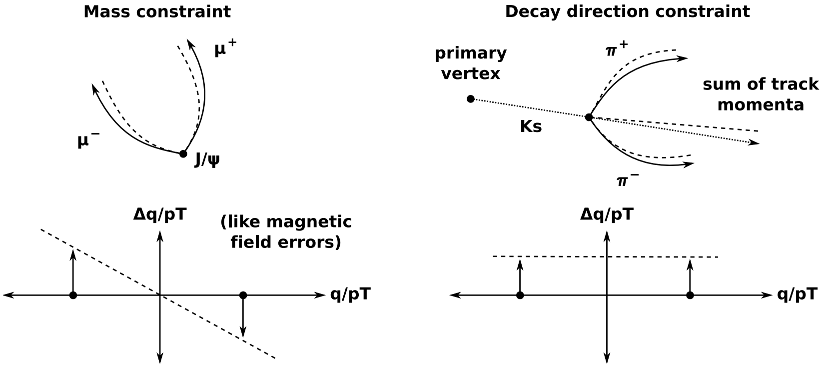






- Distribution of cosmic rays trail off at high p_T, so positive and negative distributions must both point to $q/p_T = 0$ (infinite momentum)
- Doesn't assume charge ratio, only shape of spectrum (well-known "energy$^{-2.7}$")
- Data are most consistent with $\sim 0.000\,05$ GeV^{-1}, ten times smaller than $\Delta\kappa(\text{high}) - \Delta\kappa(\text{low}) = 0.000\,5 \sin\phi$ GeV^{-1}
- Implies that the muon-residuals effect is mostly in $\Delta\kappa(\text{low})$? Can we check that?

- Momentum sum of the $\pi^+\pi^-$ system must be collinear with the displacement of the secondary vertex
- As a constraint on momenta, this is orthogonal to resonance mass

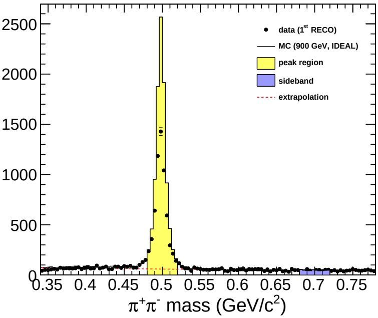


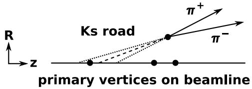
- These two are the first terms in a general $\Delta\kappa(\kappa, \phi, \theta)$ expansion in κ

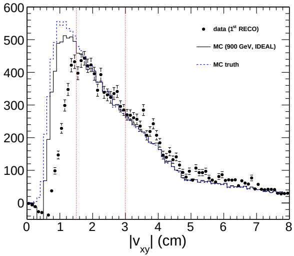
Implementing the K_S constraint

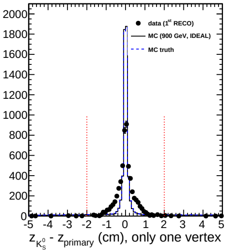
to get a sense of how tight it is from Nov-Dec 2009 data

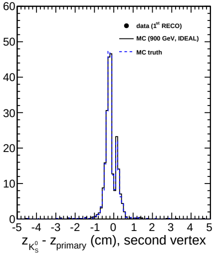
- Select events using
  - $\pi^+\pi^-$ mass with sideband subtraction
  - vertex inside the first pixel layer
- Pointing to choose the primary vertex in z projection





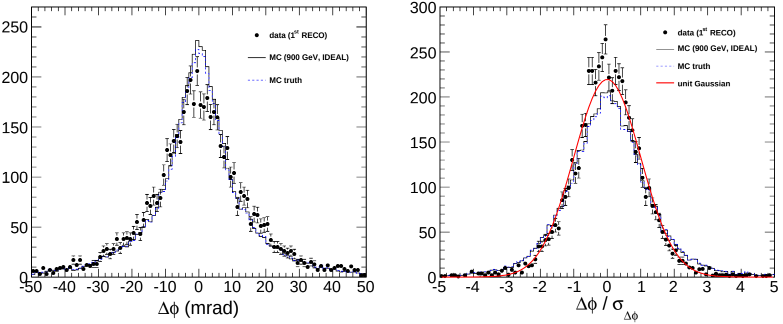






Observable: $\Delta\phi$

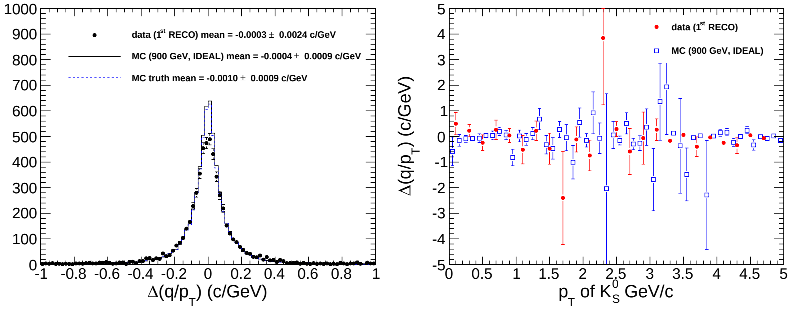
- Angle between primary-to-secondary displacement vector and $\pi^+\pi^-$ momentum sum in the transverse plane: $\Delta\phi$
- Not used up by any selection requirements



- No observed bias, with some uncertainty

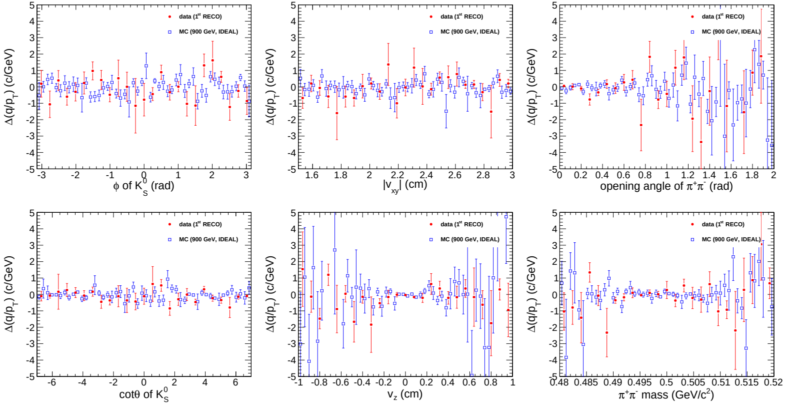
Convert to absolute $\Delta(q/p_T)$

- Compute $\frac{\partial \Delta(q/p_T)}{\partial \Delta\phi}$ by taking numerical derivatives with the vertex-fitter



- $\Delta\kappa(\text{low}) = -0.000\,3 \pm 0.002\,4\ \text{GeV}^{-1}$
- 0.24% uncertainty in bias of 1 GeV tracks
- Uncertainty in bias of 1 TeV tracks = 240% (plus a few percent from the $\Delta\kappa(\text{high}) - \Delta\kappa(\text{low})$ propagation)

Flat with respect to everything else



Conclusions

- "Muon residuals vs momentum trend" seems to be related to a distortion of the tracker
- Markus has created a true weak mode of the tracker which produces a similar signal in the muon residuals, including the curious 100 GeV characteristic scale
- Muon residuals indicate a high-low bias difference of $\Delta\kappa(\text{high}) - \Delta\kappa(\text{low}) = 0.0005 \sin\phi$ GeV^{-1}
- Cosmic spectrum endpoint excludes a $\Delta\kappa(\text{high})$ of 0.0005 GeV^{-1}, more like 0.00005 GeV^{-1}
- $K_S \to \pi^+\pi^-$ direction constraint is weak, $\Delta\kappa(\text{low}) = -0.0003 \pm 0.0024$ GeV^{-1}
  - would improve with statistics
  - perhaps K_S can help to constrain alignment procedure?
- Just as importantly: uncertainties on $\Delta\kappa(p_T, \phi, \theta)$ as a deliverable to physics analyses?