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

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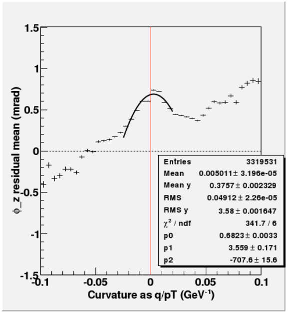
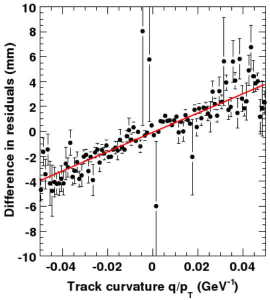
Quick-quick summary

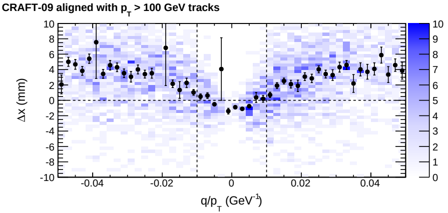
- We have known about this (unexpected and) unexplained feature in high-momentum muon residuals since first plots of CRAFT-08 data
- Evidence has been gradually mounting that it indicates a problem with the tracks from the tracker
- Markus's Millepede-generated weak mode reproduces/cancels some of its features, making the evidence strong enough for me to claim that we're identifying a real weak mode in the tracker
- But it has some unexplained features
  - why is the curvature bias for low- and high-momentum tracks different, and what is special about the 100 GeV scale where it switches? (Millepede-generated mode reproduces this)
  - why do all $\sin(N\phi)$ dependencies in raw muon residuals become $\sin((N-1)\phi)$ dependencies in curvature bias (when calculated from numerical derivatives)?
- These muon residuals indicate a problem, but are not an analysis-ready tool yet. With some work, it can become so.

The Δx vs q/p_T plot

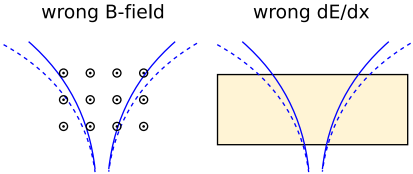


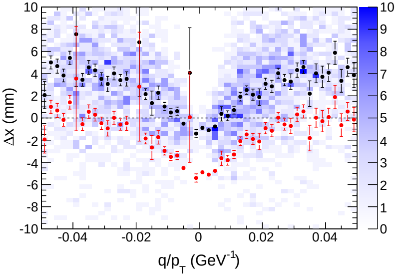


- Originally made to distinguish alignment errors from magnetic field map errors
- Top: first plot, Dec 2008, rough because all chambers combined (not yet aligned), shows the high-momentum feature
- Bottom-left: a more focused plot, single sector, $\Delta x_1 - \Delta x_2$ for two stations, shows antisymmetric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



Analysis of this plot



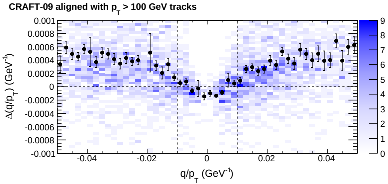


- Both magnetic field and material budget errors lead to antisymmetric effects on Δx
  - high-momentum feature effect is therefore neither
- When it is made with a single muon layer, layer misalignment (in $r\phi$) corresponds to vertical translation
  - ignore vertical offsets

- 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

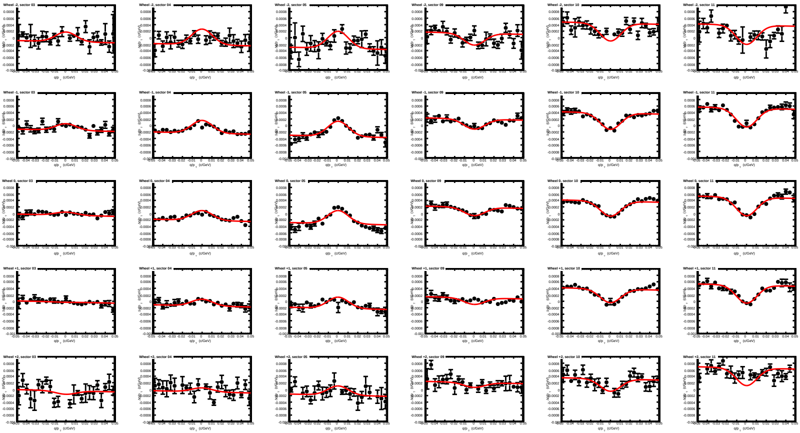
$$\Delta\kappa(\kappa, \phi, \theta) - \Delta\kappa(\infty, \phi, \theta) = (0.0005\ \text{GeV}^{-1}) \sin(\phi - 0.7) \exp\left(-\frac{(100\ \text{GeV})^2}{{p_T}^2}\right)$$

Parameterization and combined fit

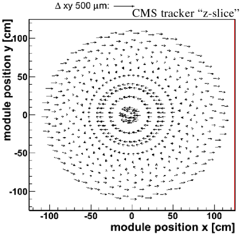
Jim Pivarski

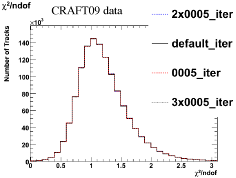
$$(A)\kappa + \Big[(F + F_\theta \cot\theta) + (S + S_\theta \cot\theta)\sin(\phi) + (C + C_\theta \cot\theta)\cos(\phi)\Big]\exp(-\kappa^2 W^2/2)$$

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



Millepede-generated mode





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

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

	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
uncertainty	0.000 0064	0.000 011	0.000 010	0.000 016	2.1

How it can be used

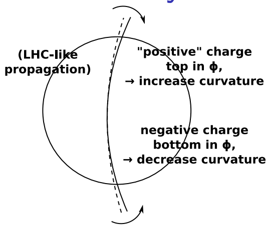
- The observed bias must be corrected in the geometry, *even* if only to verify that the diagnostic is being correctly interpreted
- However, *uncertainties* on fitted parameters quantify systematic errors in momentum for physics analyses
- Covariance matrix for fit on previous page:

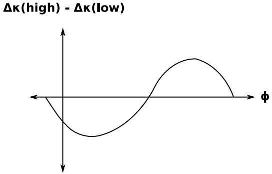
$$(A)\kappa + \left[(F + F_\theta \cot\theta) + (S + S_\theta \cot\theta)\sin(\phi) + (C + C_\theta \cot\theta)\cos(\phi)\right]\exp(-\kappa^2 W^2/2)$$

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

- 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)

What this says about charge ratio



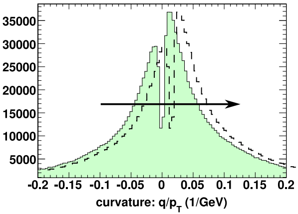


- Shape of the effect has maximum effect on cosmic rays and resonances at rest

- Top and bottom are both affected by $0.000\,5$ GeV^{-1} $\rightarrow$ 50% at 1 TeV or 0.5% at 10 GeV
- But there's a fundamental uncertainty here: we measure κ(high) $-$ κ(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} (see Ivan's slides)

- 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



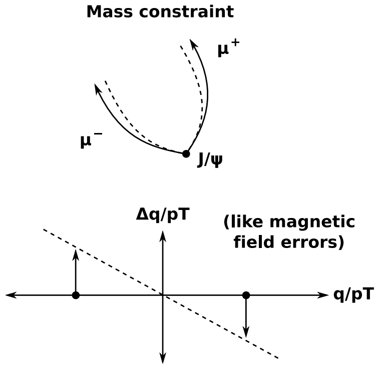
- Known resonance masses: identify linear slope in low-momentum $\Delta(q/p_T)$ vs q/p_T

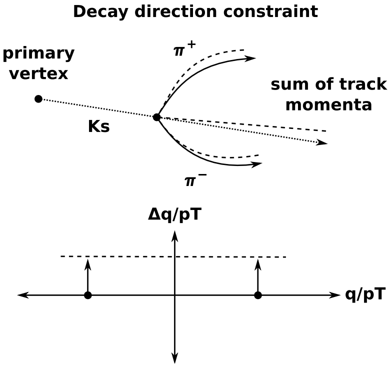
- Curvature of tracks in zero magnetic field: identify constant offset in low-momentum $\Delta(q/p_T)$ vs q/p_T

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

$K_S \to \pi^+\pi^-$ direction constraint

- 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

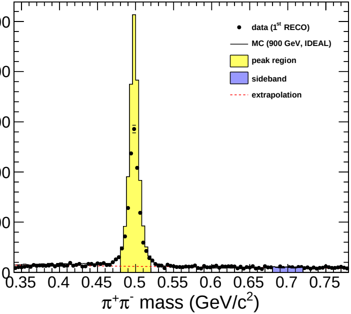


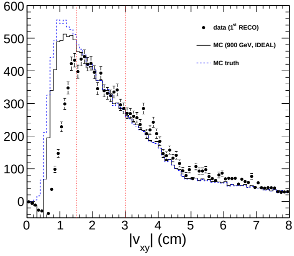


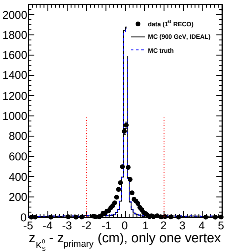
- These two are the first terms in a general $\Delta\kappa(\kappa, \phi, \theta)$ expansion in κ

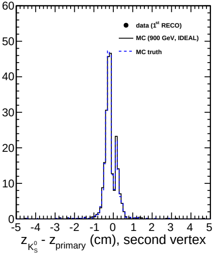
to get a sense of how tight it is from Nov-Dec 2009 data

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



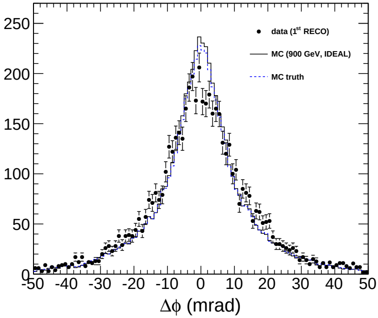


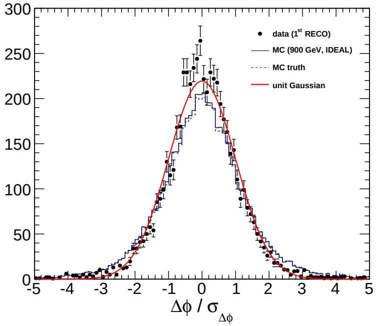


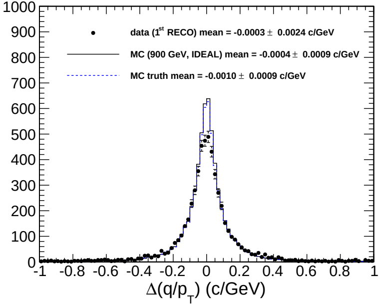


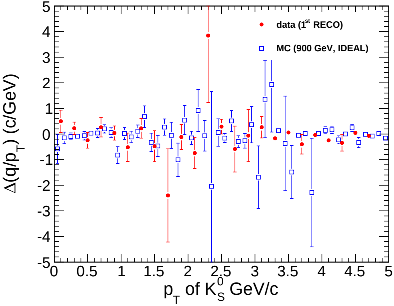
Observable: $\Delta\phi$

- Angle between primary-to-secondary displacement vector and $\pi^+\pi^-$ momentum sum: $\Delta\phi$





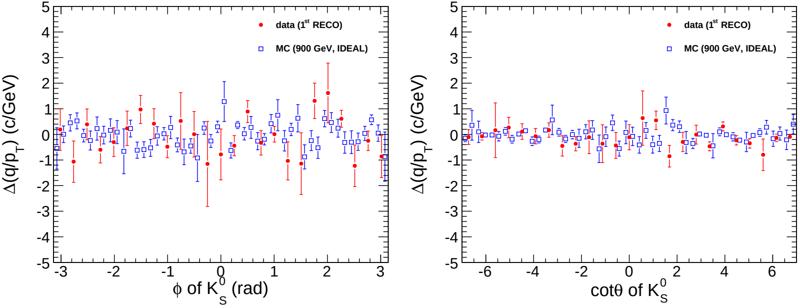


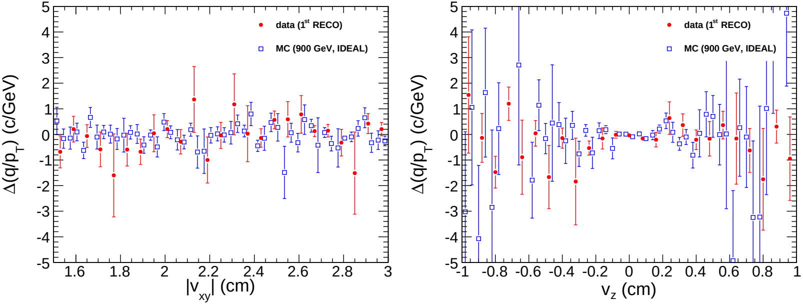


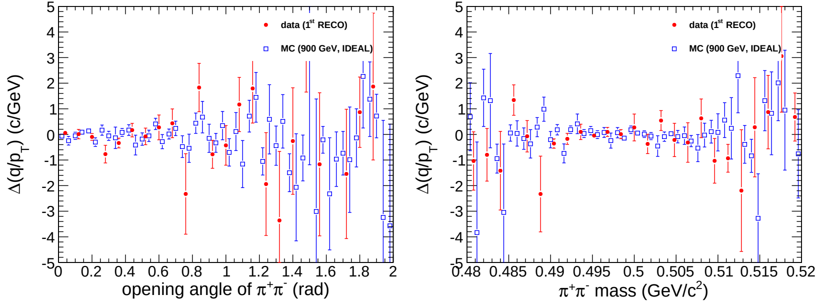
$-0.0003 \pm 0.0024\ \mathrm{GeV}^{-1}$

0.24% uncertainty in bias of 1 GeV tracks

uncertainty in bias of 1 TeV tracks = 2.4% $\oplus$ muon residuals low-to-high matching


data (1st RECO)
MC (900 GeV, IDEAL)
Δ(q/pT) (c/GeV)
φ of K0S (rad)
cotθ of K0S


data (1^{st} RECO)
MC (900 GeV, IDEAL)
$\Delta(q/p_T)$ (c/GeV)
$|v_{xy}|$ (cm)
v_z (cm)


data (1st RECO)
MC (900 GeV, IDEAL)
Δ(q/p_T) (c/GeV)
opening angle of π+π- (rad)
data (1st RECO)
MC (900 GeV, IDEAL)
Δ(q/p_T) (c/GeV)
π+π- mass (GeV/c2)