Toward Precision Muon Tracking:

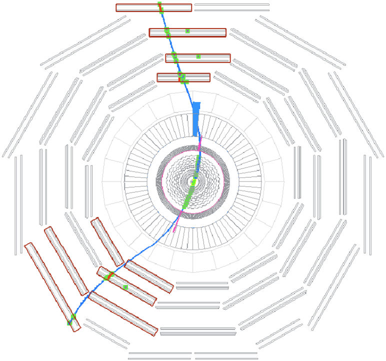
Understanding the CMS Magnetic Field and Other Effects in CRAFT

Jim Pivarski

Texas A&M University

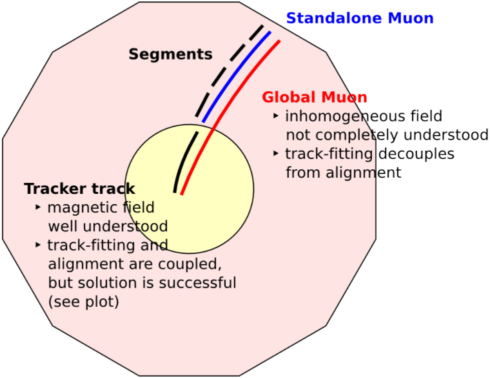
6 February, 2009

The CRAFT dataset

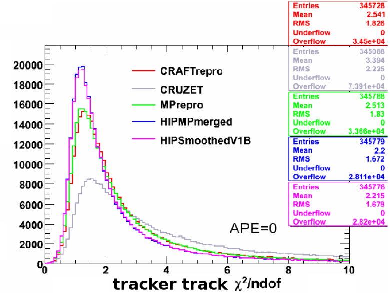


- We've all seen event displays, so we know that tracking basically works
- Now we need to use the millions of cosmic rays to test and correct tracking with high precision

Muon tracking



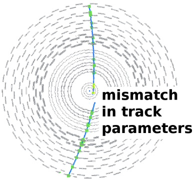
Tracker alignment group: J. Drger, R. Castello, G. Flucke, A. Gritsan, E. Migliore, M. Musich, A. Bonato, N. Tran, M. Weber et al.

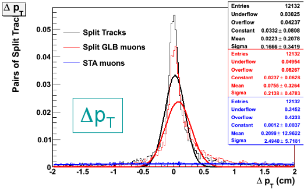


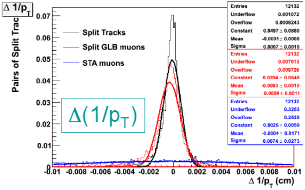
- Precision generally proceeds from the tracker outward
  - successful tracker alignment provides a good platform from which to resolve unknown $\vec{B}(\vec{x})$ in the muon system
- But also from local chamber segments outward
- In both cases, the reference has a uniform magnetic field. . .

Indication of a problem

Nhan Tran, Alessio Bonato



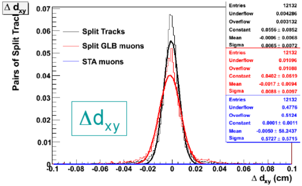


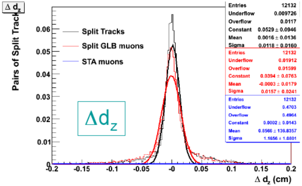


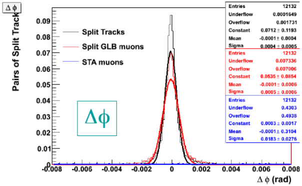
- Black: tracker track

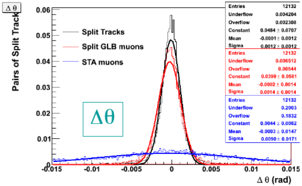
  Red: global muon

- Adding muon hits is not expected to help low-momentum tracks much, but it shouldn't hurt!



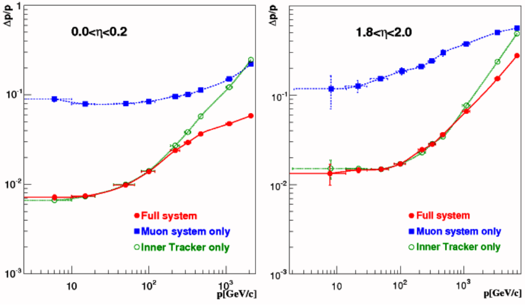






Why is this important?

- Why not use
  - tracker for high-precision tracking
  - muon system for particle-id?
- Answer: because we care about high-momentum muons!



Physics TDR

- Solving muon tracking issues could make the difference between discovering $Z' \to \mu\mu$ in 2009/2010 and not having a significant peak
- Heavy Stable Charged Particle searches also depend on good muon tracking for completely different reasons

Muon tracking issues

- Magnetic field map
  - exact shape of $\vec{B}(\vec{x})$ is difficult to model and depends on CMS's environment
- Alignment
  - for the chambers' intrinsic resolution to be useful, their positions must be known with at least equal precision
- Material budget
  - dE/dx corrections are smaller, especially for high-momentum
  - treat as negligible for now
- Calibration
  - can be solved independently of global tracking issues

Outline for this talk

1. What $\vec{B}$-field errors do to tracks
2. Aligning the muon system with an imperfectly-known field
3. Measuring the field corrections with an imperfectly-known alignment

Knowledge of magnetic field

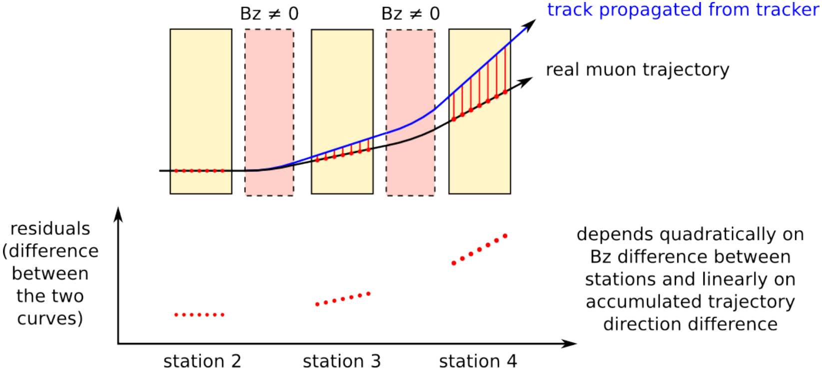
... inside the solenoid

- Magnetic field mapper, NMR probes's 2006 and 2008 data, and simulation all agree at the 0.1% level

... in the far reaches of the muon system

- Flux-loop measurements disagree with simulation as much as 20% (2006 and 2008)
- Forces on CASTOR were larger than expected
- Evidence of B_z errors in CRAFT tracks
- Evidence of B_r errors in CRAFT DT calibration

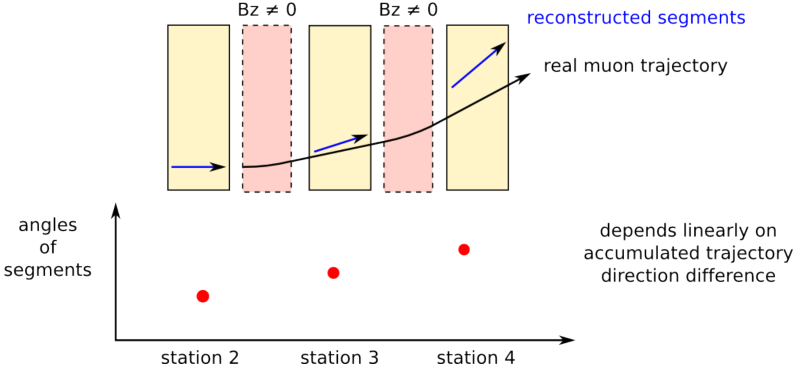
Effect of B_z errors on residuals



- Gap between propagted track and real muon grows quadratically in yoke when B_z is wrong
- Gap grows linearly elsewhere, dependent on history

  (This is like a Physics I displacement problem with regions of acceleration)

Effect of B_z errors on segments

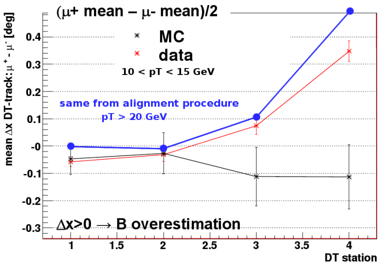


- Trajectory angle grows linearly in yoke when B_z is wrong

  (This is like a Physics I velocity problem with regions of acceleration)
- Difference in segment angles on the same track provides a direct measurement of B_z error
- Residuals method can provide a cross-check

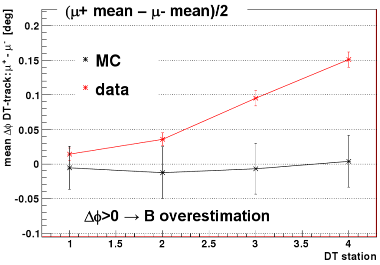
What do we observe?

Residuals



Sara Bolognesi, blue points: Jim Pivarski

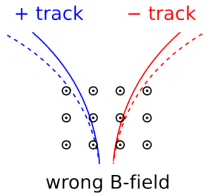
Segment angles



Sara Bolognesi

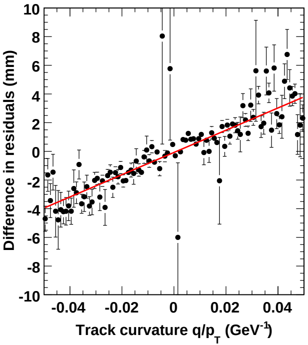
- Plots show integrated effect from tracker to each station
- Also shown to be ϕ and z symmetric within each station
- Real magnetic field is *smaller* than what is used in the simulation

B_z error and alignment



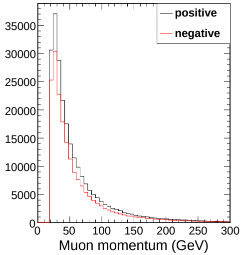
- Residuals from B_z error are as large as 5 mm
- Residuals from chamber misalignment were 5–10 mm
- How can we disentangle them?
  - magnetic field effect depends on momentum and is antisymmetric with charge

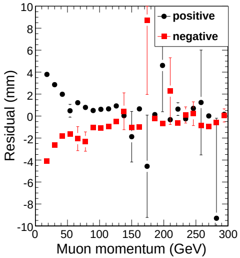
    $$\text{residual} = (q/p_T)\,\frac{\ell^2}{600\text{ cm}}\,\Delta B$$
  - misalignment effect is independent of momentum
- Residuals versus curvature (q/p_T):
  - B_z error introduces slope
  - misalignment is the value at infinite momentum $(q/p_T \to 0)$



Measuring alignment

(magnetic field is a controlled systematic error)



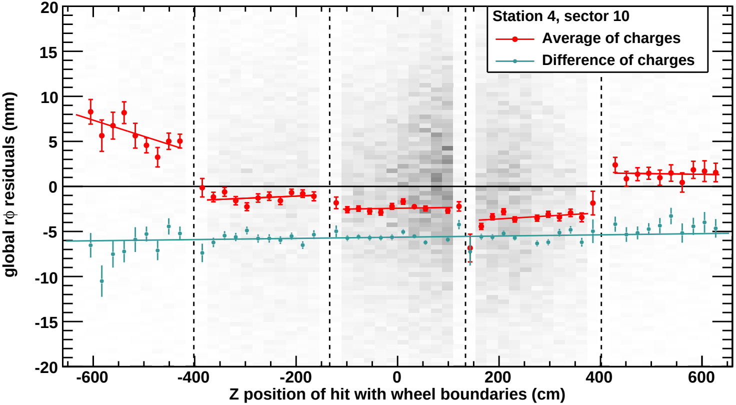


Fact: Momentum spectra for positively-charged and negatively-charged cosmic rays are equal, though the number of each differ (used in Cosmic Charge Ratio Analysis)

Fact: Effect of $\vec{B}$ on residuals flips sign with charge

- Find peak of residuals in two bins: R_+ (positively-charged) and R_- (negative)
- Misalignment residual $\equiv \dfrac{R_+ + R_-}{2}$
  - effectively scales up negatively-charged population to cancel effect of positives
- Syst. $= \left(\dfrac{R_+ - R_-}{2}\right)$ (charge confusion) $\times \dfrac{0.3}{2.3}$
  - Always plot $(R_+ - R_-)/2$ to trace systematic error (times a large factor)

- Station 4 has the largest $\vec{B}$-field errors: plot residuals across barrel
- The misalignment measure breaks cleanly at the chamber boundaries
- The tracer of $\vec{B}$-field errors is independent of chamber

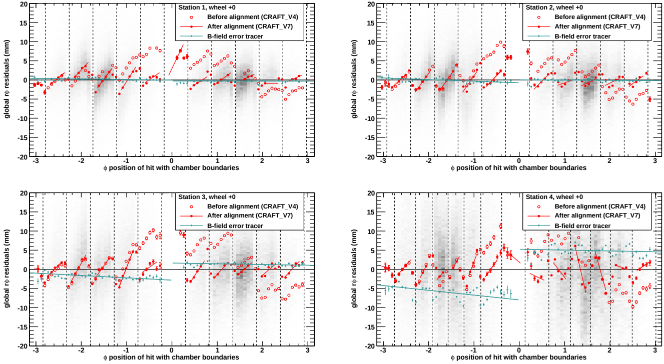


grey background is the raw 2-D residuals distribution

linear fits are only a guide for the eye: not used in alignment!

Alignment validation

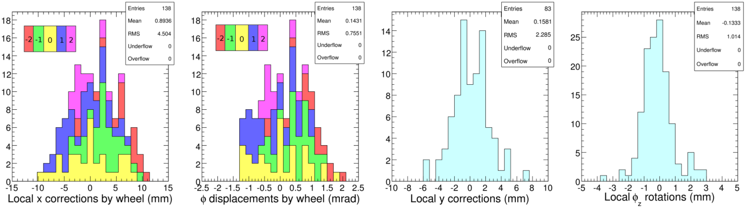
Same story when viewed as a function of ϕ (wheel 0 shown for four stations)



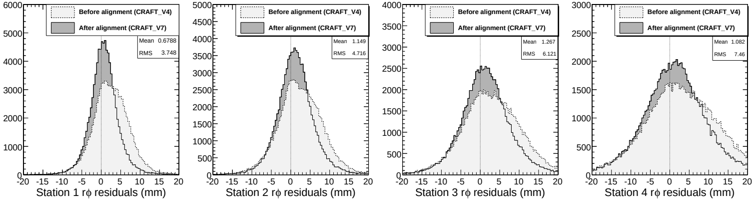
- $(R_+ - R_-)/2$ non-negligible in stations 3 and 4 only
- Flips sign in top of CMS ($\phi > 0$) because of direction of muon velocity
- Linear trend inside each chamber (sawtooth shape) is unexplained: early investigations indicate non-rigid distortion of DT chambers
- See "more information" at http://indico.cern.ch/conferenceDisplay.py?confId=51267

DT Alignment summary

- Pattern of alignment corrections do not correspond to a rotation



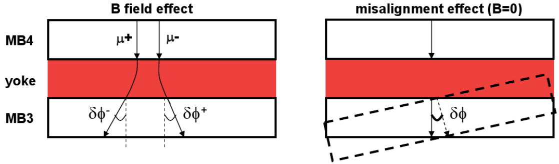
- Estimated residual misalignments: 1–2 mm (a factor-of-five improvement)
- Residuals visibly improve, despite unresolved “sawtooth” pattern



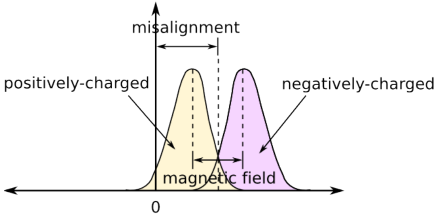
- CSCs are next, but will require a different technique due to vertical distribution of cosmic rays

Measuring B_z with segments

(misalignment is a controlled systematic error)



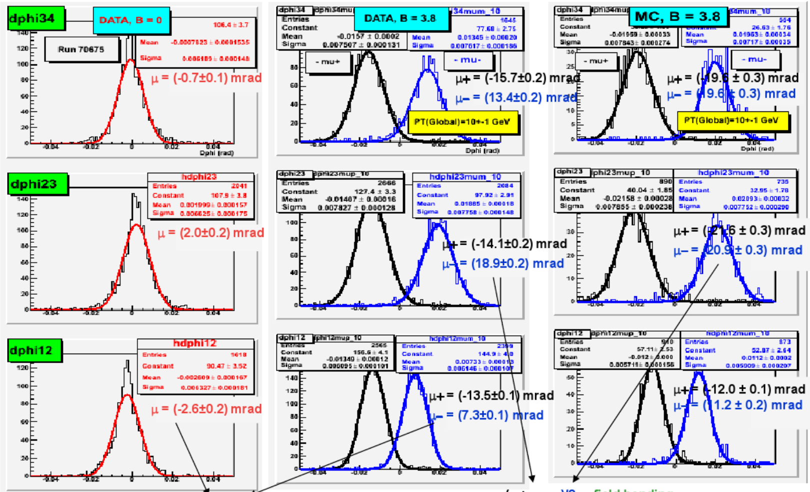
- Same principle: B_z is isolated through the difference between positive and negatively-charged bins, misalignment is the average
- Instead of residuals, plot segment angle difference between two stations on the same track
- Quantifies B_z in the yoke between them



Sample B_z measurements

Sara Bolognesi

$\delta\phi$ (wheel 0, sector 4, p_T=10±1 GeV)



(μ+ + μ-)/2 ~ misalignment

[(-13.5±0.1) + (7.3±0.1)]/2 mrad = (3.1±0.2) mrad

(μ+ - μ-)/2 ~ field bending

MC: [(-21.6±0.3) - (20.9±0.3)]/2 mrad = (42.5±0.4) mrad

DATA: [(-14.1±0.2) - (18.9±0.2)]/2 mrad = (33.0±0.3) mrad

Summary of B_z measurements

Sara Bolognesi

$(B_z|_{\text{data}}) \,/\, (B_z|_{\text{MC}})$

$10 < p_T < 50$ GeV

Real B_z is generally smaller than simulated

Comparison with flux loops

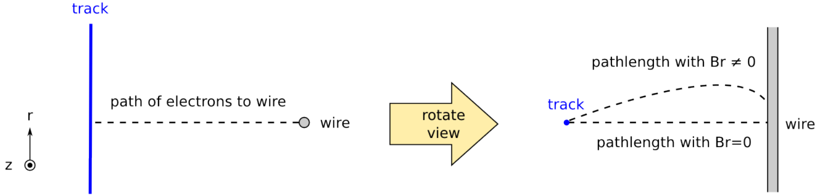
- "data/MC" is the fractional B_z error determined by segments
- The agreement is coarse at best

		MB1-2	MB2-3	MB3-4
data/MC	wheel -2	10%	26%	30%
	wheel +2	7%	25%	30%
flux-loop	wheel -2	0.1%	11.5%	21.8%
data/MC	wheel -1	4%	27%	30%
	wheel +1	2%	24%	26%
flux-loop	wheel -1	15.2%	7.0%	15.4%
data/MC	wheel 0	7%	24%	25%
flux-loop	wheel 0	0.9%	6.0%	10.5%

- **same results for opposite wheels from cosmic data**
- **deficit increasing toward outer stations in both cases**
- **rescaling is ~10% bigger in cavern (more iron in green structures and far endcap regions)**
(crazy flux-loop measurement: 2.4T)
- **measurement from comsic data made on a population not flat in z**

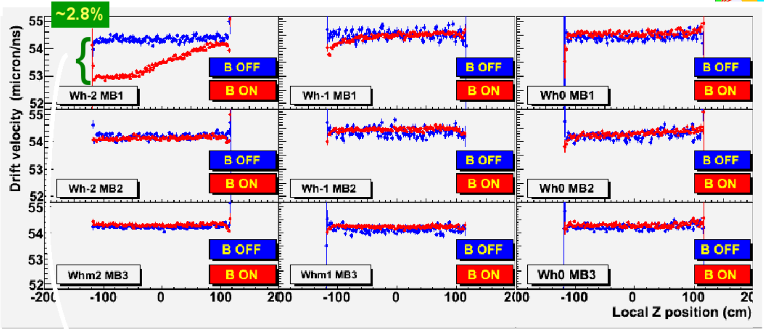
What about B_r errors?

Inside of a DT drift cell:

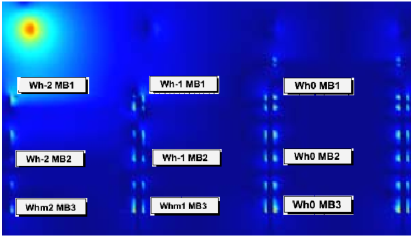


- While muon momentum may be parallel with the radial direction, current of electrons drifting to wire is always perpendicular
- Path is distorted by field, yielding a reduction in the apparent drift velocity (when computed as distance between track and wire/drift time)
- Variations in v_{drift} are sensitive to B_r, including any error with respect to simulation
- Independent of misalignment, though not a cross-check (because this is B_r, not B_z)

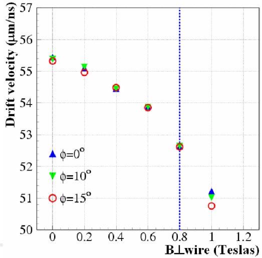
Qualitatively reproduces B_r map



Field map:



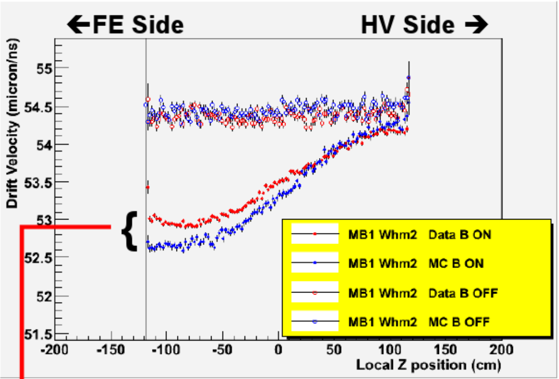
Conversion to B_r (test beam):



Mary-Cruz Fouz

B_r is also smaller than simulation

but only in high-field chambers

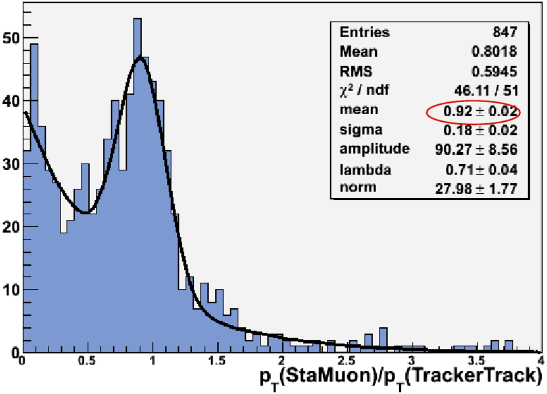


Wh +2, -2:
Smaller effect from B in data than in MC

It seems that B inside the MB chambers is lower than expected

Mary-Cruz Fouz

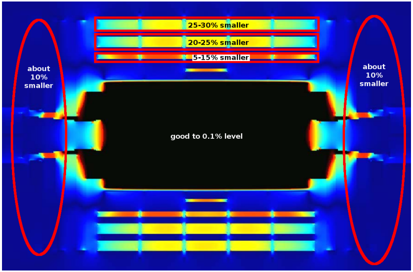
- Compares p_T of endcap stand-alone muons with tracker tracks
- Sensitive to integral of B_z error over path of tracks
- Result: B_z is about 10% lower in data than in simulation (assuming correct tracker momentum scale)
- Work in progress!



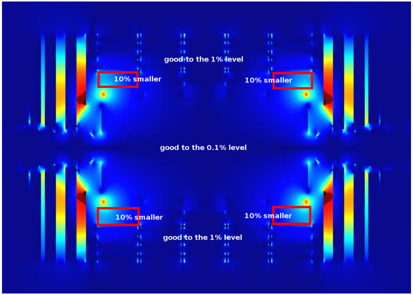
Didar Dobur

Synthesis of measurements

B_z



B_r

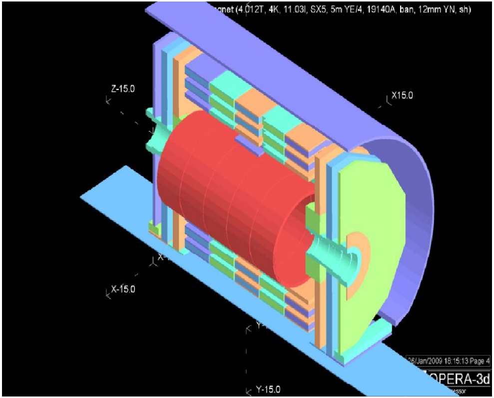


- If the field is at full strength in the tracker but smaller everywhere else, where are the field lines going?
  - close to the beamline? Maybe that explains the CASTOR forces. . . ?
- Ultimately, the field measurements must be understood in terms of an updated simulation

What went wrong?

- The magnetic field was simulated with CMS in isolation; no surrounding green structure as is in the cavern
- Quick check: adding a conducting pillbox around CMS can overcorrect for the effect
- Magnitude of corrections are therefore in the right ballpark

Dietrich Liko



- Challenge will be to make the simulation more realistic

Summary

- Muon tracking is far from perfect, but we're finding and correcting the kinds of distortions one might expect
  - improvements to barrel alignment in second CRAFT re-processing
  - emerging picture of magnetic field map
- Tracking datasets are rich: many problems that appear to be entangled can be cleanly decoupled by considering the right variables
  - but comparisons with completely independent methods, such as the hardware alignment system and $\vec{B}$-field flux loops, is always helpful
- CRAFT has been a productive shakedown cruise so far