The Alignment of the CMS Silicon Tracker

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(on behalf of the CMS Collaboration)

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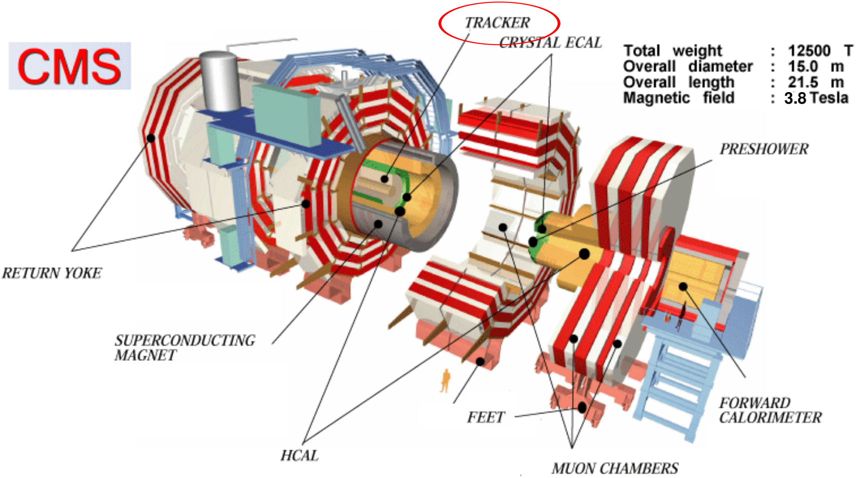
Outline

- The CMS silicon tracker
- Alignment method and tools
- Results
- Summary

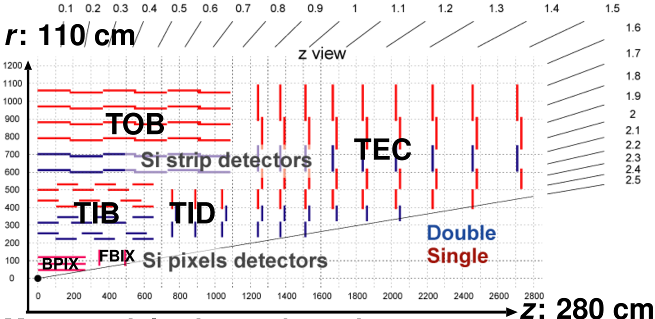
The CMS Detector at the LHC



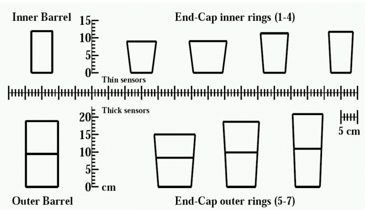
- Large Solenoid: $B = 3.8$ T.
- All Silicon Inner Tracker.

The CMS Tracker: All Silicon

***rz*-view** **(upper right quarter)**



Many module shapes for strips



Single Hit Resolution

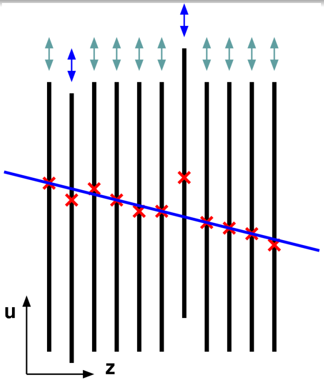
Pixel:
up to $\sigma = 9\ \mu$m

Strip:
$\sigma \approx 23 - 60\ \mu$m

- 1440 silicon pixel modules
- 15148 silicon strip modules (24244 sensors)
- Strips generally measure $r\phi$ direction
- Some radii: additional modules rotated by 100 mrad

Alignment challenge: 200 k parameters

Track Based Alignment: Principle



Simple Example

- 11 parallel planes measuring 1D
- displaced in measurement direction
- fit 10^4 straight tracks: $u = F_{\boldsymbol{a}}(z) = a_1 + a_2 \cdot z$
- residual $r_i = m_i - F_{\hat{\boldsymbol{a}}}$ at plane i:
  shift of plane i leads to $\langle r_i \rangle \neq 0$
- cannot simply shift plane by $-\langle r_i \rangle$:
  depends on shifts of other planes

$\Rightarrow$ tracks correlate alignment parameters

Proper Treatment: Global Fit Approach (e.g. Least Squares)

- Simultaneous fit of **all** parameters: shifts, track parameters!
- Minimise sum of squares of residuals, $\chi^2(\boldsymbol{a}) = \sum_k \left(\frac{m_k - F_{\boldsymbol{a}}}{\sigma_k} \right)^2$.
- $\boldsymbol{a} = (\boldsymbol{a}^{global}, \boldsymbol{a}_1^{local}, \dots, \boldsymbol{a}_n^{local})^T$
  - global: alignment parameters,
  - local: track parameters.

Track Based Alignment

Global Fit Approach

- Linearising track model and minimisation requiring $\frac{d\chi^2(a)}{da} = 0$:
  $\Rightarrow$ Normal equations of least squares $\boldsymbol{C}\,\boldsymbol{a} = \boldsymbol{b}$.
- Local parameters appear in part of the data only:
  $\Rightarrow$ Block structure in $\boldsymbol{C}$, use matrix algebra to reduce problem:

$$\boldsymbol{C'}\,\boldsymbol{a}^{global} = \boldsymbol{b'}.$$

- Matrix $\boldsymbol{C'}$, vector $\boldsymbol{b'}$ summing up contributions from all tracks.

- Solving $\boldsymbol{C'}\,\boldsymbol{a}^{global} = \boldsymbol{b'}$ provides alignment solution in one step.
  $\Rightarrow$ All correlations from tracks taken care of.
- Need clever algorithms for $> 100\,000$ global parameters:
  $\Rightarrow$Millepede II and General Broken Lines Track Refit.

Millepede II: Experiment Independent Global Fit Tool

(originally by V. Blobel, further developed by C. Kleinwort)

Task

- Setting up and Solving Matrix Equation

$$\boldsymbol{C'}\ \boldsymbol{a}^{global} = \boldsymbol{b'},$$

- from millions of tracks (containing outlier hits),
- $\boldsymbol{C'}$ is $n \times n$ matrix:
  - here $n \approx 200\,000$,
  - typically sparse.

$\Rightarrow$ Very demanding for memory and CPU.

Input from Experiment

- Linearised track fit information:
  - residuals with uncertainties,
  - derivatives $\frac{\partial F}{\partial a^{local}}$ and $\frac{\partial F}{\partial a^{global}}$,
- Global parameter constraints: $\sum d_i a_i^{global} = e$.

Millepede II

Features: Computing Aspects

- More powerful successor of Millepede I.
- Stand alone Fortran program.
- Reading (zipped) binary input from Fortran or C(++).
- Optimised for speed:
  - iterative MINRES to solve $\boldsymbol{C'}\,\boldsymbol{a}^{global} = \boldsymbol{b'}$,
  - CPU intense parts parallelised using OpenMP®,
  - local fit detects bordered band matrices ($\Rightarrow$ Broken Line Fit),

  $\Rightarrow$ reading data from disc and memory access remaining bottlenecks.
- Optimised for memory space:
  - symmetric $\boldsymbol{C'}$ would need 160 GB in double precision,
  - reduction due to sparsity
  - compression by bit packed addressing of continuous non-zero blocks,
  - and by single precision for elements summing up from few tracks.

Parameters a^{local}

Track Fit

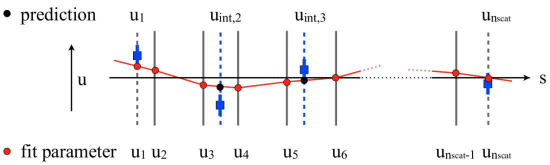
- Charged particle in magnetic field: need 5 helix parameters.
- Traversing material: multiple scattering effects.
  (relevant for "heavy" tracking detectors)
- Usually treated by progressive track fit: Kalman filter.
- Millepede II needs global fit:
  - $\Rightarrow$ 2 scattering angles per thin scatterer,
  - $\Rightarrow$ $5 + 2n_{scat}$ explicit track parameters.
- Reaching > 50 parameters for cosmic tracks in CMS tracker.

$\Rightarrow$ Danger of CPU consuming single track fits when building matrix equation $\boldsymbol{C}\,\boldsymbol{a}^{global} = \boldsymbol{b}$.

Way out:

- General Broken Lines Track Refit

General Broken Lines Track Refit



$$\begin{pmatrix} b & b & b & & \cdots & & b \\ b & m & m & & & & \\ b & m & m & m & & & \\ b & & m & m & m & & \\ \vdots & & & \ddots & \ddots & \ddots & \\ & & & & m & m & m \\ b & & & & & m & m \end{pmatrix}$$

Concept: Define Track Parameters with Local Meaning

- Reparametrise: $\boldsymbol{a}^{local} = (\Delta q/p, \boldsymbol{u_1}, \ldots, \boldsymbol{u_{n_{scat}}})$.
- $\boldsymbol{u_i}$: 2D offsets in local system at each scatterer.
- Predictions $\boldsymbol{u_{int}}$ for measurements: interpolating between scatterers.
- Kink angles from triplets of adjacent scatterers.

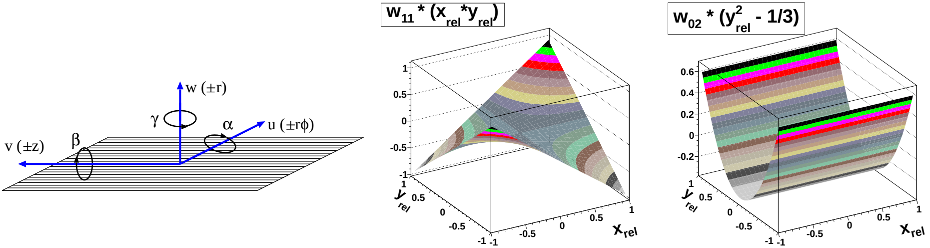
$\Rightarrow$ Local fit $\boldsymbol{A} \cdot \boldsymbol{x} = \boldsymbol{b}$:
  - bordered band matrix, band width $m \leq 5$, border size $b = 1$.
- Fast solution by root free Cholesky decomposition:
  - Effort to calculate $\boldsymbol{x}$: $\sim n_{par} \cdot (m + b)^2$, $\boldsymbol{A}^{-1}$: $\sim n_{par}^2 \cdot (m + b)$
- Equivalent to standard CMS Kalman filter track fit.

CMS 2011 Tracker Alignment: ~1 fb^{-1}

Input Data

- Loosely selected isolated muons: 15 million.
- Muon pairs from $Z \rightarrow \mu^+\mu^-$ decays: 375 thousand pairs.
- Low momentum tracks: 3 million.
- Cosmic tracks (e.g. recorded in between LHC fills): 3.6 million.

CMS 2011 Tracker Alignment



Alignment Algorithm and Parameters

- Millepede II algorithm with ~200 000 free alignment parameters.
- 8 (9) parameters per strip (pixel) sensor:
  - 5/6 rigid body like parameters (one insensitive for strips),
  - 3 bow parameters.
- Time dependent rigid body parameters for larger pixel structures:
  - 9 time periods in common fit,

  ⇒ moving structures, modules constant within.
- $Z \rightarrow \mu^+\mu^-$ combined object, adding Z mass “measurement” (⇒).

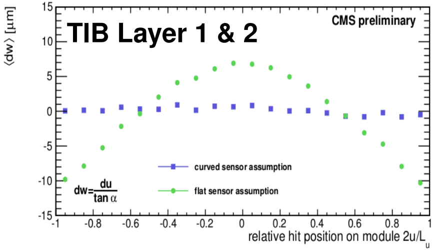
CMS 2011 Tracker Alignment

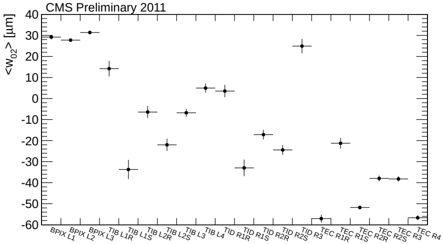
Millepede II at Work

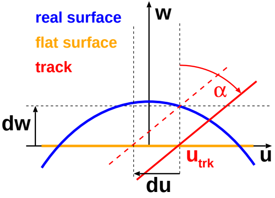
- 246 zipped binary files ($\sum$ 46.5 GB), read 13 times.
- 22.6 million local fit objects,
  - bordered band matrix structure: max(border) = 9, max(width) = 4.
- MINRES iterating 3 times (tightening outlier rejection) to solve $\boldsymbol{C'}\,\boldsymbol{a}^{global} = \boldsymbol{b'}$.
- 200 614 fit parameters (including 138 Lagrange multipliers).
- Matrix with 31% non-zero off-diagonal entries, compression ratio 40%, $\Rightarrow$ fits well into 32 GB memory.
- Total CPU 44.5 h, Wall 9:50 h using 8 threads on Intel® Xeon® L5520, 2.27 GHz.

$\Rightarrow$ **Very efficient usage of resources with fast turnaround for analysis!**

Silicon Sensors are Bowed, not Flat







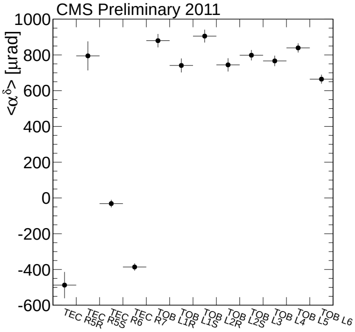
- Residual *du*, track slope $\tan\alpha$:
  map residual $\perp$ sensor, $dw = du/\tan\alpha$.

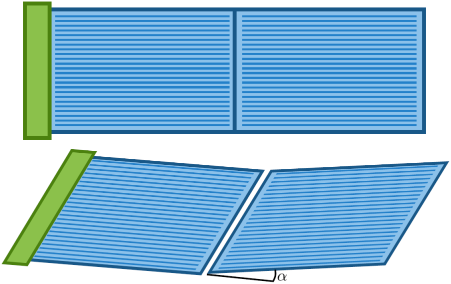
$\Rightarrow$ See bowed sensor surface.

- Alignment of bows accounts for that.
- Sensor type/mounting specific bow strengths.

- High relevance in BPIX layer 1: $\langle w_{02}\rangle = 30\ \mu m$, large track slope:
  $\Rightarrow$ systematic residuals $> 100\ \mu$m at sensor edge.

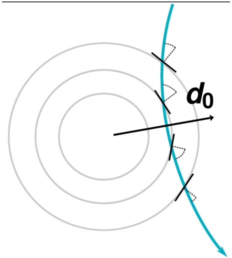
Kink within Two Sensor Modules

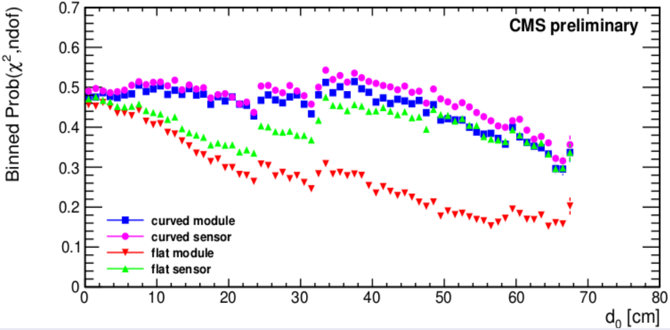




- Long modules in outer strip tracker (TOB and outer TEC): two daisy chained sensors.
- Sensors rotated against each other: kink angle.
- Typical kink is $2\alpha^{\delta} = 1.6$ mrad.
- Larger effect than sensor bow.

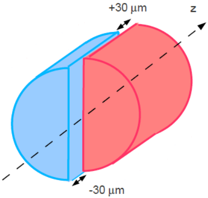
Sensor Bow Treatment Improves Cosmic Tracking

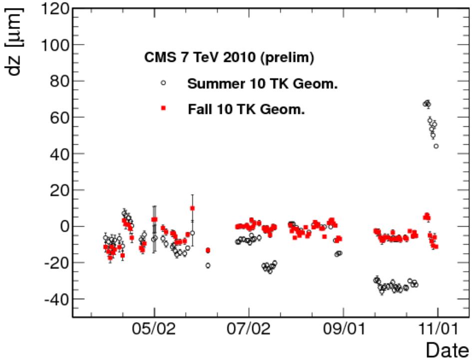


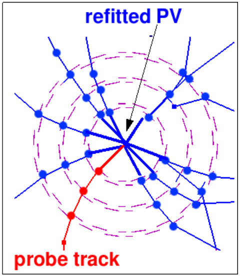


- Cosmic tracks mainly come from above.
- Increasing d_0 increases average track angle from sensor normal,
  $\Rightarrow$ increasing sensitivity to deviation from flat sensors.
- Average goodness of fit vs d_0 demonstrates improvements from flat modules via flat sensors, bowed modules to bowed sensors.
- Remaining structure related to radii of layers: material.

Pixel Movements and Monitoring





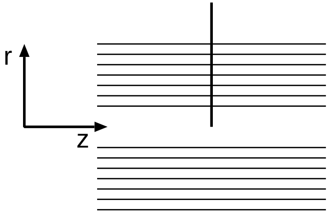


- Pixel half barrels move wrt each other in time.
- Monitoring separation along z using unbiased vertex-track residuals.
- Time dependence of pixel structure alignment: // properly caring of separation as function of time.
- B-tagging insensitive to remaining 10 μm effect.

Problem of Track Based Alignment: Weak Modes

Minimising residuals can be insensitive to certain global distortions.

- Potential bias on track parameters.
- Dependent on data fed into matrix.



Example: Telescoping

Shift in z growing linear with radius r

- Magnetic field $\boldsymbol{B} \| z$:
  tracks are straight lines in rz
- This distortion does not change that!
- $\Rightarrow$ Bias in η

  Solution:
- Adding cosmic tracks.
- Telescope effect bends track:
  not allowed by track model.

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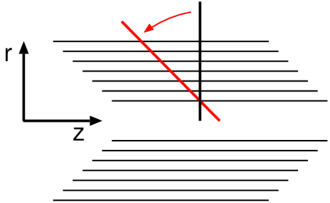

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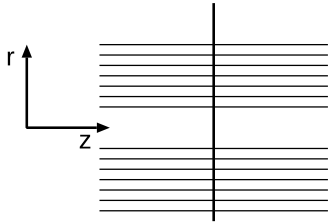

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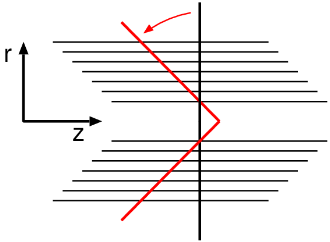

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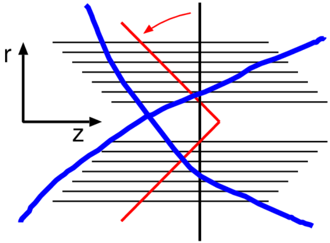

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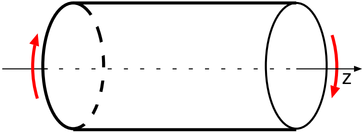
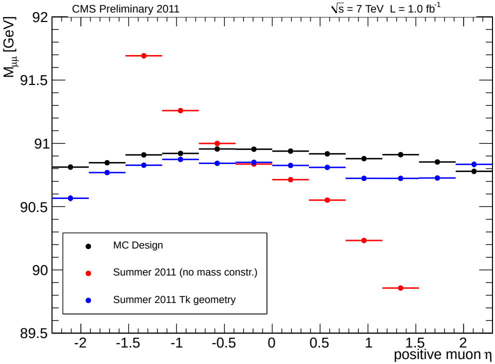
Weak Mode “Twist” and the Z Mass



$$\Delta\phi = \tau * z$$

Twist distortion is weak mode even using cosmics.

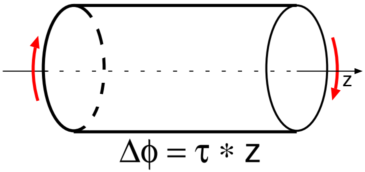


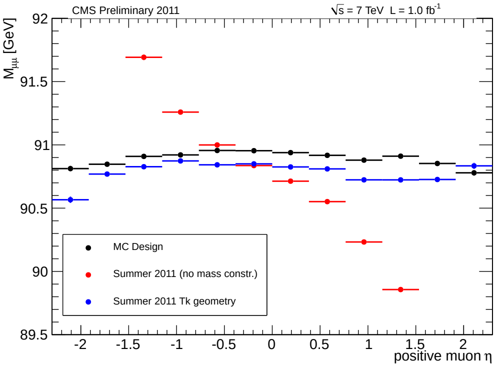
- Results in curvature changes, biasing measured p_t of positive or negative tracks oppositely.

$\Rightarrow$ Reconstructed Z mass depends on muon charge and η: red curve.

Way out:

- Use Z mass information in alignment fit.





- Re-parametrise muons from Z decay as common local fit object:
  - from 2×5 independent parameters to common set of 9.
- Add Z mass as virtual measurement, RMS as uncertainty.

$\Rightarrow$ Keeps twist under control: **blue curve**,
almost as in simulation with design conditions (**black curve**).

Summary

- Large CMS silicon tracker: a challenge for alignment.
- Track based alignment with ~200 k parameters:
  - determining sensor bows and kinks,
  - following time dependent movements of large pixel structures,
  - controlling momentum changing weak modes using the Z mass.
- Main working horse: Millepede II with General Broken Lines,
  $\Rightarrow$ global fit approach in < 10 h Wall time.

CMS Silicon Tracker Alignment

Serving physics analysis with high precision for discoveries.

Statistics Tools Group of the Helmholtz Alliance

Supporting:

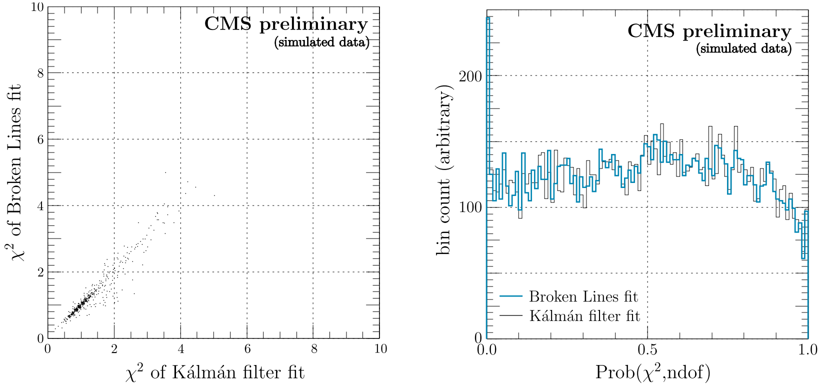
Millepede II

See Wiki https://www.wiki.terascale.de/index.php/Millepede_II.

General Broken Lines Track Refit

See GBL Wiki https://www.wiki.terascale.de/index.php/GeneralBrokenLines.

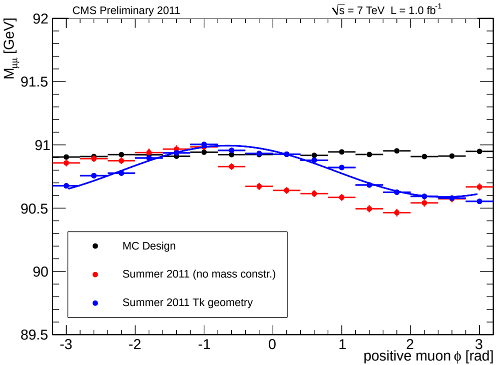
General Broken Lines: Equivalence with Kalman Fit

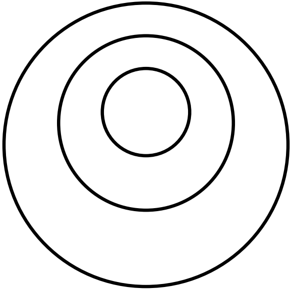


Test on Simulated Muon Tracks

- Good correlation of χ^2/ndf values.
- No difference in probability distributions.
- No momentum/track angle dependence seen (not shown).

Open Issue: ϕ Dependence of Reconstructed Z Mass





- Charge and ϕ dependent bias remains despite usage of Z mass.
- But sine wave fit reveals small amplitude of ~0.2 GeV.
- Simulation: sine wave can be modeled with sagitta-like distortion.
- Studies ongoing:
  - Increasing Z statistics?
  - Using straight cosmics from B-field off data?
  - Small biases in track model?