The Alignment of the CMS Silicon Tracker

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Large Scale Applications and Radiation Hardness of Semiconductors Detectors

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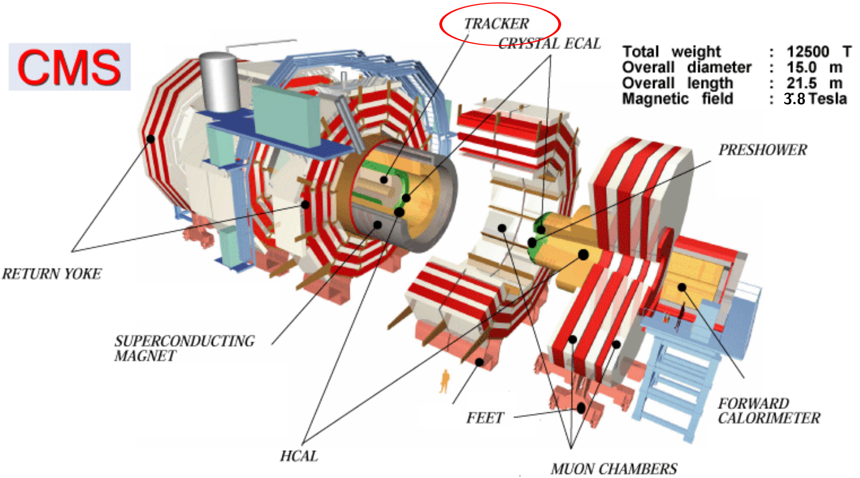
Outline

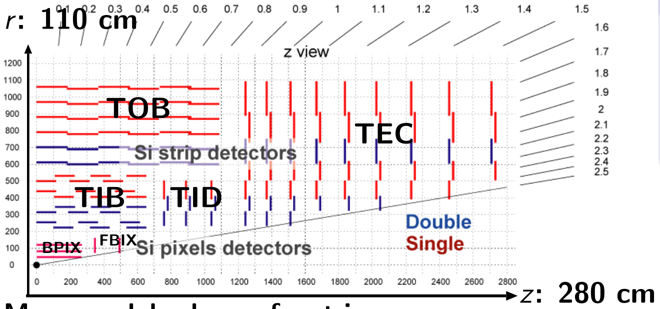
The CMS Detector at the LHC



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

The CMS Tracker: All Silicon

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



Single Hit Resolution

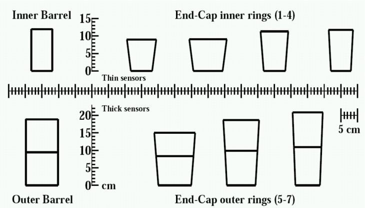
Pixel:

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

Strip:

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

Many module shapes for strips



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

Alignment challenge: 200 k parameters

Why alignment?

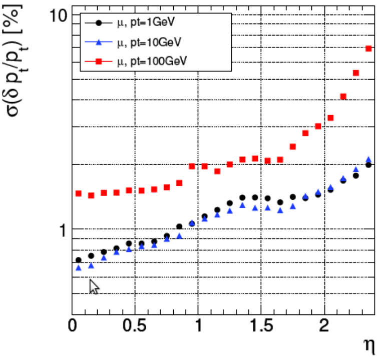
- intrinsic resolutions
  - σ_{hit}=9 μm for pixel
  - σ_{hit}=20-60 μm for strip
- $\sigma_{meas} \sim \sqrt{\sigma^2_{hit} + \sigma^2_{alignment}}$
- Momentum resolution is:

$$\boxed{\frac{\delta p_T}{p_T} = C_1 \cdot p_T \oplus C_2}$$

- where C_1 depends on geometry:

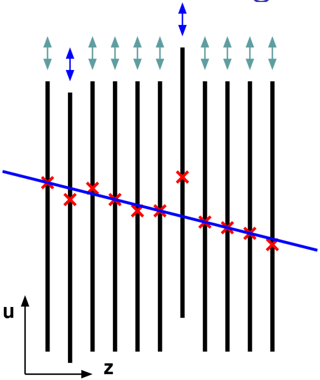
$$C_1 \sim \frac{\sigma_{meas}}{B \cdot L^2 \cdot \sqrt{n}}$$

- Need to keep $\sigma_{alignment} < 10$ μm
- track-based alignment essential to guaranteed design performance



Tracker momentum resolution for single muons, CMS Simulation, CMS P-TDR (2006)

Track Based Alignment: Principle



Simple Example

- 11 parallel planes measuring 1D
- displaced in measurement direction
- fit 10^4 straight tracks: $u = F_a(z) = a_1 + a_2 \cdot z$
- residual $r_i = m_i - F_{\hat{a}}$ 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, $\chi^2(a) = \sum_k \left(\frac{m_k - F_a}{\sigma_k} \right)^2$.
- $a = (a^{global}, a_1^{local}, \ldots, a_n^{local})^T$
  - global: alignment parameters,
  - local: track parameters.

Track Based Alignment

Global Fit Approach

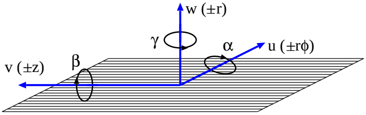
- Linearising track model and minimisation requiring $\frac{d\chi^2(a)}{da} = 0$:
  $\Rightarrow$ Normal equations of least squares $C\,a = b$.
- Local parameters appear in part of the data only:
  $\Rightarrow$ Block structure in C, use matrix algebra to reduce problem:

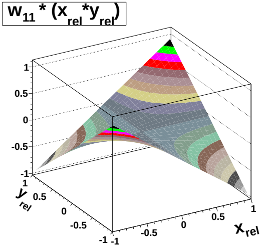
$$C'\,a^{global} = b'.$$

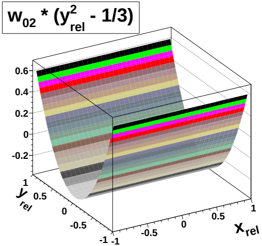
- Matrix C', vector b' summing up contributions from all tracks.

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

CMS Tracker Alignment







Alignment Algorithm and Parameters

- Millepede II algorithm with $\sim 200\,000$ 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:
  - several different time periods in common fit,

  $\Rightarrow$ moving structures, modules constant within.
- $Z \to \mu^+\mu^-$ combined object, adding Z mass "measurement".

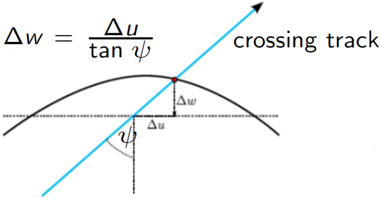
Alignment sensor deformations

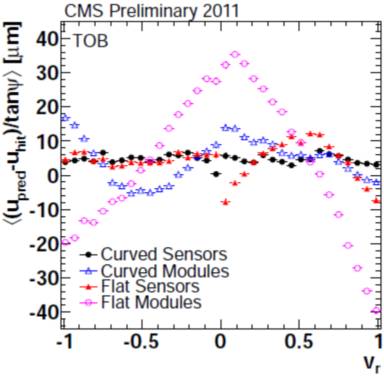
Kinks and bows

- In reality, sensors are not planar non-perpendicular tracks are biased, depending on $\tan\psi$!
- Investigation of surface shape using:

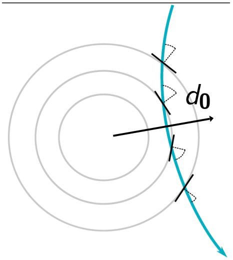
$$\boxed{\Delta u = \Delta w \cdot \tan\psi}$$

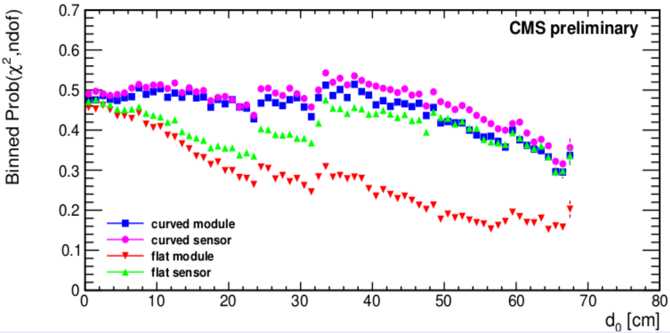
- Increasingly important for inner layers
  - high relevance for BPIX layer 1, with large track angles and $\langle w_{02}\rangle = 30\ \mu m$, systematic bias of $\sim 100\ \mu m$ at edge of the 66 mm wide module
- Alignment determines bow parameters, taken into account in hit reconstruction.
- Also angles and offsets between two daisy-chained modules in outer Tracker are corrected in alignment





Sensor Bow Treatment Improves Cosmic Tracking

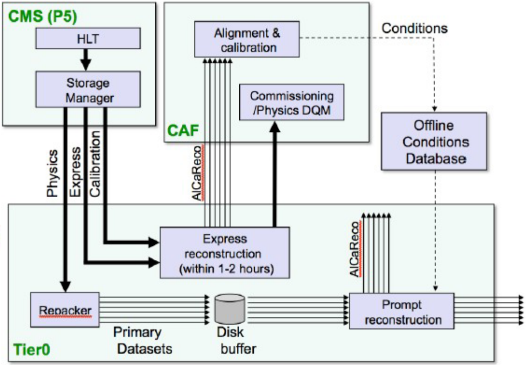




- Cosmic tracks mainly come from above.
- Increasing d_0 increases average track angle from sensor normal,
  $\Rightarrow$ increasing sensitivity to deviation from flat sensors.
- Average goodness of fit $\langle Prob(\chi^2, ndf)\rangle$ vs d_0 shows improvements from flat modules via flat sensors, bowed modules to bowed sensors.
- Remaining structure related to radii of layers: material.

Prompt Calibration Loop

- Prompt Calibration Loop (PCL)
  - calculates 6 alignment parameters for large structures of pixel
  - provides feedback within 48h with latest data to reconstruct the same run



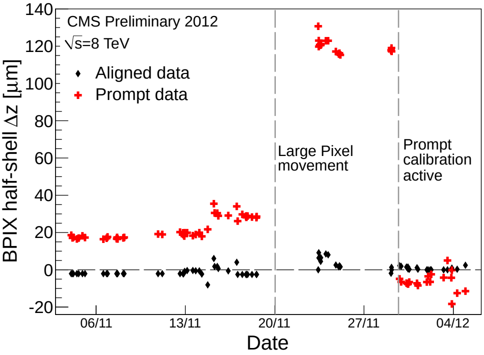
- Alignment of larger rigid structures (frames of modules, layers, subdetectors):

⇒ faster and less tracks required!

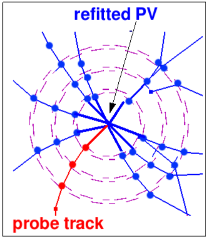
PCL and Pixel movements

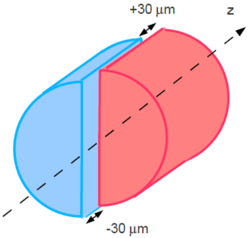
- During last month of pp-running in 2012 PCL was running for monitoring (but not active)
- Major sudden movement of pixel half-shells along z detected in Nov 22nd (cooling failure)

⇒ PCL activated on Nov 30^{th} to recover



Relative *z*-shift of BPIX half-shells in last month of *pp* data taking in 2012

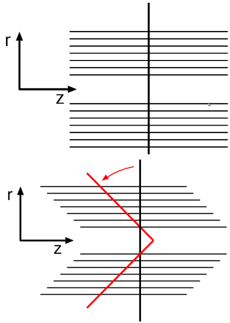




Weak Modes

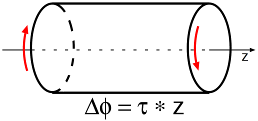
- Minimization of residuals insensitive to some global distortions
- These weak modes can however bias track parameters

- Example 1: "telescope": $\Delta z \propto r$
- creates bias in η



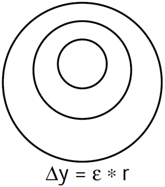
- Solution: cosmic muon tracks

- Example 2: "twist": $\Delta \phi \propto z$
- curvature bias of charged particles



- weak mode even with cosmic muon tracks
- Solution: 0T cosmic muon tracks or mass constraint ($Z \to \mu\mu$)
- 2 muons from Z decay fitted together

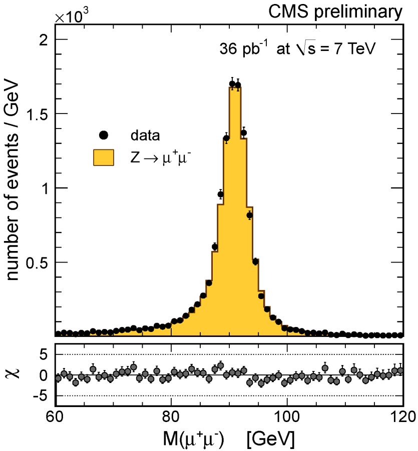
- Example 3: "sagitta": $\Delta r \propto y$



- curvature bias suspected in 2011,
- observed variation of Z mass as function of ϕ of positively charged muon
- ϕ-dependent curvature bias

Muon Curvature Bias

- Several systematic distortions can bias track curvature $\kappa \sim \pm 1/p_T$
- $Z^0 \rightarrow \mu^+\mu^-$ events reveal this bias: invariant mass fitted as function of muon direction (η, ϕ), separating μ^+ and μ^-



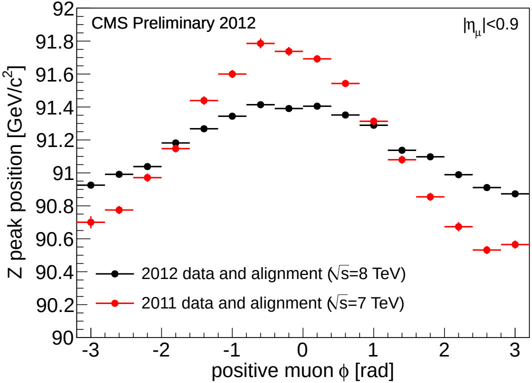
Validation with $Z \rightarrow \mu\mu$ decays

- invariant mass distribution fitted with wide fit range 75-105 GeV$/c^2$, Z^0 width set to PDG value of 2.495 GeV$/c^2$
- Fit function: a Breit-Wigner function convoluted with Crystal ball function (models finite track resolution and radiative tail) + exponential background

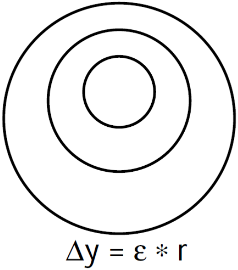
Reconstructed Z^0 mass peak

- Reconstructed $Z^0 \to \mu^+\mu^{-1}$ mass peak as function of $\phi(\mu^+)$
- Amplitude of sinusoidal shape clearly decreased with weighted input data, from 0.7 GeV$/c^2$ to 0.3 GeV$/c^2$ in barrel

Azimuthal angle ϕ of μ^+, barrel muons



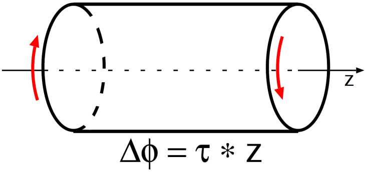
"Sagitta"-like distortion causes this kind of effect



[1] N.B.: this study does not illustrate CMS muon reconstruction and calibration performance; momentum calibration is applied in addition in physics analyses

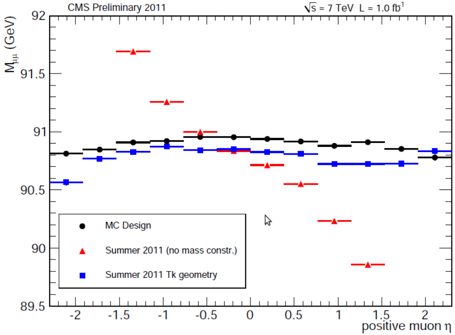
Necessity of Z^0 Events

- Reconstructed $Z^0 \to \mu^+\mu^{-2}$ mass peak as function of η_{μ^+} in 2011



Twist distortion is weak mode even using cosmics

Pseudorapidity of the positive muon $\eta(\mu^+)$



- Results in curvature changes, biasing measured p_T of positive or negative tracks oppositely.
- The red curve corresponds to the alignment without mass constraint
- Reconstructed Z mass depends on muon charge and η

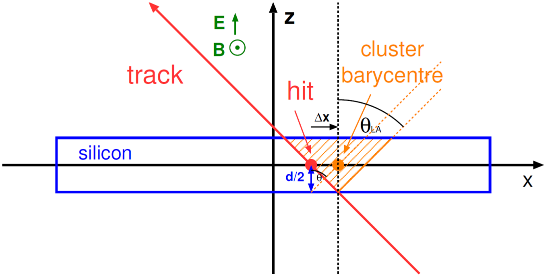
[2] N.B.: this study does not illustrate CMS muon reconstruction and calibration performance; momentum calibration is applied in addition in physics analyses

Lorentz Anlge calibration and alignment

- Charge drift in magnetic field affects the measured hit position as

$$\boxed{\Delta x = \tan(\theta_{LA}) \cdot \frac{d}{2}}$$

- Most precise way to correct this is integration of θ_{LA} calibration to Millepede II alignment procedure
- Data with magnetic field ON and OFF used simultaneously: 60 M tracks (isolated muons, $Z^0 \rightarrow \mu^+\mu^-$, cosmic ray muons and field OFF collision data)

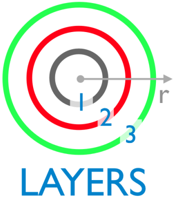


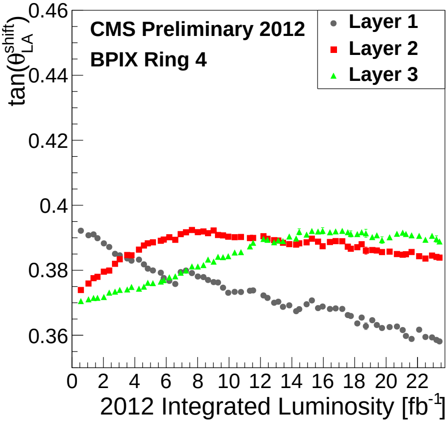
- Granularity: 3 layers, 8 rings, 65 periods of time → 1560 additional parameters
- Recent extension not yet used in full 2012 alignment

Lorentz Angle calibration and alignment

- Comparison of centermost modules from different layers

- Similar behavior for three layers:
- more intense radiation in layers 2 and 1 causes earlier decrease.

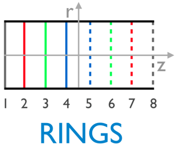


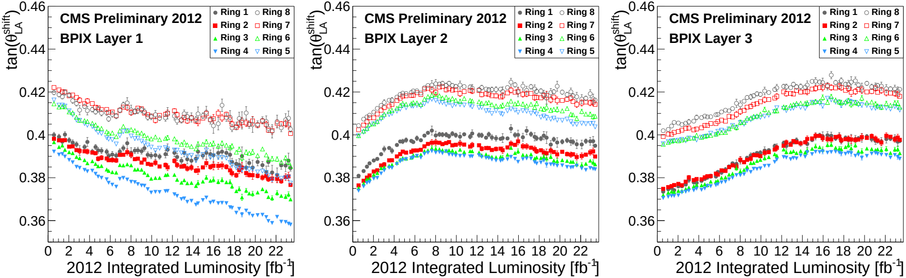


- A few μm effect, but will be relevant in 2015 with increased LHC luminosity

Lorentz Angle calibration and alignment

- For each layer: LA for modules of one ring as function of integrated luminosity
- Offset between R1-4 and R5-8 related to different bias voltages.





- Slow decrease pronounced for innermost rings
- Increase followed by a decrease; more rapid for layer 2 smaller difference between rings

Summary

- Large CMS silicon tracker: a challenge for alignment
- Alignment of $\sim$ 200.000 alignment parameters was performed routinely for 2 years
- Main working horse: Millepede II with General Broken Lines,
  $\Rightarrow$ global fit approach in < 10 h Wall time.
- Quick response to data taking with run-by-run alignment of large structures
- Improvements in 2012:
  - Sensor bows widely used
  - Prompt Calibration Loop operational (end of 2012)
  - Curvature bias modes in better control with $Z^0 \rightarrow \mu^+\mu^-$ events
  - Alignment framework extended to treat calibration parameters
  - Lorentz Angle calibration integrated to alignment

CMS Silicon Tracker Alignment

Serving physics analysis with high precision for discoveries.

Backup Slides

Alignment in CMS

- Full-scale alignment: individual sensors (sensor-level):
  - 9 degrees of freedom (DoF) for pixel modules,
  - 8 DoF's for strip sensors
  - time-dependence of large pixel structures
- Alignment of larger rigid structures (frames of modules, layers, subdetectors):
  - faster and less tracks required!
- Alignments applied in 2012:
  - Prompt reconstruction: twice. Re-reconstruction: three times

Computing aspects in Millepede II (Full-scale alignment 2011)

- Matrix equation to solve:

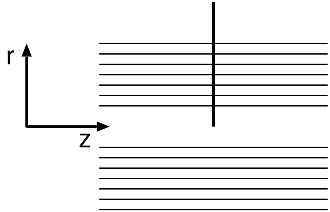
$$\boxed{C \cdot p = b}$$

- where C is $n \cdot n$ matrix, n $\sim$ 200.000 (in practice 30% of elements non-zero, depends on input data)
- Using Fortran program optimized for speed and space:
  - iterative MINRES method
  - OpenMP used for parallelized computing
  - sparsity taken into account
- CPU use 45h, Wall clock 10h with 8 threads on Intel Xeon L5520, 2.27 GHz,

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 $B \| z$:
  tracks are straight lines in rz

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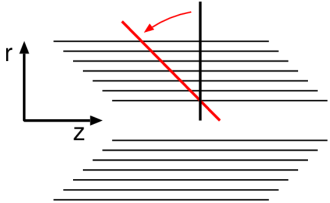

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- $\Rightarrow$ Bias in η

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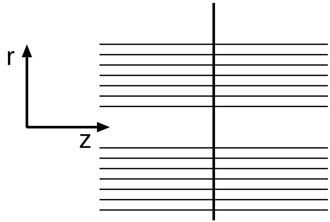

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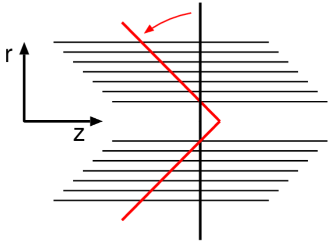

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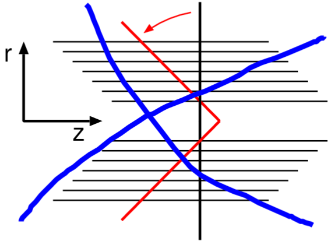

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Shift in z growing linear with radius r

- Magnetic field $B \| z$:
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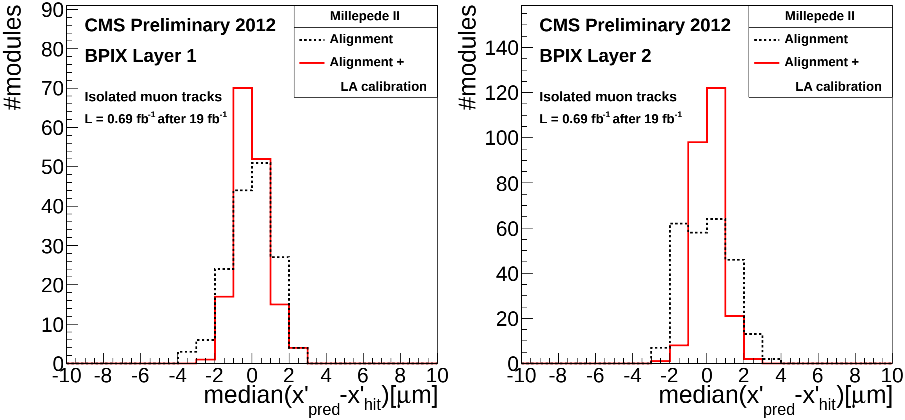
- $\Rightarrow$ Bias in η

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

Lorentz Angle validation, BPIX layers 1 and 2

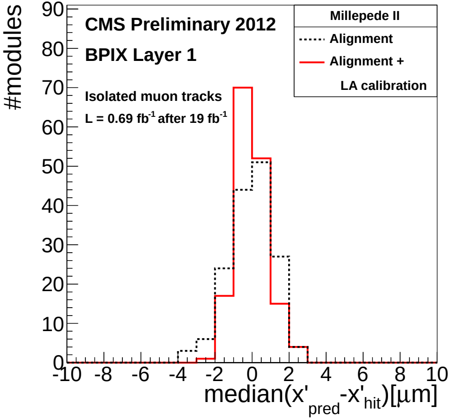
- Obtained LA calibration validated by comparing the combined Millepede approach (alignment + LA) to alignment with standalone calibration.
- Distribution of median of unbiased residuals (DMR) between measured and predicted hit position for each module. Independent set of tracks from isolated muons used in validation.



Lorentz Angle validation, BPIX layers 3

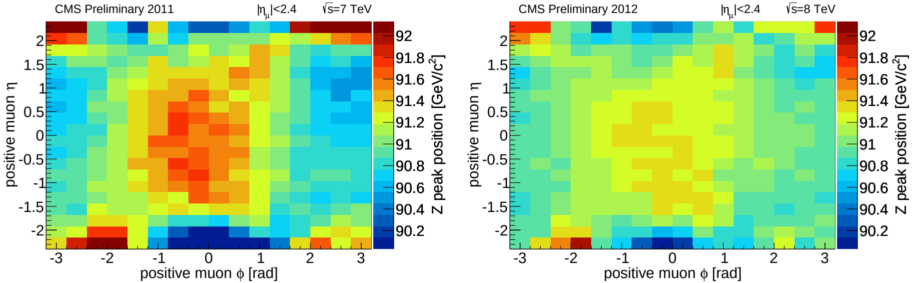
- LA calibration validated by comparing to alignment with standalone calibration.
- Distribution of median of unbiased residuals (DMR) between measured and predicted hit position for each module. Independent set of tracks from isolated muons used in validation (from end of 2012).

- Clear improvement using integrated alignment and calibration.
- Double peak illustrates inconsistency between LA and alignment, corrected in the combined approach.
- A few μm effect, but this approach will be more relevant in 2015 with increased LHC luminosity.



Improvement in $Z \to \mu\mu$ decay validation

- Reconstructed $Z \to \mu^+\mu^-$[3] mass peak as function of both pseudorapidity η and azimuthal angle ϕ of positive muon
- Z-axis same in both pictures, centered at peak value of all 2011 events (91.08 GeV/c^2)



- Overall pattern significantly reduced for 2012!

[3] N.B.: this study does not illustrate CMS muon reconstruction and calibration performance; momentum calibration is applied in addition in physics analyses

Millepede II: Experiment Independent Global Fit Tool

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

Task

- Setting up and Solving Matrix Equation

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

- from millions of tracks (containing outlier hits),
- 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 $C' \, a^{global} = b'$,
  - 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 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

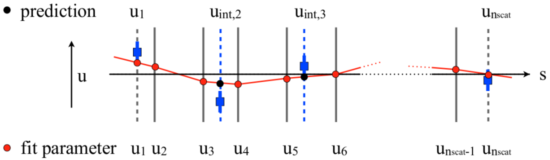
- Charged particle in magnetic field: need 5 helix parameters.
- Traversing material: multiple scattering effects.
  (relevant for "heavy" tracking detectors)
- Usually treated by progressive track fit: Kalman filter.
- Millepede II needs global fit:
  - $\Rightarrow$ 2 scattering angles per thin scatterer,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

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

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: $a^{local} = (\Delta q/p, u_{\mathbf{1}}, \ldots, u_{n_{scat}})$.
- u_i: 2D offsets in local system at each scatterer.
- Predictions u_{int} for measurements: interpolating between scatterers.
- Kink angles from triplets of adjacent scatterers.

$\Rightarrow$ Local fit $A \cdot x = b$:

- bordered band matrix, band width $m \leq 5$, border size $b = 1$.

- Fast solution by root free Cholesky decomposition:
  - Effort to calculate x: $\tilde{\ } n_{par} \cdot (m+b)^2$, A^{-1}: $\tilde{\ } n_{par}^2 \cdot (m+b)$
- Equivalent to standard CMS Kalman filter track fit.