Lessons learnt from aligning the CMS Silicon Tracker

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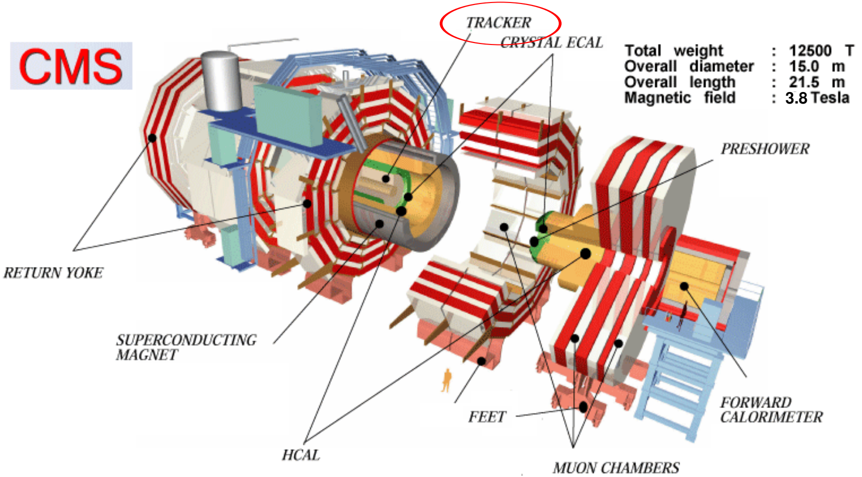
Overview

The CMS Detector at the LHC



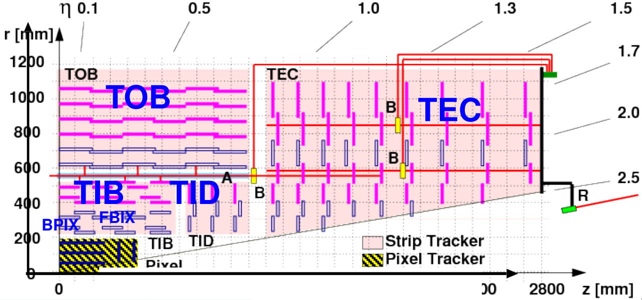
Features of the CMS Detector

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

The CMS Tracker: All Silicon

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

***r*: 110 cm**



***z*: 280 cm**

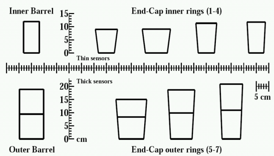
Single Hit Resolution

Pixel Tracker:

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

Strip Tracker:

$\sigma \approx 20 - 60\ \mu$m



TOB and outer TEC:

two chained sensors

- 1440 silicon pixel modules
- 15148 silicon strip modules (24244 sens.)
- Strips generally measure r-φ direction
- Some radii: additional modules rotated by 100 mrad

Alignment challenge: $\mathcal{O}(100k)$ parameters!

Why alignment is needed?

- Intrinsic resolutions:
  - σ_{hit}=9 μm for Pixel
  - σ_{hit}=20-60 μm for Strip
- $\sigma_{meas} \sim \sqrt{\sigma^2_{hit} + \sigma^2_{align}}$
- Momentum resolution is:

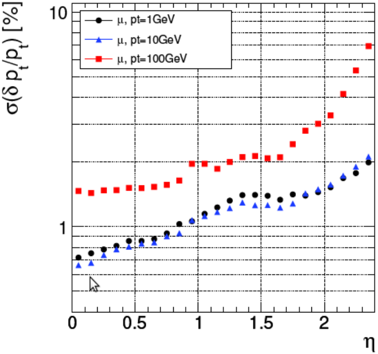
$$\boxed{\frac{\delta p_T}{p_T} = C_1 \cdot p_T \oplus C_2}$$

- C_1 depends on geometry:

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

$\Rightarrow$ Need to keep $\sigma_{align} < 10\ \mu$m!

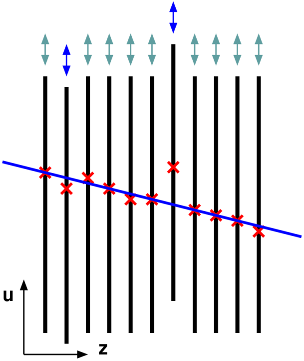
- Alignment is essential to guarantee CMS Tracker design performance!



CMS P-TDR (2006)

Tracker momentum resolution for single μ, CMS Simulation.

Track Based Alignment: Principle



Simple Example

- parallel planes measuring 1D
- displaced in measurement direction
- fit $\mathcal{O}(10^4)$ 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

Global Fit Approach (e.g. Least Squares)

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

Track Based Alignment

Global Fit Approach

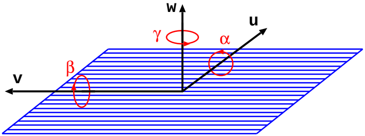
- Linearising track model and minimisation requiring $\frac{d\chi^2(a)}{da} = 0$:
  $\Rightarrow$ Normal equations of least squares $\boldsymbol{C}\,\boldsymbol{a} = \boldsymbol{b}$.
- Local parameters appear in part of the data only:
  $\Rightarrow$ Block structure in $\boldsymbol{C}$, use matrix algebra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

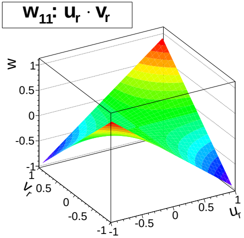
$$\boldsymbol{C'}\,\boldsymbol{a}^{global} = \boldsymbol{b'}.$$

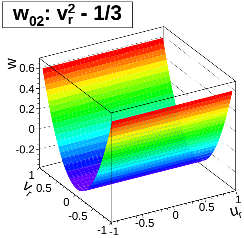
- Matrix $\boldsymbol{C'}$, vector $\boldsymbol{b'}$ summing up contributions from all tracks.
- Solving $\boldsymbol{C'}\,\boldsymbol{a}^{global} = \boldsymbol{b'}$ provides alignment solution in one step.
  $\Rightarrow$ All correlations from tracks taken care of.
- Need clever algorithms for $> 100\,000$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

[a] developed by **V. Blobel at the University of Hamburg** (maintenance and development now by **Helmholtz Terascale Alliance**)

Track-based Alignment in CMS







Alignment Parameters in CMS

- 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 structures:
  - several different time periods in common fit,

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

Tracker alignment in CMS during LHC Run I

CMS Tracker Alignment Achievements in Run-I

- In the following slides, a few benchmark results from CMS Tracker alignment will be shown.
- CMS can fairly enough claim to have been able to align the Tracker with $\mathcal{O}(1 \div 10\ \mu\text{m})$ precision.
- Results are well documented in the 2011 data alignment paper: TRK-11-001, now published as JINST 9 (2014) P06009.
  - Result of the intensive dedicated work of the members of the tracker alignment group over many years. Represents a milestone document of CMS ...
- ... nevertheless we continue learning and we hope to improve Run-II alignment with several new improvements.

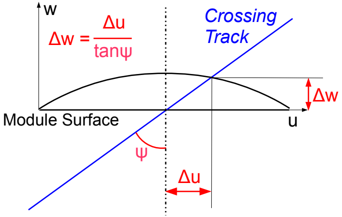
Alignment sensor deformations

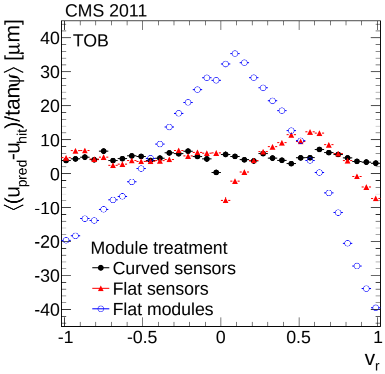
Kinks and bows

- In reality, sensors not planar: non-perpendicular tracks are biased, depending on tan ψ!
- Investigate surface shape using:

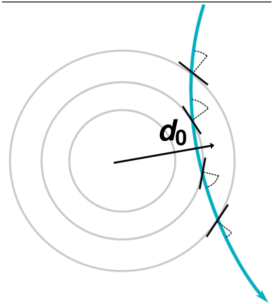
$$\boxed{\Delta u = \Delta w \cdot \tan \psi}$$

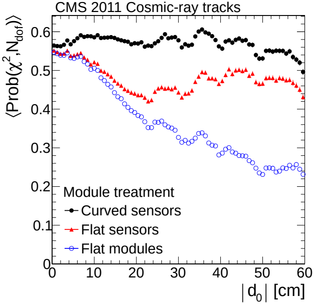
- Increasingly important for inner layers (bias up to $\sim$ 100 μm)
- Alignment determines bow parameters, taken into account in hit reconstruction.
- Also angles and offsets between daisy-chained modules in outer Tracker are corrected.





Sensor Bow Treatment Improves Cosmic Tracking





Cosmic tracks mainly come from above

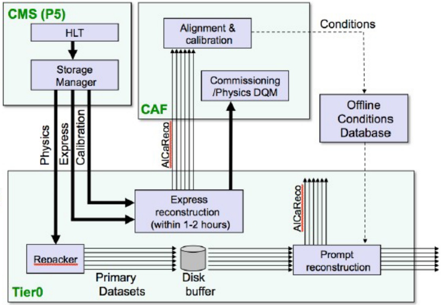
- Increasing d_0 increases average track angle from sensor normal,
  $\Rightarrow$ increasing sensitivity to deviation from flat sensors.
- Average $\langle Prob(\chi^2, ndf)\rangle$ vs d_0 shows improvements from **flat modules** via **flat sensors**, to **curved sensors.**
- Remaining structure related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

$\Rightarrow$ Nicely shows how fundamental are comsics data for alignment!

Prompt Large Structures Alignment

Prompt Calibration Loop (PCL)

1. Determines 6 alignment parameters for high-level-structures of pixel on *“express”* data.
2. if movements detected: new alignment delivered for prompt data.
3. provides feedback within 48 hours with latest data to reconstruct the same run.



Pixel Alignment in PCL

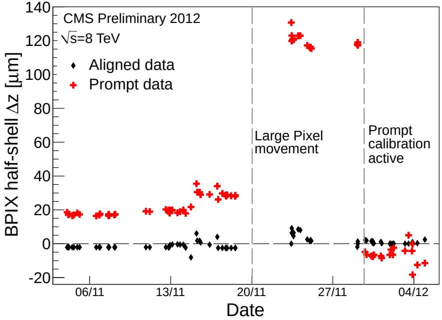
- Alignment of larger rigid structures (frames of modules, layers, subdetectors)

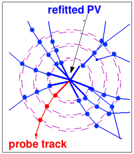
$\Rightarrow$ **faster and less tracks required!**

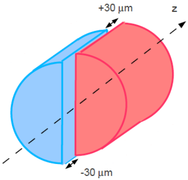
PCL and Pixel movements

- During last month of *p-p* run in 2012 PCL was running for monitoring (but not active)
- Major sudden movement of pixel half-shells along *z* detected in November 22nd ($\Delta z \approx 100$ µm! in coincidence with cooling failure)

$\Rightarrow$ **PCL activated on Nov 30th to recover.**



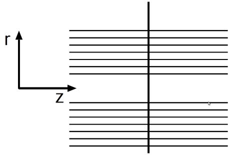


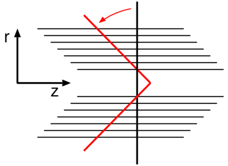


Weak Modes

- Minimization of residuals insensitive to some global distortions ($\Delta\chi^2 \approx 0$),
- These “weak modes” can however bias track parameters

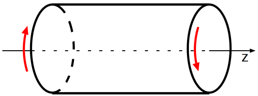
- Example 1: “telescope”: $\Delta z \propto r$
- creates bias in η





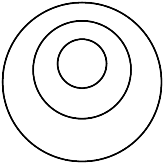
- Solution: cosmic muon tracks

- 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 ($Z \rightarrow \mu\mu$)
- 2 muons from Z decay fitted together

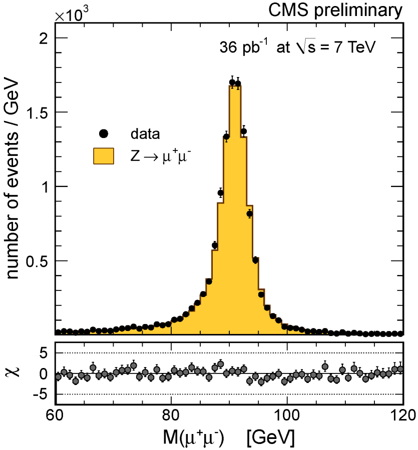
- Example 3: “sagitta”: $\Delta r \propto y$



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

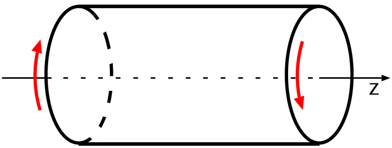


Validation with $Z \to \mu\mu$ decays

- 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

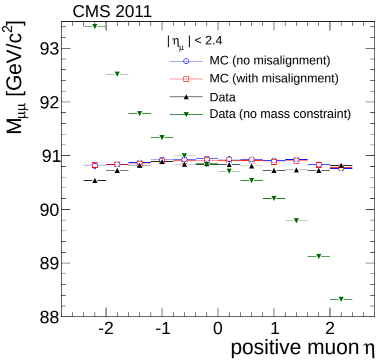
Necessity of Z^0 events in controlling weak modes

- Reconstructed $Z^0 \to \mu^+\mu^{-1}$ mass peak as function of η_{μ^+} in 2011



$\Delta\phi = \tau * z$

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



- Twist distortion is weak mode even using cosmics
- The red curve: alignment without mass constraint

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

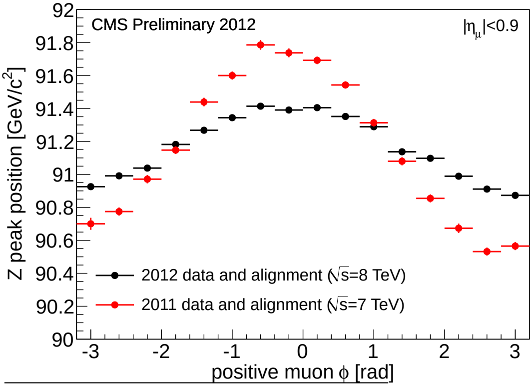
$\Rightarrow$ Reconstructed Z mass depends on muon charge and η

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

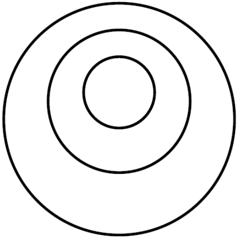
ϕ-bias in reconstructed Z^0 mass peak

- Reconstructed $Z^0 \to \mu^+\mu^-$[2] 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



$\Delta y = \varepsilon * r$

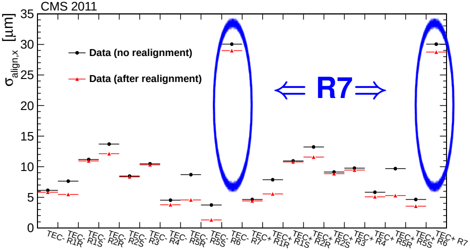
[2] N.B.: this study does not illustrate CMS muon reconstruction and calibration performance; momentum calibration is applied in addition in physics analyses

Alignment Precision and TEC Ring 7

2011 Data (not aligned)

vs

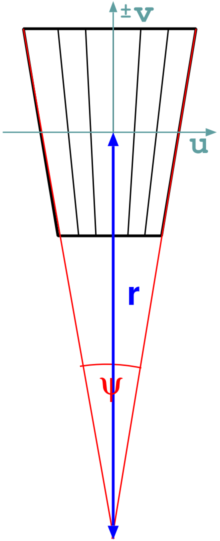
2011 Data (aligned)



Local Alignment precision measured by:

- tuning width of normalised residuals (r_{hit}/σ_{hit}) to ideal MC conditions ($\sigma^2_{hit} \rightarrow \sigma^2_{hit} + \sigma^2_{align}$): all MC/data mismatch (hit/track uncertainties, etc.) assigned to misalignment.
- This method on 2011 data revealed $\sigma_{align} < 10$ μm basically everywhere.
- Exception: TEC Ring 7 (i.e. outermost radii), although OK for MC misalignment scenario (using same alignment procedures).

Alignment of the Tracker Endcaps



Endcap module

Treatment of Local *y* in Alignment

- Just not taken into account before in alignment procedures for strip modules!
- OK in barrel where strips parallel to local *y*-axis.
- In endcaps, strips are not parallel to *y*:
  - still no *y*-measurements,
  - still probably not problematic in pattern recognition,
  - but x'-residuals noticably affected.
- Indeed have handle on this degree of freedom
- Just few thousand parameters more in the fit …

How we got rid of the ϕ-bias

- Deep investigations triggered by the fact that the APE in data in TEC Ring 7 was off by factor 3/(>20 μm) from the equivalent MC value while everywhere else it was not off by more than a few μm, found that:

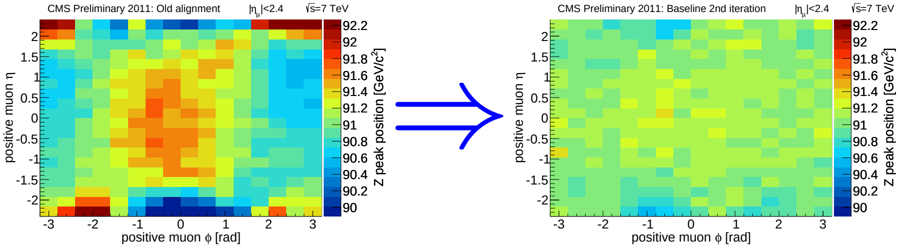
$\Rightarrow$ Geometry description in recontruction software and design drawings of TEC Ring 7 were radially off by 1.33 mm.

- this macroscopic error was not the (main) reason of the problem, it just helped to spot it:
  - Minor systematic radial ring misplacements became visible as well once local-*y* was a free parameter.
  - just the case that alll TEC modules are a bit off in *x* and *y* from design drawings (as is the case for ALL modules), $\Rightarrow$but only corrected in r-ϕ (in contrast to the barrel and FPix), lead to the ϕ bias.

Effects of cure of the ϕ-bias

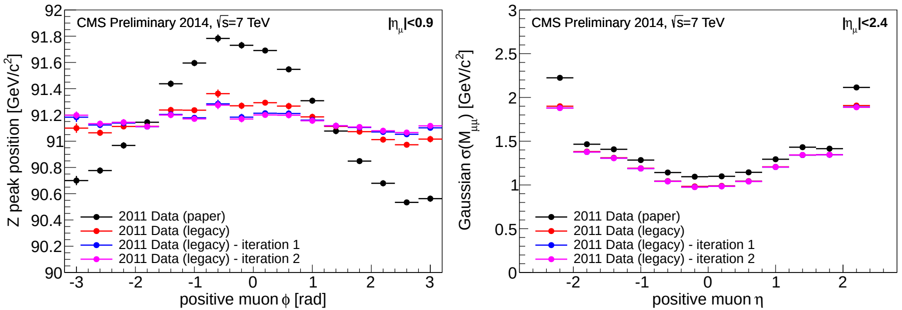
$Z \to \mu\mu$ validation for 2011 Alignment Legacy

- Mass bias in μ-track η-ϕ bins (pre and post-alignment).



- Desired result: No modulation.
- **This is the striking result!** Modulation in ϕ strongly reduced when releasing local-$\boldsymbol{y}$ in Tracker Endcap Alignment.
- Available since some time in $\sqrt{s} = 7\ \mathrm{TeV}$ reprocessed datasets.

Effects of cure of the ϕ-bias



- Left: the resonant peak position, right: Gaussian width $\sigma(M_{\mu\mu})$ minus natural width of the Z, from fit to the lineshape[3]

$$f(m_{\mu\mu}; \sigma, M_Z, \Gamma_Z) = \int_{-\infty}^{\infty} \mathrm{CB}(m_{\mu\mu}; \alpha, n, \sigma) \times \mathrm{BW}(m_{\mu\mu} - m'; M_Z, \Gamma_Z)\, dm'$$

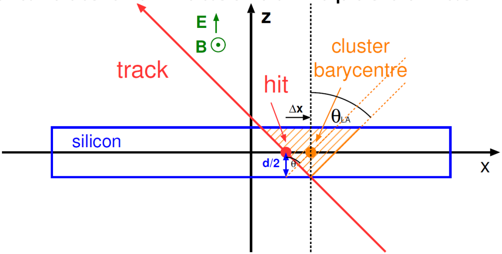
- **An overall improvement of about 10% is visible**
- We are going to repeat this for 2012 data plus something even better…

[3] (Breit-Wigner convolved with Crystal-Ball)

Lorentz Angle calibration and alignment

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

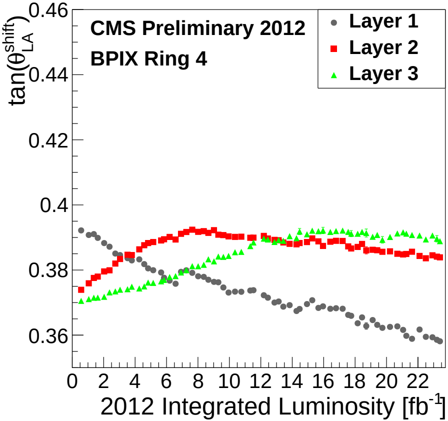
$$\Delta x = \tan(\theta_{LA}) \cdot \frac{d}{2}$$
$$\tan(\theta_{LA}) = \mu \cdot B_y$$
$$d = \text{module thickness}$$
$$\mu = \text{mobility}$$

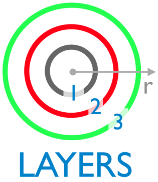


- θ_{LA} depends e.g. on bias voltage, temperature and irradiation dose.
- To correct this effect most precisely:
  $\tan(\theta_{LA})$ calibration integrated in MILLEPEDE II alignment procedure.
- Data with magnetic field ON and OFF used simultaneously: (isolated muons, $Z^0 \to \mu^+\mu^-$, cosmic ray muons and field OFF collision data)
- Granularity: 3 layers, 8 rings, 65 periods of time $\to$ 1560 additional parameters

$\Rightarrow$ foresee to use it in the "Legacy" $\sqrt{s} = 8\mathrm{TeV}$ data alignment

Lorentz Angle calibration in the Pixels (2012)





- Temperature and bias voltage stable in 2012.

⇒ Time dependence due to irradiation.

- About 3 μm effect.

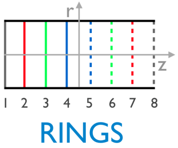
- Raising for layer 2 & 3 not fully understood.
- Less radiation at larger radii stretches curves and shifts right.

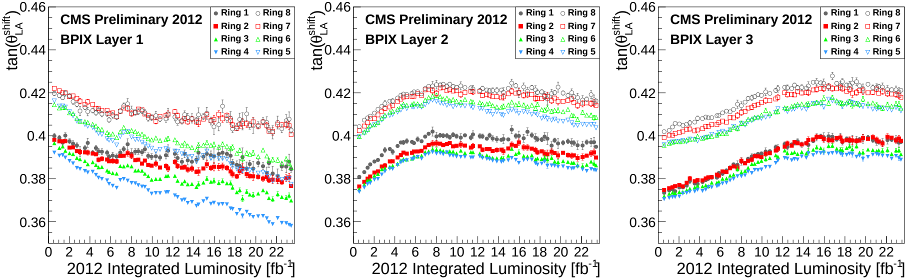
⇒ Qualitatively the same curves for all layers.

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

Lorentz Angle calibration in the Pixels (2012)

- 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 (one group not grounded).

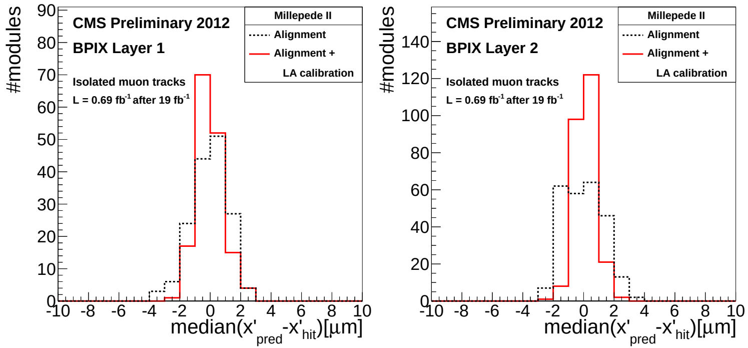




- Slow decrease pronounced for innermost rings
- Increase followed by a decrease; more rapid for layer 2 smaller difference between rings.

Lorentz Angle Validation

- LA calibration validated comparing combined Millepede approach (alignment + LA) to alignment with standalone calibration. Independent set of tracks from isolated-μ used in validation.



- Distribution of median of unbiased residuals (DMR) between measured and predicted hit position for each module.
- Small, but visible improvement using combined approach.

Summary - I

- Large CMS silicon tracker is a challenge for alignment
- Alignment of $\sim$ 200.000 alignment parameters was performed routinely for 2 years
- Alignment local precision has been brought below 10 μm in most regions of the Tracker. Track-based alignment *in situ* allowed such performance.
  1. Survey input was basically useless . . .
  2. Laser Alignment System (LAS) input not exploited to full potential, but likely not necessary (except maybe for monitoring)
- Dataset input is vital: **need plenty of tracks from different topologies**:
  1. Field-on and field-off cosmic data was instrumental to control weak modes and to measure deviation-from-flatness of sensors.
  2. Resonant di-muon ($Z \rightarrow \mu\mu$) datasets are crucial to control "twist-like" deformations.
  3. Field-off data helps in disentangling misalignment from Lorentz Angle biases.

Summary - II

- Main working horse in past 2-3 years: **Millepede-II with General Broken Lines**
- The Global fit approach is powerful, but demands clean input:
  - $\Rightarrow$ Incorrect parametrization of the geometry model can lead to large “weak mode” effects if not all the DOF are taken into account correctly (see ϕ-bias issue).
    - It is ESSENTIAL to simultaneously calibrate pure position constants and ALL other position sensitive calibration parameters such as the Lorentz Angle (LA).
- Showed capability to calibrate LA with $\sqrt{s} = 8\ \mathrm{TeV}$ data.
  - especially important in view of RUN II in the Tracker innermost region (Pixel) were high irradiation dose will generate strong time dependencies.
- Recent alignment improvements:
  - Prompt Calibration Loop operational (end of 2012): able to follow promptly movements up to 150 $\mu\mathrm{m}$!
  - Curvature bias modes in better control with $Z^0 \rightarrow \mu^+\mu^-$ events.
  - Alignment framework extended to treat calibration parameters.

A few closing words . . .

- The title of the talk should read: lessons learnt aligning the CMS silicon Tracker in Run-I;
  - ⇒ During Run-I, LHC,CMS and the Tracker were not operated at design conditions (different luminosity conditions, different detector temperatures, . . .)
    - LHC Run-II data can still provide exciting alignment challenges, small input biases are know to generate large effects ☺!

Thanks!

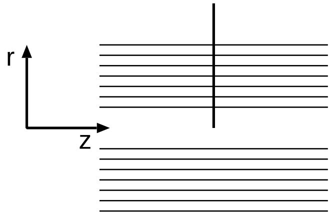
- A relevant part of the CMS Tracker Alignment effort in the last decade has been carried by the DESY-CMS Group, which I would like to acknowledge gratefully on behalf of the CMS collaboration.
- I am especially indebted, also for the material shown here, with a former member, *G. Flucke*, who paved the way to most of these results and moved on in the meantime to other projects.

Backup Slides

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

Problem of Track Based Alignment: Weak Modes

Minimising residuals can be insensitive to certain global distortions.

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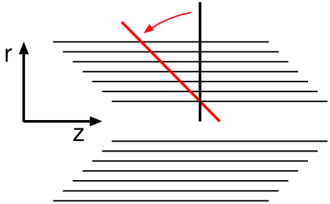

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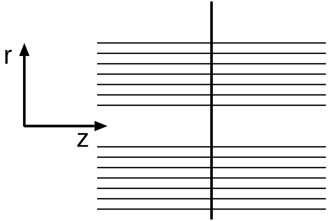

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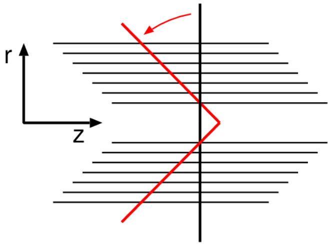

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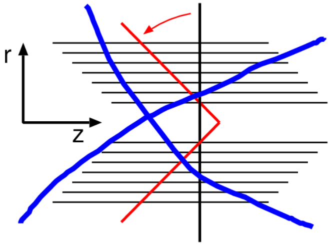

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- $\Rightarrow$ Bias in η

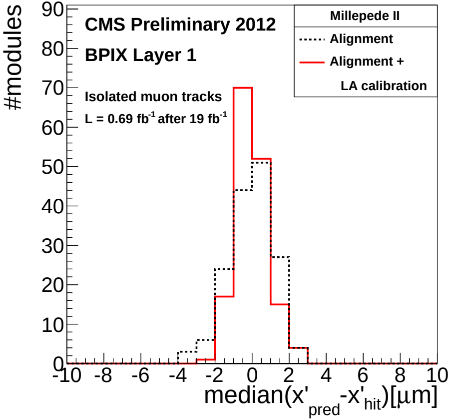
Solution:

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

Lorentz Angle validation, BPIX layers 3

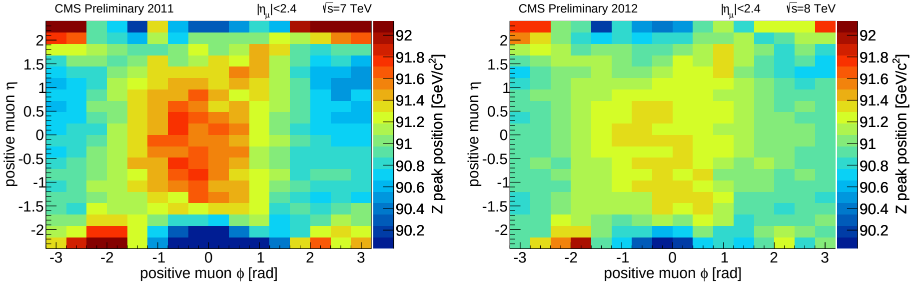
- LA calibration validated by comparing to alignment with standalone calibration.
- Distribution of median of unbiased residuals (DMR) between measured and predicted hit position for each module. Independent set of tracks from isolated muons used in validation (from end of 2012).

- 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 $Z \to \mu^+\mu^-$[4] 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!

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

Millepede II

An Experiment-Independent Global Fit Tool

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

Task of the Global Fit Tool

- 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

- Successor of Millepede I: able to deal with much larger number of parameters.
- 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

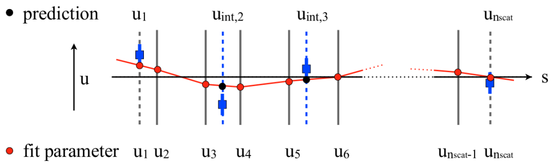
- Charged particle in magnetic field: need 5 helix parameters.
- Traversing material: multiple scattering effects.
  (relevant for "heavy" tracking detectors)
- Usually treated by progressive track fit: Kalman filter.
- Millepede II needs global fit:
  $\Rightarrow$ 2 scattering angles per thin scatterer,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

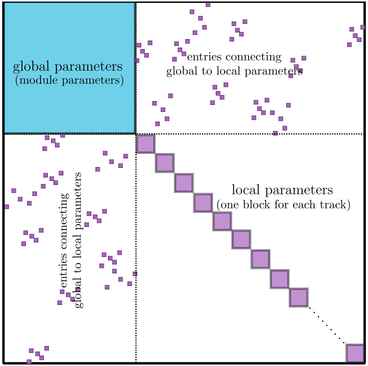
- Reparametrise: $\boldsymbol{a}^{local} = (\Delta q/p, \boldsymbol{u_1}, \ldots, \boldsymbol{u_{n_{scat}}})$.
- $\boldsymbol{u_i}$: 2D offsets in local system at each scatterer.
- Predictions $\boldsymbol{u_{int}}$ for measurements: interpolating between scatterers.
- Kink angles from triplets of adjacent 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 $\boldsymbol{x}$: ~$n_{par} \cdot (m+b)^2$, $\boldsymbol{A}^{-1}$: ~$n_{par}^2 \cdot (m+b)$
- Equivalent to standard CMS Kalman filter track fit.

Alignment is big data!



- What we call *global parameters* are the calibration constants to be determined.
- A full alignment for every module (3 positions, 3 rotation, 3 surface deformation) determines O(200 000) numbers
- We need to solve a linear equation system of this size and use special high-RAM machines for this.
- Most recent sets of alignment constants delivered by `Millepede-II`[a].
- A variety of datasets (MinBias, $Z \to \mu\mu$, single μ, Cosmics) in large numbers are required ($> 10^7$ events).
- Running one job takes about 24 hours of wall-clock time.

a) `Millepede-II` is a Physics at the Terascale project.

2012 “Legacy” alignment with $\sqrt{s} = 8$ TeV data

Offline-Validation with Isolated-μ Tracks

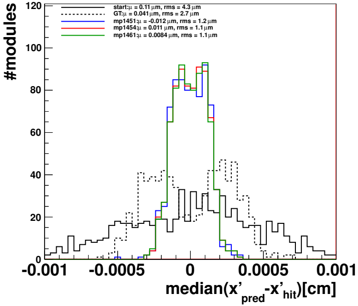
- **Goal**: to reach a stable reference alignment for 2012 data.
  - Including latest alignment procedures (Lorentz Angle & BackPlane corr. calibration).

☑ High precision after alignment.

  - Starting Tracker Alignment from 2011 Legacy Alignment

⇒ Stable after 0^{th} iteration. And we include BP as well.

Distribution of the median of the residuals in BPIX



Distribution of the median of the residuals in TEC