Alignment of the CMS Tracker at LHC Run-II
Technology and Instrumentation in Particle Physics
Beijing 2017

Patrick L.S. Connor
on behalf of the CMS collaboration

Deutsches Elektronen-Synchrotron

22 May 2017
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Tracker alignment at CMS
A picture of the challenge
Track-based approach

2 Implementation
Alignables
Weak modes
Time variations

3 Performance
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Tracker alignment at CMS

Largest silicon tracker in the world!

**Purpose:** reconstruct trajectories

Until end of 2016:

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<th>hit resolution</th>
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Typically, the precision at mounting is such that

\[ \sigma_{\text{align}} \gg \sigma_{\text{hit}} \]

Compute a correction to the mounting of the modules such that

\[ \sigma_{\text{align}} \approx \sigma_{\text{hit}} \]
A picture of the challenge
A picture of the challenge

- position
A picture of the challenge

- position
- rotation
A picture of the challenge

- position
- rotation
- curvature
A picture of the challenge

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\( \rightarrow O(10^5) \) parameters
A picture of the challenge

- position
- rotation
- curvature

$O(10^5)$ parameters
A picture of the challenge

- position
- rotation
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\[ \longrightarrow O(10^5) \text{ parameters} \]

In addition, tracks are distilled by the misalignment.
Track-based approach

Linearisation of least-square minimisation of the track fit [1, 2]

$$\chi^2(p, q) = \sum_{\text{tracks}} \sum_{\text{hits}} \left( \frac{m_{ij} - f_{ij}(p, q_j)}{\sigma_{ij}} \right)^2$$

- $p$ stands for the alignment parameters and $q$ for the track parameters,
- $m$ stands for the measurements and $f$ for the predictions,
- and $\sigma$ stands for the uncertainties.

NB: MillePede-II is an project independent from CMS [3].

MillePede-II
- global-fit approach (large linear equation system)
- minimise residuals and refit the tracks together
- take into account all correlations
- demanding in term of memory

HipPy
- local-fit approach
- remove track parameters from the $\chi^2$
- iterative procedure
- used for fine tuning
Track-based approach

Linearisation of least-square minimisation of the track fit [1, 2]

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Alignables

- Several levels of alignment:
  - high-level structures \((O(1\, \text{mm}))\)
    \(\rightarrow\) when the statistics is limited
  - modules \((O(10\, \mu\text{m}))\)
    \(\rightarrow\) requires larger statistics
  \(\rightarrow\) *alignables*

- positions, rotations and deformations can be aligned
  \(\rightarrow\) all parameters of alignables can be activated separately

(Sketch of the barrel and forward pixel subdetectors)
Weak modes

Definition
A weak mode is any transformation such that $\Delta \chi^2 \sim 0$.
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i.e. it is a transformation that changes *valid* tracks into *other valid* tracks
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Examples

Telescope

Twist

(plots from N. Bartosik’s thesis)
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(plots from N. Bartosik’s thesis)

Solution

cosmic rays other topology

$Z \rightarrow \mu\mu$ momentum constraint on the two outgoing muons
Time variations

- Magnet cycles: magnetic field may be switched off for maintenance reasons → mostly affects the large mechanical structures
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- Temperature variations: cooling operations after long shutdown  
  \[\rightarrow\] sensitive effect at module level as well
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- **Ageing of the modules:**
  high-radiation environment
  → Lorentz drift inside of the silicon modules
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- Temperature variations: cooling operations after long shutdown → sensitive effect at module level as well
- Ageing of the modules: high-radiation environment → Lorentz drift inside of the silicon modules

Align separately:
- *absolute* positions of high-level structures with time-dependence;
- *relative* position of modules to the high-level structure without time-dependence.

→ include time dependence but keep large statistics
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We present now the performance of the alignment in 2016:

- 36 intervals of time.
- Full module-level alignment
  → possible thanks to high statistics of $Z \rightarrow \mu\mu$ and cosmic rays.
- Determine global alignment with four iterations with MP
  → in case of large corrections, linear approximation of $\chi^2$ is limited.
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  $\rightarrow$ fine tuning.
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Note: 150 GB of RAM and around 30 h are needed to run MillePede
Structure of the tracker

- PXB  PiXel Barrel
- PXF  PiXel Forward
- TIB  Tracker Inner Barrel
- TOB  Tracker Outer Barrel
- TID  Tracker Inner Disks
- TEC  Tracker Endcaps
• Each point represents a module; colour is related to the high-level structure.

• One can see the movement $Y(\Delta r, \Delta z, r\Delta \phi)$ of a module initially at position $X(r, z, \phi)$.

→ clear movements between the tracker in data-taking and aligned tracker.
Validation

In the next slides, we show the effect of the alignment on various physical quantities between

- **tracker in data-taking**
- **aligned tracker**

and for reference, we show in addition:

- **MC simulation (no misalignment)**
Distribution of the medians of the residuals

• For each module, the median of the residuals is computed and histogrammed.
• **Optimally aligned detector** has smallest width
  → lower limit on width determined by statistical precision.
• Sensitive to local alignment precision.
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Ageing of the modules

(From N. Bartosik’s Thesis)

- Lorentz drift: reconstructed hit is displaced w.r.t. true hit.
- E-field and charge carrier mobility change with time.

→ Lorentz drift is not constant in time!
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- \( E \)-field and charge carrier mobility change with time.
  \[ \longrightarrow \text{Lorentz drift is not constant in time!} \]

- Distributions of the median of the residuals can be produced separately for modules with electric field pointing in- or outwards. We show here the difference of the respective means \( \Delta \mu \) over time.
- Ideal tracker would have \( \Delta \mu = 0 \).
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$\rightarrow$ The difference of the means $\Delta \mu$ in local $x$ direction indicates the recovery of Lorentz-angle effects.
Simultaneous alignment and Lorentz angle calibration in the CMS silicon tracker using Millepede II
Forward PIX Barrel ... Elektronen-Synchrotron, Germany)
on behalf of the CMS Collaboration
EPS HEP 2013 (18-24 July, Stockholm, Sweden)

Structure of
Weak modes
Track-based
CMS
Detectors at LHC.

- Solenoid
- Track-hit residuals $d$
- We show here the difference of the respective means
- BPIX module: $B = 0T$ field and charge carrier mobility change with time.
- Center of collected charge cluster depends on global module
- Drifting under E field.
- Track induces signal charge during detector operation.
- Largest irradiation dose.
- Closest to the interaction point.
- Impact parameter
- Innermost detector

$\mu = 150V$
$y = 3.8T$
$-2600$
$\Delta \mu, TID$
$24 244$
$\Delta \mu, TEC$
$24 244$
$23 \mu m$ resolution
$600$
$800$
$R$
$14 000 T$
$15 m$
$10 416$
$10 \mu m$ resolution
$\Delta \mu, TID$
$\Delta \mu, TEC$
$10 \mu m$ resolution
$1$D
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Primary-vertex validation

- Given $N$ tracks from a vertex, $N - 1$ tracks are used to refit the vertex
  $\rightarrow$ evaluate the distance of the $N$-th track to the refitted vertex
  $\langle d_{xy} \rangle$ and $\langle d_z \rangle$ as a function of the track $\phi$ and $\eta$.
- Mostly sensitive to movements in pixel subdetector.
- Global patterns suggest systematic misalignments
Primary-vertex validation

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$\rightarrow$ here, movement in barrel pixel half-shell is cured.
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The mass of the $Z$ boson is reconstructed from two outgoing muons.

The mass can be measured as a function of their kinematics — shown here as a function of the azimuthal angle for both muons.
The mass of the $Z$ boson is reconstructed from two outgoing muons.

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→ φ-modulation has been cured.
• The mass of the $Z$ boson is reconstructed from two outgoing muons.
• The mass can be measured as a function of their kinematics → shown here as a function of the azimuthal angle for both muons.

→ $\phi$-modulation has been cured.
Summary

- The topic of alignment was introduced:
  - how the **challenge** is addressed at CMS;
- its implementation at CMS was described:
  - how to deal with the **weak modes**
  - and how to include movements over **time**;
- and the performance in 2016 was shown:
  - **most elaborate** alignment campaign of the **largest** silicon tracker with around 100M simultaneously refitted tracks in 36 intervals of time;
  - the alignment **precision** in pixel part of order of 10 $\mu$m;
  - and the improvement was presented from various **validations** with data-driven methods.

Thanks a lot!
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**Thanks a lot!**
References

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Alignment of the cms silicon tracker during commissioning with cosmic rays.
*Journal of Instrumentation, 5*(03):T03009, 2010.

The CMS collaboration.
Alignment of the cms tracker with lhc and cosmic ray data.

Volker Blobel and Claus Kleinwort.
A new method for the high-precision alignment of track detectors.
*Proceedings of the Conference on Advanced Statistical Techniques in Particle Physics, 2002.*
• Linearisation of the $\chi^2$ allows to make use of linear algebra:

$$C \times (\Delta p \ \Delta q) = b$$

• Partition of the matrix $C$ into blocks for local and global parameters allows to reduce drastically the size of the matrix to invert:

$$C_j \Delta q_j = b_j \quad \text{local parameters}$$

$$C' \Delta p = b' \quad \text{global parameters}$$

where $b'$ can be determined from $\Delta q_j$ and $C'$ from $C_j^{-1}$ and some additional blocks in $C$ describing correlations between local and global parameters

• MillePede = Mille + Pede

Mille\hspace{1em}\text{determination of all the values needed to calculate the global } \chi^2 \hspace{1em} \rightarrow p, q, m, \sigma, \text{ local } df/\text{dq and global } df/dp \text{ parameters}

Pede\hspace{1em}\text{determination of local (track) refits to construct the linear equation system, then determination of global (alignment) parameters}
Pixel Barrel Module

Kapton cable (DYCONEX)
- connects module and endprint
- impedance matched (Z~40 Ω)
- glued & wirebonded to HDI

HDI (HIGHTEC MC)
High Density Interconnect Board:
- flexible, low mass PCB
- glued to sensor
- rad hard SMD components
- TMB glued & wirebonded

Power cable (PSI)
- lamination of cable in house
- soldered to HDI

ROC’s (IBM)
Read Out Chip IBM-PSI46:
- 0.25μm DeepSubMicron process
- 52x80 pixels of 150x100 µm > 66 kpixel/module
- power consumption ~28 µW/pixel
- chips thinned to 170 µm
  => reduced MB-contribution

Sensor (CIS)
- 285 µm thickness
- n–on–n devices
- moderated p–spray
- DOFZ–silicon in <111>orientation
- resistivity of 3.7 k Ωm
- processed on both sides

Overall Dimensions:
- Sensor 66.6 x 18.6 mm²
- Baseplate 65 x 26 mm²

Weight:
- Module ~2.2 g
- Cables ~1.3 g

Power consumption:
~2 W per full module

Baseplate
- 250 µm Si–Nitride material
- two small strips glued to ROC’s
  => reduced MB-contribution

Baseplate Strip
DMRs

Principle

The *Distributions of the medians of the residuals* are a measure of the local precision.

- Deviations from 0 indicate possible biases.
- The width is also sensitive to the statistics\(^1\).

Procedure

- Each track is reconstructed for different geometries.
- The hit prediction \(x'_{\text{pred}}\) for each module is obtained from all other track hits. The median of this
- The residuals \(x'_{\text{pred}} - x'_{\text{hit}}\) is histogrammed for each module.
- For each high-level structure, the median of the residuals is histogrammed and plotted.

In order to avoid statistical correlations, we use independent samples for alignment and validation.

\(^1\)In the next plots, we took care of having comparable statistics for MC and data.
DMRs in BPIX

**CMS Preliminary** 3.8T collision data 2016

Alignment: cosmic rays + collisions

- **Tracker in data taking**: $\mu = -0.004 \, \mu m$, $\sigma = 1.030 \, \mu m$
- **Aligned tracker**: $\mu = 0.048 \, \mu m$, $\sigma = 0.589 \, \mu m$
- **MC (no misalignment)**: $\mu = -0.015 \, \mu m$, $\sigma = 0.205 \, \mu m$

**CMS Preliminary** 3.8T collision data 2016

Alignment: cosmic rays + collisions

- **Tracker in data taking**: $\mu = -0.396 \, \mu m$, $\sigma = 4.432 \, \mu m$
- **Aligned tracker**: $\mu = 0.006 \, \mu m$, $\sigma = 1.210 \, \mu m$
- **MC (no misalignment)**: $\mu = 0.023 \, \mu m$, $\sigma = 0.567 \, \mu m$
DMRs in FPIX

Alignment: cosmic rays + collisions

- tracker in data taking: $\mu = 0.158 \, \mu m$, $\sigma = 1.784 \, \mu m$
- aligned tracker: $\mu = -0.003 \, \mu m$, $\sigma = 0.911 \, \mu m$
- MC (no misalignment): $\mu = -0.036 \, \mu m$, $\sigma = 0.477 \, \mu m$

- $Z \rightarrow \mu \mu$ validation

- Prompt calibration
DMRs in TIB and TOB

**TIB**

**TOB**

### CMS Preliminary

3.8T collision data 2016

**Alignment:** cosmic rays + collisions

- tracker in data taking
  - $\mu = -0.016 \, \mu m$, $\sigma = 1.735 \, \mu m$
- aligned tracker
  - $\mu = 0.010 \, \mu m$, $\sigma = 0.690 \, \mu m$
- MC (no misalignment)
  - $\mu = -0.069 \, \mu m$, $\sigma = 0.460 \, \mu m$

---

### CMS Preliminary

3.8T collision data 2016

**Alignment:** cosmic rays + collisions

- tracker in data taking
  - $\mu = -0.435 \, \mu m$, $\sigma = 3.129 \, \mu m$
- aligned tracker
  - $\mu = -0.366 \, \mu m$, $\sigma = 1.428 \, \mu m$
- MC (no misalignment)
  - $\mu = -0.453 \, \mu m$, $\sigma = 1.172 \, \mu m$
DMRs in TIB and TOB

TID

- CMS Preliminary
- 3.8T collision data 2016
- Alignment: cosmic rays + collisions
- tracker in data taking: $\mu = -0.022 \mu m, \sigma = 1.042 \mu m$
- aligned tracker: $\mu = 0.015 \mu m, \sigma = 0.492 \mu m$
- MC (no misalignment): $\mu = 0.018 \mu m, \sigma = 0.264 \mu m$

TEC

- CMS Preliminary
- 3.8T collision data 2016
- Alignment: cosmic rays + collisions
- tracker in data taking: $\mu = 0.013 \mu m, \sigma = 2.739 \mu m$
- aligned tracker: $\mu = 0.032 \mu m, \sigma = 0.967 \mu m$
- MC (no misalignment): $\mu = 0.033 \mu m, \sigma = 0.697 \mu m$
Primary-vertex validation

Selection

- **Vertex**
  - minimum-bias events,
  - at least four d.o.f. in the vertex fit,

- **Tracks**
  - at least six hits in the tracker, of which at least two in the pixel detector,
  - at least one hit in the first layer of the Barrel Pixel or the first disk of the Forward Pixel,
  - $\chi^2_{\text{track}}/\text{n.d.o.f.} < 5$

Principle

- We consider one given track from a given vertex.
- The vertex is refitted without the track under scrutiny.
- The longitudinal and transversal projections of the impact parameter $<d_{xy}>$ and $<d_z>$ of the track are computed and plotted as a function of the track $\eta$ and $\phi$.

Biases

**Random misalignments** increase the spread.

**Systematic misalignments** biase the mean (pattern depend on misalignment).
Primary-vertex validation

Transversal impact parameter

![Graphs showing transversal impact parameter for different track parameters with CMS Preliminary 3.8T collision data 2016.](image)
Primary-vertex validation

Longitudinal impact parameter

![Graph showing longitudinal impact parameter for track \( \eta \) and track \( \phi \) [rad].](image)
**$Z \rightarrow \mu\mu$ validation**

**Idea**

- Data-driven method to investigate distortions in the geometry.
- Distortions in the geometry may degrade the kinematics of the two outgoing muons coming from the decay of a $Z$ boson.
- The reconstruction of the $Z$ boson is thus investigated by measuring its mass as a function of the kinematics of the muons.

**Selection of the muons**

- $p_T > 20 \text{ GeV}/c$
- $|\eta| < 2.4$
- $80 < M_{\mu\mu} < 120 \text{ GeV}/c^2$

**NB:** Muons are reconstructed with both the tracker and the muon system, but only the geometry of the tracker is updated in the next slides.
$Z \rightarrow \mu\mu$ validation

Procedure

- The $Z$-boson mass is reconstructed with a Voigtian function\(^2\) with fixed decay width for the Breit-Wigner component.
- The background is reconstructed with an exponential function.
- The mass is then estimated from the mean of the Voigtian function as a function of different variables:
  - the azimuthal angles $\phi_{\mu^\pm}$ of each of the muons,
  - the rapidity separation $\eta_{\mu^+} - \eta_{\mu^-}$,
  - the cosine of the angle of the boson $\cos \theta_{CS}$ in the Collins-Soper frame.

Fit of the mass

Ideally, the mass should not depend on any of these variables. In order to illustrate this, a horizontal line is fitted to the distribution of the reconstructed masses (dashed lines).

\(^2\)Convolution of Gaussian and Lorentzian functions
**Z → μμ validation**

![Graph showing Z → μμ validation](image)

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<tr>
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<th>$\chi^2$/ndf</th>
<th>$p$-value</th>
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<tbody>
<tr>
<td>tracker in data taking</td>
<td>15.99</td>
<td>&lt; 0.01</td>
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<tr>
<td>aligned tracker</td>
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<td>0.14</td>
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<td>0.17</td>
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Z → μμ validation

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<td></td>
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<table>
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<td></td>
<td>1.25</td>
<td>0.21</td>
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Prompt calibration

• High-level structures in the pixel detector can be promptly aligned during data-acquisition.

• Prompt calibration was applied from 16 August to 5 December 2016 ($\mathcal{L} = 16.4 \text{ fb}^{-1}$).

We show in the next slides the variations of the corrections to the position and orientation of the high-level structures over time:

• Calibration is triggered as soon as large movements are observed in any position (depending on the coordinate)

  Alignment updates vertical dashed lines
  Update threshold horizontal continuous lines

• One can clearly correlate movements in the pixel with magnet cycles (grey bands)
  • $\Delta x \lesssim 50 \mu\text{m}$
  • $\Delta y \lesssim 50 \mu\text{m}$
  • $\Delta z \lesssim 150 \mu\text{m}$

NB: At least $20k$ minimum-bias events must be used to perform the prompt calibration.
Corrections to the position in global $x$ direction

![Graph showing corrections to the position in global $x$ direction](image)

CMS Preliminary 13 TeV data (Aug. 16 - Dec. 5, 2016)

- Tracker alignment in 2016 data-taking used as reference
- Update threshold
- Alignment update
- Magnet < 3.8 T
- FPIX(x+,z-)
- BPIX(x+)
- FPIX(x+,z+)
- FPIX(x-,z-)
- BPIX(x-)
- FPIX(x-,z+)

Time

2016-08-27
2016-09-26
2016-10-26
2016-11-25

Delta x (um)
 Corrections to the position in global $y$ direction

**Graph:**

- **CMS Preliminary**
- 13 TeV data (Aug. 16 - Dec. 5, 2016)
- Tracker alignment in 2016 data-taking used as reference
- Update threshold
- Alignment update
- Magnet < 3.8 T

**Legend:**

- FPIX(x+,z-)
- BPIX(x+)
- FPIX(x-,z-)
- BPIX(x-)
- FPIX(x-,z+)

**Axes:**

- **Δy (μm)**: y-axis
- **Time**: x-axis

**Dates:**

- 2016-08-27
- 2016-09-26
- 2016-10-26
- 2016-11-25
Corrections to the position in global $z$ direction

![Graph showing corrections to position in global z direction](image_url)

**CMS Preliminary**

13 TeV data (Aug. 16 - Dec. 5, 2016)

Tracker alignment in 2016 data-taking used as reference

- Update threshold
- Alignment update
- Magnet < 3.8 T
- FPIX(x+,z-)
- BPIX(x+)
- FPIX(x+,z+)
- FPIX(x-,z-)
- BPIX(x-)
- FPIX(x-,z+)

**Time**

2016-08-27 2016-09-26 2016-10-26 2016-11-25
Corrections to the orientation in global $x$ direction

**CMS Preliminary**

13 TeV data (Aug. 16 - Dec. 5, 2016)

Tracker alignment in 2016 data-taking used as reference

- Update threshold
- Alignment update
- Magnet < 3.8 T
- FPIX($x^+$,$z^-$)
- BPIX($x^+$)
- FPIX($x^+$,$z^+$)
- FPIX($x^-$,$z^-$)
- BPIX($x^-$)
- FPIX($x^-$,$z^+$)

Delta $\theta_x$ (micro-radians)

Time

- 2016-08-27
- 2016-09-26
- 2016-10-26
- 2016-11-25

**Back-up**

- MillePede
- Modules
- DMRs
- Primary-vertex validation
- $Z \rightarrow \mu \mu$ validation

**Prompt calibration**
 Corrections to the orientation in global $y$ direction

**CMS Preliminary**

13 TeV data (Aug. 16 - Dec. 5, 2016)

Tracker alignment in 2016 data-taking used as reference

- Update threshold
- Alignment update
- Magnet < 3.8 T
- FPIX($x^+$,$z^-$)
- BPIX($x^+$)
- FPIX($x^+,$$z^+$)
- FPIX($x^-,$$z^-$)
- BPIX($x^-)$
- FPIX($x^-,$$z^+)$

**Time**

2016-08-27
2016-09-26
2016-10-26
2016-11-25

**Δθ_y (μrad)**

-50 0 50
Corrections to the orientation in global $z$ direction

Tracker alignment in 2016 data-taking used as reference

- Update threshold
- Alignment update
- Magnet < 3.8 T

- FPIX($x^+,z^-$)
- BPIX($x^+$)
- FPIX($x^-,z^+$)
- FPIX($x^-,z^-$)
- BPIX($x^-$)

Preliminary CMS 13 TeV data (Aug. 16 - Dec. 5, 2016)