Alignment of the CMS Tracker at LHC Run-II

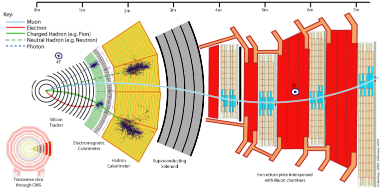
Technology and Instrumentation in Particle Physics Beijing 2017

Patrick L.S. Connor

on behalf of the CMS collaboration

Deutsches Elektronen-Synchrotron

22 May 2017


0m
1m
2m
3m
4m
5m
6m
7m
Key:
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Charged Hadron (e.g. Pion)
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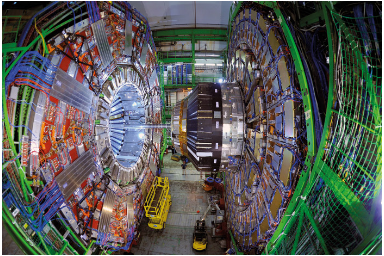


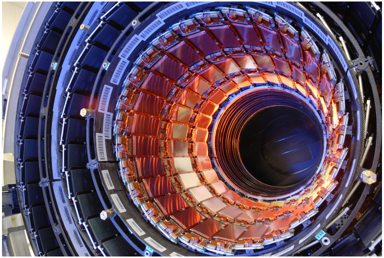
Tracker alignment at CMS

Largest silicon tracker in the world!

Purpose: reconstruct trajectories

Until end of 2016:

	units	hit resolution
pixel	1440	$9\,\mu\text{m}$
strip	15148	$20-60\,\mu\text{m}$



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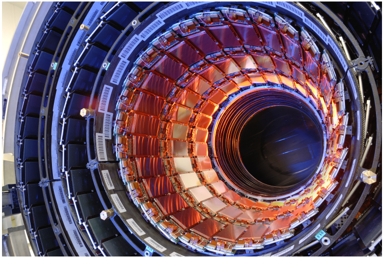


(during mounting of the tracker)

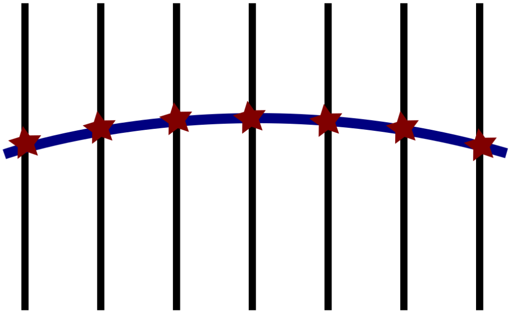
Typically, the precision at mounting is such that

$$\sigma_{\text{align}} \gg \sigma_{\text{hit}}$$

Compute a correction to the mounting of the modules such that

$$\sigma_{\text{align}} \approx \sigma_{\text{hit}}$$

A picture of the challenge



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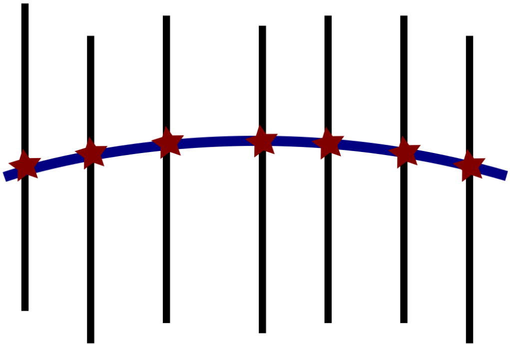

- position

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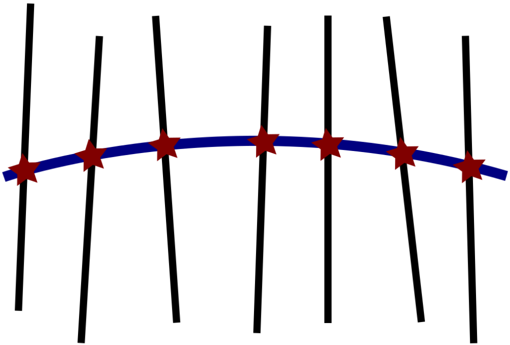

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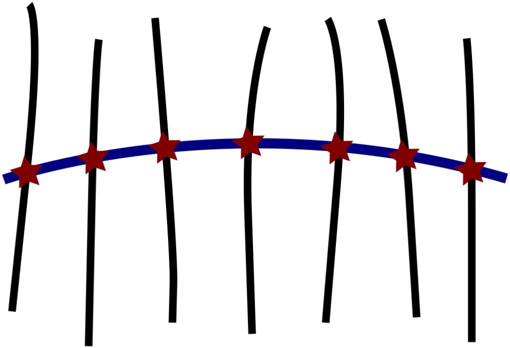

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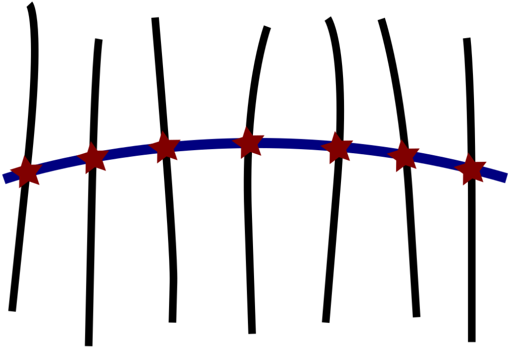

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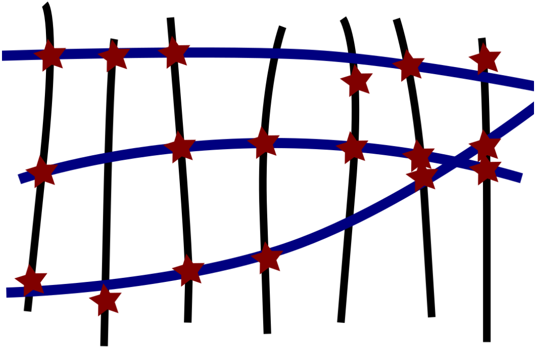

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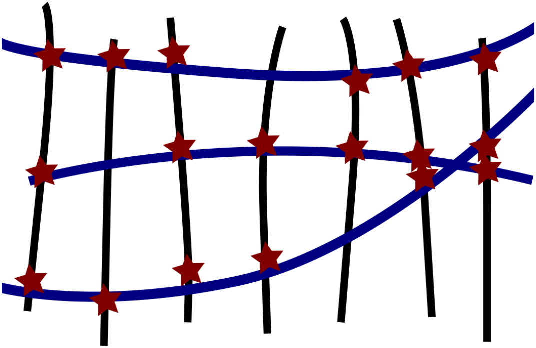

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$\longrightarrow O(10^5)$ parameters

In addition, tracks are **distorted** by the misalignment.

Track-based approach

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

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

- $\mathbf{p}$ stands for the alignment parameters and $\mathbf{q}$ for the track parameters,
- $\mathbf{m}$ stands for the measurements and $\mathbf{f}$ for the predictions,
- and σ stands for the uncertainties.

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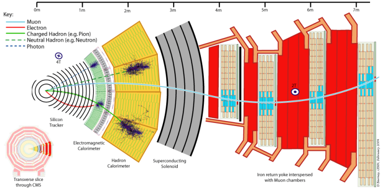
MillePede-II

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

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

HipPy

- local-fit approach
- remove track parameters from the χ^2
- iterative procedure
- used for fine tuning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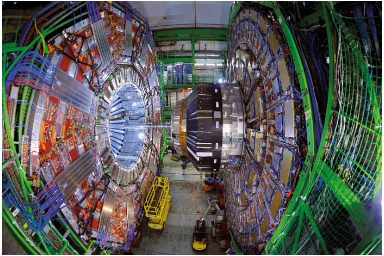
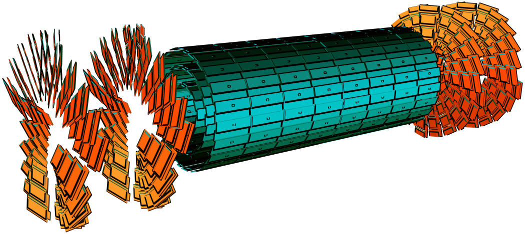


Alignables

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

  $\longrightarrow$ *alignables*
- positions, rotations and deformations can be aligned
  $\longrightarrow$ all parameters of alignables can be activated separately



(Sketch of the barrel and forward pixel subdetectors)

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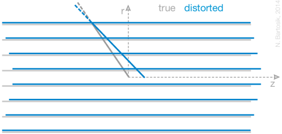
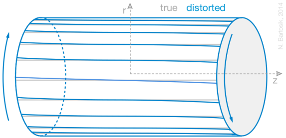


Twist



(plots from N. Bartosik's thesis)

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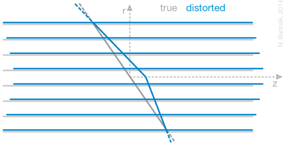

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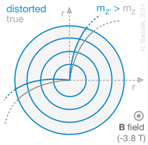

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Solution

cosmic rays other topology

$Z \to \mu\mu$ momentum constraint on the two outgoing muons

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- Magnet cycles:
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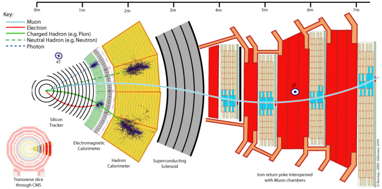
$$\Downarrow$$

Align separately:

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

$\longrightarrow$ include time dependence but keep large statistics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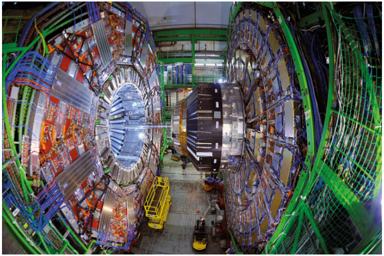

Configuration

We present now the performance of the alignment in 2016:

- 36 intervals of time.
- Full module-level alignment
  $\longrightarrow$ possible thanks to high statistics of $Z \longrightarrow \mu\mu$ and cosmic rays.
- Determine global alignment with four iterations with MP
  $\longrightarrow$ in case of large corrections, linear approximation of χ^2 is limited.

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minimum-bias tracks	$13M$	0.2 – 0.3
isolated muons	$53M$	0.25
$Z \longrightarrow \mu\mu$	$32M$	1.0
cosmic rays	$3M$	2.5

$\longrightarrow$ large statistics of minimum-bias events is available
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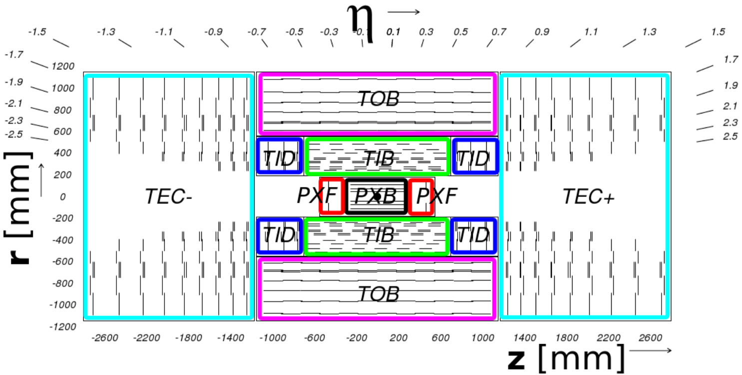
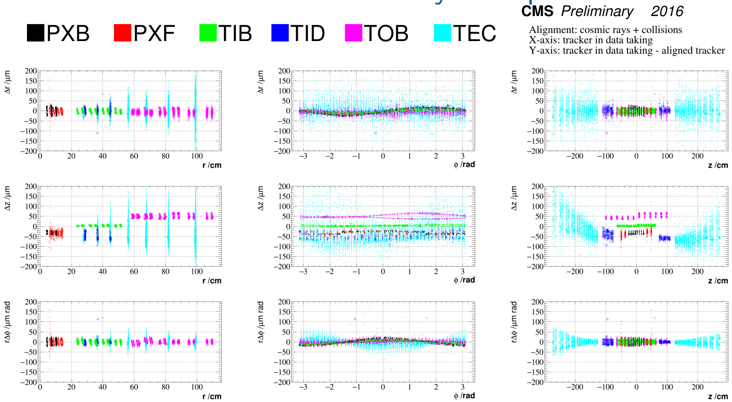
Note: $150\,\mathrm{GB}$ of RAM and around $30\,\mathrm{h}$ are needed to run MillePede

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

Geometry comparison



- 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 $X(r, z, \phi)$.

$\longrightarrow$ clear movements between the **tracker in data-taking** and **aligned tracker**.

Validation

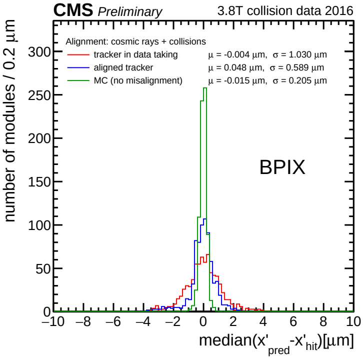
In the next slides, we show the effect of the alignment on various physical quantities between

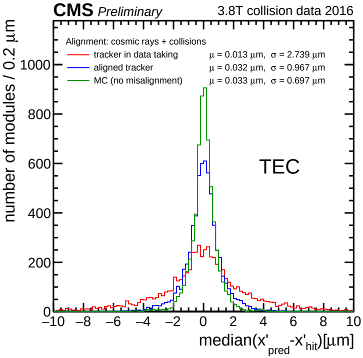
- tracker in data-taking
- aligned tracker

and for reference, we show in addition:

- MC simulation (no misalignment)

Distribution of the medians of the residuals





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- **Optimally aligned detector** has smallest width
  $\longrightarrow$ lower limit on width determined by statistical precision.
- Sensitive to local alignment precision.

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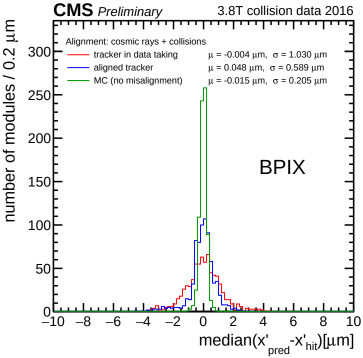

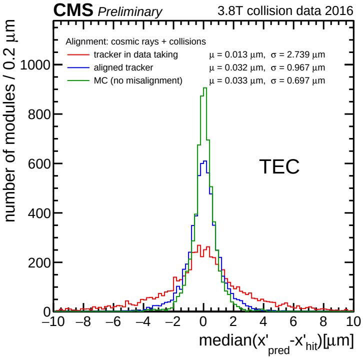

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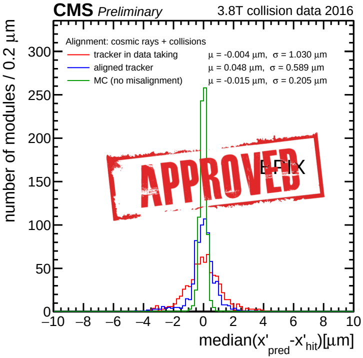

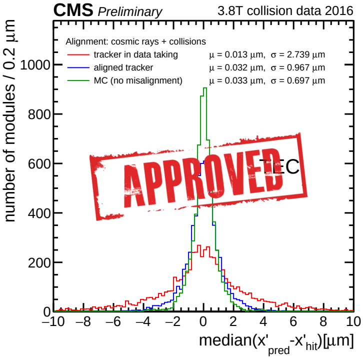

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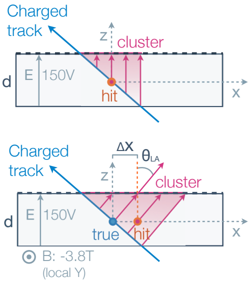

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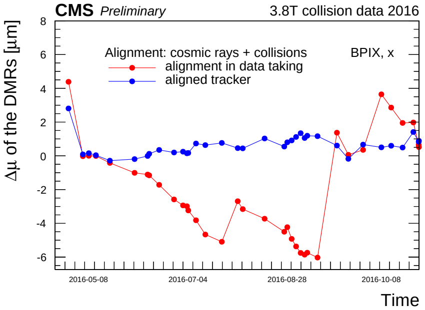

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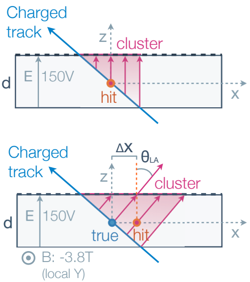

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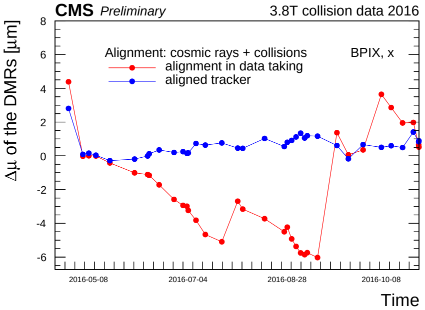

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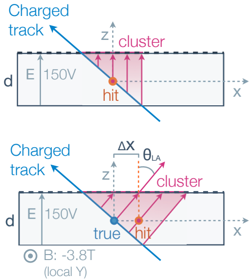

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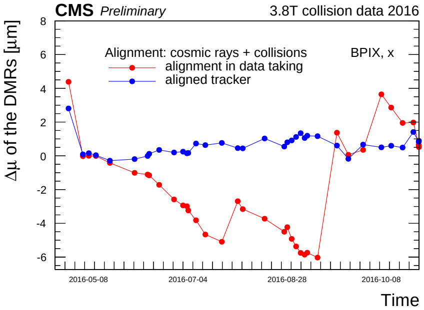

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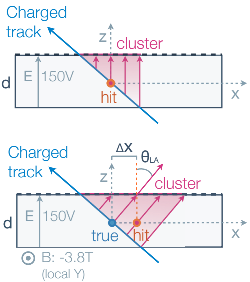

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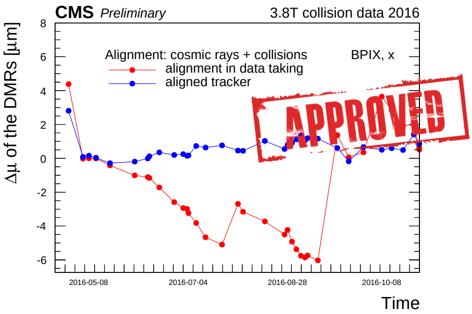

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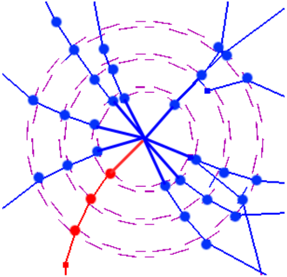

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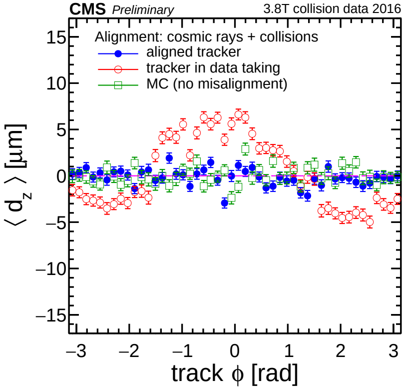

- Given N tracks from a vertex, $N-1$ **tracks** are used to **refit** the vertex
  $\longrightarrow$ evaluate the distance of the **N-th track** to the refitted vertex $<d_{xy}>$ and $<d_z>$ as a function of the track ϕ and η.
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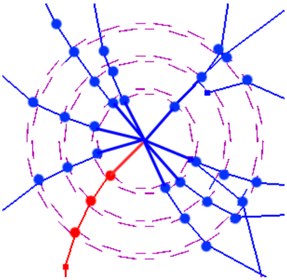

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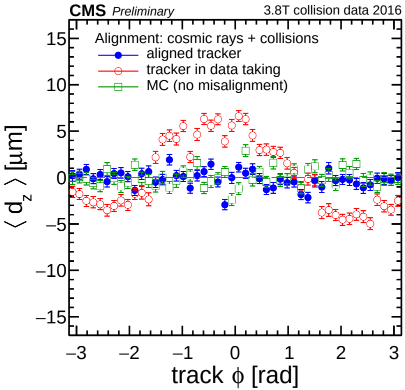

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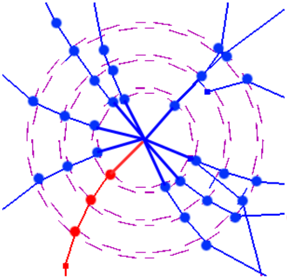
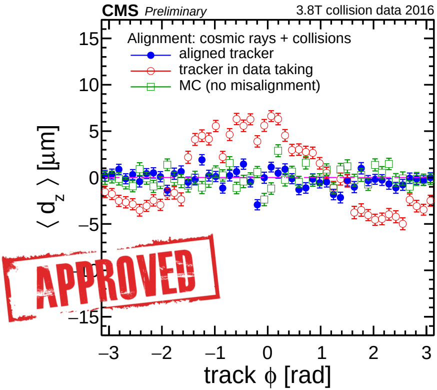
$\longrightarrow$ here, **movement** in barrel pixel half-shell is **cured**.

Primary-vertex validation



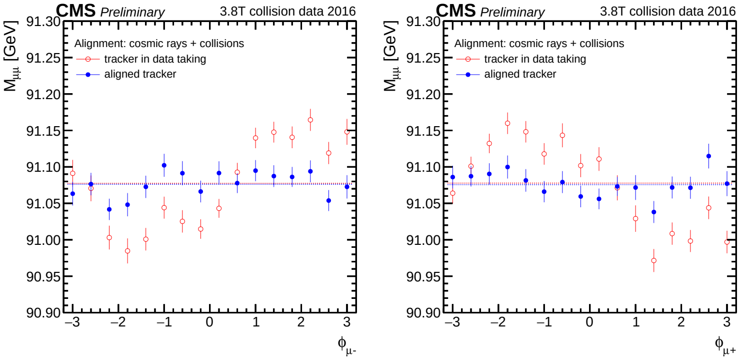
(from M. Musich)



- Given N tracks from a vertex, $N-1$ **tracks** are used to **refit** the vertex
  $\longrightarrow$ evaluate the distance of the **N-th track** to the refitted vertex $< d_{xy} >$ and $< d_z >$ as a function of the track ϕ and η.
- Mostly sensitive to movements in pixel subdetector.
- Global patterns suggest systematic misalignments

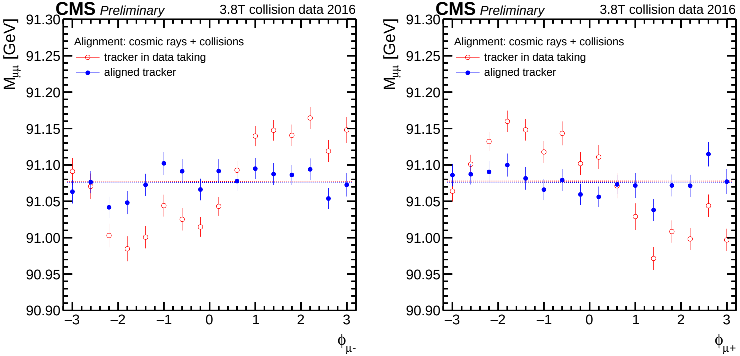
$\longrightarrow$ here, **movement** in barrel pixel half-shell is **cured**.

$Z \to \mu\mu$ validation



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

$Z \rightarrow \mu\mu$ validation



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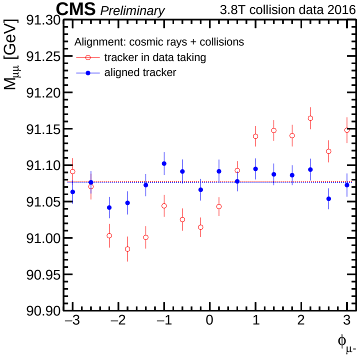
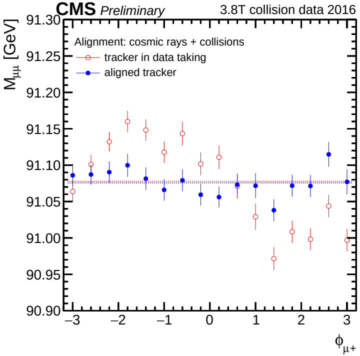
$\longrightarrow$ **ϕ-modulation** has been **cured**.

$Z \to \mu\mu$ validation





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- The mass can be measured as a function of their kinematics $\longrightarrow$ shown here as a function of the azimuthal angle for both muons.

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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 μm;
  - and the improvement was presented from various **validations** with data-driven methods.

Summary

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  - and the improvement was presented from various **validations** with data-driven methods.

Thanks a lot!

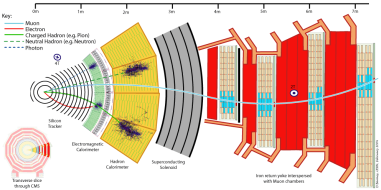
References

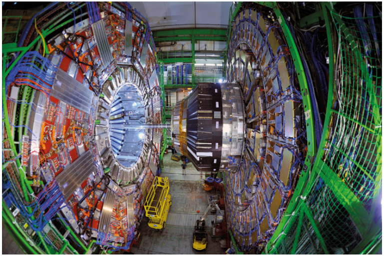
CMS Collaboration.
Alignment of the cms silicon tracker during commissioning with cosmic rays.
Journal of Instrumentation, 5(03):T03009, 2010.

The CMS collaboration.
Alignment of the cms tracker with lhc and cosmic ray data.
Journal of Instrumentation, 9(06):P06009, 2014.

Volker Blobel and Claus Kleinwort.
A new method for the high-precision alignment of track detectors.
Proceedings of the Conference on Adcanced Statistical Techniques in Particle Physics, 2002.

Back-up


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS



MillePede

- Linearisation of the χ^2 allows to make use of linear algebra:

$$\mathbf{C} \times (\mathbf{\Delta p}\ \mathbf{\Delta q}) = \mathbf{b}$$

- Partition of the matrix $\mathbf{C}$ into blocks for local and global parameters allows to reduce drastically the size of the matrix to invert:

$$\mathbf{C}_j \mathbf{\Delta q}_j = \mathbf{b}_j \qquad \text{local parameters}$$
$$\mathbf{C}' \mathbf{\Delta p} = \mathbf{b}' \qquad \text{global parameters}$$

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

- MillePede = Mille + Pede

  Mille determination of all the values needed to calculate the global χ^2
  $\longrightarrow \mathbf{p}$, $\mathbf{q}$, $\mathbf{m}$, σ, local $\mathrm{d}\mathbf{f}/\mathrm{d}\mathbf{q}$ and global $\mathrm{d}\mathbf{f}/\mathrm{d}\mathbf{p}$ parameters

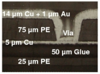
  Pede determination of local (track) refits to construct the limear equation system, then determination of global (alignment) parameters

Pixel Barrel Module

Kaptoncable (DYCONEX)

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

Layers:



HDI (HIGHTEC MC)

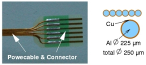
High Density Interconnect Board:

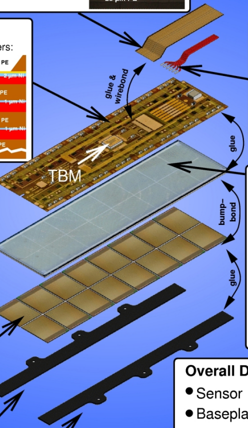
- flexible, low mass PCB
- glued to sensor
- rad hard SMD components
- TMB glued & wirebonded

Layers:

Powercable (PSI)

- lamination of cable in house
- soldered to HDI

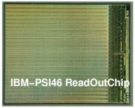




ROC's (IBM)

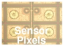
Read Out Chip IBM–PSI46:

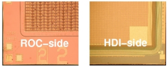
- 0.25µ DeepSubMicron process
- 52x80 pixels of 150x100 µm > 66 kpixel/module
- power consumption ~28 µW/pixel
- chips thinned to 170 µm =>reduced MB–contribution



Sensor (CIS)

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





Baseplate

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

Overall Dimensions:

- Sensor 66.6 x 18.6 mm^2
- Baseplate 65 x 26 mm^2

Weight:

- Module ~2.2 g
- Cables ~1.3 g

Power consumption:

~2 W per full module

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].

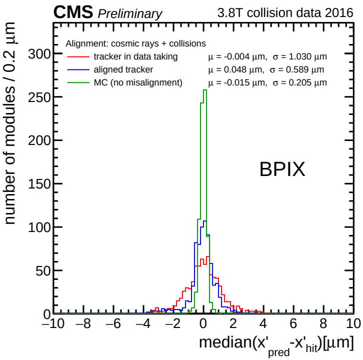
Procedure

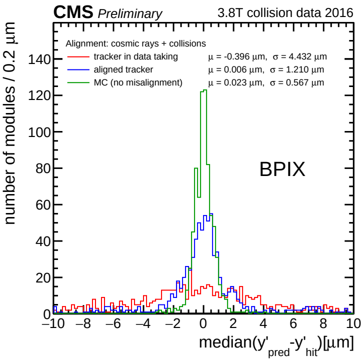
- Each track is reconstructed for different geometries.
- The hit prediction x'_{pred} for each module is obtained from all other track hits. The median of this
- The residuals $x'_{\text{pred}} - x'_{\text{hit}}$ is histogrammed for each module.
- For each high-level structure, the median of the residuals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

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

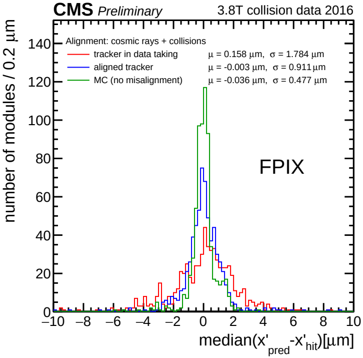
[1] In the next plots, we took care of having comparable statistics for MC and data.

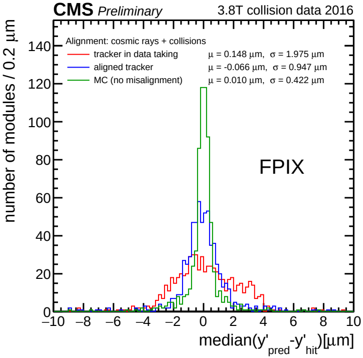
DMRs in BPIX


CMS Preliminary
3.8T collision data 2016
Alignment: cosmic rays + collisions
tracker in data taking μ = -0.004 μm, σ = 1.030 μm
aligned tracker μ = 0.048 μm, σ = 0.589 μm
MC (no misalignment) μ = -0.015 μm, σ = 0.205 μm
BPIX
number of modules / 0.2 μm
median(x'pred-x'hit)[μm]
0
50
100
150
200
250
300
−10 −8 −6 −4 −2 0 2 4 6 8 10

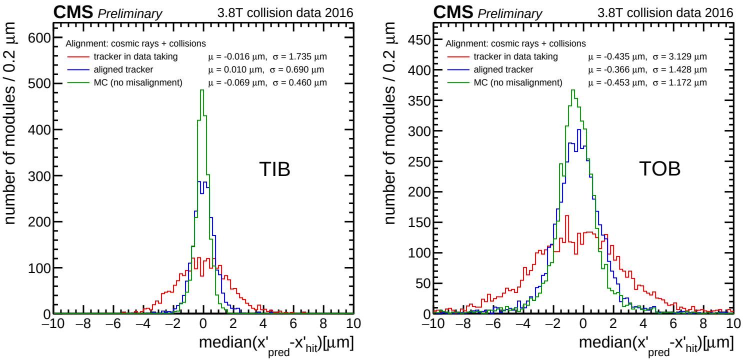

CMS Preliminary
3.8T collision data 2016
Alignment: cosmic rays + collisions
tracker in data taking μ = -0.396 μm, σ = 4.432 μm
aligned tracker μ = 0.006 μm, σ = 1.210 μm
MC (no misalignment) μ = 0.023 μm, σ = 0.567 μm
BPIX
number of modules / 0.2 μm
median(y'pred-y'hit)[μm]
0
20
40
60
80
100
120
140
−10 −8 −6 −4 −2 0 2 4 6 8 10

DMRs in FPIX

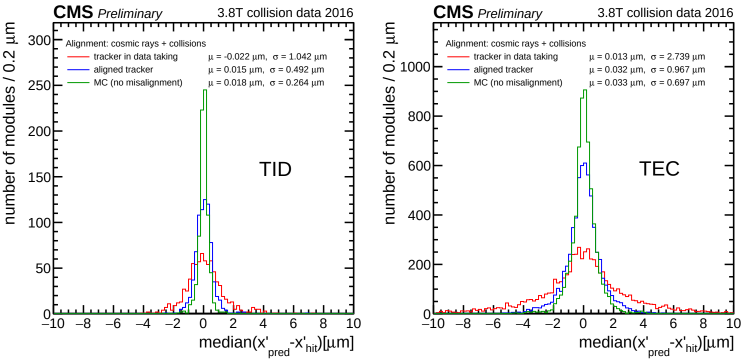

CMS Preliminary
3.8T collision data 2016
Alignment: cosmic rays + collisions
tracker in data taking μ = 0.158 μm, σ = 1.784 μm
aligned tracker μ = -0.003 μm, σ = 0.911 μm
MC (no misalignment) μ = -0.036 μm, σ = 0.477 μm
FPIX
number of modules / 0.2 μm
median(x'pred-x'hit)[μm]


CMS Preliminary
3.8T collision data 2016
Alignment: cosmic rays + collisions
tracker in data taking μ = 0.148 μm, σ = 1.975 μm
aligned tracker μ = -0.066 μm, σ = 0.947 μm
MC (no misalignment) μ = 0.010 μm, σ = 0.422 μm
FPIX
number of modules / 0.2 μm
median(y'pred-y'hit)[μm]

DMRs in TIB and TOB



DMRs in TIB and TOB



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

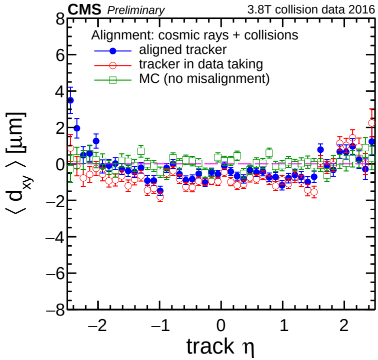
- We consider one given track from a given vertex.
- The vertex is refitted without the track under scrutiny.
- The longitudinal and transversal projections of the impact parameter $< d_{xy} >$ and $< d_z >$ of the track are computed and plotted as a function of the track η and ϕ.

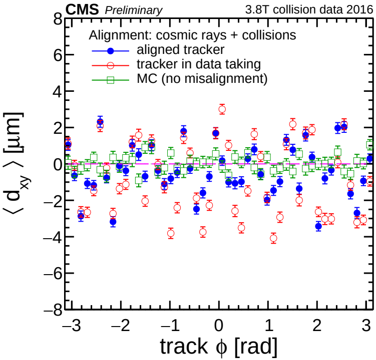
Biases

Random misalignments increase the spread.

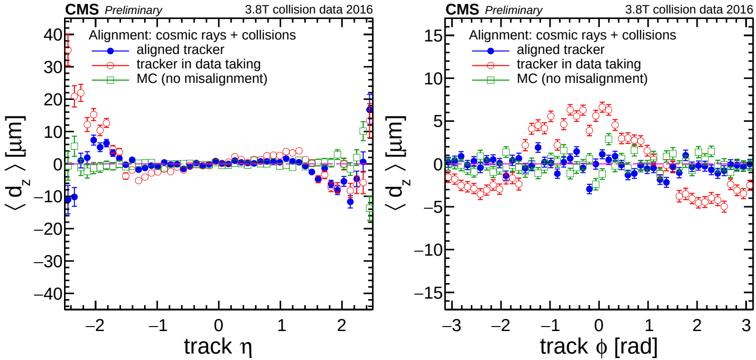
Systematic misalignments biase the mean (pattern depend on misalignment).

Primary-vertex validation
Transversal impact parameter





Primary-vertex validation
Longitundial impact parameter



$Z \to \mu\mu$ 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

- $p_{\mathrm{T}} > 20\,\mathrm{GeV}/c$
- $|\eta| < 2.4$
- $80 < M_{\mu\mu} < 120\,\mathrm{GeV}/c^2$

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.

$Z \to \mu\mu$ validation

Procedure

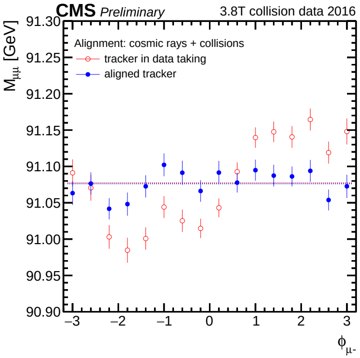
- The Z-boson mass is reconstructed with a Voigtan function[2] with fixed decay width for the Breit-Wigner component.
- The background is reconstructed with a exponential function.
- The mass is then estimated from the mean of the Voigtian function as a function of different variables:
  - the azimuthal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

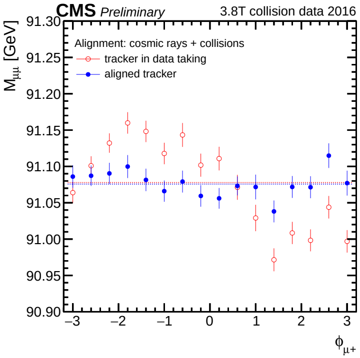
Fit of the mass

Ideally, the mass should not depend on any of these variable. 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

$Z \to \mu\mu$ validation

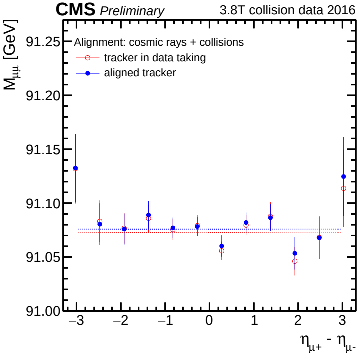


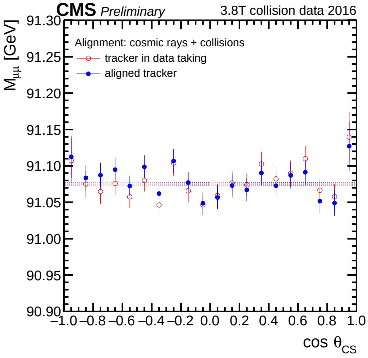


	χ^2/ndf	p-value
tracker in data taking	15.99	< 0.01
aligned tracker	1.39	0.14

	χ^2/ndf	p-value
tracker in data taking	15.76	< 0.01
aligned tracker	1.33	0.17

$Z \to \mu\mu$ validation





	χ^2/ndf	p-value
tracker in data taking	1.31	0.22
aligned tracker	0.80	0.61

	χ^2/ndf	p-value
tracker in data taking	1.43	< 0.09
aligned tracker	1.25	0.21

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 ($\mathcal{L} = 16.4\,\mathrm{fb}^{-1}$).

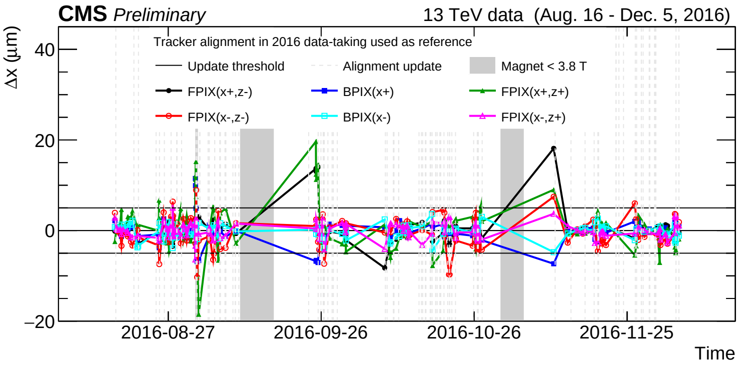
We show in the next slides the variations of the corrections to the position and orientation of the high-level structures over time:

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

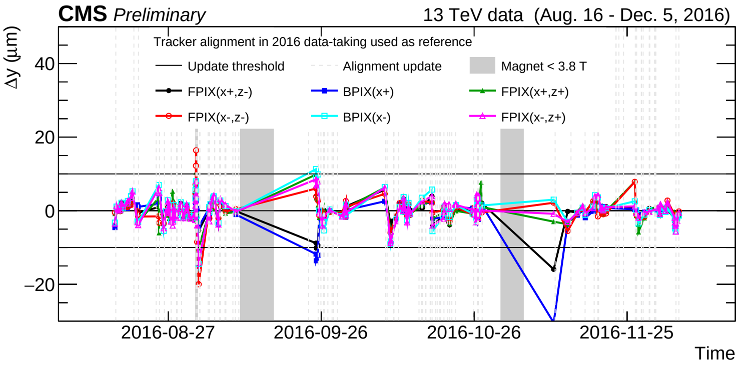
  Alignment updates vertical dashed lines
  Update threshold horizontal continuous lines
- One can clearly correlate movements in the pixel with magnet cycles (grey bands)
  - $\Delta x \lesssim 50\,\mu\mathrm{m}$
  - $\Delta y \lesssim 50\,\mu\mathrm{m}$
  - $\Delta z \lesssim 150\,\mu\mathrm{m}$

NB: At least $20k$ minimum-bias events must be used to perform the prompt calibration.

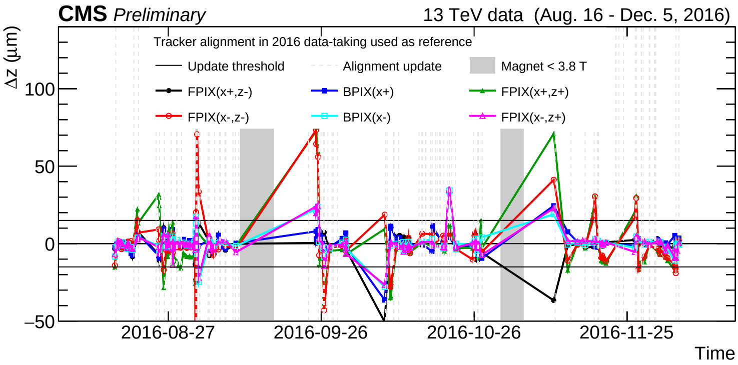
Corrections to the position in global x direction



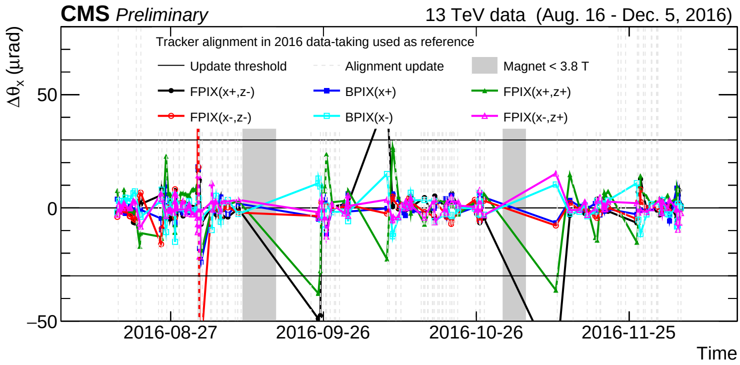
Corrections to the position in global y direction



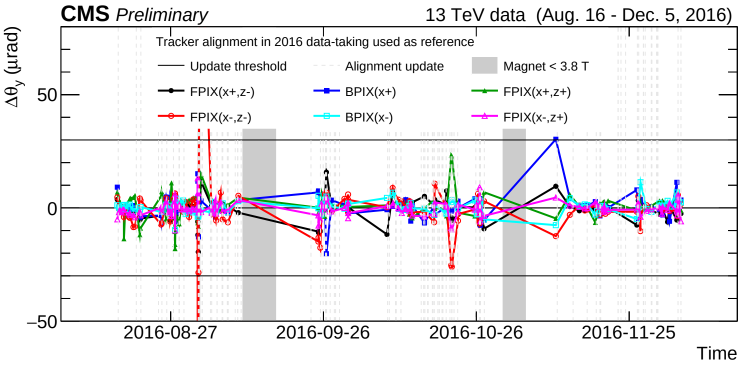
Corrections to the position in global z direction



Corrections to the orientation in global x direction



Corrections to the orientation in global y direction



Corrections to the orientation in global z direction