CMS Tracker Alignment activities during LHC Long Shutdown 2

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International Conference on High Energy Physics, Bologna, 06-13th July 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CMS tracker detector

Inner tracking system of CMS experiment

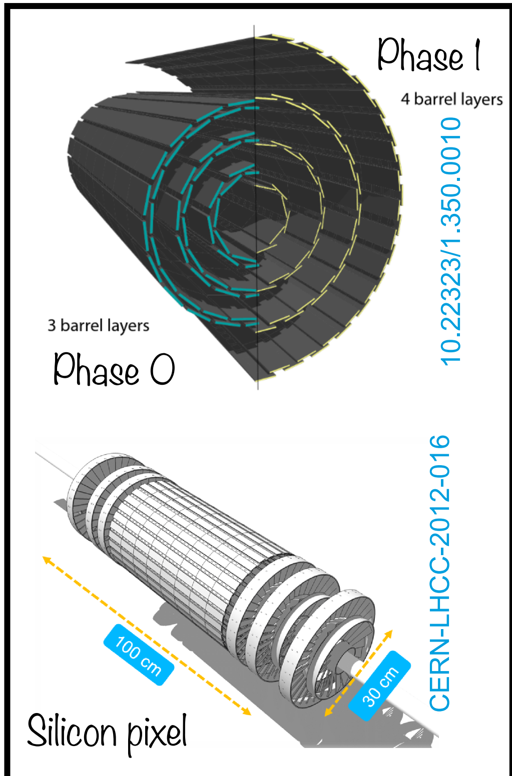
Silicon pixel detector

1440 modules until end of 2016 [ref. to Phase 0]
1856 modules after upgrade in 2017 [ref. to Phase 1]

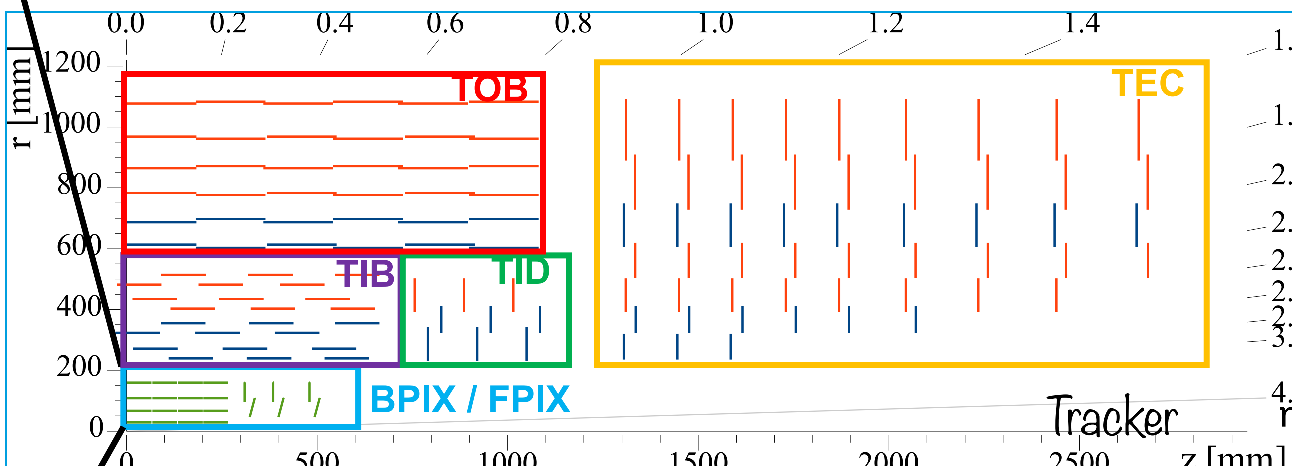
Barrel Pixel (BPIX)
Forward Pixel (FPIX)

Silicon strip detector

- **Tracker Inner Barrel (TIB)**
- **Tracker Outer Barrel (TOB)**
- **Tracker Inner Disk (TID)**
- **Tracker Endcap (TEC)**



20 292 modules



- Organized in barrel and endcaps
- Hierarchical structure ---> e.g. barrels -> half barrels -> layers -> modules
  - (details on backup)

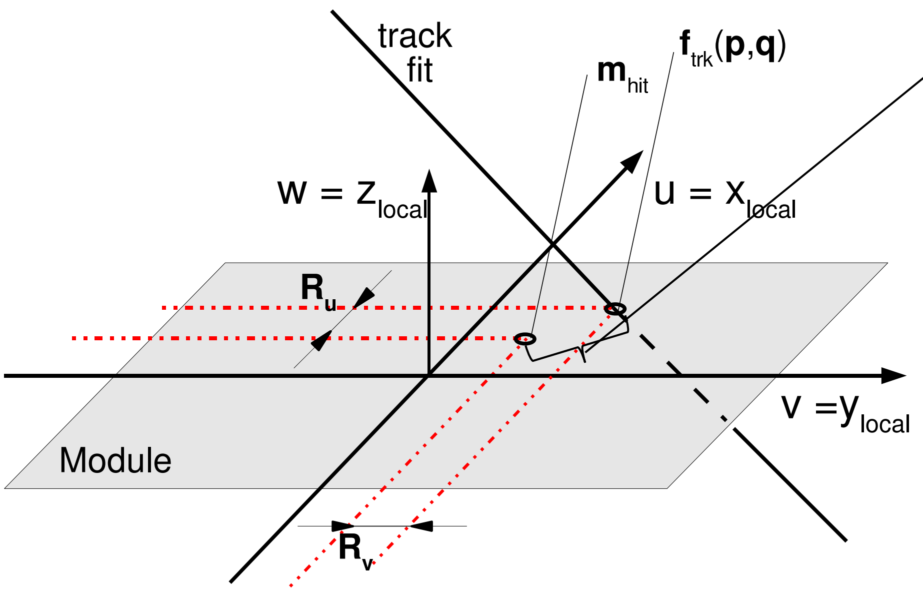
Track-based alignment

> Each time a part of the tracker is moved/removed ---> re-installation precision of mechanical alignment $\mathcal{O}(100\ \mu\mathrm{m})$

From installation precision to precision for physics analysis: **track based alignment**

Goal: determine with a precision down to a few μm the position of all 15 148 (× 6 dof) silicon modules of the tracker

> Minimisation of sum of squares of normalised track-hit residuals



CERN-THESIS-2011-435

$$r_{ij}\left(\mathbf{p},\ \mathbf{q}_j\right) = m_{ij} - f_{ij}\left(\mathbf{p}, \mathbf{q}_j\right)$$

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

p: global alignment parameters (module position & orientation)

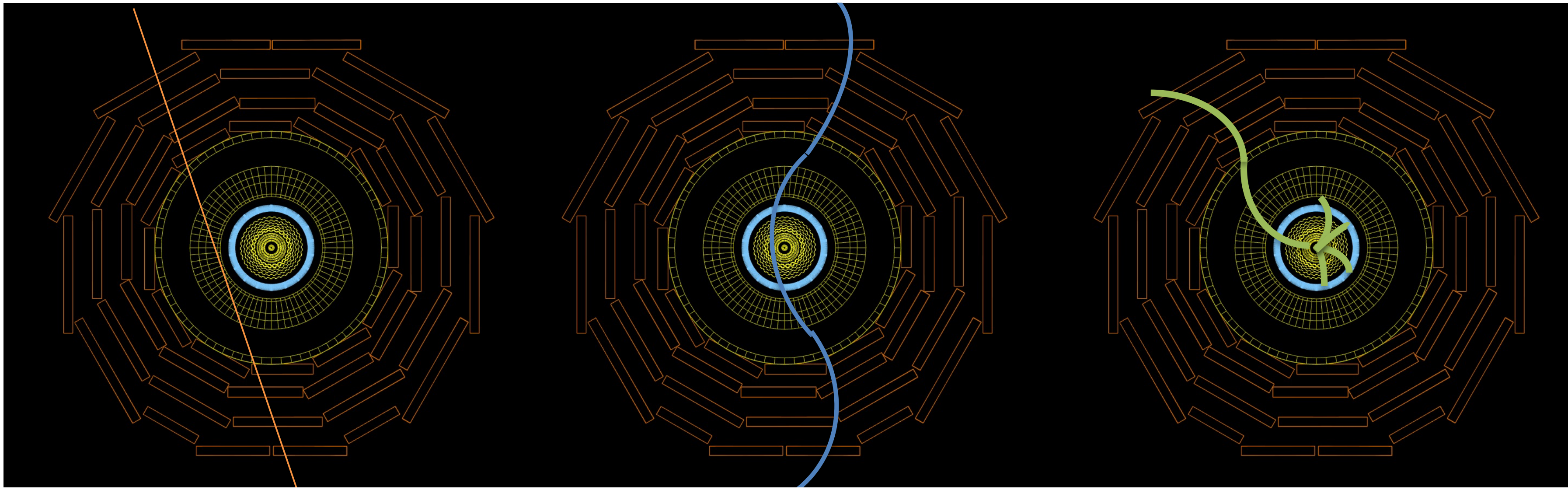
$\mathbf{q}_j$: local track parameters (e.g. parameters related to track curvature and deflection angles due to multiple scattering)

$m_{ij} \pm \sigma_{ij}$: measured hit position

f_{ij}: predicted hit position

Detector Commissioning during LHC Long Shutdown 2

- The CMS Collaboration has conducted in 2021 and 2022 a set of data-taking exercises



Cosmic Run at 0 Tesla (CRUZET)	**Cosmic Run at 3.8 Tesla (CRAFT)**	**Splashes, (stable) pilot beams**
(July-August 2021) First alignment after detector was opened for maintenance and BPIX L1 replacement	(October-November 2021) First alignment with 3.8T magnetic field of the Long Shutdown 2 (April-May 2022)	(November 2021) First alignment with collisions data of the Long Shutdown 2 ($\sqrt{s} = 900\ GeV$) (May-July 2022)

- Tracker operated together with all other subdetectors

Tracker alignment strategy

> **Automated alignment**

- continuous online monitoring of high-level structure movements of pixel detector
- geometry automatically corrected if alignment corrections exceed certain thresholds

> **Offline Alignment**

- track-based alignment run offline to polish automated alignment

Tracker geometry obtained from fit compared to starting geometry

- identify unusual movements or systematic distortions artificially introduced by the fit
- first indication that alignment fit performs well

> **Validation of the obtained geometry**

- check improvement of post-alignment track-hits residuals
- check impact of new alignment constants in physics observables

Alignment effort in 2021

> Alignment with 0T cosmic rays (green):

- geometry derived using 2.9M cosmic ray tracks recorded at 0T magnetic field
- pixel detector and tracker outer barrel aligned at level of single modules
- alignment in rest of strip partitions performed at level of half-barrels and half-cylinders

> Alignment with 3.8T cosmic rays (blue):

- geometry derived using 765k cosmic ray tracks recorded at 3.8T magnetic field
- barrel pixel detector aligned at level of single modules
- alignment in forward pixel detector and strip partitions performed at level of half-barrels and half-cylinders

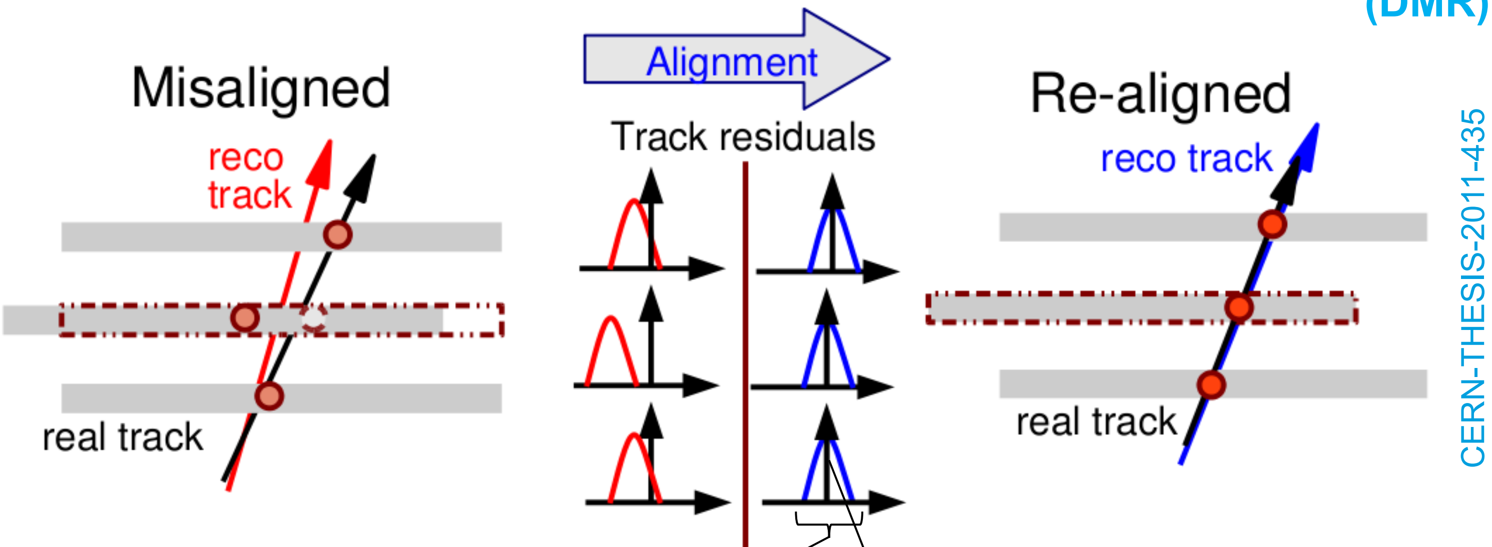
> Alignment with cosmic rays and collisions (red):

- geometry derived using 3.6M cosmic ray tracks and 255.2M collision tracks recorded during pp collision runs at $\sqrt{s} = 900$ GeV
- pixel detector and strip partitions aligned at level of single modules

Monitoring tracking performance: Distribution of median residuals

> obtain track-hit residuals from all the hits in a module -> compute median of track hit-residual values -> repeat for each module

> obtain distribution: **number of modules vs median** -> **Distribution of Median Residuals (DMR)**

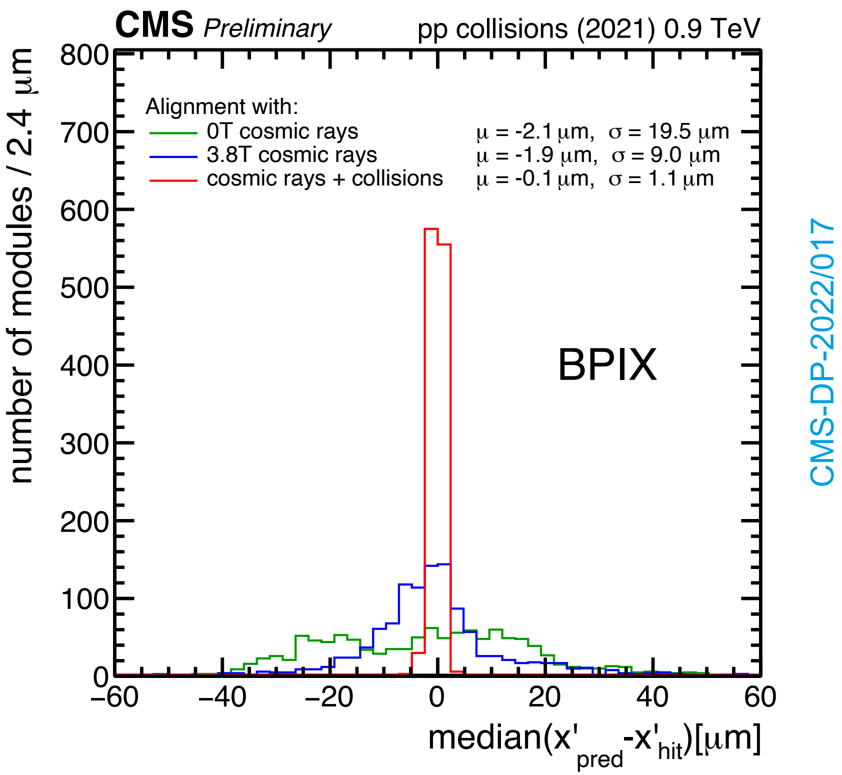


width:
measure of local precision of the alignment calibration

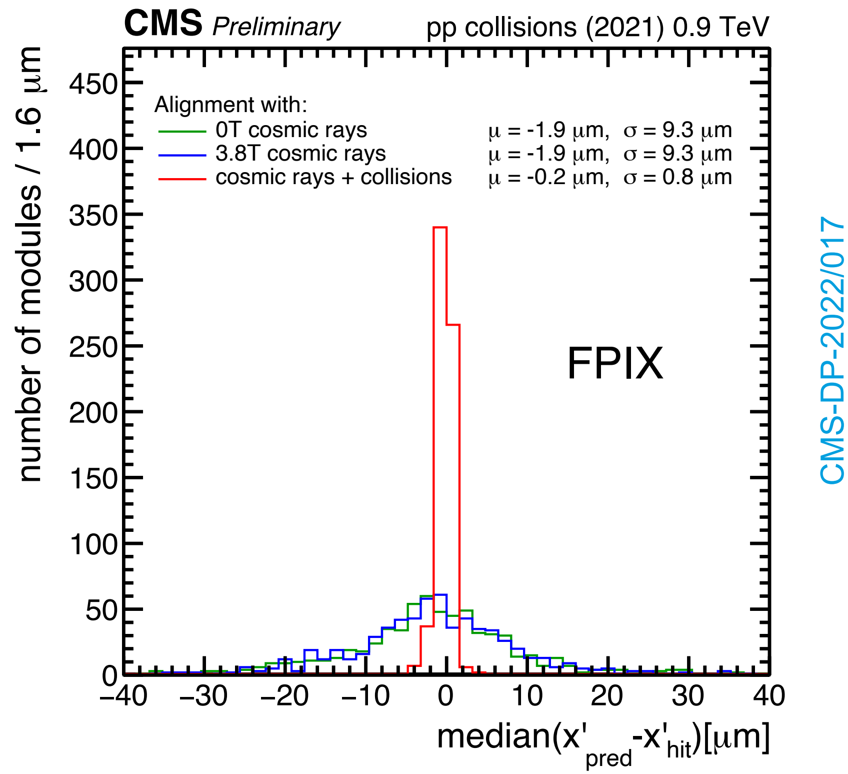
mean:
deviations from zero indicate possible bias due to change of conditions (e.g., temperature and magnetic field)

Distribution of median residuals

Barrel Pixel detector

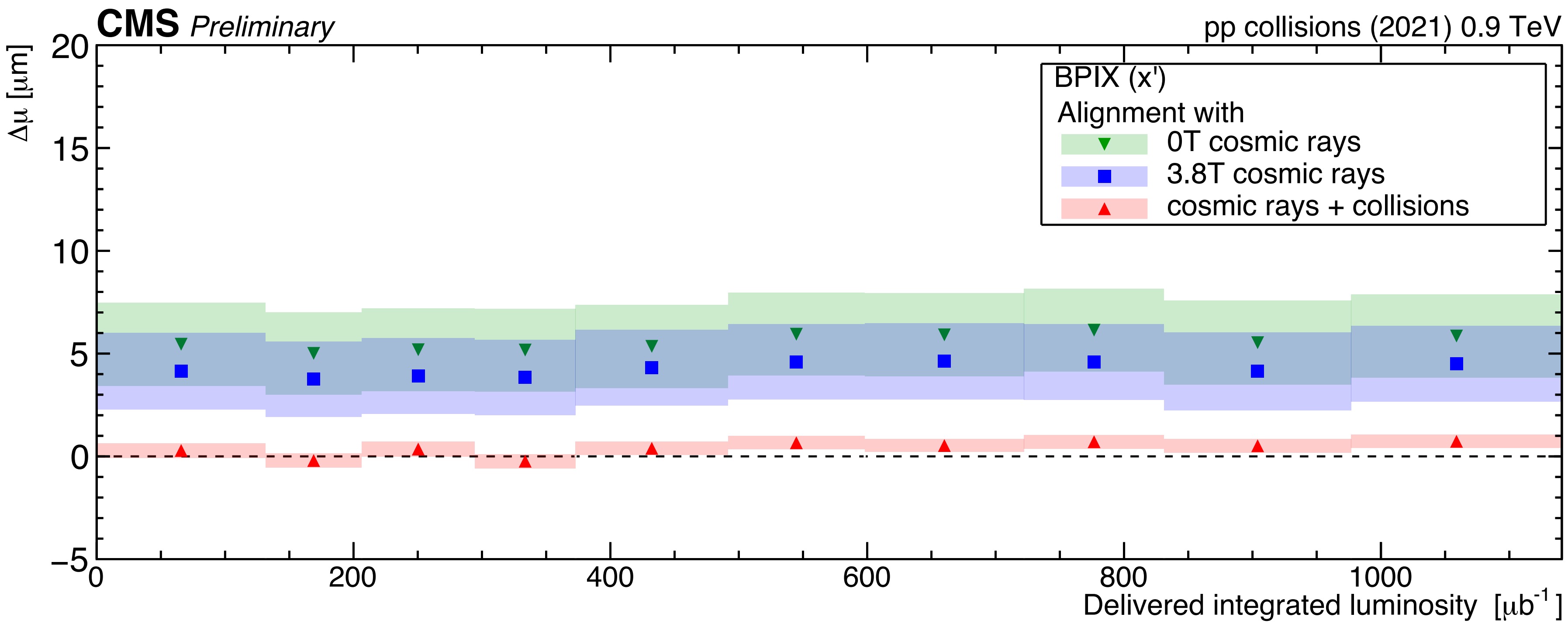


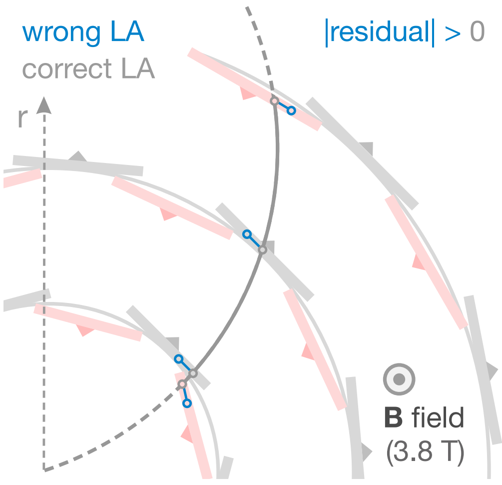
Forward Pixel detector



- Distribution of median of track-hit residuals for the modules local x-direction
- Position of pixel detector known to be very sensitive to change of conditions
- Quoted means μ and standard deviations σ -> parameters of a Gaussian fit to the distributions

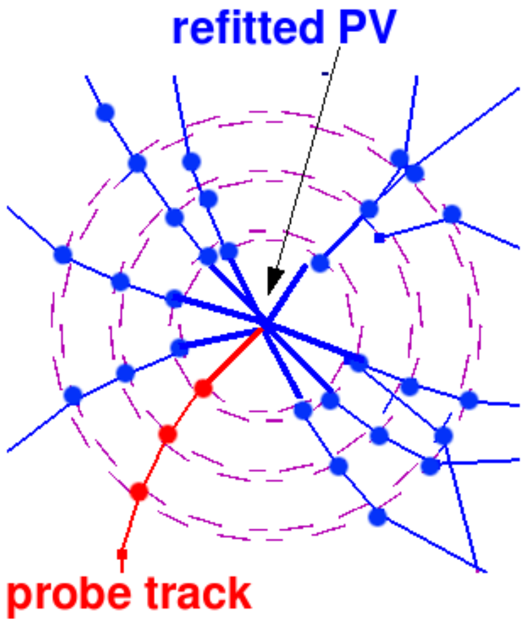
Distribution of median residuals: time dependence

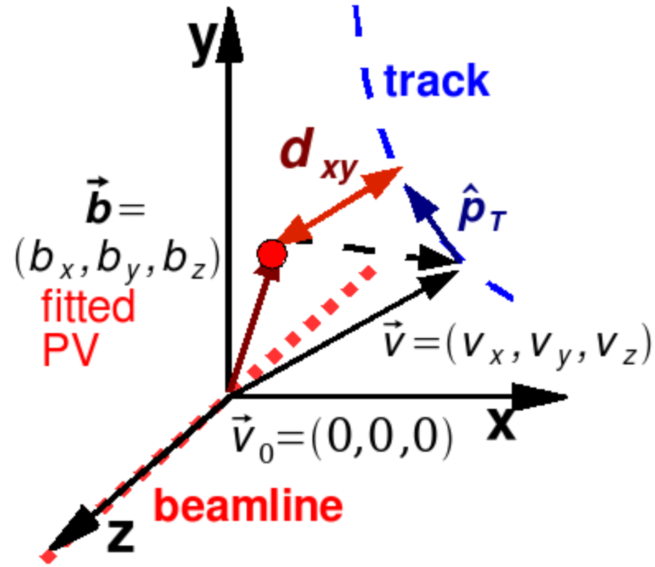




- Sign of Lorentz angle shift: -> depends on orientation of electric field -> shift in hit position in modules pointing inward opposite to shift in outward-pointing modules
- In pixel barrel region -> distribution of median residuals obtained separately for modules with electric field pointing radially inwards or outwards
- Difference of their mean values $\Delta\mu$ in local-x (x') direction in barrel pixel detector -> index of goodness in recovering from Lorentz angle effects

Vertexing performance: Track-vertex impact parameter





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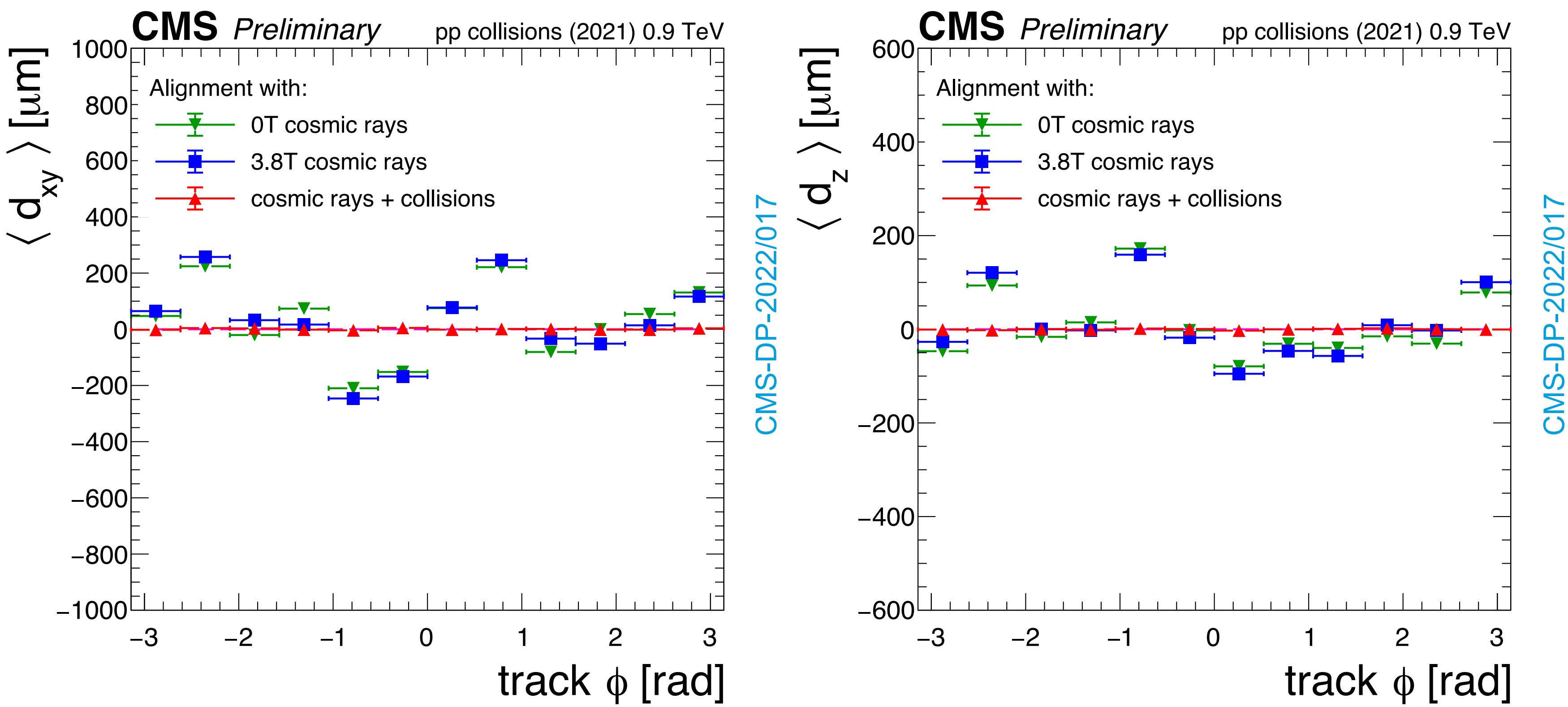
> distance between track and vertex reconstructed without track under scrutiny (unbiased track-vertex residual)

> evaluate performance of alignment in pixel detector

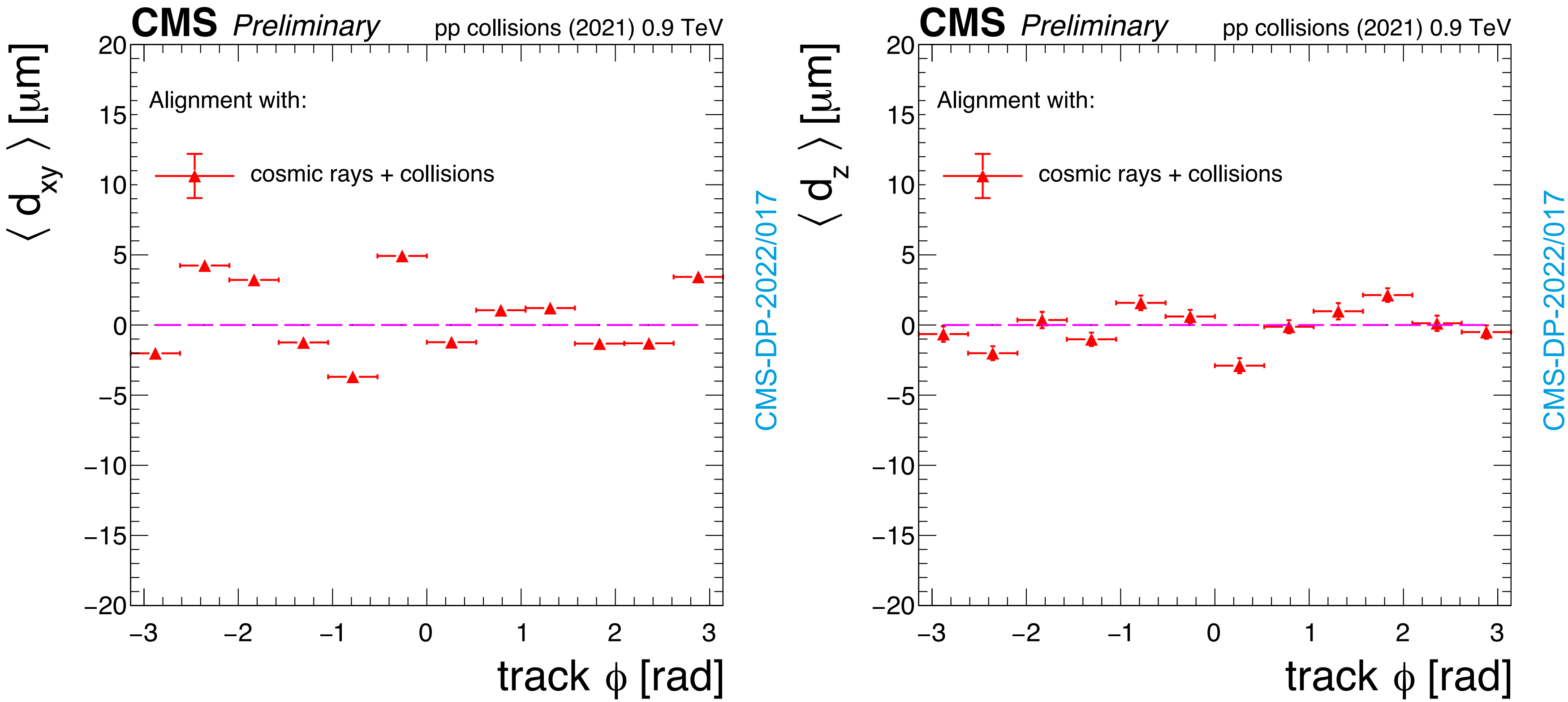
> random misalignment of modules may affect resolution of unbiased track-vertex residuals

Track-vertex impact parameter



- Distance in transverse (d_{xy}) and longitudinal (d_z) plane of tracks at their point of closest approach to a refit unbiased primary vertex studied in bins of azimuthal angle ϕ using a sample of collision events collected at $\sqrt{s} = 900$ GeV
- Improvement visible on alignment with cosmic and collision tracks (red) over alignments derived by CMS using cosmic tracks only from cosmic data taking at 0T (green) and 3.8T (blue)

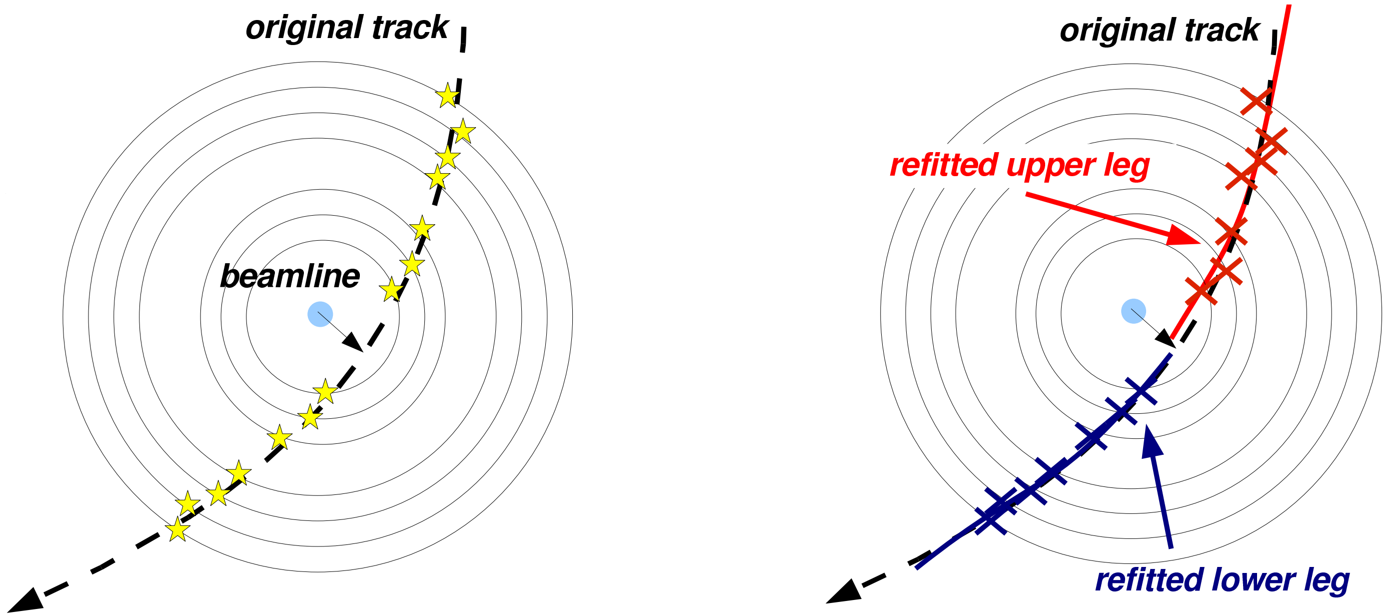
Track-vertex impact parameter



- Distance in transverse (d_{xy}) and longitudinal (d_z) plane of tracks at their point of closest approach to a refit unbiased primary vertex studied in bins of azimuthal angle ϕ using a sample of collision events collected at $\sqrt{s} = 900$ GeV

- Vertexing performance of alignment with cosmic and collision tracks

Muon track split validation



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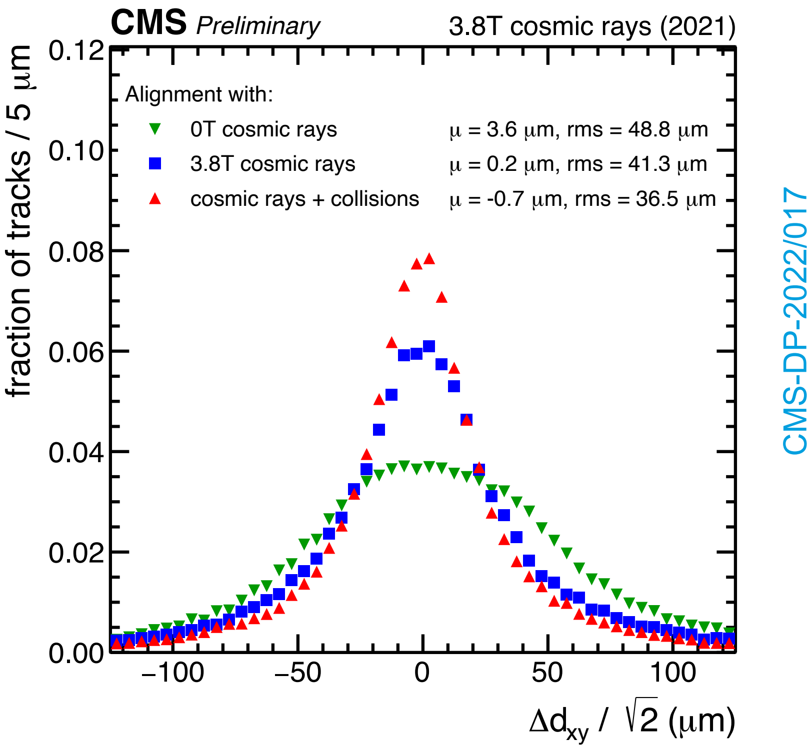
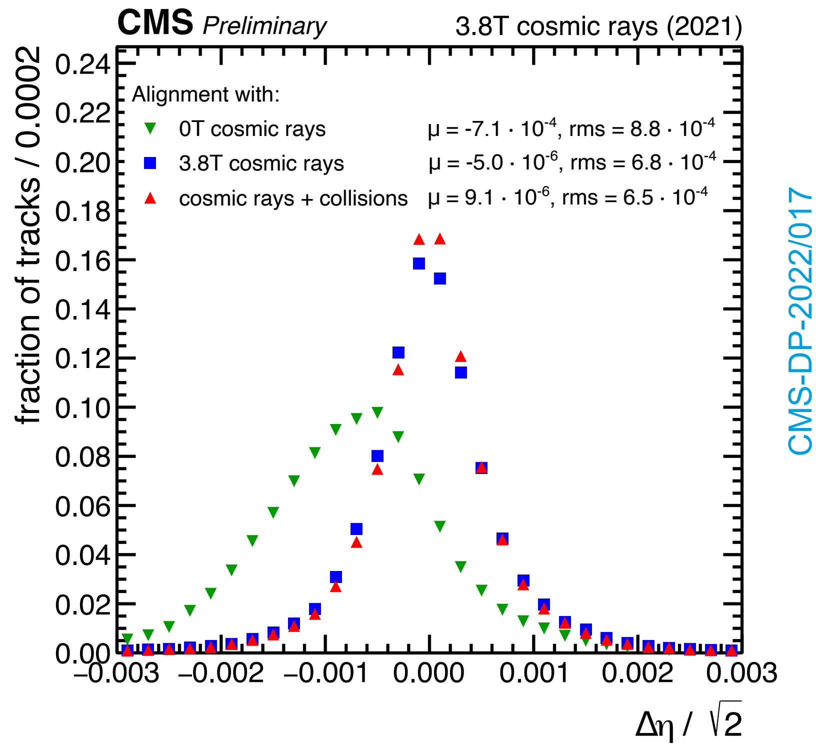
> Create two individual track candidates from each cosmic track by splitting the cosmic tracks at their point of closest approach to the interaction region

> Compare track parameters of the two track candidates
(e.g., difference of transverse and longitudinal impact parameters, pseudorapidity, and azimuthal angle)

> Method sensitive to off-centering of barrel layers and endcap rings

Muon track split validation





- Difference of transverse impact parameter (d_{xy}, left) and pseudo rapidity ($\Delta\eta$, right) between two halves of cosmic tracks split at their point of closest approach to the interaction region

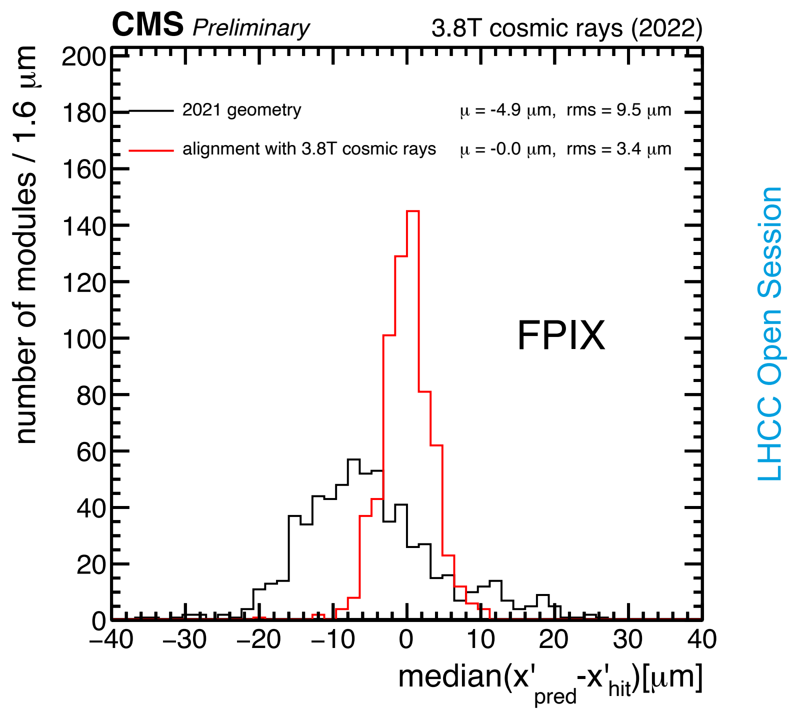
- Improvement visible on alignment with cosmic and collision tracks (red) over alignments derived by CMS using cosmic tracks only from cosmic data taking at 0T (green) and 3.8T (blue)

Alignment effort in 2022

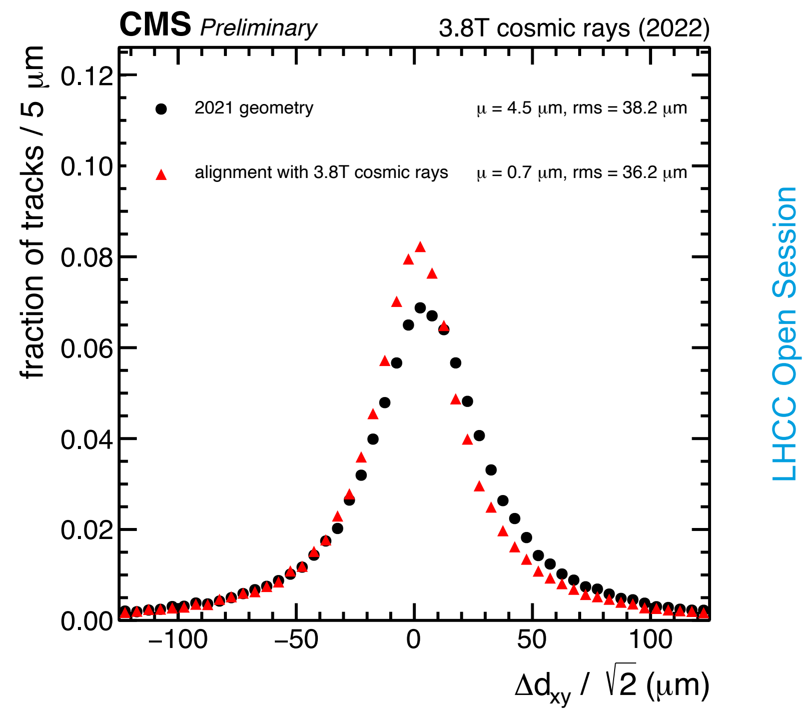
> 2021 geometry (black) -> start geometry for 2022 data taking

> Alignment with 3.8T cosmic rays (red):

- geometry derived using 6.3M cosmic ray tracks recorded at 3.8T magnetic field
- pixel detector aligned at level of single modules
- alignment in strip partitions performed at level of half-barrels and half-cylinders



- Distribution of median of track-hit residuals for the modules local x-direction in the forward pixel detector



- Difference of transverse impact parameter

Summary

Fundamentals of track based alignment method

Overview of CMS tracker alignment activities during LHC Long Shutdown 2

> Alignment effort on the derivation of first alignment after pixel reinstallation and alignment conditions for collisions data taking was summarised

> Set of validations showing improved performance of physics observables after the alignment was presented

- Tracking performance (Distribution of median residuals, including time dependence)
- Vertexing performance (Track-vertex impact parameter)
- Monitoring of systematic distortions (Muon Track split validation)

➔ **Excellent start in terms of alignment precision prior to first collisions in Run 3 at unprecedented center of mass energy $\sqrt{s} = 13.6\ TeV$!**

Looking forward the alignment challenges ahead during Run 3

Thank you!

Contact

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Backup

> Additional material

References

> Tracker alignment performance in 2021

CMS-DP-2022/017

> CMS Tracker Alignment Preliminary Results for 2022 startup with cosmic ray data

LHCC open session

> CMS Tracker Alignment Preliminary Results for 2021 startup with 900 GeV collision data

LHCC open session

> Tracker Alignment results with 2021 cosmic ray data

CMS-DP-2021-025

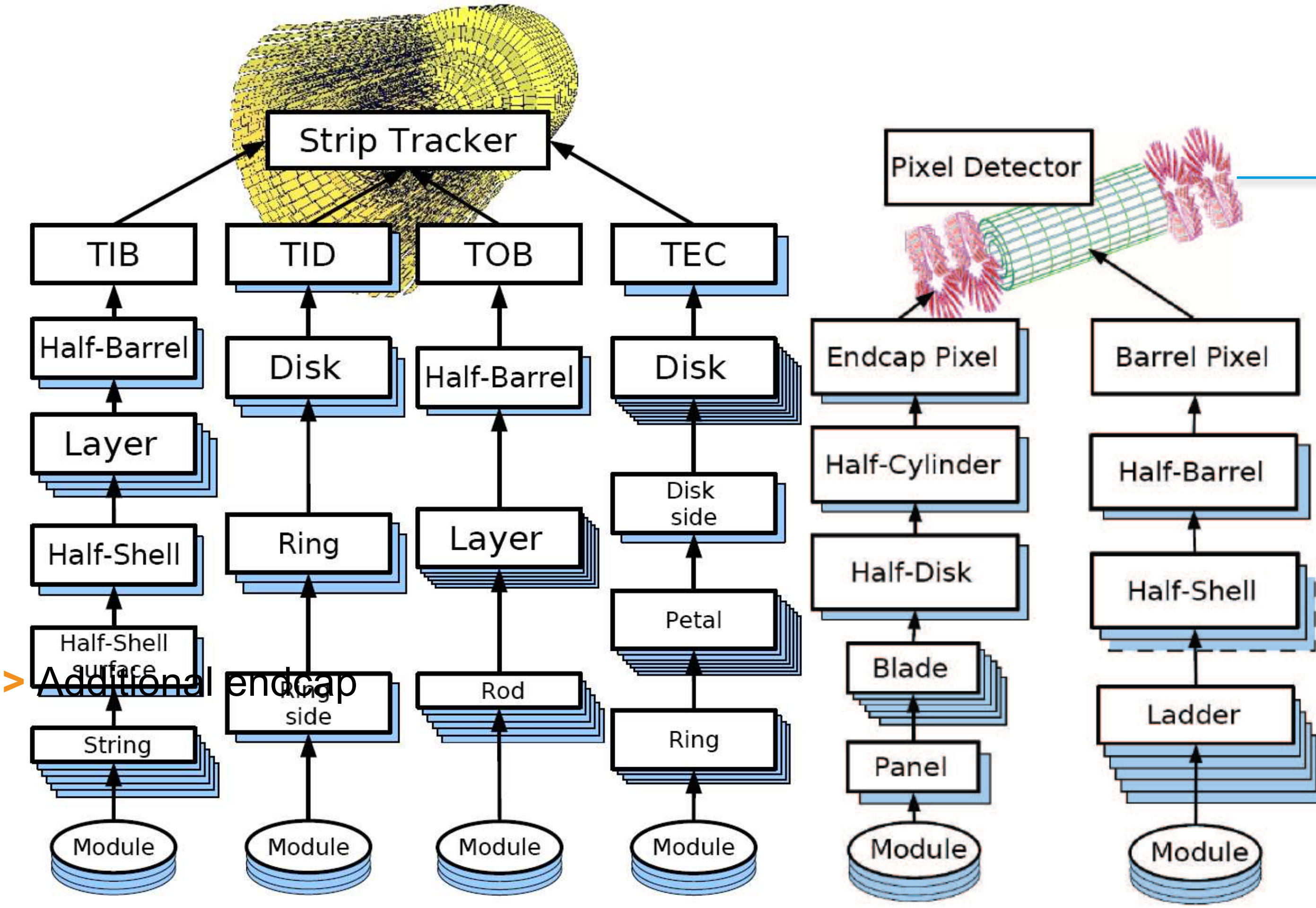
> CMS Collaboration "Strategies and performance of the CMS silicon tracker alignment during LHC Run 2" 2022 Nucl. Instrum. Meth. A 1037 166795

doi:10.1016/j.nima.2022.166795

> CMS Collaboration "Alignment of the CMS tracker with LHC and cosmic ray data" 2014 JINST 9 P06009

doi:10.1088/1748-0221/9/06/P06009

Hierarchical structure of the CMS Tracker



> Additional endcap

10.1088/1748-0221/4/07/T07001

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> Phase 0 pixel detector

For Phase 1: additional layer and additional endcap on each side)

> If number of tracks is insufficient for determination of alignment parameters at module level (i.e., for each module), procedure can be restricted to much smaller set of these substructure parameters

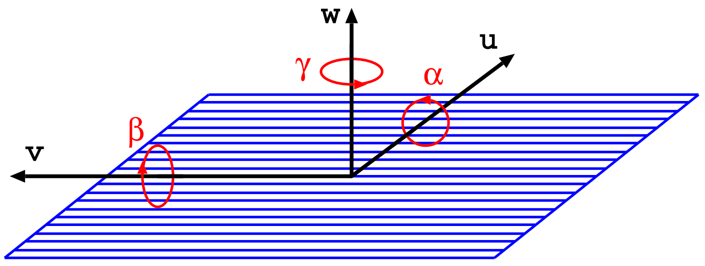
Track reconstruction: local and global reconstruction

> challenging task due to the high track multiplicity

Performed in two successive steps:

Local reconstruction (use of detector readout information to reconstruct local hit candidates)

- Digitalisation of signals
- (if below certain thresholds, signals are considered noise and discarded)
- Signals in neighbouring channels are clustered
- **Output**: Cluster positions and their uncertainties calculated and defined in the **local coordinate system** of each sensor plane



10.1088/1748-0221/9/06/P06009

Global reconstruction (combine hits to form tracks)

- Taking as input the result of the local reconstruction, hits are combined to form tracks with an iterative sequence of 4 steps:

Seed generation **Track finding** **Track fitting** **Track selection**

From track reconstruction to tracker alignment

> **tracker geometry:** set of parameters that describe the geometrical properties of the tracker modules

> **alignment:** correction of position, orientation, and curvature of the tracker modules

Track fitting step of global track reconstruction:

> repeated as part of tracker alignment workflow for validation new of alignment constants different from the ones used in central reconstruction

> output of track fitting ---> input to track selection (final step of track reconstruction)

Alignment -> direct influence on:

- Tracking efficiency
- Fake rate

Alignment algorithms

> χ^2 minimization problem requires inversion of large matrices

e.g., given N modules with six degrees of freedom (three rotation and three translations)

to solve the resulting system of equations requires inversion of huge 6N X 6N matrix

> CMS tracker ---> ~ $\mathcal{O}(20k)$ modules ---> $20\text{k} \times 6 = \mathcal{O}(120k)$ to be determined!

> Two independent implementations of track-based alignment used in CMS:

MillePede

- Performs global fit including all correlations of global alignment parameters and local track parameters

HipPy

- Position and orientation of each sensor determined independently
- Multiple iterations to solve correlations between sensor parameters
- Small matrix inversion on each iteration

} Complementary approaches

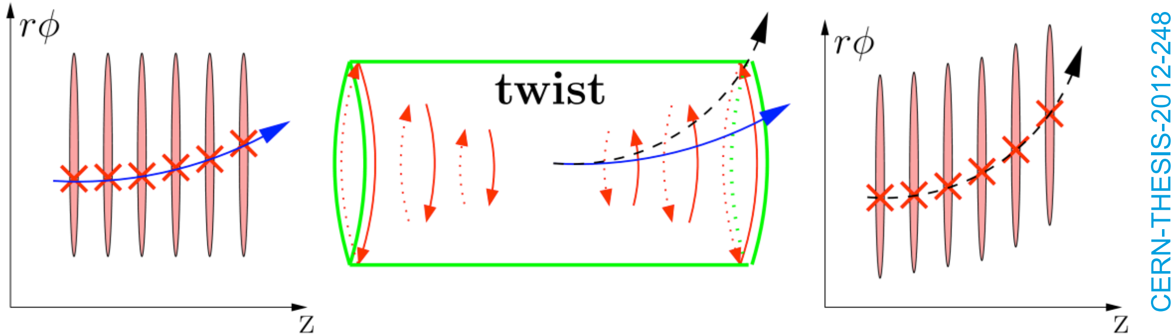
> Output of the alignment algorithms: $\mathcal{O}(120k)$ parameters which need to be validated, other challenges: **Weak modes** and **Time variations**

Weak modes

> alignment algorithm aims to find real detector geometry by minimizing the χ^2 of track-hit residuals, but often modules can be moved coherently ending with very different geometries and identical χ^2

> **weak modes:** Linear combinations of parameters that leave invariant the track-hit residuals and thus the χ^2

> Cylindrical geometry of CMS tracker results in a set of weak modes (e.g. twist)



> **Solution:**

To include in the alignment procedure a variety of tracks whose χ^2 is sensitive to them, e.g, tracks which:

- cross the detector at different angles
- cover full active detector area
- relate different detector components

[resonance tracks (e.g. Z $\rightarrow$ μμ events), cosmic ray muons, and beam halo tracks]

Time variations

> **Magnet cycles**

Magnetic field switched on and off for maintenance reasons

movements of large mechanical structures but modules's sensors remain stable relative to their large structure

> **Temperature variations**

Cooling of detector after switching it on and off

movements of not only large mechanical structures but of independent modules as well

> **Ageing of the modules**

High radiation environment

change of Lorentz drift inside the modules (details on next slide)

Time variations can be considered by means of a **differential alignment**:

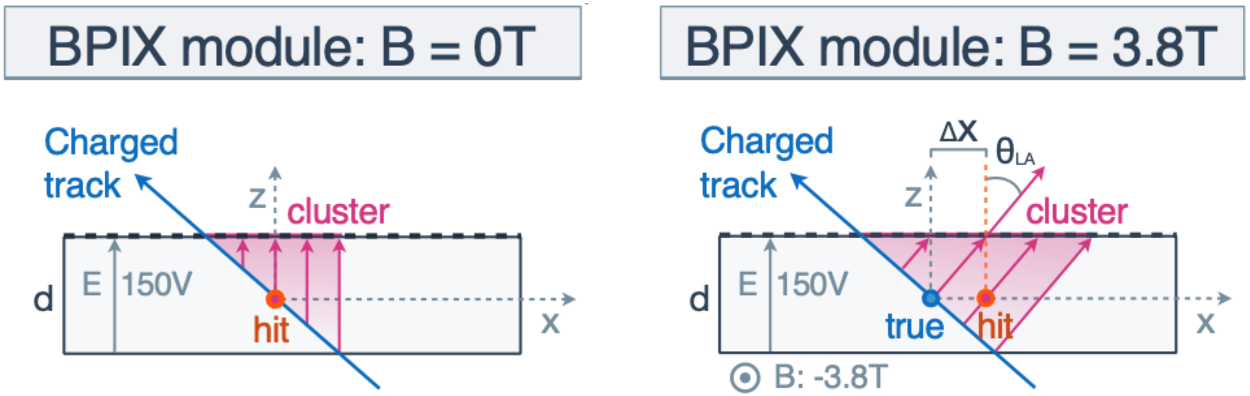
> introduce time dependence of the position of the high-level structures (HLS) in the alignment fit by means of intervals of validity (IOV)

> relative position of modules with respect to their corresponding HLS considered not to have time dependence

Run 3 prospects

> Integrated luminosity of Run 1 + Run 2 expected to be doubled

stronger variations of Lorentz drift due to larger irradiation doses



10.22323/1.180.0074

> Alignment procedure sensitive to Lorentz drift changes

> High enough alignment granularity

- inward and outward pointing modules free to move separately
- bias produced by Lorentz angle (θ_{LA}) miscalibration can be absorbed

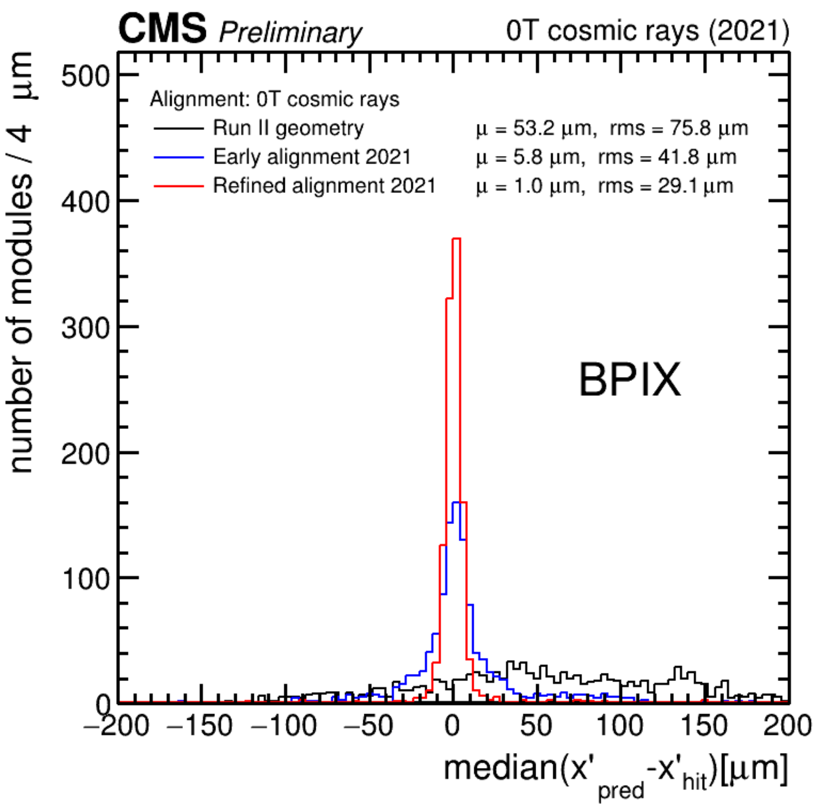
Distribution of median residuals

CRUZET (2021)

- Early alignment: 120k tracks, align half-barrels in BPIX and half-cylinders in FPIX
- Refined alignment: 1.5M tracks, align ladders in BPIX and half-cylinders in FPIX

CRAFT (2021)

- Alignment with 3.8T cosmic rays: 765k tracks, align BPIX at module level and half cylinders in FPIX
- Alignment with 3.8T cosmic rays + collisions: 22M tracks, align BPIX and FPIX at module level



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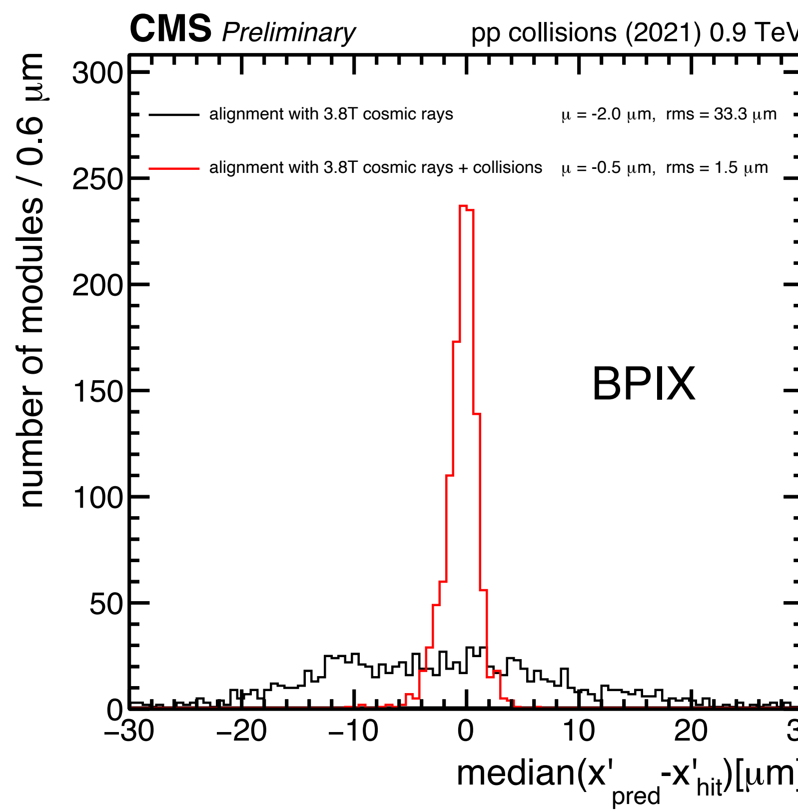

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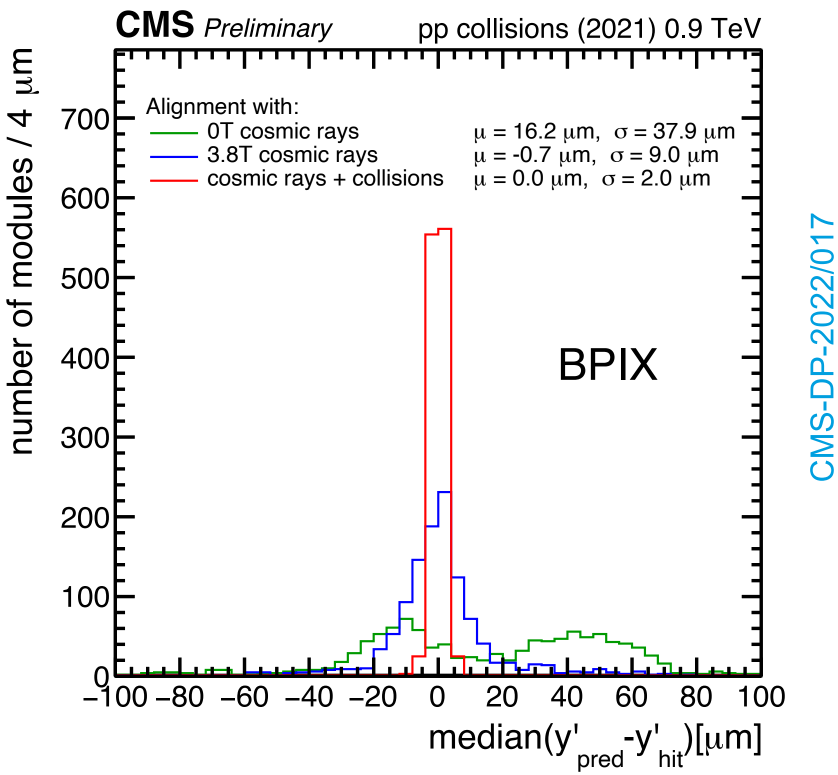
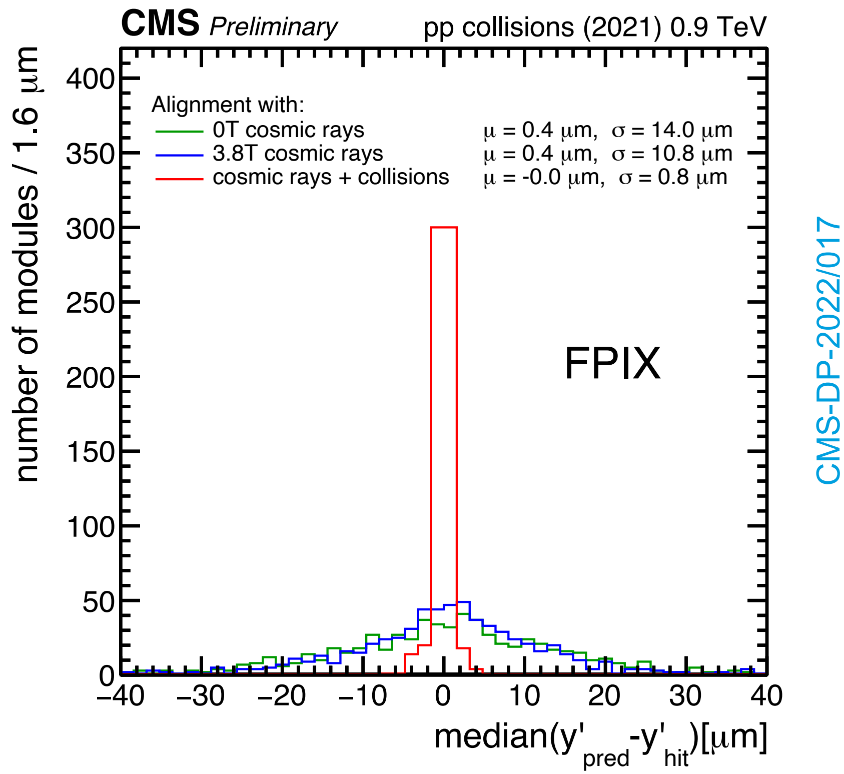
Distribution of median of track-hit residuals for the modules local x-direction

Distribution of median residuals

Barrel Pixel detector



Forward Pixel detector

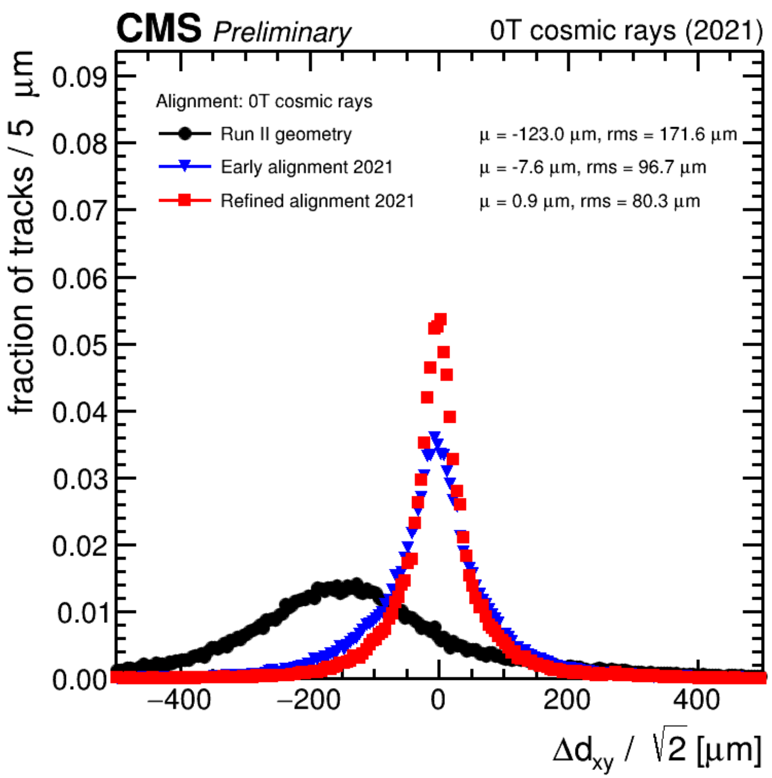


- Distribution of median of track-hit residuals for the modules local y-direction
- Position of pixel detector known to be very sensitive to change of conditions
- Quoted means μ and standard deviations σ -> parameters of a Gaussian fit to the distributions

Distribution of median residuals

CRUZET (2021)

- Early alignment: 120k tracks, align half-barrels in BPIX and half-cylinders in FPIX
- Refined alignment: 1.5M tracks, align ladders in BPIX and half-cylinders in FPIX



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CRAFT (2021)

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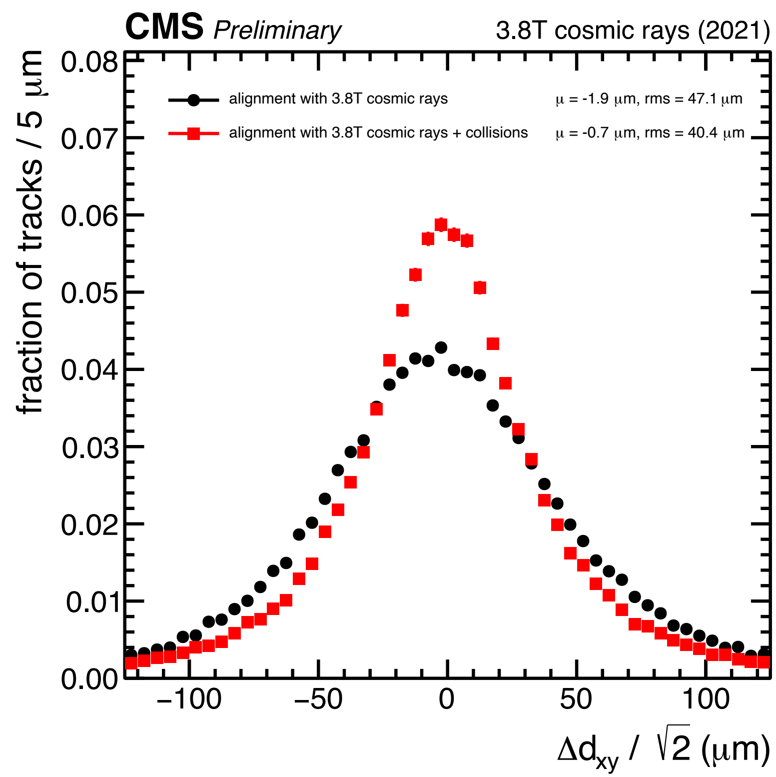

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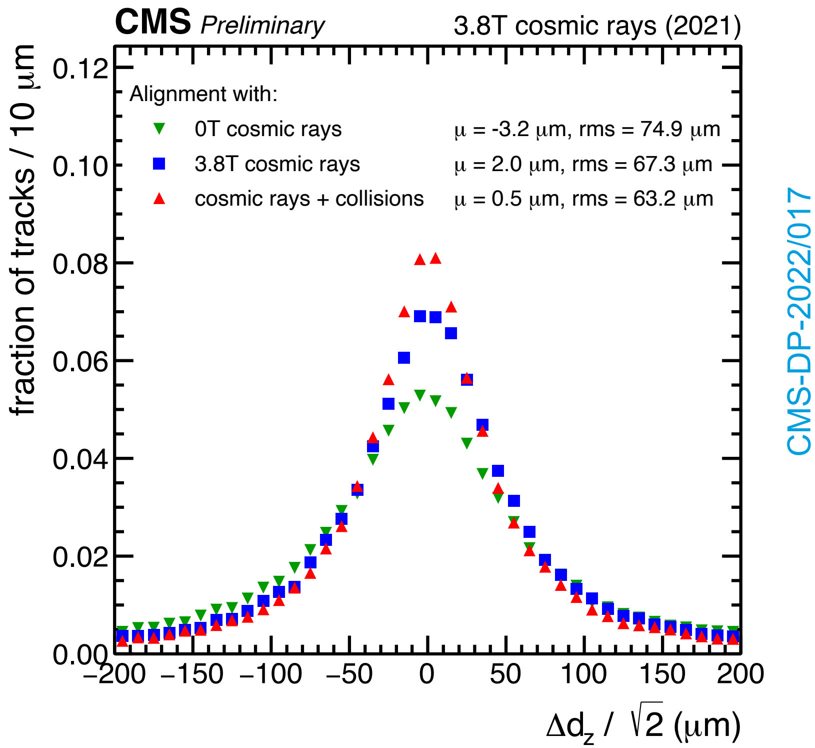
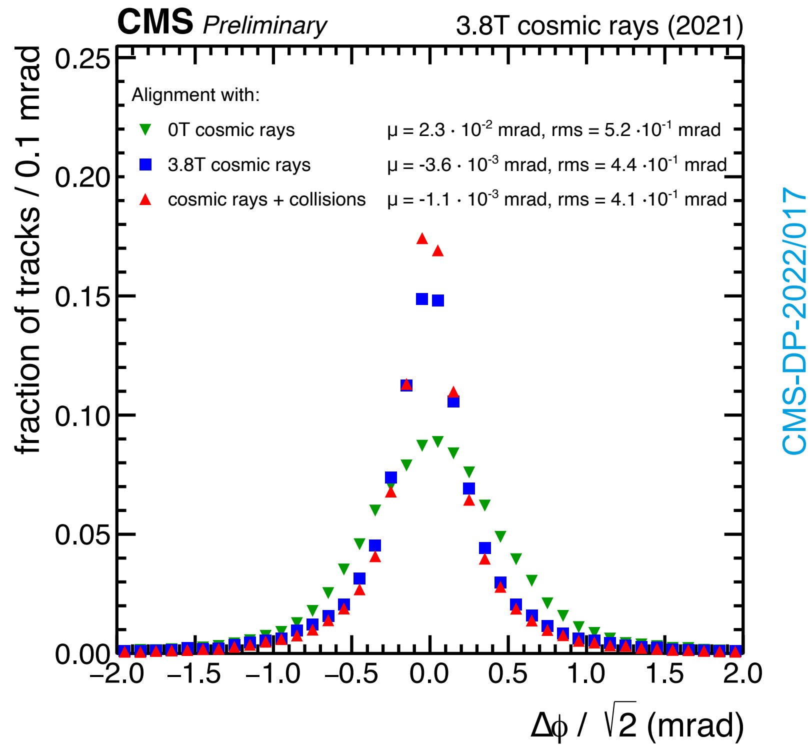
Difference of transverse impact parameter (d_{xy}) between two halves of cosmic tracks split at their point of closest approach to the interaction region

Muon track split validation





- Difference of longitudinal impact parameter (d_z, left) and azimuthal angle ($\Delta\phi$, right) between two halves of cosmic tracks split at their point of closest approach to the interaction region
- Improvement visible on alignment with cosmic and collision tracks (red) over alignments derived by CMS using cosmic tracks only from cosmic data taking at 0T (green) and 3.8T (blue)