CMS Tracker Alignment: Legacy results from LHC Run-II and Run-III prospects

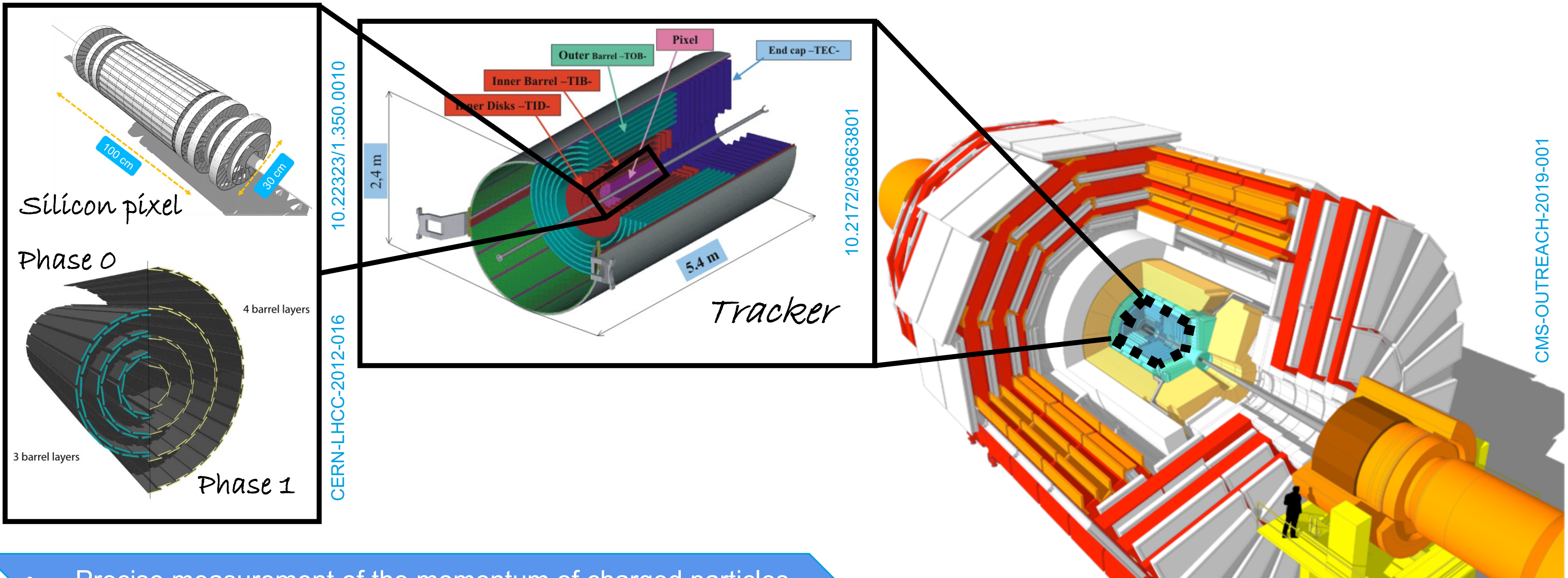
Sandra Consuegra Rodríguez (DESY) on behalf of the CMS collaboration

European Physical Society Conference on High Energy Physics, University of Hamburg and DESY, 26-30 July 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

The CMS tracker

Inner tracking system of CMS experiment
- → Silicon pixel detector → 1440 modules until end of 2016 [ref. to Phase 0]; 1856 modules after upgrade [ref. to Phase 1] in 2017
- → Silicon strip detector → 15 148 modules



- Precise measurement of the momentum of charged particles
- Reconstruction of secondary and primary vertices

Movements of different substructures of the tracker driven by operating conditions

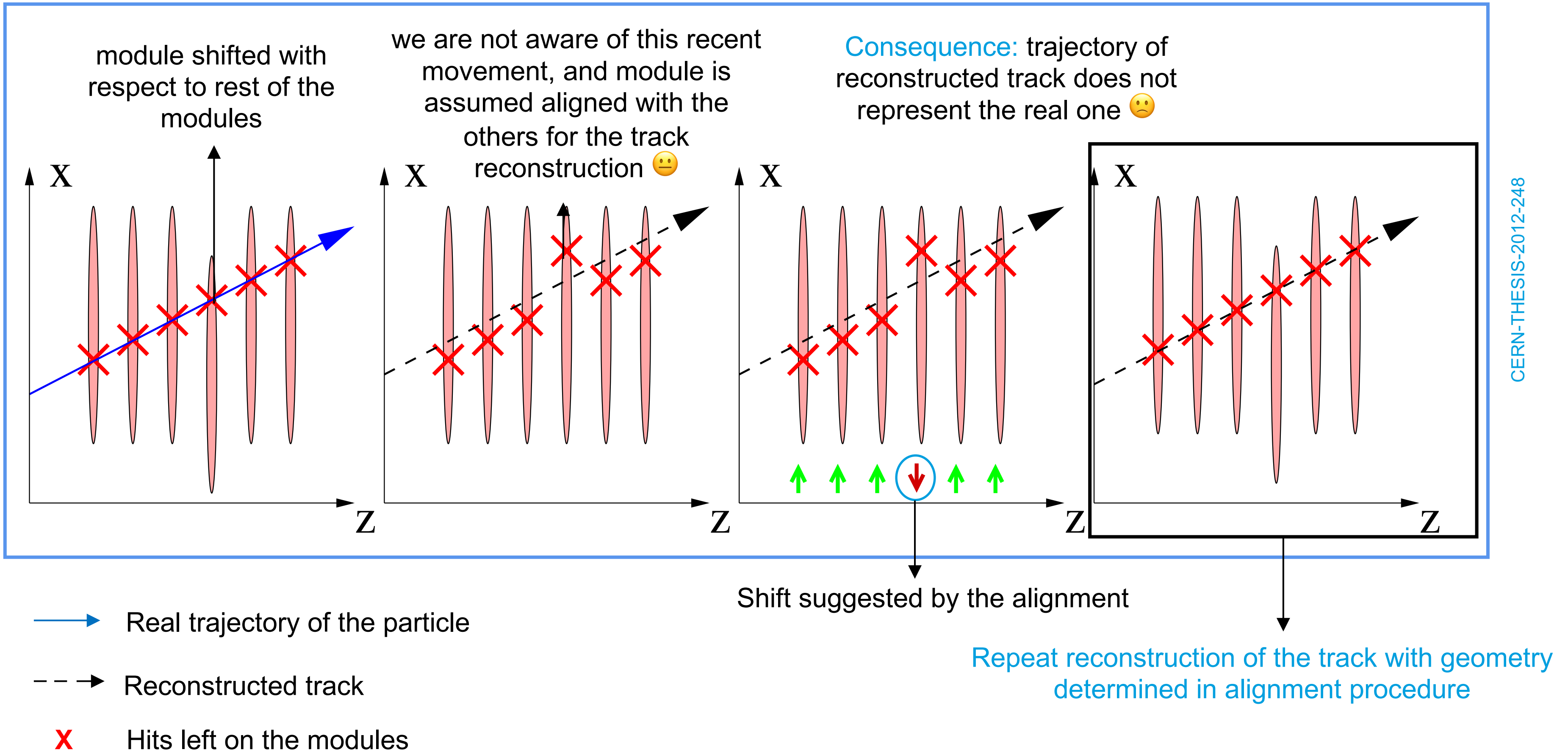
Periodic update of the detector geometry needed

Ultimate performance of track and vertex reconstruction only achieved if detector geometry is known with high accuracy

Alignment of the CMS tracker: general concepts

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

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



Track based alignment:

> Minimisation of sum of squares of normalised track-hit residuals ---> $\boxed{r_{ij}(\mathbf{p}, \mathbf{q}_j) = m_{ij} - f_{ij}(\mathbf{p}, \mathbf{q}_j)}$

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

p: global alignment parameters
$\mathbf{q}_j$: local track parameters
$m_{ij} \pm \sigma_{ij}$: measured hit position
f_{ij}: predicted hit position

> Each time a part of the tracker is moved/removed ---> re-installation precision of mechanical alignment O(100 μm) ---> one order of magnitude lower than design hit resolution O(10 μm)

> Alignment aims to push precision well below design hit resolution!

> Two independent implementations of track-based alignment used in CMS during Run-II

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

Tracker alignment strategy for data

> **Automated alignment:**

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

> **Alignment during data taking:**

- track-based alignment periodically run offline
- automated alignment refined with periodic updates from the campaigns going on in parallel offline

> **Alignment for end-of-year re-reconstruction:**

- full statistics of dataset collected during one year used to provide set of alignment conditions for the reprocessing of the data

> **Alignment for legacy reprocessing:**

- ultimate accuracy of the alignment calibration used for the final or legacy reprocessing of the data
- up to ≈ 700k parameters → 220 geometries over the three data-taking years to cover significant changes of the alignment conditions over time

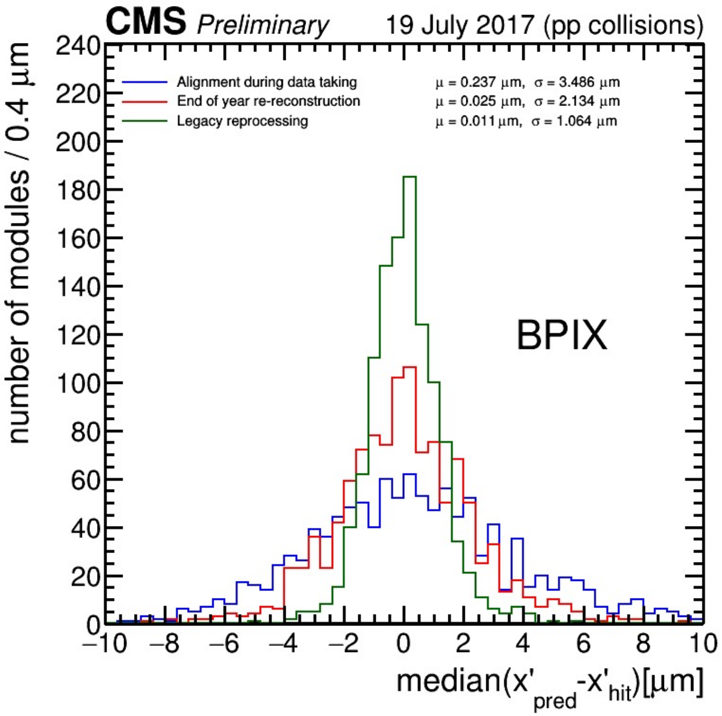
Focus of today's talk

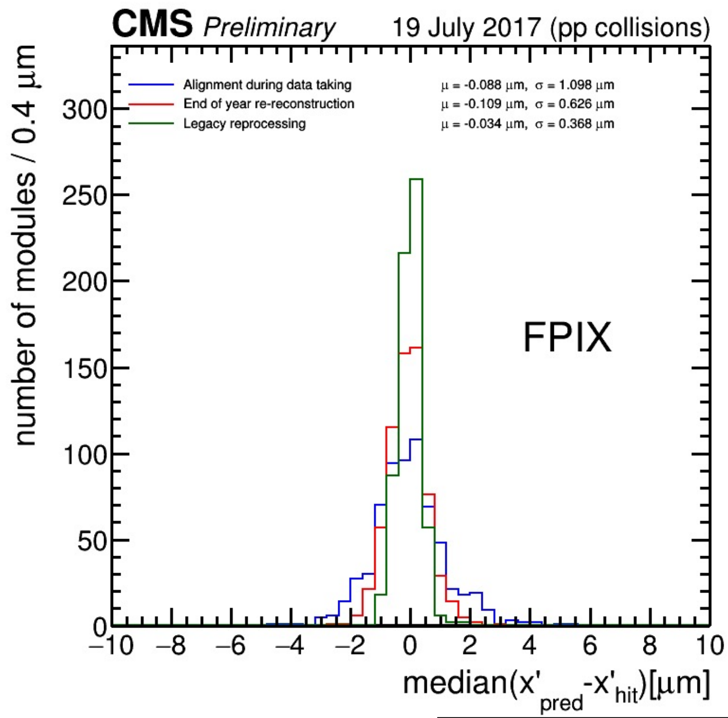
Legacy results

> 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

> Further validations of the obtained geometry are performed

Tracking performance ---> Distribution of Median Residuals (DMR) validation





width:

measure of local precision of the alignment calibration

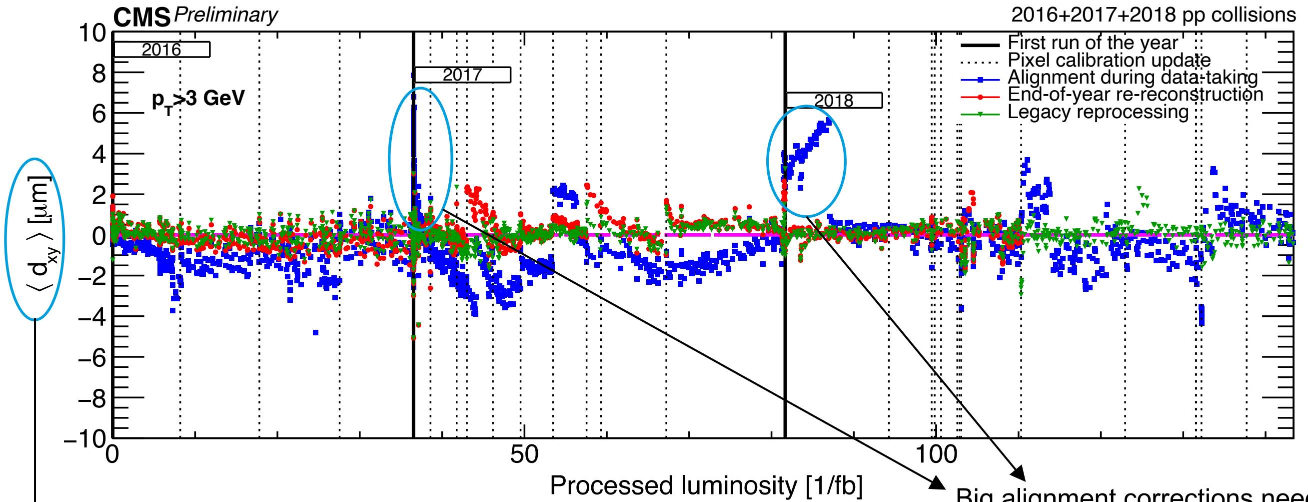
mean:

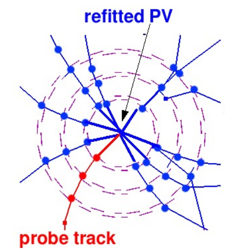
deviations from zero indicate possible bias due to change of conditions (e.g. temperature and magnetic field)

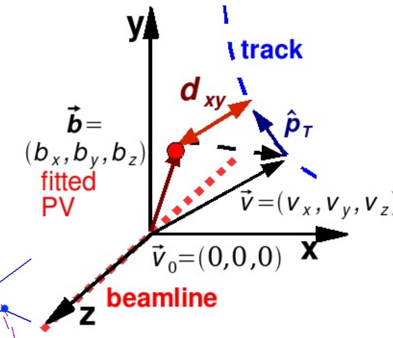
Distribution of median residuals in the barrel pixel (left) and forward pixel (right)

significant improvement for the legacy reprocessing over the alignment during data taking or end of year re-reconstruction

Vertexing performance ---> Primary Vertex (PV) validation





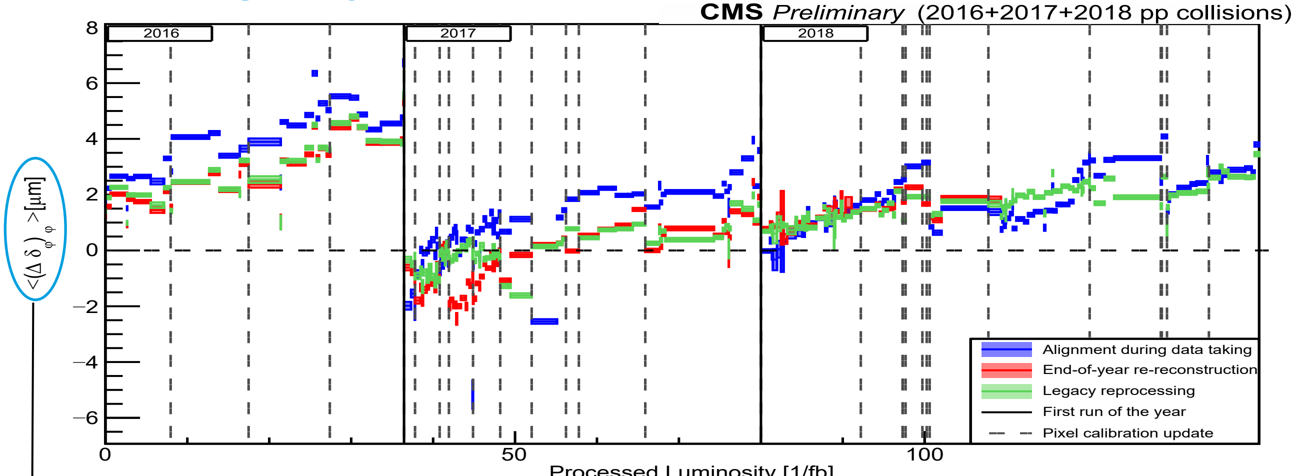


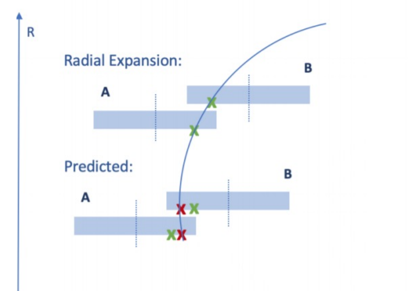
CERN-THESIS-2011-435

Big alignment corrections needed at the beginning of each year of data taking

Mean distance in the transverse plane of the tracks at their point of closest approach to a refit unbiased primary vertex

Monitoring of systematic distortions ---> Overlap validation





Expansion:
HitA – PredA – (HitB – PredB) = negative

Mean difference in ϕ residuals for modules overlapping in the ϕ direction in the barrel pixel

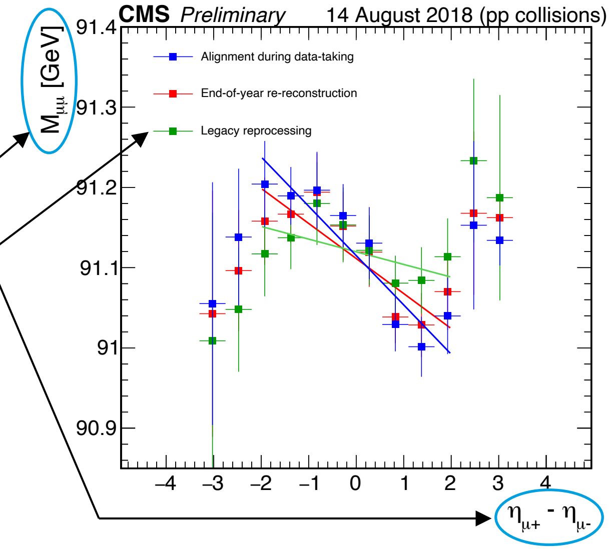
Uniformity of the reconstructed $Z \rightarrow \mu\mu$ mass

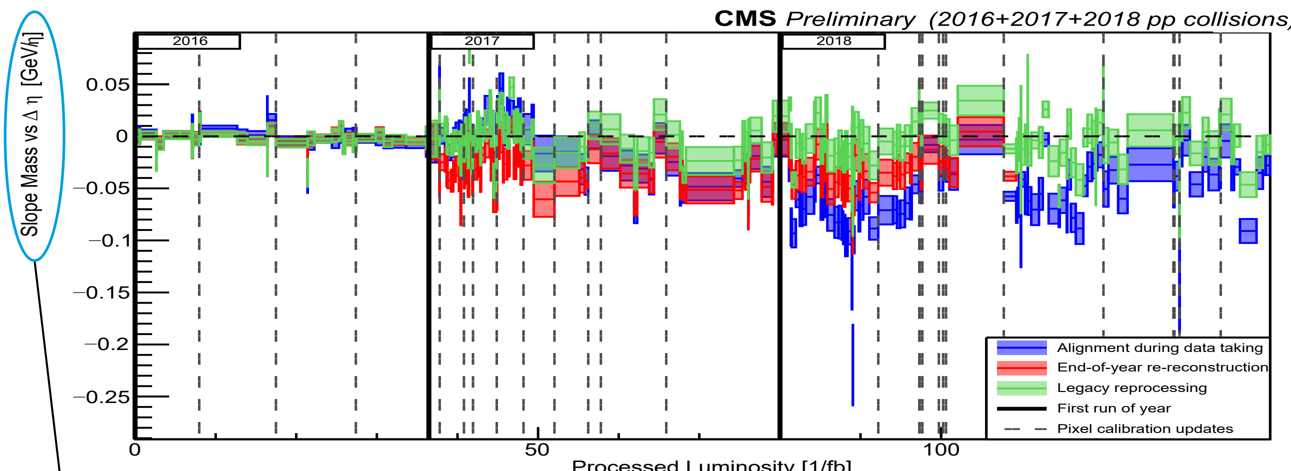
unrefined alignment constants affect the reconstructed Z boson mass

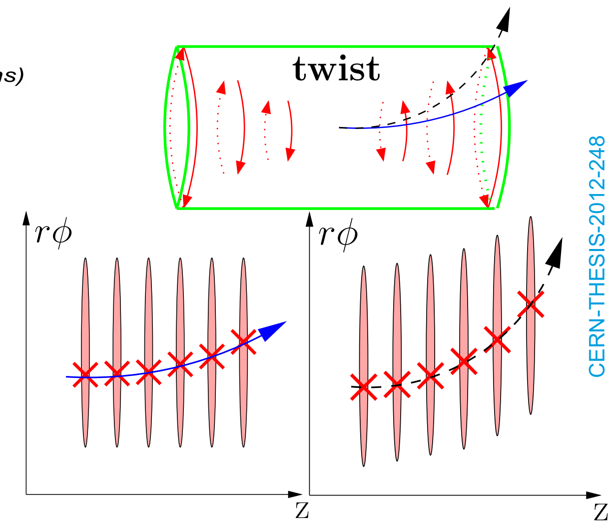
observed as non-desired dependence on the pseudorapidity η of positively and negatively charged muons

> Improvement in the uniformity of the reconstructed $Z \rightarrow \mu\mu$ mass observed for the legacy reprocessing

> Analysis relying on a very accurate determination of the mass of the Z boson benefit from the improved performance







CERN-THESIS-2012-248

Slope ε: obtained from fit to invariant mass of dimuon system versus $\Delta\eta = \eta_{\mu^+} - \eta_{\mu^-}$ as function of processed luminosity $\varepsilon\Delta\eta$+b

Alignment in simulation

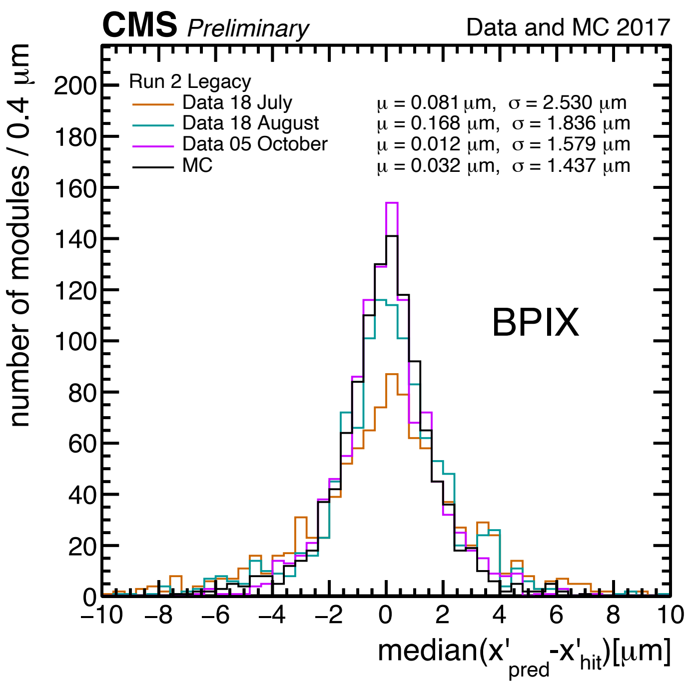
> Reproduce the procedure adopted for the data as closely as possible

- full alignment fit performed using simulated events

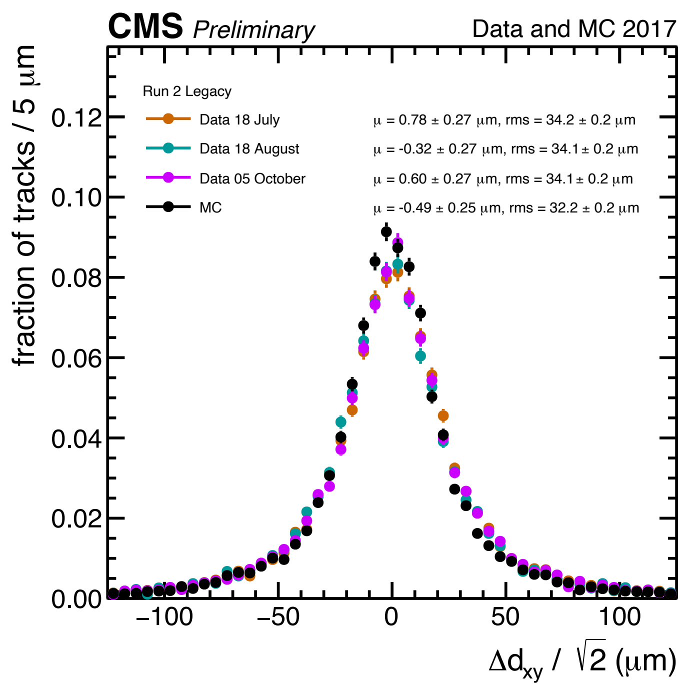
- starting geometry for the fit built from ideal detector geometry, with misalignments applied on top to reflect average accuracy of alignment constants in data after end-of-year re-reconstruction

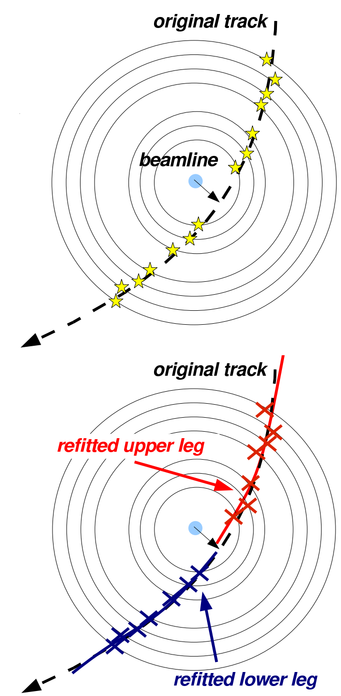
> alignment constants derived from fit validated and compared to data alignment conditions at three different dates during data taking

DMR validation



Track split validation





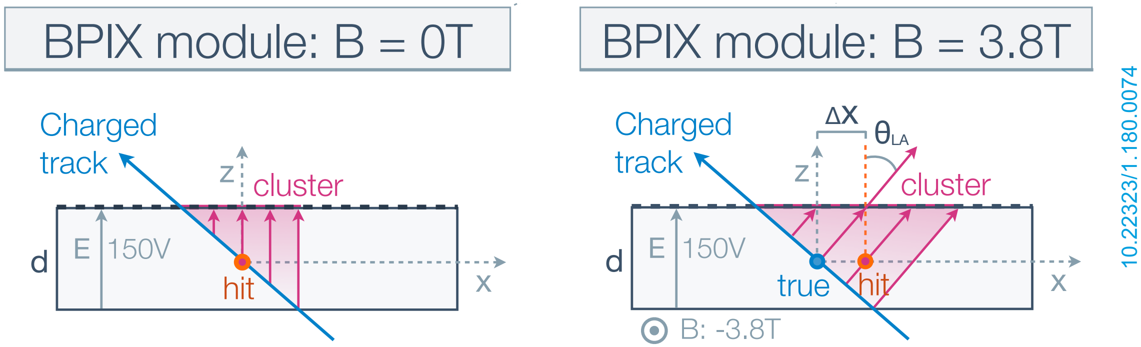
CERN-THESIS-2011-435

Difference of transverse impact parameter between the two halves of cosmic tracks split at their point of closest approach to the interaction region

Run-III prospects

Integrated luminosity of Run-II expected to be doubled

stronger variations of the Lorentz drift of charge carriers released by charged particles passing through silicon sensors foreseen due to larger irradiation doses



> Alignment procedure sensitive to Lorentz drift changes induced by accumulated radiation after ~1 fb^{-1}, while pixel local reconstruction calibration only performed after ~10 fb^{-1}

> High enough alignment granularity ---> in- and outward pointing modules free to move separately ---> bias coming from Lorentz angle (θ_{LA}) miscalibration can be absorbed

During Run-III

> Finer granularity for the automated alignment

> Finer granularity for the alignment run offline at earlier stages with respect to Run-II (e.g. in the alignment during data taking and end-of-year reconstruction), in order to better cope with radiation effects

> More geometries over the years might be needed to cover significant changes over time

Summary

General concepts of track-based alignment were explained

Tracker alignment performance corresponding to ultimate accuracy of the alignment calibration used for the legacy reprocessing of the CMS Run-II data was presented

- Alignment strategy for data and simulation was addressed
- Set of validations that monitor performance of physics observables after the alignment was presented
  - Tracking and vertexing performance (DMR and PV validation)
  - Monitoring of systematic distortions
    - Overlap validation
    - Reconstructed $\mathrm{Z} \rightarrow \mu\mu$ mass ($\mathrm{Z} \rightarrow \mu\mu$ validation)
    - Track split validation

Paper on final state towards publication

Prospects for the alignment calibration during Run-III were discussed

Thank you!

Contact

DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

Sandra Consuegra Rodríguez (DESY)
0000–0002–1383–1837
CMS, Higgs Group
sandra.consuegra.rodriguez@desy.de
+49–40–8998–3264
Personal website:
https://www.desy.de/~consuegs/

Backup

> **Additional material**

References

> CMS Tracker Performance results for full Run 2 Legacy reprocessing

CMS-DP-2020-012

> CMS Tracker Alignment Parameter Errors performance results for full Run 2 Legacy reprocessing

CMS-DP-2020-023

> Additional Run 2 CMS Tracker Alignment Performance Results

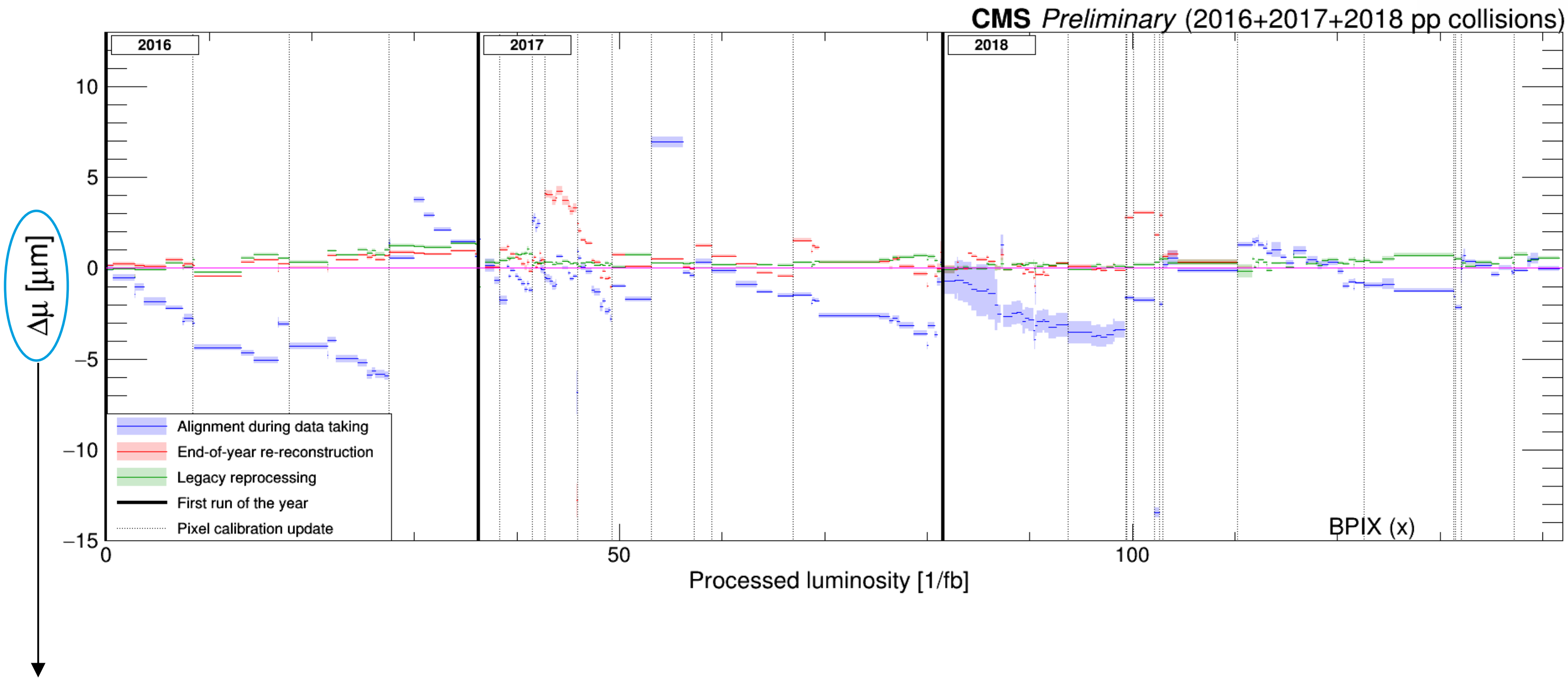
CMS-DP-2020-038

> 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

Legacy results

Tracking performance (DMR validation)



> Δμ: indicator of residual bias due to accumulated effects from radiation in the silicon sensors

Difference in the mean of a Gaussian fit to the distribution of normalized median residuals for local-*x* coordinate in the barrel pixel as a function of processed luminosity for the modules with electric field pointing radially inwards or outwards

Tracker alignment strategy for simulation

> Simulated events passed through same reconstruction chain used for data

> Full set of detector calibrations, including the tracker alignment conditions, derived for the processing of simulated events

> Tracker alignment constants provided

> **Alignment for end-of-year re-reconstruction:**

- scenarios derived separately for each data-taking year
- reasonably reproduce average performance observed in the end-of-year re-reconstruction data alignment

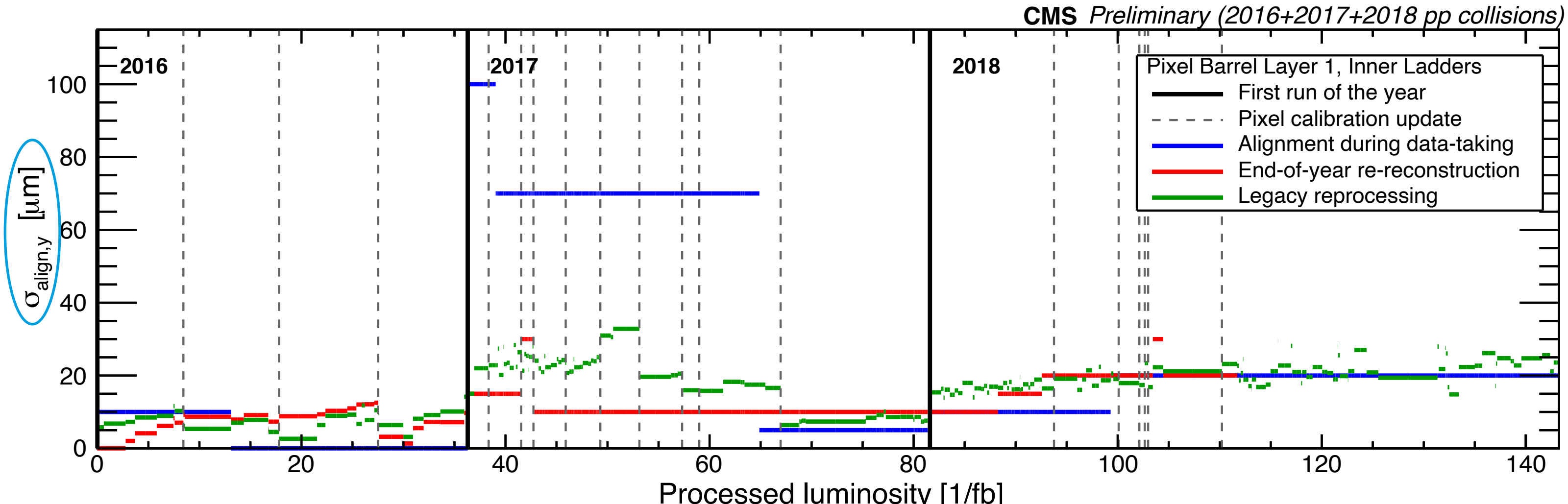
> **Alignment for legacy reprocessing:**

- emulate the effects of residual misalignment left in data after the alignment for the legacy reprocessing is derived

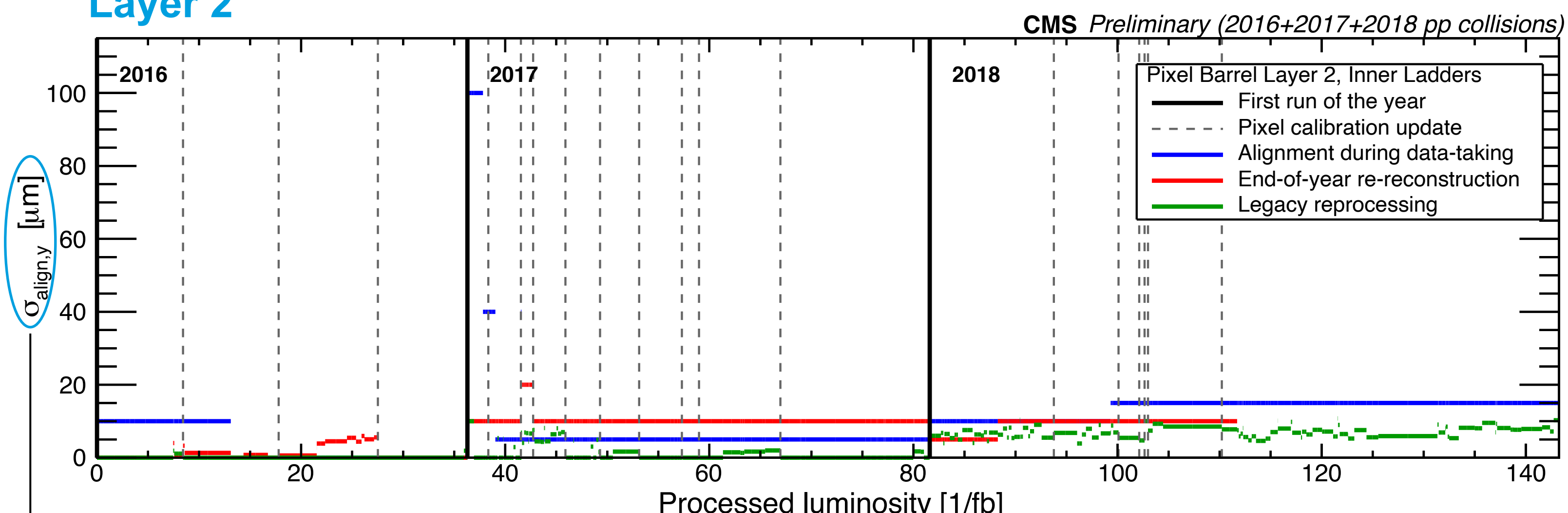
Alignment position errors (APEs)

Layer 1

$$\sigma_r{}^2 = \sigma^2 + \sigma_{align}{}^2$$



Layer 2

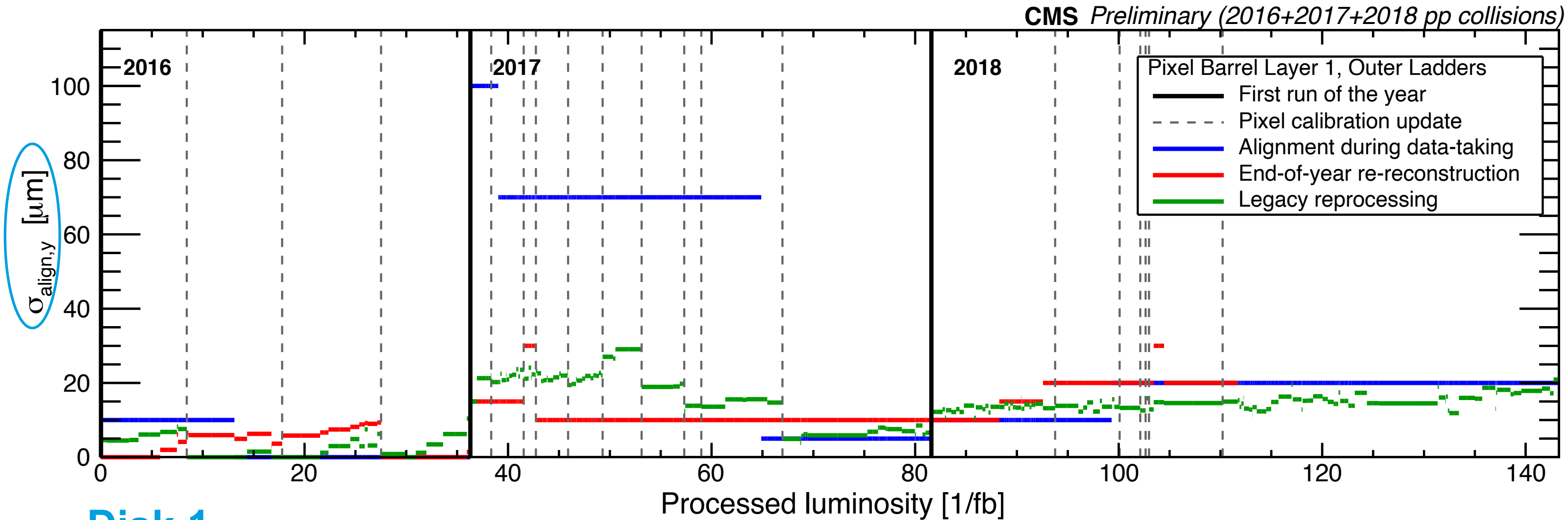


Contribution from the misalignment of the sensors to the total hit resolution for the inner ladders of the first and second pixel barrel layer in local *y*-direction

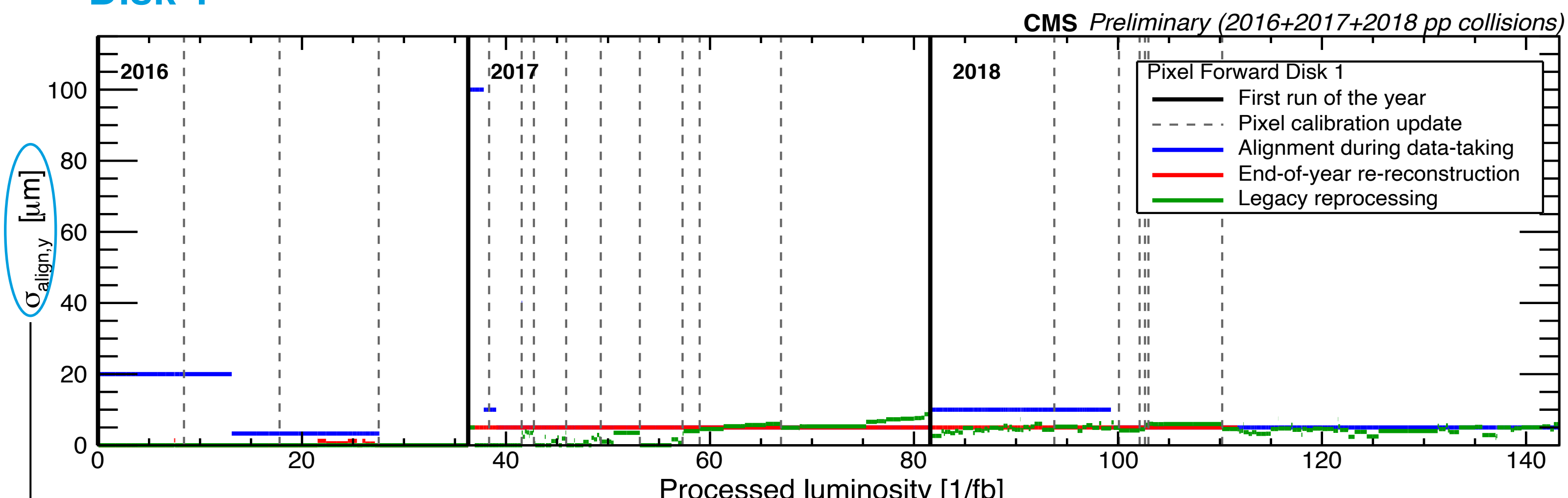
Alignment position errors (APEs)

Layer 1

$$\sigma_r{}^2 = \sigma^2 + \sigma_{align}{}^2$$

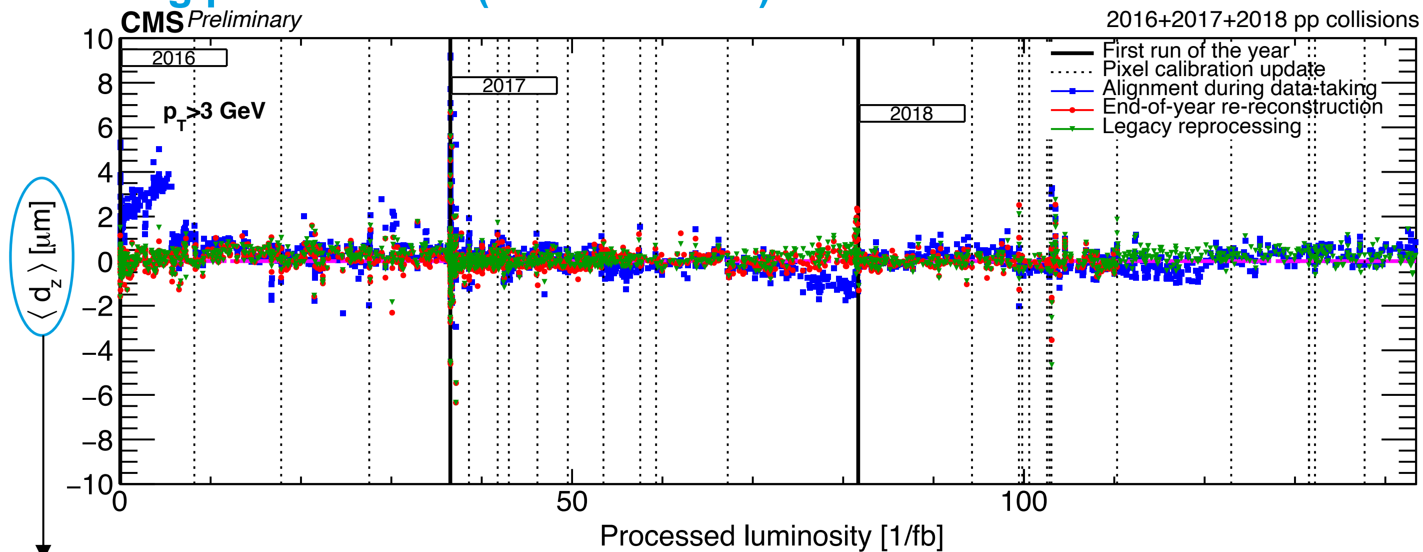


Disk 1



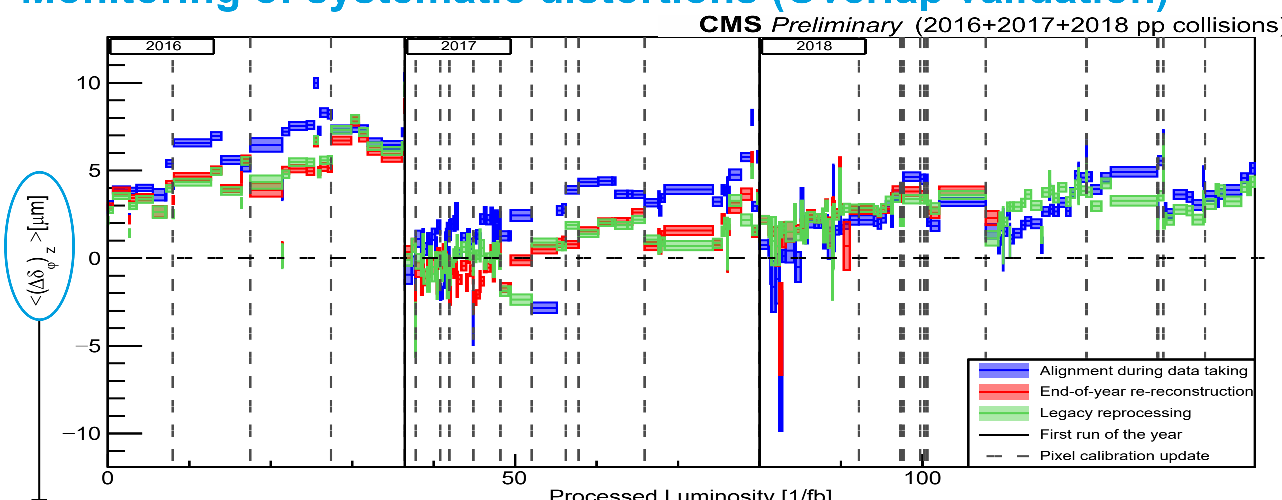
Contribution from the misalignment of the sensors to the total hit resolution for the outer ladders of the first pixel barrel layer and the first disk of the forward pixel in local *y*-direction

Vertexing performance (PV validation)



Mean distance in the longitudinal plane of the tracks at their point of closest approach to a refit unbiased primary vertex

Monitoring of systematic distortions (Overlap validation)



Mean difference in ϕ residuals for modules overlapping in the z-direction in the barrel pixel

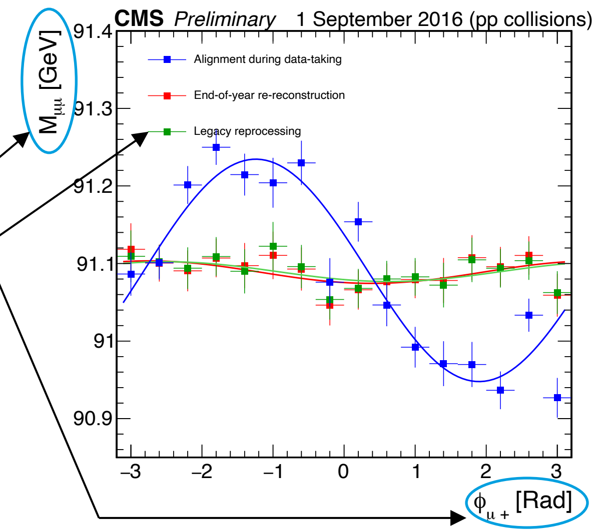
Uniformity of the reconstructed $Z \rightarrow \mu\mu$ mass

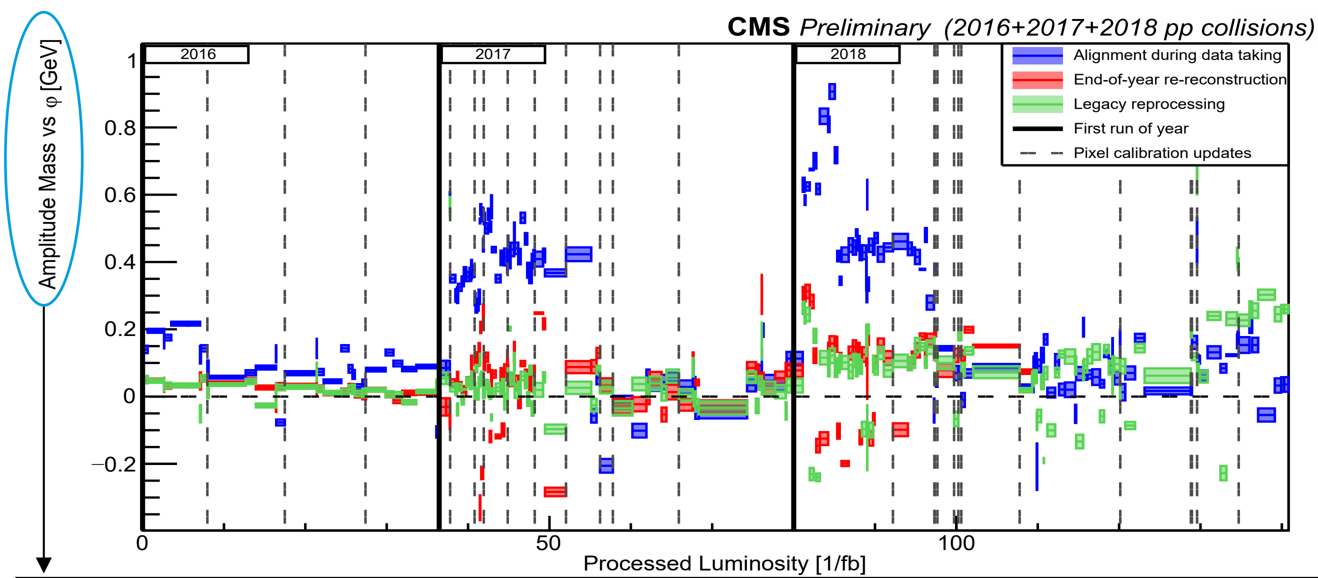
unrefined alignment constants affect the reconstructed Z boson mass

observed as non-desired dependence on the azimuthal angle ϕ of positively and negatively charged muons

> Improvement in the uniformity of the reconstructed $Z \rightarrow \mu\mu$ mass observed for the legacy reprocessing

> Analysis relying on a very accurate determination of the mass of the Z boson benefit from the improved performance





amplitude A: obtained from fit to invariant mass of dimuon system versus $\phi_{\mu+}$ as function of processed luminosity
$A \cos(\phi + \phi_0) + b$