Trigger Algorithms for Alignment and Calibration at CMS during LHC Run 3

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Philipp Nattland

For the CMS Collaboration

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Research Training Group Physics of the Heaviest Particles at the LHC

RWTH AACHEN UNIVERSITY

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

Introduction: The CMS Trigger System

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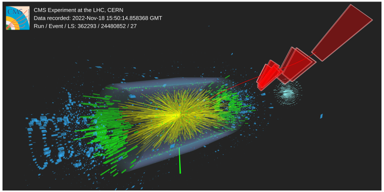
Proton-Proton Collisions



- **Collision rate: up to $4 \cdot 10^7$ Hz**

Level 1 Trigger

- **Hardware based, very fast (within $3.8\ \mu s$)**
- **Selects events with candidates, e.g. hits in the muon chambers**
- **Reduces rate to $\mathcal{O}(10^5$ Hz)**

High-level Trigger (HLT)

- **Software based, runs on computing farm at CMS (P5)**
  - → **equipped w/ CPU and GPU since 2022**
- **Access to full detector readout**
- **Selects events according to**

  HLT paths: **Algorithms that reconstruct physics objects and apply selections on these**
- **Events are grouped into non-exclusive** data streams **based on HLT paths:**
  - **E.g. prompt physics, scouting, express**
- **Nominal rate $\mathcal{O}(10^3$ Hz)**

Prompt Calibration Concept

Reasons for low-latency calibrations

- Allows efficient online event selection by HLT
- Enables analysis of data within few hours from acquisition
- Reduces need for further processing

Concept

- Stream with very low latency ($\sim$ 1-2 h for **Express**, **Calibration**) used to calibrate **physics streams** with higher latency ($\sim$ 48 h)

Data Streams

- **Prompt physics**: main data stream for physics analysis
- **Express**: Low rate data selection for calibrations
- **Calibration**: Reduced event content for calibration $\Rightarrow$ Allows for high rate
- **Scouting**: Reduced event content for high rate collection, with no offline reconstruction
- **Parking**: Events reconstructed, when resources available

Data Streams

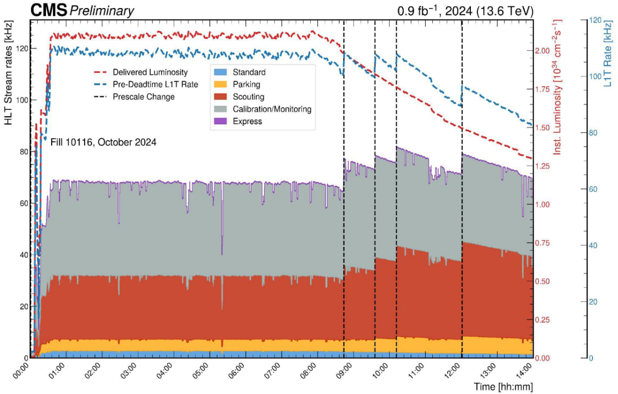


Figure: Rate of HLT output streams [CERN-CMS-DP-2025-015]

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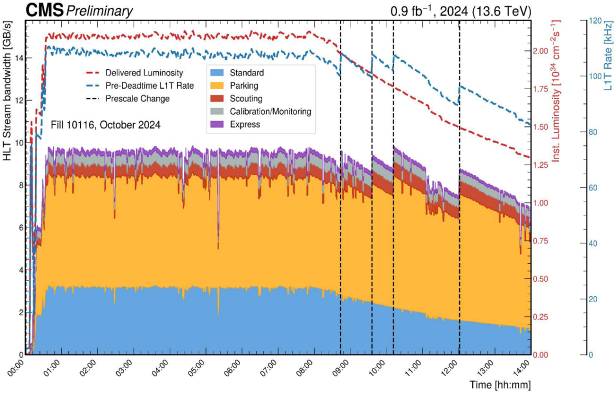

Figure: Bandwidth of HLT output streams [CERN-CMS-DP-2025-015]

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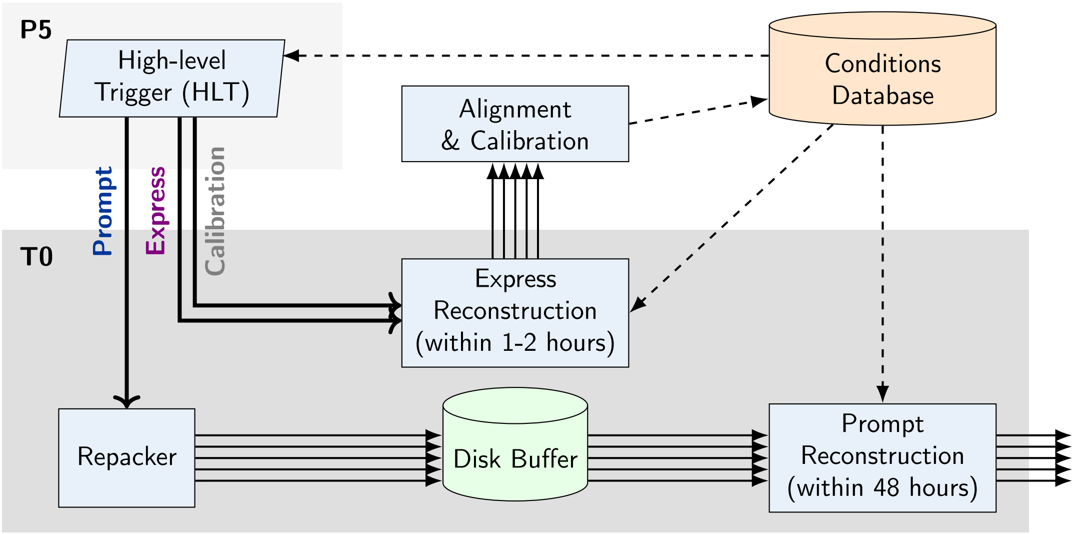
Prompt Calibration Loop



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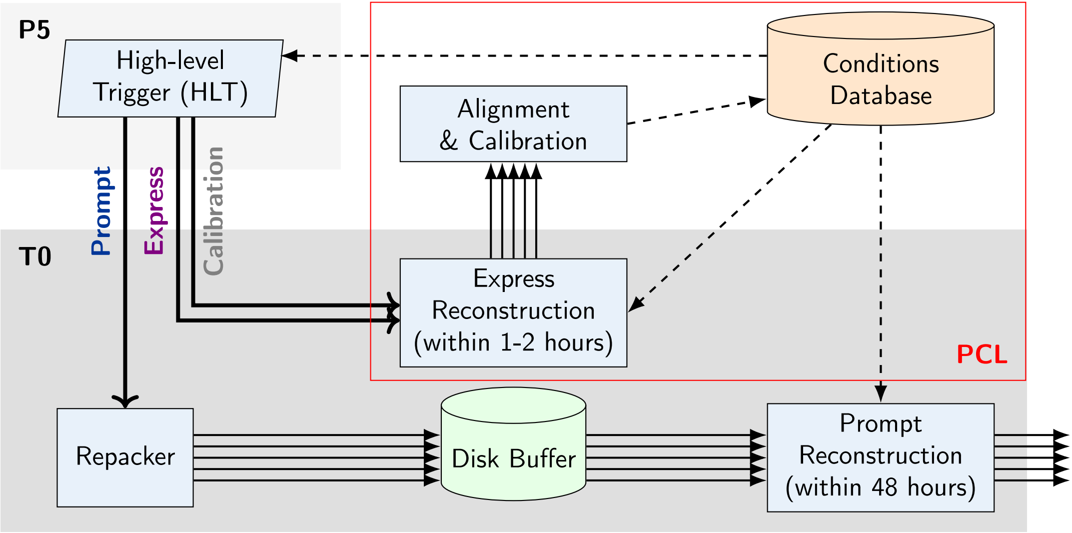

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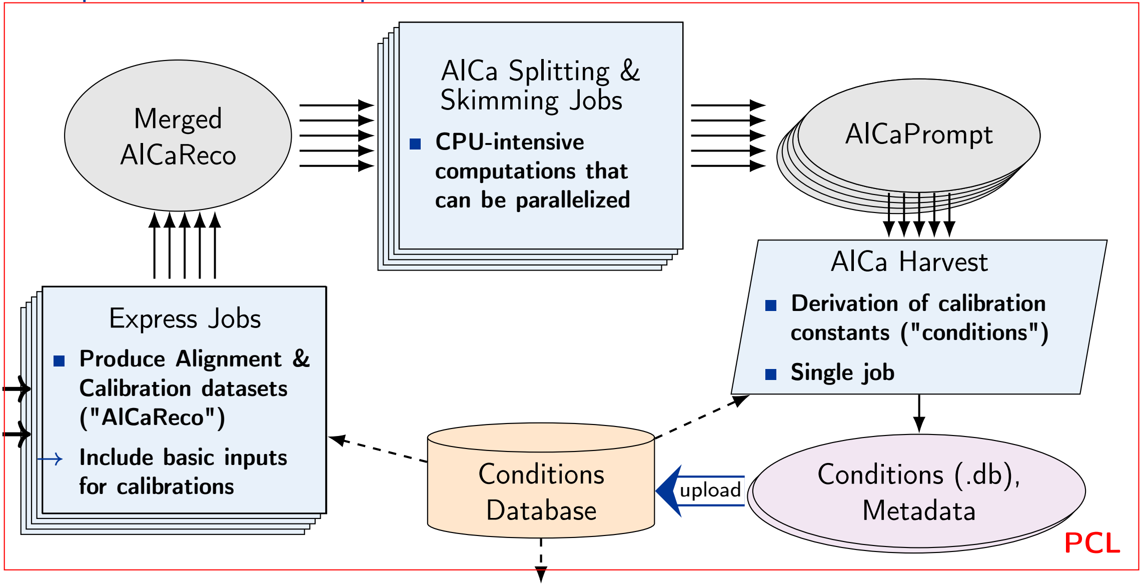

Calibration workflows running in the PCL

- Beam spot calibration
  - Determination of 3D position and width of luminous region
  - Max. 1 fit per luminosity section ($23.31\,\mathrm{s}$)
- Silicon strip tracker calibrations
  - Hit efficiency monitoring, Identification of problematic channels
  - Determination of gains
- Silicon Pixel calibrations
  - Detemination of bad components
  - Lorentz angle calibration
  - Track-based alignment of silicon pixel detector
- Additional workflows:
  - ECAL crystal radiation damage monitoring, ECAL pedestal calibration
  - Pixel cluster counting luminosity measurement
  - PPS timing calibration

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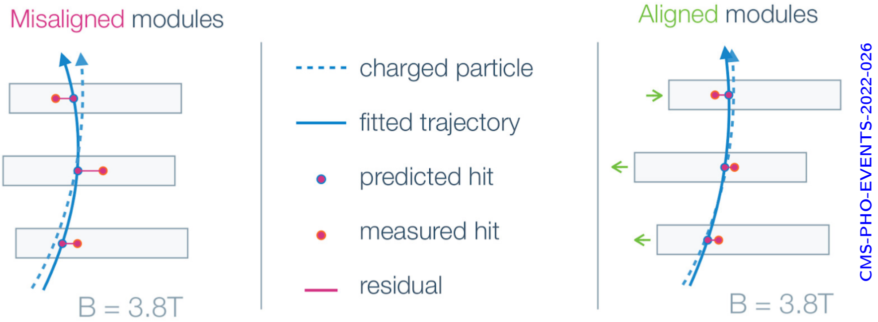
Track-based Alignment

- Determine **orientation, position and surface deformation** of CMS tracker sensors
- **Goal:** Alignment precision σ_{align} of same scale as hit resolution $\sim \mathcal{O}(10\,\mu\text{m})$
- After mechanical alignment: $\sigma_{\text{align}} \sim \mathcal{O}(100\,\mu\text{m})$

$\Rightarrow$ With track-based alignment $\sigma_{\text{align}} \sim \mathcal{O}(10\,\mu\text{m})$



Track-based Alignment

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

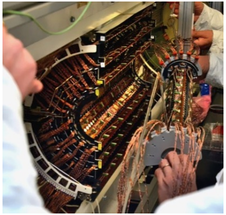
$m_{ij},\ f_{ij}$: measured and predicted hit position

$\boldsymbol{p},\ \boldsymbol{q}$: alignment and track parameters

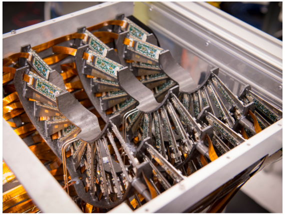
CMS-PHO-EVENTS-2022-026

Low Granularity (LG) PCL alignment

- Alignment of **large structures** (HLS) of the pixel detector
  - 2 BPIX half-barrels, 4 FPIX half-cylinders, 6 dof $\rightarrow$ $6 \times 6 = 36$ parameters
- MillePede 2 MPII algorithm runs in the Prompt Calibration Loop (PCL) at Tier-0
- Uses only Minimum Bias data (i.e. minimal trigger requirements)
- Alignment **automatically updated**, if movements significant
- Usefull to correct shifts of HLS e.g. after magnet cycles



CERN-PHO-2021-133-1



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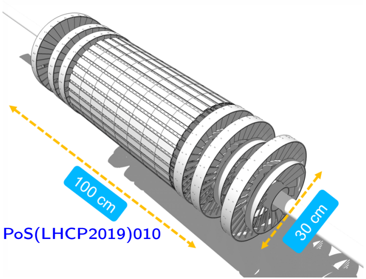
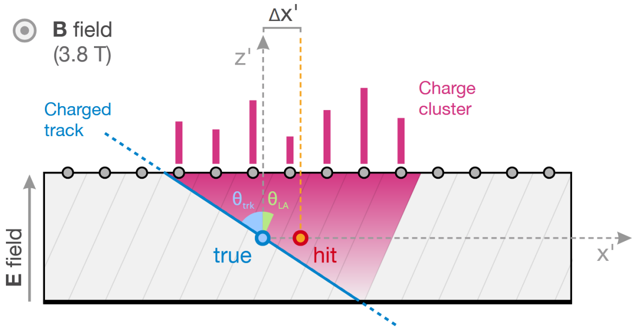


PoS(LHCP2019)010

Radiation Damage and Lorentz Drift

Lorentz drift

- Electron-hole pairs affected by strong B field
- Drift angle depends on electric field and on mobility of the charge carriers
  - ⇒ Affected by radiation damage
  - ⇒ Shift direction $\Delta x'$ depends on direction of electric field



CMS-TRK-20-001

- Radiation damage affects Lorentz angle, which shifts reconstructed hit position
- Alignment can artificially correct this effect by changing position of modules

Run 3: High Granularity (HG) PCL alignment

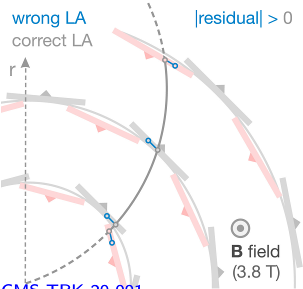
- Large radiation damage effect during Run3

$\Rightarrow$ Continuously correct for Lorentz drift effects using alignment

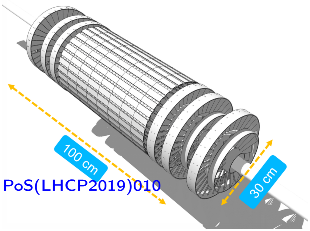
- Needs high granularity to correct in/outward facing modules separately
- Change from HLS-based to **ladder/panel-based** alignment

$\Rightarrow$ Increase free parameters from 36 to ~ 5000

- HG PCL was first activated in 2022
- Uses MinBias events only (trigger paths with minimal requirements, total rate $\sim 80\,\text{Hz}$)

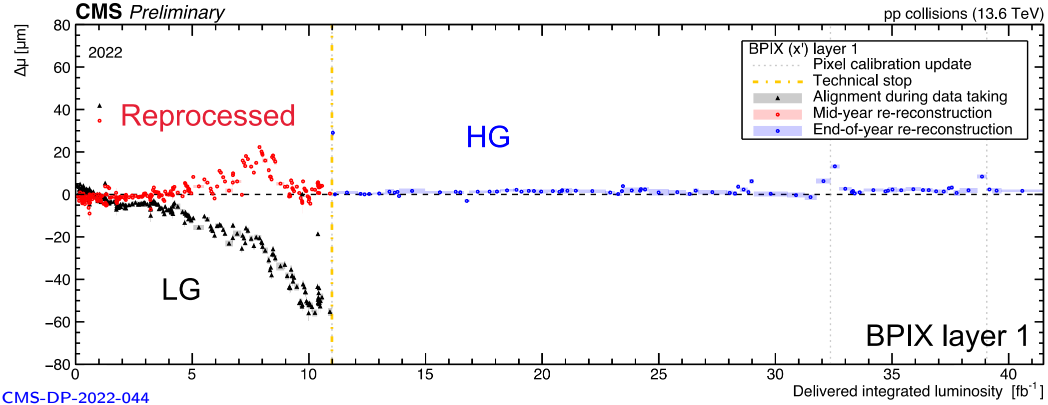


CMS-TRK-20-001



PoS(LHCP2019)010

Distribution of Median Residuals Trends 2022



CMS-DP-2022-044

⇒ HG PCL alignment corrects radiation effect successfully

⇒ Tracker alignment in PCL is instrumental for precise prompt reconstruction

HG PCL Alignment Bias

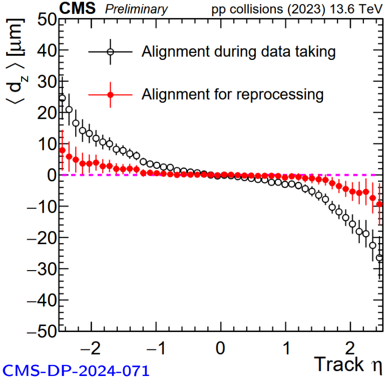
- Many more parameters than LG alignment ($\sim$5000 vs 36)

$\Rightarrow$ Cannot be fully constrained by MinBias dataset

$\Rightarrow$ "weak modes", i.e. bias introduced in some variables, e.g. $d_z(\eta)$

Primary Vertex (PV) validation: d_z vs η

- PV reconstruction driven by pixel detector
- Validation: Redetermine PV without track of interest
- $\boldsymbol{d_z}$: Longitudinal distance between track and redetermined PV
- Expect distribution of mean d_z vs track η, ϕ to be flat



CMS-DP-2024-071

HG PCL Alignment Bias

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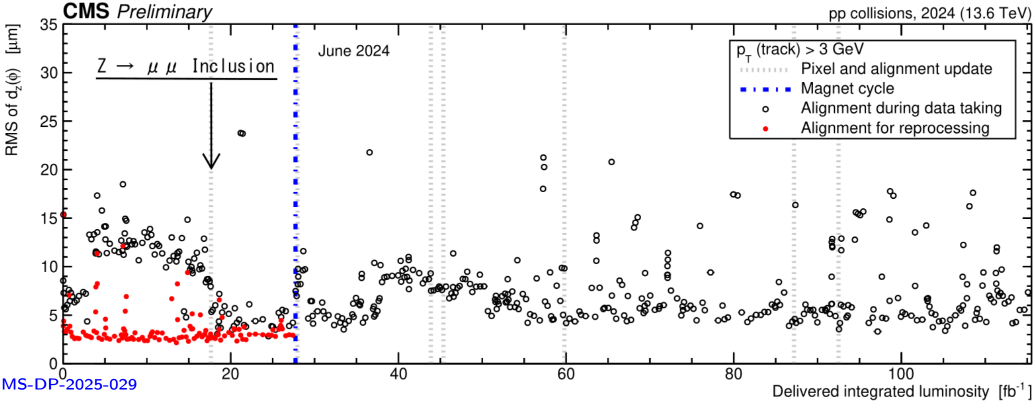
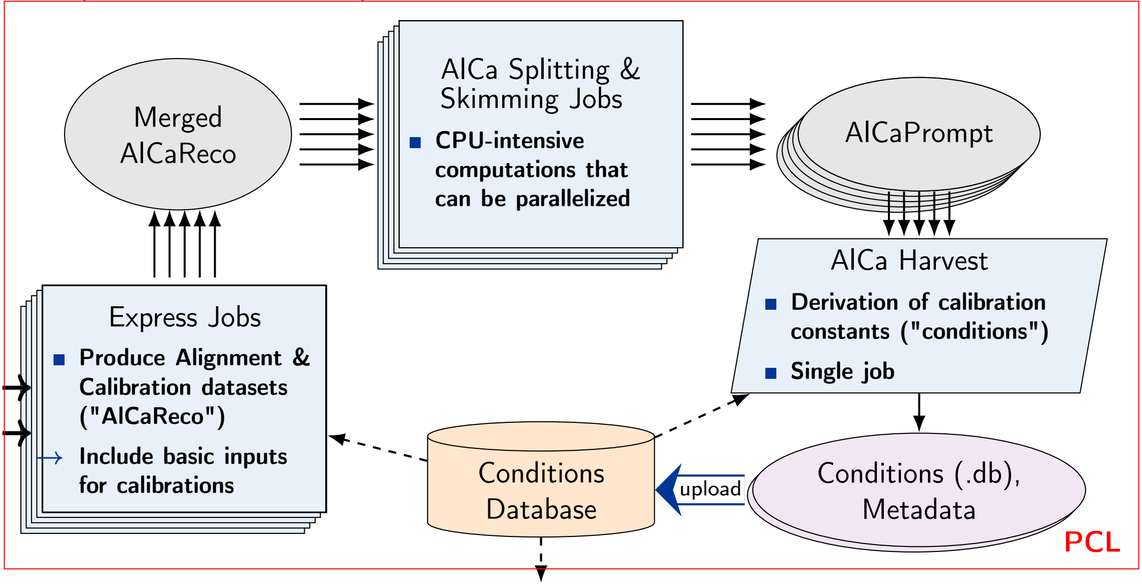
Inclusion of $Z \rightarrow \mu\mu$ data

- Z bosons often produced with little boost $\Rightarrow$ can correlate opposite ends of tracker
  - $\Rightarrow$ Try to reduce bias by performing alignment on MinBias **and** $Z \rightarrow \mu\mu$ tracks (Trigger paths requiring a.o. two muons, rate $\sim 5\,$Hz)



CMS-DP-2025-029

Prompt Calibration Loop

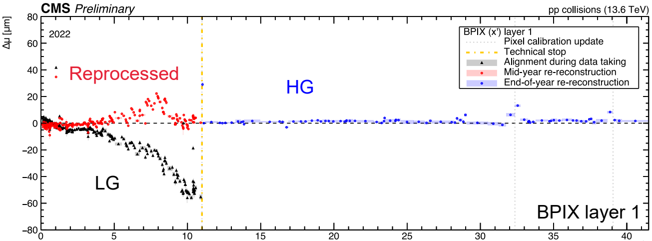


Low Latency Calibrations

- Enable efficient HLT triggering
- Essential for precise prompt physics reconstruction

Radiation Damage in Run 3

- Calibration workflows in PCL needed adaptation
- High granularity tracker alignment allows for corrections of Lorentz drift due to radiation damage



CMS-DP-2022-044

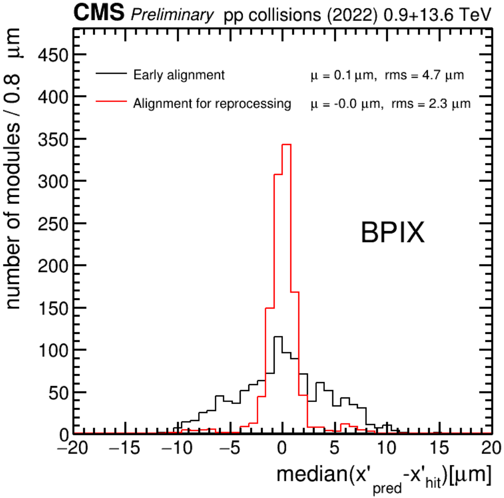
Backup

Distribution of Median Residuals

DMR validation

- Refit track without hit of interest
- Measure distance between **measured hit** and **prediction by the fit** wrt local module coordinates (denoted x' etc.)
- Calculate the median of these residual distributions for each module

$\Rightarrow$ Uncorrected Lorentz drift leads to shift in μ of DMR between in/outward facing modules



HG PCL bias: d_z vs ϕ