Calibration and performance of the CMS pixel detector in LHC Run 2

Tamás Álmos VÁMI for the CMS Collaboration

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Introduction

- The silicon pixel detector is the innermost component of the CMS tracking system.
- It determines the trajectories of charged particles originating from the interaction region with high resolution enabling precise momentum and impact parameter measurements in the tracker.
- It is designed to operate in the high particle density environment of the LHC.

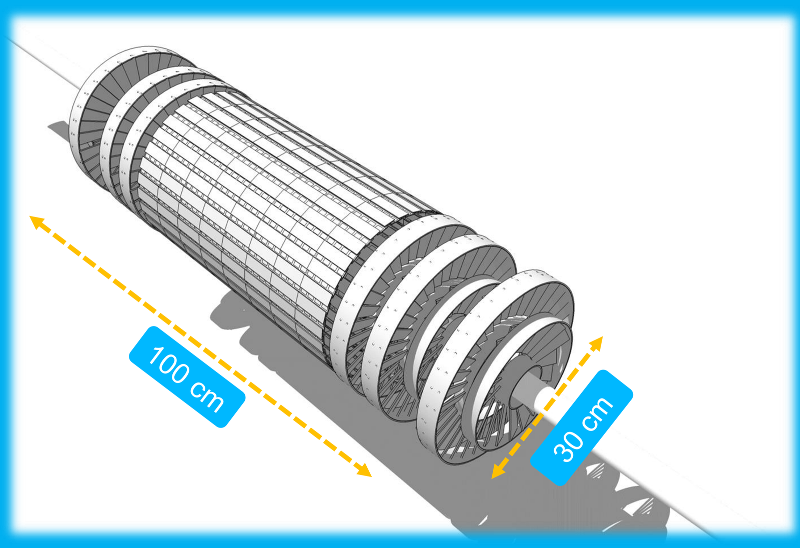

Fig. 1. CMS Phase-1 Pixel Detektor.

- In 2017 the original detector was replaced to a newly constructed detector (called the Phase-1 upgrade, shown on Fig. 1.) which has 4 concentric barrel layers and 3-3 disks containing 124 million pixels with size 100x150x285 μm^3.
- The calibration of the pixel detector plays an important role in its performance.

Calibrations & Local Reco

- Hits and pixel charges are determined from pixels with deposited charge above a certain threshold. Then adjacent pixels are combined into clusters. Cluster charge and position is then used to determine the hits.

Pixel ADC → Pixel charge → Cluster charge → Hits

- The charge carriers inside the silicon bulk are deflected by the Lorentz force due to the 3.8 T magnetic field of the CMS detector. This deflection is characterized by the Lorentz Angle (θ_{LA}).
- This parameter is sensitive to radiation effects, so ageing of the detector leads to higher θ_{LA} values.
- θ_{LA} is measured by fitting the average drift distance of electrons as a function of production depth as shown of Fig. 2. The plots shows two states of the sensor, one at the integrated luminosity of 56.5/fb and the other at 76.7/fb. θ_{LA} values through the history of the detector are stored in databases.

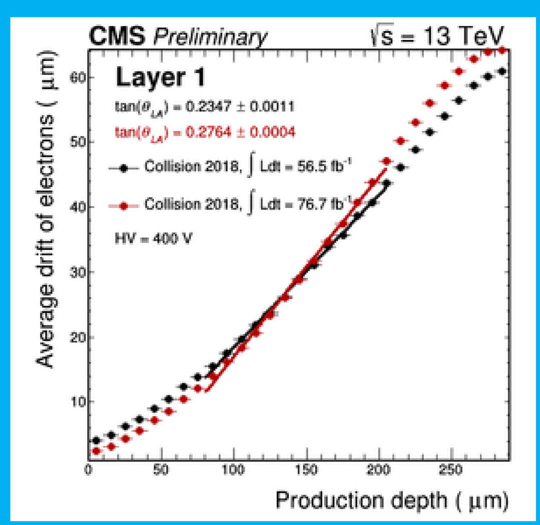

Fig. 2. Lorentz Angle measurements at the int. lumi. of 56.5/fb and 76.7/fb.

- For non irradiated, fully depleted detector, the pixel charge profile is expected to be flat as detector is fully efficient and all charge is collected, while for irradiated detector the losses are expected due to the trapping of carriers.
- To cope with the irradiation one can either (1) anneal the detector, (2) increase the high voltage or (3) use a special reconstruction and simulate ageing in MC.

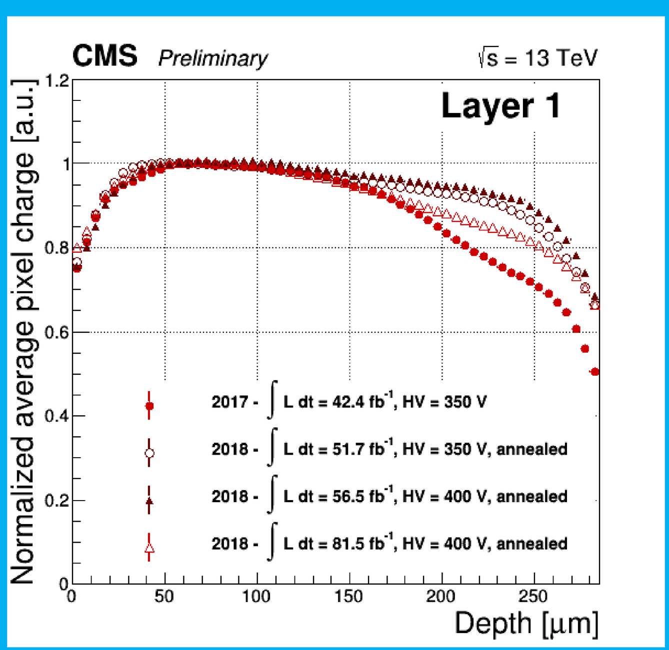

Fig. 3. Cluster charge profiles.

- During 2017 Extended Year Technical Stop, the Barrel Pixel detector was held at the temperature > 10 °C for 53 days (annealing).
- The beneficial effect of the annealing during this period is clearly visible in the flattening of the pixel charge profile (Fig. 3.).
- At the beginning of 2018 data taking, the charge collection was additionally increased in Layer 1 by raising the bias voltage from 350 V to 400 V (Fig. 3.).
- The special reconstruction method mentioned above simulates irradiated sensors in PixelAV (M. Swartz et al. Oct 2005. Nucl.Instrum.Meth.A565:212-220,2006.) corresponding to different the charges profiles and stores these as 1D projection, called template. This technique leads to superior resolution for irradiated sensor.
- The 2D projection is used from 2018 to reweight pixel charges in simulation thus simulate the ageing of the silicon bulk.

Main Parameters

- The main two parameters of a tracking detector are resolution and efficiency.
- Hit finding efficiency is defined as the fraction of all the projected trajectories where a matching cluster is found within a 1 mm radius (nearest cluster) around the expected trajectory position (expected hits).

Resolution and Efficiency

- To measure the resolution the triplet method is used with the following steps (example with disk 2):
  - Tracks with p_T > 4 GeV and hits in three disks are selected and refitted using hits in disks 1 and 3.
  - Trajectory extrapolated to disk 2, residuals with the actual hit are calculated.
  - Residual distribution is fitted with the Student-t function.
  - Positions are reconstructed with the template reconstruction algorithm.

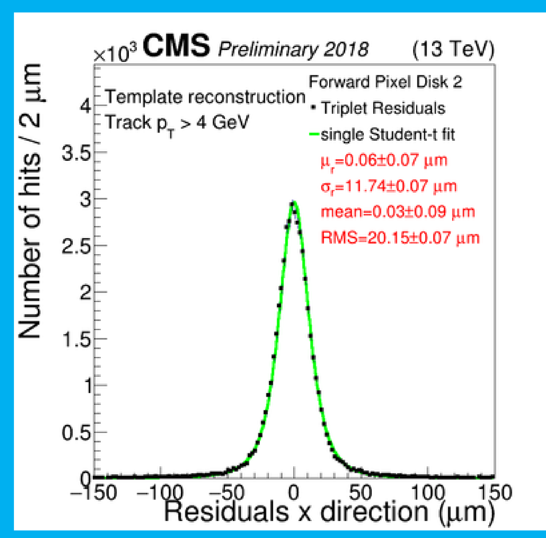

Fig. 4. Residual distribution for disk 2.

- Fig. 4. shows the residual distribution for disk 2 with the width of 11.74 μm.
- The intrinsic resolution is extracted using simulations and it corresponds to about a factor of $1/\sqrt{2}$ of the width.

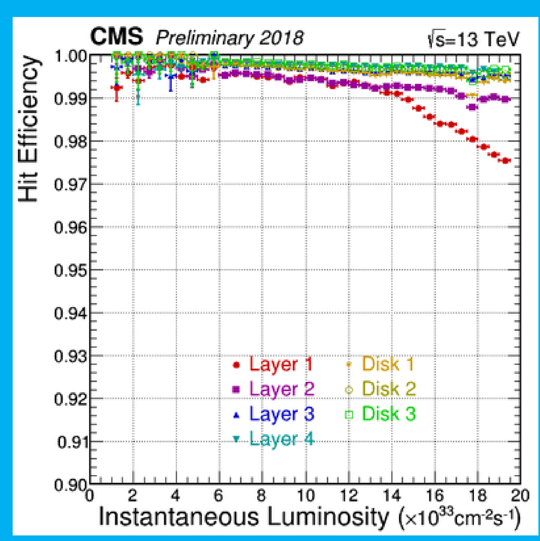

Fig. 5. Hit efficiency.

- The main reason for loosing hit efficiency is the saturation of the read-out-chip buffer.
- This is mostly relevant for high instantaneous luminosity and for the innermost layer.
- The Phase-1 pixel detector was design to cope with this effect so the worst efficiency is 97.5% for layer one and it is above 99% for the other layers and the disks, as shown on Fig. 5.

- The efficiency definition above does not contain the temporarily or permanently bad detector elements.
- Fig. 6. shows the occupancy map of layer 1, where the white areas are the non-functioning parts. From 2018 a Prompt Calibration Loop based technique is used to determine bad component based on a dynamic occupancy threshold for each lumisection.
- This information is stored in databases and propagated to tracking.

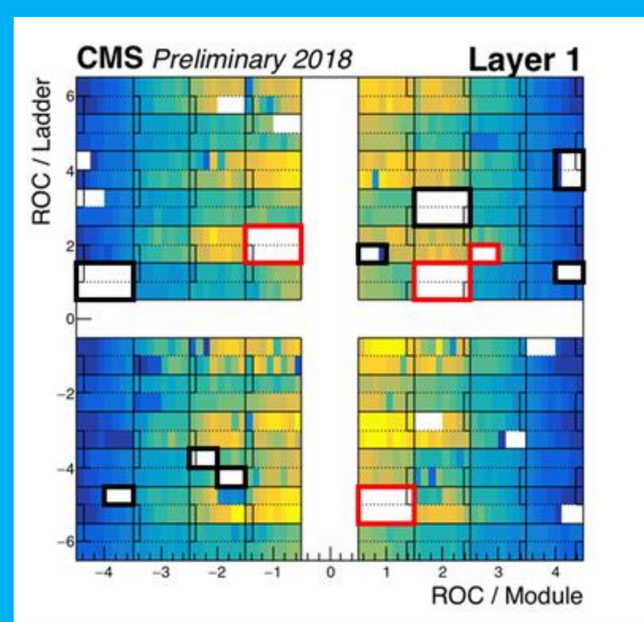

Fig. 6. Occupancy map of layer 1.

- From 2019 a dynamics bad component loss is simulated as well.

Impact Parameter

- The mean of the average impact parameter in the longitudinal plane versus track azimuth, as a function of integrated luminosity in shown on Fig. 7.
- The vertical black lines indicate changes in the calibration of the local hit reconstruction. The red points show the results with the alignment constants used during data taking, the blue points show the results with the alignment constants as obtained in the alignment procedure.
- Aligning the tracker improves the mean of this distribution.

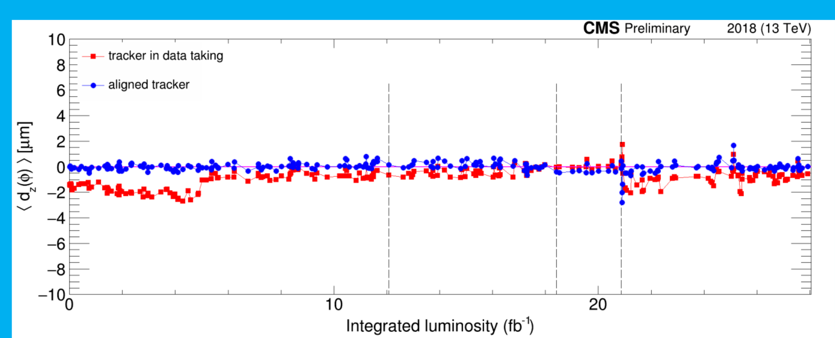

Fig. 7. The mean of the average impact parameter as a function of int. lumi.

- Outliers in the trend are understood as degraded tracking performance caused by suboptimal pixel local reconstruction calibration input.
- Recalibrations for the whole Run-2 data are in progress (called Ultra Legacy reprocessing, UL) which will further improve these results.

Conclusion & References

- The Pixel Detector captures events in every 25 nanosecond using 124 million pixels. The resolution of the detector is a tenth of the size of an individual pixel and the efficiency of it is above 99% expect for layer 1 at high luminosities.
- To achieve this several calibrations are needed. Although in Run 2 the performance was already great, it will further improve using UL reprocessing.

- [1] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlotsOctober2018
- [2] https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlotsAugust2018