CMS Silicon Strip Tracker Performance in Run 3

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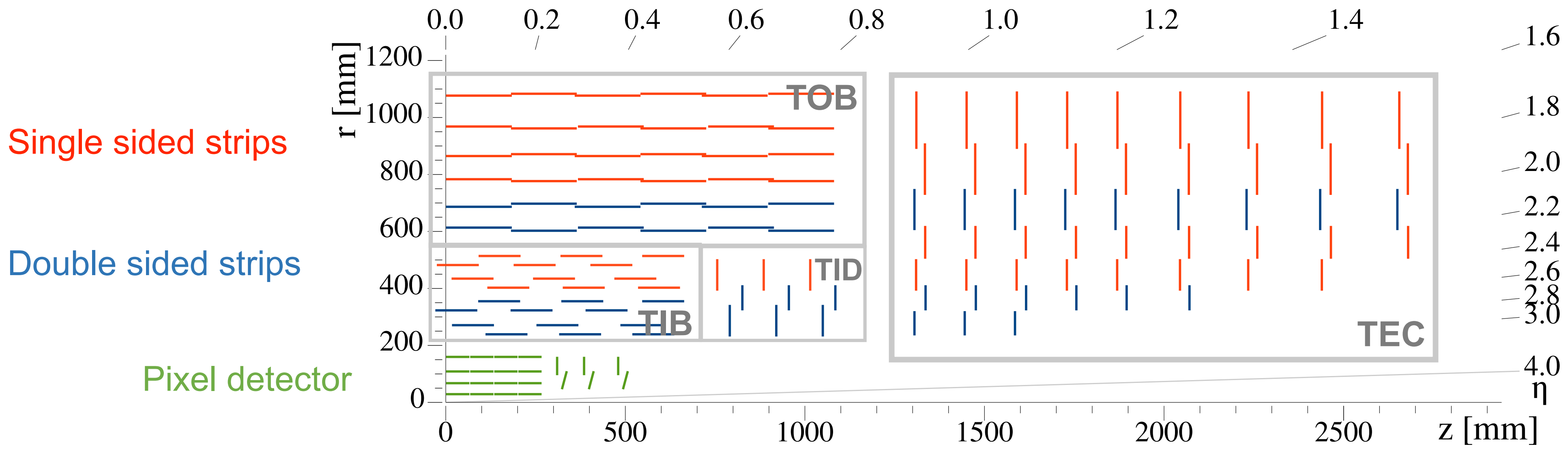
Jindrich Lidrych (Université catholique de Louvain)
on behalf of the CMS Collaboration

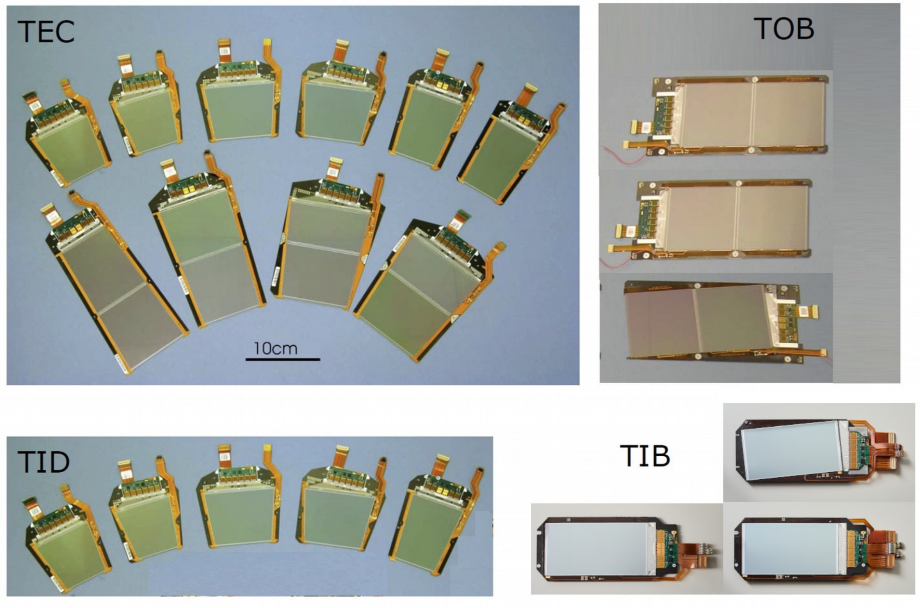
CMS Tracker detector

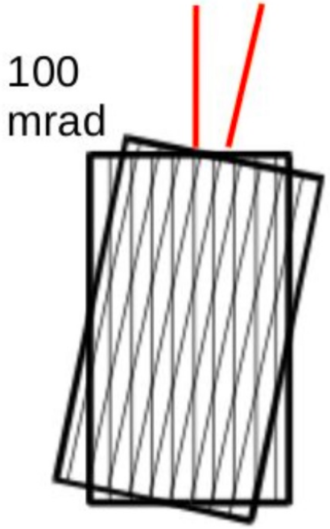
- The largest silicon tracker in the world: ~200 m^2 area, ~135 M channels
- All-silicon design
- Allows for high precision charged particle tracking
- Essential in particle identification, heavy-flavour tagging, trigger decisions, vertex reconstruction
- Comprised of:
  - **Pixel detector**: barrel (BPix) and forward endcaps (FPix)
  - **Strip detector**: inner barrel (TIB), outer barrel (TOB), inner disks (TID), end-caps (TEC)



CMS Silicon Strip Tracker

- Active area ~200 m^2 area, 5.6 m long, 2.5 diameter with 15148 silicon modules, 9.6 M channels
- 10 layers in barrel region (4 inner barrel, 6 outer barrel)
- 3 + 9 disks in the inner disks and endcaps
- Stereo modules (two modules with 100 mrad stereo angle) in 4 layers in barrel and 3 rings in endcap: 2D hits from 1D strips
- 320 μm “thin” sensors in inner layers (TIB, TID, TEC ring 1-4)
- 500 μm “thick” sensors in outer layers (TOB, TEC ring 5-7)
- Analog readout
- In operation since Run 1
  - Designed for a total integrated luminosity of 500 fb^{-1} and a lifetime of at least 10 years

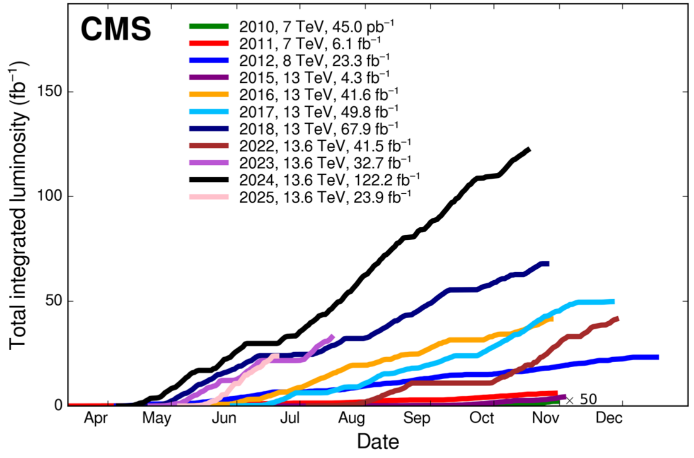




CMS Silicon Strip Tracker & LHC Run 3

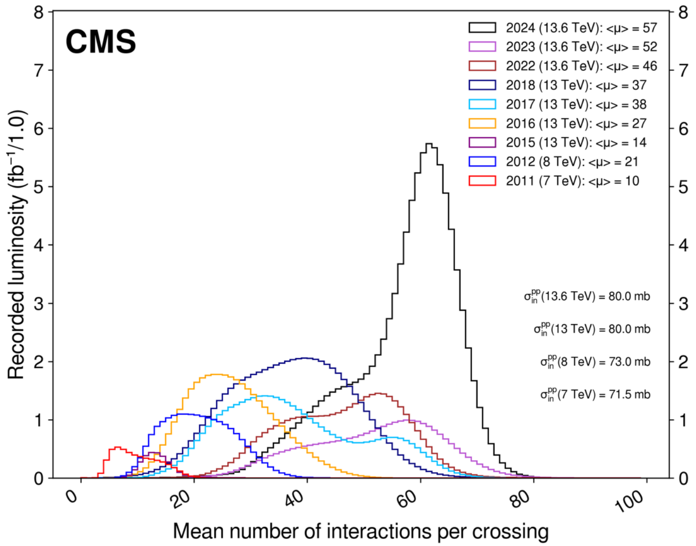
Run 3 conditions

- Luminosity delivered to CMS
  - Run 1 + Run 2 is ~192 fb^{-1}
  - Run 3 (till June 2025) is ~220 fb^{-1}
- Mean number of interactions per bunch crossing > 46
  - ~57 in 2024 vs ~37 in 2017/2028
- CMS is running at L1 trigger rate ~110 kHz



Challenging conditions: radiation damage

- Higher leakage current, less charge collected, reduced resolution, etc.

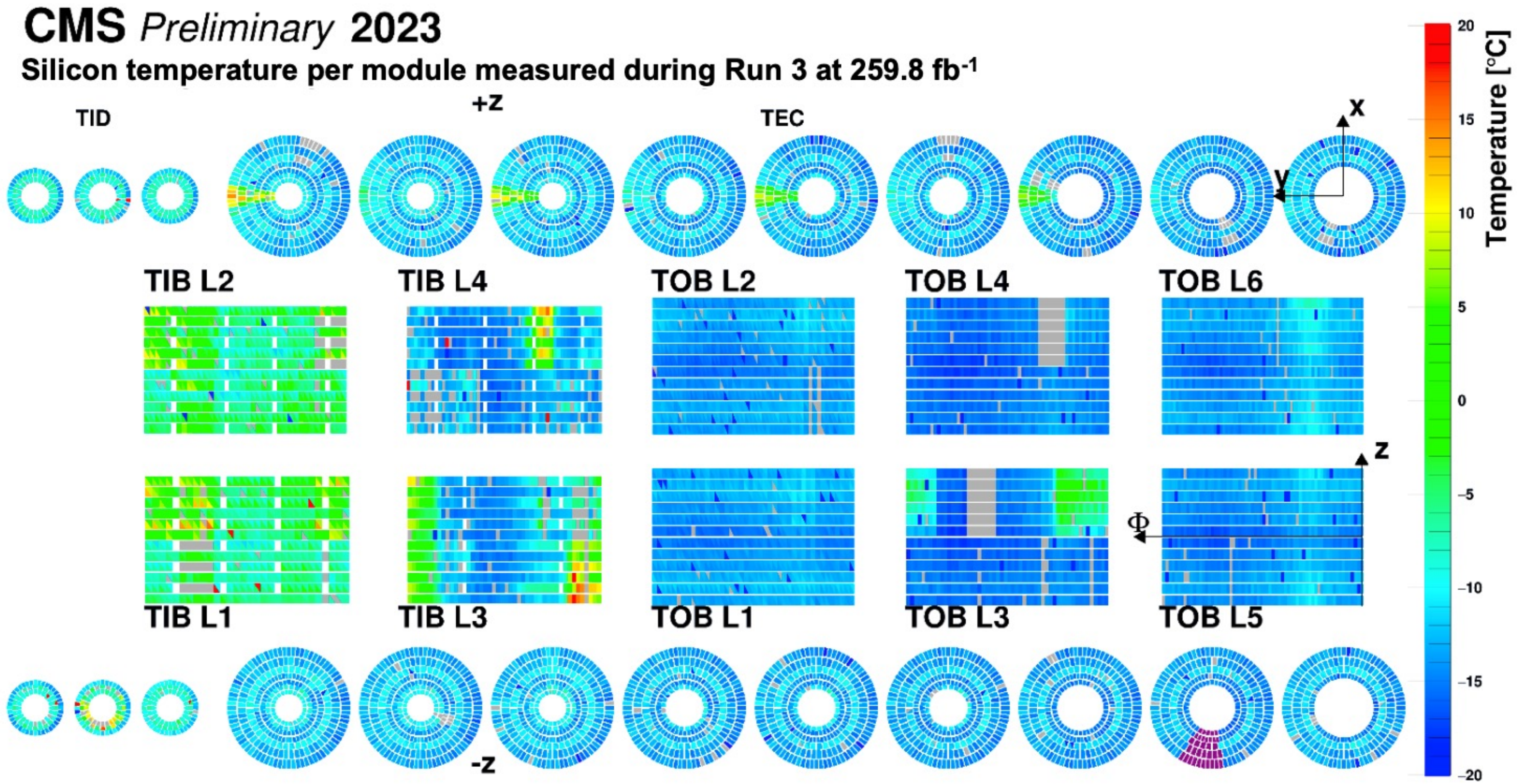


→ The last three years could represent > 50% of the pp data collected

→ How is the Strip Tracker operated after 15 years?

→ What is Strip performance after 15 years of operation?

Silicon temperature map per module during Run 3

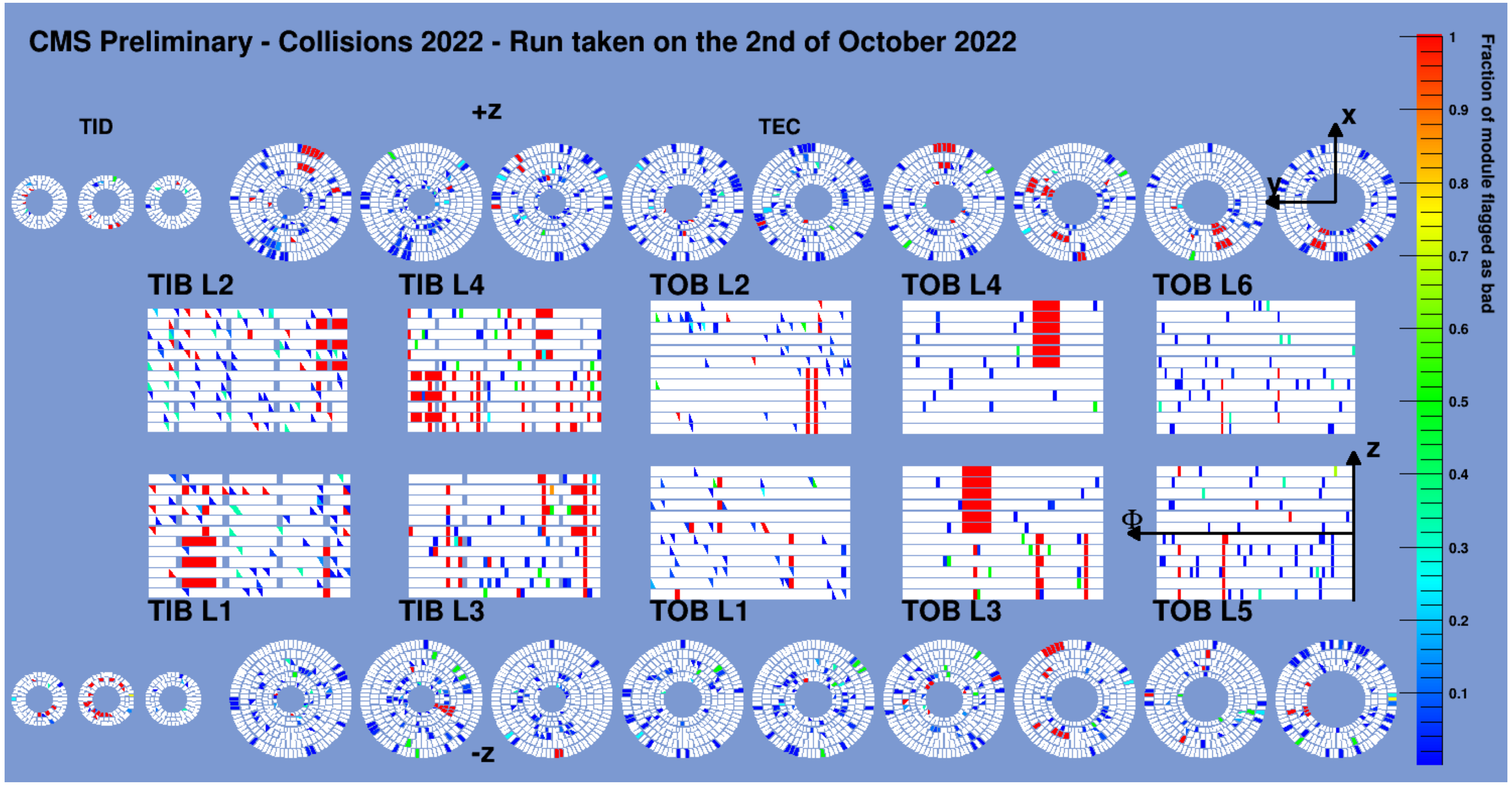


Visible features:

- Uncooled parts:
  - TOB + L3, TID –D2, TIB +/- L3, TEC + W1, W3, W5, W9, TIB L4
- Degraded cooling contacts:
  - TIB + L1, TIB + L2
- Grey regions: modules excluded from data-taking

- Detector is currently operated at -25 °C since the LHC technical stop No. 1 in June 2024
  - Detector operated at -22 °C between June 2023 and June 2024

Bad components fraction



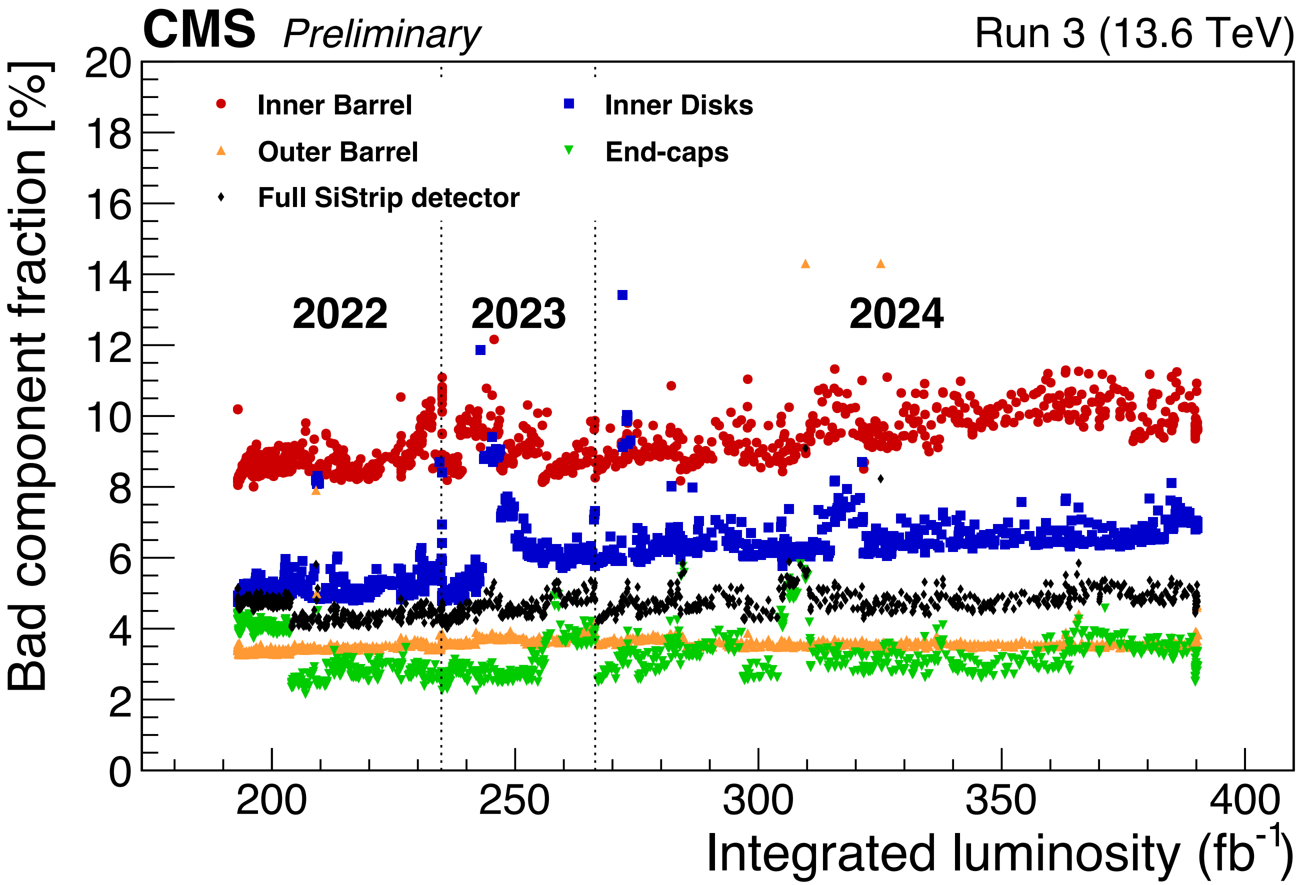
Fraction of modules flagged as bad:

- 0.9 – 1: Full module not in readout
- 0.3 – 0.9: One or more readout fiber not in readout
- 0.1 – 0.3: Single readout chip not in readout
- 0 – 0.1: Small group of strip not in readout

Knowledge of bad components is important for tracking

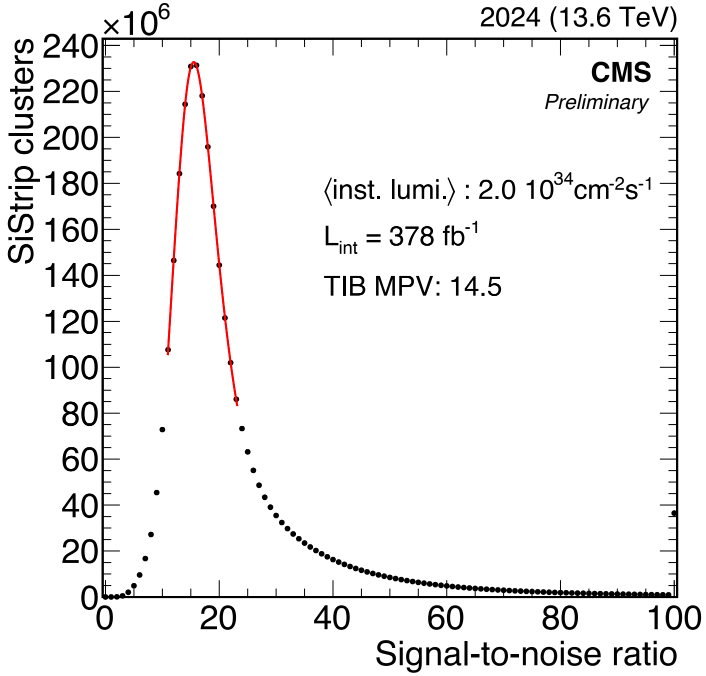
- Any strip, chip, module, power supply, electronics boards that’s misbehaving must be tagged

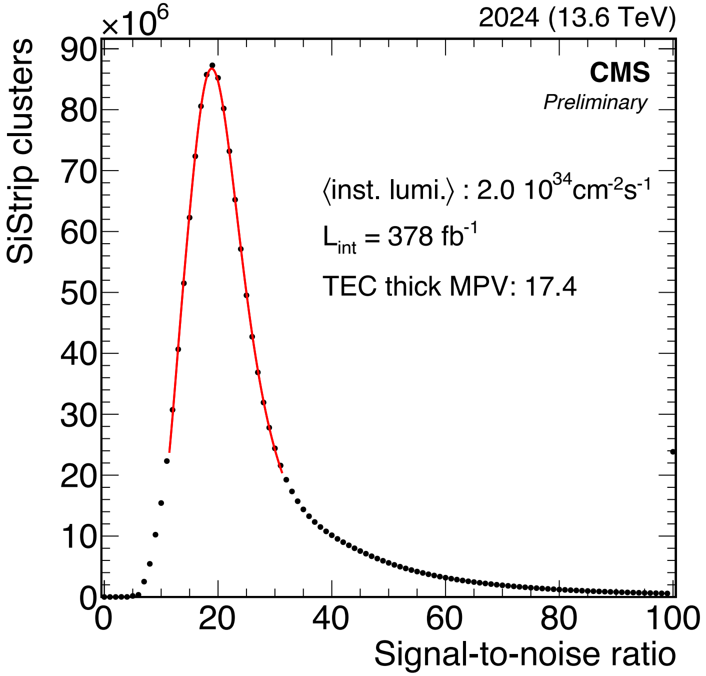
Evolution of bad components fraction

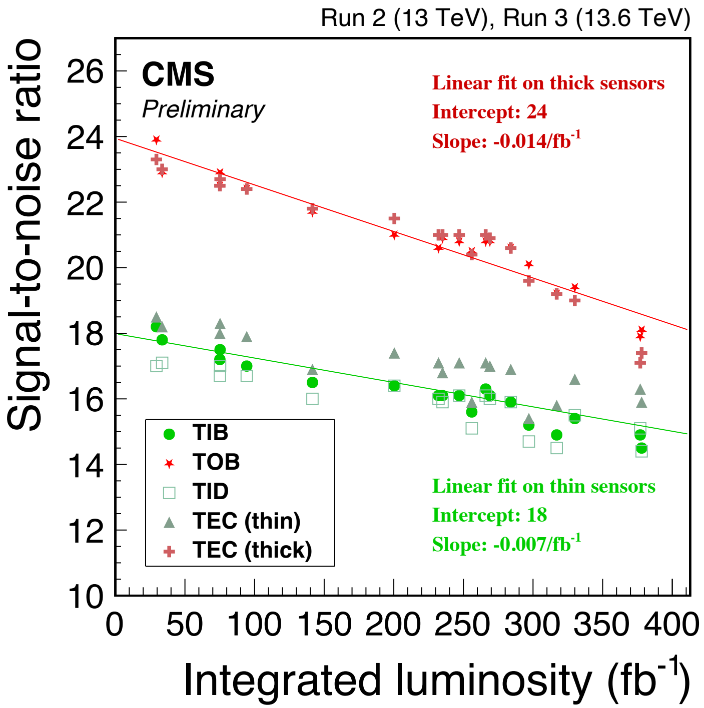


- Constantly monitored, and mostly stable
- Fraction of active channels during Run 3 ~96% (similar to Run 2)
- The drop in bad module fraction around 205 fb^{-1} is due to the recovery of a cooling loop in End-caps
- Several jumps are due to many modules whose power supplies were turned off

Signal-to-noise ratio

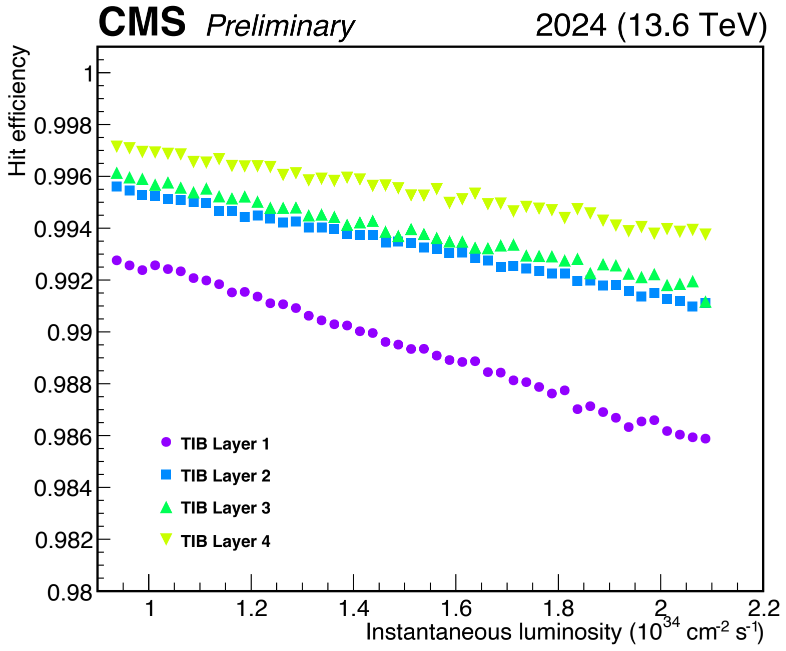


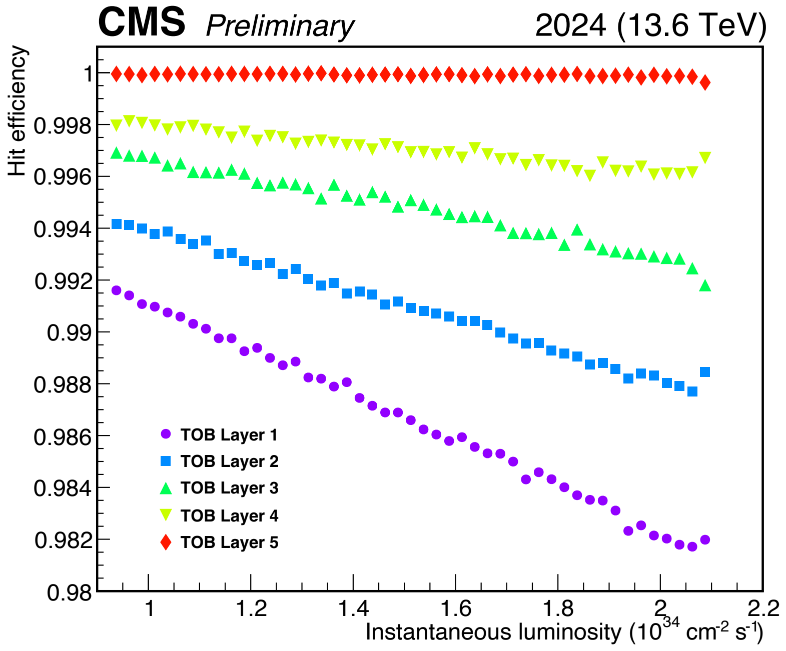




- The overall signal-to-noise ratio, corrected for pathlength inside the silicon, is shown for the end of 2024
- The position of the MPV of the peak is given, estimated from a fit to a Landau convoluted with a Gaussian distribution
- The S/N scales with integrated luminosity
  - As expected, a decrease of S/N is observed with time
  - The predicted S/N at the end of Run 3 exceeds the detector design specification of an S/N value of 10

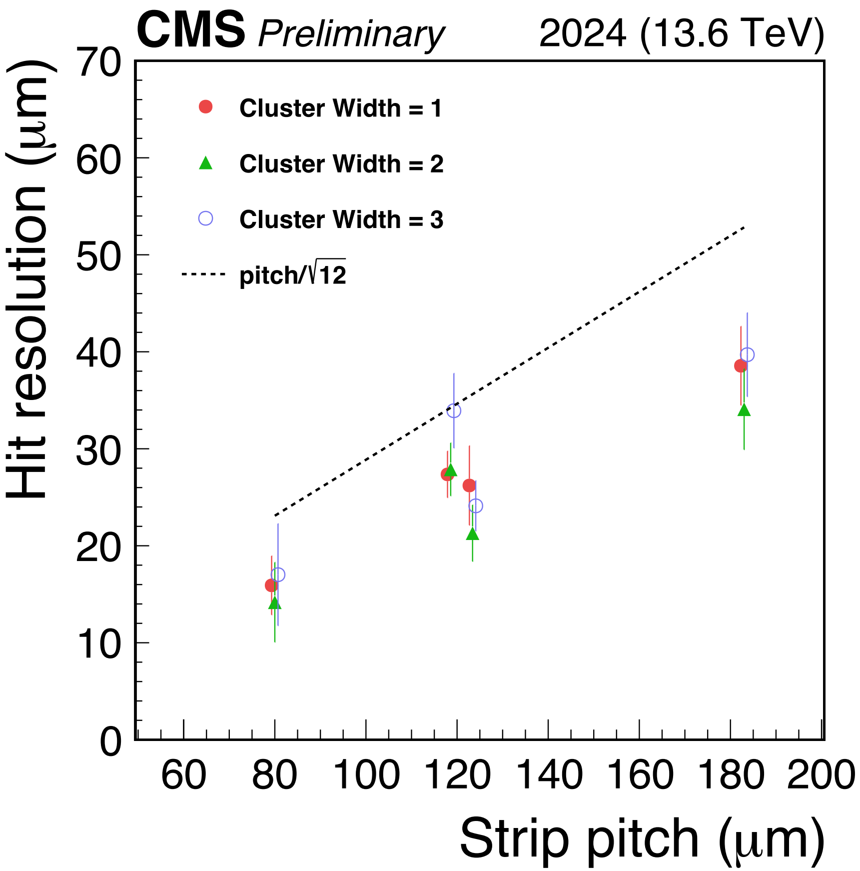
Hit efficiency



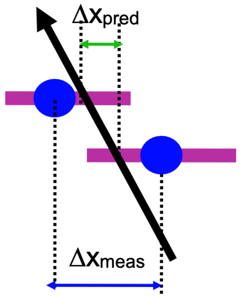


- The hit efficiency is defined as the ratio of detected hits to the number of expected hits belonging to a track.
- Regular measurements with high-quality tracks are made using collision and cosmic data
- The hit efficiency for four TIB layers (left) and five TOB layers (right) as a function of the instantaneous luminosity from a standard fill with luminosity under $2.2 \cdot 10^{34}$ $cm^{-2}s^{-1}$
- The hit efficiency > 0.985 (0.98) for the innermost layer in TIB (TOB)

Hit resolution



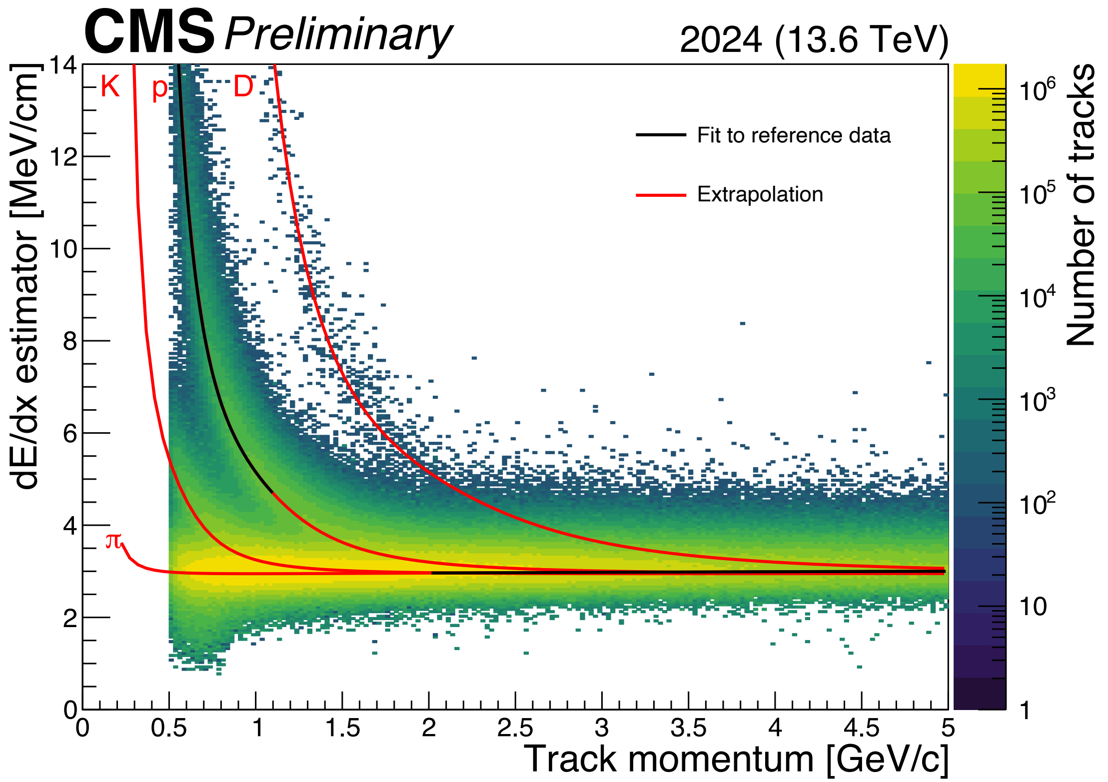
- Strip hit resolution is derived by selection pairs of hits in different types of overlapping sensors and for different cluster widths expressed in units of number of strips



$$\sigma_{\text{hit}} = \frac{\sqrt{\sigma^2_{\text{meas-pred}} - \sigma^2_{\text{pred}}}}{\sqrt{2}}$$

- Strip hit resolution is shown for 2024 data
- The theoretically expected resolution from a binary readout tracking detector (i.e., hit or no hit) is also displayed
- By measuring the fraction of charge collected by adjacent strips, the hit position can be interpolated more precisely, leading to a resolution significantly better than the binary limit

Energy loss measurement



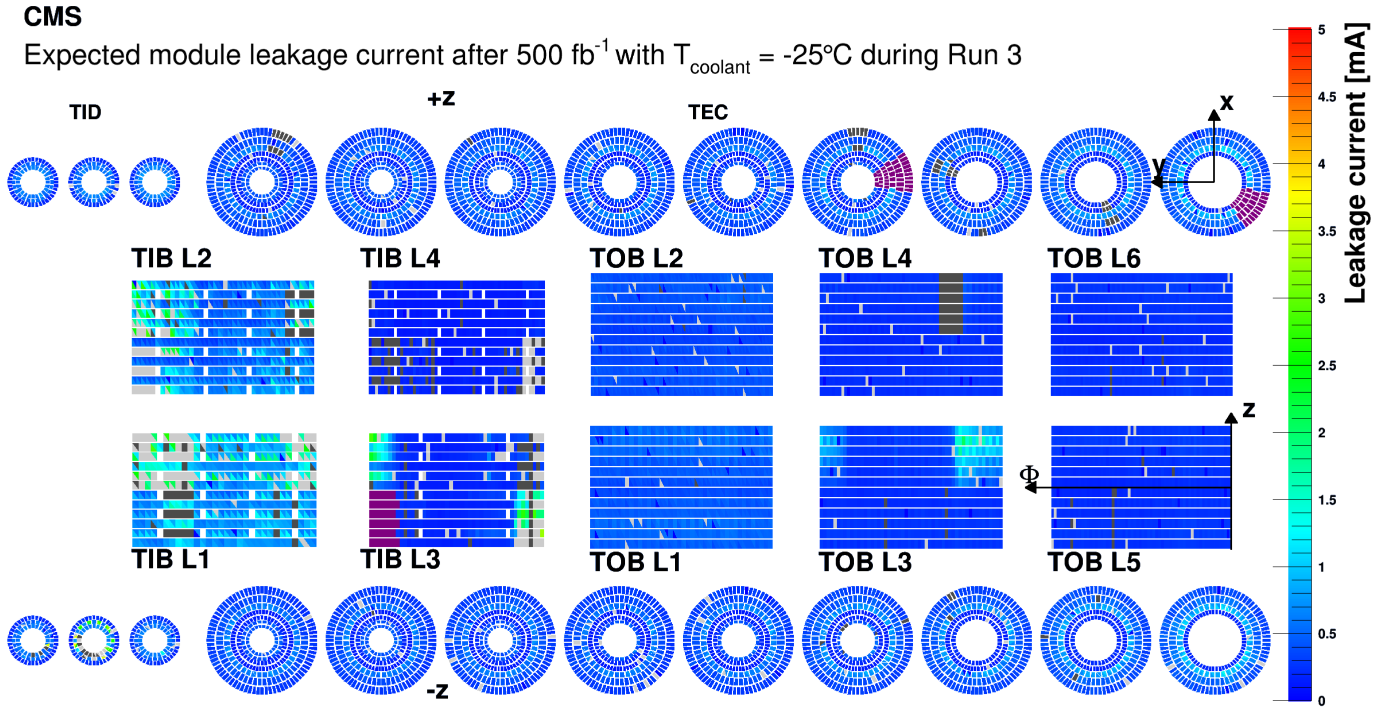
- The energy loss is estimated by using events with a good reconstructed primary vertex, tracks passing the high purity selection
- A saturation correction algorithm based on cross-talk inversion is applied to selected clusters to recover high-energy deposits
- The energy loss estimator is computed from the dE/dx of the associated hits in the silicon strip tracker using the harmonic mean of grade k = -2:

$$\frac{dE}{dx} = \left(\frac{1}{N}\sum_i (\Delta E/\Delta x)^k\right)^{\frac{1}{k}}$$

- The data were fitted on the shown proton and pion band and then extrapolated on the deuteron and kaon bands

Radiation damage projections for the end of Run 3

- The predicted status of the SST after an integrated luminosity of 500 fb^{-1} and cooled down to -25°C



Leakage current

- Some groups of modules in the TIB L1, L2, L3 show elevated leakage currents of around 2-3mA per module and these could also potentially become inoperable
- The gray areas: the maximum power supply is reached or one or more modules experienced thermal runaways
- The purple regions: lacked appropriate input parameters for the simulation

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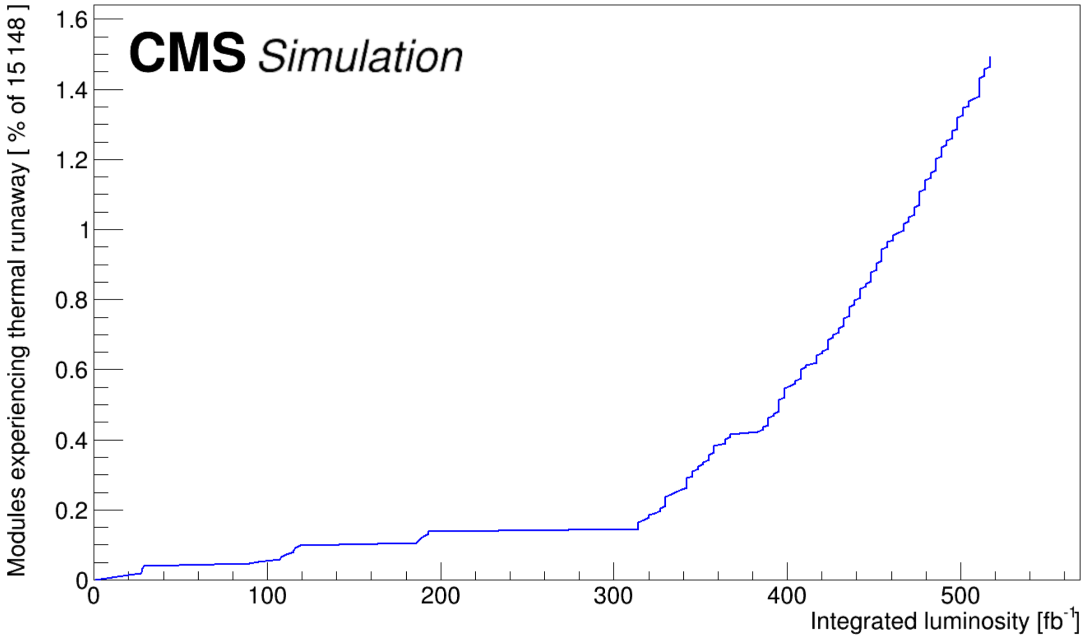


Thermal runaway

- Fraction of modules affected by thermal runaway as a function of the integrated luminosity
- A module is considered to reach thermal runaway if during the iterative simulation the self-heating contribution continues to increase
- Rapid increase above 300 fb^{-1} and reaches about 1.5% at 500 fb^{-1}

Conclusion

- The LHC is in its last years before its HL-LHC upgrade
  - Significant fraction of pp data still being collected

- CMS Silicon Strip Tracker maintains its outstanding performance
  - Run 3 performance exceeds the original detector design specifications
  - Despite being in operation since Run 1
  - Despite being exposed to radiation damage

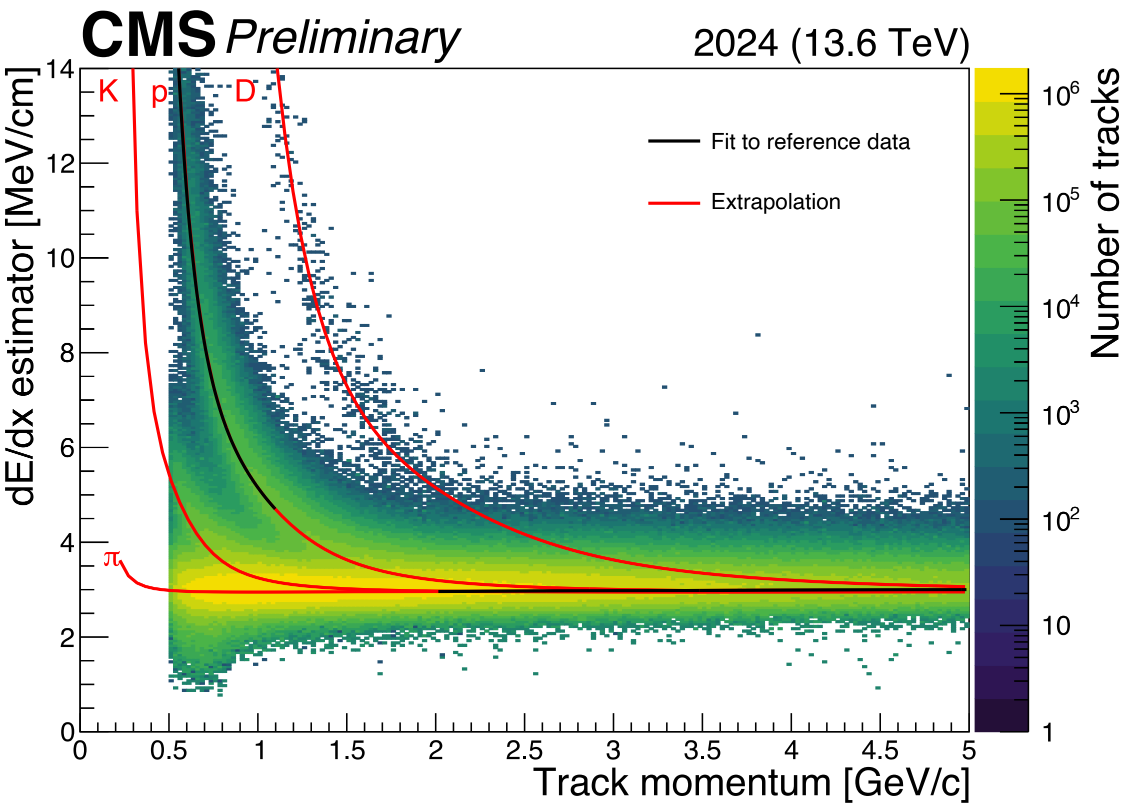
- CMS Silicon Strip Tracker is expected to continue delivering high quality tracks until end of Run 3

References:
[1] CMS Silicon Strip Tracker Performance Results in 2024, CMS-DP-2025-020
[2] Bad components of the CMS Silicon Strip Tracker with early Run 3 data, CMS-DP-2022-048
[3] CMS Silicon Strip Tracker Maps, CMS-DP-2023-083

More details about CMS Strip Performance in Run 2 and projections for the end of Run 3:
Operation and performance of the CMS silicon strip tracker with proton-proton collisions at the CERN LHC, arXiv:2506.17195, Submitted to the *Journal of Instrumentation*.

Back-up

Energy loss measurement



Energy loss measurement as a function of the track momentum using the Pixel-Less Harmonic-2 estimator. The data were fitted on the shown proton and pion band using the function

$\frac{dE}{dx} = p_1 \left(\frac{\sqrt{(\beta\gamma)^4 + 4(\beta\gamma)^2} - (\beta\gamma)^2}{2} \right)^{\frac{p_2}{2}} \ln(1 + [p_3 \beta\gamma]^{p_4}) - p_5$ where p_1, p_2, p_3, p_4 and p_5 are the fit parameters, that was then extrapolated on the deuteron and kaon bands.