# CMS Outer Tracker: Operational Experience, Performance and Lessons Learned


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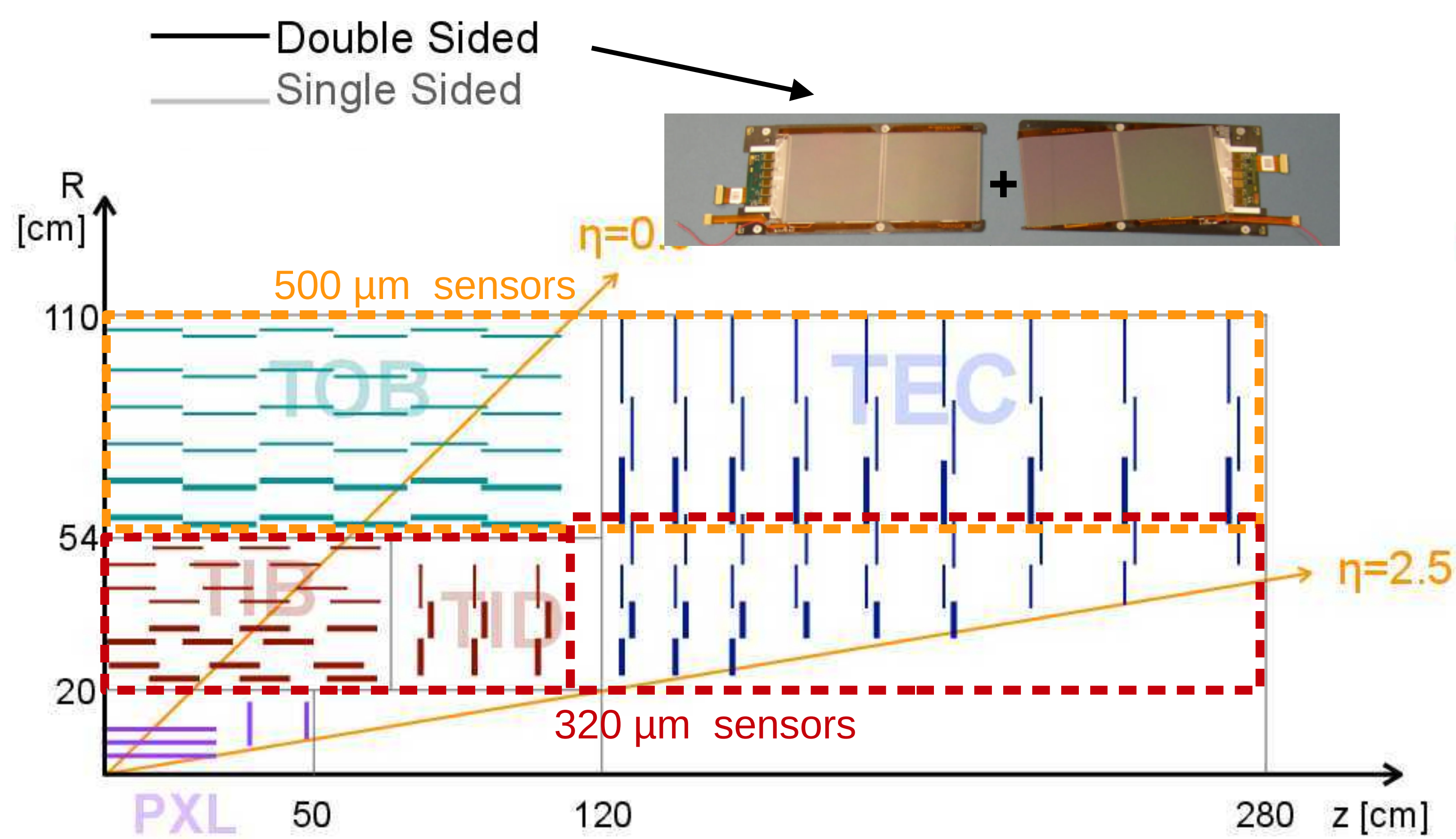
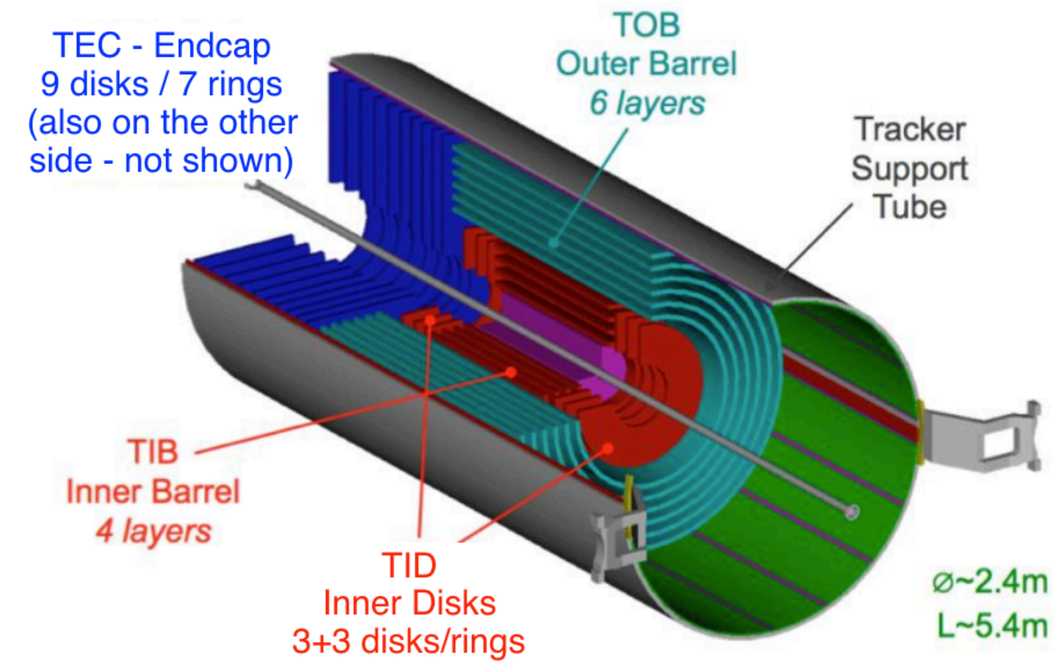
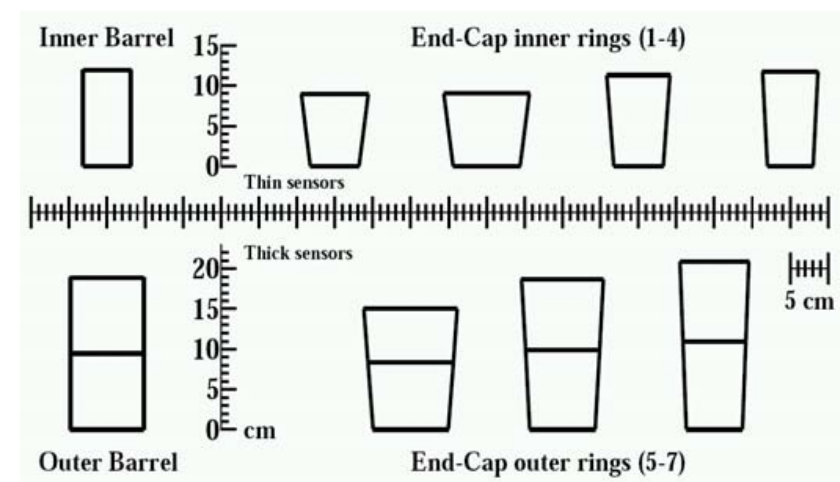
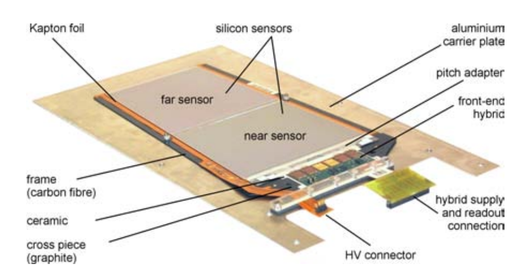
# CMS Outer Tracker




- Active area 200m$^2$, 5.6 m, 2.5 m diameter
- 15148 silicon modules, 9.6 milion electronic channels
- 10 layers in barrel region:
  - 4 Inner Barrel (TIB), 6 Outer Barrel (TOB)
- 3+9 disks in the Inner Disks (TID) and Endcaps (TEC)
- Stereo modules (two modules with 100 μrad stereo angle) in 4 layers (3 rings) in barrel (endcap)
- 320 μm Si in inner layers (TIB, TID, TEC ring 1-4)
  500 μm Si in puter layers (TOB, TEC ring 5-7)
- Analog readout

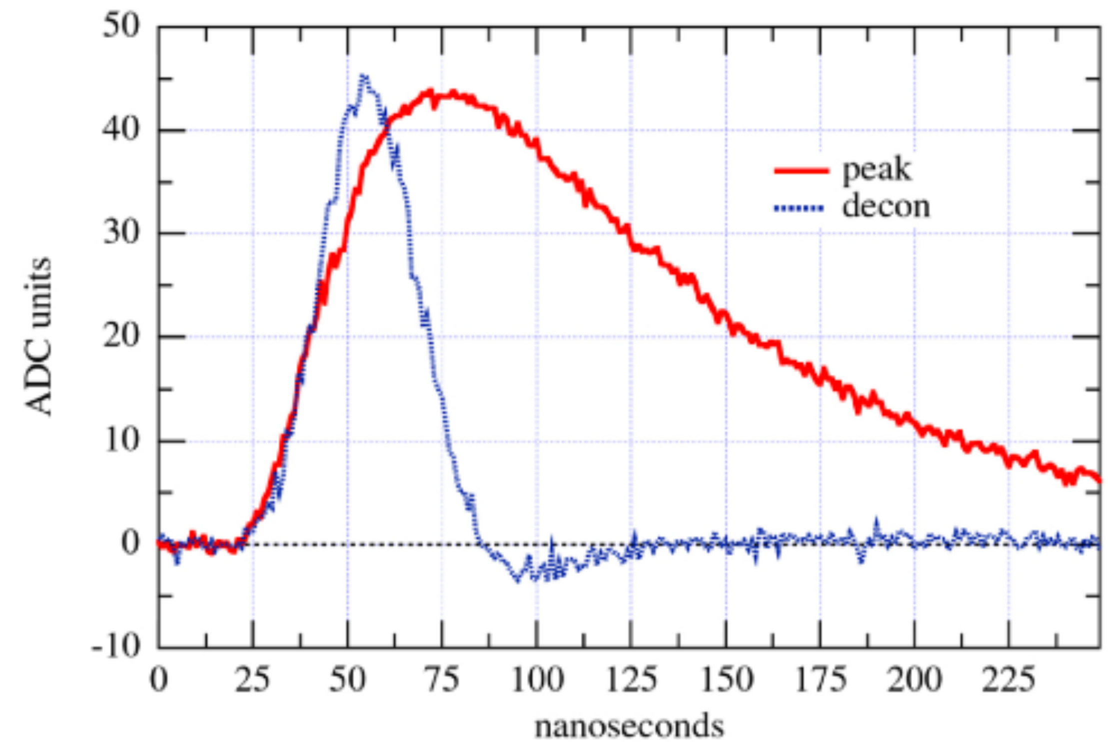


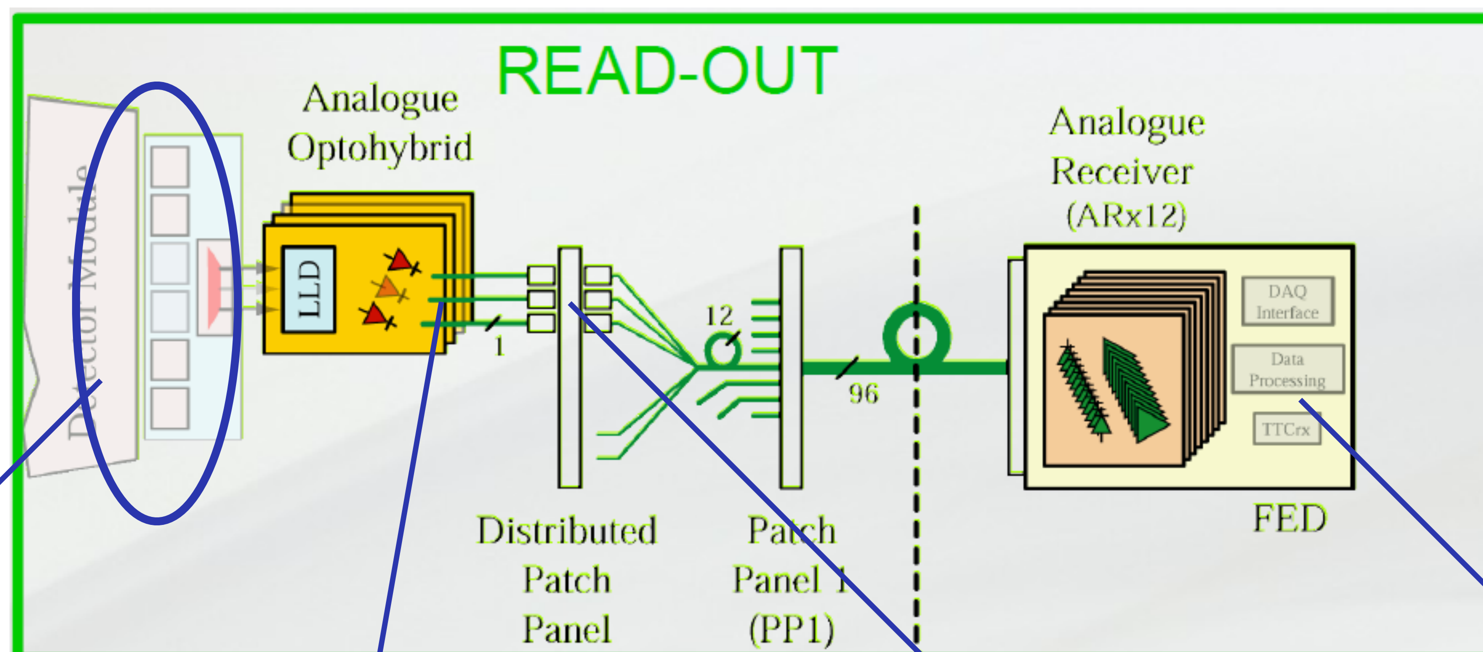

- Longer strips in outer layers/rings due to lower occupancy
- Longer strips → thicker sensors to keep high signal to noise ratio

# Tracker Readout

- Tracker readout is analog based on APV25 chips
- APV25 chip has **two readout modes**
  - **Peak mode:** single sample from CR-RC shaper
  - **Deconvolution mode:** 3-sample average to effectively shorten pulses (less out-off-time contribution)
- Each chip reads charge peak of **128 strips**
- Signals from two chips are multiplexed and sent to a laser driver
- Analog to optical conversion on Analog-opto-hybrid (AOH)
  - Linear Laser Driver
  - Edge emitting laser diodes
- Transfer to off-detector readout electronics

APV readout modes



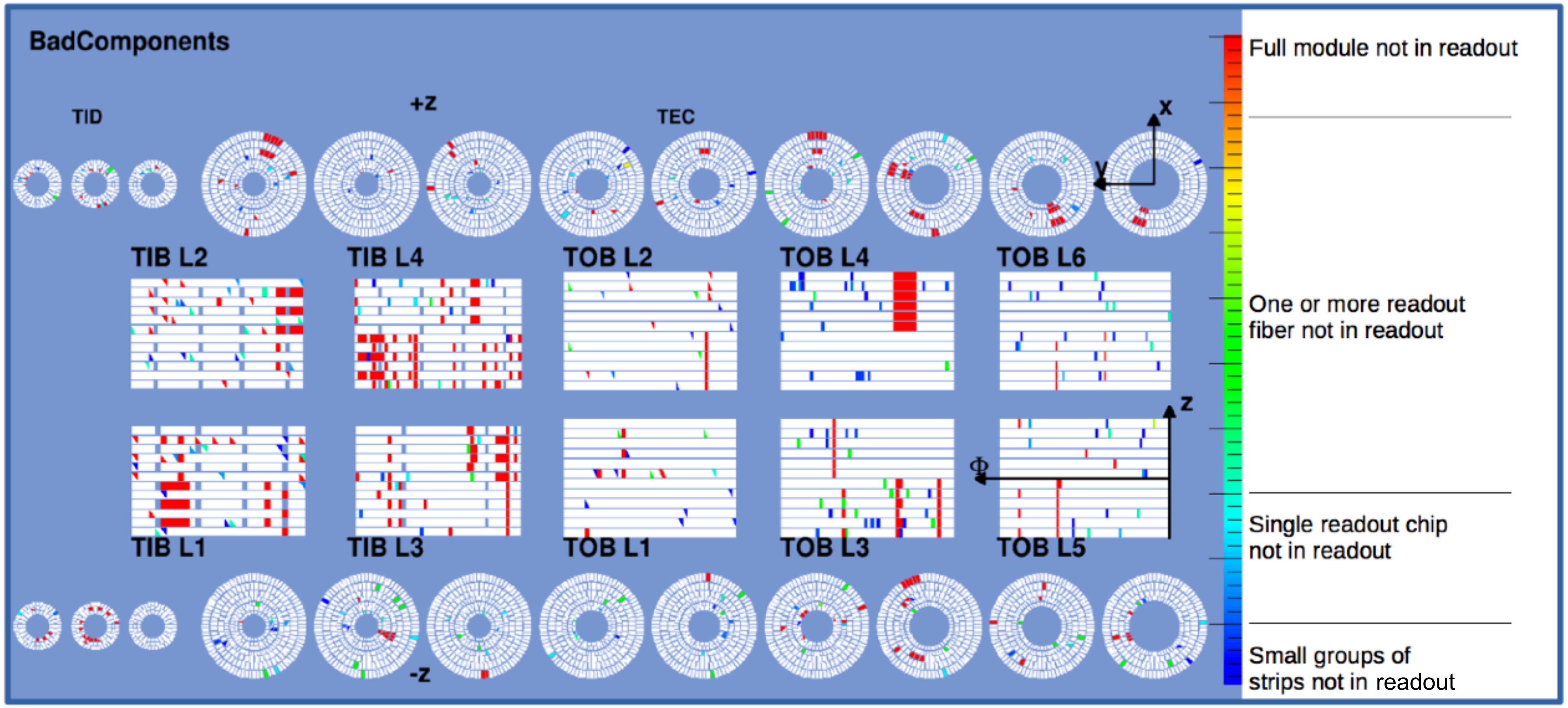

Tracker modules have 4 or 6 APV chips

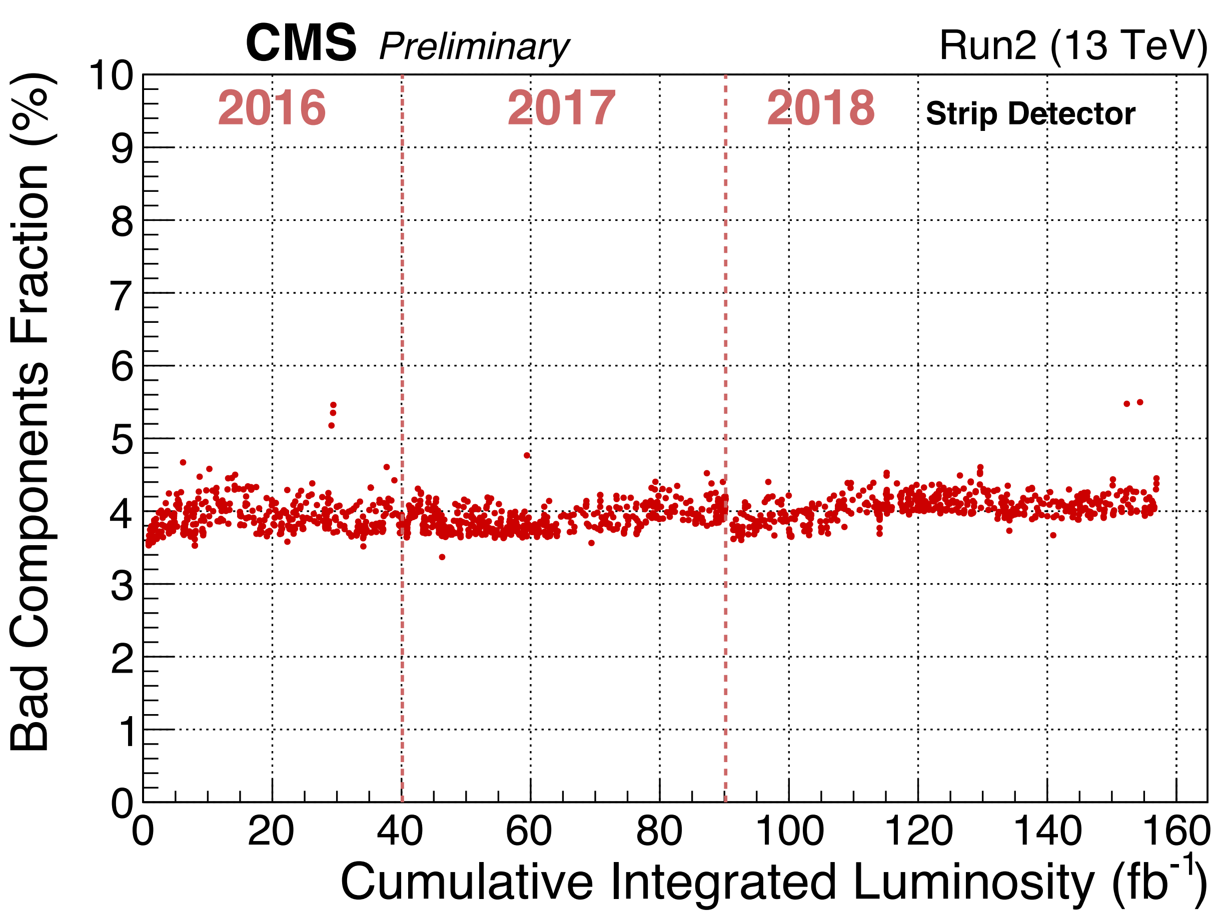
One LLD for each APV pair

One optical fibre for each APV pair

Off-detector FEDs

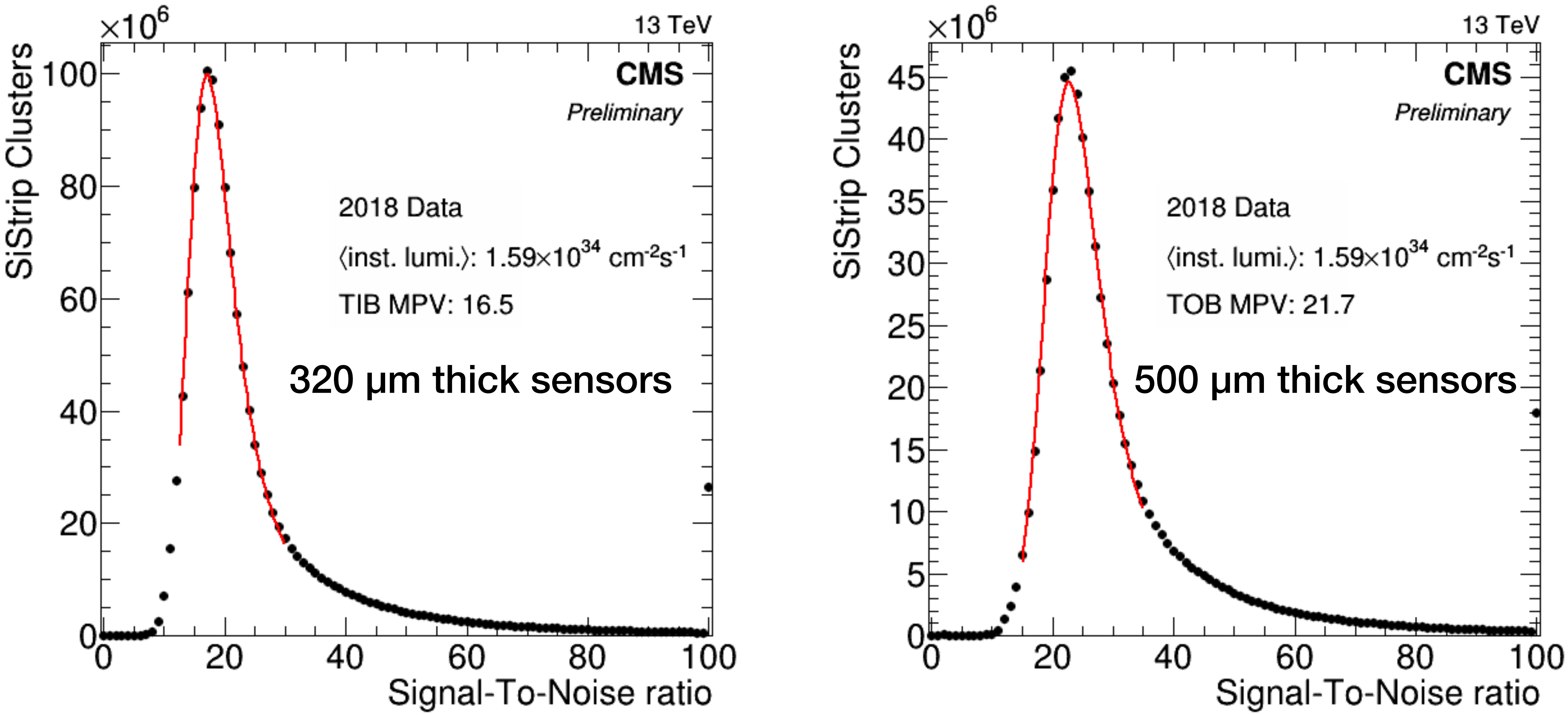
# Detector status in Run 2




- Fraction of active components **~96 %**
- The bad components include:
  - Read-out channels excluded from the cabling (typically FEDs)
  - Unpowered groups of modules
  - Single APV25 chip or groups of strips masked from the offline reconstruction by a Prompt Calibration Loop algorithm [noisy channels]
- Stable during Run 2

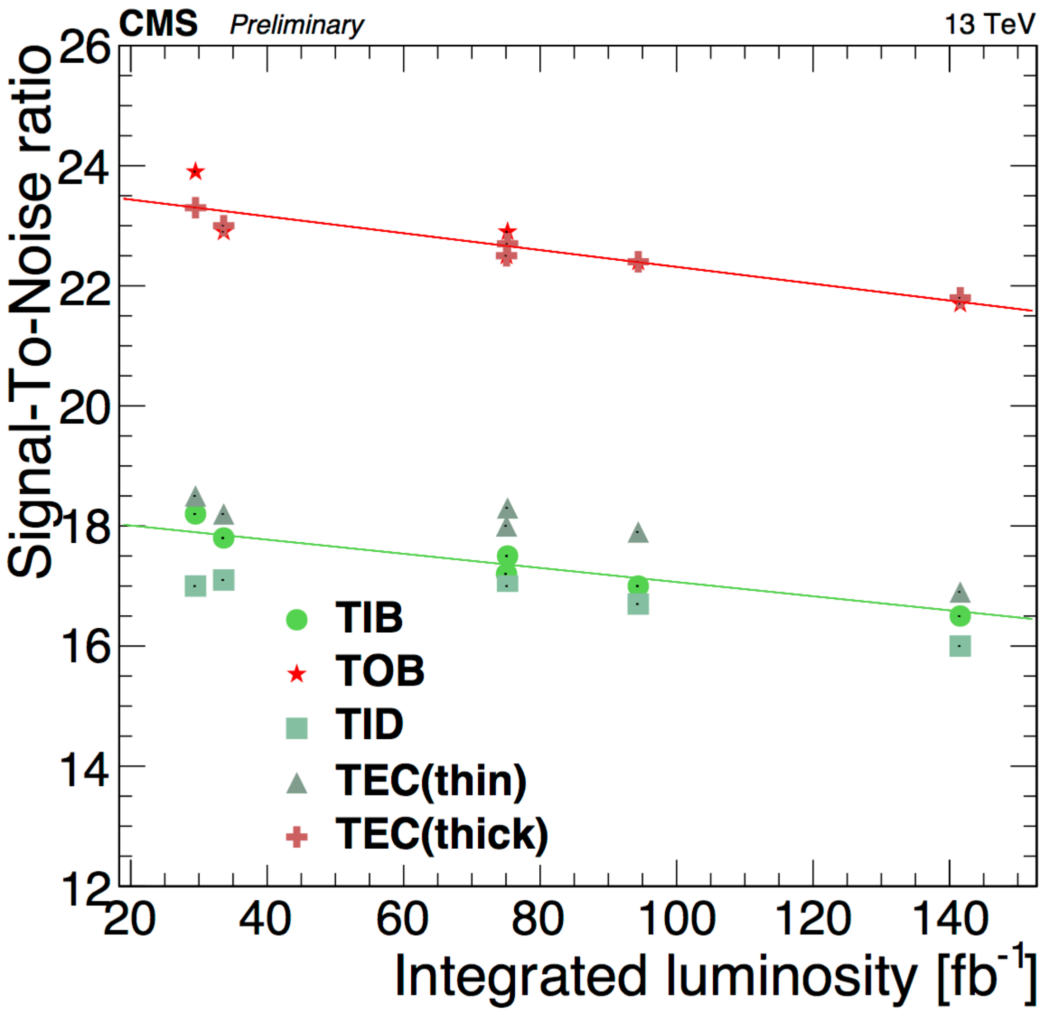
# Signal to noise performance

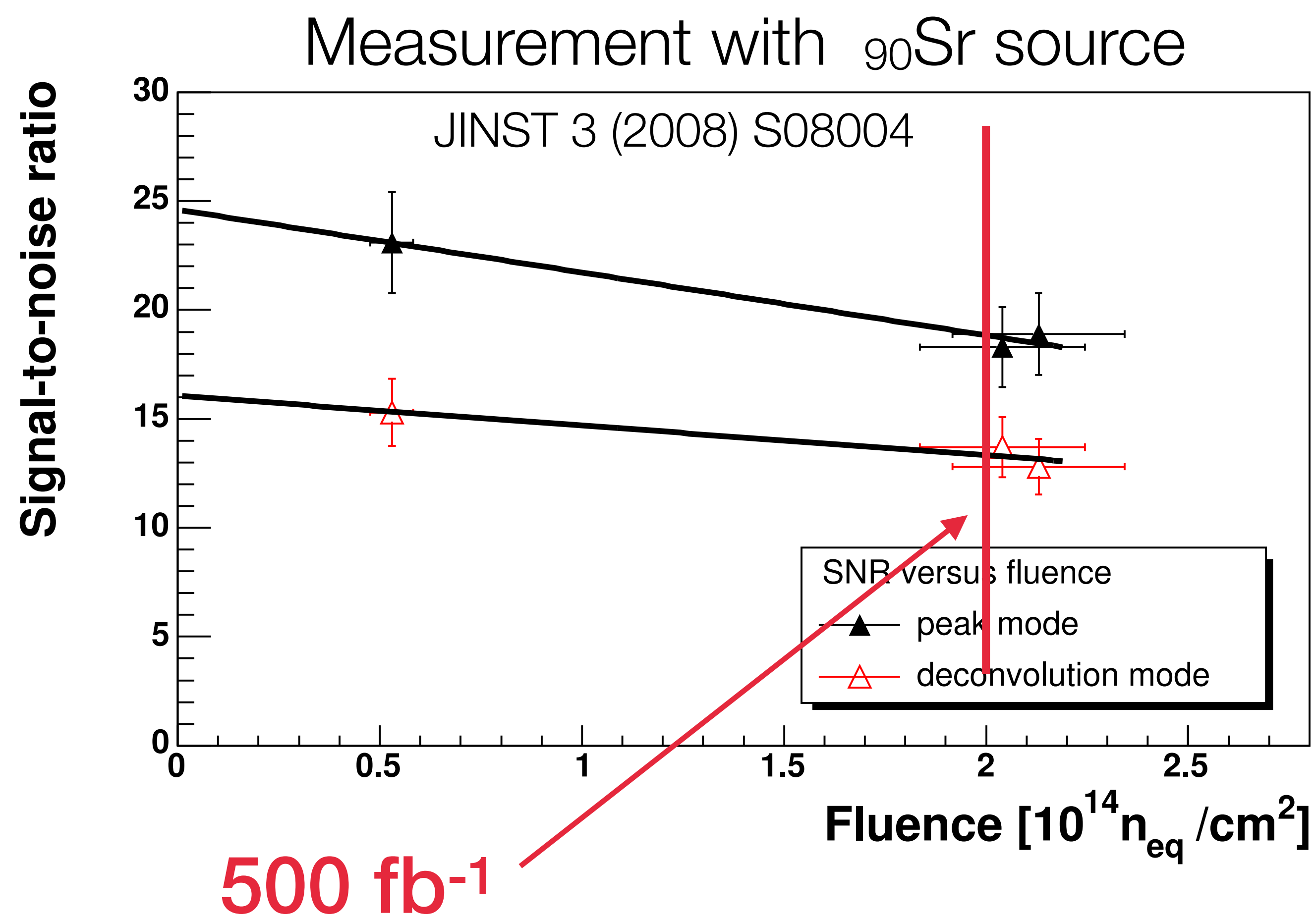



| | TIB | TOB | TID | TEC thin | TEC thick |
|---|---|---|---|---|---|
| **2018 - $\int L dt = 11.5\ fb^{-1}$** | 16.5 | 21.7 | 16.0 | 16.9 | 21.8 |

High signal to noise ratio

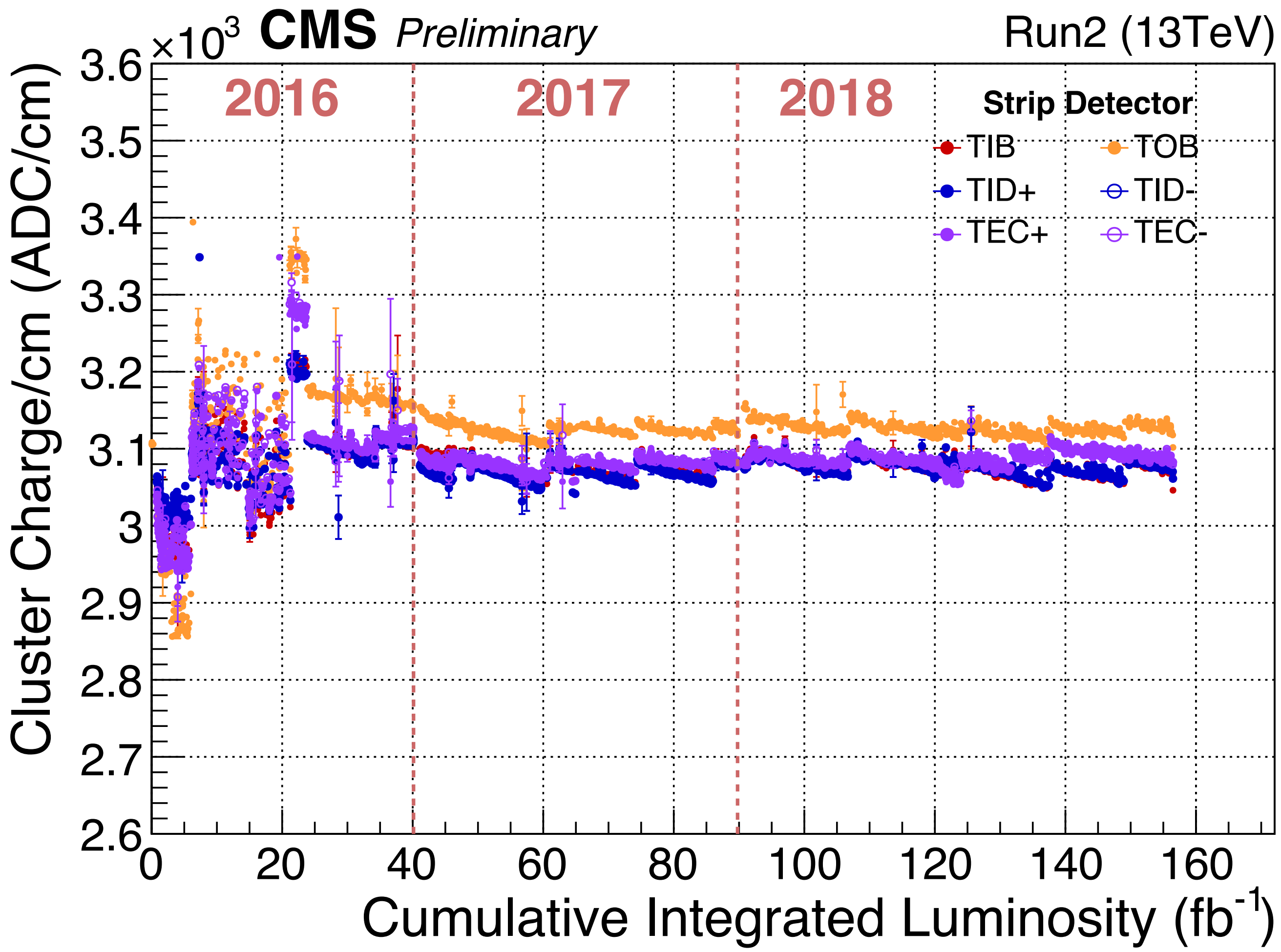
# Signal to noise performance



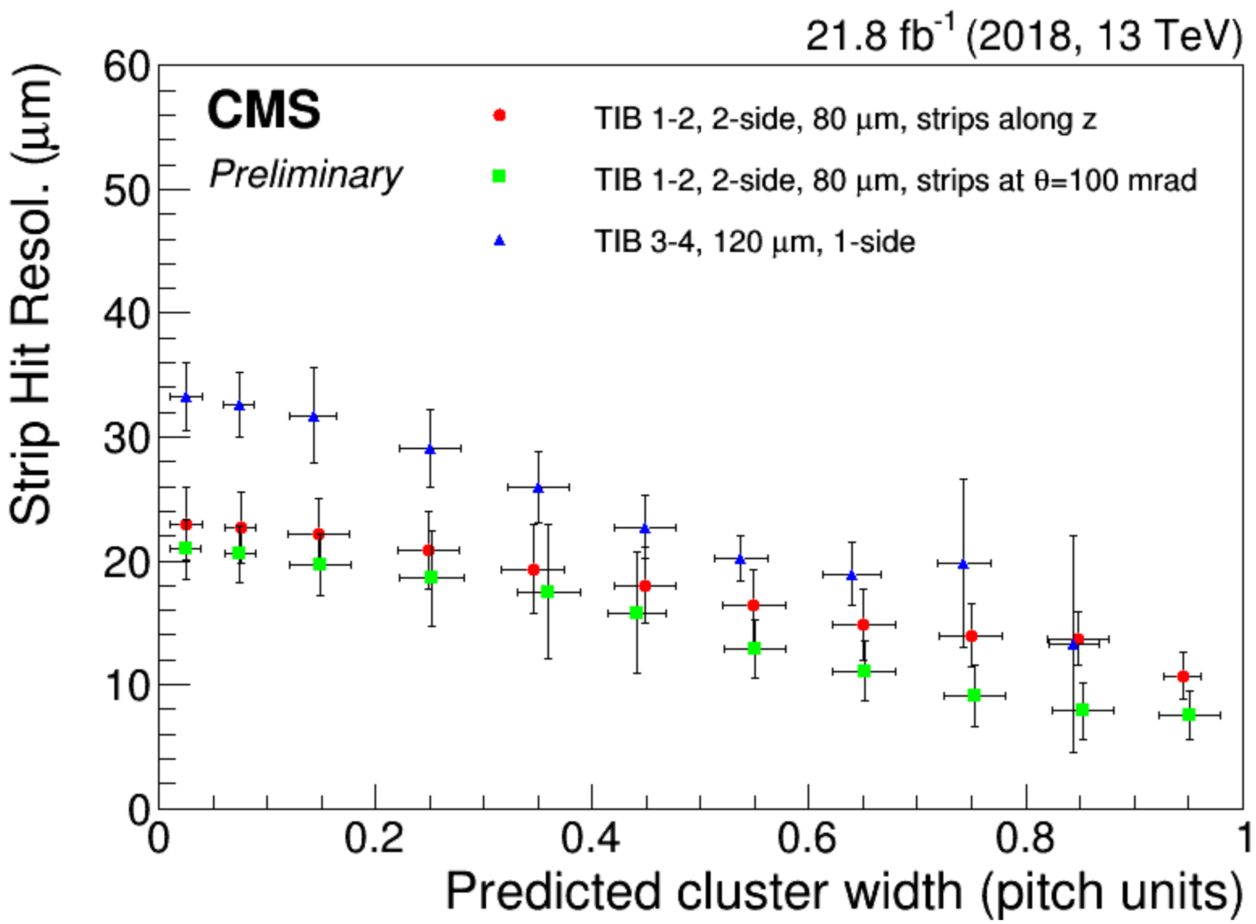

- Very high and stable signal-to-noise ratio in Run 2
- As expected, signal-to-noise ratio is decreasing with increasing sensor irradiation
- At the end of Run 3, signal-to-noise ratio of about 12 (18) expected in the thin (thick) sensors

# Cluster charge

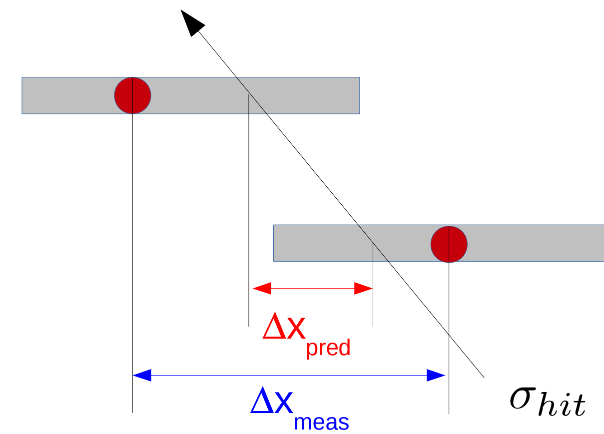



- Strip charge signal is corrected during local reconstruction to guarantee stability over time
- Large fluctuations in the first 20/fb of 2016 data caused by the saturation of the pre-amplifier of the APV chip
  - The effect will be partially mitigated with the updated calibration derived for the Legacy reprocessing of the Run 2
  - The later discontinuities in the trend are due to the updates of the gain and noise/pedestal values.
- Cluster charge is used to remove out-of-time pile-up clusters from tracking
  - Cut is placed at around 1000 ADC/cm → no in-time hits are removed

# Hit resolution

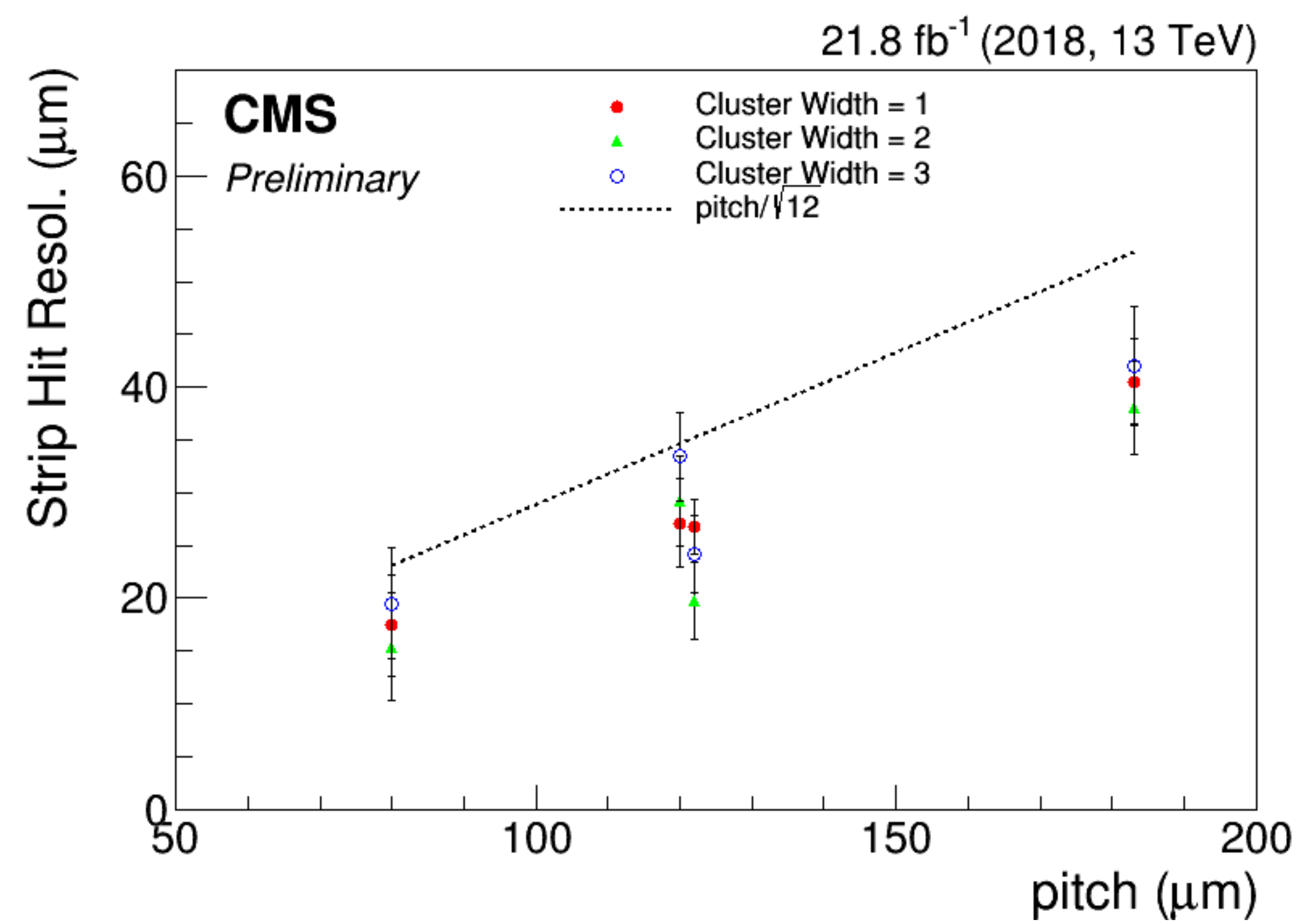


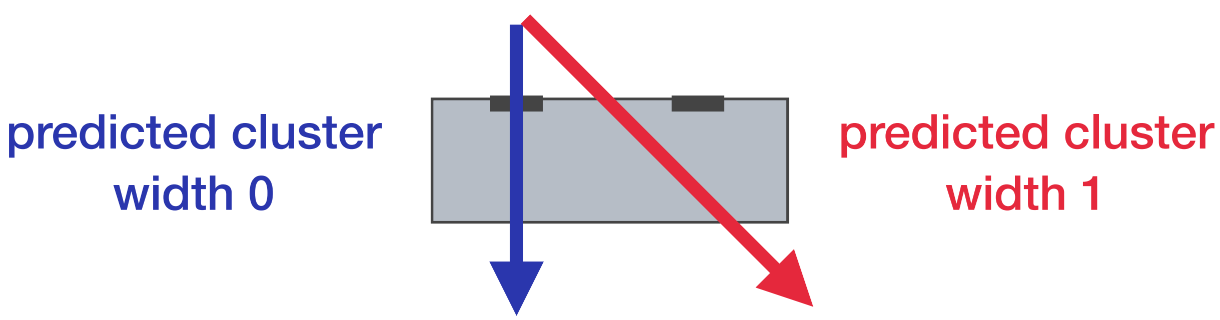

## Pair method




Hit resolution is computed by using overlapping modules in the same layer

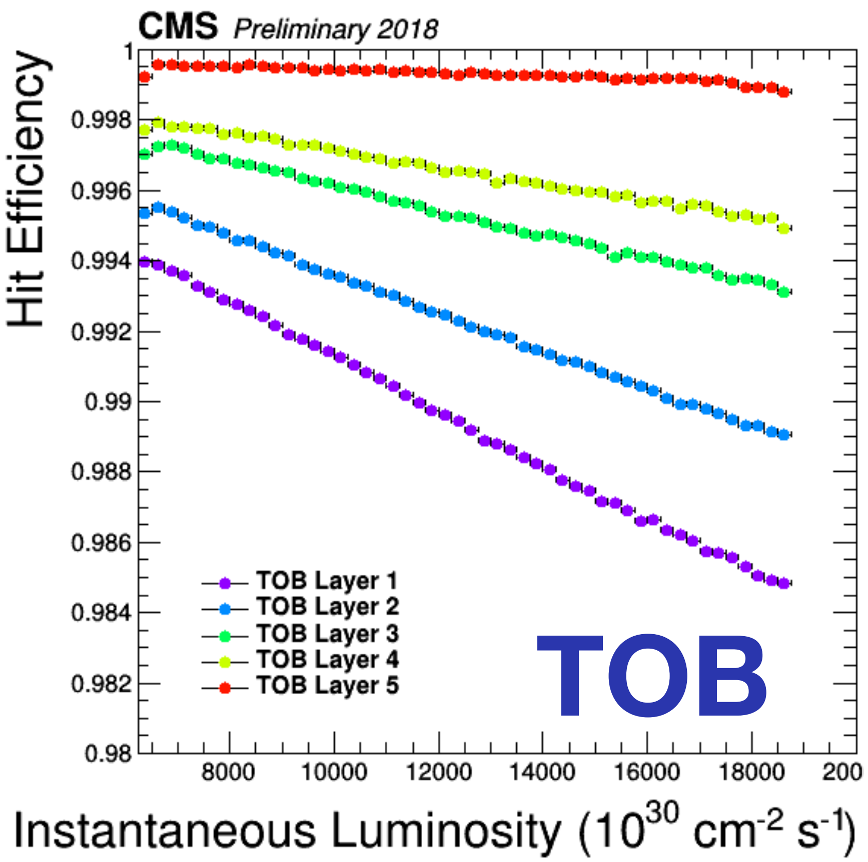
$$\sigma_{hit} = \frac{\sqrt{\sigma(meas-pred)^2 - \sigma^2_{meas}}}{\sqrt{2}}$$

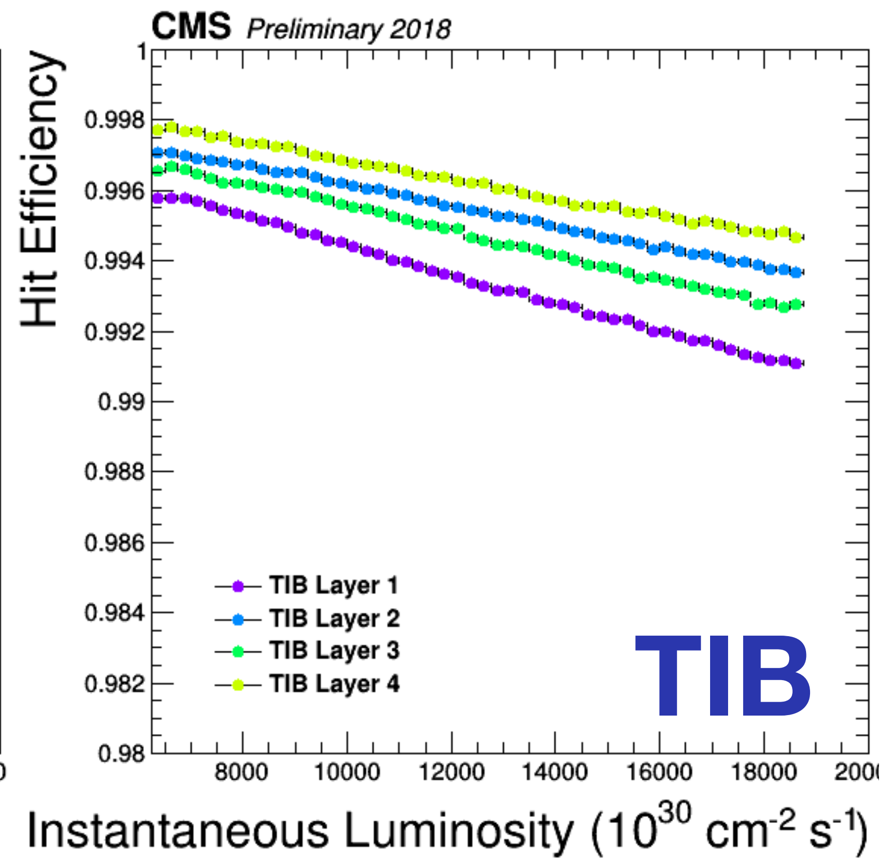


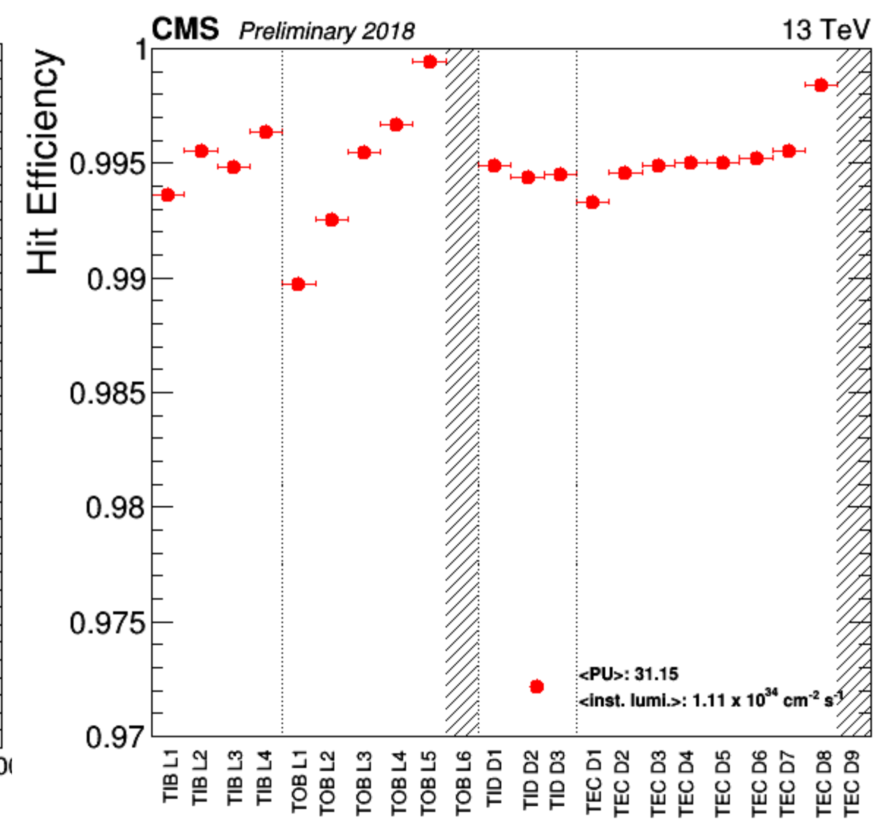



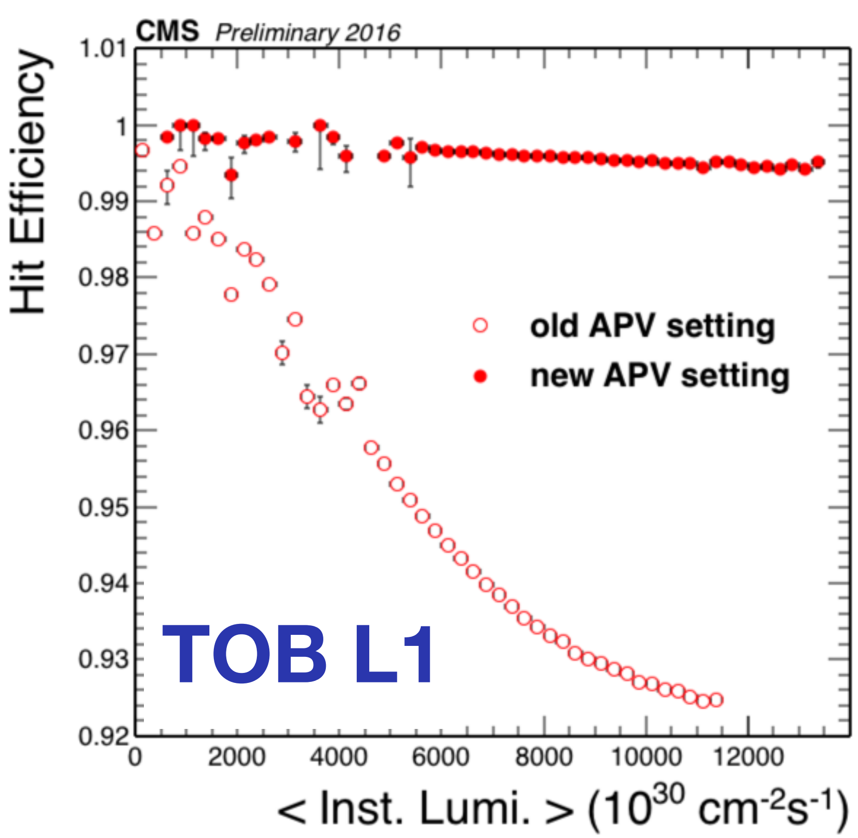

- Resolution is improving for the larger predicted cluster width due to the charge sharing
- Expected scaling with strip pitch is observed

# Hit efficiency



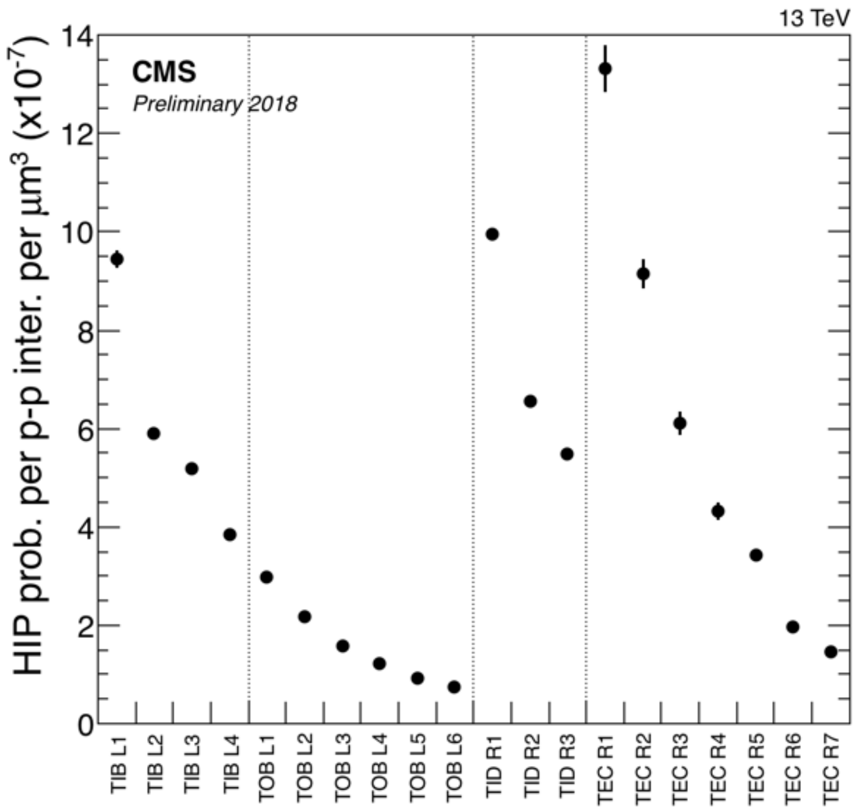




- Hit efficiency > 98 % at highest instantaneous luminosities
- Changes linearly with instantaneous luminosity
- No indication of new saturation effect in pre-amplifier
- At <PU> of 31.15 (IL 1.1x$10^{34}$cm$^{-2}$s$^{-1}$) efficiency $\gtrsim$ 99 %

# Highly ionising particles (HIP)

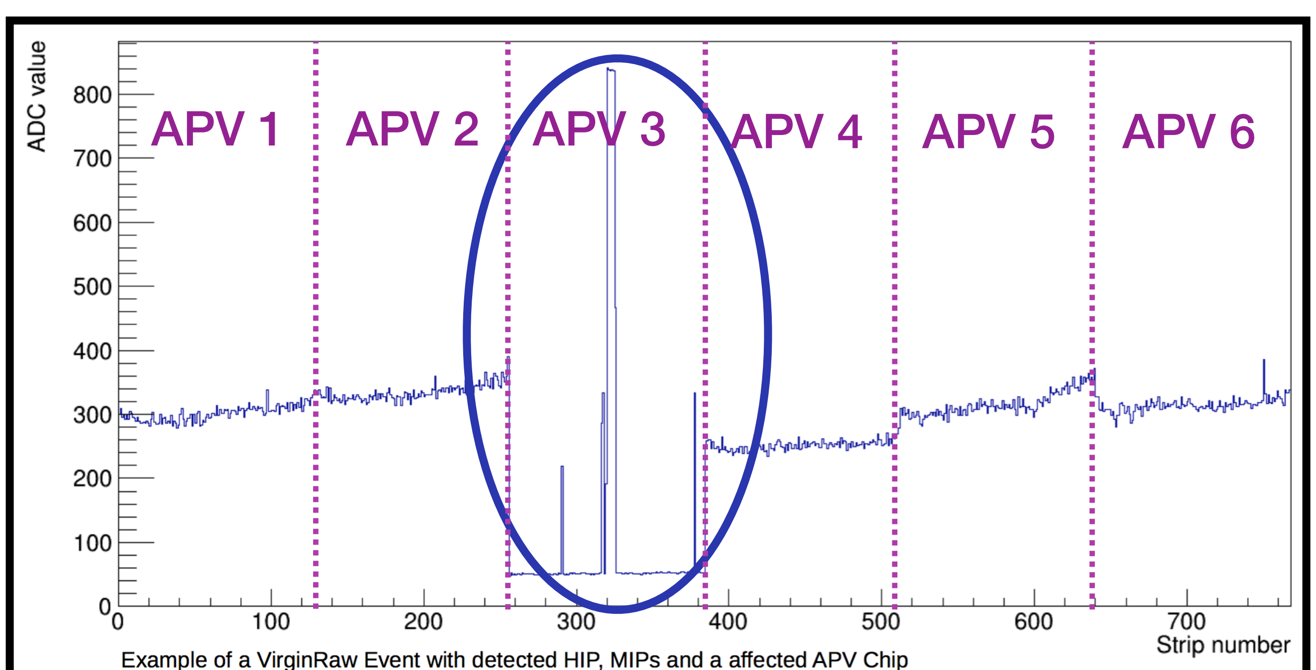
## HIP probability per p-p inter. per volume




- HIPs are particles releasing a large amount of energy (charge) in a given sensor
- The amount of energy is about 100 times larger than a MIP
- HIP probability decreases with the distance from IP as $1/r^2$

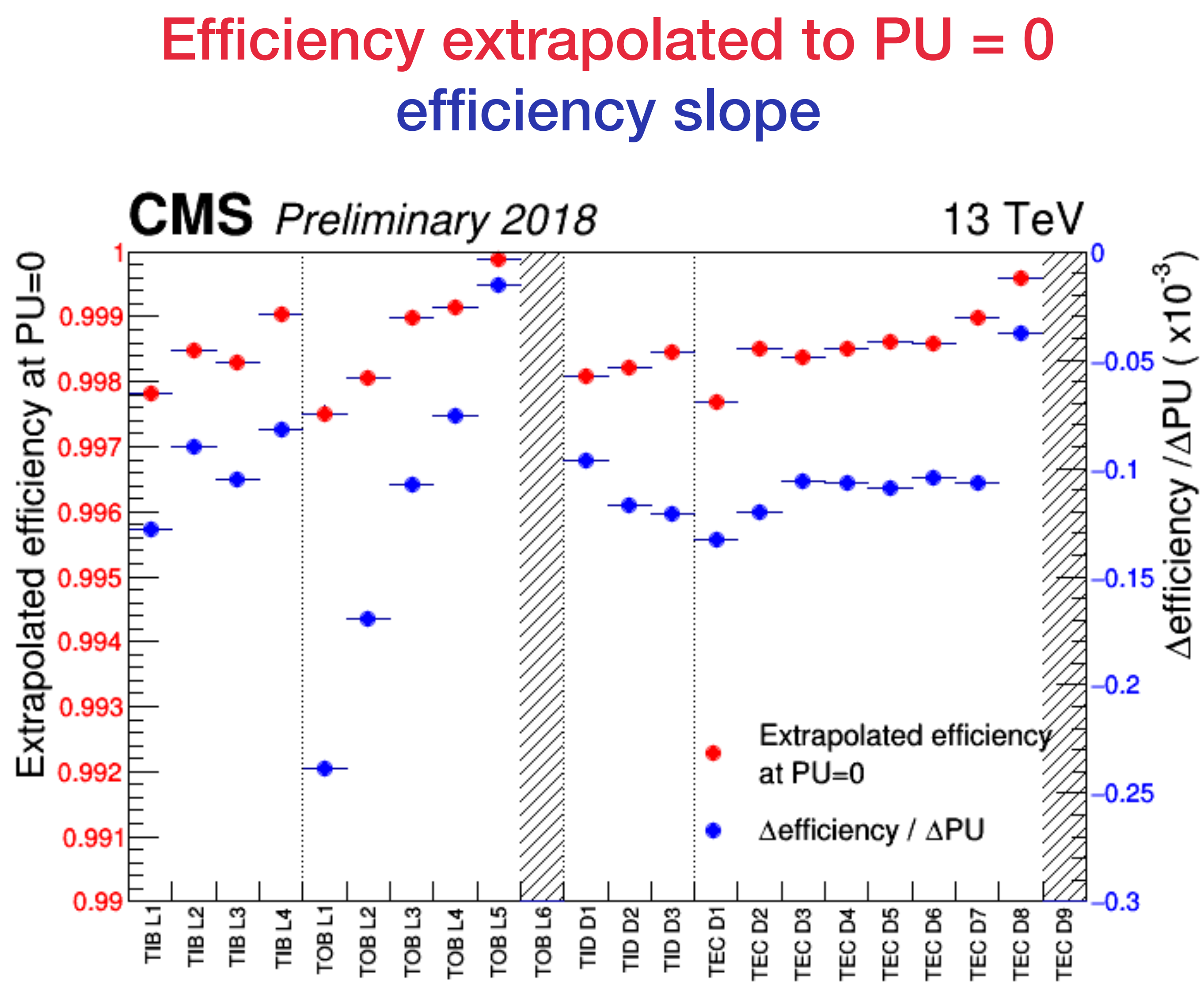
## HIP energy deposition and its effect on the APV-chip readout

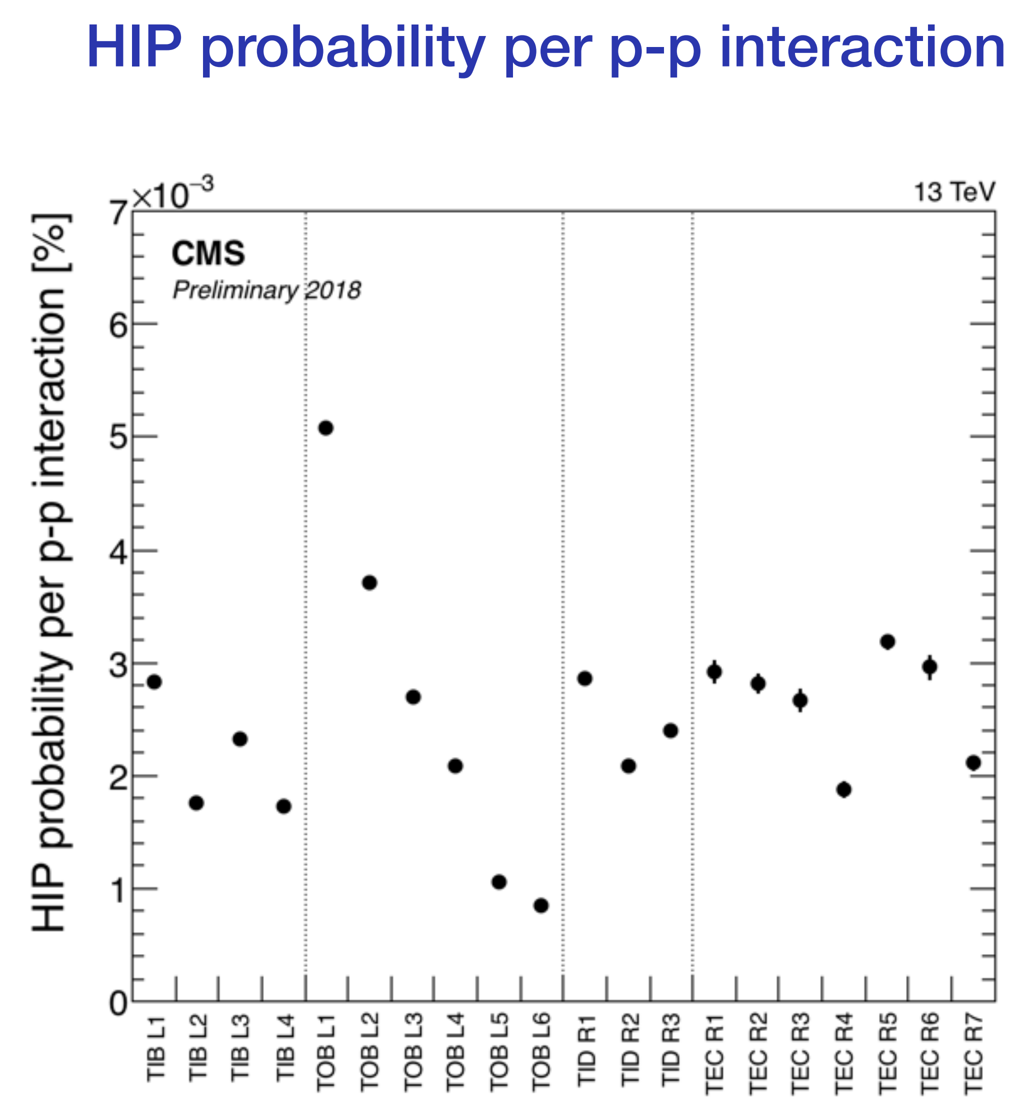
Module with 6-APV chips




- Large energy deposit only on few strips causes APV baseline to drop
- Baseline recovery can take several BXs
- Chip becomes ineffective for a number of BXs
- MIP signal not large enough to be accepted
  - Loss of efficiency

# HIP & Hit Efficiency



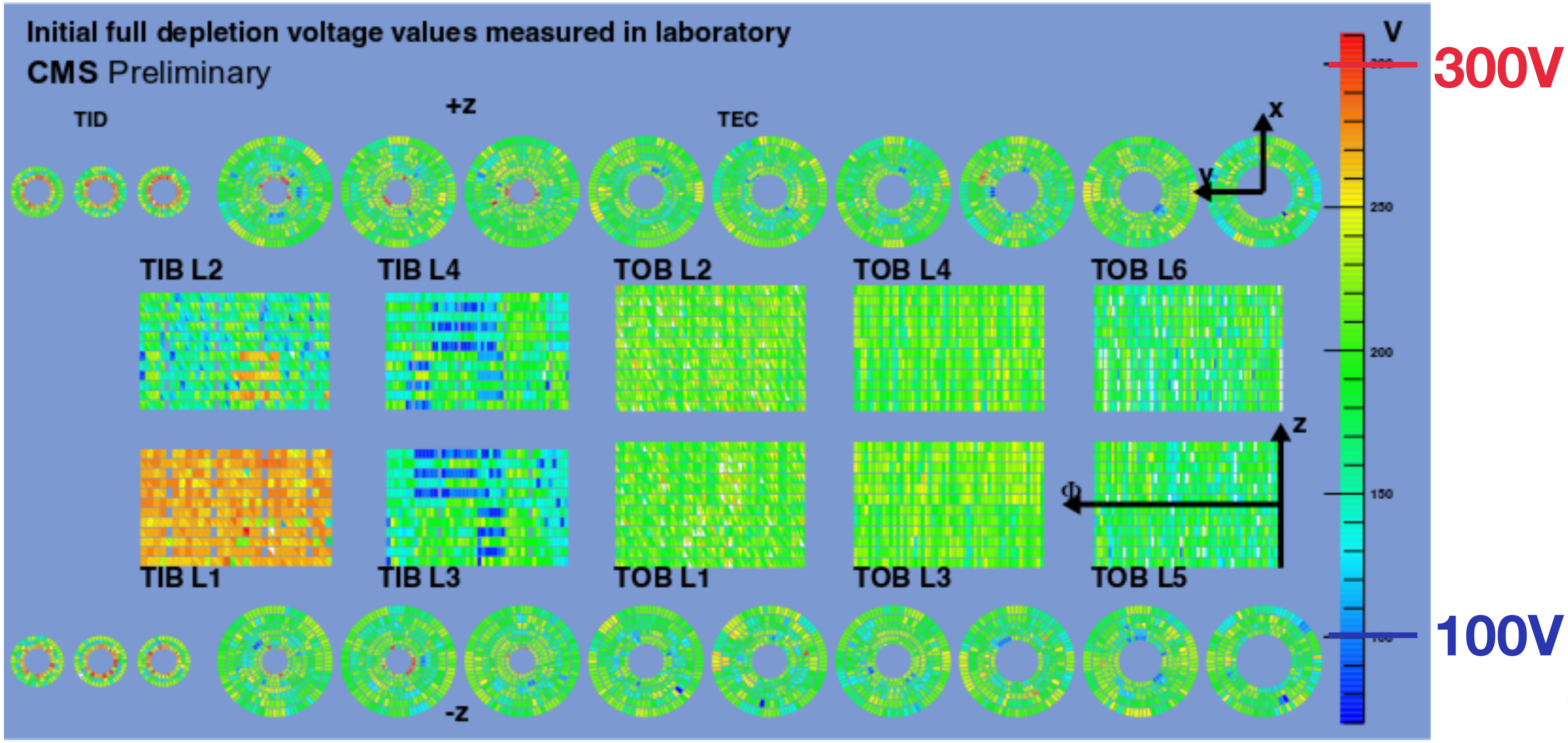




HIP main source of the observed inefficiency

# Radiation effects

- Regular measurements of radiation related quantities performed
  - **Leakage current ($I_{leak}$)**
    - Measured using power supply current and detector control units (DCUs) on individual modules
  - **Depletion voltage ($V_{depl}$)**
    - Full scans, twice per year (typically after technical stops)
    - Small scans on representative power groups ~1/month

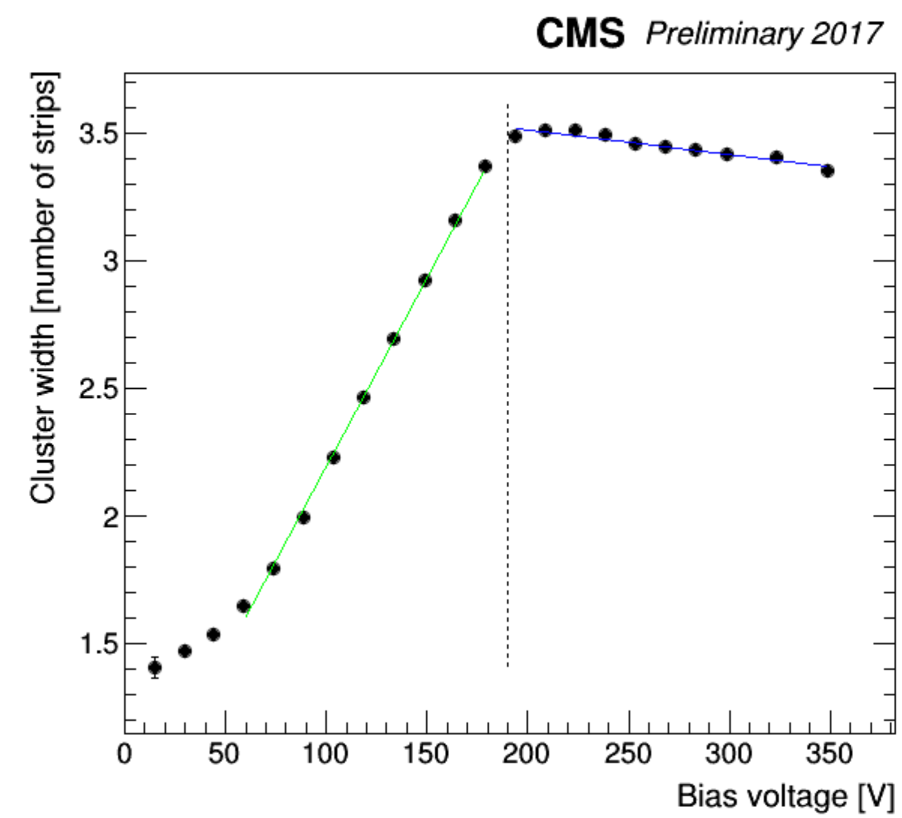
## Initial full depletion voltage values measured in lab

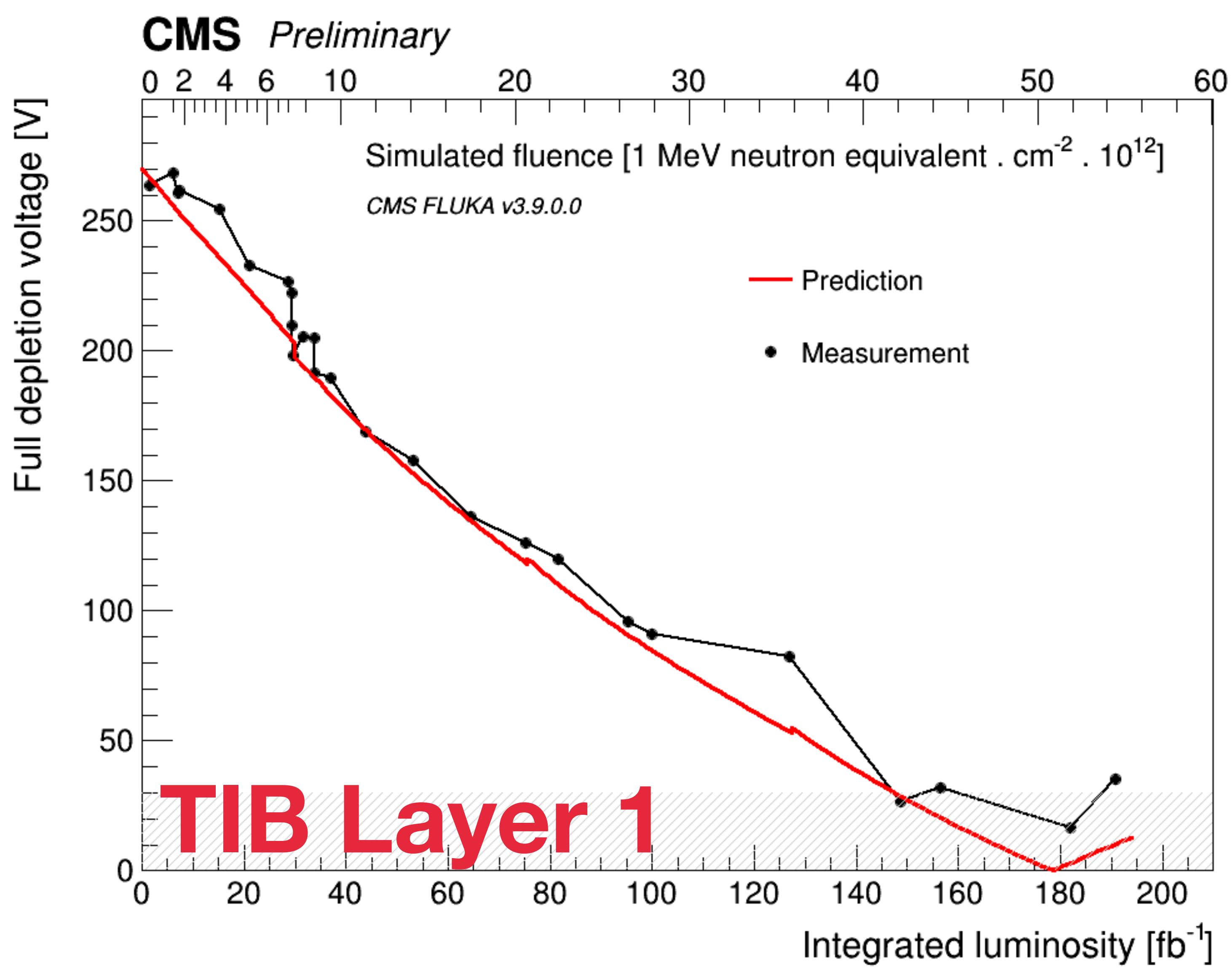


# Depletion voltage

## Cluster width

- **Determined from the cluster width**
  - Linear fit performed in two regimes
  - The crossing point → full depletion voltage
  - Not sensitive close to the inversion point




- For TIB Layer 1 inversion pointed predicted at **~180 fb$^{-1}$ (Hamburg model)**
- Delivered luminosity at the end of Run 2: **192 fb$^{-1}$**

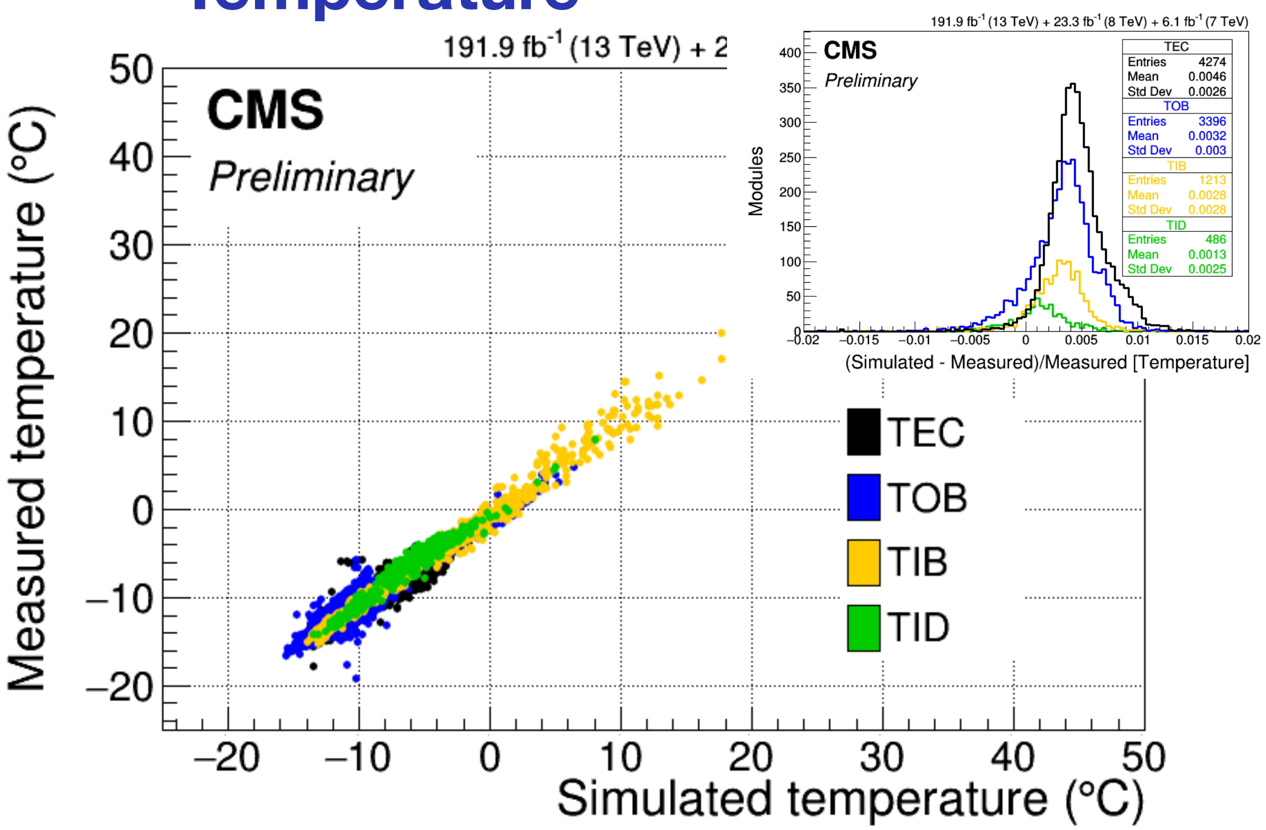
**TIB Layer 1 reached inversion point at the end of Run 2**

# Leakage current

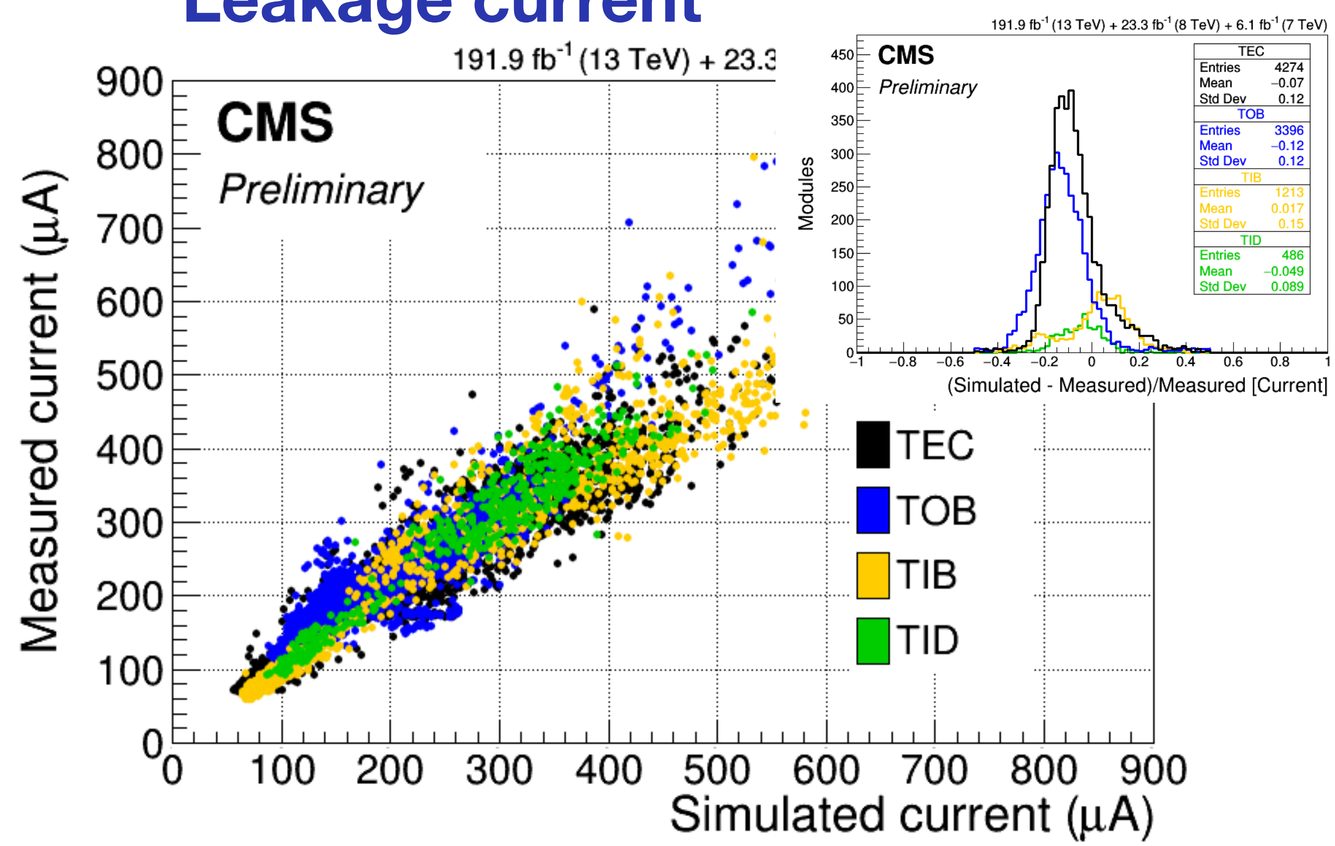
- **Leakage currents simulations** are done based on
  - Silicon sensor temperature measured at the certain “anchor points” taken **per module**
    - Temperature is extrapolated to other periods using few representative temperature probes (e.g. periods with detector off )
  - **Particle flux simulation** using FLUKA and scaled to corresponding fluencies in 1 MeV neutron eq
  - Leakage current at time t, for sensor with temperature T and fluency $\Phi_{eq}$ calculated from

$$I(t,T,\Phi_{eq}) = I_0 + \alpha(t,T)\Phi_{eq}V \qquad \text{with} \quad \alpha(t,T) = \alpha_0(T) + \alpha_I \exp\left[-\frac{t}{\tau_I(T)}\right] - \beta \ln\frac{t}{t_0}$$

## Temperature




## Leakage current



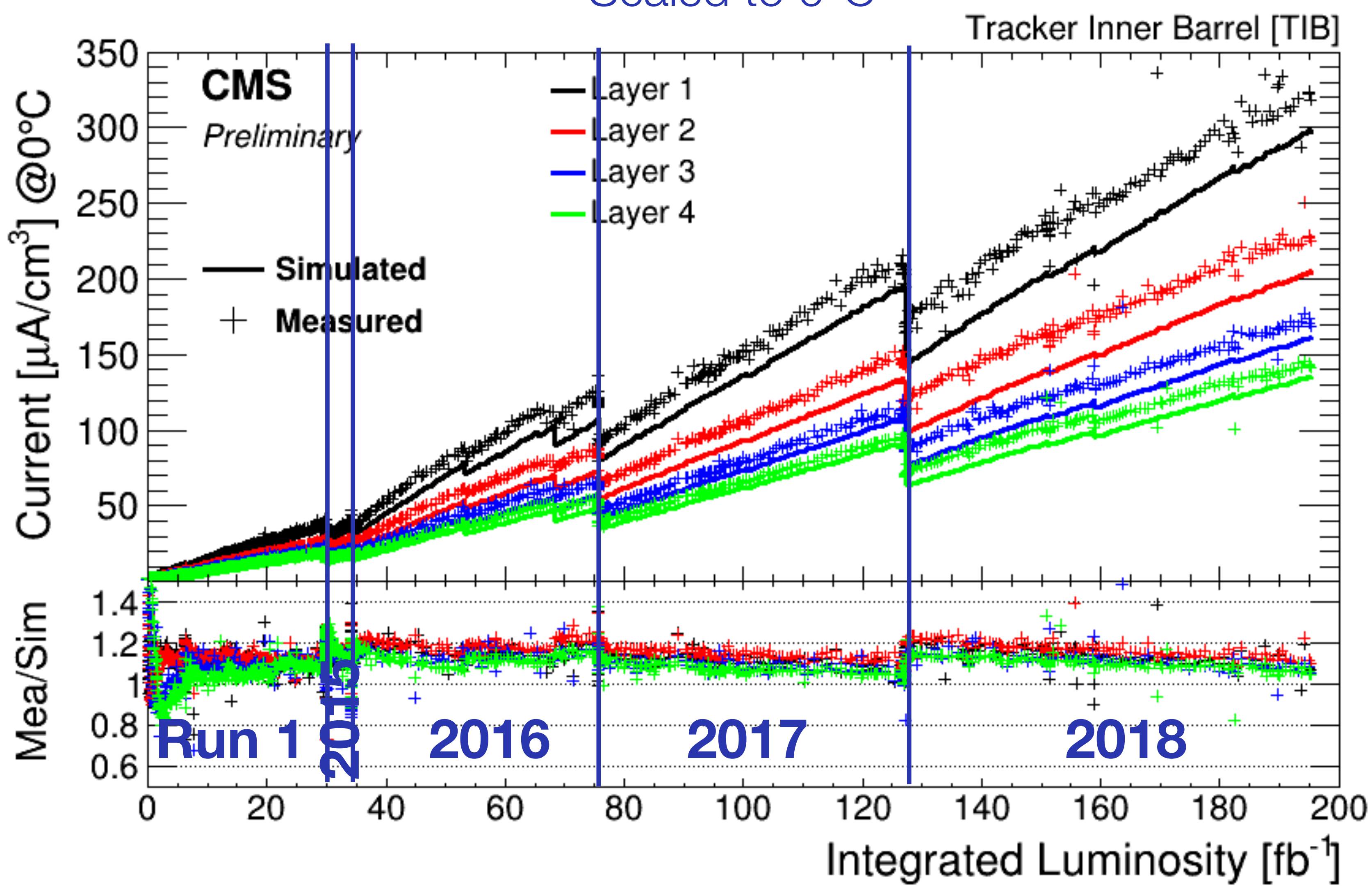

Very good overall agreement between measurement and simulation

# Leakage current

**Leakage current as a function of integrated luminosity**

Averaged over regions of equal radius and scaled to equalise for different sensor volume

Scaled to 0°C



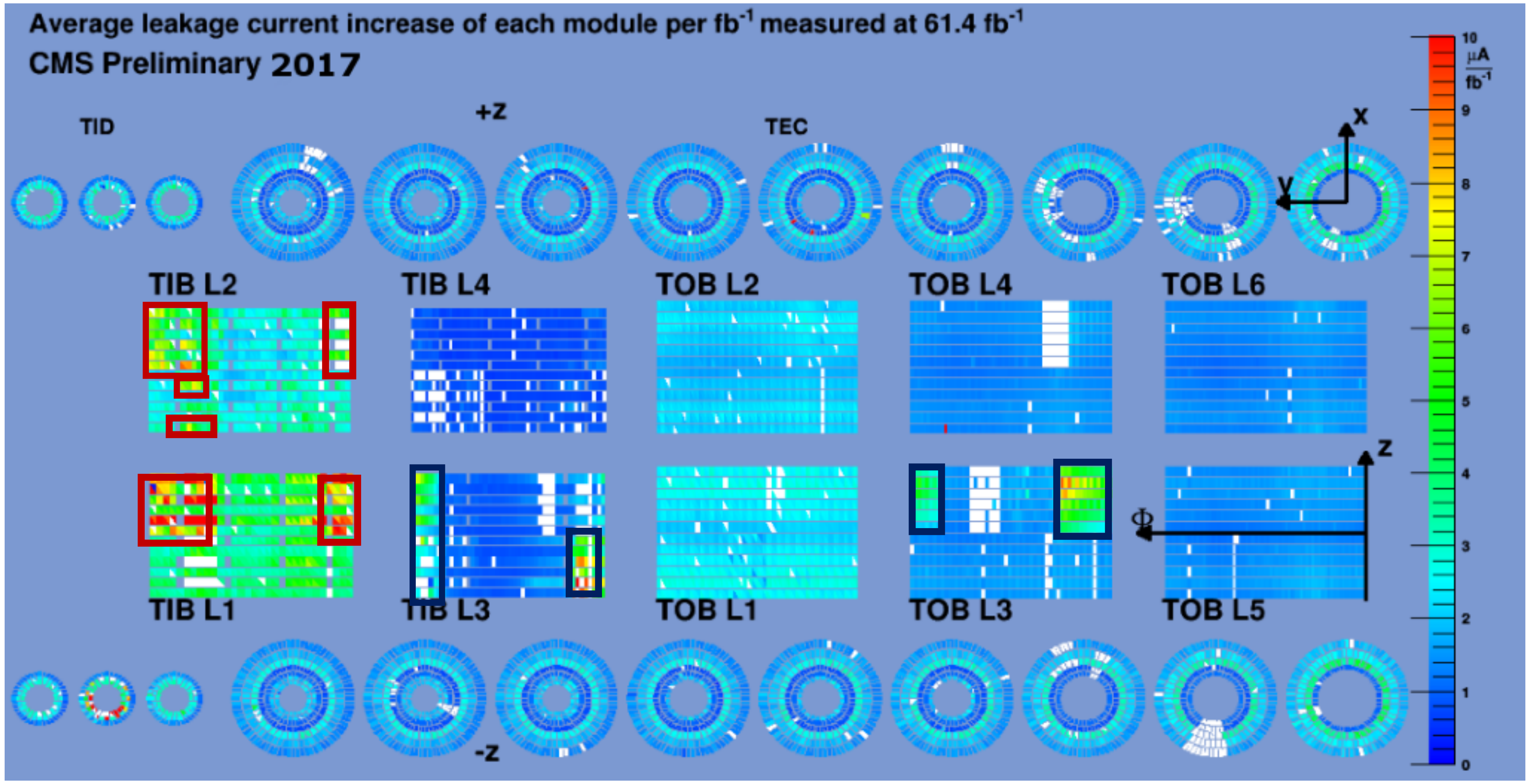

- Generally good description with about 20% constant offset
  - Compatible given uncertainties of FLUKA and modelling parameters
  - Changes of effective α can be seen after LS1 and EOYs
  - Changes due to annealing during stops and change of temperature

$T_{coolant}$ = +4 °C → $T_{coolant}$ = -15 °C → $T_{coolant}$ = -20 °C

**LS1** **EOY17**

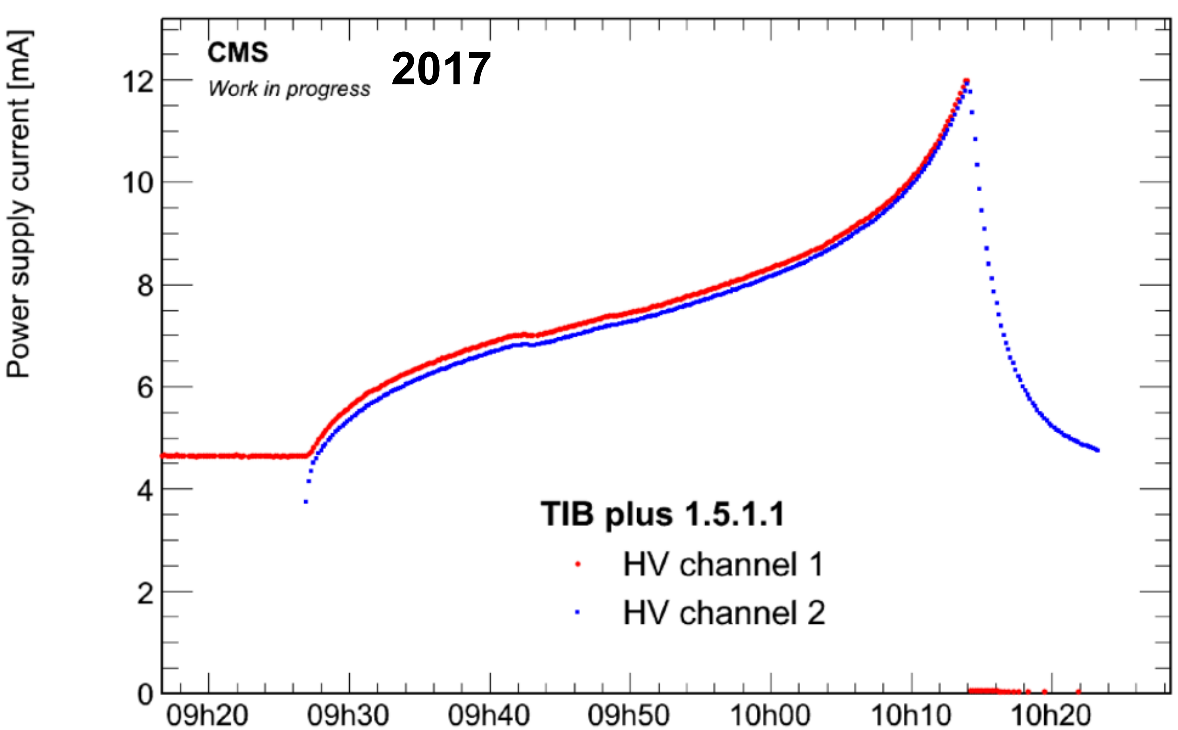
# Leakage current

## Average leakage current increase for each module (2017)




Closed (leaky) cooling loops

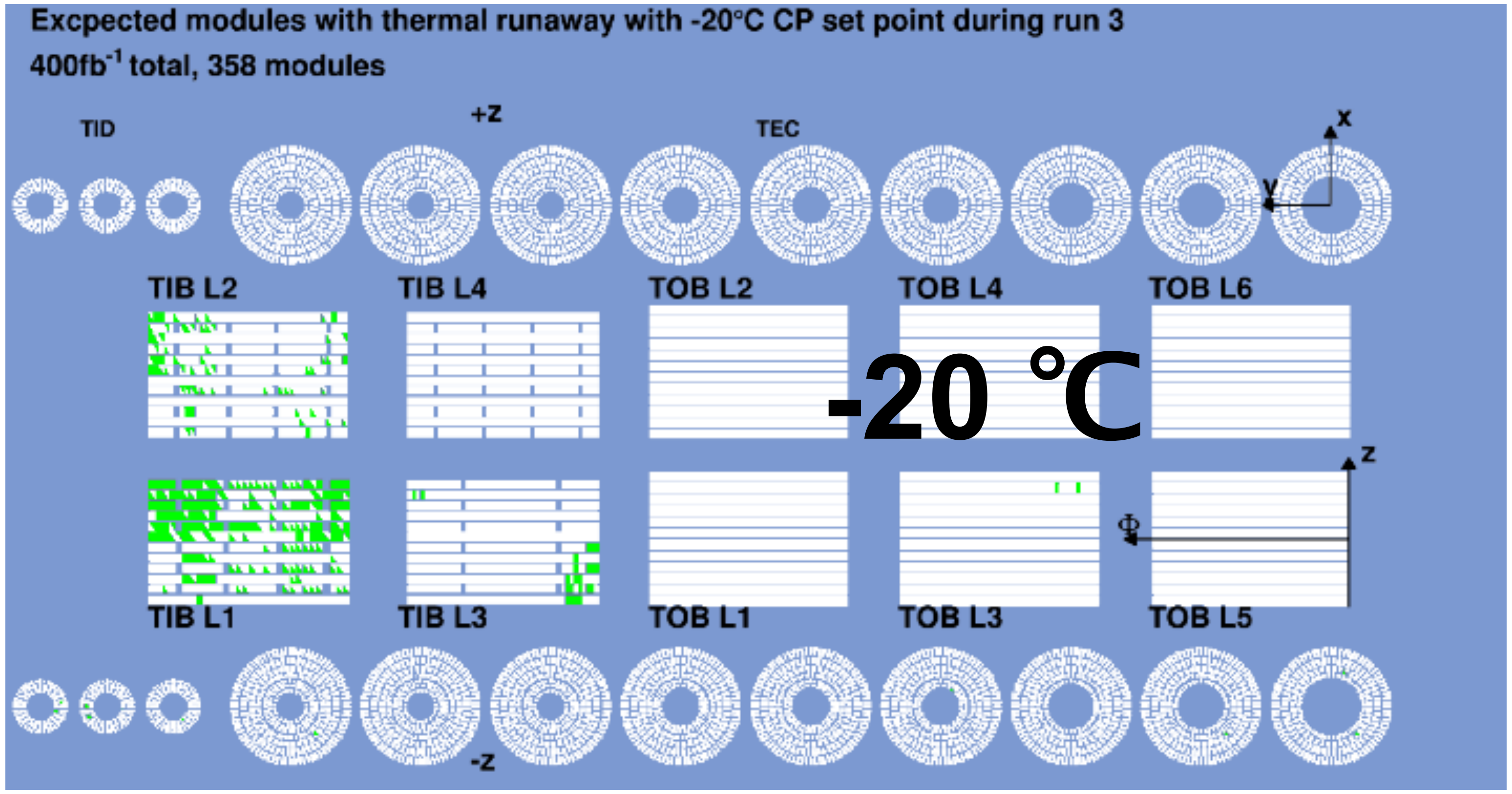
Degraded cooling contacts

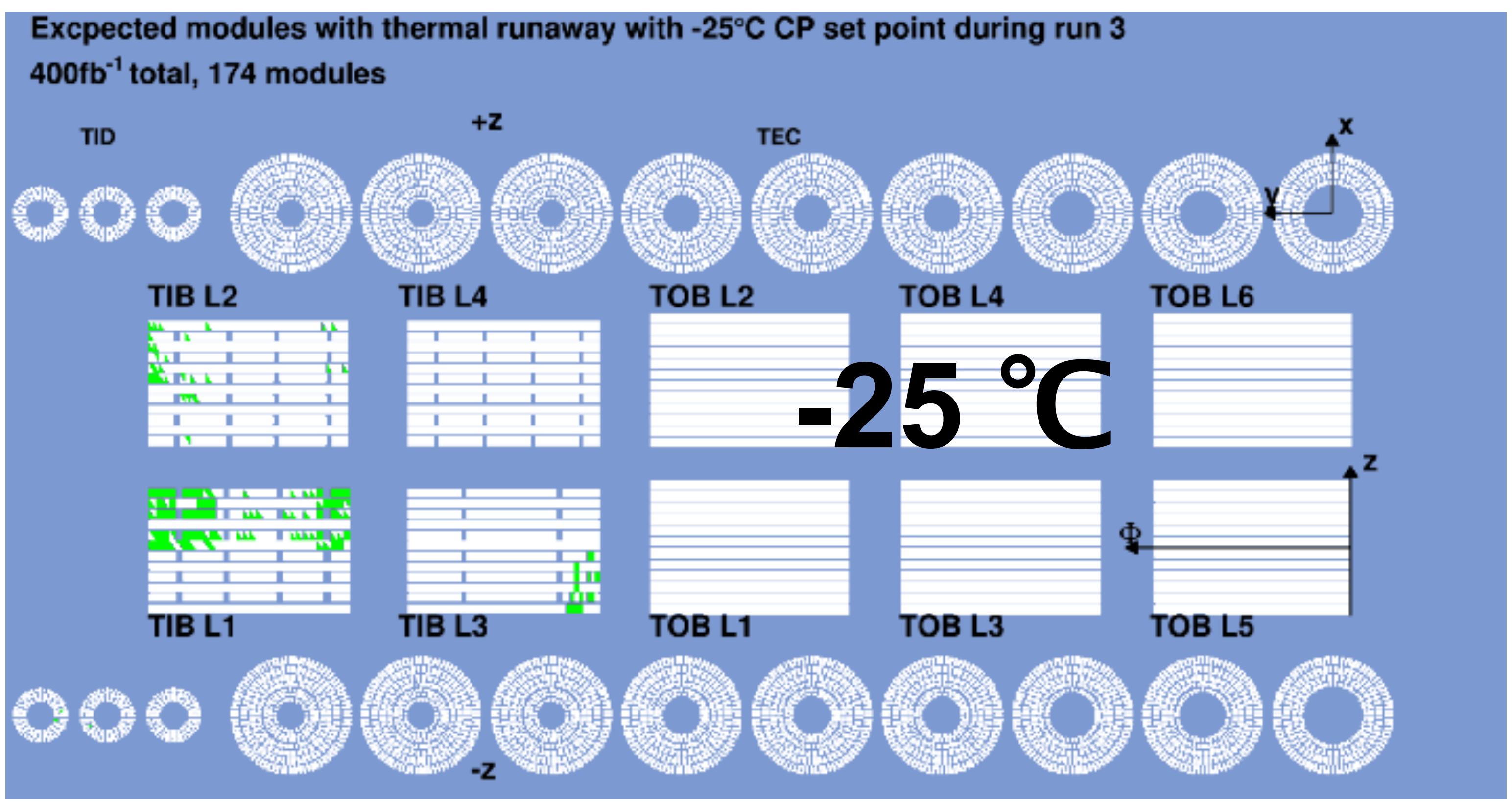



- **Thermal runaway** observed in 2017 in TIB+ modules
  - Self heating effect reduced by switching off half of stereo modules
  - Reducing bias from 300 V to 200V
- For 2018 data taking temperature decreased from $T = -15\ ^{o}C \rightarrow T = -20\ ^{o}C$

# Leakage current

## Expected modules with the thermal runaway at the end of Run 3 (400 fb$^{-1}$)



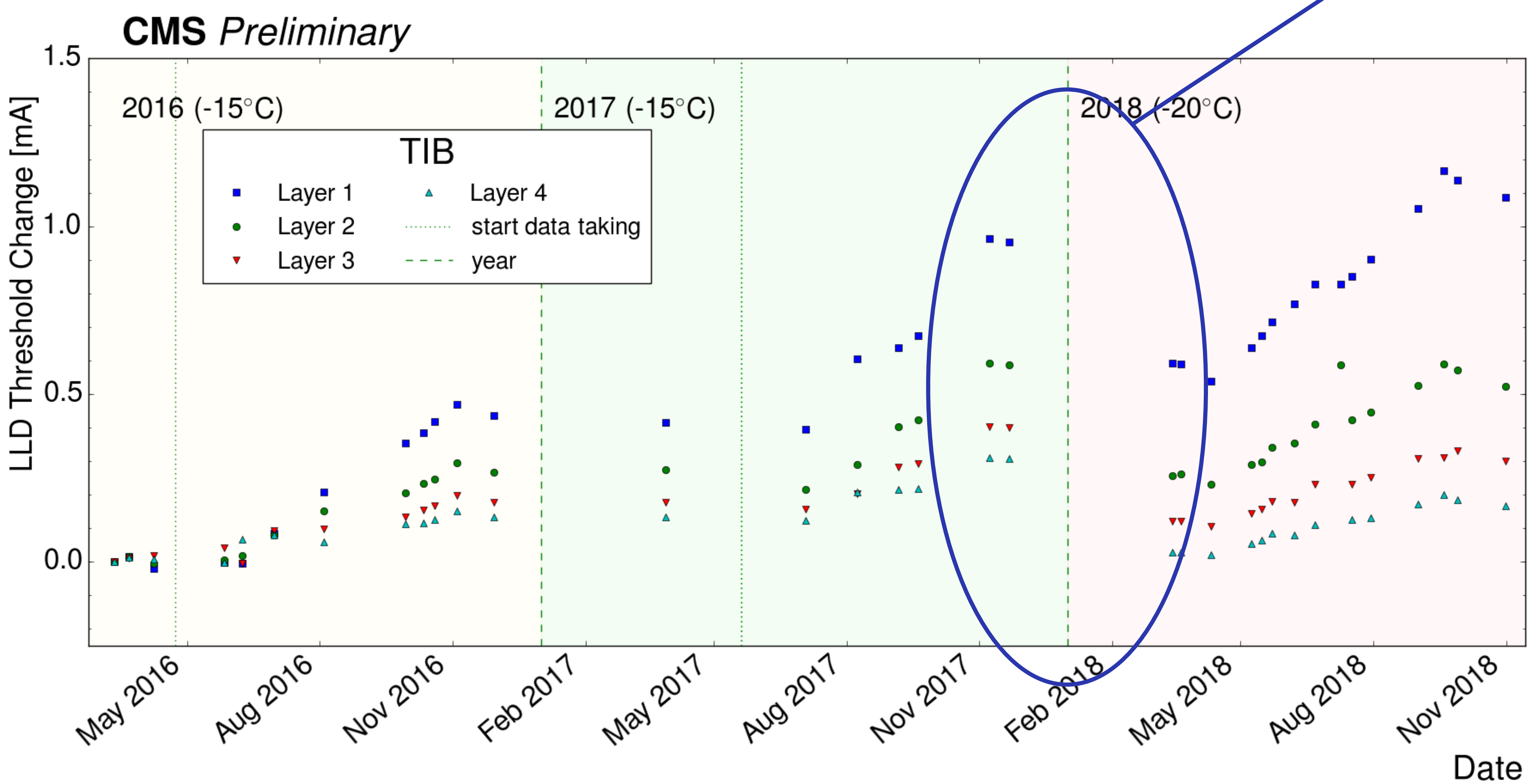

- Number of thermal runaways reduced by decreasing the cooling set points
- Can be further reduced by
  - Switching off individual modules (using so called HV jumpers)
  - Switching off half of the stereo layer modules
- Running at -25°C will be tested during LHC Long Shutdown 2

# Radiation effect in optical readout

- Radiation effects in optical readout lead to decrease in efficiency and increase in laser threshold current

Decrease after coolant temperature change

**Threshold current evolution**




- Threshold increase in high luminosity periods observed
- Annealing in off beam period
- Clear dependence on radius
- Maximum allowed threshold current 22.5

# Summary

- CMS Outer Tracker performing well after 10 years of operation
- Fraction of functional detector components stable in the last few years
- Signal to noise, hit resolution and hit efficiency are very good and in agreement with expectation
- Radiation effects are visible in all parts of the detector
  - Monitoring various effects (leakage current, depletion voltage)
  - TIB Layer 1 reached inversion point
  - Simulation effects are in good shape to model the behaviour of the system with increasing irradiation
    - Prediction of the performance at the end of Run 3 in progress
- Detector is keep cold  [at 0$^{o}$C] during LS2 except in period of pixel and beam pipe extraction [~60 days]

# Backup