Karlsruher Institut für Technologie

Operation and Performance of the CMS outer tracker

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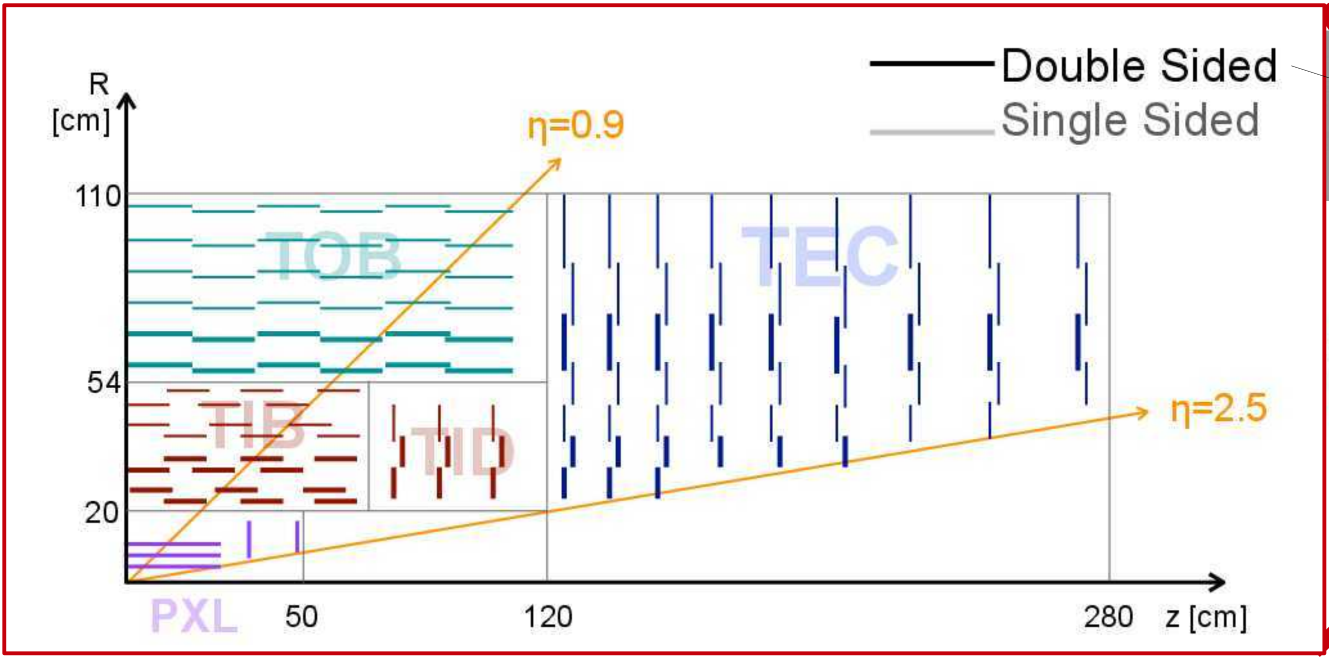
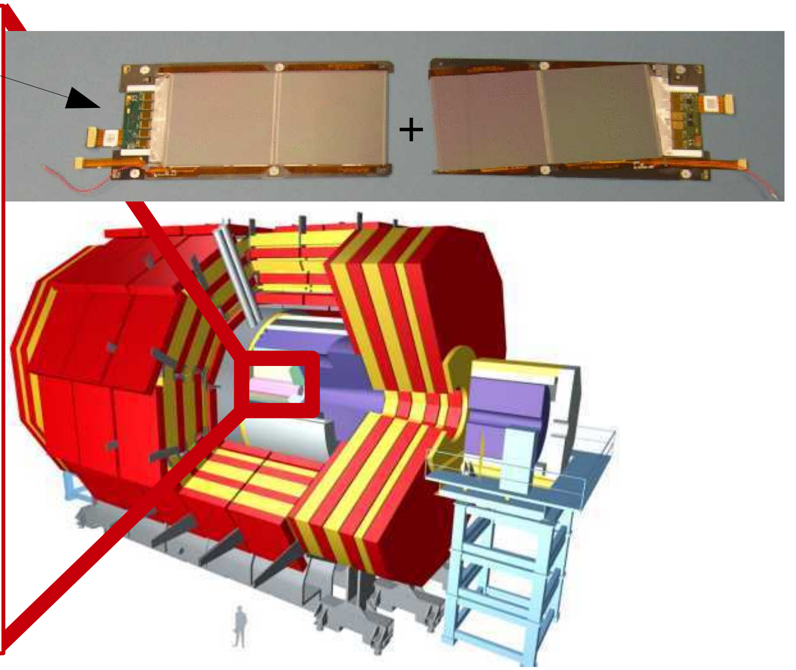
For the CMS Collaboration

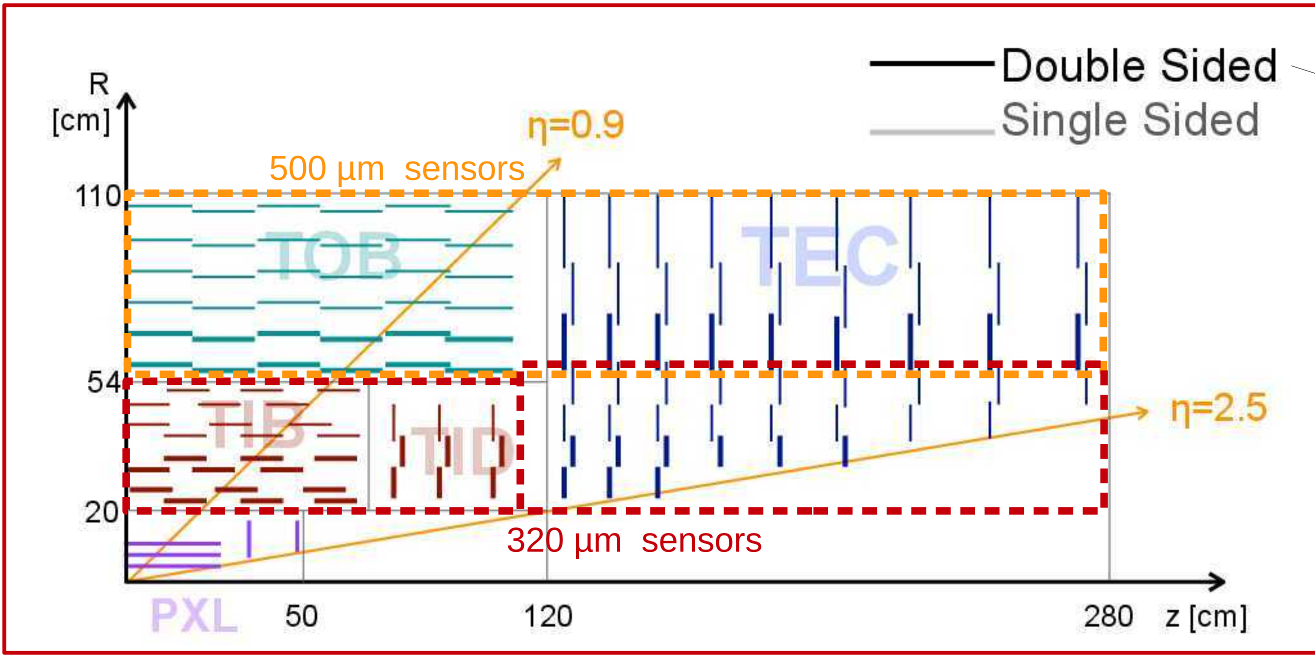
The CMS Outer Tracker

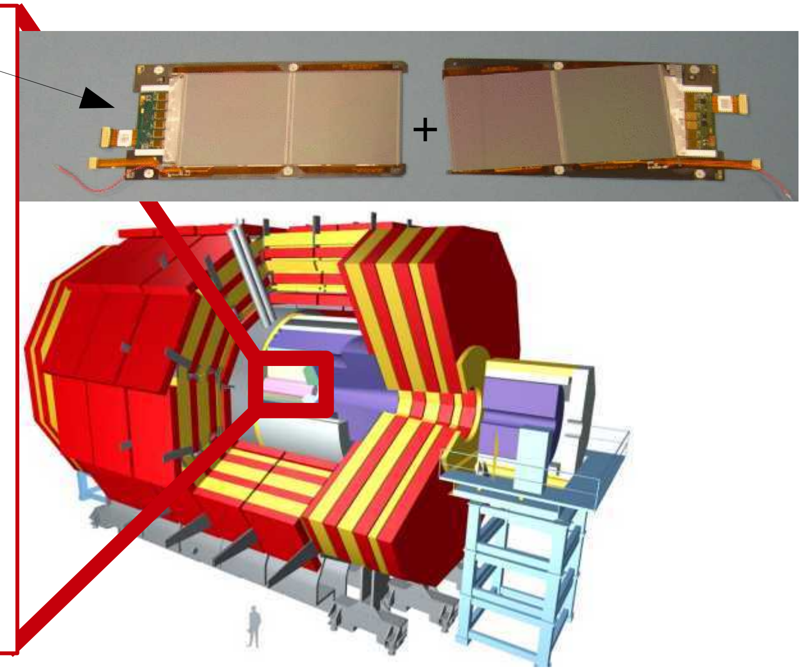




- Active area 200 m^2, 5.6 m long, 2.5 m diameter
- 15148 silicon modules, 9.6 million electronic channels
- 10 layers in barrel region, 4 Inner Barrel (TIB), 6 Outer Barrel (TOB)
- 3+9 discs in the inner disks (TID) and endcaps (TEC)
- Stereo modules (two modules with 100 mrad stereo angle) in 4 layers (3 rings) in barrel (endcap)
- 320 µm Si in inner layers (TIB, TID, TEC ring 1-4),
  500 µm Si in outer layers (TOB, TEC ring 5-7) → two silicon wafers daisy-chained
- Analog readout

The CMS Outer Tracker





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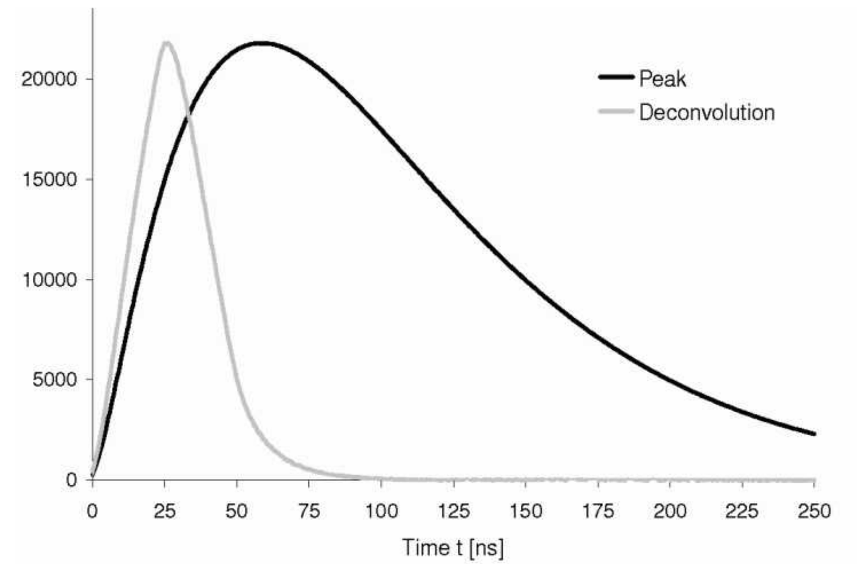
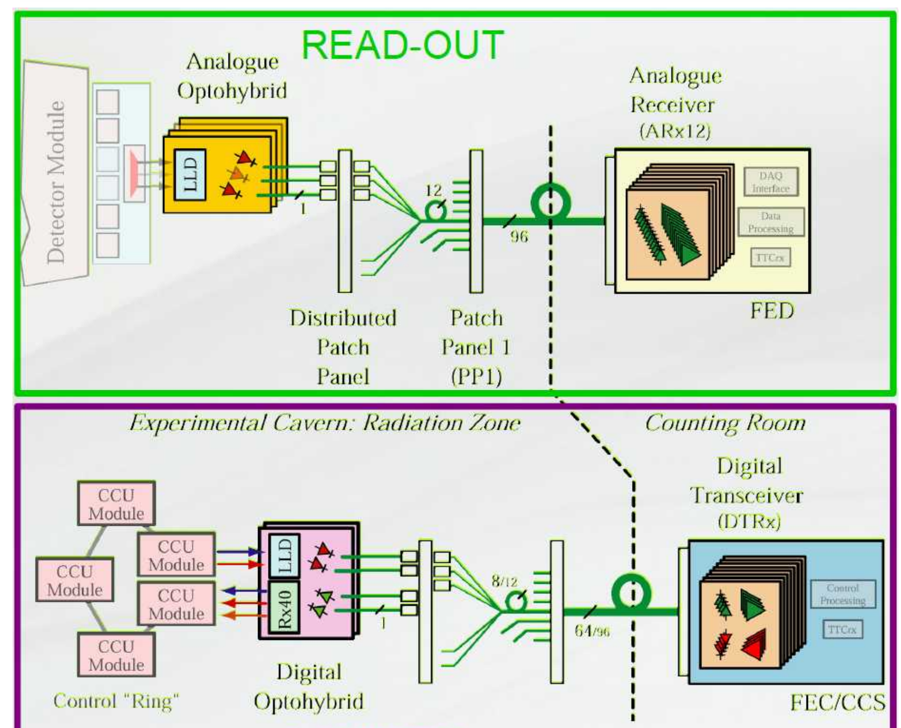
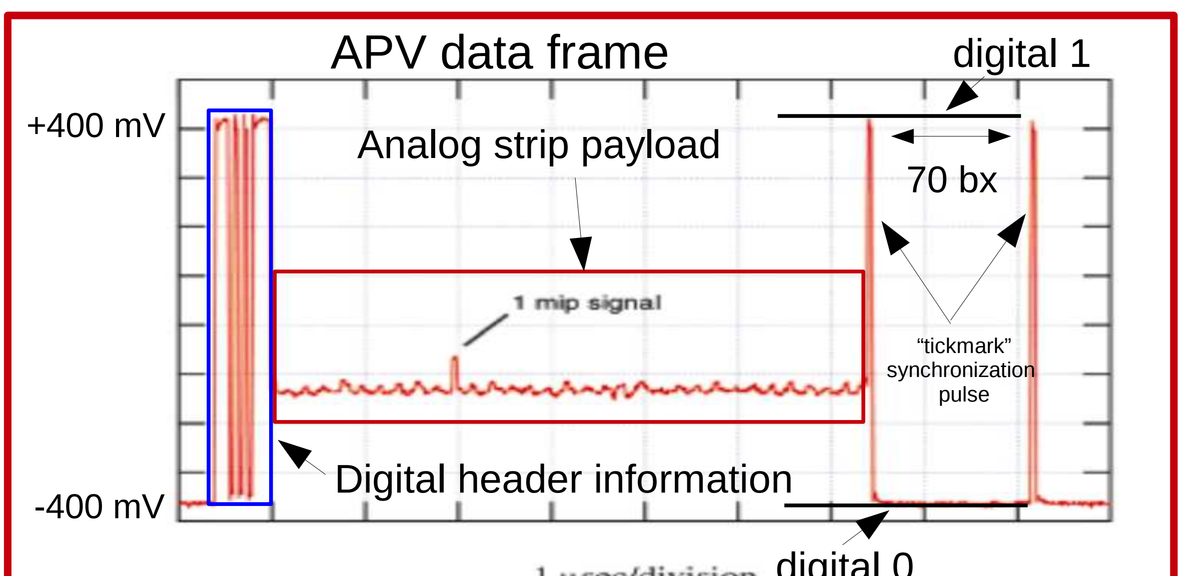
Tracker Analog Readout in (very) brief

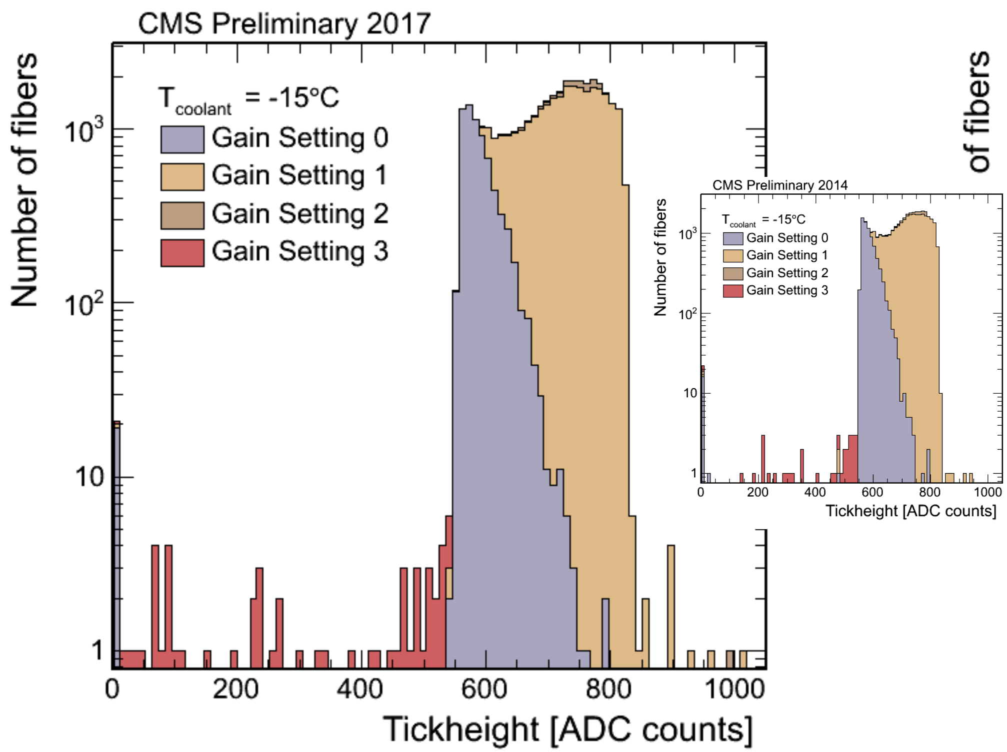
- Tracker readout is analog (signal height information is available)
- APV25 chip with two different readout modes:
  - Peak mode: single sample from CR-RC shaper
  - Deconvolution mode: 3-sample average to effectively shorten pulse (less out-of-time contributions)
- Signal from APV25 chips converted to optical signal on Analog-opto-hybrid (AOH)
  - Linear Laser Driver
  - Edge emitting laser diodes

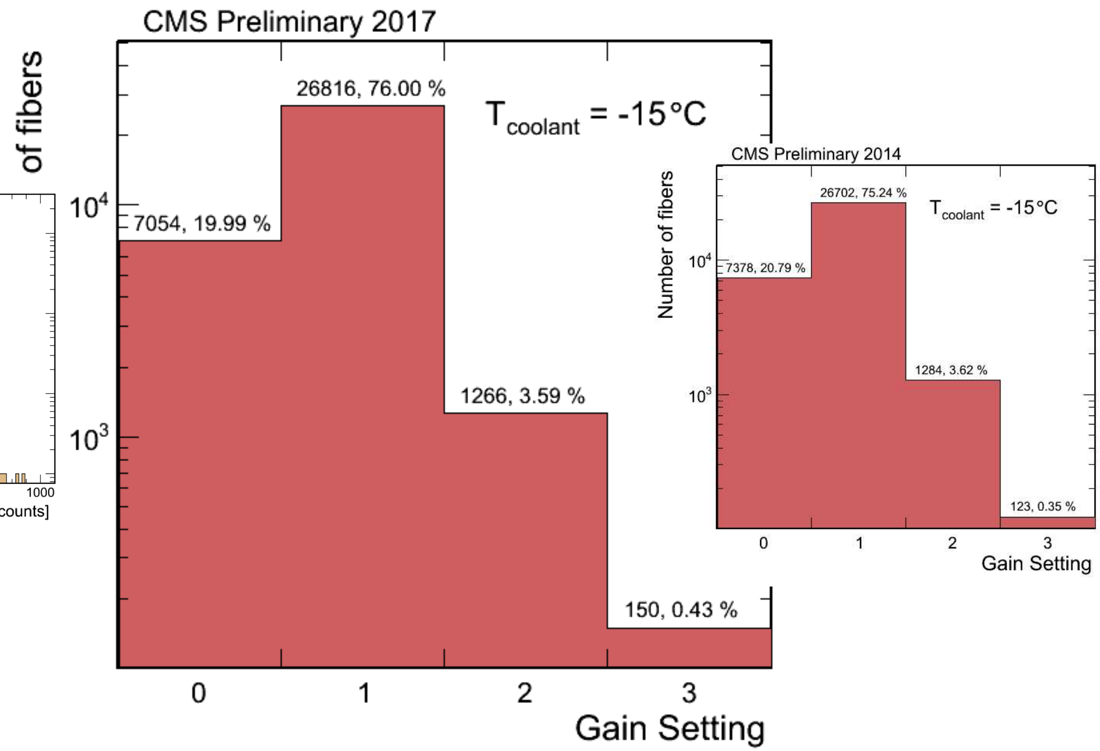






Commissioning the tracker



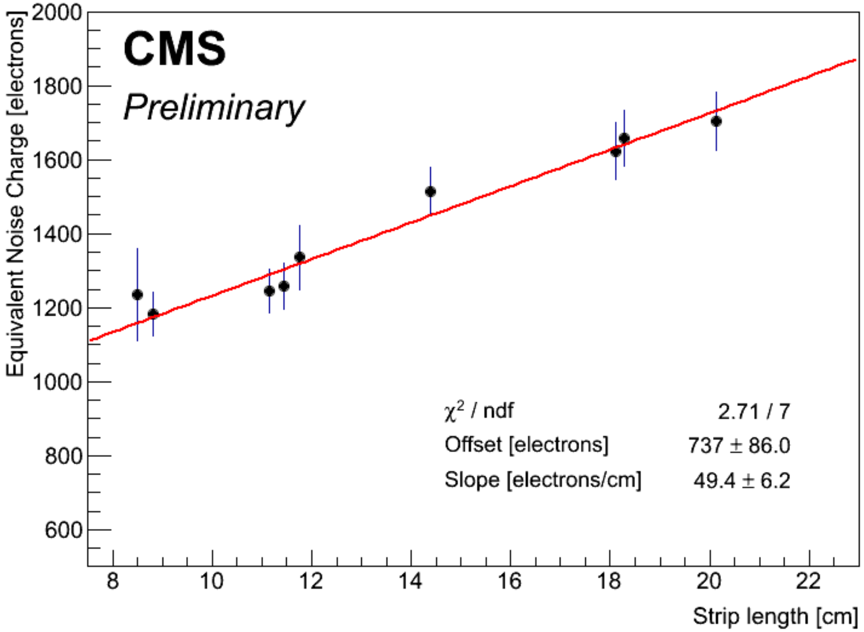


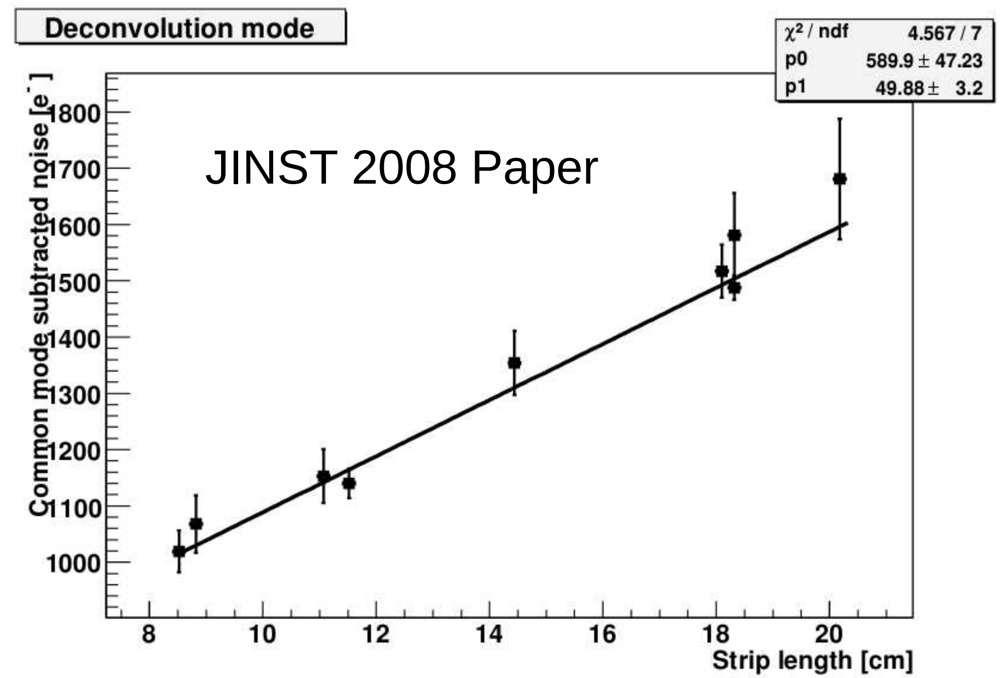
- Laser driver has four gain stages to equalize readout gain and compensate for signal loss with irradiation
- Optimizing optical link gain to about 0.8 $V_{input}/V_{ouput\ [fed\ receiver*)]}$ to have analog readout sensitive to expected charge deposited by traversing particles (few MIPs)
- Distribution of laser driver gain settings largely unchanged since 2014
  - Very few lasers need to use highest gain stage

  → No evidence of loss of efficiency for laser driver+diode
- More on radiation effects later

*) FED ADC has a gain of 1 ADC count/mV

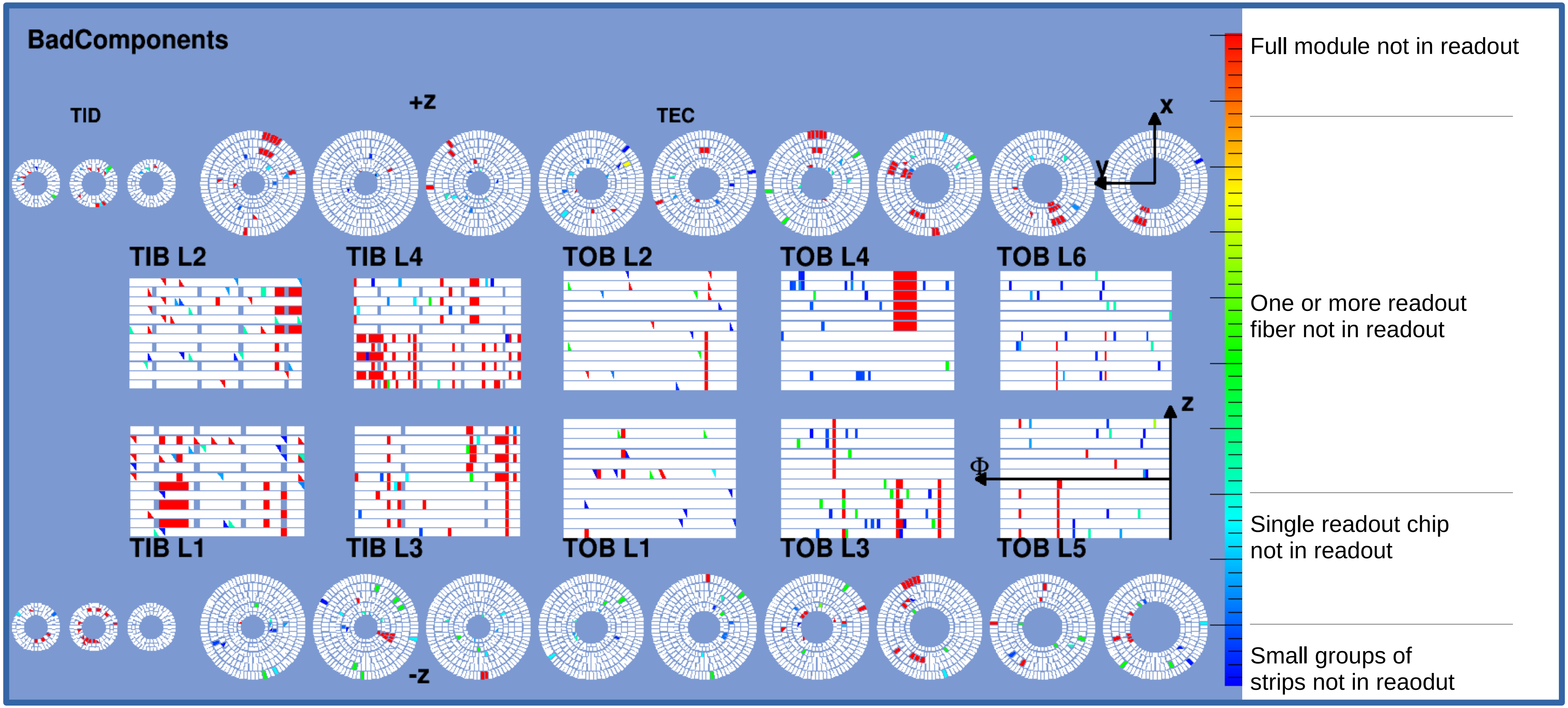
Commissioning the tracker





- Noise scaling in the strip tracker
  - Noise expected to scale linearly with strip length (backplane + interstrip capacitance)
  - Very nicely reproducing results from 2008 JINST paper for slope [electrons/cm]
  - Offset slightly larger, but compatible with old results within ~1 sigma

Detector Status in LHC Run 2

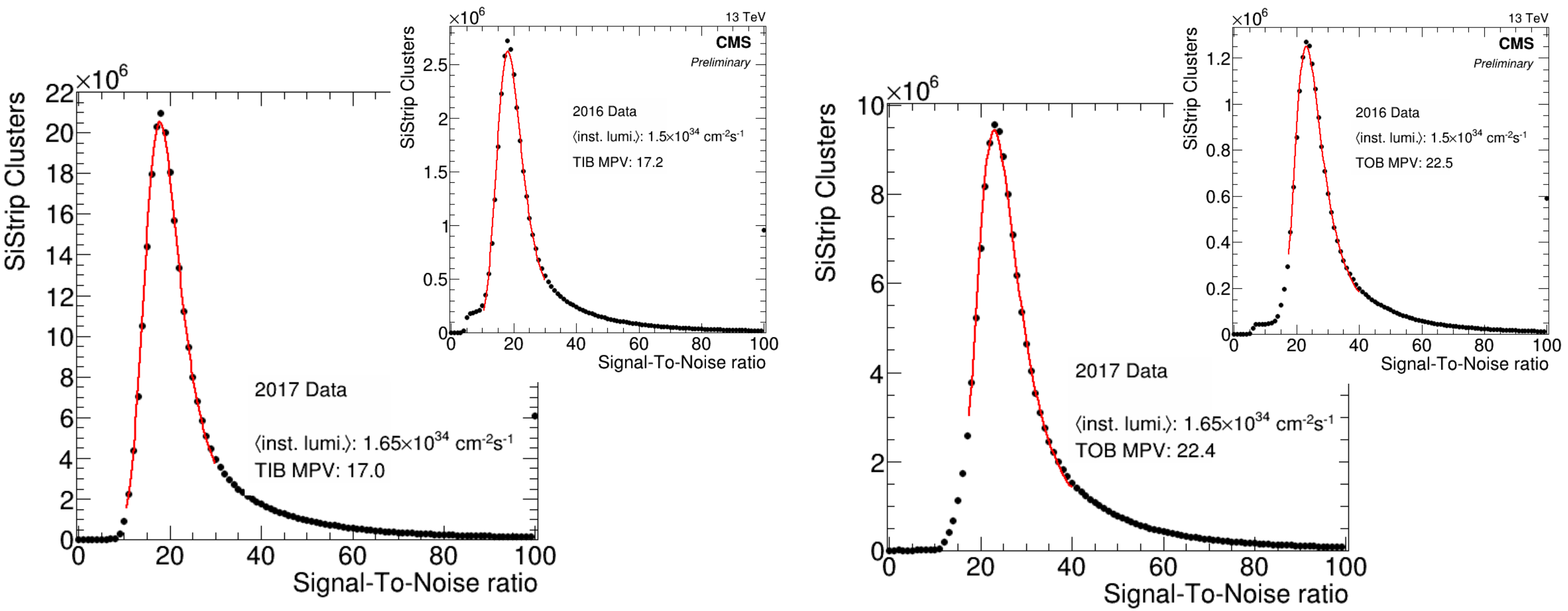


- Channels active in readout: ~96.5%

  → ~stable since 2016

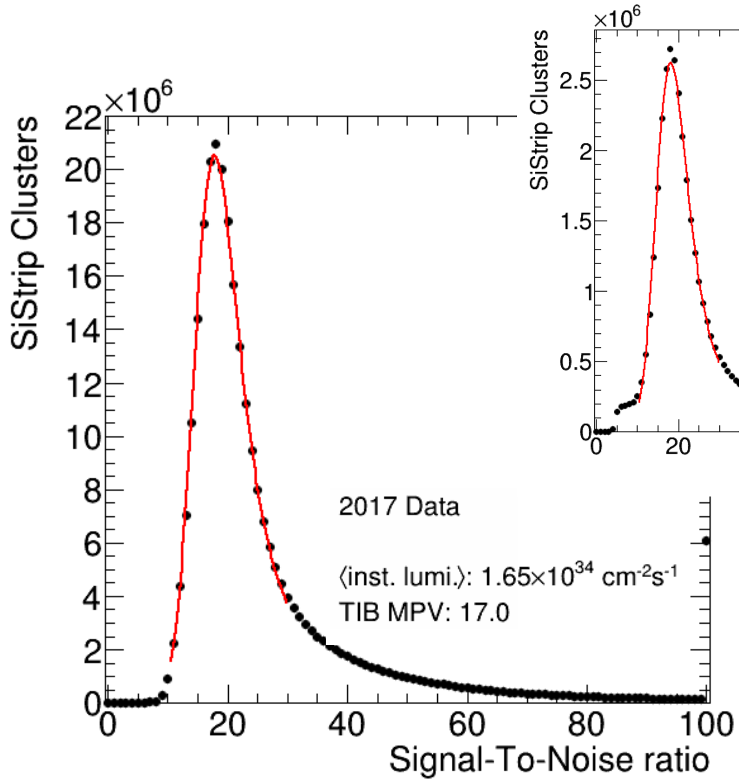
  - 12 modules in TIB layer 3 could be recovered
  - Some others are starting to show signs of deterioration and might need to be excluded from readout

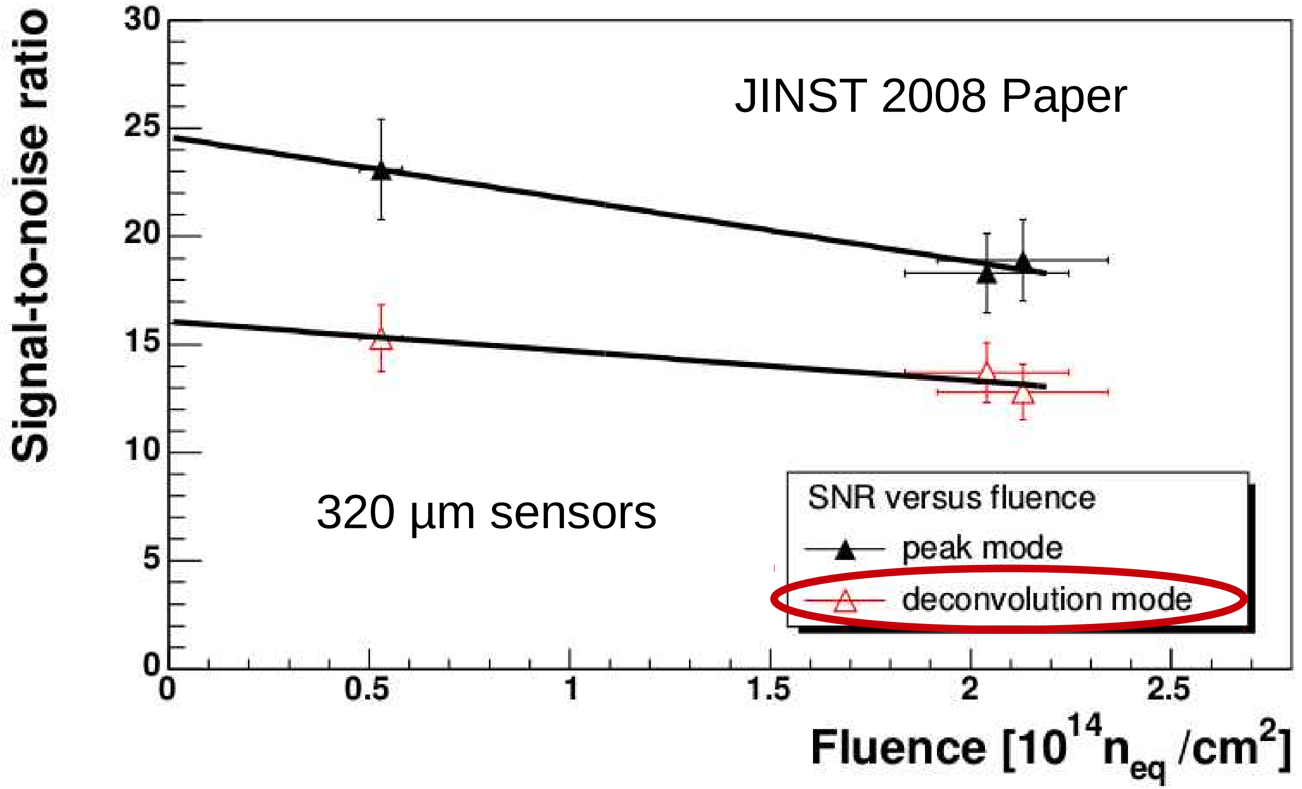
Signal to noise performance



- Signal-to-noise very high and stable from 2016
- No sign of systematic decrease with increasing sensor irradiation

Signal to noise performance





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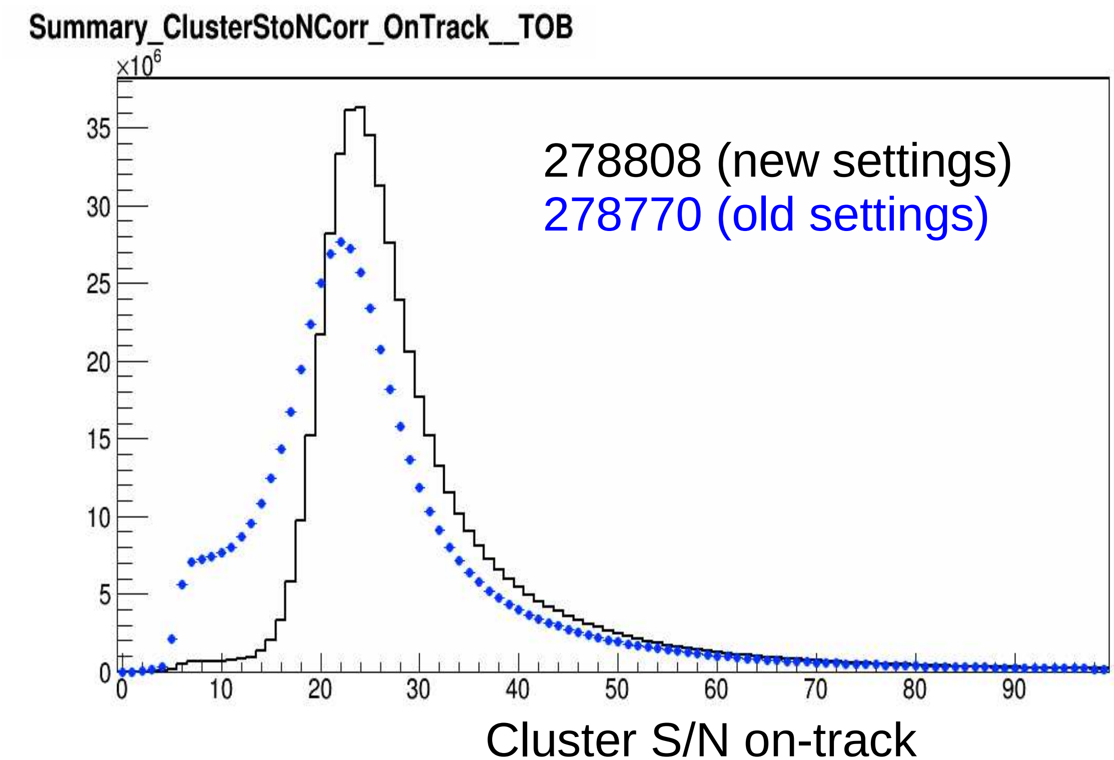
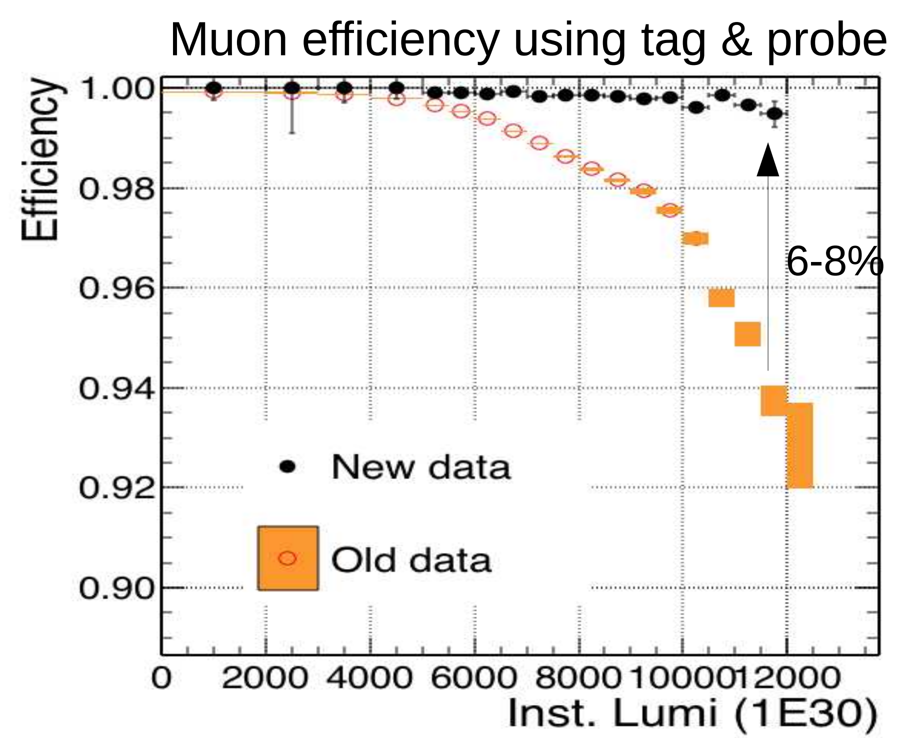
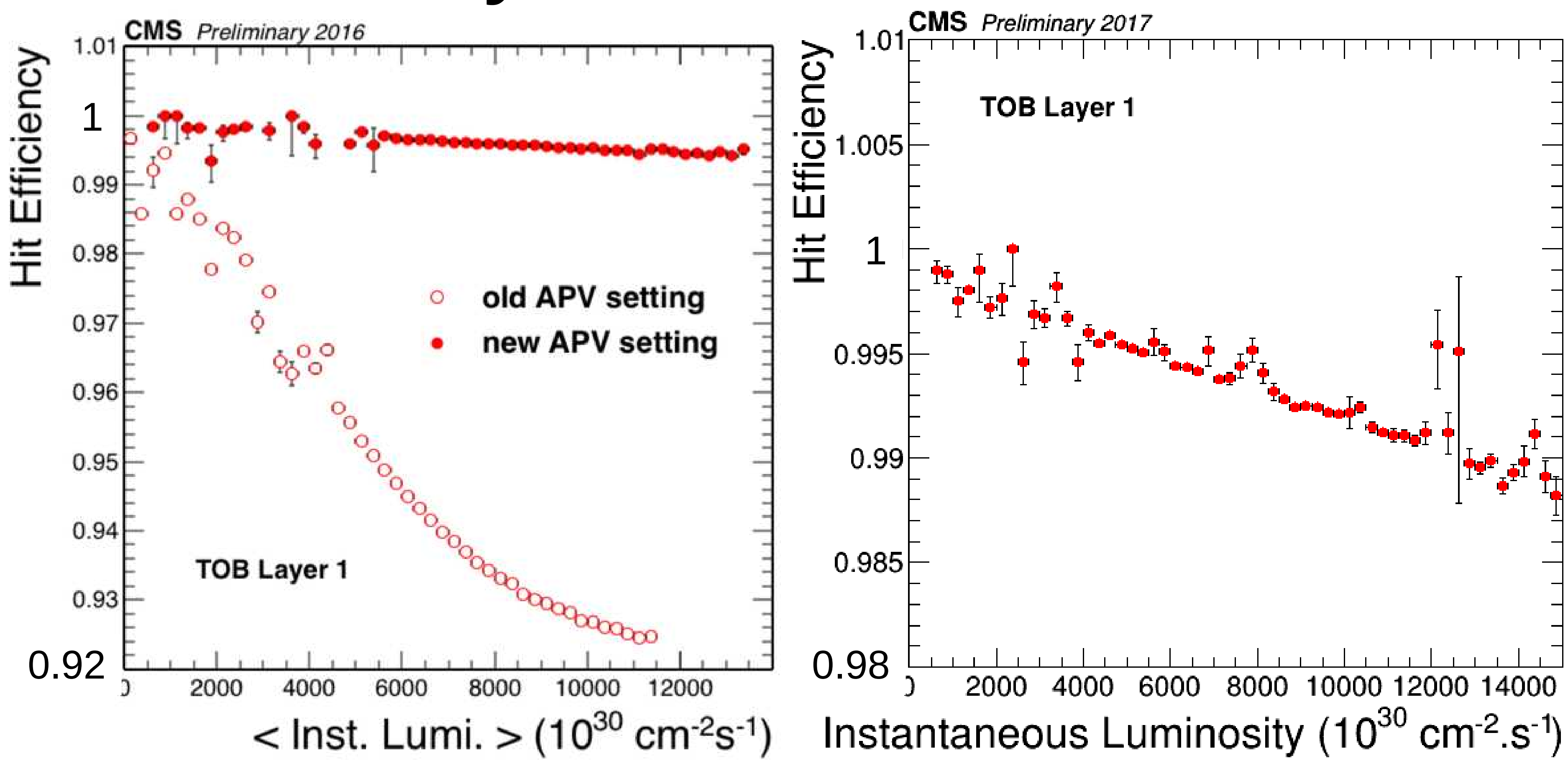
Hit efficiency – APV25 pre-amp saturation problem

- During late 2015 and early 2016 the strip tracker observed a decrease in signal to noise associated also with loss of hits on tracks
- Problem was initially believed to be due to HIPs (heavily ionizing particles)
- Later traced to saturation effects in the pre-amplifier of the APV25 readout chip
- The drain speed of the pre-amplifier was changed to allow for faster recovery
  - This fully recovered the efficiency and the signal to noise ratio



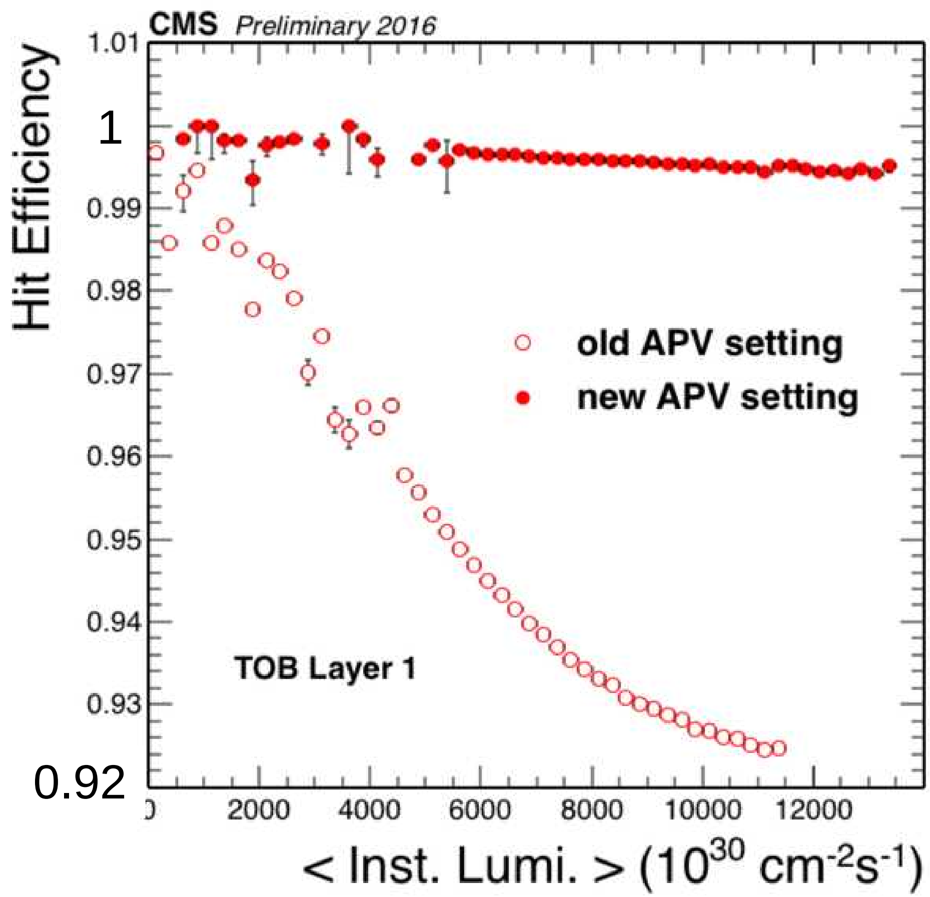


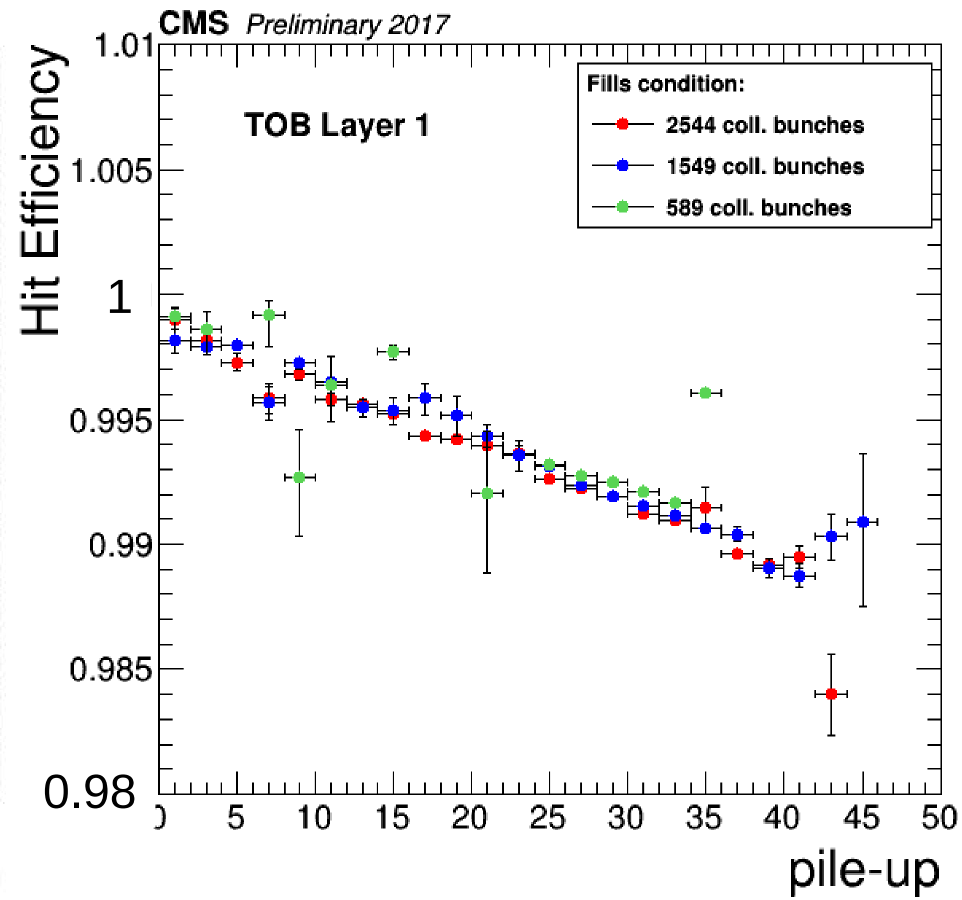
Hit efficiency



- Hit efficiency in 2017 at 99% in TOB layer 1
  - Worst affected by pre-amplifier saturation problem in 2015/6
  - No indication of onset of new saturation effects even at highest instantaneous luminosities
  - Slight difference between 2016 and 2017 under investigation (algorithmically somewhat difficult to compare due to new pixel detector)

Hit efficiency





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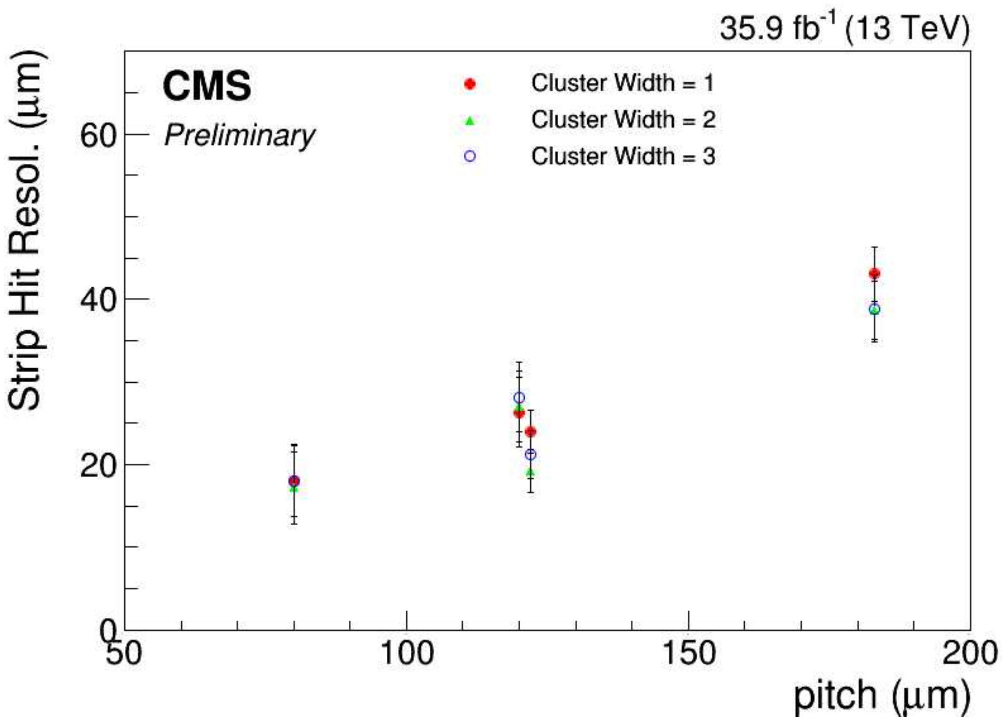
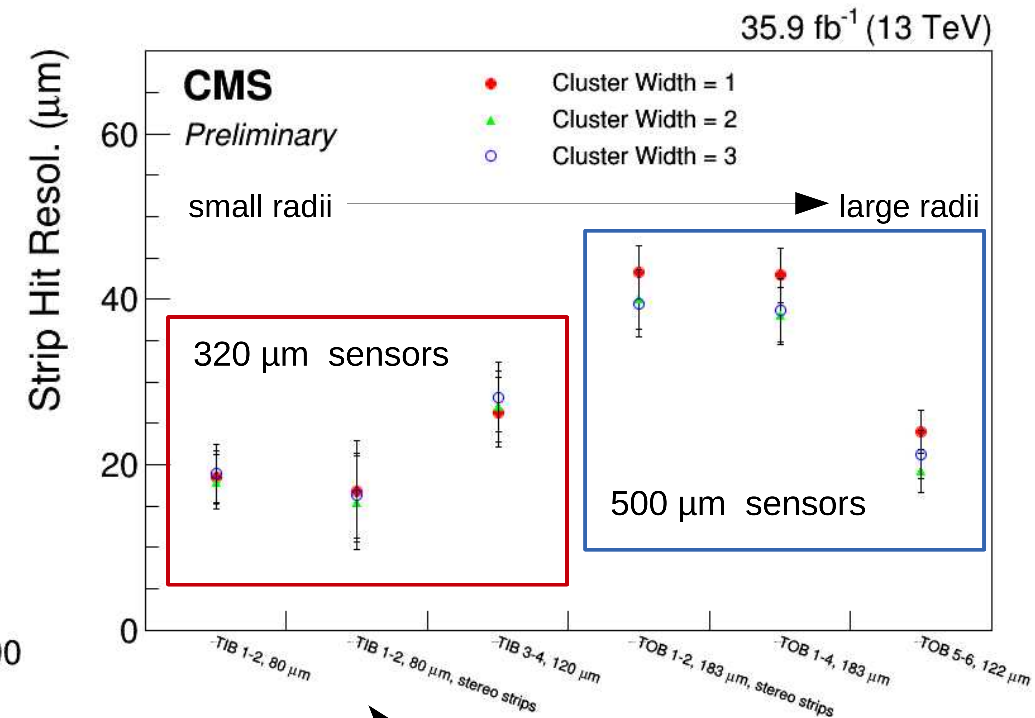
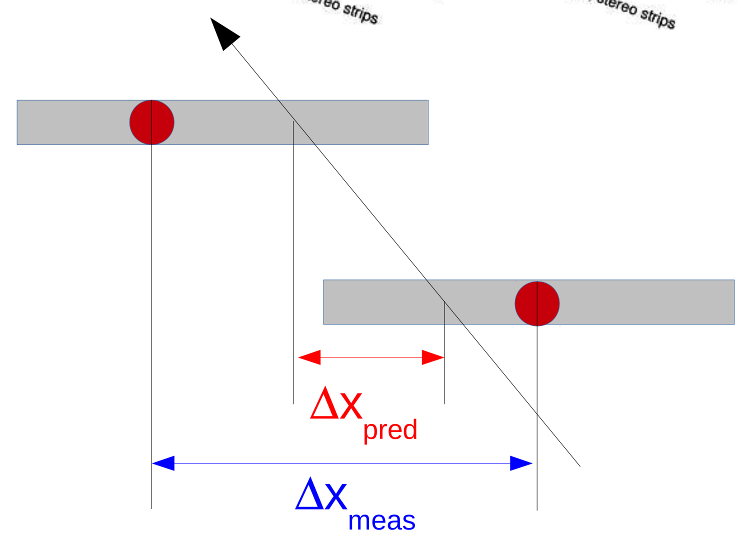
Single hit resolution





- Pair method: Hit resolution measured by using hits in overlapping modules of the same layer
- Expected scaling with strip pitch can be seen
  - Slightly better resolution in thick sensor (higher S/N)

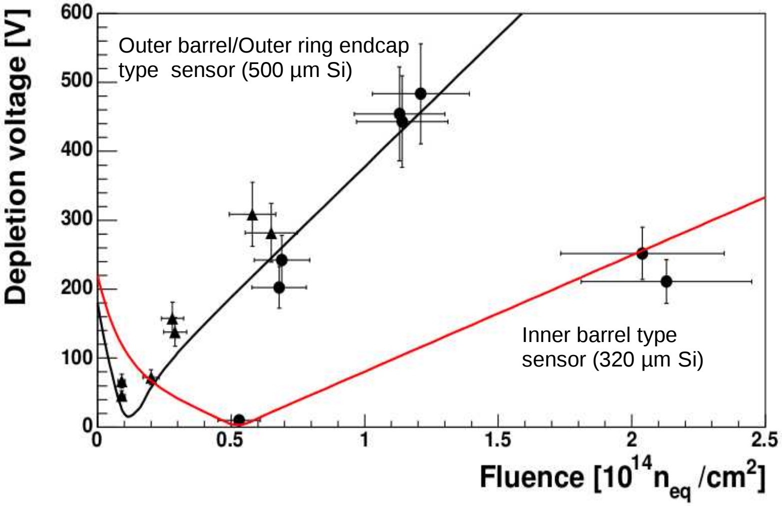


$$\sigma_{hit} = \frac{\sqrt{\sigma\left(_{meas-pred}\right)^2 - \sigma^2_{meas}}}{\sqrt{2}}$$

Radiation effects

Radiation effects – Introduction

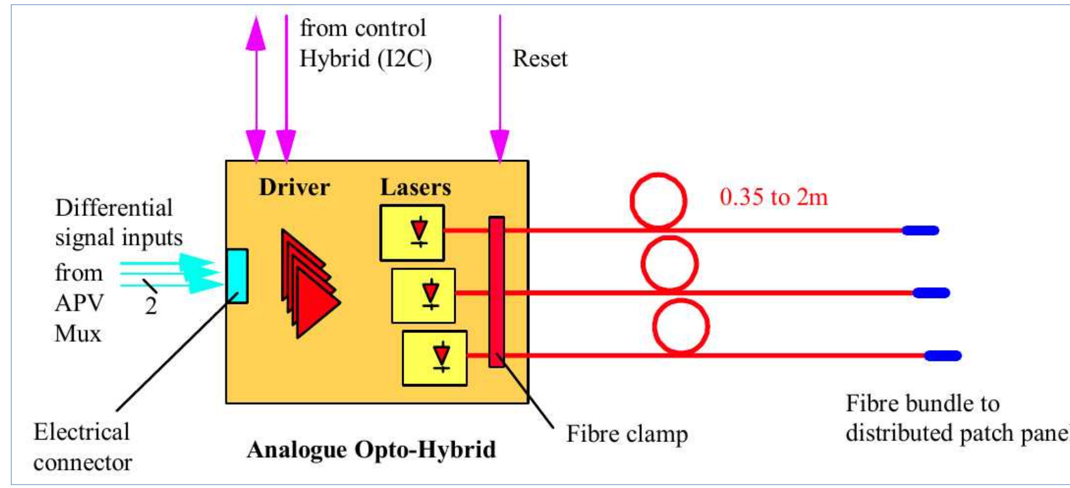
- Approaching 100 fb-1 of integrated luminosity worth of irradiation (~60 fb-1 post-LS1)
- Regular measurements of radiation related quantities performed
  - Both in pp collisions and off-beam periods, e.g. in calibration runs using cyclic triggers
- Leakage current (I_{leak}) measured using power supply current and detector control units (DCUs) on individual modules
- Depletion voltage (V_{depl})
  - signal scans using particles from pp collisions
  - full scans (typically after technical stops)
  - small scans on representative power groups 1/month
  - Measurements show that all layers of the outer tracker are still before type inversion at the moment

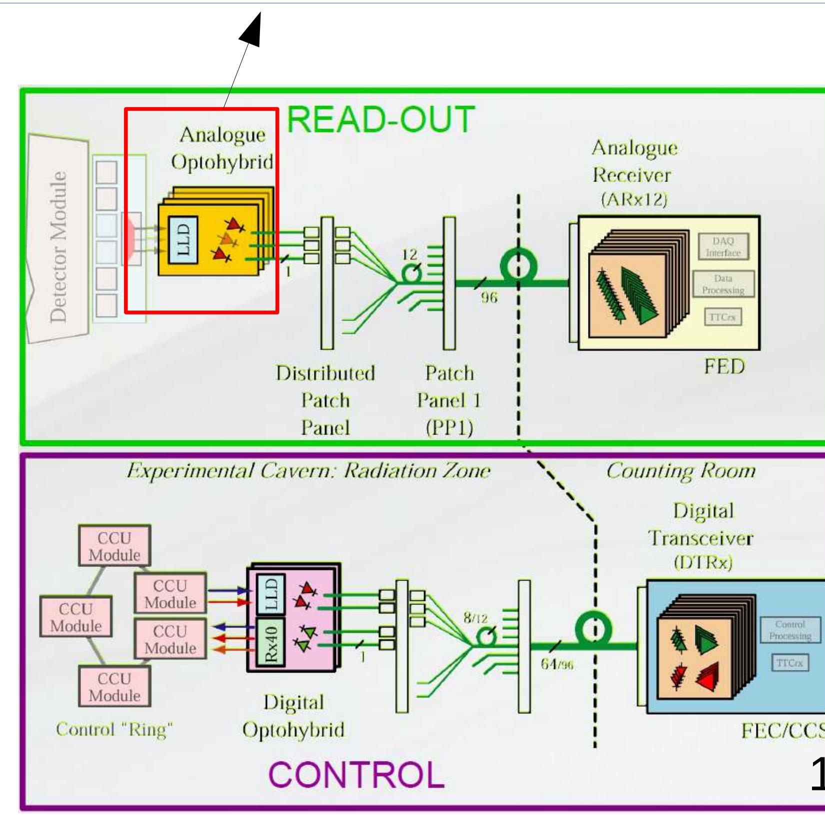


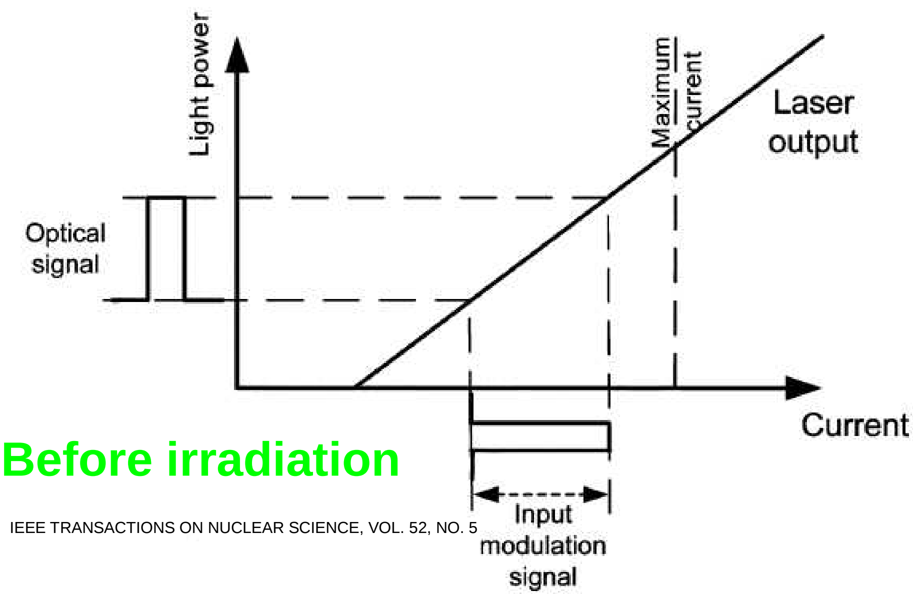
JINST 2008 Paper

Radiation effects in optical readout

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







Before irradiation

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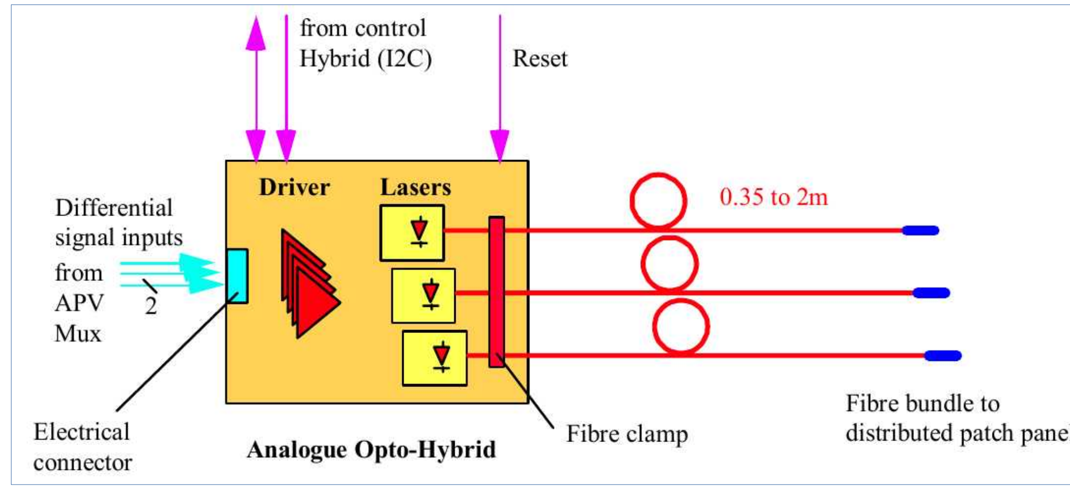

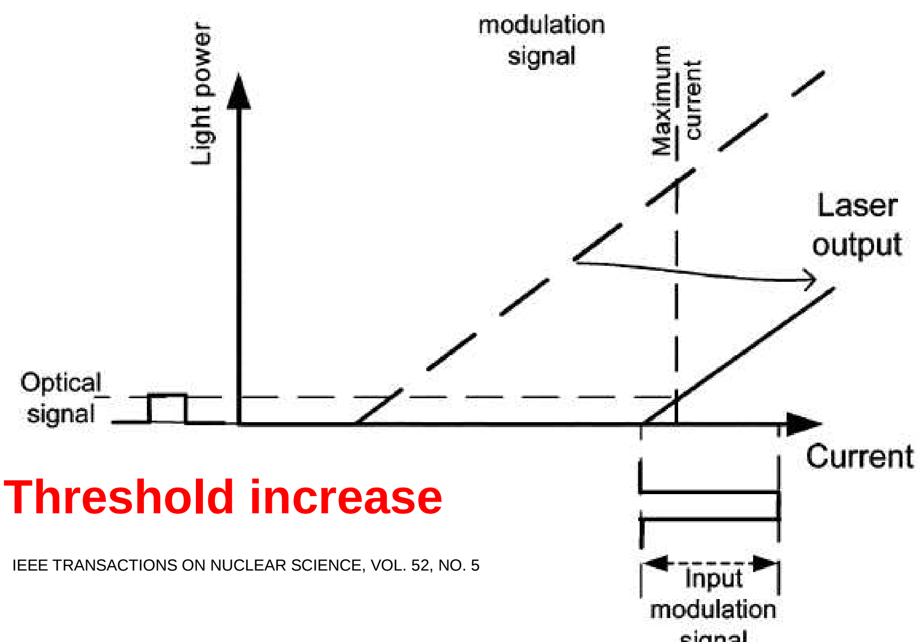

Threshold increase

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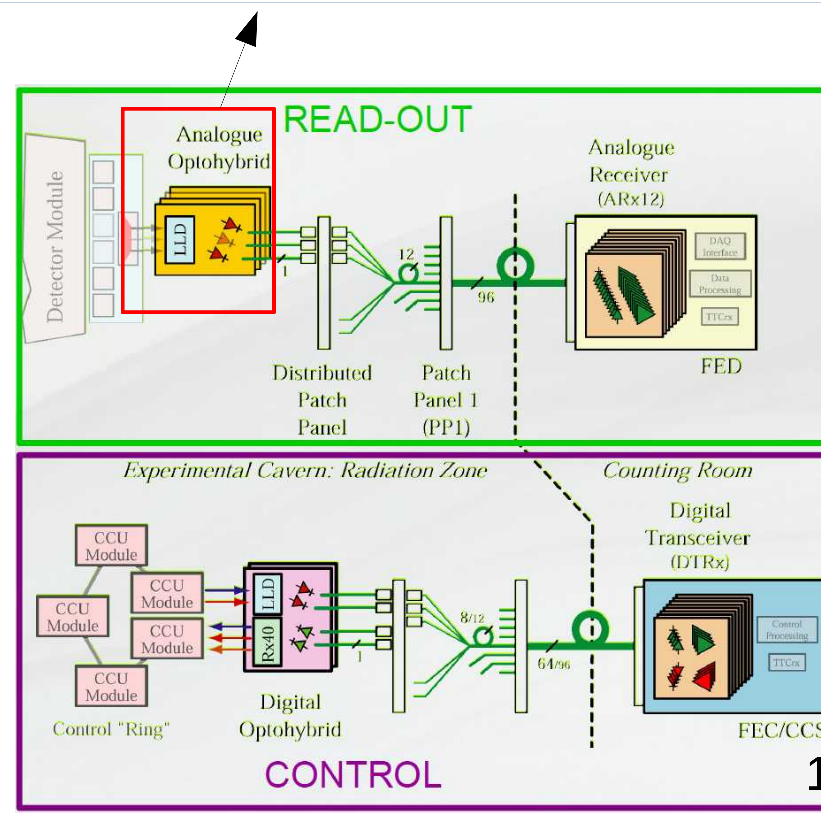
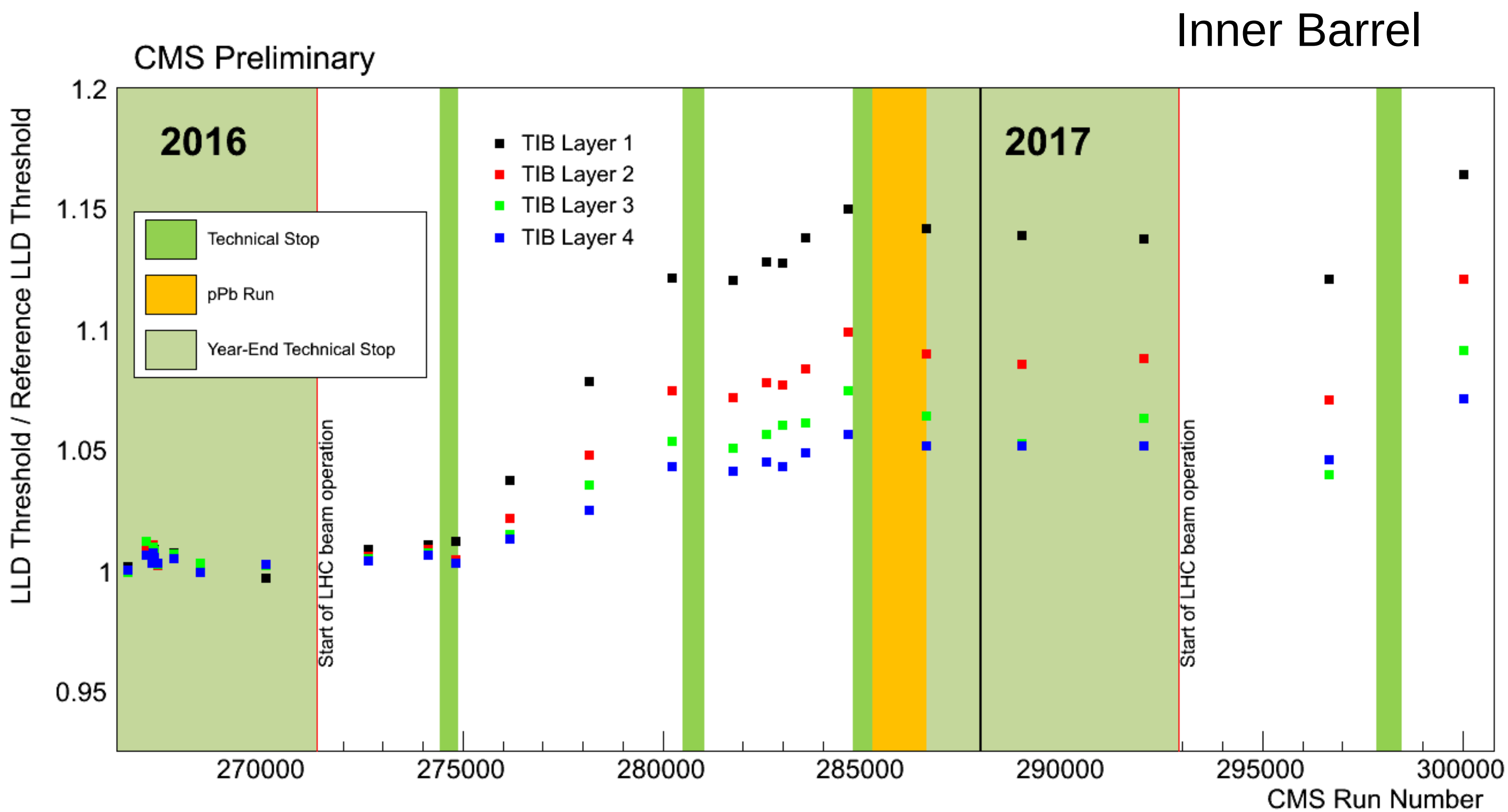
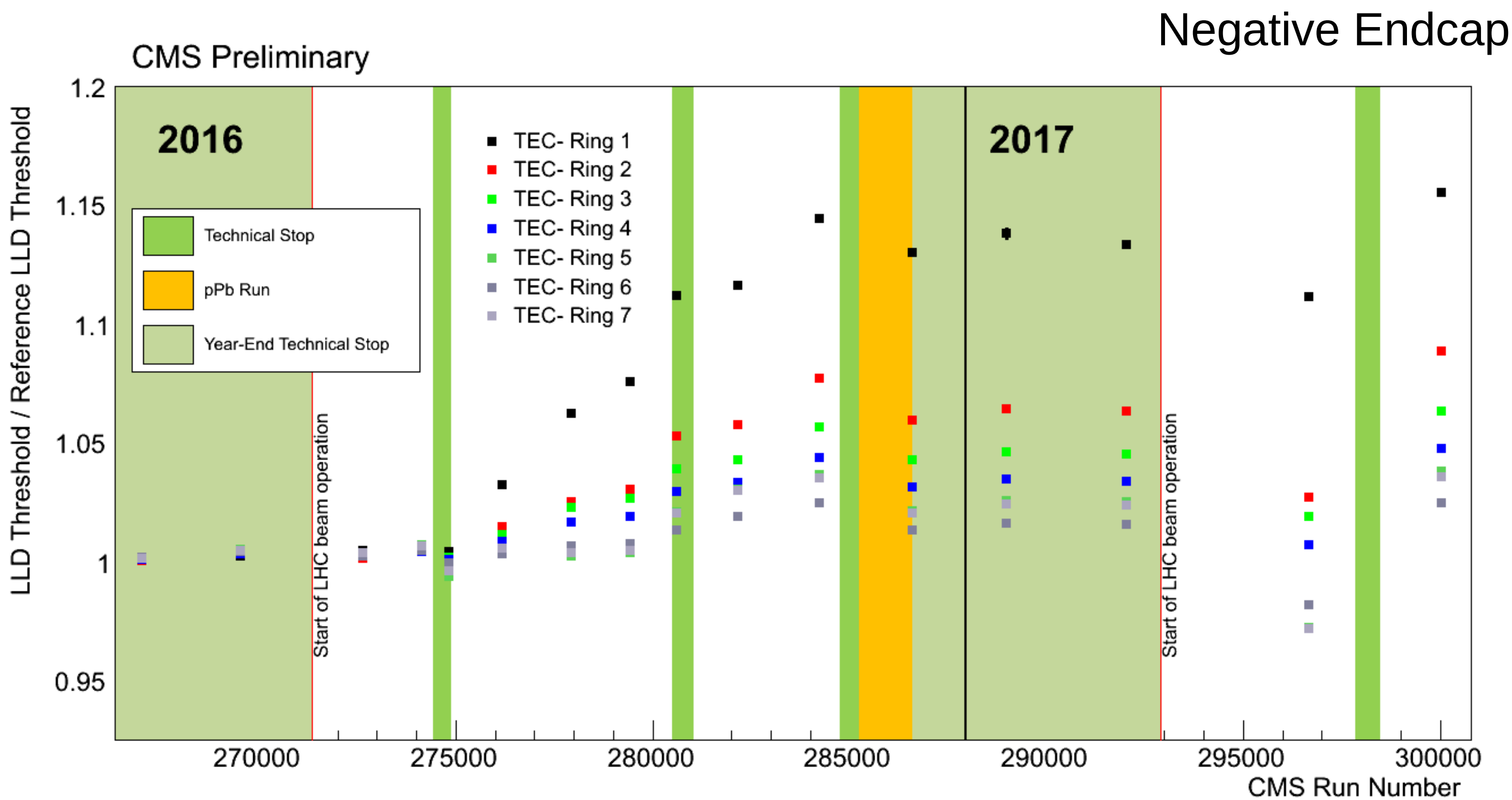


Radiation effects in optical readout



- Clear threshold increase in high luminosity periods can be seen
- Annealing in off beam periods
- Clear dependence on radius (layers in barrel, rings in endcaps)

Radiation effects in optical readout



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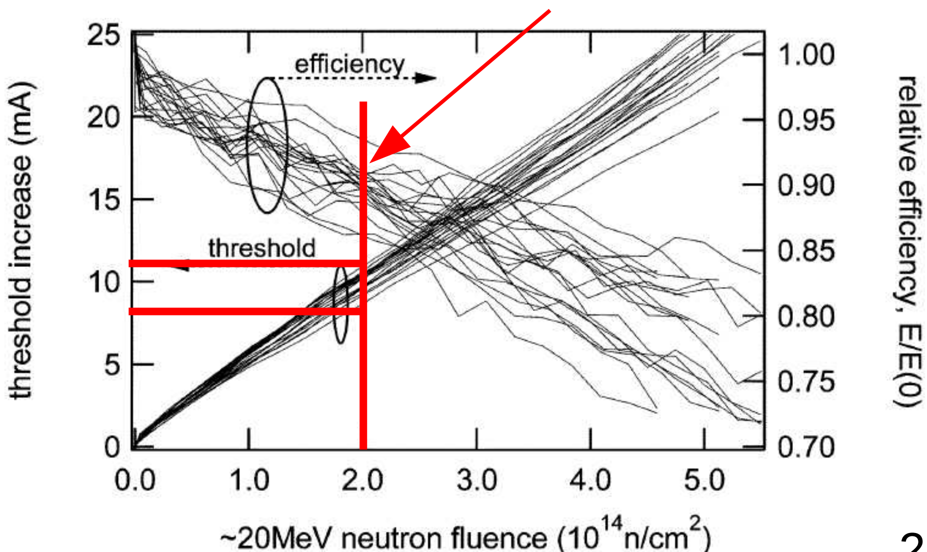
Radiation effects in optical readout

- Maximum threshold increase is about 15% over ~56 fb-1 (40[2016]+16[2017]) of radiation damage
  → about 10% of design life-time value
- Average threshold current at time of reference runs around 3 mA for all subdetectors (TIB/TOB: 3.15 mA, TEC±: 2.8 mA)
  → maximum allowable threshold current 22.5 mA
  - Threshold increase in innermost detector regions is 0.5-0.6 mA
  - Assuming linear scaling to 500 fb-1 gives 4.5 – 5.5 mA consistent with or better than expectations from e.g. IEEE Trans. on Nuc. Science, vol. 52, no. 5
    - Paper does not include annealing in this plot

Expected damage for 500 fb-1 e.g. TIB layer 1



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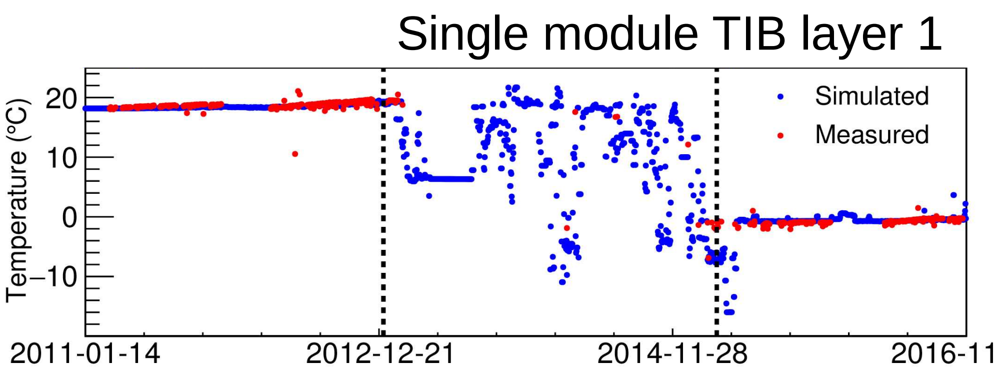
Radiation effects – Leakage current

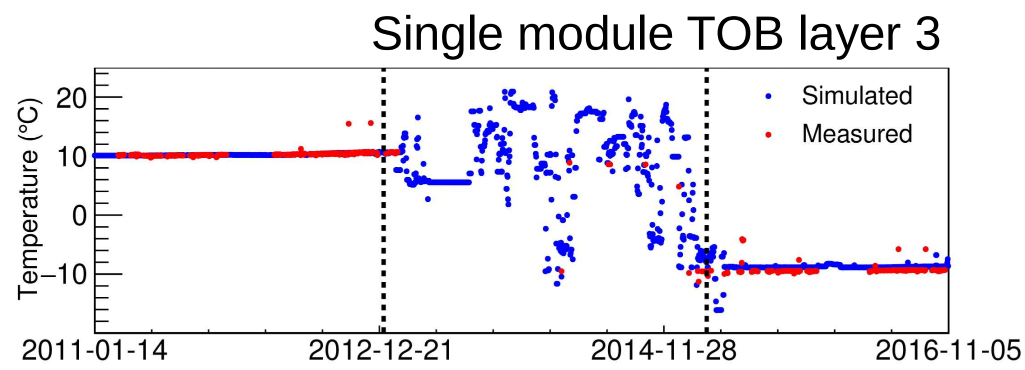
- Leakage current simulations are done based on
  - Silicon sensor temperature measurements at certain “anchor points” taken **per module**
    - Temperature is extrapolated to other periods using few representative “PLC-based” temperature probes (e.g. periods with detector off)
  - Particle flux simulations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

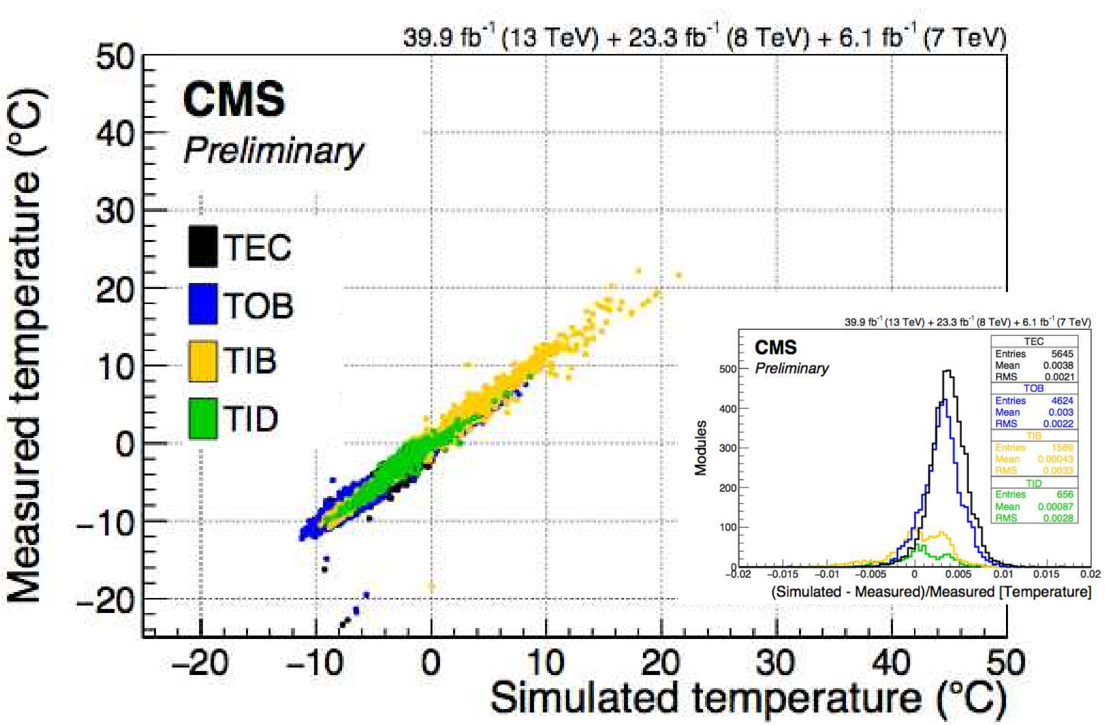
$$I(t, T, \Phi_{eq}) = I_0 + \alpha(t, T)\Phi_{eq}V$$

with $\alpha(t, T) = \alpha_0(T) + \alpha_I \exp\left[-\frac{t}{\tau_I(T)}\right] - \beta \ln \frac{t}{t_0}$

Sensor temperature simulation

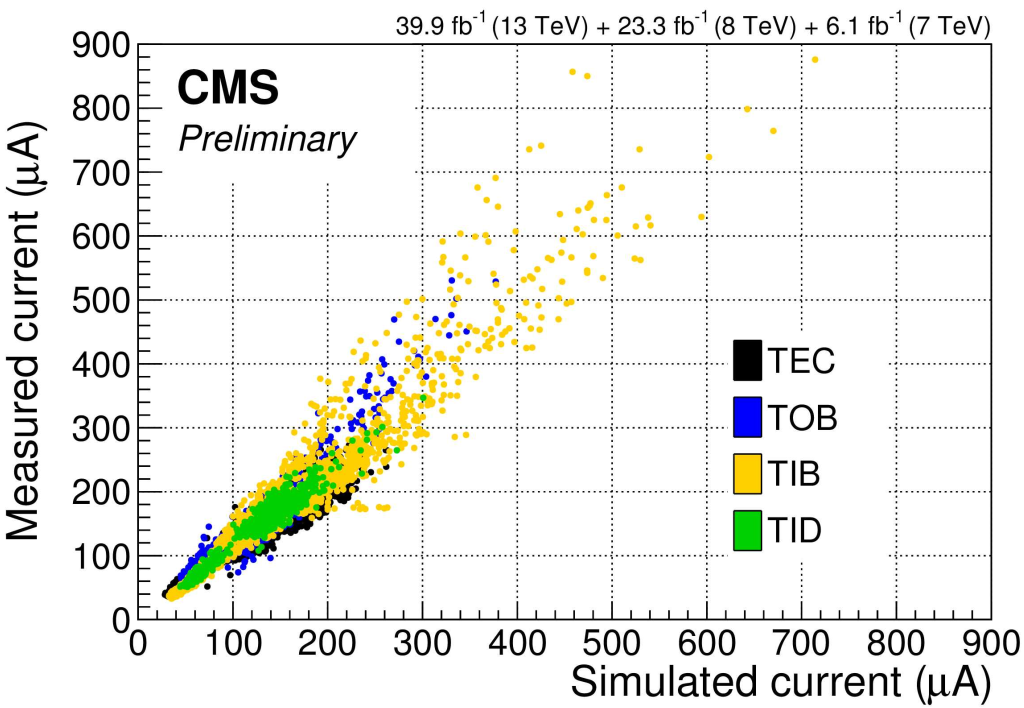


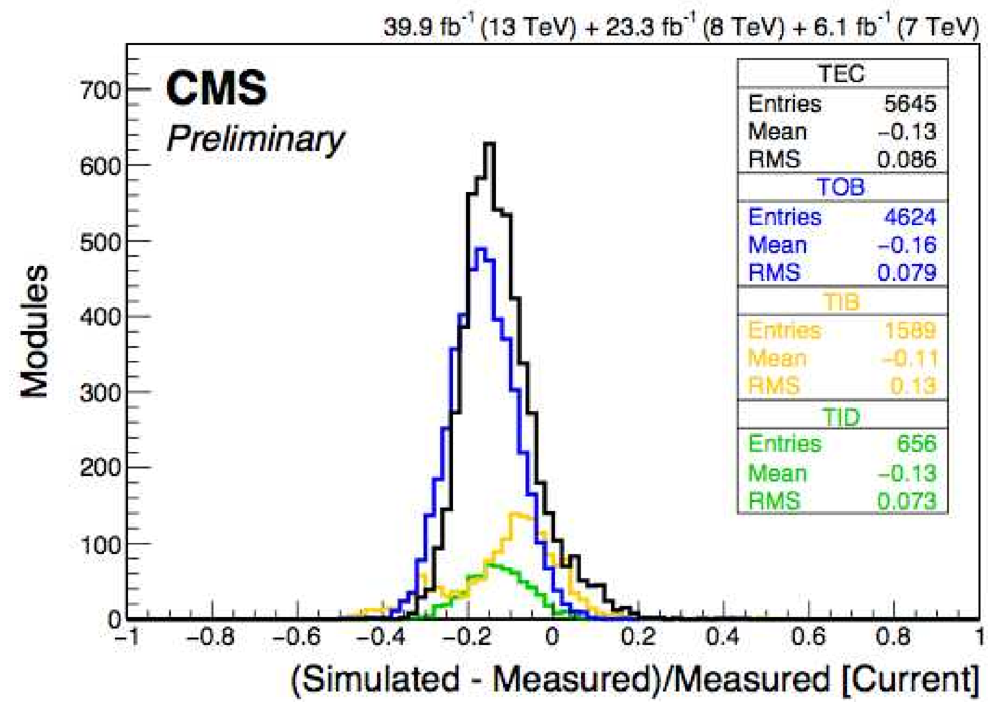




- Silicon sensor temperature generally very well modelled
  - Actual temperature ranges from ~ -10°C for the bulk of the modules to +15°C in regions with degraded cooling
  - Simulation works reasonably well for all cases

Leakage current simulation

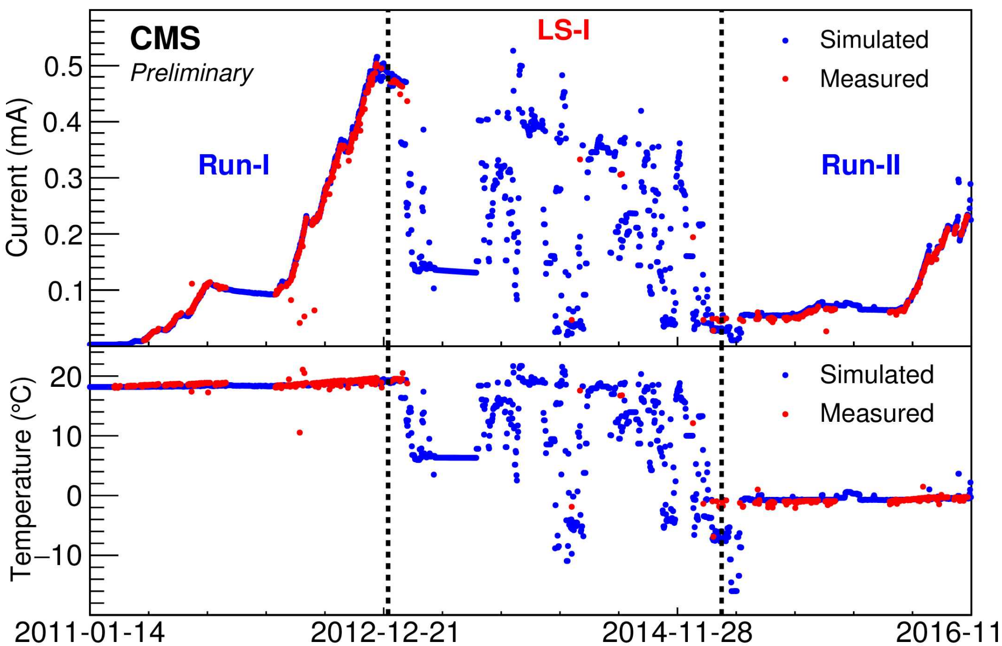




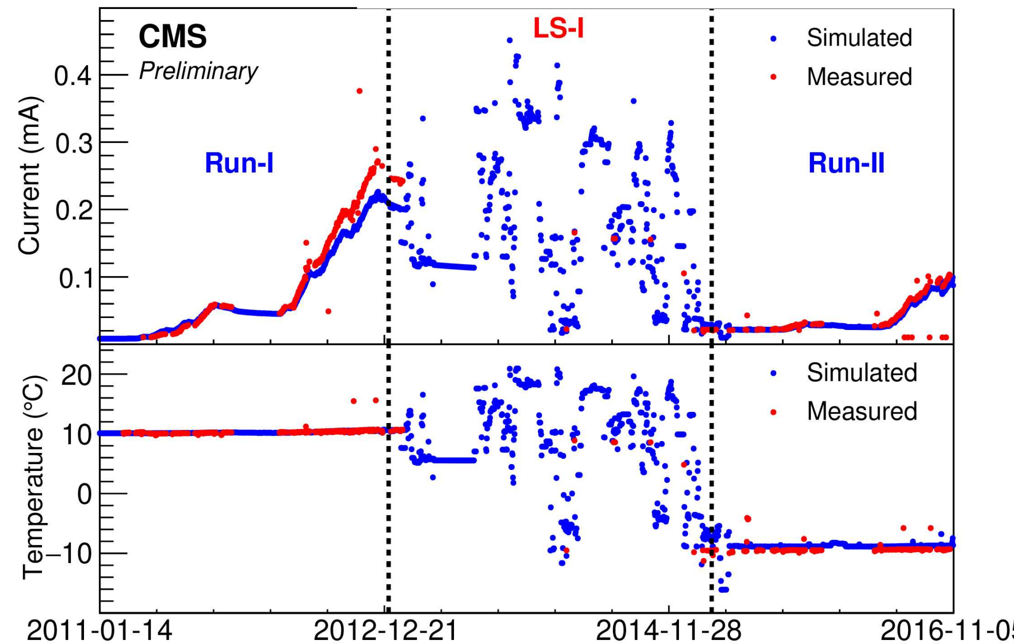
- Comparing simulated and measured leakage current after ~70 fb-1
  - Long annealing periods to be taken into account
  - Very wide distribution of leakage current values due to very different silicon sensor temperatures
    - Modules under nominal conditions but at very different radii (the vast majority)
    - Closed cooling loops (5 cooling loops with 315 modules → 2% of total)
    - Degraded cooling contacts (200 modules → 1.3 % of total)
- Overall description is very good

Leakage current simulation

Single module TIB layer 1



Single module TOB layer 3



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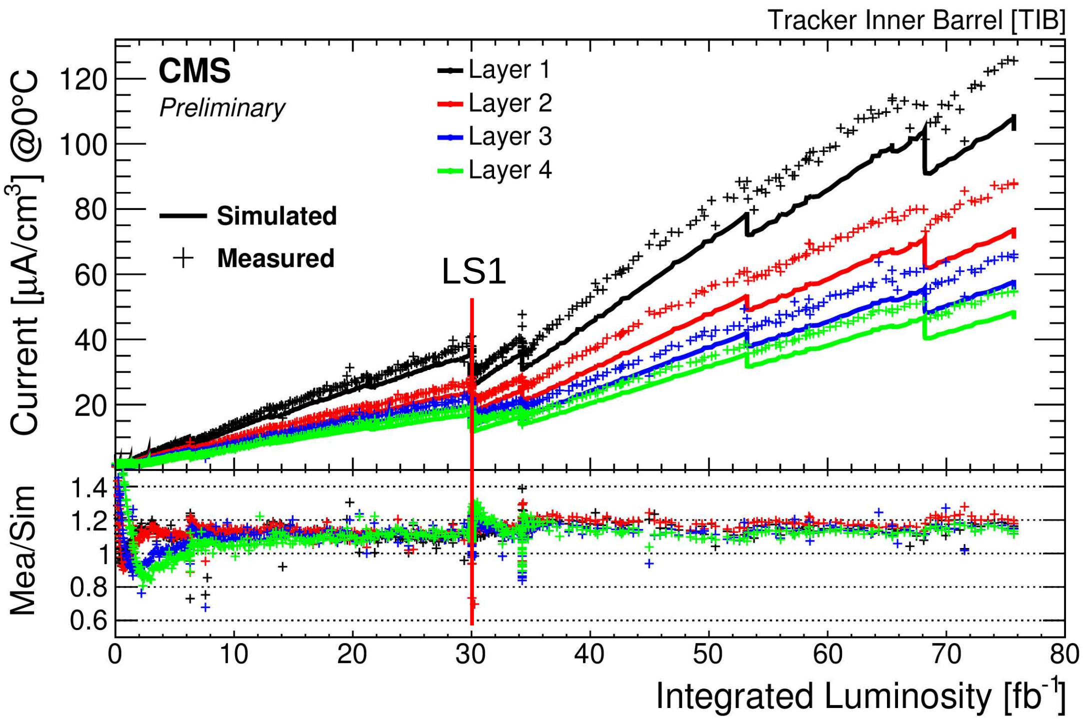
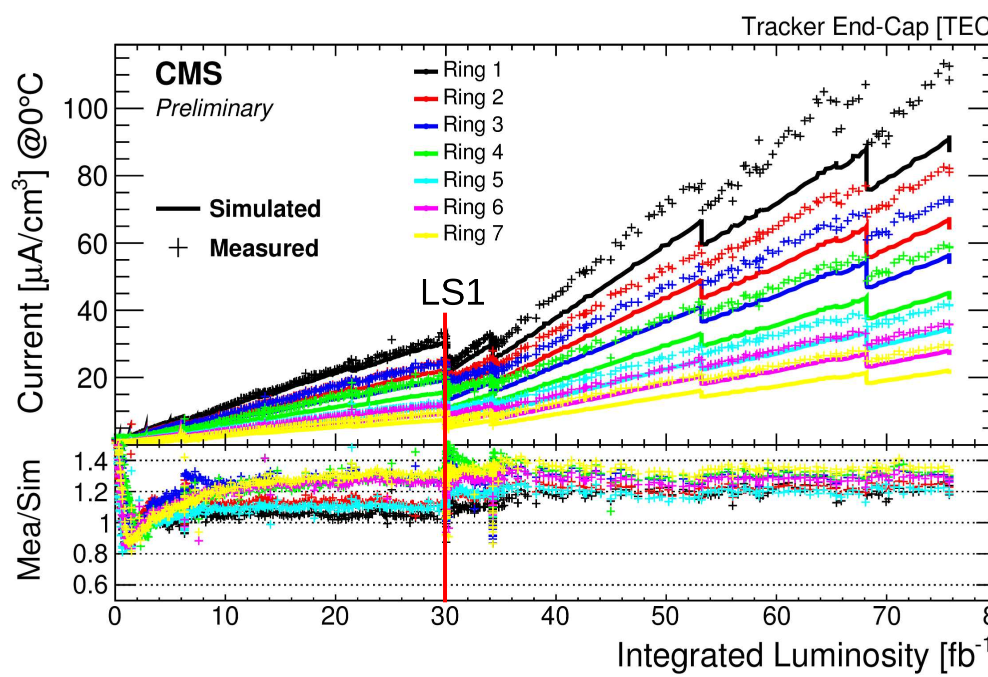
Leakage current per detector layer



- Leakage current as function of integrated luminosity averaged over regions of equal radius
  - Scaled to equalize for different sensor volume
  - Scaled to 0°C

- Generally good description with about 20% constant offset
  - Compatible given uncertainties of FLUKA simulation and modelling parameters
- Change of effective α can be seen after LS1

→ change of operating temperature from $T_{coolant}$ = +4°C to $T_{coolant}$ = -15°C



Summary and Outlook

- CMS Outer Tracker continues to perform very well also after being installed in CMS for almost 10 years
- Signal to noise, hit efficiency and hit resolution are very good and in agreement with expectations
  - APV25 pre-amplifier saturation seen at high luminosity in 2015/16 has been cured
- Radiation effects become visible in all parts of the system
  - Monitoring is in place for various effects
  - Simulation efforts are in good shape to model the behavior of the system with increasing irradiation

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