Characterization and Calibration of the RD53B CMS Chip

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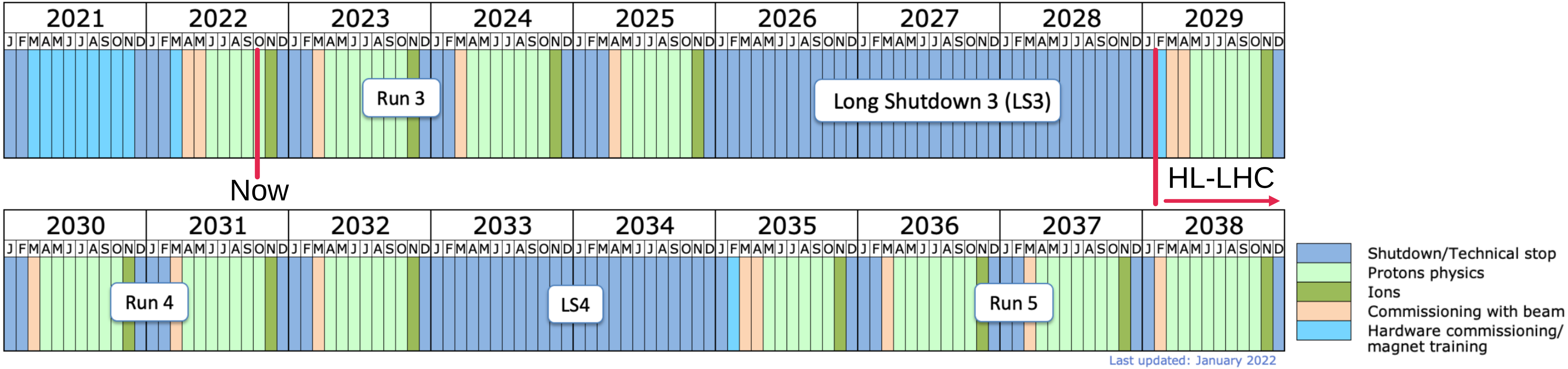
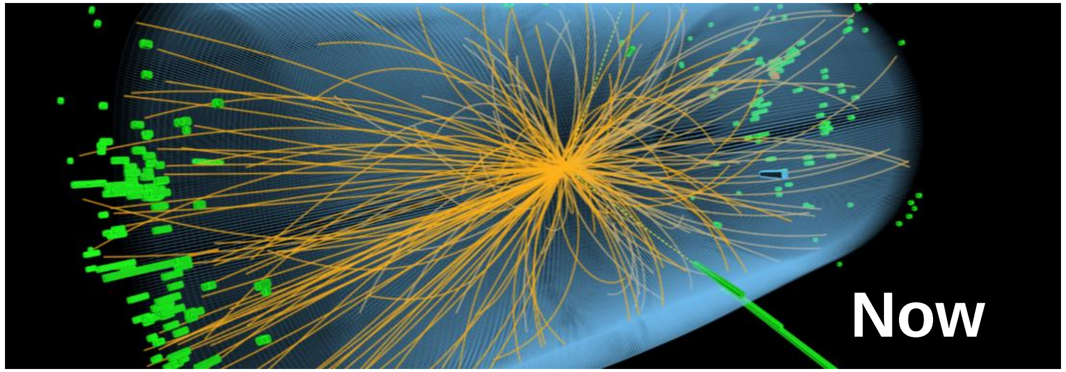
HL-LHC upgrade schedule

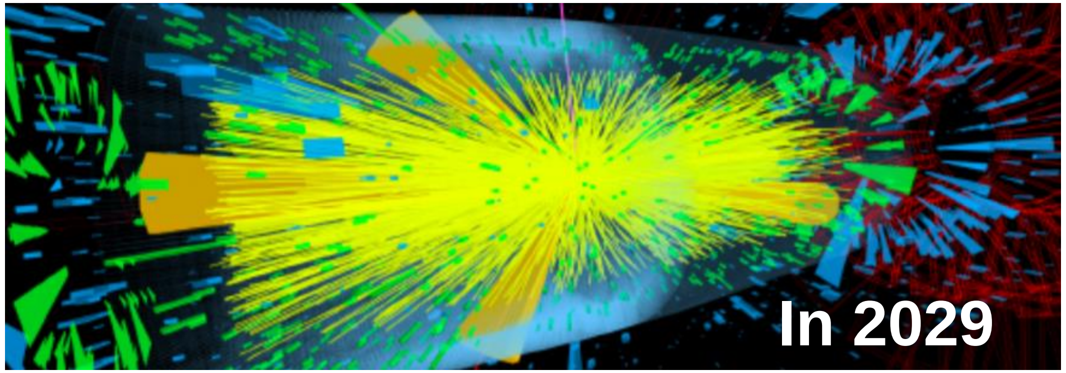
- The High Luminosity LHC upgrade will take place during LS3
- This will result in:
  - pp collisions up to 14 TeV
  - Peak instantaneous luminosity: from LHC nominal **1×**10^{34} cm^{-2}s^{-1} → to **5-7.5×**10^{34} cm^{-2}s^{-1}
  - Integrated luminosity: from nominal ~**300** fb^{-1} →to ~**3000-4000** fb^{-1}
  - Average pile-up: from nominal **20-30** → to **140-200**
  - ~5 times larger track multiplicity in the events than LHC nominal

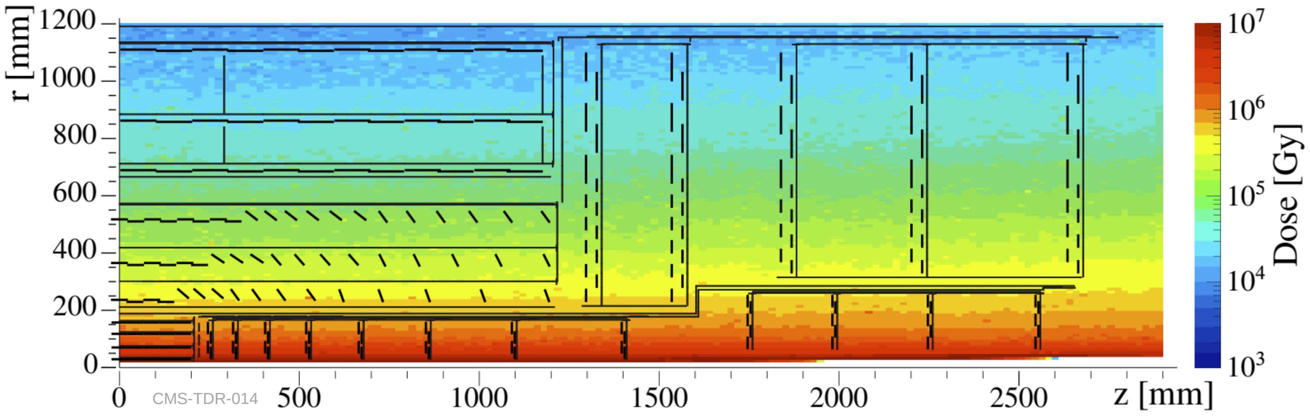


Detector requirements for Hi-Lumi

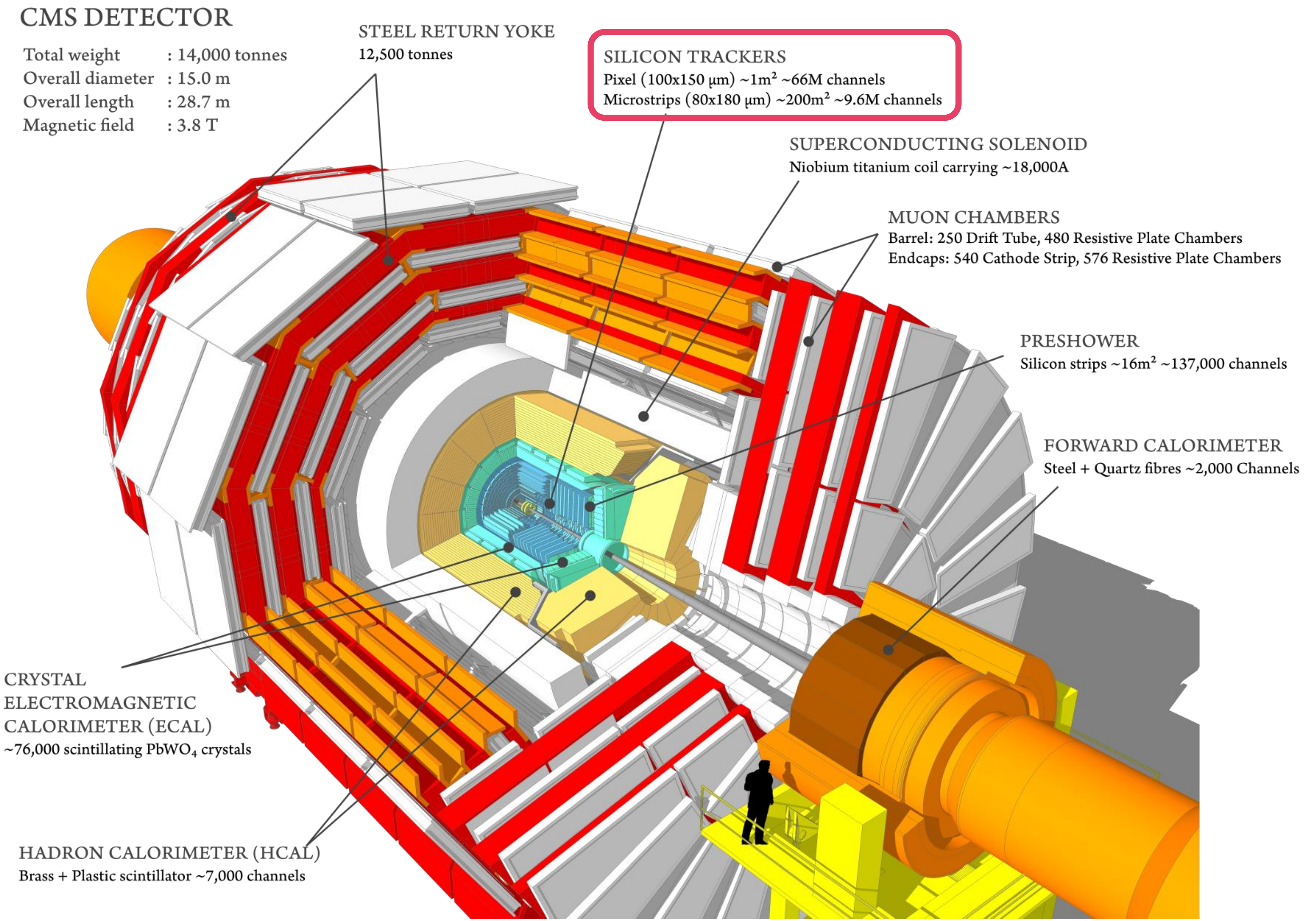
- 5x more collisions will greatly improve physics discovery potential, but there are also challenges:
  - More tracks → higher data rates, harder to separate tracks
  - More tracks → bigger radiation doses
- Therefore, the CMS tracker should satisfy the following requirements:
  - High granularity to efficiently separate tracks
  - High radiation tolerance to sustain efficiency up to 3000 fb^{-1}
  - Contribution to level-1 trigger to ensure more efficient event selection at high luminosity
  - Extended acceptance range to improve the physics potential
  - Reduced material budget
- This makes the current CMS tracker not viable for operation after the HL-LHC upgrade







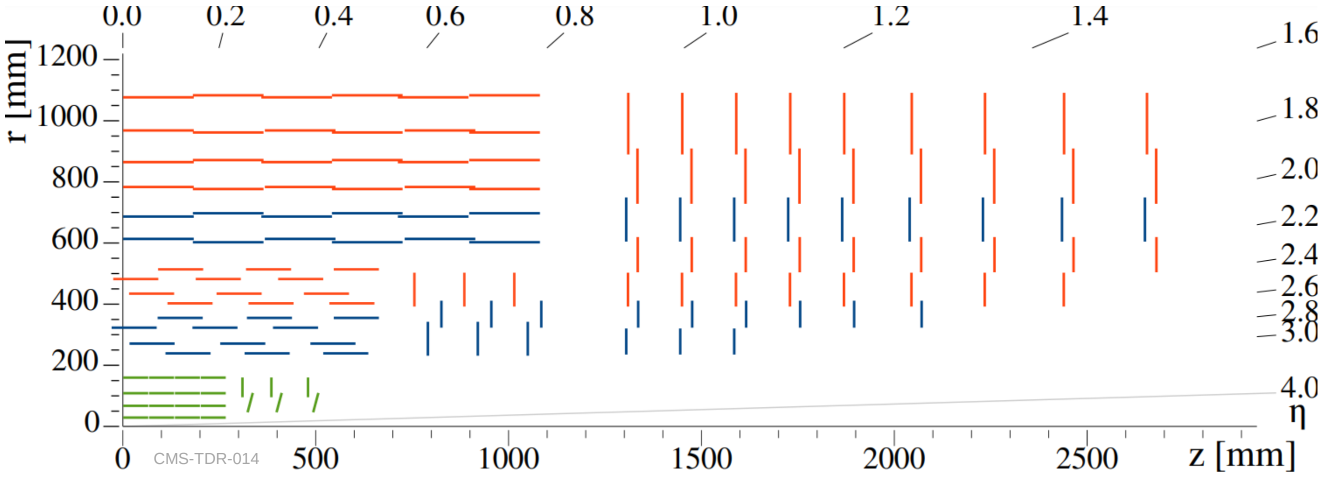
(Current) CMS tracker



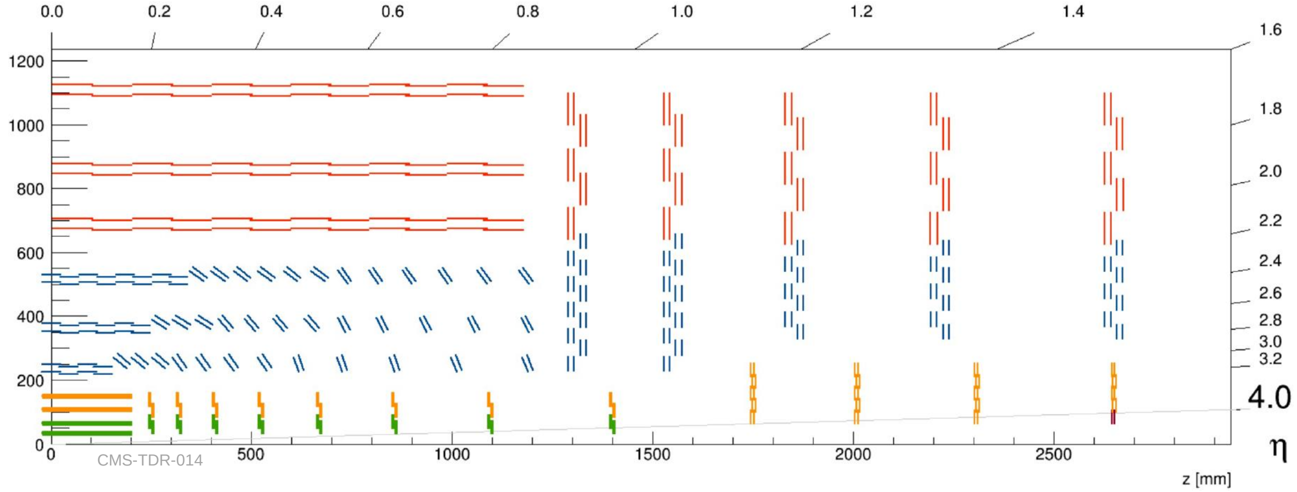
Phase-2 CMS tracker upgrade

- Both CMS Inner and Outer Tracker systems will be completely replaced
- The Outer Tracker will have 6 barrel layers and 5 endcap disks per side and will feature micro-strip and macro-pixel silicon sensors
  - Outer Tracker will also contribute to the L1 trigger
- The inner tracker will have 4 barrel layers and 12 disks (instead of the current 3 disks)
  - This will greatly increase the tracking acceptance: up to |η| < 4.0 instead of the current |η| < 3.0

Current tracker

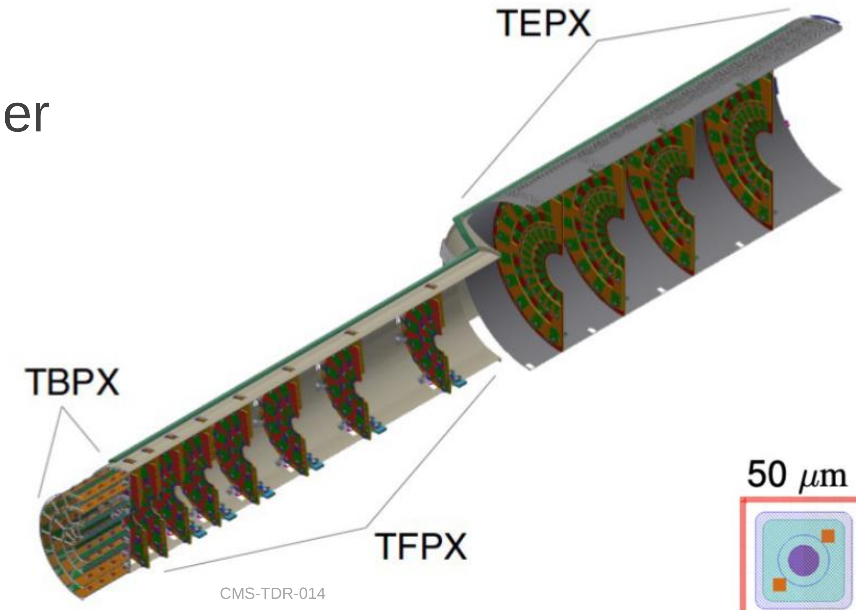


New tracker

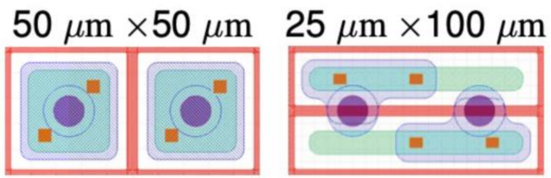


The new Inner Tracker

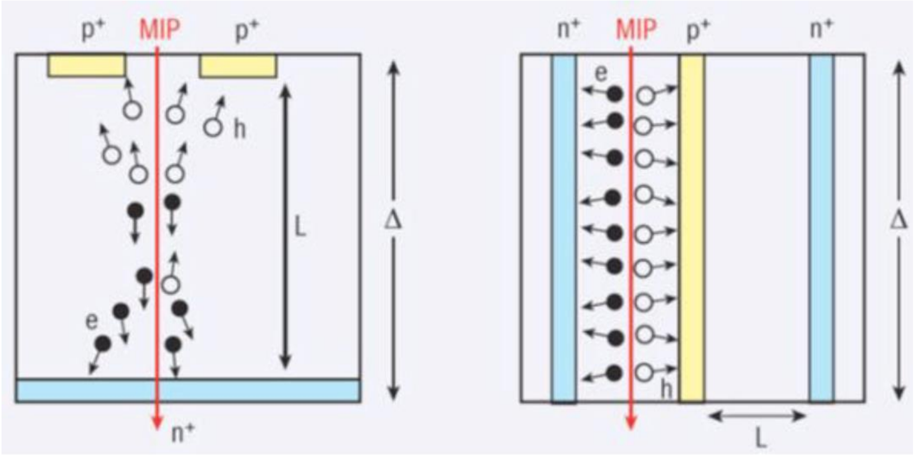
- The new Inner Tracker will feature ~6x smaller silicon pixels than the current one
  - 25×100 μm^2 or 50×50 μm^2
  - 150 μm thickness
- Total active surface – around 4.9 m^2
- Total pixel count – around 2 billion
- Two different pixel technologies will be used
  - 3D pixel sensors on barrel layer 1
  - n-in-p planar sensors everywhere else
- A readout chip based on 64 nm CMOS technology is developed by RD53 collaboration
  - RD53 is developing chips for both CMS and ATLAS with different features



CMS-TDR-014



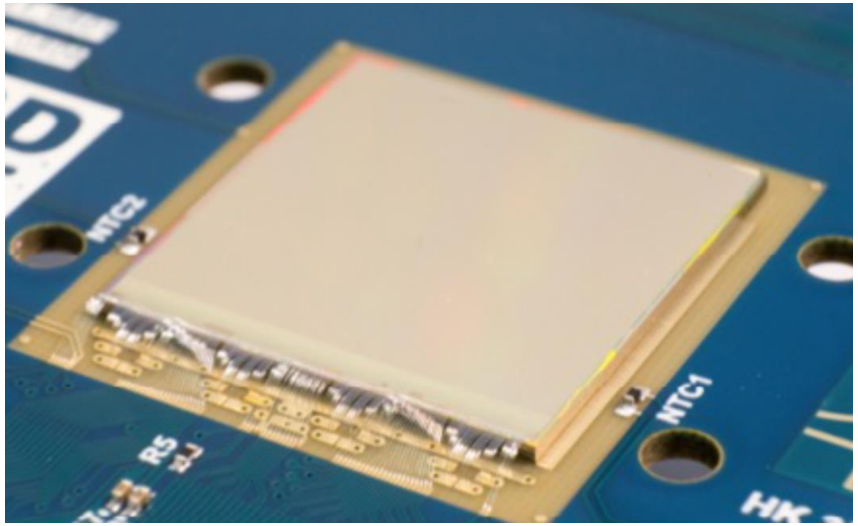
CMS-TDR-014

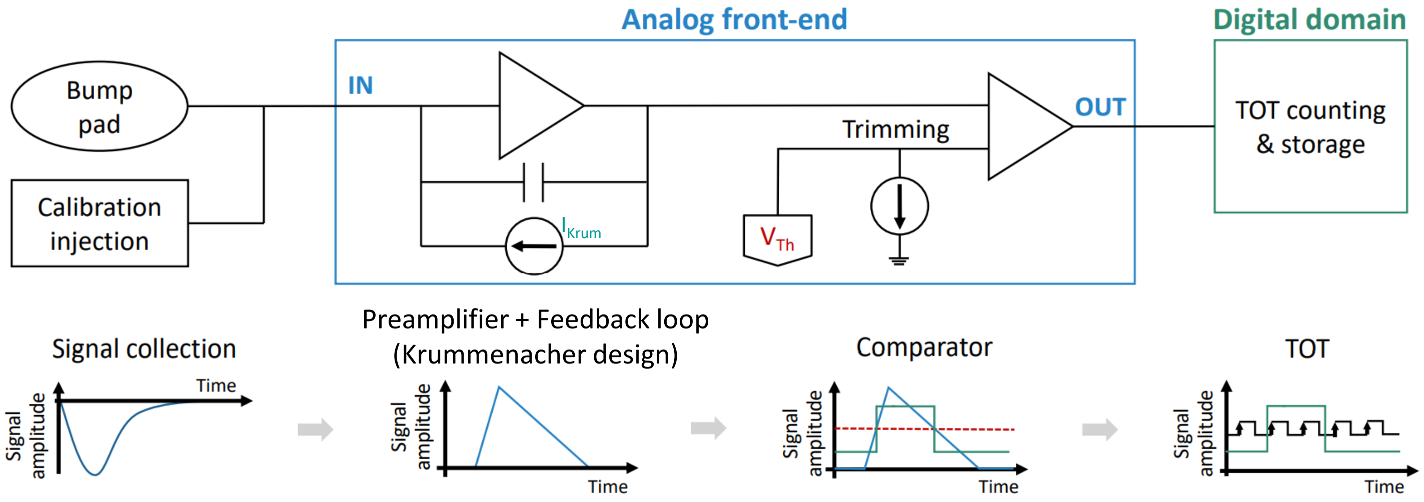


https://cerncourier.com/a/silicon-sensors-go-3d/

The CMS ReadOut Chip

- Features of the chip under development:
  - Able to withstand the radiation up to 1 Grad
  - Low power consumption of < 1 W/cm^2
  - Compatible with serial powering by using on-chip shunt-LDO regulators
- Second generation prototypes (RD53B) are undergoing tests
- The RD53B version for CMS is called CMS ReadOut Chip – CROC
  - 432×336 channels
  - Bump-bonded to the sensor
  - Wire-bonded to the readout
  - 4-bit digital readout for signal strength (ToT)



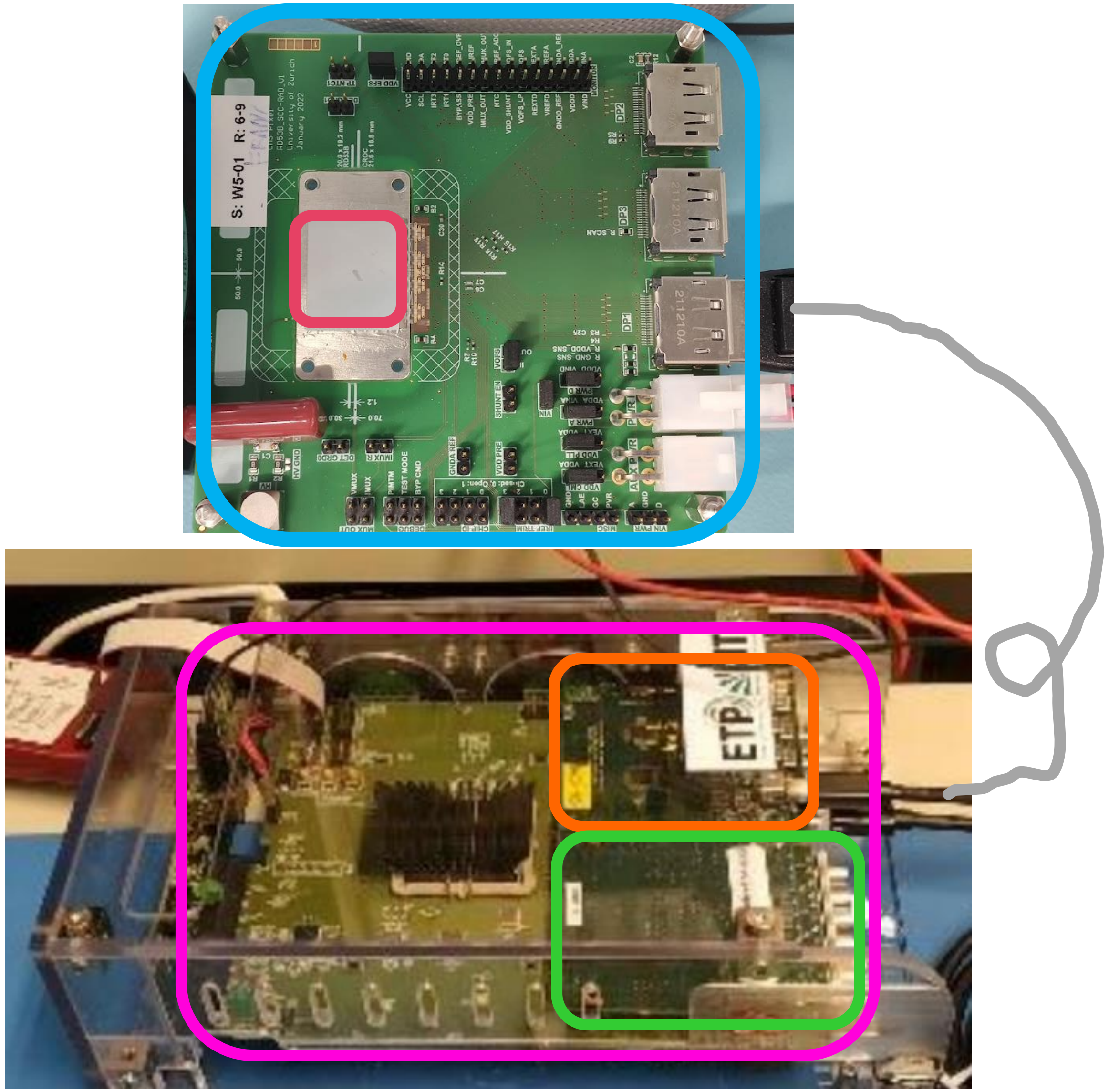


arXiv:2105.00070

Test setups

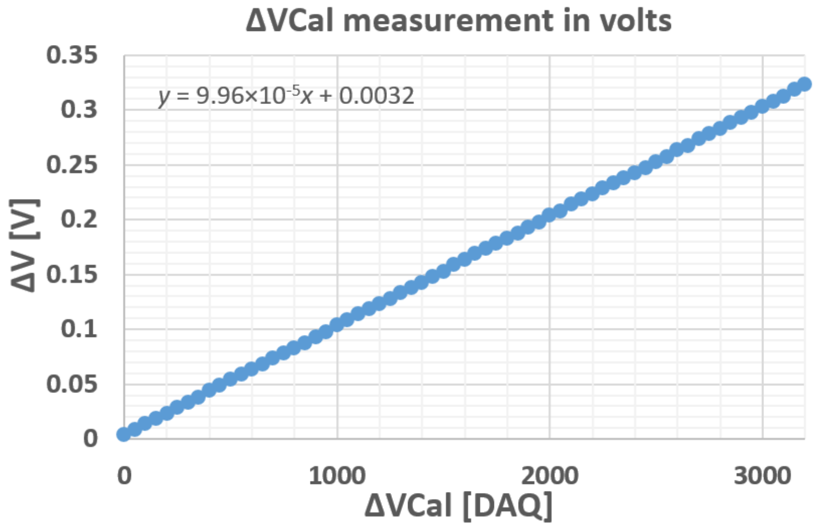
Our test setup for CROC chips consists of:

- Custom-made equipment:
  - A CROC chip mounted on a Single Chip Card (SCC)
  - Electrical readout FMC board connected to SCC via DP connection
  - FC7 board with FPGA and 2 FMC connectors
- Standard equipment:
  - DIO5 FMC board (provides external trigger, clock, etc.)
  - Low and high voltage supply
  - Computer connected to the FC7 via IPbus
    - IPbus is a protocol used to communicate between software and firmware via ethernet (https://ipbus.web.cern.ch/)
    - Computer runs the Ph2-ACF software which is designed to perform both Inner and Outer Tracker hardware tests



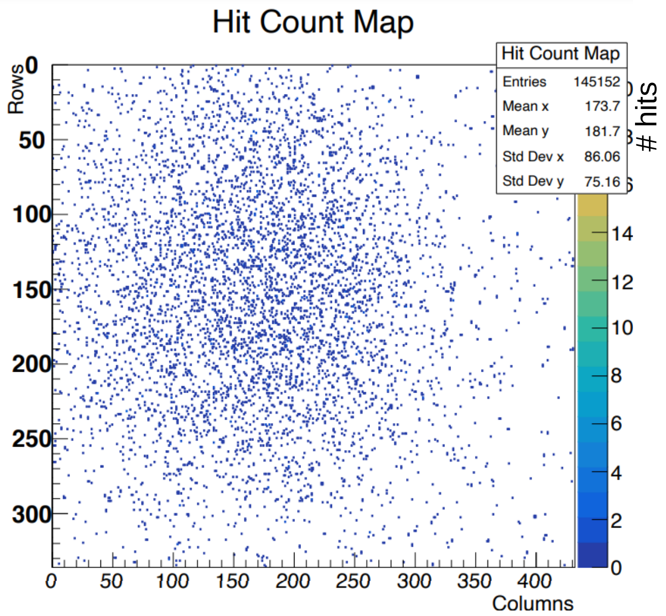
Chip threshold unit calibration

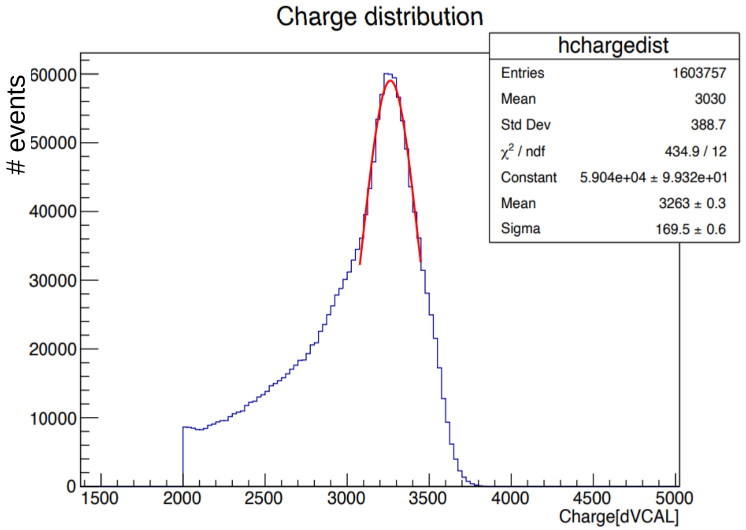
- Thresholds are measured by injecting calibration pulses of known amplitude
- The chip uses DAC units (ΔVCal) to determine the calibration pulse and, therefore, the threshold
- We have used the internal voltage multiplexer of the CROC to measure the actual value for the threshold
- The nominal value given by chip designers is 5.5 electrons of signal per ΔVCal unit
- Our measured ΔVCal values on 2 different chips were closer 5.0 electrons of signal
- The threshold unit value of ~5.0 electrons was also confirmed by using ^{241}Am x-ray source (measurement done by Oceane Poncet)
  - X-rays are monochromatic (59.54 keV) and always release the same amount of signal in the sensor (16312 electrons)



1 ΔVCal = 9.96×10^{-5} V
$C_{cal} = 7.94\times10^{-19}$ F
1 ΔVCal → 7.91×10^{-19} C
1 ΔVCal → 4.93 e⁻ of charge

Recorded pixel hits with ^{241}Am source

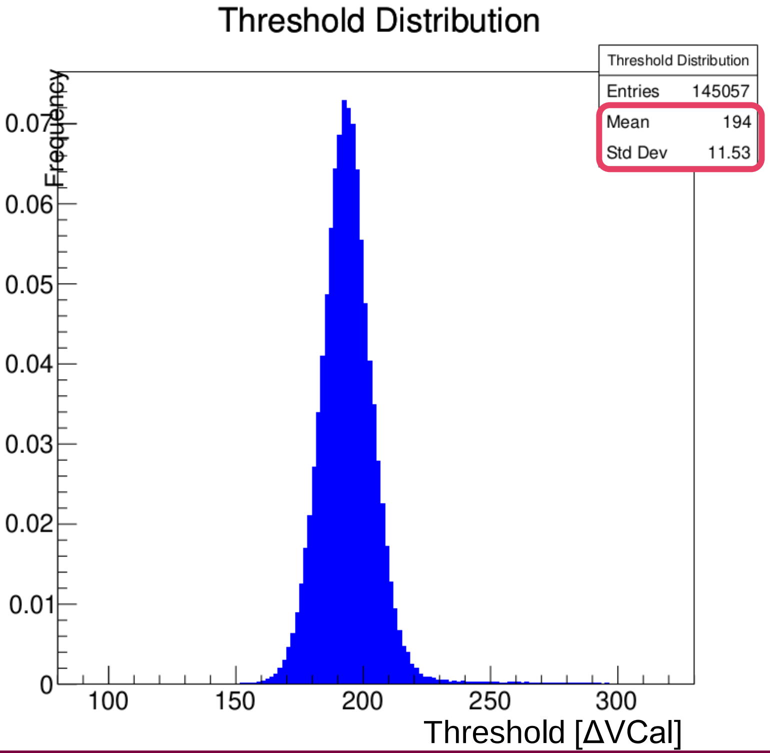


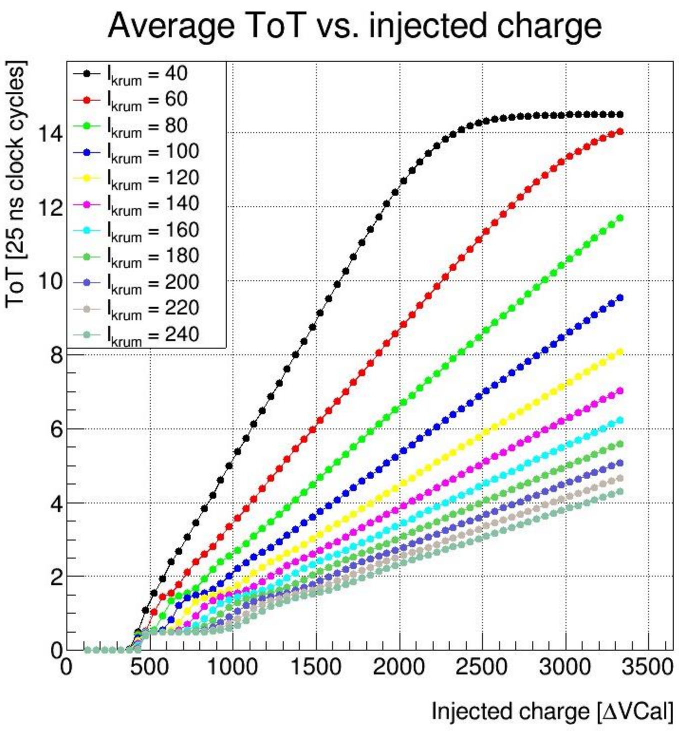


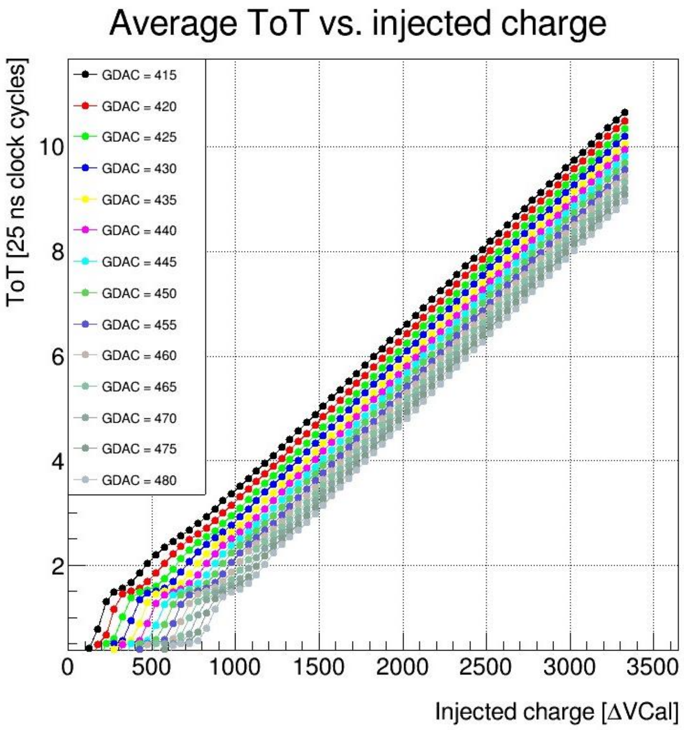
16312 electrons / 3263 ΔVCal = **4.99±0.26 e⁻/ΔVCal**

Chip threshold and ToT gain tuning

- The threshold CROC chip can be successfully tuned at 1000 e⁻ of signal (and possibly lower) with a threshold spread of only ~50 e⁻ between the pixels
  - This is made possible by the trimming DAC, having 4 bits to trim the threshold for each pixel individually
- Preamplifier feedback (“Krummenacher”) current can be tuned to obtain different ToT gain curves
  - Charge resolution can go below 1000 e⁻ per ToT (with very low dynamic range) or as high as 3500 electrons per ToT and more (with very high dynamic range)
  - ToT gain slope does not depend on the threshold itself, as expected with the linear analog front-end







Wrap-up

- The HL-LHC upgrade will highly increase the physics potential but also will pose new challenges for the detector makers
- The detectors will need higher resolution, higher data output rates, and higher radiation tolerance
- A completely new tracker is being prepared for CMS
- Pixel detector chips for the Inner Tracker are developed by the RD53 collaboration
- 2nd generation chips, called CROC, are undergoing tests and showing good performance

Thank you!

Pixel modules

- Two types of Pixel Modules
  - 1x2 and 2x2 readout chip
- 3892 module plus spares (1156 1x2, 2736 2x2)
  - 2 Billon pixels
    (124 million in current detector)
- Read Out Chip (ROC) – only active element on module