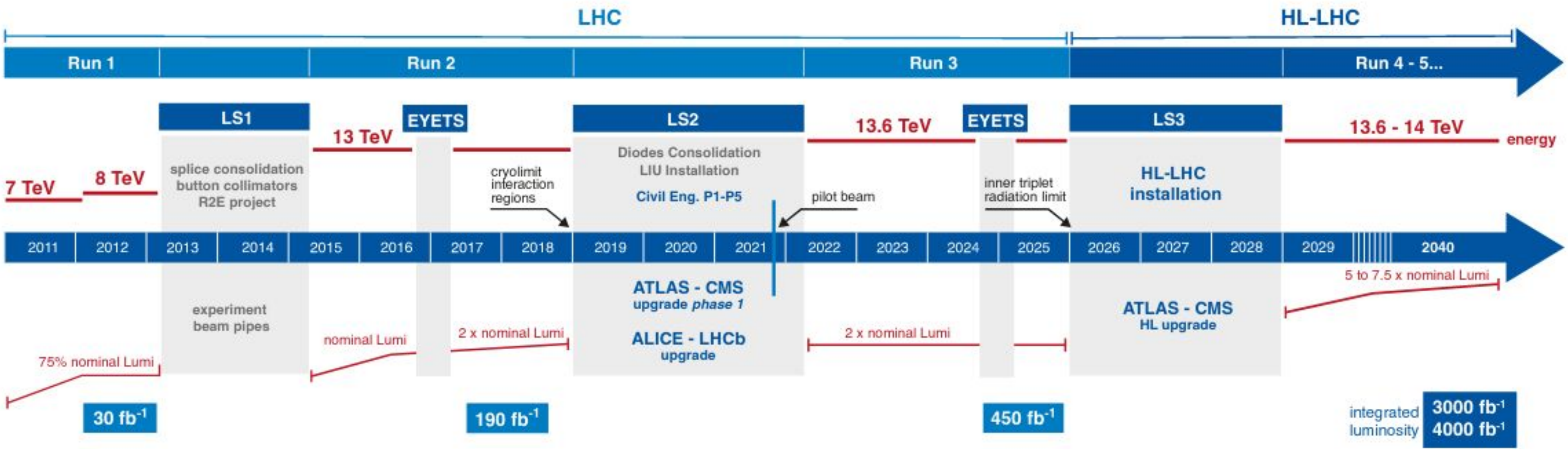
University of Zurich[UZH]

# The Phase 2 upgrade of the CMS Inner tracker

**Sergio Sánchez Cruz** for the CMS tracker collaboration

# Introduction




**High luminosity LHC features**

- pp collisions up to 14 TeV
- 5 to 7.5 x $10^{34}$ $cm^{-2}s^{-1}$
- Total integrated luminosity 3000/4000 $fb^{-1}$
- Up to 200 simultaneous interactions

→

**Ultimate physics performance**, but

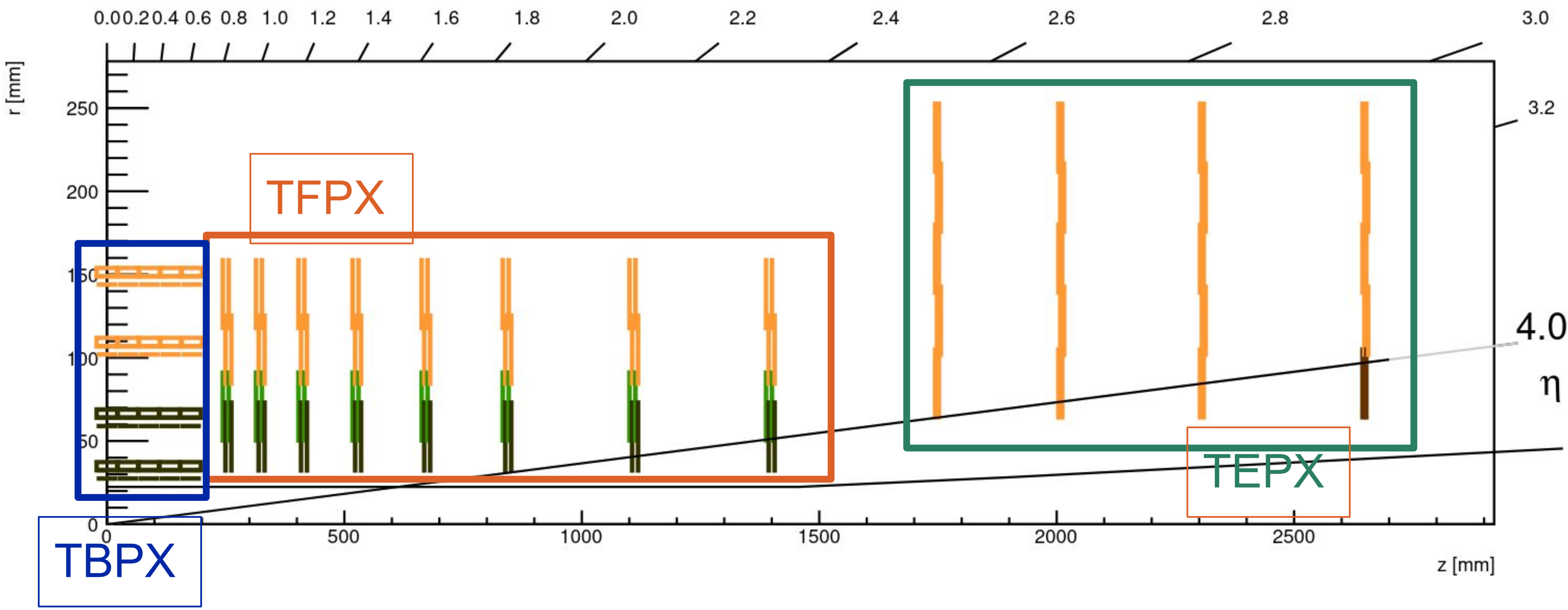
- Harsher data-taking conditions
- Radiation dose and detector fluence ~10 times higher
- 750 kHz L1 rate
- ~4 times longer L1 latency

**We aim to maintain or improve the detector performance up to 200 interactions**

# The tracker upgrade

- Being the closest detector to the interaction point, the current system cannot withstand the HL-LHC running conditions
- Both CMS' inner and outer tracker systems will be fully replaced

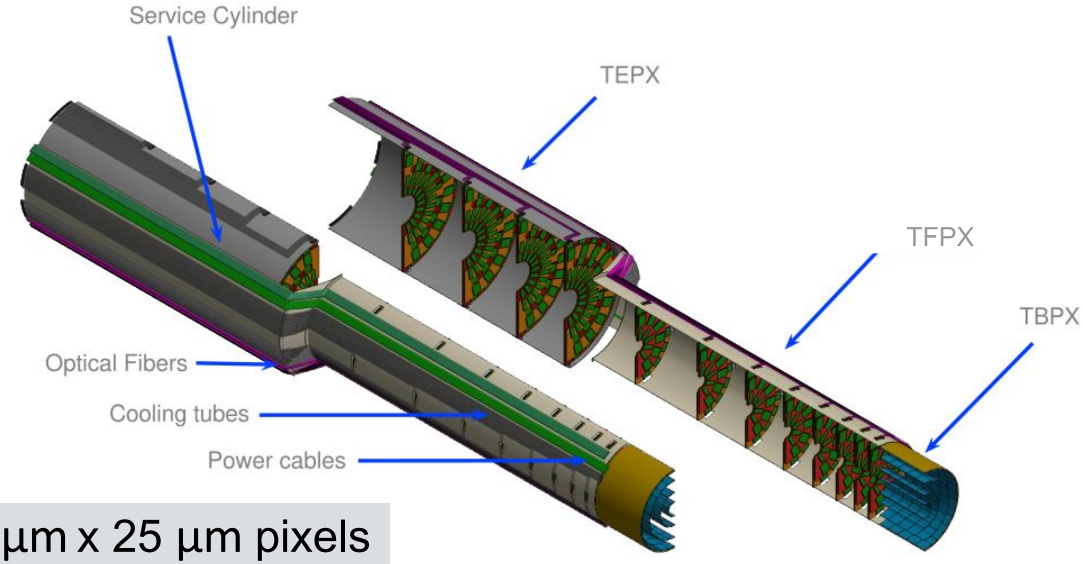
**See Jack's talk in this session**



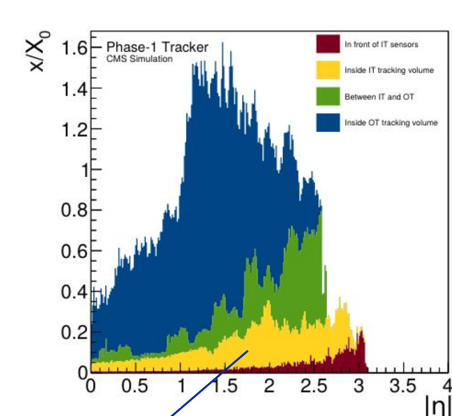

- Acceptance increased to |eta| < 4
- At least 4 layers with at least one hit in all the acceptance

# The tracker upgrade

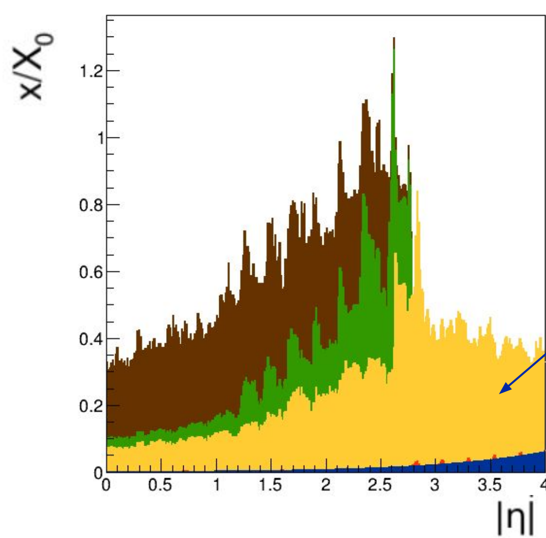
- Larger fluence → 2.6 x $10^{16}n_{eq}$
- TID → 1.5 Grad
- Higher hit rate → 3 GHz / $cm^2$




- Larger detector granularity → 100 µm x 25 µm pixels
- Detector occupancy at the permile level
- 4.9 $m^2$ active detector → 5 times wrt Phase-1
- Similar material budget wrt Ph-1 detector

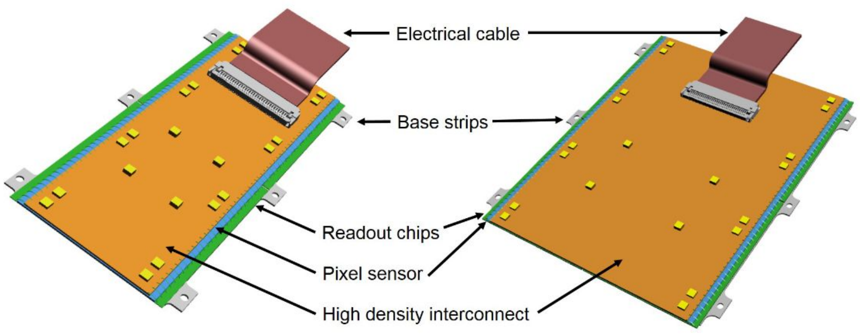


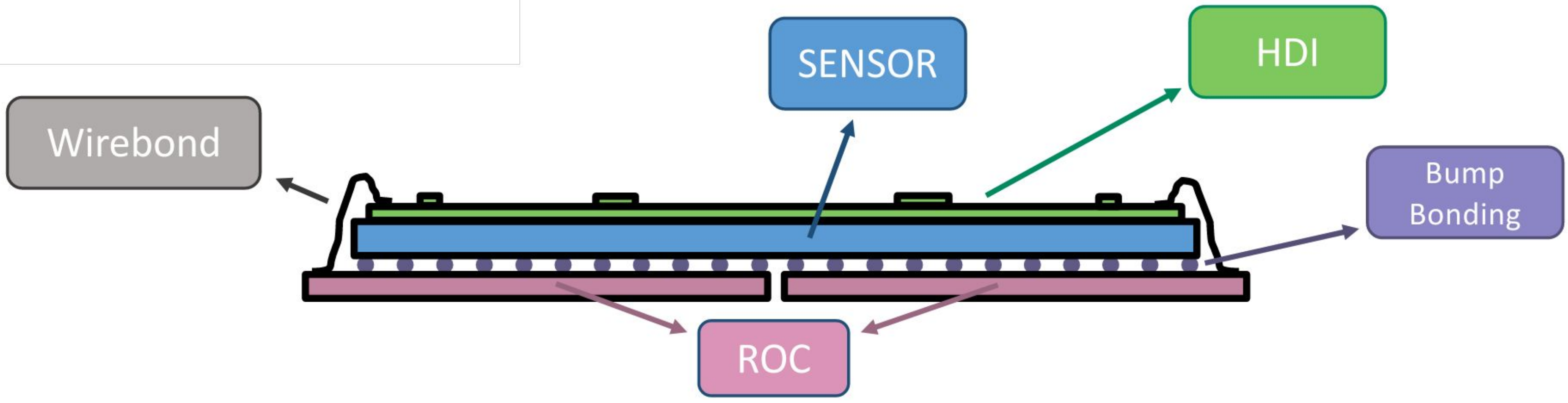

- Using n-in-p silicon hybrid sensors
- Using planar or 3D sensors depending on the layer



# Pixel modules

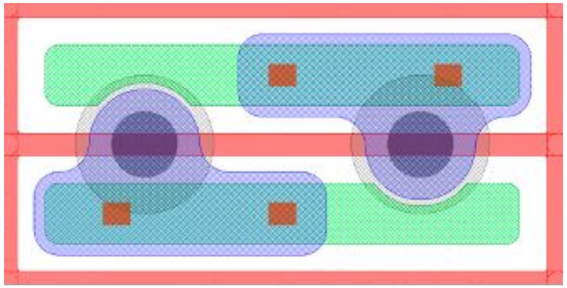
- Two types of modules:
  - 2x1 chips for higher occupancy regions
  - 2x2 chips for lower occupancy
- ~$1.4 \times 10^5$ (336x442) pixels per readout chip
- 1156 double + 2736 quad modules
- > $2 \times 10^9$ pixels in the whole system



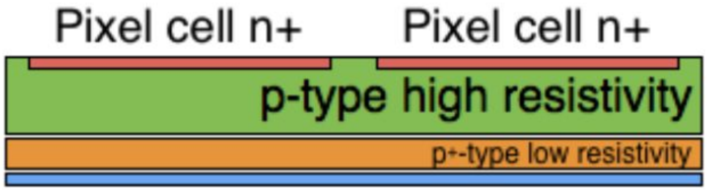



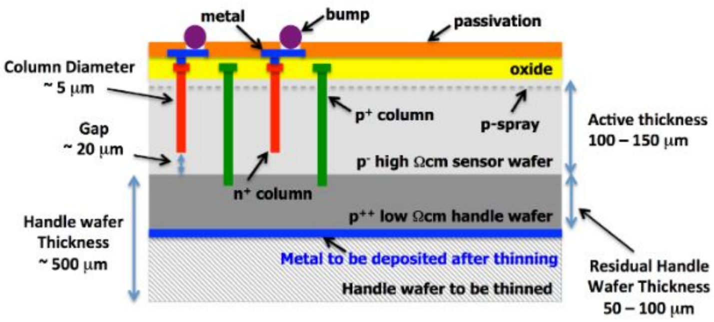
# Pixel sensors

- System will use both planar and 3D sensors
- Using 100x25 μm² pixels
- n-in-p planar sensors (150 μm thickness):
  - Bitten implant, no punch-through bias dot
  - High bias (0.6 - 0.8 kV) needed for efficient charge collection
  - **Used in most of the detector**
- 3D sensors
  - Lower bias (~150 V at the end of the lifetime) needed for efficient charge collection
    - Enhanced radiation hardness
    - Lower power consumption
  - Less homogeneous electric field
  - Complex fabrication → lower production yield
  - **Used in the first barrel layer**



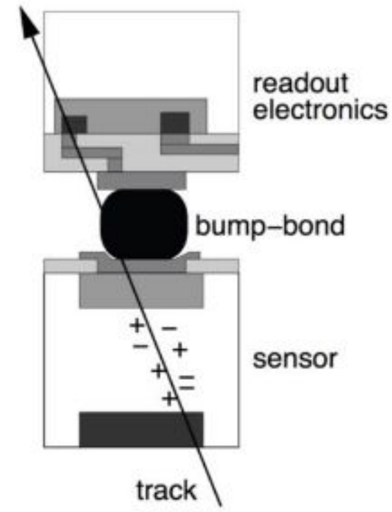
25x100 μm² pixel cell with bitten implant



# Readout chip

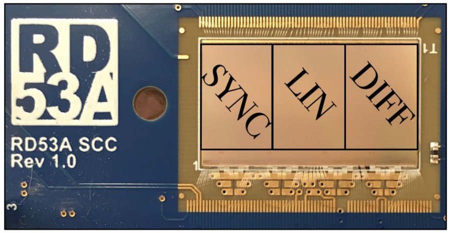
- CMS Readout chip (CROC) developed in the RD53 collaboration (ATLAS & CMS)
- Bump-bonded to the sensor




**ROC features**

- > 500 Mrad radiation tolerance
- 3 $GHz/cm^2$ hit rate
- Noise occupancy $10^{-6}$

- developed in 65 nm CMOS tech
- large current consumption → 1 $W/cm^2$



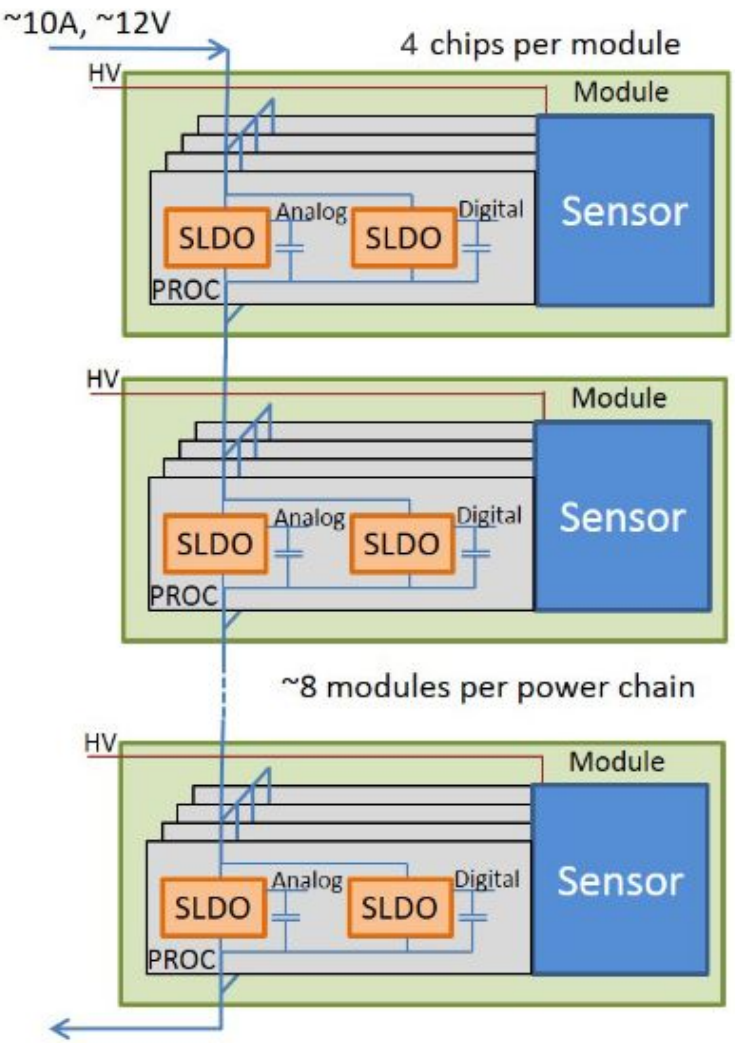

**RD53A** (400x192)
- Half-size demonstrator
- 3 analog front-ends
- 2 readout architectures
- Submitted in Aug 2017


**RD53B-CMS (CROC)** (432x336)
- Linear front-end
- Submitted on June 2021

**RD53C-CMS**
Production chip
December 2022

# Serial powering

- Total power consumption of pixels: 50 kW → parallel powering would need huge material budget
  - Modules are powered in series
  - 500 power chains, with up to 12 modules each
  - Each power chain is supplied with constant current
- In-chip shunt-LDO regulator used in the powering
  - Shunt allows serial powering
  - LDO regulators provide the constant voltage
- HV voltage is provided in parallel for each chip

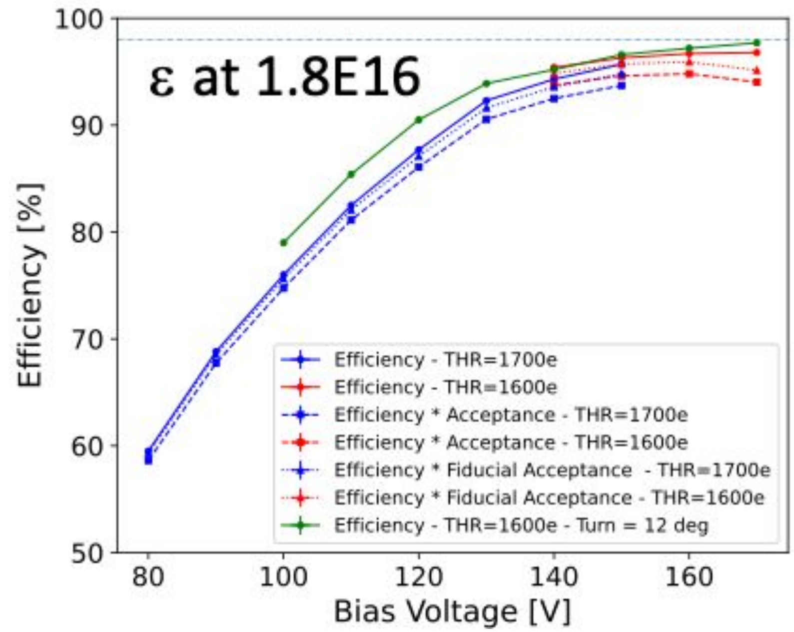



Technical challenge → first time serial powering used at this scale

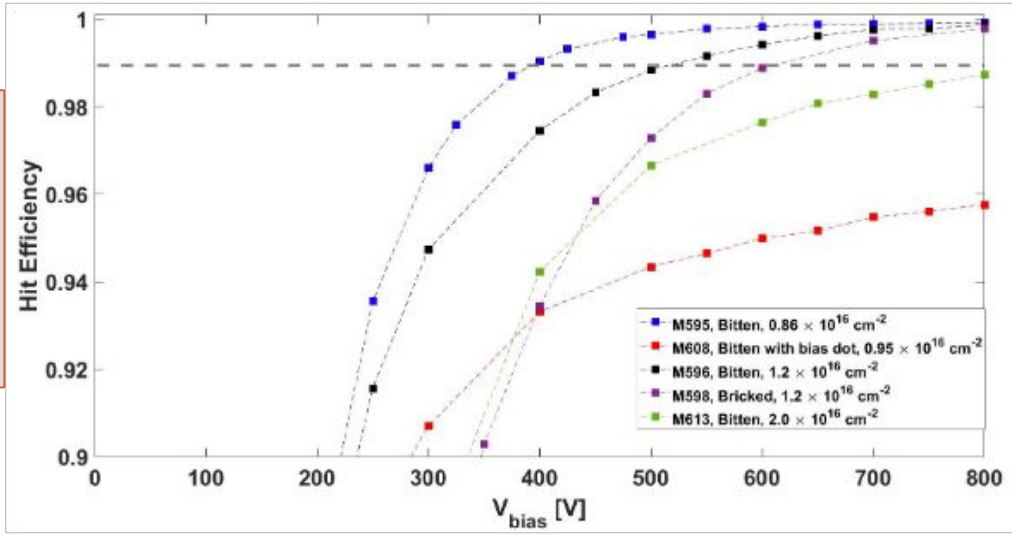
- Serial chains up to 9 modules fully tested
- Studies with up to 12 modules ongoing and looking promising

# Sensors - Performance

Performance of **3D CNM sensor**
- Irradiated up to $1.8 \times 10^{16}$ $n_{eq}/cm^2$
- Bias threshold set to ~1600 electrons
- >98% efficiency at 170 V bias voltage
- $CO_2$ cooling operating T~ -33 ºC → no risk of thermal runaway

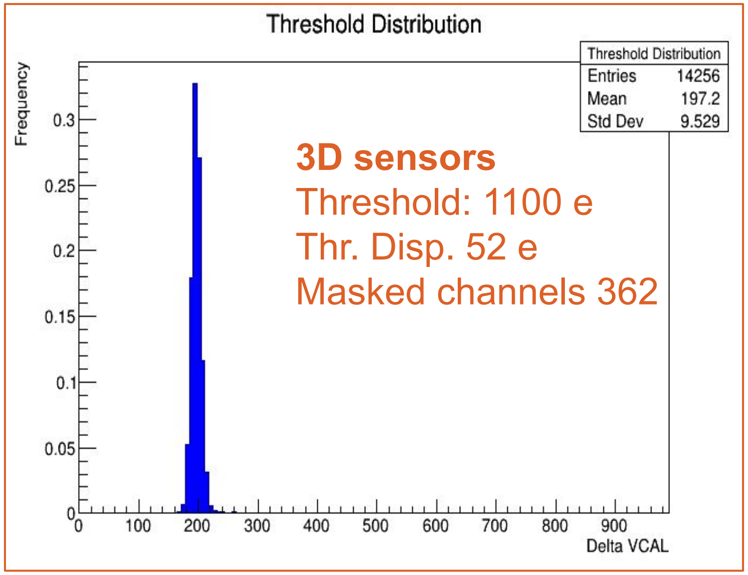


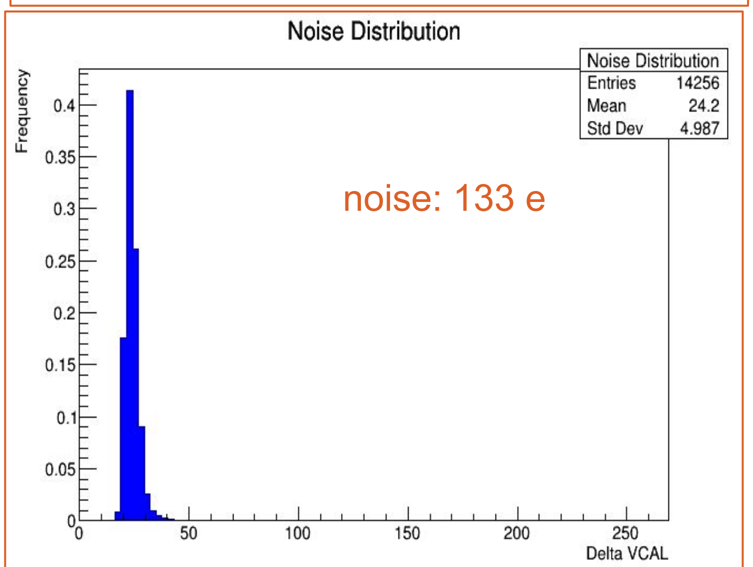

Performance of **planar HPK sensor**
- irradiated up to $2 \times 10^{16}$ $n_{eq}/cm^2$
- Safe operation up to 600 V, cooling not feasible for 800 V

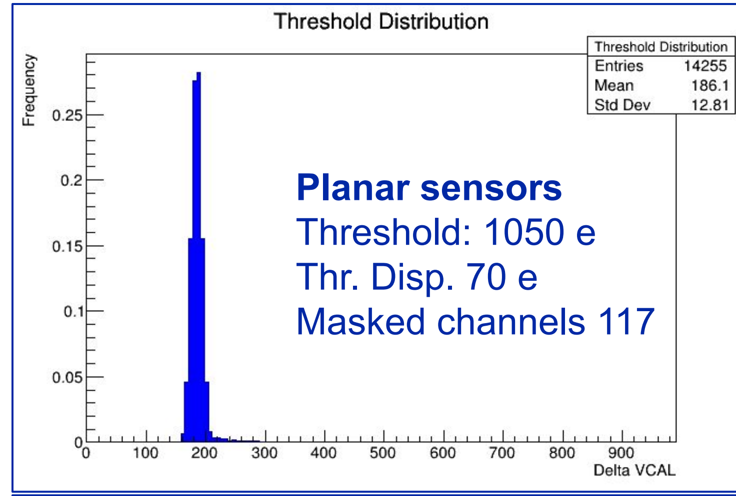


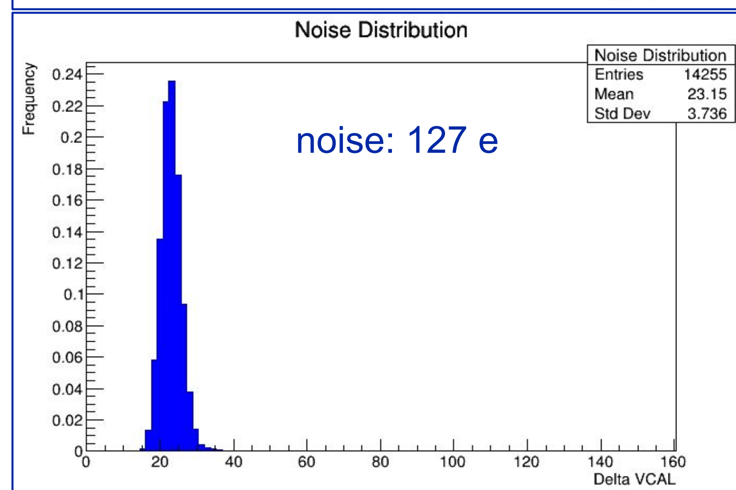
# Readout chip performance

- 4 bit digital readout with selectable 6-to-4 bit dual slope ToT mapping for charge compression
- Bias threshold in ROC allows to fix charge threshold
- Additional per-pixel configuration allows to uniformize threshold and mitigate performance difference



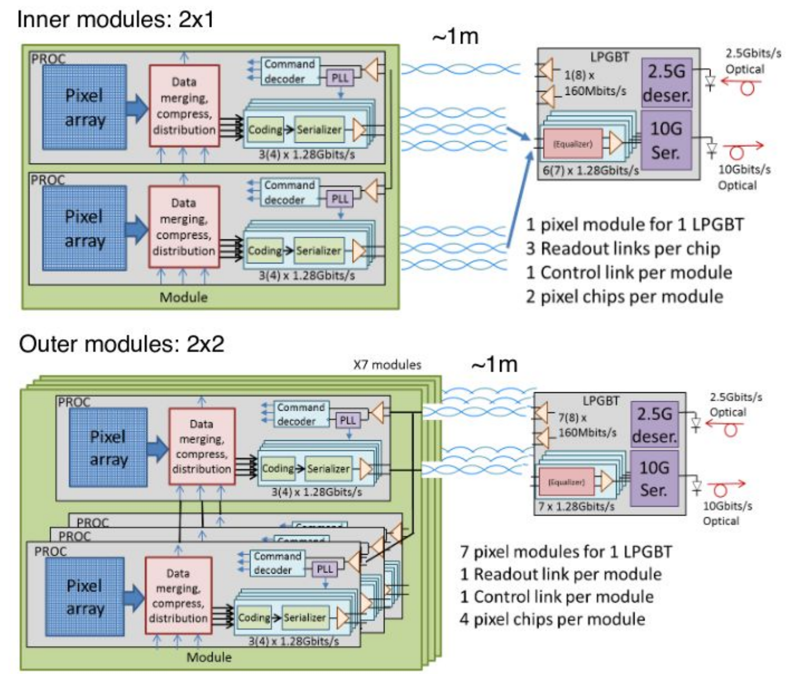



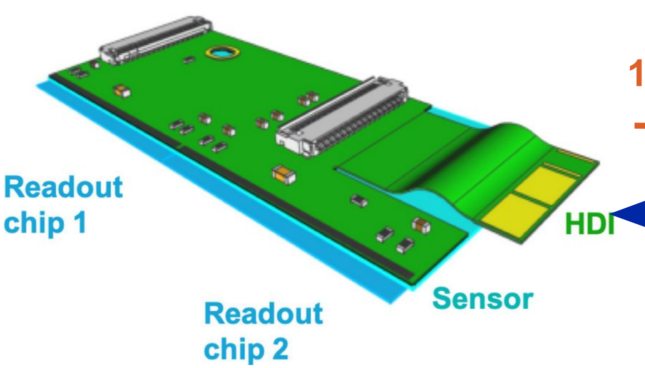



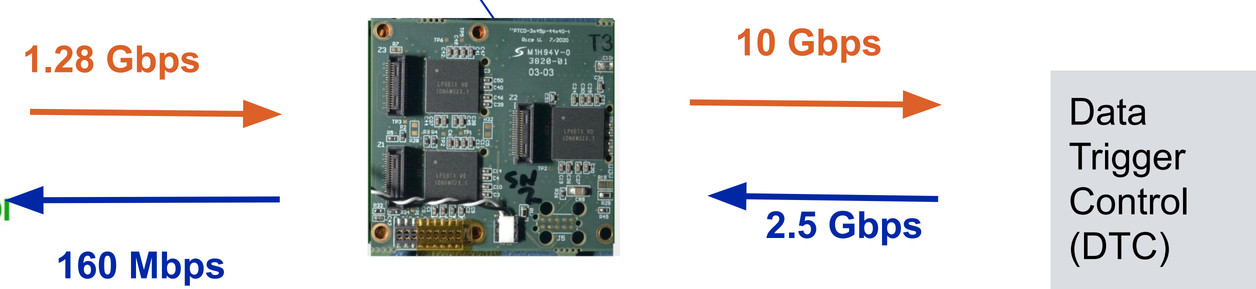



# System readout - portcard

- Signal is readout through short (< 0.5 m) electric cables
- Portcard located in the detector periphery → optical conversion
- Data is sent to/from the control room through optical links
- Portcard contains → 3 lpGBT + 3 VTRx, powered with DCDC converters

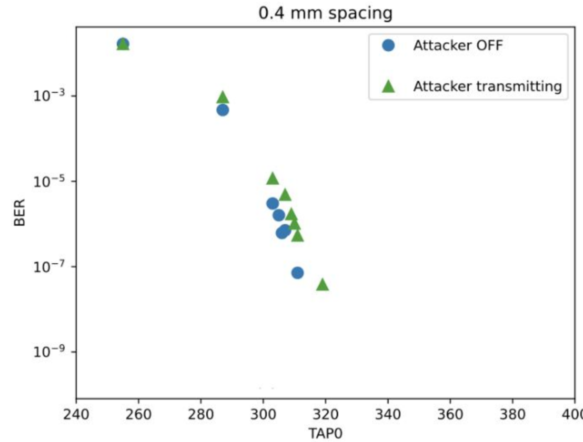


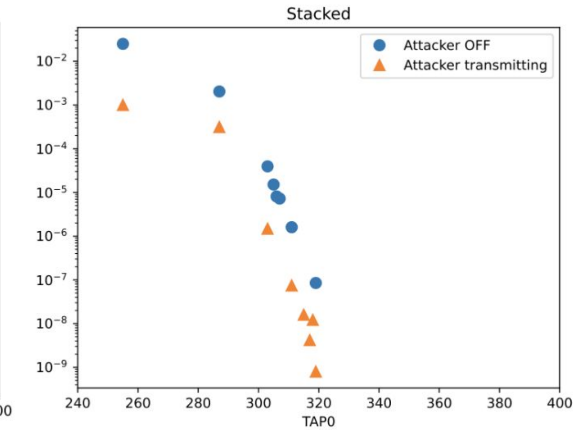



# System performance - signal integrity

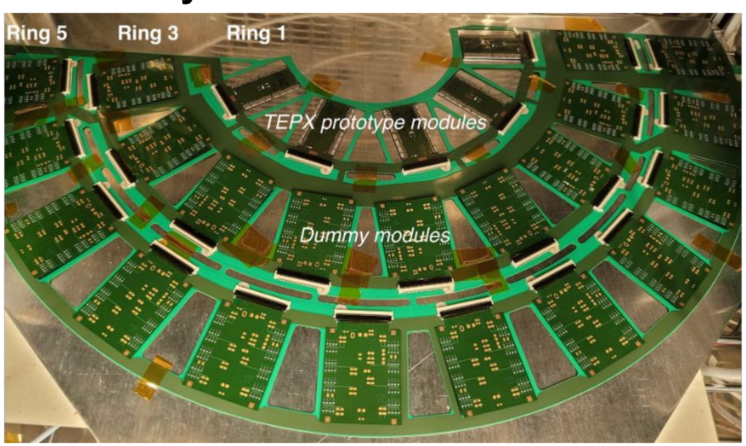
## TBPX System

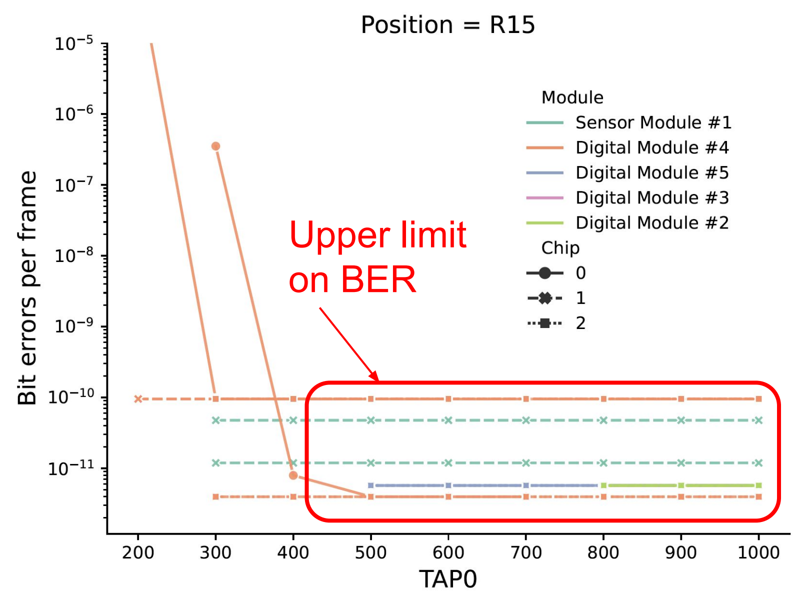



- Signal integrity as a function of driver strength
- Elinks robust to cross-talk effects from other signals

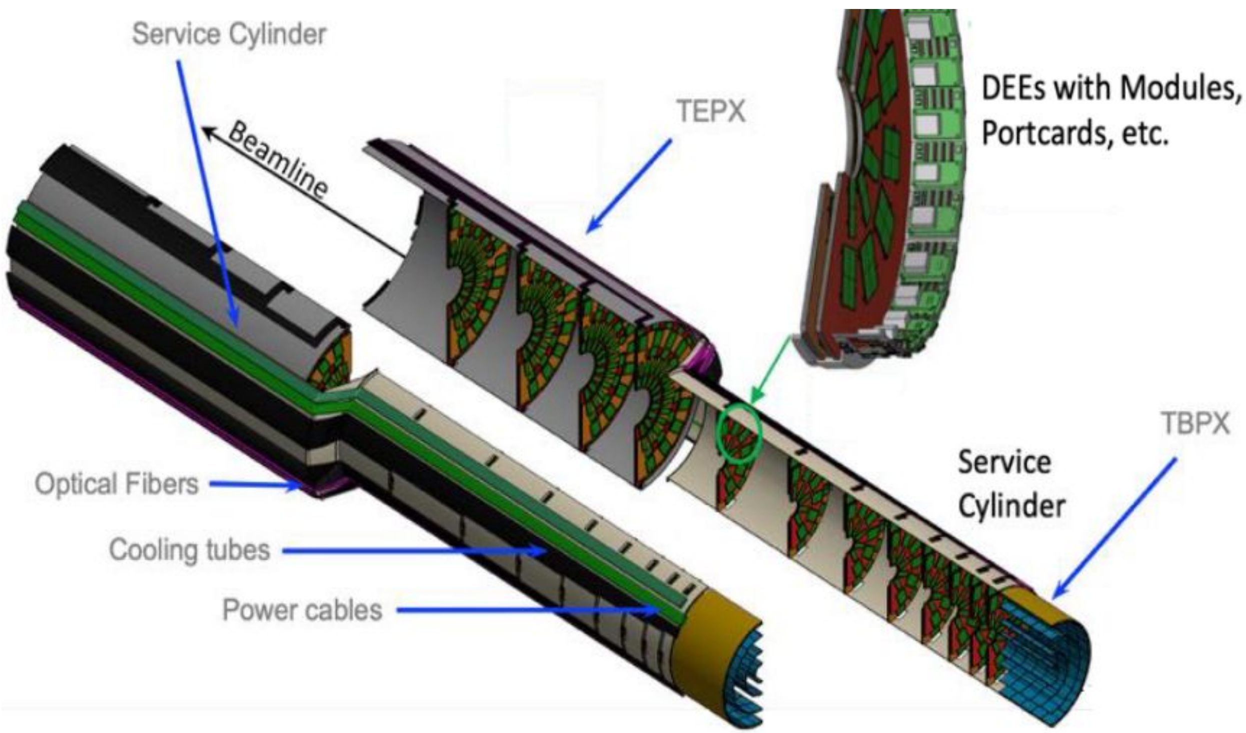
## TEPX System R1



# Detector mechanics

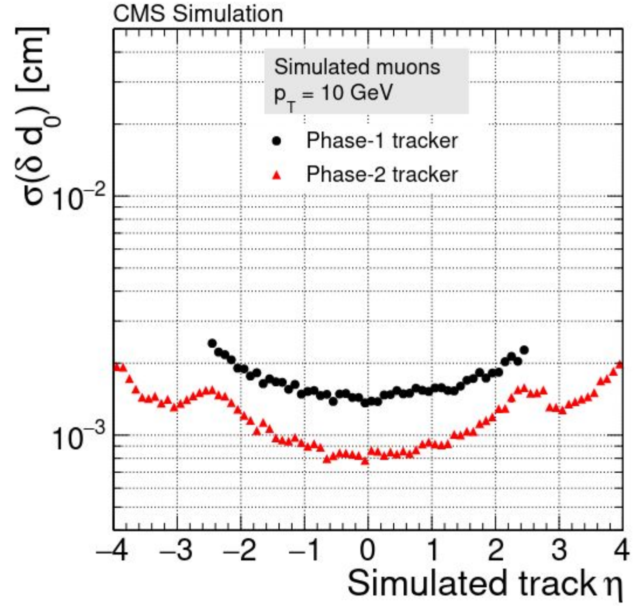
- Simple mechanics, allowing removal for maintenance
- Detector mechanics built in light carbon fiber structure
- $CO_2$ evaporative cooling at -35ºC distributed in stainless steel pipes
- Pipes embedded in the structure
- Allows to dissipate 50 kW power consumption of the whole system

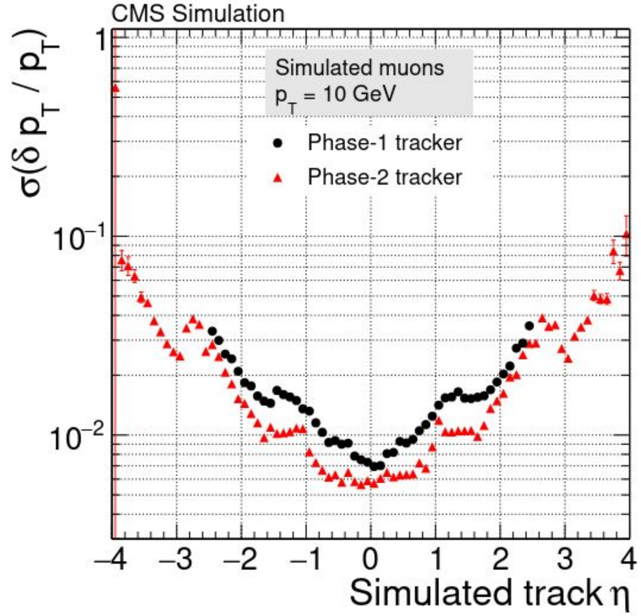



**More on temperature simulations in S. Liechti's poster**

# Performance of upgraded system

- Expected performance of inner+outer tracker determined in simulated muons
  - Very preliminary, not final version of the geometry
- Up to almost two times better impact parameter resolution and transverse momentum



# Conclusions

- Ambitious upgrade of CMS pixel detector
- Harsh data taking conditions → high occupancy and irradiation
- Newly designed detector featuring:
  - Hybrid sensor technology
  - Higher granularity, larger buffers
  - Novel serial powering design
- First modules are being assembled → many performance studies ongoing
- New tracker design is resilient enough for the HL-LHC conditions
- Improved performance with respect to Phase-I detector