CMS Phase2 Upgrade

Higgs Hunting - 14th edition

23-25 September 2024 - Orsay Paris

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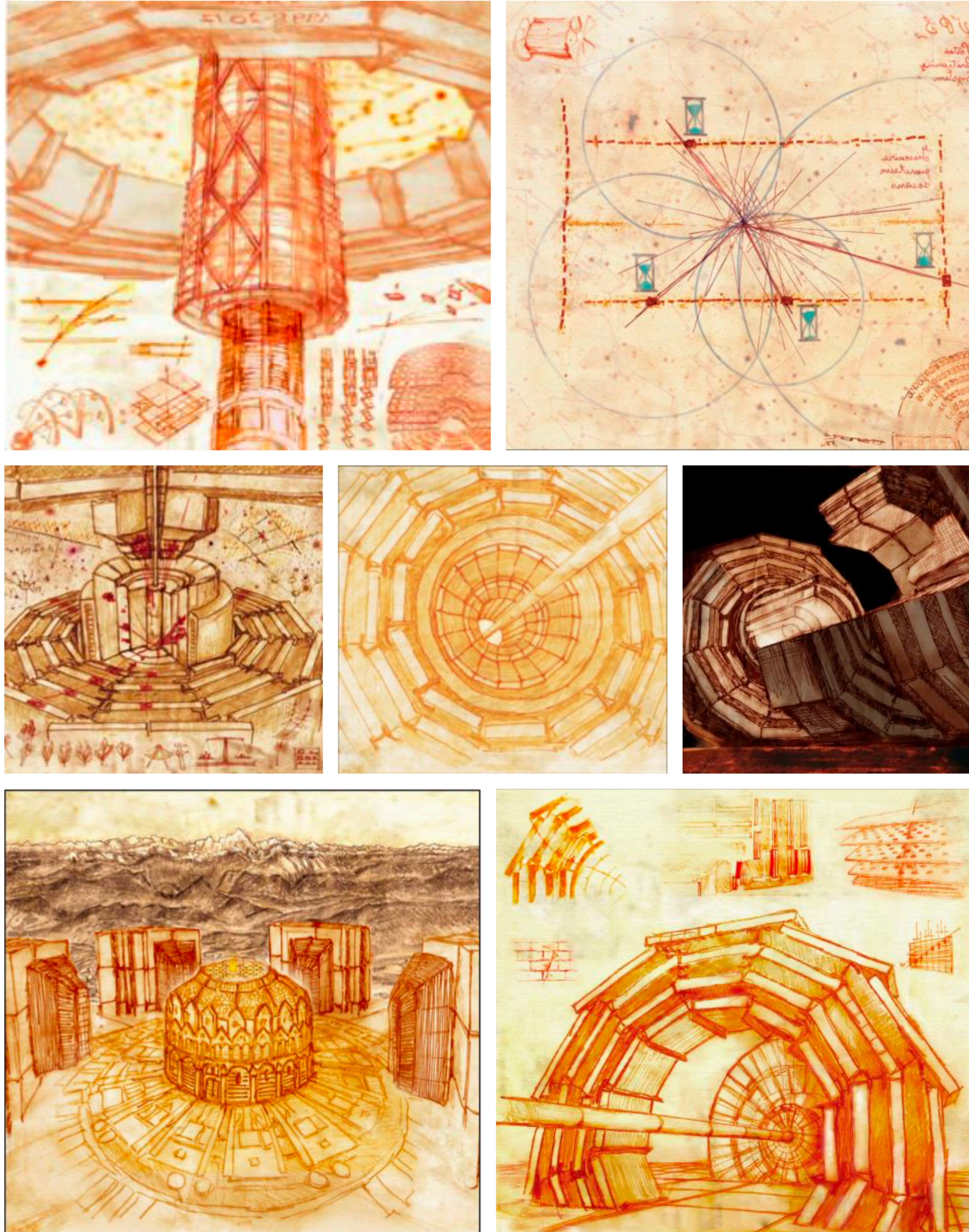
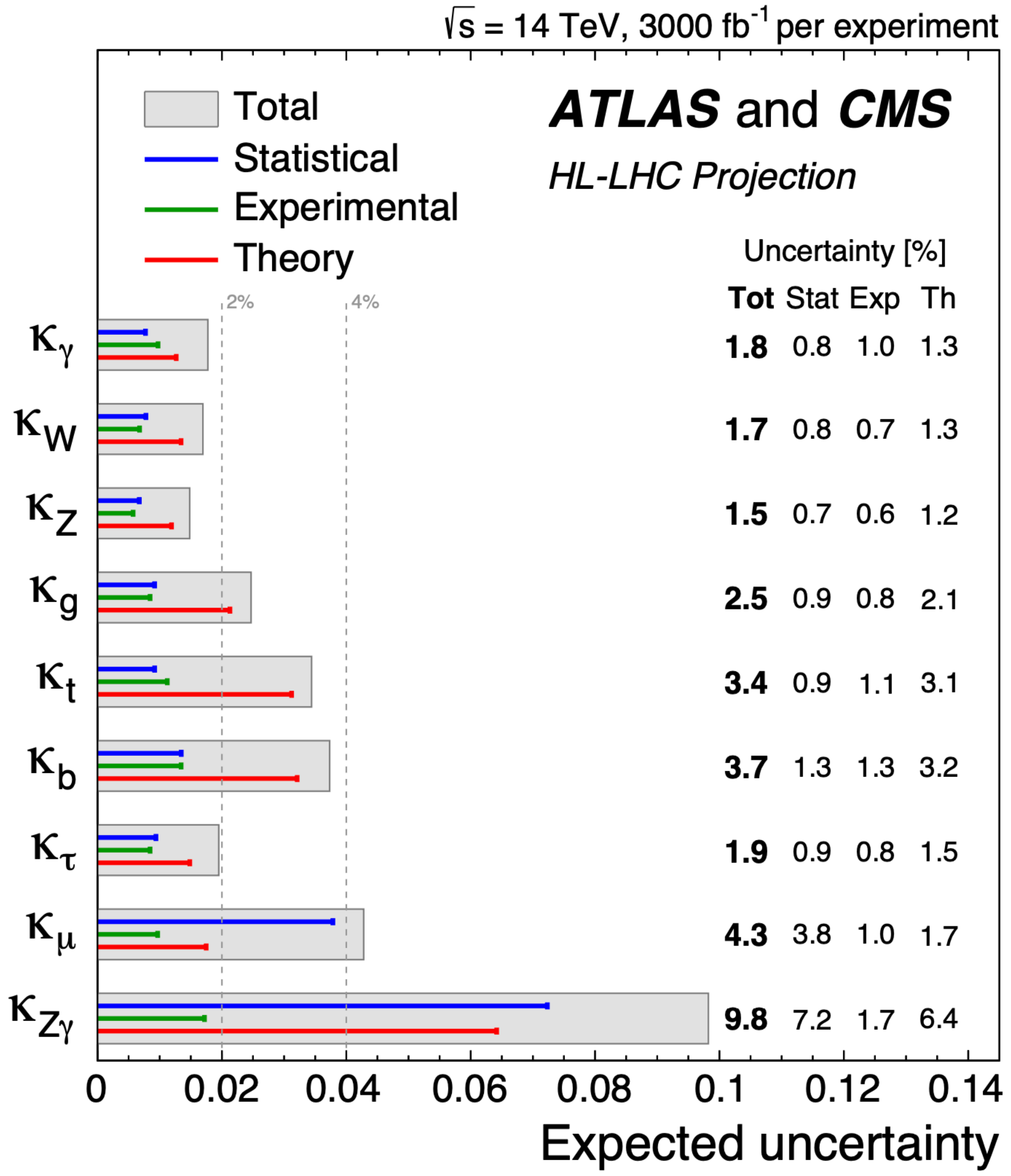
University of Milano-Bicocca and INFN
on behalf of the CMS Collaboration

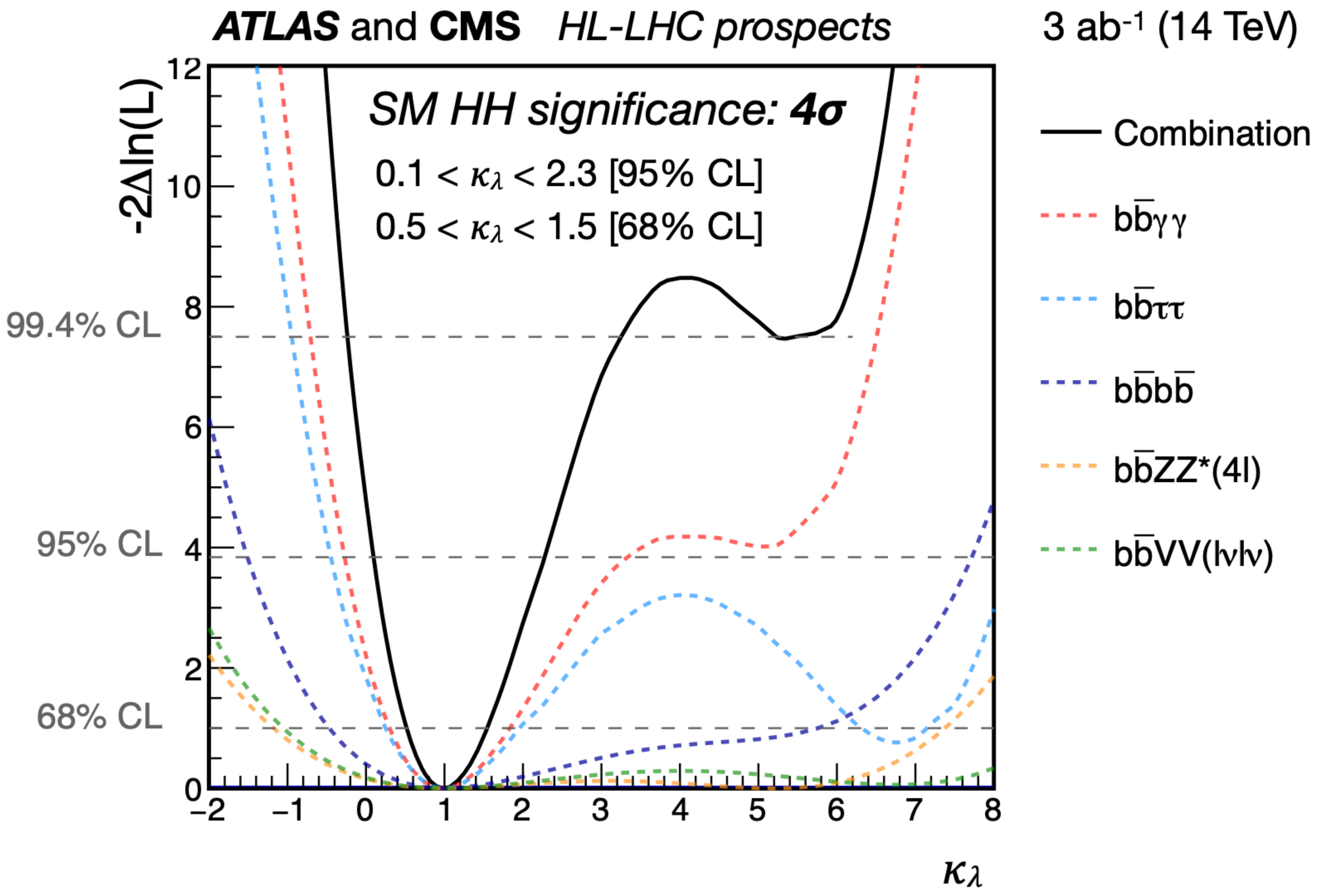


HL-LHC: unique opportunity for a rich physics program

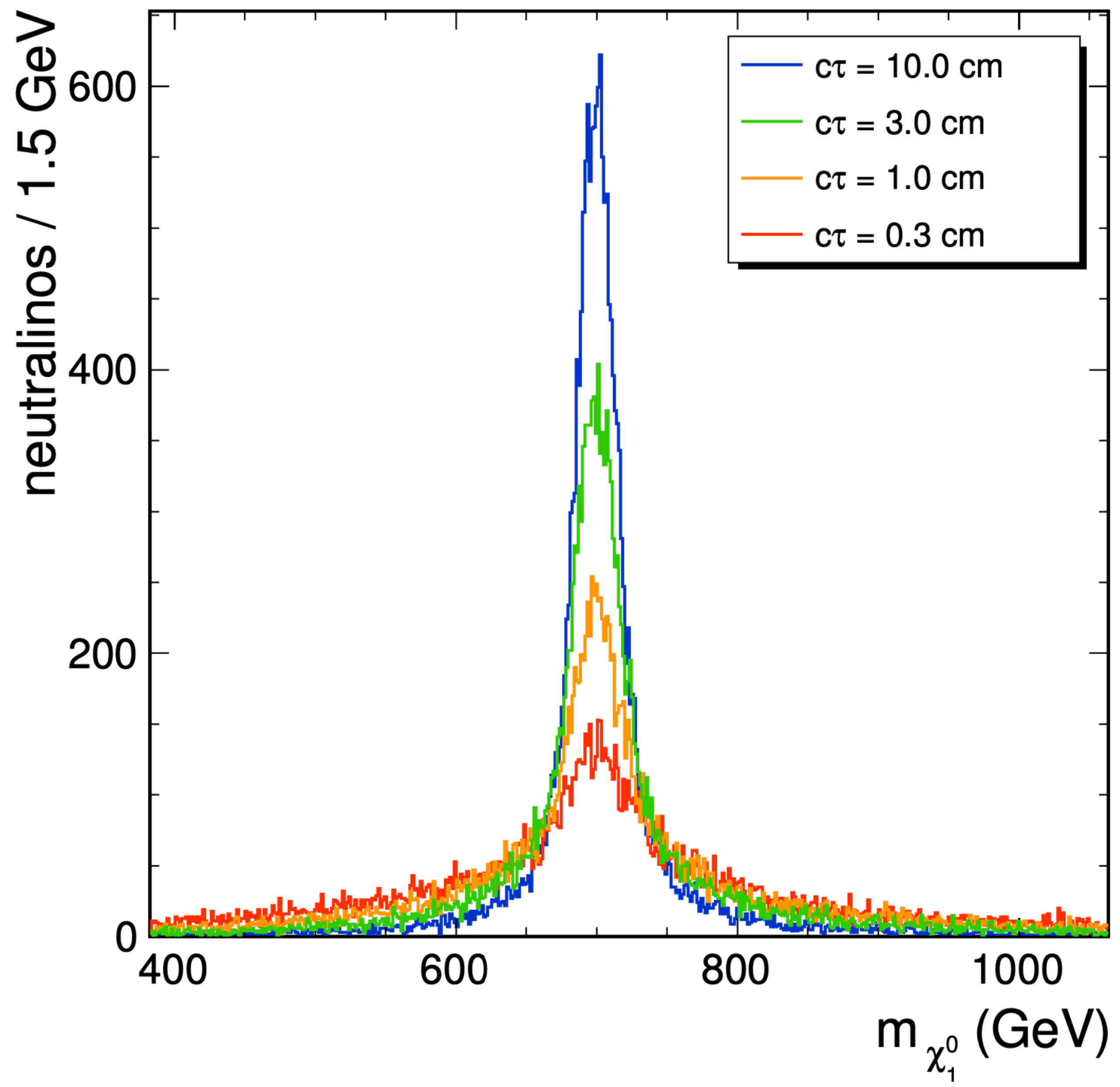
Precise measurements of the Higgs coupling



Observation of the HH production and measurement of the Higgs self-coupling

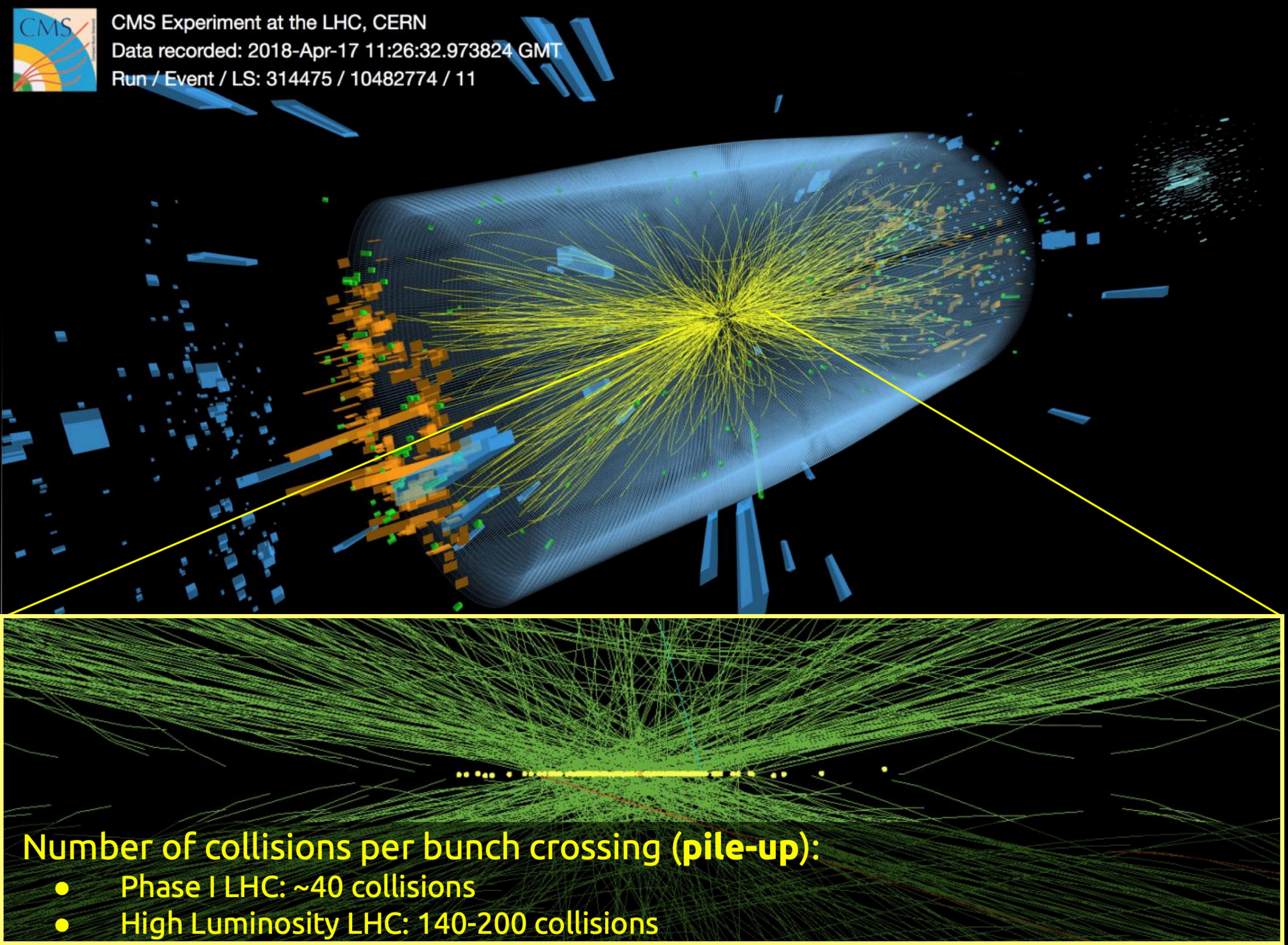


Search for dark matter candidates, long-lived particles, new gauge bosons, new interactions, etc.



- **Learn how to exploit the detectors at best means enlarging the physics reach of the high-lumi phase**
  - Already now the 2018 projections are surpassed by large factors thanks to the refinement detectors and analysis tools!
  - For the Phase2 we expect to do better than just scaling with $\sqrt{L}$

High Lumi LHC challenges

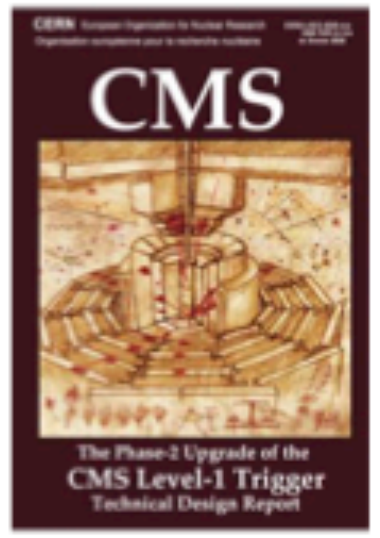


- **Extreme pileup**
  - Impacts the current CMS capability to reconstruct physics events
- **Unprecedented levels of radiation exposure**
  - A threat for many detector components

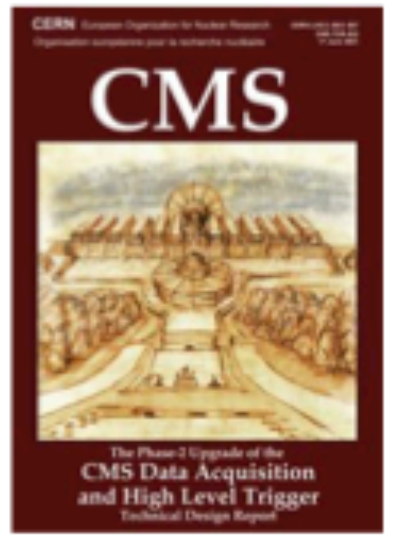
▸ **Goal:** integrate >3ab^{-1} while keeping the current performance

Need for new detectors and new methods!

Overview of the CMS Phase2 upgrade

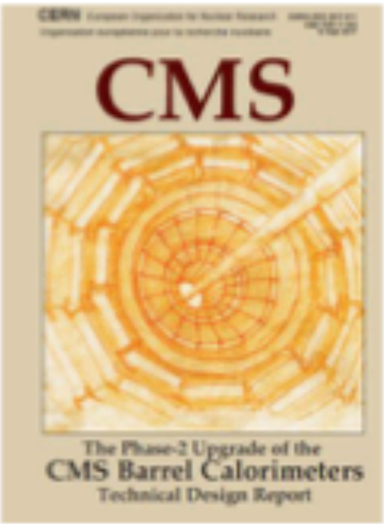


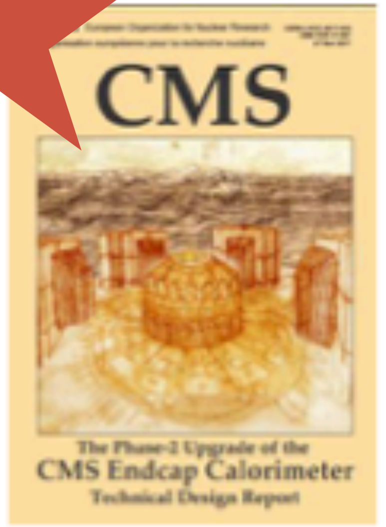
L1-Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



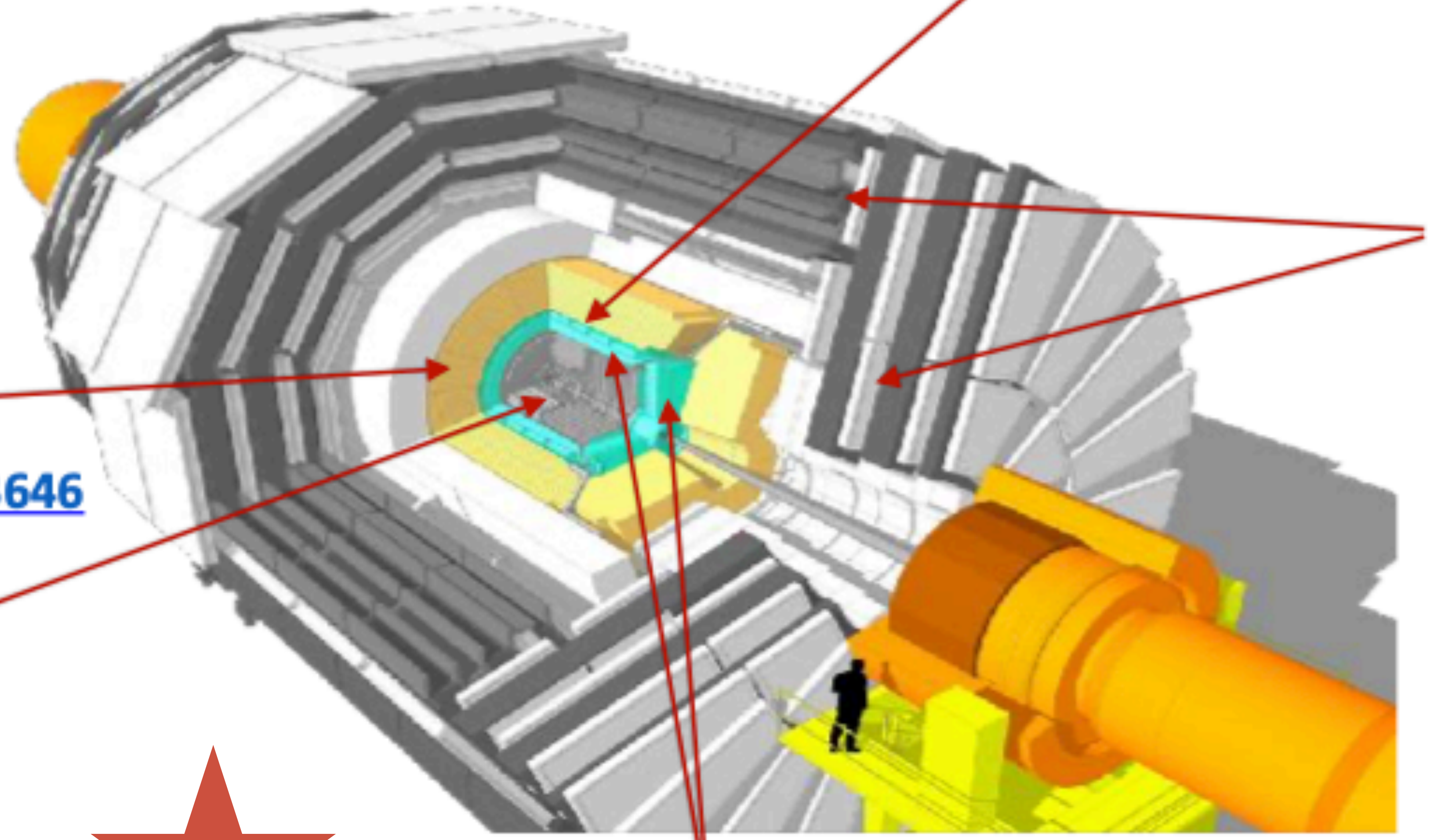
DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

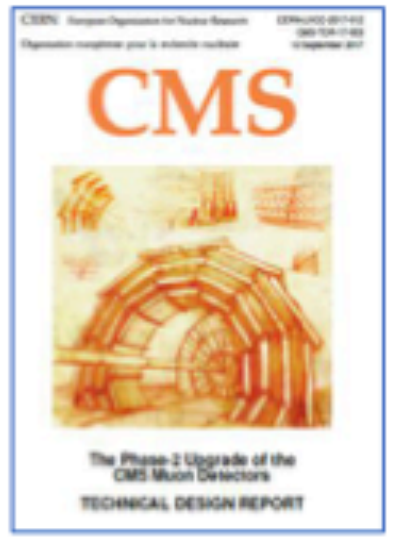


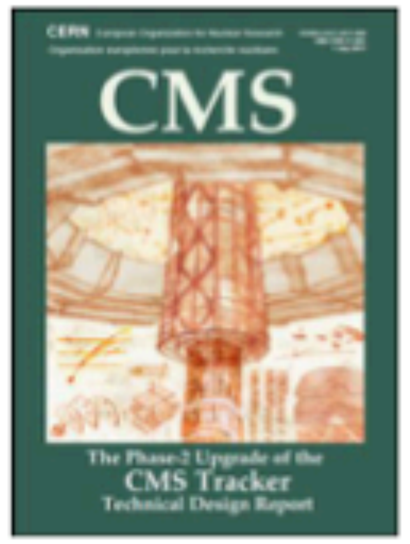


Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

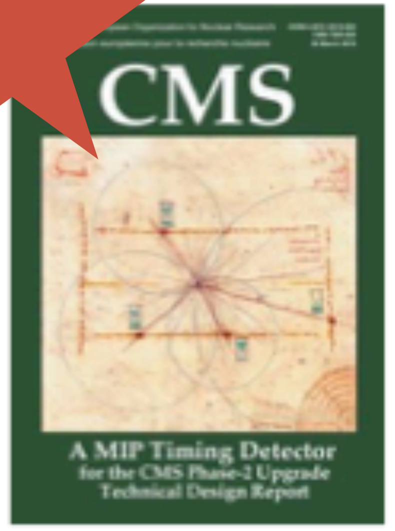


Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$





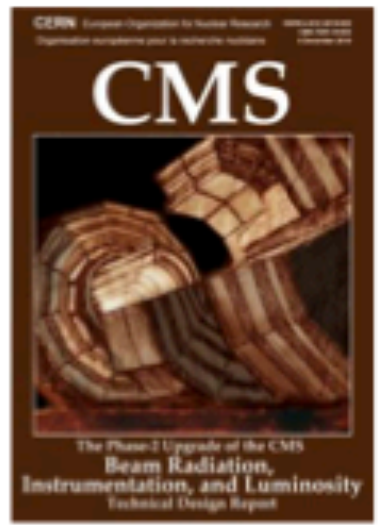
Tracker
https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



MIP Timing Detector
https://cds.cern.ch/record/2667167

Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Beam Radiation Instr. and Luminosity
http://cds.cern.ch/record/2759074
- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity: 1% offline, 2% online
- Neutron and mixed-field radiation monitors



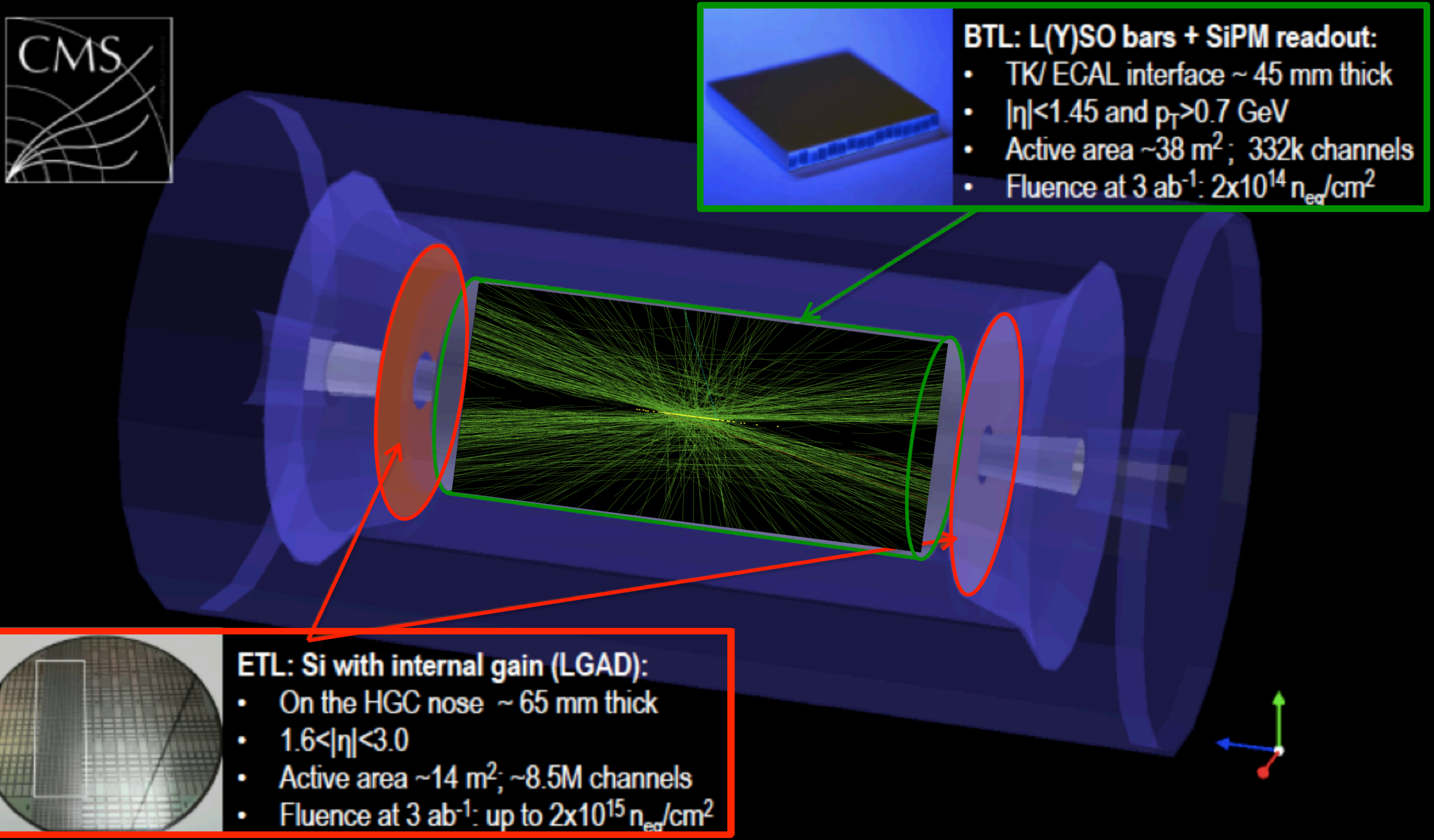
- Rad hard detectors with increases granularity and acceptance → beneficial for all analyses
- Exploit time for PU rejection and PID enabling 4D reconstruction

A new **timing** layer: the **M**ip **T**iming **D**etector

Technology choice driven by **radiation hardness** and **costs**

Barrel Timing Layer:
LYSO:Ce crystal bars coupled to SiPM

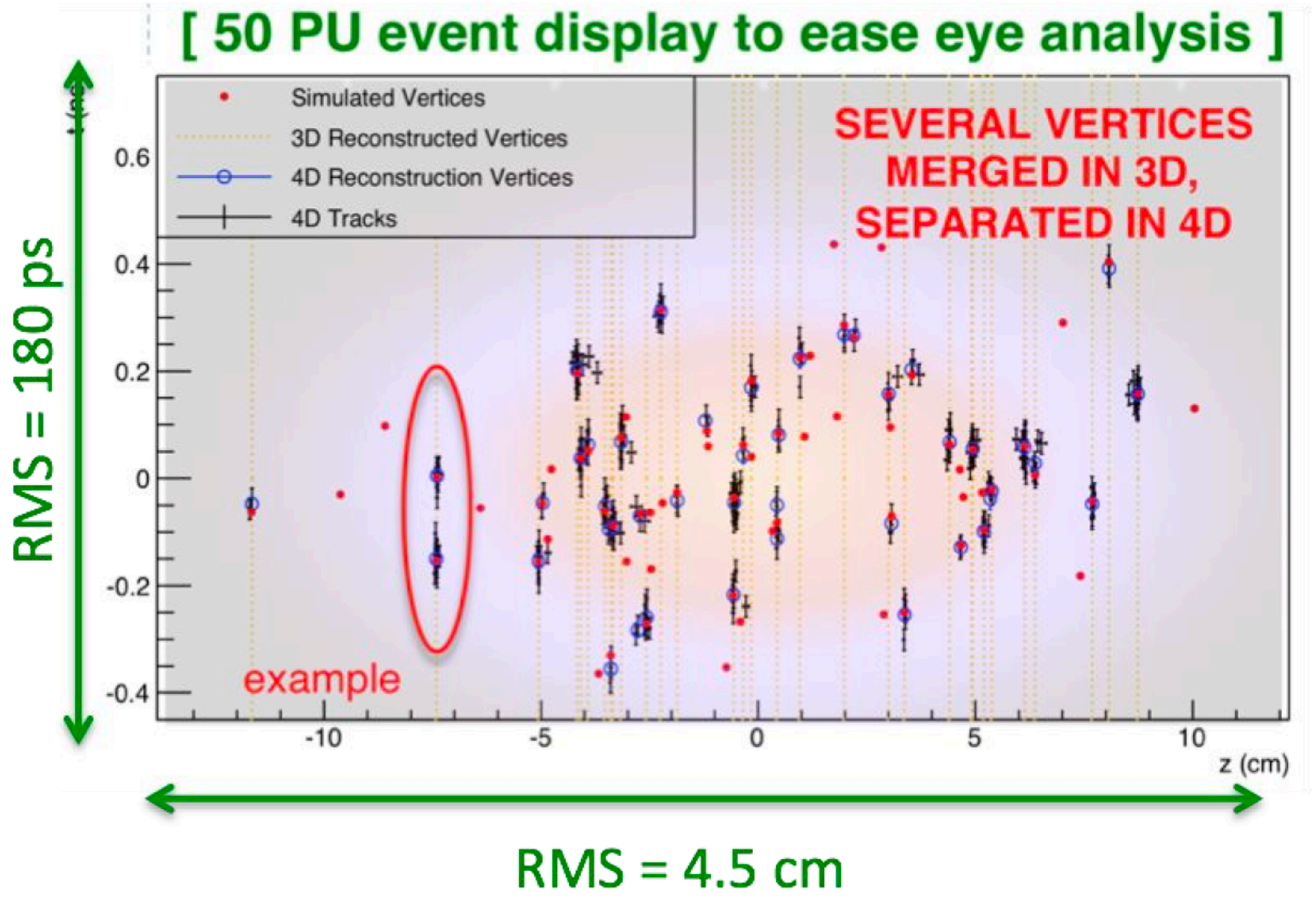
Endcap Timing Layer:
Low Gain Avalanche Diodes

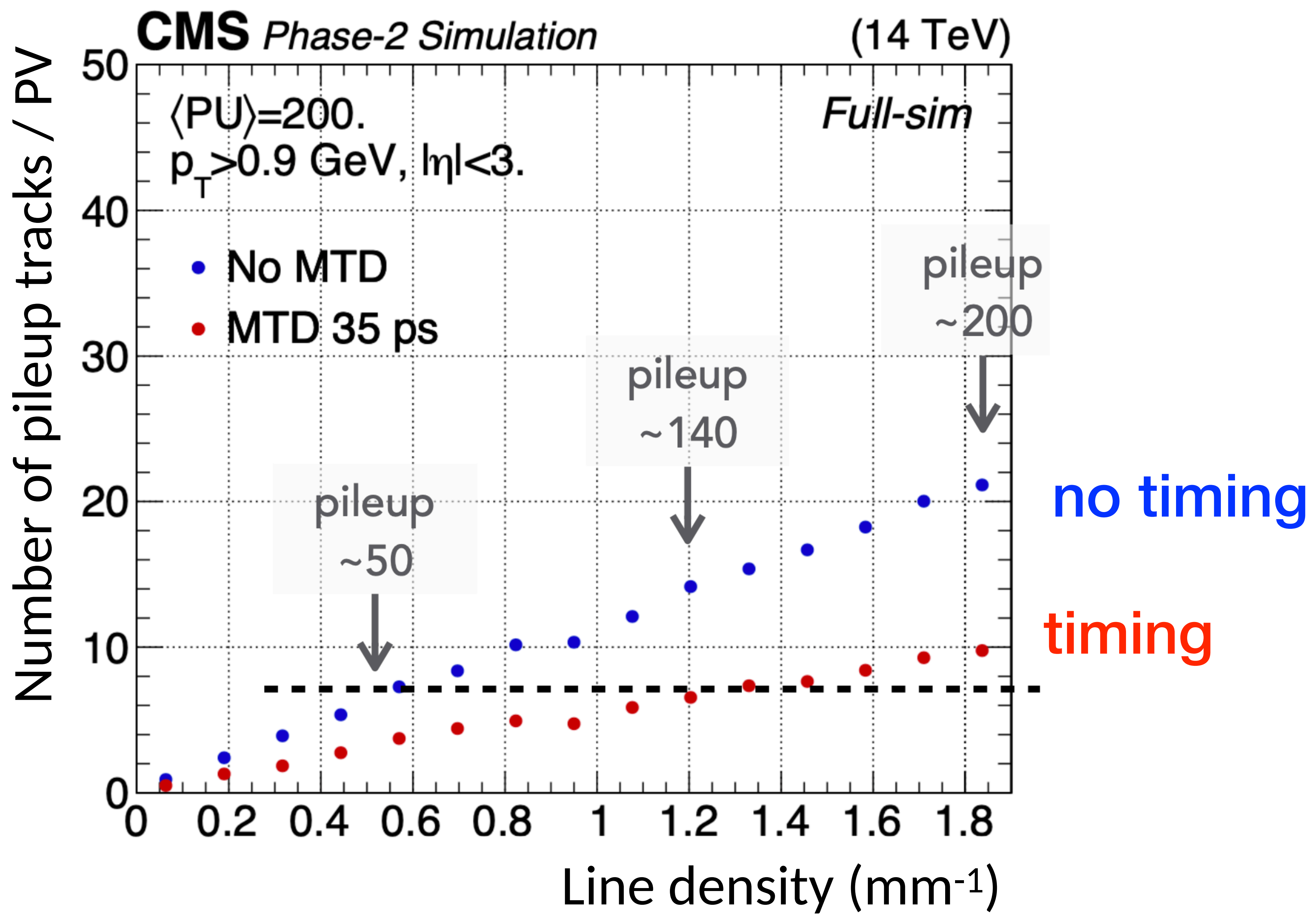


How timing will help at the HL-LHC?

- Time-tagging of charged particles allows:
  - **4D vertex reconstruction** → resolve vertices that are close in space but separated in time
  - **Time compatibility for track-vertex association** → suppress spurious pileup tracks

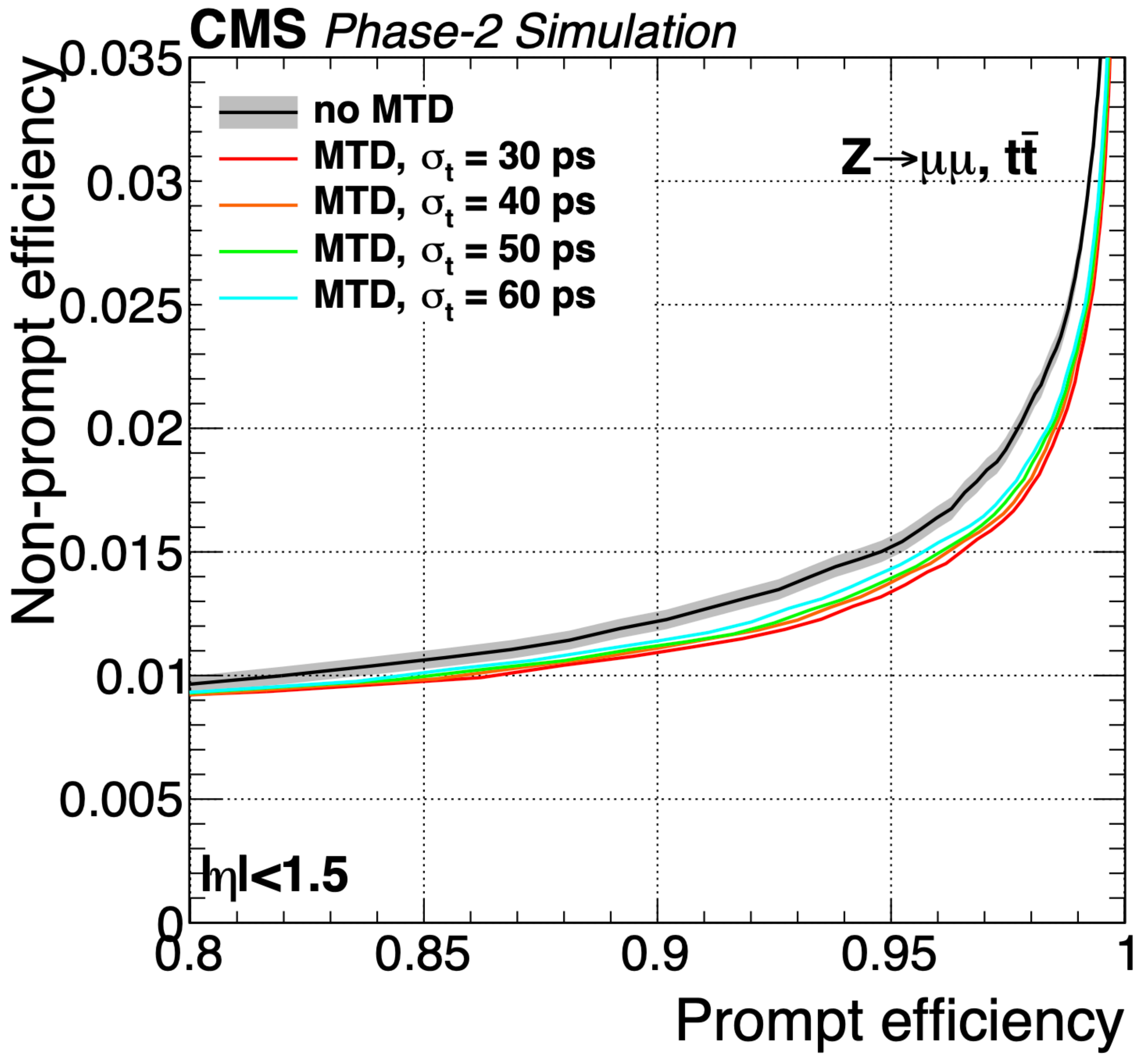
Goal:
30-40 ps time resolution





MTD performance: one physics example

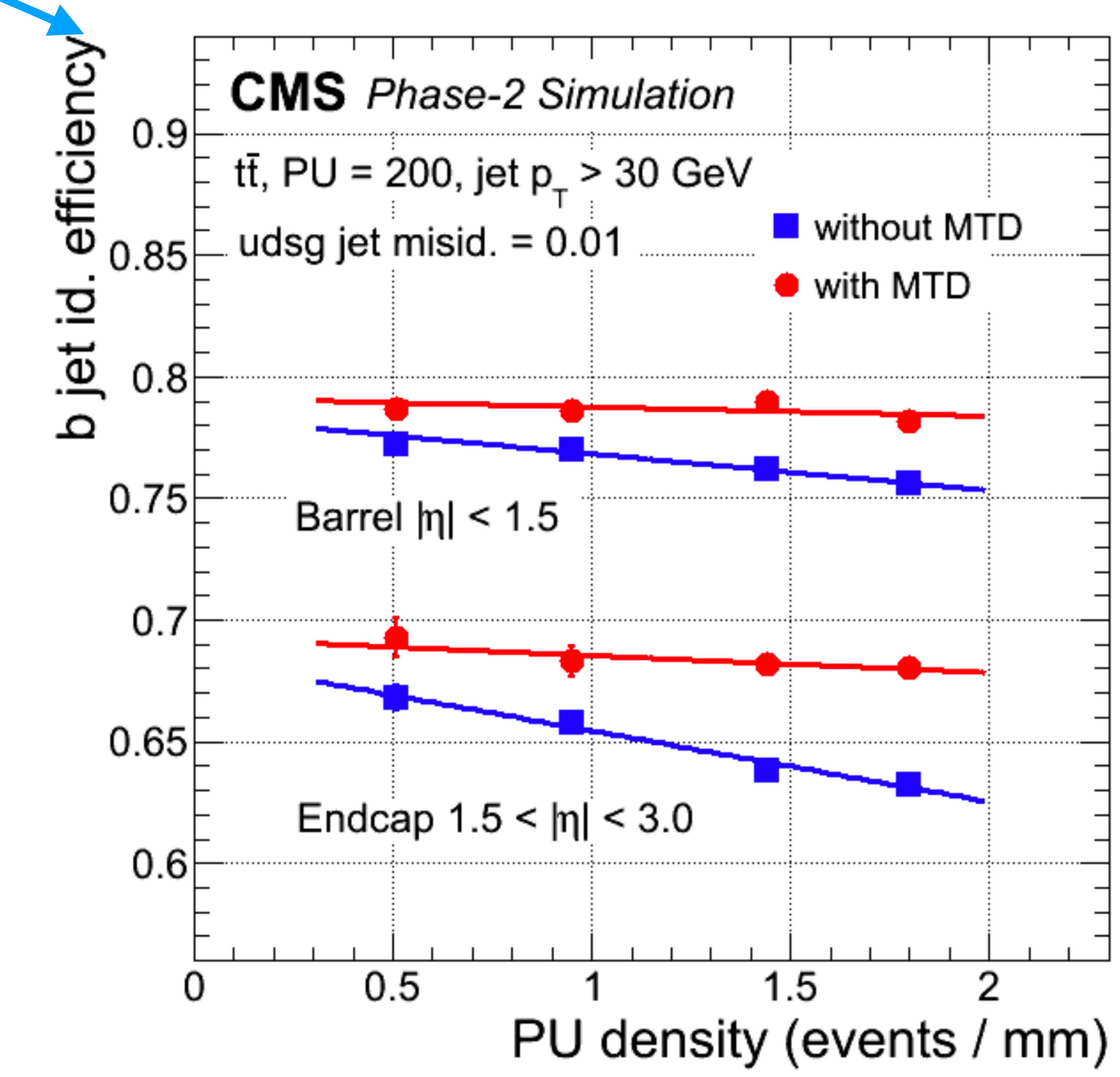
- Measure the **Higgs self coupling** is one of the main goals of the HL-LHC program
- Improvement to **lepton isolation, photon identification, MET reconstruction, rejection of fake jets** and **b-jet ID efficiency** thanks to precision timing
- → **Increased signal yield for HH:**
  - → 10%-20% gain in s/√b for many Higgs decay channels
  - → equivalent to ~20-30% more luminosity **(2-3 years of data taking!!)**



projections for 3ab^{-1} 35ps BTL, 35ps ETL

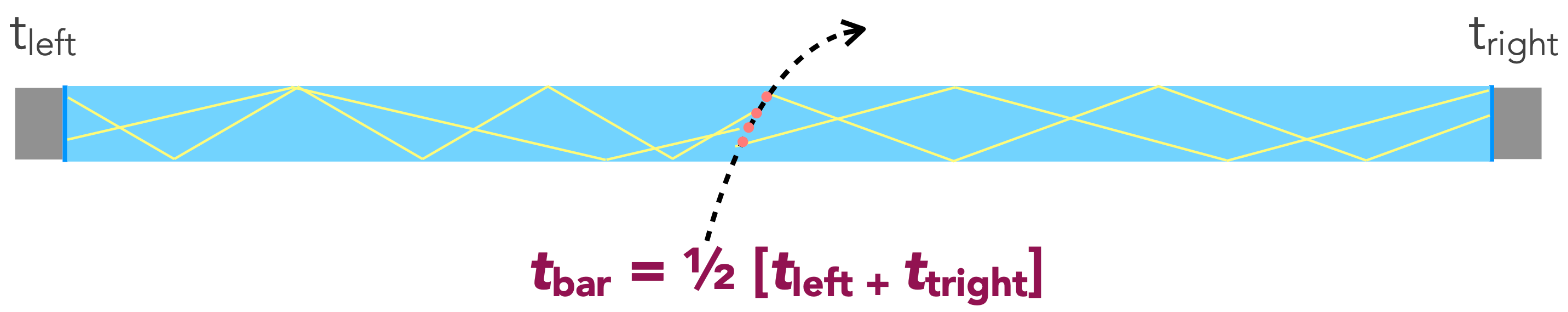
	Signal increase (%)		Expected significance	
Di-Higgs decay	BTL	BTL+ETL	No MTD	MTD
bbbb	13	17	0.88	0.95
$bb\tau\tau$	21	29	1.3	1.6
$bb\gamma\gamma$	13	17	1.7	1.9
bbWW			0.53	0.58
bbZZ			0.38	0.42
Combined			2.4	2.7

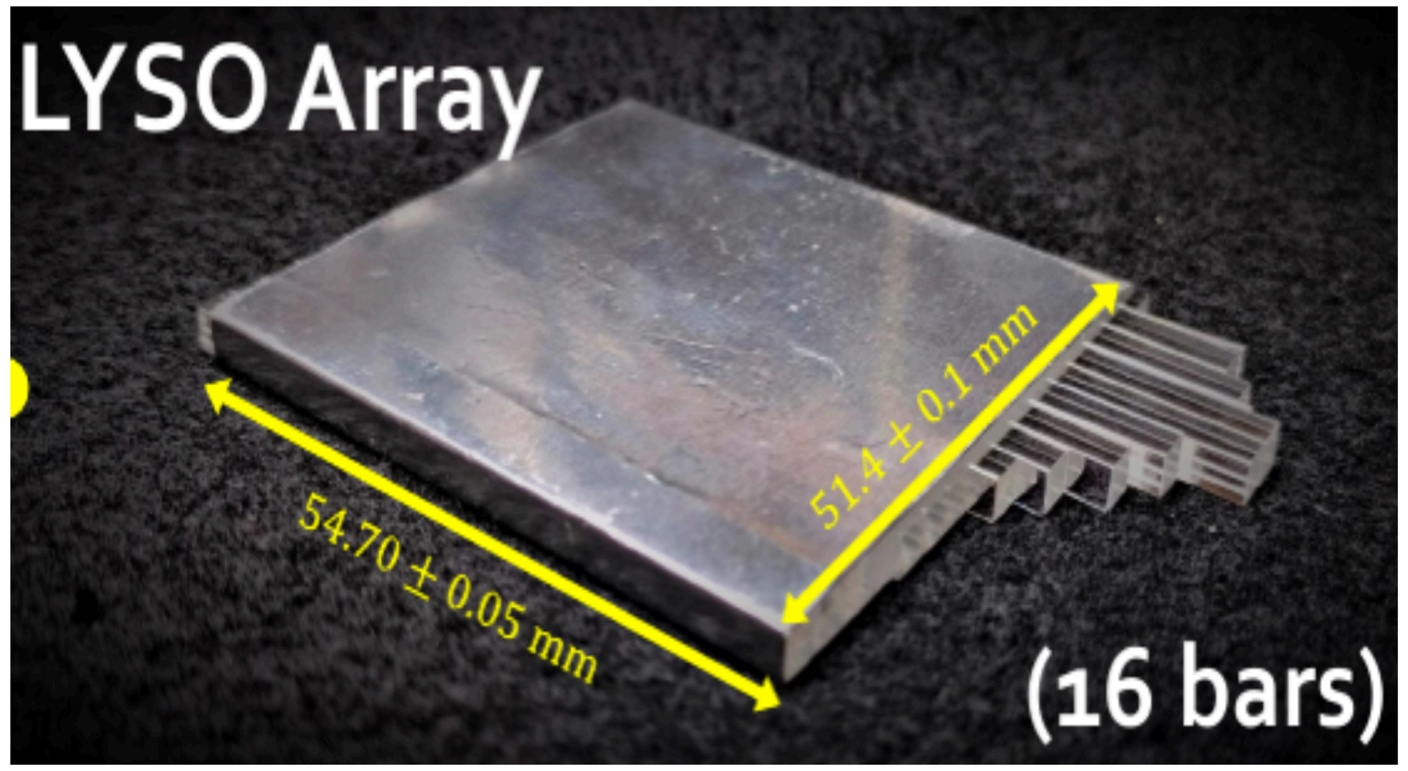
Conservative!

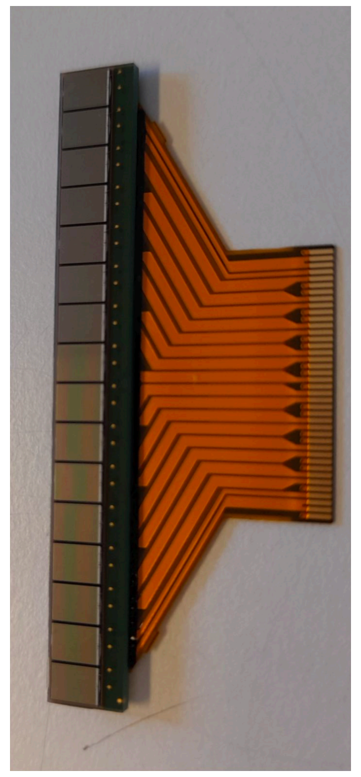


Status: The construction of BTL has started!

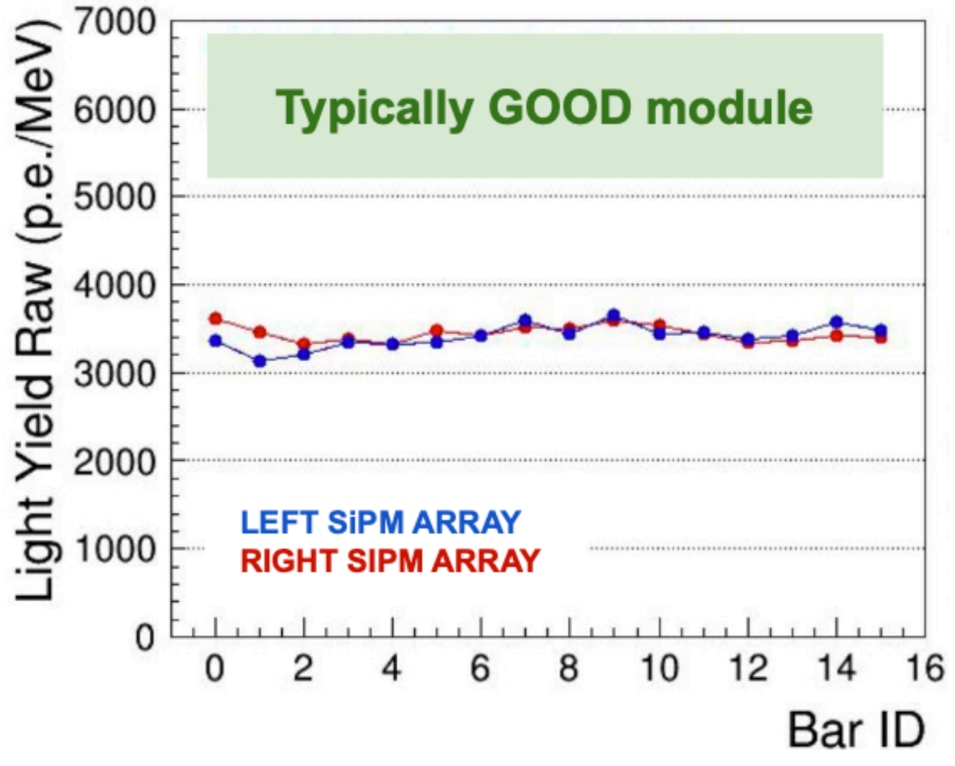
Fully transitioned to production

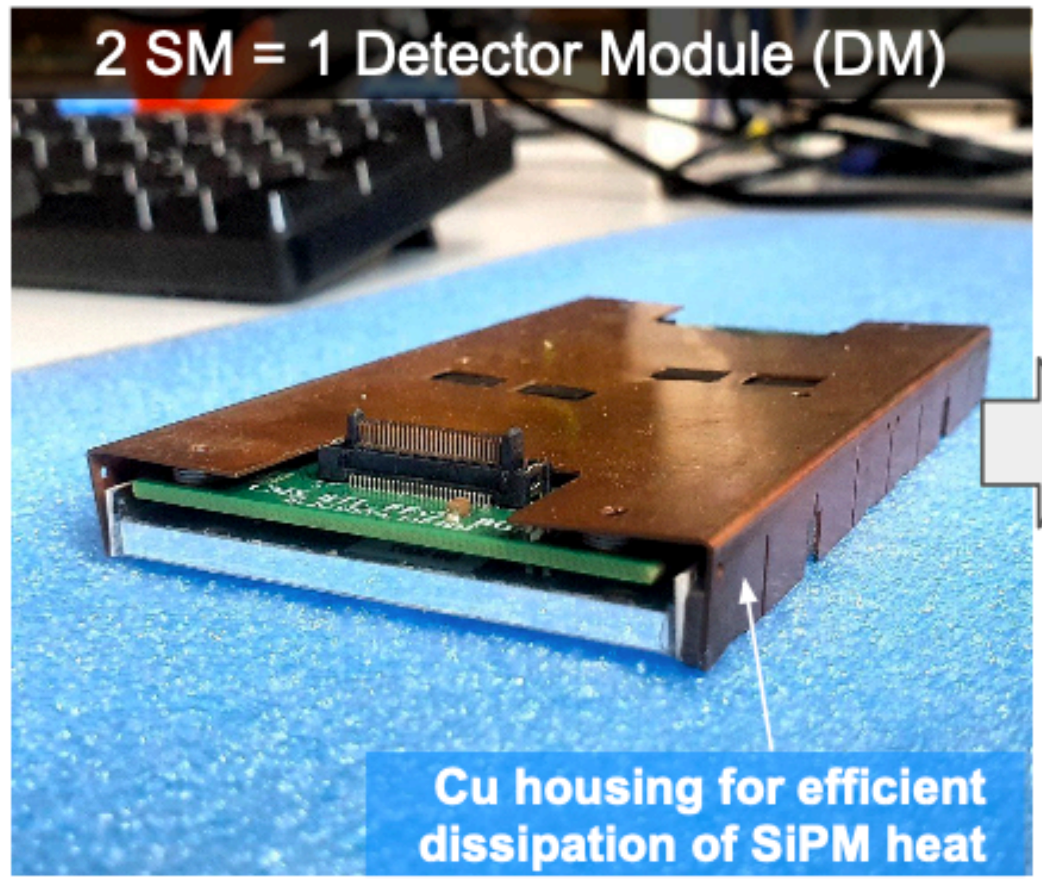


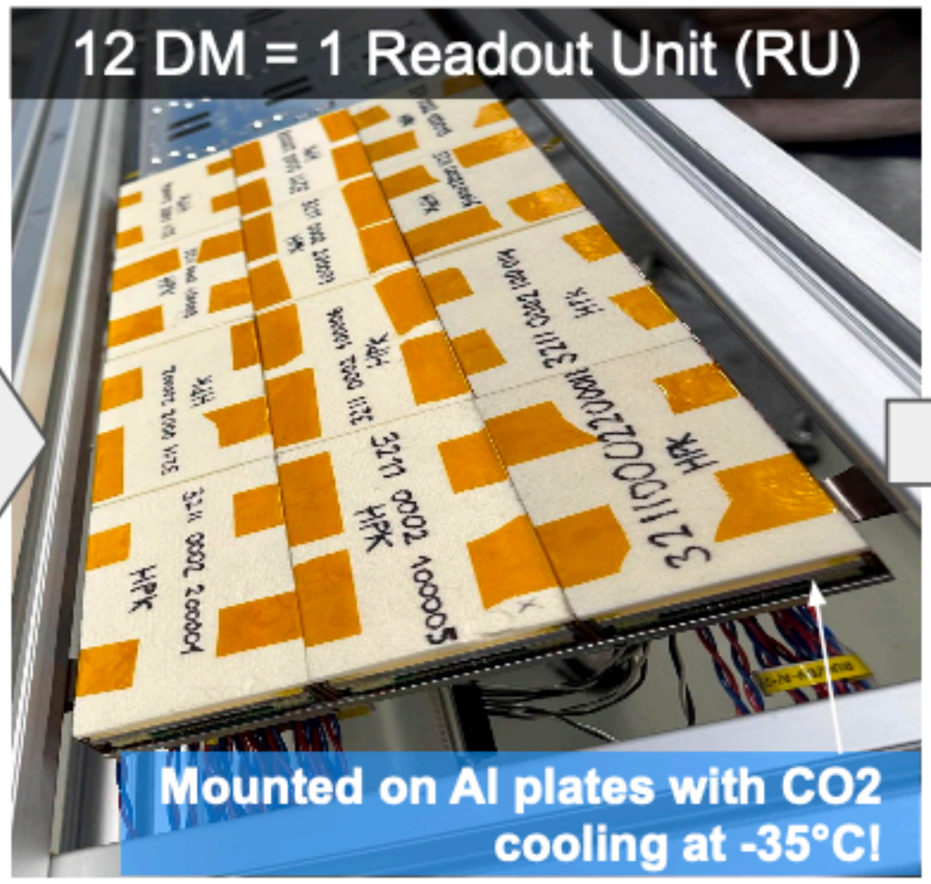


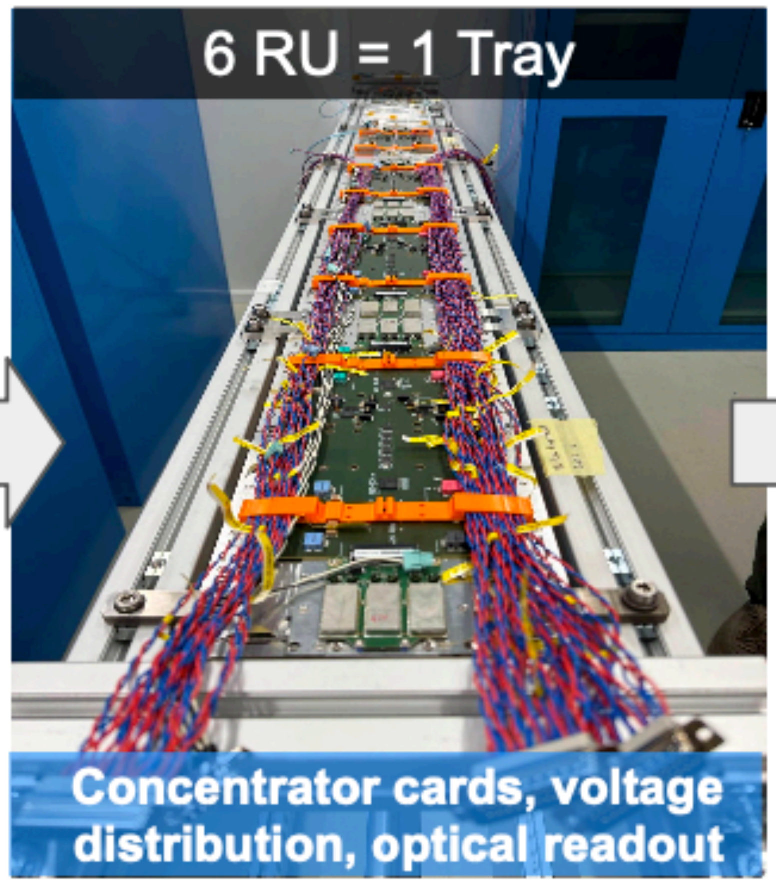


QAQC procedures defined







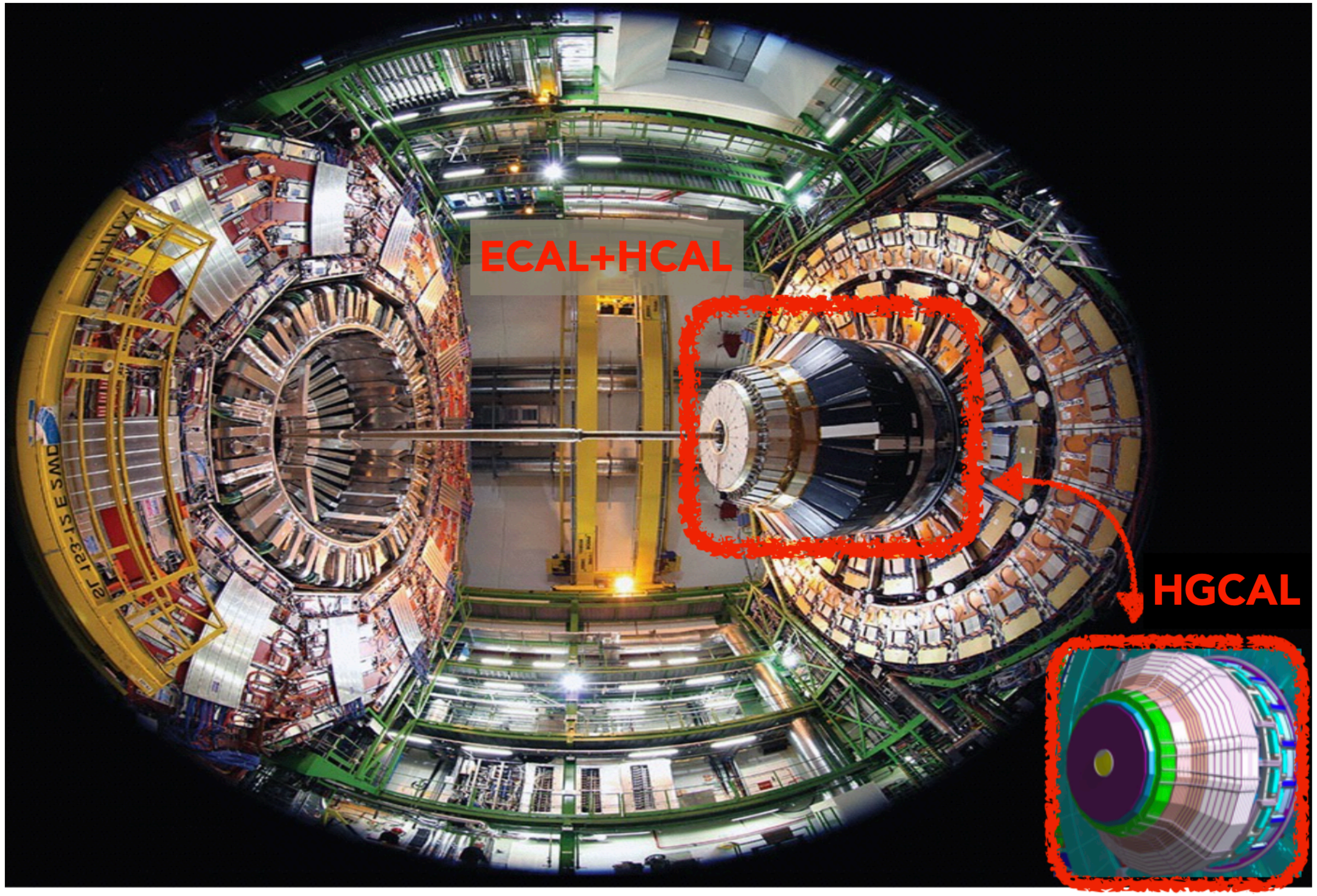


Tight schedule

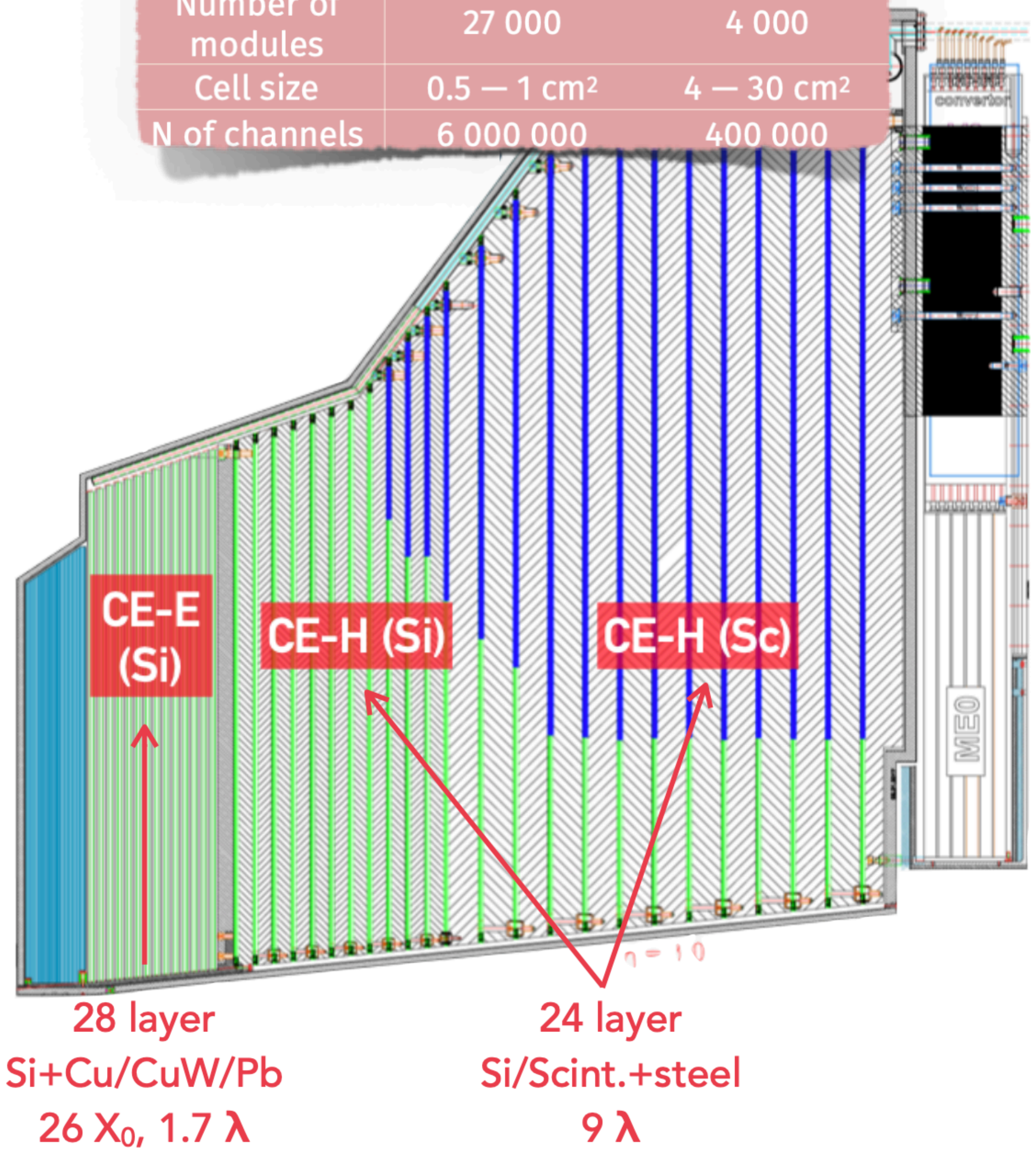
- complete assembly and integration of the whole detector by **mid 2025**
- 4 assembly centers
- 72 trays in total
- 1 RU / day / AC

A new high granularity **calorimeter**: the **HGCAL**

- ECAL+HCAL → HGCAL (High Granularity CALorimeter)
  - high granularity and timing to fight PU

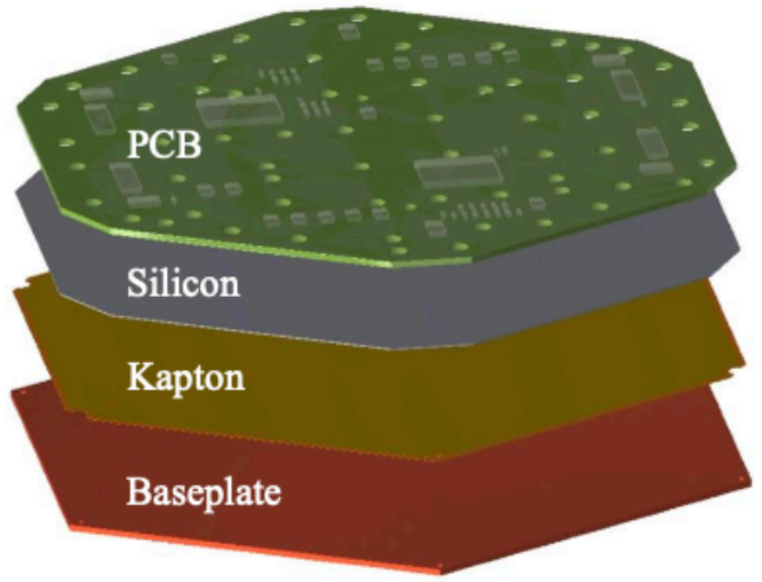


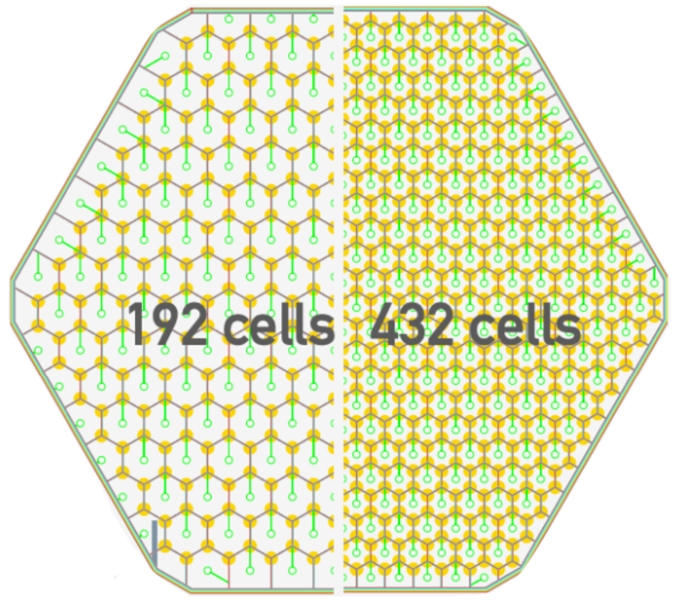
Endcap coverage: $1.5 < \|\eta\| < 3.0$		
Total	Silicon sensors	Scintillator
Area	600 m²	500 m²
Number of modules	27 000	4 000
Cell size	0.5 — 1 cm²	4 — 30 cm²
N of channels	6 000 000	400 000

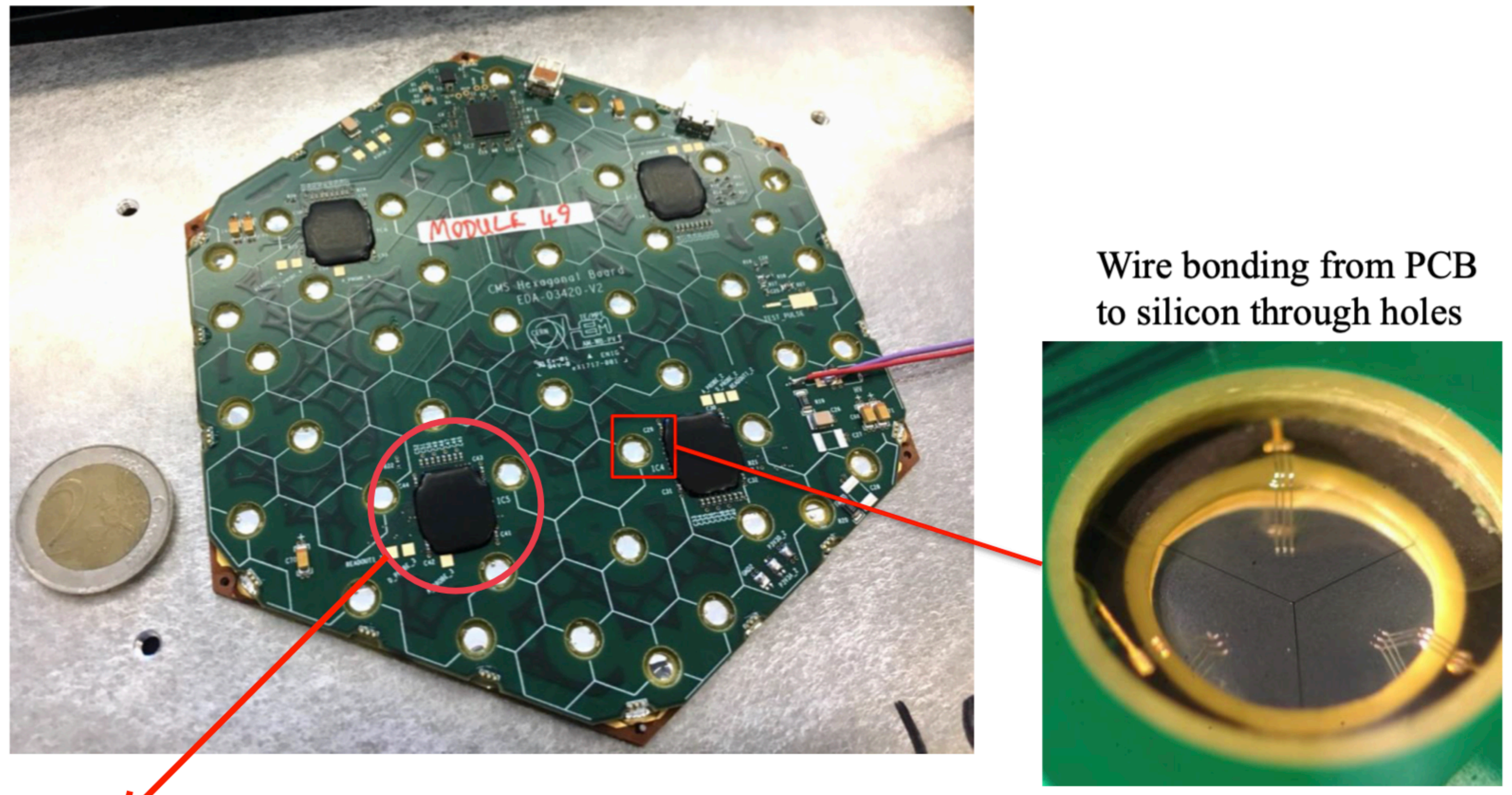


Detector layout

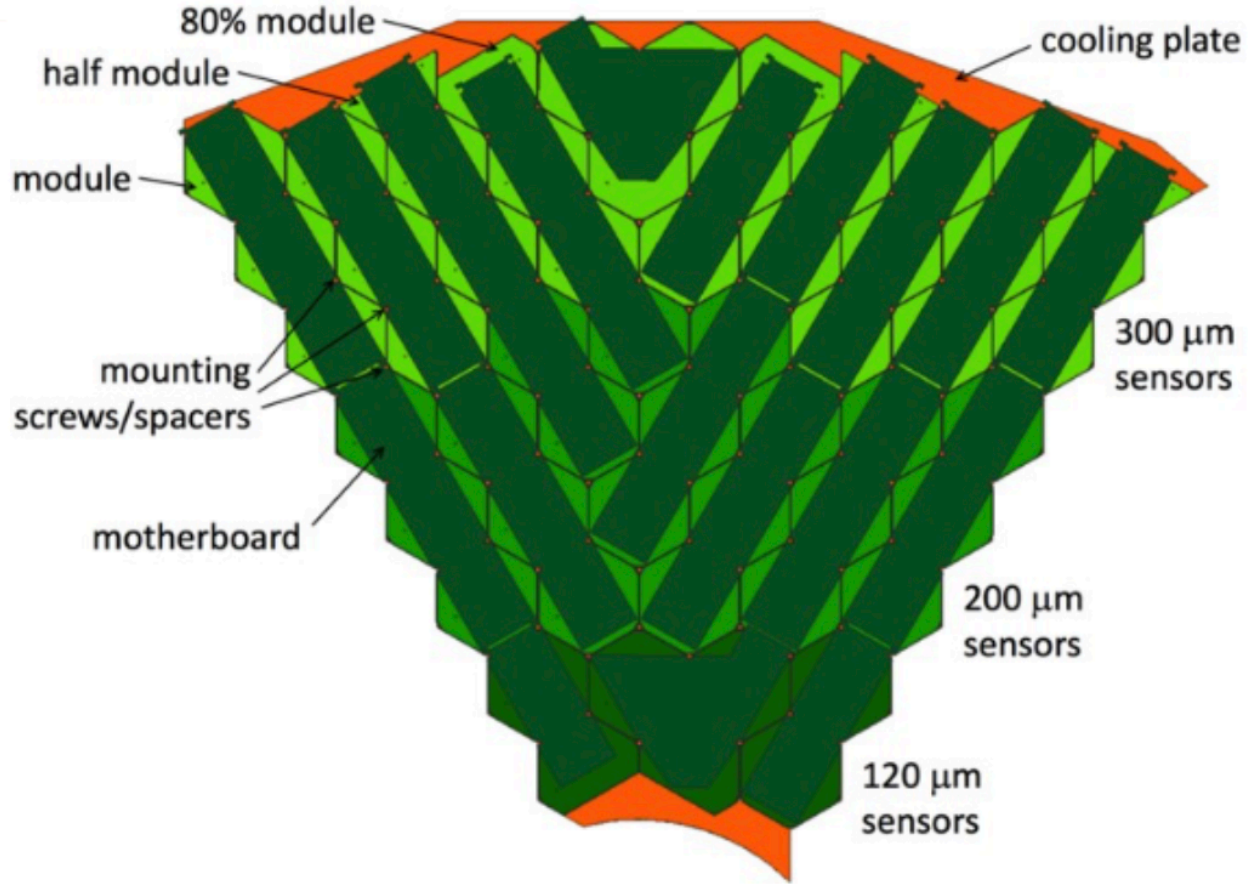
Sensors: hexagonal silicon wafers (8”) divided in cells



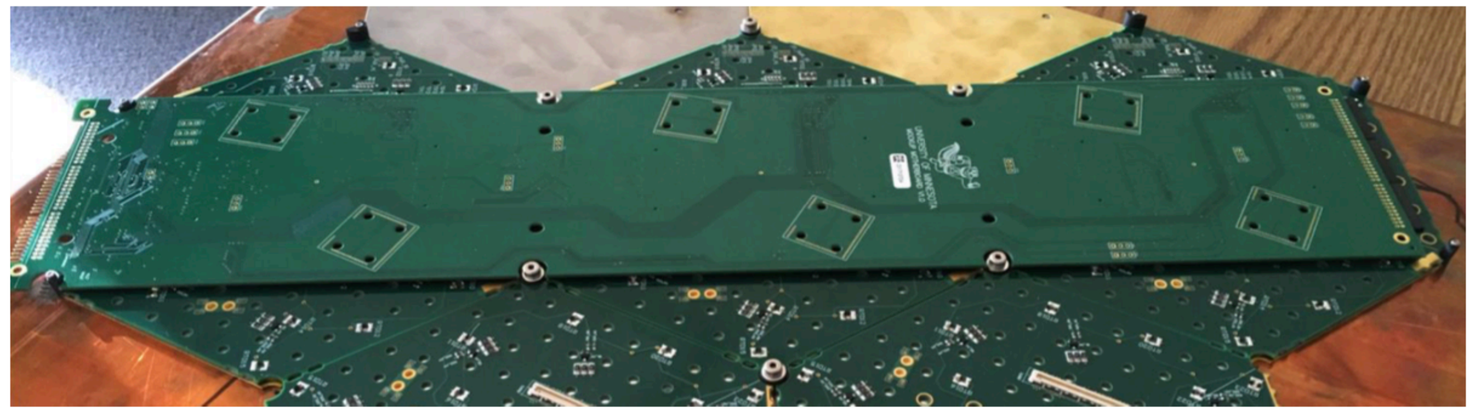


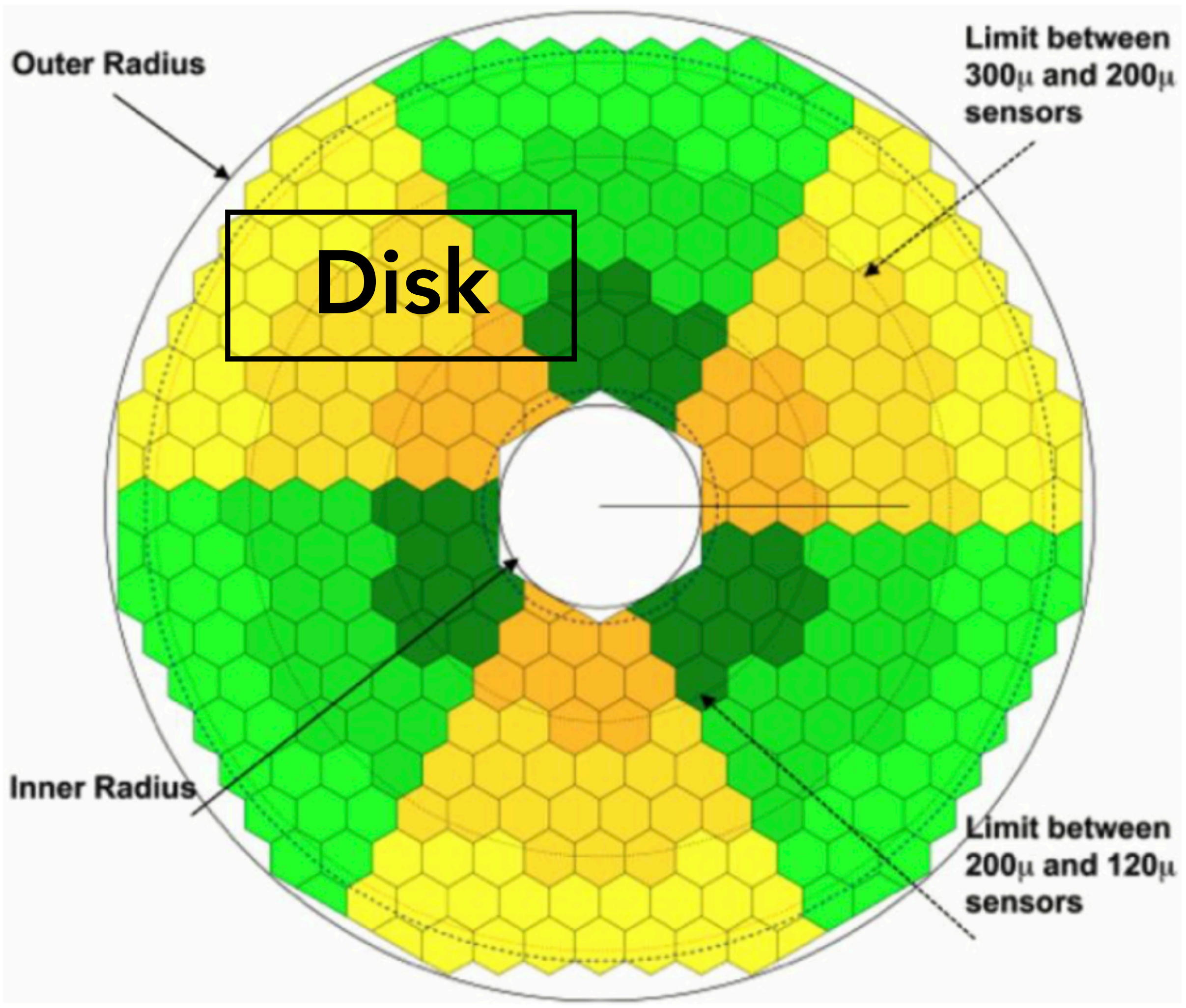


HGCROC chip: ToT meas. (∝amplitude) and timing (for signals >12fC, 3MIP)



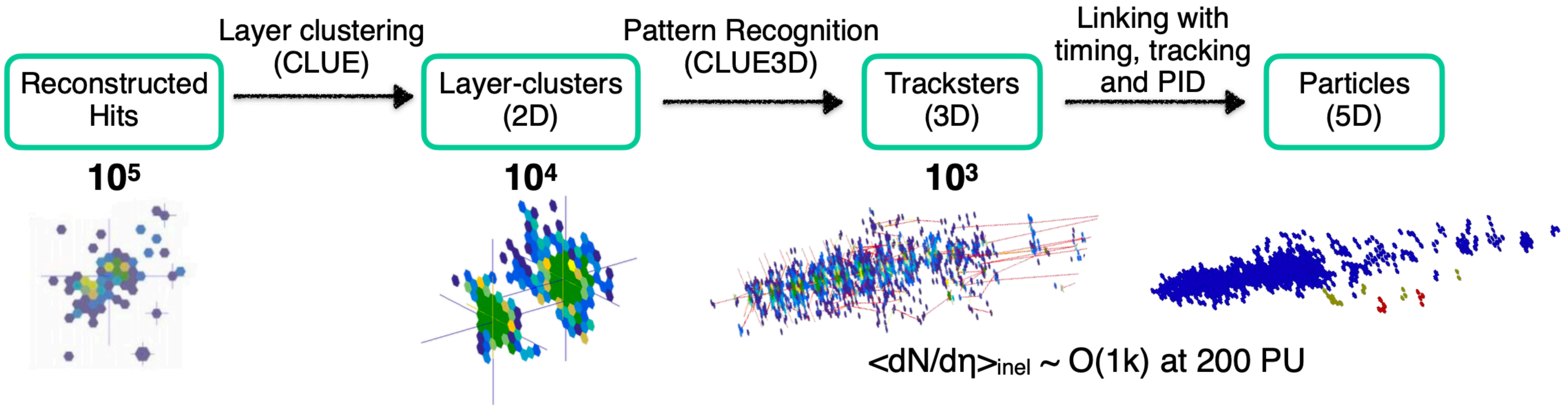
Cassettes: 30/60° sectors (sensors+support+motherboards)





Tileboards: scint tiles + SiPMs

The reconstruction challenge



The idea is to measure position, energy and time for each particle → **perfect playground for advanced pattern recognition techniques**

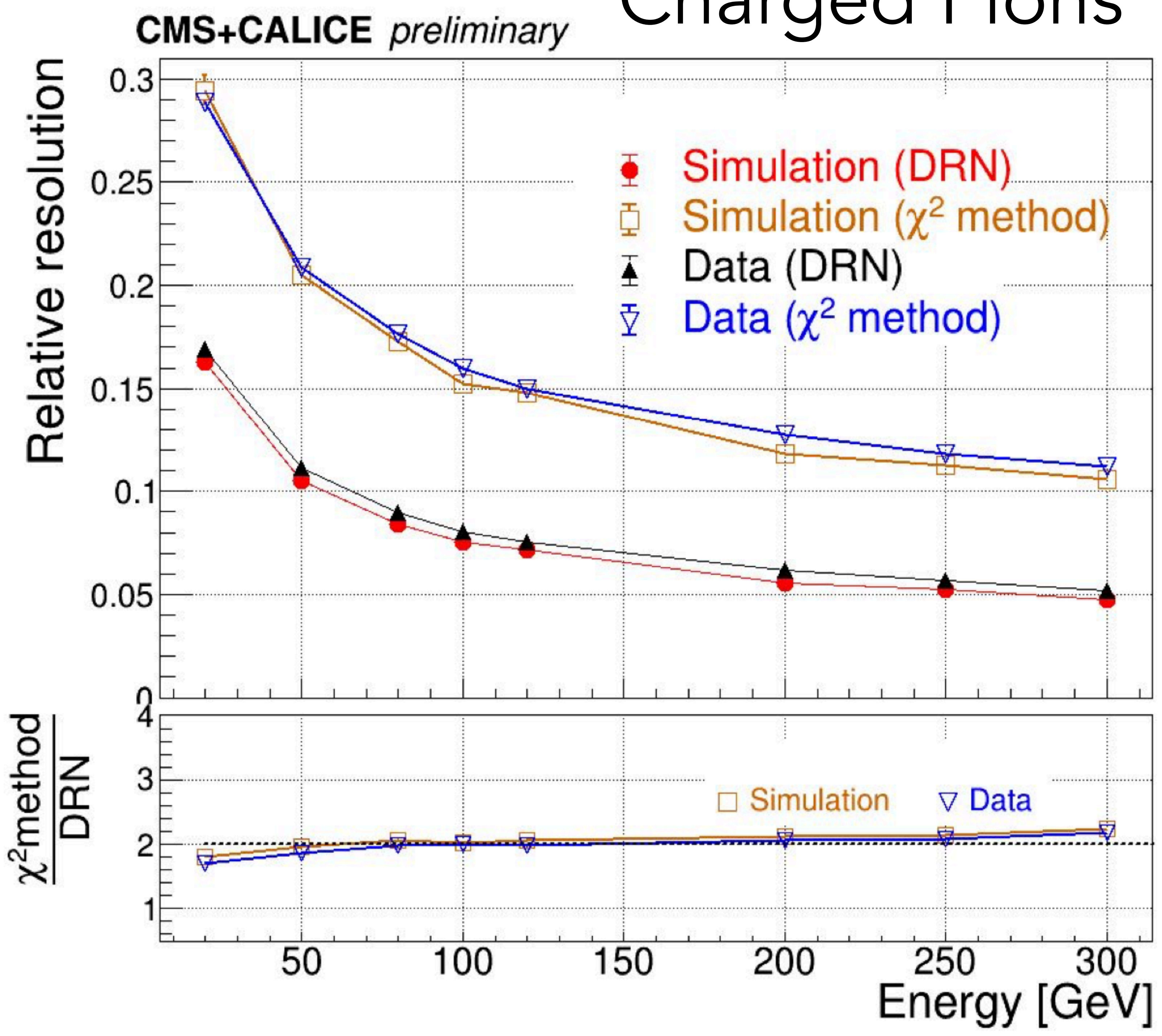
- **Enormous volumes of data** → high performance reco algos are needed
  - L1 accept @750 kHz rate
  - DAQ at 7.5 kHz with ~ 6M channels
  - Exploit heterogenous computing to maximize performance
- e/γ and hadron particle showers are reconstructed from detector hits exploiting **5D information**

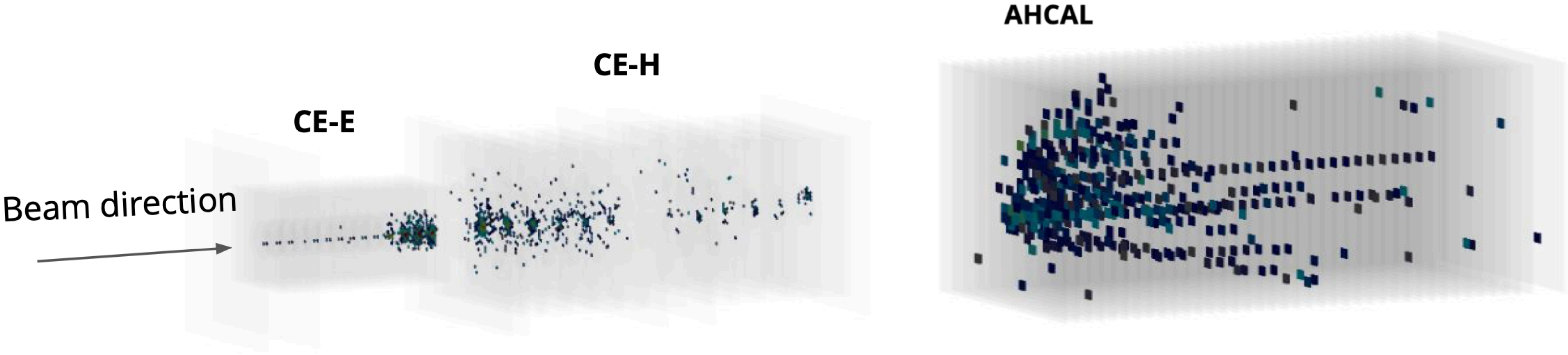
Shower reconstruction with a prototype on beam

- Very good understanding of the setup on beam
  - **Nice data-MC agreement** both for electrons and pions

- **New ML based methods** for charged pion reconstruction largely improve the resolution
  - Dynamic Reduction Network, based on GNNs
  - Exploit inputs such as energy and full 3D coordinates

Charged Pions



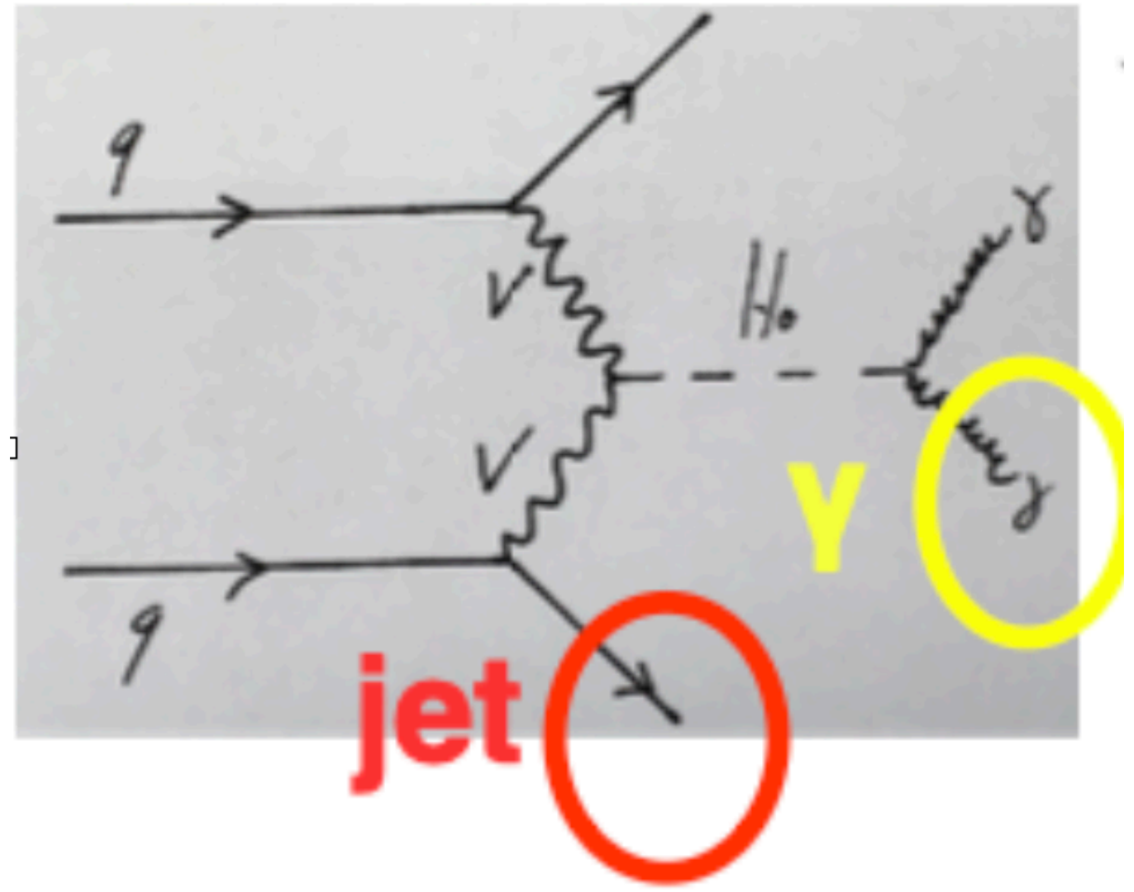


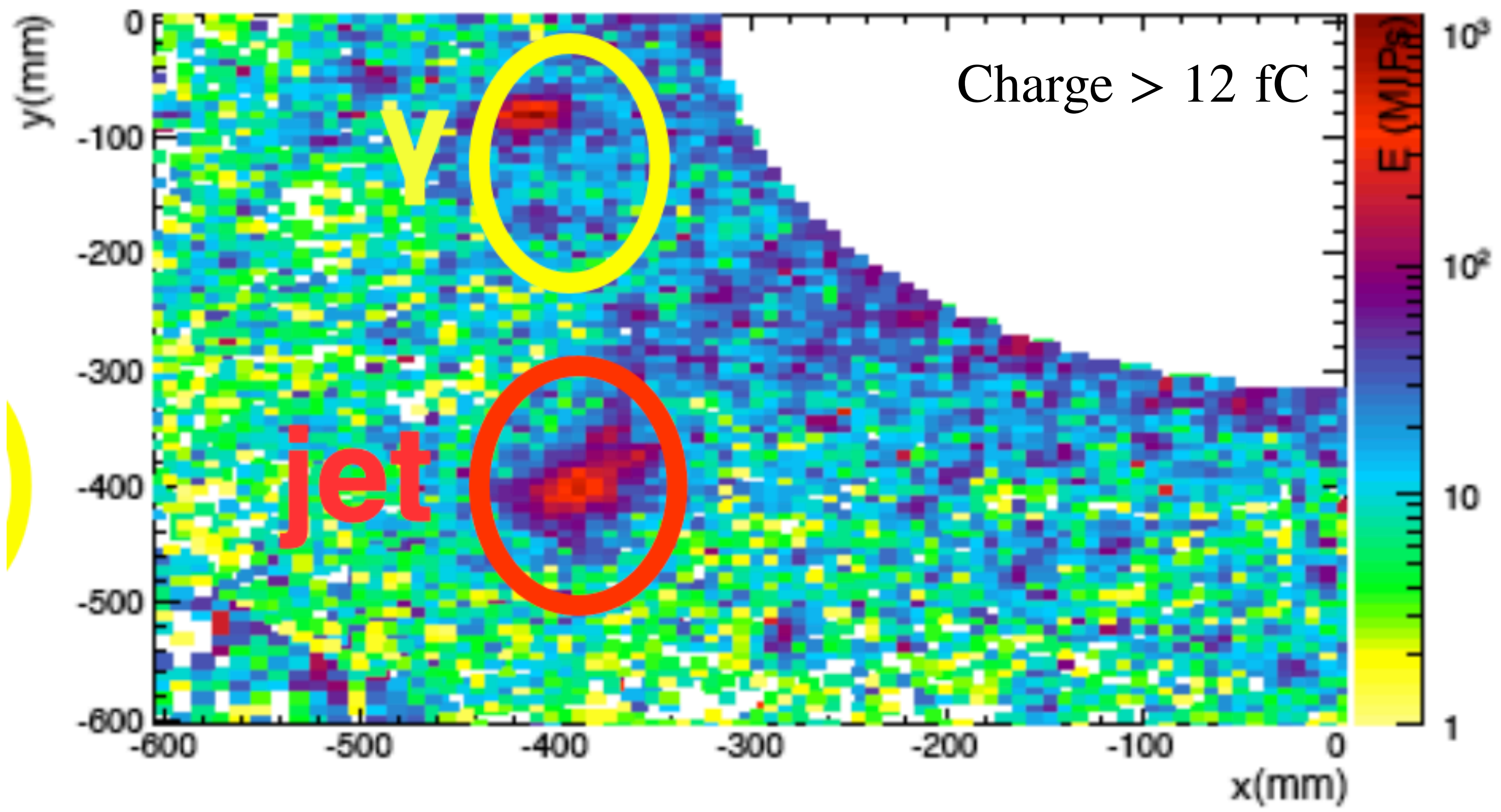
HGCAL in action on a VFB H → $\gamma\gamma$ event

High spatial granularity to **separate objects**

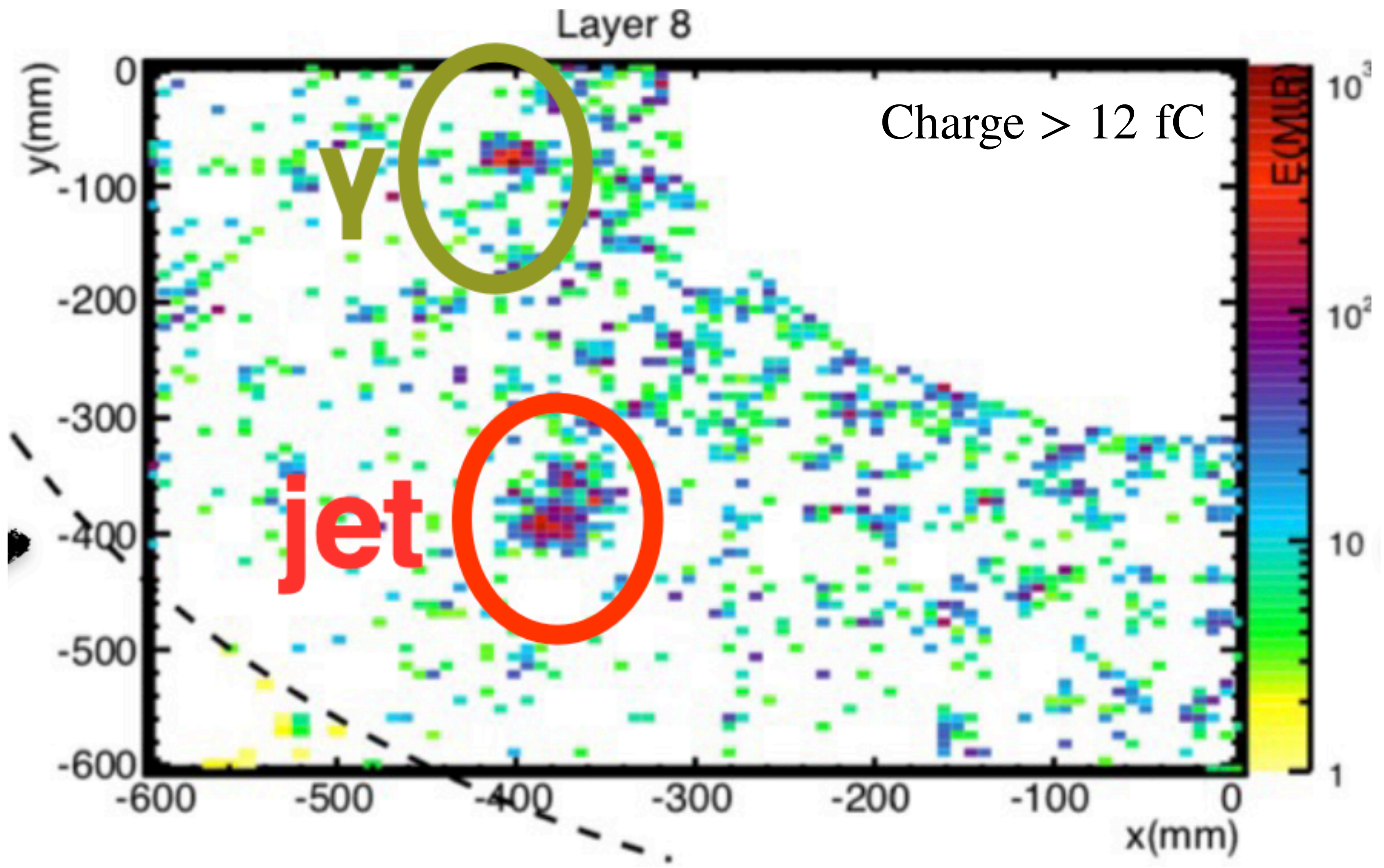
+

Timing to **mitigate pileup**





$|\Delta t| < 90$ ps



Summary

- **High luminosity needed** for searches and precision measurements
  - As a consequence, very harsh conditions are expected at the HL-LHC
- The CMS Phase2 upgrade **will allow us to profit from the HL-LHC era**
  - Keep (and improve) he high performance delivered in Phase-1
- Many detector are in the last phases of the R&D or moving to production
  → **A lot of construction expected in 2025!**

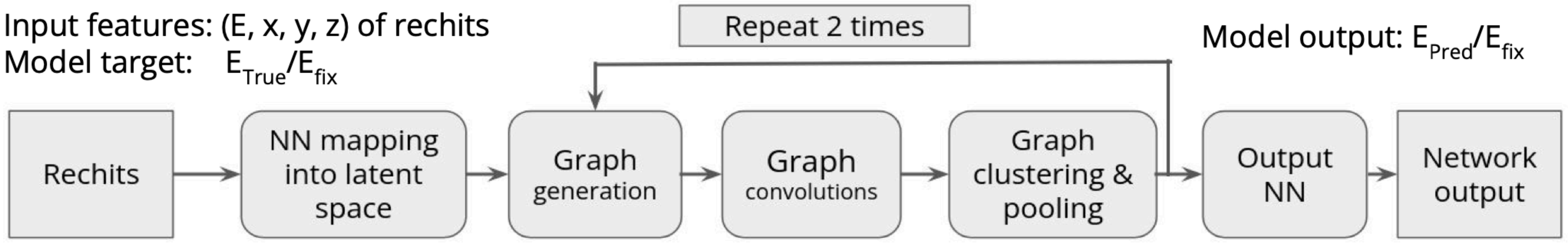
Backup slides

State of the CMS upgrade

- Tracker
  - Outer Tracker: about to start module production
  - Inner Tracker: ASIC final and in production
- HGCAL
  - Considerable progress on mechanics
  - SiPM, scintillator production started – 40% of the sensors received
- MTD
  - Barrel: started module production
  - Endcap: sensor procurement review in July; ASIC functionality proven
- Muon Detector
  - RPC and GEM chambers production ongoing

Dynamic Reduction Network (DRN)

Based on dynamic graph neural network, a model is defined which maps input features onto a higher dimensional latent space, and adds clustering and pooling steps to aggregate information. Energies (E) and (x,y,z) coordinates of individual cells (called rechits) are provided as input to the model for training to the target E_{True}/E_{fix}. Loss function is defined as (target-prediction)^2/target.



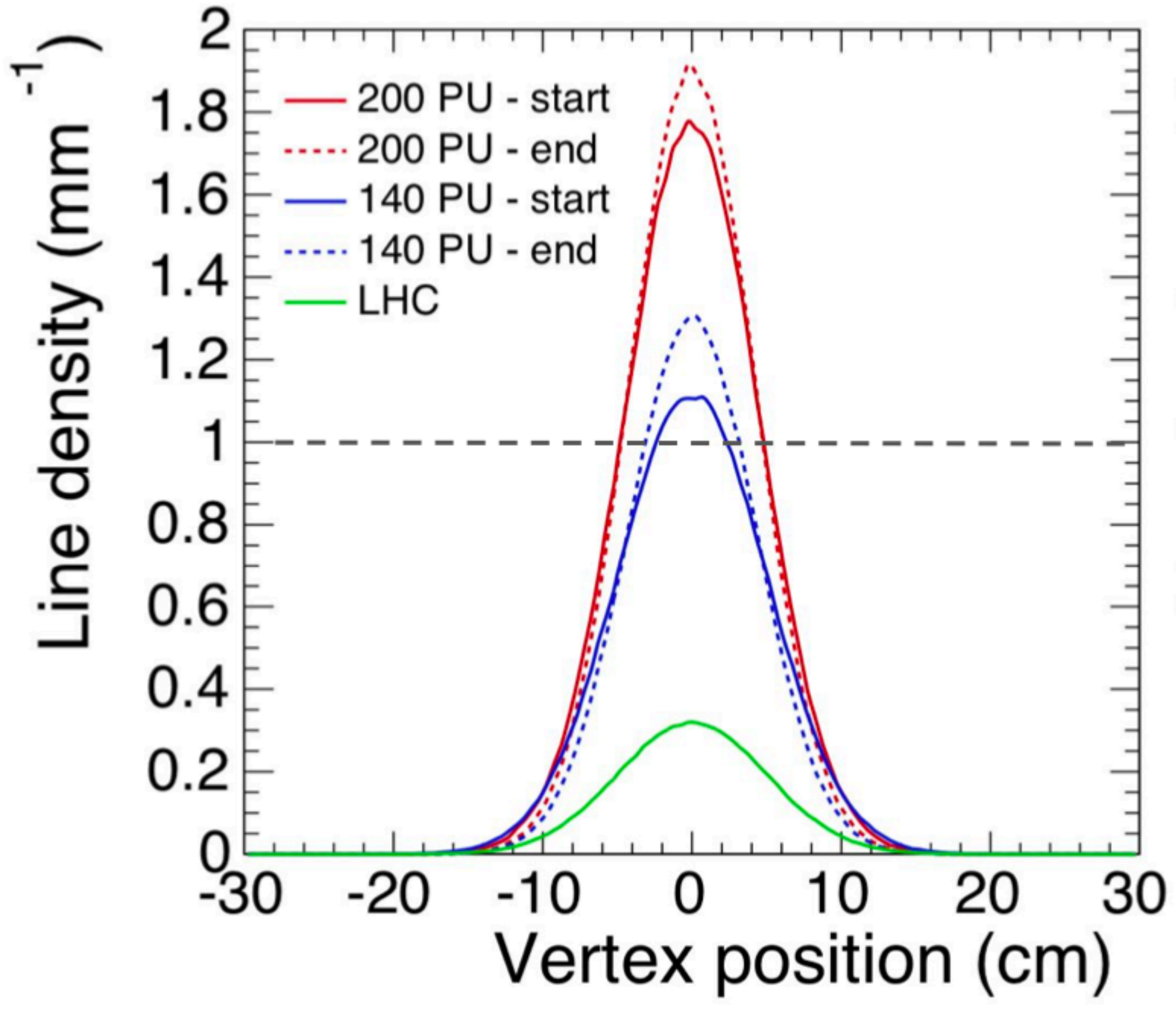
where E_{True} is the true energy of particle, E_{fix} is reconstructed energy using detector level calibration and E_{Pred} is the energy reconstruction using DRN weights.

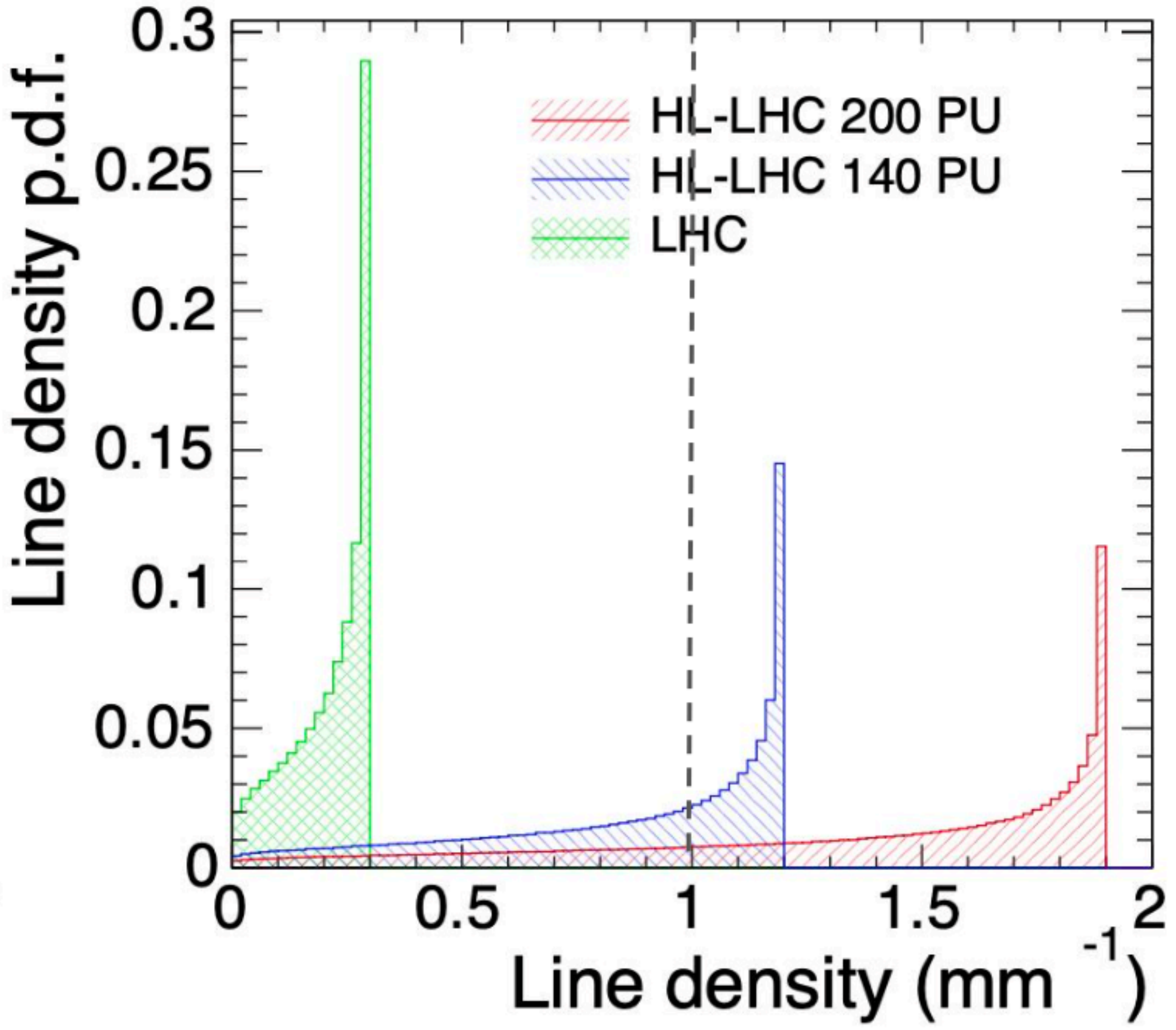
Arxiv : 2003.08013v1

The model is trained on a flat energy sample of 10-350 GeV with a total of 4.1M events simulated using GEANT4.10.4.p03 and FTFP BERT EMN hadronic physics list. Out of 39 sampling layers of AHCAL, only 10 layers are sampled (consistent with the final HGCAL geometry). AdamW optimizer with a constant learning rate of 10^{-4} is used. We have approximately 63k parameters to learn in the model and a larger fraction of model training time goes into aggregating the information.

High pileup

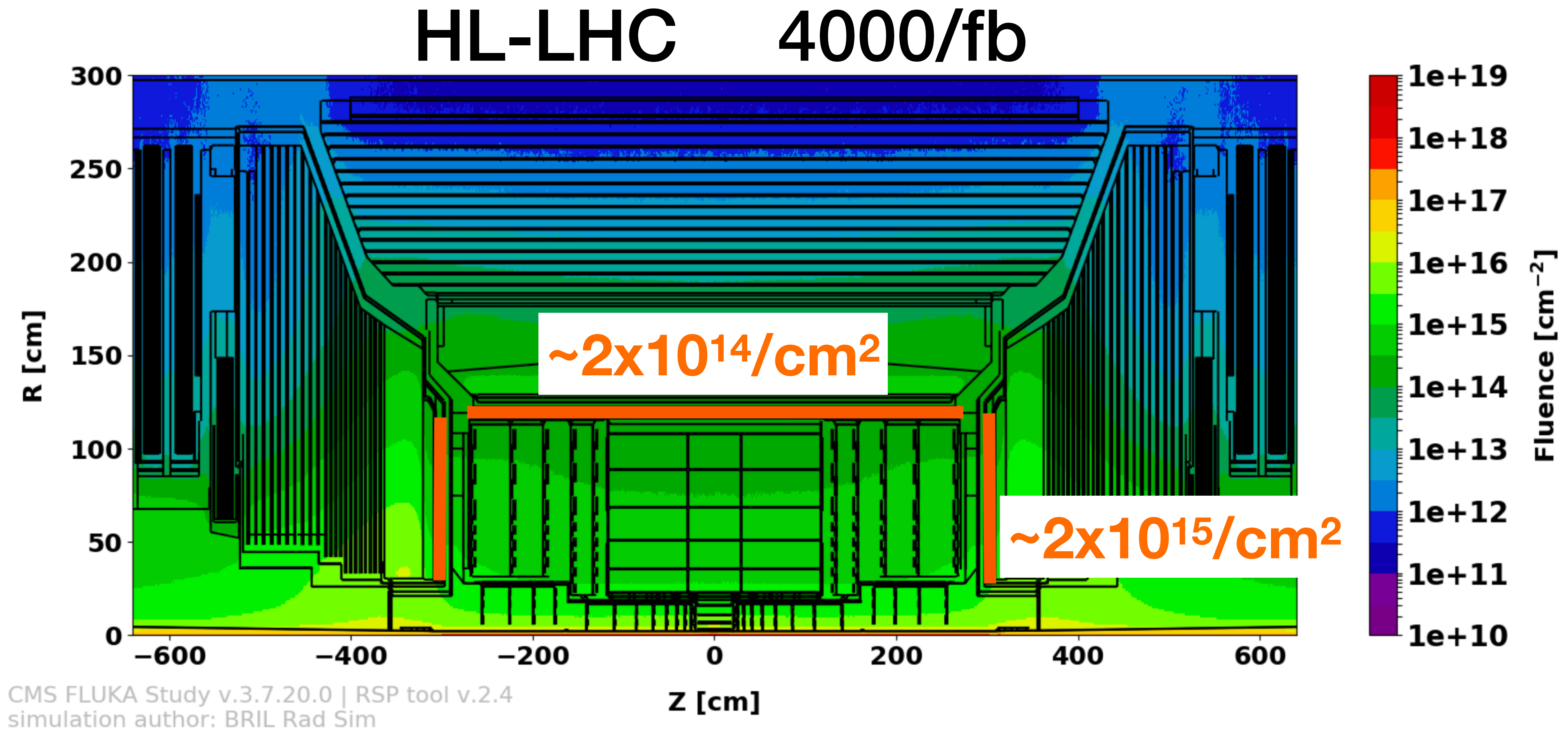
	Phase I LHC	HL-LHC
E_{beam} (TeV)	7-13.6	14
$\mathcal{L}_{peak}(cm^{-2}s^{-1})$	2×10^{34}	$5\text{-}7.5 \times 10^{34}$
$\int\mathcal{L}$ (fb^{-1})	300-500	3000-4000
PU	**40-60**	**140-200**





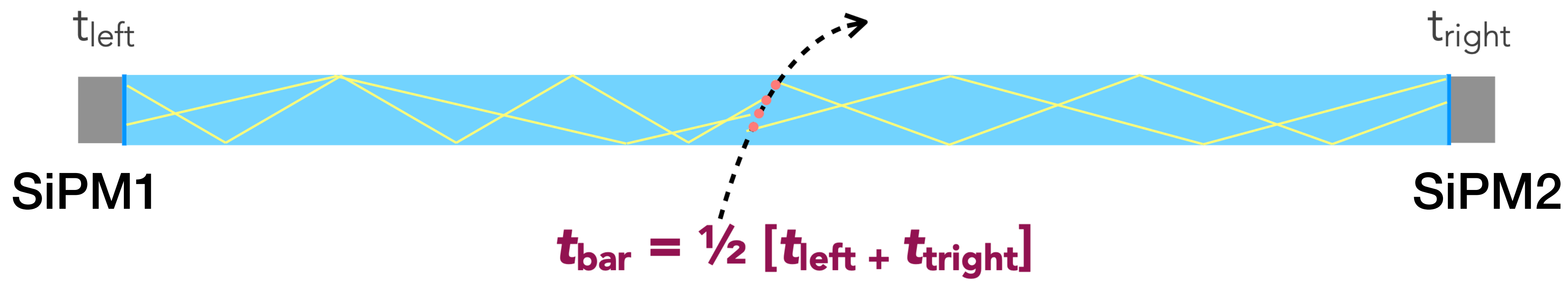
High radiation

- Expected fluence up to **several 10^{16} n_{eq}/cm^2** in the proximity of the beam pipe
- The annual dose is a factor **x10 higher** with respect to LHC



Goal: integrate >3ab⁻¹ while keeping the current performance

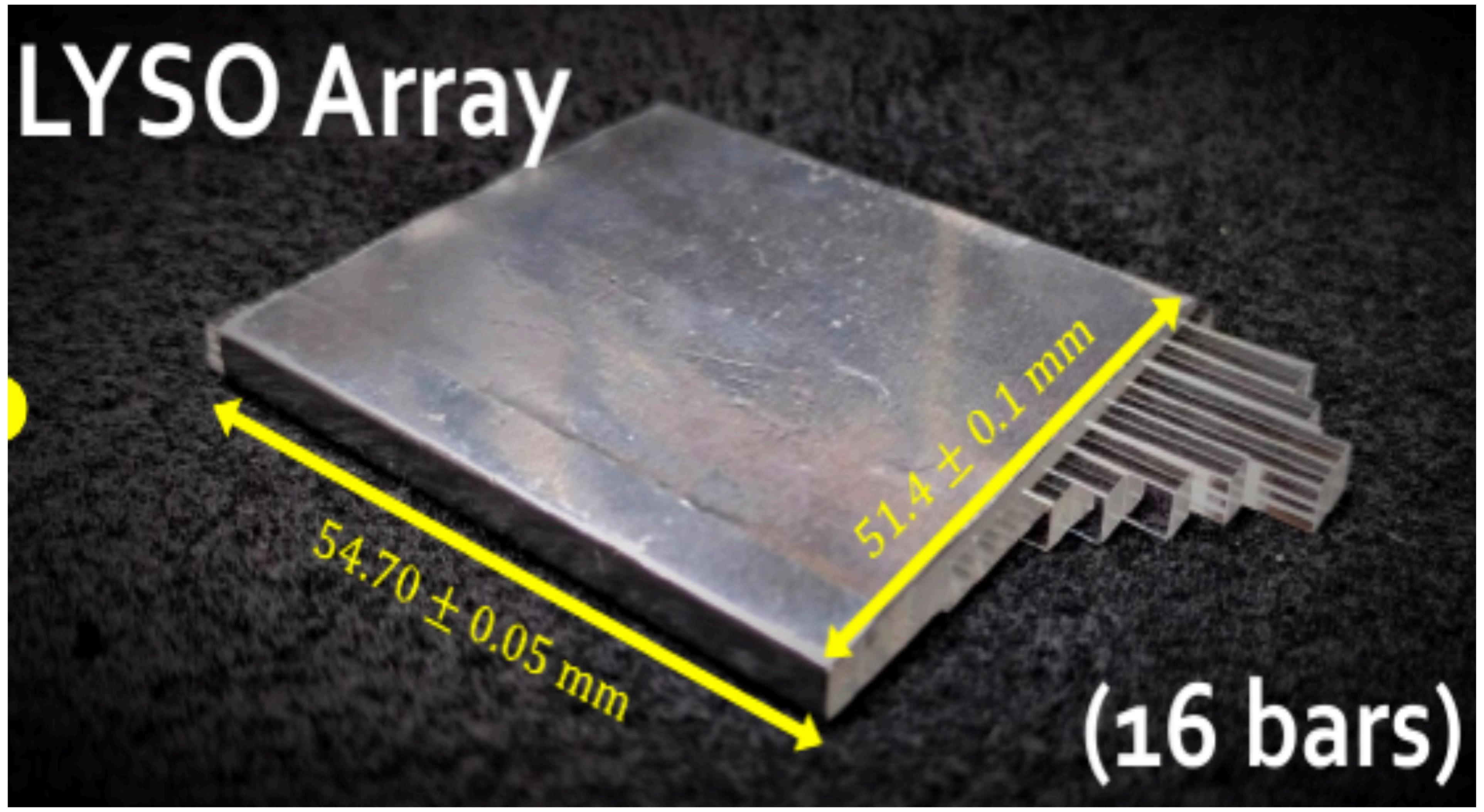
The BTL approach

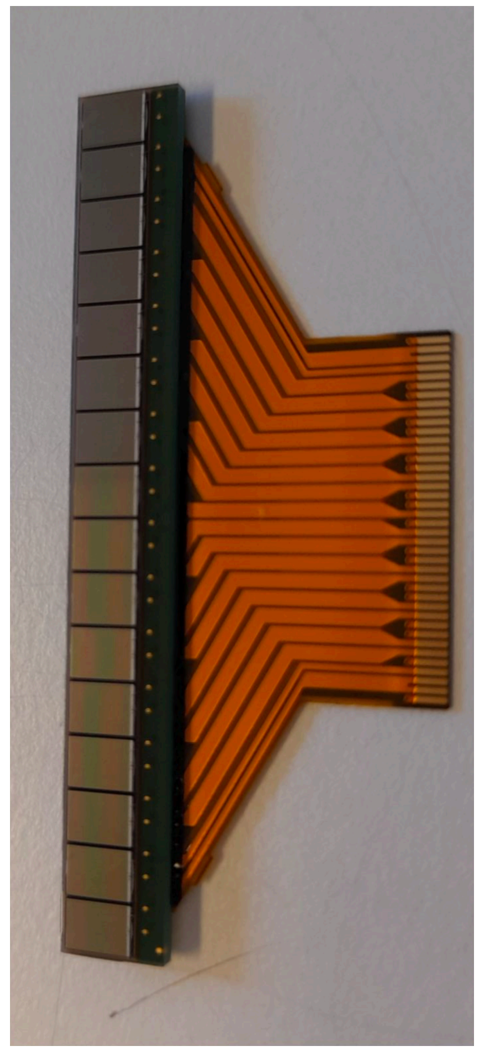


+ High aspect ratio geometry
+ LYSO bars with double end readout:
improve resolution by $\sqrt{2}$ over single-end

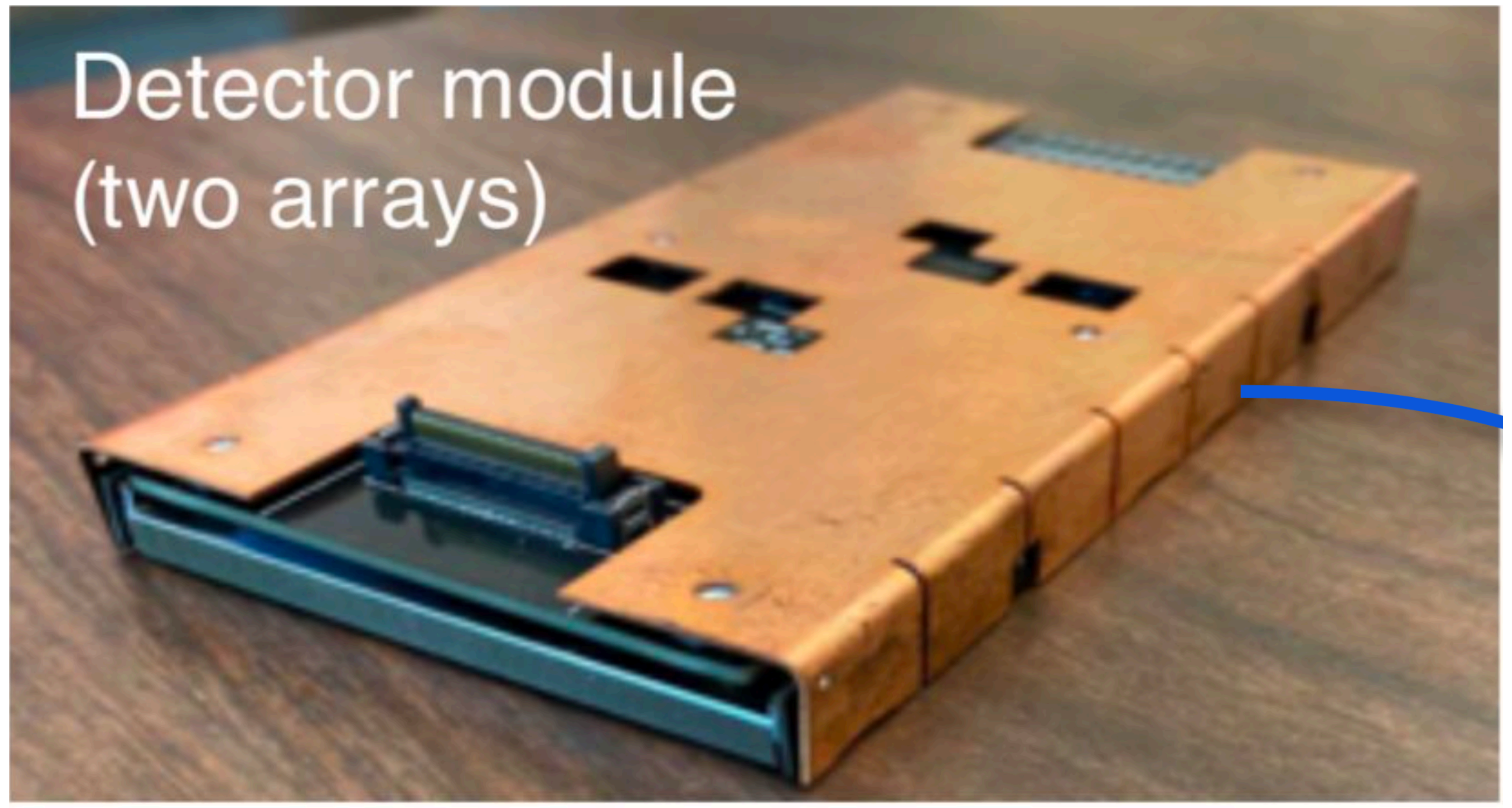
- **LYSO**
  - $\tau_{rise} \sim 100$ ps, $\tau_{decay} \sim 40$ ns
  - LY ~40000 γ/MeV

- **SiPM**
  - Insensitive to B-field
  - 20-40% PDE at LYSO emis. peak





- **Detector Module:**
  - 16 LYSO bars glued to 2 SiPM arrays (~165k crystals)
    - Time response independent from impact point
  - Dedicated ASIC (TOFHIR) for processing and digitization of SiPM signal

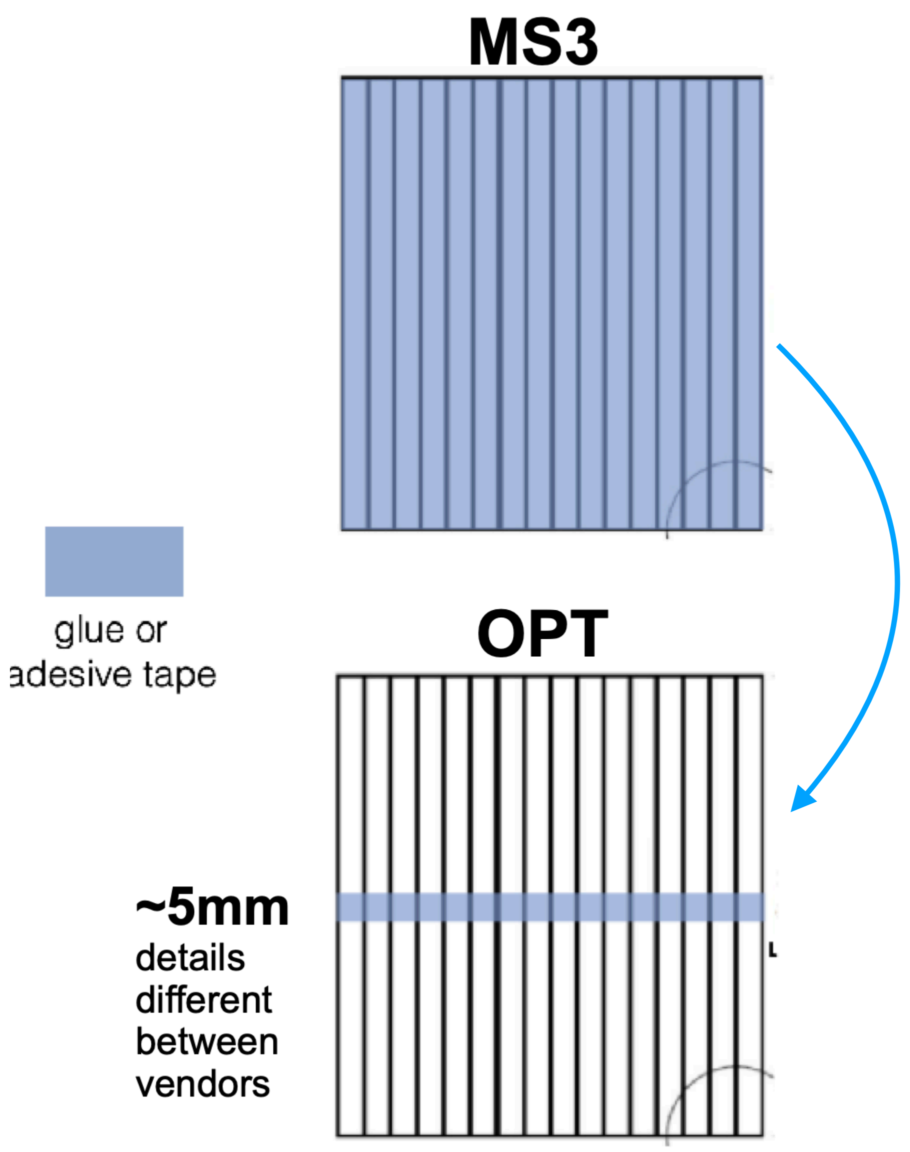


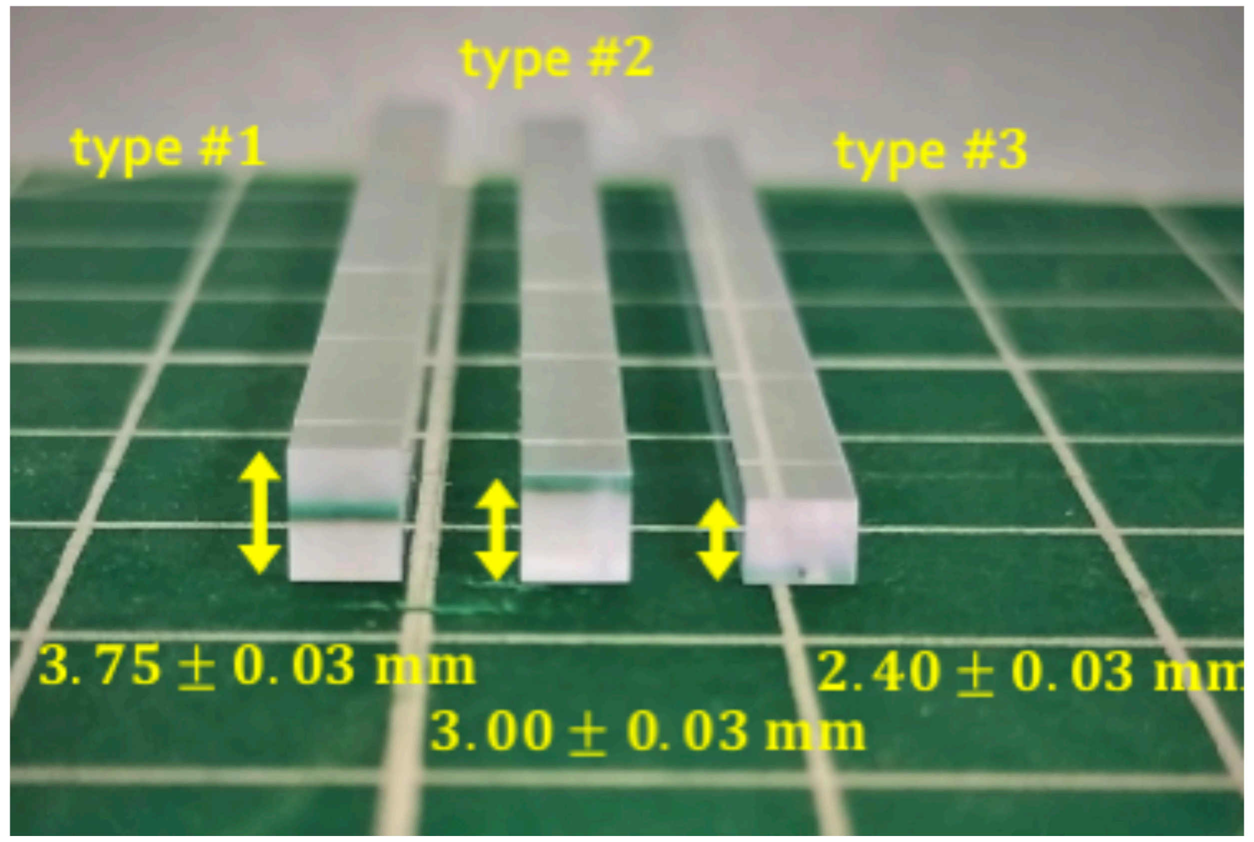
Expect a Dark Count Rate (DCR) of O(10) GHz at end of operations due to SiPM radiation damage

Strategies to improve the S/N ratio

Maximize the crystal light output

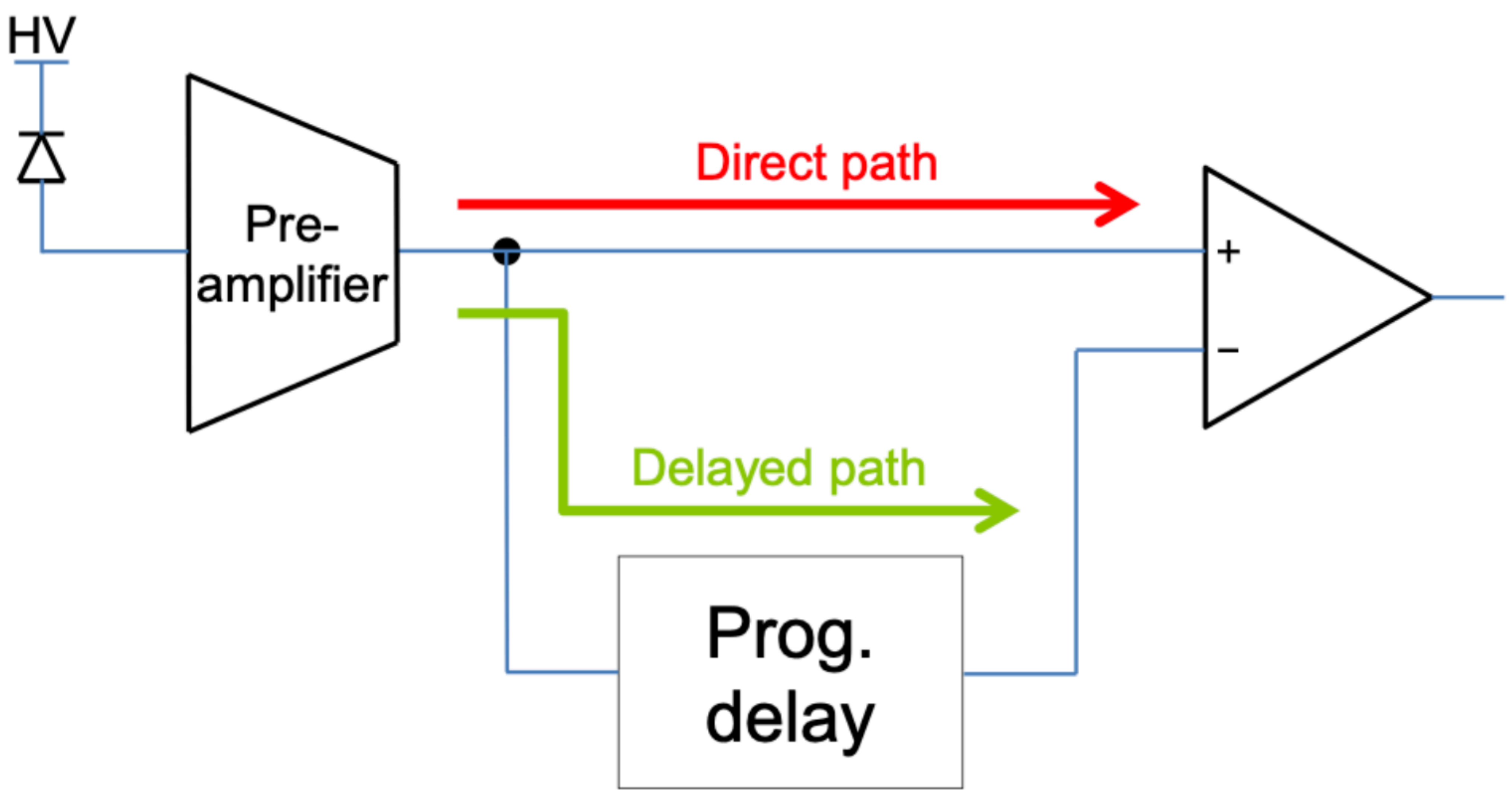
- Minimal amount of glue to **improve the total internal reflection**
  - 10% improvements in time resolution at EoO
- The option of thickening the LYSO bars is under investigation





Noise filter + high electronics gain

- **DLED**: Sum the inverted and delayed signal → cancel out correlated noise while preserving the rising edge
- **1.6x higher preamp gain** in the latest version of the TOFHIR

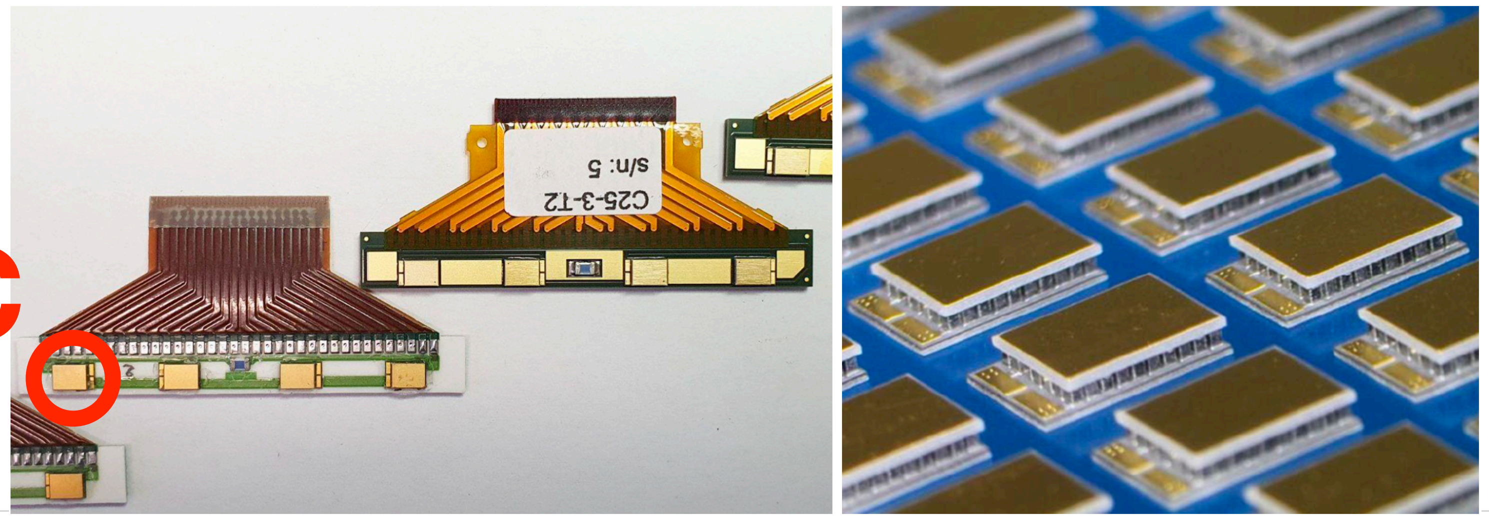


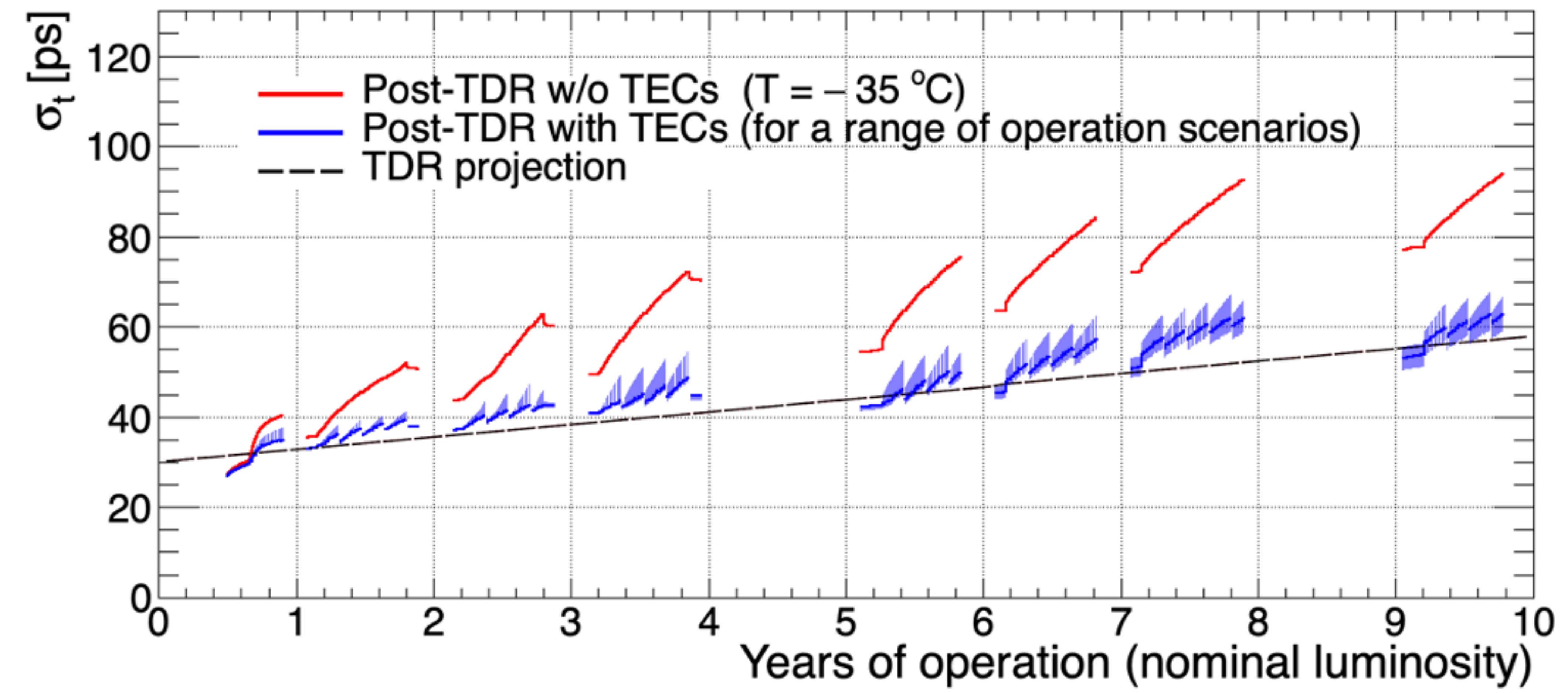
Strategies to improve the S/N ratio

Cold operations + SiPM annealing

- **CO_2 cooling at -35°C** + additional cooling down to **-45°C** using **Thermo-Electric Coolers** (TECs)
- In situ **annealing cycles at +60°C** during machine shutdowns

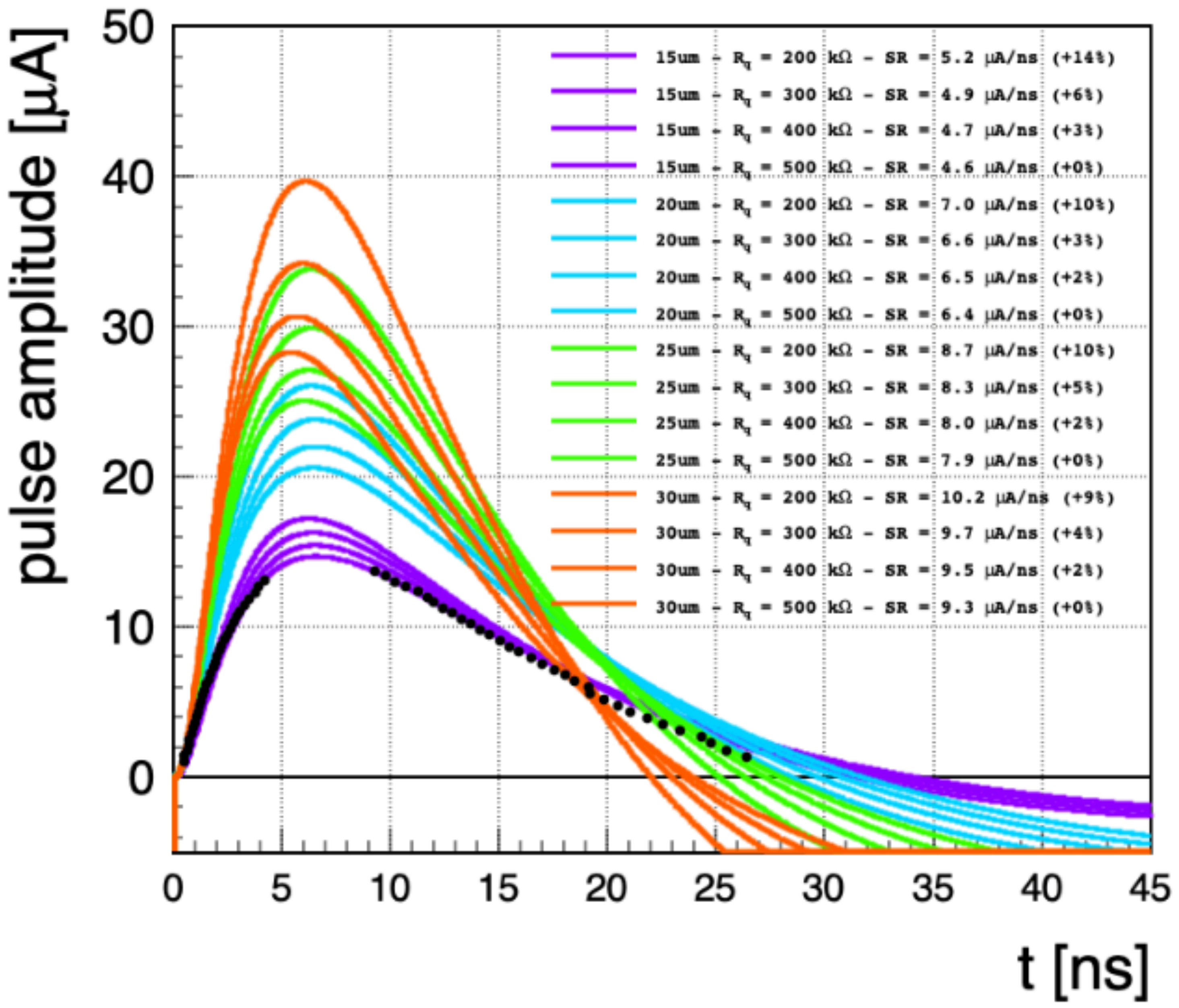
TEC





Large signal from SiPMs

- SiPMs with **larger cell size** (15um → 30um)
  - **Steeper rising edge** → lower impact of electronics noise
  - **Larger PDE** → lower impact of all resolution terms



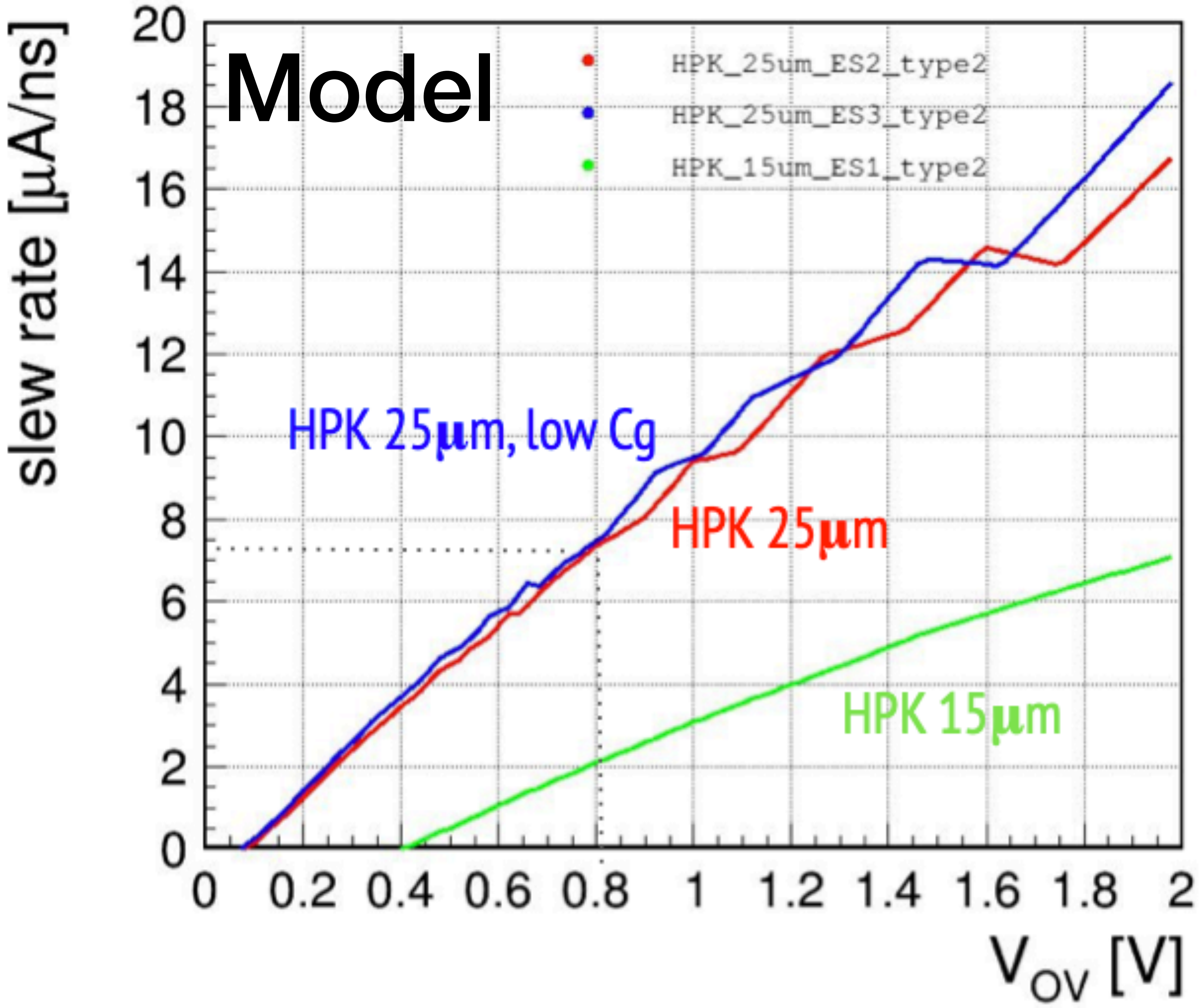
15 um
20 um
25 um
30 um

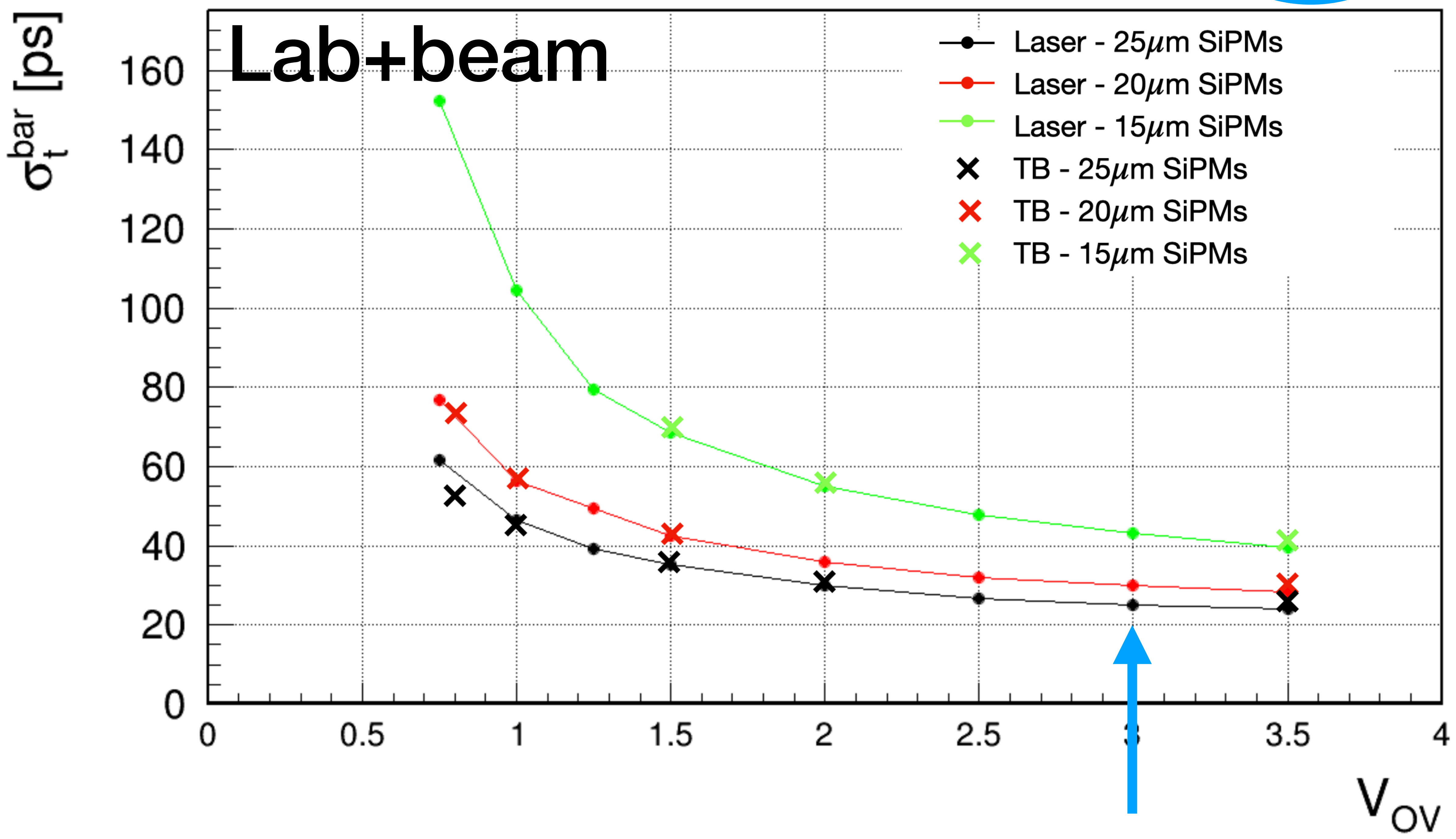
Performance validation

- Careful modelling of the SiPM response and its evolution in time
- Extensive study of sensor prototypes in test beam and in the lab
  - Results obtained with laser on LYSO have been validated on beam
- **Startup performance and uniformity confirmed!** Ongoing test beam on irradiated SiPMs.

$$\sigma_t^{BTL} = \sigma_t^{clock} \oplus \sigma_t^{digi} \oplus \sigma_t^{ele} \oplus \sigma_t^{phot} \oplus \sigma_t^{DCR}$$

dominates at EoO



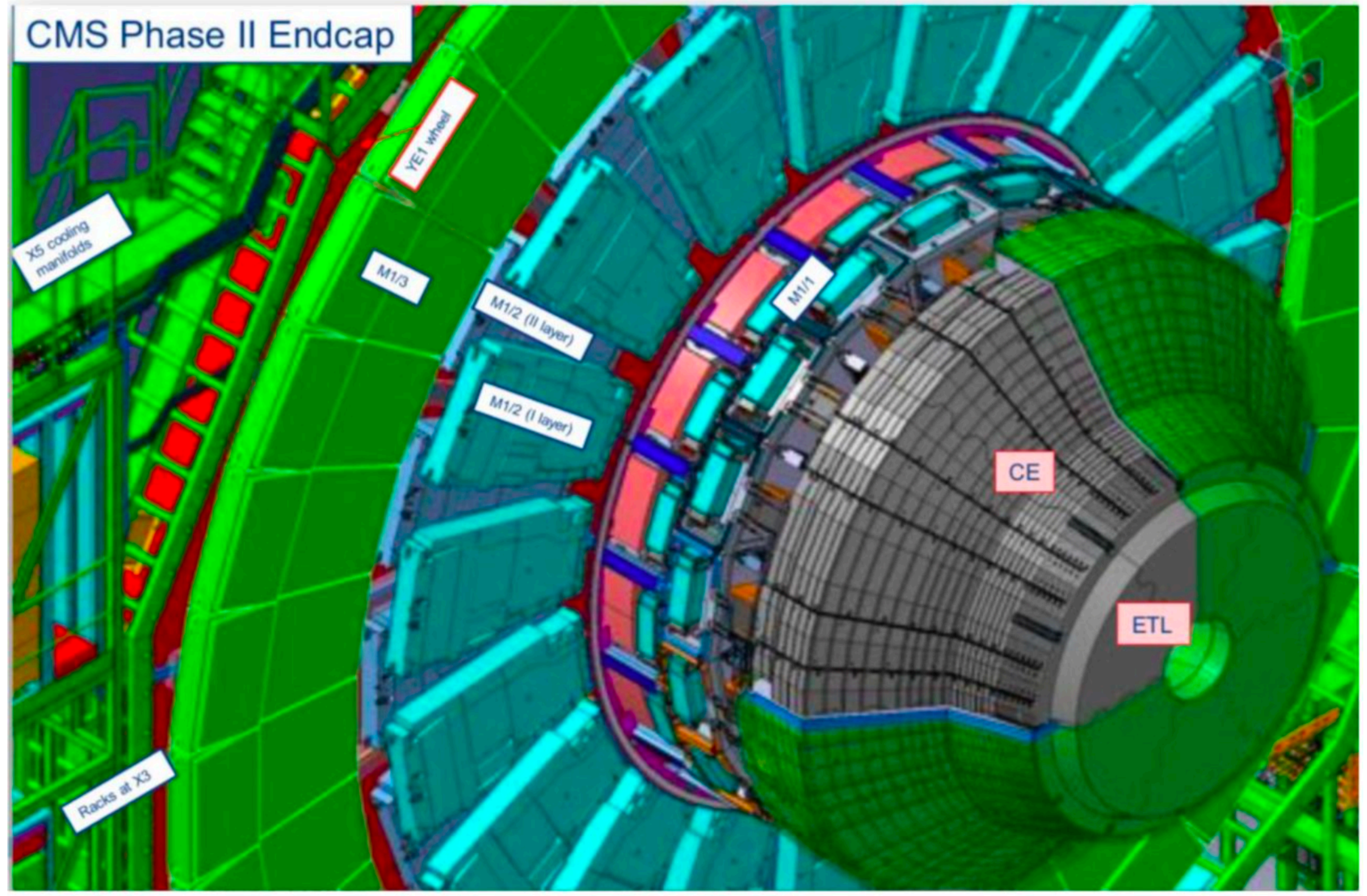


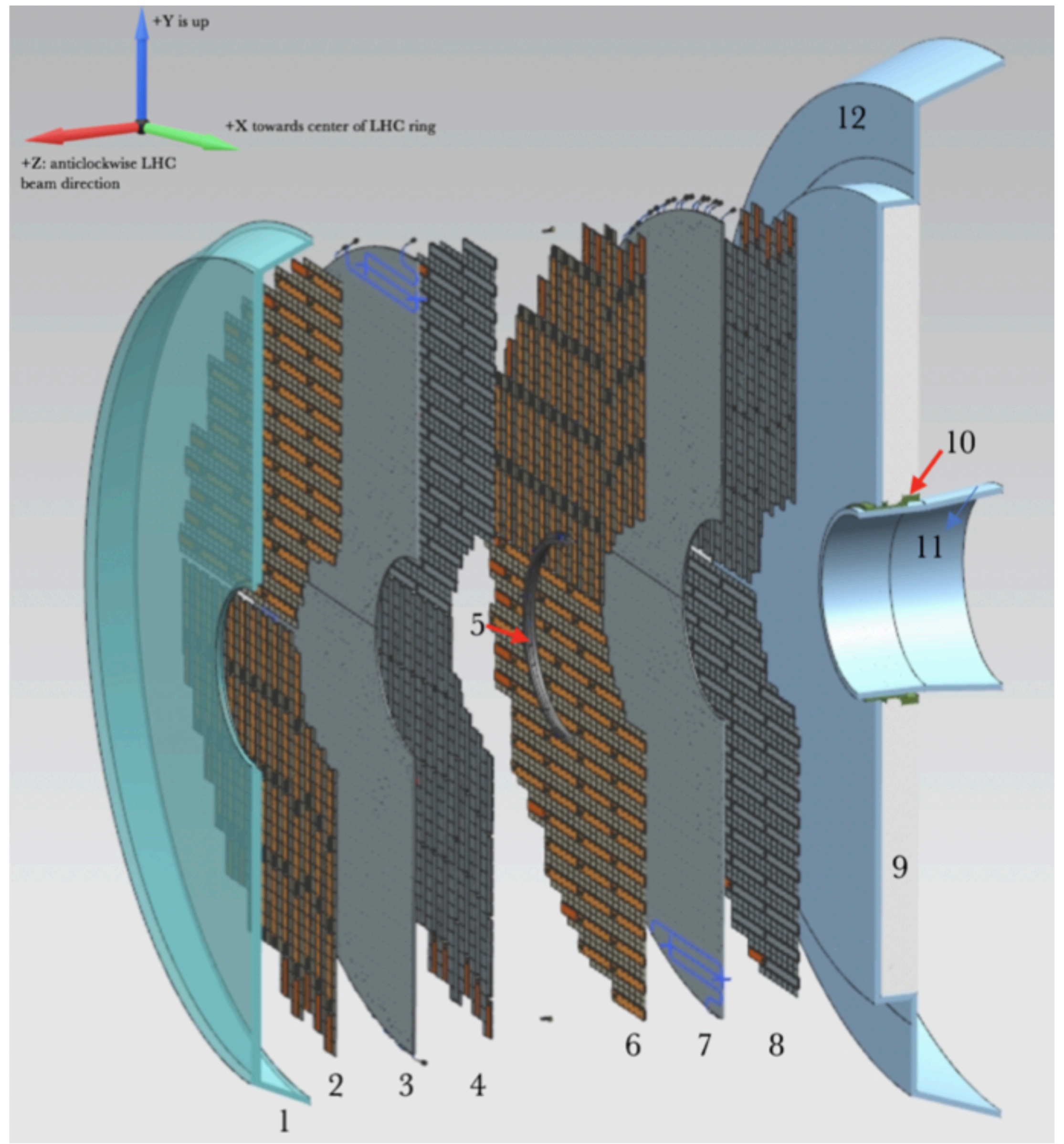
The ETL approach

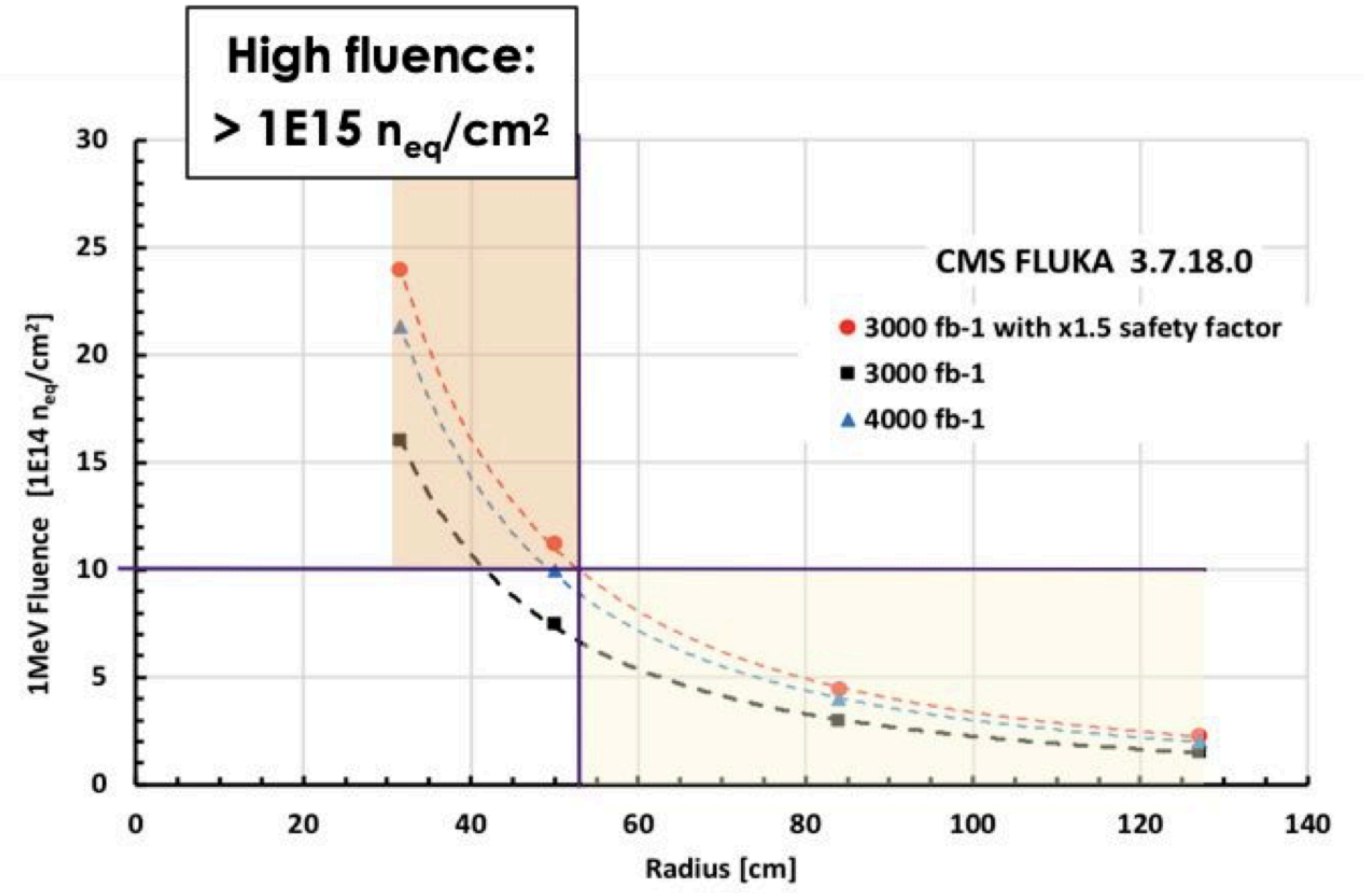
- **50 um thick silicon sensors** based on the Low-Gain Avalanche Diode (**LGAD**) technology
- 2 double-sided disks for each endcap side
  - Will be mounted on the nose of the CMS CE calorimeter
  - Large geometrical acceptance (85%/disk)
  - **Ensure two hits for each track**
- 12% of ETL surface will be exposed to fluences > $\mathbf{1x10^{15}\ n_{eq}/cm^2}$

Target time resolution

- single hit resolution < 50 ps
- track resolution < 35 ps

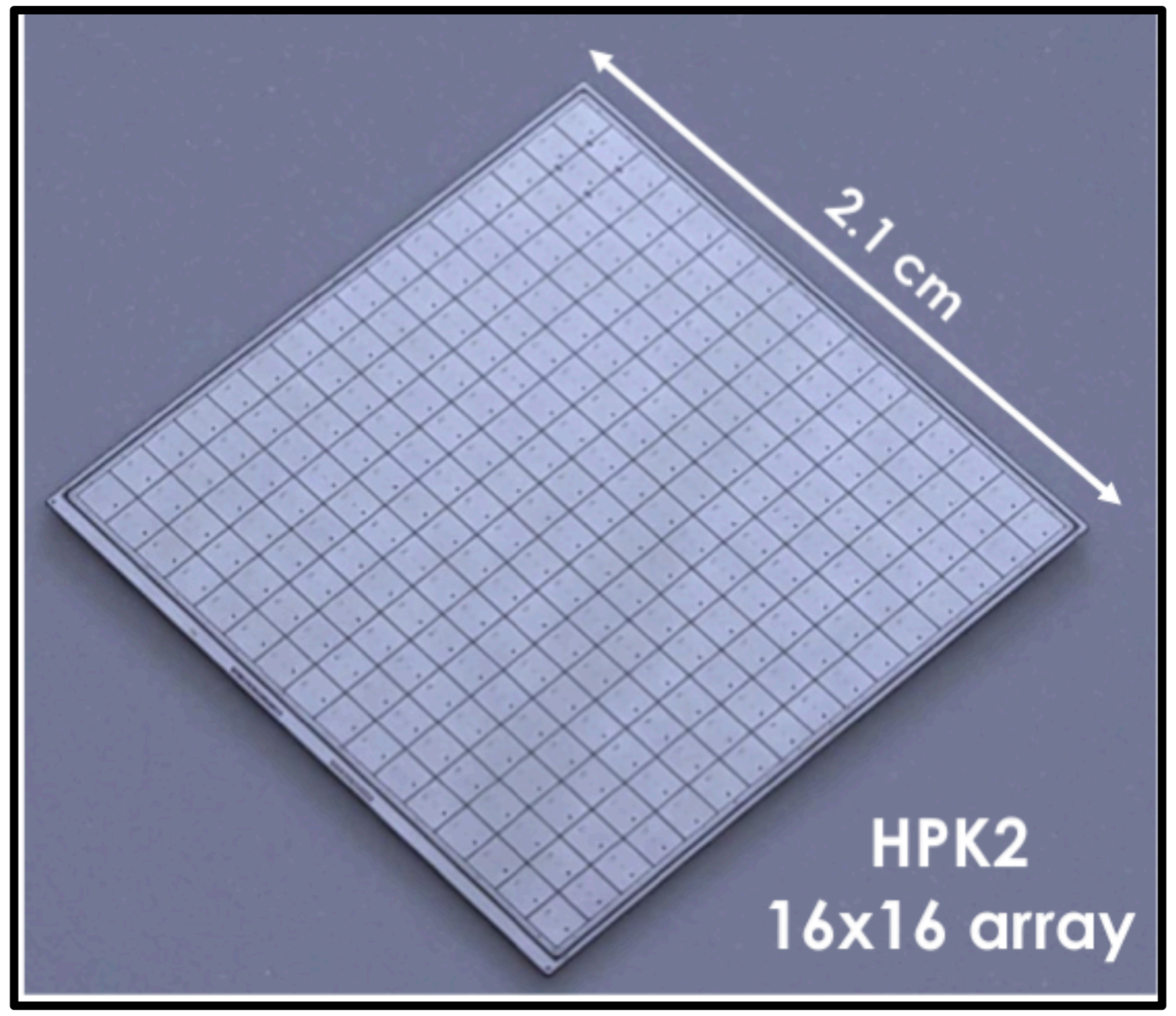


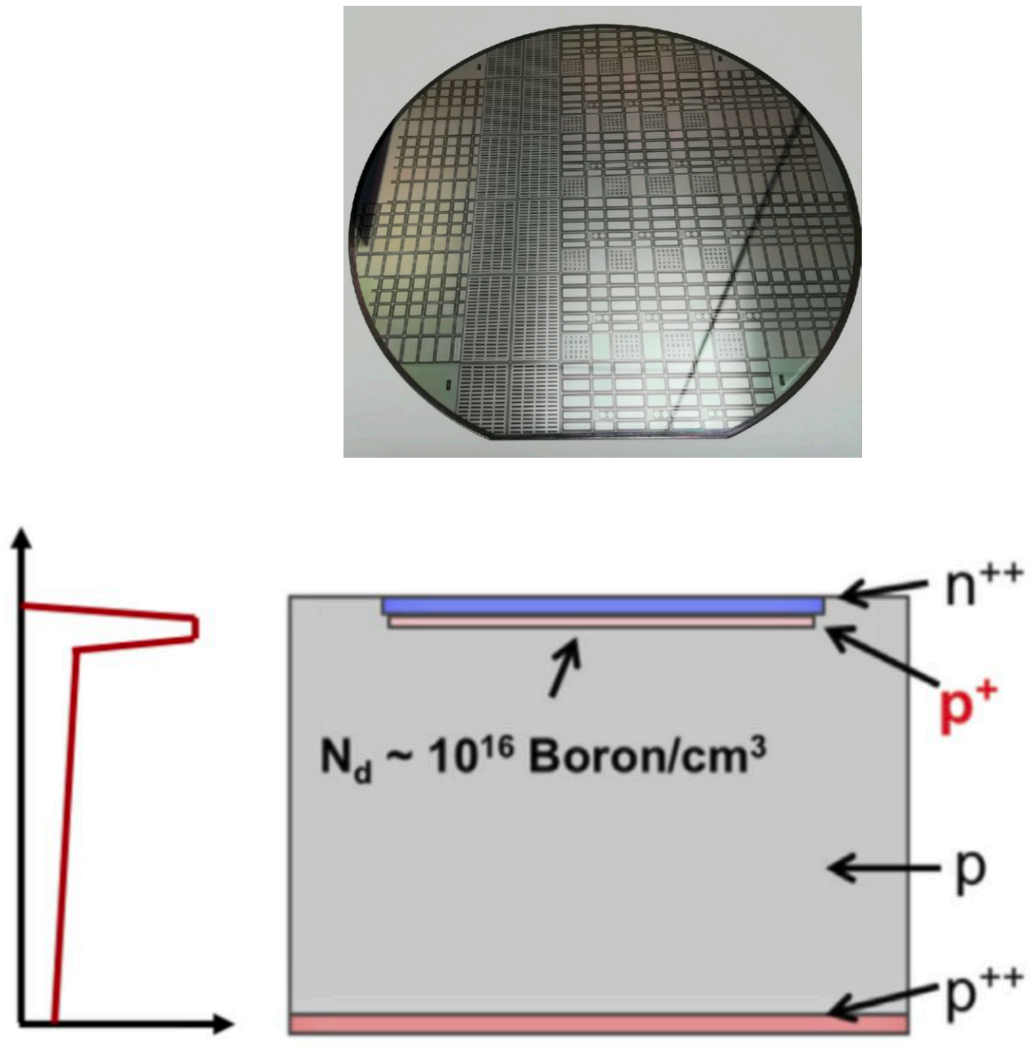




Sensor

- 16x16 pad matrix LGAD
  - 1.3x1.3 mm^2 pad size
- Uniform gain (x20-30) and low leakage current
- T_{res} = 30-40 ps for bare sensor
  - >8 fC of charge until EoO

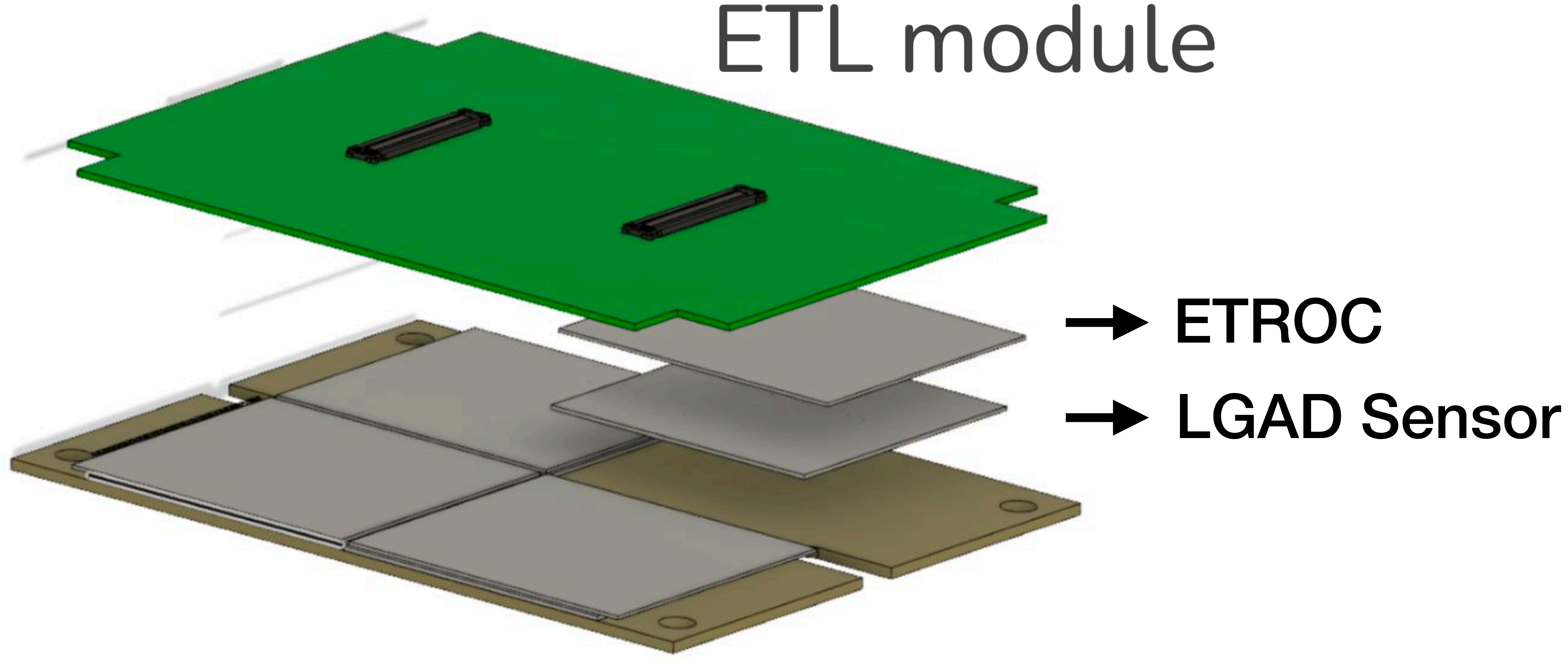




Low Gain Avalanche Diode

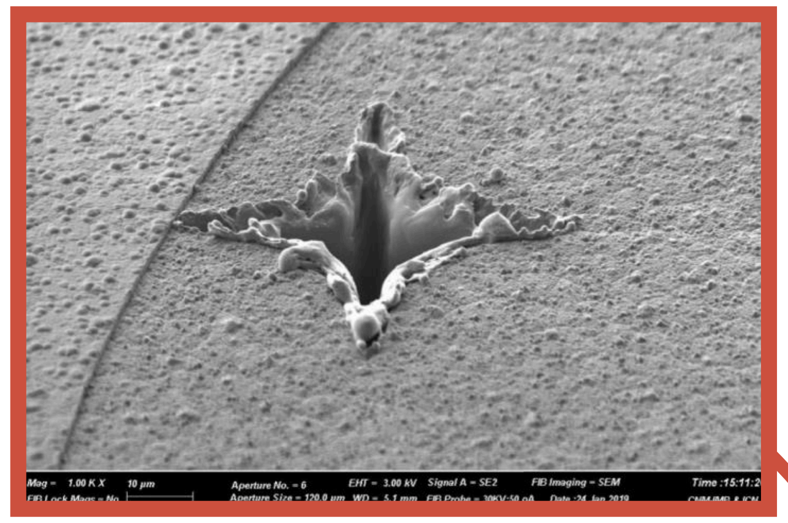
Module

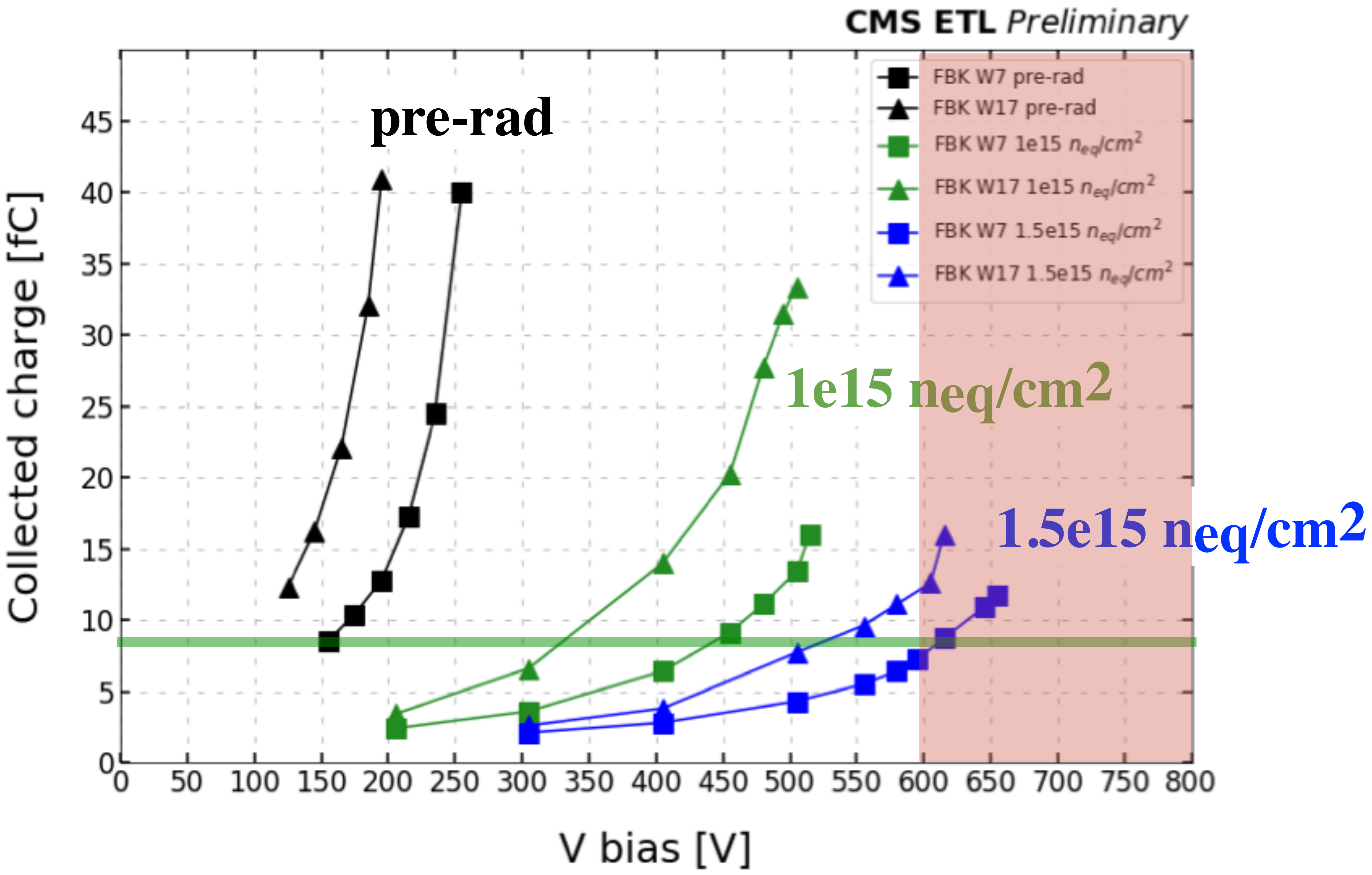
- ~8000 modules on 2 endcaps
- Sensor bump bonded to the readout ASIC (ETROC)
- Coverage: $1.6 < |\eta| < 3.0$, 0.31 m $< R < 1.2$ m

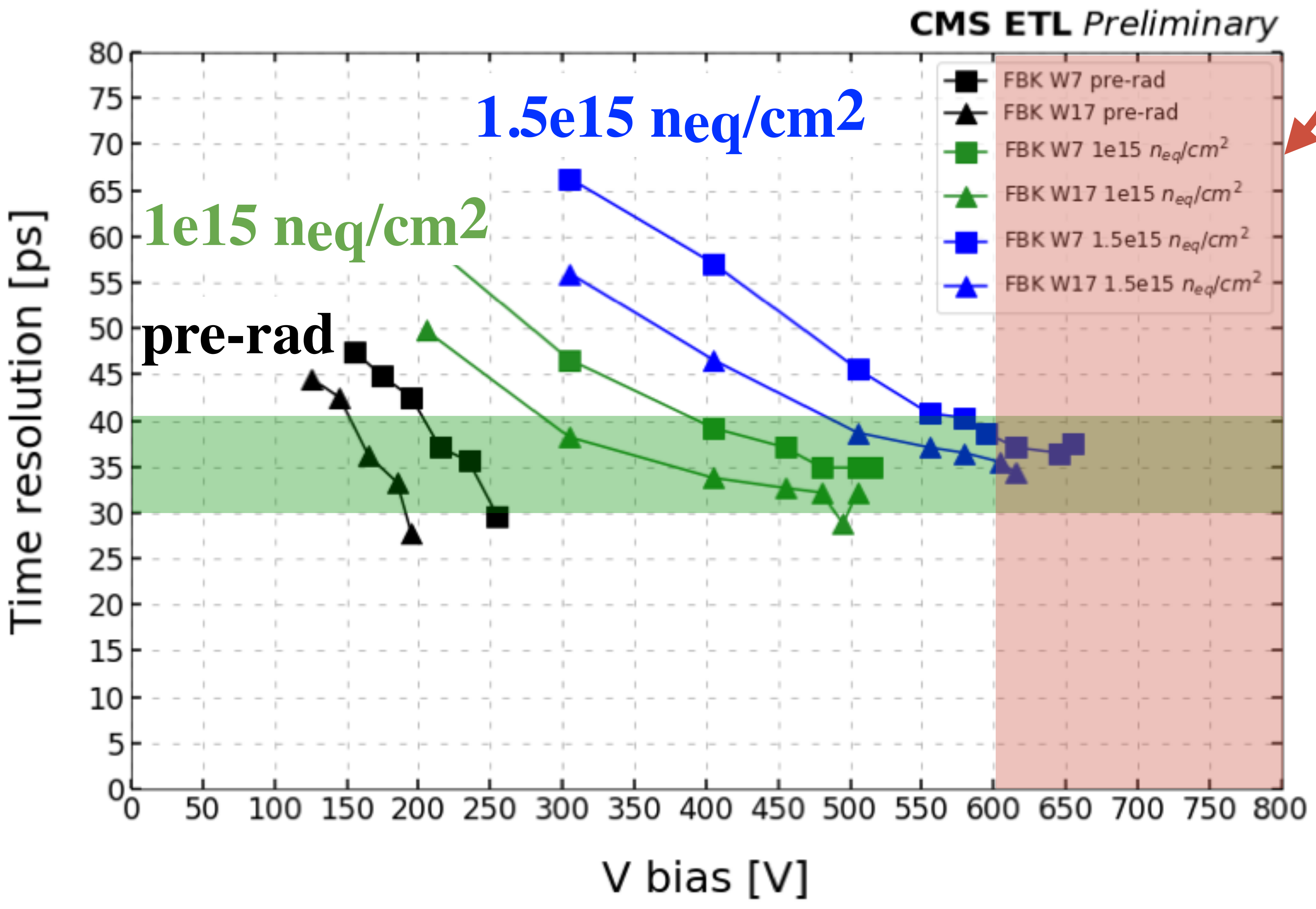


Radiation hardness confirmed in the lab

- 55um irradiated sensors characterized with a beta-source (Sr90) setup
  - Collected charge and time resolution of the bare sensors is **within requirements**
  - **Fully recover performance by increasing the bias voltage**
- Single Event Burn-out observed for $E_{bulk} > 11$ V/μm
  - **No need to work in such extreme regimes**





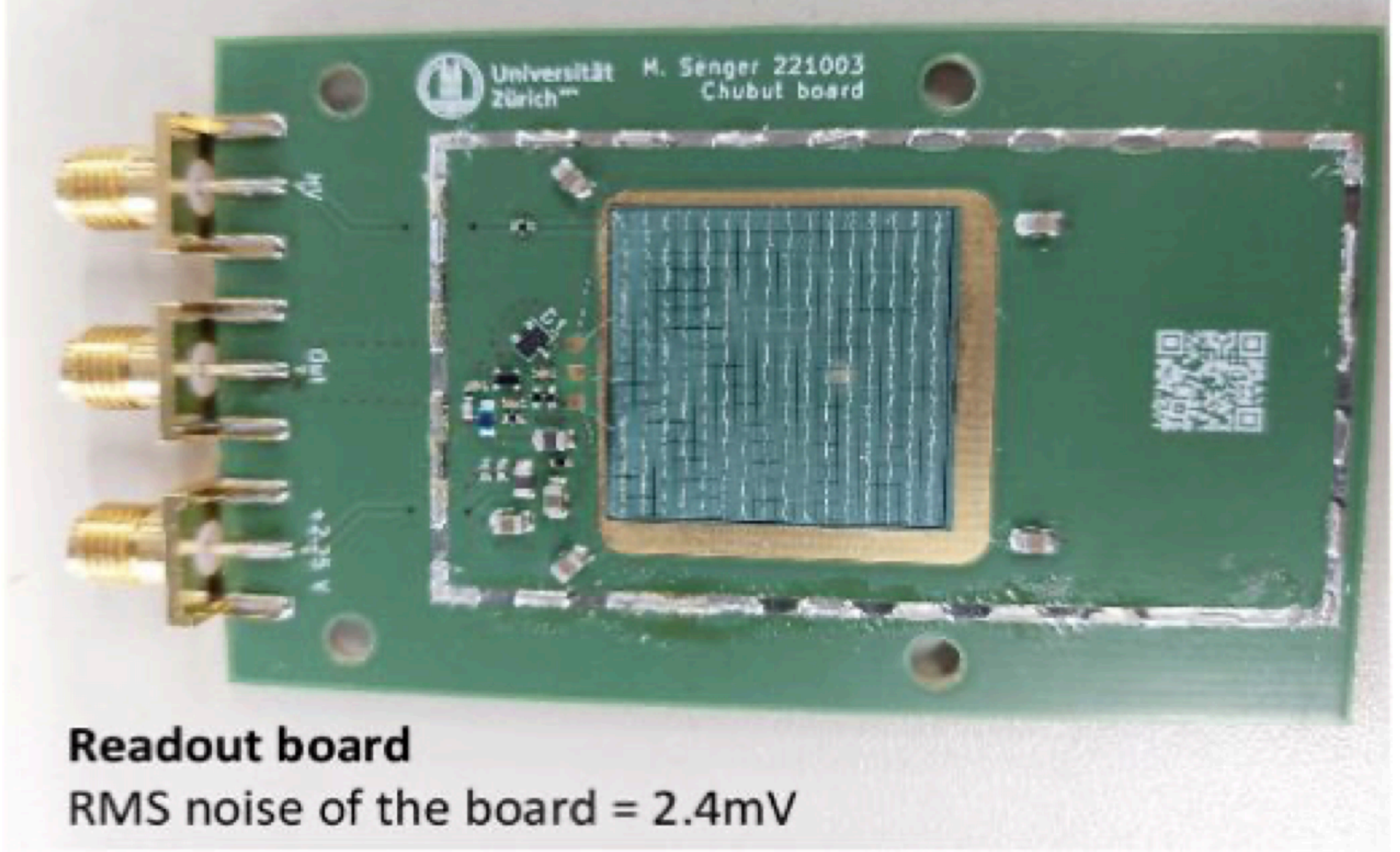


Characterization on beam

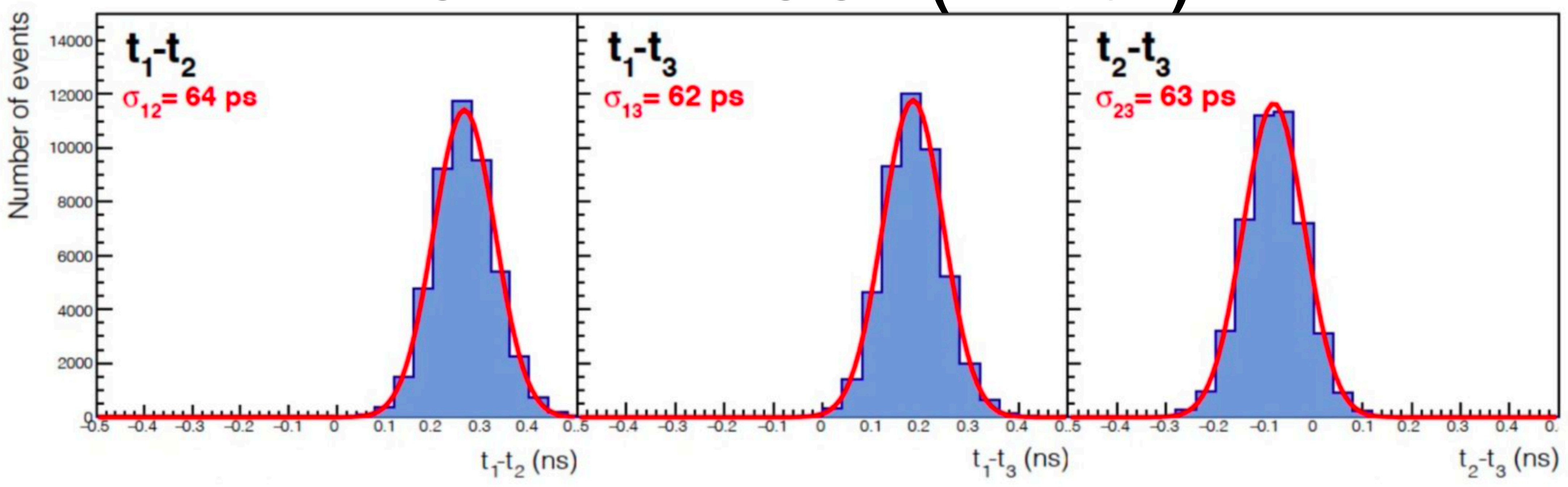
More in Lazar's talk!

- Full size 16x16 array tested on beam
  - Bare sensors: σ_t~30 ps and 100% efficiency
- Realistic readout with LGAD+ETROC1
  - First full system DAQ
  - **σ_t~45 ps**
- ETROC2 (16x16) currently under test
  - Aim to submit the final chip (ETROC3) in 2024

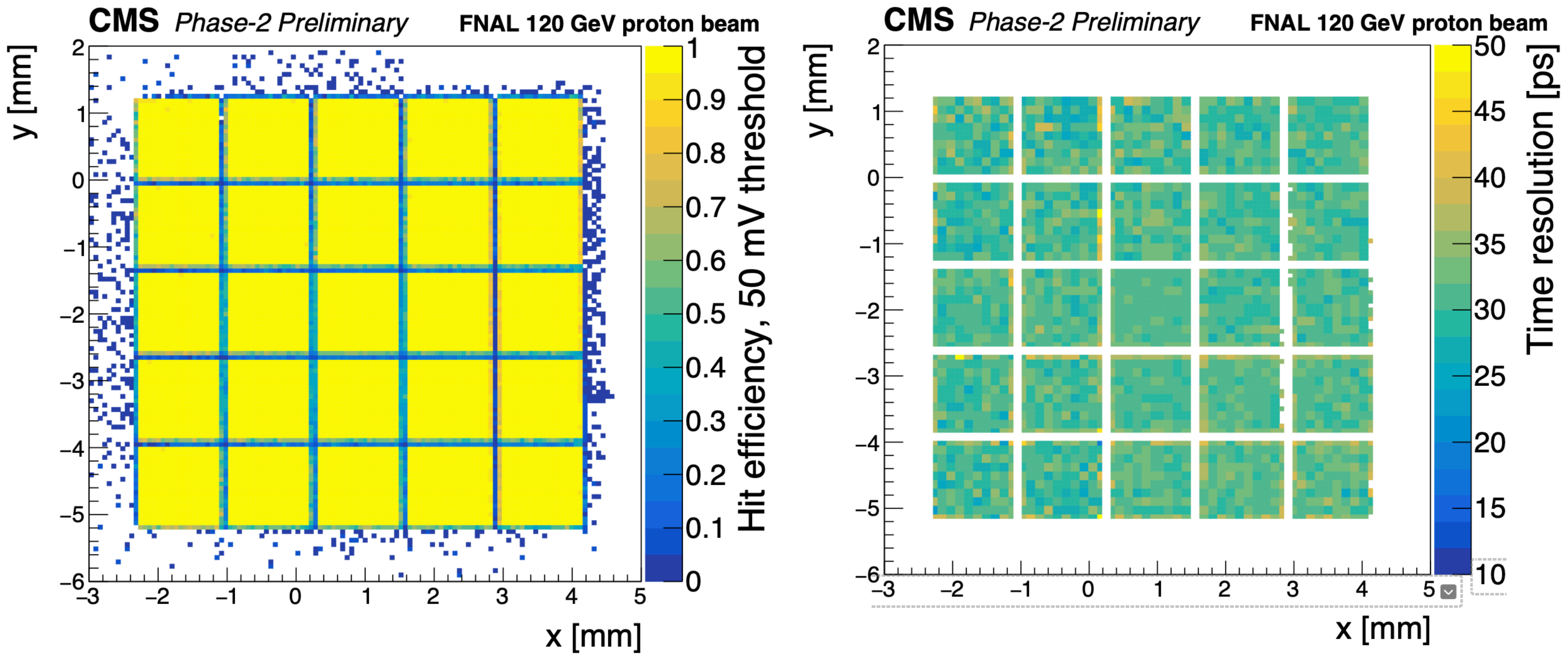
UZH-UCSC board used to stress test the final sensor (16x16 pads) in test beams and in the laboratory



LGAD+ETROC1 (4x4 ch)



BARE SENSORS



Phase-2 Tracker

- **Outer Tracker design driven by ability to provide tracks at 40 MHz to L1 trigger**
  - $\simeq$ 200 m^2 – 200x10^6 channels
  - Track stub / double sided p_T module @ bunch crossing rate of 40 MHz
  - Track finding for L1 implemented in FPGAs
  - Tilted geometry
- **Inner tracker with extended coverage in pseudo-rapidity**
  - $\simeq$ 4.9 m^2 - 2x10^9 channels
  - Innermost layer at 2.8 cm (2.9 cm in Phase-1) from beam pipe but same occupancy as in Phase-1 (~2x10^{-3})
  - One replacement foreseen for innermost layer in the barrel and first ring in the disks of the forward system at a fluence of 1-1.5 x10^{16} n_{eq}/cm^2