Precision timing with the CMS MIP timing detector for High-Luminosity LHC

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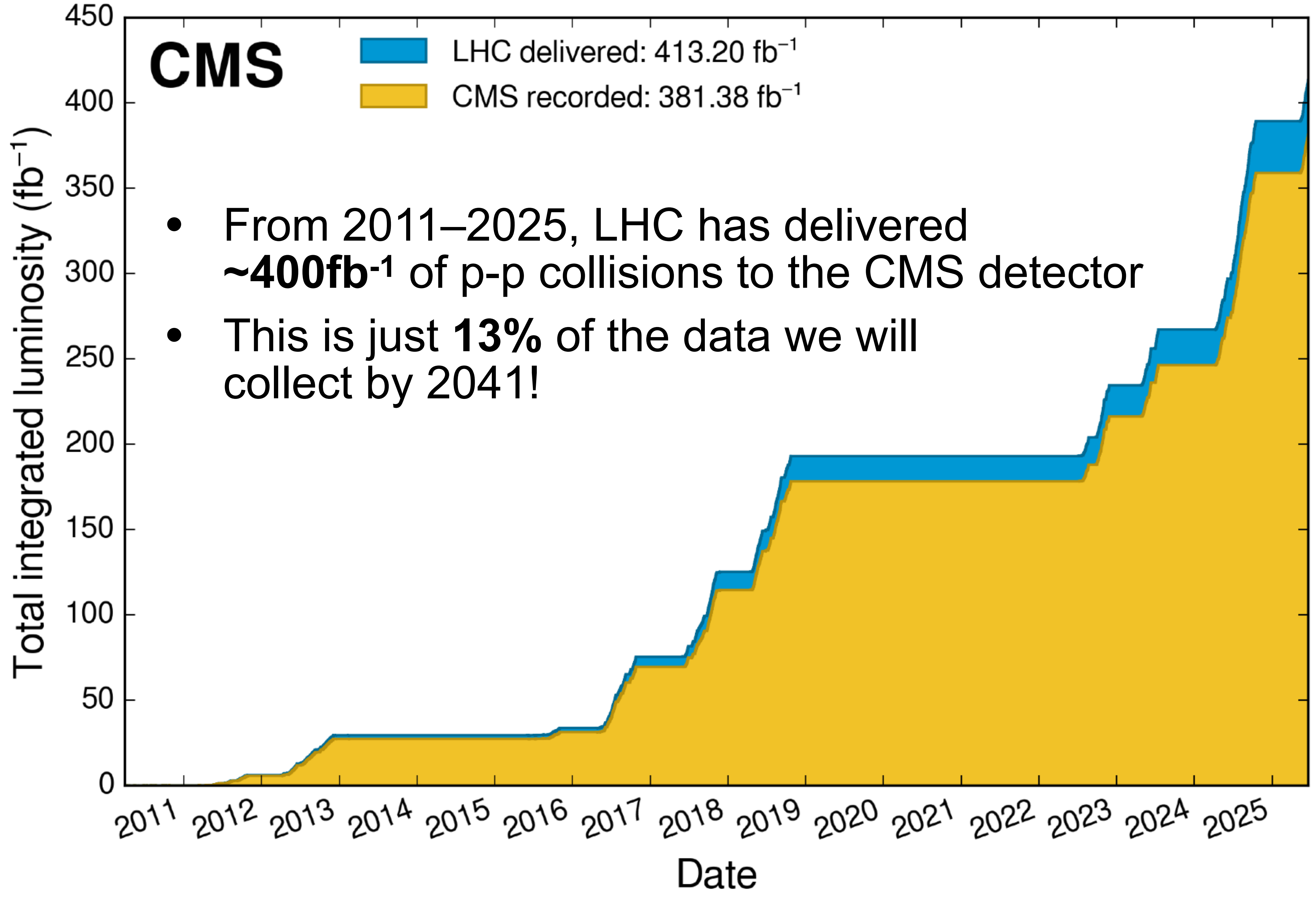
On behalf of the CMS Collaboration

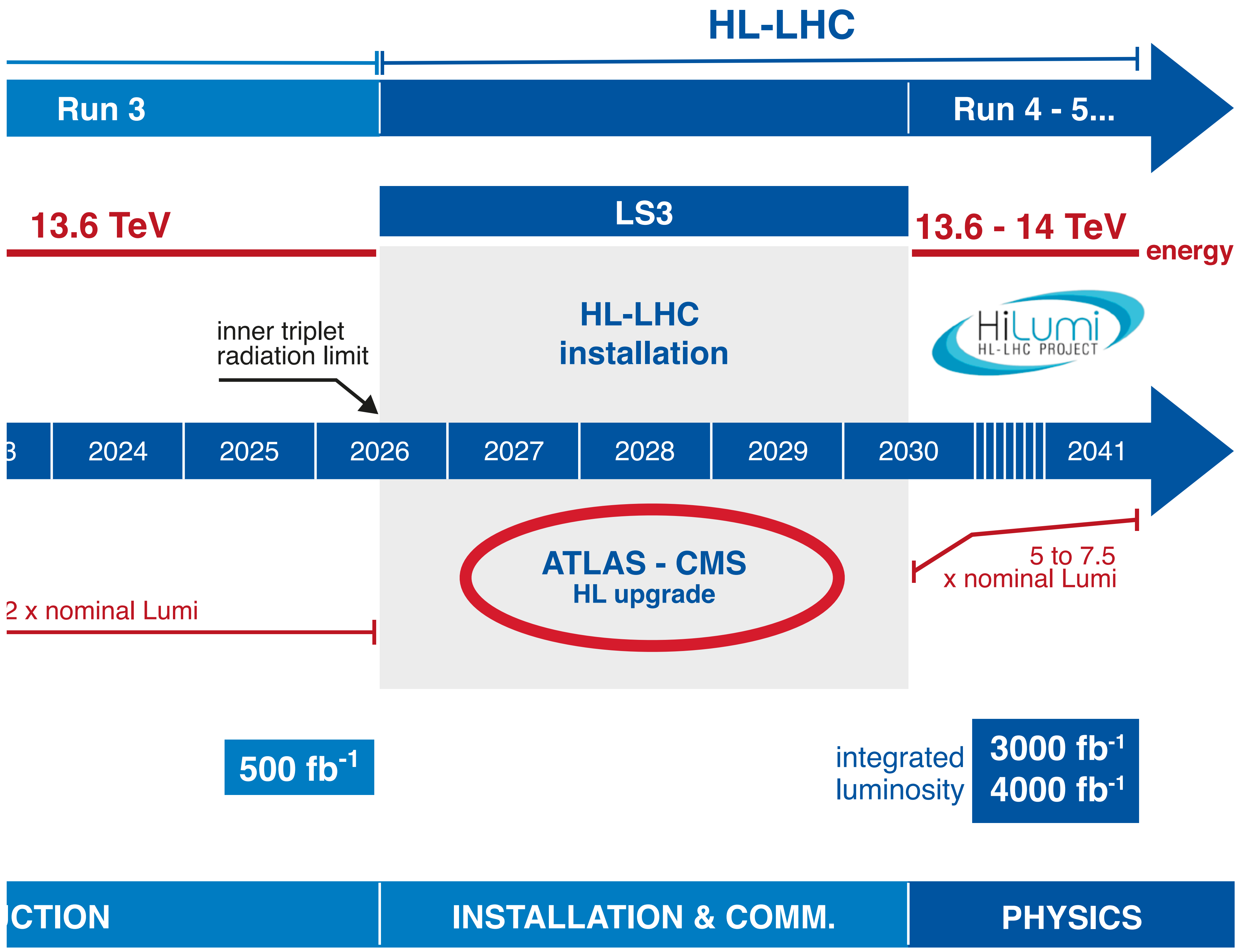
HEP2025 MARSEILLE

The road to high luminosity

*The **HL-LHC** will deliver **3000 fb^{-1}** by **2041** in order to maximize the **physics discovery potential** of the LHC*



- From 2011–2025, LHC has delivered **~400fb^{-1}** of p-p collisions to the CMS detector
- This is just **13%** of the data we will collect by 2041!



- Target important **physics benchmarks** in both SM and BSM

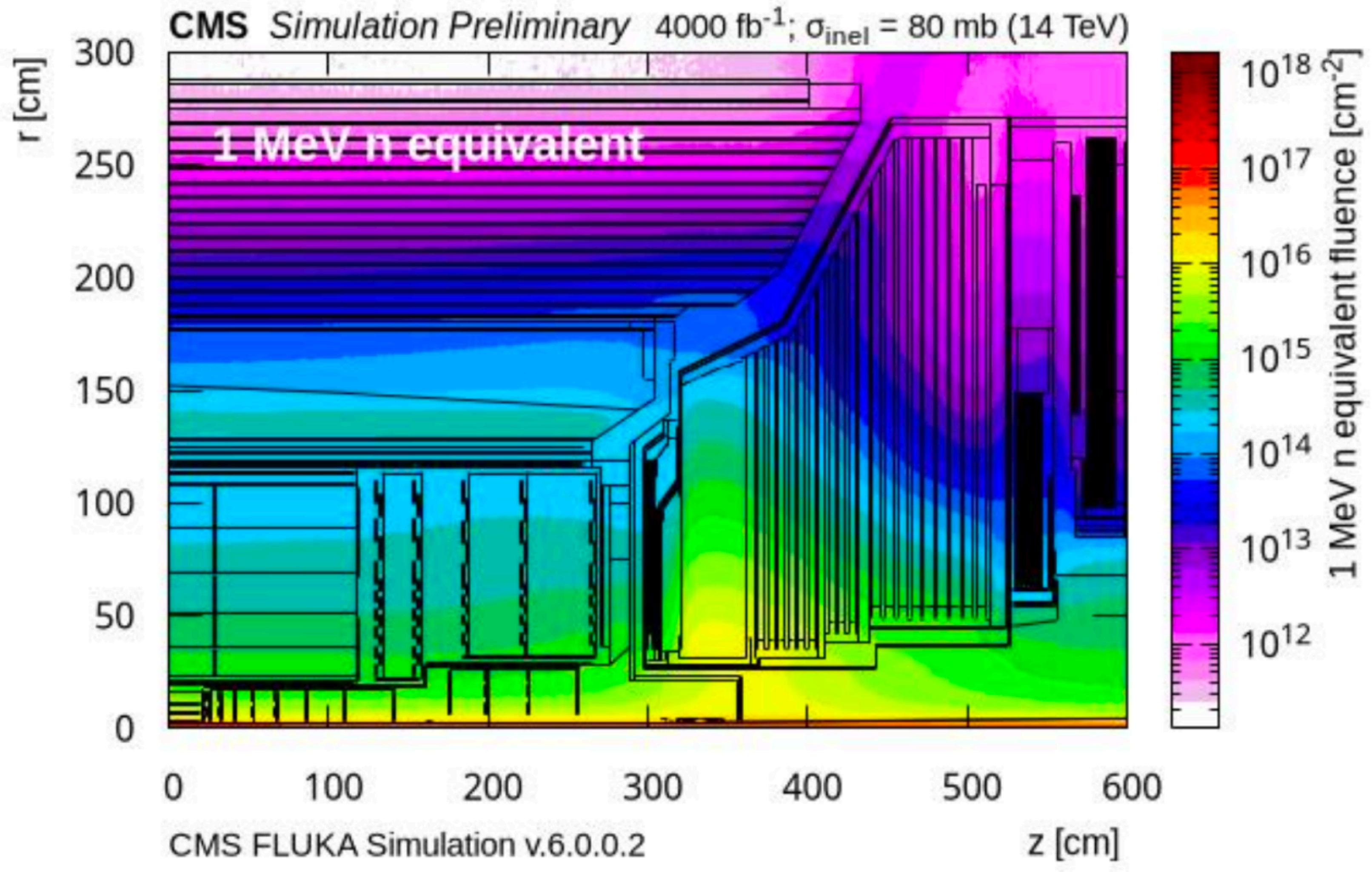
- **Complete overhaul** of many **LHC elements**
- 5× boost in **interaction rate** ($L_{inst} \geq$ 5e34 cm^{-2}s^{-1}) in baseline scenario

LHC will deliver… but can we collect?

*Achieving **target L_{int}** means coping with much more intense **pileup** and **radiation** environment in HL-LHC*

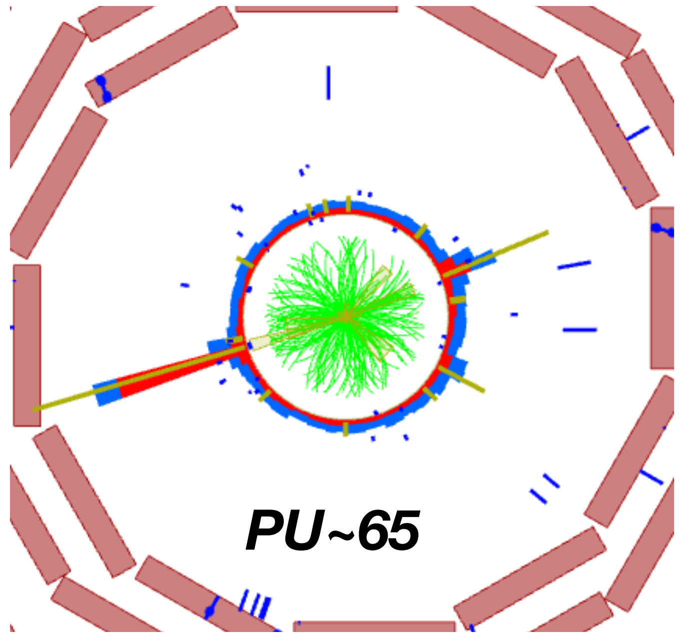
Radiation

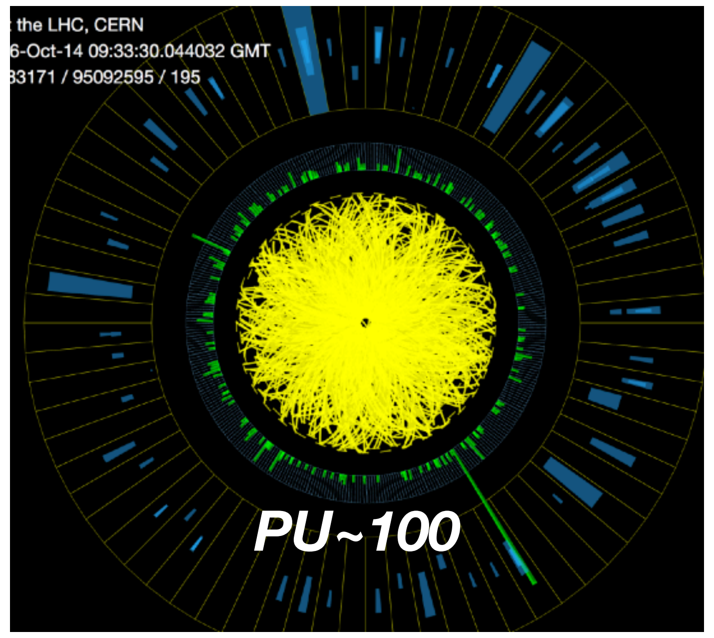
- Equivalent dosage endured by CMS subdetectors during Phase II will **substantially exceed** Phase I
- Upgraded detector must be built to operate for more than a decade

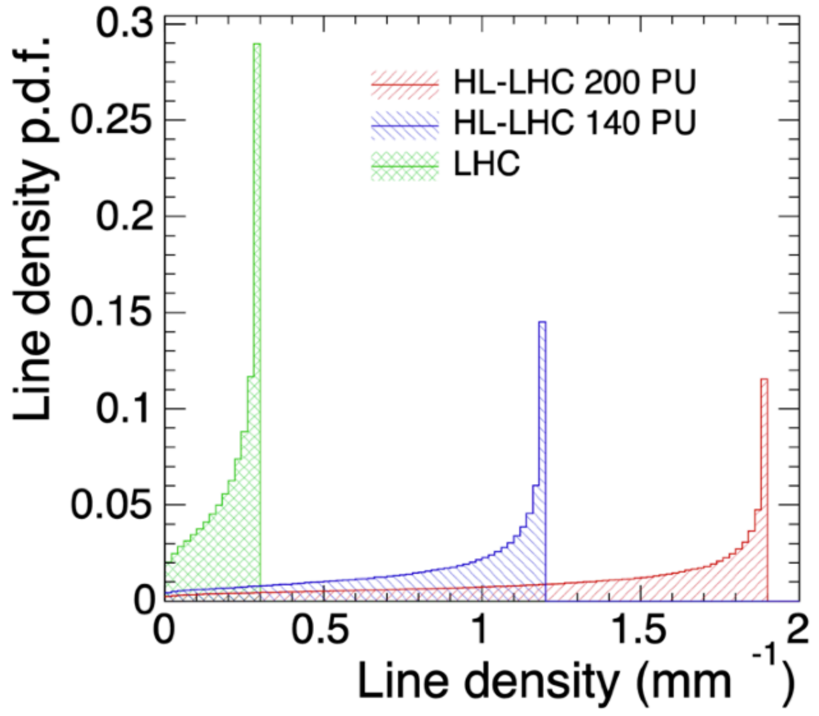


Pileup

- Average pileup will increase by an **order of magnitude**
- **30–60** in Phase I → **140** (200) in nominal (ultimate) HL-LHC scenario
- Manage pileup by associating **charged tracks** to **reco vertices**…
  - Becomes a showstopper as **line density** ≳ 1/mm
  - Particle ID, reco efficiency, physics object quality expected to **degrade**



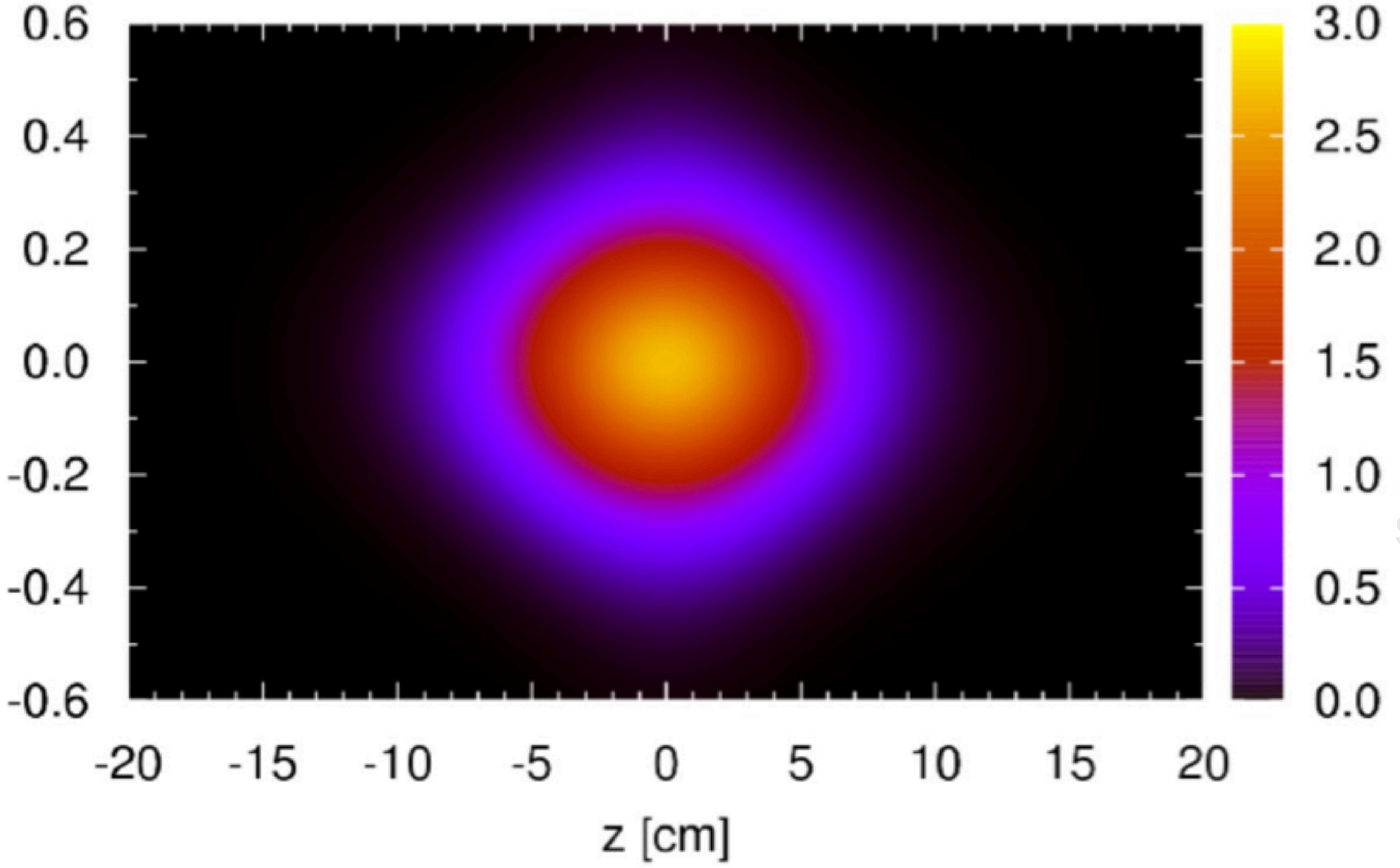


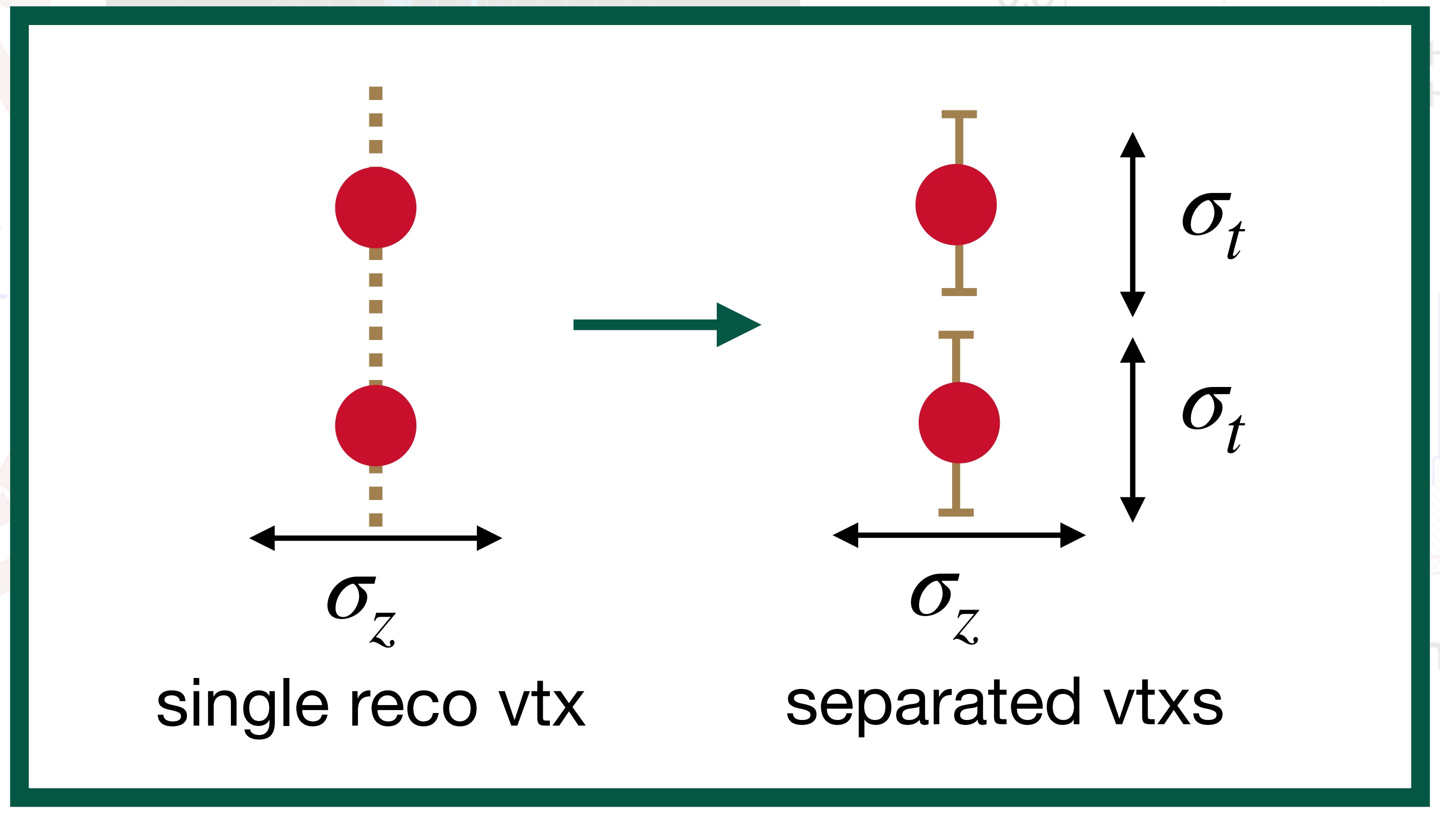


LHC will deliver… but can we collect?

Can use the RMS ~200 ps of the beamspot to **disentangle spatially-overlapping** vertices…

…and with a track-time precision of 30–40 ps, we could recover an effective pileup ***similar to Phase I.***



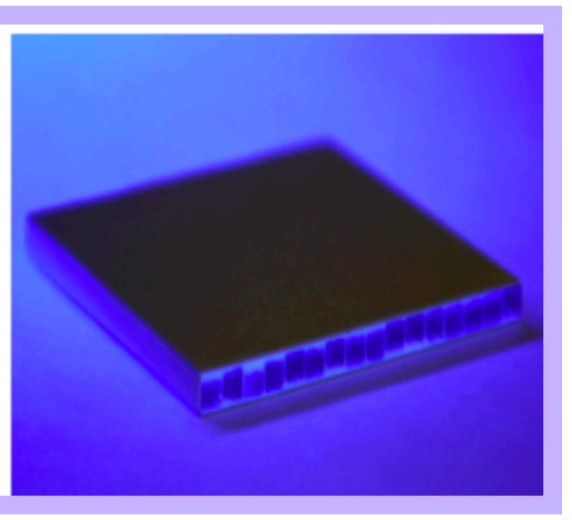


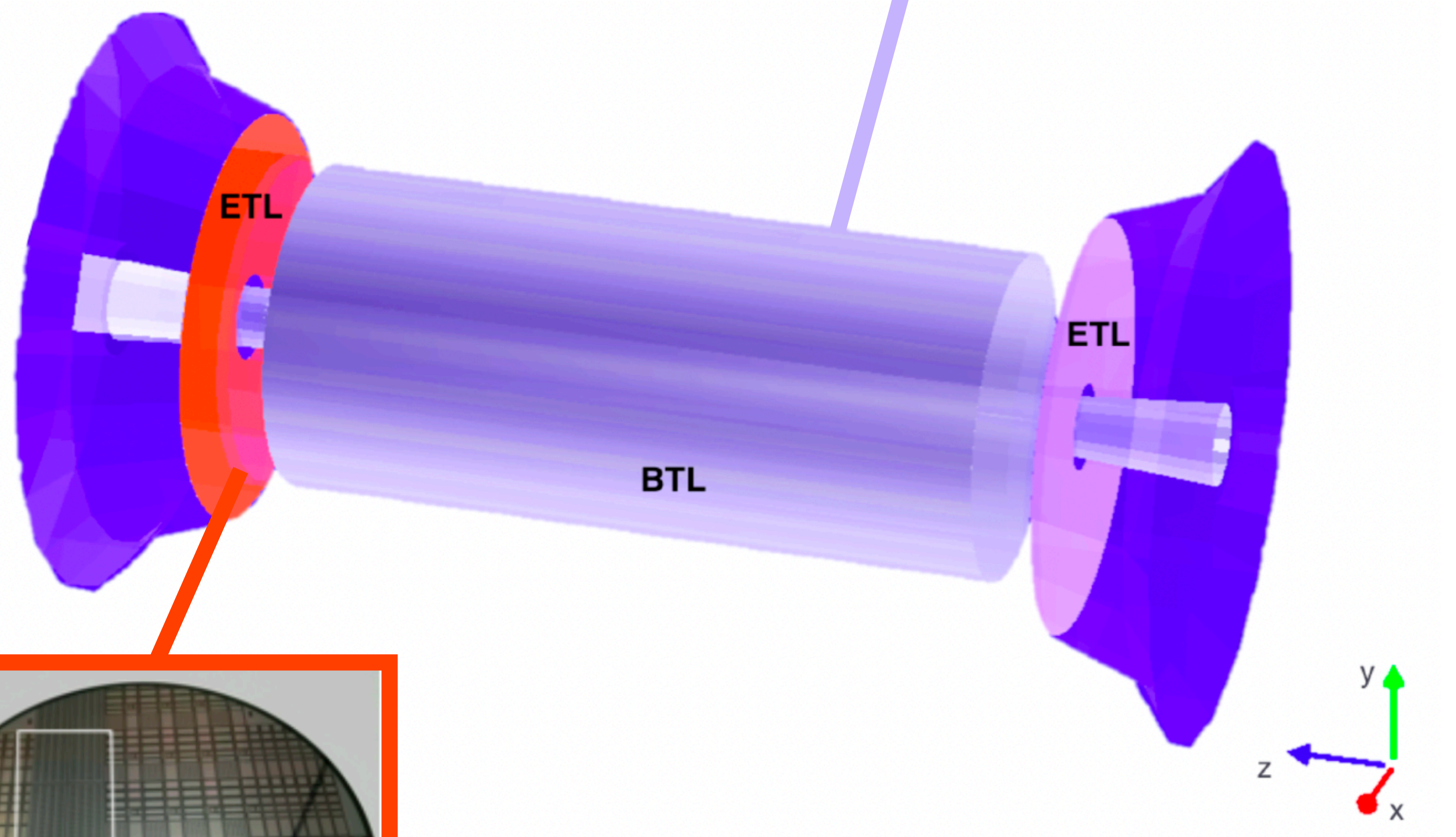
The CMS **MIP timing detector**

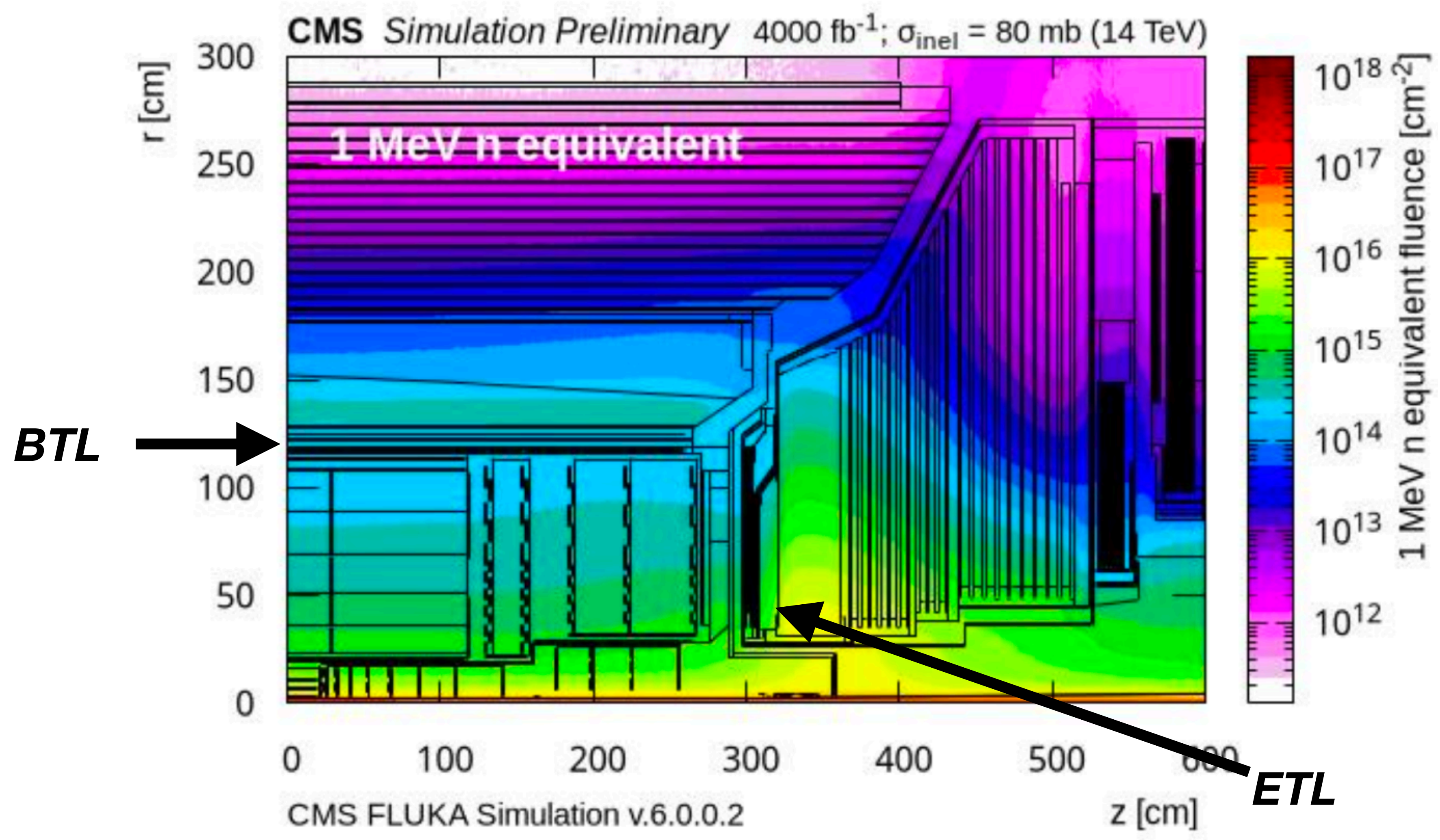
MTD** will deliver precise **time-of-flight measurements** in **HL-LHC

- **Ultra-thin** detector providing **hermetic coverage** (|η|<3) for charged particles
  - Consists of barrel (|η| < 1.6) and 2×endcap timing layers (BTL & ETL)
  - Installed between tracker and calorimeters
- **Constraints** drive **design**
  - **Radiation hardness** requirements in different regions of CMS
  - **Cost** and **power** effectiveness + **readout** considerations
  - Technology readiness is central consideration: BTL and ETL will **bookend** the upgrade installation

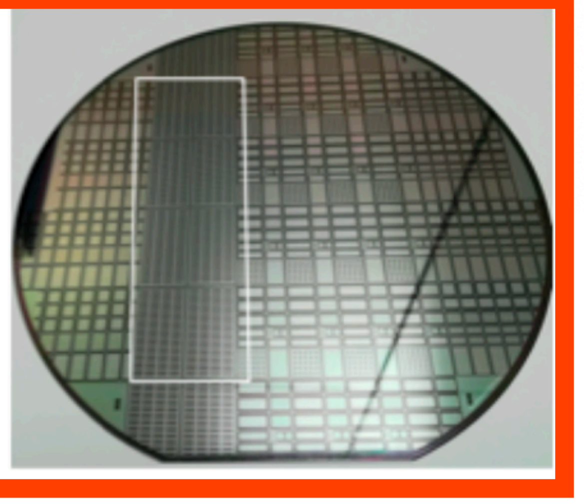
BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2







ETL: Si with internal gain (LGAD):
- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2x10^{15}$ n_{eq}/cm^2



What does this offer us?

< 40-ps timing resolution *would benefit* **nearly every aspect** *of the* **CMS physics program**

Pileup rejection & object reconstruction

New frontiers in BSM searches

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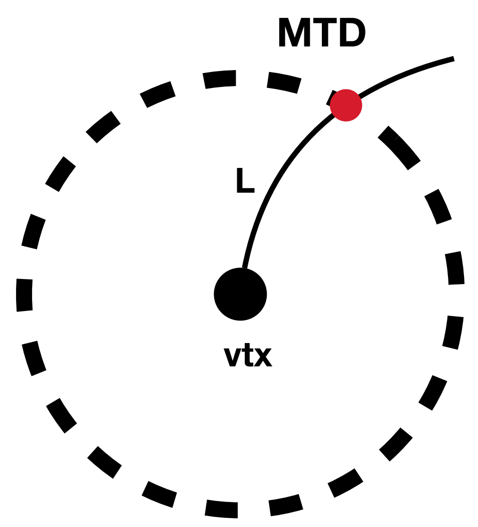
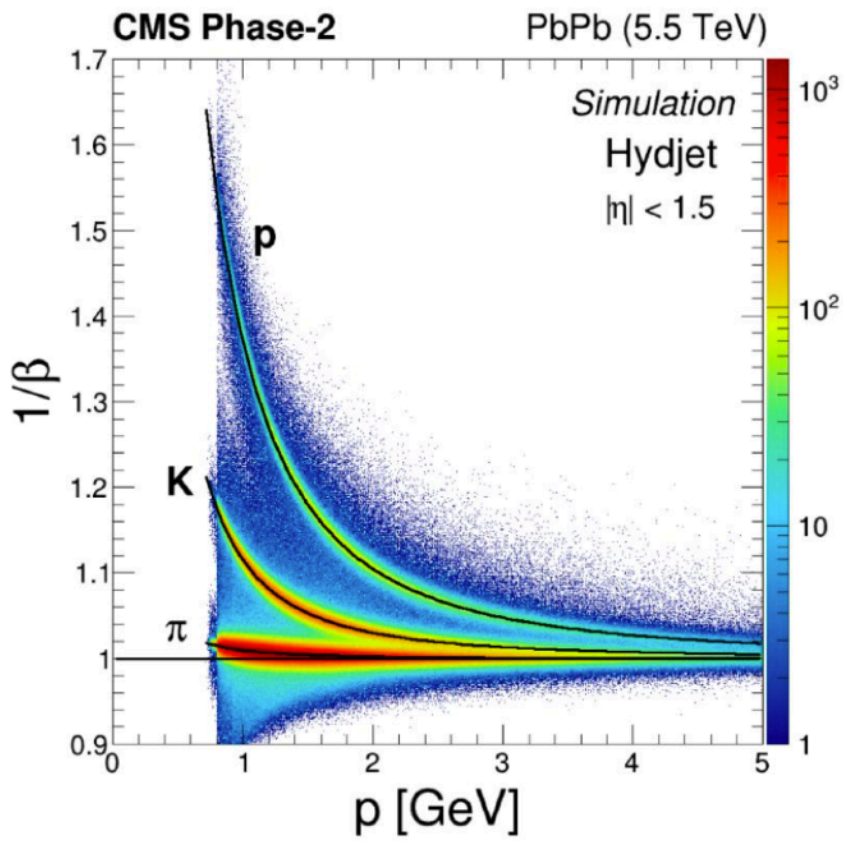
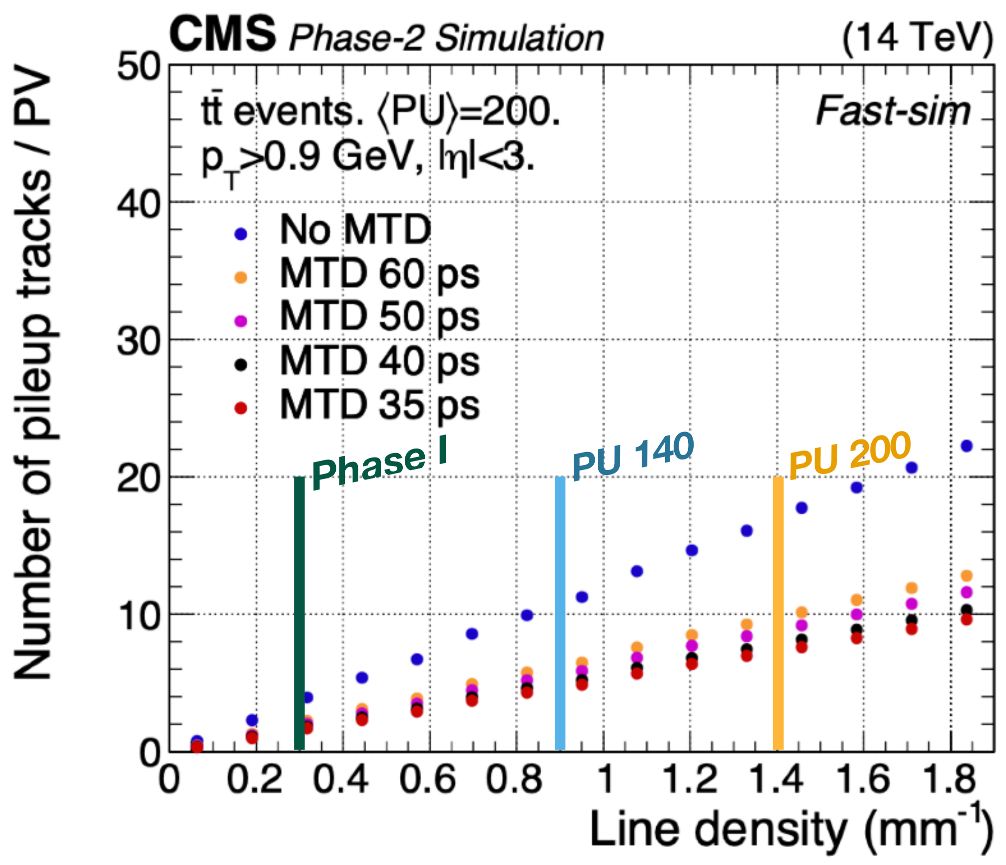
Pileup rejection & object reconstruction

- Introducing **timing** to the event record → PID from **β measurements** for HI/flavor physics
- Cut down **wrong track associations** by a factor of 2
- **Efficiency improvements** in MET selection, b-tagging, and lepton isolation



$$\frac{1}{\beta} = \frac{c(t_{MTD} - t_{vtx})}{L}$$





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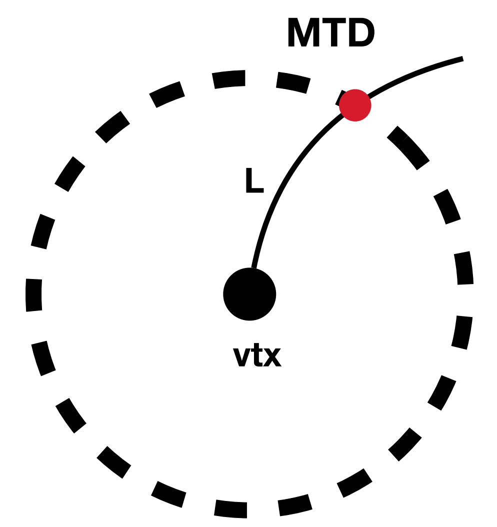

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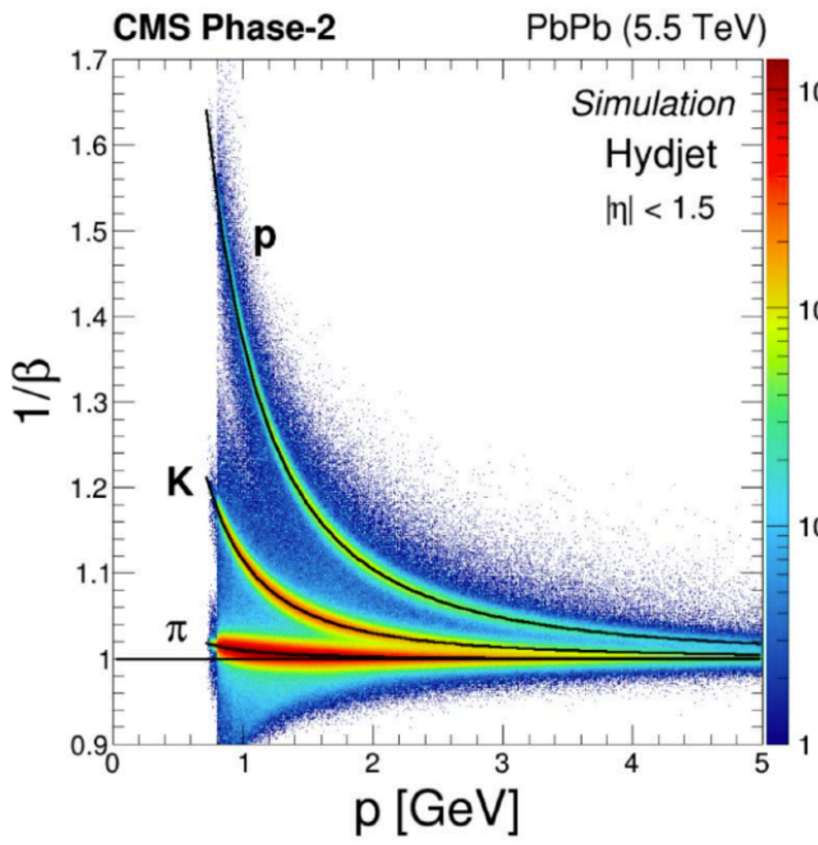
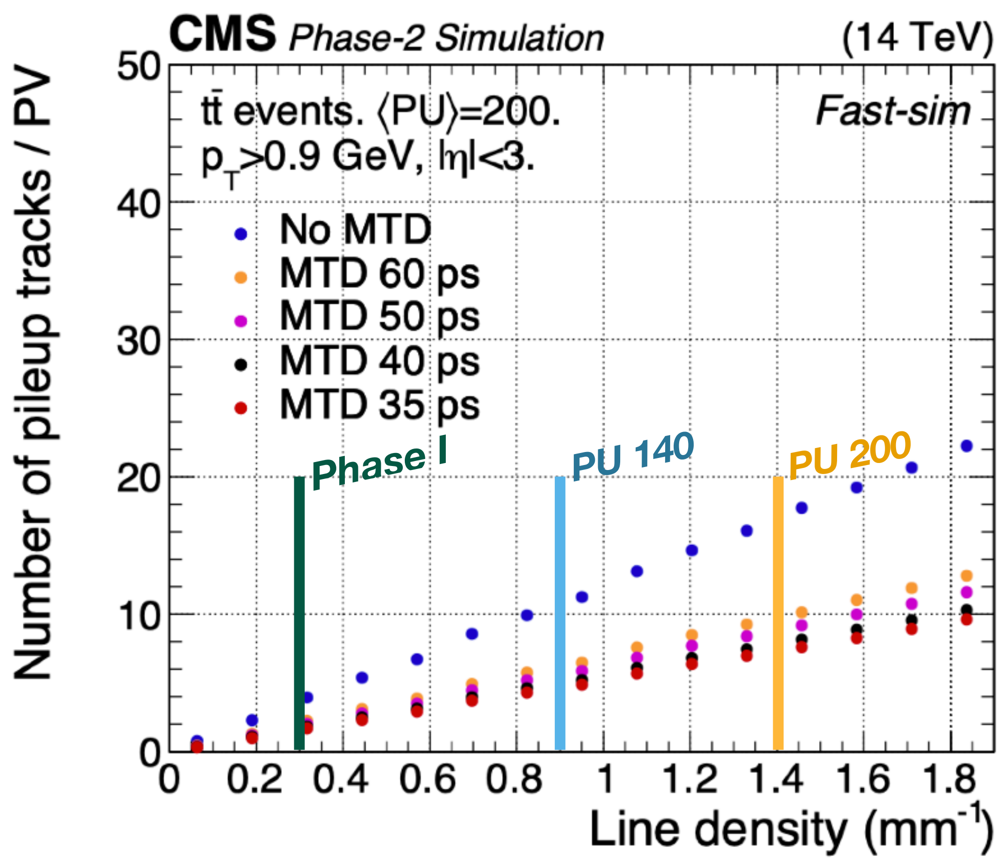
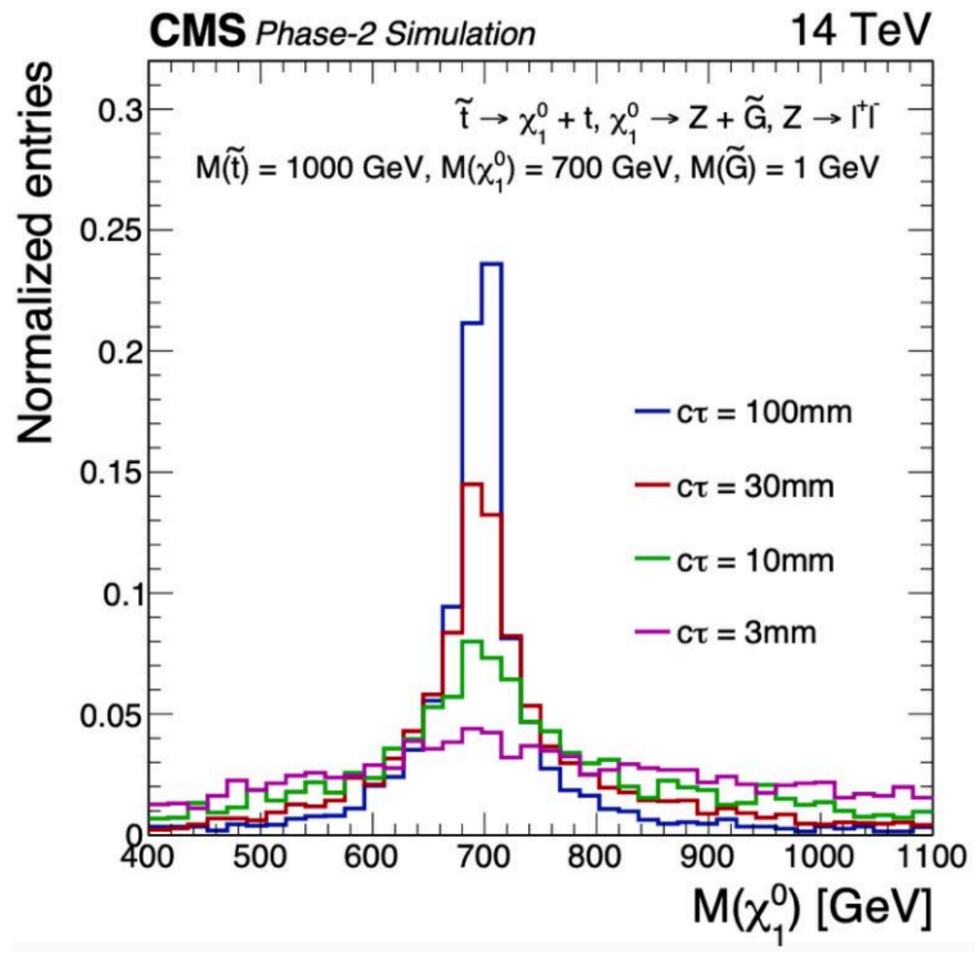
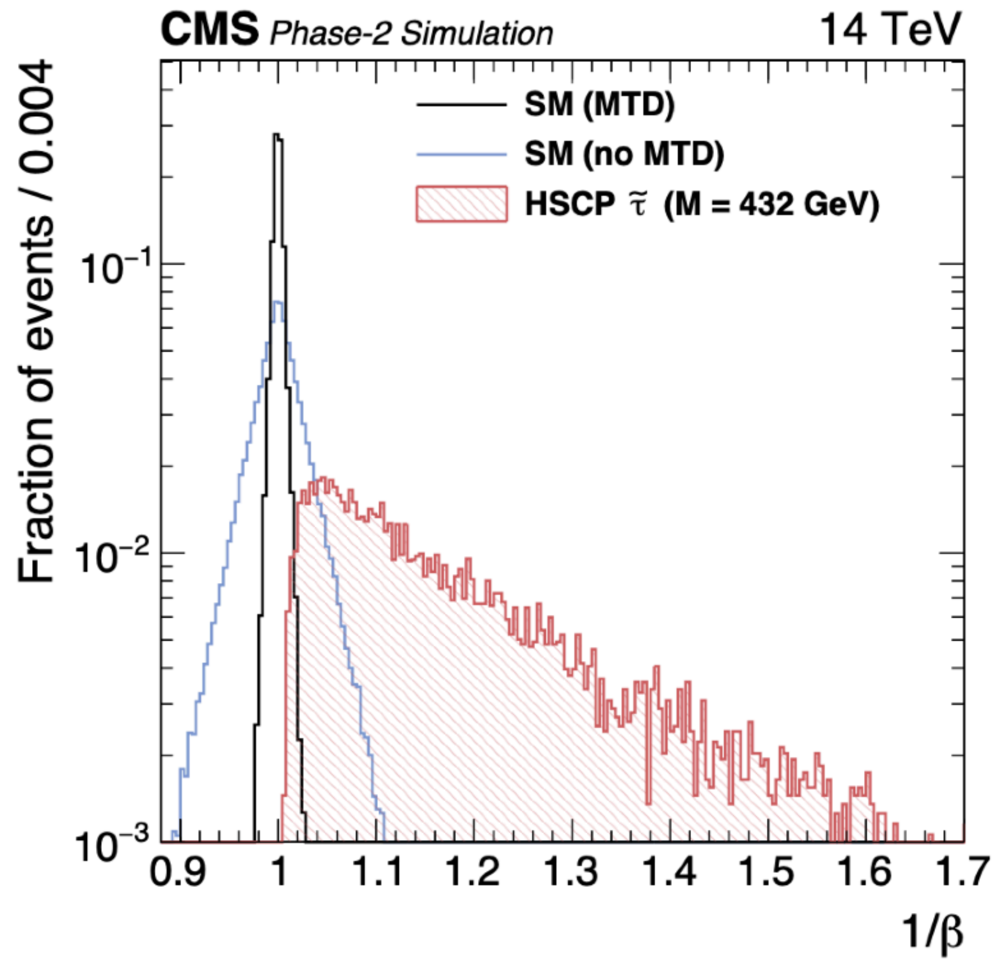




New frontiers in BSM searches

- Reconstruct LLP **masses** via **time-of-flight measurements** between primary and secondary vertices
- Distinguish HSCP signals from SM via **1/β measurements** → associated to **late MTD hits**
- Searches become **direct** in unprecedented ways!



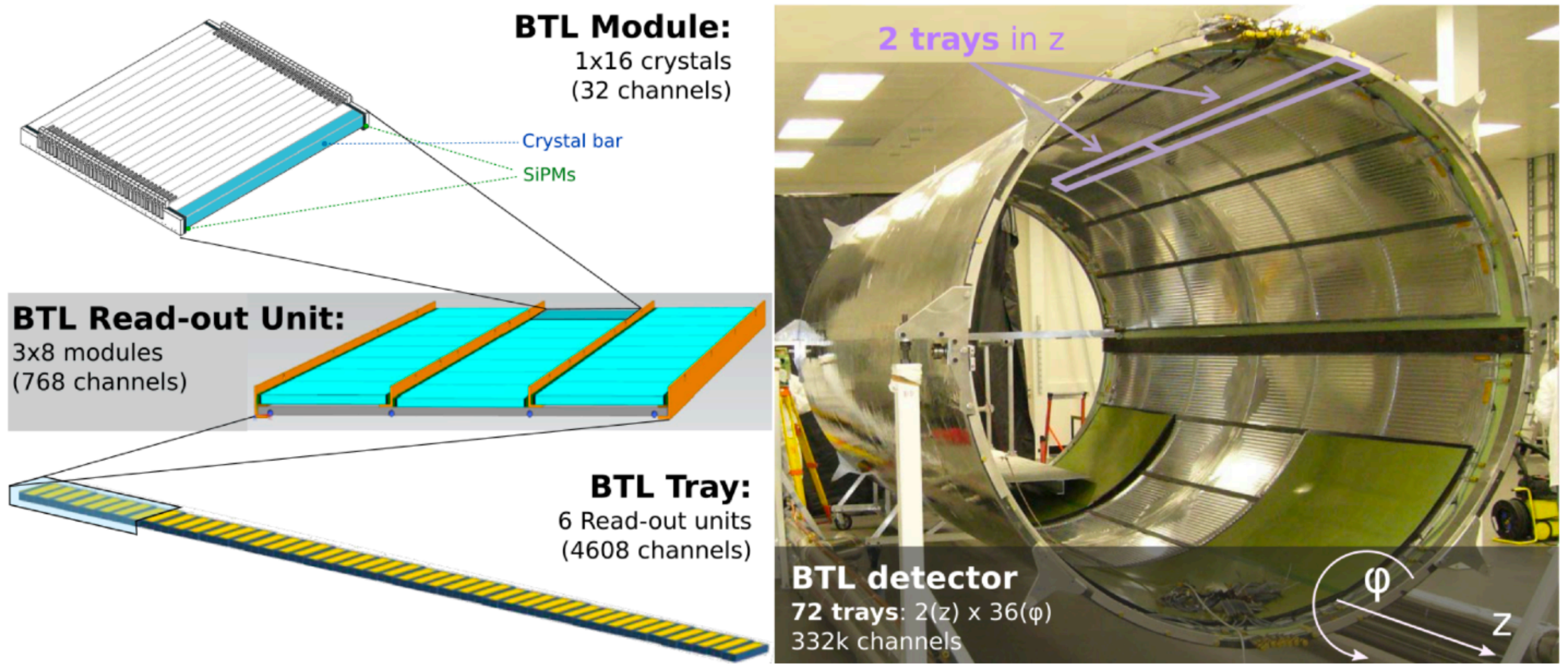


Sensor technology of BTL

BTL consists of **72 trays** containing **40mm** of **active material**, **electronics**, and **cooling infrastructure**

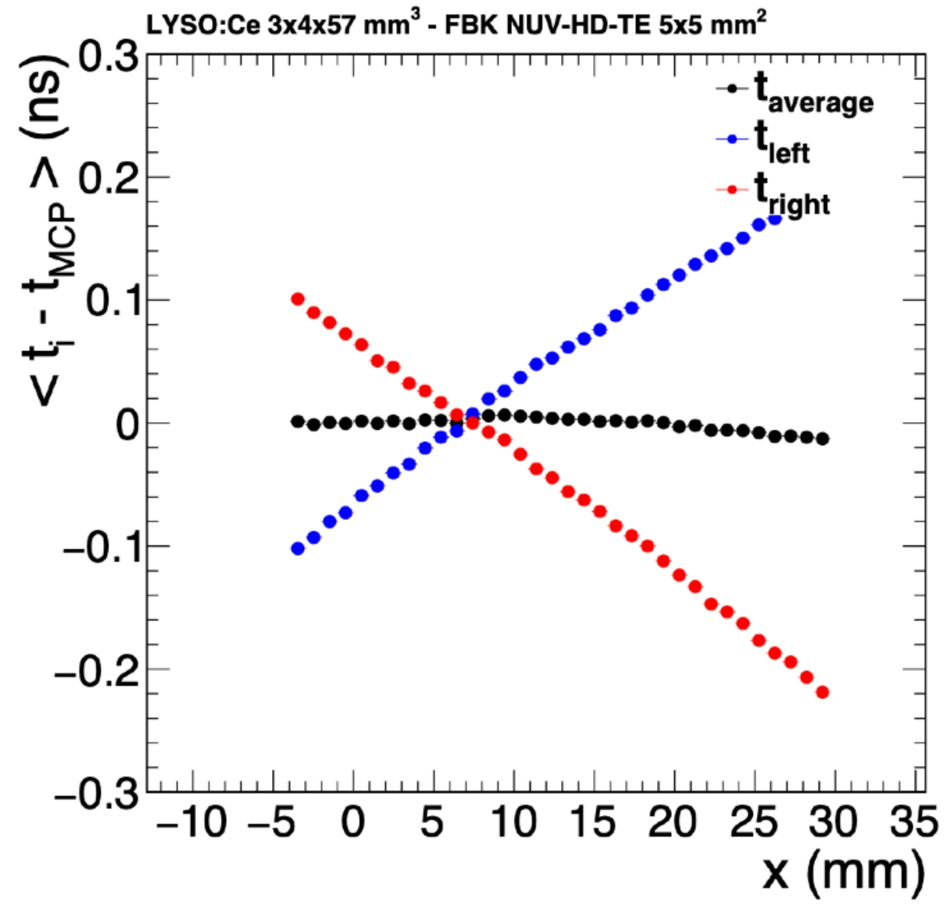
Sensor technology: LYSO+SiPM

- Cerium-doped **LYSO** is well suited for precision timing in the CMS upgrade
  - Exceptionally radiation hard (<10% LO loss by EOL)
  - Short rise (<100ps) and decay (~40ns) times
  - High light yield (~40kγ/MeV)
- **Silicon photomultipliers** (SiPMs) are compact, robust, and insensitive to magnetic fields
  - Dual readout removes propagation delay → time of arrival independent of impact point
- Readout performed by dedicated **TOFHIR ASIC**



Maintaining consistent thermal conditions

- SiPM behavior (→time resolution) highly **temperature dependent**
- **Evaporative cooling** to constant -35°C via dual-phase CO2 circulated through each tray
- **Thermoelectric coolers** (TECs) in contact with SiPMs maintain -45°C



BTL performance validation

$$\sigma_t^{BTL} = \sigma_t^{stat} \oplus \sigma_t^{elec} \oplus \sigma_t^{DCR} \oplus \sigma_t^{digi} \oplus \sigma_t^{clock}$$

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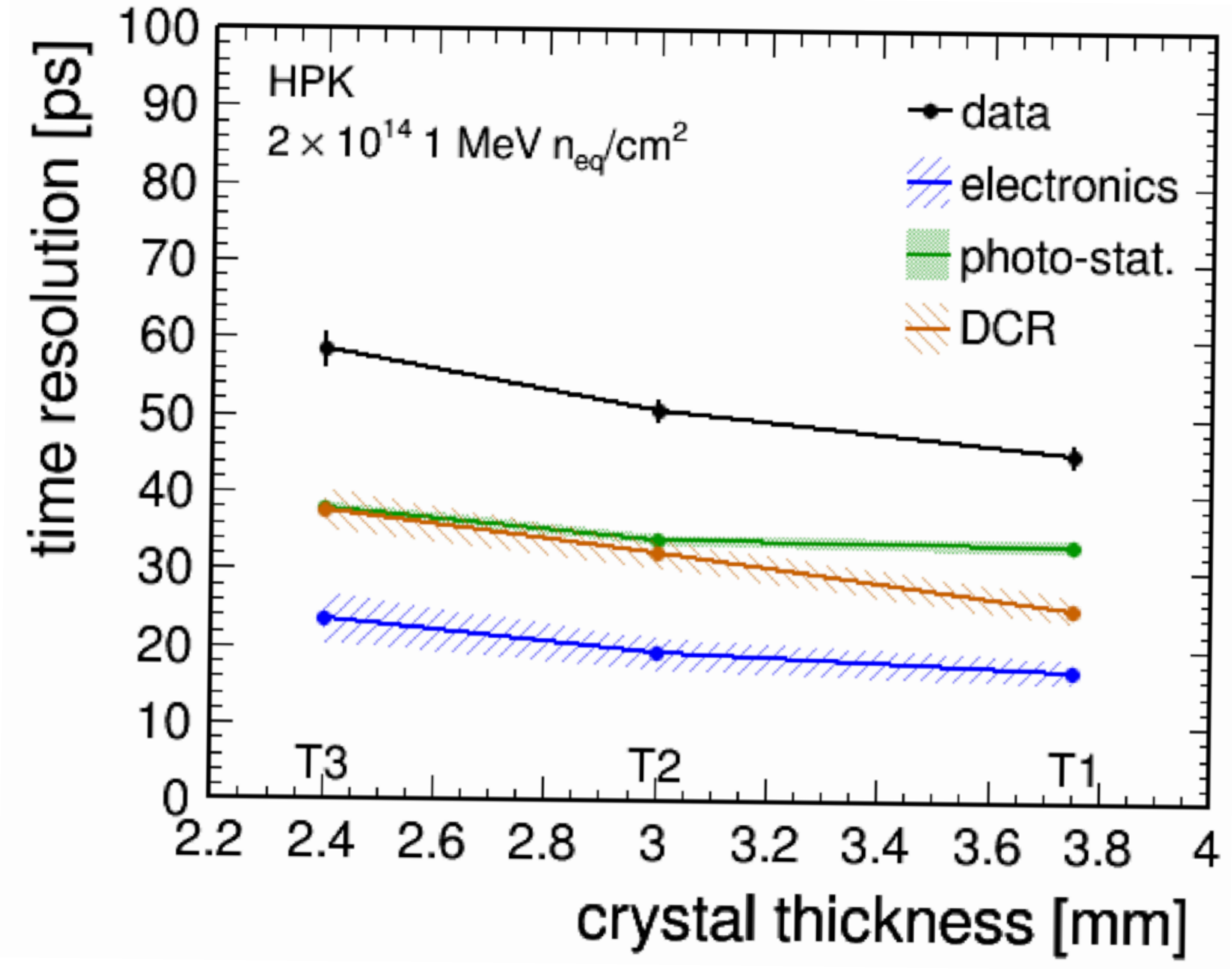
$$\propto 1/\sqrt{N_{pe}}$$

Maximize N_{pe}

- LYSO thickness and packaging optimized to maximize light output → ***3.1 × 3.75 mm²***



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$\propto \sigma_{noise}/N_{pe}$

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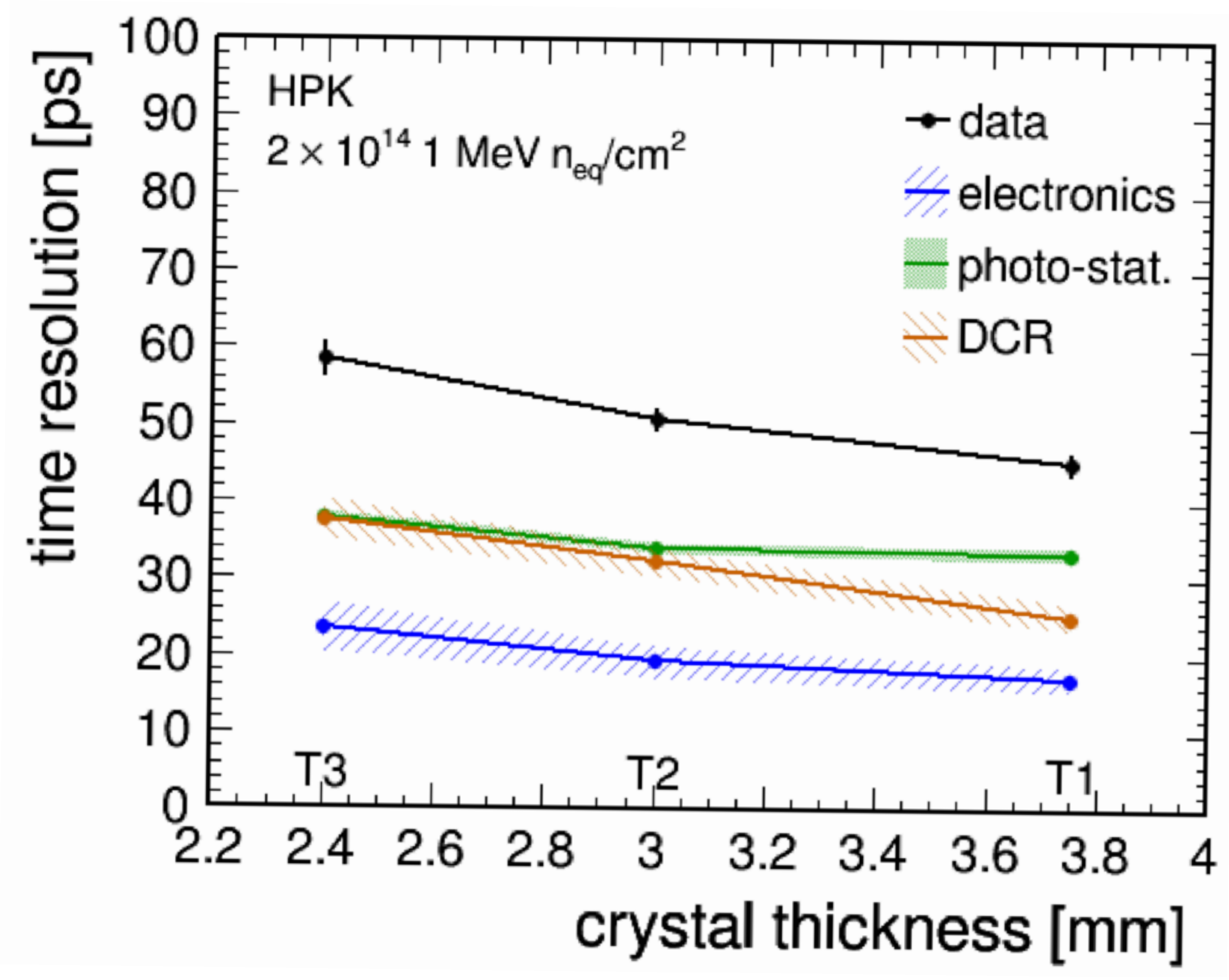
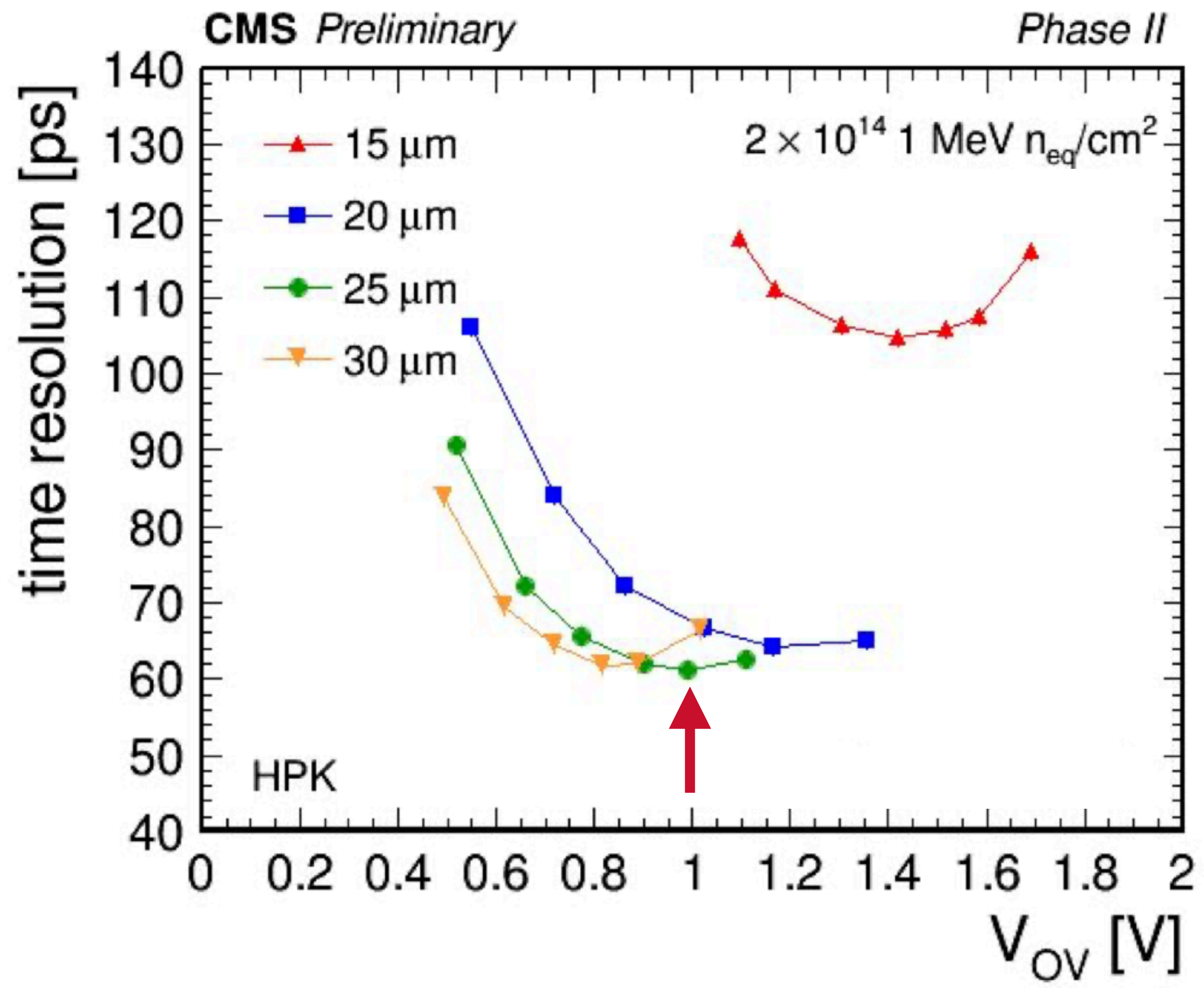


Optimize cell size

- SiPM cell size optimized against power consumption
- Maximize PDE and optimize overvoltage (OV) to reduce electronic contribution → ***25μm at 1V OV***



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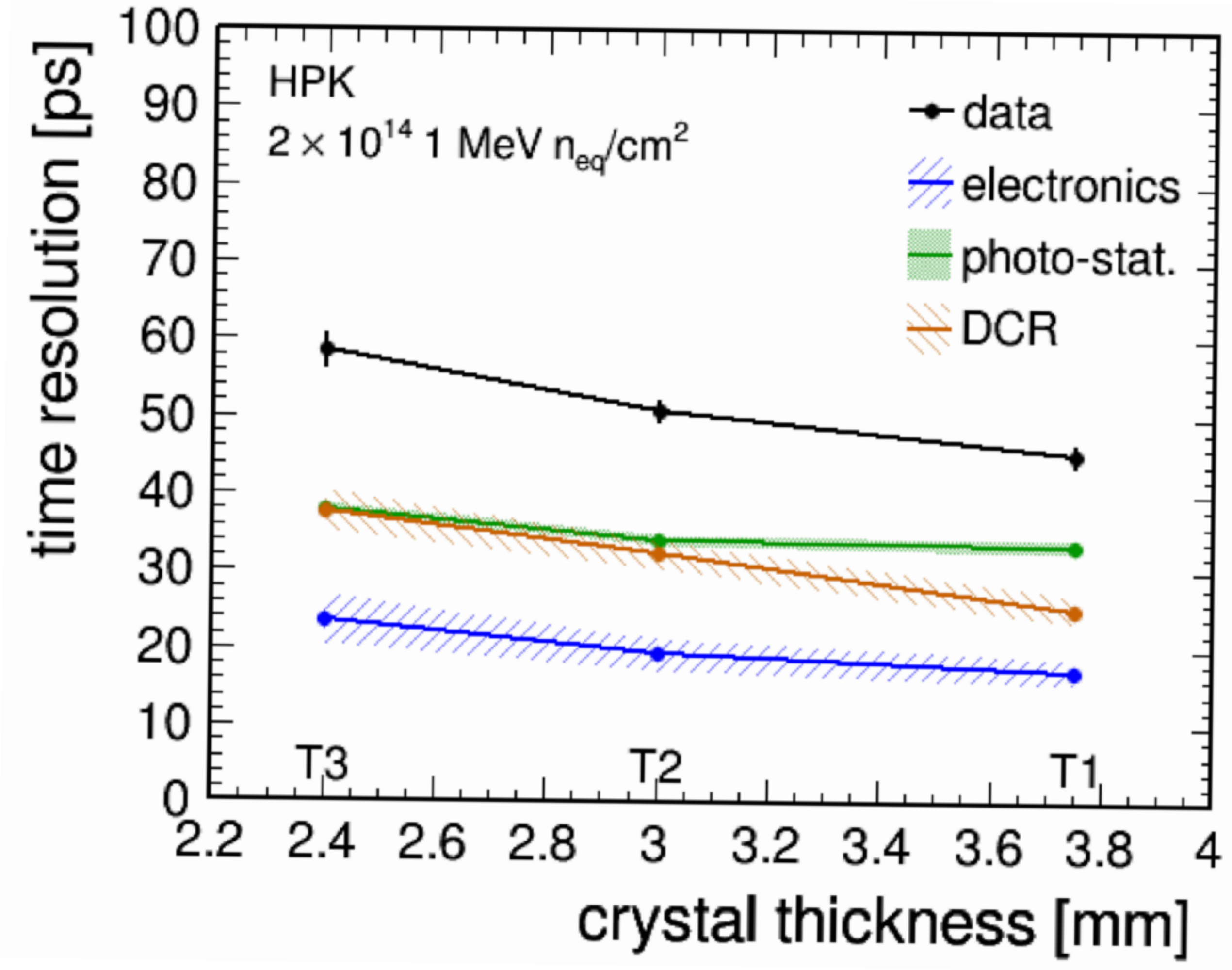

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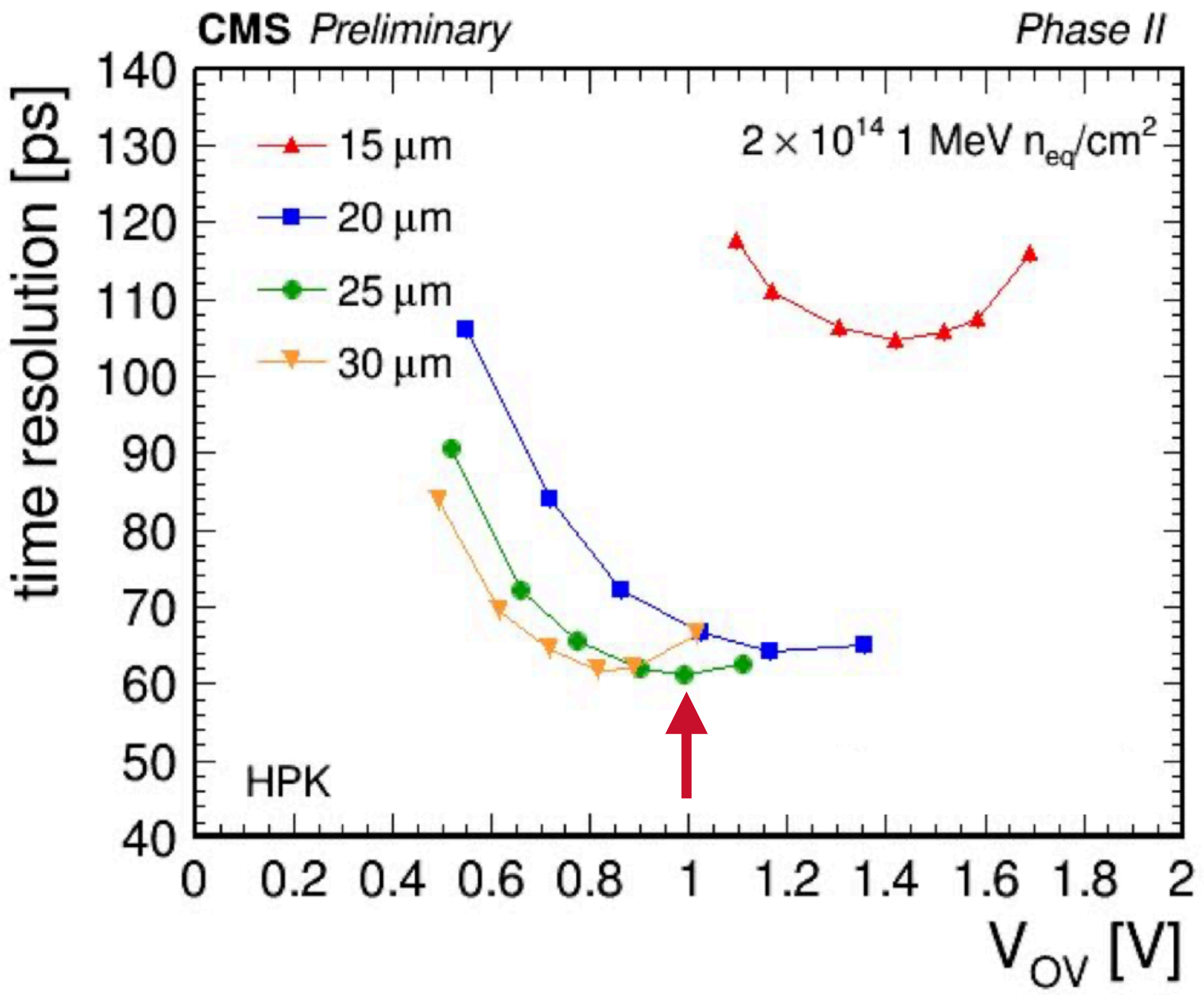
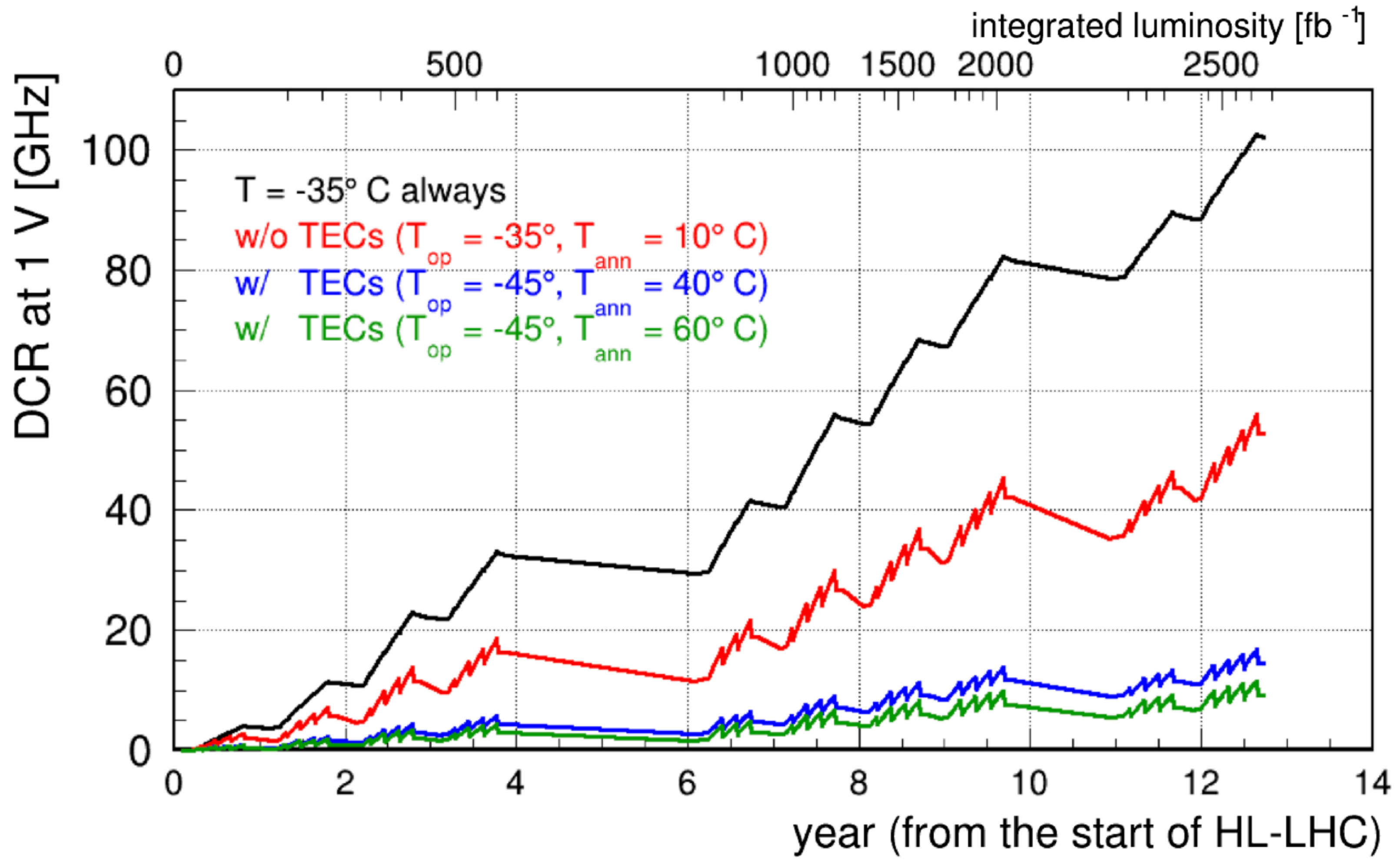


Reduce thermal noise

- Dark-count rate (DCR) caused by radiation damage to Si matrix
- Reverse TEC polarity during technical stops to anneal SiPMs
- Perform DCR cancellation in TOFHIR algorithm



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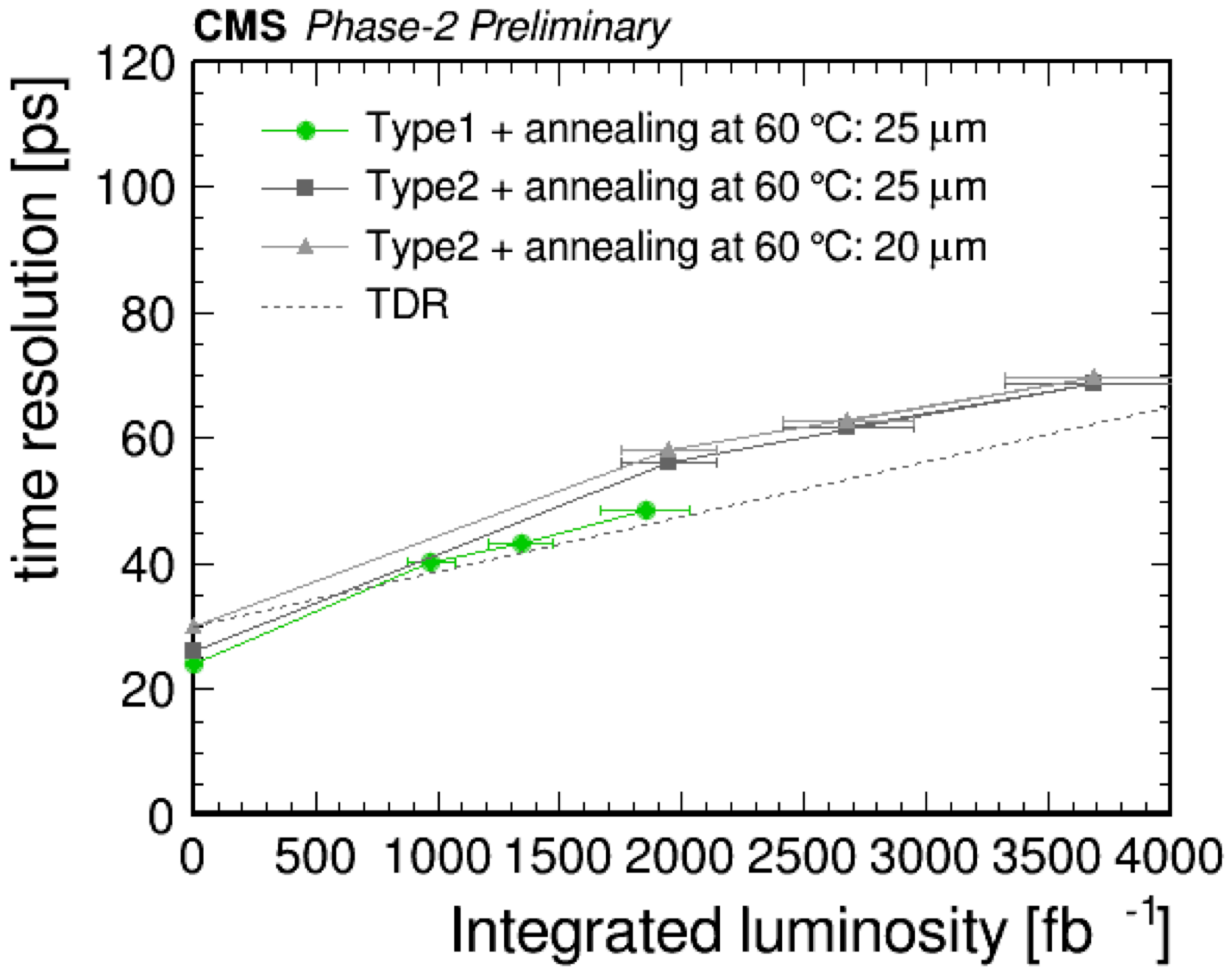
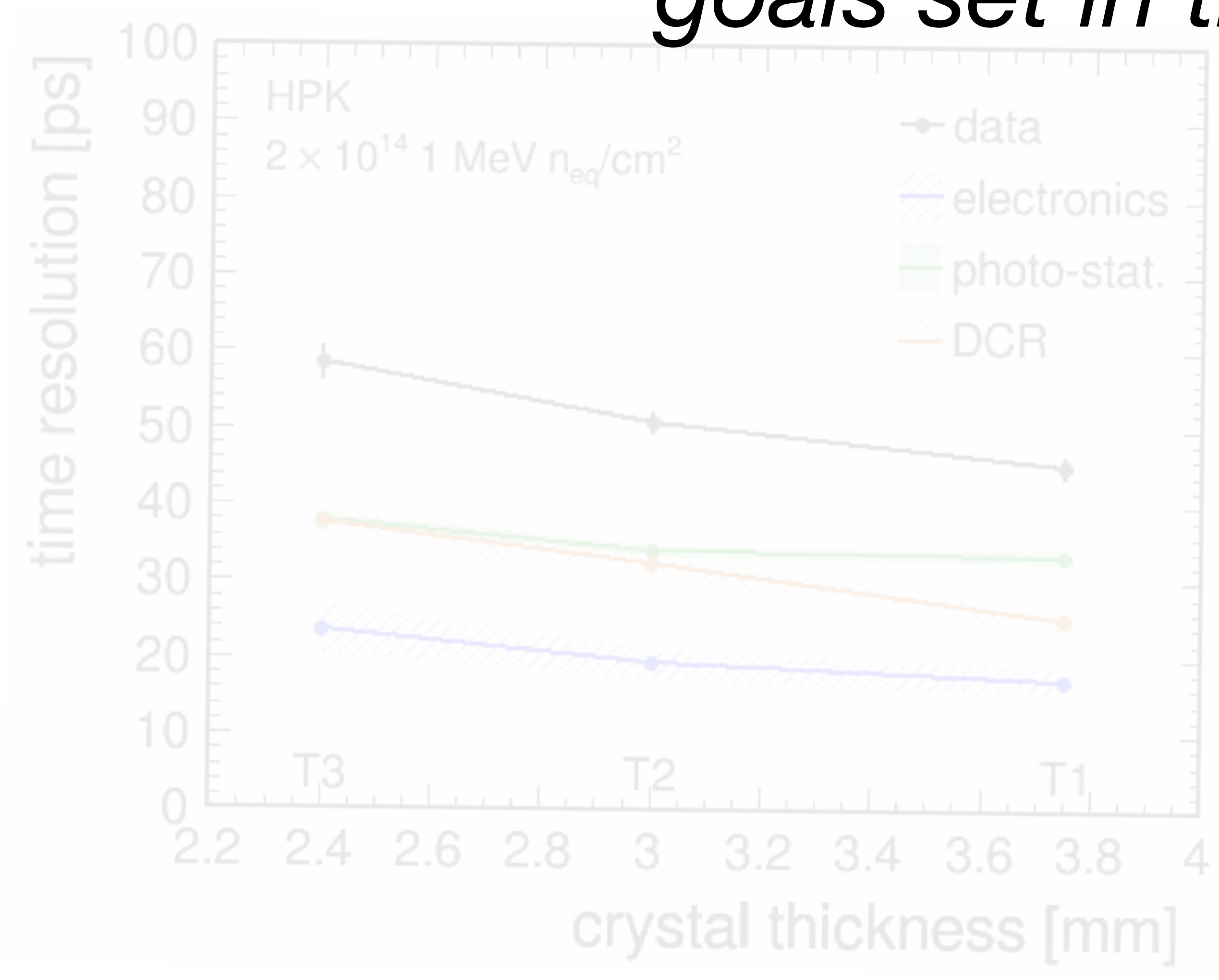
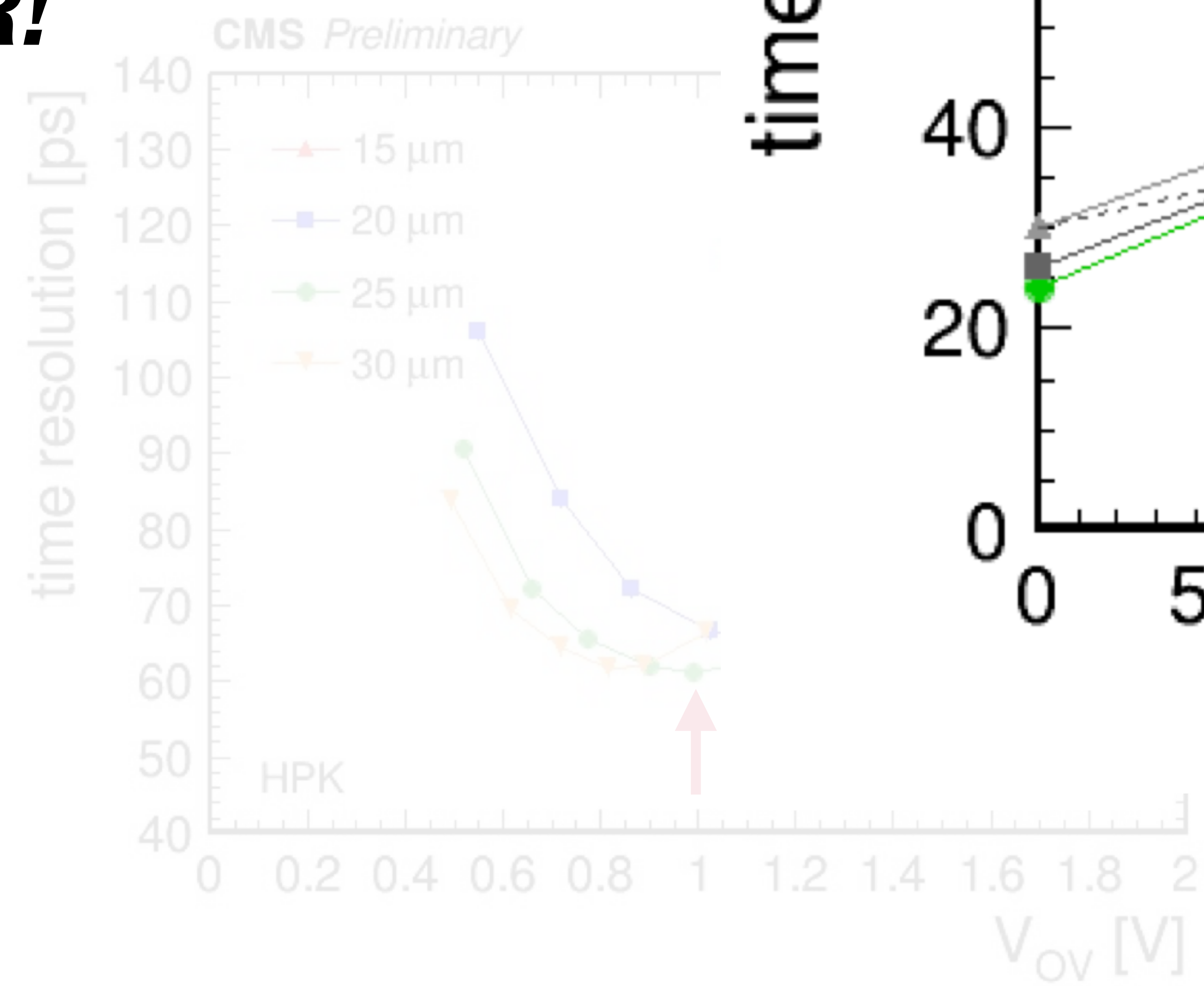
*Using **irradiated sensors** we show we can **match** the time resolution goals set in the **TDR!***



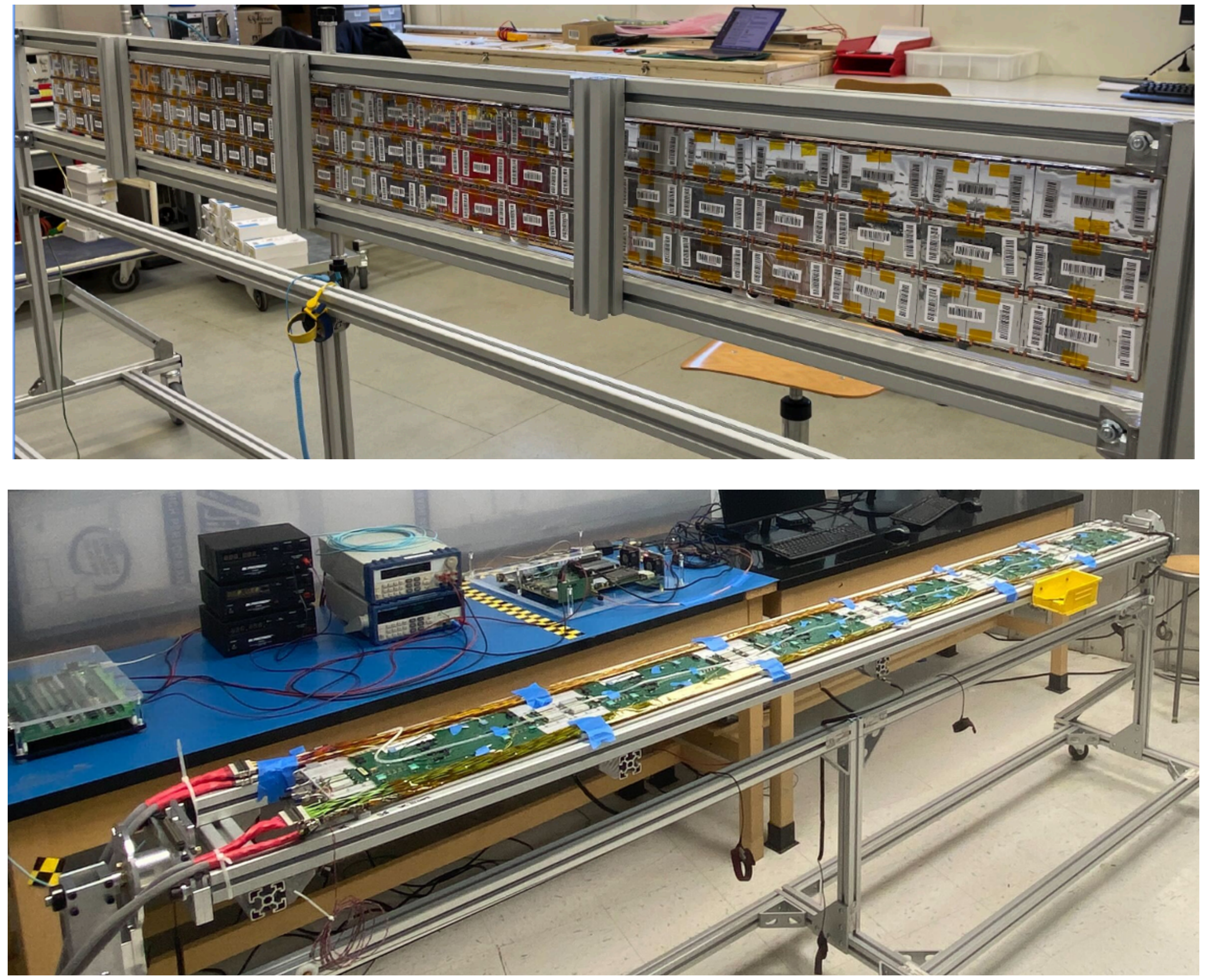




Progress of BTL construction

*Construction of BTL is **well underway,** with several trays already **fully assembled***

- Full on-detector **cooling tray** assembly **completed** in February 2025!
  - Empty trays being shipped to BTL assembly centers (Caltech, U. Virginia, INFN Milan, Peking U.)
- **Module assembly** progressing rapidly
  - LYSO and SiPM production fully complete
  - **~45%** of ~10k sensor modules assembled
- Trays being populated with **detector modules** and **full electronics** → commissioning and QA/QC activities coordinated between BACs and CERN
  - Return shipments of fully populated trays to begin soon
- **Fully-assembled tray integration** into tracker support tube to begin at CERN in 2nd half of 2025



First fully-assembled trays at Milan (top) and UVA (bottom) BACs

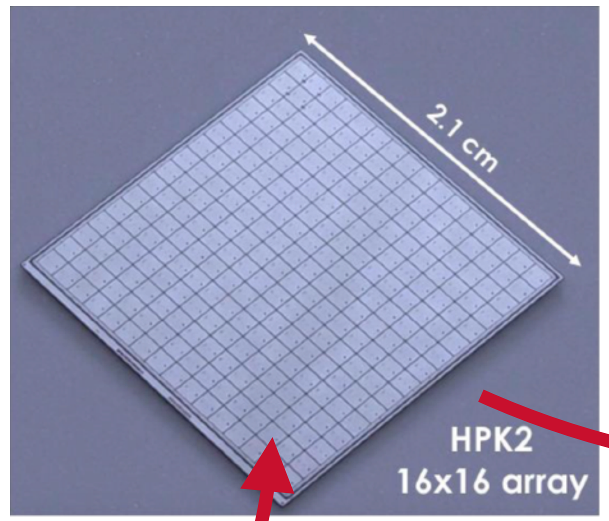
Sensor technology of ETL

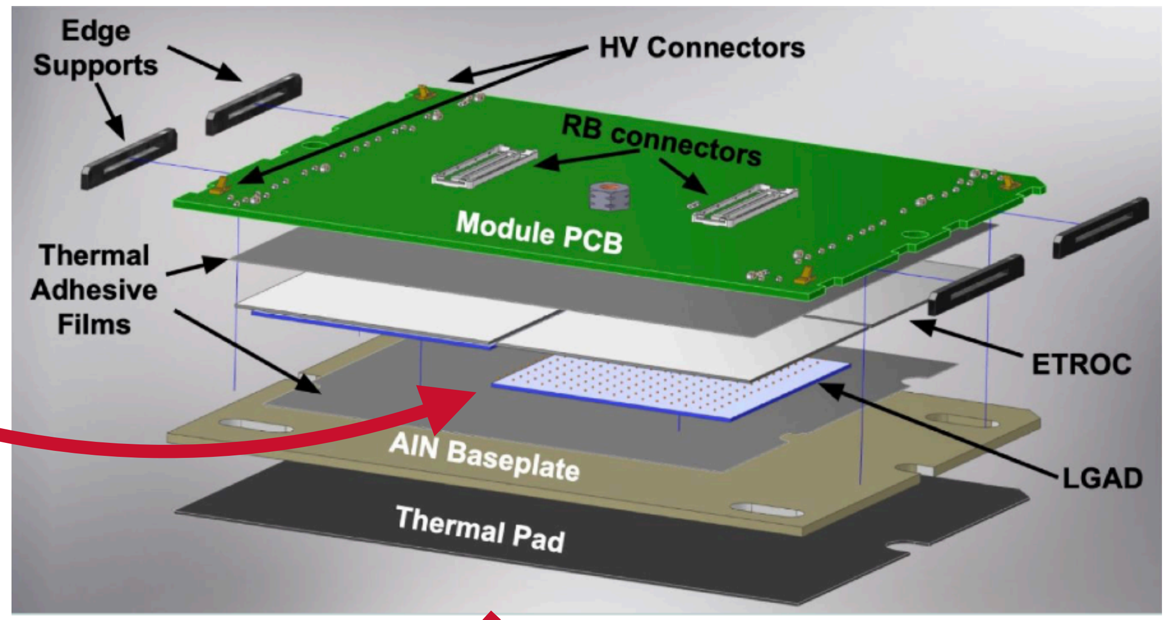
LGADs: Low-Gain Avalanche Diodes

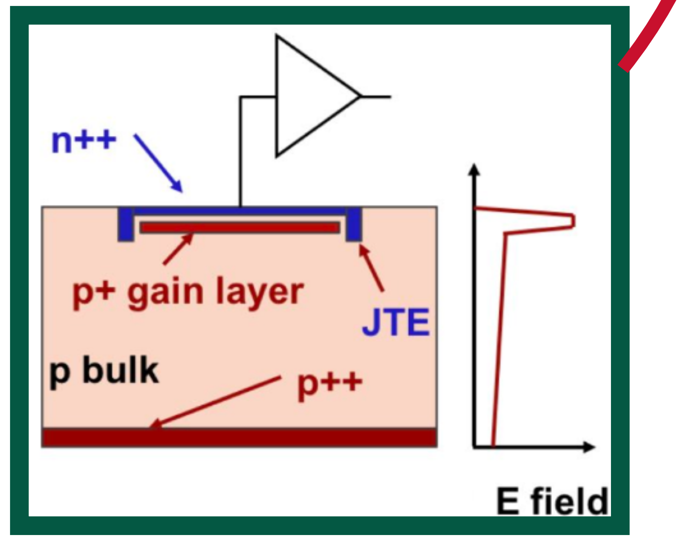
- Ultra-fast solid-state detectors with reverse-biased p-n junction
- 16×16 arrays (1.3×1.3 mm^2 active area per LGAD)
- 50μm thick active layer targeting >8fC at EOL
  - Trade-off between **signal size** and primary ionization **time jitter**
- Gain chosen (10–30) for **better S/N ratio**
- Suitable for 1e15 n_{eq}/cm^2 fluence in innermost region

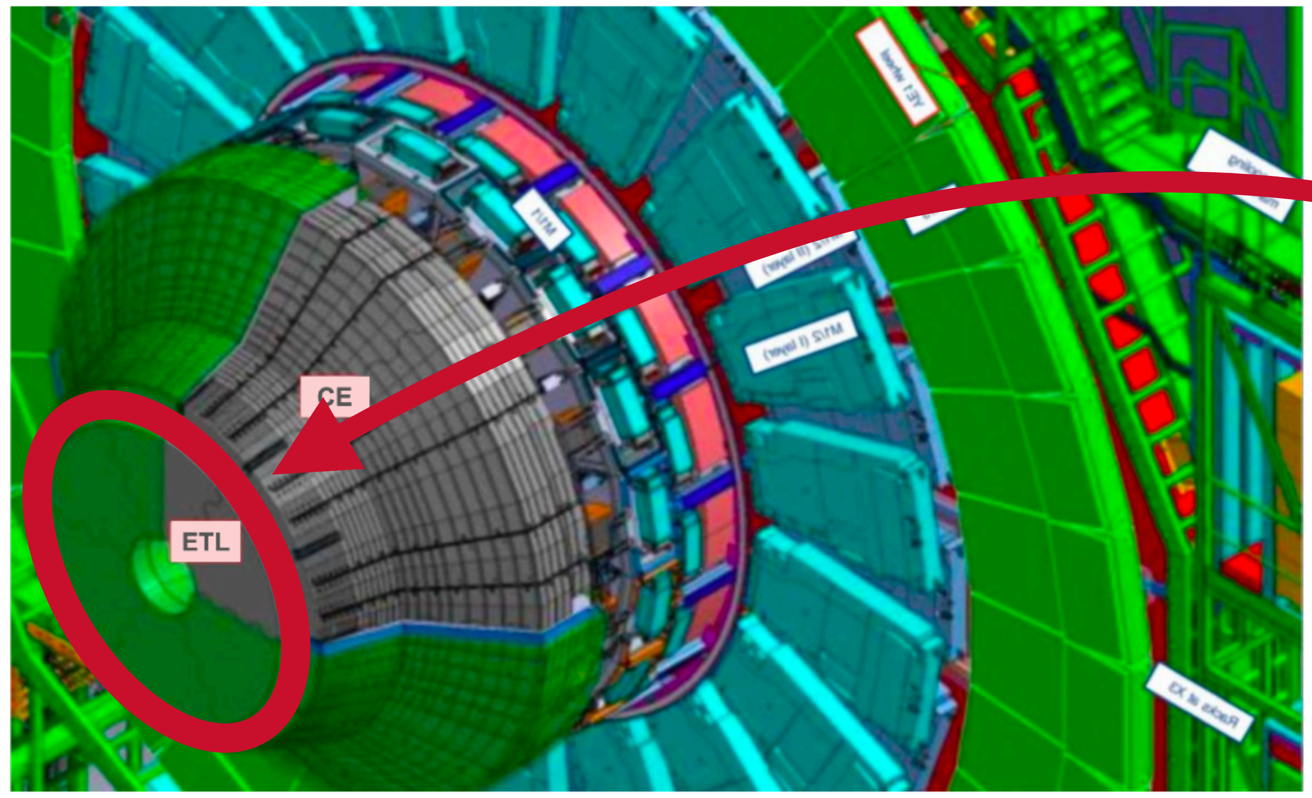
Radiation hardness

- Work with multiple vendors done to optimize **uniformity**, **fill factor**, and **production yield** per wafer (>70%)
- Target performance after irradiation met by **increasing bias voltage**
  - **Sparking damage** seen in TB studies for sensors at E > 11.5V/μm (irradiated with Sr90 β source)
  - Target performance for ETL **achievable** below 11.5V/μm
- Excellent **uniformity** + good **efficiency** and target **resolution** achieved

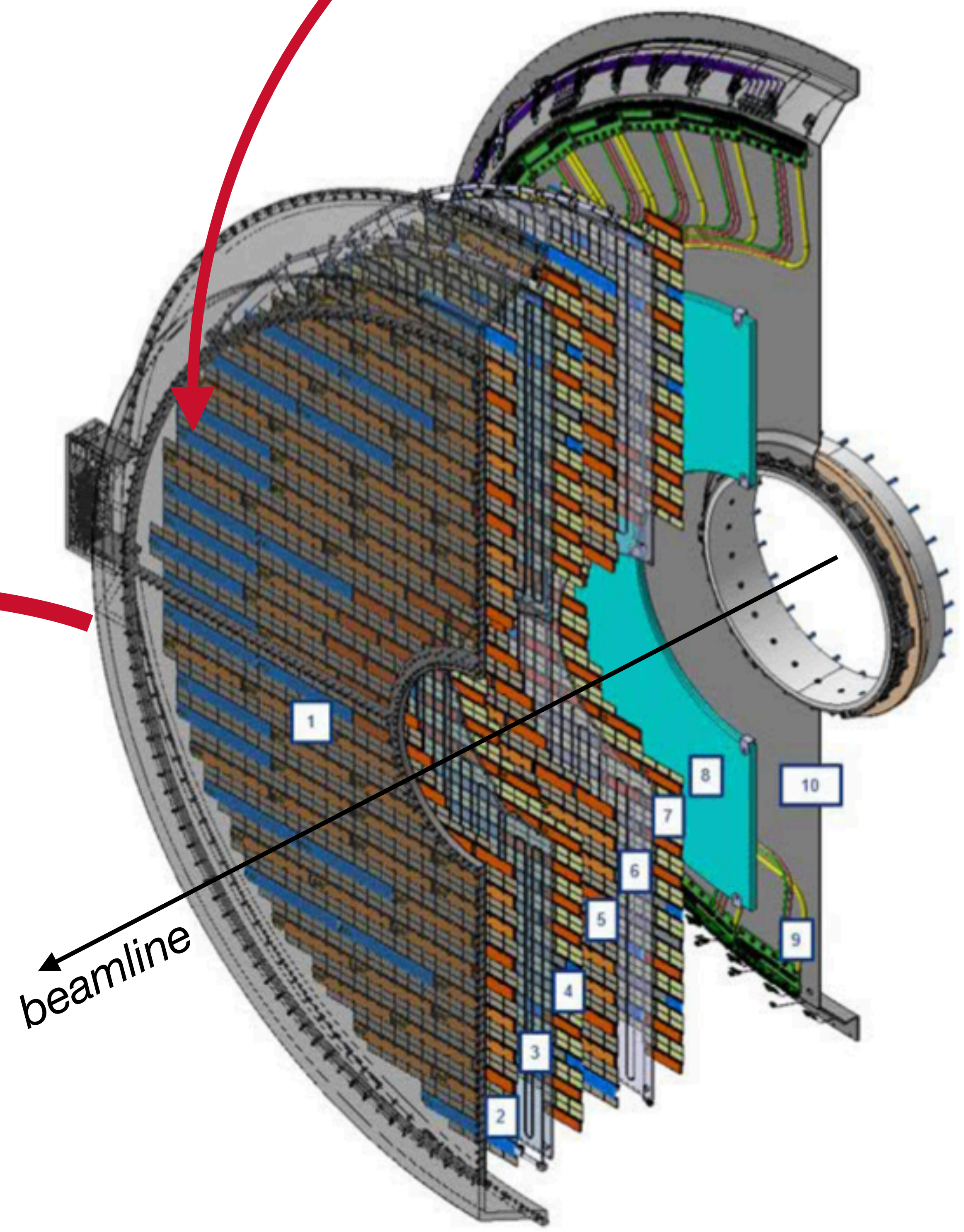








ETL installed on the nose of HGCAL



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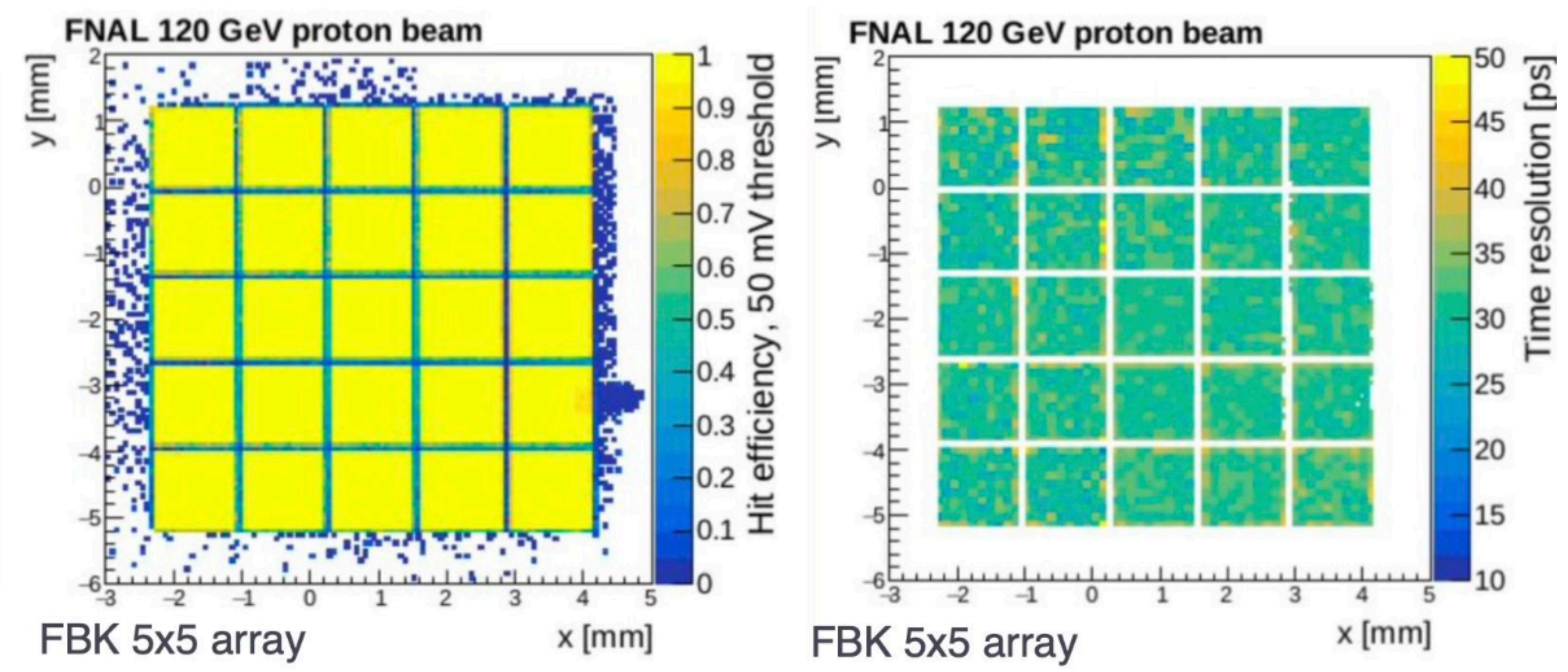

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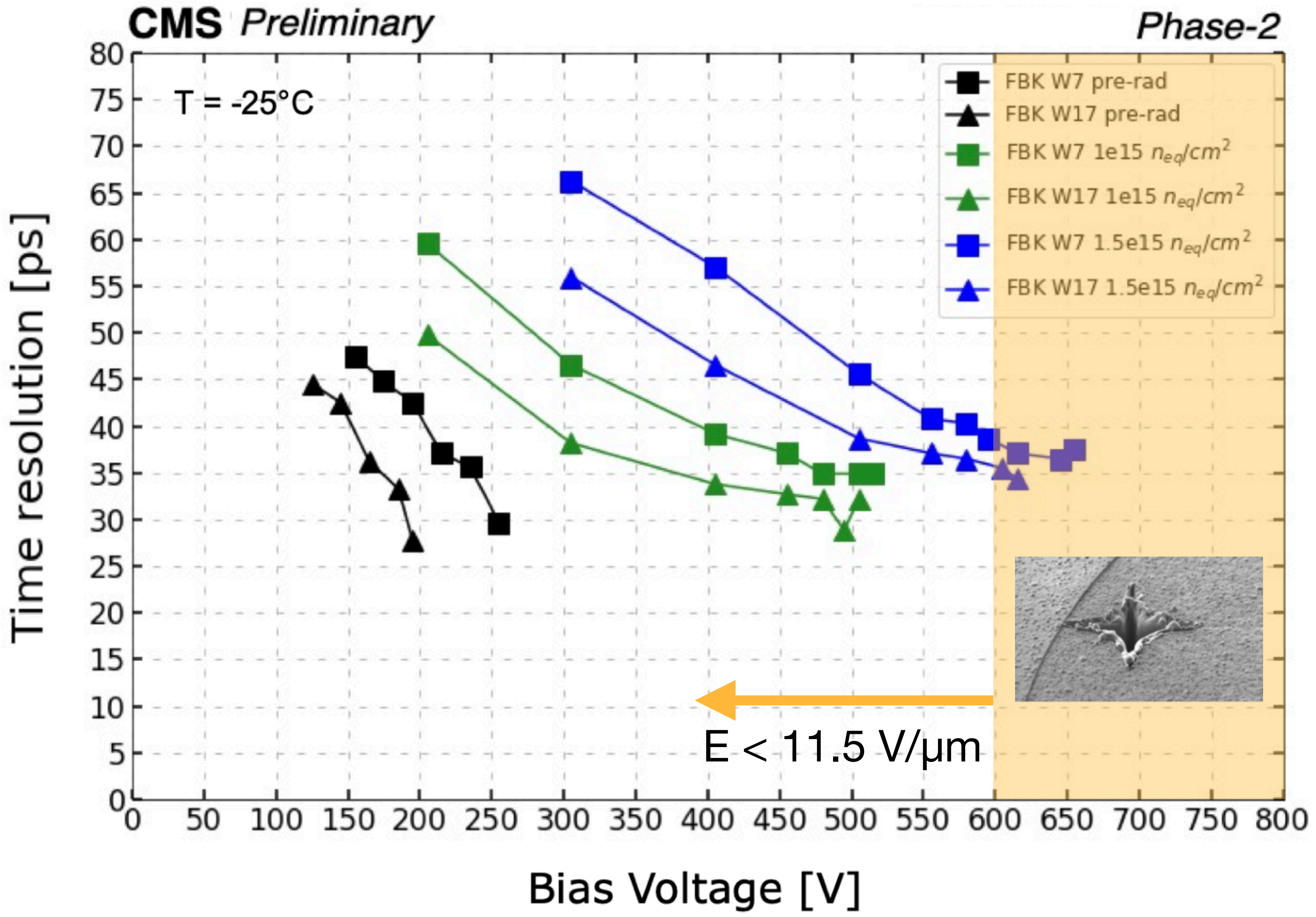
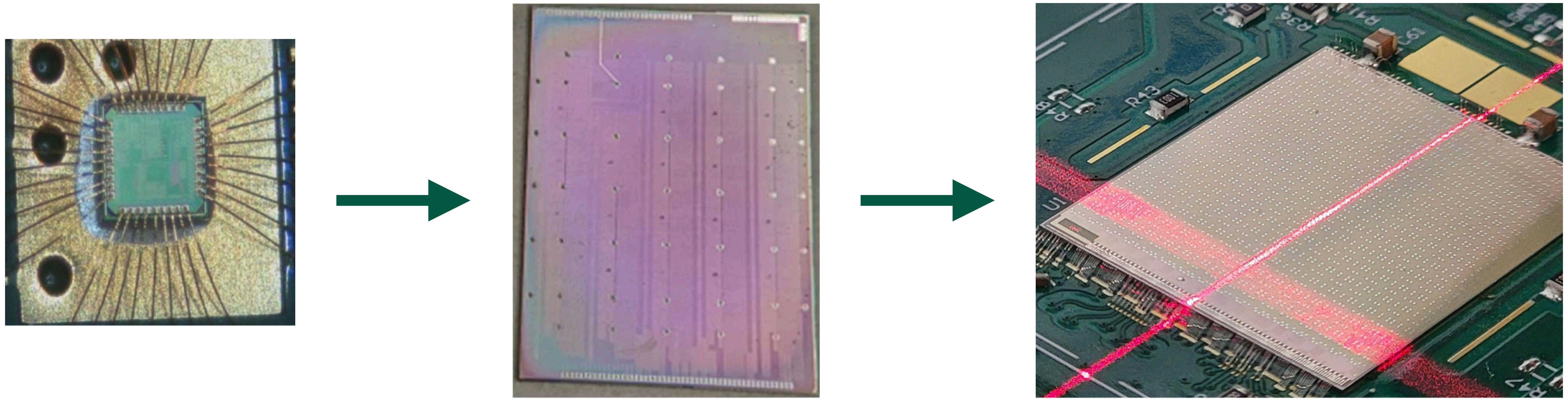
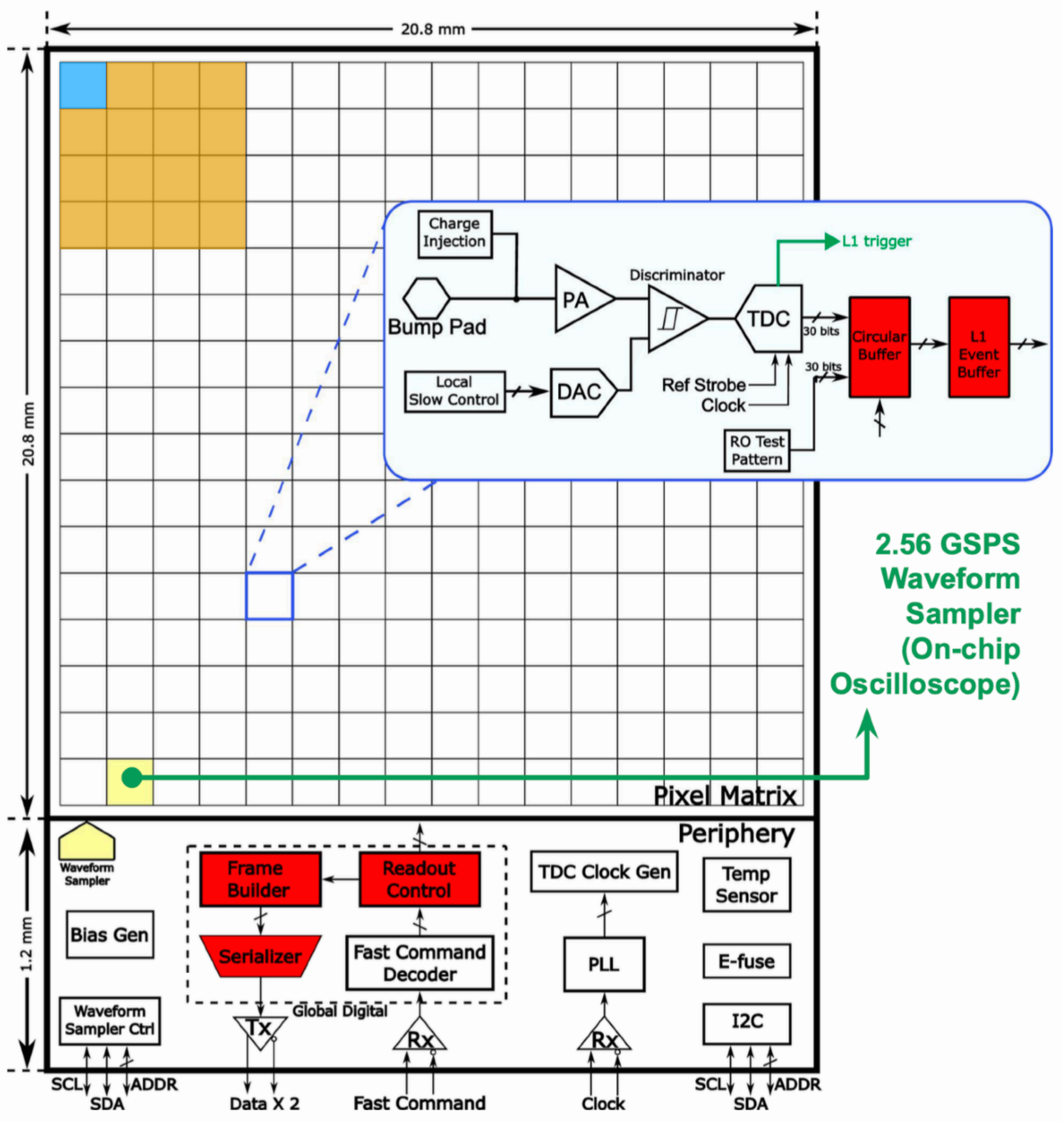


ETL **readout** + **performance validation**

ETROC: Endcap Timing Read-Out Chip

- ETL requires chip with low **noise** + **power consumption**, **radiation hardness**, **uniformity**, and sensitivity to EOL **LGAD signals**
- Two double-face disc design: **85% tracks** measured with two hits…
  - Per-hit time resolution of LGAD + ETROC = **~50ps** → **35 ps** time resolution
- Prototyped in stages*
  - **ETROC0** (2018): 1 pixel channel + preamp + discriminator
  - **ETROC1** (2019): added 4×4 clock tree + TDC ← ***First full-chain readout***
  - **ETROC2** (2022): 16×16 bump-bonded to LGAD ← ***Production chip***





- ETROC2+LGAD time resolution was measured in TB at DESY (e-) and CERN (π+)

** years designate design submission*

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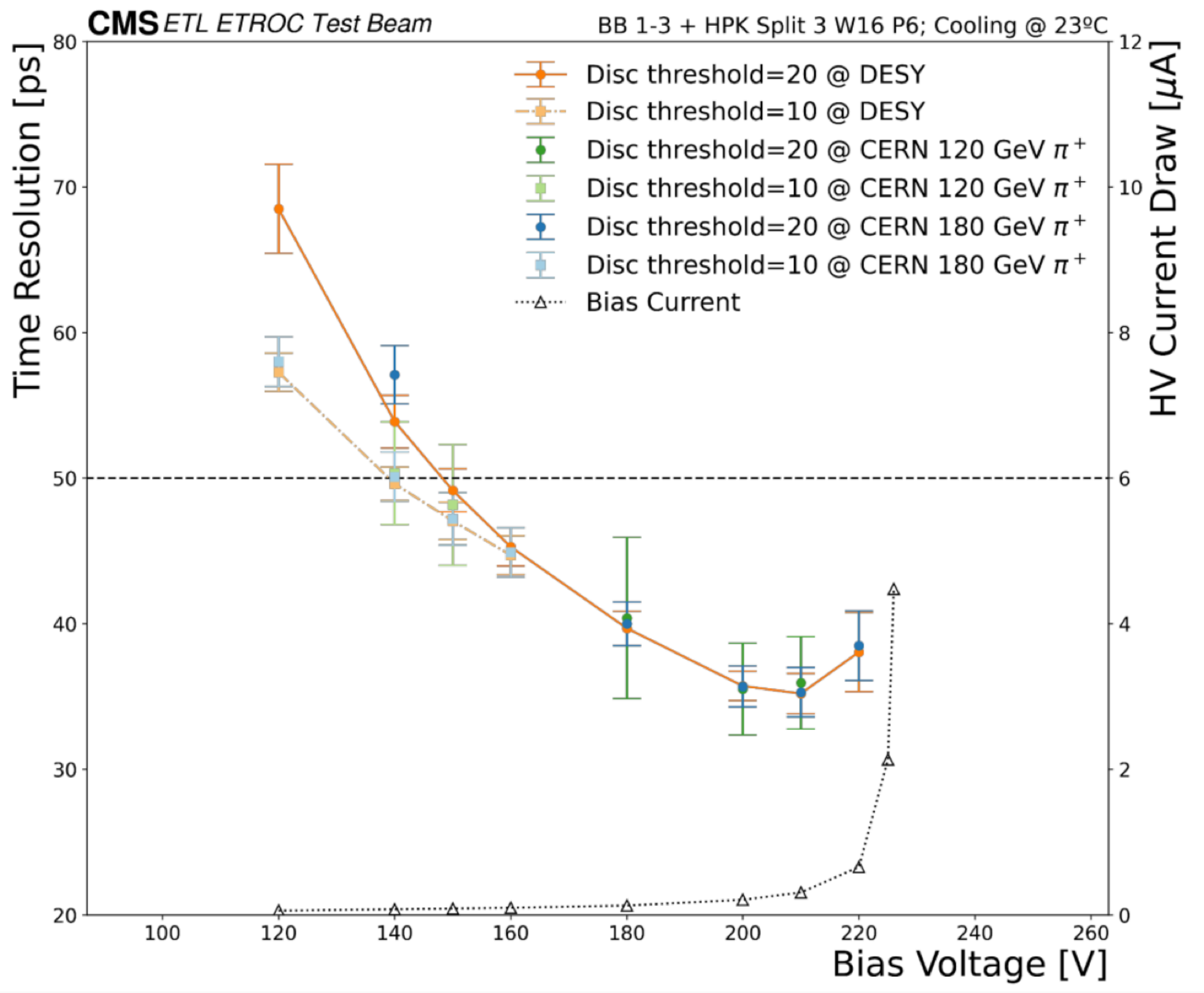
First

Produ

*Results show **full 70V bias range** where **LGAD+ETROC2** produce target **time resolution**!*



2.56 GSPS Waveform Sampler (On-chip Oscilloscope)

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Summary and conclusions

- HL-LHC will provide ample opportunity to extend the **physics reach** of the baseline LHC, but CMS must cope with an **intense pileup** and **radiation** environment
- Precise timing measurements of charged particles offer not only a means of **mitigating pileup** but also provide **completely new information** in physics analyses
- Both subdetectors of MTD meet **target specifications** for **time resolution**
- **BTL** is in production with **full complement of cold trays** + **45% of modules** assembled and trays being shipped and populated for **commissioning** in 2025
- **ETL** is well into final development with **ETROC2** meeting performance specifications to become **production ASIC**

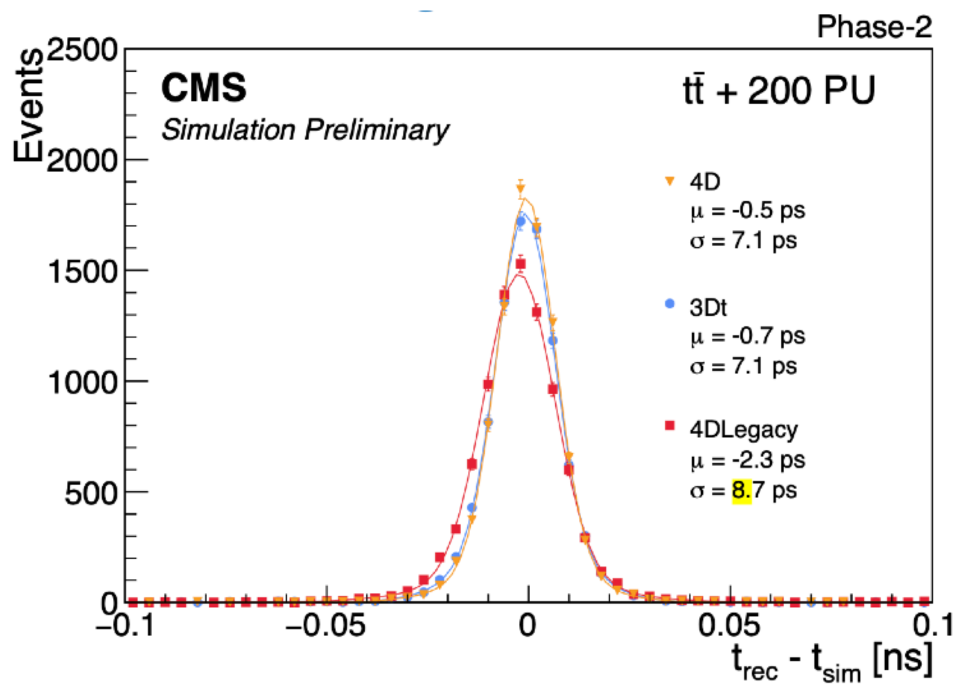
Thank you!

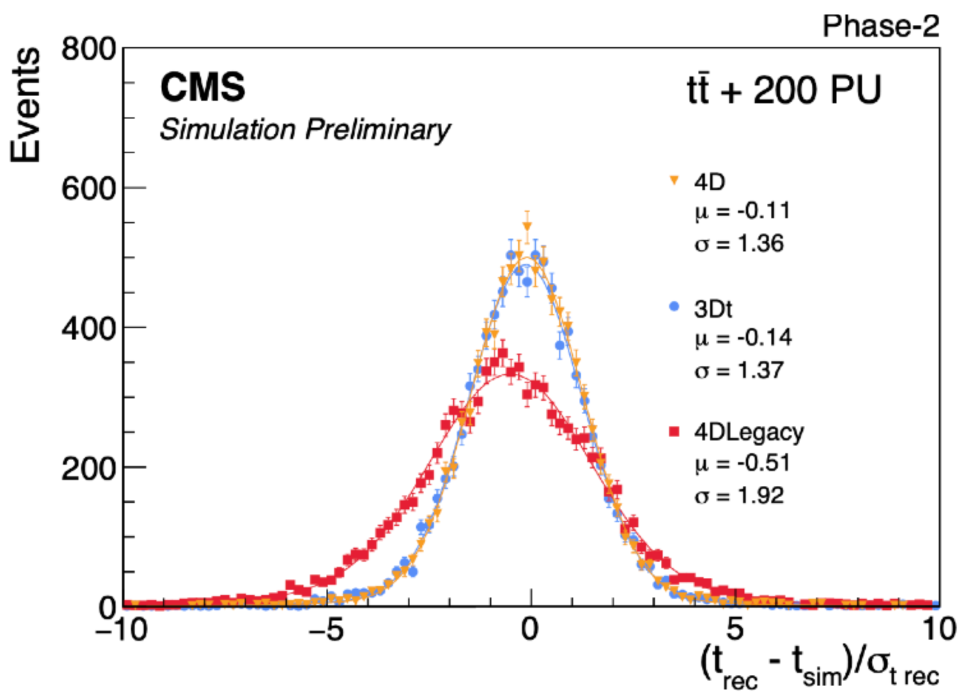
BACKUP

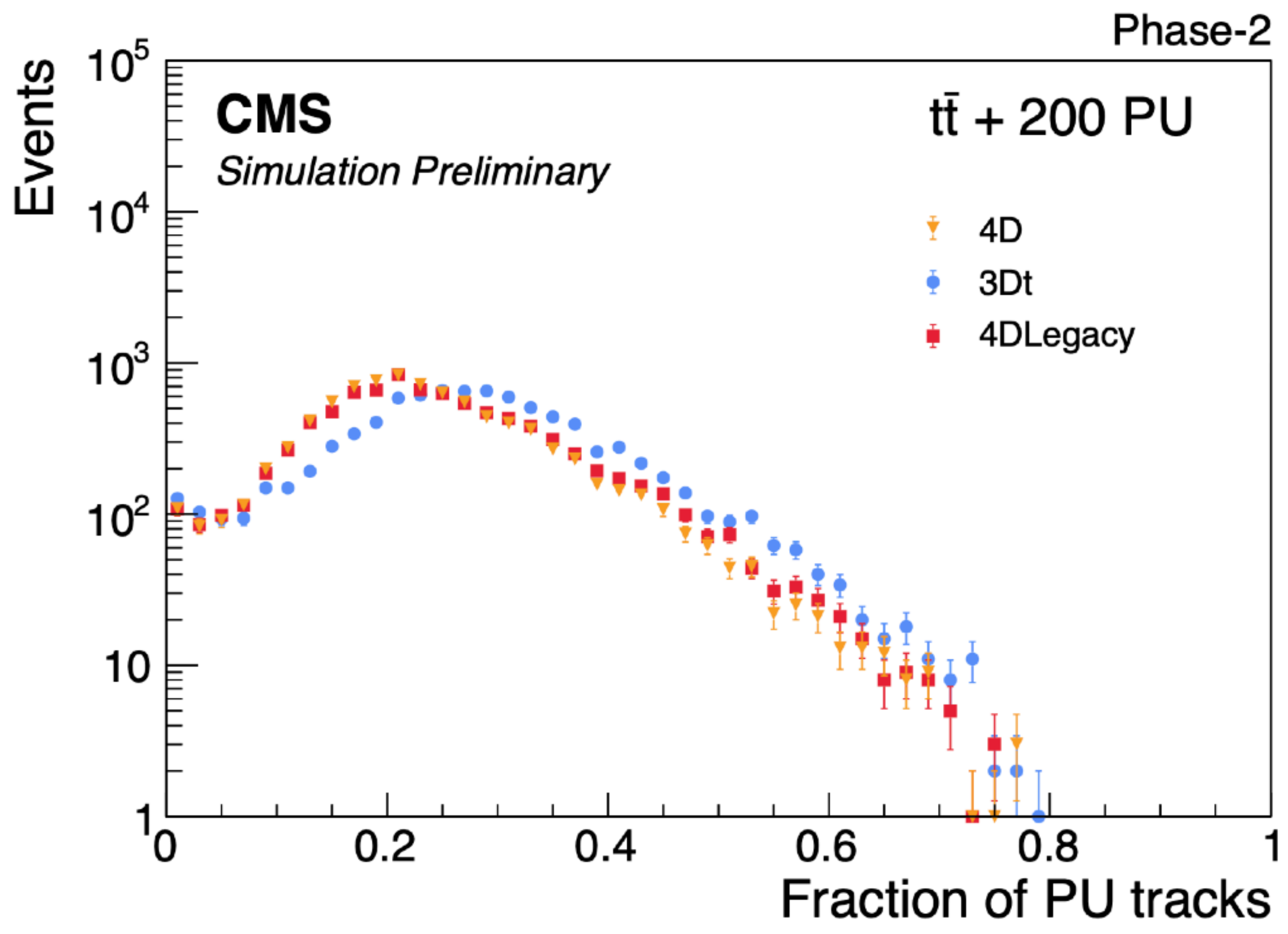
Improvements to 4D vertexing

***4D vertexing** and **particle identification** are two sides of the same coin*

- MTD gives us **sparse** but **precise** timing inputs for tracking
- **Legacy 4D algorithm**:
  1. Cluster vertex with π mass hypothesis and $\sigma_{t_0} = \sigma_t^{MTD} \oplus \Delta(TOF_p - TOF_\pi)$ + calculate vertex time and perform PID
  2. Cluster using updated track times + remove inflated uncertainty → calculate vertex time and perform PID
- Improved **primary vertex time**
  - **Deterministic annealing** algorithm combines π/K/p hypotheses simultaneously
  - In ttbar+200PU, track **time resolution** (8.7→7.1ps) and **pull** (1.92→1.36) **reduced** compared to legacy 4D algorithm
- Higher **reconstruction efficiency**
  - Updated 4D workflow replaces first 4D pass with **3D+time** for initial mass hypothesis → vertex-finding **CPU reduced by 30%**
  - Reconstructs more **real primary vertices** while keeping fake rates **below 3Dt**
- Improved **pileup rejection**
  - Fraction of PU tracks in leading PV falls by 10–15% relative to 3Dt
  - Fake vertex rate stays between 3Dt and legacy 4D







LYSO irradiation performance