MTD Barrel Timing Detector at the CMS experiment

The 2025 International Workshop on the High Energy Circular Electron Positron Collider

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on behalf of CMS MTD

Nov 8th, 2025

From LHC to HL-LHC

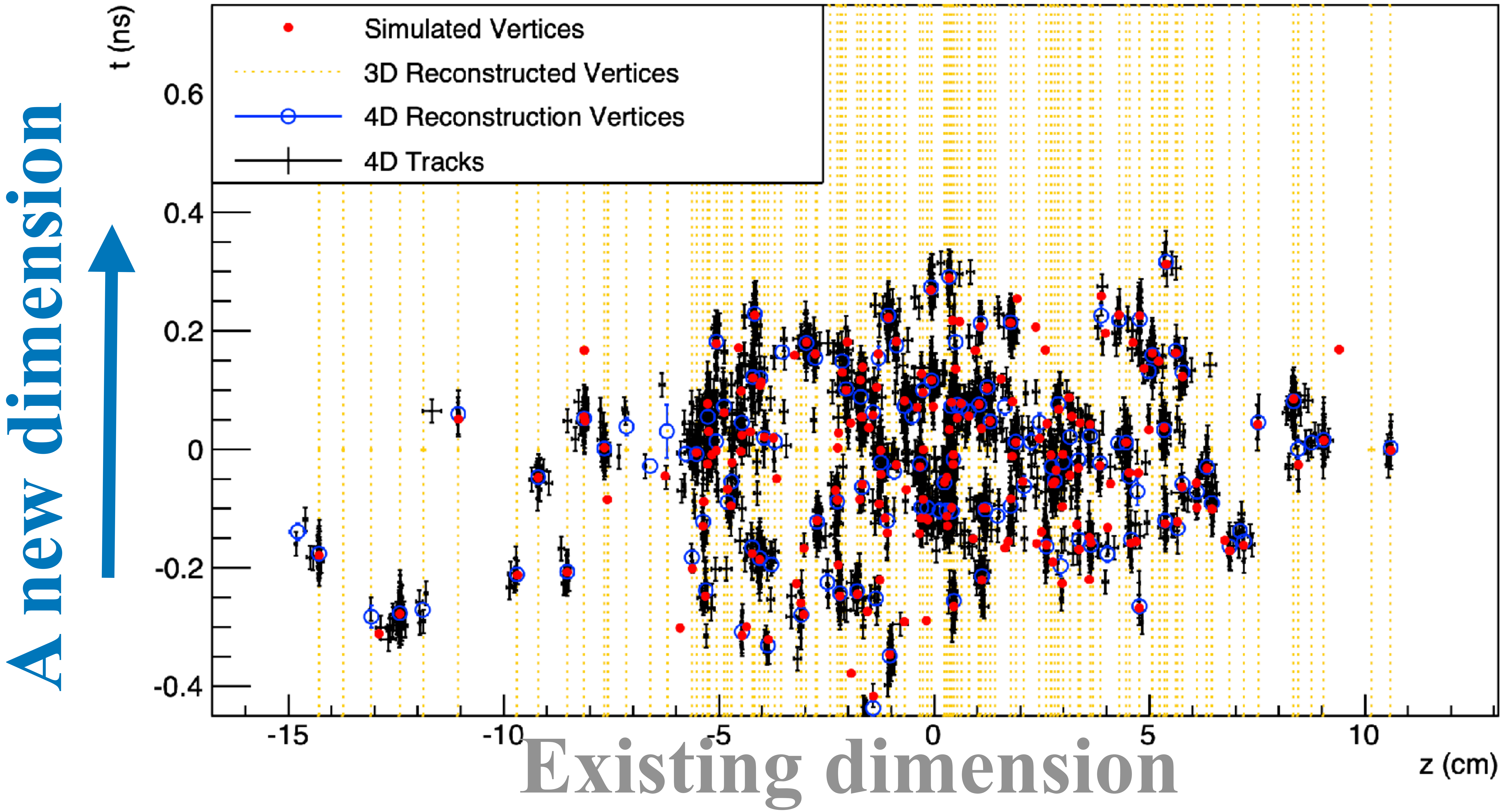
Phase-II upgrade in CMS

… 7, 8, 13, 13.6, 14 TeV

… 0.75, 1, 2, 7.5 x nominal lumi

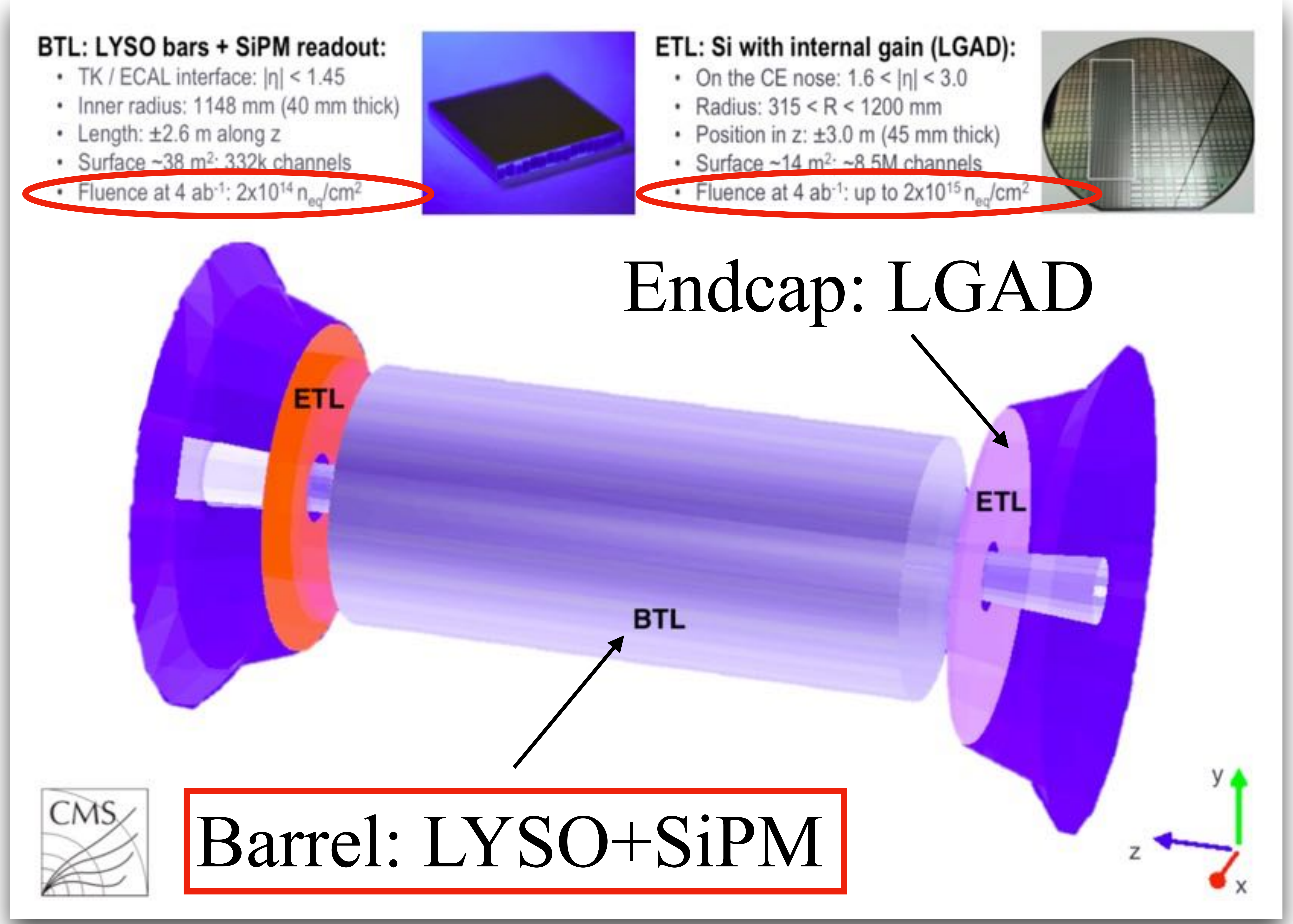
This is from a high-pileup run in 2025 with 206 vertices amongst the 9381 reconstructed tracks at one collision

Add a new dimension



Introduction

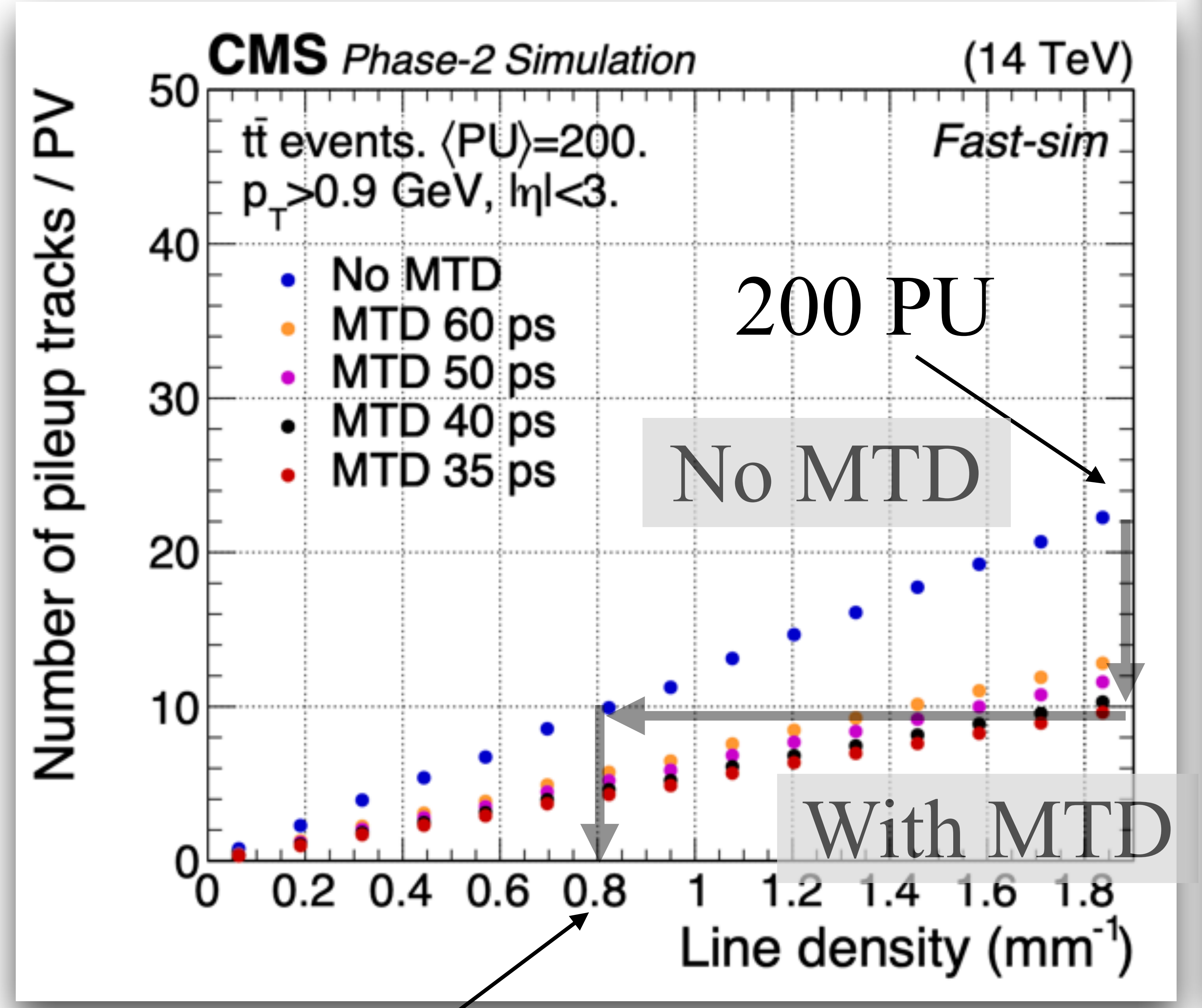
- MIP Timing Detector (MTD) is a novel detector in CMS Phase-II upgrades
- MTD is designed to measure the time of MIP particles at a precision of 30 - 60 ps
  - To cope with the high pileup in HL-LHC that will operate with about 4 times higher instantaneous luminosity wrt the current one
    - Up to about 200 vertices per bunch crossing
  - To open new windows for BSM searches at CMS
- MTD consists of a Barrel Timing Layer (BTL) and Endcap Timing Layers (ETL)
  - BTL is designed with LYSO:Ce crystal bars + silicon photomultipliers (SiPMs)
  - ETL is designed with LGAD

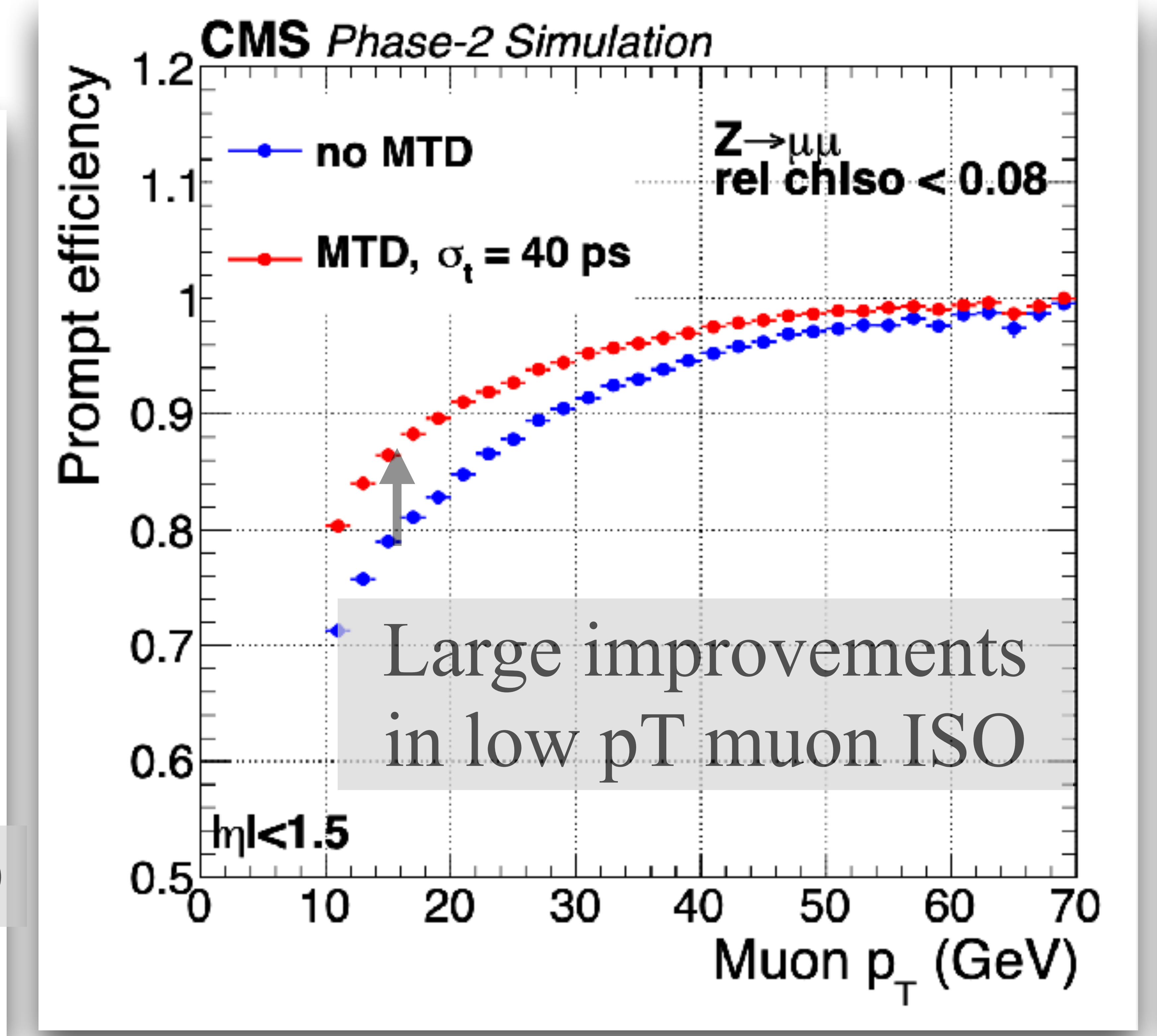


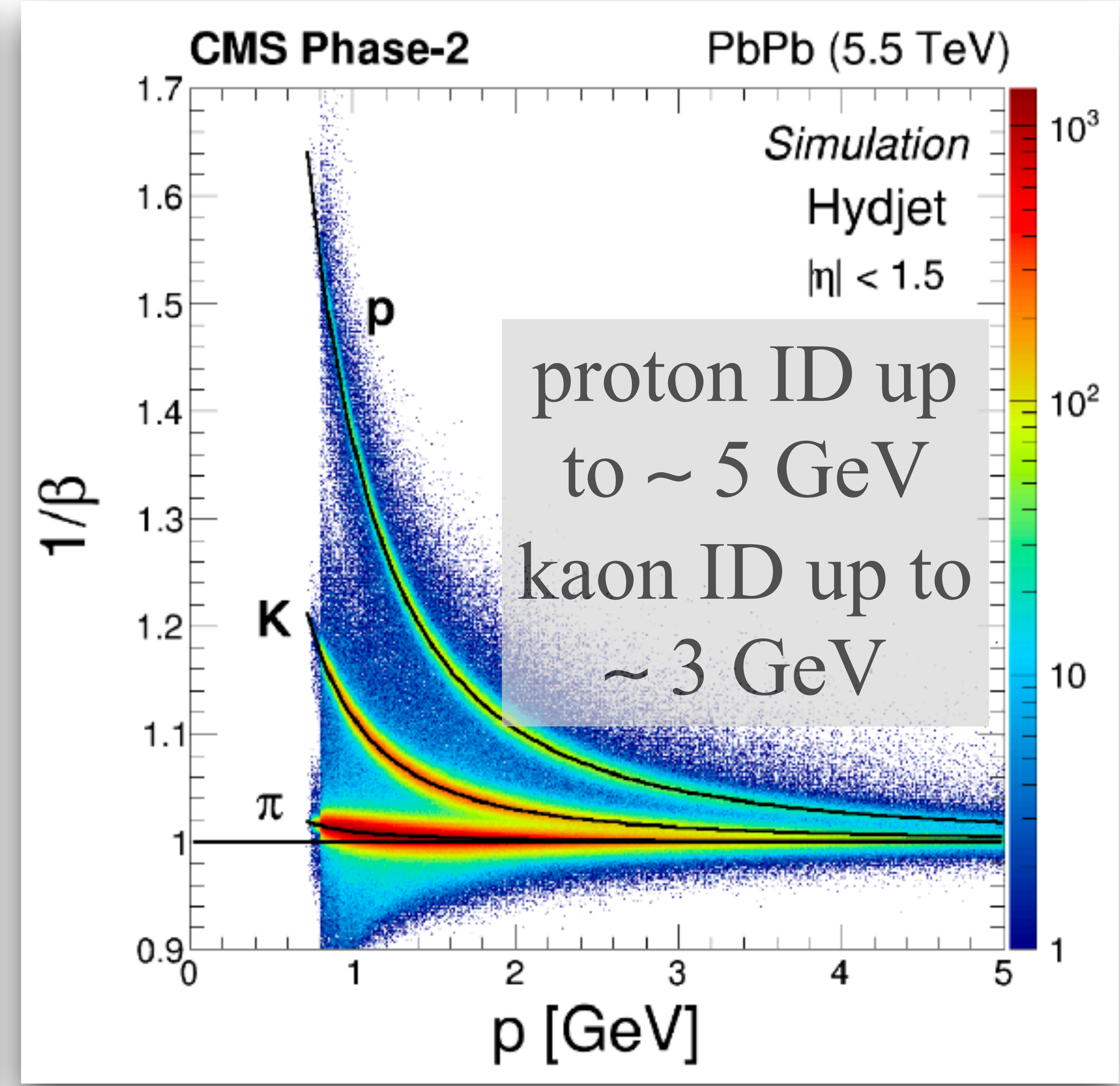
Different levels of radiation fluence in barrel and endcaps

Impact in reconstruction

- MTD will effectively suppress the pileup effect and improve the performance of reconstruction widely







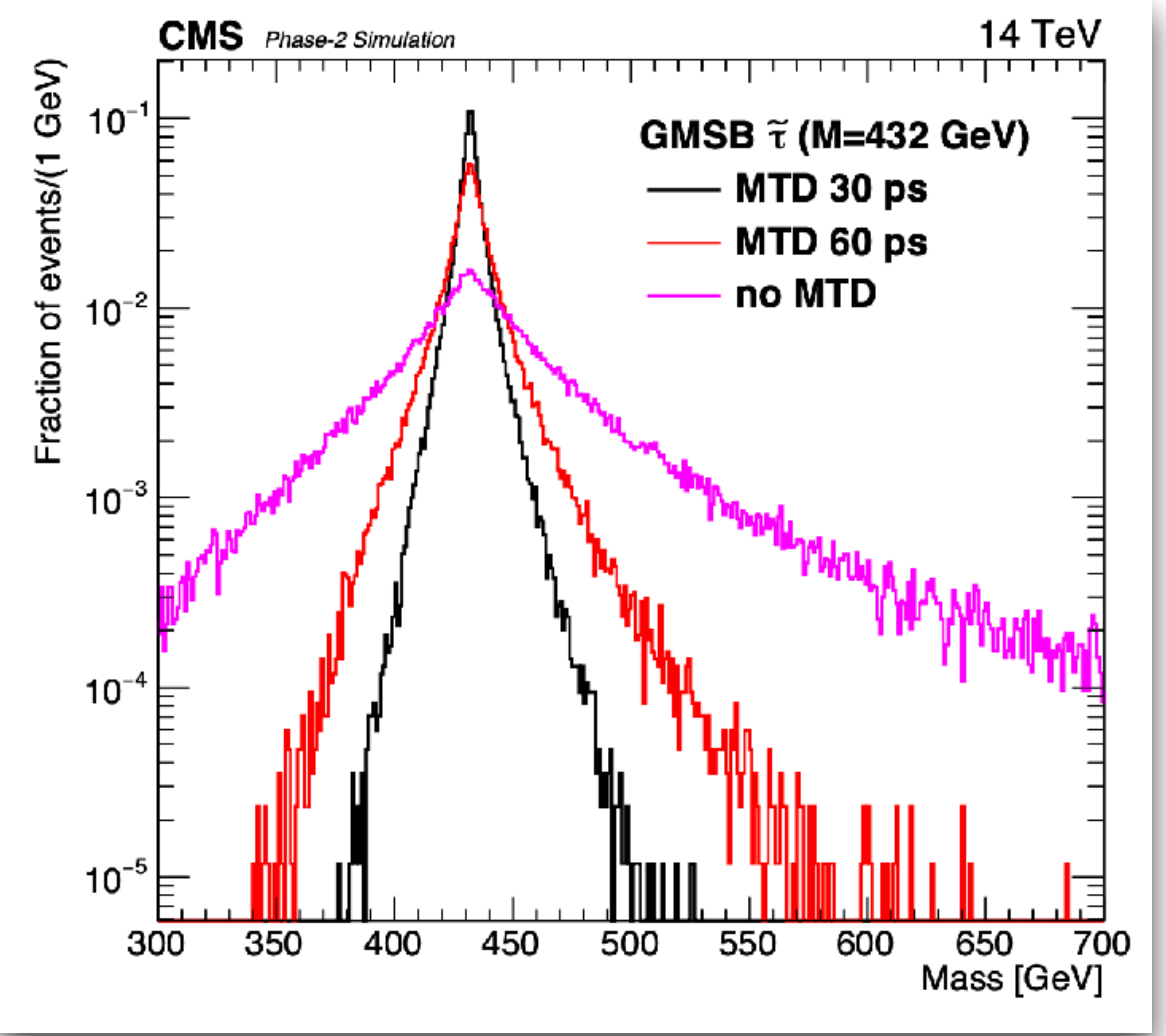
A line density of 0.8 corresponds to a pileup less than 80

Recovering PU down to roughly the Run3 level

TOFPID $$\frac{1}{\beta} = \frac{c(t_0^{\mathrm{MTD}} - t_0^{\mathrm{evt}})}{L}.$$

Impact in physics

- MTD will effectively suppress the pileup effect and bring new functionalities to search for LLP
  - Increase the HH signal acceptance by 20% from isolation, btagging etc.
  - Improve the single Higgs ($\gamma\gamma$, 4l, $\tau\tau$) precision by 20-30% from isolation, vertex identification, VBF tagging, MET etc.
  - Suppress reducible background in SUSY by 40% from btagging, MET
  - Open a new window in searches for long-lived particles (LLPs) from β_{LLP}



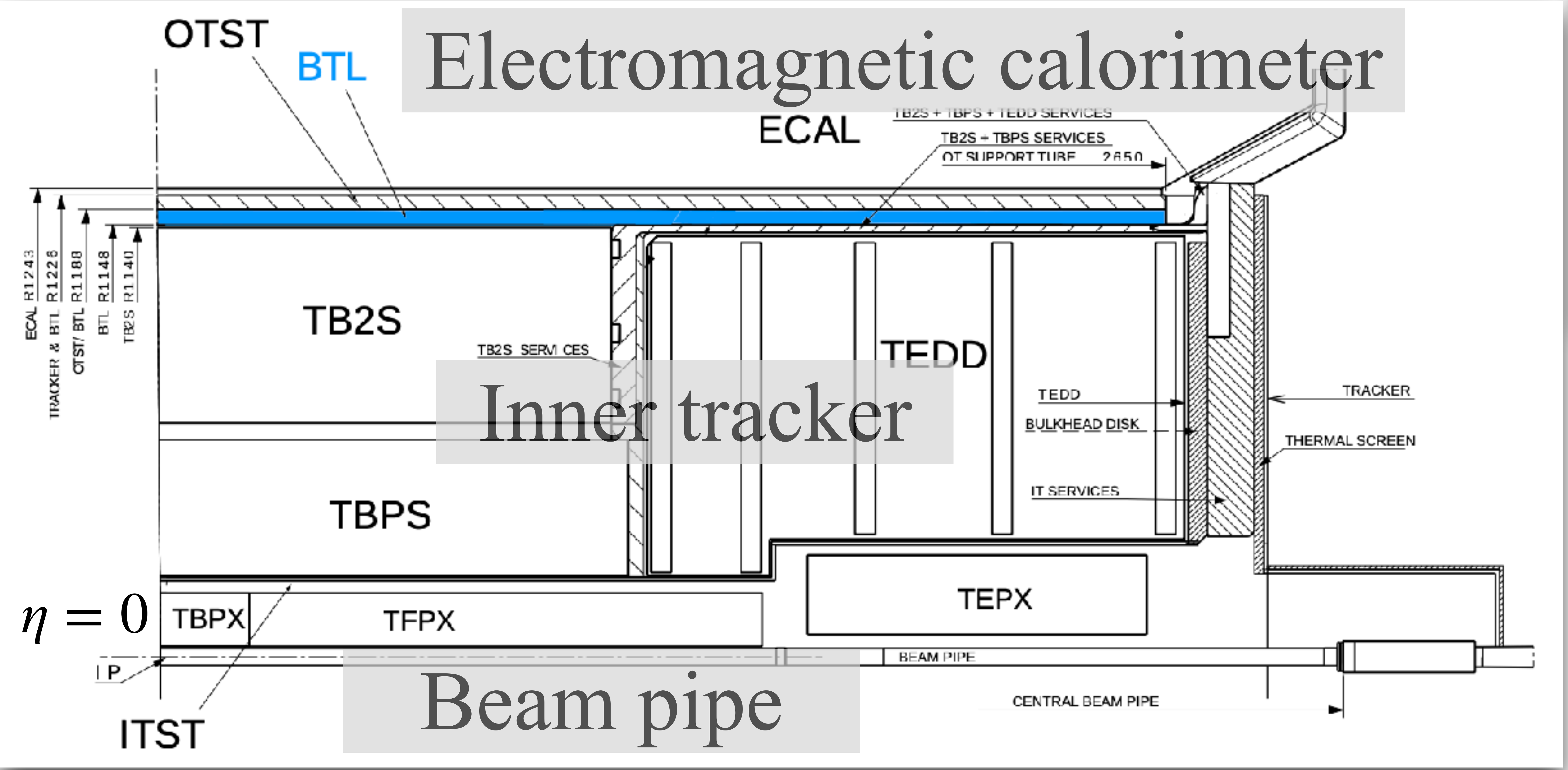
MTD impacts the resolution of the reconstructed HSCP mass significantly

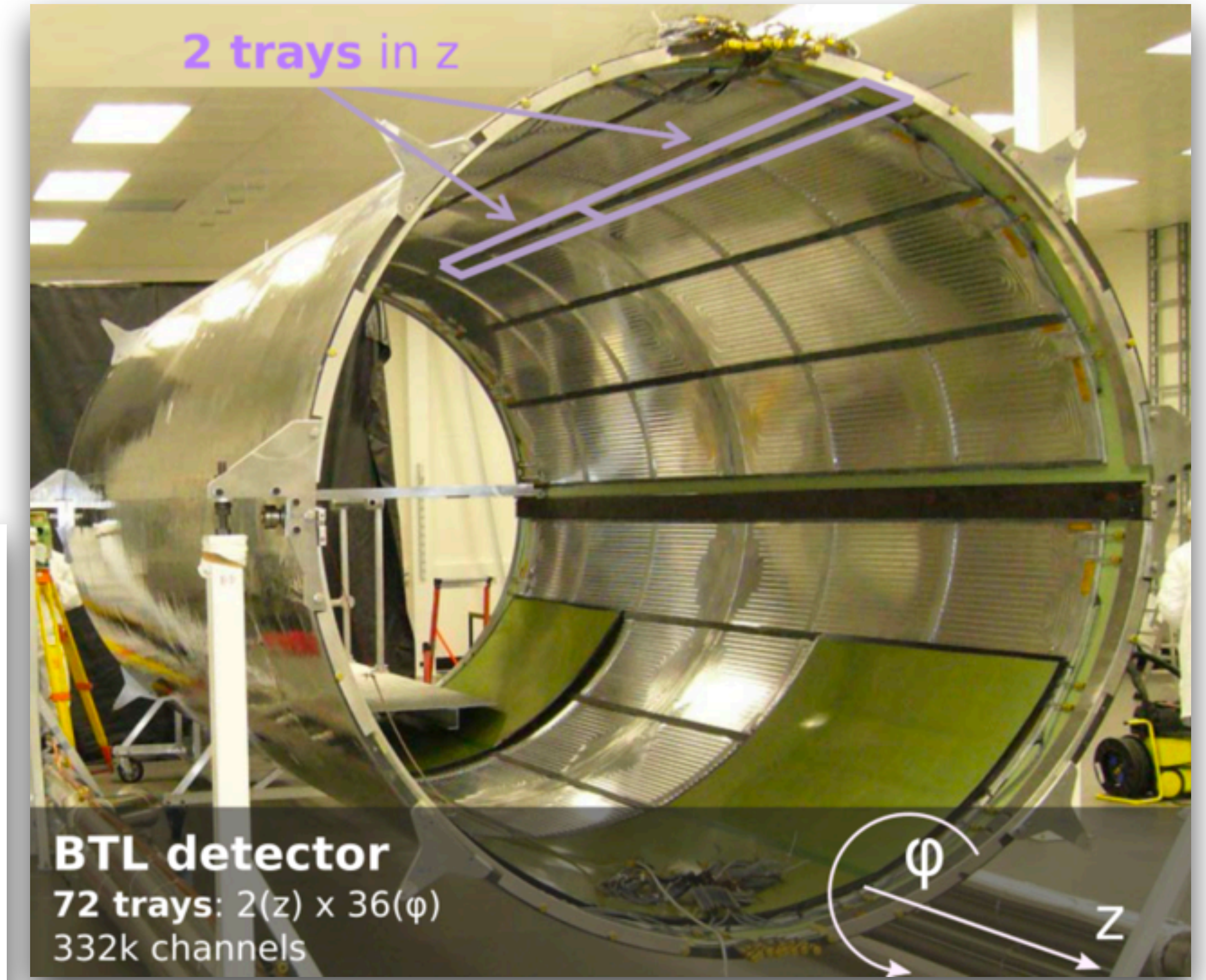
GMSB stau here has a very long lifetime crossing the full detector

Barrel Timing Layer

MTD TDR 8

- BTL will be installed between the inner tracker and the electromagnetic calorimeter of CMS
- Have one cylindrical layer covering $|\eta| < 1.48$ with an acceptance for muons ($p_T > 0.7$ GeV) of ~90% limited by supporting rails of the Tracker and small dead areas between sensor modules

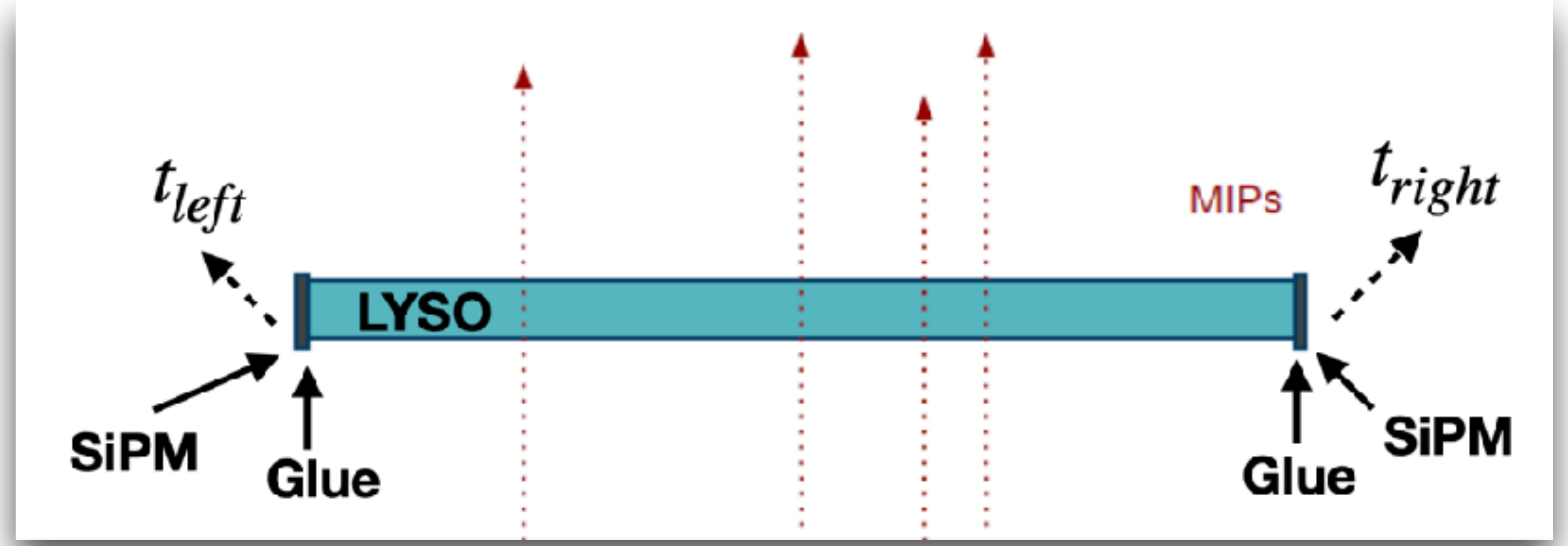


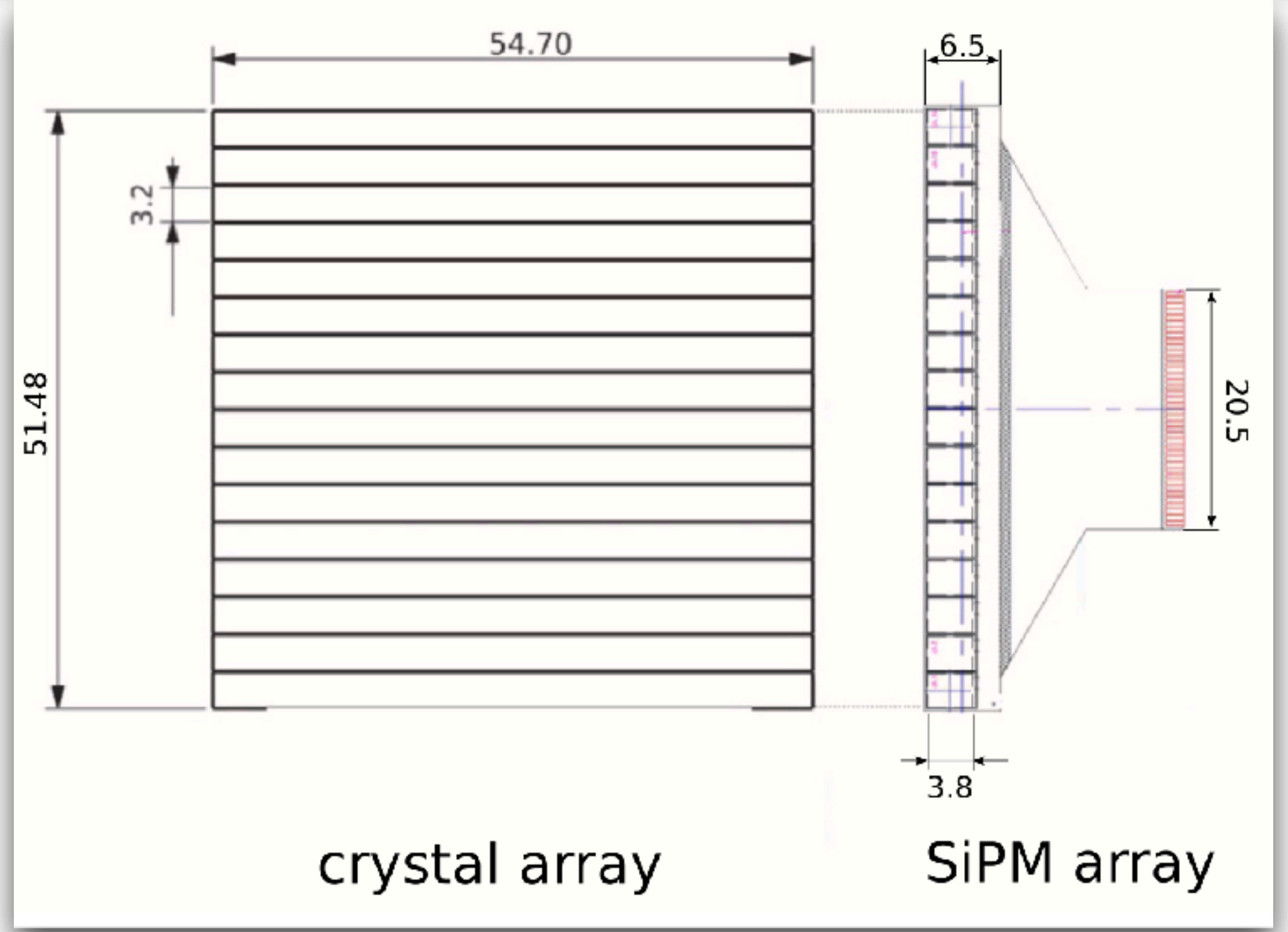


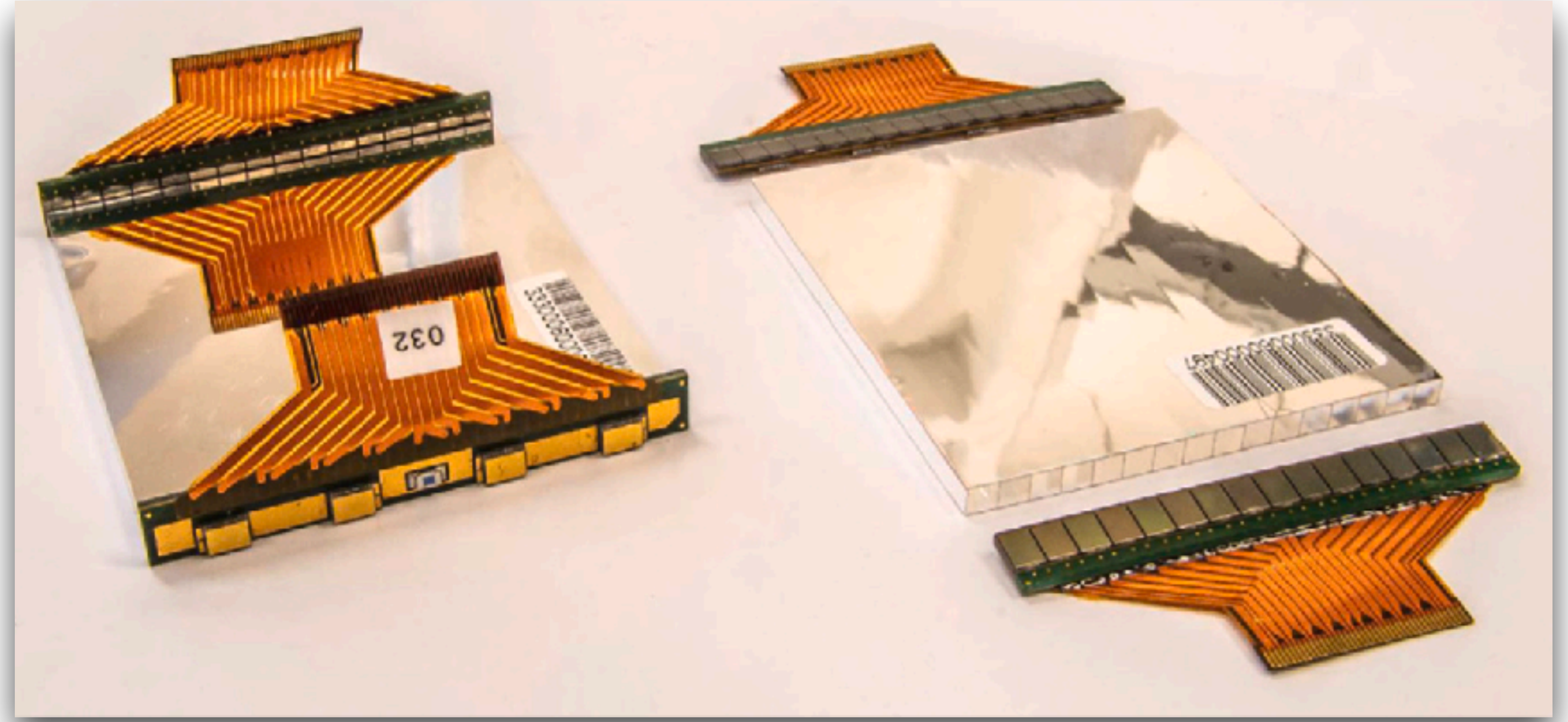
- Surface ~38 m2
- Inner radius 1148 mm
- Total thickness 40 mm
- Total length 5200 mm with 36 trays in +Z and another 36 in -Z

Sensor design

- Sensor consists of a LYSO:Ce crystal bar coupled with SiPM in two ends
  - LYSO bar: 54.7 × 3.12 × 3.75 mm^3
  - SiPM: 2.91 × 3.80 mm^2
- Sensor module is made of 1 array of 16 crystal bars and 2 arrays of 16 SiPMs

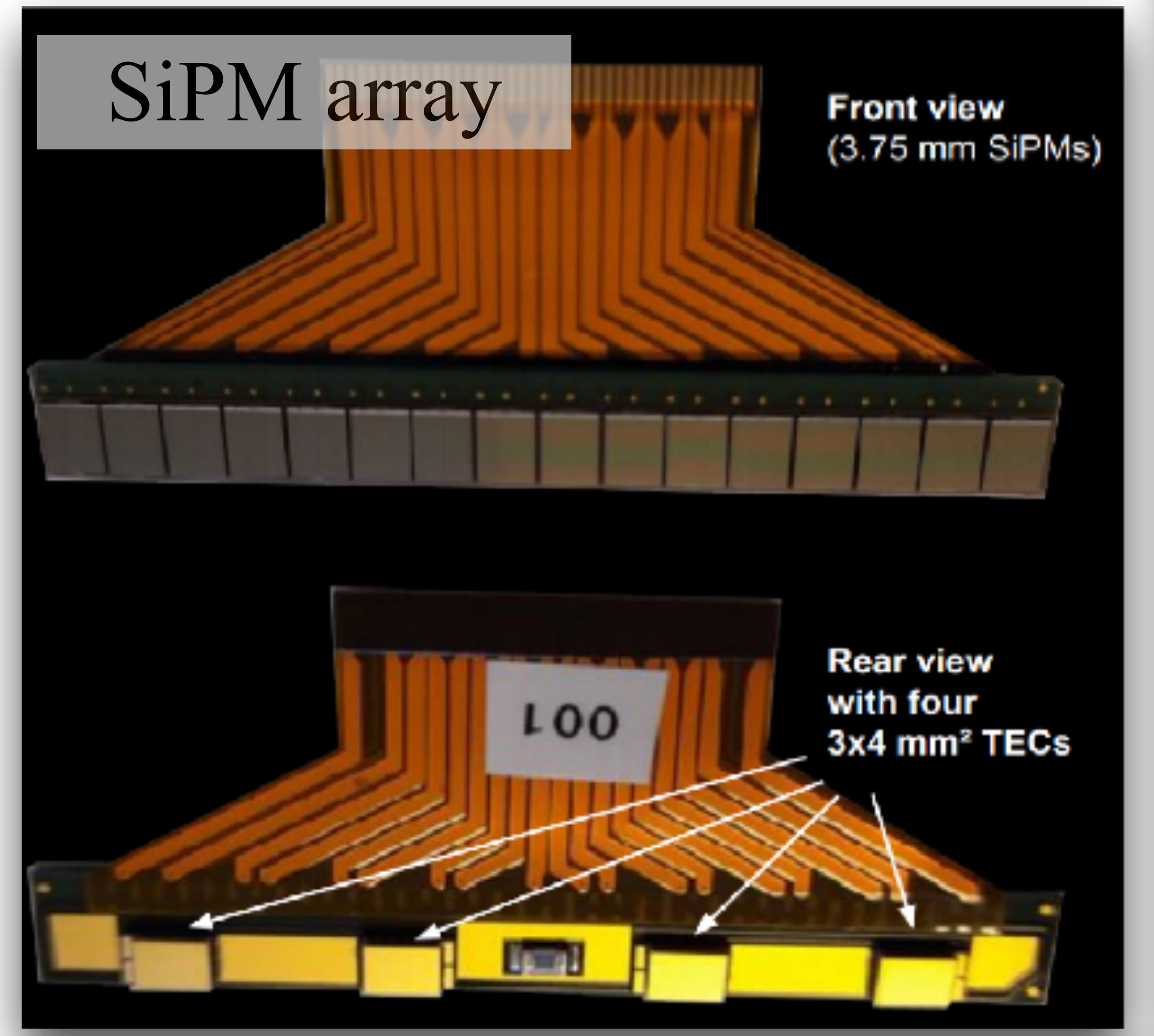


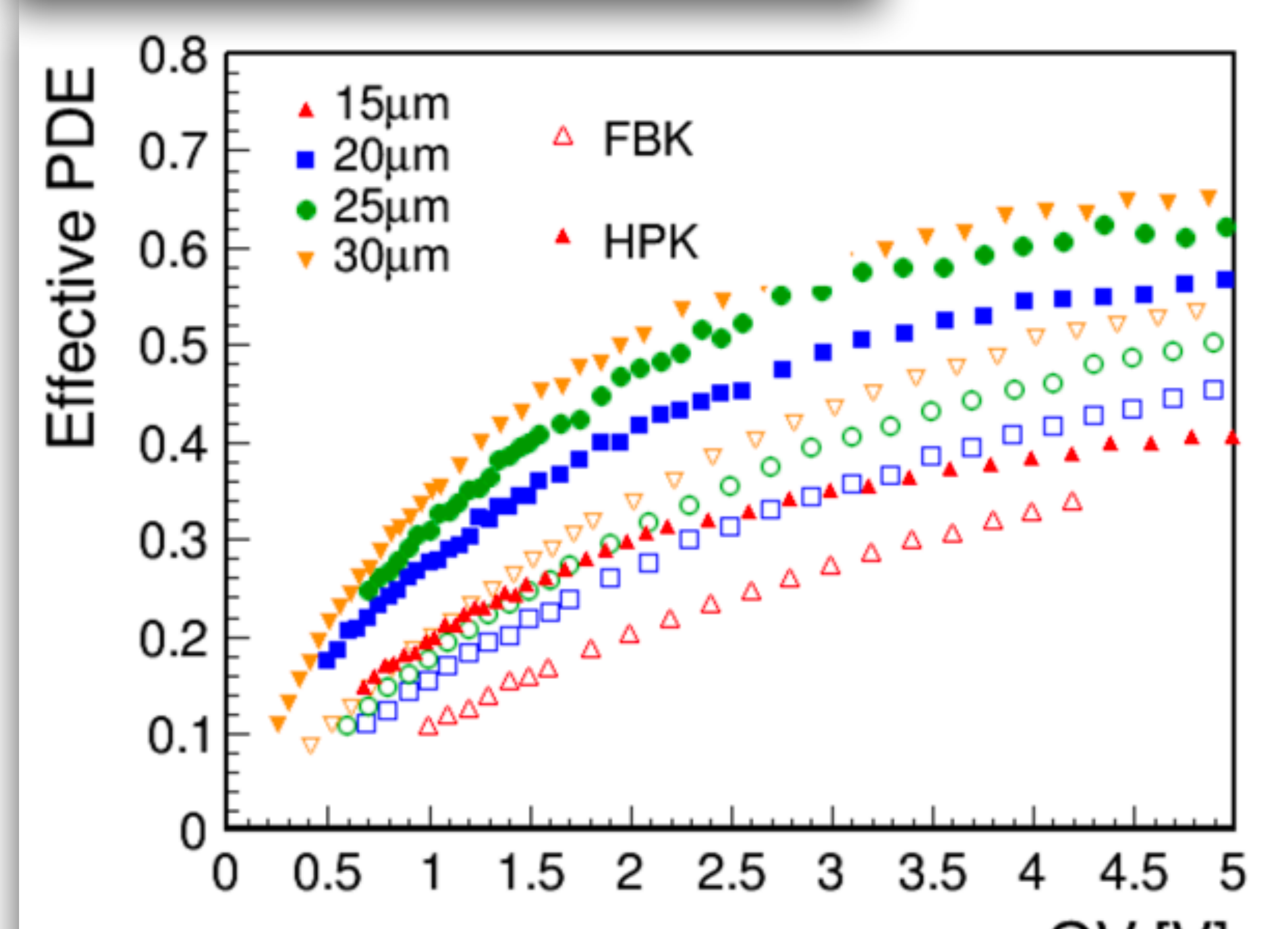




Sensor properties

- LYSO:Ce scintillator crystal bars
  - Fast rising (~100 ps) and decay time (~40 ns)
  - High light output: 40000 photons/MeV
  - Radiation hard, proven up to 50 kGy with gamma radiation from ^{60}Co and 3×10^{14} N_{eq}/cm^2 with 1 MeV neutron
  - Mature technology in industry (PET)
- SiPM
  - Compact in size, insensible to magnetic fields
  - Fast recover time < 10 ns, high gain $\times10^5$
  - PDE peak matches LYSO emission peak (~420 nm)
  - Cooled to -35 C by CO2 and further down by -10 C with TECs 3x4 mm^2 x 0.9 mm for a lower DCR [2023 JINST 18 P08020]
- Readout by ASIC TOFHIR2C with differential leading edge discriminator for DCR reduction [2024 JINST 19 P05048]





2024 JINST 19 P12020

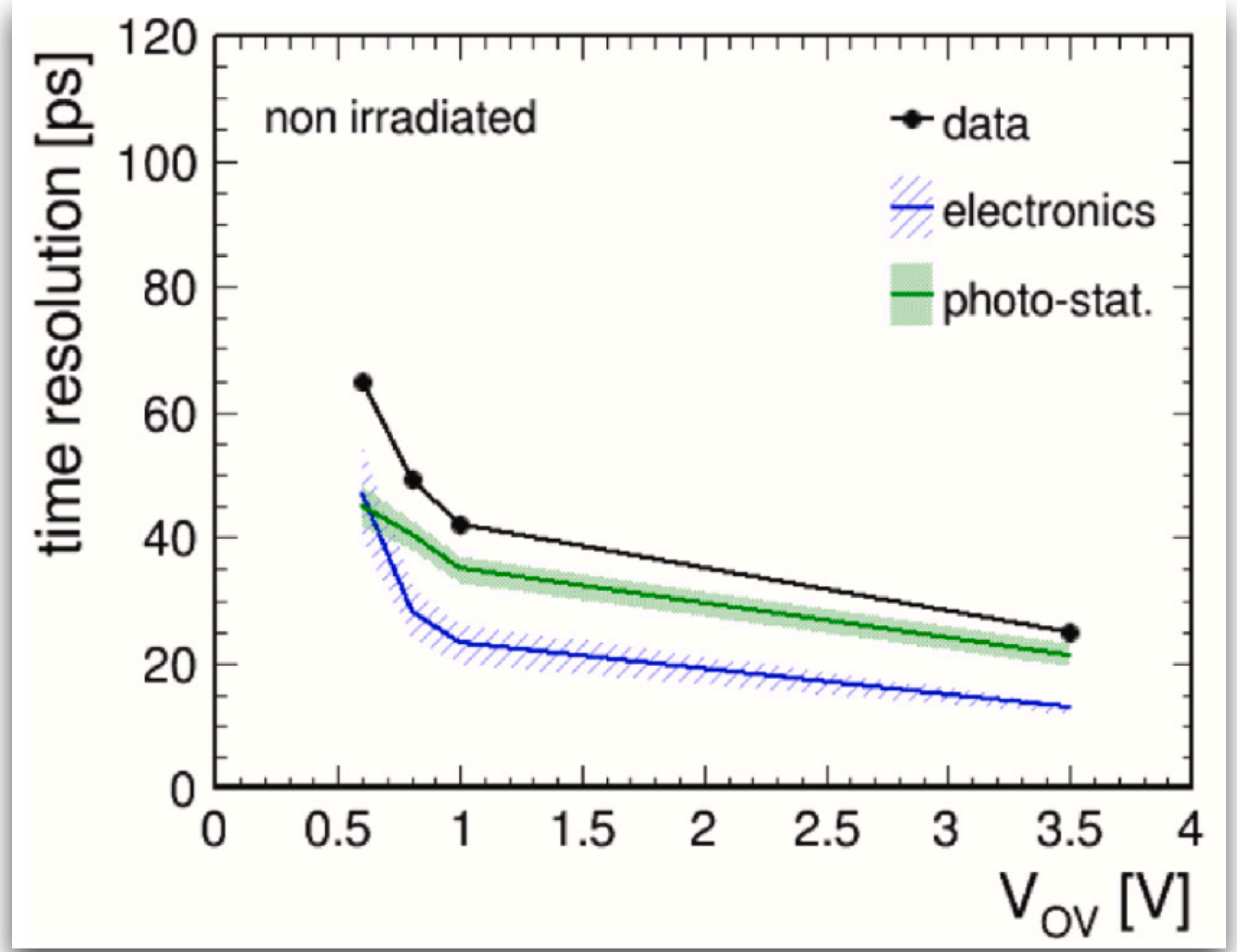
Time resolution

2024 JINST 19 P12020
NIMA 1081 (2026) 170823

- The time resolution is determined by several sources: electronic noise, photo-statistics, DCR noise and instabilities of the clock distribution (< 10 ps, negligible)

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

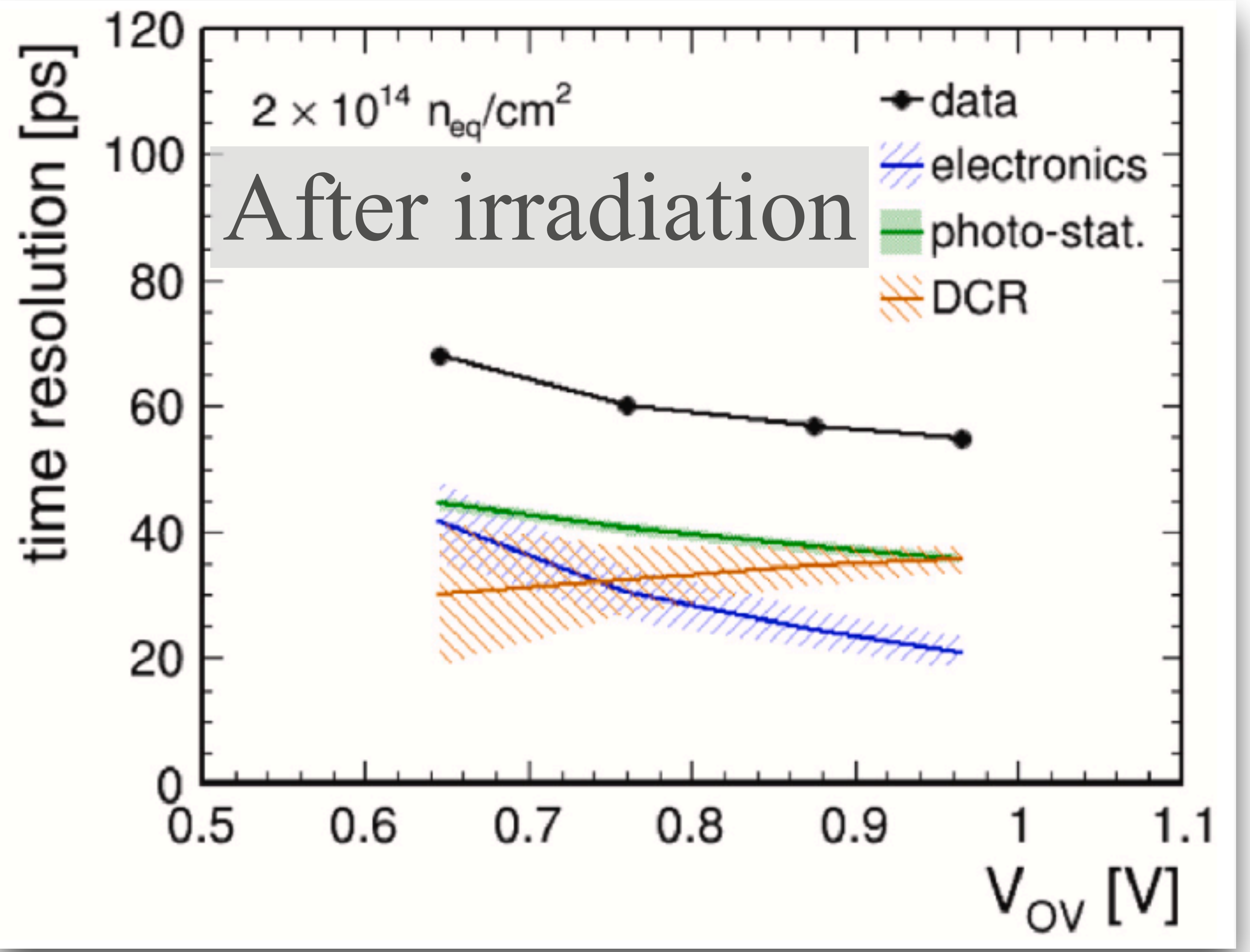
- $\sigma_t^{\text{ele}} = \frac{\sigma_{\text{noise}}}{dI/dt} \oplus \sigma_t^{\text{TDC}}$, electronic noise, depending on slope of signal pulses at the timing threshold and the TDC precision (16 ps)
  - Lower N_{pe} (number of photo-electrons) and gain at lower over-voltage, degrading dI/dt, resulting in a larger contribution of $\sigma_{noise}/(dI/dt)$, while σ_t^{TDC} dominates in higher over-voltage
- $\sigma_t^{\text{phot}} \propto \frac{1}{N_{\text{pe}}^{\alpha}}$ ($\alpha \approx 0.5$), photo-statistics, statistical fluctuations in the time of arrival of the photons detected at the SiPMs, normally the leading factor in time resolution

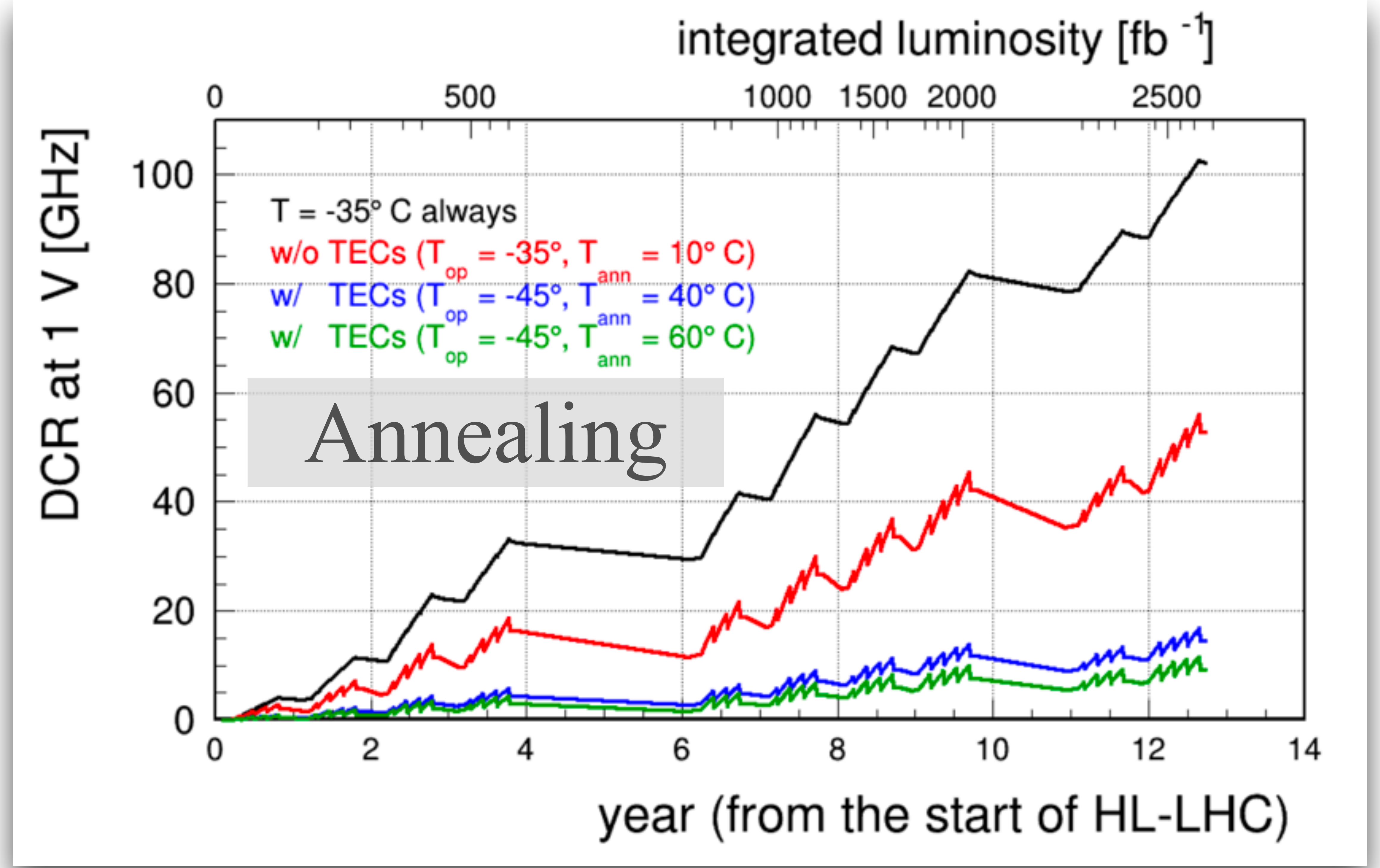


After irradiation

2023 JINST 18 P08020
NIMA 1081 (2026) 170823

- $\sigma_t^{\mathrm{DCR}} \propto \frac{\mathrm{DCR}^{\beta}}{N_{\mathrm{pe}}}$ ($\beta \approx 0.5$), DCR noise, increasing with DCR that ramps up after irradiation
  - DCR increase can be mitigated by annealing between operations
  - CO2 provides ~10 C and TECs heats up by another ~50 C, reaching ~60 C for annealing



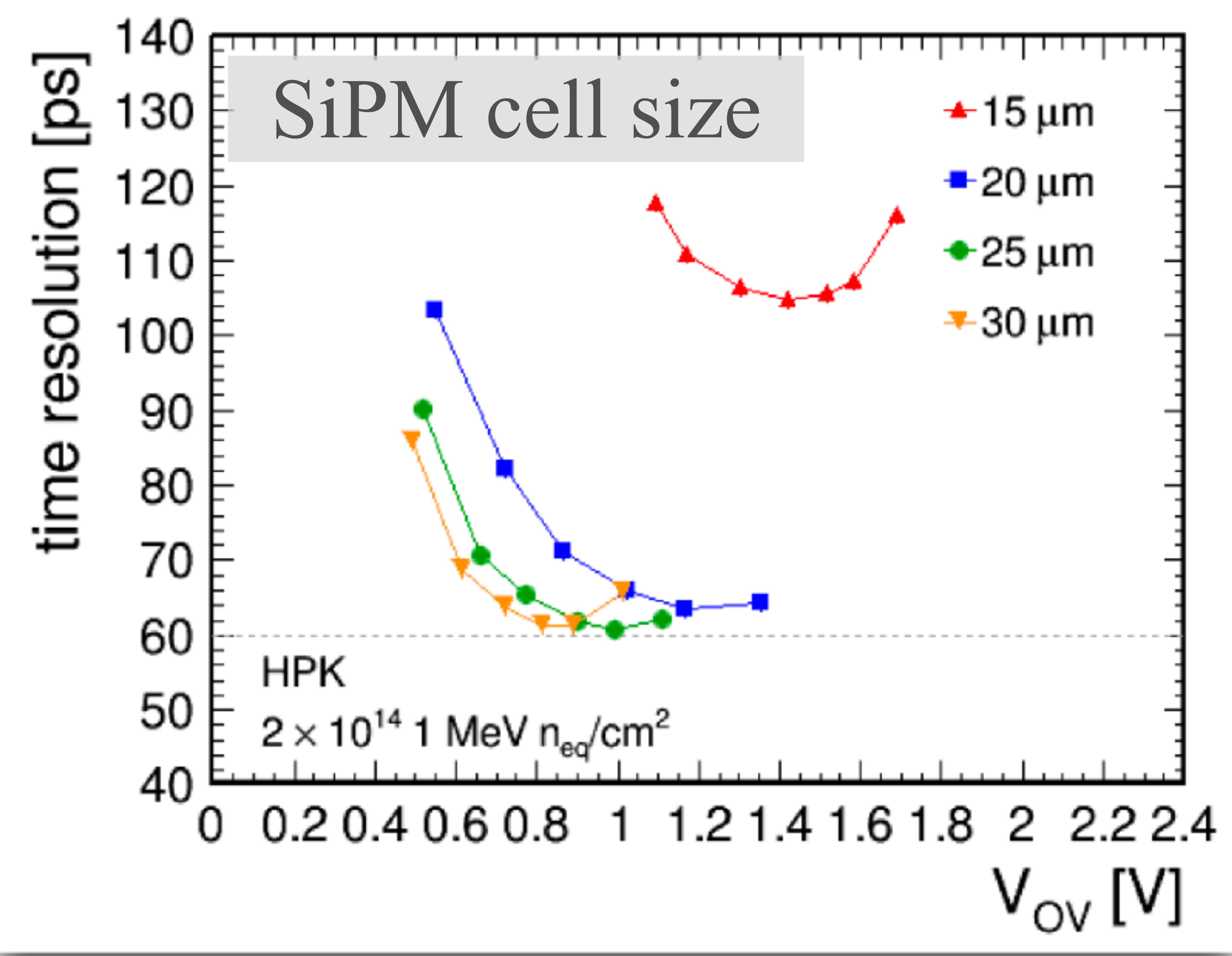


Sensor optimisation

2023 JINST 18 P08020
2024 JINST 19 P12020

$$N_{\text{pe}} = E_{\text{dep}} \cdot \text{LY} \cdot \text{LCE} \cdot \text{PDE}$$

- Lower DCR and higher N_{pe} are essential in the sensor optimization for time resolution
  - Operation with CO2+TECs at -45 C temperature (DCR reduces to half with ΔT = -10 C)
  - Annealing with TECs at 60 C to mitigate DCR
  - Larger cell-size SiPM (higher gain and PDE thus bigger N_{pe}, but larger DCR)
    - Still gain as $\sigma_t^{\text{DCR}} \propto \frac{\text{DCR}^{\beta}}{N_{\text{pe}}}$ with $\beta \approx 0.5$
  - Thicker LYSO bars to increase the energy deposit E_{dep}
  - Removal of glue between LYSO and wrapper to have higher LCE (light collection efficiency)



Beam tests

2023 JINST 18 P08020
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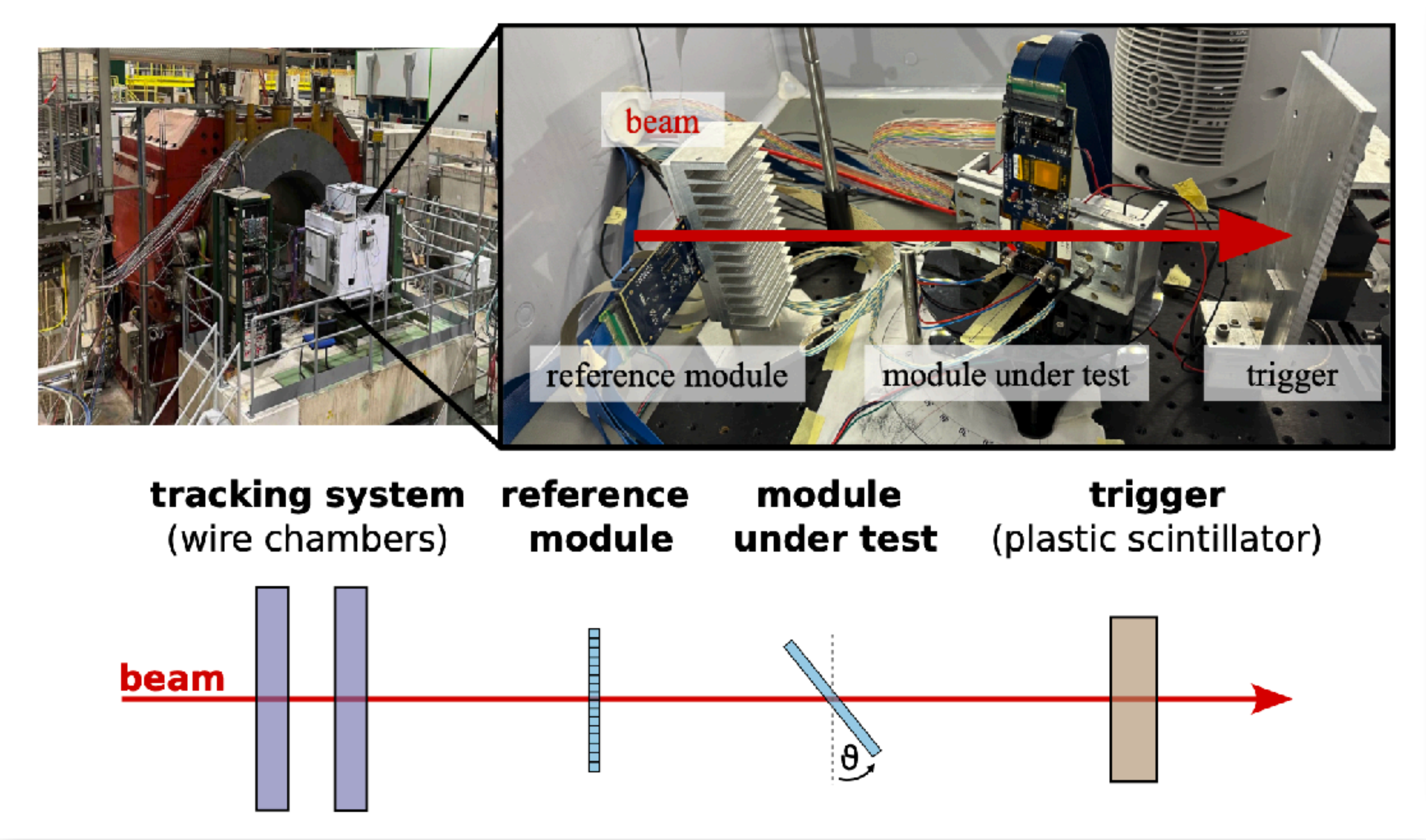
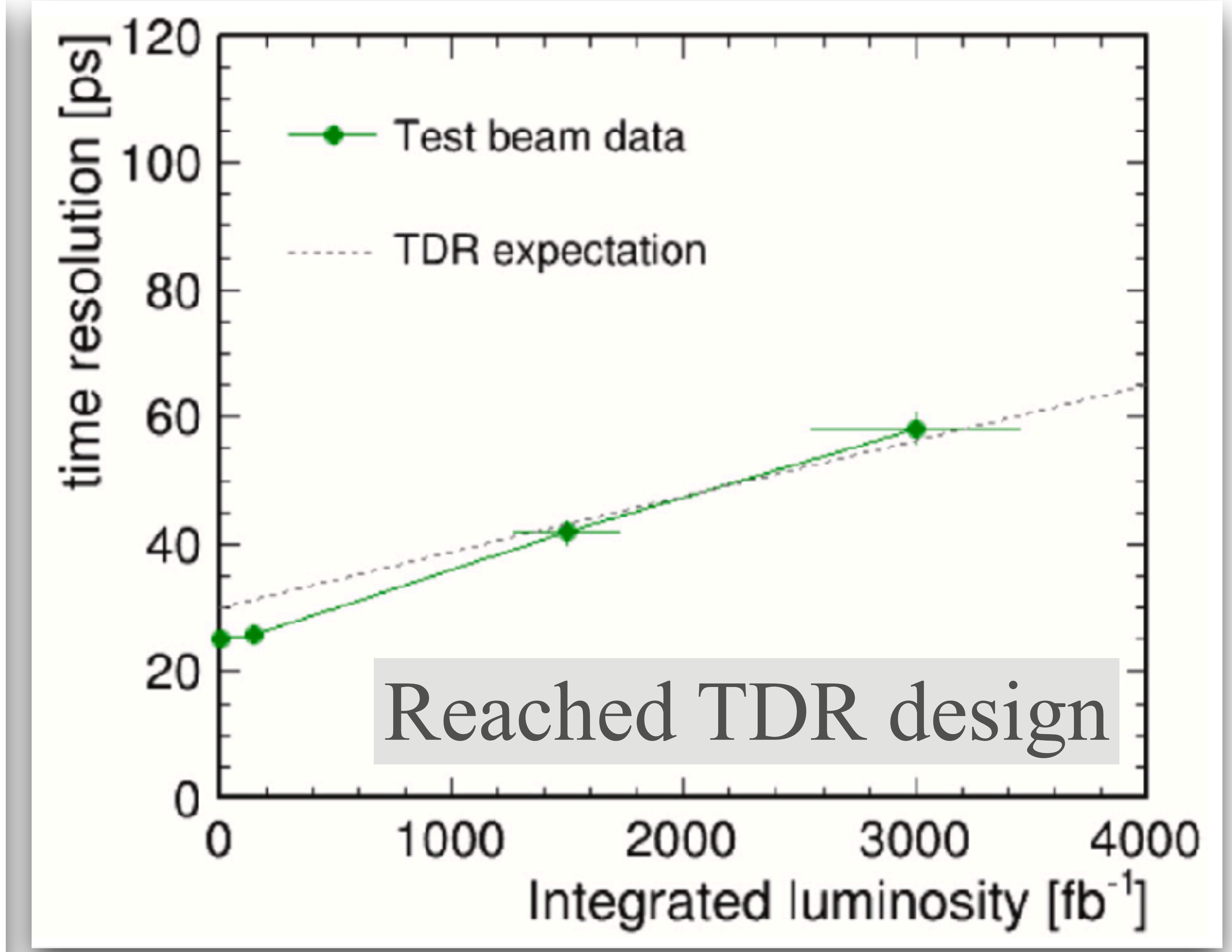
- Performed series of beam tests at CERN H8 and Fermilab
- Reached time resolution of 25 ps before irradiation and 55 ps after irradiation of HL-LHC operation



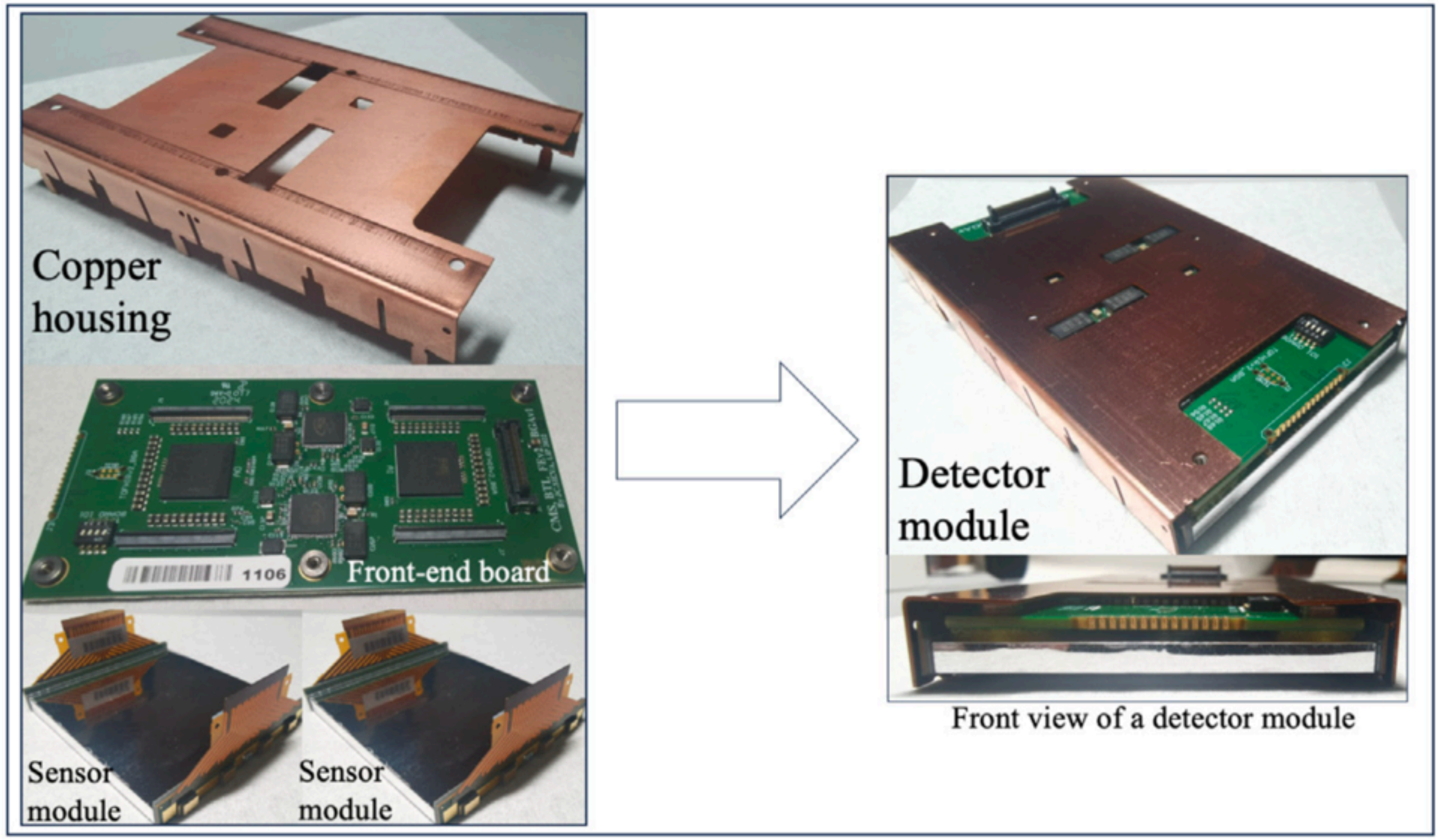


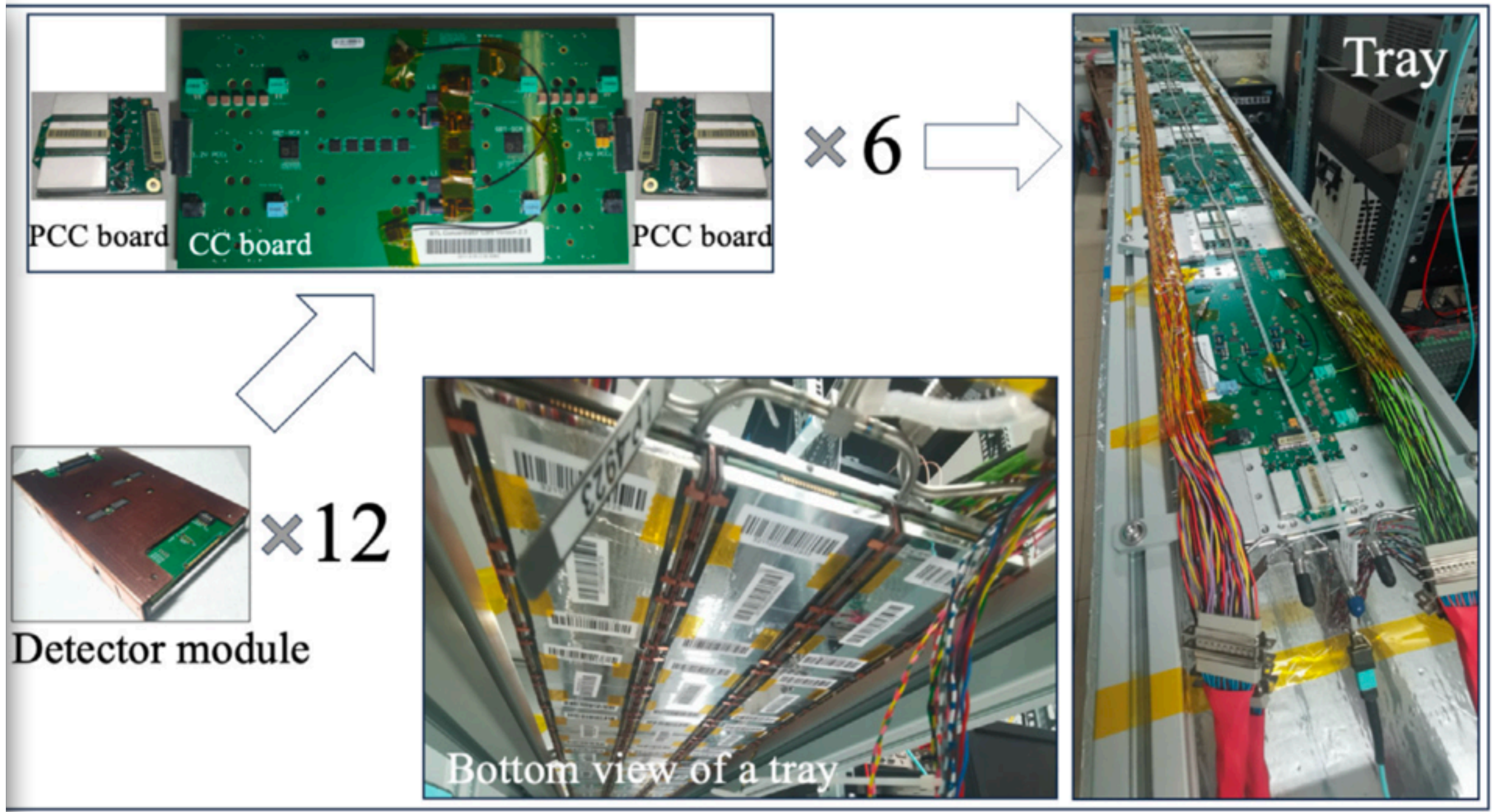
Assembly

MTD TDR
Physics Reports 1156 (2026) 1–39

- Entered the phase of assembly of the detector
- Global assembly centers: Caltech, Beijing, Milano, Virginia
- Sensor Modules → Detector Modules → Readout Unit → Tray

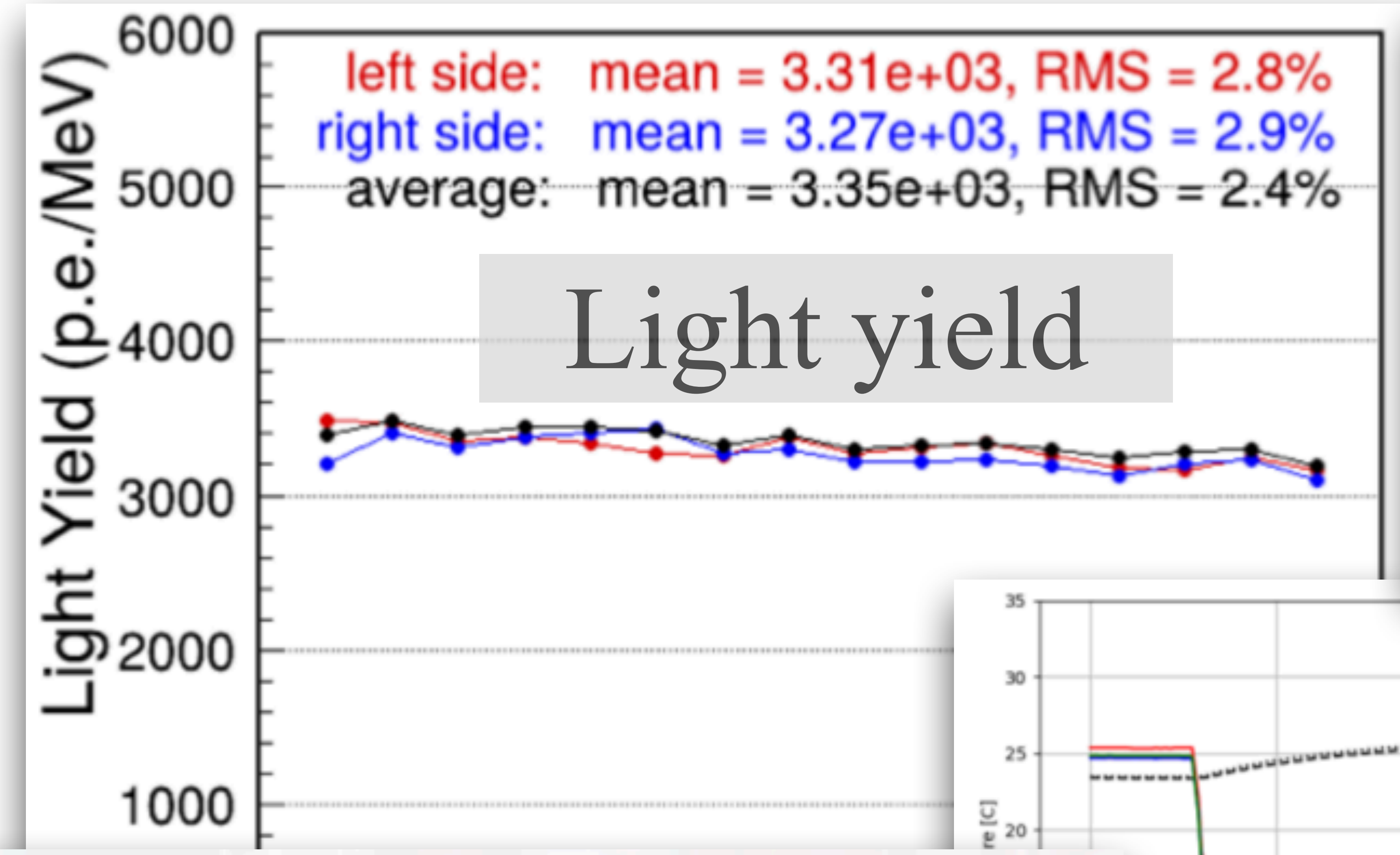
	Module	RU	Tray	Total
Channels (SiPMs)	32	768	4608	331776
Crystals	16	384	2304	165888
ASICs	1	24	144	10368
Modules	-	24	144	10368
Readout units (RU)	-	-	6	432
Trays	-	-	-	72

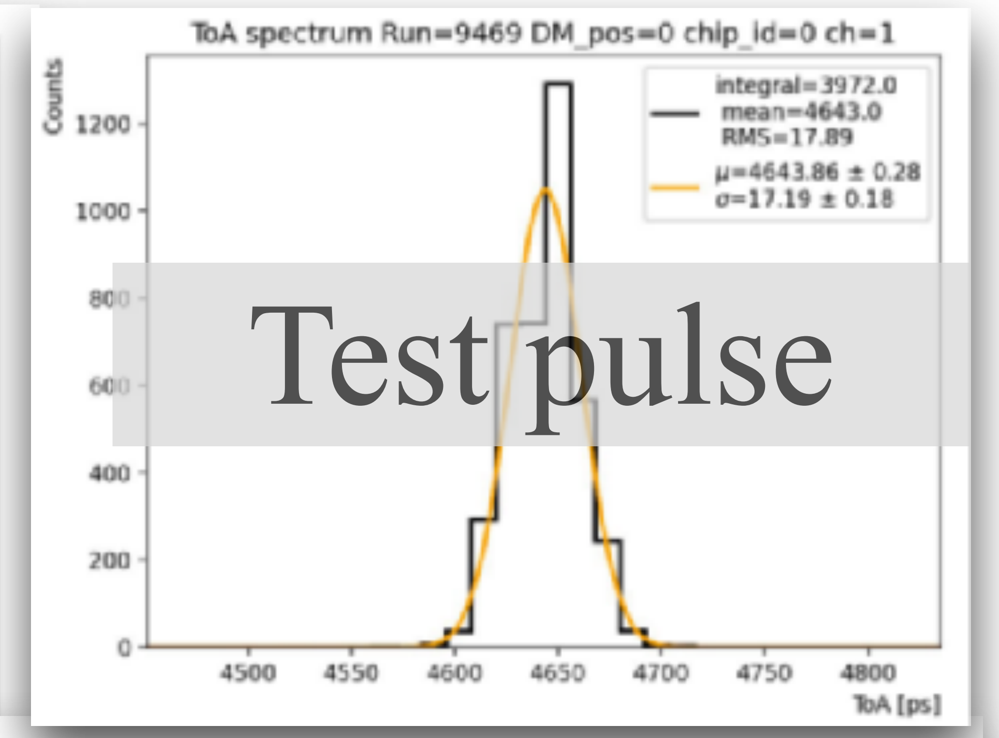


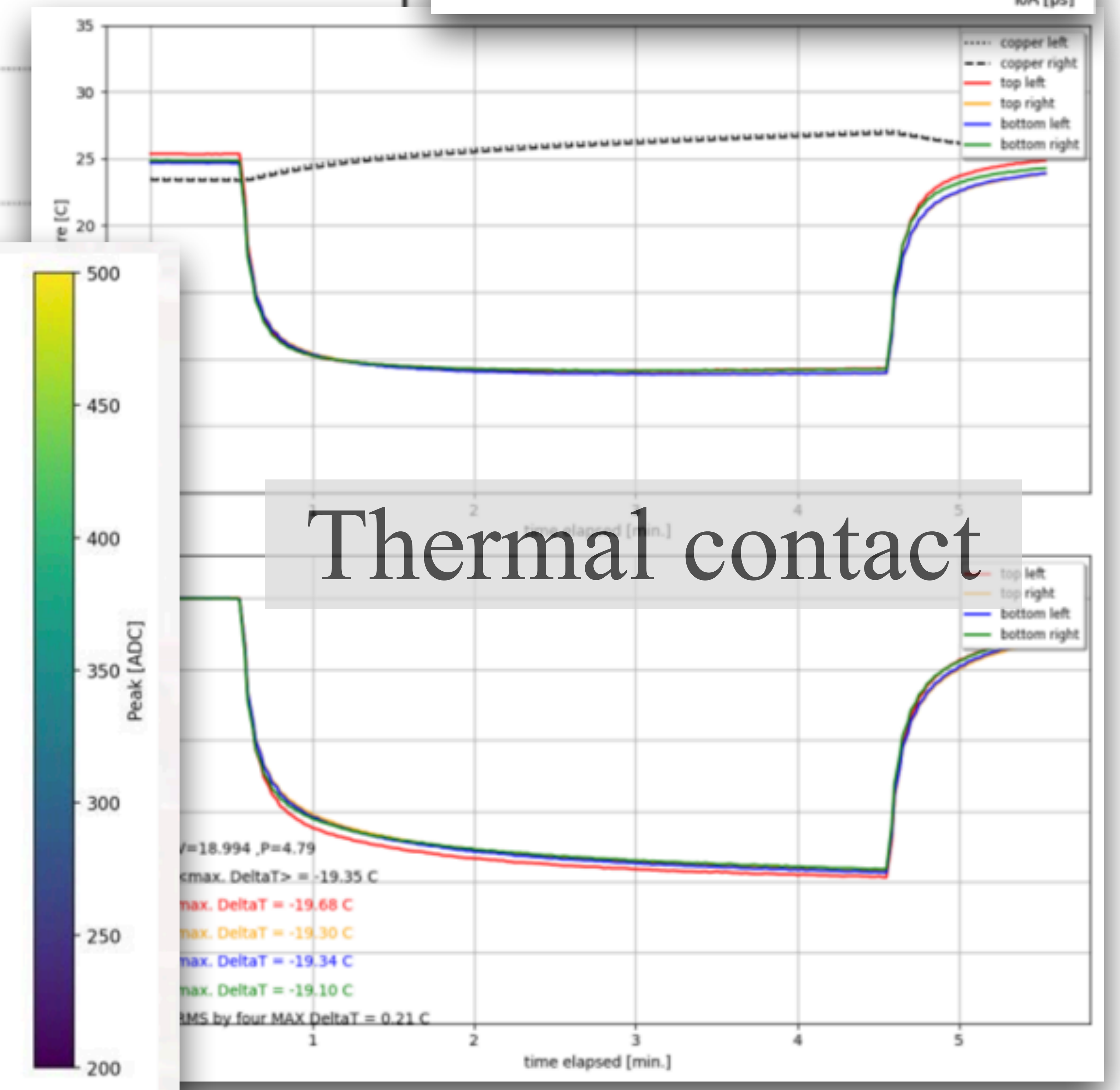


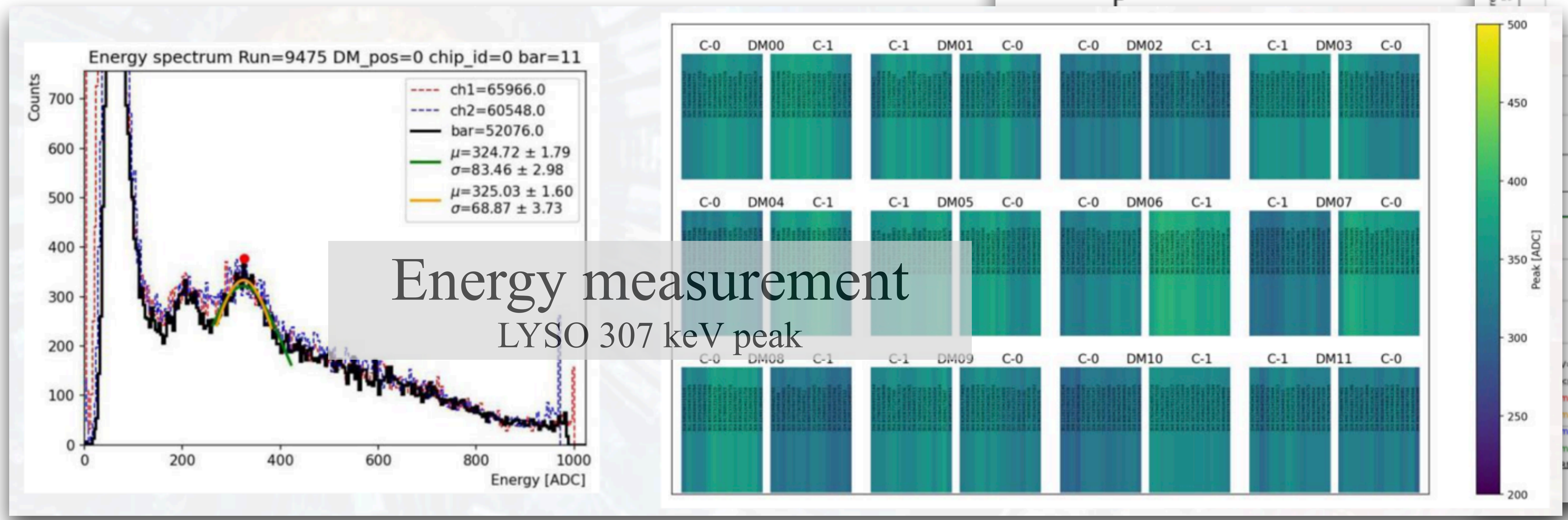
Quality assuring/control

- Stringent QA/QC are performed on each produced model and their integration
- Tests cover the light yield, energy resolution, thermal contact, readout with front-ends etc.





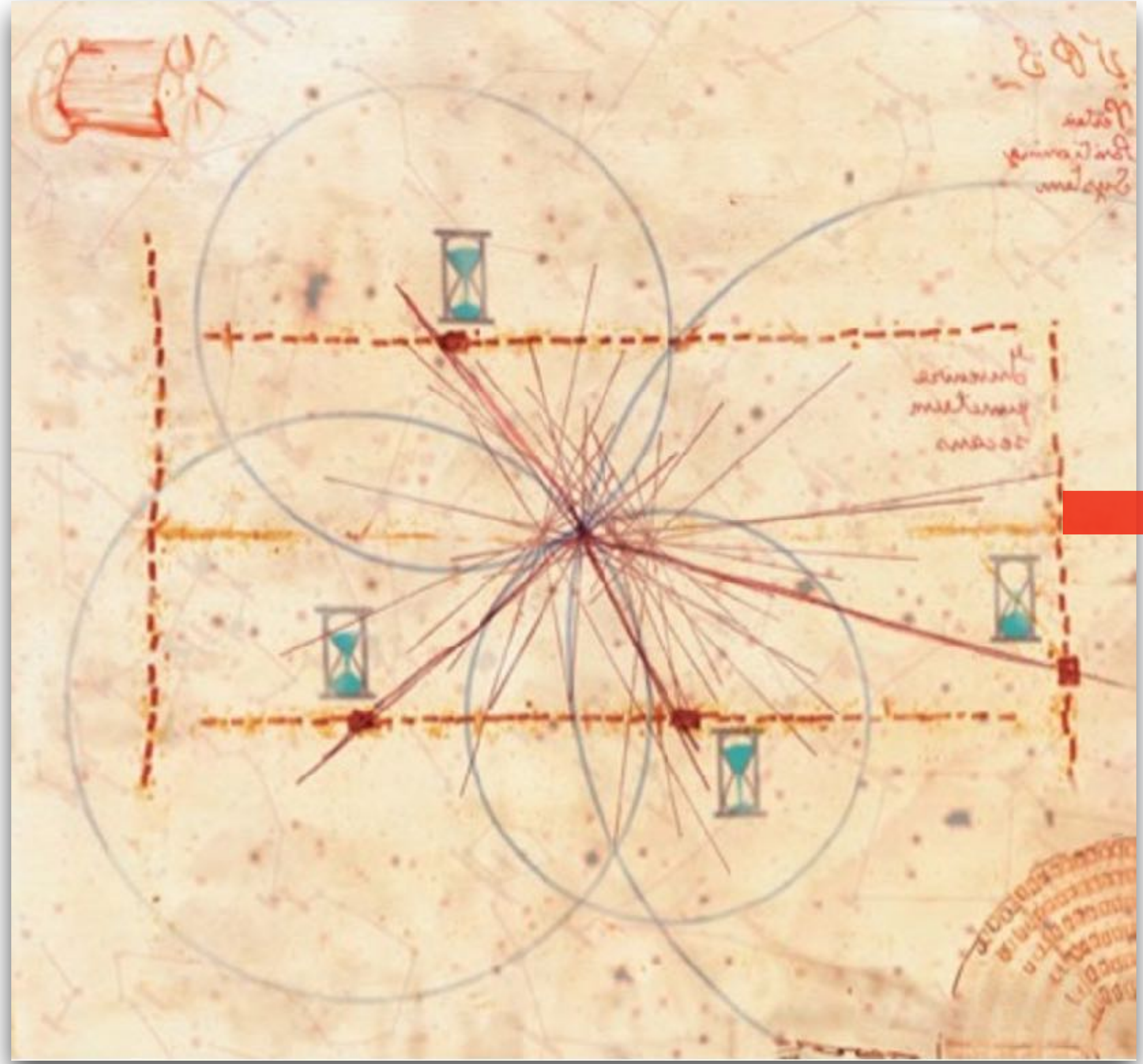


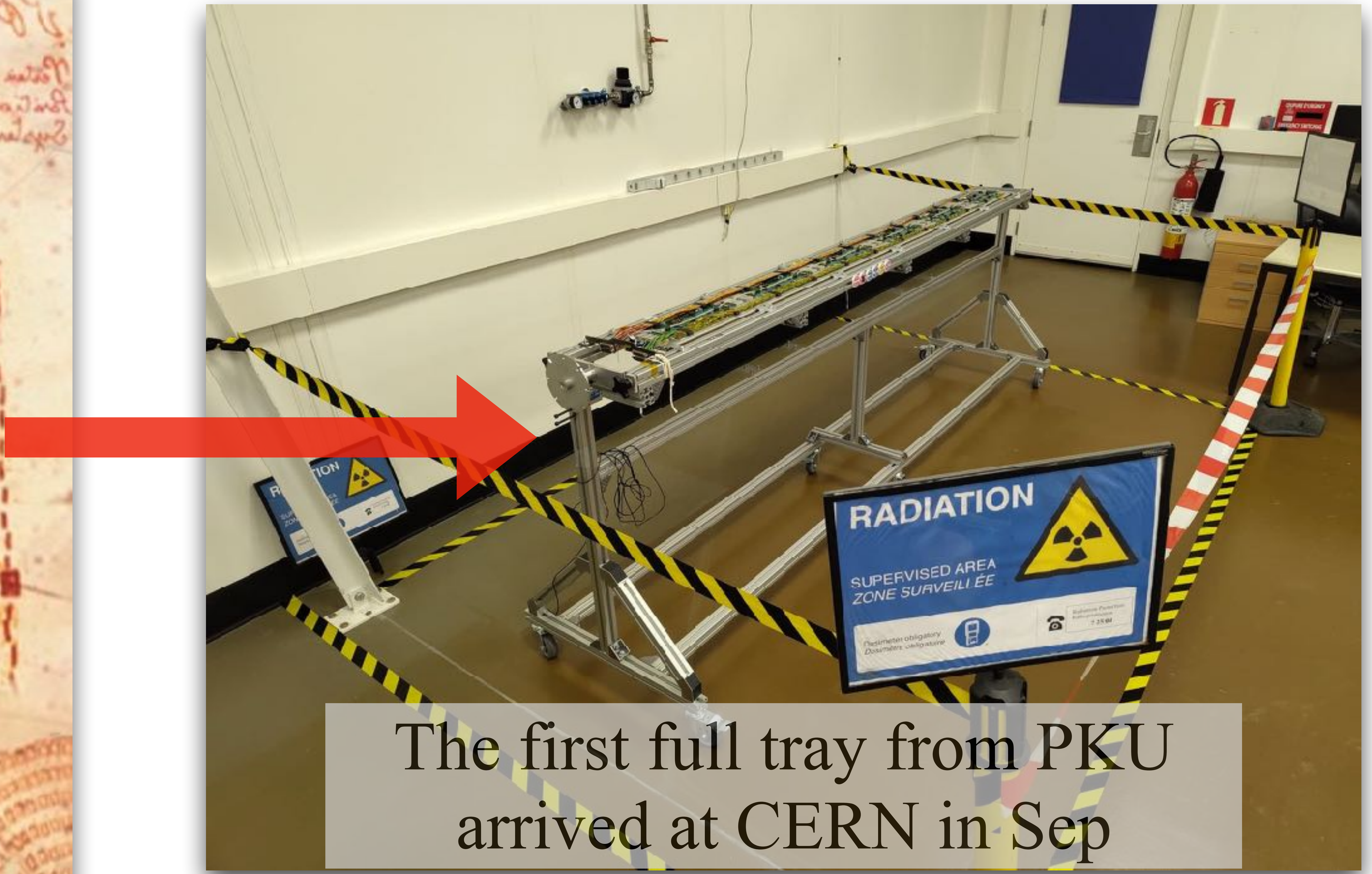


Summary

- A novel detector MTD was proposed to mitigate the high pileup effect in HL-LHC by labeling the MIP tracks with precision timing information
  - Essential to keep excellent sensitivity of CMS physics programs in the HL-LHC era
  - Open new windows to BSM searches such as LLP
- The MTD Barrel Timing Layer was designed and was verified to reach target of 25 (55) ps in the beginning (end) of HL-LHC operation at testbeam
- The assembly of the detector have started and is undergoing with high momentum
  - More than 90% of sensor modules and 70% of detector modules have been produced and qualified. About 30% of trays assembled
  - The first fully dressed tray arrived at CERN from oversea
- The installation and commissioning of BTL is expected in 2026

One step closer to the real BTL





Backup

CMS @ LHC

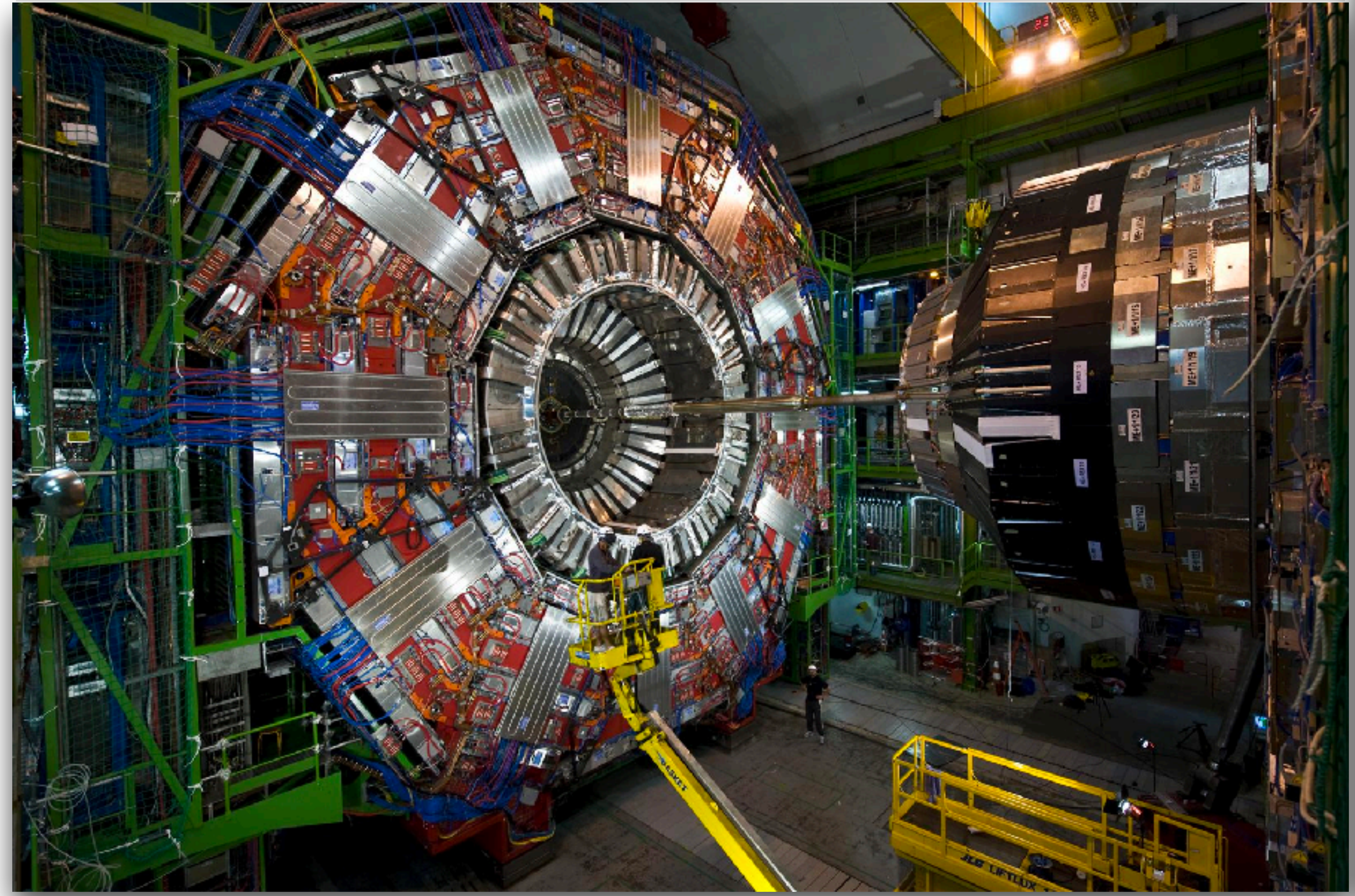
CMS a general purpose detector @ LHC

Total weight: 14000 tonnes

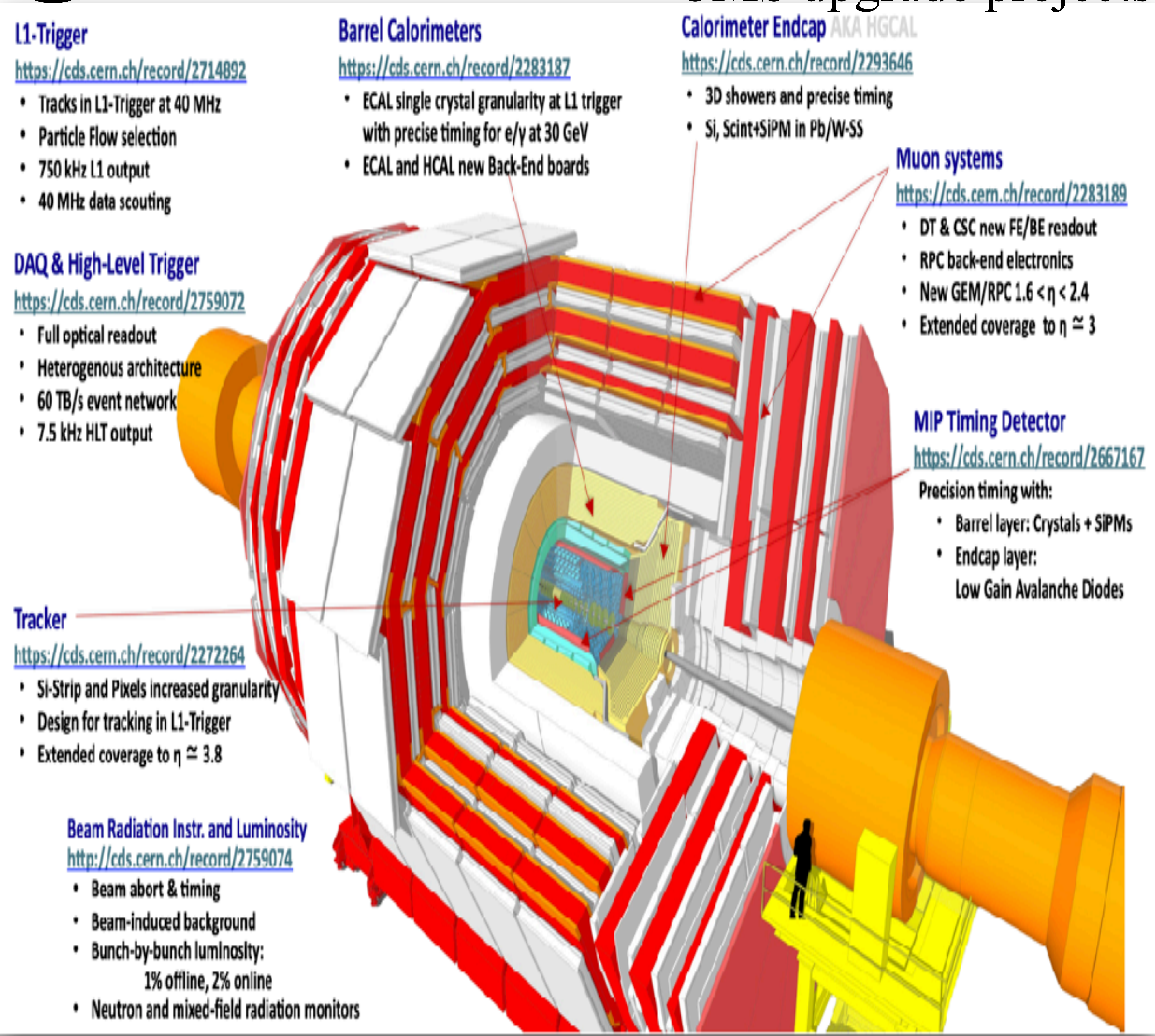
Overall diameter: 15.0 m

Overall length: 28.7 m

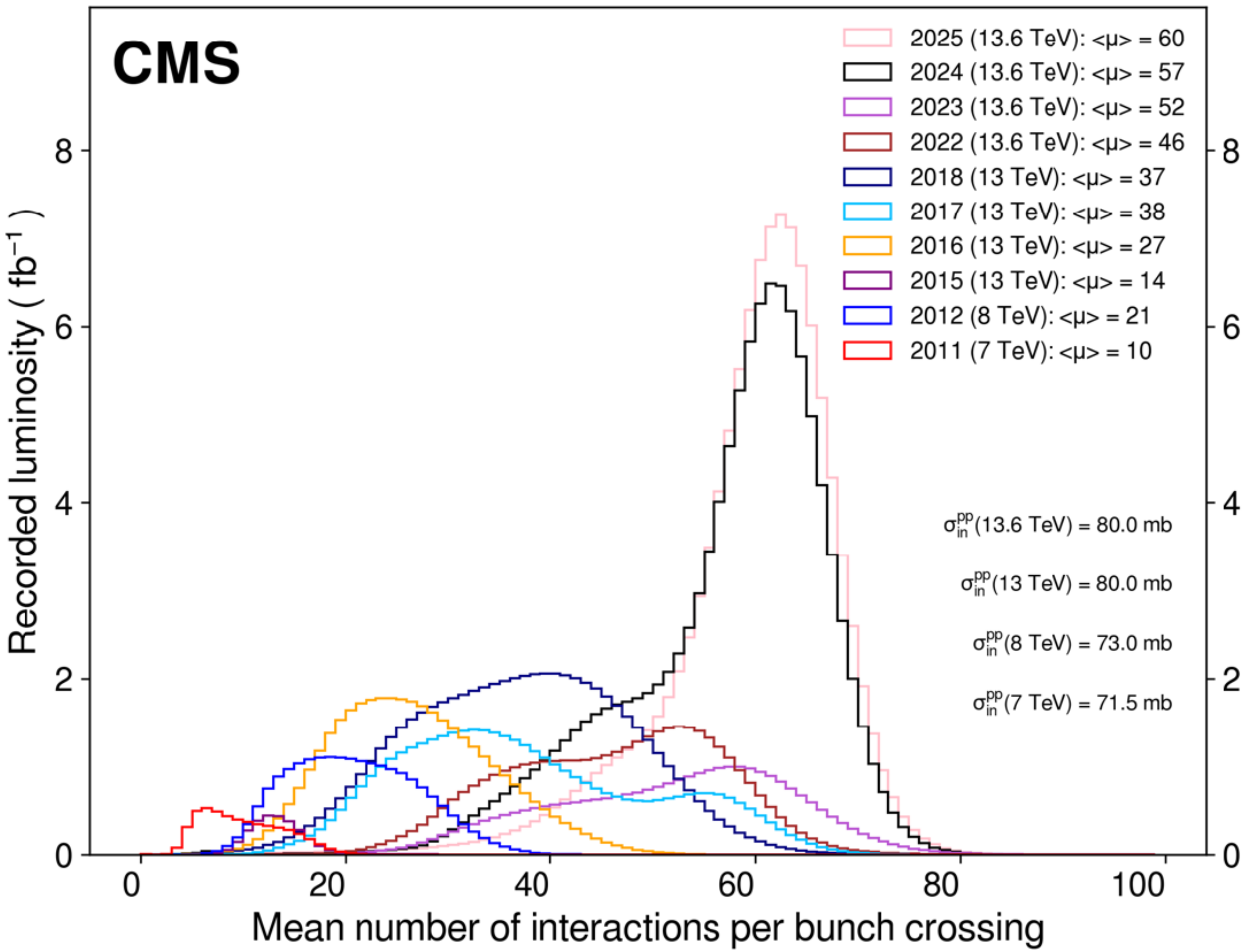
Magnetic field: 3.8 T



CMS upgrade projects



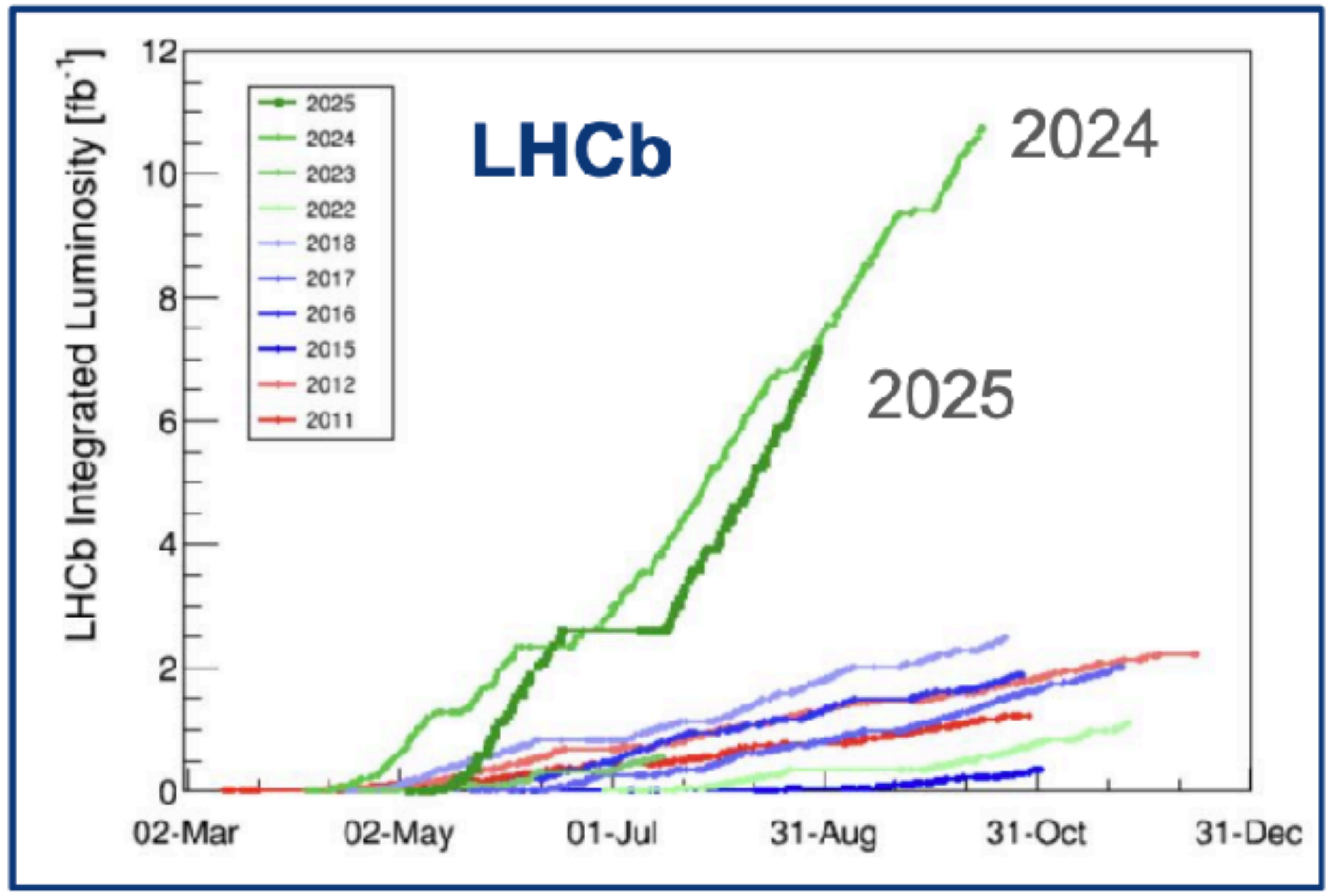
Pileup

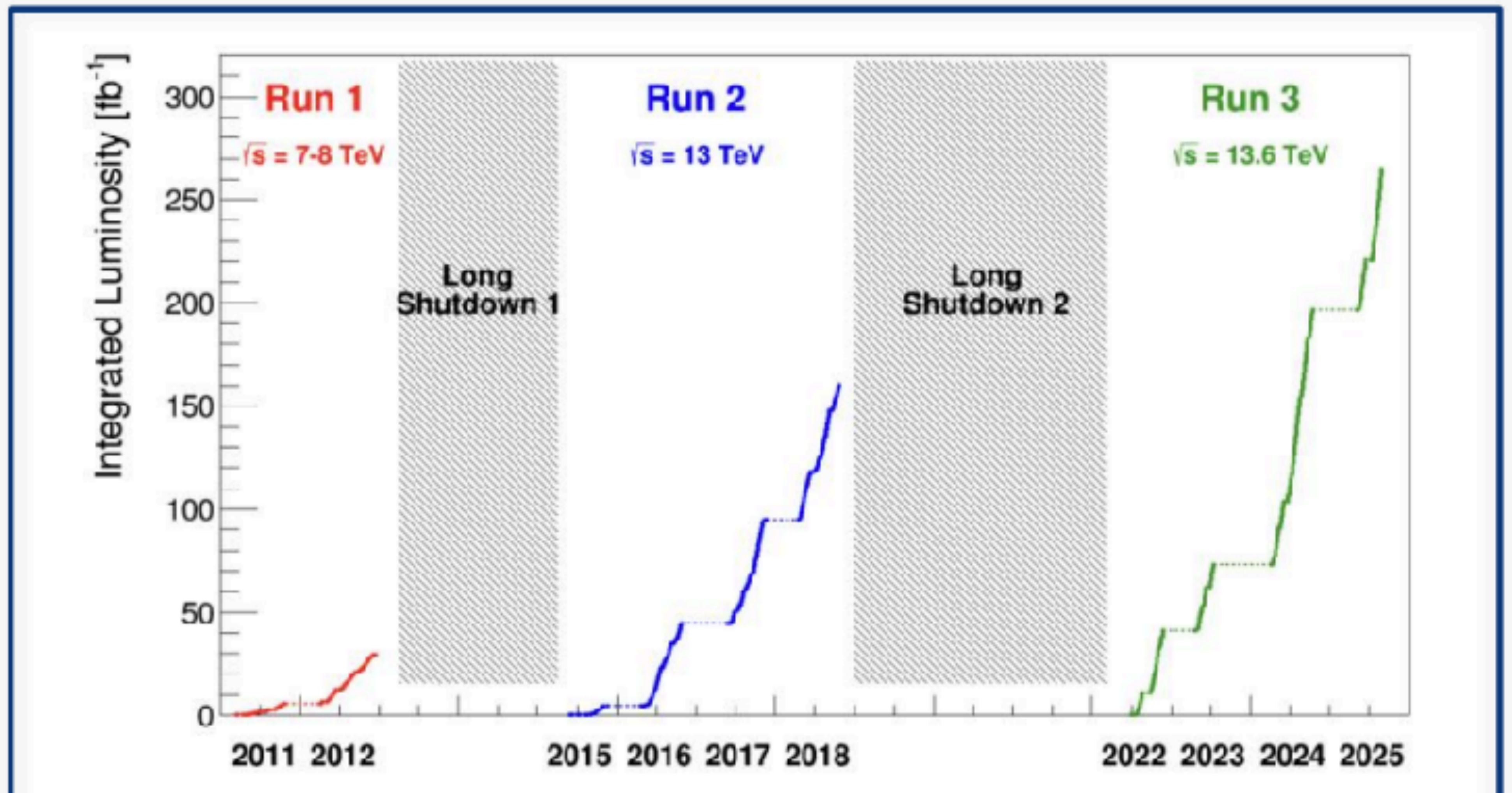

CMS
2025 (13.6 TeV): <μ> = 60
2024 (13.6 TeV): <μ> = 57
2023 (13.6 TeV): <μ> = 52
2022 (13.6 TeV): <μ> = 46
2018 (13 TeV): <μ> = 37
2017 (13 TeV): <μ> = 38
2016 (13 TeV): <μ> = 27
2015 (13 TeV): <μ> = 14
2012 (8 TeV): <μ> = 21
2011 (7 TeV): <μ> = 10
σ_{in}^{pp}(13.6 TeV) = 80.0 mb
σ_{in}^{pp}(13 TeV) = 80.0 mb
σ_{in}^{pp}(8 TeV) = 73.0 mb
σ_{in}^{pp}(7 TeV) = 71.5 mb
Recorded luminosity (fb^{-1})
Mean number of interactions per bunch crossing
0
2
4
6
8
20
40
60
80
100

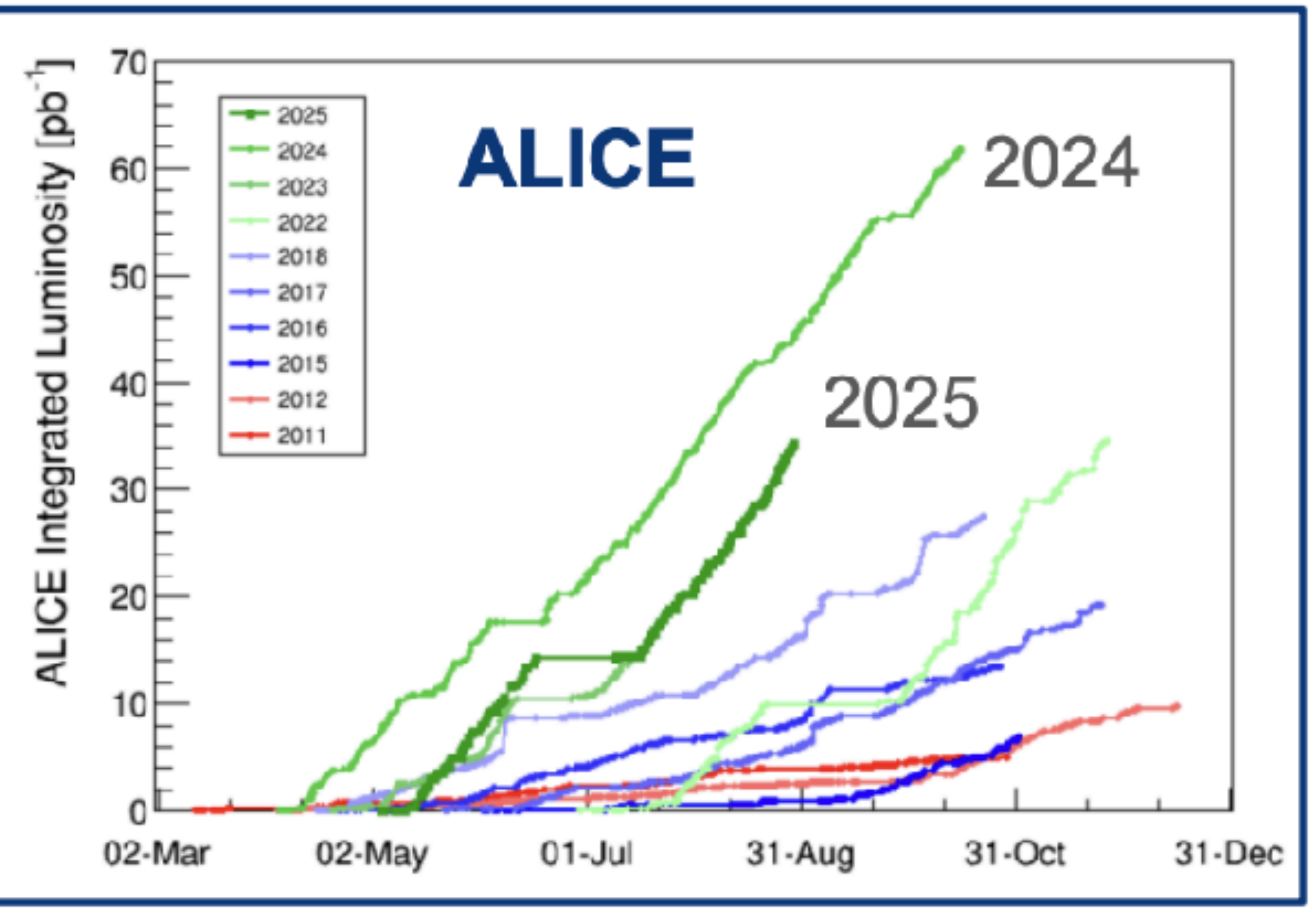
2025 so far…

- **~70 fb^{-1}** in ATLAS/CMS
- **7.2 fb^{-1}** in LHCb
- **~35 pb^{-1}** in ALICE

Full steam production on-going!

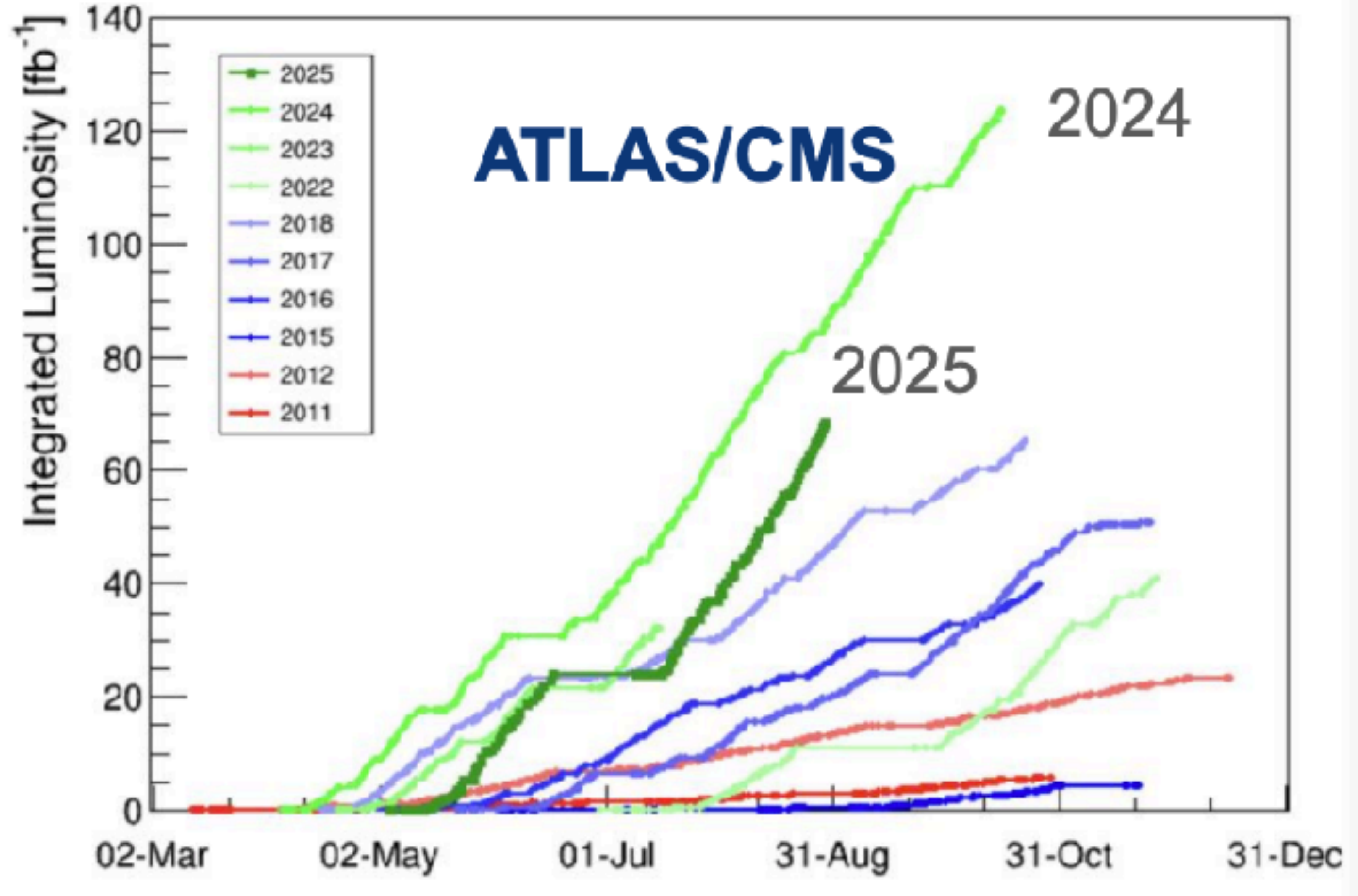






Record 24h rate = **1.7 fb^{-1}/24h**
(midnight to midnight on August 30)

Record 7-day rate = **9.1 fb^{-1} / 7d**
(August 24 to 30)



https://indico.cern.ch/event/1571894/

SiPM optimisation

Table 1. Comparative table of fill factor, PDE, and gain at $V_{OV} = 3.5$ V for different cell sizes.

Producer	Cell Size (μm)	Fill Factor	PDE	Gain ($\times 10^6$)
HPK	15	0.61	0.36	0.39
	20	0.70	0.51	0.68
	25	0.76	0.57	1.05
	30	0.80	0.60	1.49
FBK	15	0.65	0.35	0.43
	20	0.73	0.45	0.70
	25	0.77	0.50	1.02
	30	0.80	0.54	1.40