Precision timing with the CMS ETL detector in the Phase 2 upgrade

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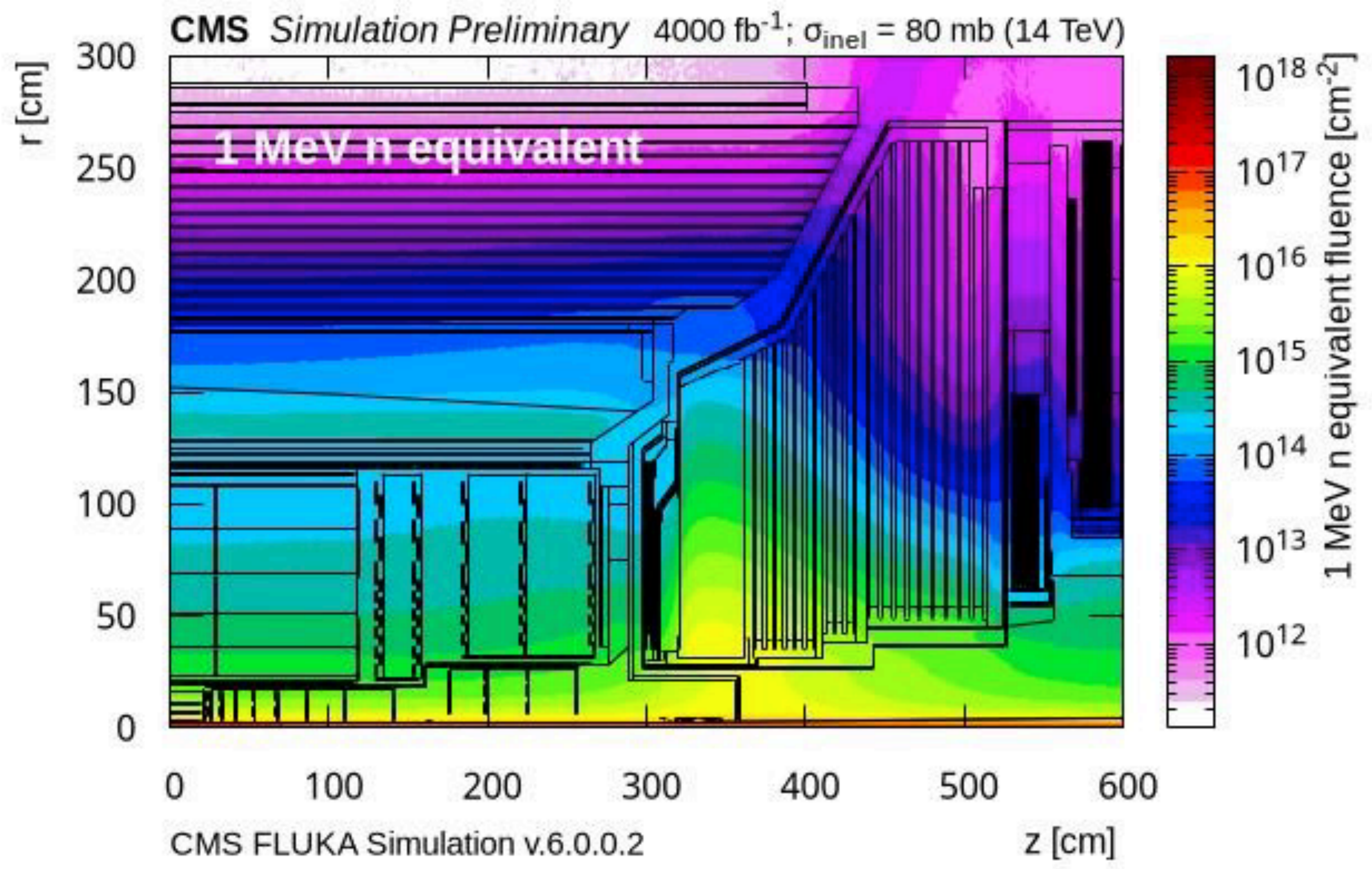
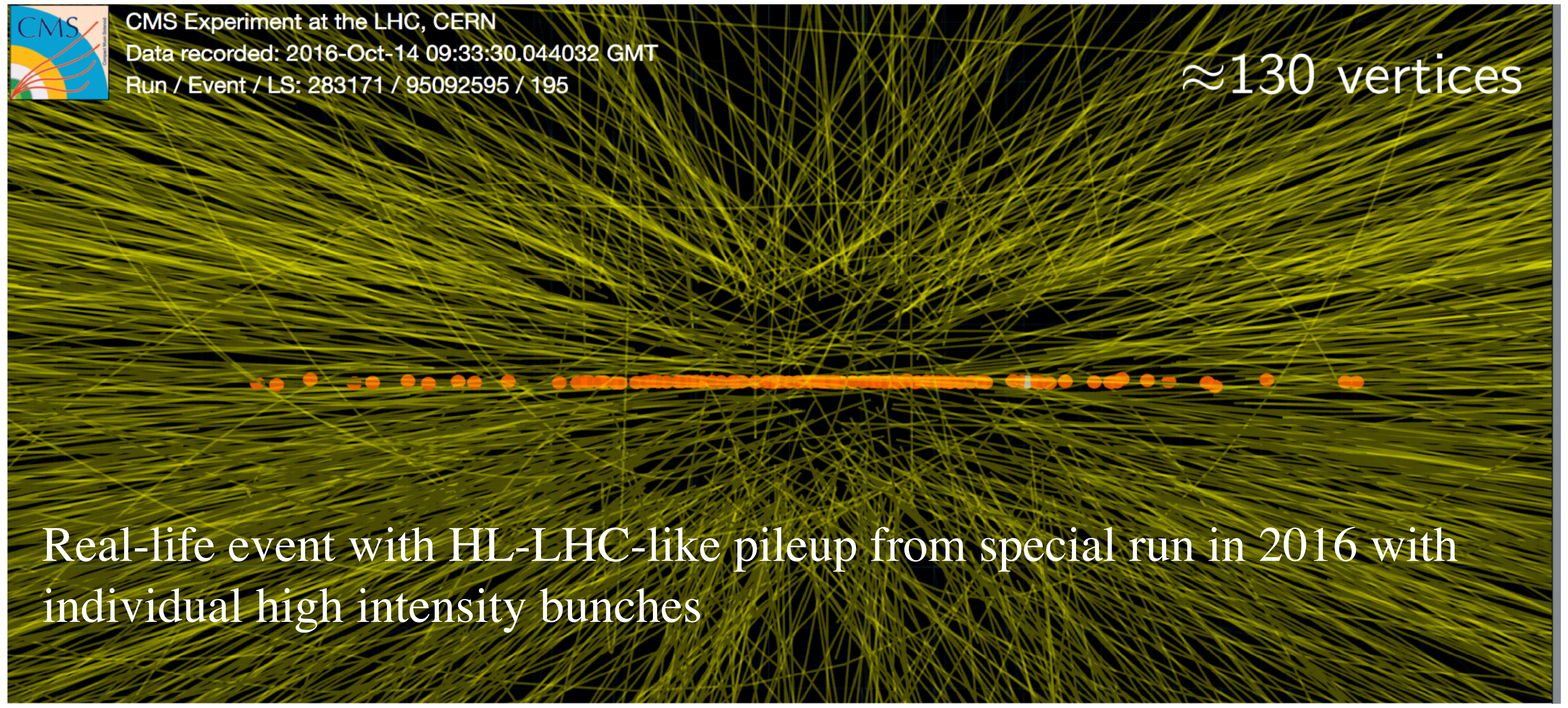
HL-LHC upgrade and pileup challenge

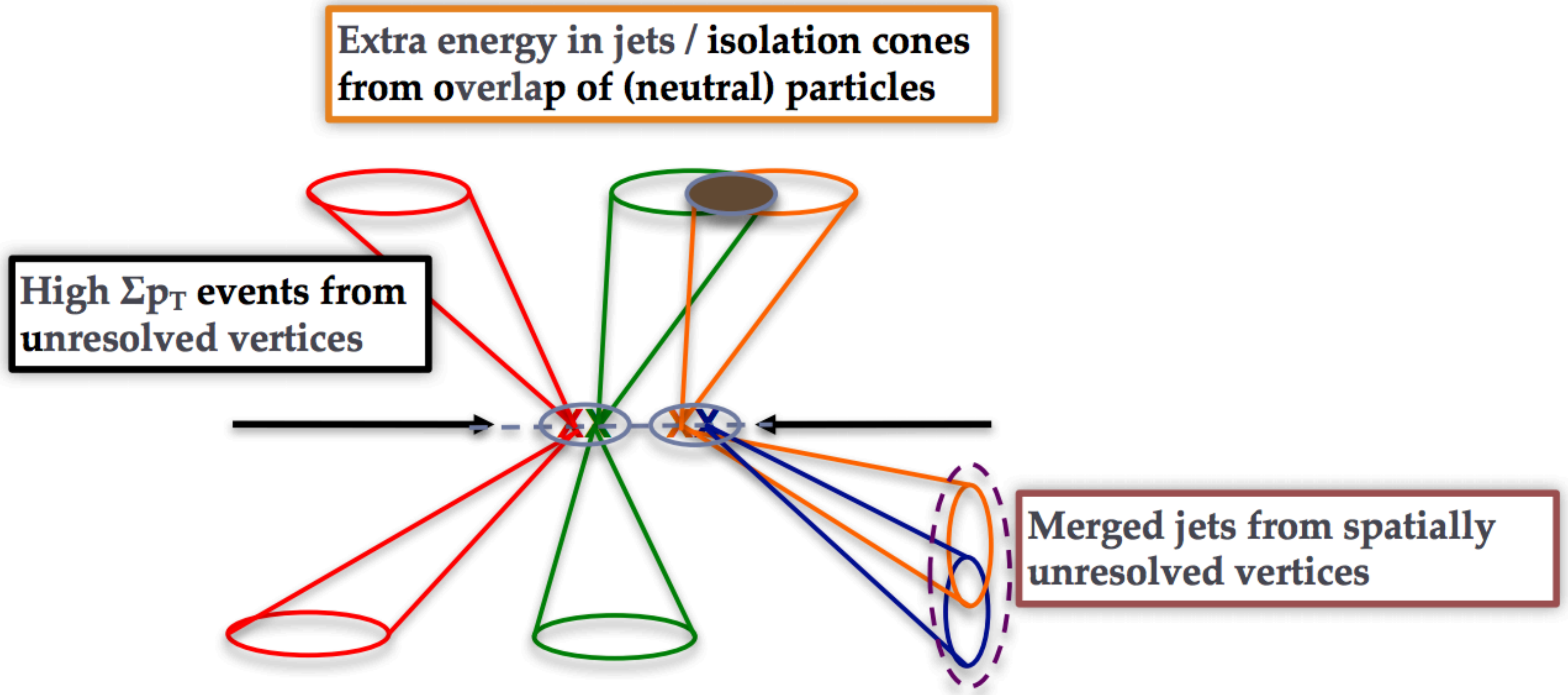
Upgrade of the accelerator complex optics and injectors to increase the beam intensity

- 140 - 200 collisions / beam crossing, > 10000 tracks / beam crossing (40 MHz)
- target luminosity 3000 fb^{-1}
- **1 year of HL-LHC equivalent to ~10 years of LHC!**



CMS DP-2023-087



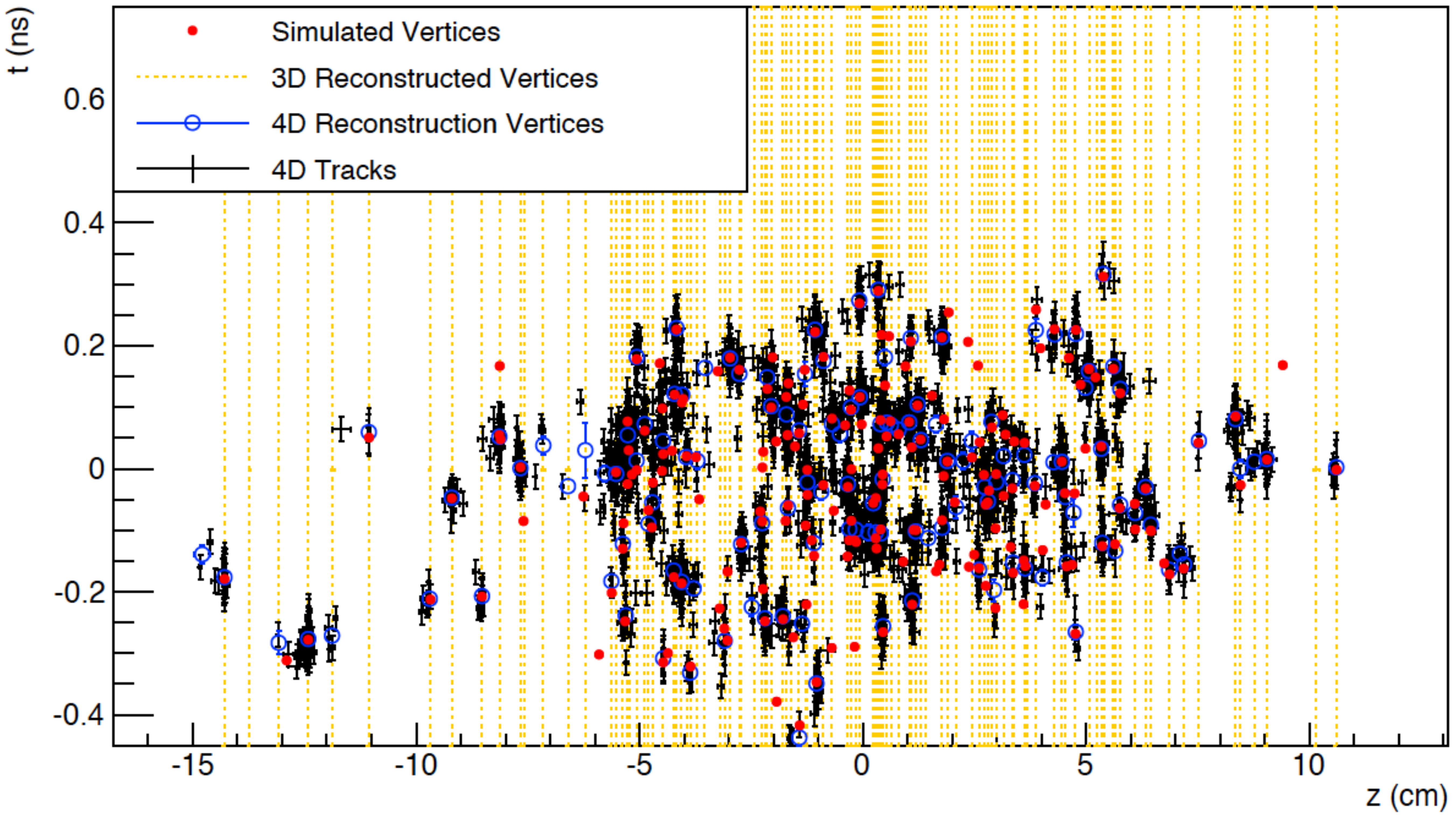


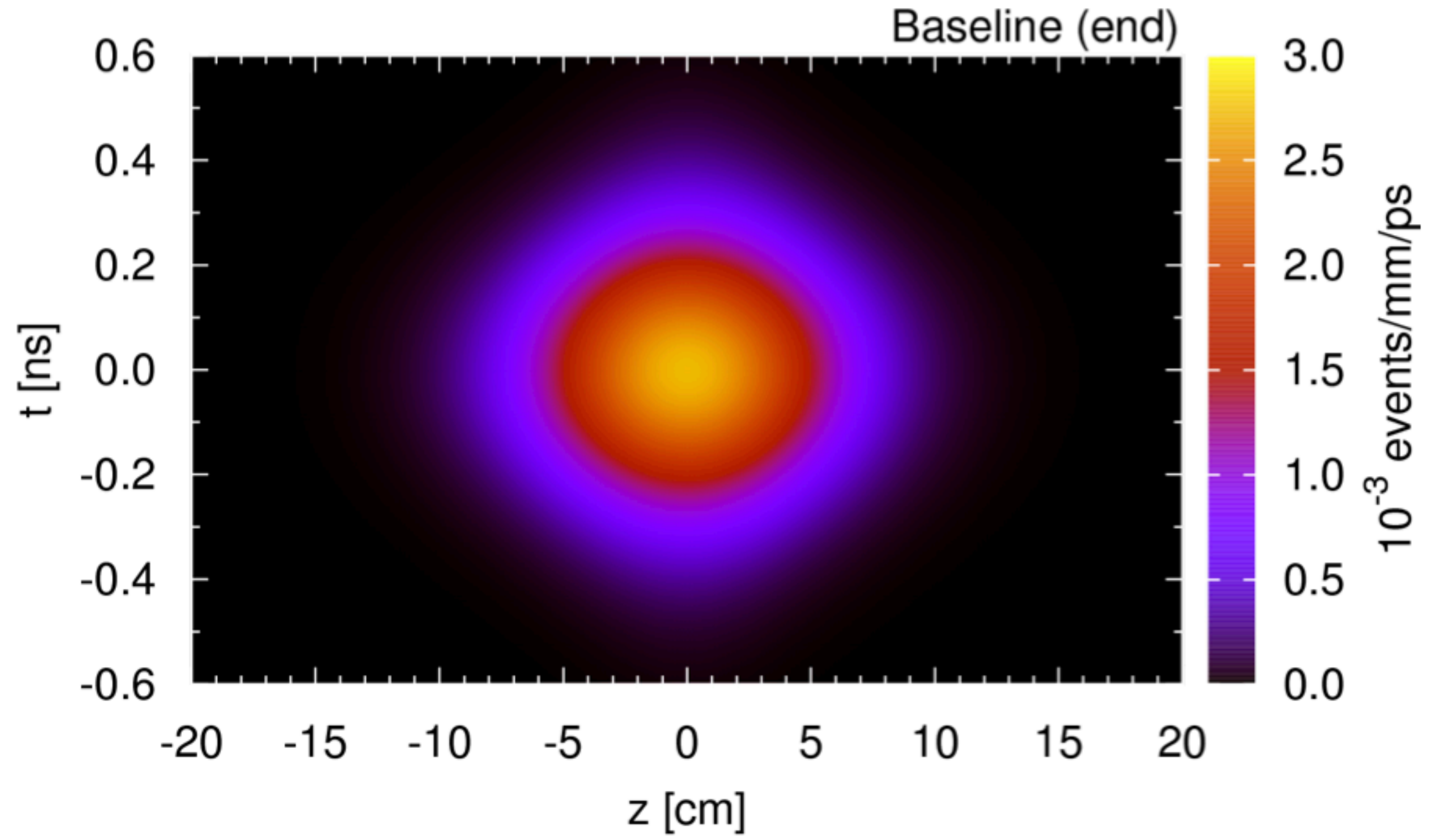
CMS MIP Timing Detector (MTD): New Precision Timing Measurement

Timing for minimum ionizing particles (MIP) particles by MTD allows 4D (x,y,z,t) track and vertex reconstruction

- Vertex merging reduced from 15% to 1%

Significant sensitivity gains across the HL-LHC physics program



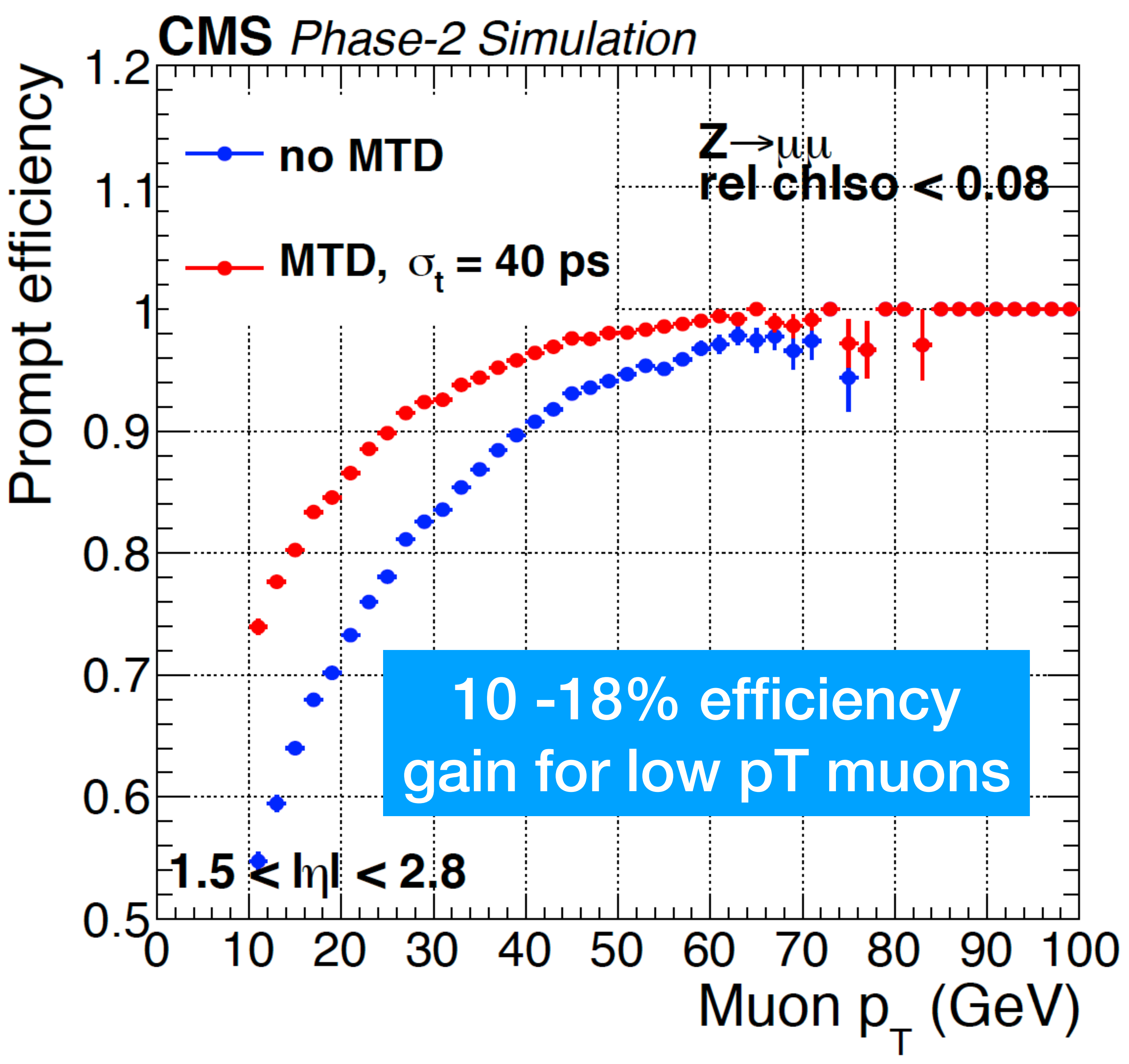


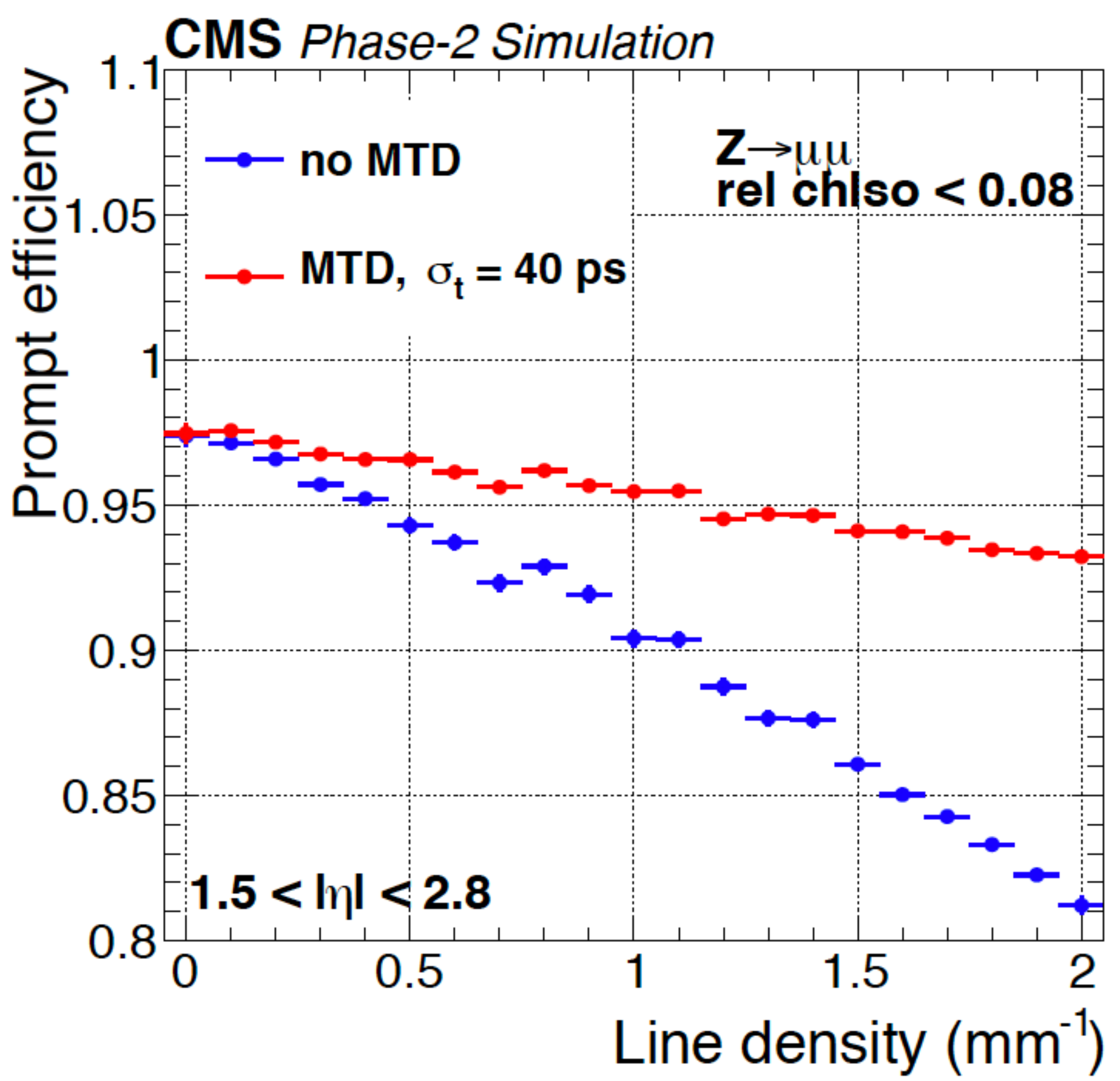
Beam spot has a spread of about 180-200 ps:

- "slice" in successive O(50) ps time frames to reduce pileup

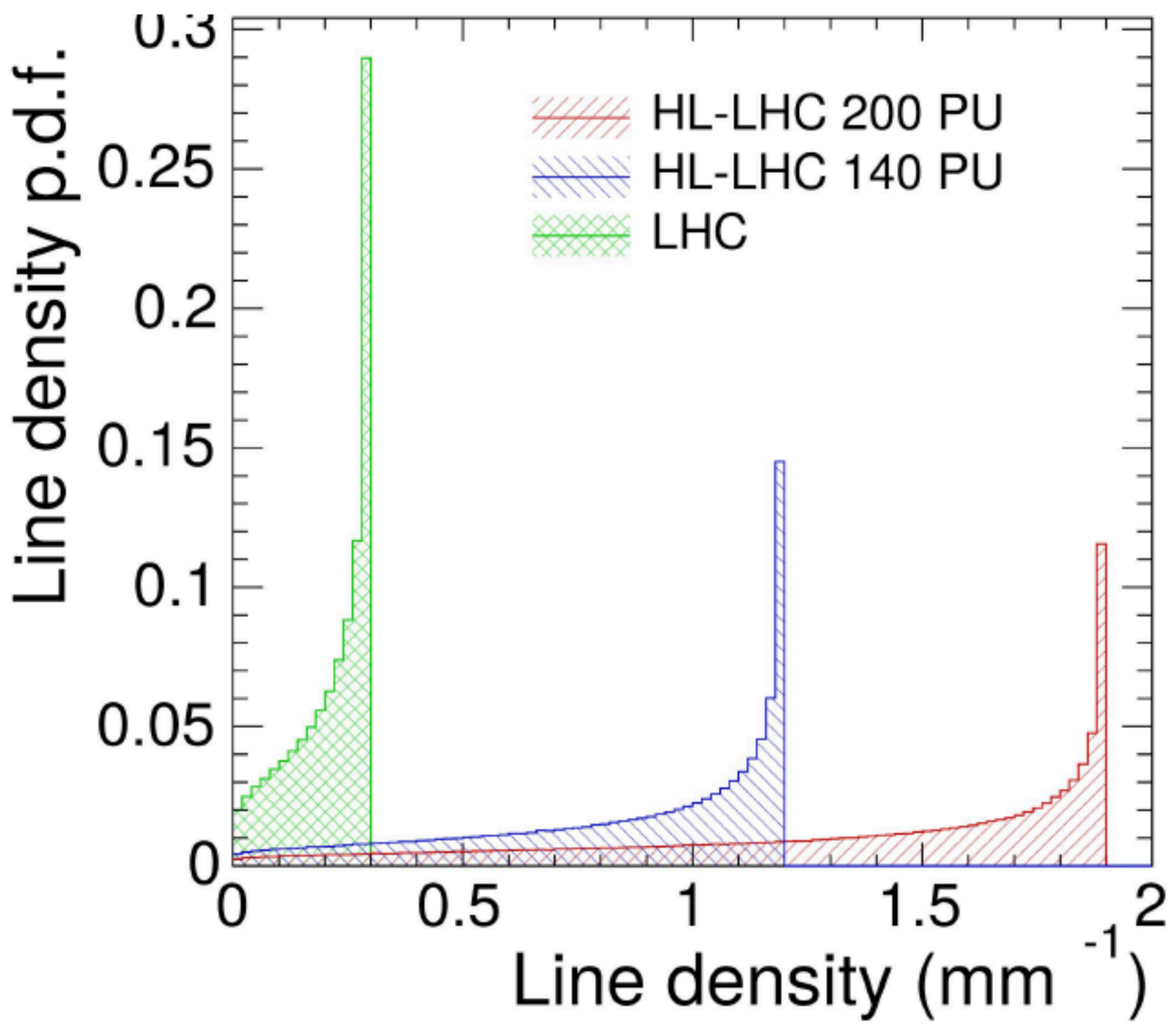
MTD TP: LHCC-P-009

Pileup mitigation with MTD





Reduction of pileup tracks in charged isolation cone of ΔR<0.3 around muons

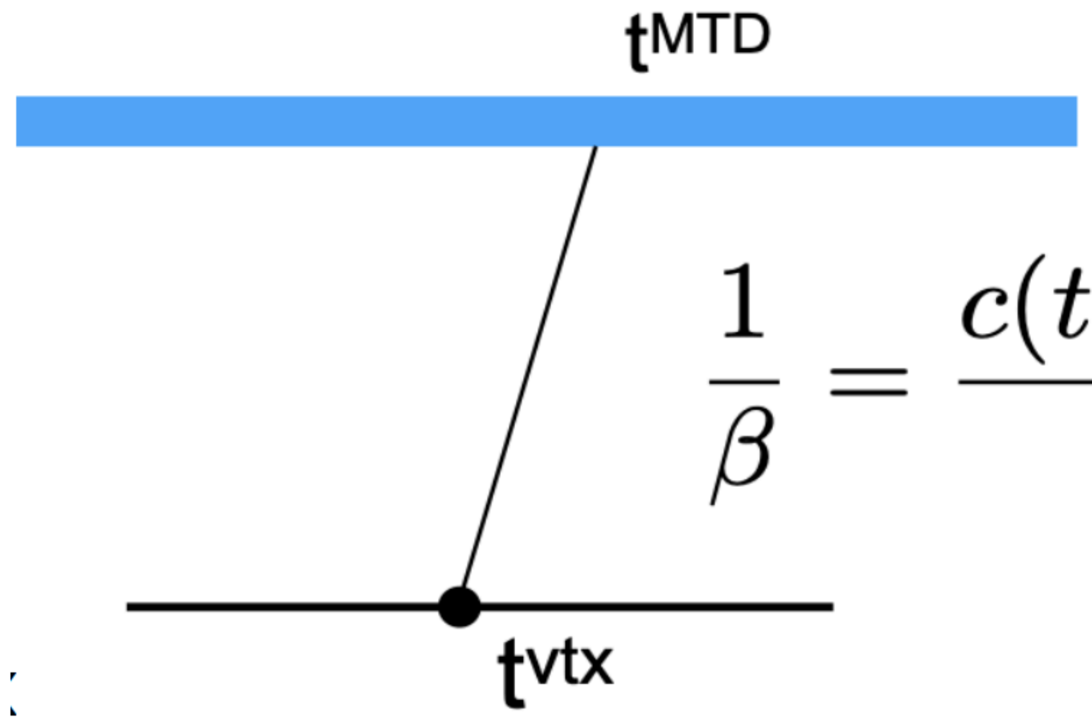


Reduction of pile-up by MTD enhances physics object reconstruction (μ, τ, b-tagged jets etc)

- especially beneficial for multi-particle final states, e.g. 10 - 20% gain in SM di-Higgs significance significance

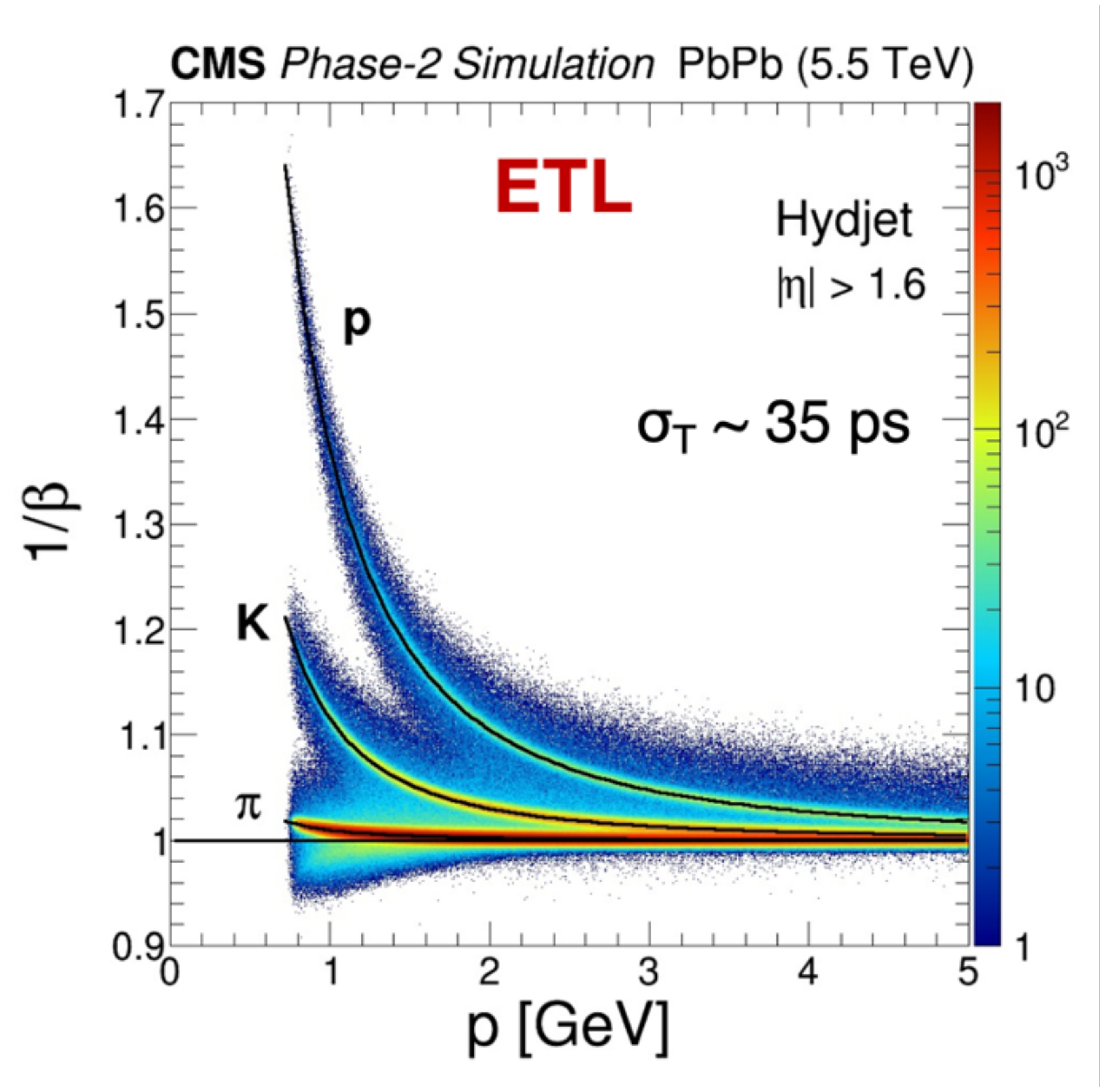
Charged hadron identification

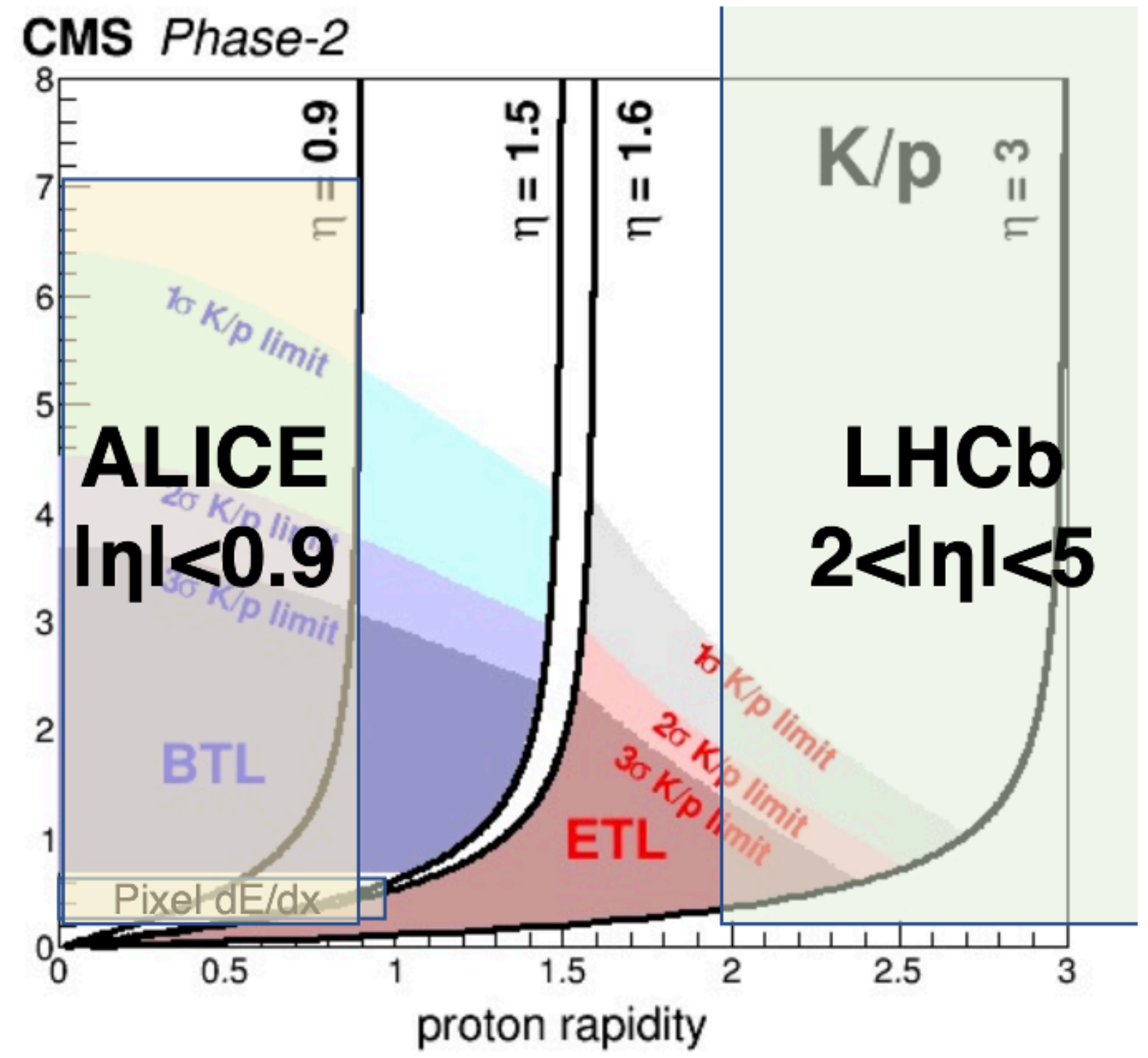
- Measurement of velocity for low p_T hadrons, enabling particle identification:
  - π/K separation up to 3 GeV
  - p/K separation up to 5 GeV



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

L: path length of a track from the beam line to the MTD.





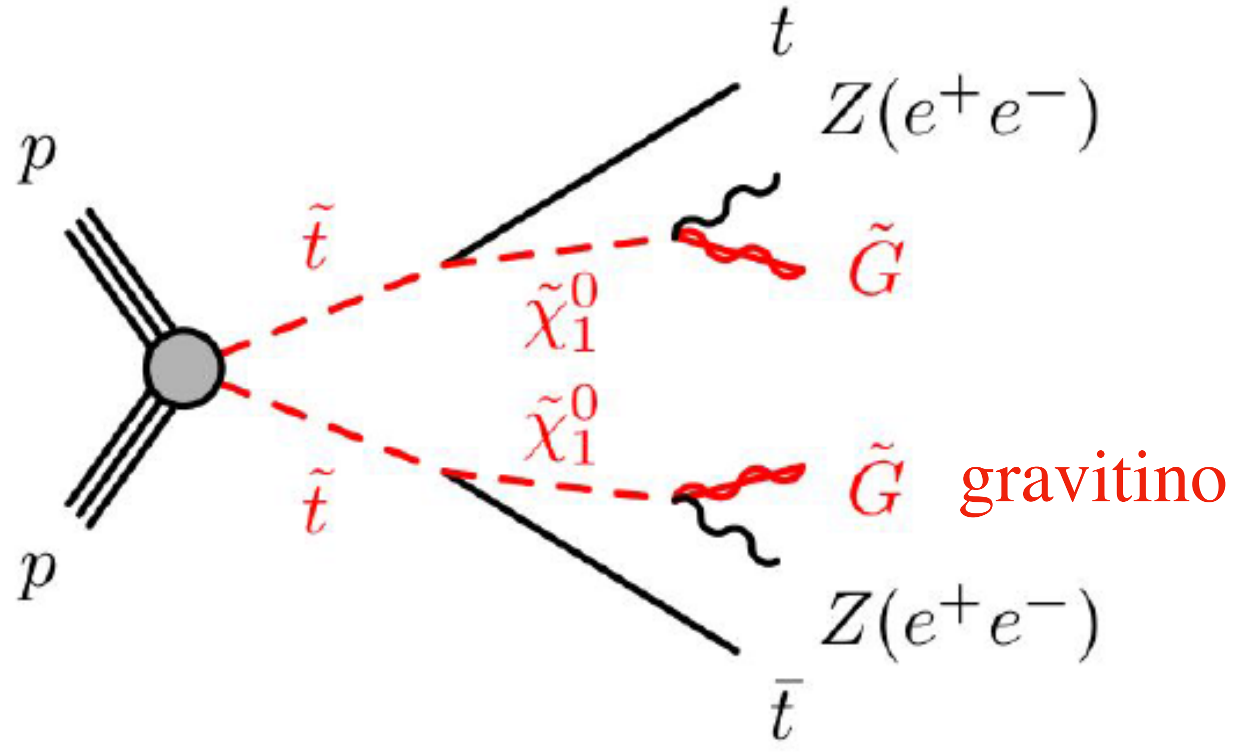
- Measurements of heavy flavor particles of interest to study evolution of QGP
- CMS, Alice and LHCb have complementary PID capabilities in terms of rapidity coverage

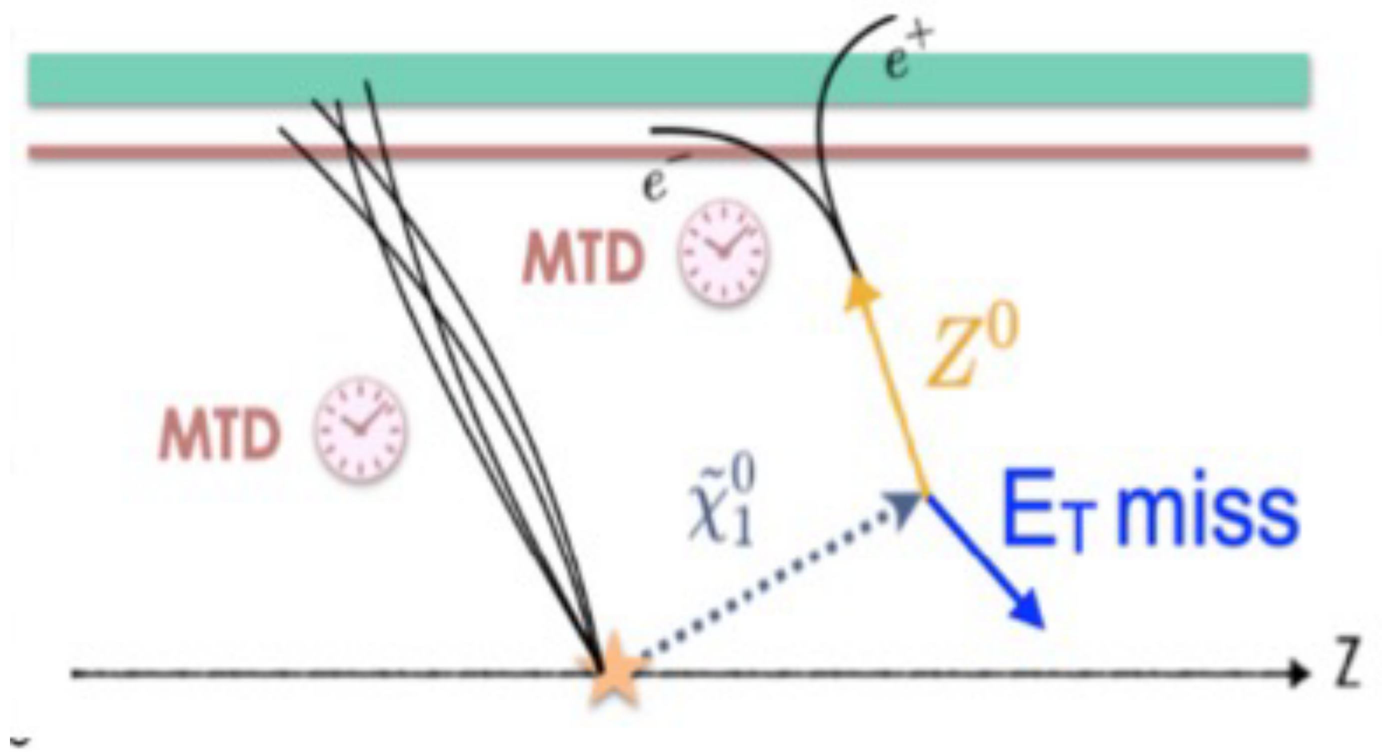
Mass reconstruction of long lived particles (LLP)

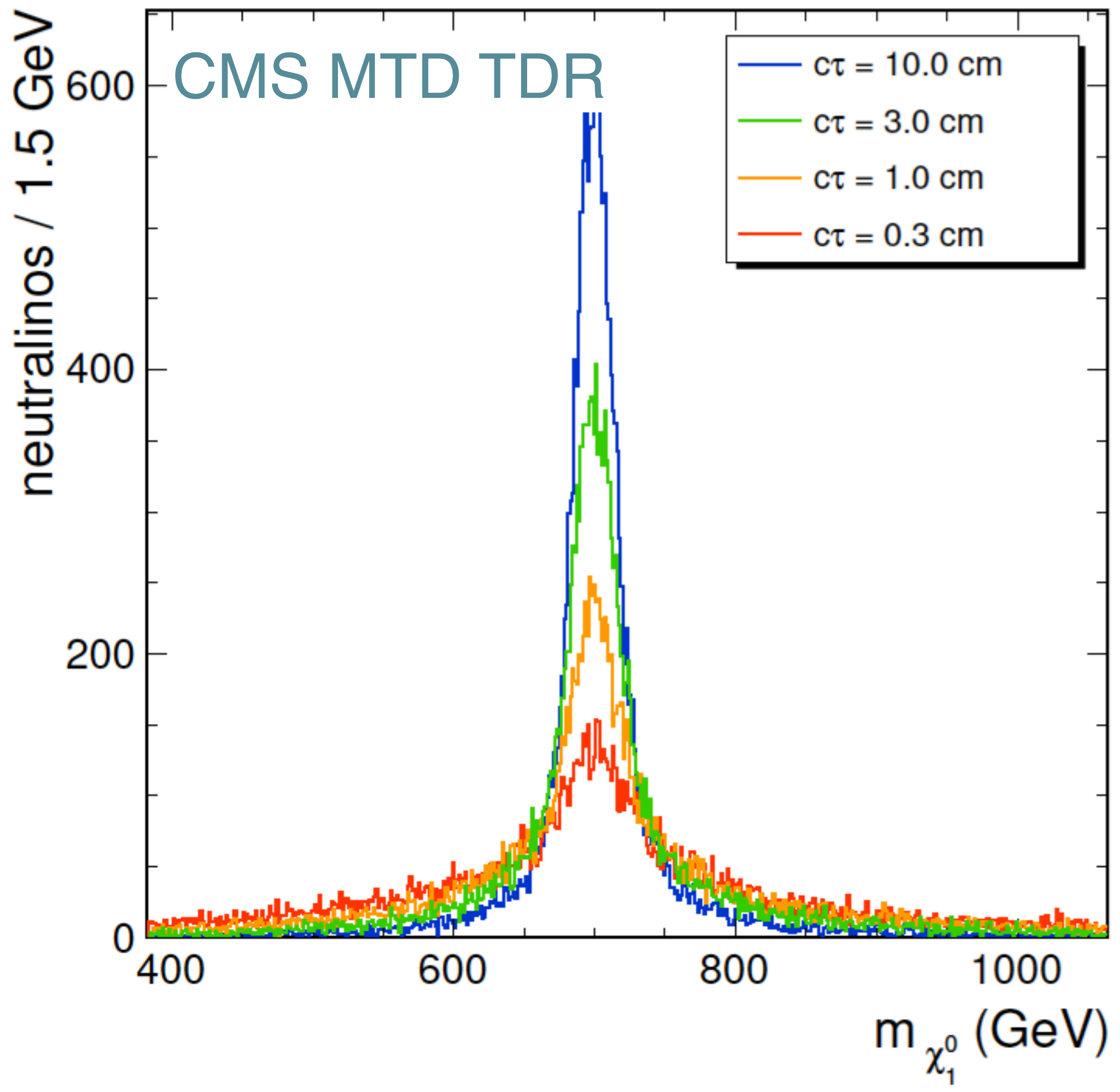
- Mass of LLP can be reconstructed with timing plus kinematics of visible part of LLP decay! Fundamentally changes how we carry out these searches

- Example: top-squark pair production and decay in gauge-mediated SUSY breaking scenario. The lightest neutralino $\tilde{\chi}_0^1$ is long-lived, velocity could be measured with MTD:

$$\beta_{\tilde{\chi}_1^0} = \frac{D}{c(T_{SV} - T_{PV})}$$

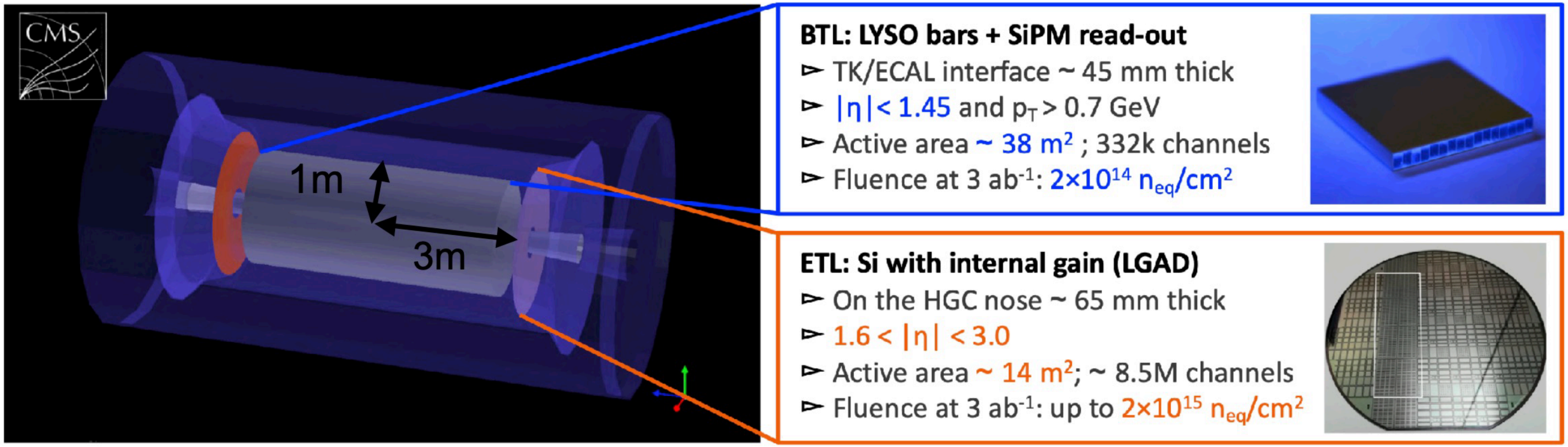






CMS MIP Timing Detector Overview

- MTD add completely new capability to CMS: measure precisely (30-70 ps resolution) the production time of MIPs



- Choice of sensor technologies for barrel and endcap timing layers driven by technology maturity, radiation hardness, power consumption, and cost and schedule considerations.

CMS-TDR-020 March 2019

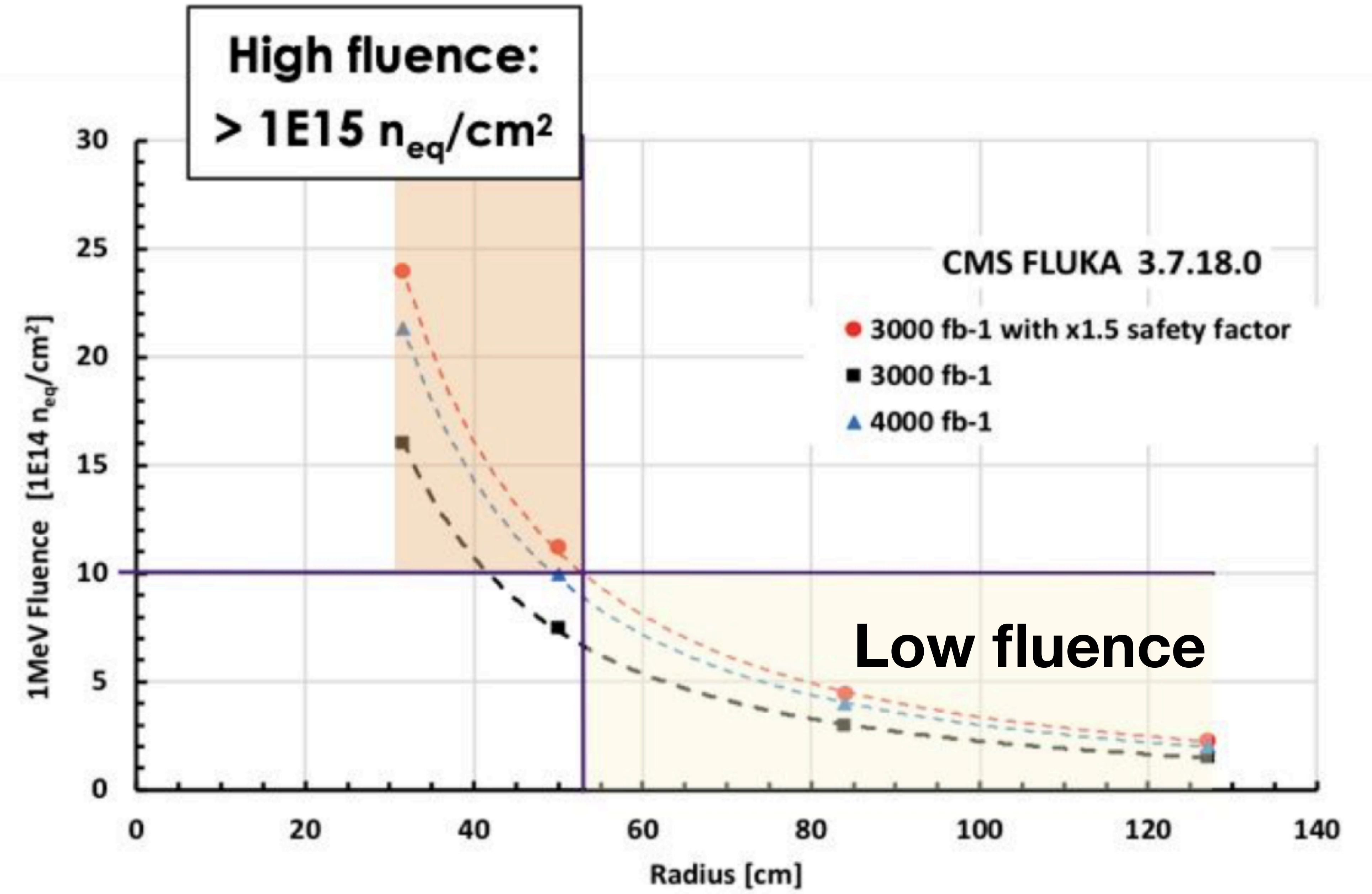
ETL detector layout

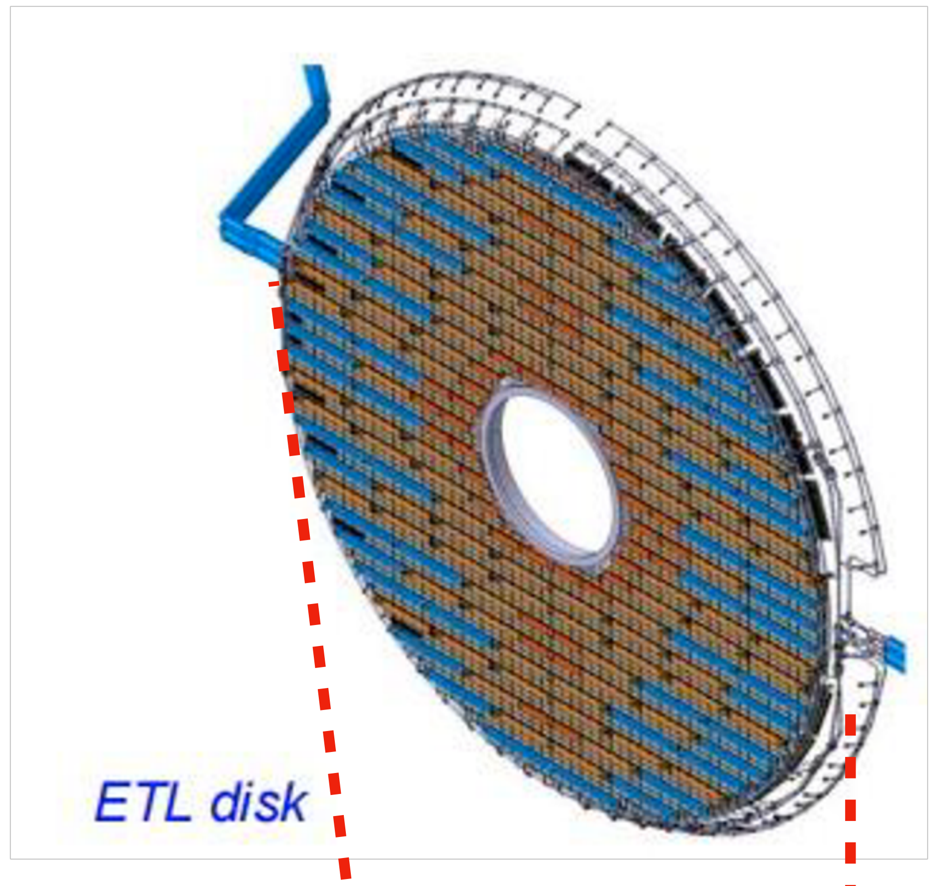
Each endcap is comprised of 2 disks

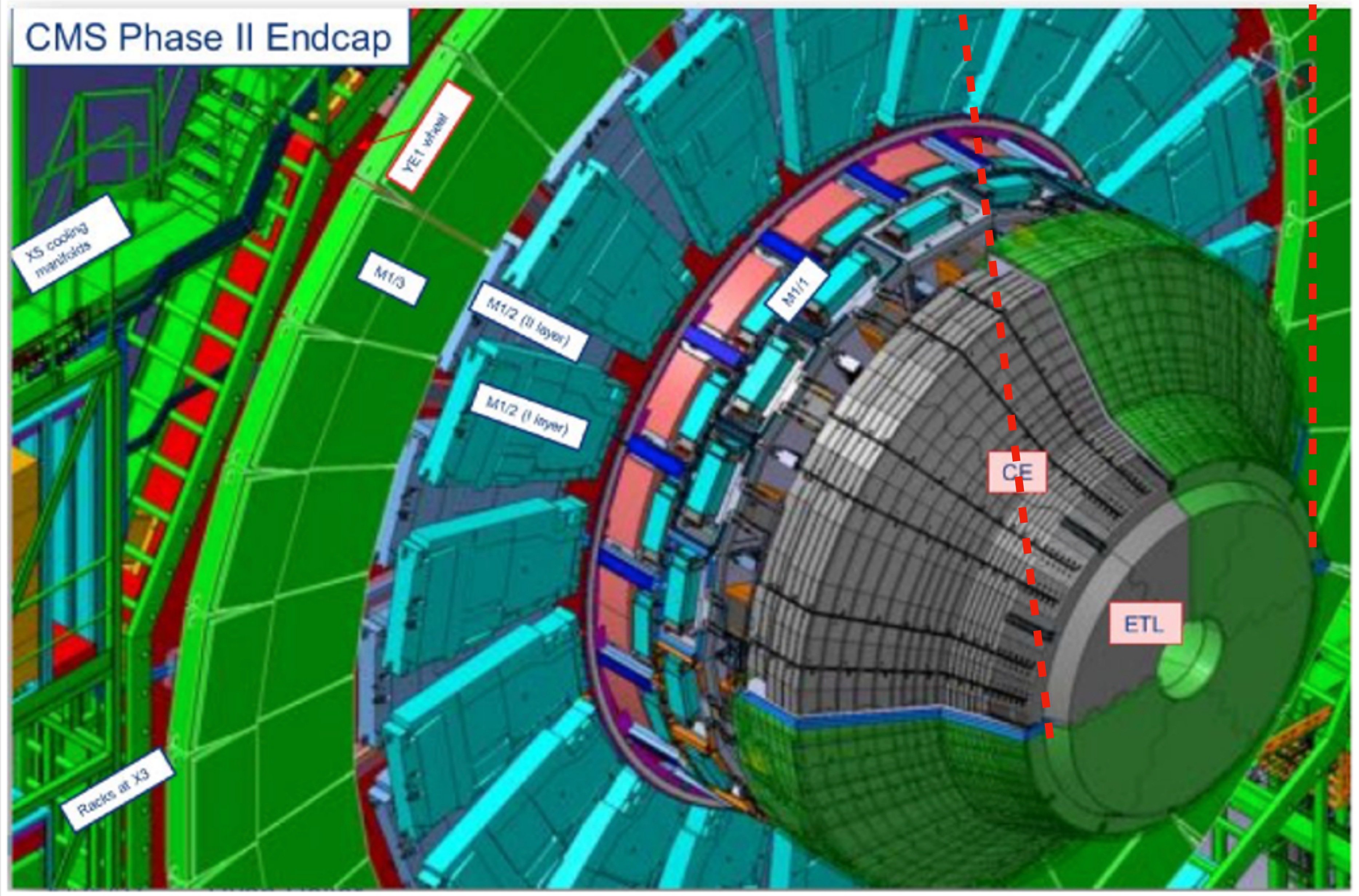
- 16x16 LGAD, bump-bonded to the ETL read-out chip (ETROC)
- providing up to two measurements (50 ps/hit) per track (40 ps)

Coverage:

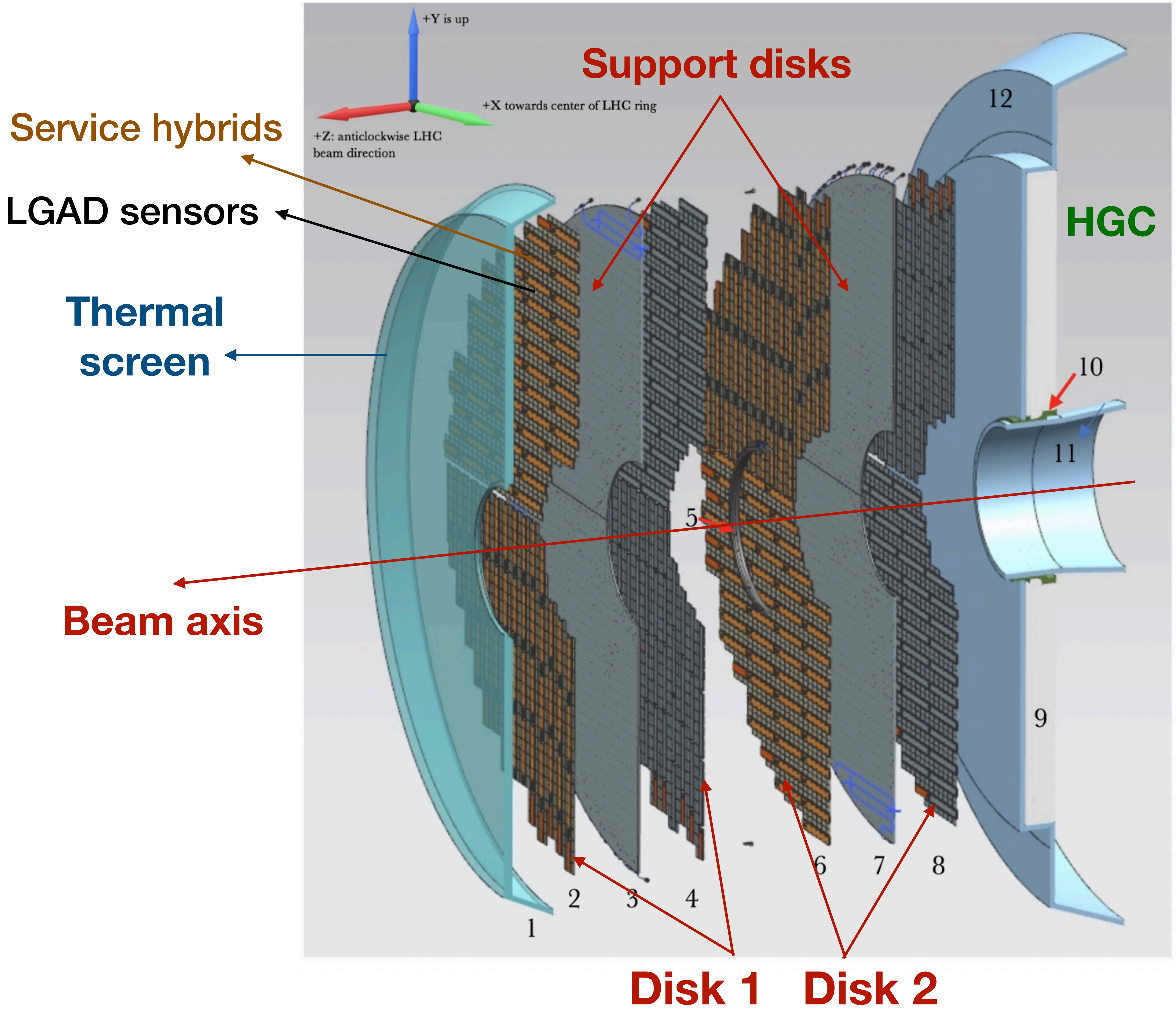
- z = 3 m from pp interaction, supported on HGC nose
- coverage 1.6 < |η| < 3.0
- 0.315 m < R < 1.2 m







ETL Detector Layout



1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

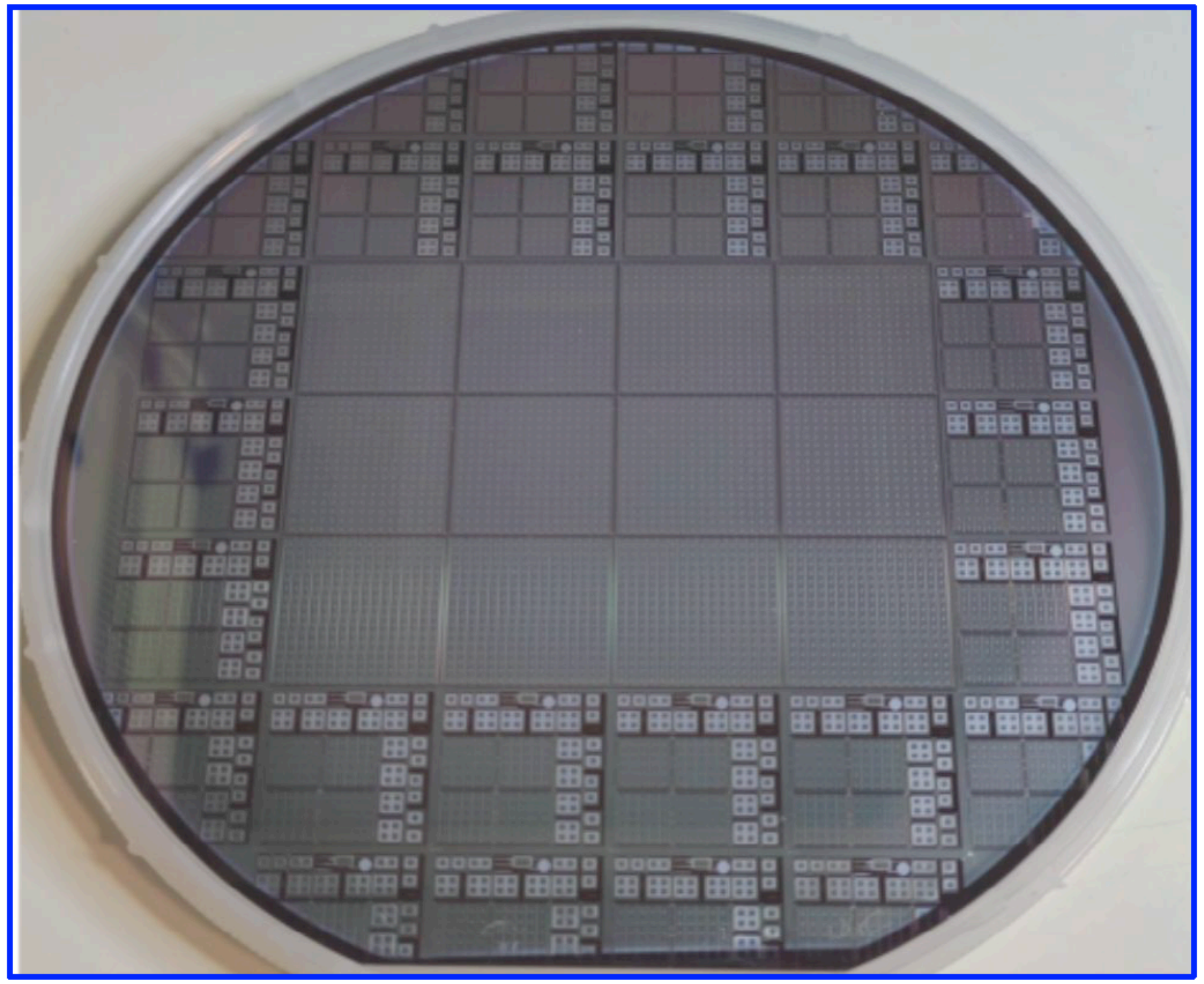
ETL sensor: LGAD

CMS ETL LGAD sensor requirements

- 1.3 x1.3 mm^2 pads for a total surface of 21.4 x 21.6 mm^2
- 16 x 16 channel per sensor
- gain 10-30
- time resolution < 50 ps (per/hit) @ 1.7×10^{15} n_{eq} /cm^2
- depletion region thickness: 50 μm
- LGAD deliver > 8 fC

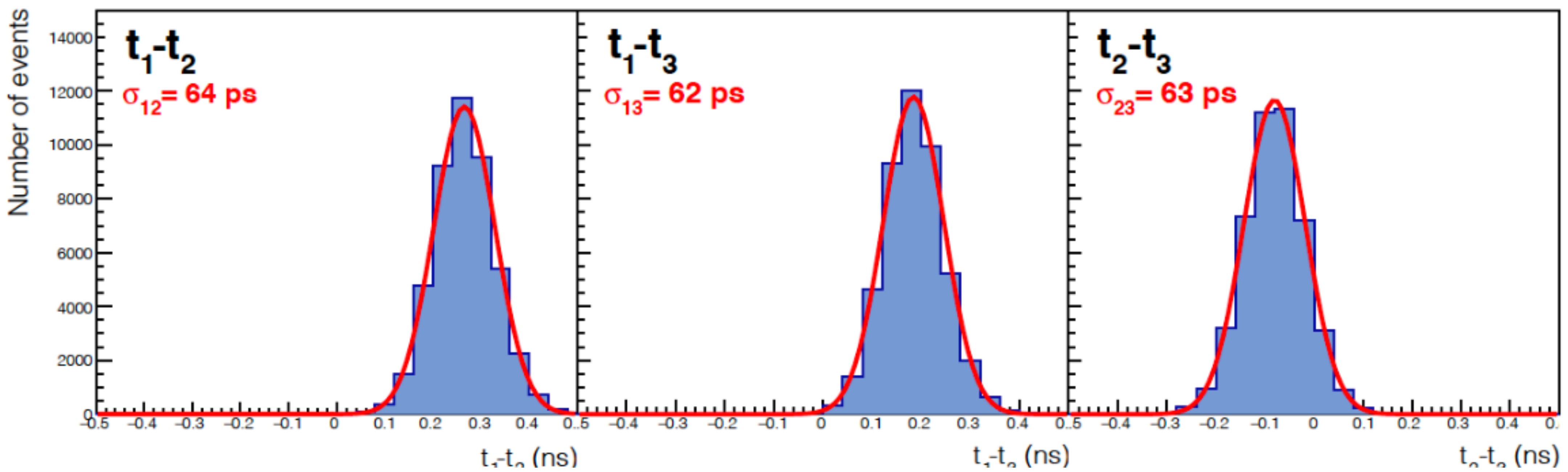
- ETL need 8.6 million channels
- ETL will comprise ~ 35k LGAD sensors (20% spare sensors included)

A wafer of the FBK UFSD4 production



Performance of prototype ETL detector

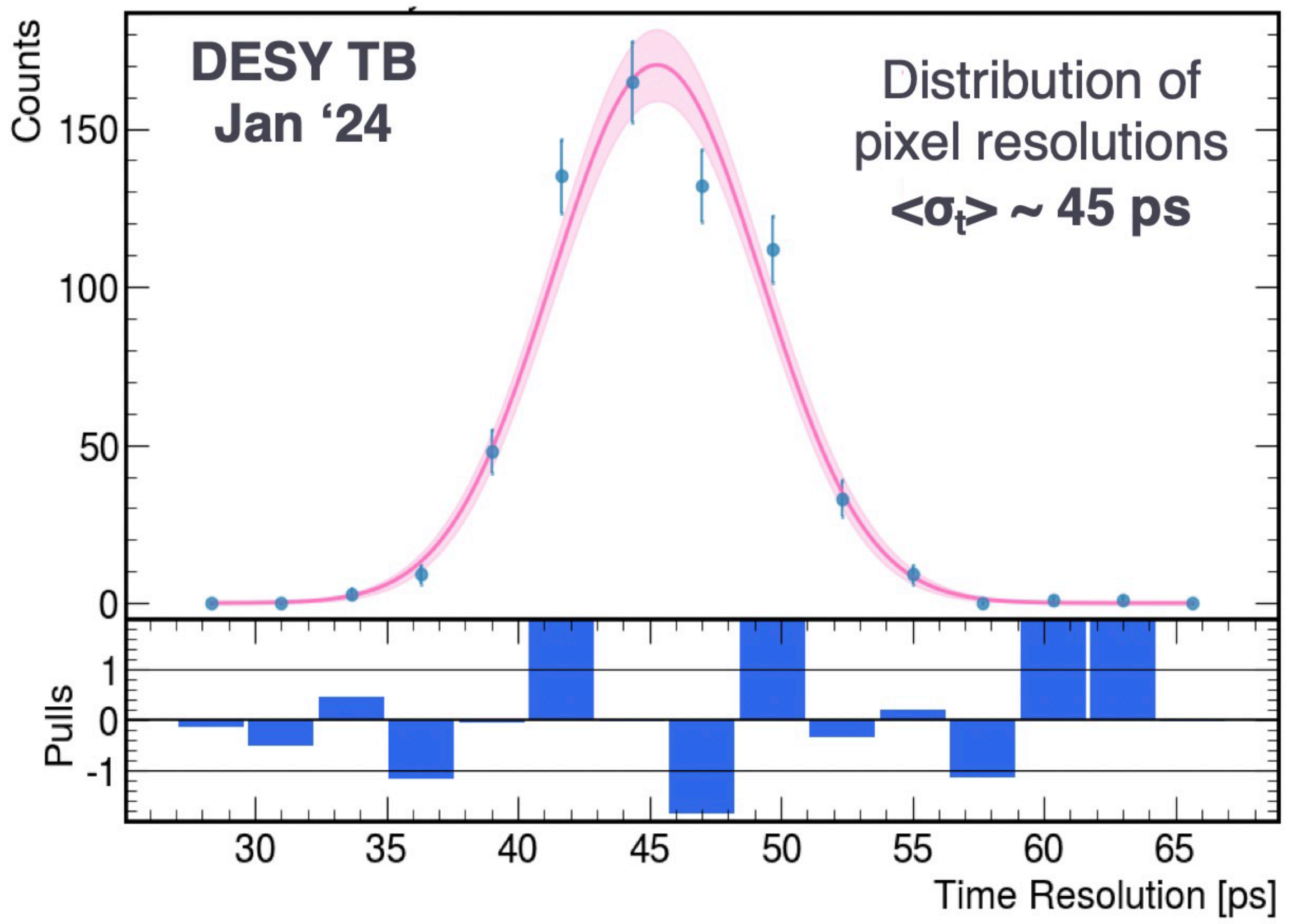
- Test results with ETROC1 wire-bonded to LGAD sensor demonstrate expected performance.



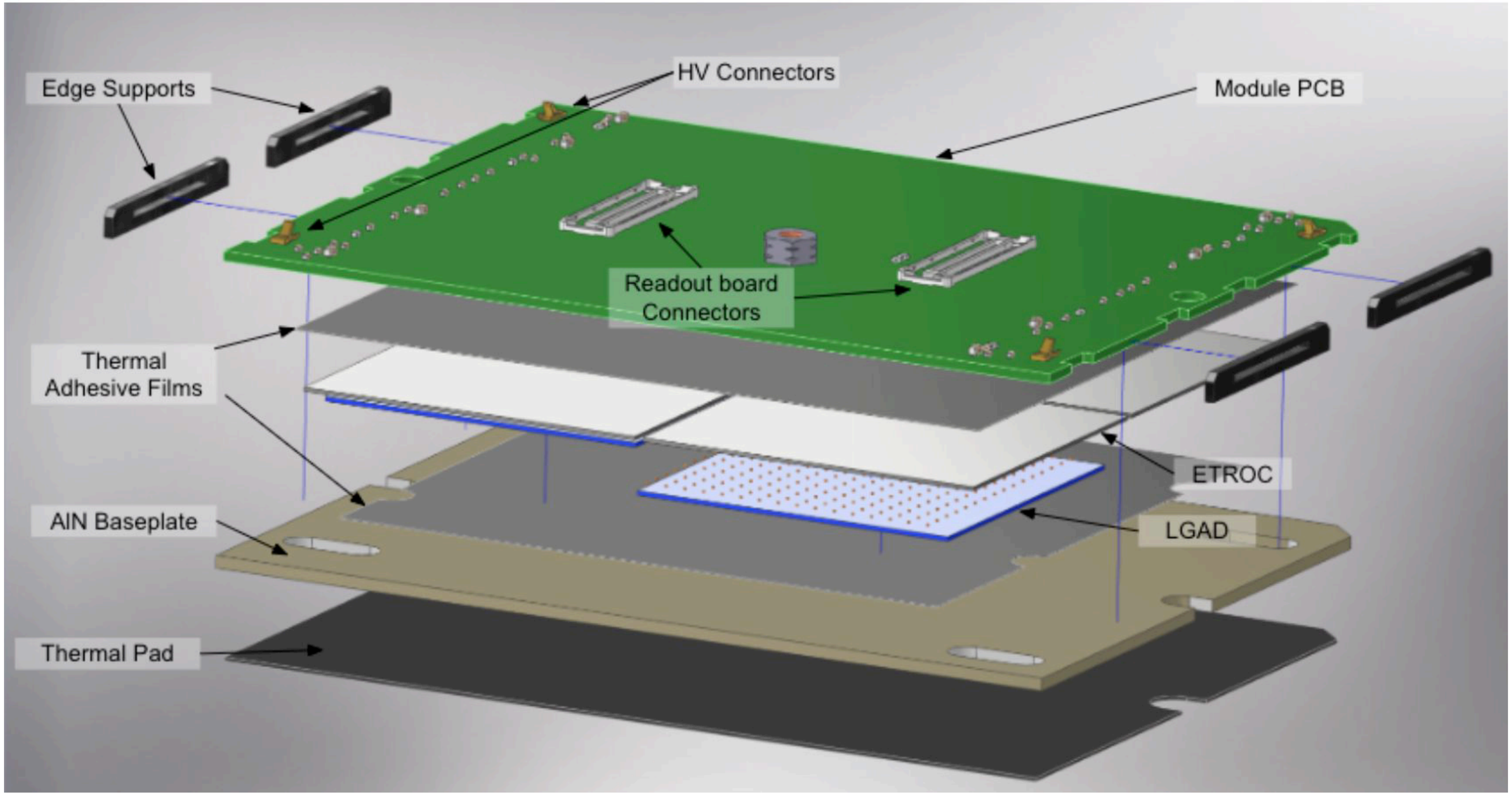
LGAD+ETROC1 resolution is 42-46 ps from TDC digital outputs

$$\sigma_i = \sqrt{0.5 \cdot (\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)}$$

- Extensive testing of ETROC2 prototypes with bump-bonded sensors underway. Initial results confirm measurements with ETROC1.



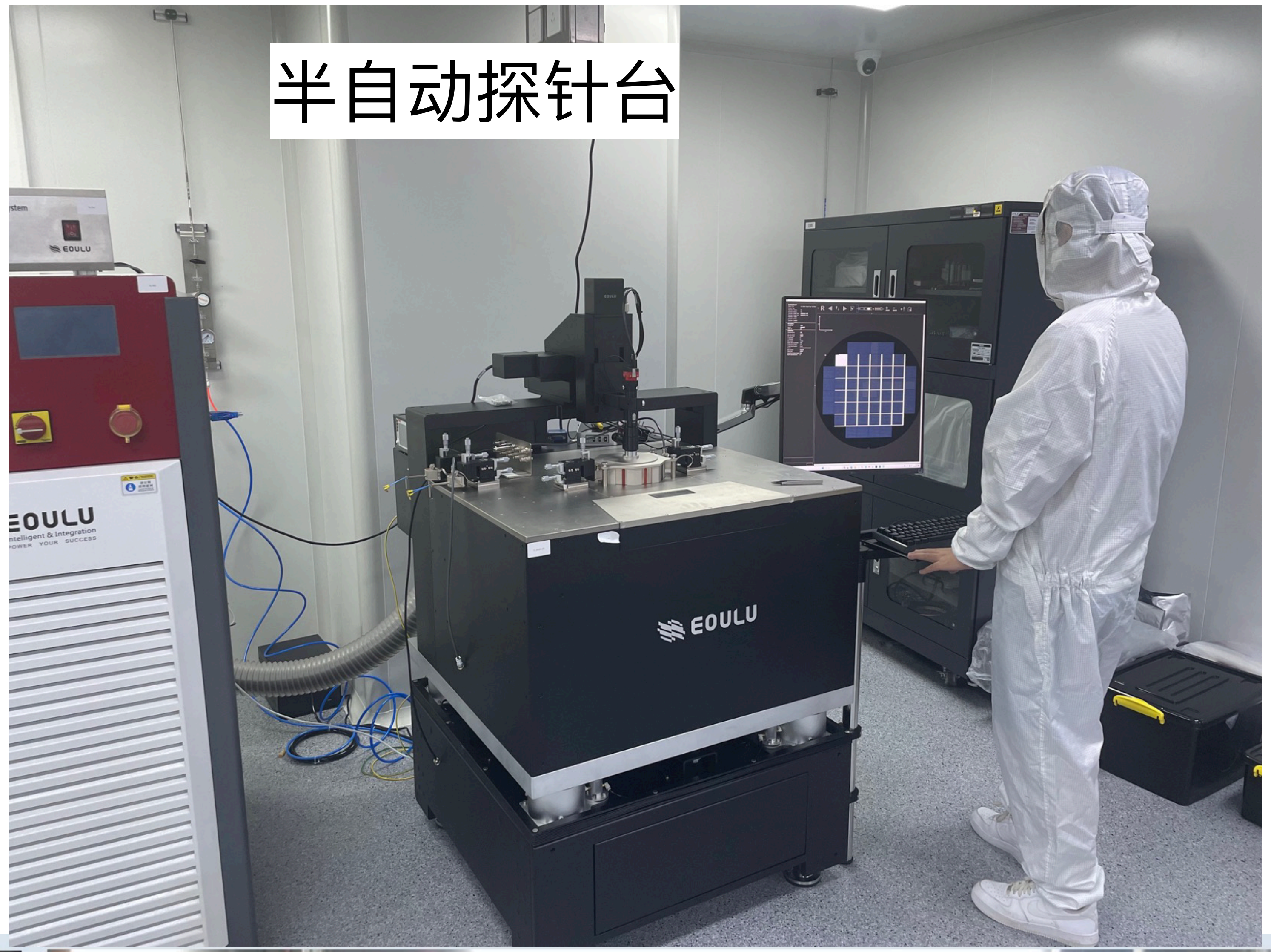
ETL sensor modules

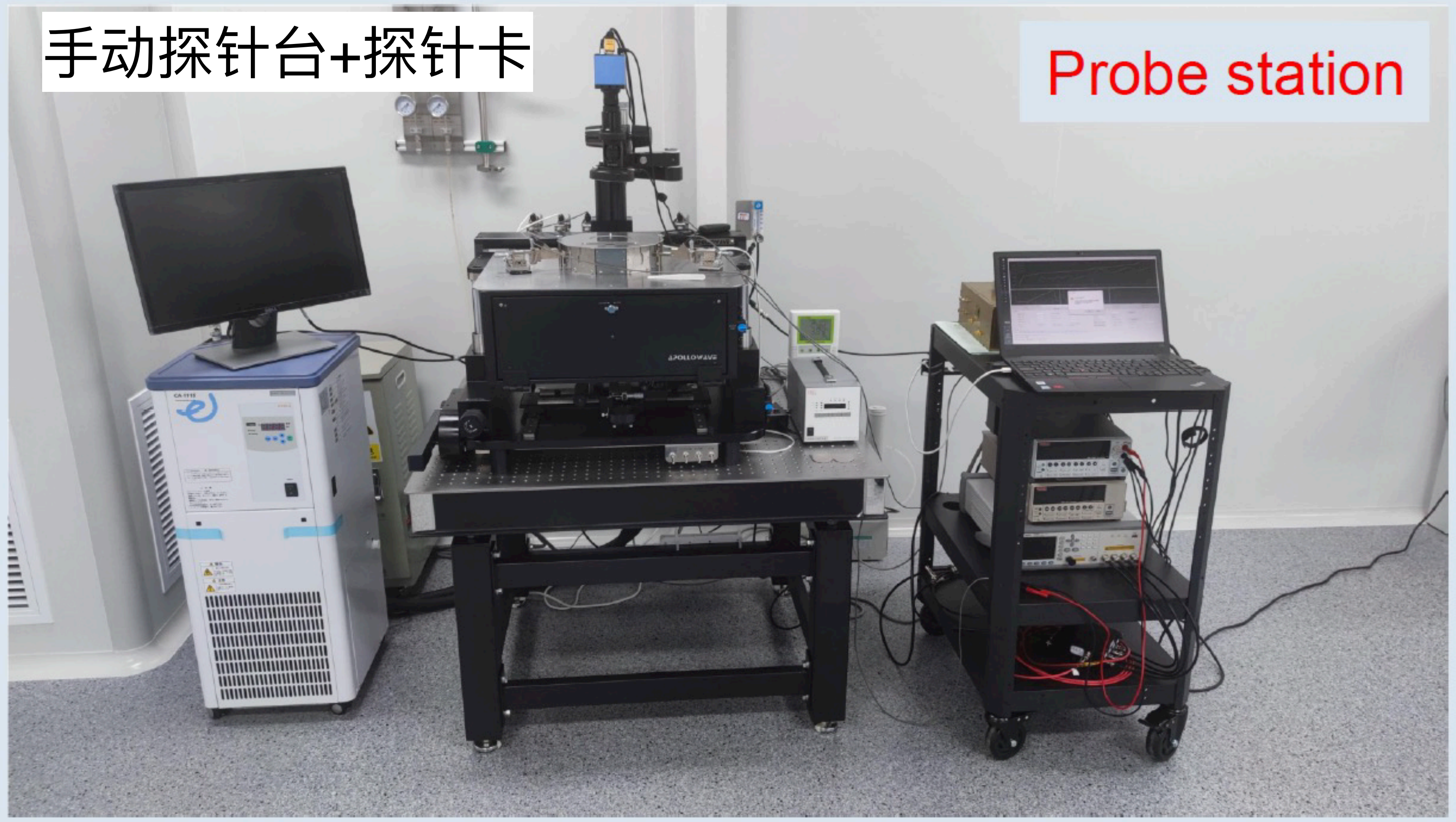


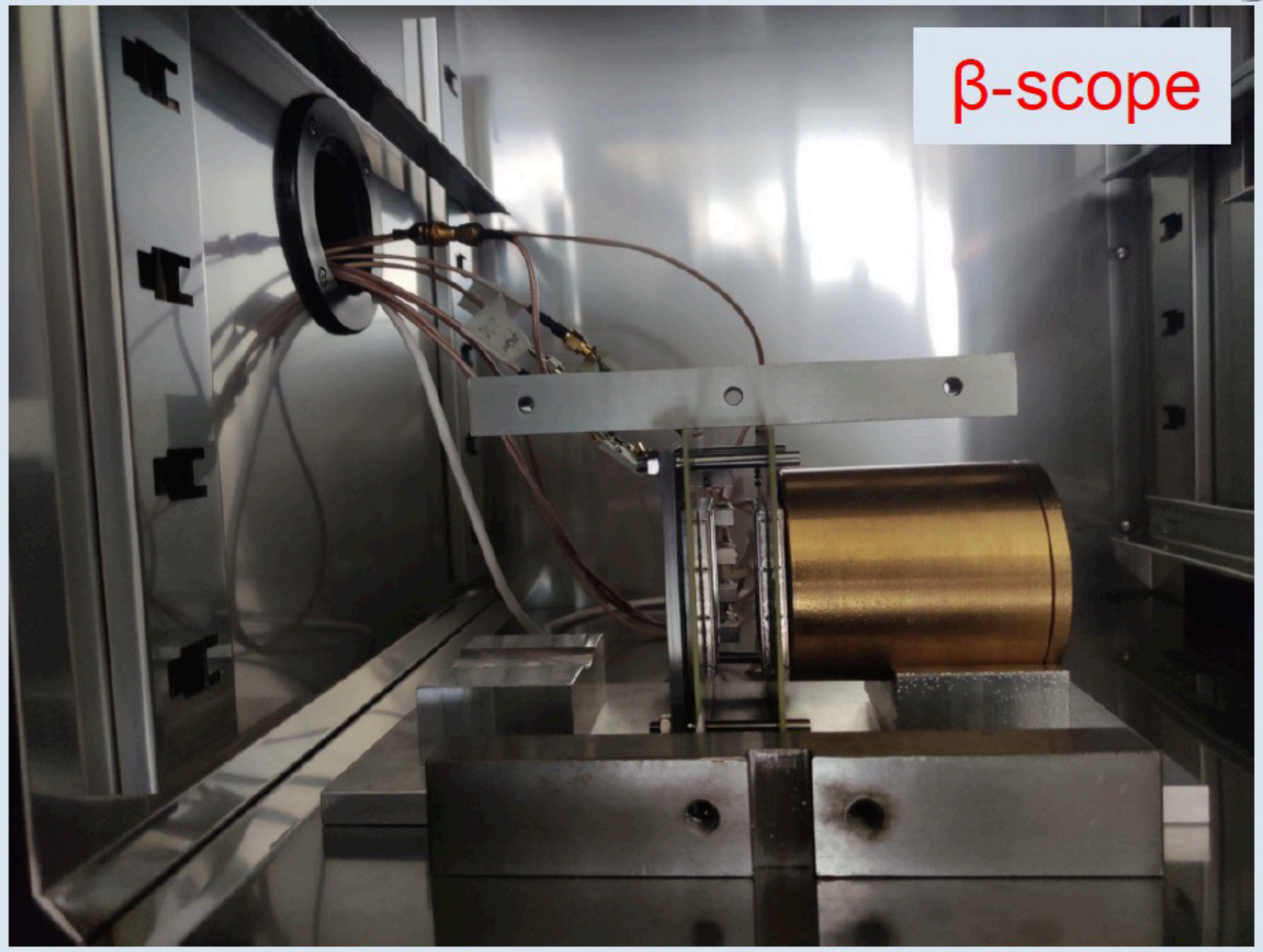
ETL module: Four LGADs bump-bonded to the ETROC ASIC, arranged between the module PCB and a baseplate

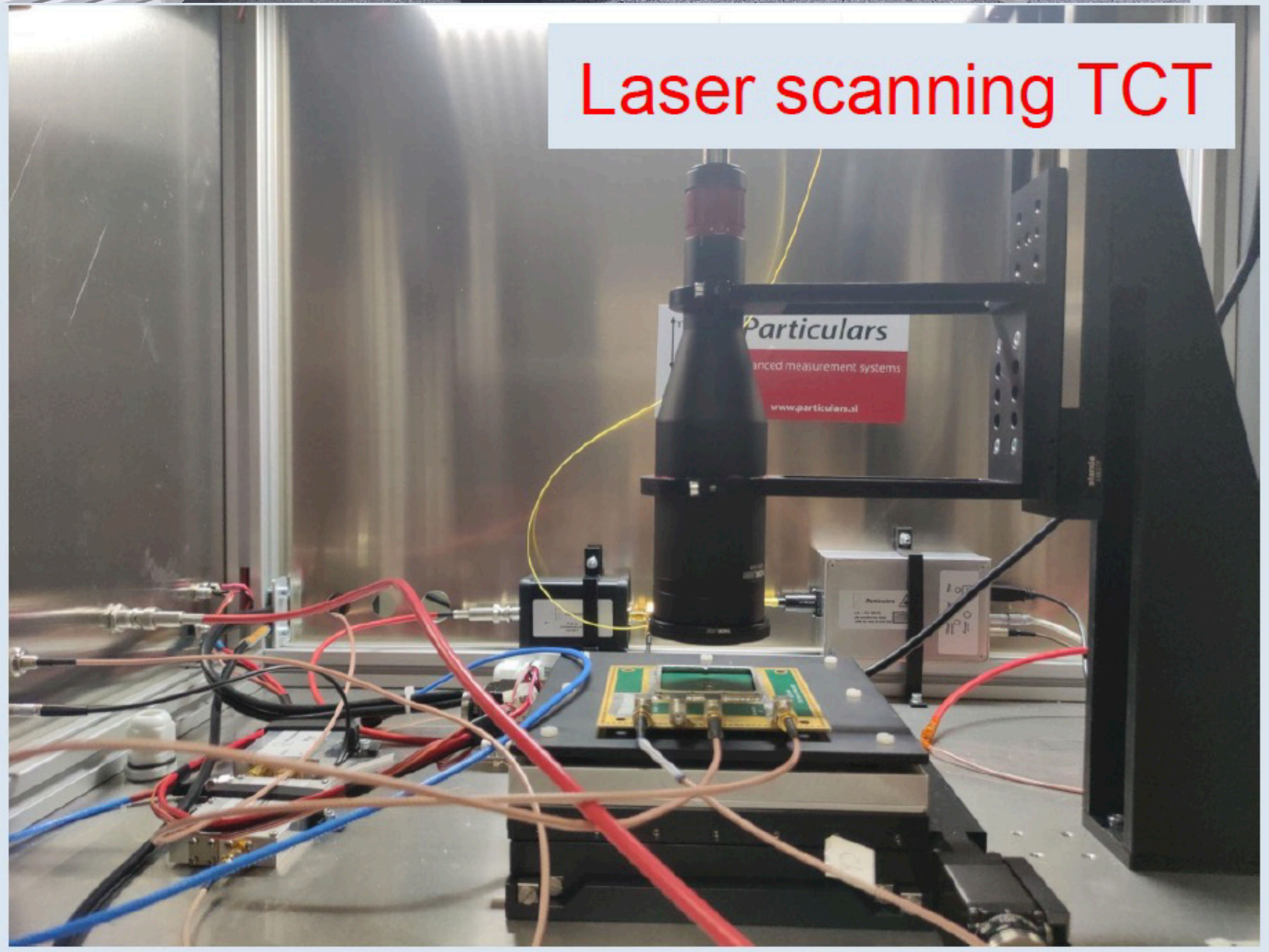
USTC joined CMS-ETL since 2023

- 依托核探测与核电子学国家重点实验室科大先进的LGAD研究测试平台
- 与华南师范大学、山东大学、 INFN Torino等单位合作
- 科大参与人员目前包括：于承君（IHEP PhD，博士后），张展，赵祥，张德，范北昆（研究生），鲁楠和胡雪野（教职工）



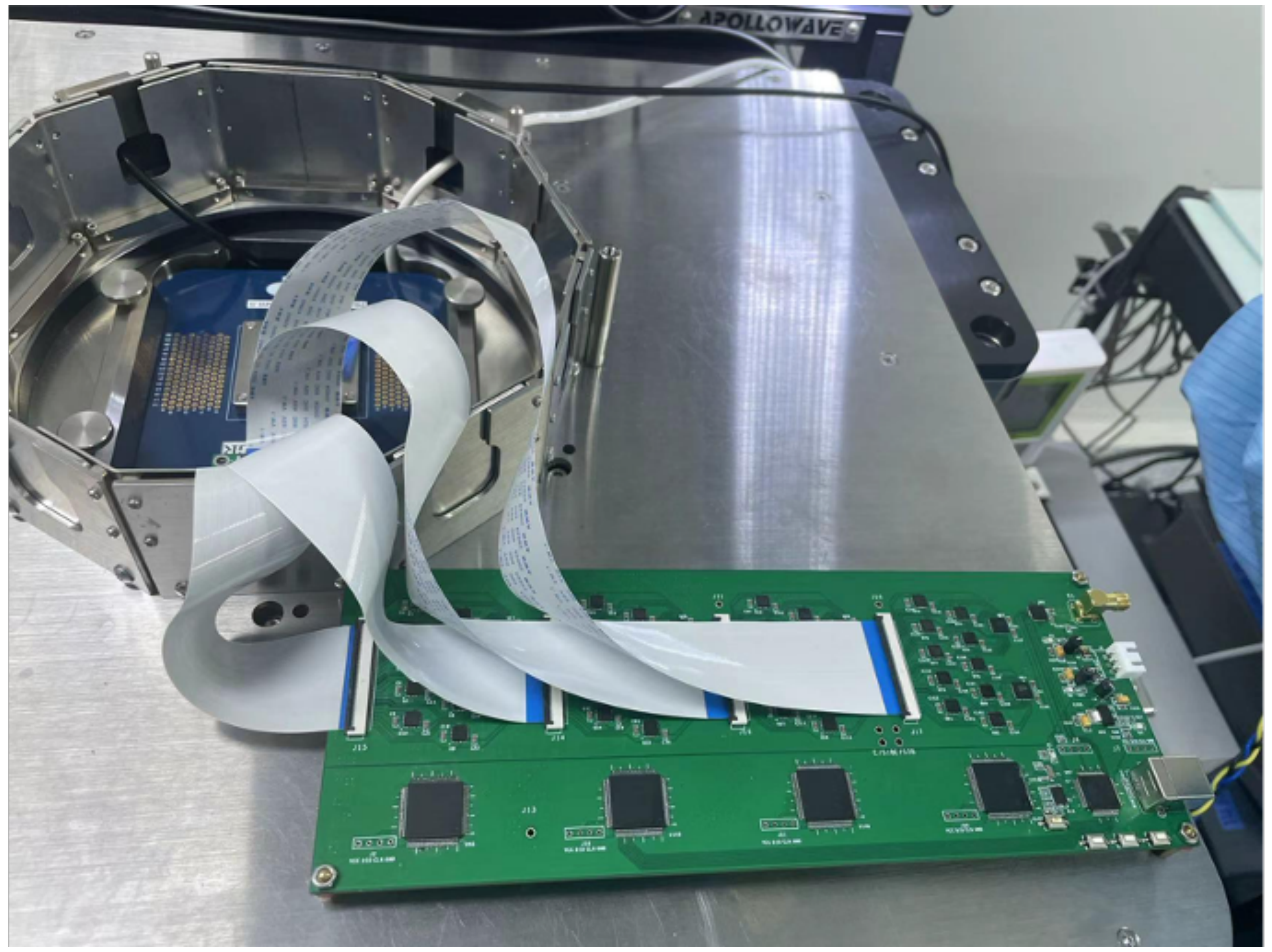


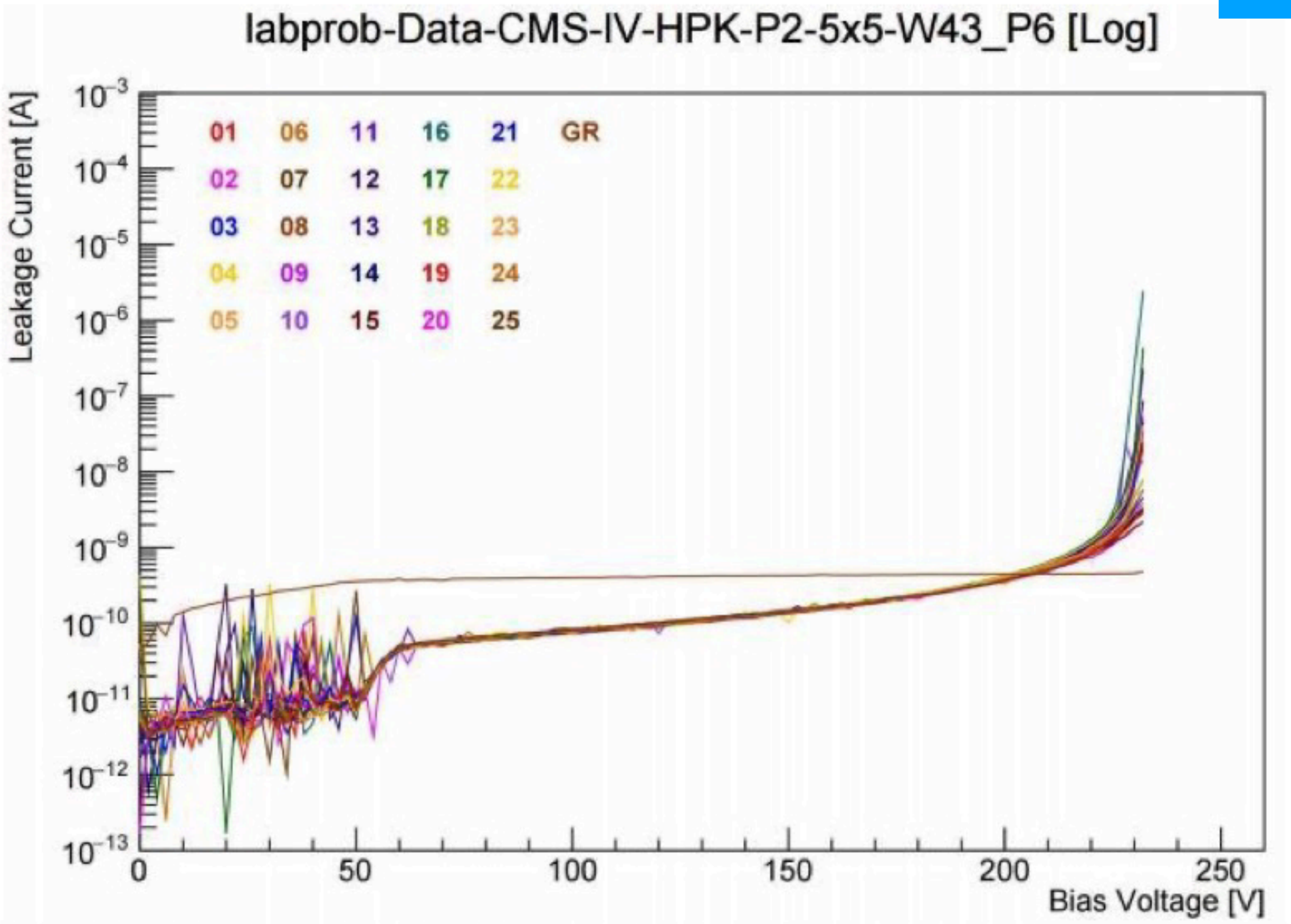




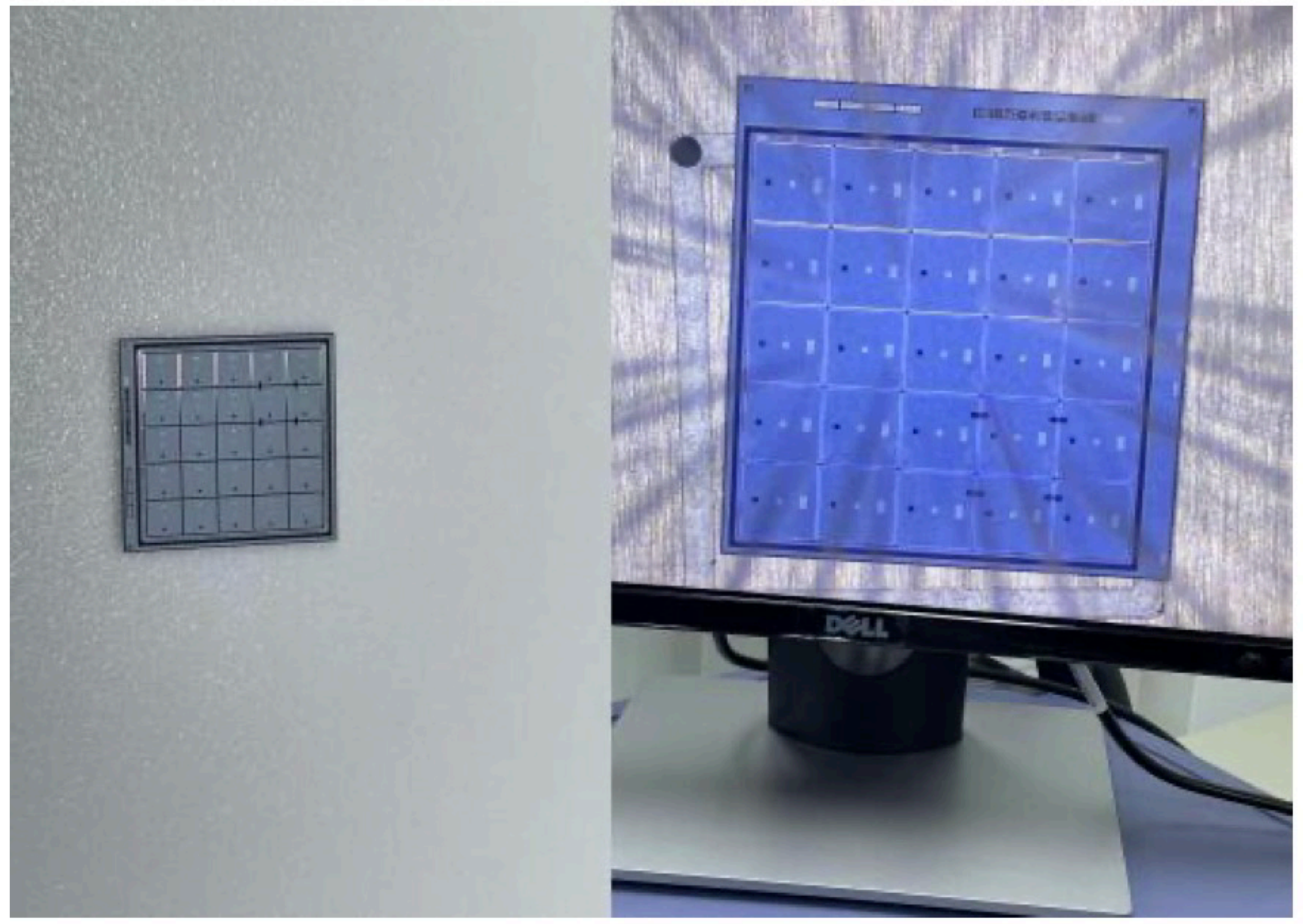
CMS Large LGAD matrix characterization at USTC

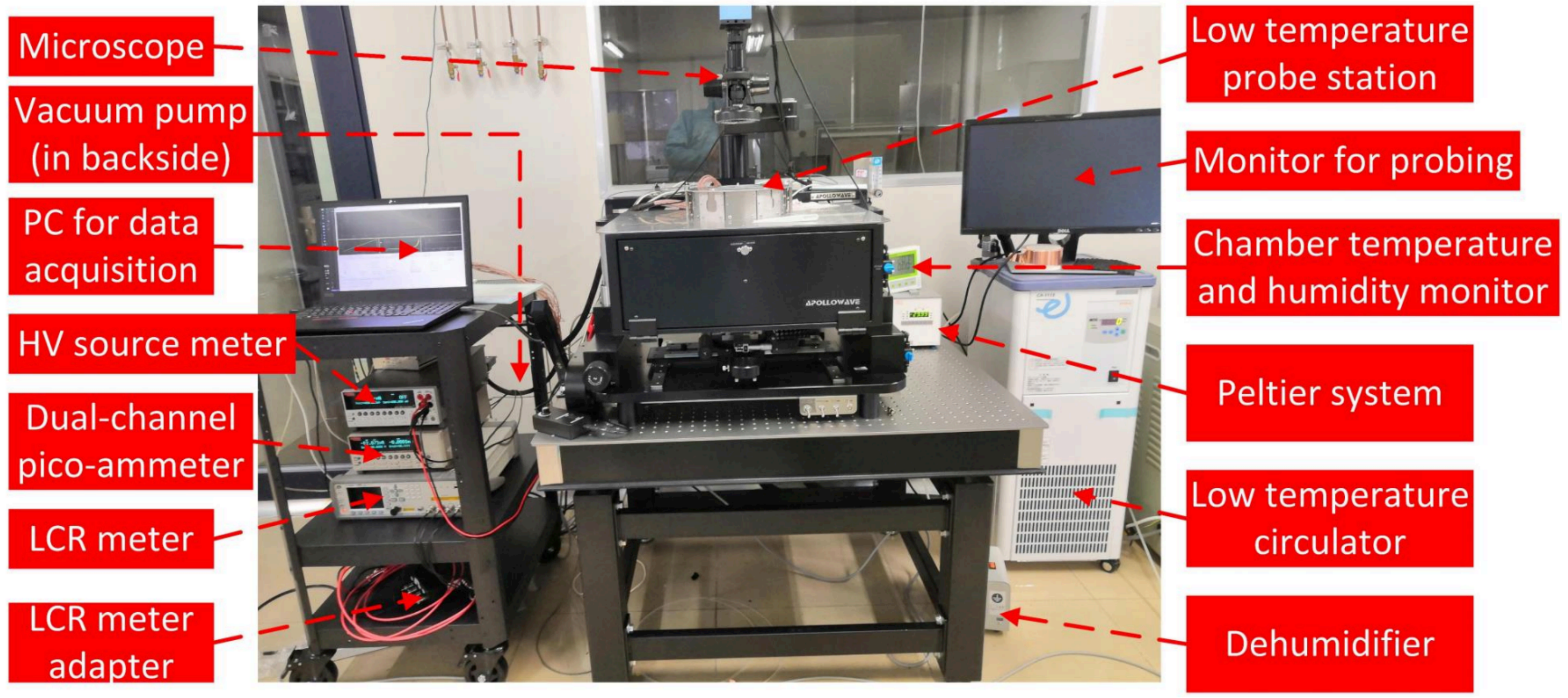
Using existing 15x15 LGAD matrix IV/CV measurement setup designed by USTC





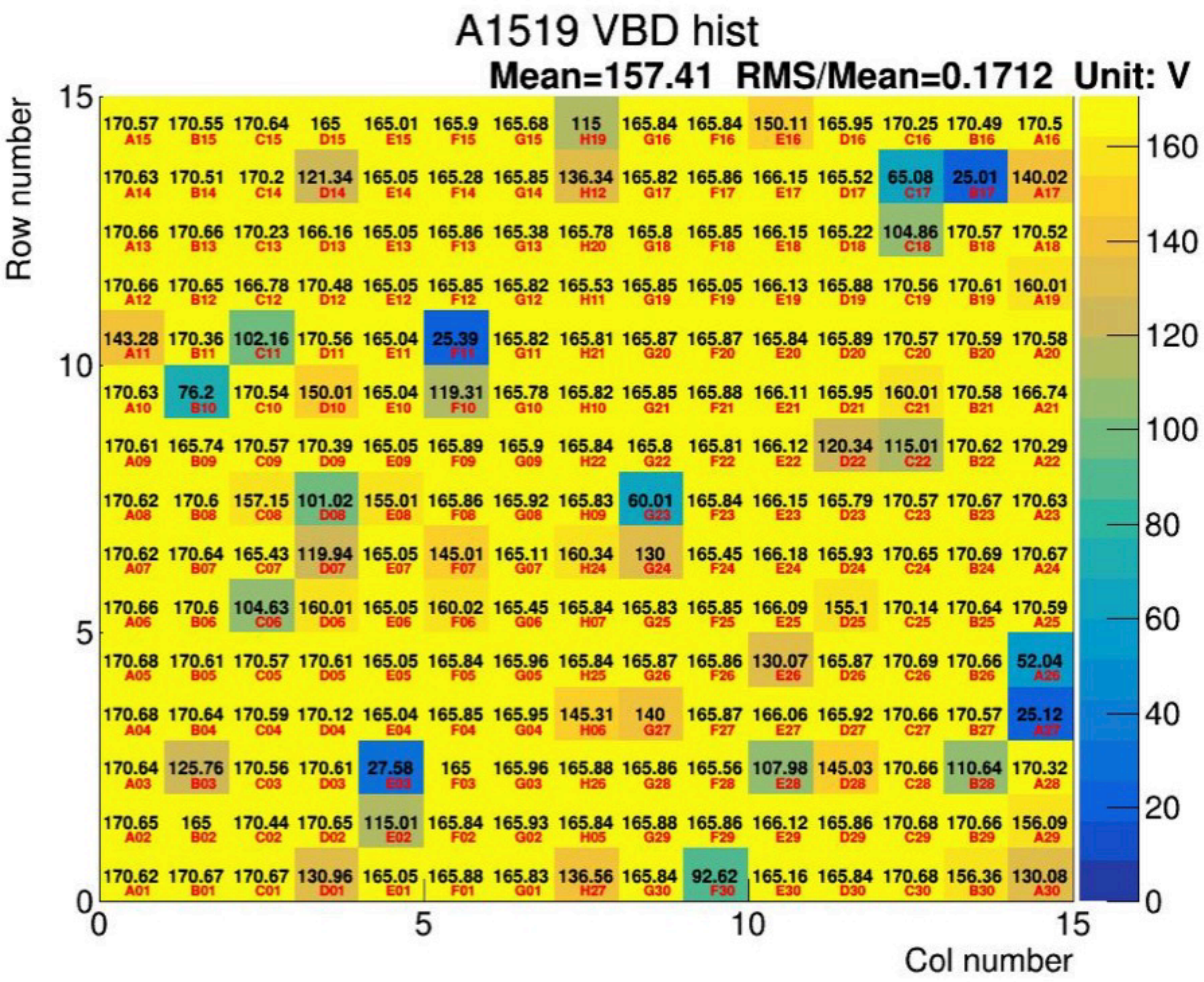
CMS LGAD HPK 5x5 sensor prototype





- Per channel IV/CV measurement enabled by probe card + switch board
  - all other channels are grounded
  - Switch board: https://doi.org/10.1016/j.nima.2022.167008

CMS Large LGAD matrix characterization at USTC



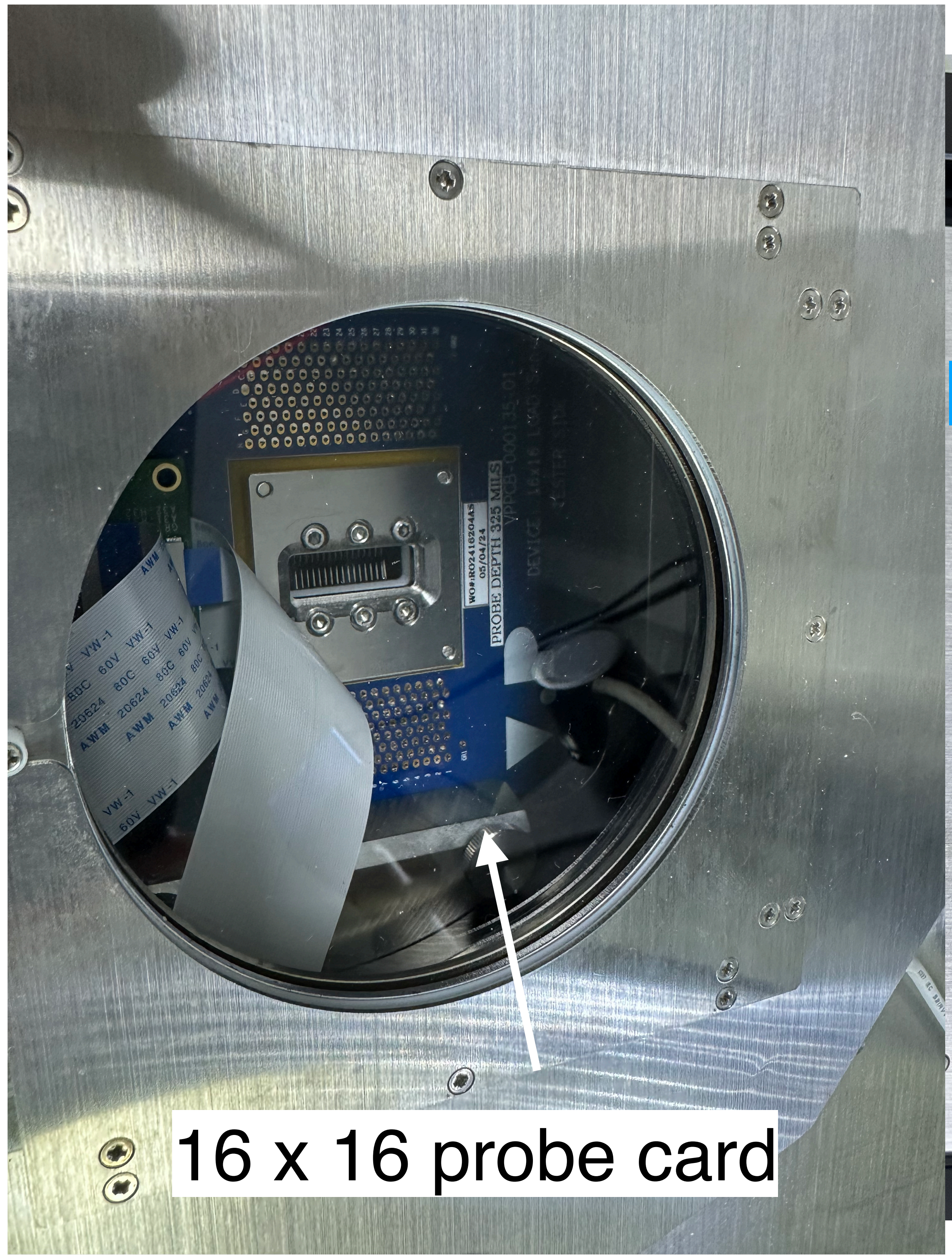
CNM is exploring in-kind contribution to ETL sensors

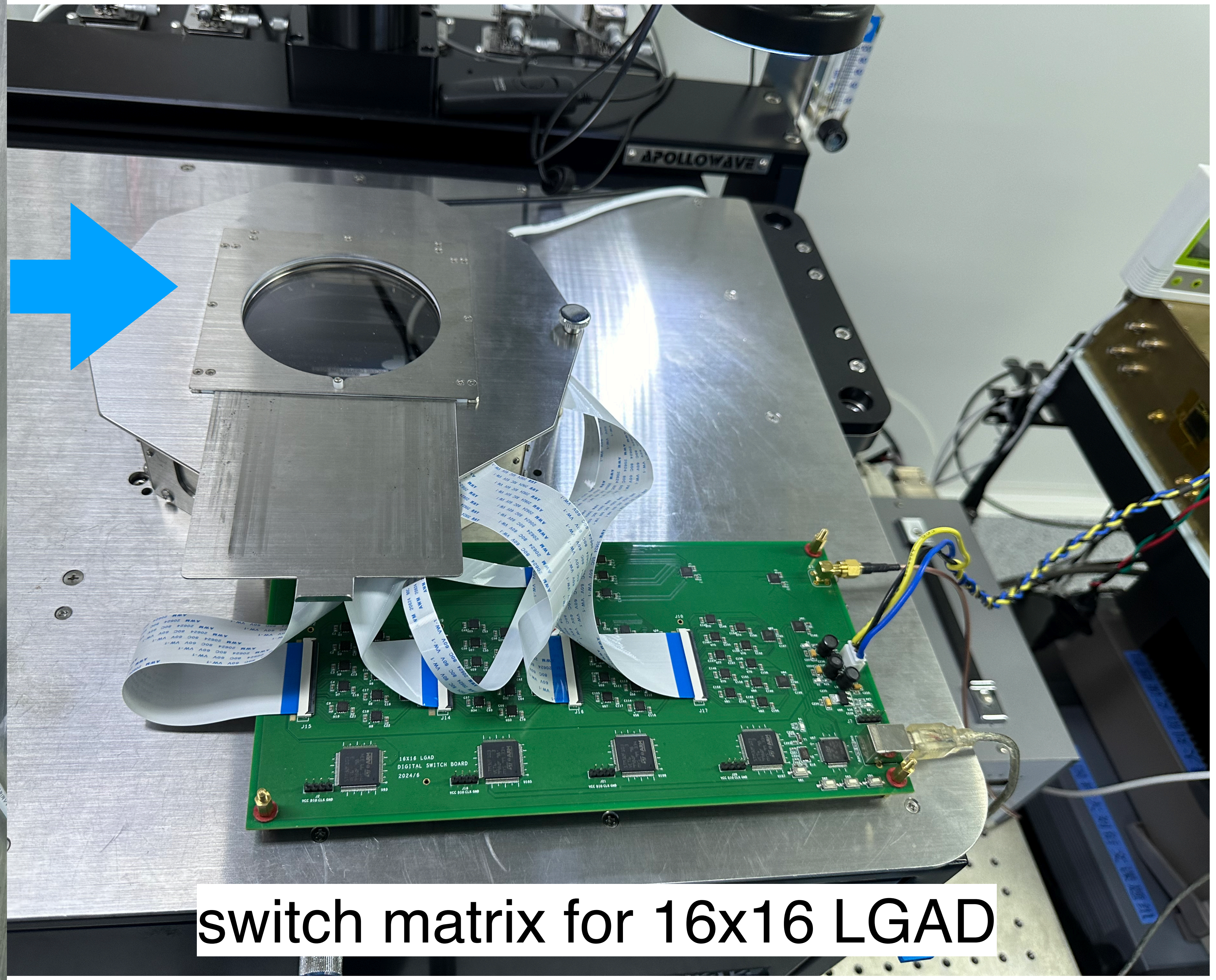
CNM provided us 15x15 sensor (ATLAS conditions) to measure breakdown voltage via IV measurement:

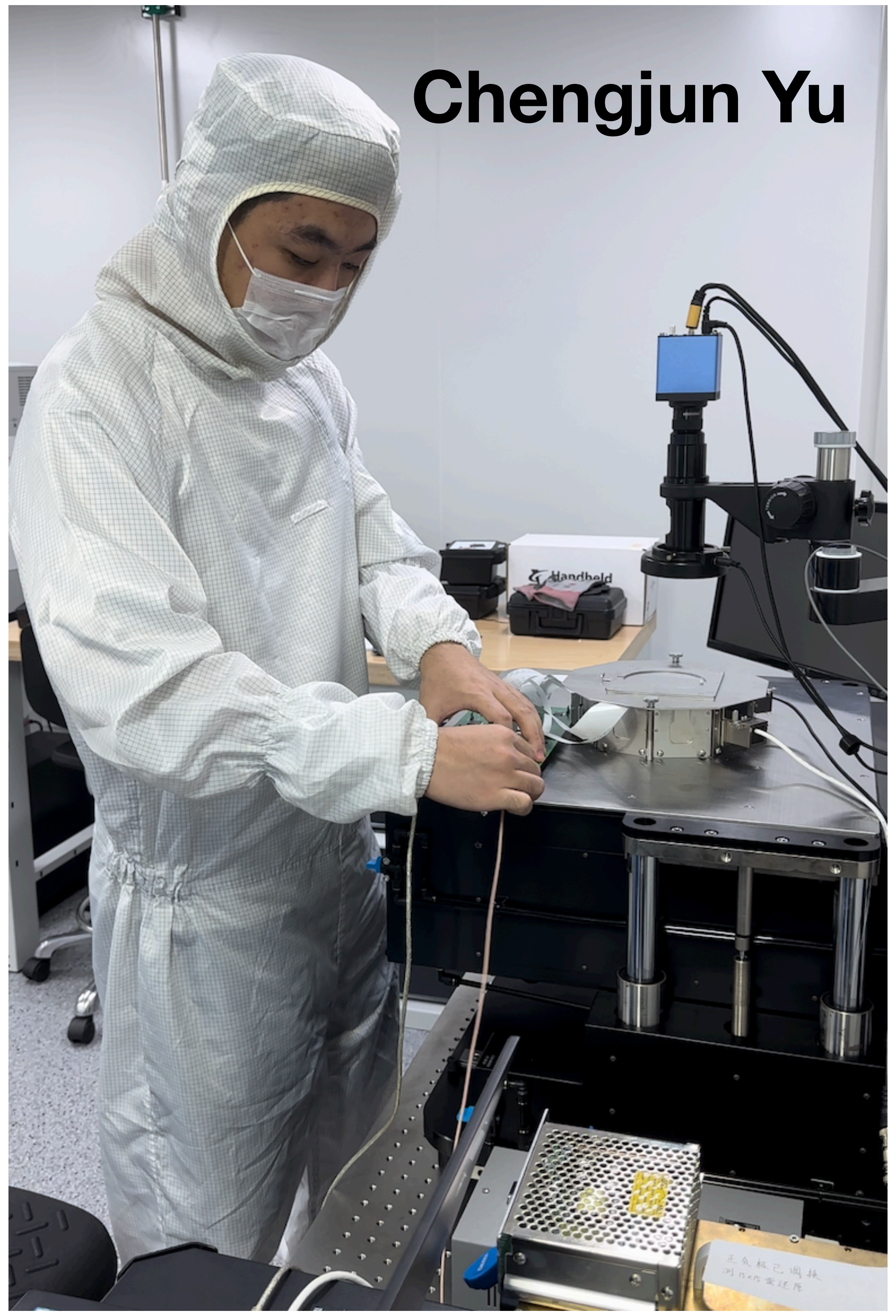
- Rate of good channels: 85% obtained from left plot
- The result is very well received: CNM very impressed by our characterization capability, they haven’t seen such measurements before!
- CNM provided us 16x16 sensor (CMS condition with better expected uniformity and performance) to characterize

CMS Large LGAD matrix characterization at USTC

- Design and build the setup for 16x16 LGAD matrix at USTC
  - Zheng De design and produce switch matrix, based on 15x15 LGAD characterization experience
  - order 16x16 probe card with collaboration with INFN Torino group
- Chengjun is leading students on commissioning the full system right now at USTC lab







ETL LGAD post-processing and preparation of QA center in China

LGAD Timeline:

- 2024: Freeze LGAD specifications + define quality management (QA/QC) procedures for the sensors production → Invitation to Tender and final selection of the vendor(s)
  - decision if LGAD post-processing at vendor
- 2025: Beginning of the sensor production for ETL

Our ongoing work:

- To provide post-processed sensors for bump-bonding and module assembly + technology validation of CMS LGAD post-processing by vendor in China
  - four FBK 8 inch LGAD wafers will be post-processed by NCAP in late August
- Build LGAD QC centers in China USTC and SCNU

Summary and outlook

CMS MTD ETL, based on the LGAD technology, at last stage of detector prototyping and soon moving ahead to pre-production&production

- sensor production to start in 2025
- detector installation in CMS in 2027 - 2028

USTC contributed to LGAD characterisation during prototyping phase:

- Excellent measurement capability for 15x15 and 5x5 CMS LGAD sensors
- Work progress to design and build the 16x16 setup

Our ongoing&future work:

- To provide post-processed sensors for bump-bonding and module assembly + technology validation of CMS LGAD post-processing by vendor in China
- Build LGAD QC centers in China USTC and SCNU

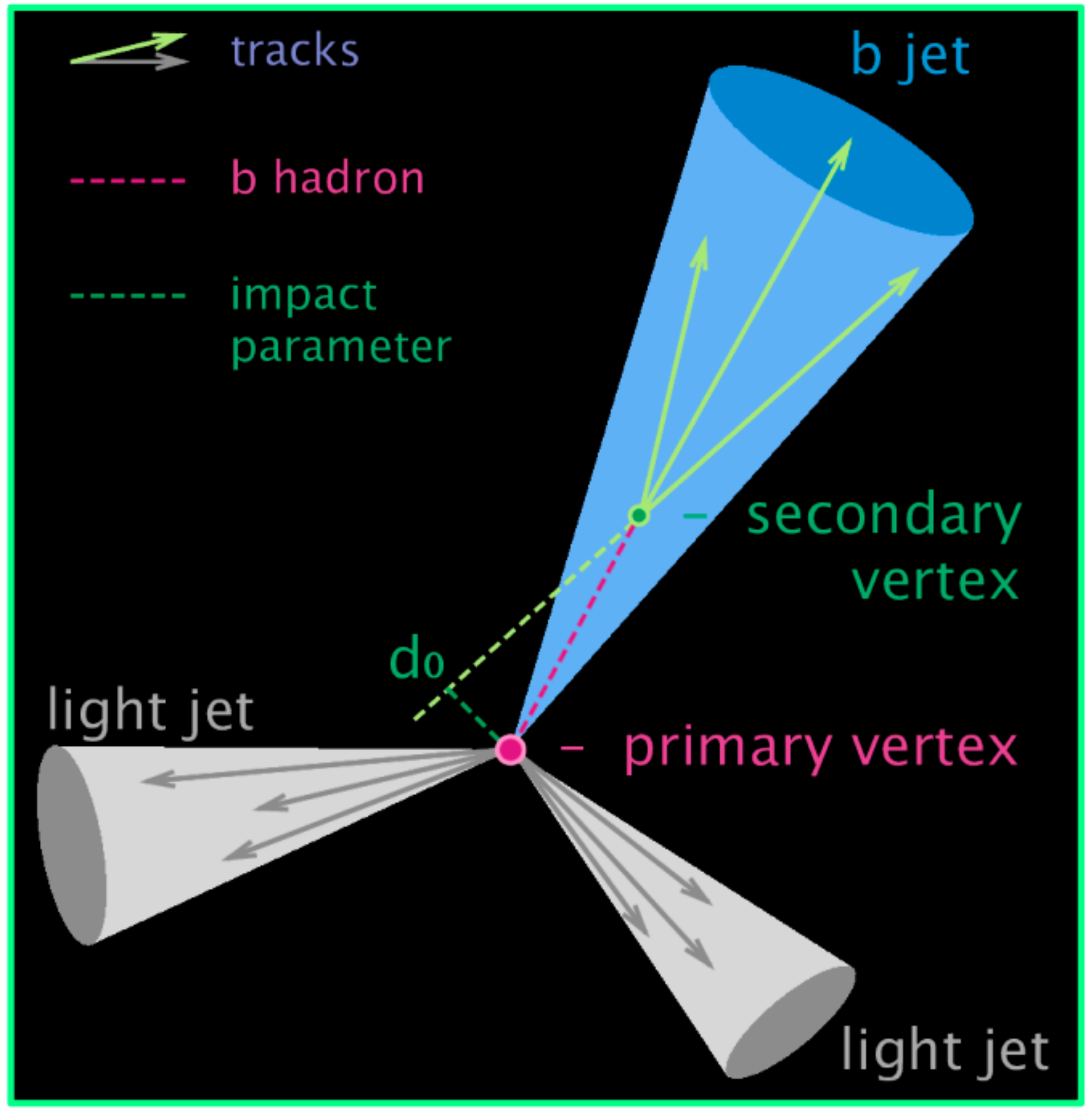
Close collaboration with SCNU, Shandong University and INFN Torino

Thank you!

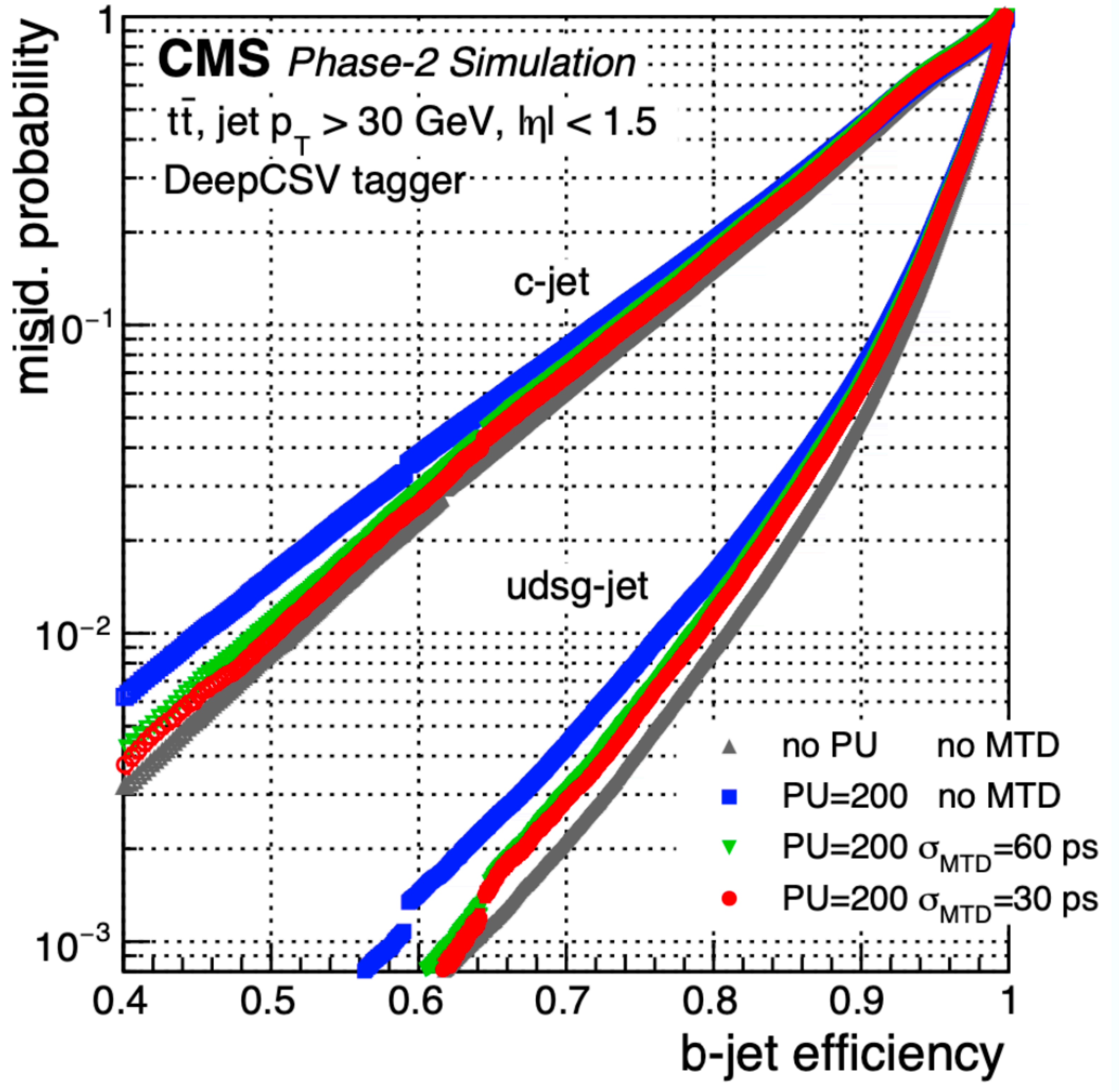
backup slides

Tagging jets originating from bottom-quark

- Improve b-jet tagging efficiency by 4–6% barrel (5–7% endcap) by reducing spurious secondary vertices
- caused by tracks from pileup interactions.



b-tagging in Phase 2



MTD Physics Potential

- 10 - 20% gain in di-Higgs significance

35 ps BTL, 35 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.38	1.52	1.60
$bb\gamma\gamma$	1.70	1.75	1.85	1.90
Combined	2.31	2.40	2.57	2.66

DP-Update_MTD_physics_case_v7:
https://twiki.cern.ch/twiki/bin/viewauth/CMS/AN-22-060

Requirements of the MIP timing detector

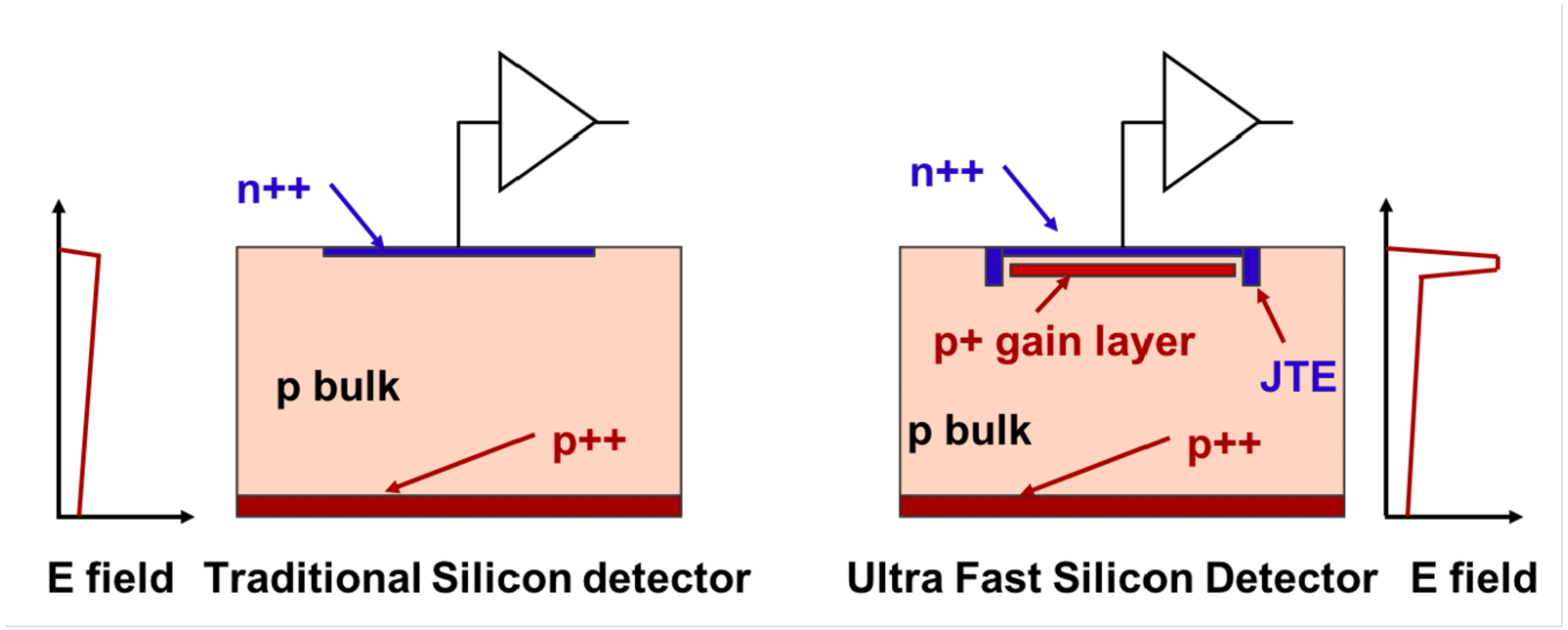
	Barrel Timing Layer (BTL)	Endcap Timing Layer (ETL)
Coverage	$\|\eta\| < 1.5$	$1.6 < \|\eta\| < 3.0$
Surface Area	$38\ m^2$	$12\ m^2$
Power Budge	$0.5\ kW/m^2$	$1.8\ kW/m^2$
Radiation Rose	$\leq 2 \times 10^{14}\ n_{eq}/cm^2$	$\leq 2 \times 10^{15}\ n_{eq}/cm^2$

BTL: lutetium-yttrium orthosilicate crystals activated with cerium (LYSO:Ce) crystal read out with Silicon Photomultipliers (SiPM)

ETL: two disks of Low Gain Avalanche Detectors (LGAD), same sensor technology as ATLAS High Granularity Timing Detector.

Low Gain Avalanche Detectors (LGADs)

- LGAD: ultra-fast silicon detectors with a highly doped p+ gain layer for charge multiplication. Gain ~10-30
- Technology choice of ATLAS High-Granularity Timing Detector (HGTD) and CMS ETL

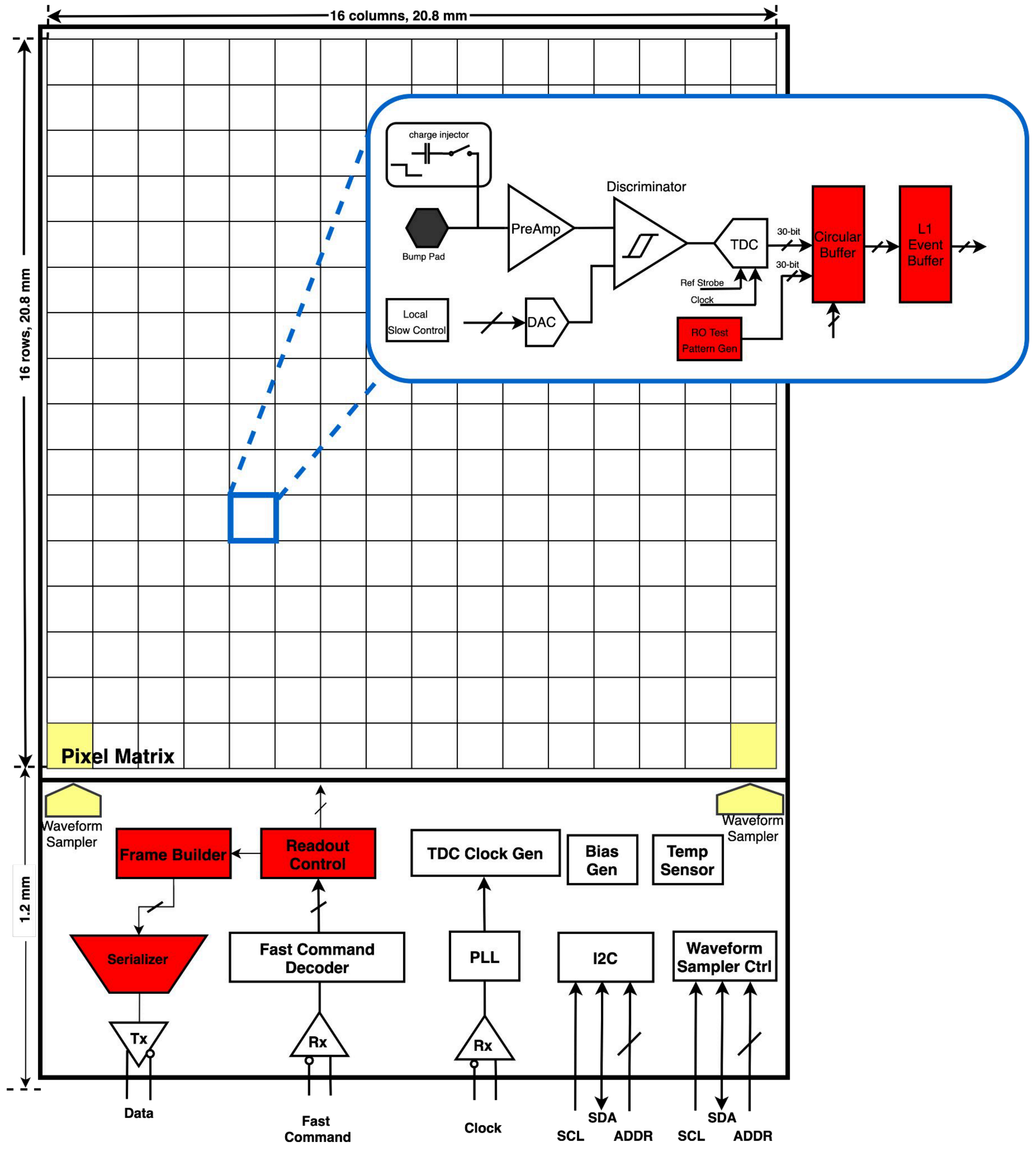


LGAD silicon sensors:

- signals that are a factor of 10-20 larger than traditional silicon detectors
- maintaining very low noise
- fine segmentation
- thin sensor

Very good S/N: 5-10 times better than current detectors

Precision timing at low power: ETROC ASIC



Performance specifications:

- TSMC 65nm technology, 100 MRad (TID spec)
- Low noise and fast rise time
- Low power: ≲ 4 mW / channel at end-of-life
- ASIC contribution to time resolution ≲ 40 ps at end-of-life

ETROC0: single analog channel
ETROC1: with TDC, 4x4 channel-clock tree
ETROC2: full size, full functionality, testing now!
ETROC3:final chip, submit next year