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

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For the CMS MTD group

CHiP Cross-Strait Workshop on
Advanced Detectors and Technologies
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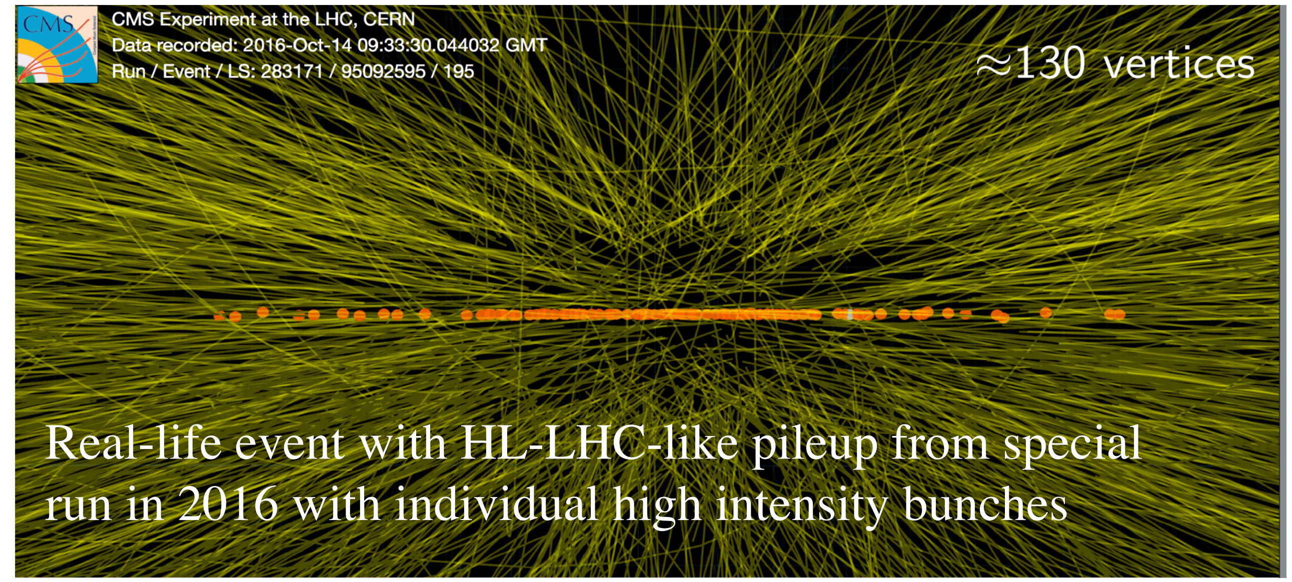
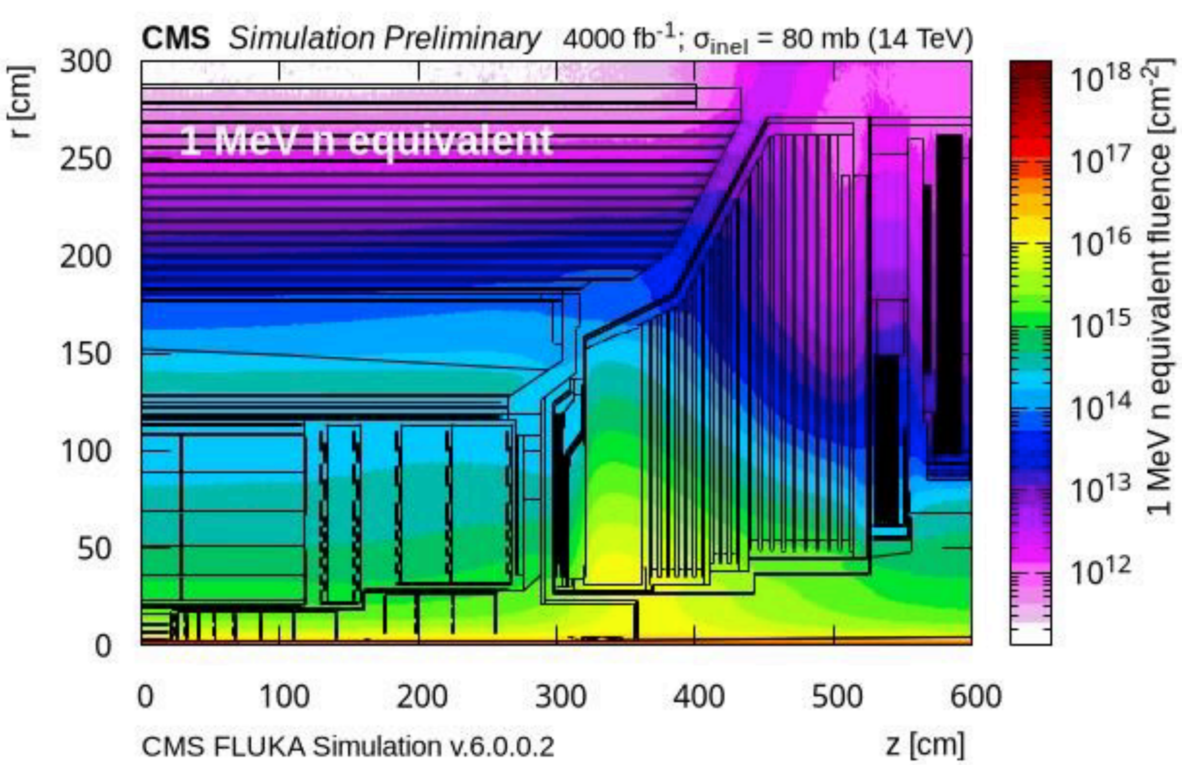
HL-LHC upgrade and pileup challenge

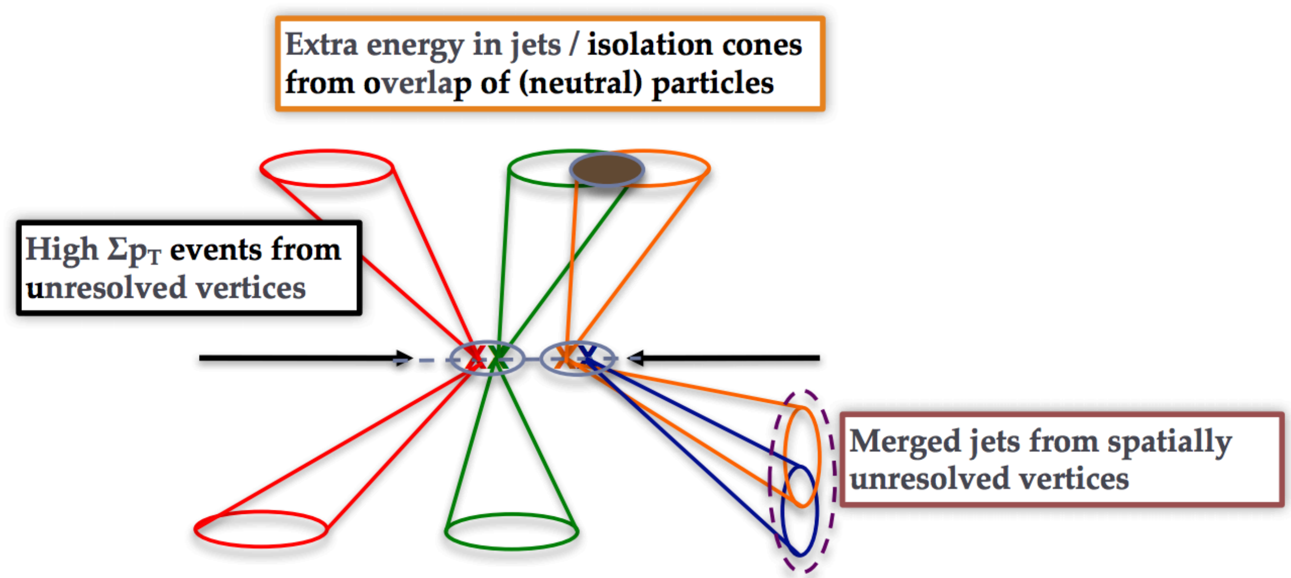
Upgrade of the accelerator complex optics and injectors to increase the beam intensity

- 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

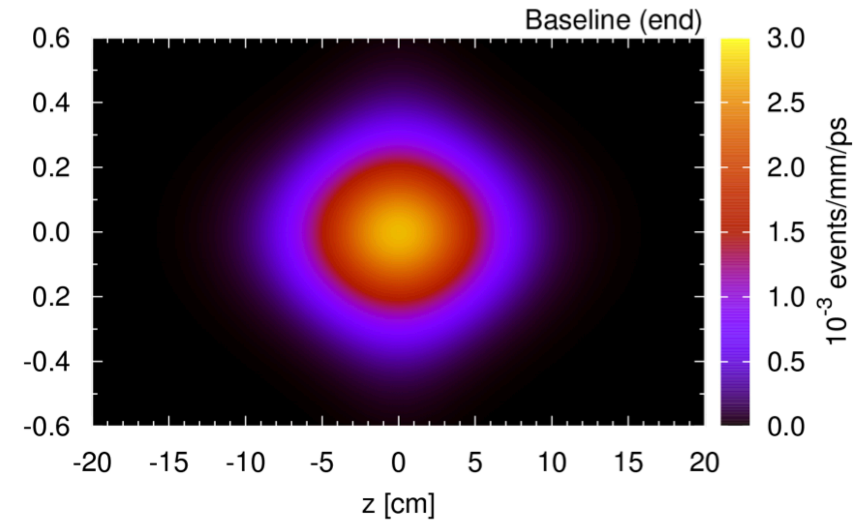


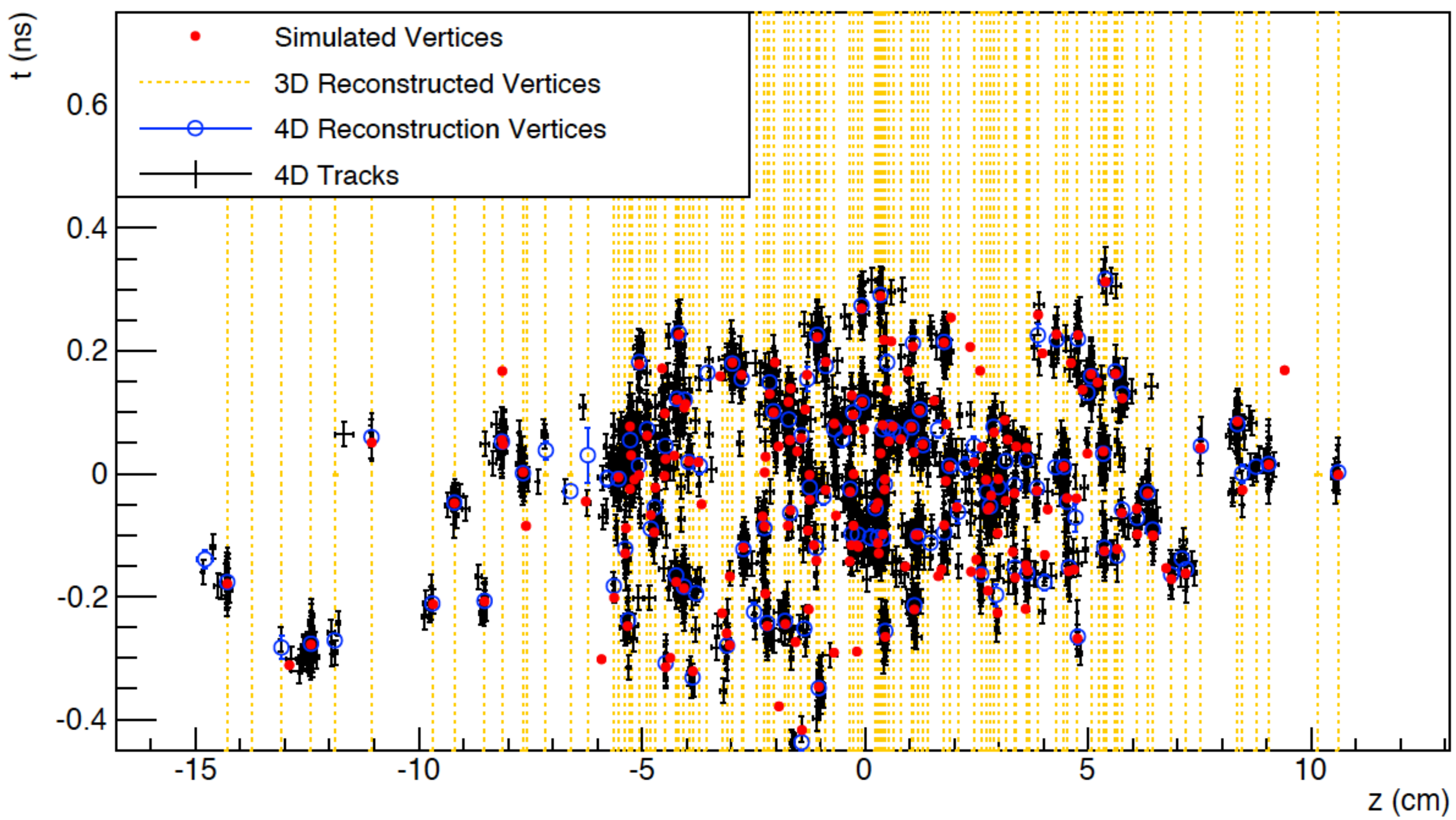
CMS MIP Timing Detector (MTD): New Precision Timing Measurement

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



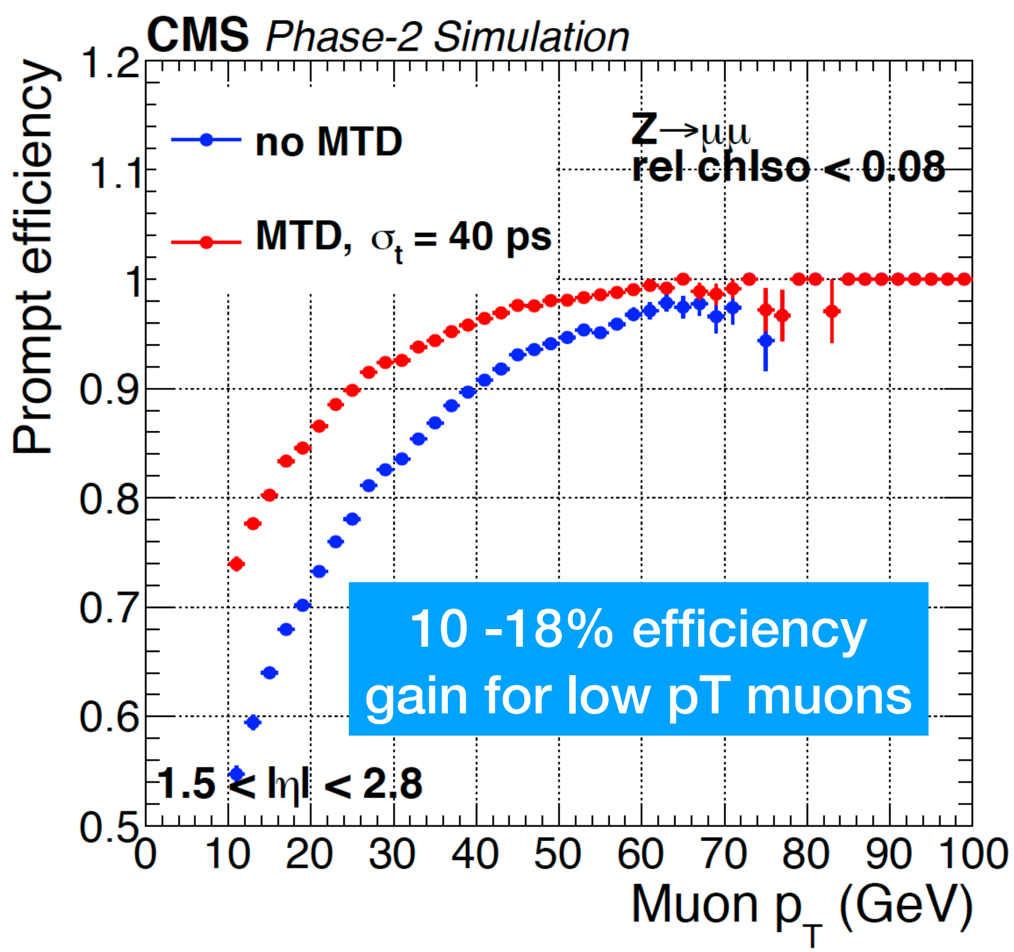


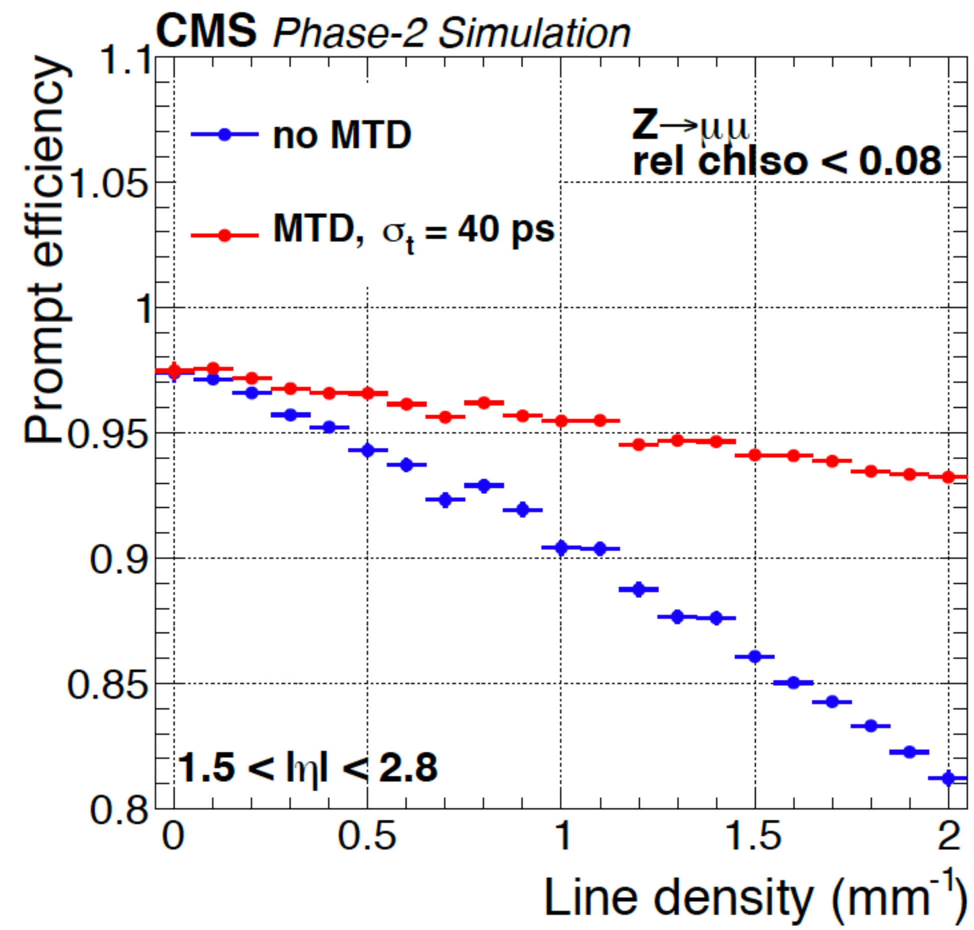
Beam spot has a spread of about 180-200 ps:

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

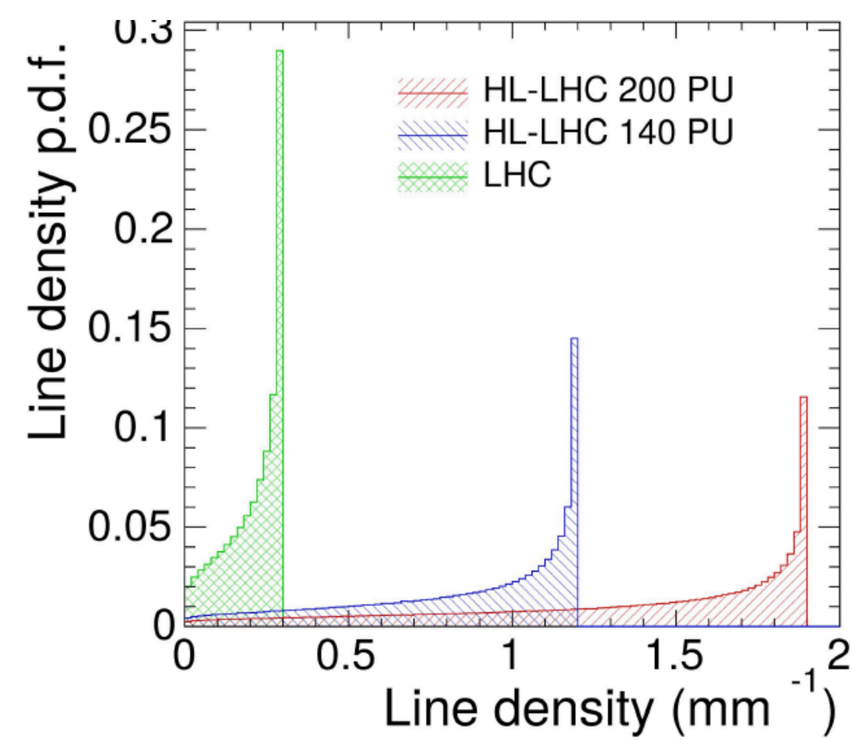
MTD TP: LHCC-P-009

Pileup mitigation with MTD





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

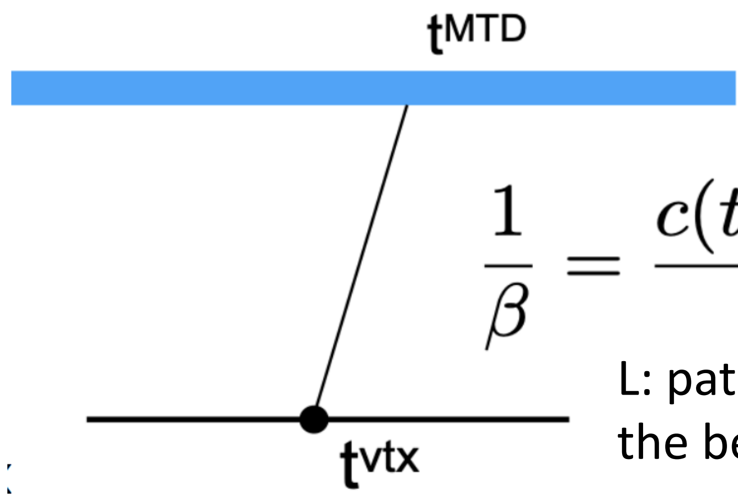


Reduction of pile-up by MTD enhances physics object reconstruction (μ, τ, b-tagged jets etc)

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

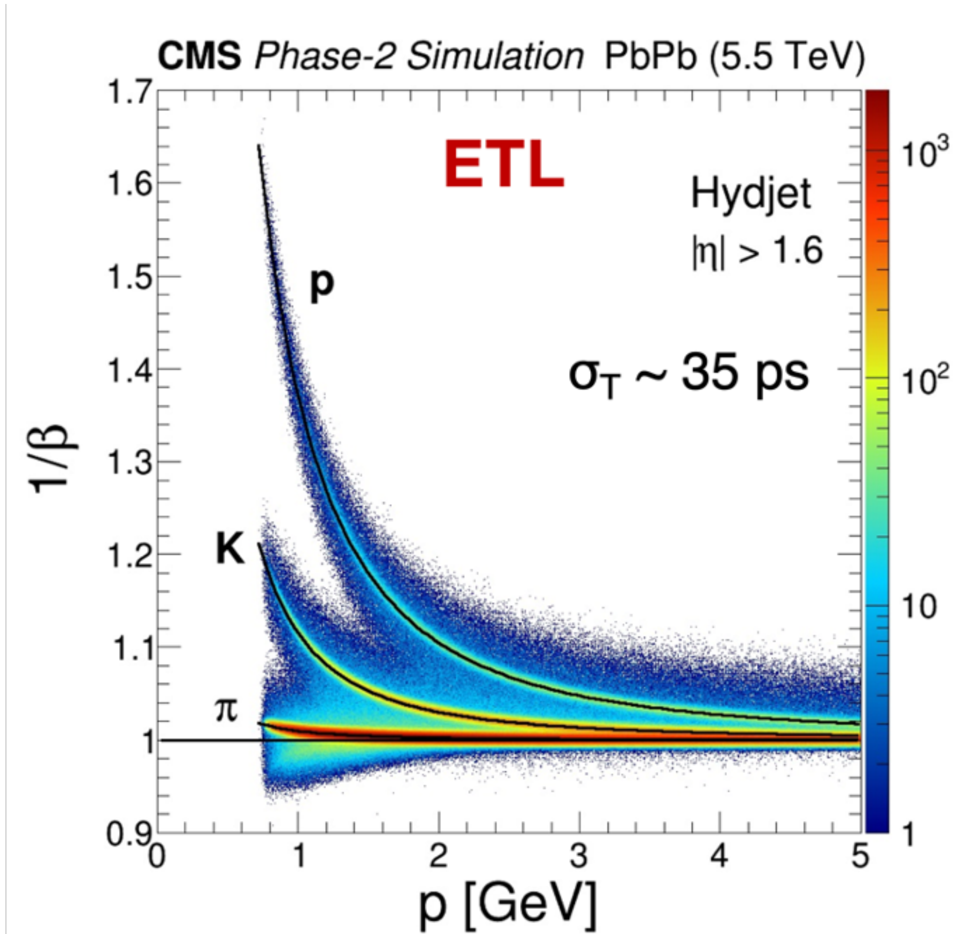
Charged hadron identification

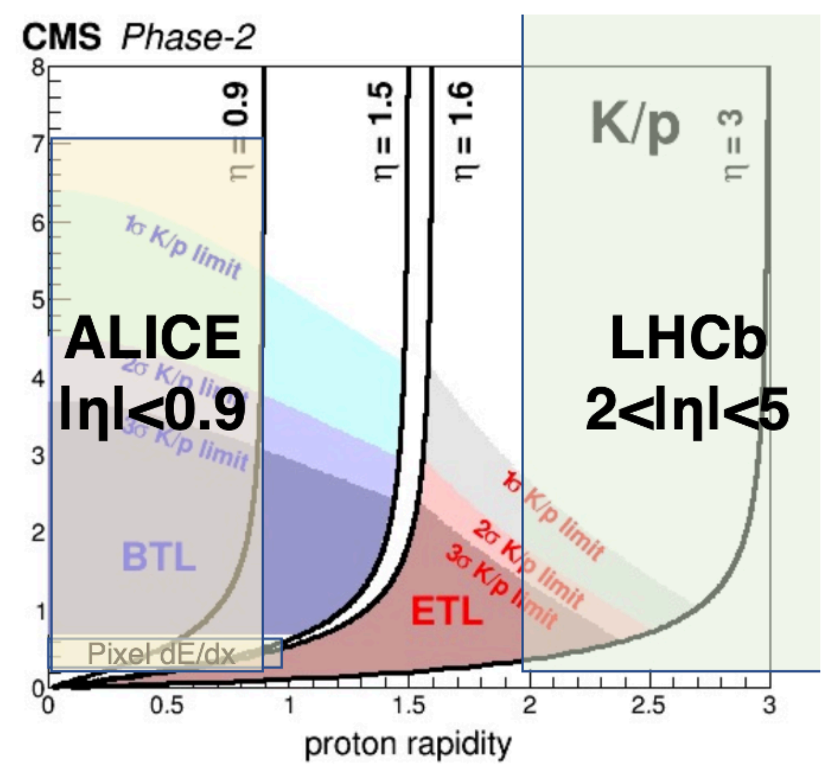
- Measurement of velocity for low p_T hadrons, enabling particle identification:
  - π/K separation up to 3 GeV
  - p/K separation up to 5 GeV



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

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





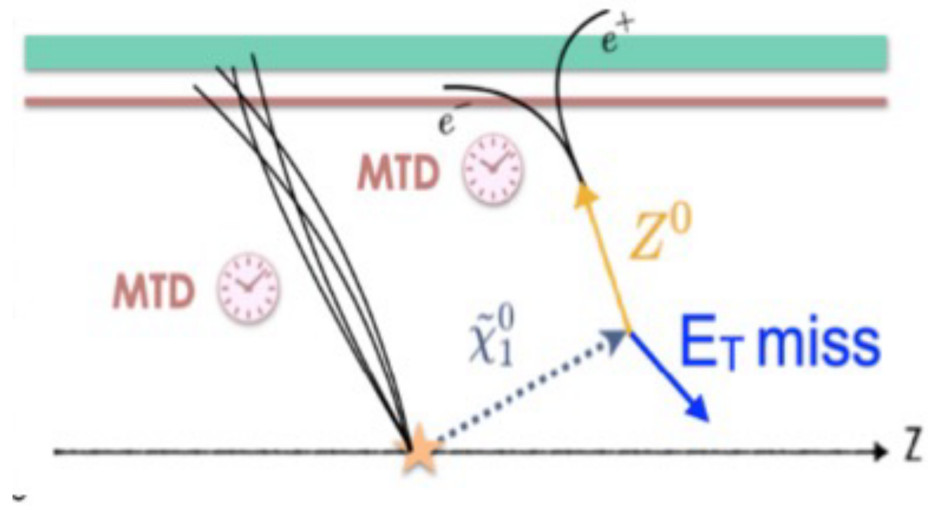
- Measurements of heavy flavor particles of interest to study evolution of QGP
- CMS, Alice and LHCb have complementary PID capabilities in terms of rapidity coverage

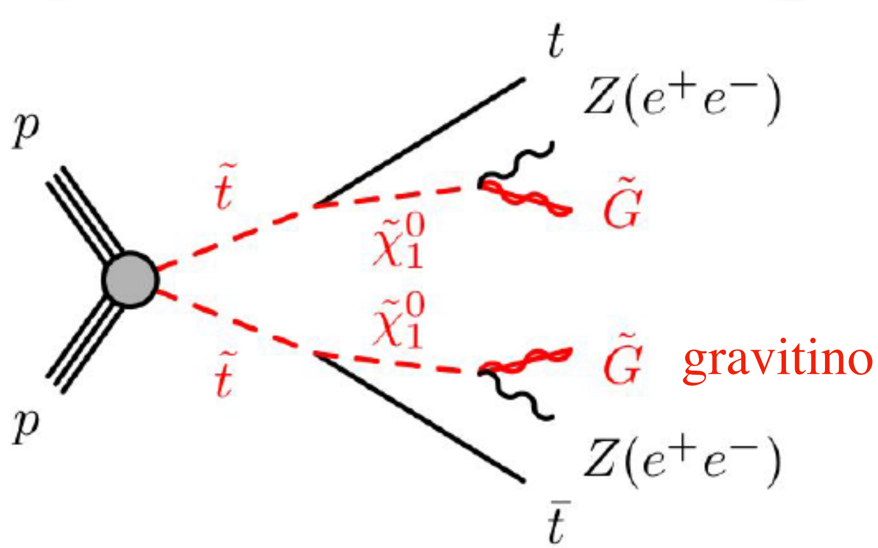
Mass reconstruction of long lived particles (LLP)

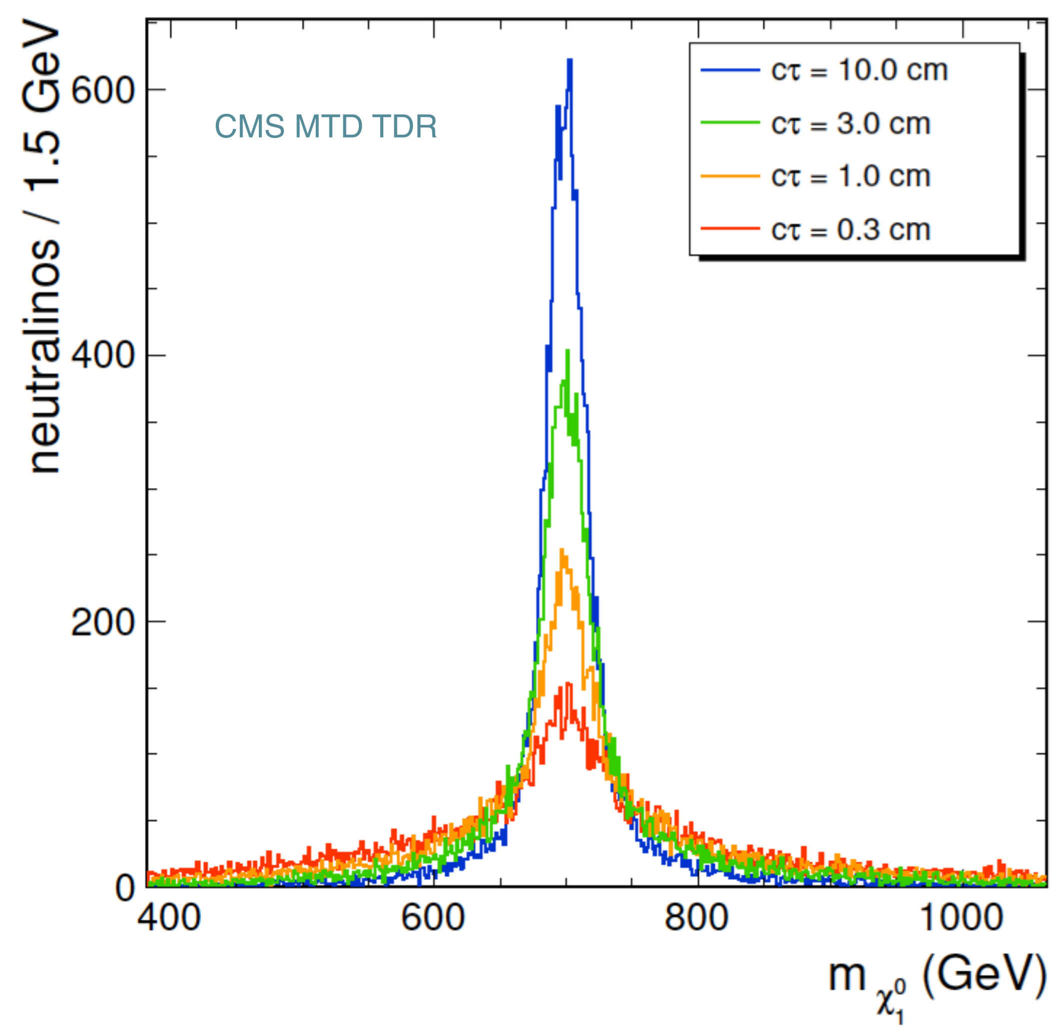
- Mass of LLP can be reconstructed with timing plus kinematics of visible part of LLP decay! Fundamentally changes how we carry out these searches

- 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:

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

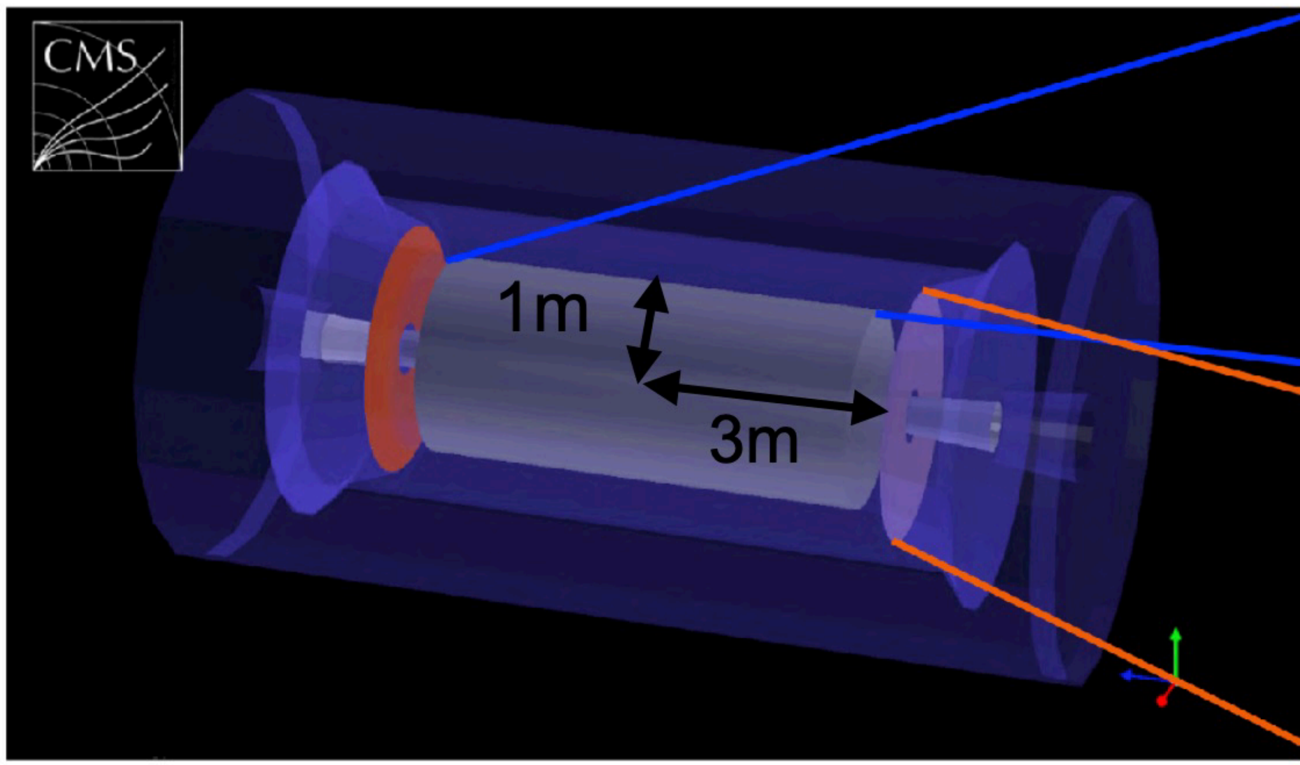






CMS MIP Timing Detector Overview

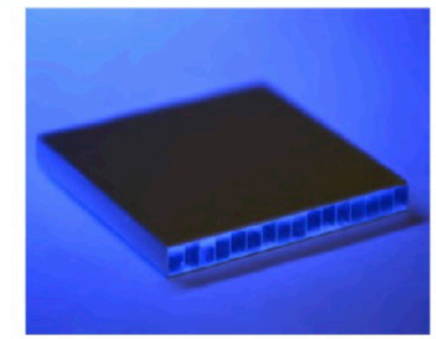
- MTD add completely new capability to CMS: measure precisely (30-70 ps resolution) the production time of MIPs



16 LYSO bars, single bar dimension: 3.75 x 3 x 54.7 mm^3

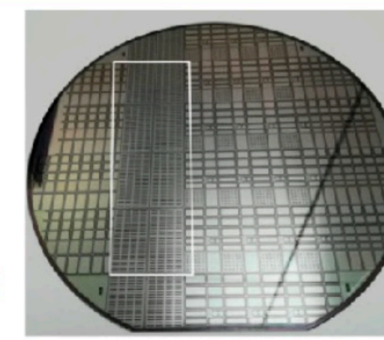
BTL: LYSO bars + SiPM read-out

- TK/ECAL interface ~ 45 mm thick
- $|\eta| < 1.45$ and $p_T > 0.7$ GeV
- Active area ~ 38 m^2 ; 332k channels
- Fluence at 3 ab^{-1}: 2×10^{14} n_{eq}/cm^2



ETL: Si with internal gain (LGAD)

- On the HGC nose ~ 65 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~ 14 m^2; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2



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

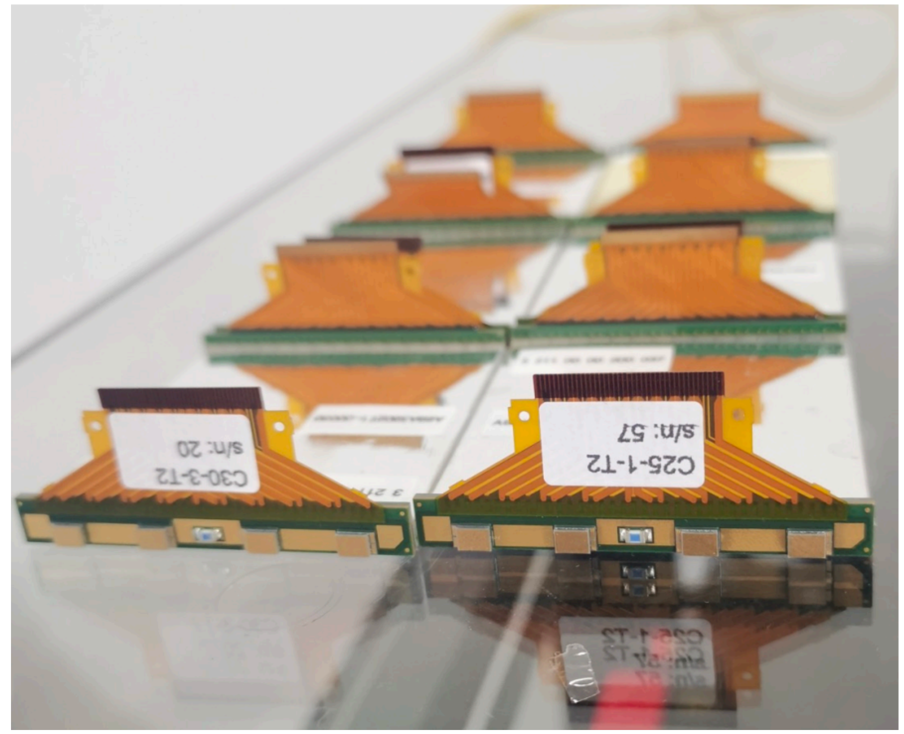
<u>CMS-TDR-020</u> March 2019

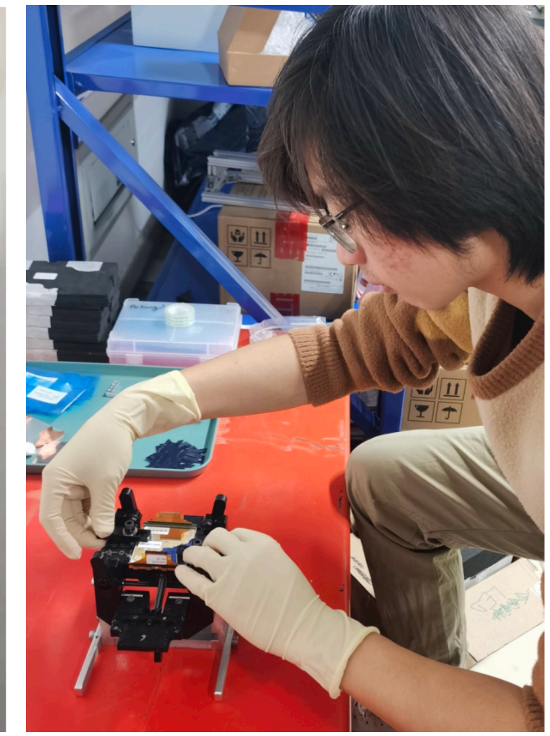
MTD-BTL contributions by Peking. U & Tsinghua and Beihang University

Joined BTL since 2021

Contribution:

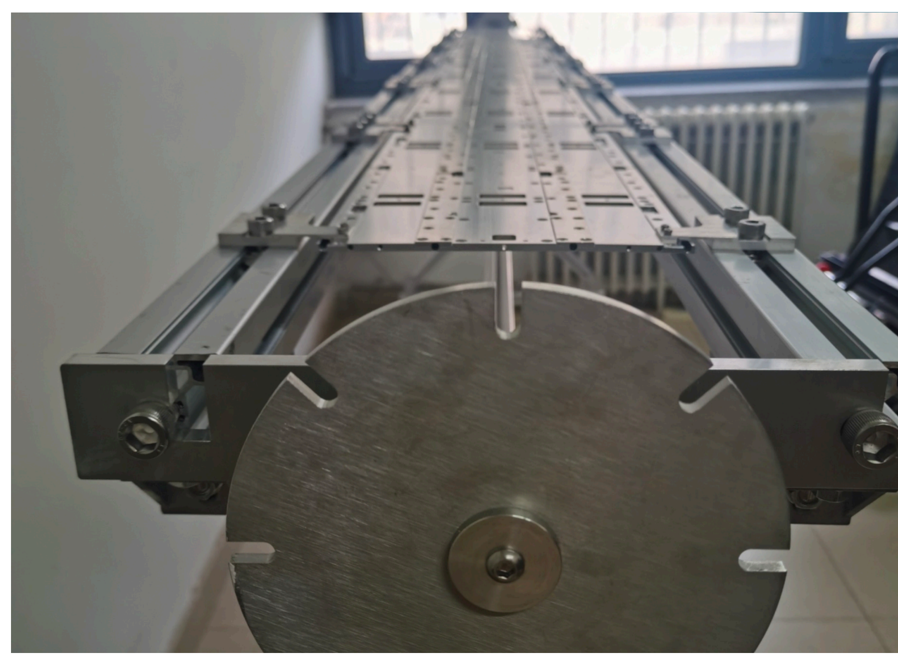
- key contribution to sensor optimization and final design
- module and tray assembly
  - **plan to assemble 1/4 of the BTL modules**
- cooling plate production

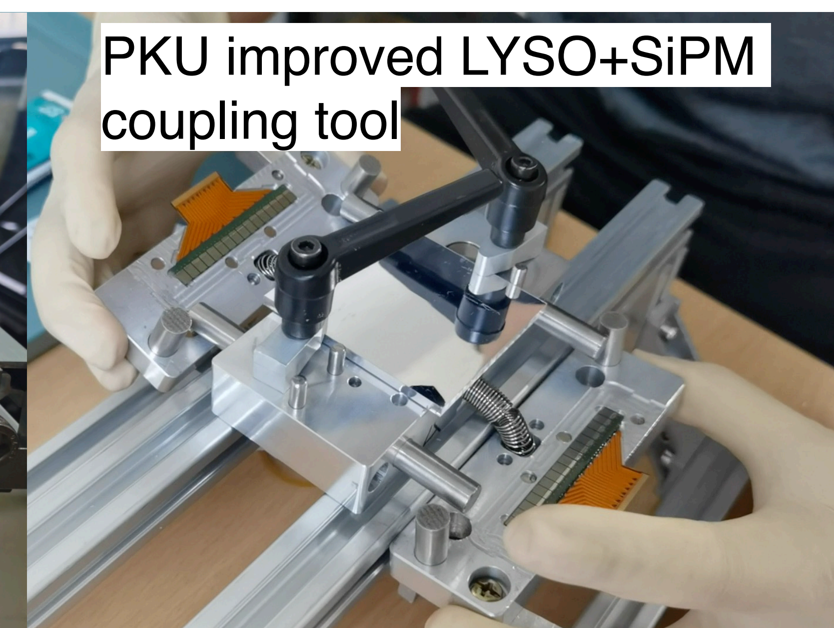




PKU BTL module assembly center:

- Improve the assembly and QA/QC in the summer of 2023
- Assembly Center Certification in the autumn of 2023
- Start mass production in summer 2024





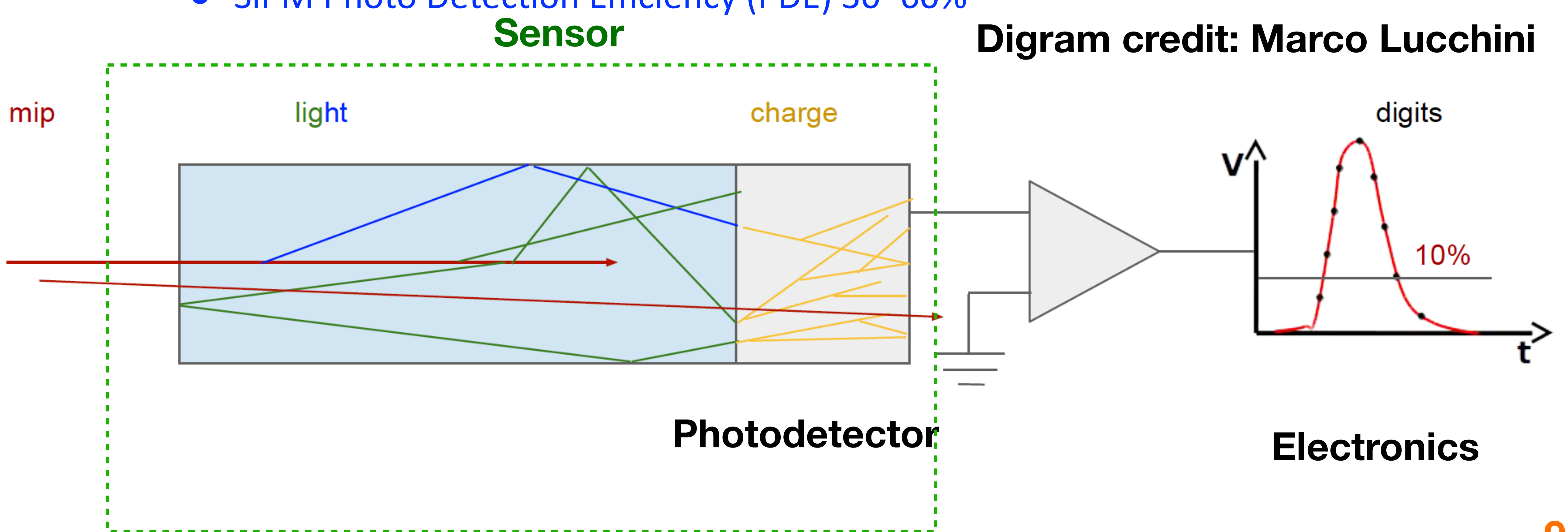
BTL: Crystal-Based Precision Timing

- Lutetium-yttrium orthosilicate crystals activated with cerium (LYSO:Ce) as scintillator
- Silicon Photomultipliers (SiPM) as photo sensors
- Stochastic fluctuations in the time-of-arrival of photons detected at the SiPM:

$$\sigma_t^{photostatistics} \propto \sqrt{1/N_{p.e.}} \propto \sqrt{1/(E_{dep} \times LY \times LCE \times PDE)}$$

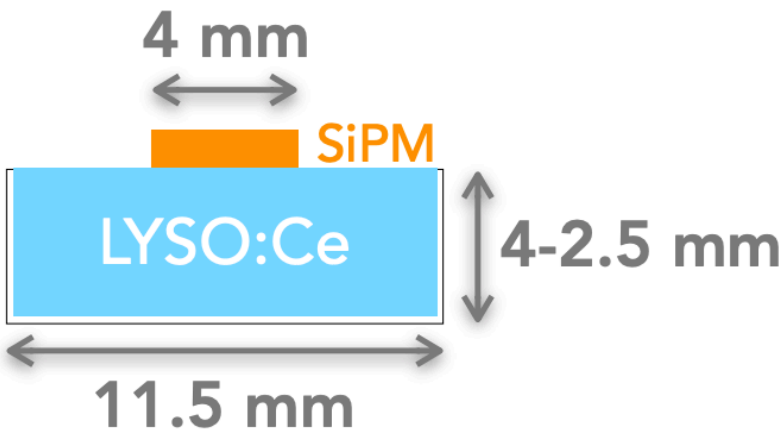
  - A MIP deposits **E_{dep} ~4.2 MeV** in BTL LYSO including impact angle
  - LYSO is bright, fast and radiation hard: light yield (LY) ~40k photons/MeV.
  - Light correction efficiency (LCE) ~25%
  - SiPM Photo Detection Efficiency (PDE) 30~60%

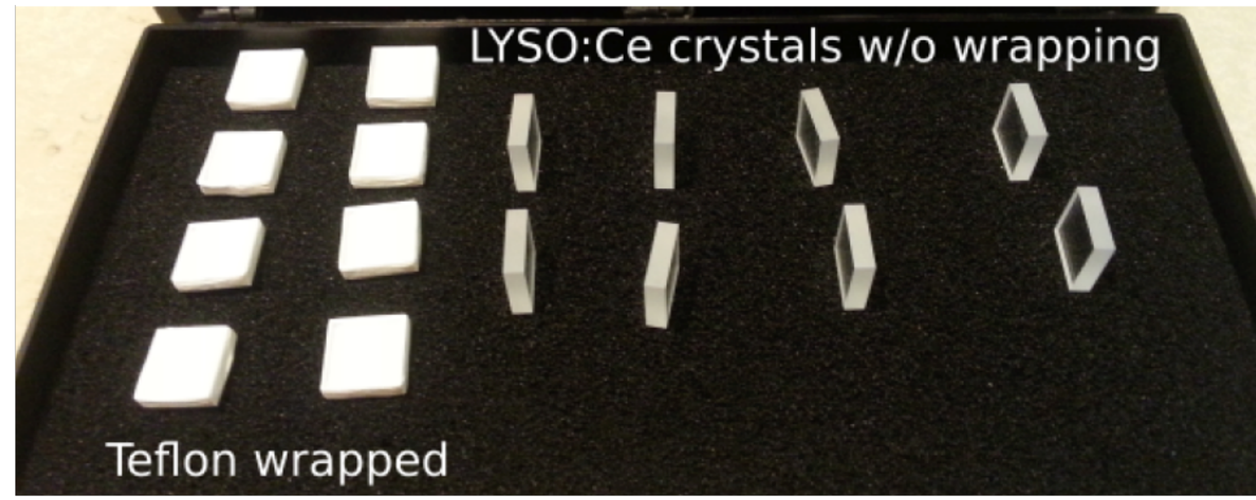
Digram credit: Marco Lucchini



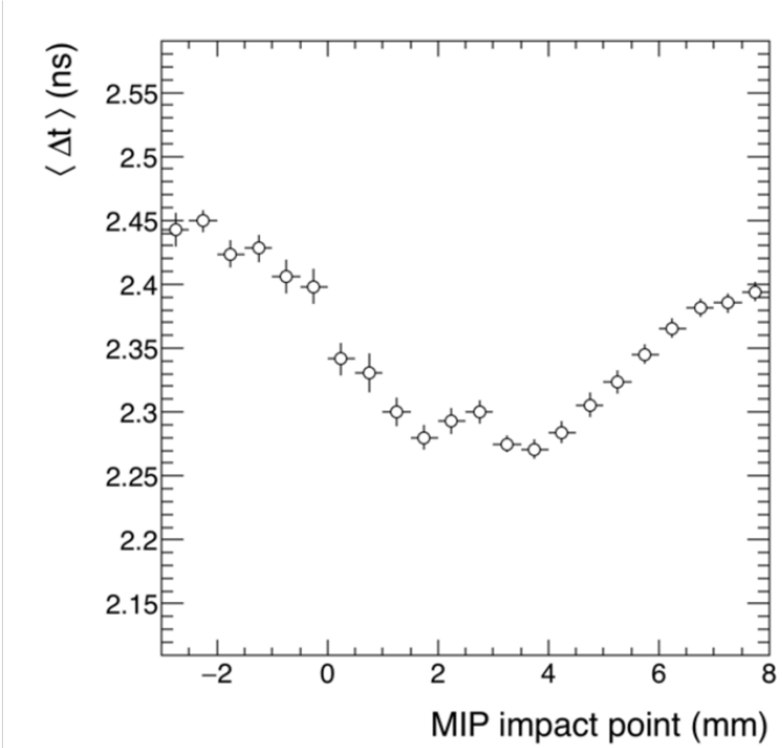
BTL sensor： early tile geometry

Sensor design in MTD Technical Proposal, Nov 2017 LHCC-P-009

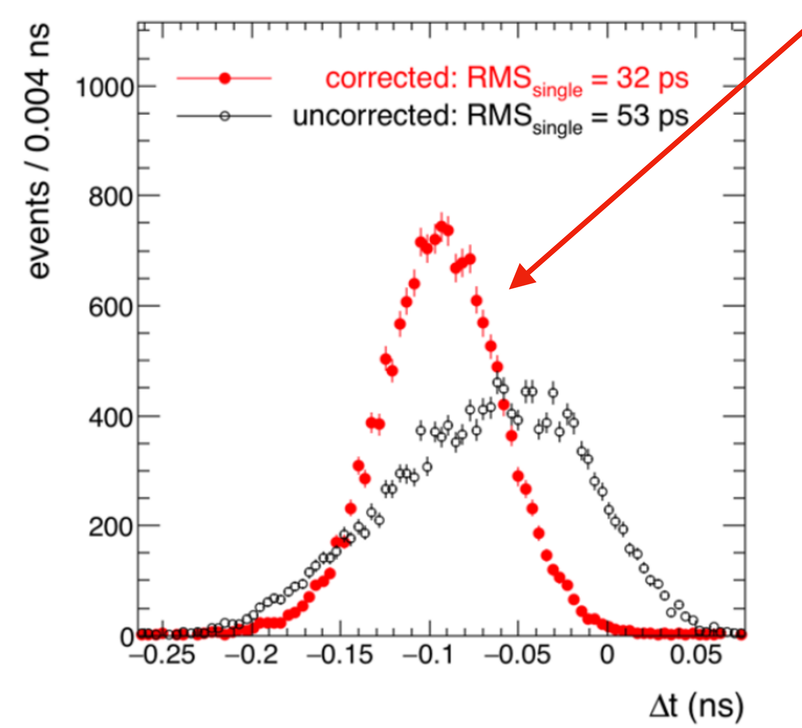


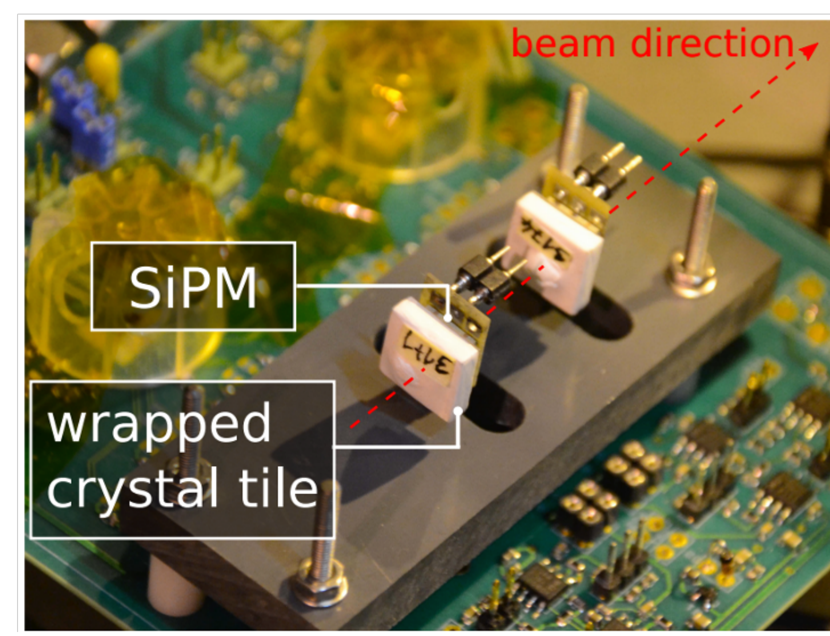


time stamp dependence on the MIP impact point on the LYSO test beam data



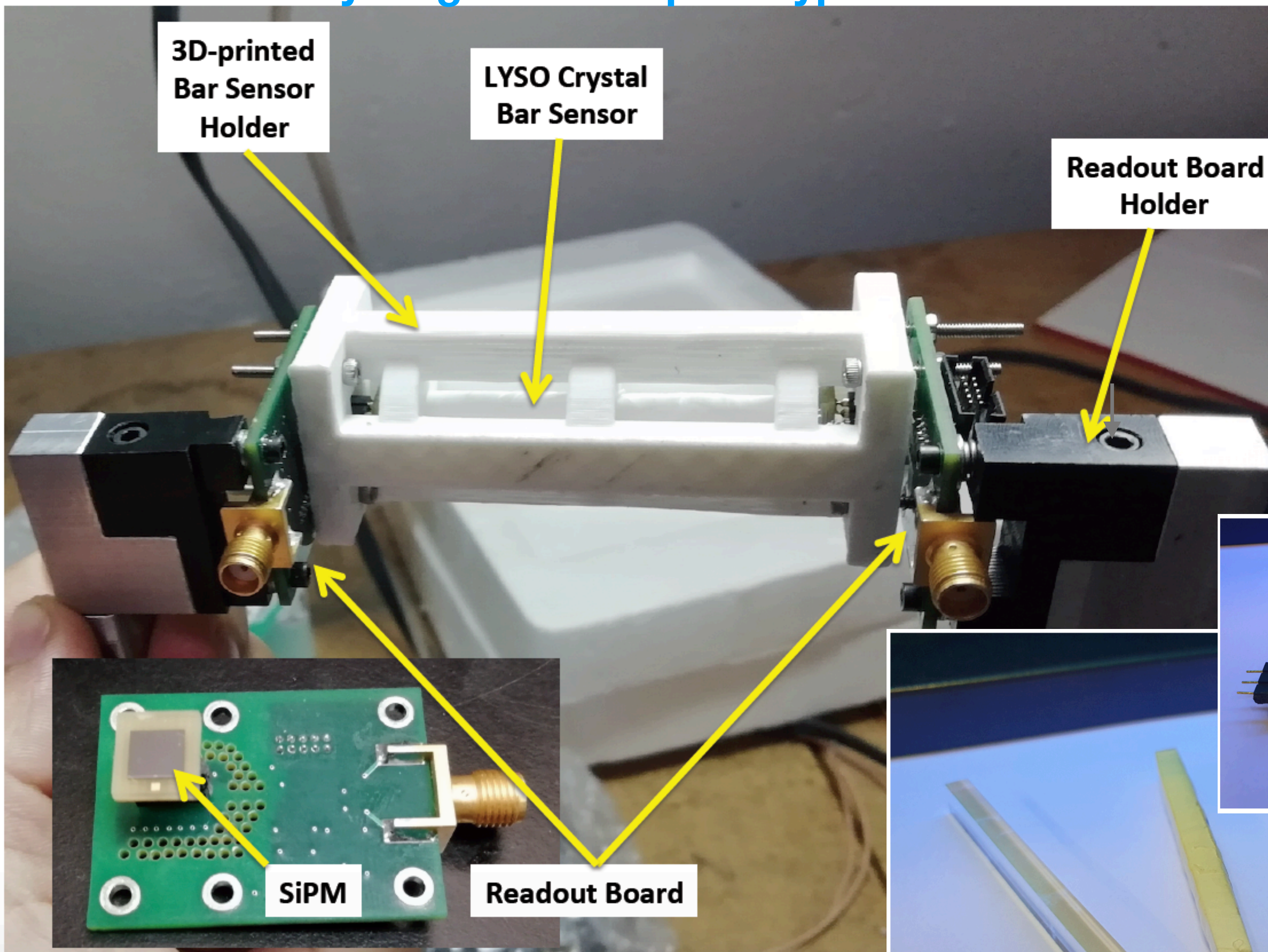
corrected for impact point dependence

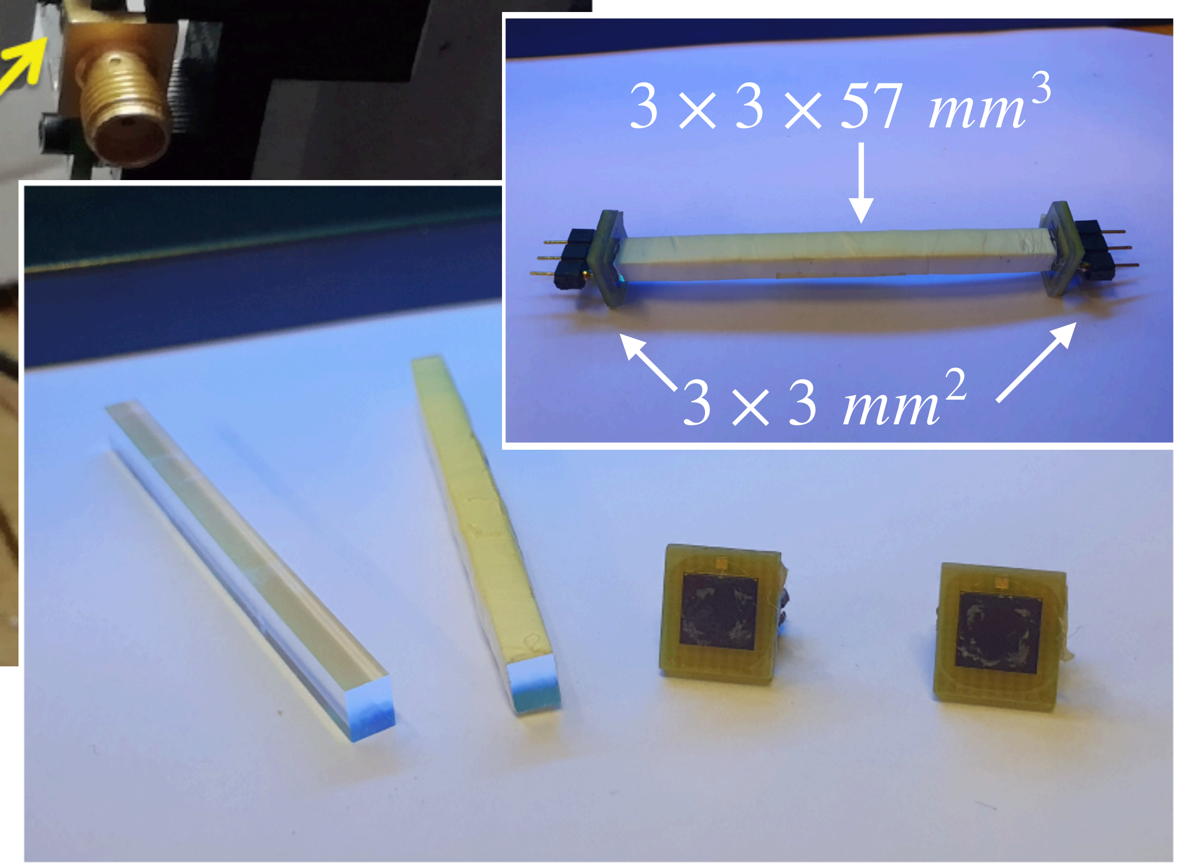




BTL Sensor: bar geometry (baseline)

Early single sensor prototype in 2019



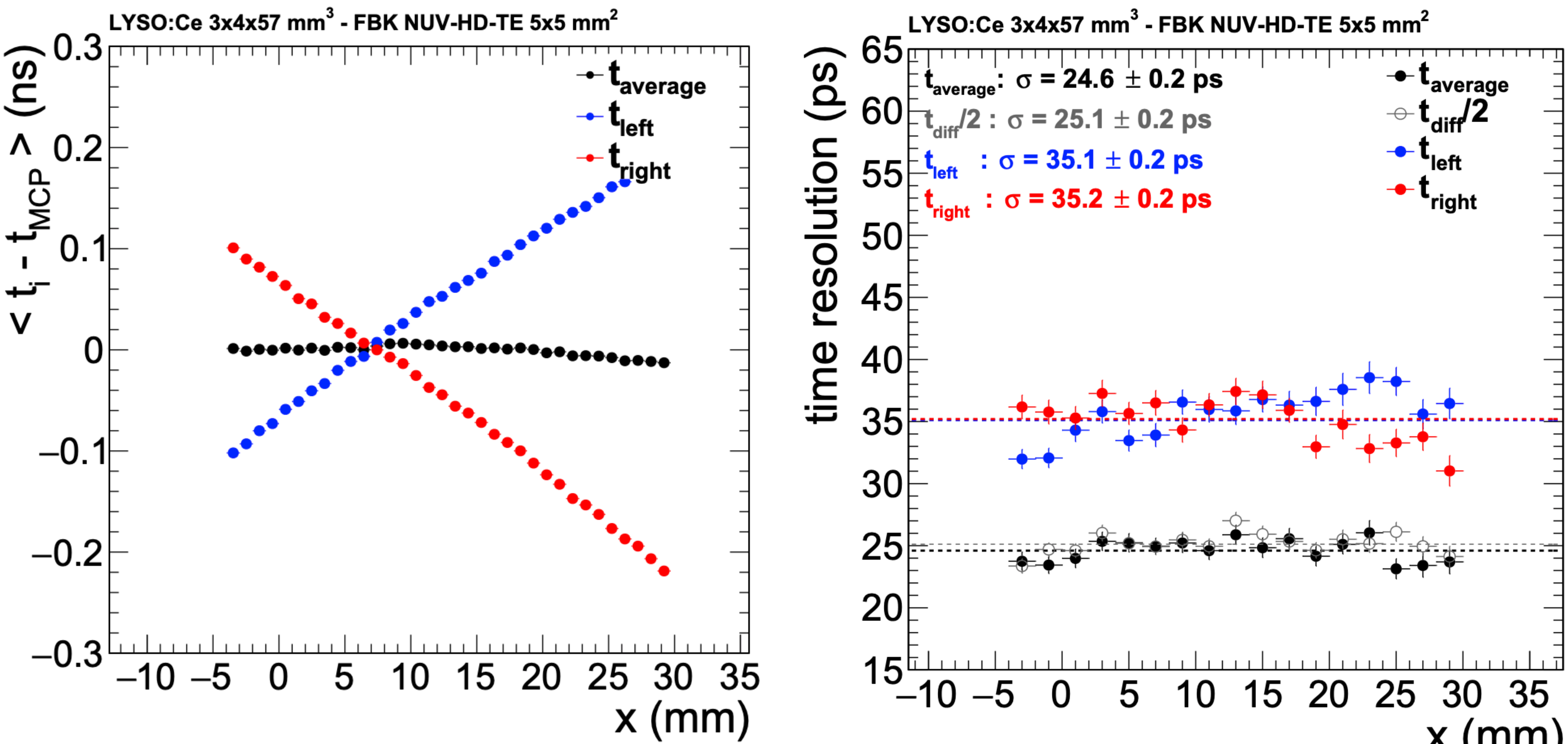


BTL sensor test beam result: JINST Volume 16 July 2021

Early BTL Sensor Performance in Test Beam in 2019

- Timestamp of a MIP traversing BTL: $t_{Ave} = (t_{left} + t_{right})/2$
  - t_{left} and t_{right} extracted from rising edge of the pulse shape
- Achieved ~25 ps time resolution per sensor **before irradiation**
- Uniform time response and resolution across sensor area

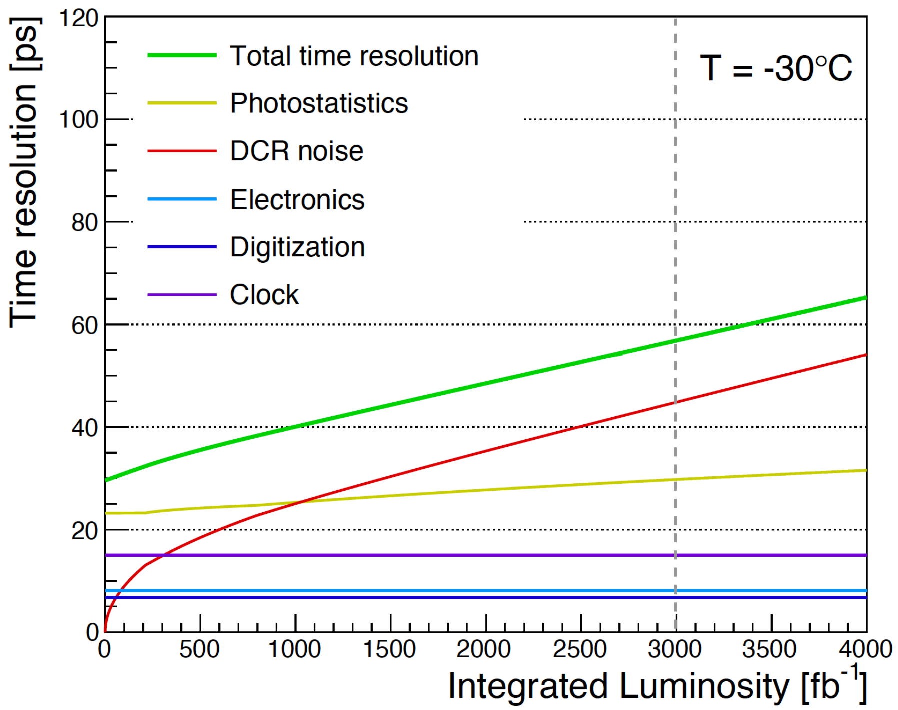
JINST Volume 16 July 2021

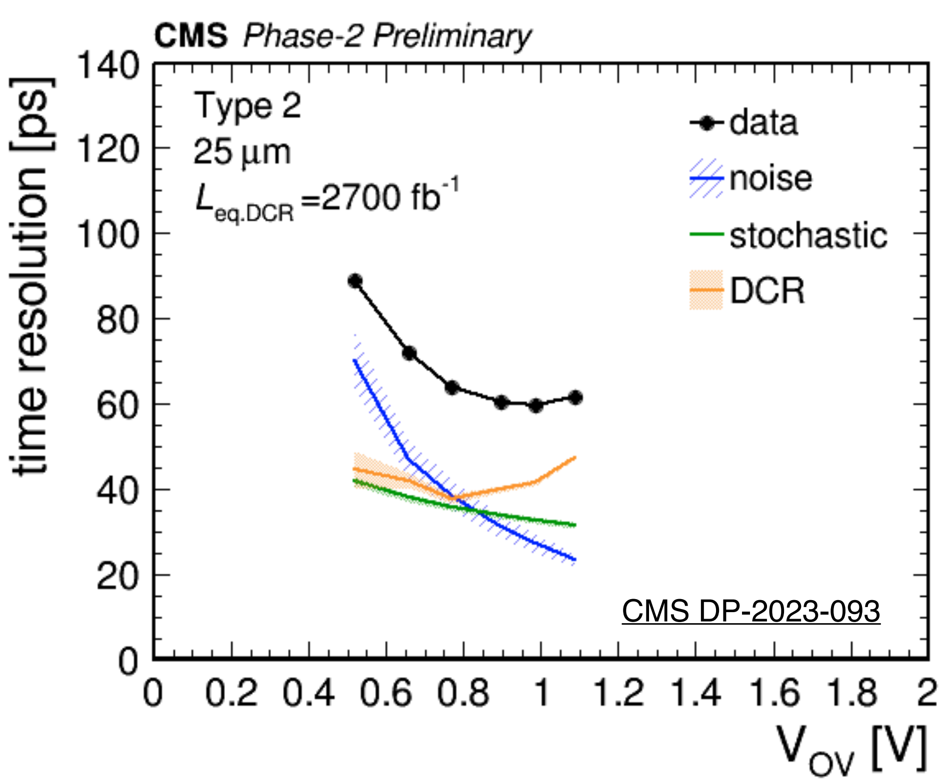


3 × 4 × 57 mm³ LYSO:Ce bar coupled to FBK SiPMs

BTL Time Resolution breakdown

- **Photostatistics and DCR noise contributions dominate timing resolution**





- Photostatistics: 25 - 35 ps, stochastic fluctuations in the time-of-arrival of photons detected at the SiPM
- DCR noise from SiPM:
  - dominating source over time. Cold operation and warm annealing thanks to improved thermal management through thermoelectric coolers
- Electronics: 7ps
- Digitization: 6 ps
- Clock distribution: 15 ps

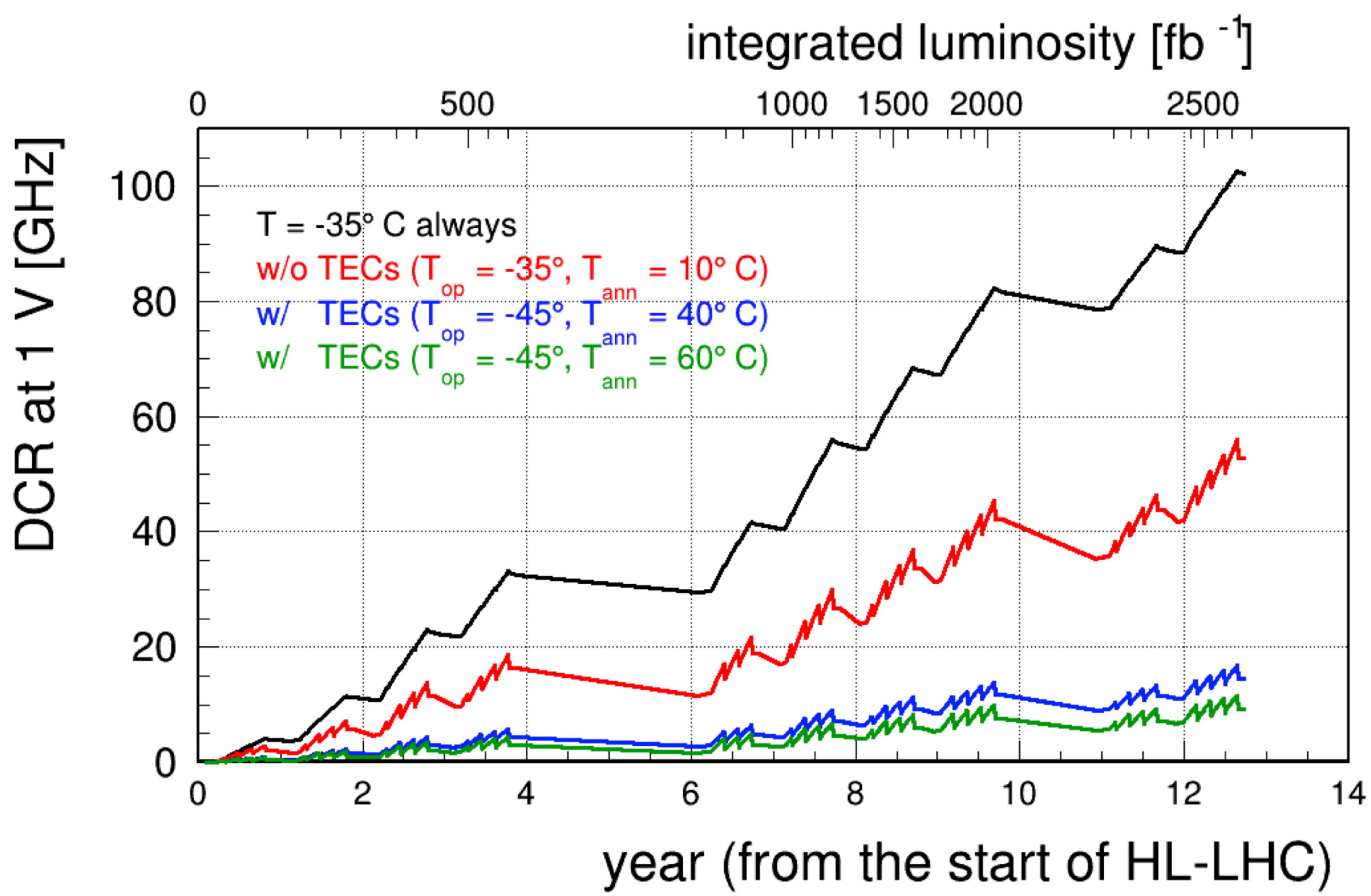
SiPM DCR noise mitigation

Strong effort to achieve TDR time resolution of 30-70ps over BTL life time:

Smart thermal management with thermoelectric coolers

• Local cooling and heating provides x10 reduction of the dark count rate with SiPMs at –45 °C during operations and in-situ annealing at +60 °C during technical stops.

DCR noise cancellation in the readout chip (TOFHIR2) with differential leading-edge discrimination

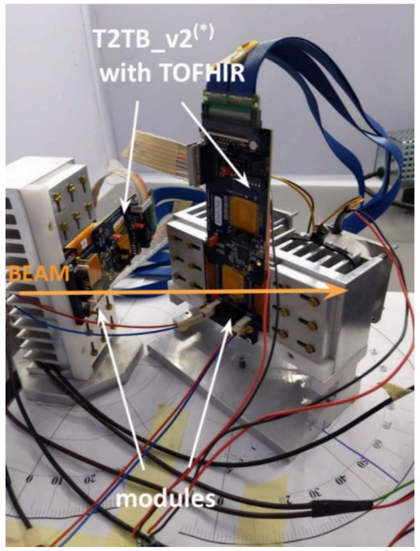


SiPM DCR noise mitigation

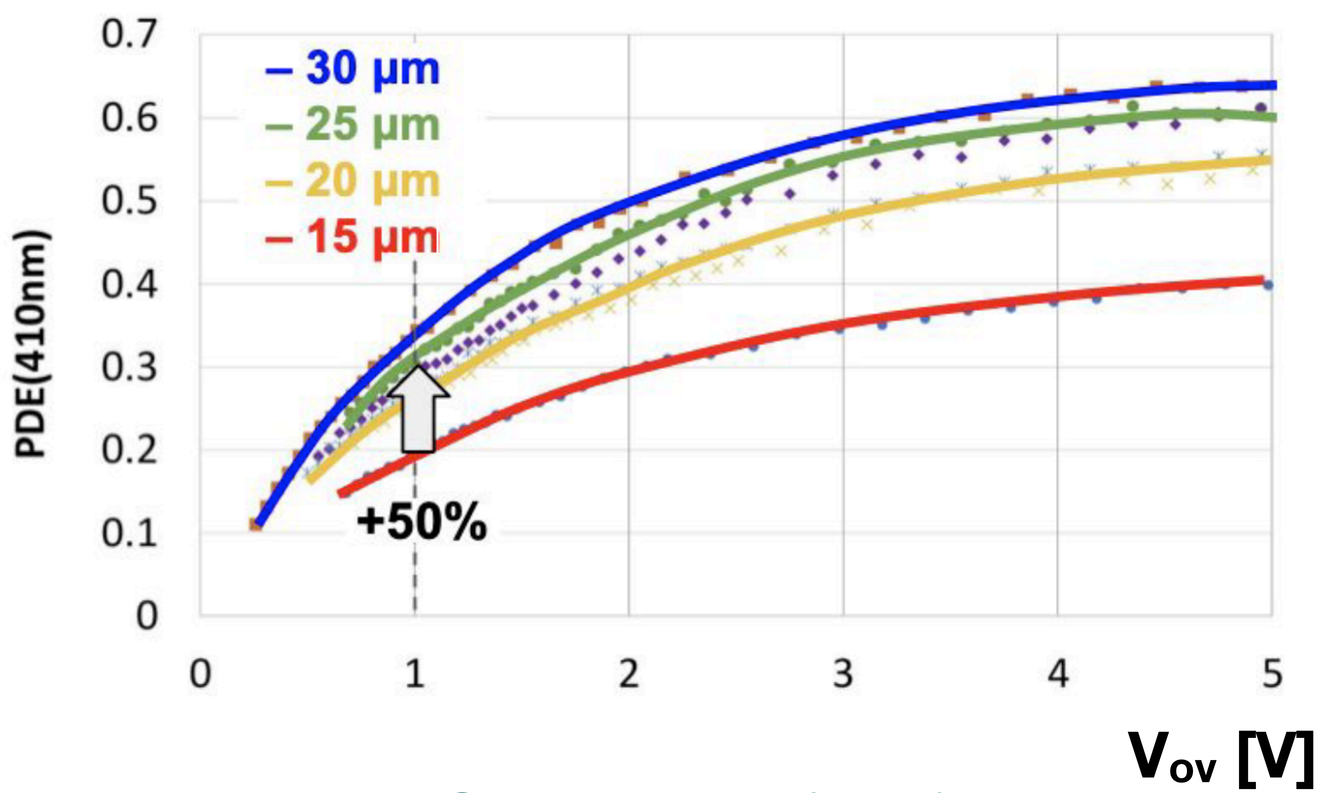
Strong effort to achieve TDR time resolution of 30-70ps over BTL life time:

Optimize SiPM cell size

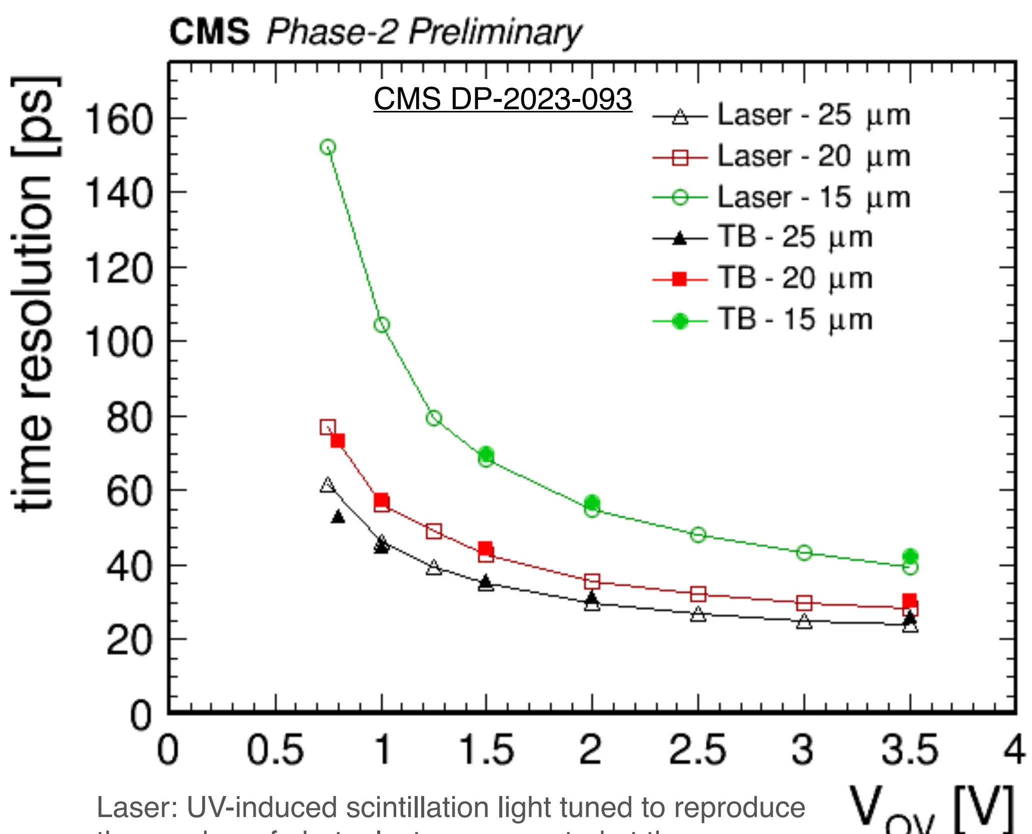
• Trade-off between photodetection efficiency and gain (better for larger cell area) and DCR/power dissipation. Cell size of 25 µm optimal for BTL.



Time resolution as a function of the SiPM over-voltage (Vov) for three modules made of LYSO:Ce bars (type 2: 3 x 3 x 54.7 mm³)



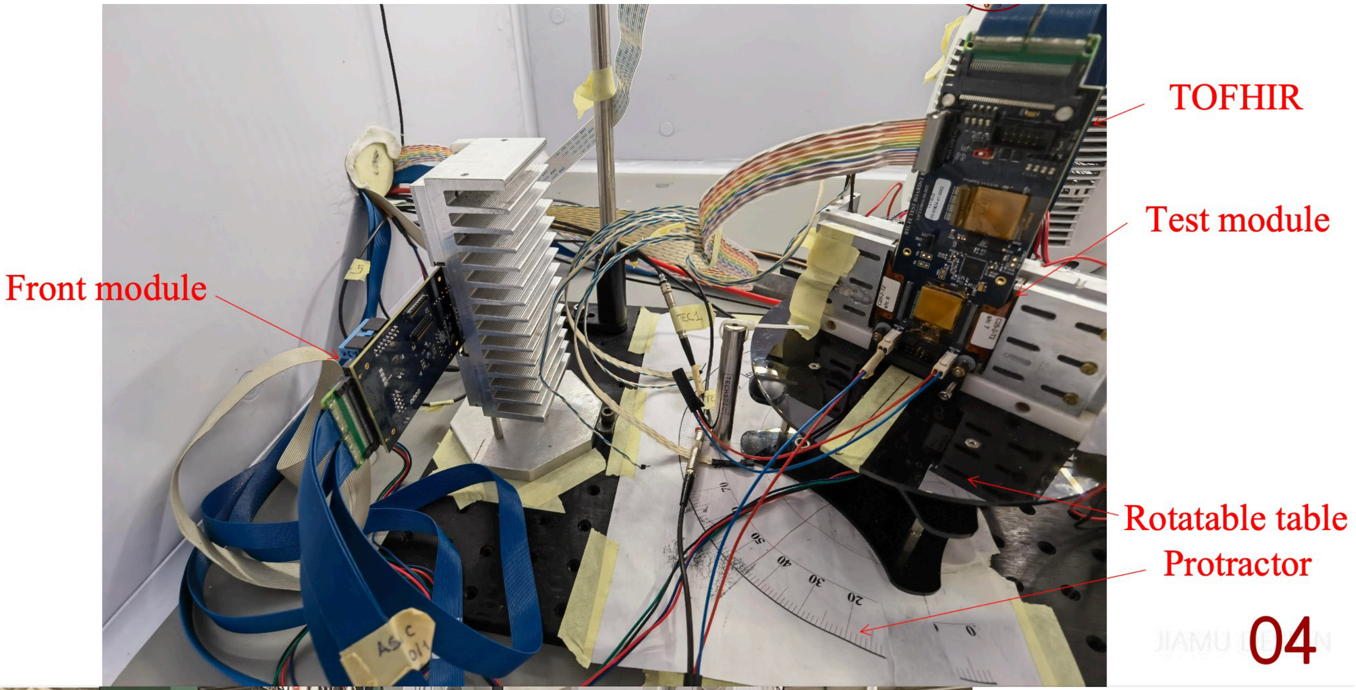
JINST 18 P08020 (2023)



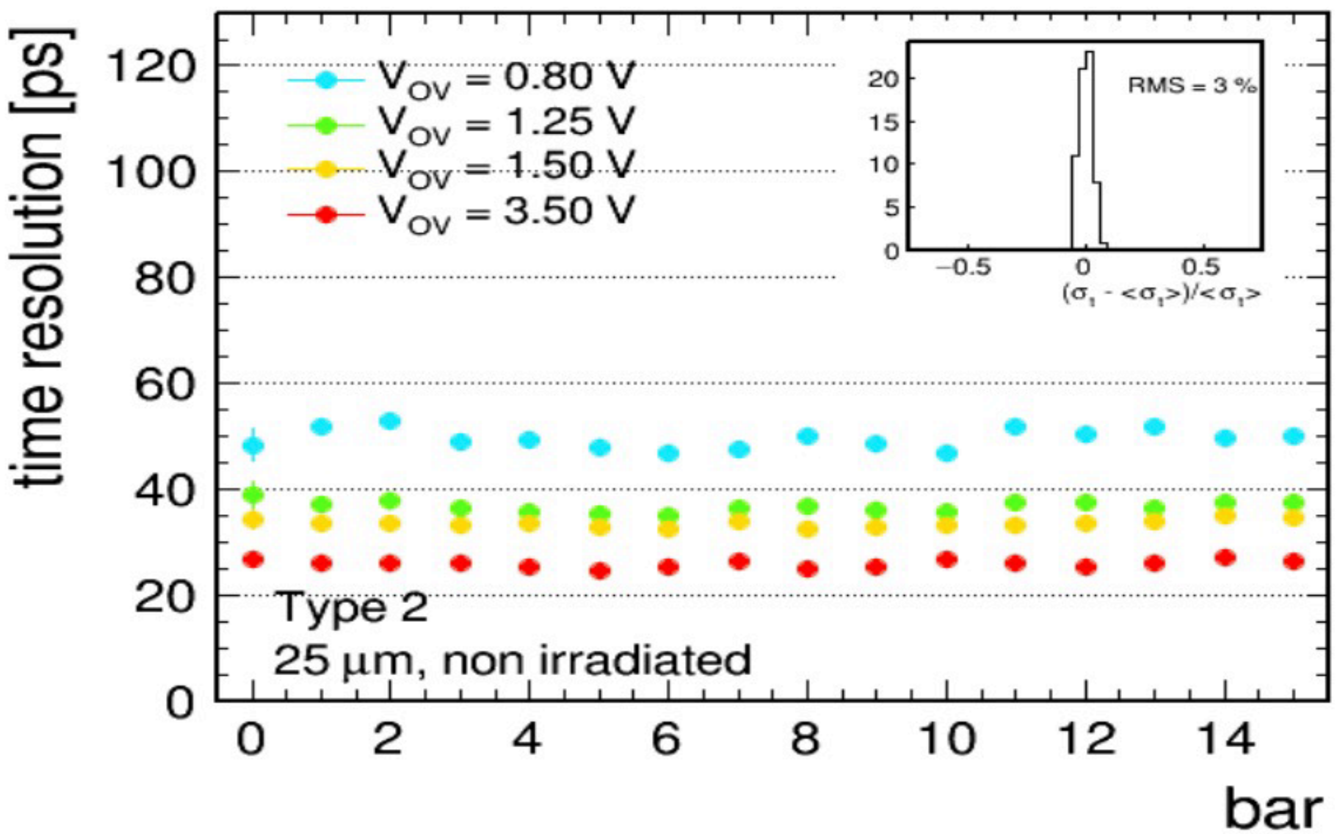
Laser: UV-induced scintillation light tuned to reproduce the number of photoelectrons expected at the beginning of operation of the BTL

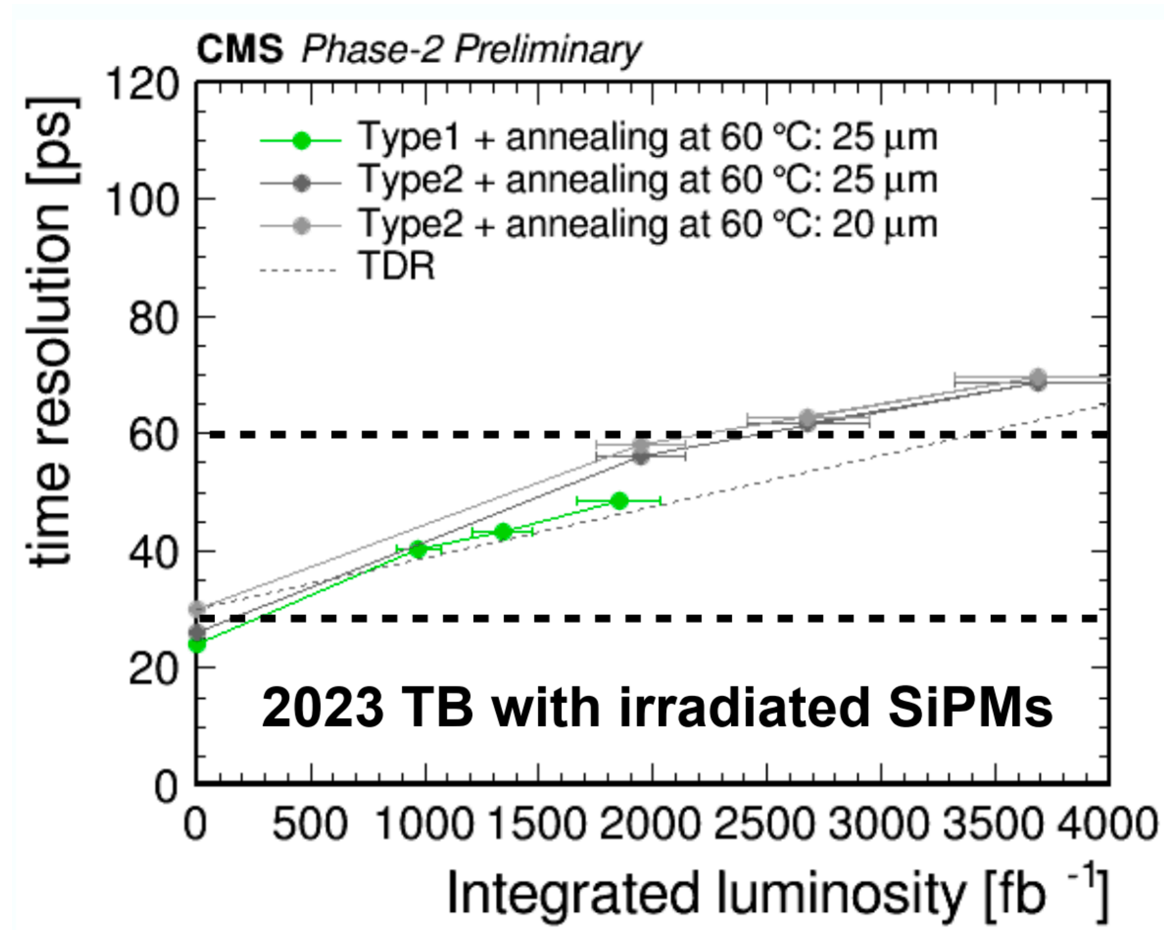
testbeam at @CERN 2023

- PKU students participation in test beam at CERN H8
- provide performance result for final sensor design



Performance of prototype BTL detector in 2023

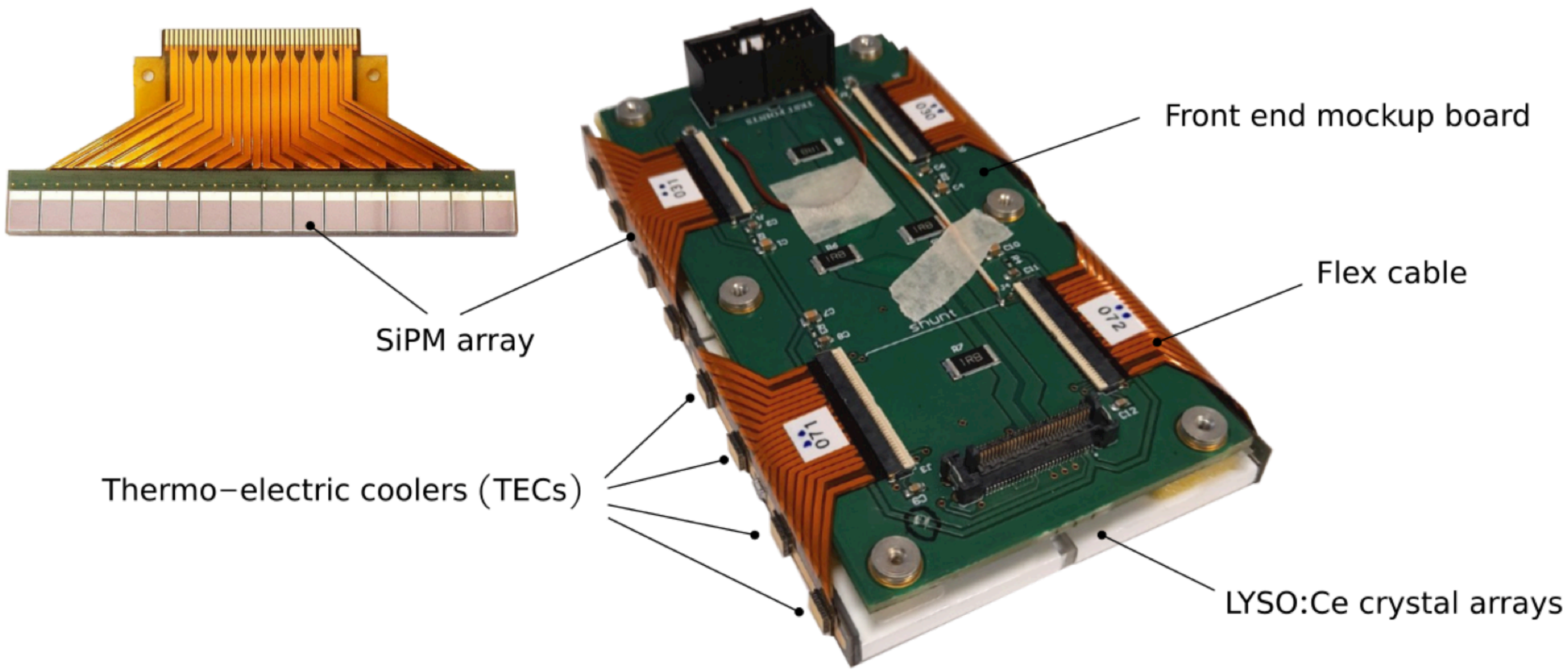


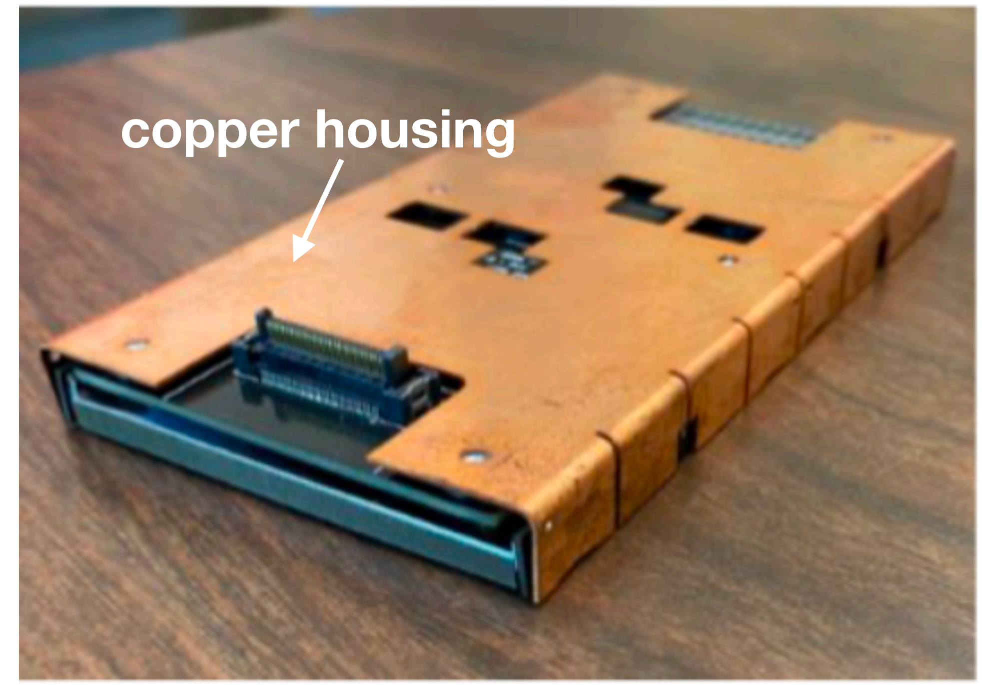


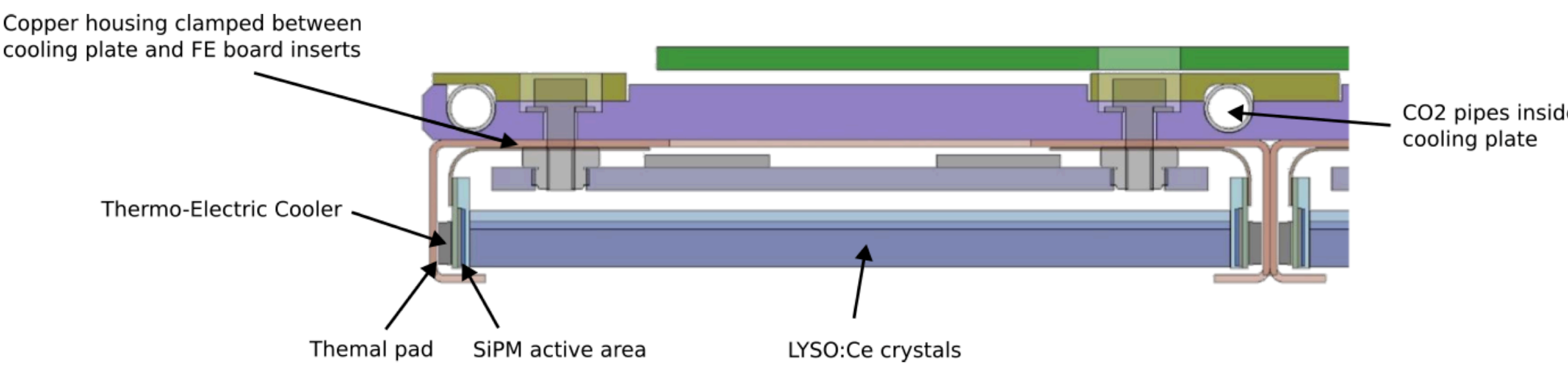
LYSO:Ce bars:
type 1: 3.75 x 3 x 54.7 mm^3
type 2: 3 x 3 x 54.7 mm^3

Performance demonstrated. Next: production, assembly, and integration (2024-2025).

BTL module





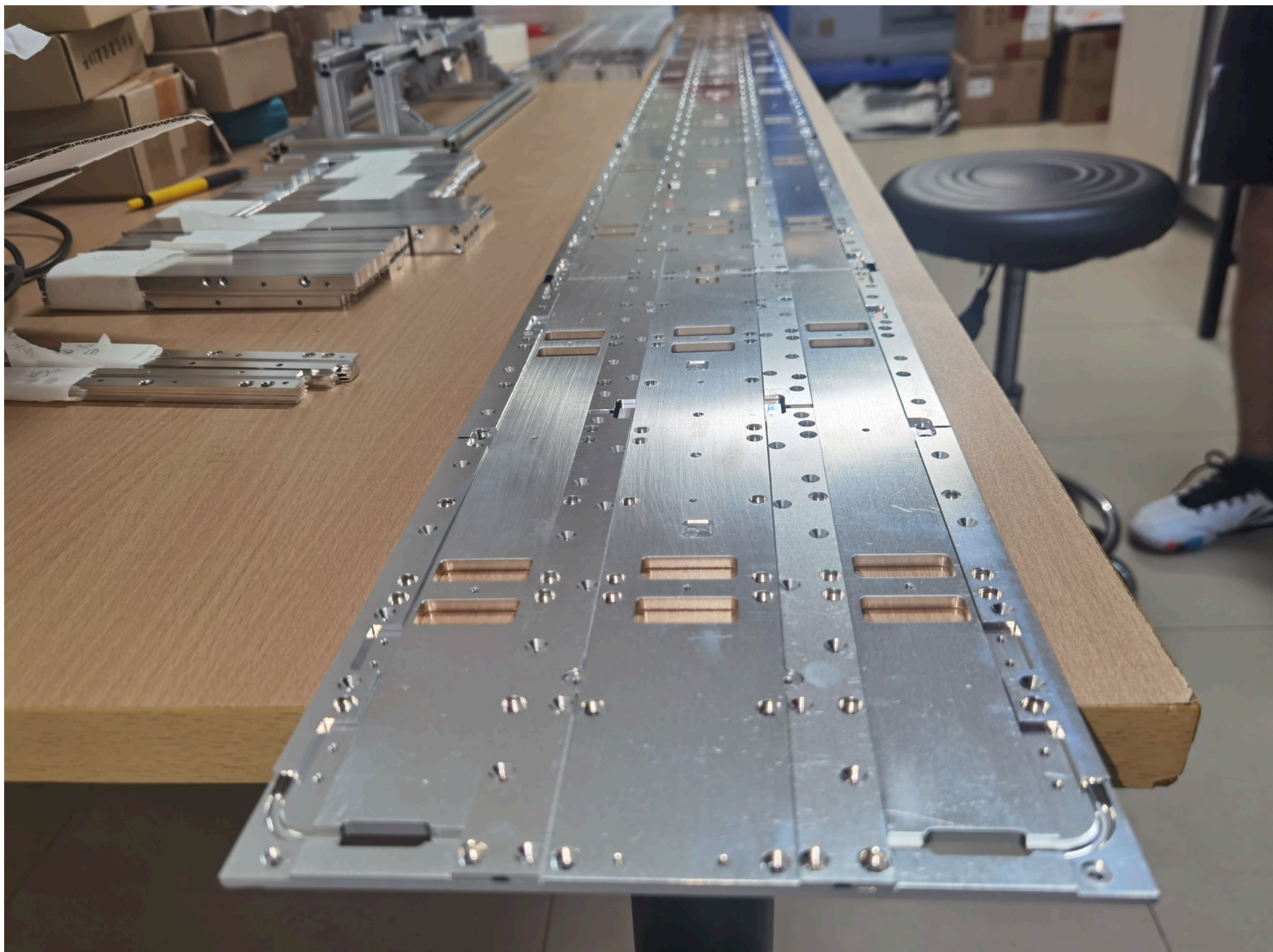


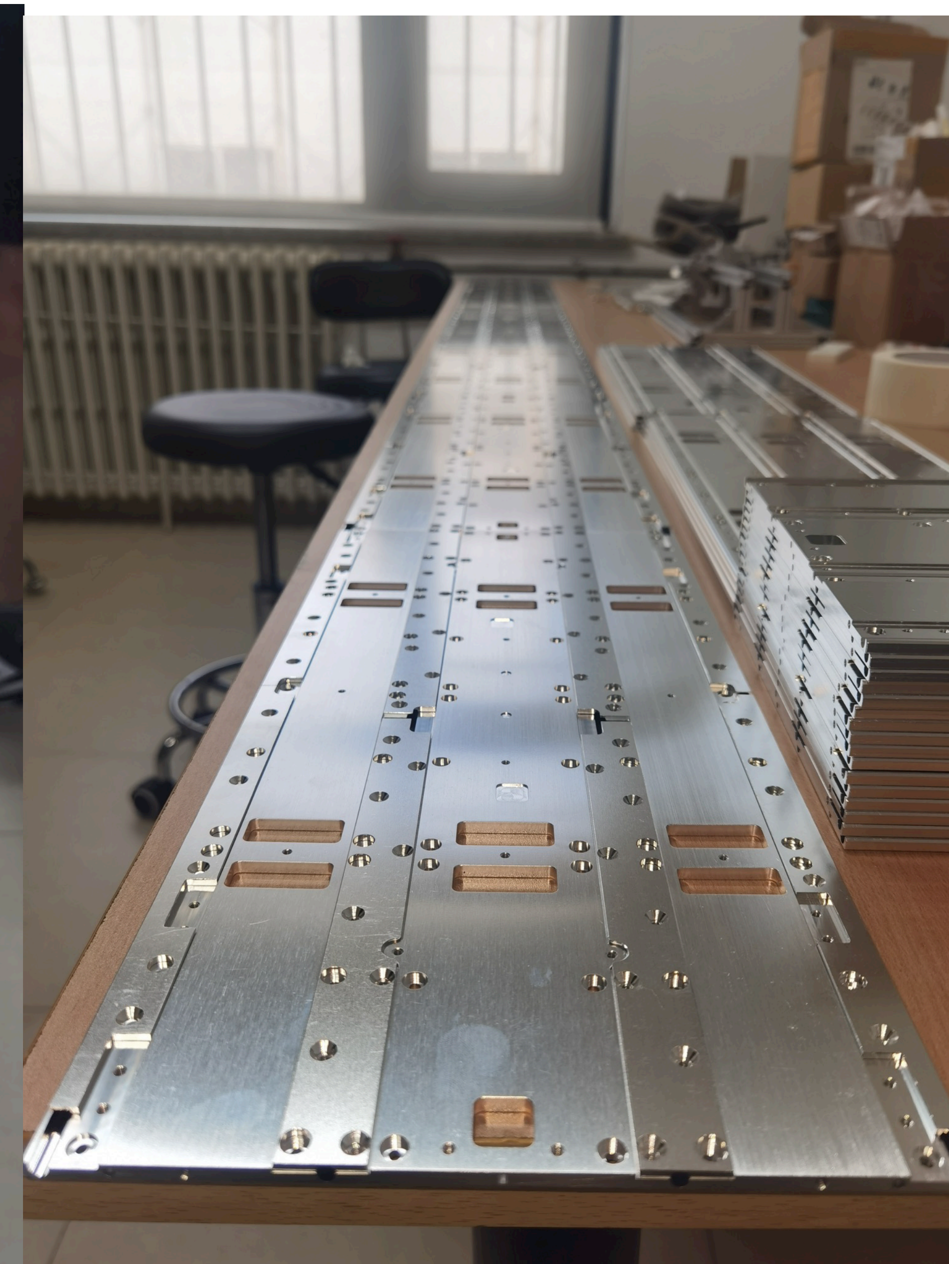
12 modules + FE electronics form one readout unit

72 trays in BTST structure → 166k LYSO bars, 332k readout channels

Cooling plate production

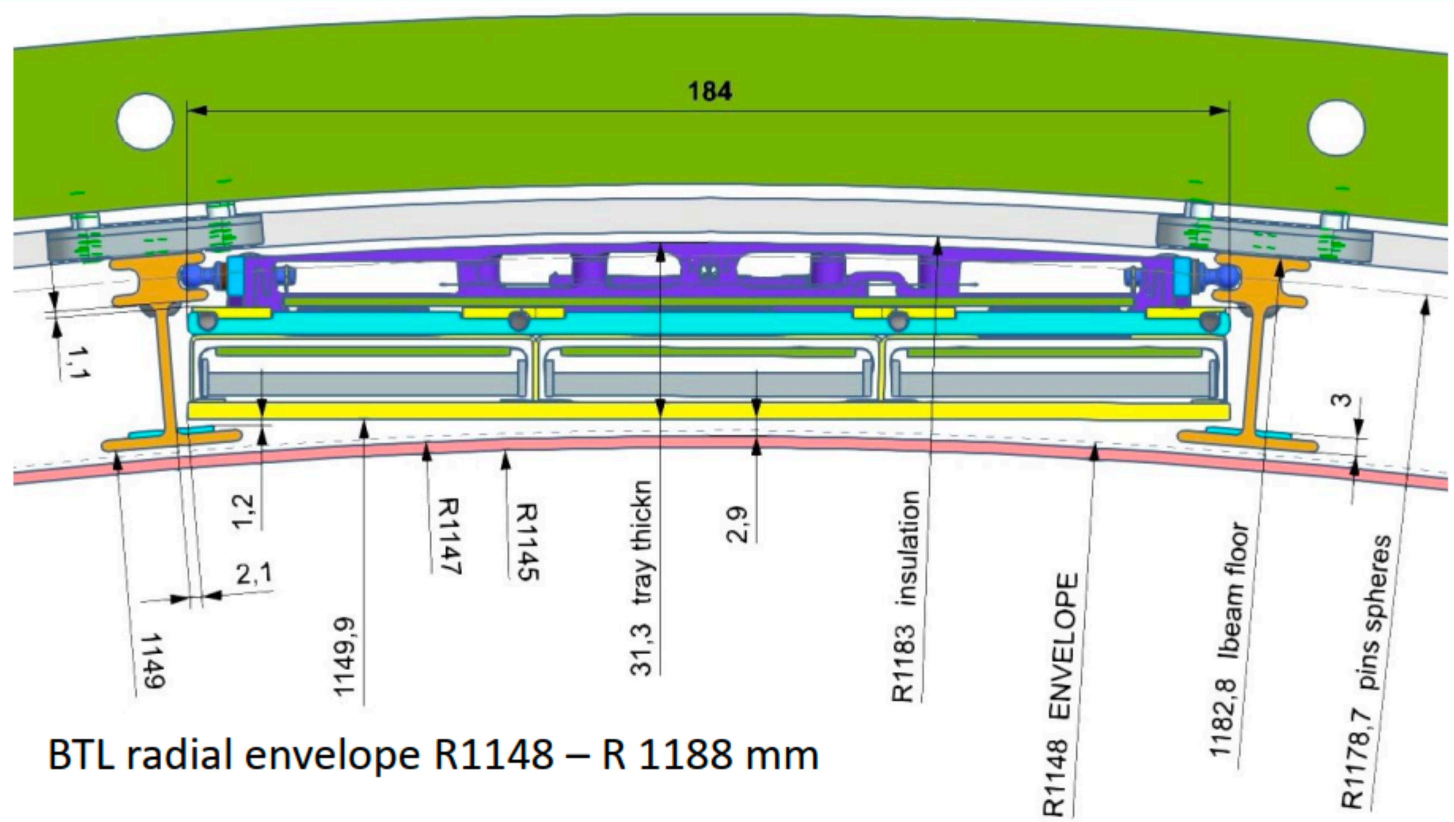
- Peking University produced 5 sets of cooling plots
- Sent to CERN, Milano, University of Virginia and Caltech for assembly and cooling test

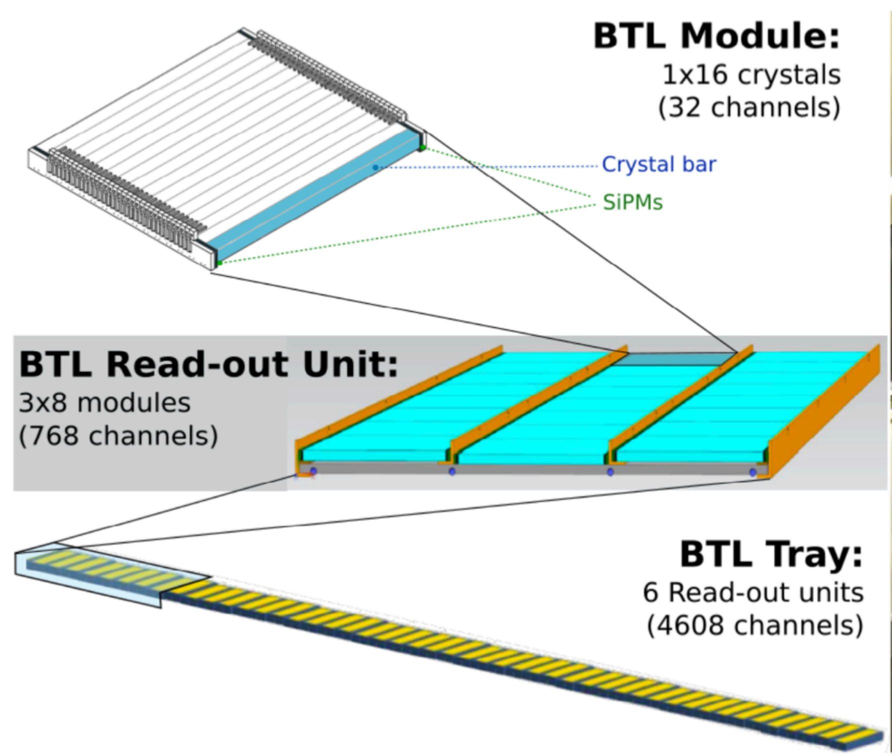


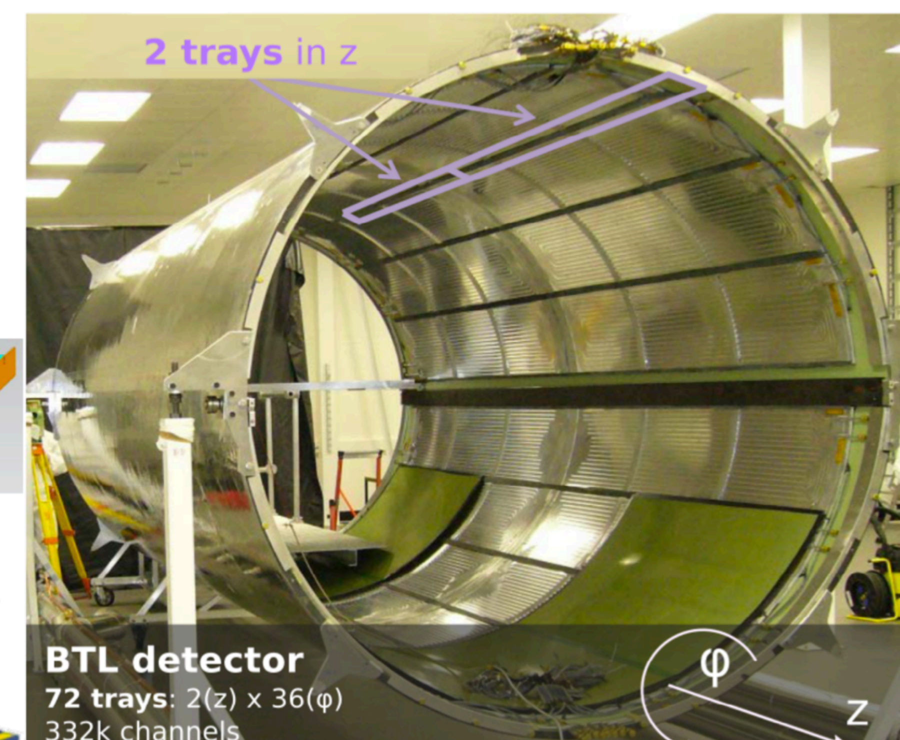


BTL assembly and integration

- BTL will be attached to the inner wall of the Tracker Support Tube
- Assembly procedures and mechanical structures are well advanced and moving towards production and installation





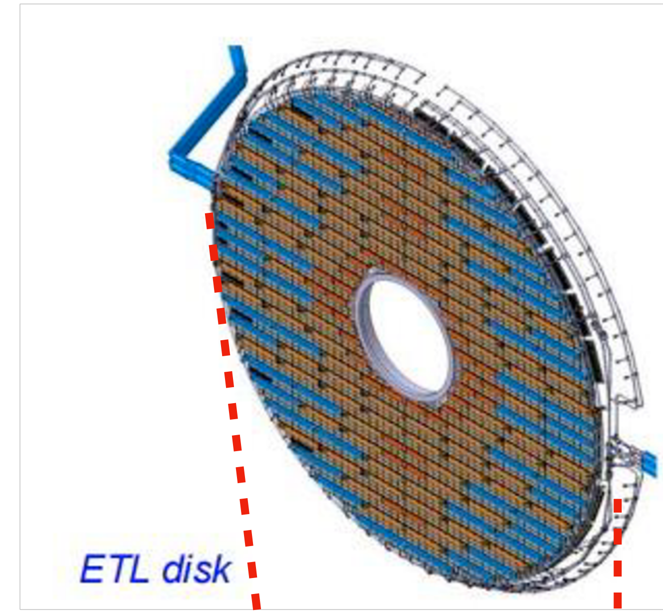


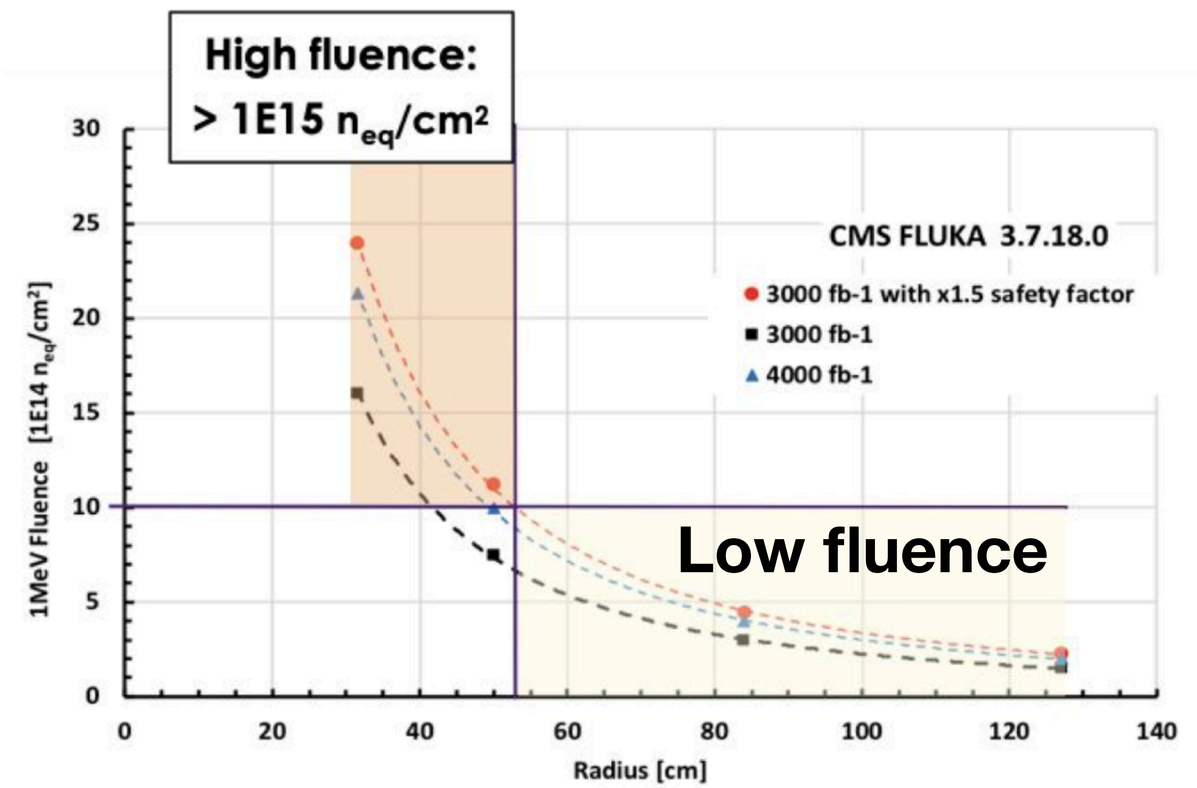
ETL

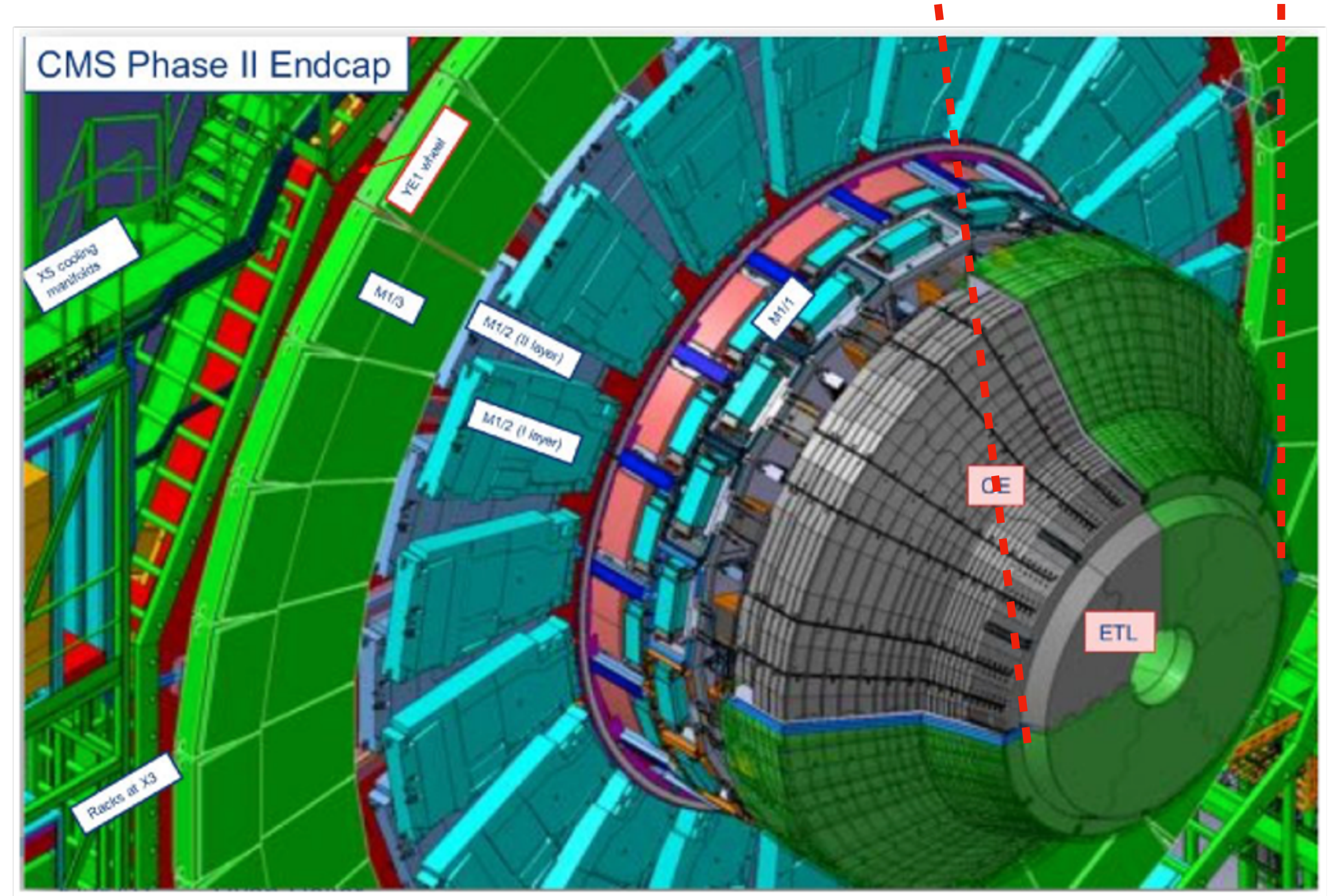
ETL detector layout

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)

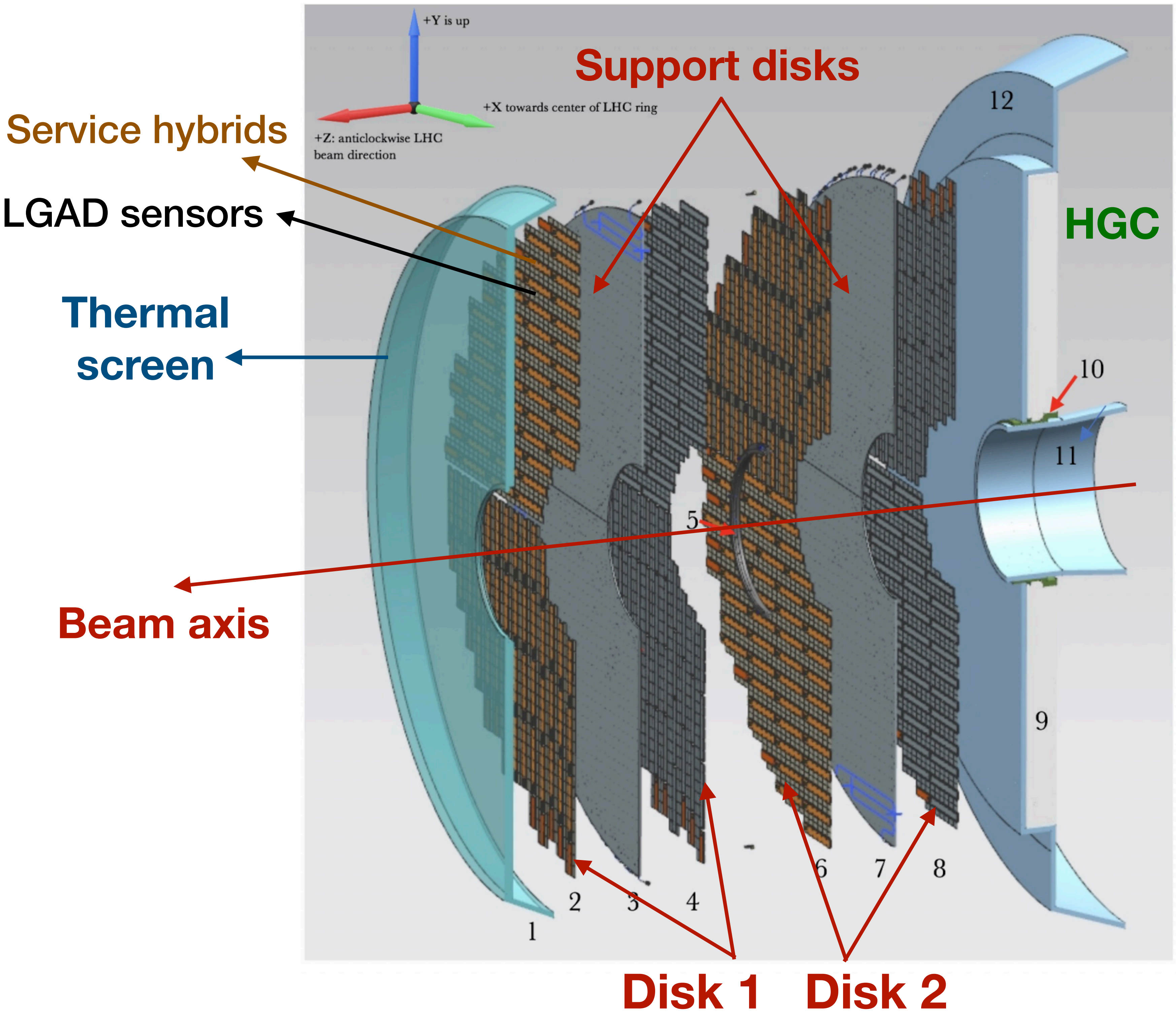
Coverage:
- z = 3 m from pp interaction, supported on HGC nose
- coverage 1.6 < |η| < 3.0
- 0.315 m < R < 1.2 m







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

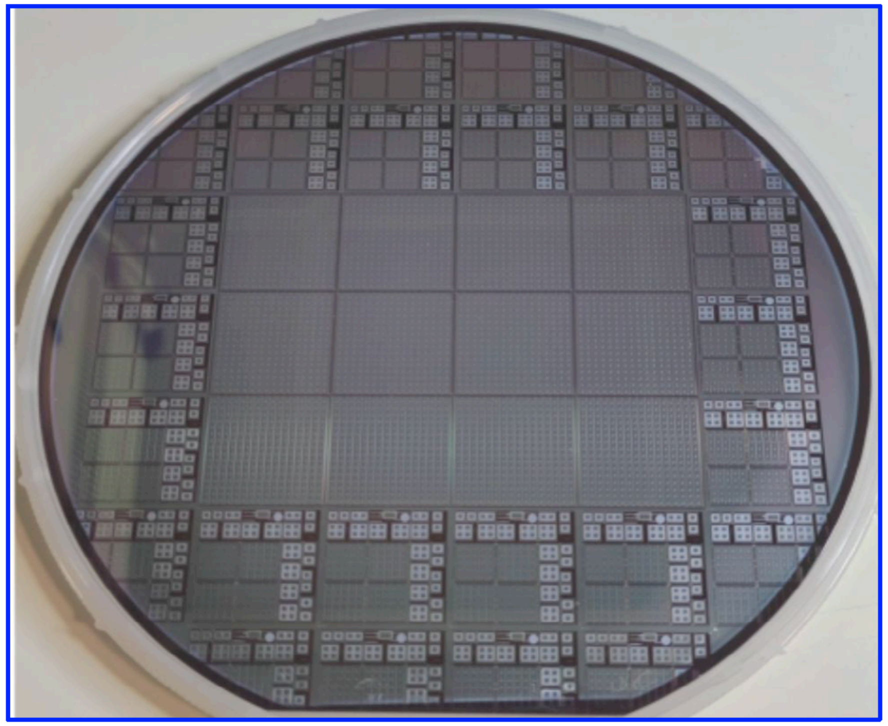
ETL sensor: LGAD

CMS ETL LGAD sensor requirements

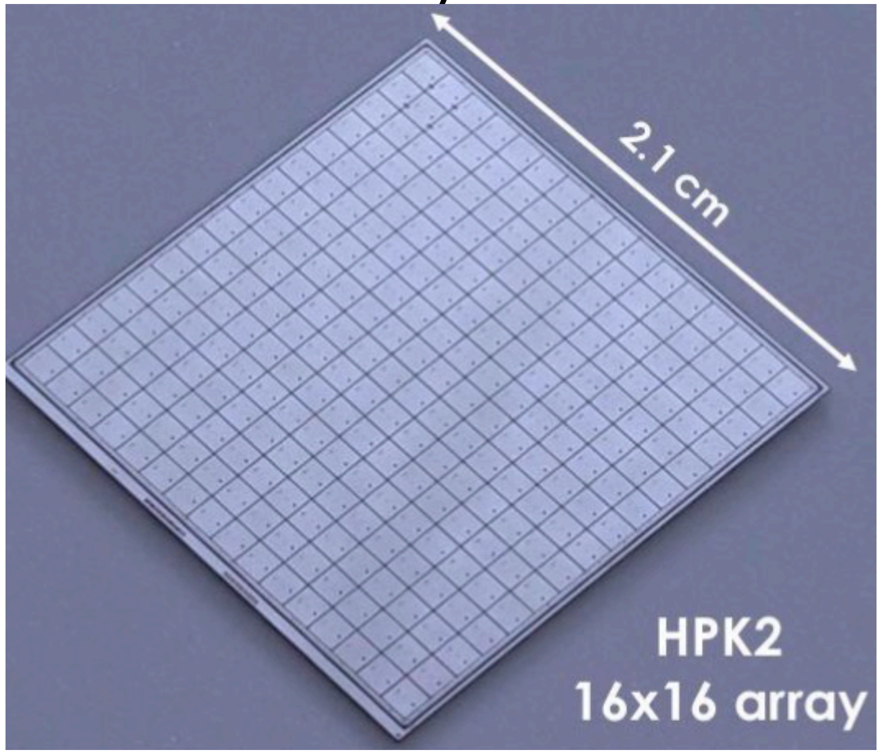
- 1.3 x1.3 mm^2 pads
- gain 10-30
- time resolution < 50 ps (per/hit) @ $1.7 \times 10^{15}\ n_{eq}/cm^2$
- depletion region thickness: 50 μm

- ETL need 8.6 million channels
- ETL will comprise ~ 35k LGAD sensors (20% spare sensors included)
  - never been done in large areas before
  - need custom ASIC (ETROC)

A wafer of the FBK UFSD4 production

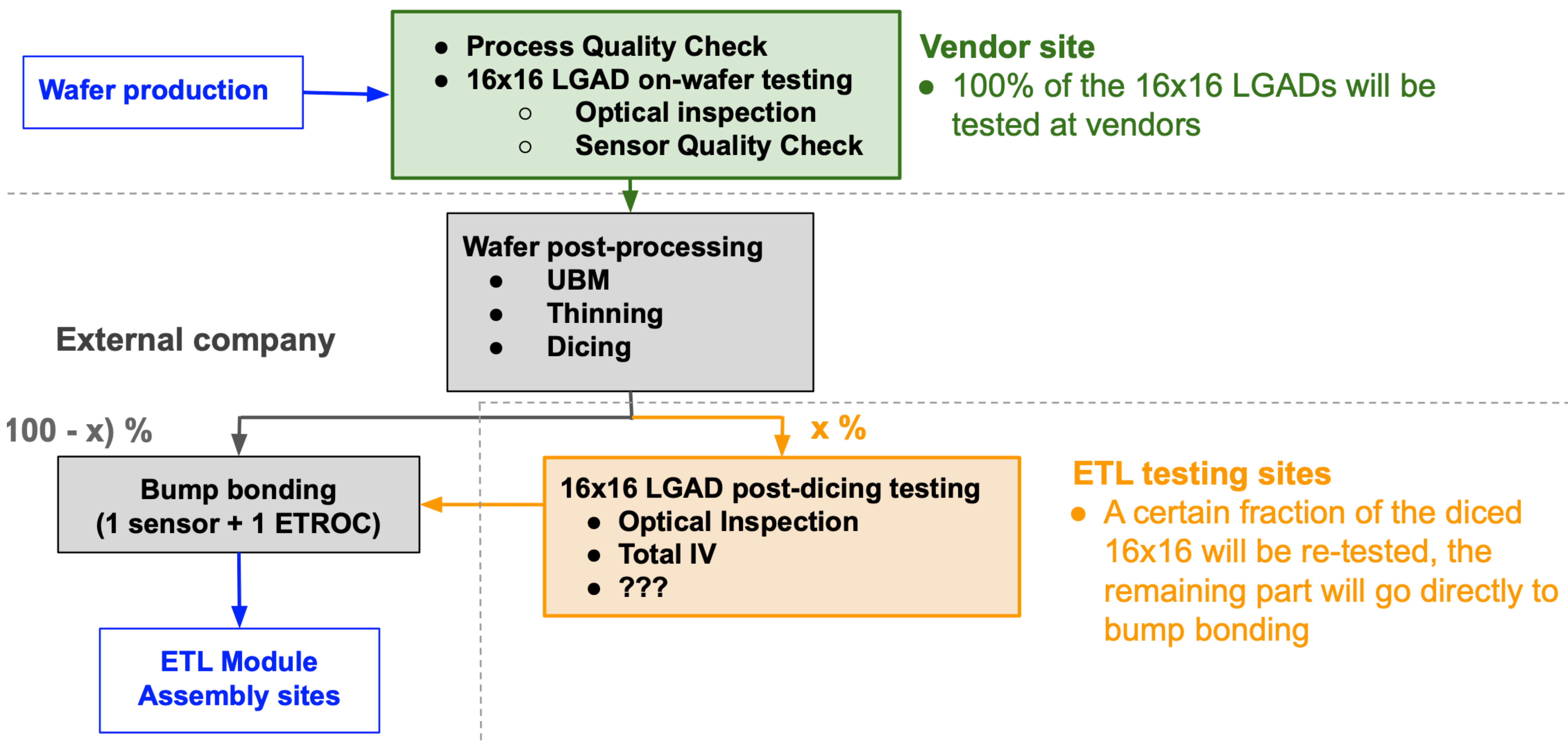


16x16 array from HPK



ETL LGAD schedule and QA/QC plan

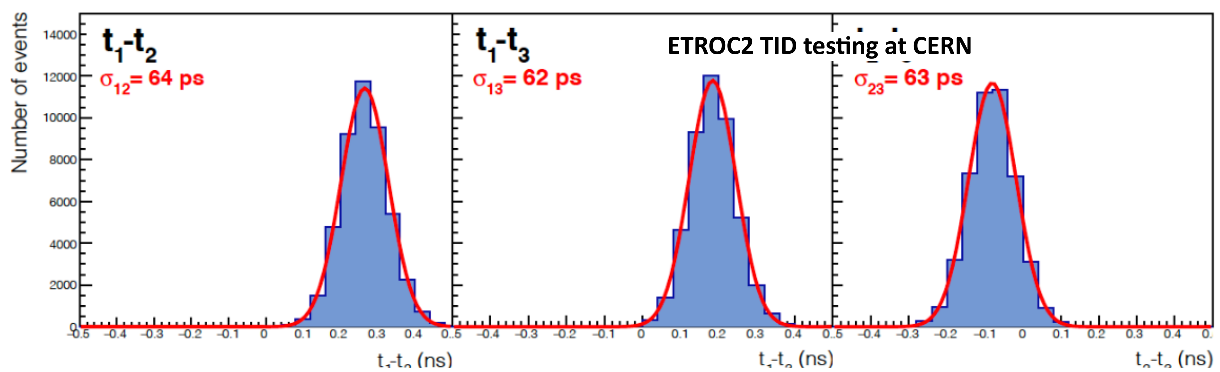
- 2023: Market Survey completed, three vendors identified
- 2024: Freeze LGAD specifications + define quality management (QA/QC) procedures for the sensors production → Invitation to Tender and final selection of the vendor(s)
- 2025: Beginning of the sensor production for ETL



More information: link to Federico Siviero's talk at TREDI 2024

Performance of prototype ETL detector

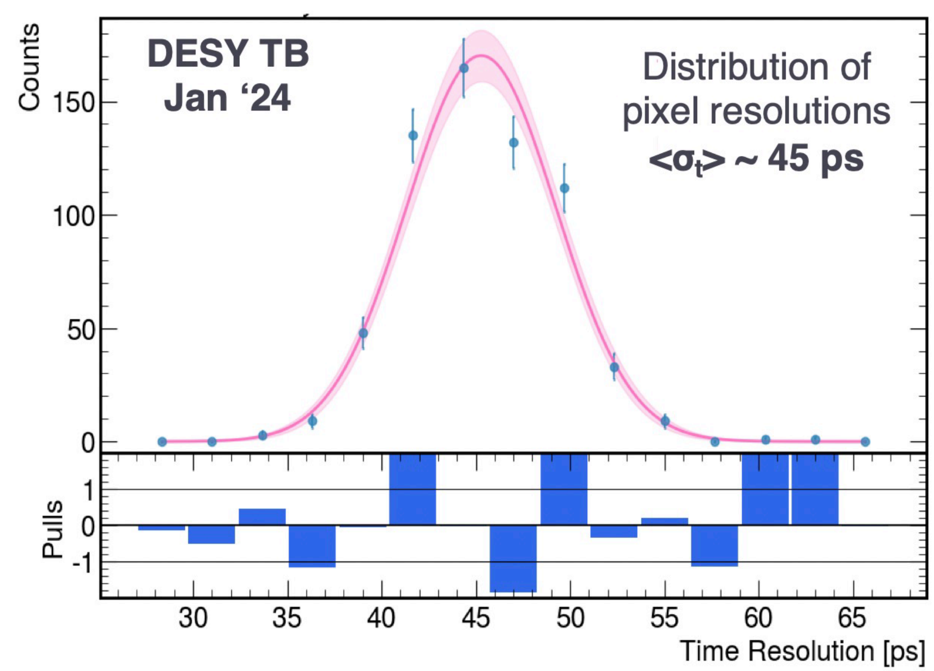
- Test results with ETROC1 wire-bonded to LGAD sensor demonstrate expected performance.



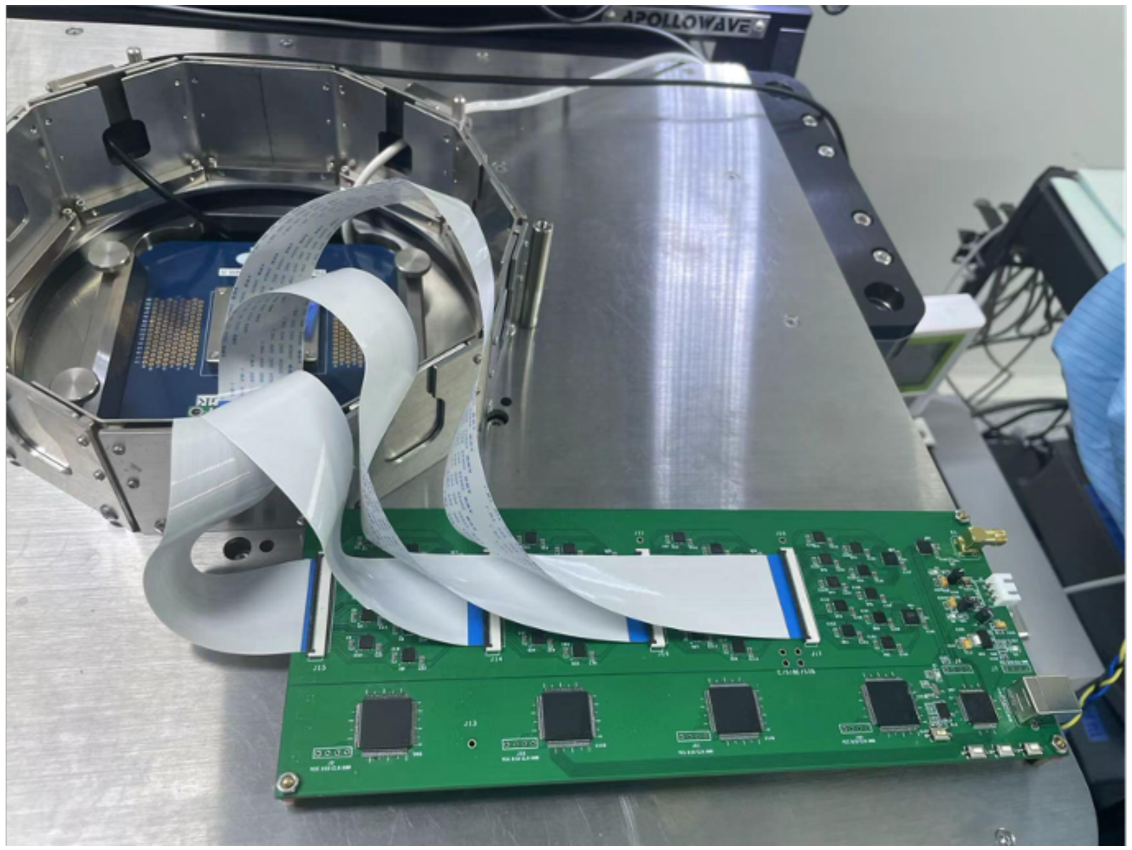
LGAD+ETROC1 resolution is 42-46 ps from TDC digital outputs

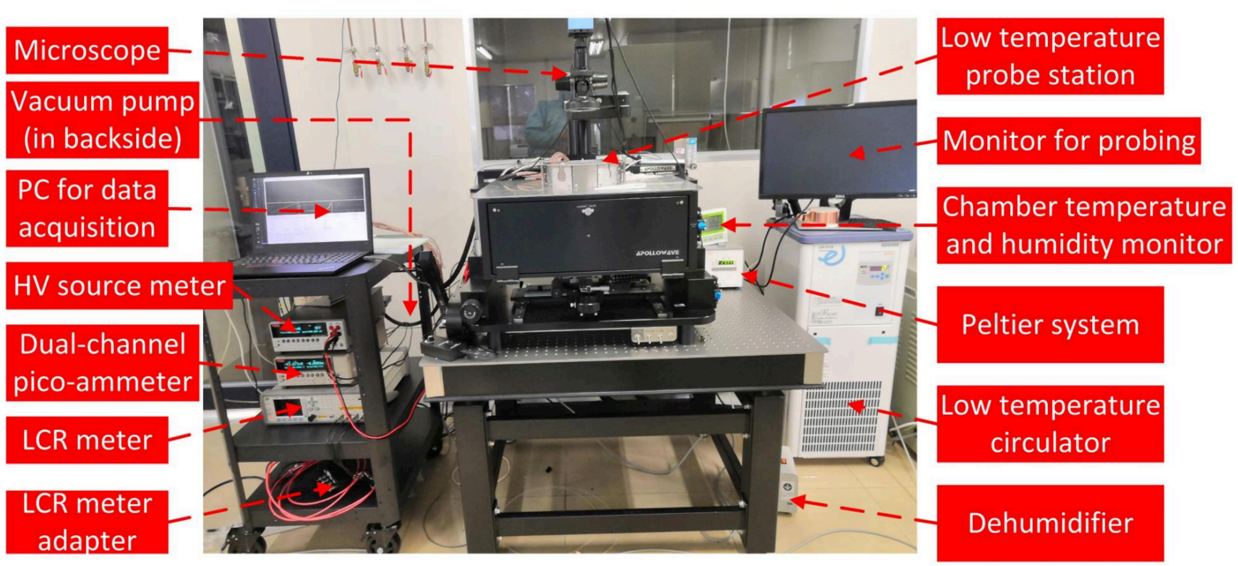
$$\sigma_i = \sqrt{0.5 \cdot (\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)}$$

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



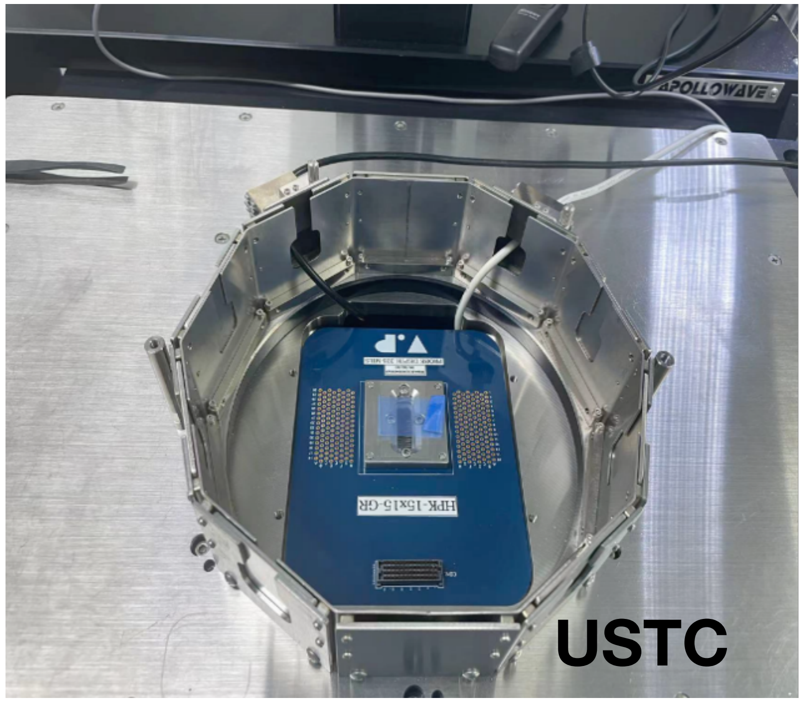
MTD-ETL contributions from USTC&South China Normal University&Shandong University

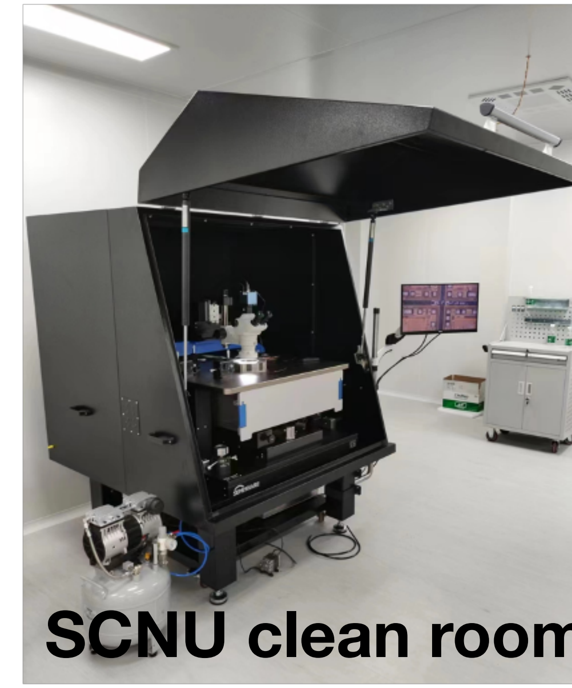


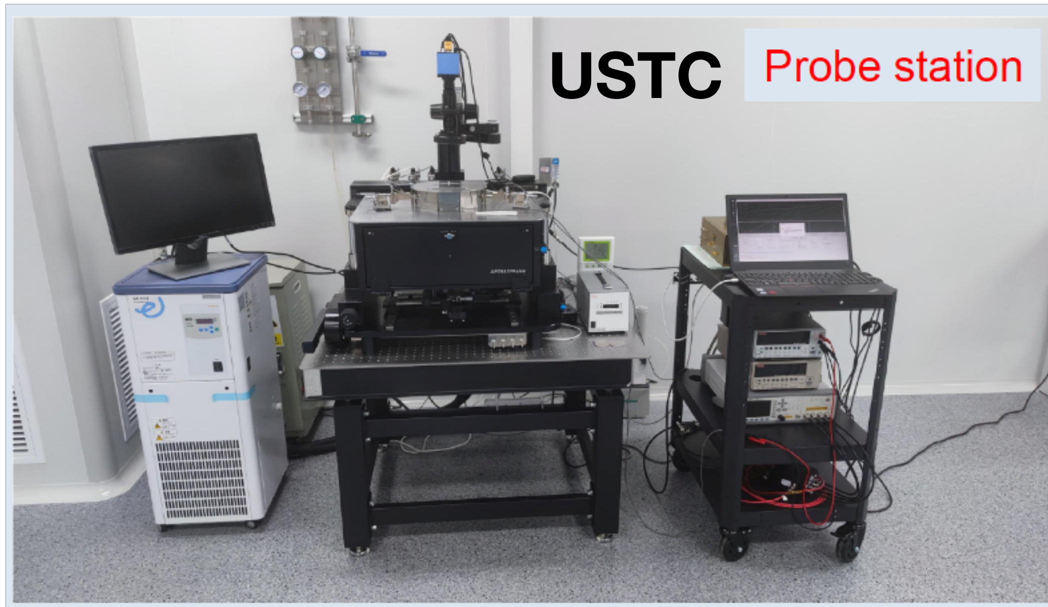


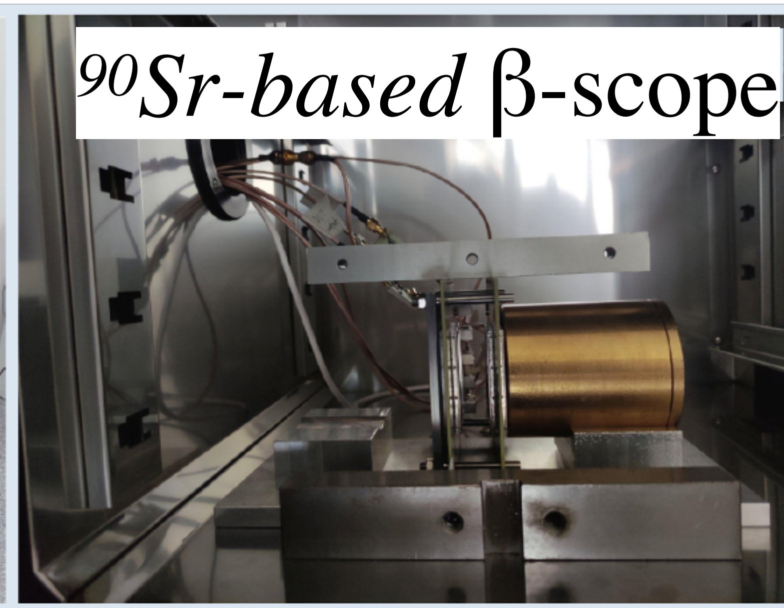
- Large LGAD matrix 16x16 characterization
  - https://doi.org/10.1016/j.nima.2022.167008
- Preparing for LGAD QC center for production
- Contribution to Front-end electronics production and testing

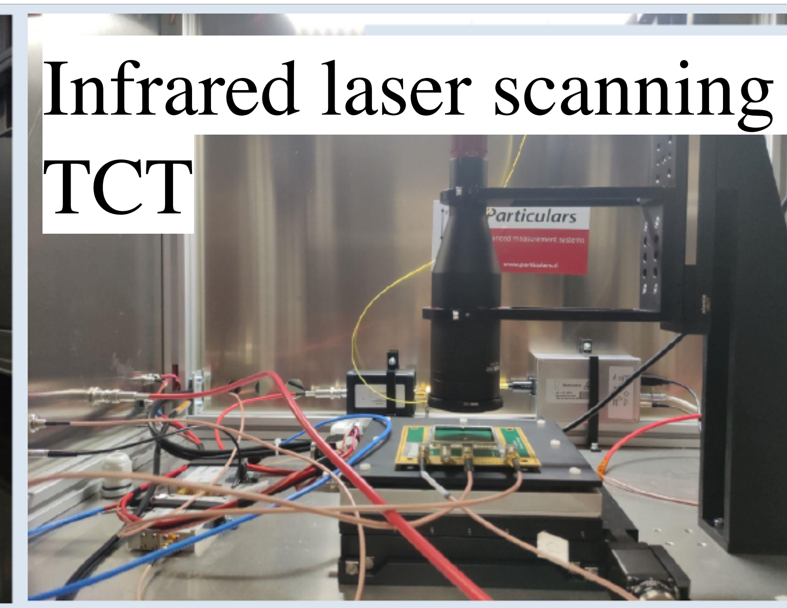
MTD-ETL contributions from USTC&South China Normal University&Shandong University











Summary

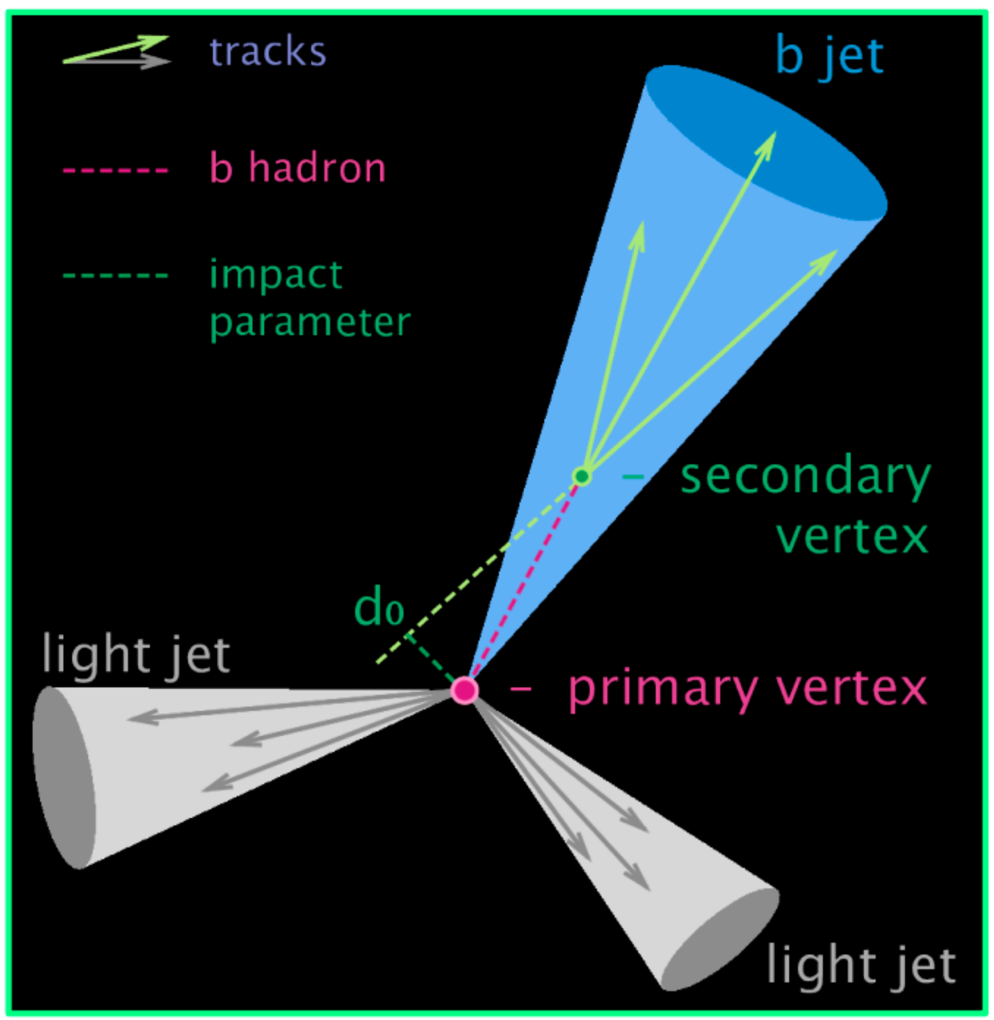
- **CMS MIP timing detector is progressing well and will meet TDR performance with a time resolution of 40-70 ps for MIPs**
  - A broad impact on CMS HL-LHC physics potential
  - Sensor technology: LYSO:Ce crystals readout by SiPM for barrel, LGAD for endcap detectors
  - Barrel timing layer starting production now, installation starts in 2025
  - Endcap timing layer in last prototyping phase, installation to start in 2027

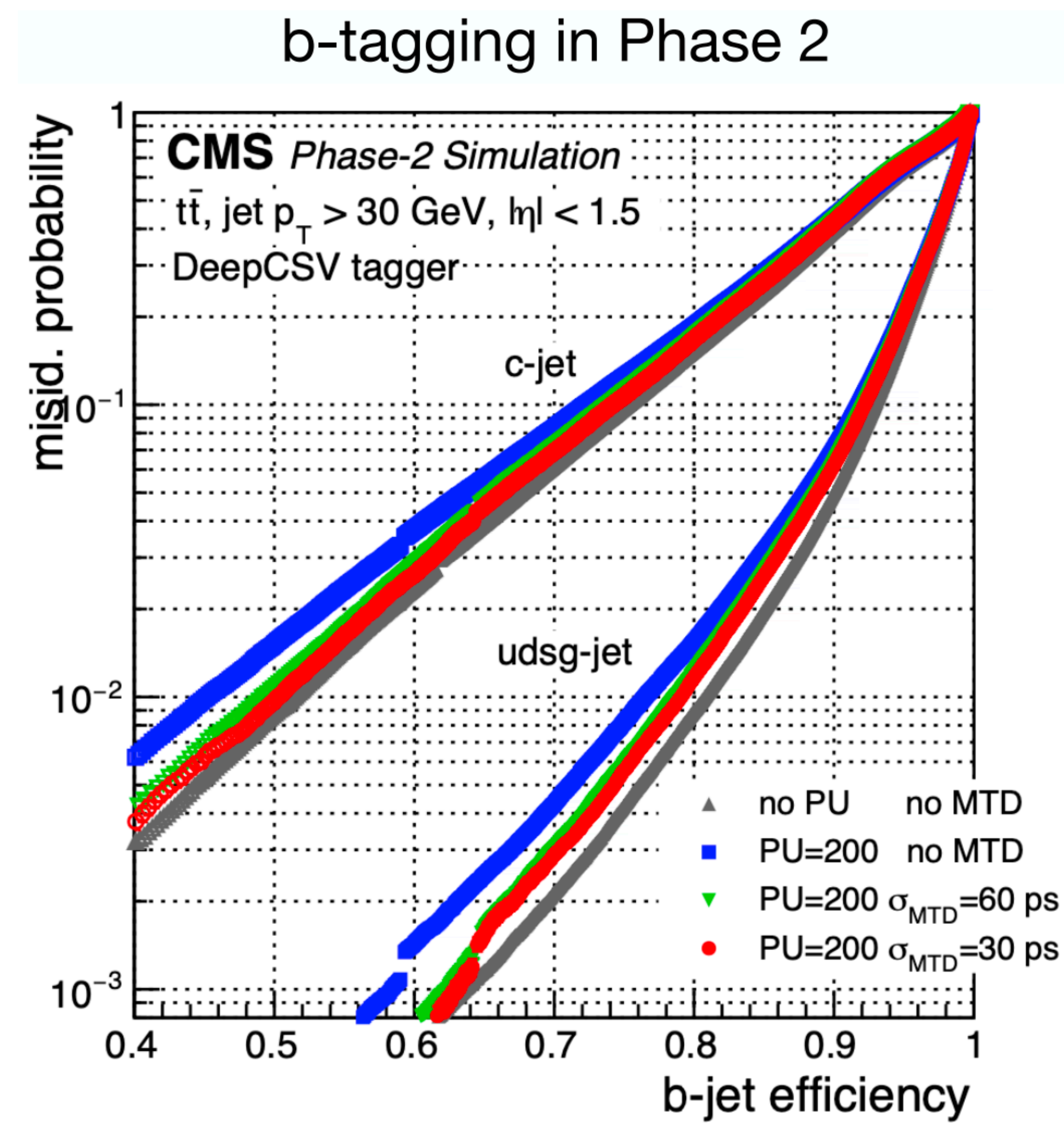
Thank you!

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.





MTD Physics Potential

- 10 - 20% gain in di-Higgs significance

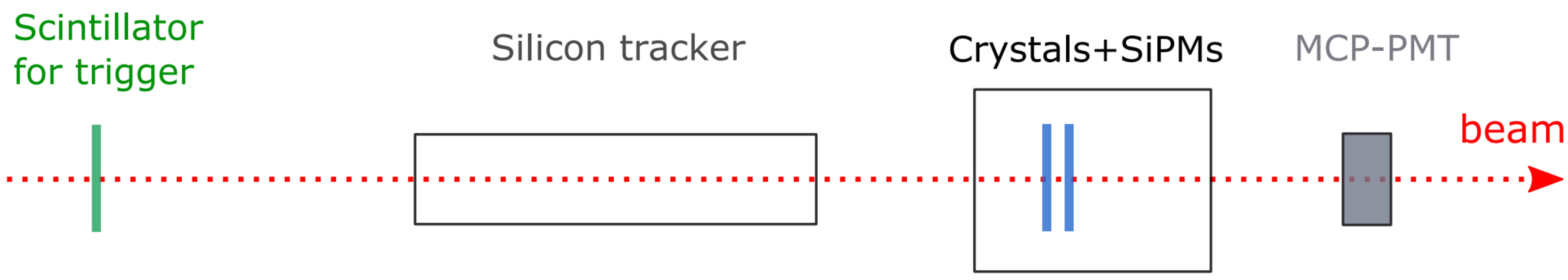
35 ps BTL, 35 ps ETL

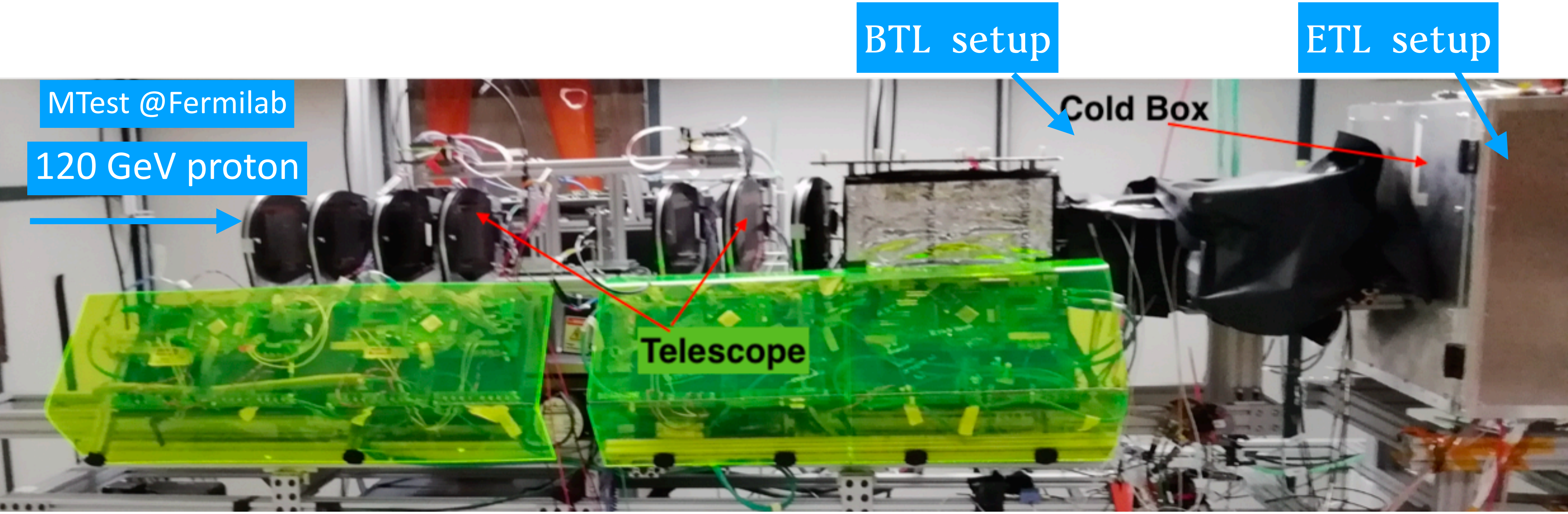
Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.38	1.52	1.60
$bb\gamma\gamma$	1.70	1.75	1.85	1.90
Combined	2.31	2.40	2.57	2.66

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

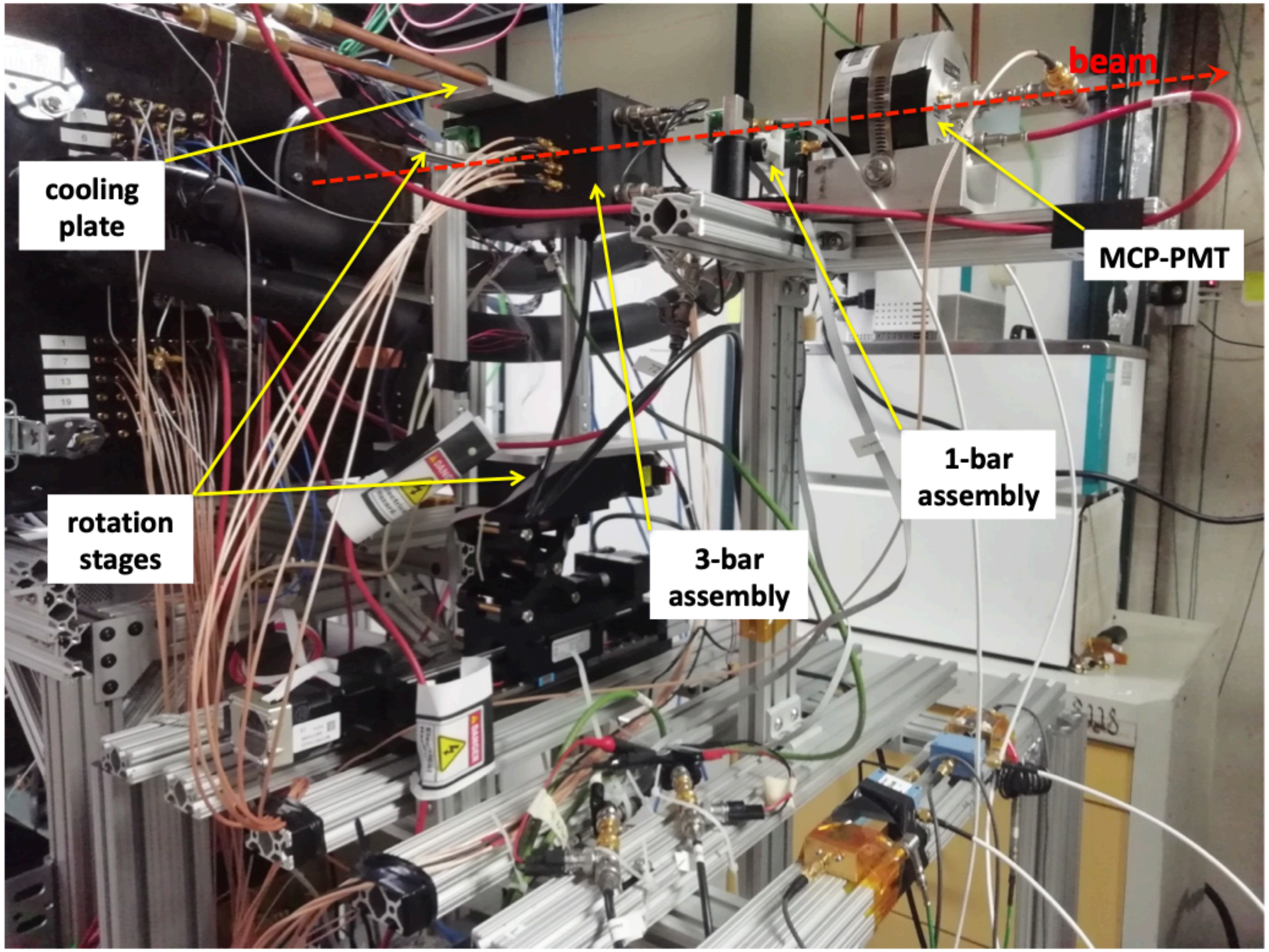
MTD Test Beam Setup

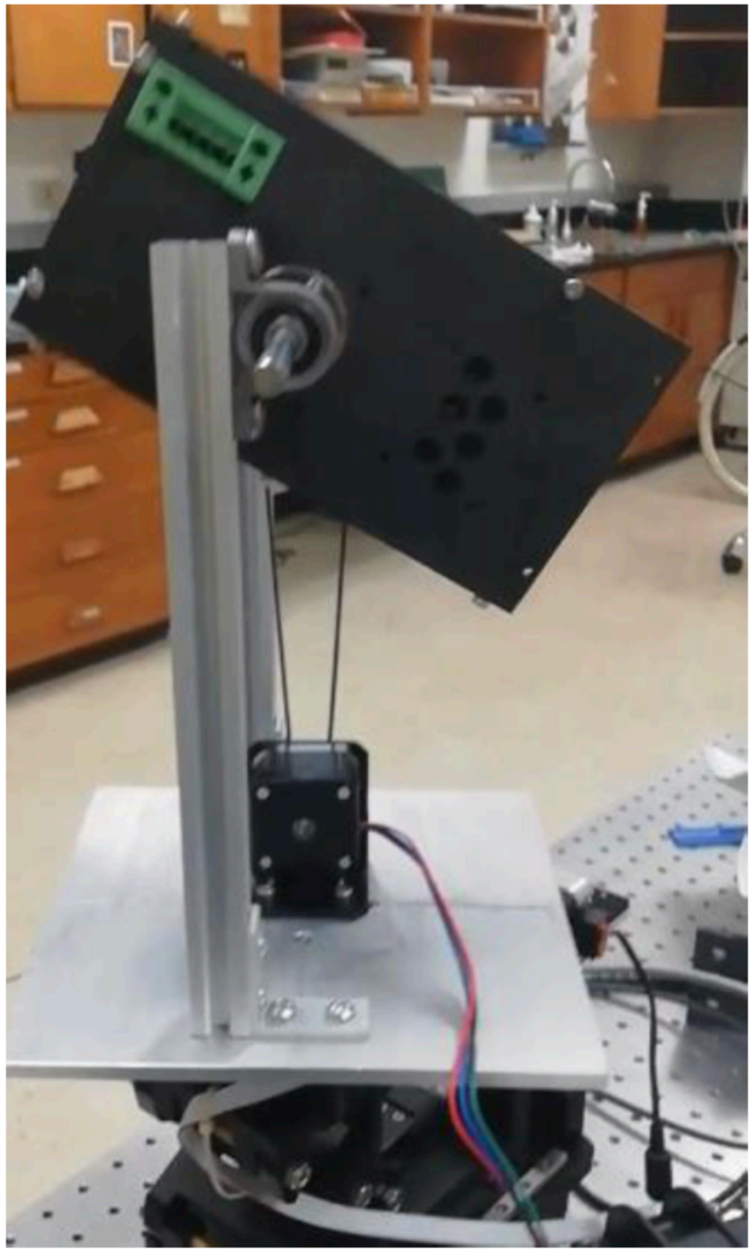
- Time resolution measured against reference timing detector (Photek 240 micro-channel plate, time resolution ~12 ps)
- Tracking of charged particles by precision telescope, 0.2 mm position resolution



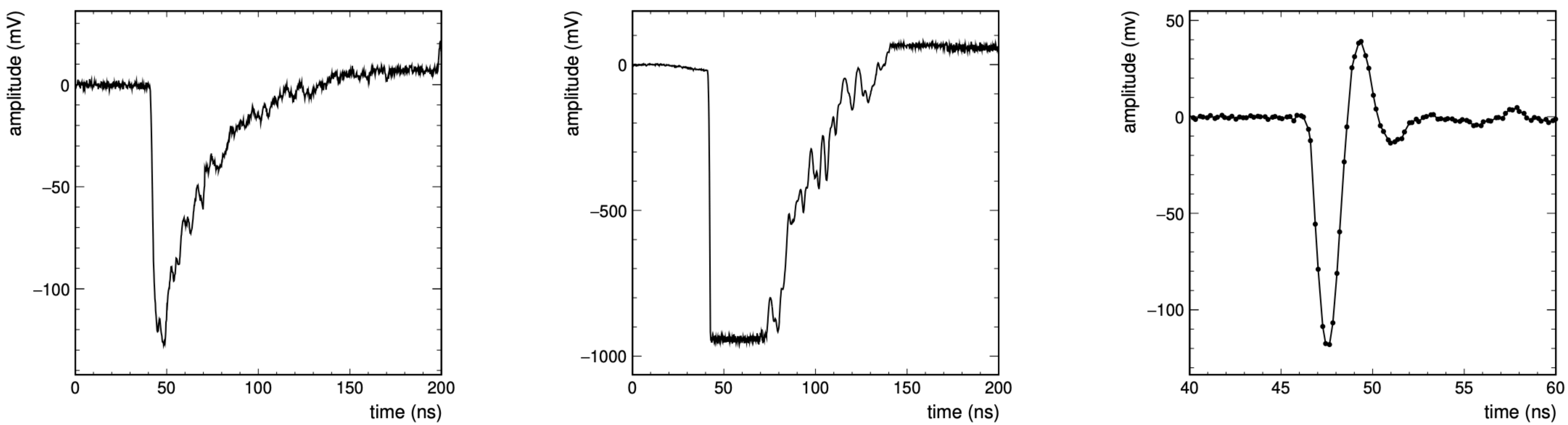


BTL test beam



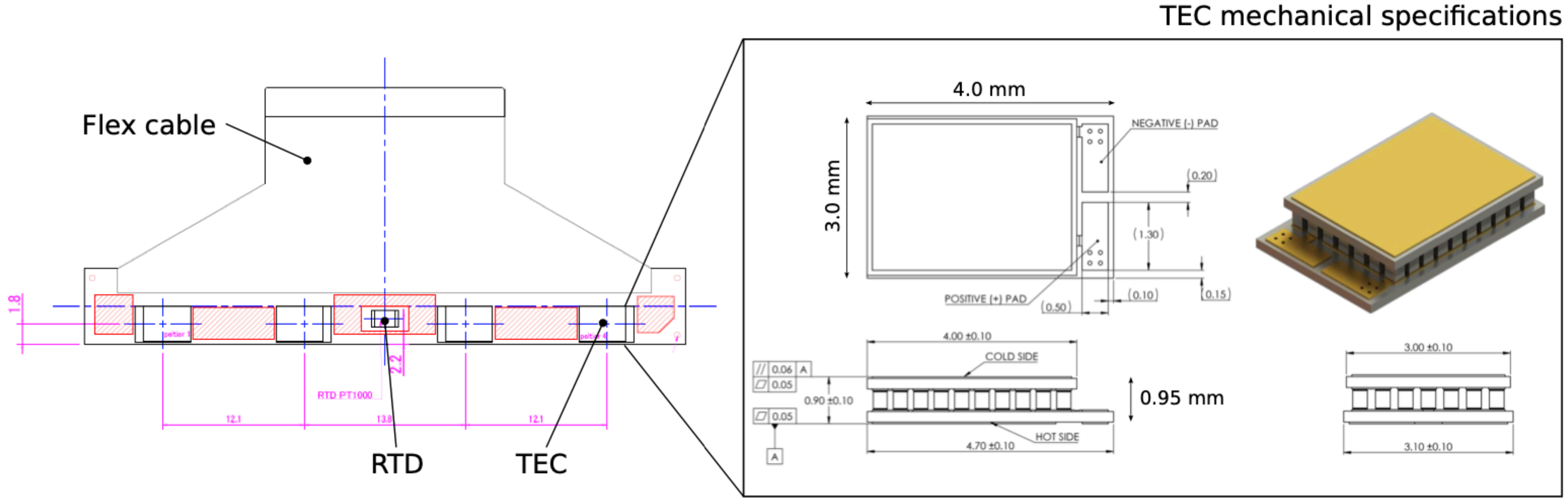


SiPM and PMT pulse shape from test beam

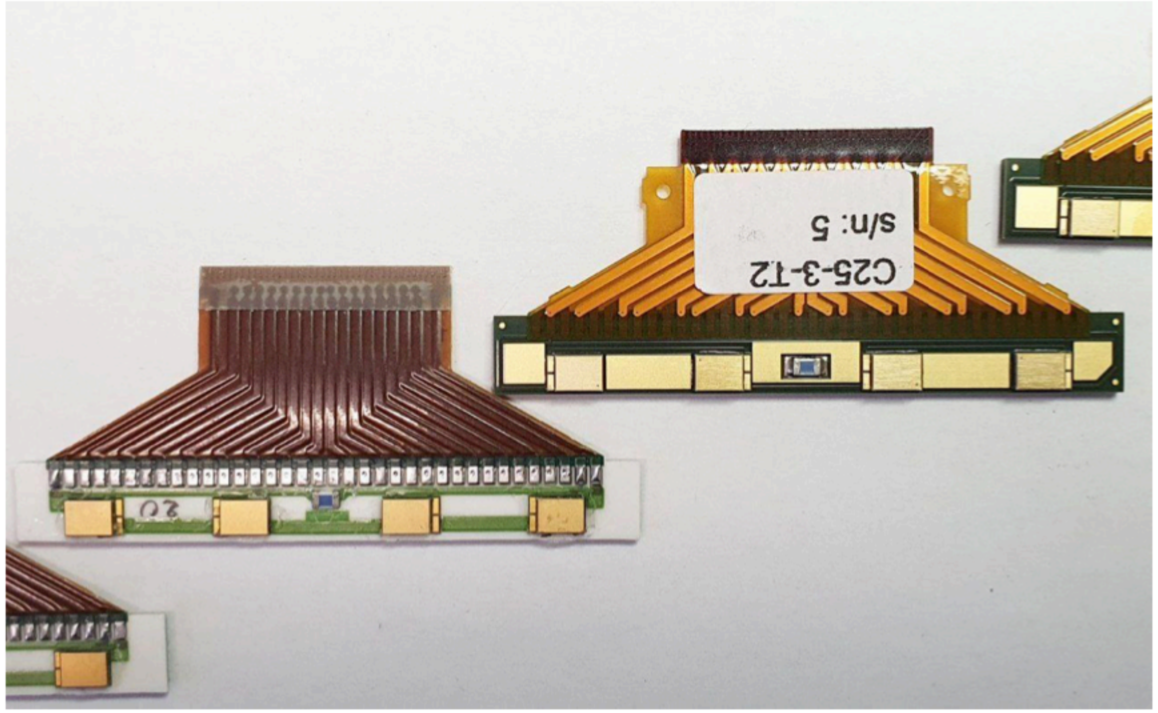


(a) SiPM (low gain) (b) SiPM (high gain) (c) MCP-PMT

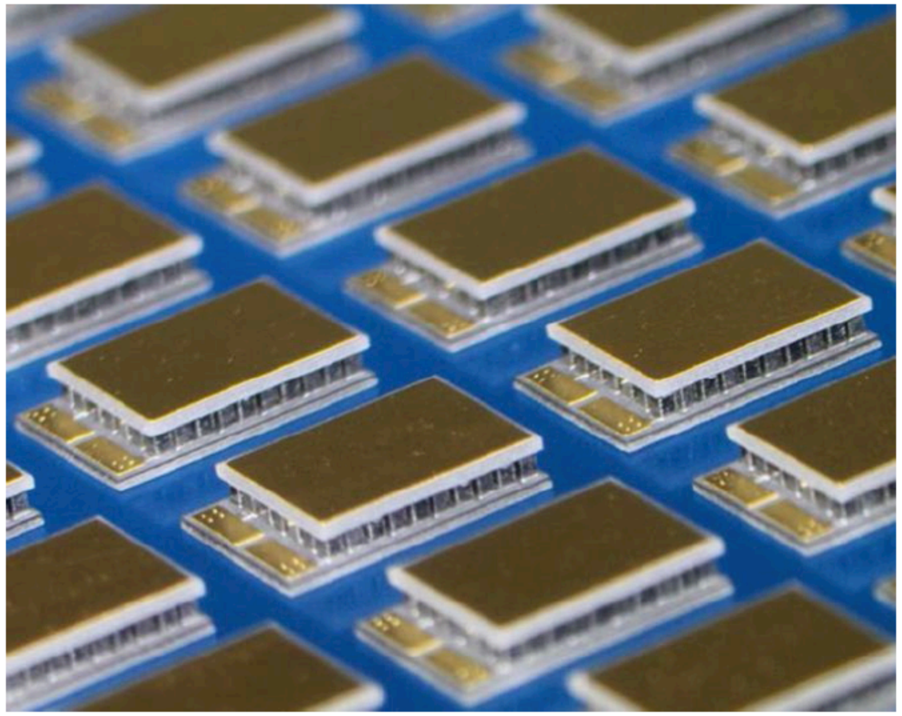
TECs



Flex cable
RTD
TEC
TEC mechanical specifications
4.0 mm
3.0 mm
NEGATIVE (-) PAD
POSITIVE (+) PAD
0.95 mm
COLD SIDE
HOT SIDE



s/n: 5
C25-3-T2



Requirements of the MIP timing detector

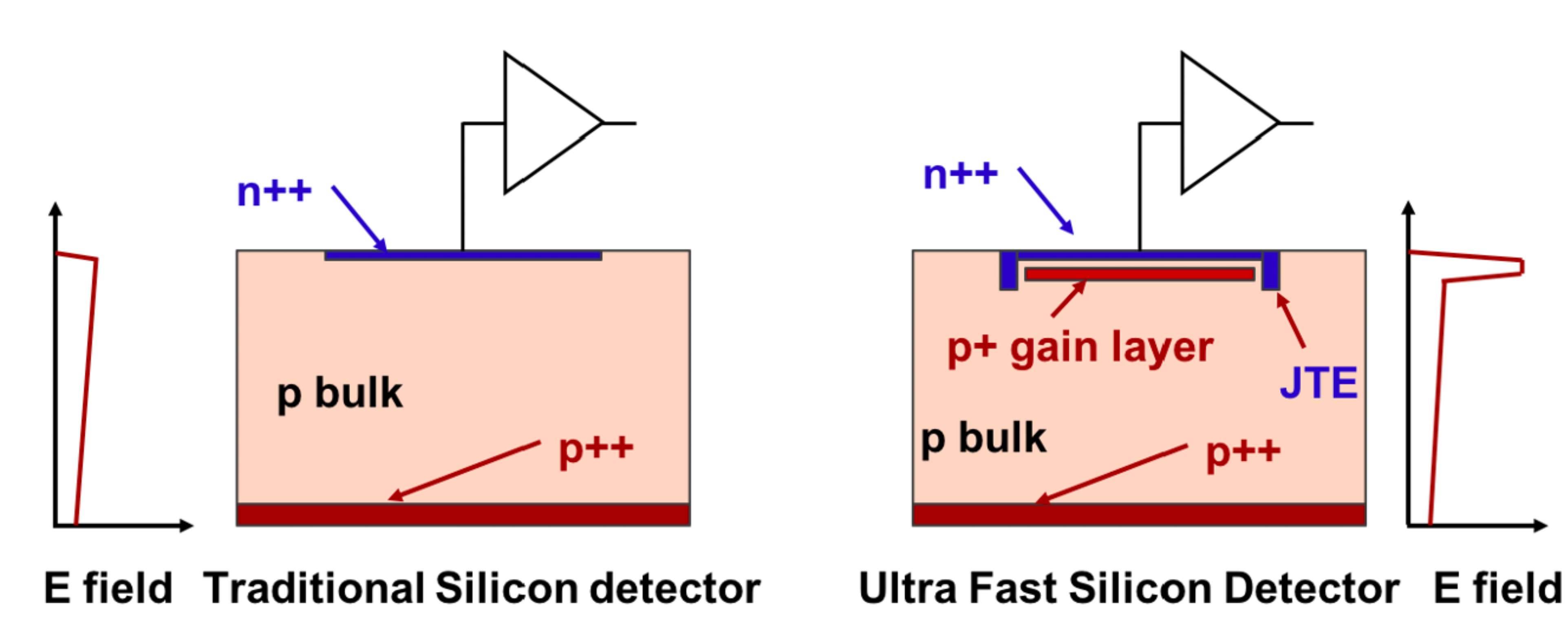
	Barrel Timing Layer (BTL)	Endcap Timing Layer (ETL)
Coverage	$\|\eta\| < 1.5$	$1.6 < \|\eta\| < 3.0$
Surface Area	$38\ m^2$	$12\ m^2$
Power Budge	$0.5\ kW/m^2$	$1.8\ kW/m^2$
Radiation Rose	$\leq 2 \times 10^{14}\ n_{eq}/cm^2$	$\leq 2 \times 10^{15}\ n_{eq}/cm^2$

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

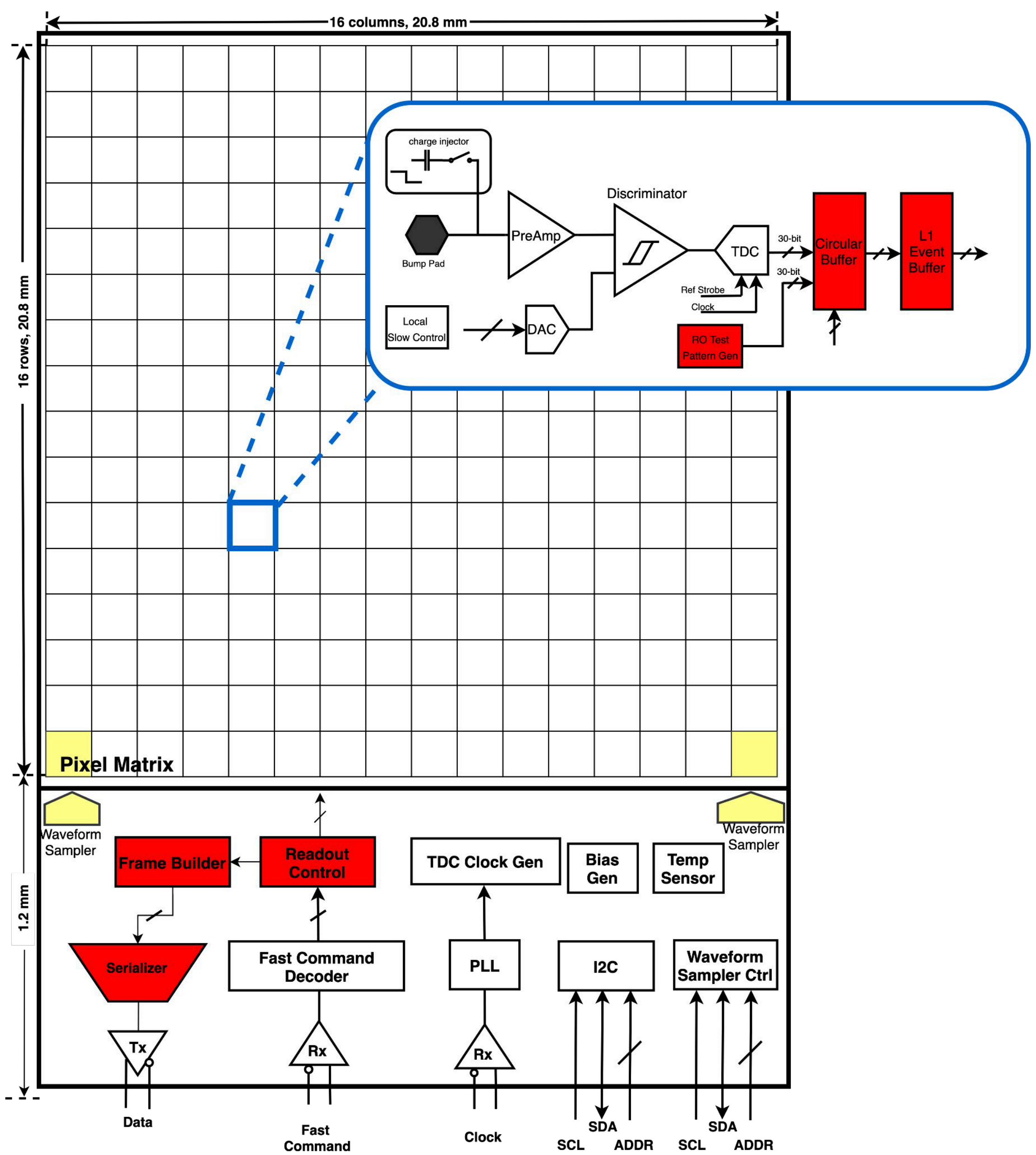


LGAD silicon sensors:

- 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



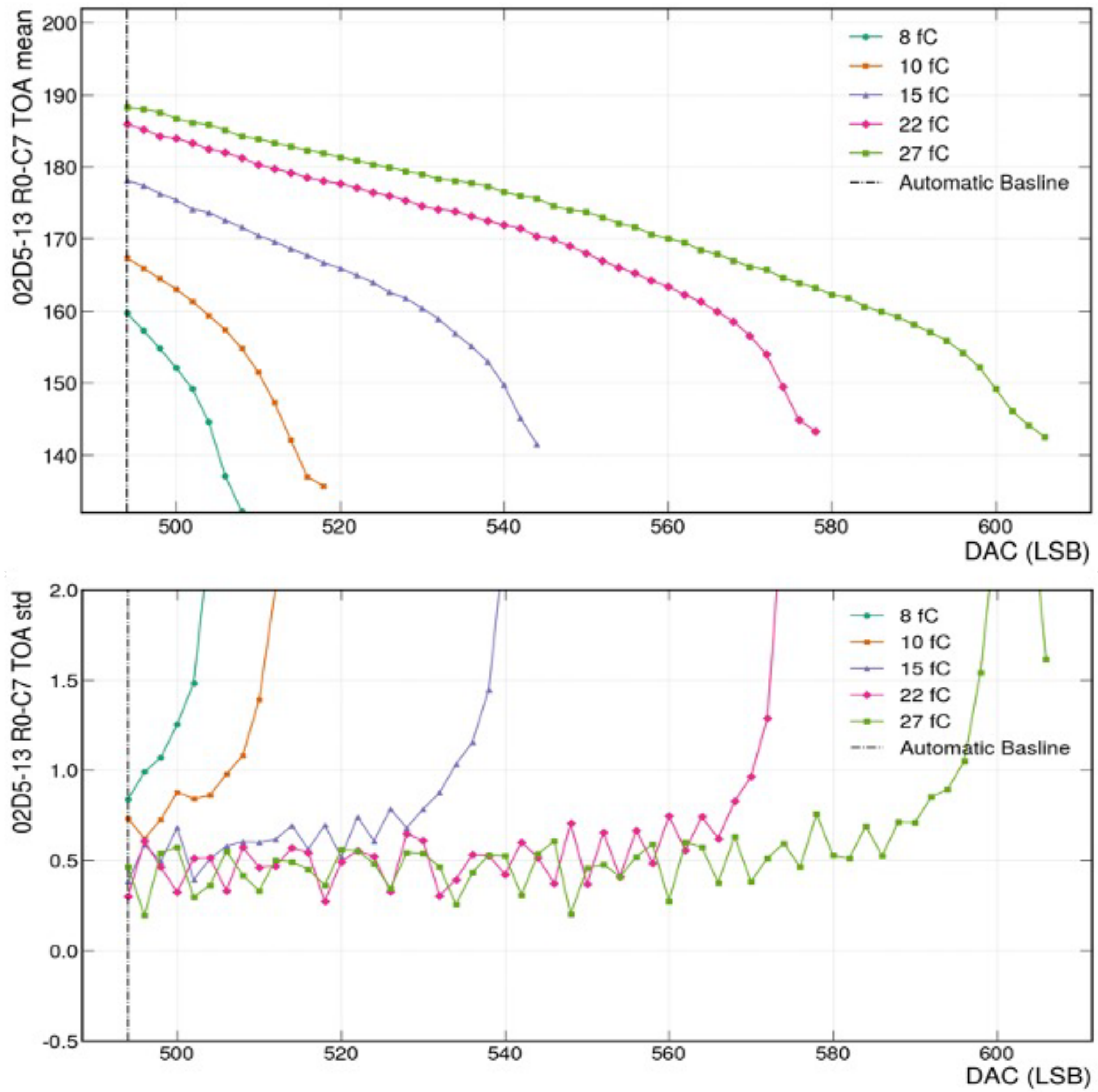
Performance specifications:

- 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

SiPM and PMT pulse shape from test beam

ETROC2 TID testing at CERN



Precision timing in high radiation environment: LGAD sensors

Worked with multiple vendors to optimize LGAD arrays.

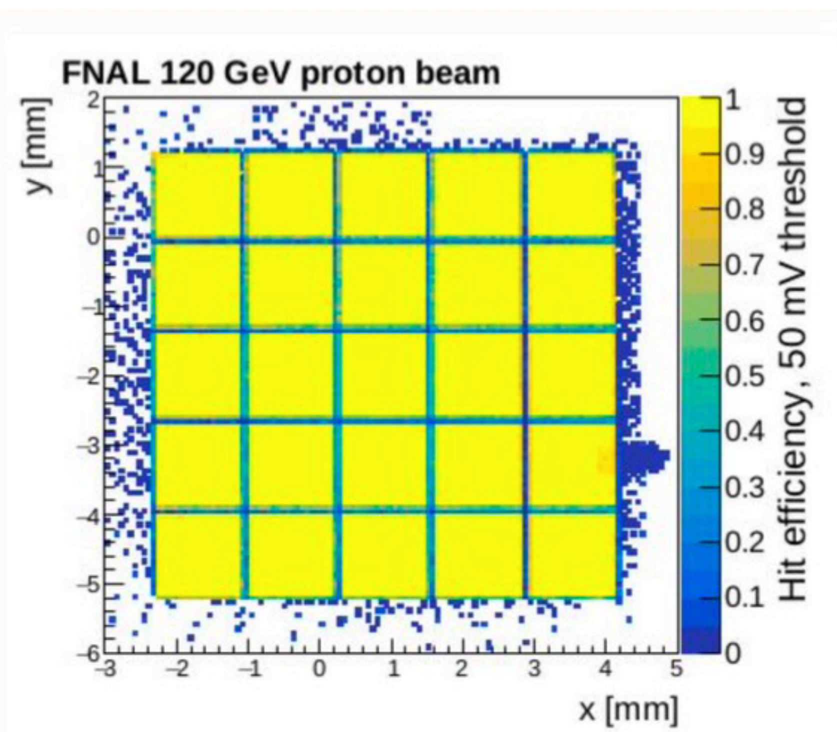
• Excellent uniformity, fill-factor, and production yield (>70%) per wafer.

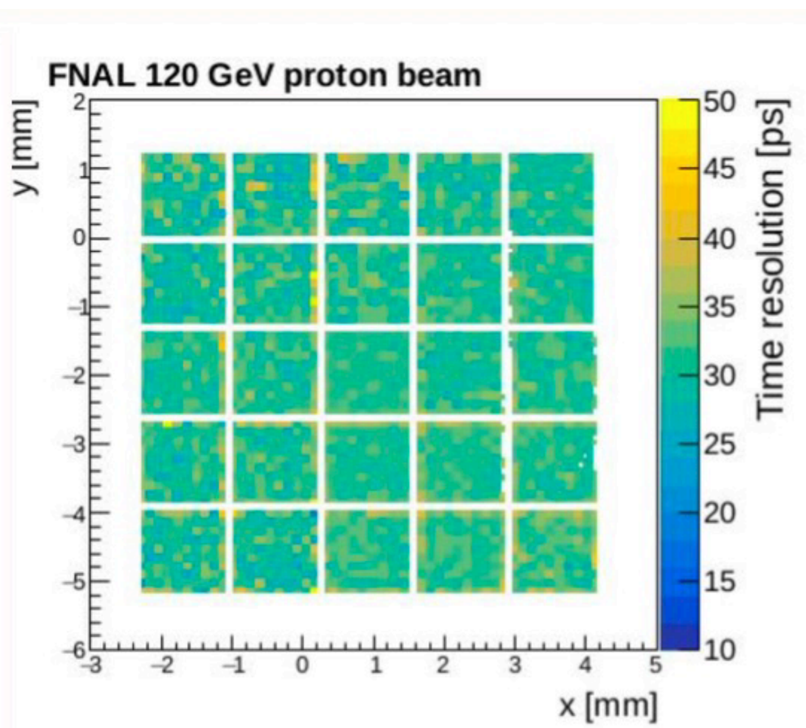
Increase bias voltage to maintain gain after irradiation.

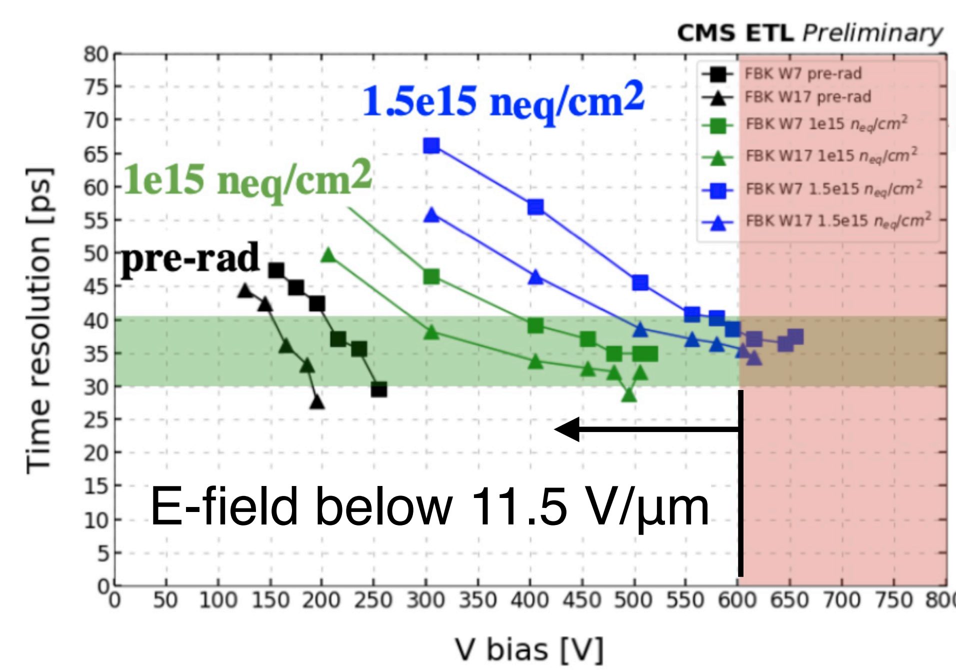
• Test beam studies show sparking damage to sensors for E-field above 11.5 V/µm.

• Prototype LGAD sensors characterized before and after irradiation proven to meet ETL requirements (>8 fC) for E-fields below 11.5V/µm.

Spark damage (microscope)







ETL sensor modules

ETL sensor 16x16 LGAD, bump-bonded to ETROC
ETL requirement:

- time resolution < 50 ps/hit, 40 ps/track (two ETL disks)
- LGAD deliver > 8 fC