北京大學
PEKING UNIVERSITY

LYSO:Ce scintillating crystals for precision timing at CMS during LHC Phase 2

PKU HEP Seminar and Workshop

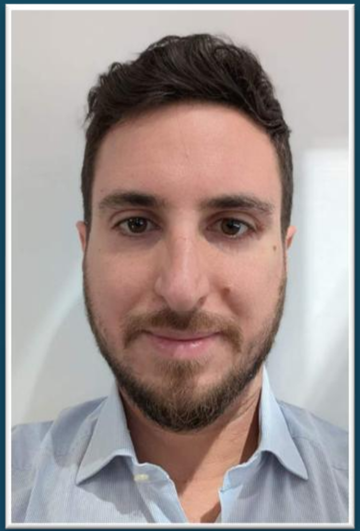
Beijing – 25 April 2025

CMS

C. Quaranta – Peking University

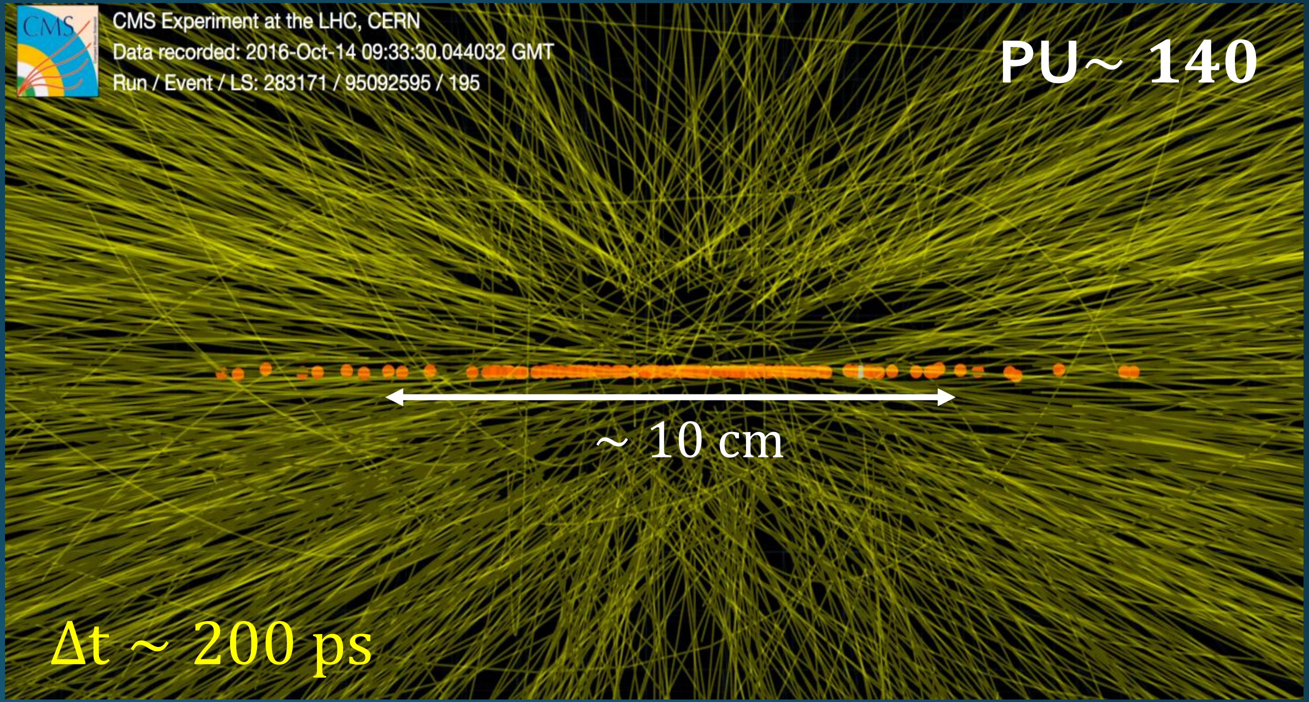
About Me

- PhD at Sapienza University of Rome (2022)
  - Thesis: search for resonances in Trijet final states
  - CMS ECAL calibration and upgrade
- Post-doctoral researcher at Sapienza (2022-2025):
  - Study of B meson rare decays
  - Development of the MIP Timing Detector
    - LYSO crystals quality control (this talk)
    - Coordination of monitoring and calibration group
- Post-doctoral researcher at Peking University (~now)



The High-Luminosity LHC challenge

- HL-LHC scenario:
  - 3-4 times higher instantaneous luminosity
  - Unprecedent amount of data to boost Higgs rare channel studied, precision measurements, new physics searches
  - higher Pile-Up (40-60 → 140-200 events) and radiation damage



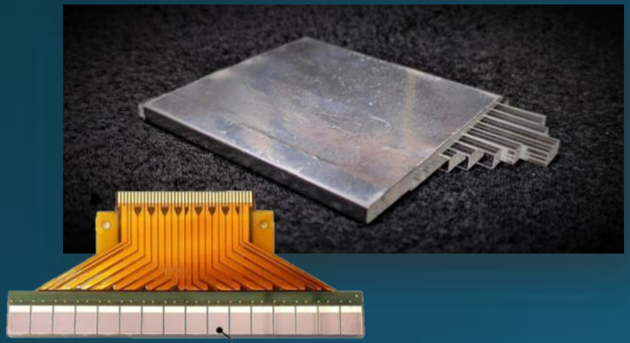
- Increased spatial overlap of vertexes
  - up to 5x higher vertex density
  - reduced efficiency of track-vertex association
  - event reconstruction degradation
  - Timing information useful to recover ~Run 2 performances in harsh HL-LHC condition

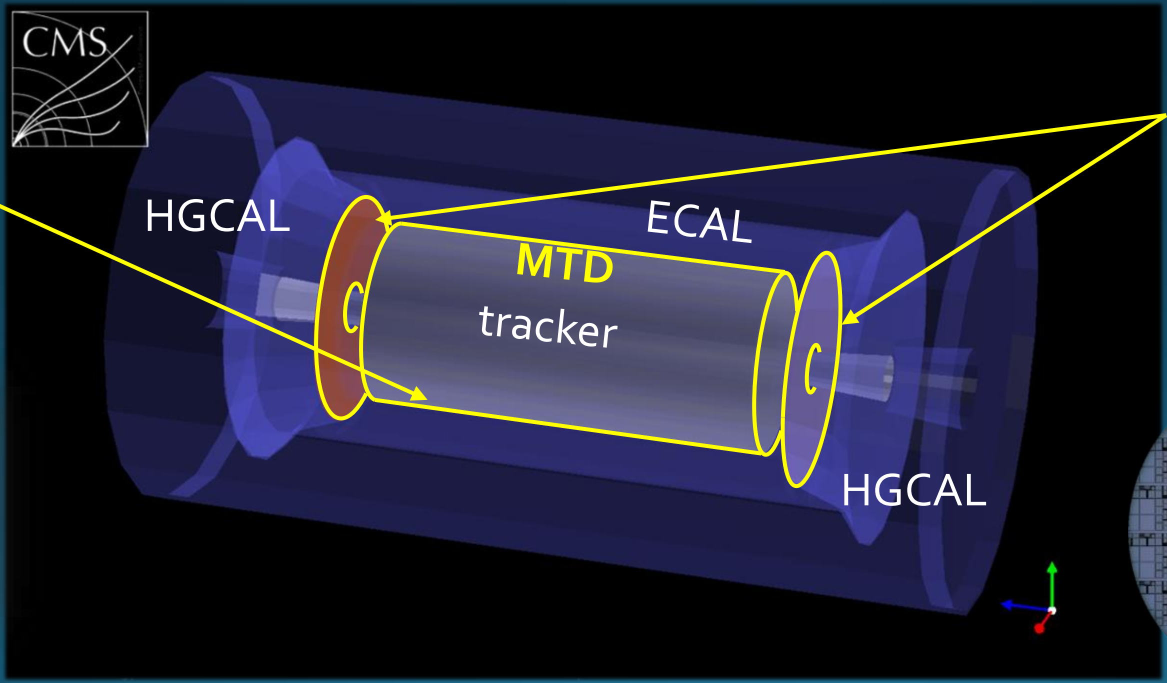
The MIP Timing Detector

New CMS layer for High-Luminosity LHC (HL-LHC):

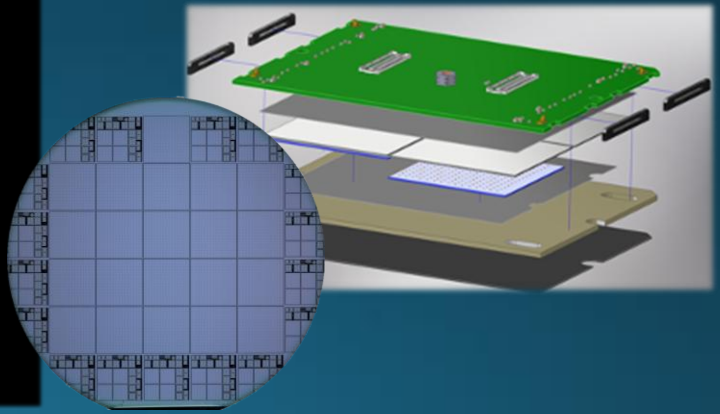
- Time measurement of min.-ionizing (charged) particles (MIP) with resolution of 30-50 ps
- Reduce effective PU at HL-LHC using timing information

Barrel Timing Layer (BTL)
LYSO scintillating crystals + SiPMs





Endcap Timing Layer (ETL)
Low Gain Avalanche Diodes (LGADs) + ETROC



MTD Technical Design Report

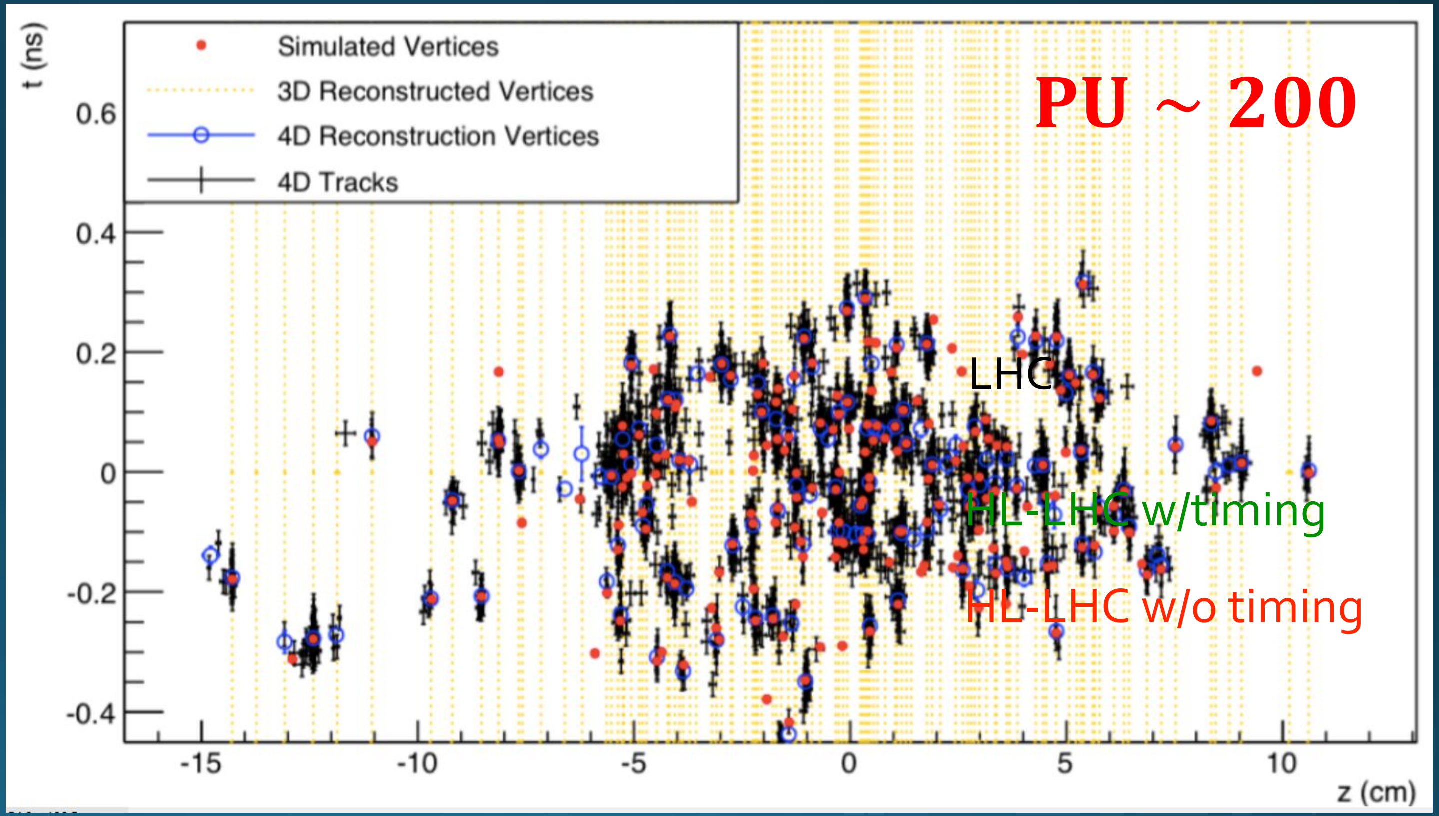
MTD impact on physics

- Enable 4D vertex reconstruction and restoring effective PU levels close to RUN 2 scenario

- Improved reconstruction of physics objects → Higher sensitivity for rare processes

- New features to CMS → Charged hadrons id, Searches for exotic time signatures

- Measure luminosity in synergy with other CMS detectors
  - Log of negative MTD zero-fraction linear wrt PU



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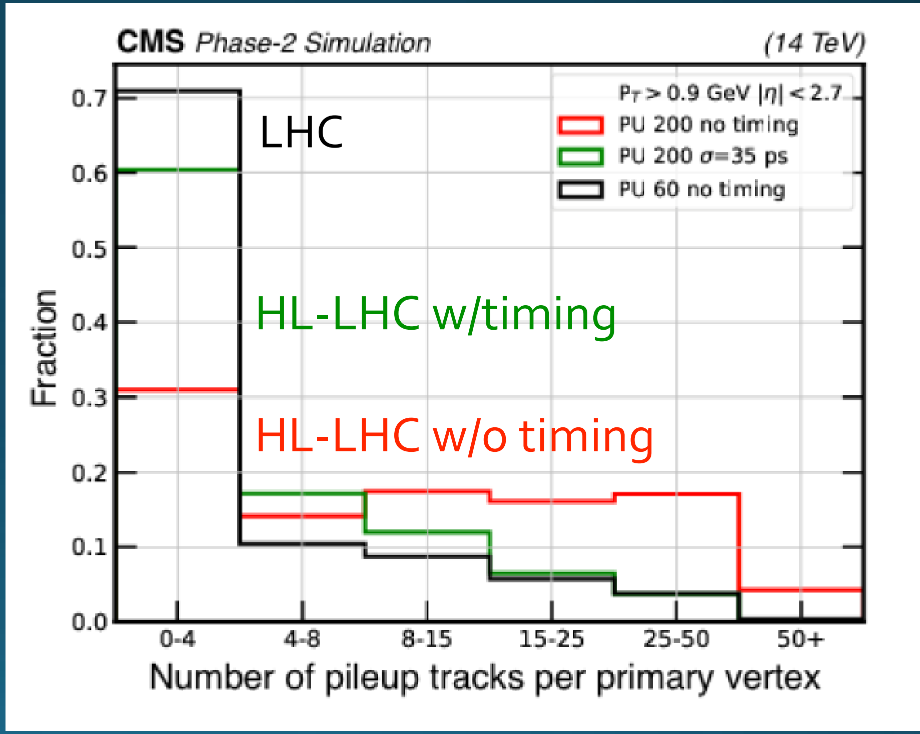

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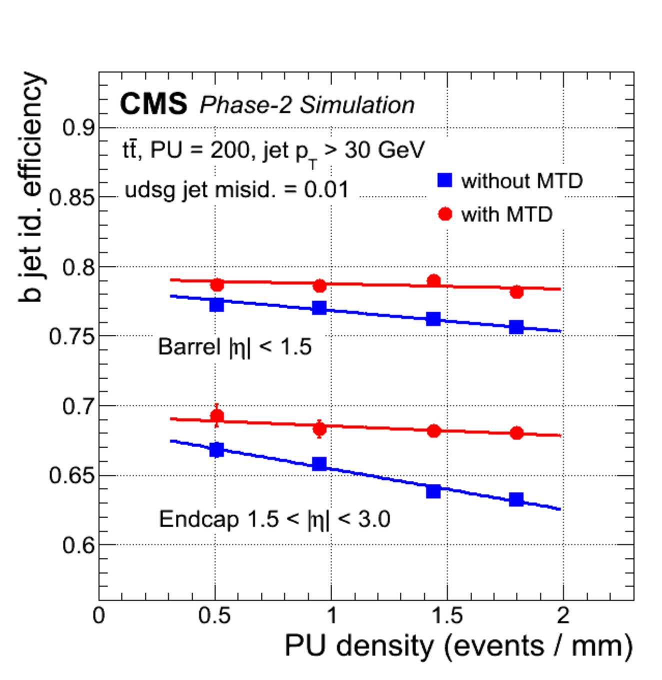
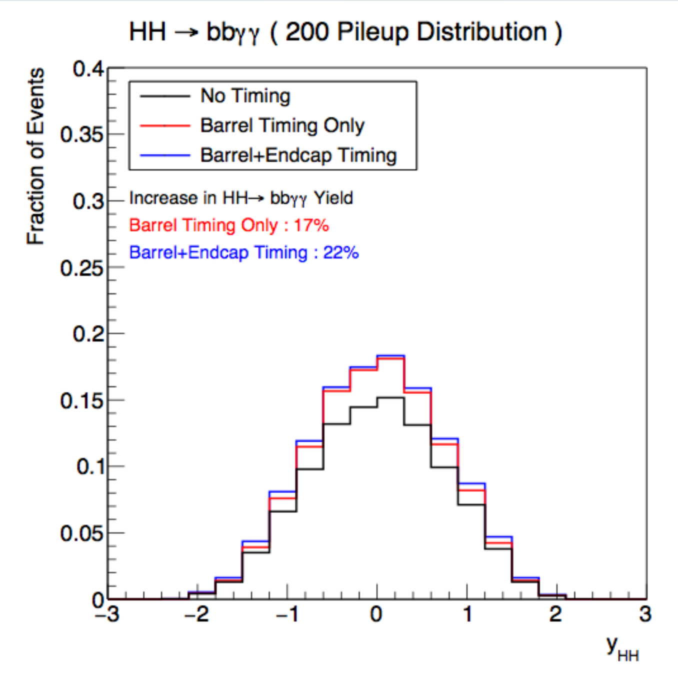
B-tagging efficiency increase



$HH \to bb\gamma\gamma$ yield inrease



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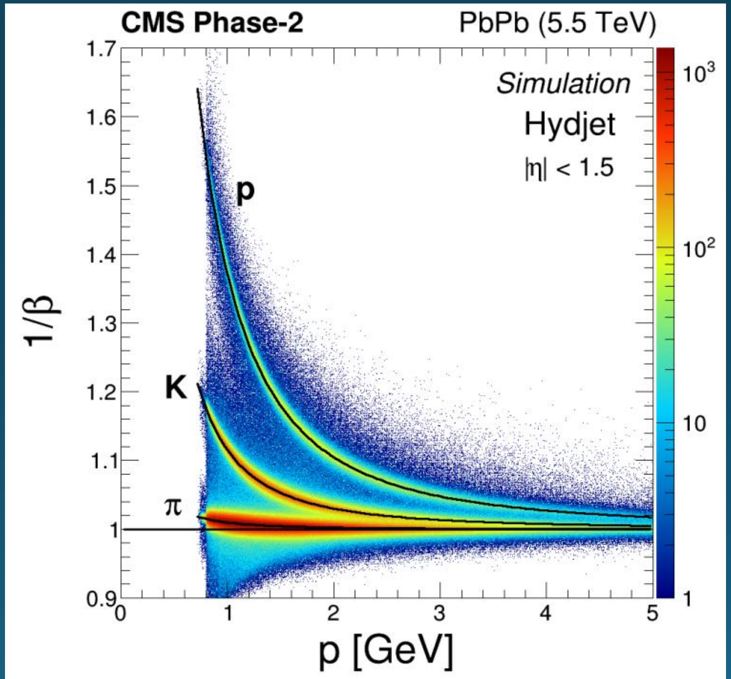
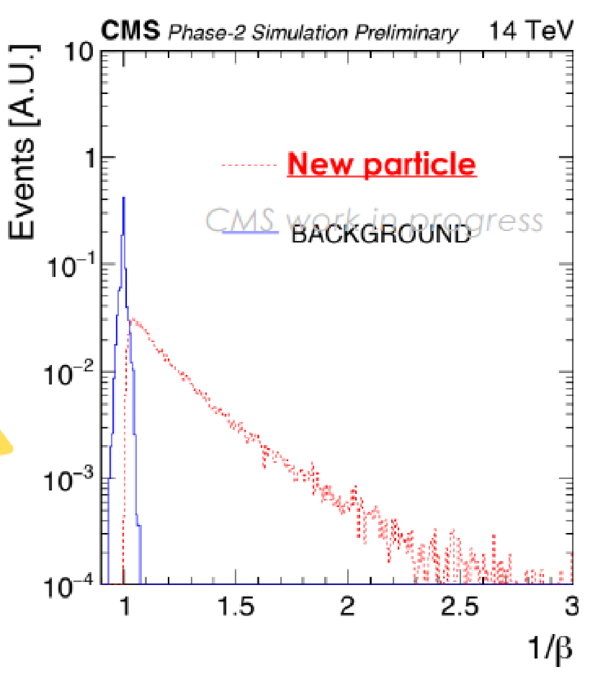
Particle ID via time-of-flight



Signals from heavy (slow) charged particles



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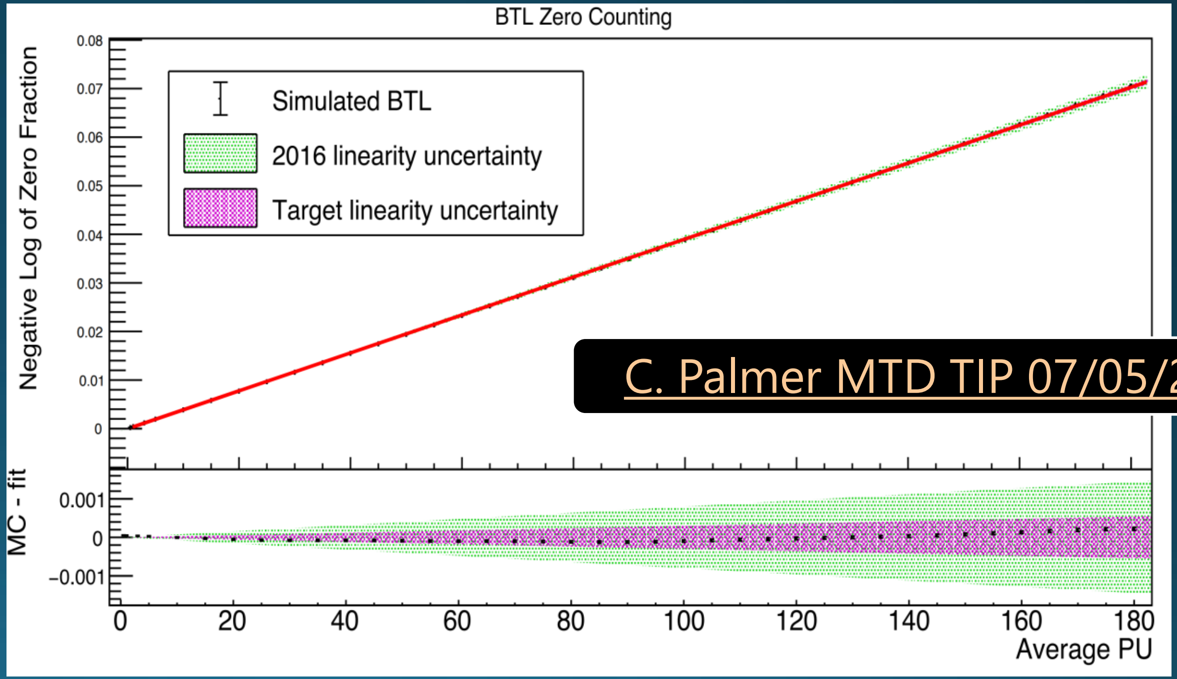
Luminosity measurement

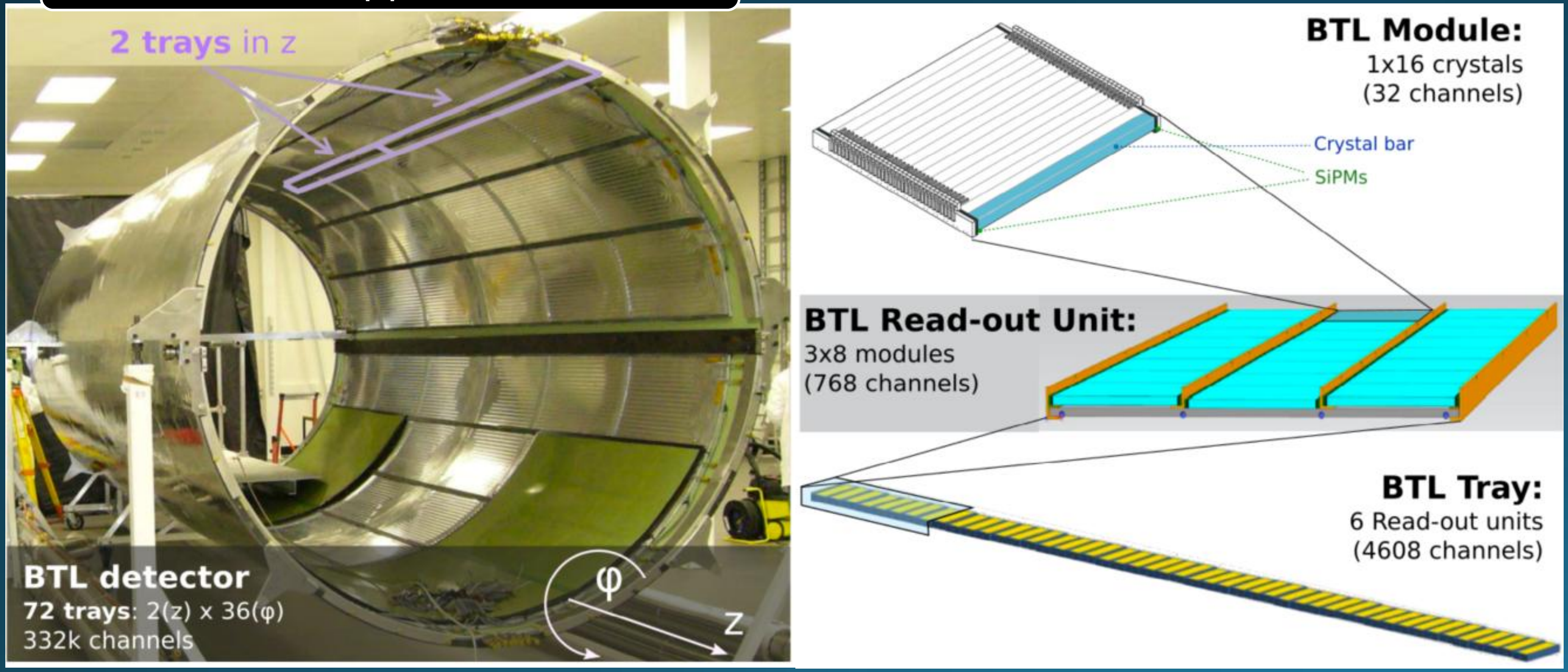


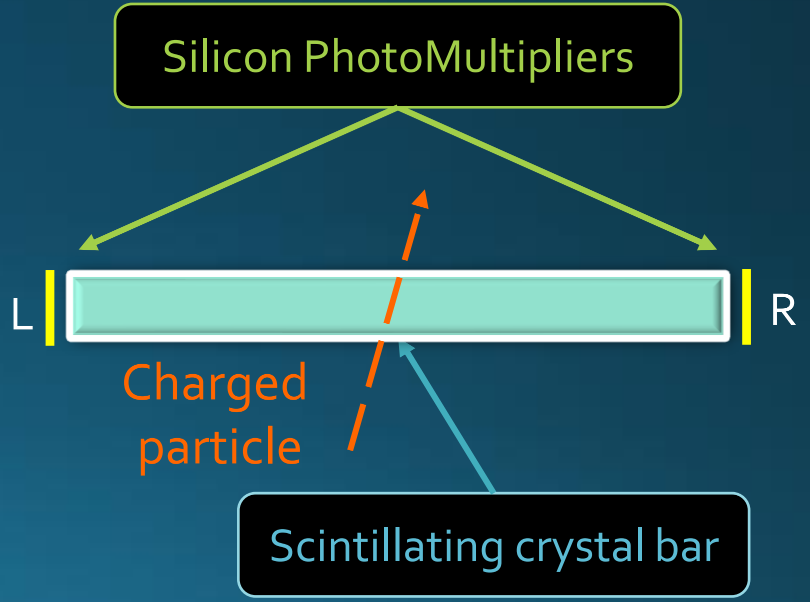
C. Palmer MTD TIP 07/05/2024

The MTD Barrel Timing Layer

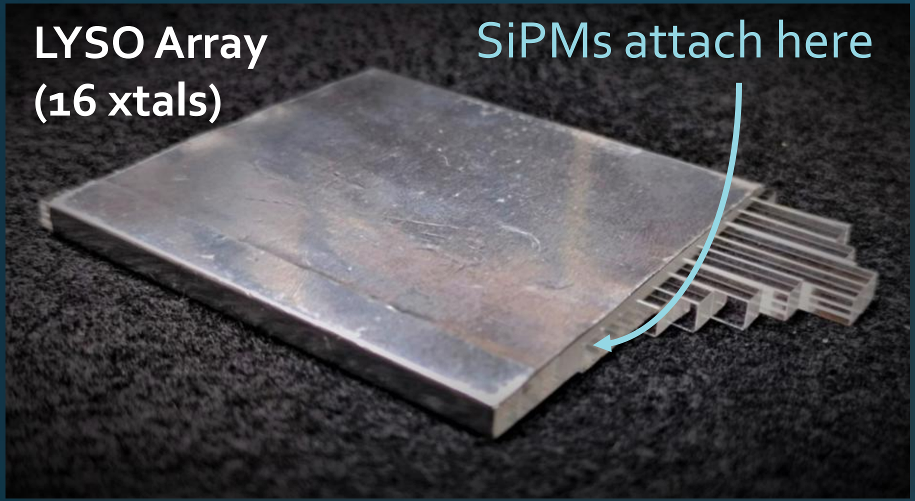
- BTL requirements
  - Radiation hardness ($1.9 \cdot 10^{14}\ \mathrm{n_{eq}/cm^2}$ end of HL-LHC)
  - Negligible impact on calorimeter performance (small energy absorption)
  - Mechanics, service, cost and schedule compatible with existing upgrades

BTL-Tracker Support Tube (BTST)





BTL Sensors

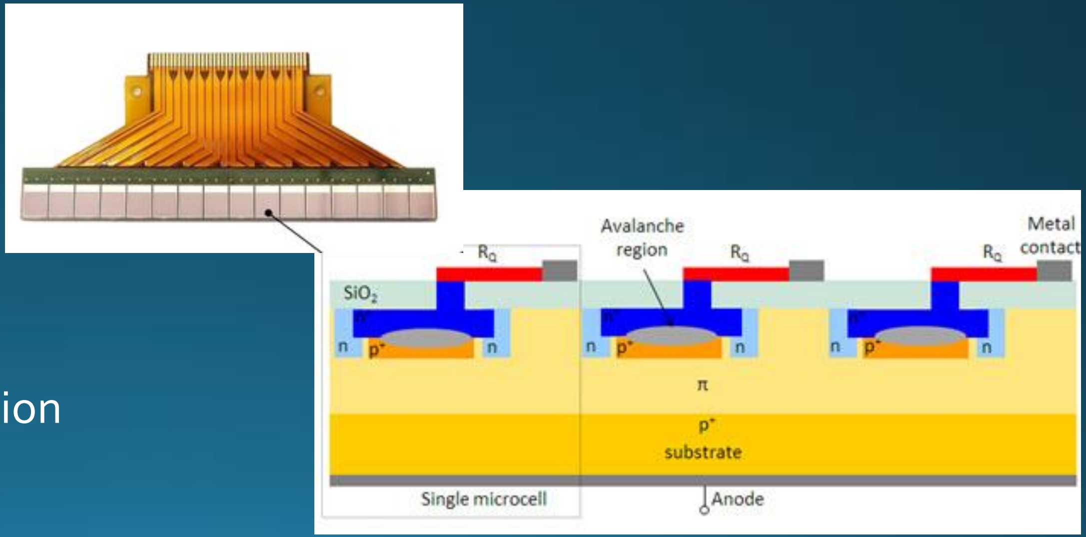


Cerium-doped Lutetium-Yttrium Oxyorthosilicate (LYSO:Ce)

- Rise time: $\tau_r \simeq 100$ ps
- Decay time: $\tau_d \simeq 40$ ns
- High Light Yield: $\mathrm{LY} \simeq 40\,000$ ph/MeV)
- High mass density (7 - 7.3 g/cm^3)
- Radiation hardness
- Easy availability (used in medical applications such as PET)

Silicon PhotoMultiplier (SiPM)

- Matrix of Avalanche PhotoDiodes (APD) in reverse bias
- Avalanche mechanism → Internal gain
- Compact and robust
- Insensitive to magnetic fields
- Operate at relatively low voltages with low power consumption
- Photo-Detection Efficiency, PDE up to 50%



BTL Time Resolution

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

$$\sigma_t^{ele} \propto \frac{\tau_r \tau_d}{Gain \cdot N_{phe}}$$

$$\sigma_t^{phot} \propto \sqrt{\frac{\tau_r \tau_d}{N_{phe}}}$$

$$\sigma_t^{DCR} \propto \frac{\sqrt{DCR}}{N_{phe}}$$

Electronic noise

- scales with the steepness of the electronic signal
- $\sim 10 - 100$ ps for MIPs (highly dependent on SiPM bias voltage and cell size)

Photo-statistics term

- related to the stochastic fluctuations in the time-of-arrival of photons detected at the SiPM
- $\sim 25 - 30$ ps for MIPs

Dark Count Rate

- Induced by radiation damage
- Dominant term after first years of HL-LHC operation

σ_t^{BTL} dependends on N_{phe}(# of photoelectrons) and $\tau_r \tau_d$ → sensors optimization and quality control is crucial

BTL Sensors Optimization and DCR Mitigation

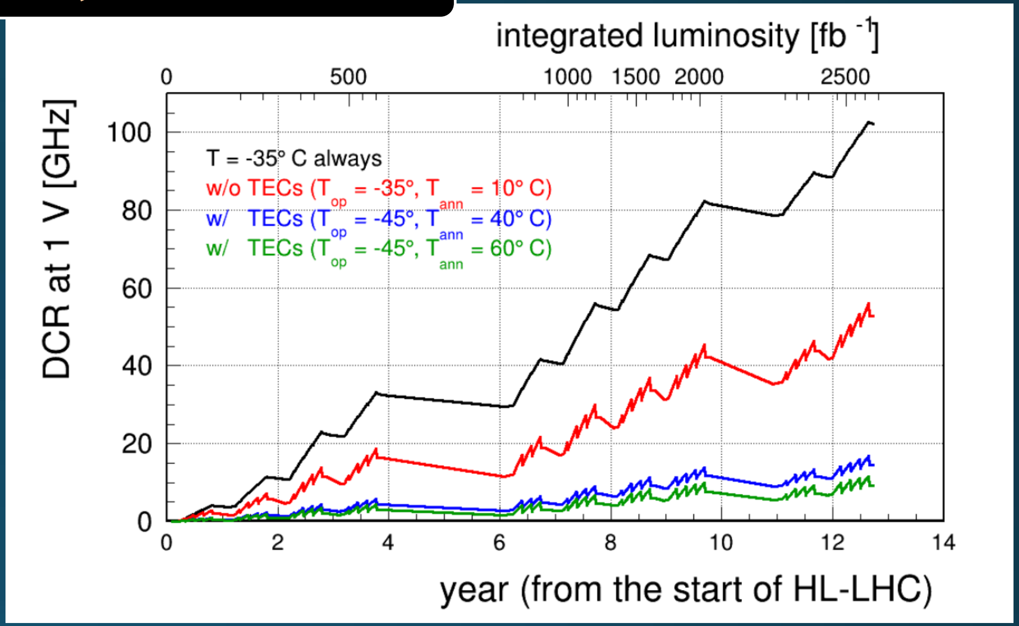
2023 JINST 18 P08020

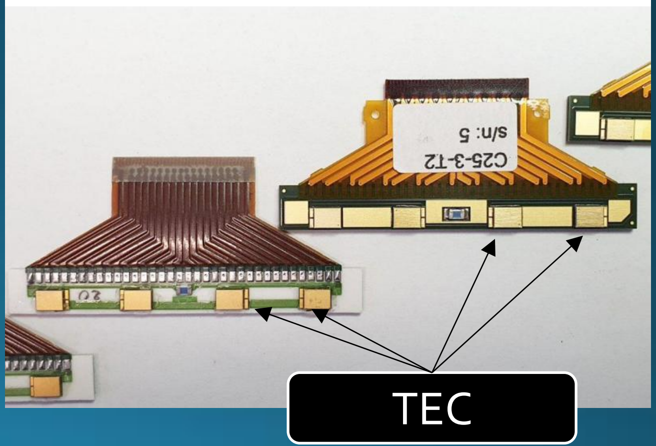
Sensors optimized to get higher $N_{phe} \propto E_{dep} \cdot LY \cdot PDE$:

- **Different crystal thickess ($\mathbf{Type\ 1, 2, 3 = 3.75,\ 3.00, 2.4\ mm}$)**
  - thicker crystals → larger E_{dep}
  - limited by available space for BTL and costs
- **SiPMs with different cell size ($\mathbf{15\mu m, 20\mu m, 25\mu m}$)**
  - larger cells → higher gain and PDE
  - increased sensitivity to radiation damage
- Final BTL sensor design: Type 1 LYSO + 25µm SiPMS

DCR mitigation using Termo Electric Coolers (TEC):

- Operating temperature from $-35°C$ (original design) to $-45°C$
- SiPM radiation damage recovering (annealing) up to $60°C$ during LHC stops





LYSO Quality Control Timeline

Market Survey				Tender	Pre-Prod	Prod
2019	2020	2021	2022	2023		2024

MS step1 (12 vendors)
Assessment on vendor production capacity

MS step2 (9 vendors) DN 2020/10
Tested LYSO single crystals and (few) arrays

MS step3 (6 vendors)
DN 2021/14
Tested larger LYSO array batch

Paper on comparative study of LYSO (JINST 2022)

Vendor choice
Sichuan Tianle Photonics

Quality monitoring
Completed in Dec 2024, in time for assembly operations

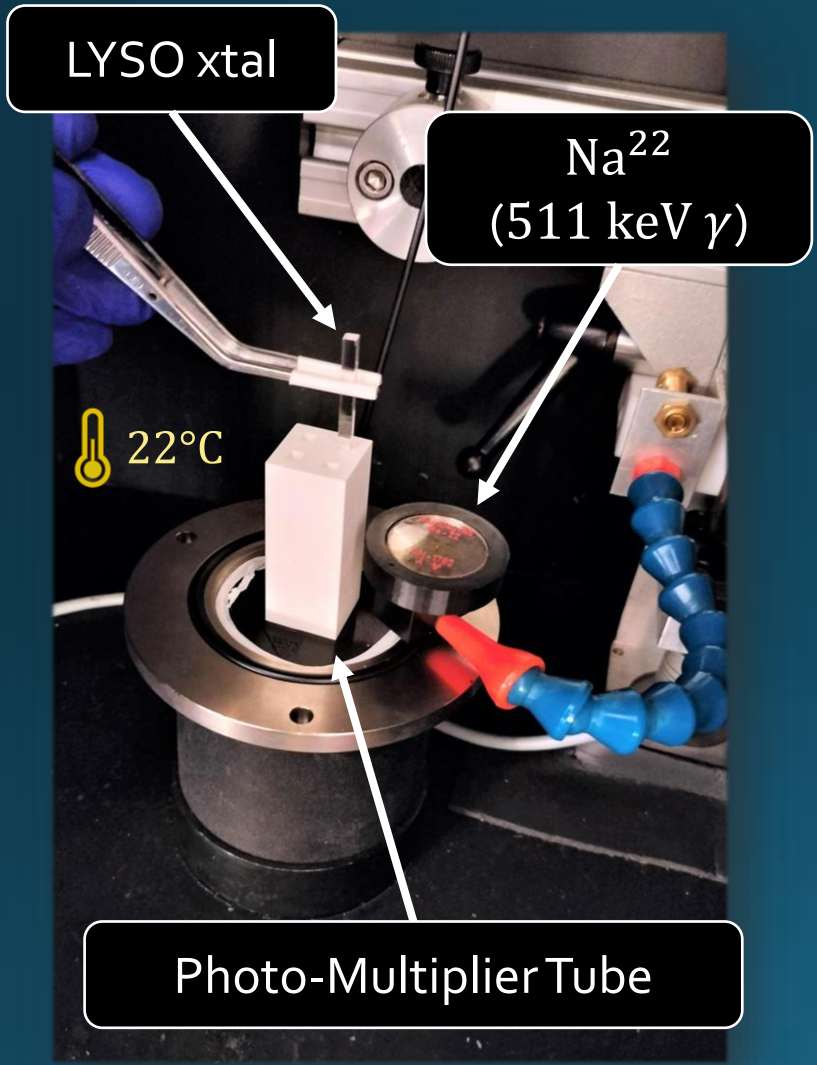
LYSO quality parameters

Optical measurements
- Ligth output (LO), τ_d
- Time resolution (array)
- Cross talk (array)
- Light transmission

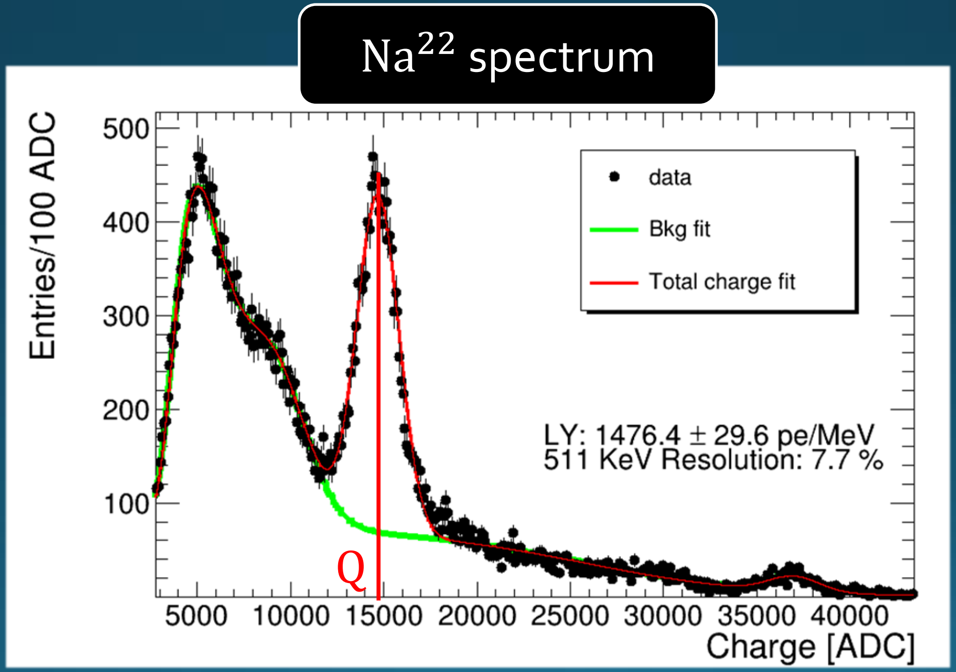
Dimensions
- Length, width, thickness
- Planarity (Array)

Radiation hardness
- LO loss after irradiation
- Transparency loss

LYSO Crystal Optical Properties



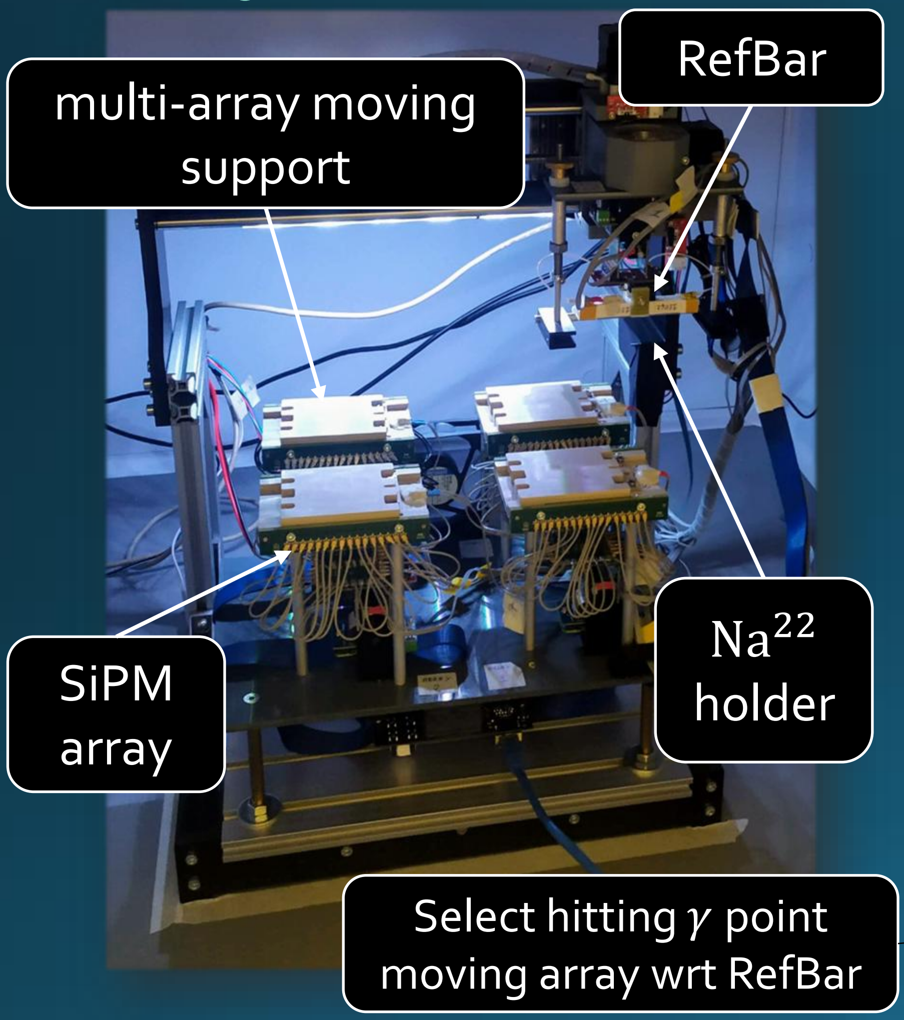
- Light Output $LO\left(\frac{ph}{MeV}\right) = \frac{Q}{\mu \cdot 0.511\ MeV} \cdot \phi$
- τ_d: extracted from fit to average signal shape



$Q =$ Charge for Na^{22} peak at 511 keV
$\mu =$ Single photo-electron (pe) charge from LED light
$\phi =$ PMT quantum efficiency (given by producer)

LYSO Array Optical Properties

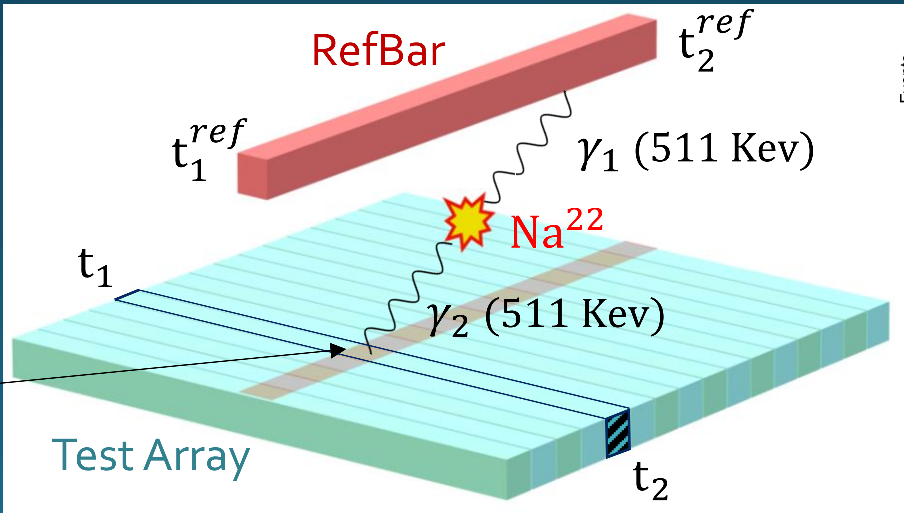
$5°C$

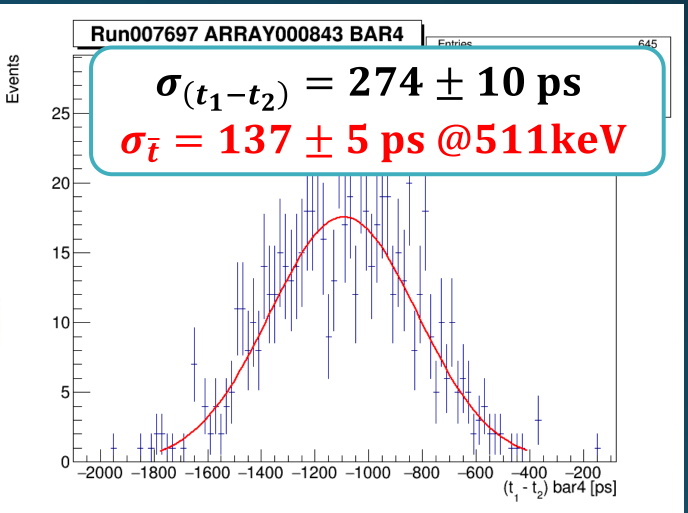


- **LO measurement** wrt reference arrays
- **Optical cross-talk** among bars
- **Time resolution (σ_t)** - coincidence of two γ from Na^{22} β-decay

$$t_{Average} = \frac{t_{left}+t_{right}}{2}; \qquad t_{Diff} = t_{left} - t_{right}$$

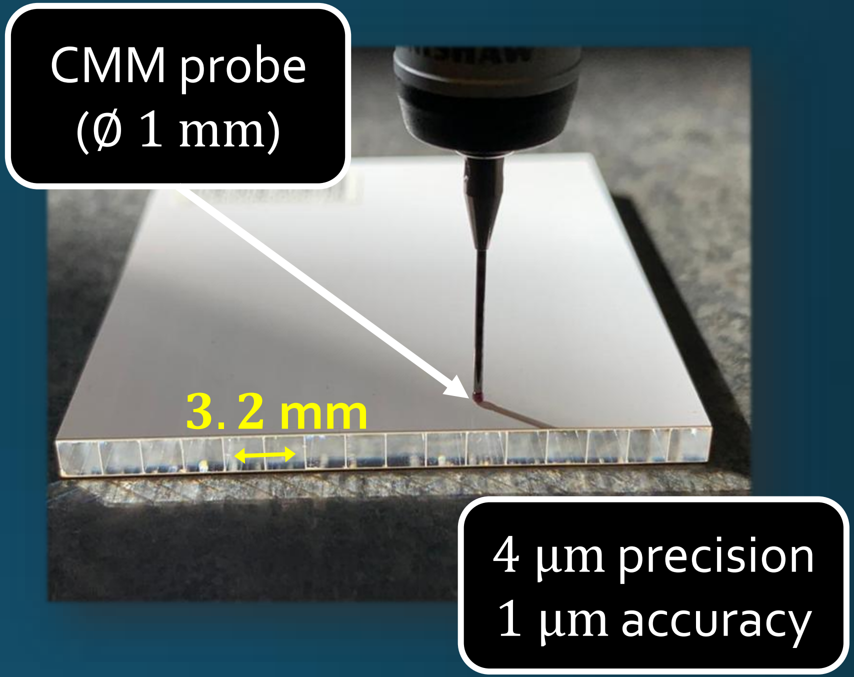
$$\sigma_{t_{Average}} = \frac{1}{2}\sqrt{\sigma^2_{t_{left}} + \sigma^2_{t_{right}}} = \frac{\sigma_{t_{Diff}}}{2}$$



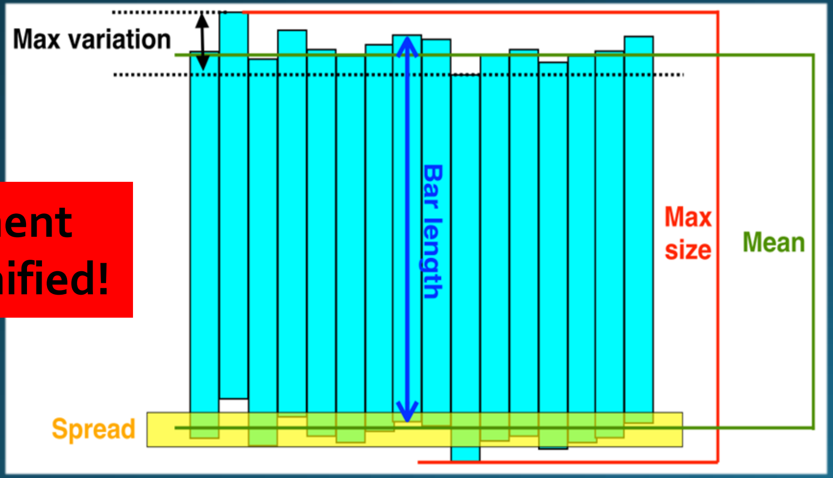


Crystal/Array dimensions

- **Dimensions measured using a Coordinate Measuring Machine (CMM)**
- **Tolerances:**
  - Width, thickness: $\pm 100\ \mu m$
  - Length: $\pm 50\ \mu m$
  - Planarity (Max variation): $\pm 60\ \mu m$



!Misalignment higly magnified!

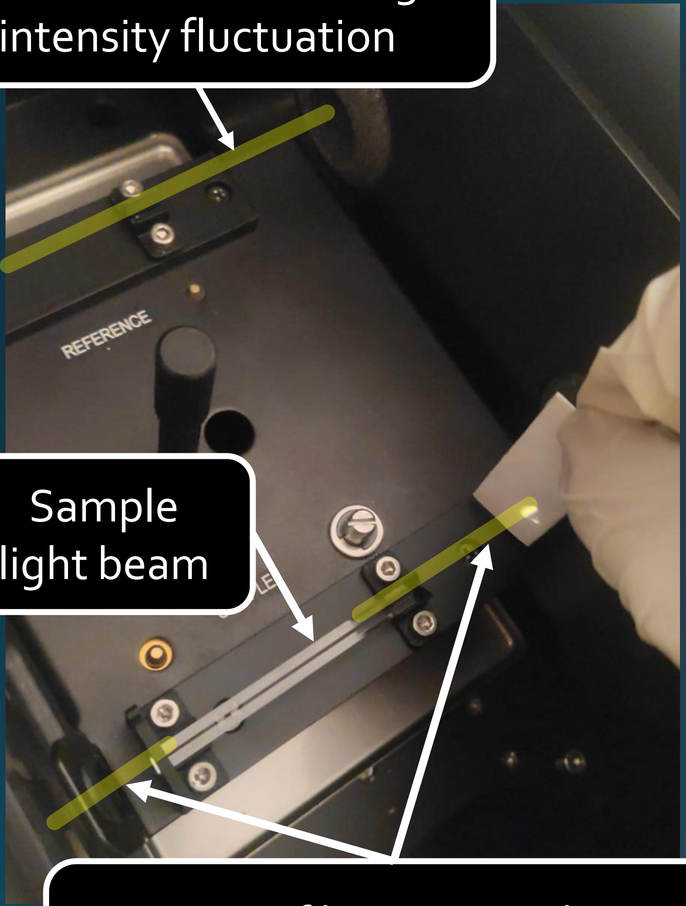


Required Max Variation smaller than glue layer between LYSO and SiPM ($\simeq 100\ \mu m$)

Crystal Light Transmission/Absorption

- Light transmission (T) spectrum measured using a UV-VIS spectrophotometer in
- Cerium concentration inferred from absorption (A) spectrum

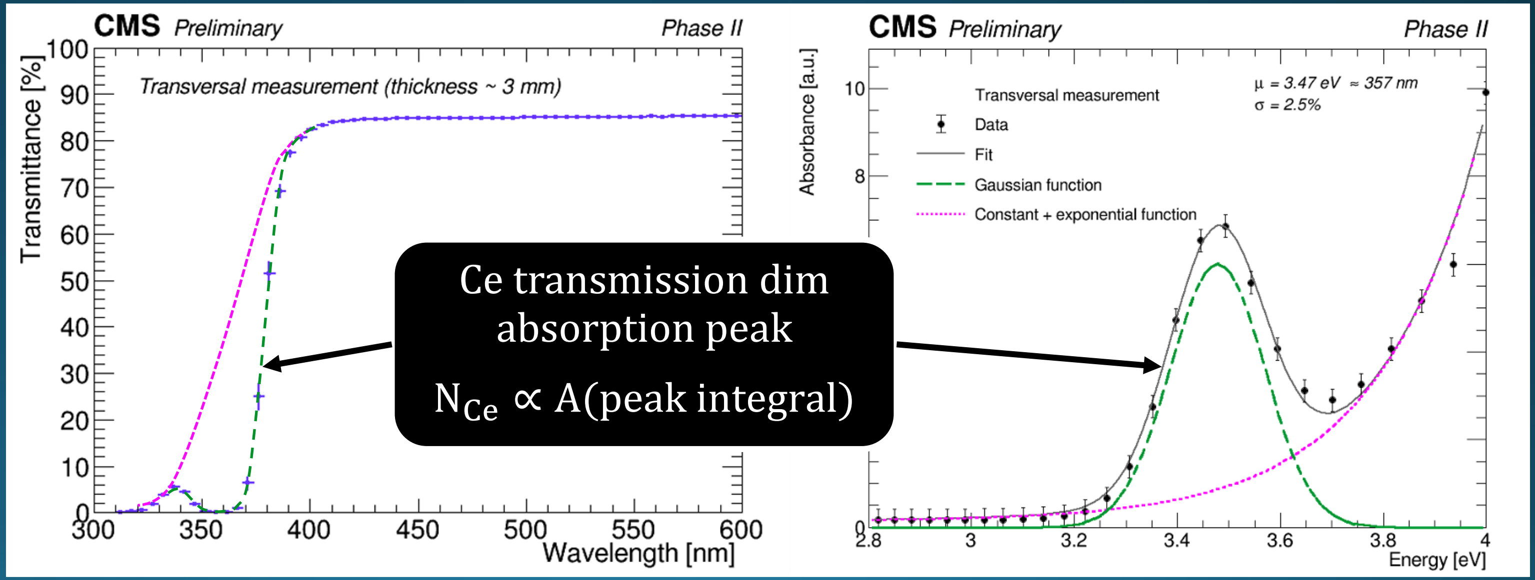
Ref. beam: correct for light intensity fluctuation



Sample light beam

Intensity of beam in and out of crystal ($\mathbf{I_{in}}$-$\mathbf{I_{out}}$)

$$\mathbf{T = \frac{I_{out}}{I_{in}} \qquad A = -\ln(T) \qquad E = \frac{hc}{\lambda}}$$



Ce transmission dim absorption peak

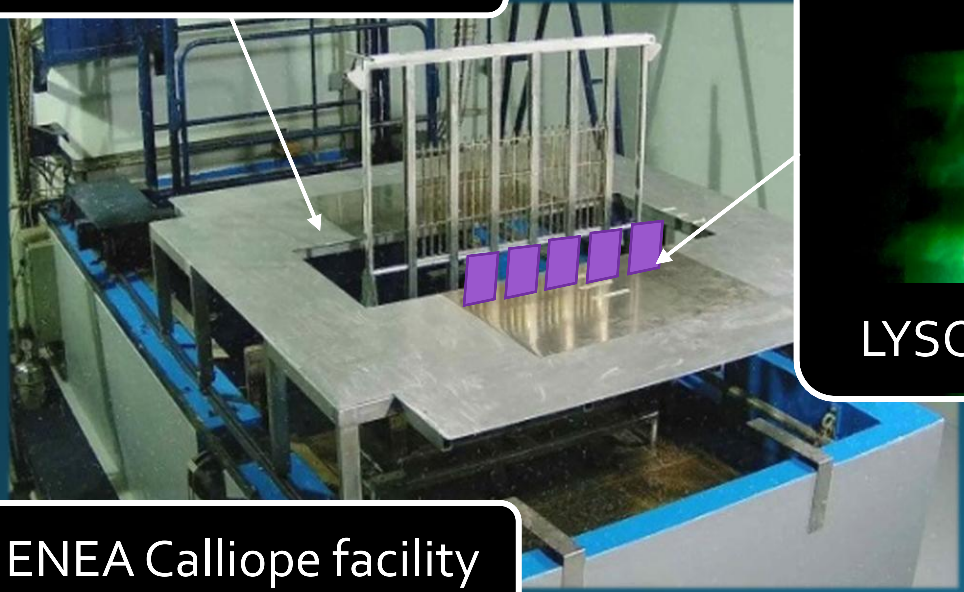
$N_{Ce} \propto A(\text{peak integral})$

Radiation hardness

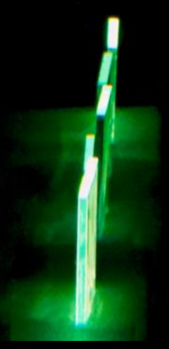
- Crystals and arrays irradiated ($< 0.1\%$ of BTL)
- γ from Co^{60}: 50 kGy, ~ 1.5 of HL-LHC
- LO and transmission re-measured after irradiation

LO reduction $\leq 10\%$

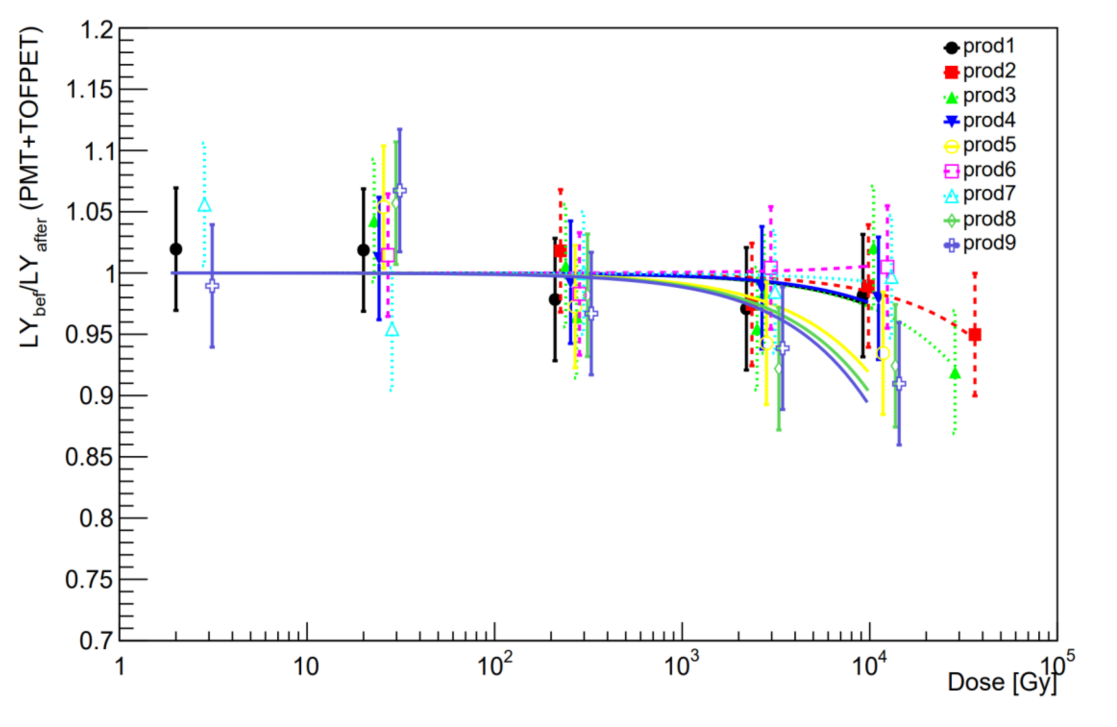
Co^{60} source exit slit



ENEA Calliope facility



LYSO arrays*

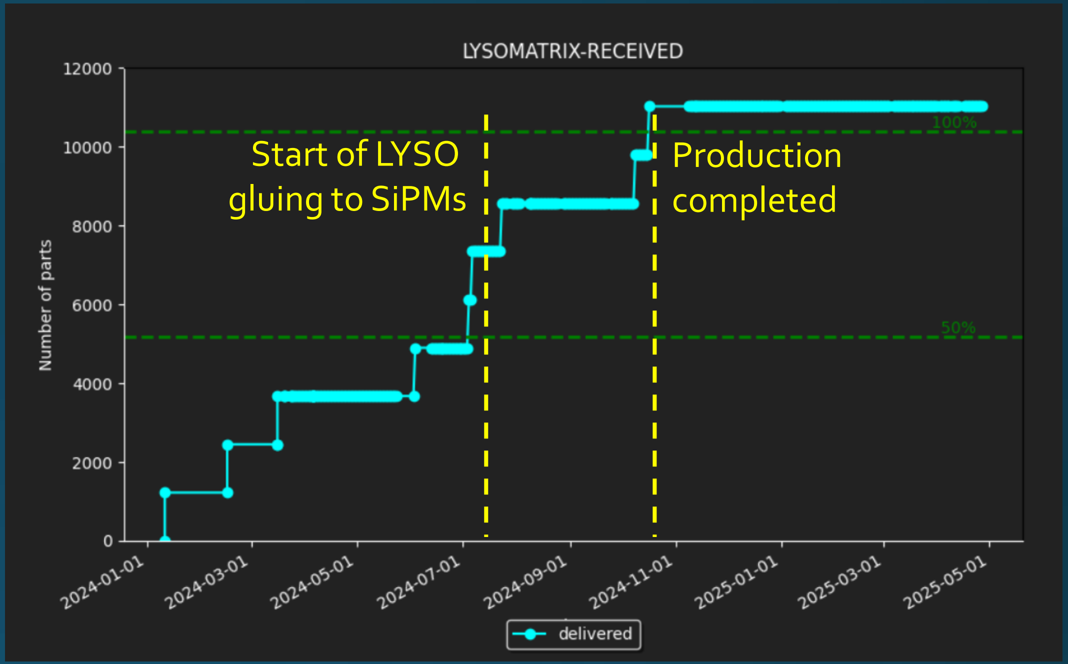


* ~violet scintillation light appearing green because of protective glass

Production Quality Assurance and Quality Control (QAQC) Schedule

- Produced 11.016 LYSO arrays (~6% more than arrays required for BTL)

- Production divided into 9 batches (one every 5 weeks) + 2 smaller pre-production batches

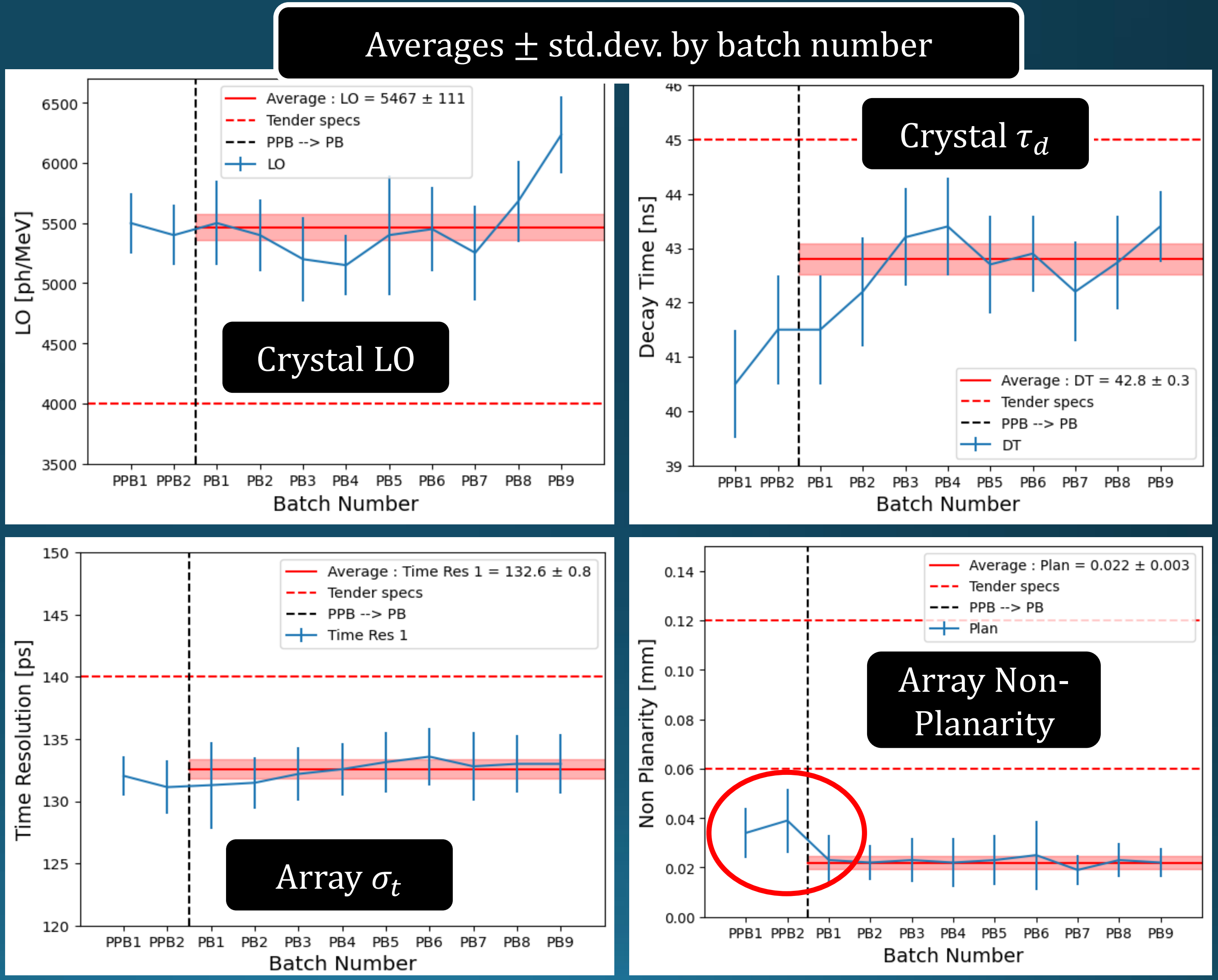


- Samples tested in Rome:
  - 5% of arrays, randomly selected from each batch
  - 6 LYSO single crystals from every ingot used in production (2 for each region bottom, middle, top)
  - Irradiated half of single crystals and 3-4 arrays per batch (0.2% of production) for radiadiation hardness test

QAQC results: general overview

- Key properties of LYSO crystals good stable over time
- All batches have been approved, with very large yield (> 99.7 %)
- Prompt feedback from interactions with vendor:
  - Small issues on non-planarity in pre-production fixed before production start
- Full list of QAQC results in backup

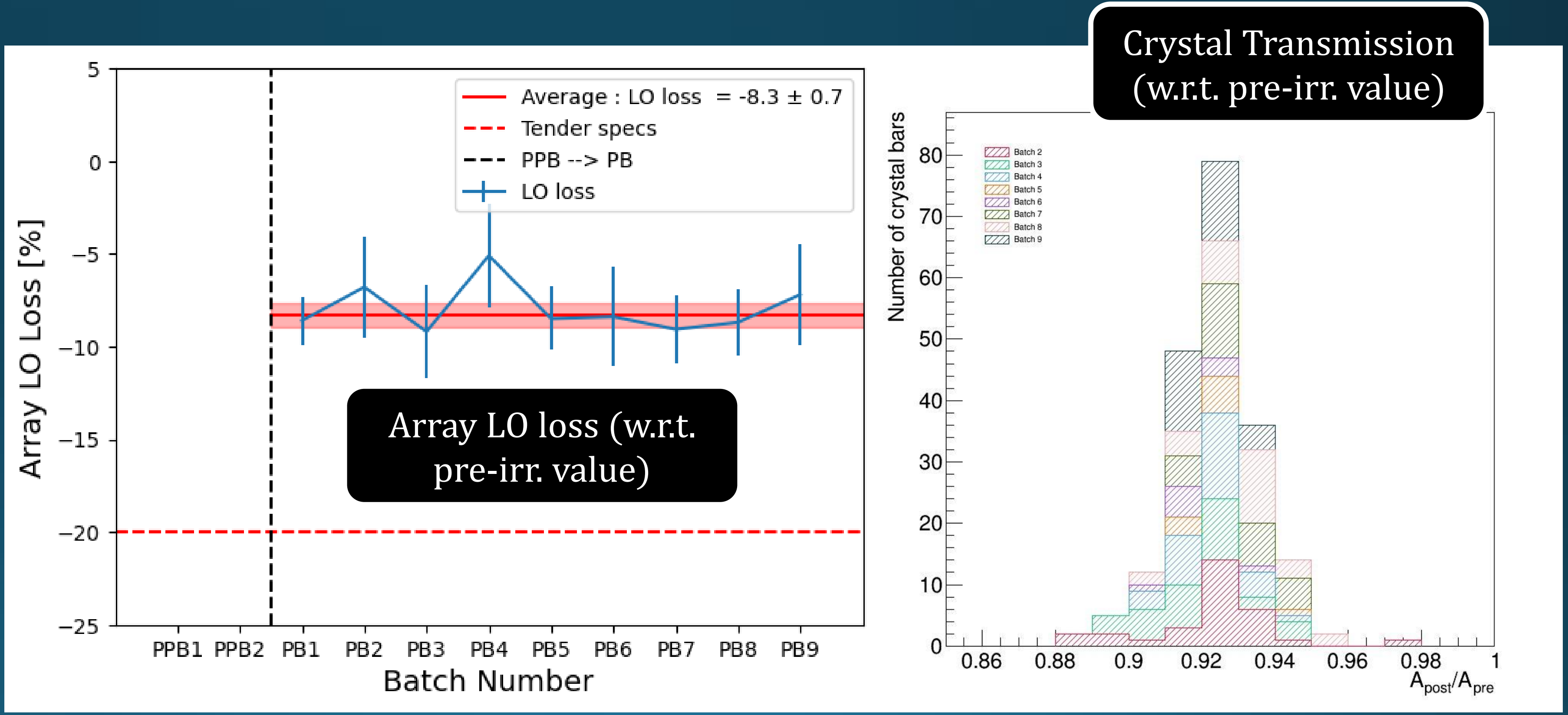
Averages ± std.dev. by batch number



QAQC results: post-irradiation

- After irradiation, LYSO arrays shows an average LO loss of ~8%, within specification and similar to previous batches
- Transmission loss on single crystals coherent on average with LO loss in arrays

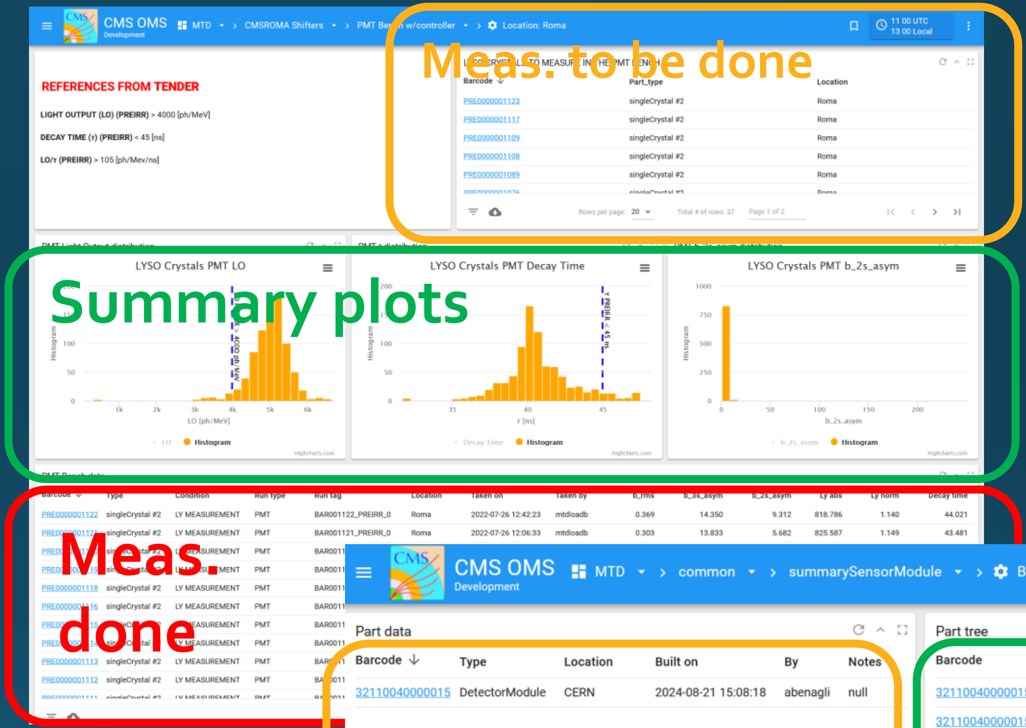
- 0.1 % of arrays kept aside because of suspect radiation softness
- 0.2% of arrays irradiated (will not be used in BTL)
- Total of 0.3% of arrays discarded from production



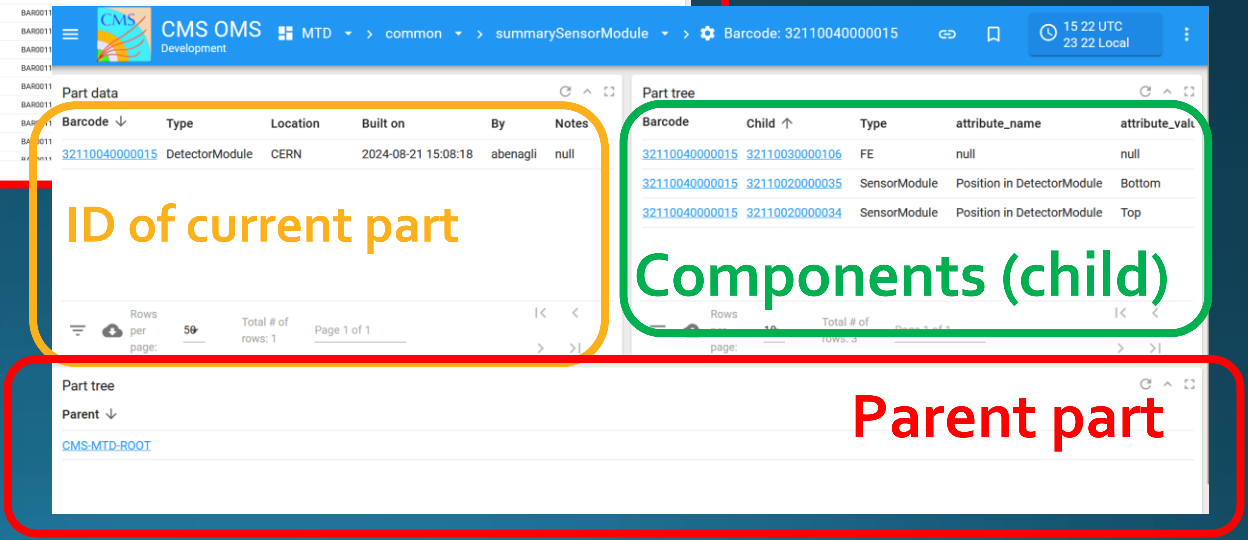
BTL construction DataBase

- Developed by Rome Group
- Keep track of LYSO parts (arrays/bars) location
- Store measurements of QAQC
- View summary plots
- Filter & Download data for further analysis
- Store assebled BTL parts (with parent/child relation to components)

LYSO Bar optical measurements view



BTL assembled part view



BTL sensors @ Test Beams

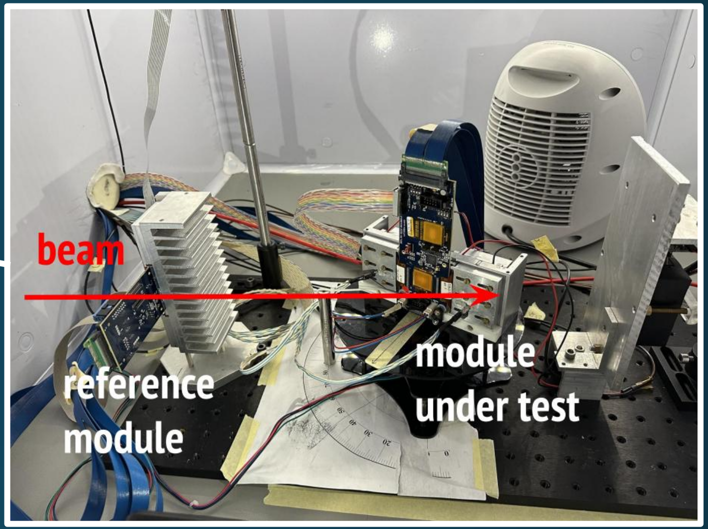
Latest test Beams

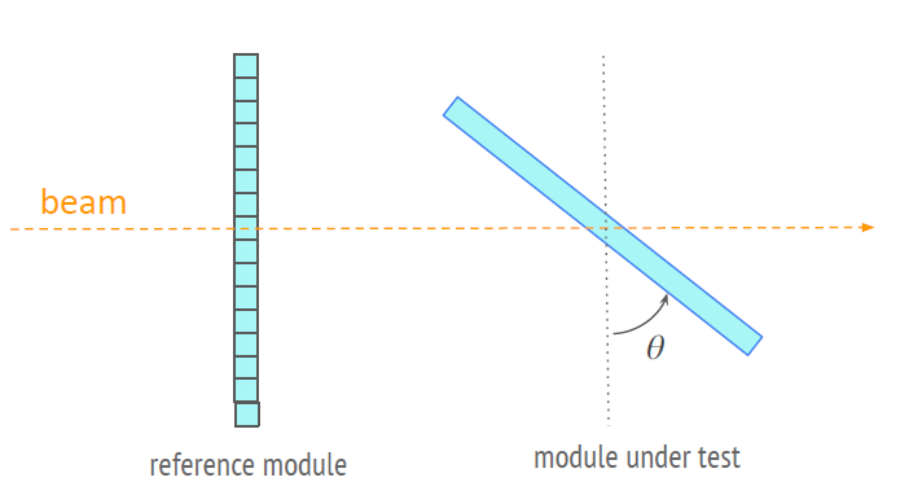
- March 2023 @FNAL
- June 2023 @CERN North Area
- September 2023 @CERN North Area

Configurations tested

- Sensor modules with 10-15-25 μm SiPM cell size
- Different LYSO thickness (**Type 1, 2, 3**)
- Tested different bias voltages for SiPMs
- Both non-irradiated and irradiated sensors
- Temperature range from −45°C to 5°C emulating different ageing conditions

CERN North Area (pion beam)



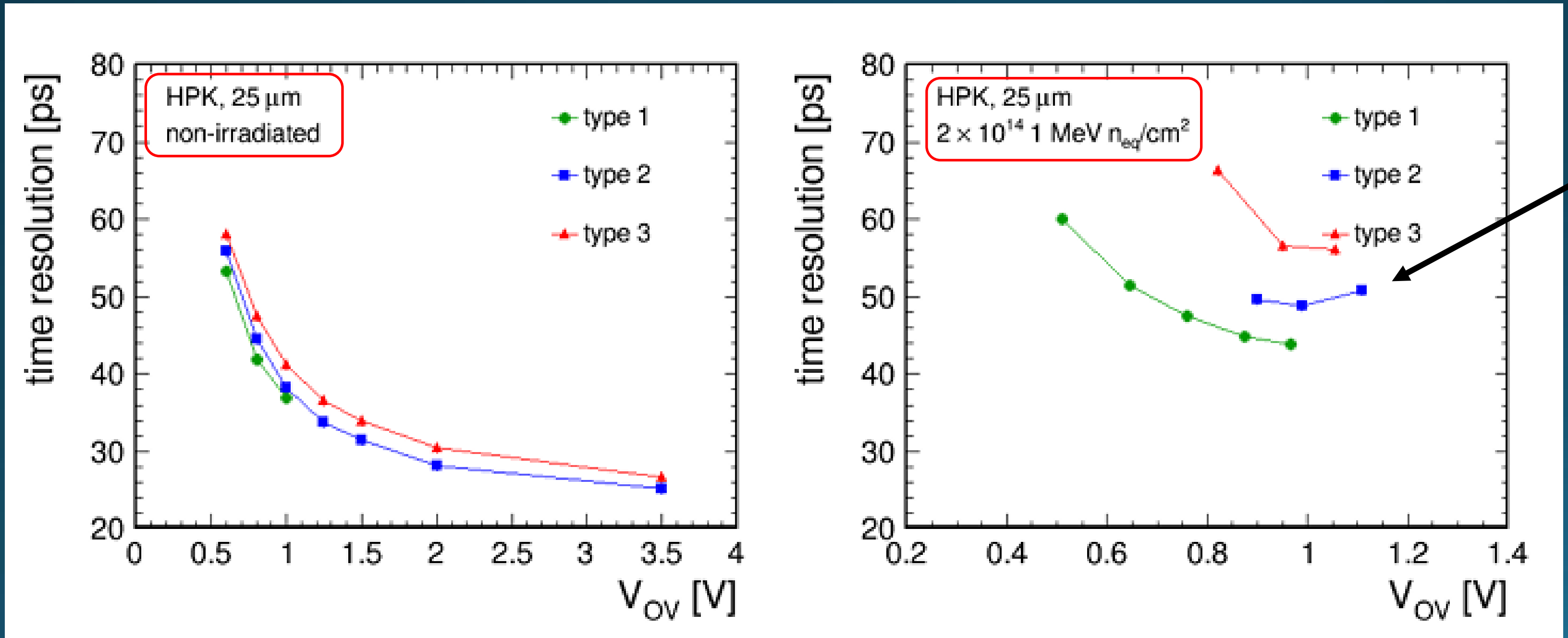


Vertically oriented bars

Horizontally oriented bars

Timing performances

- Time resolution averaged across crystals within a module
- **Different SiPMs over-voltage** $\mathbf{V_{OV} = V_{bias} - V_{breakdown}}$
  - PDE increases with $\mathbf{V_{OV}}$ → better time res.
  - At high $\mathbf{V_{OV}}$ increased DCR and power consumption (for irradiated SiPMs)
- Achieved MTD target resolution at begin and end of operation. Best performance for 25 μm cell size @3.5 V_{OV} with Type 1 LYSO



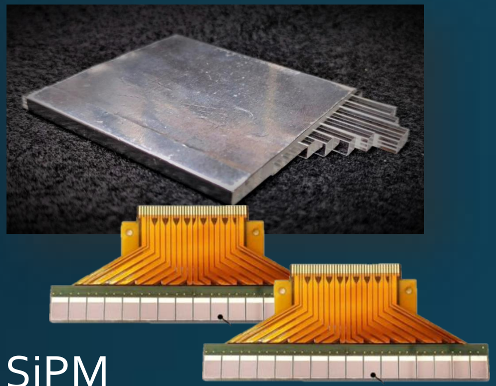
For $V_{OV} >\sim 1V$ DCR noise worsen time resolution for Irradiated modules

More results in paper 2024 *JINST* **19** P12020

Second paper with more comprehensive studies coming soon!

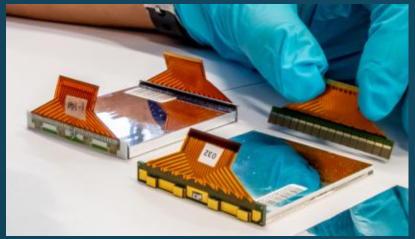
BTL Assembly

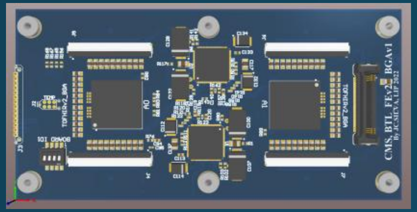
1 + 2 SiPM arrays



SiPM arrays

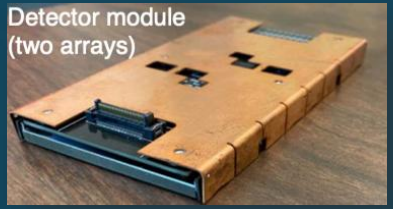
Sensor Module SM





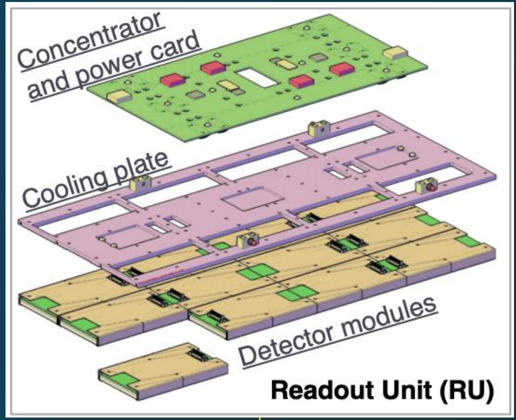
Front-End Board

Detector Module (DM)

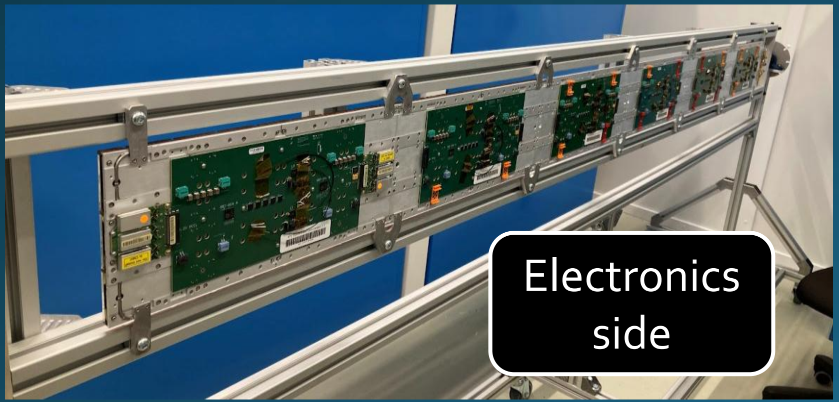


Cooling Plate (CP)

Readout unit
(12 DMs + CP + electronic)



1 tray (6 RU)

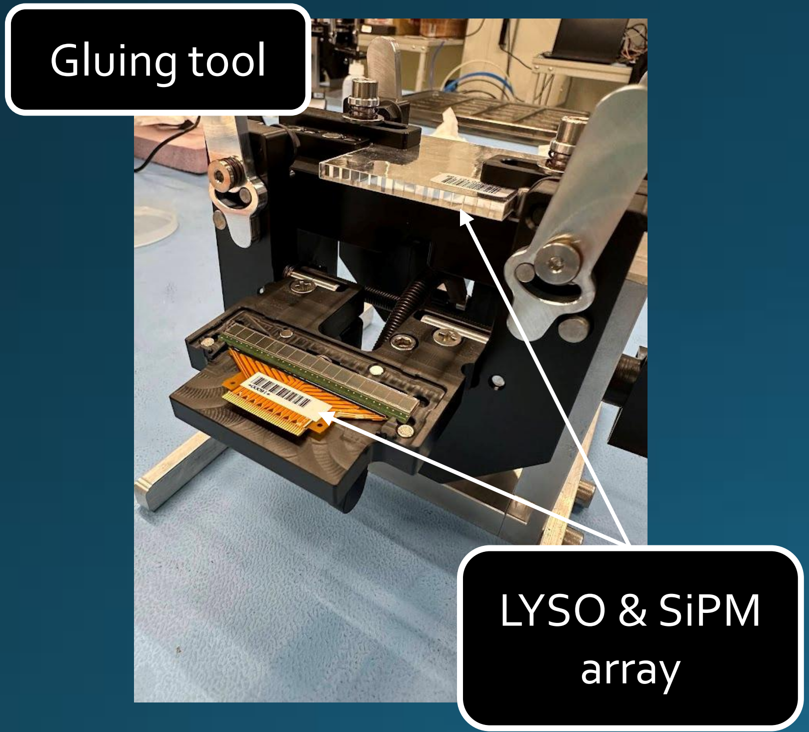


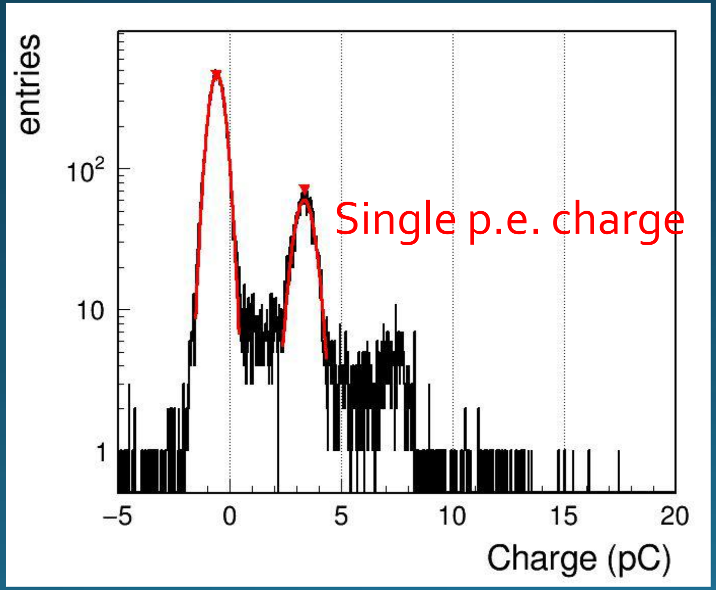
	Module	RU	Tray	Total
Channels (SiPMs)	32	768	4608	331776
Crystals	16	384	2304	165888
ASICs	1	24	144	10368
Modules	-	24	144	10368
Readout units (RU)	-	-	6	432
Trays	-	-	-	72

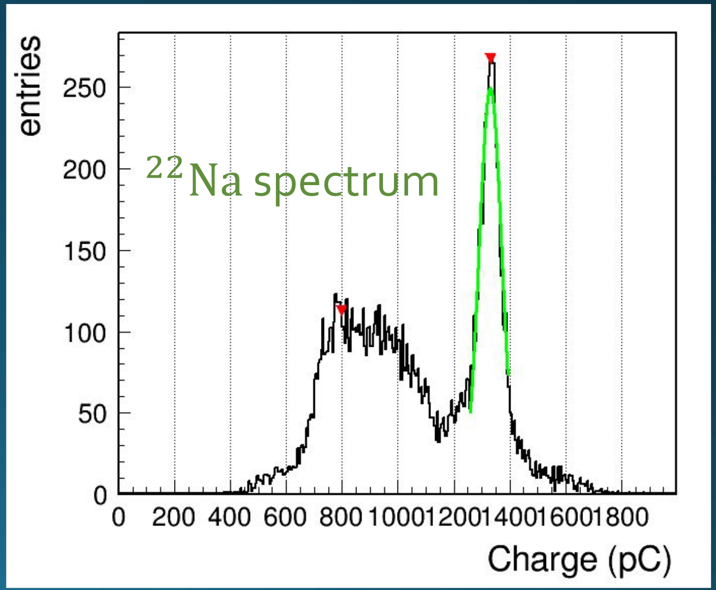
4 BTL Assembly Centers (BACs) worldwide: PKU, MIB, UVA, CIT

SM Assembly and QAQC

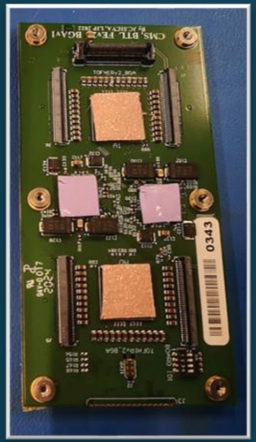
- 2 SiPM arrays are glued to bare sides of LYSO Array
- For QAQC: LO measurement using photons from ^{22}Na source
- Producing ~24 SM x day x Assembly Center (+24h for glue curing +12h QAQC)
- Production yield > 95%, should be covered by spare quota of LYSO and SiPMs, but considering buying 5% extra sensors







DM Assembly & QAQC



- 2 SM + FE board + Copper housing → 1 DM
- The DM resistance (good electrical connection, no shortcat) and temperature (good thermal coupling) are measured on a test stand
- High assembly yield, in case of problems the DM can be re-worked or re-assembled

PKU stand for DM thermal test: up to 12 DM at the same time

Tray Assembly workflow

Cooling tray assembly

- BTL aluminium plates + cooling pipes
- Assembled at Tracker-Integration facility (TIF) at CERN

Ship to BACs

Full tray assembly

- Cooling tray populated with sensors + electronics
- QA/QC of assembled parts and trays
- 4 BTL Assembly Centers (BACs)
  - Milano Bicocca 🇮🇹
  - Caltech
  - Univ. of Virginia
  - Peking university

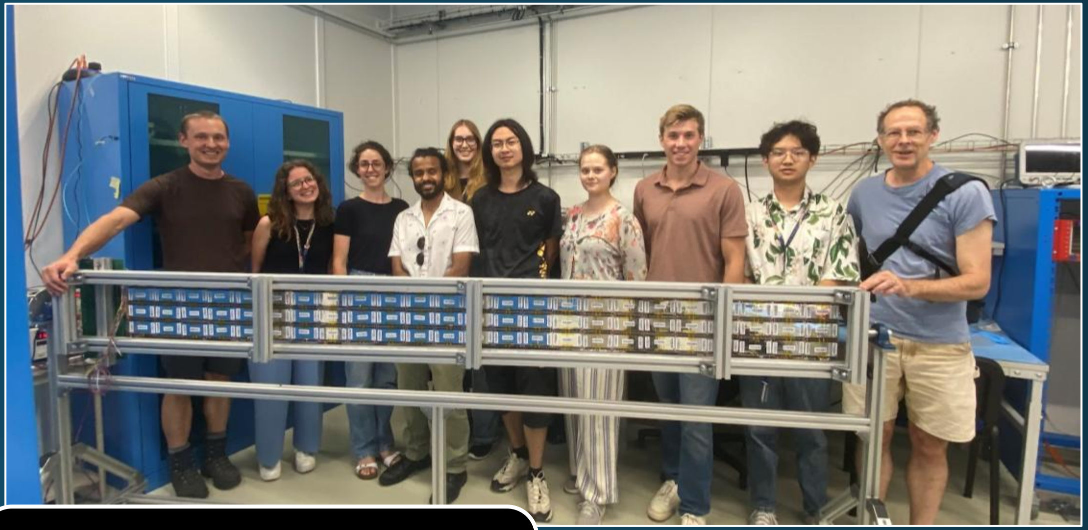
Ship to CERN

BTL integration

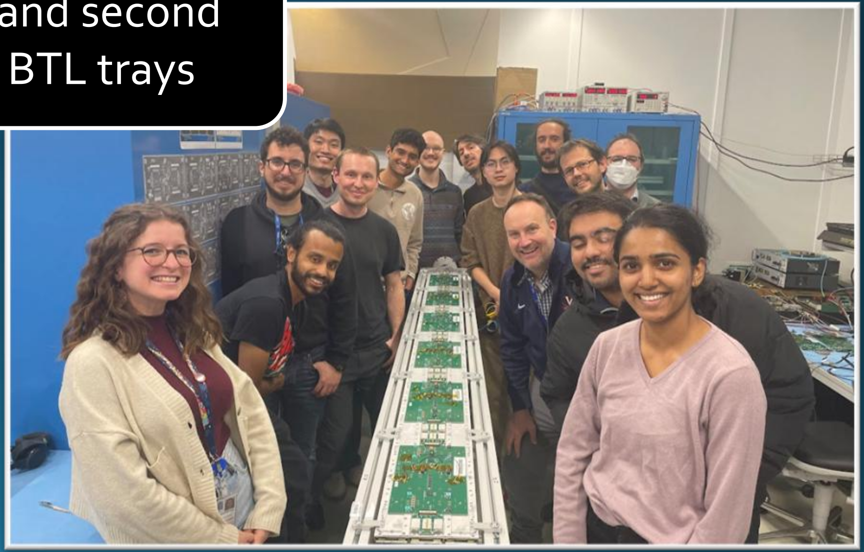
- Tray insertion in BTL-tracker Support Tube (BTST) @TIF + final testing

Tray Assembly Workshop(s)

- July '24: First ever tray assembled @CERN
  - Used as assembly exercise and development/ test of DAQ software
  - Unlikely to be installed in BTL
- March '25: Second tray assembly workshop
  - Refined assembly procedure – smooth assembly
  - Defined and exercised tray QAQC procedure
    1. Check communication with board and asics
    2. Check channels response with test pulses
    3. Measurement of LYSO intrinsic radioactivity
  - First tray moved for test with cooling @ -35°C

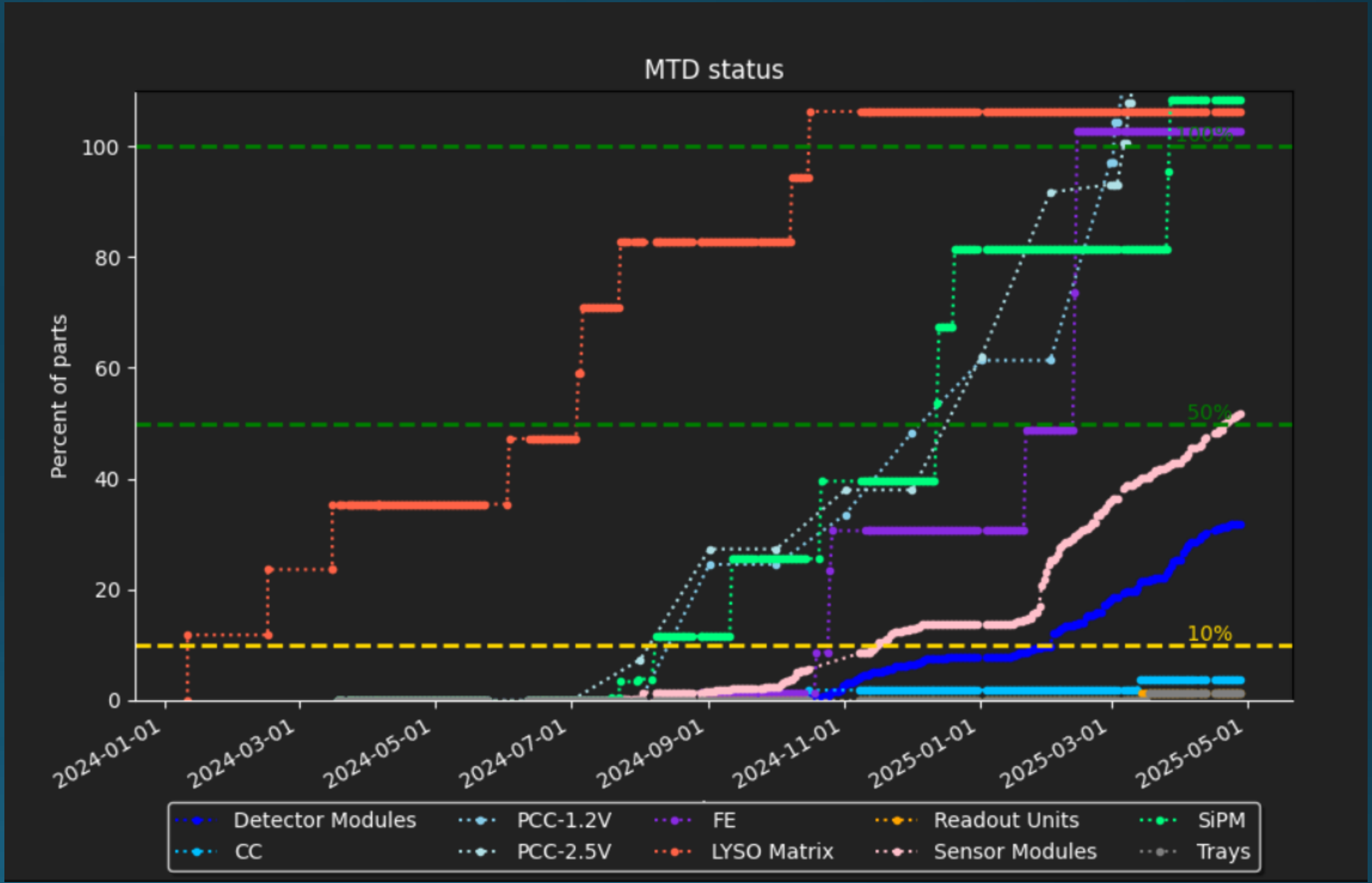


First (top) and second (bottom) BTL trays



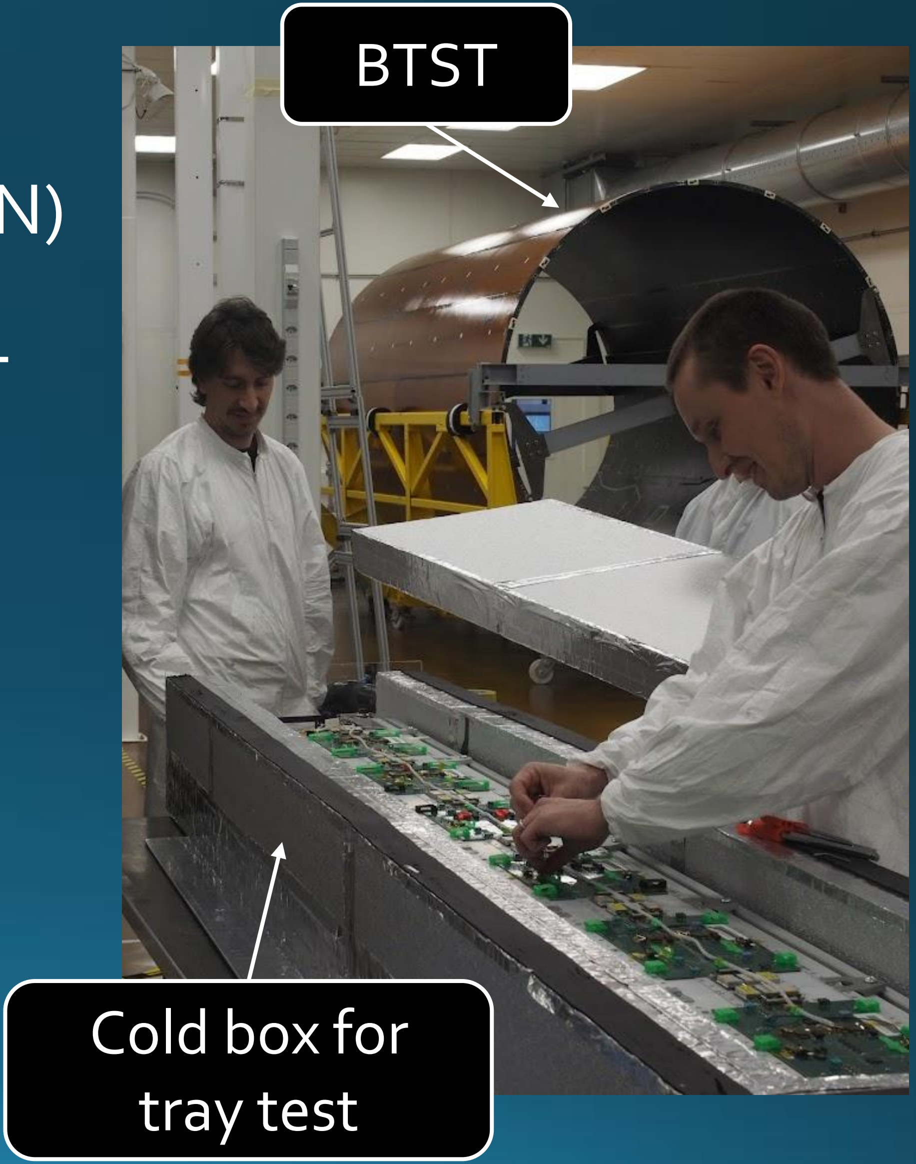
BTL assembly status

- Received all parts for SM and DM assembly
  - At full regime at BACs
  - >50% of SM
  - ~30% of DM
- Tray assembly at BACs starting ~now
  - Received all components and final instructions for 1 tray x BAC



Future Plans

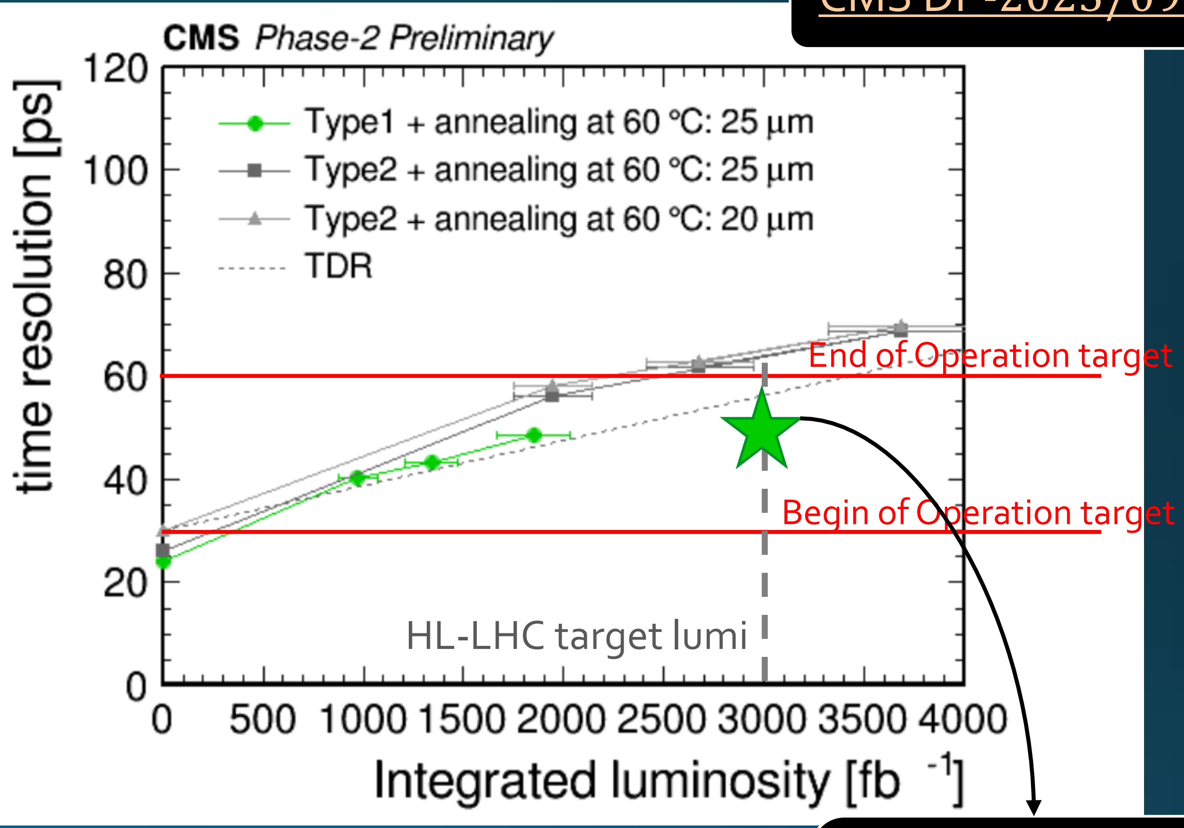
- Define procedures of tray test/calibration with cosmics/radioactive sources (at BACs or at CERN)
- Preparation for insertion and integration in BTL Tracker Support Tube (BTST)
- Preparation for next Test Beam @ CERN (Sept. 2025)
  - Test of 2 Readout Unit (up to 48 SM)
  - Final readout electronics chain
  - Online test of DAQ software (possibly integrated in CMS central analysis software)



Summary

- Precision timing will have high relevance for CMS @HL-LHC
- MTD will impact most of physics analysis
  - Better reconstruction performances
  - Charged hadron identification
  - Exotic time signatures
  - Luminosity measurement
- LYSO crystals proven to be good choice for BTL
  - Production met stringent requirements with little outlier fraction
- BTL fully moved to production phase
- New test beam campaigns planned for this year to test two BTL Readout Unit (48 modules) using the full readout chain of final design electronic

CMS DP-2023/093



Roughly extrapolated from slide 22