Precision timing with the CMS MIP Timing Detector (MTD) for High-Luminosity LHC

Tommaso Tabarelli de Fatis
University of Milano Bicocca and INFN Milano-Bicocca

- **Outline**
  - HL-LHC: Introduction and motivations
  - Experimental challenges and technology choices
  - Results from prototyping
  - Projected performance
  - Summary

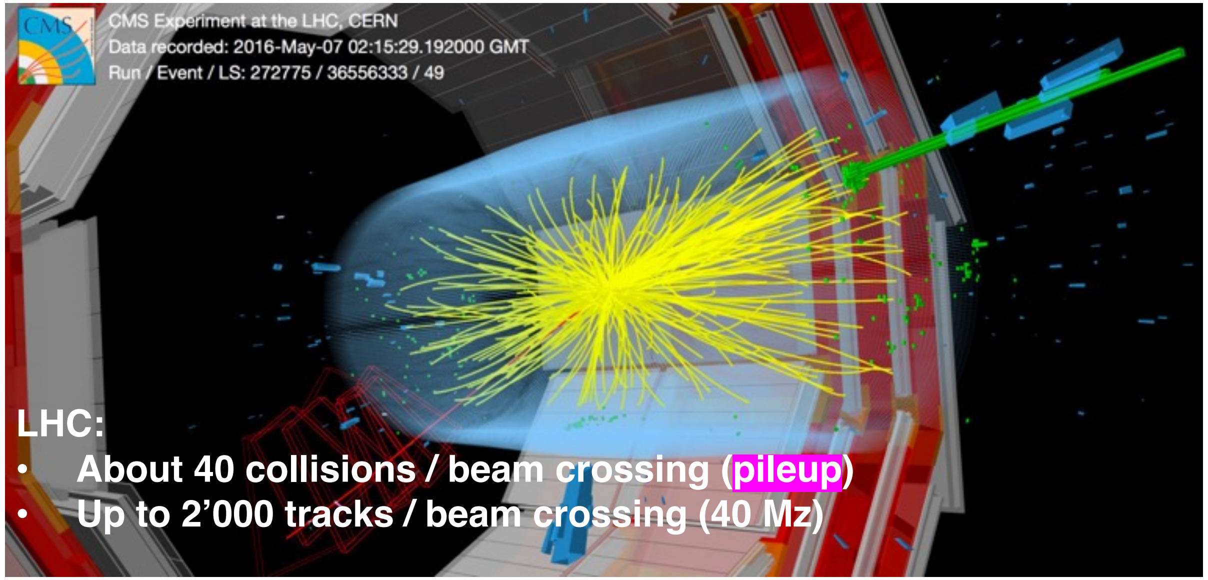
- **On behalf of the CMS MTD**
  - China, France, Finland, Hungary, Italy, **Korea**, Latvia, Portugal, Spain, Switzerland, USA

High-Luminosity LHC

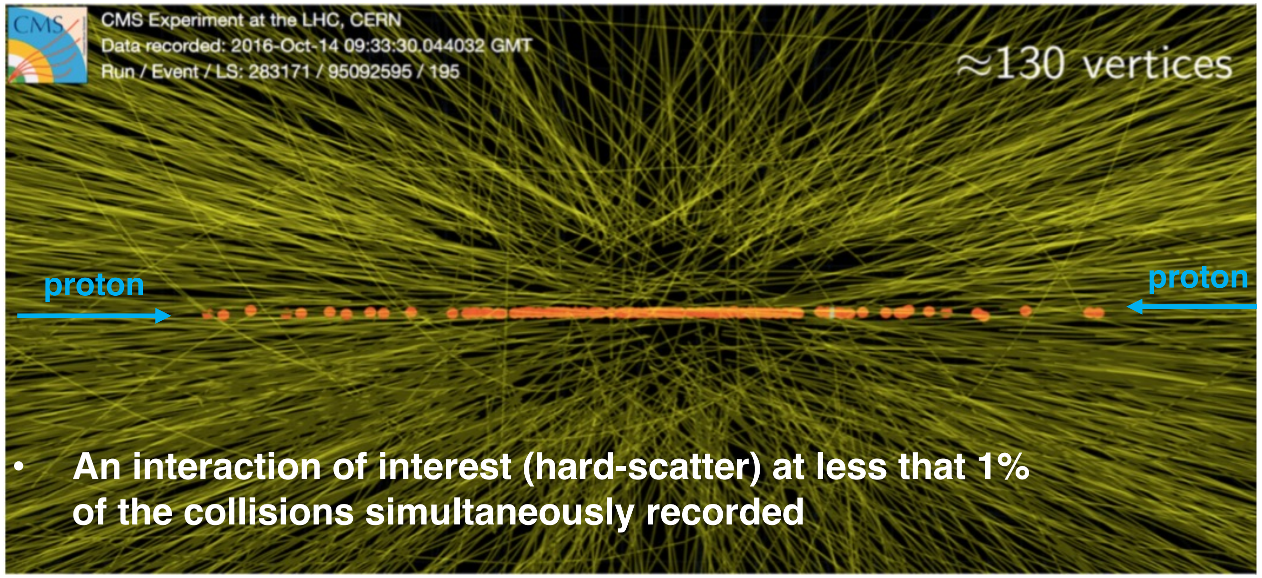
- **Goal: precision tests of the standard model, Higgs boson characterization, searches for (rare) BSM phenomena, …**
  - **Precision measurement of Higgs boson couplings** (few percent)
  - Measurement of the **Higgs boson self-coupling** via direct observation of the di-Higgs boson production
  - Search for heavy **dark matter candidates, SUSY particles, new gauge bosons, Long-Lived Particles**, …

- **Means: upgrade of the LHC optics and injectors to increase the beam intensity**
  - Luminosity delivered by **LHC** (2009-2025): **~ 400 fb^{-1} / experiment** *[~250 fb^{-1} collected so far]*
  - Target luminosity for **HL-LHC** (2029-2042): **>3000 fb^{-1} / experiment** ***[one year of HL-LHC equivalent to ~10 years of LHC]***

Collision event with 35 reconstructed vertices

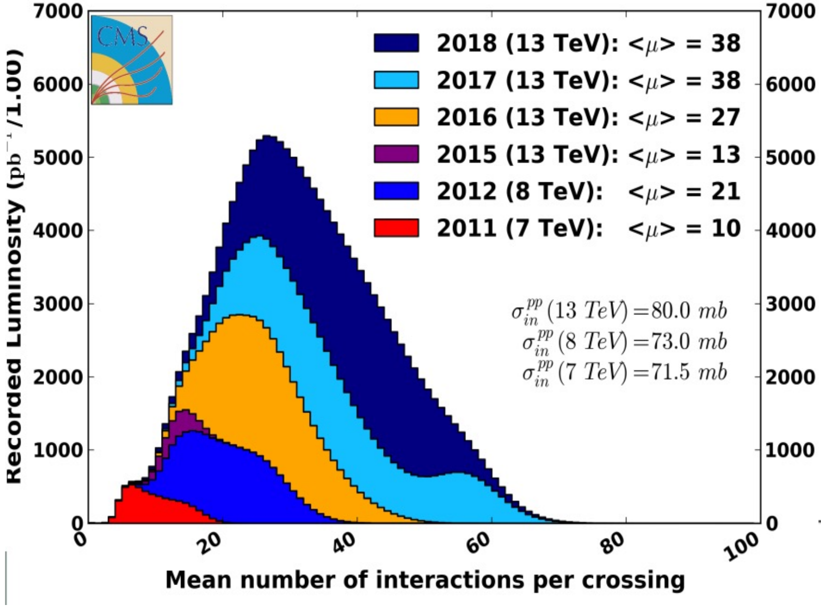


Real life event at the LHC emulating HL-LHC conditions

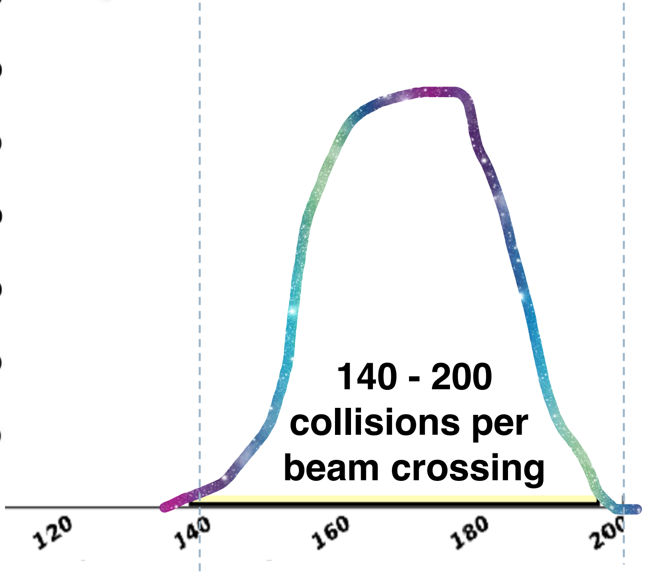


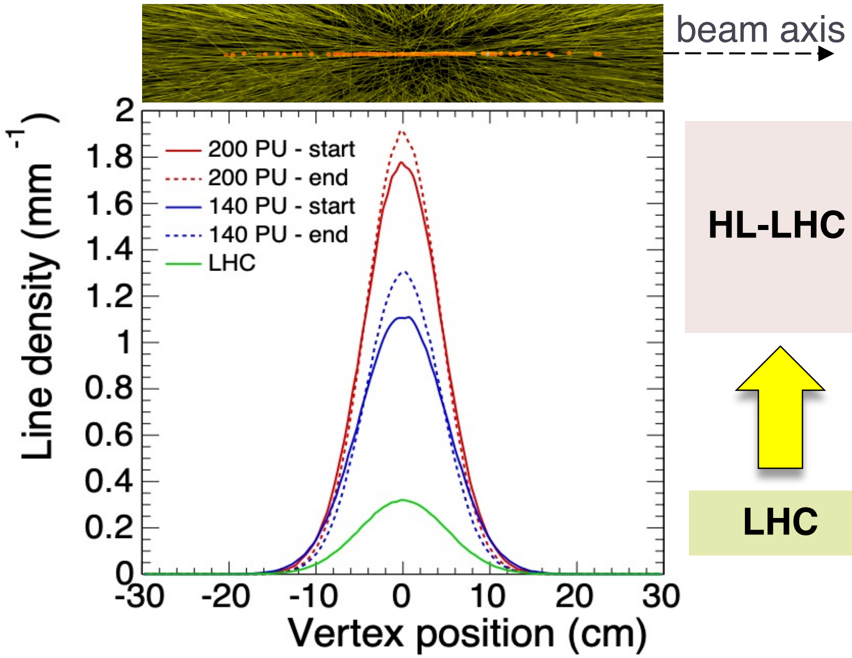
HL-LHC: experimental challenges

CMS average pileup at LHC



HL-LHC





HL-LHC

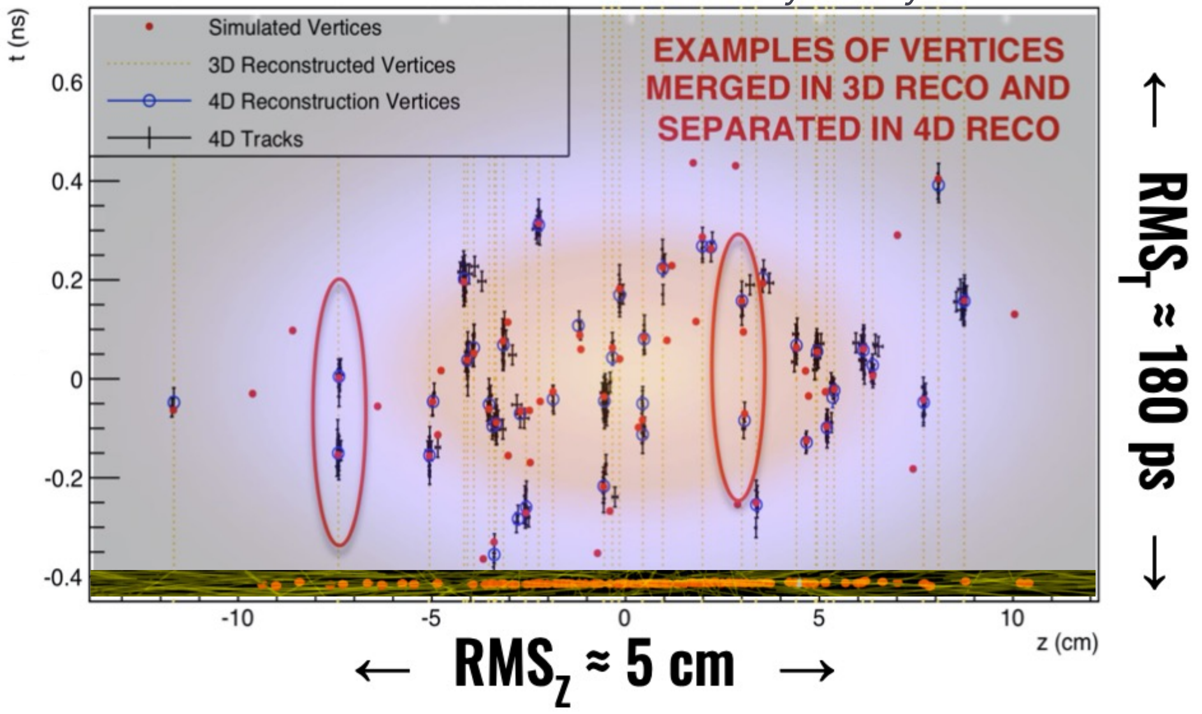
LHC

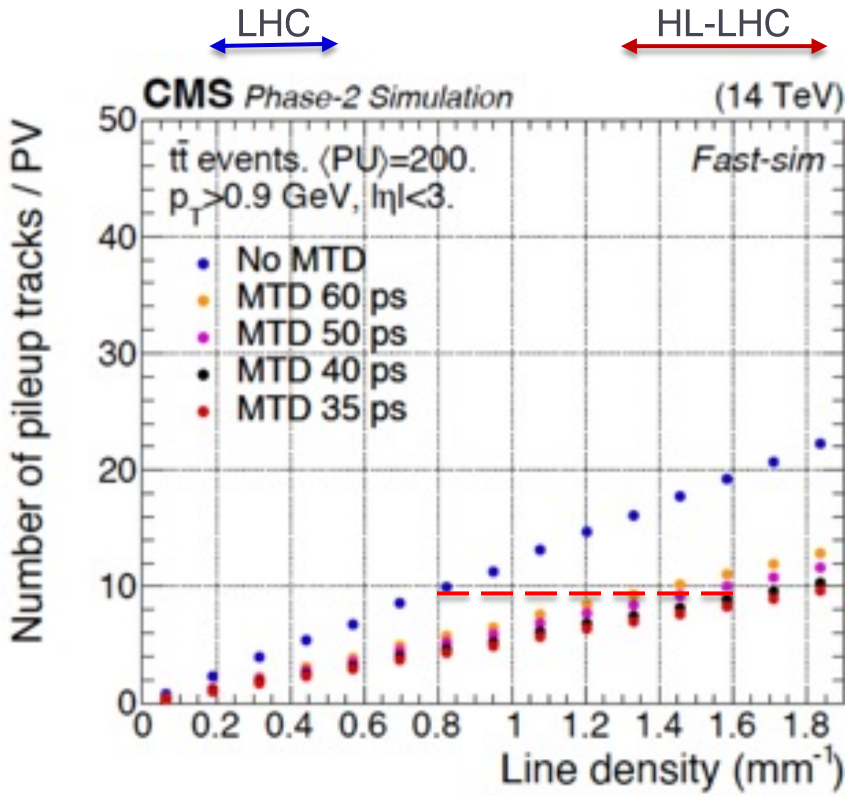
- **Detector upgrades required to deal with enhanced pileup interactions and radiation damage levels**
  - >5x collision events per beam crossing, **same spatial spread of the vertices along the beam lines**
  - Up to **200 pileup events**, about **10'000 tracks per event**, and vertex densities >1.5 mm^{-1}
- **Reconstruction quality depends on *track-vertex assignments,* which become ambiguous when track resolution is comparable to vertex separation**
  - Vertex merging, fake association of "pileup" tracks with vertices, final state kinematics distorted, jet, lepton, photon identification affected

Precision timing at CMS for HL-LHC

- **CMS upgrades for pileup mitigations**
  - Upgrade tracker and calorimeters with enhanced spatial segmentation
  - A new ***MIP Timing Detector* (MTD)** for precision timing of minimum ionizing particpes (MIPs)
- **“Slicing” the beam spot in successive O(30) ps time frames reduces the effective pileup**
  - Spatially overlapping vertices resolved in the time dimension → helps recover track-purity of vertices of LHC operation

Simulated event with 50 vertices to ease eye analysis

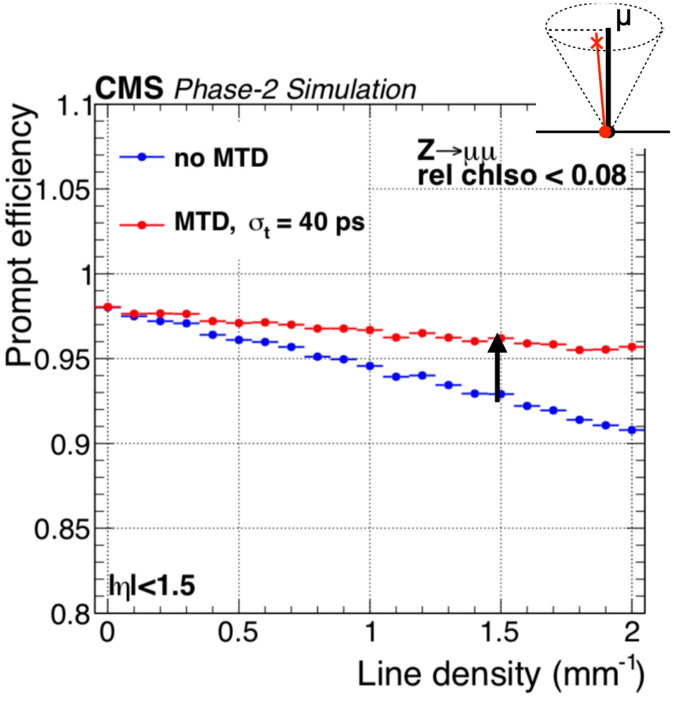


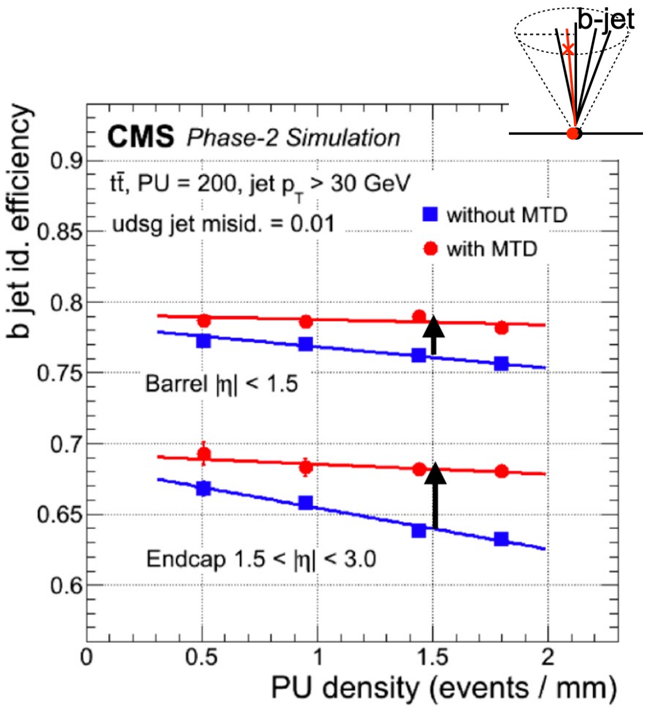


Impact of precision timing - 1

- **Significant sensitivity gains across the HL-LHC physics program**

1. **Object identification and Higgs boson physics**
   - Gains in lepton/photon identification and b-tagging (at constant background) compound in multi-object final state
   - E.g., expected HL-LHC HH significance equivalent to ~3 additional years of HL-LHC data taking



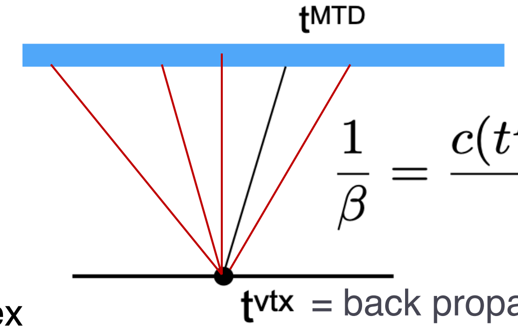


Signal	Physics measurement	MTD Impact
HH	**+25%** gain in signal yield → Consolidate searches	Isolation, b-tagging, MET
H→γγ H→4leptons	**+25%** statistical precision on xsecs → Couplings	Isolation, Vertex identification
VBF+H→ττ	**+30%** statistical precision on xsecs → Couplings	Isolation VBF tagging, MET
EWK SUSY	**40%** reducible background reduction → +150 GeV mass reach	MET

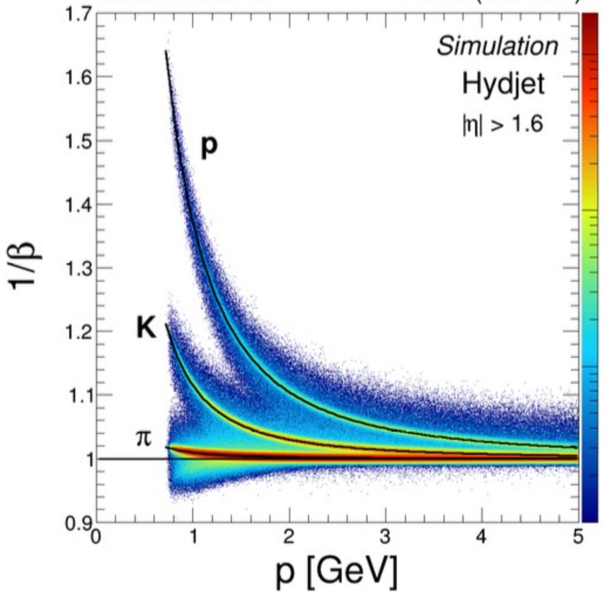
CMS MTD Technical Design Report: https://cds.cern.ch/record/2667167

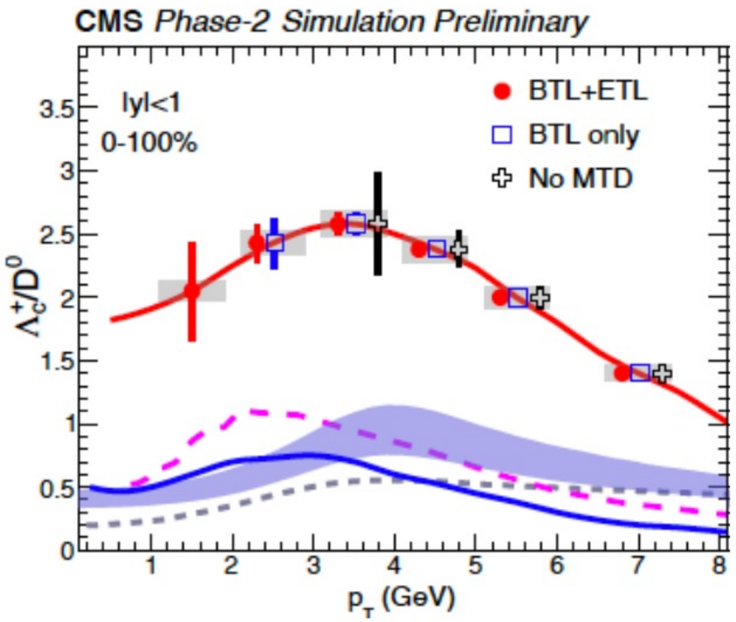
Impact of precision timing - 2

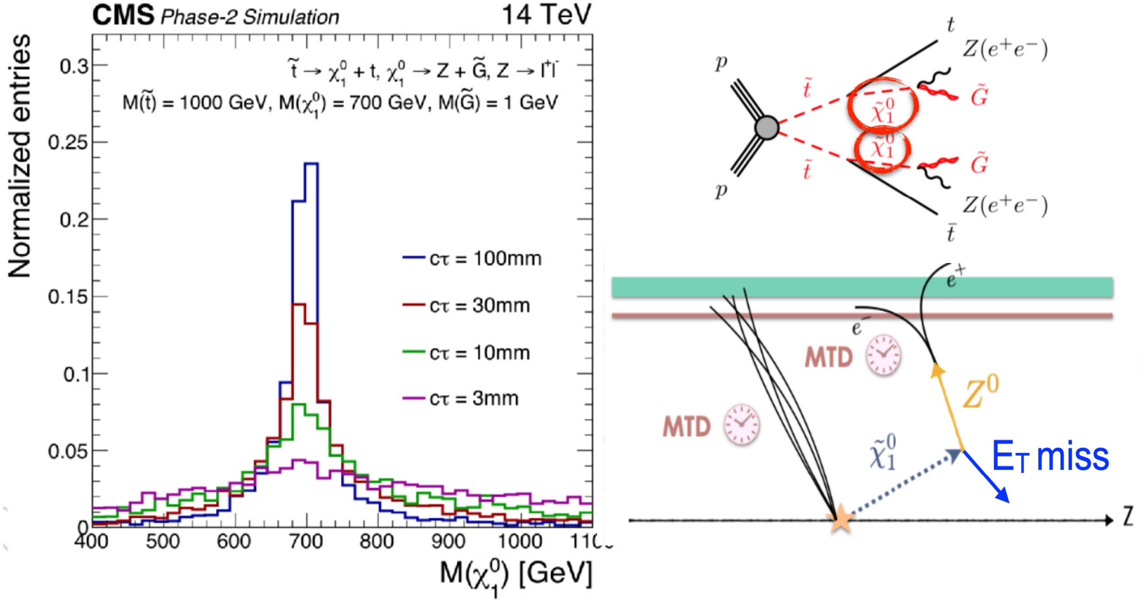
- **Significant sensitivity gains across the HL-LHC physics program**
  2. **New capability for CMS: time-of-flight particle identification**
     - Flavour physics with heavy ions (wide angular acceptance)
  3. **Search for long-lived particles**
     - Vast acceptance extension from vertex + object timing
     - LLP mass (or mass splitting) reconstruction from velocity measurement of displaced vertex



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



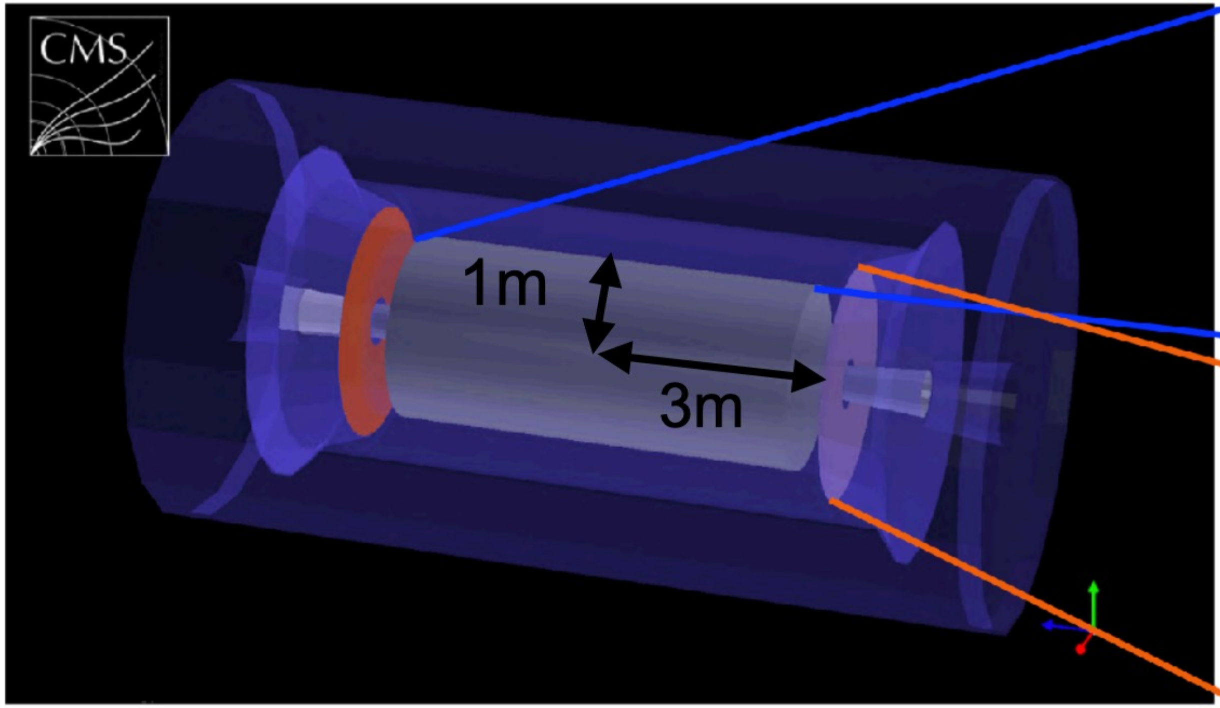




MTD fundamentally changes how we execute these searches

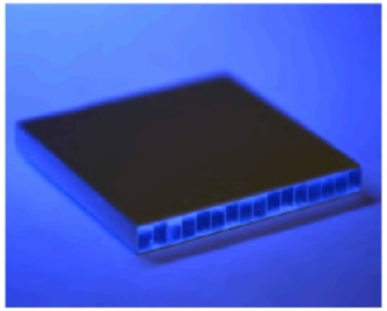
CMS MIP Timing Detector

- **Thin timing layers for minimum ionizing particles between the tracker and the calorimeters**
  - Hermetic coverage coverage for $|\eta|<3$
- **Different sensor technologies for barrel and endcap timing layers, dictated by:**
  - Technology maturity and radiation tolerance considerations
  - Compliance with CMS integration and CMS upgrade installation schedule
  - Cost and power budget effectiveness



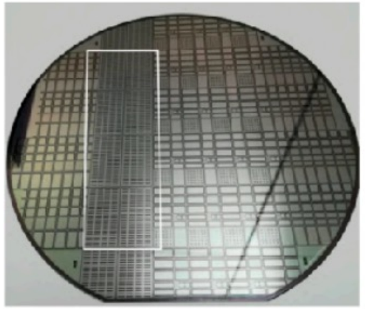
BTL: LYSO bars + SiPM read-out

- 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

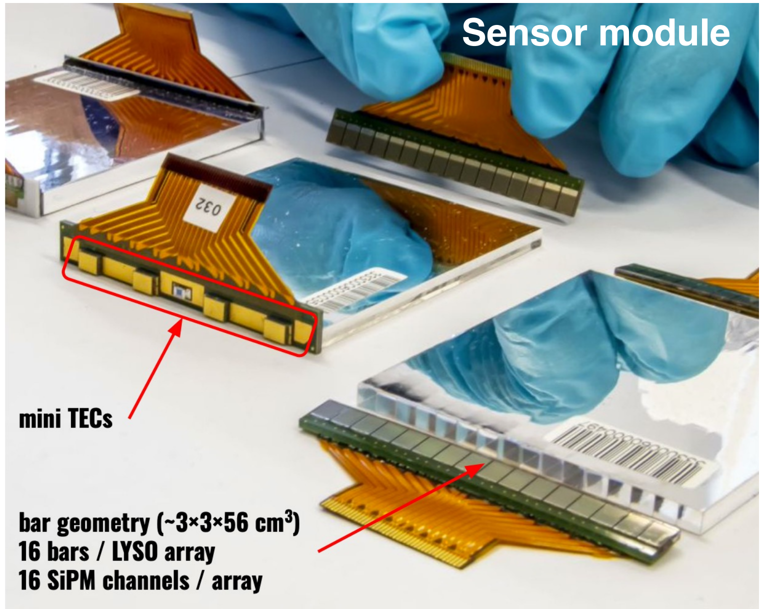


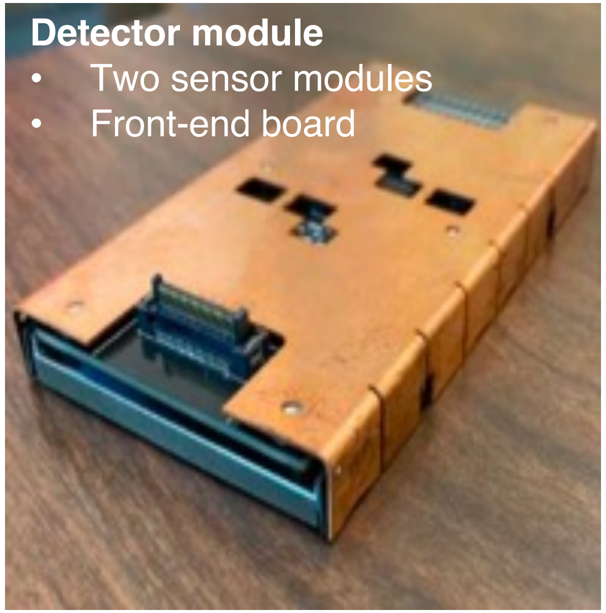
ETL: Si with internal gain (LGAD)

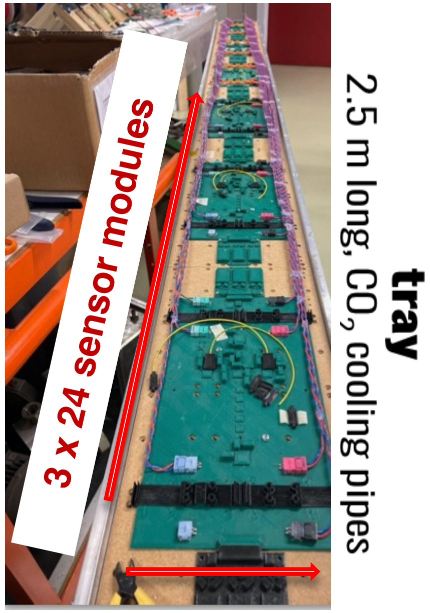
- On the HGC nose ~ 99 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~ 14 m^2; ~ 8.5M channels
- Fluence at 3 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2

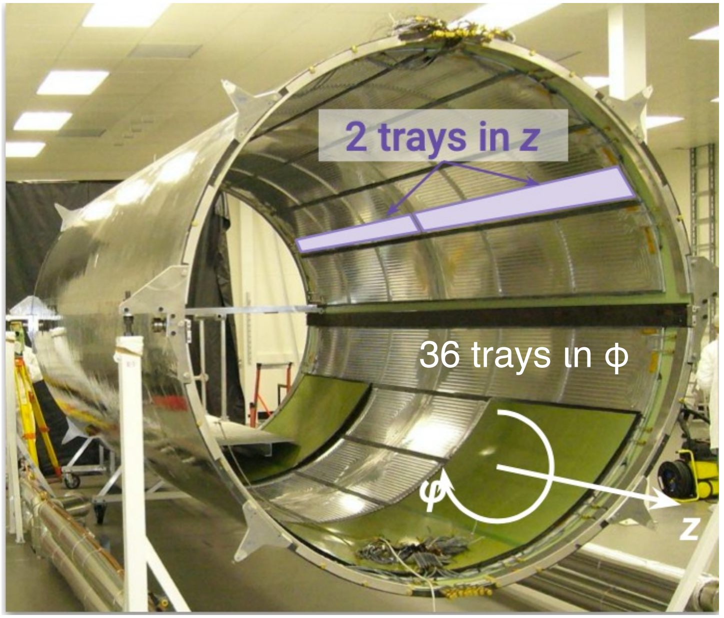


Barrel timing layer (BTL) technology and structure



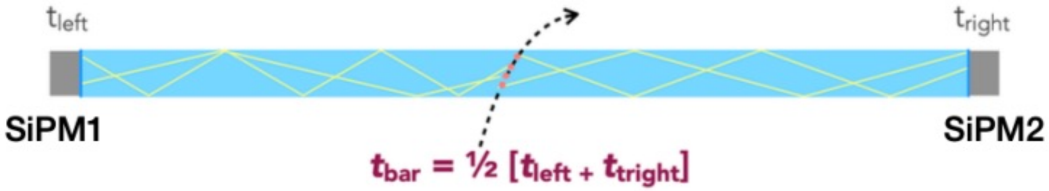






- **A single layer of sensor modules (basic detection unit):**
  - **16 LYSO:Ce crystal bars**
    - Fast and bright scintillator with excellent radiation hardness
  - **Two arrays of 16 SiPMs with thermoelectric coolers (TECs)**
    - Compact, fast, and B-field imunune photodetectors with large photon detection efficiency

- **Dual-end readout**
  - Two measurements per track → improve resolution by √2
  - Mean time independent of impact point

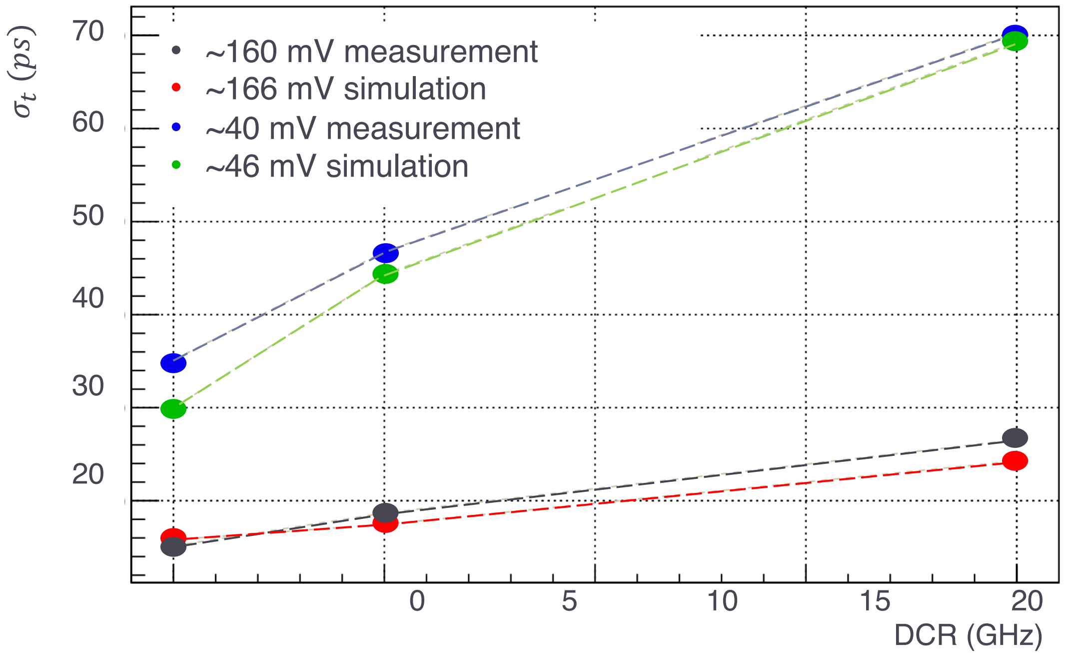


- **Biggest challenge for BTL performance and operation: SiPM radiation damage:**
  - Single-photon Dark Count Rate (DCR) **increasing up to O(10) GHz after 3000 fb^{-1}** (2x10^{14} n_{eq}/cm^2)

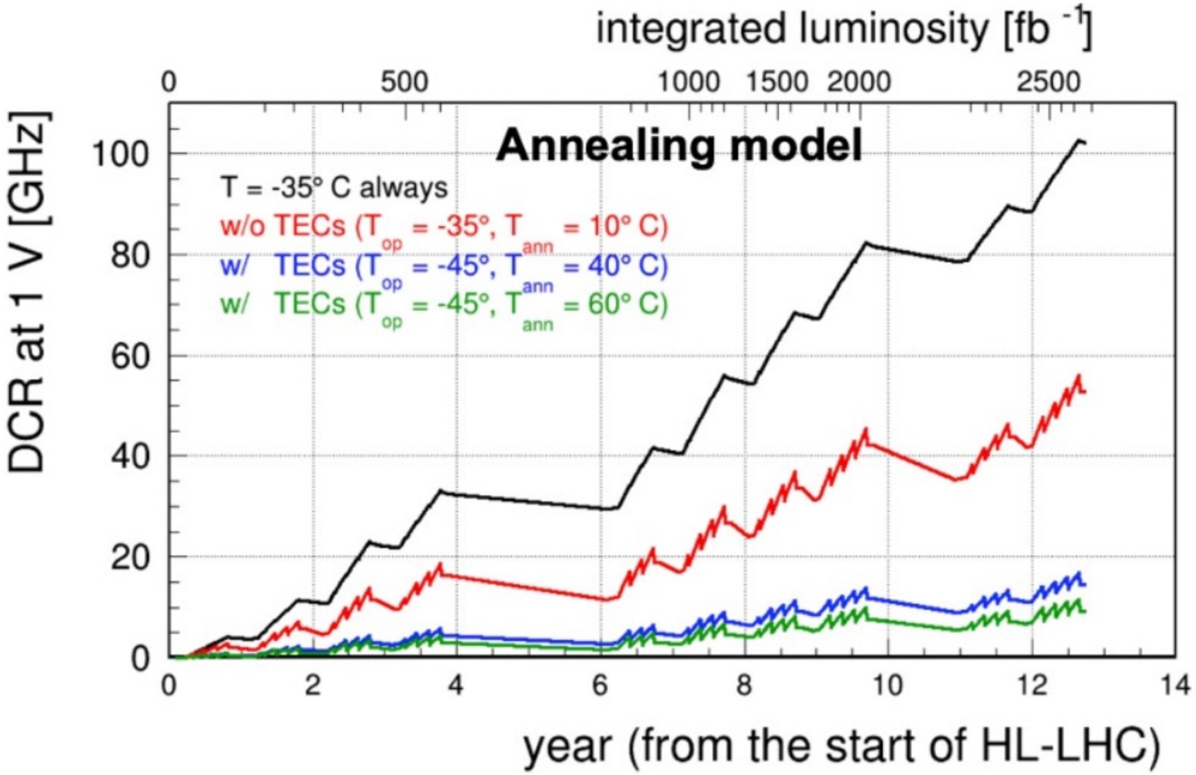
Key innovations to fight SiPM's dark count rate

- **DCR noise cancellation in the redout chip (TOFHIR2) with differential leading-edge discrimination**
  - Inverted and delayed pulse added to the original pulse
  - Preserve fast signal rising edge while cancelling correlated noise
    - Delay line approximated by a programmable RC network

Time resolution as a function of DCR before and after DLED filter [J. Varela, IEEE—NSSMIC-2020]



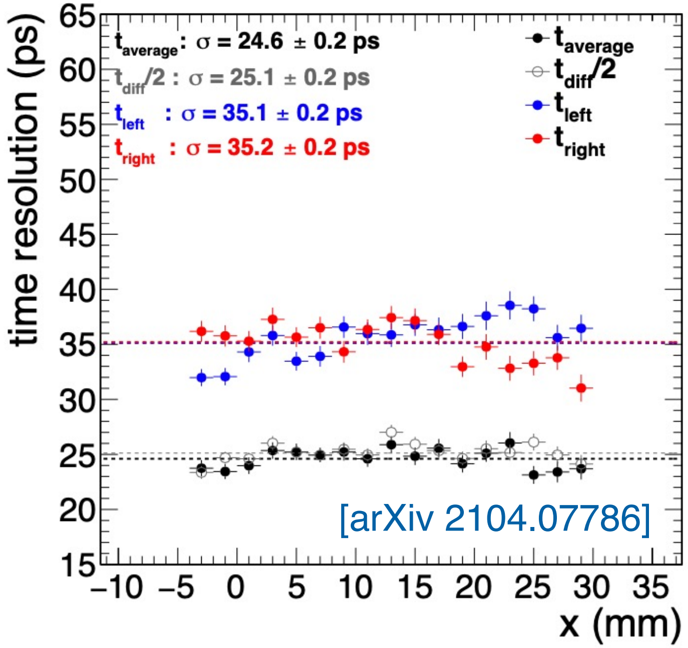
- **Smart thermal management**
  - TECs provide local cooling and heating capabilities relative to the CO_2 thermal bath → **x10 reduction of the dark count rate**
  - with SiPMs at **–45 ^{0}C** during operations (CO_2 at –35 ^{0}C) and in-situ annealing at **+60 ^{0}C** during technical stops (CO_2 at +10 ^{0}C)

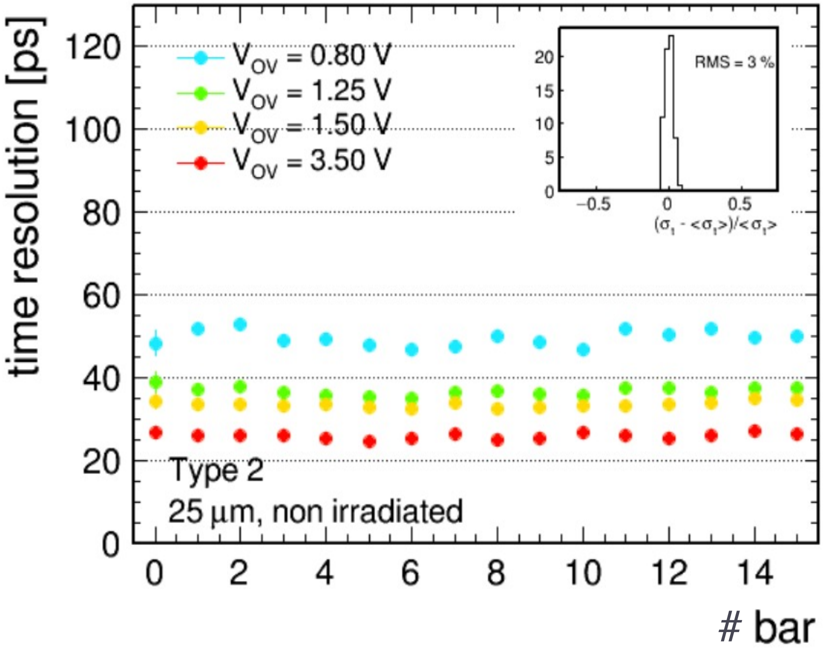


BTL prototype performance with beams

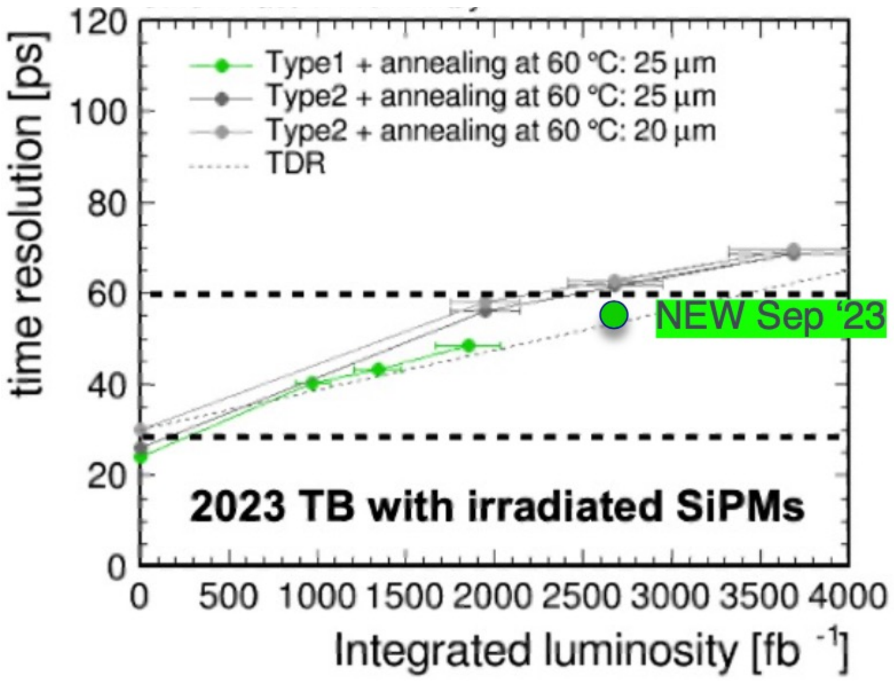
- **Module optimization and prototyping effort complete**
  - Thermal operation with CO_2 and TECs and response stability under thermal cycles validated
  - Readout ASIC (TOFHIR2) performance and functionality fully validated in laboratory and beams
  - Module prototypes with LYSO arrays (type 1) and SiPM cells (25 µm) optimized to maximize S/N validated with beam data

Uniformity along the bar (old) and across the bars (new 2023) [before irradiation]



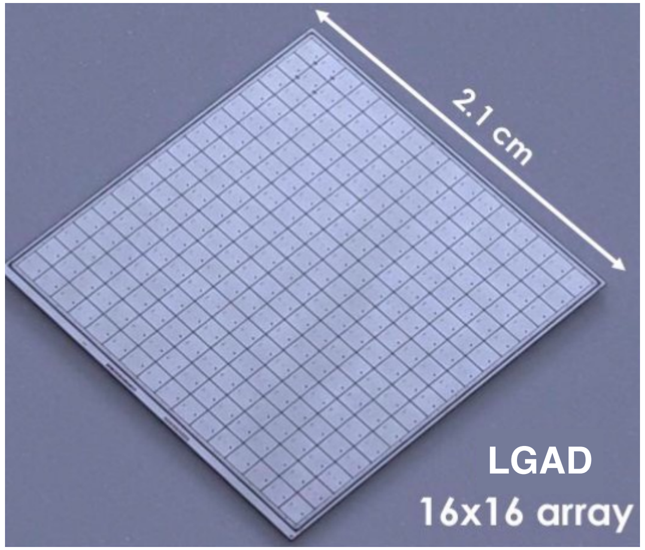


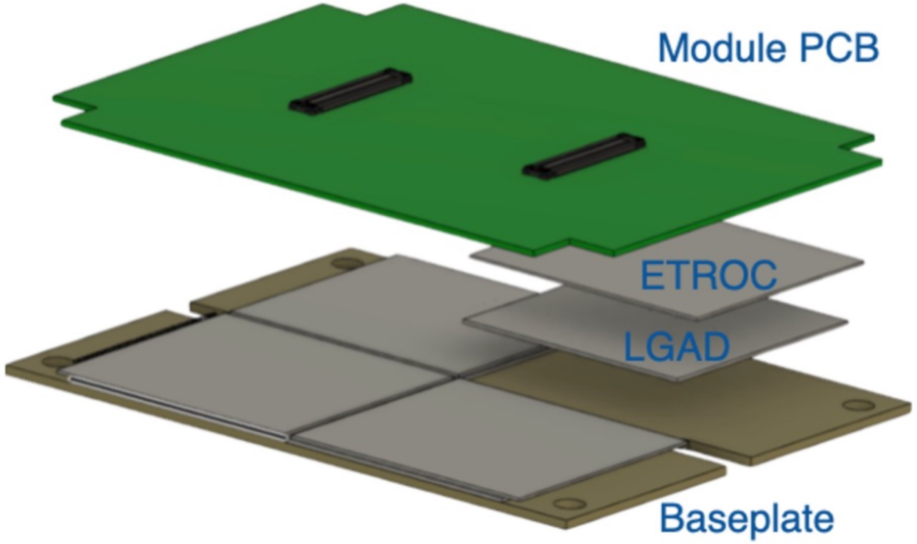
Performance evolution vs int. luminosity

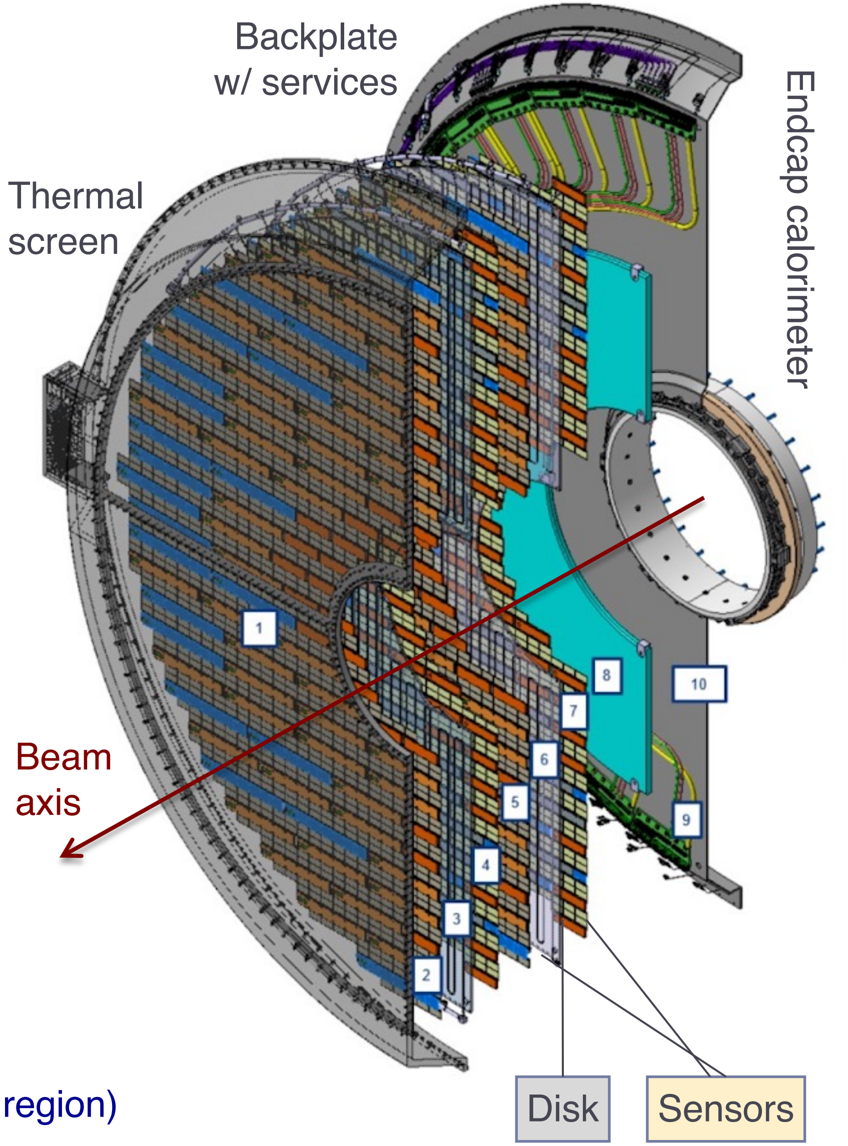


- **Target performance demonstrated → moving to production, assembly, and integration (2024-2025)**

Endcap timing layer (ETL) technology and structure



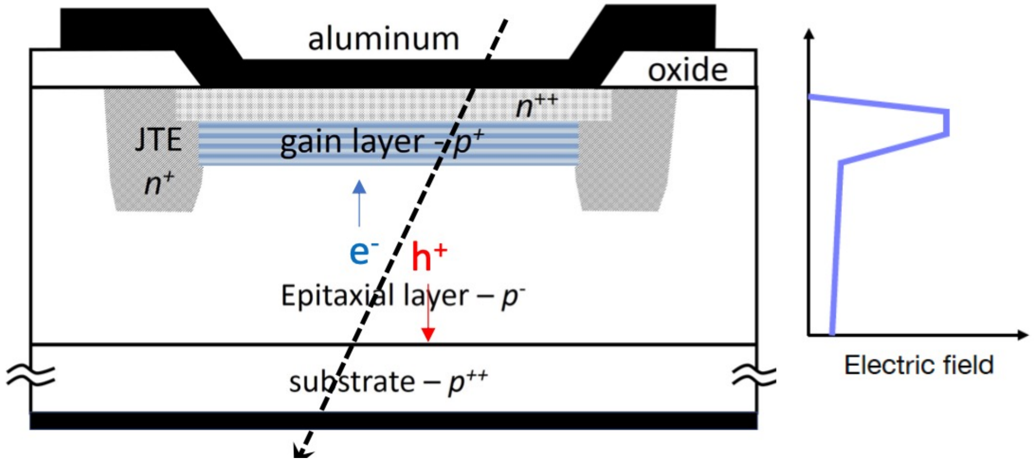


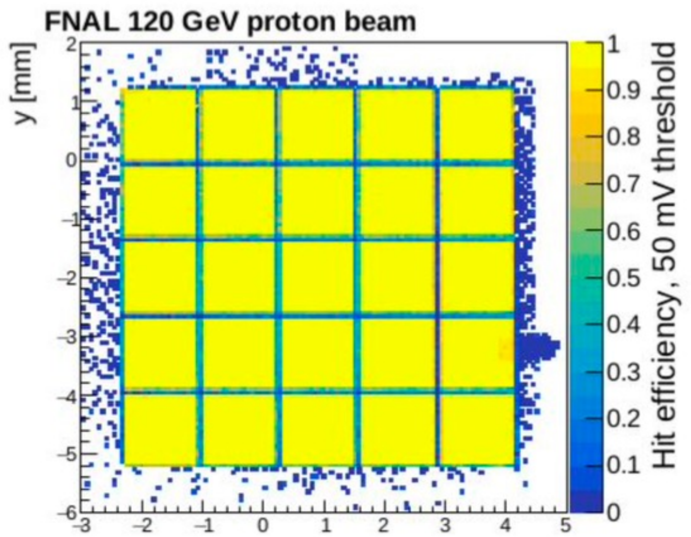


- **Modules with Low Gain Avalanche Detectors (LGADs)**
  - LGADs bump-bonded to designated readout chip (ETROC) mounted on two sides of cooling plates (disks)
- **Structure:**
  - Independent cold (–35 ^{0}C) volume : stageable, serviceable, maintainable
  - Two disks on each side provide up to 2 measurements per track
    - 50 ps per hit and 35 ps per track
- **Design and operation targets and challenge:**
  - Readout chip targets handling small signals (down to ~5 fC).
  - Sensor targets >8 fC in high radiation field (fluence >1 x 10^{15} n_{eq}/cm^2 in the 15% innermost region)

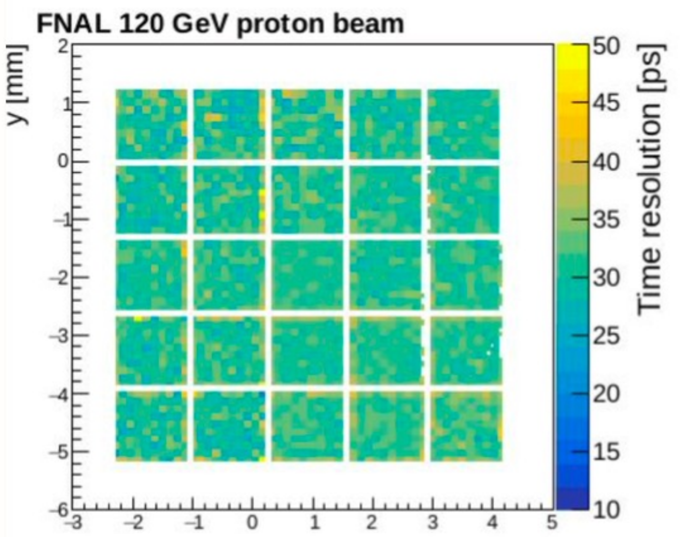
ETL sensors: key prototype features

- **Silicon structure optimized for time measurements**
  - Additional p+ implant to localize signal formation in a thin region
  - Thickness (50 µm) trade-off between signal size and time jitter of primary ionization
- **Worked with multiple vendors to optimize LGADs 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 at E>11.5 V/µm
  - Prototype LGAD sensors characterized before and after irradiation **proven to meet the ETL requirements** (>8 fC) at E≤11.5V/µm

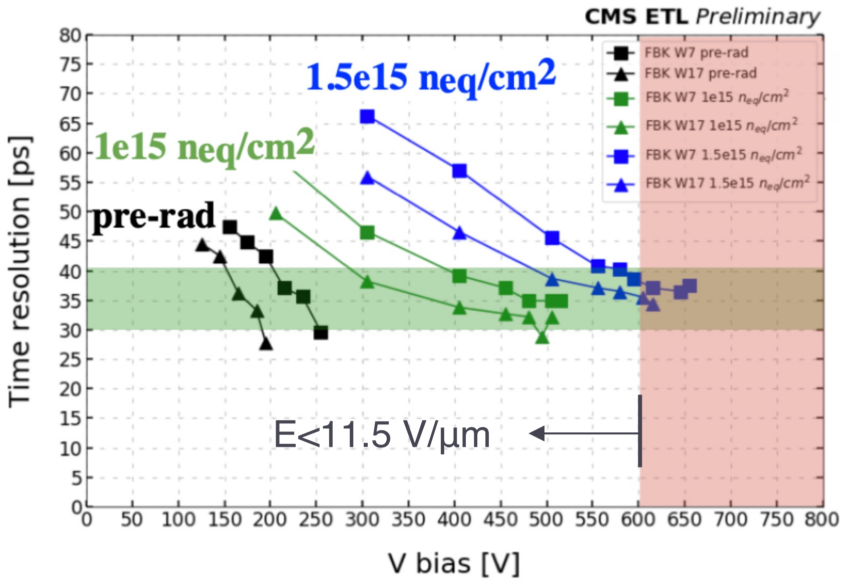




FBK 5x5 array x [mm]

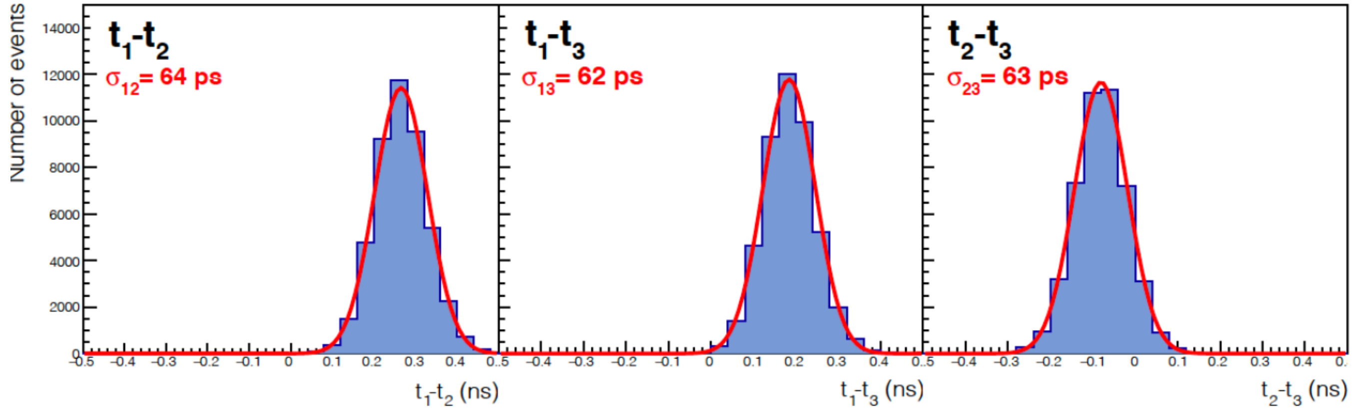


FBK 5x5 array x [mm]



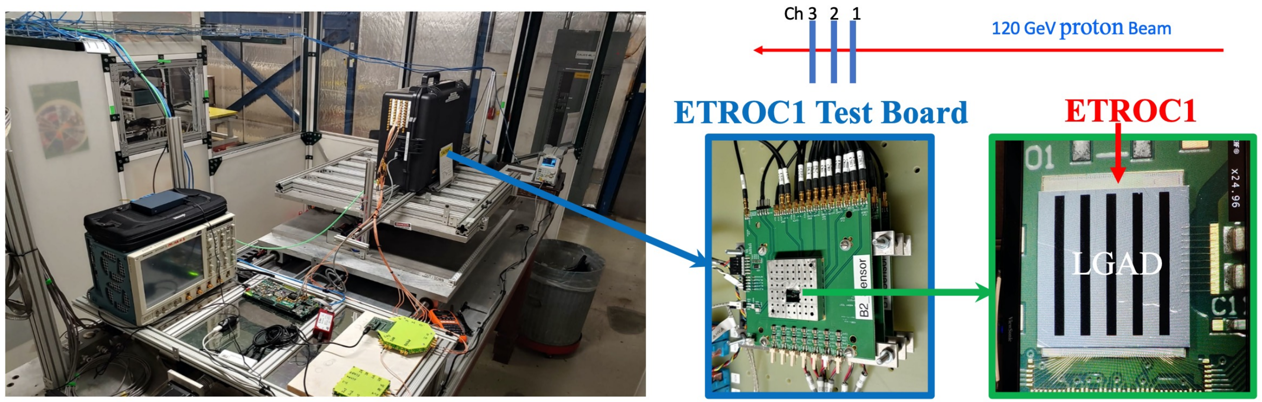
Performance validation of ETL sensor-package prototypes

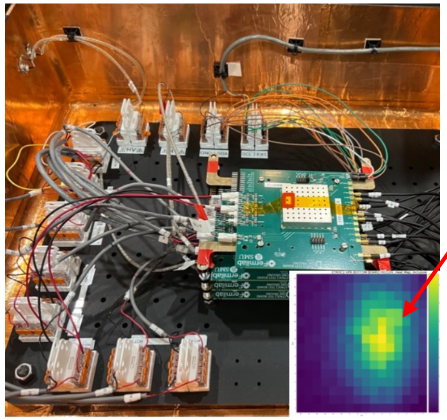
- **LGADs bump-bonded to the ETL prototype readout chips tested in beams:**
  - ✓ ETROC0 : single analog channel — Verified
  - ✓ ETROC1: with TDC and 4x4 clock tree — Meets resolution performance specifications
  - ✓ ETROC2: 16x16 full size full functionality — Functional / test beam in progress
  - ETROC3: 16x16 preproduction chip — Submission in 2024



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

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

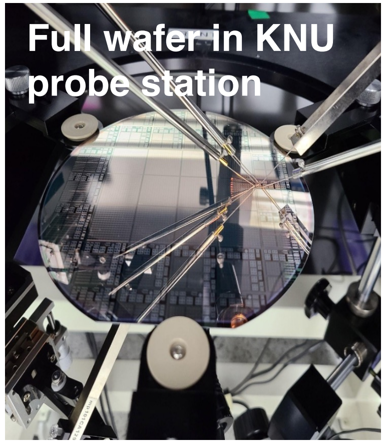


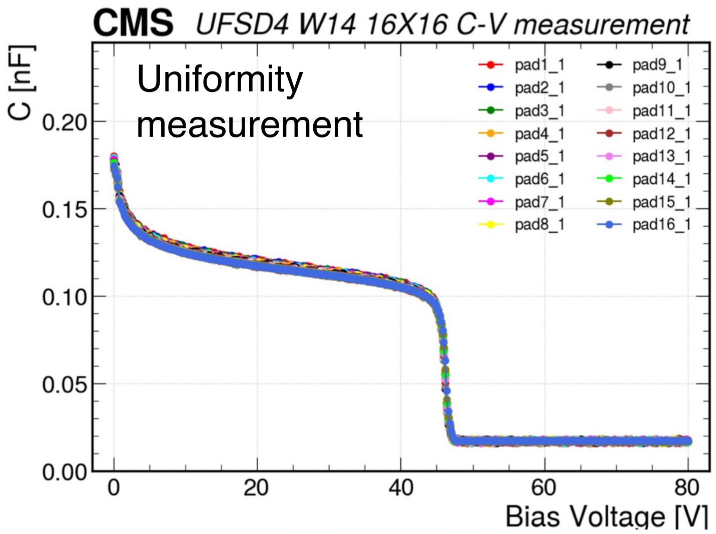


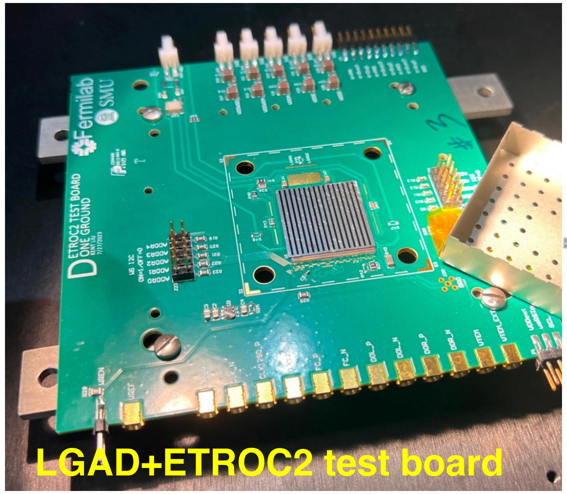
Bare ETROC2 tests and with **ETROC2 bump-bonded to LGADs** so far successful

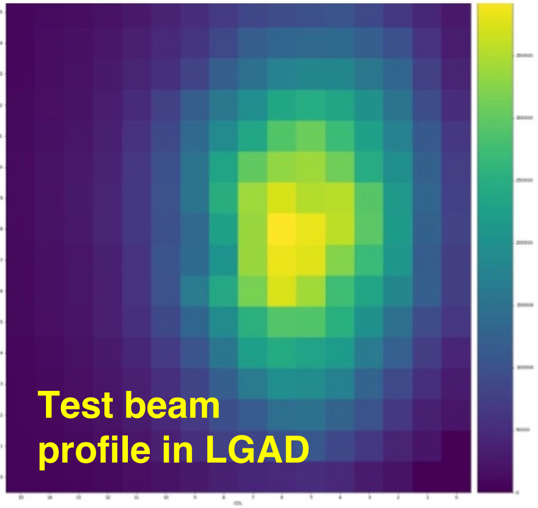
Korea contribution to the MTD

- **KCMS responsible for the delivery of one layer of ETL sensors!**
  - **25% of the total endcap coverage**
- **Significant contributions to prototyping towards production:**
  - **LGADs prototyping and validation**:
    - Detailed testing of prototype LGADs informed vendor qualification
    - Probe station measurements to verify quality and uniformity of full-size wafers
  - **ETROC2 testing**
    - Active in ETROC testing, including test beam campaigns for validation of the performance of the LGADs + ETROC chain
  - **Wafer processing:**
    - Exploring wafer processing with one of the qualified LGADs vendors for wafer thinning, dicing, and surface preparation at Korean companies for the production phase
  - **Bump-bonding:**
    - Exploring options with Korean companies for LGAD-to-ETROC bump-bonding during production









Summary

- **The MTD is one of the most challenging and rewarding detector of the CMS Upgrade**
  - It will be essential for the CMS physics program at HL-LHC with broad impact across several channels
  - Reduce pile-up contributions, improve object reconstruction, enable new physics opportunities
- **Mature design for MTD has been established through extensive prototyping and testing**
  - Key contributions from Korean institutions in the ETL sensor testing and optimization
- **Sensor technologies (*) meet the design targets for HL-LHC**
  - BTL design is fully validated and the detector is entering the production phase
  - ETL is entering a decisive phase of final prototyping before moving to construction

- **KCMS contribution to prototyping and construction is paramount!**

(*) Other detector system components (not discussed in this talk) are progressing as planned