PRECISION TIMING WITH THE CMS MIP TIMING DETECTOR FOR HIGH-LUMINOSITY LHC

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on behalf of the CMS Collaboration

ICHEP 2024 – Prague (Czech Republic)
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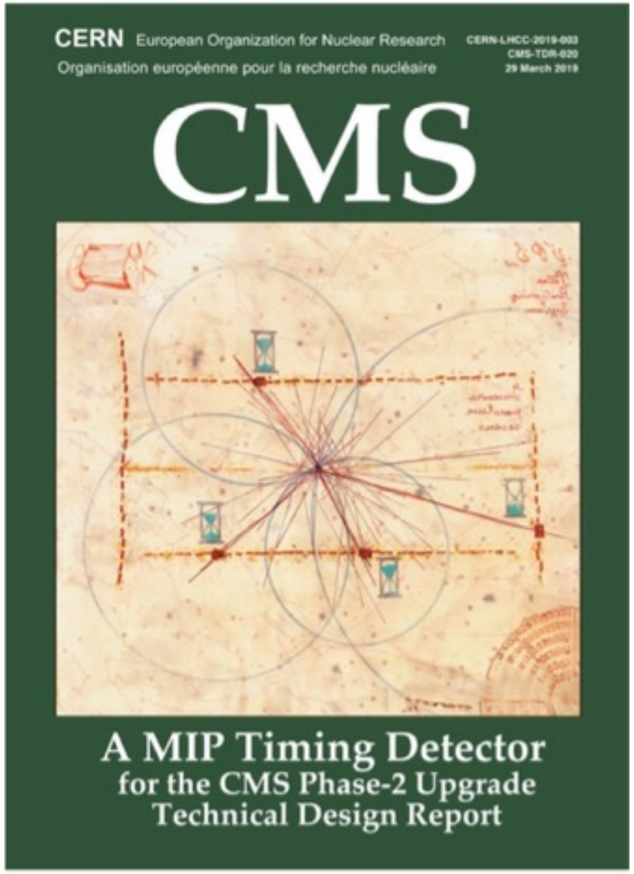
Outline

- Physics motivation
- Detector overview
  - approved in 2019
- Barrel Timing Layer
  - assembly to start ~ now
- Endcap Timing Layer
  - assembly to start in 2026
- Physics exploitation



CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire

CERN-LHCC-2019-003
CMS-TDR-020
29 March 2019

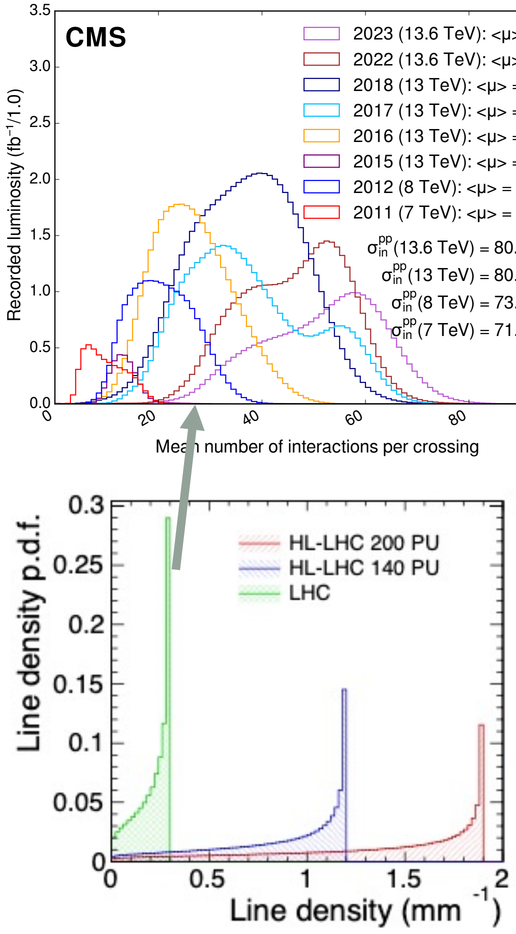
CMS

A MIP Timing Detector
for the CMS Phase-2 Upgrade
Technical Design Report

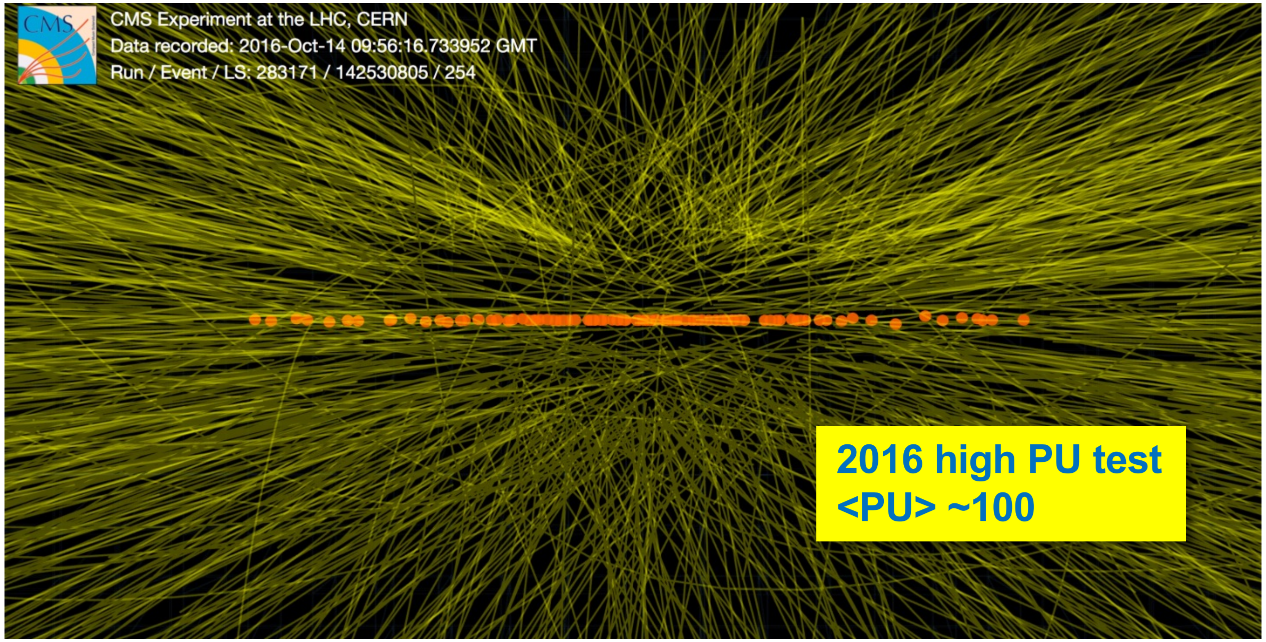
CMS-TDR-020
CERN-LHCC-2019-003

HL-LHC: more luminosity and more pileup

- HL-LHC luminosities needed to integrate 3 ab^{-1} will imply a significant increase in average pileup compared to Run1/2/3
  - ranging from <PU> ~ 140 till <PU> ~ 200
- Pileup rejection key tool: charged track association to reconstructed vertices
  - based on excellent tracker resolution, its efficiency depends on vertex line density along beam axis



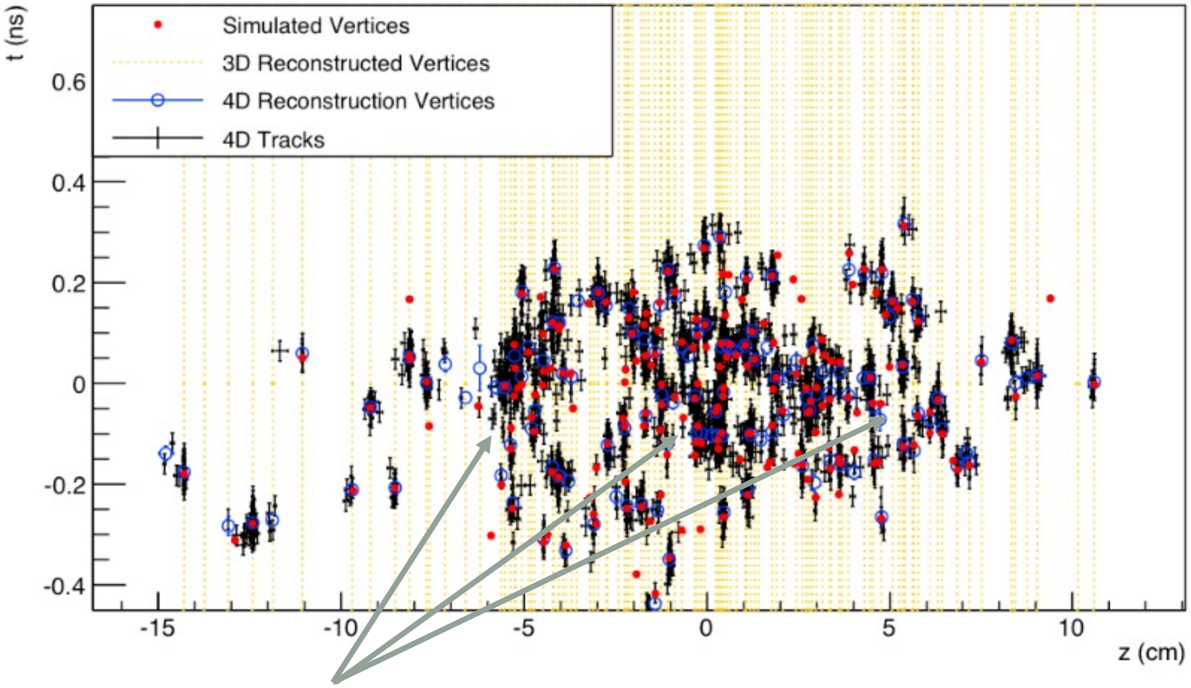
- As line density increases above 1/mm, tracker alone less and less efficient in pileup rejection, despite the upgrade
- |dz| < 1 mm typical track-vertex association criterion
- more pileup spoils physics objects quality: jet scale and resolution, b-tagging, lepton isolation,…



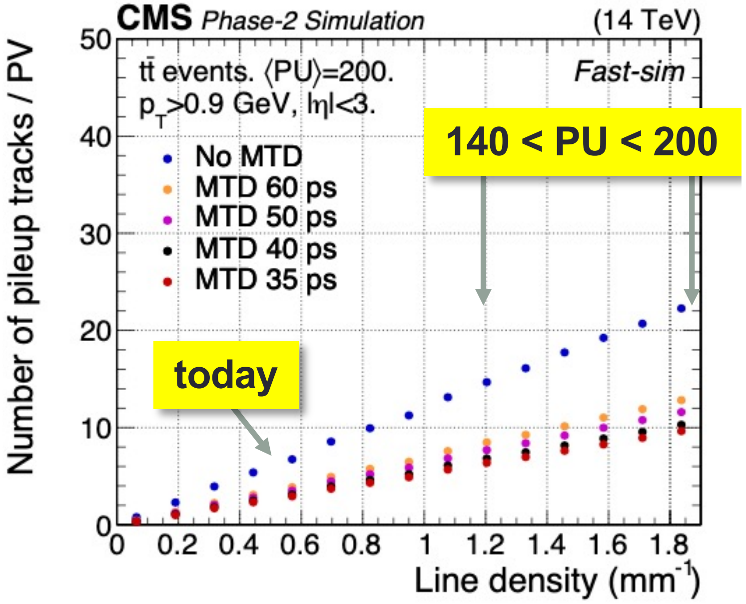
2016 high PU test
<PU> ~100

A timing detector for HL-LHC: why?

- Beam spot rms $\mathcal{O}(5\text{ cm}) \Rightarrow \sim 200$ ps, i.e. space-overlapping vertices can be separated in time by hundreds of ps



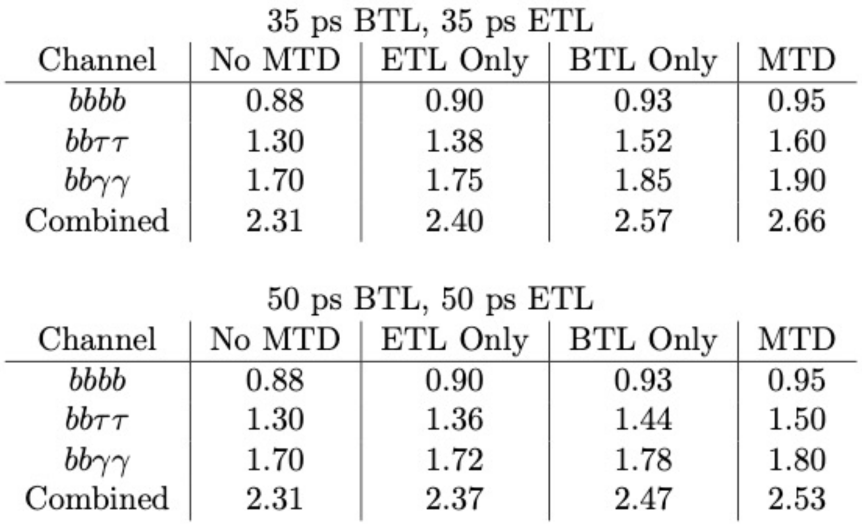
- Time resolution vs line density determines how well pileup rejection works



- If track time at the beam line can be measured with a higher precision, $\mathcal{O}(30 - 40\text{ ps})$, use time to distinguish them!
- 3D → 4D vertex reconstruction may bring back to a LHC-like density in separate time frames
  - i.e. existing PU rejection strategies can be successfully used again

Physics benefit : PU rejection and PID

- Better physics objects equivalent to more integrated luminosity
  - better MET selection, b-tagging, lepton isolation efficiencies
- E.g. double Higgs search
  - **CMS-DP/2022-025**



35 ps BTL, 35 ps ETL

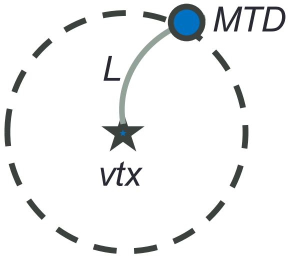
Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.38	1.52	1.60
$bb\gamma\gamma$	1.70	1.75	1.85	1.90
Combined	2.31	2.40	2.57	2.66

50 ps BTL, 50 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.36	1.44	1.50
$bb\gamma\gamma$	1.70	1.72	1.78	1.80
Combined	2.31	2.37	2.47	2.53

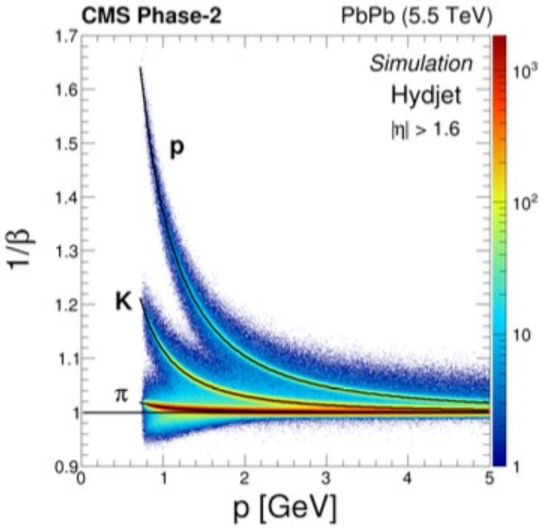
- significance gain equivalent to a luminosity increase from 20 to 31%
  - depending on achievable resolution

- Track time propagation needs a mass hypothesis



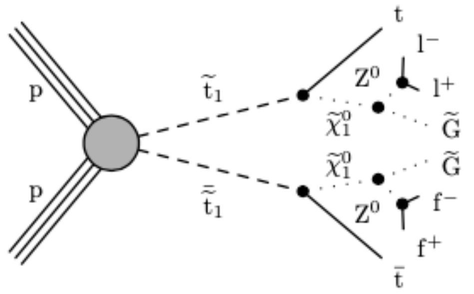
$$\frac{1}{\beta} = \frac{c(t_{MTD} - t_{vtx})}{L}$$

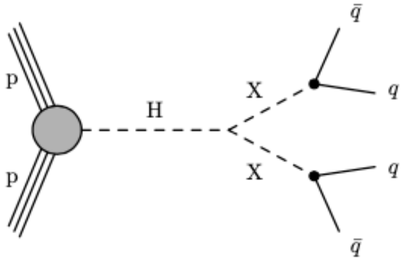
  - For well separated vertices (e.g. Heavy Ion collisions) good PID capability possible

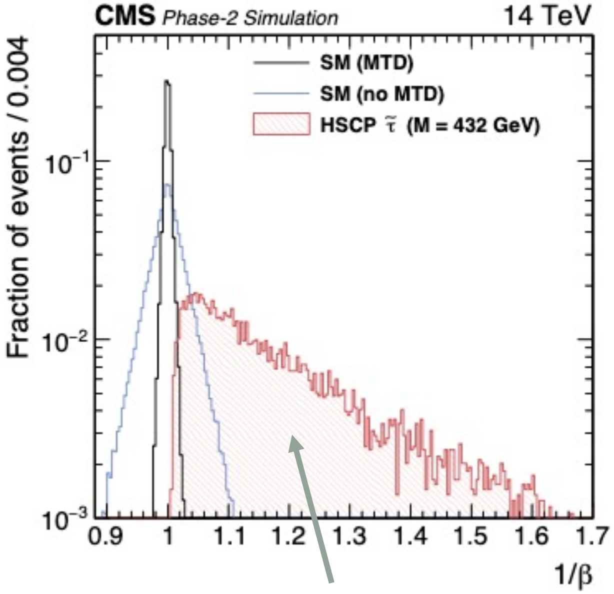


Extra physics gain: new physics search

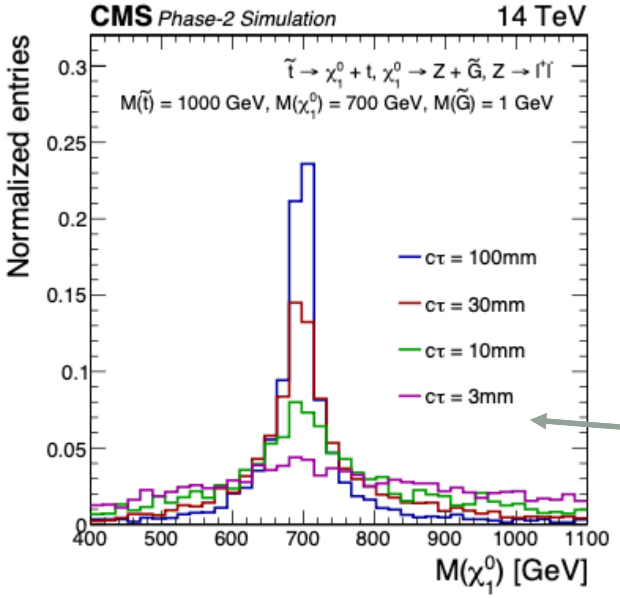
- Timing capabilities may be useful in various LLP scenarios and HSCP searches

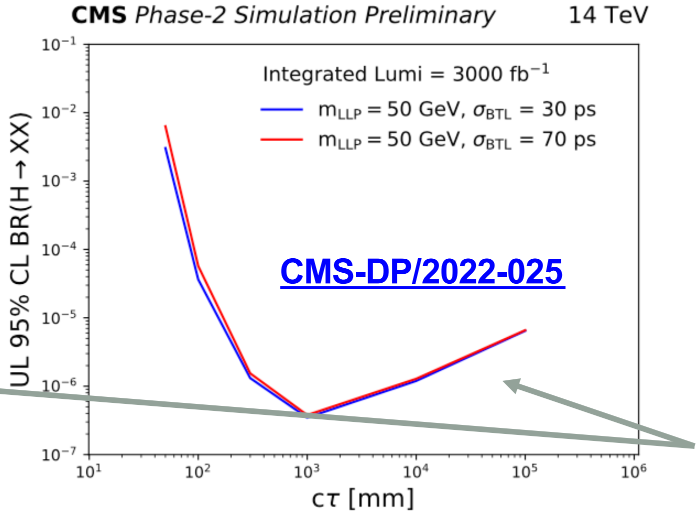






charged particle associated to a very late MTD signal compared to SM signatures



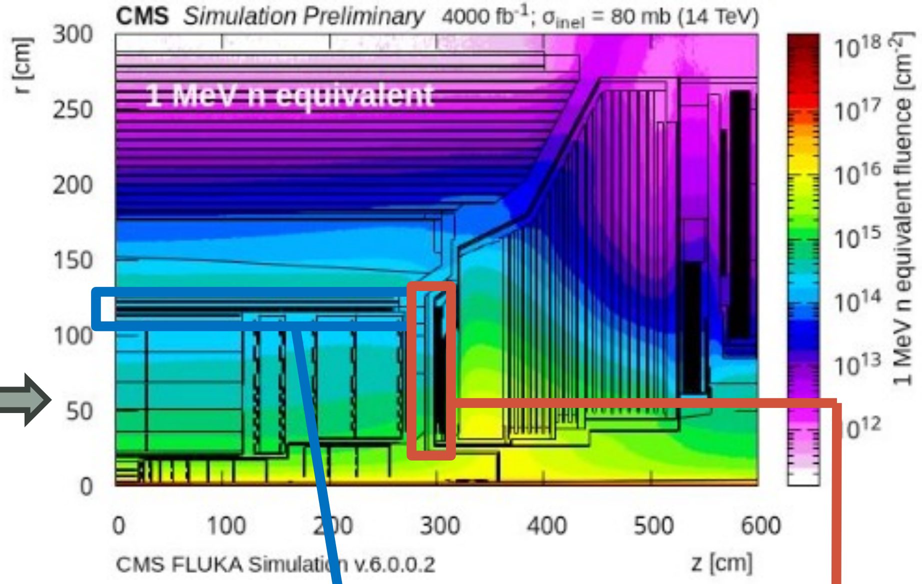


CMS-DP/2022-025

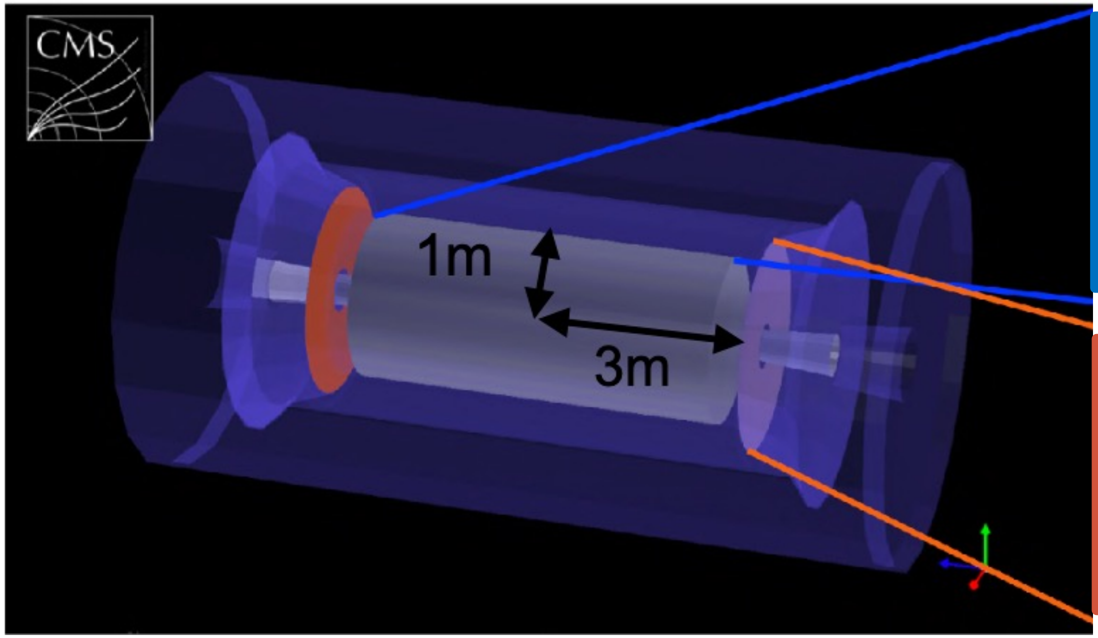
time of flight between primary and displaced vertices may discriminate SM and new particles

CMS approach: Mip Timing Detector

- Measure time of charged particles in between tracker and calorimeter
  - with hermetic coverage in $|\eta| < 3$
  - Barrel layer (BTL): inside the Barrel Tracker Support Tube
  - Endcap layer (ETL): on the HGCal nose, outside forward tracker
- Radiation hardness drives the sensor technology choice
  - together with cost and readout considerations



CMS-DP/2023-087



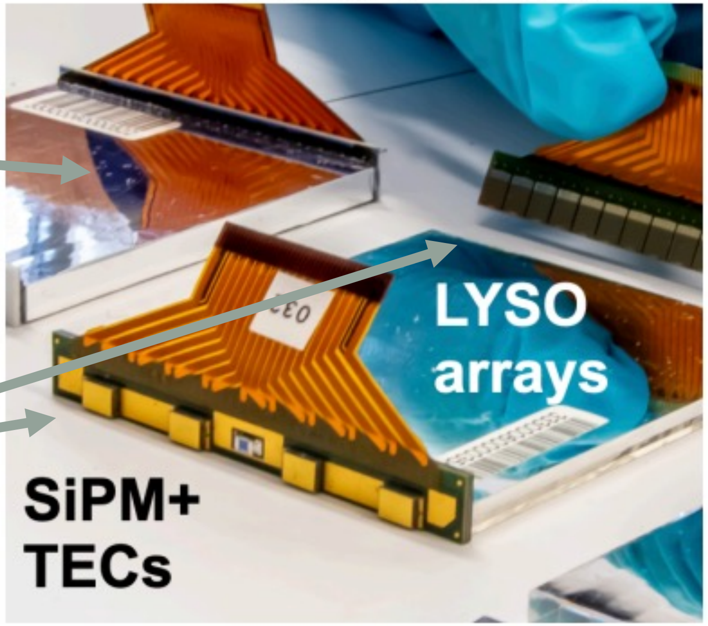
Barrel Timing Layer
- LYSO bar + 2 SiPM/bar
  - 332k channels
- $p_T > 0.7$ GeV, $|\eta| < 1.45$
- ~ 38 m^2

Endcap Timing Layer
- LGAD 16×16 pads
  - ~8.5M channels
- 2 discs/side $1.6 < |\eta| < 3$
- ~ 14 m^2

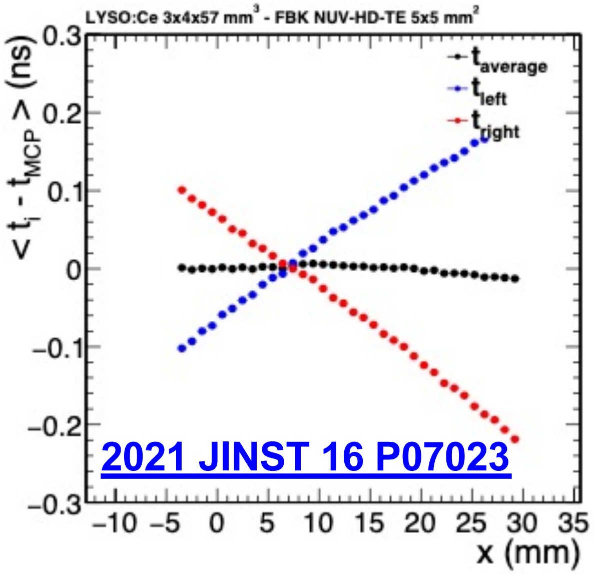
BTL: sensor technology

- LYSO:Ce scintillator
  - arrays of 16 bars, bar: 3.75×3.12×54.7 mm^3
  - fast response (40 ns decay time) and dense (~ 4.2 MeV/MIP)
  - high light yield (40k photons/MeV) ⇒ reduced photostatistics uncertainty
  - radiation hard up to tens of kGy

BTL sensor module

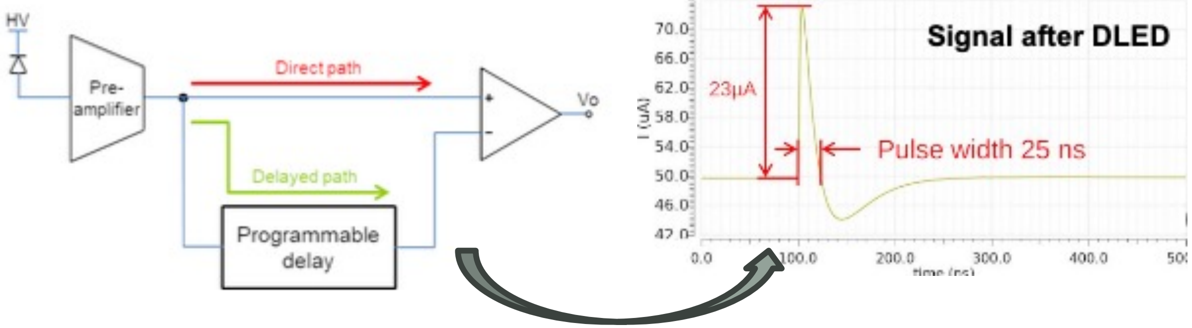


- Dual SiPM readout, one at each bar end
  - 25 μm cell size, with thermoelectric (TEC) coolers
  - $t_{ave} = (t_1+t_2)/2$ ~ independent on position, $\sigma(t_{ave}) = \sigma(t_{1,2})/\sqrt{2}$



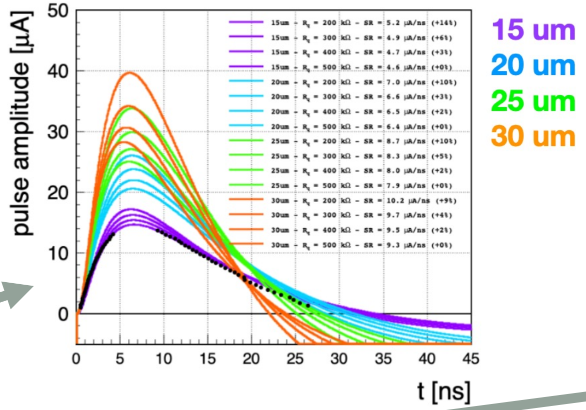
2021 JINST 16 P07023

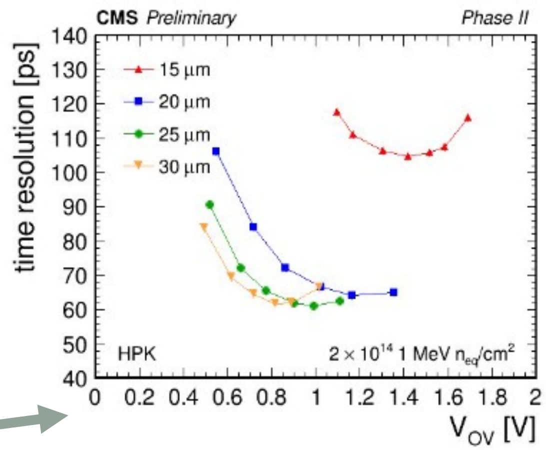
- TOFHIR readout ASIC: 2024 JINST 19 P05048
  - high gain + noise filter
  - Differential Leading Edge Discriminator: delayed and inverted signal overlapped to squeeze it in 25 ns



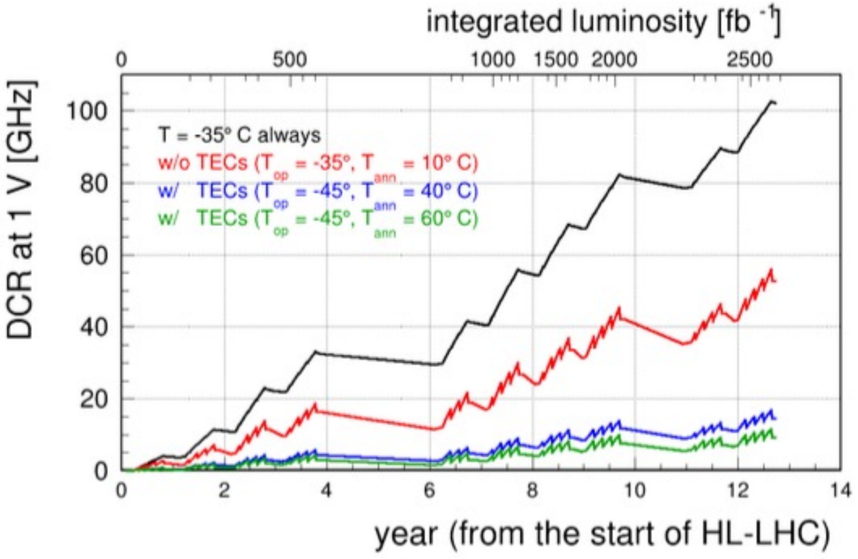
BTL: S/N response optimization

- Maximize light output
  - maximal crystal thickness everywhere
  - optimized LYSO packaging
- Optimized cell size
  - larger size: better Photon Detection Efficiency (PDE) and SiPM gain
    - higher PDE permits lower overvoltage operations ⇒ smaller noise impact
  - trade-off with power consumption
- Dark Count Rate (DCR) reduction
  - radiation damage to SiPM: DCR expected ~ tens of GHz at End-of-Life (EoL)
    - limit with cooling, CO_2 at -35 C^0
  - TEC coolers during operations: -35 C^0 ⇒ -45 C^0
  - in situ annealing cycle outside operations
    - partial damage recovery, exploiting also TECs with reverse bias





[CMS-DP/2024-049]

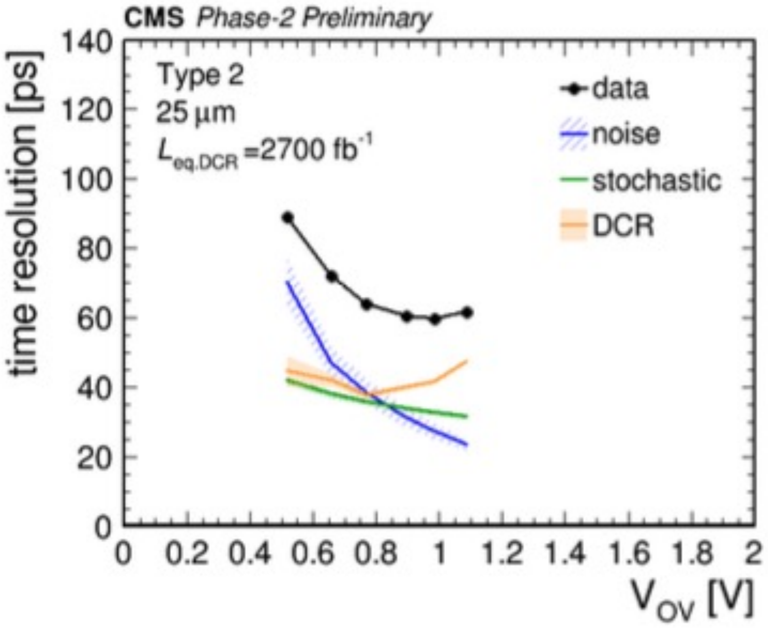


[2023 JINST 18 P08020]

BTL: achievable performances

$$\sigma_t^{BTL} = \underset{\underset{\propto \frac{1}{\sqrt{N_{pe}}}}{\swarrow}}{\sigma_t^{stat}} \oplus \underset{\underset{\propto \frac{\sigma_{noise}}{N_{pe}}}{\downarrow}}{\sigma_t^{elec}} \oplus \underset{\underset{\propto \frac{\sqrt{DCR}}{N_{pe}}}{\searrow}}{\sigma_t^{DCR}} \oplus \sigma_t^{digi} \oplus \sigma_t^{clock}$$

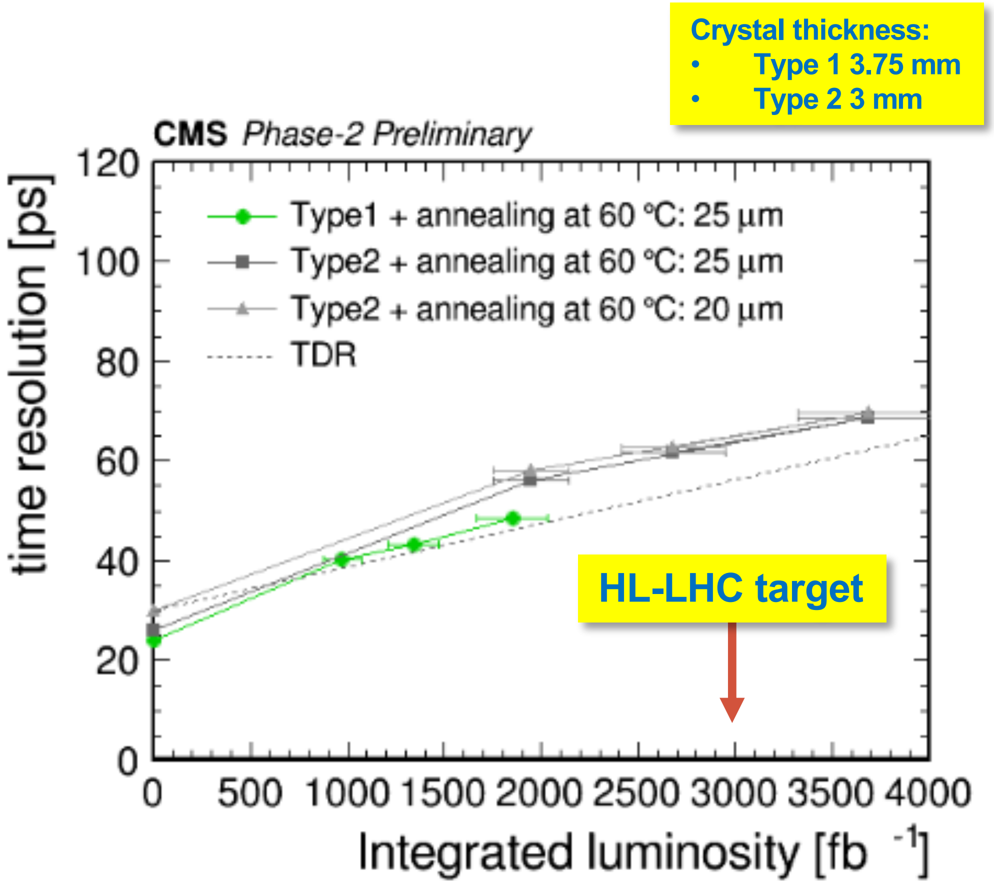
- number of photoelectrons N_{pe} determines main resolution components



- DCR term is dominating at EoL
- detector choice mitigates its deterioration with integrated luminosity

[CMS-DP/2023-093](CMS-DP/2023-093)

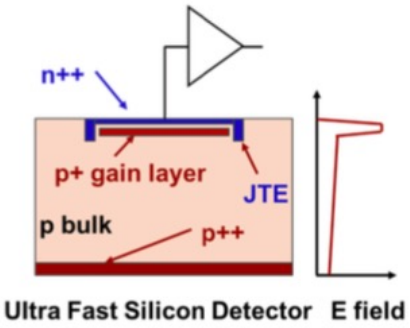
- Optimization strategy allows resolution at EoL to stay within TDR expectation of ~ 60 ps


Crystal thickness:
- **Type 1 3.75 mm**
- **Type 2 3 mm**

HL-LHC target

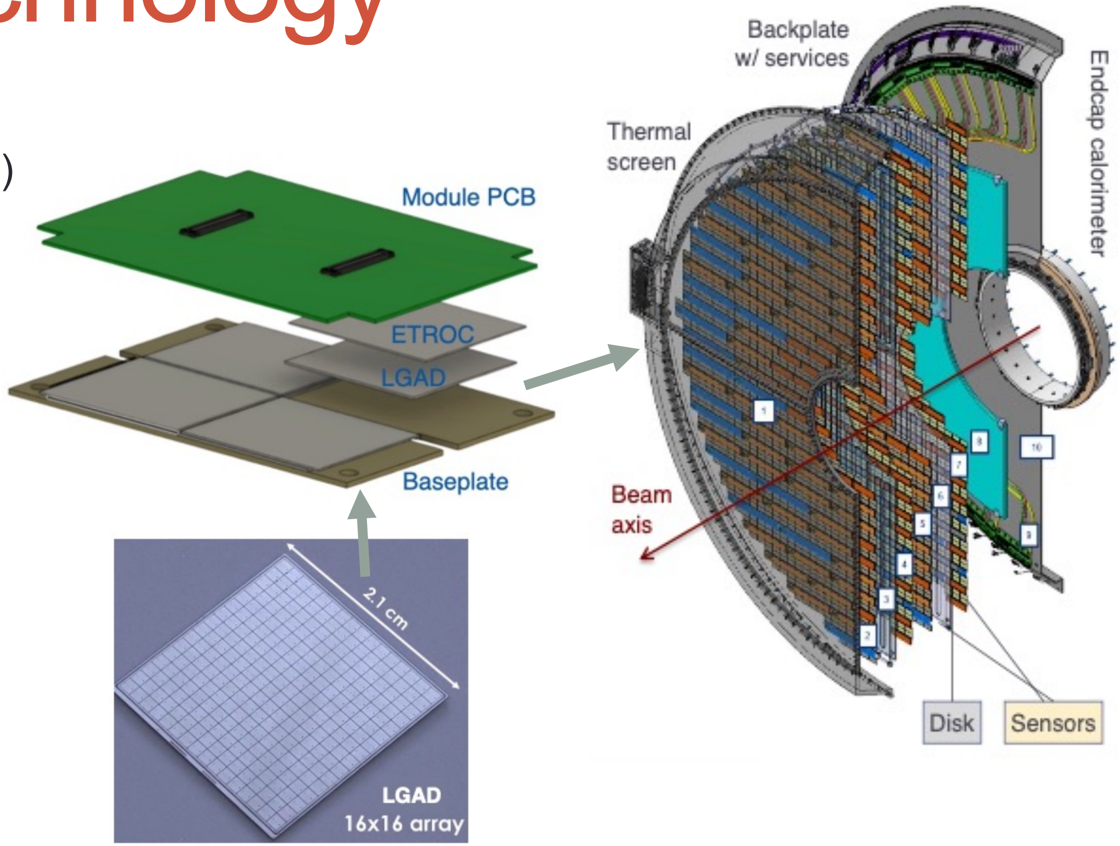
ETL: sensor technology

- Low Gain Avalanche Diode
  - LGAD 16 × 16 pads (1.3 × 1.3 mm^2 each)
  - 50 μm active layer, > 8 fC at EoL
    - trade-off between signal size and primary ionization time jitter



  - gain (10 – 30) for better S/N ratio
  - suitable for 1×10^{15} n$_{eq}$/cm^2 fluence in the innermost region

- ETROC readout ASIC
  - bump-bonded on LGAD
  - single TDC measuring Time Of Arrival (TOA) and Time Over Threshold (TOT)
  - LGAD + ETROC ~ 50 ps

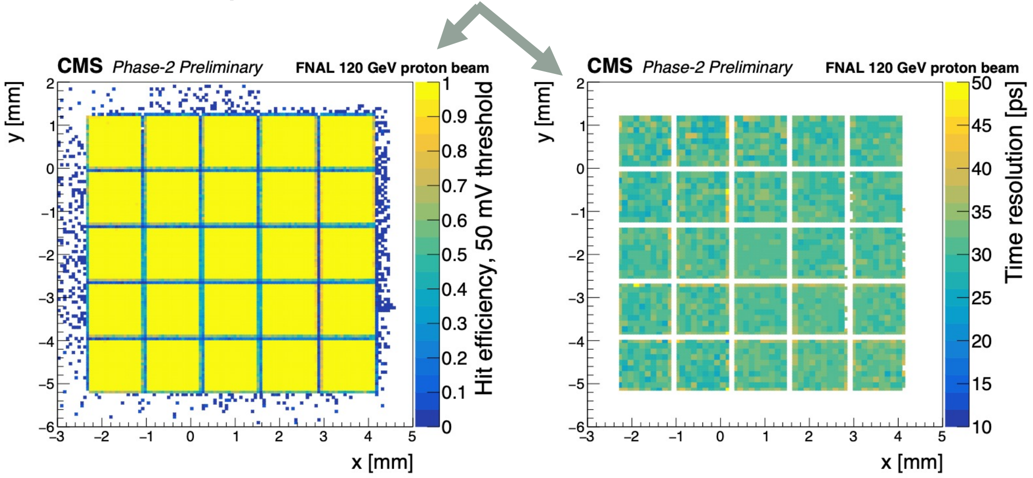


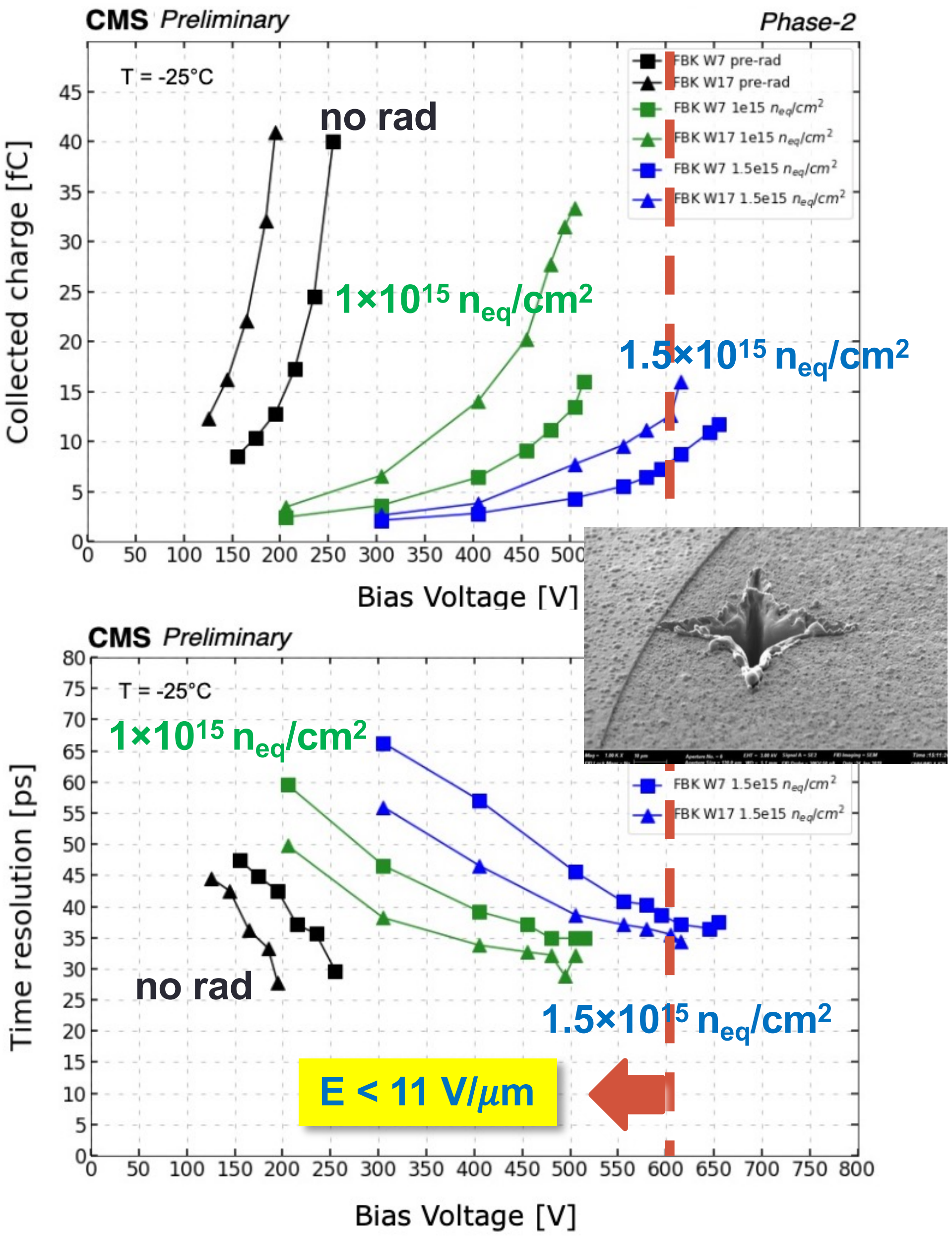
- Two double-face discs/side layout
  - 0.30 m < R < 1.19 m
  - ~ 85% tracks with two measured hits
  - ensuring target of ~ 35 ps total time resolution per track

ETL: LGAD radiation hardness

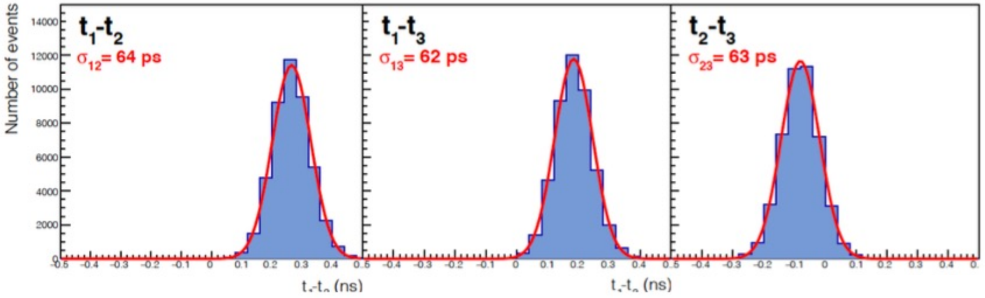
CMS-DP/2024-035

- Sensor optimization done with multiple vendors
- Target performance at EoL achievable by increasing voltage
  - LGAD irradiated with β Sr_{90} source
- Test beams show single Event Burn-out when E field > 11 V/μm
  - but target performances achievable below this field
- And excellent efficiency and resolution
  - 5×5 pads, non irradiated





ETL: performance validation

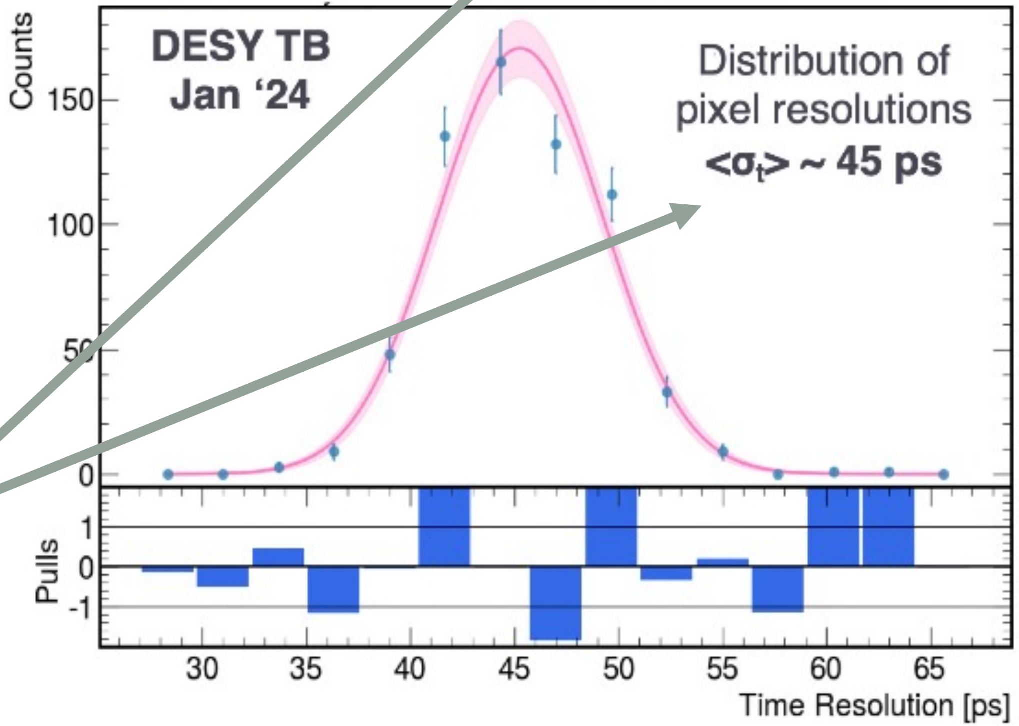


LGAD+ETROC1 resolution is 42-46 ps from TDC digital outputs

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

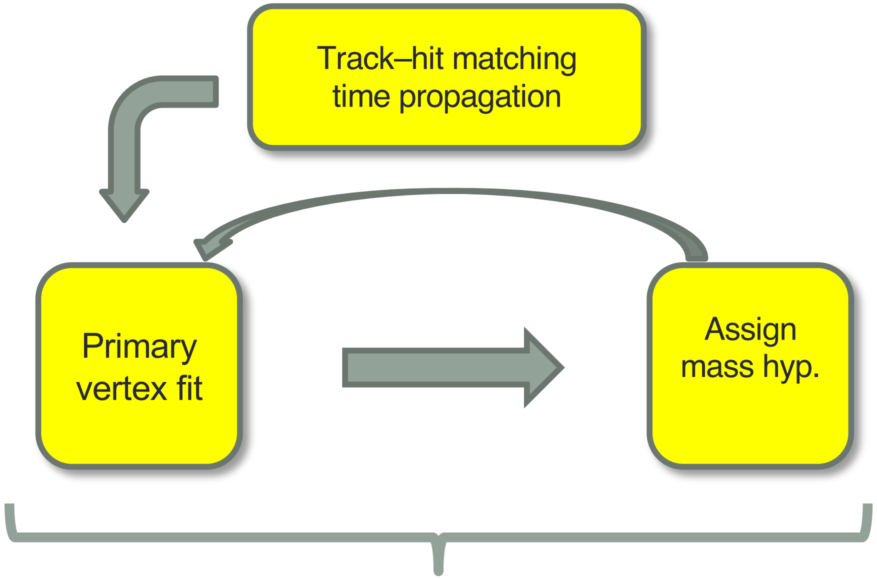
- First version of ASIC: ETROC1
  - 4×4 channel clock tree
  - tests with wire-bonding to LGAD
  - full system DAQ

- ETROC2: 16×16 layout
  - bump-bonded to LGAD
  - resolution consistent with initial tests



4D tracking with MTD: strategy and challenges

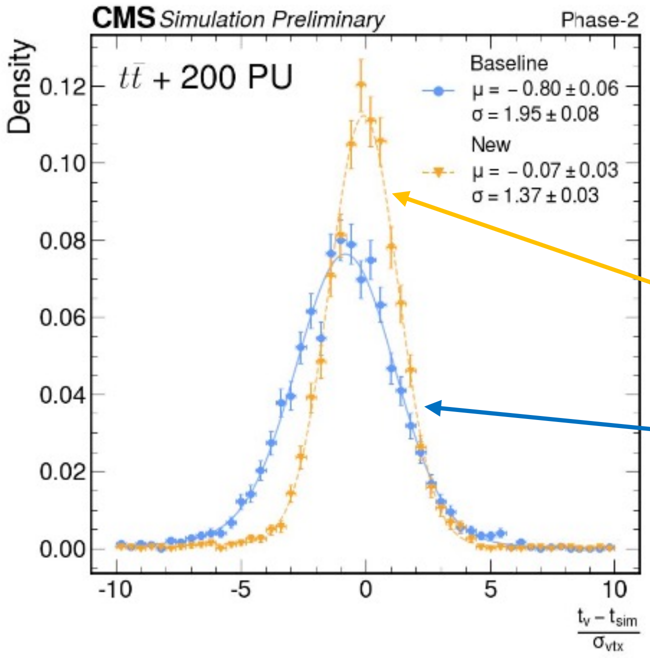
- 1 (BTL)/2 (ETL) MTD hits / track
  - time at MTD surface needs to be extrapolated back to beam line
  - we measure track momentum, speed depends on mass hypothesis, important at low p
- Resolve track mass ambiguity with “equal time at origin vertex” constraint
  - 4D vertex reconstruction is both a clustering and a classification (PID) problem


Track–hit matching time propagation

Primary vertex fit

Assign mass hyp.

- Iterative approach: initial mass hypothesis (π) refined after first vertex reconstruction
  - Add time term in Deterministic Annealing for clustering



- Vertex time
  - average track time
  - or new time determination with a dedicated Deterministic Annealing algorithm combining all mass hypotheses (π/K/p)
  - **CMS-DP/2024-048**

Summary

- The MTD detector is moving from design and R&D towards construction
  - BTL technology fully validated, assembly to start this summer
  - ETL design reaching maturity in its components, on track for assembly in 2026

- The physics exploitation of MTD will be a test bench for usage of modern timing measurement capabilities in future collider experiments