Precision Timing with the CMS MIP Timing Detector

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Outline:

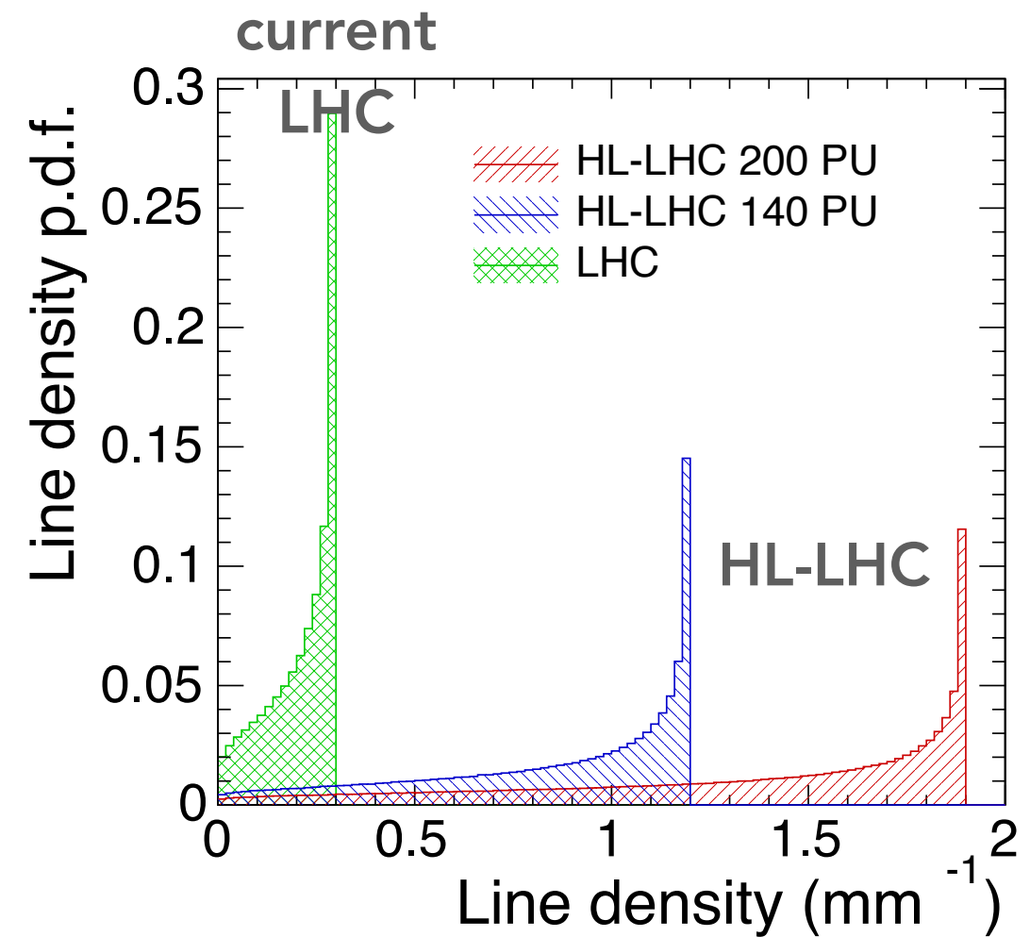
– motivations for precision timing at the HL-LHC

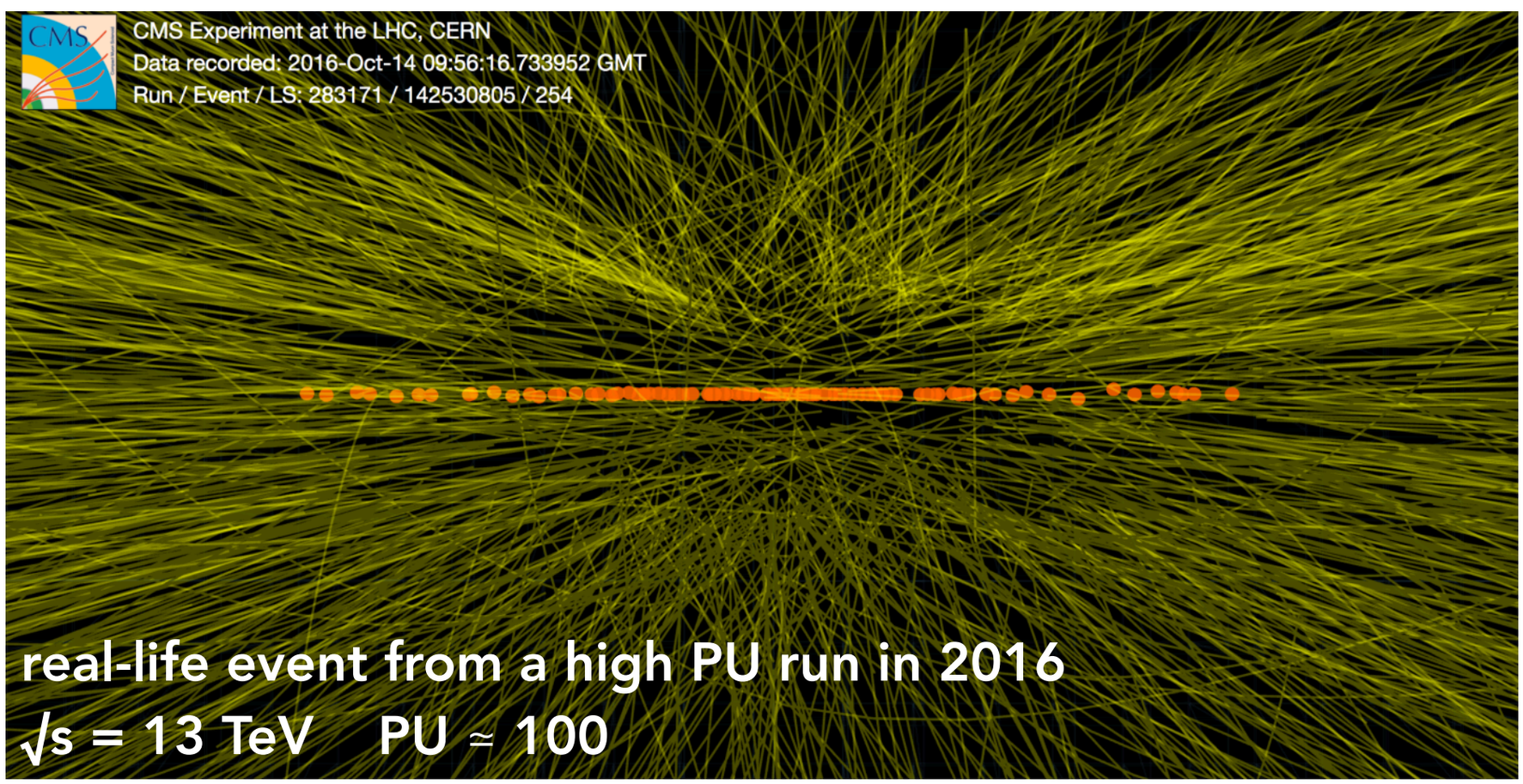
– overview and performance of the proposed detector

– beam test results and ongoing R&D

Challenges at HL-LHC

- The **High Luminosity phase** of LHC (**HL-LHC**) foresees:
  - **baseline:** $L_{inst} = 5.0\times10^{34}$ cm^{-2}s^{-1}
    140 pileup events, **~1.2 vertex mm^{-1}**
  - **ultimate:** $L_{inst} = 7.5\times10^{34}$ cm^{-2}s^{-1}
    200 pileup events, **~1.9 vertex mm^{-1}**





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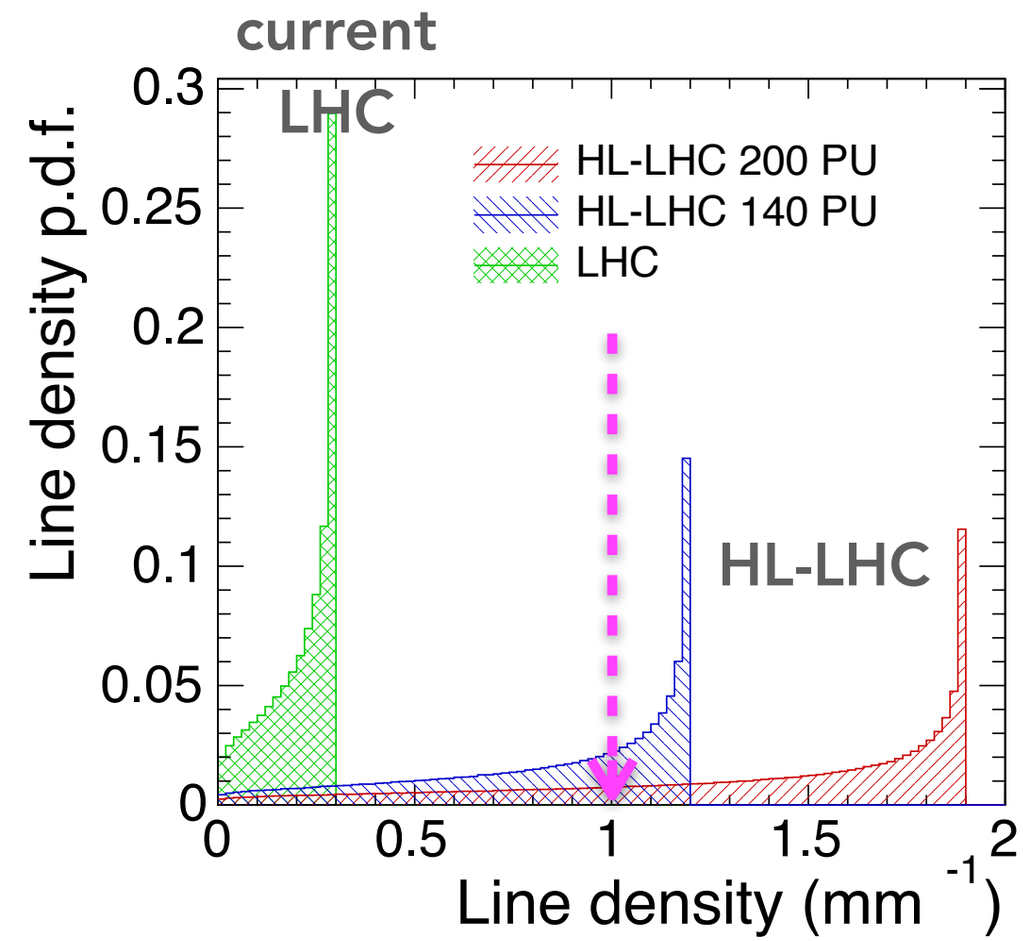
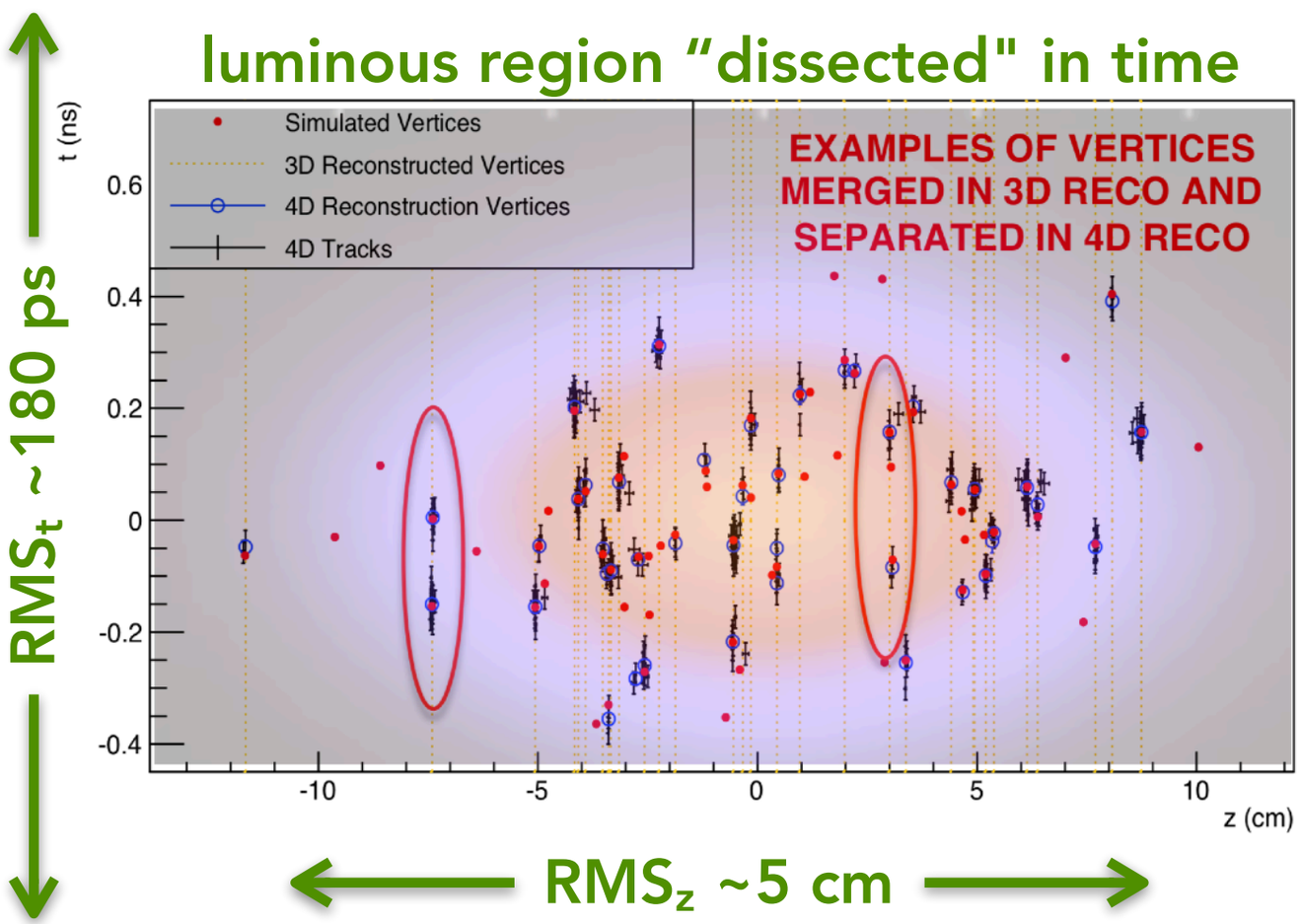


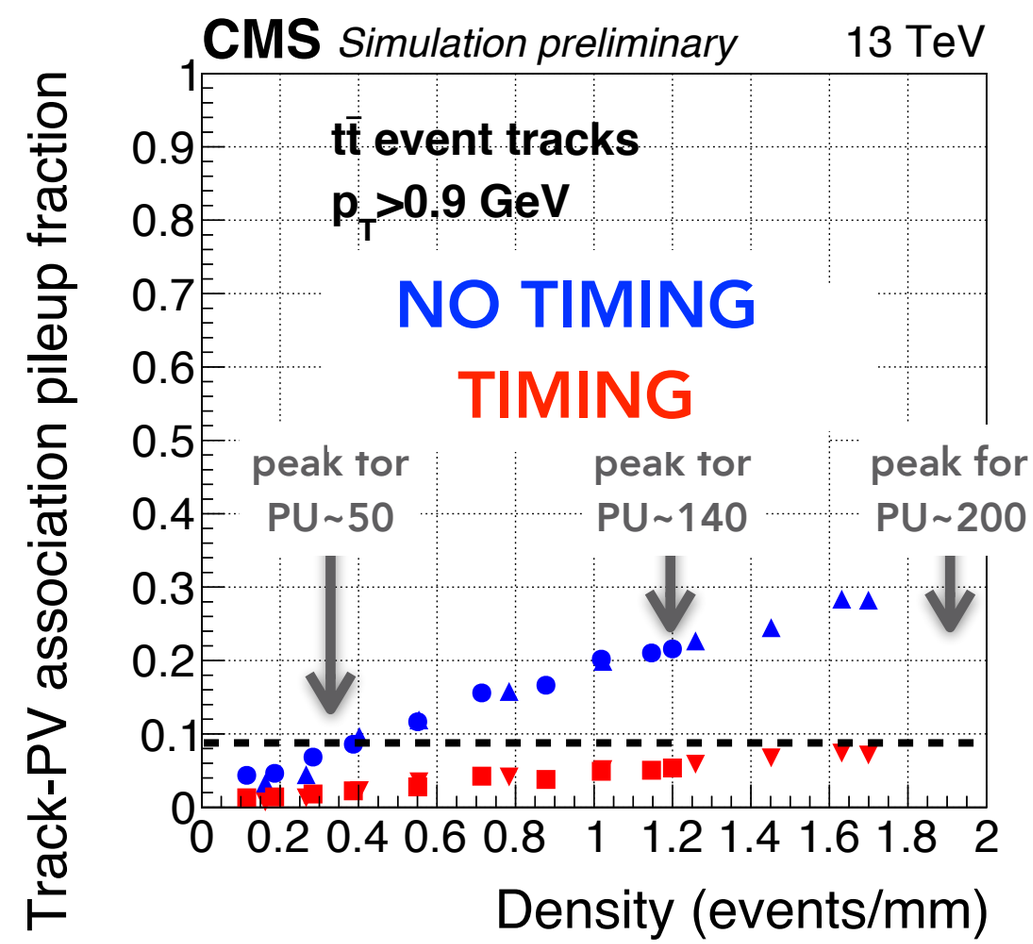
- The full CMS physics program at HL-LHC would benefit from an effective **pileup (PU) mitigation** that allows **current PU~30–50 performance** to be **maintained** at high pileup
  - **Pileup mitigation**: reject charged particles not associated with the hard interaction (PV)
  - **Optimized selection**: **|Δz(track,PV)| < 1 mm.**
    ⇒ non-negligible contamination for vertex density > 1 mm^{-1}

Pileup mitigation with track timing

- Precision track timing allows:
  - **4D vertex reconstruction**
    ⇒ resolve vertices that are close in space but separated in time
  - additional requirement in track-PV association: **$|\Delta t(\text{track,PV})| < 3 \cdot \sigma_t$**
    ⇒ suppress spurious pileup tracks

- With **~30 ps resolution**, effective vertex line density as for current LHC

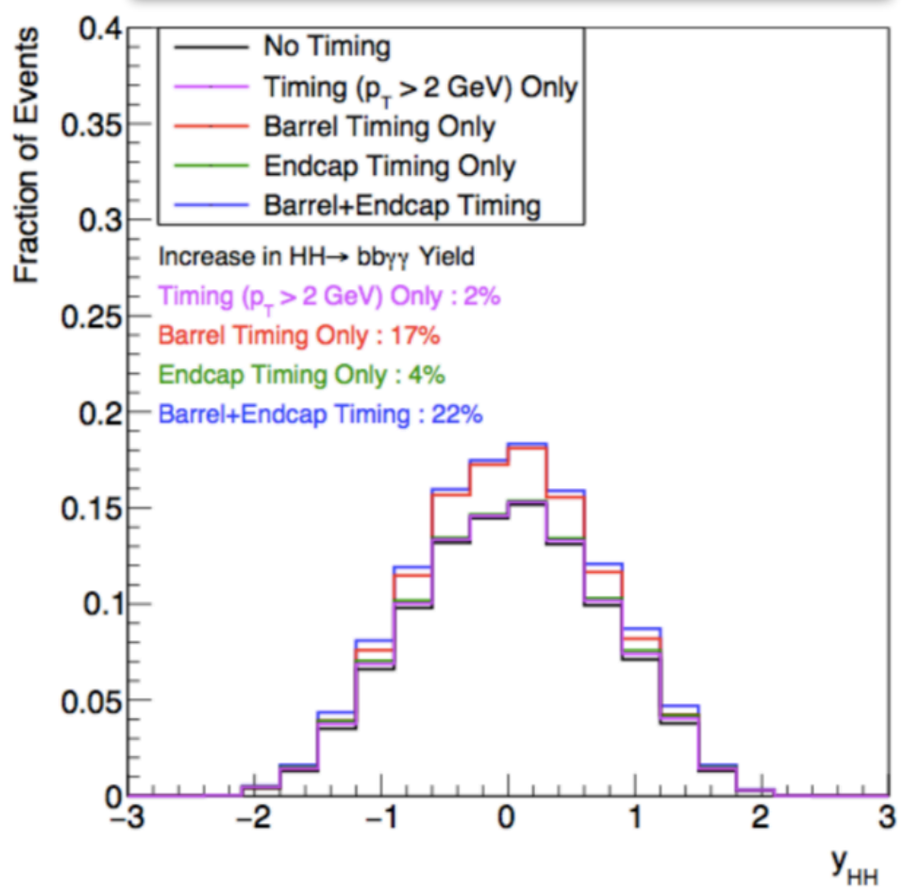




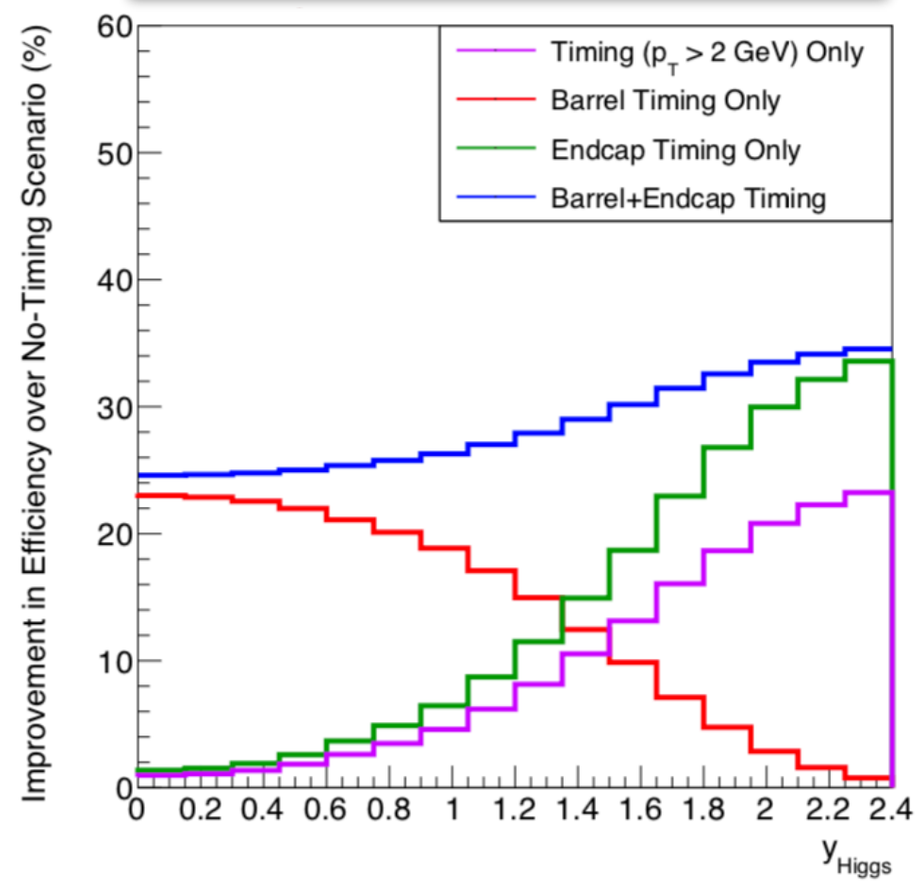
Impact on Higgs physics

- A hermetic precision timing detector allows a **20-30% gain in effective integrated luminosity** across multiple channels
  (at constant rejection power for reducible background)
  - 5-10% efficiency gains on single objects
    - » vertex identification, lepton isolation sums, secondary vertices (b-tag), jets, etc.
  - large gains on multi-object final states

Ex. 1: HH → bb γγ



Ex. 2: H → ZZ → 4l



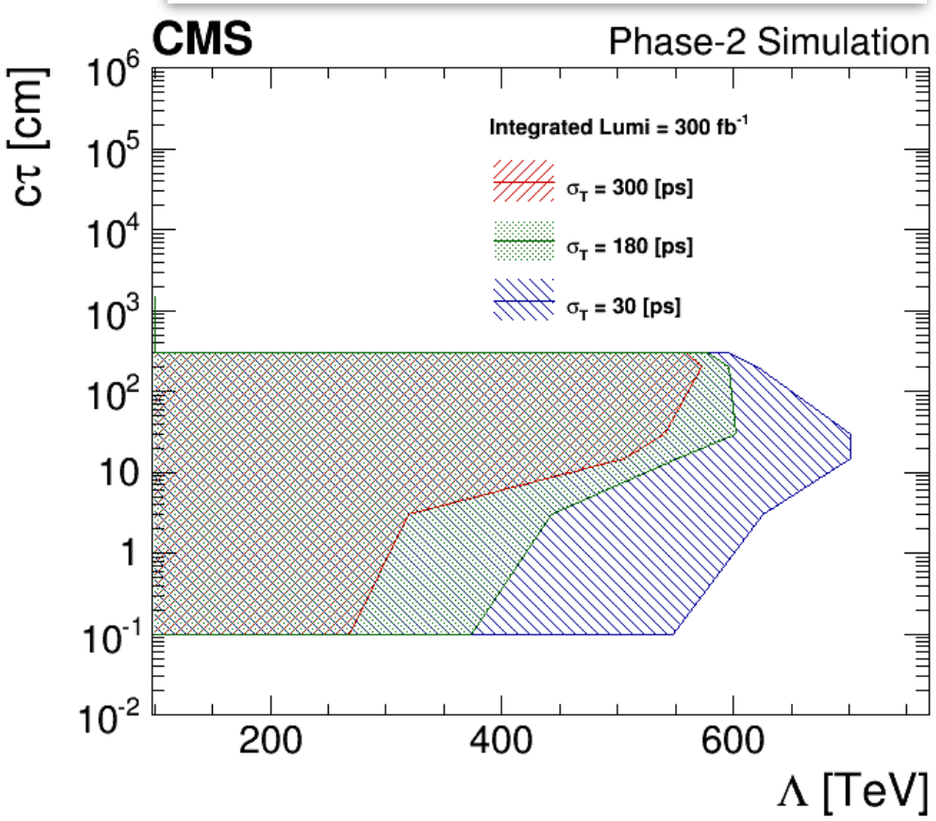
Impact on BSM and LLP searches

- 40% reduction of reducible backgrounds for $\vec{p}_T^{miss}$ tails above 140 GeV
  ⇒ **≳100 GeV extension of the mass reach** for several $\vec{p}_T^{miss}$-based searches

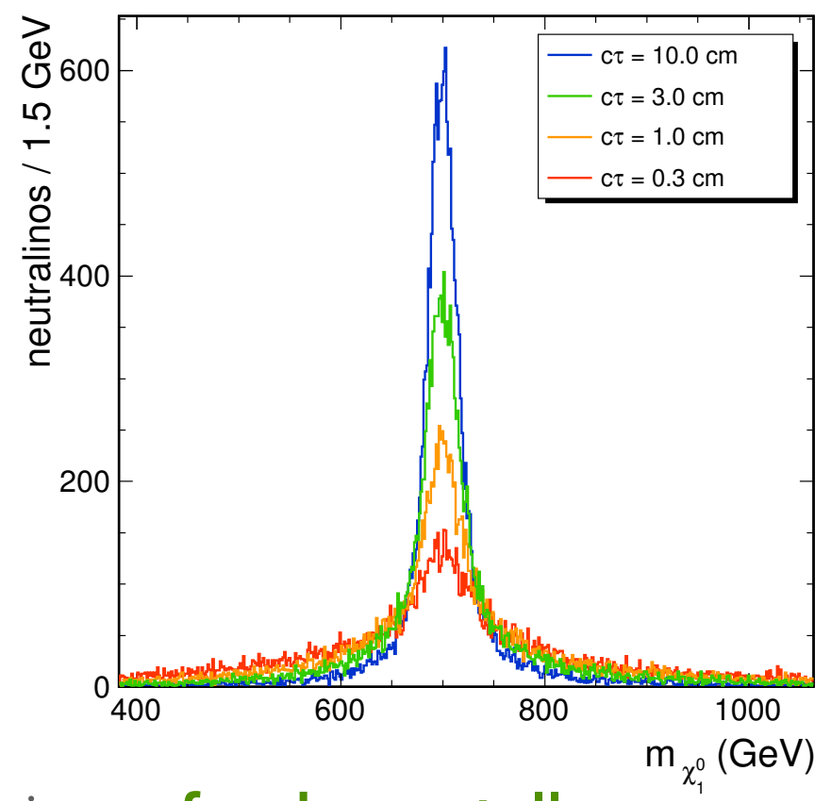
- Enhancements for massive **Long Lived Particles (LLP)** searches:

– **extension of search reach** for massive LLP decaying to photons combining vertex and calorimeter timing for photon TOF measurements

Ex. 1: $\chi_1^0 \rightarrow G + \gamma$



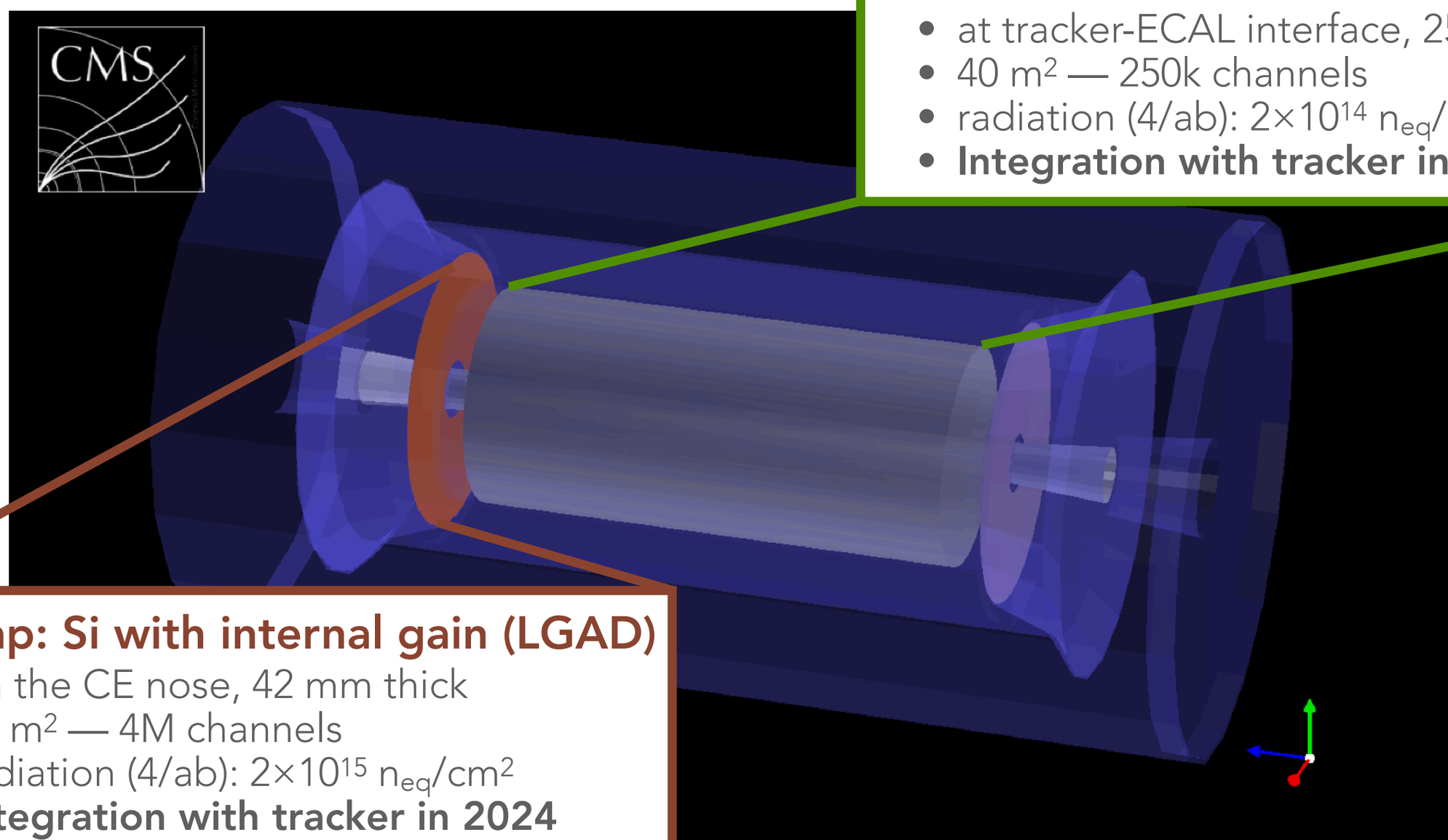
Ex. 2: $\chi_1^0 \rightarrow G + Z$



– allowing a **fundamentally new approach** through the reconstruction of a **peaking mass variable** for LLPs searches involving secondary vertices

MTD design overview

- Proposed MIP Timing Detector (MTD):
  - thin layer between tracker and calorimeters, minimal impact on cal.
  - ~30 ps resolution for charged tracks (above 0.7 GeV)
  - hermetic coverage for $|\eta| < 3.0$

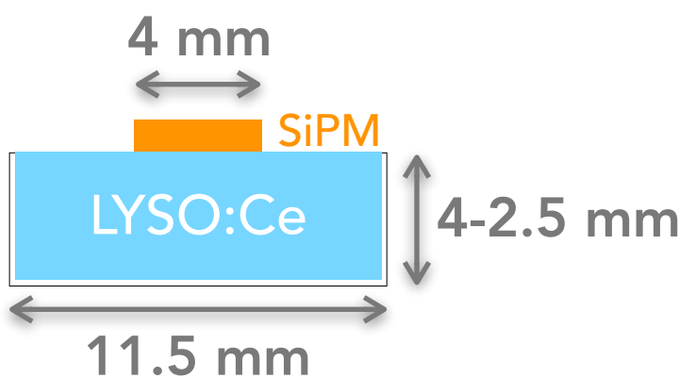


Barrel: LYSO tiles + SiPM readout
- at tracker-ECAL interface, 25 mm thick
- 40 m^2 — 250k channels
- radiation (4/ab): 2×10^{14} n_{eq}/cm^2
- **Integration with tracker in 2022**

Endcap: Si with internal gain (LGAD)
- on the CE nose, 42 mm thick
- 12 m^2 — 4M channels
- radiation (4/ab): 2×10^{15} n_{eq}/cm^2
- **Integration with tracker in 2024**

Barrel detector design

Fundamental detector unit

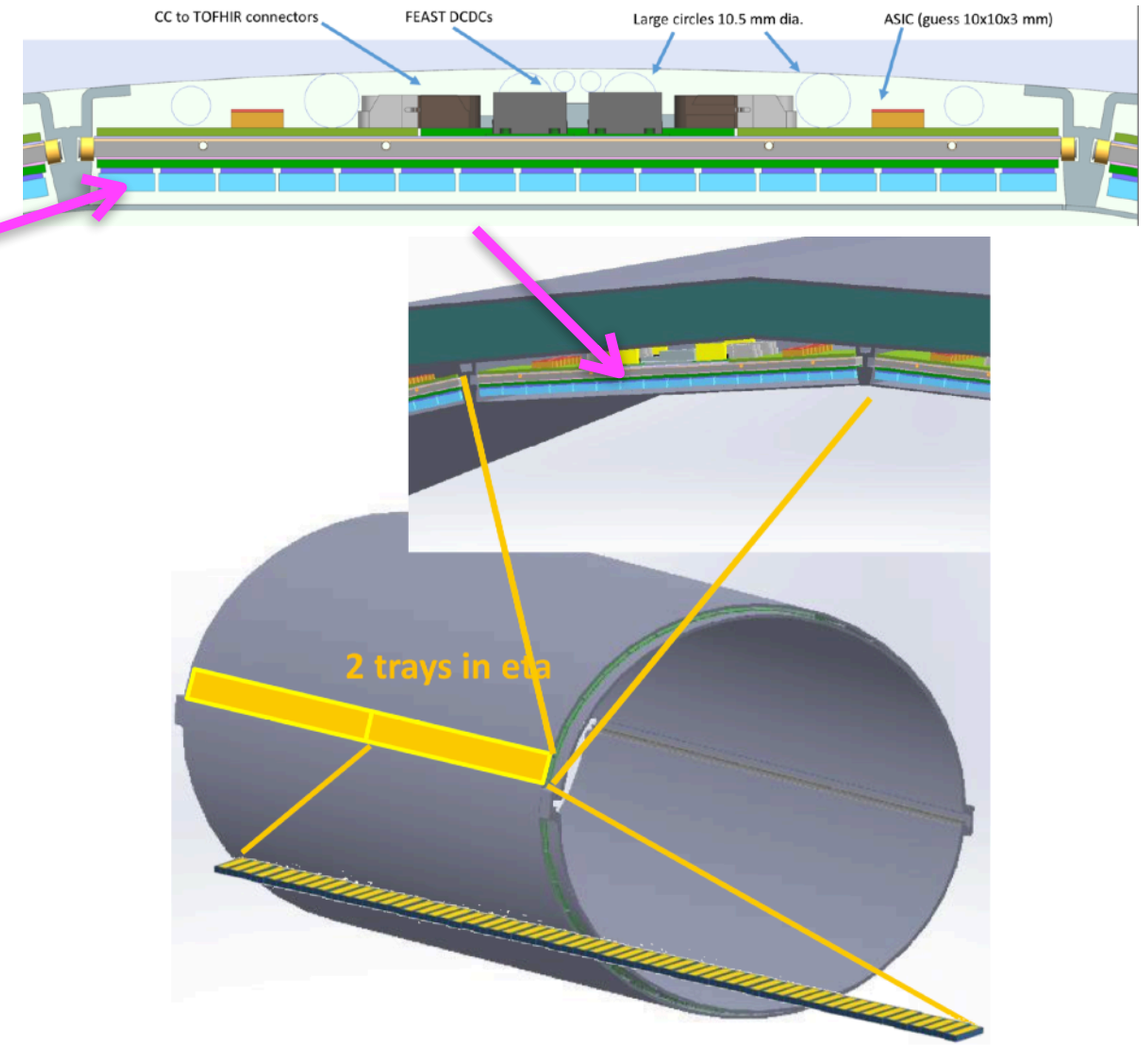


- Operated at -30° C
- SiPM active area limited to < 16 mm^2 (radiation-induced noise and power dissipation considerations)

Electronics

- ASIC: **TOFHiR** (adapted from commercially-available TOFPET)
  - leading edge discrimination + amplitude measurement for time-walk corrections
- Front-end boards: ASIC + power distribution + clock & data links (LpGBT)
  - 1.2 TB/s data volume

Integration with tracker

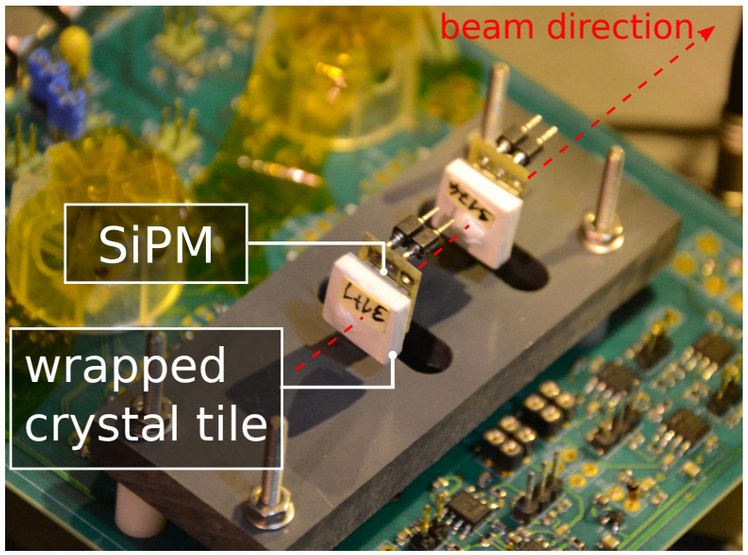


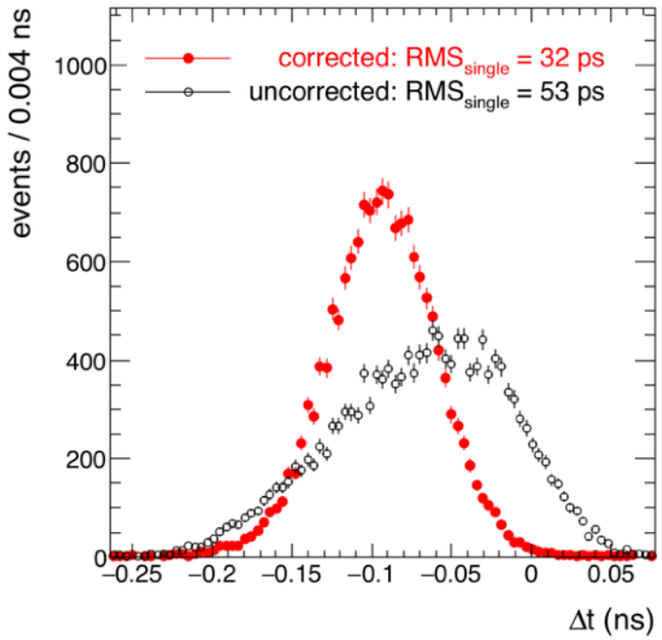
- Barrel **modules assembled in "trays"**
- **Trays** inserted and **embedded** in the **Tracker Support Tube**

challenge:
cope with SiPM dark count rate expected after irradiation

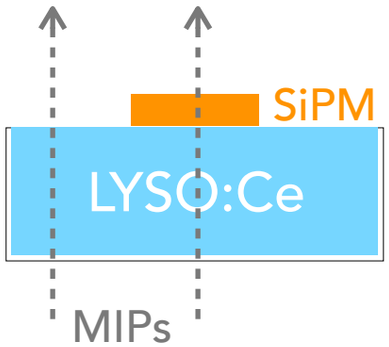
Crystal+SiPM beam tests and R&D

- **Target timing resolution** demonstrated at **beam tests**:

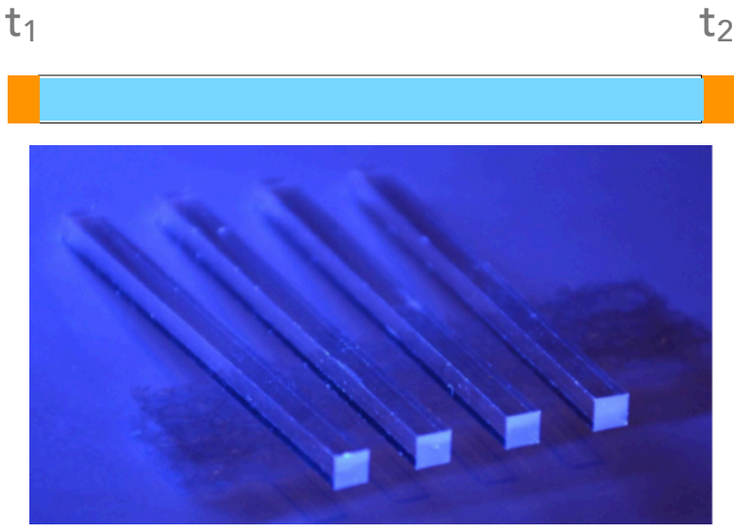




  – however, **timing dependence on hit position** on the tile observed



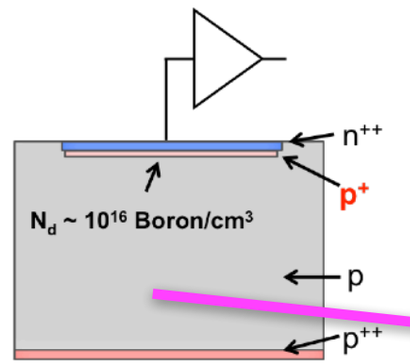
- Hardware solutions being considered:
  – tailored SiPM with **uniform tile surface coverage** at **constant active area** (Large Area Sparse Cell SiPM)
    » response is uniform by construction, but large Si area
  – replace **crystal** tiles with **bars** (dimensions 3×3×45 mm^3), read out on both sides (measure t_1 and t_2)
    » $\langle t_1+t_2 \rangle$ is ~ independent on position
    » position information deduced from t_1-t_2



Endcap detector design

Fundamental detector unit

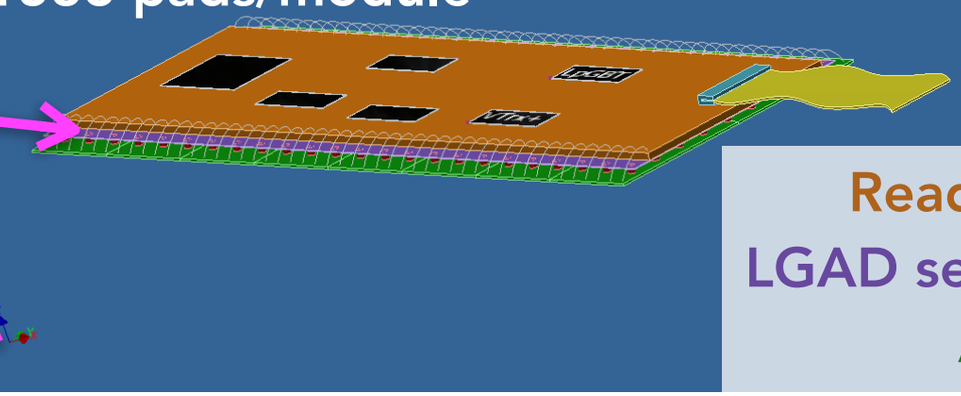
- Low-gain avalanche diode (LGAD), typical gain: 10-30
- 1×3 mm² pads
- 3-to-1 ganging for $|\eta| < 2.1$



Low gain avalanche detectors

Endcap module

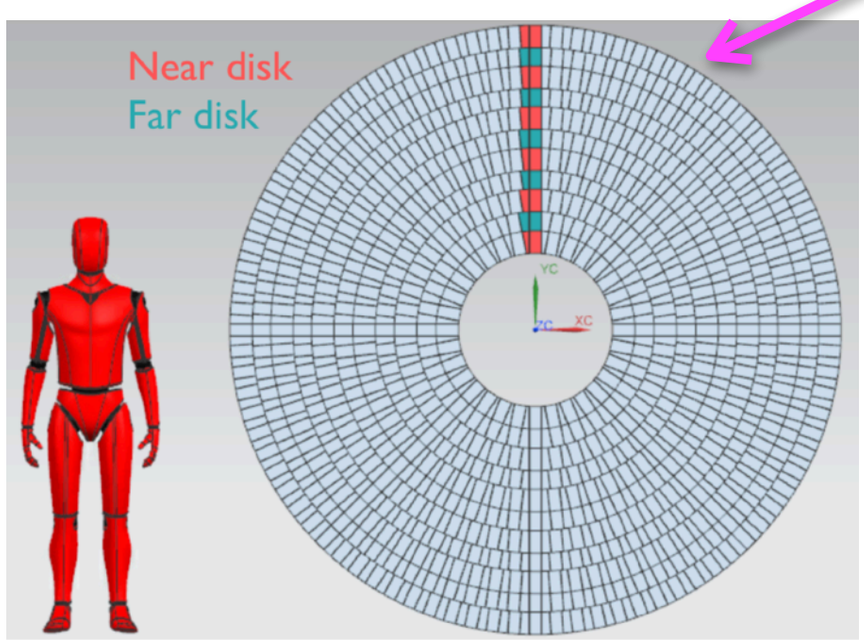
Module size: 50×100 mm²
LGAD sensor size: 48×96 mm²
1536 pads/module

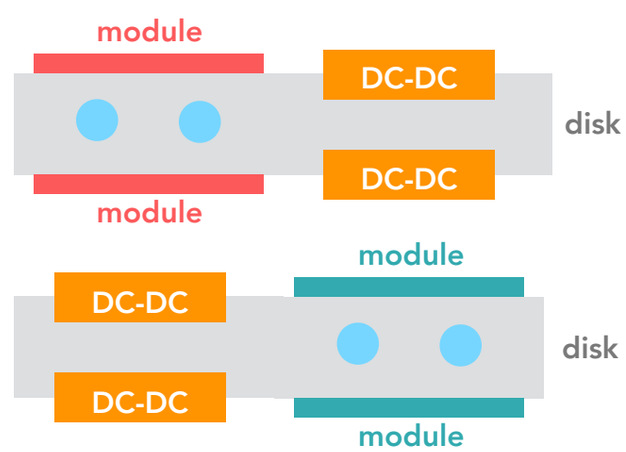


Read out
LGAD sensor
ASIC

- ASIC (design ongoing): pre-amp. + disc. + ToA + TDC

Endcap disk



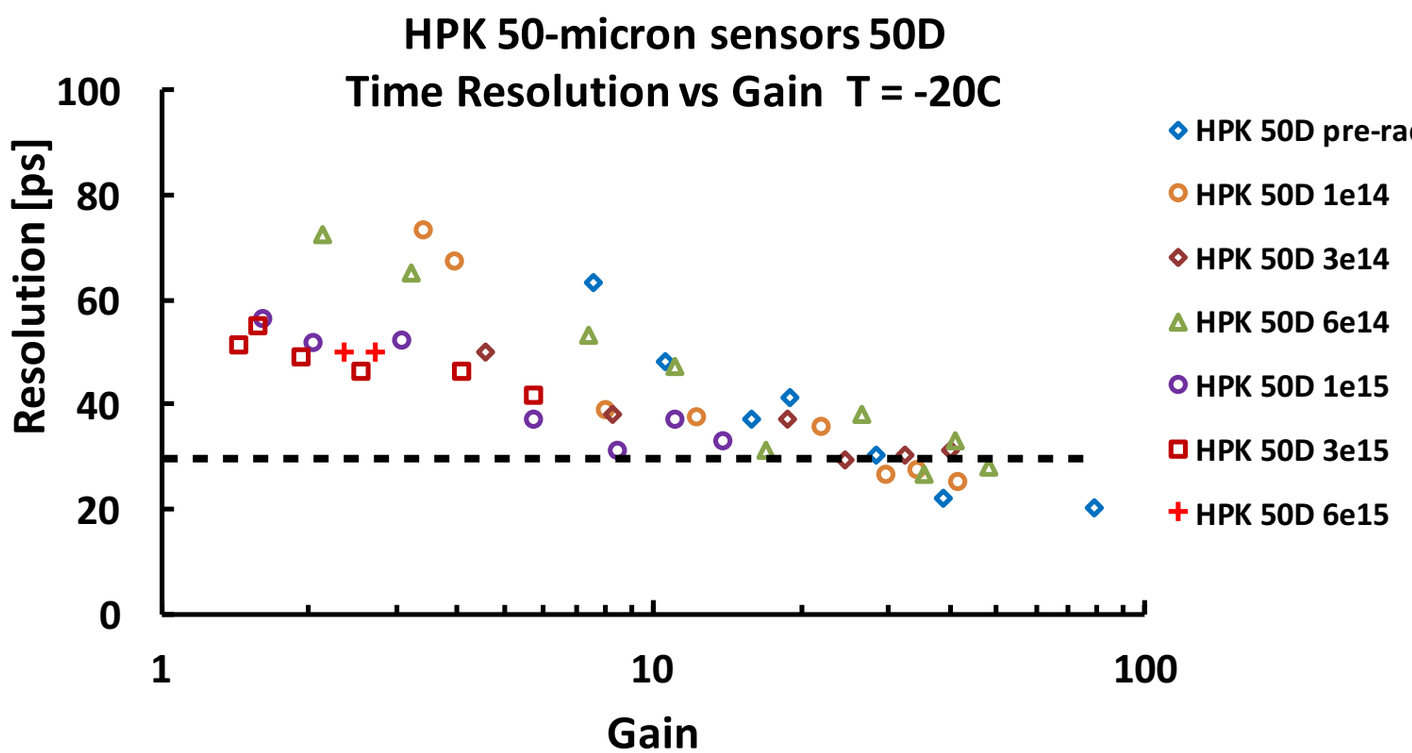


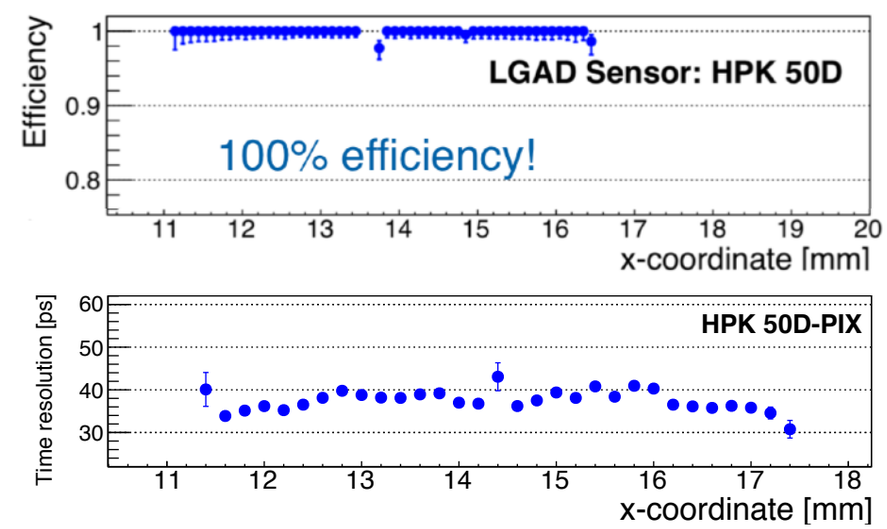
- Overlapping 2-disk structure on HGCal "nose"
- Al wedges with embedded cooling pipes (CO_2, -30° C)

challenge: ASIC with ~20 ps resolution

LGAD beam tests and R&D

- **Target timing resolution** demonstrated at **beam tests**:
  - < 40 ps throughout the whole HL-LHC (up to 1–2×10^{15} n_{eq}/cm^2)
  - resolution maintained increasing bias voltage (300 V → 600 V)





- R&D activity:
  - improve radiation resistance (reduce need of bias voltage increase)
  - increase sensor fill factor (detector has 1! sensitive layer)
  - increase sensor dimension

Summary

- The capability of measuring the time of charged tracks with ~30 ps precision is a powerful tool for pileup mitigation at the HL-LHC

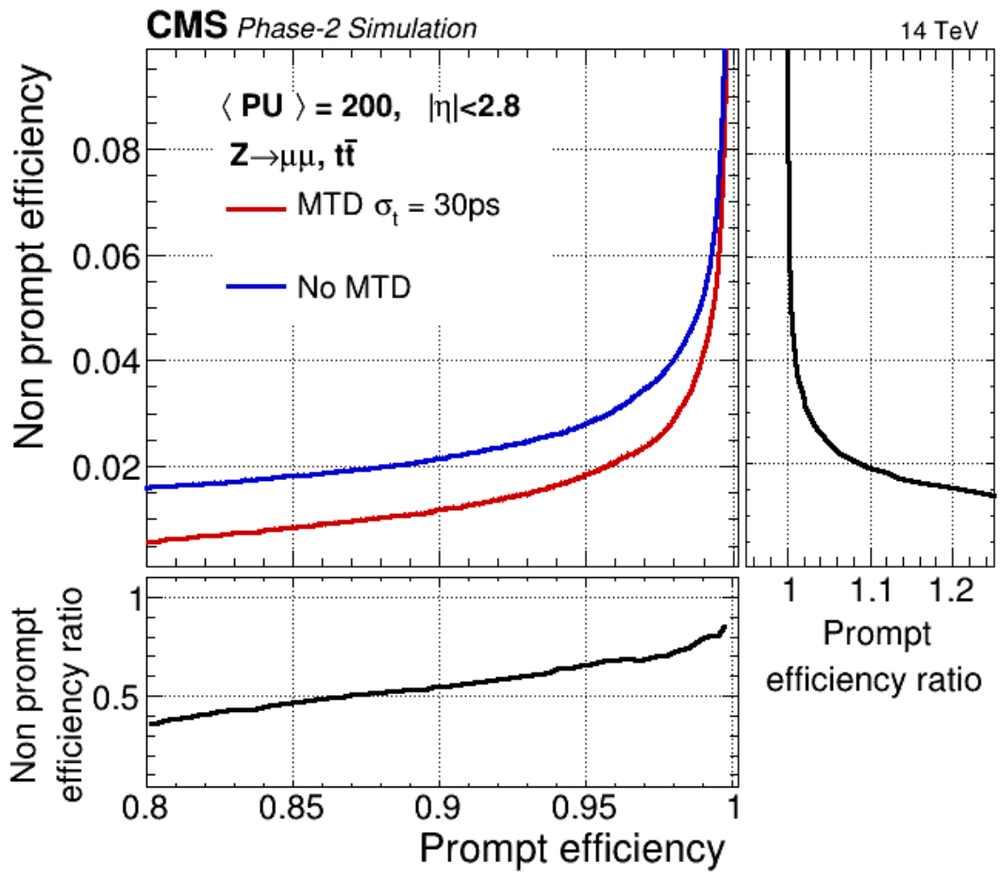
- Significant performance gains have been outlined for a wide range of physics channels that are critical for the HL-LHC program

- The CMS Collaboration has proposed a hermetic MIP timing detector with maximal p_T and η coverage for charged tracks
  - complementing timing measurements from upgraded calorimeters

- The project is well advanced, R&D on sensor and ASIC optimization is progressing to ensure the timing performance can be maintained until the end of HL-LHC operations

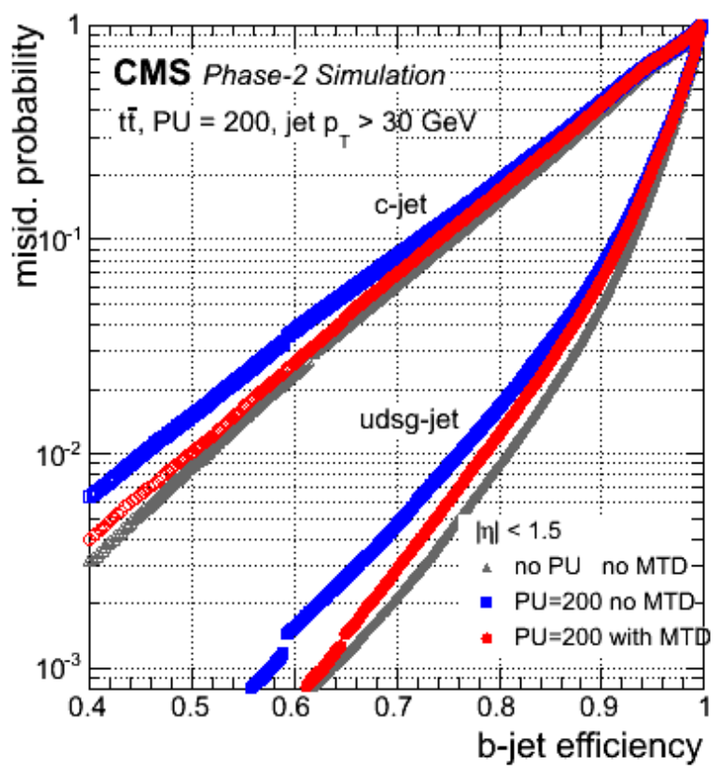
Bonus material

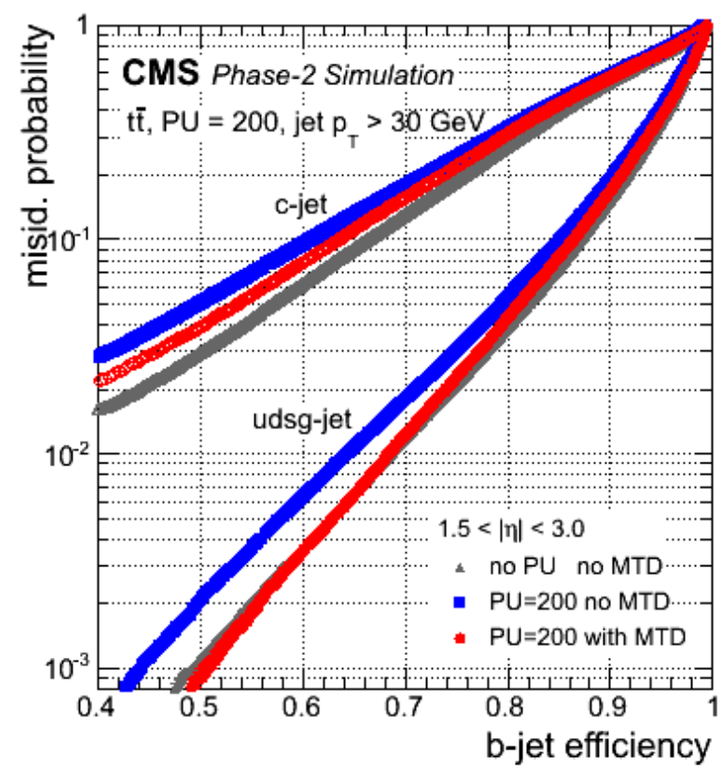
Lepton isolation and b-tagging



– **Isolation**: at 97% efficiency working point, recover ~6-7% off at the same background rejection

– **b-tagging**: removal of tracks with incompatible time with PV reduces the number of spurious secondary vertices by 30%; no-PU performance almost recovered, esp. for tight working points





Summary of impact on various benchmark channels

channel	physics measurement	timing detector impact
$H \to \gamma\gamma$ $H \to ZZ \to 4l$	+25% statistical precision on σ ⇒ couplings	Isolation, vertex identification
$qqH \to \tau\tau$ (VBF)	+25% statistical precision on σ ⇒ couplings	Isolation, VBF jet tagging, MET
$HH \to bb\ \gamma\gamma$	+25% gain in signal yield ⇒ consolidate searches	Isolation, b-tagging
EWK SUSY	40% red. background reduction ⇒ +150 GeV mass reach	MET tail reduction
Long-lived particles (LLP)	peaking variable reconstruction ⇒ unique discovery potential	β_{LLP} from displaced vertices