An overview of the reconstruction strategy for the CMS HGCAL and detector performance studies

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on behalf of the CMS Collaboration

European Organisation for Nuclear Research

20th International Conference on
Calorimetry in Particle Physics

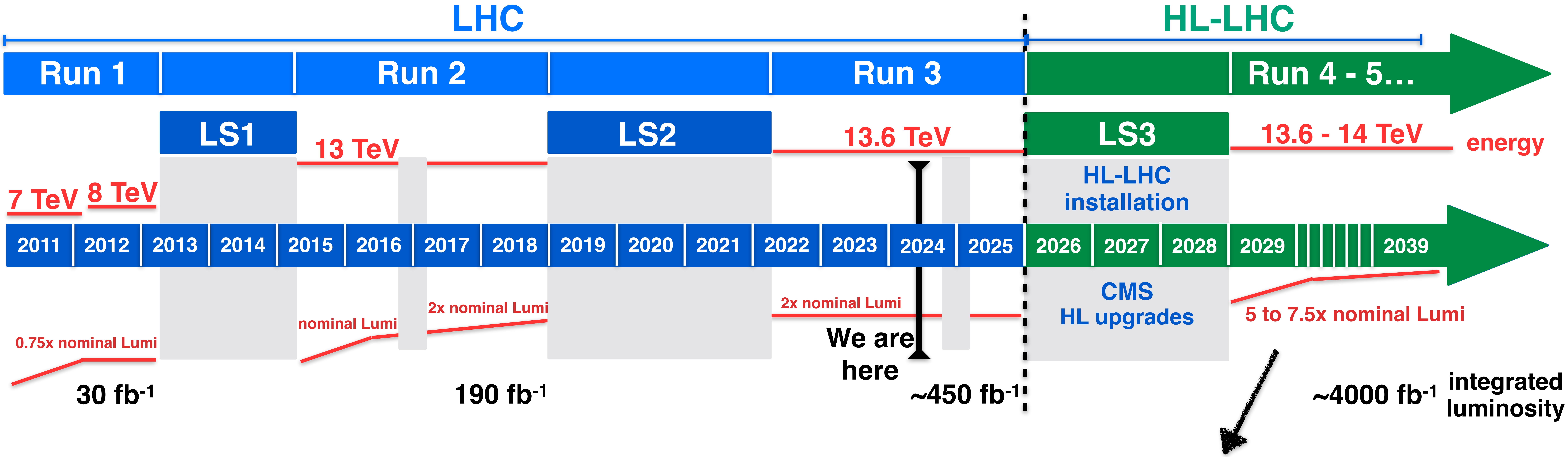
May 24th, 2024

CERN

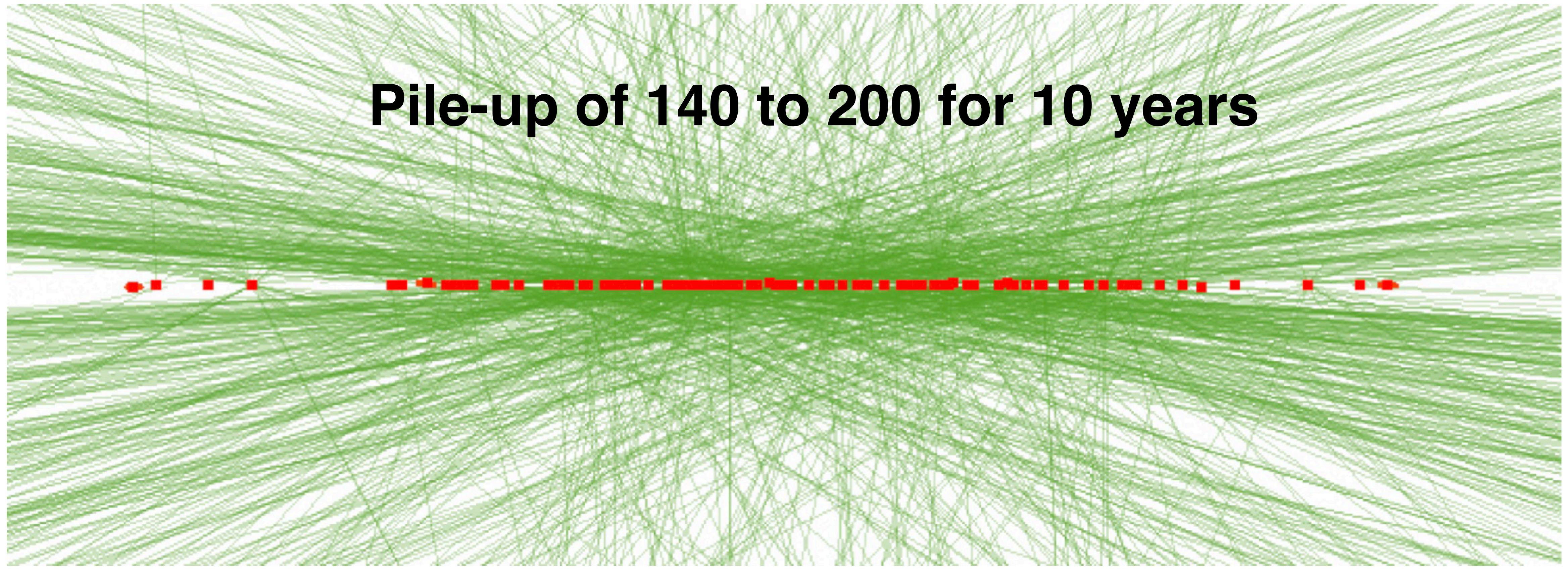
CMS
Compact Muon Solenoid

CALOR 2024
Tsukuba

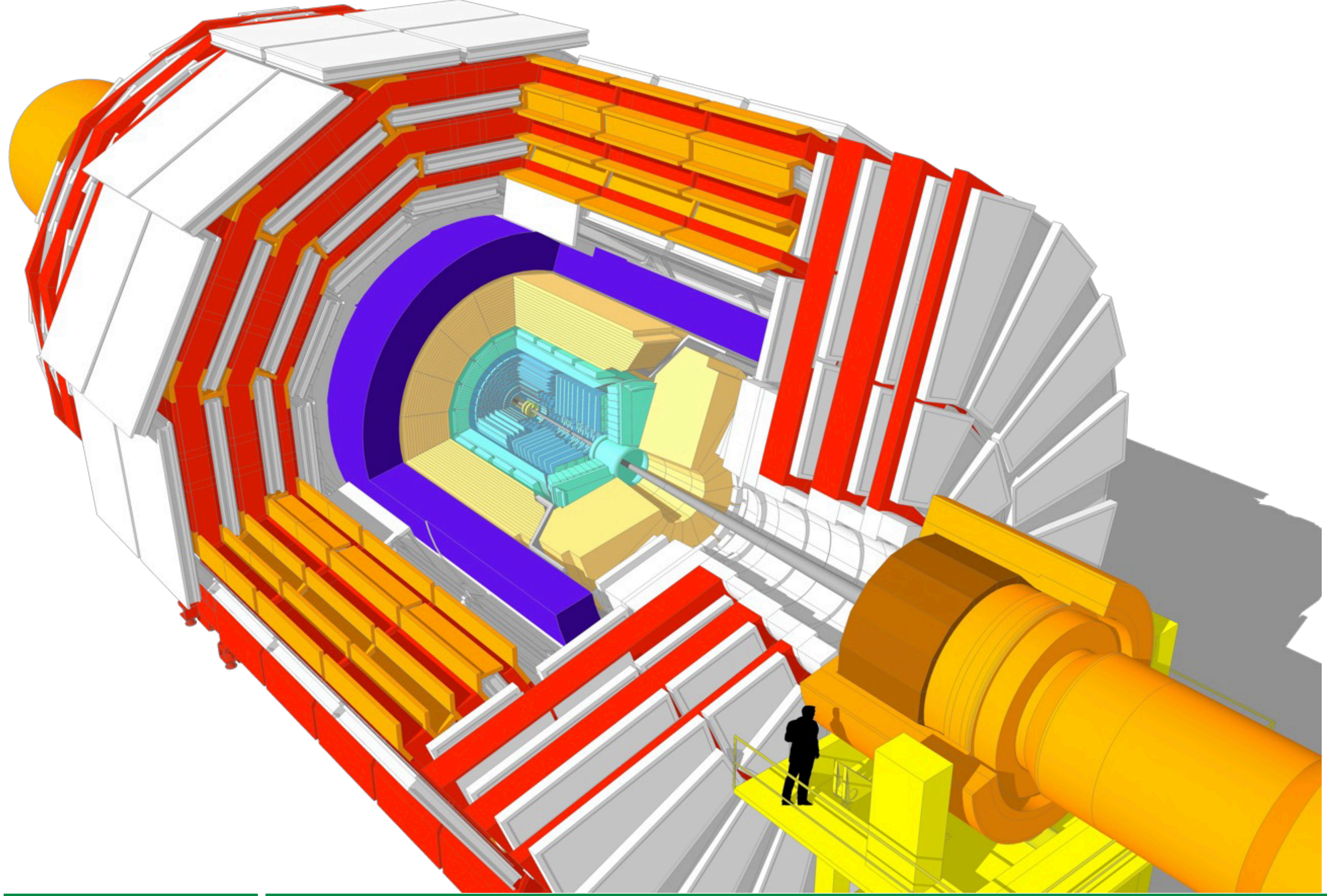
HEP program at LHC



- HL-LHC will provide PU up to 200 and higher luminosity.
- CMS will undergo a major upgrade for HL-LHC to sustain radiation levels and resolve vertex density.



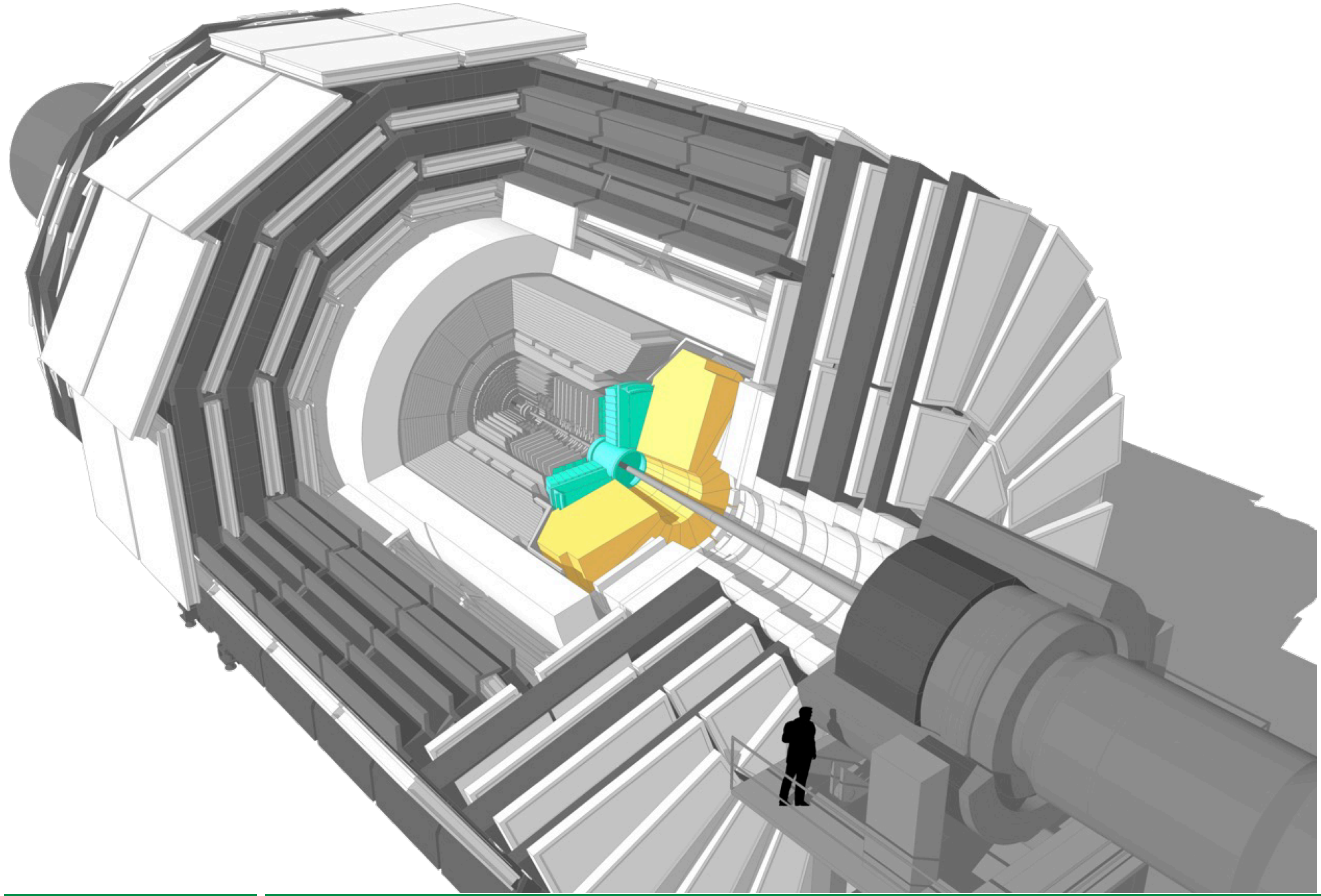
CMS upgrades for HL-LHC



Upgrades:

- Radiation tolerance
- Higher granularity
- Extended coverage
- Sub-100-ps timing precision
- Enhanced trigger capabilities

CMS upgrades for HL-LHC

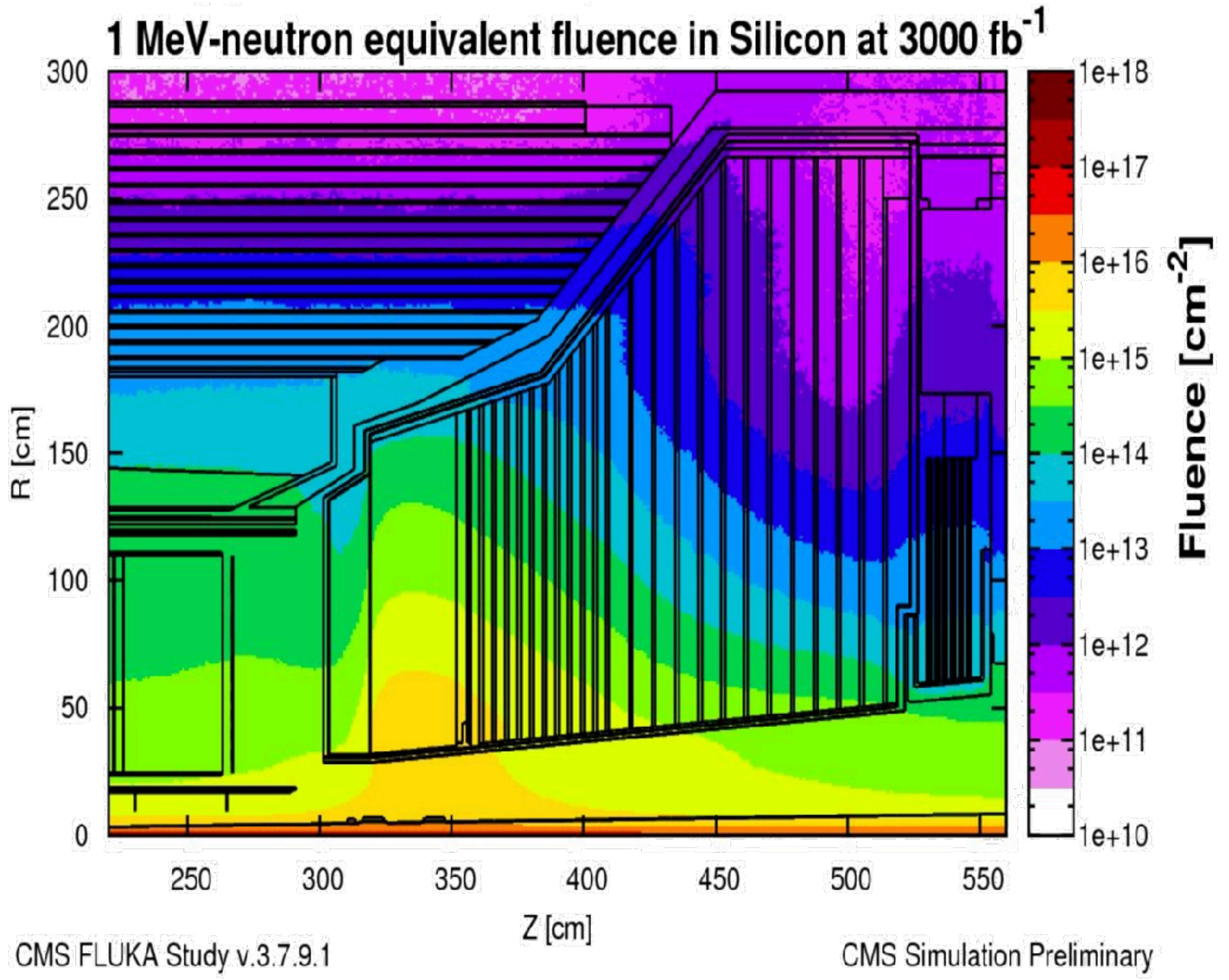


Upgrades:

- Radiation tolerance
- Higher granularity
- Extended coverage
- Sub-100-ps timing precision
- Enhanced trigger capabilities

New end-cap calorimeters:

- Higher radiation tolerance
- Fine spatial granularity
- Precise timing for showers



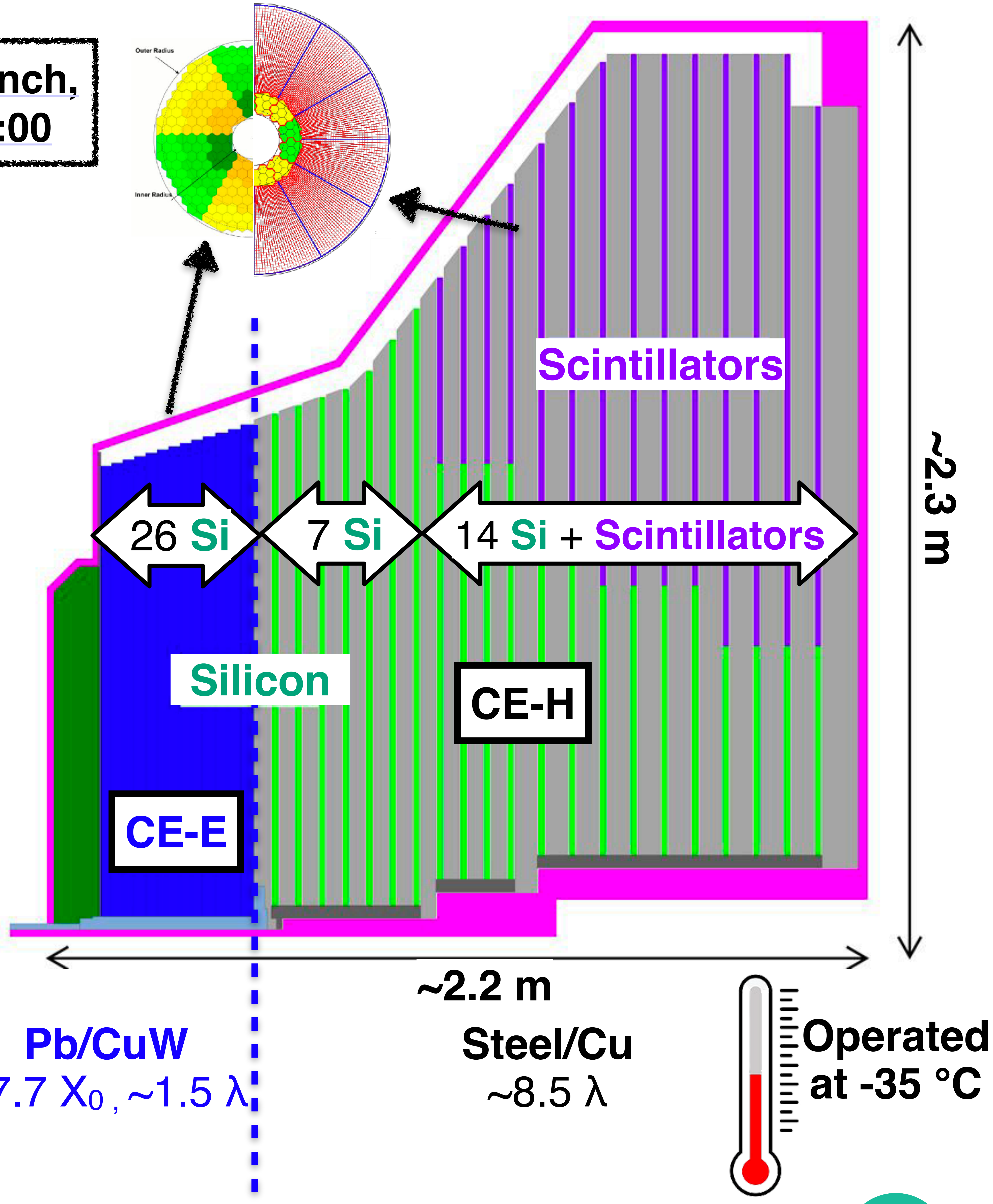
$10^{16} n_{eq}/cm^2$ (2MGy) after 3000 fb^{-1}

CMS High Granularity Calorimeter

- 5D imaging calorimeter covering $1.5 < |\eta| < 3.0$
  - 3D spatial granularity, energy and timing information.
- Sampling calorimeter separated in two sections:
  - **CE-E**: electromagnetic , **CE-H**: hadronic
- **Active materials:**
  - **Silicon sensors** (**CE-E** and **CE-H**)
    - Hexagonal, 120/200/300 µm thick, 8" wafers.
    - Low and high density modules.
    - 6M pads and 26k modules (620 m^2)
  - **Plastic scintillators** with SiPM readout (CE-H)
    - 240k tiles and 3.7k modules (370 m^2)
- **Passive materials:**
  - Pb & steel absorbers and Cu, CuW or C-fiber plates
  - Dense and compact → 225 T
- The electronic systems will be detailed in **Aidan Grummers** and **Stavros Maillos** talks.

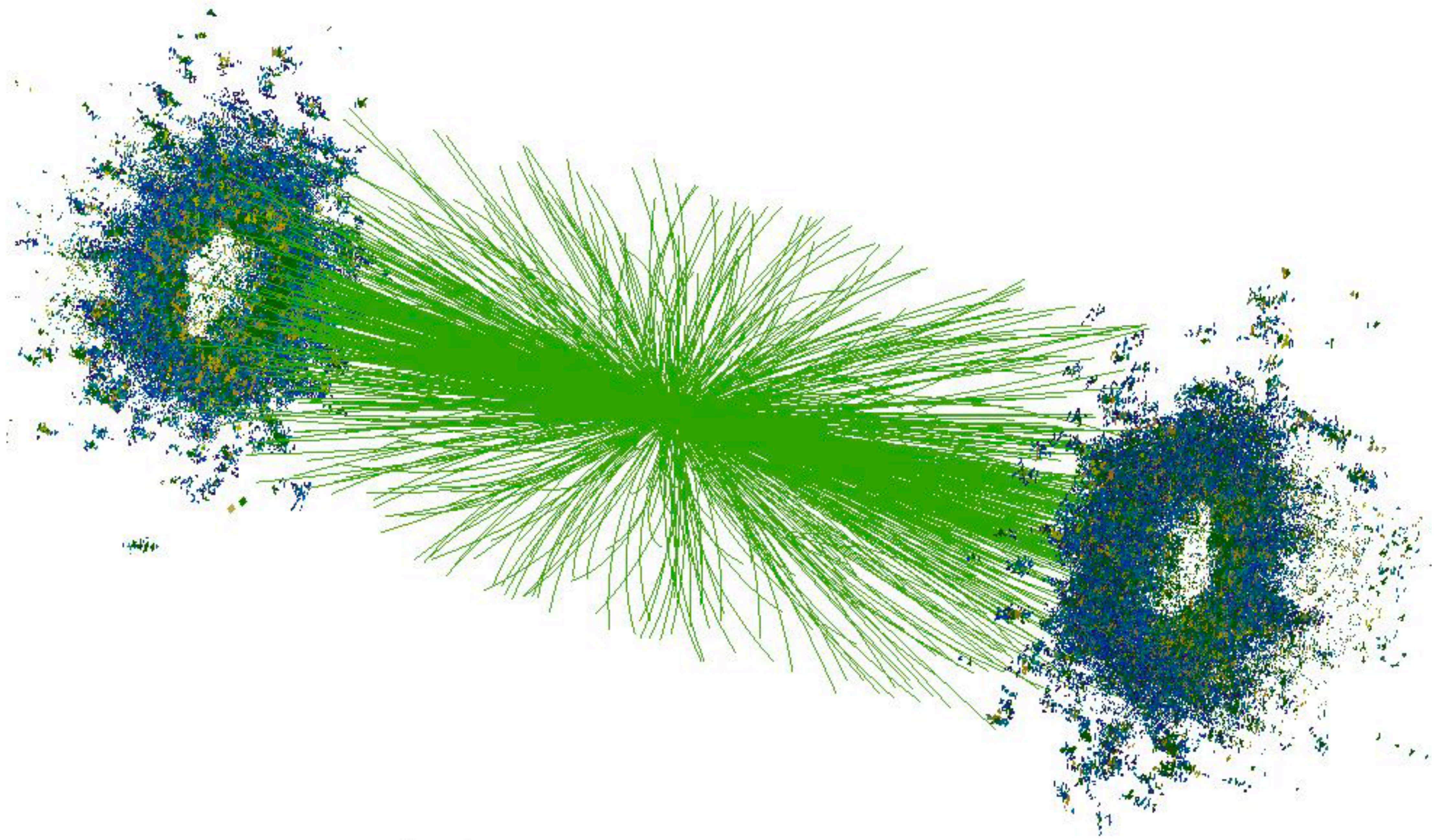
Thomas French, 24 May, 16:00

Poster Antoine Laudrain



HGCAL reconstruction challenges

- Unprecedented data volumes:
  - 750 kHz trigger rate
  - DAQ at 7.5 kHz with ~ 6M channels
- Higher event complexity:
  - 140-200 PU → dense environments



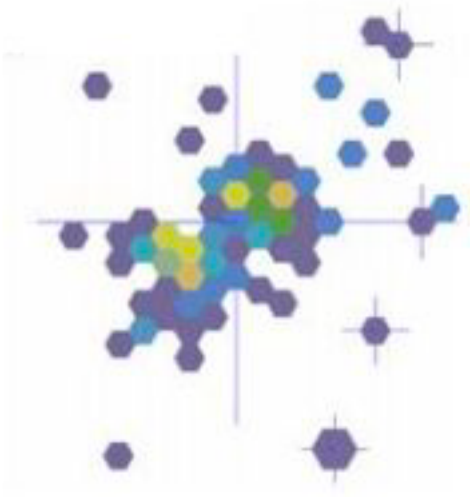
VBF jets + H→γγ

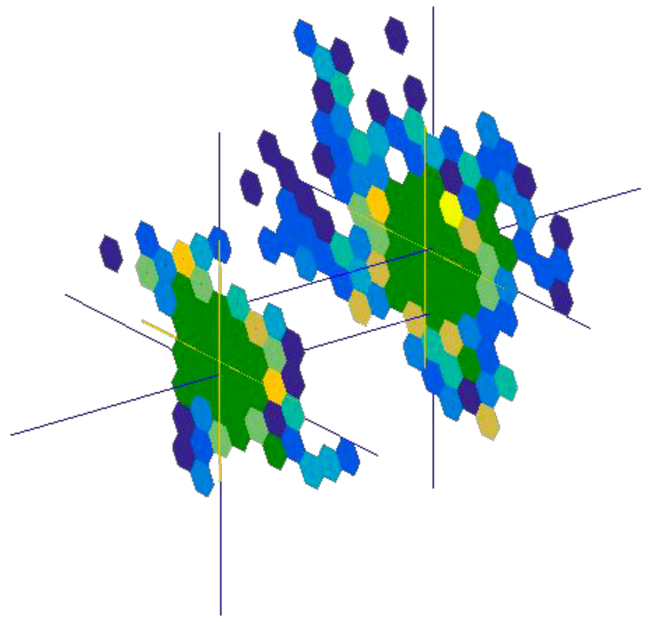
Needs dedicated reconstruction algorithms to exploit precise 5D information with high performance

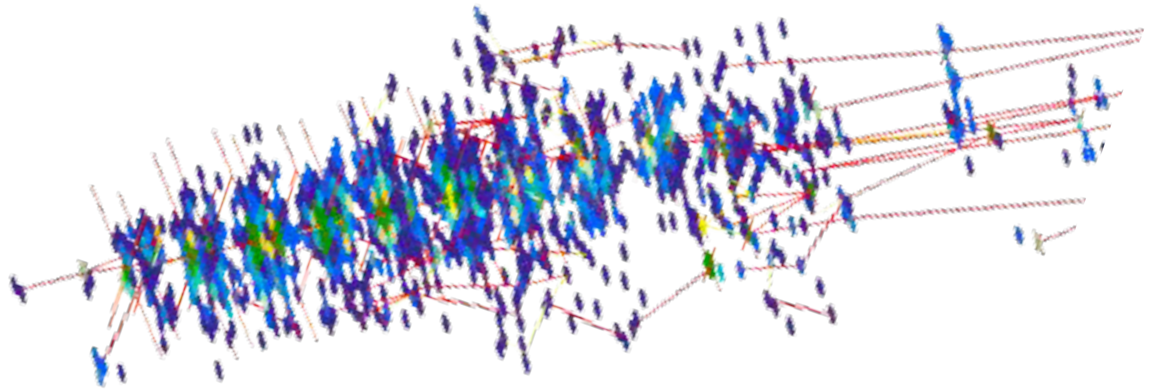
The Iterative Clustering (TICL) framework

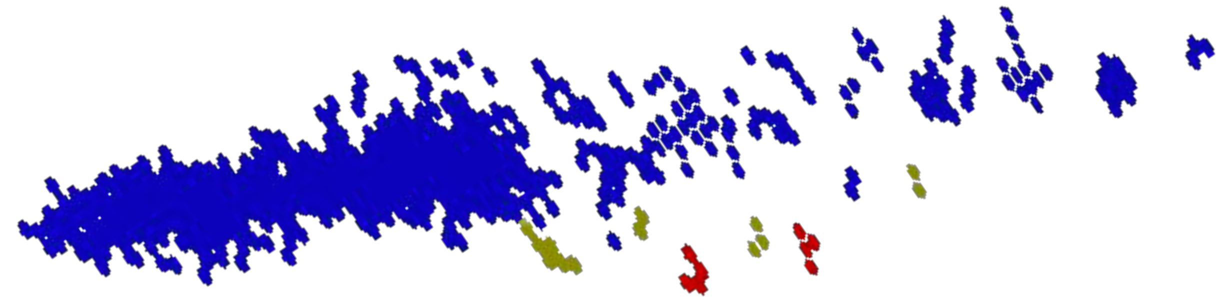
Reconstructed Hits → Layer clustering (CLUE) → Layer-clusters (2D) → Pattern Recognition (CLUE3D) → Tracksters (3D) → Linking with timing, tracking and PID → Particles (5D)

10^5 **10^4** **10^3**









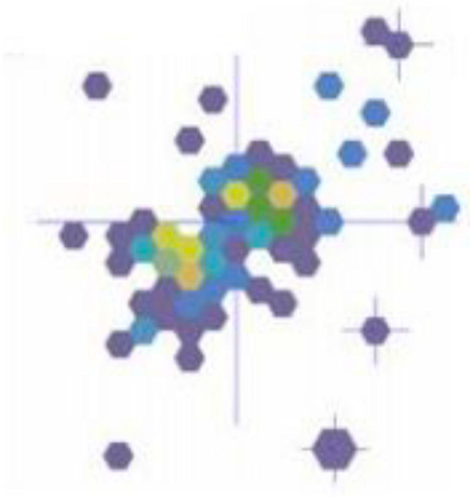
$<dN/d\eta>_{inel}$ ~ O(1k) at 200 PU

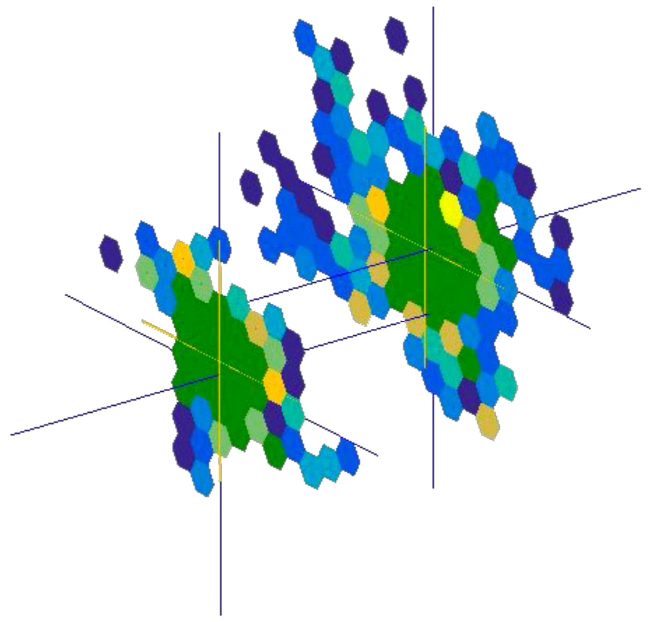
- HGCAL reconstruction developed within novel Iterative Clustering (TICL) framework
  - Modular framework allowing iterative iterations targeting different objects.
  - Reconstruct particle showers from reconstructed hits exploiting 5D information.
  - Designed considering heterogenous computing to maximize performance.
  - Use performance libraries to support different architectures.

Clustering algorithms

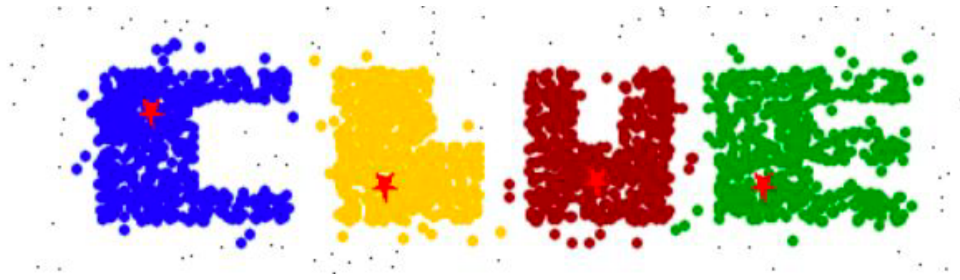
Reconstructed Hits → Layer clustering (CLUE) → Layer-clusters (2D) → Pattern Recognition (CLUE3D) → Tracksters (3D) → Linking with timing, tracking and PID → Particles (5D)

10^5 | 10^4 | 10^3





- CLUE: Clustering of Energy
  - Energy density based
  - Reduces dimensionality and removes noise
  - Operates fast (~300 events/s on GPU)
  - Minimal loss of information



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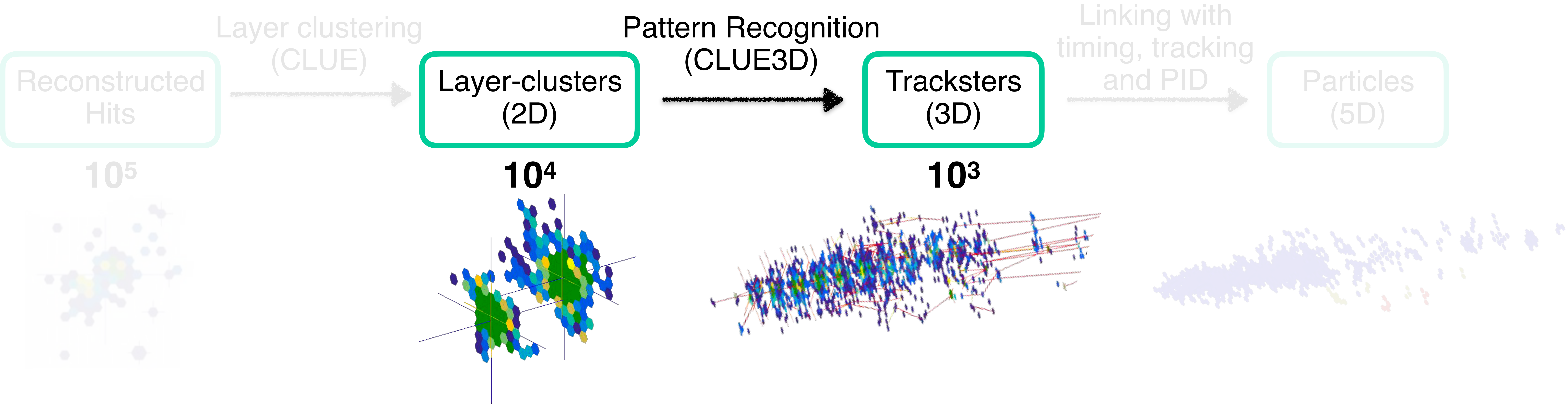
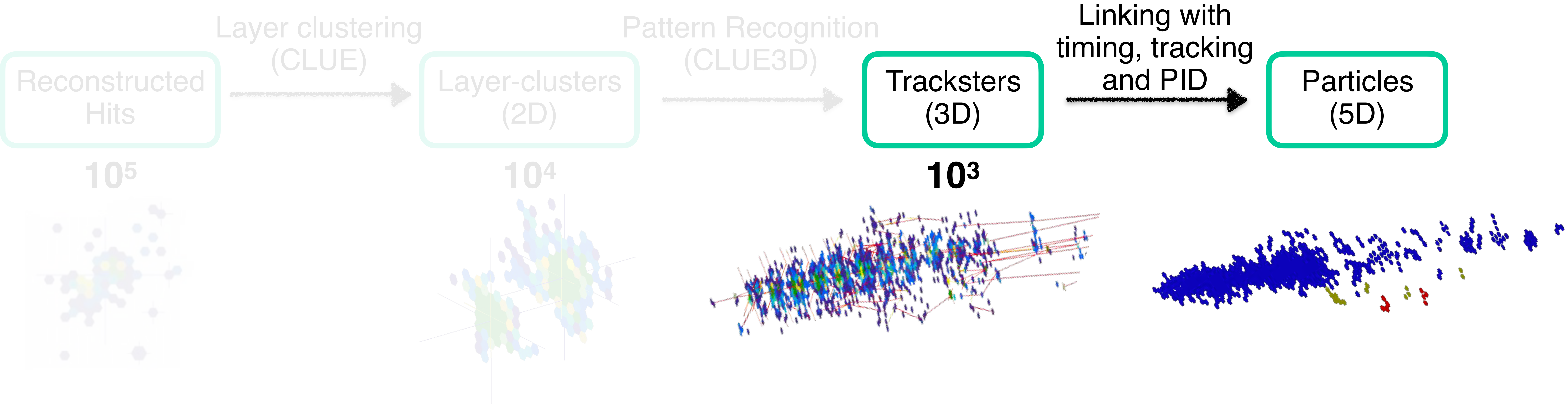
Clustering algorithms



- CLUE3D: longitudinal pattern recognition
  - Use CLUE to recluster layer-clusters considering longitudinal dimension
  - Forms directed acyclic graphs of layer clusters (tracksters)
  - Can handle > 200 events/s using GPUs

Particle flow algorithm

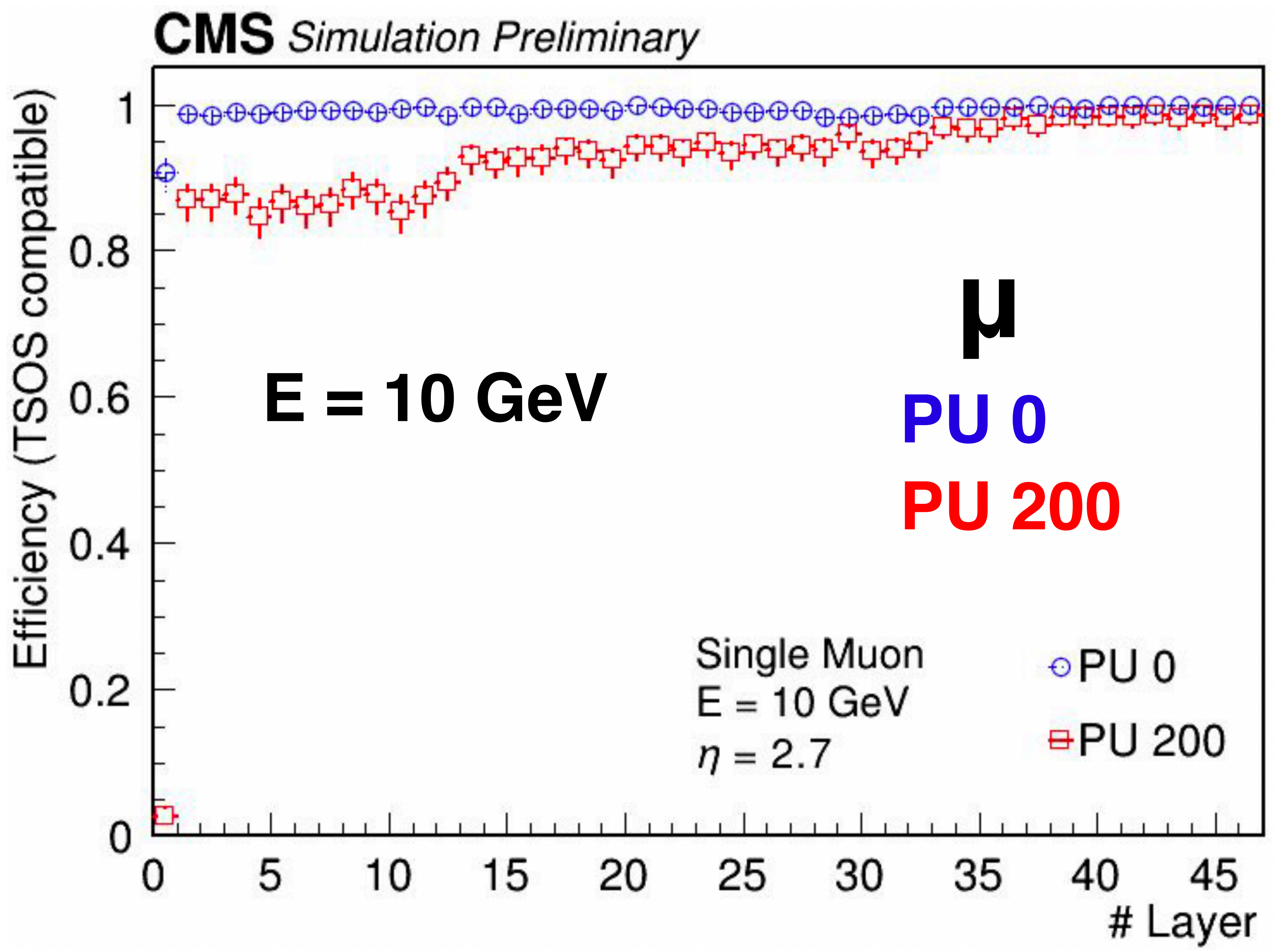


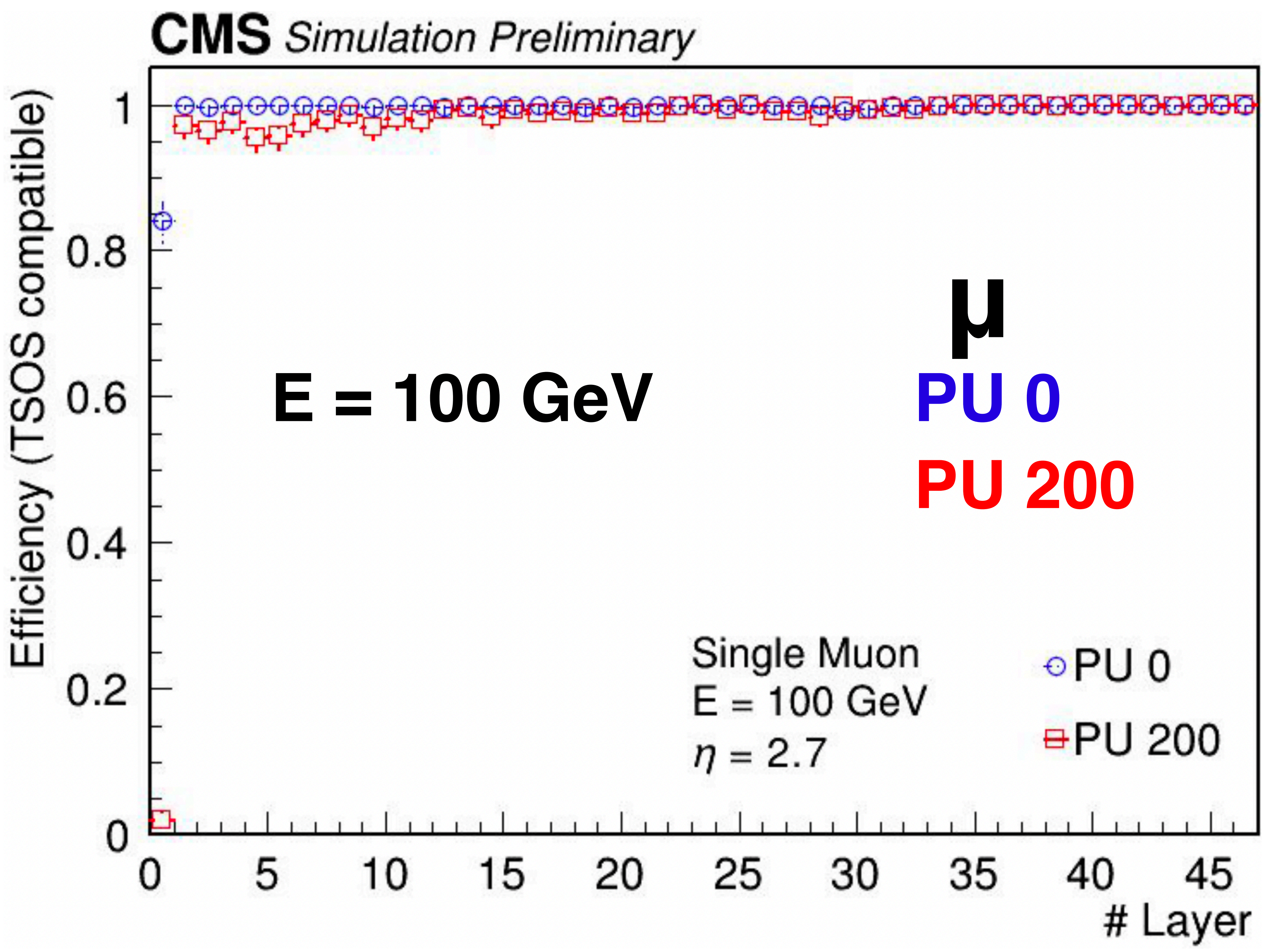
- Particle flow: combine all detector information
  - Links tracksters to form particle showers
  - Geometrical linking aided by timing and energy compatibility (5D)
  - Assigns particle properties

Muon reconstruction in HGCAL

CMS-DP-2023-078

- Intercalibration crucial to retain good energy resolution throughout lifetime of calorimeter.
- CMS extended tracker and muon detector coverage up to |η|~3.0 in HL-LHC enables the use of muons, as MIPs, for intercell calibration of endcap calorimeter.
- Muons are precisely tracked inside the HGCAL volume with a Kalman Filter fit which accounts for material budget and magnetic field.

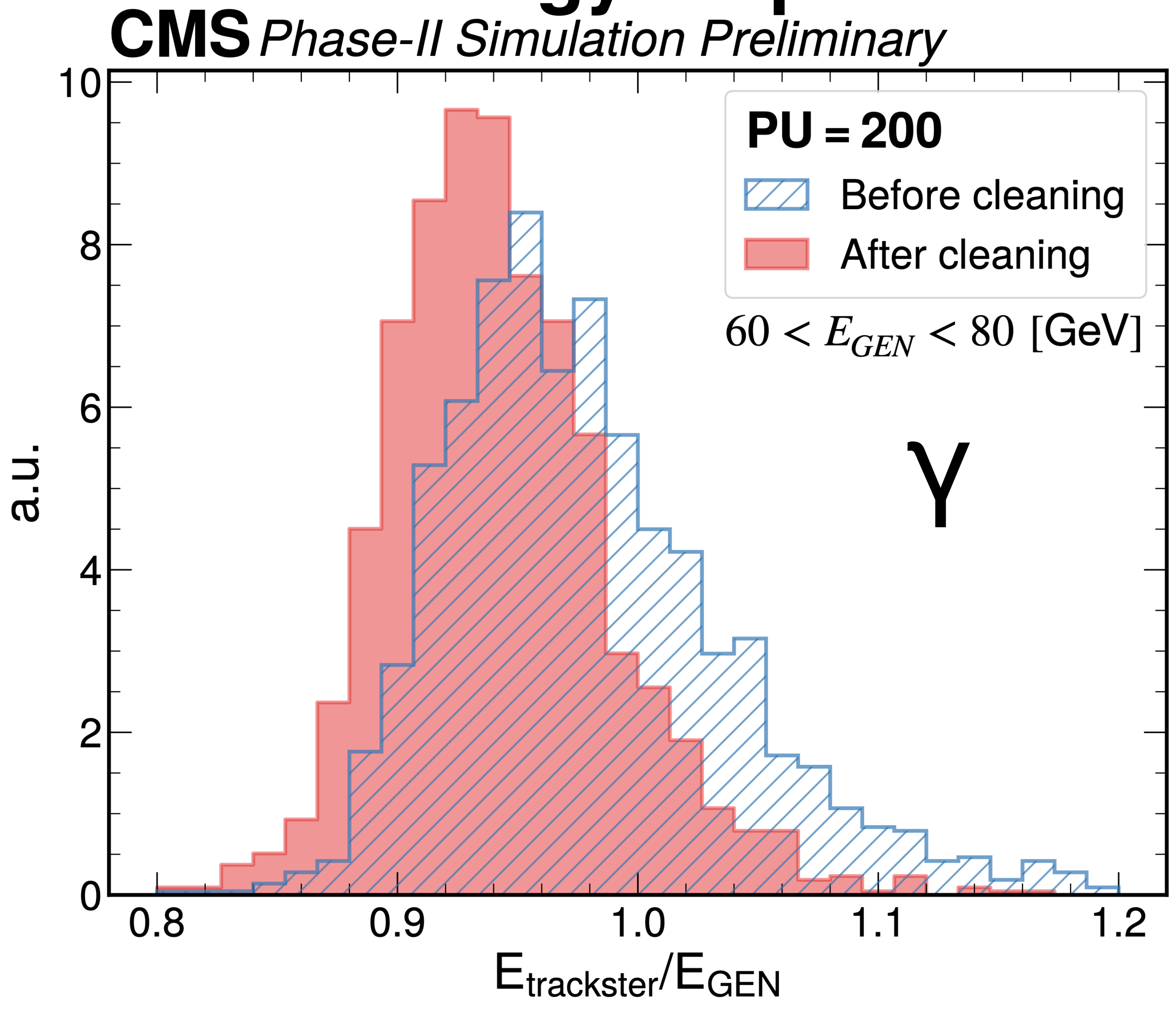




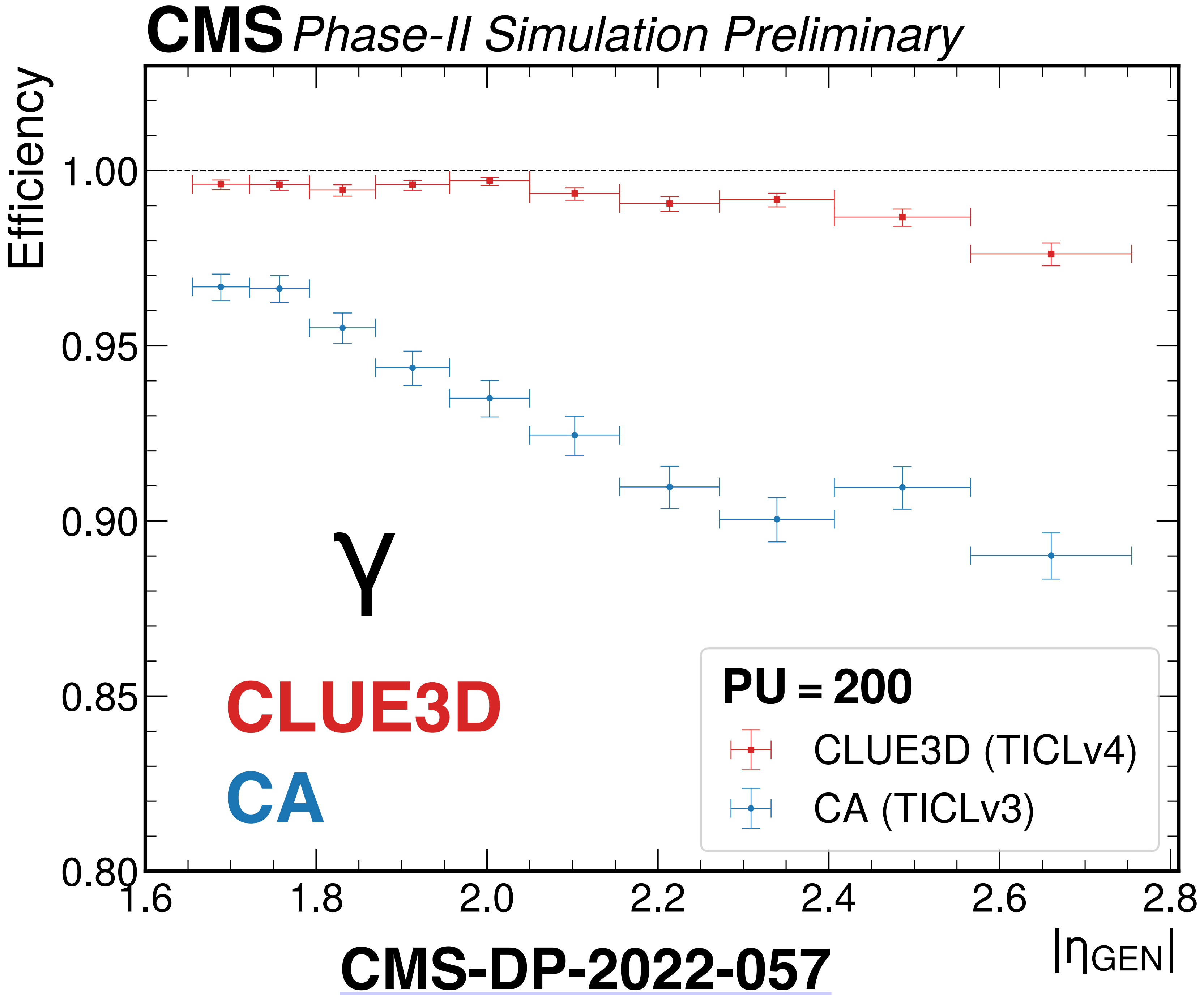
- Muon reconstruction method has an overall high efficiency even at high pileup.

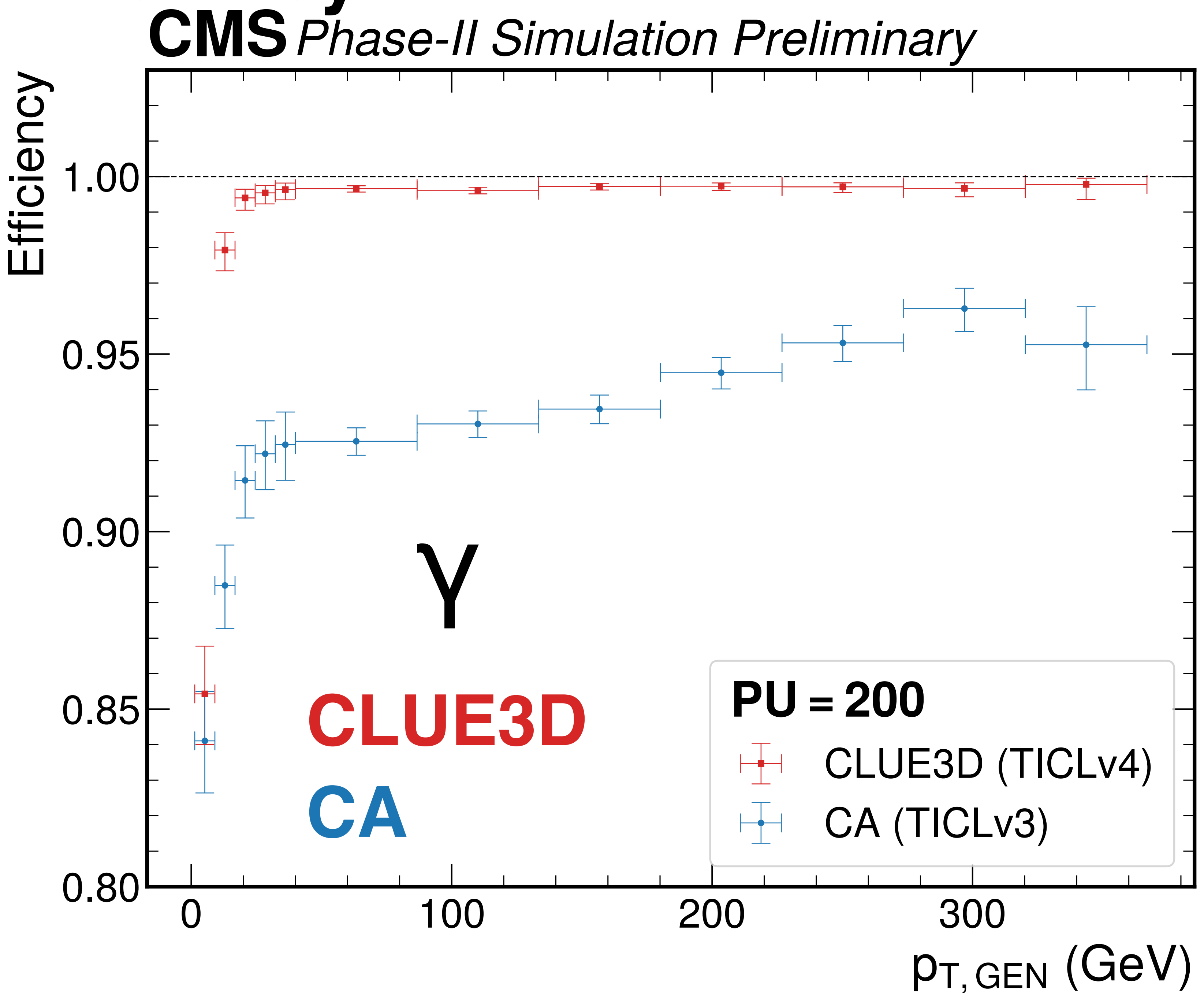
Photon performance of CLUE

Energy response



Photon efficiency





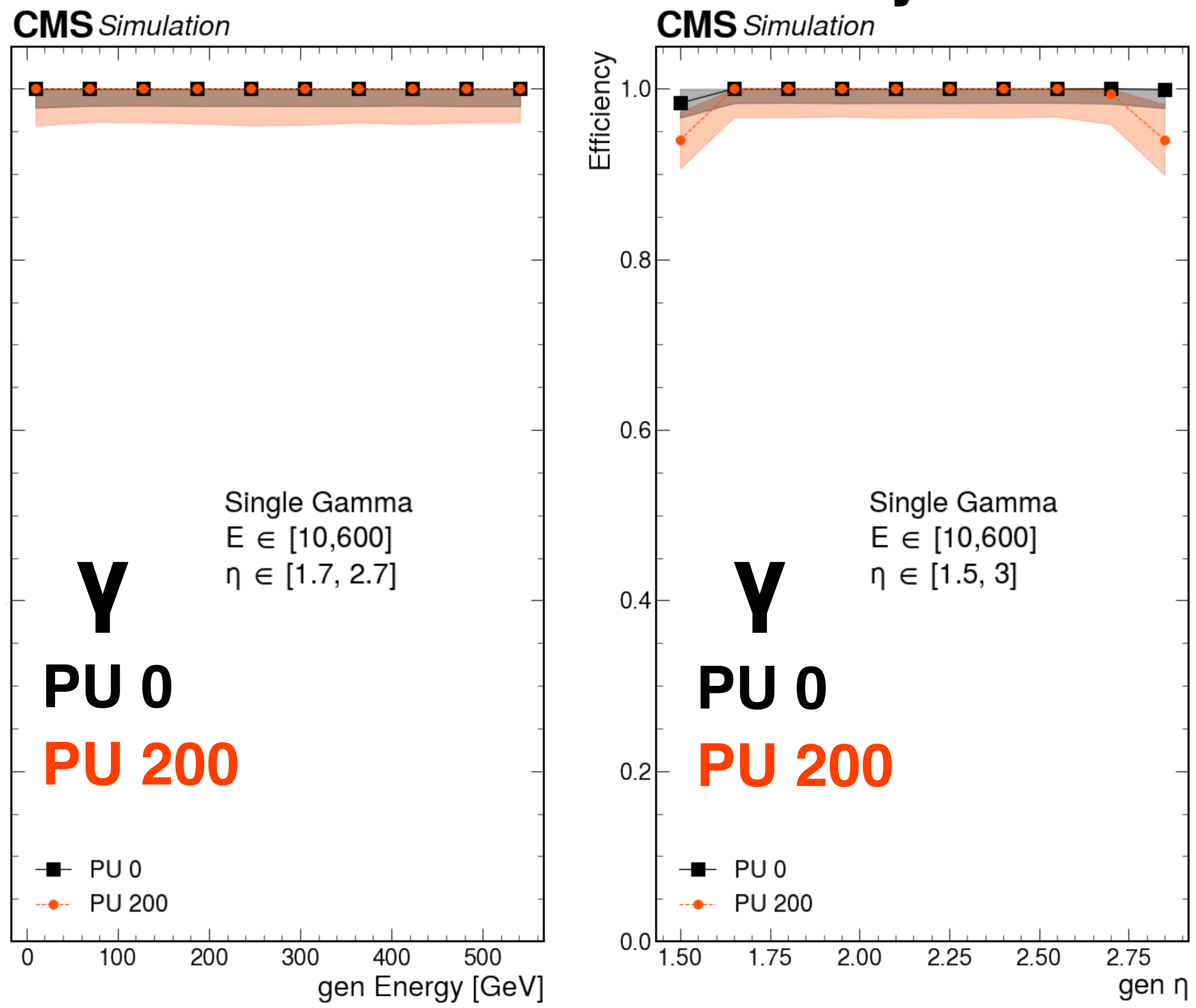
CMS-DP-2022-057

- Simple algorithm developed to clean PU by keeping particles within [+15, -12] layers from shower center.
  - Illustrates how HGCAL can be used to effectively remove PU at the HL-LHC.
- CLUE3D shows overall good performance outperforming previous algorithms (cellular automaton (CA)) in reconstruction efficiency across all η and p_T bins.

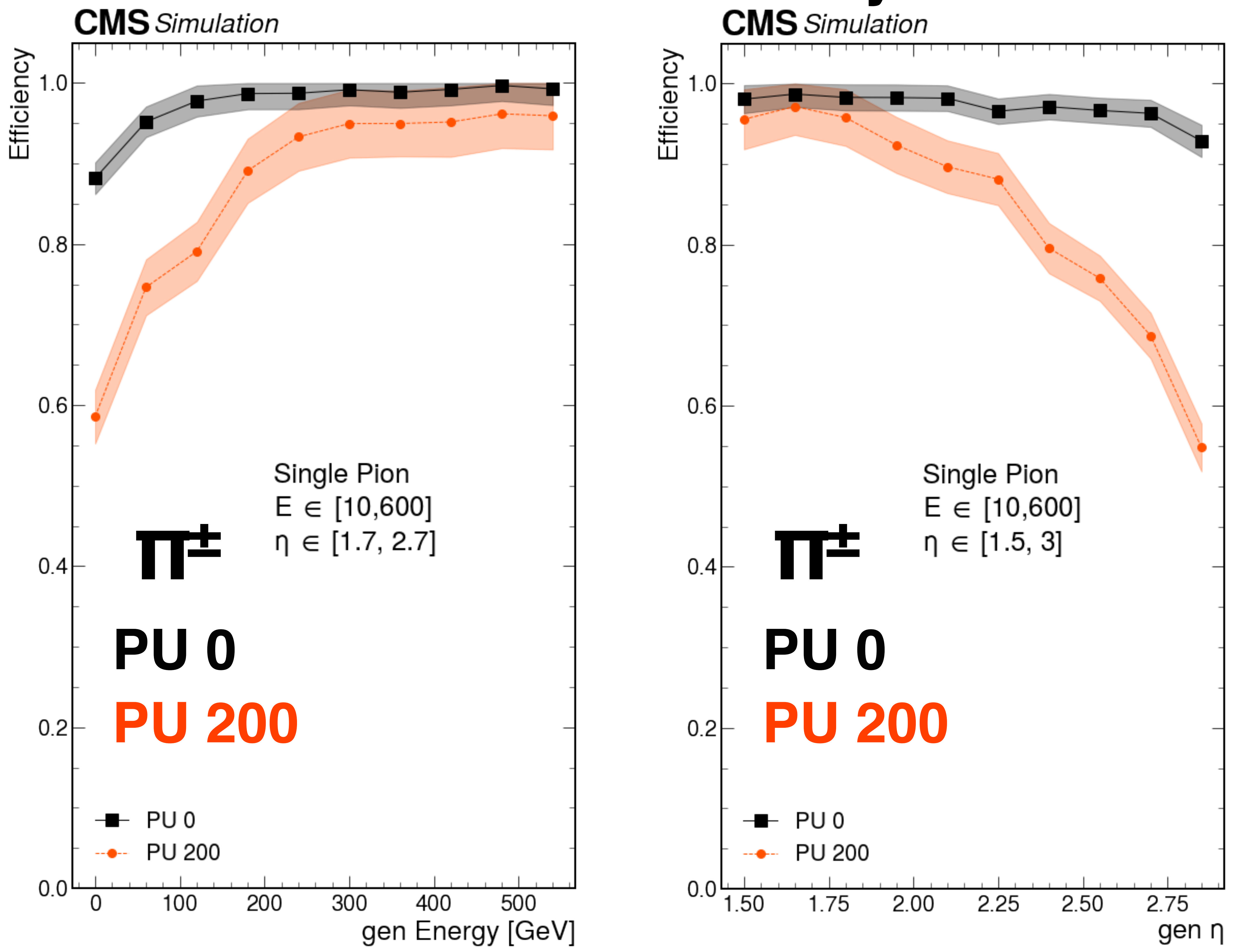
Single particle reconstruction efficiency

CMS-DP-2022-045

Photon efficiency



Pion efficiency

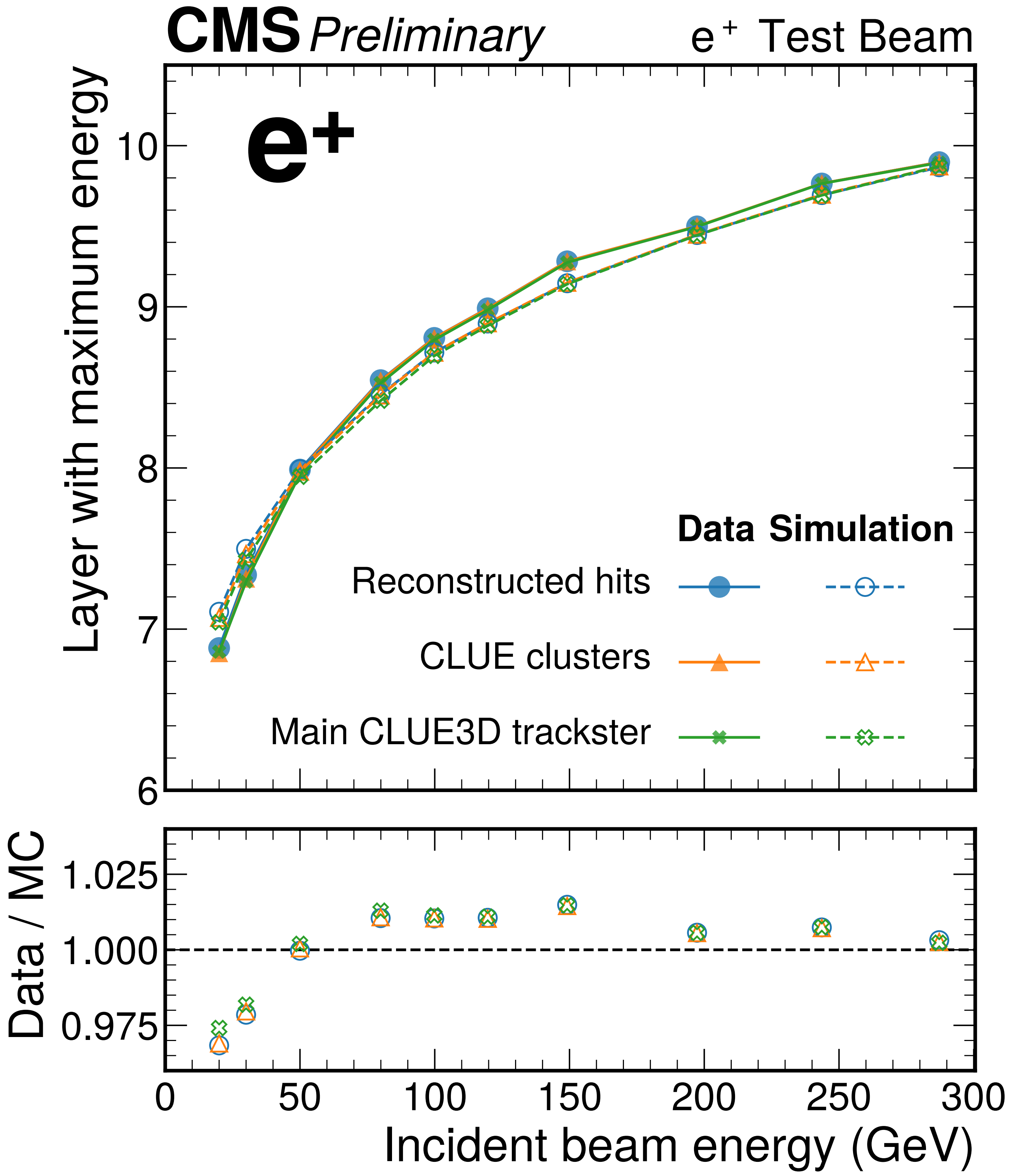


- Reconstruction of electromagnetic objects show high performance up to 200 PU.

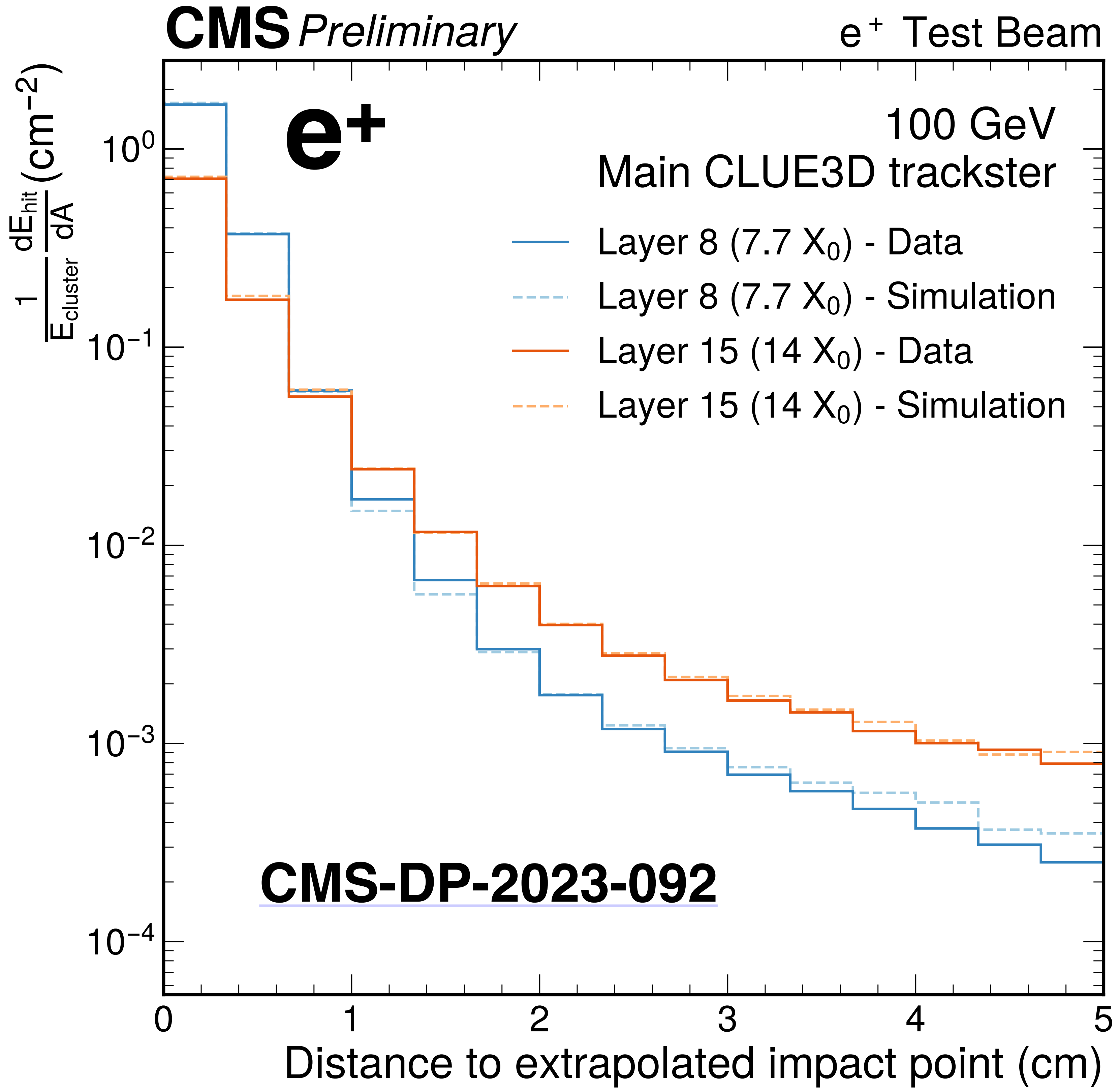
- Work on-going to improve hadron reconstruction efficiency in challenging conditions: low energy and high occupancy regions.

Comparisons with test beam data: positrons

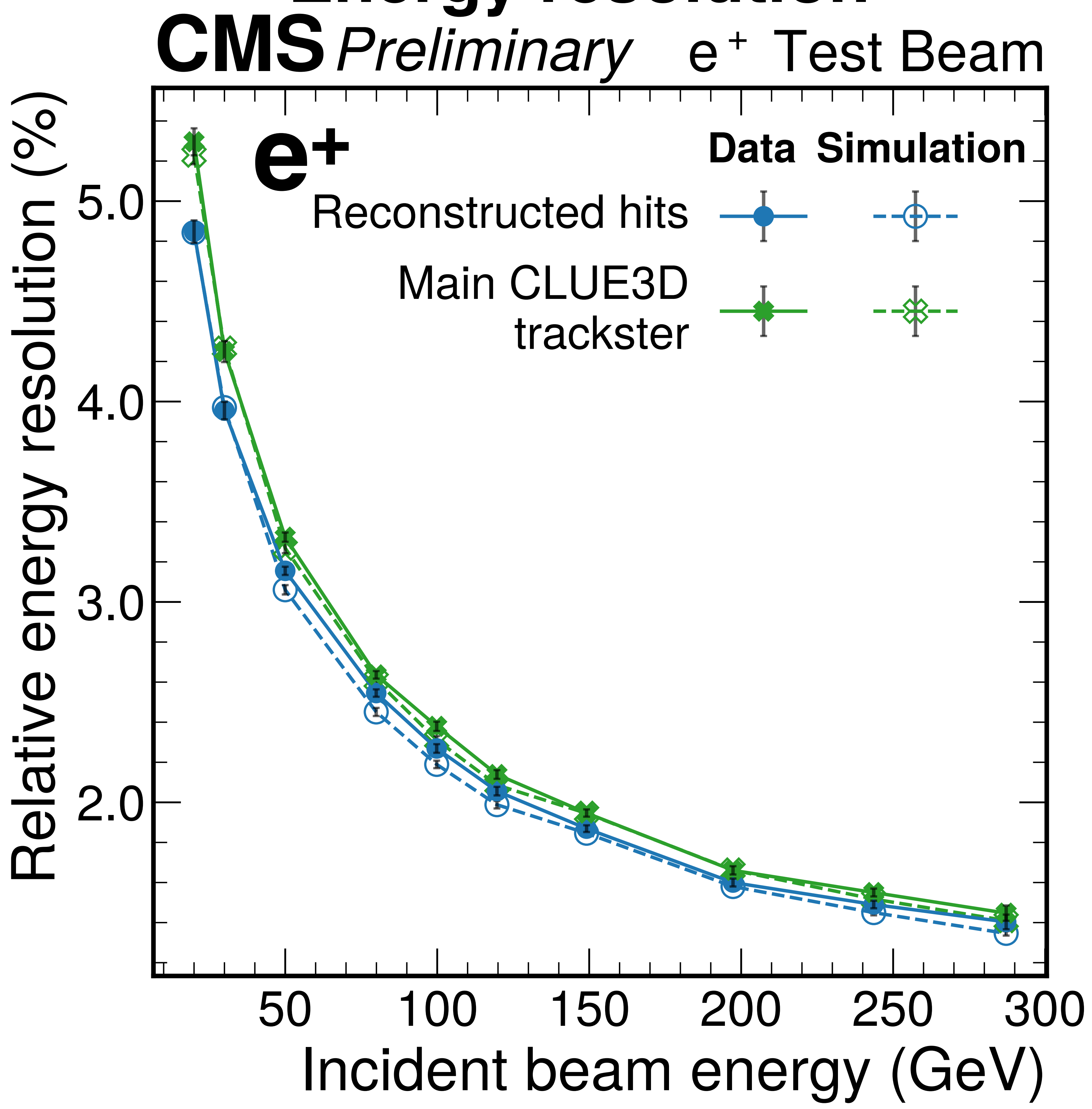
Longitudinal profile



Transverse profile

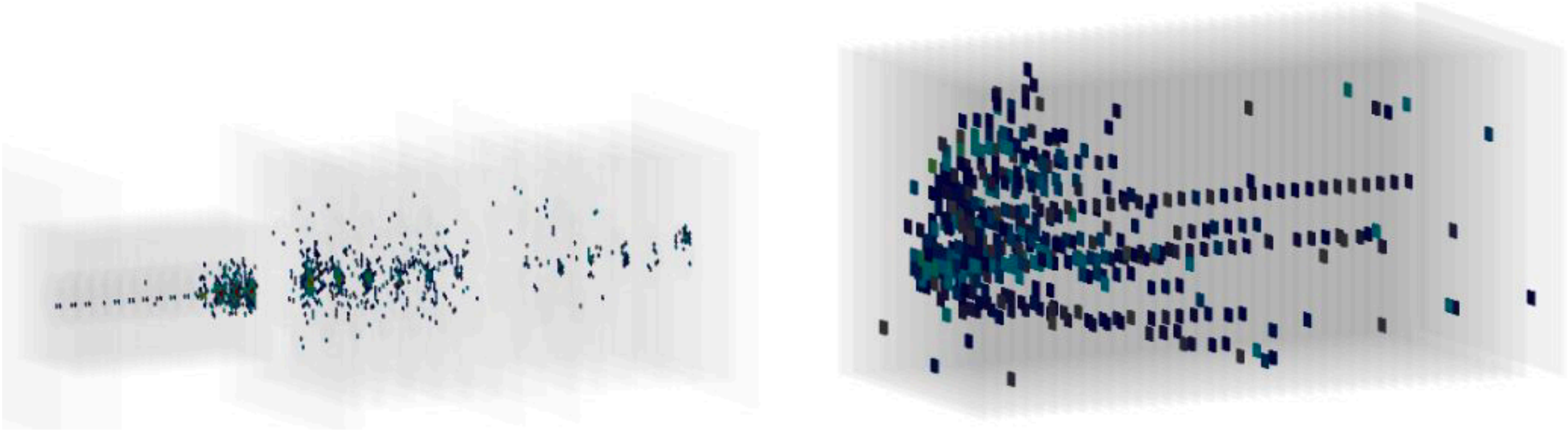


Energy resolution



- Performance of CLUE and CLUE3D in test beam data well described by simulation.

Energy estimation of pions



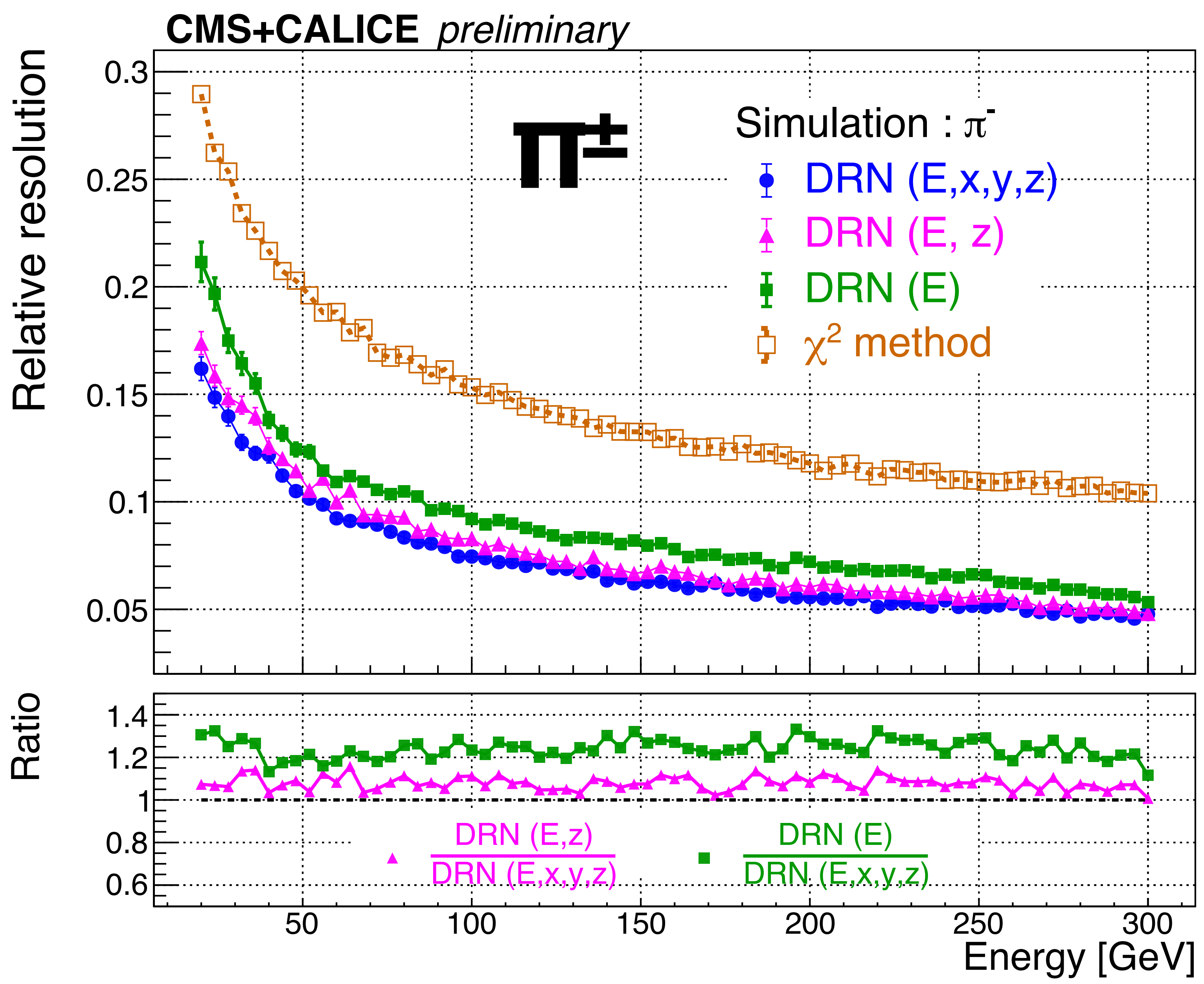
- **Challenges**:
  - Connect the right hits associated to a single particle at high PU.
  - e/h far from unity.
  - EM fraction f_{EM} of shower energy depends on incident h energy → results in a non-linear response.
  - Transverse/longitudinal leakage also contribute to fluctuations of the measured energy.

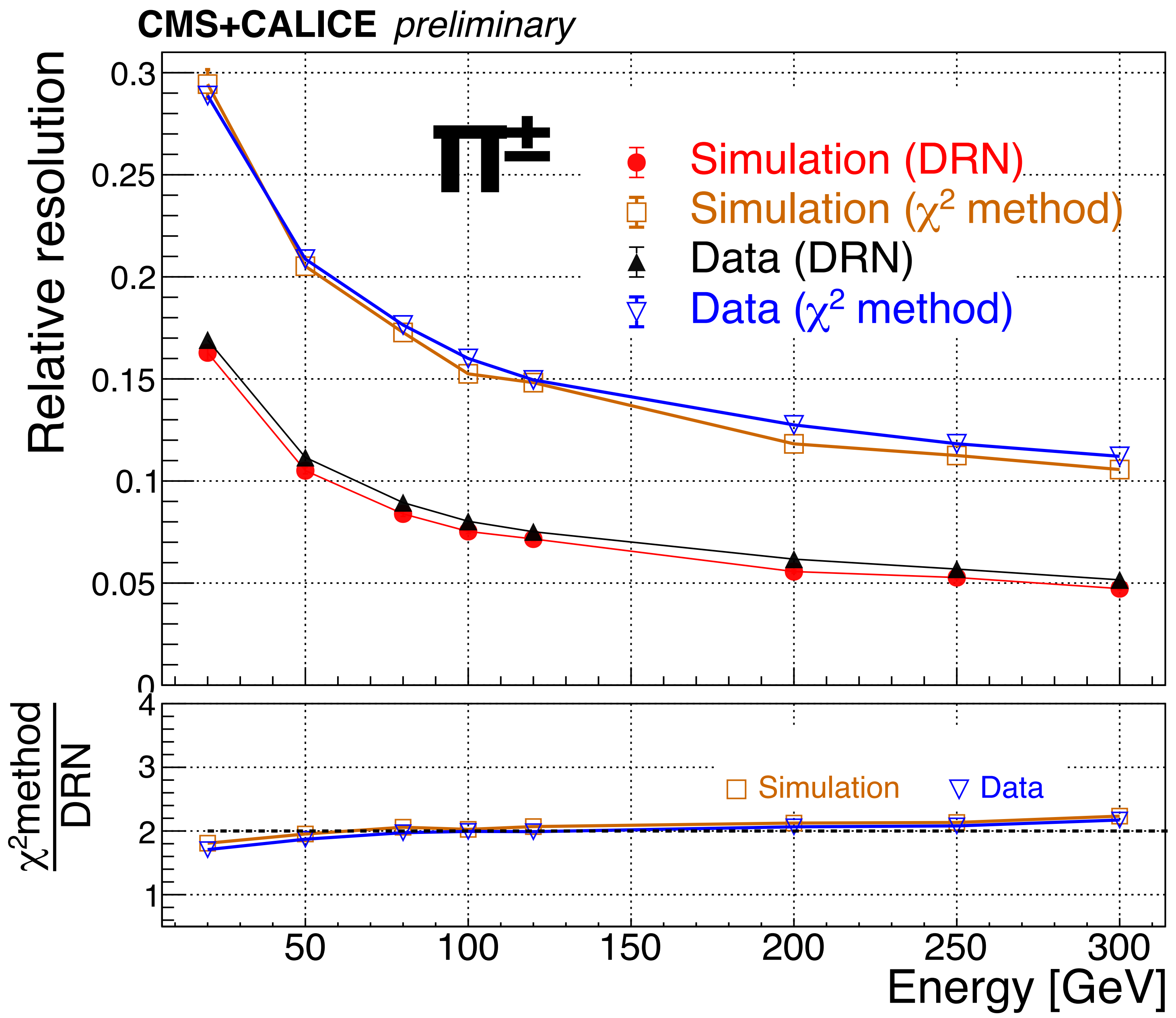
- Dynamic graph neural networks (GNN) models can be used to tackle these challenges and fully exploit the HGCAL granularity by connecting rechits using their energy and spatial information through graph convolutions.

- One such model is the **Dynamic Reduction Network** (DRN, arXiv:2003.08013v1) model, which can learn the most important relationships between data via an intermediate clustering.

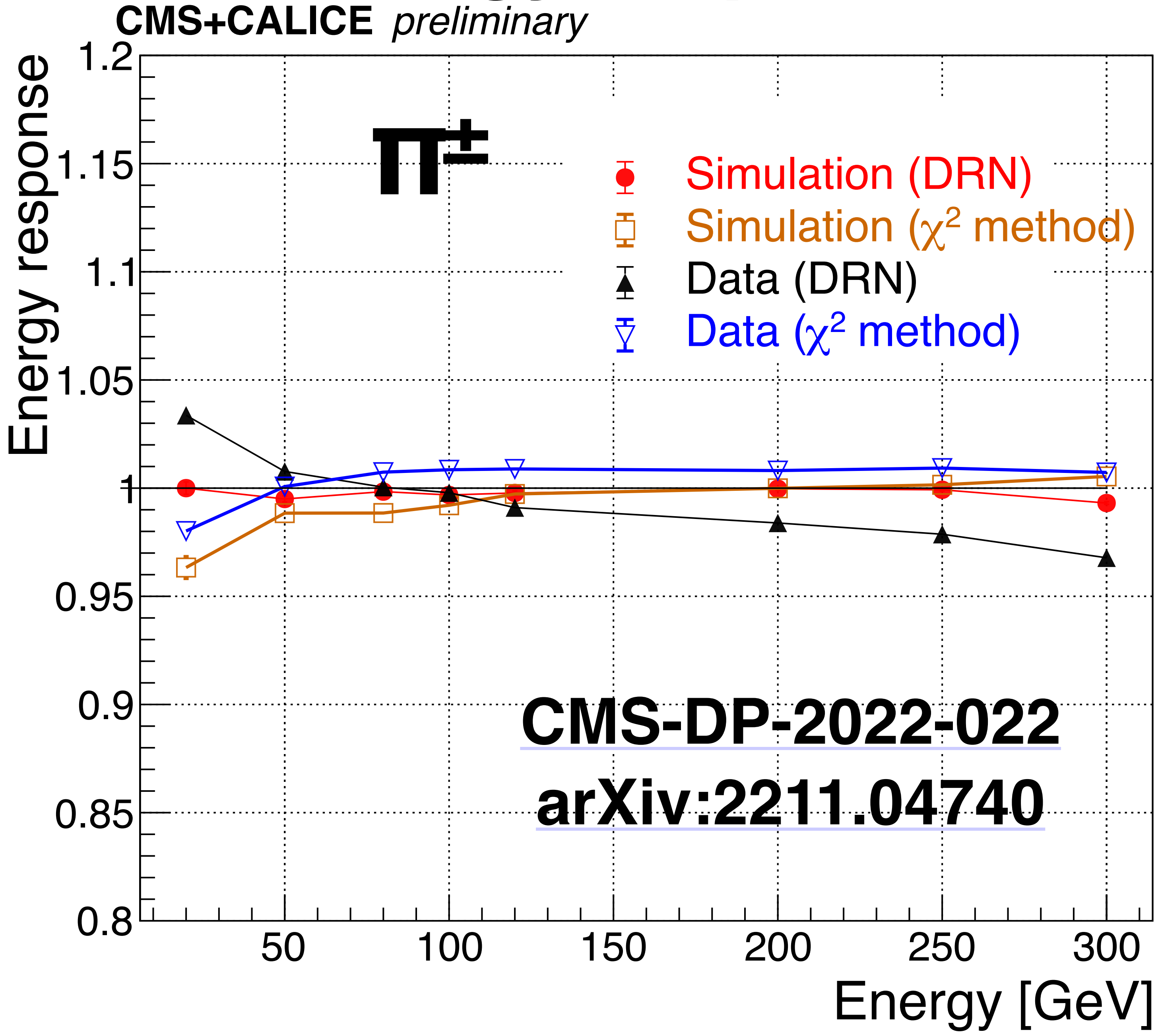
Energy estimation of pions using DRN

Relative energy resolution





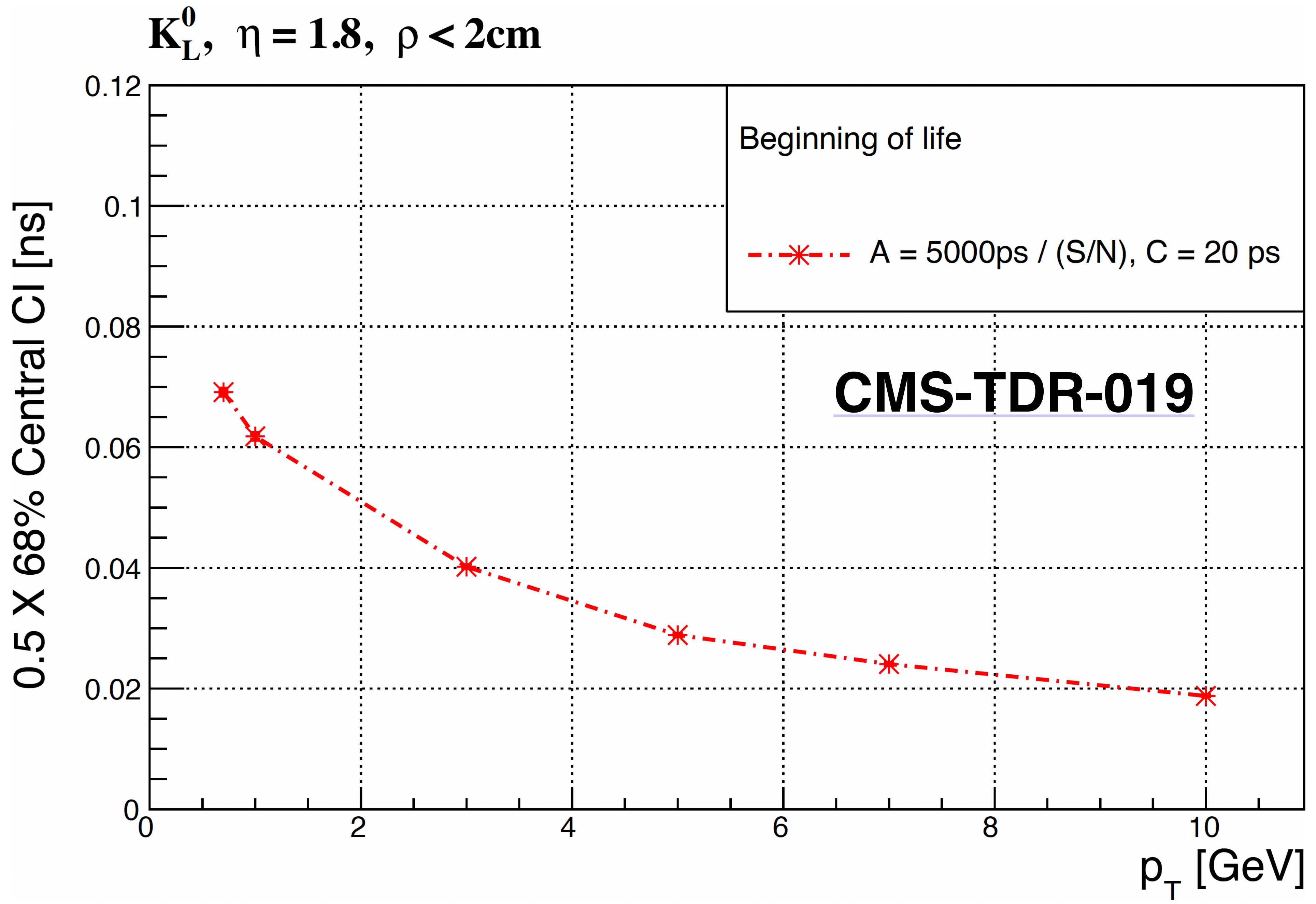
Energy response



- DRN model significantly improve the pion energy estimation compared to χ^2-method.
  - Tested different input features: energy (E) and spatial (x, y, z) → main gains from E+z information.
- Results derived in test beam data well described by simulations.
- DRN reconstruction achieves energy resolutions down to 5% and energy response ~ 1 for pions.

HGCAL timing measurement

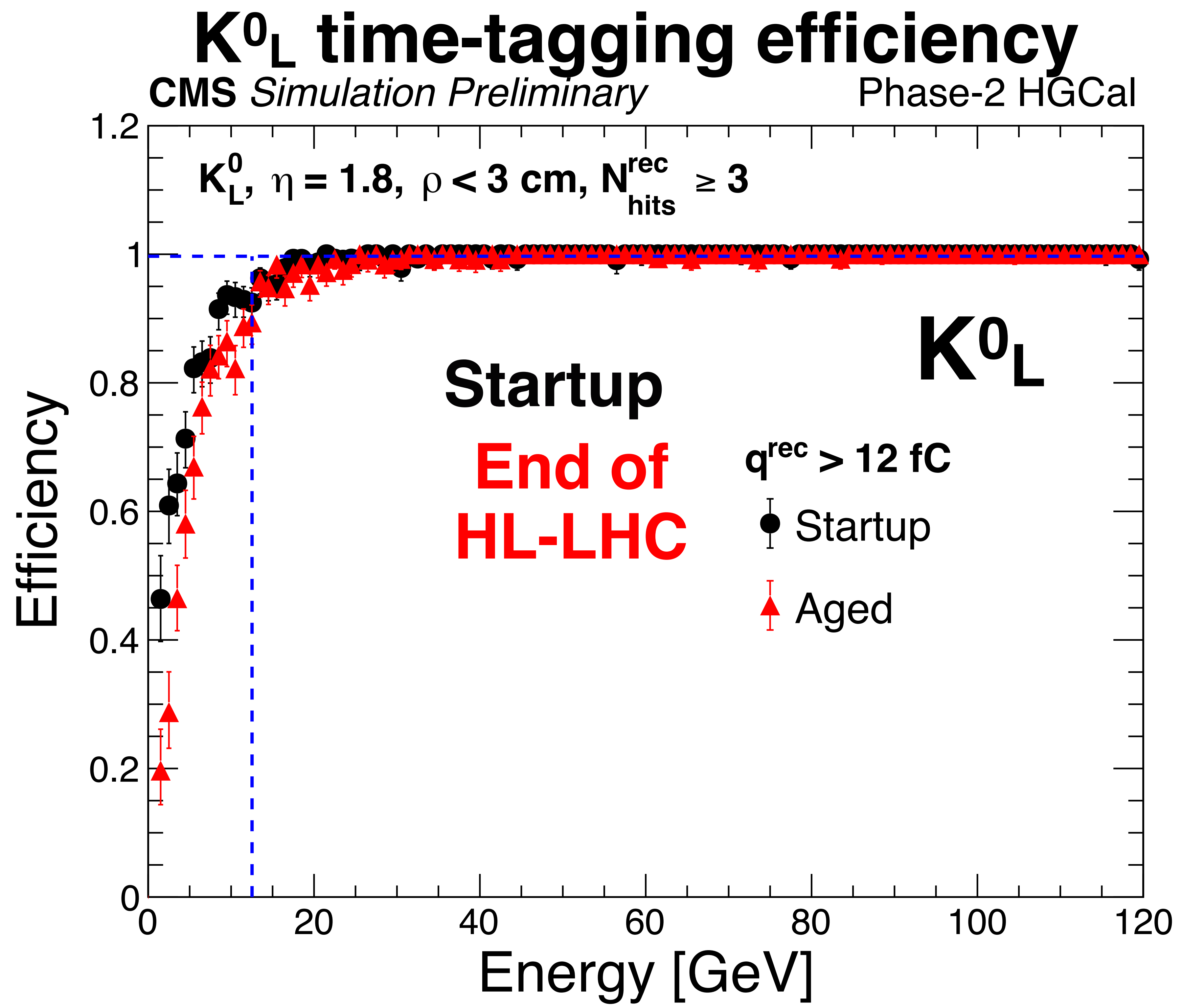
- HGCAL timing is measured for each sensor cell with enough deposited charge using a Time-Digital Converter (TDC), which runs at 160 MHz and has a 25 ns range with a bit size of 24.4 ps.
- The timing resolution relies on the intrinsically fast response of Si sensors, the front-end electronics and the clock distribution system.
  - Modulations in the baseline noise and fluctuations of the electronics and clock distribution can degrade the timing resolution.

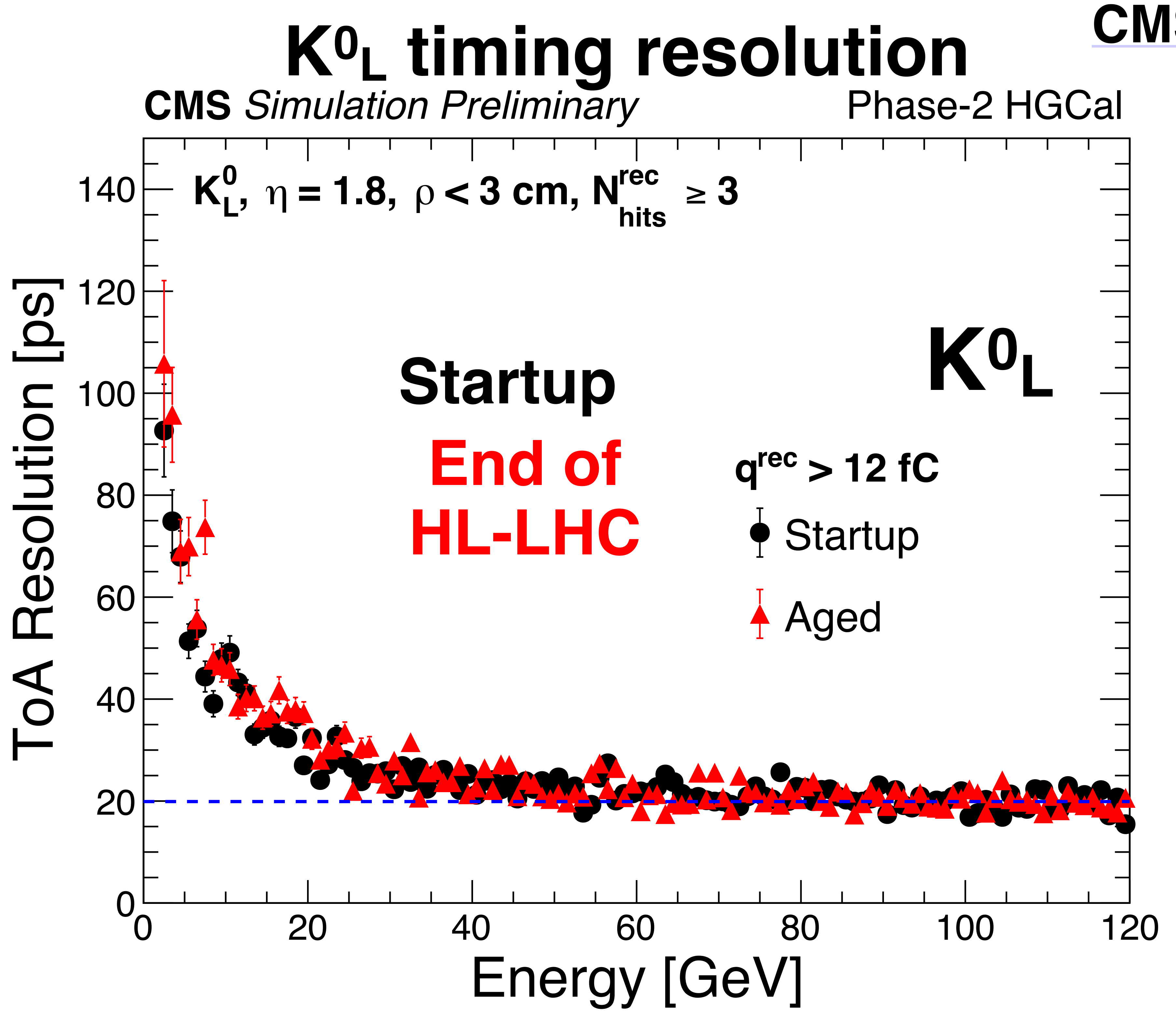


- HGCAL is designed to reach a precision as good as 20 ps at high energies at the beginning of lifetime.
- Results derived in 2018 test beam data show promising results achieving designed timing resolutions. **arXiv:2312.14622**

Simulated timing performance of showers

CMS-DP-2024-001

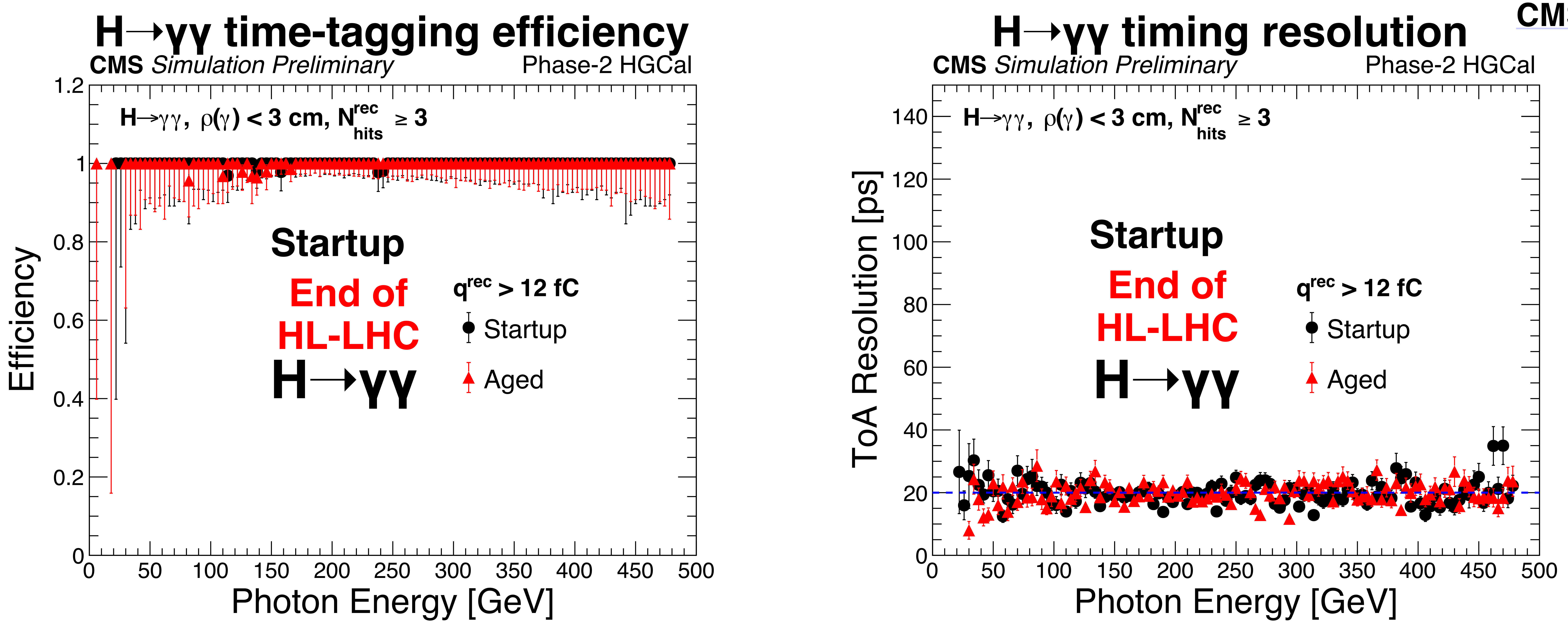




- High efficiency for time tagging neutral hadron showers at E > 20 GeV, maintaining a timing resolution ~ 20 ps until the end of the HL-LHC.

Simulated timing performance of showers

CMS-DP-2024-001

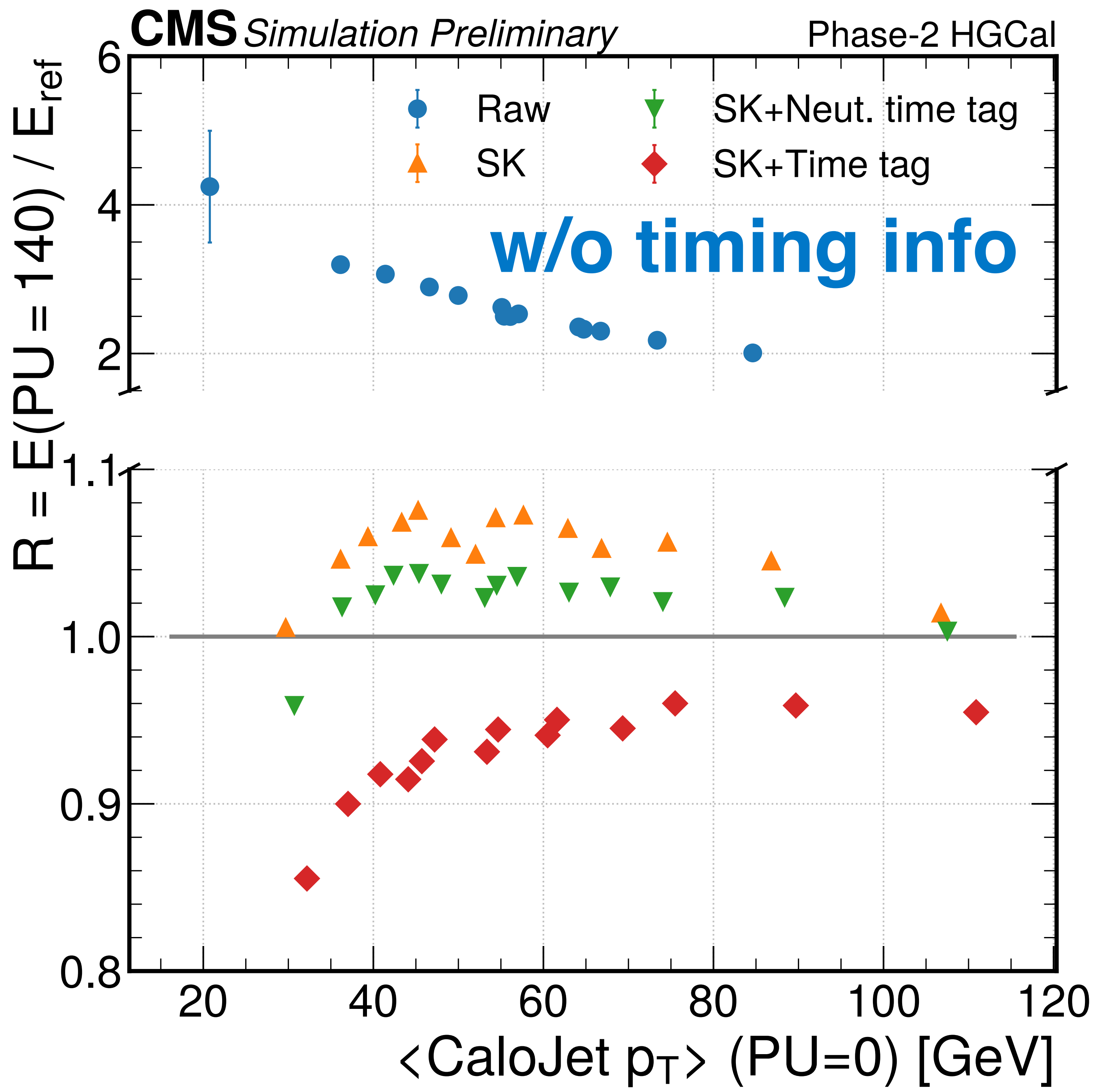


- High efficiency for time tagging neutral hadron showers at E > 20 GeV, maintaining a timing resolution ~ 20 ps until the end of the HL-LHC.
- Result for Higgs→γγ shows excellent performance for reconstructing timing vertex overall.

Simulated timing performance of showers

CMS-DP-2024-001

Energy response for VBF jets

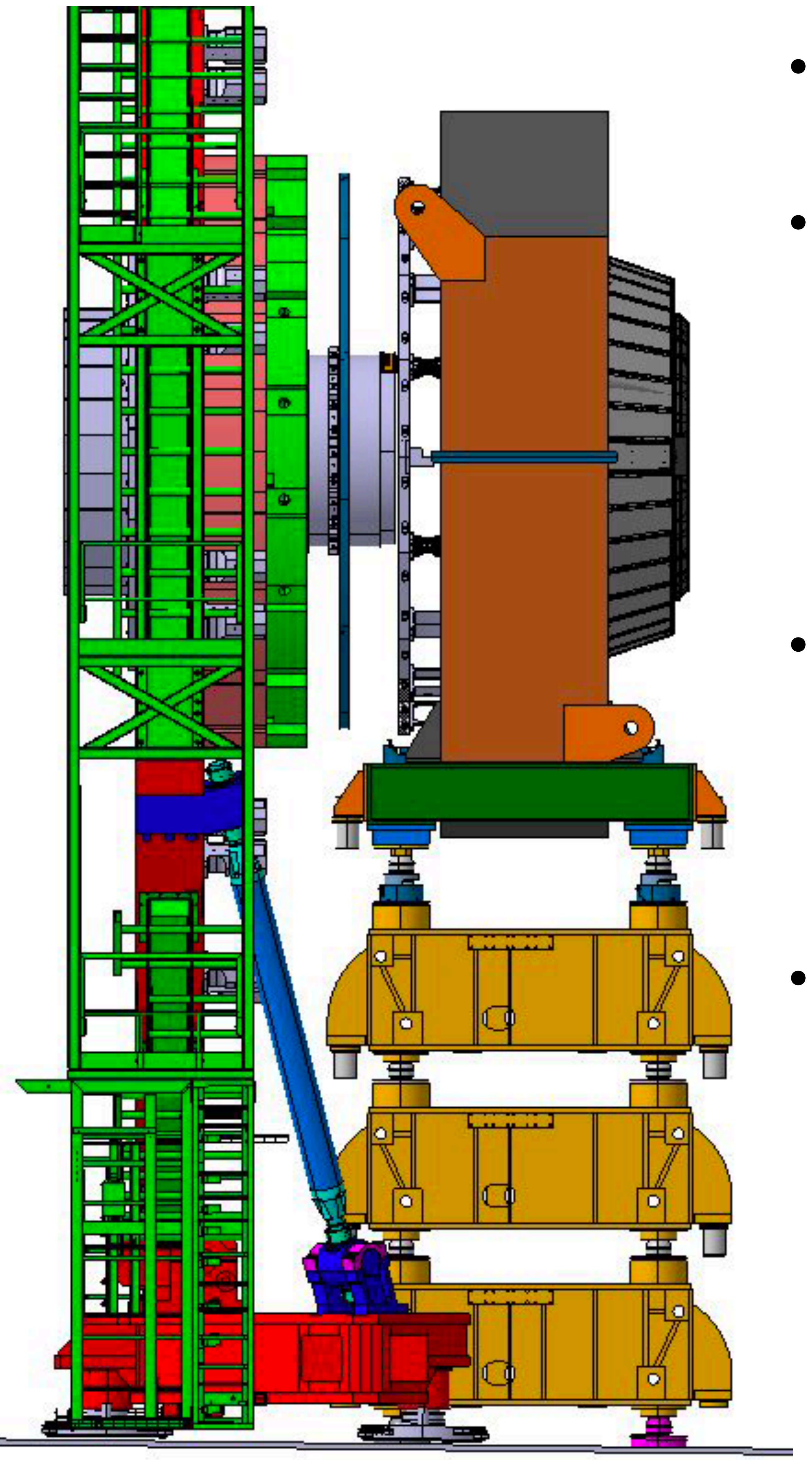


With neutral hadron timing

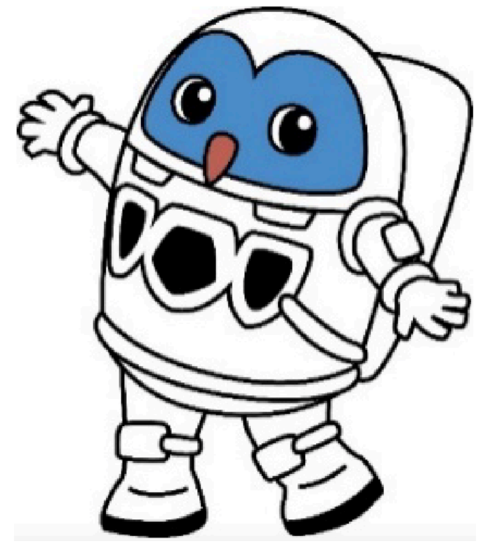
With timing from all particles

- High efficiency for time tagging neutral hadron showers at E > 20 GeV, maintaining a timing resolution ~ 20 ps until the end of the HL-LHC.
- Result for Higgs→γγ shows excellent performance for reconstructing timing vertex overall.
- Impact of PU on particle-level energy response of VBF jets reduced after including HGCAL timing.
- Work on-going to develop time-assisted reconstruction strategy for hadronic showers (see A. Perego's poster).

Summary



- CMS will have a brand new HG calorimeter as part of the HL-LHC upgrade.
- 5D shower imaging and reconstruction capability:
  - Fast and robust novel reconstruction algorithms.
  - Crucial for precise particle reconstruction.
  - Necessary to mitigate impact of pile-up at HL-LHC.
- TICL framework enables a global event description in CMS.
  - New version of TICL coming soon focussing on improving in hadron reconstruction and new clustering algorithms using machine learning.
- HGCAL physics performance shows promising results.
  - On-going efforts to further improve in the most challenging conditions.



Thank you for your attention!

BACKUP