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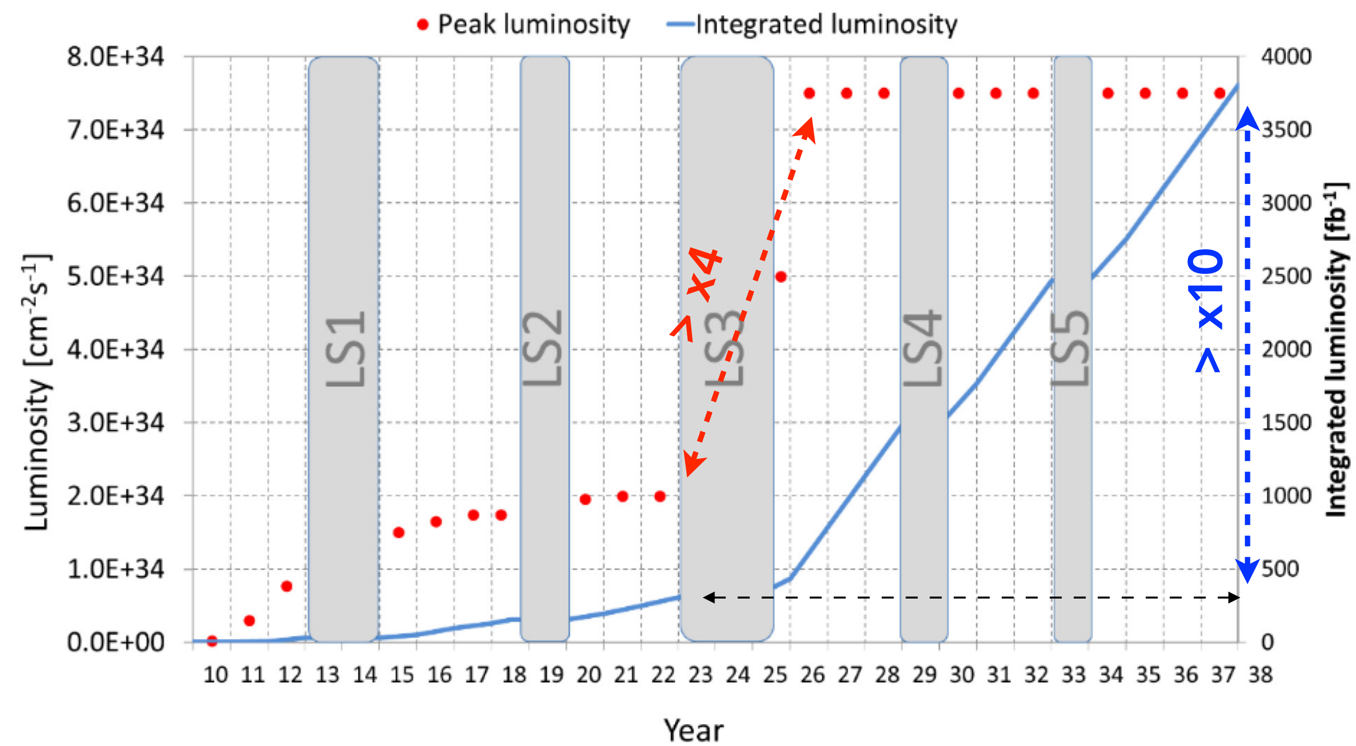
on behalf of the CMS Collaboration

Reconstruction in an imaging calorimeter for HL-LHC

Imperial College London

The High Luminosity of the LHC

- To exploit the full potential of the LHC and its physics program
  - precise measurements of the SM sector and Higgs properties (couplings, differential cross-section, Higgs self-interaction)
  - searches for new physics

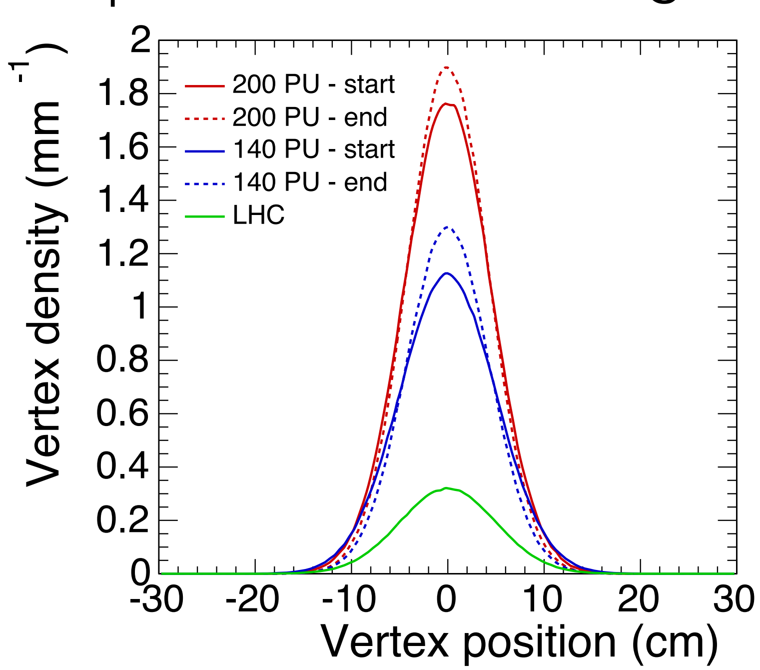


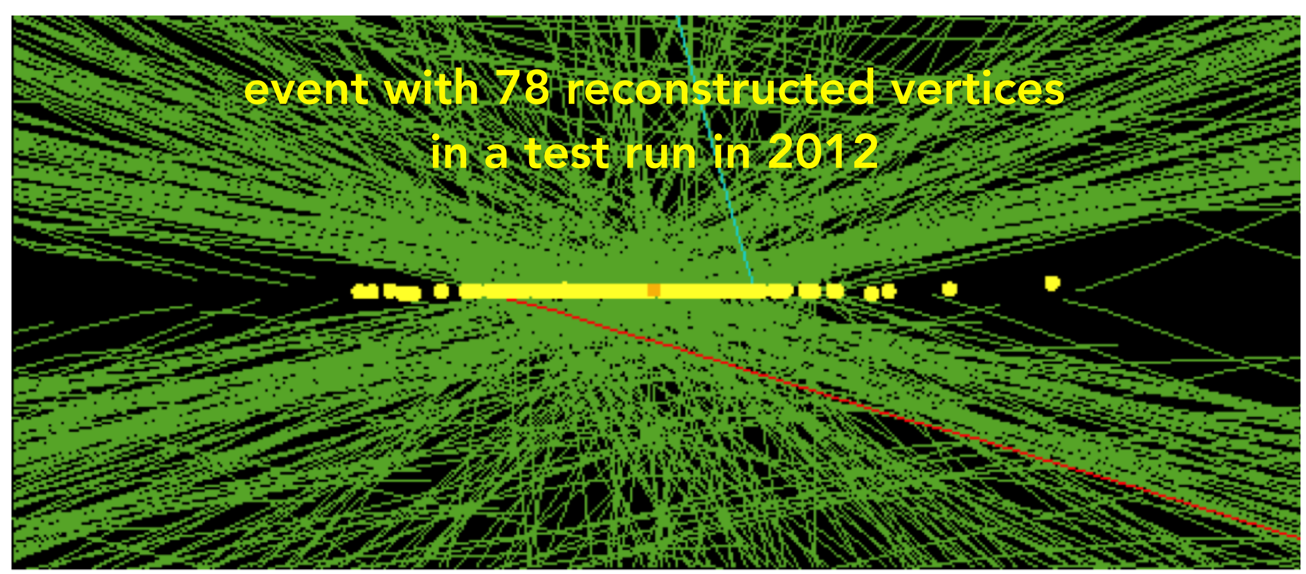
THE CHALLENGES:

- High radiation levels
  - "1 year HL-LHC ≈ 10 years LHC"

radiation hardness needed

- High pileup, 140-200 simultaneous collisions per bunch crossing
  - spread of luminous region (rms) ~4.5cm in z and ~180ps in time





need (at least) high granularity

fast timing for further help

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  - precise measurements of the SM sector and Higgs properties (couplings, differential cross-section, Higgs self-interaction)
  - searches for new physics

THE PHYSICS REQUIREMENTS:

- **Ingredients to pursue searches and precision SM measurements**
  - **boosted topologies** => **increase granularity** for reconstruction/ID of collimated objects
  - **forward boosted production** => **good performance at high η** coverage/reconstruction/ID/resolution + complement tracker upgrade ($|\eta|<4$ and reduced material budget)
  - **exploit VBF production** => **jet reco/ID at high η**, also at trigger level

- **Important role of the forward calorimeter for physics at the (HL)-LHC**

  => The **High Granularity Calorimeter (HGCAL) will replace the current CMS endcaps** for the High Luminosity LHC (HL-LHC)

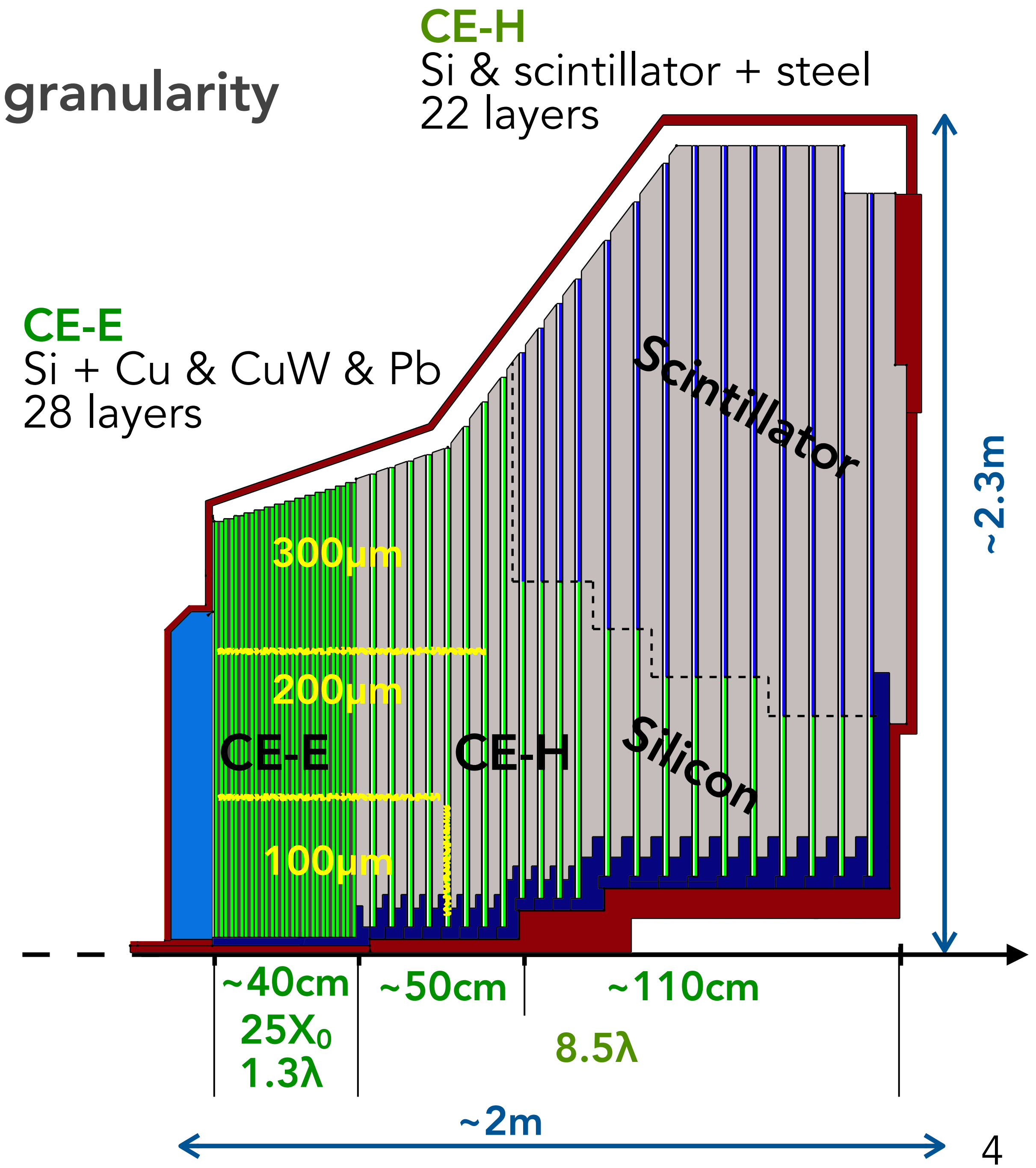
The HGCAL

- **Fine grain calorimeter for a 5D shower reconstruction**
  => Silicon/scintillator sampling calorimeter, including both em and had parts

- **Silicon for radiation hardness (and granularity)**
  - radiation level similar to that experienced in the inner tracker
- **Fine longitudinal readout segmentation + High granularity**
  - against congestion, to help "features" extraction
    => suited for imaging reconstruction

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

Key Parameters:
- **HGCAL covers 1.5 < η < 3.0**
- **Full system maintained at -30°C**
- **~620m² of silicon sensors in ~30k modules**
- **~400m² of scintillators in ~4k boards**
- **6M Si channels, 0.5 or 1cm² cell size**
- **400k Scint. channels, 4-30cm² cell size**
- Power at end of HL-LHC: ~125 kW per endcap



The HGCAL

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Distinctive feature of the detector

- **Silicon for radiation l**
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- **High granularity + lo**
  - against congestion, t
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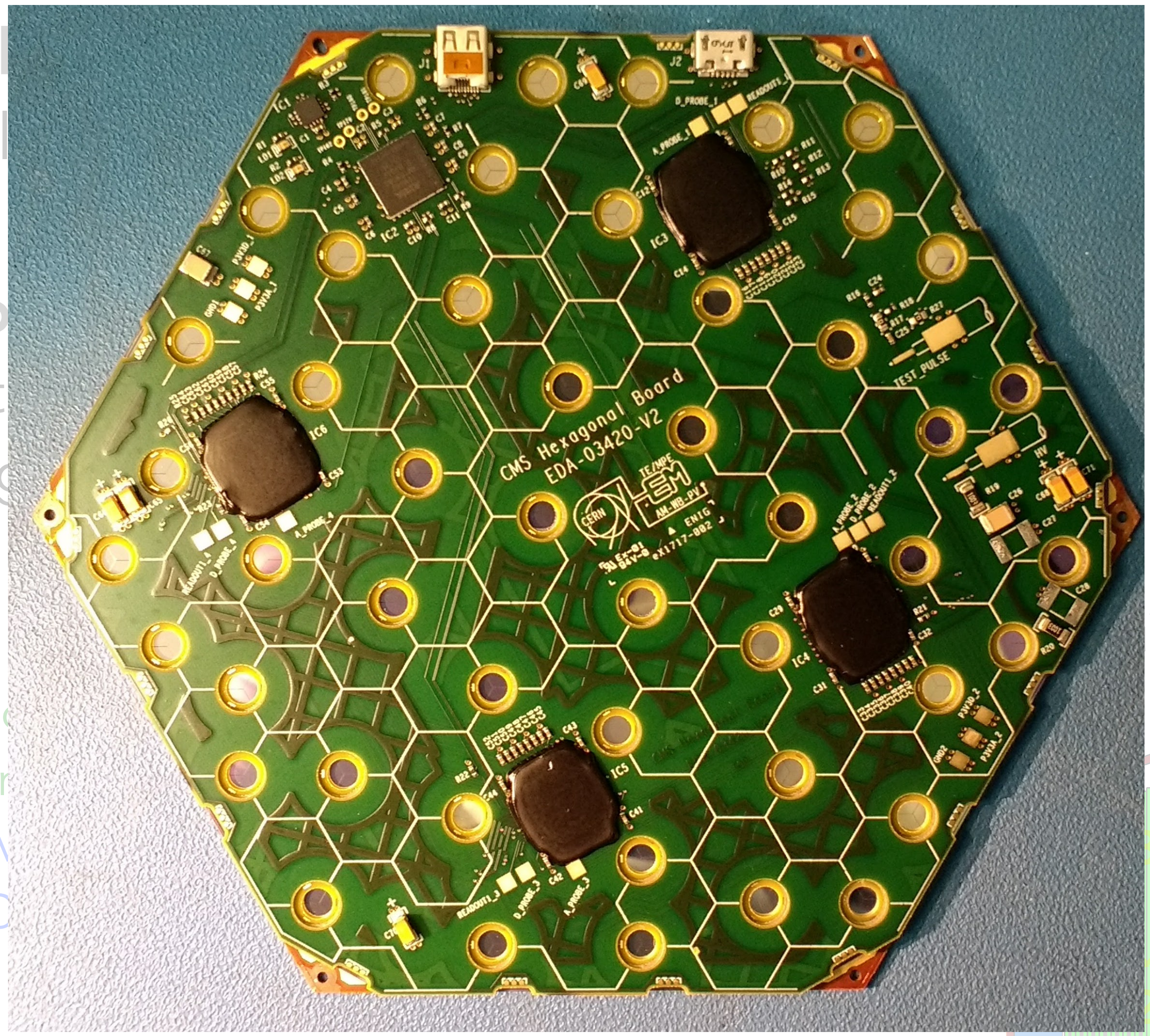


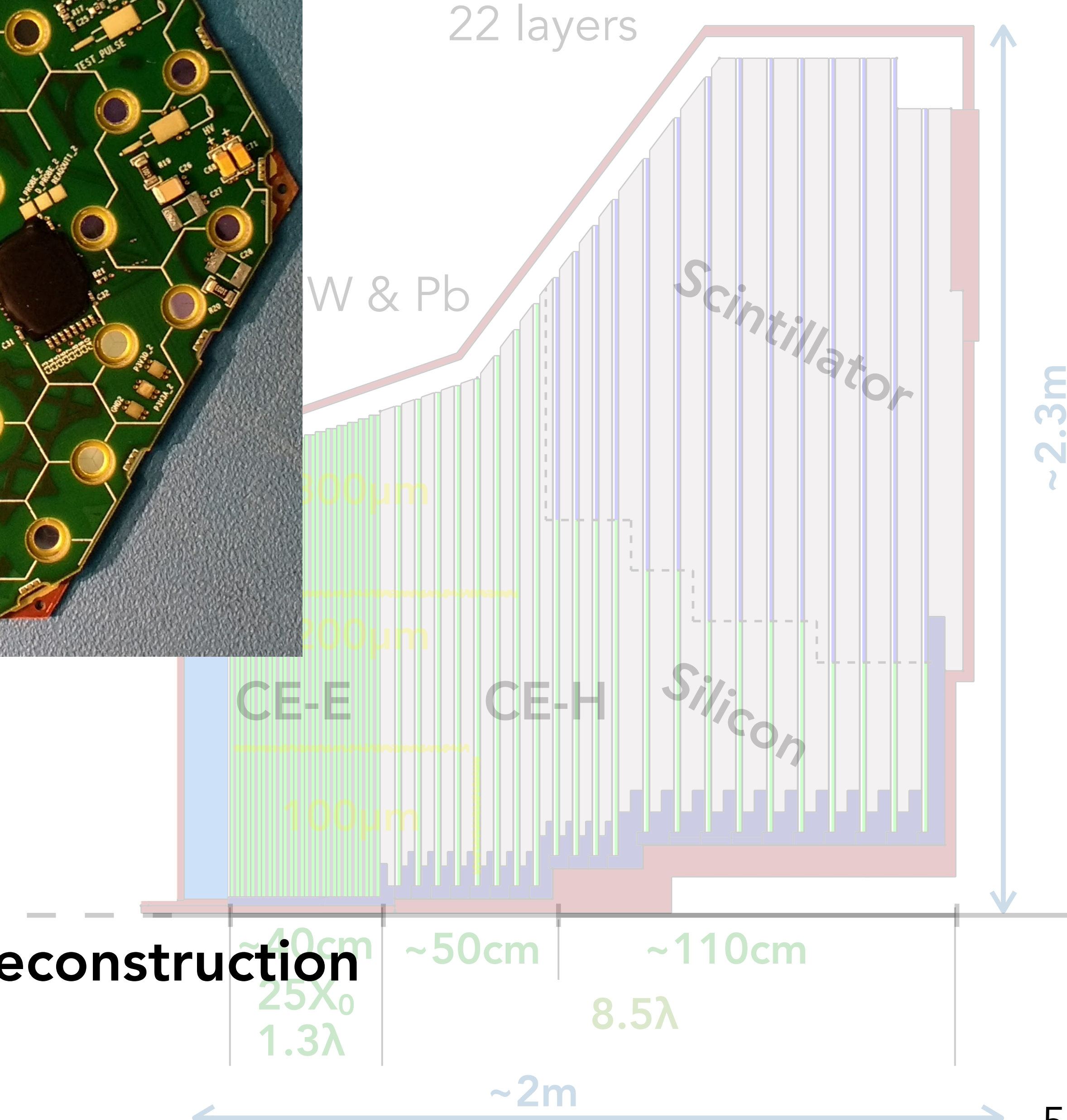
Active Elements:
- Hexagonal modules base
  in CE-E and high-radiatio
- Scintillating tiles with SiPM
  low-radiation regions of C

Key Parameters:
- HGCAL covers 1.5 < η < 3.0

Hexagonal silicon cells to make
most efficient use of circular silicon wafers

- ~400m² of scintillators in ~4k boards
- 6M Si channels, 0.5 or 1cm² cell size
- 400k Scint. channels, 4-30cm² cell size
- Power at end of HL-LHC: ~125 kW per endcap

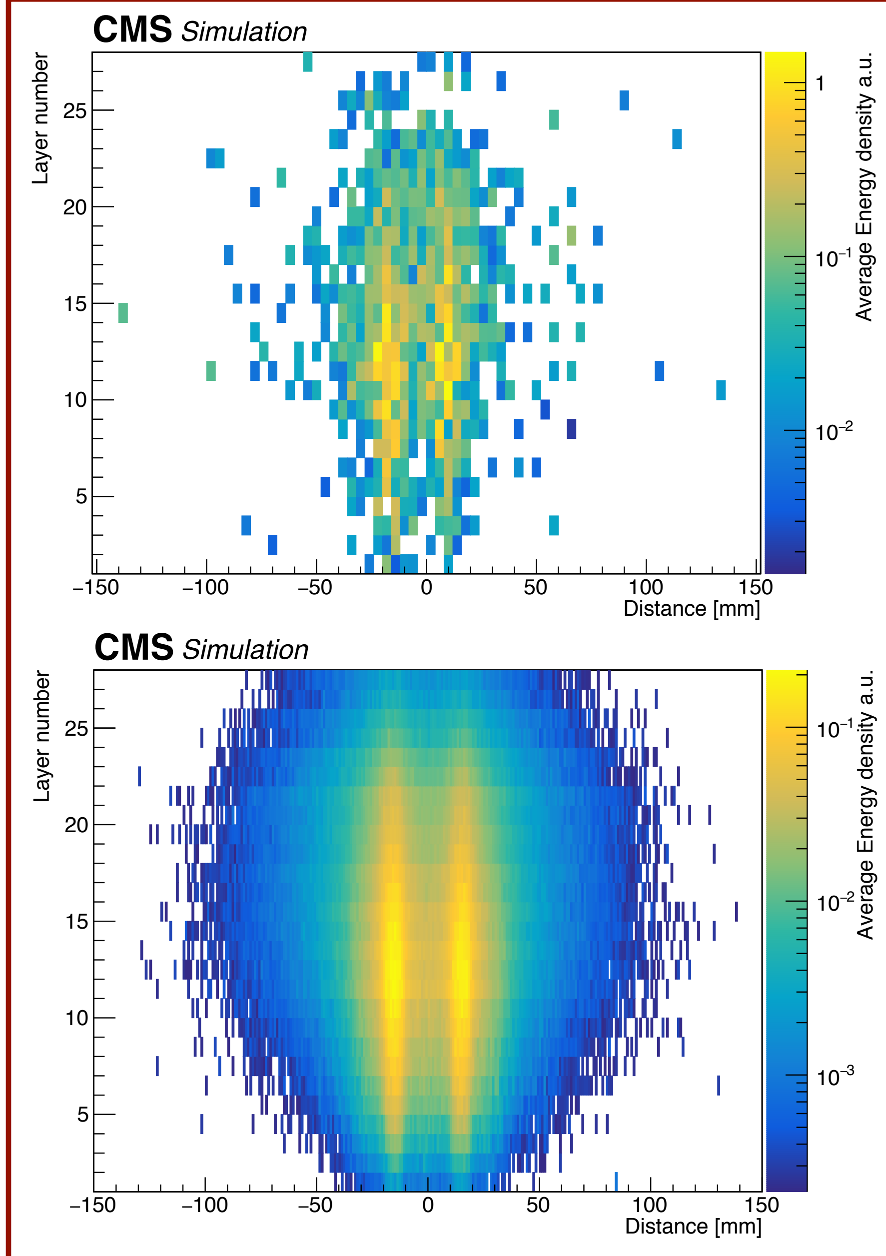
=> hexagonal geometry in the reconstruction



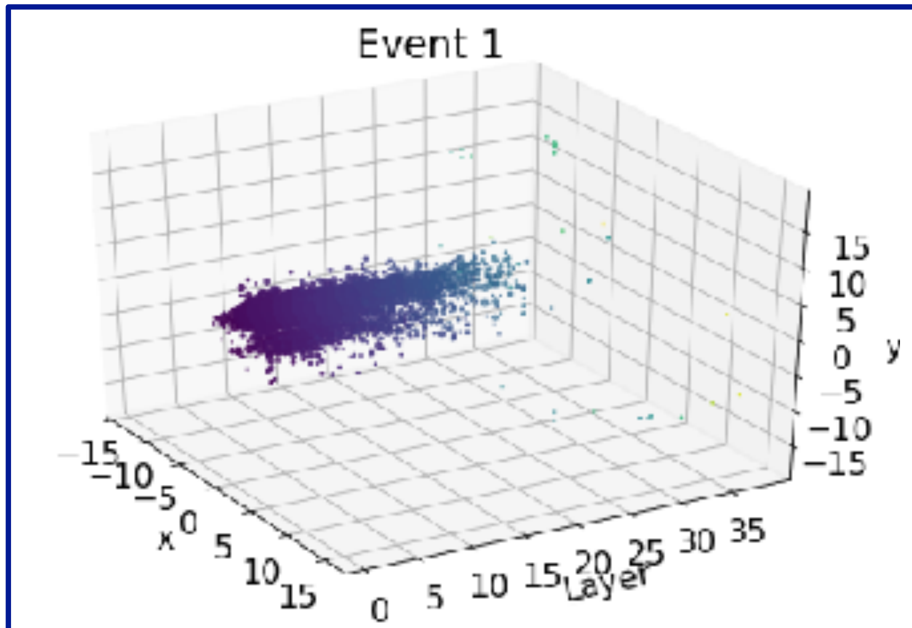
Advantage of high granularity

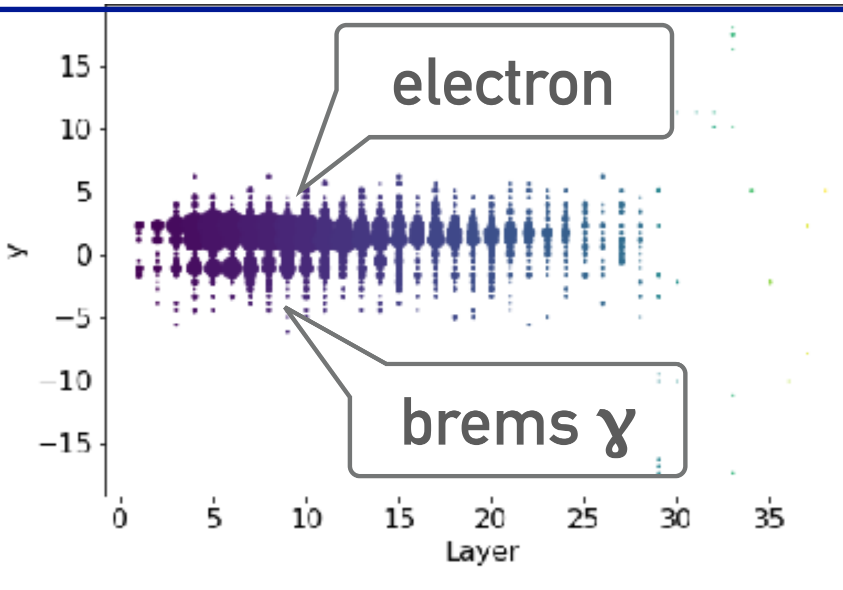
- Imaging-calorimeter: enhanced pattern recognition, good separation of nearby showers

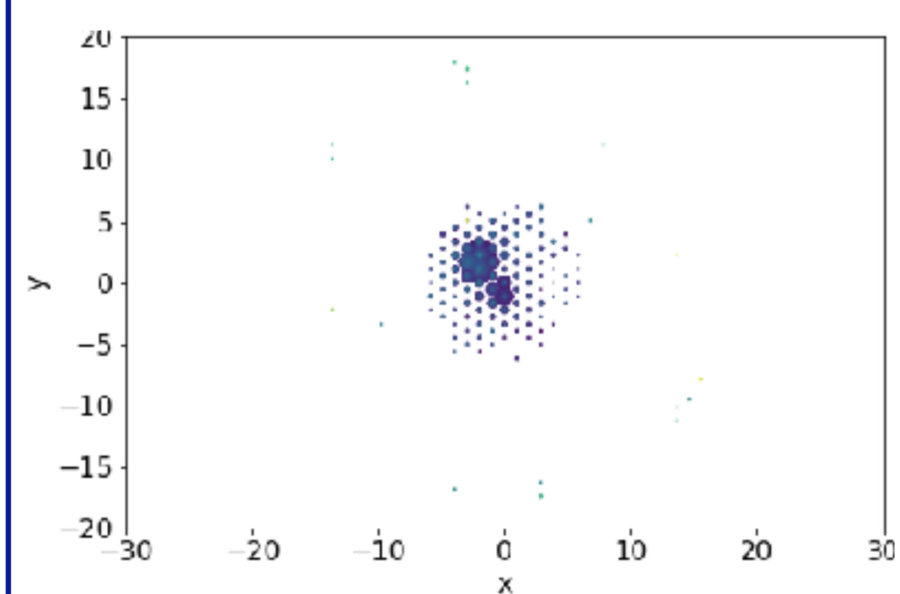
14GeV pT photons at η 2.4 [80GeV] with ~3cm separation (ΔR 0.05)

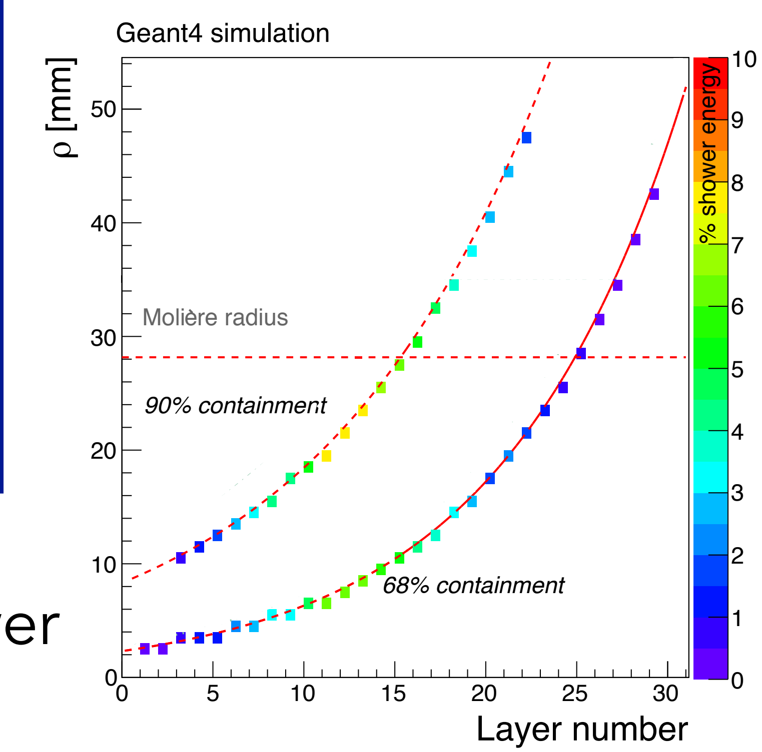


2component event from 300GeV electron beam at 2018 HGCAL tests





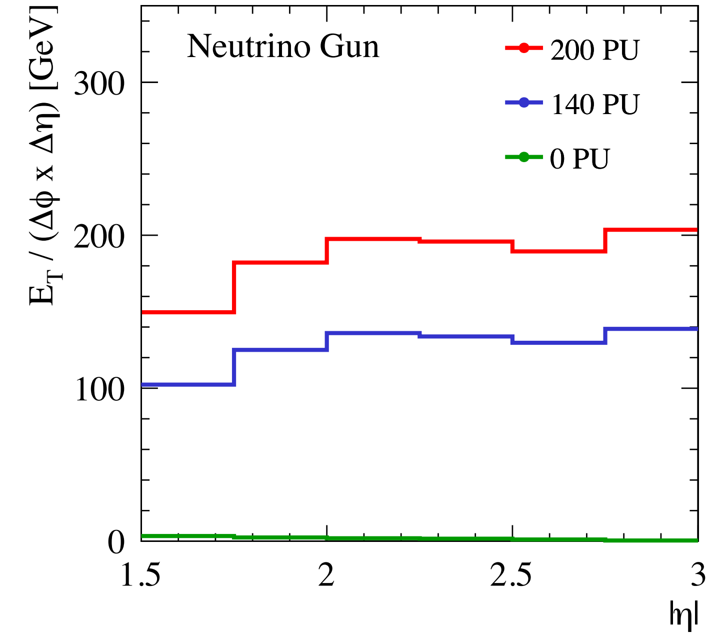




- Radial containment for photon shower

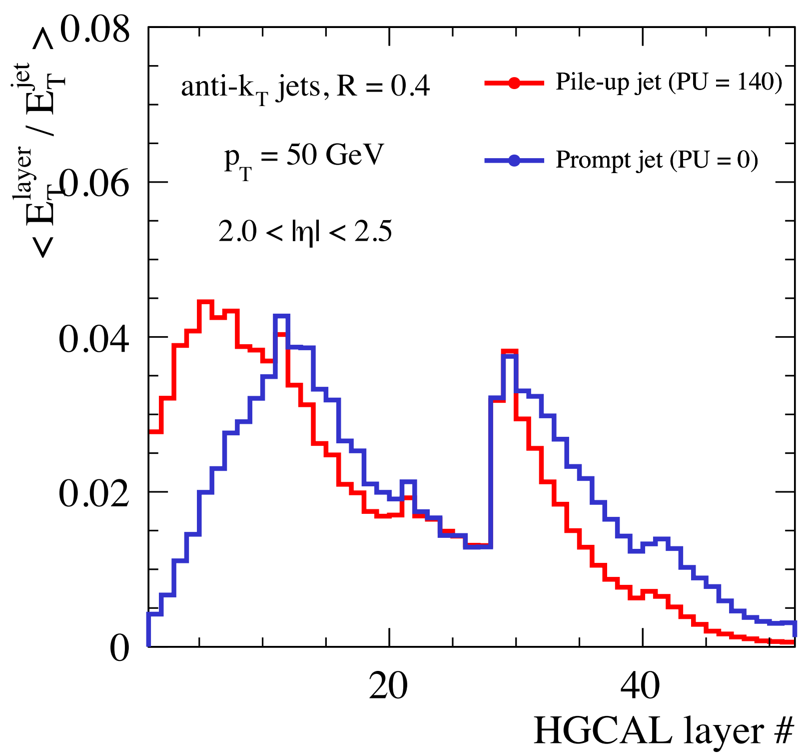
at high PU

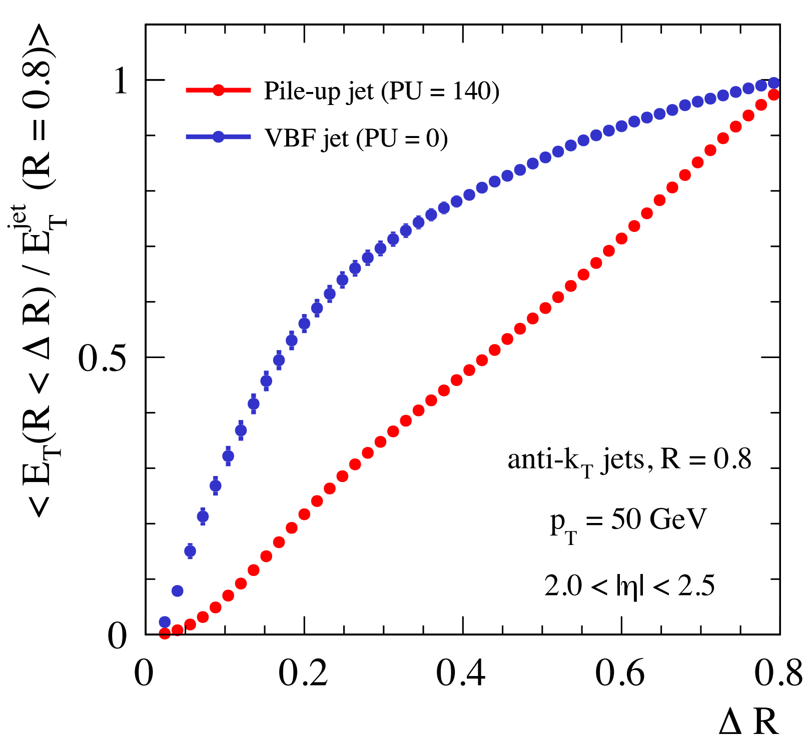
- **Energy deposition from pileup 200 is ~200GeV E_T per unit area**
  => mandatory to exploit granularity and segmentation



- Test reconstruction potential with calorimeter alone
  - Jet reconstructed with anti-kT on recHits
  - quark jets vs PU jets (overlapping soft, mainly gluon, jets)

- **Fine readout segmentation and lateral granularity helpful against pileup**

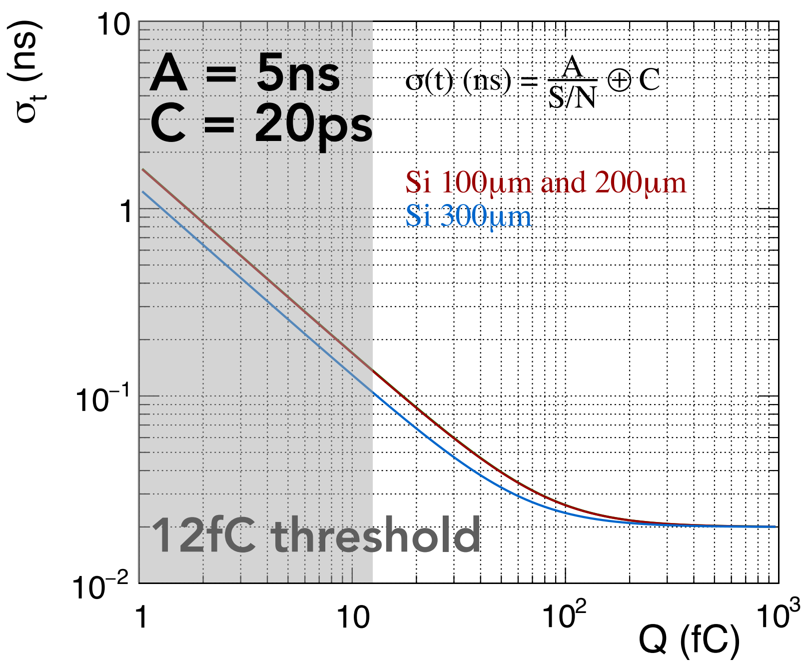




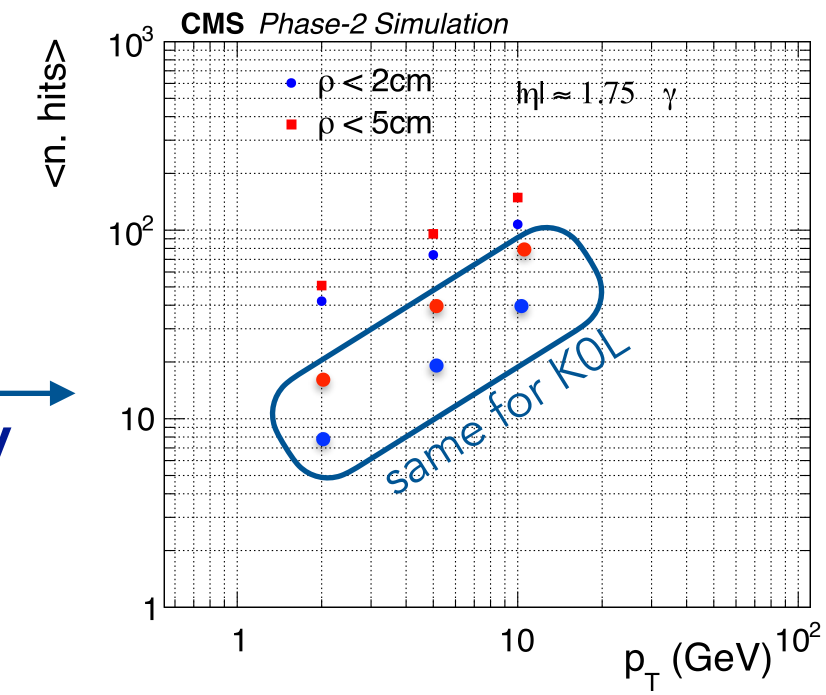
- **preliminary studies suggest potential of longitudinal and lateral energy profiles to identify VBF jets**

Precision timing

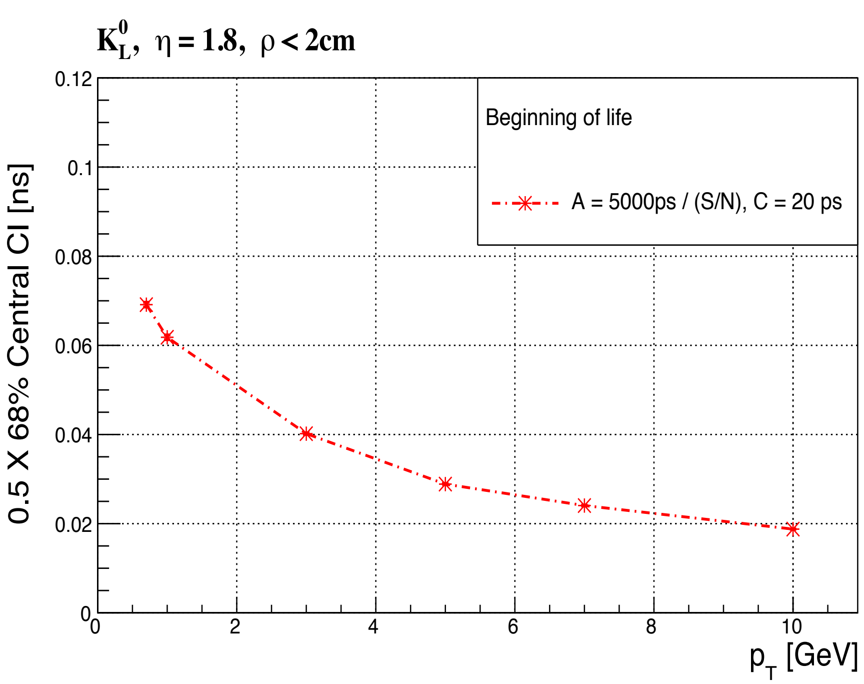
- Single cell performance from electronics simulation (Si cell + front-end electronics readout)

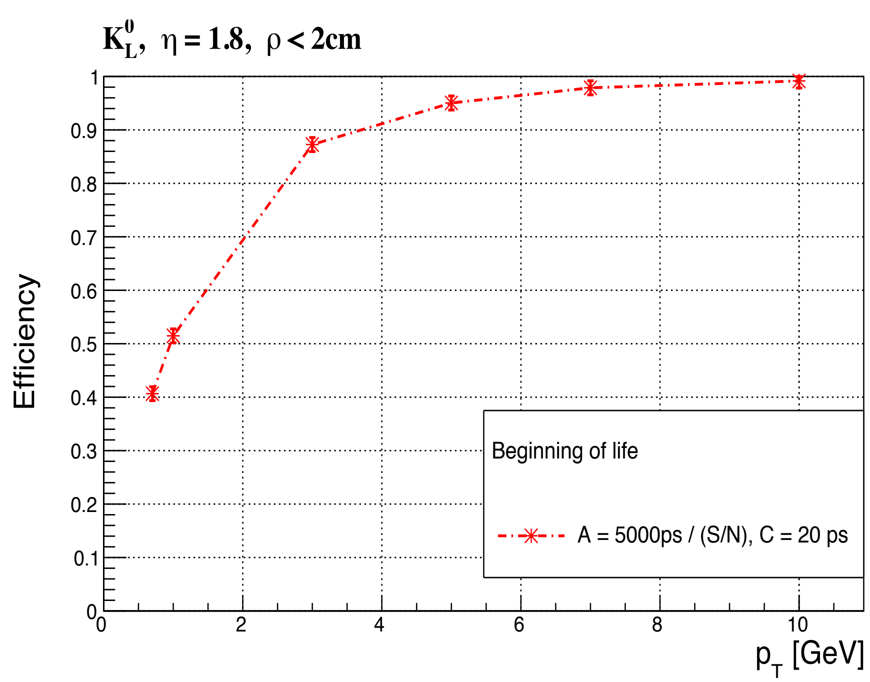


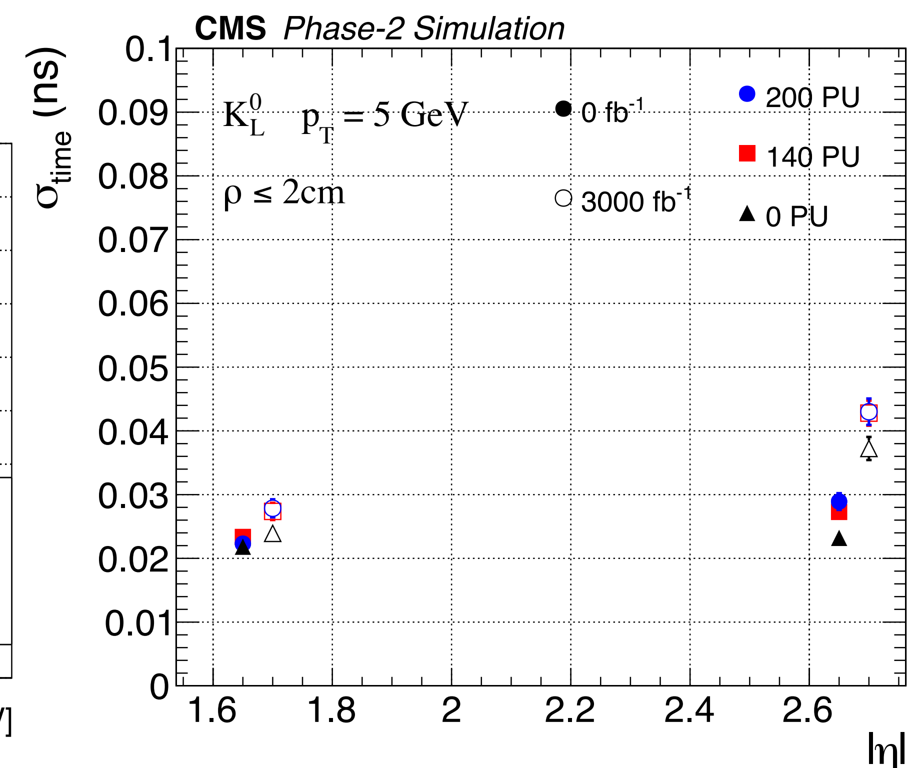
Precision timing for showers exploiting the hit multiplicity



- **photon: σt ≤ 20ps for pT≥ 2GeV**
- **hadron: σt ≤ 30ps for pT > 5GeV**
- stable performance with pileup and aged detector

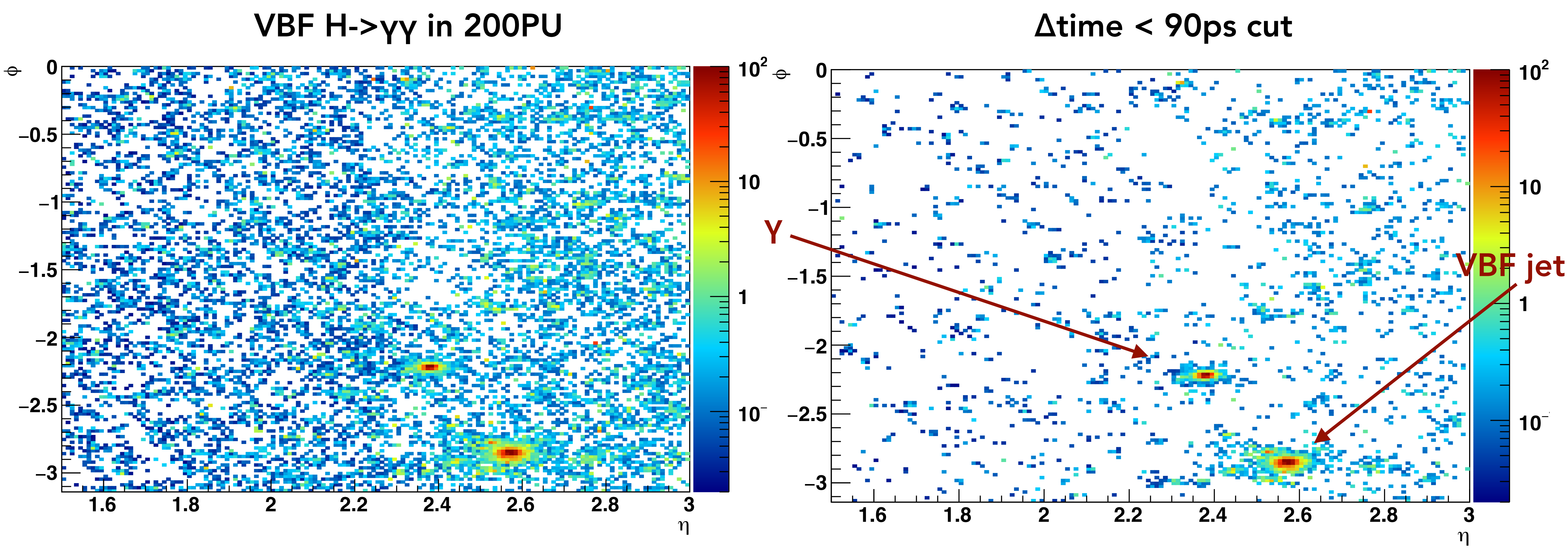






Advantage of precision timing

- Potential for 5D reconstruction using timing information



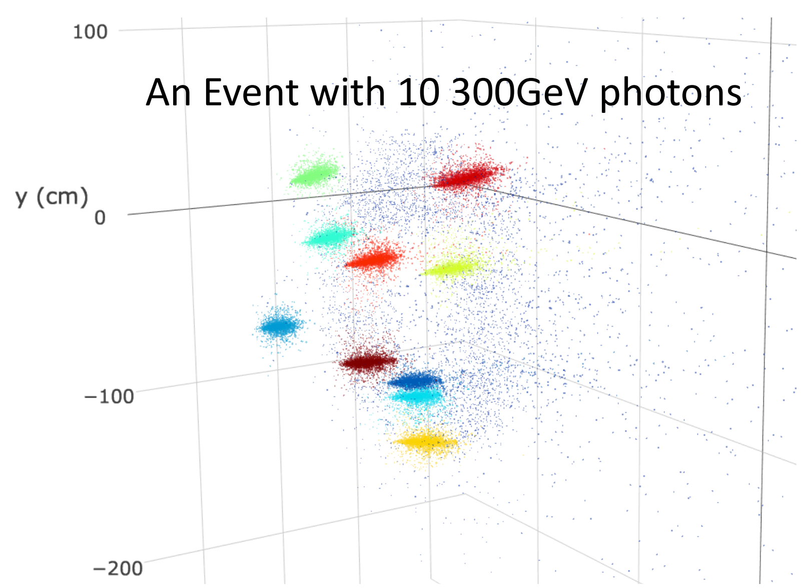
- Very powerful for pileup mitigation
  - density of hits drastically reduced
  - jet reconstruction and energy estimate less affected by pileup

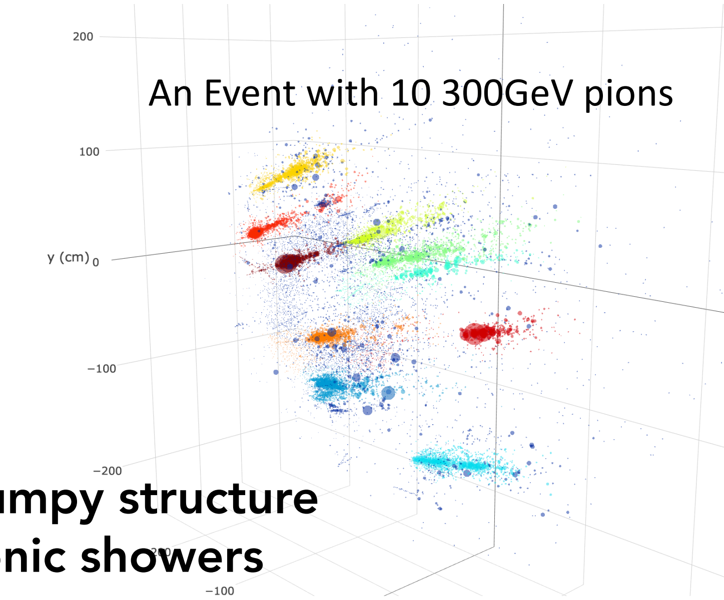
- Benefit for global particle ID exploiting time compatibility between measurements => i.e. with MTD (see talk by Adi)
  - Time compatibility = dT between measurements = time-of-flight(ID, track length)

Reconstruction: key element for performance

- New detector = new reconstruction => algorithms to best exploit the information provided

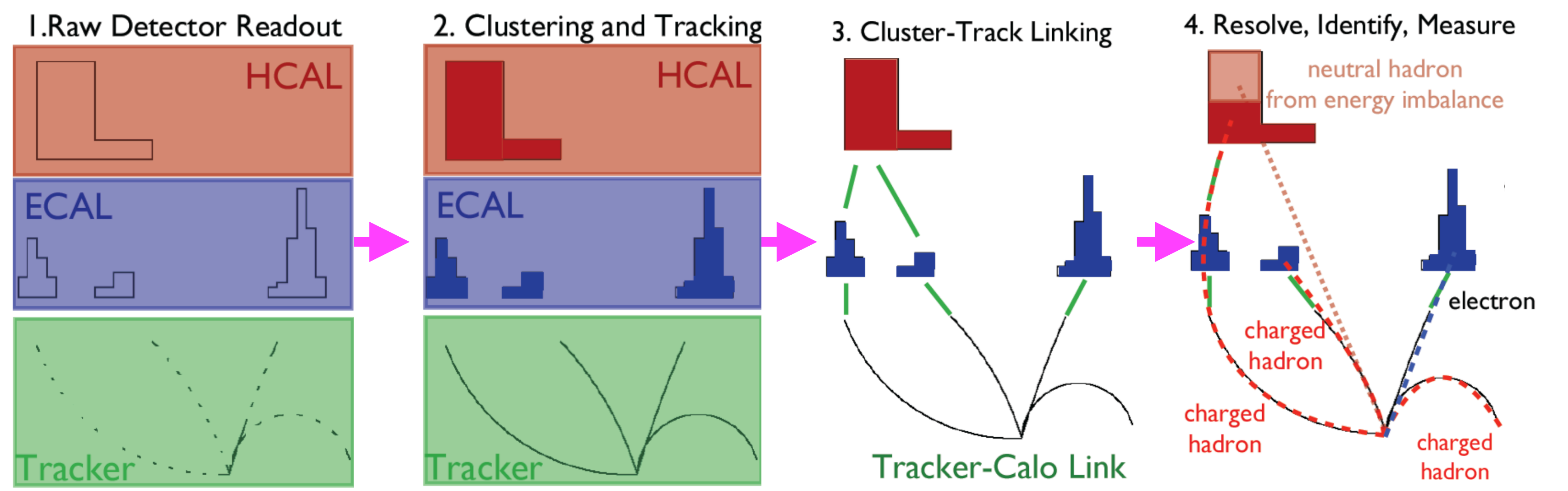
- Use the distinctive features in the shower development of different particles





visible lumpy structure of hadronic showers

- CMS relies heavily on particle flow (PF)
  - the combined information of sub detectors (i.e. tracker + calorimeters) to provide the best ID
  - HGCAL design is ideal for this
    => producing imaging of showers with high granularity

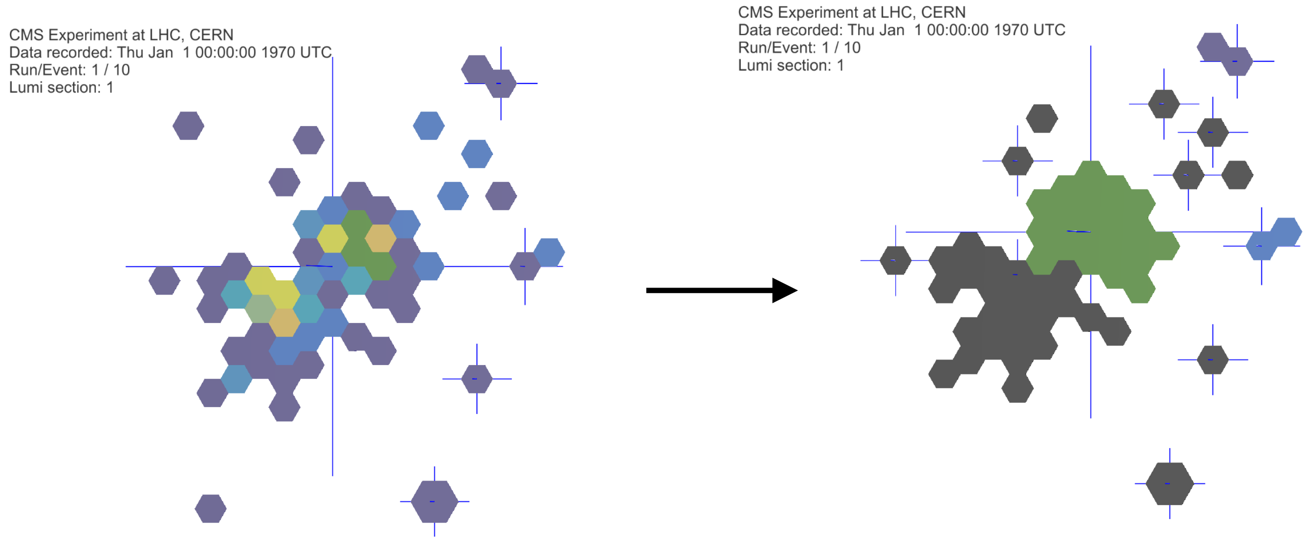


- Idea is to design a HGCAL local reconstruction PF-based
  - position, energy, time for a 5D global pf reconstruction

Layer images and The Iterative CLustering

- 1) Build **layer images "2D clusters"**
  => use a local energy density parameter

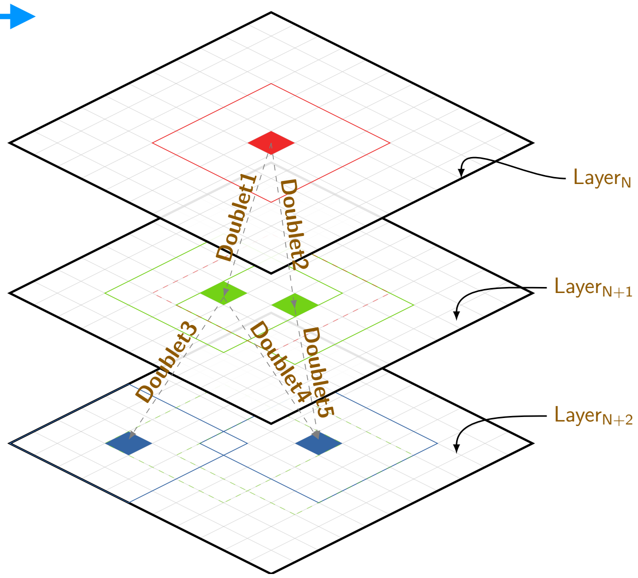
  inspired by: [A. Rodriguez, A. Laio,
  "Clustering by fast search and find of density peaks",
  Science 344 (6191), 1492-1496. (June 26, 2014)]



- 2) Associate the 2Dclusters to reconstruct 3D showers
  => each iteration to build "tracksters" (= clusters aligned like tracks)

  - start with **a seed region**
    => self-seeded (unconverted photons)
    => track seeded (e+ / e- / charged hadrons)
  - **pattern recognition** on the 2D clusters in the region
  - **linking** + **cleaning** to assign an ID with a given probability
  - **mask** what pass the criteria on the ID and repeat on what is left

topological compatibility as baseline



- **Algorithm design with parallelism, able to run on GPUs**

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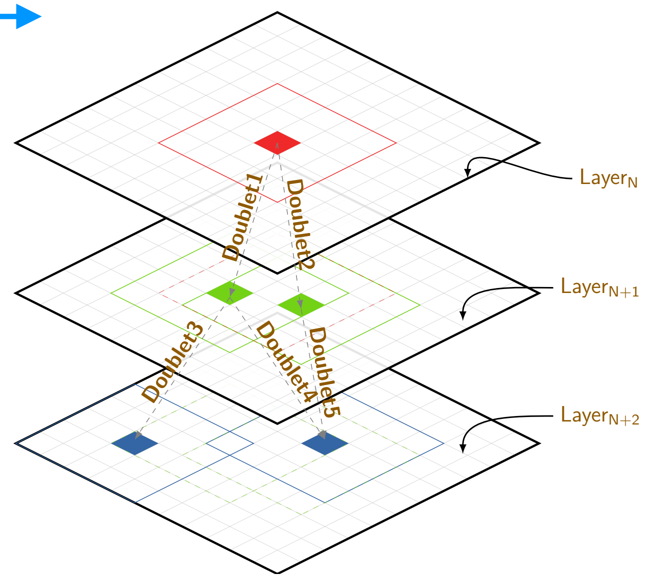
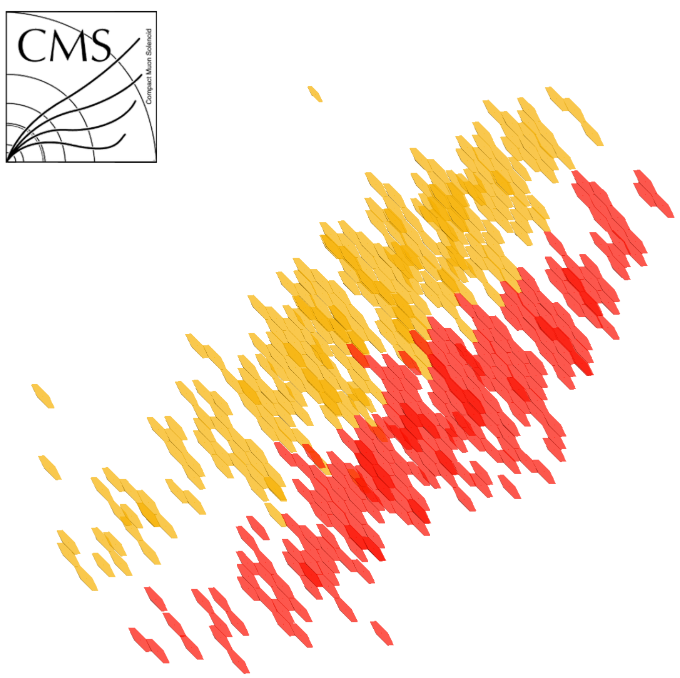


- Algorithm design with parallelism, suitable for GPUs

Self-seeded iterations in **0PU**

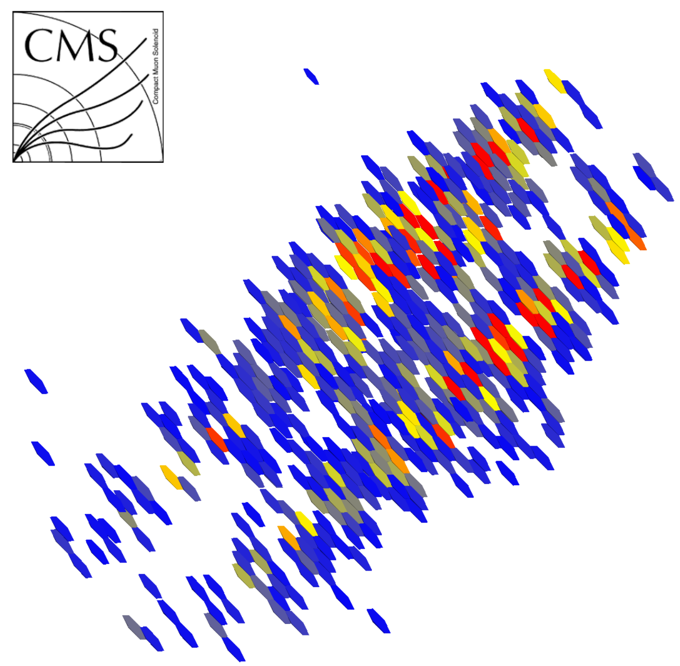
- Excellent shower separation

$e^+ e^-$ showers from γ conversion



COLOR = PARTICLE

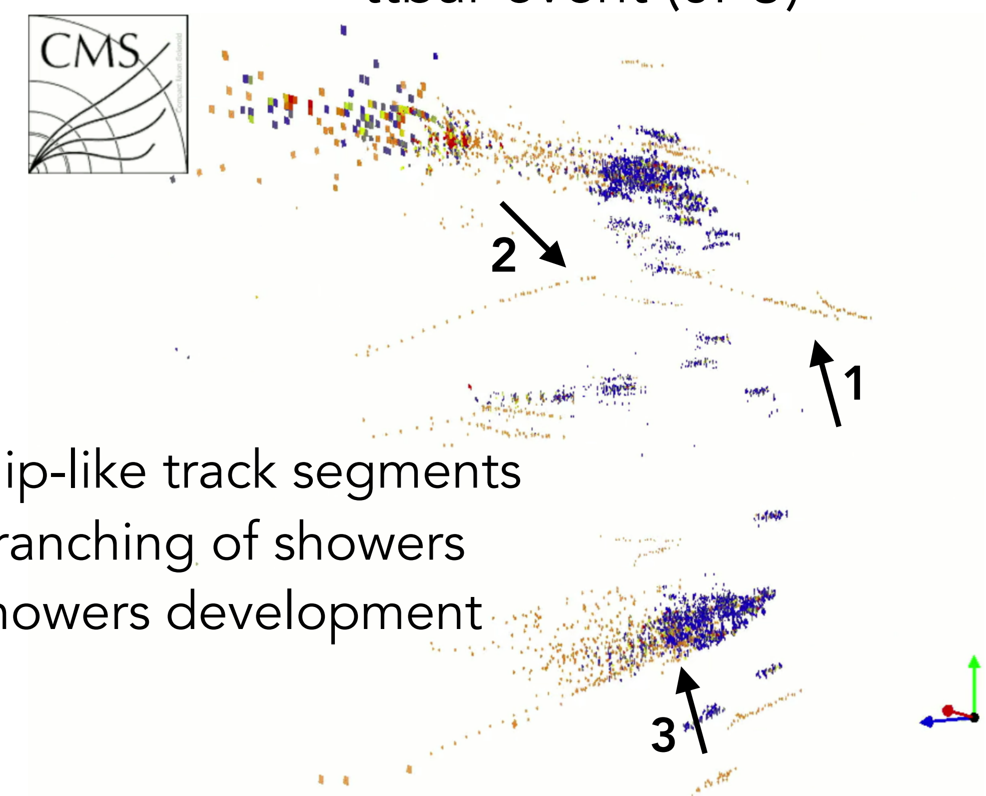
separation of nearby showers



COLOR = ENERGY

high energy core visible
in the layers with
maximum energy deposition

ttbar event (0PU)



1 mip-like track segments
2 branching of showers
3 showers development

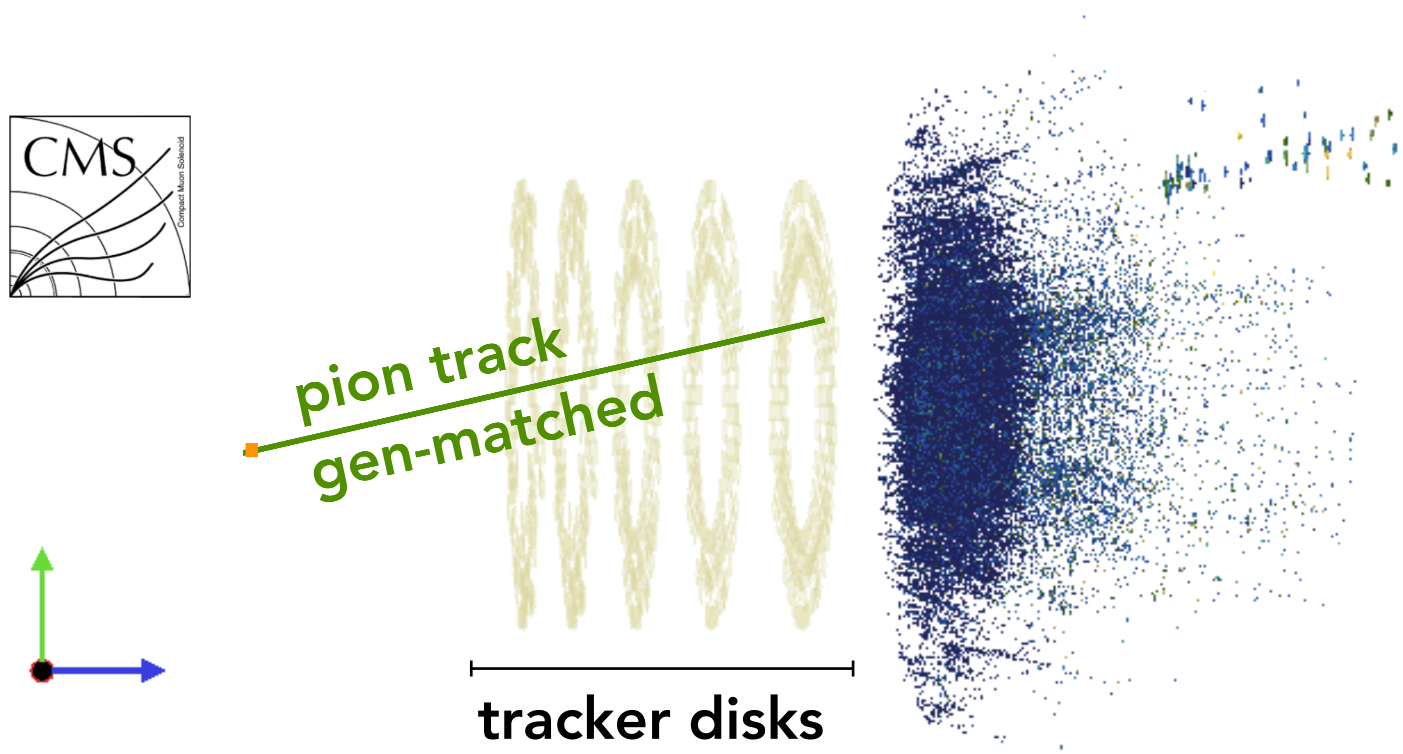
COLOR = ENERGY

- Full event description

single pion in **200PU**

- Self-seeded iterations and NO cleaning
  => essentially a typical event in 200PU

π^+ [pT 10GeV, η 1.7]

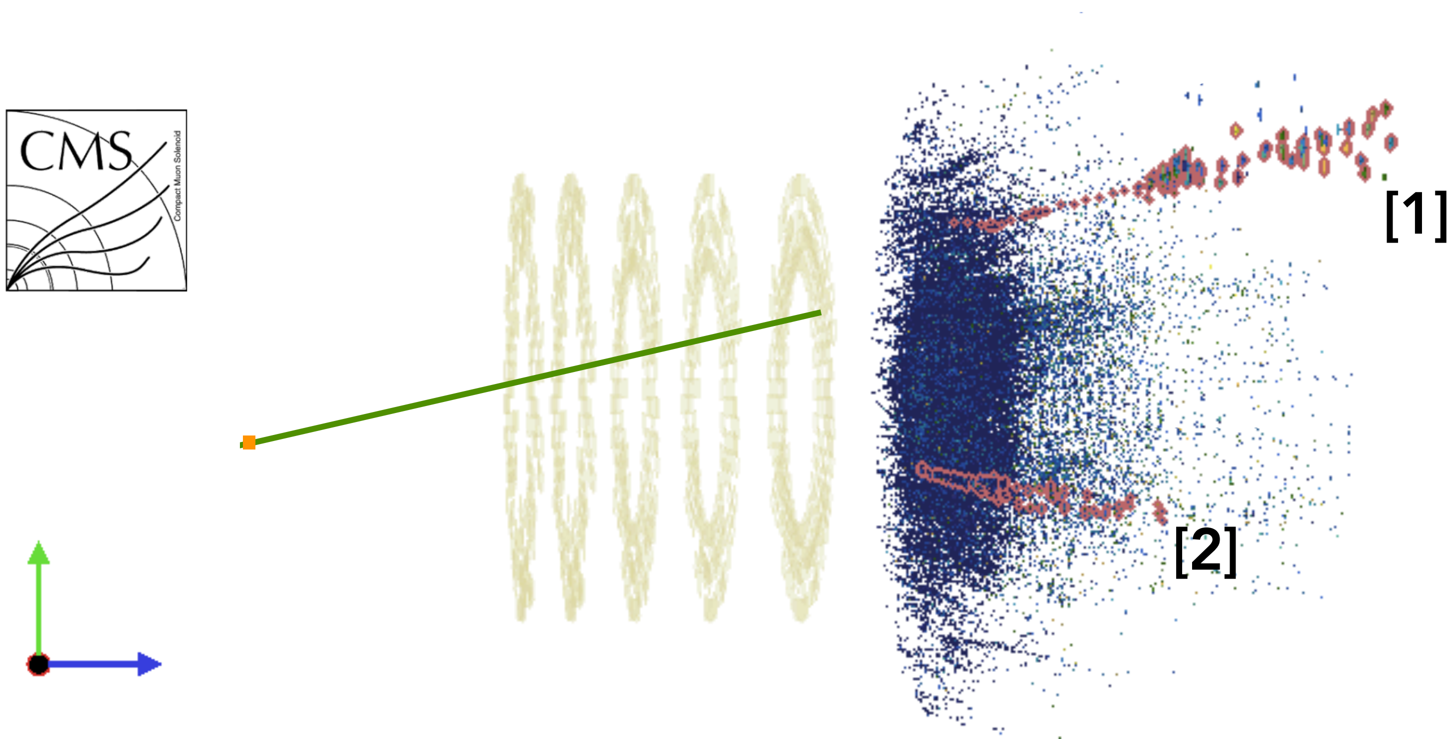


- Can use the reco-tracks to seed the pattern recognition

(Seeded iteration) **single pion** in 200PU

π⁺ [pT 10GeV, η 1.7]

- Seeding tracks: pT > 5GeV + ID criteria
  - trackster from hard-scatter pion cleanly reconstructed [1]
  - tracks from PU can satisfy the seeding criteria [2]



  - but also PU in the first layers of each seeding region collected into tracksters
- Addition of time compatibility in the pattern recognition to connect 2Dclusters over layers
  - to help the rejection of out-of-time 2Dclusters from PU
  - strongly reducing the high pT clusters built-up from PU

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topological compatibility as baseline

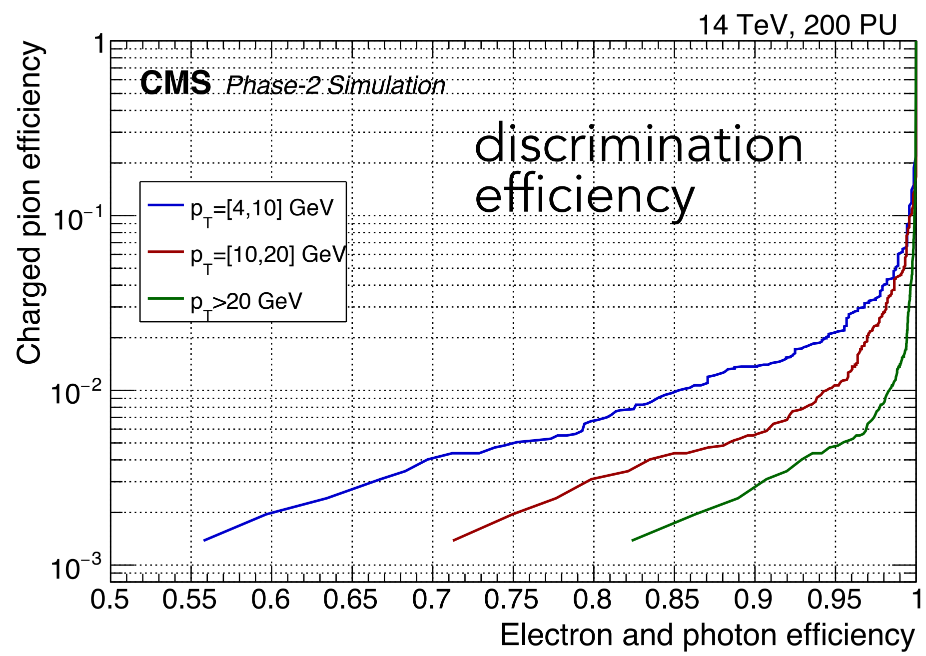
- Algorithm design with parallelism, suitable for GPUs

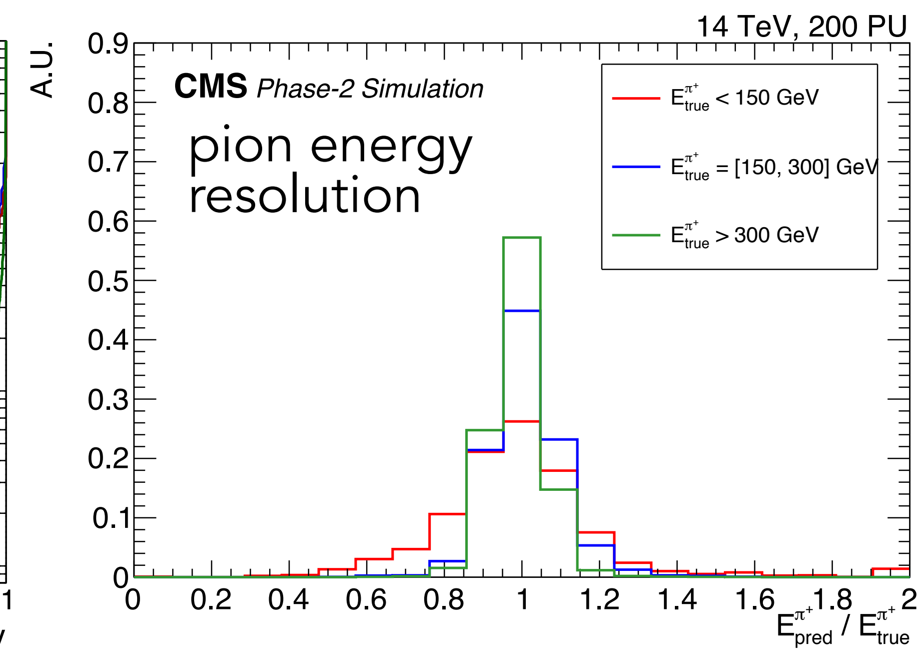
Using ML techniques

- Baseline algorithm will exploit ML for particle ID and improved shower measurements

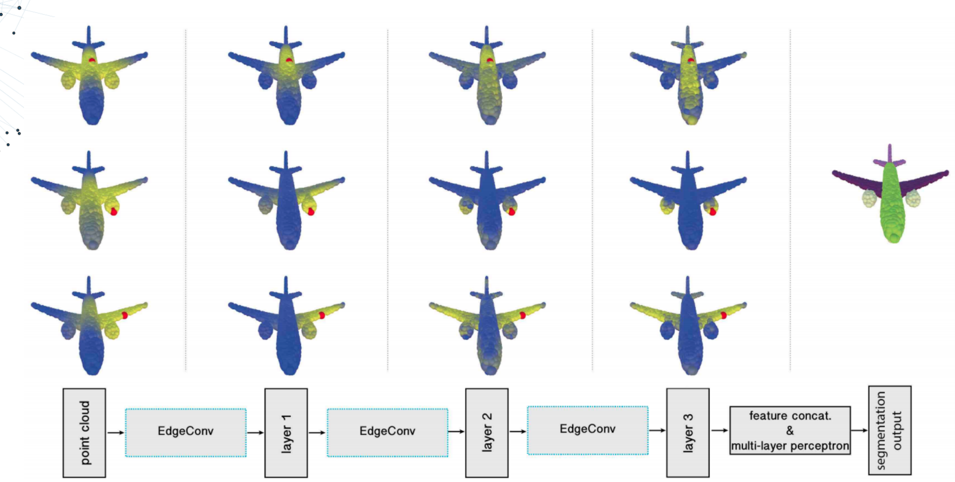
Exploratory studies in standalone simulation with simplified calorimeter

- Excellent ID capabilities





- Use of graph neural networks for ML based full reconstruction
  - Invariant w.r.t. order of inputs
  - Do not depend on a regular geometry
  - Particularly interesting: dynamic graph networks learning space transformations (e.g. local energy density taking into account sensor geometries)



Developed dedicated dynamic space transformation networks: GravNet [arxiv:1902.07987]

Summary

- **High Granularity Calorimeter for the HL-LHC is a very ambitious project!**
  - fine granularity + fine longitudinal readout segmentation => $O(10^6)$ channels
  - energy + position + time information => providing a 5D image of the shower development

- **Developing a reconstruction that fully exploits the features of the detector is a challenging & creative task**

- **Layer images + TICL are very promising solutions**
  => most of the development ongoing, first full-reconstruction sequence to converge soon
  => developments to be expected from now until start of HL-LHC

Stay tuned!