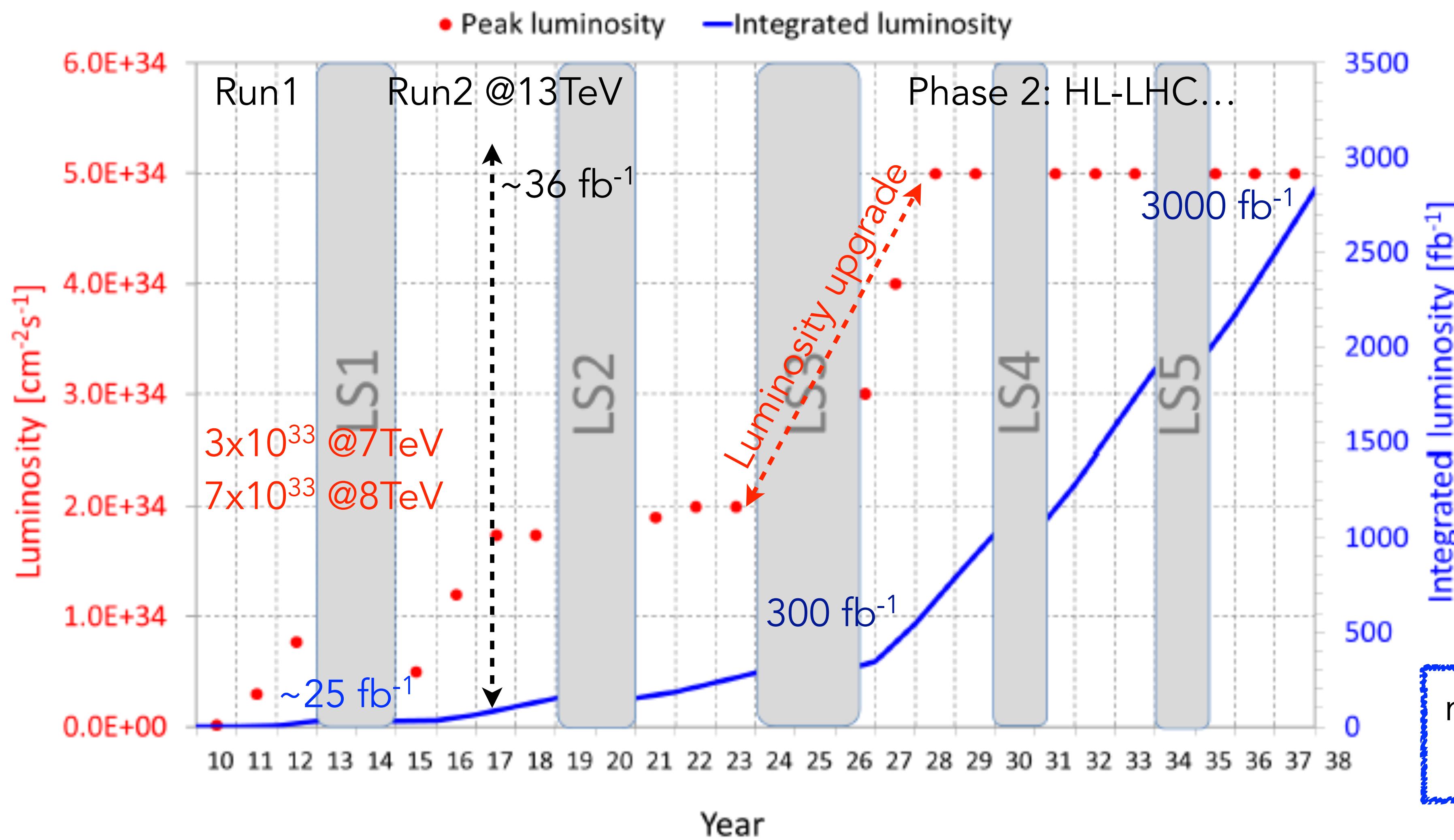
The CMS HGCAL detector for HL-LHC upgrade

Arabella Martelli (CERN)
for the CMS collaboration

LHCP2017: 5th Large Hadron Collider Physics Conference 2017
15-20 May 2017

The upgrade program…

- Machine upgrade => needed to take on the **demanding physics program for Phase 2**
- Detectors upgrade => to maintain excellent performance in the harsh HL-LHC environment
  - The current CMS electromagnetic and hadronic endcap calorimeters will suffer irrecoverable radiation damage well before the end of HL-LHC running => will be replaced



need granularity and radiation hardness

- **Important role of the forward calorimeter for physics at the (HL)-LHC**
  - searches and precision SM measurement: VBF process, VBS, H->ZZ->4e…
  - complement the tracker upgrade: extended coverage to |η|<4 and a reduced material budget

…of the CMS forward calorimeter

- The CMS collaboration has chosen to replace the forward calorimeter with a **High Granularity Calorimeter: fine grain for a 3D shower reconstruction**
  => Silicon/scintillator sampling calorimeter, including both em (EE) and had (FH+BH) parts

Key Parameters:

- HGCAL covers $1.5 < \eta < 3.0$
- Full system maintained at -30°C
- ~600m^2 of silicon sensors
- ~500m^2 of scintillators
- 6M Si channels, 0.5 or 1 cm^2 cell size
- ~22000 Si modules
- Power at end of HL-LHC: ~60 kW per endcap

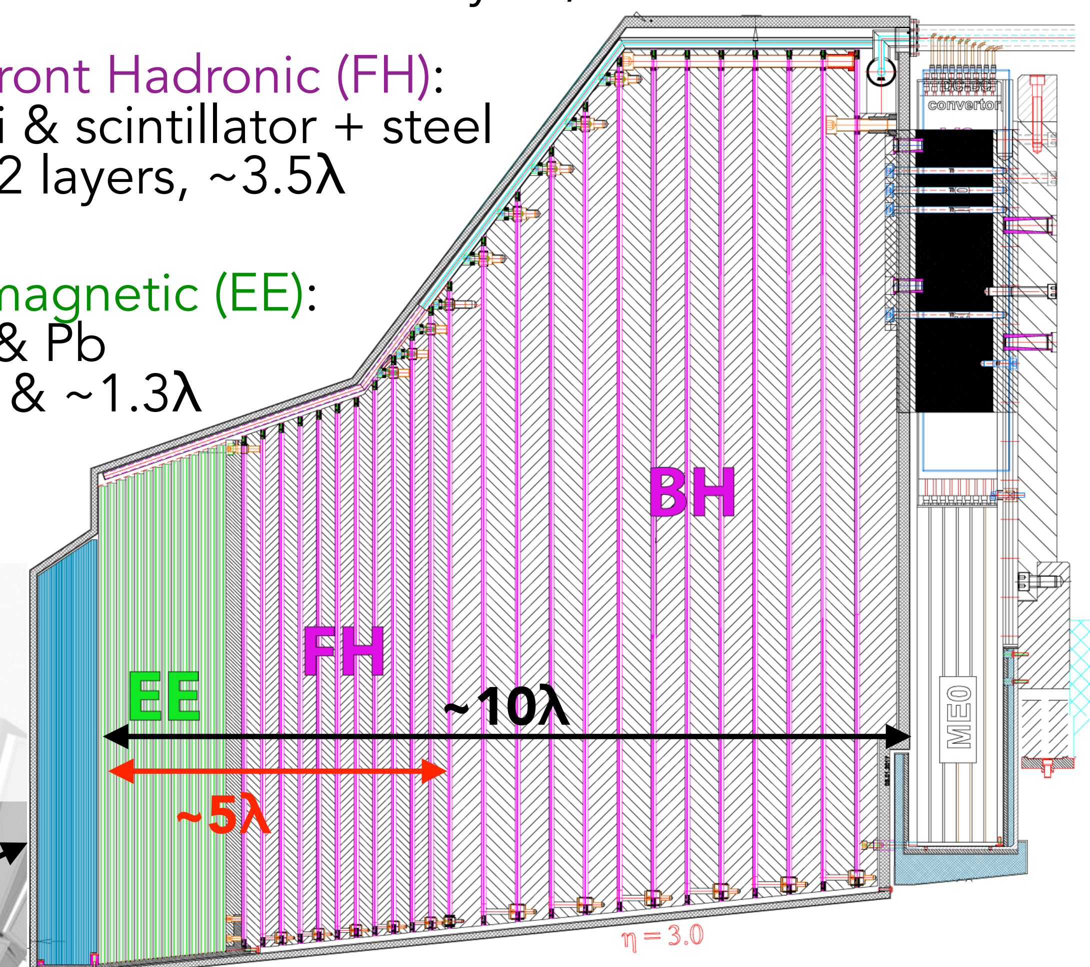
Active Elements:

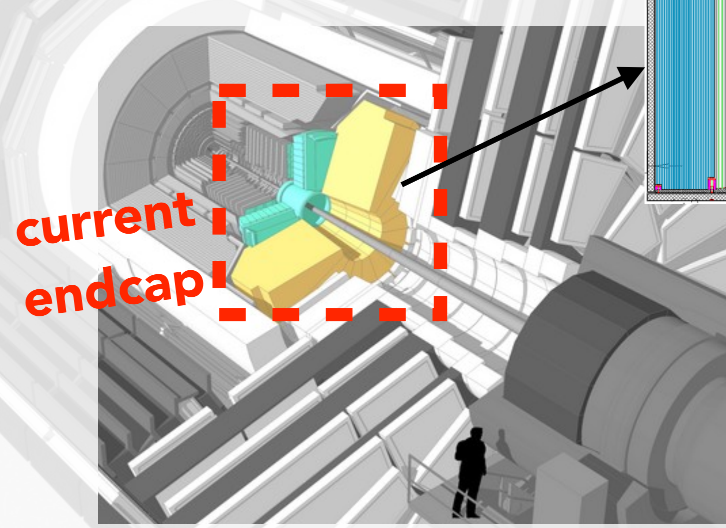
- Hexagonal modules based on Si sensors in EE and high-radiation regions of FH & BH
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with SiPM readout in low-radiation regions of FH & BH

Backing Hadronic (BH):
Si & scintillator + steel
12 layers, ~5λ

Front Hadronic (FH):
Si & scintillator + steel
12 layers, ~3.5λ

Endcap Electromagnetic (EE):
Si + Cu & CuW & Pb
28 layers, 25 X0 & ~1.3λ





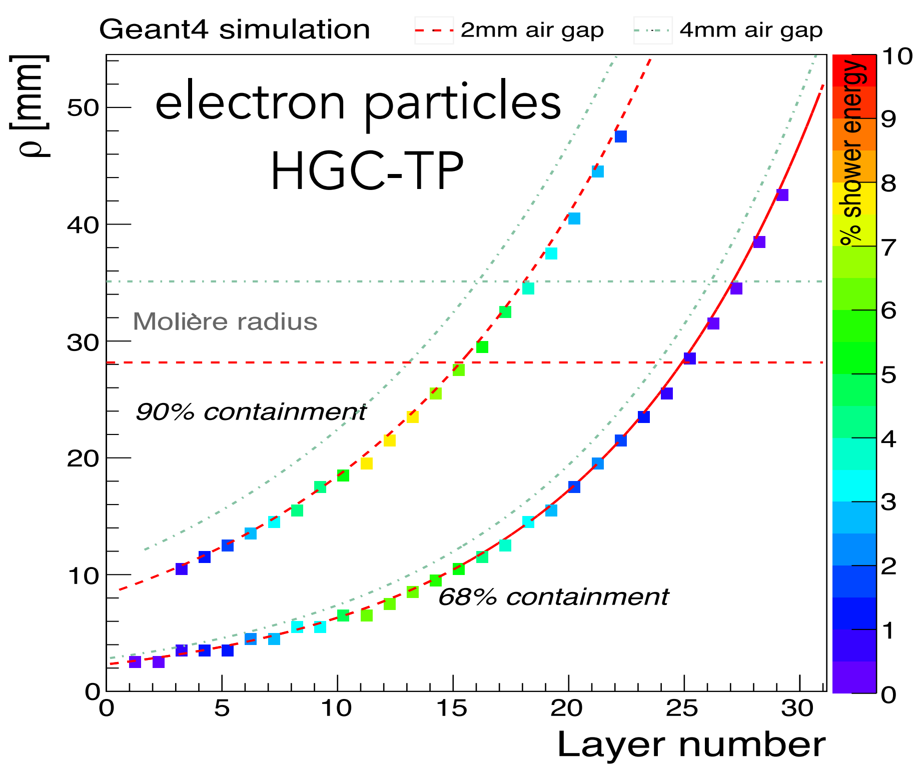
- High granularity for congestion
- Silicon for radiation hardness

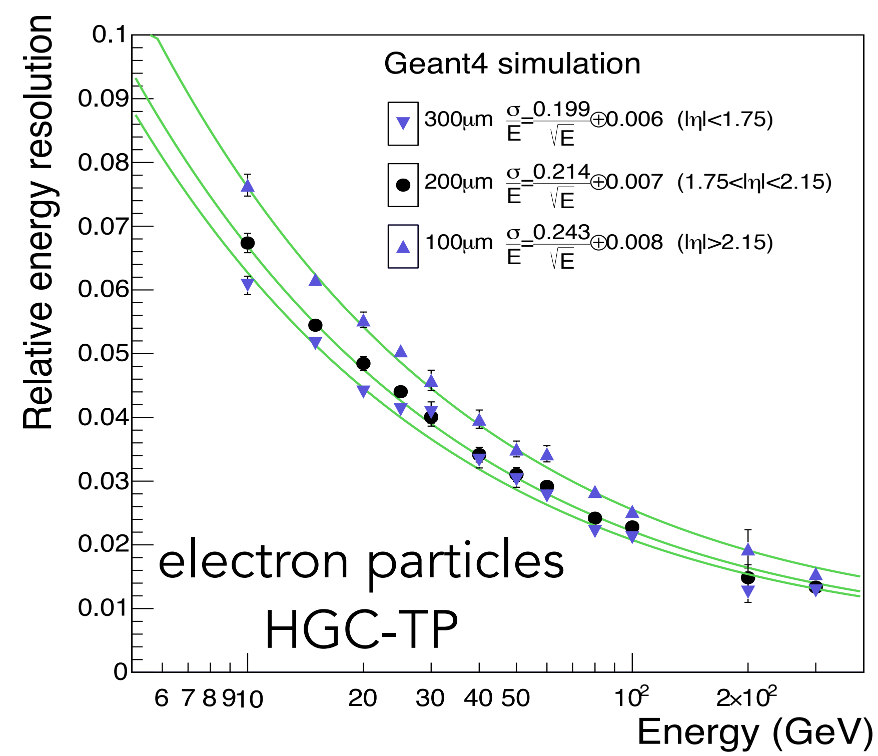
need granularity and radiation hardness

High granularity for imaging-like physics reconstruction

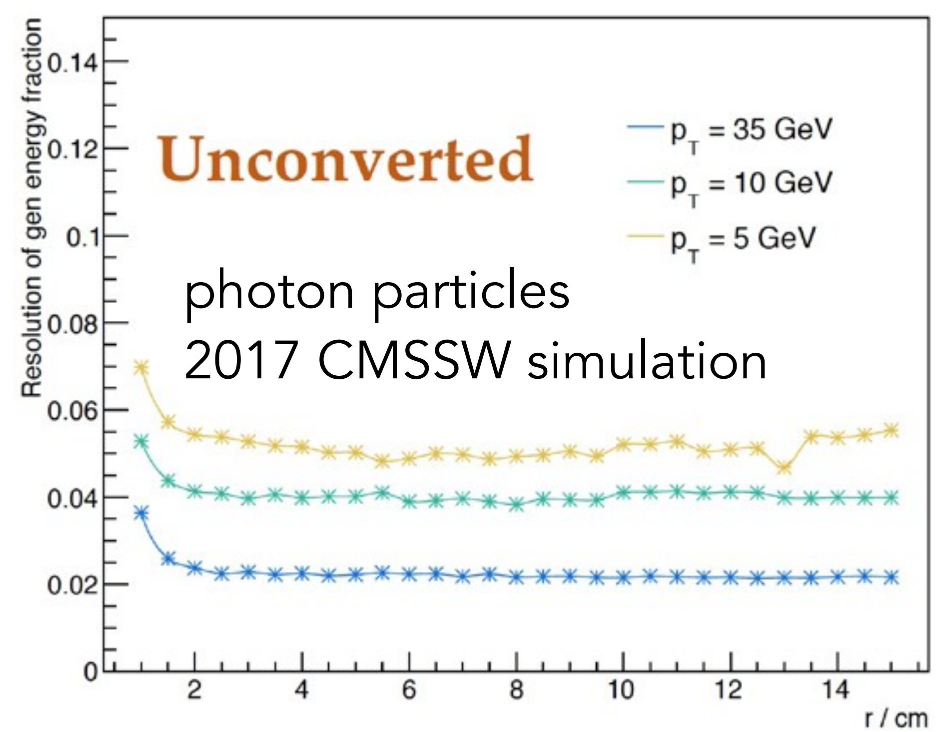
Electromagnetic showers

- From the CMS Phase II Upgrade Technical Proposal: https://cds.cern.ch/record/2020886?ln=en
  - Good energy resolution for EM showers
  - Molière Radius: 90% contained in ~2cm





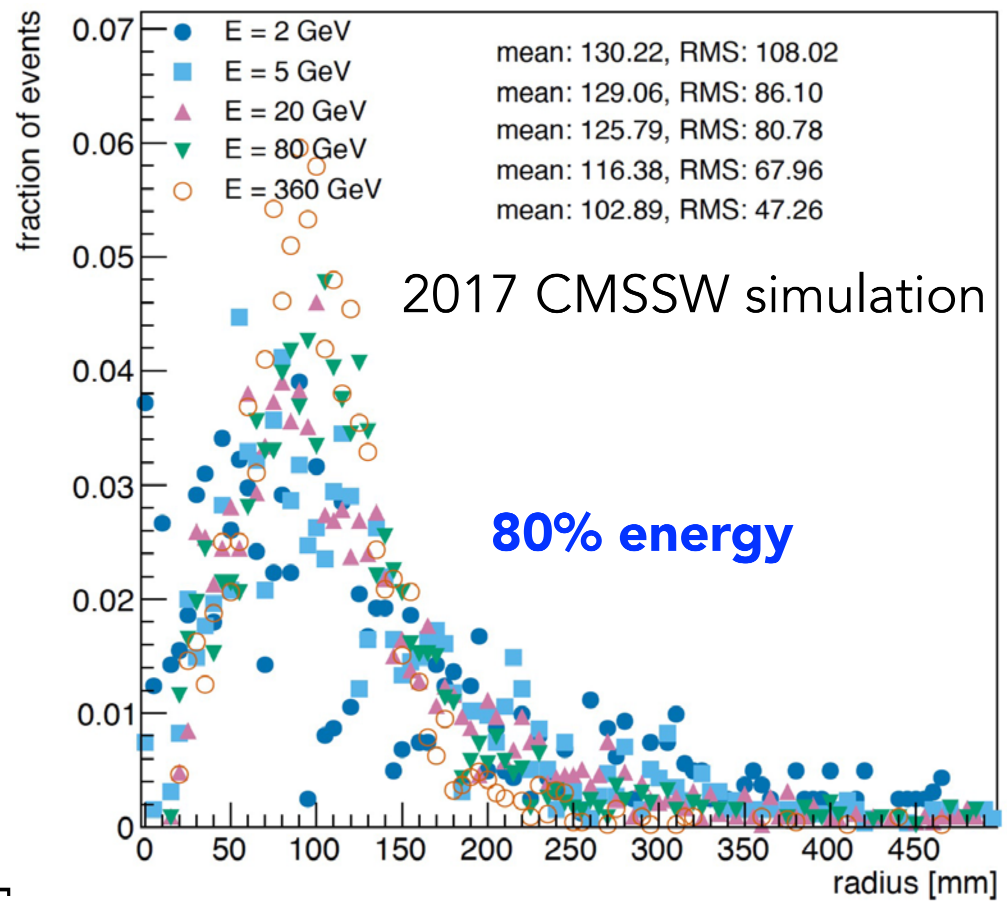
- From recent reconstruction developments*
  - measured energy resolution when considering energy deposited within a cylinder (radius r) around the shower axis
    => Indication of competitive energy resolution



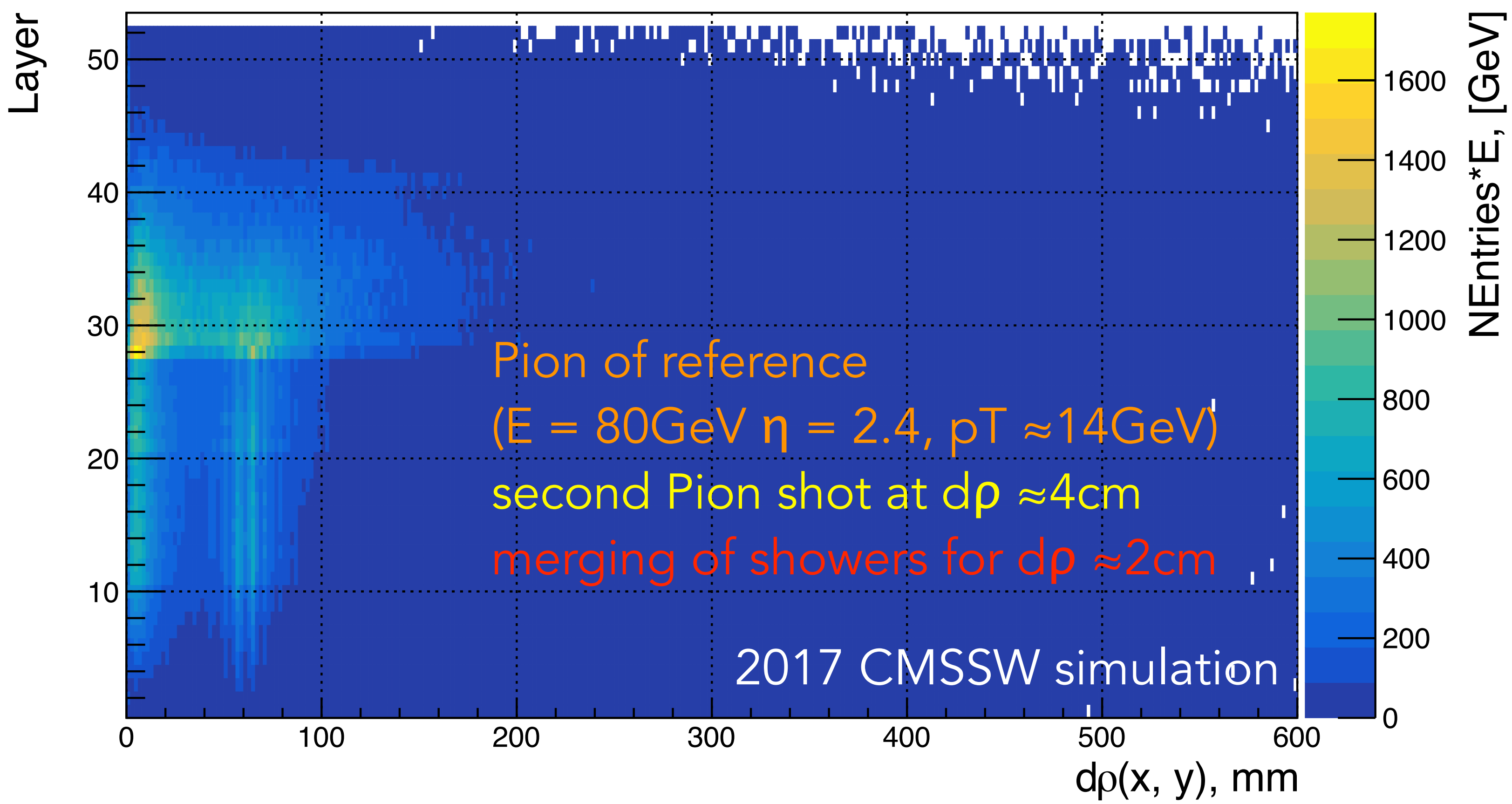
*Density-based imaging-clustering (see next)

Hadronic showers

- Charged pion showers:
  - ~80%-90% of the shower energy is contained in a ~10cm radius

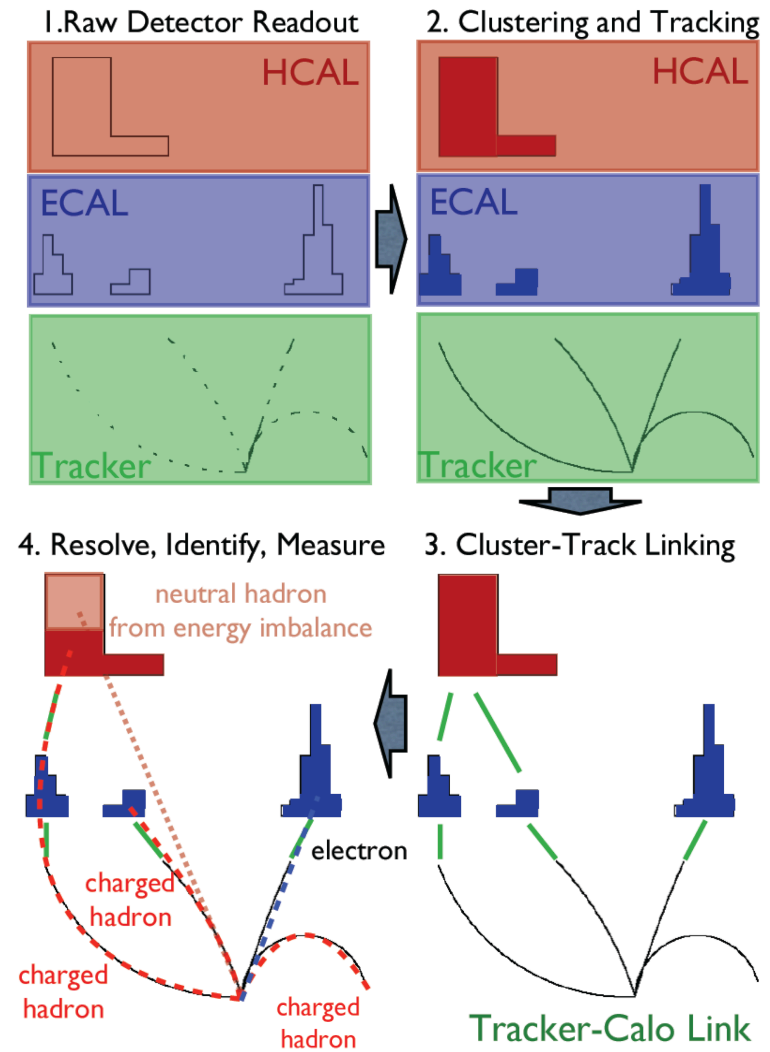


  - the minimum separation distance needed to resolve and split two different clusters is almost an order of magnitude smaller than the full containment radius

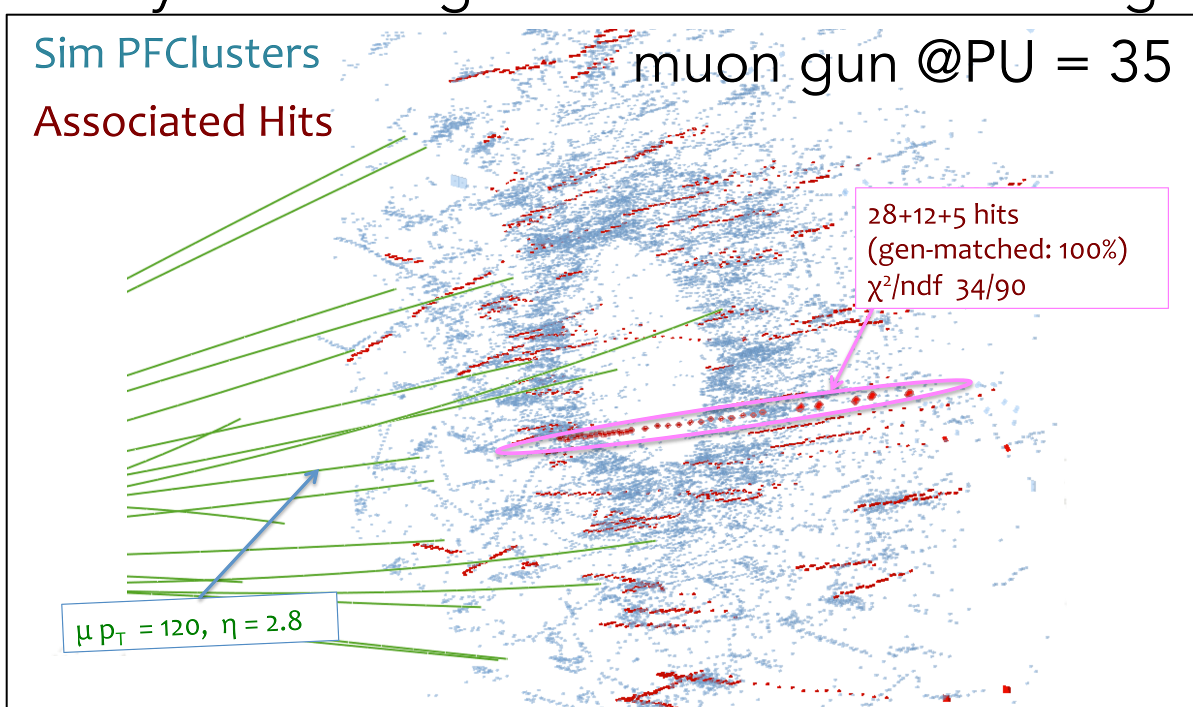


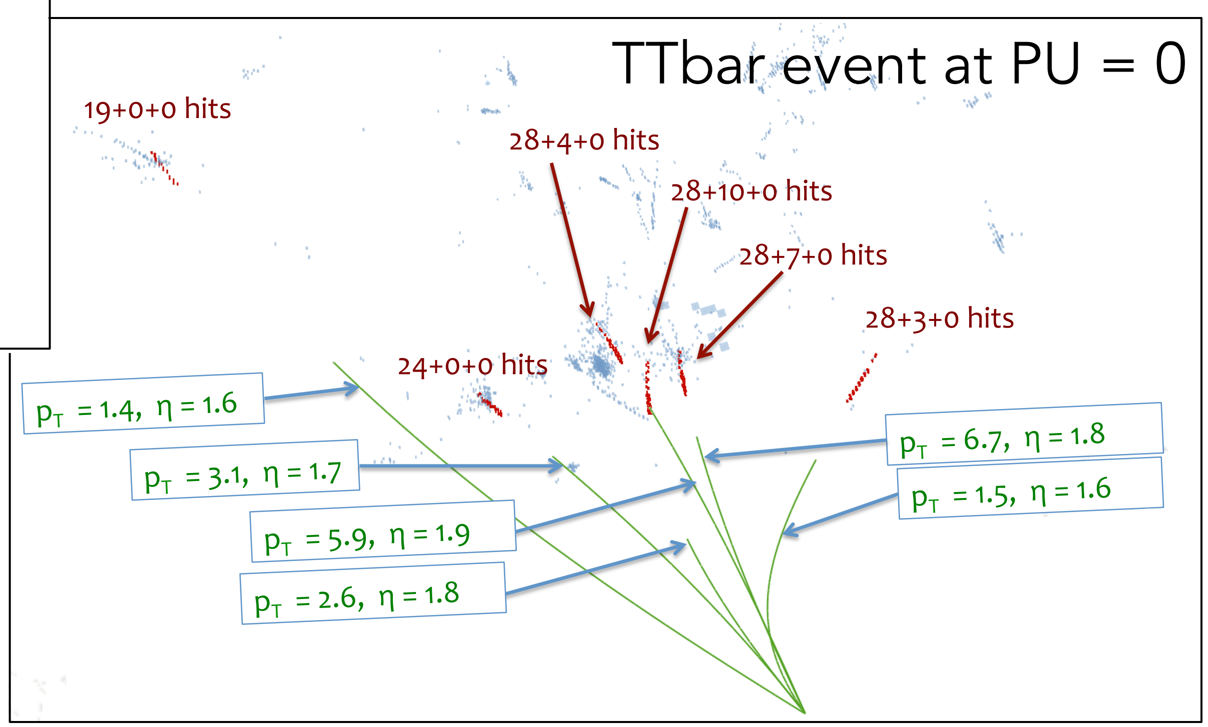
Particle ID and event reconstruction

- Exploit the calorimeter design to use in combination with the tracker for particle flow reconstruction



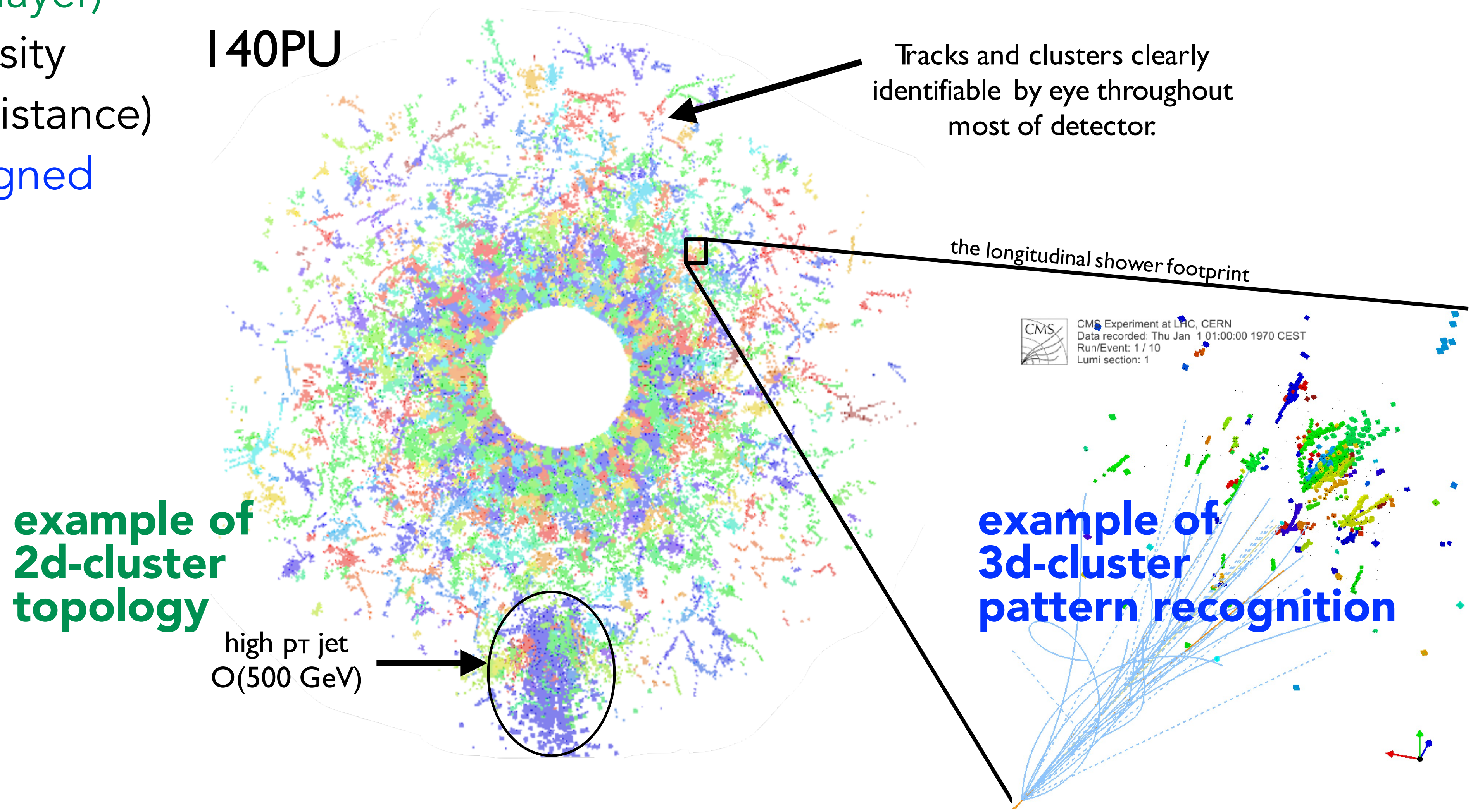
- Event display from CMS simulation
  - showing the precision achieved by combining tracks and calorimeter signals





the 3D imaging clustering

- Reconstruction: need to separate individual particles in high pile-up environment
- Current algorithm: imaging-clustering*
  => best suited for the high granularity offered by the HGCal
  - **builds 2d-clusters** (each layer) based on the energy-density of the cells (energy and distance)
  - **associate 2d-clusters** aligned along the shower axis over different layers



- Extendable to more than two dimensions:
  - 3d spatial clustering already showed improvements => exploit full spatial correlation of the shower development

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

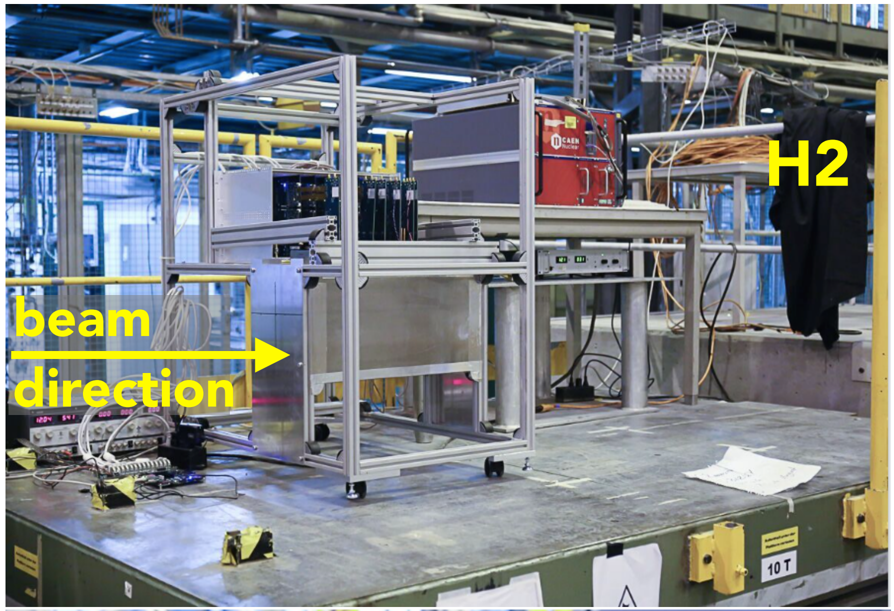
Wonderful potential and good simulation performance…

…does it work for real?

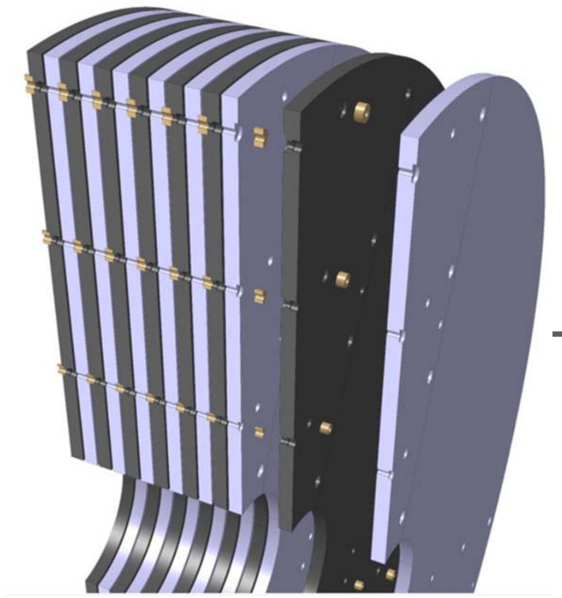
From TP to prototypes

- Since the technical proposal (end 2015): with a basic design of the detector
  - ongoing progress in design of mechanics
  - start of extensive prototyping phase

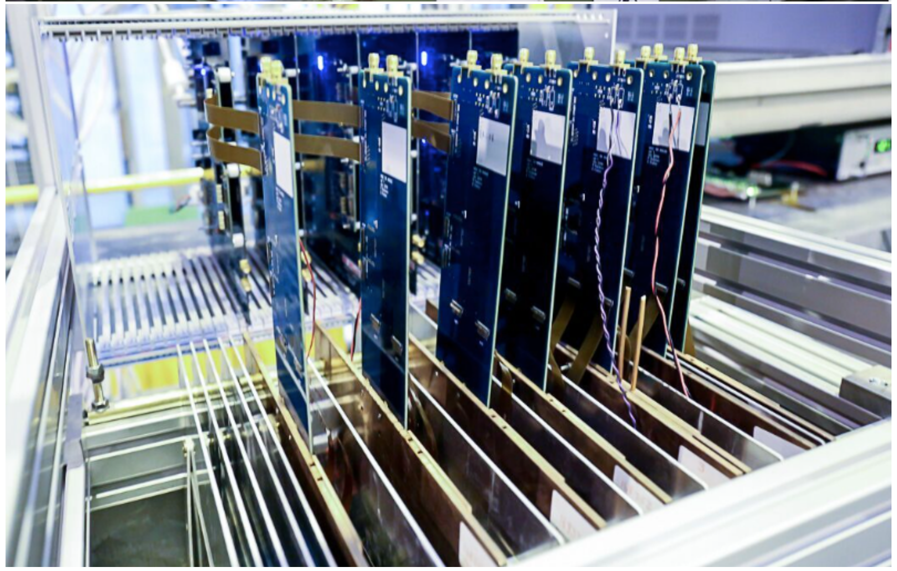
- In 2016 a series of beam tests at FNAL and CERN were carried out to test the first prototypes of the EE hexagonal Si-modules
  - to give a proof of concept of the proposed design
  - compare measured performance with a detailed simulation



design view of the full-disks mechanics with sampling layers



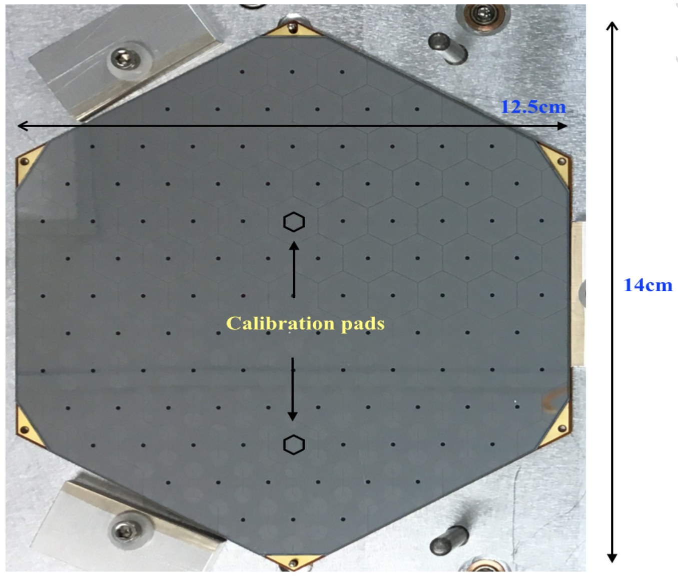
realized as a prototype with a hanging-file mechanics for flexible insertion of active layers and absorbers



prototype tested at the SPS H2 area at CERN

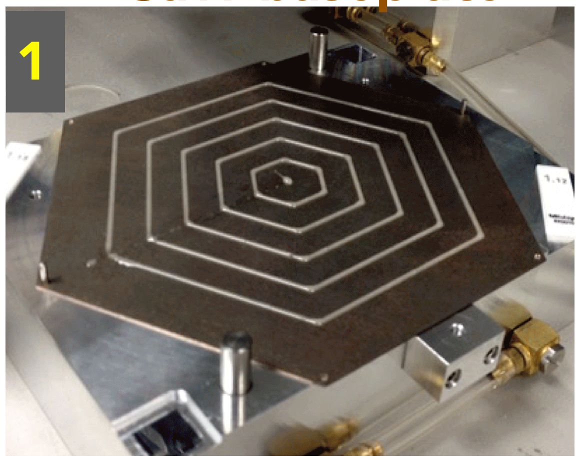
2016 TB: sensor module assembly

- 128 channels Si sensors:
  - n-type, 1cm2 cell-size, 200um depleted region

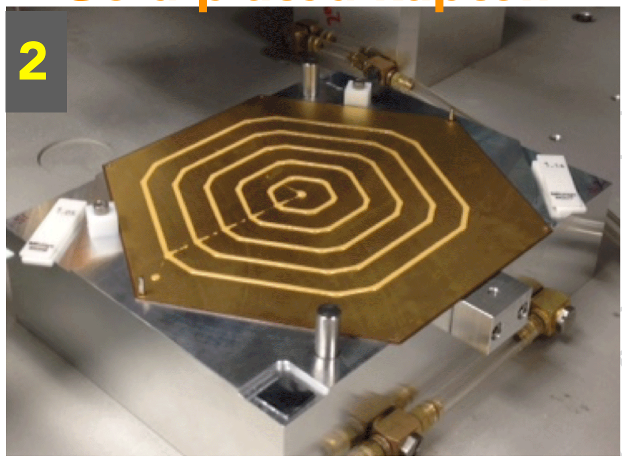


- Demonstration of assembly process:
  - module assembled as a glued stack of hexagon components

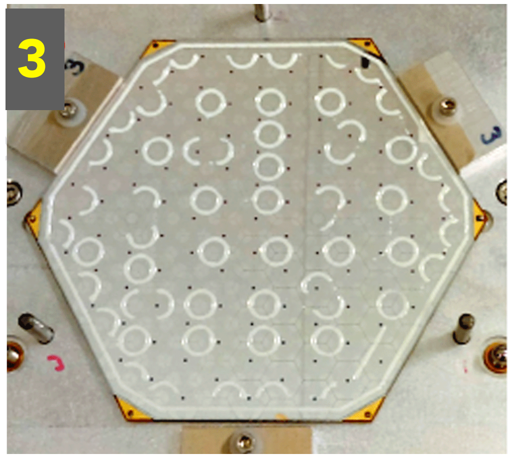
CuW baseplate



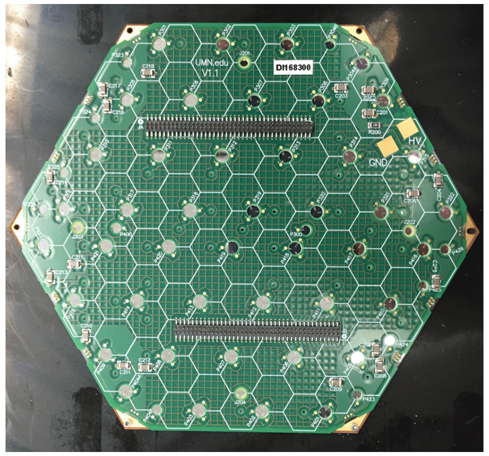
Gold plated kapton



Silicon sensor

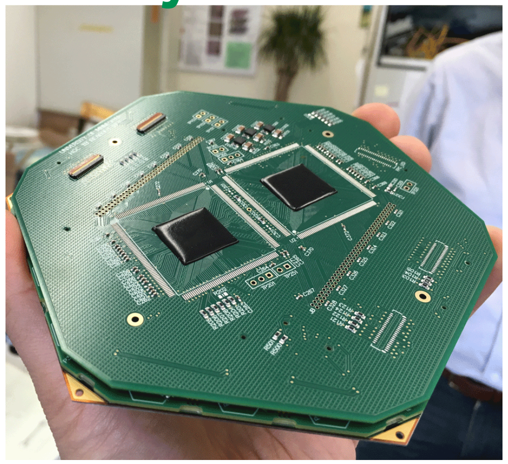


1st PCB
wire-bonded to sensor



  - with a two-layers PCB for readout

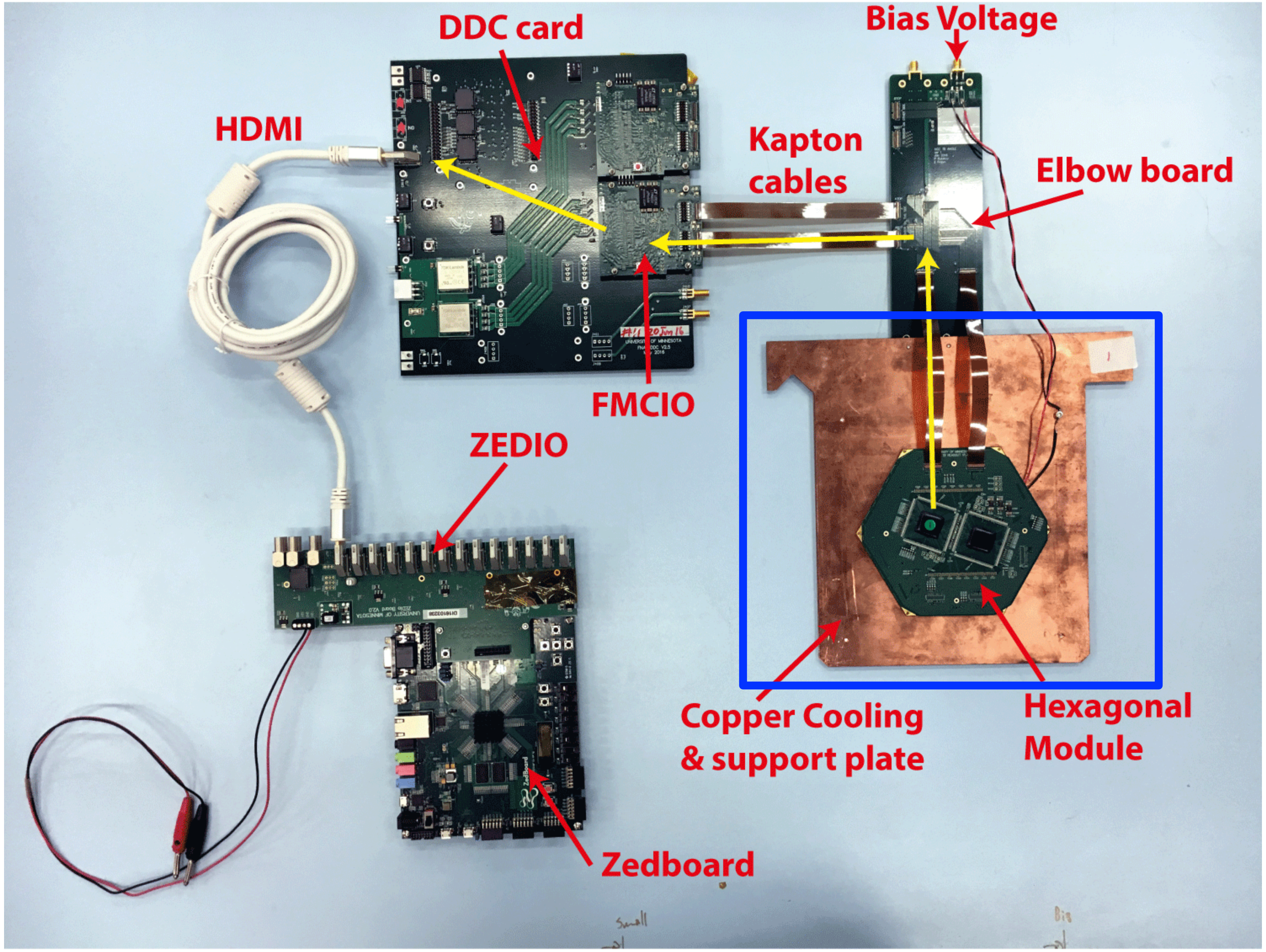
Full module with
double-layer PCB readout



- In this first set of test, the Skiroc2 ASIC were used: chip developed for CALICE collaboration
  - 64 channels per chip, 2 chips used per hexagon module

2016 TB: sensor module assembly

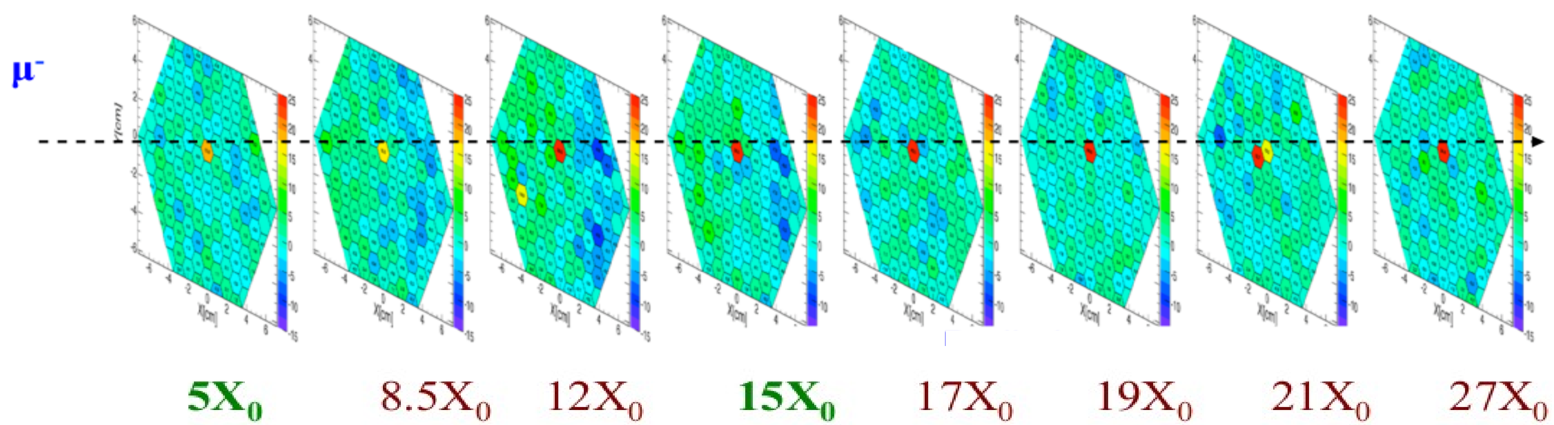
- **Full module** with double PCB readout mounted on a copper support plate
  => **ready for insertion in the hanging file mechanics**

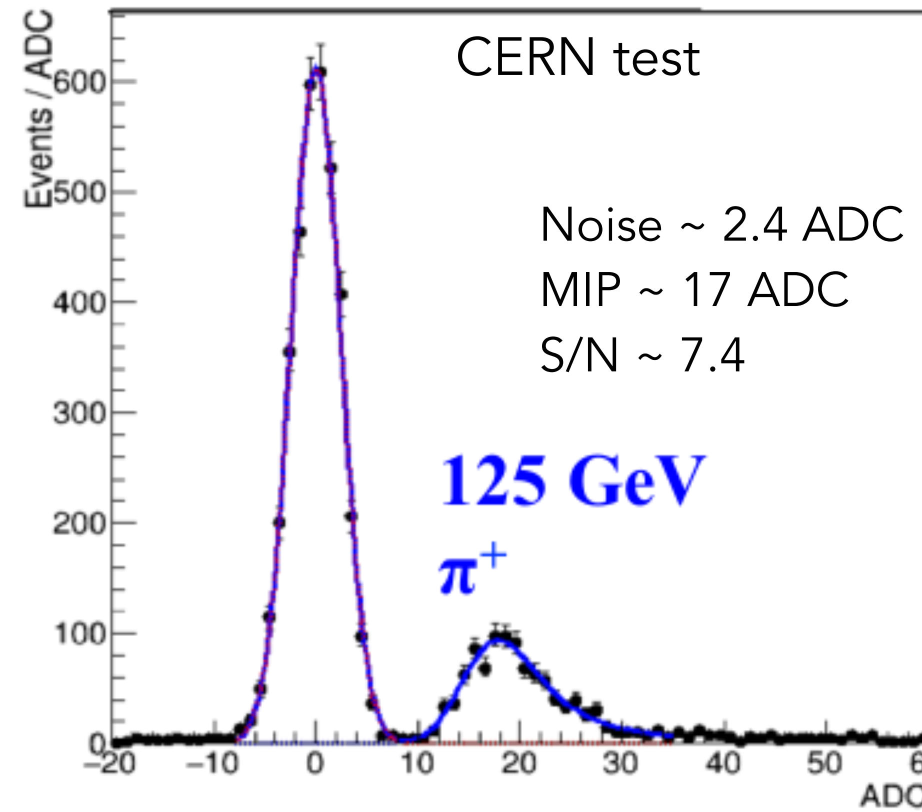


- DAQ chain used in 2016 TB campaign:
  - mainly built with off-the-shelf components in a flexible system

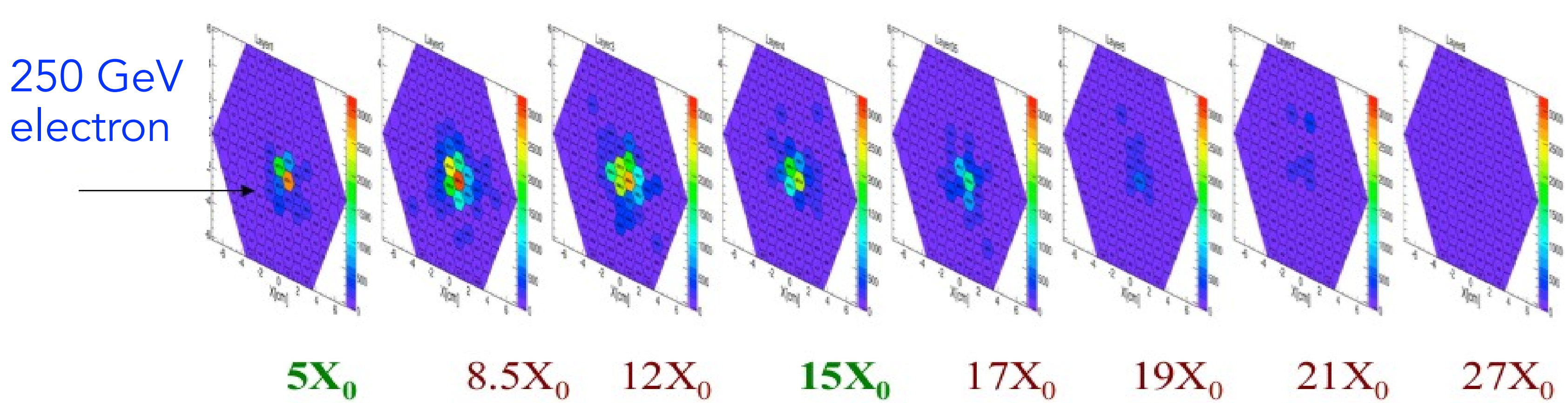
Response to MIP and electron showers

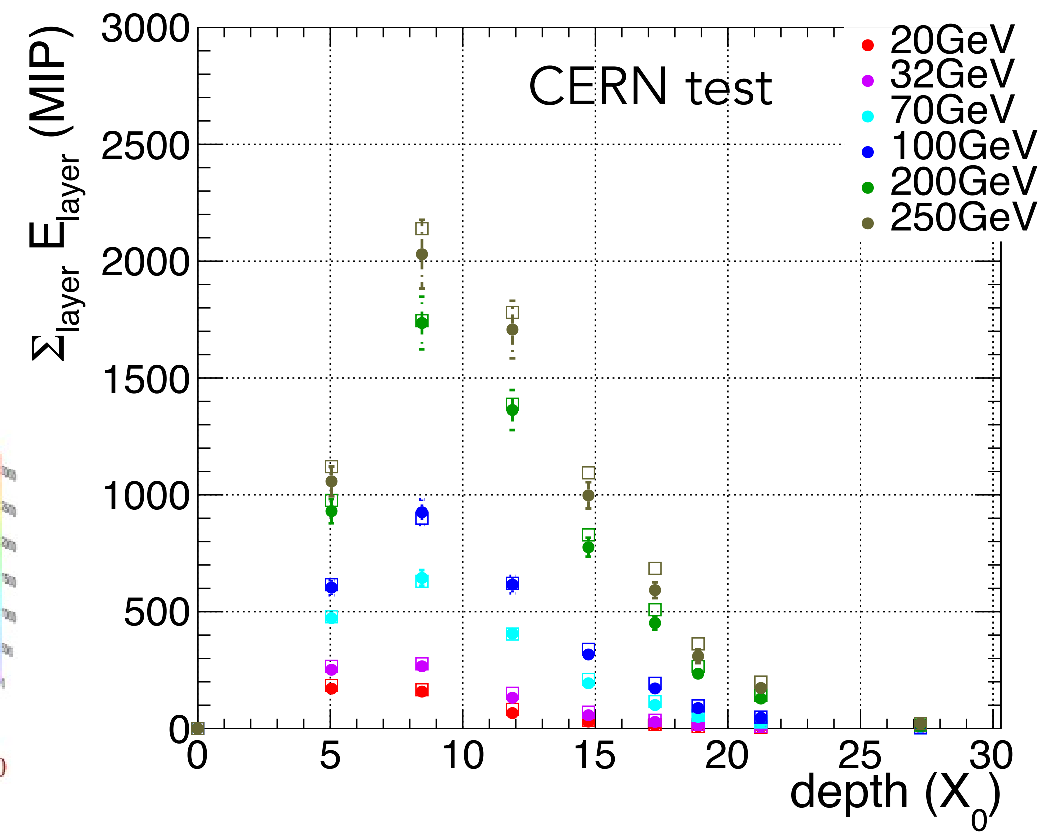
- Response to single pions used for calibration of the channel response





- Longitudinal shower profile measured in data
  - over a wide energy range 20-250GeV
  - in good agreement with simulation

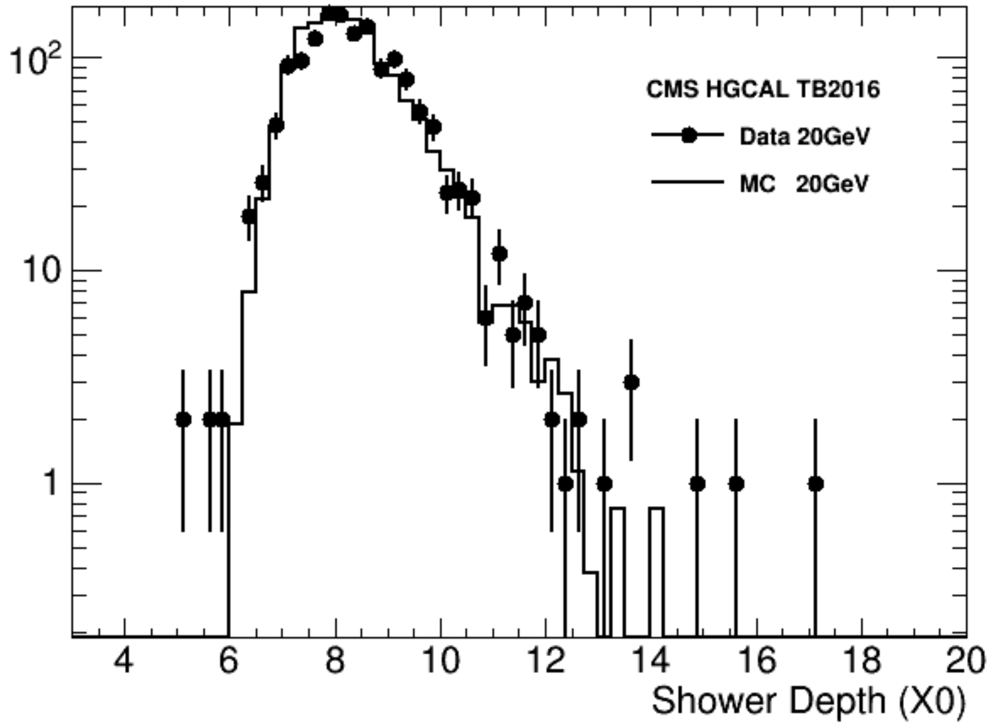


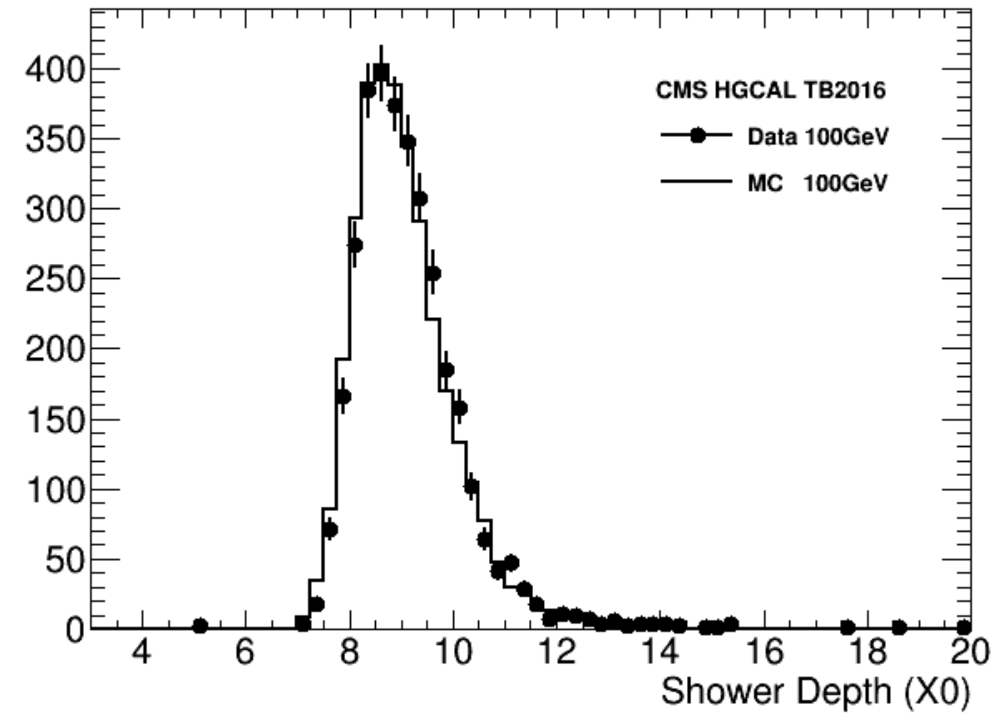


Shower shapes

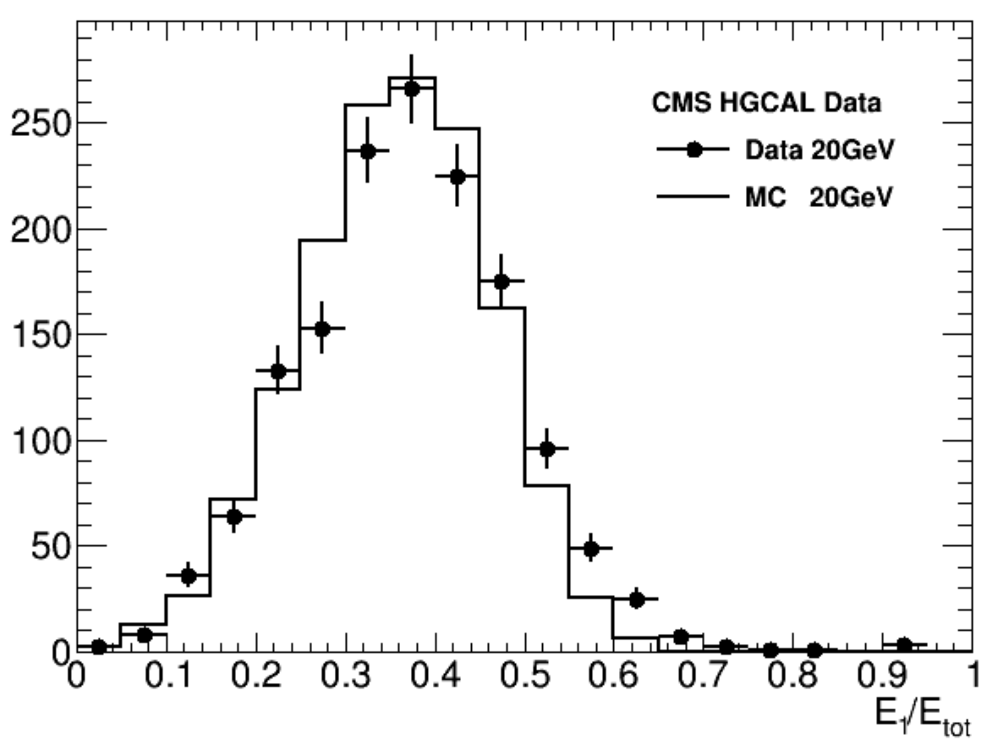
- Remarkable agreement between data and Monte-Carlo in shower shapes
  - good agreement also in the tails

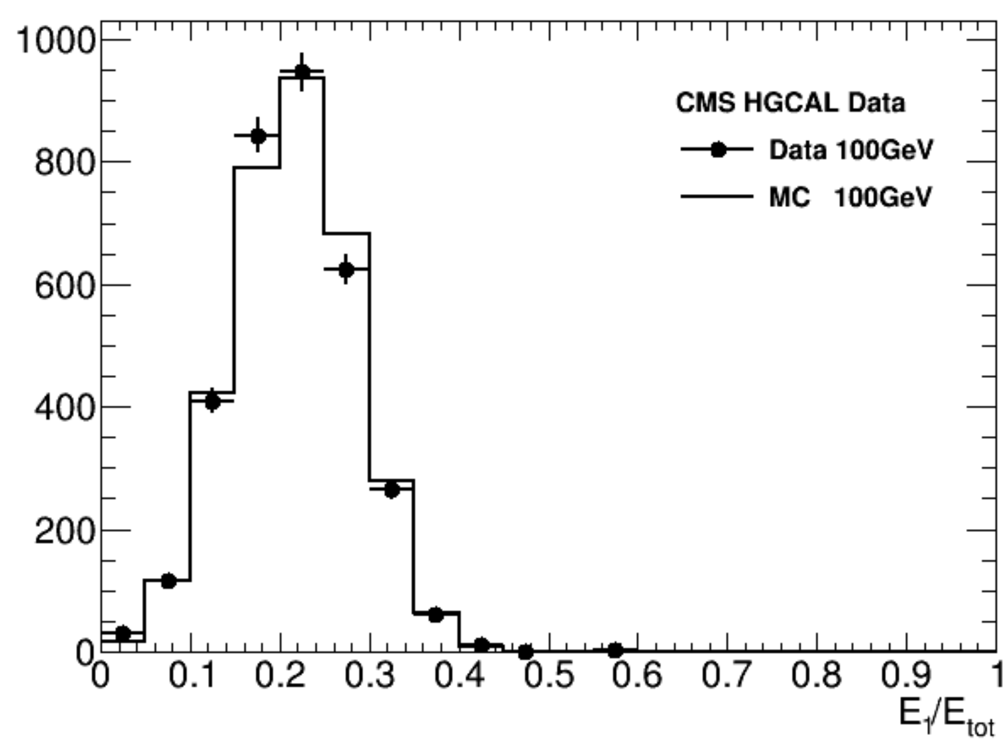
$\sum_{layer}(X0_i\ E_i)/\sum_{layer}(E_i)$





  - good simulation of upstream material (fraction of energy measured in 1st layer)



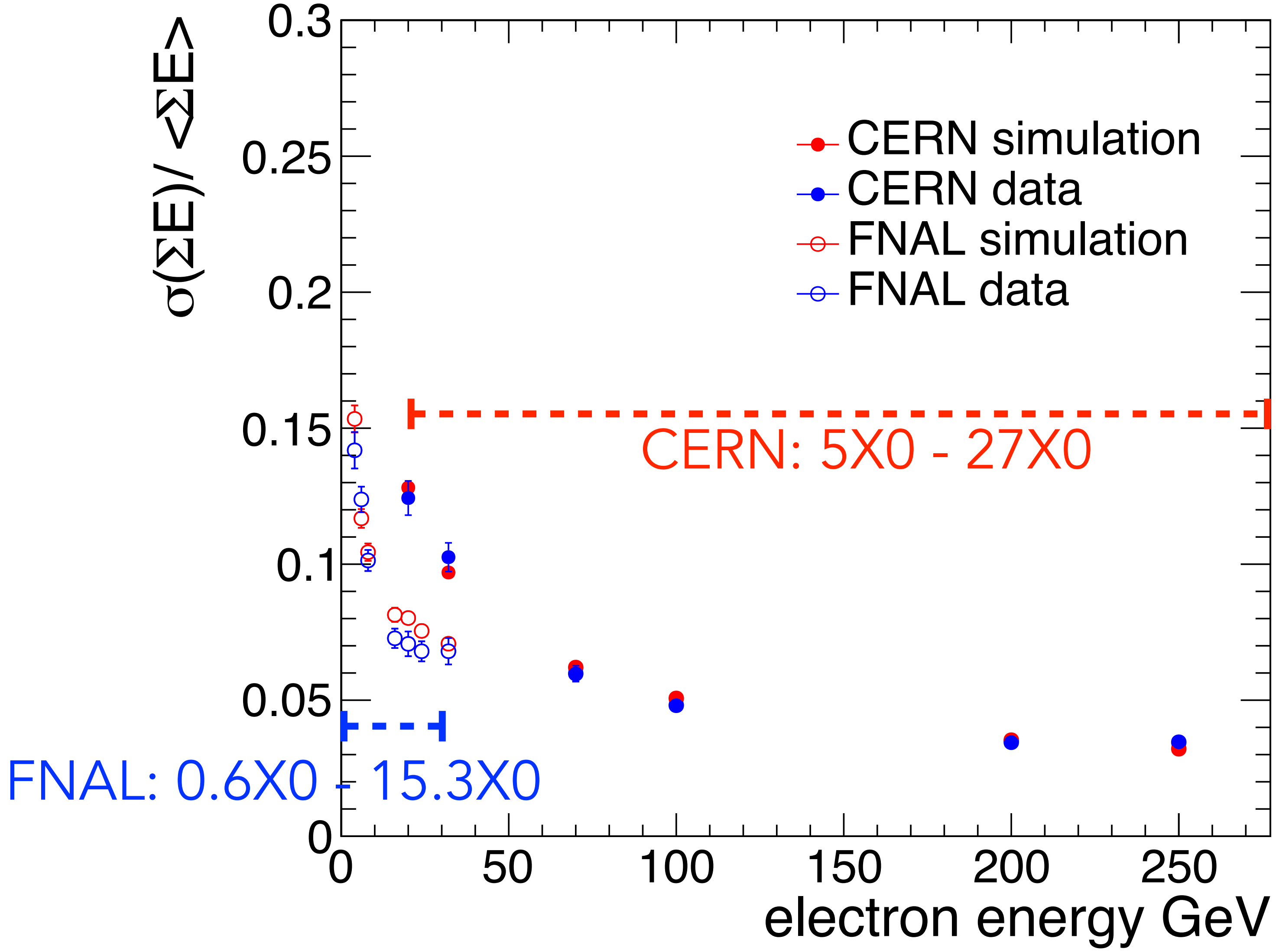


Selected result

- Energy resolution: good agreement between data and simulation

- CERN and FNAL data show different trend vs energy
  => indication of the different shower sampling in the two setups

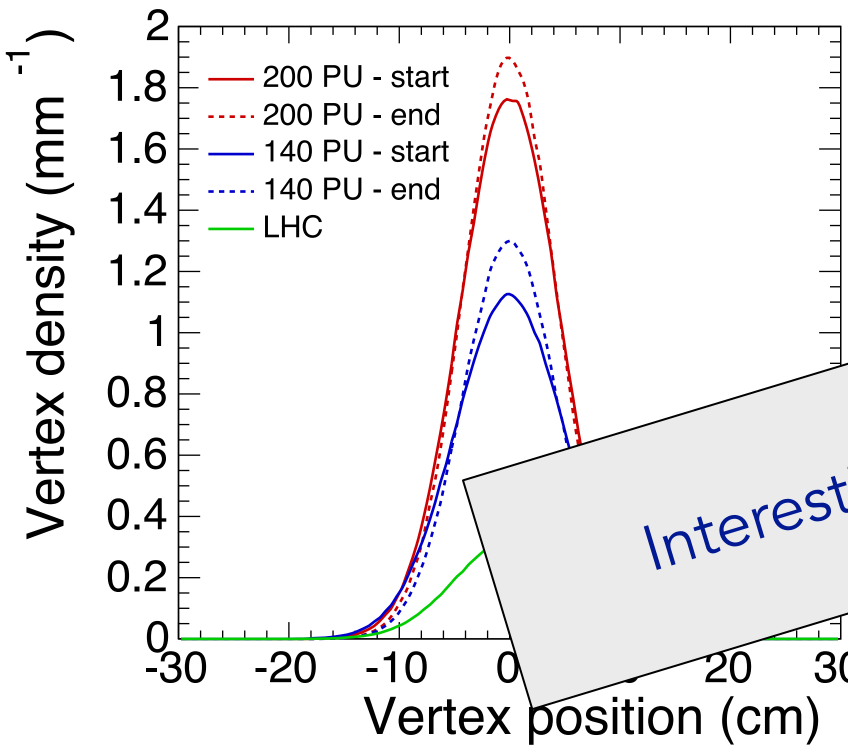
- Limit in the longitudinal sampling with 8 layers (CERN test) and 16 layers (FNAL test)
  => limit in the possible energy resolution achievable

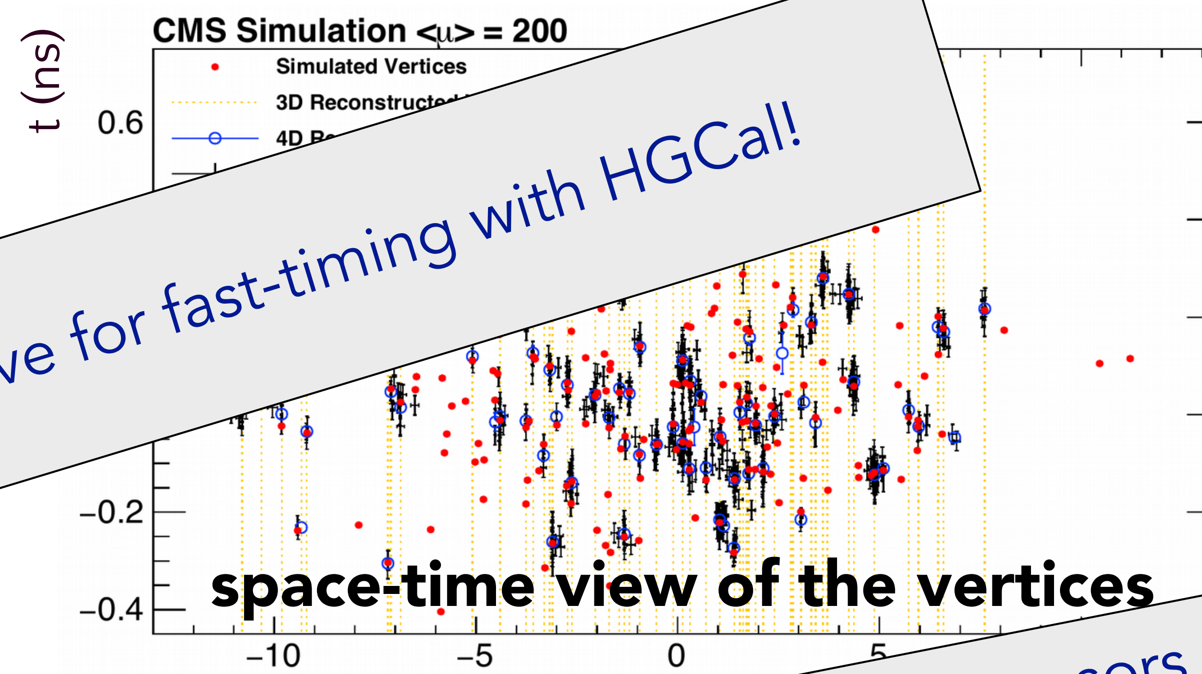


- 3d clustering also validated with TB data (CERN)

Fast timing

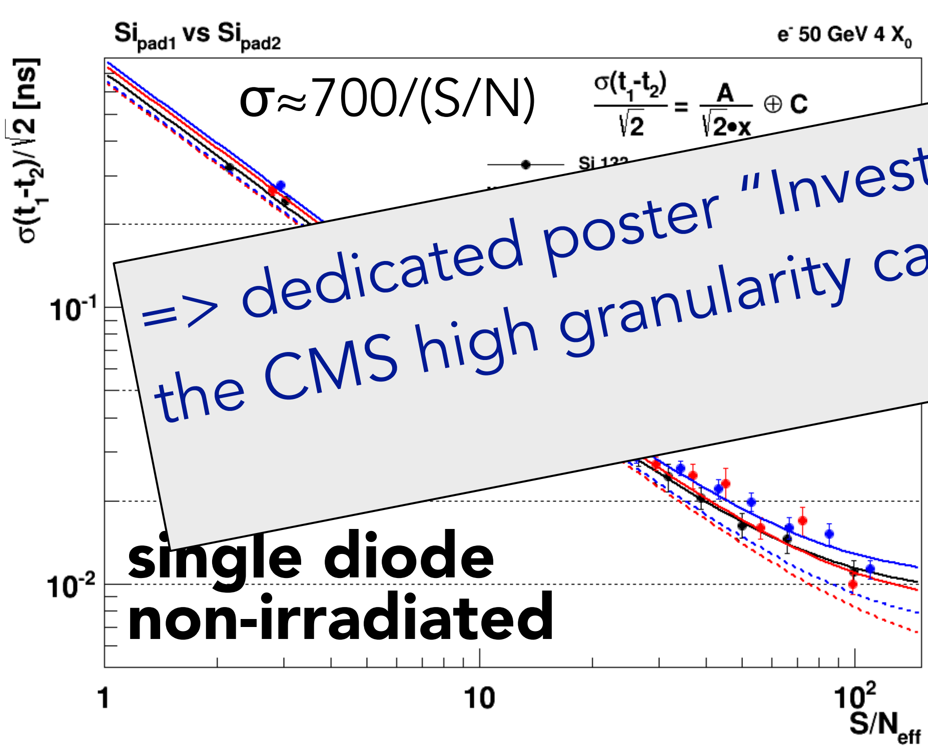
- At HL-LHC fast-timing of 20-30ps can help in disentangling the primary vertex
  => better particle ID, pileUP rejection and global event reconstruction

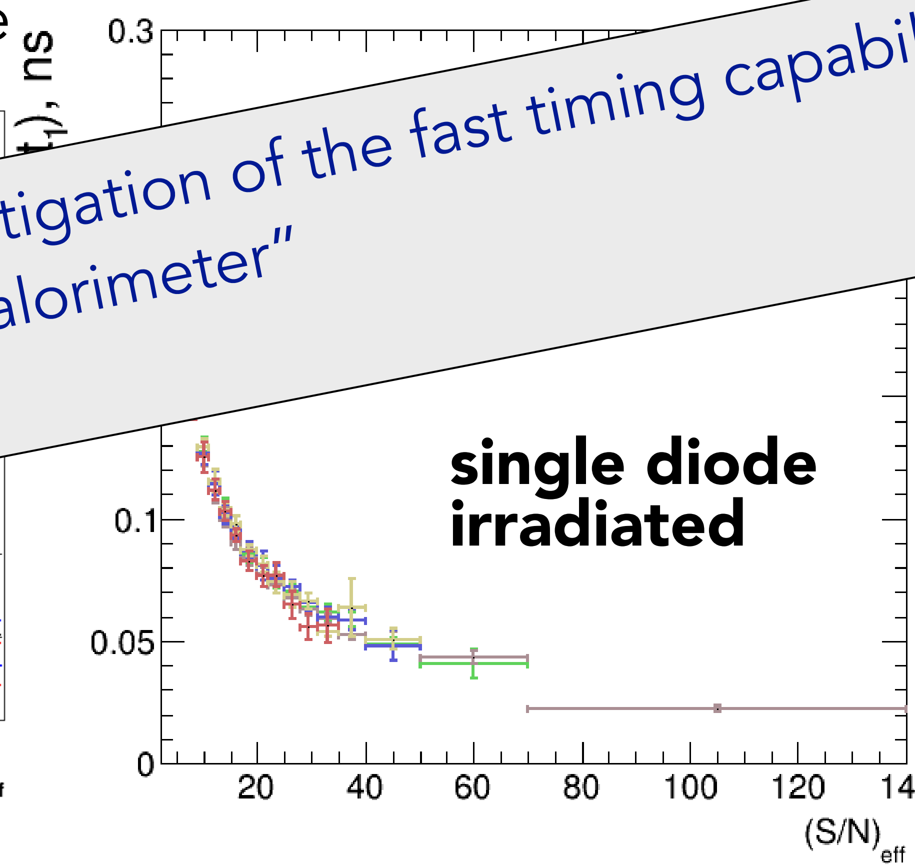


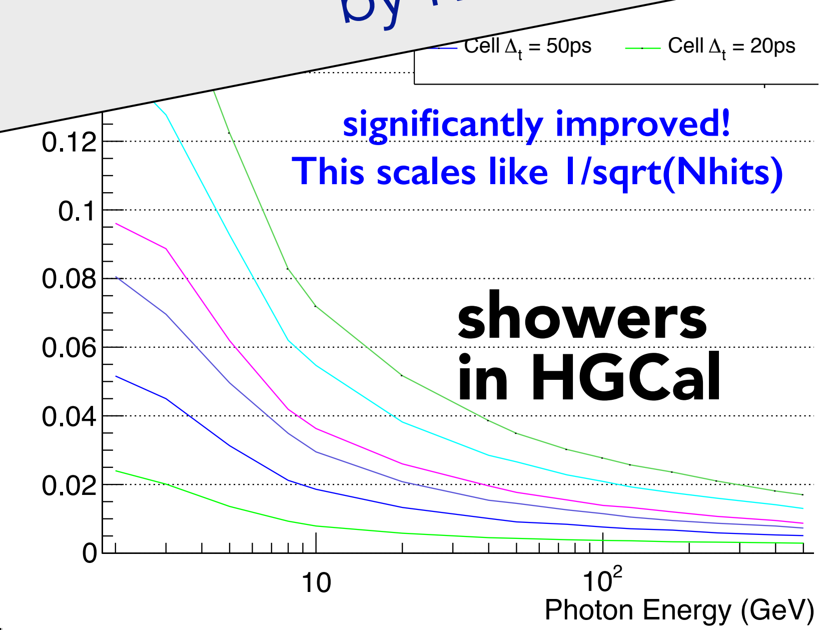


Interesting perspective for fast-timing with HGCal!

- HGCal fast-time performance







Δ$_t$ is 68% effective RMS
20ps * c = 6mm

=> dedicated poster "Investigation of the fast timing capabilities of the Silicon sensors for the CMS high granularity calorimeter"
by Raman Khurana

Outlook

- **High Granularity Calorimeter for the HL-LHC: very ambitious project!**
  => exploit combined information of time, position and pulse-height to disentangle the very complex events that we will see at the HL-LHC

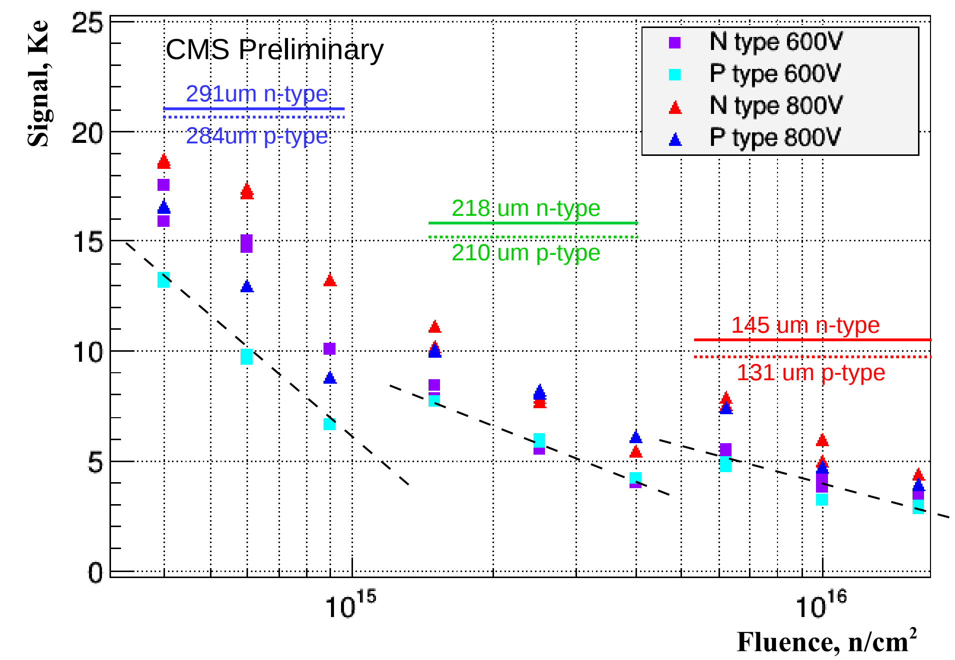
- Much progress so far, critical moment for the detector design choice, main review ongoing
  => target TDR by November 2017

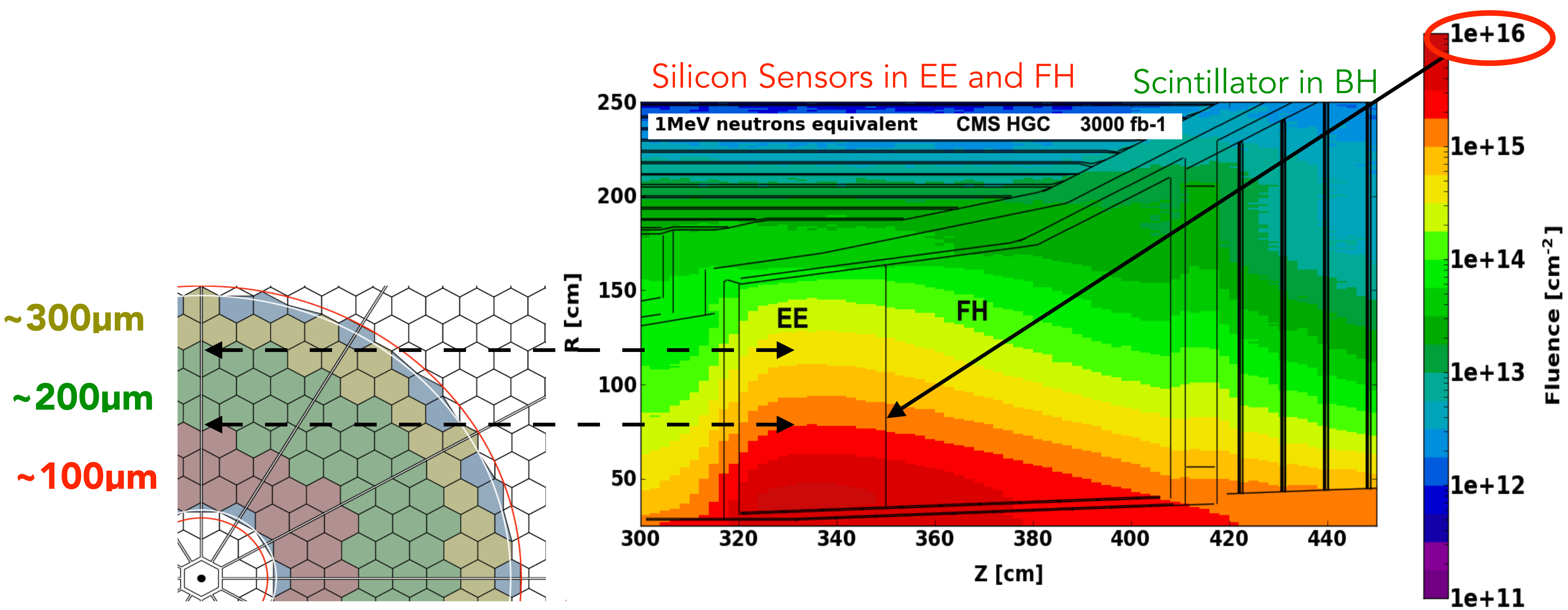
- **Test beam of the existing prototypes ongoing**
  - 2016 campaign: proof of concept of the proposed design for EE Si modules
    basic validation of the simulation
    timing for single diodes in electromagnetic showers ✓
  - 2017 campaign: aim at full system performance (EE+FH+BH) for EM and hadronic showers
    timing for hadronic shower

BACKUP

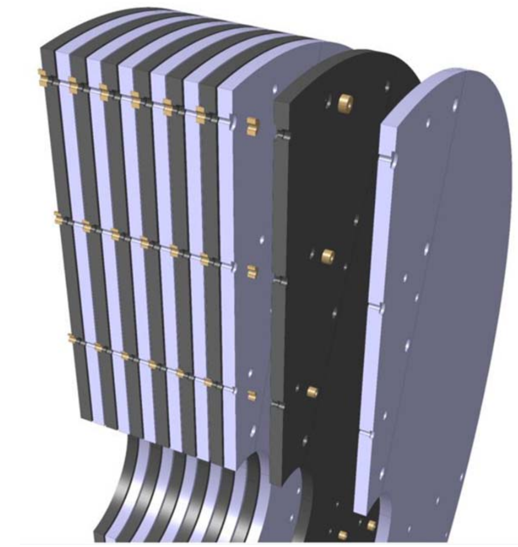
Silicon

- Silicon for radiation hardness:
  can sustain the high radiation levels
  - Fluence at η=3 in HGCAL ~ same as pixel inner layer
  - profit from extensive R&D in the past 20 years for Trackers and Pixels
  - complementary studies for neutrons irradiation up to 10^{16} n/cm^{-2}

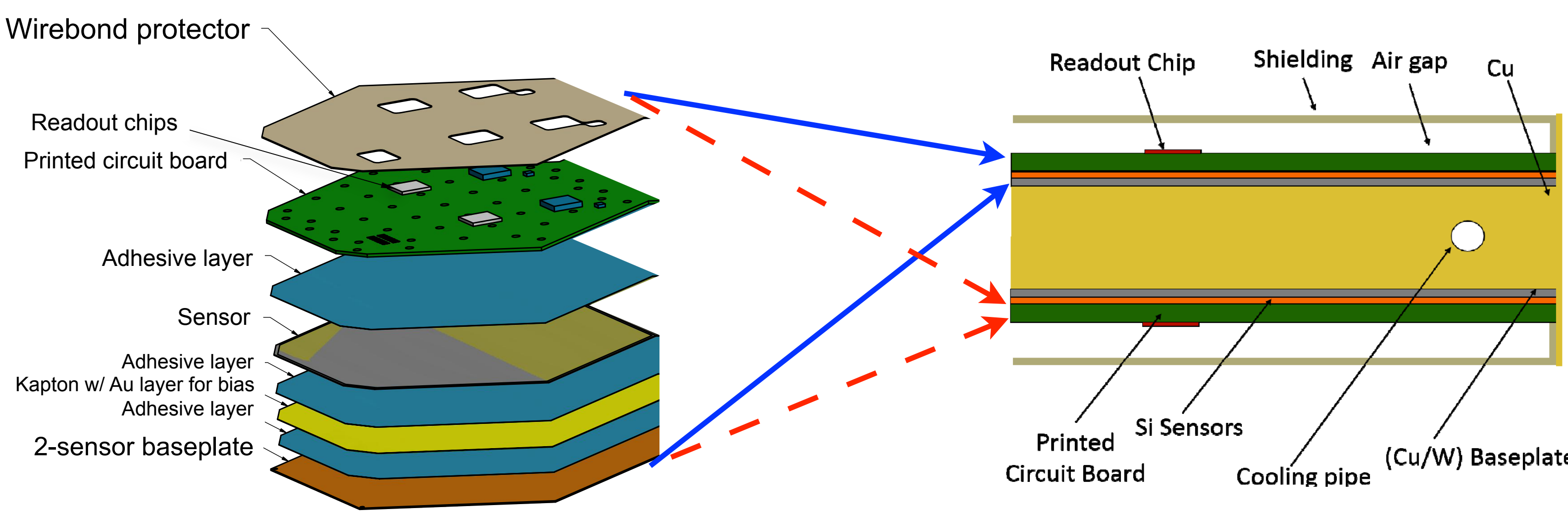




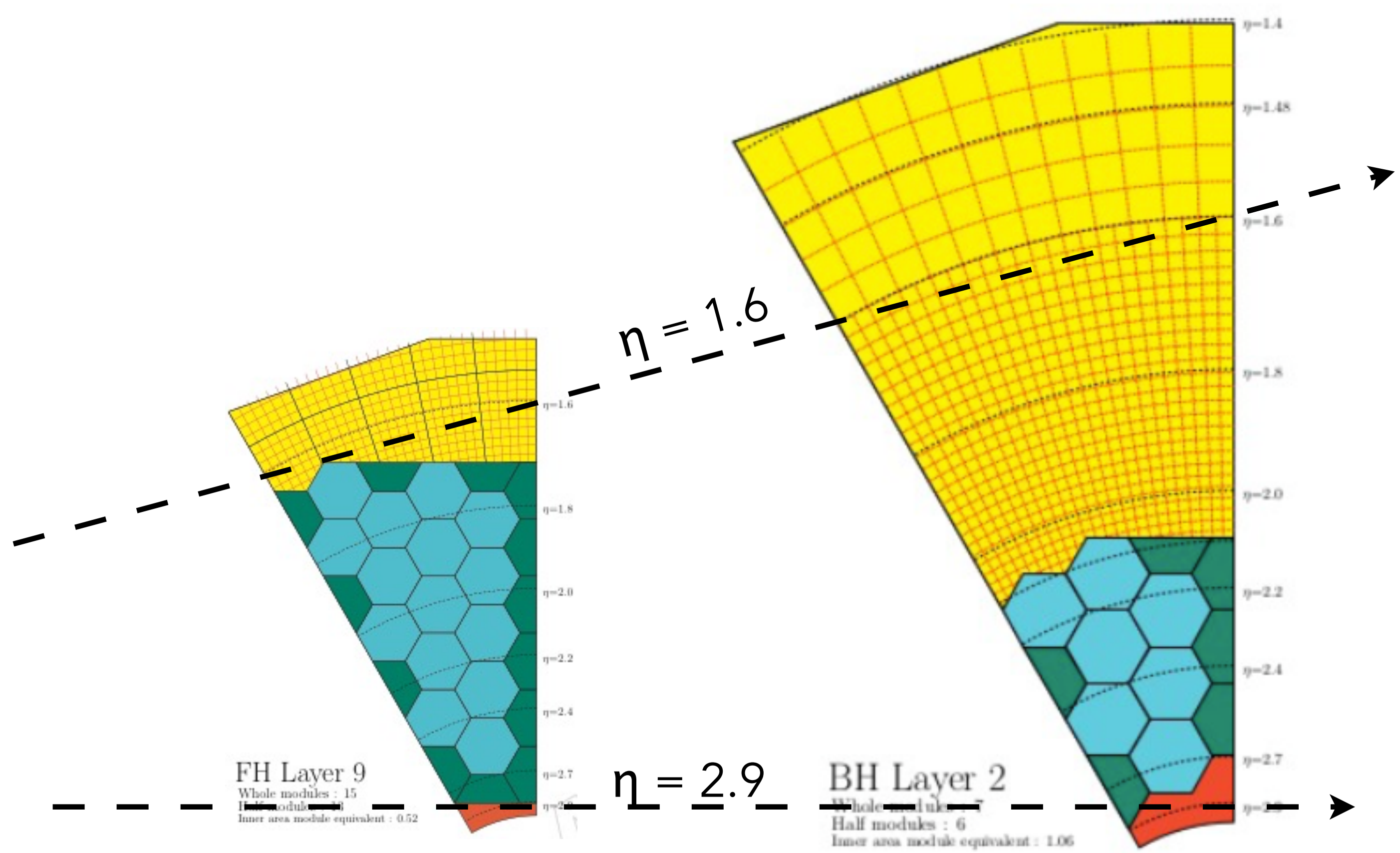
HGCal mechanics and cassettes design



- Chosen design a full disk option for all the 3 sections
  - with full disks of active material alternating full disks of absorber
- Example of cassette structure for Si module:
  - is built up on either side of a 6 mm-thick copper cooling-plate



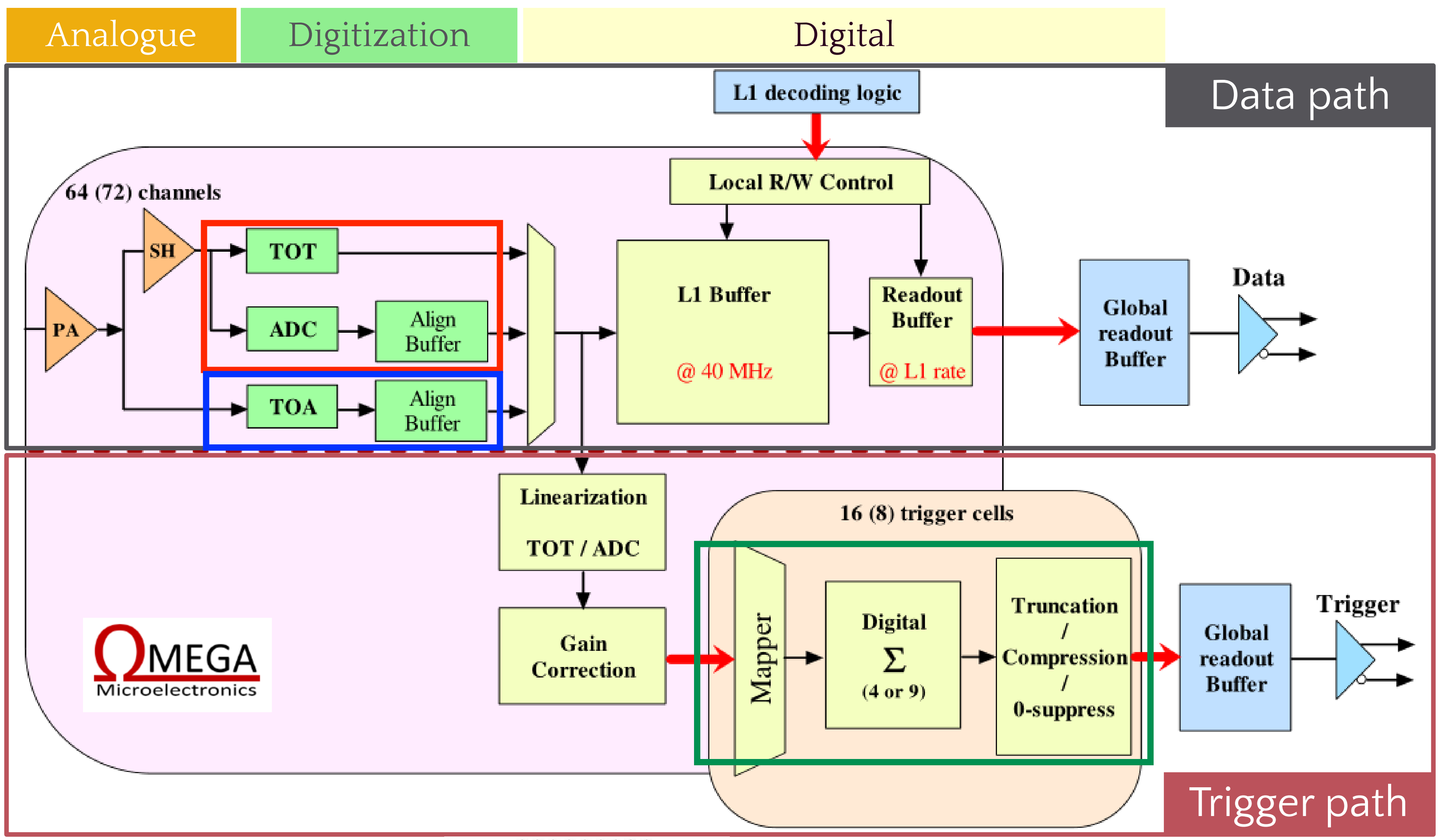
- Example of cassette structure for mixed scintillator/Si geometry
  - for BH scintillator readout with SiPMs coupled directly to scintillating tiles

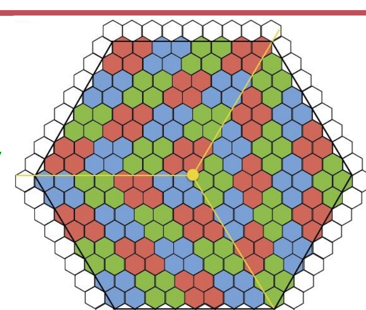


Front-End electronics

- Progressing towards final design: Skiroc (TB 2016), Skiroc2CMS (TB 2017), HGROCv1, …

- Data path: create independent **path for charge** and **time path**
  => possibility to have fast-timing information for small signals
  – aim at Si & SiPM readout with same FEE (test of readout with Skiroc2CMS successful)

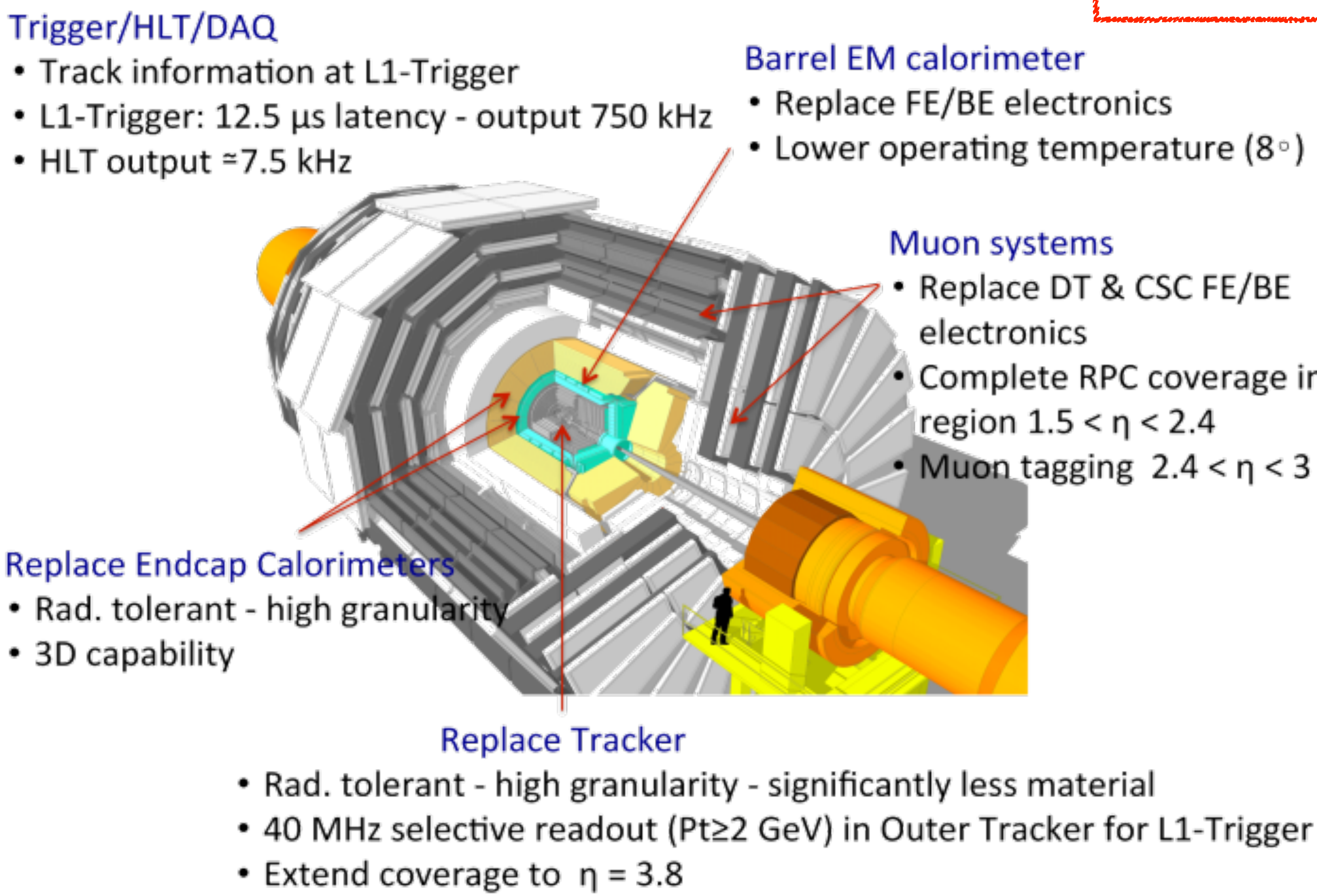


- Trigger path: **reduce granularity**  and **reduce energy resolution**

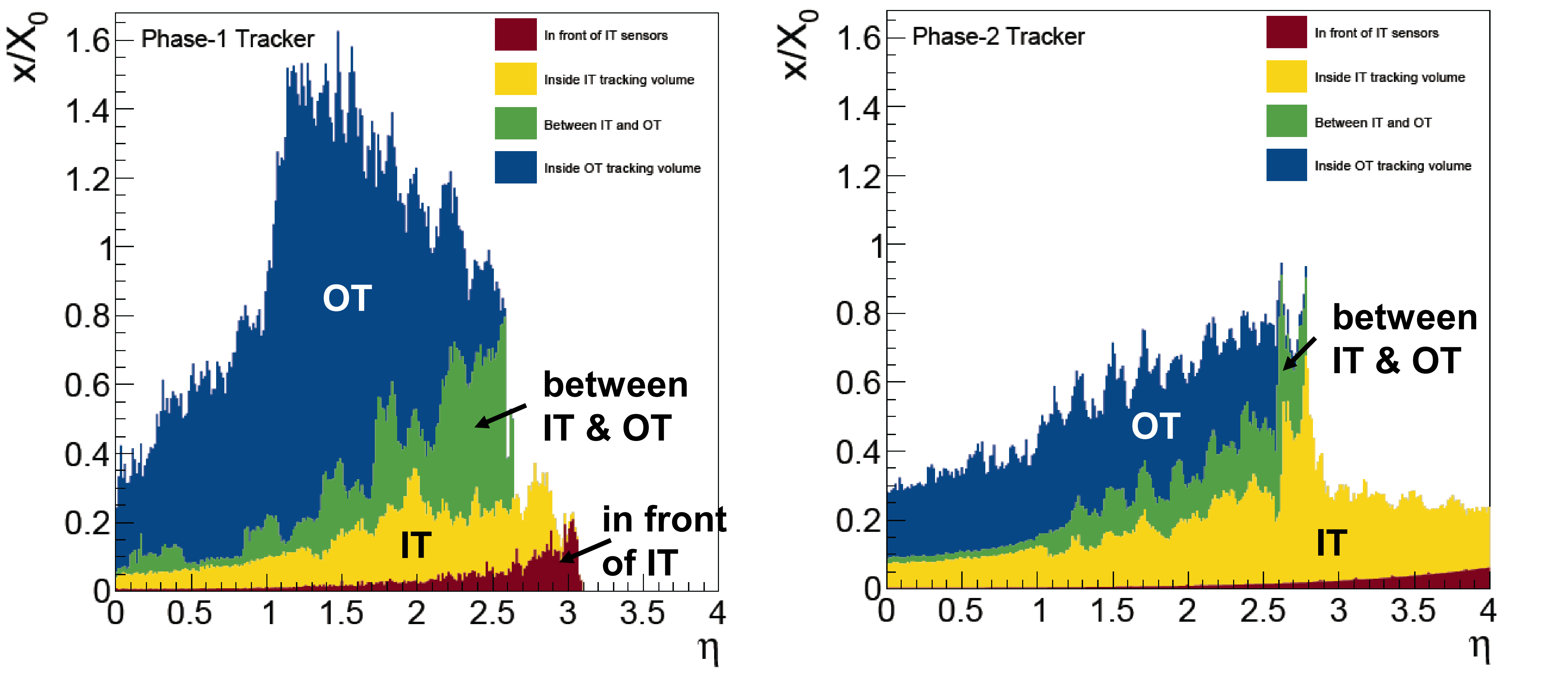
The CMS upgrade and the HGCal

- Goal is to maintain the excellent performance of the current CMS detector in terms of efficiency, resolution, and background rejection for all the physics objects used in the analysis of the data
- In the context of the CMS upgrade program

need granularity and radiation hardness



Tracker material budget



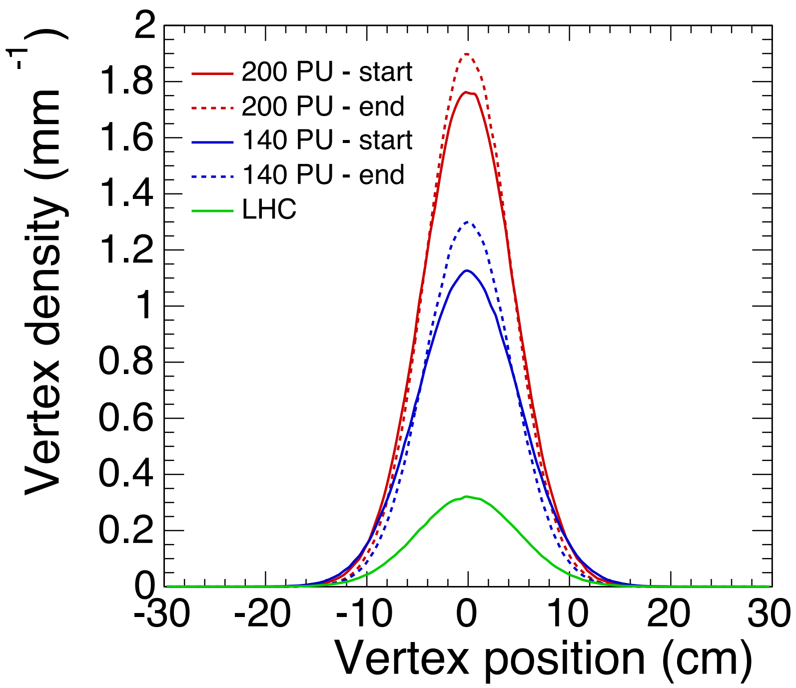
Silicon sensors (from TP)

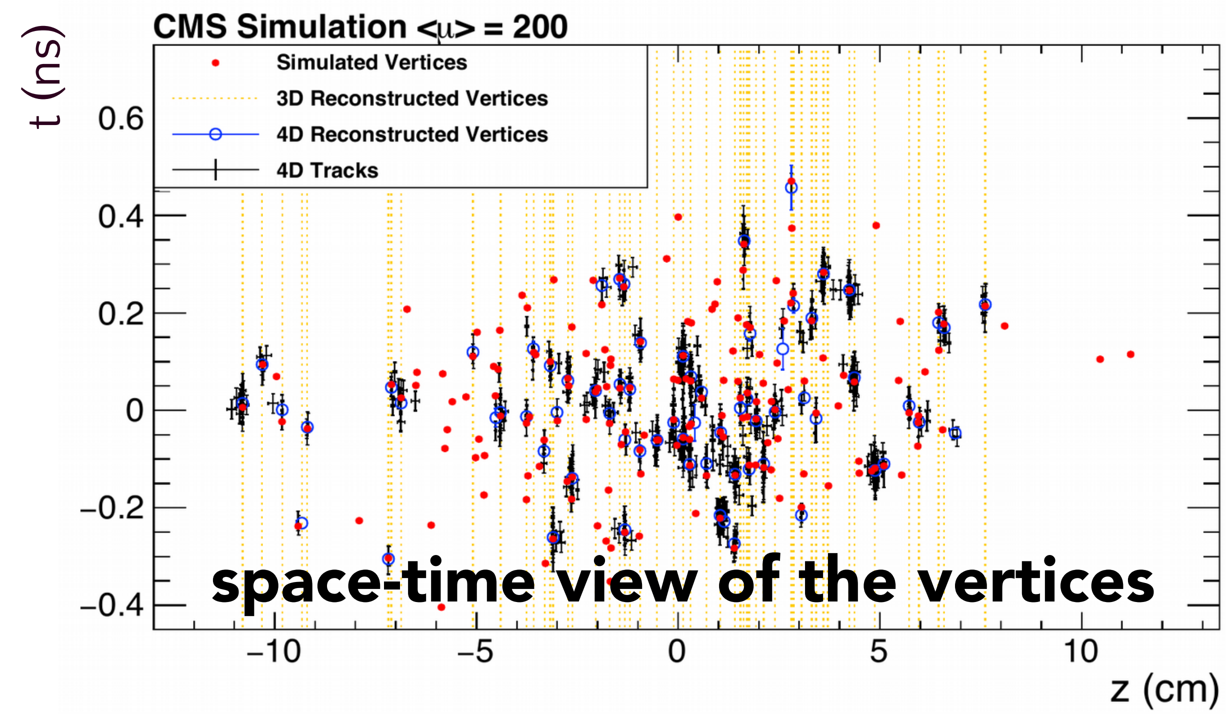
Table 3.3: Silicon sensor arrangement: thickness of active silicon layer in the EE and FH, with the associated cell size and S/N for a MIP before and after an integrated luminosity of $3000\,\mathrm{fb}^{-1}$.

Thickness	300 μm	200 μm	100 μm
Maximum dose (Mrad)	3	20	100
Maximum n fluence (cm^{-2})	6×10^{14}	2.5×10^{15}	1×10^{16}
EE region	$R > 120$ cm	$120 > R > 75$ cm	$R < 75$ cm
FH region	$R > 100$ cm	$100 > R > 60$ cm	$R < 60$ cm
Si wafer area (m^2)	290	203	96
Cell size (cm^2)	1.05	1.05	0.53
Cell capacitance (pF)	40	60	60
Initial S/N for MIP	13.7	7.0	3.5
S/N after $3000\,\mathrm{fb}^{-1}$	6.5	2.7	1.7

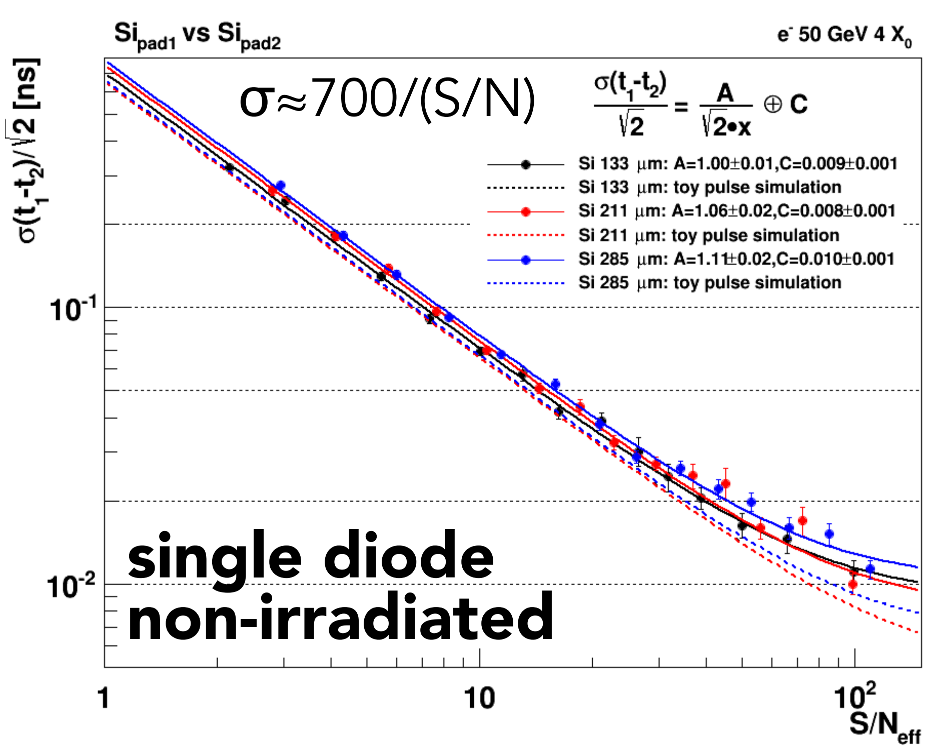
Fast timing

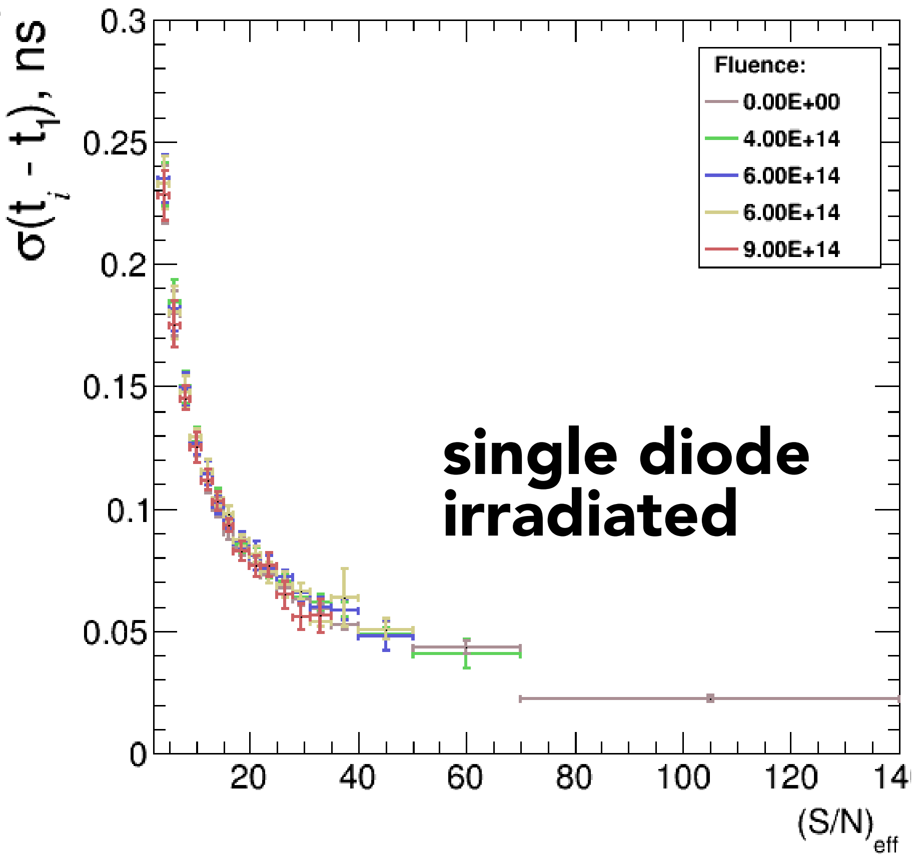
- At HL-LHC fast-timing of 20-30ps can help in disentangling the primary vertex
  => better particle ID, pileUP rejection and global event reconstruction

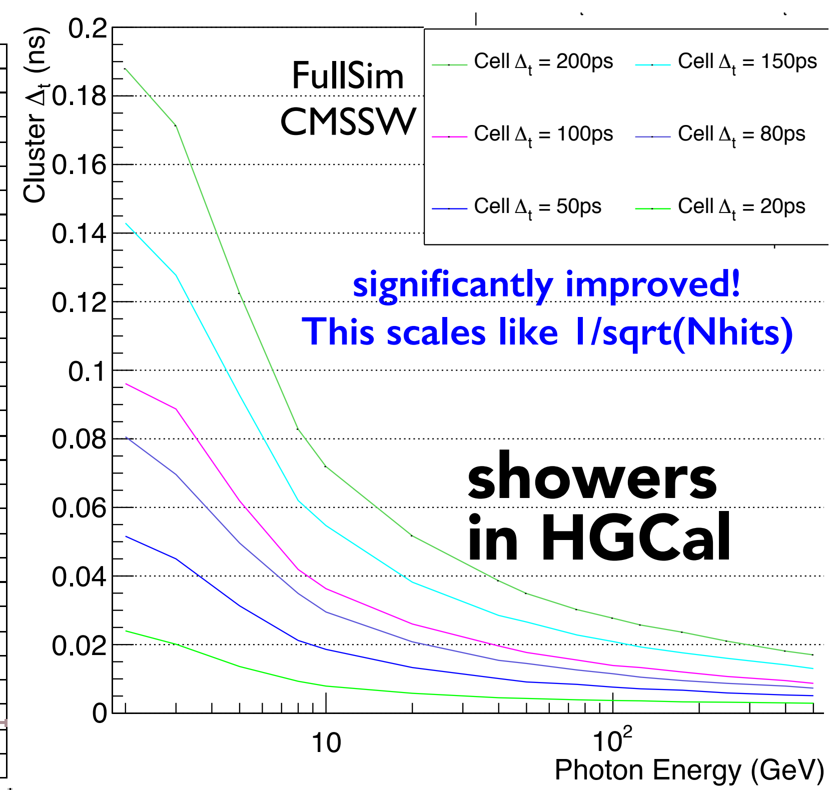




- HGCal fast-time performance



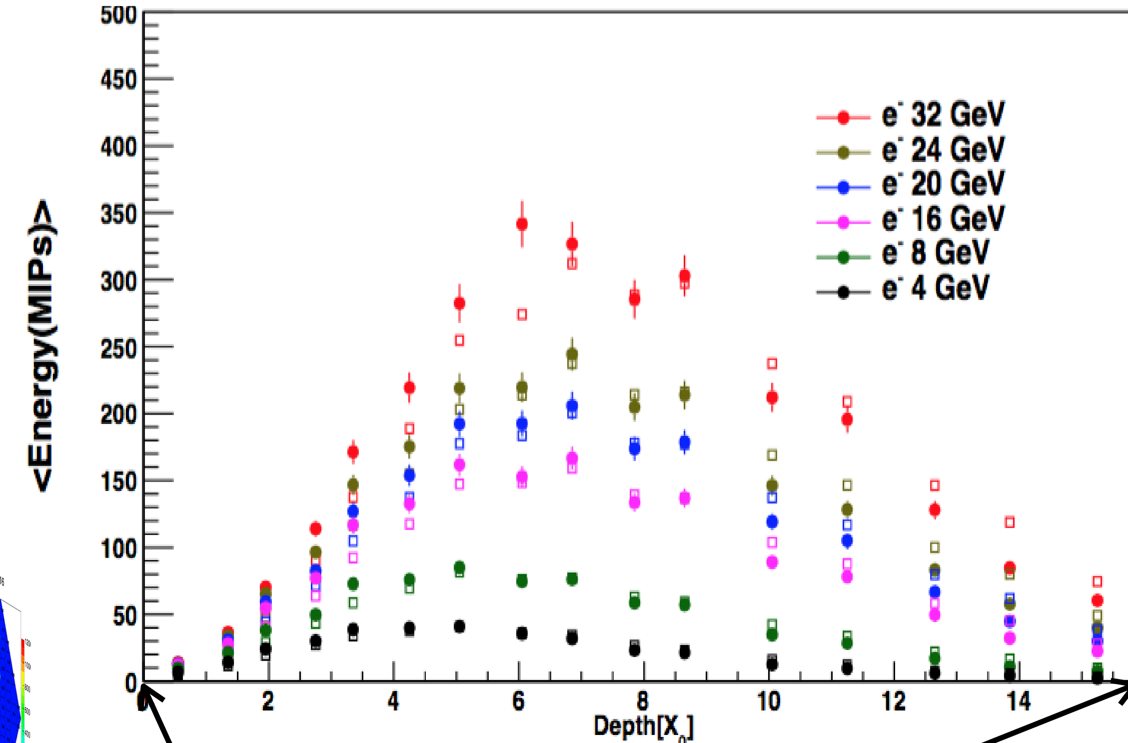




Δ_t is 68% effective RMS
20ps * c = 6mm

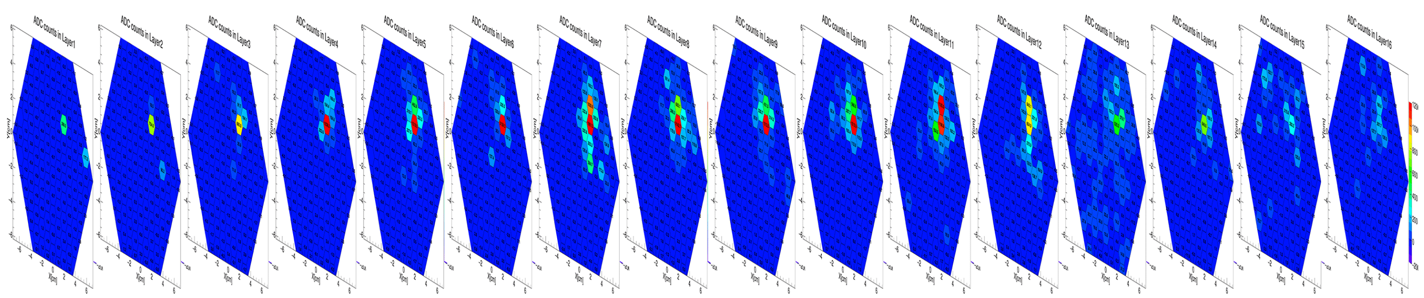
Response to electron shower

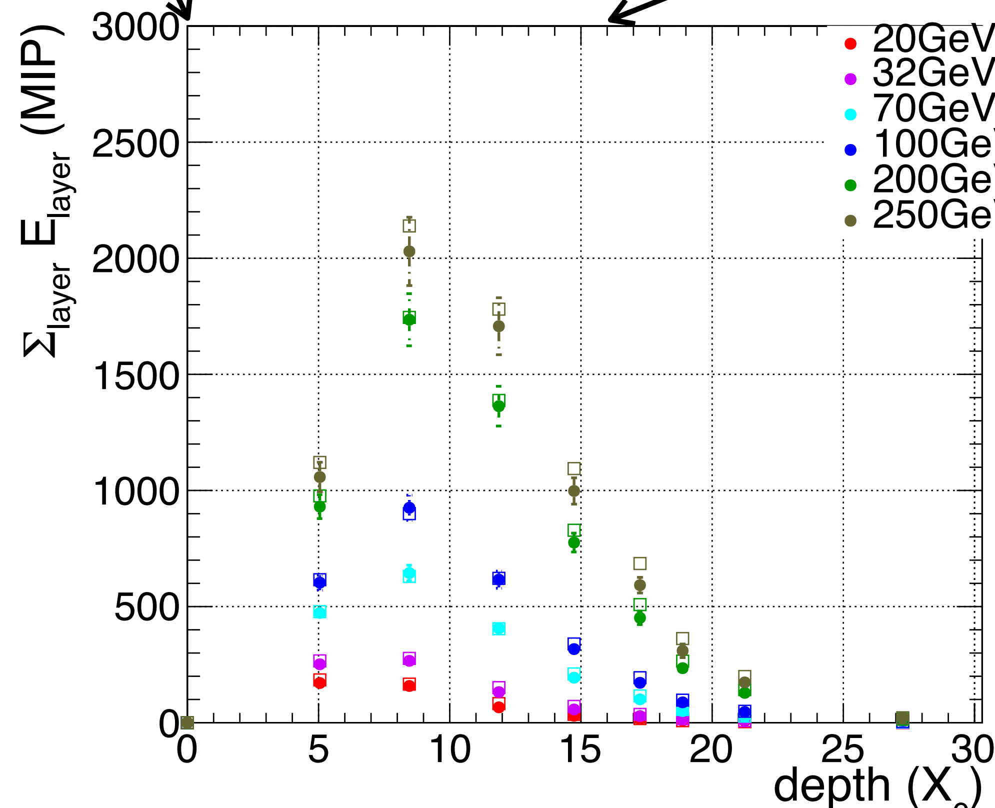
- Longitudinal shower profile measured in data over a wide energy range
  - in good agreement with simulation



@FNAL: 16 layers from ~0-16X0

32 GeV electron





@CERN: 8 layers from 5-27X0
(also tested in 6-16X0)

250 GeV electron