Two New Detectors for CMS at the HL-LHC

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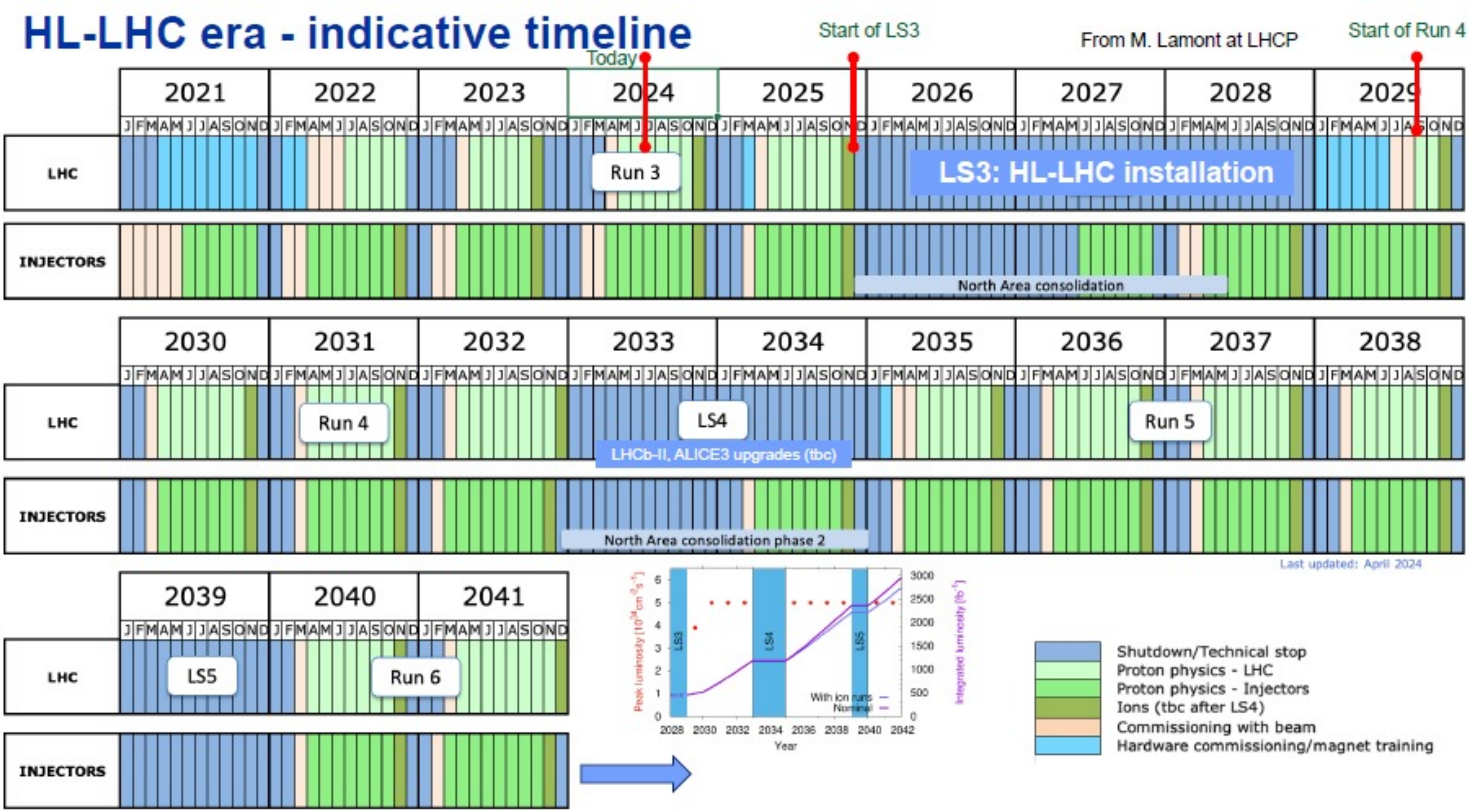
August 8, 2024

LHC Plan for Future: HL-LHC

- All experiments need more data to probe new physics. So LHC plans to improve upon the luminosity over the next 15-20 years:



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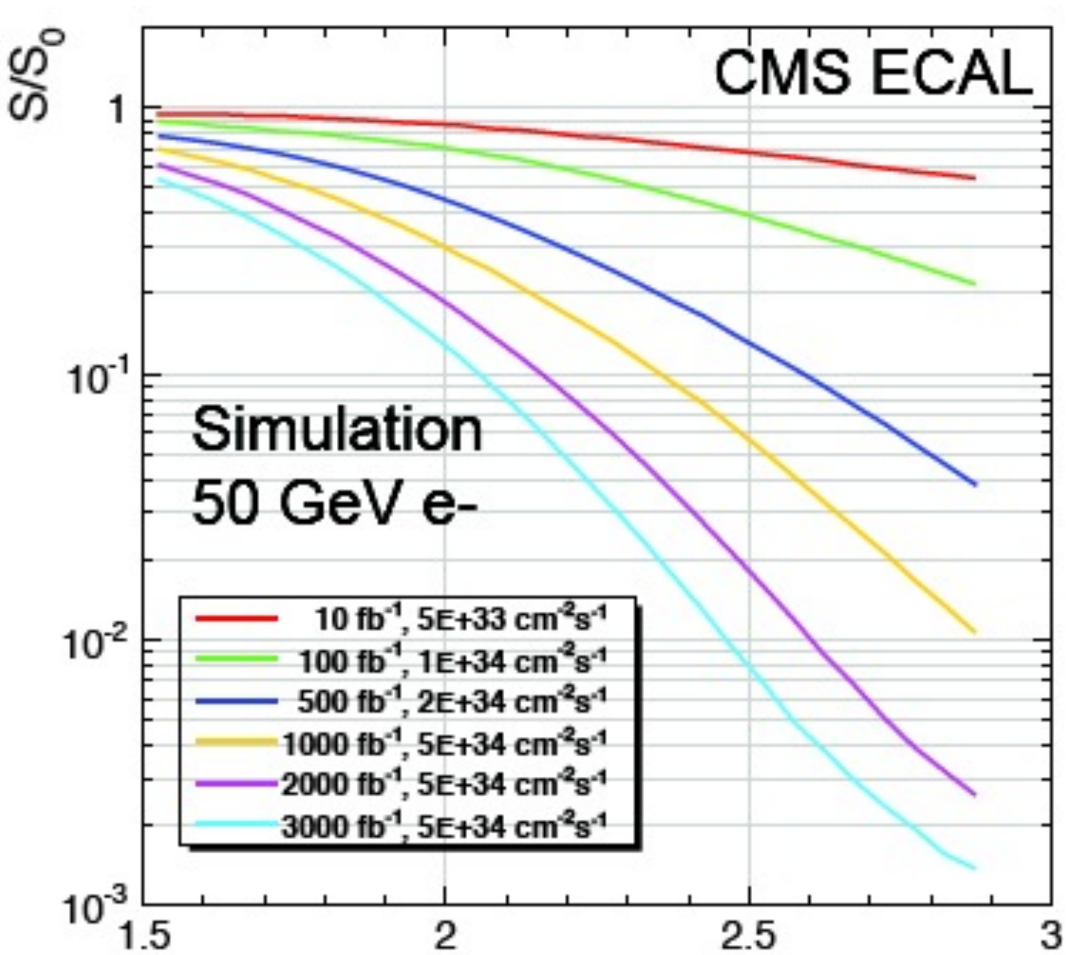
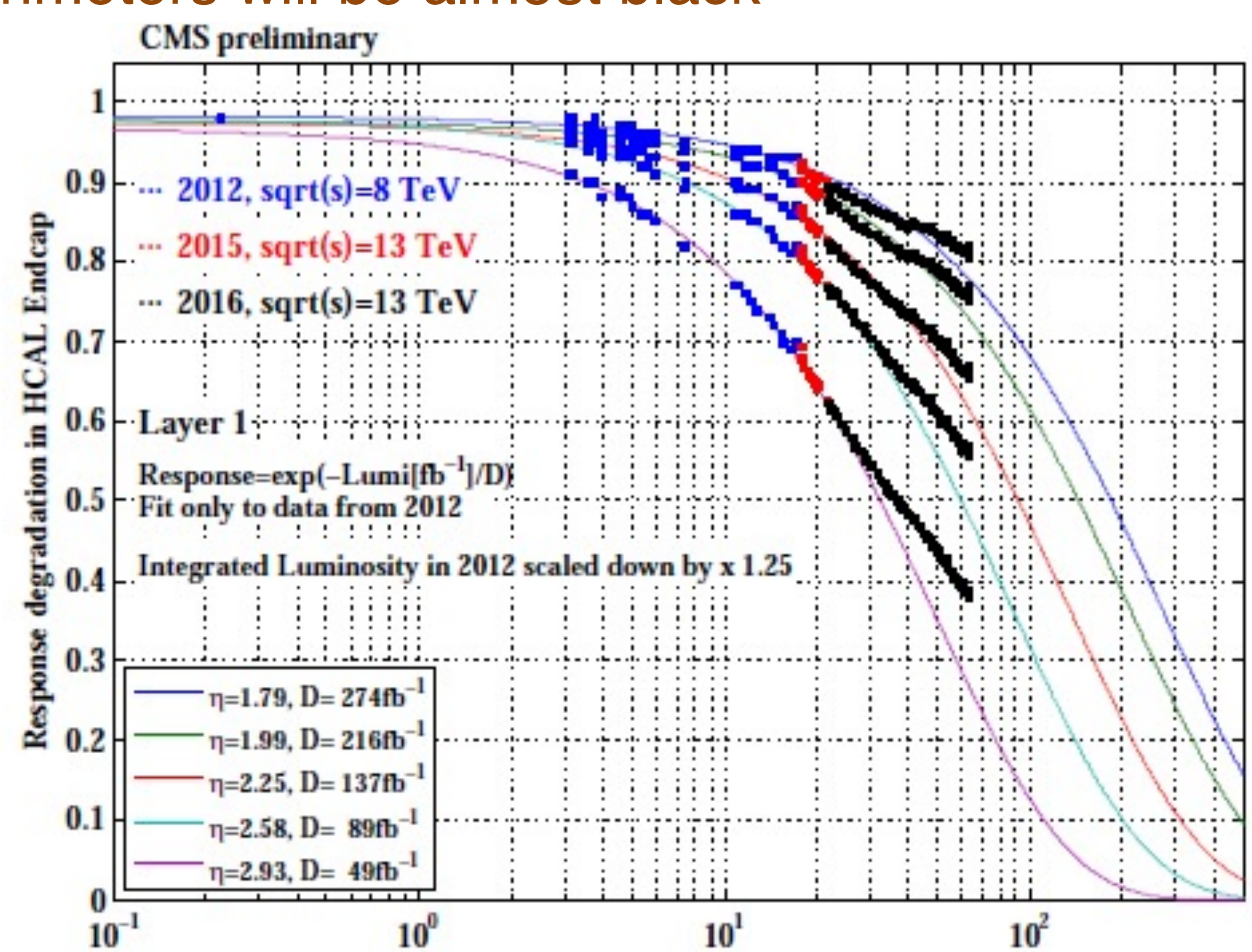
Consequence of High Luminosity

- The increase in the instantaneous luminosity will give two challenges to the experiment
  - There will be too many interactions at each bunch crossing causing the in-time pileup to grow from 35-40 (current) to 140-200 (future). Also, out-of-time pileup will grow in the same proportion
    - Impossible to separate contributions of pileup events from the events of interest
  - The detectors will face a larger radiation environment
    - The endcap detectors for both calorimeters will be almost black



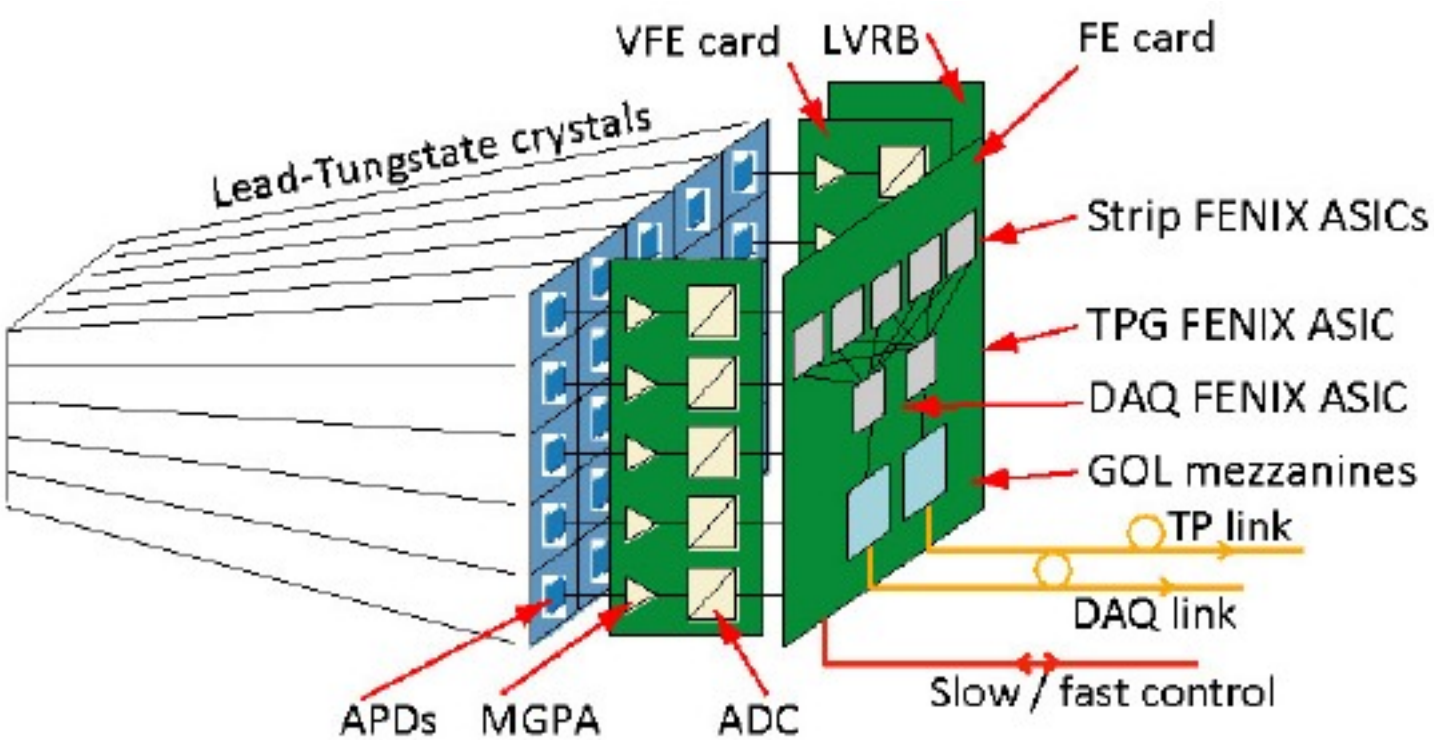


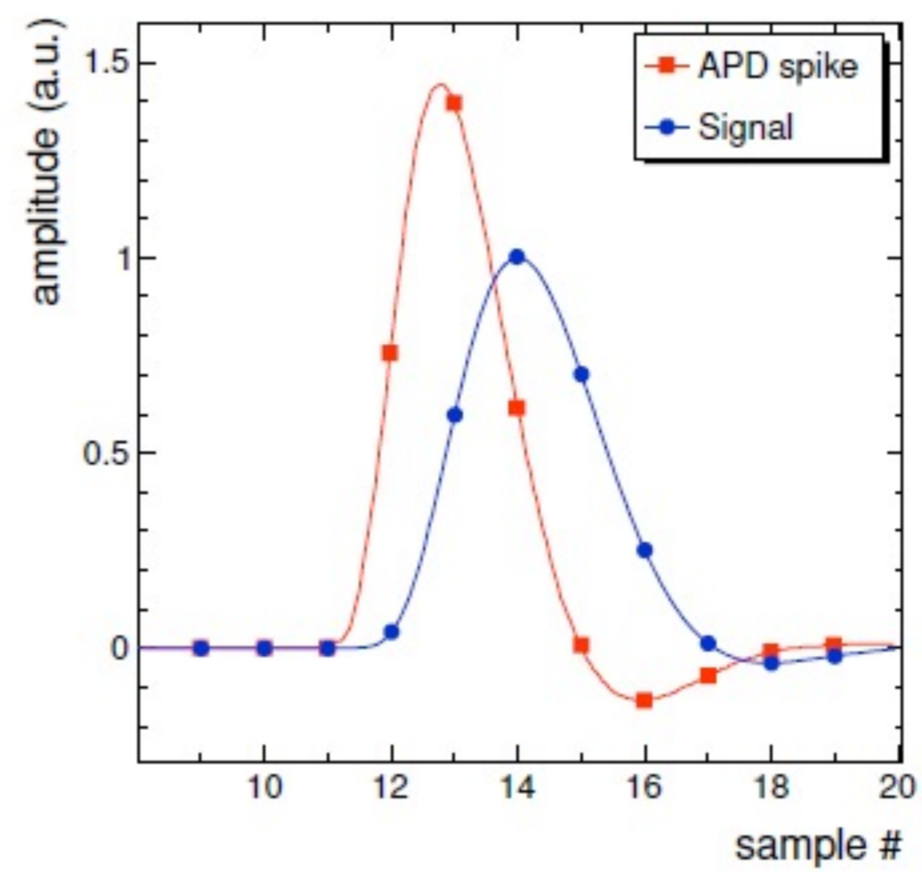
The Issue for ECAL

- The barrel electromagnetic calorimeter is made out of lead tungstate crystals where the produced light is read out using APDs.

- There is an issue with APDs regarding additional signals produced due to energy deposited in the silicon layers within the APD by highly ionizing particles. The rate of these extra signals increases a lot with more particles produced in the interaction (and hence at higher luminosity).

- The main difference between this extra signal from the signal from the crystal is the time profile of the signal

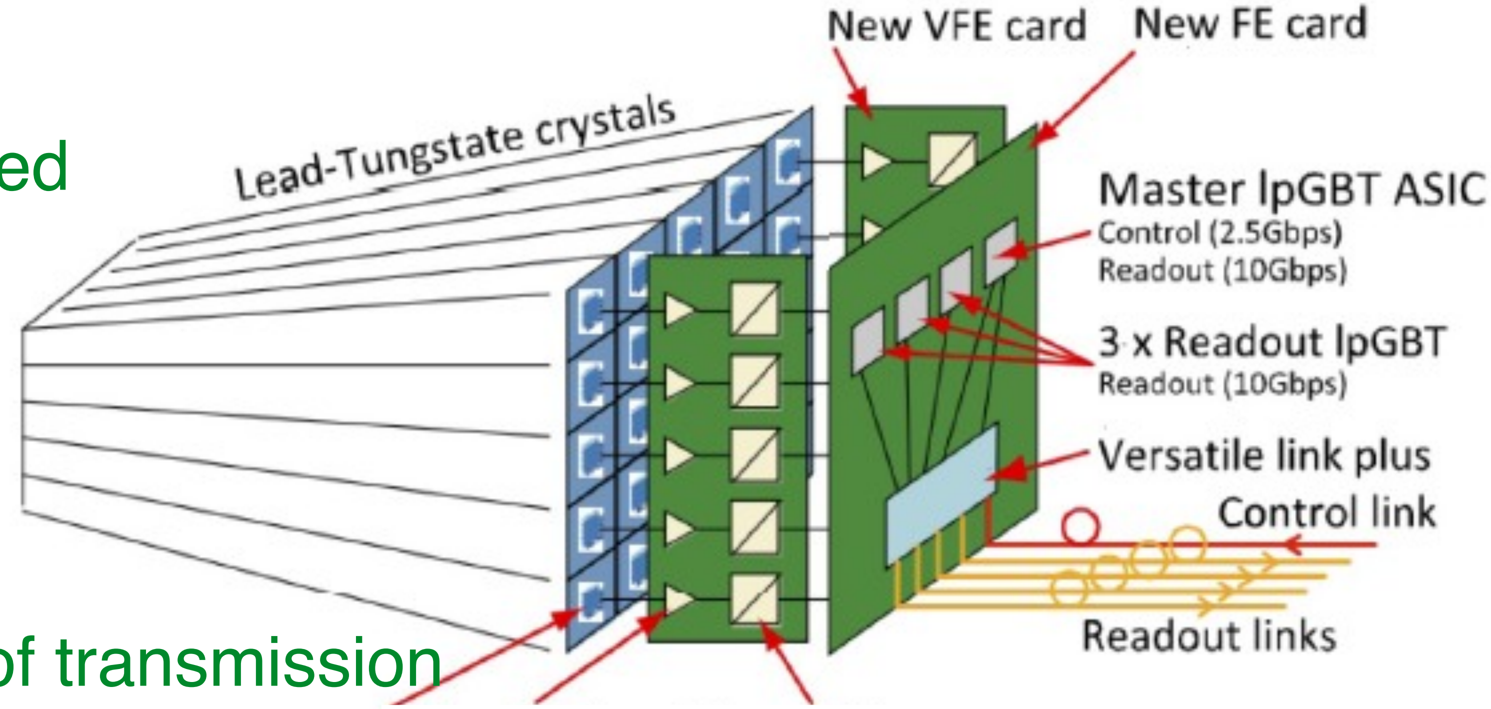




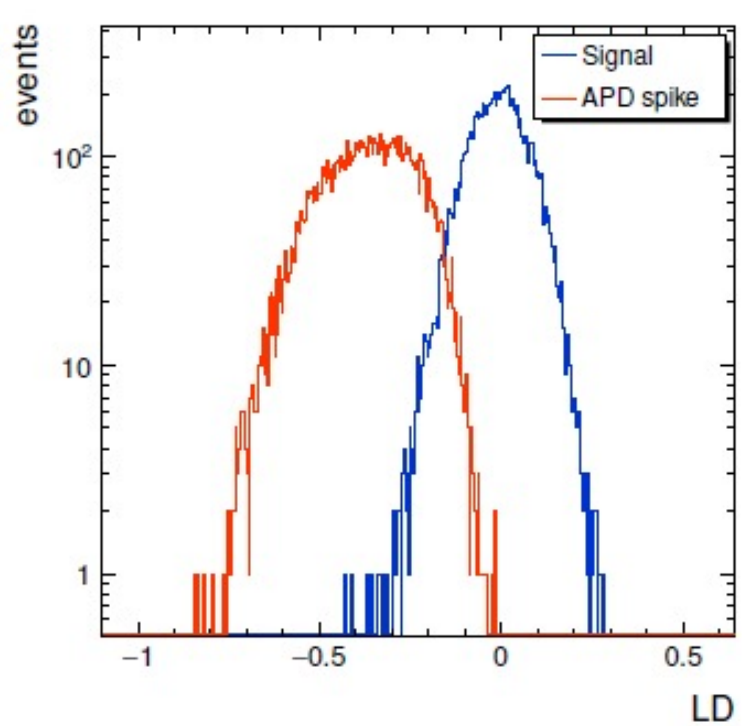
Changes to the Barrel Calorimeter

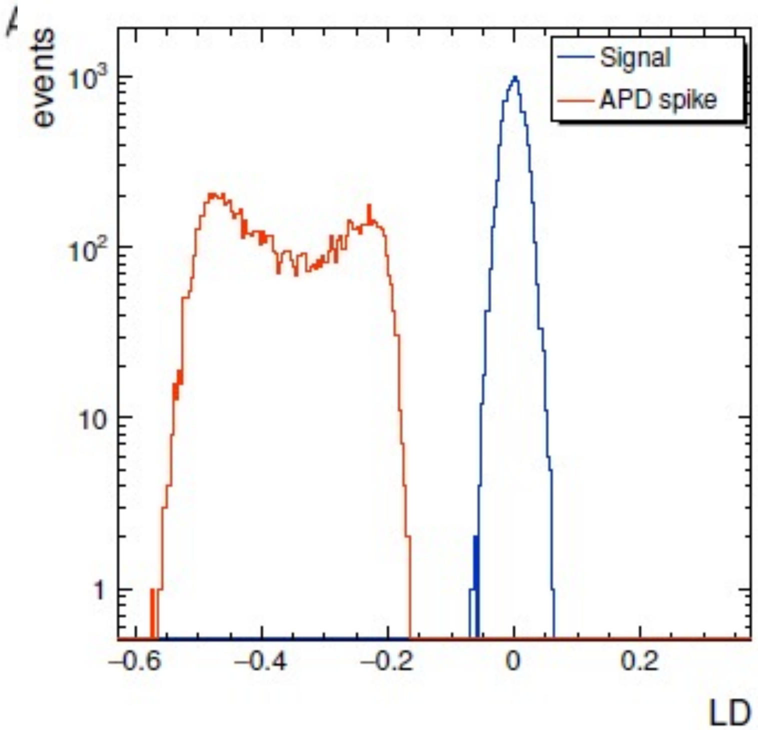
- Improve the timing resolution of the calorimeter for both EM and Hadron calorimeters
  - Change the front-end electronics of both EM and hadron barrel calorimeters

- The timing resolution is improved from 1 ns to 30 ps which will enable removal of signal from spikes (noise) particularly at higher shower energies



- Also, improves the bandwidth of transmission





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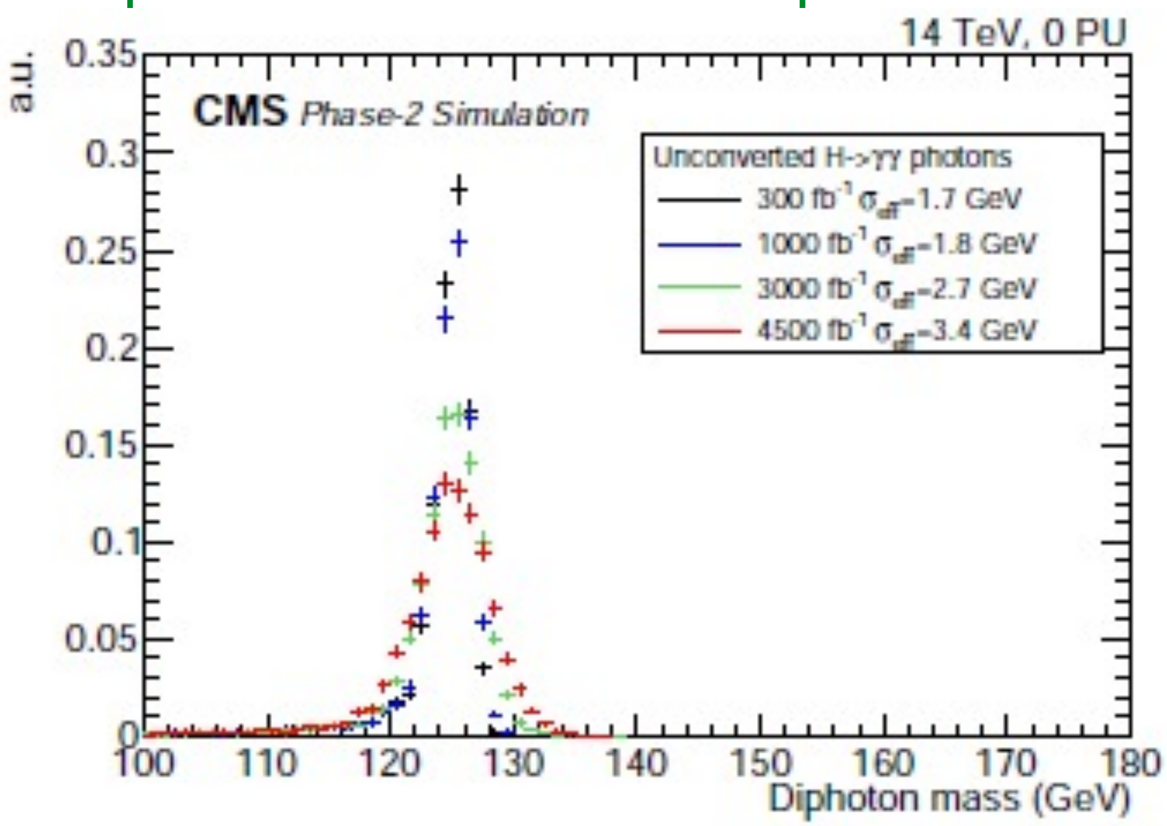
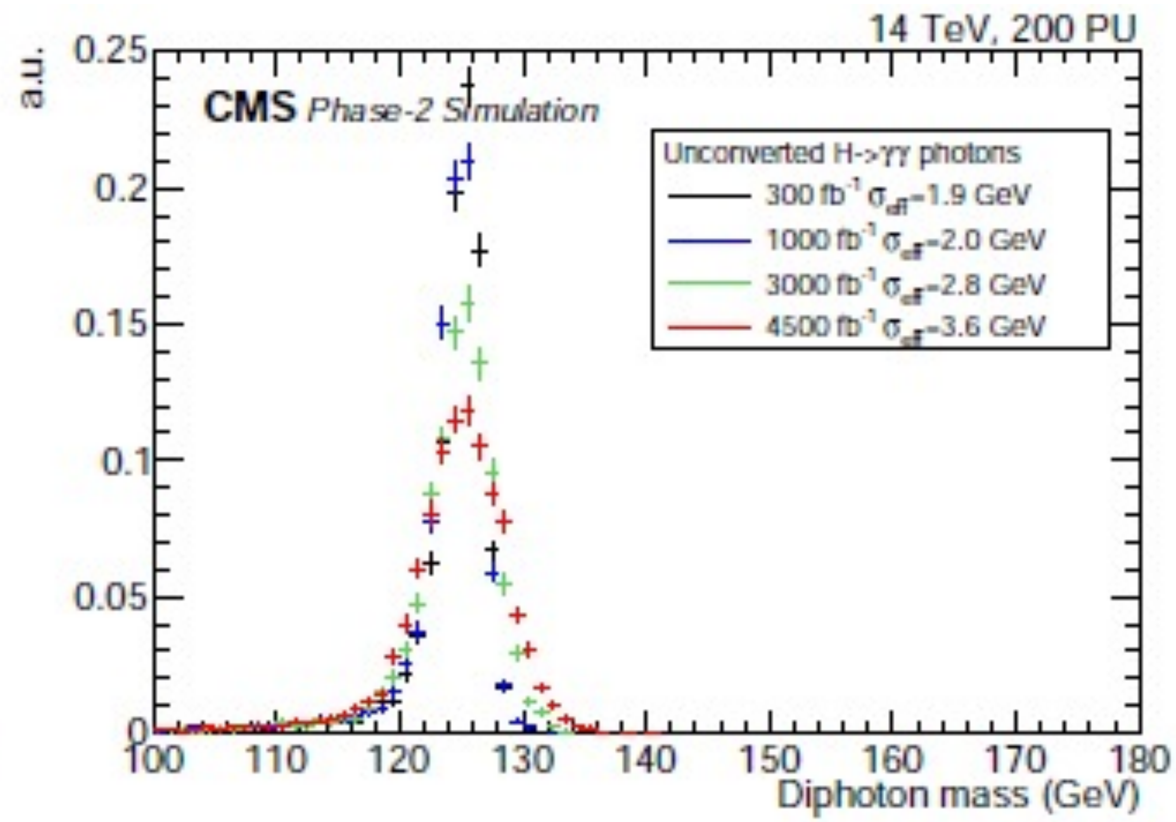
Barrel Calorimeter

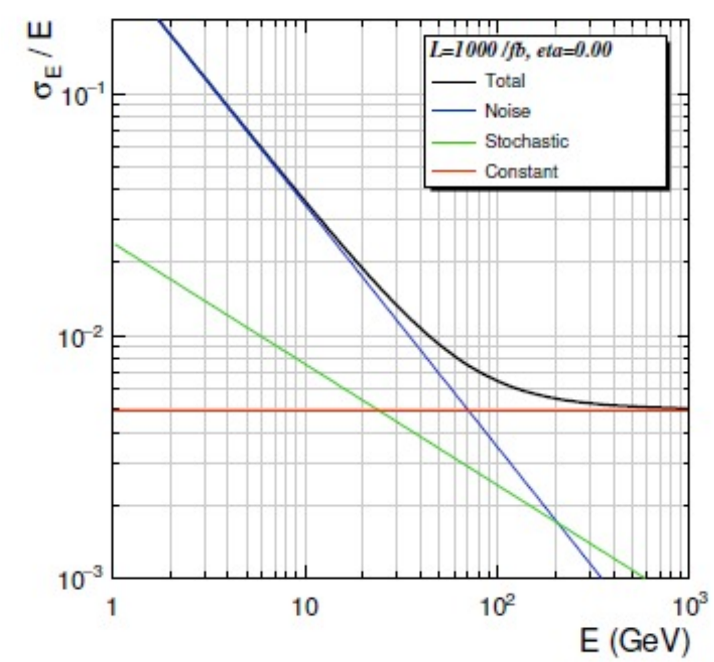
- The precision time measurement will also enable a better localisation of the production vertex for di-photon events





- Backend electronics for both ECAL and HCAL will be upgraded given the higher data rate using FPGAs and high-speed optical links to the ATCA (Advanced Telecommunications Computing Architecture) standard

- Additional cooling (-9 vs -18 degrees) will keep the noise level down to compensate for light loss and maintain energy resolution at the current level



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EndCap Calorimeter

- The issue of the endcap calorimeter is more acute. The endcap calorimeter will die by the end of Run3. Both the EM and hadron calorimeters need to be replaced by a new system which will be able to withstand the high radiation level

- Apart from radiation tolerance, the following considerations were used:
  - Dense calorimeter to preserve lateral compactness of showers
  - Fine lateral granularity with low electronic noise to give high enough S/N allowing shower separation
  - Fine longitudinal granularity enabling fine sampling of the longitudinal development of showers
  - Precision measurement of the time of high-energy showers

→ Tracking Calorimeter

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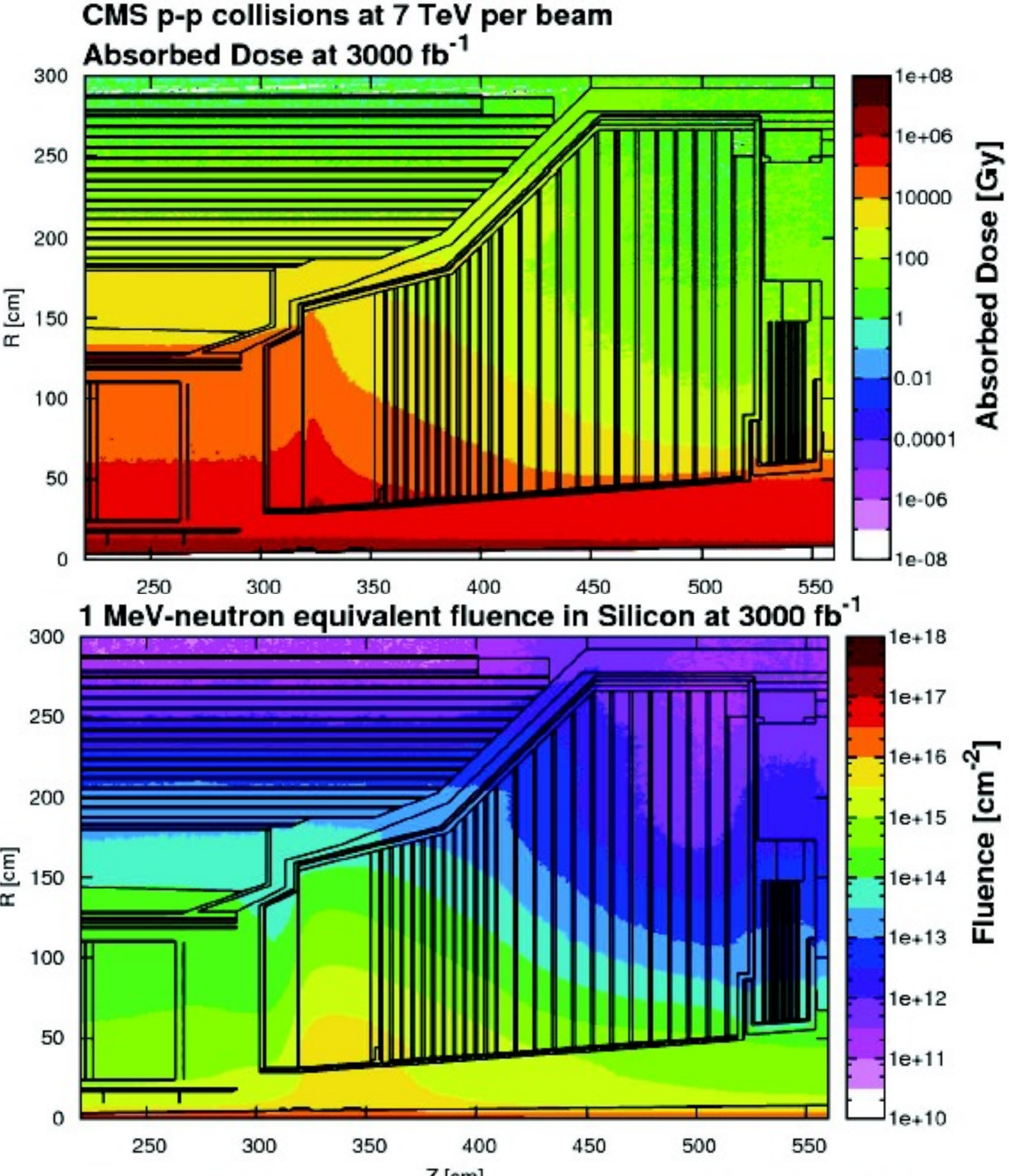
Radiation Level



- HL-LHC will accumulate ten times more luminosity than LHC consequently exposing the detector to a higher level of radiation.
- The highest fluence after an integrated luminosity of 3000 fb^{-1} is expected to be 3 kGy and $10^{16}\, \mathrm{n_{eq}/cm^2}$
- Silicon detectors operated at $-30\,°\mathrm{C}$ can withstand even 50% higher radiation level ($1.5\times10^{16}\, \mathrm{n_{eq}/cm^2}$)
- Plastic scintillators will survive in the region of lower radiation level
- A hybrid model is chosen to optimise cost and performance

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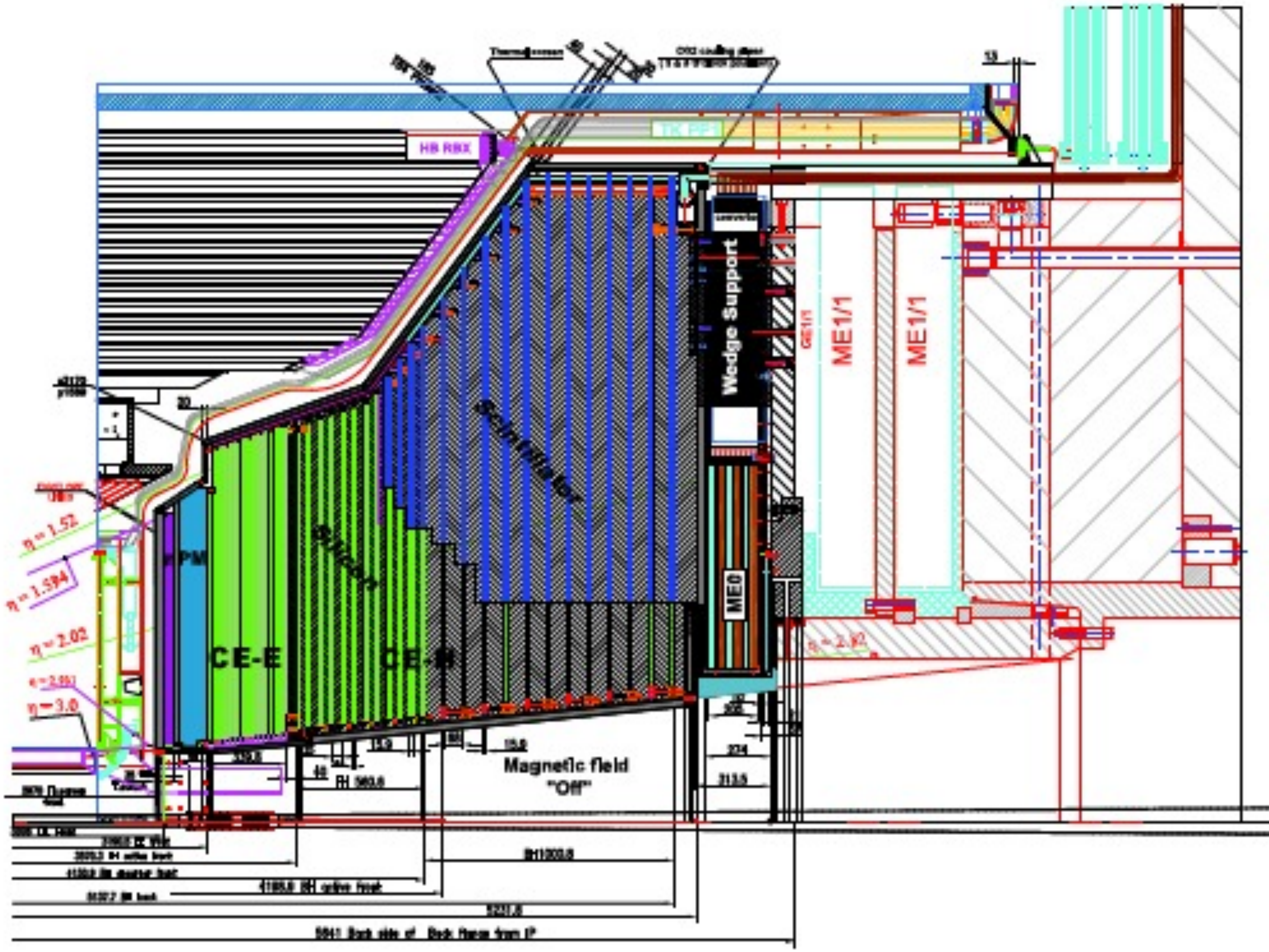
High Granularity Calorimeter

- Use silicon where radiation level is high, and plastic scintillators where radiation level is not that high

- Use lead absorber for the EM section and iron absorber for the hadronic section



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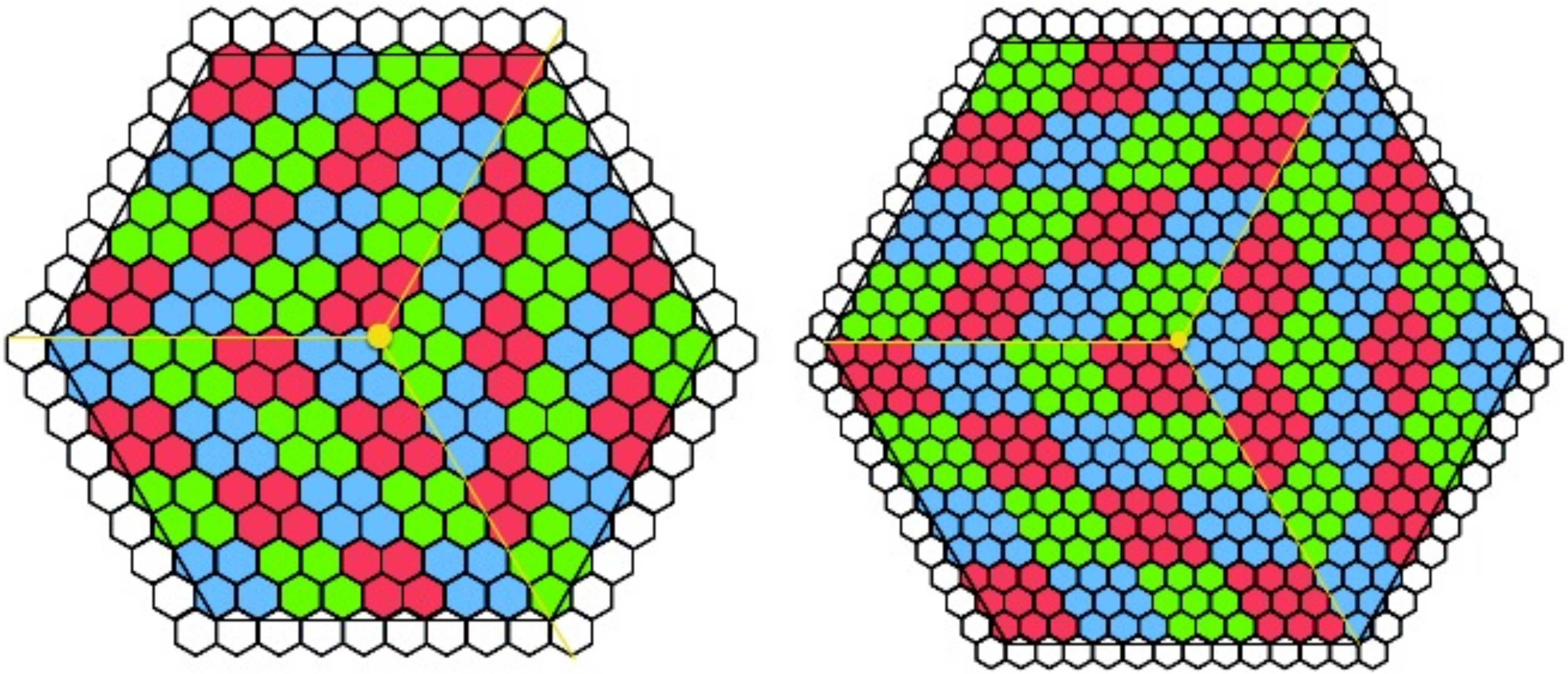
Wafers

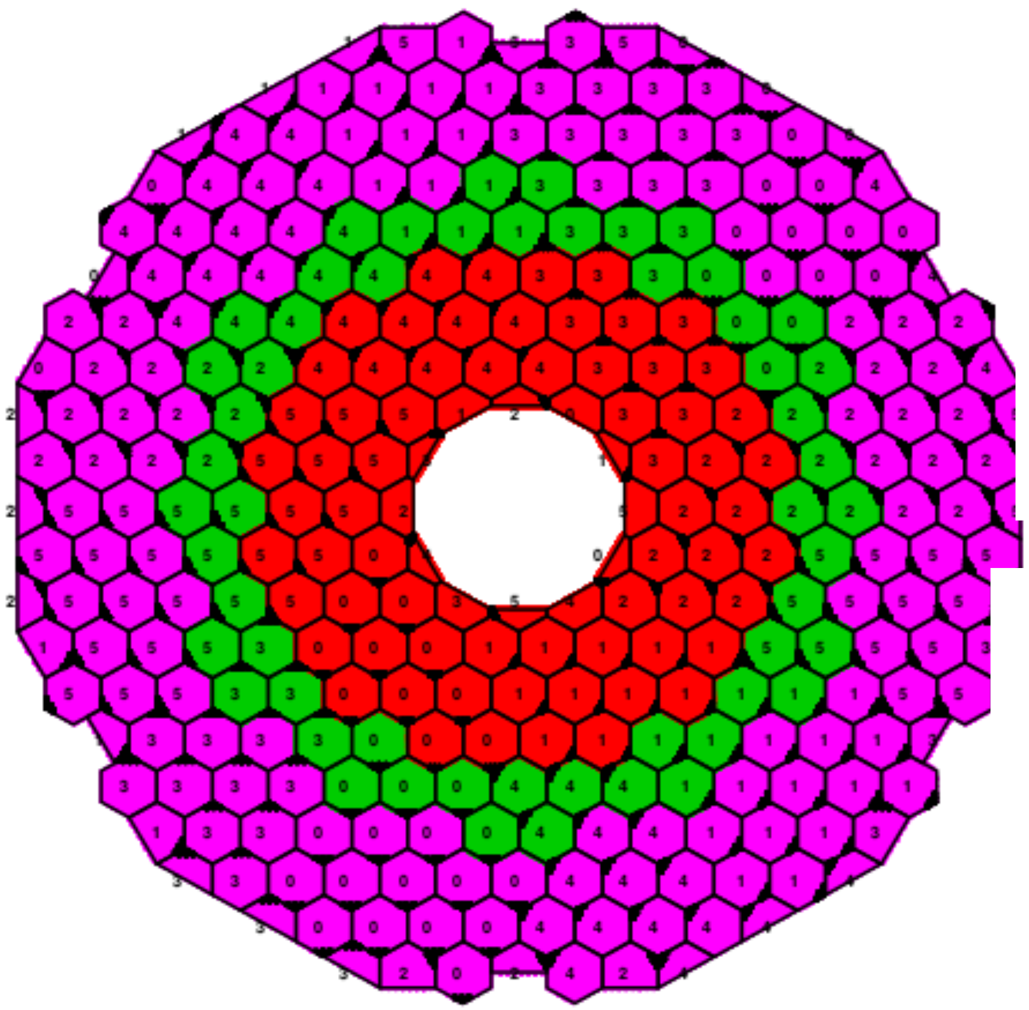
- To optimise the cost, use hexagonal wafers with hexagonal cells

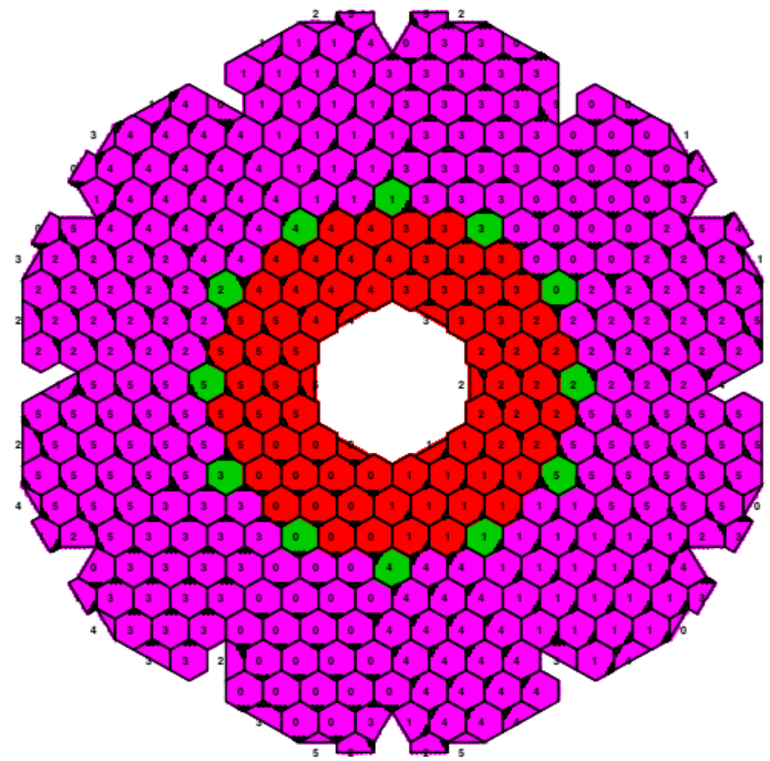


- Optimization of S/N at different radiation levels demands two types of cell densities and three types of thicknesses of the depleted part of the silicon
  - 120 µm and 200 µm depleted silicon in high density wafers
  - 200 µm and 300 µm depleted silicon in low-density wafers

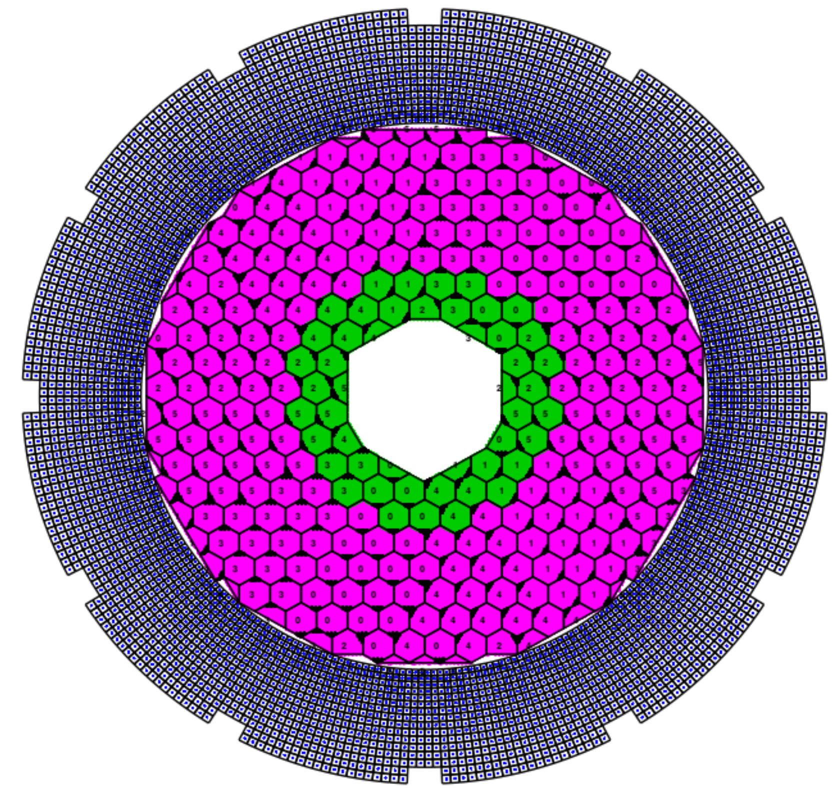
Layer Layout

EE Layer

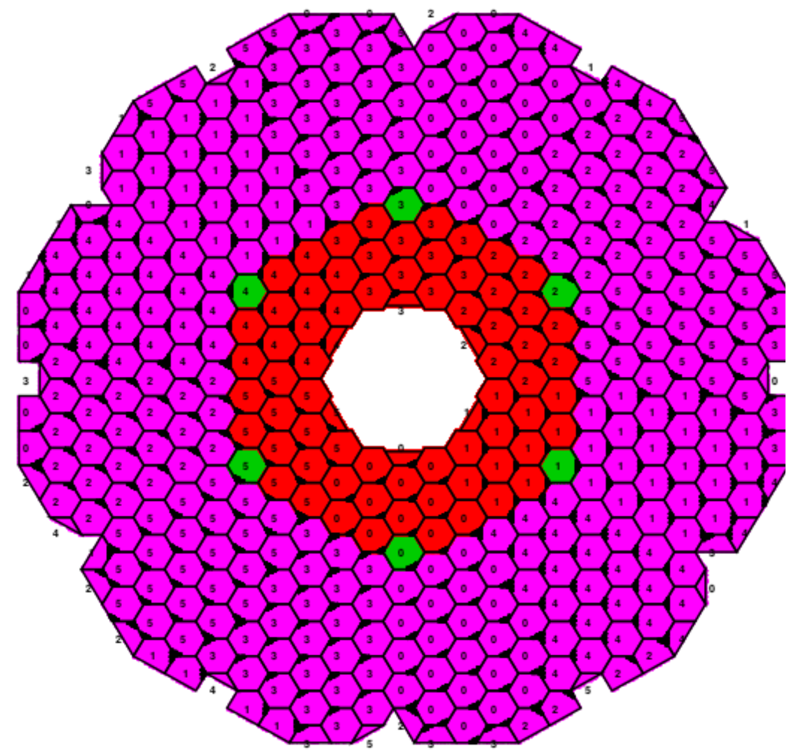


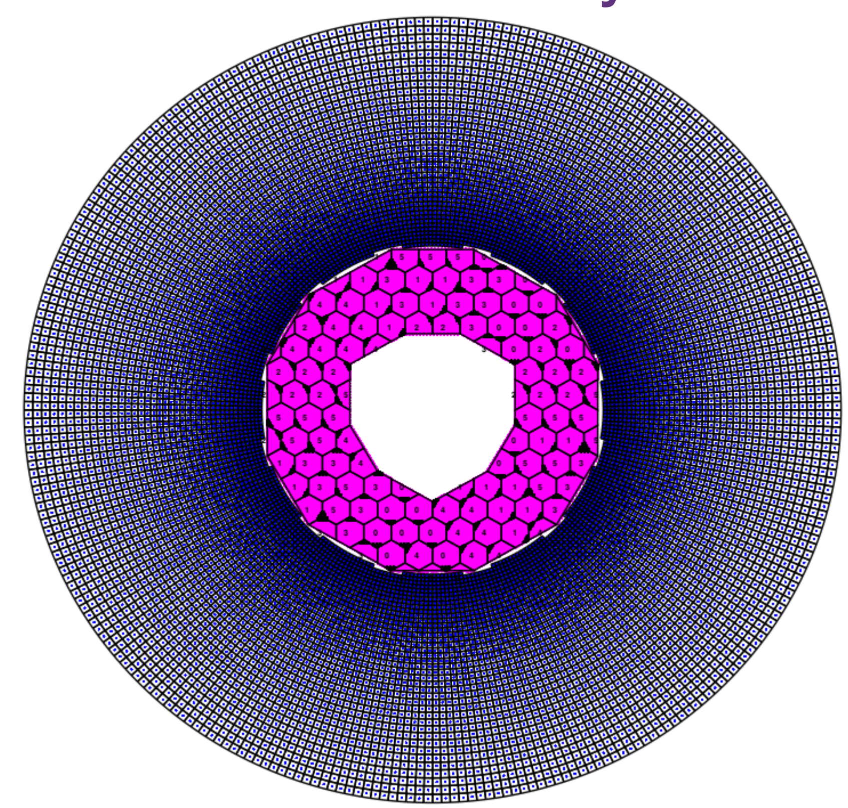


HE Rotated Layer



HE Mixed Layer



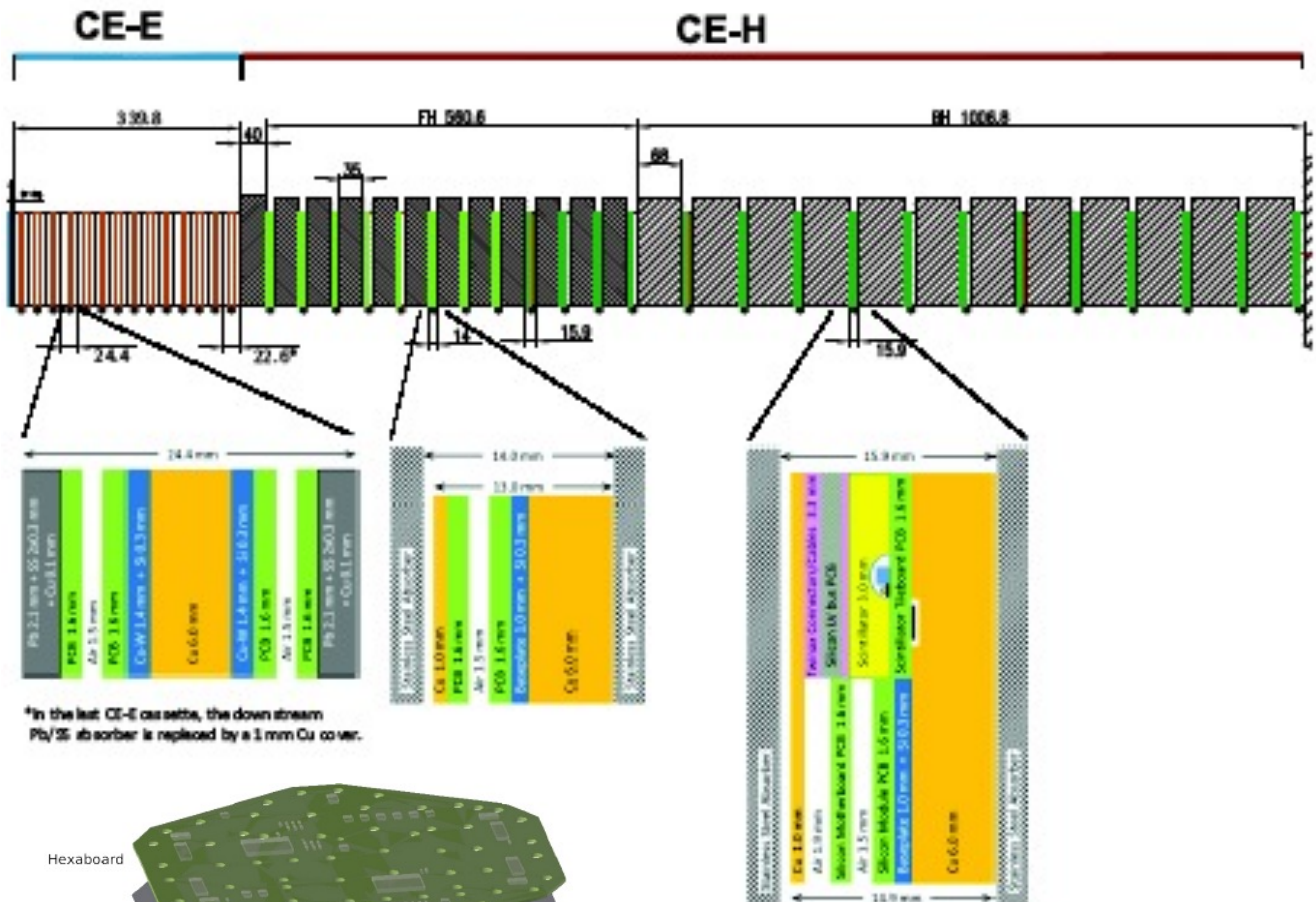


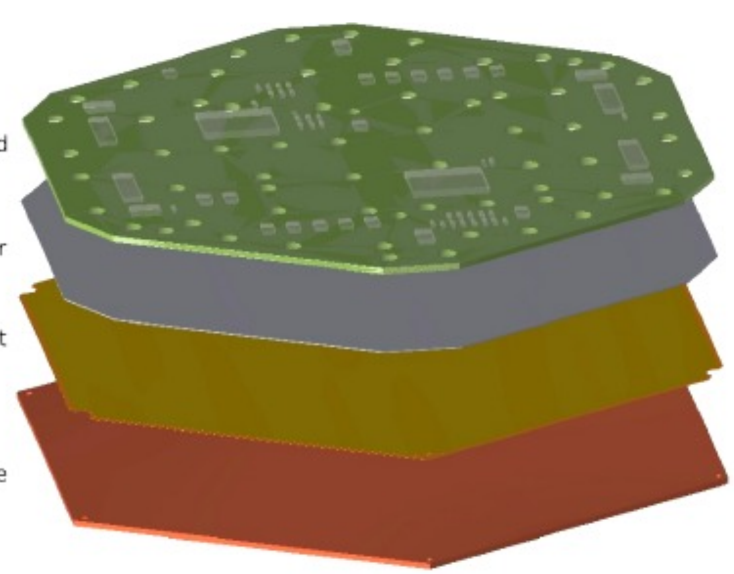
Use the right detectors (silicon vs scintillators) of the right type to have good S/N even after receiving 3000 fb^{-1} of integrated luminosity

Longitudinal Layout

- Modules are made with base plates, Kapton sheet, sensor, and hexaboard carrying the readout electronics with the copper cooling plate on one side and the absorber layer on the other side

- There are 13 double-sided layers for the electromagnetic section with lead absorbers and 21 single-ssided layers for the hadronic section with iron absorber





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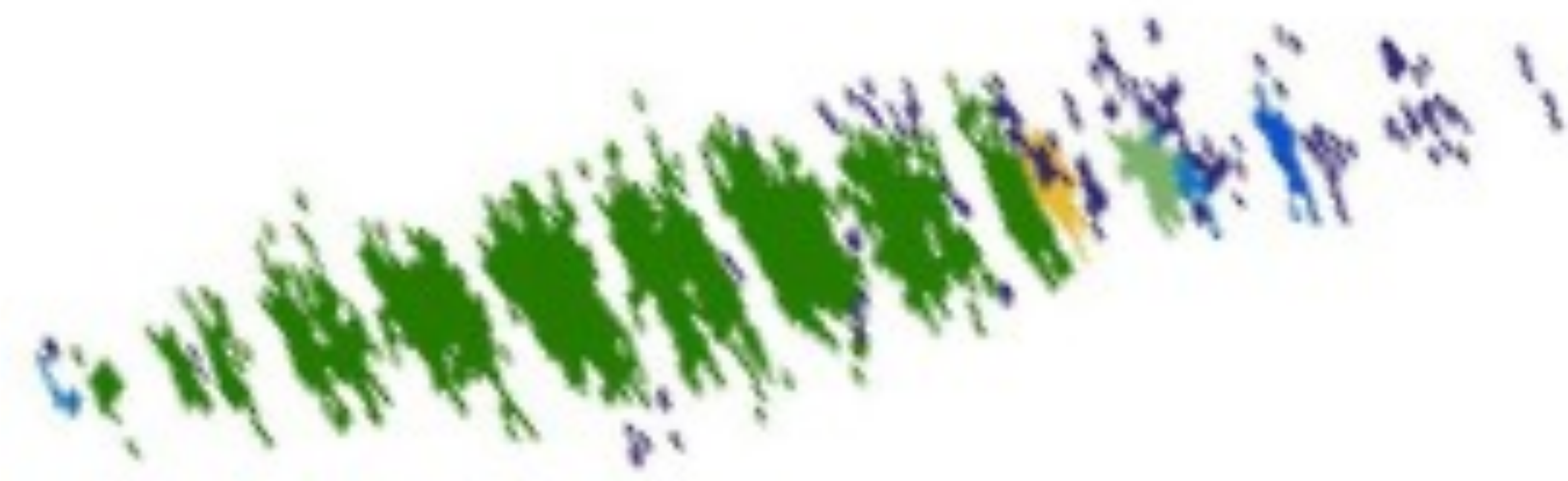
Extraction of Information

- This is a calorimeter with several million readout cells. Even a single particle illuminates several hundreds of such cells



- Shower from a single photon of 20 GeV produces thousands of hits in the 26 layers of the electromagnetic section

- Need a very sophisticated pattern recognition and energy regression algorithm to extract the best information from this detector - that too spending as little CPU time as possible

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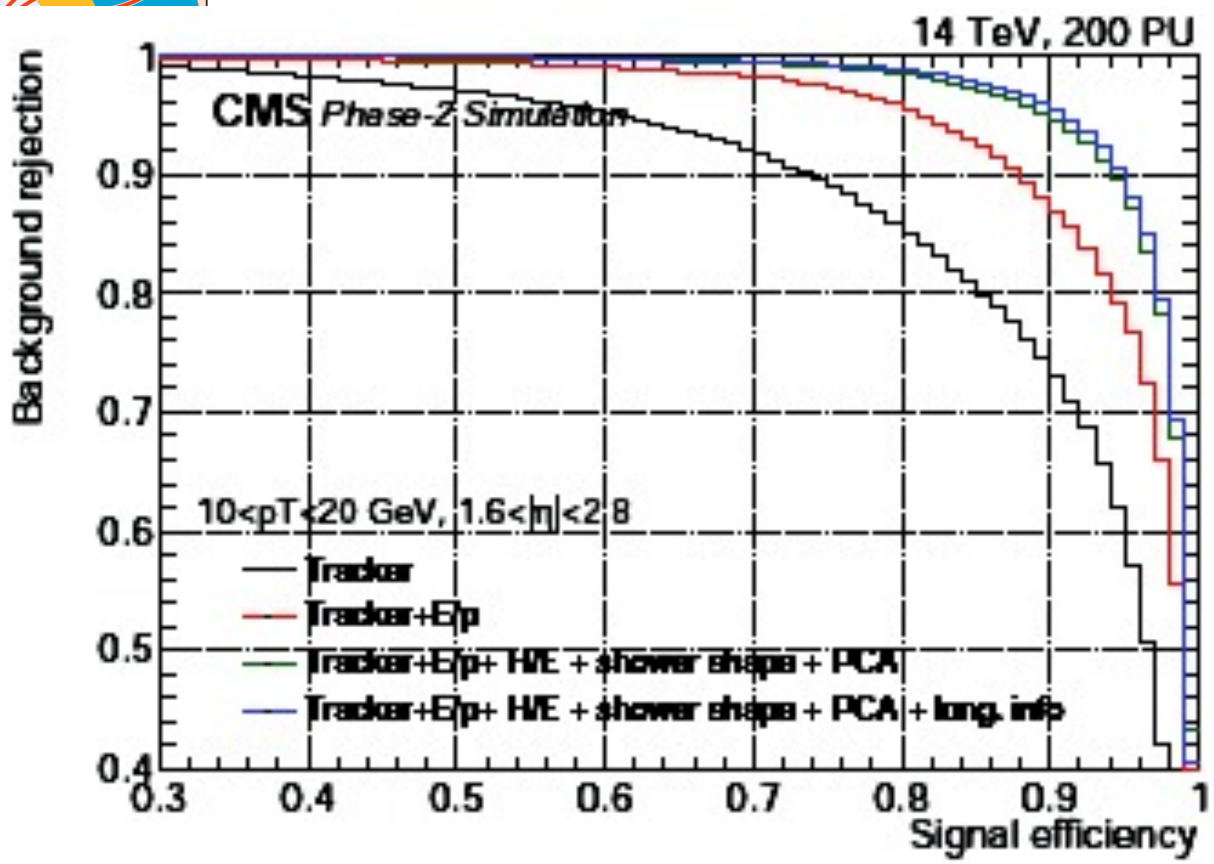
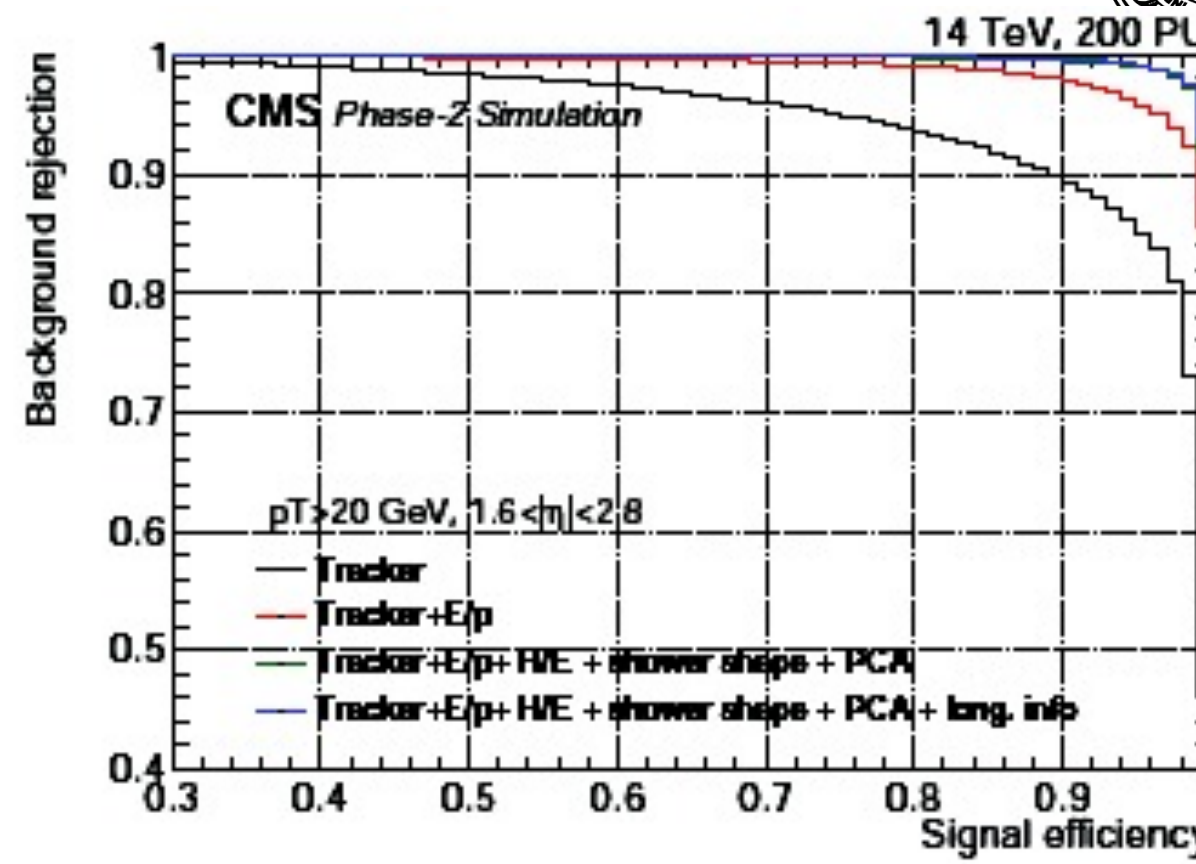
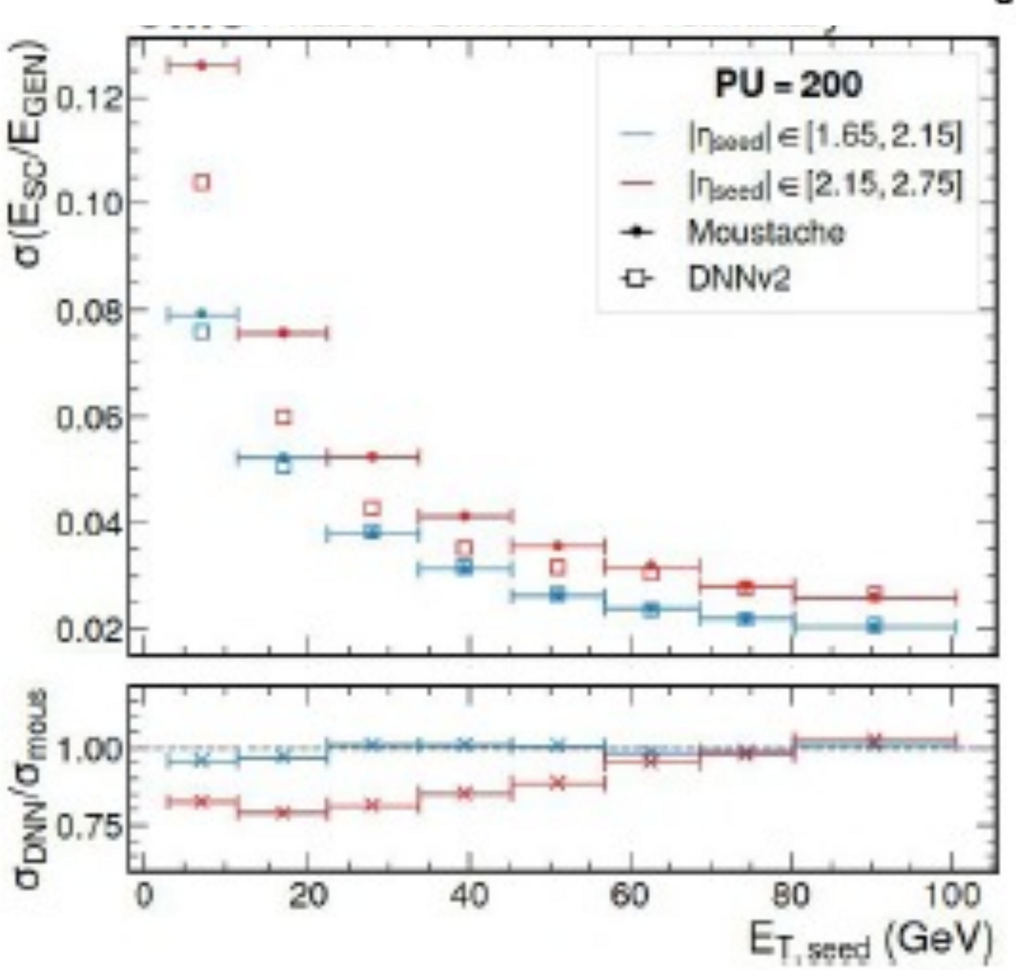
Performance for Electron/Photon







- Both lateral as well as longitudinal shower shapes are used to distinguish an EM shower from a hadronic shower
- Purity better than 95% can be achieved even for signal efficiency at 50% for electrons of energy below 20 GeV
- Energy resolution better than 5% can be achieved at 20 GeV

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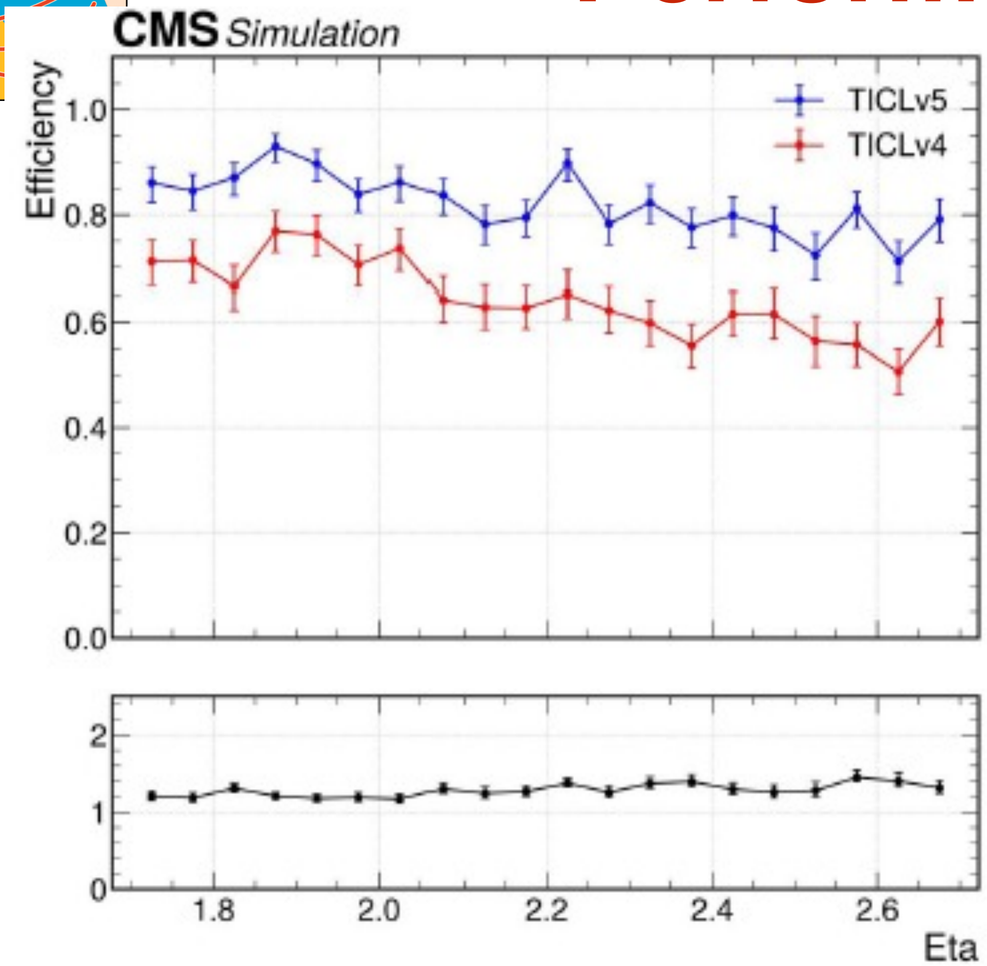
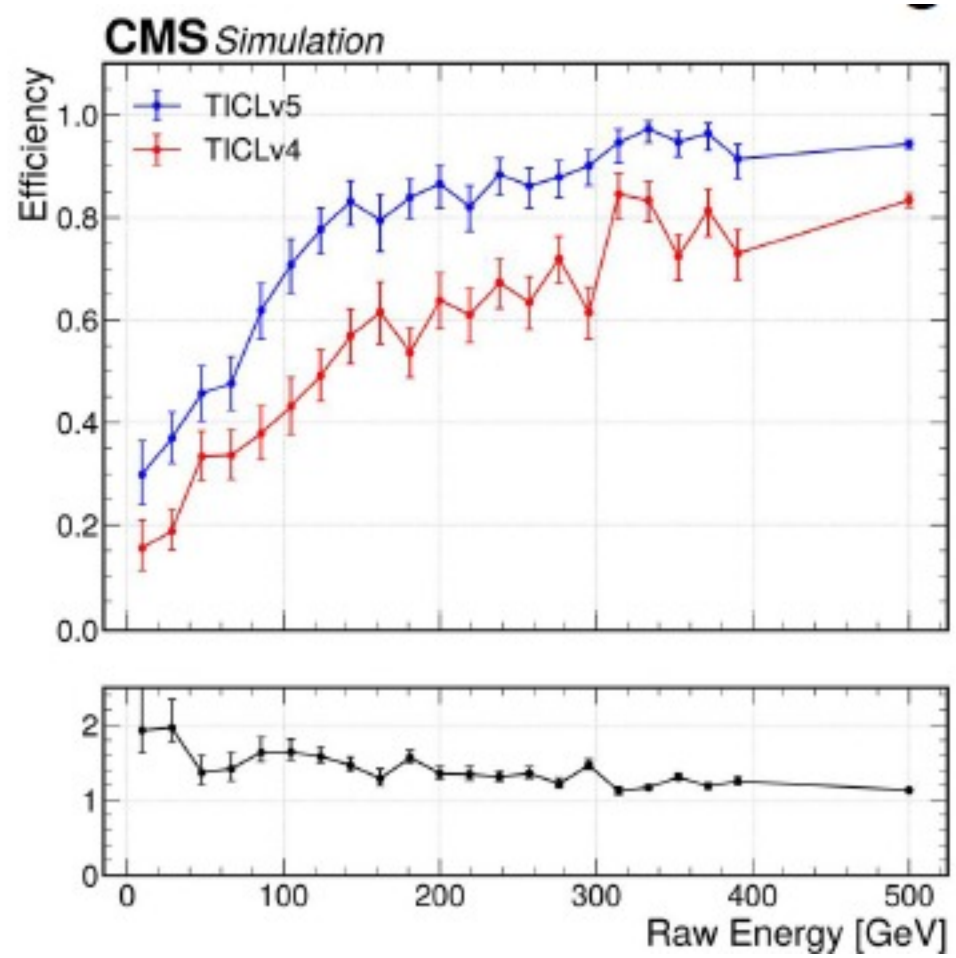
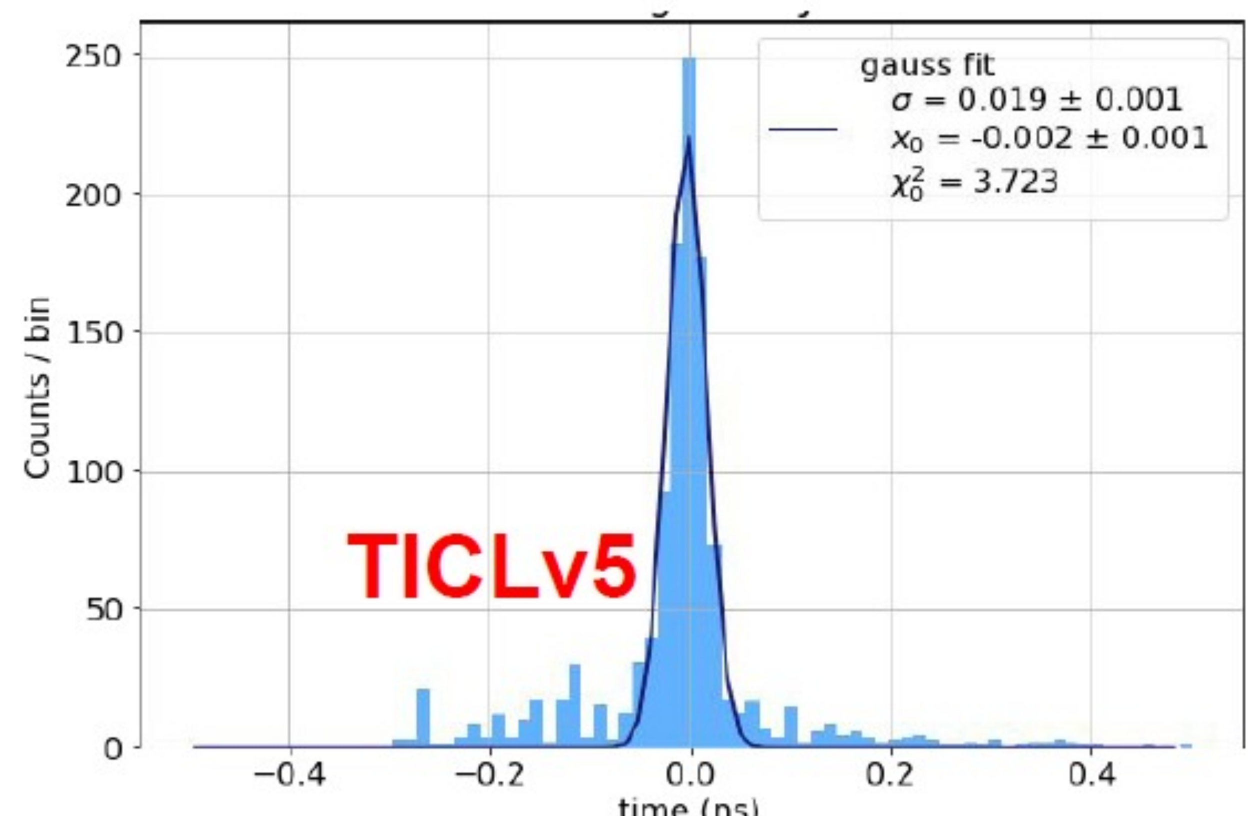
Performance for Hadrons





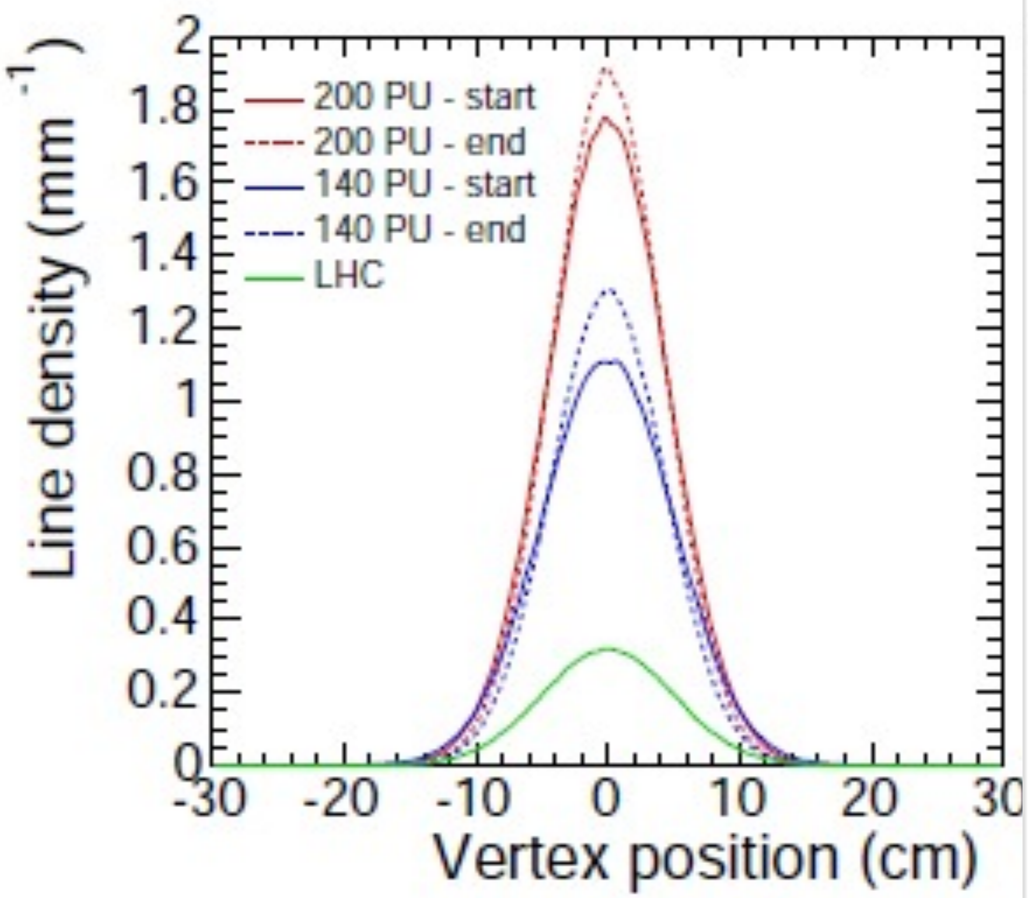
- Even with average pileup at 200, charged pion reconstruction efficiency will be above 80% over the entire |η| region and for energies above 100 GeV

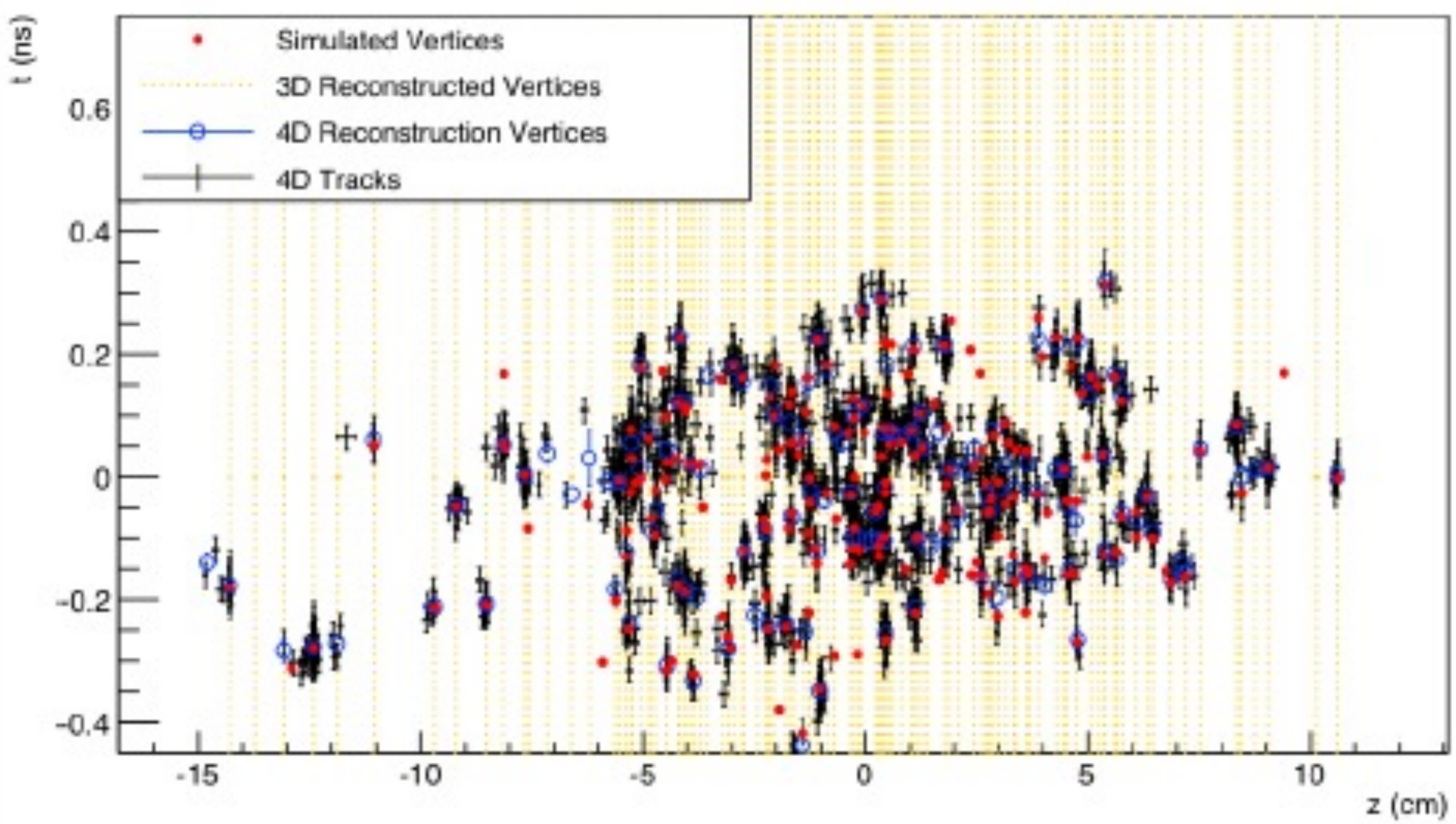
- Timing resolution better than 30ps can be achieved in the clusters



Four Dimensional Reconstruction

- Production of a large number of interactions in a bunch crossing will give rise to a very large number of charged particle trajectories
  - Vertex determination will face an unsurmountable difficulty arising due to ambiguities





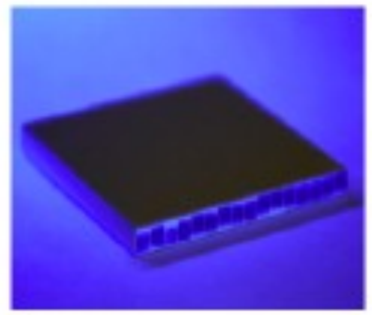
- All the interaction vertices are within ±10 cm from the IP along the beam axis. Has to bring in the fourth dimension (time) to identify the vertices
  - Need to know the track timing with a precision ≈30 ps

MIP Timing Detector

- Introduce a new layer of detector outside the CMS Tracker: MIP Timing Detector (MTD)
  - Vertex density will reach 2 per mm
  - Diving the RMS spread of the beam crossing time (180-200 ps) in slices of 30-40 ps bins, the number of vertices per slice is the same as what was seen during Run2 (40-60) which was handled well by CMS/ATLAS

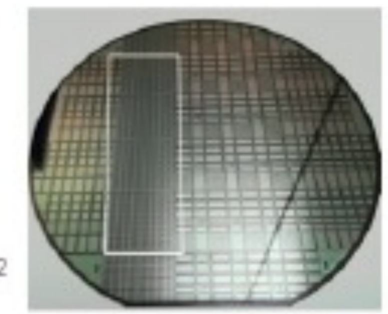
BTL: LYSO bars + SiPM readout:

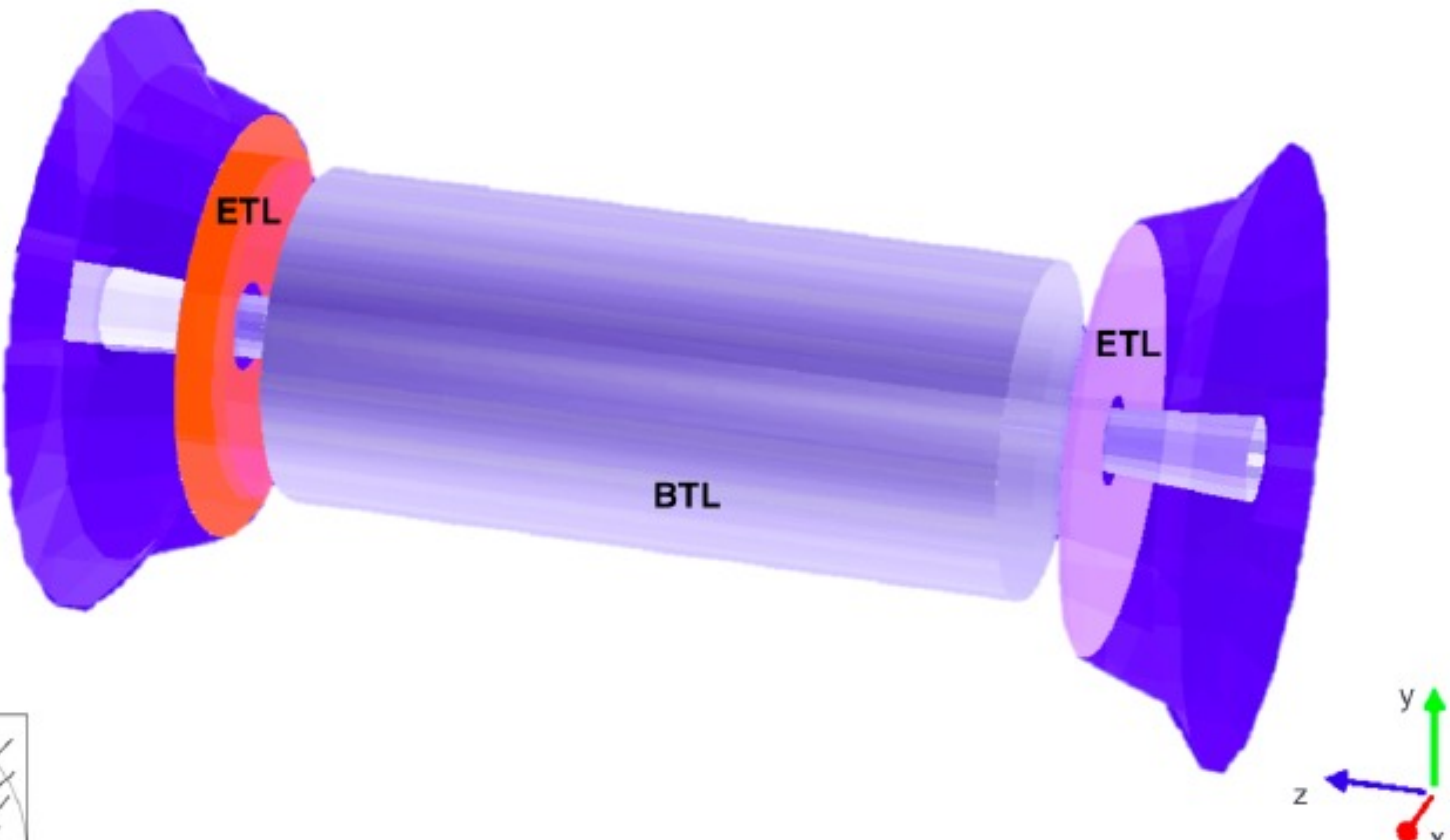
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2×10^{14} n_{eq}/cm^2



ETL: Si with internal gain (LGAD):

- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2





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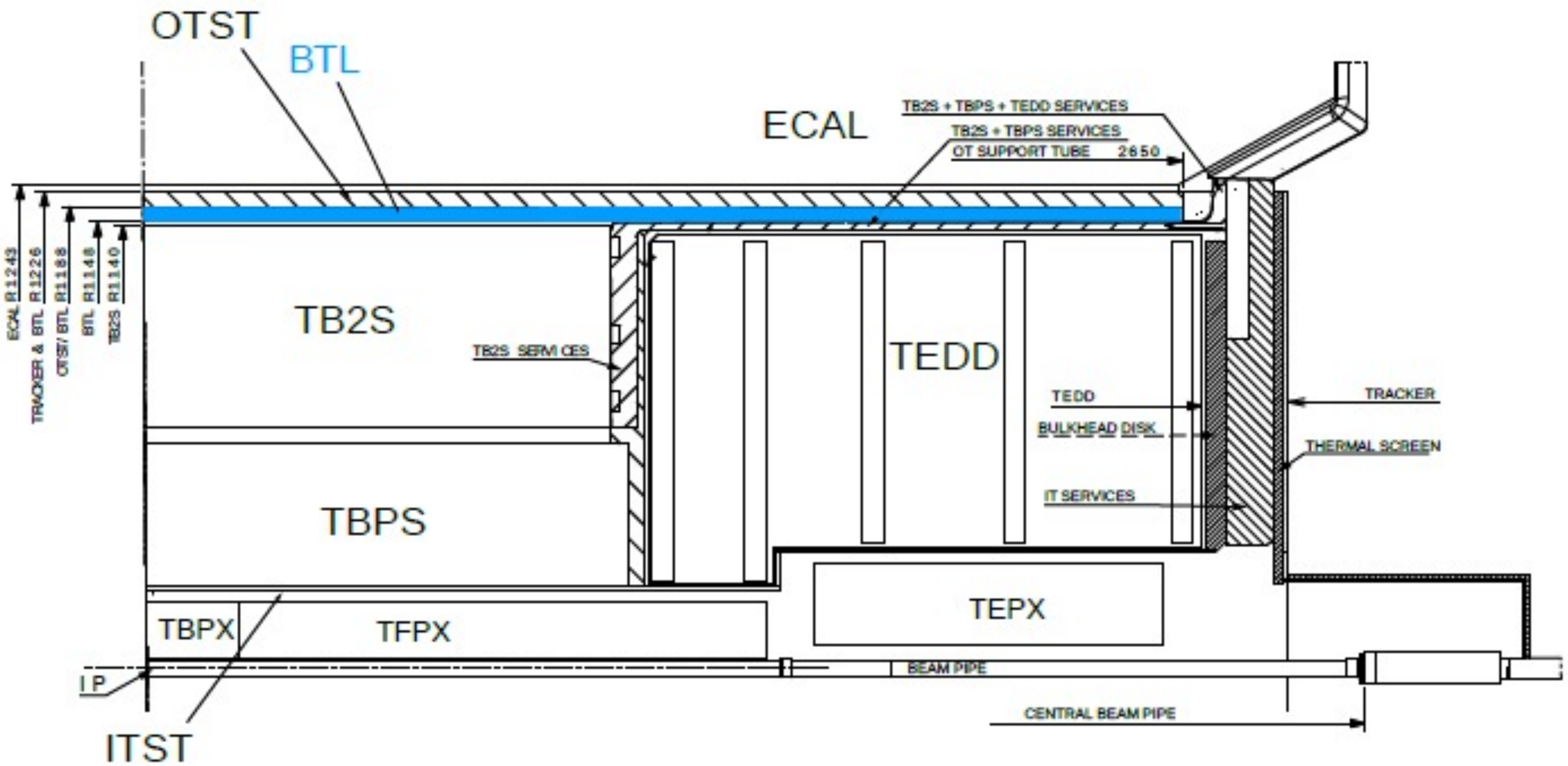
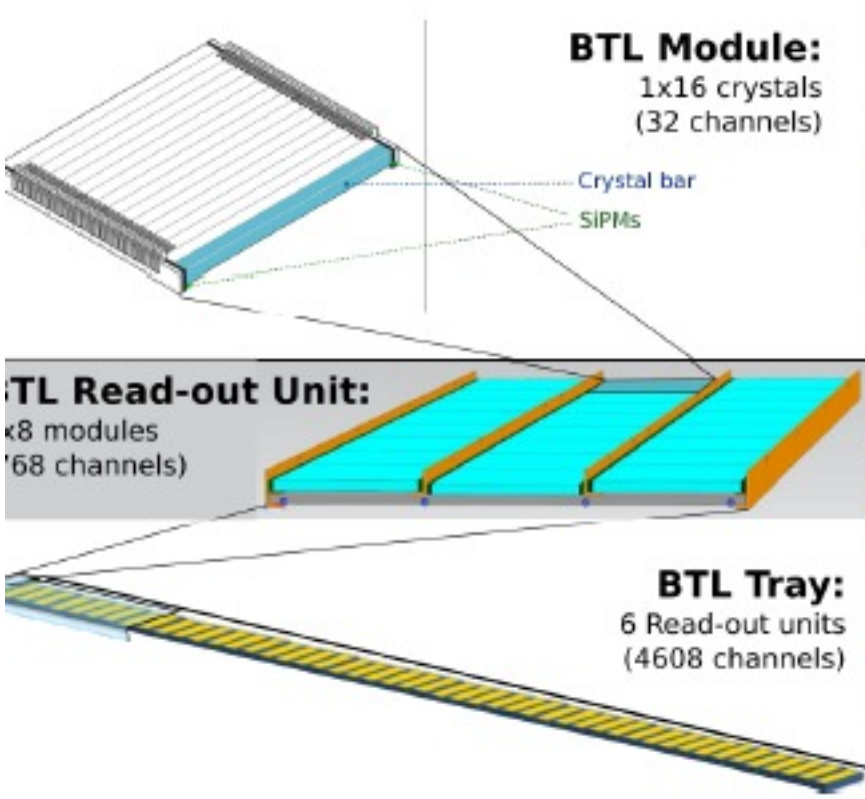
Barrel Timing Layer





- The Barrel Timing Layer (BTL) is made of LYSO crystals and is integrated into the Tracker Support Tube (TST) with a radial spread between 1148 mm and 1188 mm. Its active length is 5 m
- LYSO:Ce Crystal bar of 5.7cm length along -direction and 3.0 mm along the z-direction
- Readout by 33176 SiPMs on either side of the crystal and operated at $-30\,^\circ\mathrm{C}$.

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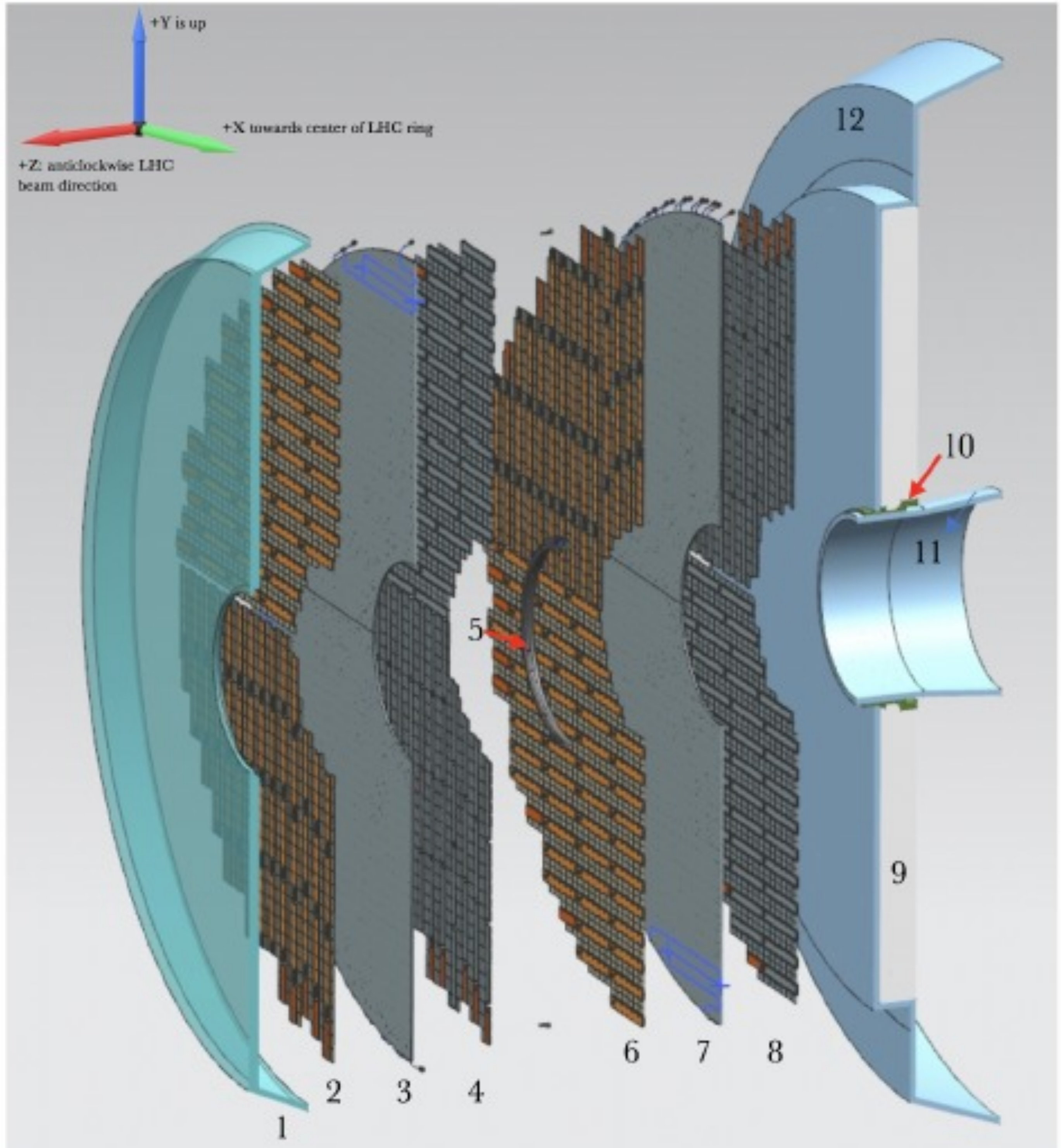
Endcap Timing Layer

- On either side of the interaction region (IR), a two-disk system of MIP-sensitive silicon devices is kept in an annular region between 315 mm and 1200 mm covering |η| between 1.6 and 3.0.

- Readout uses Low Gain Avalanche Detector (LGAD) which can operate at a harsher radiation region with a non-uniform magnetic field

- There are 4 million read-out channels of 1.3 mm x 1.3 mm pads on either side of the IP



1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

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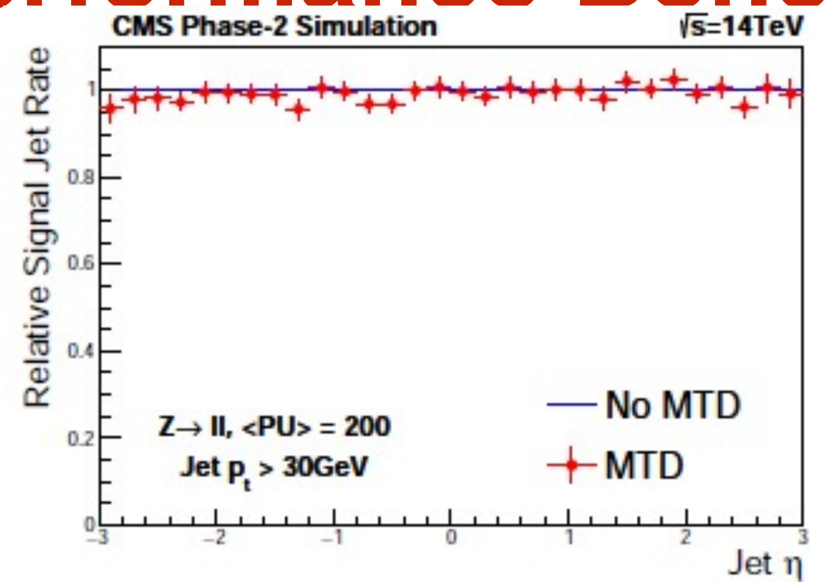
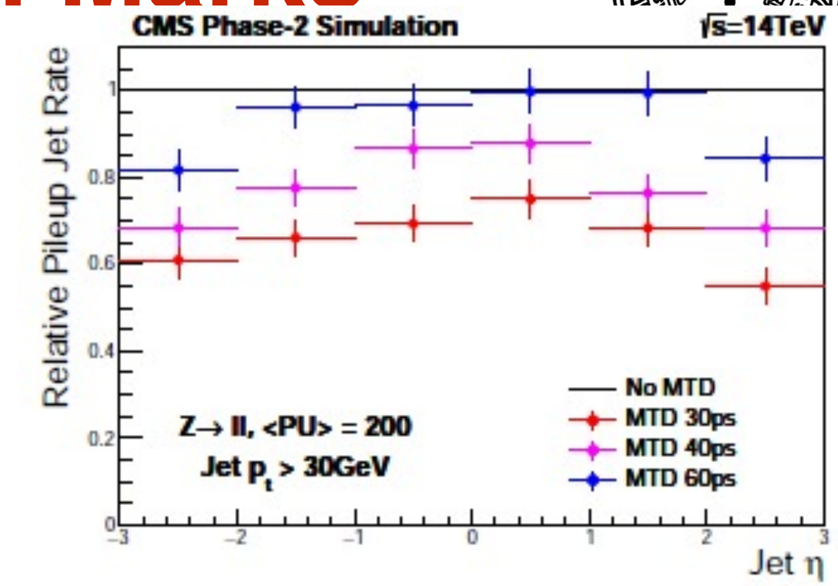
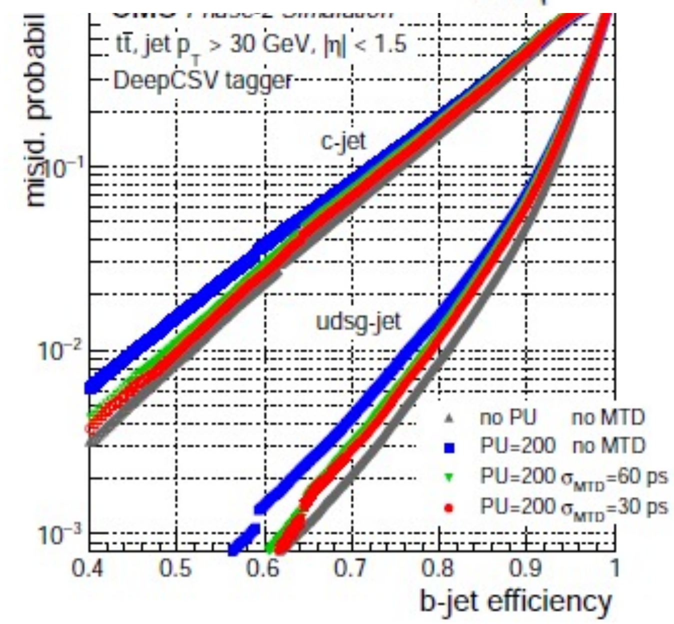
Some Performance Bench Marks

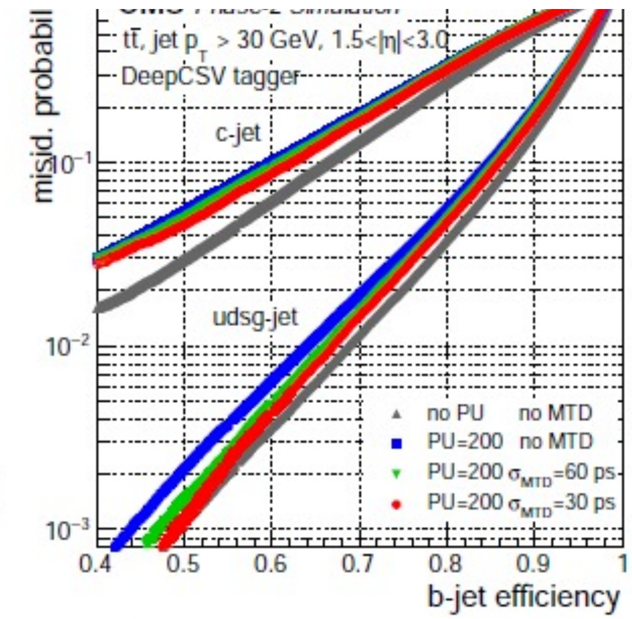
- MTDs help in identifying event vertices and reduce PU particles participating in jet reconstruction



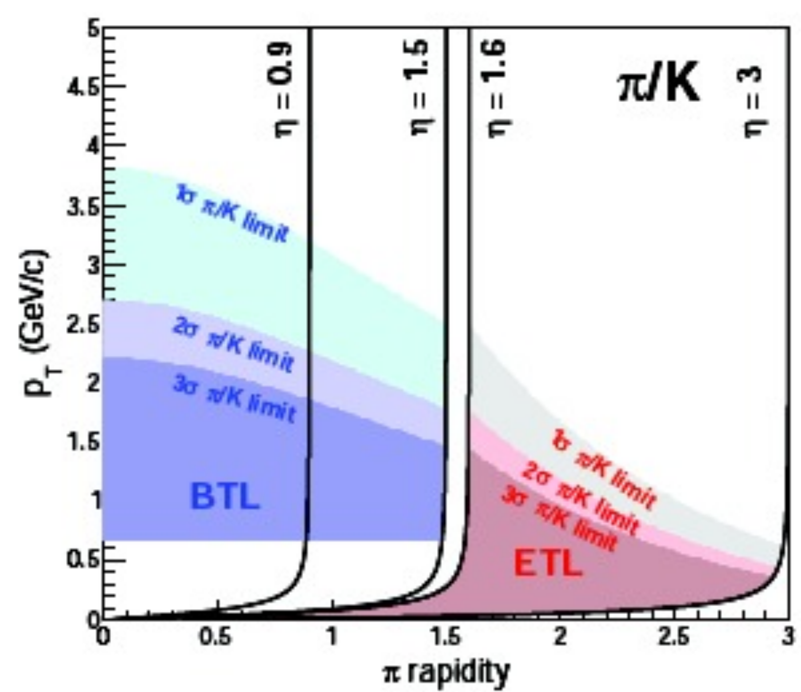


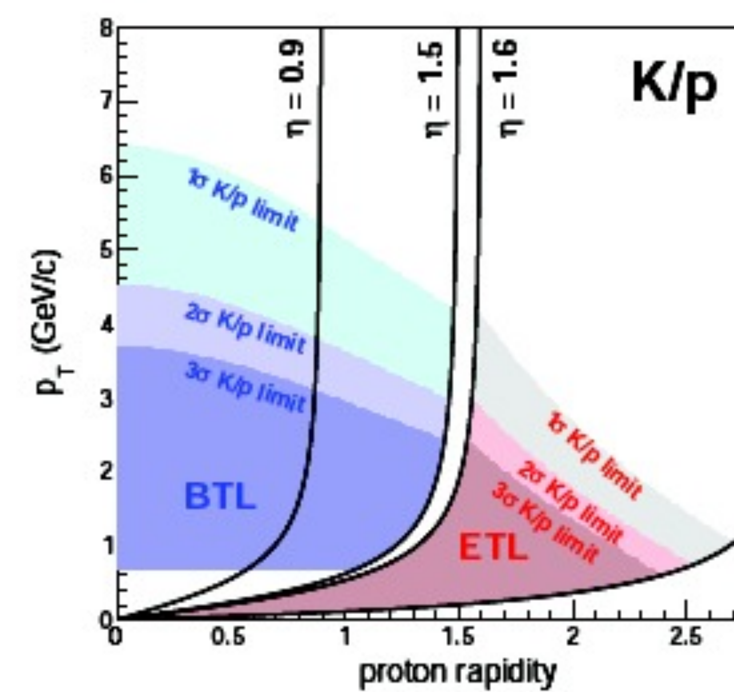
- There is substantial improvement in tagging jets of heavy flavours





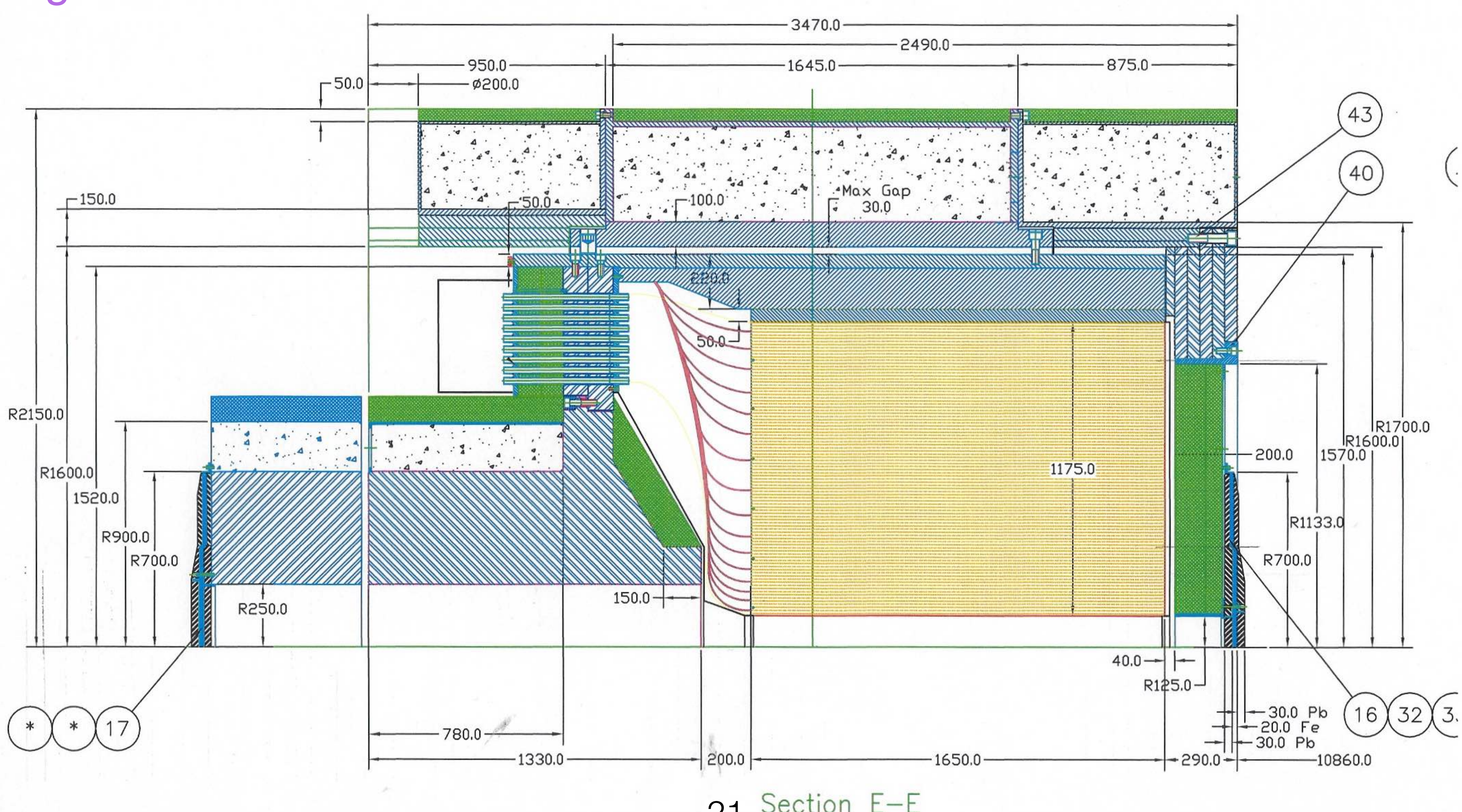
- Good timing services can be used in particle IDs for low-momentum particles (useful for heavy ion collision studies)



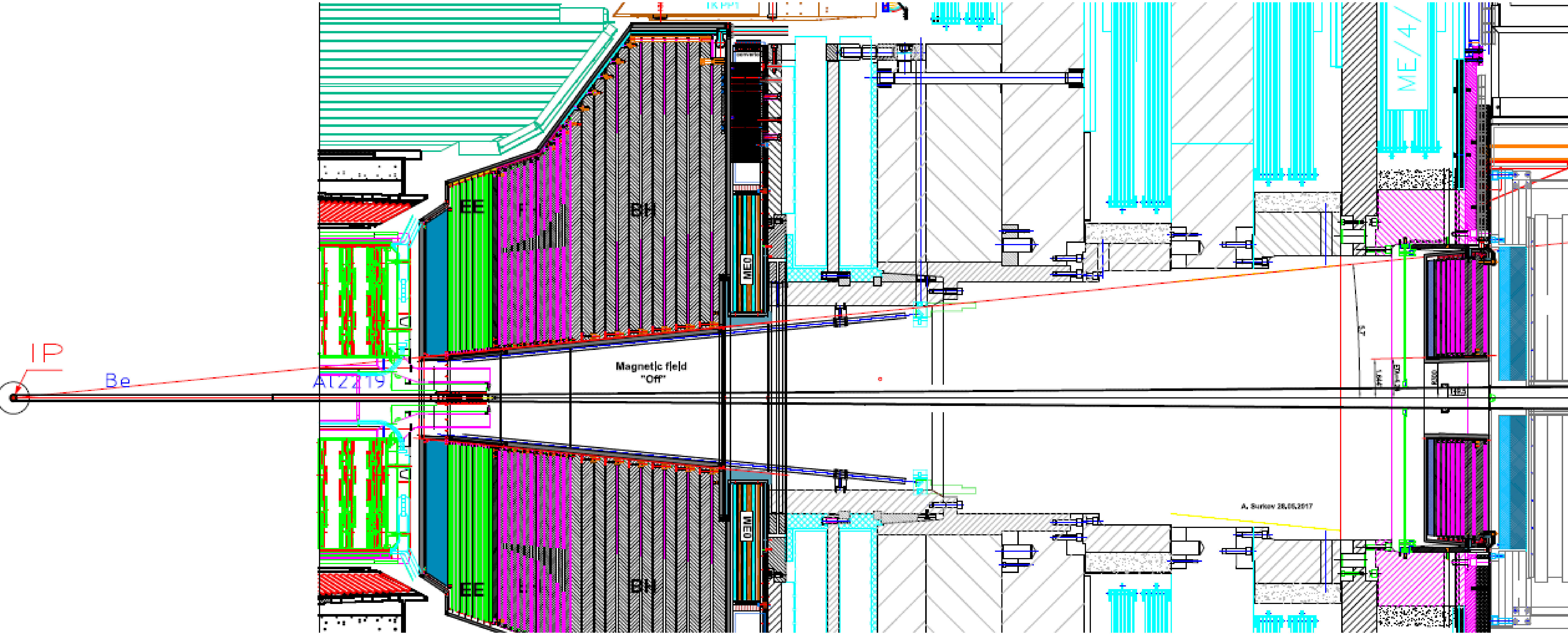


One more Proposal

- There has been a proposal for having a high-granularity calorimeter in front of the forward calorimeter (HF)
  - Physics with high mass VV scattering requires jets in the |η| region 3:5
  - This region is covered by HF
    - 1.65 m (~10λ) of steel absorber with quartz fibre to get signals from Cherenkov radiation having moderate jet energy resolution and not much handle for pileup mitigation



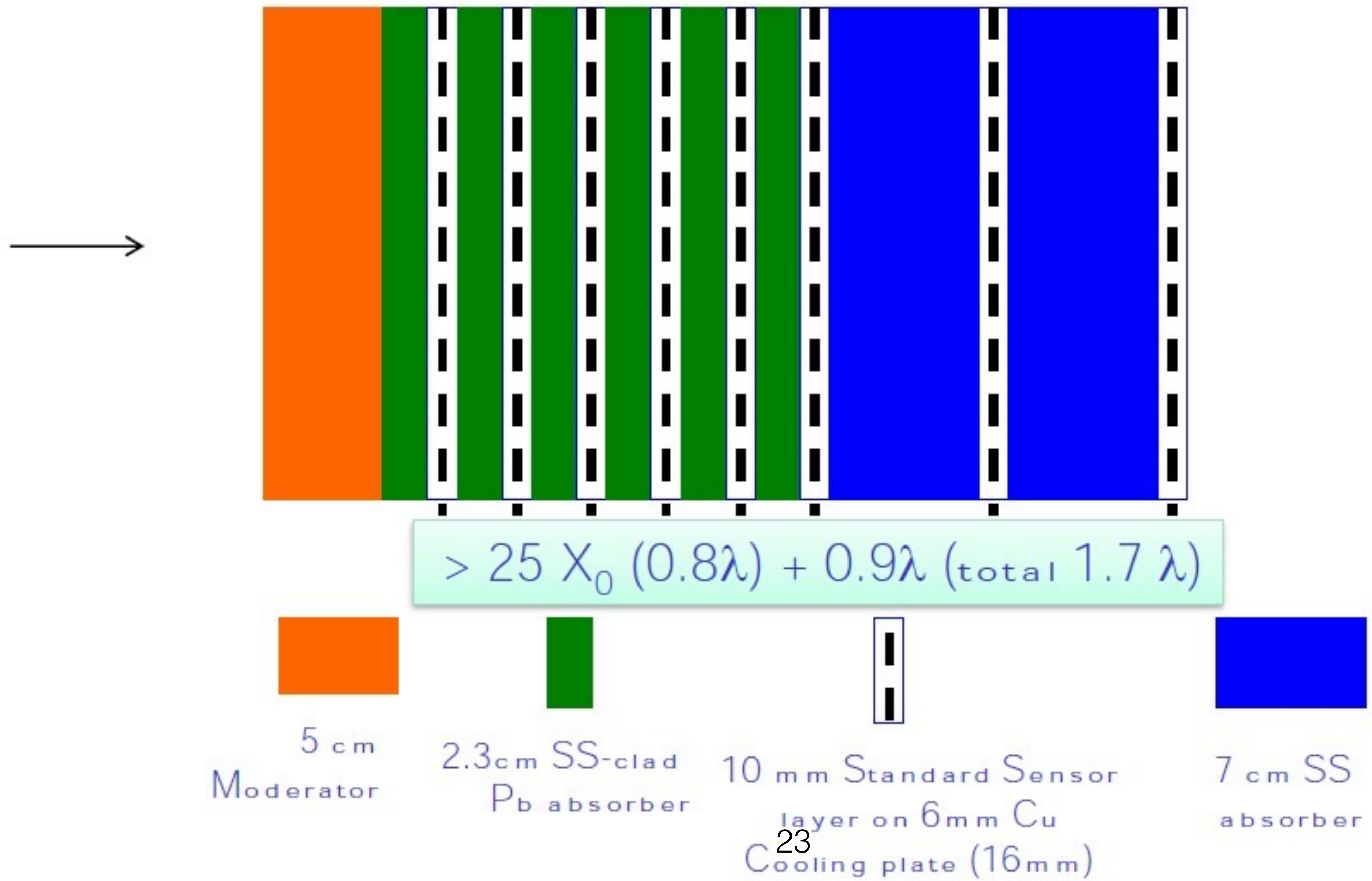
Considerations



- There will be no Totem detector (T1) during the phase 2 run of the CMS
- Place a detector in front of HF supported from the last part of the return yoke (YE4)
- It is in a high radiation zone (fluence ~ 10^{16} cm^{-2})

Possible Design

- Silicon wafers as in HGCal design sandwiched between absorber layers
  - Six layers with SS-clad lead absorbers working as EM component
  - 2 layers after stainless steel absorbers
- Calorimeter thickness
  - 28.4 cm for the EM part (including moderator)
  - 17.2 cm for the hadronic part



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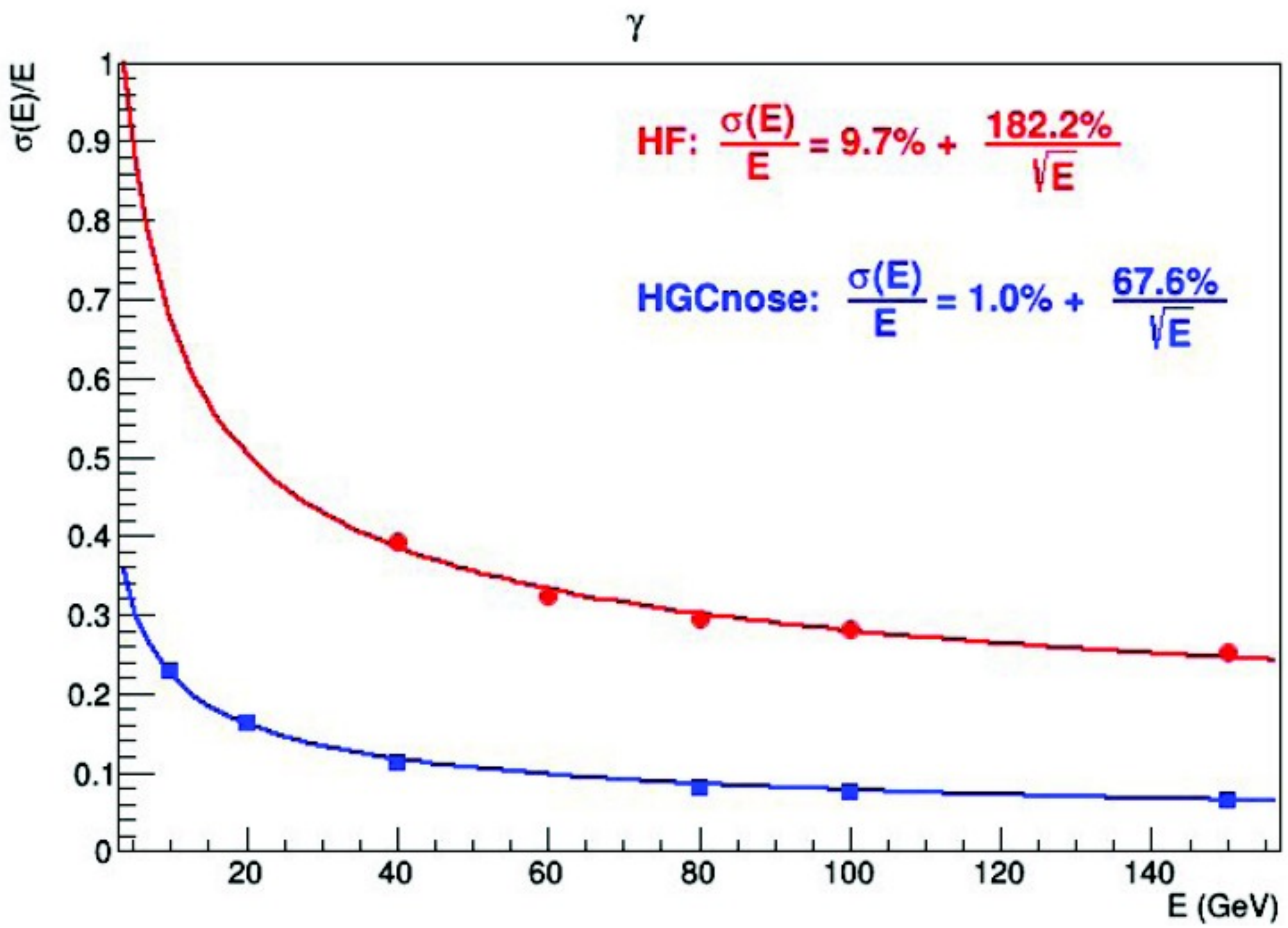
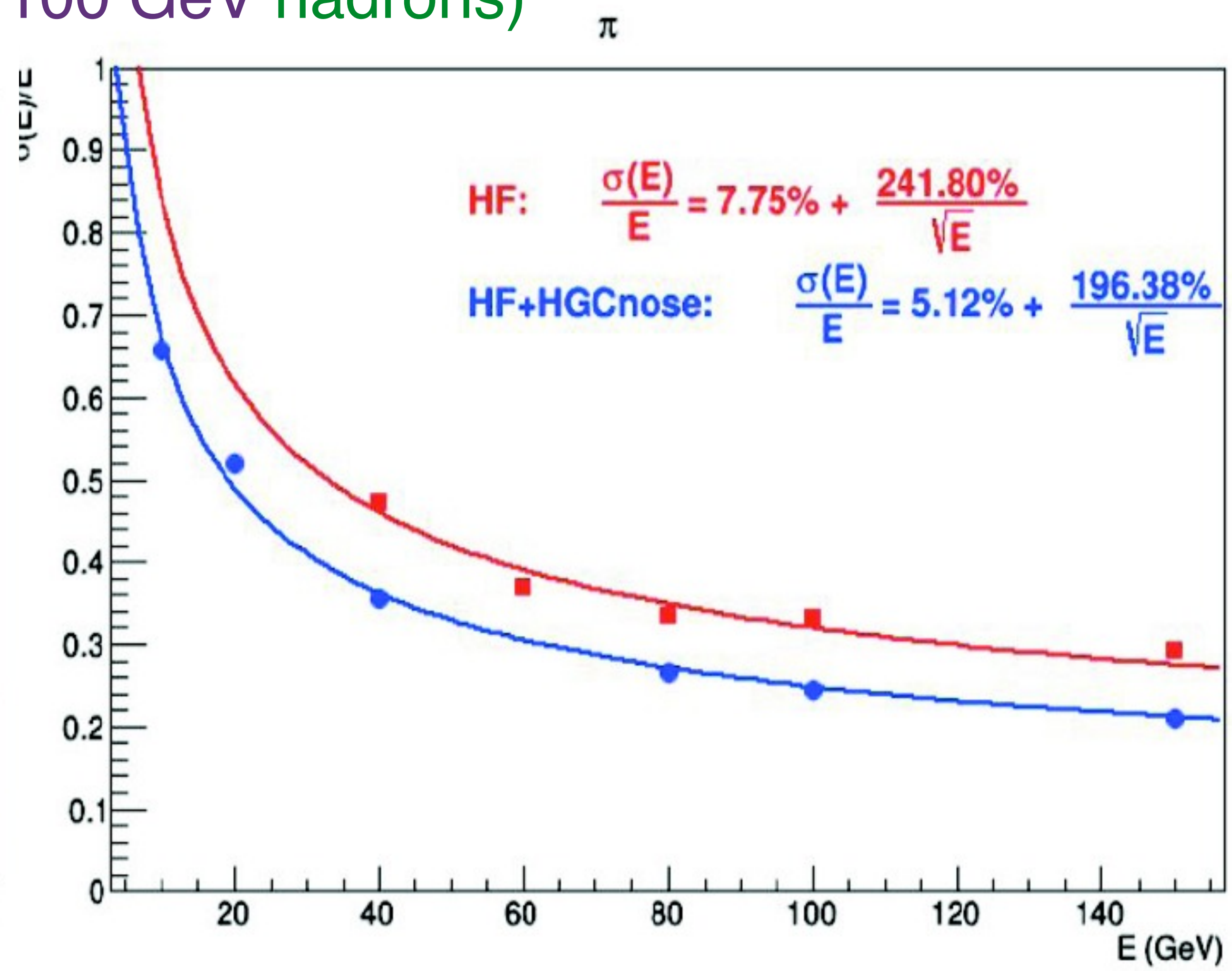
Performance

- The energy of an EM shower is measured from the first 6 layers
  - A photon of 100 GeV leaves most of its energy in layers 2 and 3
- Two layers of the hadronic section of about 1.7λ correspond to shower max
- All three sections CF-E + CF-H + HF are needed to measure hadron showers
- With software compensation, hadron energy resolution can be further improved (around 5% improvement for 100 GeV hadrons)





Outlook

- To extract meaningful physics during the HL-LHC period needs a major detector upgrade
  - Cope large particle density, use detectors with very good timing resolution for charged as well as neutral particles
  - Utilize detectors with larger radiation tolerance to provide signals with good S/N for the entire period of HL-LHC
  - Improve solid angle coverage to reach for physics which cannot be achieved with the current detector setup
- LHC detectors have taken up the challenge and are in the process of achieving this goal
  - As an illustration, the effort of CMS is given here. Similar efforts are going on in the other three experiments: ATLAS, ALICE and LHC-b

Additional Slides