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# HGCAL: a High-Granularity Calorimeter for the endcaps of CMS at HL-LHC

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ABSTRACT: Calorimetry at the High Luminosity LHC (HL-LHC) faces two enormous challenges, particularly in the forward direction: radiation tolerance and unprecedented in-time event pileup. To meet these challenges, the CMS experiment has decided to construct a High Granularity Calorimeter (HGCAL), featuring a previously unrealized transverse and longitudinal segmentation, for both electromagnetic and hadronic compartments. This will facilitate particle-flow-type calorimetry, where the fine structure of showers can be measured and used to enhance particle identification, energy resolution and pileup rejection. The majority of the HGCAL will be based on robust and cost-effective hexagonal silicon sensors with $\simeq 1\,\mathrm{cm}^2$ or $0.5\,\mathrm{cm}^2$ hexagonal cell size, with the final five interaction lengths of the hadronic compartment being based on highly segmented plastic scintillator with on-scintillator SiPM readout. We present an overview of the HGCAL project, including the motivation, engineering design, readout/trigger concept and simulated performance.

KEYWORDS: Calorimeter methods; Calorimeters; Particle identification methods; Radiation-hard detectors



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## Contents



## 1 Introduction

The High-Luminosity LHC [1] installation will happen starting from about 2024. The current schedule is given in figure 1 [1]. The CMS Collaboration [3] has proposed a highly granular new sampling calorimeter, HGCAL, to replace the present endcap calorimeters. The data taking conditions will be going well beyond current experience, and endcap regions will suffer high integrated doses/fluences up to 1 MGy and $10^{16}$ neutron/cm$^2$, as can be seen from figure 2 [2].

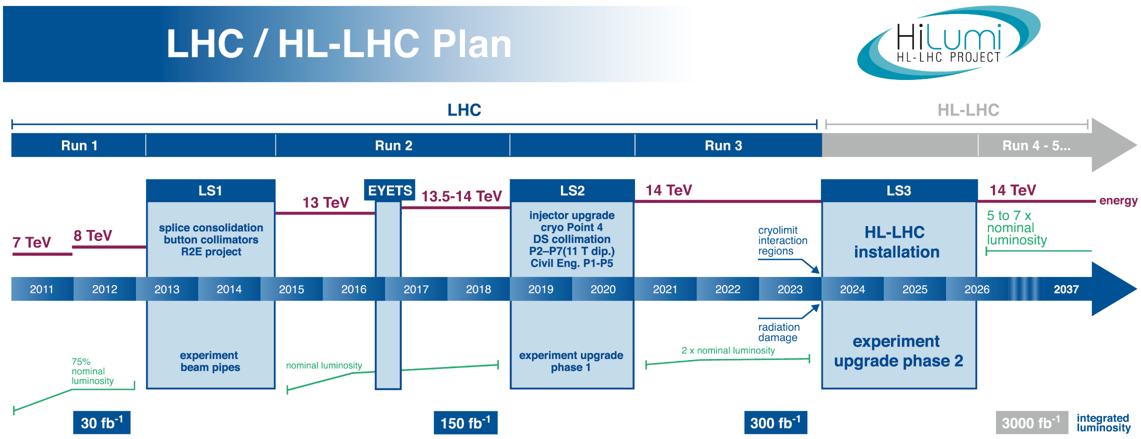


**Figure 1**. LHC schedule from current program to high-luminosity upgrade.

In the CMS Phase II Upgrade Technical Proposal [2] (UTP), the design is the following: an electromagnetic (EE) section made of 28 layers, followed by a forward-hadronic (FH) section made of 12 layers, and terminated by a backing hadron calorimeter (BH) made of 12 layers. The levels of radiation expected drive the choice of sensitive elements: radiation-hard silicon detectors for the first 40 layers (EE+FH), and scintillators for the BH. The absorber element is chosen such as to provide small Molière radius for electromagnetic showers in the EE, with tungsten, together with



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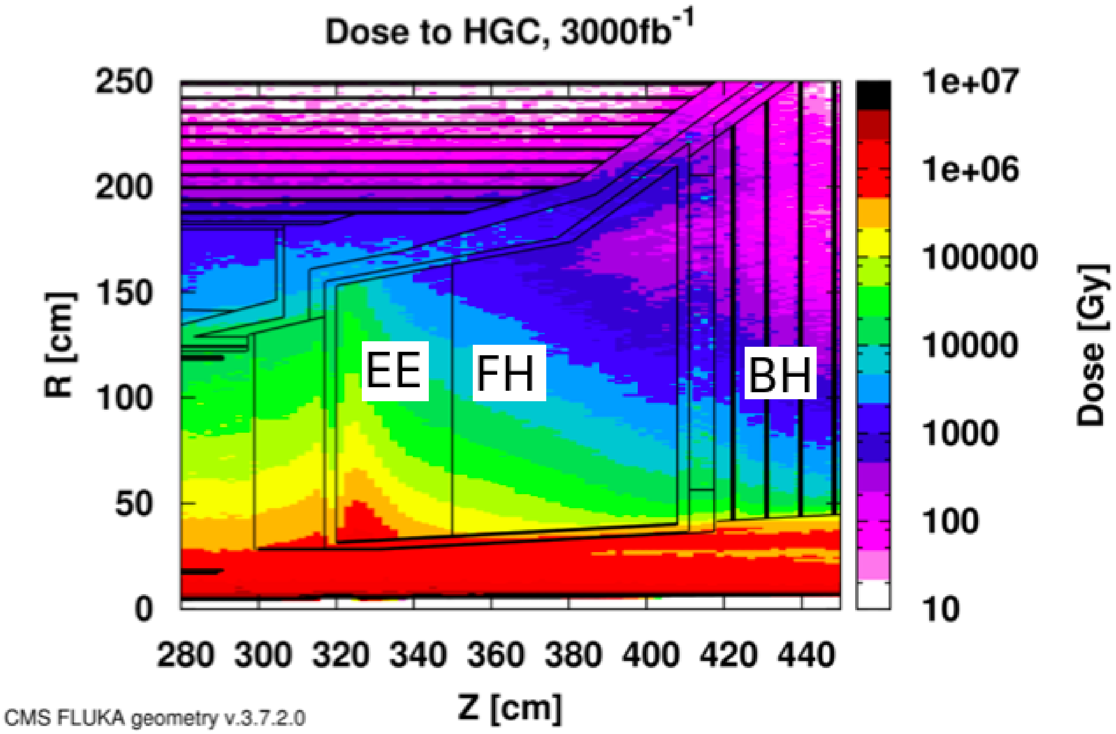


**Figure 2**. Integrated doses expected as a function of the distance to the collision point along the beam axis z, by the end of the high-luminosity LHC program (3000 fb$^{-1}$ of integrated luminosity).

copper to facilitate the cooling. The total length is about 26$X_0$ or 1.4$\lambda$. To mitigate silicon sensor radiation issues, the EE and FH will be operated at $-30$°C using bi-phase $CO_2$ cooling. For the FH and BH, the UTP proposed brass as absorber element, with lengths of respectively $\simeq 3.5$ and $\simeq 5\lambda$. Since the UTP, for cost and mechanical reasons the decision was made to use stainless steel instead, with equivalent total interaction lengths as described in the UTP.

More details on the mechanical design and readout electronics are given in section 2. The trigger requirements are detailed in section 3 followed by section 4 on the expected performance using Monte Carlo (MC) simulation.

## 2 Mechanical design and readout electronics

The baseline design described in the UTP presents a carbon-fiber alveolar structure with 30° cassettes inserted, taking existing expertise from the CALICE collaboration [4]. An alternative design has since been proposed with no alveolar structure, but self-supporting cassettes using lead as the main absorber material. The final choice is to be made by the end of 2016. The driving criteria are: (1) assembly and installation; (2) risk, reliability, maintainability; (3) physics output: impact of e.g. cracks, support cone; (4) mechanical behaviour and (5) cost.

Concerning the sensor layout, the levels of radiation expected constrain the thickness of fully-depleted silicon as shown in figure 3. To maximise the surface of silicon wafers in use (and hence reduce cost), a hexagonal wafer and cell design has been devised. The cassette on which the sensors are mounted have a layout as shown in figure 4 (left).

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| Thickness | 300 $\mu m$ | 200 $\mu m$ | 100 $\mu m$ |
|---|---|---|---|
| Maximum dose (Mrad) | 3 | 20 | 100 |
| Maximum n fluence ($cm^{-2}$) | $6 \times 10^{14}$ | $2.5 \times 10^{15}$ | $1 \times 10^{16}$ |
| 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 $fb^{-1}$ | 6.5 | 2.7 | 1.7 |

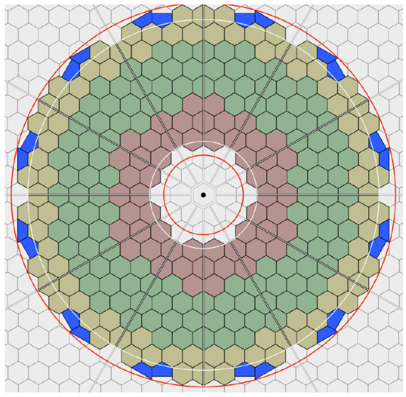

**Figure 3**. Summary of silicon thickness as a function of sensor position in the detector.

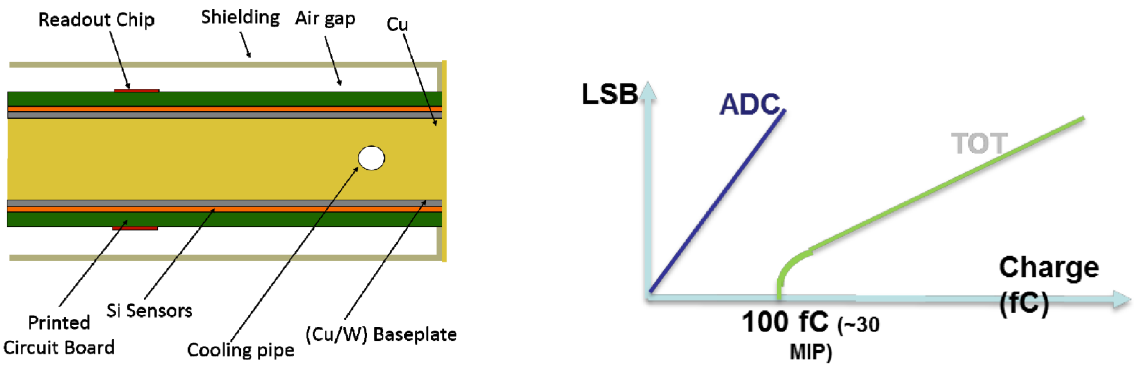


**Figure 4**. Left: cassette layout. Right: schematic view of the two different regimes of charge readout.

The front-end electronics have stringent requirements. The dynamic range should cover the 0.4 fC to 10 pC range (15 bits) in order to measure at the same time minimum ionising particles (MIP) and very energetic photon/electron or quark shower cores. A two-way charge readout system is proposed (figure 4 right), where the low charges (below 100 fC) are readout by 10-bit ADC, whilst the high charges are readout by Time-Over-Threshold (TOT) with 12-bit TDC. The noise must be kept at a level $< 2000\, e^-$ (0.32 fC) to keep the MIP visibility for thinner sensors after 3000 $fb^{-1}$ of integrated luminosity. It should have high radiation resistance (150 MRad, $10^{16}$ n/$cm^2$), and leakage current compensation. The wafer process chosen is the 130nm TSMC technology [5]. The power budget is constrained to $<$ 10 mW per channel. For the physics reach, it would be an asset to have timing information with 50 ps accuracy. The system should be on chip (digitization, processing), with high speed readout (>Gb/s), and large buffers to accommodate the 12.5 $\mu$s latency of the Level 1 trigger.

A strategy has been devised in order to obtain the final requirements in a timely manner. Starting from the CALICE “SKIROC2" chip [6], used in this year’s beam tests, a “SKIROC2-cms" chip has been designed in 0.35$\mu$m AMS technology [7] (non rad-hard) but modified to CMS needs: adding variable gain preamps, 25ns shapers, 40 MHz analogue memory, timing capabilities: ToA, ToT with $<$ 50 ps resolution, low/high gain and large dynamic range. The first version was received from the manufacturer in the summer 2016 and is being tested. In parallel 130 nm test vehicles are being prepared, with a first version received mid-september 2016, a second version (8 channels) to

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be submitted by the end of 2016 based on the results from the first one, and finally the objective to submit the first 64-channel ASIC with close-to-full functionalities by June 2017. After that, two more iterations are foreseen.

## 3 Trigger considerations

With the fine granularity, the occupancy is expected to be large. It is shown in figure 5, from minimum bias events simulated with a 200 pileup scenario, for two thresholds in the cell selection: 0.5 (left) and 5 (right) MIPs. Because of power consumption and cost arguments, the number of links that can be used to readout all channels are limited, and a choice has to be made to achieve the best physics. The compromise is between reducing longitudinal and/or transverse granularities. The current working hypothesis is to have trigger cells made of 4 channels, and read out every other layer in EE, and in all layers in FH. High threshold cuts will be necessary which means it will not be possible to have muon triggers. Efficiencies of single electron/photon and jet triggers have been

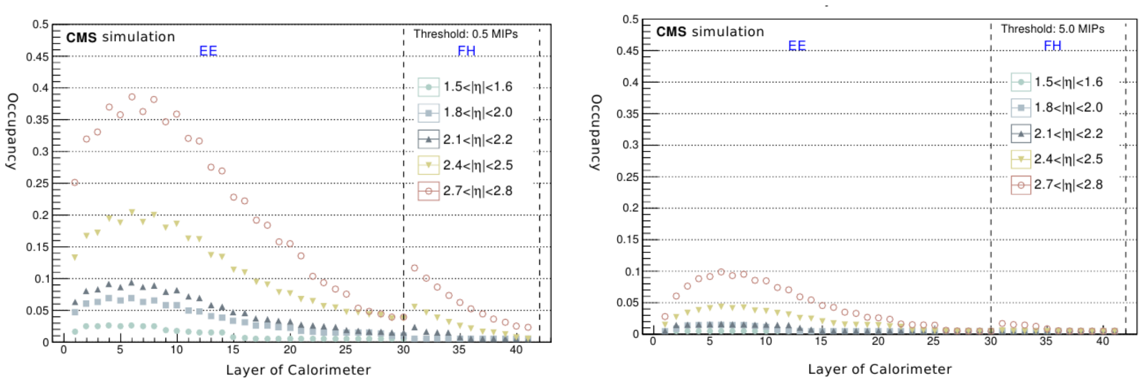


**Figure 5**. Expected occupancy as a function of layer number, for a 0.5 (left) and 5 (right) MIPs threshold, from minimum bias interactions with on average 200 pileup events.

studied in simulation. Within a factor of three and with the very preliminary design described in the UTP, the rates are under control comparing the current detector under 40 pileup with this upgrade under 140 pileup. Ultimately, tracks will be available at the level 1 of the trigger system (hardware level) and will improve further the performance.

## 4 Simulation and physics performance

The performance of the EE has been studied by characterising electromagnetic showers. The Molière radius is shown in figure 6 (left), which gives an indication of the transverse size of the shower. Having narrow showers will help particle separation as well as pileup rejection in the first layers, by minimising the area of the reconstructed object and hence the pileup contribution under it. A study has been made of the impact of in-time and out-of-time pileup on photon reconstructed energy resolution from Higgs boson decays. By using narrow shower and a very simple average pileup subtraction technique, the impact of pileup is largely mitigated. The jet energy resolution for electrons is shown in figure 6 (right) for the three different silicon thicknesses expected in the design. The stochastic term is around 20% with a constant term targetted to be $\simeq 1\%$.



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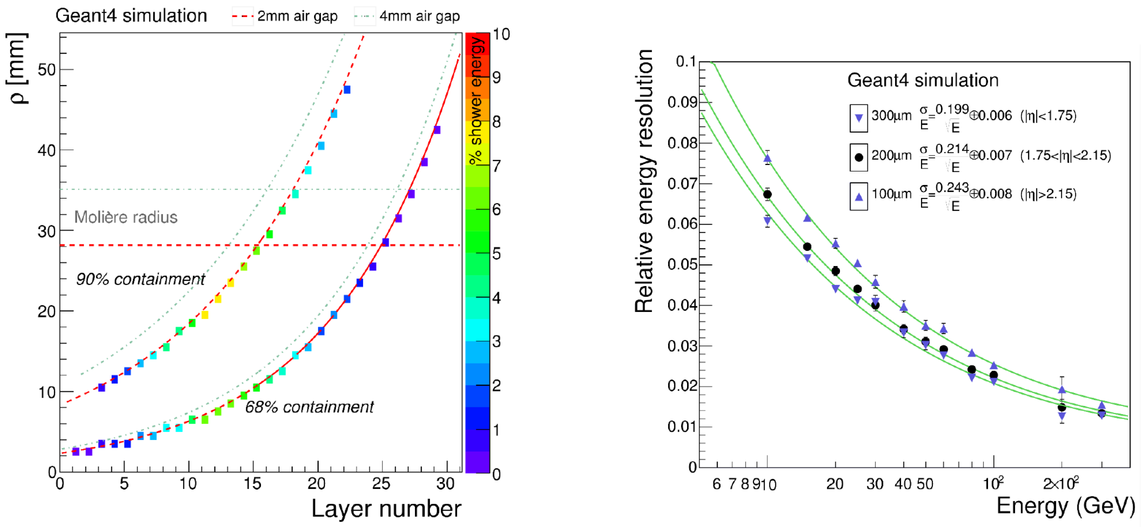


**Figure 6**. Molière radius (left) and energy resolution (right) for simulated electron showers.

The ultimate reconstruction for an imaging calorimeter such as the HGCAL will use a particle-flow approach [8]. A particle-flow algorithm classifies energy deposits into charged electromagnetic or hadronic components, photons, and neutral hadrons, in order to apply appropriate energy calibrations and improve on particle identification. With the high granularity of the HGCAL, many handles are available: the shower start, the longitudinal profile, a direction to constrain the primary vertex, possibility to apply layer-by-layer pileup rejection, and finally timing information. This is illustrated in figure 7. Despite the dense environment, clear structures are visible. Zooming in a region of interest, we can for example clearly identify MIP track segments prior to hadron showers, and clusters with directions pointing to the corresponding tracks or interaction point. The different colours are meant here to identify separate clusters, but of course the energy of each cell/cluster provides yet another handle to distinguish the hard scattering interaction from the minimum bias noise.

Preliminary criteria have been devised for electron identification, which allow to recover the run I performance in high pileup environment, as shown in figure 8 (left). With a far from optimal particle-flow algorithm, the run I performance is also recovered in terms of jet energy resolution, as shown in figure 8 (right).

## 5 Conclusion

A challenging detector is proposed to achieve the best physics performance for the high-luminosity upgrade of the endcap calorimeters of the CMS detector for HL-LHC. Building on previous years of R&D from the CALICE collaboration, a silicon-based sampling calorimeter with unprecedented granularity is studied in the high-pileup environment expected at the HL-LHC. The CMS Phase II Upgrade Technical Proposal was released in 2015, and the technical design report is expected by the end of 2017. Many decisions still have to be made on exact mechanical design, trigger architecture and final readout ASIC. In parallel, appropriate clustering and particle-flow algorithms are being developed to make the best out of the high granularity and possible timing information.



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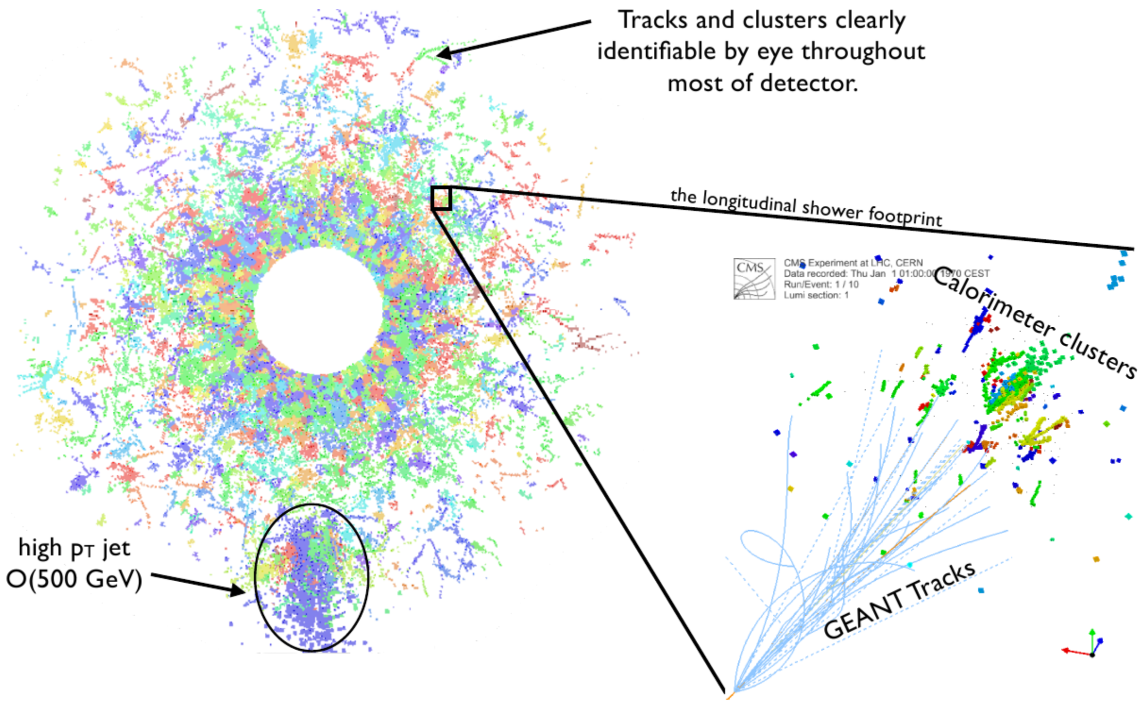


**Figure 7**. Event display of a simulated high $p_T$ jet in the HGCAL with 140 pileup overlayed. Courtesy of Lindsey Gray [9].

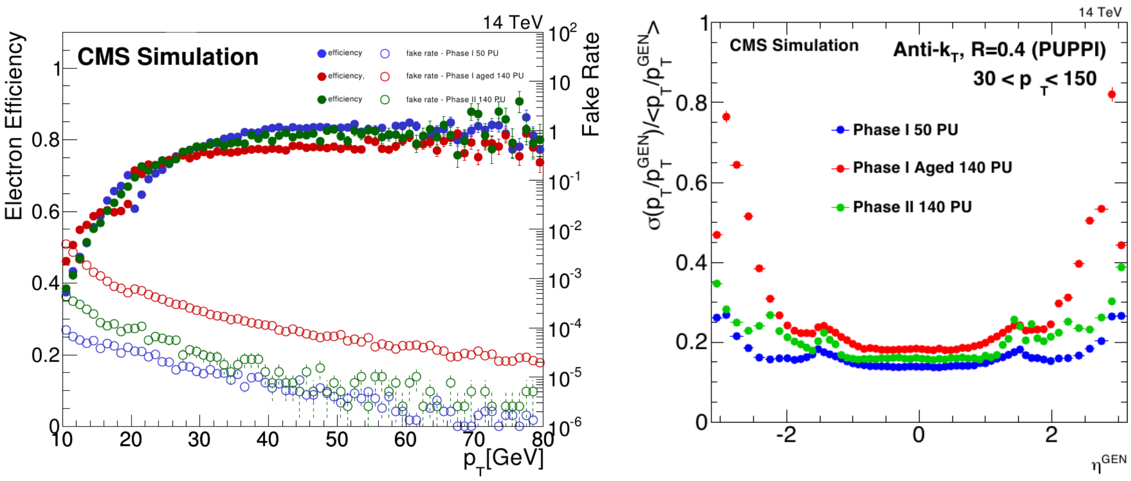


**Figure 8**. Electron identification efficiency and fake rate (left) and jet energy resolution (right) in the simulation comparing current detector with upgraded one in high pileup environment.

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