HE LONGITUDINAL STRUCTURE OPTIMISATION

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The planned upgrades of the LHC are designed to allow experiments for data taking at instantaneous luminosities around or above $5 \cdot 10^{34}$ cm$^{-2} \cdot$ s^{-1} some time after year 2020, to eventually reach an integrated luminosity of 3000 fb^{-1} at the end of that decade. Existing estimates of irradiation dose in the endcap of hadron calorimeter at shower maximum in 20 years of operation vary from 600 Rad at pseudorapidity 1.5 up to 30 MRad at pseudorapidity 3.0. The irradiation dose reduces light yield from scintillators. In order to compensate for the radiation damage of the scintillators by re-weighting technique, the calorimeter must be split in several longitudinal depths. The aim of this study is to optimise the longitudinal structure of the CMS hadron endcap calorimeter to compensate for the light yield loss.

1. INTRODUCTION

After the upgrade of the CERN accelerator complex the LHC is expected to deliver an instantaneous luminosity of at least $5 \cdot 10^{34}$ cm$^{-2} \times$ $\times$ s^{-1} [1]. The quoted luminosity corresponds to approximately 100 pileup events per bunch crossing at the operating frequency of 40 MHz. With such a scenario, CMS will eventually collect up to 3000 fb^{-1} [1] of integrated luminosity after several years of operation, so its hadron calorimeter (HCAL [2]) have to be improved in terms of radiation damage resistance and the Level-1 trigger performance.

The radiation damage of scintillator reduces its light yield (darkening effect). In order to compensate for the radiation damage the calorimeter must be divided longitudinally and instrumented with new low-noise photo detectors (SiPMs [3]) and readout electronics. The aim of this study is to optimise longitudinal structure (depths) of the HCAL end cap (HE) for the simple correction of light yield loss in each depth via the signal re-weighting. HE longitudinal structure optimisation is a compromise between:

- signal uniformity along depths;
- energy resolution degradation with radiation damage;
- number of readouts;
- SiPMs leakage current;

• longitudinal isolation of electron and photon shower;

• possibility to use it in modern methods of data analysis (PFA [4], weighting [5],...).

The last point is not a subject of this study.

2. SIMULATION DETAILS

CMSSW_4_2_8_SLHChcal version of the CMSSW simulation and reconstruction software is used for this study. Several important updates are added on top of this base version. Now these updates are included in the most recent Upgrade options of the CMSSW:

— scintillator darkening as a function of its position and integrated luminosity;

— improved Upgrade geometry;

— updated QIE10 chip simulation;

— adjusted 2TS reconstruction for HB/HE.

For the pileup simulation (pp collisions per each beam crossing every 25 ns) 14 TeV Minimum Bias events are simulated and their GEANT hits are stored. Then for every simulated signal event, some number (according to the defined mean Poissonian number) of Minimum Bias events are read and their hits are mixed with the signal event ones. Finally mixed events (signal + pileup) get digitized and reconstructed.

3. ENERGY RESOLUTION DEGRADATION WITH RADIATION DAMAGE

With the design luminosity after 10 years of LHC operation, CMS will collected 500 fb^{-1} of integrated luminosity. Figure 1 shows corresponding irradiation dose contours in HCAL from paper [2]. One can see that HE radiation dose varies from a hundred of Rads up to MRads. For the 3000 fb^{-1} the radiation dose will be increased approximately by a factor

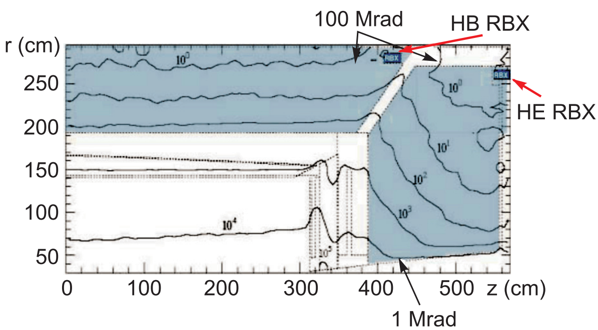

Fig. 1. Radiation level contour for CMS from FLUKA calculations after 500 fb^{-1} (units of Gray)

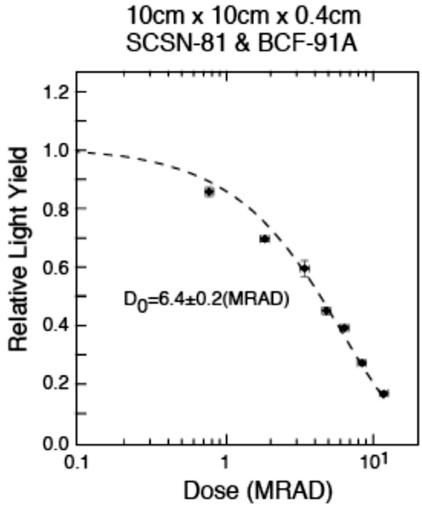

Fig. 2. Scintillator darkening as a function of ionization radiation dose

of six. At the MRads dose level HE suffers from a significant degradation of the light yield from scintillators, as shown in Fig. 2 from paper [1].

The corresponding HE scintillator light yield loss as a function of the scintillator layer and the distance from the beam pipe center is shown in Fig. 3 for several integrated luminosities. Figure 3 suggests that the

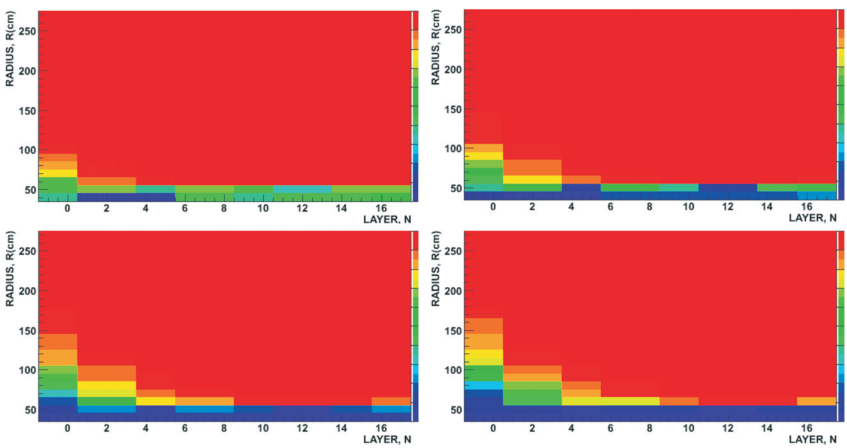

Fig. 3. HE scintillator light yield as a function of sincillator layer number and the distance (cm) from the center of the beam pipe for four integrated luminosities: 500 fb^{-1} (top left), 1000 fb^{-1} (top right), 2000 fb^{-1} (bottom left), 3000 fb^{-1} (bottom right)

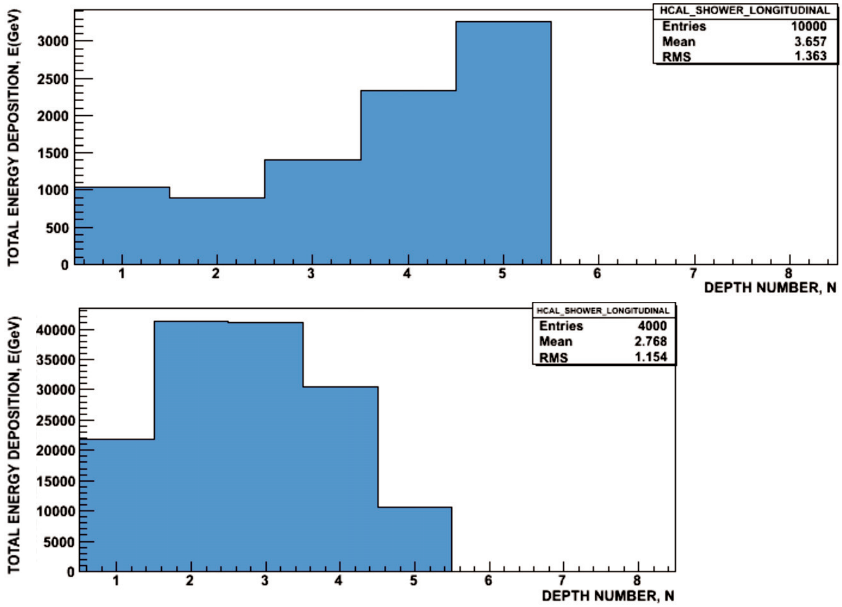

Fig. 4. Energy deposition for the HE structure $1 + 2 + 3 + 5 + 7$ for muons (top) and pions (bottom) of 300 GeV

longitudinal structure needs some optimisation for the radiation damage compensation. One can see that the most critical regions are the ones close to the beam pipe and HE front close to the CMS interactive point. Due to the hadron shower maximum position and light yield loss, the longitudinal structure $1 + 2 + 3 + 5 + 7$ a priori looks as a reasonable choice. The longitudinal energy deposition profile for this structure is shown in Fig. 4 for muons (top) and pions (bottom).

In this plot muon energy deposition is proportional to the sum of scintillator thicknesses in each depth. In the proposed structure last two depths ($5 + 7$ layers) serve primarily for collecting the energy from extended hadron showers. For the shower maximum position there is quite good longitudinal uniformity.

In order to compensate for the radiation damage of the scintillators, HCAL will be equipped with SiPMs instead of HPDs. SiPMs have a high gain and operate at much lower voltages than HPD. Muon signal with HPDs and SiPMs is shown in Fig. 5. One can see that the signal to noise ratio for SiPMs is more than ten times higher than for HPD.

In order to understand SiPMs readout noise influence on the hadron energy resolution, different HE longitudinal structures were considered in 2007 Test Beam and it was found that the readout noise doesn't really affect the hadron resolution (see Fig. 6).

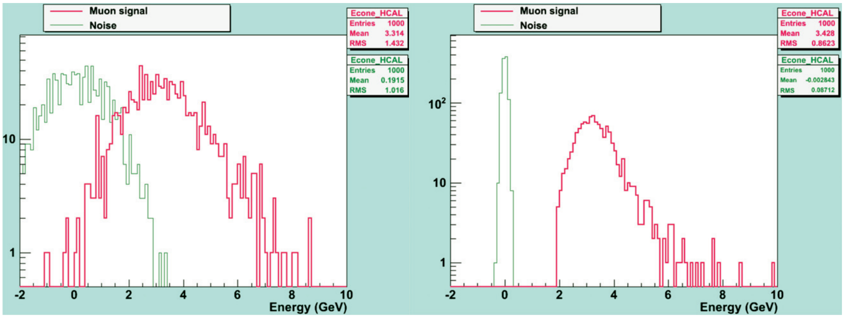

Fig. 5. Reconstructed muon signal in HE with HPDs (left) and SiPMs (right). 3×3 HE towers matrix is used

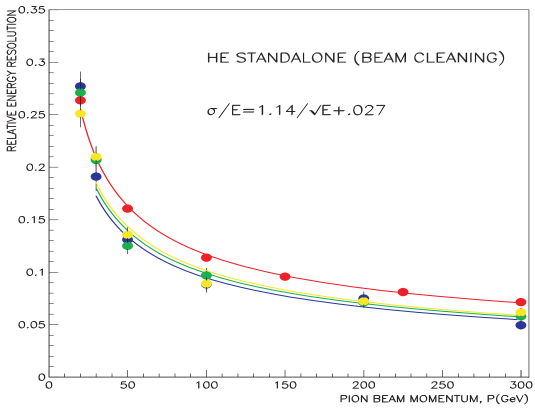

Fig. 6. HE standalone energy resolution for pions. Red line denotes the Test Beam 2007 results for HPDs $5 + 12$ option; yellow line — SiPMs $1 + 2 + 3 + 5 + 7$ option; green line — SiPMs $5 + 13$ option; blue line — SiPMs with a single readout for the entire HE tower

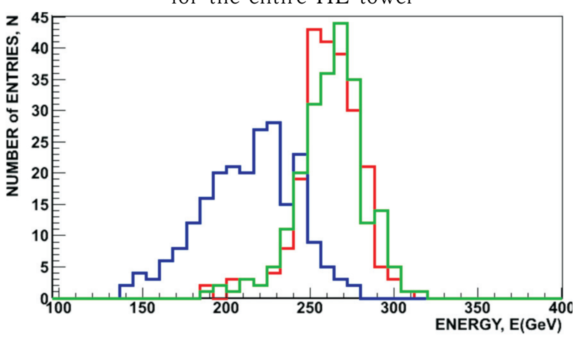

Fig. 7. HE standalone energy resolution for 300 GeV pions at $\eta = 2.4$. Red line stands for 0.1 fb^{-1} integrated luminosity; blue line — for 3000 fb^{-1} without correction; green line — for 3000 fb^{-1} with individual depth corrections applied

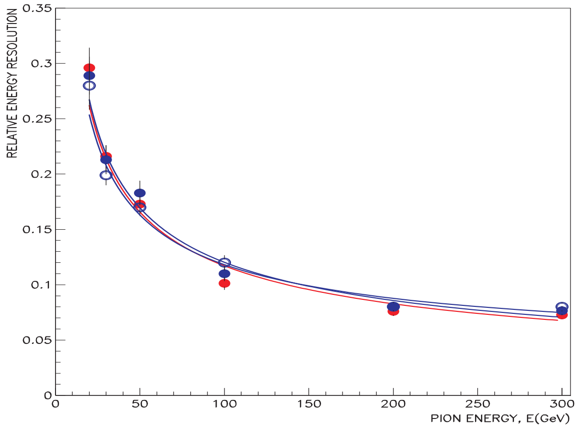

Fig. 8. HE standalone energy resolution for pions with $1+2+3+5+7$ longitudinal structure. Red line denotes 0.1 fb^{-1} integrated luminosity; blue line — 3000 fb^{-1} with corrections; open circles — 3000 fb^{-1} with corrections but with $1+4+13$ structure

In order to understand a radiation damage influence on the hadron energy resolution, various HE regions and different HE longitudinal structures are analysed and assuming various integrated luminosities (see Figs. 6–8).

The main conclusions are the following:

• HE longitudinal structure with individual depth weights is able to compensate for the radiation damage for $|\eta| < 2.5$ up to 3000 fb^{-1} integrated luminosity.

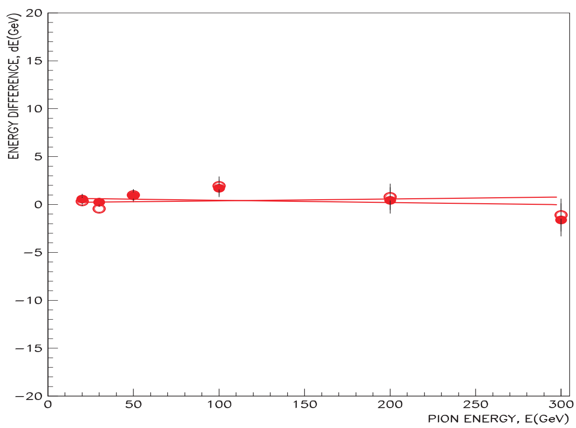

Fig. 9. Systematic shift of pion energy resolution with corrections for 3000 fb^{-1} integrated luminosity with respect to the 0.1 fb^{-1} option. Filled circles denote $1+2+3+5+7$ longitudinal structure, open circles — $1+4+13$ one

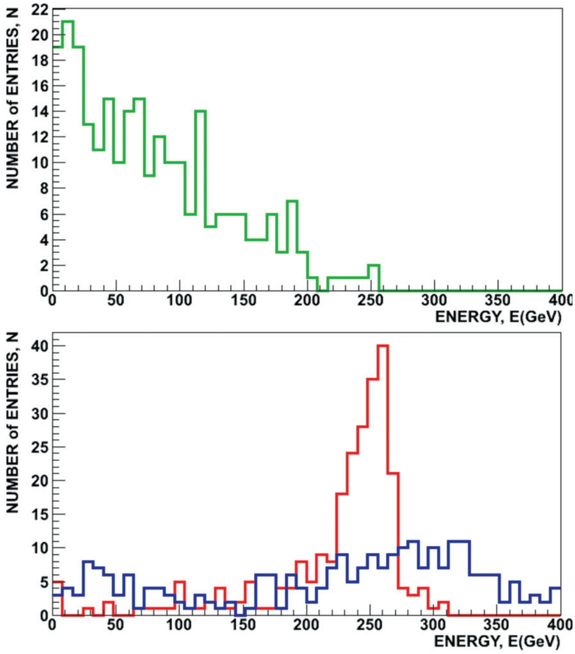

Fig. 10. HE standalone energy resolution for 300 GeV pions at $|\eta| = 2.75$. Top plot shows a distribution for 3000 fb^{-1} integrated luminosity without corrections. In the bottom plot the red line denotes 0.1 fb^{-1}; blue line — 3000 fb^{-1} with corrections

• For $|\eta| > 2.5$ the situation is more complicated (see Fig. 9). The problem is due to a significant readout signal degradation (see Fig. 10) at 3000 fb^{-1} integrated luminosity.

An example of the weights of readout signals $(1+2+3+5+7)$ for 3000 fb^{-1} integrated luminosity are presented in table. One can see that an appropriate solution (for example, [6]) is yet to be found for the left bottom corner where the weights are extremely big and ineffective.

The weights for readout signals for 3000 fb^{-1} integrated luminosity

iη	depth				
	1	2	3	4	5
22	1.265	1.054	1.028	1.005	1.003
23	1.338	1.069	1.037	1.008	1.000
24	1.703	1.128	1.059	1.007	1.007
25	2.738	1.292	1.150	1.030	1.003
26	4.757	1.473	1.241	1.044	1.007
27	4.759	4.030	2.149	1.233	1.025
28	14.261	9.969	3.441	1.873	1.457
29	118.834	200.977	22.722		

4. ENERGY RESOLUTION DEGRADATION WITH RADIATION DAMAGE AND NEUTRON FLUX

For the HE readout box region (see Fig. 1) the integrated dose of neutrons with $E > 100$ keV varies from $0.65 \cdot 10^{11}$ n/cm^2 up to $1.77 \times \times 10^{11}$ n/cm^2 [7]. Due to a significant dose, there are two negative effects on the energy resolution: (i) degradation of the signal and (ii) readout

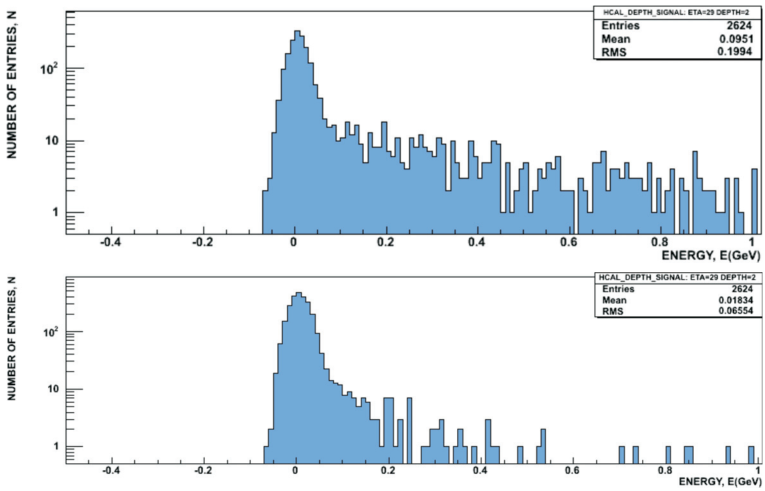

Fig. 11. Inclusive energy spectrum of reconstructed hits for pions of 300 GeV at $i\eta = 29$ and the depth 2 for 0.1 fb^{-1} integrated luminosity (bottom) and 3000 fb^{-1} (top)

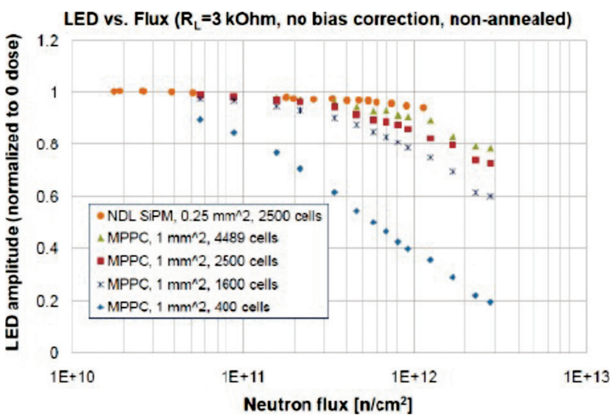

Fig. 12. LED peak value as a function of neutron flux

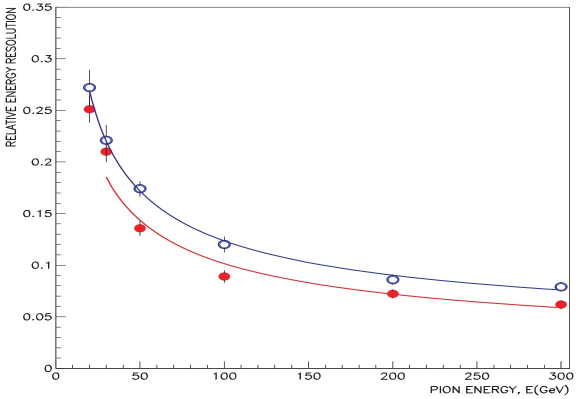

Fig. 13. Pion energy resolution degradation due to noise increase at $i\eta = 23$. Red line denotes 30 MeV noise case, blue line — 210 GeV noise one

noise increase (Fig. 11). Figure 12 from [3] demonstrates the signal amplitude degradation as a function of the neutron flux for several types of SiPMs. The most promising type of SiPMs for our purposes is denoted by triangles. For the expected doses the amplitude degradation is quite small, but the readout noise is increased by a factor of seven from initial 30 MeV to 210 GeV. Figure 13 demonstrates the pion energy resolution for the noise of 30 MeV and of 210 MeV. One can see that the neutron dose in HE readout box region ($\approx 10^{11}$ n/cm^2) for the 3000 fb^{-1} integrated luminosity doesn't dramatically degrade the resolution.

5. LONGITUDINAL ISOLATION OF ELECTROMAGNETIC SHOWERS

One of the most important uses of the HCAL energy in the trigger is for the isolation of electron and photon showers. As an example, Fig. 14 demonstrates 300 GeV electron shower leakage to HE.

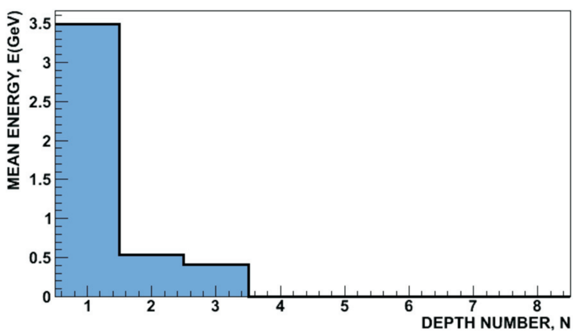

Fig. 14. HE mean reconstructed energy as a function of depth number for 300 GeV electron shower and $1 + 2 + 3 + 5 + 7$ longitudinal structure

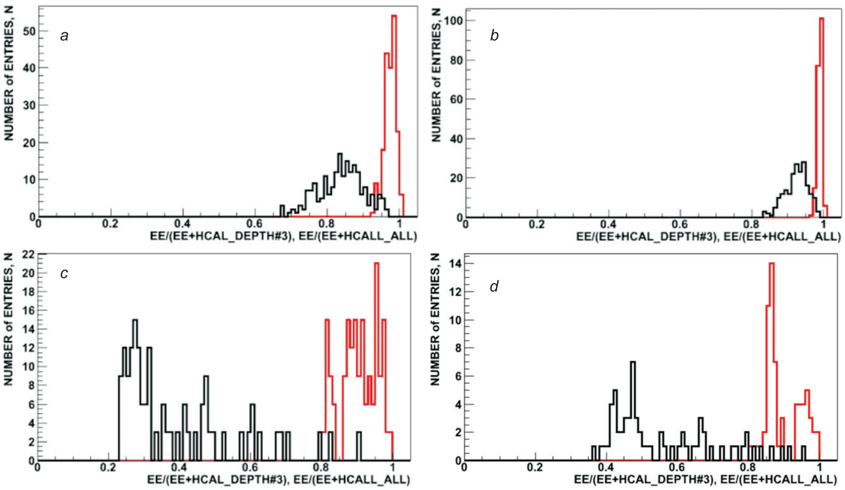

Fig. 15. Distribution of the ratio ECAL/(ECAL + HE) energy (black line) and ECAL energy to ECAL+HE energy from depth number 3 (red line) for mean pileup 50 (a, b) and 200 (c, d) and electron energy 200 GeV (a, c) and 500 GeV (b, d)

We suggest to use energy deposition in the depth 3 (or 4) for electron leakage triggering. Electron isolation capability will be critical for the integrated luminosity around 3000 fb^{-1} with the pileup number of ~ 100 on average.

Figure 15 shows distributions of a ratio of ECAL energy to the sum of ECAL+HE energy in case of full HE (black line) and in case HE energy sum starts from the depth 3 (red line) and for two pileup options: 50 (upper plots) and 200 (lower plots) and for two electron energies: 200 GeV (left two plots) and 500 GeV (right two plots).

CONCLUSIONS

HE longitudinal structure $1 + 2 + 3 + 5 + 7$ (or $1 + 2 + 3 + 12$) provides:

- uniform longitudinal signal distribution;
- no visible degradation of the pion energy resolution up to 3000 fb^{-1} integrated luminosity in $|\eta| < 2.5$;
- tiles, fibers and electronics for the (depth, iη) = (1.26–29)/(2.27–29)/(3.28–29) have to be modified for the 3000 fb^{-1} integrated luminosity;
- neutron dose in HE RBX region ($\approx 10^{11}$ n/cm^2) for the 3000 fb^{-1} integrated luminosity doesn't dramatically degrade hadron energy resolution;

• Signal from the depth 3 can be used for effective electromagnetic shower isolation cut at high pileup.

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