IMPROVEMENT OF JET ENERGY RESOLUTION FOR SEGMENTED HCAL USING LAYER WEIGHTING TECHNIQUE

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The future upgrade of CMS hadron calorimeter (HCAL) foresees increasing the number of longitudinal readout channels. It was shown that the longitudinal segmentation accompanied by the dedicated readout weighting method allows the essential improvement of the jet energy resolution.

1. INTRODUCTION

In CMS jets are reconstructed with the three main methods, which differently combine individual contributions from sub-detectors to form the inputs to the jet clustering algorithm: calorimeter jets, Jet Plus Track (JPT) jets and Particle Flow (PF) jets [1].

The future upgrade of CMS hadron calorimeter (HCAL) foresees the increasing longitudinal number of readout channels. Such new segmentation accompanied by the dedicated readout weighting method allows the essential improvement of the calorimeter jets energy resolution. In this paper H1-style software weighting method (π^0-weighting) [2] is considered for the purpose of improvement the jet energy resolution.

2. READOUT WEIGHTING TECHNIQUES

Energy resolution of non-compensated hadron calorimeters is affected by the different response of the calorimeters to the π^0 and non-π^0 components of the hadron shower. The electromagnetic (π^0) component of hadron showers is large ~ 30–60%, it increases with energy and has a big and non-Poissonian fluctuations (see, for example, Fig. 1 taken from [3]).

Electromagnetic showers from π^0 component produce large and localized energy deposits in the calorimeters as illustrated in Fig. 2 ([3]).

This feature (local deposition of high density energy) in segmented hadron calorimeter is used in the different readout weighting methods in order to reduce response of π^0 component and make it closer to the response of non-π^0 component. Such software methods can essentially improve both the energy resolution and linearity of the calorimeter [4].

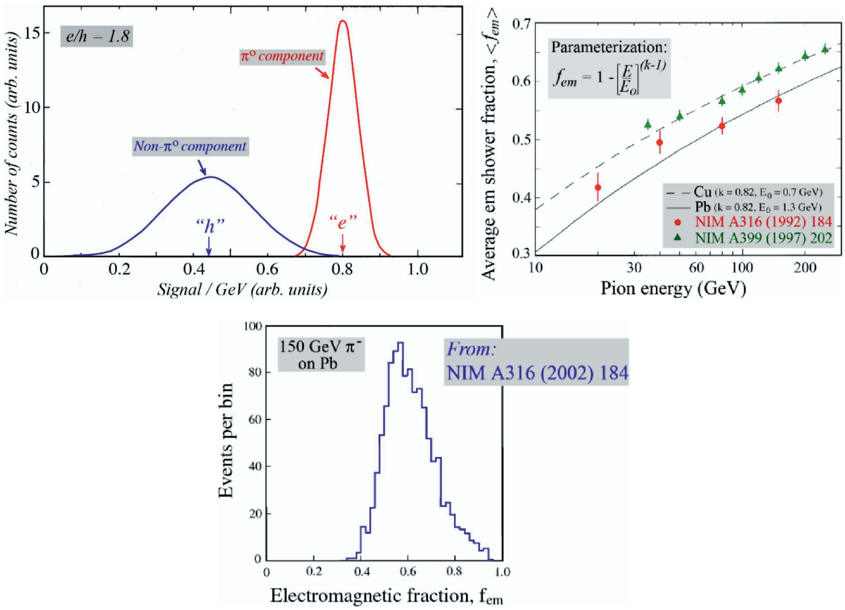

Fig. 1. Response of non-compensated calorimeter to hadronic ("*h*") and electromagnetic ("*e*") components of hadron showers and dependence of the average electromagnetic shower fraction on the energy of primary pions — two top figures. Distribution of electromagnetic component of hadron shower — bottom figure [3]

In our investigation we used π^0-weighting method which was developed in H1-collaboration [2] for fine segmented Pb–Cu liquid argon calorimeter.

CMS hadron calorimeter is a sampling calorimeter consisting of brass absorber layers (with different thickness for barrel and endcap parts) and 3.7-mm-thick scintillator layers. The additional 9-mm-thick scintillator layer (zero-layer) is located between ECAL and HCAL to sample hadronic showers developing in the dead material between these calorimeters.

Using this structure of CMS calorimeter system and supposing that the readout from each individual layer of hadron calorimeter is available, the following expression is used for the primary pion and jet energy reconstruction:

$$E_{\rm rec} = a \cdot E_{\rm ECAL} + \sum_{i=1}^{\rm layers} H_i^{\rm weighted} + c \cdot E_{\rm zero}, \qquad (1)$$

where $E_{\rm ECAL}$ is the deposited energy in electromagnetic calorimeter, $E_{\rm zero}$ — deposited energy in the zero layer and $H_i^{\rm weighted}$ is the weighted energy in each layer of hadron calorimeter. The weighted

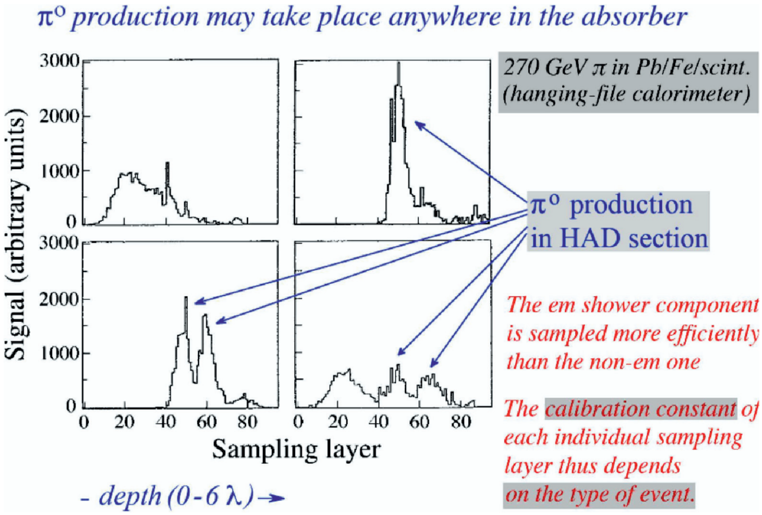

Fig. 2. Local energy deposits of high density for sampling calorimeter as consequence of π^0 production in different parts of non-compensated calorimeter [3]

layer energy H_i^{weighted} is determined by the next formula (similar to H1-weighting method) with non-weighted layer energy H_i in expression:

$$H_i^{\text{weighted}} = b_1 \cdot H_i + b_2 \cdot H_i \cdot \exp\left(-b_3 \cdot H_i\right). \tag{2}$$

The calibration constants a, b_1, b_2, b_3, c are determined for each energy of primary pion or jet by the minimizing of χ^2 from the following expression:

$$\chi^2 = \sum_{\text{events}} (E_{\text{rec}} - E_{\text{gen}})^2, \tag{3}$$

where E_{gen} is generated energy of pions or jets. And afterwards all these calibration constants are applied to determine the reconstructed energy of pions or jets. We will call this procedure "π^0-weighting" reconstruction method.

In what follows we will always compare the π^0-weighting method with the "standard" ("E + bH") reconstruction procedure, which is determined as

$$E_{\text{rec}} = E_{\text{ECAL}} + b \cdot E_{\text{HCAL}}, \tag{4}$$

where E_{ECAL} and E_{HCAL} are deposited energies in ECAL and HCAL active volumes respectively, E_{HCAL} includes also energy in zero layer. A calibration coefficient b for HCAL is determined (and fixed afterwards) for pions with 50 GeV energy and the condition that the deposited energy in ECAL corresponds to MIP (minimum ionising particle).

3. PERFORMANCE FOR SINGLE PIONS WITH STANDALONE GEOMETRY

Preliminary checking of this π^0-weighting method was performed on the base of simple GEANT4 standalone simulation program which included description of CMS ECAL and HCAL calorimeters with some dead material between. The geometrical description reproduces in general the structure of the CMS calorimeters (Hadron Endcap calorimeter with 17 sensitive layers and zero layer between ECAL and HCAL). This standalone program is used for simulation in CMS Forward Calorimetry Task Force group [5]. Such kind of simplified simulation program can provide the first and quick estimation of the calorimeter response and the different reconstruction techniques. Figure 3 shows example of two different types of events simulated with this standalone program for incident pions with the primary interaction in ECAL or HCAL calorimeter volume.

Dependence of the energy resolution $\Delta E/E$ (RMS of the distribution $(E_{\rm rec} - E_{\rm gen})/E_{\rm gen}$) obtained with the π^0-weighting method and comparison on the "standard" reconstruction procedure is presented

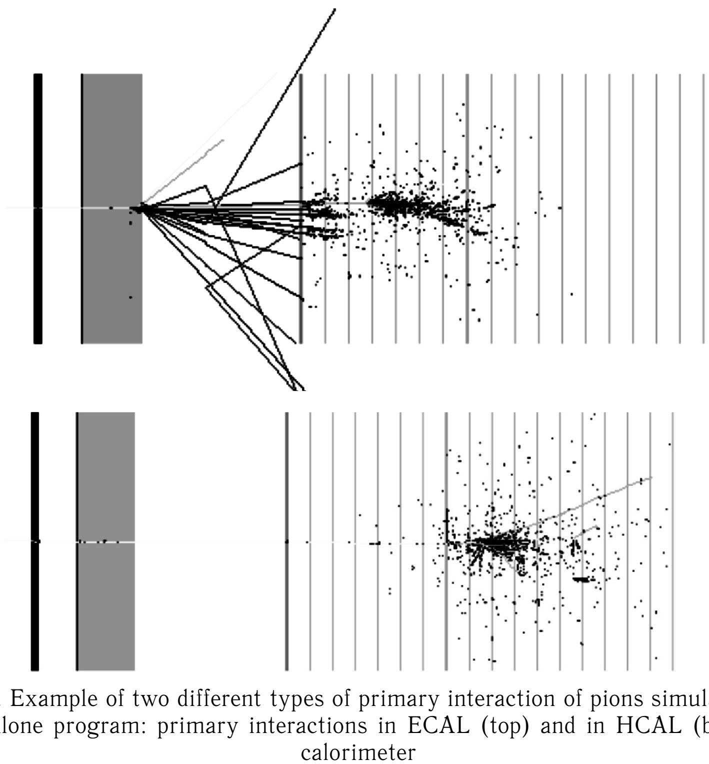

Fig. 3. Example of two different types of primary interaction of pions simulated by standalone program: primary interactions in ECAL (top) and in HCAL (bottom) calorimeter

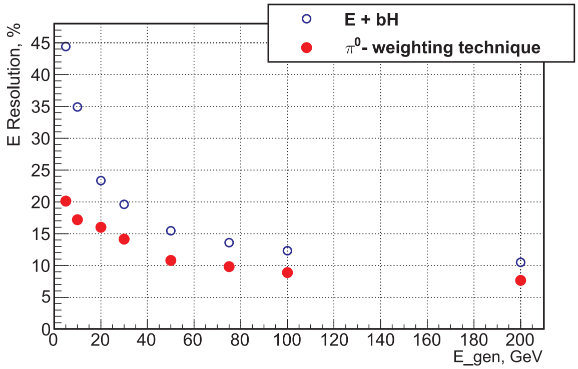

Fig. 4. Energy resolution as a function of incident pion energy for two different reconstruction procedures: open circles — for the “standard” and closed circles for the π^0-weighting technique

in Fig. 4. The big improvement in the energy resolution is clearly observed for the π^0-weighting reconstruction method in the full simulated pion energy range.

4. PERFORMANCE FOR SINGLE PIONS WITH CMSSW GEOMETRY

The Full Simulation Package CMSSW is used for checking the possibility to apply this π^0-weighting reconstruction method for the real CMS calorimeter geometry. As the present CMSSW package doesn’t simulate a separate readout for each layer of hadron calorimeter, the modification which can provide this information is introduced in CMSSW. The deposited energies in active volume of ECAL and in scintillator of HCAL layers provided by GEANT4 are considered as the response of calorimeters.

The deposited energy in ECAL and HCAL calorimeters inside cone with $R = 0.7$ $(R = \sqrt{(\Delta\eta^2 + \Delta\varphi^2)})$ around direction of incident pions are collected for reconstruction procedures. The value of pseudorapidity $\eta = 0.65$ and φ-angle range $-\pi \leqslant \varphi \leqslant \pi$ for direction of the primary pions are chosen in this simulation. Figure 5 shows the distribution of reconstructed energy for 10 GeV pions obtained with the two different reconstruction procedures (“standard” and π^0-weighting). The π^0-weighting method demonstrates essential improvement of both the quality (shape is close to Gaussian distribution) and quantity (decreasing RMS of distribution) of reconstructed pion energy.

The energy resolution obtained with π^0-weighting reconstruction method is summarized in Table 1 and presented in Fig. 6 as a function of primary pion energy. The same results for the “standard” reconstruction procedure are added for comparison. As for the standalone simulation

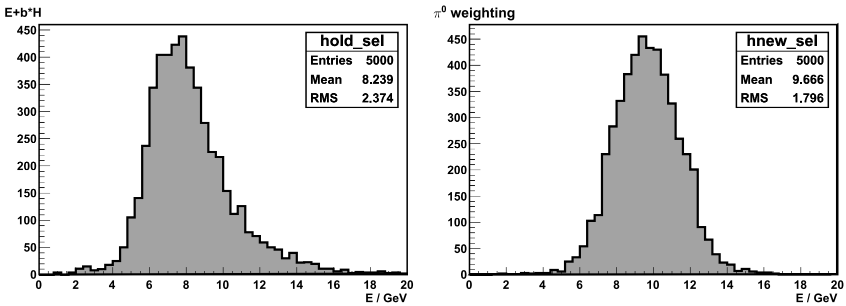

Fig. 5. Distribution of reconstructed energy for 10 GeV pions simulated with CMSSW program and reconstructed by two different reconstruction procedures: “standard” and π^0-weighting methods

Table 1. Energy resolution $\Delta E/E$ (%) as a function of incident pion energy for two different reconstruction procedures (“$E + bH$” and π^0-weighting) determined from CMSSW simulation

E_{gen}	5 GeV	10 GeV	20 GeV	30 GeV	50 GeV	75 GeV	100 GeV
$E + b \cdot H$	36.68	28.81	21.71	18.41	16.27	15.04	13.67
π^0-weighting	23.25	18.58	15.17	12.97	11.03	10.33	9.54

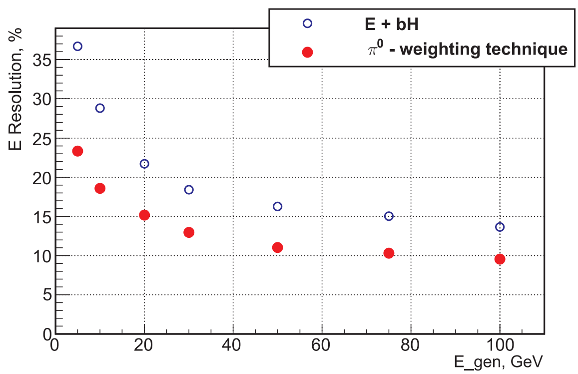

Fig. 6. Energy resolution as a function of incident pion energy for two different reconstruction procedures (“standard” and π^0-weighting) with CMSSW full simulation

case, an essential improvement of the energy resolution is also observed for the CMSSW simulation.

5. PERFORMANCE FOR JETS WITH CMSSW GEOMETRY

One of the most important characteristics of different jet reconstruction algorithms is the jet energy resolution. So, the advantage of the π^0-weighting reconstruction technique should be firstly demonstrated on jet energy resolution.

Using the modified CMSSW with separate readout from each hadron calorimeter layer gluon-jets are generated and simulated. The primary jets were generated with the pseudorapidity $\eta = 0.65$ and inside φ-range $-\pi \leqslant \varphi \leqslant \pi$. The deposited energies in ECAL and HCAL calorimeters inside a cone with $R = 0.7$ around primary jet-direction are collected for jet energy reconstruction.

The calibration coefficients a, b_1, b_2, b_3, c for jet energy reconstruction with π^0-weighting method are determined separately for each jet p_T with the same procedure given by expressions (1)–(3). For the "standard" ("$E + bH$") jet energy reconstruction the same calibration coefficient b obtained for 50 GeV pions is used.

Figure 7 shows the jet p_T resolution $\Delta p_T / p_T$ (sigma of the distribution $(p_T^{\rm reco} - p_T^{\rm gen})/p_T^{\rm gen}$) for two different reconstruction procedures: "standard" and π^0-weighting methods (jet energy correction factor is applied for "standard" reconstruction). The clear improvement in jet p_T reconstruction is observed both for RMS of distribution and for the sigma from Gaussian fit.

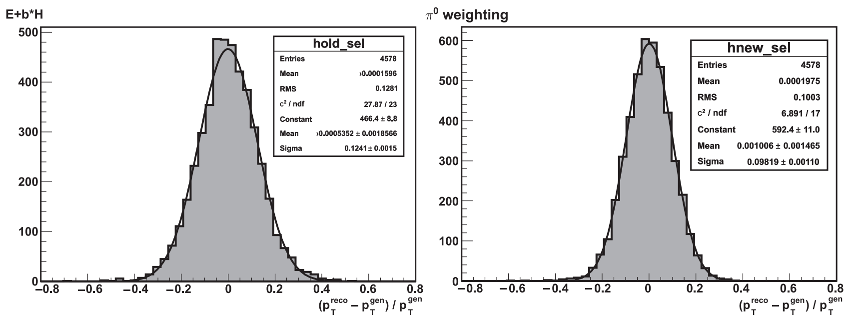

Fig. 7. p_T resolution distribution for jets with $p_T^{\rm gen} = 50$ GeV for two different reconstruction procedures: "standard" (left) and π^0-weighting (right) methods

Table 2. p_T resolution of jets $\Delta p_T / p_T (\%)$ as a function of generated jet $p_T^{\rm gen}$ for the "standard" and π^0-weighting reconstruction procedures

jet $p_T^{\rm gen}$	10 GeV	20 GeV	30 GeV	50 GeV	75 GeV	100 GeV
$E + b \cdot H$	29.37	19.97	15.81	12.41	10.27	9.06
π^0-weighting	25.86	16.36	12.84	9.82	8.12	7.06

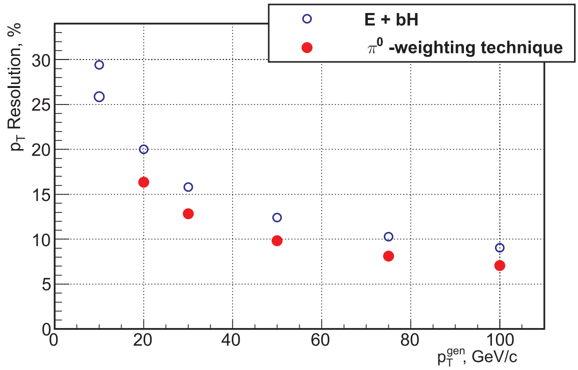

Fig. 8. Jet p_T resolution as a function of generated jet $p_T^{\rm gen}$ for two different reconstruction procedures: "standard" and π^0-weighting methods

The results of jet p_T resolution for the different $p_T^{\rm gen}$ of generated jets are summarized in Table 2 and shown in Fig. 8. The sigma of distributions is used for determination of jet p_T resolution. As was observed for single pion simulation, the π^0-weighting technique of jet p_T reconstruction demonstrates essential improvement of p_T resolution $\sim$25–30% in the broad 10–100 GeV p_T range.

6. SUMMARY

The "π^0-weighting" reconstruction technique used for segmented HCAL improves jet energy resolution by $\sim$25–30% for jets in the range 10–100 GeV.

This improvement still has to be verified with the realistic simulation of readout electronics, thresholds and with pileup simulation, taking into account radiation damage for High Lumi-LHC.

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