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Influence of beam content composition on testbeam studies of hadron calorimeters

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Abstract.
Hadron calorimeters are one of the most important detectors in the contemporary nuclear and particle physics experiments. Their construction and verification process takes years in designing, testing and data analysis of prototypes. Crucial step for the prototypes are tests performed by exposing the detectors to charge particle beams. Here we study the impact of the different beam content composition to one of the main properties of the hadron calorimeters – their energy resolution. We implement a test detector - Metal Hadronic Calorimeter (MACA) in GEANT4 environment and we perform different simulations to study the influence to the main energy resolution parameters.

1. Introduction

In the construction of hadronic calorimeters, the main verification stage is their response in tests with a beam of charged particles. The typical beam modes in test halls are electron mode and hadron mode. The hadron mode is using secondary hadrons, which are produced from the striking of 400 GeV protons at a beryllium target. This secondary beam is composed mostly of protons and pions with a small fraction of kaons. A description of such a hadron beam is given by the Atherton parametrization [1]:

$$\frac{d^2N}{dpd\Omega} = A\left[\frac{(B+1)}{p_0}\left(\frac{p}{p_0}\right)^B\right]\left[\frac{2Cp^2}{2\pi}e^{-C(p\theta)^2}\right] \quad (1)$$

$$\frac{d^2N}{dpd\Omega} = A\left[\frac{B}{p_0}e^{-B\frac{p}{p_0}}\right]\left[\frac{2Cp^2}{2\pi}e^{-C(p\theta)^2}\right]. \quad (2)$$

Here (1) is for protons and (2) is for charged pions and kaons. The values of the parameters A, B and C for the different particles is given in Table 1.

We used the patemetrization to re-compute the ratio between the three different particles constituting the beam and to use the values for our studies.

The resulting values are given in Fig. 1.

As can be seen, for energies less than ~ 100 GeV, the pions are the main components in such a beam, while for energies higher than 200 GeV, the beam composition is dominated by protons.

The kaons have almost neglectable contribution for energies higher than 100 GeV.

Table 1. Atherton parameters

Particle	A	B	C
p	0.8	-0.6	3.5
π^+	1.2	9.5	5.0
K^+	0.16	8.5	3.0

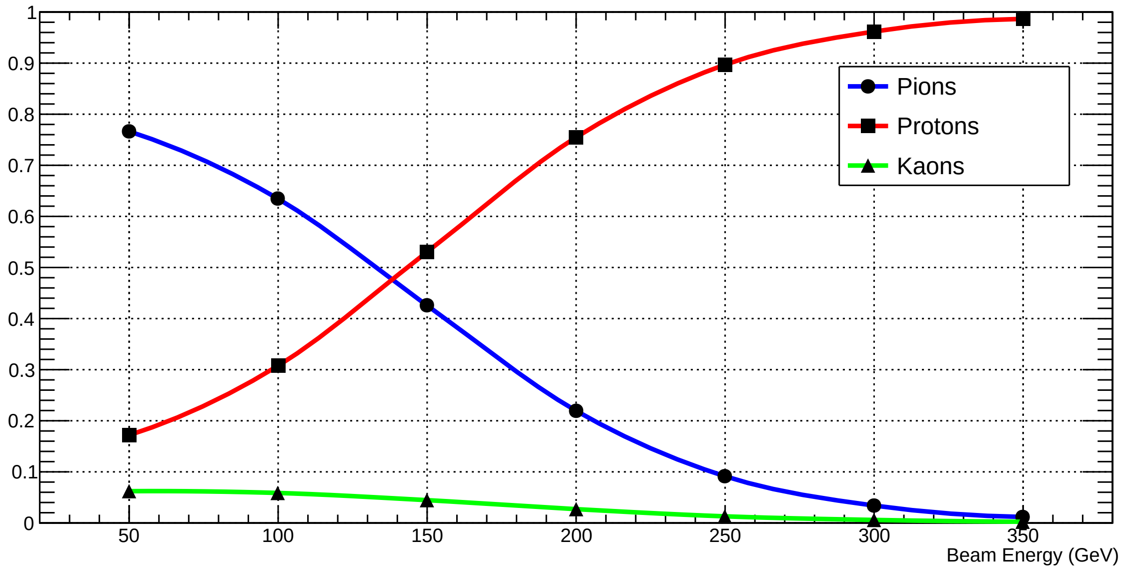

Figure 1. Beam constituents ratio given for different energy using the Atherton parametrization. For the low energies the pions are dominating, while for the higher energies, mostly protons are reaching the detector volume.

2. Design of MACA

For the purpose of study the beam content composition influence on hadron calorimeters a dedicated simulations were performed. We implemented a sandwich type calorimeter using Geant4 software package [2]. The detector consists of passive absorber and plastic scintilator square plates placed one after another with a thin layer of paper between each of them. For the absorber material we used Cu as well as W, while for the scintilator, the plates are made of polystyrene. The total length of the detector is 1m, while the cross section of each plate is 25 mm $\times$ 25 mm. Several different plate widths were used to study the properties of the detector.

The numbers of plates used in the simulation is 100. We kept the total width of one scintilator plate and one absorber plate to be 10mm.

An example image from the simulations is given in Fig. 2.

We tested several different ratios between the widths of the materials, but here we present only the ones for which the contained shower in the detector volume has deposited energy distribution that could be described.

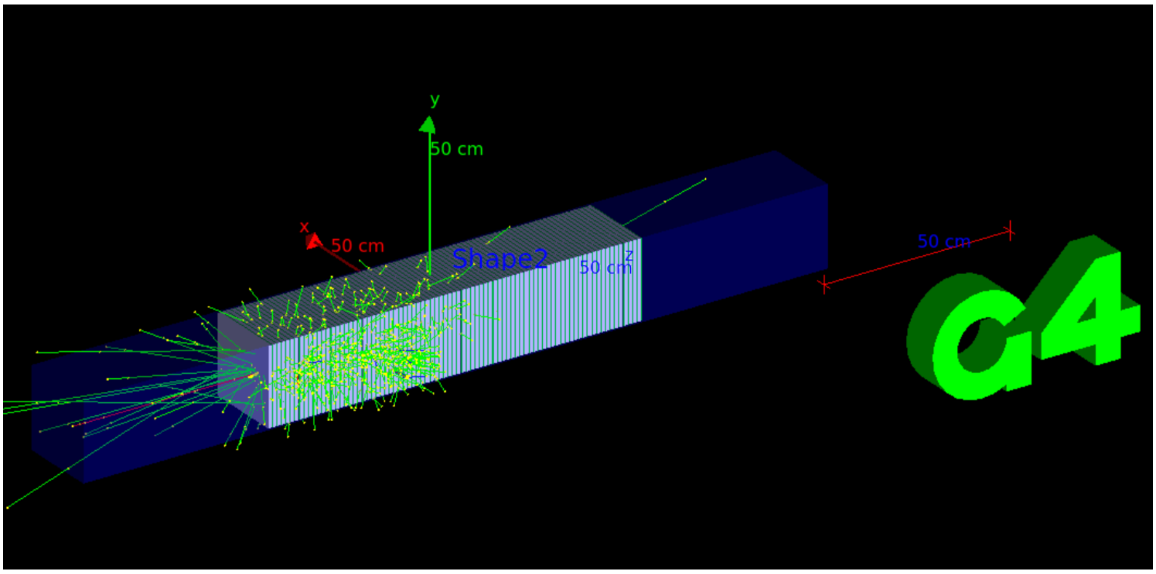

Figure 2. Illustration of a particle starting a shower inside the MACA volume. The simulation is performed using the GEANT4 toolkit.

3. Energy resolution

A dedicated analysis tool was developed based on ROOT[3] libraries. A reconstruction module is used to study the output signals from the performed simulations. Simulations with pions (Π^+) protons and Kaons (K^+) were generated for beam energies 50, 100, 150, 200, 250, 300, 350 GeV.

The physics list that we used was FTFP_BERT. Each of the simulated data files is stored in a ROOT format and is analysed at a further step.

A distribution of the total energy deposited in the detector for different beam energies is given in Fig. 3.

The distribution of the deposited energy in the detector volume differs for pions and protons, as can be seen in 4.

To not mislead the reader, the difference with the kaons is not presented here, as their contribution is quite small. However, since all three particles are part of the beam composition, the proper description of it requires their joint examination.

To achieve this, the separate distributions resulting from the simulations of the individual particles are summed with weights using the estimated values in Fig. 1.

An example of resulting distribution for 100 GeV energy of the beam is given in Fig. 4.

For each beam energy the resulting distributions are fitted using a gaussian function. The fit was done with the following steps - first a gaussian is applied to the whole range of the distribution to estimate the mean position of the peak. Then a second gaussian is used in the range 2σ from the mean for more precise description.

We use the resulting mean values of this second gaussian function to study the linear response of MACA.

For ratios scintilator to absorber (Cu) 3:7 and 1:4, the dependence on the mean of the deposited energy to the beam energy is given in Fig.

The values of the second gaussian function are used as initial parameters of a method to calculate the FWHM of the distribution. In this way we secure a proper description in not so fit-dependant way.

From the applied method we take the σ_E and E_{mean} values to compute the energy resolution

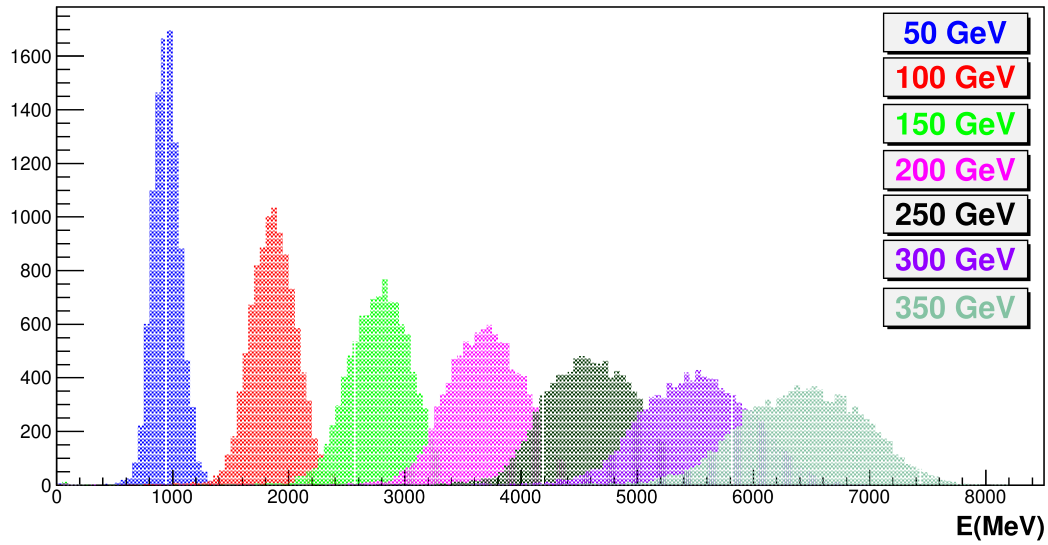

Figure 3. Distribution of the total deposited energy in the calorimeter for given beam energy in the range 50 - 350 GeV.

of MACA.

The energy resolution was fit using Eq. 3. Here σ and E are given in GeV, while the other parameters are without units. With $\oplus$ is noted a quadratic sum. The first term includes the stochastic shower fluctuations, the second term is taking into account the electronic noise of the readout chain and the last one is the constant term, which represents detector design limitations. The noise term is 0.

$$\frac{\sigma_E}{E} = \frac{a_{\text{stoch.}}}{\sqrt{E}} \oplus \frac{b_{\text{noise}}}{E} \oplus c_{\text{const.}} \tag{3}$$

In Fig. 6 is given the estimated resolution for a configuration with 2mm scintilator plates and 8 mm Cu plates. The presented results are from three different cases - using only pions, only protons and in a mix configuration with pions, protons and kaons. At low energies the trend of the mixed fit function is closer to the pion's fit, while for the higher ones it is covering the protons'.

This result has impact to the way a simulations should be performed in order to describe data from test beam experiments using beamlines with secondary hadrons. The observed differences in the detector resolution are occuring not only in the values of the $\sigma(E)/E$, but also to the stochastic and the free term in Eq. 3.

The resulting values of these terms for the performed simulations with different ratios of absorber and sctintilator widths are given in Table 2.

4. Conclusions

The hadronic calorimeters are important part of the contemporary particle physics. In their validation process, a milestone are tests performed with secondary hadrons produced from accelerated primary particles, usually protons. The proper description of the collected data relies on precise Monte-Carlo simulations. We used simulations to study the response of a hadronic calorimeter in three cases of incoming particles - only protons, only pions, and a mixture of pions, protons and kaons, according to a realistic expectations in test beam experiments. The tested modes gave differences in the estimated energy resolution parameters of the hadronic

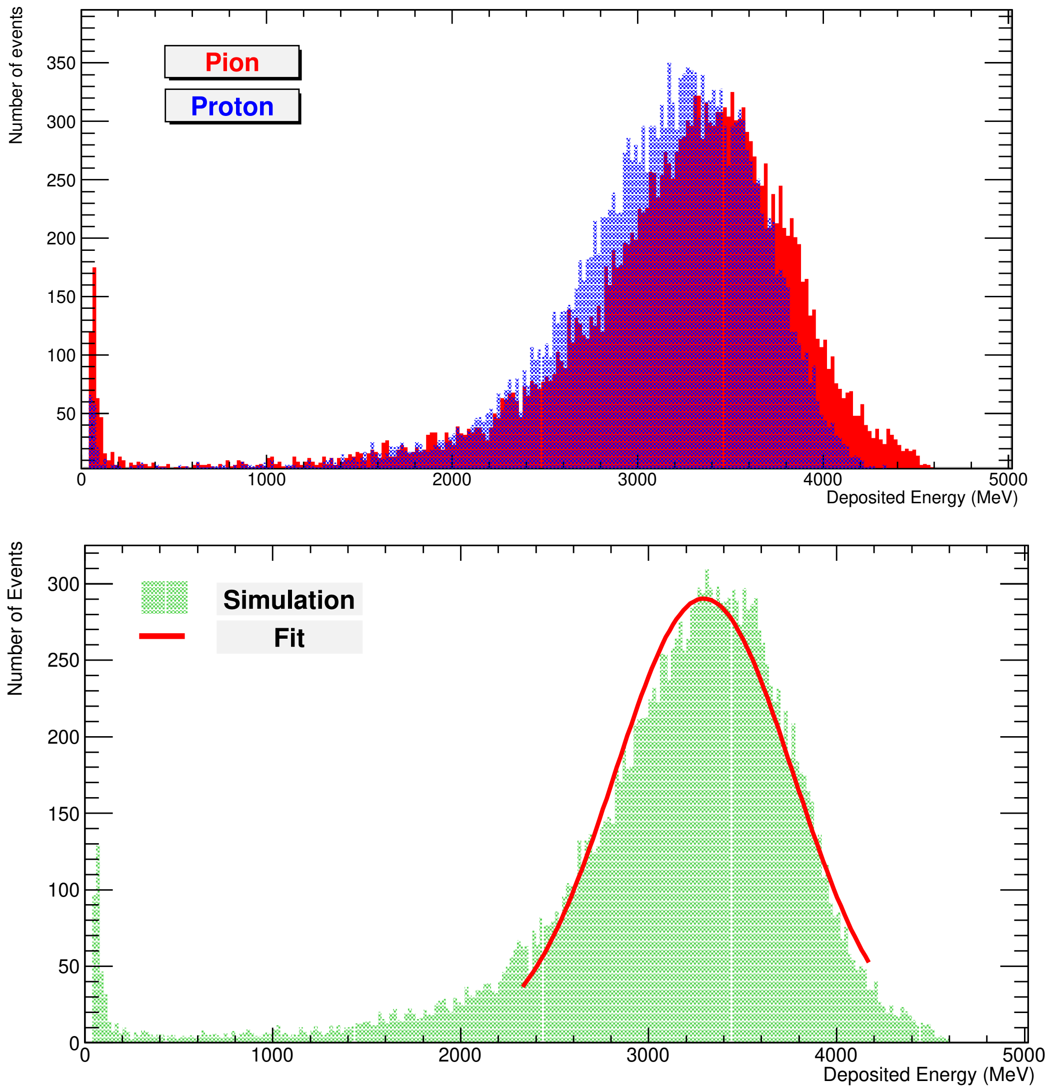

Figure 4. Distribution of the deposited energy. The distribution differs for pions and protons **(top)** and a method for summation was implemented. The resulting distribution **(bottom)** was then fitted using a gaussian function. For both plots the simulations were performed with 100 GeV beam energy.

calorimeter and showed that the proper simulation of the beam constituents is crucial for the detector validation process.

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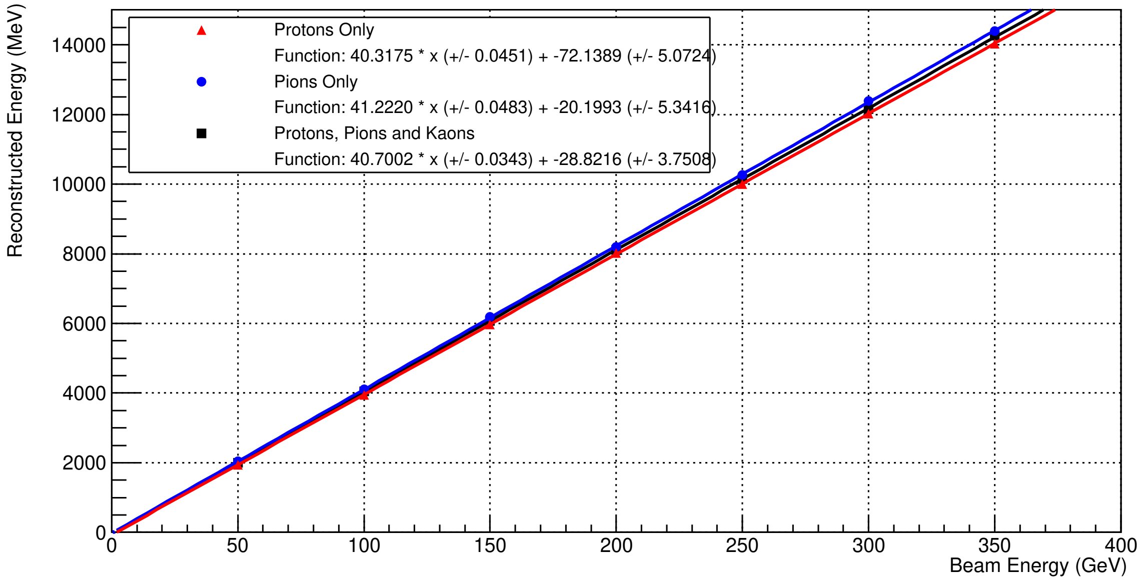

Figure 5. Reconstructed deposited energy for 50 - 350 GeV hadrons. The dependence is fitted with linear function. A difference is visible for energies higher than 200 GeV.

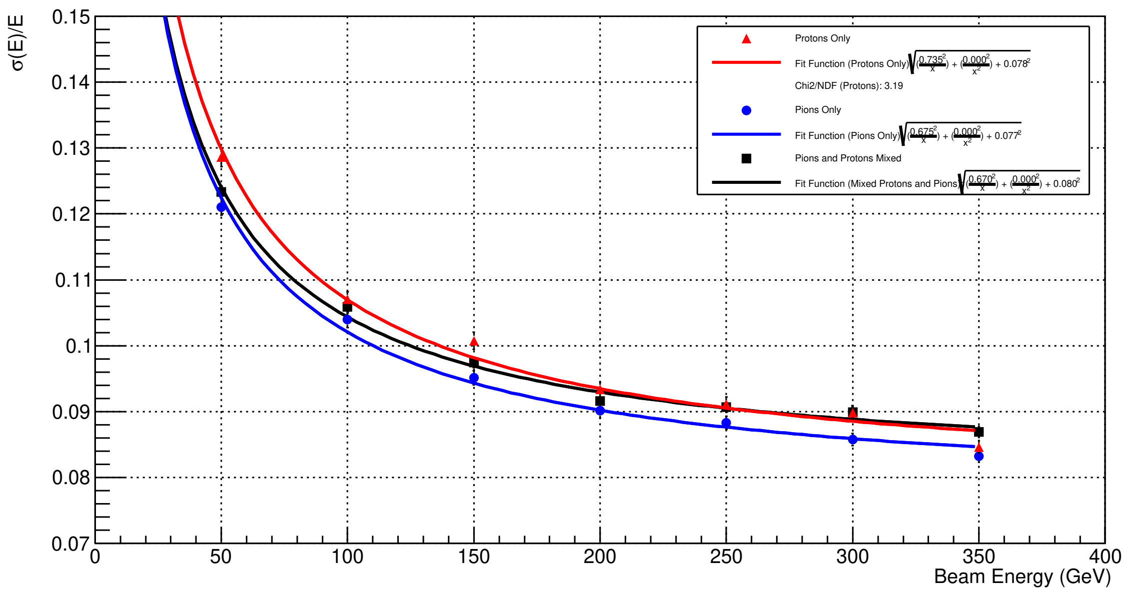

Figure 6. Energy resolution of MACA for hadron energies 50 - 350 GeV.

Table 2. Stochastic and constant terms estimated for different beam compositions. The resulting values are studied for different widths of the absorber and scintillator plates.

Scintilator (mm)	Absorber (mm)	Absorber material	Particle	a	c
2	8	Cu	proton	0.735	0.078
2	8	Cu	pion	0.675	0.077
2	8	Cu	pions, protons and kaons	0.670	0.080
3	7	Cu	proton	0.597	0.136
3	7	Cu	pion	0.517	0.146
3	7	Cu	pions, protons and kaons	0.609	0.140
2	8	W	proton	0.735	0.078
2	8	W	pion	0.675	0.077
2	8	W	pions, protons and kaons	0.670	0.080
5	5	W	proton	0.619	0.082
5	5	W	pion	0.488	0.080
5	5	W	pions, protons and kaons	0.212	0.090

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