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ELECTROMAGNETIC SHOWER PROFILE IN LEAD-GLASS CALORIMETER IN THE ENERGY RANGE OF 3–23 GEV

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Abstract

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Measurements of the electromagnetic shower profile in lead glass calorimeter at the energies of 3, 9 and 23 GeV were made. The method of obtaining shower profile did not require the use of high precision coordinate detectors. Influence of a passive material in front of the calorimeter on the shower profile was studied. A program to simulate Čerenkov light in lead glass was developed. Shower profiles from the experimental data and Monter-Carlo simulations were parameterized with a 2-dimensional function and were found to be in a good agreement. Obtained results allow us to speed up the analysis of the experimental data.

Аннотация

Бланд Л.К., Матуленко Ю.А., Мочалов В.В. и др. Профиль электромагнитного ливня в калориметре из свинцового стекла в диапазоне энергий 3–23 ГэВ: Препринт ИФВЭ 2005–46. – Протвино, 2005. – 13 с., 9 рис., 1 табл., библиогр.: 6.

Были проведены измерения профилей электромагнитных ливней в калориметре из свинцового стекла при облучении пучком электронов с энергией 3; 9 и 23 ГэВ для двух конфигураций: при наличии пассивного вещества перед калориметром и без. Использовался метод получения профиля ливня без применения прецизионных координатных детекторов. Предложена параметризация профиля с помощью двумерной функции с двумя параметрами. Разработана программа моделирования черенковского света в калориметре. Экспериментальные и Монте–Карло данные совпадают в пределах ошибок. Полученные результаты позволяют ускорить обработку экспериментальных данных.

Introduction

Reconstruction of the electromagnetic showers in calorimeters is a very important experimental task. The knowledge of the electromagnetic shower profile (shower shape) allows one to reconstruct a coordinate and an energy of the electron or the photon in the calorimeter very precisely. Also it allows to disentangle overlapping showers and to suppress hadronic background.

Two lead glass calorimeters consisting of several hundreds counters each are used now in the two experiments: PROZA-M [1] at IHEP (Protvino, Russia) and Forward Pion Detector (FPD) [2] in STAR at BNL (USA). All the counters made of the same material, have the same size and the same wrapping. The differences between these two modes of operation are as follows:

- the energy of detected photons in the calorimeter is between 1 and 6 GeV at PROZA-M, there is no significant material between an interaction point and the calorimeter;
- the single photon energy range is approximately from 3 to 40 GeV at STAR, with some material in front of the FPD.

The goal of our study was to measure shower profile for these two configurations and energy ranges. We have chosen electron beams with energies of 3; 9 and 23 GeV and precisely reproduced the FPD passive material structure in our measurements. The method which has been used did not require high precision coordinate detectors.

If an additional material is installed in front of a calorimeter, some part of the energy is deposited in this material. The shower starts earlier and thus it will be broader in the calorimeter itself. Such an influence of the material on the electromagnetic shower shape was studied in this work. The signal in lead glass is formed by Ĉerenkov light. In the paper we describe a Monte-Carlo tool for Ĉerenkov light simulation within material. GEANT 3.21 package [3] was used for these simulations. The comparison of Monte-Carlo and experimental data is also performed.

1. Measurements of Shower Shape with the use of electron beams

1.1. Experimental Setup

The measurements of the electromagnetic shower shapes were performed using the PROZA-M detector at IHEP U-70 acceleration complex. The detailed description of the detector can be found in [1]. The electromagnetic calorimeter CSPP and the electron beam line were used for this study. The CSPP is a matrix of 32×24 lead glass blocks with the sizes of $3.8 \times 3.8 \times 45.0$ cm^3. Each block was wrapped by the aluminized mylar (0.01 cm thickness) to increase the photo collection and to isolate optically one cell from another. The photomultiplier FEU-84 was attached to the end face of each counter through the optical grease. The whole matrix was inserted into a lighttight aluminium box installed on the platform which could be automatically moved in the transverse direction. Data were collected in the two configurations: without additional material in front of the calorimeter and with it. The material presents itself as the carcass assembly. It is schematically shown in **Fig. 1**. It overall contains 2.5 of radiation length (X_0) of material. Such a configuration of material was used in the FPD calorimeter in the STAR experiment. Upon necessity the assembly can be installed to pier between aluminium wall of CSPP box and counters surface.

The electron beam with energies of 3; 9 and 23 GeV was used to irradiate the detector. We used electron beams extracted from U-70 accelerator with the following characteristics:

- duration of spill: 1 second, the full accelerator cycle: 9 seconds;
- electron momenta dispersion : $\frac{\Delta p}{p} = 2\%$ — for 23 GeV beam, $\frac{\Delta p}{p} = 3\%$ — for 9 GeV beam, $\frac{\Delta p}{p} = 5\%$ — for 3 GeV beam;
- a full beam width (at 10% level) at the calorimeter surface: 2 cm;
- a number of triggered electrons per spill: 300 — for 23 GeV beam, 200 — for 9 GeV beam, 30 — for 3 GeV beam.

Overall for 90 hours of data taking we have collected: $9 \cdot 10^4$ events at 3 GeV, $5 \cdot 10^5$ events at 9 GeV without material, $1.2 \cdot 10^5$ events at 9 GeV with material, $4.4 \cdot 10^5$ events at 23 GeV without material, $6.2 \cdot 10^5$ events at 23 GeV with material.

The calorimeter was installed perpendicularly to the beam direction. Prior to the data taking for the shower shape measurements the counters have been calibrated without material in front. A detailed procedure of the calibration is described in [4]. Calibration coefficients have been tuned in such a manner that the sum of energy deposition in 5×5 cluster around cell with a maximum deposition was equal to the beam energy (these 25 counters contain $\sim 99,2\%$ of the shower energy).

For the case without material we exposed rectangular part of calorimeter with size of 19×23 (columns 12–31 and rows 1–23) by the electrons with energy 3, 9, 23 GeV. Irradiation of the calorimeter was performed in the following way. Platform was moving horizontally step by step (three points per cell). At each step after the fixed number of triggers it was moved to the next point. When it reached the last counter in this row the platform was moved vertically by a third of the cell. Thus each cell was irradiated nine times. Such a procedure allows to keep uniformity of the exposure. In the case with material only the counters covered by material have been irradiated (5×5 area — columns 15–19 and rows 2–6). In this case requirement of the exposure uniformity was also applied. Only inner 3×3 counters were used in the analysis to avoid boundary effects.

1.2. Method of the measurements

A method of the electromagnetic shower shape determination is based on finding the impact point of electron without use of position detectors. Such a method was introduced in [5]. To do so one finds the counter with a maximum energy deposition within the exposed area. After that one builds the cluster of 5×5 cells around the maximum. For the case with material one makes a verification that the maximum is positioned within the area superimposed by material in front of the calorimeter. Thus we have three values for every event: E_{cl} — total energy deposition of cluster, $< x_a >= \sum\limits_{i=1}^{25} \frac{E_i x_i}{E_{cl}}$, $< y_a >= \sum\limits_{i=1}^{25} \frac{E_i y_i}{E_{cl}}$ — center of gravity coordinates of the cluster.

Using the center of gravity coordinates one can obtain relative deviations from the center of central counter of the cluster:

$$< x >=< x_a > -[< x_a > +0.5] \ ,$$
$$< y >=< y_a > -[< y_a > +0.5] \ .$$

It is easy to see that $< x >$ and $< y >$ change in the range between -0.5 and 0.5. The main goal is to calculate $E(x, y)$ distribution – relative energy deposition in a given cell as a function of the distance between the impact point of the electron and the center of this tower along x and y, where arguments can be expressed as:

$$x = x_{cr} - x_e \ ,$$

$$y = y_{cr} - y_e \ ,$$

where x_{cr}, y_{cr} are the absolute coordinates of the counter center, and x_e, y_e — coordinates of the electron impact point. Because the values x_e and y_e are unknown a priori, it is necessary to get this information from known distributions $\frac{dN}{<dx>}$ and $\frac{dN}{<dy>}$. The last expression for generalized coordinate x can be written as:

$$\frac{dN}{d < x >} = \frac{dN}{dx} \cdot \frac{dx}{d < x >} \ . \tag{1}$$

Integrating this expression we obtain:

$$x(< x >) = \int\limits_{-0.5}^{<x>} \frac{dN/d < x >}{dN/dx} d < x > - \frac{1}{2} \ . \tag{2}$$

Now, with known $\frac{dN}{dx}$ distribution (so-called "posure") one can determine the function $x(< x >)$. We restrict ourselves to the case of the uniform "posure" because it is the simplest way and the experiment was tuned to be as close as possible to this condition. In that case relative distributions $\frac{dN}{d<x>}$ and $\frac{dN}{d<y>}$ should be identical and symmetric. Thus one can obtain a desired function $E(x, y)$, which presents the electromagnetic shower shape function.

To parameterize the shower shape one can fit distribution $E(x, y)$ by the following function, which is intrinsic for this type of calorimeter (see [5]):

$$F = g(x + \frac{d}{2}, y + \frac{d}{2}) - g(x + \frac{d}{2}, y - \frac{d}{2}) - g(x - \frac{d}{2}, y + \frac{d}{2}) + g(x - \frac{d}{2}, y - \frac{d}{2}) \ , \qquad (3)$$

where

$$g(x, y) = \frac{a}{\sqrt{2\pi}} \left(\arctan\left(\frac{x}{b}\right) + \arctan\left(\frac{y}{b}\right) + \arctan\left(\frac{xy}{b\sqrt{b^2 + x^2 + y^2}}\right)\right) \ ,$$

where a and b are free parameters, $d = 3.81$ cm — transversal size of a lead glass counter. Parameter a is connected with the height of the shape, and parameter b characterizes the width of the shape. The cumulative function F is the sum of functions $g(x, y)$ in the corners of the cell.

1.3. Results

As an example **Fig. 2** shows $< x >$ and $< y >$ distributions for the case of 9 GeV without material in front of the calorimeter. For all other expositions the distributions look similar. To increase the statistics we converted the distributions to following ones for generalized coordinate z:

$$\left.\frac{dN}{d < z >}\right|_{0 \div -0.5} = \left.\frac{dN}{d < z >}\right|_{0 \div 0.5} =$$

$$= \left.\frac{dN}{d < x >}\right|_{0 \div -0.5} + \left.\frac{dN}{d < x >}\right|_{0 \div 0.5} + \left.\frac{dN}{d < y >}\right|_{0 \div -0.5} + \left.\frac{dN}{d < y >}\right|_{0 \div 0.5} .$$

Thus we reduce the cell area to one forth. The validity of such a substitution follows from the shower symmetry in the transverse direction. As a result the distribution is reduced to single coordinate in the range from the center to the edge of the cell.

The obtained distribution for 9 GeV without material is shown in **Fig. 3**. Then applying the integration (2) we get a correction function — $x- < x >$ versus $< x >$, so called "S-curve", which is presented in **Fig. 4** for 9 GeV. Using the "S-curve" we obtain "real"(corrected) coordinate of the electron impact point in the cell. Now we can construct the desired function $E(x, y)$. We sum the data from the all 25 counters in the 5×5 array into a single two dimensional histogram: each value is plotted at the coordinate of the cell center relatively to "real" coordinate with the weight equal to the energy deposition in a given cell divided by the beam energy. For the case without material the beam energy equals to the cluster energy as mentioned above. In the case with material though this condition does not fulfill due to losing some part of electron energy in the bar.

The two dimensional shower profile distribution, $E(x, y)$, is shown in **Fig. 5**. A comparison and a parametrization of the obtained shapes will be considered in the following sections.

To control the correctness of the "real" coordinate reconstruction we built up the distributions of these coordinates. The results are shown in **Fig. 6**. It is seen that the condition of exposure uniformity fulfill sufficiently well.

2. Monte-Carlo Simulation

A Monte-Carlo simulation program is based on the GEANT package. The whole detector geometry has been coded in the program for the both cases – with and without material. For the proper Ĉerenkov light simulation in lead glass and performing light collection by PMT it is necessary to know its optical features. To reach that goal a number of measurements using the spectrophotometer were made [6]. First the features of photocathode were explored using the narrow light beam exposition from Xenon lamp in the wave length range from 300 to 650 nm with a 5 nm step. The measured quantum efficiency and refraction index are shown in **Fig. 7** as a function of wave length. There is also the result for mylar coefficient of reflection on the same plot. Then the glass-PMT setup was installed and exposed by the same light. The lead glass absorbtion length and refraction index are shown in **Fig. 8**. All these curves have been inserted into our simulation program.

As for experiment we considered 5 cases: irradiation by the electron beams with energies of 3; 9; 23 GeV without material, and 9; 23 GeV with material in front of the calorimeter. The electron beam hit the cell end face perpendicularly. The coordinates of the electron impact point were uniformly smeared. Ĉerenkov photons produced by the interactions with material have been traced through the glass and collected by the PMT photocathode. Since every single photon is traced, the process of generation is very time consuming and requires a big computational resources. Also an account must be taken of that as the electron energy increases the number of photons and the calculation time increase proportionally. Overall $2 \cdot 10^5$ events at 3 GeV were generated, $2 \cdot 10^5$ (equally for cases with and without material) — for 9 GeV and $1 \cdot 10^5$ (also equally for both cases) — for 23 GeV. The profile calculation algorithm is similar to the experimental one. The only difference is that electron impact point coordinate is known exactly. This certainly simplifies the procedure. As for experimental data we collect two dimensional distribution: ratio of the number of photoelectrons produced by a photocathode of the given counter to the full number of photoelectrons at whole 5×5 matrix cathodes as a function of relative coordinates of electron impact point. The normalization factor of the simulation with and without material comes from the average number of cluster photoelectrons (in the absence of material). The simulation results and parametrization of the shapes are discussed in the next section.

3. Comparison of the MC and Experimental results

The results of the simulation were compared to the experimental data. The obtained two dimensional distributions $E(x, y)$ were fit by the function (3). For clearness the results of the fit are combined in **Fig. 9**. The shower shapes are represented in one dimensional form on this plot which is simply a profile along x axis. The result of the experimental data fit is shown as a solid curve on this plot. The Monte-Carlo fit is omitted to not overload the picture — it goes exactly through the simulation points. **Table 1** shows the fitting parameters for the both MC and experiment. The errors on MC values are omitted due to their negligible values.

From the obtained data we may conclude the following:

- Shower shape without material does not depend on the electron energy in the both experimental and Monte-Carlo data (the parameters a and b remain unchanged within uncertainties).

- In the case with material the shape strongly depends on the energy. As electron energy decreased, the parameter a is dropping (the part of the energy deposited in passive material is growing, the shower begins earlier), the parameter b is growing (the transverse size of the shower evolving within calorimeter is increasing).
- If in the case without material we had maximum relative energy deposition (achieves if electron hit the center of the given cell) $\simeq 0.83$, then in the presence of material we have $\simeq 0.62$ at 23 GeV and $\simeq 0.55$ at 9 GeV.
- The results obtained by the Monte-Carlo program are in good agreement with the experimental data. Although in the case without material MC shape is slightly more narrow.

Table 1. Shower shape parametrization parameters. Experiment versus Monte-Carlo.

Energy(GeV)		a	b	χ^2/ndf
NO MATERIAL				
3	Exp	1.05 ± 0.03	0.13 ± 0.01	0.73
	MC	1.04	0.12	
9	Exp	1.08 ± 0.01	0.14 ± 0.01	0.91
	MC	1.04	0.11	
23	Exp	1.08 ± 0.03	0.13 ± 0.01	0.70
	MC	1.04	0.10	
WITH MATERIAL				
9	Exp	0.79 ± 0.01	0.18 ± 0.01	0.85
	MC	0.79	0.18	
23	Exp	0.83 ± 0.02	0.15 ± 0.01	0.80
	MC	0.85	0.15	

Conclusions

In the paper some features of electromagnetic shower in the lead glass calorimeter were studied with the PROZA-M detector at IHEP. The irradiation was performed by the electron beams with energies of 3; 9; 23 GeV and for the two different setups — with passive material in front of the calorimeter and without it. The shower shapes were obtained without use of coordinate detectors. The Monte-Carlo results for the same setups are also presented. The simulation tool is based on the GEANT 3.21 package with Ĉerenkov light generation accounting optical features of the detector.

The parametrization of shower shape by the two dimensional function with two parameters was introduced. The shower shape does not depend on the energy of incoming electron without a material in front of calorimeter. The shower shape becomes essentially dependent on the energy with material installed. As the electron energy decreased, the shape becomes wider. The consistency between the Monte-Carlo and the experimental data gives us a tool for getting a shower shape function for different electron energies and different configurations of material without performing special methodical experiment. All this allows us to better reconstruct and disentangle overlapping electromagnetic showers in calorimeters and suppress hadronic background more efficiently; to speed up the procedure of shower reconstruction; to calculate energy leakage out of the calorimeter boundary.

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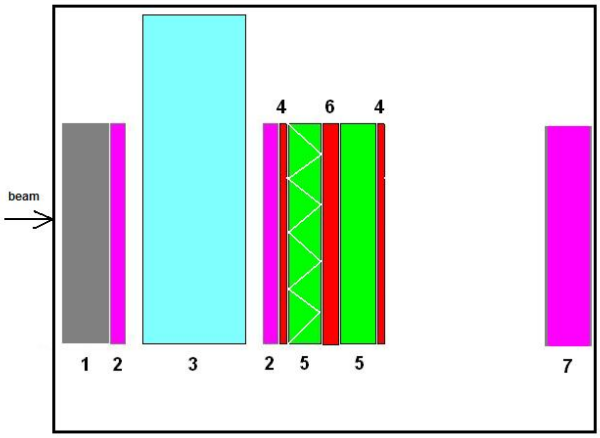

Figure 1. The material assembly in front of the calorimeter: 1 – Pb plate 1.27 cm; 2 – Aluminium 0.32 cm; 3 – Pb Glass cell (vertically) 3.81 cm; 4 – G10 plate 0.15 cm; 5 – plastic 0.7 cm; 6 – G10 0.3 cm; 7 – Aluminium 1.31 cm. Air gaps (from left to right) — 0.32 cm, 0.32 cm, 7.68 cm. Transverse dimensions — 30×30 cm^2.

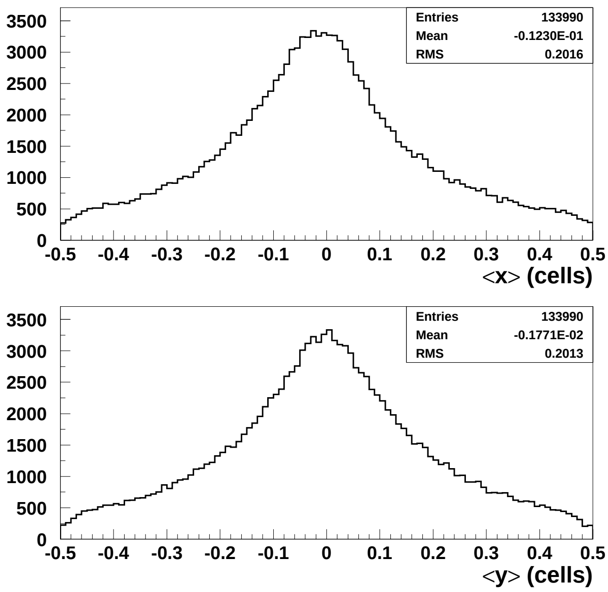

Figure 2. The relative center of gravity coordinates of the shower.

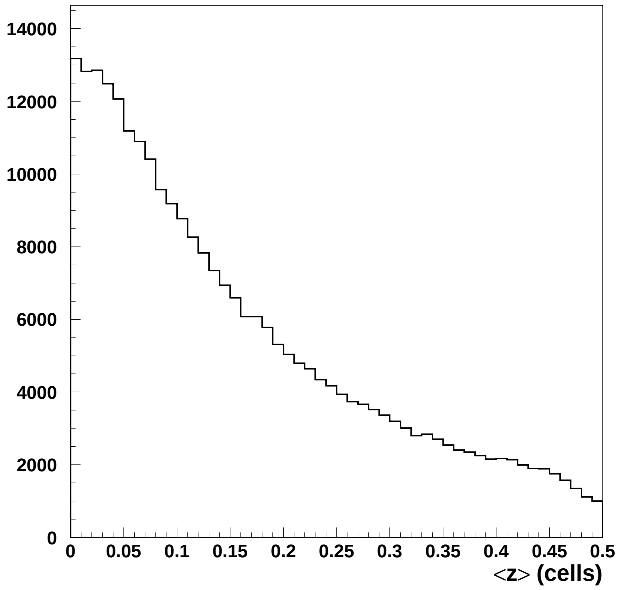

Figure 3. Generalized relative center of gravity coordinate of the shower. It varies from 0 to 0.5 cell.

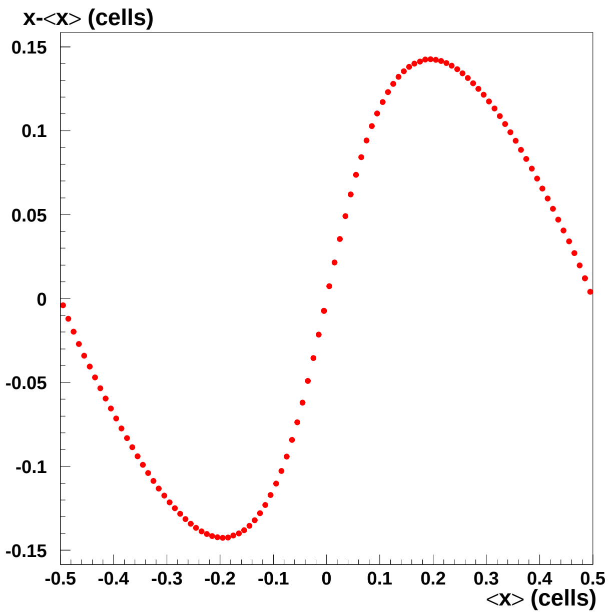

Figure 4. The correction function “S-curve” for the coordinate of electron. The errors are less then the size of the marker.

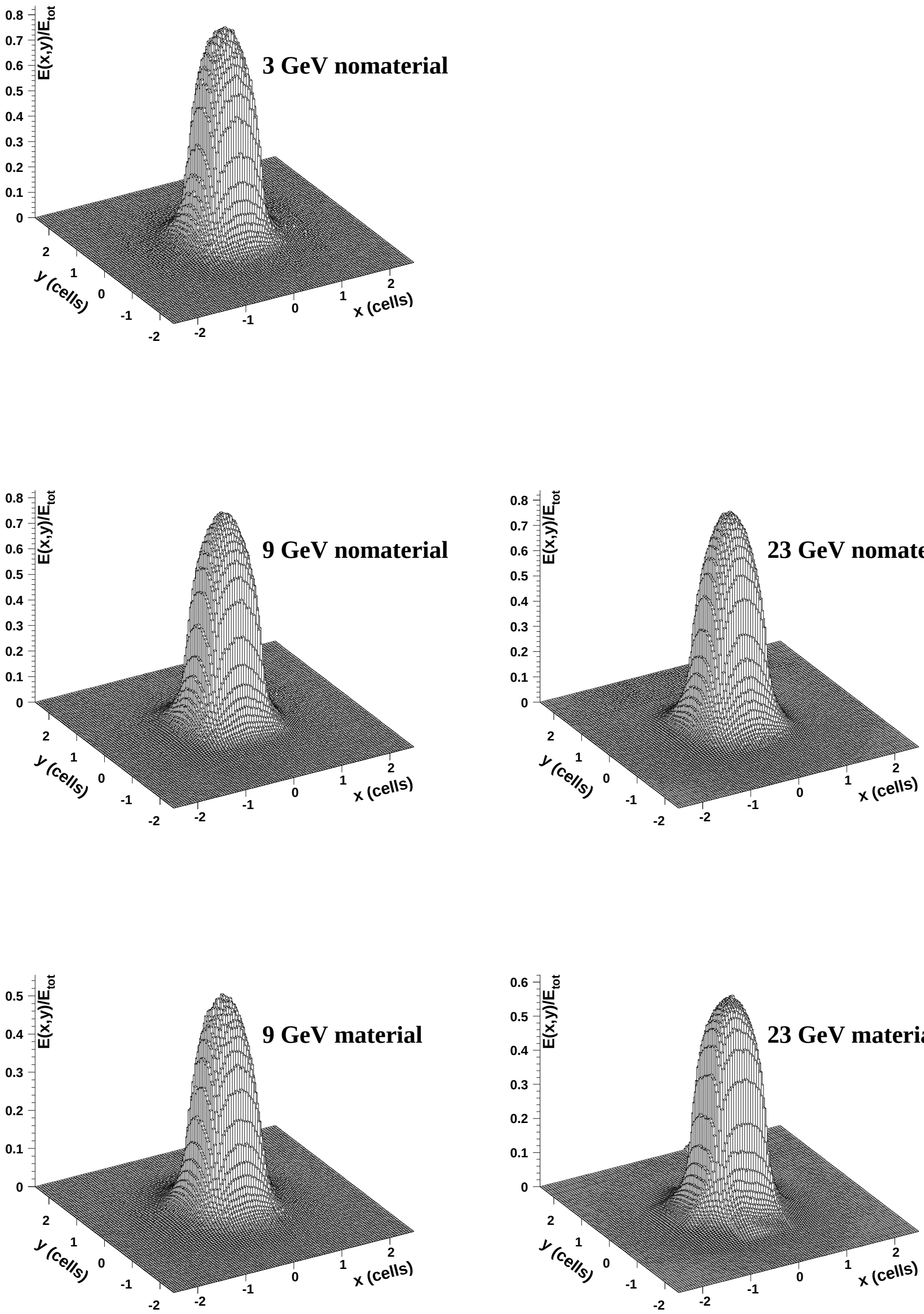

Figure 5. Two dimensional shower shapes for five cases: 3; 9; 23 GeV without material, and 9; 23 GeV with material.

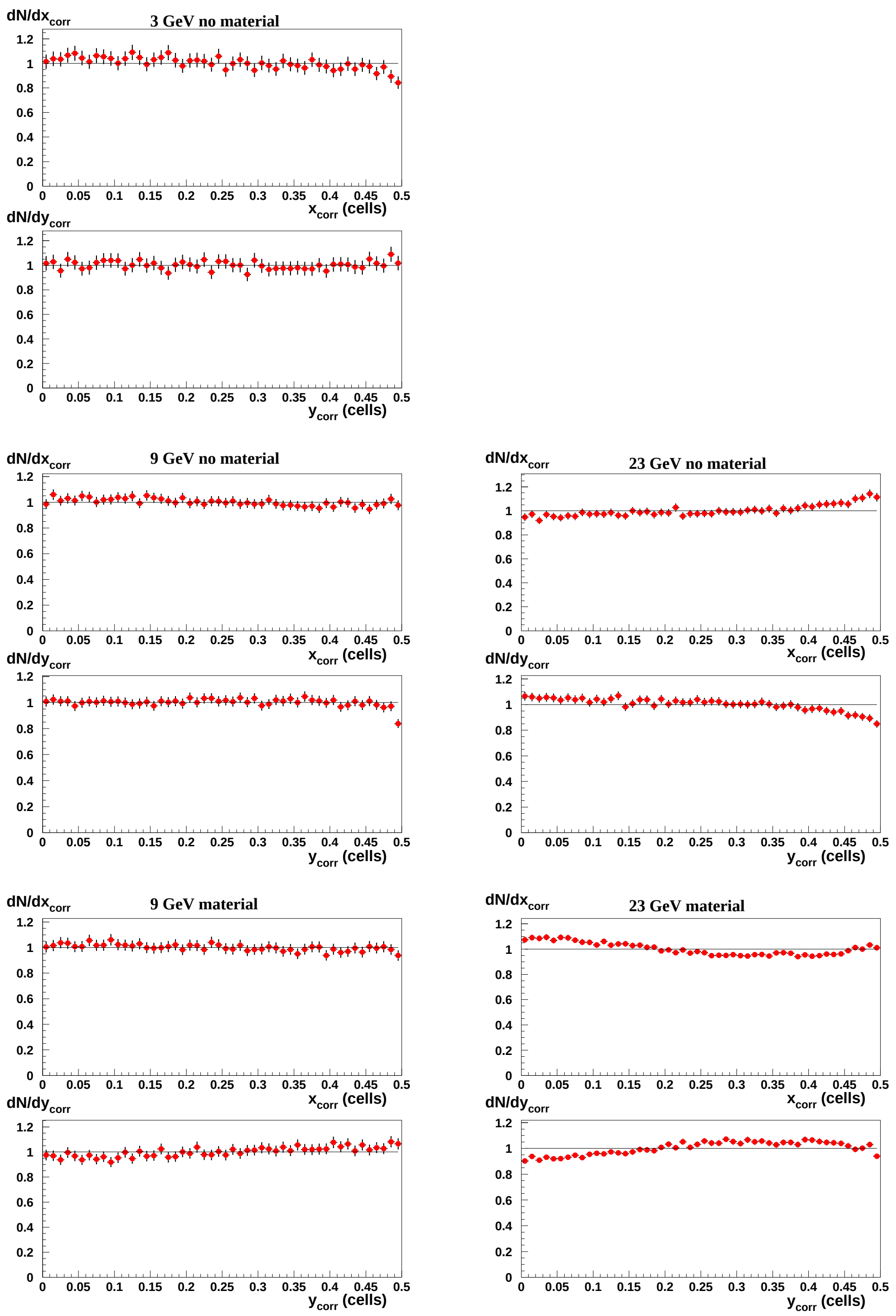

Figure 6. "Real" coordinates of the electron impact point for the five considering cases. Number of inputs (normalized to 1) is along y axis. A normalization coefficient is calculated by the fit with a constant function.

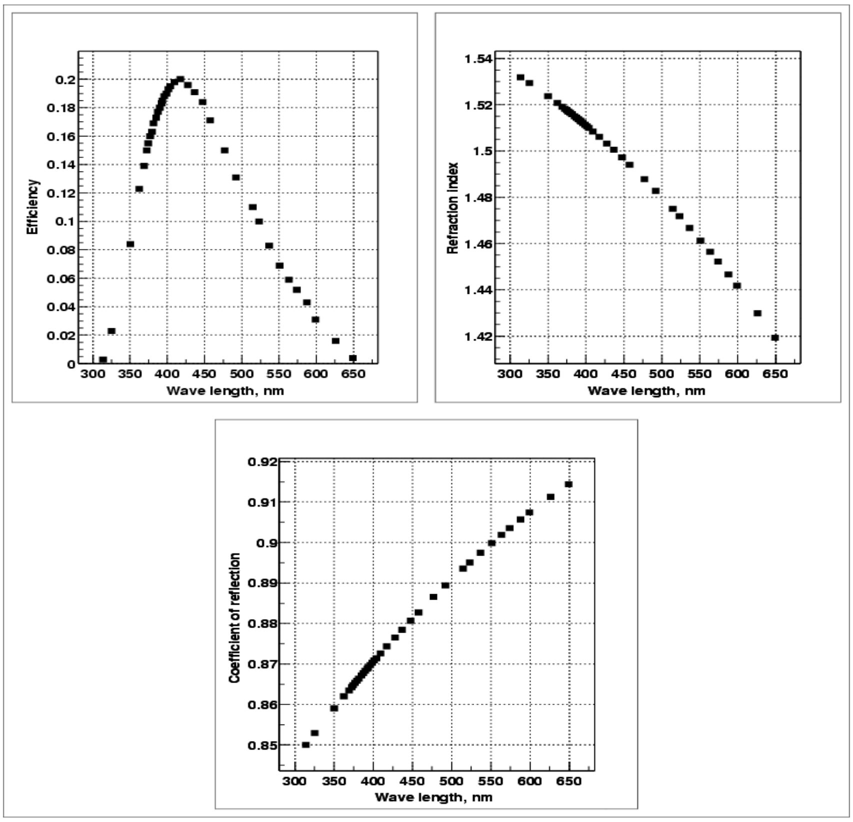

Figure 7. Left plot: quantum efficiency of PMT FEU-84, right plot: refraction index of PMT, bottom plot: aluminized mylar coefficient of reflection.

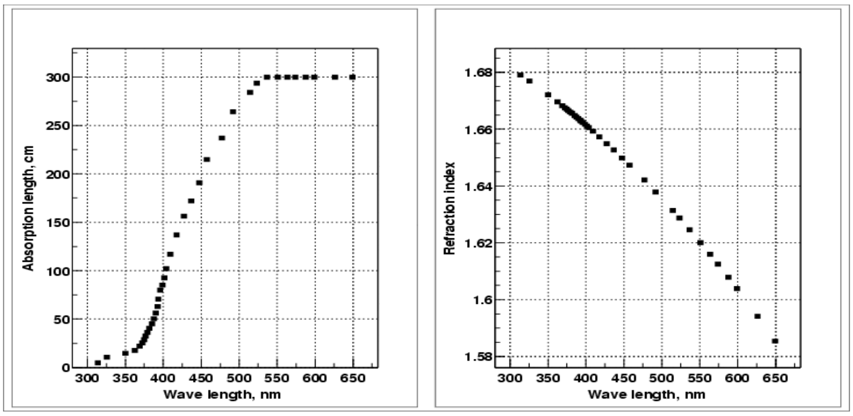

Figure 8. Left plot: Pb-glass absorbtion length, right plot: Pb-glass refraction index.

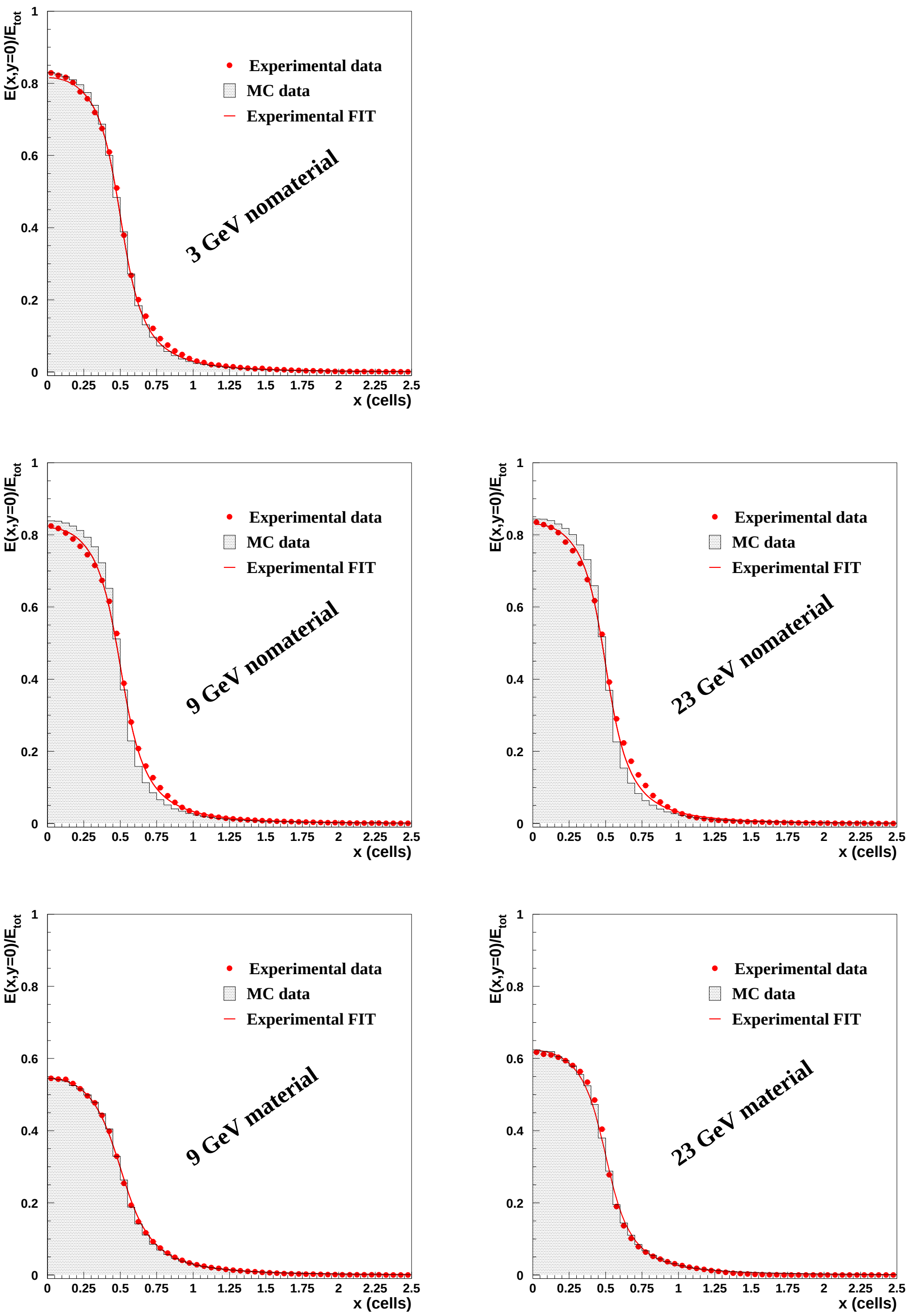

Figure 9. Comparison of MC and experimental shower shapes for the 5 different cases (the details are on the plots). One dimensional profiles along x axis are shown. Fit over MC data is omitted to not overload the plot (it goes exactly through the histogram points).

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