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# DISTRIBUTIONS OF ENERGY LOSSES OF ELECTRONS AND PIONS IN THE **CBM TRD**

Акишина Е. П. и др. E10-2007-158
Распределения потерь энергии электронов и пионов в CBM TRD

Рассмотрены потери энергии электронов и пионов в детекторе TRD эксперимента CBM. Анализируются измерения потерь энергии с помощью прототипа TRD на тестовом пучке (ГСИ, Дармштадт, февраль 2006 г.), а также результаты моделирования потерь энергии методом Монте-Карло в $n$-слойном TRD, выполненного с помощью GEANT в среде CBM ROOT. Показано, что: 1) потери энергии как для реальных измерений, так и для модельных данных с хорошей точностью аппроксимируются логнормальным распределением для $\pi$ и взвешенной суммой двух логнормальных распределений для $e$; 2) модельные данные для $e$ заметно отличаются от реальных данных, в результате чего для модельных данных мы имеем значительные потери в эффективности $e/\pi$-идентификации. Предложена процедура контроля и корректировки моделирования потерь энергии электронов в TRD.

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Akishina E. P. et al. E10-2007-158
Distributions of Energy Losses of Electrons and Pions in the CBM TRD

The distributions of energy losses of electrons and pions in the TRD detector of the CBM experiment are considered. We analyze the measurements of the energy deposits in one-layer TRD prototype obtained during the test beam (GSI, Darmstadt, February 2006) and Monte Carlo simulations for the $n$-layered TRD realized with the help of GEANT in frames of the CBM ROOT. We show that: 1) energy losses both for real measurements and GEANT simulations are approximated with a high accuracy by a log-normal distribution for $\pi$ and a weighted sum of two log-normal distributions for $e$; 2) GEANT simulations noticeably differ from real measurements and, as a result, we have a significant loss in the efficiency of the $e/\pi$ identification. A procedure to control and correct the process of the energy deposit of electrons in the TRD is developed.

The investigation has been performed at the Laboratory of Information Technologies, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 2007

## INTRODUCTION

The CBM Collaboration [1, 2] builds a dedicated heavy-ion experiment to investigate the properties of highly compressed baryon matter as it is produced in nucleus–nucleus collisions at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany. A scientific goal of the research program of the CBM experiment is to explore a phase diagram of strongly interacting matter in the region of the highest baryon densities. This approach is complementary to the activities at RHIC (Brookhaven) and ALICE (CERN-LHC) which concentrate in the region of high temperatures and very low baryon densities.

The experimental setup has to fulfil the following requirements: identification of electrons which requires a pion suppression factor of the order of $10^5$, identification of hadrons with large acceptance, determination of the primary and secondary vertexes (accuracy of $\sim 30\,\mu$m), high granularity of the detectors, fast detector response and read-out, very small detector dead time, high-speed trigger and data acquisition, radiation hard detectors and electronics, tolerance towards delta-electrons.

Figure 1 depicts a present layout of the CBM experimental setup. Inside the dipole magnet gap there are a target and a 7-planes Silicon Tracking System (STS) consisting of pixel and strip detectors. The Ring Imaging Cherenkov detector (RICH) has to detect electrons. The Transition Radiation Detector (TRD) arrays measure electrons with momentum above 1 GeV/$c$. The Time-of-Flight (TOF) detector consists of Resistive Plate Chambers (RPC). The Electromagnetic Calorimeter (ECAL) measures electrons, photons and muons. The CBM setup is optimized for heavy-ion collisions in the beam energy range from about 8 up to 45 $A$ GeV. A typical central Au+Au collision in the CBM experiment will produce up to 700 tracks in the inner tracker (see Fig. 2).

The measurement of charmonium is one of the key goals of the CBM experiment. For detecting $J/\psi$ meson in its dielectron decay channel the main task is the separation of electrons and pions. One of the most effective detectors to solve this problem is the TRD. The TRD must provide effective electron identification, sufficient pion suppression and tracking of all charged particles. The required pion suppression is a factor of about 100 and the required position resolution is of the order of $200-300\mu$m. To fulfil these requirements, a careful optimization of the detector is needed.

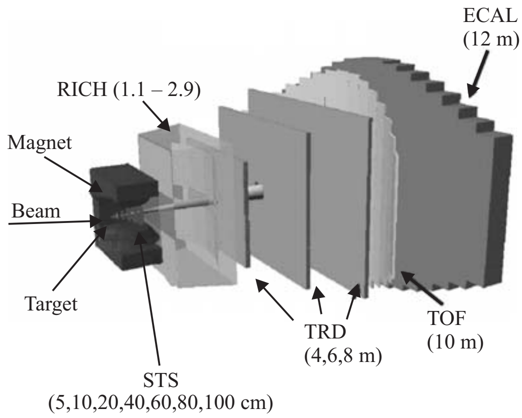


Fig. 1. CBM general layout

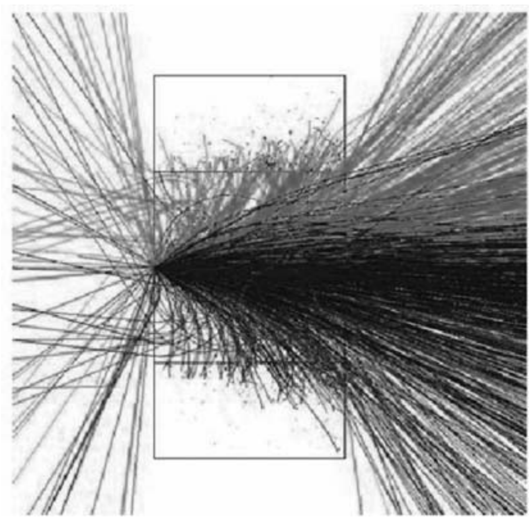

Fig. 2. Visualization of a typical CBM event

In the technical proposal of the CBM experiment preliminary results (based on Monte Carlo simulations) are presented on the estimation of the electron identification and pions suppression applying a likelihood functions ratio test (see details in [2]). The results of these studies have demonstrated that the TRD with 9 to 12 layers may fulfil the required electron/pion identification for the CBM experiment.

At the same time, it must be noted that the application of the likelihood functions ratio test requires a very accurate determination of density functions of energy losses of pions and electrons (see details on page 87 in [2]). This is very important for getting a correct result of this method, which is not so simple to be fulfilled in practice.

In this connection, there were investigated two other approaches for solving such a problem based on: 1) a layered feed-forward neural network — multilayer perceptron [4], and 2) a nonparametric $\omega_n^k$ goodness-of-fit criterion [5]. These approaches provide a reliable level of pions suppression and electrons identification.

Recently the measurements of energy deposits in one-layer TRD prototype were realized at the GSI during the test beam on February, 2006. Having analyzed these measurements, we found the functions which with a high accuracy describe the statistical distributions of energy losses in TRD layers both for pions and electrons, thus, providing a possibility to construct correct density functions of energy losses for given particles and, as a consequence, to be confident that the calculated value of the likelihood test is correct.

Taking into account that this criterion is the most powerful one among all possible statistical criteria (see, for instance, [6]), it was very important to get an estimate of this method for this specific problem, especially based on real measurements. The results of these studies have been presented in [7].

Here we compare energy deposits in the TRD prototype obtained during the test beam (GSI, Darmstadt) with GEANT3 [8] simulations of the TRD realized in frames of the CBM ROOT [9]. We also compare the efficiency of the $e/\pi$ identification for both data sets. A procedure that permits to control and correct a process of energy deposits of electrons and pions in the TRD is also discussed.

## 1. ENERGY LOSSES OF $e$ AND $\pi$ IN ONE LAYER OF THE TRD

The major part of detecting $J/\psi$ meson in its dielectron decay channel is the electron/pion separation. A schematic view of the TRD with $n$ layers to be used for the solution of this problem is shown in Fig. 3.

In order to optimize the TRD geometry and to estimate the optimal number of layers which provide the needed level of electron identification and pion suppression, here we analyze the distributions of energy losses of $e$ and $\pi$ in one layer of the TRD. In this connection, we used real measurements of the energy deposits in one-layer TRD prototype and GEANT3 simulations of the TRD realized in frames of the CBM ROOT.

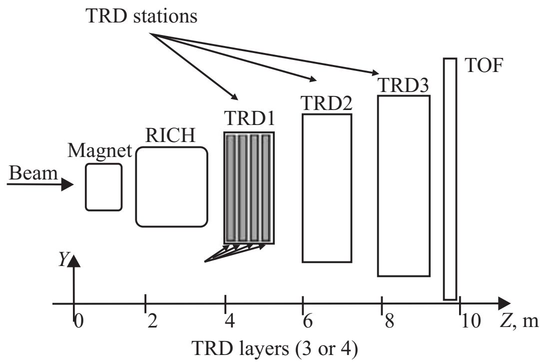


Fig. 3. Schematic view of the TRD

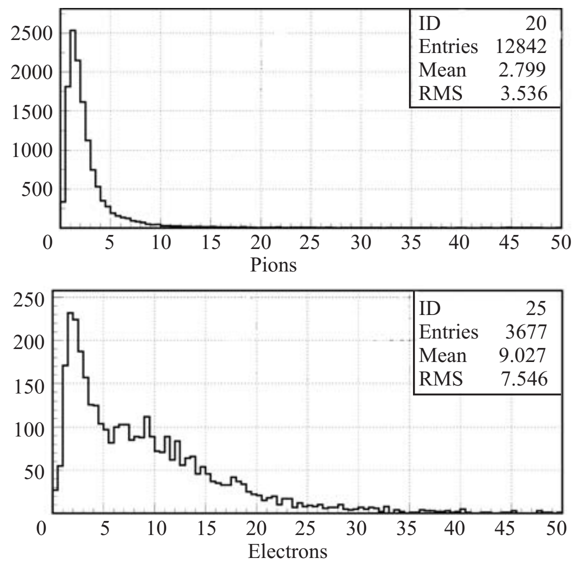


Fig. 4. Distributions of energy losses of pions (top plot) and electrons, including the transition radiation (bottom plot) in the TRD prototype: $p = 1.5$ GeV/$c$

Figure 4 shows the distributions of the measurements of ionization losses ($dE/dx$) of pions (top plot) and electrons (bottom plot), including losses on the transition radiation, in the TRD prototype with one layer: beam test (GSI, February 2006) $p = 1.5$ GeV/$c$.

We found [7] that the distribution of pion ionization losses in the TRD prototype is quite well approximated by a log-normal function [6]

$$f_1(x) = \frac{A}{\sqrt{2\pi}\sigma x} \exp\left(-\frac{1}{2\sigma^2}(\ln x - \mu)^2\right), \tag{1}$$

$\sigma$ is the dispersion, $\mu$ is the mean value, and $A$ is a normalizing factor (see Fig. 5).

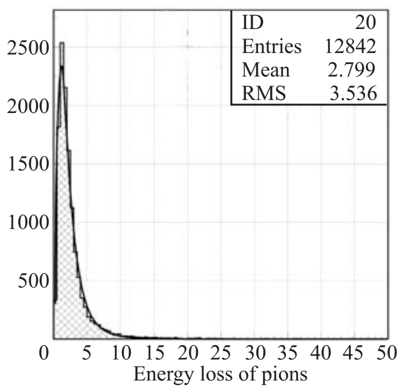


Fig. 5. Approximation of the distribution of pion energy losses in the TRD prototype by a log-normal function (1)

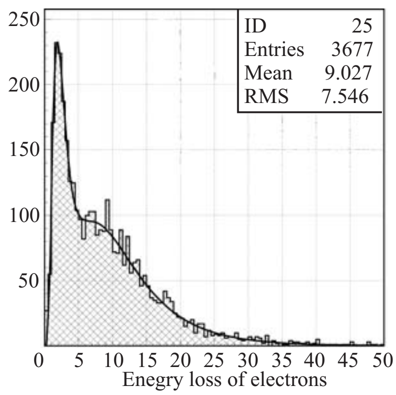


Fig. 6. Approximation of the distribution of electron energy losses in the TRD prototype by a weighted sum of two log-normal functions (2)

The distribution of energy losses of electrons (ionization and transition radiation) are approximated with a high accuracy by a weighted sum of two log-normal distributions [7] (see Fig. 6)

$$f_2(x) = B\left(\frac{a}{\sqrt{2\pi}\sigma_1 x} \exp\left(-\frac{1}{2\sigma_1^2}(\ln x - \mu_1)^2\right) + \right.$$
$$\left. + \frac{b}{\sqrt{2\pi}\sigma_2 x} \exp\left(-\frac{1}{2\sigma_2^2}(\ln x - \mu_2)^2\right)\right), \tag{2}$$

where $\sigma_1$ and $\sigma_2$ are dispersions, $\mu_1$ and $\mu_2$ are mean values, $a$ and $b = 1 - a$ are contributions of the first and second log-normal distributions, correspondingly, and $B$ is a normalizing factor.

Approximation of the distribution of electron energy losses by a weighted sum of two log-normal distributions permits one to extract individual contributions of ionization losses and energy losses on transition radiation.

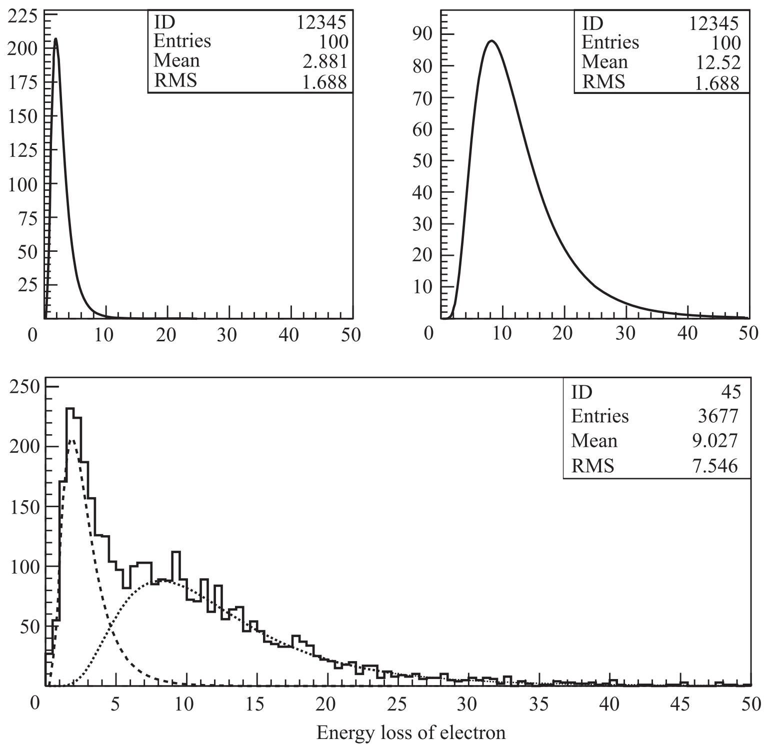


Fig. 7. Approximation of the distribution of electron energy losses in the TRD prototype by a weighted sum of two log-normal distributions (bottom plot): contributions of ionization losses (top left plot) and the transition radiation (top right plot)

Figure 7 shows the contributions of the ionization losses (top left plot) and transition radiation (top right plot) into the summary distribution of the electron energy losses in the TRD prototype.

The value of the contribution of the ionization losses — the coefficient $a_e$ in expression (2) — consists of 0.3741, and the contribution of energy losses on the transition radiation — the coefficient $b_e$ in expression (2) — is equal to 0.6259. At the same time, the mean value of ionization losses of electrons is close to what we have for pions (see Fig. 5), the root mean squared (RMS) [10] is, approximately, two times less.

The second set of data includes GEANT3 simulations for pions and electrons with momenta $1 \div 2$ GeV/$c$ passing through the CBM TRD. Figures 8 and 9 show the distributions of energy losses of pions (top plot) and electrons (bottom

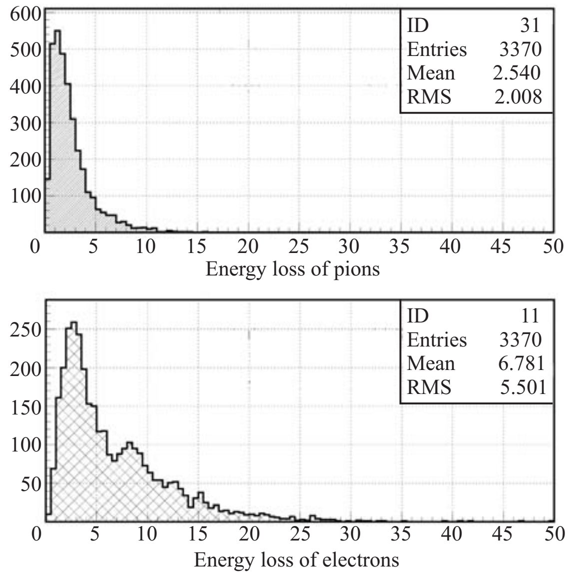


Fig. 8. Distributions of energy losses of $\pi$ (top plot) and $e$ (bottom plot) in one layer of the TRD using the GEANT3 simulations for $\pi$ and $e$ with momenta $1 \div 2$ GeV/$c$ (March 2007 data)

**Table 1. Comparison of the mean value (m.v.) and RMS of the energy deposit distributions for real measurements and GEANT simulations**

| Type of data | M.V. ($e$) | RMS ($e$) | M.V. ($\pi$) | RMS ($\pi$) |
|---|---|---|---|---|
| Real data | 9.027 | 7.546 | 2.799 | 3.536 |
| GEANT (March 2007) | 6.781 | 5.501 | 2.540 | 2.008 |
| GEANT (July 2007) | 8.595 | 7.126 | 2.861 | 3.567 |

plot) in one layer of the TRD for GEANT3 simulations in March and July 2007, respectively.

The comparision of distributions of energy losses in the TRD prototype (Fig. 4) with first set of GEANT simulations (March 2007 data) (Fig. 8) shows that for both pions and electrons the main statistical characteristics (mean value and RMS) are significantly different. This distinction is noticeable especially strong for electron distributions: compare mean values and RMS. At the same time, the mean value and RMS for July 2007 data (Fig. 9) quite well follow the real data. The results of the comparison are presented in Table 1.

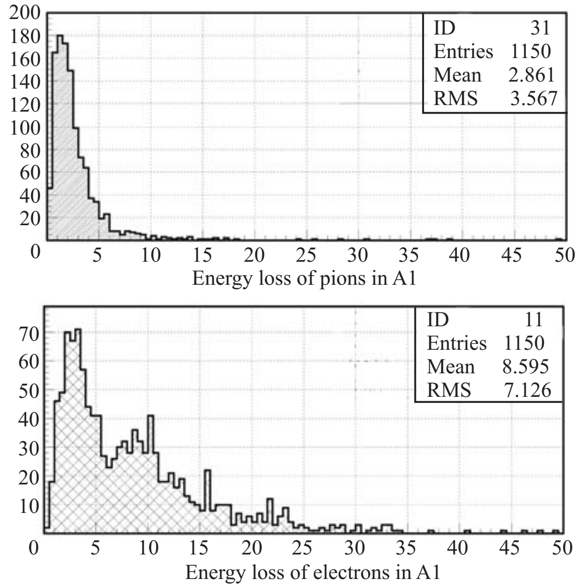


Fig. 9. Distributions of energy losses of $\pi$ (bottom plot) and $e$ (bottom plot) in one layer of the TRD detector using the GEANT3 simulations for $\pi$ and $e$ with momenta $1 \div 2$ GeV/$c$ (July 2007 data)

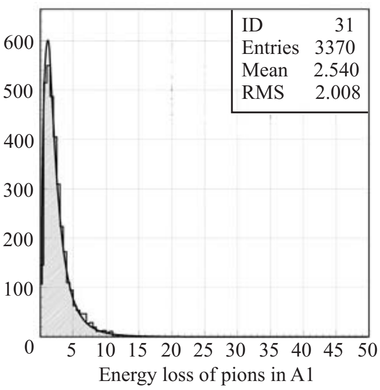


Fig. 10. Approximation of the distribution of pion energy losses in one layer of the TRD by a log-normal function (1)

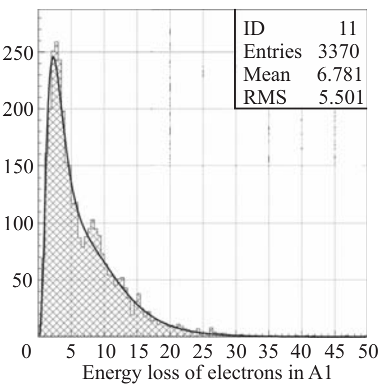


Fig. 11. Approximation of the distribution of electron energy losses in one layer of the TRD by a weighted sum of two log-normal functions (2)

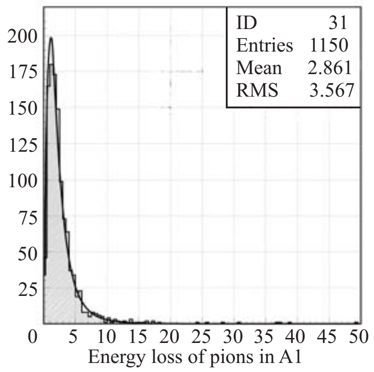


Fig. 12. Approximation of the distribution of pion energy losses in one layer of the TRD by a log-normal function (1)

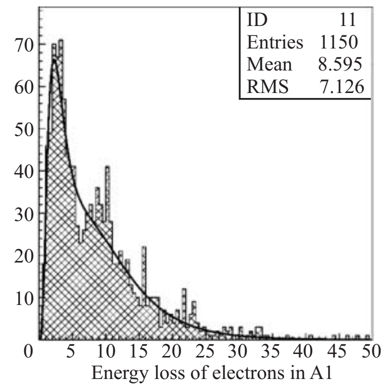


Fig. 13. Approximation of the distribution of electron energy losses in one layer of the TRD by a weighted sum of two log-normal functions (2)

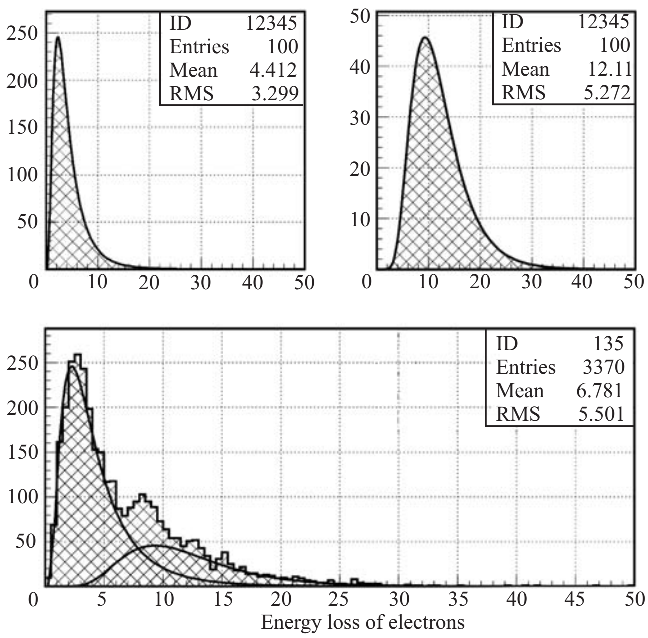


Fig. 14. Approximation of distribution of the electron energy deposit in one layer of the TRD (March 2007 data) by a weighted sum of two log-normal distributions (bottom plot): contributions of $dE/dx$ (top left plot) and transition radiation (top right plot)

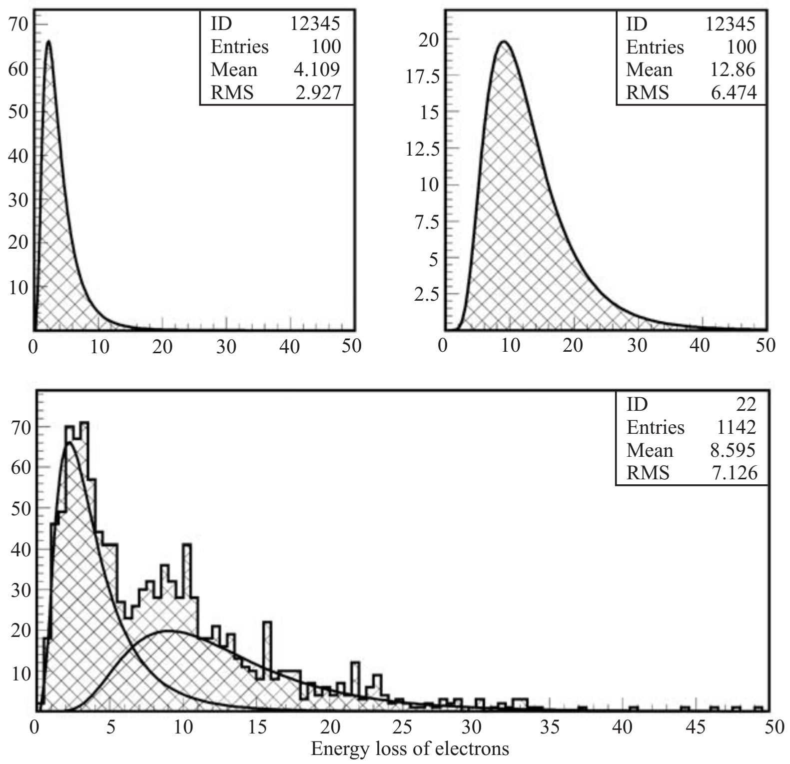


Fig. 15. Approximation of distribution of the electron energy deposit in one layer of the TRD (July 2007 data) by a weighted sum of two log-normal distributions (bottom plot): contributions of $dE/dx$ (top left plot) and transition radiation (top right plot)

The distributions of GEANT simulations are also quite well approximated by log-normal distributions: see Figs. 10, 11 (March 2007 data) and Figs. 12, 13 (July 2007 data).

Such an accurate approximation of the distribution of electron energy losses by a weighted sum of two log-normal density functions also permits us to separate the contributions of various physical processes in this distribution energy: losses on ionization and on transition radiation.

Figures 11 and 13 show that the contribution of ionization losses $a_s$ takes up 0.7044 for March 2007 data and 0.5404 for July 2007 data which is approximately two times larger compared to real measurements — $a_e = 0.3741$. Parts of the losses on the transition radiation $b_s$ equal to 0.2956 (March 2007) and 0.4596 (July 2007), which are significantly less as compared to real measurements —

$b_e = 0.6259$. Furthermore, the mean value for ionization losses of electrons significantly differs from the value obtained for pions (see Table 1 and Figs. 14 and 15).

The results of this analysis demonstrate that the simulation of the energy losses of electrons in the TRD with the help of the CBM GEANT does not fit the real measurements obtained during the beam test (GSI, Darmstadt) on the TRD prototype.

## 2. EFFICIENCY OF PARTICLE ($e$ AND $\pi$) IDENTIFICATION BASED ON REAL MEASUREMENTS AND GEANT SIMULATIONS

The problem of particle identification (in our case, pions and electrons) using $n$-layered TRD consists of the following: having a set of $n$ measurements of energy losses from $n$ layers of the TRD, one has to determine, to what kind of distribution (pion or electron) the energy losses of the particle registered by the TRD are relative.

For real measurements we have in our responsibility only measurements and distributions of the energy deposits in the one-layer TRD prototype. To prepare a set of $n$ «measurements» of energy losses corresponding to a particle (electron or pion) passing through the $n$-layered TRD, we use a subroutine HISRAN [11] that allows one to generate $n$ random values in accordance with a given distribution. The distributions related to electrons and pions were supplied in the form of histograms (Fig. 4) using a subroutine HISPRE [11] (once for each histogram).

A uniform random number is generated using RNDM [12]. This number is then transformed to the user's distribution using a cumulative probability distribution constructed from the user's histogram. The cumulative distribution is inverted by using a binary search for the nearest bin boundary and a linear interpolation within the bin.

To estimate the efficiency of particle identification, we use a method of ratio of likelihood functions: see, for example, [6, 13]. This test could be related to Neiman–Pirson criterion which is the most powerful criterion for testing the hypothesis $H_0$ (in our case, the distribution of electrons) against the alternative hypothesis $H_1$ (the distribution of pions) [6]. Therefore, for the given significance level $\alpha$ the value of $\beta$ could be considered as minimally possible. In our case, this corresponds to the maximum factor of pions suppression.

While applying the likelihood test to our problem, the value [3, 14]

$$L = \frac{P_e}{P_e + P_\pi}, \qquad P_e = \prod_{i=1}^{n} p_e(\Delta E_i), \qquad P_\pi = \prod_{i=1}^{n} p_\pi(\Delta E_i) \tag{3}$$

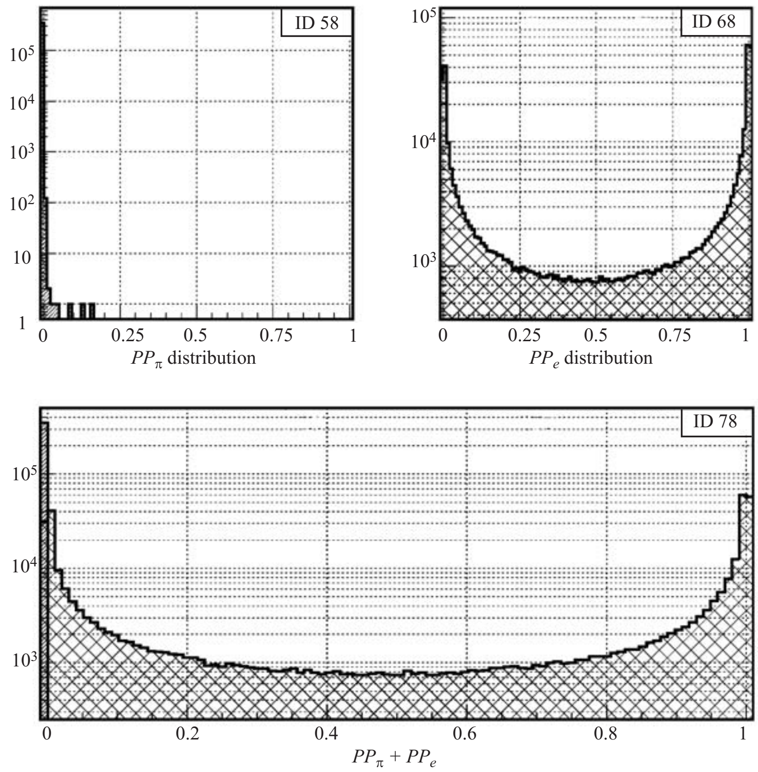


Fig. 16. Distributions (for the TRD prototype) of $L$ in cases when only pions (top left plot) or only electrons (top right plot) pass through the TRD with $n = 12$ layers; the bottom plot is a summary distribution of both particles

is calculated for each event, where $p_\pi(\Delta E_i)$ is the value of the density function $p_\pi$ in the case when the pion loses energy $\Delta E_i$ in the $i$th absorber, and $p_e(\Delta E_i)$ is the same value for electron.

Figure 16 shows the distributions of the variable $L$ for the data set generated on the basis of real measurements in accordance with the described above procedure: when only pions (top left plot) or electrons (top right plot) pass through the $n$-layered TRD; the bottom plot shows a summary distribution of both particles.

The efficiency of registering electrons is determined by the ratio of the electrons selected in the admissible region for the preassigned significance level $\alpha$ (first-order error) to part $\beta$ of pions having hit in the admissible region (second-order error).

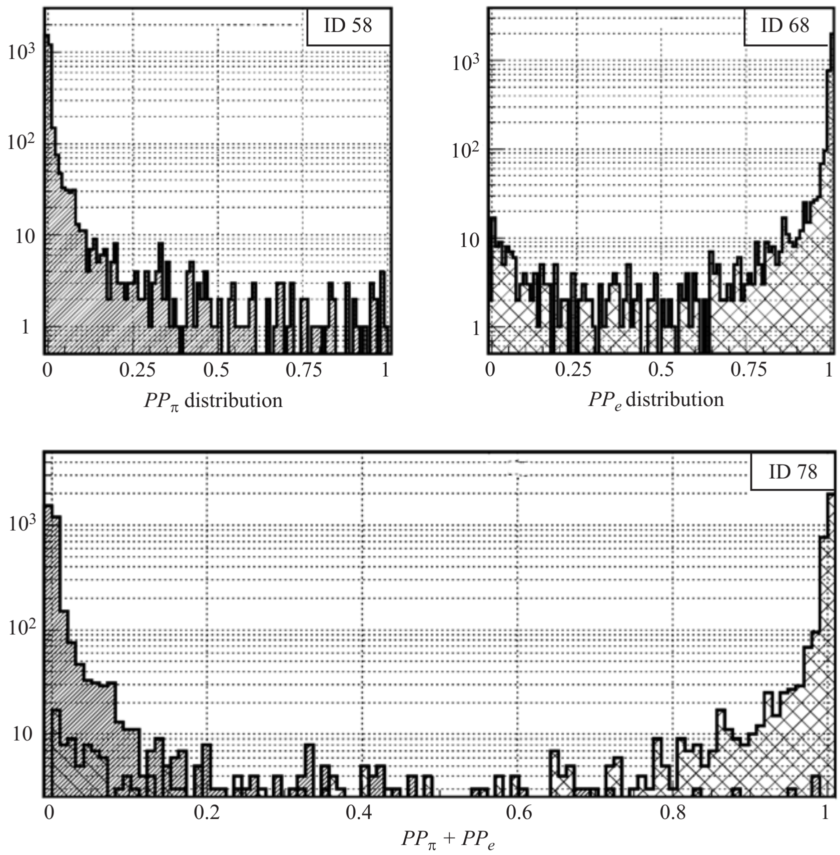


Fig. 17. Distributions of $L$ (GEANT simulations: March 2007) in cases when only pions (top left plot) or only electrons (top right plot) pass through the TRD with $n = 12$ layers; the bottom plot is the summary distribution of both particles

In our case $\alpha$ value was set approximately equal to 10%. In particular, the critical value $L_{\rm cr} = 0.00035$ corresponds to the significance level $\alpha = 10.24\%$, thus, in the admissable region there will remain 89.76% of electrons. In this case, the second-order error $\beta = 0.0274\%$. Thus, the suppression factor of pions that is equal to $100/\beta$, will make up 3646.

The distributions of the variable $L$ for the data sets based on GEANT simulations are shown in Figs. 17 (March 2007) and 18 (July 2007).

For March 2007 data the critical value $L_{\rm cr} = 0.91$ corresponds to the significance level $\alpha = 9.97\%$, thus, in the admissable region there will remain 90.03%

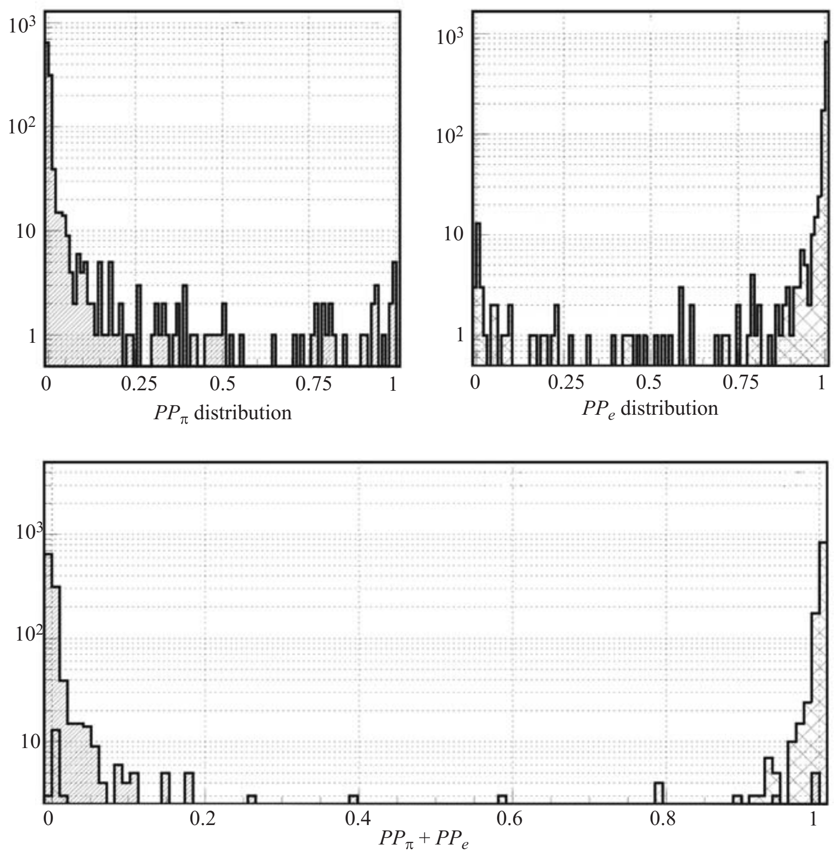


Fig. 18. Distributions of $L$ (GEANT simulations: July 2007) in cases when only pions (top left plot) or only electrons (top right plot) pass through the TRD with $n = 12$ layers; the bottom plot is the summary distribution of both particles

of electrons. In this case, $\beta = 0.3561\%$, and the suppression factor of pions will make up 281.

For July 2007 data the critical value $L_{\rm cr} = 0.975$ corresponds to the significance level $\alpha = 10\%$, thus, in the admissable region there will remain 90% of electrons. In this case, $\beta = 0.6087\%$, and the suppression factor of pions will constitute 164.

Thus, we may conclude that the noticable difference in the distributions of energy losses of pions and electrons for GEANT simulations compared to real measurements brought to the reduction of the pion suppression factor more than by the order of magnitude.

## 3. DISCUSSION OF RESULTS

The found form of the density function (2), which with a high accuracy fits the distribution of energy losses of electrons in one layer of the TRD, permits one

- to decompose the result of energy losses of electrons on two independent physical processes: 1) the process of ionization energy losses, and 2) the process related to the transition radiation;
- in the presence of real measurements of pion and electron energy losses in the TRD prototype to control and correct the process of simulation of energy losses in the GEANT package in frames of the CBM ROOT.

The analysis performed in Sec. 1 on a ratio of contributions into the electron distributions of ionization losses and transition radiation has shown that it is necessary to minimally increase the contribution of the transition radiation compared to ionization losses in accordance with the ratio obtained for real measurements. In addition, in the process of subsequent correction of the GEANT algorithm it is necessary to control statistical characteristics of the resulting process of energy losses and composing its components (obtained for real measurements).

As we have demonstrated in Sec. 2 for the TRD with $n = 12$ layers, the pion suppression factor for the 10% significance level of the electron identification (which corresponds to the 90% level of the electron registration) essentially depends on forms of the analyzed distributions.

In Table 2 we present the factors of pion suppression against the number $n$ of layers in the TRD.

**Table 2. Factor of pions suppression against the number $n$ of layers in the TRD**

| Type of data set | $n = 8$ | $n = 9$ | $n = 10$ | $n = 11$ | $n = 12$ |
|---|---|---|---|---|---|
| Prototype | 206 | 384 | 843 | 1872 | 3646 |
| GEANT (March 2007) | 50 | 77 | 135 | 198 | 281 |
| GEANT (July 2007) | 46 | 77 | 144 | 164 | 164 |

These results demonstrate that under the condition of loss $\approx 10\%$ of electrons, it is possible to achieve a reliable level of pion suppression already for $n = 8$ (suppression factor is 206 for real measurements). Approximately the same level of pion suppression for GEANT simulations is achieved only for $n = 11$ (March 2007) and $n = 12$ (July 2007).

## CONCLUSION

We have investigated the distributions of energy losses of electrons and pions in the TRD detector of the CBM experiment: 1) the energy deposits in the one-layer TRD prototype obtained during the test beam (GSI, Darmstadt, February 2006), and 2) Monte Carlo simulations of the TRD realized with the help of GEANT in frames of the CBM ROOT.

Our analysis has demonstrated that

- energy losses both for real measurements and GEANT simulations are approximated with a high accuracy by a log-normal distribution of pions and by a weighted sum of two lognormal distributions of electrons,
- GEANT simulations noticeably differ from real measurements and, as a result, we significantly lose in the efficiency of the electron identification and pion suppression.

We also demonstrate that under the condition of approximately 10% loss of electrons, it is possible to reach a reliable level of pion suppression already for $n = 8$ (factor of pion suppression constitutes 206 for real measurements).

The found forms of density functions of electrons and pions in one layer of the TRD permits to correctly decompose the energy losses of electrons in two independent physical processes:

- the process of ionization energy losses, and
- the process related to the transition radiation.

This allows one to control and correct the process of simulating the energy losses in the GEANT package in frames of the CBM ROOT.

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