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"Multiplicity distribution of neutral pions in hadron interactions (part 3)"

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Content

Introduction

The multiparticle production study in high energy physics is one of the fundamental issues. Quantum chromodynamics as the modern theory of strong interactions allows to make calculations in the region of high energy transferring. QCD can describe the process of partonic cascade after hadrons collision. However, the hadronization stage, which happens when the energy of each parton is too small to continue cascade, cannot be described with perturbation theory of QCD.

Multiplicity distribution was measured earlier in “Mirabelle” bubble chamber in proton-proton collision with energy of 50 GeV up to the number of charged particles $N_{ch} = 16$. The is kinematic limit, when all collision energy goes to masses of particles and they origin it the state of rest. For the total number of all particles there ($p + p \to N_+\pi^+ + N_-\pi^- + N_0\pi^0$) it is $N_+ + N_- + N_0 = N_{max} = \frac{\sqrt{s}-2m_p}{m_\pi} = 59$. Average multiplicity of charged particles measured in “Mirabelle” at this energy is $\langle N_{ch} \rangle = 5.4$

Studying of multiparticle production was in the project “Thermalization” [1]. Its purpose was to investigate the collective behavior of particles in the process of multiparticle production in proton or proton-nucleus interactions at the proton beam energy of 50-70 GeV in the region of high multiplicity ($n > \bar{n}$). The experiment in IHEP was carried out on modernized setup SVD-2 (Spectrometer with Vertex Detector). Before the experiment we expect collective effects, such as: formation of high density thermalized hadronic system, transition to pion Bose-Einstein condensate, events with ring topology (Cherenkov gluon radiation) and others. The SVD-2 setup detects charged particles (N_{ch}) and photons (N_γ) in every event. The data obtained at the SVD-2 setup allow us to develop and test different models of multiparticle production in the region of multiplicity that significantly higher than average value.

Mark Gorenstein and Viktor Begun in their works [2, 3] used the model of ideal pion gas, based on quantum statistics, in case of approaching Bose-Einstein condensate (BEC) state, since pions are bosons. BEC is a unique phase transition which occurs in the absence of interactions. As pions are the lightest hadrons, they copiously produced at high energy which decreases with increasing of total multiplicity. Their microcanonical ensemble calculations has shown the growth of fluctuations in the number of neutral pions at high multiplicity. These fluctuations can be detected by increasing of scaled variance ω as a function of N_{tot}, which is defined as ration of variance of the neutral pion number distribution D to its mean value $\langle N_0 \rangle$. The function $\omega(N_{tot})$, where $N_{tot} = N_{ch} + N_0$ is the sum of number of charged and neutral particles, depends on the temperature and energy density of the system. To analyze data with different N_{tot} relative values were used: $n_0 = N_0/N_{tot}$ and $r_0 = N_{ev}(N_0, N_{tot})/N_{ev}(N_{tot})$. Here $N_{ev}(N_0, N_{tot})$ is the number of events with particular value of neutral particles N_0 at given total number of particles N_{tot}, and $N_{ev}(N_{tot})$ is the number of events with N_{tot}. It is obvious that n_0 changes in range of [0; 1] and $\sum_{N_0} r_0 = 1$.

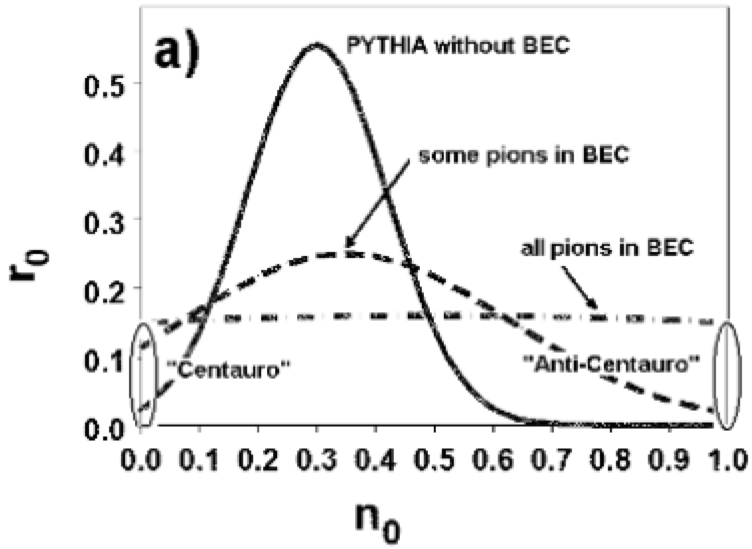


Fig. 1. Distribution for normalized multiplicity of neutral pions in case of approaching by system the BEC state.

Figure 1 schematically shows the behavior of distribution r_0 as a function of relative multiplicity n_0. There are 3 cases: pion system in the absence of condensate, all particles of the system are in BEC state, and the middle state, when some pions drop out into condensate.

Installation description

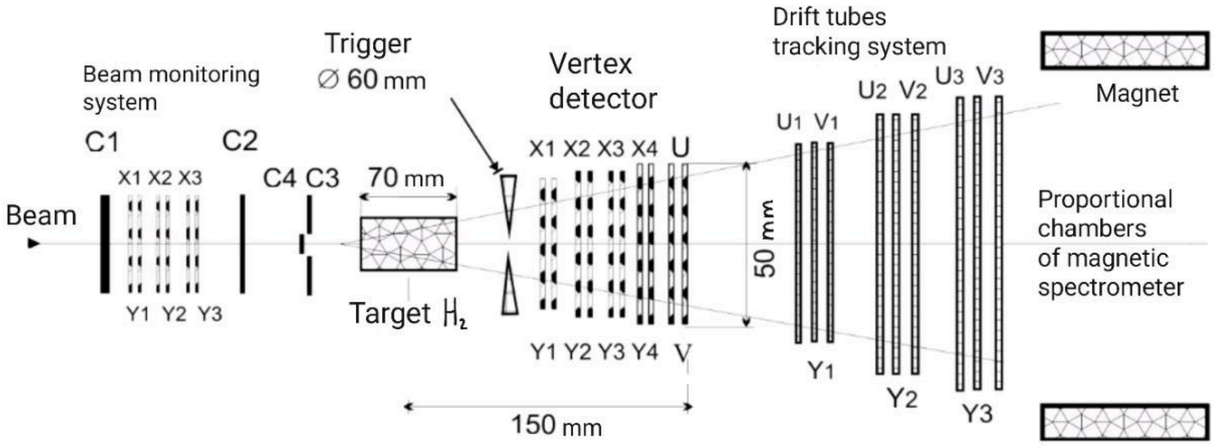


Fig. 2. The Spectrometer with Vertex Detector schematic setup [4].

The SVD-2 schematic setup is shown in the Figure 2. The basic elements of the SVD-2 setup are the liquid hydrogen target, microstrip silicon vertex detector (VD), a system of drift tubes, magnetic spectrometer with proportional chambers, a threshold Cherenkov counter and electromagnetic calorimeter (ECal) [4, 5].

Vertex detector consists of 10 planes of microstrip Si-detectors X, Y, U, V [4]. Stripes in the X and Y detectors are directed vertically and horizontally, while detectors U and V are rotated relative to the X, Y detectors by an angle of ±10,5^0. The stripes' step is $d = 50\ \mu m$. To find track's coordinate in microstrip detector the following method is used: $\bar{x} = \sum_i A_i x_i / \sum_i x_i$, where $x_i = An + d/2$ is coordinate of n stripe and A_i is an amplitude of signal. Track is described with straight line in XZ and YZ projections, which allows to clearly determine spatial coordinates and to reconstruct tracks using the oblique planes U and V placed at the end of VD.

The tracking system of drift tubes consists of 3 modules with 3 chambers UYV each (where U and V are rotated the relative to the vertical axis by an angle of ±10,5^0) [5]. Each chamber includes 2 layers of gas-filled detectors shifted by a half of diameter $d/2$ ($d = 6\ mm$) relative to each other in order to eliminate left-right uncertainty. The coordinate accuracy is $200\ \mu m$. This system is used to make tracks obtained from vertex detector more precise.

To suppress the low multiplicity event registration and to select the high charged multiplicity events SVD-2 is supplied with the scintillator hodoscope or high multiplicity (HM) trigger [6].

Simulation of π^0 registration

The presence in the SVD-2 setup of DEGA (DEtector of Gamma quants) allows to register events with production of neutral pions, which is followed by their decay into 2γ. Due to the finite aperture of DEGA and the fact that there is lower limit on the photon detection energy, it is impossible to register all π^0- mesons. However, the efficiency of neutral pion registration can be measured by means of simulation.

Using the PYTHIA5.6 code there were generated 10 million of inelastic events $p + p \to X$ at the energy of 50 GeV [7]. We take the efficiency of photon-detection in DEGA as 1, if γ is detected in calorimeter and its energy is higher than 100 MeV.

The analysis of events with $N_{ch} \geq 4$ gives following results:

- there are 83% of all events with 1 and more π^0- meson
- $\langle N_{ch} \rangle = 6.0$, $\langle N_0 \rangle = 2.3$ and $\langle N_\gamma \rangle = 4.3$
- 95% of all detected photons are produced from π^0 decay (almost all γ are originated from neutral pion decays)
- π^0- meson has to have laboratory energy higher than 1 GeV to make both photons from decay to find their way to the DEGA aperture
- 37% of all π^0 generate a signal in DEGA; for a half of them both photons from decay hit the detector, while for another half only one γ is detected

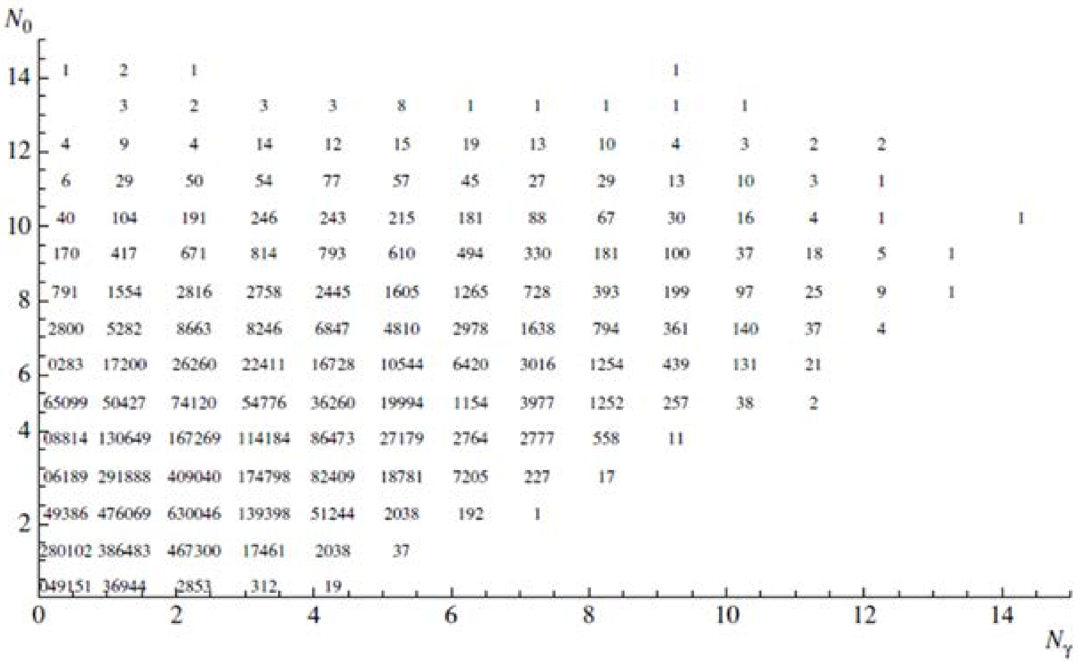
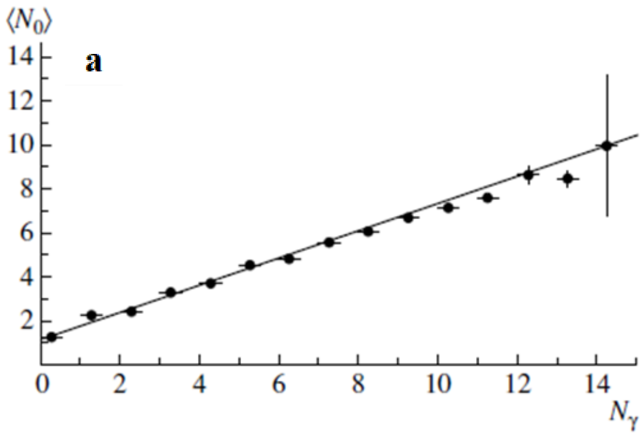


Fig. 3. The number of π^0-mesons N_0 in the event as a function of the number of photons N_γ [7]

The Figure 3 shows the behavior of number of neutral pions as a function of the number of photons. It is clear that the number of π^0 in particular event cannot be determined precisely via “event by event” method. However, we are based on the statistical method, and it is possible to determine the probability of existence particular number N_0 of neutral pions in event with N_γ photons detected in DEGA.



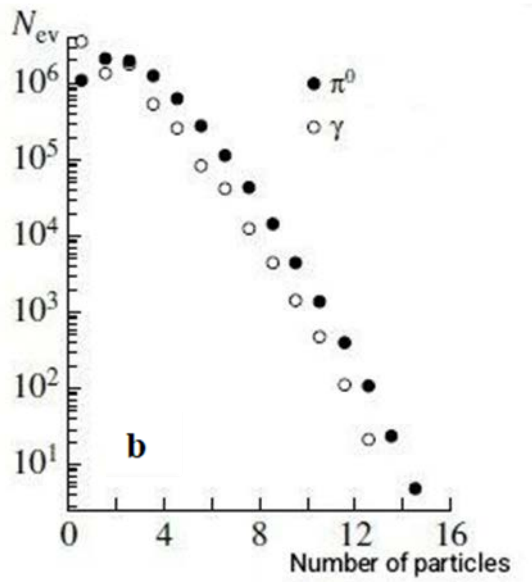


Fig. 4. a) The average number of neutral pions $\langle N_0 \rangle$ as a function of the number of photons N_γ
b) Multiplicity distribution for neutral pions and photons in DEGA [7]

It is important that there is linear correlation between mean value $\langle N_0 \rangle$ and N_γ that is shown at the Figure 4a. In the result of analysis there were obtained coefficients that relate numbers of events $N_{ev}(N_0, N_{ch})$ and $N_{ev}(N_\gamma, N_{ch})$. It will be used later for finding fluctuations of neutral pions. The Figure 4b illustrates multiplicity distribution of π^0-mesons and γ in detector. The forms of distributions look similar except region of low multiplicity.

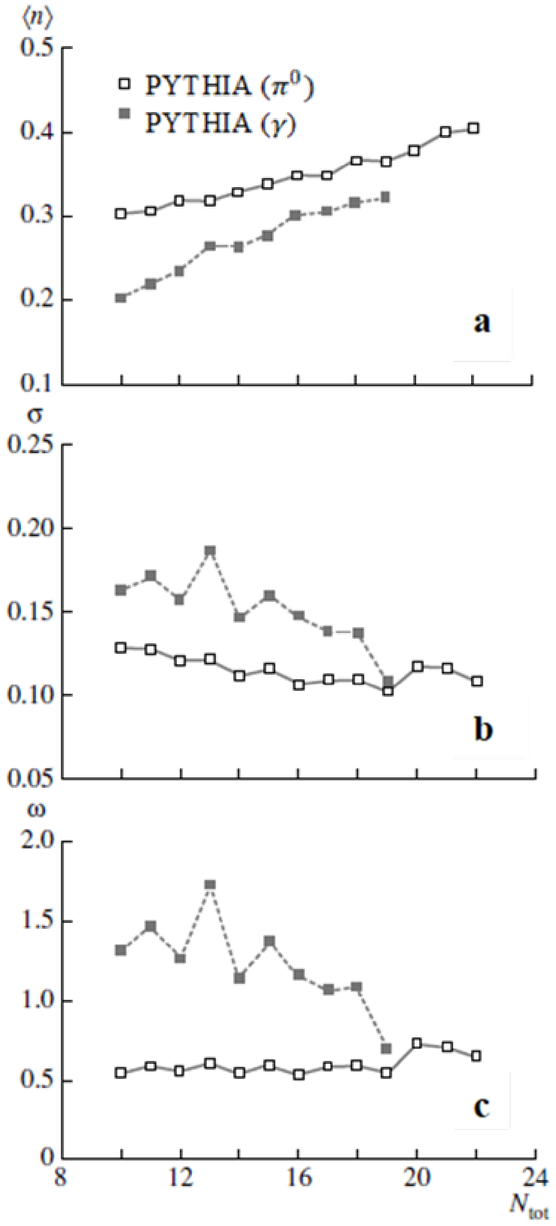


Fig. 5. The meanings of **a)** $\langle n_0 \rangle$ and $\langle n_\gamma \rangle$ **b)** standard deviation σ of n_0 and n_γ values **c)** parameter ω as a function of N_{tot} [7]

The Figure 5 illustrates the results of Monte-Carlo simulation: average values $\langle n_0 \rangle$, $\langle n_\gamma \rangle$ (where $n_{0,\gamma} = N_{0,\gamma}/N_{tot}$), their standard deviations σ and the parameter (scaled variance) $\omega = D/\langle n \rangle = \sigma^2 N_{tot}/\langle n \rangle$ as a function of total number of particles N_{tot}. The values ω slightly decreases in case of photons, while for neutral pions it remains almost constant in the total range of N_{tot} changes. Simulation does not match predictions of V. Begun and M. Gorenstein.

Measurement of neutral pion fluctuations

Researching of neutral pions fluctuations as a function of their total number requires the information about reconstructed multiplicity distribution of charged particles. Suppressing of low multiplicity events by HM trigger and possible mistakes during tracks reconstruction have to be taken into account. The weights, stipulated by a disproportionate selection of events with different multiplicities, and ultimate distributions $N_{tot} = N_{ch} + N_{\gamma}$ as a function of different meanings of N_0 and N_{γ} were obtained in the work [4].

The simulation has showed that the number of photons in DEGA depends linearly on the average multiplicity of π^0 (see Fig.4a). In order to reconstruct the numbers of neutral pions we use 2-dimensional distribution $N_{ev}(N_0, N_{\gamma})$ (see Fig.3). In the following discussion we will use designation $i = N_{\gamma}$, $j = N_0$ and $N_{ev}\left(N_0, N_{\gamma}\right) = N_{ev}(i,j)$. For each number of charged particles N_{ch} the matrix coefficients $c_{ij} = \frac{N_{ev}(i,j)}{N_{ev}(i)}$, where $N_{ev}(i) = \sum_j N_{ev}(i,j)$, can be obtained from 2-dimentional distributions. Further, the numbers of the events $N_{ev}(N_{\gamma}, N_{ch})$ are decomposed into the sum of events in which N_0 and $N_{ev}(i,j) = c_{ij}N_{ev}(i)$ takes different values at $N_{ch} = const$. For c_{ij} the following normalization condition holds: $\sum_{i,j} c_{ij} = 1$. The obtained sum $N_{ev}(j) = \sum_i N_{ev}(i,j)$ is the number of events $N_{ev}(N_0, N_{ch})$ at $N_{ch} = const$, so it is similar to $N_{ev}(N_{\gamma}, N_{ch})$ but now for neutral pions. The result is that with these coefficients from simulation we can reconstruct the table of experimental number of events for every multiplicity of neutral pions.

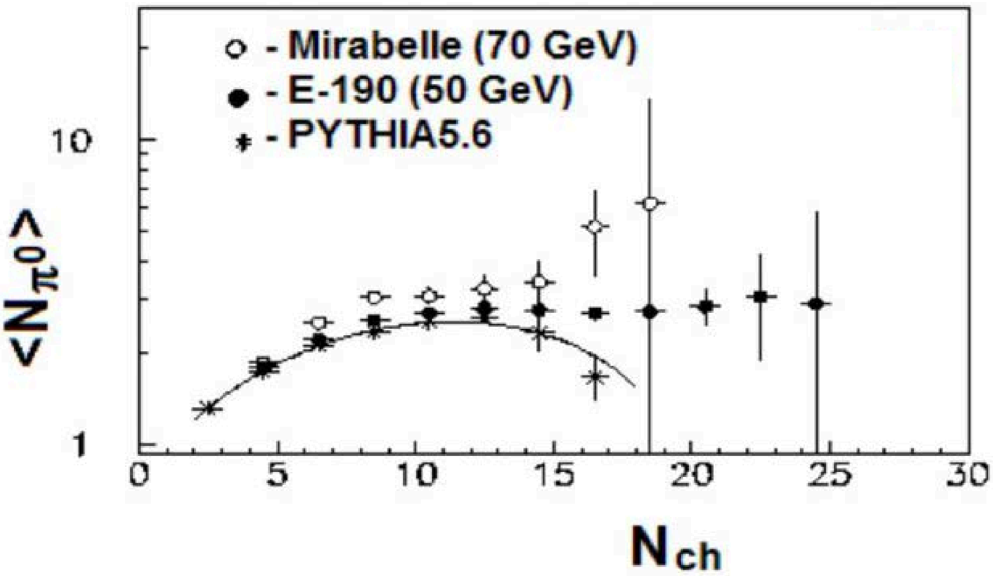


Fig. 6. The comparison of dependence of average number of neutral pions on charged multiplicity for Monte-Carlo simulation, data from Mirabelle 70 at GeV and SVD-2 at 50 GeV [8]

The Figure 6 shows that the average number of neutral pions after reconstruction is an agreement with Mirabelle data at 70 GeV. This fact confirms the correctness of reconstruction procedure.

In the beginning we introduced scaled variables $n_0 = N_0/N_{tot}$ and $r_0 = N_{ev}(N_0, N_{tot})/N_{ev}(N_{tot})$. Distributions for these values at different $N_{tot} \geq 10$ are shown in the Figure 7. The data in the region of high multiplicity $(26 + 27 + 28)$ and $(29 + 30 + 31)$ are combined due to small statistics. All distributions are parametrized with gauss function.

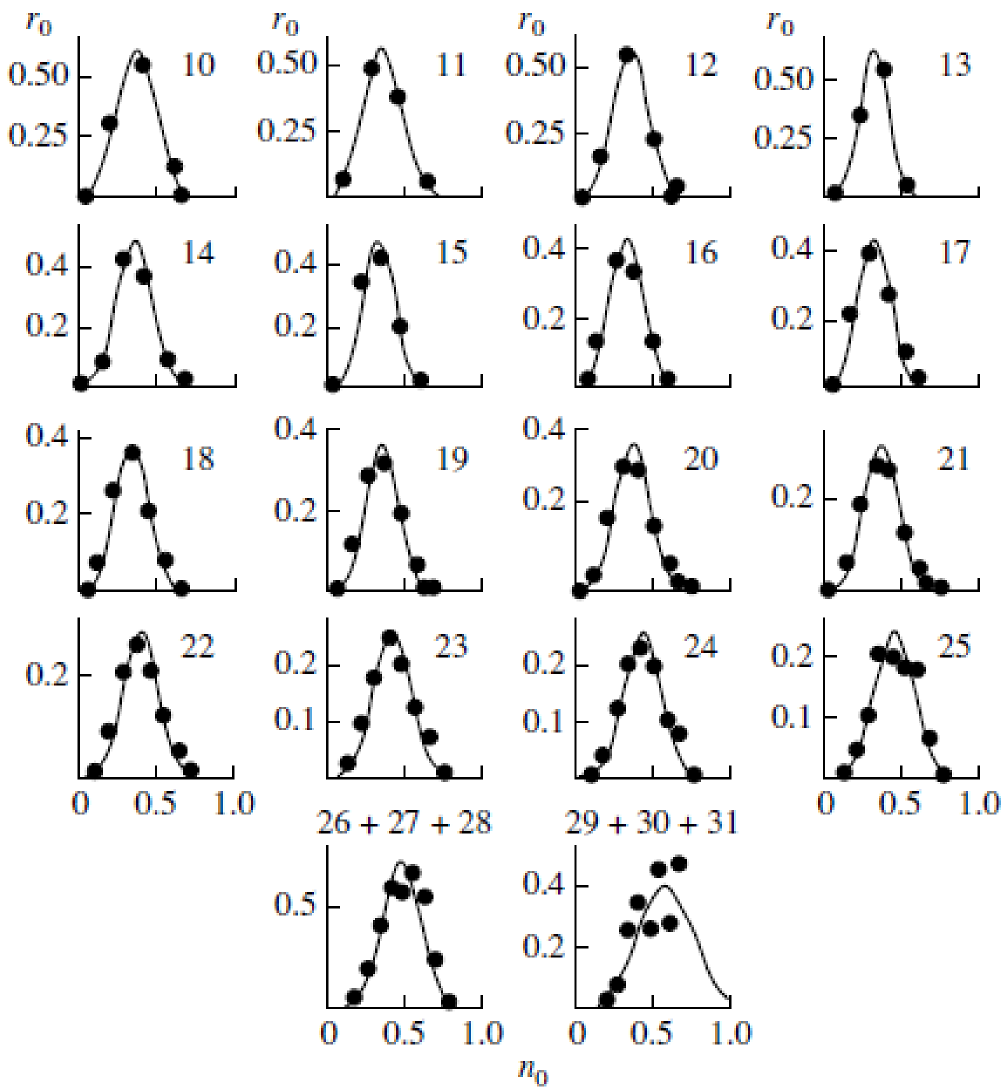
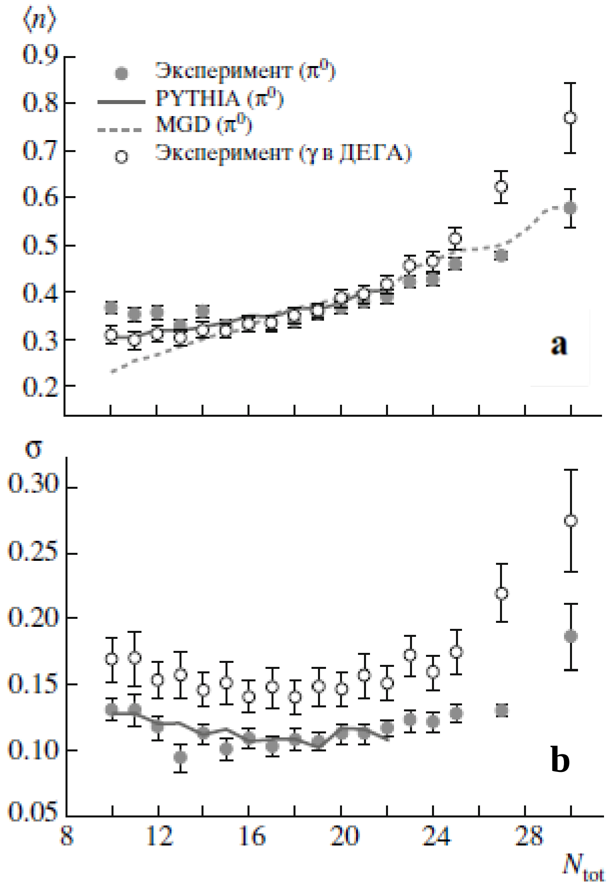


Fig. 7. Scaled π^0 number n_0 distribution for different N_{tot} (indicated in the figure) [7]

These distributions allow to calculate the mean, variance and scaled variance of neutral pion number. The results of these calculations are shown in the Figure 8. The theoretical prediction for the behavior of scaled variance ω is given in [2] for 3 different energy densities at the approach of Bose-Einstein condensate. The growth of the parameter ω at high multiplicity (see Fig. 8c) evidences for the possibility of the

BEC formation in pion system in pp-interactions at 50 GeV as it was predicted according to statistical models [2].



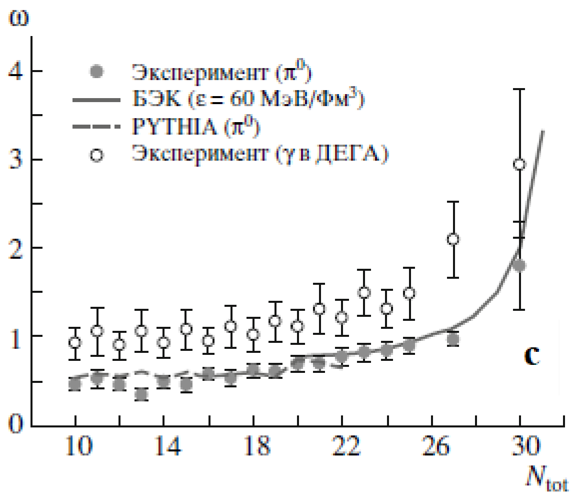


Fig. 8. Parameters of distribution as a function of N_{tot} for experimental data and Monte-Carlo events **a)** mean value of neutral pions and photons **b)** standard deviation **c)** scaled variance

Gluon dominance model

In the previous work we obtained multiplicity distribution function in pp-interaction in Gluon Dominance Model (GDM) with gluon fission and without it [9]. In case of neutral particles distribution, we do not have to consider the existence of 2 initial protons, as we did for distribution of charged particles.

$$P_n = \alpha \sum_{m}^{M_g} \frac{e^{-\bar{m}}\bar{m}^m}{m!} C_{mN}^{n} \left(\frac{\bar{n}^h}{N}\right)^n \left(1 - \frac{\bar{n}^h}{N}\right)^{mN-n} \quad (1)$$

The obtained function has 4 parameters:

- α is a coefficient of normalization
- $\bar{m}$ is an average multiplicity of gluons
- $\bar{n}^h$ is an average multiplicity of produced hadron from a single gluon at ha
- N is the maximum possible number of hadrons produced from 1 gluon at the stage of hadronization

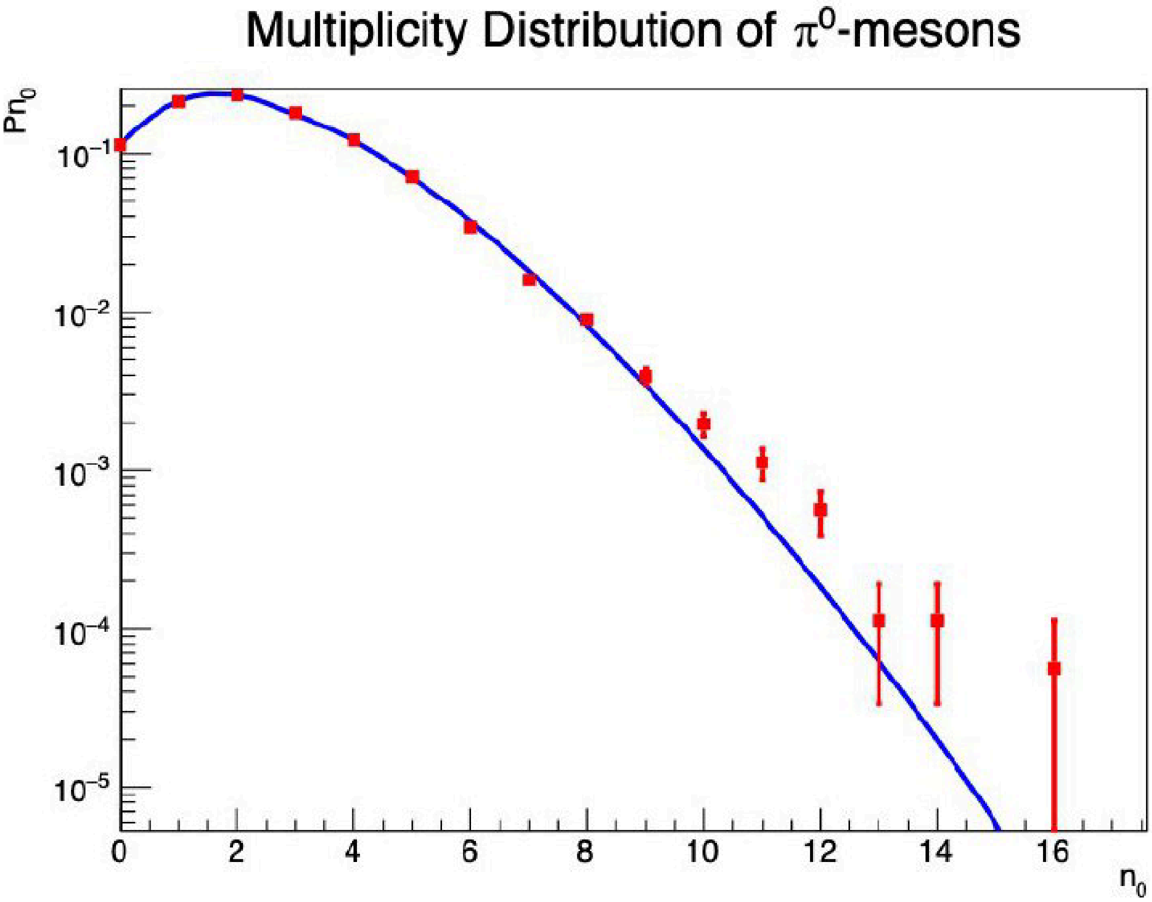


Fig. 9. The multiplicity distribution of neutral mesons: data from project “Thermalization” (marked with red squares) and distribution function in GDM without gluon fission (marked with blue line).

The Figure 9 shows the fitting of experimental data with multiplicity distribution function (1) in GDM without fission. It is seen that function in the region of high multiplicity lies below experimental data. That allows us to make a conclusion that it is necessary to take into account the contribution of gluon fission process.

In this case the multiplicity distribution function will look as (2). Here α_1 and α_2 describe the contribution of a single and double gluon groups ($\alpha_1 + \alpha_2 = 1$).

$$P_n = \alpha_1 \sum_m^{M_g} \frac{e^{-\overline{m_1}} \overline{m_1}^m}{m!} C_{mN}^n \left(\frac{\bar{n}^h}{N}\right)^n \left(1 - \frac{\bar{n}^h}{N}\right)^{mN-n} + \alpha_2 \sum_m^{M_g} \frac{e^{-\overline{m_2}} \overline{m_2}^m}{m!} C_{2mN}^n \left(\frac{\bar{n}^h}{N}\right)^n \left(1 - \frac{\bar{n}^h}{N}\right)^{2mN-n} \qquad (2)$$

The Figure 10 shows the same fitting but with function (2) that includes the contribution of gluon fission. It is clear that now the high multiplicity region of fitted function is in good agreement with experimental data.

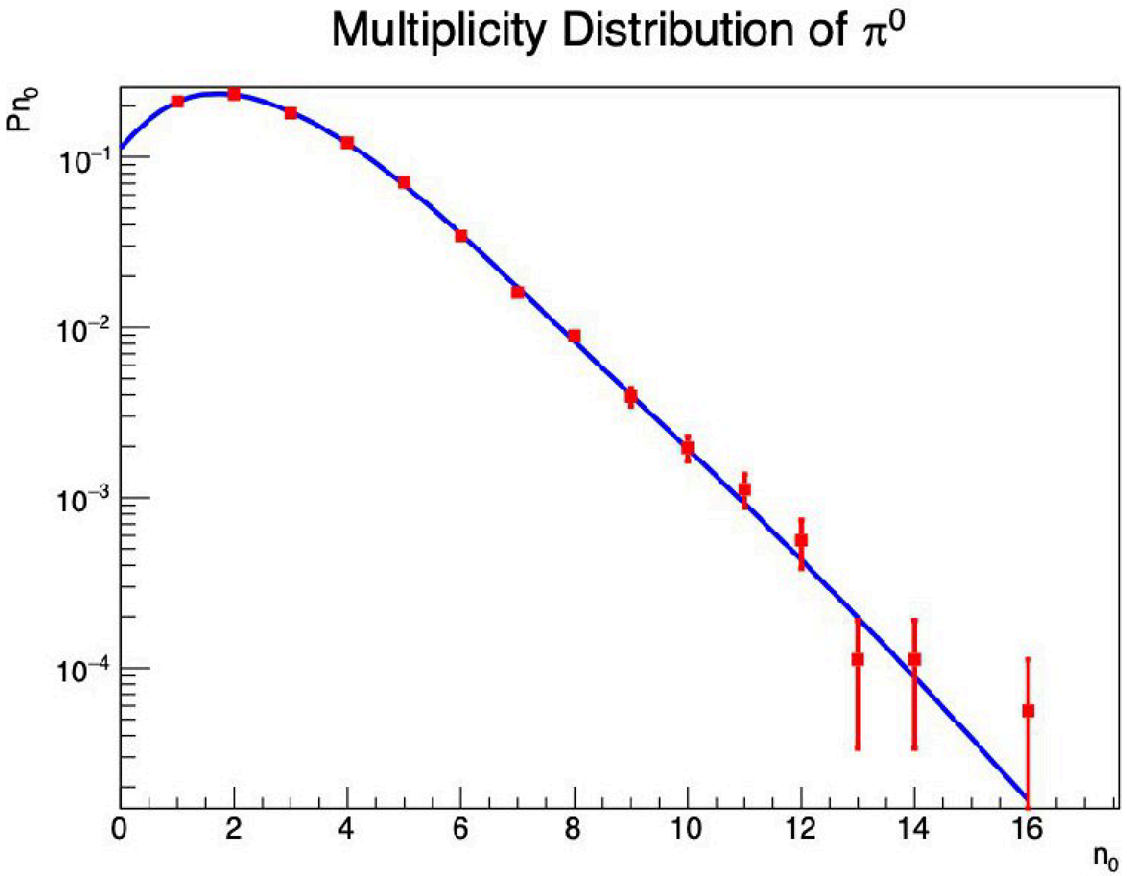


Fig. 10. The multiplicity distribution of neutral mesons: data from project “Thermalization” (marked with red squares) and distribution function in GDM with gluon fission (marked with blue line).

Conclusion

Simulation of π^0 registration has showed a linear dependence between mean value of neutral pions and the number of photons in DEGA. Distributions of scaled π^0 number for each total number of particles N_{tot} were obtained after transition from number of photons to number of neutral pions and making corrections stipulated by using HM trigger.

The measurements of number of neutral pions and their fluctuations for events with high multiplicity gave us an important result. We managed to confirm the fact of approaching the BEC state by pion system by measuring scaled variance $\omega = D/\langle N_0 \rangle$. Increasing of parameter ω at $N_{tot} > 22$ indicated about right conditions of pion condensate that were predicted by different models.

Applying of Gluon Dominance Model for the results of experiment gave the conclusion that process of gluon fission have a valuable contribution mostly in the region of high multiplicity.

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