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Fluctuations of the Number of Neutral Pions at High Multiplicity in pp Interactions at 50 GeV

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Abstract—Results obtained by measuring fluctuations of the number of neutral pions in the SERP-E-190 Experiment (Thermalization Project) upon irradiating a liquid-hydrogen target of the SVD-2 setup with a beam of 50-GeV protons are presented. A simulation of the detection of photons from the decay of neutral pions with the aid of an electromagnetic calorimeter revealed a linear relation between the number of detected photons and the mean number of neutral pions in an event. After the introduction of corrections for the loss of charged tracks because of a limited acceptance of the setup, trigger operation, and the efficiency of the data-treatment system, distributions of the number of neutral pions, N_0, were obtained for each value of the total number of particles in an event, $N_{\rm tot} = N_{\rm ch} + N_0$. The fluctuation parameter $\omega = D/\langle N_0\rangle$ was measured. In the region $N_{\rm tot} > 22$, fluctuations of the number of neutral pions increase, which, within statistical models (GCE, CE, MCE), indicates that the system involving a large number of pions approaches the pion-condensate state. This effect was observed for the first time.

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INTRODUCTION

By using SVD-2 (Spetrometer with a Vertex Detector) setup, which is irradiated with a proton beam extracted from the U-70 accelerator of the Institute for High Energy Physics (IHEP, Protvino), the SERP-E-190 experiment has been performed within the Thermalization Project. The setup in question includes a liquid-hydrogen target, a microstrip silicon vertex detector (VD), a system of minidrift tubes, a magnetic spectrometer, a threshold Cherenkov counter, and an electromagnetic calorimeter [1].

The objective of the Thermalization Project is to study multiparticle-production processes in pp interactions at the proton-beam energy of 50 GeV. Multiparticle processes are one of the fundamental regions of research into hadron physics. They cannot be described on the basis of perturbative QCD. The theory provides only a qualitative picture of the process. The multiplicity distribution of particles at the energy of 50 GeV was previously measured [2] for charged-particle numbers of up to $N_{\rm ch} = 16$. The mean multiplicity of charged particles at this energy is $\langle N_{\rm ch}\rangle = 5.3$. The kinematical limit for the total number of charged and neutral particles is $N_{\rm tot} = 56$. In this article, we present data in the ranges $N_{\rm ch} = 4$–22 and $N_{\rm tot} = 4$–31. At multiplicity values exceeding substantially the mean multiplicity, collective effects may manifest themselves in the form of large fluctuations of the numbers of charged and neutral pions because of the formation of a pion condensate, the formation of jets of identical pions (so-called multiparticle Bose–Einstein effect), the presence of ring-topology events induced by the hadronization of gluons emitted by partons in nuclear matter (analog of Cherenkov radiation), and so on. Data obtained at the

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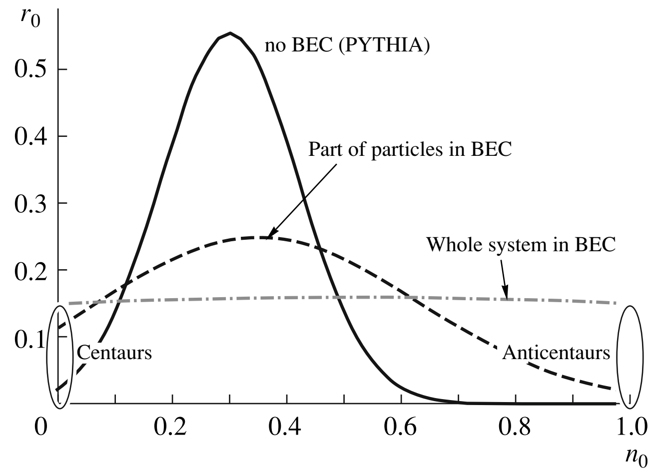

Fig. 1. Neutral-pion multiplicity as a fraction of $N_{\rm tot}$ in QCD and in the case where the pion system approaches the state of a Bose–Einstein condensate (BEC).

SVD-2 setup make it possible to test various models of multiparticle production in the region $N_{\rm tot} > \langle N_{\rm tot}\rangle$ and give impetus to a further development of such models.

Begun and Gorenstein showed [3, 4] that, within a model based on quantum statistics, fluctuations of the number of neutral pions increase in the pion system as it approaches the conditions of the formation of a Bose–Einstein condensate (BEC). These fluctuations may be revealed by the growth of the normalized variance defined as the ratio of the variance D for the distribution of the number N_0 of neutral pions to the mean value $\langle N_0\rangle$; that is,

$$\omega = D/\langle N_0\rangle.$$

The degree of growth of ω as the total number of neutral and charged particles, $N_{\rm tot} = N_{\rm ch} + N_0$, increases depends on the temperature of the pion system and on its energy density.

In searches for neutral-pion fluctuations, we employed here part of data obtained in the SERP-E-190 experiment. In each event, the setup used records the charged-particle multiplicity $N_{\rm ch}$ and the photon multiplicity N_γ. By means of a simulation, these quantities are corrected for the detection efficiency and for the acceptance of the equipment. The simulation also makes it possible to establish the number of neutral pions, N_0. In order to analyze data at various values of the total multiplicity $N_{\rm tot}$, we employed the relative values $n_0 = N_0/N_{\rm tot}$ and $r_0 = N_{\rm ev}(N_0, N_{\rm tot})/N_{\rm ev}(N_{\rm tot})$. Here, $N_{\rm ev}(N_0, N_{\rm tot})$ is the number of events where the number of neutral pions is fixed at a preset value and where the total number of particles is $N_{\rm tot}$, while $N_{\rm ev}(N_{\rm tot})$ is the number of events where the total multiplicity is $N_{\rm tot}$. The quantity r_0 is the fraction of events where the number of neutral pions is N_0 with respect to the total number of events where the value of $N_{\rm tot}$ is fixed. The quantity n_0 changes in the range [0, 1], and the sum of all r_0 is equal to unity for each $N_{\rm tot}$.

Figure 1 illustrates qualitatively the distribution of the relative neutral-pion multiplicity n_0 in a simulation of events on the basis of the PYTHIA5.6 code for the system of pions where there is no condensate, for the system of pions where part of particles form a condensate, and for the case where all particles are in the BEC state. Each distribution parameterized in terms of a Gaussian function is characterized by a mean value $\langle n_0\rangle$ and by a standard deviation σ.

SIMULATION OF NEUTRAL-PION DETECTION

The presence of a photon detector (DEGA, which stands for DEtector of GAmmas) in the SVD-2 setup makes it possible to record events where the production of neutral pions is followed by their decay to two photons. Since DEGA has a finite aperture and since there is a lower limit on the photon-detection energy, it is impossible to record all neutral pions in an event, but, via a simulation, one can determine the efficiency of neutral-pion detection. For the problem of measuring fluctuations of the number of neutral pions, the existence of a linear relation between the number of detected photons and the number of neutral pions in an event is of importance.

With the aid of the PYTHIA5.6 code, we generated about 10^6 inelastic $pp \to X$ events at 50 GeV. The efficiency of photon detection in DEGA was taken to be unity if a photon finds its way to the calorimeter aperture (a rectangle 160×122 cm in area at a distance of 1070 cm from the target) and if its energy

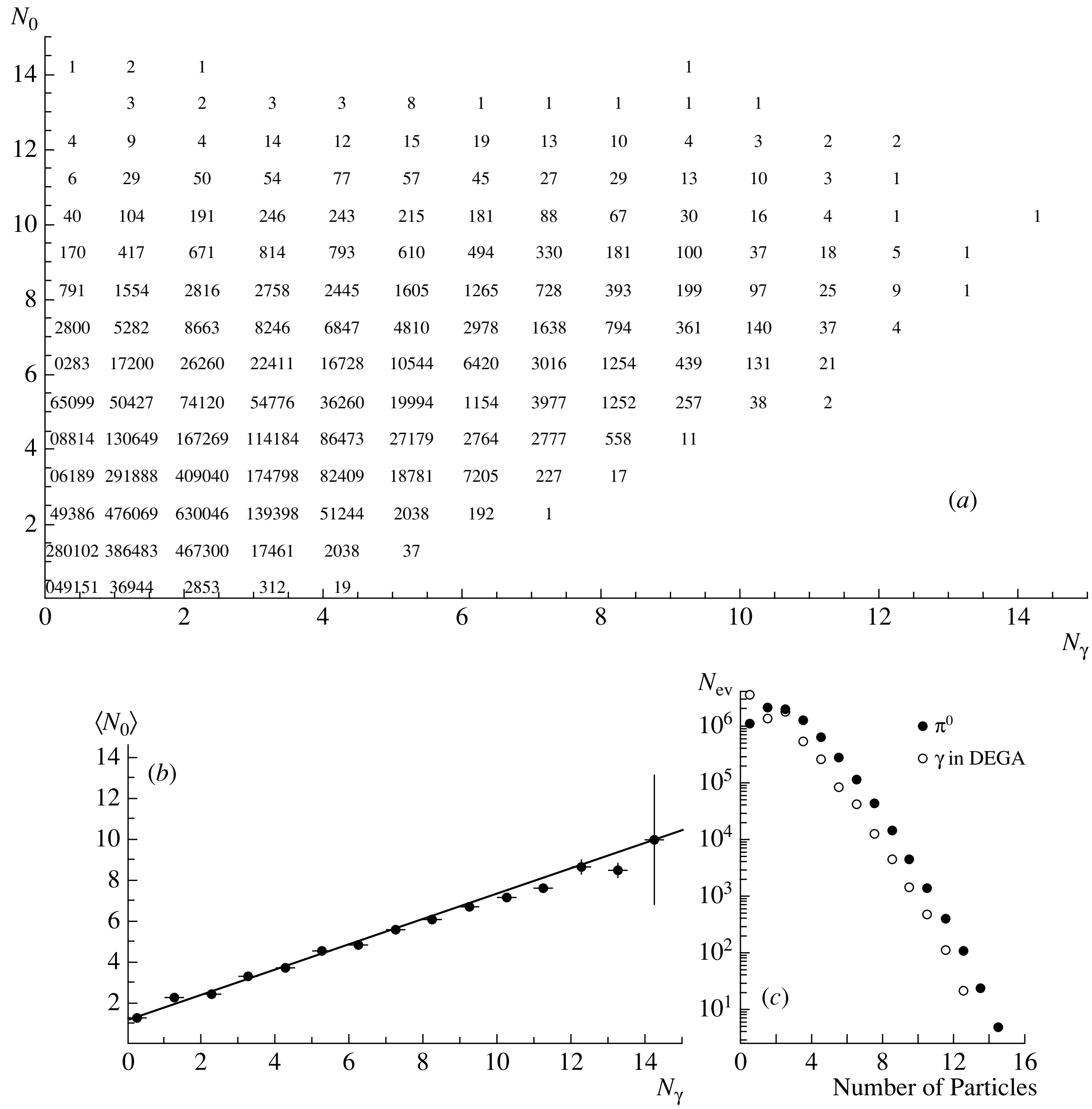

Fig. 2. (*a*) Number of π^0 mesons, N_0, in an event as a function of the number of photons, N_γ, in the photon detector (DEGA—that is, DEtector of GAmmas); (*b*) $\langle N_0 \rangle$ as a function N_γ; and (*c*) multiplicity distribution for all π^0 and γ in DEGA.

is in excess of 100 MeV. We analyzed only events in which $N_{\text{ch}} \geq 4$. Among them, the number of events featuring one or more neutral pions was 83%. The mean multiplicity of charged particles in an event was $\langle N_{\text{ch}} \rangle = 6.0$. The mean multiplicity of neutral pions was $\langle N_0 \rangle = 2.3$. The mean multiplicity of all photons was $\langle N_\gamma \rangle = 4.3$, their fraction from neutral-pion decays being 95%—that is, almost all photons in an event originated from neutral-pion decays. Our simulation revealed that the laboratory energy of a neutral pion must be higher than 1 GeV for both photons from its decay to find their way to the DEGA aperture. Only 37% of all pions generate a signal in DEGA; for half of them, both photons from neutral-pion decay hit the detector, while, for the other half, only one does this.

Figure 2 illustrates the behavior of the number of neutral pions as a function of N_γ in DEGA. One can see that, in an individual event, it is impossible to determine precisely the total number of neutral pions (Fig. 2*a*). One can only find the probability with which some number N_0 corresponds to the number N_γ of photons that hit DEGA. From our analysis, we derived coefficients that relate the numbers of events $N_{\text{ev}}(N_\gamma, N_{\text{ch}})$ and $N_{\text{ev}}(N_0, N_{\text{ch}})$ and which we use in the following to find fluctuations of the number of neutral pions. It is important that the mean value $\langle N_0 \rangle$ depends linearly on the number N_γ (see Fig. 2*b*).

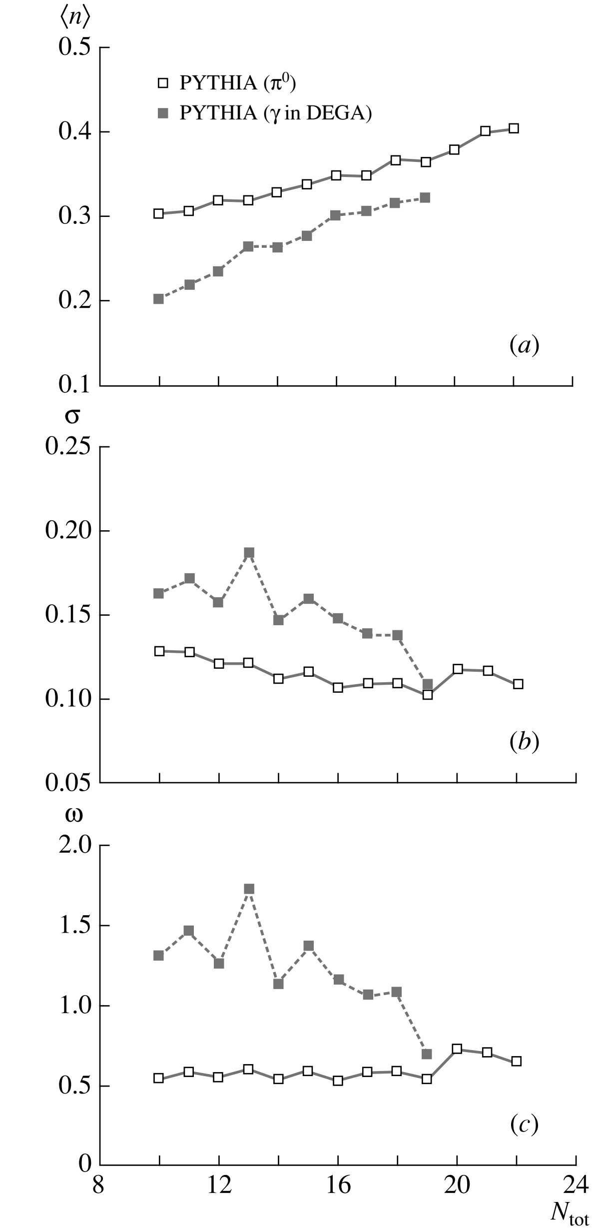

Fig. 3. (a) Mean values $\langle n_0 \rangle$ and $\langle n_\gamma \rangle$ and (b) respective standard deviations σ versus the total number of particles, N_{tot}, for Monte Carlo events; (c) parameter ω.

Figure 2c shows the multiplicity distribution of all neutral pions and photons in DEGA. Figure 3 illustrates the results obtained from our Monte Carlo (MC) simulation of the dependence of the mean values $\langle n_0 \rangle$ and $\langle n_\gamma \rangle$, the respective standard deviations σ, and the parameter ω ($\omega = \sigma^2 N_{\text{tot}}/\langle n \rangle$) on the total number of particles, N_{tot}, for MC events. Over the entire range of N_{tot}, the parameter ω decreases for photons, but it remains virtually invariant for pions.

PHOTON DETECTION

The DEGA detecting element consists of a lead-glass block (38 × 38 × 505 mm in volume) and a photomultiplier tube (PMT). Almost the entire amount of energy (98%) of the electromagnetic shower initiated by a photon hitting the lead-glass center is deposited in a cell containing 3 × 3 elements since the transverse size of the glass is equal to the Molière radius, the energy deposited in the central element of the cell being, on average, 77% of the total shower energy (Fig. 4a). The number of elements in DEGA is 32(vertical) × 42(horizontal) = 1344. The calibration of DEGA was performed by means of irradiating the center of each element with a narrow (⊘3 mm wide) beam of 15-GeV electrons. The treatment of the data from DEGA consists in searches for clusters of signals in the aforementioned 3 × 3 cell and in the application to them of criteria that select showers initiated by photons. The main criteria are the following:

(i) A cluster (3 × 3) should contain not less than two channels in which the signal is above the threshold equal to ten counts of the analog-to-digital converter (ADC) used. In the absence of signals in channels neighboring the central one because to the presence of uninvolved channels or because of a signal below the threshold, one corrects the total shower energy. It should not exceed 50 GeV.

(ii) The value of the parameter $a5$, which is defined as the ratio of the energy in the central channel to the summed energy of all nine channels, should be greater than 0.4 for a photon (see Fig. 4b). The closer to the glass center the point at which a photon enters the glass, the greater this value. For a nuclear cascade initiated by a charged particle, this quantity is below 0.5.

After processing the statistical sample used in the present study (about 500 000 events) and after selecting electromagnetic showers in accordance with the above criteria, we obtained the following results: the mean multiplicity of photons in an event is $\langle N_\gamma \rangle = 3.0$ (Fig. 5a), their mean energy is $\langle E_\gamma \rangle =$ 2.8 GeV (Fig. 5b), and the minimum detection energy is 100 MeV.

DETECTION OF CHARGED PARTICLES

In order to determine N_{ch}, we employ information from the vertex detector. An investigation of the dependence of fluctuations of the number of neutral pions on the total number of particles requires knowing the reconstructed multiplicity of charged particles with corrections for the efficiency of multiplicity reconstruction in the vertex detector and for the loss of tracks because of a limited aperture of the vertex

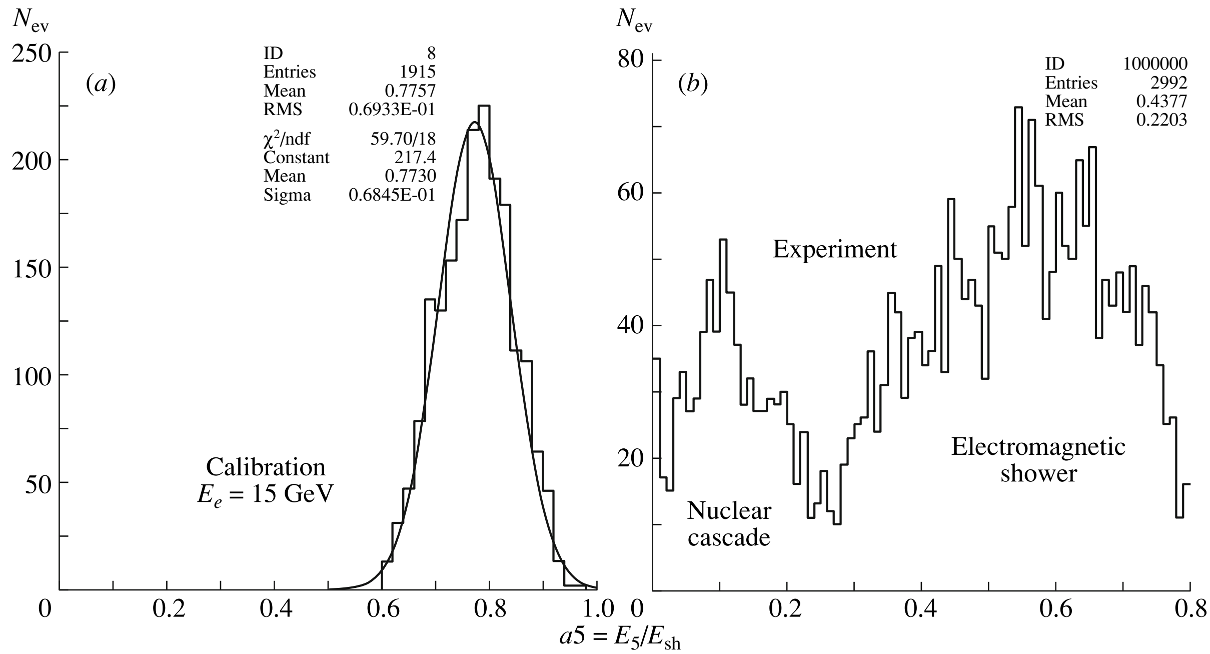

Fig. 4. Values of the parameter $a5$ (see main body of the text) for (a) electromagnetic showers in calibration and (b) reconstructed showers (3×3) in the live experiment.

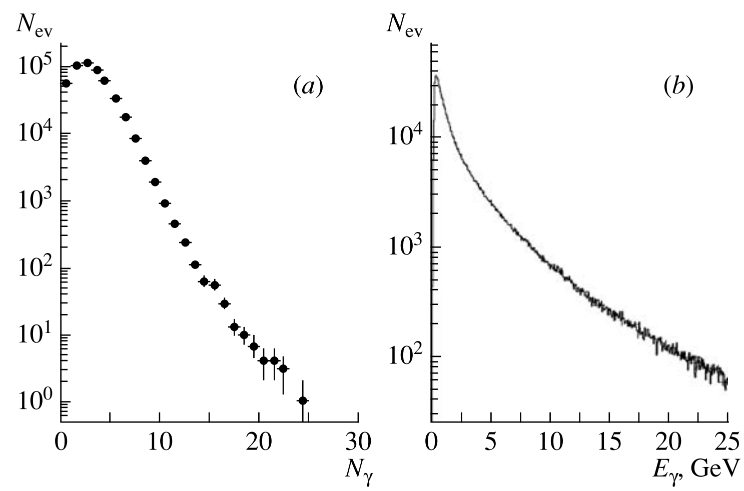

Fig. 5. Distribution of observed events with respect to (a) the number of observed photons and (b) with respect to their energy.

detector. A simulation of losses of charged tracks in the vertex detector was performed in [5], and a table of weights that represent the contribution of events featuring various true numbers of charged particles to a sample of events where a specific charged multiplicity is recorded was obtained there. In the present study, events characterized by measured N_{ch} are distributed according to the weights in question among samples of events with a reconstructed value of N_{ch} (correction 1).

In an experiment with the Mirabelle bubble chamber, topological cross sections for charged particles were measured in pp interactions at 50 GeV up to $N_{ch} \leq 16$ [2]. With allowance for these data, topological cross sections were obtained in [5] for the region of $10 \leq N_{ch} \leq 24$. The event sample used in the present study does not correspond to the true charged-multiplicity (N_{ch}) distribution of events. The deviation stems from the suppression of low-multiplicity events by the trigger conditions and from the nonproportional selection of events with different multiplicities for data processing. Therefore, it was necessary to rescale the ultimate charged-multiplicity distribution to the distribution obtained in [2, 5].

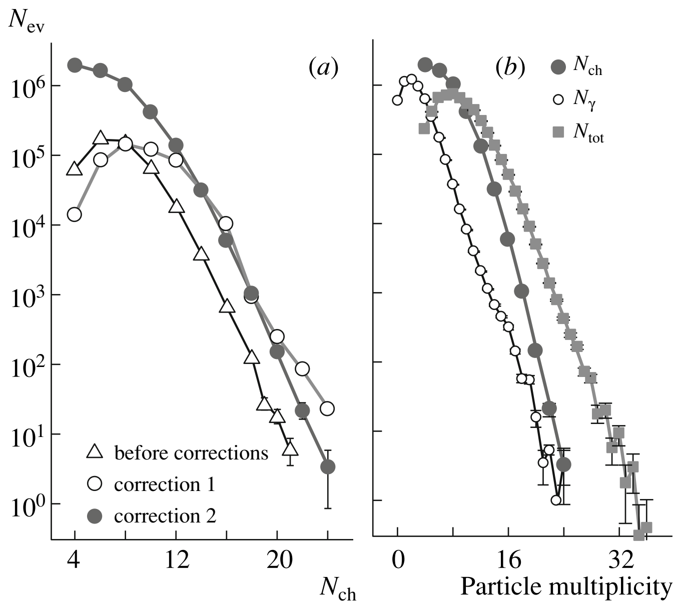

Fig. 6. Multiplicity distributions of events: (*a*) distributions of N_{ch} before and after the introduction of corrections and (*b*) distributions of corrected N_{ch}, N_γ, and N_{tot}.

We obtained correction coefficients and multiplied by them the numbers of events used in the present study for different N_{ch} [assuming that $N_{ev}(N_{ch} = 14)$ is invariable] in order to match these numbers with the measured topological cross sections (correction 2). Figure 6*a* shows the distribution of events with respect to the charged-particle multiplicity before and after the introduction of corrections 1 and 2. The corrected mean value $\langle N_{ch}\rangle$ for events where $N_{ch} > 4$ is 6.7. The reconstructed numbers of events for various values of N_{ch}, N_γ, and $N_{tot} = N_{ch} + N_\gamma$ are results of introducing the corrections in question. It is noteworthy that a change in the number of events for N_{ch} also leads a change in the number of events for N_γ. Therefore, the distribution of N_γ in Fig. 6*b* differs from the distribution in Fig. 5*a* for the observed numbers of events and $\langle N_\gamma\rangle = 2.3$. The distribution of the multiplicity N_γ for a fixed value of N_{tot} is determined by the distribution of the numbers of events $N_{ev}(N_\gamma, N_{tot})$.

MEASUREMENT OF NEUTRAL-PION FLUCTUATIONS

We have shown above that, according to the results of our simulation, the number of photons detected in DEGA depends linearly on the mean multiplicity of neutral pions in an event (see Fig. 2*b*). In order to reconstruct the number of events involving neutral pions, we employ the $N_{ev}(N_\gamma, N_0)$ two-dimensional distributions for Monte Carlo events (see Fig. 2*a*). For the sake of convenience, we introduce the notation $i = N_\gamma$ and $j = N_0$. From the $N_{ev}(N_\gamma, N_0) = N_{ev}(i, j)$ two-dimensional distribution, we can obtain, for each value of N_{ch}, the matrix of coefficients $c_{ij} = N_{ev}(i, j)/N_{ev}(i)$, where $N_{ev}(i) = \sum_j N_{ev}(i, j)$. Further, the numbers of events $N_{ev}(N_\gamma, N_{ch})$ are decomposed into the sum of events in which $N_0, N_{ev}(i, j) = c_{ij}N_{ev}(i)$ takes different values at $N_{ch} = \text{const}$. For c_{ij}, the following normalization condition holds: $\sum c_{ij} = 1$. The resulting sum $N_{ev}(j) = \sum_i N_{ev}(i, j)$ is the number of events that is similar to the number $N_{ev}(N_\gamma, N_{tot})$ at $N_{ch} = \text{fix}$, but, now, for neutral pions. A simulation with the aid of the PYTHIA5.6 code makes it possible to obtain the coefficients only for values satisfying the conditions $N_\gamma \leq 10$ and $N_{ch} \leq 14$. In order to continue reconstructing the numbers of events, the regularities that are observed for the coefficients c_{ij} were used for values in the regions of $N_\gamma > 10$ and $N_{ch} > 14$.

Figure 7*a* shows the N_0 dependence of the coefficients c_{ij} at various values of N_γ and N_{ch}. The distributions for different values of N_{ch} were shown by lines of different type for each value indicated for N_γ. The shapes of the distributions depends only slightly on N_γ and N_{ch}, but their mean value $\langle N_0\rangle$ grows with increasing N_γ. It can be seen that the distributions for different values of N_γ are shifted along the N_0 according to the requirement $N_0 \geq N_\gamma/2$ without a change in shape. Figure 7*b* shows the mean values $\langle N_0\rangle$ and the respective standard deviations (rms) versus the number N_γ. After parametrizing them by a linear

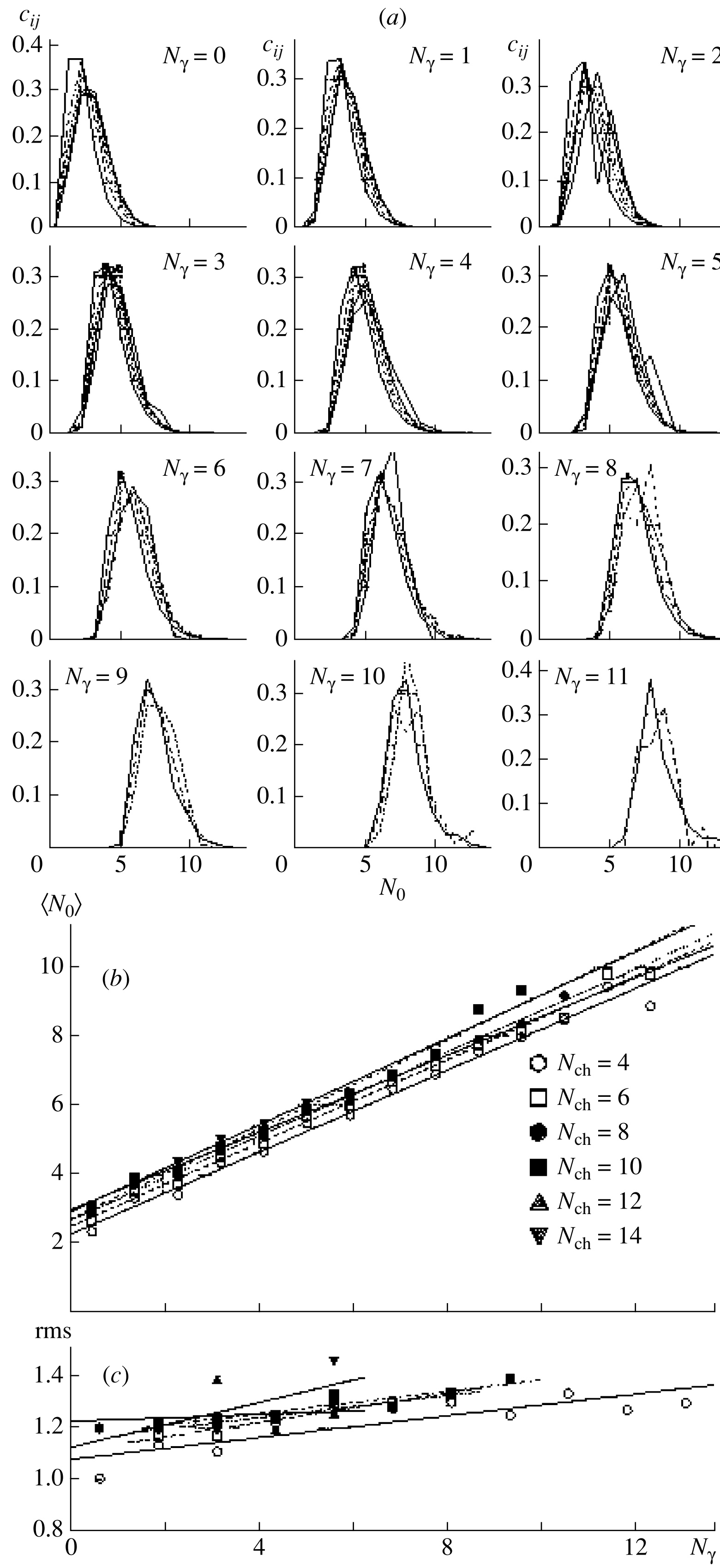

Fig. 7. (a) Distribution of the coefficients c_{ij} for the transition from N_γ to N_0; (b) parameters of the distributions of N_0 and (c) rms (standard deviation) versus N_γ.

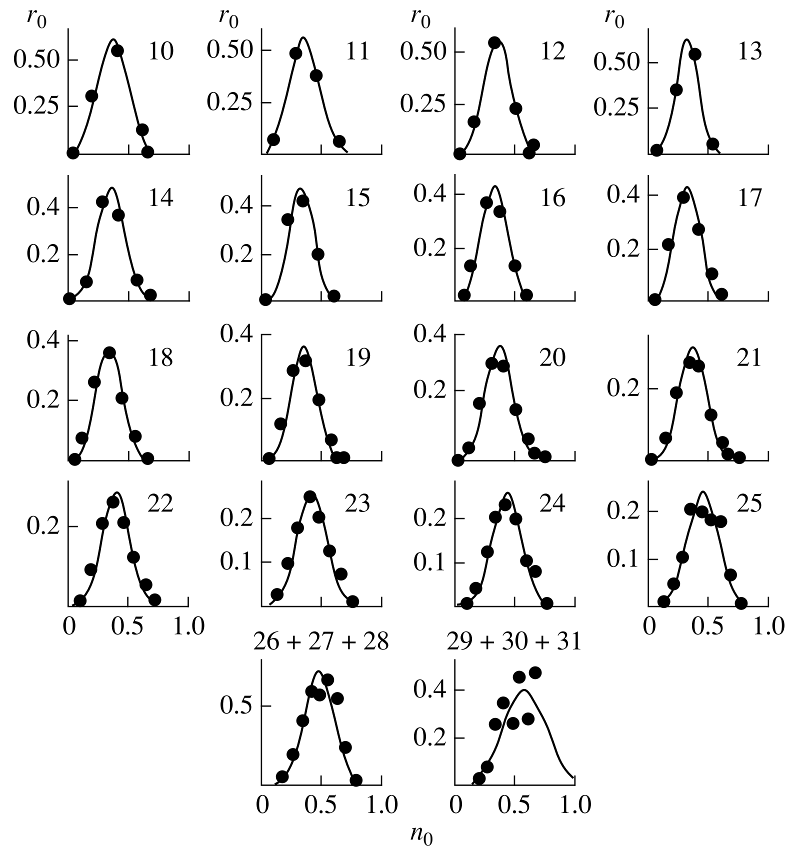

Fig. 8. Distribution of the number of neutral pions for various values of $N_{\rm tot}$ (indicated in the figure).

dependence, we calculate c_{ij} for $N_\gamma > 10$ and $N_{\rm ch} > 14$. Thus, we have a complete set of numbers of events $N_{\rm ev}(N_{\rm ch}, N_0, N_{\rm tot})$ and employ it in the following to measure fluctuations of the numbers N_0.

We have indicated earlier (see Introduction) that we use the relative quantities n_0 and r_0: $n_0 = N_0/N_{\rm tot}$ and $r_0 = N_{\rm ev}(N_0, N_{\rm tot})/N_{\rm ev}(N_{\rm tot})$. Figure 8 shows the distributions of r_0 versus n_0 for each $N_{\rm tot}$ starting from $\mathrm{N}_{\rm tot} \geq 10$. Because of a relatively small size of the statistical data sample used, data at large $N_{\rm tot}$ are combined. All of the distributions are parametrized in terms of a Gaussian function. Figure 9 shows the dependence of the parameters used on the total number of particles. The parameters at $N_{\rm tot} = 27$ were obtained by combining data for $N_{\rm tot} = 26$, 27, and 28, while the parameters at $N_{\rm tot} = 30$ were obtained upon combining data for $N_{\rm tot} = 29$, 30, and 31. One can see that the measured mean values $\langle n_0 \rangle$ (see Fig. 9a) agree with the analogous values obtained for neutral pions by means of a simulation on the basis of the PYTHIA5.6 code for $24 > N_{\rm tot} > 12$. The neutral-pion multiplicity as a function of $N_{\rm tot}$ was obtained analytically on the basis of the gluon-dominance model (GDM) [6]. We also present this dependence in Fig. 9a, and it displays fairly good agreement with experimental data in the region $N_{\rm tot} > 14$. The same figure shows the mean value $\langle n_\gamma \rangle$ for photons reconstructed in the DEGA calorimeter. The measured values of the standard deviations σ (in the case of a parametrization in terms of a Gaussian function)—see Fig. 9b—exhibit qualitative agreement with the predictions of the PYTHIA5.6 model only for $N_{\rm tot} < 22$, whereupon this quantity begins growing.

Theoretical predictions for the behavior of the parameter ω (in our case, $\omega = D(N_0)/\langle N_0 \rangle = \sigma^2 N_{\rm tot}/\langle n_0 \rangle$) for pp interactions at 50 GeV were given in [3] for various values of the energy density in the pion system approaching the BEC state (pion condensate)—see Fig. 10a. The ω values measured in the present study for photons and neutral pions (see Fig. 10b) indicate that, within the errors, there is no contradiction with the possible existence of BEC in the pion system for $N_{\rm tot} > 22$ in pp interactions at 50 GeV.

CONCLUSIONS

Our measurements of the number of neutral pions for high-multiplicity events in pp interactions at

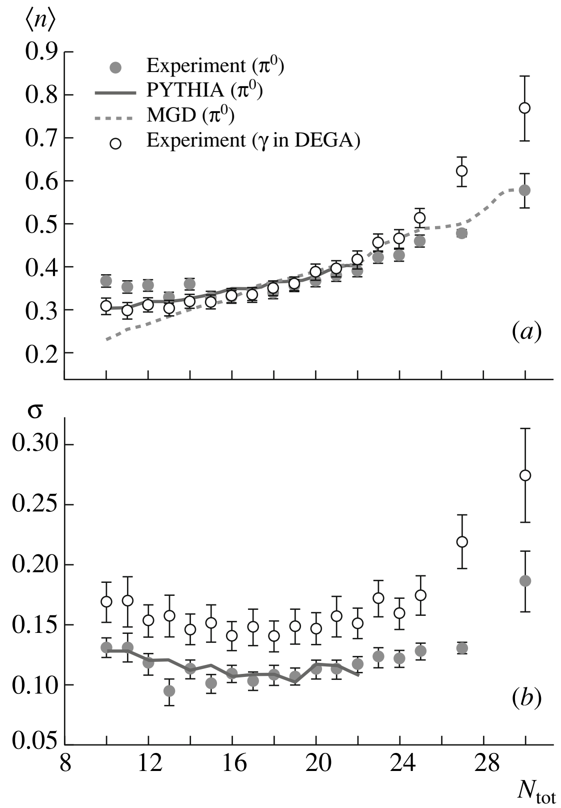

Fig. 9. $N_{\rm tot}$ dependence of the parameters of the distributions of the (*a*) number of neutral pions and photons and (*b*) standard deviations of these quantities for experimental data and for Monte Carlo events. For neutral pions, $N_{\rm tot} = N_{\rm ch} + N_0$, while, for photons, $N_{\rm tot} = N_{\rm ch} + N_\gamma$.

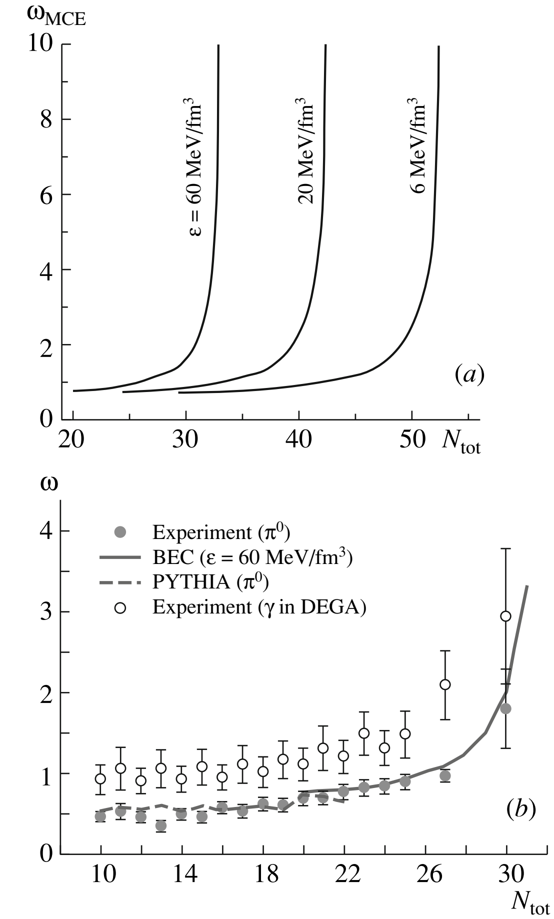

Fig. 10. Dependence of the parameter ω on $N_{\rm tot}$: (*a*) theoretical predictions from [3] and (*b*) ω values measured in the present study for neutral pions and photons in DEGA. For neutral pions, $N_{\rm tot} = N_{\rm ch} + N_0$, while, for photons, $N_{\rm tot} = N_{\rm ch} + N_\gamma$.

50 GeV (SERP-E-190 experiment), together with a simulation, have revealed the following:

(i) The mean multiplicity of neutral pions in an event depends linearly on the number of photons detected in the DEGA calorimeter; this makes it possible to obtain fluctuations of the number of neutral pions from fluctuations of the number of photons.

(ii) It is convenient represent respective data in relative scales for $n_0 = N_0/N_{\rm tot}$ and $r_0 = N_{\rm ev}(N_0, N_{\rm tot})/N_{\rm ev}(N_{\rm tot})$. The range of n_0 is [0, 1] for all $N_{\rm tot}$;

(iii) In order to obtain multiplicity distributions of neutral pions for each value of $N_{\rm tot}$ ($N_{\rm tot} = N_{\rm ch} + N_0$), it is necessary to introduce corrections in the measured numbers of events characterized by different multiplicities of charged particles; these corrections stem from the track-reconstruction efficiency in the vertex detector, its limited aperture, and trigger operation.

(iv) After the parametrizations of the distributions of r_0 versus n_0 by in terms of a Gaussian function, the dependences of the measured values of $\langle n_0\rangle$, σ, and the fluctuation parameter $\omega = D/\langle N_0\rangle$ on $N_{\rm tot}$ agree qualitatively with the respective dependences obtained from a simulation with the aid of the PYTHIA5.6 code for $N_{\rm tot} < 22$.

(v) In the region of $N_{\rm tot} > 22$, fluctuations of the number of neutral pions increase, which, in statistical models (GCE, CE, MCE) [3, 4], indicates that a system involving a large number of pions approaches the pion-condensate state (BEC).

(vi) This effect has been observed for the first time.

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