PROCEEDINGS OF SCIENCE

The evidence for the pion condensate formation in pp interactions at U-70

Kokoulina Elena[∗†]
Joint Institute for Nuclear Research, Dubna, Russia
E-mail: kokoulin@sunse.jinr.ru

Kutov Andrei
Department of Mathematics, Ural Division, Russian Academy of Sciences, Syktyvkar, Russia,
E-mail: akutov@rambler.ru

Kalyada Andrey
Gomel State University, Belarus
E-mail: 2viking@mail.ru

Salyanko Ruslan
Gomel State University, Belarus
E-mail: qwas1990@gmail.com

The results of E-190 experiment (project Thermalization) at the U-70 accelerator, IHEP, Protvino are presented. This experiment is aimed at the *pp*-interaction study at high-multiplicity area. Multiplicity distributions of neutral pions, N_0, at the given total multiplicity, N_{tot}, including charged particles, N_{ch} , have been obtained with corrections on the setup acceptance, triggering and efficiency of the event reconstruction. The scaled variance of neutral mesons, ω, equal the ratio a variance to a mean multiplicity gives evidence that the neutral pion number fluctuations grow up over $N_{tot} = 18$. According to ideal pion gas model of V. Begun and M. Gorenstein this growth may point to the pion condensate formation in high pion multiplicity system. This effect is confirmed after the increase two times of a sample volume.

XXI International Baldin Seminar on High Energy Physics Problems
September 10-15, 2012
JINR, Dubna, Russia

∗Speaker.
†On behalf of the SVD-2 Collaboration

PoS(Baldin ISHEPP XXI)007

1. Introduction

Thermalization project is aimed at the study of *pp* and *pA* interactions at U-70 accelerator of IHEP (Protvino, Russia) [1]. The incident proton beam has energy of 50 GeV. The experiment is carried out on the SVD-2 (Spectrometer with Vertex Detector) setup. The events with multiplicity considerably higher than the mean one are investigated. At this energy the total multiplicity in *pp* collisions has the kinematical limit equal to 57 pions. SVD-2 Collaboration continues to search for next collective phenomena at high multiplicity region: the Bose-Einstein condensation of pions [2, 3, 4, 5], the peak structure at the angular distributions stipulated to a Cherenkov radiation [6] or a shock wave formation [7], the anomalous soft photon yield [8, 9] and others.

The phenomenon of Bose-Einstein condensation (BEC) was predicted a long time ago. BEC is a unique phase transition, it occurs in the absence of interactions. This phenomenon was first considered in the high multiplicity area by S. Pratt [2], and the pion laser formation was predicted. This model has been solved [3], and the multiplicity dependence of single-particle momentum distribution has been estimated to use in future event-by-event measurements. The important contribution in the following works has been obtained by the Dubna school [4].

Pions are the lightest hadrons copiously produced at U-70 energy. M. I. Gorenstein and V. V. Begun had proposed to search for BEC in systems with high pion number [5]. It is evident that the increase of the total multiplicity, $N_{tot} = N_{ch} + N_0$, where N_{ch} and N_0 are multiplicities of charged and neutral pions, correspondingly, leads to the decrease of their mean energy. In this case the system can pass a condensate. It can achieve by selecting the samples of events with high number of pions. In their model the scaled variance, ω equal to the ratio of variance, D, to the mean multiplicity of neutral pions, $< N_0 >$, at given total multiplicity can give the evidence of the BEC formation: an abrupt and anomalous increase of ω [5, 10] is expected closely to the vicinity of the BEC point.

2. Event selection, tracking and correction procedure for PVD data

The basic elements of SVD-2 setup are a liquid hydrogen target, a precision microstrip silicon vertex detector (PVD), a straw tube tracker, a magnetic spectrometer consisting of 16 proportional chambers and a magnet, a Cherenkov counter and an electromagnetic calorimeter (ECal)[1].

PVD is the one of the most important elements of SVD-2 setup allowing to find the vertex of interaction position and to restore the charged particle tracks. It composes of 10 silicon planes and has more than 10000 registration channels. With the help of this detector the charged particle number was defined.

To select the events with the charged multiplicity not less than given value the scintillator hodoscope or the high multiplicity trigger (HMT) have been designed and manufactured[11]. The events originated from nuclear interactions in the trigger hodoscope are the source of noise in determining the event multiplicity. Applying additional criterium to trigger conditions the fraction of events with interactions in the trigger hodoscope is suppressed and consists not more than 4%.

The topological cross sections have been defined using the beam telescope and PVD information [12]. From the data received in 2008, 5.13 million events have been selected. From this statistics 3.85 millions of events have been taken at trigger level 8 (HMT system registers events

Table 1: The corrected cross sections (mbarn) at 50-GeV beam in pp interactions.

n_{ch}	10	12	14	16	18	20	22	24
$\sigma(n_{ch})$	1.685	0.789	0.234	0.0526	0.0104	0.0017	0.00033	0.000054
$\Delta\sigma(n_{ch})$	0.017	0.012	0.006	0.0031	0.0014	0.0006	0.00024	0.000098

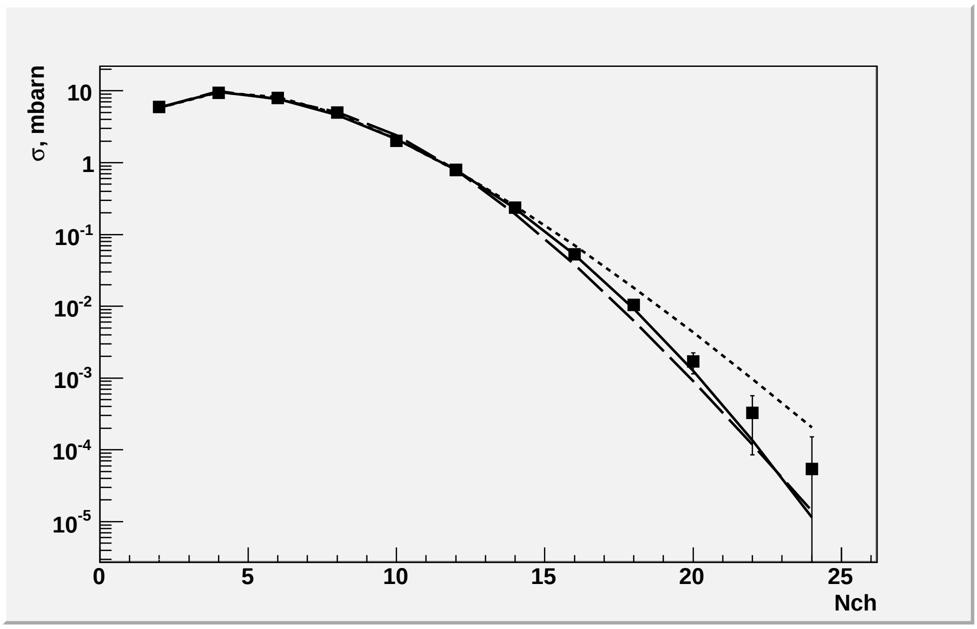

Figure 1: Comparisons data with GDM [14] (solid curve), IHEP model [15] (dashed curve) and NBD distribution [16] (dotted curve).

with multiplicity not less than L, L being called the trigger level. We used different trigger levels from $L = 2$ up to 12). Out of them 2.1 millions of events have been detected in the fiducial volume of the hydrogen target. For final analysis almost 1.0 million of events have been selected according to the following criteria of a selection: a) the number of beam tracks simultaneously hitting the target does not exceed 2 and b) the difference of the Z-coordinate (a beam direction) of the vertex reconstructed in XZ and YZ projections are smaller than 5 mm.

The correction procedure of the charged particle number was carried out taking into account an influence of the trigger conditions, an acceptance of PVD, efficiencies of track reconstruction algorithm and functioning of setup elements. We have renovated previous Mirabelle data [13] (charged multiplicity from 10 up to 16) and added 4 new points (from 18 up to 24) (Table 1). The cross section at the last point, N_{ch}=24, is three order of magnitude lower than it was obtained by Mirabelle up to N_{ch} = 16 [13]. We have defined more exactly the inelastic cross section, σ_{inel} = 31.50 ± 1.14 (stat) mb, the mean charged multiplicity, $< N_{ch} >$ = 5.45 ±0.24 (stat), the variance, D = 7.21± 2.80 (stat). In Figure 1 the comparison our results with three models is shown. The gluon dominance model (GDM) [14] and IHEP model [15] show the good agreement with data [12]. The negative binomial distribution (NBD) [16] overestimates our data at high multiplicities.

3. The Monte Carlo simulation of the neutral particle (γ's and π^0's) production.

ECal registerers photons. Because of its restricted aperture and the threshold energy of the registration, it is impossible to reconstruct all neutral pions in the each selected event. We have developed another methodic of the π^0 reconstruction [17]. To do this, the Monte Carlo simulation (FRITIOF7.02) and the transmission through a GEANT simulation of the SVD-2 setup of neutral meson production, their decay and the registration of γ-quanta had been carried out. The linear dependence between mean number of π^0 -mesons, $< N_0 >$, and the number of the registered photons, N_γ, have been established (Figure 2) for charged multiplicity $N_{ch} \leq 14$. Although this dependence, $< N_0(N_\gamma) >$, have been determined in the region $N_\gamma < 12$, we assumed it holds up to $N_\gamma \leq 24$ covering the data available. Monte Carlo simulations also has showed (Figure 3) that the value ω as function of $N_{tot} = N_{ch} + N_\gamma$ has small growth for γ's and remains constant as function of $N_{tot} = N_{ch} + N_0$ for pions within all accessible for FRITIOF a region of total multiplicities ($N_{tot} \leq$ 24).

4. Registration of γ-quanta and restoration of neutral pions

ECal consists of 1344 lead glass detecting elements with PMT. Though almost all the energy of the electromagnetic shower from γ-quantum hit into the center of an element is deposited in the cell consisted of 3 $\times$ 3 elements (the cell consisted of 5 $\times$ 5 elements was chosen for analysis). ECal was calibrated with electron beam. The threshold energy of photon registration is equal to 100 MeV.

Most of the observable in ECal photons originates from the neutral pion decays. In each event the number of detected photons, N_γ, depends on the number of neutral pions, N_0. This number can vary in the limits ($N_\gamma/2$, $2 \times N_\gamma$). We should solve the inverse task: the restoration of the neutral pion multiplicity using the observed photon multiplicity. For the decision of this task is applied procedure offered in [17]. Monte Carlo simulation allows to carry out this restoration.

5. Neutral pion number fluctuations

The scaled multiplicity $n_0 = N_0/N_{tot}$ is used for the data analysis. The variable n_0 is convenient for the comparison of distributions at different total multiplicities. The scaled multiplicity distributions $r_0(n_0)$ is shown in the left panel of Figure 4 at N_{tot} = 10, 11, ..., 25 + 26 + 27. These distributions are fitted by Gaussian to define a mean multiplicity $< N_0 >$ and a variance. The right panel of Figure 4, top shows the scaled variances for neutral particles: experimental values for restored neutral mesons and observable photons, the predictions obtained from FRITIOF7.02 simulation and the ideal pion gas model for mean energy density ε = 60 MeV/fm^3 of V. Begun and M. Gorenstein [5]. In the case of gamma-quanta we define the total multiplicity as $N_{tot} = N_{ch} + N_\gamma$. We are constrained of the total pion multiplicity to the N_{tot} = 27 because of small number of events with N_{tot} > 27. Our experimental data can testify to the Bose-Einstein condensate formation in pion system in pp-interactions at 50 GeV. We observed an increase of the neutral pion number fluctuations at high total multiplicity, $N_{tot} > 18$ (the right panel of Fugure 4, top), that can indicate approaching to BEC for the high multiplicity pion system. The growth of ω, reaches more than

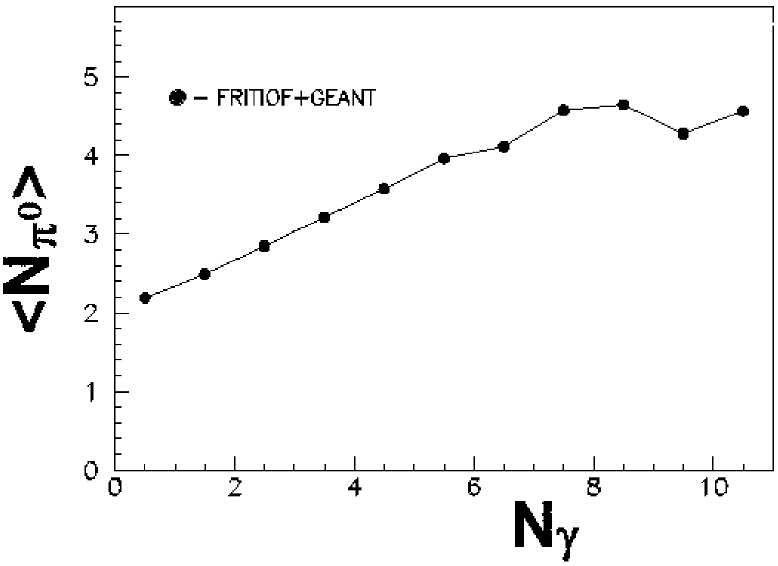

Figure 2: The mean neutral pion multiplicity versus the photon number detected in ECal.

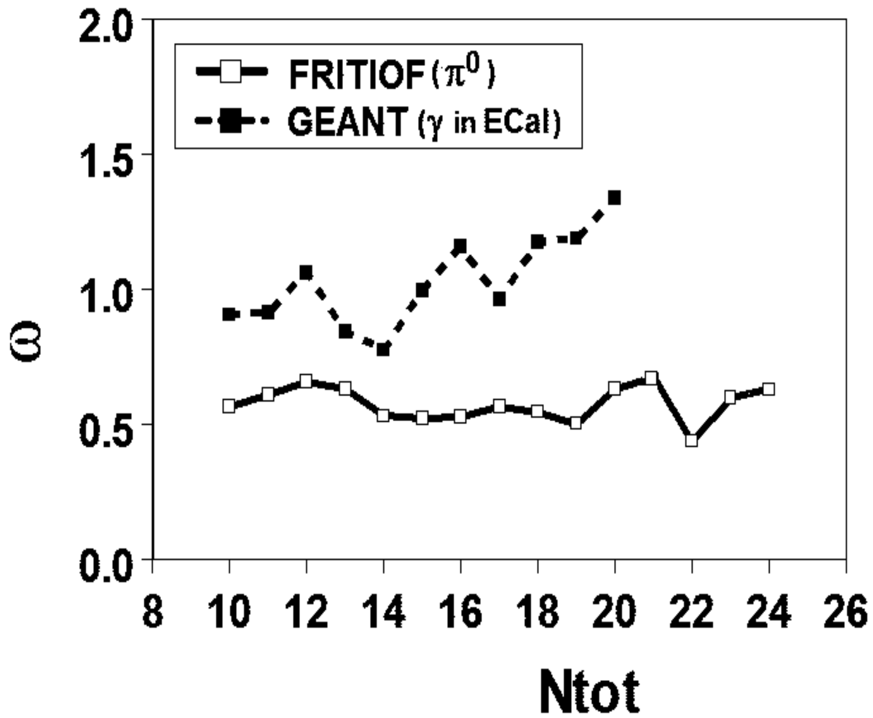

Figure 3: Monte Carlo code simulation. The scaled variance, ω, versus N_{tot} for photons (■) and π^0-mesons (□).

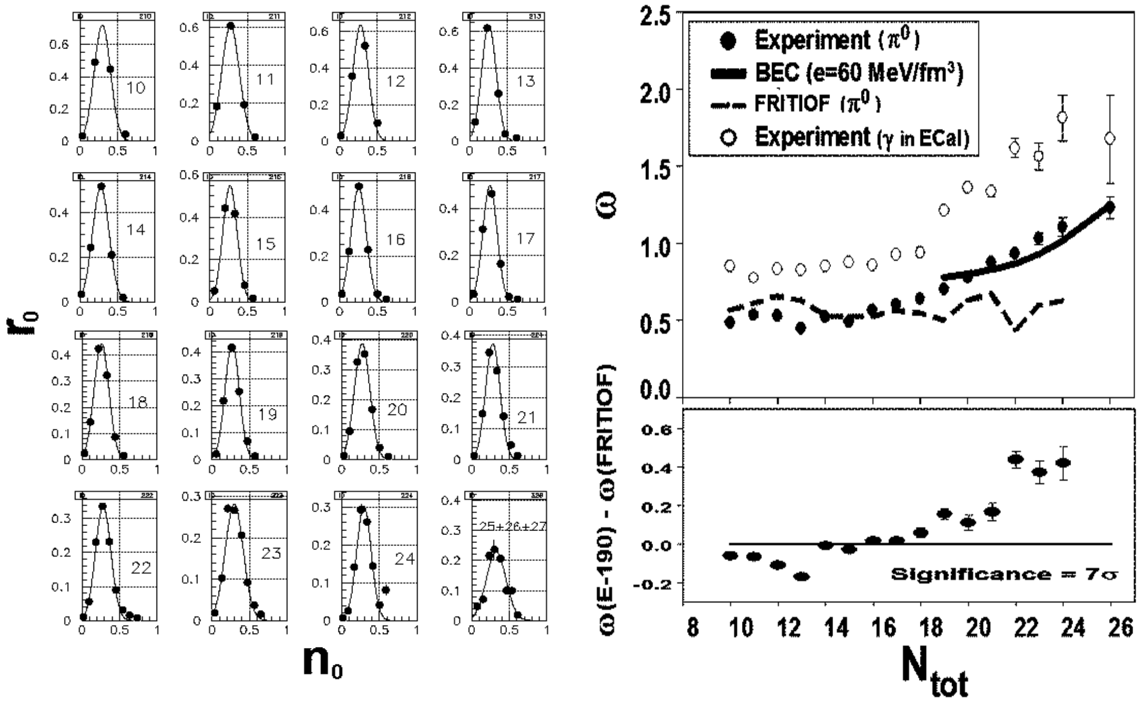

Figure 4: [Left] The neutral pion number distributions $r_0(n_0)$ versus scaled multiplicity, n_0 at difference values N_{tot} (10, 11, ..., 25+26+27). [Right] (Top) The measured scaled variance, ω, versus N_{tot} for π^0-mesons (•), photons (○), Monte Carlo code FRITIOF7.02 (the dashed curve) and theoretical prediction (solid curve) [5] for energy density ε =60 MeV/fm^3. $N_{tot} = N_{ch} + N_0$ for π^0-mesons and $N_{tot} = N_{ch} + N_\gamma$ for photons. (Bottom) The difference of experimental and simulated ω's for π^0.

7 standard deviations at total multiplicity about 30 pions as opposed to the tendency for the simulated events (the right panel of Fugure 4, bottom). This behavior has been confirmed after two-fold increase of a sample volume.

Critical point of pion condensation is determined in statistical physics: $E_{crit} = 3.3(h^2/m_\pi)\rho^{2/3}$ [18]. The density, ρ , is equal to 0.2 fm^{-3} if the interaction region size of two protons $\simeq$ 3 fm and N_{tot} = 36 (a maximal observable number of pions). In this case the critical energy is resulted to E_{crit} = 100 MeV. At 50-GeV proton beam and N_{tot} = 30 the mean energy of pion, $E_\pi = (E_{cms} - 2m_n - N_{tot}m_\pi)/N_\pi$, is equal to 120 MeV ($m_n$ – nucleon mass, N_π – pion multiplicity, m_π – pion mass). This value is compatible with E_{crit}. Thus the experimental observable growth of scaled variance at U-70 for registered γ-quanta and restored neutral pion multiplicity can testify to BEC formation in the pion system at high multiplicity events.

S. Barshay [19] considers that BEC formation leads to cold pion fireball formation which can radiate soft photons with $p_T < 50$ MeV. Our future plans are connected to install the new ECal designed with a low threshold of the registration (from 5 MeV) to study of soft photon yield versus of charged and neutral multiplicities and other properties.

I would like to thank participants of SVD Collaboration for active and fruitful work on the project. We appreciate to IHEP leadership for support in the carrying out of our investigations, thank Operations Group and Department of beams provided effective work of U-70 and twentysecond channel. The author E K. expresses deep recognition and appreciates to M. I. Gorenstein an V. V. Begun. They have developed theoretical basics to look for BEC in our experimental conditions.

References

[1] V. V. Avdeichikov et al., Proposal "*Termalization*" (in Russian), JINR-P1-2004-190 (2005).

[2] S. Pratt, *Pion lasers from high-energy collisions*, Phys. Lett. **B**301 (1993).

[3] T. Csörgő and J. Zimányi, *Analytic solution of the pion - laser model*, Phys. Rev. Lett. **80** (1998) 916; T. Csörgő and J. Zimányi, *Coherent states of the creation operator from fully developed Bose-Einstein condensates* Heavy Ion Phys. **9** (1999) 241.

[4] R. Lednicky, V. Ljuboshitz et al, *Multiboson effects in multiparticle production*, Phys. Rev. **C**61 (2000) 034901.

[5] V. V. Begun and M. I. Gorenstein, *Bose-Einstein condensation of pions in high multiplicity events*, Phys. Lett. **B** 653 (2007) 190.

[6] I. M. Dremin, *Cherenkov gluons: predictions and proposals.* Int. J. Mod. Phys. **A** 22, 3087 (2007).

[7] J. G. Ulery. STAR Collaboration. *Are there Mach cones in heavy ion collisions? Three-particle correlations from STAR*. Int. J. Mod. Phys. **E** 16, 2005 (2007).

[8] P. V. Chliapnikov et al., *OBSERVATION OF DIRECT SOFT PHOTON PRODUCTION IN K+ p INTERACTIONS AT 70-GeV/c*. Phys. Let. **141B** (1984) 276.

[9] J. Abdallah et al. DELPHI Collaboration. *Study of the Dependence of Direct Soft Photon Production on the Jet Characteristics in Hadronic Z0 Decays*. Eur. Phys. J. **C**47 (2006) 273.

[10] V. V. Begun and M. I. Gorenstein, *Bose-Einstein Condensation in the Relativistic Pion Gas: Thermodynamic Limit and Finite Size Effects*. Phys. Rev. **C**77 (2008) 064903.

[11] A. Avdeichikov *et al.*, *A trigger of events with a high multiplicity of charged particles at the SVD-2 setup*. Instrum. Exp. Tech. **2** (2011) 15.

[12] E. N. Ardashev et al. SVD-2 Collaboration. *Proton interactions with high multiplicity*. IHEP Preprint 2011-4 (2011) [hep-ex/1104.0101]. http://web.ihep.su/library/pubs/all-w.htm.

[13] V. V. Ammosov et al., *Average charged particle multiplicity and topological cross-sections in 50-GeV/c and 69-GeV/c p p interactions*. Phys. Lett. **B** 42 (1972) 519.

[14] E. S. Kokoulina and V. A. Nikitin. *7th International School-Seminar The Actual Problems of Microworld Physics*, Gomel, Belarus, Dubna. 221 (2004) [hep-ph/0308.139v1].

[15] S. V. Semenov, S. M. Troshin, N. E. Tyurin, O. A. Khrustalev, *Connection Between Elastic and Inelastic Processes at High-Energies*. (In Russian) Yad. Fiz. **22** (1975) 792.

[16] A. Giovannini and R. Ugocioni, *Clan structure analysis and QCD parton showers in multiparticle dynamics: An Intriguing dialog between theory and experiment*. Int. J. Mod. Phys. **A**20 (2005) 3897.

[17] E. N. Ardashev et al. SVD-2 Collaboration. (in Russian) *Neutral-Pion Fluctuations at High Multiplicity in pp Interactions at 50 GeV*. IHEP Preprint 2011-5 (2011). [hep-ex/1104.3673] http://web.ihep.su/library/pubs/prep2011/11-5-w.htm.; E. S. Kokoulina (On behalf of the SVD-2 Collaboration), *Neutral Pion Fluctuations in pp Collisions at 50 GeV by SVD-2*. Progr. Theor. Phys., **193** (2012) 306; V. N. Ryadovikov (On behalf of the SVD-2 Collaboration), *Neutral-Pion Fluctuations at High Multiplicity in pp Interactions at 50 GeV*. Phys. Atom. Nucl., **75** (2012) 989.

[18] L. D. Landau and I. M. Lifshitz. Vol. 5. Statistical physics, part 1 (3ed., Pergamon, 1980).

[19] Saul Barshay, *ANOMALOUS SOFT PHOTONS FROM A COHERENT HADRONIC PHASE IN HIGH-ENERGY COLLISIONS*. Phys. Lett. **B** 227 (1989) 279.