Phenomenology of high multiplicity events

E S Kokouлина on behalf of SVD Collaboration

JINR, VBLHE, Dubna, Moscow region, Russian Federation, 141980 and Gomel state technical university, Belarus, 246000
E-mail: kokoulin@sunse.jinr.ru

Abstract. Study of high multiplicity events in proton-proton (nucleus) interactions is carried out at U-70 accelerator of IHEP, Protvino. These events are extremely rare. Usually, MC codes underestimate topological cross sections in this region. Gluon dominance model has been offered to describe them. Some collective phenomena can be observed in high multiplicity events. SVD-2 Collaboration has obtained the evidence of pion condensate formation at high total multiplicity. Our future program is aimed at studying soft photon yield puzzle at U-70 and Nuclotron facility at JINR, Dubna.

1. Introduction

Multiparticle production remains an actual theme of modern high energy physics. The SVD Collaboration studies the proton-proton and proton-nucleus interactions at U-70 accelerator of IHEP, Protvino [1] (experiment E-190) with high number of secondary particles

\[ p + p(A) \rightarrow 2N + N_\pi, \]  

where \( N \) – nucleon, \( N_\pi \) – number of pions. The energy of the proton beam is equal to 50 GeV, the average charged multiplicity \( \langle N_{\text{ch}} \rangle \) is equal to 5.45. Pions are hadrons copiously produced at this energy. We study the region of high charged (\( N_{\text{ch}} \)) and total (\( N_{\text{tot}} \)) multiplicity considerably more than average one. The kinematical limit is defined from a condition of the conversion of all kinetic energy of colliding protons into pions

\[ N_{\text{thresh}} \simeq (\sqrt{s} - 2m_p)/m_\pi. \]  

At 50 GeV/c the kinematical limit is equal approximately to 59 pions. The experiment is carried out at SVD (Spectrometer with Vertex Detector) setup located at U-70 accelerator of IHEP, Protvino [1, 2]. Its main elements are a hydrogen target, a silicon vertex detector, a drift tube tracker, a magnetic spectrometer (proportional chambers and a large magnet) and an electromagnetic calorimeter [3]. The setup registers charged particles and photons. The high charged multiplicity events are extremely rare. The scintillator hodoscope (a high multiplicity trigger) has been manufactured to suppress the small multiplicity events and to register events with multiplicity higher than a given level [4].
It is known that Monte-Carlo event generators are often mistaken in their predictions of topological cross sections in the high multiplicity region [5]. They usually underestimate theirs. The existent models give diverse predictions of high multiplicity behavior [6]. So the experimental and following theoretical studies are necessary. SVD Collaboration has advanced in the measuring topological cross sections of \( pp \) interactions [1, 2] with high charged and total multiplicity. Previous Mirabelle data [7] have been renovated for \( N_{ch} \) from 10 up to 16 and we added 4 new points from 18 up to 24. Topological cross section at the last observing point, \( N_{ch} = 24 \), is three order of magnitude lower than it was obtained by the Mirabelle Collaboration at \( N_{ch} = 16 \).

Neutral particles, photons, are registered by an electromagnetic calorimeter (ECal). Owing to its restricted acceptance it is impossible to restore all neutral pions directly. That is why the original algorithm has been developed to define number of events with certain multiplicity of \( \pi^0 \)-mesons [8, 9, 10, 11, 12]. The number of events with given total multiplicity, \( N_{tot} = N_{ch} + N_0 \), where \( N_0 \) is multiplicity of neutral pions, is restored by the same method.

Some collective phenomena are predicted in this region. We are aimed to search for pion condensate or Bose-Einstein condensation (BEC) [13], the peak structure at the angular distributions stipulated to a Cherenkov radiation or a shock wave formation [14] and the study of the anomalous soft photon (\( p_T < 100 \) MeV) yield [15]. We have gotten preliminary indications at the two-humped structure in angular distribution in events with multiplicity more than average one [16, 17]. We have developed the gluon dominance model (GDM) to describe topological cross sections in high multiplicity region [16, 17]. We have estimated the size of region for the soft photon radiation by GDM [18]. This region exceeds the size of particles slightly.

In section 2 the results of search for BEC is presented. The description of high multiplicity region in the framework of GDM is added in sections 3 and 4. Section 3 demonstrates how GDM improves description of the high multiplicity tail for topological cross sections with taking into account gluon fission. Estimation of the charged exchange contribution in GDM is carried out in section 4. Section 5 states the conclusions.

2. Collective phenomena at high multiplicity

With increasing the total multiplicity of pions their average energy is decreased. Pions are bosons and can form pion condensate at low temperature. M Gorenstein and V Begun had analyzed the conditions of BEC formation in the framework of the ideal pion gas model [13, 19]. They predict the increase of fluctuations of neutral pion number at the growth of total pion multiplicity and the approach to BEC. According to their predictions, the scaled variance, \( \omega \) determined as the ratio of variance, \( D \), to the mean multiplicity of neutral pions, \( \overline{N}_0 \), at given total multiplicity, can give the evidence of the BEC formation. In this case an abrupt and anomalous increase of \( \omega \) is expected closely to the vicinity of the pion condensate point [19]. Monte-Carlo event generators do not reveal the growth of \( \omega \). SVD Collaboration has seen this growth, and the evidence of
Figure 1. (Top) The measured scaled variance $\omega$ versus $N_{tot}$ for $\pi^0$-mesons ($\bullet$), photons ($\circ$), MC code FRITIOF7.02 (the dashed curve) and theoretical prediction (solid curve) [13] for the energy density $\varepsilon = 60$ MeV/fm$^3$. $N_{tot} = N_{ch} + N_0$ for $\pi^0$-mesons and $N_{tot} = N_{ch} + N_\gamma$ for photons. (Bottom) The difference of experimental and Monte Carlo simulated $\omega$ for $\pi^0$-mesons [9].

Begun-Gorenstein predictions has obtained [8].

In the top panel of figure 1 the experimental and model values of scaled variances are shown. The experimental values agree well with $\omega$ defined by Monte-Carlo simulated events at $N_{tot} < 18$. At the same time we reveal its significant growth, reachable by more than 7 standard deviations at $N_{tot} \simeq 30$ (the bottom panel in figure 1) as opposed to the tendency for the simulated events. This growth has been observed both registered photons ($N_{tot} = N_{ch} + N_\gamma$), and restored neutral pions ($N_{tot} = N_{ch} + N_\pi$). The theoretical predictions done by V. Begun and M. Gorenstein [13] at a choice of the
reasonable values for the size of system, the energy density, the pion number density and others at the high total pion multiplicity area agree to the Bose-Einstein condensate formation since we observe the growth of the scaled variance [9].

The average energy of pion $E_\pi$ is estimated as

$$E_\pi = \frac{(E_{\text{cms}} - 2m_N - n_{\text{tot}}m_\pi)}{n_{\text{tot}}},$$

(3)

where $E_{\text{cms}}$ – energy in cms, $m_N$ – mass of a nucleon, $n_{\text{tot}}$ and $m_\pi$ – number and mass of pions. At $n_{\text{tot}} = 30$ the average energy of a pion is equal to $E_\pi = 120$ MeV.

The critical point of the pion condensation is determined by statistical physics [20]:

$$E_{\text{crit}} = 3.3(h^{2/3}/m_\pi)\rho^{2/3}$$

where $\rho$ is the density of number pions. This density is equal to $0.2$ fm$^{-3}$ if the interaction region of two protons is $\simeq 3$ fm and $n_{\text{tot}} = 36$ (max observable total multiplicity). In this case the critical energy is equal to $E_{\text{crit}} \simeq 100$ MeV. This density is comparable with $E_\pi$. In accordance with these estimations BEC can observe at high total pion multiplicity region.

The extended region of multiplicity has been described by few models. In figure 2 the comparison of these models with the measured topological cross sections is shown. The GDM [16, 17, 21, 22] is shown by a solid line, the IHEP model [23] – a dashed line and the negative binomial distribution (NBD) [24] – a dotted line. GDM and IHEP models show the good agreement with data. NBD overestimates our data at high multiplicities.

It is necessary to note that we observe events with number of $n_{\text{ch}} = 12$ and $n_0 = 24$ and vice-versa. In this region close to BEC we reveal big fluctuations of neutral pion number. We study multi particle production at higher energy selecting
rare high multiplicity events. The investigation of this region is unique, fruitful and promising one.

S Barshay [25] sees an interest connecting between BEC and an anomalous soft photon yield in hadron interactions. He considers that the BEC formation establishes a coherent state when almost all pions have the lowest energy level. In this state pions throw down the excess of energy by the soft photon radiation. To test this hypothesis SVD Collaboration manufactured the electromagnetic calorimeter of soft photons. It consists of 49 BGO crystals and photomultipliers. Now we are preparing for a test run at JINR’ Nuclotron [26].

3. GDM

GDM is a modification of the two stage model (TSM) [27, 28]. TSM describes well multiplicity distributions in $e^+e^-$ annihilation in a wide energy region. It is based on the convolution of the QCD quark-gluon cascade of initial quark pair and hadronization stage. In accordance with experimental data the binomial distribution has been chosen for hadronization. The binomial distribution uses the following parameters: the average multiplicity $\bar{n}^h_{q,g}$ and the maximum number of hadrons $N_{q,g}$ resulting from quark or gluon at their passing through this stage. The ratio of quark and gluon parameters, $\alpha = \bar{n}^h_{g}/\bar{n}^h_{q}$, reduces the number of parameters at the hadronization stage to three ones. The parameter of second stage $\pi^h_g$ is equal to 1 in all studied energy region. The main result of TSM is the confirmation of fragmentation mechanism of hadronization: one parton fragments for one hadron at hadronization in vacuum.

In $pp$ interactions attend both valency quarks and gluons. At the beginning in GDM valency quarks and some gluons produced secondary hadrons at hadronization. The comparison with experimental data has shown that multi particle production is implemented by gluons called active. Valency quarks are staying in the leading particles as passive spectators. Only in this case the description of topological cross sections becomes possible in this scheme. The hadronization parameter of gluons $\pi^h_g$ grows from 1.5 at 50 GeV/c, U-70, up to 3.3 at 62.2 GeV, ISR. The growth of hadronization parameter is the evidence of the recombination mechanism of hadronization. The second stage occurs in quark-gluon medium not in vacuum.

We used a simple scheme with two stages to describe topological cross sections in $pp$ interactions. At the first stage some active gluons appear. Then they fragment into hadrons. The convolution of two stages describes data well. In the high multiplicity region a little deviation is observed (figure 2). It is known that gluons give branching at high energies. This fission becomes predominating and gives an additional contribution to multiplicity. In GDM it is taken into account in the following way

$$\sigma_n = \alpha_1 \sum_{m_1} m_1! e^{-\bar{n}^h_{q,g}} \binom{m_1N}{n} \left( \frac{\pi^h_g}{N} \right)^{n-2} \left( 1 - \frac{\pi^h_g}{N} \right)^{m_1N-n+2}$$
Figure 3. Topological cross section versus charged multiplicity in GDM. The dashed blue line describes the contribution of single sources, the green line – sources consisted of two gluons of fission, the solid red line is the sum both of contributions.

\[ + \alpha_2 \sum_{m_2} \frac{e^{-m_2/m_2}}{m_2!} \left( \frac{2m_2}{N} \right)^{n-2} \left( 1 - \frac{n^h}{N} \right)^{2m_2N-n+2}, \]  

(4)

where \( m_{1,2} \) – multiplicities of single and double gluon sources, \( n^h \) and \( N \) – parameters of hadronization. In this scheme at the second stage the branching gluons give two times more hadrons because they are sources consisted of two gluons (second summand in \( \sigma_n \)). The ratio of two parameters \( \alpha_1/\alpha_2 \) is approximately equal to 1.8. The rest parameters do not almost change.

In the double-logarithmic approximation [29] it has been revealed that the emission of two gluon jets formed by the fission process of paternal quark (antiquark) is predominant with the increasing energy and can explain the angle broadening of secondary particles. This fission can give the broadening of topological cross sections at high multiplicity [21, 22, 29]. In figure 3 the comparison of topological cross sections [7, 1] measured with GDM (solid red line) is shown. In accordance with GDM and taking into account the gluon fission the topological cross section consists of two summands. The dash green line presents the contribution appeared from single gluon sources; the second summand (dashed blue line) in (4) describes the contribution responsible for fission gluons. Obviously accounting of the gluon fission improves the description of data a lot.
4. The charged exchange in $pp$ interactions

The experiments show that the charged exchange can be achieved at the scattering of protons off hydrogen or nucleus targets [30]. In this case one of protons gives its charged to a neutral pion and transforms into a neutron

$$p + p \rightarrow p + \pi^+ + n + N_\pi.$$  \hspace{1cm} (5)

In (5) $N_\pi$ – the number of secondary pions, $n$ – a neutron. The estimation of the charge exchange can be carried out in the inelastic channel $2 \rightarrow 2$. In accordance with the Mirabelle data [7] the elastic and inelastic cross sections are equal to $\sigma_{2,el} = 6.90 \text{ mb}$ and $\sigma_{2,inel} = 5.71 \text{ mb}$ accordingly. Their ratio is equal to $r = \sigma_{2,el}/\sigma_{2,inel} = 0.82$. In MGD cross sections $\sigma_{2,el} \sim \exp(-\overline{m})$ because the active gluons are absent. Since we do not know a contribution of the charge exchange, we can use for $\sigma_{2,inel}$ the expression $r \cdot \exp(-\overline{m})$. At the same time $\sigma_{2,inel}$ can be presented as a sum of two summands

$$\sigma_{2,inel} = \sigma_{2,inel}^{+ch} + \sigma_{2,inel}^{-ch},$$  \hspace{1cm} (6)

with a charge exchange ($+ch$) and without a charge exchange ($-ch$). GDM estimates the second summand in (6) the following way

$$\sigma_{2,inel}^{-ch} \sim \sum_m e^{-\overline{m} \overline{m}_m} \frac{1}{m!} \left(1 - \frac{\overline{m}_h}{\overline{m}}\right)^{m \cdot N - n + 2},$$  \hspace{1cm} (7)

when active gluons appear without formation of charged particles. Let $P = \sigma_{2,inel}/\sigma_{2,inel}^{-ch}$, then instead $\sigma_{2,inel}$ we use the expression (7) with factor $P$ and from fitting find $P = 2.18$. Hence the coefficient of charge exchange

$$q = \frac{\sigma_{2,inel}^{+ch}}{\sigma_{2,inel}} \cdot 100\%$$

consists of $\approx 50\%$ [31]. This estimation agreed with the experimental data [30]. This value is considerable. It is necessary to have it in mind.

5. Conclusion

In this review the main results of high multiplicity studies have been presented. The region of high multiplicity is unique, promising and fruitful one. We expect new collective phenomena will be found out and will give significant advance for understanding the multi particle production especially the hadronization stage.

6. Acknowledge

I appreciate all participants of SVD-2 Collaboration for their active and fruitful work. I also thank Piskunova Olga for tremendous job on the organization of the workshop devoted to the memory of Professor Alexei Kaidalov.
References

[1] Ryadovikov VN 2012 Topological cross sections in proton-proton interactions at 50 GeV
    Phys.Atom.Nucl. 75, Issue 3, 315-320.
[2] Kokoulina E S, Nikitin V A, Petukhov Yu P and Kutov A Ya 2012 Proton interactions with high
    multiplicity Phys.Atom.Nucl. 75, Issue 6, 664-667.
[3] Avdeichikov V V et al 2013 Spectrometer with a vertex detector for experiments at the IHEP
    accelerator Instrum.Exp.Tech. 56 9-31.
[4] Avdeichikov V V et al 2011 A trigger of events with a high multiplicity of charged particles at
    the SVD-2 setup Instrum.Exp.Tech 54 159-168.
[5] Kokoulina E S, Kutov A Ya, Nikitin V A and Popov V V 2011 Analysis of high multiplicity
    events Phys.Part.Nucl.Lett. 8 855-859. http://dx.doi.org/
[6] Kokoulina E S, Nikitin V A, Petukhov Yu P and Kutov A Ya 2010 Search for collective phenomena in
    hadron interactions Phys.Atom.Nucl. 73 2116-2124.
[7] Ammosov V V et al 1972 Phys.Lett. B42 (1972) 519-521. http://
[8] Kokoulina E S 2011 Neutral Pion Fluctuations in pp Collisions at 50 GeV by SVD-2
    Prog.Theor.Phys.Suppl. 193 306-309.
[9] Afonin A G et al 2012 Neutral pion number fluctuations at high multiplicity in pp-interactions
    at 50 GeV EPJ Web Conf. 37 06002. http://dx.doi.org/10.1051/epjconf/20123706002
[10] Ryadovikov V N 2012 Fluctuations of the number of neutral pions at high multiplicity in pp
    interactions at 50 GeV Phys.Atom.Nucl. 75, 989-998.
[11] Kokoulina E for SVD-2 Collaboration 2013 Evidence for a pion condensate formation in pp
    interactions at U-70 PoS ICHEP2012 259
[12] Kokoulina E S 2012 The evidence for the pion condensate formation in pp interactions at U-70
    PoS Baldin-ISHEPP-XXI 007
[13] Begun V V and Gorenstein M I 2008 Power Law in Micro-Canonical Ensemble with Scaling
    Volume Fluctuations Phys.Rev. C78 024904.
[14] Uleri J G. STAR Collaboration. Are there Mach cones in heavy ion collisions? Three-particle
    correlations from STAR. 2005 Int.J.Mod.Phys. E16 2005–10
[15] Chliapnikov P et al. 1984 Observation of direct soft photon production in K+ p interactions at
    70-GeV/c. Phys.Lett. 141B 276-280.
[16] Kokoulina E S, Kutov A Ya and Nikitin V A 2007 Gluon dominance model and cluster production
    Braz.J.Phys. 37 785-787.
[17] Kokoulina E S and Kutov A Ya 2008 High-multiplicity study Phys.Part.Nucl.Lett. 71, No 9,
    1573-1581.
[18] Volkov M K, Kokoulina E S and Kuraev E A 2004 Excitation of Physical Vacuum,
    Phys.Part.Nucl.Lett. Part 5, 16-23.
[19] Begun V V and Gorenstein M I 2007 Bose-Einstein condensation of pions in high multiplicity
    events. Phys. Lett. B 653, N2-4, 190-195.
[20] Landau L D and Lifshitz E M 1969 Statistical Physics ( Volume 5 of A Course of Theoretical
    Physics ) Pergamon Press.
[21] Kokoulina E S and Nikitin V A 2005 Study of multiparticle production by gluon dominance model
    17th International Baldin Seminar on High Energy Physics Problems: Relativistic Nuclear
    Physics and Quantum Chromodynamics (ISHEPP 2004)
[22] Ermolov P F, Kokoulina E S, Kuraev E A, Kutov A Ya, Nikitin V A, Pankov A A, Roufanov I
    A and Zhidkov N K 2005 Study of multiparticle production by gluon dominance model. Part II.
    17th International Baldin Seminar on High Energy Physics Problems: Relativistic Nuclear
    Physics and Quantum Chromodynamics (ISHEPP 2004)
[23] Semenov S V, Troshin S M, Tyurin N E and Khrustalev O A 1975 Connection Between Elastic
    and Inelastic Processes at High-Energies. (In Russian) Yad. Fiz. 22 792-800.
[24] Giovannini A 1979 QCD jets as Markov branching processes Nucl.Phys. B161 429-448.
[25] Barshay S 1989 Anomalous soft photons from a coherent hadronic phase in high-energy collisions. *Phys. Lett*. **B227**, N2, 279-284.

[26] White Paper http://theor.jinr.ru/twiki-cgi/view/NICA/NICAWhitePaper.

[27] Kokoulina E S 2002 Analysis of multiparticle dynamics in $e^+e^-$ annihilation into hadrons by two stage model. XXXII ISMD, Alushta, Ukraine W.Sc. publ. 340-343.

[28] Kokoulina E S 2006 Gluon Dominance Model and $e^+e^-$ annihilation, Proceedings of the 13th annual seminar "Nonlinear Phenomena in Complex Systems", Minsk, May 16-19, Joint Institute for Power and Nuclear Research-Sosny, NAS of Belarus **13** 73-82.

[29] Kuraev E A, Bakmaev S and Kokoulina E S 2011 Azimuthal correlation of gluon jets created in $pp$, $p\bar{p}$ and $e^+e^-$ collisions, *Nucl.Phys*. **B851** 551-564.

[30] Didenko L A, Murzin V S and Sarycheva L I 1979 Leading and charged exchange in pi-p interactions at 40 GeV (talk). Proceedings, 16th International Cosmic Ray Conference, Vol.6 29-33.

[31] Kuraev E A, Kokoulina E S and Tomasi-Gustafsson E 2013 Hard light meson production in (anti)proton-hadron collisions and charge-exchange reactions. e-print arxiv.org hep/ph-1306.5169.