Письма в ЭЧАЯ. 2016. Т. 13, № 1(199). С. 123–130

HIGH MULTIPLICITY STUDY AND GLUON DOMINANCE MODEL

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Study of high multiplicity events in proton–proton interactions is carried out at the U-70 accelerator (IHEP, Protvino). These events are extremely rare. Monte Carlo codes usually underestimate topological cross sections in this region. The gluon dominance model (GDM) was proposed to describe them. It is based on QCD and a phenomenological scheme of hadronization stage. This model indicates recombination mechanism of hadronization and gluon fission. Future program of the SVD Collaboration is aimed at studying a long-standing puzzle of excessive soft photon yield and its connection with high multiplicity at the U-70 and the Nuclotron facility at JINR, Dubna.

На ускорителе У-70 (ИФВЭ, Протвино) выполняются исследования событий с большой множественностью. Эти события являются крайне редкими. Обычно генераторы Монте-Карло недооценивают поперечные сечения в этой области. Для их описания была предложена модель глюонной доминантности (МГД). Она основана на КХД и феноменологической схеме адронизации. Эта модель указывает на рекомбинационный механизм адронизации и деление глюонов. Будущая программа исследований коллаборации СВД нацелена на изучение давней загадки повышенного выхода мягких фотонов и ее связи с большой множественностью на У-70 и нуклотроне ОИЯИ в Дубне.

PACS: 24.85.+p

INTRODUCTION

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

$$p + p \to 2N + N_\pi \pi, \tag{1}$$

where N is a nucleon and N_π is the number of pions. The energy of the proton beam is 50 GeV, the average charged multiplicity $\overline{N}_{\rm ch}$ at this energy is 5.45. Pions are hadrons copiously produced at this energy. We study the high charged ($N_{\rm ch}$) and high total ($N_{\rm tot}$) multiplicities that are larger than the average ones. The kinematical limit is defined from the condition of all kinetic energy transformation of colliding protons into the mass of pions

$$N_{\rm thresh} \simeq \frac{\sqrt{s} - 2m_p}{m_\pi}. \tag{2}$$

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At 50 GeV/c the kinematical limit is approximately 59 pions. The experiment is carried out at the SVD (Spectrometer with Vertex Detector) setup located at the 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) was manufactured to suppress registration of small multiplicity events and register events with multiplicity higher than the 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 them. Current models give diverse predictions of high multiplicity behavior [6]. So the experimental and subsequent theoretical studies are necessary. The SVD Collaboration has advanced in measuring topological cross sections of pp interactions [1, 2] with high charged multiplicity. Previous Mirabelle data [7] were renovated for $N_{\rm ch}$ from 10 up to 16, and we have added 4 new points from 18 up to 24. The topological cross section at the last observed point, $N_{\rm ch} = 24$, is three orders of magnitude lower than the one obtained by the Mirabelle Collaboration at $N_{\rm ch} = 16$.

Neutral particles, photons, are registered by electromagnetic calorimeter (ECal). Owing to its restricted acceptance, it is impossible to restore all neutral pions directly. That is why an original algorithm was developed to define the number of events with a certain multiplicity of π^0 mesons [8–12] and the one with the total multiplicity, $N_{\rm tot} = N_{\rm ch} + N_0$, where N_0 is the multiplicity of neutral pions.

Some collective phenomena are predicted in this region. The SVD Collaboration is aimed at searching for Bose–Einstein condensation (BEC) of pions [13–15], the peak structure at the angular distribution [16], and the study of an anomalous yield of soft photons ($p_T < 100$ MeV) [17] in the high multiplicity region.

The noticeable growth of a scaled variance (ratio of variance to average multiplicity) was revealed in proton–proton interactions in the region of high total multiplicity [8–12]. In accordance with the Begun–Gorenstein model [13–15] of an ideal hadron gas, it can be one of the indications of the pion BEC formation. The two-humped structure in angular distribution is preliminary observed in events with multiplicity higher than the average one [18, 19]. To predict the behavior of the topological cross sections in the high multiplicity region, the gluon dominance model (GDM) was proposed [20, 21]. Studying the soft photon yield puzzle is our following investigation at the U-70 and the Nuclotron (JINR, Dubna) [22–24].

The description of topological cross sections taking into account the high multiplicity region in the framework of the GDM is added in Sec. 1. Section 2 demonstrates how the GDM improves this description with inclusion of a gluon fission. Estimation of the charge-exchange contribution in the GDM is carried out in Sec. 3. The final section states the conclusions.

1. GLUON DOMINANCE MODEL

The gluon dominance model (GDM) [20, 21] is a modification of the two-stage model (TSM) [25, 26]. The TSM describes well multiplicity distributions in e^+e^- annihilation in a wide energy region. It is based on the convolution of a QCD quark–gluon cascade of an initial quark pair with hadronization. In accordance with experimental data, the binomial distribution has been chosen for the description of hadronization.

The binomial distribution uses the following parameters: the average multiplicity $\overline{n}^h_{q(g)}$ and the maximum number of hadrons $N_{q(g)}$ resulting from quark (gluon) in their passing through this stage. The ratio of the gluon and quark parameters, $\alpha = \overline{n}^h_g/\overline{n}^h_q$, reduces the number of parameters at the hadronization stage to three. As is shown in Fig. 1, the parameter $\overline{n}^h_g$ remains approximately constant and close to 1 in a wide energy region (from 10 up to 200 GeV). Such behavior of the TSM parameter is the confirmation of the fragmentation mechanism of hadronization in vacuum: one-gluon fragments into one hadron. The main source of secondary hadrons are gluons which are called "active". The average multiplicity of gluons grows with energy which can be approximated by the logarithmic dependence $\overline{m} = m_0 \log \sqrt{s}/\sqrt{s}_0$ shown in Fig. 2, where $\sqrt{s}$ is the c.m.s. (center-of-mass system) energy and m_0 and s_0 are the parameters.

In pp interactions, opposed to e^+e^- annihilation, one should take into account valency quarks and nascent gluons which form an initial quark–gluon system. The comparison with experimental data shows that multiparticle production is implemented by active gluons. Valence quarks remain in leading particles as passive spectators [20, 21]. Only in this case the description of topological cross sections becomes successful. Therefore, in our model, called

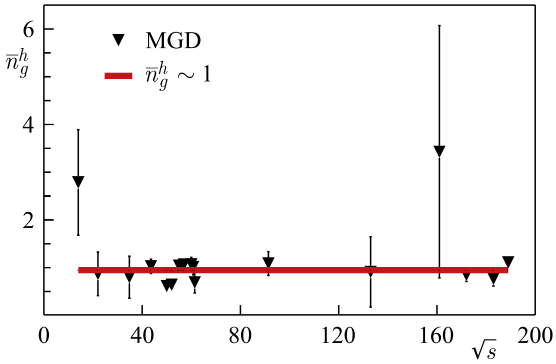

Fig. 1. Hadronization parameter of gluons $\overline{n}^h_g$

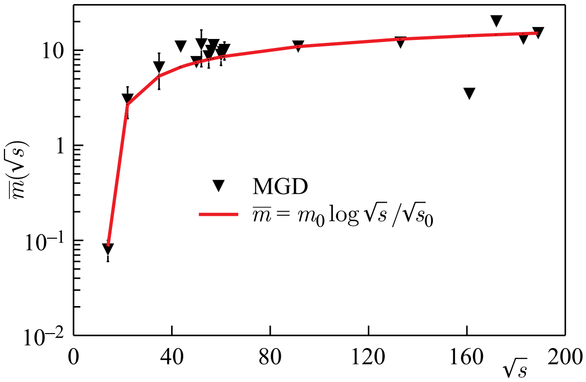

Fig. 2. Mean multiplicity of active gluons in TSM

gluon dominance model (GDM), two main schemes were considered: with and without gluon fission. Both schemes were compared with experimental data.

According to GDM, the quark–gluon system formed at the first stage then is developed owing to active gluons. These gluons can give a branch. This stage is described by the Poisson distribution with or without addition of the Farry distribution (accounting of gluon fission). The hadronization stage is described by the binomial distribution. The topological cross sections in the scheme without gluon fission have the following form:

$$\sigma_n = \sigma_{\mathrm{inel}} \sum_m \frac{\mathrm{e}^{-\overline{m}}\,\overline{m}^m}{m!} \binom{mN_g}{n-2} \left(\frac{\overline{n}_g^h}{N_g}\right)^{n-2} \left(1-\frac{\overline{n}_g^h}{N_g}\right)^{mN_g-n+2}. \qquad (3)$$

The GDM describes well all experimental topological cross sections for pp interactions from the U-70 energy up to ISR energies [21]. The hadronization parameter of gluons $\overline{n}_g^h$ grows from 1.5 at 50 GeV/c, U-70, up to 3.3 at 62.2 GeV, ISR [20, 21]. The growth of the hadronization parameter is the evidence of the implementation of the recombination mechanism of hadronization. This stage occurs in quark–gluon medium but not in vacuum. In Fig. 3, the topological cross sections at 50 GeV/c are presented. The region of low multiplicity was measured by the Mirabelle Collaboration [7]. The high multiplicity region was supplemented by the SVD Collaboration [1, 2]. The GDM (3) is presented in this figure by the solid line. The second model, based on the KNO-function obtained from the relations between the elastic and inelastic cross sections [27], is shown by the dashed line, and the third model based on the negative binomial distribution [28] is denoted by the dotted line. These models describe well the region of small multiplicity, but in the high multiplicity region small overestimation is observed for the negative binomial distribution [1, 2].

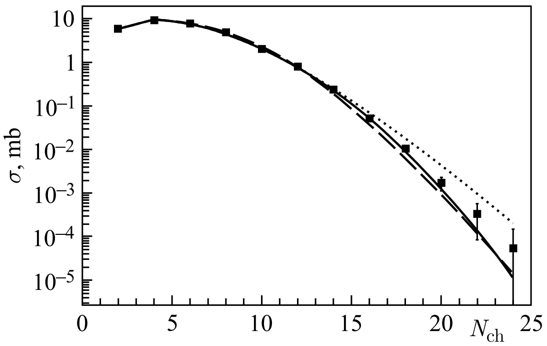

Fig. 3. Description of $\sigma(N_{\mathrm{ch}})$ data [1, 2] by GDM (3) [20,21] (solid line), KNO-based model [27] (dashed line), and the negative binomial distribution [28] (dotted line)

2. GLUON FISSION

It is known that gluons give branching at high energies. Becoming predominant, it gives an additional contribution to the multiplicity. The GDM takes it into account in the following way:

$$\begin{aligned}\sigma_n = \alpha_1 \sum_{m_1} \frac{\mathrm{e}^{-\overline{m}_1}\,\overline{m}_1^{m_1}}{m_1!} \binom{m_1N_g}{n-2} \left(\frac{\overline{n}_g^h}{N_g}\right)^{n-2} \left(1-\frac{\overline{n}_g^h}{N_g}\right)^{m_1N_g-n+2} + \\ + \alpha_2 \sum_{m_2} \frac{\mathrm{e}^{-\overline{m}_2}\,\overline{m}_2^{m_2}}{m_2!} \binom{2m_2N_g}{n-2} \left(\frac{\overline{n}_g^h}{N_g}\right)^{n-2} \left(1-\frac{\overline{n}_g^h}{N_g}\right)^{2m_2N_g-n+2}, \qquad (4)\end{aligned}$$

where $m_{1,2}$ are multiplicities of single- and double-gluon sources; $\overline{n}_h^h$ and N_g are the parameters of hadronization of gluons. In this scheme, at the second stage the branching gluons give twice as large hadrons because they are sources consisting of two gluons (the second summand in σ_n). The ratio of two parameters α_1/α_2 is approximately 1.8. Other parameters are barely changed in comparison with (3).

In the double-logarithmic approximation [29], it was revealed that the emission of two-gluon jets formed by the fission process of a paternal quark (antiquark) is predominant with increasing energy and can explain the angle broadening of secondary particles. This fission can give the broadening of topological cross sections at high multiplicity [20,21,29]. In Fig. 4, the comparison of the measured topological cross sections [1, 7] with the GDM (solid line) is shown. The dash-dotted line presents the contribution that appeared from the single-gluon sources; the dashed line (the second summand in (4)) describes the contribution responsible for gluon fission. Obviously, taking into account the gluon fission noticeably improves the description of data.

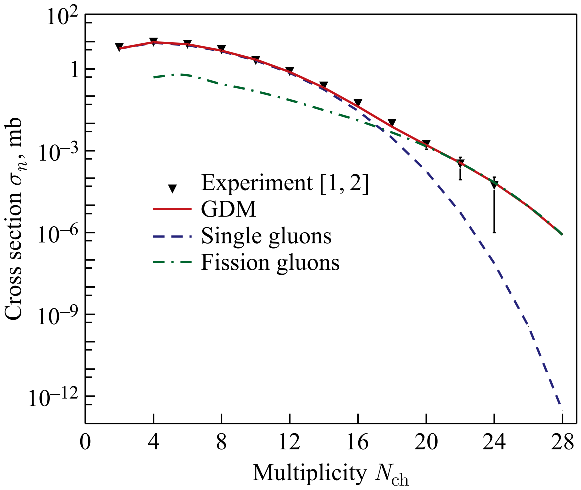

Fig. 4. Topological cross sections σ_n versus charged multiplicity N_{ch} in the GDM. The dashed line describes the contribution of single sources, the dash-dotted line is for the sources consisting of two gluons of fission, the solid line is their sum

The GDM has been modified for describing the topological cross section in the proton–antiproton annihilation by introducing intermediate charged quark topologies. This modification is based on the well-known experimental fact of two charged pions leading and an active role of gluons in multiparticle production of hadrons. Quark topologies are determined by the formation of three neutral pions or two charged and one neutral pion from the valence quarks only. Also, valence quarks can be combined with quarks from the quark–gluon system. In this case, the number of pions with valence quarks can increase up to 6. This scheme describes well the topological cross sections $\Delta\sigma_n$ of the pure $p\overline{p}$ annihilation process, which are defined as differences $\Delta\sigma_n = \sigma_n(p\overline{p}) - \sigma_n(pp)$ [20].

3. CHARGE EXCHANGE IN pp INTERACTIONS

As is known from experiments, a charge-exchange process can be realized at the scattering of protons off hydrogen or nucleus targets [30]. In this case, one of the protons gives its charge to a neutral pion and turns into a neutron

$$p + p \rightarrow p + \pi^+ + n + N_\pi. \tag{5}$$

In (5) N_π is the number of secondary pions and n is a neutron. An estimation of the charge-exchange cross sections 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 $\sigma_{2,\mathrm{el}} = 6.90$ mb and $\sigma_{2,\mathrm{inel}} = 5.71$ mb, respectively. Their ratio is equal to $r = \sigma_{2,\mathrm{el}}/\sigma_{2,\mathrm{inel}} = 0.82$. In the GDM the cross section is $\sigma_{2,\mathrm{el}} \sim \exp(-\overline{m})$ because the active gluons do not appear. Since we do not know the contribution of the charge-exchange process, we can use for $\sigma_{2,\mathrm{inel}}$ the expression $r \exp(-\overline{m})$. At the same time, $\sigma_{2,\mathrm{inel}}$ can be represented as a sum of two cross sections

$$\sigma_{2,\mathrm{inel}} = \sigma_{2,\mathrm{inel}}^{+\mathrm{ch}} + \sigma_{2,\mathrm{inel}}^{-\mathrm{ch}}, \tag{6}$$

with a charge exchange $(+\mathrm{ch})$ and without it $(-\mathrm{ch})$. One can estimate the second summand in (6) the following way:

$$\sigma_{2,\mathrm{inel}}^{-\mathrm{ch}} \sim \sum_m \frac{\mathrm{e}^{-\overline{m}}\,\overline{m}^m}{m!} \left(1 - \frac{\overline{n}^h}{N_g}\right)^{mN_g - n + 2}. \tag{7}$$

Let $P = \sigma_{2,\mathrm{inel}}/\sigma_{2,\mathrm{inel}}^{-\mathrm{ch}}$, then instead of $\sigma_{2,\mathrm{inel}}$ we use expression (7) with factor P and from fitting of data we find $P = 2.18$. Hence, the coefficient of the charge exchange

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

is $\simeq 50\%$ [31]. This estimation is in agreement with the experimental data [30]. The contribution of the charge exchange is essential, and at small multiplicity one should keep in mind this fact.

CONCLUSIONS

In this review, the main results of high multiplicity study within the GDM have been presented. The region of high multiplicity is unique, promising, and fruitful. We expect that new collective phenomena will be found out and our collaboration will advance significantly in understanding the multiparticle production especially at the hadronization stage.

Acknowledgements. The author is grateful to all participants of the SVD-2 Collaboration for their active work and useful discussions.

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Received on January 28, 2015.