PoS PROCEEDINGS OF SCIENCE

A look at hadronization via high multiplicity

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Multiparticle production is studied experimentally and theoretically in QCD that describes interactions in the language of quarks and gluons. In the experiment the real hadrons are registered. For transfer from quarks and gluons to observed hadrons various phenomenological models are used. In order to describe the high multiplicity region, we have developed a gluon dominance model (GDM). It represents a convolution of two stages. First stage is described as a part of QCD. For second one (hadronisation), the phenomenological model is used. To describe hadronisation, a scheme has been proposed, consistent with experimental data in the region of its dominance. Comparison of this model with data on e+e- annihilation over a wide energy interval (up to 200 GeV) confirms the fragmentation mechanism of hadronisation, the development of the quark-gluon cascade with energy increase and domination of bremsstrahlung gluons. The description of topological cross sections in pp collisions within of GDM testifies that in hadron collisions the mechanism of hadronisation is being replaced by the recombination one. At that point, gluons play an active role in the multiparticle production process, and valence quarks are passive. They stay in the leading particles, and only the gluon splitting is responsible for the region of high multiplicity. GDM with inclusion of intermediate quark charged topologies describes topological cross sections in $p\overline{p}$ annihilation and explains initial linear growth in the region of negative values of a secondary correlative momentum vs average pion multiplicity with increasing of energy. The scaled variance of a neutral pion number measured by us is rising abruptly in the region of high total multiplicity and differs from Monte Carlo predictions by seven standard deviations. The growth of fluctuations of the neutral pion number in this region may indicate the formation of a pion (Bose-Einstein) condensate. While searching for this collective phenomenon, events with a predominance of a large number of neutrals ($n_0 = 16$) among total multiplicity ($n_{tot} = 32$) have been found. Despite the growth of fluctuations on the neutral number, their average remains equal to 1/3 of the total pion number. Our future study of soft photon yield in the region of high multiplicity at U-70 and Nuclotron is outlined.

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1. Introduction

Development of high energy physics has been considerably accelerated after the appearance of the strong interaction theory or quantum chromodynamics (QCD) [1]. It can point out two experimental stages that influenced its development. The first stage is connected with experiments at hadron accelerators. The appearance of electron-positron beams was the second one. These experimental results required the explanation. That was specially important for description of multiparticle production. Such physicists like Fermi, Pomeranchuk, Hagedorn, Dremin, Brodsky and others developed phenomenological schemes based on statistical description. So, the bootstrap model of Hagedorn predicts the existence of extreme temperature. Now, this behaviour is interpreted as the formation of quark-gluon plasma.

Later, using QCD elementary processes, Konishi, Ukava and Veneciano [2] and A. Giovannini [3] built a system of stochastic equations to calculate multiplicity distributions (MD) of partons in quark and gluon jets at high energy collisions. The solution of that system with taking into account of two main elementary processes (gluon splitting and bremsstrahlung) gives MD of quarks and gluons in these jets. By the way, MD of partons in a quark jet is well-known the negative binomial distribution (NBD), and a Yule-Furry distribution describes MD in gluon jet..

For comparison with the experimental data these distributions cannot be used because free quarks are not observed experimentally, due to confinement, which has been accepted without proofs so far. To eliminate this difficulty, at the description of MD for e^+e^- -annihilation to hadrons, a hypothesis of local parton-hadron duality (LoPHD) has been proposed, according to which the hadronization of quarks and gluons occurs softly, without significant momentum transfer between partons. Thus, for description of MD in that process two stages had been taken: the first stage or the quark-gluon (qg) fission, to which the pQCD can be applied, and the hadronization stage, described phenomenologically. The LoPHD hypothesis was quite consistent with the experiment, while energy of accelerators was not so high to be develop qg-cascades enough. Experiments at the DESY accelerator confirmed formation of quark and gluon jets, which testified in favour of QCD.

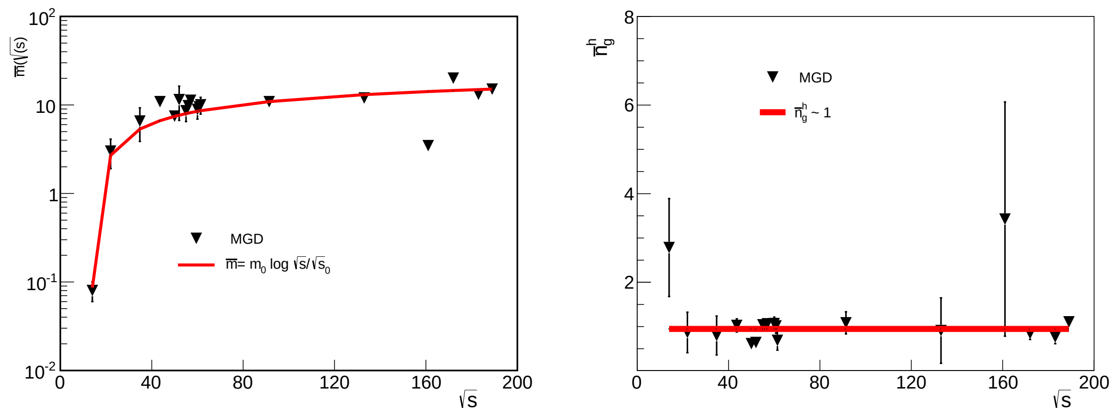
In order to describe MD in e^+e^- annihilation to hadrons at energies from several tenths to hundreds GeV, the two-stage model (it was later renamed into the gluon dominance model, GDM) has been offered [4, 5, 6, 7]. It's based on the description of MD of partons forming from $q\overline{q}$-pair at the first stage of that process by Giovannini's distributions [3]. We also added a phenomenological scheme at the second stage (hadronization of quarks and gluons). In this model, for hadrons from the parton (quark or gluon) jet at the hadronization stage, a binomial distribution (BD) with a negative second correlation moment ($f_2 = \overline{n(n-1)} - \overline{n}^2$, n - multiplicity, $\overline{n}$ - its average value) is used. This choice is based on experimental data [8]. At energies of a few GeV when the number of partons at the stage of the qg-cascade is small, the hadronization is predominant and determines the sign of the second correlation moment. Its experimental value in this area is negative.

With increasing energy, it's obvious that the qg-ascade is developing. It becomes prevailing over the hadronization stage. In accordance with the Giovannini's approach [3], this cascade is described by NBD with a positive second correlation moment and two parameters, an average gluon multiplicity and a k_p parameter that has a sense of the inverse temperature (T) of the qg-system, $k_p \sim T^{-1}$. Change of the second correlation moment sign with increasing energy is confirmed experimentally. This model is built by a convolution of two stages describing borth NBD and BD. This model describes well the experimental MD of charged particles and indicates the active role of gluons in their formation. It is interesting to follow the change of its parameters with increasing energy at both stages.

In accordance to two stage model, at the first stage, the average multiplicity of gluons ($\overline{m}$) increases with energy and can be described by a logarithmic dependence (Fig. 1, a). At the same time, the NBD parameter k_p is decreasing, that indicates an increase in temperature of the qg-system. At the second stage, the parameters of the model N_p and $\overline{n}_p^h$, where p is q or g, determine, correspondently, the maximum and the average number of hadrons produced from single quark or gluon in the region of hadronization where application of the perturbation theory of QCD is difficult. Comparison with experimental data shows the gluon jet is softer, and its parameter $\overline{n}_p^h$ remain almost constant and close to one in the energy range from 10 to 200 GeV (Fig. 1, b).

Such behaviour confirms the LoPHD hypothesis and the fragmentation mechanism of hadronization [10]. At the fragmentation mechanism, the initial high energy quark emits a bremsstrahlung gluon which splits to $q\overline{q}$ pair. Then a pair's quark picks up a convenient quark (antiquark) from a vacuum and forms an observed meson. In this case, mesons turn out predominant particles. Experiments at RHIC evidence the ratio of baryons to mesons are considerably less than one in the peripheral region. The creation of heavy quark pairs occurs but it's suppressed in comparison with the central region.

As an example, MD in e^+e^--annihilation at 189 GeV is shown in Fig. 2, a. As opposed to the predictions of numerous Monte-Carlo generators, GDM correctly describes the MD on the tail of a large multiplicity, and it also indicates what the sources of the observed oscillations of the normalised correlation moments at high energy [6] are namely developed qg-cascade hadronisation stage.



a b

Figure 1: (a) The parameter $\overline{m}$, average multiplicity of gluons formed in the qg-cascade from a single gluon. (b) The hadronization parameter $\overline{n}_g^h$ ([4]) has sense of the average multiplicity of hadrons formed from single gluon The number of hadrons formed from one gluon during its passing of the second stage. Experimental data for the MD description of hadrons by GDM was taken from about 10 GeV up to 200 GeV [5] .

The two-stage model, in particular, explains the jump between the average multiplicities in the three-gluon decay of heavy quarkonia $\Upsilon(9.4)$ and $\Upsilon(10.02)$ and in e^+e^--annihilation at the same energy [5]. The oscillations of normalised cumulative moments can be describe within this scheme [6].

The new stage, no less exciting in the study of nuclear matter, began with the appearance of high-energy hadron accelerators as well as heavy ion colliders with energies a few hundreds GeV. These studies are carried out at the large hadron collider (LHC) where particles are accelerated up to energy of several TeV. World society of physicists discusses a future project of new generation accelerators with considerably higher energy (hundreds TeV).

In 2004 at JINR (Dubna, Russia), the Thermalization project has been advanced. It was carried out by three institutes: JINR, IHEP (Protvino) and INP MSU (Moscow) at the SVD-2 setup (Spectrometer with a Vertex Detector) located on the extracted proton beam of the U-70 accelerator (IHEP). This project was aimed to search for collective phenomena in pp interactions with a 50 GeV proton beam in the region of multiplicity, which is several times larger than average value.

In this region of multiplicity, such phenomena as the formation of the pion condensate, an increased yield of soft photons, the formation of pion jets of the same sign and others are predicted. Before start of the experiment, a Monte-Carlo (MC) simulation has been performed. A comparison of it with the data obtained by the Mirabelle collaboration at the U-70 accelerator showed that it significantly (about two orders of magnitude) underestimates the data on the tail of a large multiplicity n_{ch} = 18. Therefore, we should build an improved model consistent with the data in this area.

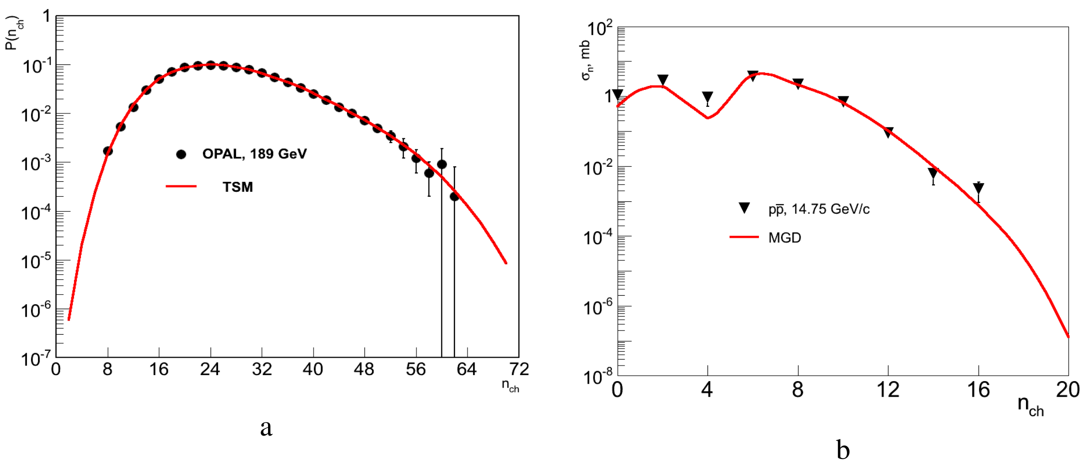


Figure 2: (a) MD of hadron in e^+e^- annihilation at 189 GeV [6]. (b) Differences of topological cross sections between proton and proton-aniproton (σ_n = σ_{pp} - $\sigma_{p\overline{p}}$) interactions at the same energy about ten GeV [5] .

We guessed what hadronization of quarks and gluons in hadron collisions occurs the same way as in e^+e^- annihilation. Just like in e^+e^- annihilation description, our modified GDM takes into account both of stages of multiparticle production. We had analysed all available for us data on topological cross sections of hadronic interactions at energies up to several hundred GeV. At that, the existing phenomenological models and Monte-Carlo codes did not predict behaviour in the region of high multiplicity. The Mirabelle Collaboration data had indicated to us the direction to develop our model.

At first, we included into the number of participants of pp interactions all valence quarks and a few, so-called, active gluons that appear at the moment of collision. The term "active" gluon is used by ourselves for those gluons that can give gluons of fission with the following quark pair formation. These quarks and antiquarks form observable hadrons (mesons and baryons) by combinatorial permutations. In this scheme, MD at the stage of hadronization of partons (valence quarks and active gluons) is described, as in the process of e^+e^--annihilation, by the binomial law.

In this case, parameters, which have the meaning of the average number of hadrons formed from quark or gluon, $\overline{n}^h_{q(g)}$, at the hadronization stage, accepted values significantly less than the same parameters at the description of e^+e^--annihilation. We assumed that not all valence quarks are active, and we consistently reduced their number from three pairs to two, then to one and, finally, all of them were completely excluded from this approach, leaving in the leading particles. And then parameter $\overline{n}^h_g$ began to grow and even slightly exceeded the value, corresponding to e^+e^--annihilation.

Thus, the analysis of pp interactions indicates the passivity of valence quarks and the active role of gluons in multiple production. Valence quarks remain in the leading nucleons, which are observed in the experiment. And active gluons are the sources of secondary particles.

Modification of GDM for MD description is performed in two scenarios. The first scenario takes into account the division of gluons arising at the time of formation of the qg-system, which is described by the Poisson distribution and their division by the Farry distribution. In the second scenario, the gluon splitting is not taken into account. The fragmentation of active gluons into hadrons is described for both scenarios the same way. It is assumed all stages of hadron interactions occur independently of each other what simplifies the model.

The description of topological cross sections in both scenarios of GDM for pp interactions at 70 GeV, measured by the Mirabelle and SVD-2 Collaborations at U-70, shows the consistency of values of $\overline{n}^h_g$, the average multiplicity of hadrons produced from one gluon during its passing of the hadronization stage, and the same parameter for e^+e^- annihilation. In the hadron collisions, it has small excess over 1: $\overline{n}^h_g = 1.63 \pm 0.12$. This is consistent with the recombination mechanism of hadronization taking place in a qg-medium, and not in vacuum as in the case of e^+e^- -annihilation.

The replacement of the hadronization mechanism at transition from the annihilation of leptons to the hadron and nuclei interactions is illustrated perfectly by B. Muller [10]. GDM indicates a logarithmic growth with the energy of $\overline{n}^h_g$, which at the energy of the ISR accelerator, reaches the value 3.23 ± 0.14 [9].

Experiments at RHIC and LHC show the ratio of baryon yield to the number of neutral pions grows and is approaching to 1 (in e^+e^--annihilation, this ratio is much less than 1) at the transition from peripheral to central collisions, which is also explained by the implementation of the recombination mechanism in central collisions.

It should note, in the first scenario, taking into account splitting of gluons, a share of active gluons is estimated as about 47% at U-70 energy. The same estimation (about 50%) has been obtained in QCD by A. H. Muller [11]. We assume that the remaining (not active, soft) gluons are picked up by the quarks formed by the splitting of active gluons. These quarks transform into observable hadrons. At the same time, energy of soft gluons can create an increased, in comparison with the existing models, yield of soft photons in the elementary process: $g+q \to \gamma+q$.

GDM indicates the predominance of splitting gluons in processes of multiple production at high energies and explains discovered in heavy ion collisions at the RHIC setup and then in proton collisions at LHC in high multiplicity events the long-radius correlations named ridges. We have shown [12] the formation of two gluons arising from a bremsstrahlung gluon by splitting takes place at small angles to the initial direction of the valence quark and this splitting prevails in comparison with the serial emission by that quark of two gluons. In this case, we can observe a very narrow hadron jet with a wide variation of particles in it in rapidity.

Analysis of experimental data obtained at SVD-2 setup at interactions of 70-GeV proton beam with a hydrogen target and three nuclear targets (C, Si, Pb) demonstrates the manifestation of a two-humped structure in a polar angle distribution in a region of large multiplicity that doesn't observe in events with small multiplicity [7]. Such behaviour is often interpreted by analogy with Cherenkov radiation by collective emission of gluons by valence quarks, or, more often, by the formation of shock waves in a qg-medium. Comparison of our data with the formula of Cherenkov radiation permits to estimate the refractive index of this medium. Its assessment is close to 1. That indicates the rarefaction of parton medium, in contrast to the medium formed in central collisions of relativistic heavy ions (the refractive index about 3).

GDM is comprised some modifications for description of differences between of topological cross sections for processes of proton-antiproton annihilation and proton-proton interactions at 10 GeV. The $p\overline{p}$ annihilation can be described by the inclusion of the so-called intermediate charged quark topologies formed due the combination of valence (predominant) and sea quarks from colliding nucleons.

We can form the following combinations from quarks (u, u, d) of the proton and antiquarks ($\overline{u}$, $\overline{u}$, $\overline{d}$) of the antiproton: "0"-, "2"-, "4"- and "6"- topologies. Neutral "0"-topology corresponds to the formation of three neutral pions from these partons , "2"-topology - the formation of two charged pions of different signs and one neutral one by using only valence quarks, the remaining "4"- and "6"-topologies form secondary pions not only from valence, but also from quarks of vacuum (sea quarks). Experiments indicate at the leading of two charged pions that confirms this scheme [8].

In the modified GDM, we can neglect of the rarest "6"-topology. The contribution of the other three combinations can be estimated from the comparison with the data. The parameters of hadronization are in good agreement with the parameters determined from pp interactions data with minor deviations. The found relation between the topologies of "0" : "2" : "4" = 15 : 40 : 0.05 indicates the main contribution is made by two main combinations of valence quarks ("0" and "2"). As shown in Fig. 2, b, GDM describes differences of topological cross sections between $p\overline{p}$ annihilation and pp scattering at the same energy of colliding hadrons, including the appearance of two local maxima at the field of formation of two and six charged secondary particles. Moreover, "4"-topology is responsible for the appearance of the tail of high multiplicity.

At lower energies the hadronization stage is predominant. In this case the second correlation moment $f_2 = \overline{n(n-1)} - \overline{n}^2$ calculated in GDM gives negative values. This moment demonstrates the linear growth in the region of negative values with the average multiplicity of active gluons in a wider energy interval as contrasted with diffraction processes in pp collisions, in which valence quarks are staying in the leading nucleons. With growth of energy, the contribution of splitting gluons goes up what leads to changing of f_2 from negative to positive sign and the broadening of MD.

The next step, the transition to neutral pion production has been taken. We assumed the universality of hadronization in hadron interactions and used the available data from bubble chambers [13] on cross sections of π^0-mesons to describe MD of neutral pions by GDM. It turned out that such parameters of hadronization as the average value and the maximum possible number of π^0-mesons, which are formed at the stage of hadronization from one gluon source (active gluon), are comparable with the corresponding values for charged particles. Moreover, in GDM, the ratio between the average multiplicities of charged and neutral mesons is close to 2 : 1, which corresponds to the theoretical value.

Carrying out our U-70 experiment, we restored the multiplicity of neutral pions and investigated the region of high total multiplicity $n_{tot} = n_{ch} + n_0$ as sum of charged and neutral particles. The SVD-2 setup allows to do that as it includes an electromagnetic calorimeter. This calorimeter registers gamma-quanta (decay products of neutral pions). That detector is located on the beam line behind the detectors registered charged particles.

The restoration of the total multiplicity allowed us to study such a collective phenomenon as the formation of pion or Bose-Einstein condensate (BEC). The theoretical substantiation of its observation has been predicted by the Begun and Gorenstein [14, 15]. They studied the fluctuations of the number of neutral pions at a fixed total pion multiplicity in the framework of the ideal pion gas statistical model and showed that the search for pion condensate have to be carried out by selecting events with high total multiplicity when the system is in thermal equilibrium but not chemical equilibrium.

At full equilibrium, the chemical potential is equal to zero, and for the formation of pion condensate it's approaching to the pion mass. Such a state can be obtained by selecting events with a large number of pions, much more than the average multiplicity. The fluctuations of the number of neutral pions in this case are due to the dynamics of multiple production. The signal of the BEC formation in proton collisions at the U-70 setup would be a growth of normalised dispersion of the number of neutral pions with an increase in the total pion multiplicity: $\omega = D/\overline{n}_0 = (\overline{n_0^2} - \overline{n}_0^2)/\overline{n}_0$.

We found out there isn't any growth of the normalised variance calculated for the simulated events in the whole simulation region. The method of reconstruction of π^0-mesons is based on using of the simulation. Event by event method is impossible in our case. Therefore, we worked out a new method for restoration of the number of events with a certain number of neutral mesons. About one million events had been processed and the number of events with given multiplicity of neutral mesons have been got. Actually, rare events with high total multiplicity are observed with the number of π^0 mesons comparable to the multiplicity of charged particles: the events with n_{tot} = 32 pions is observed with the number of charged particles n_{ch} = 16.

Our data are evidence of an increase of the normalised dispersion in the region of high total multiplicity, which reaches 7 standard deviations from simulated events at the largest value of n_{tot} [16]. The smallness of systematic errors in comparison with the statistical errors can be justified by the agreement of our data with the data of Mirabella's bubble chamber.

Theoretical estimations based on the formulas of statistical quantum physics indicate that in events with the maximum multiplicity, which are observed ourselves , the born pions are in the BEC state. The Gorenstain's estimation of temperature for the pion condensate formation are much higher than temperature for condensation of bosonic atoms. It should note that in the registered events with the highest total multiplicity (n_{tot} = 36) neutral pions are predominant. Their number fluctuates strongly with an increase of n_{tot}.

Study of high multiplicity events clarify the hadronization mechanism for both charged and neutral hadrons in different processes. We can describe e^+e^- and $p\overline{p}$ annihilation, pp interactions and three-gluon decay by introduced hadronization scheme in wide energy region.

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