# A look at hadronization via high multiplicity

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**Abstract.** 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. Various phenomenological models are used for transfer from quarks and gluons to observed hadrons. In order to describe the high multiplicity region, we have developed a gluon dominance model (GDM). It represents a convolution of two stages. The first stage is described as a part of QCD. For the second one (hadronization), the phenomenological model is used. To describe hadronization, a scheme has been proposed, consistent with the 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) has confirmed the fragmentation mechanism of hadronization, 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 GDM testifies that in hadron collisions the mechanism of hadronization 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 proposed hadronization scheme can describe the basic processes of multiparticle production.

## 1 Introduction

Development of high energy physics has been considerably accelerated after appearance of the strong interaction theory or quantum chromodynamics (QCD) [1]. The experimental results required their explanation, especially important to describe multiparticle production.

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Such physicists as Fermi, Pomeranchuk, Hagedorn, Dremin, Brodsky and others developed phenomenological schemes based on statistical description. The bootstrap model of Hagedorn predicts the existence of extreme temperature. This behaviour is now interpreted as the formation of quark-gluon plasma.

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. Taking into account the two main elementary processes (gluon splitting and bremsstrahlung) gives MD of quarks and gluons in these jets. MD of partons in a quark jet is a well-known negative binomial distribution (NBD), and a Yule-Furry distribution describes MD in a gluon jet.

## 2 $e^+e^-$ annihilation and three-gluon decay of bottomonium

For comparison with the experimental data, the parton distributions cannot be used because free quarks have not been 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 softly occurs, without significant momentum transfer between partons. Thus, to describe the MD in that process, two stages are 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 the energy of accelerators was not so high to be developing enough $qg$-cascades. 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 (later renamed as the gluon dominance model, GDM) has been offered [4–7]. It is based on the description of MD of partons forming from $q\bar{q}$-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 is obvious that the $qg$-cascade is developing. It becomes prevailing over the hadronization stage. In accordance with Giovannini's approach [3], this cascade is described by NBD with a positive second correlation moment and two parameters, an average gluon multiplicity and $k_p$ parameter that has a sense of the inverse temperature (T) of the $qg$-system, $k_p \sim T^{-1}$. The change of the second correlation moment sign with increasing energy has been confirmed experimentally. This model is built as a convolution of two stages describing both NBD and BD. It describes 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 with the 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 the increase in temperature of the $qg$-system. At the second stage, the parameters of the model $N_p$ and $\overline{n}^h_p$, where $p$ is $q$ or $g$, determine, correspondingly, the maximum and the average number of hadrons

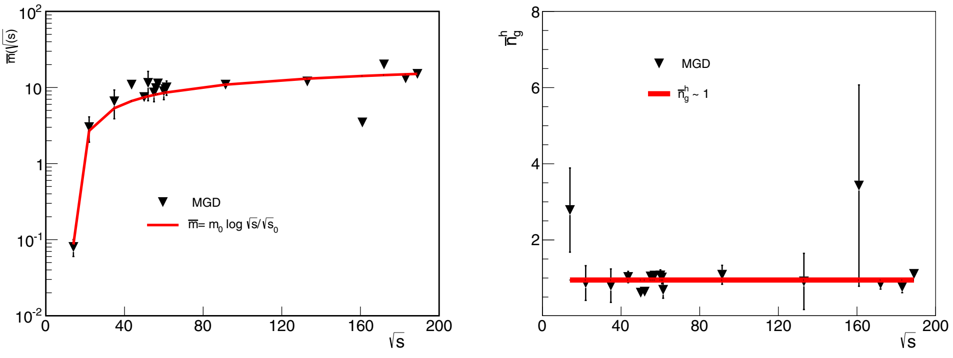

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**Figure 1.** (a) The parameter $\overline{m}$, average multiplicity of gluons formed in the qg-cascade from a single gluon. (b) The hadronization parameter $\overline{n}_g^h$ ([4]) means the average multiplicity of hadrons formed from single gluon 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]

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 that the gluon jet is softer, and its parameter $\overline{n}_g^h$ remains 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 [11]. 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 vacuum and forms an observed meson. In this case, mesons turn out predominant particles. Experiments at RHIC have shown that the ratio of baryons to mesons are considerably less than one in the peripheral region. The creation of heavy quark pairs occurs but it is suppressed in comparison with the central region.

As an example, MD in $e^+e^-$-annihilation at 161 GeV [9] 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. It also indicates that the sources of the observed oscillations of the normalized correlation moments at high energy [6] are the developed $qg$-cascade and the hadronization stage.

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 normalized cumulative moments in processes of $e^+e^-$-annihilation can be described 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 of a few hundreds GeV. These studies are carried out at the large hadron collider (LHC) where particles are accelerated up to the energy of several TeV. The world society of physicists is discussing a future project of new generation accelerators with considerably higher energy (hundreds TeV).

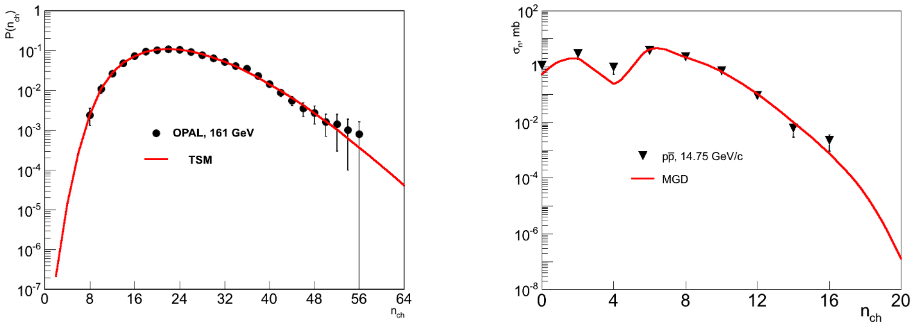

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**Figure 2.** (a) Description of MD of hadron in $e^+e^-$ annihilation at 161 GeV [9] by GDM [6]. (b) Differences of topological cross sections between proton-antiproton and proton-proton ($\sigma_n = \sigma_{p\bar{p}}$ - $\sigma_{pp}$) interactions at the same energy about ten GeV [5]

## 3 $pp$ and $p\bar{p}$ interactions with high multiplicity

The Thermalization project was advanced in 2004 at JINR (Dubna, Russia). Three institutes carried it out: 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 at searching for collective phenomena in $pp$ interactions with a 50 GeV proton beam in the region of multiplicity, which is several times larger than the average value.

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

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

We have started modeling of a scheme of multiparticle production with the most common case when all valence quarks and a few, so-called, active gluons (appear at the moment of collision) are participants of $pp$ interactions. We use the term "active" gluon for those gluons that can give gluons of fission with the following quark pair formation. These pairs of quarks form observable hadrons (mesons and baryons) by combinatorial permutations. The hadronization stage of partons is described by the binomial law as well as in $^+e^-$ annihilation.

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

Thus, in accordance to GDM, we can declare what valence quarks remain in the leading nucleons, which are observed in the experiment. And only active gluons are the sources of secondary particles.

The model is implemented in two scenarios. The first scenario takes into account the division of gluons in $qg$-system at the first stage. Their appearance is described by the Poisson distribution and 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 in both scenarios the same way. It is assumed that all stages of hadron interactions occur independently of each other.

Mirabelle and SVD-2 Collaborations measured topological cross sections of $pp$ interactions at 50 GeV. Their descriptions in both scenarios of GDM demonstrate the consistency of values of $\overline{n}_g^h$, the average multiplicity of hadrons produced from one gluon during its passing of the second stage. In the hadron collisions, it has a small excess over 1: $\overline{n}_g^h = 1.55 \pm 0.11$. 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 perfectly illustrated by B. Muller [11]. GDM indicates a logarithmic growth with the energy of $\overline{n}_g^h$, which at the top energy of the ISR accelerator, reaches the value $3.23 \pm 0.14$ [10].

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

It should be noted in the first scenario, taking into account splitting of gluons that a fraction 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 [12]. We assume that the remaining (not active, soft) gluons are picked up by the quarks formed by splitting of active gluons. These quarks transform into observable hadrons. At the same time, the excess of soft gluons can create an increased, in comparison with the existing models, yield of soft photons owing to the elementary process: $g + q \to \gamma + q$ .

GDM indicates the predominance of splitting gluons in processes of multiple production at high energies. It explains the long-radius correlations named ridges which were discovered in heavy ion collisions at the RHIC setup, and then in proton collisions at LHC in high multiplicity events. We have shown [13] the formation of two gluons arising from a bremsstrahlung gluon by splitting at small angles to the initial direction of the valence quark, 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 rapidity.

Analysis of the 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 the region of large multiplicity. This was not observed in events with small multiplicity [7]. This 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 allows us to estimate the refractive index of this medium. Its assessment is close to 1 which 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 can describe differences between topological cross sections for processes of proton-antiproton annihilation and proton-proton interactions at 10 GeV. For that, we modify our scheme for the $p\overline{p}$ annihilation 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, $\pi^+$ and $\pi^-$, and one neutral, $\pi^0$, 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 to the leading of two charged pions, which confirms this scheme [8].

In the modified GDM, we can neglect 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 agreement with the parameters determined from data of $pp$ interactions with minor deviations. The found relation between the topologies of "0" : "2" : "4" = 15 : 40 : 0.05 indicates that the main contribution is made by two main combinations of valence quarks ("0" and "2"). As shown in Fig. 2(b), GDM describes differences between topological cross sections for $p\overline{p}$ 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, calculated in GDM, the second correlation moment $f_2$ gives negative values and demonstrates the linear growth in the region of negative values with energy. In accordance with GDM, that behaviour is stipulated by increasing the average multiplicity of active gluons in a wide enough energy range in contrast to diffraction process like $pp$ collisions, in which valence quarks stay in the leading nucleons. With growth of energy, the contribution of splitting gluons goes up that leads to a sign change of $f_2$ from negative to positive and to the broadening of MD.

We have assumed the universality of hadronization in hadron interactions and used the available data from bubble chambers [14] on cross sections of $\pi^0$-mesons to describe MD of neutral pions by GDM. It has turned out that these parameters of hadronization as the average value and the maximum possible number of $\pi^0$-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.

Thereby, the study of high multiplicity events clarifies the hadronization mechanism in different processes. We have described MD in $e^+e^-$ and $p\overline{p}$ annihilation, $pp$ interactions and 3-gluon decay $\Upsilon$ introducing the hadronization scheme in a wide energy region.

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