Active role of gluons in hadron interactions at high multiplicity (part II)

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Introduction

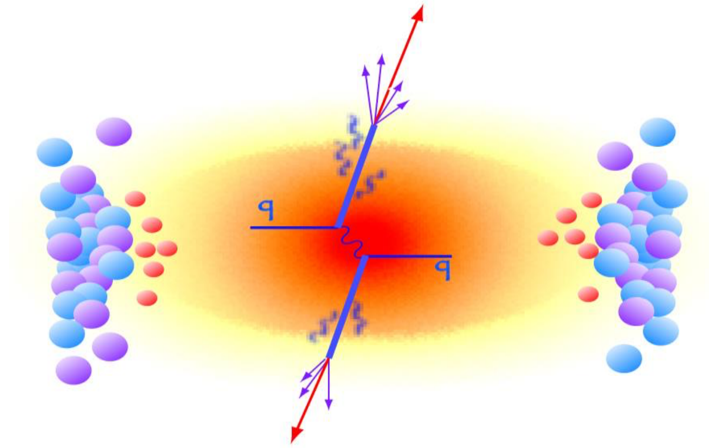
High energy physics began from the study of multiparticle processes. With an increase of the energy of the accelerators, new channels of reactions were opened, in which the number of secondaries increased, and new particles were born. This stimulated the development of phenomenological models and, subsequently, the creation, in particular, of the theory of strong interactions, quantum chromodynamics (QCD) [1-5]. It became possible with increasing of the data acquisition speed thankful to the development of electronics, on the basis of which detectors were manufactured.

The main accelerator experiments currently being carried out in high-energy physics are aimed at searching for deviations from the standard model, dark matter particles, and new states of heavy flavors. Close to high-energy physics, relativistic nuclear physics directs its main efforts to the study of quark-gluon matter.

One of the observables in the experiment is the multiplicity - the number of secondary particles. The most predominant among them is the multiplicity of charged particles. Experimenters also restore the multiplicity of neutral particles. The main statistical characteristics of multiplicity are its mean value and a variance. Most often, experimenters analyze events for which the deviation from the average multiplicity does not exceed two average values. Events with much larger multiplicity occur extremely rarely, so it is difficult to collect a large volume of statistics for them, in addition, there are difficulties in processing them. But this region of high multiplicity contents a lot of unresolved puzzles.

To understand and describe experiments carried out at accelerators, in particular, distributions in multiplicity, transverse and longitudinal momenta, Monte Carlo generators are built, in which, along with QCD description of quark-gluon interactions, phenomenological models are introduced that describe the hadronization stage (transformation of quarks and gluons into observed hadrons), as well as parton interactions. But when these generators are used to describe the data of hadron experiments in the region of high multiplicity, deviations in the distributions by several orders of magnitude occur.

Despite the fact that the number of Monte Carlo generators is increasing every year, it is still not possible to fully describe the growing amount of experimental data with them. Setting their parameters at the given energy stops working at moving to a higher energy. This evidences a significant misunderstanding of the mechanism of multiple processes. The study of events with the production of a large number of secondary will help to come to a deeper understanding of hadronic interactions, especially the hadronization stage.



In the high multiplicity region, series of collective phenomena are predicted, including those of a quantum nature. Formations of pion (Bose-Einstein) condensate, Cherenkov radiation of gluons by quarks are those phenomena. In the region of high multiplicity, the longitudinal component of the momentum approaches the transverse component, reaching it. This indicates the disappearance of the leading effect, and the formation of condensate begins in the same region. These and other collective manifestations in the behavior of secondary particles can be studied at the future NICA collider at the SPD facility. These studies will be possible, as it is planned to register events in the absence of any multiplicity trigger.

Multiparticle production (MP) is one of the most important topics in high energy physics. Using MP we can get more information about the nature of strong interactions and understand deeper the structure of matter. Over the last few years many thorough reviews devoted to MP have been done [1]. Modern accelerators have made possible MP studying more extensively and in detail. Developing theory of high energy physics quantum chromodynamics (QCD) [2] and a lot of phenomenological models are tested by the process of MP.

Multiparticle processes begin at high energy anywhere from 1 GeV. Among all producing particles we can observe a lot of hadrons. On the one hand, we want to describe MP by using Feynman's diagrams, and on the other hand, the increase of the inelastic channels makes it difficult for the describe of this process in this way. The situation concerning of the history of thermodynamics and statistical physics is much the same. Analysis of MP process is carried out using of statistical methods because the number of secondary in hadron interactions is large (more than 60 at LHC's energies) [3]. The consideration of MP begins from the behavior of charged multiplicity.

As it is generally known the multiplicity is the number of secondaries n in process of MP: $A + B \rightarrow a_1 + a_2 + \ldots + a_n$. Where A and B are the initial hadrons, a_i – secondaries ($i = 1, 2, \ldots, n$). The multiplicity distribution (MD) P_n is the ratio of cross-sections σ_n to $\sigma = \sum_n \sigma_n$: $P_n = \sigma_n / \sigma$. This quantity has the following meaning: the probability of producing of n charged particles in this process. We can also construct quantities such as mean values, moments of MD, study correlations and so on.

Investigation of MP has led to discovery of jets in heavy ion collisions. Jets phenomena can be studied at high energies.

Perturbative QCD can describe the process of fission partons (quarks and gluons) at high energy, because the strong coupling α_s is small at that energy [8-9]. This stage is called the cascade stage. After quark-gluon fission (quark bremsstrahlung, gluon fission) when partons loose their energy, they must turn into hadrons, which are observed. On this stage we shouldn't apply perturbative QCD. Therefore phenomenological models are used for description of hadronization (transformation of quarks and gluons into hadrons) in this case [10-12].

The description of the stage of the quark-gluon cascade by means of perturbative QCD as a Markov branching process was carried out in [9]. Certain features of the predictions at the parton level are expected to be insensitive to details of the hadronization mechanism. They were tested directly by using hadron distributions [10].

Gluon Dominance Model

The previously built two-stage model [6] describes successfully MD in e^+e^- annihilation. Its first stage begins from quark-antiquark creation and following development of the parton cascade describing as a Markov branching process due to gluon emission by quark ($q \to q + g$) and gluon fission ($g \to g + g$). In this reaction only two initial quarks are presented. We can call this process pure one.

In the case of the hadron interactions there are some number of gluons along with valence quarks. These gluons appear as a result of the melting of hadronic nuclear matter. In the case of proton collisions every proton has three valence quarks (u, u, d). Then these valence quarks and gluons after quark-gluon cascade must turn into observable hadrons (discoloration). This is the second stage or hadronization.

When designing such a model, which was later called the Gluon Dominance Model (GDM), we proposed that all six valence quarks (three pairs) and some number of initial gluons can create quark and gluon parton jets. With decreasing of their energy (the hadronization stage) the gluons can divide into a quark-antiquark pairs. These quarks form randomly colorless hadrons.

The unification of two stages is realized through their convolution. The branching of quark and gluon jets is describing by Polya and Farry distributions with their generating functions,

$$Q^q(s,z) = \left[1 + \frac{\bar{m}}{k_p}(1-z)\right]^{-k_p}, \qquad Q^g(s,z) = \frac{z}{\bar{m}}\left[1 - z\left(1 - \frac{1}{\bar{m}}\right)\right]^{-1}. \quad (1)$$

Correspondingly, where $\bar{m}$ is the average gluon multiplicity, k_p is the ration of two contributions: the quark bremsstrahlung to the gluon fission). We describe hadronization by binomial (Bernoulli) distribution as we did in the case of e^+e^- annihilation with generation function $Q^H(z)$ ($P_n = \frac{1}{n!}\frac{\partial^n Q^H(z)}{\partial z^n}|_{z=0}$)

$$P_n = C_N^n \left(\frac{\bar{n}^h}{N}\right)^n \left(1 - \frac{\bar{n}^h}{N}\right)^{N-n}, \qquad Q^H(z) = \left(1 + \frac{\bar{n}^h}{N} z - \frac{\bar{n}^h}{N}\right)^N, \qquad (2)$$

Where C_N^n – the binomial coefficient, $\bar{n}^h$ and N – the average and the maximum number of hadrons, which formed from single quark (gluon) at the hadronization stage. For binomial distribution the second correlative moment $f_2 = \overline{n(n-1)} - \bar{n}^2 = -\frac{(\bar{n}^h)^2}{N}$ is always negative. For Poisson distribution $f_2 \equiv 0$. The Bernoulli distribution is narrow than Poisson one, and Polya and Farry distributions are wider. For Polya and Farry distributions $f_2 > 0$, that is positive.

The choice of the Bernoulli distribution for description of hadronization is based on the experimental data [7]. At low energies f_2 is negative, with its growth f_2 changes sign and it is getting positive.

Comparison of MD calculated in GDM taking into account all valence quarks and a few gluons with data [13] have shown that the hadronization parameter $n^h_g \ll 1$ while its value obtained in the case of e^+e^- -annihilation $n^h_g \approx 1$. Due to universality of transition of partons to hadrons and proposing the participation at this stage not of all valence quark pairs, we noticed that the reduction of their number leads to the growth of this parameter but it is staying as usual smaller that 1. Exclusion from convolution of all valence quarks approaches it to one with a little excess at that.

In that way to make agree hadronization parameters with derived from e+e- annihilation we eliminated from pp-interactions all valence quarks. It corresponds that they stay in the leading particles as observers, and the sources of new born particles are the active gluons. We call gluons that form hadrons active. We analyzed two schemes: with gluon fission and without it.

In the case of inclusion in the convolution gluon fission, it turned out that almost of half of gluons do not give quark-antiquark pairs (it's possible they don't have enough energy) to transform then to secondary hadrons. The scatter on the new born quarks reradiating soft photos, $q + g \to q + \gamma$, those excess is experimentally observed more than 40 years [14]. The comprehensive explanation of their nature is absent up to now. We plan studying the soft photon (< 50 MeV) yield at the future SPD setup.

In a simplified approach without gluon fission and the normalization factor the expression for the MD description has a view (M is the maximum number of the gluons at the end of the first stage that is estimated from data at the comparison).

$$P_n(s) = \sum_{m=0}^{M} \frac{e^{-\bar{m}}\bar{m}^m}{m!} C_{mN}^{m-2} \left(\frac{\bar{n}^h}{N_g}\right)^{n-2} \left(1 - \frac{\bar{n}^h}{N_g}\right)^{mN-(n-2)}. \qquad (3)$$

In the Thermalization experiment events with multiplicity four times more than average value were registered. The KNO-function, $\Phi(z) = \bar{n}\frac{\sigma_n}{\sum_n \sigma_n}$, where z = n/$\bar{n}$, is shown in Figure 1 (left). Our SVD-2 collaboration added to world data 4 new points.

GDM describes experimental topological cross sections [15] by sum of two terms, the first summand is the result of hadronization of single gluons, the second one – of their fission. In Figure 1 (right) both contributions and their superpositions are shown. At the U-70 energy (50 GeV/c proton beam) we observe ninefold excess of bremsstrahlung under gluon fission. The region of high multiplicity is stipulated by the gluon fission [5].

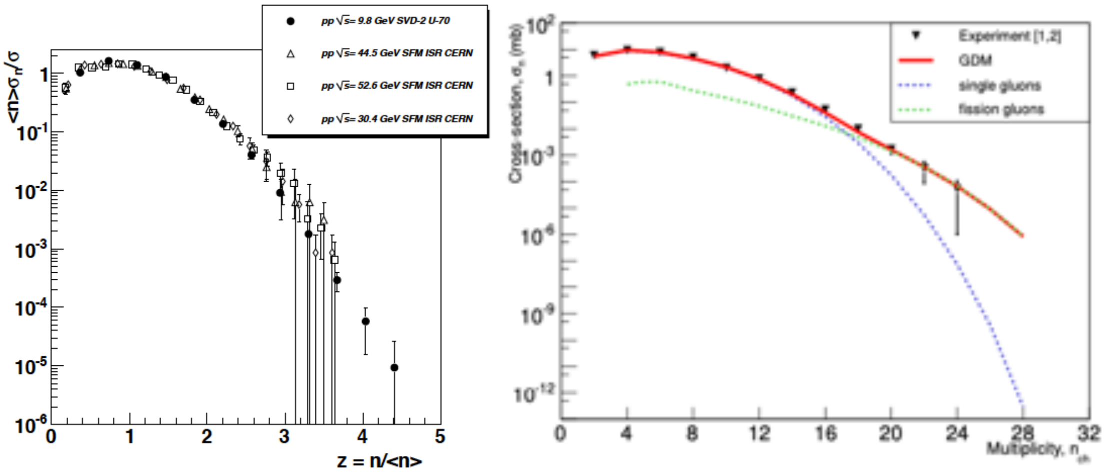


Figure 1. Left: KNO-function, $\Phi(z) = \bar{n}\frac{\sigma_n}{\sum_n \sigma_n}$, z = n/$\bar{n}$. SVD-2 results (•). right: (H) – topological cross sections, σ_n [11], GDM: contribution of active gluons in σ_n without fission is shown by blue line , the green line – with fission, the red line – superposition of both contributions.

With growth of energy of colliding protons, it should take into account terms appearing due to big number of gluon branching (g->g+g-> g+g+g …). So, the secondary hadrons form from clusters consisting from single gluons or fission gluons.

GDM describes MD in pp interactions from low energy U-70 up to ISR (~60 GeV), at that we observe the growth of the hadronization parameter of gluon $\bar{n}_g^h$ from 1.5 to 3.2. Such behavior confirms the recombination mechanism of hadronization [10] that realizes in qg-medium in hadron and ion interactions.

GDM and proton-antiproton annihilation

GDM describes proton-antiproton annihilation. At low energies the sign of f_2 is negative in pp and $p\bar{p}$ interactions. With growth of energy, f_2 changes its sign in the region ~ 5 GeV, while for $p\bar{p}$ annihilation f_2 remains negative until ~30 GeV [7]. As already noted, the negative sign of f_2 evidences the dominance of hadronization under the quark-gluon cascade.

The following mechanism of $p\bar{p}$ annihilation is proposed. As we know, there are two u quarks and one d quark in a proton. The corresponding antiquarks are in an antiproton. The formation of three hadron jets is observed at the experiment [7] in $p\bar{p}$ annihilation. Evidently, they appear at annihilation of $q\bar{q}$ pairs formed randomly from initial valence quarks.

In that case the variants are possible when three leading pions are: 1) all neutral ($u\bar{u},\ u\bar{u}, d\bar{d}$), 2) two charged and one neutral ($u\bar{d}, \bar{u}d, u\bar{u}$) and 3) to valence quarks (antiquarks) originated from gluonic medium. We can call these variants intermediate quark charged topologies “0”, “2” and “4”, correspondently.

At calculation it should take into account the contribution of charge for every topology (“0”, “2” or “4”). The generation function for MD of hadrons to the pure annihilation process, which we define as differences topological cross sections of pp and $p\bar{p}$ interactions $\Delta(pp - p\bar{p}) = \sigma_n(pp) - \sigma_n(p\bar{p})$ (diffraction processes are eliminated):

$$Q(s,z) = c_0 \sum_m P_m^G \left[1 + \frac{\bar{n}^h}{N}(z-1)\right]^{mN} + c_2 z^2 \sum_m P_m^G \left[1 + \frac{\bar{n}^h}{N}(z-1)\right]^{mN} +$$

$$+c_4 z^4 \sum_m P_m^G \left[1 + \frac{\bar{n}^h}{N}(z-1)\right]^{mN}. \qquad (4)$$

Where factors $c_{0,} c_2$ and c_4 define contributions of every topology. MD of gluons are described by Poisson $P_m^G = \frac{\bar{m}e^{\bar{m}}}{m!}$.

Ratios between contributions of topologies were obtained from description of experimental data [7] by (4): $c_0 : c_2 : c_4$ = 15 : 40 : 0.05 at χ^2/ndf = 5.77/4. The topology “2” gives the maximum contribution as the most probable. Topology “4” is suppressed but it responsible for contribution of high multiplicity.

We can interpreter the process of pure $p\bar{p}$ annihilation as superposition of three pairs of e^+e^- annihilation with gluon mix. The initial energy is sharing between these pairs that fragment into hadrons similarly to e^+e^- annihilation. At that, some part of it passes into the possession of soft gluons formed at the moment of nuclear medium melting. So, the interval of negative values f_2 increases, which is observed at experiments in comparison to e^+e^- annihilation.

Estimation of the recharge in pp interaction by GDM

GDM allows make estimation of the contribution into MD in pp interactions such a process:

$$p + p \rightarrow n + \pi^+ + n + \cdots,$$

When one of the protons gives its charge to a neutral pion turning into neutron. This pion becomes a positive pion. Using high multiplicity data, it’s possible to get the probability of recharge.

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Research program.

Good knowledge of C++ programming language and the ROOT software (http://root.cern.ch) is greeted. Students it is proposed to take part to carry out at the following themes of project:

- Calculations of multiplicity distribution for neutral and charged particles in proton-proton collisions at high energy in framework of Gluon Dominance Model.

- Calculations of multiplicity distribution for neutral and charged particles in proton-antiproton annihilation at high energy in framework of Gluon Dominance Model.

- The estimation the contribution of the exchanged charge in pp interaction.

- To calculation of the second correlative moments $f_2 = \langle n(n-1)\rangle \langle n\rangle^2$, the factorial and the factorial cumulative moments by using MD and/or the generation function G(z) for pp and $p\bar{p}$ interactions.

The number of participating students is 1-4. The project supervisors: Prof. Elena Kokoulina (Head of the hadron interaction group). Baldin and Veksler Laboratory of High Energy Physics, e- mail: kokoulina@jinr.ru