Gluon Dominance Model

Kokouлина E.S.

JINR, Dubna, Moscow region,
141980, Russia
GSTU, LPS, October av. 48, Gomel
246746, Belarus

Abstract. A new way to study the multiplicity production in high energy processes is proposed. It is based on the multiplicity distribution description by the schemes taking into account the formation of quark-gluon system and hadronization. This investigations revealed an active role of gluons and the universal mechanism of their hadronization.

INTRODUCTION

At present there is neither single consistent theory nor convincing model which could explain all the results obtained at RHIC and SPS [1]. It is evident that in these experiments the local thermal equilibrium is reached and thermalized matter is produced. Thermal statistical models based on this approach explain yields of different hadrons at high energy [1]. At the same time these models describe well the particle yields in $e^+e^-$ and $pp$ interactions where, as generally accepted, thermalization is impossible [2]. So the intensive study and insight of these processes remain to be very importance.

To investigate multiparticle production (MP) at high energy in these processes, a two stage model was proposed [3, 4]. It is based on the use of QCD and the phenomenological scheme of hadronization. The model describes well multiplicity distributions (MD) and their moments in $e^+e^-$ annihilation, $pp$ and $p\bar{p}$ interactions and gives complementary information to a better understanding of MP of relativistic heavy ion collisions.

This model confirms the fragmentation mechanism of hadronization in $e^+e^-$ annihilation and the transition to recombination mechanism in hadron and nucleus interactions. It explains the shoulder structure in MD at higher energies and the behavior of $f_2$ in $p\bar{p}$ annihilation at few tens GeV/c by including intermediate quark topologies. The mechanism of the soft photons (SP) production as a sign of hadronization and estimates of their emission region size is proposed [5].

The $e^+e^-$ annihilation is the most suitable process to study MP. It can be realized through the formation of virtual $\gamma$ or $Z^0$--boson which then decays into two quarks: $e^+e^- \rightarrow (Z^0/\gamma) \rightarrow q\bar{q}$. The $e^+e^-$--reaction is simple for analysis, as the produced state is pure $q\bar{q}$. To describe the process of parton fission (quarks and gluons) at big virtuality, pQCD may be applied. This stage can be named as the stage of cascade. When partons get small virtuality, pQCD cannot be applied. Therefore phenomenological models are used to describe hadronization in this case.

The probabilistic nature of parton fission in QCD has been established in [6].
A. Giovannini [7] had proposed to describe quark and gluon jets as Markovian branching processes with three elementary contributions: gluon fission, quark bremsstrahlung and quark pair production. He constructed a system of differential equations for generating functions (GF) and obtained solutions of MD for quark jet:

\[ P_m^{(q)} (Y) = \frac{k_p(k_p+1) \ldots (k_p+m-1)}{m!} \left( \frac{\bar{m}}{\bar{m}+k_p} \right)^m \left( \frac{k_p}{k_p+\bar{m}} \right)^{k_p}. \]  

These MD are known as negative binomial distribution (NBD). The GF for them is:

\[ Q_{(q)}(z,Y) = \sum_{m=0}^{\infty} z^m P_m(Y) = \left[ 1 + \frac{\bar{m}}{k_p} (1-z) \right]^{-k_p}, \]

where \( \bar{m} \) is the mean gluon multiplicity, \( Y \) - QCD evolution variable and \( k_p \) - NBD parameter.

In [3] MD (1) was taken for the cascade stage. For the hadronization a sub narrow binomial distribution (BD) was added:

\[ P_n^{(H)} = C^n_{N_p} \left( \frac{\bar{m}^h}{N_p} \right)^n \left( 1 - \frac{\bar{m}^h}{N_p} \right)^{N_p-n}, \]

where \( C^n_{N_p} \) - binomial coefficient, \( \bar{m}^h \) and \( N_p \) (\( p = q, g \)) have a sense of mean multiplicity and maximum number of secondary hadrons formed from parton (p) at its passing of the second stage.

We have chosen BD from the analysis of experimental data on \( e^+e^- \) annihilation. Second correlation moments \( f_2 \) were negative at low energies (less than 9 GeV). The choice of such distributions was the only one that could describe the experiment. We suppose that the hypothesis of soft decoloration is right. Therefore the hadronization stage is added to the parton stage by means of a factorization. We introduce parameter \( \alpha = N_g/N_q \) to distinguish the hadrons, produced from quark or gluon. MD of hadrons in \( e^+e^- \) - annihilation can be written as follows (\( N_q = N, \bar{m}^h = \bar{m}^q \)):

\[ P_n(s) = \sum_{m=0}^{M_g} P_m^{(q)} C^n_{(2+\alpha m)N} \left( \frac{\bar{m}^h}{N} \right)^n \left( 1 - \frac{\bar{m}^h}{N} \right)^{(2+\alpha m)N-n}. \]  

The expression (3) describes well the experimental data [8] from 14 to 189 GeV [9] (e.g. Fig. 1). The mean gluon multiplicity \( \bar{m} \) has a tendency to rise, but slower than the logarithmic one. Parameter \( k_p \) was been related with temperature in [10]. The fact that \( \alpha < 1 \) is the evidence that hadronization of a gluon is softer than a quark. It is surprising that gluon parameters of hadronization (\( N_g, \bar{m}^h \)) remain constant without considerable deviations in spite of the indirect finding: \( N_g \sim 3 - 4 \) and \( \bar{m}^h \sim 1 \) (e.g. Fig. 2). Therefore we can draw a conclusion about the universality of gluon hadronization in \( e^+e^- \) annihilation in the sufficient wide energy region.

It was shown [11] that the ratio of factorial cumulative moments over factorial moments changes the sign as a function of the order. The calculation of this ratio by using (3) was done in [8]. It has been obtained that the period of oscillations is equal to 2 before \( Z^0 \)-region and increases at higher energies.
**PP INTERACTIONS**

The study of MP in \( pp \) interactions is implemented in the framework of the project "Thermalization" [12]. This project is aimed at studying the collective behavior of secondary particles and advancement to the high multiplicity region (HMR) beyond available data [13] in \( pp \) interactions at 70 GeV/c. The calculation by the MC PHYTHIA code has shown that the standard generator predicts a value of the cross section which is in a reasonably good agreement with data at small multiplicity \( n_{ch} < 10 \), but it underestimates the value \( \sigma(n_{ch}) \) by two orders of the magnitude at \( n_{ch} = 20 \). The existing models are very much sensitive in this region [14], also (Fig. 3).

We suppose that after the inelastic collision the part of the energy of the initial impact protons is transformed to the inside energy. Several quarks and gluons become free and form quark-gluon system (QGS). Partons which can produce hadrons are named the active ones. Two schemes were proposed [4]. In the first scheme the parton fission inside the QGS is taken into account (the scheme with a branch). If we are not interested in what is going inside QGS, we come to the scheme without a branch (TSMT).
At the beginning of research we took a model with active quarks and gluons. Parameters of that model had values which differed very much from parameters obtained in \( e^+e^- \) - annihilation, especially for hadronization. It was one of the main reasons to refuse the scheme with active quarks. So, we reserve quarks remained inside of the leading particles. All of the newly born hadrons were formed by active gluons. That is why we began to name this model – the gluon dominance model (GDM).

The Poisson distribution was chosen as the simplest MD for active gluons which appeared for the first time after the collision. The number of these gluons fulfils the role of the impact parameter for nucleus. To describe MD in the gluon cascade (fission), Farry distribution was used with GF:

\[
\mathcal{Q}_k(z) = \frac{z^k}{m^k} \left[ 1 - z \left( 1 - \frac{1}{m} \right) \right]^{-k},
\]

where \( k \) – the number of initial gluons in QGS, \( m \) – the mean multiplicity of them in the end of the branch. On the second stage some of active gluons can leave QGS ("evaporate") and transform to real hadrons. Our BD (2) for hadrons on the stage of hadronization is as follows

\[
P^H_n(m) = C^n_{2mN_g} \left( \frac{\bar{n}_g^h}{N_g} \right)^{n-2} \left( 1 - \frac{\bar{n}_g^h}{N_g} \right)^{\delta mN_g - (n-2)}. \tag{4}
\]

In (4) parameter \( \delta \) is the ratio of evaporated gluons leaving QGS, to all active gluons. From the comparison with data \[13\] we have obtained that a maximum possible number of hadrons from a single gluon looks very much like the number of partons in the glob of cold QGP of L.Van Hove \[15\], the branch processes are weak. The fraction of released gluons is equal to \( \delta = 0.47 \pm 0.01 \) (the same as in \[16\]). A part of active gluons does not convert into hadrons. They stay in QGS and can become sources of soft photons (SP).

In the scheme without a branch we consider that evaporated gluons have Poisson MD, too. Using the idea of the convolution of two stages \( P_n(s) = \sum_m P_m(s)P^H_n(m) \) as well as the BD for hadronization, we obtain MD in pp-collisions. The comparison GDM with the data \[13\] (Fig. 3) gives values of parameters \( N_g = 4.24 \pm 0.13 \), \( \bar{n}_g^h = 1.63 \pm 0.12 \) and it is in agreement with the values obtained in \( e^+e^- \) annihilation \[9\]. We are restricted in sum to \( m = 6 \). Our estimation of the maximal possible observable number of charged particles is \( \leq 26 \).

We have also got MD for neutral mesons and total multiplicity by using mean multiplicities of \( \pi^0 \)-mesons \[17\] and active gluons, expected approximate equality of probabilities of the formation charged and neutral particles from single gluon at hadronization and the above-mentioned idea of the convolution \[5\]. The maximum observable number of them is estimated as 16, total - as 42, the parameter \( \bar{n}_g^h = 1.036 \pm 0.041 \) (\( h = \pi^0 \)).

The analysis of the mean multiplicity of \( \pi^0 \)-mesons versus the number of charged particles \( n_{ch} \), allows to set limitations to the number of neutral mesons at given \( n_{ch} \) and indicates the absence of AntiCentauru events (Centauro may be in HMR). The obtained estimations of probabilities for charged and neutral hadrons production from gluon while its passing through hadronization permits to get "the charged hadron/pion" ratio \[18\] in pp interactions. At 69 GeV/c this ratio is equal to 1.19 \pm 0.25.

GDM describes well MD in the region of 100 – 800 GeV/c (Fig. 4 and table 1 in \[5\]). The number of active gluons, their mean multiplicity, \( N_g \) and \( \bar{n}_g^h \) increase slowly. A growth of \( \bar{n}_g^h \) in \( pp \) interactions indicates a possible change mechanism of hadronization.
of gluons in comparison with $e^+e^-$ annihilation. It is considered that in the last case the partons transform to hadrons by the fragmentation mechanism at the absence of the thermal medium. Our MD analysis gives $\pi_h^h \sim 1$ for this hadronization \([9]\). The recombination is specific for the hadron and nucleus processes. In this situation a lot of quark pairs from gluons appear almost simultaneously and recombine to various hadrons \([19]\). The value $\pi_h^h$ becomes bigger $\sim 2 - 3$, that indicates this transition. The recombination mechanism provides justification for applying the statistical model to describe ratios of hadron yields and the explanation of the collective flow of quarks \([19]\).

In \([7]\) MP is described by means of a clan mechanism and emphasizes the gluon nature of clan. Our GDM allows to give a concrete content for the clan. The clan model uses the logarithmic distribution (LD) in a single clan. LD are similar to our BD.

At the SPS energy the shoulder structure appears in MD \([20]\). As it was marked in the branch scheme, the gluon fission is strengthened at higher energies. The independent evaporation of gluon sources of hadrons may be realized as single gluons as groups from two and more fission gluons. Following \([7]\) we name such groups - clans. GDM with two kinds of clans \([5]\) describes data \([21]\) very well (Fig. 4). Moreover "the charged hadron/pion" ratio at 62 GeV is equal to $\sim 1.6$ and agrees with Au-Au peripheral interactions at 200 GeV and with pp interactions at 53 GeV \([18]\).

The specific feature of GDM is the dominance of active gluons in MP. We expect the emergence of many of them in nucleus collisions at RHIC and the formation of a new kind of matter (QGP) at high energy. Our QGS can be a candidate for this.

Experiments \([22]\) have shown that the measured cross sections of SP are several times larger than the expected ones from QED. The phenomenological glob model explains the SP excess \([15]\). We consider that at a certain moment the QGS or excited new hadrons may set in an almost equilibrium state during a short period of time. That is why, to describe massless photons, we have used the black body emission spectrum \([23]\). At 70 GeV/c an inelastic cross section is equal to $\sim 40mb$, the SP formation cross section is about $4mb$ \([12]\) and since $\sigma_f \simeq n_f(T) \cdot \sigma_{in}$ then $n_f \approx 0.1$. If $n_f$ and temperature $T(p)$ ($p$–momentum) are known, then we can estimate the emission region size $L$ of SP. The obtained values $L \sim 4 - 6 fm$ \([5, 24]\).

In conclusion one can show how GDM may explain experimental $p\bar{p}$ annihilation data at tens GeV/c \([25]\). The differences between $p\bar{p}$ and $pp$ inelastic topological cross sections ($\Delta \sigma_{in}(p\bar{p} - pp) = \sigma_{in}(p\bar{p}) - \sigma_{in}(pp)$) point out the contribution of different mechanisms in MP. The negative values of $f_2$ indicate the predominance of the hadronization stage in MP. According to MGD, the active gluons are a basic source of secondary hadrons.

There are three valent $q\bar{q}$-pairs at the initial stage of annihilation. They can turn to the "leading" mesons which consist of: a) valent quarks or b) valent and sea quarks \([24]\). In the case a) three "leading" neutral pions (the "0"–topology) or two charged and one neutral "leading" mesons ("2"–topology) may form. In b) case the "4"- and "6"- topologies are realized. The neutron and antineutron formation is possible, too.

The active gluons emerge together with the formation of intermediate topology. At this region hadronization dominates since $f_2$ is negative. In the simple case for $m$ active gluons $GF_{Qm}(z) = \left[1 + \overline{n}^h / N(z - 1)^m N^m \right]$, and $f_2 = -m(\overline{n}^h)^2 / N$. If $m$ grows while increasing the energy of the colliding particles, then $f_2$ will decrease almost linearly.
from $m$ that agrees with the data [25]. According to GDM [5] and taking into account an intermediate charged topology ("0", "2" and "4") with active gluons, GF $Q(z)$ for final annihilation MD $(\Delta \sigma_r(p\bar{p} - pp)/\sum_n \Delta \sigma_r(p\bar{p} - pp))$ may be written as the convolution gluon and hadron components

$$Q(z) = c_0 \sum_m^{M_0} p_m G_m^H(z)^m + c_2 z^{M_2} \sum_m p_m^G [Q_m^H(z)]^m + c_4 z^4 \sum_m p_m^G [Q_m^H(z)]^m.$$ 

The parameters of $c_0$, $c_2$ and $c_4$ are parts of intermediate topologies. GDM describes data (Fig. 6) with the ratio $c_0: c_2: c_4 = 15:40:0.05$ and $M_0 \sim M_2 \sim 1 - 2$, $M_4 \sim 4$ [5].

The carried out investigations allow one to understand deeper the MP nature.

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