GLUON DOMINANCE MODEL AND MULTIPARTICLE PRODUCTION

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Abstract

Gluon dominance model is proposed to study multiparticle production. This model describes multiplicity distributions in $e^+e^-$, $p\bar{p}$ annihilation and $pp$ interactions.

1. Introduction

To investigate multiparticle production (MP) at high energy two stage model was built [1-4]. It is based on the use of QCD and the phenomenological scheme of hadronisation. The model describes well multiplicity distributions (MD) and their moments in $e^+e^-$ annihilation, $pp$ and $p\bar{p}$ interactions. It confirms of fragmentation mechanism of hadronisation in $e^+e^-$ annihilation and the transition to recombination one in hadron and nucleus interactions. It can explain the shoulder structure in MD at higher energies and the behavior of $f_2$ in pure $p\bar{p}$ annihilation at few tens GeV/c by the inclusion of intermediate quark topologies. The mechanism of the soft photons (SP) production as a sign of hadronisation and estimates the emission region size of them is proposed [5].

2. Study of $e^+e^-$–annihilation

We began our study from $e^+e^-$ annihilation. 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 $q\bar{q}$.

The perturbative QCD (pQCD) may be applied to describe the process of parton (quark or gluon) fission at big virtuality. This stage can be named as the cascade stage. When partons reach small virtuality, they change into hadrons, which we observe. At this stage we can not apply pQCD. Therefore phenomenological models are used to describe hadronisation.

At studying MP at high energy we used ideas of A. Giovannini [6] to describe quark-gluon jets as Markov branching processes. Three elementary processes contribute into QCD jets: (1) gluon fission; (2) quark bremsstrahlung and (3) quark pair production. A. Giovannini had constructed a system of differential equations for generating functions (GF) of parton ($q, g$) jet and obtained MD of partons formed from quark

$$P_0^P(Y) = \left( \frac{k_p}{k_p + \bar{m}} \right)^{k_p}, \quad P_m^P(Y) = \frac{k_p(k_p + 1)\ldots(k_p + m - 1)}{m!} \left( \frac{\bar{m}}{\bar{m} + k_p} \right)^m \left( \frac{k_p}{k_p + \bar{m}} \right)^{k_p},$$

where $\bar{m}$ is the mean multiplicity, $k_p$– parameter. These MD are known as negative binomial distributions (NBD). The GF for them is

$$Q^{(q)}(z,Y) = \sum_{m=0}^{\infty} z^m P_m(Y) = \left[ 1 + z/k_p(1 - z) \right]^{-k_p}. \quad (1)$$

Two stage model [1-2] has taken (1) to describe the cascade stage and adds to it a sub narrow binomial distribution (BD) for the hadronisation stage. We had chosen BD basing on the analysis of experimental data in $e^+e^-$–annihilation lower than 9 GeV. Second correlation

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moments were negative at these energies. We add the hadronisation stage to the parton one with the help of a factorization. MD in this process can be written as follows:

\[ P_n(s) = \sum_m P^P_m P^H_n(m, s), \]

where \( P^P_m \) is MD for partons (1), \( P^H_n(m, s) \) - MD for hadrons produced from \( m \) partons at the stage of hadronisation. Further we substitute variable \( Y \) on a center of masses energy \( \sqrt{s} \). MD of hadrons \( P^H_n \) formed from one parton and their GF \( Q^H_p(z) \) are [1-2]

\[ P^H_n = C^n_{N_p} \left( \frac{\bar{\tau}^h_p}{N_p} \right)^n \left( 1 - \frac{\tau^h_p}{N_p} \right)^{N_p-n}, \quad Q^H_p = \left[ 1 + \frac{\tau^h_p}{N_p}(z-1) \right]^{N_p}, \]

where \( C^n_{N_p} \) - binomial coefficient, \( \tau^h_p \) and \( N_p \) (\( p = q, g \)) have a sense of mean multiplicity and maximum of secondary hadrons are formed from parton at the stage of hadronisation.

MD of hadrons in \( e^+e^- \) annihilation are determined by convolution of two stages (cascade and hadronisation)

\[ P_n(s) = \sum_{m=0}^{\infty} P^P_m \frac{1}{m!} \frac{\partial^n}{\partial z^n} (Q^H)^{2+m}|_{z=0}, \]

where \( 2 + m \) is the total number of partons (two quarks and \( m \) gluons).

The parameter \( \alpha = N_g/N_q \) distinguishes the hadrons produced from quark or gluon. Introducing expressions (1), (4) in (5) we obtain MD of hadrons in \( e^+e^- \) annihilation (\( N = N_q, \bar{\tau}^h = \bar{\tau}^h_q \))

\[ P_n(s) = \sum_{m=0}^{M_q} P^P_m C^n_{(2+\alpha)m} N \left( \frac{\bar{\tau}^h_q}{N} \right)^n \left( 1 - \frac{\tau^h_q}{N} \right)^{(2+\alpha)m} N - n \]

The results of comparison of expression (6) with experimental data [7] are led in [2]. The significance of \( \alpha \) is equal to 0.2 with some deviations. If we know from our comparison \( \alpha, N_q \) and \( \bar{\tau}^h_q \) then we can determine for gluon \( N_g = \alpha N \) and \( \bar{\tau}^h_g = \alpha \bar{\tau}^h_q \). It is surprising these parameters remain constant without considerable deviations in spite of the indirect finding: \( N_g \sim 3 - 4 \) and \( \bar{\tau}^h_g \sim 1 \) (Fig. 1). This behaviour is evidence of the universality of gluon hadronisation. As \( \alpha < 0.2 \) we come to a conclusion that hadronisation of gluons is softer than of quarks.

3. Study of \( pp \) interactions

The study of MD in \( pp \) interactions is implemented in the framework of the project "Thermalization" [8]. This project is aimed at studying the collective behavior of secondary particles and advancement to the high multiplicity region (HMR) beyond of available data [9] in proton-proton interactions at 70 GeV/c.

The calculation by the MC PHOSHYIA code has shown that the standard generator predicts a value of the cross section which is in a good agreement with the experimental data at small multiplicity (\( n_{ch} < 10 \)) but it underestimates the value \( \sigma(n_{ch}) \) by two orders of the magnitude at \( n_{ch} = 18 \) (Fig. 2). The existing models are sensitive in HMR [10] (Fig. 2)

We are guided by a scheme building of hadron interactions to describe MD with the quark-gluon language as well as to investigate HMR. The existing models are sensitive in this region [e.g. 8]. We consider that at the first stage of \( pp \) interactions the initial quarks and gluons take part in the formation of quark-gluon system (QGS). On the second stage they can transform to hadrons. We proposed two schemes. In the first scheme hadroproduction is studied with account of the parton fission inside the QGS. If we are not interested in what is going inside QGS, then come to the second scheme [3].
When we took model where some of quarks and gluons from protons participate in the production of hadrons the parameters of that model differed very much from parameters obtained in $e^+e^-$ annihilation, especially for hadronisation. That is why the scheme with active quarks was rejected, and quarks from protons were remained inside of the leading particles. In according of this result all of the newly born hadrons are formed by gluons. Such gluons we name active and a model involving theirs into hadroproduction - the gluon dominance model (GDM) [4].

Both of schemes describe well MD at 69 GeV/c. From the comparison with experimental data [9] the maximum number of active gluons appeared in QGS is restricted to 6, $\bar{n}_g = 1.63 \pm 0.12$, the part of evaporated gluons from QGS equal to $0.47 \pm 0.01$. We conclude from this research that the branch processes are weak. A maximal possible number of hadrons from the gluon in first scheme looks very much like the number of partons in the glob of cold quark-gluon plasma of L.Van Hove [11]. After the evaporation the part of active gluons do not convert into hadrons. They stay in QGS and become sources of soft photons (SP) [5].

From neutral mesons data [12] hadronization parameters of $\pi^0$ were founded (the second scheme). The analysis of the mean multiplicity of $\pi^0$- mesons versus the number of charged particles $n_{ch}$ gives the limitations to the number of neutral mesons at given $n_{ch}$ [3]. The obtained estimations of probabilities for a production charged and neutral hadrons from gluon at the its passing of hadronization permits to get in framework of GDM [4] "the charged hadron/pion" ratio in pp interactions, which is in an agreement with data [13].

The application of GDM to describe MD in the region 102-800 GeV/c [14] in both schemes leads to good results [5]. Parameters of GDM in this domain are given in Table 1.

| $p$, GeV/c | $\overline{m}$ | $M_0$ | $\bar{n}$ | $\overline{n_0}$ | $\Omega$ | $\chi^2$/ndf |
|-----------|----------------|-------|---------|-----------------|--------|-------------|
| 102       | 2.75 ± 0.08    | 8     | 3.13 ± 0.56 | 1.64 ± 0.04     | 1.92 ± 0.08 | 2.2/5       |
| 205       | 2.82 ± 0.20    | 8     | 4.50 ± 0.10 | 2.02 ± 0.12     | 2.00 ± 0.07 | 2.0/8       |
| 300       | 2.94 ± 0.34    | 10    | 4.07 ± 0.86 | 2.22 ± 0.23     | 1.97 ± 0.05 | 9.8/9       |
| 405       | 2.70 ± 0.30    | 9     | 4.60 ± 0.24 | 2.66 ± 0.22     | 1.98 ± 0.07 | 16.4/12     |
| 800       | 3.41 ± 2.55    | 10    | 20.30 ± 10.40 | 2.41 ± 1.69     | 2.01 ± 0.08 | 10.8/12     |
A growth of $\pi^0$ in $pp$ interactions indicates a change mechanism of hadronization of gluons in comparison with $e^+e^-$ annihilation. It is considered that in the $e^+e^-$ process the partons transform to hadrons by the fragmentation mechanism (the thermal medium is absent). Our analysis gives $\pi^0_p \sim 1$ [2]. The recombination is specific for the hadron interactions. In these processes pairs from gluons appear almost simultaneously and recombine to various hadrons [15]. The value $\pi^0_p$ becomes bigger $\sim 2 - 3$, that indicates this transition.

At the top energy (200-900 GeV) the shoulder structure appears in $P_n$ [16]. The comparison of data with one NBD does not describe data. But the weighted superposition of two NBD gives a good description of the shoulder structure $P_n(s)$ [6]. We modify our GDM considering that the gluon fission is realized at higher energies. The independent evaporation of gluons sources of hadrons occurs by single gluons and also groups from two and more fission gluons. We name such groups of gluons - clans, too. Their independent emergence and following hadronization is a content of GDM. MD in GDM with two kinds of clans are:

$$P_n(s) = \alpha_1 \sum_{m_1=0}^{Mg_1} \frac{e^{-\overline{m}_1^h/m_1!}}{m_1!} C_{m,-2}^{m_2} \left( \frac{\overline{p}^h}{N} \right)^{m_1-N-(n-2)} \\
+ \alpha_2 \sum_{m_2=0}^{Mg_2} \frac{e^{-\overline{m}_2^h/m_2!}}{m_2!} C_{2-m_2,N}^{m_2} \left( \frac{\overline{p}^h}{N} \right)^{m_2-N-(n-2)},$$

where $\alpha_1$ and $\alpha_2$ are the contribution single and double gluon clans ($\alpha_1 + \alpha_2 = 1$). The comparison (7) with experimental data for proton interactions at $\sqrt{s} = 62.2$ GeV [16] gives the following values of parameters: $N = 7.06 \pm 3.48$, $\overline{m}_1 = 3.59 \pm 0.03$, $\overline{m}_2 = 1.15 \pm 0.25$, $\overline{p}_h = 3.23 \pm 0.14$, $Mg_1 = 8$, $Mg_2 = 4$, $\alpha_1/\alpha_2 \sim 1.8$ at $\chi^2/ndf=9.12/13$ (Fig. 3).

The main feature of our GDM approach is the dominance of active gluons in MP. We expect the emergence of them in experiments at high energy (SPS, RHIC) and the formation of quark-gluon plasma. We consider that our QGS can be a candidate for this.

### 3. Study of $p\bar{p}$ annihilation

In the midst of hadron interactions the $p\bar{p}$ annihilation shows up especially interesting. Experimental data at tens GeV/c [18] point out on some maxima in differences between $p\bar{p}$ and $pp$ inelastic topological cross sections what may witness about the contribution of different mechanisms of MP

$$\Delta \sigma_n(p\bar{p} - pp) = \sigma_n(p\bar{p}) - \sigma_n(pp).$$

The important information about them may be picked out from the analysis of the second correlative moment for negative charged particles $f_2^{--}$

$$f_2^{--} = n_-(n_--1)-\overline{n}_-^2.$$
\[ f_2 = Q''_1(z) \big|_{z=1} - [Q_1(z) \big|_{z=1}]^2 = -(\pi^h)^2/N < 0. \]

We consider that if \( m \) grows while increasing the energy of the colliding particles then \( f_2 \) will decrease almost linearly from \( m \). Such behavior qualitatively agrees with experimental data [18]. According to GDM for \( p\bar{p} \) annihilation and taking into account three intermediate charged topologies and active gluons, GF \( Q(z) \) for final MD may be written as the convolution gluon and hadron components:

\[
Q(z) = c_0 \sum_m P^G_m[1+\frac{\pi^h}{N}(z-1)]^{mN} + c_2 \sum_m z^2 P^G_m[1+\frac{\pi^h}{N}(z-1)]^{mN} + c_4 \sum_m z^4 P^G_m[1+\frac{\pi^h}{N}(z-1)]^{mN}.
\]

The parameters of \( c_0, c_2 \) and \( c_4 \) are determined as the part of intermediate topology ("0", "2" or "4") to the annihilation cross section (\( c_0 + c_2 + c_4 = 1 \)). For the sake of simplicity we are limited by cut Poisson distribution with the finite number of gluons for \( P^G_m \). The comparison of the experimental data (Fig. 4) gives the following values of parameters: \( \bar{m} = 3.36 \pm 0.18, N = 4.01 \pm 0.61, \pi^h = 1.74 \pm 0.26 \), the ratio \( c_0 : c_2 : c_4 = 15 : 40 : 0.05 \) at \( \chi^2/ndf = 5.77/4 \) and \( M_0 \sim M_2 \sim 1 - 2, M_4 \sim 4 \).

### Figure 3: MD in GDM (clan).

### Figure 4: MD in \( p\bar{p} \) at 14.75 GeV/c.

#### 3. Soft photons

The production of photons in particle collisions at high energies was studied in many experiments [19]. In project "Thermalization" it is planned to investigate low energetic photons with \( p_t \leq 0.1 GeV/c \) and \( x \leq 0.01 \) [8]. These photons are named soft photons (SP). Experiments shown that measured cross sections of SP are several times larger than the expected ones from QED inner bremsstrahlung. Phenomenological models were proposed to explain the SP excess (the glob model of Lichard and Van Hove [11]).

We consider that at a certain moment the QGS or excited new hadrons may set in an almost equilibrium state during a short time. That is why, to describe massless photons, we have used the black body emission spectrum. At 70 GeV/c an inelastic cross section is equal
to $\sim 40 \text{mb}$, the SP formation cross section is about $4 \text{mb}$ [8] and since $\sigma_\gamma \approx n_\gamma(T) \cdot \sigma_m$ then $n_\gamma \approx 0.1$. If $n_\gamma$ and temperature $T(p)$ ($p$-momentum) are known, then we can estimate the emission region size $L$ of SP. The obtained values $L \sim 4 - 6 \text{fm}$ [4,5] that is reasonable size.

In our study we had undertaken an attempt to give description in different processes of MP by means of a unified approach based on quark-gluon picture with using the phenomenological hadronisation. We have obtained agreements of our schemes with experimental data in $e^+e^-$, $p\bar{p}$ annihilation and $pp$ and nucleus collisions in a very wide energy domain.

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