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STUDY OF MULTIPARTICLE PRODUCTION BY GLUON DOMINANCE MODEL (Part I) [1]

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Abstract

The gluon dominance model offers a description of multiparticle production in e^+e^- - annihilation and proton-proton collisions. The multiplicity distributions in e^+e^- annihilation are well described. The energy dependence of model parameters gives the dynamic parton stage and hadronisation picture. It is shown that this model has confirmed oscillations in sign of the ratio of factorial cumulant moments over factorial moments of the increasing order.

The collective behavior of secondary particles in *pp*-interactions at 70 GeV/c is studied in the project **"Thermalization"**. An active role of gluons is shown in the multiparticle dynamics. This paper gives a simple thermodynamic interpretation of interactions mentioned above.

1 Introduction

At present to investigate and construct a contemporary picture of nuclear matter structure requires to develop new methods and approaches.

Since 80's the Quark-Gluon Plasma conception has undergone a lot of changes after the experiments carried out at CERN (SPS) and BNL (RHIC). Different approaches are used to explain extraordinary phenomena in behavior of the new matter produced at high energy of nuclear collisions [1].

Still there is no single theory nor the model that could explain all the results obtained at RHIC and SPS. We would like to find a solution for this difficult problem by using multiparticle production (MP) in hadron and nucleus interactions. Up to now the nature of "soft" hadronic events has not been fully understood.

A new way to investigate MP at high energy is offered in this work by means of construction a model based on the multiplicity distribution (MD) description using the QCD and phenomenological scheme of hadronisation. The model description of MD in e^+e^- annihilation is given in section 2. The application of this model approach to pp-interaction can be found in section 3.

2 MD for e^+e^--annihilation at high energies

The e^+e^- annihilation is one of the most suitable to study MP. It can be realized through the formation of virtual γ or Z^0–boson which then decays into two quarks:

$$e^+e^- \to (Z^0/\gamma) \to q\bar{q}. \quad (1)$$

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The e^+e^-–reaction is simple for analysis, as the produced state is pure $q\overline{q}$. It is usually difficult to determine the quark species on the event-by-event basis. The experimental results are averaged over the quark type. Perturbative QCD (pQCD) may be applied to describe the process of parton fission (quarks and gluons) at big virtuality, because strong coupling α_s is small. This stage can be called as the stage of cascade. When partons get 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 in this case.

Parton spectra the quark and gluon fission in QCD were studied by K. Konishi, A. Ukawa and G. Veneciano. The probabilistic nature of the problem has been established [2] while working at the leading logarithm approximation and avoiding IR divergences by considering finite x. Studying MP at high energy we used ideas of A. Giovannini [3] to describe quark-gluon jets as Markov branching processes. Giovannini proposed to interpret the natural QCD evolution parameter $Y = \frac{1}{2\pi b}\ln[1 + \alpha_s b \ln(\frac{Q^2}{\mu^2})]$, where $2\pi b = \frac{1}{6}(11N_C - 2N_f)$ for a theory with N_C colours, N_f flavours and virtuality Q as the thickness of the jets and their development as the Markov process.

Three elementary processes contribute into QCD jets: (1) gluon fission; (2) quark bremsstrahlung and (3) quark pair production. Let $A\Delta Y$ be the probability that gluon will convert into two gluons in the infinitesimal interval ΔY, $\widetilde{A}\Delta Y$ be the probability that quark will radiate a gluon, and $B\Delta Y$ be the probability that a quark-antiquark pair will be produced from a gluon. A.Giovannini constructed a system of differential equations for generating functions (GF) of quark $Q^{(q)}$ and gluon $Q^{(g)}$ jets

$$\frac{dQ^{(q)}}{dY} = \tilde{A}Q^{(q)}(Q^{(g)} - 1), \quad \frac{dQ^{(g)}}{dY} = A(Q^{(g)2} - Q^{(g)}) + B(Q^{(q)2} - Q^{(g)})$$

and obtained explicit solutions of MD in the case $B = 0$ (process of quark pair production is absent)

$$P_0^P(Y) = \left(\frac{k_p}{k_p + \overline{m}}\right)^{k_p}, P_m^P(Y) = \frac{k_p(k_p+1)\dots(k_p+m-1)}{m!}\left(\frac{\overline{m}}{\overline{m}+k_p}\right)^m \left(\frac{k_p}{k_p+\overline{m}}\right)^{k_p}, \quad (2)$$

where $k_p = \widetilde{A}/A$, $\overline{m} = k_p(e^{AY} - 1)$ is the mean gluon multiplicity. These MD are known as negative binomial distribution (NBD). The GF for them is

$$Q^{(q)}(z, Y) = \sum_{m=0}^{\infty} z^m P_m(Y) = [1 + \overline{m}/k_p(1 - z)]^{-k_p}. \quad (3)$$

Two Stage Model (TSM) [4] was taken (2) to describe the cascade stage and added with a sub narrow binomial distribution for the hadronisation stage. We have chosen it basing on the analysis of experimental data in e^+e^-- annihilation lower than 9 GeV. Second correlation moments were negative at this energy. 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 we add the hadronisation stage to the parton stage for the sake of its factorization. MD in this process can be written as follows:

$$P_n(s) = \sum_m P_m^P P_n^H(m, s), \quad (4)$$

where P_m^P is MD for partons (2), $P_n^H(m,s)$ - 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_n^H formed from one parton and their GF $Q_p^H(z)$ are [4]

$$P_n^H = C_{N_p}^n \left(\frac{\overline{n}_p^h}{N_p}\right)^n \left(1 - \frac{\overline{n}_p^h}{N_p}\right)^{N_p - n}, \quad Q_p^H = \left[1 + \frac{\overline{n}_p^h}{N_p}(z-1)\right]^{N_p}, \tag{5}$$

where $C_{N_p}^n$ - binomial coefficient, $\overline{n}_p^h$ 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)

$$P_n(s) = \sum_{m=o}^{\infty} P_m^P \frac{1}{n!} \frac{\partial^n}{\partial z^n} (Q^H)^{2+m}|_{z=0}, \tag{6}$$

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

We introduce parameter $\alpha = N_g/N_q$ to distinguish the hadrons, produced from quark or gluon. Also we have carried out simplification for designation $N = N_q$, $\overline{n}^h = \overline{n}_q^h$. Introducing expressions (2), (5) in (6) and differentiating on z, we obtain MD of hadrons in the process of e^+e^- annihilation in TSM

$$P_n(s) = \sum_{m=0}^{M_g} P_m^P C_{(2+\alpha m)N}^n \left(\frac{\overline{n}^h}{N}\right)^n \left(1 - \frac{\overline{n}^h}{N}\right)^{(2+\alpha m)N - n}. \tag{7}$$

The results of comparison of expression (7) with experimental data [5] are shown in Figs. 1-2. We have obtained that MD in TSM (solid curve) describe well the experimental e^+e^--data from 14 to 189 GeV [6]. The mean gluon multiplicity $\overline{m}$ has a tendency to rise, but lower than the logarithmic curve. Values k_p remain ~ 10 at almost all energies. One of the most interesting physical senses of this parameter is temperature T[7]: $T \sim k_p^{-1}$.

The next picture of the hadronisation stage is discovered in conformity with parameters of the second stage: N, $\overline{n}^h$ and α . The first parameter N determines the maximum number of hadrons, which can be formed from quark while its passing through this stage. We can imagine that fission is continuous but process (3) (formation $q\bar{q}$ pair) becomes comparable with the other ones (1),(2). We can not reveal a steady energy rise or fall for N.

The second parameter $\overline{n}^h$ has a sense of the mean hadron multiplicity from quark at the second stage. We have found out the tendency to a weak rise with big scattering. The value of $\overline{n}^h$ is about $5 - 6$ in the research region. A possible explanation of these rocks for N and $\overline{n}^h$: only two initial quarks exist among a lot of newly born gluons at the beginning of hadronisation.

The last parameter α was introduced to compare the quark and gluon hadronisation. It is equal to 0.2 with some deviations. If we know α, then we can determine $N_g = \alpha N$ and $\overline{n}_g^h = \alpha \overline{n}^h$ for gluon. It is surprising that gluon parameters remain constant without considerable deviations in spite of the indirect finding: $N_g \sim 3 - 4$ and $\overline{n}_g^h \sim 1$ (Fig. 3-4). Therefore we can confirm the universality of gluon hadronisation. The fact that $\alpha < 1$ shows that hadronisation of gluons is softer than that of quarks.

It was shown [8] that the ratio of factorial cumulative moments K_q over factorial moments F_q changes the sign as a function of the order. We use MD formed in TSM to explain this phenomenon. F_q and K_q are obtained from the relations

$$F_q = \sum_{n=q}^{\infty} n(n-1)\dots(n-q+1)P_n, \quad K_q = F_q - \sum_{i=1}^{q-1} C_{q-i}^{i} K_{q-i} F_i. \tag{8}$$

The ratio of their quantities is $H_q = K_q/F_q$. The generating function for MD of hadrons (7) in e^+e^- annihilation Q(z) is the convolution

$$Q(z) = \sum_{m=0} P_m^g [Q_g^H(z)]^m Q_q^2(z) = Q^g(Q_g^H(z)) Q_q^2(z). \tag{9}$$

We calculate F_q and K_q in TSM, by using (9) and the sought-for expression for H_q will be [6]

$$H_q = \frac{\sum\limits_{m=1} k_p \alpha m(\alpha m - \frac{1}{N})\dots(\alpha m - \frac{q-1}{N})(\frac{\overline{m}}{\overline{m}+k_p})^m \frac{1}{m} - 2(-1)^q \frac{(q-1)!}{N^{q-1}}}{\sum\limits_{m=0} (2+\alpha m)(2+\alpha m - \frac{1}{N})\dots(2+\alpha m - \frac{q-1}{N})P_m}. \tag{10}$$

The comparison with experimental data [8] has shown that (10) describes the ratio of factorial moments (Fig. 5). The minimum is seen at $q = 5$. We have obtained that in the region before Z^0 (91.4 GeV), H_q oscillates in the sign only with the period equal to 2 and changes the sign with parity q. At higher energies the period is increased to 4. It can be explained by influence of a more developed cascade of partons with narrow hadronisation.

3 MD in *pp*-interactions

The study of MD in *pp* interactions is implemented in the framework of the project "Thermalization". This project is aimed at studying the collective behavior of secondary particles in proton-proton interactions at 70 GeV/c [9]. On the basis of the present understanding of hadron physics, protons consist of quarks and gluons. After the inelastic collision the part of the energy of the initial motive protons are transformed to the inside energy. Several quarks and gluons become free. Our model study has shown that quark branching of initial protons in pp interactions is almost absent from 70 to 800 GeV/c. MP are realized by active gluons. Domination of gluons was first proposed by S. Pokorski and L. Van Hove [10].

Our choice of the MP model is based on comparison with the experimental partial cross section $\sigma(n_{ch})$ in *pp* interaction at 70 GeV/c on the U-70 accelerator [11] and the present picture of strong interactions.

At the beginning of 90s a successful description of MD at this energy was realized by the quark model (Fig. 6) [12]. This model suggests that one proton quark pair, two pairs or three can collide and fragment into hadron jets. MD in quark jets were described by Poisson. Second correlation moments of charged particles for MD in this model will be always negative. It is known they are become positive at higher energies. In this model gluons are absent. 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 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. 6).

We have managed to build a scheme of hadron interactions to describe MD with the quark-gluon language as well as to investigate the high multiplicity region. The mentioned models are very much sensitive in this region.

We consider that at the early stage of pp interactions the initial quarks and gluons take part in the formation of quark-gluon system (QGS). They can give branches. We offer two model schemes. In the first scheme we study hadroproduction with account of the parton fission inside the QGS and build the two stage model with branch (TSMB). If we are not interested in what is going inside QGS, we come to the thermodynamical model (TSTM). Onward we name models involving active gluons into hadroproduction as the gluon dominance models (GDM) [13].

We begin our MD analysis with the scheme of branch. MD for quark and gluon jets may be described NBD and Farry distributions [3], accordingly. On the hadronisation stage we have taken a binomial distribution (5). As in TSM we have used a hypothesis of soft decoloration for quarks and gluons at their while passing of this stage and add the hadronisation stage to the branch one by means of factorization

$$P_n(s) = \sum_m P_m^P(s) P_n^H(m), \tag{11}$$

where $P_n(s)$ - resulting MD of hadrons, P_m^P - MD of partons (quarks and gluons), $P_n^H(m)$ - MD of hadrons (second stage) from m partons. Generating function (GF) for MD in hadron interactions is determined by convolution of two stages:

$$Q(s,z) = \sum_m P_m^P(s) \left(Q^H(z)\right)^m = Q^P(s, Q^H(z)), \tag{12}$$

where Q^H and Q^P are GF for MD at hadronisation stage and in QGS.

At the beginning of research we took model where some of quarks and gluons from protons participate in the production of hadrons. Parameters of that model had values which differed very much from parameters obtained in e^+e^-- annihilation, especially hadronisation parameters. It was one of the main reasons to refuse the scheme with active quarks. After that we chose the model where quarks of protons did not take part in the production of hadrons, but remained inside of the leading particles. All of the newly born hadrons were formed by gluons. We name these gluons active. They could give a branch before hadronisation.

It is important to know how much active gluons are into QGS at the first time after the impact of protons. We can assume that their number may change from zero and higher. It is analogous with the impact parameter for nucleus. Only in the case of elastic scattering the active gluons are absent. The simplest MD to describe the active gluons formed in the moment of impact is the Poisson distribution $P_k = e^{-\overline{k}}\overline{k}^k/k!$, where k and $\overline{k}$ are the number and mean multiplicities of active gluons, correspondingly.

To describe MD in the gluon cascade formed by the branch process of k active gluons, we have used the Farry distribution [3]

$$P_m^B(s) = \frac{1}{\overline{m}^k}\left(1 - \frac{1}{\overline{m}}\right)^{m-k} \cdot \frac{(m-1)(m-2)\cdots(m-k+1)}{(k-1)!}, \tag{13}$$

$$P_m^B(s) = \frac{1}{\overline{m}}\left(1 - \frac{1}{\overline{m}}\right)^{m-1}, \tag{14}$$

at $k>1$ - (13) and at $k=1$ - (14). m and $\overline{m}$ are the number of secondary gluons and mean multiplicites of them (averaged to all gluons). Expressions (13)-(14) have been obtained from the assumption about the independent branch of gluons

$$Q_k^B = (Q_1^B)^k = \frac{z^k}{\overline{m}^k}\left[1 - z\left(1-\frac{1}{\overline{m}}\right)\right]^{-k}, \quad Q_1^B = \frac{z}{\overline{m}}\left[1 - z\left(1-\frac{1}{\overline{m}}\right)\right]^{-1}. \tag{15}$$

In the case $k=0$ (the impact was elastic and active gluons are absent) MD of hadrons in pp-scattering is equal to $P_2^{el}(s) = e^{-\overline{k}}$.

On the second stage some of active gluons may leave QGS and transform to real hadrons. We can name that gluons "evaporated". Let us introduce parameter δ as the ratio of evaporated gluons, leaving QGS, to all active gluons, which may transform to hadrons. Our binomial distributions for MD of hadrons from the evaporated gluons on the stage of hadronisation are

$$P_n^H(m) = C_{\delta m N}^{n-2}\left(\frac{\overline{n}^h}{N}\right)^{n-2}\left(1-\frac{\overline{n}^h}{N}\right)^{\delta m N-(n-2)}. \tag{16}$$

In this expression the gluon parameters are $\overline{n}^h$ and N (without index "g") which have the same meaning that of the quark parameters. An effect of two leading protons is also taken into account. GF for MD (16) has the following form:

$$Q_m^H = \left(Q_1^H\right)^{\delta m} = \left[1-\frac{\overline{n}^h}{N}(1-z)\right]^{\delta m N}, \quad Q_1^H = \left[1-\frac{\overline{n}^h}{N}(1-z)\right]^N. \tag{17}$$

MD of hadrons in the process of proton-proton scattering in two stage gluon model with branch (TSMB) is

$$P_n(s) = \sum_{k=1}^{MK}\frac{e^{-\overline{k}}\overline{k}^k}{k!}\sum_{m=k}^{MG}\frac{1}{\overline{m}^k}\frac{(m-1)(m-2)\dots(m-k+1)}{(k-1)!}\cdot$$
$$\cdot\left(1-\frac{1}{\overline{m}}\right)^{m-k} C_{\delta m N}^{n-2}\left(\frac{\overline{n}^h}{N}\right)^{n-2}\left(1-\frac{\overline{n}^h}{N}\right)^{\delta m N-(n-2)}. \tag{18}$$

In comparison with experimental data [11] the numbers of gluons in sums on k and m were restricted by values MK and MG as the maximal possible number of gluons on the transition. For comparison we have taken the data at 69 GeV/c because they do not differ from data at 70 GeV/c [11]. χ^2/ndf in are equal to about $\sim 1/3$ at 70 GeV/c and ~ 5 at 69 GeV/c and the parameters are similar. We obtained $N = 40$(fix), $\overline{m} = 2.61 \pm 0.08$, $\delta = 0.47 \pm 0.01$, $\overline{k} = 2.53 \pm 0.05$, $\overline{n}^h = 2.50 \pm 0.29$ from the comparison with [11] . We can conclude that the branch processes are absent, since parameters $\overline{m}$ and $\overline{k}$ are equal to the errors. The fraction of the evaporated gluons is equal to 0.47. A maximal possible number of hadrons from the gluon looks very much like the number of partons in the glob of cold quark-gluon plasma of L.Van Hove [14]. The gluon branch should be very active inside of QGS. At the fixed parameter of hadronisation $\overline{n}^h$ equal to 1.63 (see below the thermodynamic model) the fraction of the evaporated gluons δ is about 0.73. After the evaporation the part of active gluons do not convert into hadrons. They stay in QGS and become sources of soft photons (SP). Further we will analyze the experimental effect of SP excess (it is impossible to describe them by means QED).

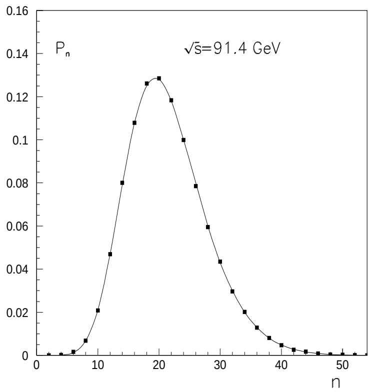

Figure 1: MD at 91.4 GeV.

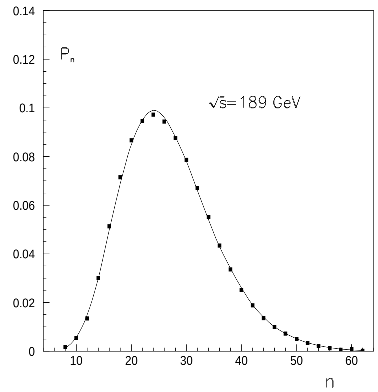

Figure 2: MD at 189 GeV.

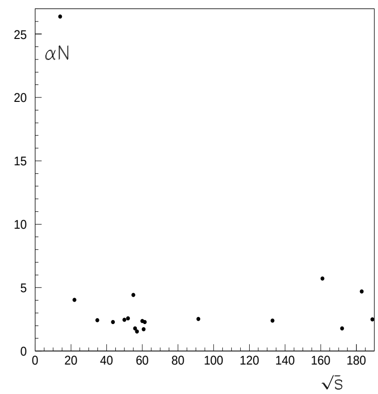

Figure 3: $N_g = \alpha N_q$.

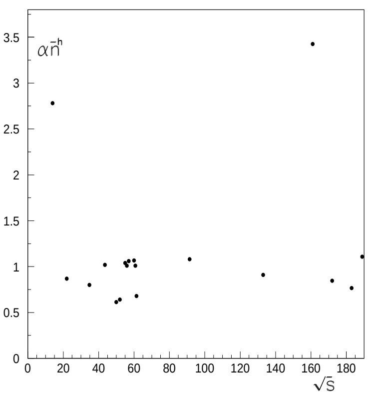

Figure 4: $\overline{n}_g^h = \alpha \overline{n}_q^h$.

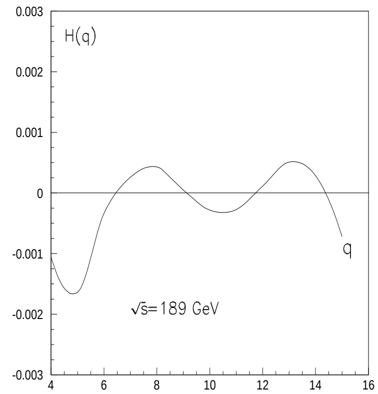

Figure 5: H_q at 189 GeV.

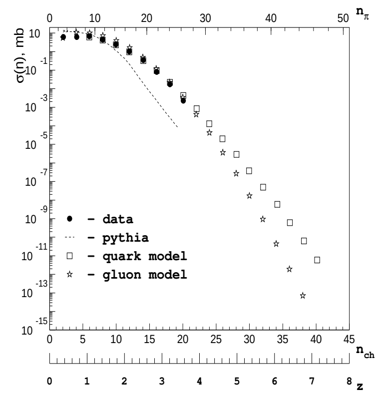

Figure 6: $\sigma(n)$ in *pp*.

In the thermodynamic model without branches the active gluons which appear in the moment of the impact may leave QGS and fragment to hadrons. We consider that active gluons evaporated from QGS have Poisson MD with a mean multiplicity $\overline{m}$. Using the idea of the convolution of two stages (11) as well as the binomial distribution for hadrons from gluons we obtain MD of hadrons in pp-collisions in framework of the two stage thermodynamic model (TSTM):

$$P_n(s) = \sum_{m=0}^{ME} \frac{e^{-\overline{m}}\overline{m}^m}{m!} C_{mN}^{n-2} \left(\frac{\overline{n}^h}{N}\right)^{n-2} \left(1 - \frac{\overline{n}^h}{N}\right)^{mN-(n-2)} (n > 2), \tag{19}$$

$P_2^{el}(s) = e^{-\overline{m}}$. Our comparison (19) with the experimental data [11] (see Fig. 8) gives values of parameters $N = 4.24 \pm 0.13$, $\overline{m} = 2.48 \pm 0.20$, $\overline{n}^h = 1.63 \pm 0.12$, and the normalized factor $\Omega = 2$ with $\chi^2/\mathrm{ndf} \sim 1/2$. We are restricted in sum (19) $ME = 6$ (the maximal possible number of evaporated gluons from QGS). The found gluon parameters N and $\overline{n}^h$ agree with the values of these parameters obtained at the e^+e^- annihilation [6]. From TSTM the maximal possible number of charged particles is 26. This quantity is the product of maximal multiplicities of active gluons and of the maximal number of hadrons forming from one gluon $ME \cdot N$. In TSMB there are no restrictions of this sort.

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