MULTIHADRON PRODUCTION AND QCD PARTON SHOWERS

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ABSTRACT

Multihadron production in high energy collisions appears to be controlled by the self-interaction of gluons, the dominant multiplication mechanism in QCD parton showers.

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Already in the 1940's the high multiplicities of cosmic ray collisions puzzled theorists (Heisenberg, Oppenheimer, ...) who wanted to explain them by strong interaction field theories. Now we have good reasons to claim that they are mainly controlled by the self-interaction of gluons, the dominant multiplication mechanism in QCD parton showers.

The experimental study of charged hadron multiplicity distributions (MDs) in full phase space and symmetric rapidity windows has revealed a remarkable set of empirical regularities, called the negative binomial (NB) regularities, common to the three classes of multihadron producing reactions: e^+e^- annihilation, deep-inelastic lepton-hadron collisions and hadron-hadron collisions [1].

Examples of NB regularities in e^+e^- annihilation at c.m. energy $\sqrt{s}$ = 22 GeV (TASSO Collaboration), in deep inelastic μp scattering at the c.m. energy of the hadronic system W =18-20 GeV (EMC Collaboration) and in π^+p collision at c.m. energy $\sqrt{s}$ = 22 GeV (NA22 Collaboration) are shown in Figure 1. Data are fitted by $NBMD$ (solid line in the Figure). According to $NBMD$ the probability of producing n charged particles, $P_n^{(NB)}(\bar{n},k)$ depends on two parameters, the average charged multiplicity $\bar{n}$ and k, which is related to the dispersion $D = (\bar{n}^2 - \bar{n}^2)^{\frac{1}{2}}$ by $\frac{D^2}{\bar{n}^2} = \frac{1}{\bar{n}} + \frac{1}{k}$. $P_n^{(NB)}$ is defined by the following relation

$$\frac{P_{n+1}^{(NB)}}{P_n^{(NB)}} = \frac{\bar{n}}{n+1}\left(1+\frac{n}{k}\right)\left(1+\frac{\bar{n}}{k}\right)^{-1} , \qquad P_0^{(NB)} = \left(1+\frac{\bar{n}}{k}\right)^{-k} \tag{1}$$

This tends to the Poisson distribution in the limit $k \to \infty$. $NBMD$ is obtained by independent emission of clusters called clans.

The number of clans, N, has Poisson (P) distribution

$$P_N^{(P)} = \frac{e^{-\bar{N}}\bar{N}^N}{N!} \text{ with } \bar{N} = k\,\ell n\left(1+\frac{\bar{n}}{k}\right) \tag{2}$$

The number of particles for average clan, n_c, has a logarithmic (L) distribution

$$P_{n_c}^{(L)} = \frac{b^{n_c}}{n_c}\left[-\ell n(1-b)\right]^{-1} \text{ for } n_c \geq 1 \text{ and } P_0^{(L)} = 0$$
$$\text{with } b = \frac{\bar{n}}{\bar{n}+k} \text{ and } \bar{n}_c = \frac{\bar{n}}{\bar{N}} = \frac{\bar{n}}{k}\left[\ell n\left(1+\frac{\bar{n}}{k}\right)\right]^{-1} \tag{3}$$

k^{-1} in this framework corresponds to the ratio of the probability of two particles belonging to the same clan to the probability of two particles belonging to two separate clans, i.e., it is a measure of aggregation.

As the energy increases,the average number of clans, $\bar{N}$, stay approximately constant within a given rapidity interval whereas the average number of particles per clan in a fixed rapidity interval increases. The two effects are shown in Figure 2 for e^+e^- annihilation and in Figure 3 for pp collisions. The result is that clans in e^+e^- annihilation are more numerous and smaller than in pp collisions.

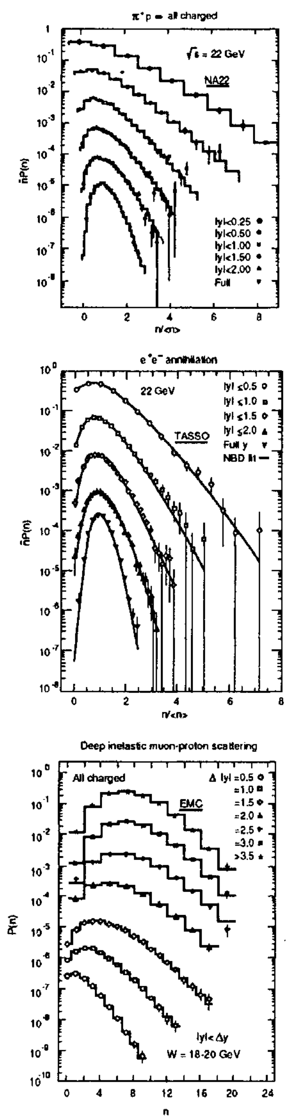

Figure 1

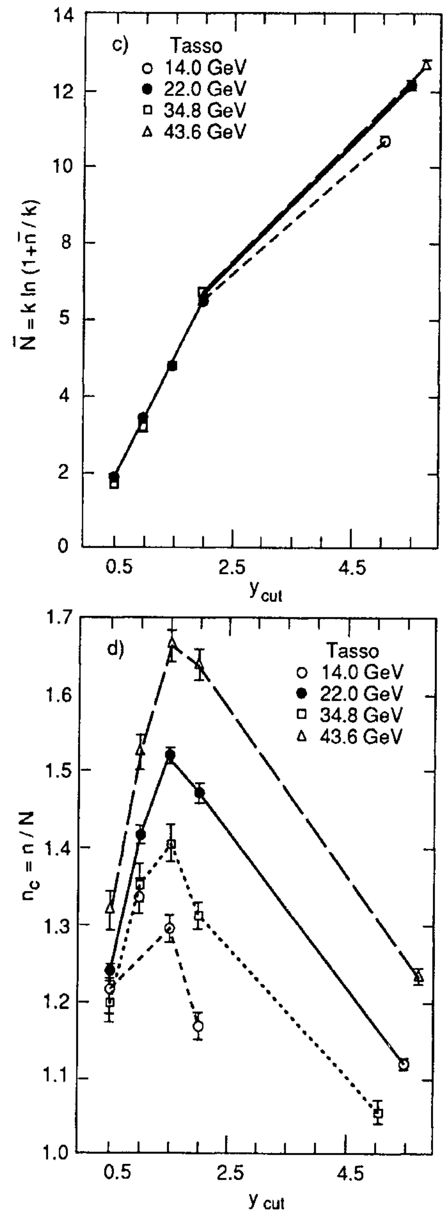

Figure 2

Only for e^+e^- annihilation has a consensus emerged on the best theoretical description of multiparticle production. It is given by the QCD Parton Shower Model consisting in a parton shower development based on perturbative QCD (Altarelli-Parisi splitting equations with dominance of gluon $\rightarrow$ 2 gluon splitting) and a non-perturbative hadronization prescription, for which the most developed choice is the Lund string fragmentation JETSET [2]. A typical development of QCD parton shower in e^+e^- from initial virtuality Q^2 to virtuality cut-off Q_0^2 and then to final hadrons is shown in Figure 4. It leads to two-jet structure. Among alternative prescriptions the HERWIG cluster hadronization [3] recently emerged as the second best possibility (hadronization prescriptions, being non-perturbative, are necessarily based on guesswork).

It is remarkable that the NB regularities found empirically are well reproduced by the QCD Parton Shower Model with Lund hadronization. Similar regularities are found in the model for the MDs of the final partons of the shower [4] with, at $\sqrt{s} \gtrsim$ 200 GeV, very simple relations between the NB parameters at hadronic and partonic level:

$$k_h \simeq k_p \quad , \quad \bar{n}_h \simeq \rho \bar{n}_p \quad , \quad \rho \simeq 2Q_O/1\text{GeV} \quad (4)$$

k_h and $\bar{n}_h$ independent of Q_O for $Q_O = 0.5 \div 2\text{GeV}$

Q_O is the parton virtuality cut off at which the shower development is stopped and the hadronization takes place [5].

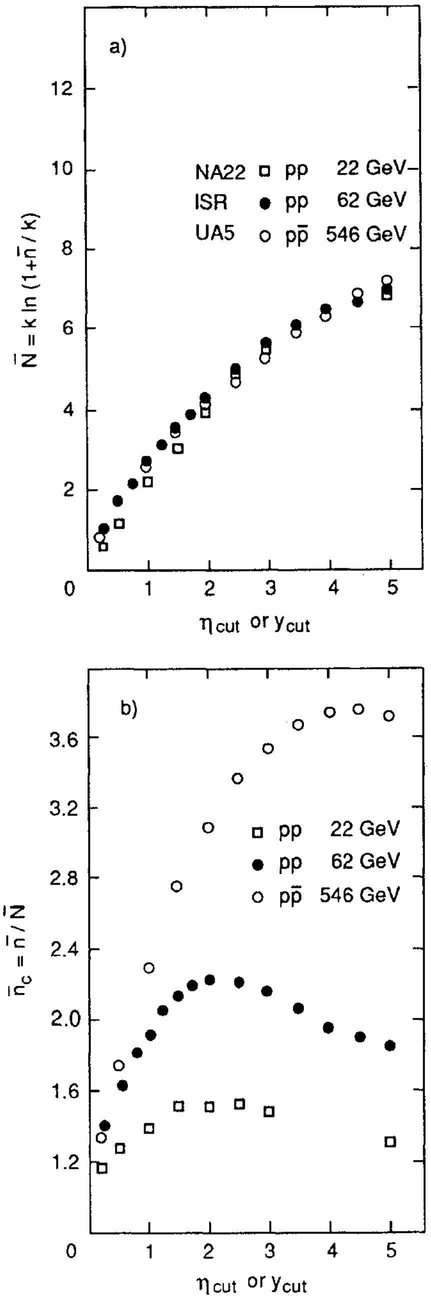

Figure 3

An illustration in terms of the clan structure analysis of the main consequences of NB regularities discovered in the QCD parton shower model on charged hadrons and partons is given in Figures 5 and 6 respectively. They show the average number of clans, $\bar{N}$, and the average number of charged particles and partons per clan, $\bar{n}_c$, for $q\bar{q}$ and gg systems at different c.m. energies ($\sqrt{s}$ = 29, 200 and 2000 GeV) in different symmetric rapidity windows $|y| < y_{\text{cut}}$. It can be seen that $\bar{N}$ is approximately constant as the energy increases within a fixed rapidity window at both levels, $\bar{N}$ (partons) being proportional to $\bar{N}$ (charged hadrons). This result led us to propose a generalized relation of local parton-hadron duality between the hadronic and partonic inclusive rapidity distribution [4,5]:

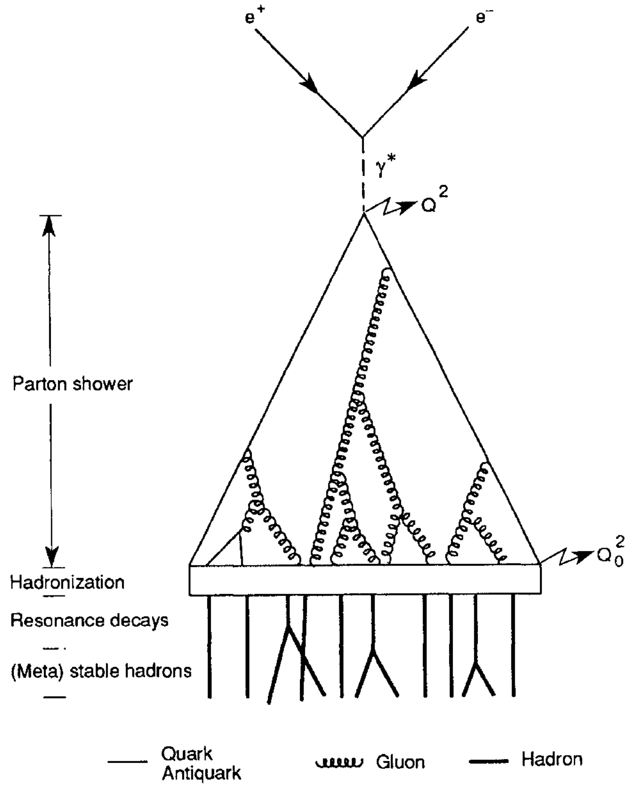

Figure 4

$$Q_h^{(n)}(y_1 \cdots y_n) \simeq \rho^n Q_p^{(n)}(y_1 \cdots y_n) \qquad (5)$$

The fact that the NB regularities observed experimentally are the same for hadron-hadron and lepton-hadron reactions as for e^+e^- annihilation suggests that their dynamical origin should also be the same [6]. In view of the impressive successes of the QCD Parton Shower Model in the description of e^+e^- annihilation, also very recently at LEP, the obvious solution is to extend the QCD Parton Shower Model to hadron-hadron and lepton-hadron reactions.

Such an extension should be straightforward for the lepton-hadron case as indicated in Figure 7. Here one photon with high space-like virtuality ΔE^2

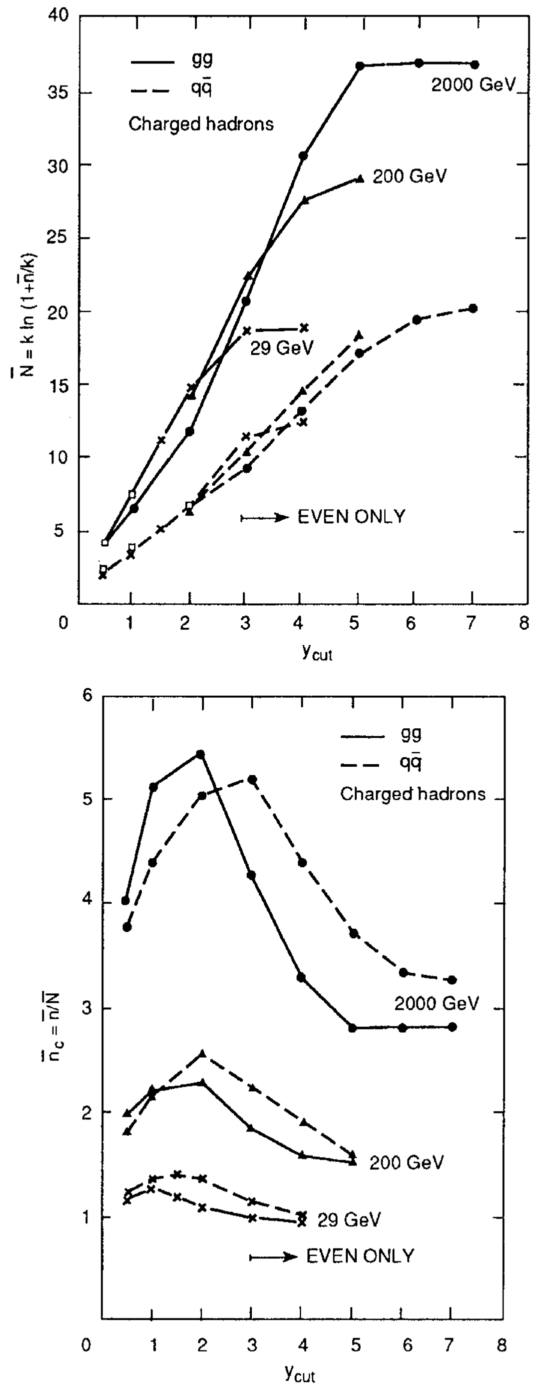

Figure 5

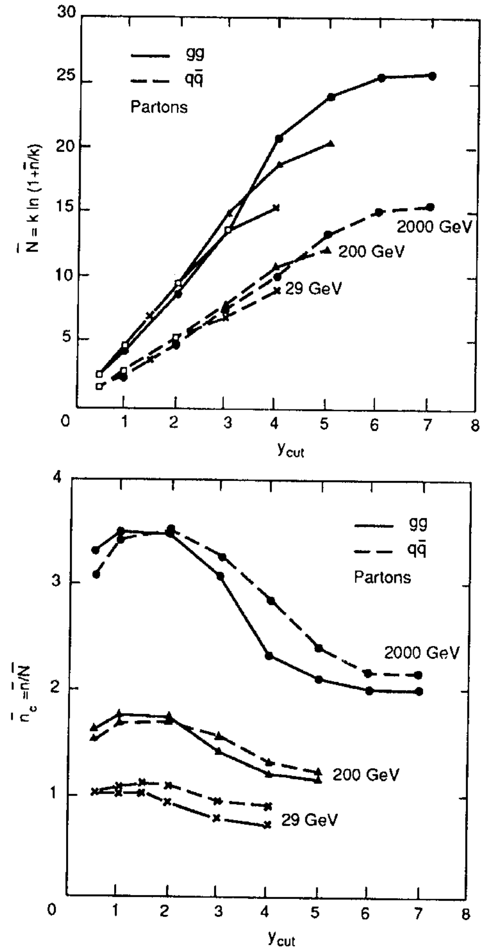

Figure 6

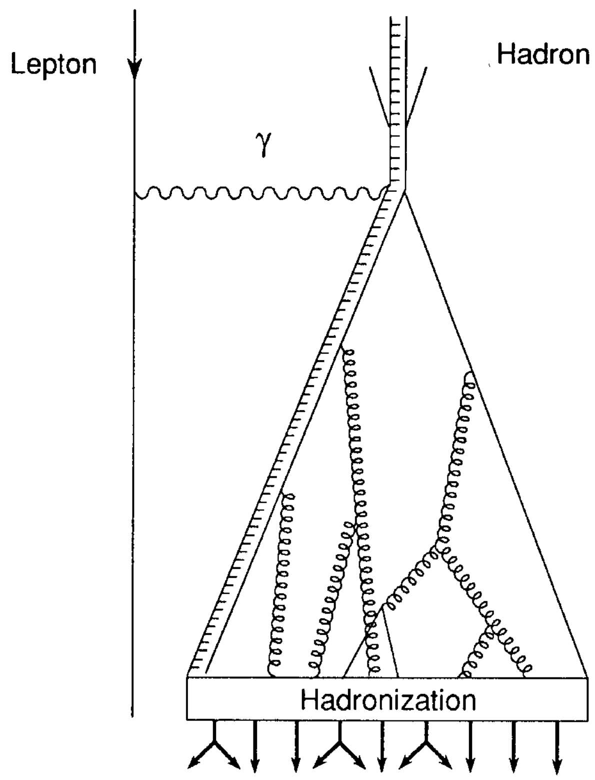

Figure 7

$-\Delta P^2 << -1\,\mathrm{GeV}^2$ is exchanged. Due to this high virtuality parton cascading starts and develops dominantly into two-jet structure.

For hadron-hadron collisions, as proposed in [7], the simplest approach would be to start from the FRITIOF model [8] or a similar model based on gluon exchange, and to replace string formation by parton shower formation. The idea is illustrated in Figure 8. Here low 4-momentum transfers dominate ($0 \geq \Delta E^2 > -1\,\mathrm{GeV}^2$), but they create high longitudinal virtualities, which are responsible for the onset of parton cascading. Two-jet structure is again dominant. NB regularities and two-jet structure dominance are therefore the common features of the above classes of reactions. They can be all explained in terms of QCD parton showers formation, which we claim to be the basic mechanism for multihadron production in high energy collisions. Finally, ultrasoft effects can also be understood in the same framework by allowing Q_0^2 to fluctuate and assuming that parton showers are continuing in the infrared domain. A *glob* of ultrasoft partons with very small virtualities is produced. Hadrons from the *glob* are expected to be concentrated in a small region in rapidity, thus leading to intermittent behaviour (see Figure 9). As we have argued in [7], this also helps to put the relation between nucleon-nucleon collision models and the problem of quark-gluon plasma formation in nucleus-nucleus collisions on a sounder basis.

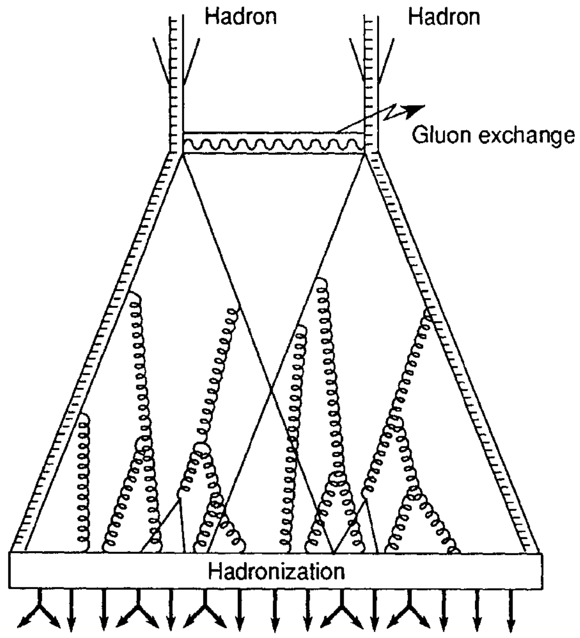

Figure 8

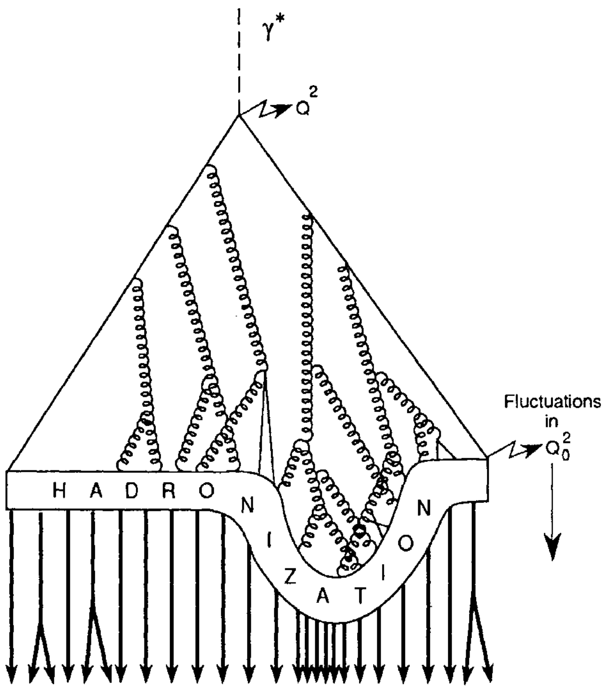

Figure 9

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