On the multiplicity distribution of secondary hadrons

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We compare the multiplicity-distribution structure in the processes of inelastic hadron scattering and e^+e^- annihilation in the Regge-like parton model in which hadrons are produced due to the decay of colored strings.

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In the simplest Regge-like model, if it is interpreted in parton terms, all the particles created in the final state are produced *a priori* in the wave function of the incident hadron. After collision and loss of coherence, the partons emerge at the mass surface as real particles. Therefore, the average multiplicity of the produced hadrons $\bar{n}(E)\approx\nu(E)$—the average parton multiplicity.

We shall discuss the distribution σ_n in the Regge-like model (which follows from QCD), in which $\bar{n}(E)\gg\nu(E)$. In this case $\nu(E)$ is small, and $\bar{n}(E)$ is formed as a result of the decay of "longitudinal clusters"—strings or tubes of a colored electric field, which are similar to those which, as is now customarily assumed, are produced in the processes $e^+e^-\to$ hadrons, because of the confinement effects in QCD.[1-4] In describing the hadron-hadron (hh) interaction, three steps must be identified in the model. 1) Before the collision there are few partons in the wave functions. Thus, for the nucleon $\nu(E)\sim 3$ at $E\lesssim 10^3$ GeV (primarily valence quarks) and it slowly increases with E [it is possible that $\nu(E)\sim 4$–6 at $E\sim 10^{(5-6)}$ GeV][1)]. 2) The collision during which generally a color exchange occurs (a gluon exchange corresponds to a pomeron and its branches, and a quark exchange corresponds to nonvacuum reggeons). 3) Longitudinal scattering of colored charges after the collision.

We assume[(2-4)] that when the charges are separated by a greater distance than the confinement radius r_0, the colored electric field lines are collected into a tube or radius $r\sim r_0$, which lengthens as the charges fly apart. The pairs of colored particles are produced in the longitudinal field of the tube which then breaks up into sections which in turn stretch. This process continues until the mass of the sections is of the order of the hadron masses. The multiple gluon exhanges, which lead to the formation of parallel and branching colored field tubes, can also occur during the collision. A gluon exchange together with the produced tube corresponds to a pomeron, and multiple exchanges of the tubes correspond to a pomeron as well as pomeron branches. The net distribution of secondary particles is the same as that from the cutting of unenhanced and enhanced reggeon diagrams. On the whole, the approach resembles the theory of a standing Gribov pomeron: small α'_p and $\partial\sigma_{\rm tot}/\partial E$, but a large inclusive vertex in the central region. It is also important that many interesting corollaries of the additive quark model remain.[5]

Let us compare the processes $e^+e^-\to q\bar{q}\to$ hadrons,[2)] and (hh) hadrons at the same energy $E=me^Y$ in the c.m.s. A difference in the structure of the final states (ignoring the spectrum edges) arises because the colored quark charges fly apart in the first case and primarily gluon charges in the second case. But the gluon tube is not simply a superposition of two quarks. Its final structure under conditions of ultrarelativistic scattering of the ends depends on $\rho_\perp$—the lateral motion of the colored charges due to collision. The value $\rho_\perp$ is of the order of the impact parameters in the gluon exchange between quarks. In events with a large $\rho_\perp \gg r$ the gluon tube breaks up into two, uncoupled antiparallel quark tubes. During separation they decay into $q\bar{q}$ pairs and, consequently, for such $\rho_\perp$ the average number of created hadrons is $n_{hh}(\rho_\perp) = 2\bar{n}_{ee}$. At $\rho_\perp \lesssim r$ the gluon pairs $(g\bar{g})$, which break the string, can also be produced.[3] It can be estimated that the $(g\bar{g})$ creation process predominates over the creation of $q\bar{q}$ pairs. Therefore, the conversion of the gluon tube to hadrons is different (via the $g\bar{g}$ step) from that in the quark tube, and hence at $\rho_\perp \lesssim r$ the value $n_{hh}(\rho_\perp \lesssim r) \neq 2\bar{n}_{ee}$. Phenomenologically,

$$n_{hh}(\rho_\perp) = a(\rho_\perp) + b(\rho_\perp)Y; \quad \bar{n}_{ee} = a_1 + b_1 Y, \tag{1}$$

where $b(\rho_\perp \gg r) = 2b_1$. The average multiplicity in the gluon tube $\bar{n}_{hh} = \bar{a} + \bar{b}Y$ is obtained by averaging $n_{hh}(\rho_\perp)$ over $\rho_\perp$ with the weight $w(\rho_\perp)$, which is determined by the $\rho_\perp$ distribution in the collision process; in this case

$$\bar{b} = \int w(\rho_\perp) b(\rho_\perp) d^2\rho_\perp,$$

where $\rho_\perp \lesssim r$ are large. In order to match this with the experimental condition[6]—$\bar{n}_{ee} \approx \bar{n}_{hh}$—we must assume that at $\rho_\perp \sim r$ $b(\rho_\perp)$ varies drastically from the value $2b_1$ and at $\rho_\perp \gg r$ it varies from the value βb_1, where $\beta < 1$ at $\rho_\perp \ll r$.[4] We shall not discuss here whether this occurs in real QCD, but rather the consequence of this assumption.

The multiplicity distribution is of most interest. In a quark tube the multiplicity distribution is Poisson-like ($D = c\sqrt{\bar{n}}$, $c \sim 1$) because of the relative independence of the creation of $q\bar{q}$ pairs in the remote sections of the tube. But large multiplicity fluctuations are possible in the gluon tube because of the $\rho_\perp$ fluctuations. It is easy to see that the multiplicity distribution is *KNO* type with a dispersion $D = \bar{n}\{1/\bar{b}[\overline{b^2} - \bar{b}^2]^{1/2}\}$.

A multiple gluon exchange (strong color transfer) due to hadron collision produces a "bundle of quark tubes." As a result, the *KNO* distribution occurs

$$\sigma_n = \sigma_{tot} \sum_k v_k \int w_k(\rho_{i\perp}) \delta(n - a_k(\rho_{i\perp}) - b_k(\rho_{ik})Y) \prod_{i=1}^{k-1} d^2\rho_{i\perp}, \tag{2}$$

were v_k is the formation probability of k quark tubes and $w_k(\rho_{i\perp})$ is the probability that the quark tubes are located at distances $\rho_{i\perp}$.

The hadron creation mechanism in the quark tube is different from that in the gluon tube in which it also depends $\rho_\perp$ (the relative weight of the $q\bar{q}$ and $g\bar{g}$ channels changes). Therefore, at $|y_1 - y_2| \sim 1$ the pair correlators $f_2(y_1, y_2)$ are generally different in the quark and gluon tubes (i.e., for example, in the e^+e^- and hh processes). In addition, since the value $\rho_\perp$ in hh is correlated with n, we can expect f_2 to depend on n in the topological hh cross sections, and at large $n \sim 2\bar{n}$ it is possible that $f_2^{hh} \approx f_2^{ee}$.

At very high energies the KNO distribution is slowly reconstructed—first, v_k in Eq. (2) depends weakly on Y [primarily via $\nu(Y)$] and, secondly, the rapidity fluctuations of the tube length are significant, since they can terminate at a soft gluon "located" in the wave function, and the average number of such gluons $\sim \nu - 3$ slowly increases with Y.

We note again that the proposed approach explains the broad KNO distribution σ_n in the inelastic processes associated with the pomeron exchange and predicts a narrow "Poisson-like" distribution σ_n for the single-stream processes e^+e^-, eP, νP...and for other processes (for example, $\pi^- P$, $P\bar{P}$) in which the large contribution from nonvacuum reggeon is isolated. There are indications[7] that the distribution is narrow in single-stream processes. It would be extremely interesting to establish this in more detailed experiments.

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[1)]The number of partons $\tilde{\nu}(E,Q)$ also depends on Q—the resolution of the parton meter. The "soft" $\nu(E) \approx \min_Q \tilde{\nu}(E,Q)$ is important in the dominant hadron processes. An increase of $\nu(E)$—the number of these "constituent" partons—leads to $\alpha'_p \neq 0$.

[2)]We have in mind the single-stream processes, without hard-gluon production.

[3)]In the literature (for example, Ref. 3) it is assumed without any basis that $n(\rho_\perp)$ is invariant at $\rho_\perp < r$ and $\bar{n}_{hh} \approx \bar{n}_{ee}$ is explained by assuming that there are always slow quark in the wave functions of fast hadrons, and then either the quark exchange or one of the quark tubes comprising the gluon tube that is short in rapidity, can dominate. This couples $\bar{n}_{ee}$ with $\bar{n}_{hh}$. But, on the other hand, the momenta of the constituent quarks fluctuate slightly $\Delta Y \sim 1$. In addition, we would not be able to explain the small contributions of nonvacuum reggeons at high E.

[4)]Two antiparallel quark tubes repel each other if their break up due to production of $q\bar{q}$ and $g\bar{g}$ pairs is disregarded. Therefore, the gluon tube would seem to break up into two quark tubes with $\rho_\perp > r$. However, under conditions of a fast scattering of the ends, the transverse separation of a part of the tube takes longer than its $g\bar{g}$ decay.

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