SEMI-HARD PROCESSES IN HADRONIC COLLISIONS*

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(Received December 13, 1983)

We review an idea that fragmentation of highly virtual quarks with four-momentum squared $q^2 \gg \Lambda^2 \sim O(1/r_h^2)$ but $q^2 \ll s$ (semi-hard processes) is the main source of the secondary hadrons in very high energy hadron-hadron collisions.

PACS numbers: 13.85.-t

1. It is generally believed that hadron production in the e^+e^- annihilation proceeds via formation of a highly virtual $q\bar{q}$ pair and its subsequent fragmentation into hadrons. The average off-shell mass squared q^2 of virtual quarks increases proportionally to Q^2 and reads (according to perturbative QCD):

$$q^2 \sim \alpha(Q^2)Q^2. \tag{1}$$

Such processes are called hard processes (the life-time $\tau_{\rm life}$ and the dimension of the virtua quarks are $\tau_{\rm life} \sim 1/\sqrt{q^2} \ll r_h$ where r_h is the typical hadronic scale $O(1{\rm f})$; the interaction time $\tau_{\rm int}$ satisfies the relation $\tau_{\rm life} \lesssim \tau_{\rm int} \sim 1/\sqrt{Q^2}$). The fragmentation of the virtual quarks into hadrons is described in QCD by perturbative branching process followed by non--perturbative hadronization. It is expected that for high enough Q^2 the perturbative branching of partons with $q^2 \sim O(Q^2)$ is responsible for the main features of the final state. In particular it can explain: a) faster than logarithmic rise with Q^2 of the average hadron multiplicity; b) rise with Q^2 of the $\frac{1}{\sigma}\, d\sigma/dy$; c) rise of the $\langle p_\perp \rangle_n$ with the final multiplicity n; d) rise of the $\langle p_\perp^2 \rangle$ with Q^2. All those features seem to be consistent with experimental observations for the e^+e^- annihilation.

The picture of hadron production in hadronic collisions at some energy s used to be quite different. While there is some contribution from hard parton-parton collisions giving

* Presented at the VIth Warsaw Symposium on the Elementary Particle Physics, Kazimierz, May 1983.

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large $p_\perp$ jets ($p_\perp^2 \sim O(s)$), it is only a small fraction of the total inelastic cross section $\sigma_{\rm hard} \sim \alpha^2(p_\perp^2)/p_\perp^2 \ll \sigma_{\rm inel} \sim r_{\rm h}^2$. For the bulk of the hadron production one usually assumes some non-perturbative mechanism (strings, chains, Field-Feynman fragmentation, etc.) involving quarks with small $q^2 \sim O(\Lambda^2) = O(1/r_{\rm h}^2)$ only.

2. We would like to review here briefly an idea, proposed on several occasions [1–5], that at a very high energy s the so-called low $p_\perp$ region in hadron production is also dominated by (or at least gets a sizable contribution from) fragmentation of highly virtual partons. However, in contrast to the hard processes, the average virtual mass squared q^2 of such partons is rising *slower than linearly* with s, with some new effective scale parameter s_0 present in the effective dependence of the q^2 on s:

$$q^2 \sim \left(\frac{s_0}{s}\right)^a s \quad (0 < a < 1). \tag{1}$$

We shall call such processes semi-hard.

3. To study the role of semi-hard processes in hadronic collisions we first recall that for the primary products (cluster/resonances) of such collisions the $\langle p_\perp \rangle \sim O$ (1 GeV). Therefore, at high energy s an important part of the cross section comes from the region

$$s \gg p_\perp^2 \gg \Lambda^2.$$

This part of the $\sigma_{\rm inel}$ can presumably be understood in terms of (calculated in perturbative QCD) parton-parton scattering with energy $\hat{s}$ and momentum transfer $\hat{t}$ such that

$$s \gg \hat{s} \sim |\hat{t}| \sim p_\perp^2 \gg \Lambda^2, \quad \alpha(\hat{t}) \ll 1. \tag{2}$$

The important point is that at high energy s such scattering can occur between partons carrying *very small fractions* x_1 *and* x_2 of the hadronic momenta:

$$x_1 x_2 = \frac{\hat{s}}{s} \approx \frac{|\hat{t}|}{s}. \tag{3}$$

Therefore, although the individual cross section

$$\frac{d\sigma_{\rm parton}}{d\hat{t}} \sim \frac{\alpha^2(\hat{t})}{\hat{t}^2}$$

is small, the overall contribution σ of the parton-parton scattering with $\hat{s} \sim \hat{t} \gg \Lambda^2$

$$\sigma \sim \int dx_1 dx_2 F(x_1, \hat{t}) F(x_2, \hat{t}) \left.\frac{d\sigma}{d\hat{t}}\right|_{\hat{t}\sim\hat{s}} \Delta\hat{t} \tag{4}$$

is sizable due to a rapid growth of the parton densities $F(x, \hat{t})$ at small x. Very roughly, we can estimate the effect on the dimensional grounds. In a hadron with radius $r_{\rm h}$ there are $(r_{\rm h}\sqrt{|\hat{t}|})^2$ partons with size $1/\sqrt{|\hat{t}|}$ and each carries $x \sim 1/r_{\rm h}^2|\hat{t}|$ of the hadron momentum.

Therefore, neglecting fluctuations in the parton momentum distribution we estimate

$$F(x, \hat{t}) \sim r_h^2|\hat{t}|\delta(x-x_0) \quad \text{and} \quad x_0 \sim \frac{1}{r_h^2|\hat{t}|} \tag{5}$$

for a hadron probed with momentum transfer $\hat{t}$. Furthermore we can use Eq. (3) to relate $x_0 \sim \sqrt{x_1x_2}$ to $\hat{s}$ or $\hat{t}$ and s. We get then

$$\frac{1}{r_h^2|\hat{t}|} = \sqrt{\frac{|\hat{t}|}{s}} \quad \text{or} \quad |\hat{t}| = \left(\frac{1/r_h^2}{s}\right)^{2/3} s. \tag{6}$$

Using (4), (5) and (6) we conclude qualitatively that scattering of very small x partons (with energy $\hat{s}$ and momentum transfer $\hat{t}\pm\Delta t$ where $|\hat{t}| \sim \hat{s}$) gives: a) a non-decreasing with the hadron scattering energy s contribution σ to σ_{inel}

$$\sigma \sim r_h^4\alpha^2(t)\Delta t,$$

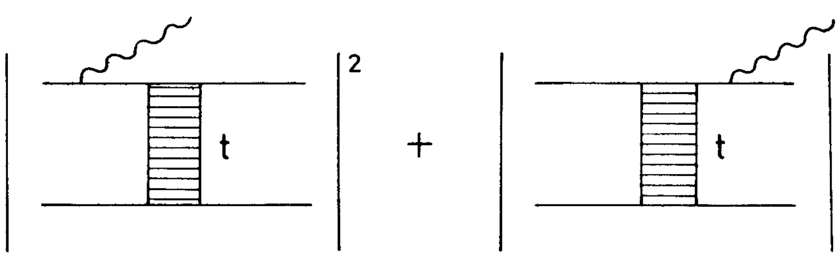
b) highly virtual partons (space-like or time-like) with the average four-momentum squared q^2 increasing like $s^{1/3}$

$$q^2 \sim \langle\hat{t}\rangle \sim \left(\frac{1/r_h^2}{s}\right)^{2/3} s.$$

According to our previous definition this is a semi-hard process with $s_0 = 1/r_h^2$.

Scattering of very small x partons and their fragmentation into final hadrons as the main mechanism of hadron production in hh collisions has been proposed some time ago to explain the observed long range multiplicity correlations [1]. More recently, the contribution of such processes to σ_{inel} has been studied in Ref. [3] and [4]. Since the discussed processes are calculated in perturbative QCD, it seems that part of the low $p_\perp$ region can be understood in this framework.

4. One can also argue [2] that at sufficiently high energies even hadronic collisions involving momentum transfers Δ_μ as low as $\Delta_\mu \sim O$ (1 GeV) generate semi-hard partons with large invariant masses. Imagine that hadrons interact due to an incoherent quark-quark scattering. At low momentum transfers hadrons consist of three quarks and the quark-quark interaction is expected to be a non-perturbative collective exchange of wee gluons with some effective coupling to quarks. However the quarks can radiate partons (mainly gluons) before and after their interaction. Thus it seems plausible that the low $t = \Delta^2$ multihadron production is described by the following diagrams



+ radiation from the lower quark line + multigluon radiation diagrams.

Here it is understood that the t exchange is described by some effective parametrization whereas the gluon radiation by perturbative QCD. An important assumption is that, due to a non-perturbative nature of the exchange mechanism, there is no interference between radiation before and after the interaction with the other quark. It can be seen [2] that in this model the average virtuality (space-like or time-like) of quarks radiating gluons grows $\sim \sqrt{s}$:

$$q^2 \sim \Delta_{\parallel} \sqrt{\hat{s}} \sim \Delta_{\parallel} \sqrt{s},$$

where $\Delta_{\parallel} \sim$ const. $\sim O(1 \text{ GeV})$, $\hat{s}$ is the quark-quark scattering energy $\hat{s} \approx s/9$, $\Delta_{\parallel}$ is the average longitudinal component of Δ_{μ} in the q–q cms[1]. The process is semi-hard in the sense introduced before, with $s_0 \sim \Delta_{\parallel}^2$. The quark fragmentation can be calculated in perturbative QCD (but not the q–q interaction).

5. With a possibility that fragmentation of highly virtual quarks is relevant for the low $p_{\perp}$ hadron production it is interesting to consider a generalized idea of universality between hadronic collisions and e.g. e^+e^- annihilation into hadrons [2]: multihadronic final states (in inclusive sense) in different reactions should be similar when they originate from fragmentation of virtual partons with similar average q^2. Therefore, in view of relations (1) and (1′) we expect a non-linear scaling law $Q^2 \to As^{(1-a)}$ for comparing e.g. $e^+e^- \to$ hadrons and pp non-diffractive data. Preliminary analysis along those lines [5] is encouraging and can explain several features of the hadron production at the $p\bar{p}$ collider and in particular their energy dependence.

Semi-hard processes may provide a new insight into the low $p_{\perp}$ hadron production and are certainly worth further theoretical and phenomenological investigation. At very high energies they may be main source of the secondary hadrons. Of special interest may be their role in heavy flavour production.

We are grateful to K. Böckmann for several stimulating discussions.

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[1] The absence of the destructive interference between the space-like and time-like gluon radiation is crucial for this result [6] and it does not break the gauge invariance as long as the quark fragmentation is calculated in the leading order.