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GLUON FRAGMENTATION FUNCTIONS FROM QUARK JETS

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ABSTRACT

The analysis of events with a fixed, different from unity, fraction of energy flowing into a solid angle $\Delta\Omega$ can be used to extract the probability functions related to the scaling violations of deep inelastic scattering. One can obtain from the study of a quark jet, both the gluon and the quark fragmentation functions into hadrons.

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In recent times there has been an increasing interest in the physics of hadronic jets as a testing ground for Quantum Chromodynamics (QCD)[1]. In this note we propose a simple test, accessible to the present generation of accelerators, using a total energy calorimeter[2),3)]. We discuss the case of e^+e^- annihilation; the extension to other reactions as wide angle hadron-hadron collisions will be briefly discussed at the end.

Let us consider a one-arm experiment using a total energy calorimeter with a solid angle acceptance $\Delta\Omega$ around an arbitrary, but fixed, direction θ in the laboratory. In the naïve parton model picture of e^+e^- annihilation into hadrons, the energy E_c which flows in the detector is either the entire electron energy E or zero, up to corrections of order $\langle p_T^2\rangle/E^2\Delta\Omega$, with p_T an average fixed transverse momentum originating in the hadronization of initial quarks. One can write for the differential cross-section

$$\frac{d\sigma}{dx} = \sigma_0 * \delta(1-x) + \mathcal{O}\left[\frac{\langle p_\perp^2\rangle}{E^2\Delta\Omega}\right] \tag{1}$$

where

$$x \equiv \frac{E_c}{E} \quad \text{and} \quad \sigma_0 \equiv \left(\frac{d\sigma}{d\Omega}\right)_0 d\Omega = \frac{\alpha_e^2}{16E^2}(1+\cos^2\theta)\Delta\Omega\sum_{\text{flavours}} 3Q_f^2$$

is the cross-section for $e^+e^- \to q\bar{q}$ in the Born approximation.

In QCD the above result is changed by the possibility for the initial quark of radiating gluons: at the lowest non-trivial order one obtains, for $x \neq 1$,

$$\frac{d\sigma}{dx} = \sigma_0 * \frac{4}{3}\,\frac{\alpha_s(Q^2)}{2\pi}\left|\ln\left(\frac{\Delta\Omega}{2\pi}\right)\right|\left[P_{qq}(x) + P_{gq}(x)\right]$$

where[4]

$$P_{qq}(x) = \frac{1+x^2}{1-x} \tag{2}$$

and

$$P_{gq}(x) = \frac{1+(1-x)^2}{x} \quad ; \quad Q^2 \equiv 4E^2$$

At $x \sim 1$ the above formula is no longer valid: in this region one has to include virtual corrections in order to make the energy integrated cross-section finite[1),3)].

The interpretation of Eq. (2) is the following. At order α_s the $q-\bar{q}$ final state produced by the photon is modified by the fragmentation of the quark in a quark-gluon system. If one and only one of the two decay partons hits the calorimeter, we detect only a fraction of the total energy: P_{qq} represents the probability that the quark and not the gluon hits the apparatus and P_{gq} corresponds to the other possibility. The quantity we calculated is infra-red finite and we can invoke its validity in asymptotic QCD perturbation theory within an assigned range of Q^2 and $\Delta\Omega$ values. In Eq. (2), these values have to be chosen so that

$$\frac{\alpha_s(Q^2)}{\pi} \left| \ln\left(\frac{\Delta\Omega}{2\pi}\right)\right| \gg \frac{\alpha_s(Q^2)}{\pi}$$

having neglected corrections of order $\alpha(Q^2)/\pi$ not enhanced by $\ln \Delta\Omega$. They depend on the geometrical shape of the detector and for a given experimental apparatus they can be taken into account. Corrections of order $\alpha_s^2 \ln^2(\Delta\Omega/2\pi)$ can be computed using the methods of Refs. 5) and 6). However, they are only relevant to the investigation of the transverse momentum structure of a QCD jet: for the purposes of this note it is convenient to take a not too small $\Delta\Omega$, in order to make

$$\frac{\alpha_s(Q^2)}{\pi} \left| \ln\left(\frac{\Delta\Omega}{2\pi}\right)\right| \ll 1$$

and to neglect higher order terms. A reasonable value is, for example, 0.2 - 0.1 st *).

In Fig. 1 we plot the two different probability functions and their sum. We note that they are separately dominating in different regions of x. Low x ($x \leq 0.4$) and high x ($x \geq 0.6$) events originate mainly from gluons and quarks, respectively. It should be clear that the object that we call quark and gluon will manifest itself as composed of quarks and gluons when probed with a resolution much smaller than $\Delta\Omega$. Indeed, with a very small resolution we see only

*) The neglected terms are important for x too near 1 or 0. However, Eq. (2) is a good description in the region $0.1 \leq x \leq 0.9$.

single hadrons (neither quarks nor gluons). The effect we proposed to measure is an indirect test of the anomalous dimensions relevant for scaling violations in deep inelastic scattering[4).

Following the same line, we can use the same experiment to find the fragmentation functions of partons (both gluons and quarks) into a given hadron. Inside our calorimeter which measures the fraction of energy $x = E_c/E$ we can study the energy distribution (E^h) of a given type of hadron as a combined function of x and $z \equiv E_h/E_c$ $(z \leq 1)$. We are led to the following cross-section

$$\frac{d\sigma}{dx\,dz} = \sigma_0 \times \frac{4}{3}\,\frac{\alpha_s(Q^2)}{2\pi}\left|\ln\left(\frac{\Delta\Omega}{2\pi}\right)\right| \times$$

$$\times \left\{ D_g^h\left(z, Q^2\frac{\Delta\Omega}{2\pi}\right) P_{gq}(x) + D_q^h\left(z, Q^2\frac{\Delta\Omega}{2\pi}\right) P_{qq}(x) \right\}$$

D_g^h and D_q^h are respectively the gluon and quark fragmentation functions into a hadron measured at an <u>effective</u> $Q^2_{eff} \equiv Q^2\Delta\Omega/2\pi$; they show a slow dependence on $Q^2\Delta\Omega/2\pi$ corresponding to scaling violations[7). It is easy to extract gluon and quark fragmentation functions from experimental data measuring the proposed cross-section. In particular, two different regimes are expected at $x \geq 0.6$ and $x \leq 0.4$.

If one locks inside what in the naïve parton model should be a single quark jet one can conclude that if $\Delta\Omega \sim 1$ the cross-section is concentrated at $x = 1$ and one measures, by definition, the fragmentation function of a quark at Q^2. If $\Delta\Omega$ is smaller, the events at $x \neq 1$ increase: they can be described as a well-defined superposition of quark and gluon fragmentation functions seen at a lower effective Q^2 $(Q^2_{eff} = Q^2\Delta\Omega/2\pi)$.

The mechanism we have described can be observed in other reactions. For example, in the decay of massive states into two gluons we can measure also P_{qg} and P_{gg} which are connected to the anomalous dimensions of singlet operators in deep inelastic scattering. Moreover, the gluon fragmentation functions into hadrons can be used to compute the hadron distributions in the decay of massive states into three gluons. A similar analysis can be developed in $pp(p\bar{p})$ scattering at large transverse momenta. One has to compute in this case the differential cross-section at lowest order in the QCD improved parton model of the energy deposed in a calorimeter at 90° with acceptance $\Delta\Omega$ in the lab.c.m. frame.

We expect that, for not too small values of the ratio of detected energy over incoming proton energy, the background made of many slow particles produced at 90° by a "soft", perturbatively unaccessible collision, should be exponentially damped with respect to the hard production mechanism. The proposed measurement would be free from experimental bias coming from a large p_T trigger, present in the standard tests based on p_T distributions. Besides, the prediction won't need the knowledge of parton fragmentation functions into hadrons. The extraction of distinct parton fragmentation functions in this case would be difficult because, in general, the jet at large angle is a superposition of quarks and gluon jets: at low p_T, where the gluon scattering seems to dominate, it might be feasible.

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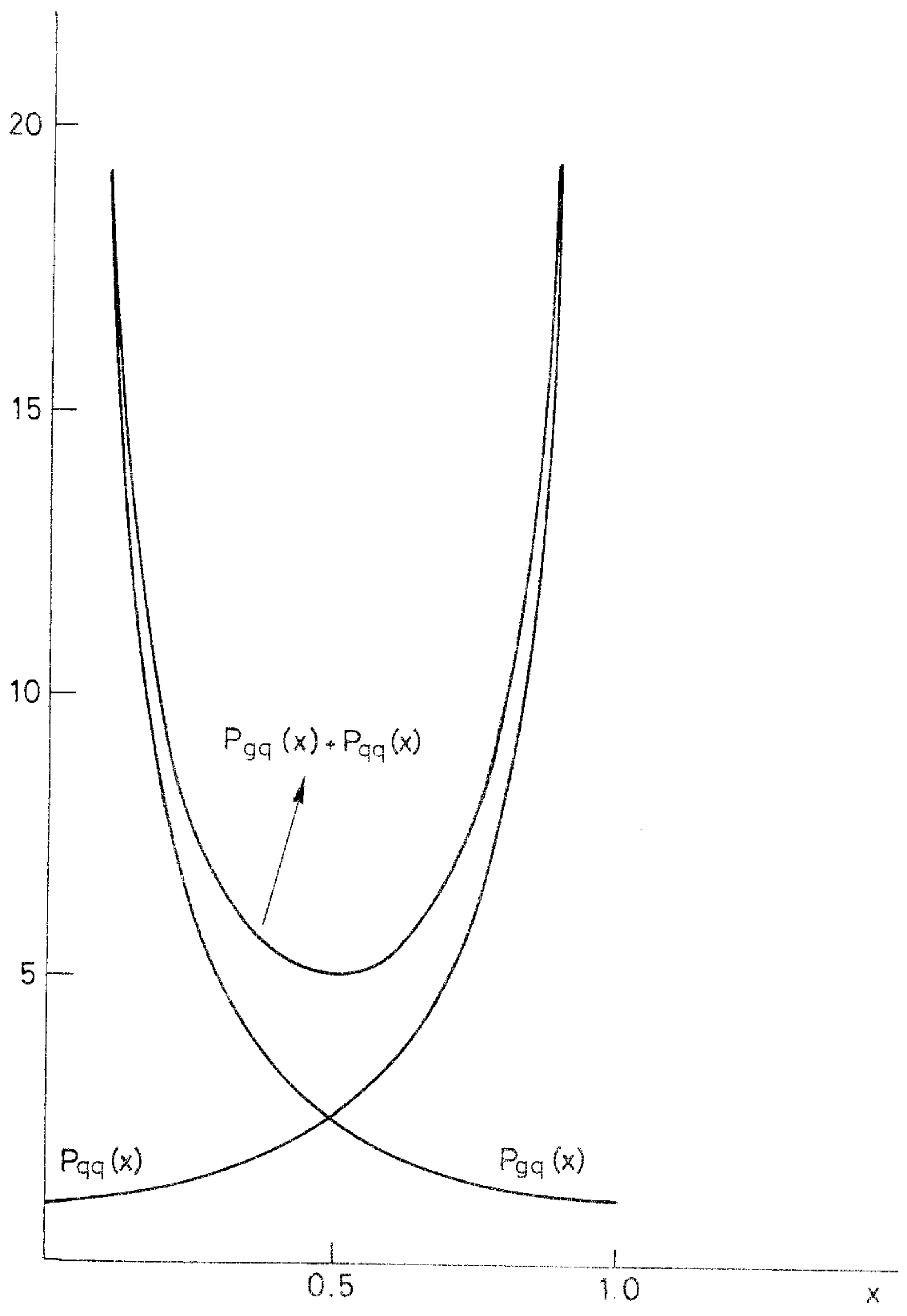
FIGURE CAPTION

$P_{qq}(x)$, $P_{gq}(x)$ and their sum.



20
15
10
5
$P_{gq}(x) + P_{qq}(x)$
$P_{qq}(x)$
$P_{gq}(x)$
0.5
1.0
x