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JETS IN PHOTON COLLISIONS AND TESTS FOR A POINTLIKE COUPLING OF THE PHOTON*

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ABSTRACT

The pointlike coupling of the photon to the quark current yields simple predictions for the leading fast mesons in high p_t $\gamma N(\ell N), e^+e^-$, and $\gamma\gamma$ reactions, e.g., for $\gamma p \rightarrow hX$ we have $K^+:K^-:K^o:\bar{K}^o = 8:0:1:0$ and $\pi^+:\pi^-:\pi^o = 8:1:9/2$. It is noted that in γN collisions the dominant jet cross section arises from the hard subprocess: $\gamma + \text{gluon} \rightarrow q + \bar{q}$. This may yield the gluon distribution via: $s\, s_o (d\sigma/ds_o) K^{-1} = f_g(x)$ and lead to a sum rule: $\int s_o^2 (d\sigma/ds_o) ds_o/sK = \int x\, f_g(x)\, dx$, where $K = 4\pi\alpha\alpha_s \ln(s/2p_{t\,min}^2)$.

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In the context of the currently popular theory of strong interactions, i.e., Quantum Chromodynamics (QCD), the photon occupies a very special role[1] because it couples to quarks in a pointlike manner as dictated by QED. However, it is also an experimentally proven fact that for on shell processes the photon possesses an important "hadronic" or vector meson dominated (VMD) component[2] which e.g. can account for an overwhelming fraction of the total photon-nucleon cross section.[3] The VMD model ideas are generally believed to be useful only for low momentum transfer reactions. The high momentum transfer phenomena are likely to be sensitive to the photon's pointlike coupling to the quark current.[1,4]

In this paper we suggest that an experimental study of photon induced jets[4] and high p_t hadron production may be a valuable probe for detecting the presence of the pointlike component of the photon and for gaining a better understanding of the transition from the region of applicability of VMD to the pointlike coupling.[5] The interaction of the photon field to the quark current in proportion to their electric charge leads to simple predictions for ratios of mesons that are produced with a large p_t and carry a large fraction of the primary quark's energy. In addition, such reactions may elucidate the dynamics of the evolution of quark and gluon jets to hadrons and may yield quite directly the distribution function of the gluons in the nucleon.

Consider the photoproduction of hadrons at high transverse momentum. In lowest order of perturbative QCD these arise through two hard subprocesses: Photon-gluon fusion (Fig. 1a):

$$\gamma + g \rightarrow q + \bar{q} \tag{1}$$

and photon-induced Compton emission of gluons (Fig. 1b):

$$\gamma + q \rightarrow q + g \tag{2}$$

Using the quark-gluon coupling:

$$\alpha_s(Q^2) = 12\pi/(33-2n_f)\ln Q^2/\Lambda^2 \tag{3}$$

we can compute the jet cross section for (1) and (2). The results are shown in Fig. 2. We have taken $\Lambda = 0.5\text{GeV.}$, $m_{\text{quark}} = 0.3$ GeV, and set $Q^2 = 4p_t^2$ (p_t is the transverse momentum of <u>each</u> jet with respect to the collision axis) and $n_f = 3$. In addition we have imposed $p_t \geq p_{t\ \min} = 1.0$ GeV so as to confine ourselves to the region where both the pointlike coupling of the photon may dominate and also the lowest order QCD calculations should be applicable.[4] The gluon distribution function $f_g(x)$ in the nucleon was assumed to have the forms $(1-x)^5/x$ and $(1-x)^9/x$ each subject to the constraint:

$$\int x f_g(x)dx = f_{\ell N} \tag{4}$$

where $f_{\ell N}(\approx\frac{1}{2})$ is the fraction of momentum that is carried by the gluons.

The total cross section (see Fig. 2) for photoproducing jets via the above two subprocesses is in the range of 1 to 8 μb for $s \geqslant 50\ \mathrm{GeV}^2$ and amounts to a few percent of the total photon nucleon cross section. Experimentally these photon induced jets can be searched for by triggering on pairs of particles each with a large p_t (say $\geqslant 1.0$ GeV) on either side of the collision axis in the lab frame. On transformation to the c.m. frame of the photon and the nucleon these events are likely to exhibit a three jet structure with one jet along the collision axis and two at a high p_t on either side of that axis. The axes of the jets can be searched for by e.g. Bjorken and Brodsky's technique of minimizing the transverse momentum of the hadrons in each of the jets.[6]

From Fig. 2 we notice that the cross section for the pair creation reaction (1) dominates over the Compton reaction (2) for $s \geqslant 300\ \mathrm{GeV}^2$. To reduce the contribution of (2) even further, consider only the subset of the high p_t jet events obtained above in which the leading particles defining the two jet axes contain a quark (q) and an antiquark ($\bar{q}$) each e.g., $\pi^+\pi^-$, $\pi^\pm\pi^0$, $\pi^\pm K^\mp$, and K^+K^-, etc. but not say π^+K^+, $\pi^+\pi^+$, etc. The contribution of the Compton reaction (2) to this sample of events will now be very small ($\leqslant 5\%$) since the outgoing gluon in (2) is flavor independent and does not favor a leading meson of one charge (or flavor) over another.

One can show that in the leading log approximation for reaction (1):

$$K^{-1} s\, s_o\, d\sigma/ds_o \approx f_g(x) \qquad (5)$$

where K equals $4\pi\alpha\,\alpha_s \ln(s/2p_{t\,\min}^2)$. Thus the invariant mass (s_o) distribution of the two high p_t jets can lead to a direct determination of the distribution of the gluons in the nucleon.

In this simple model s_o being equal to xs one can actually obtain a sum rule:

$$\int s_o^2(d\sigma/ds_o)ds_o/sK = \int x\, f_g(x)dx = f_{\gamma N} \quad . \qquad (6)$$

It would be interesting to determine $f_{\gamma N}$ experimentally and to compare it with the corresponding number ($f_{\ell N}$ Eq. (4)) deduced from deep inelastic experiments.

The expressions obtained above are almost the simplest that relate (albeit approximately) the gluon distribution in the nucleon to directly measurable quantities. Note that in this analysis we have ignored any "primordial" transverse momentum (p_{tO}) that the gluons possess. One expects p_{tO} to be a few hundred MeV's and so its effects on the high p_t ($\geqslant$ 1 GeV) phenomena should be small. However, once p_{tO} is set to zero, the dominant pair creation graph implies that the magnitude of the transverse momentum of the two jets are equal. Hence the deviation from that equality will be a reflection of the p_{tO} of the gluons. The experiments suggested here may therefore lead to some handle on determining the "primordial" p_t of the gluons.

The jet physics we have in mind can be implemented both with wide band and with tagged photons. However, for the latter the energy momentum conservation constraints can provide powerful self-consistency checks that should help the jet analysis considerably. Thus, while the jet study in γN reaction is not expected to be easy we have every reason to believe that it can be implemented, that it can be very informative and that it can complement similar studies in other reactions.

An important class of experimental tests for the presence of the pointlike component of the photon to the quark current results from a determination of the ratios of the leading mesons, that is, those mesons that contain the primary quark. To avoid complications from decays of heavy flavors (say charm to strange) or vector mesons to pseudoscalars (e.g. $\rho \to \pi\pi$, $K^* \to K\pi$) out of the entire sample of events with two high p_t jets let us consider those few events in which the leading meson that lies in the forward (defined to be the direction of the photon beam) hemisphere carries a large z, say $z \geq 0.7$ where z is the fraction of the momentum of the primary quark that that meson has.

Now in the region of interest (large z, large p_t) the contribution of the u channel Compton graph (Fig. 1b) dominates and accounts for over 90% of the total jet cross section, that is, of the sum of reactions (1) and (2).[7] In the c.m. frame the most probable resulting configuration yields the quark jet in the forward hemisphere and the gluon jet recoils in the backward hemisphere.

The fact that the photon couples to the u and d quarks in the ratio of 4:1 leads one to predict the following proportions for these high p_t, high z mesons lying in the <u>forward</u> hemisphere

$$K^+:K^-:K^o:\overline{K^o}:\pi^+:\pi^-:\pi^o = \begin{cases} 8a:o:a:o:8:1:9/2, \text{ for } \gamma p & (7a) \\ 6a:o:3a/2:o:6:3/2:15/2, \text{ for } \gamma N_o & (7b) \end{cases}$$

where N_0 denotes $(p + n)/2$ and where a is the ratio of the probability for a leading kaon to contain a primary u or d quark divided by the probability for a leading pion to contain a primary u or d quark.[8] Thus the positive mesons are expected to dominate over the negative ones, e.g., for γp, $\pi^+/\pi^- = 8$, $K^-/K^+ = 0$, etc. In contrast, if the photon interactions were purely hadronic then barring some special interferences between the vector meson dominated amplitudes any differences in the charge ratios of leading mesons are expected to be rather subtle.[9]

From (7) note also that the measurement of the leading charged K's and π's yields an experimental determination of the parameter a. This should be important both for phenomenological applications and for understanding the dynamics of QCD jets. Furthermore it is interesting to note that recoiling against these high p_t, high z mesons in the forward hemisphere are the gluon jets in the backward hemisphere. Thus not only do these rare events represent important tests for the interaction of photons, they can also lead to a study of the dynamics of quark and gluon jets.

The gluon jets in the backward hemisphere (from Fig. 1b) will yield mesons with large z in the following ratio:

$$K^+:K^-:K^0:\overline{K^0}:\pi^+:\pi^-:\pi^0 = b:b:b:b:1:1:1 \qquad (8)$$

where b is the ratio of the probability for a gluon jet to yield a large z kaon divided by the probability for a gluon jet to yield a large z pion. Using (7) and (8) we can determine the joint probabilities for photoproducing two leading mesons <u>both</u> at high p_t and <u>both</u> with large z. The expected proportion for these two particle correlations are shown in the Table.

Much of our discussion, and especially the particle ratios equations 7 and 8, are applicable to jets in ℓN collision as well. For the case of e^+e^- the leading h's in $e^+ + e^- \rightarrow h + X$ must satisfy:

$$K^{\pm}:K^{o}(\overline{K^{o}}):\pi^{\pm}:\pi^{o} = (1+4a):(1+a):5:5 \qquad (9)$$

The corresponding two particle correlation for $e^+ + e^- \rightarrow h_1 + h_2 + X$ are given in the Table.[10]

Now let us consider high p_t hadron production in two photon processes.[1] In this case the contribution of the quark jets to the final state leads to even stronger correlations because the subprocess $\gamma + \gamma \rightarrow q + \bar{q}$ varies as (quark charge)^4. The dominant contribution to hadron production proceeds via photons that are almost real so that once again we would be testing for the presence of the non-hadronic pointlike coupling of photons that are essentially on shell.

Consider first single particle inclusive reaction: $\gamma + \gamma \rightarrow h + X$. Then (the high p_t, high z) h must satisfy the following ratio:

$$K^{\pm}:K^{o}(\overline{K^{o}}):\pi^{\pm}:\pi^{o} = (1+16a):(1+a):17:17 \quad . \qquad (10)$$

Thus once again from ratios of K/π one could determine a. Similarly we can also consider the two particle inclusive reaction: $\gamma + \gamma \rightarrow h_1 + h_2 + X$. The resulting probabilities for these are given in the Table. Since the primary quark and anti-quark must yield the leading mesons, each with a large z, the same sign charge correlations e.g., $K^+K^+, K^+\pi^+, \pi^+\pi^+$ all vanish. If the photon interactions were purely hadronic (e.g., ρ-ρ scattering) in nature then the hard subprocesses involving quarks and gluons are charge independent so that the difference in the same sign to different sign two particle correlations would be expected to be small. In the region where the photons interact hadronically we should therefore find $\pi^+\pi^+$(or $\pi^-\pi^-$)/$\pi^+\pi^-$ = 1. On the other hand when the photons interact in a pointlike manner this ratio should approach zero. The experimental determination of such a ratio as a function of p_t should therefore help us sharpen our understanding of the regions where VMD holds and where the pointlike nature of the photon, so vital to some critical tests of QCD,[1] is applicable.

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Figure Captions

Fig. 1. Dominant hard subprocesses for photoproducing jets.

(a) Pair creation reaction (1): $\gamma + g \rightarrow q + \bar{q}$;

(b) Compton reaction (2): $\gamma + q \rightarrow q + g$. (g = gluon).

Fig. 2 Solid and dashed curves are for pair creation of quark antiquark jets via (1) with gluon distribution $(1-x)^5/x$ and $(1-x)^9/x$ respectively. Long and short dashed curves are for the Compton production of quark and gluon jets via (2).

Table: Relative proportions of pairs of high p_t, high z leading mesons in γN, $\gamma\gamma$ and e^+e^- collisions resulting from a pointlike coupling of the photon. a, b are defined in text.

Leading Mesons	γp	γN_0 $N_0 = (p+n)/2$	$\gamma\gamma$	e^+e^-
K^+K^+	16ab	12ab	0	0
K^+K^0	18ab	15ab	0	0
$K^+\bar{K}^0$	16ab	12ab	1	1
K^+K^-	16ab	12ab	$1+16a^2$	$1+4a^2$
$K^0 K^0$	2ab	3ab	0	0
$K^0 \bar{K}^0$	2ab	3ab	$1+a^2$	$1+a^2$
$K^+\pi^+$	16(a+b)	12(a+b)	0	0
$K^+\pi^-$	16a+2b	12a+3b	16a	4a
$K^+\pi^0$	16a+9b	12a+(15b/2)	8a	2a
$K^0 \pi^+$	2a+16b	3a+12b	a	a
$K^0 \pi^-$	2(a+b)	3(a+b)	0	0
$K^0 \pi^0$	2a+9b	3a+(15b/2)	a/2	a/2
$\pi^+\pi^+$	16	12	0	0
$\pi^+\pi^-$	18	15	17	5
$\pi^+\pi^0$	25	39/2	17/2	5/2
$\pi^0 \pi^0$	9	15/2	17/4	5/4
$\pi^-\pi^-$	2	3	0	0
$\pi^-\pi^0$	11	21/2	17/2	5/2

References and Footnotes

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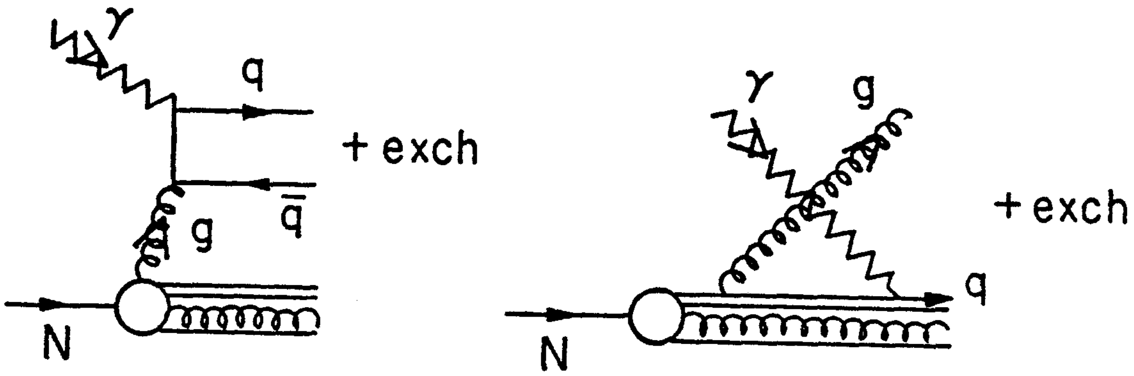
9. This can easily be seen to be the case for an isoscalar target. Compare that with (7b).
10. For a somewhat similar analysis for e^+e^- see: J. Bechteler and L. Stodolsky, preprint MPI-PAR/P Th 9/79; S. J. Brodsky and N. Weiss, Phys. Rev. D16, 2325 (1977).



(a)

(b)

Fig. 1

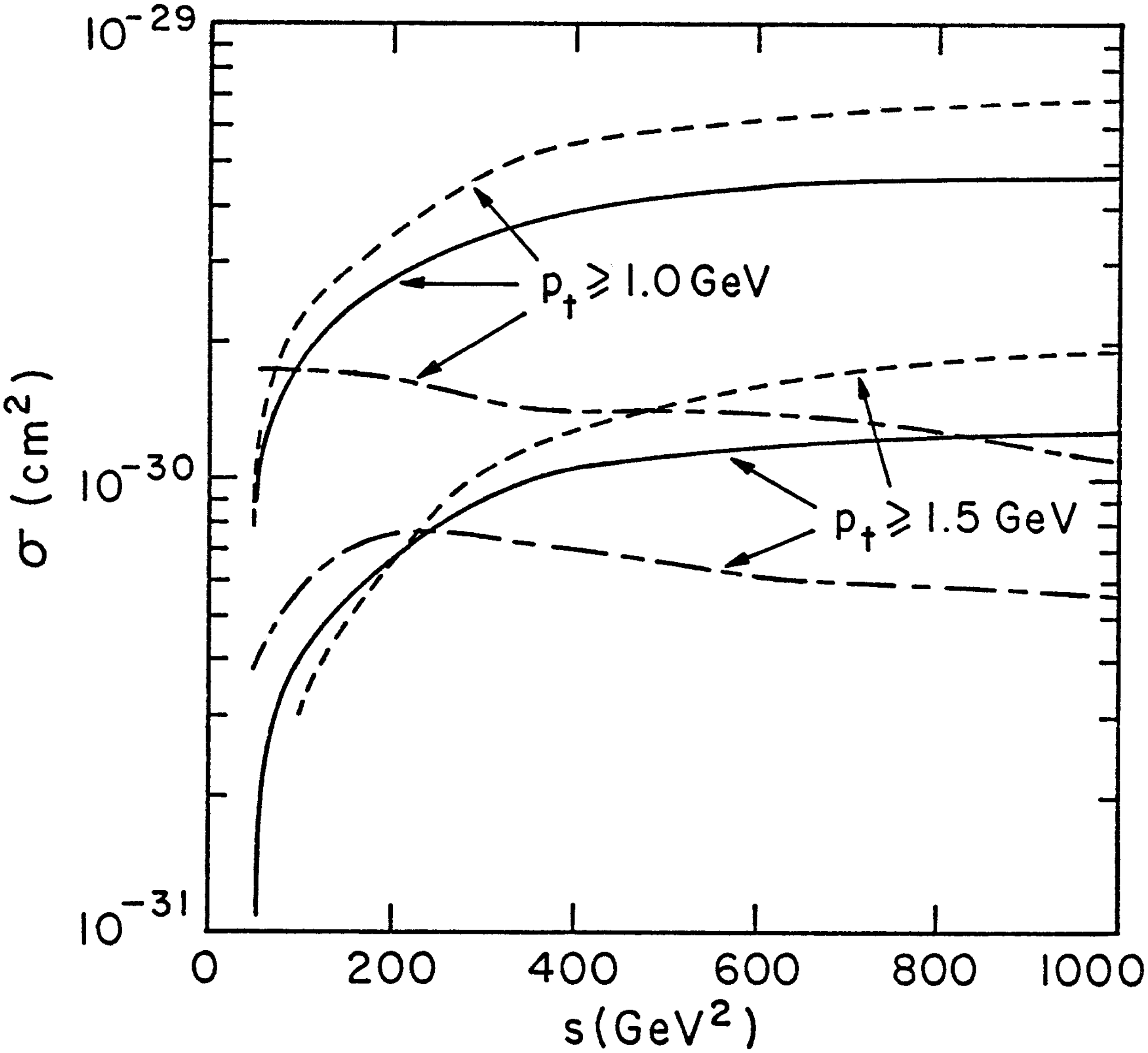

10^{-29}
10^{-30}
10^{-31}
σ (cm^2)
0
200
400
600
800
1000
s(GeV^2)
$p_t \geqslant 1.0$ GeV
$p_t \geqslant 1.5$ GeV

Fig. 2