High-Twist Correction for Inclusive Hadron Production in Photon–Photon Collisions

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Received 8 January 1986

Abstract. The contribution of the QCD high-twist subprocess $\gamma q \rightarrow \gamma q'$ to the inclusive cross section for $e^+e^- \rightarrow e^+e^- + \pi^+ + X$ is calculated both in the PETRA/PEP and the LEP energy range, in the equivalent-photon approximation. Superposed on the Born cross section and its $O(\alpha_s)$ correction, it gives agreement with the data at relatively low transverse momenta. It is suggested that this high-twist contribution may be further isolated experimentally by triggering simultaneously on both a fast hadron and the opposite-side jet.

1. Introduction

Since the time that hadron production in photon–photon collisions was introduced in the context of the parton model through the subprocess \[ (1) \]
\[ \gamma + \gamma \rightarrow q + \bar{q}, \]
the field has been developed into an important laboratory for testing several aspects [2, 3] of quantum chromodynamics (QCD).

At relatively low transverse momenta $p_T$, the inclusive hadron-production cross section for \[ (2) \]
\[ \gamma + \gamma \rightarrow h^2 + X \]
receives important contributions due to the hadronic component of the photon, as predicted by the Vector-Dominance Model (VDM), where the two-photon process is described in terms of the scattering of two vector mesons. After the subtraction of these VDM contributions from recent data [4] on the cross-section (2), obtained by almost on-shell photons, the remaining “hard” cross section still exceeds substantially [4], by a factor of 3, or 4, the Born contribution arising from (1) with subsequent quark fragmentation.

The full $O(\alpha_s)$ correction to (2), in contrast to other processes, has been found to be rather small [5, 6] and cannot enhance the Born contribution sufficiently in order to bring it to agreement with the data. This correction includes excitation of the structure of one of the photons, through the subprocess $\gamma q \rightarrow q q'$, this involves infrared singularities, which are cancelled by the corresponding virtual graphs. It is interesting to notice that the smallness of the contribution of $\gamma q \rightarrow q q'$ to the inclusive hadron cross section in $\gamma \gamma$ collisions is consistent with the early findings of [7].

Further, regarding the $O(\alpha_s^2)$ correction, at least the subprocesses $q q \rightarrow q q$, involving excitation of the structure of both of the photons, have been found [7] to give unimportant contributions to (2). However, a full $O(\alpha_s^2)$ calculation within perturbative QCD has of course to include all the corresponding virtual graphs.

In this work it is shown that a particular high-twist (HT) QCD contribution to (2), described in terms of the “subprocess” \[ (3) \]
\[ \gamma + q \rightarrow \pi + q', \]
where $q$ is due to the photon structure, becomes very important at relatively low $p_T$ in the PETRA/PEP, as well as in the LEP energy range. This is in accord with the analysis of [7], where the contribution of (3) is estimated in the spirit of the constituent-interchange model. It is demonstrated that the sum of the contributions of (3) and of the Born term (1), enhanced by its $O(\alpha_s)$ correction, is consistent with the large magnitude, as well as with the fast $p_T$ dependence of the recent PETRA data [4].

Notice that the subprocess (3) leads to a final state involving an isolated pion and an opposite-side hadron jet: It is then suggested that measuring the doubly-inclusive cross section \[ (4) \]
\[ \gamma + \gamma \rightarrow \text{hadron} + \text{jet} + X \]
can further clarify the role of the HT amplitude discussed here, relative to the Born amplitude.

The same HT amplitude is also present in the photoproduction process $\gamma + p \rightarrow h^2 + X$: However, the expected correction, relative to the Born term, is
substantially smaller than in process (2), since (i) in the latter process the structure of both photons can be excited to give an initial-state quark, (ii) this structure involves a QCD enhancement (a K-factor), relative to the $O(x^2)\,\gamma\gamma$ Born term, and (iii) the $\gamma p$ Born terms involve fragmentation of quarks as well as gluons. Indeed, with the estimated VDM background removed, recent pion photoproduction data [9] are in agreement with leading-twist QCD calculations [10] for $p_T \gtrsim 1.6$ GeV.

Section II deals with one-hadron inclusive production: most details of the formalism are given with reference to the Born cross section; we then present our results on the HT correction and compare with existing data. In Sect. III we turn to doubly-inclusive hadron and jet production: we present detailed cross sections and particular cross-section ratios, which provide better experimental tests, being insensitive to the underlying ambiguities of the calculation. Finally, Sect. IV summarizes our main conclusions.

II. Inclusive Hadron Production

Born Cross Section. Basic Formulas

In the equivalent-photon approximation the contribution of the Born graphs, given in Fig. 1a, to the inclusive cross section for producing a pion with pseudorapidity $\eta$ is

$$
\frac{d\sigma^B}{d\eta d^2 p_T} = \sum_q \int_{x_1}^{x_2} \frac{d^2 x}{x_a x_b} G_{\gamma p}(x_a) G_{\eta p}(x_b) \int_{x_1}^{x_2} \frac{d^2 x}{x_2 x_b} G_{\gamma p}(x_b)
$$

where the integration limits are

$$
x_2 = x_a x_T e^{-\eta}/(2x_a - x_T e^{-\eta}),
$$

$$
x_1(\eta) = x_T e^{\eta}/(2 - x_T e^{-\eta}).
$$

The elementary Born cross section arising from the graphs of Fig. 1a has the well-known form

$$
d\sigma^B = 2\pi^2 q^2 \frac{1}{s^2 + t^2 + u^2} d\eta d^2 p_T,
$$

and the subprocess Mandelstam invariants are given by

$$
s = x_a x_b s,
$$

$$
t = -s x_a x_T e^{-\eta}/z,
$$

$$
u = -s x_a x_T e^{\eta}/z = -s + t.
$$

The momentum fraction of the emerging pion is expressed as

$$
z = \frac{1}{2} x_T (e^\eta/x_a + e^{-\eta}/x_b)
$$

and the subprocess Mandelstam invariants are given by

$$
\hat{s} = x_a x_b s,
$$

$$
\hat{t} = -s x_a x_T e^{-\eta}/2z,
$$

$$
\hat{u} = -s x_a x_T e^{\eta}/2z = -\hat{s} - \hat{t}.
$$

The elementary Born cross section arising from the graphs of Fig. 1a has the well-known form

$$
\frac{d\sigma^B}{d\eta d^2 p_T} = 2\pi^2 q^2 \frac{1}{s^2 + t^2 + u^2} d\eta d^2 p_T,
$$

where $e_q$ is the charge of quark $q$.

In the leading-logarithmic approximation the equivalent-photon spectrum is given by

$$
G_{\gamma p}(x) = \frac{x}{2\pi} \left[ 1 + (1 - x)^2 \right] \ln s/4m_e^2,
$$

where $m_e$ is the mass of the electron.

We are using the quark fragmentation functions of [11], namely

$$
D_{\gamma p}(z, Q^2) = x_0 \frac{1 - z}{1 + z} D_{\gamma p}(z, Q^2) = \frac{1 - z}{2z} D_{\gamma p}(z, Q^2),
$$

where

$$
D(z, Q_0^2) = 0.5(1 - z), \quad Q_0 = 5 \text{ GeV}.
$$

The exponent in (11b) is in accord with counting rules and the normalization in agreement with $e^+e^-$ data [12]. The $Q^2$-dependence is determined from the well-known QCD moment equations. Neglecting the fragmentation of strange quarks into pions, the sum in (5) involves a term

$$
(e_4^s + e_4^d) \frac{1}{z^2} D(z, Q^2), \quad (e_4^s + e_4^d = 17/81).
$$

The choice of the factorization scale, $Q^2$, involves some uncertainty in all calculations of this kind. In this work three popular choices have been considered, namely

$$
Q^2 = 2s\hat{t}u/\left(\hat{s}^2 + \hat{t}^2 + \hat{u}^2\right),
$$

$$
Q^2 = 2p_T^2,
$$

$$
Q^2 = s/\xi.
$$

Provided we stay within the kinematic pseudorapidity limits, namely

$$
\ln \left[ \frac{1}{x_T} - \left(\frac{1}{x_T^2} - 1\right)^{1/2} \right] < \eta < \ln \left[ \frac{1}{x_T} + \left(\frac{1}{x_T^2} - 1\right)^{1/2} \right],
$$

the cross section (5) may be integrated within a fixed acceptance range $\eta_1 \leq \eta \leq \eta_2$ of a particular experi-