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T-odd effects in photon-jet production at the Tevatron

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Abstract

The angular distribution in photon-jet production in $p\bar{p} \to \gamma\,\mathrm{jet}\,X$ is studied within a generalized factorization scheme taking into account the transverse momentum of the partons in the initial hadrons. Within this scheme an anomalously large $\cos 2\phi$ asymmetry observed in the Drell–Yan process could be attributed to the T-odd, spin and transverse momentum dependent parton distribution function $h_1^{\perp q}(x, \boldsymbol{p}_\perp^2)$. This same function is expected to produce a $\cos 2\phi$ asymmetry in the photon-jet production cross section. We give the expression for this particular azimuthal asymmetry, which is estimated to be smaller than the Drell–Yan asymmetry but still of considerable size for Tevatron kinematics. This offers a new possibility to study T-odd effects at the Tevatron.

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1. Introduction

It is well known that the angular distribution of Drell–Yan lepton pairs displays an anomalously large $\cos 2\phi$ asymmetry. This was experimentally investigated using π^- beams scattering off deuterium and tungsten targets at center of mass energies of order 20 GeV [1–3]. A next-to-leading order (NLO) analysis in perturbative QCD (pQCD) within the standard framework of collinear factorization failed to describe the data [4]. More specifically, the observed violation of the so-called Lam–Tung relation [5–7], a relation between two angular asymmetry terms, could not be described. The NLO pQCD result is an order of magnitude too small and of opposite sign. This has prompted much theoretical work [4,8–16], offering explanations that go beyond the framework of collinear factorization and/or leading twist perturbative QCD.

More recently, pd Drell–Yan scattering was studied in a fixed target experiment ($\sqrt{s} \approx 40$ GeV) at Fermilab [17]. The angular distribution does not display a large $\cos 2\phi$ asymmetry, indicating that the effect that causes the large asymmetry in $\pi^- N$ scattering is probably small for nonvalence partons. For this reason one would like to investigate $p\bar{p}$ scattering, which is expected to be similar to the $\pi^- N$ case (an expectation supported by model calculations [10,14,18]). It is an experiment that could be done at the planned GSI-FAIR facility. It can in principle also be done at Fermilab, although the energy of the collisions is so much higher ($\sqrt{s} = 1.96$ TeV) that the Drell–Yan asymmetry may be quite different in magnitude, possibly much smaller at very high invariant mass Q of the lepton pair. Nevertheless, it would be interesting to see if NLO pQCD expectations hold at those energies. Recently, such a study of the angular distribution was done for W-boson production at the Tevatron and a nonzero result compatible with NLO pQCD [19,20] was obtained [21]. This may likely be due to the fact that chirality flip effects, such as the T-odd effect to be discussed here, do not contribute to the $\cos 2\phi$ angular distribution [22,23]. For neutral boson production they do contribute however and therefore could lead to quite a different result. This remains to be investigated.

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In this Letter we consider an asymmetry in the process $p\bar{p} \to \gamma\,\text{jet}\,X$ that potentially probes the same underlying mechanism and could have certain advantages over Drell–Yan. This photon-jet production process has already been studied experimentally in the angular integrated case at the Tevatron [24]. Here we will calculate the angular dependence within the framework as employed in Ref. [16], where transverse momentum and spin dependence of partons inside hadrons is included.[1] In that case a nontrivial polarization-dependent quark distribution (denoted by $h_1^{\perp q}$) appears, which offers an explanation for the anomalous angular asymmetry in the Drell–Yan process. The new asymmetry is proportional to the analyzing power of the Drell–Yan $\cos 2\phi$ asymmetry at the scale set by the transverse momentum of the photon or the jet. The latter asymmetry is expected to decrease with increasing scale [26], but as we will demonstrate the proportionality factor increases, leading one to expect a significant asymmetry also at higher energies.

In Section 2 we discuss the theoretical framework and the expected contributions to the new asymmetry. In Section 3 we study the phenomenology of this asymmetry, using typical Tevatron kinematics and cuts. We end with a summary of the results and the required measurement.

2. Theoretical framework: Calculation of the cross section

We consider the process

$$h_1(P_1) + h_2(P_2) \to \gamma(K_\gamma) + \text{jet}(K_j) + X, \tag{1}$$

where the four-momenta of the particles are given within brackets, and the photon-jet pair in the final state is almost back-to-back in the plane perpendicular to the direction of the incoming hadrons. To lowest order in pQCD the reaction is described in terms of the partonic two-to-two subprocesses

$$q(p_1) + \bar{q}(p_2) \to \gamma(K_\gamma) + g(K_j) \quad \text{and} \quad q(p_1) + g(p_2) \to \gamma(K_\gamma) + q(K_j). \tag{2}$$

We make a lightcone decomposition of the hadronic momenta in terms of two light-like Sudakov vectors n_+ and n_-, satisfying $n_+^2 = n_-^2 = 0$ and $n_+ \cdot n_- = 1$:

$$P_1^\mu = P_1^+ n_+^\mu + \frac{M_1^2}{2P_1^+} n_-^\mu \quad \text{and} \quad P_2^\mu = \frac{M_2^2}{2P_2^-} n_+^\mu + P_2^- n_-^\mu. \tag{3}$$

In general n_+ and n_- will define the lightcone components of every vector a as $a^\pm \equiv a \cdot n_\mp$, while perpendicular vectors $a_\perp$ will always refer to the components of a orthogonal to both incoming hadronic momenta, P_1 and P_2. Hence the partonic momenta (p_1, p_2) can be expressed in terms of the lightcone momentum fractions (x_1, x_2) and the intrinsic transverse momenta ($\boldsymbol{p}_{1\perp}$, $\boldsymbol{p}_{2\perp}$), as follows

$$p_1^\mu = x_1 P_1^+ n_+^\mu + \frac{m_1^2 + \boldsymbol{p}_{1\perp}^2}{2x_1 P_1^+} n_-^\mu + p_{1\perp}^\mu \quad \text{and} \quad p_2^\mu = \frac{m_2^2 + \boldsymbol{p}_{2\perp}^2}{2x_2 P_2^-} n_+^\mu + x_2 P_2^- n_-^\mu + p_{2\perp}^\mu. \tag{4}$$

We denote with s the total energy squared in the hadronic center-of-mass (c.m.) frame, $s = (P_1 + P_2)^2 = E_{\text{c.m.}}^2$, and with η_i the pseudo-rapidities of the outgoing particles, i.e., $\eta_i = -\ln(\tan(\frac{1}{2}\theta_i))$, θ_i being the polar angles of the outgoing particles in the same frame. Finally, we introduce the partonic Mandelstam variables

$$\hat{s} = (p_1 + p_2)^2, \qquad \hat{t} = (p_1 - K_\gamma)^2, \qquad \hat{u} = (p_1 - K_j)^2, \tag{5}$$

which satisfy the relations

$$-\frac{\hat{t}}{\hat{s}} \equiv y = \frac{1}{e^{\eta_\gamma - \eta_j} + 1}, \quad \text{and} \quad -\frac{\hat{u}}{\hat{s}} = 1 - y. \tag{6}$$

Following Ref. [27] we assume that at sufficiently high energies the hadronic cross section factorizes in a soft parton correlator for each observed hadron and a hard part:

$$d\sigma^{h_1 h_2 \to \gamma \text{jet} X} = \frac{1}{2s} \frac{d^3 K_\gamma}{(2\pi)^3 2E_\gamma} \frac{d^3 K_j}{(2\pi)^3 2E_j} \int dx_1\, d^2\boldsymbol{p}_{1\perp}\, dx_2\, d^2\boldsymbol{p}_{2\perp}\, (2\pi)^4 \delta^4(p_1 + p_2 - K_\gamma - K_j)$$
$$\times \sum_{a,b,c} \Phi_a(x_1, p_{1\perp}) \otimes \Phi_b(x_2, p_{2\perp}) \otimes \left| H_{ab\to\gamma c}(p_1, p_2, K_\gamma, K_j) \right|^2, \tag{7}$$

[1] Photon-jet angular correlations in pp and $p\bar{p}$ collisions have also recently been studied in Ref. [25] using the k_t-factorization approach applicable at small x, where gluon–gluon scattering dominates.