T-odd Effects in Photon-Jet Production at the Tevatron

C. Pisano, D. Boer and P.J. Mulders

Vrije Universiteit Amsterdam, Department of Physics and Astronomy
NL-1081 HV Amsterdam, the Netherlands

The angular distribution in photon-jet production in $p\bar{p}\rightarrow\gamma$+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 $h_1^{+/-}(x,p_{T}^\perp)$. The same function is expected to produce a $\cos(2\phi)$ asymmetry in the photon-jet production cross section. This particular azimuthal asymmetry is estimated to be smaller than the Drell-Yan asymmetry but still of considerable size for Tevatron kinematics, offering a new possibility to study T-odd effects at the Tevatron.

In this contribution to DIS 2008 we consider the process:

$$h_1(P_1)+h_2(P_2)\rightarrow\gamma(K_\gamma)\rightarrow\gamma(K_\gamma)+\text{jet}(K_j)+X,$$  \hspace{1cm} (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 $q(p_1)+\bar{q}(p_2)\rightarrow\gamma(K_\gamma)+g(K_j)$ and $q(p_1)+g(p_2)\rightarrow\gamma(K_\gamma)+q(K_j)$. Following reference [2], we will instead of collinear factorization consider a generalized factorization scheme taking into account partonic transverse momenta. 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 $n_+\cdot n_- = 1$:

$$P_1^\mu = P_1^+ n_+^\mu + \frac{M_1^2}{2P_1} n_-^\mu, \quad \text{and} \quad P_2^\mu = \frac{M_2^2}{2P_2} n_+^\mu + P_2^- n_-^\mu.$$  \hspace{1cm} (2)

In general $n_+$ and $n_-$ will define the lightcone components of every vector $a$ as $a^\pm = a \cdot n_\mp$, 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 $(p_{1\perp}, p_{2\perp})$, as follows

$$p_1^\mu = x_1 P_1^+ n_+^\mu + \frac{m_1^2 + p_{1\perp}^2}{2x_1 P_1} n_-^\mu + p_{1\perp}^\mu, \quad \text{and} \quad p_2^\mu = \frac{m_2^2 + p_{2\perp}^2}{2x_2 P_2} n_+^\mu + x_2 P_2^- n_-^\mu + p_{2\perp}^\mu.$$  \hspace{1cm} (3)

We denote with $s$ the total energy squared in the hadronic center-of-mass (c.m.) frame, $s = (P_1 + P_2)^2 = E_{c.m.}^2$, and with $\eta_i$ the pseudo-rapidities of the outgoing particles, i.e. $\eta_i = -\ln(\tan(\frac{\theta_i}{2}))$, $\theta_i$ being the polar angles of the outgoing particles in the same frame. Finally, we introduce the partonic Mandelstam variables $\hat{s} = (p_1 + p_2)^2$, $\hat{t} = (p_1 - K_\gamma)^2$ and $\hat{u} = (p_1 - K_j)^2$, which satisfy the relations

$$\frac{-\hat{t}}{\hat{s}} \equiv y = \frac{1}{e^{\eta_+ - \eta_+} + 1}, \quad \text{and} \quad -\frac{\hat{u}}{\hat{s}} = 1 - y.$$  \hspace{1cm} (4)

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Along the lines of [2, 3], 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:

$$d\sigma_{h_1 h_2 \to \gamma \text{jet}X} = \frac{1}{2s} \frac{d^3 K_\gamma}{(2\pi)^3 2E_\gamma} \frac{d^3 K_j}{(2\pi)^3 2E_j} \int dx_1 d^2 p_{1\perp} dx_2 d^2 p_{2\perp} (2\pi)^4 \delta^4(p_1 + p_2 - K_{\gamma} - K_j)$$

$$\times \sum_{a,b,c} \Phi_a(x_1, p_{1\perp}) \otimes \Phi_b(x_2, p_{2\perp}) \otimes |H_{ab \to c}(p_1, p_2, K_{\gamma}, K_j)|^2,$$

(5)

where the sum runs over all the incoming and outgoing partons taking part in the subprocesses $q \bar{q} \to \gamma g$ and $qg \to \gamma q$. The convolutions $\otimes$ indicate the appropriate traces over Dirac indices and $|H|^2$ is the hard partonic squared amplitude, obtained from the cut diagrams in Figs. 1 and 2. The parton correlators $\Phi_a$ describe the hadron $\to$ parton transitions and their parameterization in terms of transverse momentum dependent (TMD) distribution functions can be found, for instance, in [2].

We are interested in events in which the photon and the jet are approximately back-to-back in the transverse plane, therefore we define the vector $q_\perp \equiv K_{\gamma\perp} + K_{j\perp}$ and require that $|q_\perp| \ll |K_{\gamma\perp}|, |K_{j\perp}|$. Neglecting power-suppressed terms of the order $O(1/(K_{\gamma\perp}^4 s))$ and using the approximation $|K_{\gamma\perp}| \approx |K_{j\perp}|$, we obtain

$$\frac{d\sigma_{h_1 h_2 \to \gamma \text{jet}X}}{d\eta_\gamma d\eta_j d^2 K_{\gamma\perp} d^2 q_\perp} = \frac{1}{\pi^2} \frac{d\sigma_{h_1 h_2 \to \gamma \text{jet}X}}{d\eta_\gamma d\eta_j d^2 K_{\gamma\perp} d^2 q_\perp^2} \left( 1 + A(y, x_1, x_2, q_\perp^2) \cos 2(\phi_\perp - \phi_\gamma) \right),$$

(6)

with $\phi_\gamma$ and $\phi_\perp$ being the azimuthal angles, in the hadronic center-of-mass frame, of the outgoing photon and of the vector $q_\perp$ respectively. The azimuthal asymmetry is given by

$$A(y, x_1, x_2, q_\perp^2) = \nu(x_1, x_2, q_\perp^2) R(y, x_1, x_2, q_\perp^2),$$

(7)

where $\nu$ contains the dependence on the time-reversal (T) odd distribution function $h_{1T}^q(x, p_\perp^2)$ and is identical to the azimuthal asymmetry expression that appears in the Drell-Yan process [4], with the scale $Q$ equal to $|K_{\gamma\perp}|$. The function $h_{1T}^q(x, p_\perp^2)$ is interpreted as the quark transverse spin distribution in an unpolarized hadron [5]. The role of gauge links in
Figure 3: The ratio $R$ as a function of $y$, calculated according to (8) and (9) for different values of $x_1$, $x_2$, $|K_{\gamma\perp}|$ typical of the Tevatron experiments [6].

The calculation of $\nu$ is discussed in detail in [2]. The ratio $R$ only depends on the T-even unpolarized distribution functions $f_{1}^{q,g}(x, p_\perp^2)$, which integrated over $p_\perp$ give the familiar lightcone momentum distributions $f_{1}^{q,g}(x)$. The explicit expressions of $\nu$ and $R$ are given in [2].

The process $p \bar{p} \rightarrow \gamma\text{jet} \ X$ is currently being analyzed by the DØ Collaboration at the Tevatron collider. Data on the cross section, differential in $\eta_{\gamma}$, $\eta_{j}$ and $K_{2j\perp}$, have been taken at $\sqrt{s} = 1.96$ TeV [6]. Such angular integrated measurements are only sensitive to the transverse momentum integrated parton distributions. A study of the angular dependent cross section in (6) will provide valuable information on the TMD distribution function $h_{1}^{q}(x, p_\perp^2)$, if the azimuthal asymmetry $A$ turns out to be sufficiently sizeable in the available kinematic region. Model calculations [7, 8] applied to the $p \bar{p}$ Drell-Yan process have shown that the quantity $\nu$ in (8) is of the order of 30% or higher for $|q_\perp|$ of a few GeV and $Q$ values of $O(1-10)$ GeV. Therefore, a study of the order of magnitude of $A$ as a function of $x_1$, $x_2$ and $q_\perp^2$ requires an estimate of the ratio $R$ in (8). This will be obtained as follows.

First of all, the unknown TMD distribution functions appearing in the definition of $R$ are evaluated assuming a factorization of their transverse momentum dependence, that is $f_{1}^{q,g}(x, p_\perp^2) = f_{1}^{q,g}(x)T(p_\perp^2)$, with $f_{1}^{q,g}(x)$ being the usual unpolarized parton distributions and $T(p_\perp^2)$ being a generic function, taken to be the same for all partons and often chosen to be Gaussian. The $q_\perp^2$-dependence of $R$ then drops out and we get

$$R = \frac{2N^2y(1-y)\sum_q e_q^2 f_{1}^{q}(x_1)f_{1}^{q}(x_2)}{D(y, x_1, x_2)}, \quad (8)$$
where $N$ is the number of colors and

$$D(y, x_1, x_2) = \sum_q e_q^2 \left\{ N(1 - y)(1 + y^2)f_1^q(x_1)f_2^q(x_2) + Ny(1 - y^2)f_1^q(x_2)f_1^q(x_1) \\
+ 2(N^2 - 1)(y^2 + (1 - y)^2)f_1^q(x_1)f_2^q(x_2) \right\}. \tag{9}$$

Here we have used that the antiquark contribution in the antiproton equals the quark contribution inside a proton. We consider only light quarks, i.e. the sum in (9) runs over $q = u, \bar{u}, d, \bar{d}, s, \bar{s}$, and we use the leading order GRV98 set $[3]$ for the parton distributions, at the scale $\mu^2 = K^2 \gamma^\perp$.

Our results for $R$ as a function of $y$ are shown in Fig. 3 at some fixed values of the variables $x_1$, $x_2$ and $|K^2 \gamma^\perp|$, typical of the Tevatron experiments $[3]$. The values of $x_1$ and $x_2$ considered correspond to their average when both the photon and the jet are in the central rapidity region, where $\eta_j \approx \eta_\gamma \approx 0$ and $x_1 \approx x_2$. In this case $y \approx 0.5$, where $R$ turns out to be largest. Evidently, $R$ increases as $x_1$ and $x_2$ increase, due to the small contribution, in the denominator, of the gluon distributions $f_2^q(x)$ in the valence region.

Hence, we see that the asymmetry $A$ is a product of a large Drell-Yan asymmetry term $\nu$ and a factor $R$ that is estimated to be in the 10%-50% range for Tevatron kinematics. This leads us to conclude that an asymmetry $A$ in the order of 5%-15% is possible in the central region. This could allow a study of the distribution function $h_1^{1-q}$ in $p\bar{p} \to \gamma\text{jet}X$ at the Tevatron, offering a new possibility of measuring T-odd effects using a high energy collider.

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