Probing Polarized Parton Distributions with Meson Photoproduction

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Polarization asymmetries in photoproduction of high transverse momentum mesons are a flavor sensitive way to measure the polarized quark distributions. We calculate the expected asymmetries in several models, and find that the asymmetries are significant and also significantly different from model to model. Suitable data may come as a by-product of deep inelastic experiments to measure $g_1$ or from dedicated experiments.

I. MOTIVATION

In this note, we will describe a flavor sensitive tool for measuring polarized quark distributions, namely photoproduction off nucleons of mesons with high transverse momentum, using polarized initial states.

Presently, information on polarized quark distributions comes from deep inelastic electron or muon scattering with polarized beams and targets [1]. Single arm measurements of $g_1$ give information about a linear combination of polarized quark distributions. Obtaining polarized distributions of individual flavors from this data requires extra theoretical input in the analysis. Recently, coincidence measurements of $\ell^- \vec{p} (\vec{d}) \rightarrow \ell^+ X$ have been reported [2]. This data, for a proton or deuteron target, gives different linear combinations of up and down quark polarized distributions, allowing a flavor decomposition without further theoretical input [3].

The process we will discuss, $\gamma \vec{p} \rightarrow M X$ (where the photon is real, targets other than protons are possible, and $M$ is a meson), gives a complementary way to find the polarized quark distributions. The perturbative QCD that we use in the analysis is justified on the basis of high meson transverse momentum, rather than by high virtuality of an exchanged photon, and the experiment is a single arm experiment rather than a coincidence one. Good data can in fact come as a by-product of a $g_1$ experiment since the detectors that measure the final electron or muon can also pick up charged hadrons; recall that if the final lepton is not measured, the form of the cross section ensures that the virtuality of the exchanged photon will be rather low on the average.

At high enough transverse momentum, mesons are directly produced by short range processes illustrated in Fig. 1. These processes are amenable to perturbative QCD calculation [4,5] and produce mesons that are kinematically isolated in the direction they emerge. The direct processes possess several important features.

![Diagram](image)

**FIG. 1.** One lowest order perturbative diagram for direct photoproduction of mesons from a quark. There are four diagrams total, corresponding to the four places a photon may be attached to a quark line.

One important feature is that the momentum fraction of the active quark is immediately obtainable from experimentally measurable quantities. This is like the situation in deep inelastic lepton scattering, where experimenters can measure $Q^2$ and $\nu$ and determine the quark momentum fraction by $x = Q^2/2m_N \nu$. In the present case, we define the Mandelstam variables using $p$, $q$, and $k$, the momenta of the proton (or other target hadron), the photon, and the meson, respectively,

$$s = (p + q)^2,$$

$$t = (q - k)^2.$$
$$u = (p - k)^2. \tag{1}$$

These are all experimentally measurable quantities. We can show that, neglecting masses,

$$x = \frac{-t}{s + u}. \tag{2}$$

The second important feature is that the polarization asymmetry of meson production is known via easy calculation at the subprocess level. For example, if $R$ and $L$ represent photon helicities and $\pm$ represent quark helicities, then one polarization asymmetry is

$$\hat{E} = \frac{\frac{d\sigma_{\gamma p}}{dt} - \frac{d\sigma_{\gamma n}}{dt}}{\frac{d\sigma_{\gamma p}}{dt} + \frac{d\sigma_{\gamma n}}{dt}} = \frac{\hat{s}^2 - \hat{u}^2}{\hat{s}^2 + \hat{u}^2}, \tag{3}$$

where the caret represents subprocess quantities. (We should emphasize again that internal quantities such as $\hat{s}$ or $\hat{u}$ are all determinable from experimentally measurable quantities if the direct meson production is dominant.) The measured asymmetry then measures what fraction of the quarks have the same or opposite polarization, for a measured $x$, as the parent proton.

The third important feature of direct meson production is that, by changing the flavor of the meson, we observe the change of the quarks that the measurement is sensitive to. For example, if we observe a $\pi^+$, only the $u$ and $d$ quarks will contribute. If, in addition, we are in the region where valence quarks dominate, we can get formulas as simple as

$$\Delta u(x, \mu^2) = u(x, \mu^2) \frac{\hat{E}}{E}, \tag{4}$$

where $E$ is the measured polarization asymmetry, $\hat{E}$ is the calculated polarization asymmetry at the quark level, $u(x, \mu^2)$ is the by now relatively well known unpolarized quark distribution for the up quark, $\mu^2$ is a renormalization scale pertinent for the process and kinematics at hand, and $\Delta u$ is the polarized quark distribution that we want to measure.

With sensitivity to jets, one can get similar information from the fragmentation process, that is, from subprocesses producing quark and gluon final states with fragmentation turning the quarks and gluons into jets. This has the advantage of having a larger cross section overall. However, if one has data with a single hadron measured (perhaps as a by-product of a single arm deep inelastic lepton scattering experiment), then concentrating on the region where the direct process dominates will yield the information about the quark distributions in the target. And of course, flavor identification is easier for a single hadron than for a jet.

II. CALCULATIONS

At the subprocess level the direct production of mesons proceeds as in Fig. 1. For the case that the incoming photon is circularly polarized and target quark is longitudinally polarized, one gets to lowest order

$$\frac{d\hat{\sigma} (\gamma q \to M q')}{dt} = \frac{128g_F^2\pi^2\alpha^2}{27(-t)s^2} I_M \left( \frac{\epsilon_s}{\hat{s}} - \frac{\epsilon_q}{\hat{u}} \right)^2 \times \left[ \hat{s}^2 + \hat{u}^2 + \lambda h \left( \hat{s}^2 - \hat{u}^2 \right) \right], \tag{5}$$

where $\lambda$ is the helicity of the photon, $h$ is twice the helicity of the target quark, and $g_F$ is a flavor factor from the overlap of the $q\bar{q}$ with the flavor wave function of the meson. It is unity for most mesons if the quark flavors are otherwise suitable; for example

$$g_F = \begin{cases} 1/\sqrt{2} & \text{for } \pi^0 \\ 1 & \text{for } \pi^+ \end{cases}. \tag{6}$$

The integral $I_M$ is given in terms of the distribution amplitude of the meson

$$I_M = \int \frac{d\xi_1}{\xi_1} \hat{\phi}_M(\xi_1, \mu^2). \tag{7}$$

It is precisely the same integral that appears in the perturbative calculation of the $\pi^0$ electromagnetic form factor or of the $\pi^0\gamma\gamma$ form factor. Finally,

$$\hat{s} = (p_1 + q)^2, \quad \hat{u} = (p_1 - k)^2, \tag{8}$$

and $\hat{t}$ is the same as $t$.

The helicity dependent asymmetry at the subprocess level may be immediately read off and was given in Eqn. (3). The notation "$E$" comes from pion photoproduction work (see for example [6]); it is analogous to $C_{LL}$ or $A_{LL}$ in $pp$ collision studies.

Another possibly useful asymmetry is the single polarization asymmetry, where the photon has linear polarization either in or normal to the plane defined by the outgoing meson. This asymmetry is (using $\hat{\sigma}$ for $d\hat{\sigma}/dt$)
\[ \hat{\Sigma} = \frac{\hat{\sigma}_\parallel - \hat{\sigma}_\perp}{\hat{\sigma}_\parallel + \hat{\sigma}_\perp} = \frac{2\hat{s}\hat{u}}{\hat{s}^2 + \hat{u}^2}. \] (9)

It is interesting to note that both \( \hat{E} \) and \( \hat{\Sigma} \) are the same as one would obtain for Compton scattering, \( \gamma q \rightarrow \gamma q \), off the quark.

Within a hadron target, the quark has light cone momentum fraction \( x \), and \( p_1 \approx x p \). Neglecting masses, one has
\[
\hat{s} + \hat{i} + \hat{u} = 0. \tag{10}
\]

Still neglecting masses, one has that
\[
\hat{s} = xs, \quad \hat{i} = t, \quad \hat{u} = xu. \tag{11}
\]

Hence the earlier quoted equation (2) giving \( x \) in terms of measurable quantities follows.

To the overall process, the direct subprocess makes a contribution that requires no integration to evaluate,
\[
E_x \frac{d\sigma}{d^3k} = \frac{sz^2}{\pi(-i)} \frac{d\sigma(\gamma p \rightarrow M + X)}{dz dt} = \frac{sz^2}{\pi(-i)} \sum_q G_{q/p}(x, \mu^2) \frac{d\sigma(q \rightarrow M q')}{dt}, \tag{12}
\]

where the helicity summations are tacit.

The helicity dependent asymmetry is reduced from its subprocess value because not all the quarks in a hadron have the same polarization as the hadron does. This is what allows us to measure the polarized quark distributions. Take \( \pi^+ \) production off a proton target as an example. The initial active quark may be either a \( u \) or a \( d \), and
\[
E(x, u/s) = \frac{\hat{E}(u/s)}{\hat{s}} \times \frac{(\hat{s}_x + \hat{s}_u)(x \Delta u(x) + (\hat{s}_x + \hat{s}_u)\Delta \bar{d}(x))}{(\hat{s}_x + \hat{s}_u)^2 u(x) + (\hat{s}_x + \hat{s}_u)^2 \bar{d}(x)}. \tag{13}
\]

We have let
\[
q(x) = q(x, \mu^2) = G_{q/p}(x, \mu^2) \tag{14}
\]
for the unpolarized distributions, and
\[
\Delta q(x) = \Delta q(x, \mu^2) = G_{q+/p+} - G_{q-/p+}(x, \mu^2). \tag{15}
\]

Also, because of the ratio, we can write the formula in terms of the measured \( s \) and \( u \) directly rather than using the subprocess variables. At higher \( x \), where the valence quarks dominate, we may drop the \( d \) terms in the above expression and obtain the simple result (4) quoted earlier.

![Graph](image)

**FIG. 2.** Comparing direct and fragmentation photoproduction of \( \pi^+ \) off protons, for \( E_\gamma = 30 \text{ GeV} \) and \( \theta_{lab} = 5^\circ \). The solid line is direct production of \( \pi^+ \) and the dotted line is fragmentation production of \( \pi^+ \). For reference, the dashed line shows direct production of \( \pi^0 \). The abscissa is \( k = |k| \) in the lab.

We should make a few remarks on the relevance of the direct process and its relation to the values of \( x \) that are probed. The direct process is higher twist, and does not generally dominate the production of mesons. It does dominate in the region of very high transverse momentum. The main competition is the fragmentation process, where the observed meson is part of a jet. The fragmentation process tails off at the highest transverse momenta simply because of its implicit requirement that one meson take all or nearly all the momentum of the quark is unlikely to be satisfied in a jet. For illustration, a calculation comparing direct to fragmentation photoproduction of \( \pi^+ \)’s off a proton is shown in Fig. 2, based on calculations reported in [5], and using the asymptotic distribution amplitude for the pion (using the Chernyak-Zhitnitsky distribution amplitude would make the direct process calculation larger by a factor 25/9). This particular example is for photon energy \( 30 \text{ GeV} \) with the pion emerging at \( 5^\circ \) in the lab. The direct process is larger than the fragmentation process for pion momenta above \( 20 \text{ GeV} \); this corresponds to \( x \) above about 0.24. Generally, if the meson can be produced from a valence quark in the target, we will be in the valence region when the
III. RESULTS

The chief question must be how sensitive a measurement of $\Delta q$ can be made. To study this question, we use three different models or fits to the polarized quark distributions. These are the fits of Gehrmann and Stirling (GS) [7], of Glück, Reya, Stratmann, and Vogelsang (GRSV) [8], and a suggestion of Soffer et al. [9]. All fit the available data on $g_1$ from deep inelastic lepton scattering experiments. For the first two, we have obtained the renormalization scale dependent results for the polarized parton distributions directly from the authors. The Soffer et al. suggestion relates the polarized and unpolarized distribution functions, specifically,

$$\Delta u(x) = u(x) - d(x),$$

$$\Delta d(x) = -\frac{1}{3}d(x),$$

and other polarized distributions are treated as small. When we use the Soffer et al. suggestion, we team it with the CTEQ [10] quark distributions. In all cases, we set the renormalization scale $\mu^2$ to $k_T^2$, where $k_T$ is the transverse momentum of the produced meson.

The upper part of Fig. 3 shows the asymmetry $E$ for $\pi^+$ photoproduction off protons. (Both Fig. 3 and 4 are for 100% polarization of the beam and target.) We notice that the asymmetries are significant, and that the GS and GRSV polarized distributions give about the same result, but the Soffer et al. suggestion gives an asymmetry that is significantly larger. The other part of Fig. 3 shows the $\pi^-$ case. The asymmetry has the opposite sign because now the $d$ valence quark dominates, and in all the models the $u$ is polarized along the direction of the proton while the $d$ is opposite. For the $\pi^-$, it is the GRSV and Soffer et al. results that are about the same, and the GS is significantly different and usually larger in magnitude.

Electroproduction with the final electron unobserved is much akin to photoproduction. Single arm electroproduction experiments commonly get such data when a charged hadron rather than an electron triggers the detector. The form of the cross section ensures that low $Q^2$ events dominate if $Q^2$ is not measured.

Hence electroproduction with just the single hadron observed usually has the photon nearly on shell, but only the upper and lower limits of the photon energy are known. The three models for the polarized quark distributions still give distinguishable predictions, as we shall show. For a given electron energy $E_e$, the photon energy spectrum is given fairly accurately by

$$\frac{dN_\gamma}{dE_\gamma} \propto \frac{1}{E_\gamma}$$

up to close to the cutoff at $E_\gamma = E_e$. The polarization of the photon is nearly the polarization of the electron. The photon takes most of the electron's energy. Polarization details can be found in [11]; most usefully, if $P_\gamma$ and $P_e$ are the circular and longitudinal polarizations of the photon and electron, respectively, then

$$\frac{P_\gamma}{P_e} = \frac{y(4-y)}{4-4y+3y^2},$$

where $y = E_\gamma/E_e$. 

7

8
FIG. 3. The upper three curves are the helicity dependent asymmetries for $\pi^+$ photoproduction off the proton, for 30 GeV photons and lab angle 5 or 14°. The solid line is for the GRSV polarized quark distributions; the dashed line is for GS; and the dotted line is for the suggestion of Soffer et al. GRSV is about the same as GS for the $\pi^+$ case. The lower three curves are for $\pi^-$ photoproduction. GRSV and GS are well separated in the $\pi^-$ case.

Fig. 4 shows polarization asymmetry results for 50 GeV incoming electrons, with pions emerging at 5° lab angle and photon energies and polarizations weighted as indicated above. Despite the weighted average over photon energies, the models still give different predictions.

Another possibility for producing real photons with circular or linear polarization is the laser backscattering technique [12].

FIG. 4. Polarization asymmetry results for 50 GeV incoming electrons, with pions emerging at 5° lab angle and the electrons not observed. We have integrated over the energies and polarizations of the virtual (but on the average low $Q^2$) photons with weightings as indicated in the text. The upper three curves are for the $\pi^+$ and the lower three curves are for the $\pi^-$. The solid, dashed, and dotted lines are for GRSV, GS, and Soffer et al., respectively.

IV. DISCUSSION

A number of questions may be asked about the applicability of perturbative QCD. We could of course point out that we are dependent on ratios of cross sections, so that many potential problems may cancel out. However, we shall address some of the questions more directly.

One simple question is whether the "X" in $\gamma + p \rightarrow M + X$ is out of the resonance region. Letting $m_X$ be the mass of the collection of particles $X$, we should require $m_X > 2$ GeV, and neglecting the mass of the meson we have

$$m_X = \sqrt{s + t + u - m_N^2}. \tag{19}$$

For $E_\gamma = 30$ GeV and $\theta_{lab} = 5°$, the requirement becomes $k < 25$ GeV, which is easy to satisfy. Lower energies could be more troublesome. At 12 GeV incoming photon energy, with a $\pi^+$ exiting at 22°, the requirements of dominance of the direct process and of being out of the resonance region just leave a window $4.8 < k < 5.3$ GeV, corresponding to $0.62 < x < 0.74$.

Another question regards higher twist corrections, for example, corrections due to the quarks in the pion having finite momentum transverse to the pion's
overall momentum. This has been much studied in the context of the pion electromagnetic form factor [13]. As has been remarked, the integral over the pion’s distribution amplitude that appears here is the same as appears in the pion form factor. However [5], the momentum transfer scale as judged by how far the transferred gluon is off shell is much larger in pion photoproduction than in the pion form factor. To be more definite, if the photon attaches to the produced $qar{q}$ pair in Fig. (1) the gluon is off shell on the average by

$$q_x^2 = \langle q_x^2 \rangle = \langle \xi_2 \rangle x_u,$$  

(20)

The corresponding quantity if the photon attaches to the initial quark is larger, though timelike. The average $\xi_2$ is weighted by the integrand of $I_\gamma$ and is $1/3$ and $1/5$ for the asymptotic and Chernyak-Zhitnitsky distribution amplitudes, respectively. The pion electromagnetic form factor involves the distribution amplitude twice, and if the virtual photon is off shell by an amount $Q^2$, then the gluon in that process is off shell by

$$q_x^2 = -\langle \xi_2 \rangle^2 Q^2.$$  

(21)

Matching the gluon virtualities, there is a correspondence

$$Q^2 \sim \frac{\xi(-u)}{\langle \xi_2 \rangle}.$$  

(22)

This means that for the case of incoming 30 GeV photons and pions out at $5^\circ$, in the region of direct process dominance and above the resonance region, the integrals over the distribution amplitude are the same as those for $F_\pi(Q^2)$ with

$$15 \text{ GeV}^2 < Q^2 < 80 \text{ GeV}^2.$$  

(23)

Thus higher twist effects will be less significant for measurable photoproduction of high transverse momentum mesons than for meson form factors at any currently measured momentum transfers.

Perturbative corrections that are higher order in $\alpha_s$ have not been calculated. They have been calculated for the $\pi^0\gamma\gamma$ [14] and $\pi^\pm$ [15] electromagnetic form factors, and for both of those reduce the result by about 20%. We may guess the result is about the same here, and if the corrections are similar for all polarization states, they will cancel in the ratios.

One may ask about effects of the fragmentation process. Even in the region where the direct process is dominant, there will be some contribution to the polarization asymmetry from fragmentation processes [16]. We have calculated corrections to $\Sigma$ and $E$. For $E$, we find the corrections are small. For example, again using $E_r = 30 \text{ GeV}$ and $5^\circ$ in the lab outgoing pions, at $k = 22 \text{ GeV}$ including the fragmentation process increases the asymmetry by a factor 1.02. (We neglected the polarization of the gluons; in this region $\gamma g$ fusion is about 30% of the fragmentation contribution). One reason the corrections are small is that the expected asymmetry for both the quark-gluon fusion and Compton subprocesses is the same sign and roughly the same magnitude as for the direct process.

Regarding the single polarization asymmetry $\Sigma$, for the direct process, it is always negative and for forward center of mass angles it is large in magnitude. As we move to lower $k$ and the fragmentation process becomes more important, there is a significant dilution of $\Sigma$. The reduction of $\Sigma$ occurs because the $\gamma g$ fusion process becomes important, and $\Sigma$ for that process is precisely zero. If $\Sigma$ is observed and seen to be large, it is one sign that the direct process is important. For instance, for the same $E_r$ and $\theta_{lab}$ as above, the value of $\Sigma$ at $k = 22 \text{ GeV}$ is $-0.61$, $-0.94$, and $-0.86$, respectively, for the fragmentation alone, the direct process alone, and their properly weighted total (using the Soffer et al. model).

To conclude, we believe that photoproduction of high transverse momentum mesons is an accurate and flavor sensitive way to measure the polarized quark distributions in the valence region.

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