Soft contributions to hard pion photoproduction

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Hard, or high transverse momentum, pion photoproduction can be a tool for probing the parton structure of the beam and target. We estimate the soft contributions to this process, with an eye toward delineating the region where perturbatively calculable processes dominate. Our soft process estimate is based on vector meson dominance and data based parametrizations of semiexclusive hadronic cross sections. We find that soft processes dominate in single pion photoproduction somewhat past 2 GeV transverse momentum at a few times 10 GeV incoming energy. The recent polarization asymmetry data are consistent with the perturbative asymmetry being diluted by polarization insensitive soft processes. Determining the polarized gluon distribution using hard pion photoproduction appears feasible with a few hundred GeV of incoming energy (in the target rest frame).

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I. INTRODUCTION

Recent results [1] on pion photoproduction or, more precisely, low-Q^2 electroproduction show the need for a careful estimate of soft contributions. In particular, the measured polarization dependent effects are not in good overall agreement with calculations based only on QCD calculated using perturbation theory (PQCD). A key issue is where and if the high transverse momentum cross section is dominated by perturbatively calculable contributions and where soft contributions are important. In the region where perturbative contributions dominate, it is known how hard pion photoproduction can be a source of information about hadron structure [2–4].

Pion photoproduction at high transverse momentum, or hard pion photoproduction, supplements what can be learned in the standard hadron structure probes of deep inelastic scattering and Drell-Yan processes, lately joined by high-Q^2 coincident meson production [5]. A particular feature of high transverse momentum pion photoproduction with polarized initial states is the sensitivity to the polarized gluon distribution, Δg, in leading order. This contrasts to the other processes mentioned, which have no leading order gluon contribution. Additionally, in some kinematic regions the process occurs mainly due to pion production at short distances (''direct pion production''), whereupon there is sensitivity to the high-x valence quark distribution and the short distance pion wave function.

Many authors have calculated perturbative contributions to hard pion photoproduction, and recent work in this area has centered on short distance pion production [2], polarization effects [3,4], and complete next to leading order corrections [4]. These calculations do include the hard or short distance contributions from hadronic components of the photon, under the heading of resolved photon processes, but do not include the soft part. Here we present a phenomenological calculation of soft contributions, and compare its size to the PQCD results already known. The calculation relies on vector meson dominance (VMD), which is a way to represent the hadronic components of the photon as they enter into soft processes. Experimental studies, in particular the Omega [6], H1 [7], and Zeus [8] Collaborations, have shown that hadron induced and photon induced hadron production were proportional to each other up to a certain transverse momentum, and that above this transverse momentum the photon induced reactions rise relative to hadron induced ones as the pointlike piece of the photon becomes more important. For the kinematics of the above experiments it is about 2 GeV transverse momentum where the pointlike photon begins to become apparent.

In the next section, we put together known photon vector meson couplings with phenomenological representations of the hadron-hadron reactions to produce soft cross section formal results for kinematics of interest. Following that, Sec. III presents some numerical results for cross sections and polarization effects, making an assumption that the polarization dependence of the soft processes is small. We close with a discussion in Sec. IV.

II. OUTLINE OF CALCULATIONS

We are aware that quite successful descriptions of soft processes have been obtained using Regge theory inspired models [9]. However, the sophistication of these models makes them somewhat rich in parameters that need to be set from the same data that are being described or from similar data. For example, there is a need for some cutoffs whose scale parameters are not predicted from theory, a use of different Pomeron intercepts for single diffractive processes and total cross sections, and a fitting of the overall size in the

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form of the triple Pomeron coupling using related reactions. We opt for a complementary course, wherein we simply use known couplings to calculate photon to vector meson conversion and then use measured data for the hadronic cross sections.

For definiteness we will consider π^+ production off a proton target. The ρ-dominance amplitude is

$$f(\gamma p\to\pi^+X)|_\rho=\frac{e}{f_\rho}f(\rho^0 p\to\pi^+X) \tag{1}$$

and

$$d\sigma(\gamma p\to\pi^+X)=\frac{\alpha}{\alpha_\rho}d\sigma(\rho^0 p\to\pi^+X)+\text{other VMD} + \text{non VMD contributions}, \tag{2}$$

where $\alpha_\rho\equiv f_\rho^2/4\pi$ and ''other VMD'' stands for contributions of excited ρ's and of other vector mesons. The value of α_ρ can be obtained from $\Gamma(\rho\to e^+e^-)$ and is [10]

$$\alpha_\rho=2.01\pm0.10. \tag{3}$$

This reduces the problem to finding the cross section or a parametrization thereof for vector meson production of the π^+. In principle, this might be an experimentally measurable process, but in practice we will have to approximate it in terms of charged pion induced processes. The remainder of this section is mostly devoted to explaining how we do this. First we make some remarks on contributions from excited ρ's and other vector mesons.

Excited ρ contributions to $\gamma p\to\rho+X$ decrease the rate by 20%, according to Pautz and Shaw [10]. The basic relation is

$$f(\gamma p\to\rho X)=\frac{e}{f_\rho}\underbrace{f(\rho p\to\rho X)}_{\text{“}f_{\rho\rho}\text{”}}+\frac{e}{f_{\rho'}}\underbrace{f(\rho' p\to\rho X)}_{\text{“}f_{\rho'\rho}\text{”}} \tag{4}$$

and the claim is that while the couplings are about the same, the amplitudes interfere destructively,

$$f_{\rho'\rho}\approx(-16\%)f_{\rho\rho}. \tag{5}$$

The effect can be subsumed by simply calculating simple vector meson dominance with $\alpha_\rho^{eff}=2.44$. For us the question is whether the same is true for π^+ production,

$$f_{\rho'\pi}\overset{?}{\approx}(-16\%)f_{\rho\pi}, \tag{6}$$

and we shall proceed assuming it is true.

From flavor SU(3), the couplings of the photon to the vector mesons lie in the ratios

$$f_\rho^{-2}:f_\omega^{-2}:f_\phi^{-2}=9:1:2. \tag{7}$$

If the ρ, ω, and ϕ strong interaction cross sections are the same, then the other flavors add 33% to the ρ contribution. At the present level of knowledge, we will approximate the total VMD contribution by the ρ contribution multiplied by 4/3. The photoproduction cross section is now

$$d\sigma(\gamma p\to\pi^+X)=\frac{4}{3}\frac{\alpha}{\alpha_\rho^{eff}}d\sigma(\rho^0 p\to\pi^+X) + \text{non VMD contributions}, \tag{8}$$

with $\alpha_\rho^{eff}=2.44$. Off shell effects have not been considered.

We need knowledge, or a representation, of $d\sigma(\rho^0 p\to\pi^+X)$. Often used is

$$d\sigma(\rho^0 p\to\pi^+X)=\frac{1}{2}d\sigma(\pi^+ p\to\pi^+X)+\frac{1}{2}d\sigma(\pi^- p\to\pi^+X). \tag{9}$$

This will not work in the forward direction, where one cross section has a leading particle effect but $\rho^0 p\to\pi^+X$ should not. One may expect the measurable cross section most similar to $\rho^0 p\to\pi^+X$ would be $\pi^+ p\to\pi^0X$. Data from O'Neill *et al.* [11] show that $\pi^+ p\to\pi^0X$ has the same angular dependence as $\pi^+ p\to\pi^-X$ but is about 30% larger. This reduces the problem to finding a representation of the latter.

Bosetti *et al.* [12], who experimentally studied charged pion cross sections, found that the cross section $\pi^+ p\to\pi^-X$ factors in k_T and ξ, where ξ is the scaled rapidity,

$$\xi=\frac{y-y_t}{y_p-y_t} \tag{10}$$

for $p=$ projectile and $t=$target, and y is the rapidity, which may be defined in various equivalent ways including

$$y=\operatorname{arcsinh}\frac{p_L}{\sqrt{p_T^2+m^2}}. \tag{11}$$

That means

$$\omega_\pi\frac{d\sigma}{d^3k}=\omega_\pi\frac{d\sigma}{d^3k}\bigg|_{90^\circ\text{c.m.}}\times g(\xi), \tag{12}$$

where $g(\xi)$ will have some dependence on k_T to respect kinematic bounds. A choice that appears to work is

$$g(\xi)=\left(1-\frac{(\xi-\xi_0)^2}{(\xi_{max}-\xi_0)^2}\right)^2, \tag{13}$$

where ξ_0 is halfway between ξ_{max} and ξ_{min}, and $\xi_{max,min}$ are the maximum or minimum ξ for a given k_T.

Beier *et al.* [13] have analytic forms that work over a wide kinematic range for $pp\to\pi^-X$ at 90° in the c.m., and the data of Bosetti *et al.* [12] approximately agree with

$$\omega_\pi\frac{d\sigma}{d^3k}(\pi^+ p\to\pi^-X)=\frac{2}{3}\omega_\pi\frac{d\sigma}{d^3k}(pp\to\pi^-X). \tag{14}$$

In summary, calculate using

$$\omega_\pi \frac{d\sigma}{d^3k}(\gamma p \to \pi^+ X)$$

$$= + \frac{\alpha}{\alpha_\rho^{eff}} \times 1.3 \times \frac{4}{3} \times \frac{2}{3} \omega_\pi \frac{d\sigma}{d^3k}(pp \to \pi^- X)\Big|_{90^\circ \text{c.m.}} g(\xi)$$

$$+ \text{non VMD contributions.} \quad (15)$$

The ''non VMD'' contributions are discussed in, for example, [2–4]. To review the numerical factors, the single charge change reaction was about 1.3 times the double charge change reaction according to [11], the 4/3 is to account for the ω and ϕ mesons, and the 2/3 is so that we may use pp cross section parametrizations as stand-ins for meson-proton cross sections. Electroproduction data with particle identification with electron energies up to 19 GeV, reported in Wiser's thesis [14], indicate that π^- production off a proton target is about a factor of 1.3 lower than for the π^+, and that $\pi^\mp$ is produced off a neutron at about the same rate as $\pi^\mp$ off a proton.

The connection between photoproduction and electroproduction when the outgoing electron is unobserved is given by the Weizäcker-Williams equivalent photon approximation

$$d\sigma(eN \to \pi X) = \int_{E_{min}}^{E_e} dE_\gamma N(E_\gamma) d\sigma(\gamma N \to \pi X). \quad (16)$$

The expressions we use for the photon number density $N(E_\gamma)$ and the lower limit are quoted in [3].

III. SOME RESULTS

We begin by examining the differential cross section for one relevant kinematic situation, namely that with 50 GeV incoming electrons with pions emerging at 5.5° in the laboratory. This energy is typical of SLAC and not far above what can be obtained at HERMES. Figure 1 shows the unpolarized differential cross section vs pion momentum for both the π^- and π^+. There are three curves on each plot, the soft contribution represented by VMD and two perturbative contributions, namely parton production followed by fragmentation and direct or short range pion production. (Another perturbative contribution, the resolved photon process, is small enough at this energy and angle is not an issue.) The three contributions should be added incoherently.

The soft contribution continues to a momentum that is higher than expected. Nonetheless, one sees that at momenta beyond about 25 GeV for the π^- or 22 GeV for the π^+, the sum of the perturbative contributions exceeds the soft contributions. For this angle, this is about 2.4 and 2.1 GeV of the transverse momentum, respectively.

The hadron to electron ratio is also measured and reported in the experimental paper in [1]. At lower momenta the calculated π/e ratio is too small without the VMD contributions. With all contributions added together, the calculated pion to electron ratio is shown in Fig. 2. These are in reasonable accord with the plots presented in [1], which in turn are stated to be in reasonable accord with the data.

Having a reasonable description of the unpolarized cross section in hand, we need to consider the polarization asymmetry. If R and L represent photon helicities and $\pm$ represent target helicities, then the longitudinal asymmetry E or A_{LL} is defined by

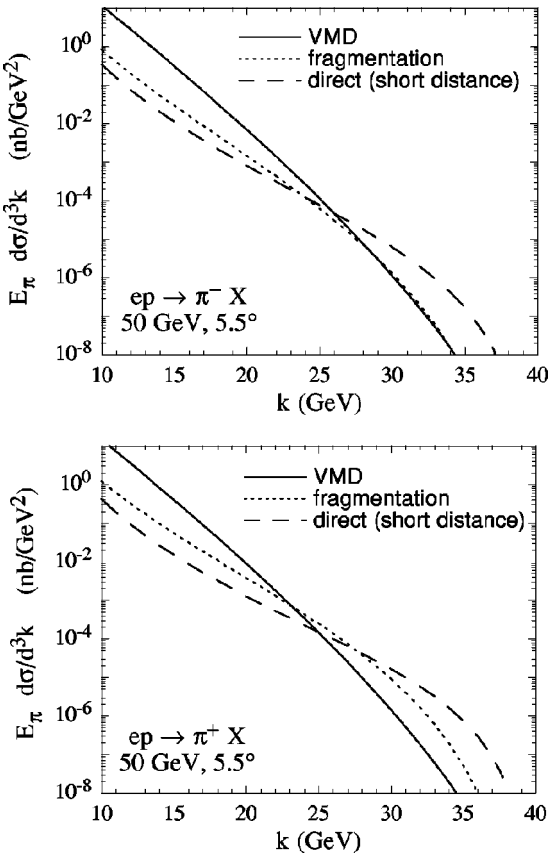

FIG. 1. The invariant differential cross sections for $ep \to \pi^- X$, above, and π^+, below. The incoming electron energy is 50 GeV, and pion laboratory angle is 5.5°.

$$E = A_{LL} \equiv \frac{\sigma_{R+} - \sigma_{R-}}{\sigma_{R+} + \sigma_{R-}}. \quad (17)$$

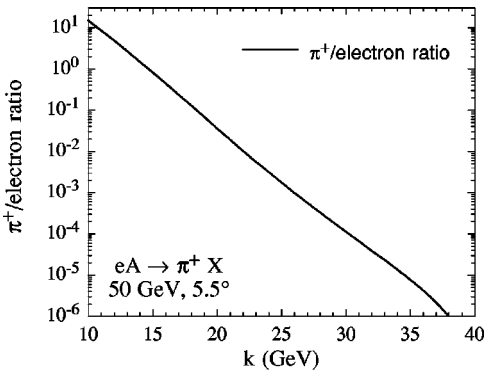

FIG. 2. The calculated pion to electron ratio for a ^{15}N He_3 target. For this target and this vertical scale, the π^- results are hardly distinct from the π^+. They are in reasonable accord with data as reported in [1].

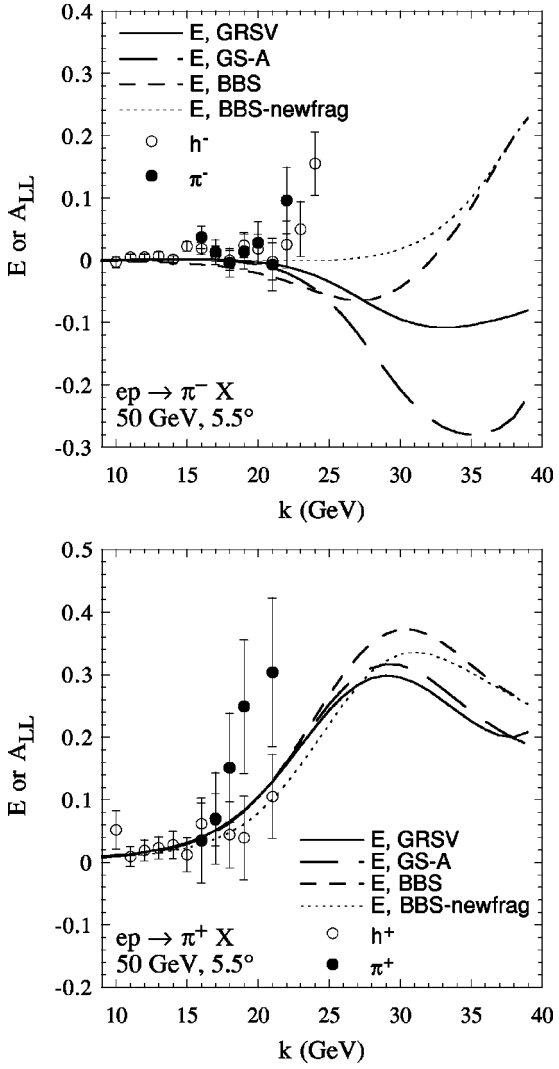

FIG. 3. Polarization asymmetries for $ep \to \pi^-$, above and π^+, below. The data for charged hadrons and for charged pions are from [1].

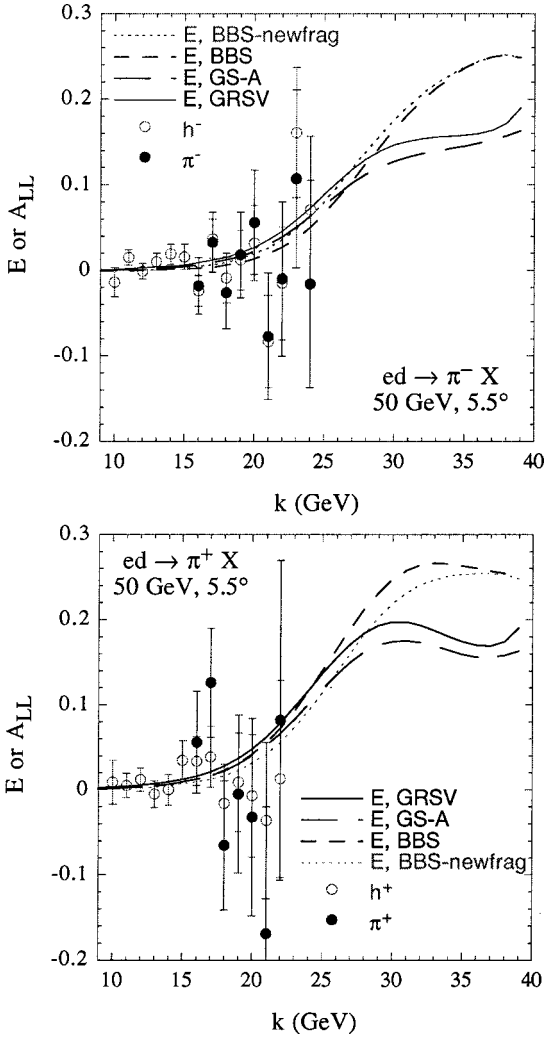

FIG. 4. Polarization asymmetries for the deuteron, with $ed \to \pi^- X$ above and $ed \to \pi^+ X$ below. The data are from [1].

The polarization dependence of the perturbative terms is calculable, but we have no direct polarization information on the VMD contributions. One class of VMD subprocess would give a negative polarization asymmetry if hadron helicity conservation holds for those diagrams. This is the reaction $V+q \to \pi+q$, where V stands for a vector meson which must have helicity ± 1 since it comes from conversion of a real photon. The vector meson and initial quark must have opposite helicity, or else the final state must have total helicity $\pm 1/2$. However, Manayenkov [15] has argued from a Regge analysis that the soft contributions to A_{LL} are small. Here, we shall assume no polarization dependence for the VMD terms. The polarization asymmetry then comes only from the perturbative terms, but it is much muted at low momentum because of the large non-perturbative cross section.

Actual polarization asymmetry results plotted vs pion momentum, again for electron energy 50 GeV and pion angle 5.5°, are shown for proton targets in Fig. 3 and for deuteron targets in Fig. 4. (The deuteron in this calculation is treated simply as a proton plus a neutron.) Also shown are polarization asymmetry data [1] for charged hadrons and for identified $\pi^{\pm}$.

A few words should be said about the distribution functions and fragmentation functions. Glück-Reya-Stratmann-Vogelsang (GRSV) [16] and Gehrmann-Stirling (GS) sets [17] are both widely used, and Brodsky, Burkandt, and Schmidt (BBS) [18] differ from them most notably in having the PQCD counting rule results for the *d*-quark to *u*-quark ratio for large *x*, and by not nicely separating sea quark contributions. Since for us the distribution functions are most needed at large *x*, the latter may not be so serious. The d/u ratio now appears, with more careful examination of how the neutron structure functions are extracted from deuteron data [19], as a PQCD ratio of 1/5 rather than zero, which makes it important to notice how different the BBS results are from the others at high momenta.

We used the fragmentation functions given in [20] and our experience has been that the results at least at SLAC or HERMES energies would not be too different for the π^+ but larger in magnitude for the π^- if we used [21]. However, recent HERMES data suggest that the ''unfavored'' frag-

mentation function (e.g., for a u quark fragmenting to a π^-) is larger than what we have been using [22]. So for the BBS distribution, we present results from one additional fragmentation function, where the sum determined from $e^+e^- \to \pi X$ is unchanged but the ratio of unfavored or secondary fragmentation function to primary (or favored minus unfavored) fragmentation function is given by

$$D_s(z)/D_p(z) = 0.5(1-z)^{0.3}/z, \tag{18}$$

where z is the fraction of quark momentum that goes into the pion.

IV. DISCUSSION

We used VMD to approximate the interactions of the photon that lead to low transverse momentum final states. In this kinematic range, VMD is a tested and apparently good approximation. As a relatively recent example, the Omega [6] experiment compared data on mesoproduction and photoproduction of single observed hadrons, and found that the photoproduction cross sections were a constant (1/215)—just the corrected α/α_V—of the mesoproduction cross sections for transverse momenta up to the 1.5–2 GeV range. At higher transverse momenta the VMD approximation fails. It fails because other processes are becoming important. We can mention two specific items.

First, there are direct interactions of the photon with the target, not just interactions mediated by vector mesons. Finding where these direct interactions are large is, of course, an ultimate interest in the present work.

Second, some of the short distance $q\bar{q}$ pairs in the photon come directly from photon splitting and the distribution of these pairs is not the same, at finite Q^2, as in the vector meson. Modelers of quark distributions of the photon [24] include components from both the vector mesons and photon splitting, mutually evolved. The photon splitting contributions to the cross section can be handled perturbatively, and are called the resolved photon contributions. The resolved photon contributions can, usually in circumstances involving higher initial energies than we are focusing on in the present work, be larger than the straightforward VMD contributions, showing a breakdown of the VMD approximation. (There is a double counting question, for which we do not have a general answer, but for our kinematics VMD and resolved photon contributions are never simultaneously large, so any double counting of contributions cannot be large either.)

By the foregoing thinking, when the soft processes as estimated by VMD are large relative to the competition, the estimates are accurate and the perturbative processes are small. When the soft processes as represented by VMD are small, then VMD is breaking down as a way to estimate the photoproduction cross section. However, small is small and the processes that are large are calculable. The soft and VMD calculations have done their primary job. They have indicated where the hard contributions are a valid approximation to the total.

We believe we have presented as accurate an estimate of the soft processes in pion photoproduction as can currently be done. Improvements could follow given more information. For examples the connections we made in Sec. II require some leaping among processes, and we have not included pions from target fracture in the perturbative cases; nor have we deeply entered into the questions newly revived about the unfavored fragmentation functions. We feel the latter is an important question that should be the subject of a separate study. Having made our caveats, we do have a clear and logical representation of the soft contributions that we can compare to the newest pion photoproduction (or low Q^2 electroproduction) data.

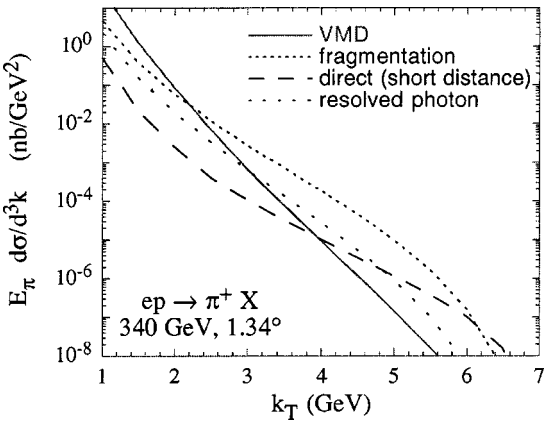

FIG. 5. The differential cross section for 340 GeV electrons impinging on an standing proton with positive pions emerging at 1.34°. (This corresponds to a collider with 4 GeV electrons hitting 40 GeV protons and pions emerging at 90° in the laboratory.)

We find that the soft process, working through VMD, can explain the total cross section at lower transverse momentum. We find further that the data are compatible with the idea that there is little polarization asymmetry in the soft interactions, as may be seen in our comparisons to the data in Figs. 3 and 4. We would like to be able to confirm or understand this by other means.

Perturbation theory can be used to calculate the cross section and polarization dependence at higher transverse momentum. The crossover is at a bit over 2 GeV for the kinematic regions we have dealt with here. The idea that hard pion photoproduction is sensitive to Δg is true in a region where PQCD is valid and the fragmentation process dominates. As a reminder, it is true because the gamma-gluon fusion process accounts for a reasonable fraction of the hard pion photoproduction, and this process has a magnitude of 100% polarization asymmetry. However, it requires somewhat more energy so that there is a region above the VMD region where the fragmentation process is important. As an example, we present in Fig. 5 a differential cross section for 340 GeV electrons impinging on a standing proton with pions emerging at 1.34°. (This corresponds to a collider with 4 GeV electrons hitting 40 GeV protons and pions emerging at 90° in the laboratory. The energies are pertinent to an electron polarized ion collider under discussion at the Indiana University Cyclotron Facility.) We see the sort of region we want between about 2 and 6 GeV of transverse momentum.

We have been greatly motivated by the idea that hard pion

photoproduction can give information on parton distributions. We note that this is already proving feasible. The H1 Collaboration, working in a region where the resolved photon process dominates, has extracted the gluon density in the photon from data on this process [23].

The idea that the ratio $d(x)/u(x)$ obeys the PQCD limit for large x, rather than falling to zero, is gaining ground. So far the relevant analyses [19] are only for the unpolarized case, but the $x\to 1$ polarization prediction of 100% polarization parallel to the parent hadron can be tested here. With direct pion production (or also with fragmentation) off valence quarks dominant at the highest E_π, one has an asymmetry for the π^- of

$$E = A_{LL} = \frac{s^2-u^2}{s^2+u^2}\,\frac{\Delta d}{d} = 0.24\frac{\Delta d}{d}, \tag{19}$$

where the number is for $E_e = 50$ GeV, pion $\theta_{lab} = 5.5°$, and the highest allowed E_π (in this case, 41.2 GeV). For PQCD as $x\to 1$ one has $\Delta d = d$, and one can see this trend in the results for the BBS [18] distribution functions since BBS follow the PQCD limit. In fact, for PQCD the limiting asymmetry is the same for $\pi^\pm$ and independent of target.

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