Hard Electroproduction of Photons and Mesons on the Nucleon

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The γ, π^0, and ρ_L^0 electroproduction reactions are studied in the Bjorken regime. They are sensitive to the recently introduced off-forward parton distributions. A factorized model for these distributions is shown to be able to interpret the few existing ρ_L^0 data. Calculations are given in different kinematics and experimental perspectives are discussed. [S0031-9007(98)06261-9]

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Deep-inelastic lepton scattering (DIS) in the Bjorken regime ($Q^2 \to \infty$ and $x_B = Q^2/2pq$ finite) has been shown to be a very informative tool for studying nucleon structure [1]. In particular, polarized DIS experiments have revealed that only about 23% of the nucleon spin is carried by the quark spin [2]. This has spurred a search for new experiments to measure and understand the remaining nucleon spin. To this end, exclusive deeply virtual Compton scattering in the Bjorken regime has been proposed recently [3,4] as a means to access a new type of parton distributions, referred to as off-forward parton distributions, generalizations of the parton distributions measured in DIS. It has been shown [3] that their second moment gives access to the sum of the quark spin and the quark orbital angular momentum to the nucleon spin. It has been proposed [5] that these distributions can also be accessed through the hard exclusive electroproduction of mesons ($\pi^0, \rho^0, \ldots$).

In this Letter, we calculate at the same time the leading order of the γ, π^0, and ρ_L^0 (i.e., longitudinally polarized ρ^0) electroproduction amplitudes and present the first estimates for the exclusive cross sections. We show that the three reactions are highly complementary as apart from isospin factors, they depend on the same off-forward parton distribution (OFPD's). The simple ansatz that we use for the OFPD's seems to be supported by the few ρ_L^0 electroproduction data. We then explore the experimental opportunities which may allow one to determine the OFPD's.

The leading twist amplitude for deeply virtual Compton scattering (DVCS) in the forward direction was shown [3] to be given by the handbag diagrams of Fig. 1(a). To calculate the hard electroproduction amplitude, it is convenient to use a frame where the virtual photon momentum q^μ and the average nucleon momentum P^μ [see Fig. 1 for the kinematics] are collinear along the z axis and in opposite directions. Furthermore, one defines the lightlike vectors $\tilde{p}^\mu = P^+/\sqrt{2}\,(1,0,0,1)$ and $n^\mu = 1/(\sqrt{2}\,P^+)\,(1,0,0,-1)$, where light-cone components $a^\pm$ are defined by $a^\pm \equiv 1/\sqrt{2}\,(a^0 \pm a^3)$.

The light-cone matrix element of the bilocal quark operator that enters in these hard electroproduction reactions [represented by the lower blob in Figs. 1(a) and 1(b)] is at leading twist given by

$$\frac{P^+}{2\pi}\int dy^-\, e^{ixP^+y^-}\langle p'|\bar{\Psi}_\beta\Big(-\frac{y}{2}\Big)\Psi_\alpha\Big(\frac{y}{2}\Big)|p\rangle\Big|_{y^+=\vec{y}_\perp=0}$$
$$= \frac{1}{4}\Big\{(\gamma^-)_{\alpha\beta}\Big[H^q(x,\xi,t)\,\bar{N}(p')\gamma^+N(p) + E^q(x,\xi,t)\,\bar{N}(p')i\sigma^{+\kappa}\frac{\Delta_\kappa}{2M_N}N(p)\Big]$$
$$+ (\gamma_5\gamma^-)_{\alpha\beta}\Big[\tilde{H}^q(x,\xi,t)\,\bar{N}(p')\gamma^+\gamma_5N(p) + \tilde{E}^q(x,\xi,t)\,\bar{N}(p')\gamma_5\frac{\Delta^+}{2M_N}N(p)\Big]\Big\}, \qquad (1)$$

where Ψ is the quark field and N the nucleon spinor. In Eq. (1), the OFPD's $H^q, E^q, \tilde{H}^q, \tilde{E}^q$ are defined for one quark flavor ($q = u$, d, and s) and depend upon the variables x, ξ, and t. The light-cone momentum fraction x is defined by $k^+ = xP^+$. The variable ξ is defined by $\Delta^+ = -2\xi P^+$, where $\Delta \equiv p' - p$ and $t = \Delta^2$. Note that $2\xi \to x_B/(1 - x_B/2)$ in the Bjorken limit. The support in x of the OFPD's is $[-1,1]$. A glance at Figs. 1(a) and 1(b) shows that the active quark with momentum $k - \Delta/2$ has a longitudinal (+ component) momentum fraction $x + \xi$, whereas the one with momentum $k + \Delta/2$ has a longitudinal momentum fraction $x - \xi$. Therefore, one can identify two regions according to whether $|x| > \xi$ or $|x| < \xi$. When $x > \xi$, both quark propagators represent quarks, whereas for $x < -\xi$ both represent antiquarks. In these regions, the OFPD's are the generalizations of the usual parton distributions from DIS. In the region $-\xi < x < \xi$, one quark propagator represents a quark and the other one an antiquark. In this region, the OFPD's behave like a meson distribution amplitude. In this paper we shall restrict our considerations to the near forward direction because this kinematical domain is the closest to the one of the inclusive DIS, which we want to use as a guide. In this domain, the contribution of E and

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$\tilde{E}$, which goes like Δ, is suppressed. So we shall keep only H and $\tilde{H}$ in the following development and note that the inclusion of E and $\tilde{E}$ is straightforward according to Eq. (1).

The first moments of these OFPD's are related to the elastic form factors as [3]

$$\int_{-1}^{+1} dx H^q(x, \xi, t) = F_1^q(t), \tag{2}$$

$$\int_{-1}^{+1} dx \tilde{H}^q(x, \xi, t) = G_A^q(t). \tag{3}$$

According to the considered reaction, the proton OFPD's enter in different combinations due to the charges and isospin factors. For the DVCS on the proton, this combination is $H^p_{\mathrm{DVCS}}(x, \xi, t) = (4/9)H^{u/p} + (1/9)H^{d/p} + (1/9)H^{s/p}$, and similarly for $\tilde{H}$. For the electroproduction of ρ^0 and π^0 on the proton, the isospin structure yields the combination $H^p_{\rho^0}(x, \xi, t) = (1/\sqrt{2})\{(2/3)H^{u/p} + (1/3)H^{d/p}\}$ and $\tilde{H}^p_{\pi^0}(x, \xi, t) = (1/\sqrt{2})\{(2/3)\tilde{H}^{u/p} + (1/3)\tilde{H}^{d/p}\}$. The elastic form factors for one quark flavor that appear in Eqs. (2) and (3) have to be related to the physical ones. Restricting oneself to the u, d, and s quark flavors, this yields $F_1^{u/p} = 2F_1^p + F_1^n + F_1^s$ and $F_1^{d/p} = 2F_1^n + F_1^p + F_1^s$, where F_1^p and F_1^n are the proton and neutron electromagnetic form factors, respectively, and where the strange form factor is given by $F_1^{s/p} \equiv F_1^s$ ($= 0$ in the following calculations). For the axial vector form factors, one uses the isospin decomposition: $G_A^{u/p} = (1/2)G_A + (1/2)G_A^o$ and $G_A^{d/p} = -(1/2)G_A + (1/2)G_A^o$. The isovector axial form factor G_A is known from experiment [$G_A(0) \approx 1.26$] and for the unknown isoscalar axial form factor G_A^o we use the quark model relation: $G_A^o(t) = (3/5)G_A(t)$.

Using the parametrization of Eq. (1) for the lower blob in Figs. 1(a) and 1(b), the leading order DVCS amplitude was derived in Ref. [3]. Notice that although the leading order DVCS amplitude (denoted as $H^{\mu\nu}_{\mathrm{L.O.\,DVCS}}$ in the following) is exactly gauge invariant with respect to the virtual photon, it is gauge invariant with respect to the real photon only in the forward direction. This violation of gauge invariance is a higher twist effect that is innocuous in the limit $Q^2 \to \infty$, but for actual experiments it may matter. We have investigated this by restoring gauge invariance in the following heuristic way:

$$H^{\mu\nu}_{\mathrm{DVCS}} = H^{\mu\nu}_{\mathrm{L.O.\,DVCS}} + \frac{\tilde{p}^\mu}{(\tilde{p} \cdot q')} (\Delta_\perp)_\lambda H^{\lambda\nu}_{\mathrm{L.O.\,DVCS}}, \tag{4}$$

where the corrective term is a higher twist effect and vanishes in the forward direction. We checked that for the cross sections and in the kinematics that we have explored, the effect of this gauge correcting term according to Eq. (4) is numerically negligible.

The factorization between the short- and long-distance processes in the DVCS amplitude to all orders in perturbation theory was addressed in several recent works [6–8]. For the electroproduction of π^0 and ρ^0_L, a QCD factorization proof was given in Ref. [5] and is illustrated in Fig. 1(b). It generalizes previous results [9,10] and applies when the virtual photon is longitudinally polarized because in this case the end-point contributions in the meson wave function are power suppressed. We calculated the leading twist amplitude given by the diagrams of Fig. 1(c) and found the following gauge invariant expressions:

$$\begin{Bmatrix} \mathcal{M}^\mu_{\rho^0_L} \\ \mathcal{M}^\mu_{\pi^0} \end{Bmatrix} = (ie4\pi\alpha_s)\,\frac{4}{9}\,\frac{x_B}{Q^2}\left[\int_0^1 dz\,\frac{\Phi(z)}{z}\right]\left\{\tilde{p}^\mu + \frac{Q^2}{2x_B^2}\,n^\mu\right\}$$
$$\times\,\frac{1}{2}\,\bar{N}(p')\begin{Bmatrix} \not{n} \\ \not{n}\gamma_5 \end{Bmatrix}N(p)\int_{-1}^{+1} dx\left[\frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon}\right]\begin{Bmatrix} H^p_{\rho^0_L}(x, \xi, t) \\ \tilde{H}^p_{\pi^0}(x, \xi, t) \end{Bmatrix}, \tag{5}$$

where $\Phi(z)$ is the meson distribution amplitude (DA). For the pion, recent data [11] for the $\pi^0\gamma^*\gamma$ transition form factor up to $Q^2 = 9\ \mathrm{GeV}^2$ support the asymptotic form for the pion DA: $\Phi_\pi(z) = \sqrt{2} f_\pi 6z(1 - z)$ with $f_\pi = 0.093$ GeV from the pion weak decay. For the rho meson, a recent theoretical analysis [12] favors a DA that is also rather close to its asymptotic form, which we adopt in this work: $\Phi_\rho(z) = \sqrt{2} f_\rho 6z(1 - z)$ with $f_\rho = 0.153$ GeV determined from the electromagnetic decay $\rho^0 \to e^+e^-$.

Although ultimately one wants to extract the OFPD's from data, in order to evaluate electroproduction observables, we need a first guess for the OFPD's. To this end, we assume that, at small $-t$, H^q is proportional to the unpolarized quark distribution for which we take the MRS (S_o) parametrization [13]. The valence parts of the quark distributions are normalized as $\frac{1}{2}\int_0^{+1} dx\, u_V(x) = \int_0^{+1} dx\, d_V(x) = 1$. Our factorized ansatz thus yields $H^{u/p}(x, \xi, t) = (1/2)u(x)F_1^{u/p}(t)$, $H^{d/p}(x, \xi, t) = d(x)F_1^{d/p}(t)$, and $H^{s/p}(x, \xi, t) = 0$, and obviously satisfies the sum rule Eq. (2). Similarly, we assume that $\tilde{H}^q(x, \xi, t)$ is proportional to the polarized quark distribution. For the latter we adopt the parametrizations of Ref. [14]: $\Delta u_V(x) = \cos\Theta_D(x)[u_V(x) - (2/3)d_V(x)]$, $\Delta d_V(x) = \cos\Theta_D(x)[-(1/3)d_V(x)]$, with $\cos\Theta_D(x) = (1 + H_o(1 - x)^2/\sqrt{x})^{-1}$, and $H_o = 0.06$ such that the Bjorken sum rule is satisfied. We have $\int_0^{+1} dx \Delta u_V(x) = 0.98$ and $\int_0^{+1} dx \Delta d_V(x) = -0.27$, which leads to the correct proton to neutron magnetic moment ratio $\mu_p/\mu_n \approx -1.47$. Our ansatz for $\tilde{H}^q$ yields $\tilde{H}^{u/p}(x, \xi, t) = \Delta u_V(x) G_A^{u/p}(t)/G_A^{u/p}(0)$ and

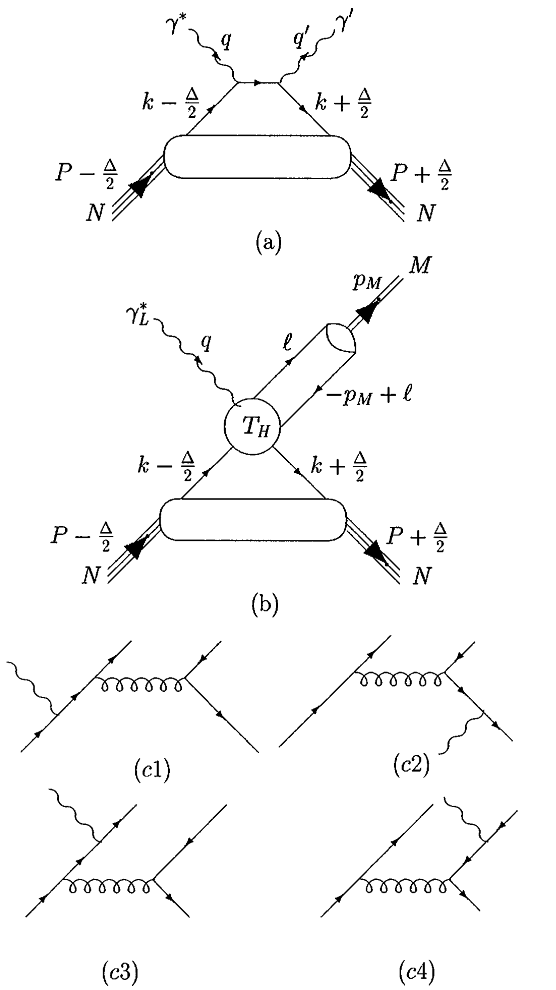

FIG. 1. (a) Handbag diagram for DVCS (the crossed diagram is not shown); (b) diagram for the factorized meson electroproduction amplitude; (c) leading order diagrams for the hard scattering part T_H of the meson electroproduction amplitude.

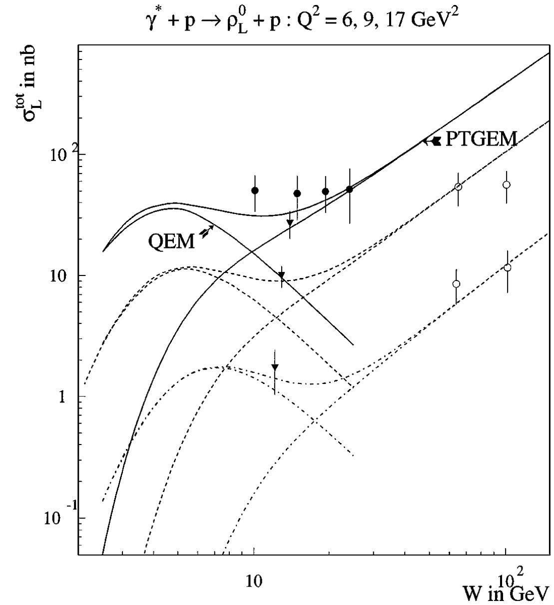

FIG. 2. Total longitudinal cross section for ρ_L^0 electroproduction. Data from NMC [18] (triangles) at $Q^2 = 5.5$ (highest point), 8.8 and 16.9 (lowest point) GeV^2, E665 [19] (black circles) at $Q^2 = 5.6$ GeV^2, and ZEUS [20] (open circles) at $Q^2 = 8.8$ (upper points) and 16.9 GeV^2 (lower points). Calculations are shown at $Q^2 = 6$ GeV^2 (full lines), $Q^2 = 9$ GeV^2 (dashed lines), and $Q^2 = 17$ GeV^2 (dash-dotted lines). The curves which grow at high W correspond with gluon exchange, whereas the curves which are peaked below $W \approx 10$ GeV correspond with quark exchange. The incoherent sum of both mechanisms is also shown.

$\tilde{H}^{d/p}(x, \xi, t) = \Delta d_V(x) G_A^{d/p}(t)/G_A^{d/p}(0)$. One can check that the sum rule of Eq. (3) is satisfied. Note that as suggested by the bag model estimate of Ji *et al.* [15], we have omitted any dependence of the OFPD's on ξ. Note also that this first guess for the OFPD's is reasonable in the region $|x| > \xi$ where the OFPD's generalize the ordinary parton distributions. In the region $|x| < \xi$, which contributes but is not predominant for the kinematical situations we consider in this Letter, this can be only a rough guess. Though the uncertainty it implies is probably small by the fact that our OFPD's satisfy the sum rules, this point should be improved in the future.

In Figs. 2 and 3 we show our results for the cross sections. In Fig. 2, the total longitudinal ρ_L^0 electroproduction cross section is shown as a function of the c.m. energy W for different values of Q^2. At high energies, the perturbative two-gluon exchange mechanism (PTGEM) [9,16] dominates for $Q^2 \geqslant 6$ GeV^2. The PTGEM cross section, calculated with Eq. (5) of [16] and using the CTEQ3L [17] gluon distribution, is shown in Fig. 2. It is seen that the PTGEM explains the fast increase at high energy of the cross section which is also confirmed by more recent ZEUS data [21]. However, the PTGEM substantially underestimates the data at lower energies (around $W \approx 10$ GeV), where the quark exchange mechanism (QEM) of Fig. 1(b) is expected to contribute since x_B is in the valence region. In Fig. 2 we show the predictions for the QEM of Eq. (5) using the factorized ansatz as outlined above. The incoherent sum of both mechanisms is also indicated (to calculate the coherent sum, one would also need to model the off-forward gluon distribution). Figure 2 provides a strong indication that the deviation from the PTGEM of the data at lower energies can be attributed to the onset of the QEM.

The QEM is studied further in Fig. 3 where the angular dependence of the fivefold differential DVCS, π^0 and ρ_L^0 muoproduction cross section is shown for kinematics accessible at COMPASS. As the DVCS amplitude is accessed through photon leptoproduction, it has the same final state and therefore interferes with the Bethe-Heitler (BH) process where the photon is emitted from the lepton lines. In our calculations we add coherently the BH and DVCS amplitude. From a phenomenological point of view, it is clear that the best situation occurs when the BH process is negligible. For fixed Q^2 and s, the only way to favor the DVCS over the BH is to increase the

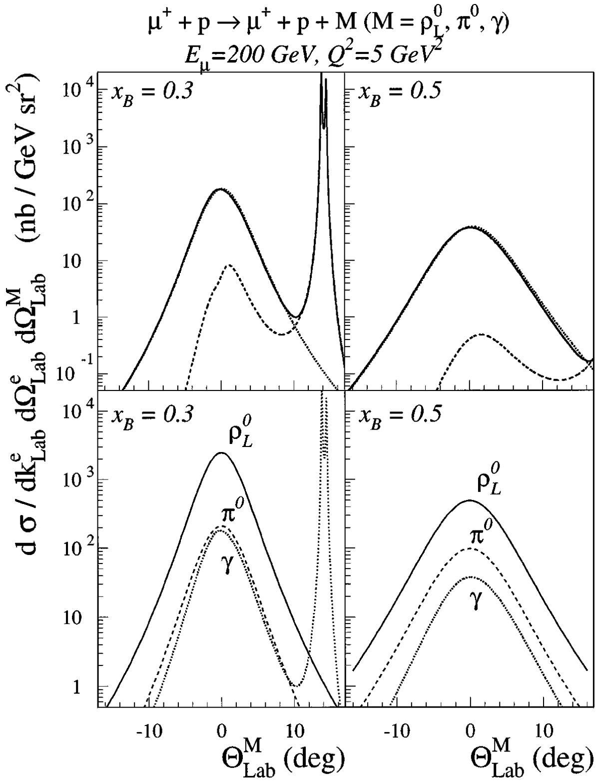

FIG. 3. Comparison between DVCS, BH, π^0, and ρ_L^0 for COMPASS kinematics. Upper part: DVCS (dotted lines), BH (dashed lines), and total γ (full lines). Lower part: Comparison between ρ_L^0 (full lines), π^0 (dashed lines), and total γ (dotted lines) muoproduction cross sections.

virtual photon flux, and this amounts to increasing the beam energy. According to our estimate, the unpolarized $(l, l'\gamma)$ cross section in the forward region is dominated by the BH process in the few GeV region, say CEBAF or HERMES. To get a clear dominance of the DVCS process one needs a beam energy in the 100 GeV range as in the COMPASS project. This is illustrated in the upper half of Fig. 3 where we show separately the BH, the DVCS, and the coherent cross section. In the forward direction, the DVCS cross section is more than 1 order of magnitude larger than the BH.

In the lower half of Fig. 3, the ρ_L^0, π^0, and γ cross sections are compared. In the valence region ($x_B \approx 0.3$), the ρ_L^0 cross section, which is sensitive to the unpolarized OFPD's, is about 1 order of magnitude larger than the π^0 cross section which is sensitive to the polarized OFPD's. The DVCS is also about 1 order of magnitude below the ρ_L^0 cross section due to the additional electromagnetic coupling. Although the ρ_L^0 cross section is the easiest to measure, the π^0 and DVCS cross sections seem large enough to encourage a study of their experimental feasibility. The three reactions are highly complementary due to their different dependence on the OFPD's. Furthermore, the differential cross sections ($d\sigma/dt$ at fixed x_B and t), for DVCS and for meson electroproduction by a longitudinal photon display a scaling behavior, respectively, as $1/Q^4$ and $1/Q^6$ (the difference being due to the extra gluon in the hard scattering amplitude for meson electroproduction compared to DVCS). Testing the scaling behavior is a prerequisite for the applicability of this PQCD formalism in actual experiments.

In summary, we have given the first estimates for the γ, π^0, and ρ_L^0 leptoproduction in the Bjorken regime. Our ansatz for the OFPD's allows one to interpret the few existing data in the Bjorken region which gives us some confidence in our estimates. We have shown that a potentially fruitful program can be considered at COMPASS. However, an exploratory window might already exist at HERMES and CEBAF ($E_e \geq 6$ GeV) at least for the meson electroproduction reactions where the problem of the Bethe-Heitler background does not exist. Although some theoretical issues (e.g., higher twist effects, ...) remain to be clarified, we are convinced that the fundamental interest of the OFPD's justifies an effort towards their experimental determination which will open up a new domain to study the quark/gluon structure of the nucleon.

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[1] G. Sterman *et al.*, Rev. Mod. Phys. **67**, 157 (1995).
[2] U. Stiegler, Phys. Rep. **277**, 1 (1996).
[3] X. Ji, Phys. Rev. Lett. **78**, 610 (1997); Phys. Rev. D **55**, 7114 (1997).
[4] A. V. Radyushkin, Phys. Lett. B **380**, 417 (1996).
[5] J. C. Collins, L. Frankfurt, and M. Strikman, Phys. Rev. D **56**, 2982 (1997).
[6] A. V. Radyushkin, Phys. Rev. D **56**, 5524 (1997).
[7] X. Ji and J. Osborne, hep-ph/9801260.
[8] J. C. Collins and A. Freund, hep-ph/9801262.
[9] S. J. Brodsky *et al.*, Phys. Rev. D **50**, 3134 (1994).
[10] A. V. Radyushkin, Phys. Lett. B **385**, 333 (1996).
[11] CLEO Collaboration, J. Gronberg *et al.*, Phys. Rev. D **57**, 33 (1998).
[12] P. Ball and V. M. Braun, Phys. Rev. D **54**, 2182 (1996).
[13] A. D. Martin, W. J. Stirling, and R. G. Roberts, Phys. Rev. D **47**, 867 (1993).
[14] M. Goshtasbpour and G. P. Ramsey, Phys. Rev. D **55**, 1244 (1997).
[15] X. Ji, W. Melnitchouk, and X. Song, Phys. Rev. D **56**, 5511 (1997).
[16] L. Frankfurt, W. Koepf, and M. Strikman, Phys. Rev. D **54**, 3194 (1996).
[17] H. L. Lai *et al.*, Phys. Rev. D **51**, 4763 (1995).
[18] M. Arneodo *et al.*, Nucl. Phys. **B429**, 503 (1994).
[19] M. R. Adams *et al.*, Z. Phys. C **74**, 237 (1997).
[20] M. Derrick *et al.*, Phys. Lett. B **356**, 601 (1995).
[21] ZEUS Collaboration, J. A. Crittenden *et al.*, in *Proceedings of Photon'97, Egmond aan Zee, The Netherlands, 1997* (World Scientific, River Edge, New Jersey, 1998).