A Letter of Intent to the Jefferson Lab PAC 21

Testing GPDs in Hard Exclusive Electroproduction of Neutral Pseudoscalar Mesons

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Abstract

Electroproduction of pseudoscalar mesons off the proton and deuterium using a 6 GeV electron beam and the CLAS detector at Jefferson Lab will be used to probe hard exclusive processes.

Significant suppression in hard exclusive production of pseudoscalar mesons on neutrons compared to protons was recently predicted in the framework of Generalized Parton Distributions (GPD). Striking differences were also predicted for relative rates of π^0 and η in the case of free protons and neutrons compared to coherent production off the deuteron. The large acceptance offered by the CLAS detector will allow measurement of final state π^0 and η mesons in coincidence with scattered electrons over a large kinematic range: $1 < Q^2 < 4.5$ GeV^2, $0.1 < x < 0.5$, and $0.1 < -t < 1$ GeV^2.

The measurement using a deuterium target, in combination with the data on π^0, η ratio rates collected during the approved DVCS measurements with the same CLAS configuration on the proton target, will provide a simple test of the applicability of GPD based predictions for hard exclusive production of pions at JLAB energies.

1 Introduction

Hard exclusive processes opened a new frontier to probe the physics of the quark bound states and basic properties of QCD. It was shown that the polarized parton densities can be probed in unpolarized collisions[1]. For the case of longitudinally polarized vector mesons, the parton densities are the regular quark momentum distributions (f_1 or q). For pseudo-scalar mesons the parton densities are the quark helicity distributions (g_1 or Δq) and for transversely polarized vector mesons, the parton densities are the quark transversity distributions(h_1 or δq).

The QCD factorization theorem has been generalized to a large group of hard exclusive processes [1],

$$\gamma^*(q) + T(p) \rightarrow M(q\,') + T'(p\,')$$

in which a photon γ^* with high energy and large virtuality $-q^2 = Q^2 > 0$ scatters off the hadronic target T and produces a meson M (where the mass is small compared to Q^2).

It was shown that the amplitude of this reaction can be written in the form [1] :

$$\sum_{i,j} \int_0^1 dz \int dx_1 f_{i/p}(x_1, x_1 - x_B; t, \mu)\, H_{ij}(Q^2 x_1/x_B, Q^2, z, \mu)\, \phi_j(z, \mu) \\ + \text{power-suppressed corrections,} \tag{1}$$

where $f_{i/p}$ is a generalized parton distribution (GPD) for partons of type i in hadron p, x_1 is the fraction of the target momentum carried by the interacting parton, ϕ_j is the distribution amplitude (DA) of the meson, and H_{ij} is a hard-scattering coefficient, computable as a power series in the strong coupling constant $\alpha_s(Q)$. Since the meson has non-zero flavor, the parton j is restricted to be a quark. The amplitude depends also on the Bjorken variable $x_B = Q^2/2(pq)$, and on the momentum transfer squared $t = (p - p\,')^2$ which is assumed to be much smaller than the hard scale Q^2. The GPDs $f_{i/p}$ and the meson DAs ϕ_j contain the non-perturbative physics and H_{ij} the perturbative one. The scale μ in Eq.(1) as usual for the factorization relations is $\sim Q$, hence there is a direct relation between meson wave functions probed in hard exclusive two-body processes and in form factor physics.

It was also shown that the ghost pole hypothesis introduced by Veneziano [2] to provide a satisfactory explanation of the spectrum of the low-lying pseudoscalar mesons in QCD, leads to observable phenomena in the hard exclusive electroproduction of pseudoscalar mesons. This means that one can probe the physics of the spontaneous chiral symmetry breaking in hard exclusive processes. A number of predictions for the ratios of certain cross sections for hard exclusive production of pseudoscaler mesons were derived from the low-energy ghost-pole physics [3].

The dominance of hard-gluon exchange processes can only be confirmed theoretically for sufficiently large values of Q^2 ($Q^2 > 10$) [4], but there are expectations that asymmetry and ratio observables may achieve *precocious scaling* already at moderate $Q^2 \sim 5GeV^2$.

CLAS measurements with 6 GeV electron beam (with inner calorimeter) of Q^2 dependencies of ratios of π^0 and η rates in hard exclusive scattering off the proton and coherent and incoherent scattering off the deuteron targets will check that experimentally.

The GPD based calculations were performed for the case when the incoming virtual photon is longitudinally polarized. The cross section for the transversely polarized photons is suppressed by a power of Q[1], but at CLAS energies it may still be significant. Comparison of ratios performed at lower beam energies (data from E94-017 e5 CLAS experiment) may give additional information on the contribution from transversely polarized photons.

2 Electroproduction of Pseudoscalar Mesons

The pion electroproduction (hard scattering) amplitude $\mathcal{M}^L_\pi$ for a longitudinal virtual photon in leading order in Q in terms of GPDs could be written in the form:

$$\begin{aligned} \mathcal{M}^L_\pi &= -ie\,\frac{4}{9}\,\frac{1}{Q}\,\left[\int_0^1 dz\frac{\Phi_\pi(z)}{z}\right]\,\frac{1}{2}\,(4\pi\alpha_s) \\ &\times \left\{A_{\pi N}\;\bar{N}(p')\,\not{n}\gamma_5\,N(p)\;+\;B_{\pi N}\;\bar{N}(p')\,\gamma_5\frac{\Delta\cdot n}{2m_N}\,N(p)\right\}, \end{aligned} \qquad (2)$$

where $\Phi_\pi(z)$ is the pion distribution amplitude, and where α_s is the strong coupling constant.

For $\pi^0 p$, the amplitudes A and B in Eq. (2) are given by [5, 6] :

$$A_{\pi^0 p} = \int_{-1}^{1} dx \, \frac{1}{\sqrt{2}} \left(e_u \, \widetilde{H}^u - e_d \, \widetilde{H}^d \right) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}, \tag{3}$$

$$B_{\pi^0 p} = \int_{-1}^{1} dx \, \frac{1}{\sqrt{2}} \left(e_u \, \tilde{E}^u - e_d \, \tilde{E}^d \right) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}. \tag{4}$$

For the η electroproduction, when neglecting the effects of the QCD axial anomaly, the corresponding amplitudes A and B as in Eq. (2) are given by [5] :

$$A_{\eta p} = \int_{-1}^{1} dx \, \frac{1}{\sqrt{6}} \left(e_u \, \widetilde{H}^u + e_d \, \widetilde{H}^d - 2 \, e_s \, \widetilde{H}^s \right) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}, \tag{5}$$

$$B_{\eta p} = \int_{-1}^{1} dx \, \frac{1}{\sqrt{6}} \left(e_u \, \tilde{E}^u + e_d \, \tilde{E}^d - 2 \, e_s \, \tilde{E}^s \right) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}. \tag{6}$$

In the forward limit, the GPD $\tilde{H}$ reduces to the quark helicity distribution $\Delta q(x)$ known from DIS :

$$\tilde{H}^q(x, 0, 0) = \begin{cases} \Delta q(x), & x > 0 \, , \\ \Delta \bar{q}(-x), & x < 0 \, . \end{cases} \tag{7}$$

In the limit of exact $SU(3)$ symmetry, neglecting the axial anomaly the ratios of yields of neutral mesons in hard exclusive diffractive electroproduction can be written in the form [3]

$$\pi^0 : \eta = \frac{1}{2} \left(\frac{2}{3} \Delta u + \frac{1}{3} \Delta d \right)^2 : \frac{1}{6} \left(\frac{2}{3} \Delta u - \frac{1}{3} \Delta d + \frac{2}{3} \Delta s \right)^2 \tag{8}$$

where Δu, Δd and Δs are the helicity distribution functions of the quarks in the target.

Within simple assumptions ($\Delta s = 0$ and $\Delta d \approx -\Delta u$), the cross section ratios for proton were predicted to behave like [1]:

$$\pi^0 : \eta = 1 : 3, \tag{9}$$

Due to the presence of the QCD axial anomaly in the neutral channel, and due to an explicit flavor $SU(3)$ breaking by the current quark masses this ratio for the same approximation ($\Delta s = 0$ and $\Delta d \approx -\Delta u$) behave like:

$$\pi^0 : \eta = 1 : 4.8. \tag{10}$$

This change was attributed to enhancement of the η coupling with the u and d quarks[3].

The same formalism in case of coherent scattering off the deuteron for naive $SU(3)$ symmetric result for the cross sections ratios is given by the relationship

$$\pi : \eta = 27 : 1 \tag{11}$$

while the calculation with account of the chiral anomaly and $SU(3)$ breaking leads to the result

$$\pi : \eta = 27 : 1.6 \tag{12}$$

which is markedly different from the case of scattering off the proton as well as off the neutron.

Equations 9-12 are only for estimates. To extract the ratios as a function of Bjorken x one has to use the realistic polarized parton distributions. The cross section ratios for η and π^0 off nucleons as a function of x_B were estimated [3] using the polarized distribution functions from [7]. Calculations were performed neglecting effects of skewedness of relevant parton densities for $Q^2 = 20\ GeV^2$. It was also shown, that due to a rather small scaling violation in the valence quark channels the results depend very weakly on Q^2 scale of the parton densities ($\leq 10\%$). The ratios of π^0 and η rates using a simple approximation for polarized distribution functions from Brodsky, Burkardt and Schmidt (BBS) [8] are plotted in Figs. 1 and 2. Due to a significant suppression of exclusive π^0 and η production off the neutron, the ratio of π^0 (η) cross section off the deuteron and proton are well below unity (see Fig. 1 (solid line for π^0)). The double ratio of π^0 to η for coherent and incoherent production on deuteron (Fig.2 solid line) shows a very significant suppression of η coherent production. Similar dependence is available for π^0 to η ratios off the proton and deuteron (coherent case) on the Fig.2 (dashed line).

The ratios of π^0, η on deuteron and proton are providing a unique possibility to probe the $\Delta d/\Delta u$ in a model independent way from unpolarized target measurements.

Strong suppression of coherent diffraction off the deuteron as compared to the breakup channel due to a spin flip in the deuteron vertex was pointed out in [3]. The shape of the t dependence of the coherent scattering off the deuteron will provide a test whether spin flip dominates or not.

The "semi-exclusive" processes $\gamma^* + N \to M + (\pi N)$, in which the target nucleon dissociates into a low mass πN system have been discussed as well [3]. The relation between the electroproduction cross sections of π, η in Δ channel calculated in the same way as in case of nucleon coincides (at low t) with the one obtained in Eq.(10)[3].

The description of "semi-exclusive" processes in terms of GPD is very important, because in the high energy experiments the resolution in the missing mass of the recoil baryonic system can be rather low. Another advantage is that strange quarks within a proton are not giving a contribution and amplitude of this production process is expressed exclusively in terms of the valence quark distributions.

In the threshold region, where $m_{\pi N} \to m_\pi + m_N$ the πN GPDs can be expressed in terms of nucleon and pion GPDs.

For neutral pions, the leading order amplitude for longitudinal $\pi\Delta$ electroproduction on the proton is given by[9, 10]

$$\begin{aligned}
\mathcal{M}^L\left(\gamma^* p \to \pi^0 \Delta^+\right) &= -ie\,\frac{4}{9}\,\frac{1}{Q}\,\left[\int_0^1 dz \frac{\Phi_\pi(z)}{z}\right]\left(\frac{1}{\sqrt{2}}\frac{e_u+e_d}{2}\right) \\
&\times \frac{1}{2}\int_{-1}^{+1} dx \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon}\right](4\pi\alpha_s) \\
&\times \bar{\psi}^\beta(p')\left\{C_1(x,\xi,t)\,n_\beta + C_2(x,\xi,t)\,\Delta_\beta\,\frac{\Delta\cdot n}{m_N^2}\right. \\
&\quad + C_3(x,\xi,t)\,\frac{1}{m_N}\,(\not{\Delta}\,n_\beta - \not{n}\,\Delta_\beta) \\
&\quad \left. + C_4(x,\xi,t)\,\frac{2}{m_N^2}\left(\Delta\cdot\bar{P}\,n_\beta - \Delta_\beta\right)\right\} N(p)\ . \quad (13)
\end{aligned}$$

The functions C_i are quark helicity dependent $p \to \Delta^+$ generalized quark distributions. Not all independent, they can be expressed in terms of nucleon GPDs.

$$\begin{aligned}
C_1(x,\xi,t) &= \sqrt{3}\left[\tilde{H}^u(x,\xi,t) - \tilde{H}^d(x,\xi,t)\right], \\
C_2(x,\xi,t) &= \frac{\sqrt{3}}{4}\left[\tilde{E}^u(x,\xi,t) - \tilde{E}^d(x,\xi,t)\right]. \quad (14)
\end{aligned}$$

For the production of neutral pseudoscalar mesons estimated relations between cross sections give : $\sigma_L^{\gamma^* p\to\eta(\eta')\Delta^+} \ll \sigma_L^{\gamma^* p\to\eta(\eta')p}$, and $\sigma_L^{\gamma^* p\to\pi^0\Delta^+} \approx 0.1\ \sigma_L^{\gamma^* p\to\pi^0 p}$.

There are already some predictions for the ratio of N to Delta [9] which is interesting quantity by itself. The missing mass distribution of two photons is typically wide and the fact that ratios are not sensitive to its value could be very important in case the final proton and deuteron are not detected.

3 Experimental Configuration and Objectives

The main goal of the proposed study is to measure the momentum transfer t and Bjorken x dependence of π, η ratios for several fixed Q^2 bins (see. Fig. 3).

The π^0, η in the exclusive and "semi-exclusive" limit are produced mainly in the forward direction, so the presence of the inner calorimeter [11] is crucial. The CLAS will be used in a configuration similar to what has been proposed for the dedicated DVCS measurement [11] with target located $\sim 60\ cm$ upstream of CLAS center. The π^0, η ratios from the proton target will be extracted during the DVCS running.

On the deuteron target the cross section ratios will be measured both in coherent (Deuteron detected) and break-up channels. The following is the list of reactions:

$$e + d = e' + d' + 2\gamma \quad (15)$$
$$e + d = e' + [N] + 2\gamma \quad (16)$$
$$e + d = e' + p' + 2\gamma \quad (17)$$
$$e + p = e' + p' + 2\gamma \quad (18)$$

The list of observables for exclusive and semi-exclusive π^0 and η production off the deuteron target :

- Single ratios of π^0 and η on deuteron and proton targets.

  the ratio of π^0 cross section off the deuteron and proton.

  the ratio of η cross section off the deuteron and proton.

  the ratio of π^0 cross section off the deuteron for coherent and incoherent production.

  the ratio of η cross section off the deuteron for coherent and incoherent production.

- The double ratio of π^0, η production cross sections for coherent and incoherent production on the deuteron as a function of x_B .

- The double ratio of π^0, η production cross sections on proton and coherent production on the deuteron as a function of x_B.

CLAS allows simultaneous measurement of the above reactions in a wide range of different kinematic variables. The deuteron reconstruction efficiency was studied and it was shown, that CLAS is capable to reconstruct the deuteron starting from momentum transfer $t = 0.15\ GeV^2$ (see.[12] and Fig. 9 in it). Although for exclusive π^0, η mesons reconstruction using the missing mass technique will be also used, the main focus will be on their reconstruction from photon clusters in the CLAS forward and inner calorimeters. A typical invariant mass distribution of two photon clusters is shown in Fig.4. The cut on the missing mass of $e'\pi^0[\eta]$ system (Fig.4 left plot) will select out the exclusive and semi-exclusive events.

The acceptance and efficiency effects are largely canceling out in ratio and double ratio measurements.

4 Conclusions

We propose a measurement of π^0, η yield ratios in hard exclusive and semi-exclusive scattering of 6 GeV electrons off a proton and deuterium target. These ratios will be studied as a function of t and x for different bins in Q^2. The Q^2 dependence of ratios for different bins in Bjorken x will provide additional information on mass effects at low Q^2. The measurements of π^0, η rate ratios and double ratios in the hard exclusive limit from a deuterium target combined with the same ratios from the proton target will provide a simple test of GPD based predictions at CLAS energies.

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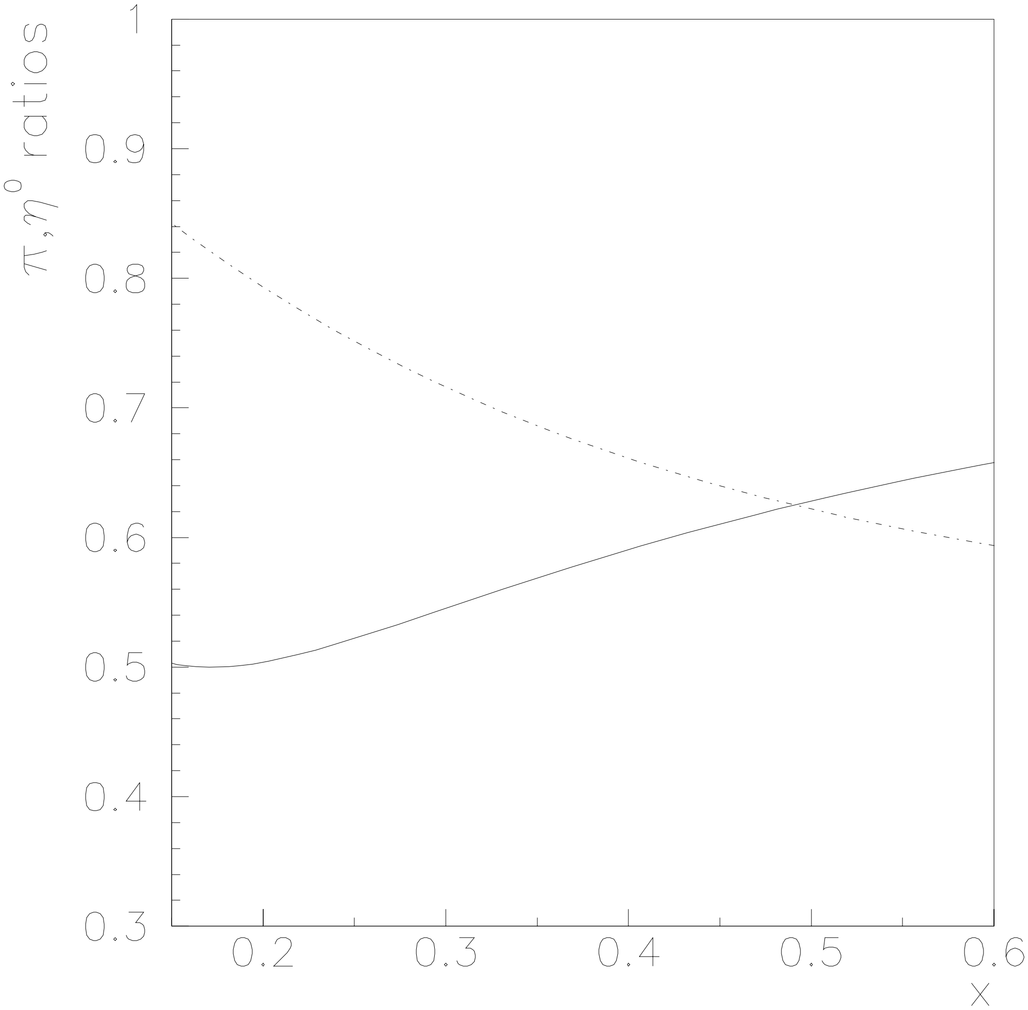

Figure 1: The x dependence of the ratio $\sigma(\gamma_L + D \to \pi^0(\eta) + N)/\sigma(\gamma_L + p \to \pi^0(\eta) + p)$ for the deuteron and proton targets calculated using BBS approximation for polarized distribution functions [8] and the Eq.8 . The solid line is for π^0 and dashed for η.

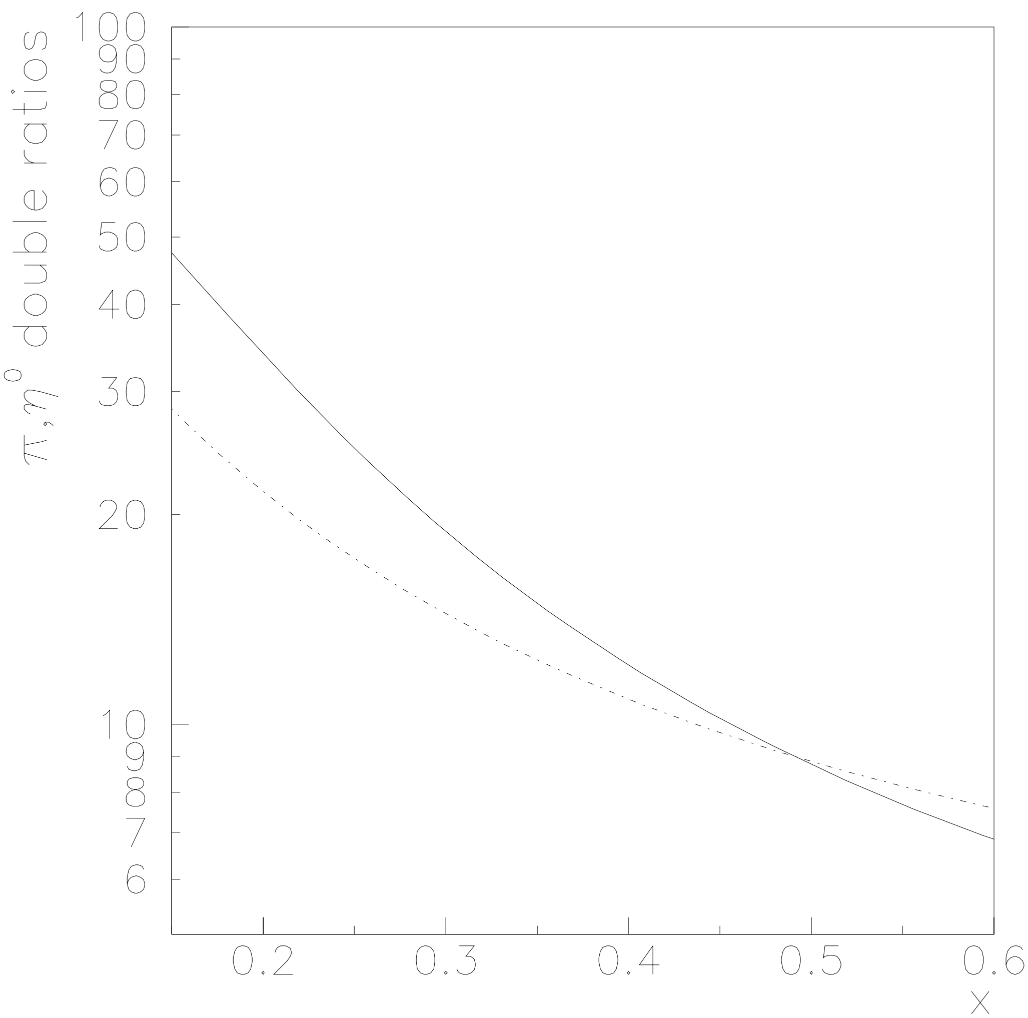

Figure 2: The x dependence of the double ratios of π/η coherent production ratios on deuteron to incoherent production off the deuteron and the proton. The $\sigma(\gamma_L + D \to \pi^0 + D)/\sigma(\gamma_L + D \to \eta + D)$ to $\sigma(\gamma_L + D \to \pi^0 + N)/\sigma(\gamma_L + N \to \eta + N)$ (solid line) and $\sigma(\gamma_L + p \to \pi^0 + p)/\sigma(\gamma_L + p \to \eta + p)$ (dashed line). Curves are calculated using the Eq.8 and polarized distribution functions from [8]

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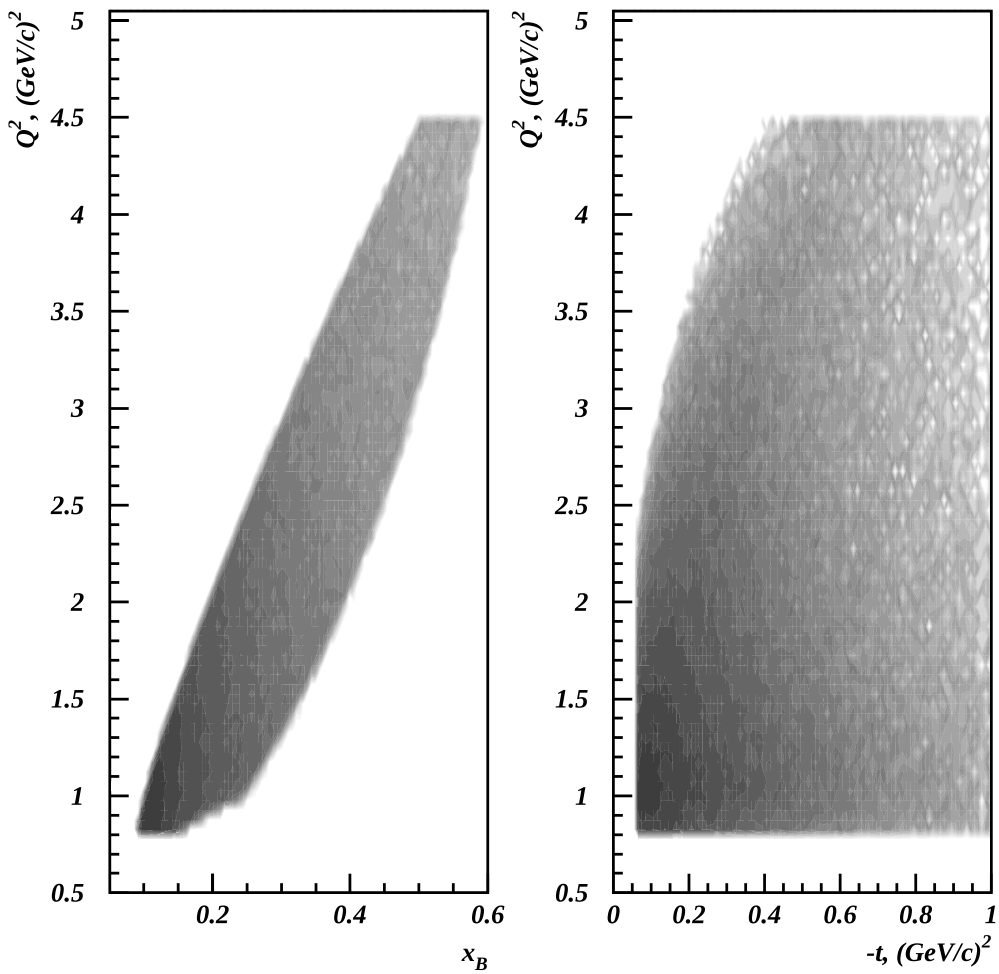

Figure 3: The Kinematic range in Q^2,x and t for the beam energy 6 GeV, torus current 3375A and target position -60cm
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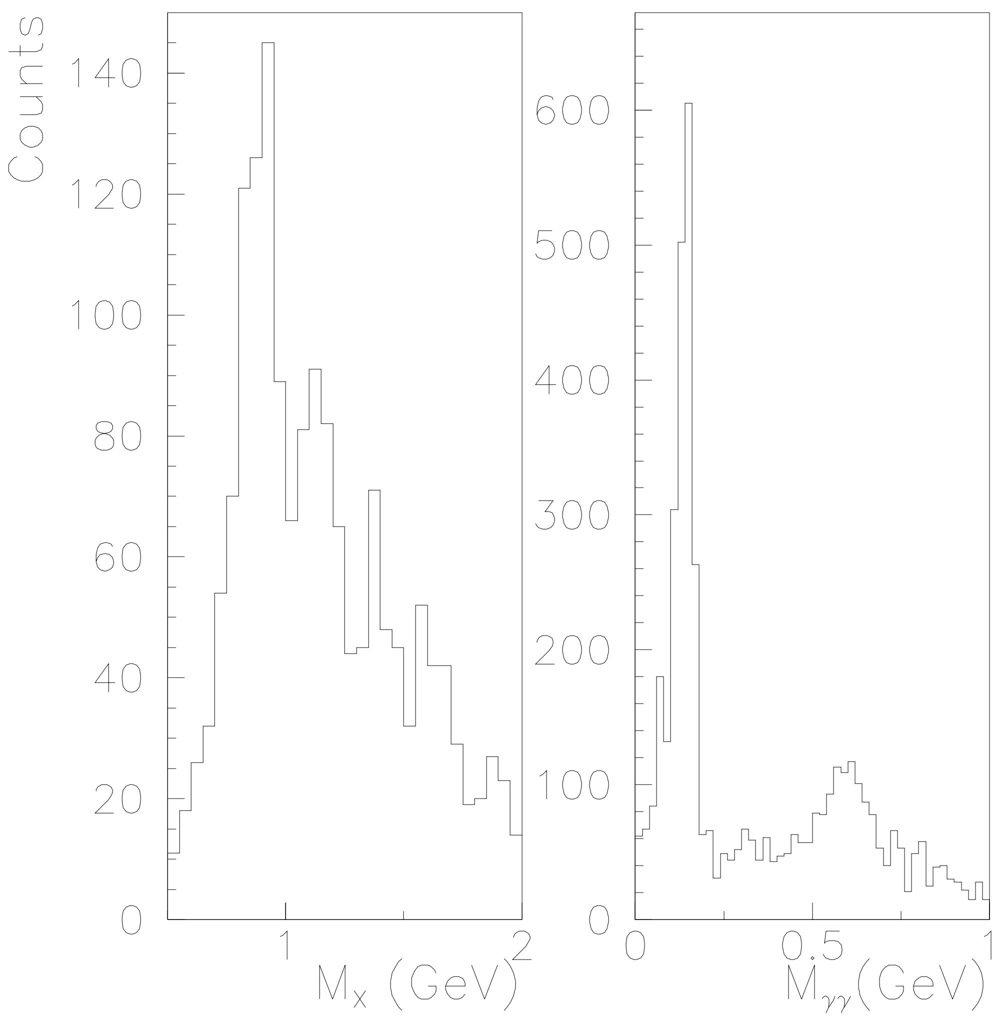

Figure 4: The missing mass of $(e'\pi^0 X)$ system (left) and the invariant mass of 2 photon clusters (right) in the exclusive limit $(-t < 1)$ for the beam energy 6 GeV (e1-6 data)
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