LOI-PAC38

e^+e^-pair production with CLAS12 at 11 GeV

R. Paremuzyan,[1] T. Horn,[2] I. Albayrak,[2] F.J. Klein,[2] Y. Ilieva,[3] P. Nadel-Turonski,[4] C. Weiss,[4] V. Guzey,[4] C. Salgado,[5] C. Hyde,[6] M. Osipenko,[7] M. Guidal,[8] F. Sabatié,[9] and S. Stepanyan*[4]

[1] *Yerevan Physics Institute, 375036 Yerevan, Armenia*

[2] *Catholic University of America, Washington, D.C. 20064*

[3] *University of South Carolina, Columbia, South Carolina 29208*

[4] *Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606*

[5] *Norfolk State University, Norfolk, Virginia 23504*

[6] *Old Dominion University, Norfolk, Virginia 23529*

[7] *Istituto Nazionale di Fisica Nucleare, Sezione di Genova e Dipartimento di Fisica dellÚniversita, 16146 Genova, Italy*

[8] *Institut de Physique Nucleaire d'Orsay, IN2P3, BP 1, 91406 Orsay, France*

[9] *CEA, Centre de Saclay, Irfu/Service de Physique Nucléaire 91191 Gif-sur-Yvette, France*

(Dated: June 29, 2011)

Electron-positron pairs are produced in large numbers in the scattering of high-energy electrons off nucleons and nuclei. The CEBAF 12 GeV upgrade will make it possible to reach di-lepton invariant masses of up to 3.4 GeV. There is a rich physics accessible with di-lepton final states in this mass range. In this letter we propose measurements of exclusive and inclusive e^+e^-pair production using the CLAS12 detector in Hall B with an 11 GeV electron beam. A large part of the proposed measurements can be carried out in parallel with other high-energy electroproduction experiments.

The proposed experimental program includes studies of Generalized Parton Distributions (GPDs) for quarks in the valence region using Time-like Compton Scattering (TCS), and the nucleon's gluonic structure at large x through J/Ψ photo- and electroproduction. TCS will be studied in the range of outgoing photon virtualities ($Q^{'2}$) from 4 GeV^2 to 9 GeV^2 (above the light–quark meson resonances and below charm threshold). J/Ψ production will be studied in the energy range from threshold (8.2 GeV) to 11 GeV.

* Contact

I. INTRODUCTION

A large fraction of the JLab 12 GeV physics program is devoted to understanding the quark and gluon structure of hadrons, and in particular, probing nucleon structure using deeply virtual exclusive reactions and the formalism of Generalized Parton Distributions (GPDs).

Deeply Virtual Compton Scattering (DVCS), $ep \to ep\gamma$, has seen intense theoretical and experimental studies in recent years, as it provides the cleanest tool for accessing the quark GPDs of the nucleon. The simplest observables in DVCS are (beam or target) spin-dependent cross section differences (asymmetries). These asymmetries measure the imaginary part of Compton Form Factors (CFFs), where GPDs enter at a specific kinematical point, $\xi = x$. Here, ξ is the generalized Bjorken variable, and x is the average light-cone momentum fraction of the struck quark. The real part of CFF is proportional to the integral of GPDs over x, and can only be accessed through measurements of the DVCS cross section, or the beam charge asymmetry. Studying the real part is important for modeling GPDs in the valence region. The real part is also sensitive to the so-called D-term, introduced in the modeling of GPDs to ensure the polynomiality of their Mellin moments.

Time-like DVCS, also known as Time-like Compton Scattering (TCS), is an inverse process of space-like DVCS that can be probed through the photoproduction of lepton pairs (l^+l^-). TCS can be an effective tool for studying the real part of the Compton amplitude. The real part of the BH–TCS interference can be extracted in a model independent way from the azimuthal angular distribution of the lepton pair. Combining space-like and time-like data thus offers additional constraints on the GPDs. With CLAS12 and an 11 GeV electron beam, angular asymmetries in TCS can be studied with sufficient statistics in wide range of outgoing photon virtuality, $Q'^2 = M^2_{e^+e^-}$, transferred momentum squared, t, and quark momentum fraction, τ.

The proposed experiment with CLAS12 would be the first measurement of J/Ψ photo– and electroproduction at low energies with a large–acceptance detector. The setup would allow the J/Ψ to be measured concurrently with other experiments. Plans for J/Ψ production at JLab have so far focused only on dedicated measurements with small–acceptance spectrometers. A proposal for J/Ψ photoproduction on nuclei close to threshold in JLab Hall C was conditionally approved by PAC32 (PR12-07-106) A Letter of Intent for J/Ψ electroproduction in Hall C at a single, relatively high Q^2 point, and hence with a significantly lower rate but better control of exclusivity, was reviewed by PAC37 (LOI12-11-002). Already with the 11 GeV beam time approved for CLAS12, J/Ψ photo- and electroproduction can be studied in great detail. Measurements on proton and nuclear targets will allow to understand the J/Ψ production mechanism close to the production threshold, access nucleon's gluonic structure, and study $J/\Psi - N$ interaction dynamics.

II. PHYSICS MOTIVATION

A. Time-like Compton Scattering

The simplest and cleanest way to probe the transverse spatial structure of the nucleon in the valence region is through Deeply Virtual Compton Scattering (DVCS), which is now well established and forms a cornerstone of the 12 GeV program at Jefferson Lab (JLab). DVCS is, however, only one limit of the general Compton process, $\gamma^* p \to \gamma^* p$, where either the initial-state or final-state photon can be real or virtual. In spacelike DVCS ($ep \to ep\gamma$), the final photon is real. Timelike DVCS, also known as Timelike Compton Scattering (TCS), is the "inverse" reaction of spacelike DVCS, where the incoming photon is real and the outgoing photon has a large timelike virtuality (Fig.1). TCS offers a complementary way of probing quark GPDs, and has recently sparked theoretical interest for ep scattering [1, 2], as well as in the context of ultraperipheral pp collisions [3] and e^+e^- radiative annihilation [4].

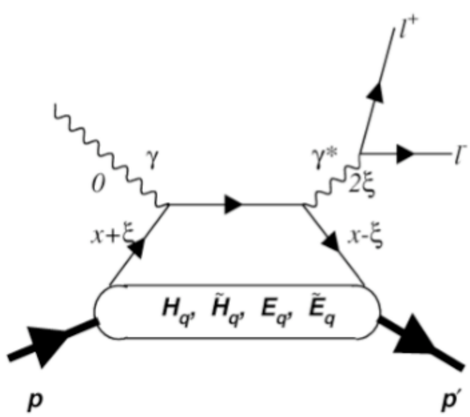

FIG. 1: "Handbag" diagram for Time-like Compton Scattering. The 'plus' component of the final state virtual photon is given by $q'^+ \approx 2\xi P^+$, with $P = (p + p')/2$. For TCS $\xi = \tau/(2 - \tau)$.

To leading order, the Compton amplitudes accessed through (spacelike) DVCS and TCS are equivalent, but the higher order corrections are not [5]. There are thus two primary reasons for performing both measurements. First, being able to extract the same amplitudes through two different processes will demonstrate that factorization and higher-order corrections are well understood for JLab kinematics, leading to a more reliable extraction of GPDs. Secondly, while measurements of the beam asymmetry in DVCS provides a great tool for probing the imaginary part, TCS provides straightforward access to the real part, which may be important at large Bjorken-x, the TCS analog of which is

$$\tau = \frac{Q'^2}{s + M^2} \tag{1}$$

Here Q' is the invariant mass of the lepton pair providing the hard scale, s is the c.m. energy squared, and M is the mass of the proton.

The simple access to the real part of the amplitude follows from TCS phenomenology. On one hand, the TCS cross section is smaller than the Bethe-Heitler (B-H) contribution for all kinematics. The TCS cross section can thus not be measured directly. However, the B-H enhances the interference term, which can be isolated with relative ease. This follows from that the Compton and B-H amplitudes transform with opposite sign under reversal of the lepton charge. Thus, while these two terms themselves are even under the exchange of the lepton momenta, the interference term is odd. Any observable that does change sign will therefore project out *only* the interference term. The angular distribution of the lepton pair (with respect to the angle φ between the reaction plane and lepton decay plane) is such an observable. The corresponding DVCS observable is the beam charge asymmetry, the measurement of which requires combining data taken with both electron and positron beams, with a very good control of the systematics.

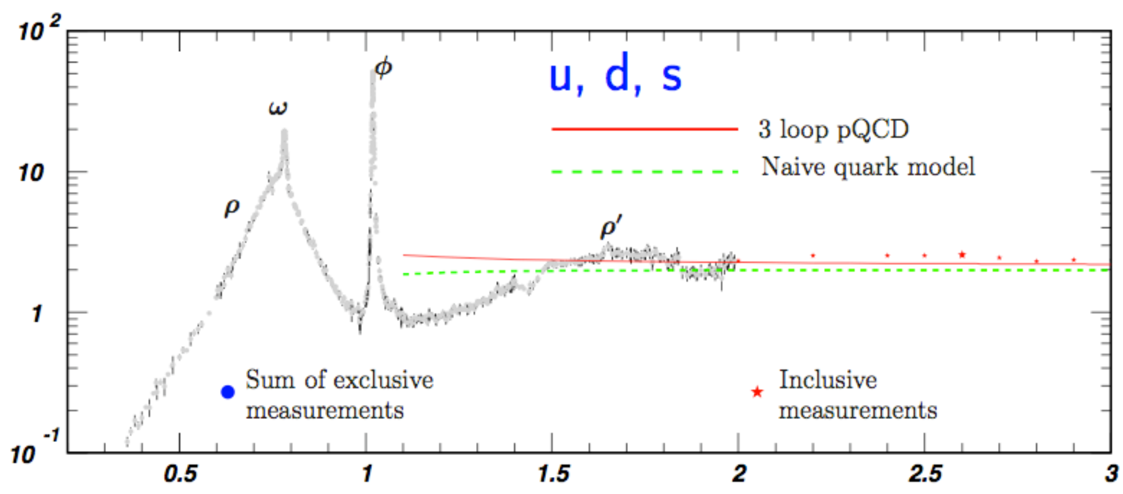

FIG. 2: The ratio $R(s) = \frac{\sigma(e^+e^- \to hadrons, s)}{\sigma(e^+e^- \to \mu^+\mu^-, s)}$ as a function of $\sqrt{s}$ (invariant mass of e$^+$e$^-$). The proposed $\gamma p \to e^+e^-p$ experiment will study the e^+e^- mass range above 1.5 GeV.

In case of an unpolarized photon beam, the interference term depends only on the real part of the Compton amplitudes. With circular photon polarization, a second part of the term is added that depends on the imaginary part and the level of photon polarization, λ:

$$\begin{aligned}\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} \;=\; & -\frac{\alpha_{em}^3}{4\pi s^2}\,\frac{1}{-t}\,\frac{M}{Q'}\,\frac{1}{\tau\sqrt{1-\tau}}\,\frac{L_0}{L}\left[\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\tilde{M}^{--}\right.\\ & \left. -\cos 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Re}\tilde{M}^{0-}+\cos 3\varphi\,\sin\theta\,\mathrm{Re}\tilde{M}^{+-}+O\Big(\frac{1}{Q'}\Big)\right]\\ & -\lambda\,\frac{\alpha_{em}^3}{4\pi s^2}\,\frac{1}{-t}\,\frac{M}{Q'}\,\frac{1}{\tau\sqrt{1-\tau}}\,\frac{L_0}{L}\left[\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\tilde{M}^{--}\right.\\ & \left. -\sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\tilde{M}^{0-}+\sin 3\varphi\,\sin\theta\,\mathrm{Im}\tilde{M}^{+-}+O\Big(\frac{1}{Q'}\Big)\right]. \end{aligned} \tag{2}$$

with L and L_0 defined as:

$$L = \left[(q-k)^2 - m_e^2\right]\left[(q-k')^2 - m_e^2\right] = \frac{(Q'^2-t)^2-b^2}{4}, \tag{3}$$

$$L_0 = \frac{Q'^4\sin^2\theta}{4}, \tag{4}$$

and $b = 2(k-k')\cdot(p-p')$.

An attractive feature of this Fourier development of the cross section is the partial separation of leading-twist and higher twist terms. The $\tilde{M}^{--}$ terms are dominated by the leading-twist GPDs. The $\tilde{M}^{0-}$ terms are twist-3 to leading order, and the $\tilde{M}^{+-}$ terms are dominated by the twist-3 transversity GPDs. Calculations of $Re[\tilde{M}^{--}]$ have, for instance, suggested a sensitivity in the t-dependence to the sign and magnitude of the Polyakov-Weiss D-term [1].

The timelike final-state does, however, also present some complications. Experimentally, meson resonances pose a constraint on the $Q^{'2}$ coverage. Fortunately, the 11 GeV beams accessible in Hall B after the 12 GeV upgrade will cover the full mass range between the ρ' and J/Ψ corresponding to $Q^{'2}$ from 4 GeV^2 to 9 GeV^2, where as we know from e^+e^- collider data that pQCD is accurate (Fig.2). Nevertheless, the reaction mechanism in the TCS process displays important differences compared to e^+e^- annihilation, and experimental data will be needed to determine applicability of leading order perturbation theory. In the experiment, azimuthal asymmetries in TCS will be studied as a function of $Q'^2 = M^2_{e^+e^-}$, quark momentum fraction, τ, and the transferred momentum squared, t.

B. J/Ψ Production

The proposed measurement of e^+e^- pairs with CLAS12 would enable us to study photo– and eletroproduction of J/Ψ mesons on the nucleon, and possibly nuclear targets. Measurements of exclusive J/Ψ production in the near–threshold region ($E_{\gamma,\mathrm{thr}} = 8.21\,\mathrm{GeV}$) provide unique information on the nucleon's gluonic structure at large x, such as the spatial structure of the gluon fields and their correlation with the valence quarks. They complement studies of the nucleon's valence quark structure through high–t form factors and GPDs and provide important new insights into the non-perturbative dynamics in the valence region. They also complement measurements of exclusive J/Ψ photo– and electroproduction at high energies (HERA, FNAL, EIC), which probe the gluon GPDs at small x. Due to the small cross sections ($0.2-0.5\,\mathrm{nb}$ for photoproduction at $11\,\mathrm{GeV}$, rapidly falling toward threshold), exclusive J/Ψ production near threshold was never measured with the precision necssary to test the reaction mechanism and extract nucleon structure. The present CLAS12 experiment represents a unique opportunity to explore this unmeasured region.

Because of the small spatial size of heavy quarkonia on the hadronic scale ~ 1 fm it is generally expected that one can use QCD to describe their interactions with hadrons and external probes. Heavy quarkonium production probes the local color fields in the target, and can reveal properties such as their response to momentum transfer and their spatial distribution. While this unique sensitivity to gluons holds at all energies, the dynamics that produces the relevant gluon fields varies considerably between high energies and the near–threshold region, creating a fascinating landscape that calls for detailed experimental study. At high energies ($W > 10\,\mathrm{GeV}$) exclusive J/Ψ production probes the gluon GPD at momentum fractions $x_{1,2} \ll 1$, where QCD radiation plays an important role and the GPD can be related to the "diagonal" gluon density at $x \sim M^2_{J/\Psi}/W^2$ (see Fig. 3a). Experiments at HERA [6, 7] have confirmed this picture through measurements of the kinematic dependences and comparison with other exclusive vector meson channels; see Ref. [8] for a review. They have also measured the t–dependence of the gluon GPD and extracted the transverse spatial distribution of gluons in the nucleon and its change with x, which represents an essential input to small–x physics and the phenomenology of high–energy pp collisions with hard processes [9]. Measurements at lower enregies were performed in the FNAL broadband beam experiment ($E_\gamma \approx 100\,\mathrm{GeV}$) [10]. A detailed program of "gluon imaging" along these lines is planned with a future Electron–Ion–Collider (EIC) [11].

In exclusive J/Ψ photo/electrproduction near threshold, the minimum invariant momentum transfer to the nucleon becomes large: $|t_{\mathrm{min}}| = 2.23\,\mathrm{GeV}^2$ at threshold, and $|t_{\mathrm{min}}| = 1.3-0.4\,\mathrm{GeV}^2$ in the experimentally covered range $E_\gamma = 8.5 - 11\,\mathrm{GeV}$. The process is thus similar to elastic eN scattering at large $|t|$, only that the "probe" couples to the gluon field in the target. Because high–momentum components of the target wave function are required in order to bring about an exclusive transition, it is expected that color correlations play an essential role in this process, suggesting a new avenue for their experimental study. Several scenarios for near–threshold exclusive

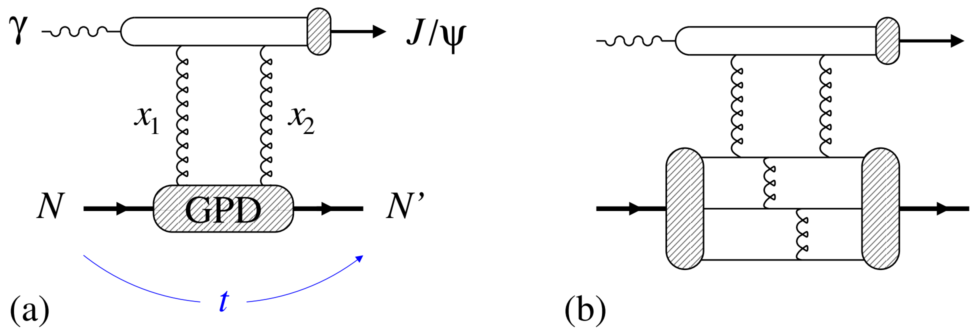

FIG. 3: Dynamical mechanisms of J/Ψ photoproduction. (a) Two–gluon exchange mechanism at high and intermediate energies, $W - W_{\rm th} \sim$ few GeV, based on QCD factorization for hard exlcusive meson production. (b) Coherent multi–gluon exchange proposed for near–threshold production, analogous to the hard scattering mechanism for high–t elastic form factors.

J/Ψ production on the nucleon have been proposed in the literature. One of them assumes that the two gluons exchanged with the small–size $c\bar{c}$ pair couple to a single valence quark in the nucleon ("handbag" diagram) [12]. The amplitude is again described by the gluon GPD, but now in the "extreme" near–threshold region characterized by large $|t_{\rm min}|$ and large "skewness" $x_1 \neq x_2$. Some support for this picture comes from the fact that the exclusive ϕ electroproduction data at JLab with 6 GeV beam energy [13, 14] can be well explained by such a factorized description with a specific model of the gluon GPD [15]. Another scenario is based on analogy with the hard scattering mechanism for high–t elastic form factors; it assumes that the production process happens in the leading 3–quark Fock component of the nucleon, and that the momentum transfer is balanced via hard gluon exchange (Fig. 3b) [16]. Other mechanisms to effect the necessary correlations in the wave function are based on the non–perturbative vacuum structure of QCD. The quantitative implementation of these scenarios are the subject of on-going theoretical research. The few existing data [17, 18] provide some rough constraints on the total cross cross section. The expected JLab 12 GeV data would allow us to discriminate between these scenarios for color correlations in the nucleon through precise differential measurements and thus greatly advance our knowledge of the gluonic structure of the nucleon at low energies.

Basic observables to be measured in exclusive J/Ψ photoproduction are the total cross section as a function of energy, $\sigma(W)$, and the t–dependence of the differential cross section $d\sigma/dt$ and its change with $W - W_{\rm th}$. In electroproduction, which would be measured for the first time with the proposed setup, additional tests of the hardness of the reaction (small size of the J/Ψ) are possible through measurements of the Q^2 dependence. Of particular interest for discriminating between different scenarios for the production mechanism near threshold is the ratio of imaginary and real parts of the production amplitude. While at high energies it is known that the production amplitude is mostly imaginary (absorptive), near threshold the real part is becoming progressively more important. With the proposed setup with CLAS12 the real to imaginary ratio could possibly be constrained through the measurement of polarization observables in electroproduction.

Measurements on nuclear targets should be considered as a way to study the gluonic structure of nuclei and the $J/\Psi - N$ interaction. There is already a significant amount of beam time approved for 11 GeV running in Hall B with deuteron and nuclear targets. The former can be used to study quasi-free J/Ψ production on the neutron, coherent production on the deuteron, and by comparison with the free proton target, for measuring rescattering effects in experimentally well defined kinematics. Such experiments could be of interest once production on the nucleon is understood.

III. EXPERIMENT

Electroproduction data from CLAS12 will be used to perform the aforementioned studies. As in the approved meson spectroscopy experiment [19], exclusive and semi-exclusive final states will be used to identify (e^+e^-) pair production over a wide range of total c.m. energy, s, and transferred momentum squared, t, for invariant masses up to $M_{e^+e^-} \sim 3.3$ GeV.

A large part of the proposed 12 GeV beam time has already been approved by the JLab PAC for running electroproduction experiments in Hall-B using a liquid hydrogen target and 11 GeV longitudinally polarized electron beam. The CLAS12 detector, shown in Fig. 4, has design features that are essential for probing the new physics in deeply virtual exclusive reactions. One of the key improvements for CLAS12 will be the increase in the operating luminosity to 10^{35} cm^{-2} sec^{-1}. At this luminosity, with a 10 cm long LH_2 target (4.2×10^{23} cm^{-2}), the flux of quasi-real photons ($Q^2 < 0.2$ (GeV/c)^2) in the energy range from 8. GeV to 11 GeV will be $\sim 4.8 \times 10^9$ sec^{-1}. The high photon flux combined with a large acceptance make CLAS12 an ideal place for studying photoproduction processes with small cross sections, such as $\gamma N \rightarrow J/\Psi N$.

Electroproduciton experiments with the same beam energy and target(s) will collect data together using a common single-electron trigger. For the presented studies, the final state contains an electron that will give rise to a standard CLAS12 electron trigger. The data can thus be collected

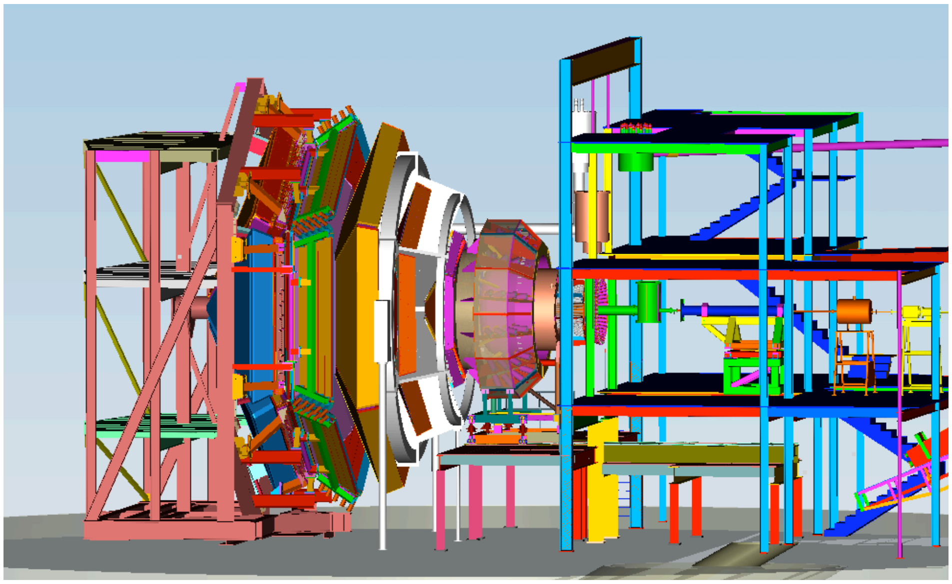

FIG. 4: The CLAS12 detector in Hall-B.

in parallel with any CLAS12 electroproduction experiment. Having been designed and built as a large acceptance spectrometer for electron scattering experiments, CLAS12 has excellent electron identification capabilities in the forward direction [20]. A combination of a High-Threshold Cherenkov Counter (HTCC) and Forward Electromagnetic Calorimeter (FEC) will provide a pion suppression factor of 10^{-4} (10^{-3} at the trigger level) for momenta up to 5 GeV. Above 5 GeV, the FEC will be the only electron ID detector, giving a π/e rejection factor at the few % level.

Production of lepton pairs will be studied in exclusive and inclusive final states:

$$ep \to e^+e^-p'(e') \tag{5}$$
$$eN \to e^+e^-e'X \tag{6}$$
$$eN \to e^+e^-X \tag{7}$$

Here, e^+e^- is the produced lepton pair, e' is the scattered electron, and p' is the recoil proton. In (5) and (7) the scattered electron escapes detection in CLAS12. In (6), the scattered electron will be detected in the CLAS12 forward tagger. With an 11 GeV electron beam, the kinematics of these reactions are such that the final-state electrons and positrons will be produced predominantly in the forward direction and will be detected in the forward detector (see the top graph in Fig.5). Either the electron or positron from the pair will always have a momentum below 5 GeV (bottom graph in Fig.5), and the pion pair rejection factor will therefore be better than 10^6. The kinematics of the recoiling proton in (5) also falls into the optimal detection range for CLAS12, as shown in Fig.6. Most protons have momenta below 1.5 GeV, and can be easily identified in either the forward or central detectors of CLAS12.

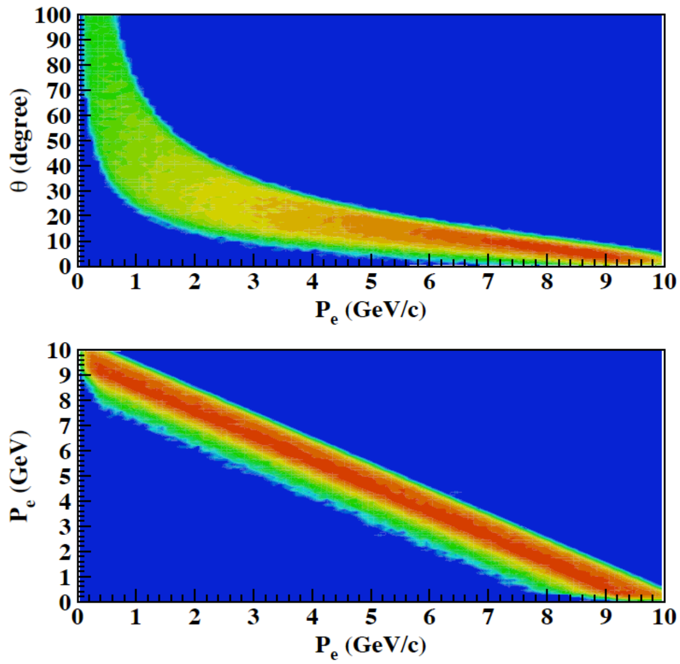

FIG. 5: Top: scattering angle vs. momentum distribution of electrons from quasi-real photoproduction of (e^+e^-) pairs on the proton for photon energy range 9.5 GeV to 10.5 GeV and M(e^+e^-) > 1.5 GeV. Bottom: electron vs. positron momentum in the same events.

J/Ψ events will be easily identified in the invariant mass distribution of (e^+e^-) pairs for all three reactions (Eq. 5–7). Time-like Compton Scattering (TCS) will be studied using the final state in Eq.(5). In (5), quasi-real photoproduction of lepton pairs will be identified in the missing momentum analysis of the (e^+e^-p') final state. Such analysis has been already done using CLAS 6 GeV data [21]. In that analysis, events with electrons scattered at forward angles ($Q^2 \sim 0$) were selected using cuts on the missing mass squared and missing transverse momentum.

To check the feasibility of selecting TCS events with an 11 GeV electron beam, the CLAS12 fast monte-carlo algorithm was used, simulating the reaction $ep \to e'p'X$, with $X \to e^+e^-$. Since t-channel production of X was assumed, the production yields were scaled as $1/Q^4$ and $e^{-3|t|}$. Fig.7 shows the missing mass squared distribution, and the distribution of X and Y components of the missing momentum of the (e^+e^-p') final state. In the simulations, the total center-of-mass energy range is 18.7 $< s <$ 20.6 GeV. The plots in Fig.7 show narrow bands in the missing mass squared and the missing transverse momentum distributions that can be used to cleanly identify TCS events.

The same simulations were used to study the CLAS12 acceptance for reactions in (5), (6), and (7). In Fig.8 CLAS12 acceptance is shown as function of the (e^+e^-) invariant mass in the c.m.

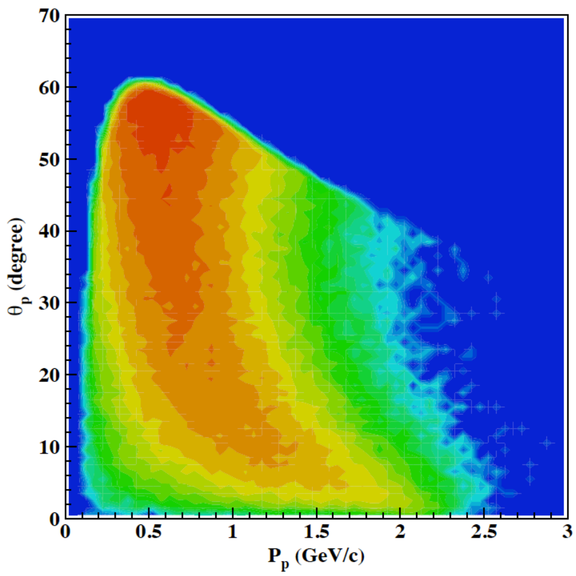

FIG. 6: Kinematics of the recoiling proton in quasi-real photoproduction of (e^+e^-) pairs on the proton for the photon energy range 9.5 GeV to 10.5 GeV and M(e^+e^-) > 1.5 GeV.

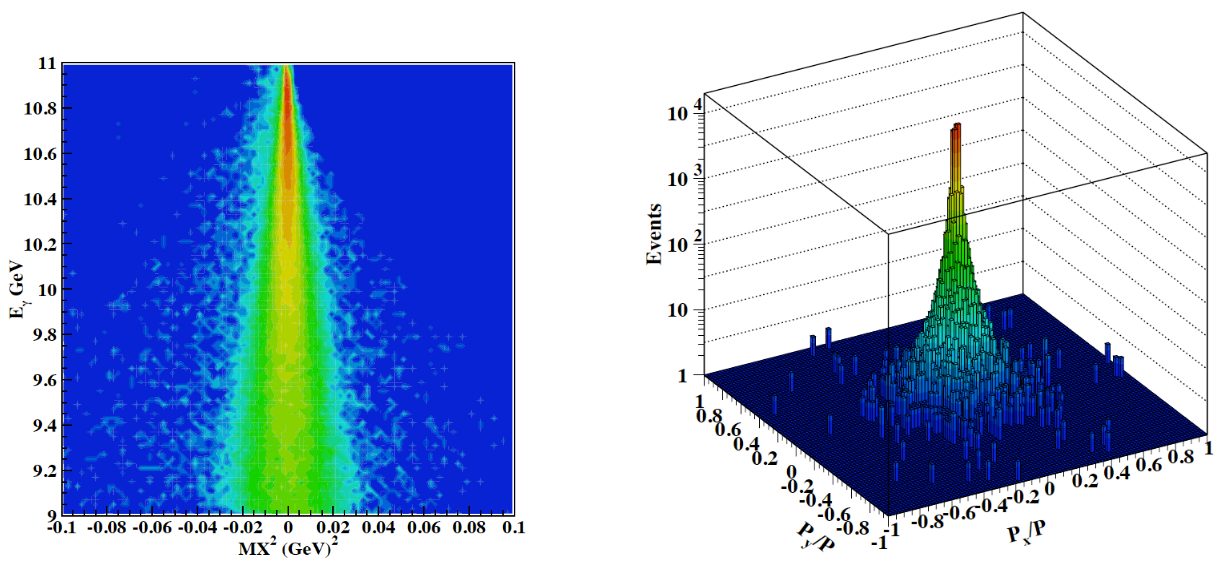

FIG. 7: Left: interacting photon energy vs. missing mass squared, right: X and Y components of the missing momentum in the reaction $ep \to e^+e^-p(e')$.

energy range of (e^+e^-p') 18.7 < s < 20.6 GeV. The solid lines in the histogram is the acceptance for detecting only (e^+e^-) pairs in CLAS12, and is relevant for reactions (6), and (7). It assumes 100% azimuthal acceptance in the CLAS12 forward tagger for detection of the scattered electron in (6). The dashed line is the acceptance for detecting the final state electron, positron, and proton in CLAS12 from reaction (5). For exclusive and inclusive J/Ψ studies, the acceptance is in range

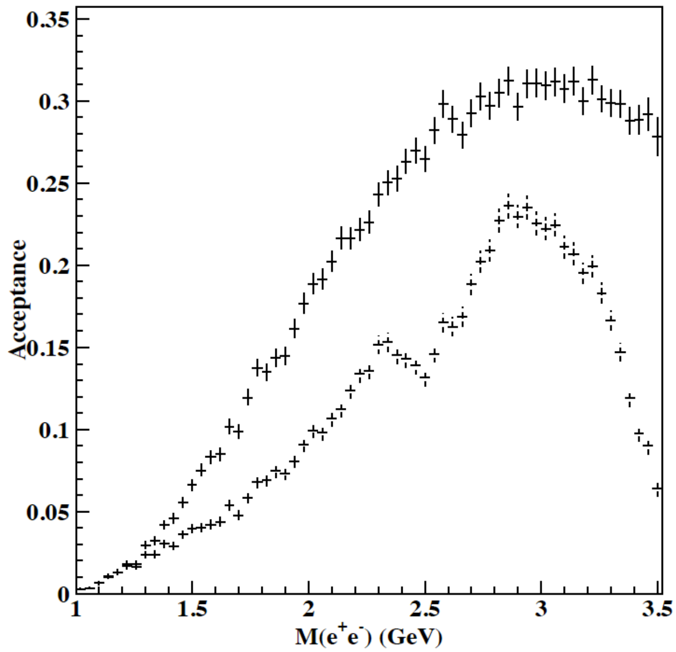

FIG. 8: The dependence of the CLAS12 acceptance on the (e^+e^-) invariant mass. The solid line (upper curve) corresponds to when only the electron and positron are detected in CLAS12. The dashed line is when the electron, positron, and proton are detected in CLAS12.

from 17% to 30%. For TCS in the relevant (e^+e^-) invariant mass range of 2 GeV to 3 GeV, the acceptance is on the order of 10% - 20%.

IV. RATE ESTIMATES

The rates for the reactions under consideration were estimated assuming an electron luminosity $L = 10^{35}$ cm^{-2} sec^{-1}. The CLAS12 performance was simulated using the Fast MC algorithm.

A. Timelike Compton Scattering and J/Ψ Photoprodution

For studies of reaction (5), the FSGEN [22] event generator is used. It assumes that the (e^+e^-) pair is produced in the t-channel off the nucleon. It includes the vector mesons ρ, ω, ϕ, and J/Ψ with the proper decay rates, and a phase-space background for Bethe-Heitler (BH) events. For all final states, an exponential t-dependence is assumed, $e^{-3|t|}$. The electron scattering kinematics were defined through $\frac{1}{Q^4}$ scaling. Here, Q^2 is the virtual photon four-momentum squared, and t is the transferred momentum squared. In the e^+e^-invariant mass range above 2 GeV, which is relevant to TCS and J/Ψ studies, only BH and J/Ψ events contribute. The cross section for the

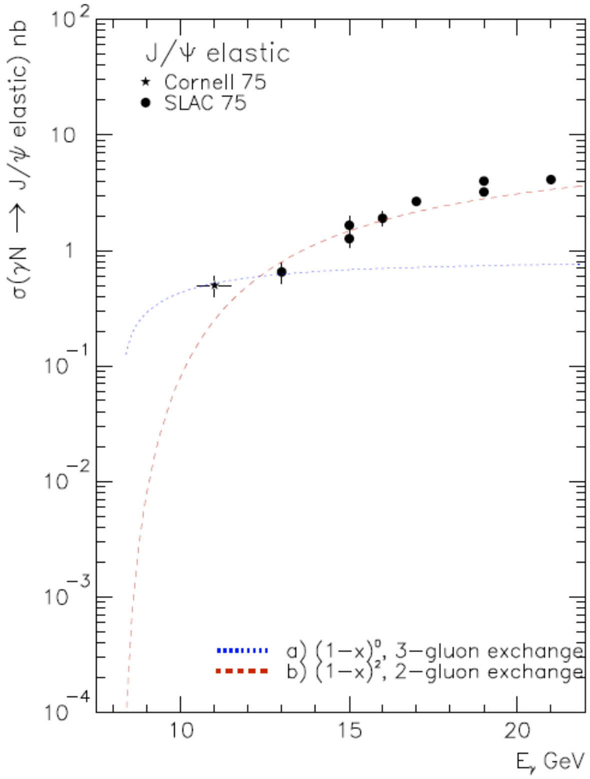

FIG. 9: Total photoproduction cross section for J/Ψ as a function of photon energy, experimental data from [17, 18].

BH process was taken from [23]. For the J/Ψ photoproduction cross section, data from [17, 18] were used, with 2-gluon exchange behavior of the total cross section close to threshold, see Fig.9.

Figure 10 shows the number of e^+e^-pairs produced in 100 days of running at a luminosity of $L = 10^{35}$ cm^{-2} sec^{-1} for two c.m. energy ranges $4. < \sqrt{s} < 4.21$ GeV (lower graph) and $4.32 < \sqrt{s} < 4.54$ GeV (upper graph). Here, $s = (p^i_{\gamma^*} + p^i_p)^2 \equiv (p^i_{e^+} + p^i_{e^-} + p^i_{p'})^2$. The number of detected J/Ψ events is ~ 5000 in the top graph, and ~ 360 in the lower graph of the Fig.10. The photon energy dependence of the number of accumulated J/Ψ events is shown in Fig.11. The statistics collected in 100 days will allow to measure the J/Ψ photoproduction cross section close to thresholds with 20%−30% statistical accuracy. This will be sufficient to unambiguously distinguish between the 2-gluon and 3-gluon exchange mechanisms close to the production threshold.

The number of BH events for TCS studies in the range of outgoing photon virtualities $4 < Q'^2 < 9$ GeV/c^2, is 20K and 25K respectively for the high- and low energy bins presented in Fig.10. TCS analysis will require binning events in Q'^2, t, and the angles θ^* and ϕ^* in the lepton c.m. frame. While more studies will be needed to determine the optimal number of bins in each variable for the extraction of Compton amplitudes, it is evident that with this statistics one can achieve statistical

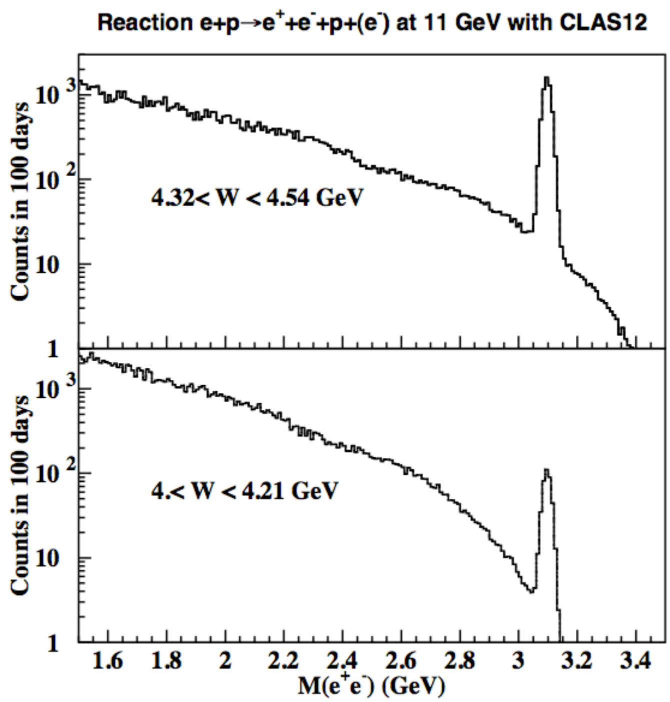

FIG. 10: Number of events produced in 100 days of running as function of (e^+e^-) invariant mass in the reaction Eq.(5) for two c.m. energy ranges ($W \equiv \sqrt{s(e^+e^-p)}$).

uncertainties of about 10% for each bin.

B. J/Ψ Electroproduction

Exclusive J/Ψ electroproduction would allow us to study J/Ψ production in more diverse kinematics. Electroproduction can be described as a virtual photon flux times the photo-absorption cross section. Depending upon the Q^2, the virtual photon flux is many orders of magnitude less than the quasi real photon flux, at the same electron luminosity. For this reason, we focus in this section on the feasibility of low Q^2 $H(e, e'J/\Psi p)$ measurements, using the proposed low Q^2 tagger.

With the J/Ψ detected via its e^+e^- decay branch, there is an in principle quantum mechanical interference arising from interchange of the two final state electrons. However, due to the narrow width of the J/Ψ, and the large kinematic mismatch for small angle electron scattering, this interference term is expected to be very small.

The low Q^2 tagger will span the angular range $2.5^\circ \leq \theta_e \leq 4.5^\circ$ for final electron energies $0.5 \leq k' \leq 4.5$ GeV. For an 11 GeV incident beam this will therefore 'tag' virtual photons of energy 6.5 to 10.5 GeV. Of course, for J/Ψ production, only virtual photons of energy greater than

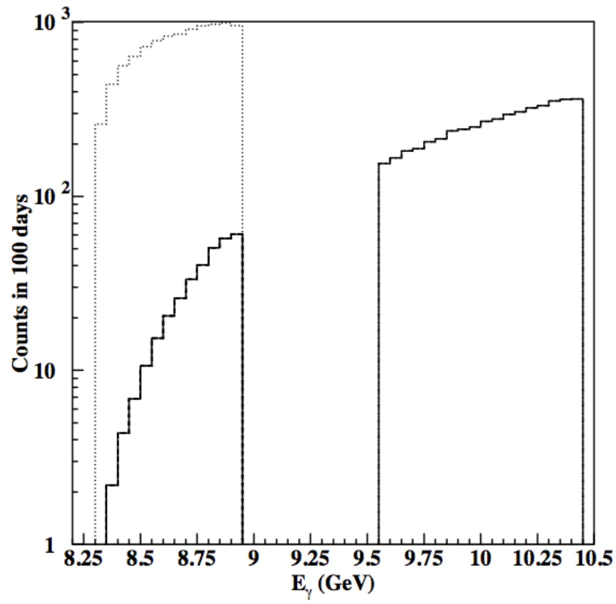

FIG. 11: Number of J/Ψ events produced in 100 days of running as a function of (virtual) photon energy in the reaction (5). In the dotted histogram, the cross section has been weighted near threshold using the 3-gluon exchange mechanism.

8.2 GeV are of interest. The lowest and highest Q^2 values above J/Ψ threshold are therefore

$$
\begin{aligned}
Q^2_{\mathrm{min}} &= 2(11\,\mathrm{GeV})(0.5\,\mathrm{GeV})(1-\cos 2.5^\circ) = 0.01\,\mathrm{GeV}^2 \\
Q^2_{\mathrm{max}} &= 2(11\,\mathrm{GeV})(2.8\,\mathrm{GeV})(1-\cos 4.5^\circ) = 0.2\,\mathrm{GeV}^2
\end{aligned}
\tag{8}
$$

For a given angular and energy bin of the tagger, the $ep \to e'pJ/\Psi \to e^+e^-$ production rate is

$$
\begin{aligned}
R(J/\Psi) &= \mathcal{L}_e \Delta\Gamma \sigma(\gamma * p \to pJ/\Psi) B.R.(J/\Psi \to e^+e^-) \\
\Delta\Gamma &= \int_{\Delta k' \Delta\Omega_e} dk' d\Omega_e \frac{\alpha}{2\pi^2} \frac{k'}{k} \frac{W^2 - M^2}{2MQ^2} \frac{1}{1-\epsilon}
\end{aligned}
\tag{9}
$$

Here $B.R.(J/\Psi \to e^+e^-) = 6\%$ and $\mathcal{L}_e = 10^{35}/\mathrm{cm}^2/s$. To obtain the actual detection rate, we must multiply by the CLAS12 e^+e^- acceptance at the J/Ψ mass. This is about 30% (Fig. 8).

Dividing the tagger into four angular bins, and four bins of equal size in $(k-k')/k'$, we obtain the effective virtual photon flux in each bin, as plotted in Fig. 12. Of course, for $J\Psi$ production, only the two highest bins in k_γ are relevant. Using the cross section model from the parameterization in Ref.[24], we obtain the $ep \to e'pJ/\Psi$ production rate of Fig. 13, including the $J/\Psi \to e^+e^-$ branching ratio, but not including the CLAS12 acceptance for the e^+e^- pair or the recoil proton (Fig. 8).

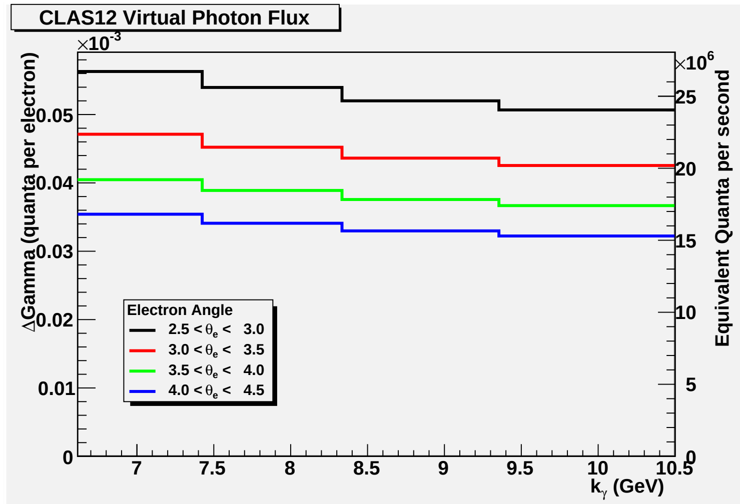

FIG. 12: Virtual photon flux $\Delta\Gamma$ in bins of $k_\gamma = k - k'$ and θ_e. Right hand axis is for an incident electron luminosity of $10^{35}/\text{cm}^2/\text{s}$ on a 5 cm liquid H_2 target.

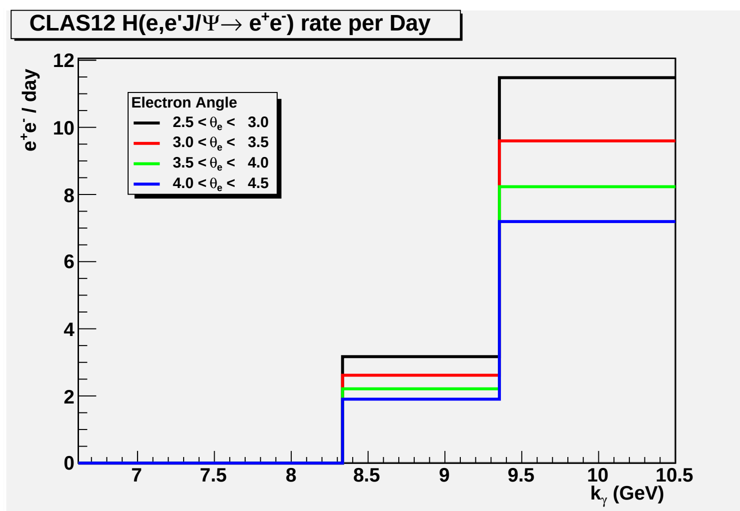

FIG. 13: Exclusive low Q^2 J/Ψ production rate (per day) in the reaction $\text{H}(e,e')pJ/\Psi \to e^+e^-$. The scattered electron is detected in the low Q^2 tagger in the specified angular ranges. The 6% branching ratio of the $J/\Psi \to e^+e^-$ decay is included, but the CLAS12 acceptance for the e^+e^- pair and the recoil proton is not (roughly 30% for the e^+e^- pair and 20% for the e^+e^-p triplet).

V. SUMMARY

In summary, we propose a broad program for studying nucleon and nuclear structure using Time-like Compton Scattering process and J/Ψ electro- and photoproduction near threshold. These measurements will compliment existing program of studying GPDs in deeply exclusive processes with CLAS12. TCS with unpolarized photon beams is an effective tool for studying real part of the Compton amplitude, information that in DVCS can be accessed directly only in beam charge asymmetry measurements. With circular photon polarization (freely available with longitudinally polarized electron beams), imaginary part of Compton amplitudes can be measured, complimenting DVCS beam charge asymmetry measurements. Higher order corrections are different for DVCS and TCS, and hence measuring both will put tighter constraints on GPD models.

Proposed studies are the first comprehensive studies of J/Ψ photo- and electroproduction in wide range of kinematics close to the production threshold. These measurements will provide important information of nucleon's gluonic structure at large x, such as the spatial structure of the gluon fields and their correlation with the valence quarks. High statistics measurements near threshold will be important for understanding J/Ψ production mechanism. With CLAS12 and forward tagger, J/Ψ eletroproduction can be studied for $Q^2 \leq 0.2$ GeV^2 for the first time, and will provide valuable information on the reaction mechanism and hardness of the reaction. With CLAS12 J/Ψ production on nuclear targets are also accessible. Measurements with nuclear targets will help our understanding of J/Ψ production, propagation and interaction in a nuclear matter.

Most of proposed studies can and will be done in parallel with other (partly approved) proposed electroproduction experiments at 11 GeV with CLAS12.

[1] E.R. Berger, M. Diehl, and B. Pire, *Eur. Phys. J.* **C23**, 675 (2002).

[2] A. Psaker, Ph.D. Thesis (Advisor: A. Radyushkin), Old Dominion University, Dec 2005, arXiv:hep-ph/0511283v2 (2005).

[3] B. Pire, L. Szymanowski, and J. Wagner, *Phys. Rev. D.* **79**, 014010 (2009).

[4] A. Afanasev, S. Brodsky, C.E. Carlson, and A. Mukherjee, *Phys. Rev. D.* **81**, 034014 (2010).

[5] B. Pire, L Szymanowski, and J. Wagner, *Phys. Rev. D.* **83**, 034009 (2011).

[6] S. Chekanov et al., *Nucl. Phys.* **B695**, 3-37 (2004).

[7] A. Aktas et al., *Eur. Phys. J.* **C46**, 585-603 (2006).

[8] L. Frankfurt, M. Strikman, and C. Weiss, *Ann. Rev. Nucl. Part. Sci.* **55**, 403-465 (2005).

[9] L. Frankfurt, C. Hyde, M. Strikman, and C. Weiss, *Phys. Rev.* **D75**, 054009 (2007).

[10] M. Binkley et al., *Phys. Rev. Lett.* **48**, 73 (1982).

[11] Summary of 2010 INT Program "*Gluons and the quark sea*", to be published (2011).

[12] L. Frankfurt and M. Strikman, *Phys. Rev.* **D66**, 031502 (2002).

[13] K. Lukashin et al., *Phys. Rev.* **C63**, 065205 (2001).

[14] J.P. Santoro et al., *Phys. Rev.* **C78**, 025210 (2008).

[15] S.V. Goloskokov and P. Kroll, *Eur. Phys. J.* **C50** 829-842 (2007).

[16] S.J. Brodsky, E. Chudakov, P. Hoyer, and J-M. Laget, *Phys.Lett.* **B498**, 23-28 (2001).

[17] U. Camerini et al., *Phys. Rev. Lett.* **35**, 483 (1975).

[18] B. Gittelman et al., *Phys. Rev. Lett.* **35**, 1616 (1975).

[19] M. Battagleri et al., JLAB experiment E12-11-005 (2011).

[20] CLAS12 Conceptual Design Report, JLAB (2008).

[21] R. Paremuzyan, PhD thesis, Yerevan (2010). http://www.jlab.org/Hall-Bgeneral/clas_thesis.html

[22] Event generator for electro- and photoproduction on nucleon and nuclei, CLAS software repository (2005).

[23] V. Guzey, Code for cross section calculations Bethe-Heitler and Time-like Compton.

[24] N. Bailie, SLAC E161 proposal Technical Note-38.