Studies of $e'\gamma X$ and of $e'\pi^0 X$ with clas and clas12

Harut Avakian

DeepPWG meeting, JLab, June 15, 2017

- Hard exclusive photon production
  - BH propagators
- Possibilities with $e'\gamma X$
- Extracting PBPT from double spin asymmetry
- Possibilities with $e'\pi^0 X$
- Summary & Conclusions
Outline

1) e'X -cross section: electron acceptance is relevant for all other measurements
   
   cons: we need the acceptance and the luminosity as well as contamination from pions under control.

2) e'π0X/ e'X ratio (ratio of semi-inclusive π0 to inclusive electron)
   For the ratio we just need the gamma acceptance, which could be defined using the KPP

   cons: need efficiency for photon detection and acceptance under good control

3) e'γX/ e'X ratio for the missing mass below \Delta (exclusive photon production)
   
   a) In the range of phi (phi<60 degree) it is totally dominated by BH and can be used to extract the eX itself from ratio and control the efficiency of our electron reconstruction.

   b) It is the same as our DVCS analysis, and can be used as a cross check for extraction with proton detection later on

   cons: need efficiency for photon detection and acceptance for photons above 3 GeV (easier than for π0) and well tuned MC to account for π0 contamination, which is item 2 and can be extracted simultaneously.

June 15
Electroproduction Kinematics

\[ Q^2 = -q_1^2 = 4EE' \sin(\theta / 2) \]
\[ \mathbf{v} = E - E' \]
\[ x_B = -q_1^2 / 2 p_1 q_1 = Q^2 / 2 M\mathbf{v} \]
\[ \gamma = \mathbf{v} / E \]
\[ t = (p_2 - p_1)^2 = \Delta^2 \]

$\gamma^* \rightarrow \gamma$ require a finite longitudinal momentum transfer defined by the generalized Bjorken variable $\xi$

\[ \Delta_{\perp}^2 \approx (1 - \xi^2)(t - t_{\text{min}}) \]
\[ t_{\text{min}} \approx \frac{M^2 x^2}{1 - x + x M^2 / Q^2} \]
\( |T_{BH}|^2 = \frac{e^6}{x_B y^2 (1 + \epsilon^2)^2 \Delta^2 P_1(\phi)P_2(\phi)} \times \left\{ c_0^{BH} + \sum_{n=1}^{2} c_n^{BH} \cos(n\phi) + s_1^{BH} \sin(\phi) \right\} \)

\( C_{BH} \)

\( I = \frac{\pm e^6}{x_B y^3 \Delta^2 P_1(\phi)P_2(\phi)} \left\{ c_0^I + \sum_{n=1}^{3} \left[ c_n^I \cos(n\phi) + s_n^I \sin(n\phi) \right] \right\} \)

\( C_{int} \)

\( A_{UL}(\phi) \sim \frac{s_{1,\text{Lp}} \sin \phi}{c_{0,\text{unp}}^{BH} + (c_{1,\text{unp}}^{BH} + c_1^I + \ldots) \cos \phi + \ldots} \)

\( C_{int} = C_{BH}^* x/y^* (1 + \epsilon^2)^2 \)

\( |T_{DVCS}|^2 = \frac{e^6}{y^2 Q^2} \left\{ c_0^{DVCS} + \sum_{n=1}^{2} \left[ c_n^{DVCS} \cos(n\phi) + s_n^{DVCS} \sin(n\phi) \right] \right\} \)

\( \mathcal{P}_1 = -\frac{1}{y(1 + \epsilon^2)} \left\{ J + 2K \cos(\phi) \right\} \)

\( J = \left( 1 - y - \frac{y\epsilon^2}{2} \right) \left( 1 + \frac{\Delta^2}{Q^2} \right) - (1-x)(2-y) \frac{\Delta^2}{Q^2} \)

- Strong dependence on kinematics of prefactor \( \phi \)-dependence, at \( t \approx t_{col}, P_1(\phi) \rightarrow 0 \)
- Do the kinematic factors with propagators in \( T_{BH} \) and \( I \) cancel in the ratio of \( 4 \)
Azimuthal moments in ep->e'p'\gamma

Ratio of different contributions to $c_{0BH}$

Different azimuthal moments become relevant in different kinematical regions
HERMES @ 27.6 GeV

- resolution: $\delta p/p \sim 2\%$, $\delta \theta < 1$ mrad
- "simple box" acceptance for photons
- measure ratios to DIS

\[ \frac{d^2\sigma}{dxd^2y} \]

Good agreement with generated BH
CLAS e1DVCS2 experiment

→ Less background than in e1dvcs
→ Large kinematical coverage in $x_B$ and $t$ (higher $E_b$)

Calorimeter and superconducting magnet within CLAS torus

dedicated calorimeter (424 PbWO4 crystals) detect photons from 5°-15°

Use e1dvcs2 data to study feasibility of DVCS/BH studies with only electron and photon detection!
e1dvcs2 distributions

Resolution consistent with expectations for CLAS12
e1dvcs2 distributions

Cuts on photon missing mass, minimum energy and the angle between $\gamma\gamma^*$, may be sufficient, but will require good MC simulation to understand better the background around 180 degrees, where $p_0$ contribution may be significant.

DVCS studies with just $e'$ and $\gamma$ are feasible and require only detailed understanding of the photon acceptance (+MC)
With full exclusivity cut the photons from asymmetric decays may have very different azimuthal distributions compared to symmetric decays, which are used to get the contamination.
γ MC vs Data

Region where BH totally dominates (small t, small photon $\theta_{\text{LAB}}$)
- Negligible DVCS x-section, small $\pi^0$ contamination
- Rapidly changing prefactors, mainly small $\phi$, hard to detect photons

Large angles
- Uniform coverage in angle $\phi$, photon measurement less challenging
- DVCS x-section non negligible introduce some model dependence
- $\pi^0$ dominates the single photon sample (in particular at low $Q^2$ and large t)

- MC Kinematic distributions in $x,Q^2,t$ consistent with the CLAS data
MC studies: BH in $A_{LL}$

The $A_{LL}$ $\phi$-dependence dominated by BH only at relatively small $\phi$
Semi-Inclusive electrons (ep->e’ π⁰X)

\[ \sigma_p^{eX} \propto 4u + d + \ldots \]
\[ \sigma_p^{\pi^0} \propto 4uD^{u \rightarrow \pi^0} + dD^{d \rightarrow \pi^0} + \ldots \]
\[ D^{u \rightarrow \pi^0} \approx D^{d \rightarrow \pi^0} \]

The ratio of e’π⁰X/e’X provides cleanest info on fragmentation function

Ratios studied using the clasDIS LUND generator
1) ratio should have weak dependence on x
2) Ratio should follow z-dependence of the fragmentation function.
π multiplicities in SIDIS $ep\rightarrow e'\pi X$

$\pi^0$ multiplicities less affected by higher twists

$0.4<z<0.7$ kinematical range, where higher twists are expected to be small
Suggestions for first publication

• First measurements could be performed using only identified electrons and photons (e’X, e’π^0X, e’γX)
• KPP data can be used to define the efficiency and acceptance for photons in the PCAL+EC

Need:
Precision calculations of the e’X x-sections
Precision MC description of the CLAS12
summary & plans

- The $e\gamma X$ with missing mass cuts can be used to study the BH observables (for PbPT, lumi monitoring,...)
  - theoretically under control with high precision
  - dominates all other processes at small $\phi$
  - need dilution factor for gammas (nuclear contributions)
- Extraction of $e\gamma X/eX$ ratios using first CLAS12 data → minimum effect from charge particle acceptance
- Extraction of $e\pi^0 X/eX$ ratios using first CLAS12 data → provide access to fragmentation functions

Plans:
Use clas12 software to study $eg1dvcs/clas6 e'\gamma X/e'X$
Check calculations of the $e'X$ x-sections using $e\gamma X$ for BH
Compare the $A_{LL}$ with calculations (eg1dvcs data) and develop procedure for extraction of the $P_B P_T$ from $e\gamma X/eX$
Precision MC description of the CLAS12 comparing with KPP
support slides...
HT and Semi-Exclusive Pion Production

- Azimuthal asymmetries with opposite sign from HT effects
- Effect may be suppressed for semi-exclusive $\pi^0$ compared to $\pi^+/-$

CLAS12 resolutions

**electrons**

5 < θ < 11 deg
11 < θ < 17
17 < θ < 23
23 < θ < 29
29 < θ < 35
**φ-dependent ratios (eg1dvcs paper)**

<table>
<thead>
<tr>
<th>Bin</th>
<th>$x_B$ bin</th>
<th>$\theta_e$ bin</th>
<th>$(x_B)$</th>
<th>$(Q^2)$</th>
<th>$(\text{GeV}/c)^2$</th>
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<tbody>
<tr>
<td>1</td>
<td>$0.1 &lt; x_B &lt; 0.2$</td>
<td>$15^\circ &lt; \theta_e &lt; 45^\circ$</td>
<td>0.179</td>
<td>1.52</td>
<td></td>
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<tr>
<td>2</td>
<td>$0.2 &lt; x_B &lt; 0.3$</td>
<td>$15^\circ &lt; \theta_e &lt; 34^\circ$</td>
<td>0.255</td>
<td>1.97</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$0.2 &lt; x_B &lt; 0.3$</td>
<td>$34^\circ &lt; \theta_e &lt; 45^\circ$</td>
<td>0.254</td>
<td>1.57</td>
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<tr>
<td>4</td>
<td>$0.3 &lt; x_B &lt; 0.4$</td>
<td>$15^\circ &lt; \theta_e &lt; 45^\circ$</td>
<td>0.345</td>
<td>2.41</td>
<td></td>
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<tr>
<td>5</td>
<td>$x_B &gt; 0.4$</td>
<td>$15^\circ &lt; \theta_e &lt; 45^\circ$</td>
<td>0.433</td>
<td>3.31</td>
<td></td>
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</table>

**GPD model independent**

\[ |\mathcal{T}_{BH}|^2 = \frac{e^6}{x_B^2 y^2 (1 + \epsilon^2)^2 \Delta^2 P_1(\phi) P_2(\phi)} \times \left\{ c_0^{BH} + \sum_{n=1}^{2} c_n^{BH} \cos(n\phi) + s_1^{BH} \sin(\phi) \right\} \]

**GPD model dependent (systematics from models)**

\[ \frac{C_{0L}^{BH} + C_{1L}^{BH} \cos\phi}{C_{0U}^{BH} + C_{1U}^{BH} \cos\phi + C_{2U}^{BH} \cos2\phi} \]

\[ \frac{C_{0L}^{Int} + C_{1L}^{Int} \cos\phi}{C_{0U}^{Int} + C_{1U}^{Int} \cos\phi + C_{2U}^{Int} \cos2\phi} \]

Empty symbols correspond to separate nominator and denominator calculations and filled symbols to calculation of the ratio (right plot is for ratio)

- Difference ~5% from calculating as ratio of structure functions
$\phi$-dependent amplitude

<table>
<thead>
<tr>
<th>Bin</th>
<th>$\tau_\mu$ bin</th>
<th>$\theta_\mu$ bin</th>
<th>$(\tau_\mu)$</th>
<th>$(\theta_\mu)$</th>
<th>$(G^2) ((GeV/c)^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1 $&lt; \tau_\mu &lt; 0.2$</td>
<td>$15^\circ &lt; \theta_\mu &lt; 48^\circ$</td>
<td>0.179</td>
<td>1.52</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.2 $&lt; \tau_\mu &lt; 0.3$</td>
<td>$15^\circ &lt; \theta_\mu &lt; 34^\circ$</td>
<td>0.255</td>
<td>1.97</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.2 $&lt; \tau_\mu &lt; 0.3$</td>
<td>$34^\circ &lt; \theta_\mu &lt; 48^\circ$</td>
<td>0.255</td>
<td>2.41</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.3 $&lt; \tau_\mu &lt; 0.4$</td>
<td>$15^\circ &lt; \theta_\mu &lt; 45^\circ$</td>
<td>0.345</td>
<td>2.60</td>
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<tr>
<td>5</td>
<td>$\tau_\mu &gt; 0.4$</td>
<td>$15^\circ &lt; \theta_\mu &lt; 45^\circ$</td>
<td>0.453</td>
<td>3.31</td>
<td></td>
</tr>
</tbody>
</table>

Bin $-t$ range $(GeV/c)^2$ $(-t)$ $(GeV/c)^2$

<table>
<thead>
<tr>
<th>Bin</th>
<th>$-t$ range</th>
<th>$(GeV/c)^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.08 $&lt; -t &lt; 0.18$</td>
<td>0.137</td>
</tr>
<tr>
<td>2</td>
<td>0.18 $&lt; -t &lt; 0.3$</td>
<td>0.234</td>
</tr>
<tr>
<td>3</td>
<td>0.3 $&lt; -t &lt; 0.7$</td>
<td>0.467</td>
</tr>
<tr>
<td>4</td>
<td>0.7 $&lt; -t &lt; 2.0$</td>
<td>1.175</td>
</tr>
</tbody>
</table>

$A_{LL}$

$\langle Q^2 \rangle = 1.52 (GeV/c)^2$

$\langle \phi \rangle = 0.179$

June 15

$^23$
The $\phi$-dependence of prefactor doesn't cancel: should be accounted in calculations.

$C_{\text{int}}/C_{\text{BH}} = -x/y^*(1+\epsilon^2)^2$

June 15

The $\phi$-dependence of prefactor doesn't cancel: should be accounted in calculations.
$\phi$-dependent amplitude

$$t_{\text{min}} \approx \frac{M^2 x^2}{1 - x + x M^2 / Q^2}$$

$<Q^2> = 3.31 \text{(GeV/c)}^2$

$<\phi> = 0.45^\circ$
azimuthal moments in DVCS (example)

\[ I = \frac{\pm e^6}{x_B y^3 \mathcal{P}_1(\phi) \mathcal{P}_2(\phi) \Delta^2} \left\{ c_0^I + \sum_{n=1}^{3} \left[ c_n^I \cos(n\phi) + s_n^I \sin(n\phi) \right] \right\}, \]

\[ \begin{cases} c_{1,\text{unp}}^I \\ s_{1,\text{unp}}^I \end{cases} = 8K \begin{cases} -(2 - 2y + y^2) \\ \lambda y(2 - y) \end{cases} \begin{cases} \Re \\ \Im \end{cases} \left( \mathcal{C}^I_{\text{unp}}(\mathcal{F}) \right), \]

\[ C_{\text{LP}}^I = \frac{x_B}{2 - x_B} (F_1 + F_2) \left( \mathcal{H} + \frac{x_B}{2} \mathcal{E} \right) + F_1 \tilde{\mathcal{H}} - \frac{x_B}{2 - x_B} \left( \frac{x_B}{2} F_1 + \frac{\Delta^2}{4M^2} F_2 \right) \tilde{\mathcal{E}}, \]

All moments involve several contributions with different Form Factors and GPDs multiplied by a kinematic term involving propagators
\( \phi \)-dependent ratios (eg1dvcs paper)

- The \( \phi \)-dependence of prefactor doesn’t cancel: should be accounted in calculations

\[ \frac{C^{BH}_{0LP} + C^{BH}_{1LP} \cos \phi}{C^{BH}_{0Unp} + C^{BH}_{1Unp} \cos \phi + C^{BH}_{2Unp} \cos 2\phi} \]

GPD model independent

\[ \frac{C^{BH}_{0LP} + C^{BH}_{1LP} \cos \phi + C^{int}_{0LP} + C^{int}_{1LP} \cos \phi}{C^{BH}_{0Unp} + C^{BH}_{1Unp} \cos \phi + C^{BH}_{2Unp} \cos 2\phi} \]

GPD model dependent (systematics from models)

\[ \frac{C^{BH}_{0LP} + C^{BH}_{1LP} \cos \phi + C^{BH}_{0Unp} + C^{BH}_{1Unp} \cos \phi}{C^{BH}_{0Unp} + C^{BH}_{1Unp} \cos \phi + C^{BH}_{2Unp} \cos 2\phi + C^{int}_{0Unp} + C^{int}_{1Unp} \cos \phi} \]
Target Polarization Measurement from BH Double Spin Asymmetry

H. Avakian, V. Burkert, S. Chen, L. Elouadrhiri
Jefferson Lab, Newport News, VA 23606

Abstract

We present studies of the double spin asymmetry in the hard exclusive photon production. The double spin asymmetry which is dominated by the BH, is discussed as an alternative source of information on the product of beam and target polarizations for CLAS12 polarized target runs.

\[ A_{LL} = \frac{\left( \frac{N^{\uparrow \uparrow}}{Q^{\uparrow \uparrow}} - \frac{N^{\uparrow \downarrow}}{Q^{\uparrow \downarrow}} \right) + \left( \frac{N^{\downarrow \uparrow}}{Q^{\downarrow \uparrow}} - \frac{N^{\downarrow \downarrow}}{Q^{\downarrow \downarrow}} \right)}{f \left( \frac{N^{\uparrow \uparrow}}{Q^{\uparrow \uparrow}} + \frac{N^{\uparrow \downarrow}}{Q^{\uparrow \downarrow}} + \frac{N^{\downarrow \uparrow}}{Q^{\downarrow \uparrow}} + \frac{N^{\downarrow \downarrow}}{Q^{\downarrow \downarrow}} \right)} \]

\[ A_{LL} \sim \frac{C_{0,LP}^{BH}}{C_{0,unp}^{BH}} \]

Figure 2: \( P_B \cdot P_T \) extracted using the \( A_{LL} \) as a function of \( t \) from E811 data.
\[ I = \frac{\pm e^6}{x_B y^3 \Delta^2 P_1(\phi) P_2(\phi)} \left\{ c_0^T + \sum_{n=1}^{3} [c_n^T \cos(n\phi) + s_n^T \sin(n\phi)] \right\}, \]

\[ t_{\text{min}} \approx \frac{M^2 X^2}{1 - x + xM^2/Q^2} \]

- Strong dependence on kinematics of prefactor $\phi$-dependence, at $t=t_{\text{col}} P_1(\phi)=0$ require special attention in interpretation of beam averaged beam SSA and in particular $x$-section differences
- Fraction of pure DVCS increases with $t$ and $\phi$
Sensitivity on theory input

M. Kirch (2006)

Dynamical HT may decrease the beam SSA at small $t$

Evolution effects significant at small $Q^2$

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Contributions to the DVCS cross section

Azimuthal moments in the DVCS MC (BMK-open symbols) and Vanderhaeghen et al (filled symbols).

Reason for difference under studies (2002)

June 15

VGG x-section described as a sum of moments
GPDs from ep->e’p’γ

Requirements for precision (<15%) measurements of GPDs from DVCS SSA:

• Define the procedure to extract GPDs from $A_{LU}$
  • effect of finite bins (prefactor variations) $\sim 10\%$
  • other moments
• Define background corrections (>1γ)
  • pion contamination $\sim 10\%$
  • radiative background
  • ADVCS

A complete simulation of the whole chain from particle detection to GPD extraction, including the DVCS and background (counts, asymmetries) as well as extraction procedure (averaging over kinematic factors) required to ensure the reliability of measured GPDs.

June 15
Correction factor as a function of bin size

\[ P_1 = -\frac{1}{y(1 + \epsilon^2)} \left\{ J + 2K \cos(\phi) \right\} \]

\( \phi \) – dependence of

The \( \phi \) dependence of \( P_1 \) in BH and INT terms doesn’t cancel for finite bins.
\( \pi^0 \) contamination in \( ep\gamma \)-sample

- At large angles detected photon can be used as veto (epX-sample).
- Cut on the direction of the measured photon (require detection of proton) significantly reduce the contamination (ep\( \gamma \)-sample).
Main unknown in corrections of photon SSA are the $\pi^0$ contamination and its beam SSA.

Extract from $ep\pi^0$ MC the ratio of single to double photon detection probability

$$N_{\gamma}^{Data}(\pi^0) = N_{\gamma}^{Data} \frac{N_{\gamma}^{MC}(\pi^0)}{N_{\pi^0}^{MC}},$$

MC the ratio for $0_\gamma$

Use $ep\pi^0$ MC and data to estimate the contribution of $\pi^0$ in the $ep\gamma$ and $epX$ samples

Contamination from $\pi^0$ photons increasing at large t and x.
$\phi$-dependence and collinearity cut

Collinearity cut $y_{\text{col}} > 0.025$ eliminates low $\phi$ and large $t$ (the beam direction)

$$y = y_{\text{col}} \equiv \frac{Q^2 + \Delta^2}{Q^2 + x\Delta^2}$$
• Exclusive photon production simulated using a realistic MC (based on S. Korotkov’s code)

• Kinematic distributions in $x, Q^2, t$ consistent with the CLAS data
GPDs from ep→e′p′γ

Requirements for precision (<10%) measurements of GPDs from DVCS SSA:

- Define the procedure to extract GPDs from $A_{LU}$
  - effect of finite bins ~10%
- Define background corrections
  - pion contamination ~10%
  - radiative background

π⁰ dominates the single photon sample at low $Q^2$ in the kinematics where BH is small.

$\pi^0 \sim Q^{-6}$
BH cosφ moment can generate ~3% sin2φ in the $A_{LU}$

$A_{LU} \propto \frac{\lambda s_2^I \sin \phi}{c_0^{BH} (1 + c_1^{BH} / c_0^{BH} \cos \phi)} \approx \frac{\lambda s_2^I \sin \phi - \lambda s_2^I (c_1^{BH} / 2c_0^{BH}) \sin 2\phi}{c_0^{BH}}$