Results from Hall A on $\pi^0$ and photon electroproduction

M. Defurne

CEA Saclay - IRFU/SPhN

August 30\textsuperscript{th} 2017
A lot have been already said in the previous days about experiment or theory for DVCS and DVMP (Raphael, Tanja, Silvia, Vladimir, Kresimir,...).

- This talk will include some reminders and skip a lot of introduction (Do not hesitate to stop me if something is missing).
- This talk was built according to the content and remarks from previous talk (so sorry if they are some discontinuities).
- This talk will focus on last results from Hall A for $\pi^0$ and photon electroproduction.
- I have some questions to ask you for next measurements.
**TMDs**: Fraction of longitudinal momentum $x$ and transverse momentum $k$

**GPDs**: Fraction of longitudinal momentum $x$ and transverse position $b$

---

Scan in momentum

![Diagram](image1)

Scan in position

![Diagram](image2)
By measuring the cross section of deep exclusive processes, we get insights about the structure of the nucleon.

1. The electron interacts with the proton by exchanging a hard virtual photon (with polarization +, -, 0).

2. The proton emits a particle ($\gamma$, $\pi^0$, $\rho$, ...)

How to connect this amplitude to the generalized parton distributions? The Factorization

We will first discuss $ep \rightarrow ep\gamma$ and then $ep \rightarrow ep\pi^0(\gamma\gamma)$. 
The amplitudes at twist-$(n+1)$ are suppressed by a factor $\frac{1}{Q}$ with respect to the twist-$n$ amplitudes, with $Q$ the virtuality of the photon.
The generalized parton distributions

At leading twist there are 8 GPDs for the proton:

- 4 chiral-even GPDs: $H$, $E$, $\tilde{H}$ and $\tilde{E}$.
- 4 chiral-odd GPDs: $H_T$, $E_T$, $\tilde{H}_T$ and $\tilde{E}_T$.

By Fourier transform of the GPD $H$, we obtain the distribution in the transverse plane of the partons as a function of their longitudinal momentum.

Keeping the correlation between longitudinal momentum and transverse spatial distribution of partons, we can study the total angular momentum of quarks.
\( \pi^0 \) electroproduction in the Hall A of Jefferson Laboratory
In DVMP, there is an additional non-perturbative structure: the meson.

The amplitude is given by the product of two twist-expansions:

\[ \mathcal{M} = \text{GPDs}(x, \xi, t, \mu_{F1}) \otimes \text{HARD}(x/\xi, z, \mu_{F1}, \mu_{F2}) \otimes \text{DA}(z, \mu_{F2}) \]
Cross section and twist

The unpolarized cross section can be written as the sum of responses according to the polarization of the virtual photon.

\[
\frac{d^4\sigma}{dt d\phi dQ^2 dx_B} = \frac{1}{2\pi} \Gamma_{\gamma^*}(Q^2, x_B, E_e) \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{TL}}{dt} \cos(\phi) + \epsilon \frac{d\sigma_{TT}}{dt} \cos(2\phi) \right],
\]

Only the longitudinal response is leading-twist, involving \( \tilde{H} \) and \( \tilde{E} \).

Results from CLAS and Hall A are \( \times10 \) higher than leading-twist predictions!

\[
Q^2 = 2.3 \text{ GeV}^2, \quad x_B = 0.36
\]
\[
\epsilon=0.651
\]

Fuchey E. et al. (Hall A collaboration), PhysRevC.83.025201 (2011)
What’s going on?

\[
\frac{d^4\sigma}{dt d\phi dQ^2 d\chi_B} = \frac{1}{2\pi} \Gamma_{\gamma^*}(Q^2, x_B, E_e) \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{TL}}{dt} \cos(\phi) + \epsilon \frac{d\sigma_{TT}}{dt} \cos(2\phi) \right],
\]

Hints of a large transverse contribution:

- Asymmetries of $\pi^+$ from HERMES and L/T separation on $\pi^+$ (Hall C).
- Large amplitude of $\frac{d\sigma_{TT}}{dt}$ from CLAS and Hall A ($\phi$-dependence).

\[
Q^2 = 1.75 \text{ GeV}^2, \quad x_B = 0.22, \quad t' = 0.12 \text{ GeV}^2, \quad \epsilon = 0.457
\]

I. Bedlinskiy et al. (CLAS collaboration), PhysRevC.90.025205 (2014)
Transversity GPDs and twist-3 DAs

At leading twist there are 8 GPDs:

- 4 chiral-even GPDs: $H$, $E$, $\tilde{H}$ and $\tilde{E}$.
- 4 chiral-odd GPDs: $H_T$, $E_T$, $\tilde{H}_T$ and $\tilde{E}_T$.

The twist-3 DAs are chiral-odd and might couple to transversity GPDs. Although $\frac{1}{Q}$-suppressed, twist-3 DAs are associated to a kinematical coefficient:

$$\mu_\pi = \frac{m_\pi^2}{m_u + m_d} \approx 2.5 \text{ GeV}$$

which is higher than our $Q$-values.

Assuming the factorization for transversely polarized photon:

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'} \frac{\mu_\pi^2}{Q^8} \left[ (1 - \xi^2) |\mathcal{H}_T|^2 - \frac{t'}{8m^2} |2\tilde{\mathcal{H}}_T + \mathcal{E}_T|^2 \right],$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{2k'} \frac{\mu_\pi^2}{16m^2} \frac{t'}{Q^8} |2\tilde{\mathcal{H}}_T + \mathcal{E}_T|^2,$$
We need to separate $\sigma_L$ and $\sigma_T$ to confirm the large transverse contribution.

$$
\frac{d^4\sigma}{dtd\phi dQ^2 dxB} = \frac{1}{2\pi} \Gamma_{\gamma^*}(Q^2, x_B, E_e) \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{TL}}{dt} \cos(\phi) + \epsilon \frac{d\sigma_{TT}}{dt} \cos(2\phi) \right],
$$

<table>
<thead>
<tr>
<th>Setting</th>
<th>$E$ (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$x_B$</th>
<th>$\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-Kin1</td>
<td>(3.355 ; 5.55)</td>
<td>1.5</td>
<td>0.36</td>
<td>(0.52 ; 0.84)</td>
</tr>
<tr>
<td>2010-Kin2</td>
<td>(4.455 ; 5.55)</td>
<td>1.75</td>
<td>0.36</td>
<td>(0.65 ; 0.79)</td>
</tr>
<tr>
<td>2010-Kin3</td>
<td>(4.455 ; 5.55)</td>
<td>2</td>
<td>0.36</td>
<td>(0.53 ; 0.72)</td>
</tr>
</tbody>
</table>

Rosenbluth separation: Measure $\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt}$ for two different $\epsilon$-values at same $Q^2$, $x_B$ and $t'$. 

Results

\[
\frac{2\pi}{d\Phi} \frac{d\sigma}{dQ^2} (\text{mb/GeV}^2) \quad \Phi \quad 0 \quad 60 \quad 120 \quad 180 \quad 240 \quad 300 \quad 360
\]

- \( Q^2 = 1.5 \text{ GeV}^2 \)
  - Triangles

- \( Q^2 = 1.75 \text{ GeV}^2 \)
  - Squares

- \( Q^2 = 2 \text{ GeV}^2 \)
  - Circles
\[ \frac{\sigma_T}{dt} \text{ (red)}, \frac{\sigma_L}{dt} \text{ (blue)}, \frac{\sigma_{TL}}{dt} \text{ (orange)}, \frac{\sigma_{TT}}{dt} \text{ (green)} \]

The Q-dependence is $9 \pm 2$ for T, $4 \pm 2$ for TT, $26 \pm 5$ for TL.

NB: 3% normalization uncertainty has a dramatic effect for the separation.
Data has been collected on Deuterium to study the neutron at $Q^2 = 1.75 \text{ GeV}^2$.

- As expected $\tau$ is found to be the dominant contribution.
- Almost no coherent $\pi^0$ electroproduction.

Combining proton and neutron, let’s try flavor separation.

Mazouz et al., PRL 118.222002, 2017
Conclusion about $\pi^0$ electroproduction

- $\pi^0$ electroproduction is a beautiful example of process for which the dominant contribution is not the leading-twist contribution.
- Offer exciting opportunity to access transversity GPDs (if factorization holds for transversely polarized photons).
- Good example of systematic uncertainties affecting differently the different harmonics of a cross section.
- Large lever arm in $\epsilon$ and $L/T\tilde{1}$ are the key for a successful (full of information) measurement of $\pi^0$ electroproduction.
Photon electroproduction in the Hall A of Jefferson Laboratory
**DVCS and GPDs**

- \( Q^2 = -q^2 = -(k - k')^2 \).
- \( x_B = \frac{Q^2}{2p \cdot q} \).
- \( x \) longitudinal momentum fraction carried by the active quark.
- \( \xi \sim \frac{x_B}{2 - x_B} \) the longitudinal momentum transfer.
- \( t = (p - p')^2 \) squared momentum transfer to the nucleon.

The GPDs enter the DVCS amplitude through a complex integral. This integral is called a *Compton form factor* (CFF).

\[
\mathcal{H}(\xi, t) = \int_{-1}^{1} H(x, \xi, t) \left( \frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) dx.
\]
Photon electroproduction and GPDs

Experimentally we measure the cross section of the process $ep \to ep\gamma$.

$$\frac{d^4\sigma(\lambda, \pm e)}{dQ^2 dx_B dt d\phi} = \frac{d^2\sigma_0}{dQ^2 dx_B} \frac{2\pi}{e^6} \times \left[ |\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 \mp J \right],$$

with $\lambda$ the helicity of the electron.
A parameterization of cross section

We can partially unfold the contributions, studying the $\phi$-dependence.

$$|\mathcal{J}^{BH}|^2 = \frac{e^6 \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)}{x_B^2 ty^2 (1 + \epsilon^2)^2 P_1(\phi) P_2(\phi)} \leftarrow \text{KNOWN!}$$

$$|\mathcal{J}^{DVCS}|^2 = \frac{e^6}{y^2 Q^2} \left\{ c_0^{DVCS} + \sum_{n=1}^{2} \left[ c_n^{DVCS} \cos(n\phi) + \lambda s_1^{DVCS} \sin(n\phi) \right] \right\}$$

$$J = \frac{e^6}{x_B y^3 P_1(\phi) P_2(\phi) t} \left\{ c_0^j + \sum_{n=1}^{3} \left[ c_n^j \cos(n\phi) + \lambda s_n^j \sin(n\phi) \right] \right\}$$
A parameterization of cross section

The CFFs are encapsulated in $c_n$ and $s_n$, offering a parameterization of the cross section. In the leading twist approximation for unpolarized target:

$$c_0^{DVCS} \propto \mathcal{C}^{DVCS}(\mathcal{F}, \mathcal{F}^*) = 4(1 - x_B)\mathcal{H}\mathcal{H}^* + \cdots$$

$$c_1^j \propto \text{Re}\ C^j(\mathcal{F}) = F_1 \text{Re}\mathcal{H} + \xi (F_1 + F_2) \text{Re}\mathcal{H} \mathcal{H} - \frac{t}{4M^2} F_2 \text{Re}\xi,$$

$$s_1^j \propto \text{Im}\ C^j(\mathcal{F}) = F_1 \text{Im}\mathcal{H} + \xi (F_1 + F_2) \text{Im}\mathcal{H} \mathcal{H} - \frac{t}{4M^2} F_2 \text{Im}\xi.$$

By studying the $\phi$-dependence of the observables, we can extract the CFFs. However there are too many CFFs to extract them all... We have to make some assumptions.

A first experiment in the Hall A in 2004

At leading twist, the cross section should be mostly given by $C^{DVCS}(\mathcal{F}, \mathcal{F}^*) (\cos 0\phi), \ Re \ C^j(\mathcal{F}) (\cos \phi) \ and \ Im \ C^j(\mathcal{F}) (\sin \phi)$ (considered all independent).

If there is mainly leading-twist at JLab, we can measure them and see if they are $Q^2$-independent.

<table>
<thead>
<tr>
<th>Setting</th>
<th>E (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$x_B$</th>
<th>W (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-Kin1</td>
<td>5.7572</td>
<td>1.5</td>
<td>0.36</td>
<td>1.9</td>
</tr>
<tr>
<td>2004-Kin2</td>
<td>5.7572</td>
<td>1.9</td>
<td>0.36</td>
<td>2.06</td>
</tr>
<tr>
<td>2004-Kin3</td>
<td>5.7572</td>
<td>2.3</td>
<td>0.36</td>
<td>2.23</td>
</tr>
</tbody>
</table>

NB: In the paper of 2006, DVCS$^2$ was neglected and only CFFs from interference were kept. The $\phi$-modelated uncertainty showed by Kresimir on Monday is the uncertainty related to the choice of parameterization.
Cross section and effective CFFs extraction

\[ d^4\sigma \ [\text{nb}/\text{GeV}^4] \]

\[ \Delta^4\sigma \ [\text{nb}/\text{GeV}^4] \]

\[ \phi \ [\text{deg}] \]

- Total
- DVCS-Twist2
- Int.-Twist2
- Int.-Twist3
- Bethe-Heitler
People were somewhat happy of this conclusion, but:

- All parameters are considered independent but it is not...
- And there is Vladimir’s work.
Here are the cross sections results!

\[ -t = 0.17 \text{ GeV}^2 \]

\[ -t = 0.23 \text{ GeV}^2 \]

\[ -t = 0.28 \text{ GeV}^2 \]

\[ -t = 0.32 \text{ GeV}^2 \]

\[ -t = 0.37 \text{ GeV}^2 \]

\[ d^4 \sigma [\text{nb/GeV}^4] \]

\[ \phi [\text{deg}] \]

**Kin2**

\[ x_B = 0.34 - 0.38 \]

\[ Q^2 = 1.8 - 2.0 \text{ GeV}^2 \]

- **Bethe-Heitler**
- **KM10a**

*Kumericki, Müller, Nucl. Phys. B841, 1 (2010)*
Here are the cross sections results!

\[ -t = 0.17 \text{ GeV}^2 \]
\[ -t = 0.23 \text{ GeV}^2 \]
\[ -t = 0.28 \text{ GeV}^2 \]

\[ -t = 0.32 \text{ GeV}^2 \]
\[ -t = 0.37 \text{ GeV}^2 \]

**Kin2**
\[ x_B = 0.34 - 0.38 \]
\[ Q^2 = 1.8 - 2.0 \text{ GeV}^2 \]

- **Bethe-Heitler**
- **KM10a**
- **KM10a + TMC**

*Braun et al., Phys. Rev. D89, 074022*
A lot of new DVCS data
The $\phi$-dependence is not enough to disentangle the contributions (We neglected terms). Using the beam energy dependence, we can add constrains on the model (separation of DVCS and interference contribution)

<table>
<thead>
<tr>
<th>Setting</th>
<th>$E$ (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$x_B$</th>
<th>$W$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-Kin1</td>
<td>5.7572</td>
<td>1.5</td>
<td>0.36</td>
<td>1.9</td>
</tr>
<tr>
<td>2004-Kin2</td>
<td>5.7572</td>
<td>1.9</td>
<td>0.36</td>
<td>2.06</td>
</tr>
<tr>
<td>2004-Kin3</td>
<td>5.7572</td>
<td>2.3</td>
<td>0.36</td>
<td>2.23</td>
</tr>
<tr>
<td>2010-Kin1</td>
<td>(3.355 ; 5.55)</td>
<td>1.5</td>
<td>0.36</td>
<td>1.9</td>
</tr>
<tr>
<td>2010-Kin2</td>
<td>(4.455 ; 5.55)</td>
<td>1.75</td>
<td>0.36</td>
<td>2</td>
</tr>
<tr>
<td>2010-Kin3</td>
<td>(4.455 ; 5.55)</td>
<td>2</td>
<td>0.36</td>
<td>2.1</td>
</tr>
</tbody>
</table>

But, before, let’s take a closer look to the kinematical power corrections.
Where do the kinematical power corrections come from?

Belitsky, Muller and Ji decomposed the DVCS amplitude in helicity amplitude, using the lab frame as reference frame. In the BMJ formalism, the cross section is parametrized by a set of CFFs:

$$\mathcal{F}_{\mu\nu} \in \{ \mathcal{H}_{\mu\nu}, \mathcal{E}_{\mu\nu}, \tilde{\mathcal{H}}_{\mu\nu}, \tilde{\mathcal{E}}_{\mu\nu} \}$$  \hspace{1cm} (3)

where $\mu$ ($\nu$) is the helicity of the virtual (real) photon. Therefore we can distinguish three cases:

- $\mathcal{F}_{++}$ are the *helicity-conserved CFFs*. They are the regular leading-twist CFFs which describes diagram for which virtual and real photon have the same helicity.

- $\mathcal{F}_{0+}$ are the *longitudinal-to-transverse helicity flip CFFs*. They are *twist-3* CFFs related to the contribution of the longitudinal polarization of the virtual photon.

- $\mathcal{F}_{-+}$ are the *transverse-to-transverse helicity flip CFFs*. At leading-order, these CFFs are *twist-4*. But at NLO order, these CFFs involves the *twist-2* gluon transversity GPDs.
Where do the kinematical power corrections come from?

In the BMP formalism, the reference frame is taken such as both photons have purely longitudinal momentum. This choice makes easier the inclusion of kinematically suppressed terms (in $t/Q^2$ or $M^2/Q^2$). In the BMP formalism, the cross section is parametrized by a set of CFFs:

$$ F_{\mu\nu} \in \{ H_{\mu\nu}, E_{\mu\nu}, \tilde{H}_{\mu\nu}, \tilde{E}_{\mu\nu} \} $$

(4)

where $\mu$ ($\nu$) is the helicity of the virtual (real) photon. Therefore we can distinguish three cases:

- $F_{++}$ are the helicity-conserved CFFs. They are twist-2 CFFs.
- $F_{0+}$ are the longitudinal-to-transverse helicity flip CFFs. They are twist-3 CFFs.
- $F_{--}$ are the transverse-to-transverse helicity flip CFFs. At LO, these CFFs are twist-4. At NLO, these CFFs involves the gluon transversity GPDs.
But let’s stay at leading-order. The BMP CFFs are not the same as the BMJ CFFs. The BMP CFFs are more complex terms. As an example, $\mathcal{H}_{++}$, we have:

$$
\mathcal{H}_{++} = T_0 \otimes H,
$$

$$
\mathcal{H}_{++} = T_0 \otimes H + \frac{-t}{Q^2} \left[ \frac{1}{2} T_0 - T_1 - 2 \xi D_\xi T_2 \right] \otimes H + \frac{2t}{Q^2} \xi^2 \partial_\xi T_2 \otimes (H + E) .
$$

We can go from BMP to BMJ CFFs by making the following replacement:

$$
\mathcal{F}_{++} = F_{++} + \frac{\chi}{2} \left[ F_{++} + F_{--} \right] - \chi_0 F_{0+} ,
$$

$$
\mathcal{F}_{--} = F_{--} + \frac{\chi}{2} \left[ F_{++} + F_{--} \right] - \chi_0 F_{0+} ,
$$

$$
\mathcal{F}_{0+} = -(1 + \chi) F_{0+} + \chi_0 \left[ F_{++} + F_{--} \right] ,
$$

with: $\chi_0 \propto \sqrt{t'/Q}$ and $\chi \propto t'/Q^2$. The leading-twist assumption gives different results between BMP and BMJ.
Assuming leading-twist and LO in BMJ, we have $F_{-+} = 0$ and $F_{0+} = 0$. It is important when regarding the DVCS amplitude. We have:

$$c_{0,\text{unp}}^{\text{VCS}} = 2^{2-2y+y^2+\frac{\epsilon^2}{2}y^2} \frac{1}{1+\epsilon^2} c_{\text{unp}}^{\text{VCS}}(F_{\pm+}, F_{\pm+}^*) + 8^{1-y-\frac{\epsilon^2}{4}y^2} \frac{1}{1+\epsilon^2} c_{\text{unp}}^{\text{VCS}}(F_{0+}, F_{0+}^*) , \quad (10)$$

$$\begin{cases} c_{1,\text{unp}}^{\text{VCS}} \\ s_{1,\text{unp}}^{\text{VCS}} \end{cases} = \begin{array}{c} 4\sqrt{2} \sqrt{1-y-\frac{\epsilon^2}{4}y^2} \\ 1+\epsilon^2 \end{array} \begin{cases} 2-y \\ -\lambda y \sqrt{1+\epsilon^2} \end{cases} \begin{array}{c} \Re \\ \Im \end{array} c_{\text{unp}}^{\text{VCS}}(F_{0+}\mid F_{++}, F_{--}) , \quad (11)$$

$$c_{2,\text{unp}}^{\text{VCS}} = 8^{1-y-\frac{\epsilon^2}{4}y^2} \frac{1}{1+\epsilon^2} \Re c_{\text{unp}}^{\text{VCS}}(F_{-+}, F_{++}^*) . \quad (12)$$

which reduces to:

$$c_{0,\text{unp}}^{\text{VCS}} = 2^{2-2y+y^2+\frac{\epsilon^2}{2}y^2} \frac{1}{1+\epsilon^2} c_{\text{unp}}^{\text{VCS}}(F_{++}, F_{++}^*) \quad (13)$$

The DVCS amplitude is $\phi$-independent with a single beam-energy dependence.
Differences in the LT-LO assumption: BMP

Assuming leading-twist and LO in BMP, we have $F_{-+} = 0$ and $F_{0+} = 0$.

\[
F_{++} = (1 + \frac{\chi}{2}) F_{++}, \quad (14)
\]

\[
F_{-+} = \frac{\chi}{2} F_{++}, \quad (15)
\]

\[
F_{0+} = \chi_0 F_{++}, \quad (16)
\]

It is important when regarding the DVCS amplitude.

\[
c_{VCS}^{0, unp} = 2 \frac{2 - 2y + y^2 + \frac{\epsilon^2}{2} y^2}{1 + \epsilon^2} c_{VCS}^{0, unp} (F_{\pm+}, F_{\pm+}^*) + 8 \frac{1 - y - \frac{\epsilon^2}{4} y^2}{1 + \epsilon^2} c_{VCS}^{0, unp} (F_{0+}, F_{0+}^*),
\]

\[
\begin{align*}
\left\{ c_{VCS}^{1, unp} \right\} &= 4 \sqrt{2} \sqrt{1 - y - \frac{\epsilon^2}{4} y^2} \frac{2 - y}{1 + \epsilon^2} \left\{ -\lambda y \sqrt{1 + \epsilon^2} \right\} \left\{ \Re \right\} c_{VCS}^{0, unp} (F_{0+}, F_{++}^*, F_{+++}^*),
\end{align*}
\]

\[
c_{VCS}^{2, unp} = 8 \frac{1 - y - \frac{\epsilon^2}{4} y^2}{1 + \epsilon^2} \Re c_{VCS}^{0, unp} (F_{-+}, F_{++}^*).
\]

The DVCS amplitude is \textbf{no longer} $\phi$-independent with \textbf{multiple} beam-energy dependences.
Differences in the LT-LO assumption: BMP

Assuming leading-twist and LO in BMP, we have $F_{-+} = 0$ and $F_{0+} = 0$.

\[
F_{++} = \left(1 + \frac{\chi}{2}\right) F_{++} ,
\]

\[
F_{--} = \frac{\chi}{2} F_{++} ,
\]

\[
F_{0+} = \chi_0 F_{++} ,
\]

It is important when regarding the DVCS amplitude. With $c^{VCS}_{unp}(F_{++}, F^{*+})$ in factor,

\[
c^{VCS}_{0, unp} = 2 \frac{2 - 2y + y^2 + \frac{\epsilon^2}{2} y^2}{1 + \epsilon^2} \left(\left(1 + \frac{\chi}{2}\right)^2 + \left(\frac{\chi}{2}\right)^2\right) + 8 \frac{1 - y - \frac{\epsilon^2}{4} y^2}{1 + \epsilon^2} (\chi_0)^2 ,
\]

\[
c^{VCS}_{1, unp} = \left(1 + \frac{\chi}{2}\right) \left(\chi_0 + \frac{\chi}{2}\right) \frac{4\sqrt{2}}{1 + \epsilon^2} \sqrt{1 - y - \frac{\epsilon^2}{4} y^2} (2 - y) ,
\]

\[
c^{VCS}_{2, unp} = 8 \frac{1 - y - \frac{\epsilon^2}{4} y^2}{1 + \epsilon^2} \left(1 + \frac{\chi}{2}\right) \frac{\chi}{2} .
\]

The DVCS amplitude is no longer $\phi$-independent with multiple beam-energy dependences.
A complicated Rosenbluth separation

By changing the beam energy, we also change the polarization of the virtual photon.

We must take them into account. Let’s fit the real and imaginary parts of $H_{++}E_{++}\tilde{H}_{++}\tilde{E}_{++}$:

- simultaneously on unpolarized and polarized cross sections,
- simultaneously on the two beam energies,
- simultaneously for the three $Q^2$-values (but I neglect the $Q$-evolution),
A glimpse of gluons through DVCS

Figure: $Q^2 = 1.75 \text{ GeV}^2, -t = 0.3 \text{ GeV}^2$. $E=4.445 \text{ GeV}$ (left) and $E=5.55 \text{ GeV}$ (right)

- **LT/LO:** $H_{++}, E_{++}, \tilde{H}_{++}, \tilde{E}_{++}$.
- **HT:** $H_{++}, \tilde{H}_{++}, H_{0+}, \tilde{H}_{0+}$.
- **NLO:** $H_{++}, \tilde{H}_{++}, H_{--}, \tilde{H}_{--}$.

Equally good fit between the HT and NLO scenario. M. Defurne et al., Hall A collaboration, arXiv:1703.0944 (Accepted in Nat. Commun.)
Separation of DVCS and interference

Despite an equally good fit, slight differences appear when separating the interference and DVCS term.

In the HT scenario, the beam helicity dependent cross section is not a pure interference term, as it is usually assumed in most phenomenological analyses. M. Defurne et al., Hall A collaboration, arXiv:1703.0944 (Accepted in Nat. Comms.)
Conclusion on photon electroproduction from 6 GeV era in Hall A

- Kinematical power corrections are sizeable at our moderate $Q^2$ (even at 4 GeV$^2$).
- Taking them into account, the leading-twist/leading-order fails to describe the data.
- Only conclusion is that we need higher-twist or Gluon GPDs at NLO.

Although it is an important conclusion... it is also disappointing that we have only a partial answer.
And people seem a bit skeptical about these kinematical power corrections.
How to convince everyone?
What are we looking at?
Finally it is less straightforward to know what we are measuring with photon electroproduction because of the Bethe-Heitler.
Data has been collected at 6.6 ($Q^2=3.2$), 8.8 ($Q^2=3.6$) and 10.6 GeV ($Q^2=4.2$) in Hall A, still at $x_B=0.36$.

Assuming $Q^2$-independence (I would have tried to do something better but lack of time), we can expect this:
If we stay at $Q^2=2$, but use higher beam energy

- High $Q^2$ to “increase” the validity of Leading-twist/Leading-order assumptions.
- But not too high or you will only measure Bethe-Heitler.
Do a clean separation, assumption-free, with positrons!

Positrons beam is a solution to get a clean picture of the DVCS$^2$.

\[
\frac{d^4\sigma(\lambda, \pm e)}{dQ^2 dx_B dt d\phi} = \frac{d^2\sigma_0}{dQ^2 dx_B} \frac{2\pi}{e^6} \times \left[ |\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 \mp \mathcal{J} \right],
\]

with $\lambda$ the helicity of the electron.
Think better about the next measurements

I have the feeling that people think we just need to measure accurately cross sections. But there are still many questions left to be answered and we need to keep an open-mind:

- We tried to test scaling to check the regime in JLab. Still need to be done.
- What is the weight of the different GPDs? 25% measurement of missing observables can be more constraining than 1%-accuracy on unpolarized cross sections.
- Don’t we have a lot of answers if we do a simultaneous analysis of DVCS and DVMP?
- Bethe-Heitler is good as long as it is not most of the signal. Because we want to measure deviation from Bethe-Heitler.
- Run experiments to determine what we are measuring.
- What are the best observables? (Moments? or cross sections?)
Some warnings about the future

Technologically we are good. But upcoming data will require:
- the finest data analysis ever made at JLab. (Systematics at 1%?)
- intense theoretical effort for the radiative corrections,…!

The radiative corrections are different for $J$, $|J_{DVCS}|^2$ and $|J_{BH}|^2$
Kinematical power corrections are large. They should be also present in DVMP:
Could it explain the sharp rise of $\sigma_{TL}$ when $Q^2$ decreases?
Take $\chi_0$ and $\chi$ into account for Rosenbluth separation?
If $\pi^0$ teaches us something: You can have surprises about the dominant contribution.
We are sensitive to gluon or 3-parton correlations in DVCS. Might have additionnal information with CLAS12 data.
But positron beam would be the cleanest way to access DVCS$^2$, which will immediately tell us what’s going on.
Not a single experiment/facility/channel will reconstruct the GPD puzzle. PARTONS!
DSE gives already DAs for mesons… very good for DVMP analysis. It will also be interesting when they will deliver us a GPD for the nucleon. But I think both experiment and non-perturbative approached are required to perform the tomography of the nucleon.