Deeply Virtual Compton Scattering and Hard Exclusive $\pi^0$ Muoproduction at COMPASS

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Plan

1. Generalized Parton Distribution functions
2. Measurements at COMPASS and experimental setup
3. DVCS cross-section extraction and its $t$-dependence
4. $\pi^0$ cross-section and its sensitivity to chiral-odd GPDs
5. Outlook and summary
Generalized Parton Distributions (GPDs)

Deeply Virtual Compton Scattering

\[ \gamma^* + N \rightarrow \gamma + N' \]

- No nucleon spin flip
  \[ H^f(x, \xi, t) \]
  \[ \tilde{H}^f(x, \xi, t) \]

- With nucleon spin flip
  \[ E^f(x, \xi, t) \]
  \[ \tilde{E}^f(x, \xi, t) \]

GPDs are not experimentally accessible, but related to Compton Form Factors (CFFs)

CFFs are observables in cross section measurements

\[ \mathcal{H}(\xi, t) = \int_{-1}^{1} \frac{H(x, \xi, t)}{x - \xi - i\epsilon} \, dx \]
GPDs and Hard Exclusive Meson Production

Chiral-even GPDs
helicity of parton unchanged

$$\begin{align*}
H^{q,g} & \quad \tilde{H}^{q,g} \\
E^{q,g} & \quad \tilde{E}^{q,g}
\end{align*}$$

Chiral-odd GPDs
helicity of parton changed

$$\begin{align*}
H_T^{q} & \quad \tilde{H}_T^{q} \\
E_T^{q} & \quad \tilde{E}_T^{q}
\end{align*}$$

- factorisation proven only for $\sigma_L$, $\sigma_T$ suppressed by $1/Q^2$
- wave function of meson (DA) additional non-perturbative term
Measurement at COMPASS

Diff. cross section \( \frac{d\sigma^4}{dQ^2d\nu d|t|d\phi} \)

Kinematic dependence:
- \( Q^2 = -q^2 \): virtual photon virtuality
- \( \nu = E_\mu - E'_\mu \): energy of virt. photon
- \( t = (p_P - p_{P'})^2 \): 4-mom. transfer to nucleon squared
- \( \phi \): angle between scattering and production planes

Measured quantities:
- \( \mu \): beam muon
- \( \mu' \): scattered muon
- \( P' \): recoil proton
- \( \gamma \): real photon

- **2012** pilot run for 4 weeks → analysis finished and published
- **2016/17** long runs (2 × 6 months) dedicated to DVCS → analysis ongoing, preliminary results
COMPASS experiment setup

**Common Muon and Proton Apparatus for Structure and Spectroscopy**

- **2.5m long Liquid Hydrogen target**
- **Beam energy is 160 GeV**
- **Beam polarisations**: $\mu^+\downarrow$ and $\mu^-\uparrow$

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu \quad P_{\mu^+} \approx -80\% \\
\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad P_{\mu^-} \approx +80\%
\]
COMPASS experiment setup

Two stage forward spectrometer **SM1 + SM2**

- Beam flux determined with \( \approx 1\% \) precision
- **ECAL0, ECAL1 and ECAL2** for photon detection
- 300 tracking detector planes, muon trigger system
- Muon identification system
- CAMERA for recoil proton detection
Deeply Virtual Compton Scattering

\[ \mu p \rightarrow \mu' p' \gamma \text{ process} \]
The observable products of these reactions are identical, therefore they can not be separated on per-event basis.

\[ \sigma_\gamma \propto |A_{DVCS}|^2 + |A_{BH}|^2 + \text{Interference Term} \]

**Interference Term** \( \equiv A_{DVCS}A_{BH} \) - allows to study DVCS on the amplitude level.
Selection of events with a single $\gamma$ topology

**Vertex candidates:**
- $\mu$ Beam muon
- $\mu'$ Scattered muon

**Real photon candidate $\gamma$:**
Single photon with the energy above DVCS threshold $E_\gamma > 4, 5, 10$ GeV in ECAL0, 1, 2

**Recoil proton candidate $P'$:**
$|t|_{\text{exp}}^{\text{max}} = 0.64\ (\text{GeV}/c)^2$

**Exclusivity selections:**
- $|\Delta p_T| < 0.3 \text{ GeV}/c$
- $|\Delta \phi| < 0.4 \text{ rad}$
- $|\Delta z_A| < 16 \text{ cm}$
- $|M^2_{\text{Undet}}| < 0.3 (\text{GeV}/c^2)^2$
- $0.08 (\text{GeV}/c)^2 < |t_{\text{fit}}| < 0.64 (\text{GeV}/c)^2$

**Perform kinematic fit:**
- constrain on kinematic variables $\chi^2 < 10$

**Only events with single valid combination**
- Vertex candidate $\times$ Real photon candidate $\times$ Recoil proton candidate
Exclusive selections (COMPASS 2016 preliminary results)

\[ \Delta \phi = \Delta \phi_{\text{Cam}} - \Delta \phi_{\text{Spec}} \]

Entries / 0.025 rad

\[ \Delta p_T = \Delta p_{T,\text{Cam}} - \Delta p_{T,\text{Spec}} \]

Entries / 0.02 GeV/c

\[ \Delta Z_A = Z_{A,\text{Cam}} - Z_{A,\text{Interp}} \]

Entries / cm

\[ M_{\text{undet}}^2 = (k+p-k'-q'-p')^2 \]

Entries / 0.025 (GeV/c)^2

Anatolii Koval
The binned DVCS cross section

DVCS cross section in bins of $t$, $\phi$, $Q^2$, $\nu$:

$$\left\langle \frac{d\sigma_{\text{DVCS}}}{dt d\phi dQ^2 d\nu} \right\rangle_{t_i \phi_j Q^2_k \nu_l}^{\pm} = \frac{1}{\mathcal{L}^{\pm} \Delta t_i \Delta \phi_j \Delta Q^2_k \Delta \nu_l} \left[ (a_{ijkl}^{\pm})^{-1} (\text{data} - BH_{\text{MC}} - \pi^0_{\text{MC}}) \right]$$

- $a_{ijkl}^{\pm}$: Acceptance
- BH\text{MC}: Exclusive single photon MC sample
- $\pi^0_{\text{MC}}$: $\pi^0$ MC sample (background estimation)
The Bethe-Heitler contribution

Bethe-Heitler process is well known, pure QED → evaluated using **Monte-Carlo sample** for BH

- Kinematic range where **BH is dominant** → The BH contribution is evaluated for the experimental integrated luminosity
- **BH subtracted** from the data in the DVCS region (small $\nu$)
- data / BH = $(98.6 \pm 1 \pm 4)$% (for this bin)
The $\pi^0$ background contamination

- Photons from $\pi^0$ decay
- One photon identified as exclusive photon event $\rightarrow$ above DVCS energy threshold in ECALs

- **Visible** (both $\gamma$ are detected)
  - *subtracted*
  Combine $\gamma_{he}$ and $\gamma_{le}$ (below DVCS energy threshold)

- **Invisible** (second $\gamma$ lost)
  - *estimated by MC*
    - **Inclusive**: LEPTO
    - **Exclusive**: HEPGEN $\pi^0$
$\phi$ distribution of exclusive photon events

$1 < Q^2 < 10 \ (\text{GeV}/c)^2$

- $80 < \nu \ [\text{GeV}] < 144$
  - $\langle x_B \rangle = 0.0085$
  - $\langle Q^2 \rangle = 1.8 \ (\text{GeV}/c)^2$

- $32 < \nu \ [\text{GeV}] < 80$
  - $\langle x_B \rangle = 0.020$
  - $\langle Q^2 \rangle = 2.0 \ (\text{GeV}/c)^2$

- $10 < \nu \ [\text{GeV}] < 32$
  - $\langle x_B \rangle = 0.063$
  - $\langle Q^2 \rangle = 2.1 \ (\text{GeV}/c)^2$

- **BH dominates**
  - DVCS negligible
  - 64% of events in data

- **BH and DVCS are comparable**
  - 24% of events in data

- **DVCS dominates BH**
  - 12% of events in data, where:
    - 37% BH contribution
    - 10% inv. $\pi^0$ contribution
The binned DVCS cross section

DVCS cross section in bins of $t$, $\phi$, $Q^2$, $\nu$:

$$
\left\langle \frac{d\sigma_{DVCS}}{dt|d\phi dQ^2 d\nu} \right\rangle_{t_i \phi_j Q_k^2 \nu_l}^{\pm} = 
\frac{1}{\mathcal{L}^\pm \Delta t_i \Delta \phi_j \Delta Q_k^2 \Delta \nu_l} \left[ (a_{ijkl}^\pm)^{-1} (\text{data} - \text{BH}_{MC} - \pi^0_{MC}) \right]
$$

$$
\pi^0_{MC} = (1 - R) \times \pi^0_{\text{HEPGEN}} + R \times \pi^0_{\text{LEPTO}}
$$

- **BH$_{MC}$**: BH MC sample
- **$\pi^0_{\text{HEPGEN}}$**: exclusive $\pi^0$ MC sample
- **$\pi^0_{\text{LEPTO}}$**: inclusive $\pi^0$ MC sample
- **$R$**: relative contrib. of LEPTO ($\approx 40\%$)
- **$a_{ijkl}^\pm$**: acceptance

**Binning and kinematic range:**

- 4 bins in $|t|$ between 0.08 and 0.64 (GeV/c)$^2$ (equistatistics)
- 4 bins $\nu$ between 10 and 32 GeV (equidistant)
- 4 bins $Q^2$ between 1 and 5 (GeV/c)$^2$ (equidistant)
- 8 bins $\phi$ between $-\pi$ and $+\pi$ (equidistant)

Analysis limited to region with mostly flat acceptance
avg. acc. $\approx 40\%$, good agreement between $\mu^+$ and $\mu^-$.
Accessing the $t$-dependence of the cross section

From $\mu p$ to $\gamma^* p$:  
$$ \frac{d\sigma^{\mu p}}{d|t|\phi dQ^2 d\nu} = \Gamma(Q^2, \nu) \times \frac{d\sigma^{\gamma^* p}}{d|t|\phi dQ^2 d\nu} $$

by weighting each event in data and MC by the inverse flux of the transverse polarized photons

→ Integrate over $Q^2$ and $\nu$ and average over $\mu^+/\mu^-$, then $t$-dependence of the cross section:

$$ \left\langle \frac{d\sigma_{DVCS}}{d|t|} \right\rangle_{t_i} = \frac{1}{2} \left( \left\langle \frac{d\sigma_{DVCS}}{d|t|} \right\rangle_{t_i}^+ + \left\langle \frac{d\sigma_{DVCS}}{d|t|} \right\rangle_{t_i}^- \right) $$

$$ S_{CS,U} = d\sigma^{+\downarrow} + d\sigma^{-\uparrow} = $$

$$ 2 \left[ d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos\phi + c_2^{DVCS} \cos2\phi + s_1^I \sin\phi + s_2^I \sin2\phi \right] $$
Analyse the cross section $t$-slope

\[ \frac{d\sigma^{\text{DVCS}}}{dt} \sim e^{-B|t|} \propto c_0^{\text{DVCS}} = (Im\mathcal{H})^2 \]

Perform binned maximum Likelihood-fit.

\[ B = (6.6 \pm 0.6_{\text{stat}} \pm 0.3_{\text{sys}}) (\text{GeV}/c)^{-2} \]

Dominant source of systematics:
MC normalisation to visible $\pi^0$ in data.
Analyze the cross section $t$-slope

$t$-slope $\Rightarrow$ proton trans. ext.

$$\langle b_{\perp}^2 (x_{Bj}) \rangle = 2 \langle B(x_{Bj}) \rangle \hbar^2$$

$$d\sigma^{DVCS}/dt \sim e^{-B|t|} \propto c_0^{DVCS} = (ImH)^2$$

Perform binned maximum Likelihood-fit.

$$B = (6.6 \pm 0.6_{stat} \pm 0.3_{sys}) (GeV/c)^{-2}$$

Dominant source of systematics:
MC normalisation to visible $\pi^0$ in data.

$$B = (4.3 \pm 0.6_{stat}^{+0.1}_{-0.3}|_{sys}) (GeV/c)^{-2}$$

2012 results PLB 793 (2019) 188
Hard Exclusive $\pi^0$ Meson Production

$\mu p \rightarrow \mu' p' \pi^0$ process
Selection of events with $\pi^0$ topology

**Vertex candidates:**
- $\mu$ Beam muon
- $\mu'$ Scattered muon

**2-$\gamma$ candidate:**
from $\pi^0$ decay, with invariant mass $M_{\gamma\gamma}$ cut

**Recoil proton candidate $P'$:**
- $|t|_{\text{max}}^{\text{exp}} = 0.64(\text{GeV}/c)^2$

**Exclusivity selections:**
- $|\Delta p_T| < 0.3\text{GeV}/c$
- $|\Delta \phi| < 0.4\text{rad}$
- $|\Delta z_A| < 16\text{cm}$
- $|M_{\text{Undet}}^2| < 0.3(\text{GeV}/c^2)^2$
- $0.08(\text{GeV}/c)^2 < |t_{\text{fit}}| < 0.64(\text{GeV}/c)^2$

**Perform kinematic fit:**
- constrain on kinematic variables $\chi^2 < 10$

Only events with single valid combination
- Vertex candidate $\times$ 2-$\gamma$ candidate $\times$ Recoil proton candidate
Exclusive selections (COMPASS 2016 preliminary results)

\[ \Delta \phi = \phi_{\text{cam}} - \phi_{\text{spect}} \]

\[ \Delta p_T = |p_{T,\text{cam}}| - |p_{T,\text{spect}}| \]

\[ \Delta Z_A = Z_{A,\text{cam}} - Z_{A,\text{extrapolated}} \]

\[ M^2_{\text{Undet}} = (p_\mu + p_P - p_{\mu'} - p_{P'} - p_\gamma)^2 \]

\[ \text{COMPASS 2016 } \mu^+ \text{ data} \]

\[ \text{HEPGEN + LEPTO} \]

\[ \text{HEPGEN} \]

\[ \text{LEPTO} \]

LEPTO share: (35 ± 10)%
Exclusive $\pi^0$ production: SIDIS background estimation

- Main background of $\pi^0$ production $\Rightarrow$ non-exclusive DIS process
- 2 MC simulations with the same $\pi^0$ selection criteria:
  - LEPTO for the non-exclusive background
  - HEPGEN++ shape of distributions of exclusive $\pi^0$ production (signal contribution)
- Search for best description of data fitting by mixture of both MC

![Graph](image)

- Non-exclusive background fraction is $(35 \pm 10)\%$
- Background fit method is the main source of systematic uncertainty
Exclusive $\pi^0$ cross section

$$\frac{d^2\sigma}{dt\,d\phi} = \frac{1}{2\pi} \left[ \left( \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} \right) + \epsilon \cos 2\phi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1 + \epsilon)} \cos \phi \frac{d\sigma_{LT}}{dt} \right]$$

Factorization proven for $\sigma_L$, not for $\sigma_T$ which is expected to be suppressed by a factor $1/Q^2$ BUT large contributions are observed at JLab.

$$\frac{d\sigma_L}{dt} \sim |\langle \tilde{H} \rangle|^2 - \frac{t'}{4m^2} |\langle \tilde{E} \rangle|^2$$

$$\frac{d\sigma_T}{dt} \sim |\langle H_T \rangle|^2 - \frac{t'}{8m^2} |\langle E_T \rangle|^2$$

$$\frac{d\sigma_{TT}}{dt} \sim \frac{t'}{16m^2} |\langle E_T \rangle|^2$$

$$\frac{d\sigma_{LT}}{dt} \sim \frac{\sqrt{-t'}}{2m} \text{Re} \left[ \langle \tilde{H} \rangle \langle \tilde{E} \rangle \right]$$

$t' = t - t_{min}$, where $|t_{min}|$ is minimum value of $|t|$

Impact of $E_T$ should be visible in $\frac{d\sigma_{TT}}{dt}$, and also a dip at small $t$ of $\frac{d\sigma_T}{dt}$
Exclusive $\pi^0$ cross section

as a function of $t$

![Graph showing $d\sigma/d|t|$ as a function of $|t|$ (GeV/c)^2.]

- **GK 16**: Goloskokov Kroll (2016)
- **other models**: Golstein Gonzalez Liuti PRD91 (2015)

as a function of $\phi$

![Graph showing $d^2\sigma/d|t|d\phi$ as a function of $\phi$ (rad).]
Outlook and summary

- **Analyse full statistics** of 2016 and 2017 (3 times more data than 2016)
- **DVCS**
  - Cross section study in few $x_{Bj}$ regions $\rightarrow$ tomography
  - More detailed studies of **systematic uncertainties**
  - **Study the azimuthal dependence** of the cross section
    $\rightarrow$ Determine $c_0^{DVCS}$, $c_1^{DVCS}$, $c_2^{DVCS}$, $s_1^\uparrow$ and $s_2^\uparrow$
  - **Cross section difference** $D_{CS,U} = d\sigma^{+\downarrow} - d\sigma^{-\uparrow}$
    $\rightarrow$ Access to $Re\mathcal{H}$ and quark pressure distribution in the nucleon
- **Exclusive $\pi^0$**
  - New, preliminary results of 2016 COMPASS measurement at $\langle x_{Bj} \rangle = 0.096 \Rightarrow$ constraining phenomenological models (e.g. Goloskokov and Kroll; Goldstein, Gonzales and Liuti, etc.)
Thank you for your attention!
Backup
Cross section

\[ d\sigma \propto |A_{BH}|^2 + |A_{DVCS}|^2 + \text{Interference Term} \]

\[
\frac{d^4\sigma(lp \rightarrow lp\gamma)}{dx_B dQ^2 dt d\phi} = d\sigma^{BH} + \left( d\sigma_{DVCS}^{\text{unpol}} + P_l d\sigma_{DVCS}^{\text{pol}} \right) + \left( e_l ReI + e_l P_l ImI \right)
\]

\[ D_{CS,U} = d\sigma^{\uparrow\downarrow} - d\sigma^{\downarrow\uparrow} = 2 \left[ e_\mu a^{BH} ReA^{DVCS} + |P_\mu| d\sigma_{DVCS}^{\text{pol}} + ReI \right] \]

\[ = 2 \left[ s_1^{DVCS} \sin \phi + c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi \right] \]

\[ S_{CS,U} = d\sigma^{\uparrow\downarrow} + d\sigma^{\downarrow\uparrow} = 2 \left[ d\sigma^{BH} + d\sigma_{DVCS}^{\text{unpol}} - |P_\mu| ImI \right] \]

\[ = 2 \left[ d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi + s_1^{I} \sin \phi + s_2^{I} \sin 2\phi \right] \]
Cross section

\[ S_{CS,U} = d\sigma^{+\downarrow} + d\sigma^{-\uparrow} \]

\[ D_{CS,U} = d\sigma^{+\downarrow} - d\sigma^{-\uparrow} \]

- \[ S_{CS,U} \] \( \propto c_0^{BH} + c_1^{BH} \cos \phi + c_2^{BH} \cos 2\phi \)
- \( S_{CS,U} \) \( \propto c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi \)
- \( D_{CS,U} \) \( \propto s_1^{DVCS} \sin \phi \)
- \( D_{CS,U} \) \( \propto c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi \)
- \( D_{CS,U} \) \( \propto s_1^I \sin \phi + s_2^I \sin 2\phi \)

\[ S_{CS,U} \] \( \propto c_0^{BH} + c_1^{BH} \cos \phi + c_2^{BH} \cos 2\phi \)

LO, Twist-2

\[ S_{CS,U} = d\sigma^{+\downarrow} + d\sigma^{-\uparrow} \]

LO, Twist-3

NLO, Twist-2

\[ D_{CS,U} = d\sigma^{+\downarrow} - d\sigma^{-\uparrow} \]