GPD measurements at COMPASS

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Outline

1 Introduction
2 DVCS
3 DVMP
4 $\pi^0$ production
5 Vector mesons
6 Conclusion
4 chiral-even, 4 chiral-odd (subscript $T$).
2 T-odd ($E, \bar{E}_T$).
Introduction: COMPASS

- M2 beamline of CERN’s SPS.
- 24 institutes, 13 countries.

- **SIDIS** with 160 GeV (200 GeV) $\mu^+$ beam and longitudinally/transversely-polarised proton ($\text{NH}_3$) or deuteron ($^6\text{LiD}$) target.
  - A. Martin (Wed, TMDs),
  - G. Reicherz (Wed, Polarised targets),
  - B. Parsamyan (Thu, plenary)

- **Hadron spectroscopy** with hadron beams and nuclear targets.

- **Drell–Yan** with 190 GeV $\pi^-$ beam and $p^+$ ($\text{NH}_3$), Al, W targets.
  - V. Andrieux (Wed, TMDs),
  - A. Vijayakumar (poster).

- Hard exclusive processes and **SIDIS** with 160 GeV/c $\mu^\pm$ beam and liquid $\text{H}_2$ target.
  - This talk and SIDIS on Tue in TMDs.

2022 setup with $^6\text{LiD}^+$ target: Experiments concluded, now in analysis phase.
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1. Introduction
2. DVCS
3. DVMP
4. $\pi^0$ production
5. Vector mesons
6. Conclusion
Deeply virtual Compton scattering

- GPDs appear in the cross-sections via Compton form-factors
  \[ \mathcal{H}(\xi, t) = \mathcal{P} \int_{-1}^{1} dx \frac{H(x, \xi, t)}{x - \xi} - i\pi H(\pm \xi, t). \]
  (convolution GPD \( \otimes \) hard process).
- Sensitive to
  - \( H \) (unpolarised proton target),
  - \( E, \tilde{H}, \tilde{E} \) (neutron or polarised targets).
- Interference with Bethe–Heitler process.

\[ q = (p_\mu - p_{\mu'}): \text{4-momentum of virtual photon} \]
\[ Q^2 = -q^2: \text{virtual photon virtuality} \]
\[ t = (p_P - p_{P'}^2): \text{4-momentum transfer to nucleon squared} \]
\[ x: \text{average longitudinal momentum fraction} \]
\[ \xi: \text{half of longitudinal momentum fraction transfer} \]
DVCS: Experimental setup

- 160 GeV/c beam
  - $\mu^+$: $P_{\mu^+} \approx -80\%$ (from $\pi^+ \to \mu^+ \nu_\mu$)
  - $\mu^-$: $P_{\mu^-} \approx +80\%$ (from $\pi^- \to \mu^- \bar{\nu}_\mu$)
- 2.5 m long liquid H target.
- 2-stage magnetic spectrometer.
- CAMERA, ECAL0, ECAL1, ECAL2.
- 2012 pilot run (1 month)
  - Published results [PLB 793 (2019) 188]
- 2016–2017 runs
  - Larger ECAL0.
  - $10 \times$ more statistics.
  - The same $\mu^+$ and $\mu^-$ beam intensity.
  - Preliminary results using 1/3 statistics.

Event selection:

- $\mu p \to \mu' p' \gamma$
- $E_\gamma > 4, 5, 10$ GeV in ECAL 0, 1, 2.
CAMERA recoil proton detector

- Exclusive $\mu p \rightarrow \mu' p' \gamma$:
- $|\Delta p_T| < 0.3 \text{ GeV/c}$,
- $|\Delta \phi| < 0.4 \text{ rad}$,
- $|\Delta z_A| < 16 \text{ cm}$,
- $|M_X^2| < 0.3 (\text{GeV/c}^2)^2$
- Over-constrained measurement – Kinematic fit performed
- $\chi^2_{\text{fit}} < 10.$
DVCS: Kinematic domain, Bethe–Heitler

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

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

- $a_{ijkl}^{\pm}$ Acceptance $\approx$ 40\% and flat
- BH$_{MC}$ Exclusive single photon MC sample
- $\pi^0_{MC}$ $\pi^0$ MC sample (background estimation)

- 160 GeV/c beam
- $Q^2 \in (1, 10)$ (GeV/c)$^2$
- $|t| \in (0.08, 0.64)$ (GeV/c)$^2$

- Bethe–Heitler (BH) background:
  - Well known – QED MC.
  - Checked in BH-dominated region of $\nu \in (80, 144)$ GeV.
  - Subtracted in the DVCS region of $\nu \in (10, 32)$ GeV.
DVCS: Kinematic domain, Bethe–Heitler

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

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

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

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

- $a_{ijkl}^\pm$: Acceptance $\approx 40\%$ and flat
- $\text{BH}_{MC}$: Exclusive single photon MC sample
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**Visible $\pi^0$ background**
- Both $\gamma$ detected.
- Rejected in event selection.
- Used to normalize $\pi^0$ MC

**Non-visible $\pi^0$ background**
- Only one $\gamma$ detected.
- Subtracted using $\pi^0$ MC.
- Inclusive (LEPTO) and exclusive (HEPGEN) MC.
**DVCS: Results**

Measurement as a function of $|t|$, integrating over $\phi$:

\[
\frac{d\sigma}{dt} \leftrightarrow \frac{d\sigma}{d\phi} = 2[do^{BH} + do^{DVCS}_{impol} + \text{Im } I] \\
= 2[do^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi + s_1^I \sin \phi + s_2^I \sin 2\phi]
\]

$c_0^{DVCS}$: related to the Compton form-factor $H$.

In COMPASS kinematics ($\frac{2\xi}{1+\xi} = x_B \approx 0.06$):

- Dominance of $\text{Im } H$  
  (97% in GK model, 94% in KM model)
- $c_0^{DVCS} \propto (\text{Im } H)^2$
- $H$: related to the GPD $H$ (at LT and LO): 
  $H(x, t) = \mathcal{P} \int_{-1}^{1} dx \frac{H(x, \xi, t)}{x-\xi} - i\pi H(\pm \xi, t)$.
- $q(x, b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-ib_\perp \cdot \Delta_\perp} H(x, 0, -\Delta_\perp^2)$

\[
\langle b_\perp^2 \rangle = \frac{\int d^2b_\perp b_\perp^2 q(x, b_\perp)}{\int d^2b_\perp q(x, b_\perp)} = -4 \frac{\partial}{\partial t} \ln H(x, 0, t) \bigg|_{t=0}
\]

\[
\frac{d\sigma^{DVCS}}{dt} \propto e^{-B|t|} = e^{-\frac{1}{2} \langle b_\perp^2 \rangle |t|}
\]
DVCS: Results

Measurement as a function of $|t|$, integrating over $\phi$:

$$\begin{align*}
d\sigma^{\uparrow} + d\sigma^{\downarrow} &= 2[ d\sigma^{BH} + d\sigma^{DVCS}_{impol} + \text{Im } I ] \\
&= 2[ d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi + s_1^I \sin \phi + s_2^I \sin 2\phi ] \\
\end{align*}$$

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$$\frac{d\sigma^{DVCS}}{dt} \propto e^{-B|t|} = e^{-\frac{1}{2} \langle b_\perp^2 \rangle |t|}$$

2016: preliminary, 1/3 of available statistics.
Re-analysis of 2016 data is being finalised → publication soon.

Study the $\phi$-dependence
- $s_1^I \propto \text{Im} H$ → further constrain transverse extension of partons.

Cross-section difference to be extracted
- $d\sigma^+ - d\sigma^- \propto \text{Re} F \propto \text{Re} H$ → related to D-term and pressure distribution.

2017 data analysis starting.

Study the $x_B$-dependence → tomography.

Analysis slowed down recently due to lack of people.

New groups interested in GPD analyses joined COMPASS recently.
DVMP: Introduction

- Factorisation (collinear) proven only for longitudinally polarised $\gamma^*$.
- Phenomenological models postulating $k_\perp$-factorisation.
- Flavour separation possible thanks to different quark content of mesons.
- **Pseudoscalar mesons**
  - At leading twist: sensitive to $\tilde{H}, \tilde{E}, H_T, \tilde{E}_T$.
- **Vector mesons**
  - Gluons and quarks enter at the same order of $\alpha_S$
  - Sensitive to $H, E, H_T, \tilde{E}_T$.
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π^0 production: Event selection

- 2012 pilot run (1 month)
  - Published results [PLB 805 (2020) 135454]
- 2016–2017 runs
  - Larger ECAL0.
  - 10× more statistics.
  - The same μ^+ and μ^- beam intensity.
  - Preliminary results using 1/3 statistics.

μp → μ'p'π^0
π^0 → γγ

E_γ thresholds in ECAL 0, 1, 2.

Exclusivity with CAMERA:
- ∆φ < 0.4 rad,
- ∆p_T < 0.3 GeV/c,
- ∆z_A < 16 cm,
- M_X^2 < 0.3 (GeV/c^2)^2

Kinematic fit
- χ^2_{fit} < 10

Kinematic domain:
- ν ∈ (6.4, 40) GeV,
- Q^2 ∈ (1, 8) (GeV/c)^2,
- |t| ∈ (0.08, 0.64) GeV/c.

Improved acceptance with respect to 2012.
**Non-exclusive background**

- $\pi^0$ from deep inelastic scattering.
- Simulated by LEPTO MC.
- Exclusive $\pi^0$ simulated by HEPGEN MC.
- Mix of HEPGEN and LEPTO fitted to exclusivity distributions in the data.
- Result: $(17 \pm 5)\%$ of nonexclusive background.
\[ \frac{d\sigma_{\mu^+p\to\mu'p+\pi^0}}{dtd\phi} + \frac{d\sigma_{\mu^-p\to\mu'p-\pi^0}}{dtd\phi} = \frac{\Gamma(Q^2, \nu)}{2\pi} \]

\[ \times \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \cos 2\phi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi \frac{d\sigma_{LT}}{dt} \right] \]

Cross section in 2012 kinematic range.
GK'16 model: Goloskokov–Kroll (2016),
Other models: Goldstein–Gonzalez–Liuti, PRD91 (2015)

Statistical uncertainty shown, the systematic one is 10% to 20% (in low cross section bins).
$\pi^0$ production: Results

\[
\frac{d\sigma^{\mu^+ p \rightarrow \mu^' p^+ \pi^0}}{dt d\phi} + \frac{d\sigma^{\mu^- p \rightarrow \mu^' p^- \pi^0}}{dt d\phi} = \frac{\Gamma(Q^2, \nu)}{2\pi} \\
\times \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \cos 2\phi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi \frac{d\sigma_{LT}}{dt} \right]
\]

\[d\sigma_L \propto \langle H_T \rangle^2 - \frac{t^'}{4m^2} |\langle E_T \rangle|^2\]

\[d\sigma_T \propto |\langle H_T \rangle|^2 - \frac{t^'}{8m^2} |\langle E_T \rangle|^2\]

\[\sigma_{TT} \propto \frac{t^'}{16m^2} |\langle E_T \rangle|^2\]

\[\sigma_{LT} \propto \frac{\sqrt{-t^'}}{2m} \text{Re} \left[ \langle H_T \rangle^* \langle E_T \rangle \right]\]

Cross section in **2012 kinematic range.**
GK16 model: Goloskokov–Kroll (2016),
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**New 2016 preliminary results** [K. Lavičková, IWHSS 2023, Prague] (using 1/3 statistics):
Statistical uncertainty shown, the systematic one is 10% to 20% (in low cross section bins).

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The 2016 analysis is being finalised → publication soon.
Comparison with theory predictions, once they are available in our kinematic domain.
2017 data analysis starting.
Study the $\nu, x_B$ or $Q^2$ dependence.
Cross-section difference $(d\sigma^+ - d\sigma^-) \to \sin \text{ modulation amplitude.}$
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Vector mesons: Transverse asymmetries

- $\mu p \rightarrow \mu' p' \rho^0$ and $\mu p \rightarrow \mu' p' \omega$
- $\rho^0 \rightarrow \pi^+ \pi^-$
- $\omega \rightarrow \pi^+ \pi^- \pi^0$
- No recoil proton detector.
- Exclusivity imposed via energy conservation.
- Target: transversely polarised $p$ (H in NH$_3$).

Contribution of pion pole important for $\omega$, as $\Gamma(\omega \rightarrow \pi^0 \gamma) \approx 9 \Gamma(\rho^0 \rightarrow \pi^0 \gamma)$
Spin density matrix elements (SDMEs) – parametrize experimental angular distributions of vector meson production on unpolarised target:
2012 data with LH target, not using CAMERA here (to access low $t$).

- *s*-channel helicity conservation model (SCHC): $\lambda_\gamma = \lambda_V$
  
  Sum of SDMEs in the yellow boxes should be 0, all others 0.
Vector mesons: SDMEs

Natural (N) to unnatural (U) parity exchange

\[ P = \frac{2r_{1-1}^1}{1 - r_{00}^{04} - 2r_{1-1}^{04}} \approx \frac{d\sigma_T^N (\gamma^*_T \rightarrow V_T) - d\sigma_T^U (\gamma^*_T \rightarrow V_T)}{d\sigma_T^N (\gamma^*_T \rightarrow V_T) + d\sigma_T^U (\gamma^*_T \rightarrow V_T)} \]

- NPE: GPDs \( H, E \),
- UPE: GPDs \( \tilde{H}, \tilde{E} \) and the pion pole.

Pion pole exchange contributes to UPE,
\[ \Gamma(\omega \rightarrow \pi^0 \gamma) \approx 9 \Gamma(\rho^0 \rightarrow \pi^0 \gamma) \]

\( \rho^0 \): \( P \approx 1 \rightarrow \) dominance of NPE

\( \omega \): \( P \approx 0 \rightarrow \) NPE \( \approx \) UPE
Longitudinal-to-transverse cross section ratio for $\rho^0$ production

$$R = \frac{d\sigma_L(\gamma^*_L \rightarrow V)}{d\sigma_T(\gamma^*_T \rightarrow V)}$$

To obtain it from the data:

- Assuming SCHC: $R' = \frac{1}{\epsilon} \frac{r_{04}^{00}}{1-r_{00}^{04}}$
  (standard, used by many experiments)
- Assuming only NPE: $\tilde{R}$

![Graph showing data points and line of fit]

for all the experiments with $Q^2 > 1$ GeV$^2$
Vector mesons: Outlook

- Exclusive $\phi$ production: ongoing analysis (SMDEs, cross section).
- Exclusive $J/\psi$ production: feasibility studies.
Conclusion

- **2016–2017 data** with LH target and 160 GeV/c $\mu^{\pm}$ beam
- Preliminary results using 1/3 of statistics (part of 2016 data)
  - DVCS $t$-slope of the cross section \(\rightarrow\) transverse extension of partons at \(x_B = 0.06\).
  - Deep virtual $\pi^0$ production cross-section: **new results (6/2023).**
    \(\rightarrow\) large contribution of $\sigma_{TT}$ confirmed – significant role of $\gamma_T$ and the GPD $\bar{E}_T$.
  - Both measurements are being finalised, to be published soon.

- **SDMEs in hard $\omega$ production** [EPJC (2021) 81 126]
- **SDMEs in hard $\rho^0$ production:** Paper accepted to EPJC [hep-ex/2210.16932]
  \(\rightarrow\) Importance of $\gamma_T$ and the GPD $H_T$
- $\rho^0$ and $\omega$ production on polarised target [NPB 915 (2017) 454] [PLB B731 (2014) 19]

**Outlook:**

- **2017 data:** starting with new people joining the analysis – promising!
- Extensions of the DVCS and $\pi^0$ analyses:
  - Kinematic dependencies \((\nu, x_B, Q^2)\),
  - Azimuthal dependence of the DVCS cross section,
  - Cross section difference \(d\sigma^+ - d\sigma^-\)
- **Deep virtual $\phi$ production cross section and SDMEs:** work in progress on 2016 data.
- **Deep virtual $J/\psi$ production:** feasibility studies.
Conclusion

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Thank you for your attention!