Hard Exclusive Reactions at COMPASS at CERN

Exclusive photon (DVCS) and meson (HEMP) production at small transfer for GPD studies

**DVCS** : \( \mu \ p \rightarrow \mu' \ p' \ \gamma \)

**Pseudo-Scalar Meson** : \( \mu \ p \rightarrow \mu' \ p' \ \pi^0 \)

**Vector Meson** : \( \mu \ p \rightarrow \mu' \ p' \ \rho \ or \ \omega \ or \ \phi \ ...

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**Measurement of exclusive cross sections at COMPASS**

**DVCS**: $\mu \ p \rightarrow \mu' \ p' \gamma$ at small transfer

Both $\mu^+$ and $\mu^-$ beams
Polarisation $\sim \pm 80\%$
Momentum $160$ GeV/c

COMPASS: Two stage magnetic spectrometer for large angular & momentum acceptance
Particle identification with RICH, HCALs, ECALs and muon filters

2012: 1 month pilot run

2016 - 17: 2 x 6 month data taking

DVCS: $\mu p \rightarrow \mu' p \gamma$

+ SIDIS on unpolarized protons
Deeply virtual Compton scattering (DVCS)

The GPDs depend on the following variables:

- $\bar{x}$: average quark longitudinal momentum fraction
- $\xi$: transferred momentum fraction
- $t$: proton momentum transfer squared related to $b_\perp$ via Fourier transform
- $Q^2$: virtuality of the virtual photon

DVCS: $\ell p \rightarrow \ell' p' \gamma$

the golden channel because it interferes with the Bethe-Heitler process

also meson production $\ell p \rightarrow \ell' p' \pi, \rho, \omega$ or $\phi$ or $J/\psi$

The variables measured in the experiment:

$E_\ell, Q^2, \bar{x}_B \sim 2\xi/(1+\xi)$,
$t$ (or $\theta_{\gamma^*\gamma}$) and $\phi$ ($\ell\ell'$ plane/$\gamma\gamma^*$ plane)
**Deeply virtual Compton scattering (DVCS)**

The amplitude DVCS at LT & LO in $\alpha_s$ (GPD $H$):

$$
\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\epsilon} = \mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi} - i \pi H(x = \pm \xi, \xi, t)
$$

In an experiment we measure Compton Form Factor $\mathcal{H}$.
Deeply virtual Compton scattering (DVCS)

Lepton ($P_l$, $e_l$) and $\phi$

\[
\frac{d^4\sigma(\ell p \rightarrow \ell p\gamma)}{dx_B dQ^2 d|l|d\phi} = d\sigma^{BH} + (d\sigma^{DVCS_{unpol}} + P_\ell d\sigma^{DVCS_{pol}}) - (e_\ell \text{Re } I + e_\ell P_\ell \text{Im } I)
\]

Well known

With unpolarized target:

Belitsky, Müller, Kirner, NPB629 (2002)

\[
\begin{align*}
\frac{d\sigma^{BH}}{dx_B dQ^2 d|l|d\phi} &\propto c_0^{BH} + c_1^{BH} \cos \phi + c_2^{BH} \cos 2\phi \\
\frac{d\sigma^{DVCS_{unpol}}}{dx_B dQ^2 d|l|d\phi} &\propto c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi \\
\frac{d\sigma^{DVCS_{pol}}}{dx_B dQ^2 d|l|d\phi} &\propto s_1^{DVCS} \sin \phi \\
\text{Re } I &\propto c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi \\
\text{Im } I &\propto s_1^I \sin \phi + s_2^I \sin 2\phi
\end{align*}
\]
Deeply virtual Compton scattering (DVCS)

With both $\mu^+$ and $\mu^-$ beams we can build:

1. beam charge-spin sum

$$\Sigma \equiv \sigma^+ - \sigma^-$$

2. difference

$$\Delta \equiv \sigma^+ - \sigma^-$$

\[\begin{align*}
\Sigma & \equiv \sigma^+ + \sigma^- \\
\Delta & \equiv \sigma^+ - \sigma^-
\end{align*}\]

\[\begin{align*}
d\sigma^{BH} & \propto c_0^{BH} + c_1^{BH} \cos \phi + c_2^{BH} \cos 2\phi \\
d\sigma_{unpol}^{DVCS} & \propto c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi \\
d\sigma_{pol}^{DVCS} & \propto s_1^{DVCS} \sin \phi \\
\text{Re } I & \propto c_0^I + c_1^I \cos \phi + c_2^I \cos 2\phi + c_3^I \cos 3\phi \\
\text{Im } I & \propto s_1^I \sin \phi + s_2^I \sin 2\phi
\end{align*}\]

\[\begin{align*}
\Sigma & \equiv \sigma^+ + \sigma^- \Rightarrow s_1^I \propto \text{Im } F \\
\Delta & \equiv \sigma^+ - \sigma^- \Rightarrow c_1^I \propto \text{Re } F
\end{align*}\]

And $c_0^{DVCS} \propto (\text{Im } H)^2$

\[F = F_1 H + \xi_s (F_1 + F_2) H - t/4m^2 F_2 E \]

for proton

at small $x_b$

COMPASS domain
**COMPASS 2016 data** Selection of exclusive single photon production

Comparison between the observables given by the spectro or by CAMERA

**DVCS:** $\mu \ p \rightarrow \mu' \ p \ \gamma$

1) $\Delta \varphi = \varphi_{cam} - \varphi_{spec}$
2) $\Delta p_T = p_T^{cam} - p_T^{spec}$
3) $\Delta z_A = z_A^{cam} - z_A^{spec}$ and vertex
4) $M^2_{X=0} = (p_{j\mu}^{in} + p_{j\mu}^{out} - p_{\mu}^{out} - p_{\gamma})^2$

Good agreement between $\mu^+$ and $\mu^-$ yields important achievement for:

1) $\sum \equiv d\sigma^+ - d\sigma^-$ **Easier, done first**
2) $\Delta \equiv d\sigma^+ - d\sigma^-$ **Challenging, but promising**

1) proton azimuthal angle
2) proton momentum
3) proton track position
4) Energy momentum balance
COMPASS 2016 data

DVCS+BH cross section at $E_\mu=160$ GeV

$$\Sigma = d\sigma (\mu^+) + d\sigma (\mu^-)$$

$$d\sigma \propto |T^{BH}|^2 + \text{Interference Term} + |T^{DVCS}|^2$$

$80 < v [\text{GeV}] < 144$

$32 < v [\text{GeV}] < 80$

$10 < v [\text{GeV}] < 32$

Pure BH contribution

$x_B \approx 0.0085$

$Q^2 \approx 1.8 \text{ GeV}^2$

$y \approx 0.75$

$32 < v [\text{GeV}] < 80$

$x_B \approx 0.020$

$Q^2 \approx 2 \text{ GeV}^2$

$y \approx 0.3$

$10 < v [\text{GeV}] < 32$

$x_B \approx 0.063$

$Q^2 \approx 2.1 \text{ GeV}^2$

$y \approx 0.1$

Data/BH = 98.6 ±1±4%

MC: BH contribution evaluated for the integrated luminosity

$\pi^0$ background contribution from SIDIS (LEPTO) + exclusive production (HEPGEN)
At COMPASS using polarized positive and negative muon beams:

\[
\sum \equiv \frac{d\sigma^+}{d\nu} + \frac{d\sigma^-}{d\nu} = 2[\frac{d\sigma^{BH}}{d\nu} + \frac{d\sigma^{DVCS}}{d\nu} + Im I]
\]

\[
= 2[\frac{d\sigma^{BH}}{d\nu} + c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi + s_1^I \sin \phi + s_2^I \sin 2\phi]
\]

All the other terms are cancelled in the integration over \( \phi \).

 Flux for transverse virtual photons

COMPASS preliminary

\[ e^{-B|t|} \]

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

given by a binned maximum likelihood technique
\[ \frac{d\sigma^{\text{DVCS}}}{dt} = e^{-B|t|} = c_0^{\text{DVCS}} \propto (\text{Im} \mathcal{H})^2 \]

\[ c_0^{\text{DVCS}} \propto 4(\mathcal{H}^{*} \mathcal{H} + \tilde{\mathcal{H}}^{*} \tilde{\mathcal{H}}) + \frac{t}{M^2} \mathcal{E} \mathcal{E}^* \]

In the COMPASS kinematics, \( x_B \approx 0.06 \), dominance of \( \text{Im} \mathcal{H} \)
97% (GK model) 94% (KM model)

\( \text{Im} \mathcal{H} = H(\xi = \zeta, \xi, t) \)
\( x = \xi \approx x_B / 2 \) close to 0

\[ q(x, b_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-ib_\perp \cdot \Delta_\perp} H^q(x, 0, -\Delta_\perp^2). \]

\[ \langle b_{\perp}^2 \rangle_x = \left. \frac{\int d^2 b_\perp b_\perp^2 q_f(x, b_\perp)}{\int d^2 b_\perp q_f(x, b_\perp)} \right| = -4 \frac{\partial}{\partial t} \log H^f(x, \xi = 0, t) \bigg|_{t=0} \]

\[ \langle b_{\perp}^2(x) \rangle \approx 2B(\xi) \]
\[ \frac{d\sigma^{\text{DVCS}}}{dt} = e^{-B|t|} = c_0^{\text{DVCS}} \propto (\text{Im} \mathcal{M})^2 \]

\[ \langle b_1^2(x) \rangle \approx 2B(\xi) \]

3σ difference between 2012 and 2016 data

- more advanced analysis with 2016 data
- \( \pi^0 \) contamination with different thresholds
- binning with 3 variables \((t,Q^2,v)\) or 4 variables \((t,\phi,Q^2,v)\)

2012 statistics = Ref
2016 analysed statistics = 2.3 \times \text{Ref}
2016+2017 expected statistics = 10 \times \text{Ref}
Possible next steps for DVCS

- DVCS and the sum $\sum \equiv d\sigma^+ + d\sigma^-$

  - $c_0 \sim (\text{Im}\ H)^2$ final conclusion using all the data sets 2012, 2016, 2017
  - $s_1 \sim \text{Im}\ H$

  constrain on $\text{Im}\ H$ and Transverse extension of partons

- DVCS and the difference $\Delta \equiv d\sigma^+ - d\sigma^-$

  - $c_1$ and constrain on $\text{Re}\ H$ (>0 as H1 or <0 as HERMES)

  for D-term and pressure distribution
Factorisation proven only for $\sigma_L$

The meson wave function is an additional non-perturbative term

**Quark contribution**

For *Pseudo-Scalar Meson, as $\pi^0$*

- Chiral-even GPDs: helicity of parton unchanged
  $$\tilde{H}^q(x, \xi, t) \quad \tilde{E}^q(x, \xi, t)$$

- Chiral-odd or transversity GPDs: helicity of parton changed
  $$\tilde{H}^q_T(x, \xi, t)$$ (as the transversity TMD)
  $$\tilde{E}^q_T = 2 \tilde{H}^q_T + E^q_T$$ (as the Boer-Mulders TMD)

$\sigma_T$ is asymptotically suppressed by $1/Q^2$ but large contribution observed

GK model: $k_T$ of $q$ and $\bar{q}$ and Sudakov suppression factor are considered

Chiral-odd GPDs with a twist-3 meson wave function
COMPASS 2012 - 16  Exclusive $\pi^0$ production on unpolarized proton

$\mu^\pm p \rightarrow \mu^\pm \pi^0 p$

$F_\pi^0 = 2/3 F_u + 1/3 F_d$

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

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

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

$\frac{d\sigma_{LT}}{dt} \propto \frac{t'}{16m^2} \left| \langle E_T \rangle \right|^2$

$\langle \frac{d\sigma_T}{dt} \rangle = (8.2 \pm 0.9_{\text{stat}} \pm 1.2_{\text{sys}}) \text{nb} (\text{GeV}/c)^2$

$\langle \frac{d\sigma_L}{dt} \rangle = (-6.1 \pm 1.3_{\text{stat}} \pm 0.7_{\text{sys}}) \text{nb} (\text{GeV}/c)^2$

$\langle \frac{d\sigma_{LT}}{dt} \rangle = (1.5 \pm 0.5_{\text{stat}} \pm 0.3_{\text{sys}}) \text{nb} (\text{GeV}/c)^2$

$\sigma_{TT}$ large - impact of $E_T$

$\sigma_{LT}$ small but significantly positive as at CLAS

COMPASS

$Q^2 = 2.0$ GeV$^2$

$x_B = 0.093$

$|t| \sim 0.26$ GeV$^2$

$\epsilon$ close to 1

$8.5 < y < 26$ GeV

$1 < Q^2 < 5$ GeV$^2$

PLB 805 (2020)

Next steps for pi0

Analysis of the 2016 data set should be completed by the end of the month

Extended kinematical domain at small and large $\nu$ to provide $x_B$ evolution
\[8.5 < \nu < 26 \text{ GeV}\]
\[6.4 \, \checkmark \quad \nrightarrow \quad 40 \text{ GeV}\]

The 2017 data set will still increase the statistics
GPDs and Hard Exclusive Meson Production

Factorisation proven only for $\sigma_L$
The meson wave function
Is an additional non-perturbative term

**For Vector Meson, as $\rho, \omega, \phi...$**

**Quark contribution**

chiral-even GPDs: helicity of parton unchanged

\[ H_q(x, \xi, t) \quad E^q(x, \xi, t) \]

+ chiral-odd or transversity GPDs: helicity of parton changed

\[ H_T^q(x, \xi, t) \quad (as \ the \ transversity \ TMD) \]

\[ \hat{E}_T^q = 2 H_T^q + E_T^q \quad (as \ the \ Boer-Mulders \ TMD) \]

**Gluon contribution at the same order in $\alpha_s$**

Neutral Vector Meson $q\bar{q}$
$\rho^0 \rightarrow \pi^+ \pi^-$

$$E_{\rho^0} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} E^u + \frac{1}{3} E^d + \frac{3}{4} E^a \right)$$

$\omega \rightarrow \pi^+ \pi^- \pi^0$

$$E_{\omega} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} E^u - \frac{1}{3} E^d + \frac{1}{4} E^a \right)$$

$E^u$ and $E^d$ of opposite sign

$\omega$ is more promising (see the larger scale) but there is the inherent pion pole contribution

$\Gamma(\omega \rightarrow \pi^0 \gamma) = 9 \times \Gamma(\rho^0 \rightarrow \pi^0 \gamma)$

Same for $\pi \omega$ FF but sign unknown

COMPASS, NPB 865 (2012) 1-20, PLB731 (2014) 19

COMPASS, NPB 915 (2017)

$\sin(\phi_{\pi \pi})$

$\sin(\phi_{\pi \pi})$

$A_{UT}$

$A_{UT}$

$\sin(\phi_{\pi \pi})$

$\sin(\phi_{\pi \pi})$

$E_{\rho^0}$

$E_{\omega}$

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

$P_T (\text{GeV}^2/c^2)$

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

$P_T (\text{GeV}^2/c^2)$

$\Gamma(\omega \rightarrow \pi^0 \gamma) = 9 \times \Gamma(\rho^0 \rightarrow \pi^0 \gamma)$

positive $\pi \omega$ form factor

no pion pole

negative $\pi \omega$ form factor

GK EPJC42,50,53,59,65,74
exclusive VM production with Unpolarised Target and SDME

experimental angular distributions:

\[ \mathcal{W}^{U+L}(\Phi, \phi, \cos \Theta) = \mathcal{W}^U(\Phi, \phi, \cos \Theta) + \mathcal{P}_L \mathcal{W}^L(\Phi, \phi, \cos \Theta) \]

15 'unpolarized' and 8 'polarized' SDMEs

\[ \mathcal{W}^U(\Phi, \phi, \cos \Theta) = \frac{3}{8\pi^2} \left[ \frac{1}{2} (1 - r_{10}^{04}) + \frac{1}{2} (3r_{00}^{04} - 1) \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{04}\} \sin 2\Theta \cos \phi - r_{11}^{04} \sin^2 \Theta \cos 2\phi \right. \\
- \epsilon \cos 2\Phi \left( r_{11}^{04} \sin^2 \Theta + r_{00}^{11} \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{11}\} \sin 2\Theta \cos \phi - r_{11}^{11} \sin^2 \Theta \cos 2\phi \right) \\
- \epsilon \sin 2\Phi \left( \sqrt{2} \text{Im}\{r_{10}^{11}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{11}^{11}\} \sin^2 \Theta \sin 2\phi \right) \\
\left. + \sqrt{2} (1 + \epsilon) \cos \Phi \left( r_{11}^{05} \sin^2 \Theta + r_{00}^{05} \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{05}\} \sin 2\Theta \cos \phi - r_{11}^{05} \sin^2 \Theta \cos 2\phi \right) \\
+ \sqrt{2} (1 + \epsilon) \sin \Phi \left( \sqrt{2} \text{Im}\{r_{10}^{05}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{11}^{05}\} \sin^2 \Theta \sin 2\phi \right) \right] \\
\]

\[ \mathcal{W}^L(\Phi, \phi, \cos \Theta) = \frac{3}{8\pi^2} \left[ \sqrt{1 - r^2} \left( \sqrt{2} \text{Im}\{r_{10}^{11}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{11}^{11}\} \sin^2 \Theta \sin 2\phi \right) \\
+ \sqrt{2} (1 - \epsilon) \cos \Phi \left( \sqrt{2} \text{Im}\{r_{10}^{11}\} \sin 2\Theta \sin \phi + \text{Im}\{r_{11}^{11}\} \sin^2 \Theta \sin 2\phi \right) \\
+ \sqrt{2} (1 - \epsilon) \sin \Phi \left( r_{11}^{08} \sin^2 \Theta + r_{00}^{08} \cos^2 \Theta - \sqrt{2} \text{Re}\{r_{10}^{08}\} \sin 2\Theta \cos \phi - r_{11}^{08} \sin^2 \Theta \cos 2\phi \right) \right] \\
\]

\( \epsilon \) close to 1, small \( \mathcal{W}^L \)
no L/T separation
SCHC

\[ \sum_{\text{SDME}} \approx 0 \text{ for } \gamma^*_L \rightarrow \omega_L \text{ and } \gamma^*_T \rightarrow \omega_T \]

The other SDMEs should be \( = 0 \)

\[ r_{00}^5 \propto \text{Re} \left[ (E_T)_{LT}^* (H)_{LL} + \frac{1}{2} (H_T)_{LT}^* (E)_{LL} \right] \]

COMPASS

Accepted in EPJC

\[ Q^2 = 2.4 \text{ GeV}^2 \]
\[ W = 9.9 \text{ GeV} \]
\[ p_T^2 = 0.18 \text{ GeV}^2 \]

COMPASS

EPJC81 (2021) 126

\[ Q^2 = 2.1 \text{ GeV}^2 \]
\[ W = 7.6 \text{ GeV} \]
\[ p_T^2 = 0.16 \text{ GeV}^2 \]
Natural (N) to Unnatural (U) Parity Exchange for $\gamma_T^* \rightarrow V_T$

The pion pole exchange (UPE) is large for $\omega$ compared to $\rho^0$

$$\Gamma(\omega \rightarrow \pi^0 \gamma) = 9 \times \Gamma(\rho^0 \rightarrow \pi^0 \gamma)$$

as for $\pi^0$ Vector Meson FF

It plays an important role in $\omega$ production for:

$\gamma_T^* \rightarrow V_T$

and

$\gamma_L^* \rightarrow V_T$

$\rho^0$: P~1 $\Rightarrow$ NPE dominance P~1
NPE with GPDs $H, E$

$\omega$: P~0 $\Rightarrow$ NPE ~ UPE
UPE dominance at small W and $p_T^2$
UPE with GPDs $\tilde{H}, \tilde{E}$ and the dominant pion pole
$R = \frac{\sigma_L}{\sigma_T}$ for exclusive $\rho^0$ production

![Graph showing $R$ and $\tilde{R}$ vs. $Q^2$](graph.png)

In COMPASS domain, evaluation of $R$ and $\tilde{R}$ considering violation of SCHC (and only NPE).

Deviation from the pQCD LO prediction in $Q^2/M_{\rho}^2$: QCD evolution and $q_T$

Transversize size effects of the meson smaller for $\sigma_L$ than for $\sigma_T$
Analysis of the exclusive $\phi$ production is currently in progress

(with cross section and SDMEs)
**COMPASS 2016+17**

**Outlook for DVCS and HEMP**

- **DVCS** and the sum \( \sum \equiv d\sigma^+ + d\sigma^- \)
  - \( c_0 \) and \( s_1 \) and constrain on \( \text{Im} \mathcal{H} \) and Transverse extension of partons

- **DVCS** and the difference \( \Delta \equiv d\sigma^+ - d\sigma^- \)
  - \( c_1 \) and constrain on \( \text{Re} \mathcal{H} \) (>0 as H1 or <0 as HERMES)
    - for D-term and pressure distribution

- On-going analysis (Cross section, SDME) for HEMP of \( \pi^0, \rho^0, \omega, \phi, J/\psi \)
  - Transversity GPDs
  - Gluon GPDs
  - Flavor decomposition

**Importance of e\(^+\) beam**
- For Jlab 20+ GeV

**Importance of large luminosity**
- For DVCS, TCS, DDVCS, J/\( \psi \) ...
**ImH** and **ReH** using global fits of the world data

**Global Fit KM15**  
Compared to GK Model GK  

**Global Fits using PARTONS framework**  
Compared to GK and VGG Models  

ReH is still poorly known (importance of DVCS with $\mu^\pm$ at COMPASS, $e^\pm$ at JLab  
or TCS at JLab and EIC)