Use of positive and negative polarized muon beams to study exclusive reactions at COMPASS at CERN. 

Positron beams at JLab

Beryllium target

Proton reaction products:
- $p, \pi^+, K^+, \mu^+$
- $\bar{p}, \pi^-, K^-, \bar{\mu}^-$
COMPASS: a fixed target exp. at SPS, a versatile facility with hadron ($\pi^\pm$, $K^\pm$, $p$ ...) & lepton (~80% polarized $\mu^+$) beams of high energy ~160 GeV
Positive and Negative Polarized Muon Beam at COMPASS

Weak decay \( \pi^+ \rightarrow \mu^+ + \nu_\mu \)
Parity violation and helicity conservation the muons are 100% polarized in the pion rest frame

Left-handed \( \nu_\mu \) and \( \mu^+ \)
Right-handed \( \bar{\nu}_\mu \) and \( \mu^- \)

In the lab the muon polarization of the muon depends on momenta of both meson and muon

Optimisation of both polarization & muon fluxes: 160 GeV/c ~80% polarization

500mm Be 20 \( 10^7\mu^+\)/spill but only 7.4 \( 10^7\mu^+\)/spill
to get about 7.4 \( 10^7\mu^+\)/spill
Advantage of positive and negative polarized muon beams for:

1. Deeply Virtual Compton Scattering (DVCS)

2. Exclusive $\pi^0$ production
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

CAMERA recoil proton detector surrounding the 2.5m long LH2 target

2012:
1 month pilot run

2016 -17:
2 x 6 month data taking
Deeply virtual Compton scattering (DVCS)

The GPDs depend on the following variables:
- $x$: 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

The variables measured in the experiment:
- $E_\ell$, $Q^2$, $x_B$ $\sim 2\xi/(1+\xi)$
- $t$ (or $\theta_{\gamma^*\gamma}$) and $\phi$ ($\ell\ell'$ plane/$\gamma^*$ plane)

DVCS: $\ell p \rightarrow \ell' p' \gamma$
the golden channel because it interferes with the Bethe-Heitler process
also meson production $\ell p \rightarrow \ell' p' \pi^0, \rho, \omega$ or $\phi$ or $J/\psi$...

The variables measured in the experiment:
- $E_\ell$, $Q^2$, $x_B$ $\sim 2\xi/(1+\xi)$
- $t$ (or $\theta_{\gamma^*\gamma}$) and $\phi$ ($\ell\ell'$ plane/$\gamma^*$ plane)
Deeply virtual Compton scattering (DVCS)

after talks given by Sebastian, Hervé, Pierre...

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

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

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

M. Burkardt, PRD66(2002)

Mapping in the transverse plane

\[ q(x, b_{\perp}) \]

The amplitude DVCS at LT & LO in \( \alpha_S \) (GPD \( \mathcal{H} \)) :

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

In an experiment we measure Compton Form Factor \( \mathcal{H} \)

\[ \text{Re} \mathcal{H}(\xi, t) = \pi^{-1} \int_0^1 dx \frac{2x \text{Im} \mathcal{H}(x, t)}{x^2 - \xi^2} + \Delta(t) \]


Pressure Distribution

\[ r^2 p(r) \text{ in GeV fm}^{-1} \]

The integral \( \int_0^\infty dr \ r^2 p(r) = 0 \)
Deeply virtual Compton scattering (DVCS)

With unpolarized target:

Belitsky, Müller, Kirner, NPB629 (2002)

\[
\frac{d^4 \sigma(\ell p \to \ell p' \gamma)}{dx_B dQ^2 dl d\phi} = \frac{d\sigma_{BH}^{\text{BH}}}{\text{Well known}} + \left( d\sigma_{\text{DVCS}}^{\text{DVCS}} + P_\ell d\sigma_{\text{DVCS}}^{\text{DVCS pol}} \right) - (e_\ell \Re I + e_\ell P_\ell \Im I)
\]

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

Well known lepton \((P_\ell, e_\ell)\) and \(\phi\)

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

Interference Term

Deeply virtual Compton scattering (DVCS)

With unpolarized target:

Belitsky, Müller, Kirner, NPB629 (2002)

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

With polarized electrons

\(d\sigma^{\leftarrow} - d\sigma^{\rightarrow}\)

With electrons and positrons

\(d\sigma^{+} - d\sigma^{-}\)
Deeply virtual Compton scattering (DVCS)

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

1. **beam charge-spin sum**
   \[ \sum \equiv d\sigma^+ + d\sigma^- \]
   \[ \sum \equiv d\sigma^+ + d\sigma^- \Rightarrow s_1^I \propto \text{Im } F \]
   and \( c_0^{\text{DVCS}} \propto (\text{Im } H)^2 \)

2. **difference**
   \[ \Delta \equiv d\sigma^+ - d\sigma^- \]
   \[ \Delta \equiv d\sigma^+ - d\sigma^- \Rightarrow c_1^I \propto \text{Re } F \]

**for proton**

**at small \( x_B \)**

\[ F = F_1 H + \xi \left( F_1 + F_2 \right) \tilde{H} - \frac{t}{4m^2} F_2 E \]

\[ \text{COMPASS domain} \]
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) $\Delta \varphi = \varphi^{\text{cam}} - \varphi^{\text{spec}}$

2) $\Delta p_T = p_T^{\text{cam}} - p_T^{\text{spec}}$

3) $\Delta z_A = z_A^{\text{cam}} - z_A^{\text{spec}}$ and vertex

4) $M_{X=0}^2 = (p_{\mu \text{in}} + p_{\mu \text{out}} - p_{\mu \text{in}} - p_{\mu \text{out}})^2$

Good agreement between $\mu^+$ and $\mu^-$ yields

Important achievement for:

1) $\sum \equiv d\sigma^+ - d\sigma^-$  \text{ Easier, done first}

2) $\Delta \equiv d\sigma^+ - d\sigma^-$  \text{ Challenging, but promising}

Necessity to use the same $\mu^+$ and $\mu^-$ flux
**COMPASS 2016 data**

**DVCS+BH cross section at \(E\mu=160\) GeV**

\[ \sum = d\sigma (\mu^+) + d\sigma (\mu^-) \]

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

**Pure BH contribution**

- \(x_{Bj} \approx 0.0085\)
- \(Q^2 \approx 1.8 \text{ GeV}^2\)
- \(y \approx 0.75\)

**Data/BH=98.6 ±1±4%**

**MC:** BH contribution evaluated for the integrated luminosity

\(\pi^0\) background contribution from SIDIS (LEPTO) + exclusive production (HEPGEN)

**DVCS above the BH contrib.**
At COMPASS using polarized positive and negative muon beams:

\[
\sum \equiv d\sigma^+ + d\sigma^- = 2[d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \text{Im } I]
\]

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

calculable

can be subtracted

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

\[ \frac{d^3\sigma_{\mu p}^{\mu p}}{dQ^2 d\nu dt} = \int_{-\pi}^{\pi} d\phi \left( d\sigma - d\sigma^{BH} \right) \propto c_0^{DVCS} \]

\[ \frac{d\sigma^{* \mu}}{dt} = \frac{1}{\Gamma(Q^2, \nu, E_\mu)} \frac{d^3\sigma_{\mu p}^{\mu p}}{dQ^2 d\nu dt} \]

Flux for transverse virtual photons

**COMPASS preliminary**

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

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

given by a binned maximum likelihood technique
**COMPASS 12-16 Transverse extension of partons in the sea quark range**

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

\[ \langle b_{\perp}^2(x) \rangle \approx 2B(\xi) \]

3\(\sigma\) difference between 2012 and 2016 data

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

2012 statistics = Ref
2016 analysed statistics = \(2.3 \times\) Ref
2016+2017 expected statistics = \(10 \times\) Ref

**Graph:**
- **2012**
- **2016**

- COMPASS: \(<Q^2> = 1.8\ (GeV/c)^2\)
- COMPASS: \(<Q^2> = 1.8\ (GeV/c)^2\)
- ZEUS: \(<Q^2> = 3.2\ (GeV/c)^2\)
- H1: \(<Q^2> = 4.0\ (GeV/c)^2\)
- H1: \(<Q^2> = 8.0\ (GeV/c)^2\)
- H1: \(<Q^2> = 10.\ (GeV/c)^2\)

**Models:**
- KM15 model from Kumericki & Mueller
- GK model from Goloskokov & Kroll

**Reference:**
- PLB793
Possible next steps for DVCS

✓ DVCS and the sum \[ \Sigma \equiv d\sigma^+ + d\sigma^- \]

\[ c_0 \sim (\text{Im}\ H)^2 \] 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 \[ \Delta \equiv d\sigma^+ - d\sigma^- \]

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

for D-term and pressure distribution
**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


Reminder with BCA: \( \text{ReH} < 0 \) at HERMES
> 0 at H1 (but not used in PARTONS?)

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

\[
\frac{x \text{ImH}}{t} = \begin{array}{ll}
\text{GK} & \text{KM15} \\
Q^2 = 2 \text{GeV}^2 \\
t = 0 & t = -0.3 \text{GeV}^2
\end{array}
\]

\[
\frac{x \text{ReH}}{t} = \begin{array}{ll}
\text{H1, ZEUS} & \text{COMPASS} & \text{HERMES} & \text{JLab} \\
\text{t = 0} & t = -0.3 \text{GeV}^2
\end{array}
\]

\[
\xi \sim \frac{x_B/(2-x_B)}{t = -0.3 \text{ GeV}^2 \text{ and } Q^2 = 2 \text{ GeV}^2}
\]
GPDs and Hard Exclusive Meson Production

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

- Chiral-even GPDs: helicity of parton unchanged
  \[ \widetilde{H}^q(x, \xi, t) + \widetilde{E}^q(x, \xi, t) \]

- Chiral-odd or transversity GPDs: helicity of parton changed
  \[ \tilde{H}_T^q(x, \xi, t) \text{ (as the transversity TMD)} \]
  related to the transverse spin structure and to the tensor charge

  \[ \widetilde{E}_T^q = 2 \widetilde{H}_T^q + E_T^q \text{ (as the Boer-Mulders TMD)} \]
  related to the distortion of the polarized quark distribution in the transverse plane for an unpolarized nucleon

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

GK model: \(k_T\) of \(q\) and \(\overline{q}\) and Sudakov suppression factor are considered

Chiral-odd GPDs with a twist-3 meson wave function

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

Quark contribution

Meson $qq$

The meson wave function
Is an additional non-perturbative term

p

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

1. The beam charge-spin sum, or spin-independent cross section

$$\Sigma \equiv \frac{d^2\sigma_{\gamma^*P}}{dt\,d\phi} = \frac{1}{2} \left( \frac{d^2\sigma_{\gamma^*P}^+}{dt\,d\phi} + \frac{d^2\sigma_{\gamma^*P}^-}{dt\,d\phi} \right)$$

2. The difference

$$\Delta \equiv \left( \frac{d^2\sigma_{\gamma^*P}^+}{dt\,d\phi} - \frac{d^2\sigma_{\gamma^*P}^-}{dt\,d\phi} \right)$$
Comparison between the observables given by the spectro or by CAMERA

$$\mu^+ p \rightarrow \mu'^+ p \pi^0$$

\[\Delta \phi = \phi_{\text{cam}} - \phi_{\text{spec}}\]
\[\Delta p_T = p_{T_{\text{cam}}} - p_{T_{\text{spec}}}\]

Good description of the data with MC including

Exclusive $\pi^0$ production (HEPGEN)
+ Semi-inclusive $\pi^0$ production (LEPTO)

Good agreement between $\vec{\mu}^+$ and $\vec{\mu}^-$ yields
\( \mu^\pm p \rightarrow \mu^\pm \pi^0 p \)

\( \mu^\pm \) beams with opposite polarization

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

COMPASS 2012 - 16 spin-independent cross section for exclusive \( \pi^0 \)

\( \langle x_B \rangle = 0.10 \)

\( \epsilon \) close to 1

NEW Oct 2023

Models: GK Kroll Goloskokov EPJC47 (2011)

Also GGL: Golstein Gonzalez Liuti PRD91 (2015)
μ± p → μ± π⁰ p
μ± beams with opposite polarization

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

\[
\frac{d\sigma_L}{dt} \propto |\langle \vec{H} \rangle|^2 - \frac{t'}{4m^2} |\langle \vec{E} \rangle|^2
\]

\[
\frac{d\sigma_T}{dt} \propto |\langle HT \rangle|^2 - \frac{t'}{8m^2} |\langle ET \rangle|^2
\]

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

\[
\frac{\sigma_{LT}}{dt} \propto \frac{\sqrt{-t'}}{2m} \text{Re} \langle HT^* \langle \vec{E} \rangle \rangle
\]

**NEW Oct 2023**

2016 data

**COMPASS preliminary**

\[ \gamma^* p \rightarrow \pi^0 p' \]

ν ∈ [6.4, 40] GeV

Q² ∈ [1, 8] GeV²/c²

**In a larger (ν, Q²) domain**

**NEW Oct 2023**

2016 data

**COMPASS preliminary**

\[ \gamma^* p \rightarrow \pi^0 p' \]

ν ∈ [6.4, 40] GeV

Q² ∈ [1, 8] GeV²/c²

| ∈ [0.08, 0.64] GeV²/c²
$\mu^\pm p \rightarrow \mu^\pm \pi^0 p$

$\mu^\pm$ beams with opposite polarization

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

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

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

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

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

NEW Oct 2023

$$\langle \sigma_T \rangle + \epsilon \frac{\sigma_L}{|t|} = (6.9 \pm 0.3_{\text{stat}} \pm 0.8_{\text{syst}}) \frac{\text{nb}}{(\text{GeV}/c)^2}$$

$$\langle \sigma_{TT} \rangle = (-4.5 \pm 0.5_{\text{stat}} \pm 0.2_{\text{syst}}) \frac{\text{nb}}{(\text{GeV}/c)^2}$$

$$\langle \sigma_{LT} \rangle = (0.06 \pm 0.2_{\text{stat}} \pm 0.1_{\text{syst}}) \frac{\text{nb}}{(\text{GeV}/c)^2}$$

$\sigma_{TT}$ is negative and large comparatively to $\sigma_T + \epsilon \sigma_L$

$\Rightarrow$ impact of $E_T$

$\sigma_{LT}$ rather small

We will present soon the evolution in 3 bins in $\nu$ and 4 bins in $Q^2$

The 2017 data set will still increase the statistics

COMPASS

$\langle x_B \rangle = 0.13$

$\epsilon$ close to 1

$v \in [6.4, 40] \text{ GeV}$

$Q^2 \in [1, 8] \text{ GeV}^2/c^2$

$|t| \in [0.08, 0.64] \text{ GeV}^2/c^2$
Lessons on experiments with data collected with ℓ+ and ℓ- beams

For ex: \( \sigma^\pm = (\varepsilon \sigma_L + \sigma_T) + a \cos 2\phi \sigma_{TT} + b \cos \phi \sigma_{LT} + c \sin \phi \sigma_{LT'} \)

With polarized electron beams we change continuously from one to the other polarization to build directly only 1 observable: asymmetry = \((N^+ - N^-) / (N^+ + N^-)\) gives the \(\sin \phi\) term with small systematic errors

Richness but complexity dealing with runs with ℓ+ and ℓ- beams \(\Rightarrow\) we build 4 correlated observables or 4 cross sections:

- \(\sigma^+\) \(\Rightarrow\) Constant, \(\cos \phi\), \(\cos 2\phi\) and \(\sin \phi\) terms
- \(\sigma^-\) \(\Rightarrow\) Constant, \(\cos \phi\), \(\cos 2\phi\) and \(\sin \phi\) terms
- \(\sigma^+ + \sigma^-\) \(\Rightarrow\) Constant, \(\cos \phi\), \(\cos 2\phi\) terms
- \(\sigma^+ - \sigma^-\) \(\Rightarrow\) \(\sin \phi\) term

✓ Necessity of accurate acceptance and efficiency determination

✓ Requirement of detector stability for ℓ+ and ℓ- runs not taken at the same time

✓ Background depending on the lepton flux (recommendation to use the same lepton flux)

✓ Relative positions of background (mainly electrons) and signal are not located at the same place in the detectors with ℓ+ and ℓ- beams \(\Rightarrow\) precise MC description

✓ Radiative corrections of opposite sign for ℓ+ and ℓ- for the 2 photon exchange (see Andrei Afanasev....)
ImH and ReH using global fits of the world data

Reminder with BCA: $\text{ReH} < 0$ at HERMES, $> 0$ at H1 not used?

### Table 2: DVCS data used in this analysis.

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<th>Collab.</th>
<th>Year</th>
<th>Ref.</th>
<th>Observable</th>
<th>Kinematic dependence</th>
<th>No. of points used / all</th>
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SUM: 2624 / 3996