Exclusive Single-Photon Muoproduction at COMPASS

A. Ferrero (CEA-Saclay/IRFU/SPhN) for the COMPASS Collaboration

Spin 2016 Workshop - UIUC, 25-30/9/2016
Where does the spin of the nucleons come from?

Proton spin sum rule: \( \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \)

The “proton spin crisis” (EMC, 1988):
\[
\Delta \Sigma \rightarrow \begin{cases} 
\text{Static quark model: } & \Delta \Sigma = 1 \\
\text{Weak baryon decays: } & \Delta \Sigma \approx 0.58 \\
\text{Experiments: } & \Delta \Sigma \approx 0.3
\end{cases}
\]

\( \Delta G = ?? \quad L_{q,g} = ?? \)

COMPASS experimental tools:

- (semi-incl.) DIS
- Deep inelastic scattering
- DVCS
- DVMP
- Drell-Yan process
- GPDs

E. Kabuß, GPD2010, Trento, 12.10.2007
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This talk:

COMPASS experimental tools:

Drell-Yan process

DVCS

(semi-incl.) DIS
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- (semi-incl.)DIS
- Drell-Yan process
- DVMP


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N. Makke

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PDFs: 1-D structure

Longitudinal momentum

\[ k^+ = xP^+ \]

Transverse plane

Partons

\((x_B, Q^2)\)
Wigner distributions

$$\rho(x, k_T, b_T)$$

5-D correlations

Longitudinal momentum

$$k^+ = xP^+$$

Transverse plane

($$x_B, Q^2$$)

see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)
Towards a 3D Picture of the Nucleon...

Form Factors \((t)\)

- Fourier transform \((b_T)\)
- & \(\int GPDs(x, t) \cdots dx\)

GPDs \((x, b_T)\)

\[ \int dk_T \]

PDFs \((x)\)

\[ \int GPDs(x, b_T) \cdots db_T \]

\[ \int TMDs(x, k_T) \cdots dk_T \]

PDFs \(\rightarrow \Delta \Sigma, \Delta G\)

TMDs, GPDs \(\rightarrow \left\{ \text{nucleon“tomography”} \right\} L_{q,g}\)

Wigner Distributions

TMDs \((x, k_T)\)

\[ \int db_\perp \]

\[ \int TMDs(x, k_T) \cdots dk_T \]
“GPDs are non-perturbative objects entering the description of hard exclusive leptoproduction”

Definition of variables:
- \( q \): exchanged photon four-momentum
- \( x \): average long. momentum - NOT ACCESSIBLE
- \( \xi \): long. mom. difference \( \approx x_B/(2 - x_B) \)
- \( t \): four-momentum transfer
“GPDs are **non-perturbative** objects entering the description of **hard exclusive** leptoproduction”

They encode **CORRELATIONS** between the long. mom. $x$ and the transv. position of partons

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Experimentally accessible through Compton Form Factors (CFFs):

$\text{Im} H(\xi, t) = H(x = \xi, \xi, t)$

$\text{Re} H(\xi, t) = \mathcal{P} \int \frac{dx H(x, x = \xi, t)}{(x - \xi)} + \mathcal{D}(t)$

$\mathcal{D}(t)$ connected to energy-momentum tensor (Polyakov, PLB 555 (2003) 57-62)
“GPDs are non-perturbative objects entering the description of hard exclusive leptoproduction”

They encode **CORRELATIONS** between the long. mom. $x$ and the transv. position of partons

They allow to perform so-called ”nucleon tomography”:

$$d\sigma^{DVCS}/d|t| \sim \exp(-B|t|)$$

$$\langle r^2_\perp(x_B) \rangle \approx 2B(x_B)$$

$r_\perp$: distance between the struck parton and the spectators

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COMPASS: Versatile facility to study QCD with hadron ($\pi^\pm, K^\pm, p \ldots$) and lepton (polarized $\mu^\pm$) beams of $\sim 200$ GeV for hadron spectroscopy and hadron structure studies using SIDIS, DY, DVCS, DVMP...
The COMPASS set-up for the GPD programme

Two stage magnetic spectrometer for large angular & momentum acceptance

Particle identification with:
- Ring Imaging Cerenkov Detector
- Electromagnetic calorimeters (ECAL0, ECAL1 & ECAL2)
- Hadronic calorimeters
- Muon absorbers

DVCS: $\mu \ p \rightarrow \mu' \ p \ \gamma$
The COMPASS set-up for the GPD programme

**DVCS**

$\mu p \rightarrow \mu' p \gamma$

- Electromagnetic calorimeters (ECAL1 and ECAL2)
- Hadronic calorimeters
- Muon absorbers

**Main new equipments**

- Two stage magnetic spectrometer for large angular & momentum acceptance
- Particle identification with:
  - Ring Imaging Cerenkov Detector
  - Electromagnetic calorimeters
  - Hadronic calorimeters
  - Hadron absorbers

**Key features of COMPASS**

- Muon beams with opposite charge and polarization
  - $E_\mu = 160\text{ GeV}$
  - $\sim 4 \times 10^8 \mu$/spill, 9.6s/40s duty cycle
- Reconstruction of the full event kinematics
- Recoil proton momentum from target TOF detector
- Photon energy and angle from ECALs

**Experimental Setup**

- 2.5m-long Liquid H$_2$ Target
- Target TOF System
  - 24 inner & outer scintillators
  - 1 GHz SADC readout
  - Goal: 310 ps TOF resol.
- ECAL0 Calorimeter
  - Shashlyk modules + MAPD readout
  - $\sim 2 \times 2 $ m$^2$, $\sim 2200$ ch.
The COMPASS set-up for the GPD programme

The COMPASS experiment at COMPASS
NIM A 577 (2007) 455

SM1
SM2
ECAL1
ECAL2
DVCS : $\mu^+ p \rightarrow \mu'^+ p \gamma$

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The COMPASS set-up for the GPD programme

ECAL1

ECAL2

Main new equipments

Target TOF System
24 inner & outer scintillators
1 GHz SADC readout
goal: 310 ps TOF resol.

ECAL0 Calorimeter
Shashlyk modules + MAPD readout
~ 2 x 2 m², ~2200 ch.

2.5m-long Liquid H₂ Target
The COMPASS set-up for the GPD programme

Key features of COMPASS:

- Muon beams with opposite **charge** and **polarization**
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Exclusive single-photon muoproduction at COMPASS

\[ \mathbf{Bethe-Heitler} \]

\( \nu = E_\mu - E_\mu' \)

\( x_{\text{Bj}} = \frac{Q^2}{2m_p \nu} \)

\( Q^2 = -q^2 \)

\( t = (p_p - p_{p'})^2 \)

\[ \mathbf{DVCS} \]

\[ d\sigma \propto |T_{\text{DVCS}}|^2 \]

\[ \text{bilinear combination of GPDs} \]

\[ |T_{\text{BH}}|^2 \]

\[ \text{known to 1\%} \]

\[ \text{linear combination of GPDs} \]

\[ \text{interference term} \]
A. Ferrero (CEA-Saclay/IRFU/SPhN) On behalf of the COMPASS Collaboration

Exclusive single-photon muoproduction at COMPASS

\[ x_B = \frac{Q^2}{2m_p^2} \]

\[ Q^2 = -q^2 \]

\[ t = (p_p - p_{p'})^2 \]

Bethe-Heitler & DVCS Cross Sections at 160 GeV

**DVCS**

\[ d\sigma \propto |T_{DVCS}|^2 \]

**Bethe-Heitler**

\[ d\sigma \propto |T_{BH}|^2 \]

\[ d\sigma \propto \text{interference term} \]

Bilinear combination of GPDs

Linear combination of GPDs

known to 1%

Large \( x_B \): DVCS dominates

Low \( x_B \): BH dominates

Reference yield of almost pure Bethe-Heitler

Study DVCS with:

\[ \text{Re}(T^{DVCS}) \] & \[ \text{Im}(T^{DVCS}) \]

via \( (d\sigma^{+-} \pm d\sigma^{--}) \)

Transverse Imaging:

\[ d\sigma^{DVCS}/d|t| \]

via \( (d\sigma^{+-} + d\sigma^{--}) \)
Transverse Nucleon Imaging at COMPASS

Beam Charge and Spin SUM:

\[ S_{CS, U} \equiv d\sigma(\mu^+) + d\sigma(\mu^-) \propto d\sigma^{BH} + d\sigma^{DVCS}_{\text{unpol}} + Ks_{1}^{\text{Int}} \sin \phi \]

Integration over \( \phi \) and BH subtraction \( \rightarrow d\sigma^{DVCS}/d|t| \sim \exp(-B|t|) \)

\[ < r_{\perp}^2(x_B) > \approx 2B(x_B) \]

Distance between struck and spectator partons

COMPASS

H1 PLB681 (2009)

0.64±0.02

\[ \langle r_{\perp}^2 \rangle \]

\[ \sqrt{0.5} \]

\[ \sqrt{1} \]

\[ 0 \]

\[ 1 \]

\[ 10^{-4} \]

\[ 10^{-3} \]

\[ 10^{-2} \]

\[ 10^{-1} \]

\[ 1 \]

\( x_B \)
Transverse Nucleon Imaging at COMPASS

Beam Charge and Spin SUM:

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Integration over \( \phi \) and BH subtraction \( \rightarrow d\sigma^{DVCS}/d|t| \sim \exp(-B|t|) \)

Currently available HERA measurements:

Ansatz at small \( x_B \):

\[ B(x_B) \approx B_0 + 2\alpha' \ln(x_0/x_B) \]

(inspired by Regge phenomenology)
A. Ferrero (CEA-Saclay/IRFU/SPhN) On behalf of the COMPASS Collaboration

Exclusive single-photon muoproduction at COMPASS

2012 Pilot Run - 4 weeks

Full-scale CAMERA recoil detector and liquid $\text{H}_2$ target

Partially equipped ECAL0
Exclusive Photon Events Selection

Reconstructed interaction vertex in **target volume**

**One single photon** above DVCS production threshold

\[ Q^2 > 1 \text{ (GeV/c)}^2, \quad 0.05 < y < 0.9, \]
\[ 0.08 \text{ (GeV/c)}^2 < t < 0.64 \text{ (GeV/c)}^2 \]
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Exclusivity conditions:
- \( \Delta \phi = \phi_{\text{proton meas}} - \phi_{\text{proton reco}} \)
**Exclusive Photon Events Selection**

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Exclusivity conditions:

- \( \Delta \varphi = \varphi_{\text{proton meas}} - \varphi_{\text{proton reco}} \)
- **Vertex pointing** \((\Delta Z_A)\)

![Diagram](image1)

![Diagram](image2)
Exclusive Photon Events Selection

Reconstructed interaction vertex in **target volume**

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Exclusivity conditions:

- \[ \Delta \phi = \phi_{\text{proton meas}} - \phi_{\text{proton reco}} \]
- Vertex pointing (\( \Delta Z_A \))
- Transv. mom. balance:
  \[ \Delta p_T = p_{T,\text{meas}} - p_{T,\text{reco}} \]
Exclusive Photon Events Selection

Reconstructed interaction vertex in target volume

One single photon above DVCS production threshold

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- Transv. mom. balance:
  \[ \Delta p_T = p_{\text{proton } T, \text{meas}} - p_{\text{proton } T, \text{reco}} \]
- Four-momentum balance:
  \[ M_x^2 = (p_{\mu_{\text{in}}} + p_{\text{in}} - p_{\mu_{\text{out}}} - p_{\text{out}} - p_{\gamma})^2 \]
Kinematically constrained fit

- constrained $\chi^2$ minimisation with NDF=9
- full 4-momentum conservation of the reaction $\mu p \rightarrow \mu p\gamma$
- vertex constraints for $\mu, \mu'$ and $p'$ included in the fit

$\Rightarrow$ most accurate determination of $t$
Exclusive $\gamma$ Azimuthal Distributions for DVCS

Kinematically constrained vertex fit applied

$\pi^0$ bgd. MC
MC (BH + $\pi^0$ bgd.)
MC (BH + $\pi^0$ bgd.)
MC (BH)
MC (excl. $\pi^0$ bgd.)
MC (LEPTO $\pi^0$ bgd.)

$0.005 < x_{Bj} < 0.01$
Exclusive $\gamma$ Azimuthal Distributions for DVCS

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Kinematically constrained vertex fit applied

BH Monte Carlo normalization based on integrated luminosity
- BH process dominant at small $x_{Bj}$
- $\pi^0$ background contributing at large $x_{Bj}$
- clear excess of DVCS at large $x_{Bj}$

Data
- MC (BH)
- $\pi^0$ bgd. MC
- MC (BH + $\pi^0$ bgd.)
- MC (LEPTO $\pi^0$ bgd.)
- MC (excl. $\pi^0$ bgd.)

$0.005 < x_{Bj} < 0.01$

$0.01 < x_{Bj} < 0.03$

$1 \text{ (GeV/c)}^2 < Q^2 < 20 \text{ (GeV/c)}^2$

$32 \text{ GeV} < \nu < 80 \text{ GeV}$

$1 \text{ (GeV/c)}^2 < Q^2 < 5 \text{ (GeV/c)}^2$

$10 \text{ GeV} < \nu < 32 \text{ GeV}$

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

$0 \text{ GeV} < \nu < 20 \text{ (GeV/c)}^2$

$0 \text{ GeV} < \nu < 10 \text{ GeV}$

$0 \text{ GeV} < \nu < 5 \text{ (GeV/c)}^2$

$0 < \nu < 2 \text{ (GeV/c)}^2$

$0 < \nu < Q^2 < 1 \text{ (GeV/c)}^2$
t-dependence of DVCS cross-section for $x_{Bj} > 0.03$:

- Subtract BH contribution
- Subtract $\pi^0$ background
- Experimental acceptance correction & luminosity normalization

⇒ DVCS cross-section in 4 bins of $|t|$
**π° Background Estimation**

π°s are one of the main **background sources** for excl. photon events.

Two possible cases:

- **visible** (both γ detected, **subtracted**)
- **invisible** (one γ “lost”, **estimated with MC**)
  - Semi-inclusive → LEPTO
  - Exclusive → HEPGEN/π°
    (Goloskokov-Kroll model)

MC samples normalized to $M_{γγ}$ peak in real data.
Experimental acceptance for DVCS events

Symmetric acceptance around $\phi = 0$
Experimental acceptance for DVCS events

Acceptance binning in $Q^2$, $\nu$ and $|t|$
DVCS x-section and t-slope extraction

Kinematically constrained vertex fit applied

\[ \langle x_{Bj} \rangle = 0.056 \]
\[ \langle Q^2 \rangle = 1.8 \text{ (GeV/c)}^2 \]
\[ \langle W \rangle = 5.8 \text{ GeV/c}^2 \]

\[ \frac{d\sigma(\gamma^* p \rightarrow \gamma p)}{dt} \text{ (nb (GeV/c))^2} \]

\[ B = 4.31 \pm 0.62 ^{+0.09}_{-0.25} \text{ (GeV/c)^2} \]

1 \text{ (GeV/c)^2} < Q^2 < 5 \text{ (GeV/c)^2}

10 \text{ GeV} < \nu < 32 \text{ GeV}
Comparison with HERA results

\[ \langle r_1^2 \rangle \approx 2B(x_{Bj}) \]

- COMPASS 2012: \( \langle Q^2 \rangle = 1.8 \text{ (GeV/c)}^2 \)
- ZEUS: JHEP 0905 (2009) 108 \( \langle Q^2 \rangle = 3.2 \text{ (GeV/c)}^2 \)
- H1: Eur. Phys. C44 (2005) 1 \( \langle Q^2 \rangle = 4.0 \text{ (GeV/c)}^2 \)
- H1: Phys. Lett. B681 (2009) 391 \( \langle Q^2 \rangle = 8.0 \text{ (GeV/c)}^2 \)
Comparison with HERA results

$< r_\perp^2 > \approx 2B(x_{Bj})$

COMPASS performed the first model-independent measurement of $r_\perp$ in the sea-quarks domain using the pilot 2012 data set

OUTLOOK:

- Dedicated beam time for GPD studies in 2016-17
- $x_{Bj}$-dependence of t-slope parameter in sea-quarks domain
- Real and imaginary parts of CFF $\mathcal{H}$ from interference term
- Complementary measurements with exclusive mesons: $\pi^0, \rho^0, \phi, \omega...$
Kinematic Distributions for DVCS

\( < x_{Bj} > = 0.056 \)

\( < Q_{Bj}^2 > = 1.8 \text{ (GeV/c)}^2 \)

\( < W > = 5.8 \text{ GeV/c}^2 \)
The GPD Physics Programme at COMPASS

2008: Very short test run, short LH$_2$ target
   ○ Observation of exclusive photon production
   ○ Confirmed the global efficiency $\approx 10\%$ used for projections

2009: **10 days**, short LH$_2$ target
   ○ Coarse binning in $x_B$
   ○ First hint of DVCS at large $x_B$

2003-10: Exclusive $\rho^0$ and $\omega^0$ meson production on a **transv. pol. target** and **no recoil detector**

2012: **4 weeks**, full-scale LH$_2$ target and recoil detector

2016-7: **2 x 6 months** with LH$_2$ target and recoil det. $\rightarrow$ **GPD H**

>2018: DVCS with **transv. pol. target** and **recoil detector** $\rightarrow$ **GPD E**
Future addendum to COMPASS-II proposal