The DVCS Physics Program at COMPASS

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for the COMPASS Collaboration

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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":

\[
\Delta \Sigma \rightarrow \begin{cases} 
\text{Static quark model: } \Delta \Sigma = 1 \\
\text{Weak baryon decays: } \Delta \Sigma \approx 0.58 \\
\text{Experiments: } \Delta \Sigma \approx 0.3 
\end{cases}
\]

\[
\Delta G = ?? \quad L_{q,g} = ??
\]

COMPASS experimental tools:

- Deep inelastic scattering
- DVCS
- HEMP
- Pol. Drell-Yan

(semi-incl.)DIS
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\end{cases} \]

\[ \Delta G = ?? \quad L_q = ?? \quad L_g = ?? \]

This talk:

COMPASS experimental tools:

- Deep inelastic scattering (DIS)
- DVCS
- HEMP
- Pol. Drell-Yan
- GPDs

\( \gamma^* \rightarrow q \quad q' \rightarrow \gamma \)
PDFs: 1-D structure

Longitudinal momentum

$$k^+ = x P^+$$

Transverse plane

$$(x_B, Q^2)$$
Wigner distributions
\[ \rho(x, k_T, b_T) \]

5-D correlations

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

**Form Factors** $(t)$

Fourier transform $(b_T)$ & $\int \text{GPDs}(x, t) \, dx$

**GPDs** $(x, b_T)$

$\int dk_T$

**PDFs** $(x)$

$\int \text{TMDs}(x, k_T) \, dk_T$

**Wigner Distributions**

**TMDs** $(x, k_T)$

$\int db_{\perp}$

**PDFs** $\rightarrow \Delta \Sigma, \Delta G$

**TMDs, GPDs** $\rightarrow \{\text{nucleon "tomography"} \}$

$L_{q,g}$
``GPDs are non-perturbative objects entering the description of hard exclusive electroproduction''

Definition of variables:

- $x$: average long. momentum - NOT ACCESSIBLE
- $\xi$: long. mom. difference $\approx x_B/(2 - x_B)$
- $t$: four-momentum transfer related to $b_\perp$ via Fourier transform
``GPDs are **non-perturbative** objects entering the description of **hard exclusive** electroproduction''

They encode **CORRELATIONS** between the long. mom. \( x \) and the transv. position \( b_\perp \) of partons

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- \( x \): average long. momentum - NOT ACCESSIBLE
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Introduction to GPDs

``GPDs are non-perturbative objects entering the description of hard exclusive electroproduction''

They encode CORRELATIONS between the long. mom. $x$ and the transv. position $b_\perp$ of partons

Experimentally accessible through Compton Form Factors (CFFs):

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

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

Definition of variables:

- $x$: average long. momentum - NOT ACCESSIBLE
- $\xi$: long. mom. difference $\approx x_B/(2 - x_B)$
- $t$: four-momentum transfer related to $b_\perp$ via Fourier transform
COMPASS: Versatile facility to study QCD with hadron ($\pi^\pm$, $K^\pm$, $p$ ...) and lepton (polarized $\mu^\pm$) beams of ~200 GeV for hadron spectroscopy and hadron structure studies using SIDIS, DY, DVCS, DVMP...
The COMPASS set-up for the GPD program

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 program

Main new equipments

ECAL1

ECAL2

2.5m-long Liquid H₂ Target

The DVCS experiment at COMPASS

NIM A 577 (2007) 455

SM1

SM2

ECAL1

ECAL2

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

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

Two stage magnetic spectrometer for large angular & momentum acceptance

Particle identification with:

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ECAL0 Calorimeter

Shashlyk modules + MAPD readout

\( \sim 2 \times 2 \text{ m}^2 \), \( \sim 2200 \text{ ch.} \)

Key features of COMPASS:

- Muon beams with opposite charge and polarization
  \( E_\mu = 160 \text{ GeV} \)

- Reconstruction of the full event kinematics

- Recoil proton momentum from target TOF detector

- Photon energy and angle from ECALs
The COMPASS set-up for the GPD program

Main new equipments

ECAL1

ECAL2

2.5m-long Liquid H₂ Target

Target TOF System
24 inner & outer scintillators
1 GHz SADC readout
goal: 310 ps TOF resol.
The COMPASS set-up for the GPD program

Main new equipments

ECAL1
ECAL2

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
~ 2 x 2 m$^2$, ~2200 ch.
The COMPASS set-up for the GPD program

Key features of COMPASS:

- Muon beams with opposite charge and polarization
  - $E_\mu = 160$ GeV
  - $\sim 4 \cdot 10^8 \mu$/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
The GPD Physics Program 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 $x_B$

2004-10: 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
The DVCS Process at COMPASS Kinematics

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

Monte-Carlo Simulation for COMPASS set-up with only ECAL1+2

Missing DVCS acceptance without ECAL0

\[ 0.005 < x_B < 0.01 \]
\[ 0.01 < x_B < 0.03 \]
\[ 0.03 < x_B \]

BH dominates
study of Interference

DVCS dominates
study of \( d\sigma^{\text{DVCS}}/dt \)

\( \rightarrow \text{Re } T^{\text{DVCS}} \)
\( \rightarrow \text{Im } T^{\text{DVCS}} \)

Transverse Imaging

BH dominates
excellent reference yield

Deep VCS
Bethe-Heitler
Measurements of DVCS and BH Cross-sections

cross-sections on proton for $\mu^+\downarrow$, $\mu^-\uparrow$ beam with opposite charge & spin ($e_\mu$ & $P_\mu$)

$$d\sigma_{(\mu p \rightarrow \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS\text{unpol}} + P_\mu d\sigma^{DVCS\text{pol}}$$

$$+ e_\mu a^{BH} R\varepsilon A^{DVCS} + e_\mu P_\mu a^{BH} I\text{m} A^{DVCS}$$

**Charge & Spin Difference and Sum:**

$$D_{CS,U} \equiv d\sigma(\mu^+ \downarrow) - d\sigma(\mu^- \uparrow) \propto C_0^{Int} + C_1^{Int} \cos \phi$$

and

$$c_{0,1}^{Int} \sim F_1 R\varepsilon H$$

$$S_{CS,U} \equiv d\sigma(\mu^+ \downarrow) + d\sigma(\mu^- \uparrow) \propto d\sigma^{BH} + c_0^{DVCS} + K s_1^{Int} \sin \phi$$

and

$$s_1^{Int} \sim F_1 I\text{m} H$$

$$c_1^{Int} \propto R\varepsilon \left( F_1 H + \xi (F_1 + F_2) \tilde{H} - t/4m^2 F_2 E \right)$$

**NOTE:**

✓ dominance of $H$ with a proton target at COMPASS kinematics

✓ only leading twist and LO
Transverse Nucleon Imaging at COMPASS

Beam Charge and Spin SUM:

\[ S_{CS,U} = d\sigma(\mu^{+}) + d\sigma(\mu^{-}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + K_{S1}^{int} \sin \phi \]

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

\[ \sqrt{< r_{\perp}^2 >} \]

\[ x < 0.01 \quad x \sim 0.1 \quad x \sim 0.3 \]

\[ < r_{\perp}^2(x_B) > \approx 2B(x_B) \]
Transverse Nucleon Imaging at COMPASS

Beam Charge and Spin SUM:

\[ S_{CS,U} \equiv d\sigma(\mu^+) + d\sigma(\mu^-) \propto d\sigma^{BH} + d\sigma^{DVCS} + Ks^{\text{Int}}_1 \sin \phi \]

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

2 x 6 months of data in 2016-2017
2.5 m LH\(_2\) target
\( \varepsilon_{\text{global}} = 10\% \)

Ansatz at small \( x_B \):

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

expected statistical and systematic uncertainties are shown
Transverse Nucleon Imaging at COMPASS

Beam Charge and Spin **SUM:**

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

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

2012: **we can expect one mean value of \( B \) in the COMPASS kinematic range**
2012 Pilot Run - 4 weeks

Full-scale CAMERA recoil detector and liquid $H_2$ target

Partially equipped ECAL0
The Recoil TOF Detector CAMERA

Ring A:
- 24 slabs
- 4mm thick
- 2.75m long

Ring B:
- 24 slabs
- 50mm thick
- 3.6m long
The Recoil TOF Detector CAMERA

Ring A:  
- 24 slabs
- 4mm thick
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Ring B:  
- 24 slabs
- 50mm thick
- 3.6m long

Time resolution measurement with cosmics

Time Resolution: > 350 ps

Time Resolution: 160 ps

OK
The Recoil TOF Detector CAMERA

Ring A: \( \{ \) 24 slabs, 4mm thick, 2.75m long

Ring B: \( \{ \) 24 slabs, 50mm thick, 3.6m long

Time resolution measurement with cosmics

Time Resolution: \( > 350 \) ps

Bad scintillator quality!

Replacement in 2015

Time Resolution: \( 160 \) ps

OK
Exclusive Photon Events Selection

Reconstructed interaction vertex in target volume

One single photon above DVCS production threshold

\( Q^2 > 1 \text{ (GeV/c)}^2, \quad 0.05 < y < 0.9, \quad 0.06 \text{ (GeV/c)}^2 < t < 0.64 \text{ (GeV/c)}^2 \)

Exclusivity conditions:

- \( \Delta \varphi = \varphi_{\text{proton,meas}} - \varphi_{\text{proton,reco}} \)
- Vertex pointing (\( \Delta Z \))
- Transv. momentum balance: \( \Delta p_\perp = p_{\perp,\text{meas}} - p_{\perp,\text{reco}} \)
- Four-momentum balance:
  \[ M_X^2 = (p_{\mu_{\text{in}}} + p_{p_{\text{in}}} - p_{\mu_{\text{out}}} - p_{p_{\text{out}}} - p_\gamma)^2 \]
- Missing energy:
  \[ ((p_{\mu_{\text{in}}} + p_{p_{\text{in}}} - p_{\mu_{\text{out}}} - p_\gamma)^2 - M_p^2) / 2M_p \]
Exclusivity Variables: $\Delta \varphi$

$$\Delta \varphi = \varphi_{\text{proton meas}} - \varphi_{\text{proton reco}}$$

COMPASS 2012

- Data
- MonteCarlo

Applied cut
Exclusivity Variables: $\Delta Z$

![Graph showing data and Monte Carlo comparison for $\Delta Z$](image)

- **Data**
- **Monte Carlo**

**Variables:**
- $\Delta Z$
- $\mu_{in}$
- $\gamma_{out}$
- $\mu_{out}$
- Target
- Inner scintillator
- Outer scintillator
- Proton
- Reconstructed hit
- Vertex

**Axes:**
- $\Delta Z$ (cm)
- Entries

**Legend:**
- Data
- Monte Carlo

**Note:**
- Preliminary COMPASS 2012
Exclusivity Variables: $\Delta p_\perp$

$$\Delta p_\perp = p_{\perp, \text{meas}} - p_{\perp, \text{reco}}$$
Exclusivity Variables: $M_X^2$

$$M_X^2 = (p_{\mu_{in}} + p_{\rho_{in}} - p_{\mu_{out}} - p_{\rho_{out}} - p_{\gamma})^2$$
Proton Signal in Recoil Detector

Signal amplitude in outer scintillators vs. beta of recoiling particle

Proton signature clearly visible after all exclusivity conditions
$\pi^0$ Background Estimation

$\pi^0$s are one of the main background sources for exclusive photon events.

Two possible cases:

- **visible** (both $\gamma$ detected, easy to reject)
- **invisible** (one $\gamma$ "lost", only estimated with MC)
$\pi^0$ Background Estimation

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``Visible'' part estimated by combining the exclusive $\gamma$ candidates with all additional low-energy $\gamma$s in the event
\(\pi^0\) Background Estimation

\(\pi^0\)s are one of the main background sources for exclusive photon events.

Two possible cases:

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- **invisible** (one \(\gamma\) ``lost'', only estimated with MC)

``Visible'' part estimated by combining the **exclusive \(\gamma\) candidates** with all additional **low-energy \(\gamma\)s** in the event.

``Invisible'' part estimate via **MC simulations**:

- **Semi-inclusive** contribution from LEPTO
- **Exclusive** contribution from HEPGEN/\(\pi^0\) (Goloskokov-Kroll model)
- MC samples normalized to the ``visible'' \(\pi^0\) in real data
- Two extreme cases considered:
  1. Fully **semi-inclusive** background
  2. Fully **exclusive** background
    \(\rightarrow\) Gives **lower** and **upper** limits
**π^0** Background Estimation

π^0's are one of the main background sources for exclusive photon events.

Two possible cases:

- **visible** (both γ detected, easy to reject)
- **invisible** (one γ ``lost'', only estimated with MC)

![M_{γ_{excl}γ_{bgd}} distribution (``Visible'' π^0)](attachment:image.png)

LEPTO and HEPGEN/π^0 MC normalized to M_{γ_{excl}γ_{bgd}} peak from real data.
Exclusive $\gamma$ Azimuthal Distribution in 3 $x_{Bj}$ Bins

BH contrib. only
Normalized to lowest $x_{Bj}$ bin
Exclusive $\gamma$ Azimuthal Distribution in 3 $x_{Bj}$ Bins

Dominant **Bethe-Heitler** process clearly visible at small $x_{Bj}$

$\phi_{\gamma^*\gamma}$ peak shape well reproduced by MC simulations

First estimation of $\pi^0$ **background** at large $x_{Bj}$

Data at large $x_{Bj}$ show an **excess** compared to BH+background
Exclusive $\gamma$ Azimuthal Distribution in 3 $x_{Bj}$ Bins

Dominant Bethe-Heitler process clearly visible at small $x_{Bj}$

$\phi_{\gamma\gamma}$ peak shape well reproduced by MC simulations

First estimation of $\pi^0$ background at large $x_{BJ}$

Data at large $x_{BJ}$ show an excess compared to BH+background

Next steps:
- **cross-section** extraction and **beam charge difference**
- **t-slope** extraction and nucleon tomography
Backup Slides
Recoil particle Measurement in CAMERA

A. Ferrero (CEA-Saclay/IRFU/SPhN) On behalf of the COMPASS collaboration

COMPASS II

E_{\text{loss}} \sim \sqrt{\text{Ampl}_{\text{up}} \times \text{Ampl}_{\text{down}}}

\text{TOF} \rightarrow (t_{\text{up}} + t_{\text{down}})_{A,B}

z \rightarrow t_{\text{up}} - t_{\text{down}}

Count rates: > 5 MHz in ring A
\sim 1 MHz in ring B

Preliminary
What Makes COMPASS Unique?

COMPASS covers the unexplored region between collider (H1+Zeus) and low-energy fixed target (Hermes+JLab) experiments

- $\mu^+$ and $\mu^-$ beams
- momentum: 100 – 190 GeV/c
- beam polarization: 80 %
  opposite for $\mu^+$ and $\mu^-$
- coverage of intermediate $x_B$
  - low $x_B$: pure BH
    useful for normalization
  - high $x_B$: DVCS predominance
  - unexplored region between ZEUS+H1 and HERMES+JLab
**DVCS: What Can We Learn?**

Phase 1: Polarized beam, unpol. target

- **GPDs**
  - GPDs parameter from slope of $d\sigma_{DVCS}/dt$

**x_B-dependent transv. size of nucleon**

- DVCS dominance at large $x_B$
- BH/DVCS interf. at intermediate $x_B$

**Interference between BH and DVCS**

- "Boost" of DVCS through int. term

Measurement of $Re\mathcal{H}(\xi, t)$ and $Im\mathcal{H}(\xi, t)$ via $\phi$-modulation of cross section

- $Re\mathcal{H}(\xi, t) = P \int dx\, H(x, \xi, t)/(x - \xi)$
- $Im\mathcal{H}(\xi, t) = H(x = \xi, \xi, t)$

**Exp. constrain to GPD $H$**
CAMERA Readout

Freiburg and Saclay teams CAMERA calibration and studies 23.04.2014 5 / 43

GANDALF
Virtex-5 VSX95
8 channels
1 GS/s
12 bit resolution

TIGER
Virtex-6 VLX365
onBoard GPU
2x SFP+
COM Express
Past, Present and Future GPD Experiments

Current DVCS data at colliders:
- ZEUS- total xsec
- ZEUS- do/dt
- H1- total xsec
- H1- do/dt
- H1- A_{CU}

Current DVCS data at fixed targets:
- HERMES- A_{LT}
- HERMES- A_{CU}
- HERMES- A_{LU}, A_{UL}, A_{LL}
- HERMES- A_{UT}
- Hall A- CFFs
- CLAS- A_{LU}
- CLAS- A_{UL}

Planned DVCS at fixed targets:
- COMPASS- do/dt, A_{CSU}, A_{CST}
- JLAB12- do/dt, A_{LU}, A_{UL}, A_{LL}

EIC $\sqrt{s}=140$ GeV, $0.01 \leq y \leq 0.95$

$$Q^2=100 \text{ GeV}^2$$

$$Q^2=50 \text{ GeV}^2$$

EIC $\sqrt{s}=45$ GeV, $0.01 \leq y \leq 0.95$

$y \leq 0.6$

$y \leq 0.6$

Gluons
Sea quarks
Valence quarks

COMPASS
JLab