GPD Program at COMPASS

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

IPN Orsay - 29/5/2017
Proton spin sum rule: \[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

How the proton spin is decomposed in terms of parton's spins (\( \Delta \Sigma, \Delta G \)) and orbital angular momentum (\( L_q, L_g \)) is still one of the big open questions in hadronic physics...

COMPASS experimental tools:

COMPASS experimental tools: Deep inelastic scattering (DIS), GPDs, DVCS, DVMP, Drell-Yan process...
PDFs: 1-D structure

Longitudinal momentum

\[ k^+ = xP^+ \]

Transverse plane

Partons

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

\[ \rho(x, \vec{k}_T, \vec{b}_T) \]

5-D correlations

Transverse plane

Longitudinal momentum

\[ k^+ = x P^+ \]

\((x_B, Q^2)\)

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

Form Factors \( (t) \)

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

GPDs \( (x, b_T) \)

Wigner Distributions

TMDs \( (x, k_T) \)

PDFs \( (x) \)

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

\( \int \text{GPDs}(x, t) \ldots dx \)

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

TMDs, GPDs \( \rightarrow \{ \text{nucleon}^{\text{"tomography"}} \} L_{q,g} \)
GPDs: correlation between fractional long. momentum $x$ and transverse position $b_\perp$ of partons

GPDs depend on the following variables:
- $x$: average long. momentum (NOT MEASURABLE)
- $\xi$: long. mom. difference $\approx x_B/(2 - x_B)$
- $t$: four-momentum transfer related to $b_\perp$ via Fourier transform

DVCS ($l \, p \rightarrow l' \, \gamma \, p'$): “golden” channel for GPD studies

GPDs enter in the DVCS amplitude through Compton Form Factors (CFF):

$$ \mathcal{H}(\xi, t) = \int_{-1}^{1} dx \frac{H^q(x, \xi, t)}{x - \xi + i\epsilon} = \mathcal{P} \int_{-1}^{1} dx \frac{H(x, \xi, t)}{x - \xi} + i\pi H(x = \pm \xi, \xi, t) $$
COMPASS: Versatile facility to study QCD with hadron ($\pi^\pm$, K$^\pm$, p ...) 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

Two stage magnetic spectrometer for large angular & momentum acceptance

Particle identification with:
- Ring Imaging Cerenkov Detector
- Electromagnetic calorimeters
- Hadronic calorimeters
- Hadron absorbers

2.5m-long Liquid $\text{H}_2$ Target

ECAL1

ECAL2

Main new equipments
The COMPASS set-up for the GPD programme

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
- Muon absorbers

Two stage magnetic spectrometer for large angular & momentum acceptance

Particle identification with:
- Ring Imaging Cerenkov Counter
- Electromagnetic calorimeters 
  - (ECAL0, ECAL1, ECAL2)
- Hadronic calorimeters

2.5m-long Liquid $H_2$ Target

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

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)
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- Hadron absorbers

Two stage magnetic spectrometer for large angular & momentum acceptance

Particle identification with:
- Ring Imaging Cerenkov Counter
- Electromagnetic calorimeters
- Hadronic calorimeters
- Hadron absorbers

2.5m-long Liquid H$_2$ Target

ECAL0 Calorimeter
Shashlyk modules + MAPD readout
$\sim 2 \times 2$ m$^2$, $\sim 2200$ ch.

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

Key features of COMPASS:

- Muon beams with opposite **charge** and **polarization**
  - $E_\mu = 160$ 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
Exclusive muon-induced reactions at COMPASS

**Bethe-Heitler & DVCS Cross Sections at 160GeV**

- DVCS: Small $t$
- Bethe-Heitler: All $t$
- DVCS vs Bethe-Heitler
  - Large $x_B$: DVCS dominates
  - Low $x_B$: BH dominates

**Cross Section**

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

- Bilinear combination of GPDs
- Known to 1%
- Linear combination of GPDs
Exclusive muon-induced reactions at COMPASS

\[ x_{\text{Bj}} = \frac{Q^2}{2m_p\nu} \]

\[ \nu = E_\mu - E_{\mu'} \]

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

\[ t = (p_p - p_p')^2 \]

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

Bethe-Heitler & DVCS Cross Sections at 160GeV

\[ \text{DVCS} \]

\[ \text{Bethe-Heitler} \]

\[ d\sigma \propto \left| T_{\text{DVCS}} \right|^2 + \left| T_{\text{BH}} \right|^2 + \text{interference term} \]

bilinear combination of GPDs known to 1% linear combination of GPDs

Low \( x_B \): BH dominates

|BH+DVCS|^2

|DVCS|^2

|BH|^2

|BH=0.01|

Transverse Imaging:

\[ d\sigma^{\text{DVCS}} / dt \]

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

Study DVCS with:

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

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

Large \( x_B \): DVCS dominates

|BH+DVCS|^2

|DVCS|^2

|BH|^2

|BH=0.1|

reference yield of almost pure Bethe-Heitler
Transverse Nucleon Imaging at COMPASS

Beam Charge and Spin SUM:

\[ S_{CS,U} \equiv d\sigma(\mu^+\rightarrow) + d\sigma(\mu^-\rightarrow) \propto d\sigma^{BH} + d\sigma^{DVCS} + K_{S_1}^{Int} \sin \phi \]

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

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

distance between struck parton and baricenter of momentum

Ansatz at small \( x_B \):

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

(inspired by Regge phenomenology)
2012 Pilot Run - 4 weeks

ECAL2

µ±

ECAL1

Partially equipped ECAL0

Full-scale CAMERA recoil detector and liquid $H_2$ target
Exclusive Photon Events Selection

Reconstructed interaction vertex in target volume

One single photon above DVCS production threshold

\[ Q^2 > 1 \text{ (GeV/c)}^2, \quad 0.05 < y < 0.9, \]
\[ 0.08 \text{ (GeV/c)}^2 < t < 0.64 \text{ (GeV/c)}^2 \]
Exclusive Photon Events Selection

Reconstructed interaction vertex in target volume

One single photon above DVCS production threshold

\[ Q^2 > 1 \text{ (GeV/c)}^2, \quad 0.05 < y < 0.9, \quad 0.08 \text{ (GeV/c)}^2 < t < 0.64 \text{ (GeV/c)}^2 \]

Exclusivity conditions:

- \( \Delta \phi = \phi_{\text{proton meas}} - \phi_{\text{proton reco}} \)
- Vertex pointing (\( \Delta Z_A \))
- Transv. mom. balance:
  \( \Delta p_T = p_{T,\text{meas}}^{\text{proton}} - p_{T,\text{reco}}^{\text{proton}} \)
- Four-momentum balance:
  \( M_x^2 = (p_{\mu,\text{in}} + p_{p,\text{in}} - p_{\mu,\text{out}} - p_{p,\text{out}} - p_{\gamma})^2 \)
Exclusive $\gamma$ Azimuthal Distributions for DVCS

Kinematically constrained vertex fit applied

pure B.H contribution

$x_{Bj} > 0.03$

$x_{Bj} < 0.01$

$x_{Bj} < 0.03$
Exclusive $\gamma$ Azimuthal Distributions for DVCS

- 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 $x_{Bj}$
Exclusive $\gamma$ Azimuthal Distributions for DVCS

$t$-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 $|t|$
**π⁰ Background Estimation**

π⁰s 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/π⁰
    (Goloskokov-Kroll model)

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

Acceptance binning in $Q^2$, $\nu$ and $|t|$
Experimental acceptance for DVCS events

Symmetric acceptance around $\phi = 0$
Kinematically constrained vertex fit applied

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

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

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

1 \text{ (GeV/c)}^2 < Q^2 < 5 \text{ (GeV/c)}^2
10 \text{ GeV} < \nu < 32 \text{ GeV}
Comparison with HERA results

\[ \sqrt{\langle r^2 \rangle} \approx 2B(x_B) \]

\[ \langle Q^2 \rangle = 1.8 \text{ (GeV/c)}^2 \]
\[ \langle Q^2 \rangle = 3.2 \text{ (GeV/c)}^2 \]
\[ \langle Q^2 \rangle = 4.0 \text{ (GeV/c)}^2 \]
\[ \langle Q^2 \rangle = 8.0 \text{ (GeV/c)}^2 \]

To be compared to:

\[ \sqrt{4 \frac{d}{dt} F^P_1} \bigg|_{t=0} = 0.66 \pm 0.01 \text{ fm} \]

\[ \frac{1}{\sqrt{\kappa / m_p}} \sqrt{4 \frac{d}{dt} G^P_E} \bigg|_{t=0} = 0.72 \pm 0.01 \text{ fm} \]

\[ r_p = 0.88 \text{ fm} \]
COMPASS OUTLOOK:

- Dedicated beam time for GPD studies in 2016-17
- $x_B$-dependence of t-slope parameter in sea-quarks domain

\[ \sigma_{\text{DVCS}} / d\eta \sim \exp(-B|t|) \] as soft Pomeron

H1 PLB659(2008)

- Real and imaginary parts of CFF $\mathcal{H}$ from interference term
- Complementary measurements with exclusive mesons: $\pi^0, \rho^0, \phi, \omega...$
What kind of "proton transverse size" are we measuring?

\[ d\sigma^{DVCS}/dt \sim \exp(-B|t|) \]
\[ B(x_B) = \frac{1}{2} < r_{\perp}^2 (x_B) > \]

distance between the active quark and the center of momentum of spectators

Transverse size of the nucleon

mainly dominated by \( H(x=\xi, \xi, t) \)

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

Note 0.65 fm = \( \sqrt{2/3} \times 0.8 \) fm

0.65 \( \pm 0.02 \) fm

H1 PLB659(2008)

\[ A_{DVCS \text{ linked to } ImH} \sim \exp(-B'|t|) \]
\[ B'(x_B) = \frac{1}{4} < b_{\perp}^2 (x_B) > \]

distance between the active quark and the center of momentum of the nucleon

Impact Parameter Representation

\[ q(x, b_{\perp}) \leftrightarrow H(x, \xi=0, t) \]

< \( r_{\perp} > \sim < b_{\perp} > / (1-x) \]

A. Ferrero (CEA-Saclay/IRFU/SPhN) for the COMPASS Coll.
Constraining the GPD $H$ @ COMPASS

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

$$d\sigma(\mu p \rightarrow \mu p \gamma) = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol} + e_\mu a^{BH}ReA^{DVCS} + e_\mu P_\mu a^{BH}ImA^{DVCS}$$

Charge & Spin Difference and Sum:

$D_{CS,U} \equiv d\sigma(\mu^+\downarrow) - d\sigma(\mu^-\uparrow) \propto c_{0,1}^\text{Int} + c_{1}^\text{Int} \cos \phi$ and $c_{0,1}^\text{Int} \sim F_1 Re H$

$S_{CS,U} \equiv d\sigma(\mu^+\downarrow) + d\sigma(\mu^-\uparrow) \propto d\sigma^{BH} + c_0^{DVCS} + K s_1^\text{Int} \sin \phi$ and $s_1^\text{Int} \sim F_1 Im H$

$C_{1}^\text{Int} \propto Re \left( F_1 H + \xi (F_1 + F_2) \tilde{H} - t/4m^2 F_2 E \right)$

**NOTE:** ✓ dominance of $H$ with a proton target at COMPASS kinematics
✓ only leading twist and LO
Constraining the GPD $\mathcal{H}$ @ COMPASS

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

$$d\sigma(\mu p \rightarrow \mu p \gamma) = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu d\sigma^{DVCS}_{pol}$$
$$+ e_\mu a^{BH} \Re A^{DVCS} + e_\mu P_\mu a^{BH} \Im A^{DVCS}$$

Charge & Spin Difference and Sum:

$$D_{CS,U} \equiv d\sigma(\mu^+\downarrow) - d\sigma(\mu^-\uparrow) \propto c_{0,1}^{Int} \cos \phi$$
$$S_{CS,U} \equiv d\sigma(\mu^+\downarrow) + d\sigma(\mu^-\uparrow) \propto d\sigma^{BH} + c_0^{DVCS} + K s_{1}^{Int} \sin \phi$$

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

Re part of the Compton Form Factors linked to the $D$ term

Re$H$ and Im$H$ from Recent Models

Is it rather well known?

Re$H$ linked to the D term is still poorly constrained

Beam Charge & Spin Difference

$c_1^I = \text{Re } F_1^H$

Predictions with VGG and D. Mueller KM10

$\text{Re } H > 0$ at H1
$< 0$ at HERMES

Value of $x_B$ for the node?

$E_\mu = 160$ GeV
$1 < Q^2 < 8$ GeV$^2$

COMPASS 2 years of data
HERMES
JLab

A. Ferrero (CEA-Saclay/IRFU/SPhN) for the COMPASS Coll.
Deeply Virtual Meson Production @ COMPASS

This talk: $\rho^0$ and $\omega$

M. Gorzellik this afternoon: $\pi^0$
Exclusive $\rho^0$ production

\[
\left[ \frac{\alpha_{em} \frac{y^2}{Q^2} \right] \left[ \frac{1 - x_B}{1 - \varepsilon} \frac{1}{x_B} \right]^{-1} \frac{d\sigma}{dx_B dQ^2 dt d\phi_d\phi_s} = \frac{1}{2} (\sigma_{++}^{++} + \sigma_{+-}^{--}) + \varepsilon (\sigma_{00}^{++} - \varepsilon \cos(2\phi) \Re \sigma_{+-}^{++} - \sqrt{\varepsilon(1 + \varepsilon)} \cos \phi \Re (\sigma_{0+}^{++} + \sigma_{0-}^{--})

- P_l \sqrt{\varepsilon(1 - \varepsilon)} \sin \phi \Im (\sigma_{0+}^{++} + \sigma_{0-}^{--})

- S_T \begin{bmatrix}
\sin(\phi - \phi_s) \Im (\sigma_{++}^{++} + \varepsilon \sigma_{00}^{++}) + \frac{\varepsilon}{2} \sin(\phi + \phi_s) \Im \sigma_{+-}^{++} + \frac{\varepsilon}{2} \sin(3\phi - \phi_s) \Im \sigma_{--}^{++}

+ \sqrt{\varepsilon(1 + \varepsilon)} \sin \phi_s \Im \sigma_{0+}^{++} + \sqrt{\varepsilon(1 + \varepsilon)} \sin(2\phi - \phi_s) \Im \sigma_{0-}^{++}
\end{bmatrix}

+ S_T P_l \begin{bmatrix}
\sqrt{1 - \varepsilon^2} \cos(\phi - \phi_s) \Re \sigma_{++}^{++}

- \sqrt{\varepsilon(1 - \varepsilon)} \cos \phi_s \Re \sigma_{+-}^{++} - \sqrt{\varepsilon(1 - \varepsilon)} \cos(2\phi - \phi_s) \Re \sigma_{--}^{++}
\end{bmatrix}

\]

Dominant interference terms:

\begin{align*}
&\text{LL} & \gamma^*_L \rightarrow \rho^0_L \\
&\text{LT} & \gamma^*_T \rightarrow \rho^0_L
\end{align*}

\( \sigma_{ij} \) for nucleon helicity

\( \sigma_{mn} \) for photon helicity
Selection of $\mu p \rightarrow \mu' V p_{\text{undet}}$. Events

$V = \rho^0 \rightarrow \pi^+ \pi^-$

$E_{\text{miss}} = \frac{(M^2_X - M_p^2)}{2M_p}$

$M_X^2 = (p_{\mu_{\text{in}}} + p_{\mu_{\text{out}}} - p_V)^2$

$-2.5 < E_{\text{miss}} < 2.5 \text{ GeV}$

$0.1 < p_T^2 < 0.5 \text{ GeV}^2$

Background $\sim 22\%$

$V = \omega \rightarrow \pi^+ \pi^- \pi^0 \text{ BR}=89\%$

$E_{\text{miss}} = \frac{(M^2_X - M_p^2)}{2M_p}$

$-3 < E_{\text{miss}} < 3 \text{ GeV}$

$0.05 < p_T^2 < 0.5 \text{ GeV}^2$

Background $\sim 34\%$
**Excl. $\rho^0$ Production with Transv. Pol. Target**

$\mu^+ p \rightarrow \mu'^+ + \rho^0 + p_{\text{non detected}}$

$W = 8.1 \text{ GeV}/c^2$, $p_T^2 = 0.2 \text{ (GeV}/c)^2$, $Q^2 = 2.2 \text{ (GeV}/c)^2$

$A_{UT} \propto \text{Im}(E^*H)$

$E_{\rho^0} \propto 2/3 E^u + 1/3 E^d + 3/8 E^g$

✓ Cancellation between gluon and sea contributions

✓ $E^u \text{ val} \sim -E^d \text{ val}$

COMPASS, NPB 865 (2012) 1-20

$E_{\omega} \propto 2/3 E^u - 1/3 E^d + 3/8 E^g$
Excl. $\rho^0$ Production with Transv. Pol. Target

$\mu^+ p \rightarrow \mu^+ + \rho^0 + p_{\text{non detected}} \rightarrow \pi^+ \pi^-$

$W = 8.1 \text{ GeV}/c^2$, $p_T^2 = 0.2 \text{ (GeV}/c)^2$, $Q^2 = 2.2 \text{ (GeV}/c)^2$

$A_{\text{UT}} \propto \text{Im}(E^*H)$

$A_{\text{UT}} \propto \text{Im}(E^*E - H^*H)$

$A_{\text{UT}} \propto \sin(\phi - \phi_S)$

$A_{\text{UT}} \propto \sin(2\phi - \phi_S)$

$H_T$ should not be small

COMPASS 2007-2010, without recoil detector

COMPASS, PLB731 (2014) 19
Excl. $\rho^0$ Production with Transv. Pol. Target

Exclusive $\mu p \rightarrow \mu' + \rho^0 + p_{\text{non detected}} \rightarrow \pi^+\pi^-$

Comparison with a phenomenological GPD-based model

- Goloskokov and Kroll (EPJ C74 (2014))
  - Phenomenological ‘handbag’ approach
  - Includes twist-3 $\rho^0$ meson wave functions
  - Includes contributions from $\gamma_L^*$ and $\gamma_T^*$

Large contribution of the GPDs E and $H_T$

$\langle x_{Bj} \rangle \approx 0.039$, $\langle Q^2 \rangle \approx 2.0$ GeV$^2$, $\langle p_T^2 \rangle \approx 0.18$ GeV$^2$
Exclusive $\omega$ production with Transv. Pol. Target

\[ \mu p \rightarrow \mu' + \omega + p_{\text{non détecté}} \]

GK model predictions (EPJ A50 (2014)) including all the GPDs and transverse GPDs

- the pion pole exchange which is large for $\omega$ production

\[ \gamma^* \rightarrow \pi^0 \rightarrow \pi^+\pi^-\pi^0 \]

- positive $\pi\omega$ form factor
- no pion pole
- negative $\pi\omega$ form factor

No unambiguous determination of the sign

$E_H$, $T_H$

$Q^2$, $x_{Bj}$, $p_T^2$ [GeV$^2$], $W$ [GeV]

$\langle x_{Bj} \rangle \approx 0.049$, $\langle Q^2 \rangle \approx 2.2$ GeV$^2$

$\langle p_T^2 \rangle \approx 0.17$ GeV$^2$, $\langle W \rangle \approx 7.1$ GeV$^2$
Backup Slides
Proton « radius » measured at JLab

Fit of 8 CFFs at L.O and L.T.
Dupré, Guidal, Vanderhaeghen, PRD95, 011501(R)(2017)

\[ S_1^I = \text{Im} \, F_1 H \]

- CLAS \( \sigma \) and \( \Delta \sigma \)
- HallA \( \sigma \) and \( \Delta \sigma \)
- CLAS \( A_{UL} \) and \( A_{LL} \)

\[ \langle b_{\perp}^2 \rangle \approx 4 \, B' \]

HERMES + 8 points from JLab

\[ x = \xi \; \text{and} \; \xi \rightarrow 0 \]
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 LH₂ target
  ○ Observation of exclusive photon production
  ○ Confirmed the global efficiency $\approx 10\%$ used for projections

2009: 10 days, short LH₂ 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 LH₂ target and recoil detector

2016-7: 2 x 6 months with LH₂ 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
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 $t$
“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

- $\gamma, \rho, \rho^+, \omega, \phi...$
Introduction to GPDs

“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

Definition of variables:
- $q$: exchanged photon four-momentum
- $x$: average long. momentum - NOT ACCESSIBLE
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- $t$: 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

Experimentally accessible through Compton Form Factors (CFFs):

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

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

$\mathcal{D}(t)$ connected to energy-momentum tensor (Polyakov, PLB 555 (2003) 57-62)
Introduction to GPDs

“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”:

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

$$<b^2_{\perp}(x_B) > \approx 2B(x_B)$$

$b_{\perp}$: distance between the struck parton and center of momentum

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
Towards a 3D Picture of the Nucleon...

Form Factors $(t)$

Fourier transform $(b_T)$

& $\int GPDs(x, t) ... dx$

$GPDs$ $(x, b_T)$

$\int dk_T$

$PDFs$ $(x)$

$\int GPDs(x, b_T) ... db_T$

$TMDs$ $(x, k_T)$

$\int db_\perp$

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

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

Wigner Distributions

$\int TMDs(x, k_T) ... dk_T$
PDFs: 1-D structure

Longitudinal momentum

\[ k^+ = xP^+ \]

Transverse plane

partons

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

\[ \rho(x, \vec{k}_T, \vec{b}_T) \]

**5-D correlations**

- Longitudinal momentum: \( k^+ = x P^+ \)
- Transverse momentum: \( \vec{k}_T \)
- Transverse position: \( \vec{b}_T \)
- Partons

see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)