Exclusive Physics at HERMES and COMPASS

- Hard exclusive reactions and GPDs
- The experiments
- DVCS
- DMVP
- Outlook

Caroline Riedl

EDS Blois 2015, 16th International Conference on Elastic and Diffractive Scattering
Borgo-Corsica, June 29 - July 3, 2015
Hard-exclusive reactions

\[ lp \rightarrow lp\gamma \quad \text{Deeply Virtual Compton Scattering (DVCS)} \]

\[ lp \rightarrow lpM \quad \text{Deeply Virtual Meson Production (DVMP)} \]

Generalized Parton Distributions

<table>
<thead>
<tr>
<th>4 chiral-even quark GPDs</th>
<th>flips nucleon helicity</th>
<th>conserves nucleon helicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>does not depend on quark helicity</td>
<td>(E \leftrightarrow \text{Sivers} )</td>
<td>(H \rightarrow q(x))</td>
</tr>
<tr>
<td>depends on quark helicity</td>
<td>(\tilde{E})</td>
<td>(\tilde{H} \rightarrow \Delta q(x))</td>
</tr>
</tbody>
</table>

@leading twist for a spin-\(\frac{1}{2}\) target

GPD \(E\) and Sivers function involve switch of nucleon helicity: related to OAM

Transverse imaging: transverse size of nucleus

\[ b = \text{“t-slope”} = \text{average impact parameter} \]

\[ d\sigma^{\text{DVCS}} / dt \propto e^{-b|t|} \]

4 chiral-odd quark GPDs

\(H_T \leftrightarrow \text{transversity TMD}\)

\(2H_T + E_T \leftrightarrow \text{Boer-Mulders} \)

\(E_T \)

impact-parameter representation:

\[ q_f(x, b_\bot) = \int \frac{d^2 \Delta_\bot}{(2\pi)^2} e^{-i \Delta_\bot \cdot b_\bot} H^f(x, 0, -\Delta_\bot^2) \]

at DESY: exclusive measurements

- 1995-2007
- 1996-2007: H, D, He, N, Ne, Kr, Xe
- 2006/2007: H, D with recoil
- 1996/97: H→
- 1999/2000: D→
- 2002-2005: H↑

H, D, He, N, Ne, Kr, Xe

e^+ / e^− beam
27.6 GeV
gas target
internal to lepton ring
at CERN

since 2002

\[\mu^\pm \text{beam: } 160/200 \text{ GeV, } \mu^+ 5 \times 10^8/\text{s, } \mu^- 2 \times 10^8/\text{s}\]

More than 300 tracking planes

18 mrad < \theta_{\mu} < 180 mrad

DVMP:
- 2002/03: D \rightarrow (\rho)
- 2002-2004: D \uparrow (\rho)
- 2007/2010: H \uparrow (\rho, \omega)

DVCS:
- 2008/09: H with short recoil (test run)
- 2012: H with long recoil (pilot run)
- 2016/17: H with long recoil

Polarized solid \text{NH}_3 & \text{^6LiD}

or unpolarized liquid \text{NH}_2

Dynamic Nuclear Polarization

Dilution refrigerator (\sim 60\text{mK})

Superconducting solenoid (\sim 2.5\text{T})

dipole magnet (\sim 0.5\text{T})
HERMES =
HEra MEasurement of Spin

Hamburg, Germany

HERA @ DESY retired 30.6.2007

COMPASS
= CCommon Muon and Proton Apparatus for Structure and Spectroscopy

Geneva, Switzerland /
Prevessin, France

COMPASS will add data in the so-far unexplored kinematic space between the fixed-target experiments HERMES and @JLab, and the collider experiments H1/ZEUS
Deeply Virtual Compton Scattering

\[ e \rightarrow e', \gamma^* \rightarrow \gamma \]

\[ x^+, x^- \]

\[ GPDs(x, \xi, t) \]

\[ p \rightarrow p', t \]
The $\gamma^* N \rightarrow \gamma N$ cross section

$$\sigma_{\gamma^* N} = \sigma_{\text{DVCS}} + \sigma_{\text{Bethe-Heitler (BH)}}$$

$$= |T_{\text{BH}}|^2 + (T_{\text{DVCS}} T_{\text{BH}}^* + T_{\text{DVCS}}^* T_{\text{BH}}) + |T_{\text{DVCS}}|^2$$

expand as harmonic series in $\phi$ (and $\phi_S$).

Experimental access: through azimuthal asymmetries

$$\sigma(\phi; P_B, C_B) = \sigma_{UU}(\phi) \cdot \left[ 1 + P_B A_{LU}^{\text{DVCS}}(\phi) + C_B P_B A_{LU}^T(\phi) + C_B A_C(\phi) \right]$$

Compton Form Factors

$$\mathcal{F}(\xi, t) = \sum_q \int_{-1}^{1} dx \ C_q^x(\xi, x) F^q(x, \xi, t)$$

integral of GPDs over $x$
Azimuthal asymmetries and GPDs

**Unpolarized Target:**

\[
F_1 \mathcal{H} + \frac{x_B}{2-x_B} (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}
\]

- Dominant for the proton
- Dominant for the neutron

**Beam-Helicity Asymmetry**

\[
A_{LU} (\phi) \equiv \frac{d\sigma^\rightarrow - d\sigma^\leftarrow}{d\sigma^\rightarrow + d\sigma^\leftarrow}
\]

**Beam-Charge Asymmetry**

\[
A_C (\phi) \equiv \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}
\]

**Longitudinally Polarized Target:**

\[
\frac{x_B}{2-x_B} (F_1 + F_2) \left( \mathcal{H} + \frac{x_B}{2} \mathcal{E} \right) + F_1 \tilde{\mathcal{H}} - \frac{x_B}{2-x_B} \left( \frac{x_B}{2} F_1 + \frac{t}{4M^2} F_2 \right) \tilde{\mathcal{E}}
\]

**Longitudinal Target-Spin Asymmetry**

\[
A_{UL} (\phi, e_i) \equiv \text{Longitudinal target-spin asymmetry}
\]

\[
\frac{[\sigma^\rightarrow (\phi, e_i) + \sigma^\leftarrow (\phi, e_i)] - [\sigma^\leftarrow (\phi, e_i) + \sigma^\rightarrow (\phi, e_i)]}{[\sigma^\leftarrow (\phi, e_i) + \sigma^\rightarrow (\phi, e_i)] + [\sigma^\rightarrow (\phi, e_i) + \sigma^\leftarrow (\phi, e_i)]}
\]

**Transversely Polarized Target:**

\[
\frac{t}{4M^2} \left[ (2-x_B) F_1 \mathcal{E} - 4 \frac{1-x_B}{2-x_B} F_2 \mathcal{H} \right]
\]

**Double-Spin Targets**

- **Double-Spin (LL) Asymmetry**
- **Double-Spin (LT) Asymmetry**

**Transverse Target-Spin Asymmetry**

\[
A_{UT} (\phi, \phi_S) \quad A_{IL} (\phi, \phi_S)
\]

\[
R_{LT} (\phi, \phi_S) \quad R_{BH+DVCS} (\phi, \phi_S)
\]
“Traditional” DVCS Analysis at HERMES

“exclusive region” in (missing mass)$^2$

![Diagram of HERMES detector setup]

- No other charged tracks reconstructed
- No other untracked clusters in the calorimeter

**Missing-mass technique**

$$M_{X}^2 = (k + p - k' - q')^2$$

- ep $\rightarrow$ eX$\gamma$ sample
  - Unresolved for associated production
  - Semi-inclusive neutral pion production corrected for about 12%
  - about 3%

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BLOIS 2015, Borgo, June 2015
HERMES: beam-charge asymmetry

Global fit including data from JLab, HERMES and HERA colliders
(dashed excludes JLab Hall A cross section)

GGL11
Model calculation

All 1996–2007 proton data. No recoil-proton detection
Associated fraction ep→eΔ⁺γ (from MC simulation)

HERMES: JHEP 07 (2012) 032
HERMES: transverse target-spin asymmetry

Model curves: VGG Regge, no D-term
3 different values for $J_u$ fixed $J_d=0$

HERMES: JHEP 06 (2008) 066
The HERMES Recoil Detector

- SC Solenoid (1 Tesla)
- Beam
- Photon Detector PD
- Scintillating Fiber Tracker SFT
- Silicon Strip Detector SSD
- Target Cell

Purpose: tagging of exclusive events

Momentum reconstruction down to 125 MeV (protons).
Want as low $-t$ as possible!
(corresponds to $-t=0.016$ GeV$^2$)

2006/2007 unpolarized proton and deuteron data

JINST 8 (2013) P05012
Adding the Recoil Proton

Kinematic event fitting

\[ \chi^2_{\text{pen}} = \sum_{i=1}^{9} \frac{(r_i^{\text{fit}} - r_i^{\text{meas}})^2}{\sigma_i^2} + T \cdot \sum_{j=1}^{4} \frac{[f_j(r_1^{\text{fit}}, \ldots, r_9^{\text{fit}})]^2}{(\sigma_j^f)^2} \]

\( f_j \): 4 constraints of 4-momentum conservation & assuming proton mass

Hypothesis: ep→eγ event \( \Rightarrow \) require: \( \chi^2 < 13.7 \)

Only eγ detection

unresolved sample

pure sample

\( >99.8\% \) ep→eγ purity

unresolved for \( \Delta^+ \)

~88% ep→eγ purity

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BLOIS 2015, Borgo, June 2015
HERMES (with recoil proton): beam-helicity asymmetry

Global fit of world data
JLab, HERMES and HERA,
dashed excludes JLab Hall A cross section

GPD model calculation “VGG Regge”

HERMES: JHEP 10 (2012) 042
HERMES (with recoil proton): beam-helicity asymmetry

Global fit of world data
JLab, HERMES and HERA,
dashed excludes JLab Hall A cross section

GPD model calculation “VGG Regge”

epy detection: >99.8% purity of ep→ epγ
★ ey detection: sample unresolved for 12% resonant production, e.g. ep→ eΔ⁺γ
▲ ey detection in recoil acceptance (reference)
The charged particle of (πN) reconstructed by the recoil detector.

This result is consistent with the slight increase of the beam-helicity asymmetry amplitude with recoil proton.

Associated process acts as small dilution in the asymmetries for the unresolved sample.

Only existing model prediction for sinφ amplitude:
π^0p: -0.15, π^+n: -0.10
DVCS Amplitudes

(A) Beam-charge asymmetry: GPD H


(B) Beam-helicity asymmetry: GPD H


(C) Transverse target-spin asymmetry: GPD E

\[ \text{GPD E} \quad [\text{JHEP 06 (2008) 066}] \]

(D) Double-Spin (LT) asymmetry: GPD E

\[ \text{GPD E} \quad [\text{Phys. Lett. B 704 (2011) 15-23}] \]

(E) Longitudinal target-spin asymmetry: GPD H~


(F) Double-spin (LL) asymmetry: GPD H~


\[ <Q^2>=2.46 \text{ GeV}^2, \quad <x_B>=0.10, \quad <-t>=0.12 \text{ GeV}^2 \]
DVCS on hadrons other than the proton

- **Spin-1**
  - $H_1, H_2, H_3, H_4, H_5, \tilde{H}_1, \tilde{H}_2, \tilde{H}_3, \tilde{H}_4$
  - $b_1(x)$
  - tensor structure function

- 9 chiral-even quark GPDs at LT
- $H_3, H_5$ associated with 5% D-wave component of deuteron wave function

**Tensor polarized deuteron**

- Vector polarization $P_z \approx 0.85$
- Tensor polarization $P_{zz} \approx 0.83$
- Dedicated data set with $P_{zz} = -1.656$ & $P_z \approx 0$

\[ P_z = \frac{n^+ - n^-}{n^+ + n^- + n^0} \]
\[ P_{zz} = \frac{n^+ + n^- - 2n^0}{n^+ + n^- + n^0} \]

**Nuclear targets**

<table>
<thead>
<tr>
<th>Target</th>
<th>Spin</th>
<th>L (pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1H$</td>
<td>1/2</td>
<td>227</td>
</tr>
<tr>
<td>He</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td>51</td>
</tr>
<tr>
<td>Ne</td>
<td>0</td>
<td>86</td>
</tr>
<tr>
<td>Kr</td>
<td>0</td>
<td>77</td>
</tr>
<tr>
<td>Xe</td>
<td>0, 1/2, 3/2</td>
<td>47</td>
</tr>
</tbody>
</table>

Coherent and tensor signatures; nuclear medium

**Coherent scattering**

- Deuteron: probe spin-1 object
- Nucleon: probe spin-1/2 object

Kinematic cut in $-t$ determines the domain: "coherent enriched" and "incoherent enriched" data samples
Target-Spin Asymmetry on p and d

Search for coherent signature

Proton: 
$\text{Re}(\mathcal{H})$ (incoherent)

Deuteron: 
$\text{Re}(\mathcal{H}_1)$ (coherent @ low $-t$)

$\text{Re}(\mathcal{H})$ (incoherent @ larger $-t$)

1998–2000 longitudinally polarized deuteron data

$\text{Nucl. Phys. B 842 (2011) 265-298}$
Beam-Helicity Asymmetry on $p$ and $d$

Search for tensor signature

$A_{LZZ} \sin \phi$ for coherent scattering at low values of $-t$

unpolarized: $\text{Re}(H_1)$

tensor-polarized ($P_{zz}=0.827$):

$\text{Re}(H_1-\frac{1}{3}H_5)$

$H_5 \equiv$ tensor structure function in the forward limit

$\nu(2\phi) = -0.074 \pm 0.196 \pm 0.022$ (-$t<0.06 \text{ GeV}^2$, 40% coherent)

1998–2000 longitudinally polarized deuteron data

GPDs $H_1, H_5$

**DVCS Nuclear Mass Dependence**

![Graphs showing nuclear mass dependence](image)

**Beam-charge asymmetry**

- $A_{C}^{\cos\phi}$ vs. $A$
- $A_{C}^{\sin\phi}$ vs. $A$

**Beam-helicity asymmetry**

- $A_{LU}^{\sin\phi}$ vs. $A$

**Questions**

- How does the nuclear medium modify parton-parton correlations?
- How do the nucleon properties change in the nuclear medium?
- Is there an enhanced ‘generalized EMC effect’, which could be revealed through the rise of $\tau_{DVCS}$ with $A$?

**Average**

- $A_{LU}^{A}/A_{LU}^{H}$:
  - $0.91 \pm 0.19$
  - $0.93 \pm 0.23$

**Normalization to hydrogen $^1$H**

**References**


**Contacts**

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COMPASS upgrade for GPD run 2016/17

Long recoil detector CAMERA
ToF between 2 rings of scintillators
- 24 inner and 24 outer scintillators
- ToF resolution 300 ps
- $p_{\text{min}}=260$ MeV
- $0.06 \text{ GeV}^2 < -t < 0.8 \text{ GeV}^2$

ECaI0
to extend angular acceptance for photons

The distribution of the selected proton is presented in Fig. 27 (compared to the simulation in Fig. 13) and the distribution of the position of selected photon in the ECALs in Fig. 14. One can see that the background clusters in ECAL1 are mostly found in the noisy region below and on the Jura side of the hole, while for ECAL2 they are quite evenly distributed across the whole surface (and most likely single-cell clusters since the position seems to be exactly aligned with the block matrix).

The Pulse Shape Analysis of the ECALs signals, performed recently, will have a direct impact on this figure and on the resulting photon resolution. This new method should be included in the next production of the data.
COMPASS DVCS pilot run 2012

- Full-scale recoil CAMERA detector and only central part of ECal0 installed = 25%

- Visible $\pi^0$ background (2 photons reconstructed): measured and corrected for

- Invisible $\pi^0$ background (1 photon escapes): estimated by MC. SIDIS: LEPTO; exclusive: HEPGEN/$\pi^0$

+ cuts on missing mass w/o proton, $\Delta E$, and $\Delta Z$

from forward spectrometer

Expected minus measured kinematics

recoil in CAMERA

MC: HEPGEN/BH + DVCS/2 with GEANT4 simulation of detectors & full COMPASS reconstruction chain.

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DVCS vs. BH at COMPASS

2012 DVCS pilot run

\[ |T_{BH}|^2 + (T_{DVCS} T_{BH}^* + T_{DVCS}^* T_{BH}) + |T_{DVCS}|^2 \]

\[ 0.005 < x_{Bj} < 0.01 \]

\[ 0.01 < x_{Bj} < 0.03 \]

\[ 0.03 < x_{Bj} < 0.27 \]

High-x bin:
- Largest fraction of $\pi^0$ background
- Pure DVCS events after subtraction of (BH + measured SIDIS $\pi^0$ + max. simulated exclusive $\pi^0$) $\Rightarrow$ excess

BH reference yield

DVCS amplitude: $\Phi$-modulations in cross section

Transverse imaging: $\Phi$-integrated cross section

Data

\[ \gamma^* \Phi \]

\[ \gamma \]

\[ \gamma^* \Phi \]

\[ \gamma \]

\[ \gamma^* \Phi \]

\[ \gamma \]

\[ \gamma^* \Phi \]

\[ \gamma \]

\[ \gamma^* \Phi \]

\[ \gamma \]
DVCS at COMPASS-II

\[ S_{CS,U} \equiv d\sigma^\pm + d\sigma^\to = 2(d\sigma^{\text{BH}} + d\sigma^{\text{DVCS\ unpol}} + e_\mu P_\mu \text{Im } \mathcal{I}) \]

\[ D_{CS,U} \equiv d\sigma^\pm - d\sigma^\to = 2(P_\mu d\sigma^{\text{DVCS\ pol}} + e_\mu \text{Re } \mathcal{I}) \]

@COMPASS:
H-dominance

\[ \text{Im } \mathcal{H}(\xi, t, Q^2) \overset{\text{LO}}{=} \pi \sum_f e_f^2 \left( H^f(\xi, \xi, t, Q^2) + H^f(-\xi, \xi, t, Q^2) \right) \]

\[ \text{Re } \mathcal{H}(\xi, t, Q^2) \overset{\text{LO}}{=} \sum_f e_f^2 \left[ \mathcal{P} \int_{-1}^{1} dx \ H^f(x, \xi, t, Q^2) \left( \frac{1}{x - \xi} + \frac{1}{x + \xi} \right) \right] \]

Kinematic range (DVCS 2012 pilot run):

1 GeV^2 < Q^2 < 20 GeV^2
0.005 < x_\text{Bj} < 0.27
0.06 < |t| < 0.64 GeV^2

integral of GPDs over x

GPDs @ x=\xi
COMPASS-II projections for spin & charge asym.

Projection compared with HERMES beam-charge asymmetry’s $\cos\Phi$-modulation

- Question: magnitude of $\cos\Phi$-modulation in COMPASS data?

- Changes sign in between H1 and HERMES!

Kroll, Moutarde, Sabatié,
Test of GPD universality: use DVMP data to constrain GPD params

$A_{CS,U}(\phi) \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{D_{CS,U}}{S_{CS,U}}$

COMPASS $x=0.05$, $Q^2=2\text{GeV}^2$, $-t=0.2\text{GeV}^2$
Transverse imaging from DVCS and DVMP

\[ \frac{d\sigma^{DVCS}}{dt} \propto e^{-b|t|} \]

2 years of data
beam energy 160 GeV
4 \cdot 10^8 \mu^+/spill (\mu^- 2.6x less)
duration 9.6s every 48s
2.5m target
Lumi=10^{32} cm^{-2}s^{-1}
\( \varepsilon_{\text{global}} = 10\% \)

Regge-trajectory ansatz
\[ b(x_B) = b_0 + 2\alpha' \ln(x_0/x_B) \]
\[ \alpha' \approx 0.25 \text{ GeV}^{-2} \]
soft pomeron

1-bin-extraction already possible from DVCS test in 2012

Zeus \( <Q^2> = 3.2 \text{ GeV}^2 \)
H1-HERA I \( <Q^2> = 4 \text{ GeV}^2 \)
H1-HERA II \( <Q^2> = 8 \text{ GeV}^2 \)
COMPASS \( <Q^2> = 2 \text{ GeV}^2 \)
280 days at 160 GeV
Deeply Virtual Meson Production
Selection of exclusive meson sample

- No recoil proton detection: missing-energy technique assuming proton mass
- MC simulation of non-exclusive background and subtraction in exclusive $\Delta E$ bin (11% HERMES, 35% COMPASS)
**Ip→IpV: Exclusive vector meson production**

- pQCD at sufficiently large $Q^2$ and $W$: 1. $\gamma^*\rightarrow(qq\text{bar})$ 2. $(qq\text{bar})$ scatters off nucleon 3. formation of observed vector meson.
- Translated into Regge phenomenology: reggeon exchange with $J^P=0^+, 1^-, 2^+, ...$ (Natural Parity Exchange) $\leftrightarrow\text{GPDs } H, E$
  $J^P=0^-, 1^+, ...$ (Unnatural Parity Exchange) $\leftrightarrow\text{GPDs } H\sim, E\sim$
- Cross section for exclusive leptoproduction of vector mesons:
  \[
  \frac{d\sigma}{dx_B dQ^2 dt} W(x_B, Q^2, t, \phi, \phi_S, \varphi, \vartheta)
  \]
- $W$ parametrized by Spin Density Matrix Elements (SDME)
- SDME describe the helicity transfer from $\gamma^*$ to $V$.
- Hierarchy of helicity amplitudes:
  \[
  |T_{00}| \sim |T_{11}| \gg |T_{01}|>|T_{10}|>\sim|T_{1-1}|
  \]
Rho, Phi, and Omega SDME

- **ρ**
  - (EPJC 62 (2009) 659-694)
  - Hierarchy of amplitudes ✓
  - Small deviation from 0 for helicity-flip amplitudes
  - Contributions of UPE

- **ω**
  - (EPJC 74 (2014) 3110)
  - Hierarchy of amplitudes ✗
  - Significant role of UPE

- Cross section ratio of longitudinal to transverse vector mesons

\[
R(W, Q^2, t) \equiv \frac{d\sigma_L}{dt}/\frac{d\sigma_T}{dt}
\]


Analysis of HERMES ω SDMEs using a set of GPDs extracted from ρ^0, Φ, π^+ data.

Importance of pion pole for ω production.

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Transverse asymmetry for exclusive $\rho^0$ & $\omega$

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

GPD $E$ linked to quark orbital angular momentum.

$$A_{UT}^{\sin \phi_S}$$ sensitive to chiral-odd GPD $H_T$ (analogous to transversity TMD).

$$E^{\rho^0} = 1/\sqrt{2}(2/3E_u + 1/3E_d + 3/8E_g)$$
$$E^{\omega} = 1/\sqrt{2}(2/3E_u - 1/3E_d + 3/8E_g)$$

Cancellation effects expected for $\rho$ production.
Asymmetry in $l p^\uparrow \rightarrow lp\rho^0$: $\sin(\Phi - \Phi_S)$

**HERMES proton** *Phys. Lett. B679 (2009) 100-105*

**COMPASS proton** *PLB B731 (2014) 19*

**COMPASS deuteron** *NPB 865 (2012) 1*

Blue curves: prediction from phenomenological GPD-based GK model 2009
COMPASS $\mu p \uparrow \rightarrow \mu p \rho^0$: all amplitudes

$A_{\sin (\phi - \phi_S)}$  
$A_{\sin (\phi + \phi_S)}$  
$A_{\sin (2\phi - \phi_S)}$  
$A_{\sin (3\phi - \phi_S)}$  
$A_{\sin \phi_S}$  
$A_{\cos (\phi - \phi_S)}$  
$A_{\cos (2\phi - \phi_S)}$  
$A_{\cos \phi_S}$

with $\bar{\mathcal{E}}_T = 2\tilde{\mathcal{H}}_T + \mathcal{E}_T$

$A_{\sin (\phi - \phi_S)} \propto \text{Im} (\mathcal{E}^* \mathcal{H})$

$A_{\sin (\phi + \phi_S)} \propto \text{Im} (\bar{\mathcal{E}}_T \mathcal{H}_T)$

$A_{\sin (2\phi - \phi_S)} \propto \text{Im} (\bar{\mathcal{E}}_T \mathcal{E})$

$A_{\sin (3\phi - \phi_S)} \propto \text{Im} (\mathcal{H}_T^* \mathcal{H} - \bar{\mathcal{E}}_T \mathcal{E})$

$A_{\cos (\phi - \phi_S)} \propto \text{Re} (\mathcal{H}_T^* \bar{\mathcal{E}}_T)$

$A_{\cos (2\phi - \phi_S)} \propto \text{Re} (\bar{\mathcal{E}}_T \mathcal{E})$

$A_{\cos \phi_S} \propto \text{Re} (\mathcal{H}_T^* \mathcal{H} - \bar{\mathcal{E}}_T \mathcal{E})$

$A_{\sin \phi_S} = -0.019 \pm 0.008 \text{(stat.)} \pm 0.003 \text{(syst.)}$

Evidence for existence of $H_T$

All amplitudes consistent with GK 2014

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*Slide courtesy Katharina Schmidt (University of Freiburg)*

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HERMES: asymmetry in ep $\uparrow \rightarrow$ ep$\omega$

HERMES proton publication in preparation


@ W=4.8 GeV, Q$^2$=2.42 GeV$^2$
- positive $\pi\omega$ form factor
- no pion pole
- negative $\pi\omega$ form factor

@ W=8 GeV, Q$^2$=2.42 GeV$^2$
- positive $\pi\omega$ form factor
- negative $\pi\omega$ form factor

HERMES: too large experimental uncertainties to constrain sign of $\pi\omega$ transition form factor.

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COMPASS: asymmetry in $\mu p \uparrow \rightarrow \mu p \omega$

COMPASS: results do not allow unambiguous determination of $\pi \omega$ transition form factor.

COMPASS proton publication in preparation

GK 2014

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

COMPASS 2010 proton data preliminary

reconstruction of 2 charged hadrons & 2 photons

$M_{\pi^+\pi^-}$ [GeV/$c^2$]
Global analysis of exclusive data

Test of GPD universality

P. Kroll, H. Moutarde and F. Sabatié,

Use DVMP data, FF and PDFs to constrain GPD parameters (LO, LT):
- GK model
  - Compare to DVCS observables - good for HERA and HERMES, fair for JLab

Global fit to $H(x,\xi=x,t)$ from DVCS data (NNLO)
Kumericki, Müller

- HERMES $A_C$, CLAS $A_{LU}$ and Hall A $x$-section.
- Small-$x$ behavior from HERA collider data.
Outlook

• **COMPASS 2016/17:**
  - LH2 target + recoil detector
  - GPD $H$ from DVCS
  - Transverse imaging of the nucleon from DVCS and DVMP

• **COMPASS >2018 (?)**:
  - NH$_3$↑ target + recoil detector
  - GPD $E$ from DVCS
  - GPD $E$ and **chiral-odd** GPDs from DVMP
    - vector mesons $\rho^0$, $\rho^+$, $\omega$, $\Phi$
    - pseudoscalar mesons $\pi^0$

Preparing upgrade of CAMERA recoil proton detector: replace scintillators of inner ring to achieve better attenuation length (2015).
Summary: Exclusive Physics at HERMES & COMPASS

- HERMES: many pioneering measurements. Data set will remain unique in the near future.
- COMPASS allows to probe unexplored region in kinematic space.
- Exclusive meson production: complementary to Deeply Virtual Compton scattering.
- COMPASS GPD program will be continued in 2016/17 and possibly beyond 2018.
Backup
HERMES: unresolved reference sample

Disentangling the effects of recoil-detector acceptance and purification

Loss due to
- lower-mom. threshold
- $\Phi$-gaps of SSD

Deficit due to
- removal of background
- inefficiencies of $\chi^2$ cut
- recoil-det. ineffciencies

~88% $ep\rightarrow ep\gamma$ purity

>99.8% $ep\rightarrow ep\gamma$ purity

Unresolved sample (traditional analysis)
Unresolved-reference
Pure sample

Experimental data
Simulation (sum)
$ep\rightarrow ep\gamma$
$ep\rightarrow e\Delta^+\gamma$
semi-inclusive

Traditional sample plus acceptance function
Track Reconstruction

with recoil detector

Hermes 2007 data

Recoiling proton candidates
DVCS

azimuthal-angle resolution: 4 mrad
polar-angle resolution: 10 mrad
(for p>0.5 GeV)

Momentum reconstruction down to
125 MeV (protons).
Want as low -t as possible!
(corresponds to -t=0.016 GeV^2)

pions: \( \Delta p/p = 0.12 \)

protons
magnetic bending only

energy deposit & bending
In the same reference a theoretical prediction for $A_1^ρ$ was presented, which is based on the description of forward exclusive $ρ^0$ leptonproduction and inclusive inelastic lepton-nucleon scattering by the off-diagonal Generalised Vector Meson Dominance (GVMD) model, applied to the case of polarised lepton-nucleon scattering. At the values of Bjorken variable $x < 0.2$, with additional assumptions [11], $A_1^ρ$ can be related to the $A_1$ asymmetry for inclusive inelastic lepton scattering at the same $x$ as

$$A_1^ρ = \frac{2A_1}{1 + (A_1)^2}. \tag{4}$$

given by Eq. 4, which relates $A_1^ρ$ to the asymmetry $A_1$ for the inclusive inelastic lepton-nucleon scattering. To produce the curve the inclusive asymmetry $A_1$ was parameterised as $A_1(x) = (x^\alpha - \gamma^\alpha) \cdot (1 - e^{-\beta x})$, where $\alpha = 1.158 \pm 0.024$, $\beta = 125.1 \pm 115.7$ and $\gamma = 0.0180 \pm 0.0038$. The values of the parameters have been obtained from a fit of $A_1(x)$ to the world data from polarised deuteron targets [26–31] including COMPASS measurements at very low $Q^2$ and $x$ [32]. Within the present accuracy the results on $A_1^ρ$ are consistent with this prediction.
DVCS Asymmetries on Nuclei

- Targets with 2 beam charges available. $A_C$ and charge-difference $A_{LU}$ sensitive to DVCS-BH interference term

  - Targets with only one beam charge available. No $A_C$ and single-charge $A_{LU}$ with entangled $s_1$ coefficients

1996–2005 nuclear data
**HERMES Nuclear Data Sets**

<table>
<thead>
<tr>
<th>Target</th>
<th>Spin</th>
<th>L (pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>1/2</td>
<td>227</td>
</tr>
<tr>
<td>He</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
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<td>Ne</td>
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<td>86</td>
</tr>
<tr>
<td>Kr</td>
<td>0</td>
<td>77</td>
</tr>
<tr>
<td>Xe</td>
<td>0, 1/2, 3/2</td>
<td>47</td>
</tr>
</tbody>
</table>

Heavy target data taken at the end of each HERA fill (“high density runs”)

- Separation of coherent-enriched and incoherent-enriched data samples by t-cutoff such that ≈same average kinematics for each target.
  - Coherent enriched samples: ≈65% coherent fraction
  - Incoherent enriched samples: ≈60% incoherent fraction
Vector meson production and decay

lepton scattering–plane

\rho^0–production–plane

\rho^0–decay–plane

\pi^+ \pi^0 \pi^–
Exclusive π⁺ on transversely polarized protons

\[ A_{UT,\ell}^{\sin(\phi - \phi_S)} \propto - \frac{\sqrt{-t'}}{M_p} \cdot \text{Im}(\tilde{E}^* \tilde{H}) \]

- Consistent with zero. A vanishing Fourier amplitude in this model implies the dominance (due to the pion pole) of Etilde over Htilde at low \(-t'\). Excludes a pure pion-pole contribution to Etilde.

- \(\sin\Phi_S\) amplitude is large and positive: implies presence of a sizeable interference between contributions from longitudinal and transverse virtual photons.

\[ A_{UT,\ell}^{\sin(\phi - \phi_S)} \]

\[ -t' \quad [\text{GeV}^2] \]

\[ 0 \quad 0.2 \quad 0.4 \quad 0.6 \]

\[ 0 \quad 0.5 \quad 1 \]

