Hard exclusive reactions and generalized parton distributions

I. Brodski, M. Düeren, E. Etzmüller, Avetik Hayrapetyan, M. Stahl, H. Stenzel

Justus-Liebig-Universität Gießen

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The start point, proton spin

The proton has a spin 1/2.
we have learned to use it

With MRI devices you can check whether it make sense to play Football
lets open it

Kindergarden Event

University Event
Why GPDs

- Multidimensional description of nucleon structure (longitudinal momentum versus transverse position)

- Include parton distribution functions and form factors as forward limits and moments, respectively

- Can provide access to the total (and hence orbital) angular momentum of quarks in the nucleon via Ji relation

\[
J_q = \lim_{t \to 0} \int_{-1}^{1} dx \, x[H_q(x, \xi, t) + E_q(x, \xi, t)]
\]

- In case of proton target four GPDs
  \[ H, \tilde{H}, E, \tilde{E} \]

GPDs, how to access them

quantum number of final state selects different GPDs:

- theoretically very clean
  DVCS ($\gamma$): $H, E, \tilde{H}, \tilde{E}$

- VM ($\rho, \omega, \phi$): $H, E$

- info on quark flavors
  PS mesons ($\pi, \eta$): $\tilde{H}, \tilde{E}$

P. Kroll, S. Goloskokov

$2J^u + J^d$

$J^u - J^d$

$2J^u - J^d$

$\rho^0$

$\rho^+$

$\omega$

$A_{UT}$ measurement

K. Goeke, M. Polyakov, M. Vanderhaegen PPNP 47(2001)
Deeply Virtual Compton Scattering (DVCS)

DVCS is the cleanest way to access GPDs

Handbag diagram separates
- hard scattering process (QED & QCD) (NLO) and
- non-pertubative structure of the nucleon: GPD(x,ξ,t,Q²)

GPDs = probability amplitude for a nucleon to emit a parton with $x+\xi$ and to absorb it with momentum fraction $x-\xi$
Today: most complete experimental access:
- charge reversal (e\(^+\) and e\(^-\) beams)
- beam spin reversal (both beam helicities)
- target spin reversal (longitudinal, transverse, unpolarized)
- target mass variation (H, D, He, N, Ne, Kr, Xe)
- recoil and spectator proton detection

HERA
- 27.5 GeV
- e\(^+\) and e\(^-\)
- spin rotators
The Detector

- Spectrometer
  - particle identification
  - recoil proton detection (in 2006-07)
  - complete DVCS kinematics $e p \rightarrow ep\gamma$

- Today: most complete experimental access:
  - charge reversal ($e^+$ and $e^-$ beams)
  - beam spin reversal (both polarized and unpolarized)
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  - recoil and spectator proton detection
The Recoil Detector

Recoil fibre detector made in Giessen

JINST 8 (2013) P05012
Detection scheme

“Missing mass” without/with recoil detector

1. unresolved sample
   no recoil detector
   missing mass technique
   88% purity

2. unresolved-reference sample
   as 1. (no recoil detector)
   proton in recoil acceptance

3. pure sample
   recoil proton detection
   kinematic fit
   99.8% purity
But the process $\text{ep} \rightarrow \text{ep} \gamma$ is dominated by Bremsstrahlung.

- Bethe-Heitler dominates at HERMES kinematics
- The same initial and final state, hence interference

$$|T|^2 = |T_{\text{DVCS}}|^2 + |T_{\text{BH}}|^2 + T_{\text{DVCS}} T^*_{\text{BH}} + T^*_{\text{DVCS}} T_{\text{BH}},$$

- Access to GPDs through azimuthal asymmetries
Azimutal Asymmetries in DVCS, Beam polarization, charge

Cross section $\sigma_{LU}(\phi, P_B, C_B) =$

$\sigma_{UU}[1 + P_B A_{LU}^{DVCS} + C_B P_B A_{LU}^I + C_B A_C ]$

Beam-charge asymmetry

$A_C(\phi) = \frac{\sigma^+(\phi) - \sigma^-(\phi)}{\sigma^+(\phi) + \sigma^-(\phi)} \propto \Re \mathcal{H}$

Charge-difference beam-helicity asymmetry

$A_{LU}^I(\phi) = \frac{(\sigma^{+\rightarrow}(\phi) - \sigma^{+\leftarrow}(\phi)) - (\sigma^{-\rightarrow}(\phi) - \sigma^{-\leftarrow}(\phi))}{(\sigma^{+\rightarrow}(\phi) - \sigma^{+\leftarrow}(\phi)) + (\sigma^{-\rightarrow}(\phi) - \sigma^{-\leftarrow}(\phi))} \propto \Im \mathcal{H}$

Charge-averaged beam-helicity asymmetry

$A_{LU}^{DVCS}(\phi) = \frac{\sigma^{+\rightarrow}(\phi) + \sigma^{-\rightarrow}(\phi)) - (\sigma^{+\leftarrow}(\phi) + \sigma^{-\leftarrow}(\phi))}{(\sigma^{+\rightarrow}(\phi) + \sigma^{-\rightarrow}(\phi)) + (\sigma^{+\leftarrow}(\phi) + \sigma^{-\leftarrow}(\phi))} \propto \Im [\mathcal{H} \mathcal{H}^* + \widetilde{\mathcal{H}} \widetilde{\mathcal{H}}^*]$

Separation of contribution from DVCS and interference term

Dependence from beam Charge($C_B$) and Polarization($P_B$)
Azimuthal Asymmetries in DVCS, Target Polarization

Transverse target-spin asymmetry $A_{UT}(\phi, \phi_S)$ [TTSA]:

$$d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi) \propto \text{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi - \phi_S) \cos \phi$$

$$+ \text{Im}[F_2\tilde{\mathcal{H}} - F_1\xi\tilde{\mathcal{E}}] \cdot \cos(\phi - \phi_S) \sin \phi$$
Transverse target asymmetries
Sensitive to GPD E and Orbital angular momentum
HERMES DVCS results: "Beam Helicity Asymmetry" WO/with RD

[Graph showing Asin(\phi) and Asin(2\phi) as a function of various variables like t, x_B, and Q^2]
HERMES DVCS results:

"Beam Helicity Asymmetry" compared to models

- $t$
- $x_B$
- $Q^2$

VGG Regge (b$_{val} = 1...\infty$)
- $b_{sea} = \infty$
- $b_{sea} = 1$

KM = Global fit of world data: Kumericki-Müller, Nucl. Phys. B 841 (2010) 1
(JLab, HERMES and HERA, dashed excludes JLab Hall A cross section)

HERMES DVCS results:
"Beam Helicity Asymmetry” with GPD model from HEMP

GPD Model for exclusive meson production: Kroll, Moutarde, Sabatié, Eur. Phys. J. C (2013) 73:2278 compared to HERMES data:

- ● = no recoil
- □ = HERMES recoil (pure)

unresolved

pure
HERMES DVCS

GPD sensitivity

Measurement type

\[ \Re(H) \]

\[ \Im(H) \]

\[ \Im(H - E) \]

\[ \Re(H + E) \]

\[ \Im(\tilde{H}) \]

\[ \Re(\tilde{H}) \]
HERMES did its BEST to contribute in GPDs investigation, from pioneering first result ....

**Figure 1.** Single-spin asymmetry as a function of azimuthal angle $\phi$. First DVCS asymmetry published.
...to an almost complete coverage

Beam-charge and beam-spin asymmetry

- PRL 87 (2001) 182001
- PRD 75 (2007) 011103
- JHEP 11 (2009) 083

Transverse target-spin asymmetry

- JHEP 06 (2008) 066

Transverse double-spin asymmetry


Longitudinal target spin asymmetry

- JHEP 06 (2010) 019

Longitudinal target & double spin asymmetry

Conclusions

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GDPs are promising to play a main role in nucleon structure study

- HERMES was a pioneering and the only single experiment that could offer all flavours of DVCS (+associated + HEMP not shown here) measurement
- The recoil data showed importance of clean measurement to be done in future facilities
- If we add all mentioned results together then it is natural that currently almost all theoretical studies uses HERMES data for constrain GPDs
Let check whether I can type in Armenian

Շնորհակալություն

Danke

Thanks

Спасибо

Ευχαριστούμε