Are GPDs universal?
Experimental Access at HERMES, PANDA and ATLAS

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PS: I was here last time in 1999 talking about HERMES...
Generalized Parton Distributions

Quantum phase-space „tomography“ of the nucleon
Generalized Parton Distributions
and Generalized Distribution Amplitudes

GPDs and GDAs describe quarks and gluons in the nucleon

- spatial distributions (Form Factors)
- momentum distributions (Structure Functions)
- correlations in phase space (Wigner Distribution)
- spin and orbital angular momentum (Ji Sum Rule)
Wigner distribution in QM phase-space

- Wigner introduced the first well-defined phase-space distribution in quantum mechanics (1932) (despite of the uncertainty principle)
- Wigner function: \[ W(x,p) = \int \psi^*(x - \frac{\eta}{2})\psi(x + \frac{\eta}{2})e^{ip\eta} \, d\eta \]

The Wigner function contains the most complete (one-body) info about a quantum system.

Example of a Wigner function (a particle passing an interferometer)
Generalized Parton Distribution

- A Wigner operator can be defined that describes quarks and gluons in the nucleon
- The reduced Wigner distribution is related to Generalized Parton distributions (GPDs)

GPDs describe e.g. correlations of transverse position and longitudinal momentum
Are GPDs/GDAs universal?

holo\textit{graphic picture of quarks in the nucleon}
Are GPDs/GDAs universal?

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ATLAS/AFP
CERN

GPD

104,000,000 GeV

GPD

27 GeV

HERMES
DESY

1.5-15 GeV

Energy of projectile in proton rest frame

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HERMES: a pioneering experiment

... from Ellis-Jaffe to Ji et al. ...
The HERMES Experiment

- Designed at times of the spin crisis
  - Ellis-Jaffe & Bjorken sum rule
  - strange quark polarization
- 12 years data taking 1995-2007

- Pioneering results of DVCS

- Today: most complete experimental access:
  - charge reversal (e⁺ and e⁻ beams)
  - beam spin reversal (both beam helicities)
  - target spin reversal (parallel, transverse, unpolarized)
  - target mass variation (H, D, He, N, Ne, Kr, Xe)
  - recoil and spectator proton detection
  - ...

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Deeply Virtual Compton Scattering (DVCS)

DVCS is the cleanest way to access GPDs

Factorization theorem is proven!

Handbag diagram separates
- hard scattering process (QED & QCD) (NLO) and
- non-perturbative structure of the nucleon: \( \text{GPD}(x, \xi, t, Q^2) \)

GPDs = probability amplitude for a nucleon to emit a parton with \( x+\xi \) and to absorb it with momentum fraction \( x-\xi \)

\[
\xi \approx \frac{x_{Bj}}{2 - x_{Bj}}
\]

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Exclusive $ep \rightarrow e\gamma\gamma$ cross section at HERMES

\[ \frac{d\sigma}{dx_B \, dq^2 \, dt \, d\phi} = \frac{x_B \, e^6}{32 \, (2\pi)^4 \, Q^4 \, \sqrt{1 + \epsilon^2}} \left[ |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \frac{1}{\tau_{DVCS} \, \tau_{BH} + \tau_{DVCS}^*} \right] \]

**Direct access to DVCS matrix elements**

- **BH**: LARGE + known
- **DVCS**: small + unknown
- **Interference**: medium + non-zero azimuthal asymmetries
Separation of amplitudes

- reversal of charge and spin

Asymmetry of interference term

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

Asymmetry of DVCS

\[
A_{LU}^{DVCS}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{\leftrightarrow}) \odot (d\sigma^{\rightarrow\rightarrow} - d\sigma^{\rightarrow\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{\leftrightarrow}) + (d\sigma^{\rightarrow\rightarrow} + d\sigma^{\rightarrow\leftarrow})}
\]
Separation of amplitudes

- reversal of charge and spin
- Fourier analysis of azimuthal modulation

Interference term asymmetrie

\[ \mathcal{A}_{LU}^{I}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) \bigotimes (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})} \]

\[ = \frac{-K_{I}}{\mathcal{P}_{1}(\phi)\mathcal{P}_{2}(\phi)} \left[ \sum_{n=1}^{2} s_{n}^{1} \sin(n\phi) \right] \]

\[ = \frac{K_{BH}}{\mathcal{P}_{1}(\phi)\mathcal{P}_{2}(\phi)} \sum_{n=0}^{2} c_{n}^{BH} \cos(n\phi) + \frac{1}{Q^2} \sum_{n=0}^{2} c_{n}^{DVCS} \cos(n\phi) \]
### Access to GPD H, $\tilde{H}$, E

- **JHEP 11 (2009) 083**
- **Nucl. Phys. B829**
- **JHEP 06 (2008) 066**
- **JHEP 06 (2010) 019**
- **Nucl. Phys. B 842**

#### HERMES DVCS

<table>
<thead>
<tr>
<th>Amplitude Value</th>
<th>$\text{Re}(H)$</th>
<th>$\text{Im}(H)$</th>
<th>$\text{Re}(\tilde{H})$</th>
<th>$\text{Im}(\tilde{H})$</th>
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</thead>
<tbody>
<tr>
<td>$e^{+/-}$</td>
<td>$A_C^{\cos(0)}$</td>
<td>$A_C^{\sin(\phi)}$</td>
<td>$A_{LU,\text{DVCS}}$</td>
<td>$A_{L,\text{DVCS}}^{\sin(\phi)}$</td>
</tr>
<tr>
<td>$e_{RL/L}$</td>
<td>$A^{\cos(\phi)}$</td>
<td>$A^{\sin(\phi)}$</td>
<td>$A_{LT,\text{DVCS}}^{\cos(\phi)}$</td>
<td>$A_{LT,I}^{\sin(\phi)}$</td>
</tr>
<tr>
<td>$p_{\perp}$</td>
<td>$A_{UT,I}^{\cos(\phi)}$</td>
<td>$A_{UT,I}^{\sin(\phi)}$</td>
<td>$A_{LT,I}^{\cos(\phi)}$</td>
<td>$A_{LT,I}^{\sin(\phi)}$</td>
</tr>
<tr>
<td>$e_{RL/L}p_{\perp}$</td>
<td>$A_{UL}^{\cos(\phi)}$</td>
<td>$A_{UL}^{\sin(\phi)}$</td>
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<tr>
<td>$p_{RL/L}$</td>
<td>$A^{\cos(\phi)}$</td>
<td>$A^{\sin(\phi)}$</td>
<td>$A^{\cos(\phi)}$</td>
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<tr>
<td>$e_{RL/L}p_{RL/L}$</td>
<td>$A^{\cos(\phi)}$</td>
<td>$A^{\sin(\phi)}$</td>
<td>$A^{\cos(\phi)}$</td>
<td>$A^{\sin(\phi)}$</td>
</tr>
</tbody>
</table>

*Sensitive to $J_u$*
HERMES recoilet detector

- Kinematic fit of complete DVCS event: $e p \rightarrow e' p' \gamma$
  - $e'$: spectrometer
  - $\gamma$: calorimeter
  - $p'$: recoil detector
- >99.9% purity

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Beam helicity asymmetry with/without recoil detection

HERMES PRELIMINARY 2006/07 data

3.4% scale uncertainty

$e^+ p \rightarrow e^+ p \gamma$

HERMES: $<Q^2>=2.46 \text{ GeV}^2$,
$<x_B>=0.10$, $<-t>=0.12 \text{ GeV}^2$

- Indication of $A(ep\rightarrow ep\gamma) > A(\text{no Recoil})$.
- Extraction of $A(\text{resonant})$ subject of an ongoing dedicated analysis.

fraction of $ep\rightarrow ep\gamma$

$ep\rightarrow e\Delta\gamma$
HERMES: Conclusion and Outlook

- GDPs are THE access to the nucleon structure
- HERMES is a pioneering experiment of DVCS
- Many more results from HERMES:
  - nuclear DVCS
  - exclusive meson production
  - ...

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PANDA: an experiment with time-reversed protons

... from spectroscopy to internal structure...
Time reversal / crossed diagrams

Scattering

Annihilation

Transition Distribution Amplitudes

Generalized Parton Distributions

Generalized Distributions Amplitudes
Measure GDAs at PANDA

Predictions and simulations in the QCD handbag approach

\[ p\bar{p} \rightarrow \gamma\gamma \]

\[ p\bar{p} \rightarrow \gamma\pi^0 \]

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Another Ansatz: Transition Distribution Amplitudes (TDA)

\[ p\bar{p} \rightarrow \gamma\gamma^* \rightarrow \gamma e^+e^- \]

and

\[ p\bar{p} \rightarrow \pi^0\gamma^* \rightarrow \pi^0 e^+e^- \]

Whatever the theory is ... ... PANDA should measure it

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Data taking >2018?

Disc DIRC is designed in Giessen
Highest luminosities needed for GDAs ... not before ... 202X
AFP at ATLAS

... ATLAS forward protons...
GPDs at LHC

diffractive Higgs production (~120-1200 GeV)
Diffractive Physics at LHC

1/3 of events at LHC are diffractive: rich physics
- more effort is needed to understand it

\[ pp \to p + \gamma\gamma + p \]
ATLAS Forward Detectors

LUCID

ZDC in TAN

ALFA

AFP: 220m, 420m

Scattered Proton Tagging Region

\[ \eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right) \]

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Hamburg Beam Pipe

Moveable beam pipe with pockets to replace "Roman Pots"

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Cherenkov timing detectors

Quartz bars
Quartz fibres

10 ps time resolution needed to reconstruct vertex position at ATLAS IP within 2 mm
ALFA detector at +/- 240 m from ATLAS

ALFA hit map y vs x minimum bias trigger

ALFA fibre detector made in Giessen

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First elastic pp-data from the ALFA detector at ATLAS/LHC at $E=7$ TeV

**ALFA hit maps y vs x**
- minimum bias trigger
- coincidence trigger

**ALFA y-postion west vs east**

**Beam optics:** $\beta^*=90m$

*June 28th, 2011*

**Elastic proton scattering:**
- Proton stays intact after collision at 7 TeV

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Conclusions and Outlook

- New concepts of GPDs, Double Distributions, etc. are used to describe hard exclusive reactions, especially DVCS asymmetries.
- HERMES and JLab have done first explorative measurements of the orbital angular momentum of quarks in the proton.
- Results are consistent with models of the nucleon and with lattice QCD calculations.
- GPDs are also important for experiments at FAIR and LHC.
- PANDA will measure crossed processes.
- ATLAS will measure hard diffractive processes.
- A precision mapping of GPDs requires a polarized high luminosity ep-collider, EIC, e.g. at FAIR.
Thanks to …

- my group in Giessen
- my collaborators at HERMES, PANDA, ATLAS
- especially thanks for plots and transparencies from Ji, I. Brodski, Riedl, Yaschenko, Stenzel, and others …
- and the organizers for inviting me here