towards a 3D imaging of hadrons: GPDs

- a brief introduction (an experimentalists point of view)
- a personal selection of recent results
- models & data
- conclusion & perspectives
nucleon studied for decades:

form factors
location of partons in nucleon

parton distributions
longitudinal momentum fraction $x$

generalised parton distributions (GPDs)
longitudinal momentum fraction $x$ at transverse location $b_\perp$

only known framework to gain information on 3D picture of hadrons
why GPDs?

→ **3D structure of hadrons**: nucleon tomography
nucleon tomography

[M. Burkardt, M. Diehl 2002]

$FT(GPD)$: momentum space $\rightarrow$ impact parameter space:
probing partons with specified long. momentum @transverse position $b_\perp$

**polarised nucleon:**

- **u-quark**
- **d-quark**

From lattice
why GPDs?

→ 3D structure of hadrons: nucleon tomography

→ complementary to TMDs:

Wigner distribution: ("mother" function)

\[ W_p^u(\vec{r}, k) \]

probability to find a quark \( u \) in a nucleon \( P \) with a certain polarisation in a position \( r \) and momentum \( k \)

→ phenomena of single-spin asymmetries
what do we know about GPDs?

form factors

$$\sum_q e_q \int dx H^q(x, \xi, t) = F_1(t)$$

PDFs

$$H^q,g(x,0,0) = q(x)$$
$$\tilde{H}^{q,g}(x,0,0) = \Delta q(x)$$

$$E, \tilde{E} : \text{nucleon helicity flip} \rightarrow \text{don't appear in DIS}$$
$$\rightarrow \text{new information}$$

appear in factorisation theorem for hard exclusive processes
what do we know about GPDs?

\[ Q^2, t << \]

appear in factorisation theorem for hard exclusive processes

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

form factors

PDFs

\[ x \neq x_{Bj}, \quad \xi \sim x_{Bj} \]

\[ x \xi \]

anti-quarks

qq-pair

quarks

\[ x \]

\[ -1, -\xi, 0, \xi, +1 \]
GPDs and the spin puzzle

**nucleon spin:**

\[ S_z^n = \frac{1}{2} = \frac{1}{2} \sum_q \Delta q + L_z^q + \Delta G + L_z^g = J_q + J_g \]

\[ \approx 30\% \]

\[ \approx \text{zero} \]

[X. Ji, 1997]

\[ J_{q,g} = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} x dx \left[ H_{q,g}^q (x, \xi, t) + E_{q,g}^q (x, \xi, t) \right] \]

\[ E^q \neq 0 \quad \text{requires orbital angular momentum} \]

proton helicity flipped but quark helicity conserved
how to access GPDs?
how to access GPDs?

quantum number of final state selects different GPDs:

- VM (ρ, ω, φ): H, E
- PS mesons (π, η): ̃H, ̃E
- DVCS (γ): H, E, ̃H, ̃E

<table>
<thead>
<tr>
<th>meson</th>
<th>GPDs</th>
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<tbody>
<tr>
<td>π^0</td>
<td>2Δu+Δd</td>
</tr>
<tr>
<td>η</td>
<td>2Δu−Δd</td>
</tr>
<tr>
<td>ρ^0</td>
<td>2u+d, 9g/4</td>
</tr>
<tr>
<td>ω</td>
<td>2u−d, 3g/4</td>
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<tr>
<td>φ</td>
<td>s, g</td>
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<tr>
<td>ρ^+</td>
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<tr>
<td>J/ψ</td>
<td>g</td>
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→ DVCS most clean process for gaining information on GPDs
→ meson provide info on quark flavours
  VM: quark and gluon GPDs appear at same order α_s

deeply virtual Compton scattering
wide angle Compton scattering
form factors
orbital angular momentum transverse localisation

lattice

exclusive meson production deep virtual / large t
deep inelastic scattering PDFs

ρ̅̅̅̅ annihilation γ → ππ, ...
timelike Compton scattering

→ DVCS most clean process for gaining information on GPDs
→ meson provide info on quark flavours
  VM: quark and gluon GPDs appear at same order α_s
accessing GPDs: caveats

- $H(x, \xi, t)$ but only $\xi$ and $t$ accessible experimentally
- $x$ is mute variable (integrated over):
  - apart from cross-over trajectory ($\xi = x$) GPDs not directly accessible: deconvolution needed! (model dependent)
  - GPD moments cannot be directly revealed, extrapolations $t \to 0$ are model dependent

\[ T^{DVCS} \sim \int_{-1}^{+1} H(x, \xi, t) \frac{dx}{x \pm \xi + i\varepsilon} + \ldots \]

\[ \sim P \int_{-1}^{+1} H(x, \xi, t) \frac{dx}{x \pm \xi} + i\pi H(\pm \xi, \xi, t) + \ldots \]

cross sections & beam-charge asymmetry $\sim \text{Re}(T^{DVCS})$
beam or target-spin asymmetries $\sim \text{Im}(T^{DVCS})$
the ideal experiment for measuring hard exclusive processes
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- high+variable beam energy
  - hard regime
  - wide kinematic range

- high luminosity
  - small cross sections
  - measure in 3 kinematic variables simultaneously

- complete event reconstruction
  - ensure exclusivity

... doesn’t exist (yet)...
the menu

- data from exclusive VM over wide kinematic range
  - JLab $\rightarrow$ HERMES $\rightarrow$ COMPASS $\rightarrow$ HERA-collider
    $\rightarrow$ role of quarks and gluons
    $\rightarrow$ NLO corrections

- exclusive PS mesons production
  $\rightarrow$ role of power corrections

- DVCS: from first signals $\rightarrow$ detailed measurements

reminder: for meson production factorisation only for $\sigma_L$ ($\sigma_T$ suppressed by $1/Q^2$)
VM production @small x

$W$ & $t$ dependences: probe transition from soft $\rightarrow$ hard regime

$\sigma \sim W^\delta$

$\rightarrow$ steeper energy dependence of $\sigma$ with increasing hard scale
**VM production @small x**

$W$ & $t$ dependences: probe transition from soft $\rightarrow$ hard regime

$\sigma \sim e^{-b|t|}$

$\rightarrow$ universality of b-slope parameter: point-like configurations dominate
VM production: small $\rightarrow$ high $x$

- $\times_B$: $10^{-3}$ to $0.2$ to $0.5$

  - HERA-collider: $g+(\text{sea})$
  - COMPASS/HERMES: $g+(\text{sea})+q_v(\rho,\omega)$
  - JLab: $q_v(\rho,\omega)$

- NLO corrections to VM production are large: [M. Diehl, W. Kugler arXiv0708.1121]

- $\rho^0$ cross section @typical kinematics of compass / hermes / jlab12
VM production: small \( \rightarrow \) high \( x \)

\[ 10^{-3} \quad 10^{-1} \quad 0.2-0.5 \]

\[ x_{\text{Bj}} \]

HERA-collider  \( g+(\text{sea}) \)

COMPASS/HERMES  \( g+(\text{sea})+q_{v}(\rho,\omega) \)

JLab  \( q_{v}(\rho,\omega) \)

- ...despite: LO GPD model (handbag fact.) [S. Goloskokov, P. Kroll arXiv0711.4736]

- LO+power corrections

\( Q^2=3.8 \text{ GeV}^2 \)

\( \rho^0 \)

\( \sigma (\rho,\rho') \) [nb]
VM production: small $\rightarrow$ high $x$

$10^{-3}$ | $10^{-1}$ | $0.2$-$0.5$  
HERA-collider | COMPASS/HERMES | JLab  
g+(sea) | g+(sea)+$q_v\,(\rho,\omega)$ | $q_v\,(\rho,\omega)$

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• LO+power corrections
deeply virtual compton scattering

DVCS

\[ \rightarrow H, \tilde{H}, E, \tilde{E} \]

most clean channel for interpretation in terms of GPDs (full factorisation proof)

@HERMES/JLab:

DVCS << Bethe-Heitler

\[
\frac{d^4\sigma}{dx_B dQ^2 dt d\phi} \propto |T_{DVCS} + T_{BH}|^2 = |T_{DVCS}|^2 + |T_{BH}|^2 + T_{DVCS}^* T_{BH}^* + T_{DVCS}^* T_{BH}
\]

\[ \rightarrow \text{leads to non-zero azimuthal asymmetries:} \]
DVCS @amplitude level

\[ d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH}) \]

\[ I \sim \Delta \sigma \]

\[ \Delta \sigma_C \sim \cos\phi \cdot \text{Re}\{H + \tilde{\xi}H + \ldots\} \]

\[ \Delta \sigma_{LU} \sim \sin\phi \cdot \text{Im}\{H + \tilde{\xi}H + kE\} \]

\[ \Delta \sigma_{UL} \sim \sin\phi \cdot \text{Im}\{\tilde{H} + \tilde{\xi}H + \ldots\} \]

\[ \Delta \sigma_{UT} \sim \sin(\phi - \phi_S)\cos\phi \cdot \text{Im}\{k(H - E) + \ldots\} \]

\(\xi = x_B/(2-x_B), k = t/4M^2\) kinematically suppressed @HERMES and JLab energies

\(\to\) different charges: e\(^+\) e\(^-\) (only @HERA!):

\(\to\) polarisation observables:
first DVCS signals: $A_{LU}$

-- from interference term --

[PRL87(2001)]

$\sin \phi$ dependence indicates dominance of handbag contribution
call for high statistics

**JLab:** E1-DVCS beam-spin asymmetry

Integrated over $t$

3D binning in $x$, $Q^2$ and $t$
call for new analysis methods

HERMES: combined analysis of charge & polarisation dependent data

→ separation of interference term + DVCS²

\[
\sigma_{LU}(\phi; P_1, e_1) = \sigma_{UU}(\phi) \cdot \left\{ 1 + P_1 A_{LU}^{DVCS}(\phi) + e_1 P_1 A_{LU}^{I}(\phi) + e_1 A_C(\phi) \right\}
\]

\[
\sum_{n=1}^{2} s_n \sin(n\phi) + \sum_{n=0}^{3} c_n \cos(n\phi)
\]
call for new analysis methods

**HERMES**: combined analysis of charge & polarisation dependent data

→ separation of interference term + DVCS$^2$

**GPD models**: VGG

- w/o D-term
- with D-term

**dual**

- regge-ansatz for t-dependence
- factorised t-dependence

[Guzy, Teckentrup 2006]
call for new analysis methods

**HERMES:** combined analysis of charge & polarisation dependent data

→ separation of interference term + DVCS$^2$

**beam spin asymmetry:** HERMES preliminary

$\propto \text{Im}[F_1 H]$

**GPD models:** VGG

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a word about GPD models

**VGG:** [Vanderhaegen, Guichon, Guidal 1999]

- double distributions; factorised or regge-inspired t-dependence
- D-term to restore full polynomiality
- skweness depending on free parameters $b_{val}$ & $b_{sea}$
- includes tw-3 (WW approx)

**dual:** [Guzey, Teckentrup 2006]

- GPDs based on infinite sum of t channel resonances
- factorised or regge-inspired t-dependence
- tw-2 only
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→ describes well $A_c$ and $A_{UT}$ data
→ fails for $A_{LU}$
→ $A_c$ favour ‘no D-term’ ← contradicts $\chi$ QSM & lattice results

→ call for new, more sophisticated parametrisations of GPDs

... more models on the way: e.g. generalisation of Mellin transform technique
...nevertheless: first attempts to constrain $J_q$

observables sensitive to $E$:
($J_q$ input parameter in ansatz for $E$)

$$J_q = \frac{1}{2} \int_{-1}^{1} x \, dx \left( H^q + E^q \right)$$

• DVCS $A_{UT}$ : HERMES
• nDVCS $A_{LU}$ : Hall A
• $\rho^0 A_{UT}$ : HERMES
...nevertheless: first attempts to constrain $J_q$

$J_q$ input parameter in ansatz for $E$:
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$J_q$ input parameter in ansatz for $E$:

![Diagram showing $A_{UT}$ and $\text{Im}(C_n)$ as functions of $Q^2$ and $x_B$, with different $J_q$ values depicted.

$A_{UT,1}$

$J_u = 0.4$  $J_d = 0.2$

$J_u = 0.3$

$J_u = 0.6$

$J_d = 0.8$

VGG

HallA nDVCS $A_{LU}$

[PR99(2007)]
...nevertheless: first attempts to constrain $J_q$

$J_q$ input parameter in ansatz for $E$:

- demonstrates model dependence of these analyses
- data are free to be reused at any time with new models 😊
conclusions

**GPDs** contain a wealth of new information on hadron structure at parton level → only known framework allowing a 3D imaging of hadrons ⬅️

... BUT they are intricate functions...

complementary to **TMDs**: relations **GPDs** ⬅️→ **TMDs** [M. Burkardt, M. Schlegel]

**GPDs** offer a way to measure transversity!

- increasing amount and precision of experimental data
- large “flow” of new data expected soon (JLab, HERMES, COMPASS)
- ‘standard’ models/parametrisations of GPDs too simple
  → models should describe large variety of different observables over wide kinematic range

prior to any conclusion about GPDs from data: call for new, more sophisticated parametrisations
perspectives for GPDs

@ new facilities:

- high beam energy (hard regime, wide kinematic range)
- very high luminosity (small xsections, multi-D analyses)
- complete event reconstruction (ensure exclusivity)

→ exploration of new channels: WACS, time like DVCS, ...

→ ideas for accessing GPDs @LHC, @GSI, ...

“gold rush” for studying hard exclusive processes & GPDs

“extraction” of GPDs requires filling the gap in kinematic coverage
perspectives for GPDs & TMDs

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