Delia Hasch

hunting the OAM @

- a brief introduction
- GPDs & OAM
- observables: $A_{UT}$ in DVCS & exclusive $\rho^0$
- conclusion & perspectives

workshop on Partonic Transverse Momentum in Hadrons, DUKE-University, March 12/13, 2010
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]

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

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

proton helicity flipped but quark helicity conserved
**GPDs: nucleon tomography**

[M. Burkardt, M. Diehl 2002]

$FT(GPD)$: momentum space $\rightarrow$ impact parameter space:

distribution of partons in plane transverse to longitudinal momentum $x$

**polarised nucleon:** spin-orbit correlations (TMDs)

u-quark

d-quark

from lattice [QCDSF]
TMDs $\leftrightarrow$ GPDs

3D structure of hadrons: nucleon tomography

$\rightarrow$ complementary:

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 $k$

$\rightarrow$ relations between TMDs and GPDs (?)

see talk by L.Gamberg
spin-orbit correlations @

Sivers fct., Boer-mulders fct., pretzelosity

see talk by N. Makins

\( \Delta L = 1 \)

\( \Delta L = 1 \)

\( \Delta L = 2 \)
what do we know about GPDs?

$Q^2$, $t <<$ appear in factorisation theorem for hard exclusive processes.

$H(x, \xi, t)$, $x \neq x_{Bj}$, $\xi \sim x_{Bj}$

- **form factors**
  - $\sum_q e_q \int dx \, H^q(x, \xi, t) = F_1(t)$
  - $\ldots$

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

$E, \tilde{E}$: nucleon helicity flip → don’t appear in DIS
  → new information!
GPDs: caveats

\[
T_{\mu\nu} = \left[ \mathcal{H}, \mathcal{E}, \mathcal{H}, \mathcal{E} \right] (\xi, t, Q^2),
\]

\[
\mathcal{F}(\xi, t, Q^2) = \int_{-1}^{1} dx \, C^- (\xi, x) \, F(x, \xi, t, Q^2).
\]

- \(x\) is mute variable (integrated over):
  - apart from cross-over trajectory (\(\xi = x\)) GPDs not directly accessible
- extrapolation \(t \rightarrow 0\) is model dependent

\(\Rightarrow\) double DVCS: \(|x| < \xi\)

Cross sections & beam-charge asymmetry \(\sim \text{Re}(T^{DVCS})\)

Beam or target-spin asymmetries \(\sim \text{Im}(T^{DVCS})\)
attempts to constrain $J_q$

$$J_q = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} x dx \left[ H^q(x, \xi, t) + E^q(x, \xi, t) \right]$$

GPD models: $J_q$ free parameter in ansatz for $E$

observables sensitive to $E$:

- DVCS $A_{UT}$: HERMES
- nDVCS $A_{LU}$: Hall A
- excl. $\rho^0$ $A_{UT}$: HERMES, COMPASS

$A_{UT}$

beam target

U, L U, T

Unpolarised
Longitudinally
Transversely polarised
deeply virtual compton scattering

@HERMES, JLab:

DVCS $<<$ Bethe-Heitler

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

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

→ different charges: \( e^+ e^- \)

\[ d\sigma(e^+, \phi) - d\sigma(e^-, \phi) \propto \text{Re}[F_1 \mathcal{H}] \cdot \cos \phi \]
DVCS interference term

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

→ different charges: \(e^+ e^-\)

\[ d\sigma(e^+, \phi) - d\sigma(e^-, \phi) \propto \text{Re}[F_1 \mathcal{H}] \cdot \cos \phi \]

→ polarisation observables:

- beam spin asymmetry \(A_{LU}\):
  \[ d\sigma(\bar{e}, \phi) - d\sigma(\bar{e}, \phi) \propto \text{Im}[F_1 \mathcal{H}] \cdot \sin \phi + \ldots \]

- longitudinal target spin asymmetry \(A_{UL}\):
  \[ d\sigma(\bar{P}, \phi) - d\sigma(\bar{P}, \phi) \propto \text{Im}[F_1 \tilde{\mathcal{H}}] \cdot \sin \phi + \ldots \]

- transverse target spin asymmetry \(A_{UT}\):
  \[ d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi) \propto \text{Im}[F_2 \mathcal{H} - F_1 \mathcal{E}] \cdot \sin (\phi - \phi_S) \cos \phi + \text{Im}[F_2 \tilde{\mathcal{H}} - F_1 \tilde{\mathcal{E}}] \cdot \sin (\phi - \phi_S) + \ldots \]

\([F_1, F_2: \text{Pauli and Dirac FF, } \mathcal{H}, \mathcal{E}, \tilde{\mathcal{H}}, \tilde{\mathcal{E}}: \text{Compton FF: moments of corresponding GPDs }\]
sensitivity to $E$ ($J_q$) from both interference and DVCS$^2$ term:

$$
\sigma(\phi, P_\ell, S_T) = \sigma_{UU}(\phi) \times \left[ 1 + S_T A_{UT}^{DVCS}(\phi, \phi_s) + S_T e_\ell A_{UT}^I(\phi, \phi_s) + e_\ell A_C(\phi) \right]
$$

$$
A_{UT}^I(\phi, \phi_S) = \sum_{n=0}^{2} A_{UT,I}^{\sin(\phi-\phi_S) \cos(n\phi)} \sin(\phi - \phi_S) \cos(n\phi)
$$

$$
+ \sum_{n=1}^{2} A_{UT,I}^{\cos(\phi-\phi_S) \sin(n\phi)} \cos(\phi - \phi_S) \sin(n\phi)
$$

analogous modulations for DVCS$^2$ term

$n = 0, 1$ terms found to be most sensitive to values of $J_u$
attempts to constrain $J_q$

$J_q$ free parameter in ansatz for $E$

separate contributions from DVCS and interference terms:

\[ J_d = 0 \]

[JHEP06(2008)]

[VGG]
attempts to constrain $J_q$

$J_q$ free parameter in ansatz for $E$

difference of polarised cross sections on LH$_2$ & LD$_2$ $\rightarrow$ nDVCS: [PRL99(2007)]

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

\textbf{p target: } $C^I_n \sim \mathcal{H}$

\textbf{n target: } $C^I_n \sim \mathcal{E}$  $\rightarrow$ $F_1$ small

$\rightarrow$ cancellation between $u$ and $d$ quark pol. pdfs in $\tilde{\mathcal{H}}$
attempts to constrain $J_q$

$J_q$ free parameter in ansatz for $E$

difference of polarised cross sections on LH$_2$ & LD$_2$ → nDVCS: [PRL99(2007)]

\[
\frac{1}{2}\left(\frac{d^4\sigma^{+}}{dQ^2 dx_B dtd\phi_{\gamma\gamma}} - \frac{d^4\sigma^{-}}{dQ^2 dx_B dtd\phi_{\gamma\gamma}}\right) \text{ (nb/GeV$^4$)}
\]

**VGG**: tw-2 CFF
attempts to constrain $J_q$

$J_q$ free parameter in ansatz for $E$

difference of polarised cross sections on LH$_2$ & LD$_2$ $\rightarrow$ nDVCS: [PRL99(2007)]
A word about ‘user friendly’ GPD models

**VGG**: [Vanderhaegen, Guichon, Guidal 1999]
- double distributions [Radyshkin]; factorised or regge-inspired t-dependence
- D-term to restore full polynomiality
- skewness depending on free parameters $b_{\text{val}}$ & $b_{\text{sea}}$
- includes tw-3 (WW approx)

**Dual**: [Guzey, Teckentrup 2006, 2009]
- GPDs based on infinite sum of t channel resonances (minimal: truncated $k=\{0,2\}$)
- factorised or regge-inspired t-dependence
- tw-2 only

→ more models & new approaches [... an incomplete list]
- polynomials [Belitsky etal.(00), Liuti etal.(07), Moutarde(09)]
- analytical [Belitsky, Muller, Kirchner(01)]
- dispersion integral fits & flexible GPD modelling [Kumericki, Muller(08,09)]
a word about ‘user friendly’ GPD models

VGG: [Vanderhaegen, Guichon, Guidal 1999]
  • double distributions [Radyshkin]
  • D-term to restore full polynomiality
  • skewness depending on free parameters
  • includes $t$-tw-3 (WW approx)

Dual: [Guzey, Teckentrup 2006, 2009]
  • GPDs based on infinite sum of $t$ channel resonances
    (minimal: truncated $k=0,2$)
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→ more models & new approaches

  • polynomials [Belitsky et al.(00), Liuti et al.(07), Moutarde(09)]
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→ describes well beam charge & target spin asymmetries
→ fails for beam spin asymm. & cross sections
→ charge asymm. favours ‘no D-term’ ← contradicts
  $\chi$QSM & lattice results

→ describes well kinematic dependencies of beam
  charge & beam spin asymmetries
→ after correction in calculations: magnitude off by
  factor 2-4
...nevertheless: constraining $J_q$

$J_q$ free parameter in ansatz for $E$

- highly model dependent extraction !!!

[NOTE: uncorrected Dual !]

[VGG]

- data are free to be re-used at any time with new models 😊
exclusive $\rho^0$ production

$$A_{UT}^{\gamma_L^*}(\phi, \phi_s) \propto \frac{\text{Im}(\mathcal{E}_\rho^* \mathcal{H}_\rho)}{|\mathcal{H}_\rho|^2} \propto \frac{\mathcal{E}_\rho}{|\mathcal{H}_\rho|}$$
exclusive $\rho^0$ production

after the full glory of transverse SDME extraction [formalism: M. Diehl (2007)] :

$(\gamma_L^* \rightarrow \rho^0_L)$:

\[ A^\gamma^*_{UT}(\phi, \phi_s) = \frac{\text{Im} n_{00}^{00}}{u_{00}} \]

\[ \rho^0 \]

\[ \mathcal{N}_{\mu\mu'}^{\nu\nu'} \]

$\mu, \nu = 0, \pm 1$

long.pol: 0
transv.pol: $\pm 1$

$\gamma^*$

\[ <Q^2> = 2.0 \text{ GeV}^2 \]
\[ <x> = 0.09 \]
\[ <t'> = 0.13 \text{ GeV}^2 \]

→ more data coming: COMPASS, CLAS12 with transverse target
→ more models: Goloskokov, Kroll (09)
lattice’s opinion about $J^q$

\[ J^u = 0.236(6) \approx 47\% \text{ of } 1/2 \]
\[ J^d = 0.0018(37) \approx 1\% \text{ of } 1/2 \]

\[ J^{u+d} \approx 0.238 \pm 0.008 \approx 48\% \text{ of } 1/2 \]

[MS at 4 GeV$^2$]

[P. Hägeler et al. 2009]
lattice’s opinion about $J^q \to L^q$

\[ L^d \approx -L^u \approx 0.185 \pm 0.06 \approx 36\% \text{ of } 1/2 \]
\[ L^u + d \approx 0.030 \pm 0.012 \approx 6\% \text{ of } 1/2 \]
conclusion

presence of OAM w/o debate → how to measure it?

- **GPDs**: only known framework to *quantify OAM* [Ji - SR]
  - we got an idea how to measure it but still a long way to go:
    - → more data needed over a much wider kinematic range
    - → call for more sophisticated GPD models & new approaches

- prior to any interpretation of data: what is OAM? [M. Burkardt, ...]

- **complementary information from TMDs**:
  - role of transverse momenta & *spin-orbit correlations*

**GPDs** — a much wider concept: nucleon *tomography*
  - → correlated information on longitudinal momentum fraction of quarks and their
    spatial distribution in the transverse plane → multi-D picture

relations **GPDs** ↔ **TMDs**?
perspectives

hunting the OAM

contribution to nucleon spin:
• determination of $\Delta \Sigma$ and $\Delta G$ → missing piece attributed to OAM

quest for $\Delta G$:
• from scaling violation of $g_1$
• charm production & high pT hadrons over wide $x_B$ range

'direct' measurement via Ji-SR (GPDs)
spin-orbit correlations from TMDs
backup
DVCS @ HERMES

- Beam charge asymmetry
  \[ \text{Re}\mathcal{H} \]

- Beam spin asymmetry
  \[ \text{Im}\mathcal{H} \]

- Transverse target spin asymmetry
  \[ \text{Im}(\mathcal{H} \mathcal{E}) \]

- Longitudinal target spin asymmetry
  \[ \text{Im}\widetilde{\mathcal{H}} \]

- Double spin asymmetry
  \[ \text{Re}\widetilde{\mathcal{H}} \]
exclusive $\rho^0$ production
exclusive meson production

GPD model: Goloskokov, Kroll

\[ W = 5 \text{ GeV} \quad Q^2 = 3 \text{ GeV}^2 \]

variant 1, 2, 3, 4