Delia Hasch

GPDs

-- status of measurements --

- a very brief introduction
- prerequisites and methods
- DVCS & DVMP: selected results
- on the way to an EIC

→ see additional slides for results not covered

why GPDs?

‘spin puzzle’

\[ s_z = \frac{1}{2} = J^q + J^g = \frac{1}{2} \sum_q \Delta q + L^q_z + \Delta g + L^g_z \]

\[ \approx 30\% \]

\[ \approx \text{zero} \]

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

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

[\text{[X. Ji (1996)]}]

proton helicity flipped while quark helicity is conserved
why GPDs?

‘spin puzzle’

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[nucleon imaging:

FT (GPD) \rightarrow \text{impact parameter space } b \perp : \text{spatial distribution in}

transverse plane

(transverse distance from

proton center of momentum)

\[ x \approx 0.003 \quad x \approx 0.03 \quad x \approx 0.3 \]

[fig: courtesy C. Weiss]

[M. Burkardt(2001), M. Diehl(2002)]
how to constrain GPDs?

appear in factorisation theorem for hard exclusive processes

$Q^2 \gg, t \ll$

$H(x, \xi, t)$

$x \neq x_{Bj}$

$\xi \sim x_{Bj}$
how to constrain GPDs?

- **spin $\frac{1}{2}$ target:**
  - 4 leading-tw, chiral even $q$ & $g$ GPDs: $H, \tilde{H}$ conserve nucleon helicity
  - $E, \tilde{E}$ involve nucleon helicity flip
  - + 4 chiral odd (‘transversity’) GPDs, which flip the parton helicity

\[ H(x, \xi, t) \quad x \neq x_{Bj} \quad \xi \sim x_{Bj} \]

$Q^2 \gg$, $t \ll$

appear in factorisation theorem for hard exclusive processes

- $\gamma^* L$
how to constrain GPDs?

Q^2 \ggg, t \lll

appear in factorisation theorem for hard exclusive processes

***DVCS***: most clean process, (some) flavour dependent information from p & n target OR: *evolution*

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

\[ x \neq x_{Bj} \]

\[ \xi \sim x_{Bj} \]

\[ \rightarrow H, \tilde{H}, E, \tilde{E} \]
how to constrain GPDs?

- **DVCS**: most clean process, (some) flavour dependent information from p & n target OR: *evolution*

- **DVMP**: flavour decomposition & gluons

Q^2 >>, t <<

appear in factorisation theorem for *hard exclusive* processes

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

\[ x \neq x_{Bj} \]

\[ \xi \sim x_{Bj} \]

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

VM \rightarrow H, E

PS \rightarrow \tilde{H}, \tilde{E}, \tilde{H}_T, \tilde{E}_T
how to constrain GPDs?

- **DVCS**: most clean process, (some) flavour dependent information from p & n target OR: evolution

- **DVMP**: flavour decomposition & gluons

\[ Q^2 \ggg, t \ll \]

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

\[ x \neq x_{Bj} \]

\[ \xi \sim x_{Bj} \]

\[ \gamma, p^0, \pi, \ldots \]

\[ Q^2 \]

\[ e', e \]

\[ N, N' \]

\[ x + \xi, x - \xi \]

\[ x_{Bj} \]

\[ \phi, \rho^0, \rho^+, J/\psi \]

<table>
<thead>
<tr>
<th>Particle</th>
<th>Quark Combinations</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho^0 )</td>
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</tr>
<tr>
<td>( \omega )</td>
<td>2u−d, 3g/4</td>
</tr>
<tr>
<td>( \phi )</td>
<td>s, g</td>
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how to constrain GPDs?

- **DVCS**: most clean process, (some) flavour dependent information from p & n target OR: evolution
- **DVMP**: flavour decomposition & gluons

**BUT**
- factorisation only for $\sigma_L$
- meson distribution amplitude needed
- large NLO & power corrections

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link GPDs & observables

\[ T_{\mu\nu} = \left[H, \mathcal{E}, \bar{H}, \mathcal{E}\right](\xi, t, Q^2), \quad F(\xi, t, Q^2) = \int_{-1}^{1} dx \, C^{-}(\xi, x) F(x, \xi, t, Q^2), \]

complex DVCS amplitude \quad \text{Compton Form Factor (CFF)}

- \( x \) is mute variable (integrated over), needs deconvolution
  \( \Rightarrow \) apart from ‘cross over’ trajectory \( (x = \pm \xi) \) GPDs not directly accessible
- extrapolation \( t \to 0 \) model dependent

\[ \mathcal{H}(x, \xi, 0) \]

- cross section & beam charge asymmetry \( \sim \text{Re}(T^{DVCS}) \):
  \( \text{integral of GPDs over } x \)

- beam or target spin asymmetries \( \sim \text{Im}(T^{DVCS}) \),
  i.e., GPDs @ \( x = \pm \xi \)
link GPDs & observables

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

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

complex DVCS amplitude

Compton Form Factor (CFF)

- $x$ is mute variable (integrated over), needs deconvolution
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- cross section & beam charge asymmetry
  - $\sim \operatorname{Re}(T_{\text{DVCS}})$:
    - integral of GPDs over $x$

- beam or target spin asymmetries
  - $\sim \operatorname{Im}(T_{\text{DVCS}})$,
    - i.e., GPDs @ $x = \pm \xi$

- $x$ scan of GPDs:
  - ‘double’DVCS: JLab12 (?)
  - $Q^2$ evolution: EIC
the ideal experiment for measuring hard exclusive processes

- high & variable beam energy
  - ensure hard regime
  - wide kinematic range
  - L/T separation for ps meson prod.

- high luminosity
  - small cross sections
  - fully differential analysis

- hermetic detectors
  - ensure exclusivity
the ideal experiment for measuring hard exclusive processes

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- high luminosity
  - small cross sections
  - fully differential analysis

- hermetic detectors
  - ensure exclusivity

... doesn’t exist (yet)...

\[ Q^2 >>, t \ll \]
experimental prerequisites

- polarised 27GeV $e^+/e^-$
- unpolarised 920GeV $p$
- $\approx$full event reconstruction

- polarised 27GeV $e^+/e^-$
- long+transv polarised $p$, $d$ targets
- unpolarised nuclear targets
- missing mass technique
- 2006/7 data taken with recoil det.
experimental prerequisites

- **polarised** 27GeV e+/e−
- unpolarised 920GeV p
- ≈full event reconstruction

- **polarised** 27GeV e+/e−
- long+transv polarised p, d targets
- unpolarised nuclear targets
- missing mass technique
- 2006/7 data taken with recoil det.

- highly **polarised**, high lumi 6GeV e−
- long **polarised** effective p, n targets
- **CLAS**: full event reconstruction
- **Hall-A**: missing mass/energy technique
experimental prerequisites

- polarised 27GeV $e^+/e^-$
- unpolarised 920GeV $p$
- ≈ full event reconstruction

- polarised 27GeV $e^+/e^-$
  - long + transv polarised $p$, $d$ targets
  - unpolarised nuclear targets

- missing mass technique
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- highly polarised, high lumi 6GeV $e^-$
  - long polarised effective $p$, $n$ targets
  - CLAS: full event reconstruction
  - Hall-A: missing mass/energy technique

- highly polarised, 160GeV $\mu$
  - long + transv polarised effective $p$, $d$ targets

- missing mass/energy technique
results on /off the menu

data over wide kinematic range: HERA-collider $\rightarrow$ (COMPASS) $\rightarrow$ HERMES $\rightarrow$ JLab

- VM production $\rightarrow H, E$
  - low $x$: gluon imaging
  - high $x$: quarks & gluons; role of NLO contributions
  - low $W$ data from Jlab
  - SDMEs / amplitudes

- ps meson production $\rightarrow \tilde{H}, \tilde{E}, \tilde{H}_T, \tilde{E}_T$
  - role of transverse photons, power corrections & chiral-odd GPDs

- DVCS $\rightarrow H, E, \tilde{H}, \tilde{E}$ ... the golden channel & most rich plate
  - nuclear modification of DVCS amplitudes: HERMES

- hunting the OAM
VM production \@ low $x$

energy dependence probes transition from soft to hard regime

$$d\sigma/dt \sim e^{-b|t|}$$
VM production \textit{at low x}

energy dependence probes transition from soft to hard regime

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

\( \rho, \phi, J/\psi, DVCS \)

\[ Q^2 \rightarrow \text{hard} \]

\[ \rightarrow J/\psi, \phi \]

\[ \rho, \gamma \]

 universality of \( b \) slope parameter

\( \rightarrow \) point like configurations dominate
gluon imaging: $J/\psi$

energy dependence probes hard regime; $FT \rightarrow \text{average impact parameter}$

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

- $FT \rightarrow \text{average impact parameter}$

$$\langle b_{\perp}^2(x_{Bj}) \rangle$$

distance between active quark/gluon and proton center of momentum

[M. Burkardt(2001), M. Diehl(2002)]

[fig: courtesy C. Weiss]
gluon imaging: \( J/\psi \)

energy dependence probes hard regime; \( FT \rightarrow \) average impact parameter

\[
d\sigma/dt \sim e^{-b|t|}
\]

- \( FT \rightarrow \) average impact parameter
  \[
  \langle b_{\perp}^2(x_{Bj}) \rangle
  \]
  distance between active quark/gluon and proton center of momentum

\[Q^2 \rightarrow \text{hard} \rightarrow J/\psi, \phi \rightarrow \rho, \gamma\]

\[
\hat{Q}_{\text{eff}}^2 \approx 3 \text{GeV}^2
\]

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

[Frankfurt, Strikman, Weiss (2011)]

\[Q^2 \rightarrow \text{hard} \rightarrow J/\psi, \phi \rightarrow \rho, \gamma\]

\[
\hat{Q}_{\text{eff}}^2 \approx 3 \text{GeV}^2
\]

\[\langle b_{\perp}^2(x_{Bj}) \rangle
\]

distance between active quark/gluon and proton center of momentum

[M. Burkardt (2001), M. Diehl (2002)]

[fig: courtesy C. Weiss]
\textbf{VM production: from low \( \rightarrow \) high \( x \)}

- \textit{NLO corrections} to VM production are \textit{large} \( @ \) typical kinematics of COMPASS/ HERMES/ CLAS12 \ [M. Diehl, W. Kugler (2007)]

- \textit{... despite, LO GPD model} (handbag fact.; DD ansatz): \ [S. Goloskokov, P. Kroll (2007, 2010)]

\[ + \text{power corrections}\]
VM production: from low $\rightarrow$ high $x$

- **NLO corrections** to VM production are *large* @ typical kinematics of COMPASS/ HERMES/ CLAS12 [M. Diehl, W. Kugler (2007)]

- ... *despite*, LO GPD model (handbag fact.; DD ansatz): [S. Goloskokov, P. Kroll (2007, 2010)]
  + *power corrections*

...does NOT work for low $W$ of CLAS
NLO corrections to VM production are large @typical kinematics of COMPASS/ HERMES/ CLAS12 [M. Diehl, W. Kugler (2007)]

... despite, LO GPD model (handbag fact.; DD ansatz): [S. Goloskokov, P. Kroll (2007, 2010)]

+ power corrections

dominance of gluon exchange contrib.
ps meson production

-- role of power corrections & longitudinal-transverse transitions --

$ep \rightarrow n \pi^+$  $ep \rightarrow p \pi^0$

Hermes  Hall-A
ps meson production

-- role of power corrections & longitudinal-transverse transitions --

\[ \gamma^* p \rightarrow n \pi^+ \]

[PLB659(2008)]

GPD model for \( \frac{d\sigma_L}{dt'} \)

Vanderhaeghen, Guichon, Guidal  PRD60(1999)094017
ps meson production
--- role of power corrections & longitudinal-transverse transitions ---

\[ \gamma^* p \rightarrow n \pi^+ \]

\[ \text{GPD model for } \frac{d\sigma_L}{dt'} \quad \text{leading-order calculations} \]

\[ \text{with power corrections} \]

\[ \text{Regge model} \quad \text{[Laget(2008)]} \]

\[ \sigma_{\text{tot}} \quad \sigma_L \]

\[ \text{need of L/T separation, especially for lower } Q^2, \text{ higher } t \]

\[ 1 < Q^2 < 2 \text{ GeV}^2 \quad 0.02 < x_B < 0.15 \]

\[ 2 < Q^2 < 3 \text{ GeV}^2 \quad 0.06 < x_B < 0.23 \]

\[ 3 < Q^2 < 4 \text{ GeV}^2 \quad 0.11 < x_B < 0.31 \]

\[ 4 < Q^2 < 11 \text{ GeV}^2 \quad 0.15 < x_B < 0.55 \]
\[ ep \rightarrow n \pi^+ \quad A_{UT}^{\sin(\phi-\phi_S)} \]

- arises from pure \( \sigma_L \) contribution
- NLO/power corrections cancel to large extend in asymmetry

[PLB682(2010)]

Curves: GPD model [GK(2009)]
ps meson production
-- role of power corrections & longitudinal-transverse transitions --

\[ ep \rightarrow n \pi^+ \]  \[ A_{UT}^{\sin(\phi - \phi_S)} \]

- arises from pure \( \sigma_L \) contribution
- NLO/power corrections cancel to large extend in asymmetry

\[ \sin(\theta_{UT} - \theta) \sin(\theta_{UT} + \theta) \]

[PLB682(2010)]

\[ A_{UT,1}^{\sin(\phi - \phi_S)} \]

\[ A_{UT,1}^{\sin\phi_S} \]

\( -t^* \) [GeV^2]

\( -t^* \) [GeV^2]

\( A_{UT,1}^{\sin(\phi - \phi_S)} \)

curves: GPD model [GK(2009)]

\( \rightarrow \) significant contribution from L/T interference, need to go beyond leading-tw description
ps meson production

-- role of power corrections & longitudinal-transverse transitions --

\[ ep \rightarrow p \pi^0 \quad A_{LU}^{\sin \phi} \]

\[ \text{any non-zero beam-spin asymmetry indicates L-T interference} \]

\[ ep \rightarrow n \pi^+ \quad [\text{PLB682}(2010)] \]

\[ \Rightarrow \text{significant contribution from L/T interference, need to go beyond leading-tw description} \]
ps meson production

-- role of transversity GPDs --

\[ ep \rightarrow p \pi^0 \]

- cross sections vs \( t \) \( \rightarrow \sigma_T \) parametrized employing transversity GPDs (and assuming factorization)  
  [Goldstein et al. (2011), Goloskokov and Kroll (2011)]

Curves: GPD model calc.s with dominant contributions from transversity GPDs

---

[Goloskokov Kroll(2011)]

[Goldstein et al. (2011)]
Deeply virtual Compton Scattering

![Diagram of DVCS and Bethe-Heitler processes]

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

\(\rightarrow\) bilinear in GPDs  \(\rightarrow\) linear in GPDs
Deeply virtual Compton Scattering

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

\( \rightarrow \) bilinear in GPDs  \( \rightarrow \) linear in GPDs

@H1&Zeus

DVCS \approx \text{Bethe-Heitler}

LO sea quarks + NLO gluons
DVCS

extracted transverse size (as before for VM) \[ [H1, PLB659(2008)] \]

\[
\sqrt{\langle b_T^2 \rangle} = (0.65 \pm 0.02) \text{ fm}
\]

@ \( x_B = 10^{-3} \)

\[ <Q^2> = 8.0 \text{ GeV}^2 \]
DVCS

@H1&ZEUS
DVCS ≈ Bethe-Heitler

@HERMES / JLab
DVCS << Bethe-Heitler

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

\( \rightarrow \) bilinear in GPDs

\( \rightarrow linear \) in GPDs, information about phase

\( \rightarrow access to Re \) and \( Im \) parts of CFFs
**DVCS**

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

- \( \rightarrow \) bilinear in GPDs
- \( \rightarrow \) linear in GPDs, information about phase

**Isolate interference term:**

- different beam charges: \( e^+e^- \) only @HERA, upcoming @COMPASS
- polarisation observables: \( \Delta \sigma_{UT} \)
  
  \[ \begin{align*}
  &\text{beam} \quad \text{target} \\
  &U, L \quad U, L, T \\
  &\text{Unpolarised, Longitudinally, Transversely polarised}
\end{align*} \]
DVCS interference term

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau_{BH}^* \tau_{DVCS} + \tau_{DVCS}^* \tau_{BH})$$

- different beam charges: $e^+e^-$ only @HERA, upcoming @COMPASS
- polarisation observables:

$$\Delta\sigma_{UT}(\phi, \phi_S, ...)$$

beam target
U, L U, L, T

Unpolarised,
Longitudinally,
Transversely polarised
DVCS cross section in full glory:  

\[ d\sigma(\ell p \rightarrow \ell \gamma p) \sim \]

\[ d\sigma_{UU}^{BH} + e_\ell d\sigma_{UU}^{I} + d\sigma_{UU}^{DVCS} \]

\[ + P_\ell S_L d\sigma_{LL}^{BH} + e_\ell P_\ell S_L d\sigma_{LL}^{I} + P_\ell S_L d\sigma_{LL}^{DVCS} \]

\[ + P_\ell S_T d\sigma_{LT}^{BH} + e_\ell P_\ell S_T d\sigma_{LT}^{I} + P_\ell S_T d\sigma_{LT}^{DVCS} \]

\[ + e_\ell P_\ell d\sigma_{LU}^{I} + P_\ell d\sigma_{LU}^{DVCS} \]

\[ + e_\ell S_L d\sigma_{UL}^{I} + S_L d\sigma_{UL}^{DVCS} \]

\[ + e_\ell S_T d\sigma_{UT}^{I} + S_T d\sigma_{UT}^{DVCS}. \]

\( e_\ell \) beam charge

\( P_\ell \) longitudinal beam polarisation

\( S_L, S_T \) Longitudinal or transverse target polarisation
DVCS interference term

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

DVCS cross section in full glory:

\[ d\sigma(\ell p \rightarrow \ell \gamma p) \sim \]

\[ d\sigma_{UU}^{BH} + e_\ell d\sigma_{UU}^{I} + d\sigma_{UU}^{DVCS} \]

\[ + P_\ell S_L d\sigma_{LL}^{BH} + e_\ell P_\ell S_L d\sigma_{LL}^{I} + P_\ell S_L d\sigma_{LL}^{DVCS} \]

\[ + P_\ell S_T d\sigma_{LT}^{BH} + e_\ell P_\ell S_T d\sigma_{LT}^{I} + P_\ell S_T d\sigma_{LT}^{DVCS} \]

\[ + e_\ell P_\ell d\sigma_{LU}^{I} + P_\ell d\sigma_{LU}^{DVCS} \]

\[ + e_\ell S_L d\sigma_{UL}^{I} + S_L d\sigma_{UL}^{DVCS} \]

\[ + e_\ell S_T d\sigma_{UT}^{I} + S_T d\sigma_{UT}^{DVCS} . \]

\( e_\ell \) beam charge

\( P_\ell \) longitudinal beam polarisation

\( S_L, S_T \) Longitudinal or transverse target polarisation
DVCS interference term

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

DVCS cross section in full glory: [M. Diehl]

\[
d\sigma(\ell p \to \ell' \gamma p) \sim d\sigma_{\text{BH}}^{UU} + e_\ell d\sigma_{UU}^I + d\sigma_{UU}^{DVCS} + P_\ell S_L d\sigma_{LL}^{BH} + e_\ell P_\ell S_L d\sigma_{LL}^{I} + P_\ell S_L d\sigma_{LL}^{DVCS} + P_\ell S_T d\sigma_{LT}^{BH} + e_\ell P_\ell S_T d\sigma_{LT}^{I} + P_\ell S_T d\sigma_{LT}^{DVCS} + e_\ell S_L d\sigma_{UL}^{I} + S_L d\sigma_{UL}^{DVCS} + e_\ell S_T d\sigma_{UT}^{I} + S_T d\sigma_{UT}^{DVCS}. \]

Fourier coefficients \( c_n \) and \( s_n \) provide experimental constrain on CFFs.

Example:

\[
d\sigma_{LU}^I \propto -e_\ell \left( \sum_{n=0}^{3} c_n^I \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^I \sin(n\phi) \right) \]
DVCS interference term

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

DVCS cross section in full glory: [M. Diehl]

\[ d\sigma(\ell p \to \ell' p) \sim d\sigma_{BH}^{UU} + e_\ell d\sigma_{UL}^{UU} + d\sigma_{DD}^{DVCS} \]
\[ + P_\ell S_L d\sigma_{LL}^{BH} + e_\ell P_\ell S_L d\sigma_{LL}^{DVCS} \]
\[ + P_\ell S_T d\sigma_{LT}^{BH} + e_\ell P_\ell S_T d\sigma_{LT}^{DVCS} \]
\[ + e_\ell P_\ell d\sigma_{LU}^{DVCS} + P_\ell d\sigma_{UU}^{DVCS} \]
\[ + e_\ell S_L d\sigma_{UL}^{DVCS} + S_L d\sigma_{UL}^{DVCS} \]
\[ + e_\ell S_T d\sigma_{UT}^{DVCS} + S_T d\sigma_{UT}^{DVCS}. \]

Fourier coefficients \( c_n \) and \( s_n \) provide experimental constrain on CFFs.

Example:

\[ d\sigma_{LU}^I \propto -e_\ell \left( \sum_{n=0}^{3} c_n^I \cos(n\phi) + \lambda \sum_{n=1}^{2} s_n^I \sin(n\phi) \right) \]

Accessible linear combinations of CFFs, hence GPDs:

\[ d\sigma_{LU}^I \propto F_1 \tilde{H} + \frac{x_{Bj}}{2 - x_{Bj}} (F_1 + F_2) \tilde{H} - \frac{t}{4M^2} F_2 E + \ldots \]

Dominant contribution for proton

For neutron

\( F_1, F_2 \ldots \) Pauli & Dirac FF
first DVCS signals

-- interference term --

\[ A_{LU} \sim \frac{(BH)^*Im(DVCS)^*\sin\phi}{(BH^2+DVCS^2)} \]

\rightarrow \sin\phi \text{ dependence indicates dominance of handback contribution}
call for high statistics

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

\[ \sigma_{UU} = \frac{d^4\sigma}{dQ^2 dx_B dz d\phi_{\gamma\gamma}} \text{ (nb/GeV}^4\text{)} \]

[Graphs showing data and fits with legend indicating BH and DVCS with GPD model: VGG(1999)]
call for high statistics

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

\[ \sigma_{UU} = \frac{d^4\sigma}{dQ^2dx_Bdtd\phi_{\gamma\gamma}} \text{ (nb/GeV}^4) \]

\[ \Delta\sigma_{LU} = \frac{1}{2}(\frac{d^4\sigma^+}{dQ^2dx_Bdtd\phi_{\gamma\gamma}} - \frac{d^4\sigma^-}{dQ^2dx_Bdtd\phi_{\gamma\gamma}}) \text{ (nb/GeV}^4) \]

[PRL97(2006)]

Hall-A
call for high statistics

DVCS beam-spin asymmetry [PRL100(2008)]

\[ A_{LU} \approx \frac{a \sin \phi}{1 + c \cos \phi} \]

\[ A_{LU} \sim \frac{(BH)^* \text{Im}(DVCS)^* \sin \phi}{(BH^2 + DVCS^2)} \]
call for high statistics

DVCS beam-spin asymmetry [PRL100(2008)]

\[ A_{LU} \approx \frac{a \sin \phi}{1 + c \cos \phi} \]

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

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

combined analysis of charge & polarisation observables

→ separation of Interference & DVCS\(^2\) amplitudes
call for new analysis methods

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

combined analysis of charge & polarisation observables

\[ \rightarrow \text{separation of Interference & DVCS}^2 \text{ amplitudes} \]

e.g., beam-spin asymmetry:

\[ \sigma_{LU}(\phi, P_l, e_l) = \sigma_{UU}(\phi) \cdot \left\{ 1 + P_l A_{LU}^{DVCS}(\phi) + e_1 P_l A_{LU}^I(\phi) + e_1 A_C(\phi) \right\} \]
call for new analysis methods

dσ ∝ |τ_{BH}|^2 + |τ_{DVCS}|^2 + (τ_{BH}^* τ_{DVCS} + τ_{DVCS}^* τ_{BH})

combined analysis of charge & polarisation observables
→ separation of Interference & DVCS² amplitudes

e.g., beam-spin asymmetry:

σ_{LU}(φ; P_l, e_l) = σ_{UU}(φ) \cdot \left\{ 1 + P_l A_{LU}^{DVCS}(φ) + e_l P_l A_{LU}^{I}(φ) + e_l A_C(φ) \right\}

- charged-averaged beam-spin asymmetry:

A_{LU}^{DVCS}(φ) = (σ^+→ - σ^+←) + (σ^-→ - σ^-←) / ∑ \propto s_1^{DVCS} \sin φ
call for new analysis methods

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

combined analysis of charge & polarisation observables

→ separation of Interference & DVCS\(^2\) amplitudes

e.g., beam-spin asymmetry:

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

- **charged-averaged** beam-spin asymmetry:

\[ A_{LU}^{DVCS}(\phi) = \left( \sigma^{+\rightarrow} - \sigma^{+\leftarrow} \right) + \left( \sigma^{-\rightarrow} - \sigma^{-\leftarrow} \right) / \sum \propto s_1^{DVCS} \sin \phi \]

- **charge-difference** beam-spin asymmetry:

\[ A_{LU}^{DVCS}(\phi) = \left( \sigma^{+\rightarrow} - \sigma^{+\leftarrow} \right) - \left( \sigma^{-\rightarrow} - \sigma^{-\leftarrow} \right) / \sum \propto \sum_{n=1}^{2} s_n \sin(n\phi) \rightarrow \text{Im}(CFF) \]
call for new analysis methods

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

combined analysis of charge & polarisation observables

\[ \rightarrow \text{separation of Interference & DVCS}^2 \text{ amplitudes} \]

e.g., beam-spin asymmetry:

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

- charged-averaged beam-spin asymmetry:

\[ A_{LU}^{DVCS}(\phi) = \left( \sigma^{+\to} - \sigma^{+\leftarrow} \right) + \left( \sigma^{-\to} - \sigma^{-\leftarrow} \right) / \Sigma \propto s_1^{DVCS} \sin \phi \]

- charge-difference beam-spin asymmetry:

\[ A_{LU}^{DVCS}(\phi) = \left( \sigma^{+\to} - \sigma^{+\leftarrow} \right) - \left( \sigma^{-\to} - \sigma^{-\leftarrow} \right) / \Sigma \propto \sum_{n=1}^{2} s_n \sin(n\phi) \rightarrow \text{Im}(CFF) \]

- beam-spin averaged charge asymmetry:

\[ A_C(\phi) = \left( \sigma^{+\to} + \sigma^{+\leftarrow} \right) - \left( \sigma^{-\to} + \sigma^{-\leftarrow} \right) / \Sigma \propto \sum_{n=0}^{3} c_n l \cos(n\phi) \rightarrow \text{Re}(CFF) \]
call for new analysis methods

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

combined analysis of charge & polarisation observables

→ separation of Interference & DVCS\(^2\) amplitudes

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

\[ s_1^{DVCS} \sin \phi \quad \sum_{n=1}^{2} s_n^{I} \sin(n\phi) \quad \sum_{n=0}^{3} c_n^{I} \cos(n\phi) \]
call for completeness

- charge asymmetry
  
  \[ Re (H) \]

- beam-spin asymmetry
  
  \[ Im (H) \]

- transverse target spin asymmetry
  
  \[ Im (H-E) \]

- transverse-target double-spin
  
  \[ Re (H-E) \]

- longitudinal target spin asymmetry
  
  \[ Im (\tilde{H}) \]

- longitudinal-target double-spin
  
  \[ Re (\tilde{H}) \]
hunting the OAM

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

lattice results:

\[ J^u = 0.236(6) \approx 47\% \text{ of } 1/2 \]
\[ J^d = 0.0018(37) \approx 1\% \text{ of } 1/2 \]
\[ J^{u+d} \approx 0.238 \pm 0.008 \approx 48\% \text{ of } 1/2 \]
hunting the OAM

\[ \frac{1}{2} = J^q + J^g, \quad J^{q,g} = \frac{1}{2} \int_{-1}^{1} xdx \left[ H^{q,g}(x, \xi, t) + E^{q,g}(x, \xi, t) \right]_{t=0} \]

- **lattice results:**
  [P. Hägler et al. (2011)]

- **GPD model tuned to VM:**
  [Goloskokov, Kroll (2008)]

<table>
<thead>
<tr>
<th>$J^u$</th>
<th>$J^d$</th>
<th>$J^s$</th>
<th>$J^g$</th>
</tr>
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<tbody>
<tr>
<td>0.250</td>
<td>0.020</td>
<td>0.015</td>
<td>0.214</td>
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<tr>
<td>0.276</td>
<td>0.046</td>
<td>0.041</td>
<td>0.132</td>
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<tr>
<td>0.225</td>
<td>-0.005</td>
<td>-0.011</td>
<td>0.286</td>
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<tr>
<td>0.209</td>
<td>0.013</td>
<td>0.015</td>
<td>0.257</td>
</tr>
<tr>
<td>0.230</td>
<td>0.024</td>
<td>0.015</td>
<td>0.228</td>
</tr>
<tr>
<td>0.234</td>
<td>0.028</td>
<td>0.019</td>
<td>0.214</td>
</tr>
</tbody>
</table>

**variants for GPD $E$**

- $J^u = 0.236(6) \approx 47\%$ of $1/2$
- $J^d = 0.0018(37) \approx 1\%$ of $1/2$
- $J^{u+d} \approx 0.238 \pm 0.008 \approx 48\%$ of $1/2$
hunting the OAM

→ GPD models: $J^q$ free parameter in ansatz for $E$

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

▪ sensitivity to GPD $E$ (@fixed target exp. kinematics)

▪ pDVCS: $A_{UT} \rightarrow$ HERMES

▪ nDVCS: $A_{LU} \rightarrow$ Hall A

▪ meson prod. $A_{UT}$: $\rho^0 \rightarrow$ HERMES, COMPASS

...also $\omega, \phi, \rho^+, K^0$
hunting the OAM
-- pDVCS: transverse target-spin asymmetry --

→ GPD models: $J^q$ free parameter in ansatz for $E$

[JHEP06(2008)]

[VGG]
hunting the OAM

-- nDVCS : beam-spin cross section difference --

→ GPD models: $J^q$ free parameter in ansatz for $E$

[PRL99(2007)]

[VGG]
hunting the OAM

- **model dependent** [VGG(1999)] constrain of $J_u$ vs $J_d$
- lattice
- GPD & TMD models

![Graph](figure.png)

- Goloskokov & Kroll, EPJ C59 (09) 809
- Diehl et al., EPJ C39 (05) 1
- Guidal et al., PR D72 (05) 054013
- Liuti et al., PRD 84 (11) 034007
- Bacchetta & Radici, PRL 107 (11) 212001
- LHPC–1, PR D77 (08) 094502
- LHPC–2, PR D82 (10) 094502
- QCDSF, arXiv:0710.1534
- Wakamatsu, EPJ A44 (10) 297
- Thomas, PRL 101 (08) 102003
- Thomas, INT 2012 workshop

[figure taken from Bachetta&Radici, PRL107(2011)]
conclusions

HERA collider  COMPASS  HERMES / JLab

$10^{-3}$  $10^{-1}$  0.2-0.5  $x_B$

$10^{-4} < x_B < 0.02$  $0.02 < x_B < 0.4$  /  $0.1 < x_B < 0.6$

sea quarks & gluons  (gluons) (valence) quarks

DVCS, VM  DVCS, (mesons)

- increasing amount and precision of experimental data
- large variety of different observables (however, many still with limited precision)
- progress in model calculations, *plenty of room for more work*...
conclusions & perspectives

- increasing amount and precision of experimental data
- large variety of different observables (however, many still with limited precision)
- progress in model calculations, *plenty of room for more work*...

- bright future for GPD studies:
  - JLab12: DVCS in valence kinematic region
  - COMPASS-II with recoil: DVCS & VM in transition kinematic region

HERA collider  \[10^{-3}\]  \[10^{-1}\]  \[0.2-0.5\]  \[X_B\] HERMES / JLab

JLab12GeV
Compass-II
EIC

\(\text{HERA collider} \rightarrow \text{HERMES / JLab} \rightarrow \text{JLab12GeV} \rightarrow \text{Compass-II} \rightarrow \text{EIC}\)
### 12 GeV Approved Experiments by Physics Topics

[http://www.jlab.org/12GeV/](http://www.jlab.org/12GeV/)

<table>
<thead>
<tr>
<th>Topic</th>
<th>Hall A</th>
<th>Hall B</th>
<th>Hall C</th>
<th>Hall D</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Hadron spectra as probes of QCD (rated) (GlueX and heavy baryon and meson spectroscopy)</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td>2</td>
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<tr>
<td>The transverse structure of the hadrons (rated) (Elastic and transition Form Factors)</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td></td>
<td>9</td>
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<tr>
<td>The longitudinal structure of the hadrons (rated) (Unpolarized and polarized parton distribution functions)</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>The 3D structure of the hadrons (unrated) (Generalized Parton Distributions and Transverse Momentum Distributions)</td>
<td>3</td>
<td>8 (*)</td>
<td>4</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Hadrons and cold nuclear matter (rated) (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Low-energy tests of the Standard Model and Fundamental Symmetries (rated)</td>
<td>2</td>
<td></td>
<td>1</td>
<td></td>
<td>3</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td>12</td>
<td>15</td>
<td>16</td>
<td>2</td>
<td>45</td>
</tr>
</tbody>
</table>

*Current PAC approved experiments represent over 6 years of running at 35 weeks/year*

*(* 3 new approved proposals on the topic @Hall B since then*
DVCS @CLAS12 [2014+]

- fully differential analysis
- watch requirement $t \ll Q^2$
DVCS @ Hall A [2014+]

- fully differential analysis
- watch requirement $t << Q^2$

[http://www.jlab.org/12GeV/]
DVCS @COMPASS-II 2014+

[http://cdsweb.cern.ch/record/1265628]
DVCS cross section: slope parameter \( b \): \( \frac{d\sigma}{dt} \sim e^{-b|t|} \)

[COMPASS projections: http://cdsweb.cern.ch/record/1265628]
DVCS @ COMPASS-II 2014+

- DVCS beam helicity & charge asymmetry $A_C^{\cos \phi}(t, x_B)$

[http://cdsweb.cern.ch/record/1265628]
**conclusions & perspectives**

- increasing amount and precision of experimental data
- large variety of different observables (however, many still with limited precision)
- progress in model calculations, *plenty of room for more work*...

- bright future for GPD studies:
  - JLab12: DVCS in valence kinematic region
  - COMPASS-II with recoil: DVCS & VM in transition kinematic region
  - EIC: mapping GPDs from $Q^2$ evolution of DVCS & from meson production
additional slides
exclusivity

@ the HERA collider experiments

\[ \approx \text{hermetic detector} \]
\[ \rightarrow p \text{ escapes through beam pipe} \]

LPS: \( p \) tagged control sample
exclusivity
@ the HERA collider experiments

LPS: $p$ tagged data sample

- **e-sample**: BH control sample
- **e+$e^-$, $J/\psi$ bg-sample
- **BH+$e^+e^-$+$J/\psi$$\gamma$-sample**: BH+DVCS
- **BH**
- **BH+FFS (DVCS)**
- **(BH+DVCS) - BH**
- **FFS (DVCS)**
exclusivity

@ the HERA collider experiments

full data sample

- e-sample: BH control sample
- e+e-, J/ψ bg-sample
- BH + e⁺e⁻ + J/ψ
- BH
- γ-sample: BH+DVCS
- BH
- BH+FFS (DVCS)
- (BH+DVCS) - BH
- FFS (DVCS)
exclusivity
fixed target: via missing mass / energy

\((ep \rightarrow e' \gamma X)\)

\(X=p\)

Resonant excitation: \(X=\Delta^+\)

\(X=\pi^0+...\)

part of the signal

subtracted
very well understood

\(1000N/N_{\text{dis}}\)

\(1000N/N_{\text{dis}}\)

\(M^2_X (\text{GeV}^2)\)
exclusivity
fixed target: via missing mass / energy

(ep → e' γ X)

Resonant excitation: X=Δ^+

with p detection &
Δ^+ ID: transition GPDs
exclusivity

fixed target: via missing mass / energy

(ep → e' γ X)

x = p

Resonant excitation: X = Δ^+

part of the signal

Raw H(e,e'γ)X Missing Mass^2 (after accidental subtraction).

\[ [ H(e,e'γ)X - H(e,e'γ)Y ]: Missing Mass^2 \]

Hall-A

+H(e,e'γp) sample,Normalized to H(e,e'γ)

***H(e,e'γp) simulation
exclusivity: HERMES with recoil
exclusivity: HERMES with recoil

Event Selection with Recoil Detector

- Events with one DIS lepton and one trackless cluster in the calorimeter.
- “Unresolved” for associated process $e p \rightarrow e \Delta^+ \gamma \approx 12\%$

- “Unresolved reference” sample.
- “Hypothetical” proton required in the Recoil Detector acceptance.

- “Pure Elastic” sample.
- Kinematic event fitting technique. Allows to achieve purity > 99.9\%
exclusivity: HERMES with recoil

Beam-Spin asymmetry with Recoil

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

Indication of slightly larger magnitude of leading amplitude for pure elastic sample compared with reference sample

Unresolved Reference
Pure Elastic

Fractional contributions of elastic and associated processes for different samples

HERMES target spin asymmetries

Longitudinal Single Target-Spin and Double-Spin asymmetries

\[ A_{UL}(\phi) = \frac{(\sigma^{\rightarrow\rightarrow} + \sigma^{\rightarrow\leftarrow}) - (\sigma^{\rightarrow\leftarrow} + \sigma^{\leftarrow\leftarrow})}{(\sigma^{\rightarrow\rightarrow} + \sigma^{\rightarrow\leftarrow}) + (\sigma^{\rightarrow\leftarrow} + \sigma^{\leftarrow\leftarrow})} \]

**VGG: Model calculation**
M. Vanderhaeghen, P. Guichon, M. Guidal

\[ \propto \Im [F_1 \tilde{H}] \]

**Longitudinal Target Spin Asymmetry**
- non-zero negative value of the leading \sin(\phi) amplitude
- mild kinematic dependence

\[ A_{LL}(\phi) = \frac{(\sigma^{\rightarrow\rightarrow} + \sigma^{\rightarrow\leftarrow}) - (\sigma^{\rightarrow\leftarrow} + \sigma^{\leftarrow\leftarrow})}{(\sigma^{\rightarrow\rightarrow} + \sigma^{\rightarrow\leftarrow}) + (\sigma^{\rightarrow\leftarrow} + \sigma^{\leftarrow\leftarrow})} \]

**Longitudinal Double-Spin Asymmetry**
- constant term is positive
- leading \cos(\phi) amplitude is consistent with zero

\[ \propto \Re [F_1 \tilde{H}] \]

Asymmetry amplitudes are attributed not only to squared DVCS and interference terms but also to squared BH term
HERMES target spin asymmetries

Transverse Single Target-Spin and Double-Spin asymmetries

\[ A_{UT}^{D_{V C S}}(\phi, \phi_S) = \frac{(\sigma^{+\uparrow} - \sigma^{+\downarrow})(\sigma^{-\uparrow} - \sigma^{-\downarrow})}{(\sigma^{+\uparrow} + \sigma^{+\downarrow}) + (\sigma^{-\uparrow} + \sigma^{-\downarrow})} \]

Charge-difference Transverse Target-Spin asymmetry
- Non-zero leading \( \cos(n\phi) \) amplitudes.

\[ \text{VGG: Model calculation} \]
M. Vanderhaeghen, P. Guichon, M. Guidal

Leading cos(\( \phi \)) amplitude of charge difference target-spin asymmetry \( A_{UT} \) is sensitive to CFF \( \mathcal{E} \), therefore \( J_u \).

\[ \text{Phys. Lett. B704 (2011) 15-23} \]

Charge-difference Transverse Double-Spin asymmetry
- Leading amplitudes are consistent with zero
- Sensitivity to is suppressed \( J_u \) is suppressed by kinematic prefactor

\[ \propto \text{Re} \left[ F_2 \mathcal{H} - F_1 \mathcal{E} \right] \]

HERMES VM SDMEs

Exclusive Vector Meson Production

pQCD description of the process.
I) dissociation of the virtual photon into quark-antiquark pair
II) scattering of a pair on a nucleon
III) formation of the observed vector meson

\[
\frac{d\sigma}{dx_B dQ^2 dt d\Phi \cos \theta d\phi} \propto \frac{d\sigma}{dx_B dQ^2 dt} W(x_B, Q^2, t, \Phi, \cos \theta, \phi)
\]

production and decay angular distribution: $W$ decomposition

\[
W = W_{UU} + P_\ell W_{LU} + S_L W_{UL} + P_\ell S_L W_{LL} + S_T W_{UT} + P_\ell S_T W_{LT}
\]

parameterization in terms of helicity amplitudes or SDMES

\[
T_{\lambda\lambda}^{\rho} \quad \gamma^* \\
\rho^{\rho} \quad \gamma^*
\]
HERMES VM SDMEs

$\rho^0$ and $\phi$ SDMEs on an unpolarized target

$|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2$

- $\gamma^* \rightarrow V_L$ & $\gamma^* \rightarrow V_T$
  - SDMEs are significantly different from zero
  - 10-20% difference between $\rho$ and $\phi$ SDMEs

- $\gamma^* \rightarrow V_T$ & $\gamma^* \rightarrow V_T$
  - SDMEs are consistent with zero

- $\gamma^* \rightarrow V_L$
  - Pronounced difference between $\rho$ and $\phi$ SDMEs
  - 2-10 $\sigma$ level violation from SCHC for $\rho$

- Selected hierarchy is confirmed
  - No differences between proton and deuteron
HERMES VM SDMEs

Comparison of $\rho^0$ SDMEs to GPD model

GPD model: S. Goloskokov, P. Kroll (2007)

$W=5$ GeV (HERMES)
$W=10$ GeV (COMPASS)
$W=75$ GeV (H1, ZEUS)

$\gamma^* L \rightarrow \rho^0_L \& \gamma^*_T \rightarrow \rho^0_T$

$1 - r_{00}^{04}, r_{1-1}^{1}, -Im r_{1-1}^{2} \propto T_{11}$

model is in agreement with data

interference $\gamma^*_L \rightarrow \rho^0_L \& \gamma^*_T \rightarrow \rho^0_T$

model does not describe the data

model predicts phase difference between $T_{00}$ and $T_{11}$, $\delta_{11}=3.1$ deg.

$\tan \delta_{11} = \frac{Im(T_{11}/T_{00})}{Re(T_{11}/T_{00})}$

HERMES result $\delta_{11}=31.5 \pm 1.4$ deg.

Large phase difference was observed also by H1 ($\delta_{11}=20$)

HERMES VM SDMEs

Observation of Unnatural-parity exchange

At large $W^2$ and $Q^2$ the transition should be suppressed by $M/Q$

- direct helicity amplitude ratio analysis: $U_{11}/T_{00}$
- the combination of SDMEs is expected to be zero in case of NPE

\[ u_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{11} - 2r_{1-1}^{11} \]

\[ u_2 = r_{11}^{5} + r_{1-1}^{5} \]

\[ u_3 = r_{11}^{8} + r_{1-1}^{8} \]

---

EPJ C 62 (2009) 659-694

EPJ C 71 (2011) 1609

- Significant UPE contribution for $\rho^0$
- Sensitivity to GPD $\widetilde{H}$
- No signal of UPE contribution for $\phi$

VM production @ low x

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

$$\sigma(W) \propto W^\delta$$

$$\frac{d\sigma}{dt} \propto e^{-b|r|}$$

→ expect $\delta$ to increase from $\sim0.2$ to $\sim0.8$

$b$ to decrease from $\sim10$ to $\sim4$-5 GeV$^2$
VM production @ low x

$W$ dependence: probe transition from soft to hard regime

two ways to set a hard scale:
- large $Q^2$
- mass of produced VM

universality: $\rho$ and $\phi$ at large $Q^2+M^2$ similar to $J/\Psi$, $Y$
VM production from low $\rightarrow$ high $x$

$10^{-3}$  $10^{-1}$  0.2-0.5

HERA-collider  COMPASS / HERMES / Jlab

$g^+$(sea)  $g^+$(sea)$+q_v(\rho,\omega)$  $q_v(\rho,\omega)$

- NLO corrections to VM production are large: [M. Diehl, W. Kugler (2007)]

$\rho^0$ cross section @typical kinematics of COMPASS / HERMES / JLab12
Deeply Virtual Compton Scattering

$\rightarrow H, \tilde{H}, E, \tilde{E}$

- **DVCS cross sections @ low $x$$\,$

\[
d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + I
\]

- $t$ slope provides absolute normalisation
- $FT \rightarrow$ average impact parameter
DVCS cross section

- $t$ slope measurement provides absolute normalisation

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$
DVCS cross section

- $t$ slope measurement provides absolute normalisation

$$\frac{d\sigma}{dt} \propto e^{-b|t|}$$

- Universality of slope parameter: pointlike configurations dominate
DVCS cross section

- $t$ slope measurement provides absolute normalisation
  \[ \frac{d\sigma}{dt} \propto e^{-b|t|} \]

- Universality of slope parameter: pointlike configurations dominate

- \( FT \rightarrow \) average impact parameter
  \[ \sqrt{\langle b_T^2 \rangle} = (0.65 \pm 0.02) \text{ fm} \]
  \[ @ x_B = 10^{-3} \]
  \[ <Q^2> = 8.0 \text{ GeV}^2 \]

[PLB659(2008)]

[Zeus (p' tagged events)]

[JHEP05(2009)]
sea quark & gluon imaging

\( \gamma + p \rightarrow J/\psi + p \)

\( \frac{d\sigma}{dt} \sim \exp(B_{J/\psi} t) \)

\( \tilde{Q}^2 \approx 3 \tilde{\text{GeV}}^2 \)

\[ \sqrt{\langle b_T^2 \rangle} = (0.65 \pm 0.02) \text{ fm} \]

@ \( x_B = 10^{-3} \)

\( \langle Q^2 \rangle = 8.0 \text{ GeV}^2 \)

- universality of slope parameter:
  - pointlike configurations dominate

\( FT \rightarrow \) average impact parameter
call for high statistics

DVCS beam-spin asymmetry [PRL100(2008)]

\[ \alpha \propto \text{Im}(F_1 H) \]
hunting the OAM

-- $\rho^0$ : transverse target-spin asymmetry --

after the full glory of SDME extractions

[formalism by M. Diehl (2007)]

$$(\gamma_L^* \rightarrow \rho_L^0):$$

$$A_{UT}^{\gamma^*}(\phi, \phi_S) = \frac{\text{Im} n_{00}^{00}}{u_{00}^{00}}$$

$\rho^0$

$$n_{\mu\nu'}^{\nu\nu'}$$

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

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

[PLB679(2009)]
hunting the OAM

-- $\rho^0$ : transverse target-spin asymmetry --

after the full glory of SDME extractions
[formalism by M. Diehl (2007)]

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

$$A_{UT}^{\gamma^*_L}(\phi, \phi_S) = \frac{\text{Im} n^{00}_{00}}{u_{00}}$$

$\rho^0$

$\gamma^*$

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

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

- more data coming: COMPASS, JLab12 with transv. Target
- more models: Goloskokov, Kroll
**DVCS nuclear effects**

**Beam-charge asymmetry**

How does the nuclear medium modify parton-parton correlations?

How do nucleon properties change in the nuclear medium?

Enhanced ‘generalized EMC effect’, rise of $T_{DVCS}$ with $A$?

**Beam-helicity asymmetry**

<table>
<thead>
<tr>
<th>Average $A_{LU}^A / A_{LU}^H$:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.91 \pm 0.19$</td>
</tr>
<tr>
<td>$0.93 \pm 0.23$</td>
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</table>
towards GPDs

recent developments (beyond VGG(1999)...) 

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  - LO GPD model using *DD, regge t dep., power corrections*
  - fit to *exclusive meson production data*
towards GPDs

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towards GPDs

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towards GPDs

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- Guidal (2011):
  - model independent extraction of $CFF$ (GPD extr. requires model ansatz)
  - kinematic fitting of DVCS data (per experiment)
towards global analysis of GPDs

[Guidal '08, Guidal and Moutarde '09], seven CFF fit (blue squares), [Guidal '10] $H$, $\tilde{H}$ CFF fit (green diamonds), [Moutarde '09] $H$ GPD fit (red circles)

(slide from K. Kumericki, Photons11)
towards global analysis of GPDs

-- employ all available exclusive data (DVCS & meson production) --

\[ A_{BS}^{(I)} \]

\[ A_{BC}^{(0)} \]

\[ A_{BC}^{(I)} \]

\[ A_{BS}^{(I)} \]

HERMES

KM09a
KM09b
KM10b
GK07

\[ \Sigma_{BS}^{(I),w} \]

CLAS

HALLA

\[ \nabla \]

GK (2007) comparison to KM09,10