A glimpse of gluon through
Deeply Virtual Compton Scattering on the proton

J. Roche (Ohio University)

- Hard exclusive reactions allow the study of the 3D structure of nucleon through the measure of Generalized Parton Distributions that goes beyond what can be achieved with Elastic and Deep Inelastic Scattering.

- Dedicated experiments are conducted world-wide. In the valence region, the growing set of existing results is helping refine our approach to extracting the GPDs from the data.

- DVCS experiments are an essential part of the comprehensive GPD program with the 12 GeV CEBAF beam and the EIC.
Nucleons are perfect laboratories for studying QCD.

Lepton beams are well understood probes of their internal structure.

Lepton: electron or muon of energy $E_{\text{beam}}$

QED: $\alpha = 1/137$

one photon exchange dominates

momentum $\vec{q}$ and energy $\nu$

$Q^2 = \nu^2 - q^2$ and $x_B^{\text{lab}} = Q^2/2m\nu$
How is the structure of the nucleon studied?

At $Q^2$ fixed

Elastic:

$$F(Q^2, x_B = 1)$$

Form factors:
Transverse spatial structure

Deep Inelastic:

$$F(Q^2 \text{ independent}, x_B)$$

Parton distribution functions:
Longitudinal momentum structure
3D picture of the nucleon

**Generalized Parton Distribution Function**: 3-D imaging of the nucleon with access to **correlations** between transverse spatial distribution and longitudinal momentum distributions.
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Exclusive reactions: handbag diagram

**Definition of variables:**

- $x$: average long. momentum - NOT ACCESSIBLE
- $\xi$: long. mom. difference $\approx x_B/(2 - x_B)$
- $t$: four-momentum transfer related to $b_\perp$ via Fourier transform

**DVCS:** $\ell p \rightarrow \ell' p' \gamma$ (golden channel)

**HEMP:** $\ell p \rightarrow \ell' p' \pi$ or $\rho$ or $\phi$ or $J/\psi$, ...

Slide from N d’Hose, Tranversity 2014
GPDs and factorization

In the Bjorken limit:

\[ Q^2 = \frac{-q^2}{\nu} \rightarrow \infty \]

\[ x_B = \frac{Q^2}{2M\nu} \quad \text{fixed} \]

Hard process
LO: QED
NLO: QCD perturbative

Soft process
Non perturbative QCD described by GPDs

The minimal \( Q^2 \) at which the factorization holds must be tested and established by experiments.
Exclusive reactions

Deeply Virtual Compton Scattering (DVCS):

\[ \gamma^* \rightarrow \gamma^{\ast} \rightarrow \gamma \]

Hard Exclusive Meson Production (HEMP):

\[ \gamma^* \rightarrow \gamma^{\ast} \rightarrow \gamma \]

\[ Q^2 \]

\[ x + \xi \quad x - \xi \]

\[ p \quad t \quad p' \]

GPDs

\[ x + \xi \quad x - \xi \]

\[ p \quad t \quad p' \]

GPDs

Quark contribution

Gluon contribution

\[ \gamma_L^* \text{ factorization} \]

Meson w.f.

Very slow scaling

Slide from N d’Hose, Tranversity 2014
Generalized Parton Distributions

\[ N(p) \stackrel{t = \Delta^2}{\rightarrow} N(p + \Delta) \]

\( \lim_{t \rightarrow 0} (GPD) \rightarrow PDF \)

\[ H^q(x,0,0) = q(x), -\bar{q}(-x) \]
\[ \tilde{H}^q(x,0,0) = \Delta q(x), \Delta \bar{q}(-x) \]

\[ \int_{-1}^{+1} dx H^q(x,\xi,t) = F_1^q(t) \quad \int_{-1}^{+1} dx \tilde{H}^q(x,\xi,t) = g_A^q(t) \]
\[ \int_{-1}^{+1} dx E^q(x,\xi,t) = F_2^q(t) \quad \int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = h_A^q(t) \]

No relation for the GPD \( E \) and \( \tilde{E} \)

<table>
<thead>
<tr>
<th>Nucleon Helicity</th>
<th>conserving</th>
<th>non-conserving</th>
</tr>
</thead>
<tbody>
<tr>
<td>unpolarized GPD</td>
<td>( H )</td>
<td>( E )</td>
</tr>
<tr>
<td>polarized GPD</td>
<td>( \tilde{H} )</td>
<td>( \tilde{E} )</td>
</tr>
</tbody>
</table>
The “Holy grail” of GPDs physics

Contribution of the angular momentum of quarks to proton spin:

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + J_g \quad \Rightarrow \quad J_q = \frac{1}{2} \int_{-1}^{1} dx \: x[H^q(x, \xi, 0) + E^q(x, \xi, 0)]
\]

Ji’s sum rule

\[
\frac{1}{2} = \text{Spin of all Quarks} + \text{Spin of Gluons} + \text{Angular Momentum of all Quarks} + \text{Angular Momentum of Gluons}
\]

GPD H connects to the PDFs (symmetric initial-final states) Known from polarized DIS data

GPD E is the unknown

Experimentally, producing enough data to support the integration over the whole x range is a challenge.
Measuring DVCS to access GPDs information

When only considering the handbag diagram (at leading twist)

\[ d^5 \sigma - d^5 \bar{\sigma} = \Im m (T^{BH} \cdot T^{DVCS}) \]

\[ d^5 \sigma + d^5 \bar{\sigma} = |BH|^2 + \Re e (T^{BH} \cdot T^{DVCS}) + |DVCS|^2 \]

Known to 1%

Bilinear combinations of GPDs

Linear combinations of GPDs
DVCS sensitivities to GPDs

\[
\Delta \sigma = d^5 \overline{\sigma} - d^5 \sigma
\]

\[\xi = x_B/(2-x_B), \quad k = -t/4M^2\]

Polarized beam, unpolarized proton target:
\[\Delta \sigma_{LU} \sim \sin \phi \text{Im} \{F_1 H + \xi (F_1 + F_2) \tilde{H} + kF_2 E\} \, d\phi\]

Unpolarized beam, longitudinal proton target:
\[\Delta \sigma_{UL} \sim \sin \phi \text{Im} \{F_1 \tilde{H} + \xi (F_1 + F_2) (H + ...)\} \, d\phi\]

Unpolarized beam, transverse proton target:
\[\Delta \sigma_{UT} \sim \sin \phi \text{Im} \{k (F_2 H - F_1 E) + ...\} \, d\phi\]

Polarized beam, unpolarized neutron target:
\[\Delta \sigma_{LU} \sim \sin \phi \text{Im} \{F_1 H + \xi (F_1 + F_2) \tilde{H} - kF_2 E\} \, d\phi\]

\[H_p, \tilde{H}_p, E_p\]

\[H_p, \tilde{H}_p\]

\[H_p, E_p\]

\[H_n, \tilde{H}_n, E_n\]

\[H_p(x, \xi, t) = \frac{4}{9} H_u(x, \xi, t) + \frac{1}{9} H_d(x, \xi, t)\]

\[H_n(x, \xi, t) = \frac{1}{9} H_u(x, \xi, t) + \frac{4}{9} H_d(x, \xi, t)\]
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The DVCS program worldwide

Experimental timeline

- Pioneering results from non-dedicated experiments (Hall B and Hermes): ~2001
- First round of dedicated experiments (Hall A/B, Hermes, H1&ZEUS): ~ 2005
- Second round of dedicated experiments (Halls A/B): ~2010
- Compelling DVCS program at JLab-12 GeV and Compass: 2015 and later
- EIC program...

In the valence region (JLab 6 and JLab 12)

Partially complimentary, overlapping

- Hall A/C:
  - high accuracy (~5%)
  - limited kinematic
  Test the validity of the formalism

- Hall B:
  - limited accuracy (15+%)
  - wide kinematic range
Map the GPDS
The ideal experiment

High beam energy

- ensure hard regime and large kinematic domain
- polarized beam
- availability of positive and negative leptons

variable energy for:
- L/T separation for pseudo scalar production
- $\varepsilon$ separation for $DVCS^2$ and Interference (DVCS+BH)

H$_2$, D$_2$, Longitudinally and Transversely Polarized Target

High luminosity

- small cross section
- fully differential analysis ($x_B, Q^2, t, \phi$)

Hermetic detectors

- ensure exclusivity

but does not exist (yet)
Dedicated apparatus eg the Hall A scheme

Luminosity of $\sim 5 \times 10^{37}$ Hz/cm$^2$

208 PbF2 blocks

1 GHz digitizer
Exclusivity
eg Hall A 2004 data

$H(e,e'\gamma)X$
$X$ can be
- $p: ep \rightarrow ep\gamma$
- $\gamma p: ep \rightarrow ep\pi^0, \pi^0 \rightarrow \gamma\gamma$
- $N\pi: ep \rightarrow eN\gamma\pi$
...

$M_{ep\rightarrow e\gamma X}^2$ (GeV$^2$) vs Counts
Hall A E00-110: cross section azimuthal analysis

$x_B = 0.37$, $Q^2 = 2.36$ GeV$^2$, $-t = 0.32$ GeV$^2$

$d^4\sigma = \mathcal{T}_{\text{BH}}^2 + \mathcal{T}_{\text{BH}} \text{Re}(\mathcal{T}_{\text{DVCS}}) + \mathcal{T}_{\text{DVCS}}^2$

$\text{Re}(\mathcal{T}_{\text{DVCS}}) \sim c_0^T + c_1^T \cos \phi + c_2^T \cos 2\phi$

$\mathcal{T}_{\text{DVCS}}^2 \sim c_0^{\text{DVCS}}$

$\Delta^4\sigma = \frac{d^4\sigma \uparrow - d^4\sigma \downarrow}{2} = \text{Im}(\mathcal{T}_{\text{DVCS}})$

$\text{Im}(\mathcal{T}_{\text{DVCS}}) \sim s_1^T \sin \phi + s_2^T \sin 2\phi$
Hall A E00-110: cross section $Q^2$ dependence

No $Q^2$ dependence within this limited range => leading twist dominance
Need to be checked over a larger $Q^2$ bite
Goal:

To separate the BH.DVCS interference contribution from the DVCS\(^2\) contribution.
Hall A E07-007: a glimpse of gluons through DVCS

Goal:

To separate the BH.DVCS interference contribution from the DVCS$^2$ contribution.

<table>
<thead>
<tr>
<th>Kin 1</th>
<th>Kin 2</th>
<th>Kin 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2$ (GeV$^2$)</td>
<td>1.5</td>
<td>1.75</td>
</tr>
<tr>
<td>$X_B$</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>$E_{beam}$ (GeV)</td>
<td>3.36</td>
<td>5.55</td>
</tr>
</tbody>
</table>
Towards the 3D Structure of the Proton (past 10 years)

the CFF $H$ in $Im$ DVCS

To "extract the GPDs", one can:

- Compare data to models of the GPDs
- Extract GPDs from data:
  - world-wide data fitted at once (8 quantities varying with $x_B$ and $t$), fit data points versus $\phi$ at one kinematic point choosing a limited set of GPDs.

Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013)

An encouraging proof of concept: one is looking forward to much refined data and analysis.
L/T pion production separation: E07-007

M. Defurne et al. PRL 117, 26 (2015)

4 chiral-even GPDs
4 chiral-odd GPDS (not seen in DVCS)

Leading twist, leading order factorization is only proven for $d\sigma_L/dt$

$$\frac{d^4\sigma}{dt\,d\phi\,dQ^2\,dx_B} = \frac{1}{2\pi} \Gamma_{\gamma^*(Q^2, x_B, E_e)} \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_TL}{dt} \cos(\phi) + \epsilon \frac{d\sigma_TT}{dt} \cos(2\phi) \right]$$

<table>
<thead>
<tr>
<th>Setting</th>
<th>$E$ (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$x_B$</th>
<th>$\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-Kin1</td>
<td>(3.355 ; 5.55)</td>
<td>1.5</td>
<td>0.36</td>
<td>(0.52 ; 0.84)</td>
</tr>
<tr>
<td>2010-Kin2</td>
<td>(4.455 ; 5.55)</td>
<td>1.75</td>
<td>0.36</td>
<td>(0.65 ; 0.79)</td>
</tr>
<tr>
<td>2010-Kin3</td>
<td>(4.455 ; 5.55)</td>
<td>2</td>
<td>0.36</td>
<td>(0.53 ; 0.72)</td>
</tr>
</tbody>
</table>

Dominance of $d\sigma_T/dt$ observed like at
- Hermes & Hall C $\pi^+$
- Hall B, Hall A $\pi^0$
E07-007: $\pi^0$ fully separated contributions

Models with $d\sigma_T$ factorization scheme
- G-H-L (JPG:NPP39 '12)
- G-K (EPJA47 '11)

Small $d\sigma_L$, large $d\sigma_T$: models ok on these
Wrong sign and t dependence on $d\sigma_{TL}$ and $d\sigma_{TT}$
$d\sigma_{TL}$ sizeable $\Rightarrow d\sigma_L$ is small but not null
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Physics topics:
• Search for exotic mesons
• Search for Physics beyond the Standard Model
• Study of the spin and flavor dependence of valence PDFs
• Study of modification of the quark structure in dense nuclear medium
• Study of the 3-D structure of the nucleon (GPDs-TMDs)
Overall JLab 12 GeV DVCS proposals

- E12-06-114: Hall A unpolarized protons
- E12-06-119: Hall B unpolarized protons
- E12-11-003: Hall B unpolarized neutrons
- E12-06-119: Hall B long polarized protons
- E12-12-010: Hall B tran polarized protons
- E12-13-010: Hall C unpolarized protons

Q^2 scans at various x_B
(data taking “completed” at the end of 2016)
E12-06-114 DVCS/Hall A experiment at 11 GeV

$\pi^0$'s reconstructed in DVCS calorimeter

Excellent coincident time resolution:
250 MHz beam structure

$e p \rightarrow e \gamma X$ missing mass squared

DVCS events
(1.5 h of beamtime)

Some preliminary results on $\pi^0$
E12-13-010: DVCS at 11 GeV in Hall C

- Energy separation of the DVCS cross section
- Higher $Q^2$: measurement of higher twist contributions
- Low $x_B$ extension (thanks to sweeping magnet)

- Sweeping magnet
- 1116-block PbWO$_4$ calorimeter
- Hall C HMS
- Calorimeter under construction

$Q^2$ vs $x_B$ coverage in Halls A and C

- Hall C 11 GeV
- Hall C 8.8 GeV
- Hall C 6.6 GeV
- Hall A 11 GeV
- Hall A 8.8 GeV
- Hall A 6.6 GeV
- Hall A 5.75 GeV
Towards the 3D Structure of the Proton (next 7 years?)

6 GeV data:
Hall B beam-spin asymmetries and cross sections data show potential for imaging studies from analysis in x, Q^2 and t.

6 GeV data:
Hall A data over limited Q^2 range agree with hard-scattering

12 GeV projections for Hall B:
(beam-spin and target-spin asymmetries)
transverse spatial maps

12 GeV projections for Hall A/C:
confirm formalism
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Thank you for your attention
Hall B E01-113 cross sections

$$\text{BSA} = \frac{\Delta^4 \sigma}{d^4 \sigma} \quad \text{(PRL 2006)} \quad \Rightarrow \quad \Delta^4 \sigma \quad \text{and} \quad d^4 \sigma \quad \text{(PRL115, Nov 2015)}$$

110 bins in ($x_B$, $Q^2$ and $t$)

- Compatible with Hall A results in overlapping regions
- Leading twist models describe the data within uncertainties (more than 15%)
The past and future experiments

Collider mode e-p forward fast proton
- Polarised 27 GeV e-/e+
- Unpolarised 920 GeV p
- Full event reconstruction

Fixed target mode slow recoil proton
- Polarised 27 GeV e-/e+
- Long, Trans polarised p, d target
- Missing mass technique
- 2006-07 with recoil detector

High lumi, highly polar. 6 & 12 GeV e-
- Long, (Trans) polarised p, d target
- Missing mass technique

Highly polarised 160 GeV $\mu^+$/\$\mu$-p target, (Trans) polarised target
- with recoil detection

Slide from N d’Hose, Tranversity 2014
Higher twist corrections might be necessary to fully explain experimental data. Confirmation of the significant deviation from BH => Need to measure $T^2_{DVCS}$.
Measuring DVCS to access GPDs information

\[
\frac{d^4 \sigma(\text{lp} \to \text{lp}\gamma)}{dx_B dQ^2 dt d\phi} = d\sigma^{\text{BH}} + d\sigma^{\text{DVCS}}_{\text{unpol}} + P_1 d\sigma^{\text{DVCS}}_{\text{pol}} + e_1 (\text{Re}(I) + P_1 \text{Im}(I))
\]

\( P_1 \): polarization target or beam
\( e_1 \): charge of the lepton beam
New Calorimeter

- 25 ms at 4m (two times larger than DVCS Hall A)
- PW0₄ (larger light yield-better energy resolution) or PbF₂ (Cerenkov light- no need to temperature control)
- Radiation hardness is a must (expect dose in excess of 2 Mrad)
PbF$_2$ 3X3X18 cm block
~1000 pe
for 1 GeV outgoing photon

Calorimeter energy resolution is our limiting factor in the missing mass reconstruction.

HRS $\rightarrow$ $\delta p/P \sim 10^{-4}$
Excellent!

Hall A/JLab

Simulated $M^2_X$ resolution

$\sigma_{\text{PbF}_2} = 0.229$
$\sigma_{\text{PbWO}_4} = 0.127$
Preliminary: re-analysis of 2006 data
(by grad student M. Defurne – CEA Saclay)

Better correction for events lost in reconstruction algorithm for VCD

Fiducial cuts on calorimeter to take into account $\pi^0$ subtraction efficiency

Better description of the energy resolution of the calorimeter.

Cross-sections have changed some, but the conclusions from the first article hold:
• Large contribution from the DVCS$^2$
• No contribution from the twist 3 part of the interference.
Extracting Compton form factor from the data

\[ \frac{d^4 \sigma}{dx_b dt d\phi_\gamma dQ^2} = \Gamma^G |BH|^2 + \Gamma^1 C^I(\mathcal{F}) + \Gamma^2 \Delta C^I(\mathcal{F}) + \Gamma^3 C^I(\mathcal{F}^{eff}) \]

\( \Gamma^i \): kinematic factors (calculable in experimental setup simulation)

\( C^i (= C^i, \Delta C^i, C^i_{eff}) \): Compton Form Factors obtained by fit on the data

\[ \chi^2 = \frac{(N_{\text{MC}} - N_{\text{Exp}})^2}{\sigma^2} \]

\[ N_{\text{MC}} = \int \frac{d\sigma}{d\Omega} d\Omega = \sum_{i=1}^{3} (\int \Gamma^i d\Omega) C^i \]

\( \langle t \rangle = -0.25 \text{ GeV}^2 \)

**Status:**
- Independent cross-check completed
- Rosenbluth-type fits in progress (add a \( C^{DVCS} \) term)

Black dot: data / Red histogram: MC fit

Slide from C. Desnault
DVCS on the neutron: experiment E03-106 at JLab

LD\textsubscript{2} target ($F_{2}^{n}(t) \gg F_{1}^{n}(t)$ !)

\[ \sigma^{\rightarrow} - \sigma^{\leftarrow} = \Gamma(A \sin \varphi + \ldots) \]

\[ A = F_{1}(t)\mathcal{H} + \frac{x_{B}}{2-x_{B}}[F_{1}(t) + F_{2}(t)]\mathcal{H} - \frac{t}{4M^{2}} \cdot F_{2}(t) \cdot \mathcal{E} \]

Main contribution for neutron
Ji’s sum rule on the fraction of the proton spin carried by quarks:

\[ \frac{1}{2} = J_q + J_g \quad \text{and} \quad J_q = \lim_{t \to 0} \int_{-1}^{+1} dx \ x \ [H_q(x, \xi, t) + E_q(x, \xi, t)] \]


VGG model with various parameters defining the GPD E (\( \rightarrow \) different values of \( J_u \) and \( J_d \))

Hermes:
Unpolarized beam, transversely polarized proton target

Ji, PRL 78:610 (97) VGG, Phys Rev D 60: 094017 (99)
The full DVCS amplitude (ep->epγ) is:

\[ T_{\text{DVCS}}(e^\pm) = \bar{u}(k', \lambda) \gamma_\mu u(k, \lambda) \frac{(\pm e)}{q^2} H^{\mu\nu} e^\dagger_\nu \]

The hadronic tensor is:

\[
H_{\text{LO,twist}2}^{\mu\nu} = \frac{1}{2} (-g^{\mu\nu}) \sum \left( n \cdot \gamma \mathcal{H}(\xi, t) + \frac{i}{2M} \sigma^{\kappa\lambda} \Delta \mathcal{E}(\xi, t) U(p) \right)
- (e^{\mu\nu}) \sum \left( n \cdot \gamma_5 \mathcal{H}(\xi, t) + (\gamma_5 n \cdot \Delta) \mathcal{E}(\xi, t) \right) U(p),
\]

CFFs

In practice, one exploits the azimuthal modulation of the DVCS (and its interference):

\[ |T_{\text{DVCS}}|^2 = \frac{e^6 (s_e - M^2)^2}{x_B^2 Q^6} \left\{ \sum_{n=0}^{2} c_n^{\text{DVCS}} \cos(n\phi_{\gamma\gamma}) + \sum_{n=1}^{2} s_n^{\text{DVCS}} \sin(n\phi_{\gamma\gamma}) \right\} \]

Harmonic coefficients

\[
c_0^{\text{DVCS}} = f(\text{kine}) \left\{ 4(1 - x_{Bj}) \mathcal{H} \mathcal{H}^* + 4 \left( 1 - x_{Bj} + \frac{2Q^2 + t}{Q^2 + x_{Bj}t} \frac{e^2}{4} \right) \hat{\mathcal{H}} \hat{\mathcal{H}}^* + \ldots \right\}
\]

CFFs

\[ c_{\text{unp}}^I = g(\text{kine}) \left\{ F_1 \mathcal{H} - \frac{t}{4M^2} F_2 \mathcal{E} + \frac{x_{Bj}}{2 - x_{Bj} + x_{Bj}t} \left( F_1 + F_2 \right) \hat{\mathcal{H}} + \ldots \right\} \]
At $Q^2=1.75$ GeV$^2$ and $x_B=0.36$, half of the data taken on a LD2 target.

Below the two pions threshold:

$$D(e, e'\pi^0)X = d(e, e'\pi^0)d + n(e, e'\pi^0)n + p(e, e'\pi^0)p.$$
Events with missing mass squared below 0.95 GeV$^2$:

- are divided in 12 x 2 x 5 x 30 bins in $\phi$, $E$, $t$ and $M_x^2$

  $\phi$, $E$ allow for L, T, LT and TT separation
  $M_x^2$ allows for the n/d separation

- fitted with eight cross-section function structure

$$d\sigma_{\Lambda}^{n,d}(t) \quad \Lambda = T, L, LT, TT$$

$Q^2=1.75$ GeV$^2$ and $x_B=0.36$

$E=4.45$ GeV

$t' = 0.025$ GeV$^2$

$E=5.55$ GeV

$t' = 0.021$ GeV$^2$
DVCS2n results: fully separated contributions

$Q^2 = 1.75 \text{ GeV}^2$ and $x_B = 0.36$

Goloskokov and Kroll

\[
\frac{d\sigma_T}{dt} = \Lambda \left[ (1 - \xi^2) \left| \langle H_T \rangle \right|^2 - \frac{t'}{8M^2} \left| \langle \bar{E}_T \rangle \right|^2 \right]
\]

\[
\frac{d\sigma_{TT}}{dt} = \Lambda \frac{t'}{8M^2} \left| \langle \bar{E}_T \rangle \right|^2.
\]

\[\bar{E}_T = 2 \tilde{H}_T + E_T\]
DVCS2n results: flavor separation

\[ \left| \langle H_T^{p,n} \rangle \right|^2 = \frac{1}{2} \left| \frac{2}{3} \langle H_{T,u,d} \rangle + \frac{1}{3} \langle H_{T,d,u} \rangle \right|^2 \]

Q^2=1.75 GeV^2, x_B=0.36

account for the unknown phase variation between u and the d amplitude \( \gamma^* q \rightarrow q' \pi^0 \) convoluted with \( (H,E)_T \)

Goloskokov and Kroll

- u quark
- d quark