Reminder on Generalized Parton Distributions (GDPs):
- Nucleon spin puzzle and GDPs
- Experimental access to GDPs
  - Deeply Virtual Compton Scattering
  - Deeply Virtual Meson Production ($\pi^0$)

DVCS/$\pi^0$ program at Jefferson Lab:
- Measurements at 6 GeV ($p$-DVCS, $n$-DVCS, $ep \rightarrow ep\pi^0$, $en \rightarrow en\pi^0$):
  - Results: Highlights and open questions;
  - Measurements at 12 GeV:
    - A taste of Hall A (preliminary) results
    - Ongoing and upcoming measurements and projections
Reminder on Generalized Parton Distributions (GPDs)

**Nucleon spin puzzle and GPDs**

**Nucleon Spin puzzle:**

\[ S_N = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \Rightarrow \Delta \Sigma \sim 0.3, \Delta G \sim 0.1 \text{ (ep experiments), } L_{q,g} \text{ unknown} \]

**Nucleon spin is more than the sum of the spins of its constituents!**

**Generalized Parton Distributions (GPDs)**

\[ \Rightarrow \text{Correlation } r_\perp \leftrightarrow xP \]

\[ \Rightarrow \text{constraint on partons Orbital Angular Momentum } L_{q,g} \]

\[ \int dx, \int d^2r_\perp \]

April 11th 2019
Introduction to Generalized Parton Distributions (GPDs)
Experimental access

Deeply Virtual Compton Scattering (DVCS)

Exclusive reactions
(DVCS: ℓp → ℓpy, DVMP: ℓp → ℓph)

Factorization
proved for:
Q² → ∞;
t << Q²;
finite x_Bj.

GPD(x, ξ, t)

4 “chiral-even” GPD: H, E, \tilde{H}, \tilde{E}
+ Measurement on: (p) (p⁺, n)
4 “chiral-odd” GPD: H_T, E_T, \tilde{H}_T, \tilde{E}_T

=> Access to total angular momentum J = L+S via Ji sum rule: \int dx x [H+E](t=0) = 2J

Advantages of DVCS measurement:
- “clean” (no other non-perturbative quantity than GPDs)
- DVCS amplitude accessible with DVCS/BH interference

\[ \sigma_{lp\rightarrow lp\gamma} \propto |BH|^2 + |DVCS|^2 + 2|DVCS||BH| \]
Generalized Parton Distributions: Experimental access (cont’d)

Deeply Virtual Meson Production (DVMP) $\Rightarrow \pi^0$

Exclusive reactions
(DVCS: $\ell p \rightarrow \ell p\gamma$, DVMP: $\ell p \rightarrow \ell ph$

DVMP measurements:
* not as “clean” as DVCS: depends on distribution amplitude (DA)

Advantages:
* Flavor decomposition
  (depending on meson quark content)
* different combinations of GPDs
  (depends on meson quantum numbers)

Meson electroproduction:
GPD $\Rightarrow \sigma_L(\alpha 1/Q^6)$;
GPD$_T \Rightarrow \sigma_T$: NLO but significant contribution (see $\pi^0$ results)

Here, will focus on $\pi^0$ measurements;
Come “for free” with (i.e., significant contamination of) DVCS measurements
(comparable final state and phase space)

Factorization
proved for:
$Q^2 \rightarrow \infty$;
t $\ll Q^2$ ;
finite $x_{Bj}$.

4 “chiral-even” GPD: $H, E, \tilde{H}, \tilde{E}$
+ 4 “chiral-odd” GPD$_T$: $H_T, E_T, \tilde{H}_T, \tilde{E}_T$

=> Access to total angular momentum $J$
via $Ji$ sum rule: $\int dx x [H+E](t=0) = 2J$
Reminder on Generalized Parton Distributions (GDPs):
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**DVCS/$\pi^0$ program at Jefferson Lab:**
- **Measurements at 6 GeV** ($p$-DVCS, $n$-DVCS, $ep \rightarrow ep\pi^0$, $en \rightarrow en\pi^0$):
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DVCS/$\pi^0$ program at Jefferson Lab: 6 GeV era

Jefferson Lab @ 6 GeV: $E_{\text{max}} \sim 6$ GeV in Halls A, B, C
Continuous wave electron beam, High luminosity ($I_{\text{max}} \sim 200$ µA), high polarization ($\geq 85\%$),
=> Great facility for DVCS/DVMP measurements in valence region

DVCS/$\pi^0$ measurements in Halls A, B
Measurements at 6 GeV experimental setups

Hall A:
- High luminosity: \( (\mathcal{L} \sim 10^{37} \text{ cm}^{-2} \text{ s}^{-1}) \)
- High resolution equipment:
  High Resolution Spectrometer (HRS)
  + PbF\(_2\) Calorimeter

High precision measurements

2 runs (LH\(_2\), LD\(_2\)): \( x_{Bj} = 0.36 \)

2004:
- \( E_{\text{beam}} = 5.75 \text{ GeV} \)
- \( Q^2 = 1.5, 1.9, 2.3 \text{ GeV}^2 \)

2010:
- Rosenbluth separation (2 \( E_{\text{beam}} / \text{kin} \),
- \( \text{DVCS}^2/\text{DVCS-BH}, \sigma_T/\sigma_L \)):
- \( Q^2 = 1.5, 1.75, 2.0 \text{ GeV}^2 \)

CLAS (Hall B):
- CEBAF Large Acceptance Spectrometer
  + inner calorimeter

Measurements on large kinematic coverage

=> complementarity between both halls
6 GeV measurements
Results: DVCS on proton

CLAS
First evidence of DVCS with Beam Spin Asymmetry (BSA) (ex aequo with HERMES)

Compton Form Factor $\mathcal{H}$ from cross sections [Jo et al.: Phys. Rev. Lett. 115 (2015), 212003]

\[
\begin{align*}
Q^2=1.11 \text{ GeV}^2 & \quad x_B=0.126 \\
A_f=5.30\pm0.95 & \quad b_f=4.25\pm0.98 \\
Q^2=1.63 \text{ GeV}^2 & \quad x_B=0.185 \\
A_f=4.98\pm0.56 & \quad b_f=3.03\pm0.55 \\
Q^2=2.23 \text{ GeV}^2 & \quad x_B=0.335 \\
A_f=1.44\pm1.25 & \quad b_f=1.04\pm3.68
\end{align*}
\]

CFF $\mathcal{H}$: VGG in fair agreement w/ data
CFFs $\mathcal{E}, \bar{\mathcal{E}}$ neglected
VGG:

Large data sets over large kinematic coverage

+ DVCS off longitudinally polarized proton target => GPD $\tilde{H}$
6 GeV measurements
Results: DVCS on proton

Hall A


Compton Form Factors ($x_{_Bj} = 0.36$) extracted from high precision cross sections measurements
(Defined in Belitski, Mueller, PRD82 (2010), 074010)

=> no deviation from $Q^2$ scaling.
“Generalized Rosenbluth” (DVCS\(^2\)/DVCS-BH) separation data:
Evidence of contribution beyond leading order/leading twist (gluons ?)
[Defurne et al. Nature Commun. 8 (2017) no. 1, 1408]

\[ Q^2 = 1.75 \text{ GeV}^2, \ x_{Bj} = 0.36, \ t = -0.30 \text{ GeV}^2 \]

\[ E_{\text{beam}} = 4.455 \text{ GeV} \]

\[ E_{\text{beam}} = 5.55 \text{ GeV}, \ Q^2 = 1.75 \text{ GeV}^2, \ x_{Bj} = 0.36, \ t = -0.30 \text{ GeV}^2 \]

Lingering ambiguity on what this higher order contribution is
**6 GeV measurements**

**Highlights / open questions:** $p$-DVCS off $^4$He

**Coherent $^4$He-DVCS data** [Hattawy et al., Phys. Rev. Lett. 119 (2017) no.20, 202004]
Well described by LO/LT calculations

**Incoherent $p$-DVCS off $^4$He** [Hattawy et al., arXiv:1812.07628 [nucl-ex]]
Suppressed wrt free $p$-DVCS (EMC-like effect) No existing model describes this

---

For more details on EMC, check F. Hauenstein's slides from Wednesday, session: “Production and Decays”

Solide curves: Off shell calculations: [S. Liuti and K. Taneja, Phys. Rev. C 72, 032201 (2005)]
6 GeV measurements
Highlights: global $p$-DVCS analysis

Proton tomography:
Transverse spatial distribution of partons $= f(\text{partons momentum } x)$

$$H^q_-(x,0,t) = q_v(x)e^{B^0_-(x)t} \Rightarrow \langle b^2_\perp \rangle^q(x) = 4 B^0_-(x)$$

[Dupré, Guidal, Vanderhaeghen, Phys. Rev. D95 (2017) no.1, 011501]

Model dependent extraction of GPD $H$ from $p$-DVCS data using VGG
[Vanderhaeghen, Guichon, Guidal, Phys. Rev. D60, 094017 (1999)]

Proton shrinks with increasing parton momentum

NB: COMPASS/HERA has performed a similar work, but with a different method
(see N. d’Hose talk on Friday, session “GPDs and TMDs”)
**Proton Pressure Distribution**

**Gravitational Form Factors** evaluated with DVCS data, *exploiting the relations between GPDs and proton momentum-energy tensor*:

[Burkert, Elouadrhiri, Girod, Nature volume 557, pages 396–399 (2018)]

\[
\int x \, H\left(x, \xi, t\right) \, dx = M_2(t) + 4/5 \xi^2 \, d_1(t)
\]

- \(d_1(t)\): shear force and pressure distribution term;
- \(M_2(t)\): mass term (\(M_2(0) = M_p\))

**Model dependent**

**extraction of GPD** \(H\)

**from** \(p\)-**DVCS data**

**using** VGG

[Vanderhaeghen, Guichon, Guidal, Phys. Rev. D60, 094017 (1999)]

See V. Burkert's slides from Wednesday, 1st plenary session, for more details

**Proton Internal pressure > pressure in neutron stars!!!**
**n-DVCS => GPD $E$**


$x_B = 0.36$, $Q^2 = 1.9 \text{ GeV}^2$

$n$-DVCS measurement $\Rightarrow$ **Constraint on $J_d$**

+HERMES TTSA on proton: $(J_{u,d})$

$n$-DVCS analysis with Rosenbluth separation *not finalized*, but evidence for a positive $n$-DVCS signal


April 11th 2019
6 GeV measurements

Results: $ep \rightarrow ep\pi^0$

Hall A

First $\pi^0$ cross section in valence region


$ep \rightarrow ep\pi^0$ with Rosenbluth ($\sigma_T/\sigma_L$) separation:


Experimental confirmation:

dominance of $\sigma_T(\pi^0) +$ need of GPD$_T$ for description of $ep \rightarrow ep\pi^0$.

Right: calculations with chiral odd GPDs (GPD$_T$) agree pretty well with data

**6 GeV measurements**

**Results: highlights / open questions:** \( en \rightarrow en\pi^0 \)

\( en \rightarrow en\pi^0 \) cross sections w/ Rosenbluth separation:

Combination with proton data: **first flavor separation**


(solid: \( u \); dashed: \( d \))

Fair agreement of these calculations with Hall A data.

\[
\bar{E}_T = 2 \bar{H}_T + E_T
\]

**Uncertainty of the relative phase between \( u \) and \( d \)**

Would need a \( \eta \) measurement at similar kinematic (Hall A PbF\(_2\) too small)
Curves: calculations with chiral-odd GPDs => mainly contribute to $\sigma_T$


Good agreement between these calculations and CLAS data.

**First $\pi^0$ Beam Spin Asymmetry** [De Masi et al., Phys. Rev. C77, 042201 (2008)]


CLAS


Large data sets over large kinematic coverage Confirms need of GPD$_T$ for $ep \rightarrow ep\pi^0$ description

More details in A. Kim’s talk (17:30 today, this session)
Reminder on Generalized Parton Distributions (GDPs):
• Nucleon spin puzzle and GDPs
• Experimental access to GDPs
  ➔ Deeply Virtual Compton Scattering
  ➔ Deeply Virtual Meson Production ($\pi^0$)

**DVCS/$\pi^0$ program at Jefferson Lab:**
• Measurements at 6 GeV ($p$-DVCS, $n$-DVCS, $ep \rightarrow ep\pi^0$, $en \rightarrow en\pi^0$):
  ➔ Results: Highlights and open questions;
• Measurements at 12 GeV:
  ➔ A taste of Hall A (preliminary) results
  ➔ Ongoing and upcoming measurements and projections
Measurements at 12 GeV: experimental setups/kinematic coverage

11 GeV polarized $e^-$ beam in Halls A, B, C

**HALL A+C**

*High precision measurements*

**Novelty wrt 6 GeV:**
- Hall C HMS + NPS allowing Rosenbluth separation
  (DVCS$^2$/DVCS-BH, $\sigma_T/\sigma_L$)

**Measurements on large kinematic coverage**

**Novelties:**
- Central neutron detector + LD$_2$ tgt
- ALERT + D$_2$, $^4$He targets

$\Rightarrow$ $n$-DVCS (GPD $E$), nuclei GPDs

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

$E = 11$ GeV

$W > 2$ GeV

$\Rightarrow$ complementarity between both halls
High precision DVCS cross section measurement

Analysis credit: F. Georges (IPN Orsay)

Presented at Jefferson Lab Hall A collaboration meeting 2019 (1/30/2019) by H. Rashad (ODU)

\[ d^4\sigma = \frac{d^4\sigma + d^4\sigma}{2} = |T_{BH}|^2 + |T_{DVCS}|^2 + \Re(\mathcal{F}) \]

\[ \Delta^4\sigma = \frac{d^4\sigma - d^4\sigma}{2} = \Im(\mathcal{F}) \]

(Q^2 = 3.6 \text{ GeV}^2, \quad x_B = 0.36, \quad t - t_{\text{min}} = -0.155 \text{ GeV}^2)

(As of current analysis, Q^2 scaling of CFF seems to hold)
12 GeV measurements:
A taste of Hall A 12 GeV preliminary $ep \rightarrow ep\pi^0$ results

High precision $\pi^0$ cross section measurement
Analysis credit: M. Dlamini (Ohio U.)
Presented at Jefferson Lab Hall A collaboration meeting 2019 (1/30/2019) by H. Rashad (ODU)

As of current analysis, $\sigma_T$ dominance can still be inferred from data
12 GeV upcoming measurements:
Upcoming experiments: $p$-DVCS/$\pi^0$ with Hall C HMS/NPS

NPS: Neutral Particle Spectrometer (calorimeter + sweeping magnet)

DVCS/$\pi^0$ proposal (Munoz, Paremuzian, Horn, Hyde, Roche):

NB: Other measurements planned with NPS (TCS, WACS, SIDIS, etc.)

PbF$_2$ → PbWO$_4$:
Better calorimeter resolution

Projection: $x_B = 0.6$, $Q^2 = 10$ GeV$^2$

Capability for good statistical accuracy at high $Q^2$, $x_{Bj}$

=> potential to confirm/infirm gluon contribution in valence region evidenced by Hall A Rosenbluth separation data.
12 GeV upcoming measurements:
Ongoing/upcoming experiments: $p$-DVCS/$\pi^0$ with CLAS12

DVCS measurement on proton (U+L)
(Sabatie, Biselli, Egiyan, Elouadrhiri, Holtrop, Ireland, Kim)
https://www.jlab.org/exp_prog/proposals/06/PR12-06-119.pdf

$\pi^0/\eta$ measurement on proton
(Stoler, Joo, Kubarovsky, Ungaro, Weiss)

New DVCS/$\pi^0/\eta$ measurements on large kinematic coverage

Improve statistical accuracy on:
* proton tomography;
* proton pressure distribution;
12 GeV upcoming measurements:

**Upcoming experiments: $n$-DVCS/$\pi^0$ with CLAS12**

- DVCS measurement on (unp) $D_2$ with **recoil neutron detection** (Niccolai, Sokhan)
  

- DVCS measurement on (L. pol) $D_2$ with **recoil neutron detection**
  
  (Niccolai, Biselli, Keith, Pisano, Sokhan)
  
  [https://www.jlab.org/exp_prog/proposals/16/E12-06-109A.pdf](https://www.jlab.org/exp_prog/proposals/16/E12-06-109A.pdf)

**$n$-DVCS measurements on large kinematic coverage** (mostly unexplored for n-DVCS)

Reduce systematics on the evaluation of $J_\delta$ from data
12 GeV upcoming measurements:
Upcoming experiments: CLAS12 with ALERT

DVCS ($\pi^0$) measurements on $D_2$, $^4$He, with recoil/measurement
Coherent measurements (Hadifi, Hattawy, Dupré, Meziani, Paolone)
https://www.jlab.org/exp_prog/proposals/17/PR12-17-012.pdf
Incoherent measurement (Armstrong, Hadifi, Dupré, Meziani)
https://www.jlab.org/exp_prog/proposals/17/PR12-17-012B.pdf

ALERT: A Low Energy Recoil Tracker

Detection of low energy $p$, $^3$H, $^3$He, $^4$He:
=> Recoil detection / spectator tagging
=> Unambiguous identification of coherent and incoherent DVCS
=> reduced systematics on $n$-DVCS and bound $p$-DVCS

For more details on coherent DVCS and ALERT, check Z.E. Meziani’s slides from today, session: “3D imaging”
GPDs: promising tool to solve the nucleon spin puzzle;

Jefferson Lab is a great facility to study GPDs (high luminosity, beam polarization)

A wealth of DVCS/$\pi^0$ data produced at Jefferson Lab 6 GeV, which lead to improved knowledge on nucleon structure:

=> constraint on $J_d/J_u$
=> Nucleon tomography in valence region
=> Pressure distribution in the proton
=> Role of transverse GPDs in meson production
=> First flavor separation of GPDs

Yet data did not address or raise many other questions:

=> Role of gluons in valence region
=> Ambiguities on GPD flavor separation
=> Suppression of CFF in incoherent DVCS off nuclei

By extending kinematic coverage of existing measurements, or allowing new ones, Jefferson Lab at 12 GeV will help address these questions

I could not talk about: * other DVMP channels (DV$\phi$P);
    * EIC program
    * etc...
Thank you for your attention!
Hall A

First $\pi^0$ cross section in valence region [EF et al., Phys. Rev. C83 (2011), 025201]

$\Rightarrow$ unsatisfactory description by LO GPD models + Suspicion of $\sigma_T(\pi^0)$ dominance

(reinforced by surprisingly large $\sigma_T(\pi^+)$ from Hall C data [T. Horn et al., Phys. Rev. C78 (2008), 058201])

Curves: left: VGG: [Vanderhaeghen, Guichon, Guidal, Phys. Rev. D60, 094017 (1999)]

Right: calculations with chiral odd GPDs ($\text{GPD}_T$) agree pretty well with data
$ep \to ep\pi^0$ analysis in Hall A:
Comparison with $ep \to en\pi^+$

$ep \to en\pi^+$ in Hall C

\[ \sigma_L(\pi^+) \sim 1/Q^6 \]

\[ \sigma_T(\pi^+) \sim 1/Q^5 \equiv \sigma_T + \epsilon \sigma_L(\pi^0) \]

A priori
\[ \sigma_L^{\pi^0} << \]
\[ \sigma_L^{\pi^+} \]

$\Rightarrow \sigma_T(\pi^0)$ dominant?

Longitudinally polarized proton target => GPD $\tilde{H}$

**Target single spin assymetry**

**Double spin asymmetries**

VGG
GK
KMM (Hybrid GPD fit model)
GGL (quark-diquark model)


Highlights:
DVCS on longitudinally polarized proton

Fair agreement of these GPD models with data
6 GeV measurements

Highlights: $e\vec{p} \rightarrow ep\pi^0$ (longitudinally polarized proton)

CLAS


Curves: calculations with chiral-odd GPDs $\Rightarrow$ mainly contribute to $\sigma_T$
solid: [Goldstein, Gonzalez-Hernandez, Liuti, Phys. Rev. D84, 034007 (2011)]
Overall agreement between GGL and data except for $A_{LL}^{\cos \phi}$.

More details in Andrey Kim’s talk
(17:30 today, this session)
Coherent $^4$He-DVCS

$^4$He: spin 0 => One GPD ($H_A$) to describe the system

$\Rightarrow$ \textit{CFF extracted from BSA (w/o model-dep assumptions)}

$$A_{LU}(\phi) = \frac{\alpha_0(\phi) \Im m(H_A)}{\alpha_1(\phi) + \alpha_2(\phi) \Re e(H'_A) + \alpha_3(\phi) \Re e(H''_A) + \Im m(H''_A)}$$

valid at LO, LT

DVCS/$\pi^0$ measurements at 6 GeV: Hall A setup

Hall A: **valence** region
High Resolution Spectrometer+Calorimeter
*Polarized* $e^-$ beam ($\leq 6$ GeV), fixed target:
Hydrogen, deuterium
- **High luminosity**: ($\mathcal{L} \sim 10^{37}$ cm$^{-2}$ s$^{-1}$)
- **High resolution equipment**
$\Rightarrow$ **High precision measurements**
**DVCS/π⁰ measurements at 6 GeV: Hall B setup**

**CLAS: valence region (x_{Bj} > 0.1)**

Large acceptance spectrometer

*Polarized* e⁻ beam (≤ 6 GeV), fixed target:
- hydrogen, L polarized proton
- **Kinematic coverage**;
- **multiple exclusive channels** (π, ρ, ω, ...)

2 runs during 6 GeV era:
- e1-dvcs (proton);
- eg1-dvcs (L polarized proton)
Applications:
* Tagged EMC (DIS) measurements,
* Tagged coherent/incoherent DVCS => off $D_2$, $^4He$

Separation power of recoil nuclei

$p$: det. thr.: 75 MeV/c

$^4He$: det. thr.: 244 MeV/c
COMPASS (+HERA) proton tomography
(just in case...)

Spin and charge cross section Sum: Proton size

\[ S_{CS,U} \equiv d\sigma(\mu^+) + d\sigma(\mu^-) \rightarrow d\sigma^{DVCS}/dt \sim \exp(-B|t|) \]

[R. Akhunzyanov et al., arXiv:1802.02739 [hep-ex]]

\[ b(x_{Bj}) = \frac{1}{2} \langle r^2 \rangle \]
Nucleon structure and QCD

Nucleon Spin Puzzle

\[ S_N = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

Static quark model:
\[ \Delta \Sigma = 1... \]

Experiments:
\[ \Rightarrow \Delta \Sigma \approx 0.3 \]

\[ \Delta G \ ? \ (\text{phenix, compass}) \]
\[ \Delta g/g = 0.113\pm0.038(\text{stat.})\pm0.036(\text{syst.}) \]
[Compass coll.: arXiv:hep-ex/1512.05053]

Nucleon spin is more than the sum of its constituents!

Orbital Angular Momentum \( L_{q,g} \Rightarrow \text{missing piece of spin puzzle} \)
\[ \Rightarrow \text{needs “3D” parameterization} \]
Nucleon Structure: what we "know"

Form Factors

\[ t = Q^2 \]
\[ x = x_{Bj} \]
\[ \gamma^* (Q^2, x_{Bj}=1) \]

Parton Distribution Functions

\[ x_{Bj} = Q^2 / 2p \cdot (k-k') \]
\[ W = \sqrt{s} \]
\[ s = (p+k-k')^2 \]

"Polarized" PDFs: (spin structure functions):
polarization of quarks;
Obtained with polarized \( \ell, N \)
Generalized Parton Distributions (GPDs): '3D' Structure of nucleon

In practice: GPDs encapsulated in Compton Form Factors (CFFs)

\[ F(\xi, t, Q^2) = \int_{-1}^{+1} dx \ C \left( x, \xi, \alpha_S(\mu_R), \frac{Q}{\mu_F} \right) F(x, \xi, t, \mu_F) \]

- **CFF** (complex quantity)
- **Integration kernel** (calculated up to NLO)
- **Factorization scale**
- **GPD**

Sometimes *effective* CFFs: combinations of CFFs with same kinematic dependence