Generalized Parton Distributions

Current and future programs for hard exclusive physics at JLab Hall A & C

Marie Boër (Virginia Tech)
CIPANP, Lake Buena Vista, FL, Sept 1st, 2022
Hall A and Hall C “inside the hills”

Hall A & C low acceptance high resolution spectrometer, medium energy, high intensity beam, dedicated experiments

1995 – present
Current configurations
Hard Exclusive reactions and Generalized Parton Distributions

Leading order diagrams for Compton-like, light or heavy flavored meson production at JLab

**Compton like**: DVCS, TCS, DDVCS with spacelike and/or timelike photons; multi-photons…

**Mesons**:  
- VM with the same spin-parity as for photons, factorization is proved, complement multi-channel approaches in fitting GPDs  
- Pseudo-Scalar: access “parity odd” combinations  
- Other and multi-mesons: chiral-odd GPDs… / Transitition GPDs  
- Heavy mesons, quarkonia: can we interpret in terms of GPDs at JLab?

Flavor decomposition with P vs N and with mesons
Generalized Parton distributions: 2+1D in position space

GPDs contain information about correlation between transverse distribution and longitudinal mom x.

Proton remains intact, all final particle detected: exclusive scattering

without nucleon spin flip

unpolarized GPDs

“vector”

polarized GPDs

“axial-vector”

with nucleon spin flip

quark spin

proton spin

“tensor”

“pseudo-scalar”
Motivations

3D mapping of the nucleon \Rightarrow tomography

Transverse parton distributions for different regions in $x$
\rightarrow probabilistic interpretation $\equiv$ gluons, valence quark regions

"momentum dissected Form Factors"

integral over $x$

parton densities from Deep Inelastic Scat.

Spin physics: sum rules...
Multi-reactions fitting approach

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

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

Compton Form Factor
Indirect access to GPDs
Here: propagator for DVCS or TCS. With DDVCS or HEMP, “lever arm” with \( Q'^2 \) or \( M \)

\[ \xi, \ t = \text{measurable} \]
\[ x = \text{loop} \]
\[ x \pm \xi = \text{propagator} \]

Im part \( \rightarrow \) GPD at \( x = \pm \xi \)
DVCS and TCS unpol \( \sigma \), single spin pol. \( \sigma \)

Off diagonal:
DDVCS, HEMP

\( \Rightarrow \) multi-observables / multi-reactions fitting approach
Here LO and leading twist
Context

Complementarity with world-wide experiments and JLab 6 GeV era measurement (fig. From C. Munoz, 2014, not the most up to date)
DVCS recent measurements in Hall A

E12-006-114 experiment
2014-2016
11 GeV electron

PbF2 calorimeter
Electron in spectrometer
Missing mass for the proton
DVCS in Hall A
Published in PRL 128, 252002 (2022), F. Georges et al.

Kinematics and unpolarized cross sections

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_B$</td>
<td></td>
<td>0.36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_p$ (GeV)</td>
<td>7.38</td>
<td>8.52</td>
<td>10.59</td>
<td>4.49</td>
<td>8.85</td>
<td>8.85</td>
<td>10.99</td>
<td>8.52</td>
<td>10.59</td>
</tr>
<tr>
<td>$Q^2$ (GeV$^2$)</td>
<td>3.20</td>
<td>3.60</td>
<td>4.47</td>
<td>2.70</td>
<td>4.37</td>
<td>5.33</td>
<td>6.90</td>
<td>5.54</td>
<td>8.40</td>
</tr>
<tr>
<td>$E_t$ (GeV)</td>
<td>4.7</td>
<td>5.2</td>
<td>6.5</td>
<td>2.8</td>
<td>4.7</td>
<td>5.7</td>
<td>7.5</td>
<td>4.6</td>
<td>7.1</td>
</tr>
<tr>
<td>$-t_{min}$ (GeV$^2$)</td>
<td>0.16</td>
<td>0.17</td>
<td>0.17</td>
<td>0.32</td>
<td>0.34</td>
<td>0.35</td>
<td>0.36</td>
<td>0.66</td>
<td>0.70</td>
</tr>
<tr>
<td>$\int Q dt$ (C)</td>
<td>1.2</td>
<td>1.7</td>
<td>1.3</td>
<td>2.2</td>
<td>2.2</td>
<td>3.7</td>
<td>5.7</td>
<td>6.4</td>
<td>18.5</td>
</tr>
</tbody>
</table>

Number of data bins

672 912 480

12 CFFs with higher twists, fix xbj & t with E, Q², t, xbj dependence.

All CFF extracted and correlations taken into account. H (Im and Re) extracted
Compatible with 0 for helicity-flip CFFs: complementary measurements to come / other Halls
Hard Exclusive neutral pion in Hall A
Published in PRL 127, 152301 (2021), M. Dlamini et al.

Kinematics

<table>
<thead>
<tr>
<th>$x_B$ label</th>
<th>0.36</th>
<th>0.36</th>
<th>0.36</th>
<th>0.48</th>
<th>0.48</th>
<th>0.46</th>
<th>0.46</th>
<th>0.59</th>
<th>0.60</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle x_B \rangle$</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
<td>0.48</td>
<td>0.45</td>
<td>0.46</td>
<td>0.46</td>
<td>0.59</td>
<td>0.60</td>
</tr>
<tr>
<td>$E$ (GeV)</td>
<td>7.38</td>
<td>8.52</td>
<td>10.59</td>
<td>4.49</td>
<td>8.85</td>
<td>8.85</td>
<td>10.99</td>
<td>8.52</td>
<td>10.59</td>
</tr>
<tr>
<td>$Q^2$ (GeV$^2$)</td>
<td>3.11</td>
<td>3.57</td>
<td>4.44</td>
<td>2.67</td>
<td>4.06</td>
<td>5.16</td>
<td>6.56</td>
<td>5.49</td>
<td>8.31</td>
</tr>
<tr>
<td>$W^2$ (GeV$^2$)</td>
<td>6.51</td>
<td>7.29</td>
<td>8.79</td>
<td>3.81</td>
<td>5.62</td>
<td>6.67</td>
<td>8.32</td>
<td>4.58</td>
<td>6.46</td>
</tr>
<tr>
<td>$-t_{\text{min}}$ (GeV$^2$)</td>
<td>0.16</td>
<td>0.17</td>
<td>0.17</td>
<td>0.33</td>
<td>0.35</td>
<td>0.35</td>
<td>0.36</td>
<td>0.67</td>
<td>0.71</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>0.61</td>
<td>0.62</td>
<td>0.63</td>
<td>0.51</td>
<td>0.71</td>
<td>0.55</td>
<td>0.52</td>
<td>0.66</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Extracted pion structure function (all kinematics): large higher twist effects? L/T separation will be complemented by other experiments

$\sigma_{TT}$ (blue triangles), $\sigma_{LT}$ (red squares), $\sigma_{LT0}$ (green stars)
--- with transversity GPDs (GK)
Upcoming DVCS program in Hall C

Complement phase space and statistics
DVCS “moved” to Hall C with new spectrometer
HMS and NPS

Up to 11 GeV electron
Missing mass for proton

DVCS proton experiment expected in 2023

Neutron experiment approved at PAC52 (2022)
New calorimeter: Neutral Particle Spectrometer (NPS)

FIGURE 3: Hall C Layout for the DVCS.

(a) Structural design of the calorimeter.
(b) Earliest design of the carbon frame for the calorimeter.

From Ho-San Ko, 2020
NPS spectrometer currently being assembled (by the end of the year)
Pictures from July 2022
NPS spectrometer currently being assembled (by the end of the year)
Pictures from July 2022

Many contributors and institutes, here the Orsay group engineers and technicians in July 2022 at JLab
Future with positron beam? (projections for Hall C)

Projected cross sections at various kinematics

hep/ex-2105.06540, Afanasev et al.
Future with positron beam? (projections for Hall C)

Projected extracted CFFs with electron+positron DVCS results

hep/ex-2105.06540, Afanasev et al.
Other reactions for multi-channel CFF extraction

- some meson measurements have been done, but not with a “GPD physics” emphasis (not presented here)

- non-DVCS (or pion) measurements belong to the future in Hall A & C

Compton-like reactions (proposed projects for Hall A & C presented here)

Hard Exclusive Meson production (not discussed here)
Future: proposed Timelike Compton Scattering in Hall C

**Experimental setup**

\[ \gamma P \rightarrow e^+ e^- P' \]

**All 3 final particles in coincidence detected**

Integrated luminosity: \(5.85 \times 10^5 \text{ pb}^{-1}\) for 30 PAC days of "physics"

- 11 GeV
- 85\% pol.
- 2.5 \(\mu\)A

**Electron (CEBAF)**

- Compact Photon Source (CPS)
- Transverse polarized \(\text{NH}_3\) target (DNP)
  - 3 cm long (JLab/UVa)
- 5.5-11 GeV photons, 50-85\% circularly polarized
  - \(1.5 \times 10^{12}\) \(\gamma/\sec\)

**Top view cartoon**

- ~2m
- ~1.5m

**Trigger:** GEMs, hodoscopes, calorimeters (all 3 particles)

PAC52 (deferred) encourages the efforts and loves the physics, but several technical aspects need more efforts/people in particular to handle high rates. The collaboration is actively working on returning
Future: proposed Timelike Compton Scattering in Hall C

Compact Photon Source

Compact Photon Source under development in Hall C at JLab:

• Combines polarized photon source, collimator and beam dump;
• High intensity directed brem. photon beam \(1.5 \times 10^{12} \text{ y/s in [5.5 GeV, 11 GeV]}\) range from 2.5 \(\mu\text{A primary e- beam on 10\% } X_0 \text{ Cu radiator}, \sim 1 \text{ mm spot size at 2 m from radiator)};\n• 3.2 T warm magnet to bend incoming electrons to local beam dump;
• Highly shielded design (W/Cu alloy) to minimize prompt and residual radiation.

CPS can also be used in Hall A and with SoLID (later in this talk) for high intensity un-tagged photon beam measurements. For GPDs: TCS, heavy mesons, multiple mesons...
Future: proposed Timelike Compton Scattering in Hall C

Dependence in GPD parametrization and $J_u$, $J_d$ (VGG model) vs $\varphi$ and $\varphi_S$

TSA with various quark angular momenta scenarios (choice of same parameters as Jlab DVCS experiments)

- strong model dependence
- large sensitivity to angular momenta

Sinus momenta versus spin angle
=> discriminates model
=> huge dependence in J(quarks)

BH cancels: asym from Compton contribution
TCS with SoLID spectrometer

Unpolarized and beam polarized cross sections

SoLID spectrometer

High intensity and large acceptance. Highly considered for future in Hall A.
TCS with SoLID high precision measurement for GPDs universality

unpolarized x-sec vs $\phi$, sensitivity to D-term (GPD $H = VGG$)

Unpolarized cross section
- Beam spin asymmetry

parametrization and $t$-dependence of beam spin asymmetry

statistics in 2 bins in $t$, bin #3 ($Q'^2, \xi$)
Global fits of Compton Form Factors with TCS

5) $\sigma, \Delta \sigma_{LU}, \Delta \sigma_{UT}$ (x2)
$\Delta \sigma_{UL}, \Delta \sigma_{LL}, \Delta \sigma_{LT}$ (x2)
1% error/16 bins $\phi$

8 independent variables for each process: all unpolarized and polarized cross section differences
$t=.2 \text{ GeV}^2, \xi=.15, Q^2=2 \text{ GeV}^2 \text{ or } Q'^2=4.5 \text{ GeV}^2, E=11 \text{ GeV for DVCS, } \theta=90^\circ \text{ for TCS}
at asymptotic limit

This figure: assumes Hall A + Hall C + complementary measurements.
SoLID only: universality studies for GPD H, with Hall C: GPD E
SoLID DDVCS: LOI in 2015, not yet turned into full proposal. Recent physics and technical developments taken into consideration, the collaboration aims at coming soon with a new version.

Hall C DDVCS: in progress, not yet proposed.

Going “off-diagonal” with DDVCS, extrapolation to zero skewness for tomographic interpretations.

\[ T^{DDVCS} \sim \int_{-1}^{1} \frac{H(x, \xi, t)}{x - (2\xi' - \xi) + i\varepsilon} \, dx + \ldots \sim P \int_{-1}^{1} \frac{H(x, \xi, t)}{x - (2\xi' - \xi)} \, dx - i\pi H(2\xi' - \xi, \xi, t) + \ldots \]

\[ \xi' = \frac{x_B}{2 - x_B}, \quad \xi = \xi' \cdot \frac{Q^2 + Q'^2}{Q^2} \]

→ lever arm by varying \( Q^2 \) vs \( Q'^2 \) to vary the propagator and extract CFF at \( x \neq \pm \xi \)
→ equivalent to meson mass in DVMP, without adding complication from DA parametrization.
Accessing GPDs with Double Deeply Virtual Compton Scattering

• $\xi = +$ component of $P=(p+p')$ in light cone frame. GPDs depend on it. "skewness"

• $\xi' = +$ component of $\overline{q}=(q+q')/2$ in light cone frame. Quark propagator can be related to $x_{bj}$

Special cases (at asymp. limit):
DVCS: $\xi'=\xi$; TCS: $\xi'=-\xi$

What do we learn?
M. Diehl's representations:

DGLAP $\overline{q}$

ERBL

DGLAP $q$

limit between the 2 regions:
Im(CFFs) from DVCS and TCS

accessible with DDVCS

(q)

partonic interpretation from M. Diehl in ERBL region

(q)
11 GeV “off diagonal”

“spacelike”

access only at large -t

this zone will be statistically excluded and risk of too high systematics

“timelike”
DDVCS with SoLID: proposed experimental setup

- $J/\Psi$ setup: electrons, (proton)
- CLEO muon chambers: muon pair

50 days at $10^{37}$ cm$^{-2}$

“reasonable” rates: measurement feasible

Figure 10: CLEO II setup with muon chambers installed inside the iron yoke.
Muon detection @ SoLID

Detector Configuration

SoLID (DDVCS, JPsi/TCS)

(citation A Camsonne)
Prospects for DDVCS at JLab Hall C: \( e \; P \rightarrow e' \; \mu^+ \mu^- \; P \)

- Measurements: \( \sigma(\text{unpol.}) + \text{asymmetry(beam)} \)
- GPDs can be extracted from 2D fits: \( \phi_{\text{pair}} \) vs \( \phi_L \) at fix \( E, x_{bj}, t, (Q^2, Q'^2) \) if no evolution

"off diagonal" GPD access: \( \xi' (\pm x) \) vs \( \xi \),

\[ \langle -t \rangle = 0.25 \text{ GeV}^2 \]

One idea for a setup in Hall C:
80 days at 75 \( \mu \)A, LH2 target. \( L=5.10^{38} \text{ cm}^{-2}\text{s}^{-1} \)

Other setups “investigated”
- DVCS-like setup with proton detector + HMS + muon segmented hodoscopes
- Similar with Hall A SBS spectrometer, for experiment in Hall C
SUMMARY

History of high precision DVCS measurement since 2005, in the 6 GeV era

Recent publications of DVCS Hall A results

CFFs extracted from DVCS

Upcoming DVCS in Hall C with new NPS spectrometer

Flavor decomposition with neutron

Multichannel:

CPS for high intensity photon beam

TCS, DDVCS programs (proposed/in progress)

Meson: worth more experiments

Future SoLID spectrometer, potential energy upgrade, positron beam, new reactions...