Multichannel approach for new GPD sensitive experimental measurements

Marie Boër et al., Virginia Tech

Presented work also includes: Debaditya Biswas, Brannon Semp, Tyler Schroeder, Erik Wrightson, Camille Zindy (VT); Vardan Tadevosyan (ASNL), Alexandre Camsonne (JLab), Zhiwen Zhao (Duke); And other Hall A and Hall C collaborators

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Motivations

Among other interpretations: tomographic views
- need to extrapolate GPDs to zero skewness
- need to constrain all GPDs and reduce correlation uncertainties
* focusing on quarks and “JLab” energies here

3D mapping of the nucleon ⇒ tomography

Transverse parton distributions for different region in x
→ probabilistic interpretation ≡ gluons, valence quark regions

"momentum dissected Form Factors"

parton densities from Deep Inelastic Scat.

transverse charges from Elastic Scat.

gluons dominate

 gluons, sea quarks "meson cloud"

valence quarks region

t=0
Motivations

GPDs with Compton-like reactions

Leading order / leading twist generic handbag diagram
For “lower” energy experiments (JLab…)

DVCS: final photon is real, incoming is spacelike
(calling it Spacelike Deeply Virtual Compton Scattering)

TCS: incoming is real, final is timelike
(calling it Timelike Deeply Virtual Compton Scattering)

DDVCS: incoming is spacelike, outgoing is timelike
Double Deeply Virtual Compton Scattering

Quark GPDs; as function of x (∥ momentum fraction), xi (skewness), t (squared momentum transfer)

+ $Q^2$, $Q'^2$: evolution not being taken into account in this work. $Q^2/Q'^{2}$ relevant for DDVCS

Can be seen as the “cleanest” way to access GPDs, since only one non-perturbative part
Most measurements = DVCS; GPD models constrained by DVCS mainly
(see Pierre’s and Kresimir’s talks this session for TCS and complementarity in GPD modeling)
Complementarity
Compton-like processes

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

\[ (\text{similar for TCS}) \]

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

With \( \xi' = \frac{x_B}{2 - x_B} \) and \( \xi = \xi' \cdot \frac{Q^2 + Q'^2}{Q^2} \) (our notations, VGG models for JLab projections)

TCS and DVCS access \( \text{Im}(\text{CFFs}) \) at \( x = x_i \)

\( \Rightarrow \) complementary measurements, access same CFFs,
- GPD universality studies with independent TCS data set
- higher twist/order studies in comparison, can help understanding “effects” seen in DVCS
- combined data set for additional constraints to GPDs

DDVCS gives a lever arm for going “off diagonal”, needed to extrapolate to zero skewness
- tomographic interpretations
- can move from “timelike” to “spacelike” region
- complementary observables for GPD data sets
Multichannel fit approach

“diagonals” with DVCS and TCS, “off diagonal” ERBL region with DDVCS

Slightly off diagonal with light mesons (meson mass gives lever arm)

However, unclear for gluon GPDs in this approach (gluon loop)

\[ \text{Re part} \rightarrow \int dx \text{ GPD}
\]

\[ \text{DVCS and TCS, unpol or double pol. } \sigma \]

or charge asymmetries

\[ \text{Im part } \rightarrow \text{GPD at } x = \pm \xi 
\]

DVCS and TCS unpol \( \sigma \), single spin pol. \( \sigma \)

Off diagonal: DDVCS, HEMP

GPD in VGG model, from Guichon, Vanderhaeghen, Guidal
Image: M. Guidal
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 $\bar{q}=(q+q')/2$ 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 $\bar{q}$ accessible with DDVCS
- ERBL
- DGLAP $q$

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

Partonic interpretation from M. Diehl in ERBL

$q$ accessible with DDVCS

$(q)\ (\bar{q})$ (partonic interpretation from M. Diehl in ERBL region)
Full phase space to go “off diagonal” with DDVCS using a 11 GeV beam.
What can we do with meson?

- Several measurements at JLab, mainly Hall B. Rho is the “easiest” to measure given larger cross section and pion decay channel. *see presentations related to Hall B.

For JLab Hall A & C, high precision measurements with lower acceptance

- measurements of pseudo-scalars (pion…) together with DVCS
- Other mesons can be measured up to J/psi mass with 11 GeV beam

* Light vector meson:
  - no officially existing program yet for Hall C
  - projection made by SoLID collaboration (Hall A)
  => can existing data be used?
  => developing dedicated experiments for rho and omega

* Quarkonia
  - J/psi measured in Hall C (unpolarized) and approved with SoLID (see J/psi-007 and SoLID collaborations results/projections)
  - can we have a GPD interpretation near threshold?

No results yet for Hall C, Projections in progress
Working on developing such a program (Deb. Biswas et al)

Exploring what can be done further: polarized targets… (Erik Wrightson et al)

VT group & collaborators
Other groups have independent approaches also interesting in a GPD perspective
Experimental programs with SoLID for GPDs

SoLID (SIDIS and J/ψ)

TCS: approved experiment, together with J/ψ (ranked A by PAC50)
DDVCS: LOI in 2015, collaboration has updated projections but no full proposal yet
Mesons: some approved measurements, other projections in progress
TCS with SoLID high precision measurement for GPDs universality

\[
\gamma P \rightarrow e^+e^- P' = \text{TCS}
\]

\[
\gamma(q) \rightarrow \gamma^*(q')
\]

\[
\gamma^*(q') \rightarrow e^+(k')
\]

\[
e^-(k)
\]

\[
\text{GPD} \quad (x, \xi, t)
\]

\[
\text{FF} \quad (t)\]

SoLID: using quasi-real photon from 5 to 11 GeV, circularly polarized

5 independent variables if unpolarized

+1 with transverse target (phi_S)
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 polarized cross section differences

large acceptance and high intensity measurement will enable access to cross sections
- extracting GPD $H$ with enough precision level for GPD universality studies
- complement other TCS programs (need unpolarized cross section as “basis”)
- complement DVCS measurement in multi-channel fit approach
TCS with SoLID high precision measurement for GPDs universality

- Unpolarized cross section
- Beam spin asymmetry

Projections with quasi-real photon beam. Possibility for dedicated experiment with real photon, using CPS and slightly modified design

Compact Photon Source under development in Hall C at JLab:

- Combines polarized photon source, collimator and beam dump;
- High intensity directed bremsstrahlung photon beam \(1.5 \times 10^{12} \text{ photon/s in [5.5 GeV, 11 GeV]}\) range from 2.5 \(\mu\text{A}\) primary electron beam on 10% \(X_0\) Cu radiator, \(\sim 1\) mm spot size at 2 m from radiator;
DDVCS with SoLID

Unpolarized DDVCS. Below: Feynman diagram at leading twist/order for DDVCS & interfering BH

DDVCS
Access GPDs
\( Q^2 \neq Q^2 \) & greater than 1 GeV²
Depends on \( x, x_i, t + \) evolution

BH “type I”
(behavior similar to DVCS one)
depends on Form Factors (t), calculable

BH “type II”
(behavior similar to TCS one)

With 11 GeV polarized electron beam
7 independent variables for unpolarized DDVCS
DDVCS with SoLID: proposed experimental setup

- J/Ψ setup: electrons, (proton)
- CLEO muon chambers: muon pair

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

“reasonnable” rates: measurement feasible
Perspectives for high precision measurements with dedicated high intensity experiments at JLab Hall C

TCS: off proton and neutron, polarized and unpolarized

Opens to multi-observables to constrain all leading order, leading twist CFFs
+ flavor separation with neutron

DDVCS: dedicated setup will enable high intensity measurement

- statistics is the limiting factor with DDVCS, besides technical difficulties
- need a muon detector
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/\text{sec}

Top view cartoon

\(\sim 2\text{m}\)
\(\sim 1.5\text{m}\)

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

PAC50 (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...
Proposed Timelike Compton Scattering in Hall C

\[ \gamma + p \rightarrow \gamma^* (e^+ + e^-) + p' \]

Compact Photon Source and Neutral Particle Spectrometer collabs, JLab Hall C

- Detect \(e^+, e^-, p\) in coincidence
- CPS bremsstrahlung photon beam
- UVA/Jlab NH\(_3\) target, transversely polarized
- Detectors arranged in 4 quarters, oriented to target
- Triple-GEMs for \(e^+, e^-, p\) tracking
- Hodoscopes for recoil proton detection/PID
- PbWO\(_4\) calorimeters for \(e^+, e^-, p\) detection/PID

Slide Credit: V. Tadevosyan
Proposed Timelike Compton Scattering in Hall C

To be measured: single and double spin asymmetries with transversely polarized target

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 \( J(\text{quarks}) \)

BH cancels: asym from Compton contribution
Double spin asymmetries, 1 bins as example (from B. Semp)

Projected (ideal) BTSA distributions
Evolutions of the shapes vs $\Phi$, bins in $\Phi_s$ from 0 to $\pi$ at intermediate $\xi$ and for 2 bins in $t$

Low - $t$ (intermediate $\xi$)

- Harmonic structure of BTSA mostly depends on $t$ and $\xi$ bins
- BH doesn’t cancel, nor is it TCS “only”. Harder to interpret but any information is a major input to models and especially for discriminating Double Distribution “types” vs other kinds (strongly differ on Re CFF)

Unique access to real part. GPDs H and E, best way to access them

Doing TCS is technically more difficult than DVCS, but real photon beam off polarized target enables use of DNP transverse target without much depolarization effects
Double spin asymmetries, 1 bins as example (from B. Semp)

TCS+BH Interference

0<Φₜ<π/4

Asymmetry vs phi for 0.200000 c < 1.000000
and 0.200000 c > 0.590000

Entries: 4
Mean: -0.21
Std Dev: 0.31

π/4<Φₜ<π/2

Asymmetry vs phi for 0.200000 c < 1.000000
and 0.200000 c > 0.590000

Entries: 421
Mean: 0.18
Std Dev: 0.18

θ integrated over [70°, 110°]

0.22 < ξ < 0.35,

Asymmetry vs phi for 0.200000 c < 1.000000
and 0.200000 c > 0.590000

Entries: 6
Mean: -0.21
Std Dev: 0.31

π/2<Φₜ<3π/4

Asymmetry vs phi for 0.200000 c < 1.000000
and 0.200000 c > 0.590000

Entries: 0
Mean: 0
Std Dev: 0

3π/4<Φₜ<π

Asymmetry vs phi for 0.200000 c < 1.000000
and 0.200000 c > 0.590000

Entries: 0
Mean: 0
Std Dev: 0

Dominated by BH

0<Φₜ<π/4

Asymmetry vs phi for 0.200000 c < 1.000000
and 0.200000 c > 0.590000

Entries: 598
Mean: 0.18
Std Dev: 0.18

π/4<Φₜ<π/2

Asymmetry vs phi for 0.200000 c < 1.000000
and 0.200000 c > 0.590000

Entries: 87
Mean: 0.18
Std Dev: 0.18

θ integrated over [0°, 70°] and [110°, 180°]

0.2 < -t < 1 GeV²

Asymmetry vs phi for 0.200000 c < 1.000000
and 0.200000 c > 0.590000

Entries: 17
Mean: -0.21
Std Dev: 0.31

Asymmetries integrated inside [70°, 110°] show more extreme negative values compared to outside, which is only RH

Observable: BTSA, reduced from BH. Will fit the “full” BTSA in dynamic theta integration range. As a function of phi and phi_S
Other (yet to be proposed to PAC) upcoming TCS in Hall C
For universality studies and multi-channel DVCS+TCS fit approach

From C. Zindy

-t dependent cross sections, projection
For 30 days in hall C with similar setup as for polarized TCS, LH2 and LD2 targets

- Both found to be measurable
- Background easier than polarized (less “high rate” in transverse region)
- CFFs can be extracted

x6 statistics between proton and neutron

Binning in these studies, 5-11 GeV photon:

Status: updating projections with setup and background,
To be proposed in 2023.
Unpolarized+beam p & n. Next: longitudinal target
Global fits of Compton Form Factors with TCS

8 independent variables for each process: all unpolarized and polarized cross section differences
- $t=0.2\text{ GeV}^2$, $\xi=0.15$, $Q^2=2\text{ GeV}^2$ or $Q'^2=4.5\text{ GeV}^2$, $E=11\text{ GeV}$ for DVCS, $\theta=90^\circ$ for TCS
at asymptotic limit

7% error/16 bins $\phi$

5) $\sigma, \Delta\sigma_{LU}, \Delta\sigma_{UT}$ (x2)
$\Delta\sigma_{UL}, \Delta\sigma_{LL}, \Delta\sigma_{LT}$ (x2)

DVCS

TCS

DVCS+TCS

This figure: assumes Hall A + Hall C + complementary measurements.

SoLID only: universality studies for GPD H, with Hall C: GPD E
Prospects for DDVCS at JLab Hall C: $e P \rightarrow e' \mu^+\mu^- P$

- measurements: $\sigma$(unpol.) + asymmetry(beam)
- GPDs can be extracted from 2D fits: $\varphi_{\text{pair}}$ vs $\varphi_L$ at fix $E$, $xbj$, $t$, ($Q^2$, $Q'^2$ if no evolution)

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

- one idea for a setup in Hall C:
  80 days at 75 μA, LH2 target. $L=5.10^{38}$ cm$^{-2}$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
Binning in $\xi$, $\xi'$, all $t$

Bins in $t$: (1) $0 < -t < 0.15$ GeV$^2$, (2) $0.15 < -t < 0.35$ GeV$^2$, (3) $0.35 < -t < 0.55$ GeV$^2$ (indicated ', '')

- choice of limited acceptance: few bins, high intensity → some bins may be empty or limited statistic
- no binning in $Q^2$ and $Q'^2$: the above selections are cutting bands in the $Q^2$ vs $Q'^2$ distribution
- next 3 slides: same figure $\xi'$ vs $\xi$, separated for the 3 bins in $t$
Kinematic region we access with Hall C and setups we are looking for

excluded
interpretation?

where do we want to have measurement?
this show how much "out of diagonal" we can go

excluded, out of perturbative handbag approach (assuming small t)
→ playing with larger t could get data in this region?
→ but in this case all approximations need to be waved and must be very careful about interpretations
→ also need to be very careful in this region: resolution in t !!!
ideal detector position for different bins, assuming previous distributions "at vertex" are similar to the one with magnetic field symmetric configuration for $\mu^+$ and $\mu^-$ ⇒ better for interpretation and treatment of BH2

We need to detect all final particles for resolution in $t$

Trigger on muon pair

LH2 target

11 GeV polarized $e^-$

recoil proton $10^\circ \rightarrow 40^\circ$

Dedicated recoil (GEM, hodos)

$P'$

$\mu^+$

Segmented 4 layers hodoscopes

$\mu^-$

Will measure TCS+DVCS at the same time

Extension of TCS setup
ideal detector position for different bins, assuming previous distributions "at vertex" are similar to the one with magnetic field symmetric configuration for $\mu^+$ and $\mu^-$ ⇒ better for interpretation and treatment of BH2

We need to detect all final particles for resolution in $t$

Trigger on muon pair

11 GeV polarized $e^-$

LH2 target

recoil proton $10^\circ \rightarrow 40^\circ$

Dedicated recoil (GEM, hodos)

$P'$

HMS or SBS

Segmented 4 layers hodoscopes

Extension of DVCS setup
With recoil detector
And muons hodoscopes + trigger
Can get DVCS, J/psi and limited TCS at the same time
Our plans for transversely and longitudinally polarized J/ψ in Hall C

- similar as TCS setup
- larger calorimeter angles

Goal: J/ψ production mechanism with 2 gluons exchange or dominated by higher twist
- bringing constrain to models
- when can we start to have a GPD interpretation?

(E. Wrightson et al)
SUMMARY

Accessing GPDs from multiple reactions
- GPD models with multichannel fits
- universality
- extrapolation to zero skewness

Existing programs at JLab (not in this talk)

SoLID large acceptance spectrometer
- several approved experiments: TCS…

Hall C dedicated experiments
- several DVCS measurements approved
- TCS program partially submitted, still some work and other observables to submit
- light VM program in progress
- going further with polarized J/psi?

THANK YOU