Experimental Overview of Deeply Virtual Exclusive Reactions

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Nucleon spin comes from the spin and orbital motion of quarks and gluons
--- Chairman Mao
Deeply Virtual Exclusive Processes - Kinematic Coverages

Study of high $x_B$ domain requires high luminosity

Volker Burkert, Workshop on Positrons at JLab
Bethe-Heitler and Virtual Compton Scattering (VCS)

\[ ep \rightarrow ep \gamma \]

\[ k \rightarrow k' \quad q' \]

\[ p \rightarrow p' \]

\[ q' = \Delta + q \]

- **BH-DVCS interference**
  - Access to DVCS amplitude, linear in GPDs
Leading Order (LO) QCD Factorization of DVCS

• Symmetrized Bjorken variable:

\[ \xi = \frac{-(q + q')^2}{2(q + q') \cdot P} \]

\[ \Delta^2 \ll Q^2 \]

\[ \frac{x_B}{2 - x_B} \]

• SCHC
  - Tranversely polarized virtual photons dominate to \( O(1/Q) \)
HERA-H1 DVCS-dominated and BH-dominated events

$e p \rightarrow e \gamma X$

$X$ is ultra-forward, no visible energy $\rightarrow$ dominated by exclusive

$e^+ $
HERA DVCS, fits by D. Müller et al., 2012 for EIC whitepaper

**good DVCS fits at LO, NLO, and NNLO with flexible GPD ansatz**

- **(a)**
  - $\frac{d\sigma}{dl} \left( \gamma^* p \rightarrow \gamma p \right)$ [nb/(GeV$^2$)] vs $-l$ [GeV$^2$]
  - $W = 82$ GeV

- **(b)**
  - $\sigma(\gamma^* p \rightarrow \gamma p)$ [nb]
  - $\sigma_W$ vs $Q^2$ [GeV$^2$]
  - Data points for $H1$ (HERA I), $W = 82$ GeV, $H1$ (HERA II), $W = 82$ GeV, ZEUS, $W = 89$ GeV

- **(c)**
  - $\sigma(\gamma^* p \rightarrow \gamma p)$ [nb]
  - $\sigma_W$ vs $W$ [GeV]
  - Legend: same as on (a)

- **(d)**
  - $F_2$ vs $Q^2$ [GeV$^2$]
  - Graphs showing $F_2$ for different $Q^2$ values
What do DVCS experiments measure?

- \( d\sigma(ep \rightarrow ep\gamma) = \text{twist-2 (GPD) terms} + \Sigma_n [\text{twist-}n]/Q^{n-2} \)
  - Isolate twist-2 terms \( \rightarrow \) cross sections vs \( Q^2 \) at fixed \((x_{Bj}, t)\).

- \( GPD \) terms are `Compton Form Factors’

\[
CFF(\xi, \Delta^2) = \frac{1}{\pi} \int_{-1}^{1} dx \frac{GPD(x, \xi, \Delta^2; Q^2)}{x \pm \xi \mp i\varepsilon}
\]

- \( Re \) and \( Im \) parts (accessible via interference with BH):

\[
\text{Im} \left[ CFF(\xi, \Delta^2) \right] = \pi \left[ GPD(\xi, \xi, \Delta^2) \pm GPD(-\xi, \xi, \Delta^2) \right]
\]

\[
\text{Re} \left[ CFF(\xi, \Delta^2) \right] = \varnothing \int dx \frac{GPD(x, \xi, \Delta^2)}{x \pm \xi}
\]

\[
\text{D.R.} \rightarrow \varnothing \int d\xi' \frac{GPD(\xi', \xi', \Delta^2)}{\xi' \pm \xi} + D(\xi)
\]
**DVCS, GPDs, Compton Form Factors (CFF), and Lattice QCD**

(at leading order:)

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

Cross-section (\(\sigma\)) measurement and beam charge difference (Re\(T\)) integrate GPDs with \(1/(x \pm \xi)\) weight.

Beam or target spin \(\Delta \sigma\) contain only Im\(T\), therefore GPDs at \(x = \xi\) and \(-\xi\).

Lattice Moments

\[
= \int x^n H(x, \xi, t) \, dx
\]
Exploiting the harmonic structure of DVCS with polarization

The difference of cross-sections is a key observable to extract GPDs

With polarized beam and unpolarized target:
\[ \Delta \sigma_{LU} \sim \sin \varphi \left\{ F_1 H + \xi (F_1 + F_2) \tilde{H} + \left( t / 4 M^2 \right) F_2 E \right\} d \varphi \]

With unpolarized beam and Long. polarized target:
\[ \Delta \sigma_{UL} \sim \sin \varphi \left\{ F_1 \tilde{H} + \xi (F_1 + F_2) H + \left( t / 4 M^2 \right) F_2 E \right\} d \varphi \]

With unpolarized beam and Transversely polarized target:
\[ \Delta \sigma_{UT} \sim \cos \varphi \sin (\phi_S - \varphi) \left\{ \left( t / 4 M^2 \right) F_2 H - \left( t / 4 M^2 \right) F_1 E + ... \right\} d \varphi \]

Separations of CFFs \( H(\pm \xi, \xi, t), E(\pm \xi, \xi, t), \ldots \)
HERMES overview

27.6 GeV e+/e- HERA beam

Access to valence and sea

Electron and Hadron ID

Data taking: 95-07

Internal gaseous target
(no nuclear effects)

96-00 (H/D) Lpol + Upol
02-05 (H) Tpol + Upol
06-07 (H/D) Upol+Recoil

M. Contalbrigo

DIS 2011, 13th April 2011, Newport News
HERMES-Transversely Polarized $H(e,e'\gamma)X$, SSA

- Azimuthal moments
- Differential in $x_{Bj}$, $Q^2$, or $t$, integrated over other 2 variables.
- $\sin \phi$ moments
  - Sensitive to $E(\xi, \xi, t)$
- $\sin 2\phi$ moments $\approx 0$
  - $\approx$ Twist 3
- $\sin 3\phi$ moments
  - $\approx$Gluon Transversity
Deeply virtual Compton scattering

Theoretically cleanest way to access GPDs

@ HERMES:

Large BH amplitude enhances DVCS signal via interference

Complete set of beam helicity, beam charge, target polarization asymmetries

Recoil detector to tag exclusivity

1T SC Solenoid
Photon Detector
Scintillating Fiber Tracker
Silicon Strip Detector
Unpolarized H and D targets

Contalbrigo M.
DESY PRC 71, 28th April 2011, Hamburg
The recoil detector

Without Recoil Detector

In Recoil Detector acceptance

With Recoil Detector

Similar background

Background-free

Similar kinematics

Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation

- No requirement for Recoil
- Charged recoil track in acceptance
- Kinematic fit probability > 1 %
- Kinematic fit probability < 1 %
Within the present level of precision, the signal is stable with respect background subtraction.

Indication that the leading amplitude for pure elastic process (background < 0.1%) is slightly larger in magnitude than the one for not-resolved elastic+associated processes.
HERMES summary 2011

- next to final
- averaged over $Q^2$ and $t$
- Transversely polarized H-target $\rightarrow$ sensitivity to $E(\xi,\xi,\Delta^2)$, $\xi \approx 0.1$
THE CLAS DETECTOR

- Toroidal magnetic field
  - (6 superconducting coils)
- Drift chambers (argon/CO2 gas, 35000 cells)
- Time-of-flight scintillators
- Electromagnetic calorimeters
- Cherenkov counters
  - (e/π separation)

Performances:
- Nearly 4π acceptance
- Large kinematical coverage
- Detection of charged and neutral particles
JLab/Hall B – Eg1  Non-dedicated experiment (no inner calorimeter), but \( H(e,e'\gamma p) \) fully exclusive.

Higher statistics and larger acceptance (Inner Calorimeter) run Feb-Sept. 2009

FIG. 5: The left panel shows the \(-t\) dependence of the \( \sin\phi\) moment of \( A_{UL} \) for exclusive electroproduction of photons, while the right shows the \( \xi \) dependence. Curves as in Fig. 5.

5 Tesla Solenoid
420 PbWO$_4$ crystals:
~10x10x160 mm$^3$
APD+preamp
readout
Orsay / Saclay /
ITEP / Jlab
CLAS 6 GeV: Exclusivity and Kinematics

- $H(e,e'\gamma p')x$
- Overcomplete triple coincidence

Co-linearity of $\gamma$ with $q-p'$

Missing Energy $E_x$

- Example angular distribution of Beam Spin Asymmetry
  - One $(Q^2,x_B)$ bin
  - Two $t$-bins.
• $\sin \phi$ moments of $A_{LU}$
  - Solid blue curves: VGG GPD model
• Data set doubled by Fall/Winter 2008/2009 run
**DVCS Target Spin Asymmetry**

\[ A_{UL} = \frac{N^+ - N^-}{f(P^-N^+ + P^+N^-)} \]

- \( N^{+(-)} \): number of DVCS events with a positive (negative) target polarization
- \( P^{+(-)} \): target polarization
- \( F \): dilution factor

Fitting function:

\[ A_{UL} \sim \alpha \sin \Phi + \beta \sin 2\Phi \]

- \( x_B \sim 0.21 \)
- \( Q^2 \sim 2.15 \text{ GeV}^2 \)

- \( x_B \sim 0.46 \)
- \( Q^2 \sim 3.00 \text{ GeV}^2 \)

Plots and analysis done by Erin Seder
DVCS: JLab Hall A 2004, 2010

$L \geq 10^{37} \text{ cm}^2/\text{s}$

Precision cross sections
  • Test factorization
  • Calibrate Asymmetries

16chan VME6U: ARS
128 samples@1GHz

Digital Trigger Validation

132 PbF$_2$
Beam helicity-independent cross sections at $Q^2=2.3\text{ GeV}^2$, $x_B=0.36$

- Contribution of $\text{Re}[\text{DVCS}^*\text{BH}] + |\text{DVCS}|^2$ large.
- Positron beam or measurements at multiple incident energies to separate these two terms and isolate Twist 2 from Twist-3 contributions

\[ \langle t \rangle = -0.33 \quad \langle t \rangle = -0.28 \quad \langle t \rangle = -0.23 \quad \langle t \rangle = -0.17 \]

\[ d^4\sigma = d\sigma(|BH|^2) + 2\text{Re}[\text{DVCS}^*\text{BH}] + |\text{DVCS}|^2 \]

\[ c_0 \Gamma_0 + c_1 \cos(\phi_{\gamma\gamma}) \Gamma_1 + c_2 \cos(2\phi_{\gamma\gamma}) \Gamma_2 + \ldots \]

\[ P_1(\phi_{\gamma\gamma}) P_1(\phi_{\gamma\gamma}) \]

\[ c_{0,1}(t) \approx \text{Re}[C^I(GPD)] + C^{\text{DVCS}} \left( GPD^2 \right) + \ldots + \text{Re} \left[ \Delta C^I(GPD) \right] \]

\[ c_2(t) = \text{Twist} - 3 = (qGq) \]
DVCS-Deuteron, Hall A

- **E03-106:**
  - $D(e,e'\gamma)X \approx d(e,e'\gamma)d+n(e,e'\gamma)n+p(e,e'\gamma)p$
  - Sensitivity to $E_n(\xi,\xi,t)$ in $\text{Im}[DVCS*BH]$.

- **E08-025 (5.5 GeV- 2010)**
  - Reduce the systematic errors
    - Expanded PbF$_2$ calorimeter for $\pi^0$ subtraction
  - Separate the $\text{Re}[DVCS*BH]$ and $|DVCS|^2$ terms on the neutron via two beam energies.

$Q^2=2.3$ GeV$^2$, $x_B=0.36$
- GPDs & TMDs
- Nucleon Spin Structure
- N* Form Factors
- Baryon Spectroscopy
- Hadron Formation
DVCS with CLAS at 12 GeV

- 80 days on H₂ target at \( \sim 10^{35} \) /cm²/s
- 120 days on Longitudinially Polarized NH₃ target
  - Total Luminosity \( 10^{35} \) /cm²/s, dilution factor \( \sim 1/10 \)
- \( D(e,e'\gamma n)p_s \)
- Ambitions/options for Transversely polarized targets
  - NH₃ target has 5 T transverse field
    - need to shield detectors from “sheet of flame”
    - Reduce (Luminosity)(Acceptance) by factor of 10 (my guess)
  - HD-ice target (weak holding field, less dilution)
    - Currently taking data with photon beam
    - Polarization measurements incomplete
    - Test with electron beam in 1-2 months.
DVCS at 12 GeV in Hall A:
100 days HRS ×PbF₂

All equipment in-hand. Ready for beam!

DVCS measurements in Hall A/JLab

\[ Q² \text{ (GeV}^²) \]

\[ W² < 4 \text{ GeV}^² \]

Unphysical with \( E_{\text{beam}} \leq 11 \text{ GeV} \)

- \( E_{\text{beam}} = 6.6 \text{ GeV} \)
- \( E_{\text{beam}} = 8.8 \text{ GeV} \)
- \( E_{\text{beam}} = 11.0 \text{ GeV} \)
- \( E_{\text{beam}} = 5.75 \text{ GeV} \)

\( x_{Bj} \)
Figure 50: Top view of the 2010 COMPASS spectrometer setup.
COMPASS Recoil Proton Detector + ECALO

Image of a detailed diagram of the COMPASS spectrometer setup with various components labeled. The diagram includes views of the detector setup, showing the interaction of particles with different elements like target, veto, and trigger systems. The setup is viewed from a top-down perspective, indicating the arrangement of components along the beam path. A photograph of the actual setup is shown alongside the diagram, providing a real-world context for the theoretical representation.
COMPASS DVCS Projections

- 160 GeV
  \( \bar{\mu}^+ \) and \( \bar{\mu}^- \)
- Spin\( \times \)Charge averaged
  \[ d\sigma \approx |H(\xi, t)|^2 \]

- Spin\( \times \)Charge difference
  \[ \Delta \sigma \approx F_1(-t) \text{Re}[H(\xi, t)] \cos \phi \]
Gluon and quark GPDs enter to same order in $\alpha_S$.
SCHC: $\sigma_L \sim [Q^2]^{-3}$ $\sigma_T \sim [Q^2]^{-4}$
Spin/Flavor selectivity

[Diffractive channels only]
Semi Universal behavior of exclusive reactions at high $W^2$

- **Two views:**
  - Extracting leading twist information is hopeless for $Q^2+q'^2<10$ GeV$^2$
  - Perturbative $t$-channel exchange even for modest $Q^2$, but convolution of finite size of nucleon and probe.

- **Fitting data** (cf C.Weiss) requires setting scale of gluon pdf $\mu^2 << Q^2$
  - Finite transverse spatial size $b\approx1/\mu$ of $\gamma \rightarrow V$ amplitude
\( \sigma_L/\sigma_T \) in vector meson production at HERA

- **SCHC**: \( \rho \rightarrow \pi \pi, \ \omega \rightarrow \pi \pi \pi, \ \phi \rightarrow \text{KK} 
  - Validate SCHC from decay angular distribution (Schilling & Wolf)
  - Extract \( d\sigma_L \) from
- **Rapid rise in** \( r_{04} \) vs \( Q^2 \):
  - Validation of perturbative exchange in \( t \)-channel.
- **Sub-asymptotic saturation** of \( d\sigma_L/d\sigma_T \)
  - Extra mechanism for \( d\sigma_T \)?

\[
r_{00}^{04} = \frac{\varepsilon R}{1 + \varepsilon R} = \frac{\varepsilon d\sigma_L}{d\sigma_T + \varepsilon d\sigma_L}
\]
Vector Mesons at JLab

• Deep $\rho$
  ▪ SCHC observed at 20% level
  ▪ Anomalous rise in $d\sigma_L$ at low $W$

• Deep $\omega$
  ▪ SCHC strongly violated in CLAS data
  ▪ No (??) SCHC tests from HERMES or HERA.

• Deep $\phi$
  ▪ SHCH validated
  ▪ Model of P. Kroll consistent with world data set
    • Perturbative $t$-channel exchange ($2g$), but
      factor of 10 suppression relative to collinear
      factorization from Sudakov effects in $\gamma \rightarrow \phi$
LONGITUDINAL CROSS SECTION $\sigma_L(\gamma^*_{LP} \rightarrow p\rho_L^0)$

Two different behaviors:
- low $W$: $\sigma_L$ drops
- high $W$: $\sigma_L$ slowly rises

GPD approaches based on Double-Distributions

- GK [*]
- thin blue VGG [*]
- thick blue VGG + strong D-term [*]
- dash-dotted JLM calculation à la Regge [*]

Deep $\phi$

- $Q^2 \approx 2$ GeV$^2$
  - CLAS, HERMES, HERA
- Model of S. Goloskokov and P. Kroll

![Graph showing the longitudinal cross section for $\phi$ production at $W = 7.5$ GeV. Data taken from [13], [37], and [38]. Left: Full (dashed, dash-dotted, dotted) line represents the handbag predictions for the cross section (gluon, gluon-sea interference, sea contribution). Right: Predictions for the cross section with error bands resulting from the Hessian errors of the CTEQ parton distributions (full line) and compared to the leading-twist result (dashed line).]

![Graph showing the longitudinal cross section for $\rho$ production at $W = 7.5$ GeV. Data taken from [11, 39] and [12]. For other notations cf. Fig. 7.]

Proposals/LOI in Hall B and Hall A
LOI for J/$\Psi$ in Halls B and C.
The next 20 years of DVCS experiments

- **First 5 years**
  - Precision tests of factorization with $Q^2$ range $\geq 2:1$ for
    - $x_B \in [0.25, 0.6]$. $t_{\text{min}} - t < 1 \text{ GeV}^2$ + COMPASS : $x_B \in [0.01, 0.1]$
    - Proton unpolarized target observables
    - $\text{Im}[\text{DVCS}^* \text{BH}], \text{Re}[\text{DVCS}^* \text{BH}], |\text{DVCS}|^2$.
  - Longitudinal, target spin observables
    - Primary sensitivity to $H, \tilde{H}$, at $x = \pm \xi = \pm x_B/(2-x_B)$ point.
  - Partial $u,d$ flavor separations from quasi-free neutron.
  - Coherent Nuclear DVCS on D, He

- **5-10 years**
  - Transversely Polarized H, D, $^3\text{He}$ in JLab Halls A,B,C
    - Optimize targets
    - Improved recoil/spectator detection?
  - Polarized targets at COMPASS

- **10-15 years**: Build electron ion collider with $s \geq 1000 \text{ GeV}^2$ and $L > 2 \cdot 10^{34} \text{ /cm}^2/\text{s}$. 
Back-up Slides
• Spatial imaging of gluons at small $x_B$
Unraveling DVCS observables

- Twist-2 terms ≈ 1, cosφ, sinφ
- Twist-2 terms ≈ sin2φ
- Not a pure Fourier series: 1/[A + Bcosφ + Ccos2φ] from BH propagators.
- GPDs enter with different weights for each azimuthal term for different polarization (lepton helicity, target-longitudinal or – transverse) observables
  - Single and Double spin observables
  - Beam charge difference (e⁺e⁻ HERMES, JLab; µ⁺µ⁻ COMPASS)
  - Energy dependence (JLab)
- Complete separation of Re and Im parts of CFF of E, H,... in-principle possible (D.Mueller, next)
- u, d flavor separations require neutron targets (or deep meson electroproduction)
HERMES DVCS $p(e,e'\gamma)X$

27 GeV polarized $e^\pm$ on
Internal Gas Jet
/ Atomic Beam Source targets

2001 BSA

2006 BCA
Hall A Helicity Dependent Cross Sections E00-110

$Q^2 = 2.3 \text{ GeV}^2$

$\Gamma_{s1,2} = \text{kinematic factors}$

$$\sum h d\sigma(h) = s_1 \sin(\phi_{\gamma\gamma}) \Gamma_{s1} + s_2 \sin(2\phi_{\gamma\gamma}) \Gamma_{s2}$$

Twist-2(GPD) + …

Twist-3(qGq) + …

C. MUNOZ CAMACHO, et al.,
• $Q^2$-independance of $\text{Im}[\text{DVCS} \times \text{BH}]$
• Twist-2 Dominance (GPD)
• Model « Vanderhaeghen-Guichon-Guidal (VGG) » accurate to $\approx 30\%$

Compensate the small lever-arm in $Q^2$ with precision in $d\sigma$. 
CLAS12 – Central Detector SVT, CTOF

- Charged particle tracking in 5T field
- $\Delta T < 60\text{psec}$ in for particle id
- Moller electron shield
- Polarized target operation $\Delta B/B < 10^{-4}$
HD ice: a transversely polarized target for CLAS

Operates at $T \sim 500-750\text{mK}$
- Long spin relaxation times (months)
- Weak transverse magnetic field

- 25+ years of development...
- Successful operation at LEGS photon beam
- Just in time for DVCS!!!!

Test in 2010 with electron beam, Experiment conditionally scheduled in 2011

Heat extraction is accomplished with thin aluminum wires running through the target

<table>
<thead>
<tr>
<th>Material</th>
<th>gm/cm$^2$</th>
<th>mass fraction</th>
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<tbody>
<tr>
<td>HD</td>
<td>0.735</td>
<td>77%</td>
</tr>
<tr>
<td>Al</td>
<td>0.155</td>
<td>16%</td>
</tr>
<tr>
<td>CTFE ($\text{C}_2\text{ClF}_3$)</td>
<td>0.065</td>
<td>7%</td>
</tr>
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</table>
CLAS: Coherent $^4$He($e,e'\gamma\alpha$)

• A single GPD
  - $H(\xi,\xi,t)=(4/9)H_u+(1/9)H_d$.
  - $G_E=\int dx[(2/9)H_u-(1/9)H_d]$.

• E08-024, Autumn 2009
  - BoNuS GEM radial TPC

\[
\frac{H_{He}(x,0,t)}{H_N(x,0,t)}
\]

\[R_A\]

[\(t=0.0\)] $\rightarrow$ EMC effect,
[\(t=-0.1\)] $\rightarrow$ GPD
(Liuti & Taneja, Guzey & Strickman)
DVCS in Hall A

• Elastic form factors, Real Compton Scattering: Correlated two-body final state,
  - Spectrometers have the advantage over large acceptance:
    • product of (Luminosity)(Acceptance)
    • Precision of absolute cross sections

• DVCS is a 3-body final state
  - For $-t/Q^2<<1$, final photon close to $\mathbf{q}$-direction.
  - Quasi two-body final state for limited $t$ coverage