Deeply Virtual Compton Scattering with a Positron Beam

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Generalized Parton Distributions

Deep Exclusive Scattering

\[ \gamma^* p \rightarrow \gamma p', \rho p', \omega p', \phi p' \]

Bjorken regime:
\[ Q^2 \rightarrow \infty, x_B \text{ fixed} \]
\[ t \text{ fixed} \ll Q^2, \xi \rightarrow \frac{x_B}{2-x_B} \]

\[ \frac{P^+}{2\pi} \int dy^- e^{ixP^+y^-} \langle p' | \bar{\psi}(0) \gamma^+(1+\gamma^5)\psi(y) | p \rangle \]

\[ = \tilde{N}(p') \left[ H^q(x, \xi, t) \gamma^+ + E^q(x, \xi, t) i\sigma^+\nu \frac{\Delta_\nu}{2M} \right. \]
\[ + \tilde{H}^q(x, \xi, t) \gamma^+ \gamma^5 + \tilde{E}^q(x, \xi, t) \gamma^5 \frac{\Delta^+}{2M} \left. \right] N(p) \]

3-D Imaging conjointly in transverse impact parameter and longitudinal momentum

<table>
<thead>
<tr>
<th>spin</th>
<th>N no flip</th>
<th>N flip</th>
</tr>
</thead>
<tbody>
<tr>
<td>q no flip</td>
<td>H</td>
<td>E</td>
</tr>
<tr>
<td>q flip</td>
<td>( \tilde{H} )</td>
<td>( \tilde{E} )</td>
</tr>
</tbody>
</table>
GPDs and Transverse Imaging \((x_B, t)\)

\[
q_x(x, \vec{b}_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} \left[ H^q(x, 0, t) - \frac{E^q(x, 0, t)}{2M} \frac{\partial}{\partial y} \right] e^{-i\Delta_\perp \cdot \vec{b}_\perp}
\]
Energy Momentum Tensor \((x, \xi)\)

Form Factors accessed via second \(x\)-moments:

\[
\langle p' | \hat{T}^{q}_{\mu \nu} | p \rangle = \bar{N}(p') \left[ M_2^q(t) \frac{P_\mu P_\nu}{M} + J^q(t) \frac{\nu(P_\mu \sigma_\nu \rho + P_\nu \sigma_\mu \rho) \Delta^\rho}{2M} + d_1^q(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu \nu} \Delta^2}{5M} \right] N(p)
\]

Angular momentum distribution

\[
J^q(t) = \frac{1}{2} \int_{-1}^{1} dx \times [H^q(x, \xi, t) + E^q(x, \xi, t)]
\]

Mass and force/pressure distributions

\[
M_2^q(t) + \frac{4}{5} d_1^q(t) \xi^2 = \frac{1}{2} \int_{-1}^{1} dx \times H^q(x, \xi, t)
\]

\[
d_1^q(t) = 15M \int d^3r \frac{j_0(r \sqrt{-t})}{2t} p(r)
\]

Distribution of pressure

\[
\int_{0}^{\infty} dr \ r^2 p(r) = 0
\]

\[
\int_{0}^{\infty} dr \ r^2 p(r) = 0
\]
Deeply Virtual Compton Scattering

The cleanest GPD probe at low and medium energies

\[ \sigma(ep \rightarrow ep\gamma) \propto \left| A_{BH} + A_{DVCS} \right|^2 = |A_{BH}|^2 + |A_{DVCS}|^2 - e_I I \]

\[ \frac{d\sigma}{dx_B dQ^2 dt d\phi} \propto \left| A_{BH} + A_{DVCS} \right|^2 \]

\[ A_{LU} = \frac{d^4 \sigma \rightarrow - d^4 \sigma \leftarrow}{d^4 \sigma \rightarrow + d^4 \sigma \leftarrow} \quad \text{twist-2} \quad \approx \frac{\alpha \sin \phi}{\beta \cos \phi + \gamma} \]

\[ \mathcal{H}(\xi, t) = i \pi H(\xi, \xi, t) + \mathcal{PV} \int_{-1}^{1} dx \frac{H(x, \xi, t)}{x - \xi} \quad \text{Compton Amplitude} \]

\[ \alpha \propto \text{Im} \left( F_1 \mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \right) \quad \to A_{LU} \]

\[ \beta \propto \text{Re} \left( F_1 \mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \right) \quad \to A_C \]

\[ \gamma \propto 4(1 - x_B) \left( \mathcal{H} \mathcal{H}^* + \mathcal{H} \tilde{\mathcal{H}}^* \right) + \cdots \quad \to \sigma_U \]

\[ A_{UL} \propto \text{Im} \left( F_1 \mathcal{H} + \xi G_M \mathcal{H} + G_M \frac{\xi}{1 + \xi} \mathcal{E} + \cdots \right) \sin \phi \]
Observables sensitivities to GPDs

A global analysis is needed to fully disentangle GPDs

$A_C$ gives access to $d_1(t)$ through a direct separation of $\mathcal{R}e\mathcal{H}$
Dispersion and the DVCS Amplitude

Analyticity and Unitarity applied to the Compton Amplitude

\[ A(\xi, t) = \int dx \left( \frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) H(x, \xi, t) \]

give the once subtracted fixed-t dispersion relation

\[ \text{Re} \mathcal{H}(\xi, t) = D(\xi, t) + \mathcal{PV} \int dx \left( \frac{1}{\xi - x} - \frac{1}{\xi + x} \right) \text{Im} \mathcal{H}(\xi, t) \]

Where \( \text{Im} \mathcal{H}(\xi, t) = \pi H(\xi, \xi, t) \) and \( \text{Re} \mathcal{H}(\xi, t) = \mathcal{PV} \int_{-1}^{1} dx \frac{H(x, \xi, t)}{x - \xi} \)

The subtraction constant is called the D-term and its Gegenbauer expansion is linked to the Energy Momentum Tensor:

\[ D(\xi, t) = (1 - \xi^2) \left[ d_1(t) C_1^{3/2}(\xi) + d_3(t) C_3^{3/2}(\xi) + d_5(t) C_5^{3/2}(\xi) + \cdots \right] \]

Calculations in the Chiral Quark Soliton Model indicate that:

\[ d_1 \approx -4.0 , \quad d_3 \approx -1.2 , \quad d_5 \approx -0.4 \]

with various uncertainties, including the scale

A measurement of the beam charge asymmetry \( A_C \) gives direct access to the D-term
Beam requirements in Hall B
# Hall B Beamline Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Value (?)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Up to 11 GeV</td>
</tr>
<tr>
<td>Energy spread</td>
<td>Better than 0.1%</td>
</tr>
<tr>
<td>Beam current</td>
<td>Up to 800 nA</td>
</tr>
<tr>
<td>Current measurement</td>
<td>Better than 1%</td>
</tr>
<tr>
<td>Helicity correlated charge asymmetry</td>
<td>Less than 0.1%</td>
</tr>
<tr>
<td>Beam polarization measurement</td>
<td>Better than 2.5% (relative)</td>
</tr>
<tr>
<td>Beam spot size</td>
<td>Smaller than 400 µm</td>
</tr>
<tr>
<td>Spot/Tail ratio</td>
<td>Better than $10^4$</td>
</tr>
<tr>
<td>Beam position</td>
<td>Measured and stable better than 100 µm</td>
</tr>
<tr>
<td>Emittance</td>
<td>$\epsilon &lt; 10$ nm-rad</td>
</tr>
</tbody>
</table>
Hall B Published Data
Precision in a large phase-space \((x_B, Q^2, t)\)
Qualitative model agreement
quantitative constraints on parameters

Change of \(t\)-slopes across \(x_B\)
Nucleon size change
DVCS Unpolarized Cross-Sections 6 GeV

\[
\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}\text{ (nb/GeV}^4)\]

- \text{BH}
- \text{VGG (H only)}
- \text{KM10}
- \text{-- KM10a}

\text{VGG : Vanderhaeghen, Guichon, Guidal} \quad \text{KM : Kumericki, Mueller}
The t-slope becomes flatter with increasing $x_B$:
valence quarks (higher $x_B$) at the center of the nucleon and sea quarks (small $x_B$) at its periphery.
Target Longitudinal Spin DVCS 6 GeV

\[ F_1 \bar{H} + \xi G_M \left( \mathcal{H} + \frac{\xi}{1+\xi} \mathcal{E} \right) \]

FIG. 19. (Color online) Target-spin asymmetry for the reaction \( ep \rightarrow e^0 p^0 \) as a function of \(-t\) for the various \(Q^2\)-\(x_B\) bins and \(t\) bins. The point-by-point systematic uncertainties are represented by the shaded bands. The solid black curve is the fit with the function in Eq. (43). In the highest \(t\) bin of the third \(Q^2-x_B\) bin, the \(Q^2\) was set to zero due to the limited coverage, while no fit is performed on the first \(t\) bin of the highest \(Q^2-x_B\) bin, where only one data point is present. The curves show the predictions of the VGG [23] (red-dashed) and KMM12 [26] (blue-dotted) models.

FIG. 22. (Color online) Double-spin asymmetry for the reaction \( ep \rightarrow e^0 p^0 \) as a function of \(-t\) for the various \(Q^2\)-\(x_B\) bins and \(t\) bins. The point-by-point systematic uncertainties are represented by the shaded bands. The solid black curve is the fit with the function in Eq. (45). In the highest \(t\) bin of the third \(Q^2-x_B\) bin, the \(Q^2\) was set to zero due to the limited coverage, while no fit is performed on the first \(t\) bin of the highest \(Q^2-x_B\) bin, where only one data point is present. The red-dashed and cyan-dotted curves are predictions of the VGG and KMM12 models, respectively. The pink two-dot-dashed curves are the calculations for the Bethe-Heitler process.
GPD dependencies versus $x_B$ mirror their respective ordinary PDFs

\[ \tilde{H} \text{ and } H \leftrightarrow \Delta q(x) \text{ and } q(x) \]

Change of t-slope vs $x_B$
less for $\Delta q(x)$ than for $q(x)$

Different spatial distributions of
Axial charge vs EM charge
Hall B Future Measurements
<table>
<thead>
<tr>
<th>Number</th>
<th>Title</th>
<th>Contact</th>
<th>Days</th>
<th>Energy</th>
<th>Target</th>
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<tr>
<td>E12-06-108</td>
<td>Hard Exclusive Electroproduction of $\pi^0$ and $\eta$</td>
<td>Kubarovski</td>
<td>80</td>
<td>11</td>
<td>$IH_2$</td>
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<td>E12-06-119</td>
<td>Deeply Virtual Compton Scattering</td>
<td>Sabatie</td>
<td>80</td>
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<td>E12-12-001</td>
<td>Timelike Compton Scat. &amp; $J/\Psi$ prod. in $e^+e^-$</td>
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<td>E12-11-003</td>
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<td>90</td>
<td>11</td>
<td>$ID_2$</td>
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<tr>
<td>E12-06-119</td>
<td>Deeply Virtual Compton Scattering</td>
<td>Sabatie</td>
<td>120</td>
<td>11</td>
<td>$NH_3$</td>
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<tr>
<td>C12-12-010</td>
<td>DVCS with a transverse target</td>
<td>Elouadrhiri</td>
<td>110</td>
<td>11</td>
<td>HD-ice</td>
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<tr>
<td>E12-16-010</td>
<td>DVCS with CLAS12 at 6.6 GeV and 8.8 GeV</td>
<td>Elouadrhiri</td>
<td>50+50</td>
<td>6.6 &amp; 8.8</td>
<td>$IH_2$</td>
</tr>
</tbody>
</table>
Proton BSA DVCS $A_{LU}$

$80 \text{ days} \@ \mathcal{L} = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ with 85\% polarized beam

$A_{LU} \propto F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 \mathcal{E}$

Beam Spin Asymmetries
$\phi$ dependence

Statistical uncertainties:
from 1\% (low $Q^2$) to 10\% (high $Q^2$)

Unprecedented statistics
over the full $\phi$ range
up to high $x = 0.6$
80 days @ \( \mathcal{L} = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \) with 85% polarized beam

\[
A_{LU} \propto F_1 \mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}
\]

Beam Spin Asymmetries
\( \phi \) dependence

Statistical uncertainties:
- from 1% (low \( Q^2 \))
- to 10% (high \( Q^2 \))

Unprecedented statistics over the full \( \phi \) range up to high \( x = 0.6 \)
Proton DVCS TSA $A_{UL}$

120 days @ $\mathcal{L} = 2 \times 10^{35}$ cm$^{-2}$s$^{-1}$ with 80% polarized NH$_3$

$$A_{UL} \propto F_1 \hat{\mathcal{H}} + \xi G_M \left( \mathcal{H} + \frac{\xi}{1+\xi} \mathcal{E} \right) - \cdots$$

Target Spin Asymmetries
$
\phi$ dependence

Statistical uncertainties:
from 2% (low $Q^2$) to 30% (high $Q^2$)

Unprecedented statistics over the full $\phi$ range up to high $x = 0.6$
120 days @ $\mathcal{L} = 2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ with 80% polarized NH$_3$

\[ A_{UL} \propto F_1 \hat{\mathcal{H}} + \xi G_M \left( \mathcal{H} + \frac{\xi}{1+\xi} \mathcal{E} \right) - \cdots \]

Target Spin Asymmetries $\phi$ dependence

Statistical uncertainties: from 2% (low $Q^2$) to 30% (high $Q^2$)

Unprecedented statistics over the full $\phi$ range up to high $x = 0.6$
120 days @ $\mathcal{L} = 2 \times 10^{35}$ cm$^{-2}$s$^{-1}$ with 80% polarized NH$_3$

$A_{UL} \propto F_1 \hat{H} + \xi G_M \left( \hat{H} + \frac{\xi}{1+\xi} \mathcal{E} \right) - \cdots$

TSA t-slopes

Sample kinematics for target asymmetry

Change of $t$-slope with $x_B$ ↔ imaging $\Delta q(x_B, b_\perp)$
Gluons at large $x$

- Large glue density at $x > 0.1$
  
  PDF from global fits
  ($F_2$ evolution, $\nu_{\text{DIS}}$, jets)

  Gluons carry more than 30% of the momentum for $0.1 < x$

- 3D imaging of the nucleon
  
  spatial distribution of valence quarks: elastic scattering, DVCS, ...

  Nucleon gluonic radius?
  exclusive $\phi$
Extraction of gluonic profiles

**Longitudinal cross-section**

\[ x_B = 0.2-0.3 \]

\[ Q^2 = 4-5 \text{ GeV}^2 \]

\[ \frac{d\sigma}{dt} (\gamma p \rightarrow \phi p) \]

\[ x_B = 0.4-0.5 \]

\[ Q^2 = 4-5 \text{ GeV}^2 \]

**Corresponding sensitivity in transverse position space**

\[ b = \frac{1}{\sqrt{-t}} \]

**Error propagation study**

Skewness \( \xi \neq 0 \) neglected
Projected Impact on GPD Extractions
Projected Impact on GPD Extraction

Using simulated data based on VGG model. Input GPD H extracted with good accuracy.
Projected Impact on GPD Extraction

Using simulated data based on VGG model. Input GPD H extracted with good accuracy.
Projected Impact on GPD Extraction

Using simulated data based on VGG model. Input GPD H extracted with good accuracy.
Projection for the Nucleon transverse profile

Model profile

Projected error band

$Q^2 = 3.75 \text{ GeV}^2$

$q(b^\perp x^B) = \text{FT}[H(x,\xi=x,t)]$

Precision tomography in the valence region
Global Fits to extract the D-term

Beam Spin Asymmetries

\[ \text{Im} \mathcal{H}(\xi, t) = \frac{r}{1 + x} \left( \frac{2\xi}{1 + \xi} \right)^{-\alpha(t)} \left( \frac{1 - \xi}{1 + \xi} \right)^b \left( \frac{1 - \xi}{1 + \xi} \frac{t}{M^2} \right)^{-1} \]

Unpolarized cross-sections

Use dispersion relation:

\[ \text{Re} \mathcal{H}(\xi, t) = D + \mathcal{P} \int dx \left( \frac{1}{\xi - x} - \frac{1}{\xi + x} \right) \text{Im} \mathcal{H}(\xi, t) \]

pure Bethe-Heitler
local fit + uncertainty range
resulting global fit
D-term and Pressure distribution

\[ D^q(\frac{x}{\xi}, t) = \left(1 - \frac{x^2}{\xi^2}\right) \left[d_1^q(t)C_1^{3/2}(\frac{x}{\xi}) + d_3^q(t)C_3^{3/2}(\frac{x}{\xi}) + \cdots\right] \]

t-dependence of the D-term:
- Dipole gives singular pressure at \( r = 0 \)
- Quadrupole implied by counting rules?
- Exponential?
  \[ \cdots \]

Resulting pressure distribution

Stability condition: \( \int_0^\infty dt \ r^2 p(r) = 0 \)

World data fit
CLAS 6 GeV data
Projected CLAS12 data
DVCS with positrons

- Partonic Transverse Imaging and Energy Momentum Tensor
- First Generation of Experiments successful
- 12 GeV era already underway
- Extraction frameworks established
- Challenges ahead for precision measurements
- A positron beam allows a straightforward clean separation of the BH/DVCS interference
- Invaluable handle on systematics on a novel approach to confinement