New ML-based Analysis of Deeply Virtual Exclusive Processes

A.I. for Nuclear Physics Workshop
March 4-6, 2020

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“The average peak pressure near the center is about $10^{35}$ pascals, which exceeds the pressure estimated for the most densely packed known objects in the Universe, neutron stars.”
How is the pressure distribution extracted from data?

(How does the proton/neutron get its mass and spin?)
Introducing the complete formalism

We provide the general expression of the cross section for exclusive deeply virtual photon electroproduction from a spin 1/2 target using current parameterizations of the off-forward correlation function in a nucleon for different beam and target polarization configurations up to twist three accuracy. All contributions to the cross section including deeply virtual Compton scattering, the Bethe-Heitler process, and their interference, are described within a helicity amplitude based framework which is also relativistically covariant and readily applicable to both the laboratory frame and a collider kinematic setting. Our formalism renders a clear physical interpretation of the various components of the cross section by making a connection with the known characteristic structure of the electron scattering coincidence reactions. In particular, we focus on the total angular momentum, $J_z$, and on the orbital angular momentum, $L_z$. On one side, we uncover an avenue to a precise extraction of $J_z$, given by the combination of generalized parton distributions, $H + E$, through a generalization of the Rosenbluth separation method used in elastic electron proton scattering. On the other, we single out for the first time, the twist three angular modulations of the cross section that are sensitive to $L_z$. The proposed generalized Rosenbluth technique adds constraints and can

✓ Supersedes previous work by Belitsky Kirchner Mueller and Kumericki Mueller

✓ The main advantages are:

✓ Covariance (not just Lab frame): a desirable feature for the EIC
✓ Transparent description of observables that ties into the TMD and other coincidence experiments picture
A multi-step, multi-prong process

- Deeply Virtual Compton Scattering
- Timelike Compton Scattering
A multi-step, multi-prong process

- Deeply Virtual Meson Production
- Exclusive Drell Yan

\[ k + q \]

\[ k \]

\[ e \]

\[ e' \]

\[ q' = q + \Delta \]

\[ q \]

\[ p' = p - \Delta \]

\[ t = \Delta^2 \]

\[ \pi^0, \pi^\pm \]
A multi-step, multi-prong process

Deeply Virtual Meson Production

Exclusive Drell Yan

\[ \pi^\pm \qquad k+q \]

\[ q' = q + \Delta \quad p' = p - \Delta \]

\[ t = \Delta^2 \]
\[
\frac{d^5 \sigma}{dx_B dQ^2 d|t|d\phi d\phi_S} = \frac{\alpha^3}{16\pi^2 (s - M^2)^2 \sqrt{1 + \gamma^2}} |T|^2,
\]

\[T(k, p, k', q', p') = T_{DVCS}(k, p, k', q', p') + T_{BH}(k, p, k', q', p'),\]

\[k' = k + q, \quad q' = q + \Delta\]

\[k\]
\[q\]
\[\Delta\]
\[p\]
\[p'\]

DVCS

BH

BH
\[
\frac{d^3\sigma_{DVCS}}{dx_B dQ^2 dt d\phi d\phi_S} = \frac{\alpha^3}{16\pi^2 (s - M^2)^2 \sqrt{1 + \gamma^2}} |T_{DVCS}|^2
\]

\[
twist \text{ two GPDs}
\]

\[
twist \text{ three GPDs}
\]

\[
\Gamma \frac{Q^2(1 - \epsilon)}{\sqrt{\epsilon(\epsilon + 1)}} \left\{ F_{UU,T} - \epsilon F_{UU,L} + \epsilon \cos 2\phi F_{UU}^{\cos 2\phi} \right\}
\]

\[
+ \sqrt{\epsilon(\epsilon + 1)} \left[ \cos \phi F_{UU}^{\cos \phi} + \sin \phi F_{UU}^{\sin \phi} \right] \lambda_e \sqrt{2\epsilon(1 - \epsilon)} \sin \phi F_{LU}^{\sin \phi}
\]

\[
+ S_L \left[ F_{LT}^\epsilon + \sqrt{\epsilon(\epsilon + 1)} \sin \phi F_{UL}^{\sin \phi} + \epsilon \sin 2\phi F_{UL}^{\sin 2\phi} \right]
\]

\[
+ \lambda_e \sqrt{1 - \epsilon^2} F_{LL}^\epsilon + 2 \lambda_e \sqrt{\epsilon(1 - \epsilon)} \sin \phi F_{LU}^{\cos \phi}
\]

\[
+ |S_T| \left[ \sin(\phi - \phi_S) \left( F_{UT,T}^{\sin(\phi - \phi_S)} + \epsilon F_{UT,T}^{\sin(\epsilon - \phi_S)} \right) \right.
\]

\[
+ \epsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi + \phi_S)} + \epsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi - \phi_S)}
\]

\[
+ \sqrt{2\epsilon(1 + \epsilon)} \left( \sin \phi_S F_{UT}^{\sin \phi_S} + \sin(2\phi - \phi_S) F_{UT}^{\sin(2\phi - \phi_S)} \right) \]

\[
+ \lambda_e S_L \left[ \sqrt{1 - \epsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi - \phi_S)} + \sqrt{2\epsilon(1 - \epsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \right.
\]

\[
+ \sqrt{2\epsilon(1 - \epsilon)} \cos(2\phi - \phi_S) F_{LT}^{\cos(2\phi - \phi_S)} \right] \right.
\]

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### Observables

**Spin Orbit**
- Orbital angular momentum
- Transverse Orbital angular momentum

**Newly accessible configurations!**

<table>
<thead>
<tr>
<th>GPD</th>
<th>Twist</th>
<th>$P_{1\gamma}$, $P_{2\gamma}$</th>
<th>TMD</th>
<th>$P_{\text{Beam}} P_{\gamma}$ (DVCS)</th>
<th>$P_{\text{Beam}} P_{\gamma}$ ($\vec{T}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H + \frac{\xi}{1 - \xi} E$</td>
<td>2</td>
<td>$UU$</td>
<td>$f_1$</td>
<td>$UU, LL, UT\sin(\phi - \phi_1), LT\cos(\phi - \phi_1)$</td>
<td>$UU\cos \phi, LL\sin \phi$</td>
</tr>
<tr>
<td>$\vec{H} + \frac{\xi}{1 - \xi} \vec{E}$</td>
<td>2</td>
<td>$LL$</td>
<td>$g_1$</td>
<td>$UU, LL, UT\sin(\phi - \phi_1), LT\cos(\phi - \phi_1)$</td>
<td>$UU\cos \phi, LL\sin \phi, UT\cos \phi, LT\sin \phi$</td>
</tr>
<tr>
<td>$E$</td>
<td>2</td>
<td>$UT$</td>
<td>$f_L^{(\ast)}$</td>
<td>$UT\sin(\phi - \phi_1), LT\cos(\phi - \phi_1)$</td>
<td>$UU\cos \phi, UL\sin \phi, LT\cos \phi, UT\sin \phi$</td>
</tr>
<tr>
<td>$\vec{E}$</td>
<td>2</td>
<td>$LT$</td>
<td>$g_L$</td>
<td>$UT\sin(\phi - \phi_1), LT\cos(\phi - \phi_1)$</td>
<td>$UL\cos \phi, LT\cos \phi, UT\sin \phi, LT\sin \phi$</td>
</tr>
<tr>
<td>$E + E'$</td>
<td>2</td>
<td>$-$</td>
<td>$-$</td>
<td>$-$</td>
<td>$UU\cos \phi, LT\sin \phi, UL\cos \phi, UT\sin \phi$</td>
</tr>
</tbody>
</table>

- $2H_{2T} + E_{2T} - \xi E_{2T}$
- $2H_{2T} + E_{2T} - \xi E_{2T}$
- $H_{2T} + t_o - t H_{2T}$
- $H_{2T} + t_o - t H_{2T}$
- $E_{2T} - \xi E_{2T}$
- $E_{2T} - \xi E_{2T}$
- $H_{2T}$
- $H_{2T}$

- Newly accessible configurations!
\[
\frac{d^5 \sigma_{BH}}{dx_{Bj} dQ^2 d|t| d\phi d\phi_S} = \frac{\Gamma |T_{BH}|^2}{t} \left\{ F_{UU}^{BH} + (2\Lambda)(2h)F_{LL}^{BH} + (2\Lambda_T)(2h)F_{LT}^{BH} \right\}
\]

\[
\frac{d^5 \sigma_{BH}^{unpol}}{dx_{Bj} dQ^2 d|t| d\phi d\phi_S} = \frac{\Gamma}{t} F_{UU}^{BH} = \frac{\Gamma}{t} \left[ A(y, x_{Bj}, t, Q^2, \phi) \left( F_1^2 + \tau F_2^2 \right) + B(y, x_{Bj}, t, Q^2, \phi) \tau C_M^2(t) \right]
\]

\[
A = \frac{16 M^2}{t(k' q')(k q')^3} \left[ 4\tau \left( (k P)^2 + (k' P)^2 \right) - (\tau + 1) \left( (k \Delta)^2 + (k' \Delta)^2 \right) \right]
\]

\[
B = \frac{32 M^2}{t(k' q')(k q')^3} \left[ (k \Delta)^2 + (k' \Delta)^2 \right].
\]
\[ |T_{BH}|^2 = \frac{\epsilon^6}{x_B^2(1 + \epsilon^2)^2 \Delta^2 \mathcal{P}_1(\phi) \mathcal{P}_2(\phi)} \times \left\{ c_0^{BH} + \sum_{n=1}^{2} c_n^{BH} \cos(n\phi) + s_1^{BH} \sin(\phi) \right\}, \]

\[ c_{0,unp}^{BH} = 8K^2 \left\{ \left( 2 + 3\epsilon^2 \right) \frac{Q^2}{\Delta^2} \left( F_1^2 - \frac{\Delta^2}{4M^2} F_2^2 \right) + 2x_B^2(F_1 + F_2)^2 \right\} \]

\[ + (2 - y)^2 \left\{ (2 + \epsilon^2) \left[ 4x_B^2 \frac{M^2}{\Delta^2} \left( 1 + \frac{\Delta^2}{Q^2} \right)^2 \right. \right. \]

\[ + 4(1 - x_B) \left. \left( 1 + x_B \frac{\Delta^2}{Q^2} \right) \left( F_1^2 - \frac{\Delta^2}{4M^2} F_2^2 \right) \right. \]

\[ + 4x_B^2 \left. \left( 1 - x_B + \frac{\epsilon^2}{2} \right) \left( 1 - \frac{\Delta^2}{Q^2} \right)^2 \right. \]

\[ - x_B(1 - 2x_B) \frac{\Delta^2}{Q^4} (F_1 + F_2)^2 \right\} \]

\[ + 8(1 + \epsilon^2)(1 - y - \frac{\epsilon^2 y^2}{4}) \times \left\{ 2\epsilon^2 \left( 1 - \frac{\Delta^2}{4M^2} \right) \left( F_1^2 - \frac{\Delta^2}{4M^2} F_2^2 \right) - x_B^2 \left( 1 - \frac{\Delta^2}{Q^2} \right)^2 (F_1 + F_2)^2 \right\}. \]

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...compared to BKM, NPB (2001)

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\[ c_{1,unp}^{BH} = 8K(2 - y) \left\{ \left( 4x_B^2 M^2 \frac{\Delta^2}{\Delta^2} - 2x_B - \epsilon^2 \right) \left( F_1^2 - \frac{\Delta^2}{4M^2} F_2^2 \right) \right. \]

\[ + 2x_B^2 \left. \left( 1 - (1 - 2x_B) \frac{\Delta^2}{Q^2} \right) (F_1 + F_2)^2 \right\}. \]

\[ c_{2,unp}^{BH} = 8x_B^2 K^2 \left\{ 4M^2 \frac{\Delta^2}{\Delta^2} \left( F_1^2 - \frac{\Delta^2}{4M^2} F_2^2 \right) + 2(F_1 + F_2)^2 \right\}. \]
BH-DVCS interference

\[ \frac{d^5\sigma}{dx_BdQ^2d|t|d\phi d\phi_s} = e_1 \Gamma (T_{BH}^* T_{DVCS} + T_{DVCS}^* T_{BH}) \]

\[ = e_1 \frac{\Gamma}{Q^2 |t|} \left\{ F_{\tilde{U}U}^T + (2h) F_{LU}^T + (2\Lambda) F_{UL}^T + (2h)(2\Lambda) F_{LL}^T + (2\Lambda_T) F_{UT}^T + (2h)(2\Lambda_T) F_{LT}^T \right\} \]

Unpolarized

\[ F_{\tilde{UU}}^T = F_{UU}^T + \frac{K}{\sqrt{Q^2}} F_{UU}^{T,\text{tw}3} \]

\[ F_{\tilde{UU}}^{T,\text{tw}2} = A_{UU}^T \text{Re} (F_1 \mathcal{H} + \tau F_2 \mathcal{E}) + B_{UU}^T G_M \text{Re} (\mathcal{H} + \mathcal{E}) + C_{UU}^T G_M \text{Re} \mathcal{H} \]

\[ F_{\tilde{UU}}^{T,\text{tw}3} = \text{Re} \left\{ A_{UU}^{(3)T} \left[ F_1 (2\mathcal{H}_{2T} + \mathcal{E}_{2T}) + F_2 (\mathcal{H}_{2T} + \tau \mathcal{H}_{2T}) \right] \right\} 
\[ + B_{UU}^{(3)T} G_M \tilde{E}_{2T} + C_{UU}^{(3)T} G_M \left[ 2\xi H_{2T} - \tau (\tilde{E}_{2T} - \xi E_{2T}) \right] \]
Rosenbluth separation for Bethe-Heitler contribution

\[
\frac{d^5 \sigma_{\text{BH unpol}}}{dx_B j dQ^2 dt d\phi d\phi_S} = \frac{\Gamma}{t^2} \left[ A_{\text{BH}} (F_1^2 + \tau F_2^2) + B_{\text{BH}} \tau G_M^2(t) \right]
\]
Rosenbluth Separated Data for BH-DVCS

\[
\frac{d^5 \sigma^I_{unpol}}{dx_B dQ^2 d|t| d\phi d\phi_S} = \frac{\Gamma}{Q^2(-t)} \left[ A_I \left( F_1 \Re H + \tau F_2 \Re E \right) + B_I G_M \Re (H + E) + C_I G_M \Re \tilde{H} \right]
\]

- \( Q^2 = 1.820 \text{ GeV}^2 \)
- \( x_B = 0.343 \)
- \( t = -0.172 \text{ GeV}^2 \)

Hall A data, Defurne
$E_e = 5.75 \text{ GeV} \quad Q^2 = 1.8 \text{ GeV}^2 \quad x_{Bj} = 0.34$
Comparison with other/BKM based analyses
Impact on pressure extraction through dispersion relations

\[ Q^2 = 2 \text{ GeV}^2 \quad t = -0.3 \text{ GeV}^2 \]

Skewness dependence induced by finite threshold effects

\[ \text{Phys.Rev. D80 (2009) 071501} \]
The University of Virginia is stepping up this truly interdisciplinary effort.
Femtography Imaging with Neural Networks (FINN)

Strategy:
1. A fully connected neural network maps input kinematic data to a vector of eight form factors (see diagram).
2. Use a code developed by our Data Analysis Team to evaluate the cross sections and in terms of the CFFs.

Jake Grigsby

We translate the x-sec. code into TensorFlow

- Automatically differentiable
- At variance with other efforts we can train CFF extraction network with backpropagation and variants of stochastic gradient descent.
Compton Form factors

\[ \mathcal{R}(H) \quad \mathcal{R}(E) \quad \mathcal{R}(\bar{H}) \quad \mathcal{R}(\bar{E}) \]

\[ \Im(H) \quad \Im(E) \quad \Im(\bar{H}) \quad \Im(\bar{E}) \]

\[ x_B \text{ Dependence} \]

\[ \phi(\text{deg}) \]

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We provide a new key to interpreting polarized degrees of freedom in deeply virtual exclusive experiments

Please check out our new formalism!!

arXiv:1903.05742