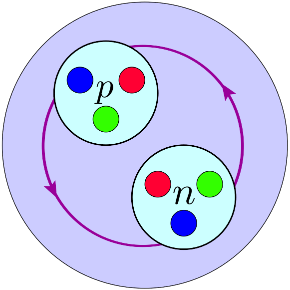
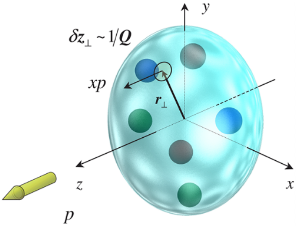
DVCS on the Neutron in the Deuteron

Alan Sosa

With Wim Cosyn





GPDs

$$\int \frac{dz^-}{2\pi} \langle p'_N | e^{iz^- k^+} \bar{q}(0)\gamma^+ q(z) | p_N \rangle_{z^-=0, z_\perp=0} \tag{1}$$

$$= \frac{1}{2P^+} \bar{u}(p'_N) \left[H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t) \frac{i\sigma^{+\alpha}\Delta_\alpha}{2m} \right] u(p_N)$$

GPDs → Cool Information

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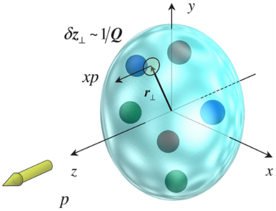
2D transverse spatial +1D momentum
distribution of partons
(Müller, 2005)



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2D transverse spatial +1D momentum
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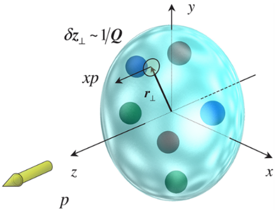
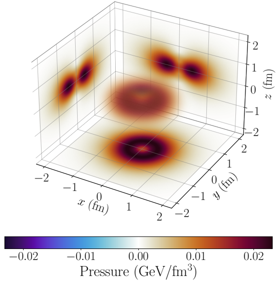


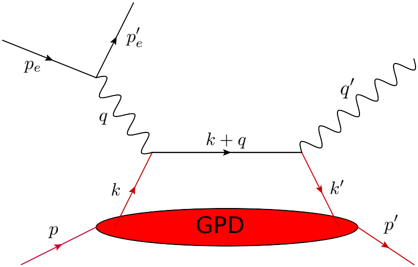
(Müller, 2005)

GPDs → **EMT-FFs** → Mechanical Properties



Deuteron (Cosyn et al. (2026))

Nucleon DVCS $e^- + p \to e^- + p + \gamma$



$$A_{DVCS} = \left[-\frac{|e|^3}{Q^2} [\bar{u}(p'_e)\gamma^\rho u(p_e)] \epsilon^*_\mu(q') g_{\rho\nu} \right] \times \tag{2}$$

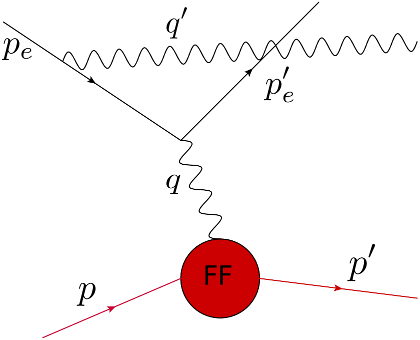
$$\sum_q e_q^2 \frac{1}{2P^+} \bar{u}(p'_N) \left\{ g_\perp^{\mu\nu} \left[\mathscr{H}^q(\xi,t)\gamma^+ + \mathscr{E}^q(\xi,t) \frac{i\sigma^{+\alpha}\Delta_\alpha}{2m} \right] \right.$$

$$\left. + \, i\epsilon^{\mu\nu+-} \left[\tilde{\mathscr{H}}^q(\xi,t)\gamma^+\gamma_5 + \tilde{\mathscr{E}}^q(\xi,t) \frac{\gamma_5\Delta^+}{2m} \right] \right\} u(p_N)$$

$$\mathscr{H}^q(\xi,t) = \int dx \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon} \right] H^q(x,\xi,t) \tag{3}$$

Bethe-Heitler Nucleon $e^- + p \to e^- + p + \gamma$

We need to look at all terms that contribute to reaction $e^- + p \to e^- + p + \gamma$



$$A_{BH} = \left[-\frac{|e|^3}{t} \bar{u}(p'_e) \not{\epsilon}^*(q') \frac{\not{p}_e - \not{q}'}{(p_e - q')^2} \gamma_\mu u(p_e) \right] \tag{4}$$

$$\times \left[F_1(t) \bar{u}(p'_N) \gamma^\mu u(p_N) + F_2(t) \bar{u}(p'_N) \frac{i\sigma^{\mu\nu}\Delta_\nu}{2m} u(p_N) \right]$$

$e^- + p \to e^- + p + \gamma$

Class of collinear frames (BKM,Breit,...)

$$\frac{d\sigma}{dxdQ^2dtd\phi'_q} = \frac{|A|^2}{e^6}\frac{\alpha_{em}^3 xy^2}{8\pi Q^4}\frac{1}{\sqrt{1+\gamma^2}} \tag{5}$$

$$|A|^2 = |A_{DVCS}|^2 + |A_{BH}|^2 + A_{BH}^* A_{DVCS} + A_{DVCS}^* A_{BH} \tag{6}$$

$$A_{DVCS} \propto \text{CFFs} \tag{7}$$

$$A_{BH} \propto \text{FFs} \tag{8}$$

Quark-Flavor Separation

Complications with this process $e^- + p \to e^- + p + \gamma$

$$\frac{d\sigma}{dxdQ^2dtd\phi'_q} = \frac{|A|^2}{e^6}\frac{\alpha_{em}^3 xy^2}{8\pi Q^4}\frac{1}{\sqrt{1+\gamma^2}} \tag{9}$$

$$|A|^2 = |A_{DVCS}|^2 + |A_{BH}|^2 + A^*_{BH}A_{DVCS} + A^*_{DVCS}A_{BH} \tag{10}$$

$$A_{DVCS} \propto \textcolor{red}{\text{CFFs}} \tag{11}$$

$$A_{BH} \propto \textcolor{red}{\text{FFs}} \tag{12}$$

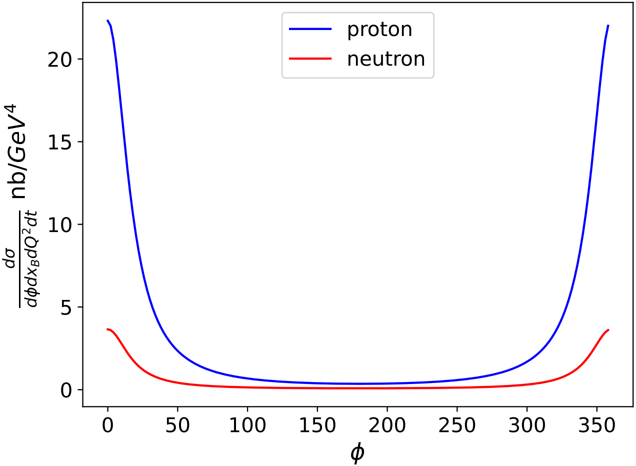
For extraction of GPDs, need more data than just proton, need also neutron data

$$H^n_d(x,\xi,t) = H^p_u(x,\xi,t), \quad H^n_u(x,\xi,t) = H^p_d(x,\xi,t)$$

$$H^n_{\bar{d}}(x,\xi,t) = H^p_{\bar{u}}(x,\xi,t), \quad H^n_{\bar{u}}(x,\xi,t) = H^p_{\bar{d}}(x,\xi,t)$$

Proton Vs Neutron Cross Sections

Total Cross sections for $e^- + p \to e^- + p + \gamma$ vs $e^- + n \to e^- + n + \gamma$

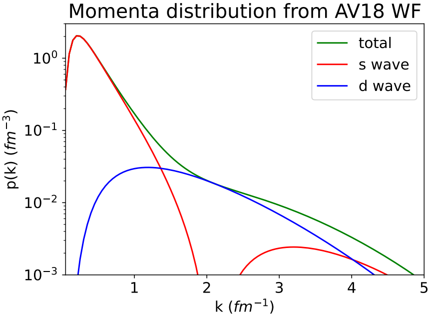


Kinematics: $x = 0.2$, $t = -0.17$ GeV^2, $Q^2 = 2.2$GeV^2, BeamEnergy $= 6$ GeV

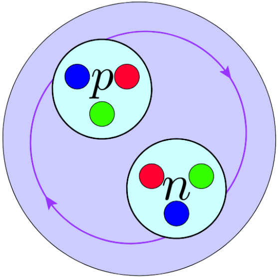
No free Neutron → Deuteron

Use Deuteron

- Nucleus with one proton and one neutron
- Spin-1 Hadron
- Nucleons in Deuteron can be described with non-relativistic wavefunction (Wiringa et al., 1995)



Reaction we look at now
$\mathbf{e^- + D \rightarrow e^- + p + n + \gamma}$

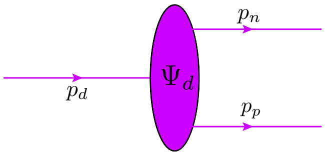


How do we model this reaction?

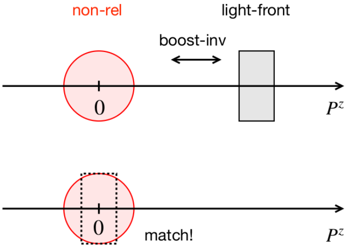
LFWF for Deuteron

$$\Psi_d = \bar{u}(p_n)\Gamma_\alpha v(p_p)\epsilon^\alpha_{pn}(p_{pn}) \rightarrow \qquad \Gamma^\alpha = \gamma^\alpha G_1(\alpha_p, p_T) + (p_p - p_n)^\alpha G_2(\alpha_p, p_T)$$

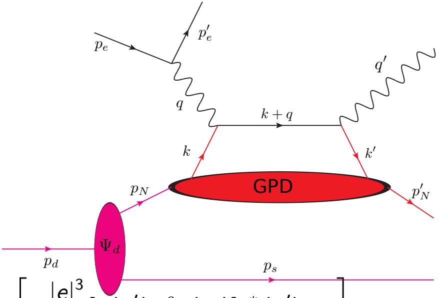
G_1 , G_2 $\propto$ S and D-Wave contributions in NR wavefunctions through matching in CM frame. (Kondratyuk and Strikman, 1984)



- Off-shellness effects remain finite at large momentum transfer, unlike in the instant form
- Reaction dynamics can be formulated using on-shell nucleon degrees of freedom
- The LF naturally supports a factorization between nuclear and nucleonic structure



Incoherent DVCS PWIA $e^- + D \to e^- + p + n + \gamma$



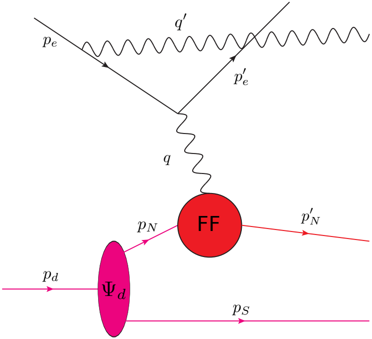
$$A_{DVCS} = \left[-\frac{|e|^3}{Q^2} [\bar{u}(p'_e)\gamma^\rho u(p_e)] \epsilon^*_\mu(q') g_{\rho\nu} \right] \times \tag{13}$$

$$\sum_q e_q^2 \frac{1}{2P^+} \bar{u}(p'_N) \left\{ g_\perp^{\mu\nu} \left[\mathscr{H}^q(\tilde{\xi}, \tilde{t})\gamma^+ + \mathscr{E}^q(\tilde{\xi}, \tilde{t}) \frac{i\sigma^{+\alpha}\tilde{\Delta}_\alpha}{2m} \right] \right.$$

$$\left. + i\epsilon^{\mu\nu+-} \left[\tilde{\mathscr{H}}^q(\tilde{\xi}, \tilde{t})\gamma^+\gamma_5 + \tilde{\mathscr{E}}^q(\tilde{\xi}, \tilde{t}) \frac{\gamma_5 \tilde{\Delta}^+}{2m} \right] \right\} u(p_N)$$

$$\times \frac{2(2\pi)^{\frac{3}{2}}}{2 - \alpha_p} \bar{u}(p_N)\Gamma_\alpha v(p_S) \epsilon^\alpha_{pn}(p_{pn})$$

Incoherent BH $e^- + D \to e^- + p + n + \gamma$



$$A_{BH} = \left[-\frac{|e|^3}{t} \bar{u}(p'_e) \not{\epsilon}^*(q') \frac{\not{p}_e - \not{q}'}{(p_e - q')^2} \gamma_\mu u(p_e) \right] \tag{14}$$

$$\times \; \bar{u}(p'_N) \left[F_1(\tilde{t})\gamma^\mu + F_2(\tilde{t}) \frac{i\sigma^{\mu\nu}\tilde{\Delta}_\nu}{2m} \right] u(p_N)$$

$$\times \; \frac{2(2\pi)^{\frac{3}{2}}}{2 - \alpha_p} \bar{u}(p_N) \Gamma_\alpha v(p_S) \epsilon^\alpha_{pn}(p_{pn})$$

A new problem

7-fold Differential Cross Section can be written as

$$\frac{d\sigma}{dxdQ^2dtd\phi'_q d\alpha_p d^2p_T} = \frac{|A|^2}{e^6}\frac{\alpha_{em}^3 xy^2}{8\pi Q^4}\frac{1}{\sqrt{1+\gamma^2}}\frac{1}{(2\pi)^3\alpha_p(2-\alpha_p)} \tag{15}$$

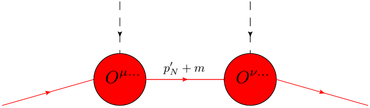
Where $\alpha_p = \frac{2p_p^+}{p_{pn}^+}$ and $p_{pn} = p_p + p_n$
Both proton and neutron interactions can happen in this process. New interference contributions that cause more mess will appear

$$|A|^2 = |A_n|^2 + |A_p|^2 + A_p^* A_n + A_n^* A_p \tag{16}$$

$$\begin{aligned} |A|^2 = {} & |A_{nDVCS}|^2 + |A_{nBH}|^2 + 2\mathrm{Re}(A_{nDVCS}^* A_{nBH}) \\ & + |A_{pDVCS}|^2 + |A_{pBH}|^2 + 2\mathrm{Re}(A_{pDVCS}^* A_{pBH}) \\ & + 2\mathrm{Re}(A_{nDVCS}^* A_{pDVCS}) + 2\mathrm{Re}(A_{nDVCS}^* A_{pBH}) \\ & + 2\mathrm{Re}(A_{nBH}^* A_{pDVCS}) + 2\mathrm{Re}(A_{nBH}^* A_{pBH}) \end{aligned} \tag{17}$$

Bound vs Free Nucleons $|A_N|^2$

For the free nucleons we have

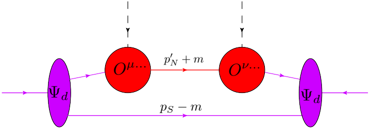


$$|A|^2 \propto \mathrm{Tr}\left[\Pi_N^{\text{free}} O^{\mu\cdot\cdot}(\not{p}' + m) O^{\nu\cdot\cdot}\right]$$

Where

$$\Pi_N^{\text{free}} = \frac{1}{2}(\not{p} + m)(1 + \$\gamma^5)$$

For the bounds nucleons we have



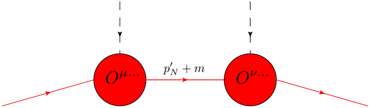
$$|A|^2 \propto \mathrm{Tr}[\rho^{\alpha\beta}(\not{p}_N + m)(\not{p}_S - m)$$
$$(\not{p}_N + m) O^{\mu\cdot\cdot}(\not{p}' + m) O^{\nu\cdot\cdot}]$$

Where

$$\rho^{\alpha\beta} = \rho_U^{\alpha\beta} + \rho_V^{\alpha\beta} + \rho_T^{\alpha\beta}$$

Bound vs Free Nucleons $|A_N|^2$

For the free nucleons we have



$$|A|^2 \propto \mathrm{Tr}\left[\Pi_N^{\text{free}} O^{\mu\cdot\cdot}(\not{p}' + m) O^{\nu\cdot\cdot}\right]$$

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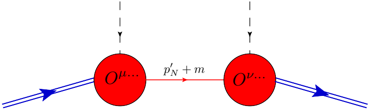
$$\Pi_N^{\text{free}} = \frac{1}{2}(\not{p} + m)(1 + \not{s}\gamma^5)$$

For the bounds nucleons we have



$$|A_N|^2 \propto \mathrm{Tr}\left[\Pi_N^{\text{bound}} O^{\mu\cdot\cdot}(\not{p}' + m) O^{\nu\cdot\cdot}\right]$$

Where

$$\Pi_N^{\text{bound}} = \frac{1}{2}(\not{p} + m)(u_N + \not{s}_N\gamma^5 + t_N)$$

Bound vs Free Nucleons

For the free nucleons we have

$$|A|^2 \propto \mathrm{Tr}\left[\Pi_N^{\text{free}} O^{\mu..}(\not{p}' + m) O^{\nu..}\right]$$

Where

$$\Pi_N^{\text{free}} = \frac{1}{2}(\not{p} + m)(1 + \not{S}\gamma^5)$$

Free nucleon covariant spin density matrix

$$O_i(x_B, t, Q^2)$$

For the bounds nucleons we have

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Where

$$\Pi_N^{\text{bound}} = \frac{1}{2}(\not{p} + m)(u_N + \not{s}_N\gamma^5 + t_N)$$

Bound nucleon covariant spin density matrix

$$O_i(\tilde{x}_B, \tilde{t}, \tilde{Q}^2)$$

- LF Energy not conserved $+$Nucleons Moving $\rightarrow$ **Effective Kinematics!**
- Polarized Deuteron $\rightarrow$ **Effective Polarizations**

Both depend on α_p, p_T, ϕ_N

Effective Polarizations of Nucleons $\left(\alpha_p = \frac{2p_p^+}{p_d^+}\right)$

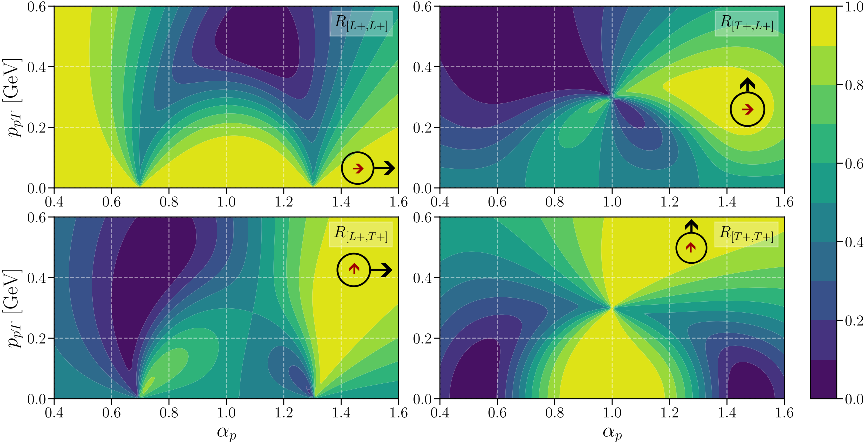
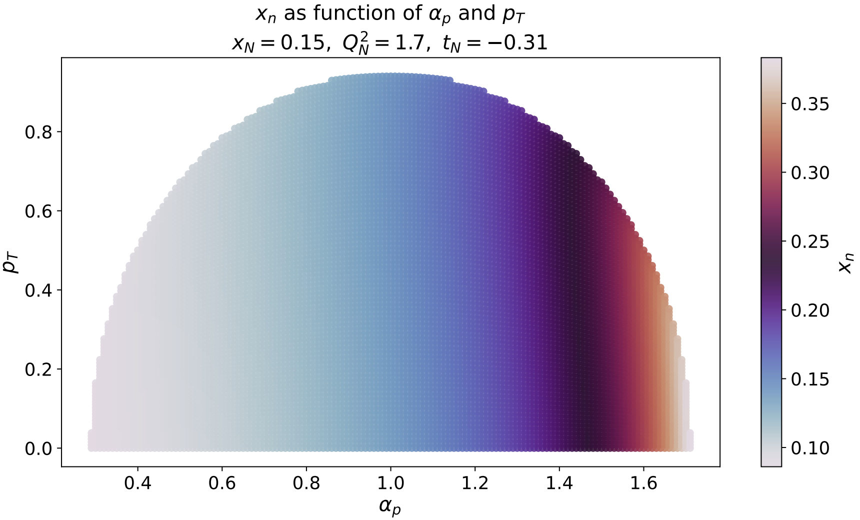
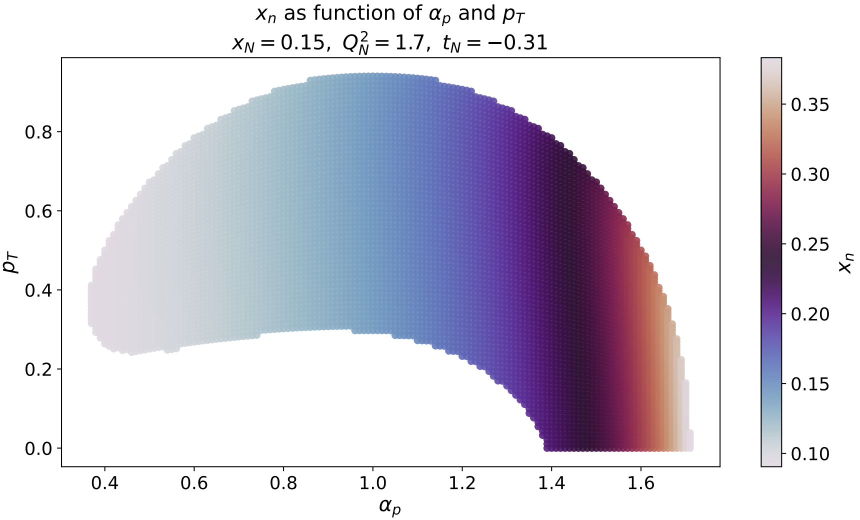


Figure: Cosyn and Weiss (2026)

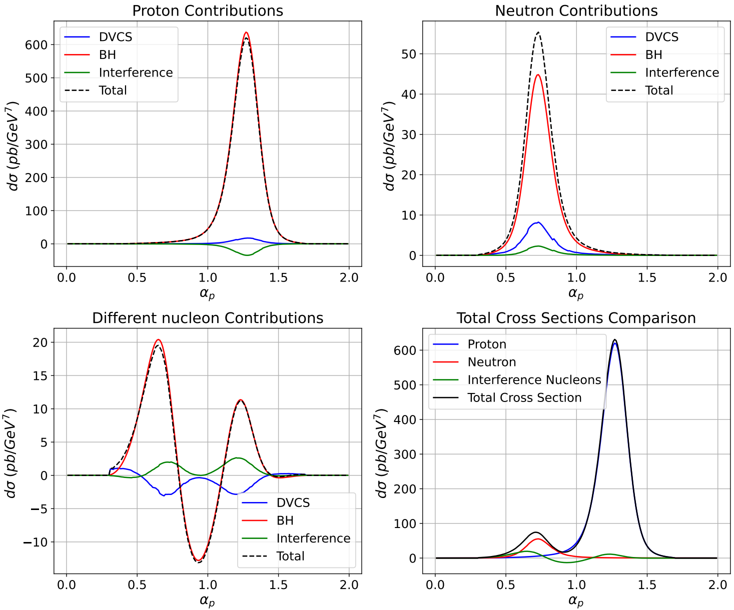
Effective Kinematics



Effective Kinematics with experimental cuts

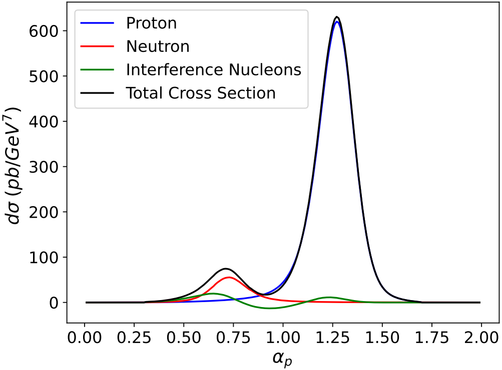


Varying α_p no cuts

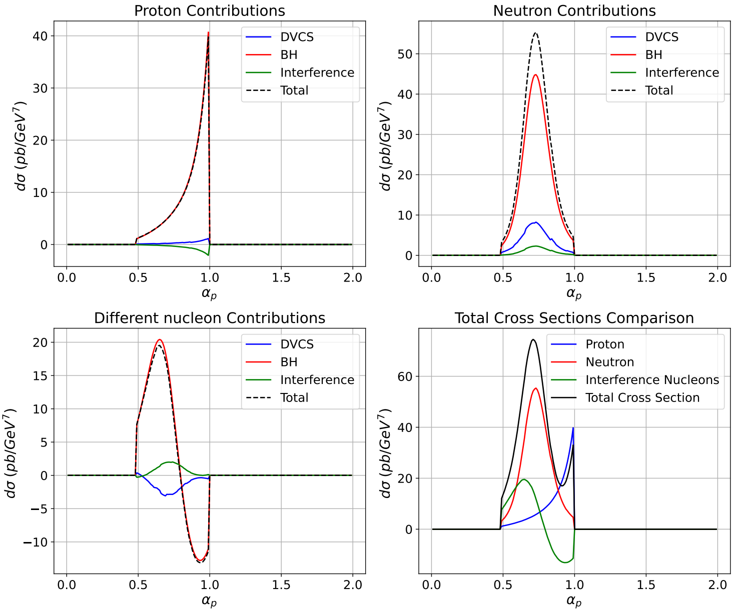


Varying α_p no cuts

$$|A|^2 = |A_n|^2 + |A_p|^2 + A_p^* A_n + A_n^* A_p$$

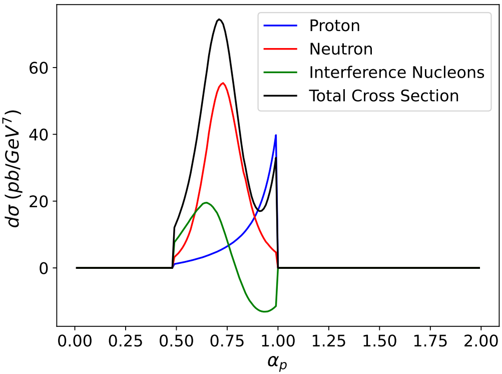


Varying α_p with cuts

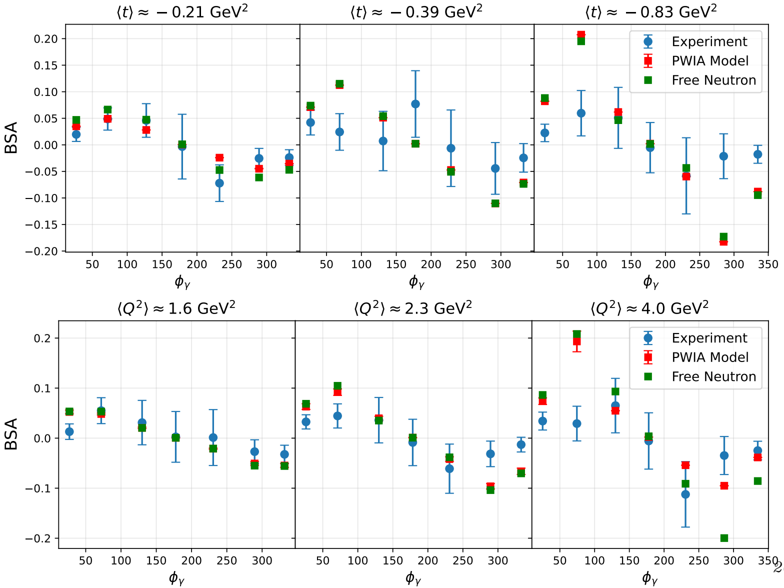


Varying α_p with cuts

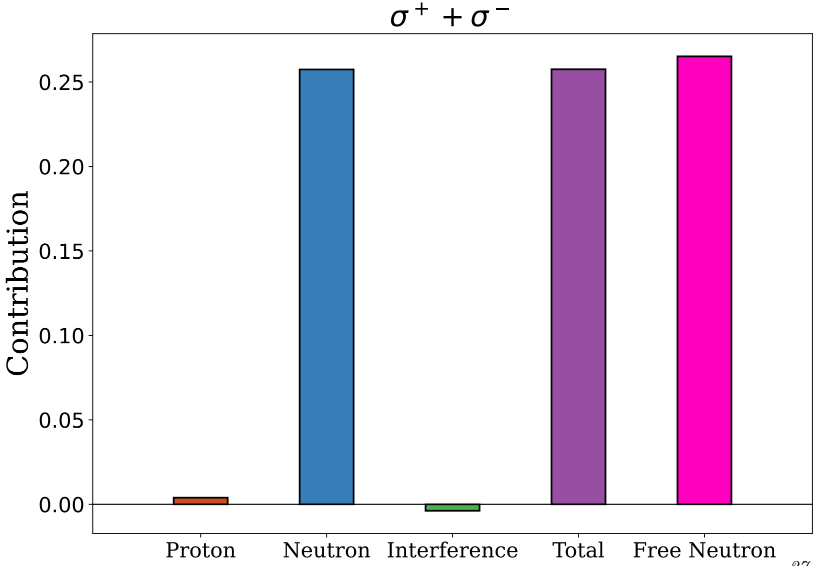
$$|A|^2 = |A_n|^2 + |A_p|^2 + A_p^* A_n + A_n^* A_p$$



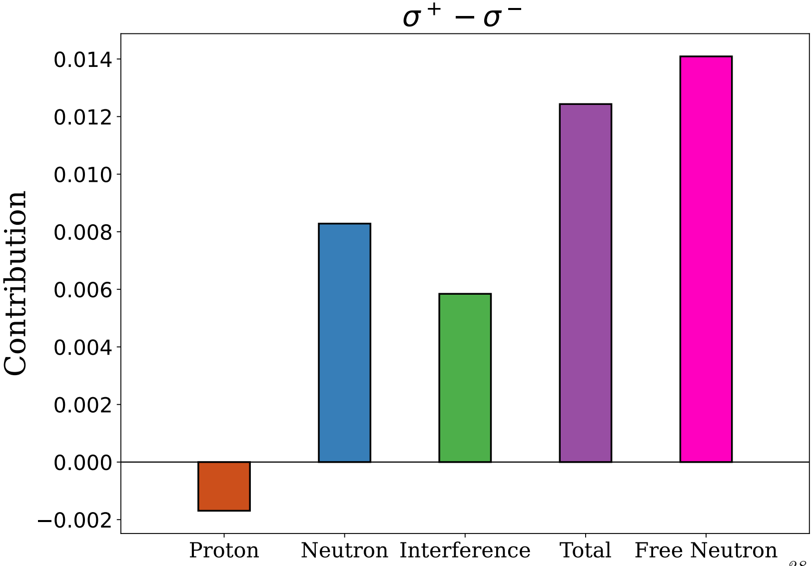
BSA with experimental cuts+integrated $d^3 p_p$
CLAS12 et al. CLAS12 (2024)



$PWIA\ with\ cuts \neq Free\ Neutron$



$PWIA\ with\ cuts \neq Free\ Neutron$



Summary of results so far

Modeled the Incoherent DVCS Cross Sections using techniques of LF Quantization and with inputs-

- Model GPDs from Partons Framework (Berthou et al. (2018))
- Proton and Neutron Form Factors
- Deuteron Non-Relativistic Wavefunction

Amplitudes for process of form

$$A_{N,PWIA} \propto \text{(Perturbative Part)(Non-Perturbative Function)(Deuteron LFWF)}$$

Found that the 7-fold Differential Cross Section can be written as

$$\frac{d\sigma}{dxdQ^2dtd\phi_q' d\alpha_p d^2p_T} = \frac{|A|^2}{e^6}\frac{\alpha_{em}^3 xy^2}{8\pi Q^4}\frac{1}{\sqrt{1+\gamma^2}}\frac{1}{2(2\pi)^3\alpha_p(2-\alpha_p)} \tag{18}$$

- **Even in PWIA model potential contamination in experimental data of nDVCS**
- **External kinematics are not the ones the Neutron is being probed at!**
- **Tagged Measurements allow this knowledge!**

Next Steps for this work

Talk to experimentalists to apply cuts properly

↓

Compare to Experiments

↓

Take into account Final State Interactions

↓

Get Cross Sections with FSIs and make comparisons

↓

Look into kinematics where nuclear effects are either suppressed/dominant

Final State Interactions (Potential Model)

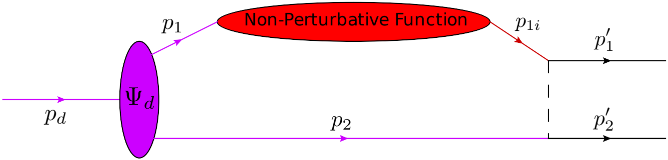


Figure: Dash Line corresponds to interaction between nucleons

$$\mathscr{M}_{\lambda_1'\lambda_2';\lambda_1\lambda_2} = (\bar{u}_{\lambda_1'}(p_1'))_a(\bar{u}_{\lambda_2'}(p_2'))_b M_{ab;cd}(u_{\lambda_1}(p_1))_c(u_{\lambda_2}(p_2))_d \tag{19}$$

$$\begin{aligned} M_{ab;cd} &= F_S(s,t)\delta_{ac}\delta_{bd} + F_V(s,t)\gamma_{ac}\cdot\gamma_{bd} + F_T(s,t)\sigma^{\mu\nu}_{ac}(\sigma_\mu\nu)_b d \\ &+ F_P(s,t)\gamma^5_{ac}\gamma^5_{bd} + F_A(s,t)(\gamma^5\gamma)_{ac}\cdot(\gamma^5\gamma)_{bd} \end{aligned} \tag{20}$$

$\mathscr{M}_{\lambda_1'\lambda_2';\lambda_1\lambda_2}$ is a helicity amplitude that is accessible via SAID parametrizations of nucleon nucleon scattering data (Arndt et al. (2000)). Need to do this matching with Lightfront spinors!!

References

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Mellin Moments of GPDs

Moments of GPDs (Belitsky and Radyushkin, 2005)

$$\int dx\, x^n \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \bar{q}(0)\gamma^+ q(z^-) = \frac{1}{(P^+)^{n+1}} \bar{q}(0)\gamma^+ \left(\frac{i}{2}\overleftrightarrow{D}^+\right)^n q(0) \quad (21)$$

With $n = 0$ which is first moment we have

$$\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \bar{q}(0)\gamma^+ q(z^-) = \frac{1}{P^+} \bar{q}(0)\gamma^+ q(0) \quad (22)$$

Remember though these are matrix elements for Electromagnetic Form Factors

$$\langle p'|\bar{q}(0)\gamma^+ q(0)|p\rangle = F_1^q(t)\bar{u}(p')\gamma^+ u(p) + F_2^q(t)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m} u(p) \quad (23)$$

Therefore we have

$$\int H_q(x,\xi,t)dx = F_1^q(t) \quad (24)$$

$$\int E_q(x,\xi,t)dx = F_2^q(t) \quad (25)$$

$$\int dx\, x \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \bar{q}(0)\gamma^+ q(z^-) = \frac{1}{(P^+)^2} \bar{q}(0)\gamma^+ \left(\frac{i}{2}\overleftrightarrow{D}^+\right) q(0) \tag{26}$$

Which the operator $i\gamma^\mu D^\nu = T^{\mu\nu}$ is the Energy Momentum tensor. Parametrize this matrix element with Energy Momentum Tensor form factors.

$$\begin{aligned}\langle p'|\bar{q}(0)T^{\mu\nu}q(0)|p\rangle = \bar{u}(p',s')\Bigg[&\frac{P^\mu P^\nu}{M}A_a(t) + \frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M}D_a(t) \\ &+Mg^{\mu\nu}\bar{c}_a(t) + \frac{P^{\{\mu}i\sigma^{\nu\}\lambda}\Delta_\lambda}{2M}J_a(t) - \frac{P^{[\mu}i\sigma^{\nu]\lambda}\Delta_\lambda}{2M}S_a(t)\Bigg]u(p,s)\end{aligned} \tag{27}$$

Therefore

$$\int H_q(x,\xi,t)xdx = A_q(t) + 16\xi^2 D_q(t) \tag{28}$$

$$\int \frac{1}{2}[H_q(x,\xi,t) + E_q(x,\xi,t)]xdx = J_q(t) \tag{29}$$