Beam Single Spin Asymmetries in Electron-Proton Scattering

Pratik Sachdeva

Washington University in St. Louis

Mentors:

Wally Melnitchouk

Jefferson Laboratory Theory Center

Peter Blunden

University of Manitoba

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Jefferson Lab
Thomas Jefferson National Accelerator Facility

Outline

1. Introduction
   - Beam Single Spin Asymmetries (BSSA)
   - Transverse and Normal Polarizations
   - Motivation: Q-weak Collaboration
2. Elastic Scattering
   - Beam Normal SSA
   - Beam Transverse Single Spin Asymmetry
   - Combination of Asymmetries
3. Inelastic Hadronic Intermediate State
   - $\mathscr{M}_{\gamma}^{*}\mathscr{M}_{\gamma\gamma}$ Interference
   - Leptonic and Hadronic Tensors
   - Normal BSSA
4. Conclusion

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Consider the scattering amplitude:

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- At the Born level, the spin orientation has no effect on $|\mathscr{M}_\gamma|^2$, so the asymmetry vanishes.
- Higher order effects result in asymmetries dependent on whether the spin is transversely, normally, or longitudinally polarized.

Transverse and Normal Polarization

- Transverse asymmetry B_t behaves like $\cos\phi_s$ and normal asymmetry B_n behaves like $\sin\phi_s$.

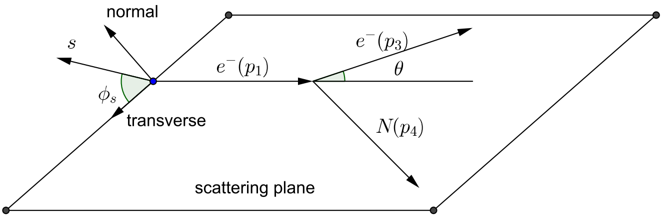

Figure 2. Electron-Proton Scattering

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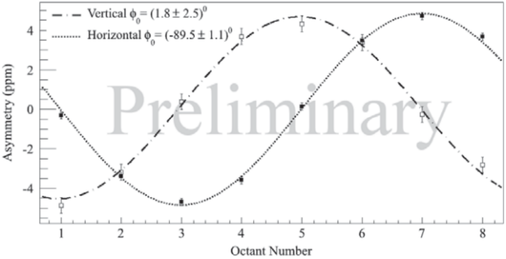

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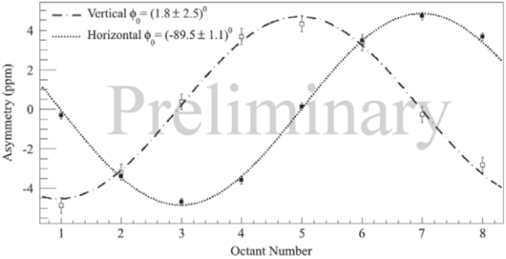

- Concerned about possible phase offsets due to unconsidered BSSA effects.

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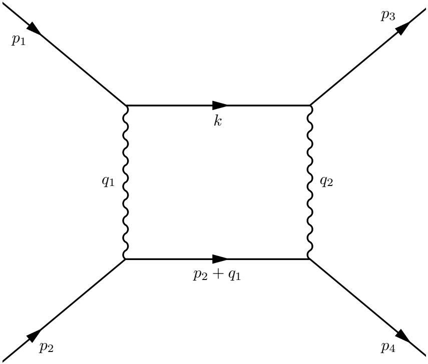
- Hadronic Inelastic Intermediate State
  - Pasquini and Vanderhaeghen (**PRC 70**, 2004) showed that inelastic hadronic intermediate states have a larger contribution to the asymmetry than the elastic case.
  - Consider the case of near forward limit.

Elastic Scattering

Elastic scattering for electron-proton scattering,

$$e(p_1) + N(p_2) \rightarrow e(p_3) + N(p_4).$$



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$$P = \frac{p_2 + p_4}{2}, \qquad K = \frac{p_1 + p_3}{2}, \qquad q = p_1 - p_3, \qquad Q^2 = -q^2;$$

$$s = (p_1 + p_2)^2, \qquad \tau = \frac{Q^2}{4M^2}, \qquad \nu = P \cdot K, \qquad \epsilon = \frac{\nu^2 - M^4\tau(1+\tau)}{\nu^2 + M^4\tau(1+\tau)};$$

$$W^2 = (p_2 + q_1)^2, \qquad Q_1^2 = -q_1^2, \qquad Q_2^2 = -q_2^2,$$

for electron mass m_e and hadron mass M.

Beam Normal Single Spin Asymmetry: Setup

Using six invariant amplitudes given by Goldberger et al. (Ann. Phys. 2, 1957), we can construct a general elastic lepton-nucleon scattering amplitude:

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$$T^{\text{non-flip}} = \frac{e^2}{Q^2}\bar{u}_e(p_3)\gamma_\mu u_e(p_1)\cdot\bar{u}_N(p_4)\left(\widetilde{G}_M\gamma^\mu - \widetilde{F}_2\frac{P^\mu}{M} + \widetilde{F}_3\frac{\not{K}P^\mu}{M^2}\right)u_N(p_2)$$

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$$T^{\text{flip}} = \frac{e^2}{Q^2}\frac{m_e}{M}\left[\bar{u}_e(p_3)u_e(p_1)\cdot\bar{u}_N(p_4)\left(\widetilde{F}_4 + \widetilde{F}_5\frac{\not{K}}{M}\right)u_N(p_2)\right.$$
$$\left. + \widetilde{F}_6\bar{u}_e(p_3)\gamma_5 u_e(p_1)\cdot\bar{u}_N(p_4)\gamma_5 u_N(p_2)\right].$$

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We can also write

$$\widetilde{G}_E = \widetilde{G}_M - (1+\tau)\widetilde{F}_2.$$

Beam Normal SSA

Gorchtein et al. found that for a spin parallel (anti-parallel) to the normal polarization vector

$$S^\mu = (0, \vec{S}_n), \qquad \vec{S}_n = (\vec{p}_1 \times \vec{p}_3) \, / \, |\vec{p}_1 \times \vec{p}_3|$$

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$$B_n = \frac{2m_e}{Q}\sqrt{2\epsilon(1-\epsilon)}\sqrt{1+\frac{1}{\tau}}\left(G_M^2 + G_E^2\right)^{-1} \\ \times \left\{-\tau\, G_M \,\mathrm{Im}\left(\widetilde{F}_3 + \frac{1}{1+\tau}\frac{\nu}{M^2}\widetilde{F}_5\right) - G_E \,\mathrm{Im}\left(\widetilde{F}_4 + \frac{1}{1+\tau}\frac{\nu}{M^2}\widetilde{F}_5\right)\right\}.$$

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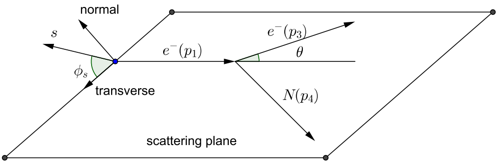

Figure 3. Transverse Spin Polarization

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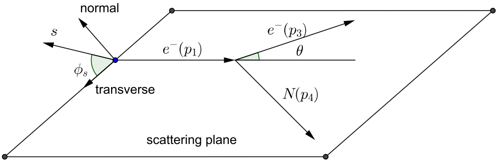

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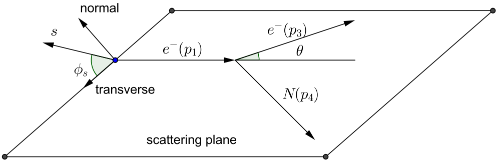

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$$\times \left\{ g_V^e G_M G_M^Z \tau(\tau+1) + g_A^e \left(G_M G_A^Z \tau(1+\tau-\nu) + G_E G_E^Z (1-\tau-\nu) \right) \right\},$$

where G_M^Z and G_E^Z are the weak form factors and G_F is Fermi's coupling constant.

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For a general transverse spin,

$$B_{t,\text{ gen}} = B_t \cos \phi_s.$$

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The combination of these two asymmetries gives

$$\begin{aligned} B &= B_t \cos\phi_s + B_n \sin\phi_s \\ &= \sqrt{B_t^2 + B_n^2}\, \sin(\phi_s + \delta) \end{aligned}$$

where $\delta = \tan^{-1}\left(\frac{B_t}{B_n}\right)$.

Combination of Asymmetries: Q-weak Kinematics

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$\rightarrow$ This is too small to affect the Q-weak measurements.

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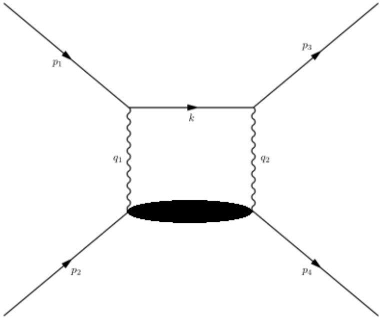
- What factors contribute to B_n?

Inelastic Hadronic Intermediate State

Scattering process:

$$e(p_1) + N(p_2) \to e(p_3) + N(p_4)$$

with intermediate leptonic momentum k and intermediate hadronic momentum $W = p_2 + q_1$.



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- The BSSA comes from the absorptive part of the two-photon exchange amplitude (Pasquini & Vanderhaeghen PRC 70, 2004):

$$B_n = \frac{2\,\mathrm{Im}\left(\sum_{\text{spins}} \mathscr{M}_\gamma^* \cdot \text{Abs } \mathscr{M}_{\gamma\gamma}\right)}{\sum_{\text{spins}} |\mathscr{M}_\gamma|^2}.$$

Leptonic and Hadronic Tensors

We can write this as

$$B_n = \frac{e^6}{(2\pi)^3 Q^2}\left(\sum_{\text{spins}} |\mathscr{M}_\gamma|^2\right)^{-1} \int \frac{d^3\vec{k}}{E_k}\frac{1}{Q_1^2 Q_2^2}\,\mathrm{Im}\left\{L_{\alpha\mu\nu}H^{\alpha\mu\nu}\right\},$$

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where (de Rujula et al. Nucl. Phys. B35, 1971)

$$W^{\mu\nu} = \left(-g^{\mu\nu} + \frac{q_1^\mu q_1^\nu}{q_1^2} \right) W_1 + \frac{1}{M^2} \left(p_2^\mu - \frac{p_2 \cdot q_1}{q_1^2} q_1^\mu \right) \left(p_2^\nu - \frac{p_2 \cdot q_1}{q_1^2} q_1^\nu \right) W_2.$$

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$$B_n = -\frac{1}{(2\pi)^3}\frac{e^2 Q^2}{D(s,Q^2)}\frac{1}{8E_1E_3M}\int_0^{2\pi} d\phi_k \int_{M^2}^{s} dW^2 \int_0^{Q^2_{1,\max}} dQ_1^2 \\ \times \frac{\mathrm{Im}\left\{L_{\alpha\mu\nu}H^{\alpha\mu\nu}\right\}}{Q_1^2|\vec{k}|\left(1-\cos\theta\cos\theta_k-\sin\theta\sin\theta_k\cos\phi_k\right)}$$

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where E_1 and E_3 are the energies of the incoming and outgoing leptons, θ_k is the angle between $\vec{p}_1$ and $\vec{k}$, ϕ_k is the azimuthal angle, and

$$D(s,Q^2) = \frac{8Q^4}{1-\epsilon}\left\{G_M^2 + \frac{\epsilon}{\tau}G_E^2\right\},$$

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The tensor contraction is

$$\mathrm{Im}\, L_{\alpha\mu\nu}H^{\alpha\mu\nu} = \frac{8m_e}{M^2Q_1^2}\Big[2W_1M^2Q_1^2\left(\epsilon^{p_1p_2qs}+\epsilon^{p_2qq_1s}\right) \\ +W_2\epsilon^{p_2qq_1s}\Big((M^2-Q_1^2-W^2)(p_1\cdot p_2)-M^2Q_1^2\Big)\Big].$$

Once again,

$$B_n = -\frac{1}{(2\pi)^3}\frac{e^2 Q^2}{D(s,Q^2)}\frac{1}{8E_1E_3M}\int_0^{2\pi} d\phi_k \int_{M^2}^{s} dW^2 \int_0^{Q^2_{1,\max}} dQ_1^2$$
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$\rightarrow$ Currently evaluating for Q-weak kinematics.

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6. The framework developed here could potentially be used to compute other beam or target SSA at near-forward angles.

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Questions?