Our new Greek friend


This


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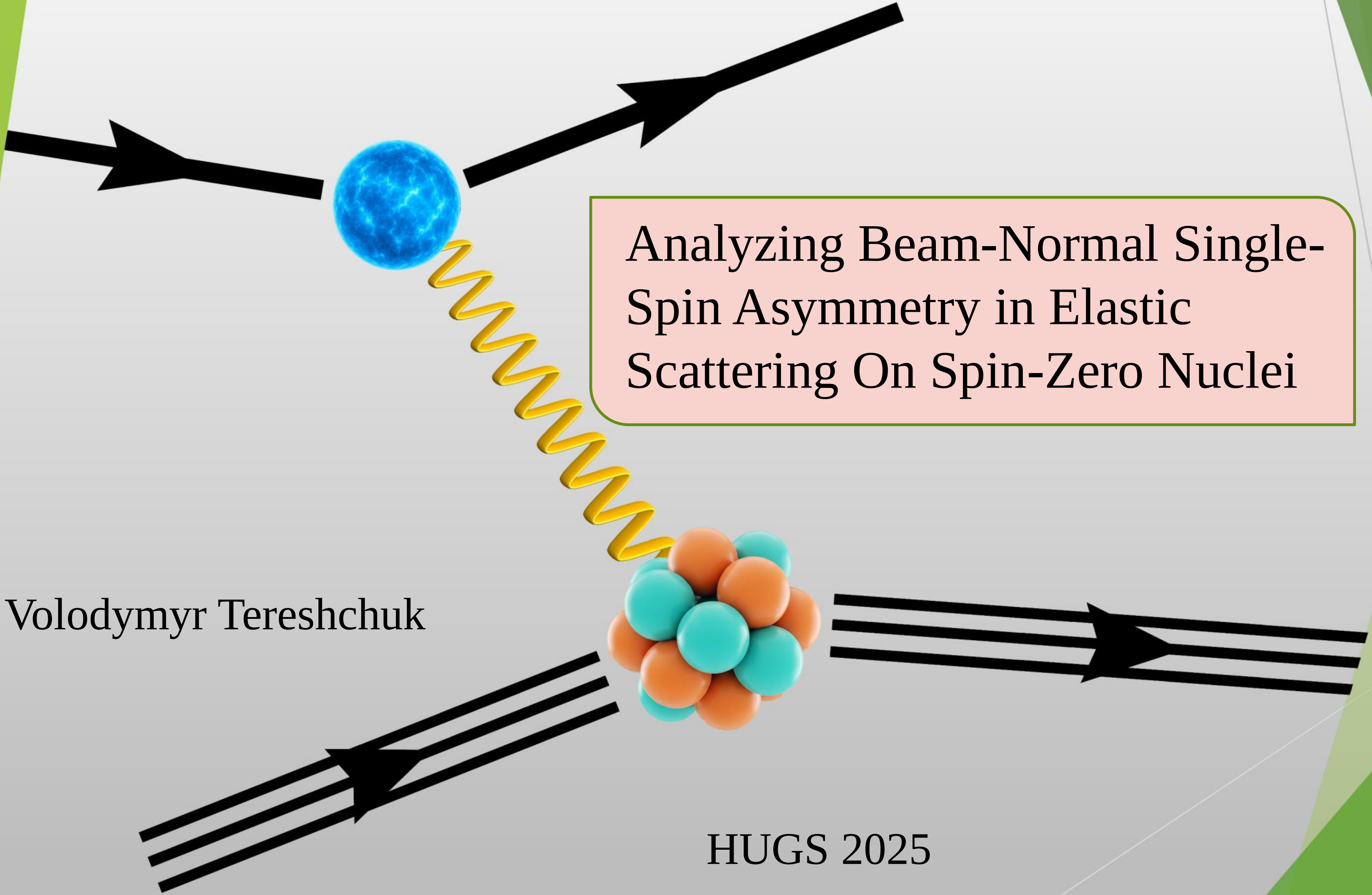
Sparta!

Analyzing Beam-Normal Single-Spin Asymmetry in Elastic Scattering On Spin-Zero Nuclei



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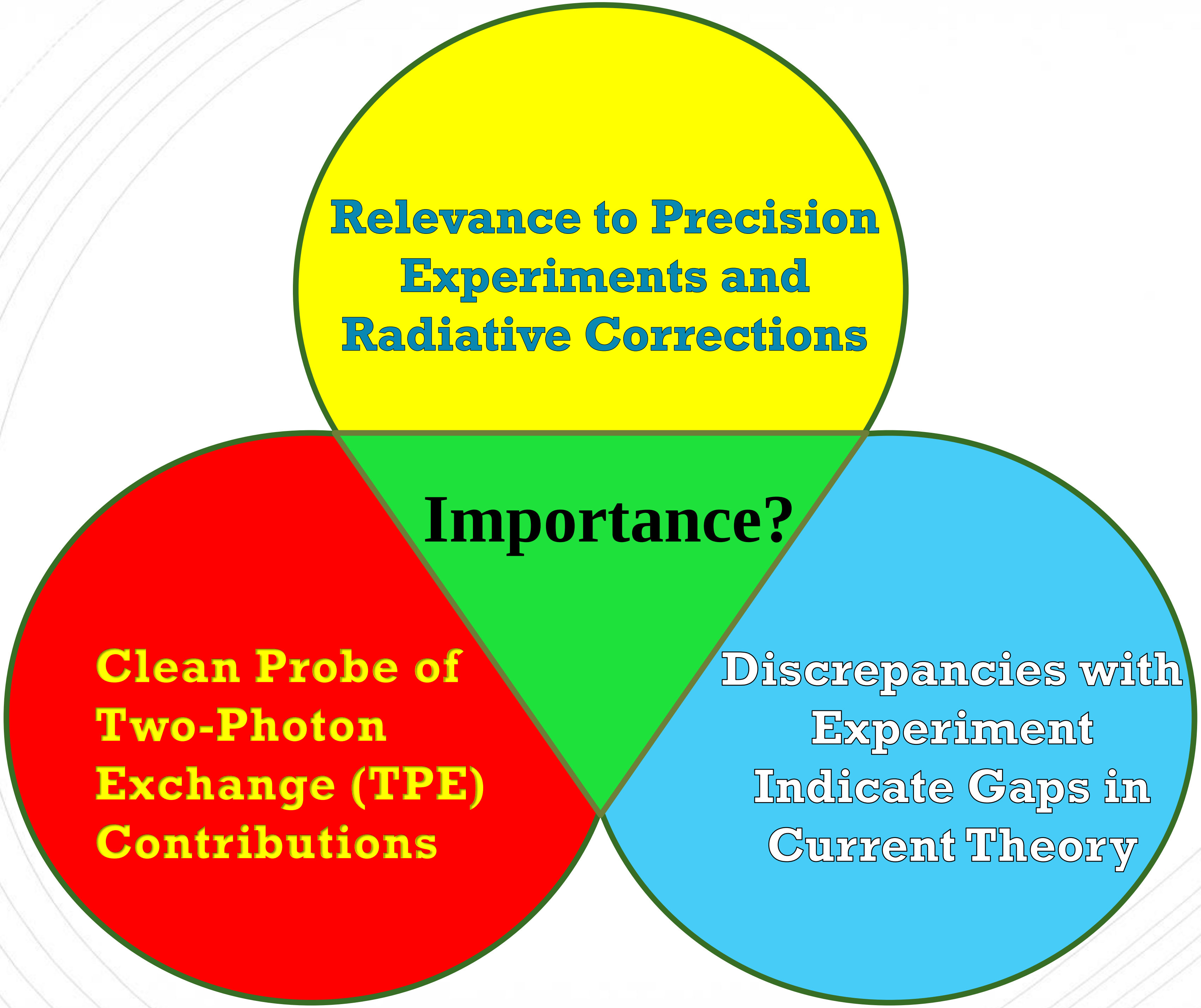
HUGS 2025


Relevance to Precision Experiments and Radiative Corrections
Importance?
Clean Probe of Two-Photon Exchange (TPE) Contributions
Discrepancies with Experiment Indicate Gaps in Current Theory

Outline of Presentation

- Beam-normal single spin asymmetry (SSA). Definition and basic assumptions
- Role of two-photon exchange (TPE) in the generation of beam-normal single-spin asymmetry (SSA) in elastic scattering
- TPE effects and the calculation of beam-normal SSA in elastic scattering
- Existing challengers
- Ongoing developments

Elastic lepton-nucleon scattering with transversely polarized beam

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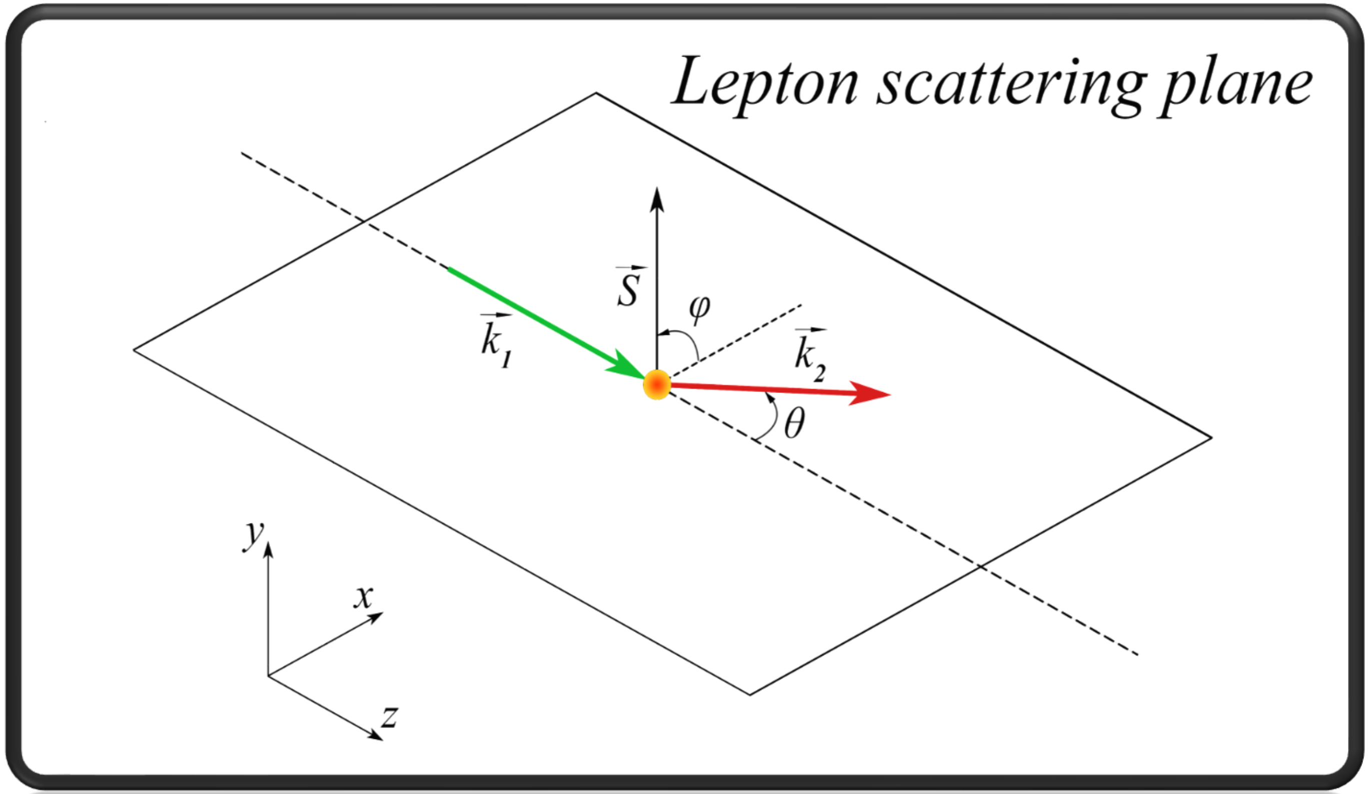
$$d\sigma_T(\varphi) = d\sigma_U + \frac{\vec{S}\cdot(\vec{k}_1 \times \vec{k}_2)}{\left|\vec{k}_1 \times \vec{k}_2\right|} d\sigma_y$$

$$= \quad d\sigma_U + d\sigma_y \sin(\varphi)$$

$$B_T^l(\varphi) = \frac{d\sigma_T(\varphi) \ - d\sigma_T(\varphi+\pi)}{d\sigma_T(\varphi) + d\sigma_T(\varphi+\pi)} = \ B_y^l \, sin(\varphi)$$

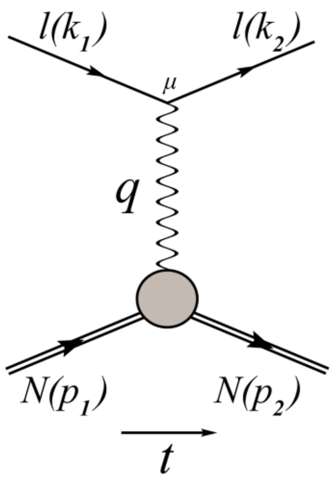
$$where \;\; B_y^l = {d\sigma_y}/{d\sigma_U}$$

$$d\sigma_T(\varphi) = d\sigma_U(1 \ + B_y^l \, sin(\varphi))$$

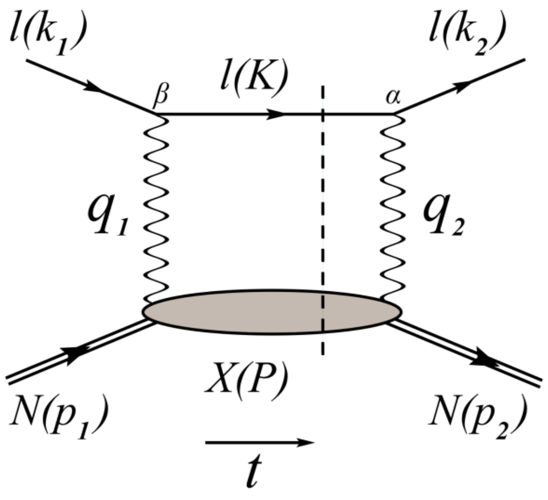


Theoretical definition of the beam-normal SSA

- There is no contribution to the beam-normal SSA from one-photon exchange amplitude.
- Two-photon exchange processes need to be considered



and



$$B_y^l = \frac{2M_\gamma\, Abs[M_{\gamma\gamma}^*]}{|M_\gamma|^2}$$

M_γ - one-photon exchange amplitude

$Abs[M_{\gamma\gamma}^*]$ – imaginary (absorptive) part of the two-photon exchange, TPE, amplitude

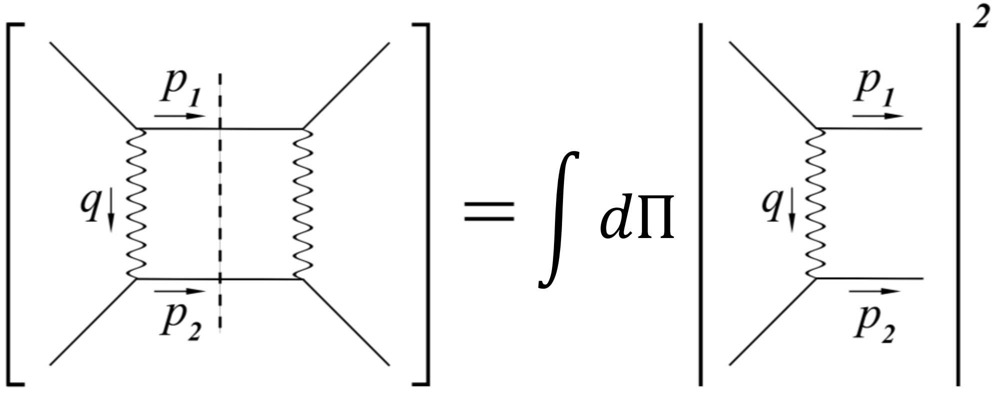
How do we calculate $Abs[M_{\gamma\gamma}]$?

The imaginary part is calculated by using Cutkosky cutting rules

$$\int \frac{d^4q}{(2\pi)^4} \to \int \frac{d^4p_2}{(2\pi)^4} \int \frac{d^4p_1}{(2\pi)^4} (2\pi)^4 \delta^{(4)}(p_1 + p_2 - k)$$

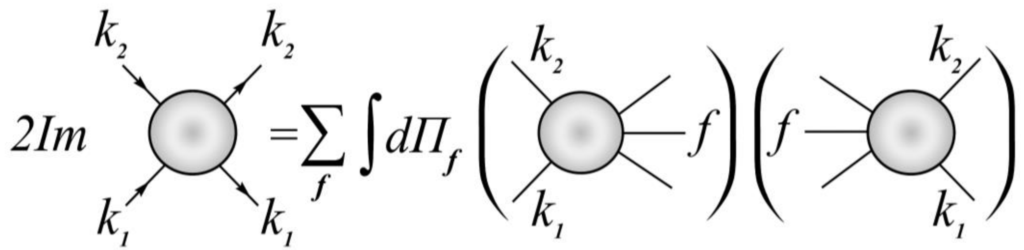
where k is the total four-momentum of the system

$$\frac{1}{p_i^2 - m^2 + i\varepsilon} \to -2\pi i \delta(p_i^2 \; - m^2)$$



Optical theorem (forward scattering):

$$ImM(k_1, k_2 \longrightarrow k_1, k_2) = 2E_{CM}p_{CM}\sigma_{tot}\,(k_1, k_2 \longrightarrow anything)$$



Total cross section:

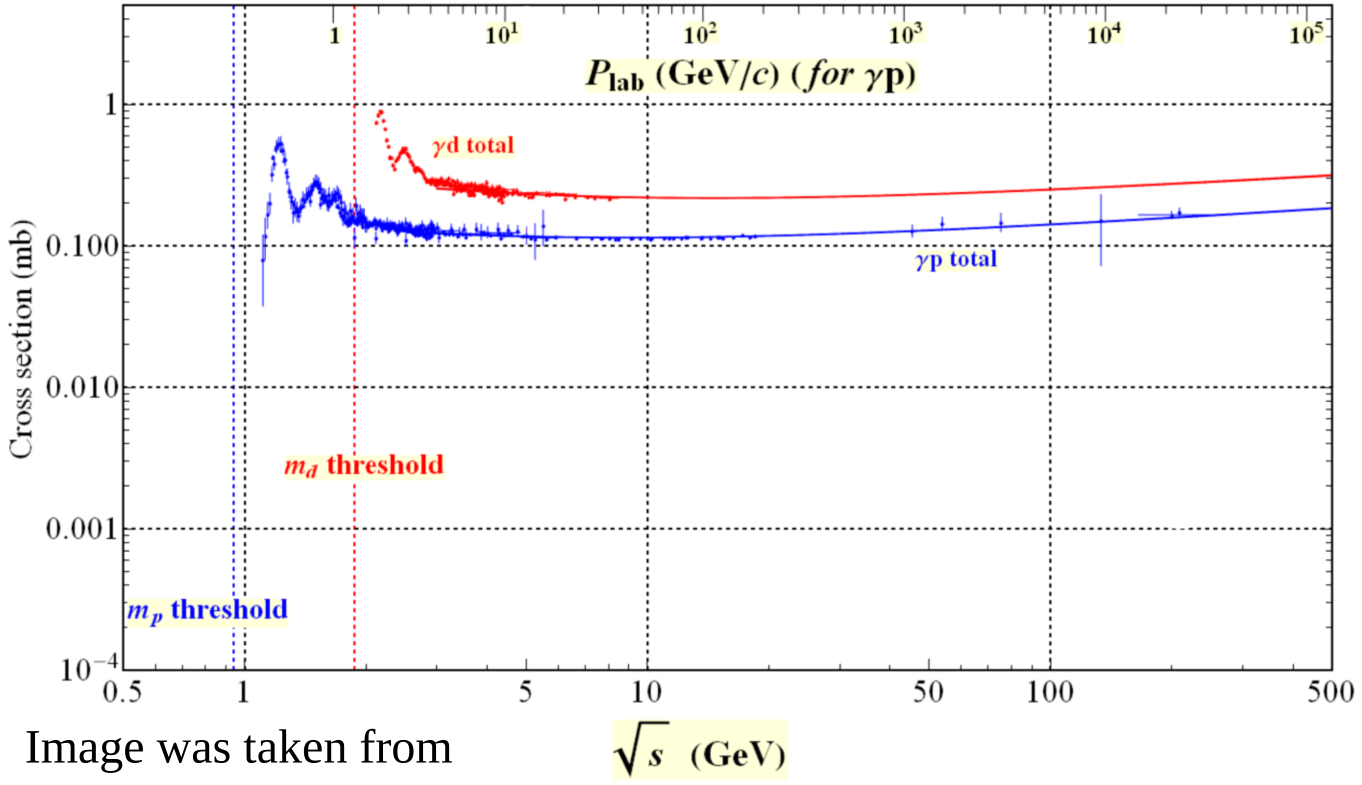


Image was taken from the Particle Data Group

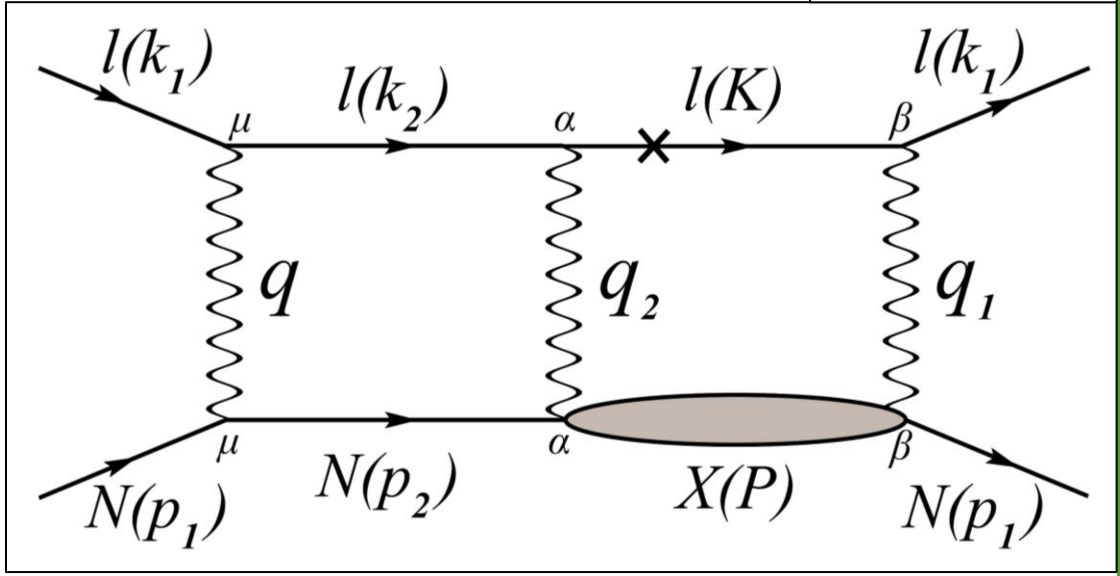
Optical theorem establishes a connection between the imaginary part of the two-photon exchange amplitude and total cross section in the forward limit

To depart from zero scattering angle used the slope of the differential Compton cross section for the proton target:

$$\frac{d\sigma}{dt} \approx \left[\frac{d\sigma}{dt}\right]_{t=0} e^{Bt}$$

where $B = 8\ GeV^{-2}$

Beam-normal SSA. Existing results



For proton target at forward angles the expression takes the form:

$$B_y^l = \frac{m_e\sqrt{Q^2}\sigma_{tot}^{\gamma p}}{8\pi^2}\frac{F_1 - \tau F_2}{F_1^2 + \tau F_2^2}\left(-log\frac{Q^2}{m_e^2} + 2\right)$$

- Beam-normal SSA has logarithmic enhancement
- At fixed values of Q^2 the beam-normal SSA does not depend on the beam energy if the total photoabsorption cross section, $\sigma_{tot}^{\gamma p}$, is energy-independent.

References:

- Afanasev, A.V. and Merenkov, N.P. (2004) ‘Collinear photon exchange in the beam normal polarization asymmetry of elastic electron-proton scattering’, Physics Letters B, 599(1–2), pp. 48–54. doi:10.1016/j.physletb.2004.08.023
- Gorchtein, M. and Horowitz, C.J. (2008) ‘Analyzing power in elastic scattering of electrons off a spin-0 target’, Physical Review C, 77(4). doi:10.1103/physrevc.77.044606

Experimental results for $^{12}C, ^{40}Ca, ^{48}Ca, ^{208}Pb$

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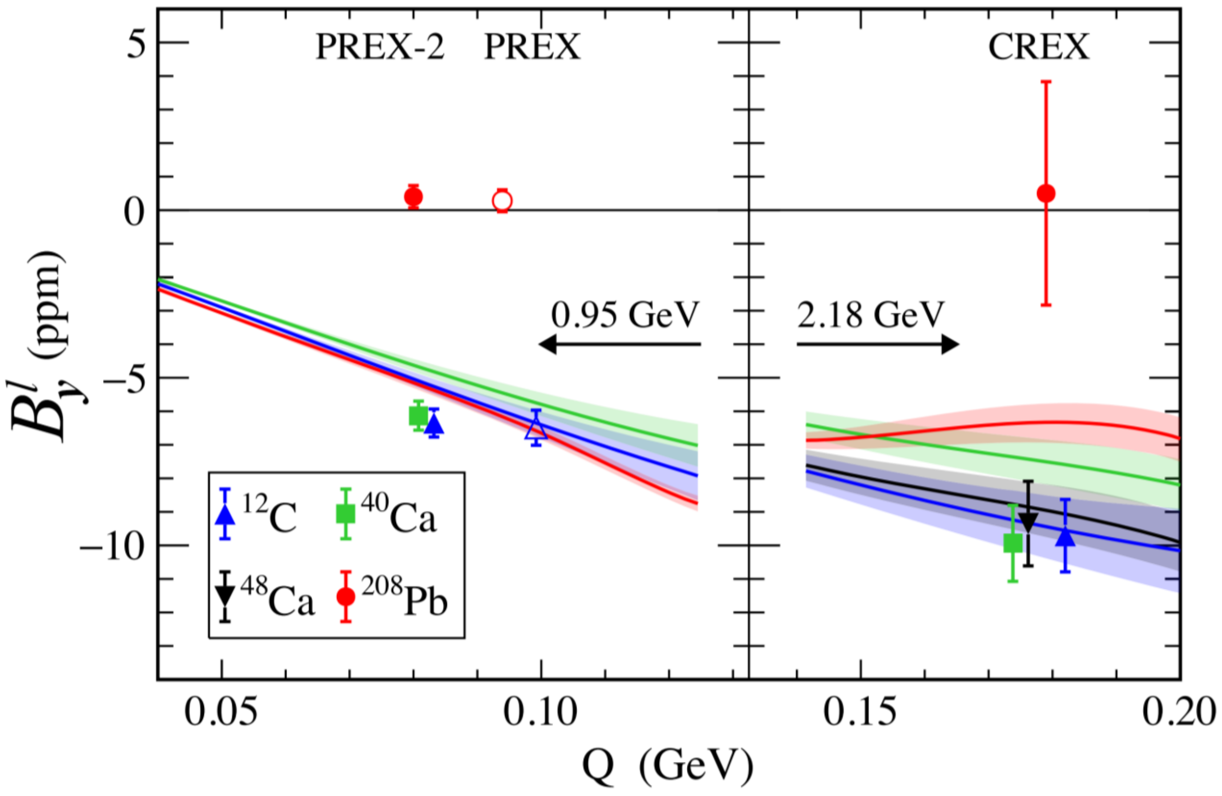
E_{beam} (GeV)	Target	B_y^l(ppm)	$B_{avg}^{Z\leq 20}$ (ppm)	$[(B_y^l - B_{avg}^{Z\leq 20})$ /uncert]
0.95	^{12}C	-6.3 ± 0.4	-6.2 ± 0.2	
0.95	^{40}Ca	-6.1 ± 0.3		
0.95	^{208}Pb	0.4 ± 0.2		21σ
2.18	^{12}C	-9.7 ± 1.1	-9.7 ± 0.6	
2.18	^{40}Ca	-10.0 ± 1.1		
2.18	^{48}Ca	-9.4 ± 1.1		
2.18	^{208}Pb	0.6 ± 3.2		3.2σ

B_y^l results for the four nuclei along with the corresponding total uncertainties (statistical and systematic uncertainties combined in quadrature)



B_y^l measurements from PREX-2, PREX and CREX at beam energies of 0.95 GeV, 1.06 GeV, and 2.18 GeV, respectively. The solid lines show theoretical calculations at 0.95 GeV and 2.18 GeV together with their respective one sigma uncertainty bands. The color of each band represents the calculation for the same color data point. Overlapping points are offset slightly in Q to make them visible.

Reference:
Adhikari, D. et al. (2022) 'New measurements of the beam-normal single spin asymmetry in elastic electron scattering over a range of spin-0 nuclei', Physical Review Letters, 128(14).
DOI: https://doi.org/10.48550/arXiv.2111.04250

Calculation of beam-normal SSA for spin-0 nuclei, namely ^{4}He, ^{12}C, and ^{208}Pb

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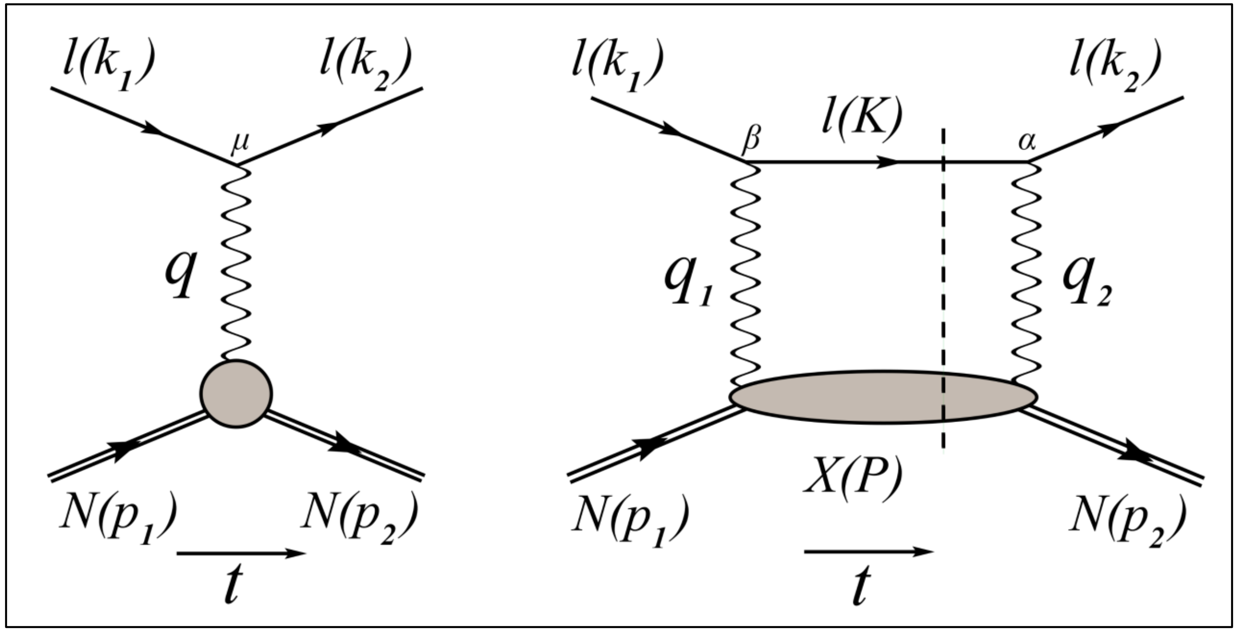
Necessary steps

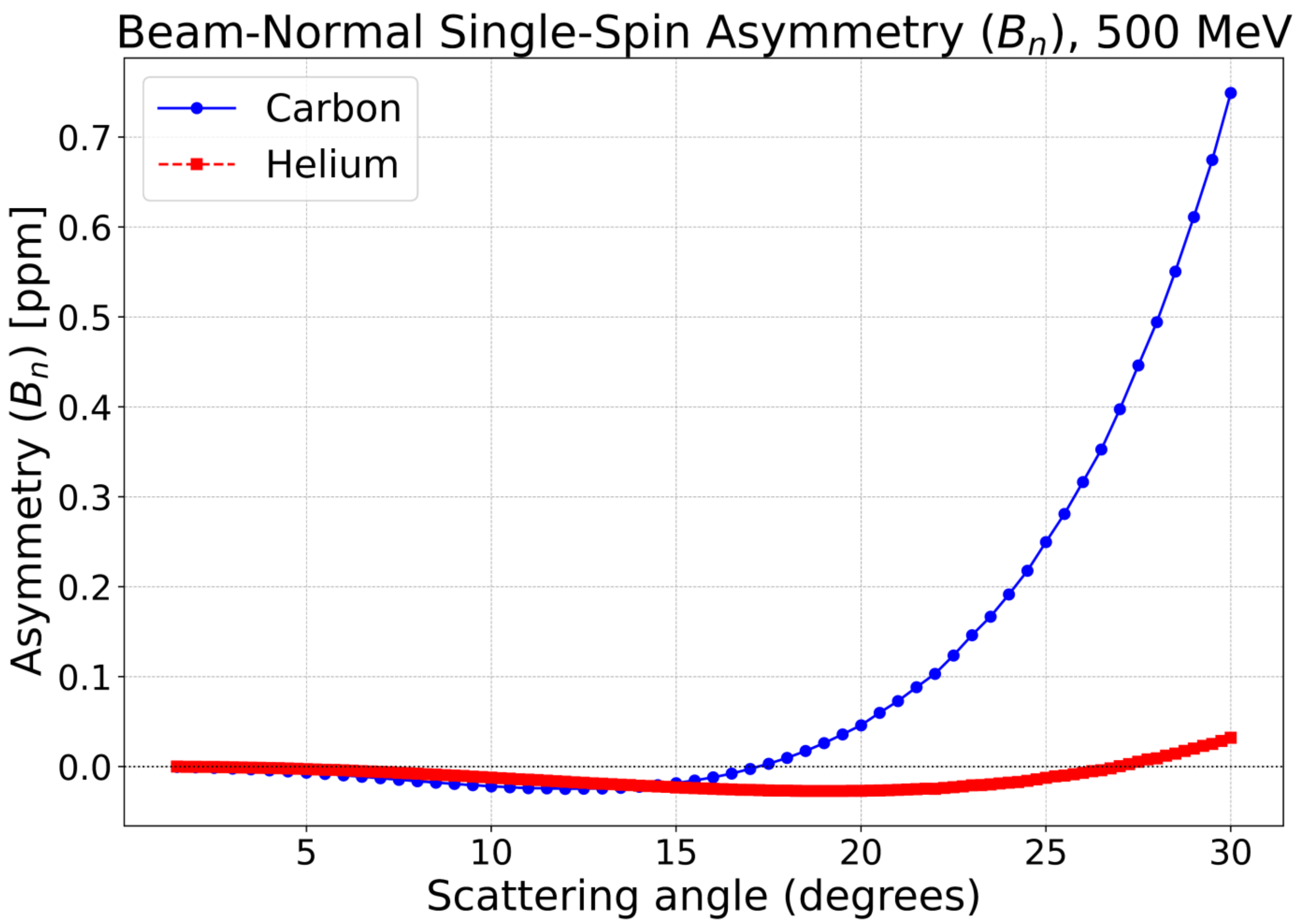
1. Calculate the square of one-photon exchange amplitude, $\sum_{spins} |M_\gamma|^2$
2. Determine the interference between the one-photon and two-photon exchange amplitudes, $(2M_\gamma\, Abs[M^*_{\gamma\gamma}])$ for elastic case (no intermediate resonance state is excited):
   a) Establish the form of leptonic, $l_{\mu\nu}$, and hadronic, $H^{\mu\nu}$, tensors
   b) Use Cutkosky cutting rules to put intermediate particles on shell: $K^2 = m_e^2, P^2 = M^2_{nucleus}$
   c) Reduce dimensionality $\int \frac{d^4q}{(2\pi)^4} \longrightarrow \int \frac{d\Omega}{(2\pi)^2}$
   d) Calculate the integral
3. Calculate beam-normal SSA, B_y^l
4. Repeat steps 2, 3 for the inelastic part (intermediate resonance state **IS** excited)

$$B_y^l = \frac{2M_\gamma\, Abs[M^*_{\gamma\gamma}]}{|M_\gamma|^2}$$

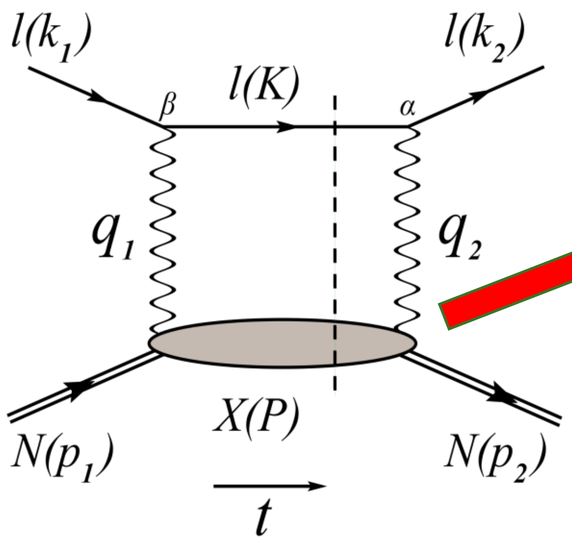


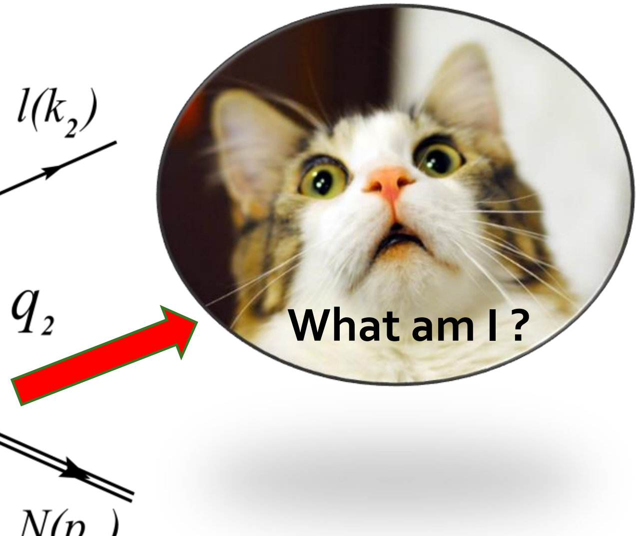
Elastic case (nucleus stays in the ground state)

Pretty straightforward. All that is required is the knowledge of the elastic form factors for the nucleus under study.



"Inelastic" case (intermediate resonance state is excited)





What do we do?

- For the case of a dipole resonance we write an expression for the vertex in terms of independent four-vectors
- Enforce the condition of current conservation: $q_\mu \Gamma^{\cdots\mu} = 0$

Vertex expressions for the dipole resonances

- 1^+ resonance: $\Gamma^{\nu\tau}_{\gamma^* N\to R}(p_1, P) = F\left(q_1^2\right)\varepsilon^{\nu\tau\kappa\lambda}q_{1\kappa}P_\lambda$
- 1^- resonance: $\Gamma^{\mu\nu}_{\gamma^* N\to R}(q_1, P) = D(q_1^2)\left(q_1^\nu q_1^\mu - q_1^2 g^{\mu\nu}\right) + B(q_1^2)(q_1^\nu P^\mu - (q_1 \cdot P)g^{\mu\nu})$

Future developments

1) Use similar reasoning to construct the vertex for the 2^+ resonance state

2) Calculate the asymmetry for 1^+, 1^- and 2^+ resonance states and determine the role of dispersion effects at low beam energies and forward angles

3) Develop a model that evaluates the aggregate role of dispersion effects at higher beam energies ($\sim 1\ GeV$)

Summary

- Beam-normal single-spin asymmetry (BNSSA) vanishes in the one-photon exchange approximation and arises from the imaginary part of the two-photon exchange amplitude.
- Carbon targets are used for parity-violation studies, where BNSSA constitutes an important background.
- Existing theoretical models, especially at GeV-scale energies, fail to account for the unexpectedly small BNSSA measured in lead, revealing the so-called "PREX puzzle."
- This work aims to systematically calculate both elastic and inelastic contributions (namely resonant intermediate states) to quantify the role of dispersion at low beam energies.
- The ultimate goal is to develop a consistent model of BNSSA that can explain the existing data and guide future experiments.

Thank you!