Measuring the Fifth Structure Function in $D(\vec{e}, e'p)n$

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Physics Motivation

A goal of nuclear physics is to understand the transition from the hadronic picture of atomic nuclei composed of protons, neutrons, pions, *etc.* to one based on quark-gluon degrees of freedom [1]. An essential step in understanding that transition is to establish a baseline for the hadronic model to understand clearly where it begins to fail and the quark-gluon description becomes manifest.

Physics Goals

1. Measure the imaginary part of the longitudinal-transverse (LT) interference term (the fifth structure function) in the region $Q^2 < 3$ GeV^2.
2. Unravel the mixture of effects like final state interactions (FSI), meson-exchange currents (MEC), isobar configurations (IC), and relativistic corrections (RC) needed to describe the NN interaction in the simplest nucleus; the deuteron.
3. Study the effect of the spin-orbit part of the NN scattering amplitude in a 'clean' environment.

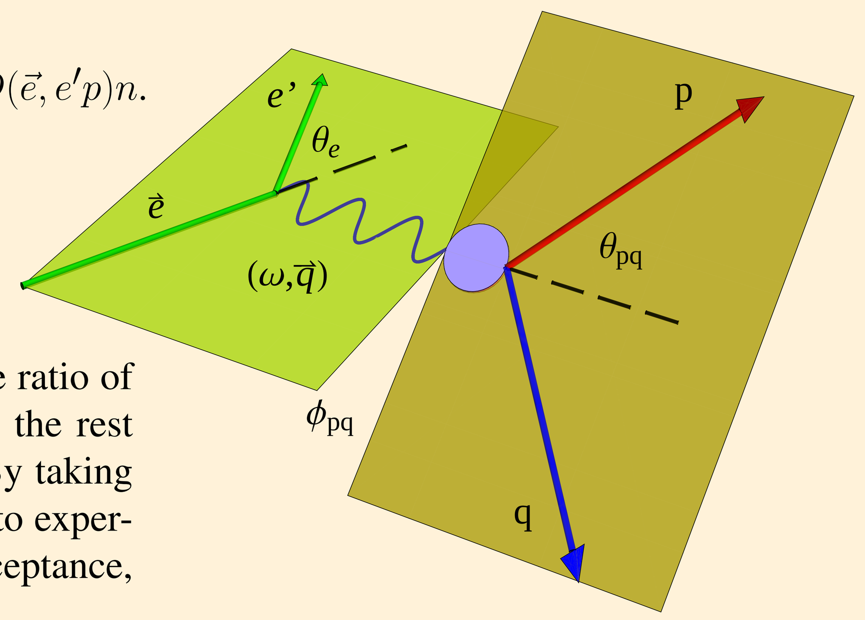
The Method

1. To measure the fifth structure function consider the form of the cross section for polarized beam and unpolarized targets

$$\frac{d^3\sigma}{d\omega d\Omega_e d\Omega_p} = \sigma^{\pm} = \sigma_L + \sigma_T + \sigma_{LT}\cos(\phi_{pq}) + \sigma_{TT}\cos(2\phi_{pq}) + h\sigma'_{LT}\sin(\phi_{pq}) \qquad (1)$$

where $h = \pm 1$ is the beam helicity, the superscript $\pm$ refers to different beam helicities, the angles are defined in Fig 1, σ'_{LT} (in red) is the fifth structure function.

Fig 1. Kinematics definitions for $D(\vec{e}, e'p)n$.



2. The helicity asymmetry A'_{LT} is the ratio of the fifth structure function σ'_{LT} to the rest of the cross section (see Eq. 1). By taking the ratio we reduce the sensitivity to experimental effects like luminosity, acceptance, PMT gain, *etc.*
3. Using a large-acceptance spectrometer with good azimuthal angle coverage we can extract a slightly modified form of A'_{LT} that takes advantage of the wide solid angle coverage. We use the ϕ_{pq}-dependent moments of the data in each each bin in p_m where $\vec{p}_m = \vec{q} - \vec{p}_p$ and p_p is the proton 3-momentum so

$$\langle \sin\phi_{pq}\rangle_{\pm} = \frac{\int_{-\pi}^{\pi}\sigma^{\pm}\sin\phi_{pq}d\phi_{pq}}{\int_{-\pi}^{\pi}\sigma^{\pm}d\phi_{pq}} = \pm\frac{\sigma'_{LT}}{2(\sigma_L+\sigma_T)} = \pm\frac{A'_{LT}}{2} \quad . \qquad (2)$$

Note that previous definitions of A'_{LT} included the σ_{TT} term in the denominator [2].

4. If there is a sinusoidally-varying component to the acceptance, then

$$\langle \sin\phi_{pq}\rangle_{\pm} = \pm\frac{A'_{LT}}{2} + \alpha_{acc} \quad \Longrightarrow \quad \langle\sin\phi_{pq}\rangle_{+} - \langle\sin\phi_{pq}\rangle_{-} = A'_{LT} \qquad (3)$$

and we can cleanly extract the helicity asymmetry.

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The Experiment: Data Collection with CLAS

The experiment was performed at the Thomas Jefferson National Accelerator Facility (JLab) using the Continuous Electron Beam Accelerator Facility (CEBAF) to produce 2.6 GeV and 4.2 GeV electron beams. See Fig. 2. CEBAF is the 7/8-mile-long, racetrack-shaped electron accelerator at JLab that produces continuous electron beams up to 6 GeV.

Fig 2. The CEBAF accelerator site.

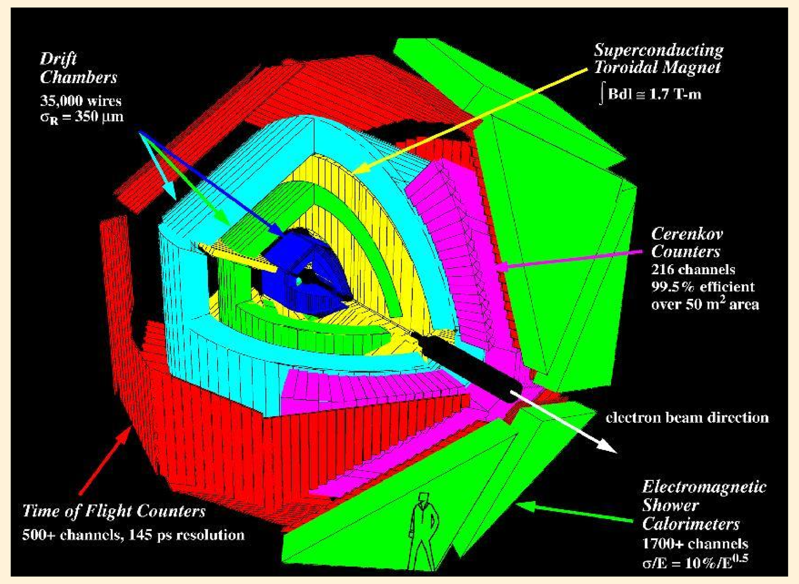

Fig 3. The CLAS detector.

The CEBAF large acceptance spectrometer (CLAS) in Hall B is a 45-ton, six-sector detector covering most of 4π, with drift chambers to measure charge particle trajectories, scintillators for time-of-flight, Cherenkov counters to identify electrons, and calorimeters to measure energy. A toroidal magnetic field determines momentum. See Fig. 3.

The Data Set

1. Two beam energies, 4.23 GeV and 2.56 GeV, with normal torus polarity (electrons inbending).
2. One beam energy 2.56 GeV with reversed torus polarity (electrons outbending) to reach lower Q^2.
3. Recorded 2.3 billion triggers, $Q^2 = 0.2 - 4.8 (GeV/c)^2$.
4. Novel dual target cell with liquid hydrogen and deuterium enabled us to collect calibration and production data simultaneously and under the same running conditions.
5. The beam polarization was 0.736 ± 0.017.

Fig 4. Dual-cell E5 target. Hydrogen calibration target was downstream (left in the picture) while deuterium production target was upstream.

Data Selection, Corrections, and Consistency Checks

1. Select $e-p$ coincidences in quasi-elastic kinematics using a cut on the energy transfer so $\nu = \frac{Q^2}{2M_N} {}^{+0.03}_{-0.01}$ GeV.
2. Select neutrons with missing mass squared $0.84 \text{ GeV}^2 \le \text{MM}^2 \le 0.92 \text{ GeV}^2$.
3. Corrections: momentum, beam charge asymmetry.
4. Check beam helicity using measured A'_{LT} from proton calibration target and comparing our results (bottom panel of Fig. 5) for the $ep \to ep\pi^0$ reaction with previous ones (upper panel) [3].
5. Test analysis algorithms with GSIM using the QUEEG event generator. In Fig. 6 user-defined asymmetry and simulation analysis results agree.

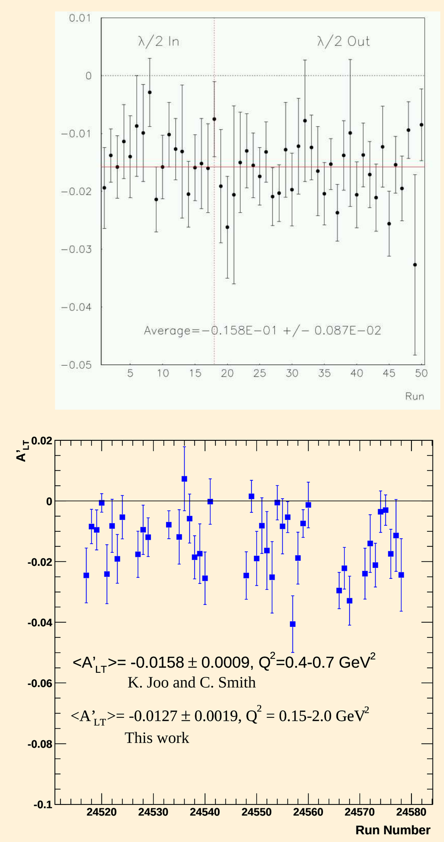

Fig 5. Test of helicity sign.

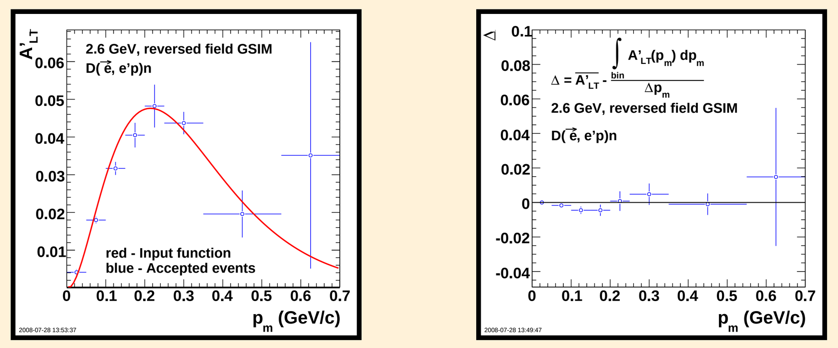

Fig 6. Comparison of user inputs and simulation results.

Preliminary Results

1. The helicity asymmetry A'_{LT} as a function of p_m for $D(\vec{e}, e'p)n$ is shown in the left-hand panel of Fig. 7.
2. The data were integrated over Q^2 for each data set. The right-hand panel of Fig 7. shows the Q^2 distribution of each data set.
3. There is statistically significant structure in both 2.6-GeV data sets which show dips at low p_m and then a peak at high p_m.
4. The statistics for the 4.2-GeV data are low so no conclusions can be drawn.

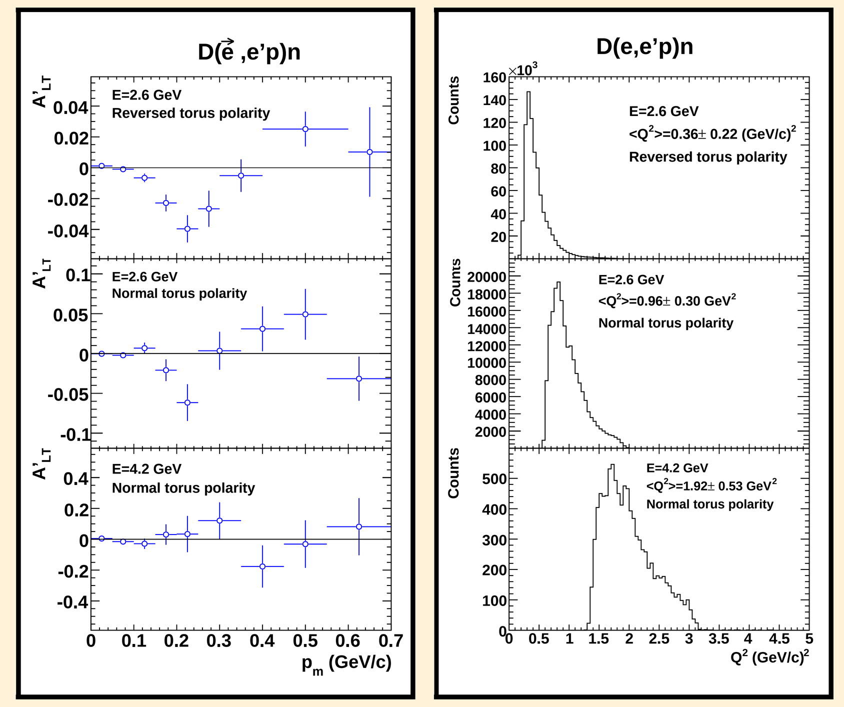

Fig 7. Preliminary results for A'_{LT} for the three E5 data sets (left-hand panel) and the associated Q^2 distributions (right-hand panel).

Comparison with Theory

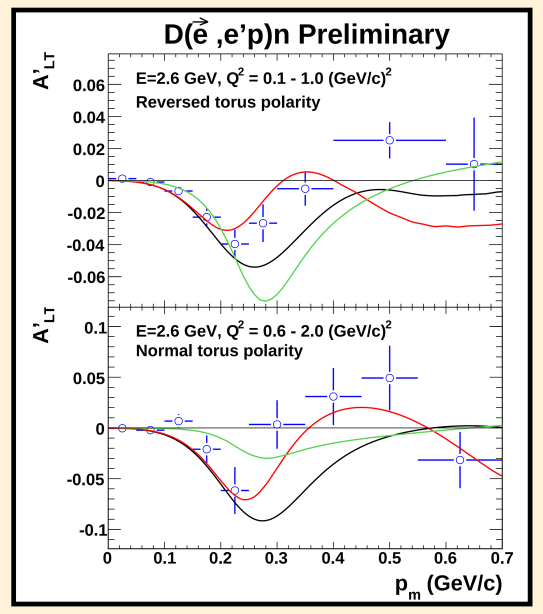

Fig 8. Comparison of A'_{LT} with several calculations.

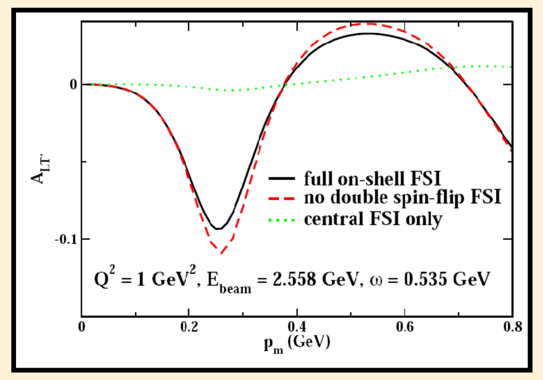

Fig 9. Effect of spin-orbit FSI forces calculated by JVO.

1. Hartmuth Arenhövel (black) - Starts with the non-relativistic Schrödinger Equation and adds RC, MEC, IC, and FSI. Averaged over the CLAS acceptance.
2. Jean-Marc Laget (green) - Uses a diagrammatic approach for $Q^2 = 1.1$ GeV^2 (lower panel) and $Q^2 = 0.7$ GeV^2 (upper panel).
3. Jeschonnek and Van Orden (JVO in red) - Relativistic calculation in the impulse approximation using the Gross equation for the deuteron ground state and the SAID parameterization of the NN scattering amplitude for FSI [4]. Off-shell form factor cutoff set to $\Lambda_N = 1.0$ GeV. Averaged over the CLAS acceptance.
4. At higher Q^2 in Fig. 8 JVO agrees with the data across the full p_m range. At lower Q^2, JVO has good agreement for $p_m < 0.4$ GeV, but diverges from the data at larger p_m. This is possibly a sign of the rising importance of meson-exchange currents not included in JVO.
5. Helicity asymmetry is a sensitive probe of FSI. Fig 9 shows the calculated A'_{LT} from JVO [4]. Without the spin-flip scattering amplitude, A'_{LT} goes nearly to zero. When turned on the double-spin components have little effect implying that the spin-orbit part of the interaction is the primary contributor.

Conclusions

1. We have cleanly extracted the fifth structure function for $D(\vec{e}, e'p)n$ for the range $Q^2 = 0.2 - 2.0$ GeV^2.
2. The calculation by Jeschonnek and Van Orden reproduces the data for $Q^2 \approx 1$ GeV^2 across the full p_m range. At lower Q^2 there are signs of additional effects (MEC).

References

[1] *The Frontiers of Nuclear Science: A Long-Range Plan for Nuclear Physics*, Nuclear Science Advisory Committee, US Department of Energy, 2007.

[2] S.M.Dolfini *et al.*, Phys. Rev. C **60** 064622 (1999).

[3] K.Joo and C.Smith, *Measurement of Polarized Structure Function σ'_{LT} for $p(e,e'p)\pi^0$ in the Delta(1232) Resonance Region*, CLAS Analysis Note 2001-009, 2001.

[4] S.Jeschonnek and W. Van Orden, arXiv:0805.3115v1[nucl-th], 20 May 2008.