Measuring the Fifth Structure Function in $^{2}\mathrm{H}(\vec{e}, e'p)n$

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Outline

1. Introduction and Background.
2. Extracting the Fifth Structure Function.
3. Event Selection and Corrections.
4. Results and Preliminary Comparison with Theory.
5. Conclusions.

Scientific Motivation

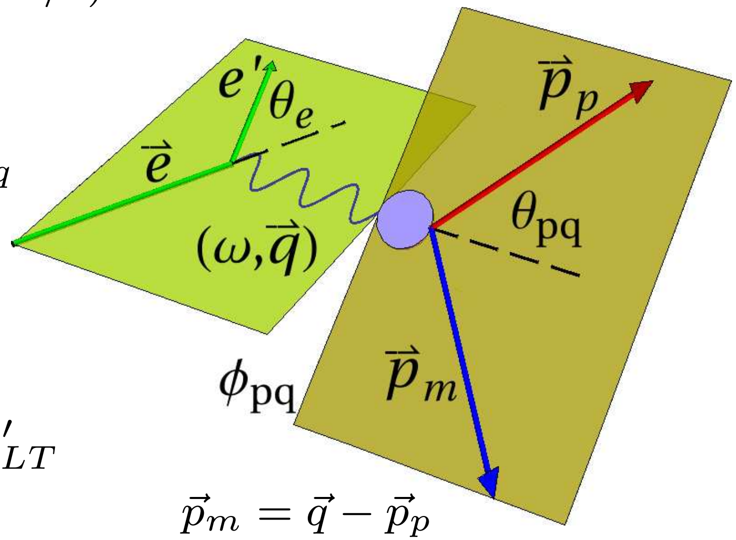
- Establish a baseline for the hadronic model to meet so we can clearly see the transition to quark-gluon degrees of freedom.
- The deuteron is an essential testing ground because it is the simplest nucleus.
- Differing mix of relativistic corrections (RC), meson-exchange currents (MEC), final-state interactions (FSI), and isobar configurations (IC) depending on kinematics.
- Learn more about FSI in quasielastic kinematics.
  - The fifth structure function is zero in PWIA and is dominated by FSI.
  - Deuteron as neutron target, N^*N interaction ...
  - Short-Range Correlations (SRC).

Some Necessary Background

- Goal: Measure the imaginary part of the quasielastic (QE) LT interference term (fifth structure function) of ${}^2\mathrm{H}(\vec{e},e'p)n$ at $Q^2 \approx 1\ (\mathrm{GeV/c})^2$.
- The cross section is

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

where $\pm$ and $h = \pm 1$ refer to beam helicities.



$\vec{p}_m = \vec{q} - \vec{p}_p$

- Use the helicity asymmetry: $A_h = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \propto \sigma'_{LT}$
- Take the ϕ_{pq}-dependent moments of the data in each p_m bin.

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

- A bonus: get rid of a sinusoidal background by taking the difference of the helicities

$$\langle \sin\phi_{pq}\rangle_{+} - \langle \sin\phi_{pq}\rangle_{-} = \left(\frac{A'_{LT}}{2} + \alpha_{acc}\right) - \left(-\frac{A'_{LT}}{2} + \alpha_{acc}\right) = A'_{LT}$$

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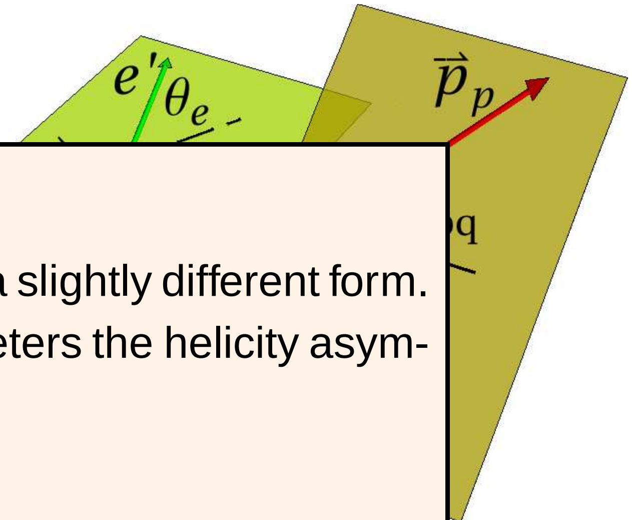

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An aside:

Past measurements in the literature of A'_{LT} used a slightly different form. In particular, for fixed, small-solid-angle spectrometers the helicity asymmetry was determined using

$$A_h(\mathrm{Q}^2, p_m, \phi_{pq} = 90^\circ) = \frac{\sigma^+_{90} - \sigma^-_{90}}{\sigma^+_{90} + \sigma^-_{90}} = \frac{\sigma_{LT'}}{\sigma_L + \sigma_T - \sigma_{TT}}$$

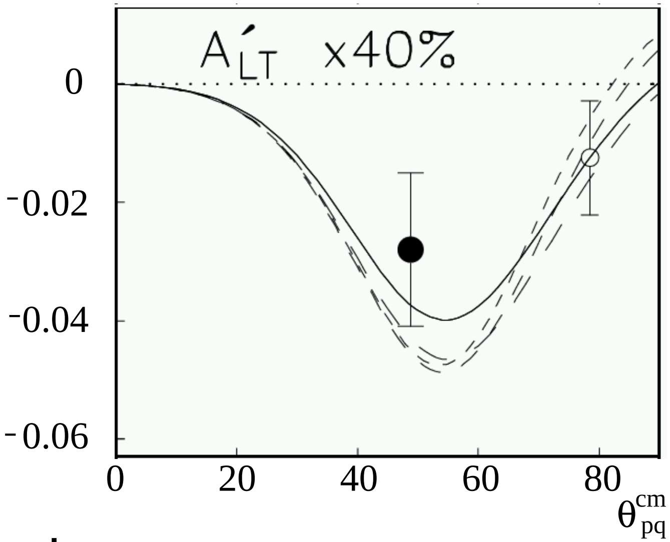
where the subscripts refer to $\phi_{pq} = 90^\circ$ and there is an additional term σ_{TT} in the denominator. The contribution of this term is small.

- A bonus: get rid of a sinusoidal background by taking the difference of the helicities

$$\langle \sin\phi_{pq}\rangle_+ - \langle \sin\phi_{pq}\rangle_- = \left(\frac{A'_{LT}}{2} + \alpha_{acc}\right) - \left(-\frac{A'_{LT}}{2} + \alpha_{acc}\right) = A'_{LT}$$

Existing Measurements of Helicity Asymmetry

- Several results from Bates in the 1990's for different structure functions and kinematics (*i.e.* quasielastic, 'dip' region) using the Out-Of-Plane Spectrometer. See S.Gilad, *et al.*, NP *A631*, 276c, (1998) and references therein.



- JLab efforts to measure deuteron structure functions in quasielastic kinematics.
  - W. Boeglin *et al.* PRL, *107*, 262501 (2011) - extracted high-momentum component of deuteron wave function.
  - C. Hanretty *et al.* Hall A E08-008 - deuteron electrodisintegration near threshold; analysis in progress.
  - M. Mayer *et al.* Data mining project - extracting fifth structure function from E6 data.

The Data Set

- Analyze data from the E5 run period in Hall B.
- Two beam energies, $4.23\ \mathrm{GeV}$ and $2.56\ \mathrm{GeV}$, with normal torus polarity (electrons inbending).
- One beam energy $2.56\ \mathrm{GeV}$ with reversed torus polarity (electron outbending) to reach lower Q^2.
- Recorded about 2.3 billion triggers, $Q^2 = 0.2 - 5.0(\mathrm{GeV/c})^2$.
- Dual target cell with liquid hydrogen and deuterium.
- Beam polarization:

$$0.736 \pm 0.017$$

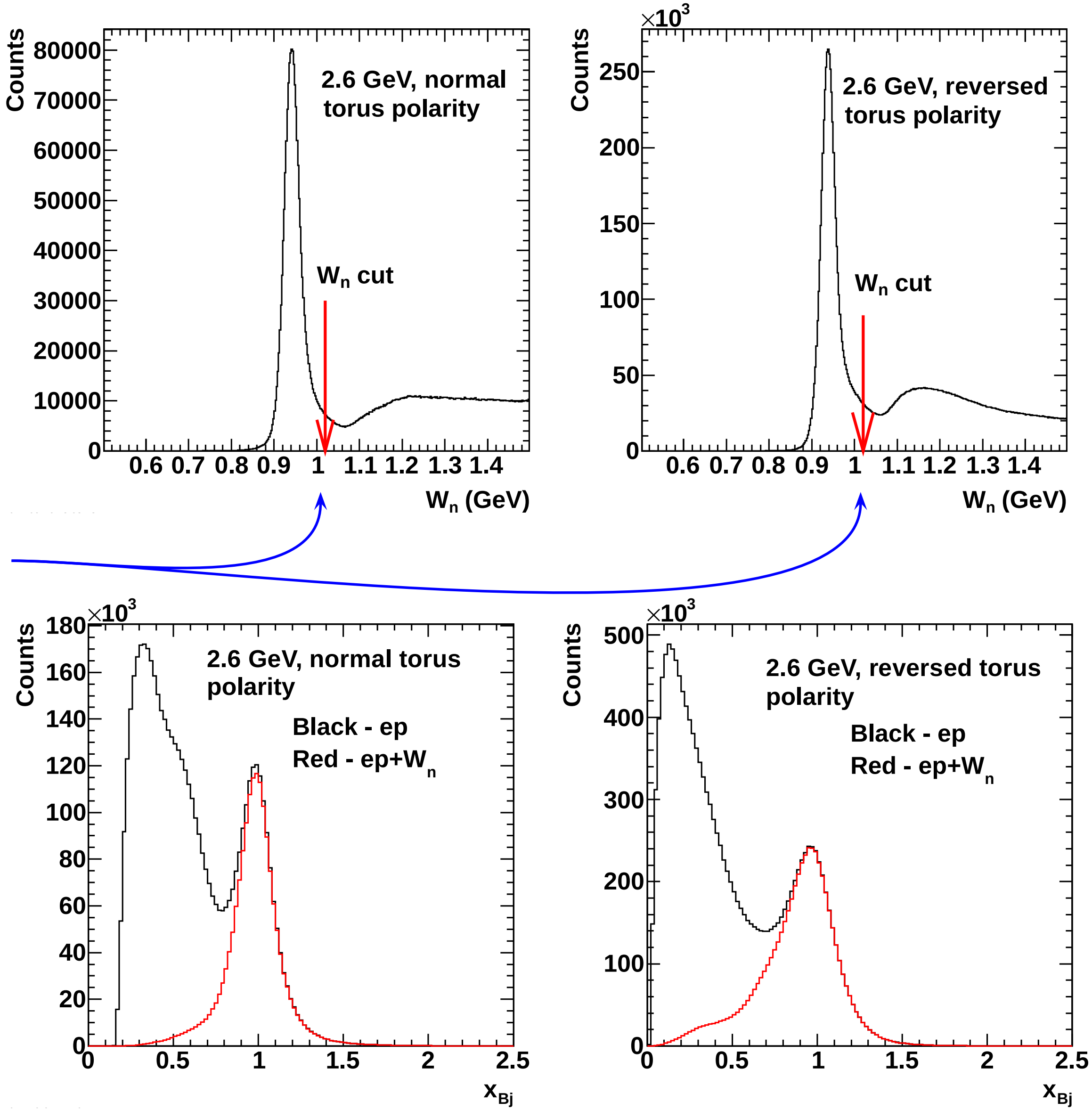
- Limited statistics at $4.23\ \mathrm{GeV}$ so only lower energy data shown here.

Event Selection Cuts and Corrections

For electrons	CC photoelectrons	$n_{phe} > 25$
	Energy-momentum match	$0.325p_e - 0.13 < E_{total} < 0.325p_e + 0.06$
	Reject pions	$ec\_ei \geq 0.100$ and $nphe \geq 25$
	EC track fiducial	$\lvert dc\_ysc\rvert \leq 165(dc\_xsc - 80)/280$
	EC fiducial	No tracks within $10\ cm$ of the end of a strip
	Egiyan threshold cut	$p_e \geq (214 + 2.47 \cdot ec\_threshold) \cdot 0.001$
	Electron fiducial	Protopopescu *et al.*, CLAS-NOTE 2000-007.
	Select target	$-11.5\ cm < v_z < -8.0\ cm$
For protons	Proton fiducial cut	Nyazov *et al.*, CLAS-NOTE 2001-013.
	ep vertex cut	$\lvert v_z(e) - v_z(proton)\rvert \leq 1.5\ cm$
	mass cut	$0.88\ \mathrm{MeV/c^2} < m_p < 1.02\ \mathrm{MeV/c^2}$
Both	Momentum corrections	K. Y. Kim *et al.*, CLAS-NOTE 2001-018
Beam charge	2.6 GeV, reversed field:	0.9936 ± 0.0007
asymmetry	2.6 GeV, normal field:	0.9944 ± 0.0007
Radiation	EXCLURAD	Gilfoyle *et al.*, CLAS-NOTE 2005-022

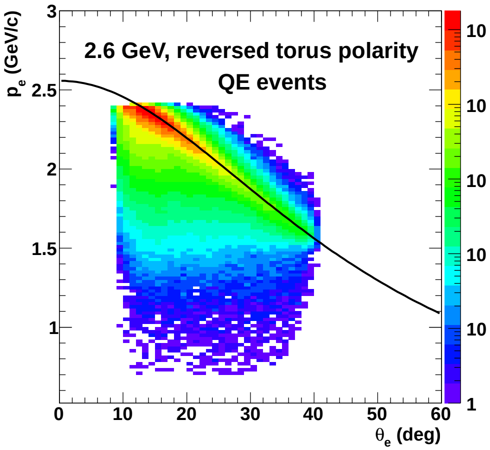
Quasielastic Electron Selection

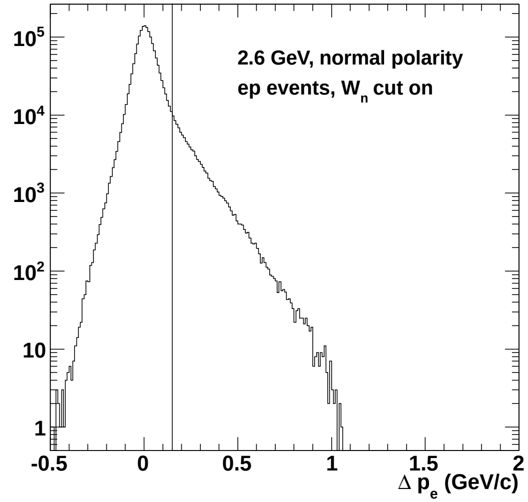
- Start with the residual epX mass W_n.
- Fit the neutron peak in the distribution to determine the the W_n resolution σ_n.
- Set the W_n cut at the pion threshold minus $3\sigma_n$ to remove pion contamination.
- Effect of W_n cut on the Bjorken x distribution.

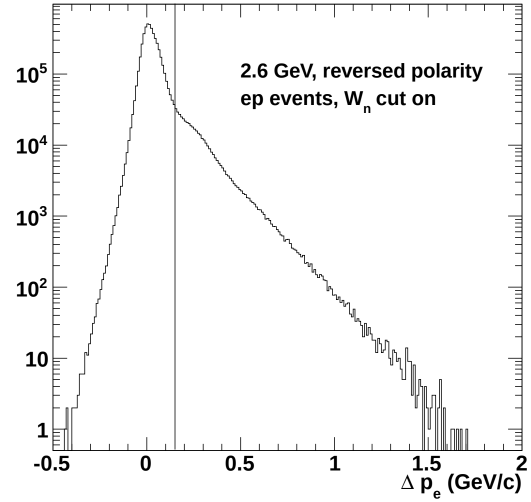


Quasielastic Electron Selection

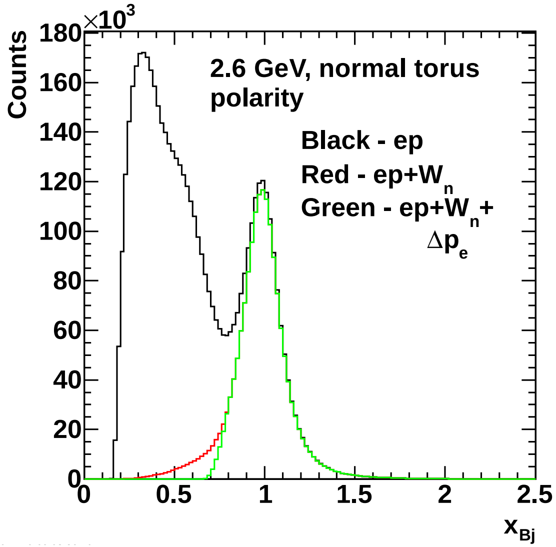
- Consider $\Delta p_e = p_e(\text{measured}) - p_e(\text{calculated})$ where $p_e(\text{calculated})$ is extracted from the angles.

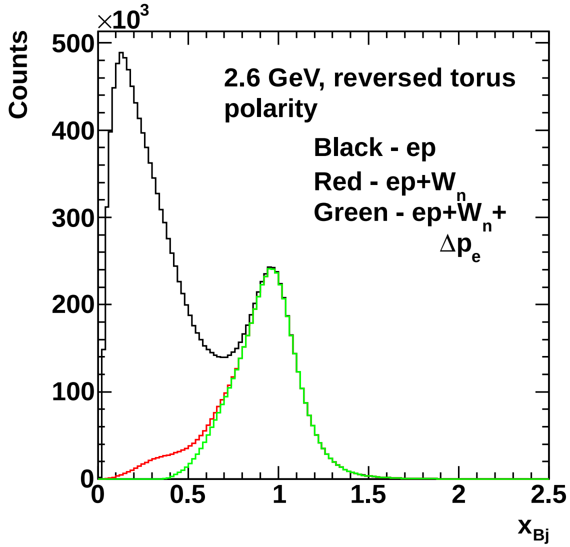




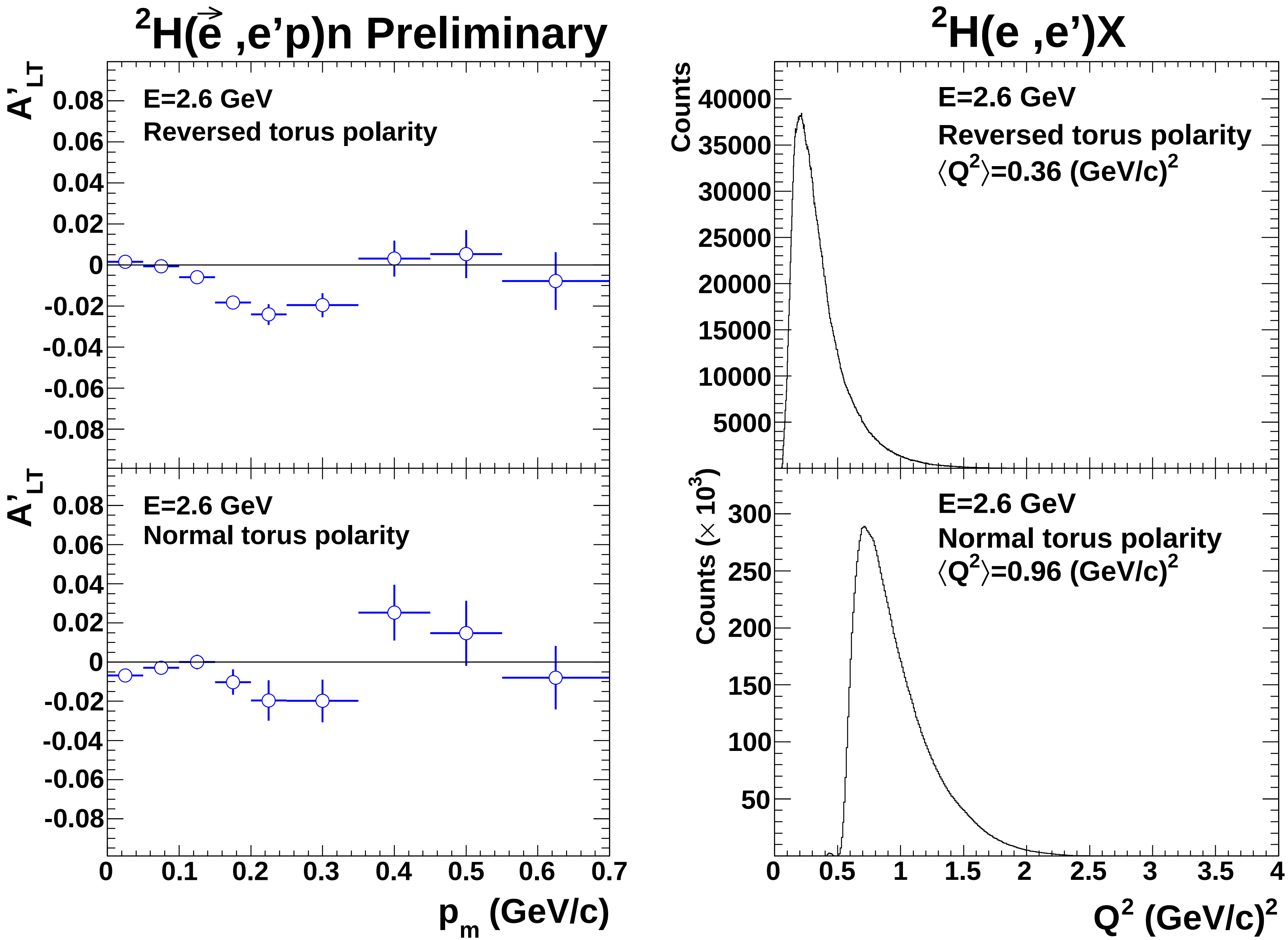


- Set the Δp_e cut at the slope change.
- Effect on the Bjorken x distribution.
- EXCLURAD used to correct for radiative effects.



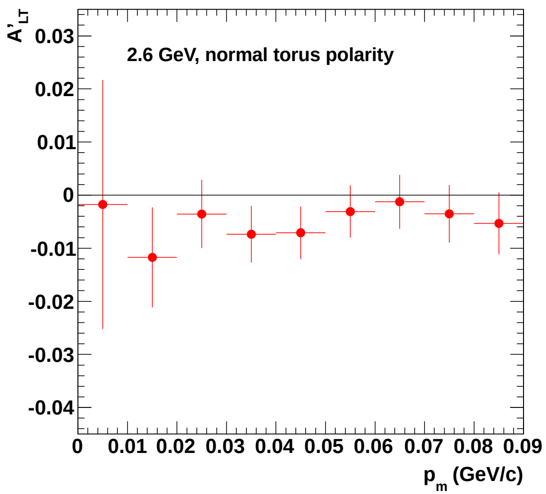


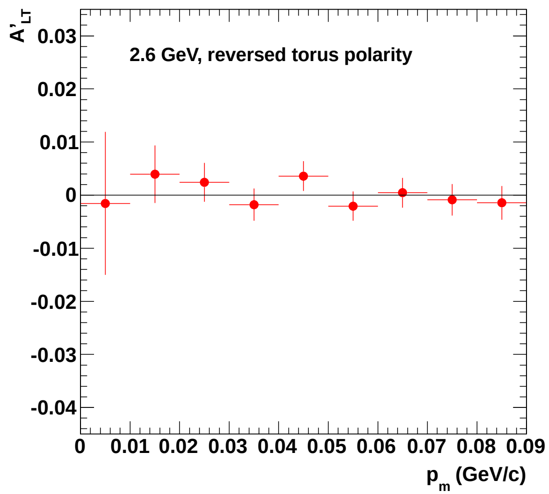
Preliminary A'_{LT} Results for $^2\mathrm{H}(\vec{e}, e'p)n$



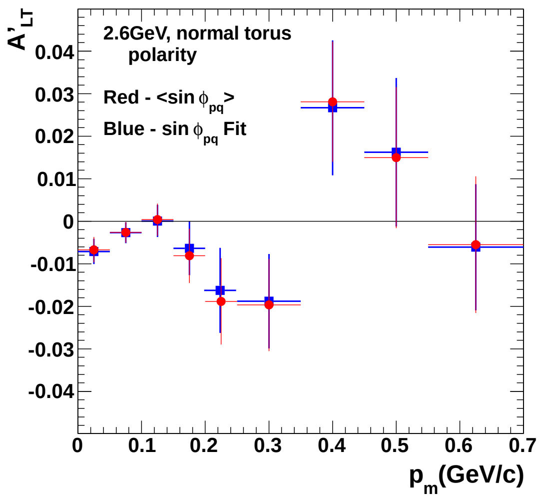
Consistency Checks

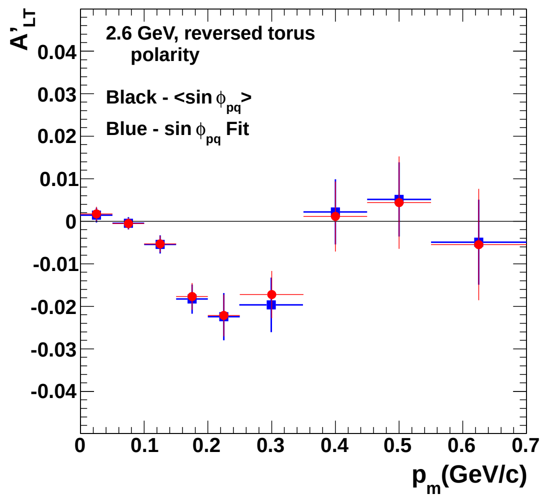
- Check beam helicity with $ep \rightarrow e'p\pi^0$.
- At $p_m \approx 0 \text{ GeV/c}$ the asymmetry should go to zero.





- The $\sin\phi_{pq}$ weighted distributions should give the same results as fitting the ϕ_{pq} dependence.



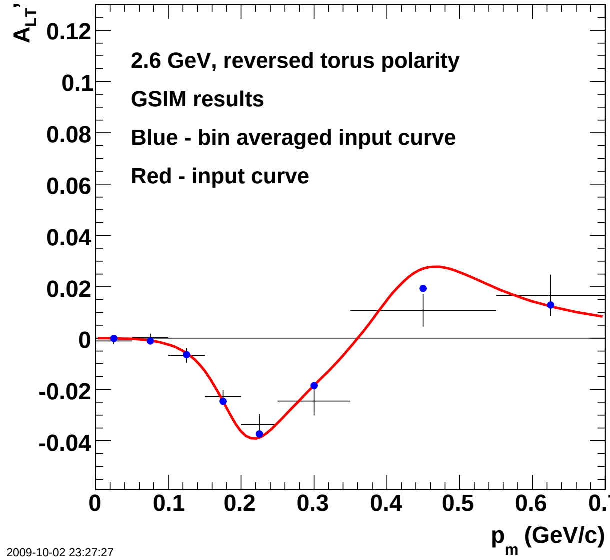


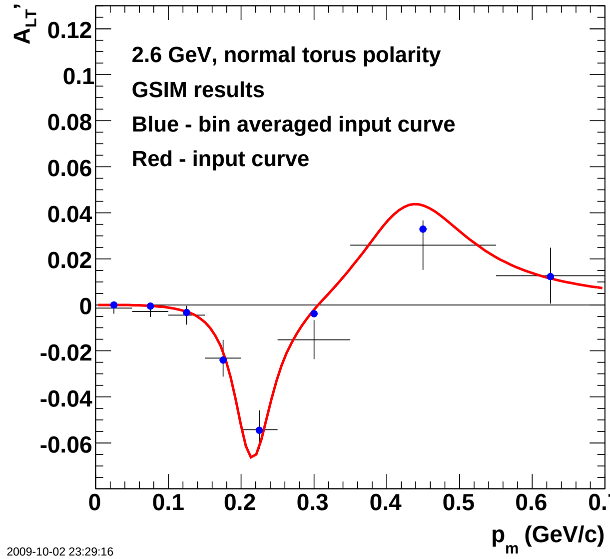
Consistency Checks

- Use GSIM to validate analysis algorithms.
- Parameterize measured helicity asymmetries.

$$A'_{LT} = \frac{a_1 x^2 + a_2 x^4}{1 + a_3 x + a_4 x^2 + a_5 x^4 + a_6 x^6}$$

- Quasi-Elastic Event Generator (J. Lachniet).
  - Fermi motion of proton - Hulthen momentum distribution + isotropic direction.
  - Boost to moving proton frame and elastically scatter electron from proton.
  - Choose ϕ_{pq} from parameterized distribution.
  - Boost back to the lab frame.
- Send events through GSIM and the same analysis routines used on the data.





Inventory of Systematic Uncertainties

Methods for Largest Effects

1. Changed cut position by $\pm 10\%$ and took half the difference of A'_{LT}.
2. Changed threshold by $\pm\sigma$ where σ is the uncertainty in the width of the neutron peak.
3. Half the difference of the change in A'_{LT} with the radiative corrections on and off.
4. Same as 1.
5. Remaining details in draft CLAS Analysis Note.

Row	Quantity	$\delta A'_{LT}$
1	Number of CC Photoelectrons	< 0.004
2	W_n cut	< 0.003
3	Radiative correction	< 0.003
4	m_p cut	< 0.003
5	Δp_e cut	< 0.002
6	EC track coordinate cut	< 0.002
7	EC sampling fraction	< 0.002
8	EC pion threshold	< 0.002
9	electron/proton fiducial cuts	< 0.002
10	Beam Polarization	< 0.001
11	Beam charge asymmetry	< 0.001

Main contributions to the systematic uncertainty and maximum values for both data sets.

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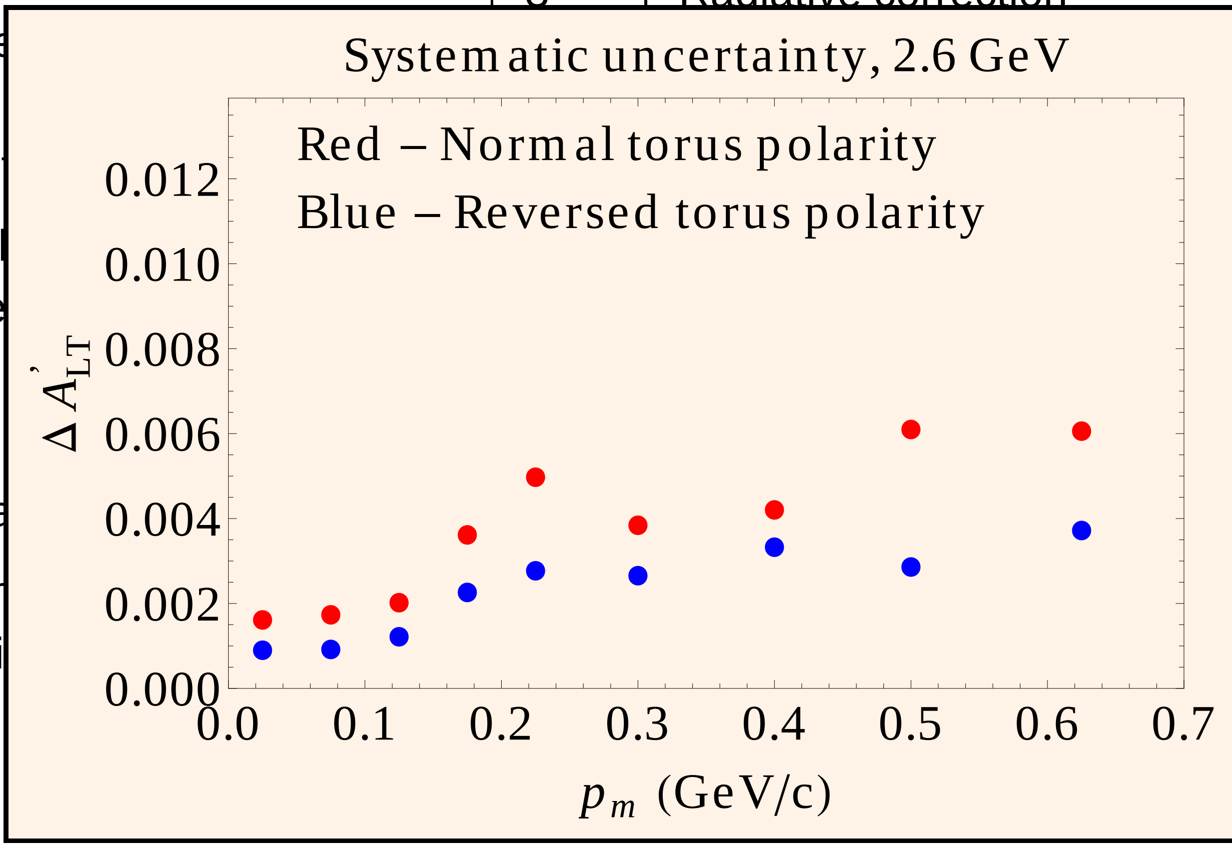
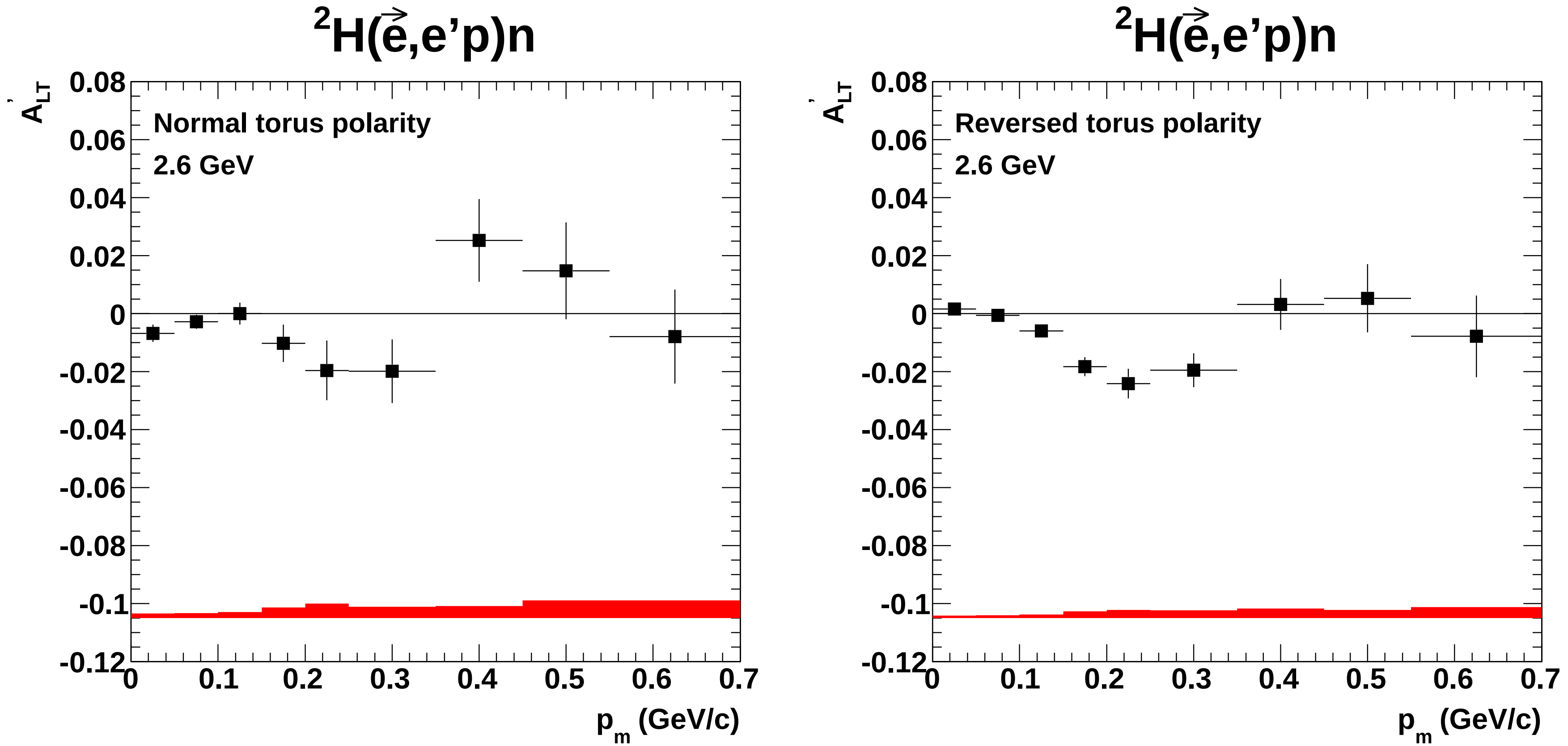
matic uncer- th data sets.

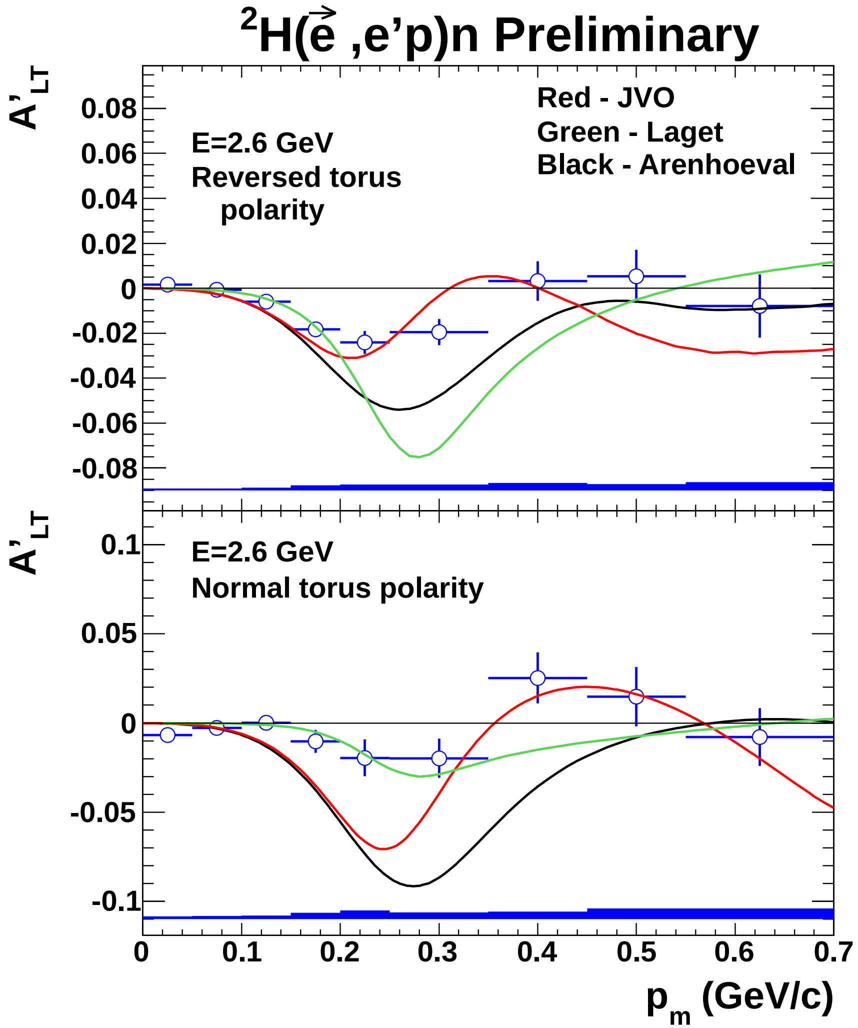


Preliminary Results with Uncertainties



Preliminary Comparison With Theory

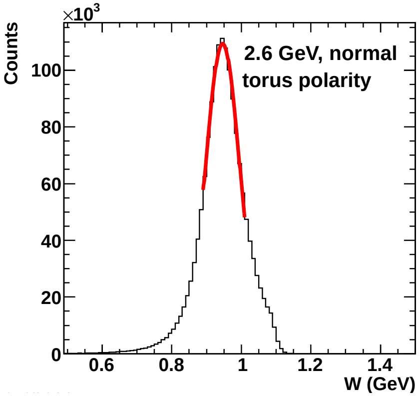
1. Arenhövel (black) - Non-relativistic Schrödinger Equation with RC, MEC, IC, and FSI. Averaged over the CLAS acceptance.
2. Laget (green) - Diagrammatic approach for $Q^2 = 1.1\ \mathrm{GeV}^2$ (lower panel) and $Q^2 = 0.7\ \mathrm{GeV}^2$ (upper panel).
3. Jeschonnek and Van Orden (JVO in red) - Relativistic calculation in IA, Gross equation for the deuteron ground state, SAID parameterization of the NN scattering amplitude for FSI . Off-shell form factor cutoff set to $\Lambda_\mathrm{N} = 1.0\ \mathrm{GeV}$ (PRC, *81*, 014008, 2010). Averaged over the CLAS acceptance.

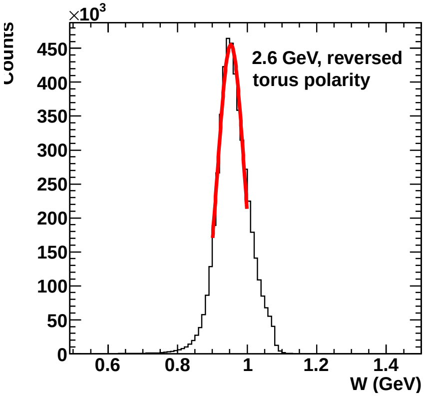


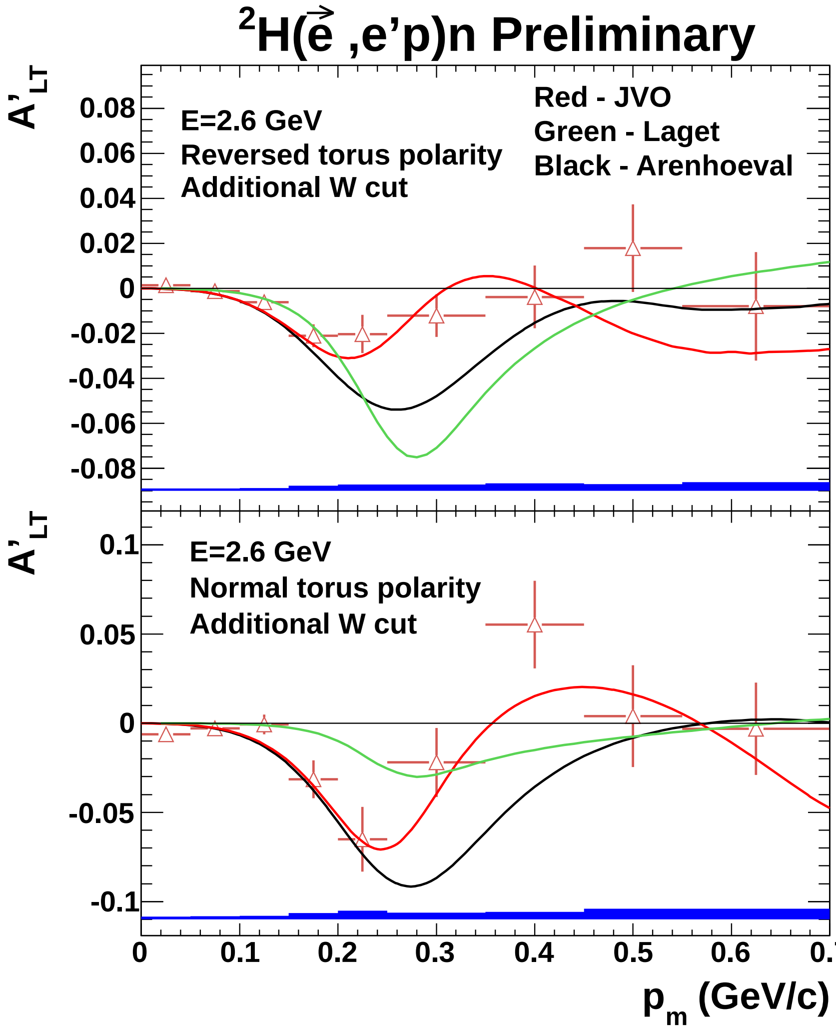
Effect of Narrow W cut

1. The original A'_{LT} results at Bates measured a narrow range in the energy transfer at the QE peak. This is equivalent to a narrow cut in W, the residual mass for inclusive electron events.

2. To compare our results with the Bates measurements we added a W cut. It is wider that the Bates one ($100\ \mathrm{MeV}$ versus $17\ \mathrm{MeV}$) in order to obtain adequate statistics.







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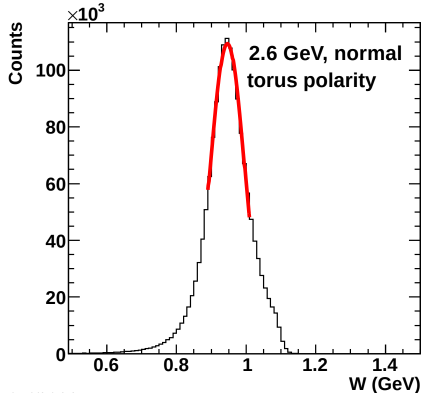
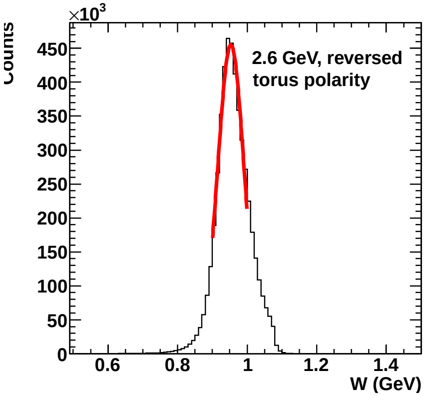
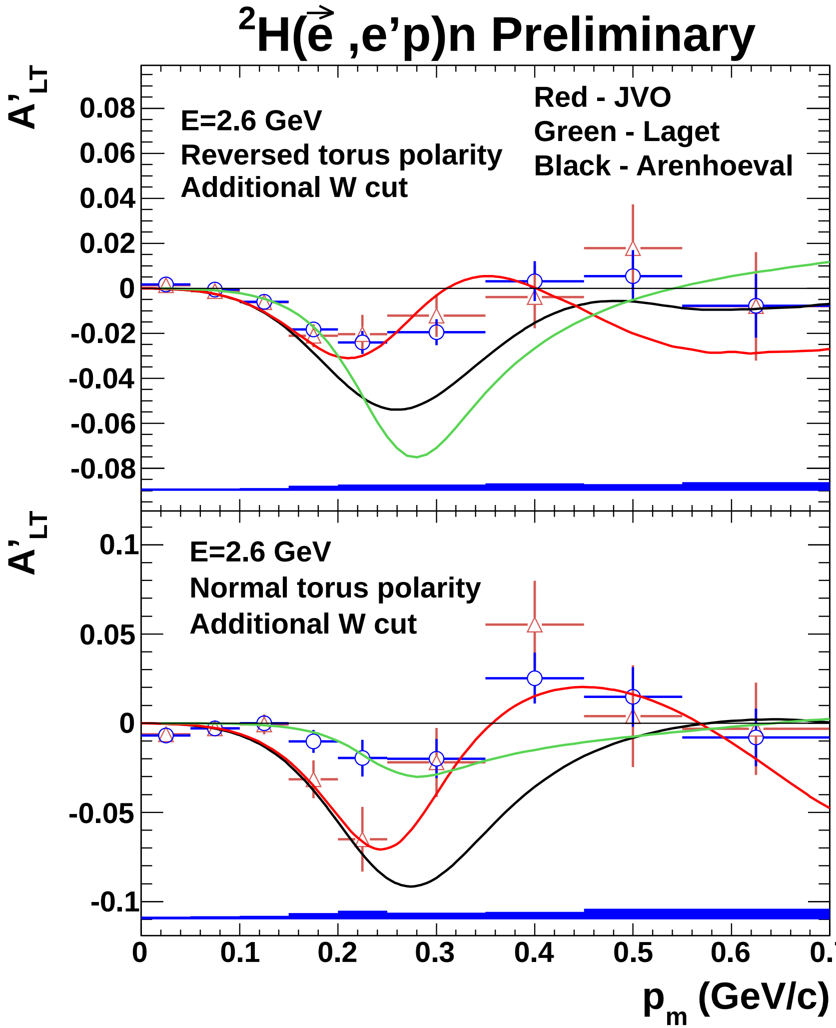




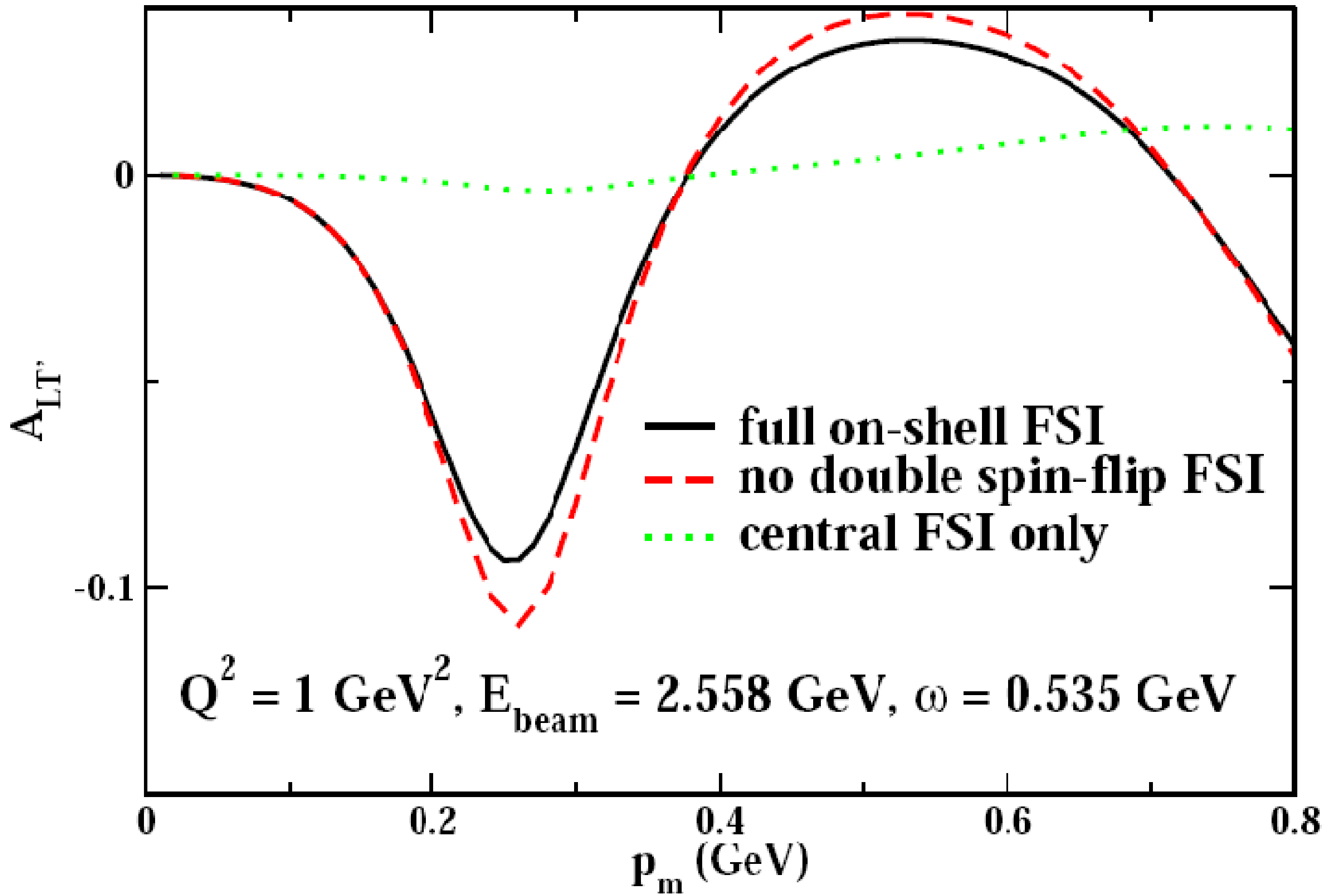


Conclusions

- The $\langle \sin\phi_{pq} \rangle$ technique works well including the subtraction of the two different beam helicities to eliminate sinusoidal components of the acceptance.
- We observe a 2% dip in A'_{LT} at $p_m \approx 220\ MeV/c$ in both 2.6-GeV data sets.
- In the low-Q^2 data ($\langle \mathrm{Q}^2 \rangle = 0.36\ (\mathrm{GeV/c})^2$) the JVO calculation shows reasonable agreement with the data across the full p_m range.
- In the high-Q^2 data ($\langle \mathrm{Q}^2 \rangle = 0.96\ (\mathrm{GeV/c})^2$) the JVO calculation predicts a much greater dip than observed.
- At low p_m, the calculations by Arenhövel reproduce the low-Q^2 data, but diverge (they're too negative) above $p_m = 250\ MeV/c$. At high-Q^2, the calculation predicts too great a dip.
- At low Q^2, the Laget calculations reproduce the low-p_m data, but predicts to great a dip at higher p_m. At high Q^2, the calculation reproduces the magnitude of the dip.
- The effect of the narrow W cut on A'_{LT} for the high-Q^2 data is a puzzle.

Additional Slides

Effect of spin-orbit FSI forces calculated by JVO



Corrections

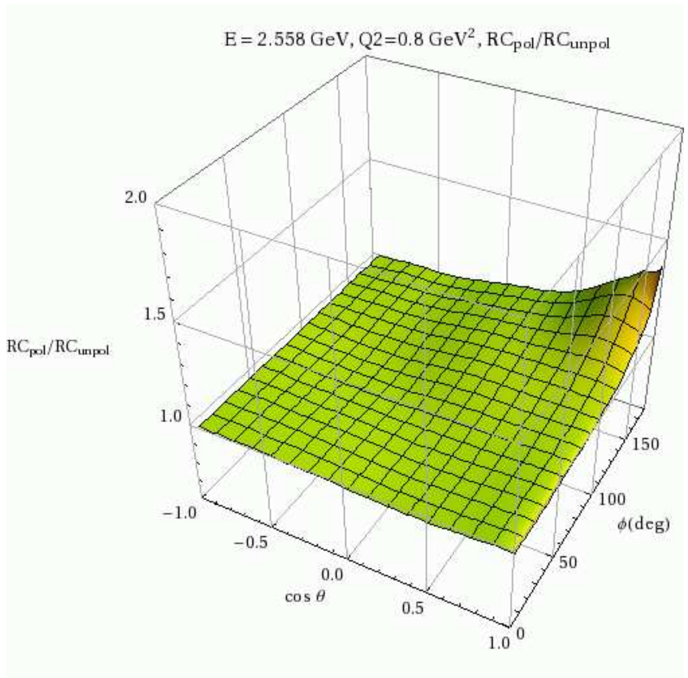
- Momentum corrections.
  - Determine θ_e for elastically scattered electrons and extract W^2.
  - Minimize the difference between W^2 and M_p^2 as a function of the electron θ_e and ϕ_e and for each data set.
  -

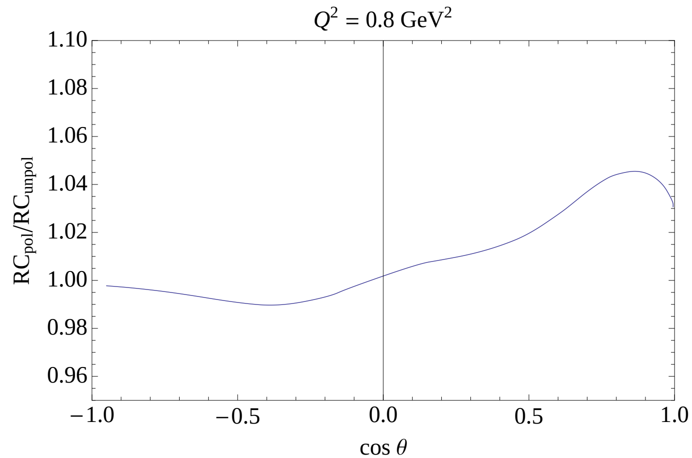
W^2	Data Set
$0.875 \pm 0.027\ \mathrm{GeV}^2$	2.6 GeV, reversed torus polarity
$0.879 \pm 0.028\ \mathrm{GeV}^2$	2.6 GeV, normal torus polarity
$0.873 \pm 0.032\ \mathrm{GeV}^2$	4.2 GeV, normal torus polarity

- Radiative corrections.
  - Expected them to be small (they were in the G_M^n analysis from the same data set).
  - They weren't small enough.
  - First, need to see the measured, preliminary A'_{LT}.

Radiative Corrections (RC)

- EXCLURAD - Applies a more sophisticated method than the usual approach of Mo and Tsai or Schwinger to account for exclusive measurements. See CLAS-Note 2005-022 and Afanasev *et al.*, PRD 66, 074004 (2002).
- They aren't small enough to ignore.
- Method
  - Calculate polarized and unpolarized RC surfaces as functions of $\cos\theta_{pq}$ and ϕ_{pq} over broad range of Q^2.
  - Convert $\cos\theta_{pq}$ to p_m.
  - Store results in a three dimensional histogram in ROOT.
  - Interpolate this histogram to get $RC(Q^2, p_m, \phi_{pq})$ and apply it as a weight event-by-event.
- Q^2 (GeV^2): 0.2, 0.5, 0.8, 1.1, 1.4, 1.7.





Choosing *vcut*

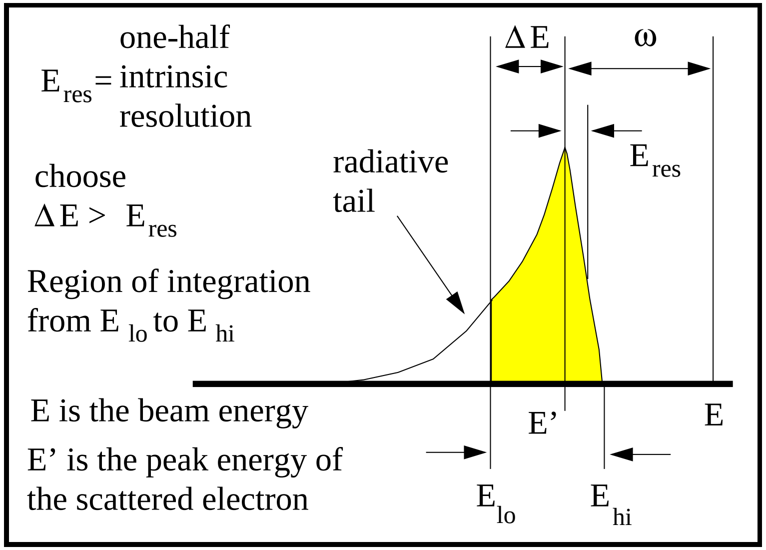
Some of the quantities needed to correct for radiative effects are shown in the plot. The tail is integrated using the covariant 'inelasticity' v defined as

$$v = \Lambda^2 - m_u^2$$

$$= W_0^2 + m_h^2 - m_u^2 + 2\Delta E\left(M + 2E\sin^2\frac{\theta}{2}\right) - 2E_h\sqrt{W_0^2 + 2\Delta E\left(M + 2E\sin^2\frac{\theta}{2}\right)}$$

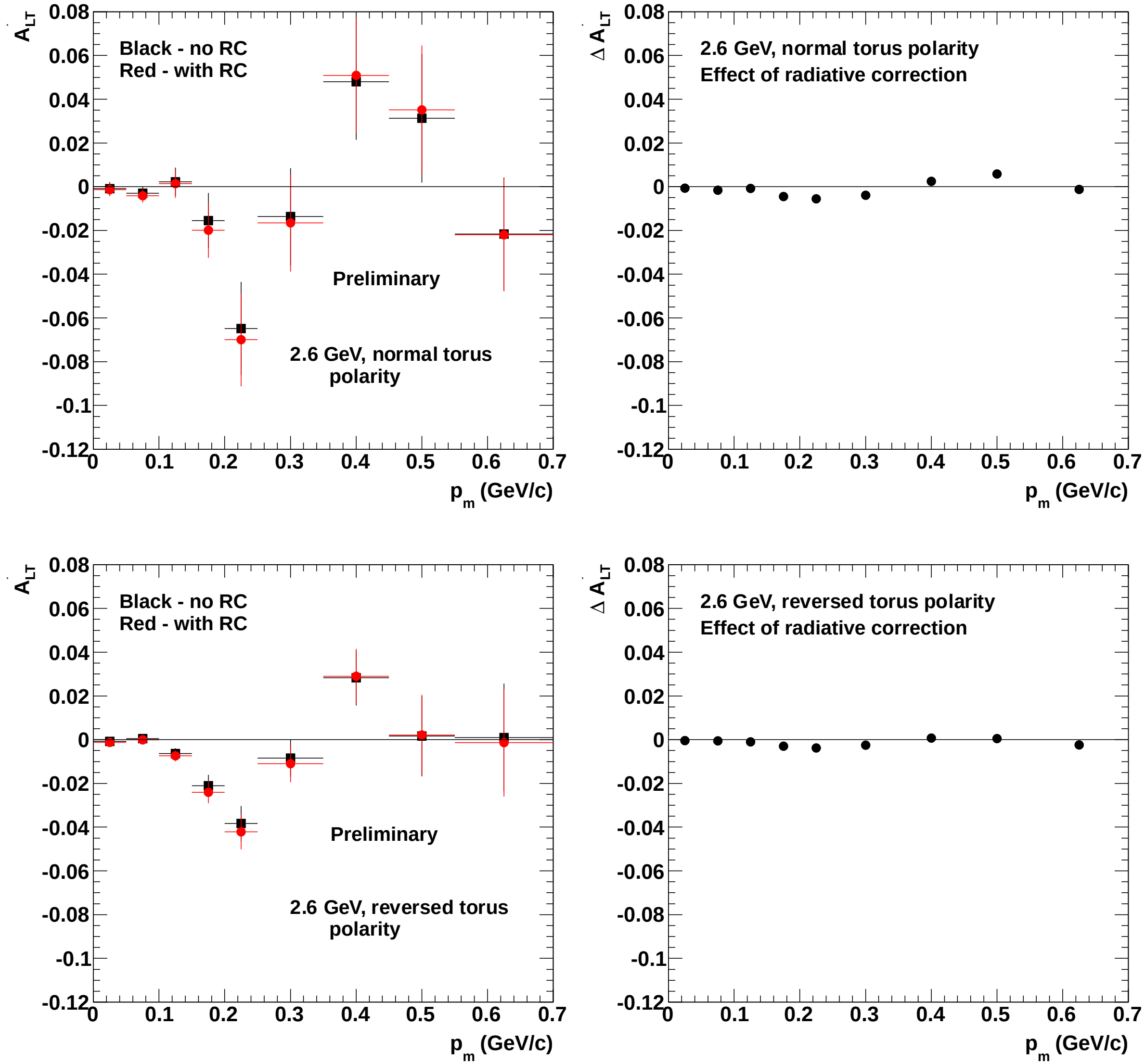
where m_u is the mass of the undetected hadron, Λ is the four-momentum of the missing or undetected particles, and

$$W_0^2 = M^2 + 2M(E - E') - 4EE'\sin^2\frac{\theta}{2}$$



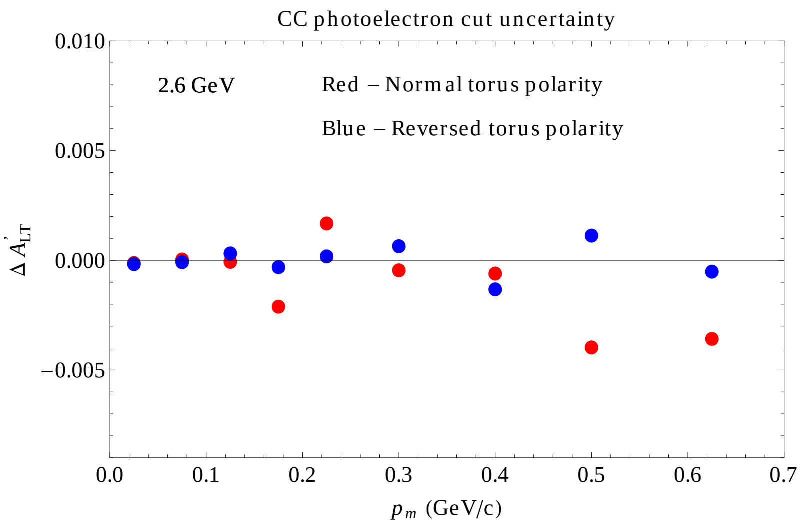
and the quantities E, E', and θ are determined by the electron kinematics. The hadron energy E_h is determined by the choice of the angle of the outgoing hadron relative to $\vec{q}$, the three-vector of the momentum transfer. The masses M, m_h, and m_u are all known.

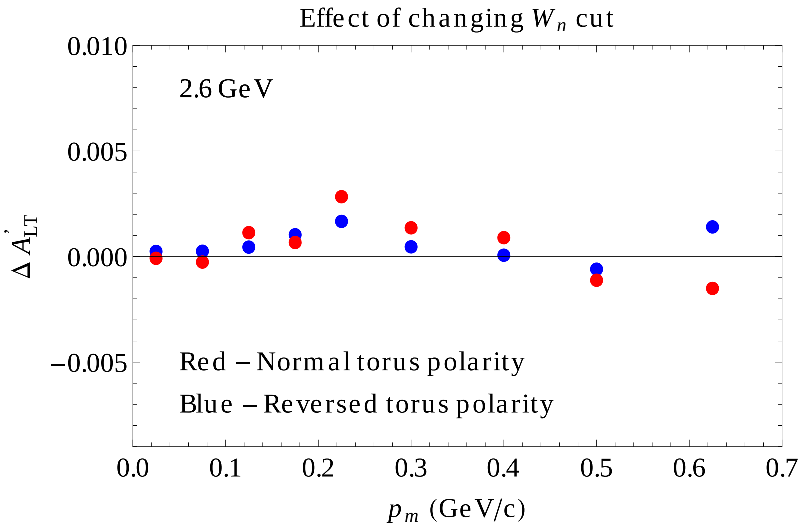
Effect of Radiative Corrections

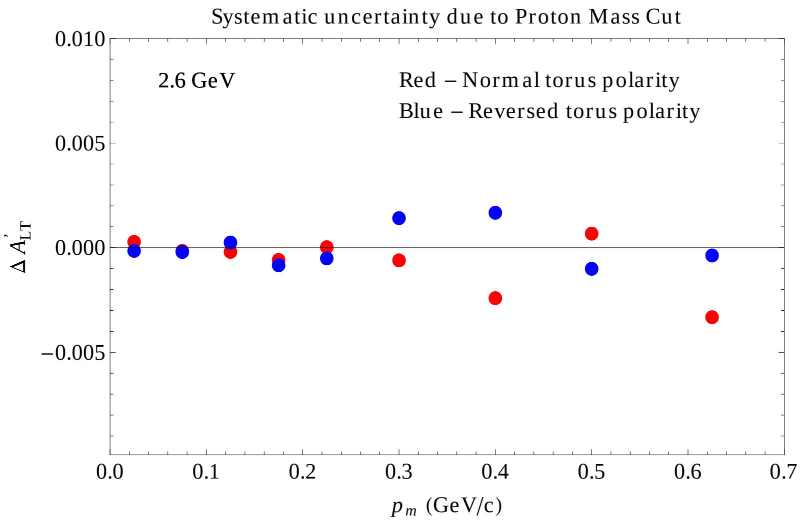


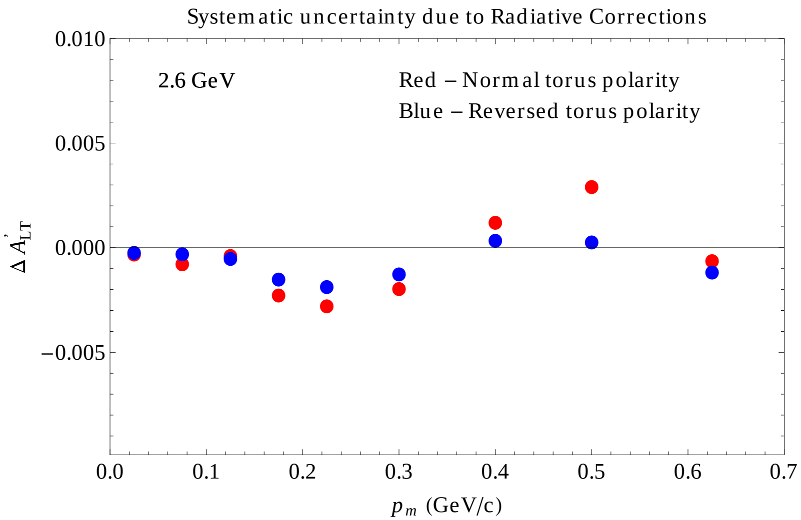
The radiative correction turns out to be much smaller than the statistical uncertainty.

Systematic Uncertainties



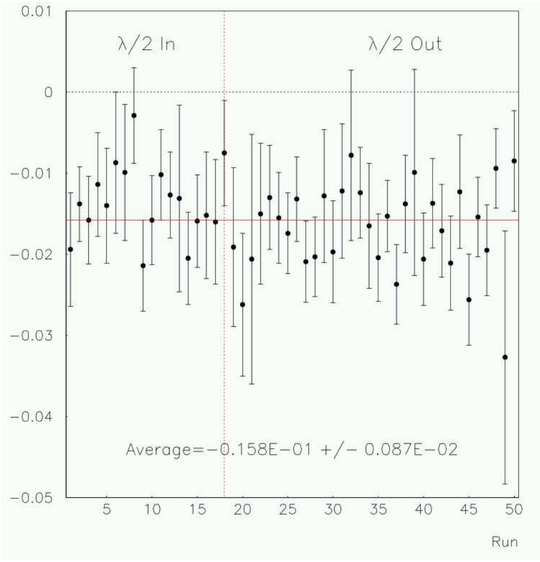




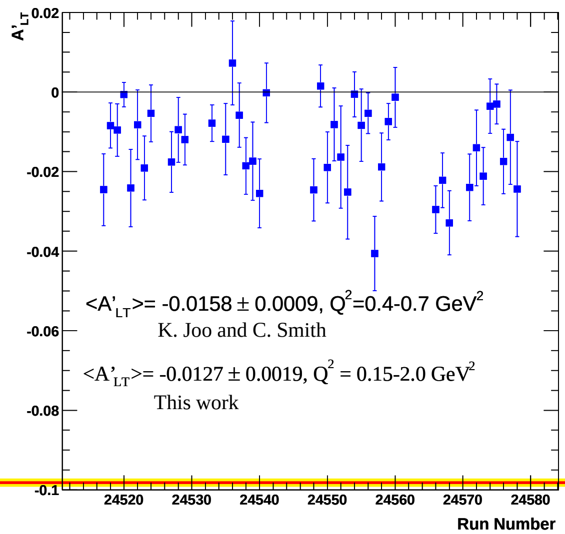


Consistency Checks - Beam helicity

$ep \rightarrow e' p \pi^0$ Comparison



K.Joo and C.Smith, CAN 2001-008.



W_n Equation

$$W_n = \sqrt{M_d^2 - 2M_dE_p + m_p^2 + 2(M_d - E_p)\nu - Q^2 + 2|\vec{p_p}||\vec{q}|\cos\theta_{pq}}$$

where M_d is the deuteron mass, m_p is the proton mass, p_p is the magnitude of the proton 3-momentum, $E_p = \sqrt{p_p^2 + m_p^2}$ is the proton energy, $\nu = E - E'$ is the energy transfer where E is the beam energy and E' is the scattered electron energy, $Q^2 = 4EE'\sin^2\frac{\theta}{2}$ is the square of the electron 4-momentum transfer and θ is the electron scattering angle, $q = |\vec{q}| = \sqrt{Q^2 + \nu^2}$ is the magnitude of the electron 3-momentum transfer, and θ_{pq} is the angle between the proton 3-momentum $\vec{p}_p$ and the 3-momentum transfer $\vec{q}$.

Fitting A_h to get a'_{LT}

The fivefold differential cross section for the quasielastic $^2\mathrm{H}(\vec{e}, e'p)n$ reaction as

$$\frac{d^5\sigma}{d\mathrm{Q}^2 dp_m d\phi_{pq} d\Omega_e d\Omega_p} = \sigma^{\pm} = \sigma_L + \sigma_T + \sigma_{LT}\cos\phi_{pq} + \sigma_{TT}\cos 2\phi_{pq} + h\sigma_{LT'}\sin\phi_{pq}$$

where the superscript on $\sigma^{\pm}$ refers to the helicity and the σ_i's are the partial cross sections for each component. The helicity asymmetry is defined in the following equation and the expression for the cross section substituted for $\sigma^{\pm}$ to obtain the following.

$$A_h(\mathrm{Q}^2, p_m, \phi_{pq}) = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\sigma_{LT'}\sin\phi_{pq}}{\sigma_L + \sigma_T + \sigma_{LT} cos\phi_{pq} + \sigma_{TT}\cos 2\phi_{pq}}$$

If σ_{LT} and σ_{TT} are small relative to σ_T and σ_L, then

$$A_h(\mathrm{Q}^2, p_m, \phi_{pq}) \approx \frac{\sigma'_{LT}\sin\phi_{pq}}{\sigma_L + \sigma_T} = A'_{LT}\sin\phi_{pq}$$

so the amplitude of the A_h is A'_{LT}.