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

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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 ${}^2\text{H}(\vec{e}, e'p)n$ at $Q^2 \approx 1 \text{ (GeV/c)}^2$ ($\sigma'_{LT} \propto \text{Im}(J_{fi}^z(\vec{q})^* J_{fi}^y(\vec{q}))$).

- The cross section is

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

where $h = \pm 1$ for different beam helicities.

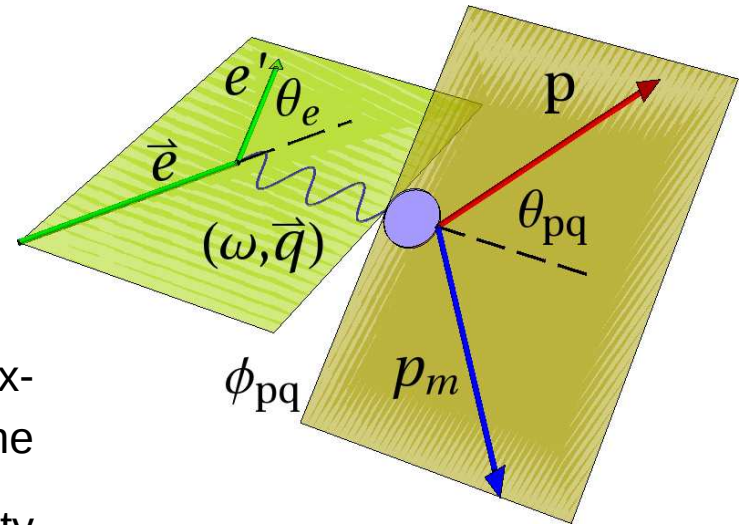
- Use a variation of the helicity asymmetry extracted from the ϕ_{pq} -dependent moments of the data in each $\vec{p}_m = \vec{q} - \vec{p}_p$ bin.

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

beam helicity

- Get rid of a sinusoidally-varying background, by taking the difference of the two 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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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

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

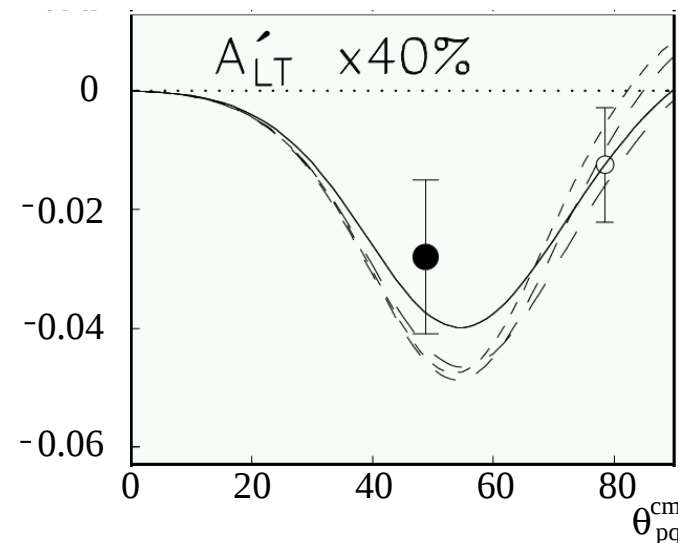
where the subscripts refer to $\phi_{pq} = 90^\circ$ and there is an additional term σ_{TT} in the denominator. The contribution of this term is small.

- Get rid of a sinusoidally varying background, by taking the difference of the two 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 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 GeV and 2.56 GeV, with normal torus polarity (electrons inbending).
- One beam energy 2.56 GeV with reversed torus polarity (electron outbending) to reach lower Q^2 .
- Recorded about 2.3 billion triggers, $Q^2 = 0.2 - 5.0(\text{GeV}/c)^2$.
- Dual target cell with liquid hydrogen and deuterium.
- Beam polarization:
 0.736 ± 0.017
- Limited statistics at 4.23 GeV so only lower energy data shown here.

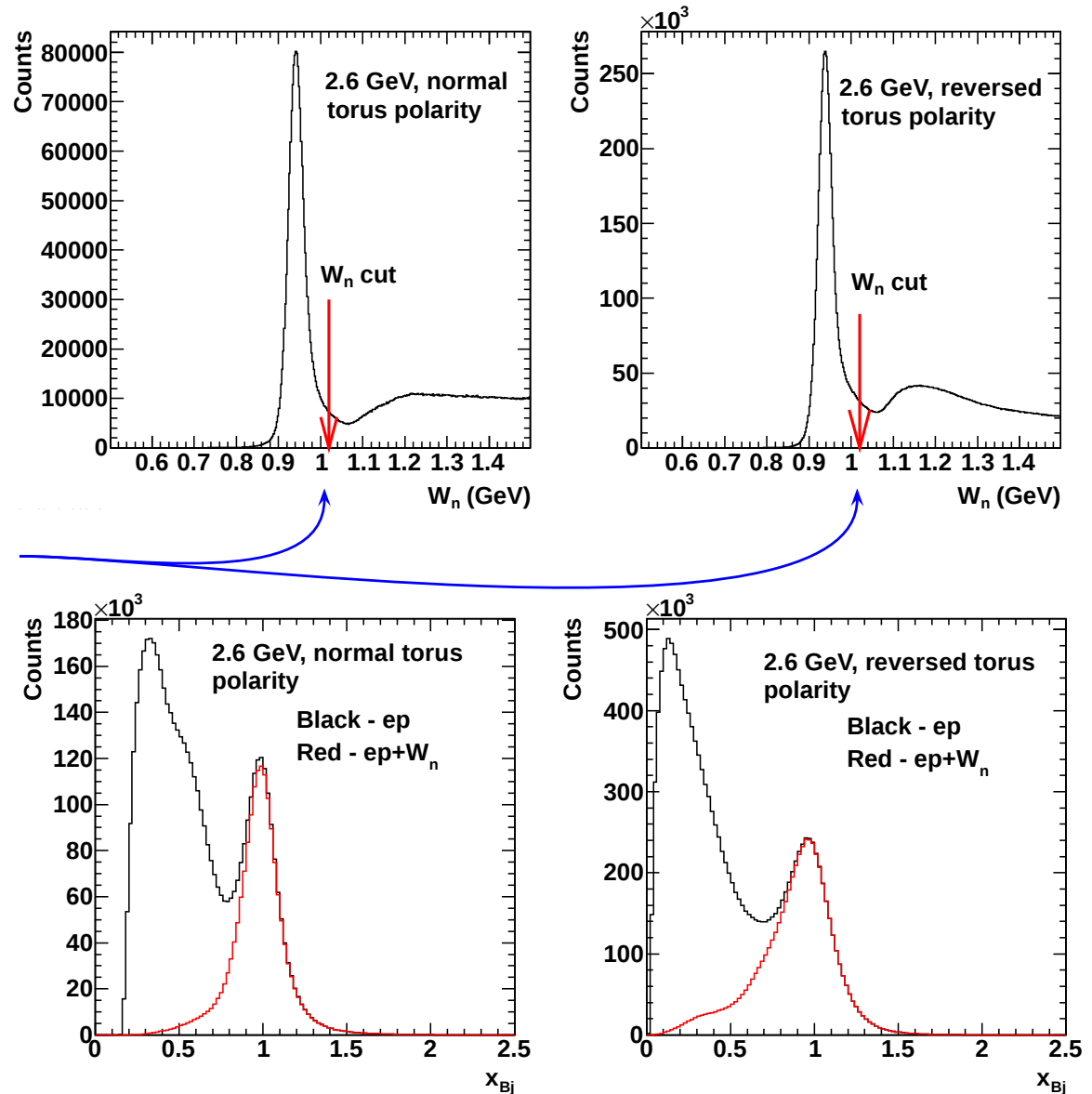


Event Selection Cuts and Corrections

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 $n_{phe} \geq 25$
	EC track fiducial	$ dc_ysc \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 <i>et al.</i> , CLAS-NOTE 2000-007.
	Select target	$-11.5 \text{ cm} < v_z < -8.0 \text{ cm}$
	Momentum corrections	Kim <i>et al.</i> , CLAS-Note 2001-018.
For protons	Proton fiducial cut	Nyazov <i>et al.</i> , CLAS-NOTE 2001-013.
	ep vertex cut	$ v_z(e) - v_z(proton) \leq 1.5 \text{ cm}$
	mass cut	$0.88 \text{ MeV}/c^2 < m_p < 1.02 \text{ MeV}/c^2$
	Momentum corrections	K. Y. Kim <i>et al.</i> , 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 <i>et al.</i> , CLAS-NOTE 2005-022

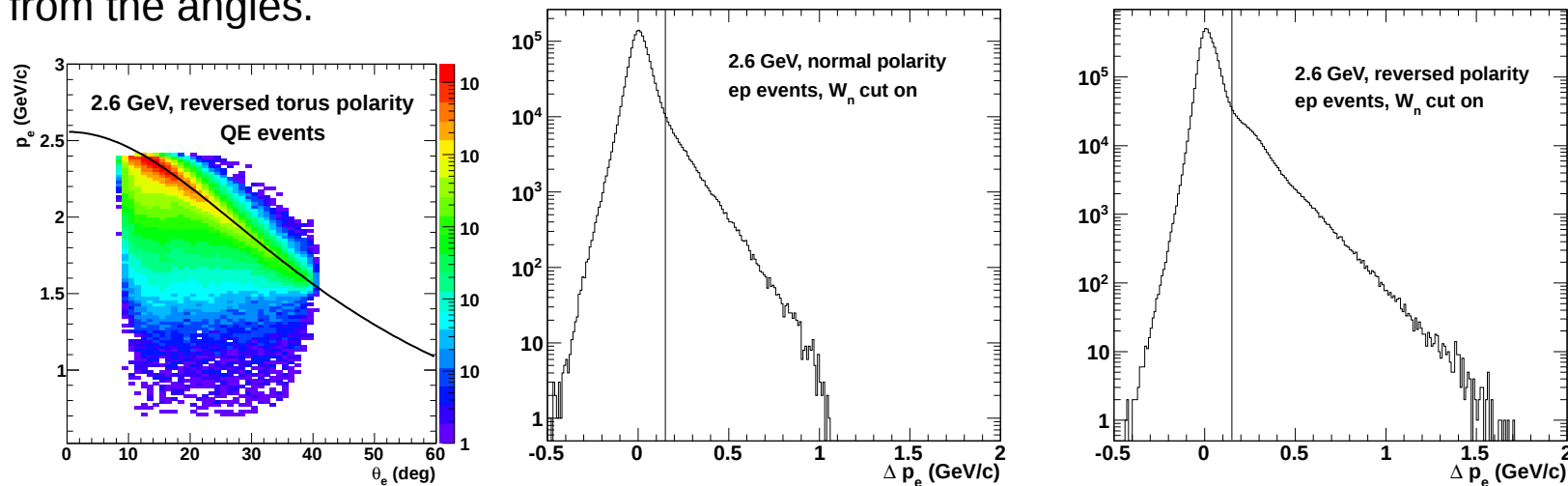
Quasielastic Electron Selection

- Start with the residual epX mass W_n .
- Fit the neutron peak in the distribution to determine the 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.

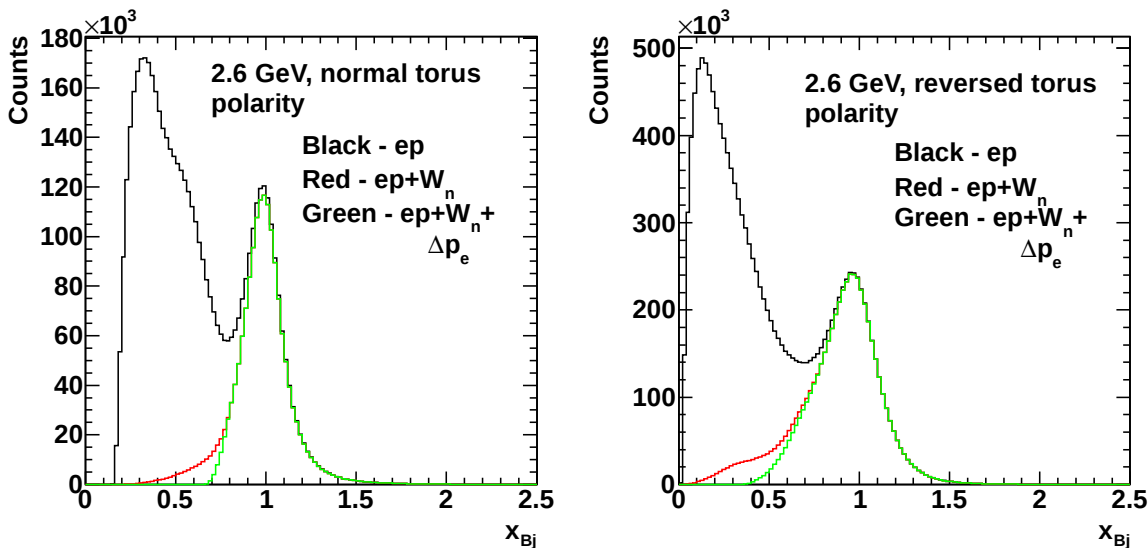


Quasielastic Electron Selection

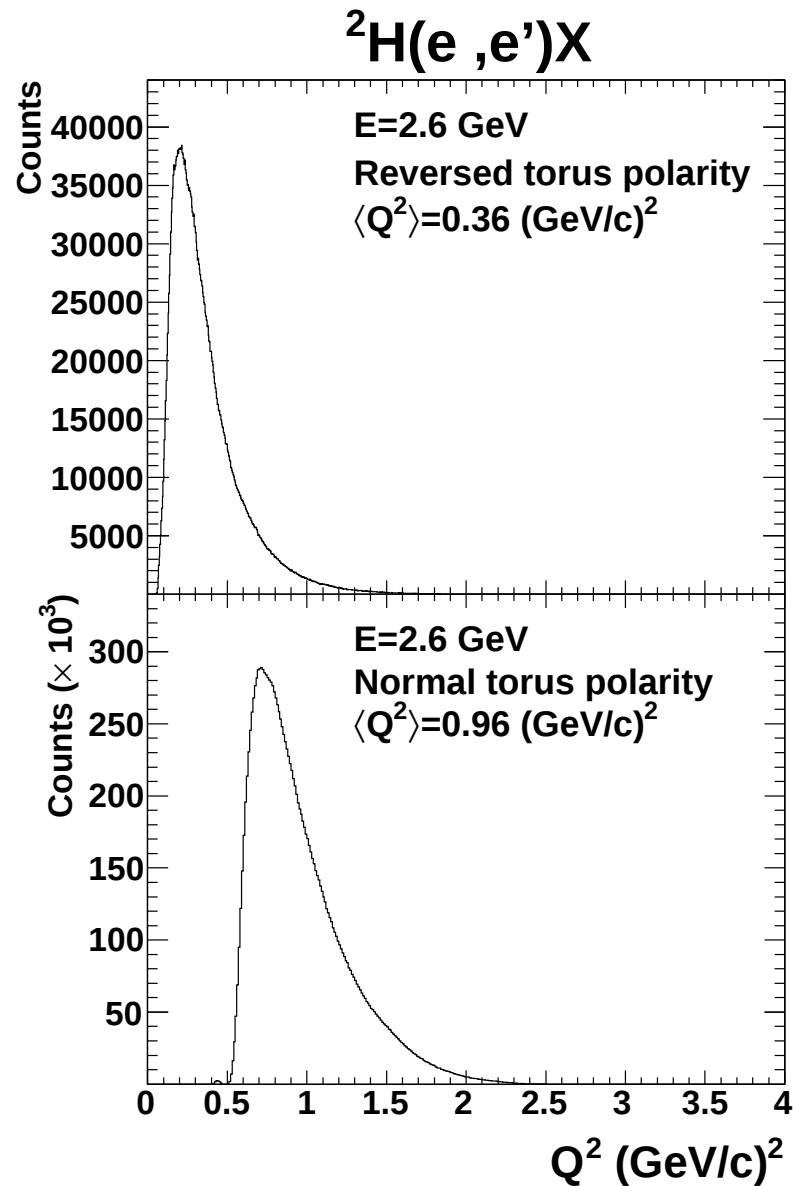
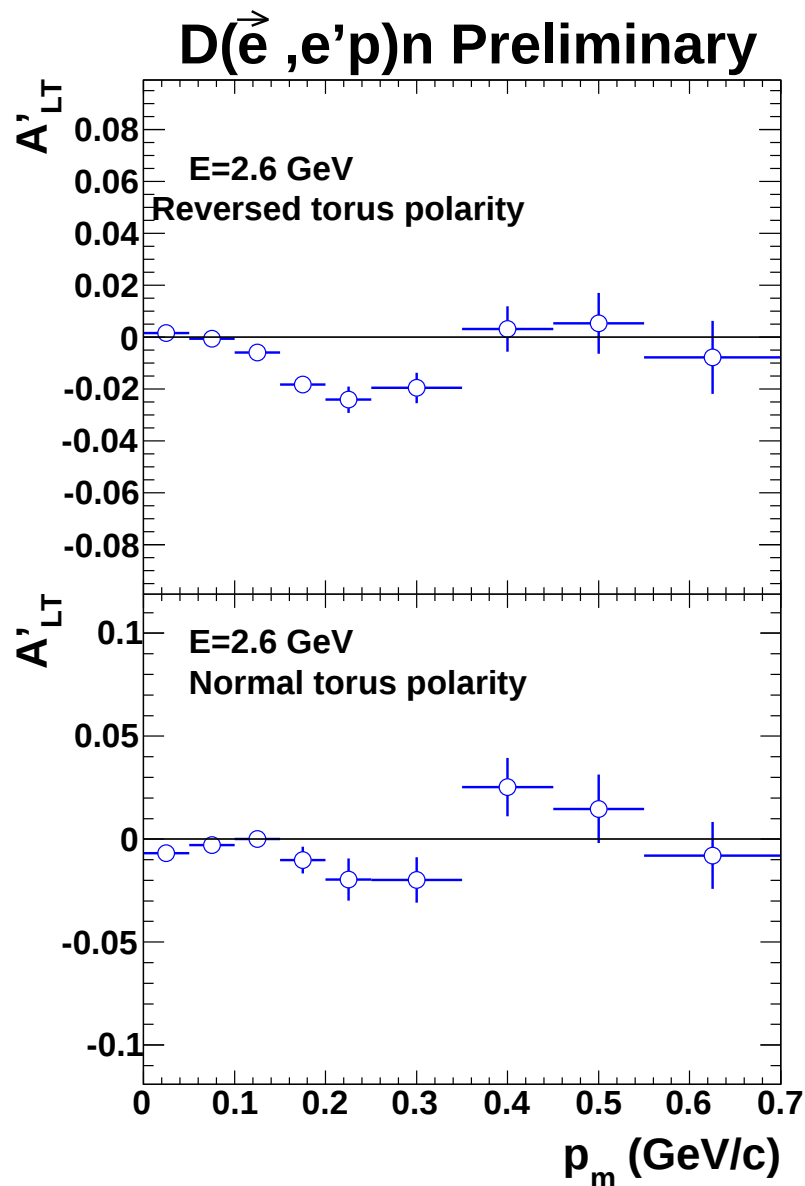
- Consider $\Delta p_e = p_e(\text{measured}) - p_e(\text{calculated})$ where $p_e(\text{calculated})$ is extracted from the angles.



- 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 $D(\vec{e}, e'p)n$

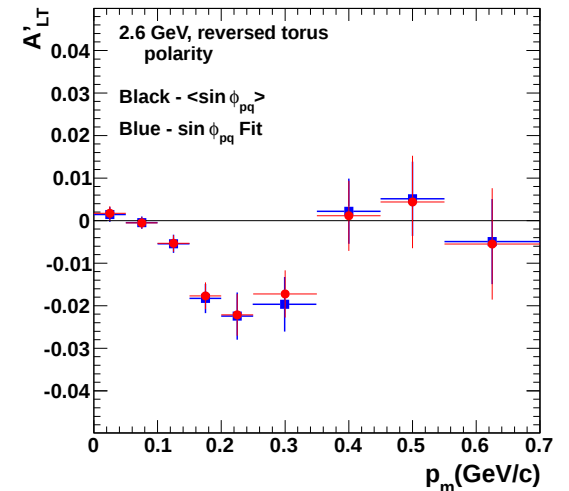
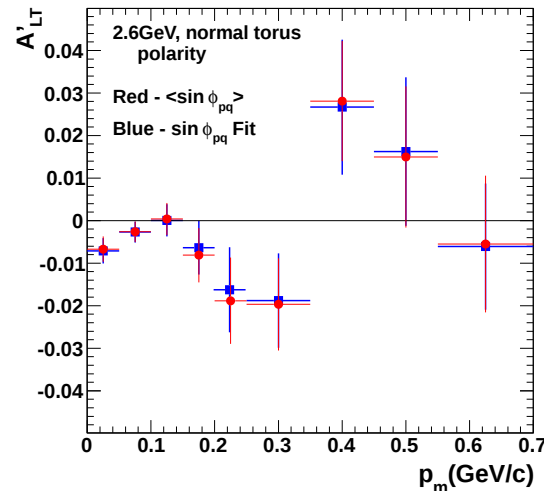
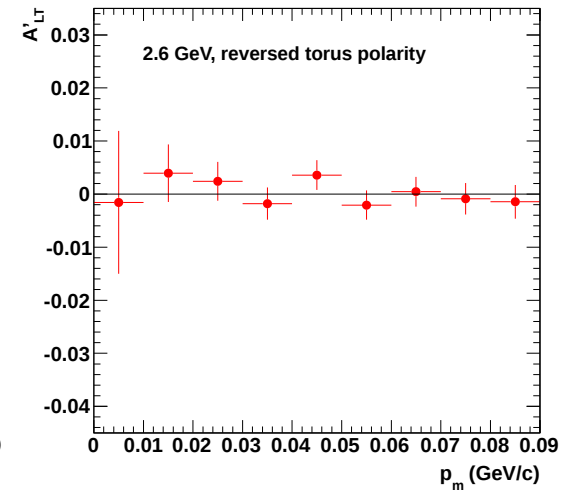
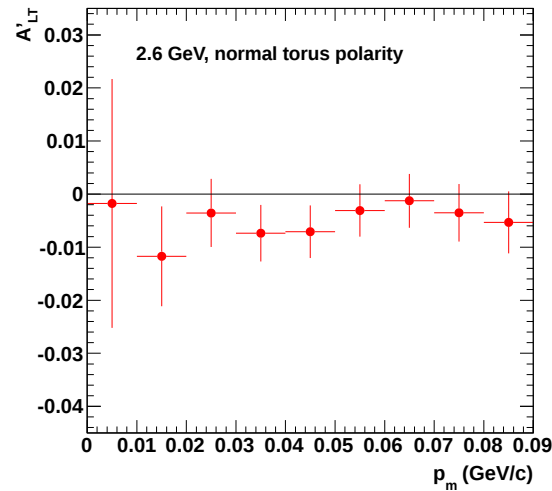


Consistency Checks

- Check beam helicity with $ep \rightarrow e'\pi^0$.

- At $p_m \approx 0$ 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.

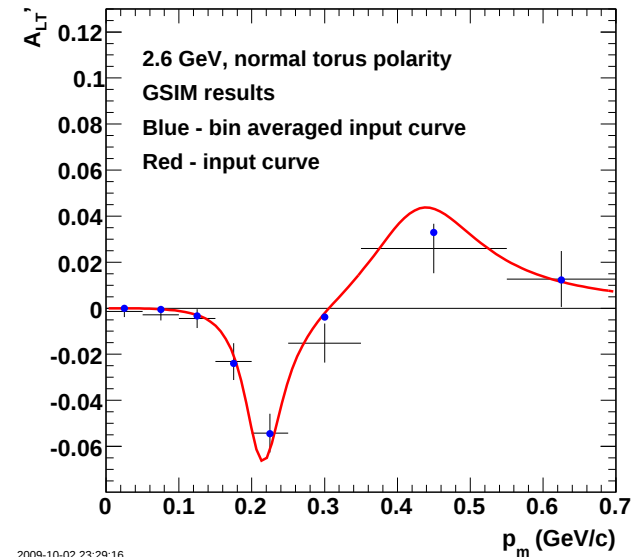
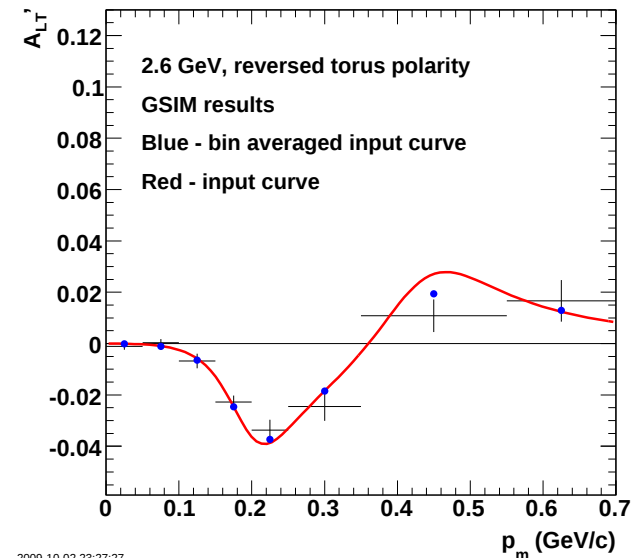


Consistency Checks

- 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 (QUEEG).
 - 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	RC 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.

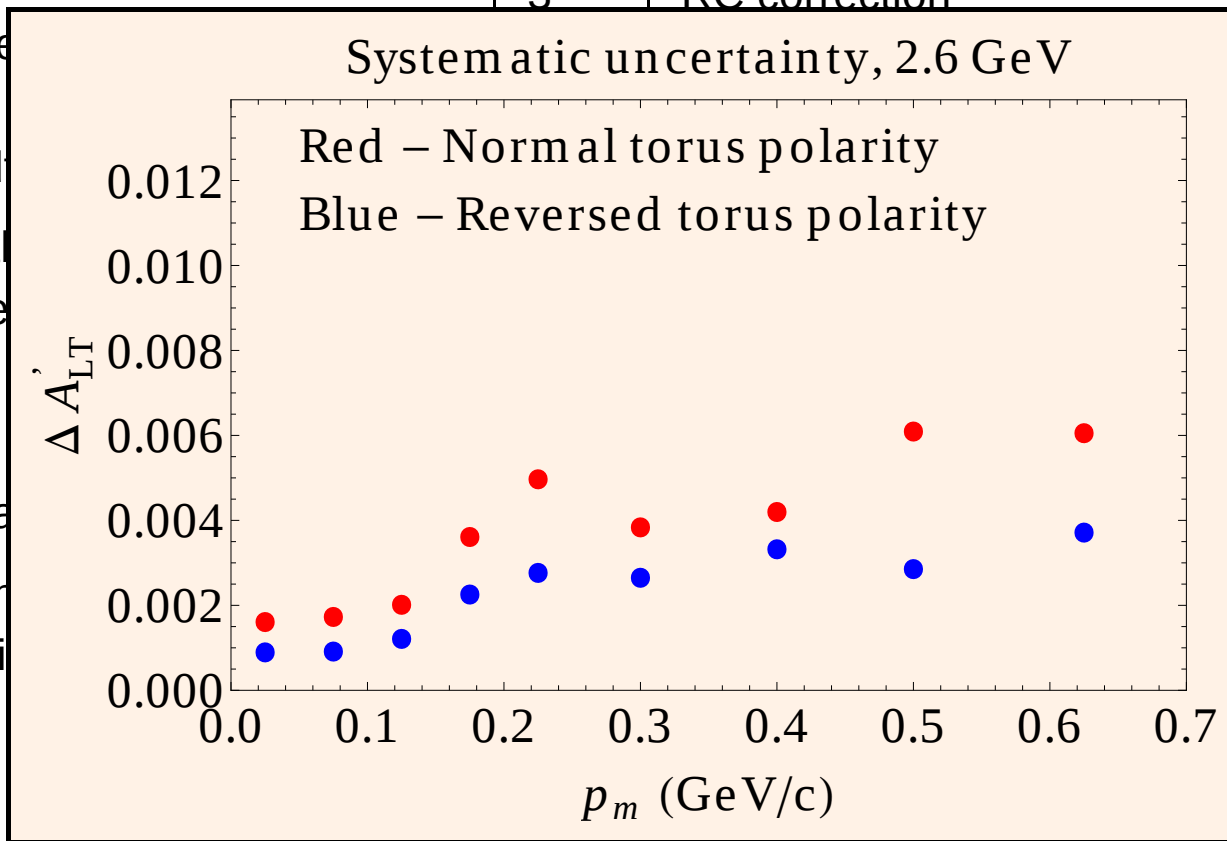
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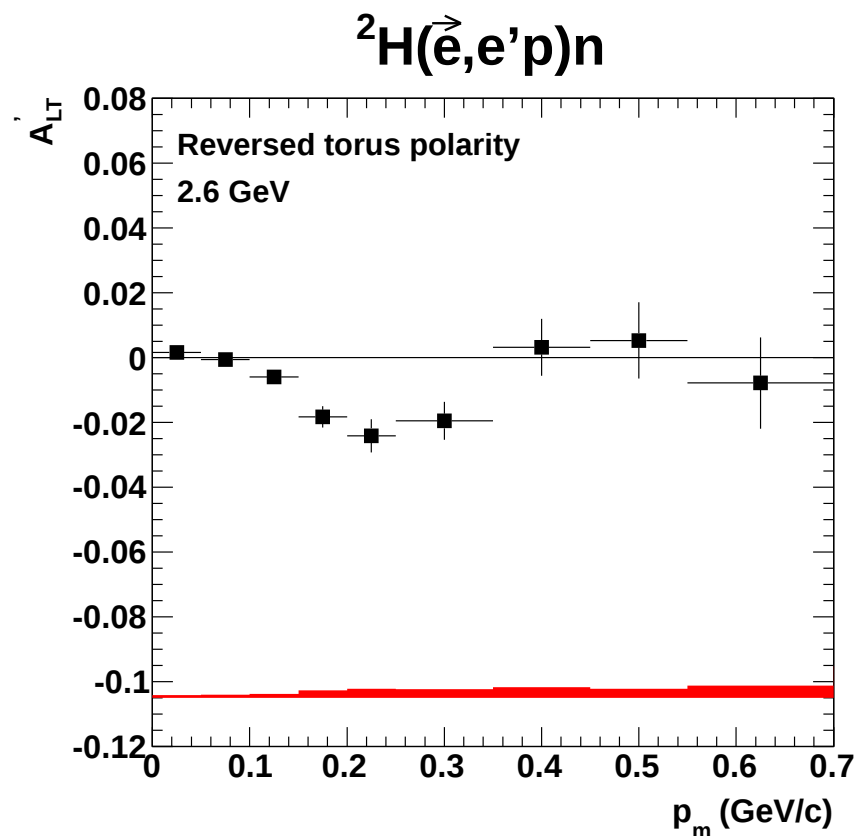
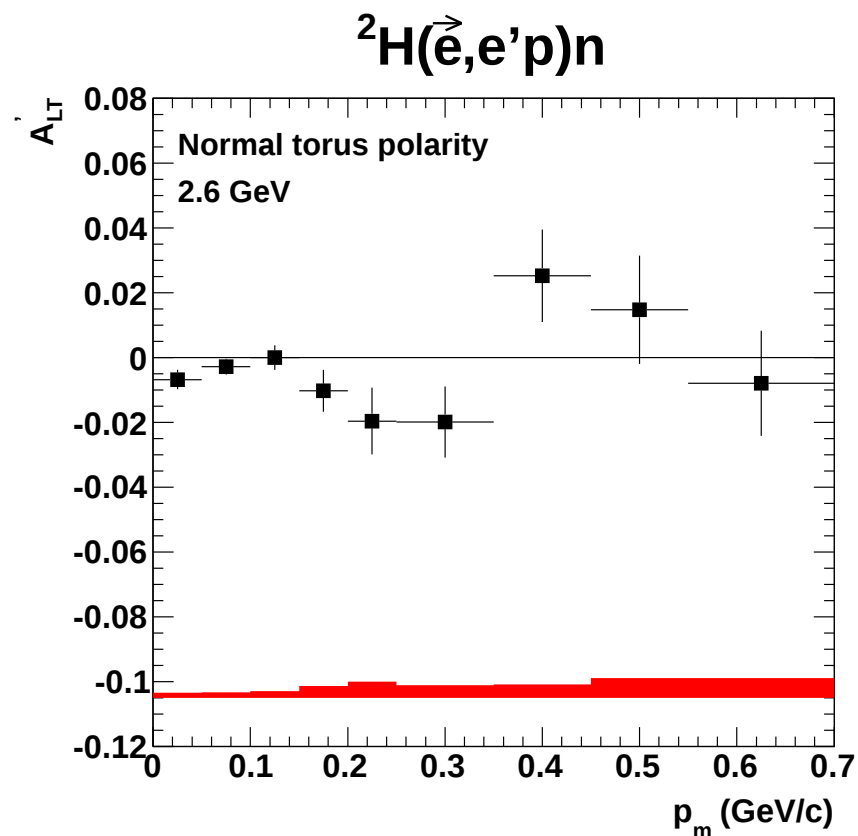
Row	Quantity	$\delta A'_{LT}$
1	Number of CC Photoelectrons	< 0.004
2	W_n cut	< 0.003
3	RC correction	< 0.003
		< 0.003
		< 0.002
		< 0.002
		< 0.002
		< 0.002
		< 0.002
		< 0.001
		< 0.001

2. Change where the width
3. Half the change diative off.
4. Same as
5. Remain Analysis



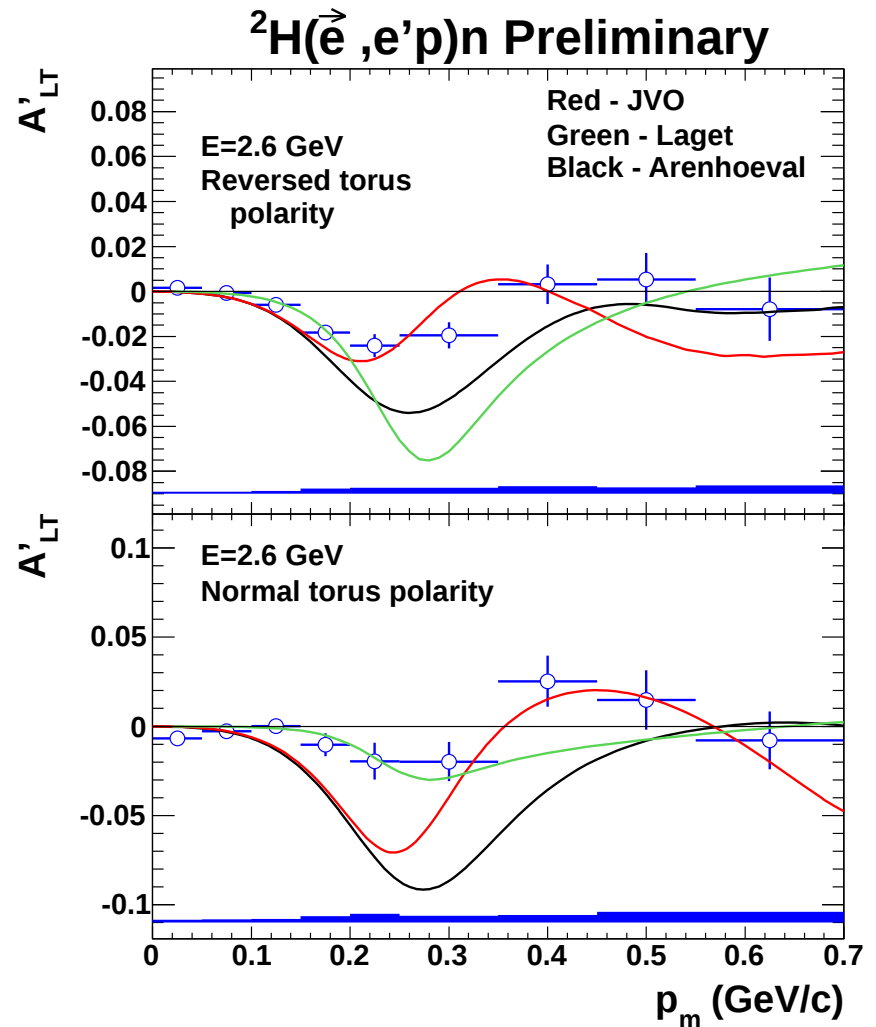
Systematic uncertainty for both data sets.

Preliminary Results with Uncertainties



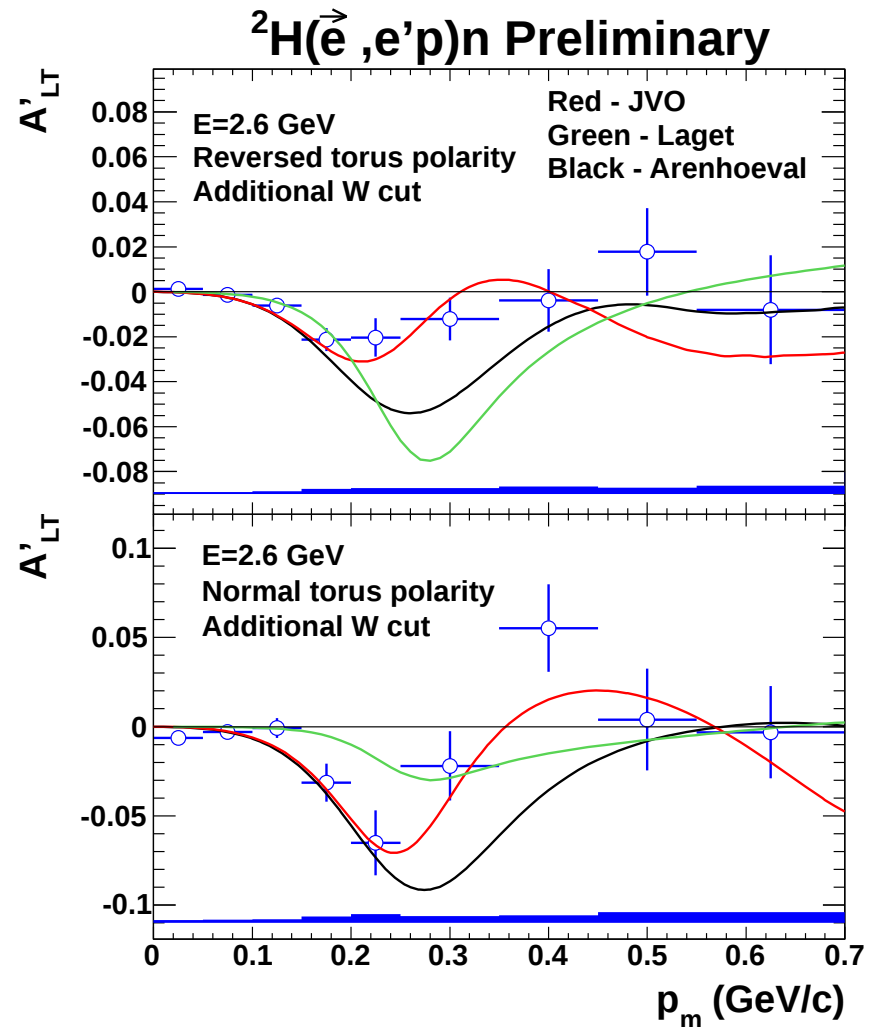
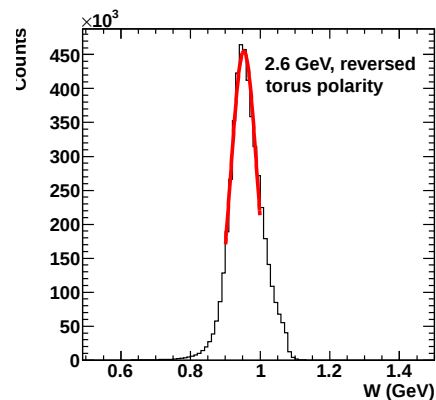
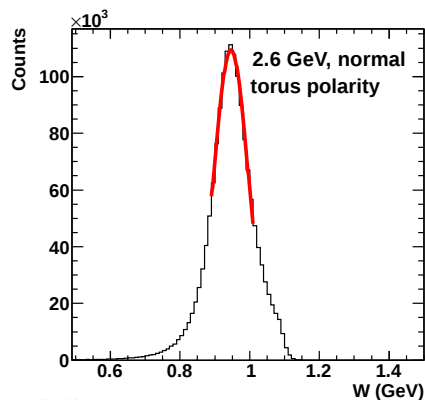
Preliminary Comparison With Theory

1. Arenhövel (black) - Non-relativistic Schrödinger Equation with RC, MEC, IC, and FSI. Averaged over the CLAS acceptance.
2. Laget (green) - Diagrammatic approach for $Q^2 = 1.1 \text{ GeV}^2$ (lower panel) and $Q^2 = 0.7 \text{ GeV}^2$ (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 $\Lambda_N = 1.0 \text{ GeV}$ (PRC, 81, 014008, 2010). Averaged over the CLAS acceptance.



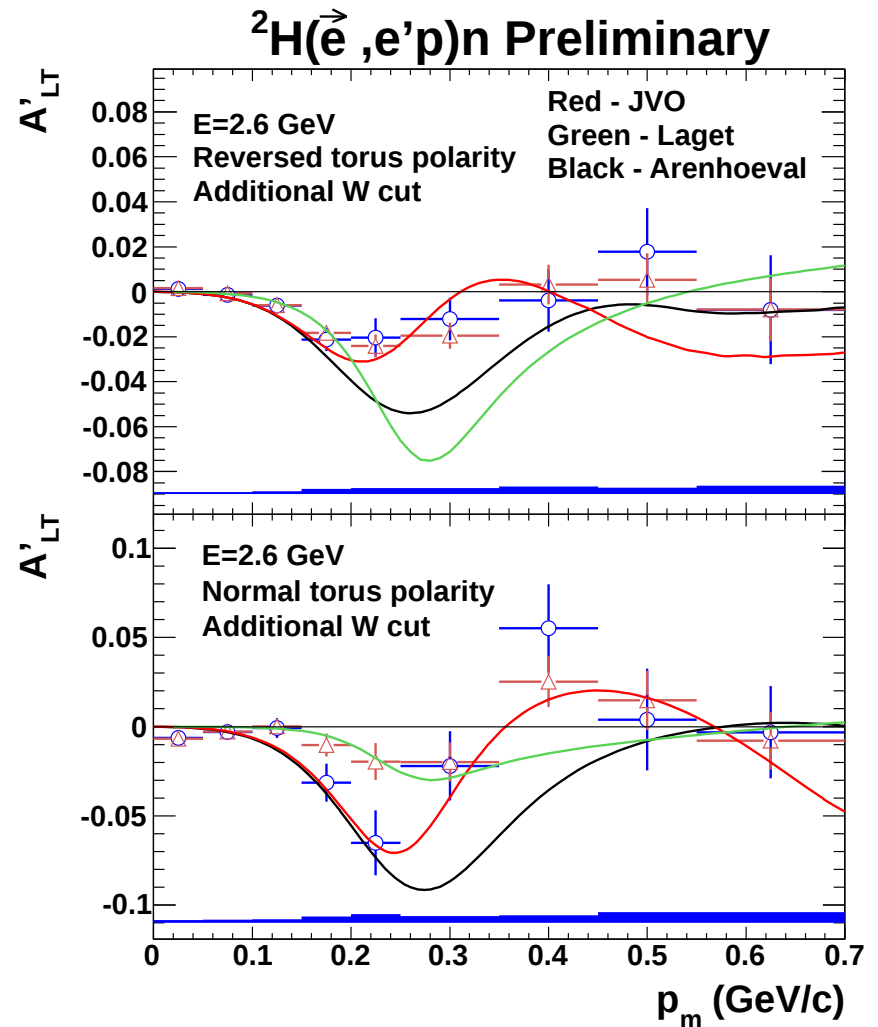
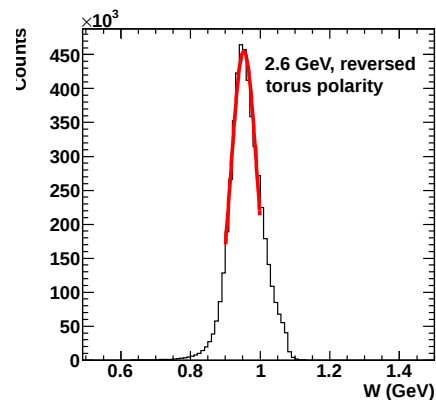
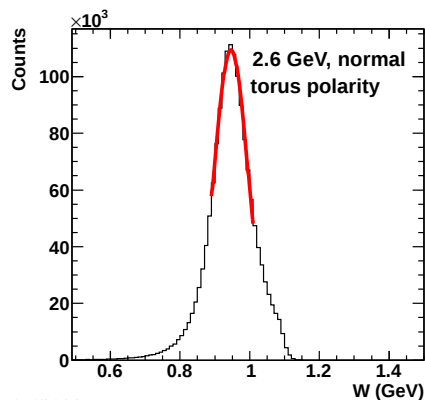
Effect of Narrow W cut

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 than the Bates one (100 MeV versus 17 MeV) in order to obtain adequate statistics.



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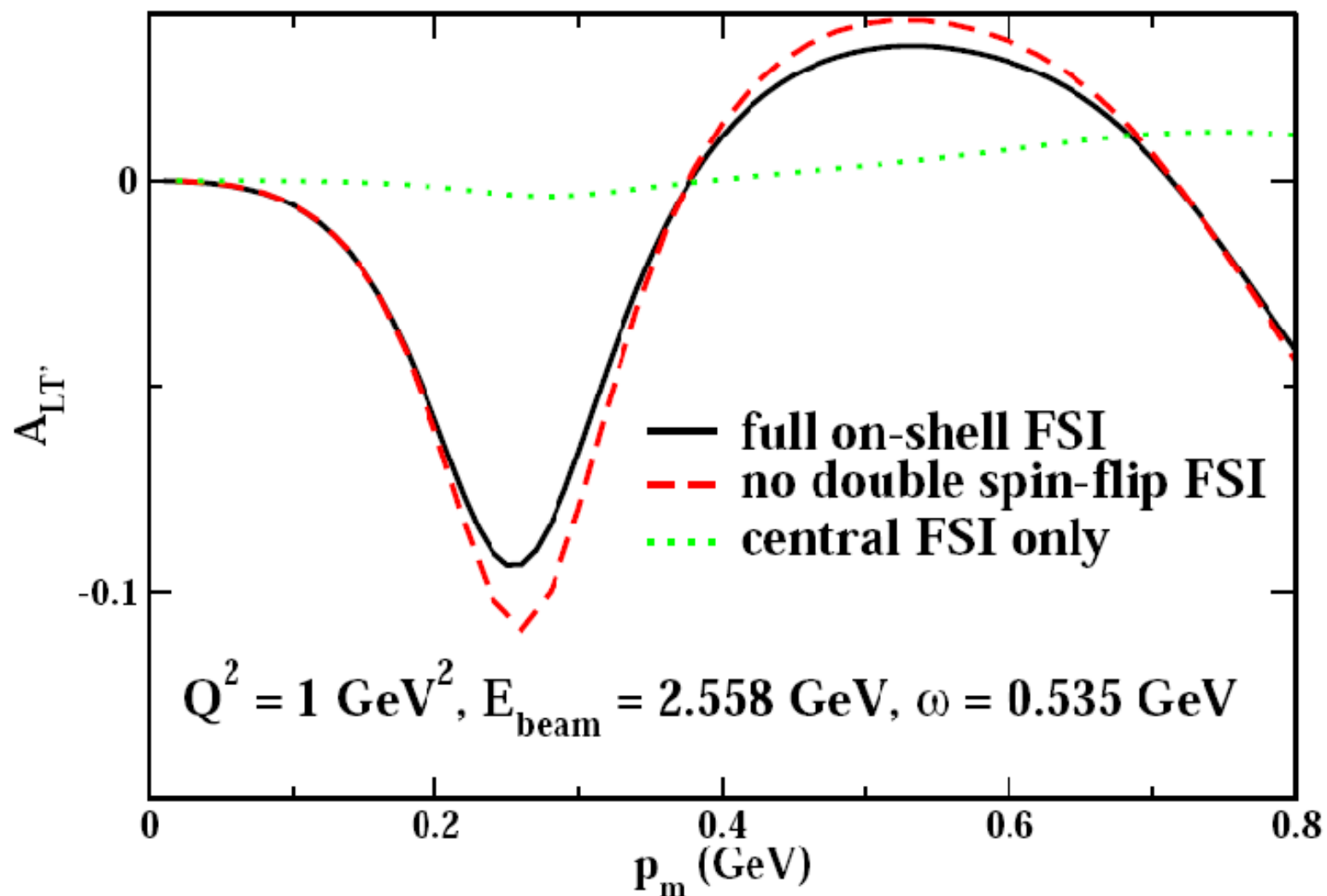


Conclusions

- 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 $p_m \approx 220 \text{ MeV}/c$ in both 2.6-GeV data sets.
- In the low- Q^2 data ($\langle Q^2 \rangle = 0.36 \text{ (GeV}/c)^2$) the JVO calculation shows reasonable agreement with the data across the full p_m range.
- In the high- Q^2 data ($\langle Q^2 \rangle = 0.96 \text{ (GeV}/c)^2$) 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 $p_m = 250 \text{ MeV}/c$. 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 too 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.

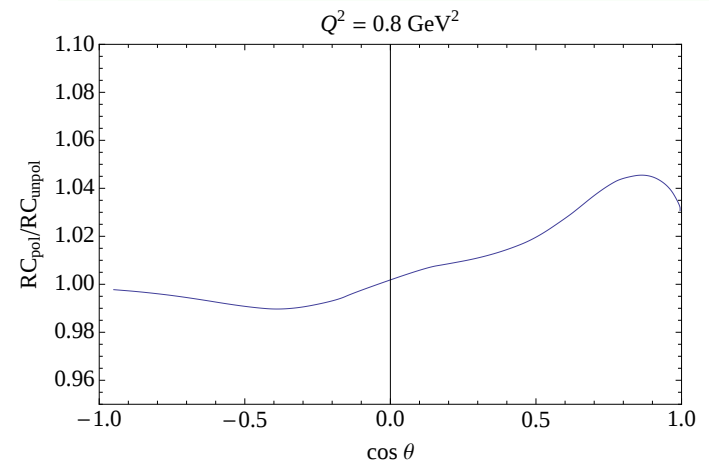
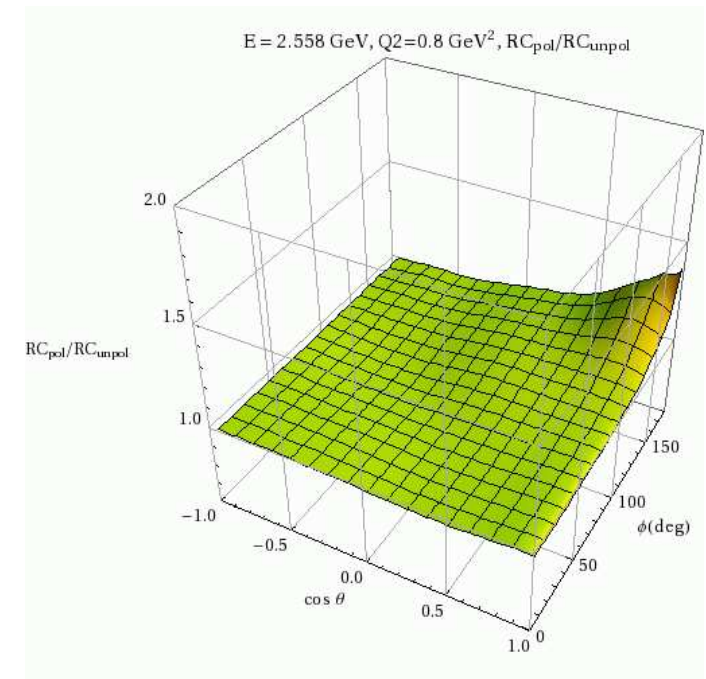
- | W^2 | Data Set |
|---------------------------------|----------------------------------|
| $0.875 \pm 0.027 \text{ GeV}^2$ | 2.6 GeV, reversed torus polarity |
| $0.879 \pm 0.028 \text{ GeV}^2$ | 2.6 GeV, normal torus polarity |
| $0.873 \pm 0.032 \text{ GeV}^2$ | 4.2 GeV, normal torus polarity |

● 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 (GeV²): 0.2, 0.5, 0.8, 1.1, 1.4, 1.7.



Choosing v_{cut}

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

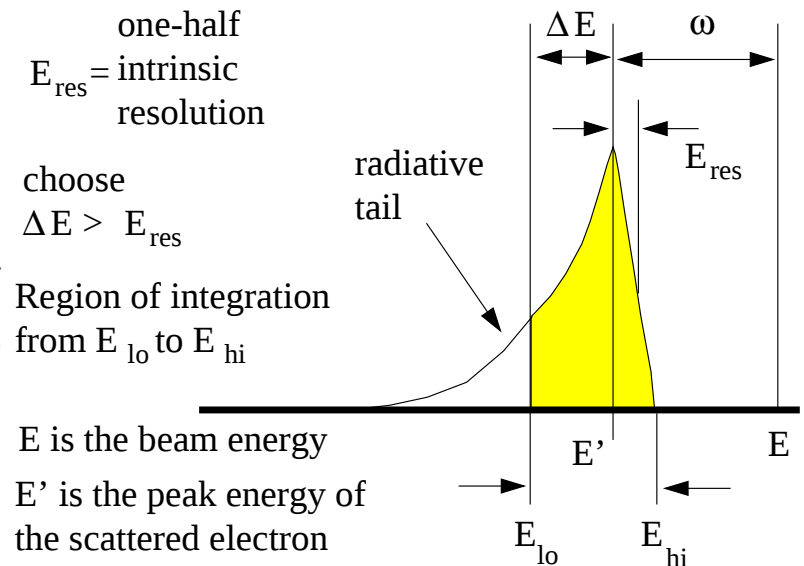
$$v = \Lambda^2 - m_u^2$$

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

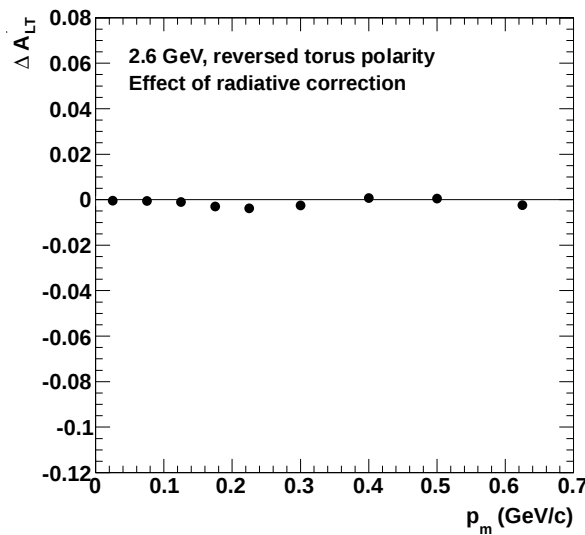
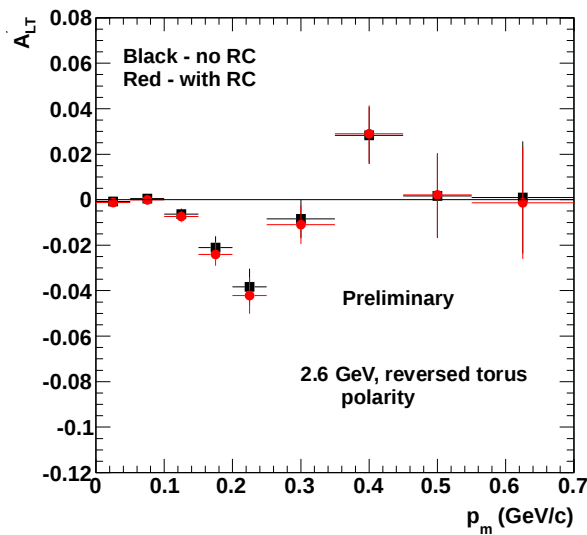
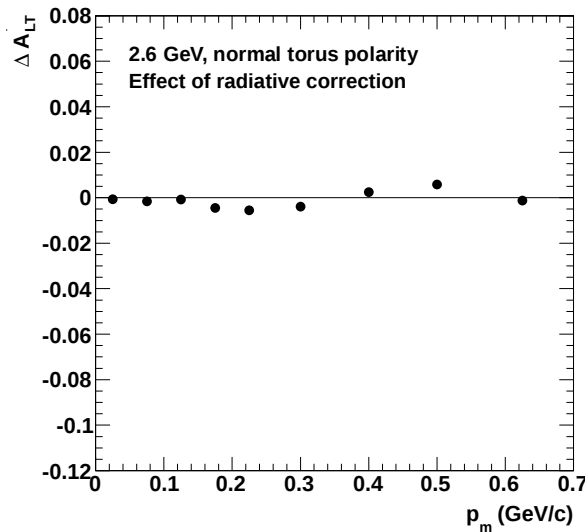
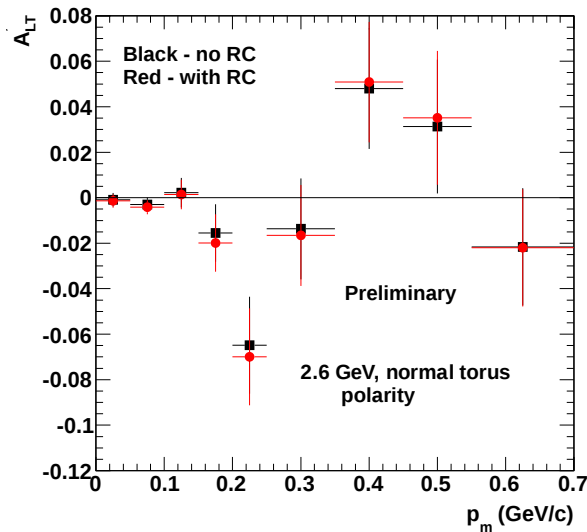
where m_u is the mass of the undetected hadron, Λ is the four-momentum of the missing or undetected particles, and

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

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.

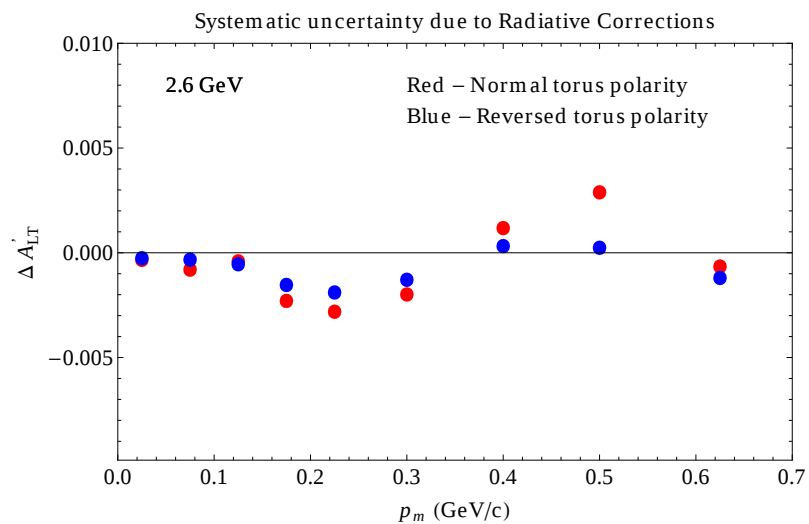
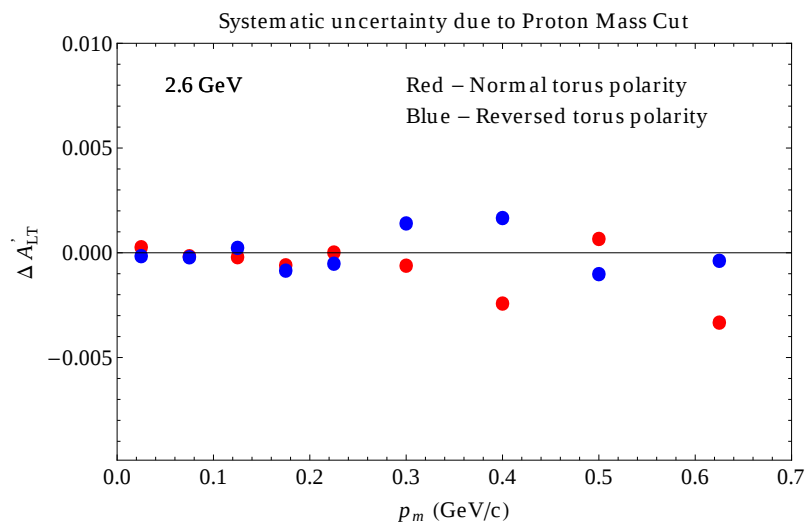
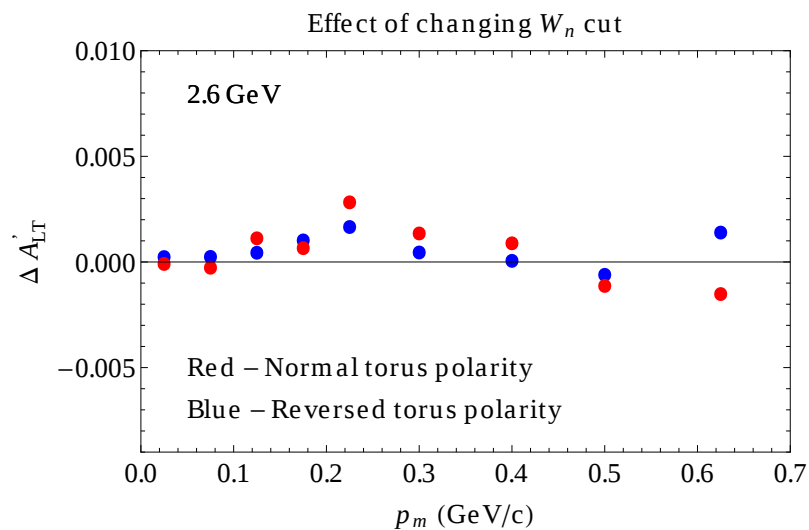
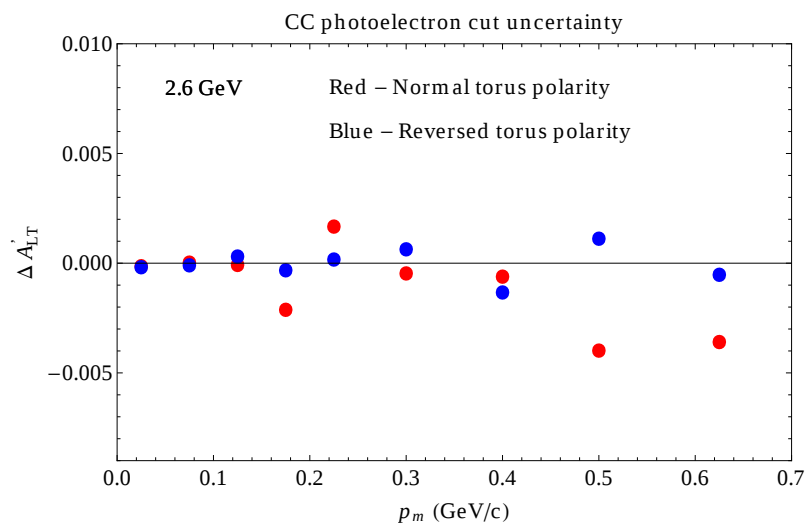


Effect of Radiative Corrections

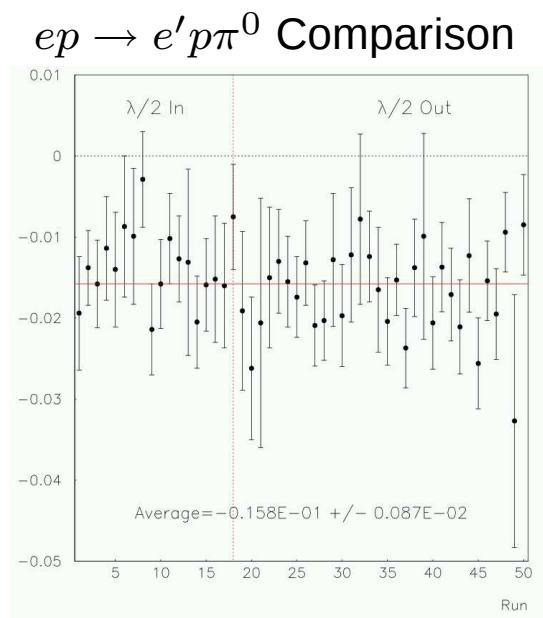


The radiative correction turns out to be much smaller than the statistical uncertainty.

Systematic Uncertainties



Consistency Checks - Beam helicity



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

