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

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Outline

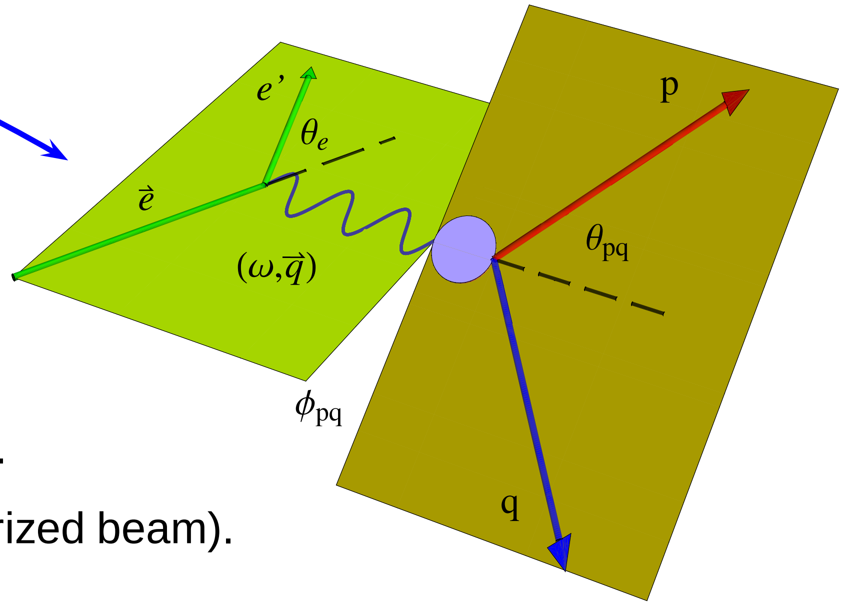
1. Introduction and Background.
2. Extracting the Fifth Structure Function.
3. Event Selection and Corrections.
4. Results and Preliminary Comparison with Theory.
5. Conclusions.

Scientific Motivation

- Establish a baseline for the hadronic model to meet. 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.
  - Short-Range Correlations (SRC).
  - Deuteron as neutron target, N^*N interaction ...

Some Necessary Background

- Goal: Measure the imaginary part of the LT interference term (the fifth structure function) of $D(\vec{e}, e'p)n$ at $Q^2 \approx 1\ (\mathrm{GeV/c})^2$ ($\sigma'_{LT} \propto Im(J^z_{fi}(\vec{q})^* J^y_{fi}(\vec{q}))$).
- Kinematic quantities.
- The cross section is



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

where $\pm$ refers to different beam helicities.

- Use the helicity asymmetry (requires polarized beam).

beam helicity

$$A'_{LT}(90) = \frac{\sigma^+_{90} - \sigma^-_{90}}{\sigma^+_{90} + \sigma^-_{90}} = \frac{\sigma'_{LT}}{\sigma_L + \sigma_T - \sigma_{TT}}$$

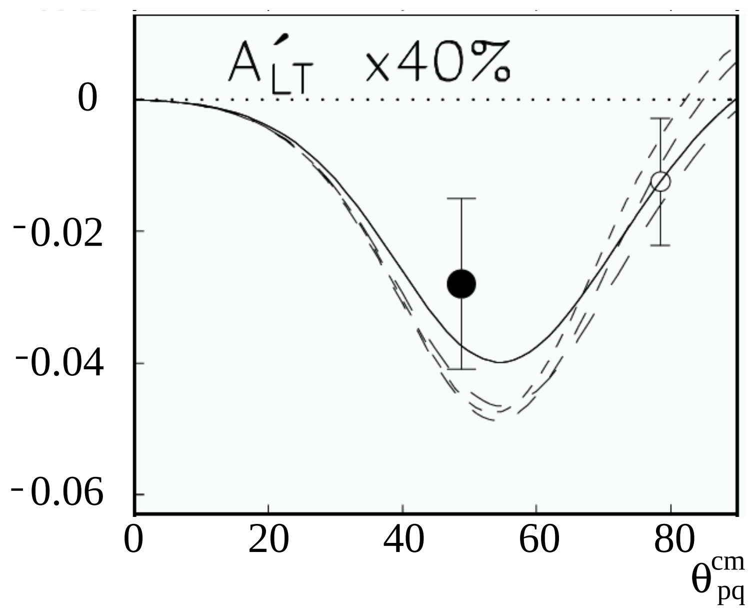
ϕ_{pq}

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

This form of the asymmetry is for particular angles only!

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.
- Existing efforts at JLab to measure deuteron structure functions in quasielastic kinematics.
  - W. Boeglin *et al.* Hall A E01-020 - measure R_{LT} - analysis near completion.
  - B. Norum *et al.* Hall A E08-008 - study MEC - data collection recently completed.



Method for Extracting A'_{LT}

- CLAS has nearly complete coverage in ϕ_{pq}
- Extract ϕ_{pq}-dependent moments of the data in each p_m bin.

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

no σ_{TT} term

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

$$\langle \sin\phi_{pq} \rangle_{\pm} = \pm \frac{A'_{LT}}{2} + \alpha_{acc}$$

- Get rid of that background by subtracting the results for the different helicities.

$$\langle \sin\phi_{pq} \rangle_{+} - \langle \sin\phi_{pq} \rangle_{-} = A'_{LT}$$

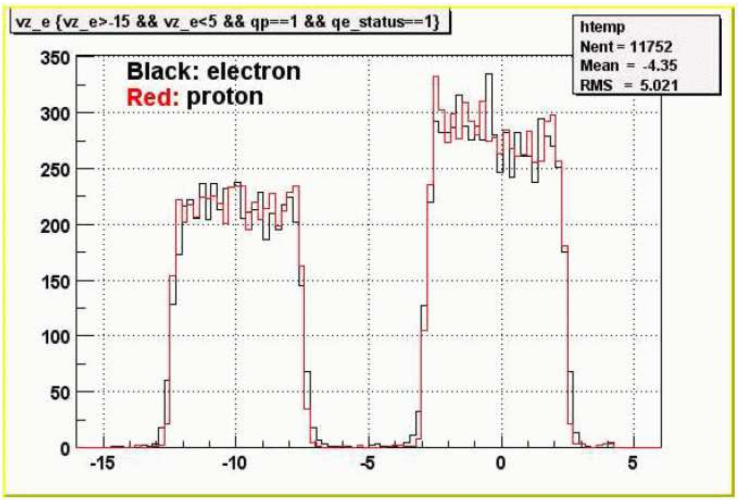
The Data Set

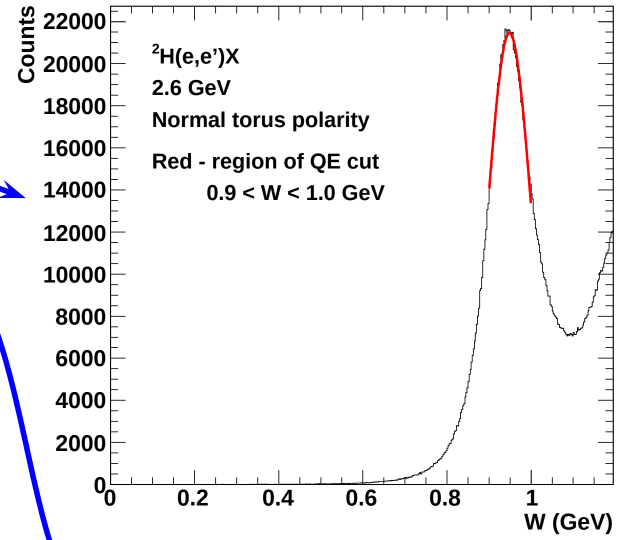
- Analyze data from the E5 run period in Hall B.
- Two beam energies, $4.23\ \mathrm{GeV}$ and $2.56\ \mathrm{GeV}$, with normal torus polarity (electrons inbending).
- One beam energy $2.56\ \mathrm{GeV}$ with reversed torus polarity (electron outbending) to reach lower Q^2.
- Recorded about 2.3 billion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

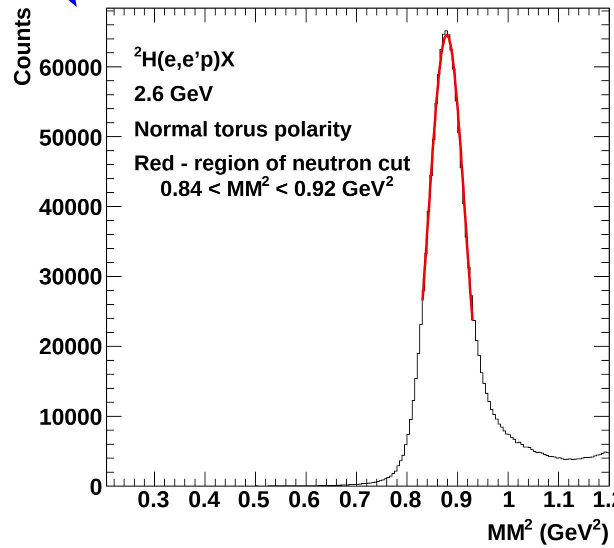
$$0.736 \pm 0.017$$

Event Selection Summary

- Select quasi-elastic , $e-p$ events with a cut on the residual mass W.
- Missing mass cut to select neutrons.
- EC: sampling fraction, fiducials, track coordinates, π threshold.
- Fiducials: electron and proton.
- Number of photoelectrons.
- Target.







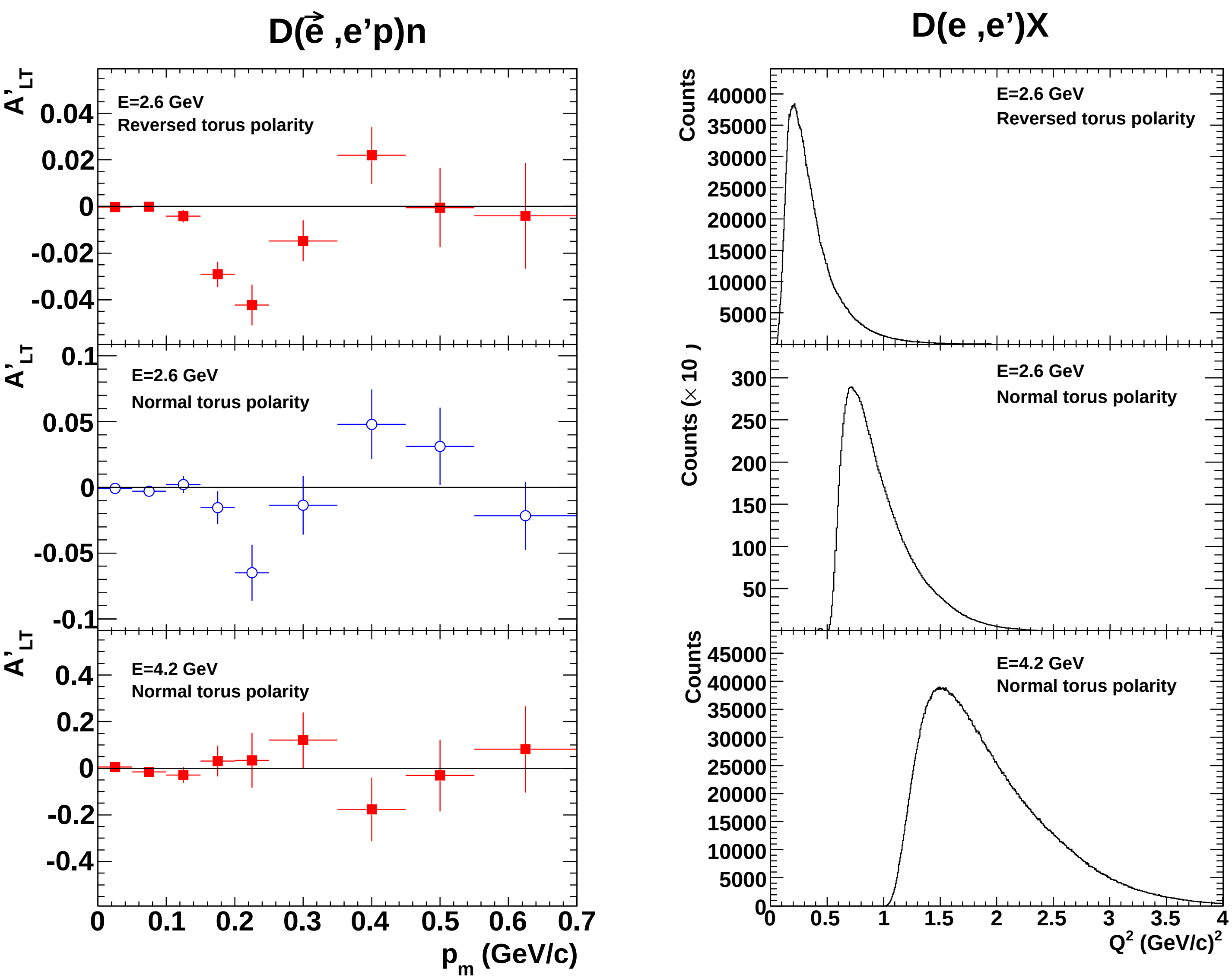
Corrections

- 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 ± 0.027 GeV^2	2.6 GeV, reversed torus polarity
0.879 ± 0.028 GeV^2	2.6 GeV, normal torus polarity
0.873 ± 0.032 GeV^2	4.2 GeV, normal torus polarity

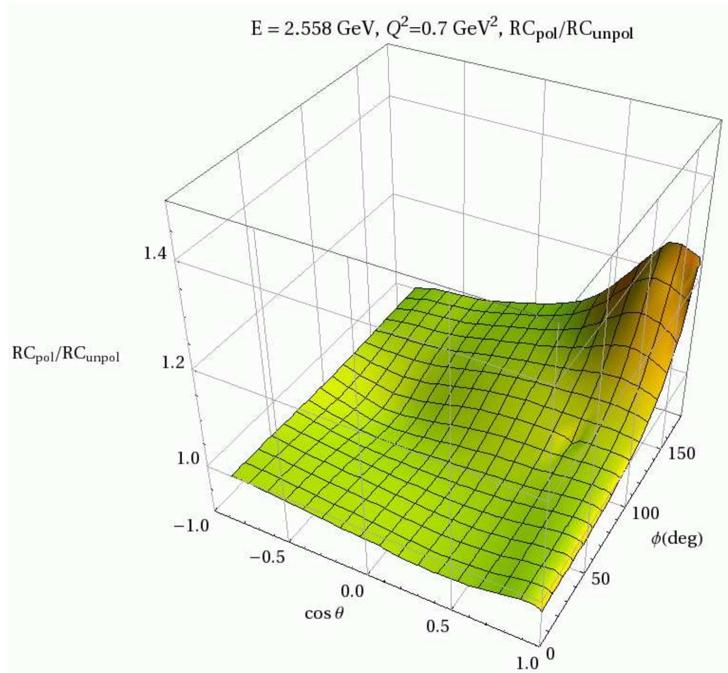
- Radiative corrections.
  - Expected them to be small (they were in the G_M^n analysis from the same data set).
  - They weren't small enough.
  - First, need to see the measured, preliminary A'_{LT}.

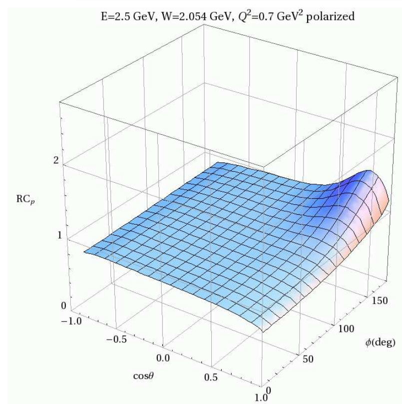
Preliminary A'_{LT} Results for $D(\vec{e}, e'p)n$

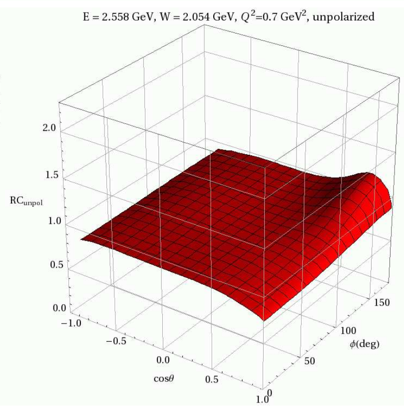


Radiative Corrections (RC)

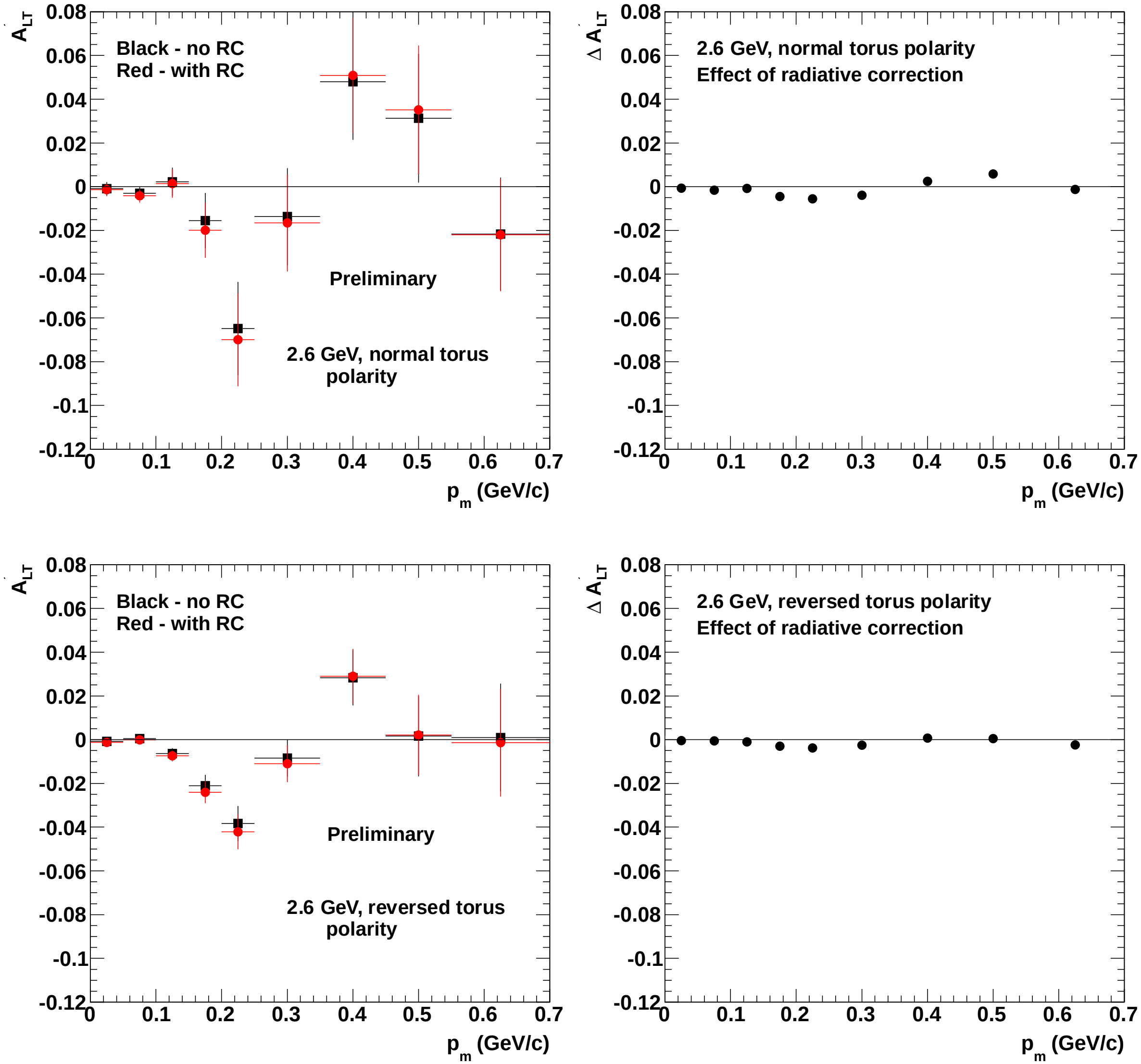
- EXCLURAD - Applies a more sophisticated method than the usual approach of Mo and Tsai or Schwinger to account for exclusive measurements. See CLAS-Note 2005-022 and Afanasev *et al.*, PRD 66, 074004 (2002).
- They aren't small enough to ignore.
- Method
  - Calculate polarized and unpolarized RC surfaces 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, 0.7, 1.0, 1.5, 2.5.







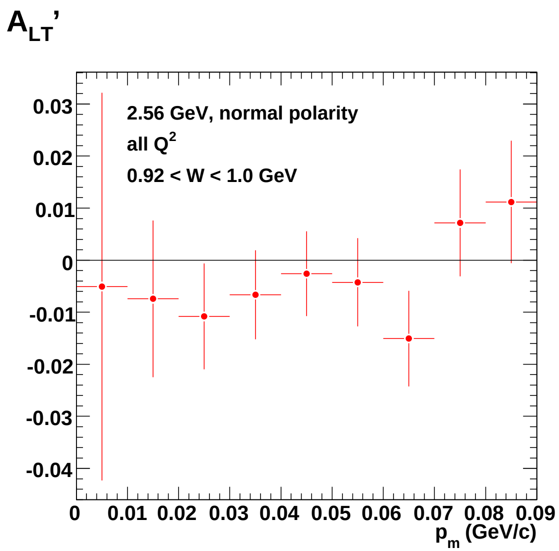
Effect of Radiative Corrections

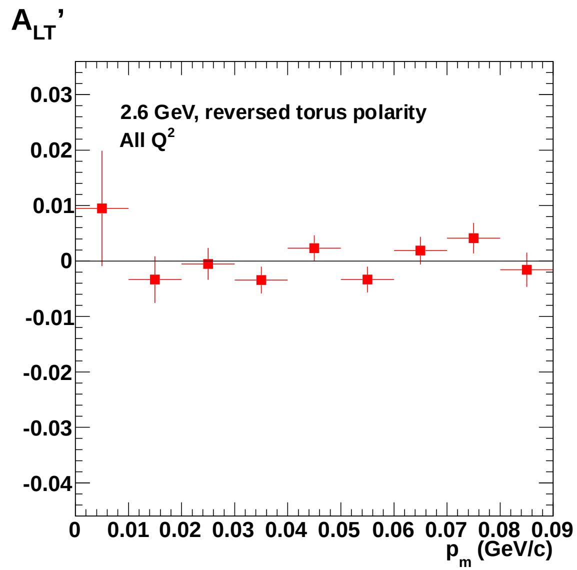


The radiative correction turns out to be much smaller than the statistical uncertainty.

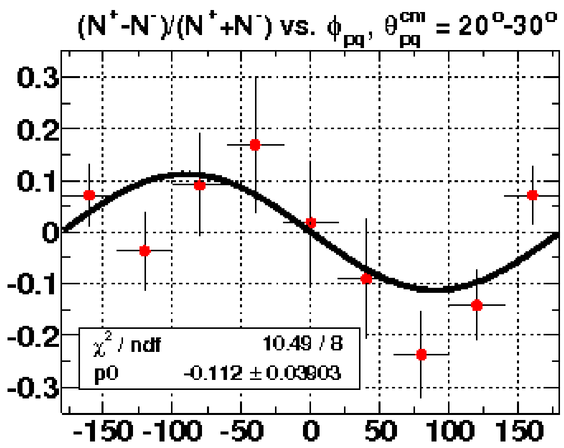
Consistency Checks

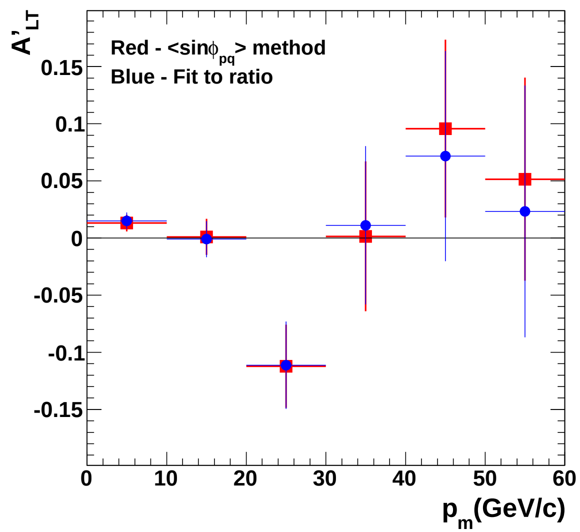
- At $p_m \approx 0$ GeV/c the asymmetry should go to zero.





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

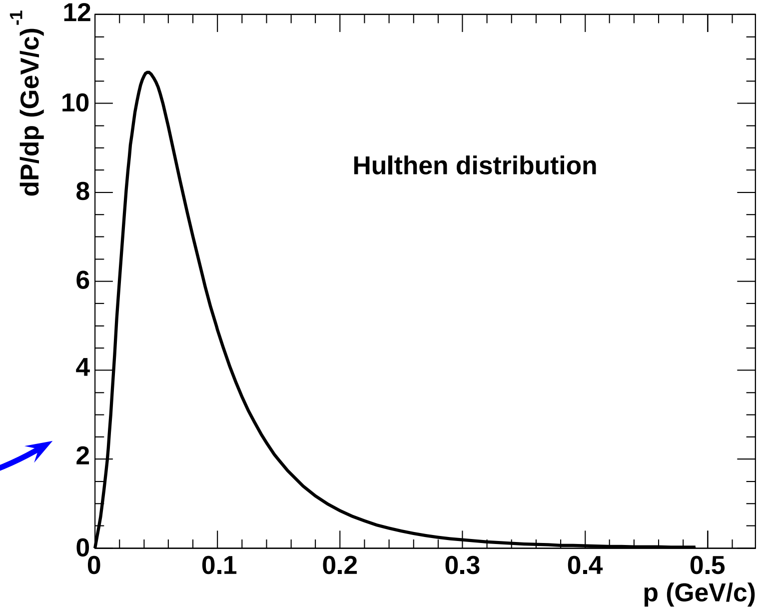




Consistency Check - GSIM Simulations

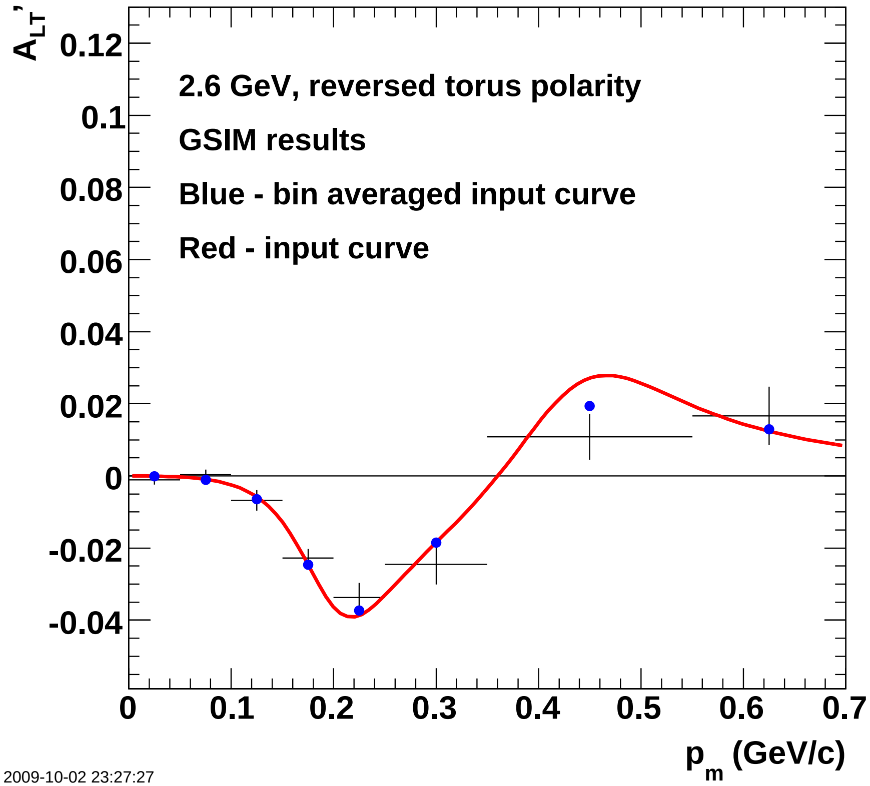
- Use GSIM to validate analysis algorithms.
- Parameterize measured helicity asymmetries.

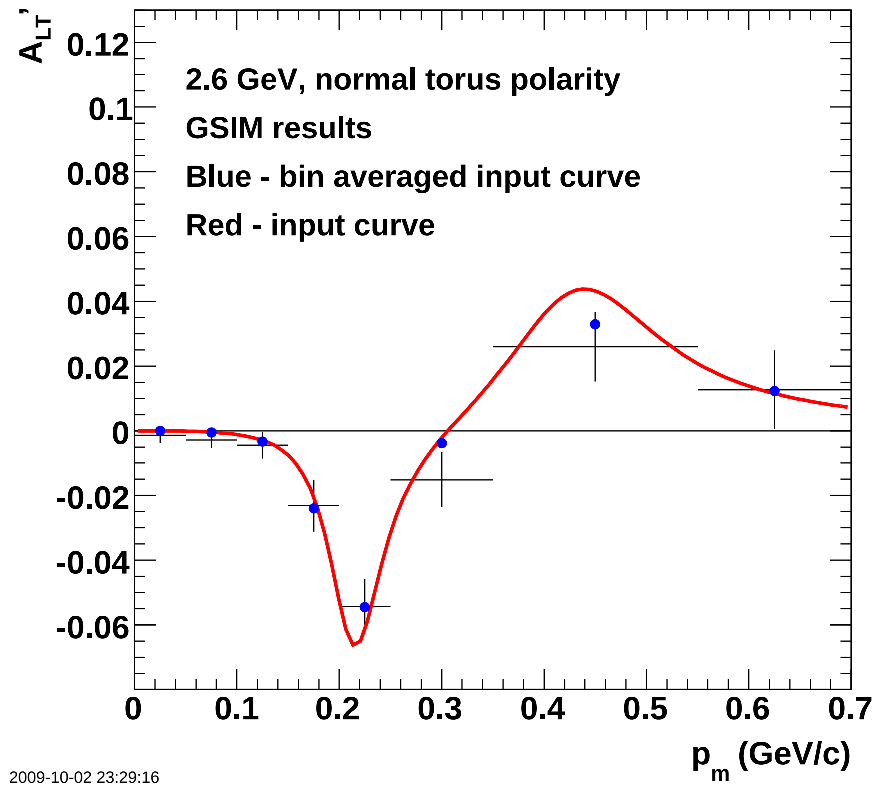
$$A'_{LT} = \frac{a_1 x^2 + a_2 x^4}{1 + a_3 x + a_4 x^2 + a_5 x^4 + a_6 x^6}$$



- 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.

Consistency Check - GSIM Simulations



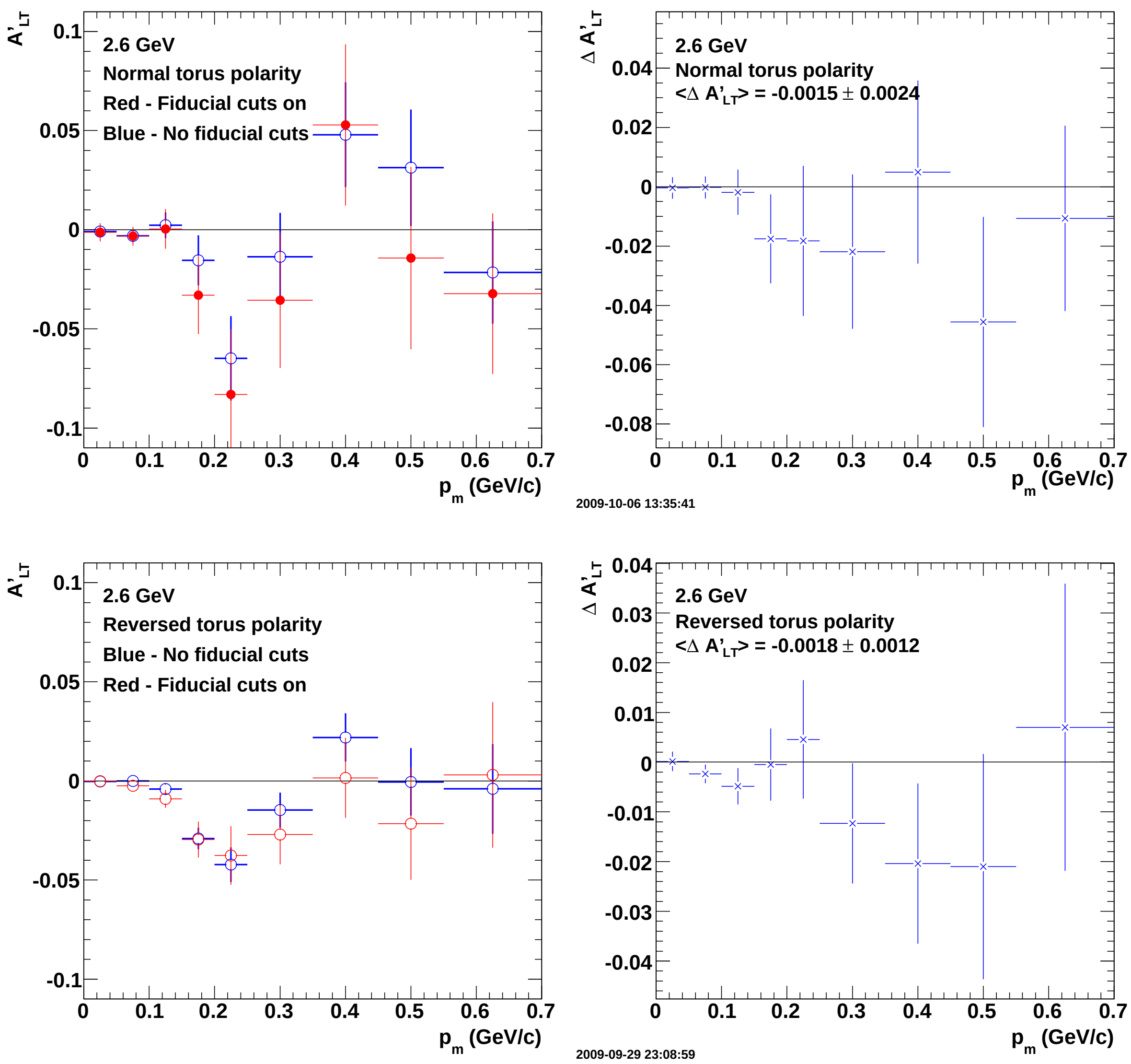


Within Monte Carlo uncertainties, simulation results are consistent with simulated asymmetry.

Consistency Check - Fiducial Cuts

- Our electron and proton fiducial cuts are designed to remove regions where the acceptance is not well known from the data set.
- This reduces our statistics considerably.
- To extract the helicity asymmetry we take the ratio of the $\sin\phi_{pq}$ weighted events to the same events (same Q^2, p_m, and ϕ_{pq}) weighted by unity.
- These two sets of events have the same acceptance (they are only weighted differently) so in the ratio the acceptances should cancel.
- Try turning them off.

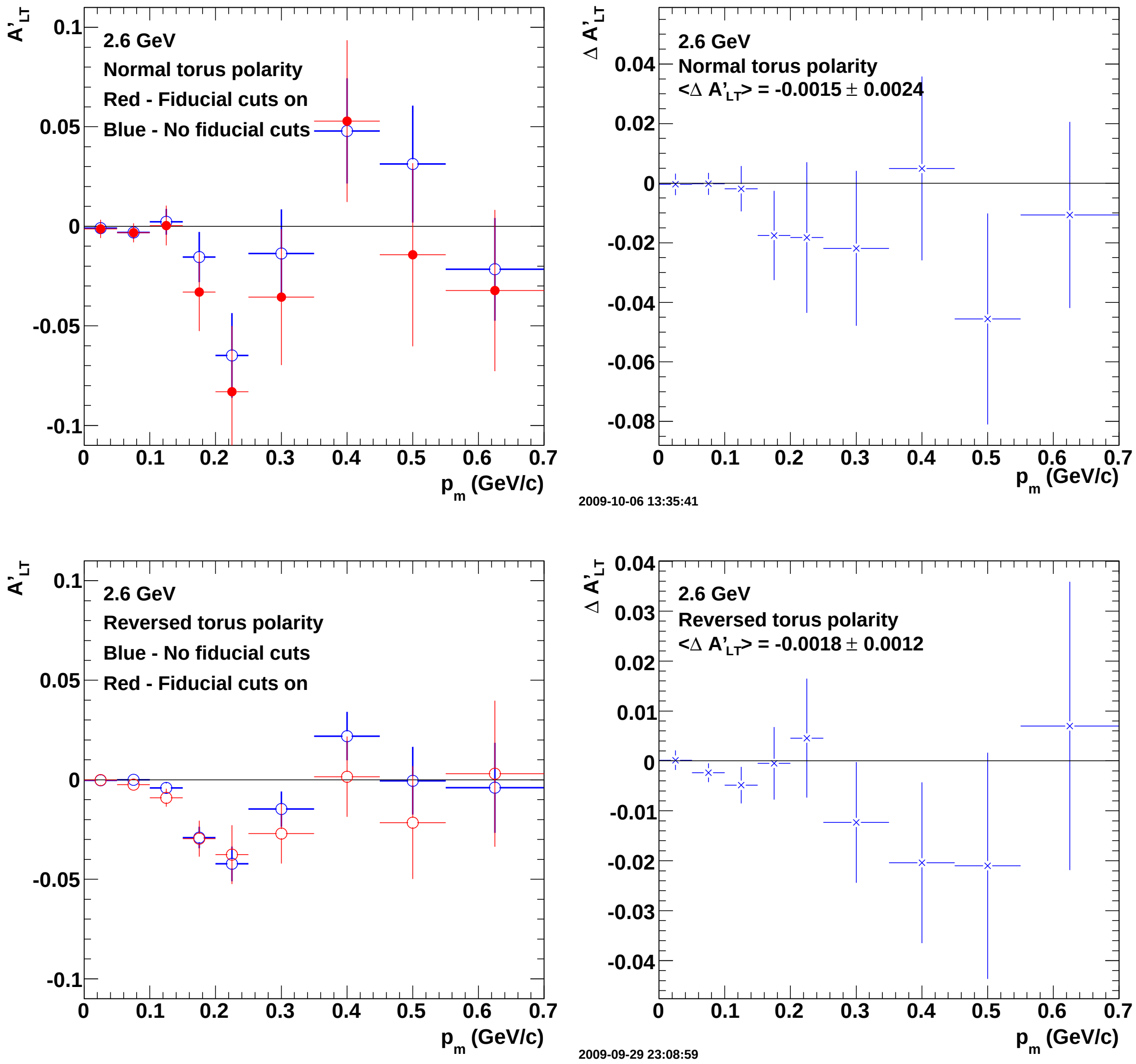
Consistency Check - Removing Fiducial Cuts



We take the ratio of events in a particular $d\Omega$ for different beam helicities; acceptance corrections should be identical.

Compare A'_{LT} with the electron and proton fiducial cuts on and off.

Consistency Check - Removing Fiducial Cuts



We take the ratio of events in a particular $d\Omega$ for different beam helicities; acceptance corrections should be identical.

Compare A'_{LT} with the electron and proton fiducial cuts on and off.

Within the statistical uncertainty the two sets are the same.

Inventory of Systematic Uncertainties

Main contributions to the systematic uncertainty and their maximum values for either data set.

Total systematic uncertainty calculated with

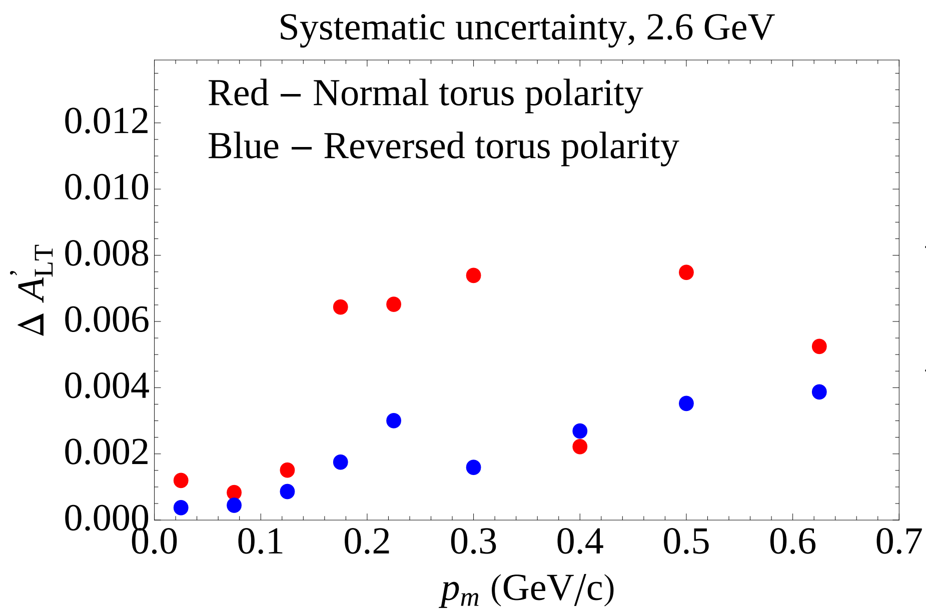
$$(\Delta A'_{LT})^2 = \sum_i \left(\delta A'_{LT_i}\right)^2$$

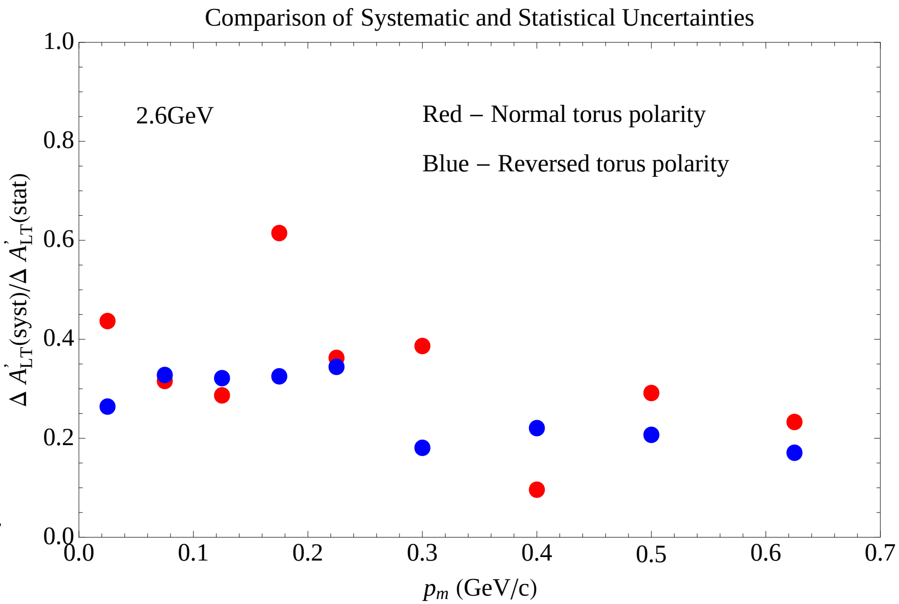
where i is the sum over the set of parameters $\vec{f}$ used to determine A'_{LT} and

$$\delta A'_{LT_i} = \frac{A'_{LT}(1.1 \times f_i) - A'_{LT}(0.9 \times f_i)}{2}$$

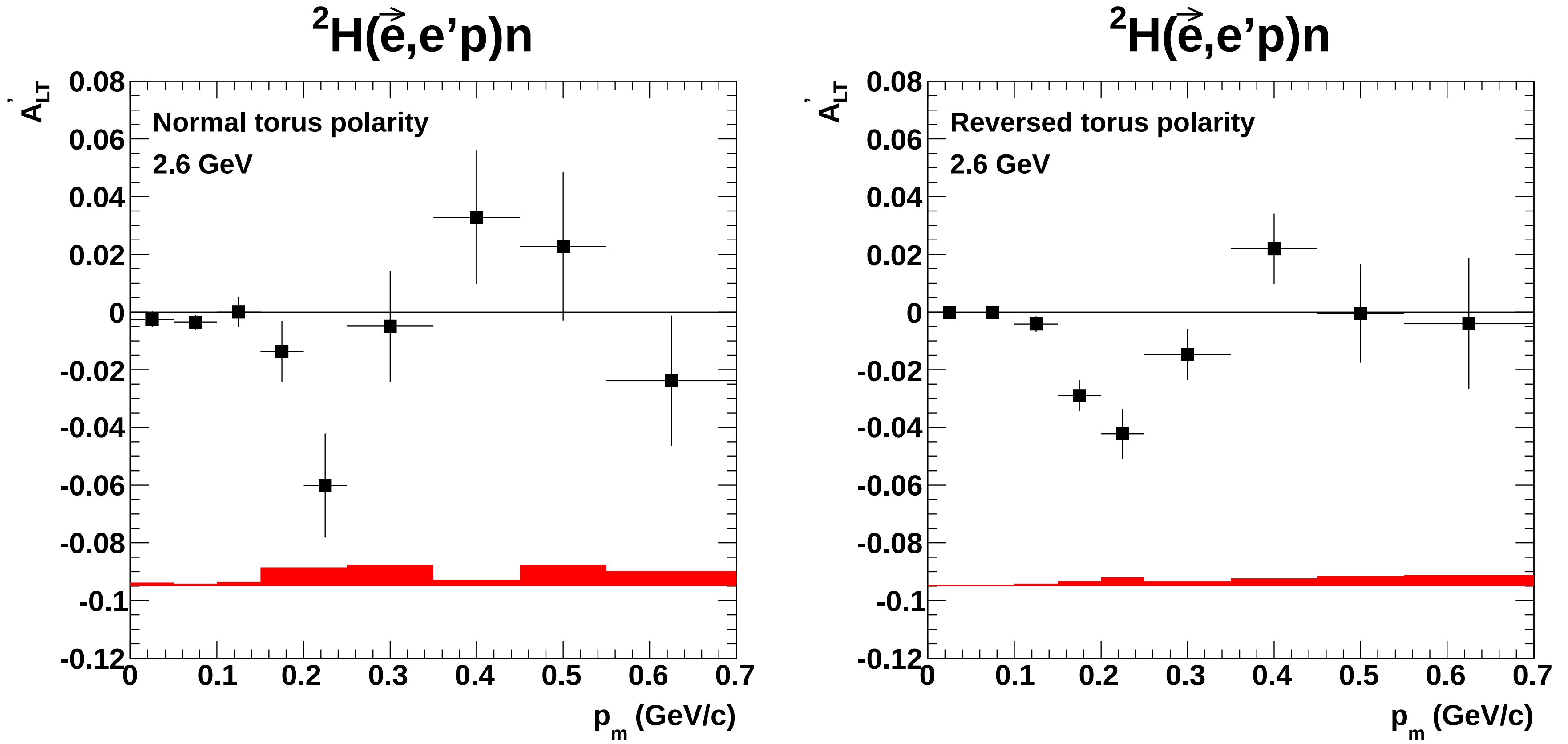
Row	Quantity	$\delta A'_{LT}$
1	MM^2 cut	< 0.004
2	W cut	< 0.005
3	EC track coordinate cut	< 0.007
4	EC sampling fraction	< 0.002
5	EC pion threshold	< 0.002
6	Number of Photoelectrons	< 0.005
7	Beam Polarization	< 0.001
8	Beam charge asymmetry	< 0.002
9	RC correction	< 0.004

Inventory of Systematic Uncertainties - Results



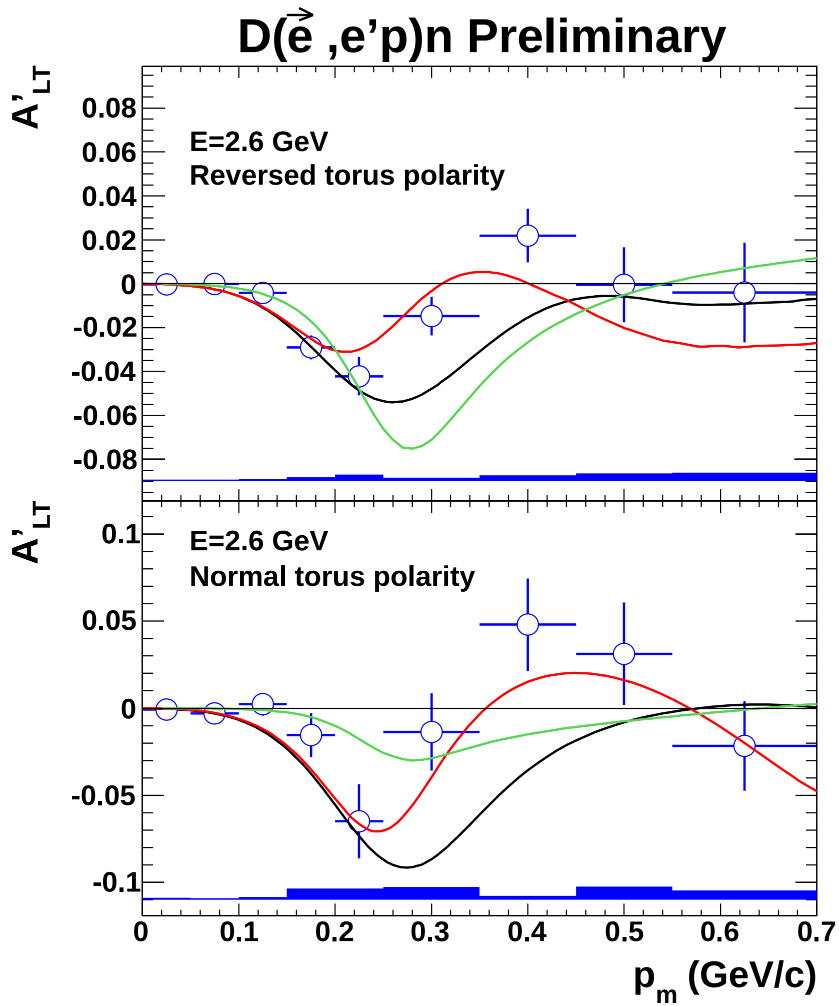


Preliminary Results with Uncertainties



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.

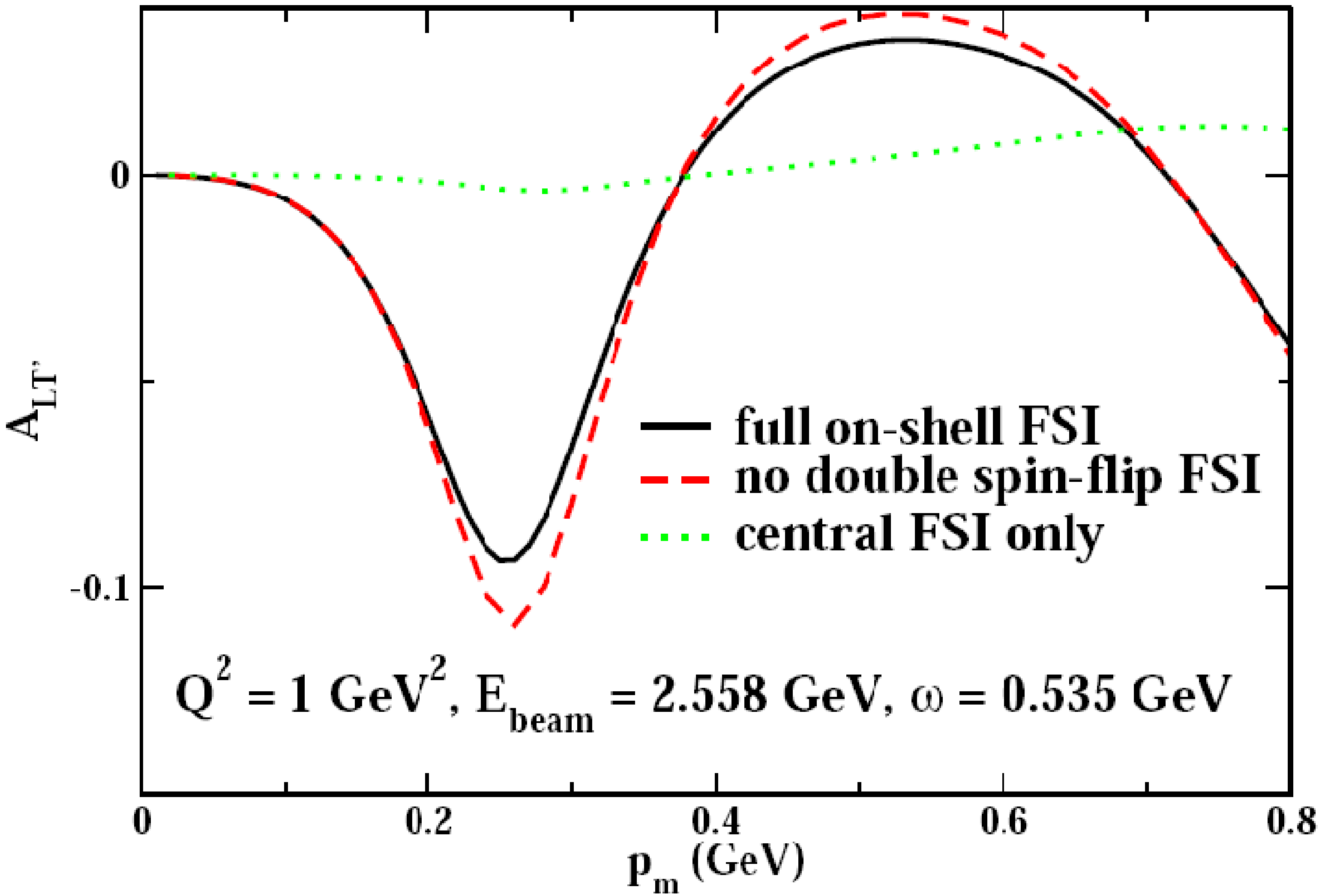


Conclusions

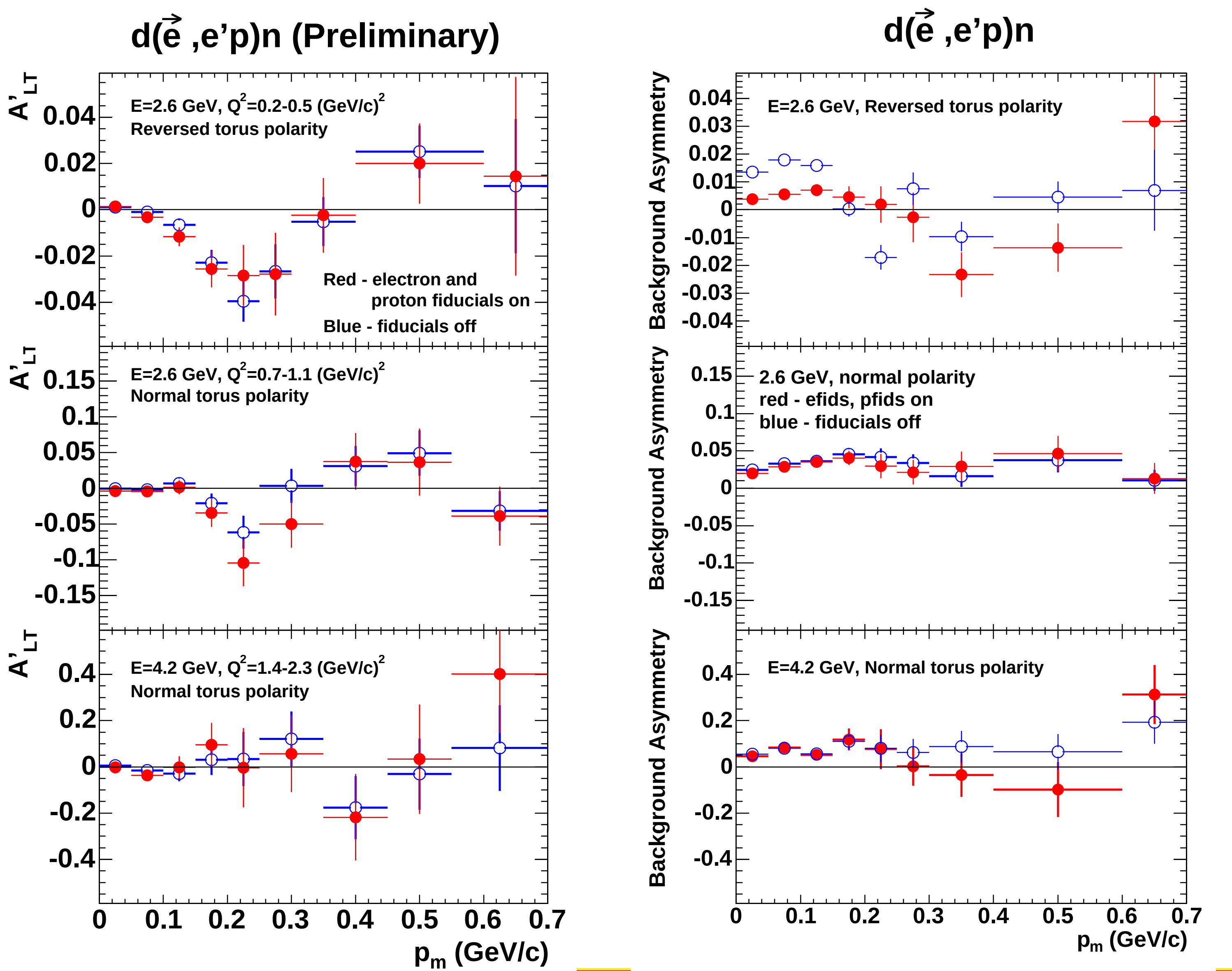
- We observe a 4% dip in A'_{LT} at $p_m \approx 220\ MeV/c$ in the low Q^2 data set and a 6% dip in A'_{LT} at the same p_m in the middle Q^2 range. The high-Q^2 data has poor statistics for A'_{LT}.
- The $\langle \sin \phi_{pq} \rangle$ technique works well including the subtraction of the two different beam helicities to eliminate sinusoidal components of the acceptance.
- At higher Q^2 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. Possible a sign of the increasing importance of meson-exchange currents not included in JVO.
- At low p_m, the calculations by Arenhövel reproduce the data, but diverge (they're too negative) above $p_m = 250\ MeV/c$.
- At low p_m, the Laget calculations reproduce the low-Q^2 data, but are too small in magnitude in the middle Q^2 range.

Additional Slides

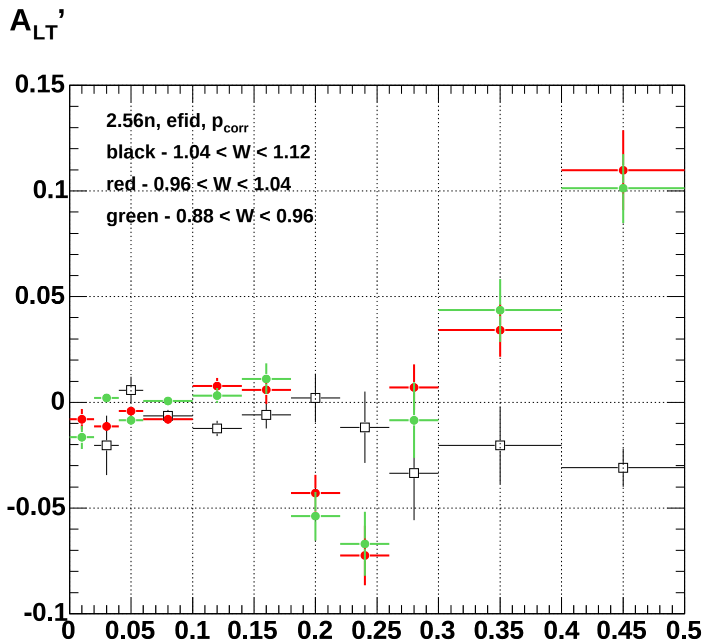
Effect of spin-orbit FSI forces calculated by JVO

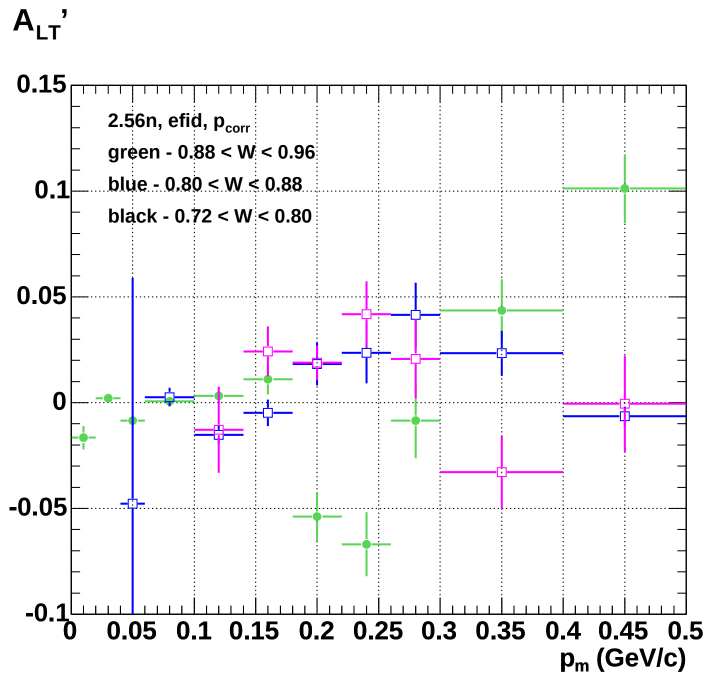


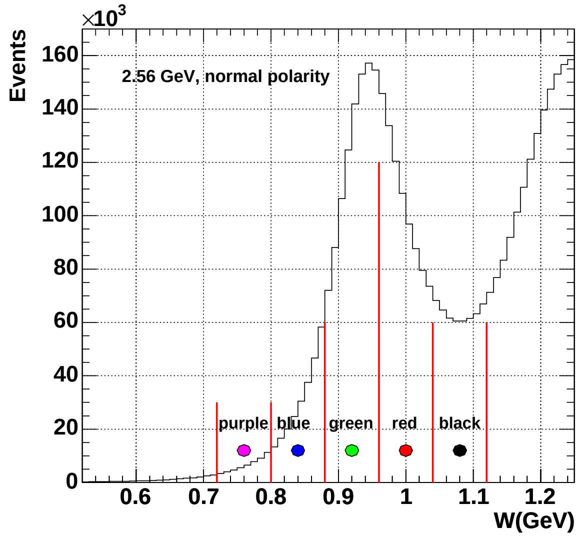
Asymmetry Background Results



W dependence of A'_{LT} at the Quasi-elastic Peak







Event Selection and Corrections

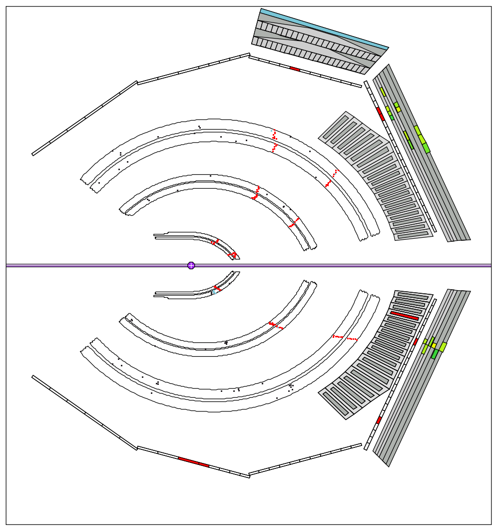
Electrons:	Good CC, EC, SC status	$cc > 0$, $ec > 0$, $sc > 0$, $stat > 0$
	Energy-momentum match	$0.325p_e - 0.13 < E_{total} < 0.325p_e + 0.06$
	Reject pions	$ec\_ei \geq 0.100$ and $nphe \geq 25$
	EC track coordinates fiducial	$\|dc\_ysc\| \leq 165(dc\_xsc - 80)/280$
	EC fiducial	No tracks within $10\ cm$ of the end of a strip
	Egiyan threshold cut	$p_e \geq (214 + 2.47 \cdot ec\_threshold) \cdot 0.001$
	Electron fiducial	CLAS-Note 2000-007.
	Quasi-elastic scattering	$0.92\ \mathrm{GeV} \leq \mathrm{W} \leq 1.0\ \mathrm{GeV}$
	Select target	$-11.5\ cm < v_z < -8.0\ cm$
	Momentum corrections	CLAS-Note 2001-018, Analysis Note 2008-103
Protons:	Proton fiducial cut	CLAS-NOTE 2001-013.
	ep vertex cut	$\|v_z(e) - v_z(proton)\| \leq 1.5\ cm$
	Momentum corrections	See CLAS-Note 2001-018

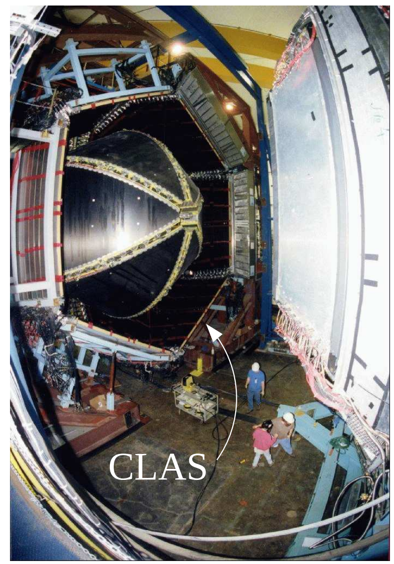
Event Selection and Corrections

Neutrons:	Missing mass cut	$0.84\ \mathrm{GeV}^2 \leq \mathrm{MM}^2 \leq 0.92\ \mathrm{GeV}^2$
Beam charge asymmetry:	2.6 GeV, reversed field:	0.9936 ± 0.0007
	2.6 GeV, normal field:	0.9944 ± 0.0007
	4.2 GeV, normal field	0.9987 ± 0.0009
Radiative corrections:	EXCLURAD	Adding helicity dependent model
Beam polarization:	All Runs	0.736 ± 0.017

Data Collection with CLAS

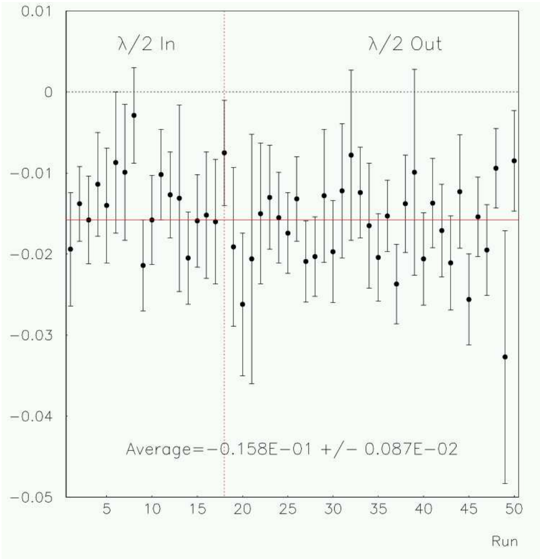
- CEBAF is the 7/8-mile-long, racetrack-shaped electron accelerator at JLab that produces continuous electron beams up to 6 GeV.
- CLAS is a 45-ton, six-sector detector covering most of 4π, with drift chambers to measure trajectories, scintillators for TOF, Cerenkov counters to identify electrons, and calorimeters to measure energy. A toroidal magnetic field determines momentum.



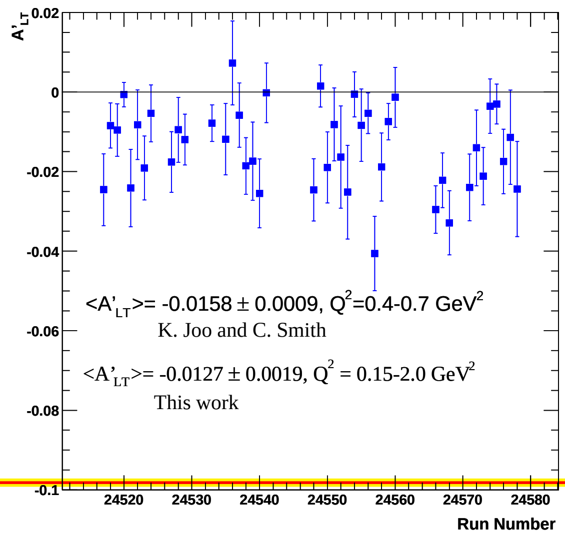


Consistency Checks - Beam helicity

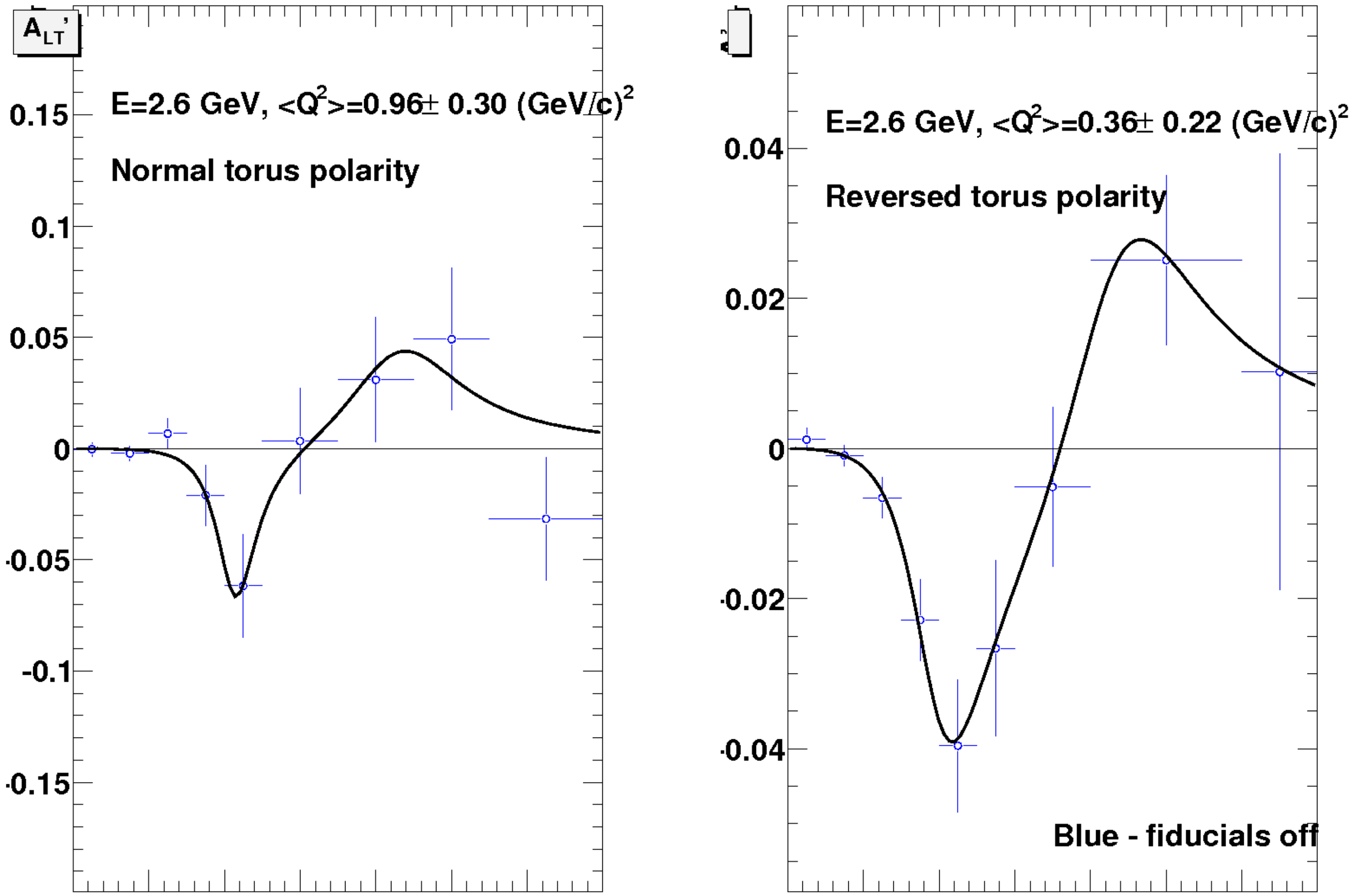
$ep \rightarrow e'p\pi^0$ Comparison



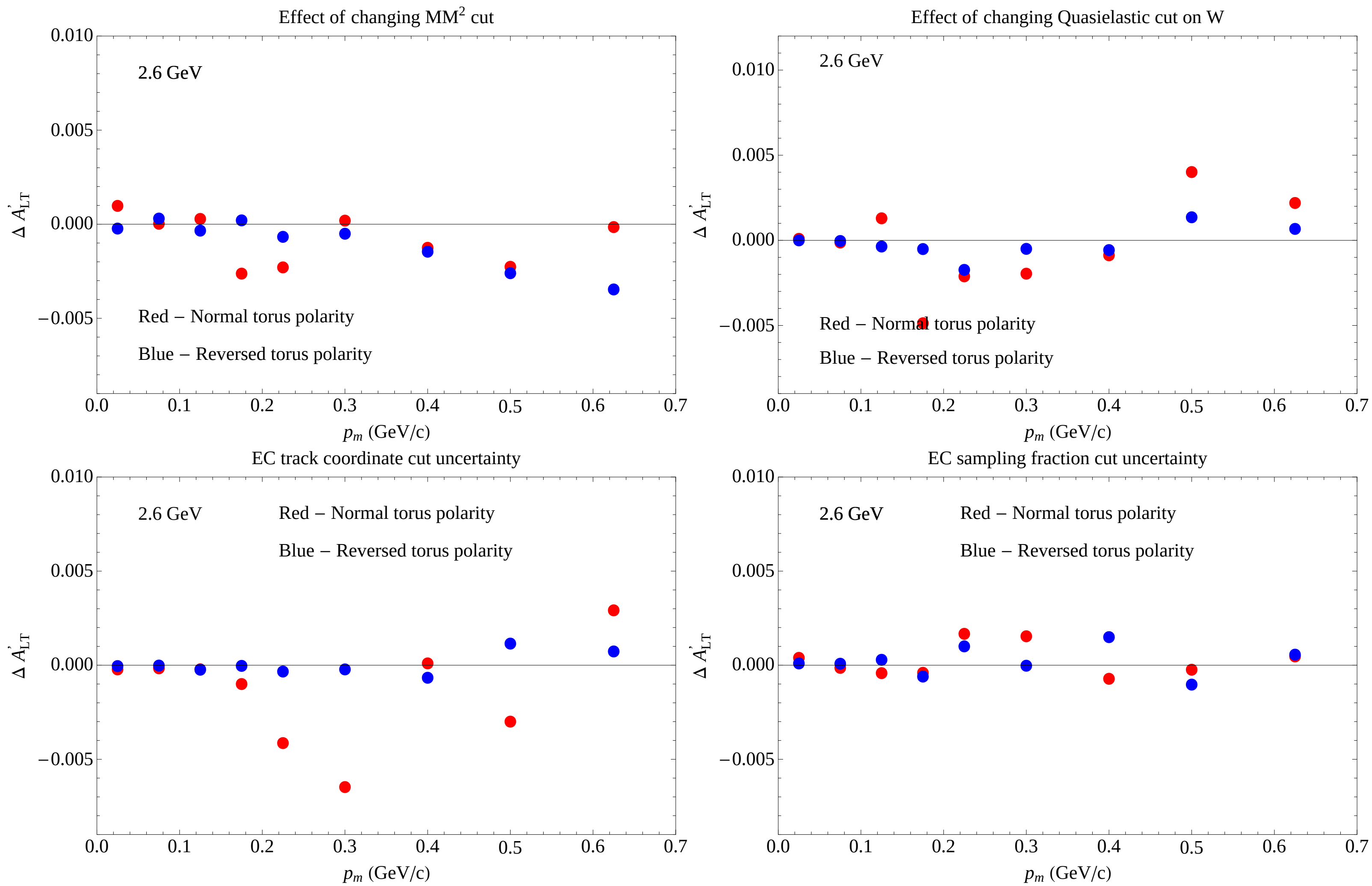
K.Joo and C.Smith, CAN 2001-008.



Parameterizing A'_{LT}



Systematic Uncertainties



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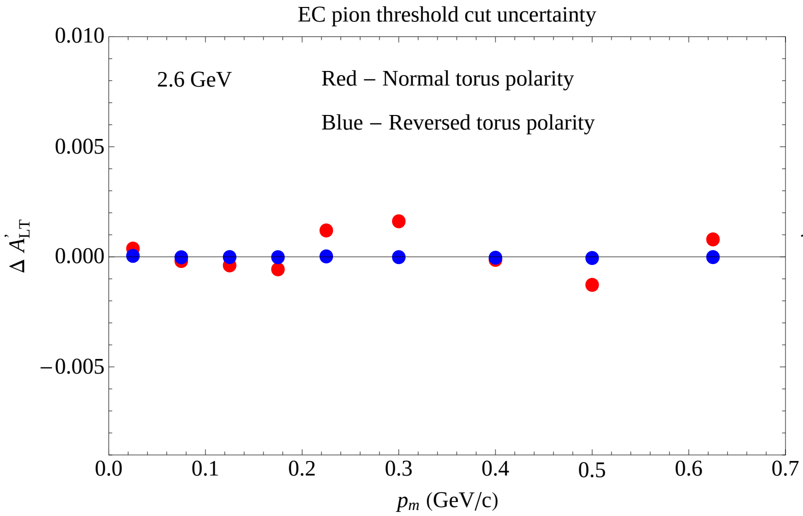

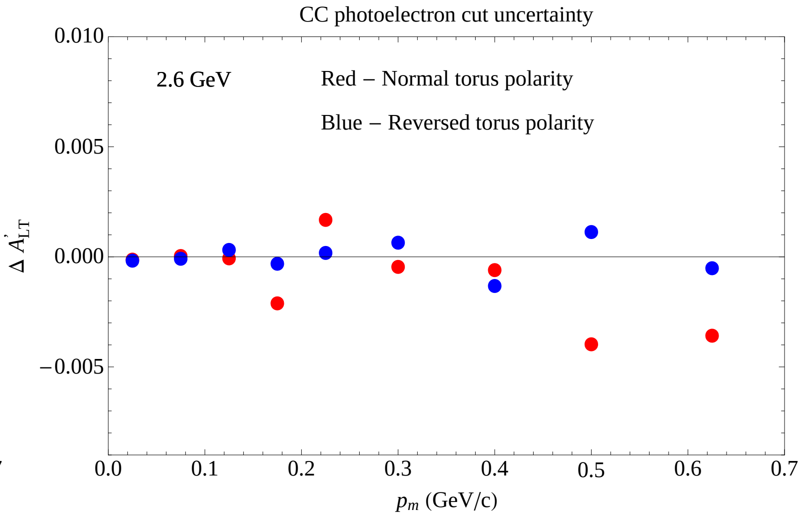

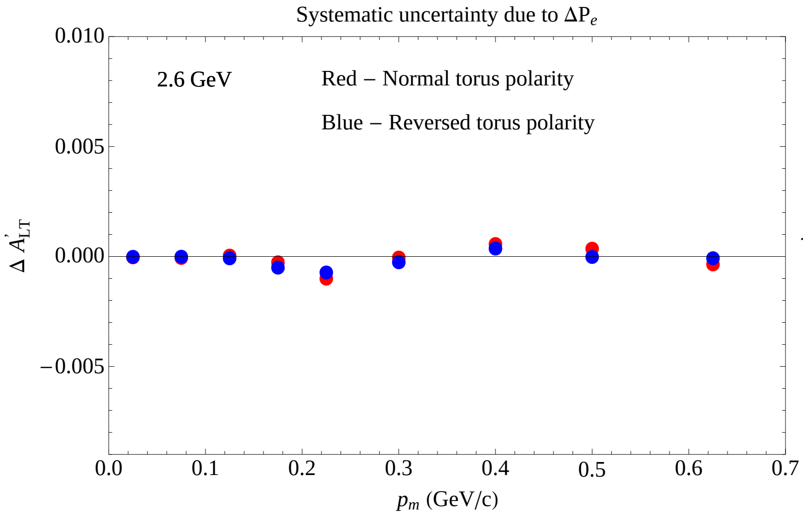

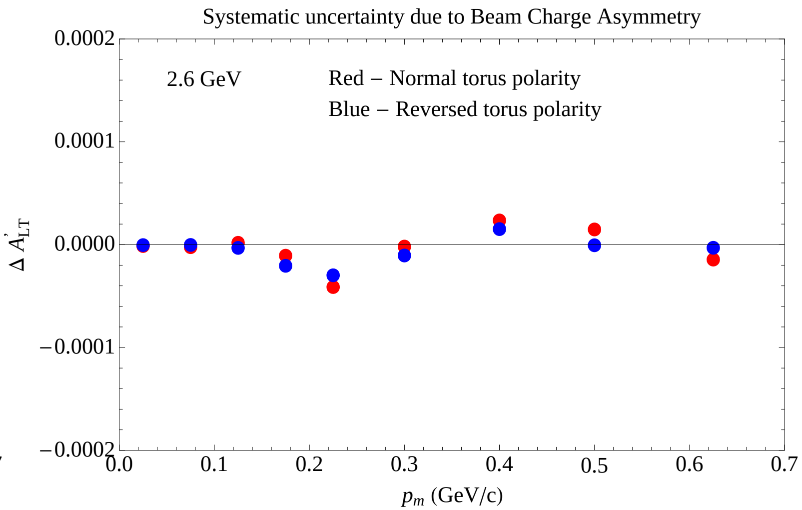

Systematic Uncertainties