Out-of-plane Measurements of the Structure Functions of the Deuteron

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- Physics Motivation
- Formalism
- Current Status
- Extracting Response Functions with CLAS
- Work Plan
- Conclusions

Physics Motivation

1. Can the deuteron be understood with the ‘standard model’ of nuclear physics?

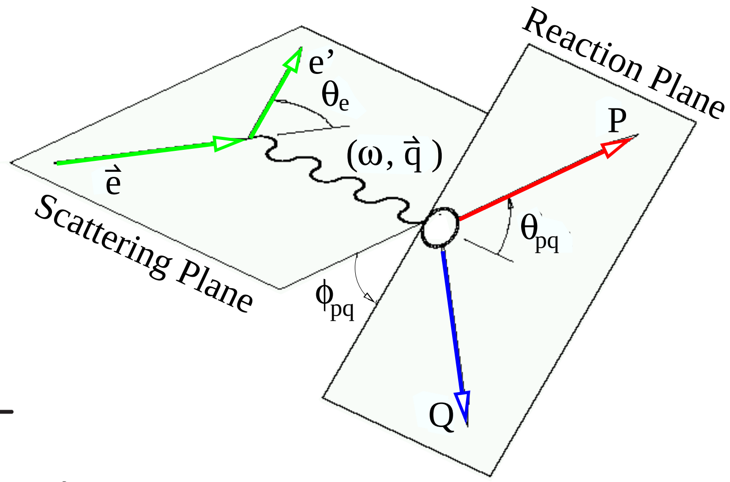
   - The deuteron is one of the essential testing grounds for our understanding of the nucleon-nucleon (NN) interaction.
   - Can we properly incorporate relativistic effects into our description of the deuteron and heavier nuclei?
   - Can we properly account for final-state interactions (FSI)?
   - What other effects are needed in the nuclear ‘standard model’ (meson-exchange currents, isobar configurations, *etc.*)?

2. Are quark-gluon degrees of freedom required to describe selected properties of the deuteron?

   - How do we distinguish between quark-gluons effects and the poorly-understood effects of ‘conventional nuclear physics’ in the 1 GeV energy region?
   - Can we observe the onset of color transparency and at what energy does this occur?

Kinematics and Formalism

- Kinematics:



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

- Cross section:

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

- Out-of-plane measurements of deuteron electrodisintegration are a unique tool to dissect the structure functions. CLAS is well suited for these measurements.

- Conventional asymmetries are proportional to the corresponding structure function:

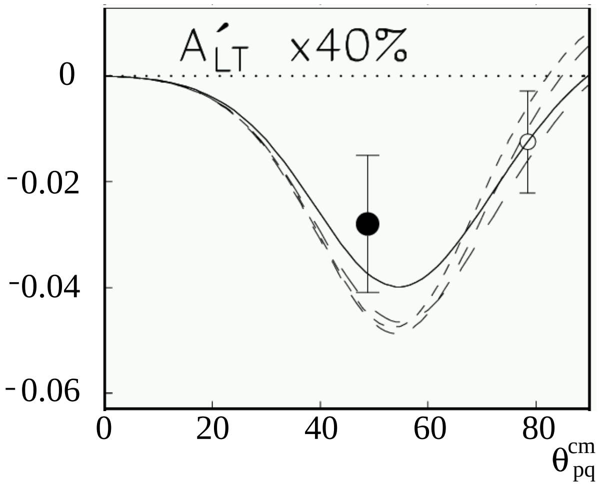
$$A_{LT} = \frac{\sigma_0 - \sigma_{180}}{\sigma_0 + \sigma_{180}} \qquad A'_{LT} = \frac{\sigma_{90}^{+} - \sigma_{90}^{-}}{\sigma_{90}^{+} + \sigma_{90}^{-}}$$

$$A_{TT} = \frac{\sigma_0 + \sigma_{180} - 2\sigma_{90}}{\sigma_0 + \sigma_{180} + 2\sigma_{90}}$$

Subscripts - ϕ_{pq}. Superscripts - beam helicity.
$A_{\lambda\lambda'} \propto f_{\lambda\lambda'}$.

Experimental Status

- Some measurements have already been made for $Q^2 \approx 0.1 - 0.3\ (GeV/c)^2$, but some suffer from limited statistics or angular range. The adjacent plot is from S.Gilad, *et al.*, NP **A631**, 276c, 1998. Despite the technical challenges these experiments posed the results show hints of interesting physics to be uncovered.



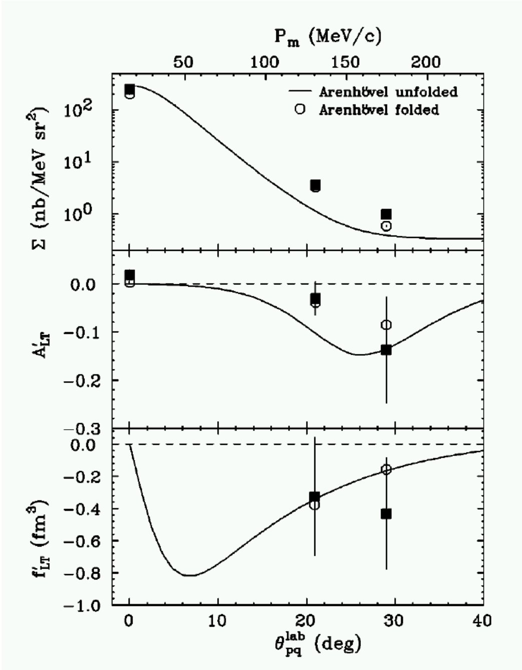
- Hall A experiment E01-020 completed data collection last fall. It is focused on determining cross sections and σ_{LT} at $Q^2 = 0.8, 2.35, 3.15\ (GeV/c)^2$.

- Hall A experiment (E02-101) will examine electrodisintegration near threshold at Q^2 =0.47 $(GeV/c)^2$ to extract all five structure functions.

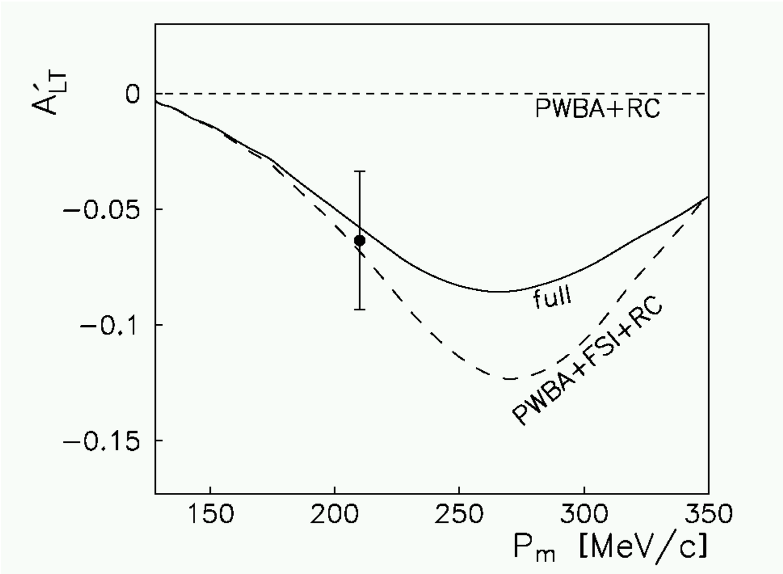
- This project will analyze data from the E5 run period.
  - Recorded about 2.3 billion triggers.
  - $Q^2 = 0.2 - 5.0 (GeV/c)^2$.
  - Dual target cell with liquid hydrogen and deuterium.
  - Two beam energies: 4.23 GeV, 2.56 GeV (inbending and outbending electrons).

Theoretical Status 1

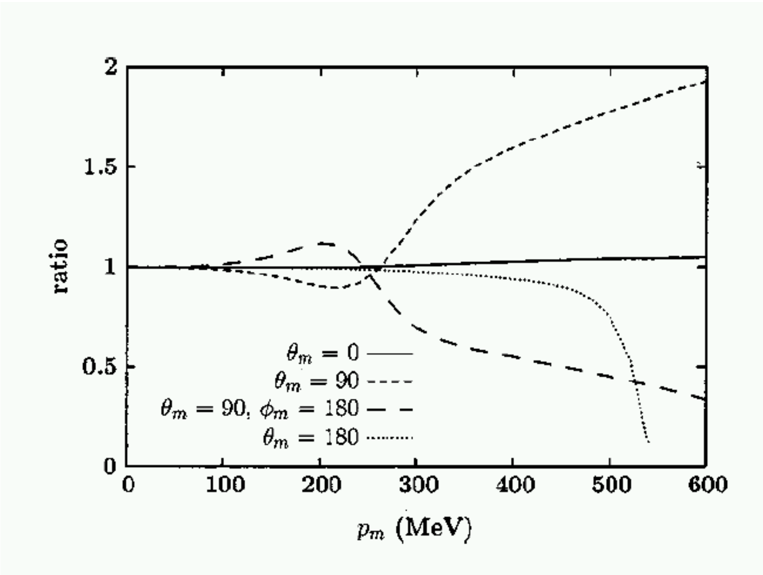
There has been some success at lower $Q^2 \approx 0.13(GeV/c)2$ at describing A'_{LT} for quasielastic kinematics. The adjacent figure shows the results from S.M.Dolfini, *et al.* (PRC **60**, 064622).



Away from the quasielastic region the theory still agree with the data, but the uncertainties on the measurements are large. Figure is from Z.-L.Zhou, *et al.*, PRL **87**,172301.



Analysis of different components of the theory reveal that we can expect significant effects that will enable us to discriminate among competing models. Figure is from S.Jeschonnek, PRC **63**, 034609 and shows the effect of using the factorization approximation in calculating the cross section.

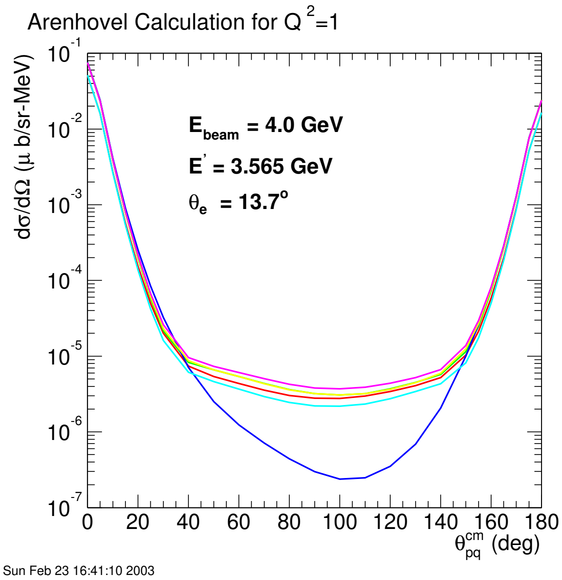


Theoretical Status 2

'Conventional Nuclear Physics' Models (Hartmuth Arenhövel)

- Plane Wave Born Approximation (PWBA) with final-state interactions (FSI), relativistic corrections (RC), meson exchange currents (MEC), and isobar configurations (IC) added.

- Full calculations have been done at 19 values of Q^2 in the range $0.2 - 1.2(GeV/c)^2$, mostly for quasielastic kinematics, but some calculations at higher W.



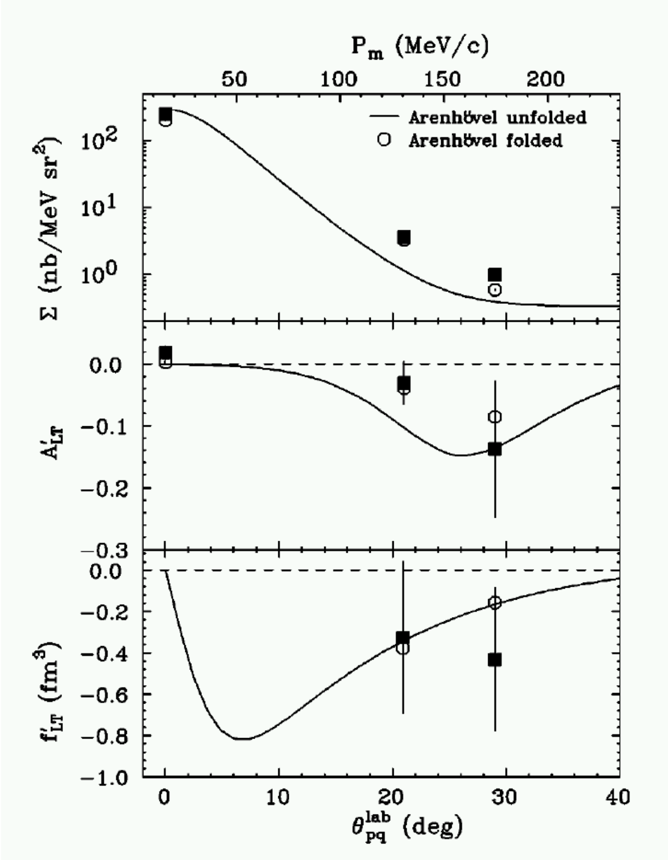
Relativistic Models

- J.W.Van Orden: Fully relativistic plane-wave Born approximation (PWBA) model of the $^2\mathrm{H}(\mathrm{e},\mathrm{e}'\mathrm{p})\mathrm{n}$ structure functions (DEEP code).

- S.Jeschonnek: Adds in final-state interactions using the Glauber theory (which treats absorption by the nucleus with an imaginary potential).

Theory Support

'Conventional Nuclear Physics' Models (Hartmuth Arenhövel)



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Theoretical Status 3

What are the theoretical issues to address?

- Relativistic boost, retardation effects, and corrections to the electromagnetic current.
- Microscopic calculation of final-state interactions.
- Factorization breaking - Differential cross section is proportional to the electron-proton cross section times the spectral function.
- Which meson exchange currents (MEC) to include.
- Isobar configurations (IC).

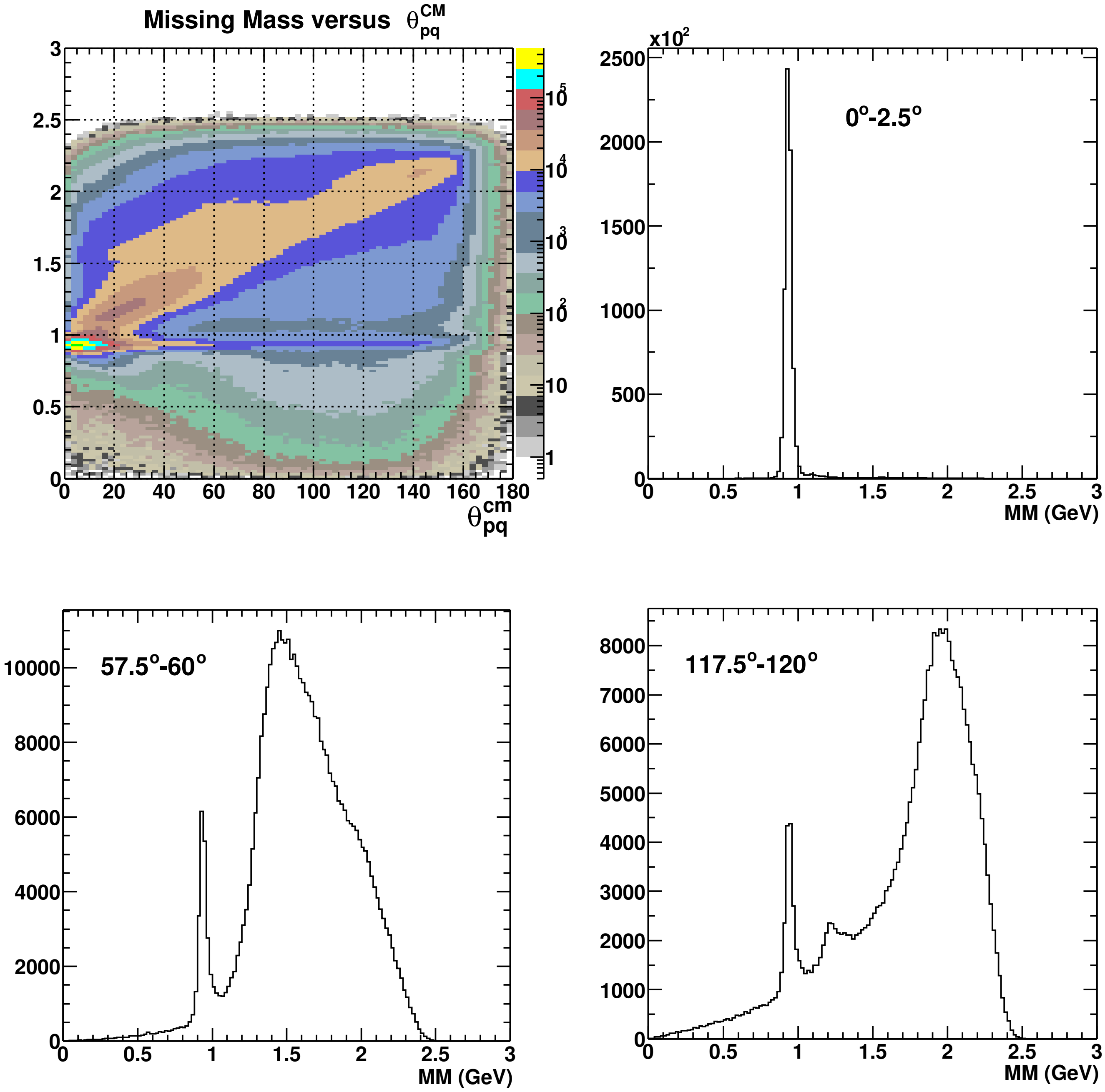
What can we learn from the structure functions?

- For quasielastic (QE) kinematics σ'_{LT} is sensitive to final-state interactions and less sensitive to MEC and IC.
- For QE, σ_{TT} is more sensitive to MEC and IC, but not relativistic corrections (RC).
- For QE, σ_{LT} is sensitive to RC, but not MEC and IC, the opposite of σ_{TT}.
- Measuring these structure functions is an opportunity to untangle the deuteron response.

Extracting Structure Functions with CLAS

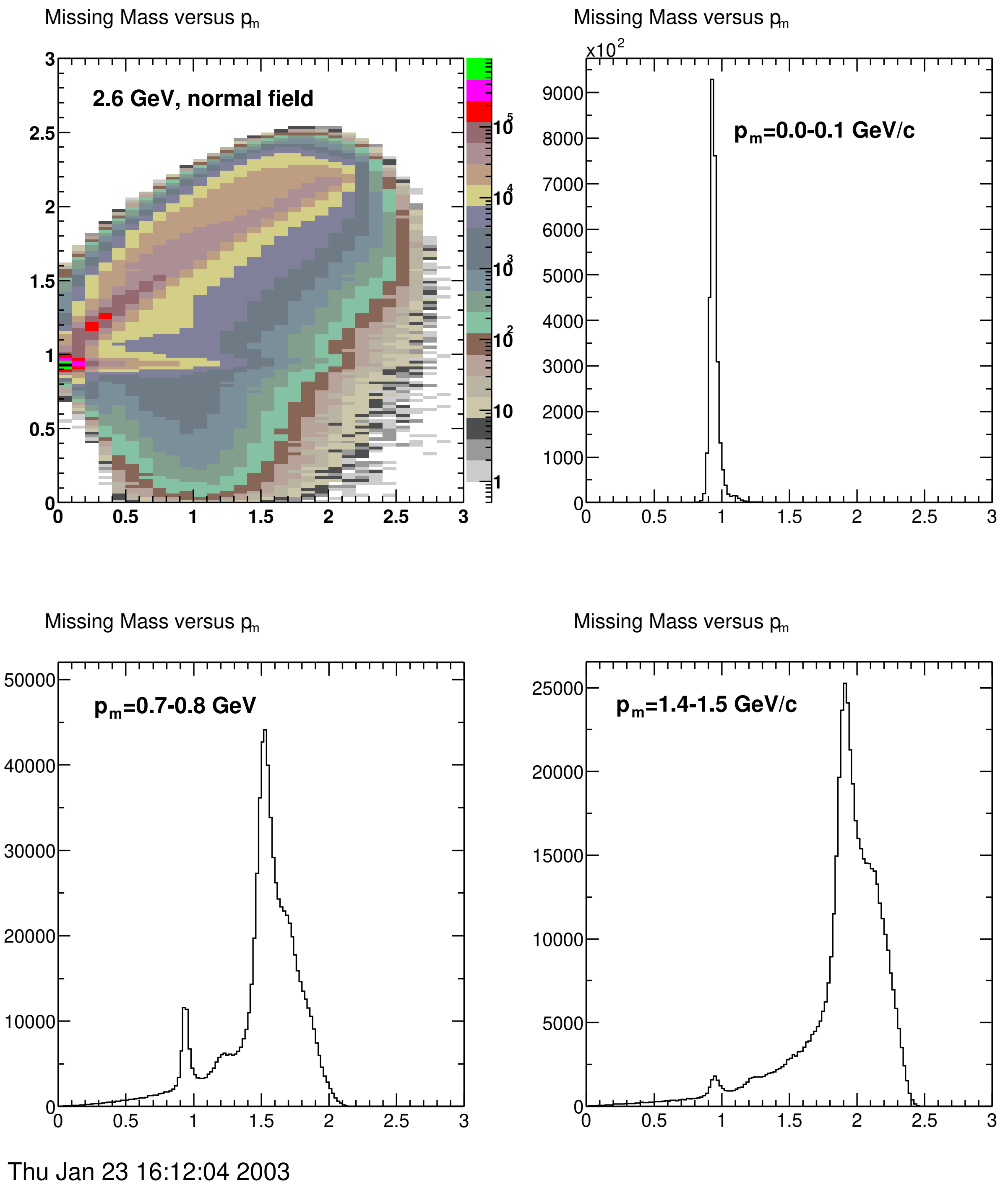
- CLAS is well-suited for the out-of-plane measurements because of its large acceptance.
- Can we demonstrate that we can measure small asymmetries especially A'_{LT}?
- Analysis methods.
  - Conventional asymmetries method.
  - Analysis of moments (*e.g.* $\langle \sin \phi_{pq} \rangle$ and others).
  - Helicity difference analysis.
  - Helicity ratio analysis.
- Restrict the analysis to the quasielastic peak.
  - Comparison with other results at low Q^2.
  - Theory is better understood (MEC and IC less important).
- Use missing mass technique to isolate neutrons.

How high in θ_{pq} can we go?



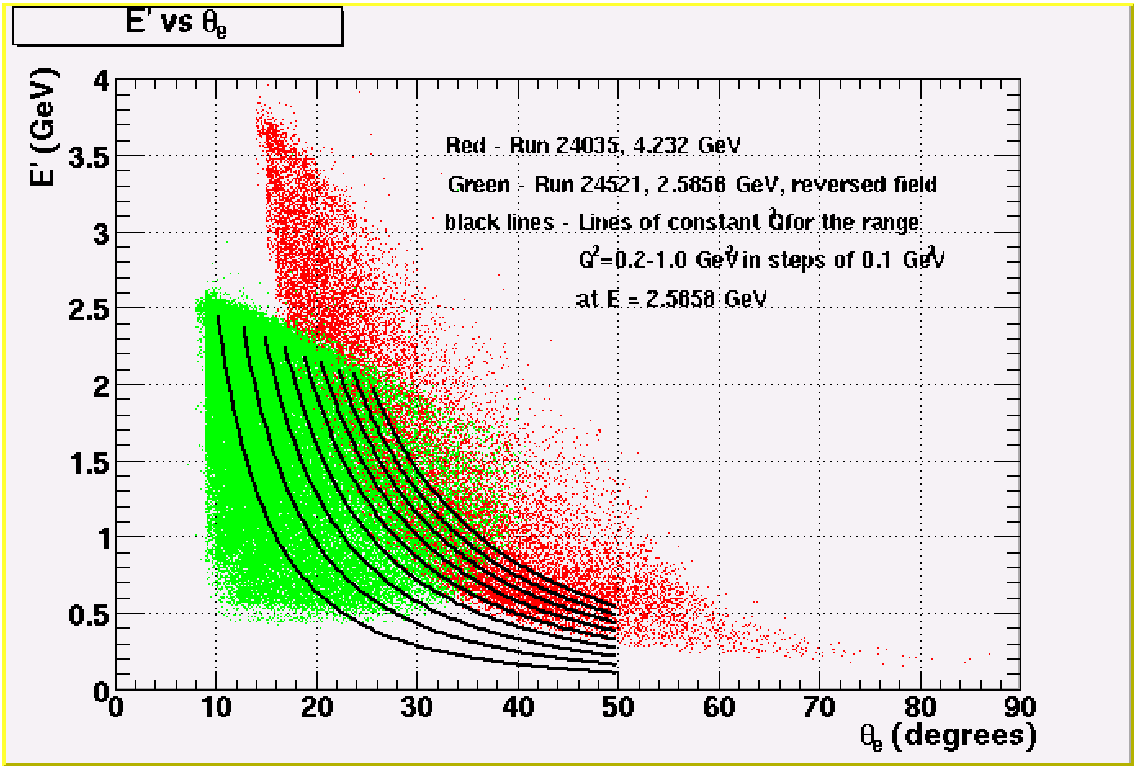
Missing mass spectrum for $d(\vec{e}, e'p)n$, 2.558 GeV, normal field, not acceptance corrected.

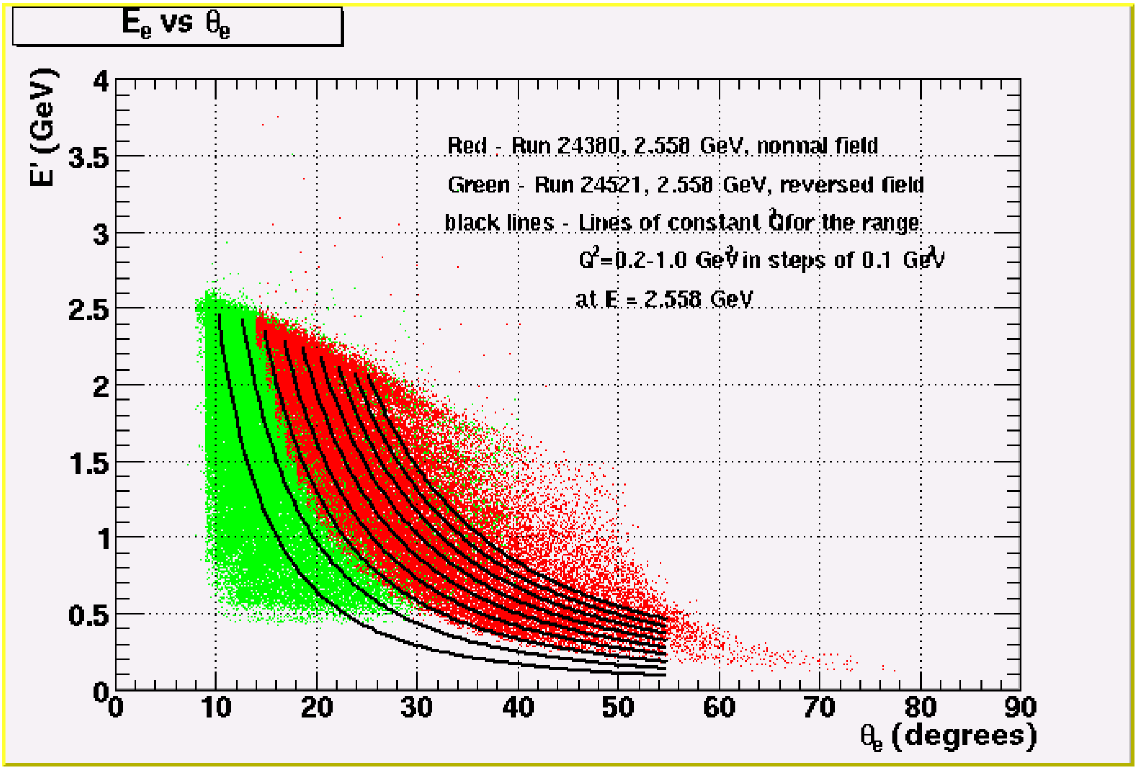
How high in p_m can we go?



Missing mass spectrum for $d(\vec{e}, e'p)n$, 2.558 GeV, normal field, not acceptance corrected.

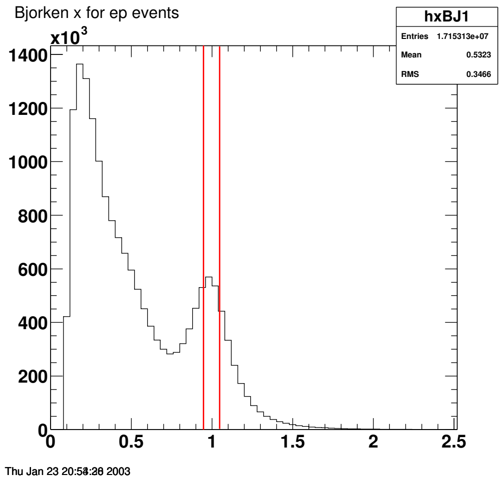
E5 Acceptance for $d(\vec{e}, e'p)n$



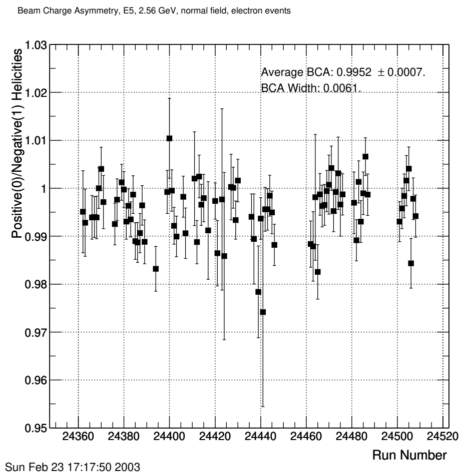


Cuts and Corrections

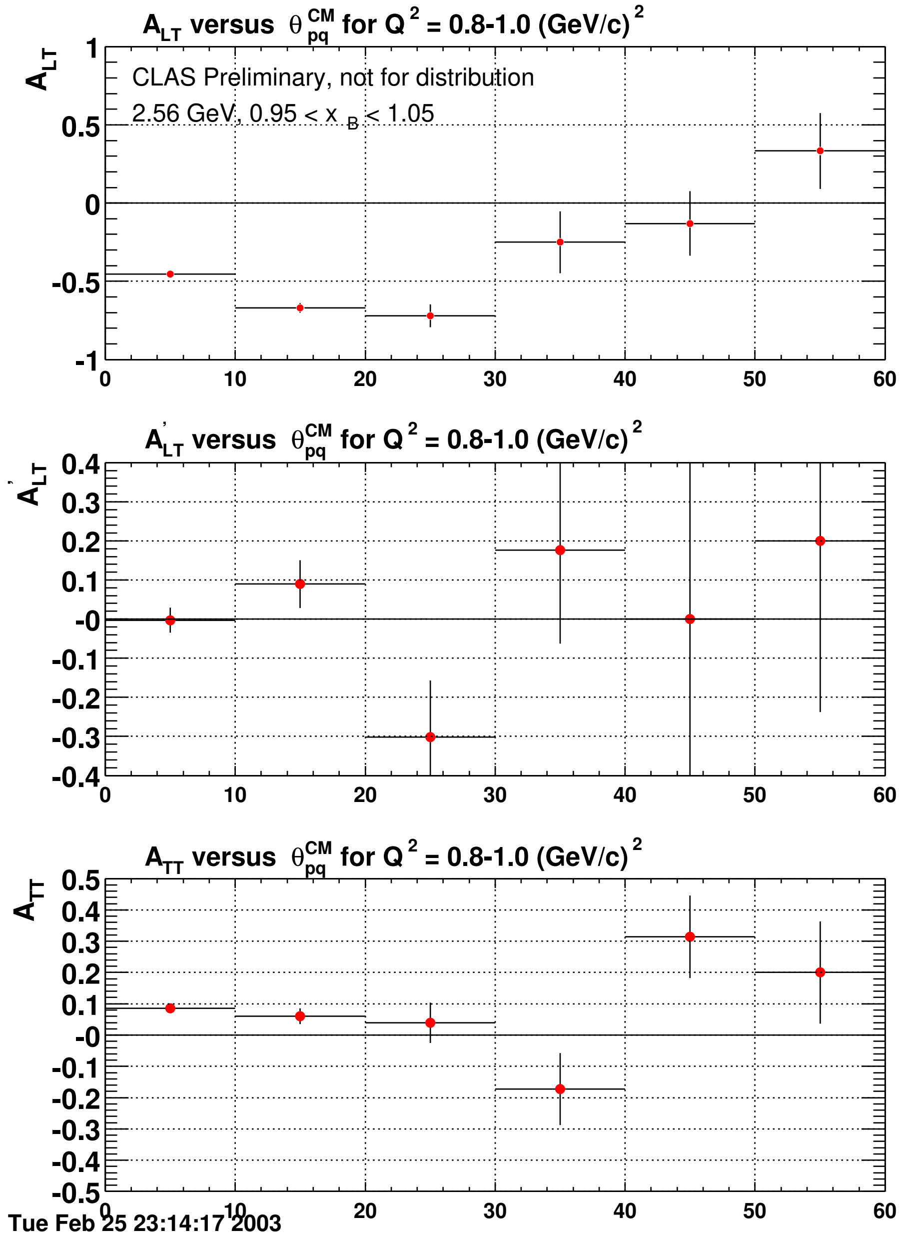
- Start with the EVNT bank.
- Impose electron fiducial and vertex cut.
- Cut on the number of photoelectrons in the Cerenkov counters ($\mathrm{nphe} > 2.5$) to reduce π^- contamination of the electron sample.
- Restrict the analysis to $0.95 < x_B < 1.05$ in Q^2 bins of width $0.20\ (GeV/c)^2$ to focus on quasielastic region.



- Correct for the beam-charge asymmetry. The average correction for the 2.6 GeV, normal field run is 0.9952 ± 0.0007.



Preliminary Results for Conventional Asymmetries.



- 2.558 GeV, normal field, not acceptance corrected.
- Good statistics for A_{LT}, and A_{TT}.
- Poor statistics for A'_{LT}; consistent with zero.

$\langle \sin\phi_{pq} \rangle_\pm$ Moments Analysis

- Recall

$$\sigma_d^\pm = \sigma_L + \sigma_T + \sigma_{LT}\cos(\phi_{pq}) + \sigma_{TT}\cos(2\phi_{pq}) + h\sigma'_{LT}\sin(\phi_{pq})$$

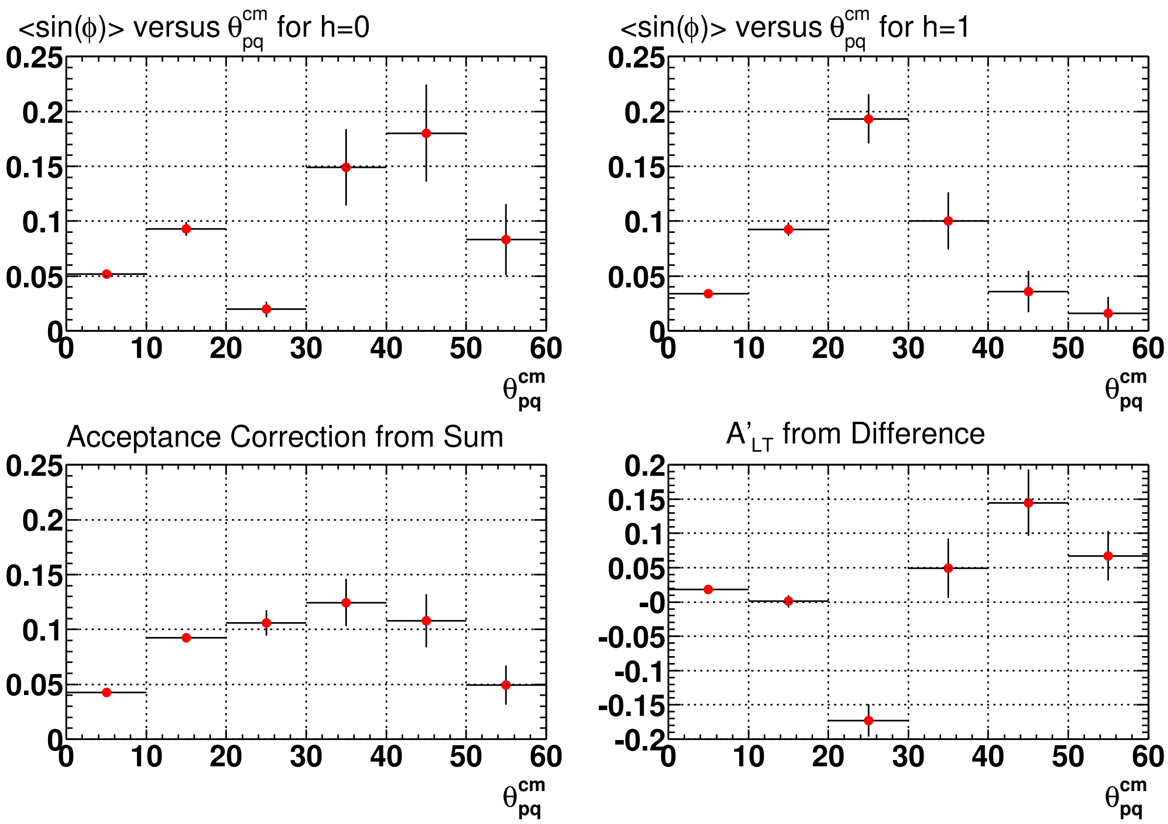
- Let

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

- For a sinusoidally-varying component to the acceptance

$$\langle \sin\phi_{pq} \rangle_\pm = \pm\frac{\sigma'_{LT}}{2(\sigma_L+\sigma_T)} + \alpha_{acc} \qquad .$$

- Preliminary results for 2.56 GeV, normal field, not acceptance corrected, $0.8 < Q^2 < 1.0\ (GeV/c)^2$, $0.95 < x_B < 1.05$.



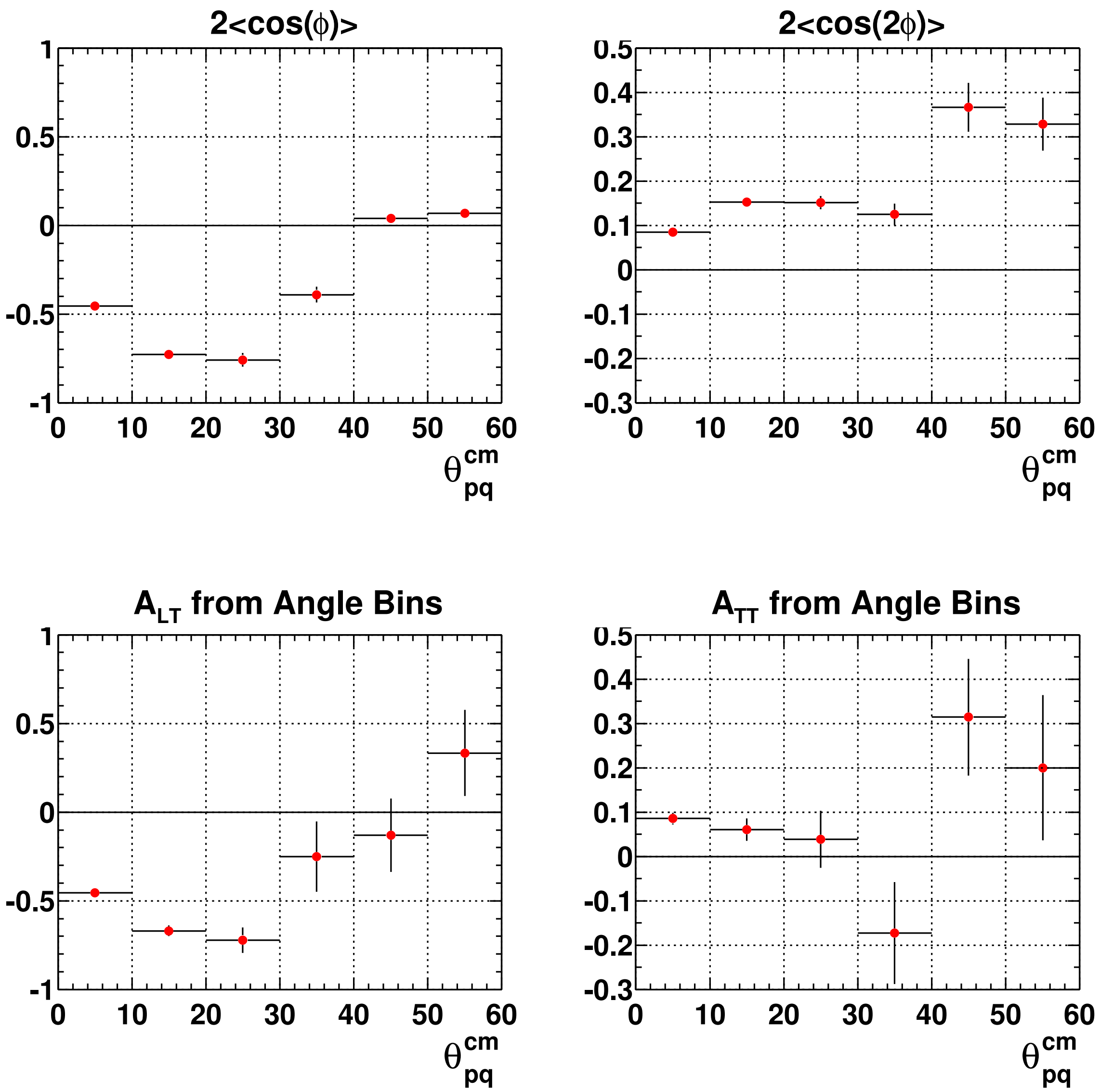
- A'_{LT} is NONZERO!

Other Moments

- Recall

$$\sigma_d^{\pm} = \sigma_L + \sigma_T + \sigma_{LT}\cos(\phi_{pq}) + \sigma_{TT}\cos(2\phi_{pq}) + h\sigma'_{LT}\sin(\phi_{pq})$$

- Preliminary results for 2.56 GeV, normal field, not acceptance corrected, $0.8 < Q^2 < 1.0\ (GeV/c)^2$, $0.95 < x_B < 1.05$.



- The $\langle\cos\phi\rangle$ and $\langle\cos(2\phi)\rangle$ moments are consistent with the angle bin analysis.

Helicity Difference Analysis

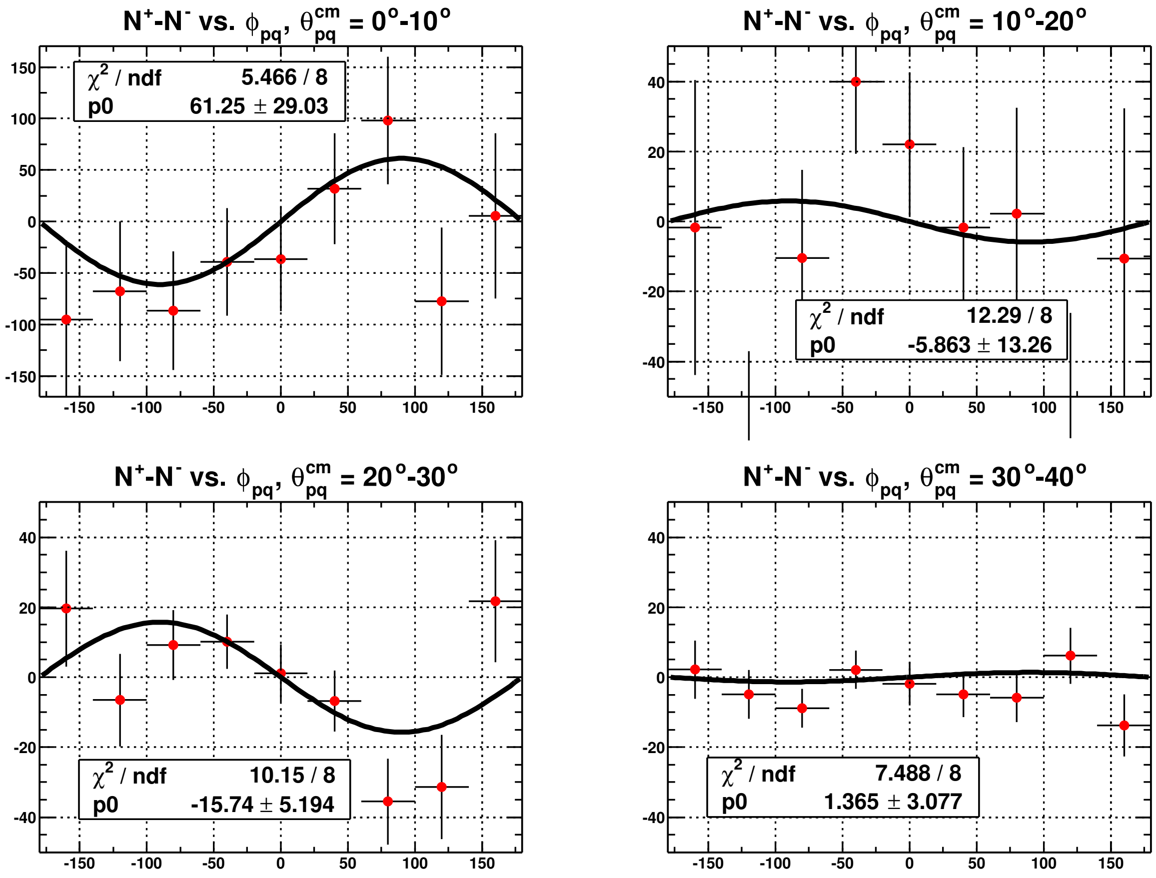
- Recall

$$\sigma_d^{\pm} = \sigma_L + \sigma_T + \sigma_{LT}\cos(\phi_{pq}) + \sigma_{TT}\cos(2\phi_{pq}) + h\sigma'_{LT}\sin(\phi_{pq})$$

- Define the difference between helicities.

$$\frac{N^+ - N^-}{Acceptance} = d\sigma^+ - d\sigma^- = 2\sigma'_{LT}\sin\phi_{pq}$$

- Preliminary results for 2.56 GeV, normal field, not acceptance corrected, $0.8 < Q^2 < 1.0\ (GeV/c)^2$, $0.95 < x_B < 1.05$.



Helicity Ratio Analysis

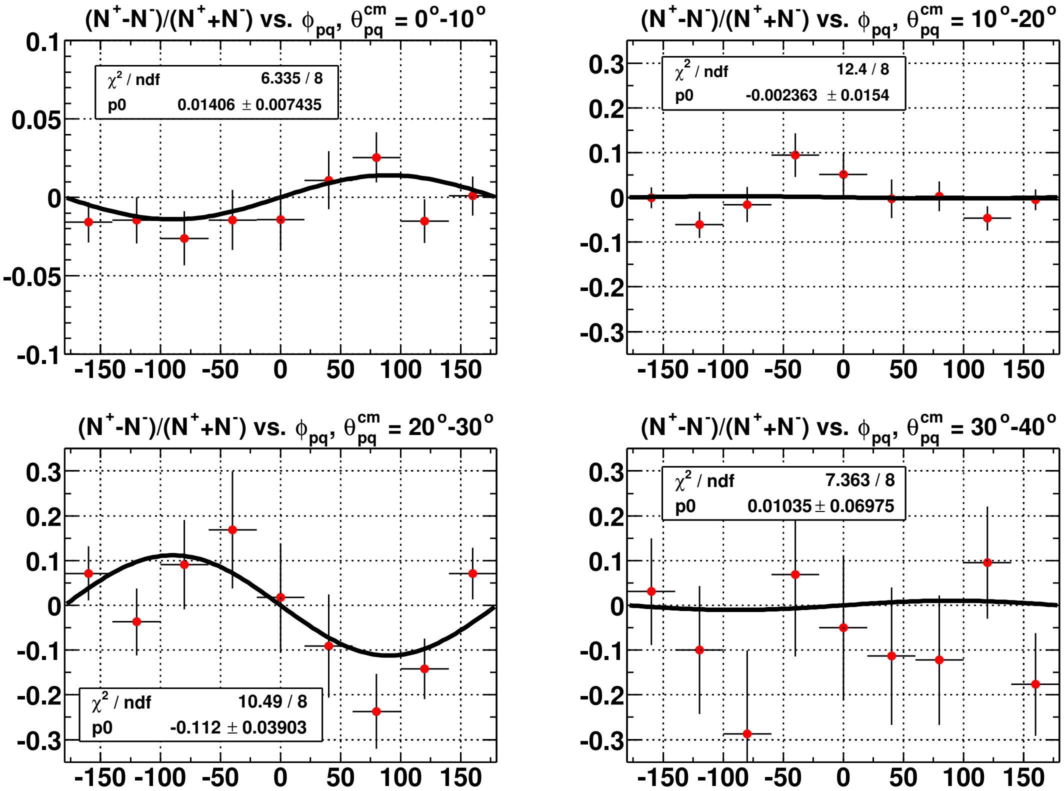
- Recall

$$\sigma_d^{\pm} = \sigma_L + \sigma_T + \sigma_{LT}\cos(\phi_{pq}) + \sigma_{TT}\cos(2\phi_{pq}) + h\sigma'_{LT}\sin(\phi_{pq})$$

- Define A'_{LT} in a more general way.

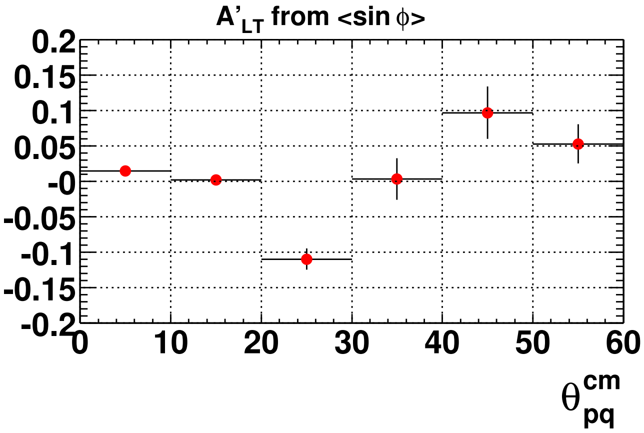
$$\frac{N^+ - N^-}{N^+ + N^-} = \frac{\sigma'_{LT}\sin\phi_{pq}}{\sigma_L + \sigma_T + \sigma_{LT}\cos(\phi_{pq}) + \sigma_{TT}\cos(2\phi_{pq})}$$

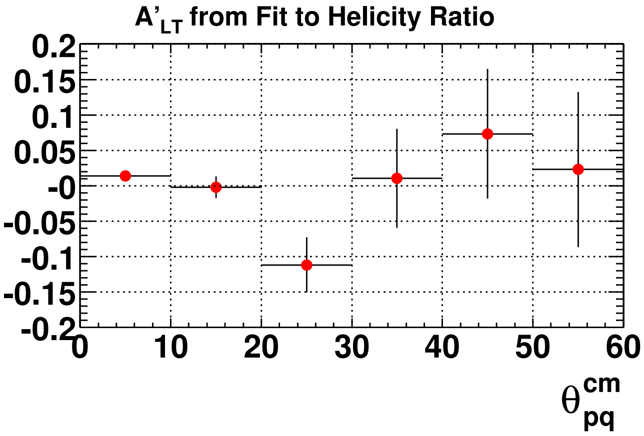
- Less sensitive to acceptance corrections, but extracting results may be more complex since the denominator depends on ϕ_{pq}.
- Preliminary results for 2.56 GeV, normal field, not acceptance corrected, $0.8 < Q^2 < 1.0\ (GeV/c)^2$, $0.95 < x_B < 1.05$.

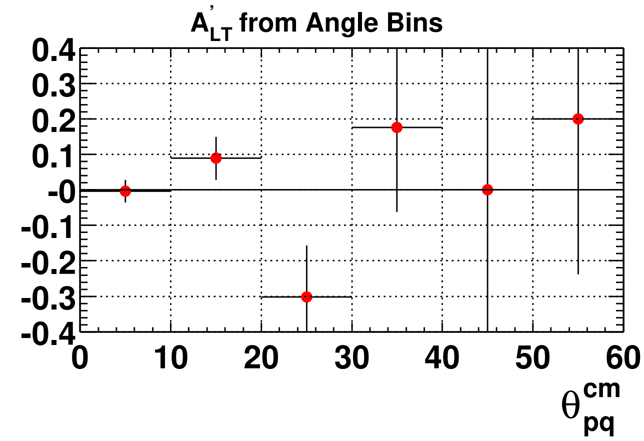


- Compare fit amplitudes with moments analysis and conventional asymmetries.

Comparison of Different Analysis Methods

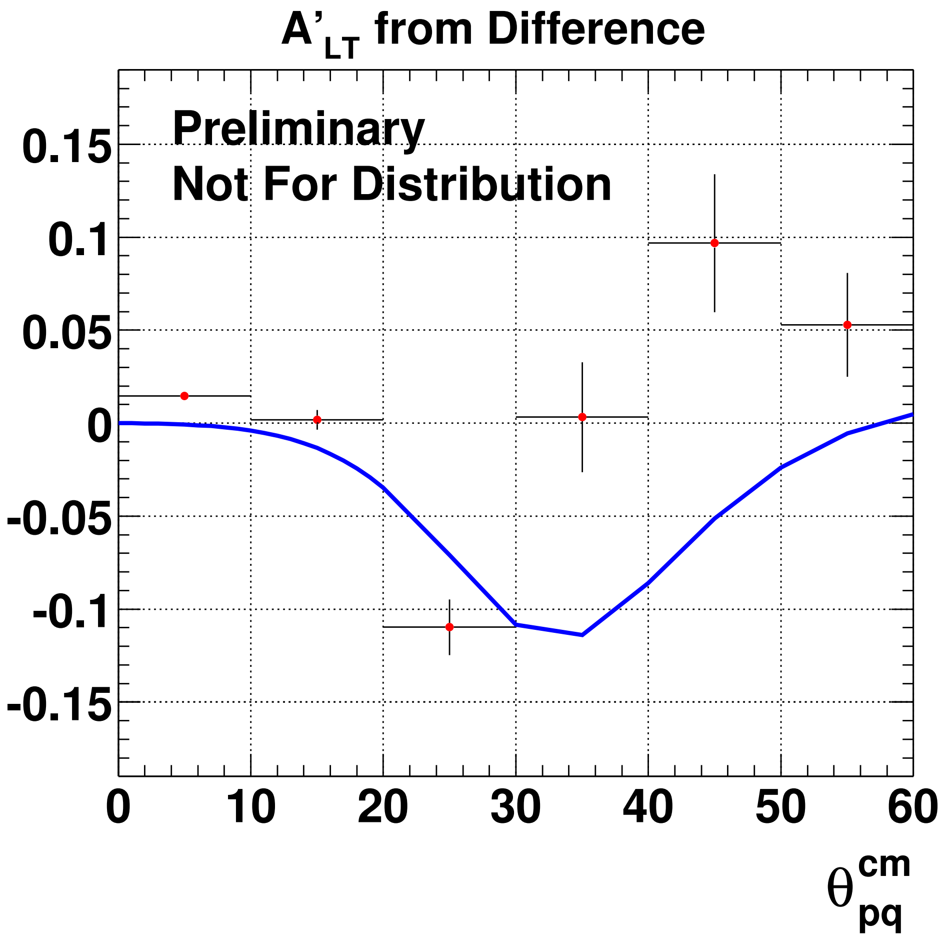






- The shapes are consistent! We can measure small A'_{Lt}.
- 2.56 GeV, normal field, not acceptance corrected, $0.8 < Q^2 < 1.0\ (GeV/c)^2$, $0.95 < x_B < 1.05$.

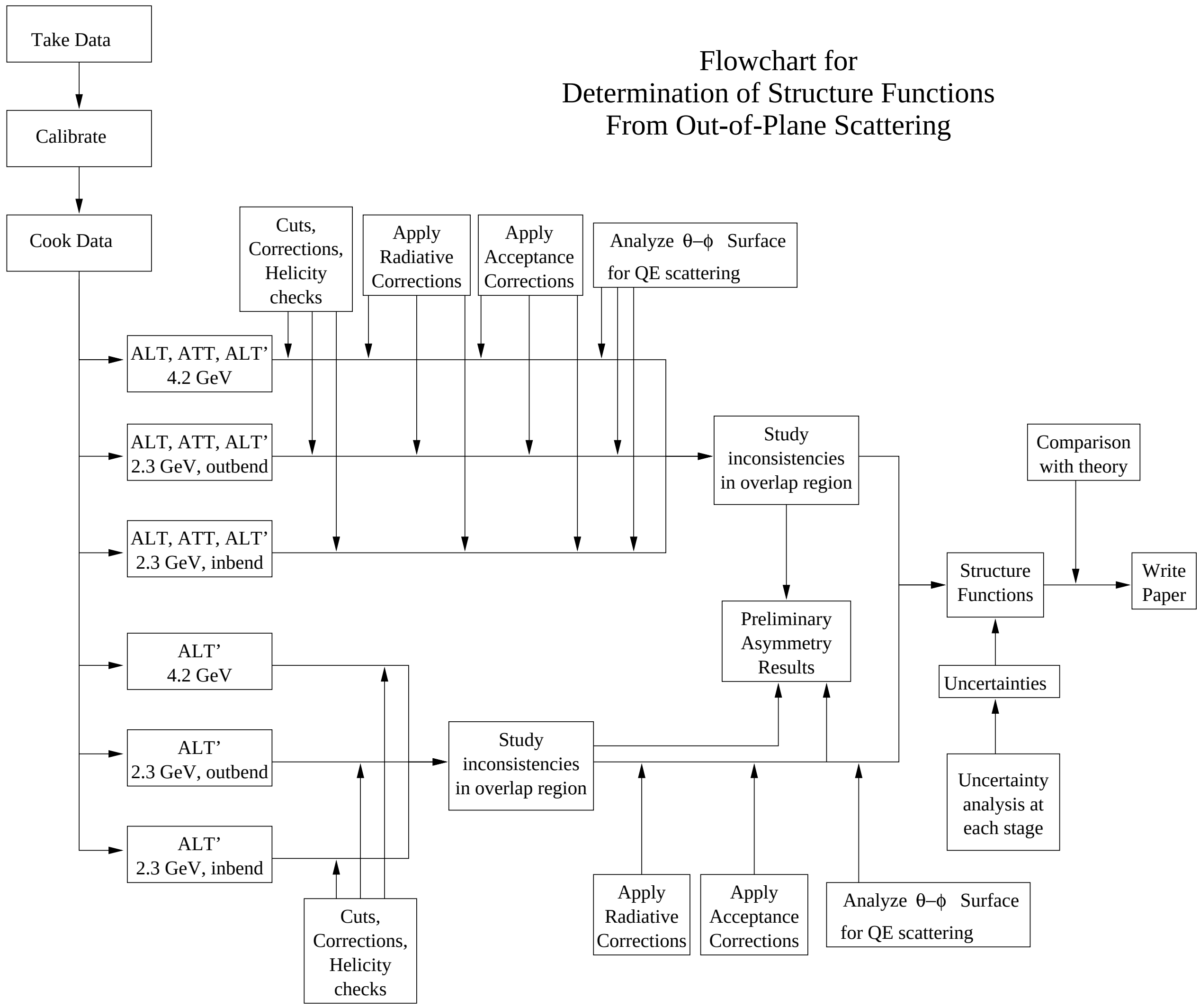
Preliminary Comparison with Theory



- 2.56 GeV, normal field, not acceptance corrected, $0.8 < Q^2 < 1.0\ (GeV/c)^2$, $0.95 < x_B < 1.05$.
- Blue curve from Arenhoevel.

Work Plan

- Analysis flowchart.



- Spiderwulf - The Richmond computing cluster has been commissioned and is regularly performing analysis of the E5 data. DST's for all three run conditions have been copied to UR and in 'round robin' mode (data files are stored on slave node disks) one of these data sets can be analyzed in about 30 minutes.

Radiative Corrections 1

- Use the procedure of A.Afanasev, *et al.* previously applied to pion electroproduction on hydrogen (Phys. Rev. D, **66**, 074004, (2002)).
- Changed original code from pion electroproduction to e5 conditions.
  - Changed the masses from $^{1}\mathrm{H}(\mathrm{e},\mathrm{e}'\pi^{+})\mathrm{n}$ to $^{2}\mathrm{H}(\mathrm{e},\mathrm{e}'\mathrm{p})\mathrm{n}$ values.
  - Replaced physics models (AO and MAID $\rightarrow$ DEEP).
- The numerical integration performed for the full calculation has proven to be slow and unreliable because of the rapid change of the differential cross section with angle for the $d(\vec{e}, e'p)n$ case.
  - A new version is available with only the leading log approximation and not the full numerical integration. It runs quickly and reliably.
  - A modified version is expected that will have an improved numerical integration algorithm.

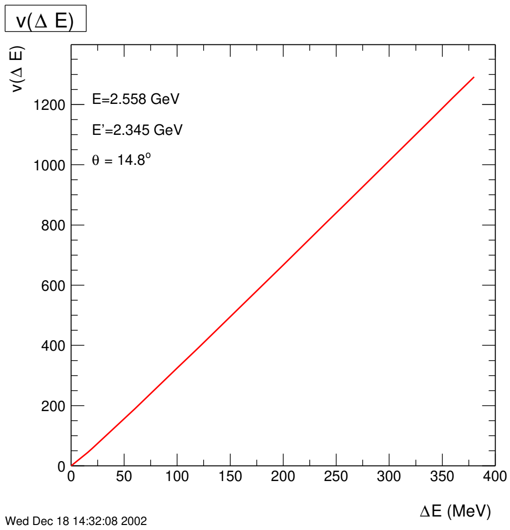
Radiative Corrections 2

- Comparison with traditional Schwinger method.
  - Schwinger calculations available at CSLA website.
  - Relationship between integration parameters of the two methods ($\Delta E \to v_{cut}$) is

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

where

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



- Need to put in Arenhövel and other physics models.

Conclusions

- Strong physics motivation to test the nuclear 'standard model' in a new energy range.
- E5 has abundant data to accomplish this goal.
- There is significant structure in A_{LT} and A_{TT} (and σ_{LT} and σ_{TT}) which is an encouraging sign that we can uncover new physics.
- The preliminary A'_{LT} (and σ'_{LT}) results show this structure function is small, but nonzero.
- We have only tested the analysis at $Q^2 \approx 0.9\ (GeV/c)^2$. We expect better statistics at lower Q^2.