Hunting for Quarks

Out-of-plane Measurements of the Structure Functions

of the Deuteron

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1. Physics Motivation
2. Experiments at Jefferson Lab
3. Measuring Structure Functions
4. Preliminary Results and Conclusions

What Do We Know?

- The Universe is made of quarks and leptons and the force carriers.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

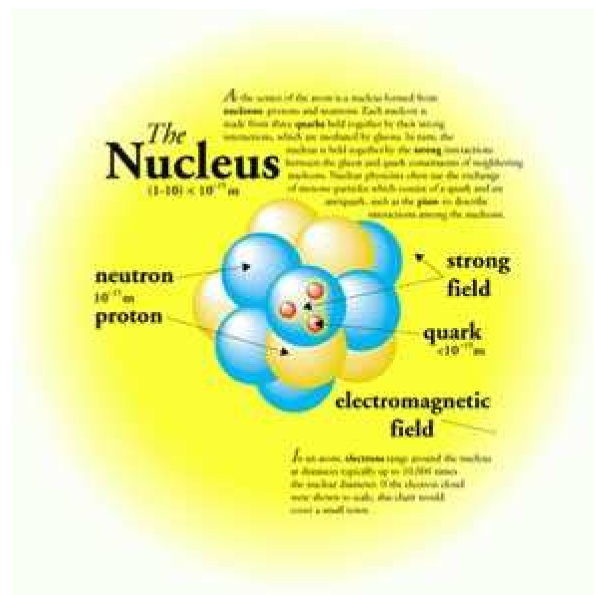
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

- The atomic nucleus is made of protons and neutrons bound by the strong force.

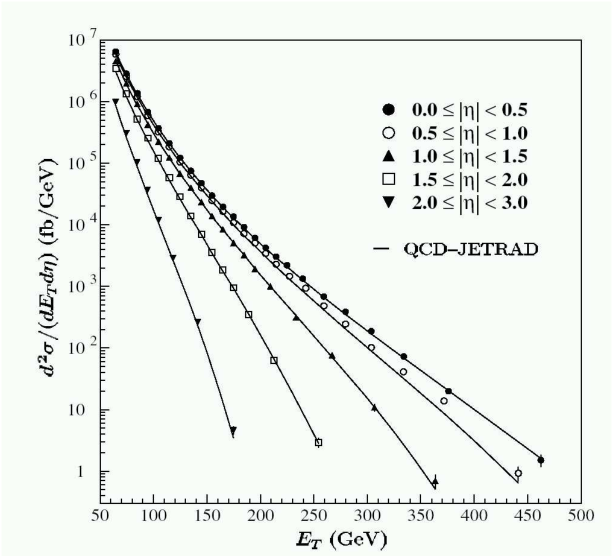


- The quarks are confined inside the protons and neutrons.
- Protons and neutrons are NOT confined.

How Well Do We Know It?

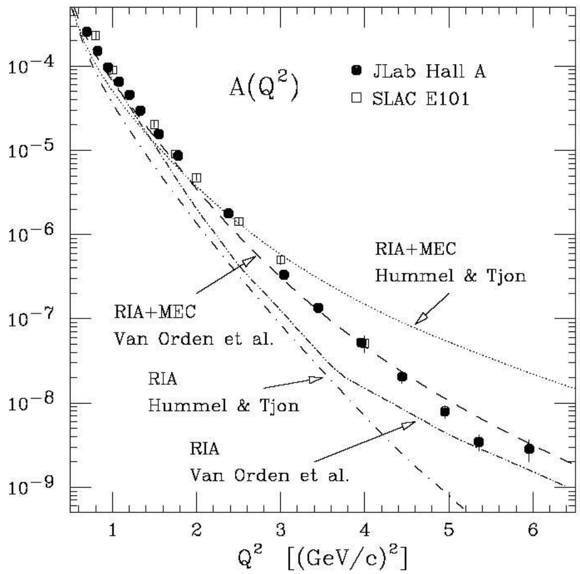
- We have a working theory of strong interactions: quantum chromodynamics or QCD.

  B.Abbott, *et al.*, Phys. Rev. Lett., **86**, 1707 (2001).



- The coherent hadronic model (the standard model of nuclear physics) works too.

  L.C.Alexa, *et al.*, Phys. Rev. Lett., **82**, 1374 (1999).



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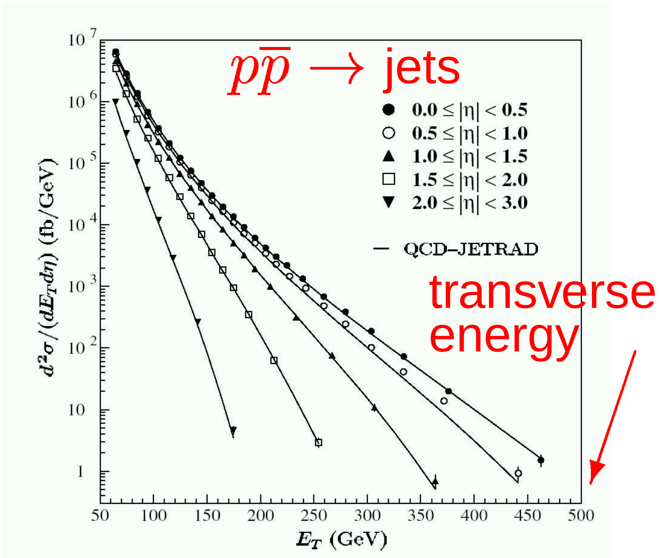

effective area of the target

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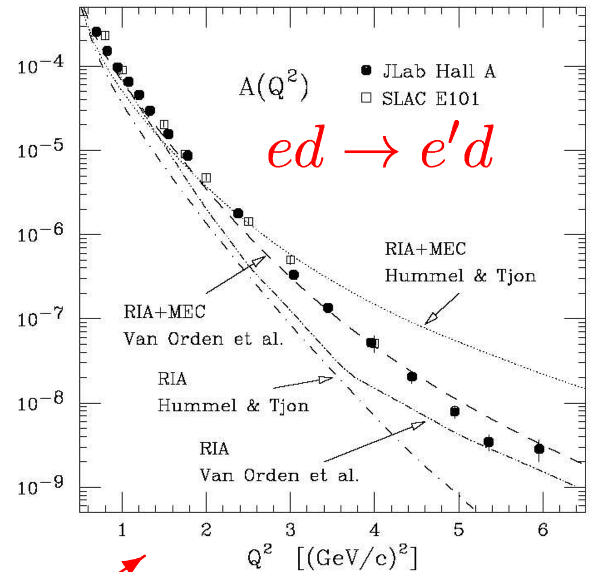


4-momentum transfer squared

What Don't We Know?

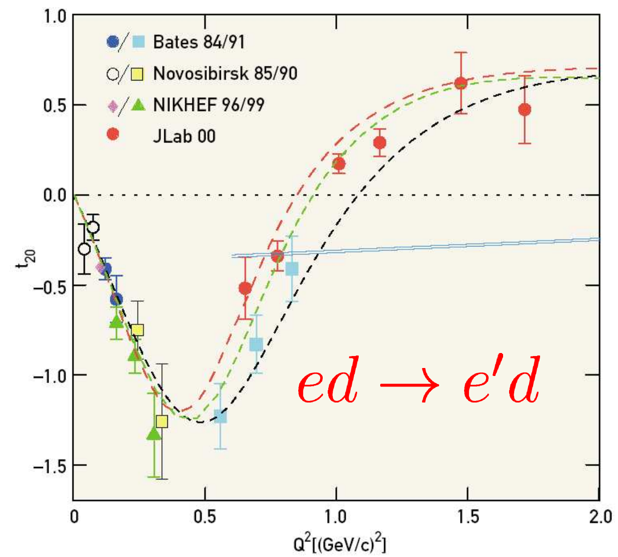
1. We can't get QCD and the hadronic model to line up.

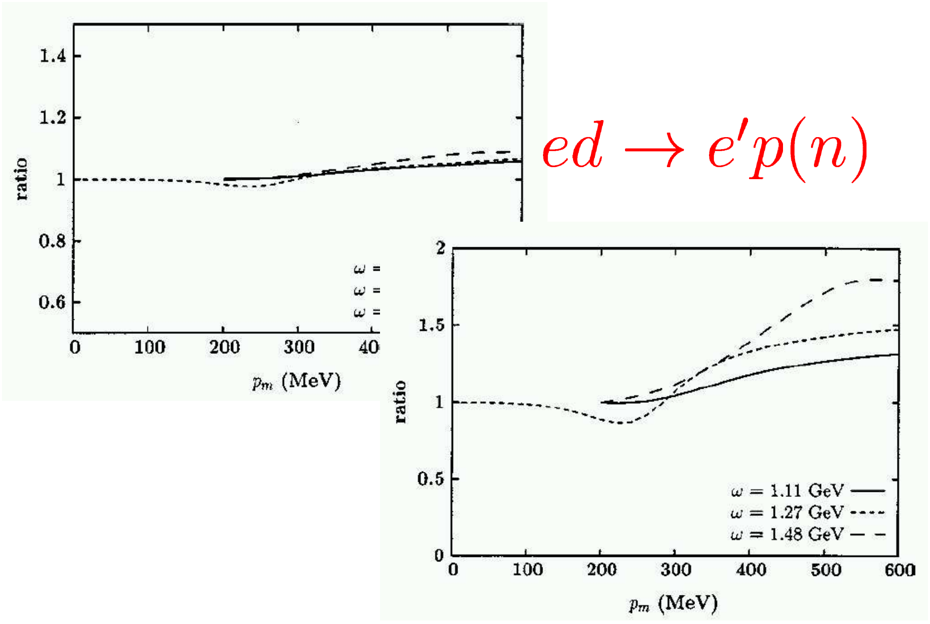
   D. Abbott, *et al.*, Phys. Rev Lett. **84**, 5053 (2000).

2. We have to find the hadronic model 'baseline' to see the transition to QCD.

3. The deuteron is the simplest case.

   S. Jeschonnek, Phys. Rev. C, **63**, 034609 (2001).

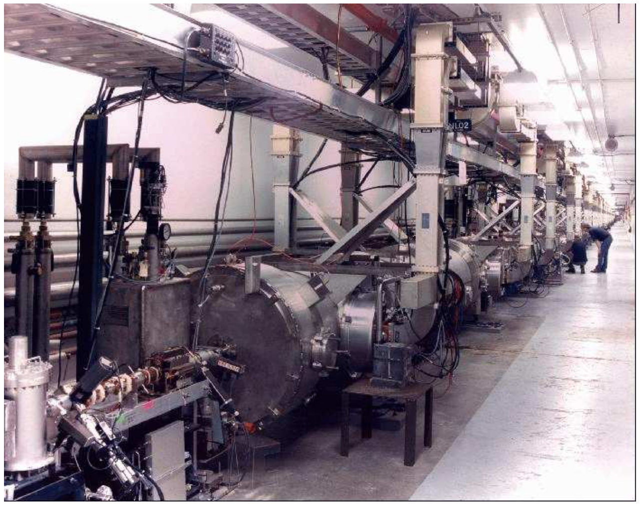




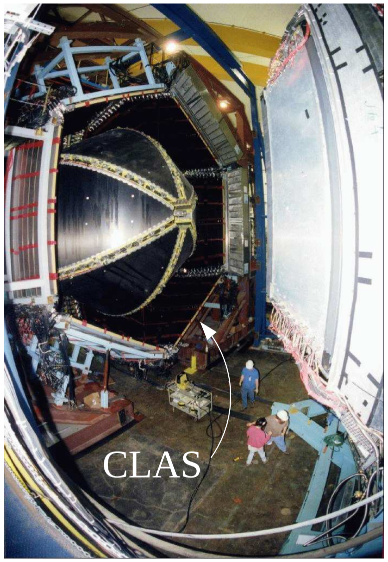
Experiments at Jefferson Lab

- Jefferson Lab is a US Department of Energy national laboratory and the newest 'crown jewel' of the US.
- The centerpiece is a 7/8-mile-long, racetrack-shaped electron accelerator that produces unrivaled beams.

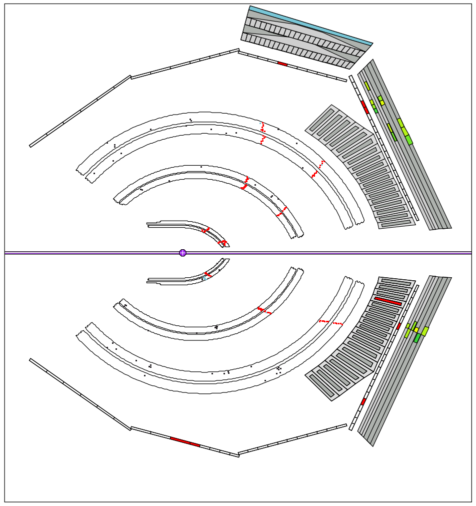
- The electrons do up to five laps around the Continuous Electron Beam Accelerator Facility (CEBAF) and are then extracted and sent to one of three experimental halls.
- All three halls can run simultaneously.



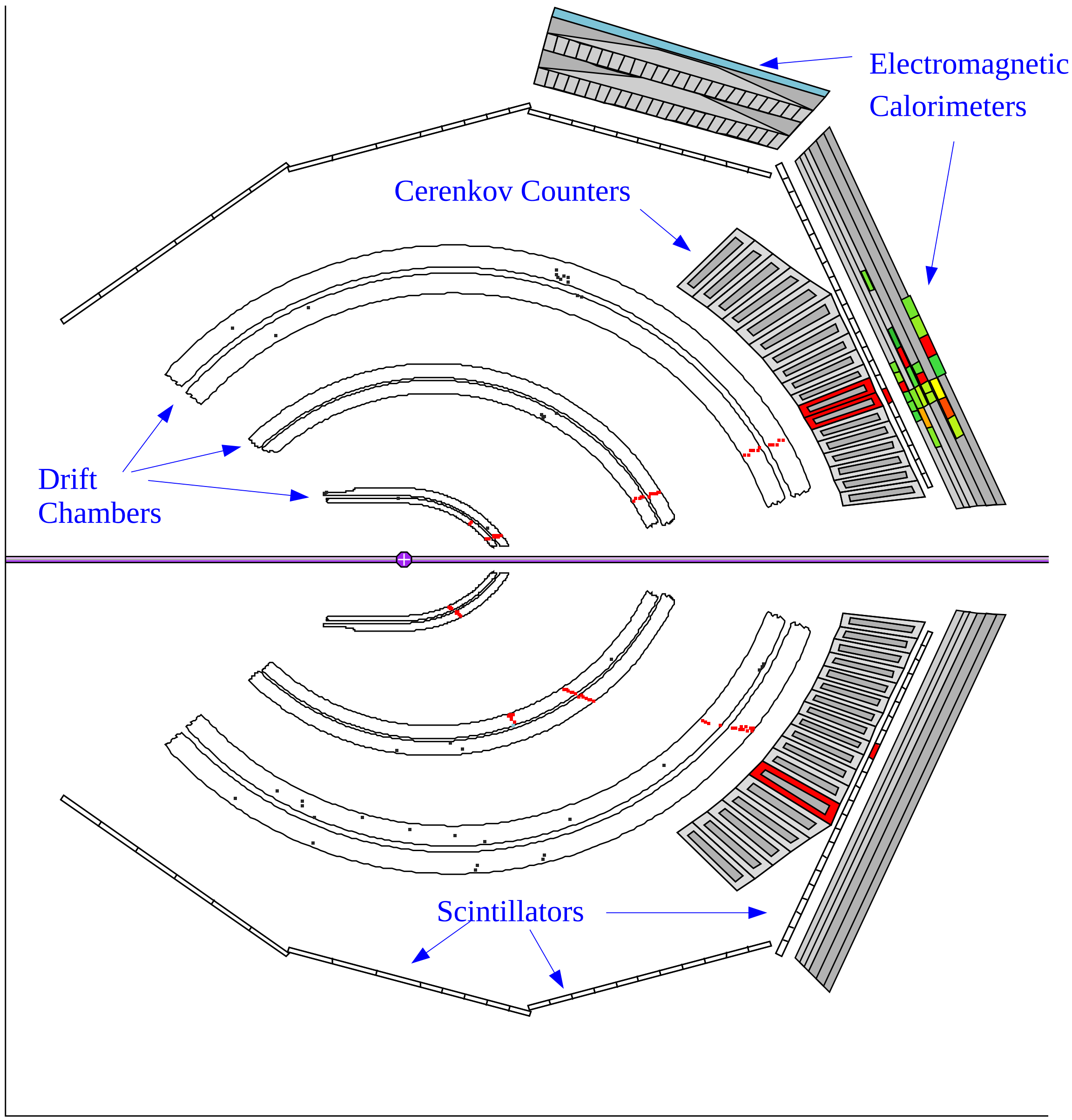
The CEBAF Large Acceptance Spectrometer (CLAS)



- CLAS is a 45-ton, $50-million radiation detector.
- It covers almost all angles.
- It has about 40,000 detecting elements in about 40 layers.
- Drift chambers map the trajectory of the collision. A toroidal magnetic field bends the trajectory to measure momentum.
- Plastic scintillators measure the time-of-flight.
- Cerenkov counters identify particles.
- The electromagnetic calorimeter measures energy.

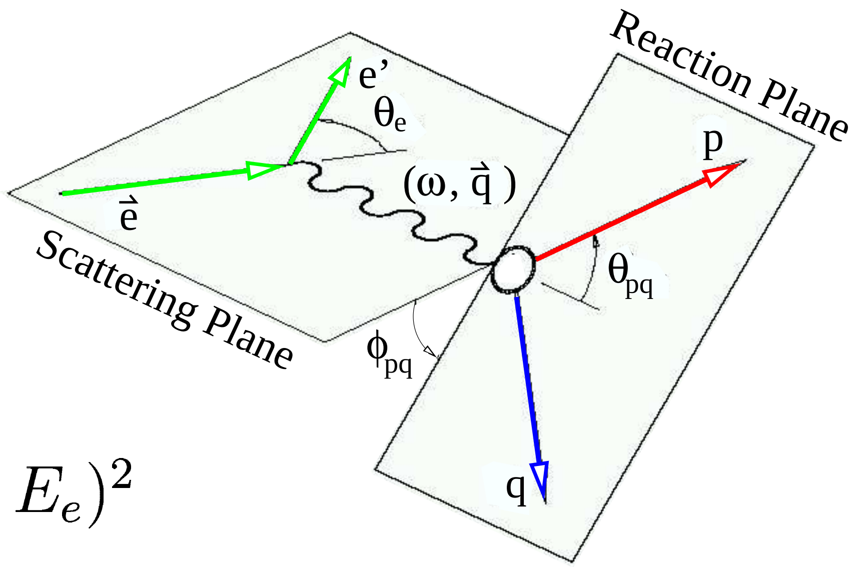


A CLAS Event



Electromagnetic
Calorimeters
Cerenkov Counters
Drift
Chambers
Scintillators

Some Necessary Jargon



- Kinematics:

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

- 4-momentum transfer:

  $$Q^2 = (\vec{p}_{beam} - \vec{p}_e)^2 - (E_{beam} - E_e)^2$$

- Cross section for a given Q^2, energy transfer ω, and θ_{pq}:

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

- σ'_{LT} is the interference between parts of the deuteron wave function.
- The quantity $h = \pm 1$ is the beam helicity.

Measuring the Fifth Structure Function σ'_{LT} in CLAS

- Recall the expression for the cross section.

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

where $h = \pm 1$ depending on the spin of the beam.

- Recall the orthogonality of sines and cosines.

$$\frac{1}{\pi}\int_{-\pi}^{\pi} \sin mx \sin nx dx = \delta_{mn} \qquad \frac{1}{\pi}\int_{-\pi}^{\pi} \cos mx \cos nx dx = \delta_{mn}$$

$$\int_{-\pi}^{\pi} \sin mx \cos nx dx = 0$$

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- How do we get σ'_{LT}?

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- How do we get σ'_{LT}? Start with $\sigma^{\pm}$ and construct an asymmetry.

$$A'_{LT}(Q^2, \omega, \theta_{pq}) = \frac{\sigma^+_{90} - \sigma^-_{90}}{\sigma^+_{90} + \sigma^-_{90}} = \frac{\sigma'_{LT}}{\sigma_L + \sigma_T - 2\sigma_{TT}} \approx \frac{\sigma'_{LT}}{\sigma_L + \sigma_T}$$

Subscripts on $\sigma^{\pm}$ refer to ϕ_{pq}.

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Subscripts on $\sigma^{\pm}$ refer to ϕ_{pq}.

- For a given Q^2, θ_{pq}, and energy transfer consider

$$\langle \sin\phi_{pq}\rangle_{\pm} = \frac{\int_{-\pi}^{\pi} \sigma^{\pm}(\phi_{pq})\sin\phi_{pq}d\phi}{\int_{-\pi}^{\pi} \sigma^{\pm}(\phi_{pq})d\phi}$$

Measuring the Fifth Structure Function σ'_{LT} in CLAS

- The numerator is

$$\int_{-\pi}^{\pi} [\sigma_L + \sigma_T + \sigma_{LT} \cos(\phi_{pq}) + \sigma_{TT} \cos(2\phi_{pq}) + h\sigma'_{LT} \sin(\phi_{pq})\,] \sin\phi_{pq} d\phi =$$

- The denominator is

$$\int_{-\pi}^{\pi} [\sigma_L + \sigma_T + \sigma_{LT} \cos(\phi_{pq}) + \sigma_{TT} \cos(2\phi_{pq}) + h\sigma'_{LT} \sin(\phi_{pq})] d\phi =$$

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$$\int_{-\pi}^{\pi}[\sigma_L + \sigma_T + \sigma_{LT}\cos(\phi_{pq}) + \sigma_{TT}\cos(2\phi_{pq}) + h\sigma'_{LT}\sin(\phi_{pq})]d\phi = 2\pi(\sigma_L + \sigma_T)$$

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- Put all this together and the result is

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

Measuring the Fifth Structure Function σ'_{LT} in CLAS

- To get $\langle \sin \phi_{pq} \rangle_{\pm}$ out of real event data use the following.

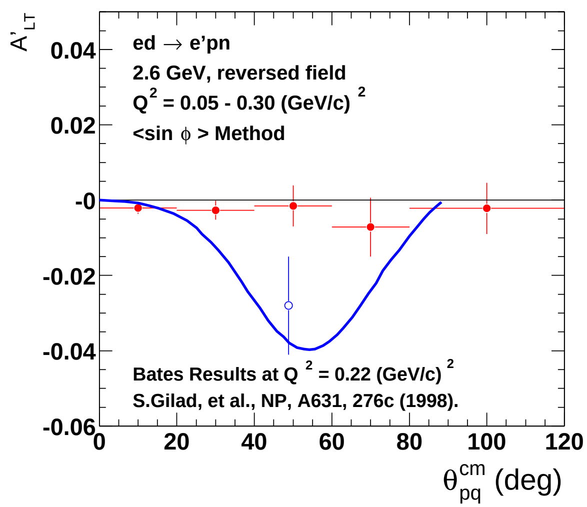
$$\langle \sin \phi_{pq} \rangle_{\pm} = \frac{\sum_i^{\pm} \sin \phi_i}{N^{\pm}}$$

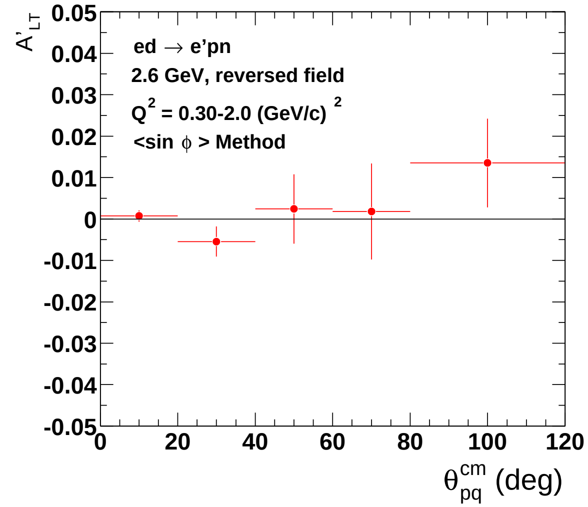
where $N^{\pm}$ is the number of events for each beam helicity and the sum is over the different helicities. This is for a given bin in Q^2, θ_{pq}, and energy transfer.

- By dividing we reduce our vulnerability to detector artifacts.

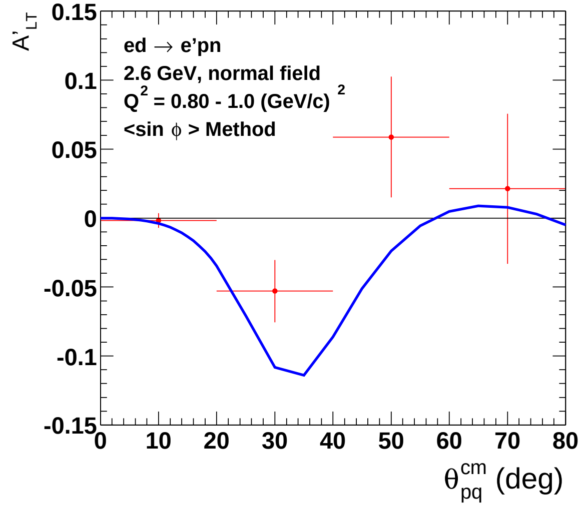
Preliminary Results (not for distribution)

- For 2.6 GeV, reversed field.





- For 2.6 GeV, normal field.

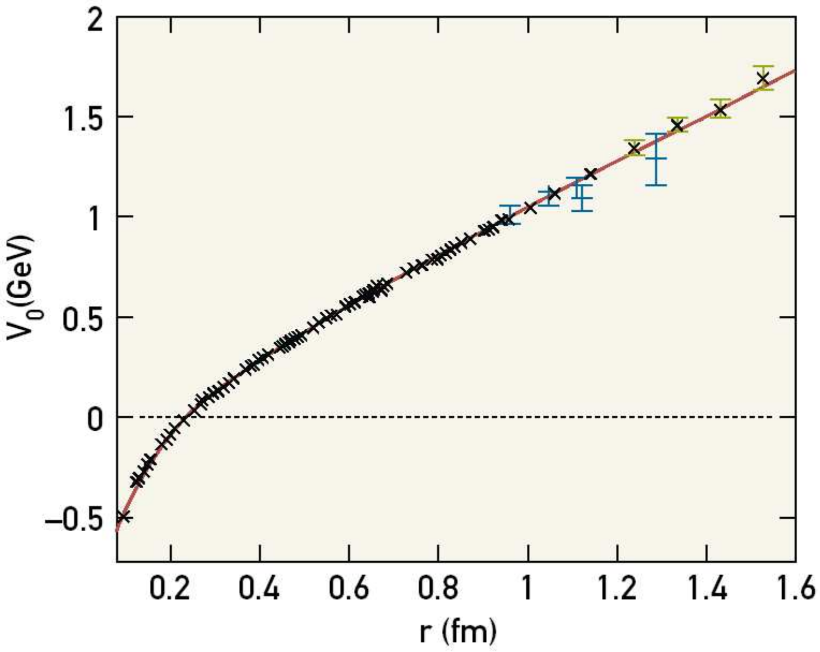


Conclusions

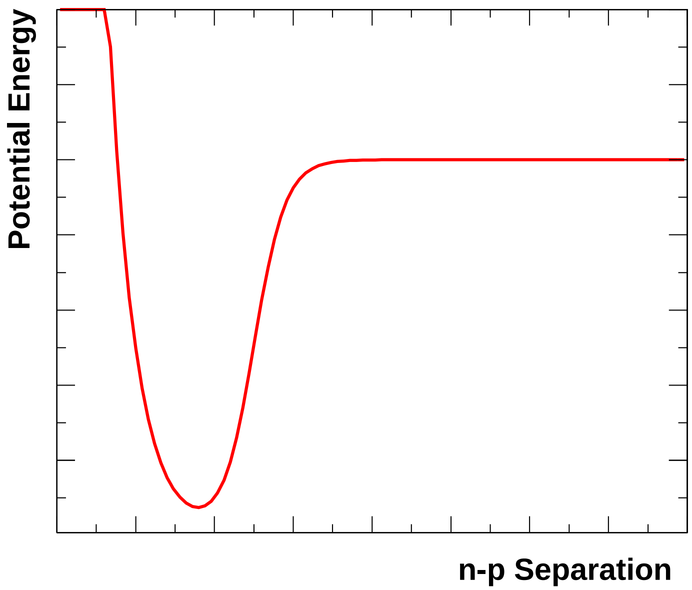
- We are hunting for quarks (and gluons) hidden inside the nucleus.
- Strong physics motivation to test the nuclear 'coherent hadronic model' in a new energy range and push it to its limits.
- Establish a baseline for observing the onset of quark-gluon effects.
- The preliminary A'_{LT} results show this structure function is close to zero at low Q^2. This is a surprising difference with previous results and theoretical calculations. At higher Q^2 the agreement is better.
- Talking about the deuteron is a good reason to hit South Beach in Miami Beach in February.

What is the Force?

- QCD looks like the right way to get the force at high energy.



- The hadronic model uses a phenomenological force fitted to data at low energy. This ‘strong’ force is the residual color force.



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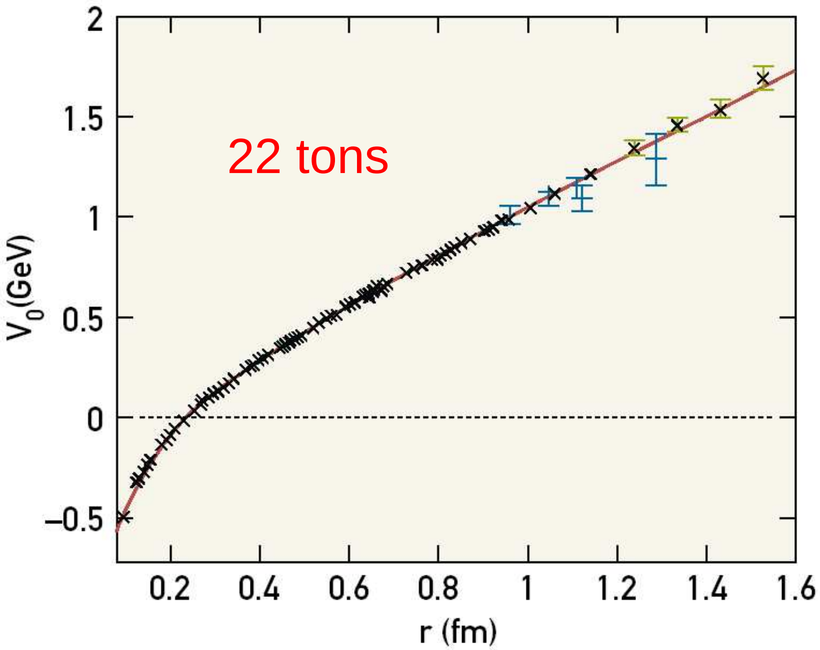

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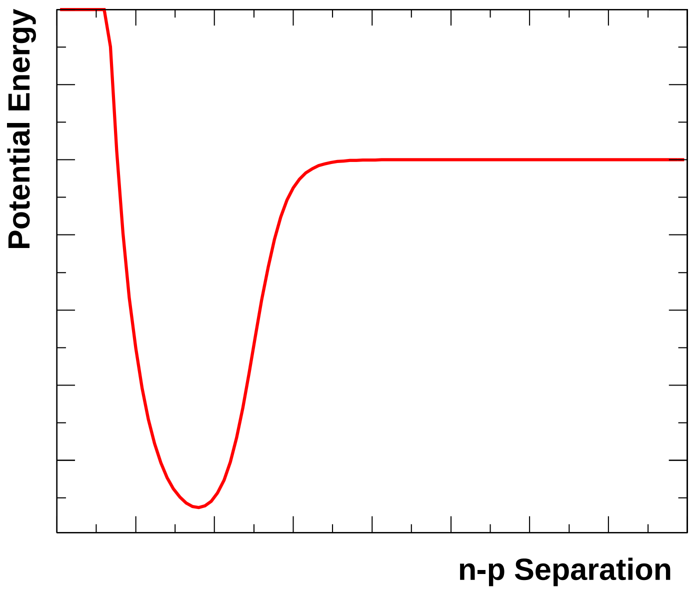
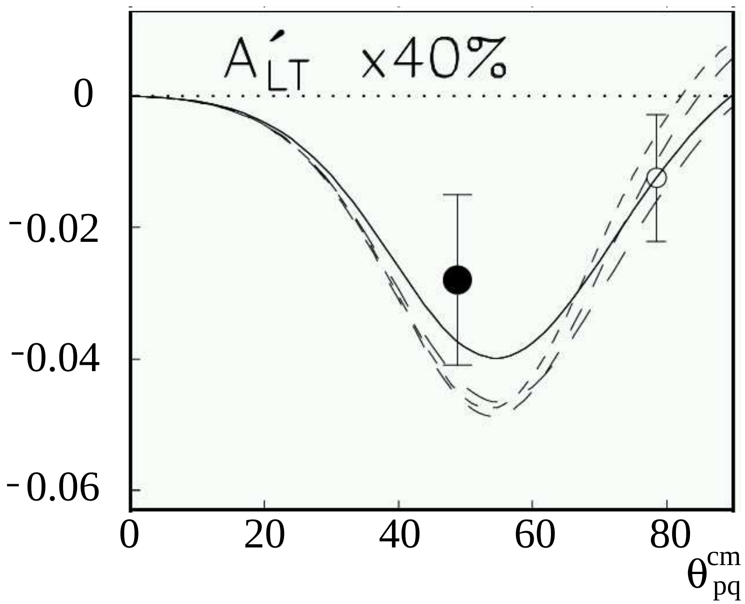


Experimental Status

- Some measurements have already been made for $Q^2 \approx 0.1 - 0.3\ (GeV/c)^2$, but suffer from limited statistics or angular range. The plot is from S.Gilad, *et al.*, NP **A631**, 276c, 1998.



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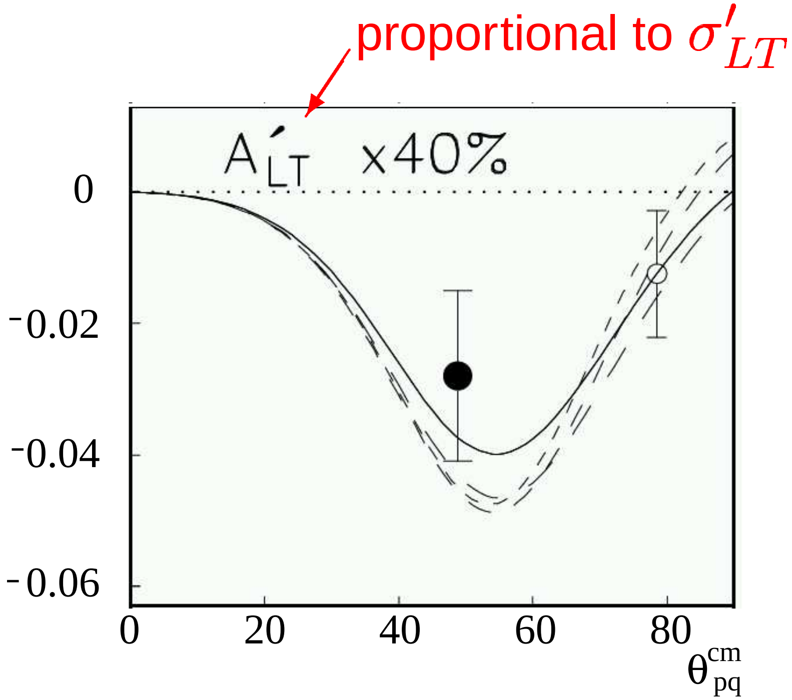

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Measuring Electrodisintegration of the Deuteron

- Running conditions:

  $E = 4.23\ GeV$

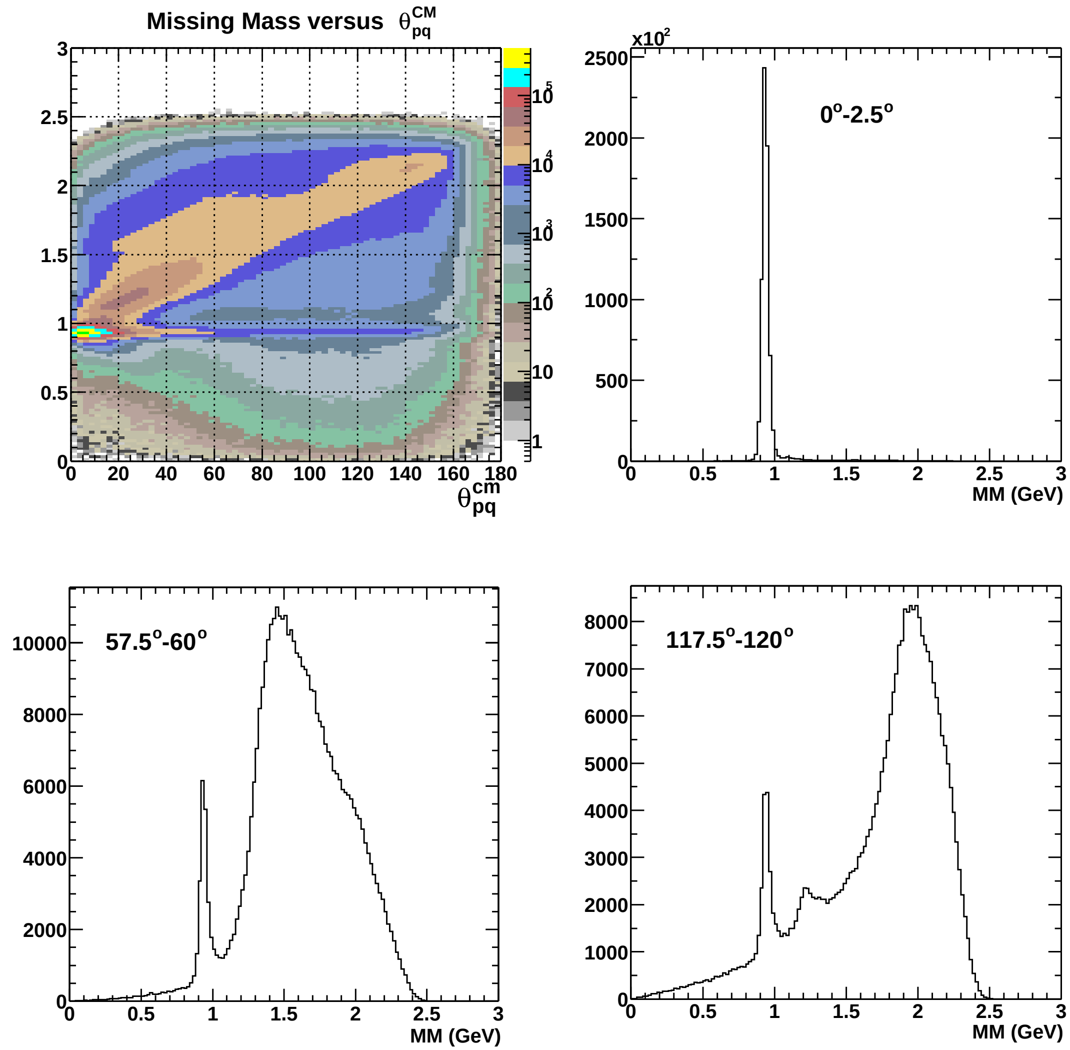
  $E = 2.6\ GeV$

  deuteron target

  polarized beam

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

- Detect the scattered electron and proton.
- Use conservation laws to identify what's left over to find the neutron (missing mass).



Living in an Imperfect World

- The CLAS acceptance distorts the cross section with a sinusoidally-varying component so

$$\langle \sin\phi_{pq} \rangle_{\pm} = \frac{\int_{-\pi}^{\pi} \sigma^{\pm} \sin\phi_{pq}(1 + a\sin\phi_{pq})d\phi}{\int_{-\pi}^{\pi} \sigma^{\pm}(1 + a\sin\phi_{pq})d\phi}$$

- The integral in the numerator is

$$\int_{-\pi}^{\pi} [\sigma_L + \sigma_T + \sigma_{LT}\cos(\phi_{pq}) + \sigma_{TT}\cos(2\phi_{pq}) + h\sigma'_{LT}\sin(\phi_{pq})] \sin\phi_{pq}(1 + a\sin\phi_{pq})d\phi = \pm\pi\sigma'_{LT} + a\pi(\sigma_L + \sigma_T)$$

and the one in the denominator is

$$\int_{-\pi}^{\pi} [\sigma_L + \sigma_T + \sigma_{LT} \cos(\phi_{pq}) + \sigma_{TT} \cos(2\phi_{pq}) \\ + h\sigma'_{LT} \sin(\phi_{pq})](1 + a \sin \phi_{pq}) d\phi \\ = 2\pi(\sigma_L + \sigma_T) \pm a\pi\sigma'_{LT}$$

Living in an Approximate, Imperfect World

- Now combine these results so

$$\langle \sin \phi_{pq} \rangle_{\pm} = \frac{\pm\pi\sigma'_{LT} + a\pi(\sigma_L + \sigma_T)}{2\pi(\sigma_L + \sigma_T) \pm a\pi\sigma'_{LT}}$$

and we can punt the second term in the denominator since $\sigma'_{LT} \ll \sigma_L + \sigma_T$ and $a \ll 1$. This gives us

$$\begin{aligned}\langle \sin \phi_{pq} \rangle_{\pm} &= \frac{\pm\pi\sigma'_{LT}}{2\pi(\sigma_L + \sigma_T)} + \frac{a\pi(\sigma_L + \sigma_T)}{\pi(\sigma_L + \sigma_T)} \\ &= \pm\frac{A'_{LT}}{2} + a\end{aligned}$$

We're there!

- Consider

$$\begin{aligned}\langle\sin\phi_{pq}\rangle_+ - \langle\sin\phi_{pq}\rangle_- &= (\frac{A'_{LT}}{2}+a) - (-\frac{A'_{LT}}{2}+a) \\ &= A'_{LT}\end{aligned}$$

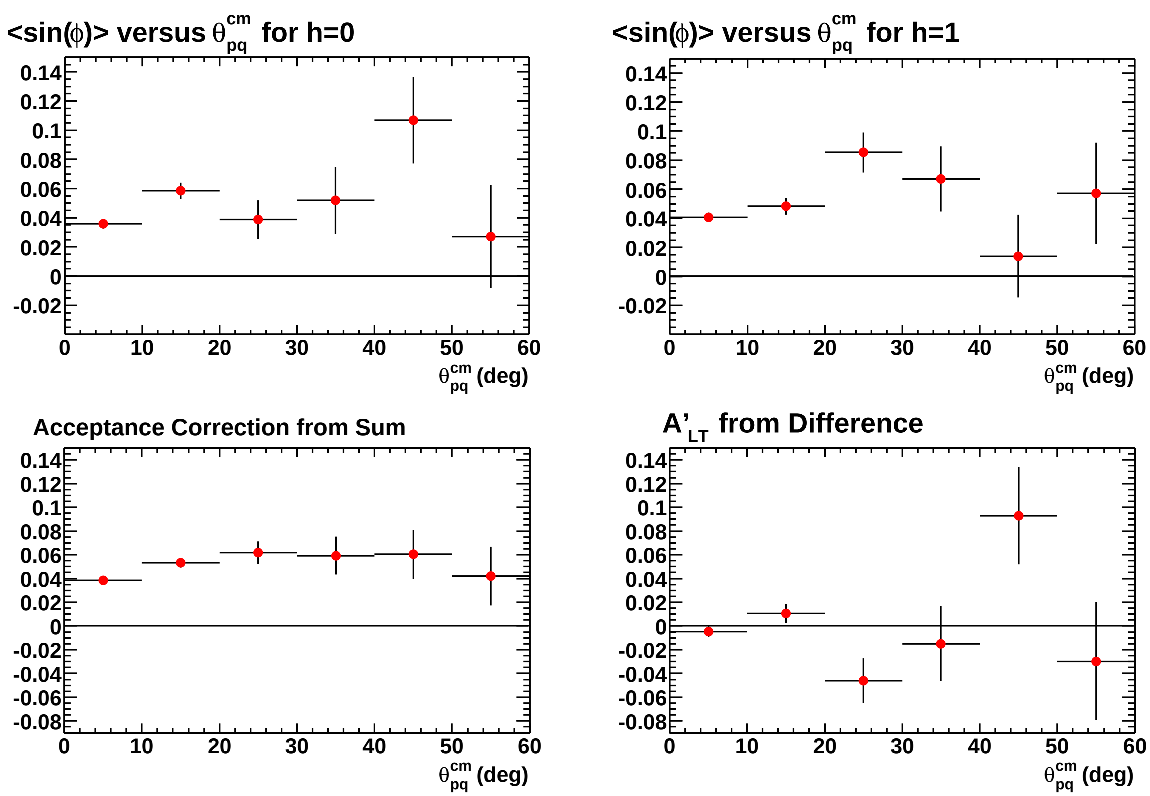
and

$$\begin{aligned}\langle\sin\phi_{pq}\rangle_+ + \langle\sin\phi_{pq}\rangle_- &= (\frac{A'_{LT}}{2}+a) + (-\frac{A'_{LT}}{2}+a) \\ &= 2a\end{aligned}$$

$\langle \sin\phi_{pq} \rangle_{\pm}$ Moments Analysis For A'_{LT}

- For a sinusoidally-varying component to the acceptance $$\langle \sin\phi_{pq} \rangle_{\pm} = \pm \frac{A'_{LT}}{2} + a \quad .$$

- 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 Asymmetry Analysis for A'_{LT}

- 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 analysis may be more complex since denominator depends on ϕ_{pq}.

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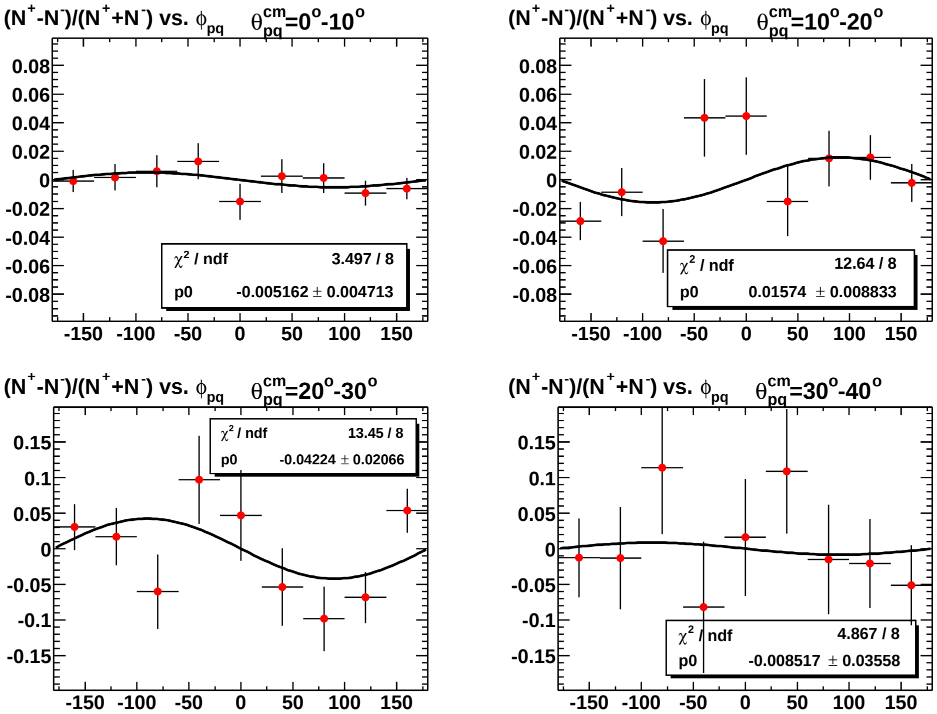

Comparison of Different Analysis Methods for A'_{LT}

- The shapes and uncertainties are consistent. We can measure small A'_{LT}.

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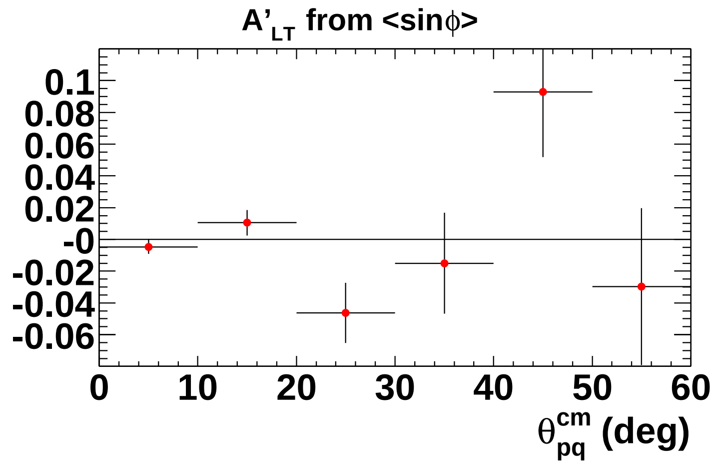
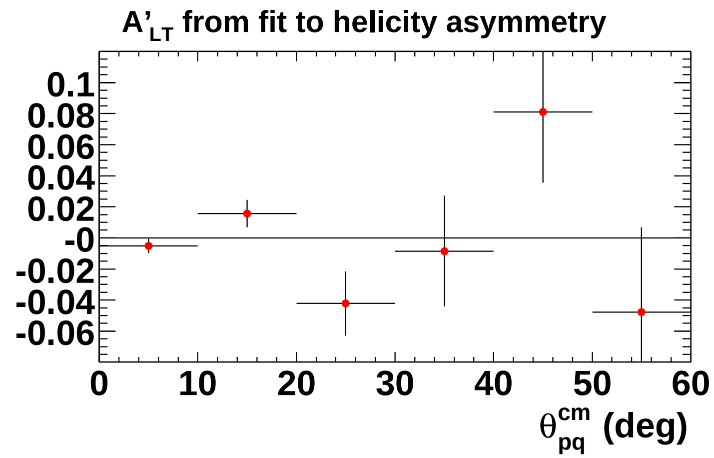




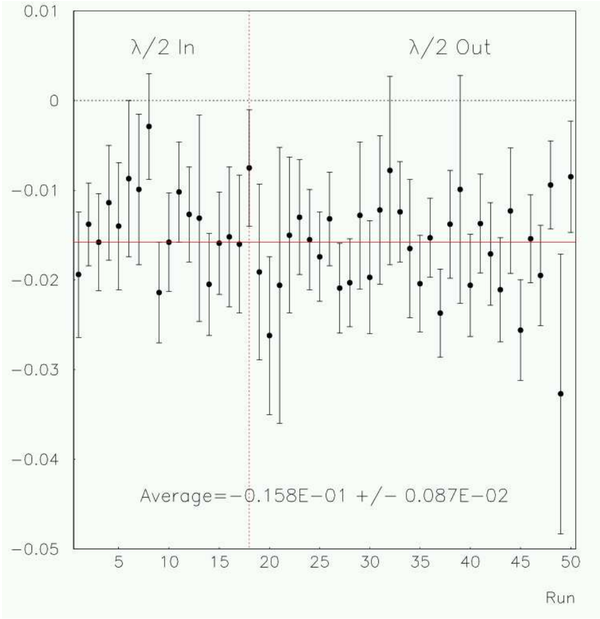
Analysis Cross Checks for A'_{Lt}

- $ep \to e'p\pi^0$
- Test our analysis against the known results from 'Single π^0 Electroproduction in the $\Delta(1232)$ Resonance from E1A Data' by K. Joo and C. Smith (CLAS Analysis 2001-008).
- Check the helicity signal on a run-by-run basis.
- Takes advantage of the *in situ* hydrogen calibration target.
- Similar data selection, but requires Bethe-Heitler suppression to use missing mass to measure the π^0.

Comparison of Asymmetries Run By Run.

- K. Joo and C. Smith

  for 1.52 GeV (upper panel).



- This analysis for

  2.6 GeV, reversed

  field (lower panel).

- Our results for A'_{LT} are consistent with K. Joo and C. Smith in sign (the two experiments use different ϵ and Q^2 ranges) and with helicity sign recorded in the elog.