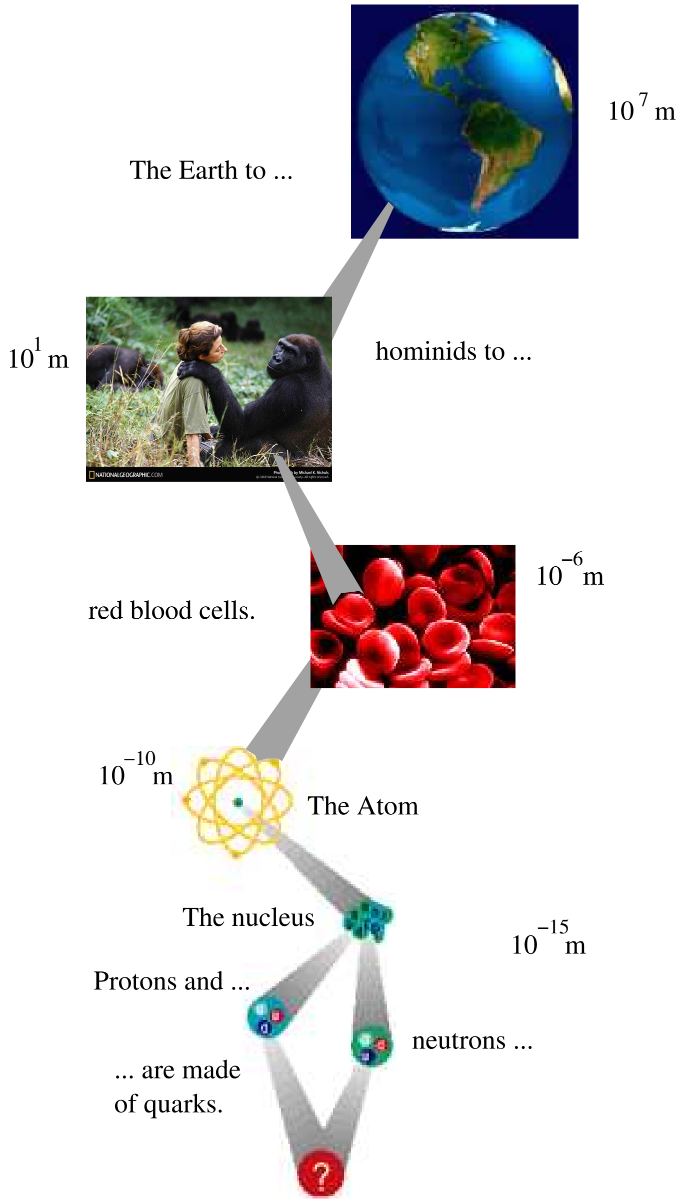
Hunting for Quarks

Jerry Gilfoyle, University of Richmond

"The Periodic Table"

What Do We Know?



What Else Do We Know?

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

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

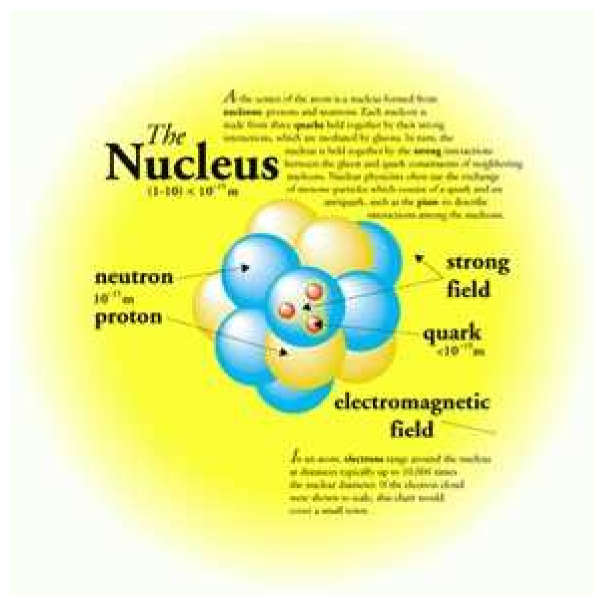
Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

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

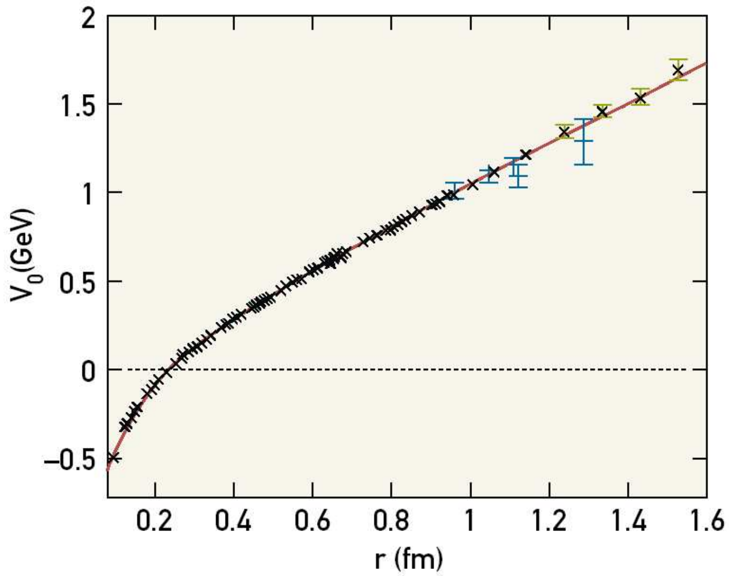
- The atomic nucleus is made of protons and neutrons bound by the strong force.
- The quarks are confined inside the protons and neutrons.



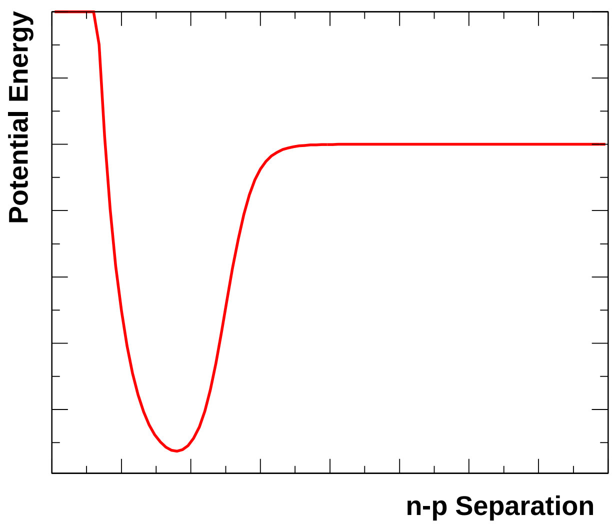
- Protons and neutrons are NOT confined.

What is the Force?

- Quantum chromodynamics (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 force between quarks.



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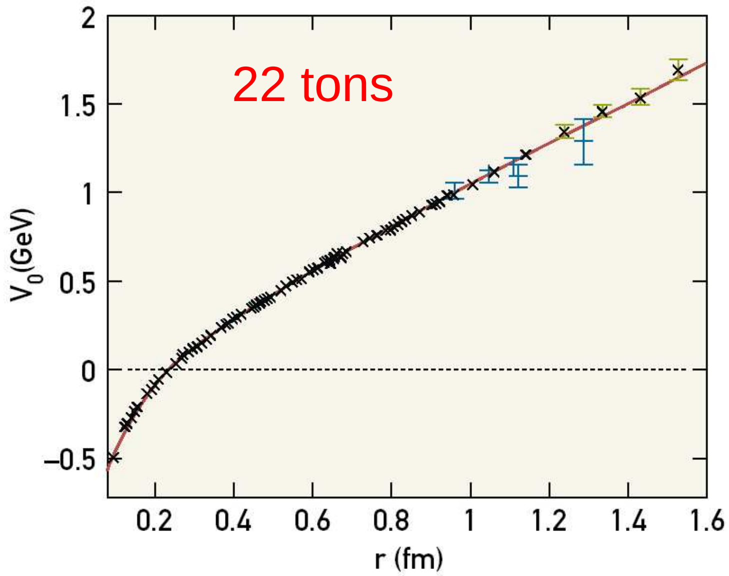

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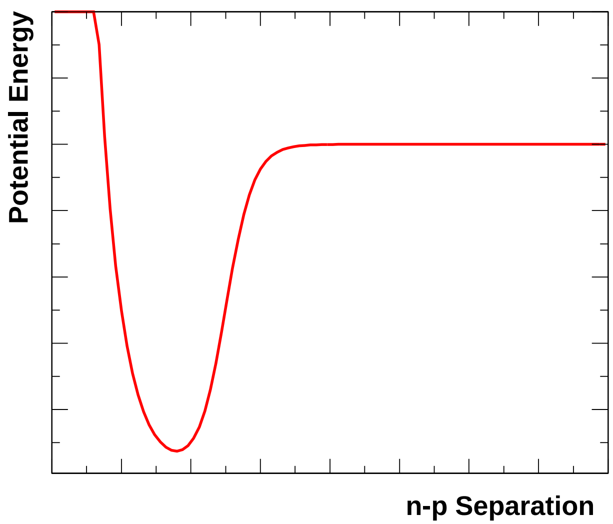
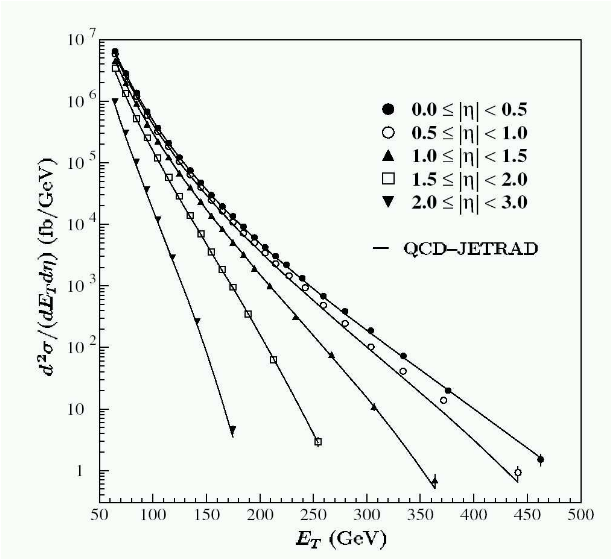


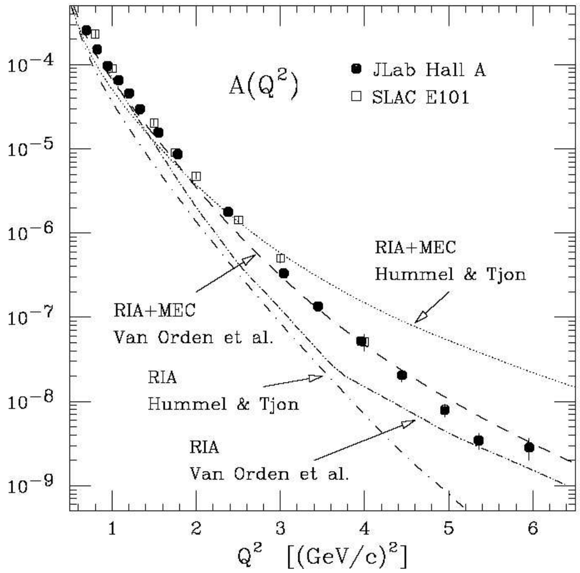
How Well Do We Know It?

- 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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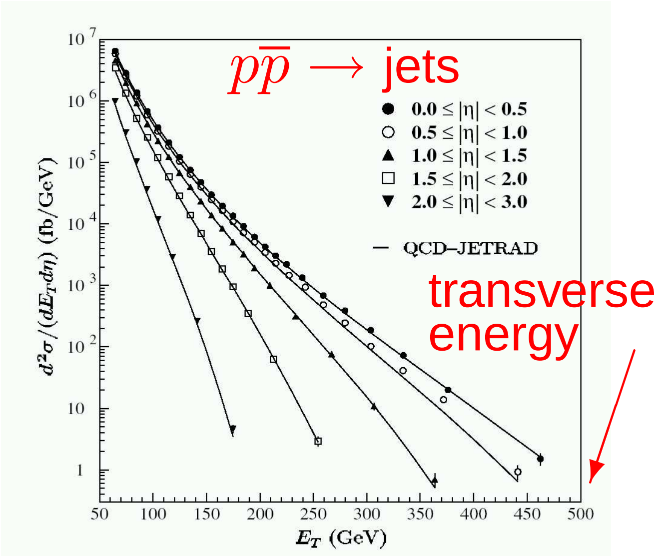

effective area of the target

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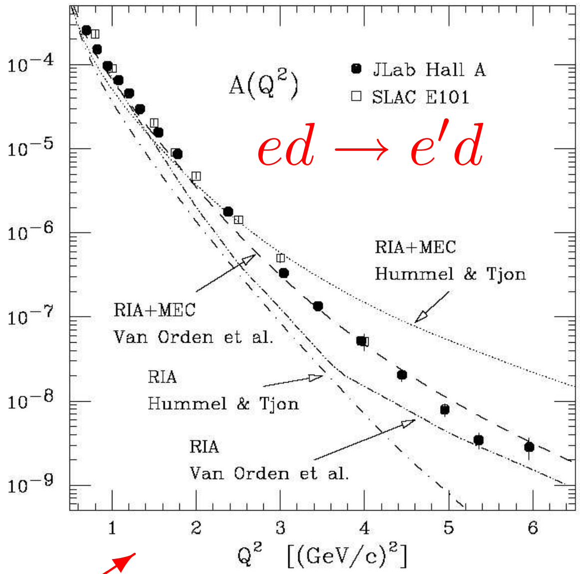


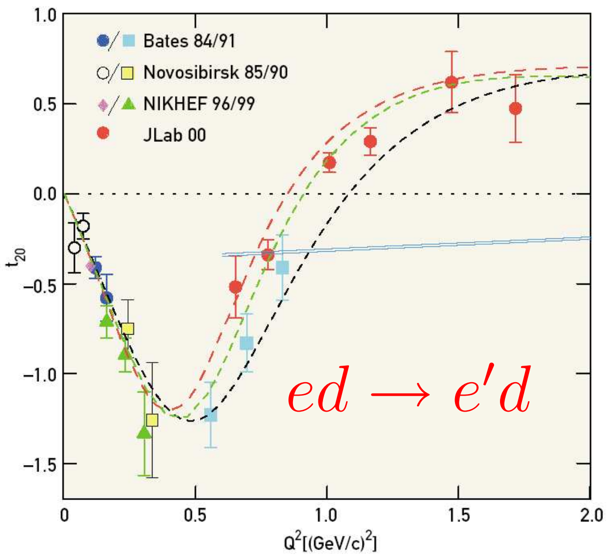
4-momentum transfer squared

What Don't We Know?

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

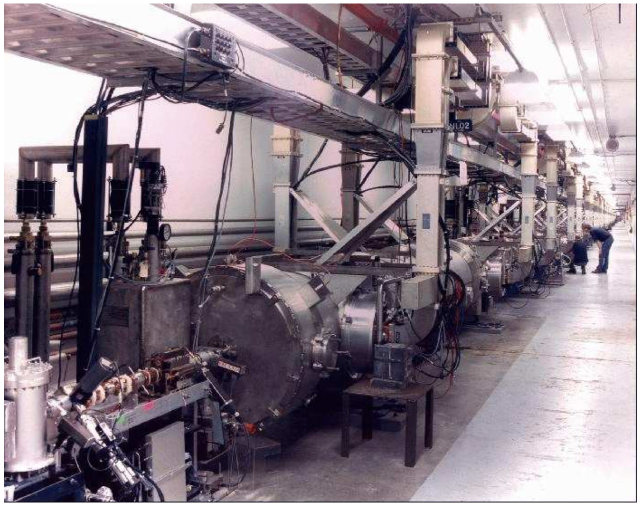
   D. Abbott, *et al.*, Phys. Rev Lett. **84**, 5053 (2000).

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



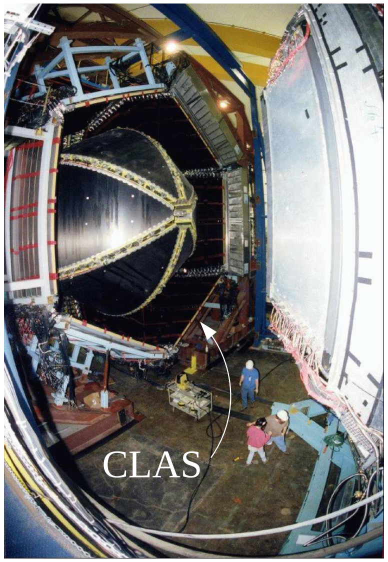
Experiments at Jefferson Lab

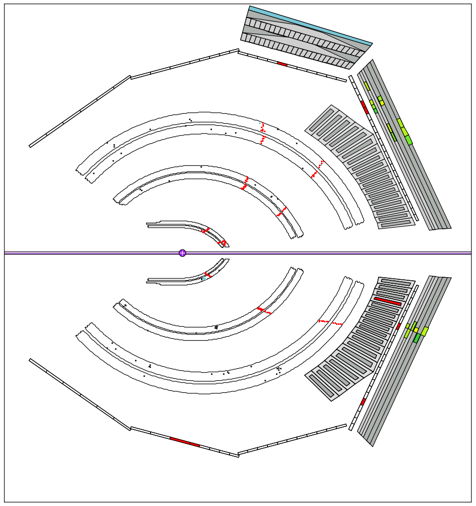
- Jefferson Lab is a US Department of Energy national laboratory and the newest ‘crown jewel’ of the US.
- The centerpiece is a 7/8-mile-long, racetrack-shaped electron accelerator that produces unrivaled beams.
- The electrons do up to five laps around the Continuous Electron Beam Accelerator Facility (CEBAF) and are then extracted and sent to one of three experimental halls.
- All three halls can run simultaneously.



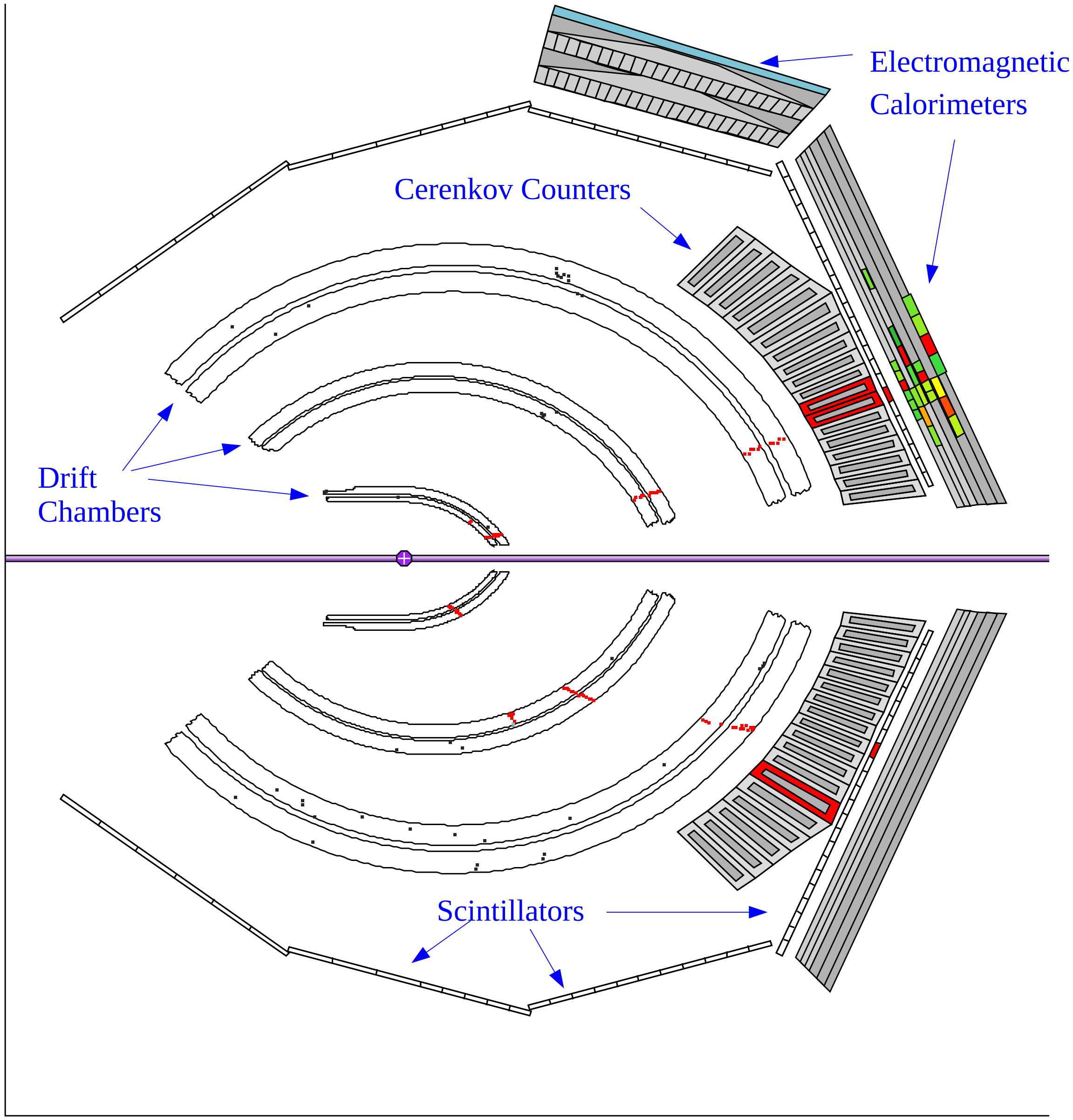
The CEBAF Large Acceptance Spectrometer (CLAS)

- 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.
- Other layers measure energy, time-of-flight, and particle identification.
- Each collision is reconstructed and the intensity pattern reveals the forces and structure of the colliding particles.

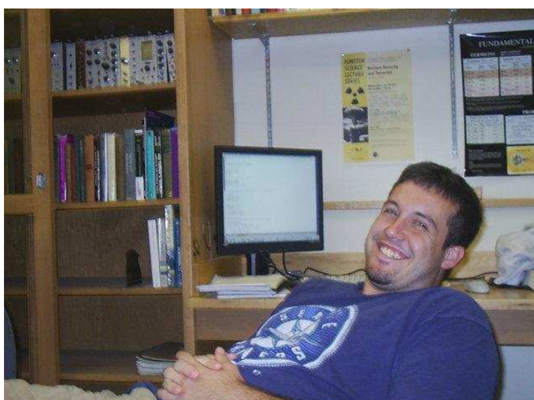


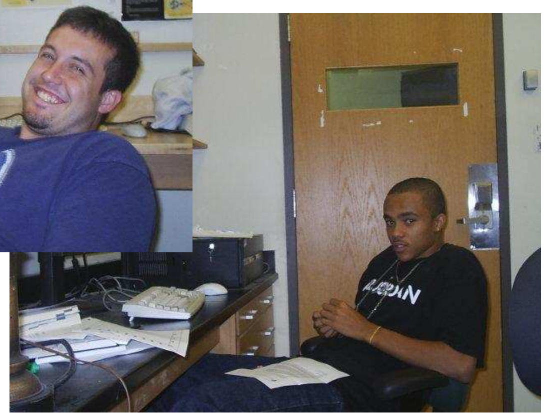


A CLAS Event


Electromagnetic
Calorimeters
Cerenkov Counters
Drift
Chambers
Scintillators

Life on the Frontiers of Knowledge

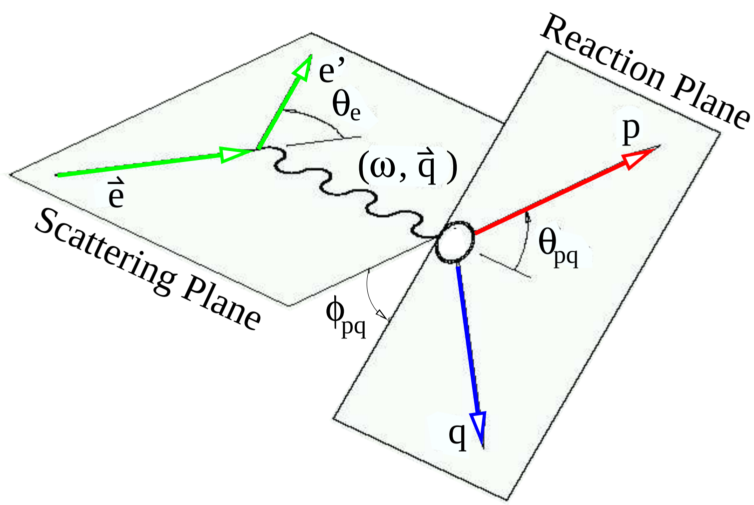




Measuring the Fifth Structure Function in $d(\vec{e}, e'p)n$ - Introduction

- Goal: Measure the imaginary part of the LT interference term of $d(\vec{e}, e'p)n$ to test the hadronic model at low Q^2 ($\approx 1\ (GeV/c)^2$).

- Use the out-of-plane production to extract the fifth structure function.



- Cross section:

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

Introduction - 2

- Asymmetry

$$A'_{LT} = \frac{\sigma_{90}^{+} - \sigma_{90}^{-}}{\sigma_{90}^{+} + \sigma_{90}^{-}} \approx \frac{\sigma'_{LT}}{\sigma_L + \sigma_T} = \langle \sin\phi_{pq} \rangle_{+} - \langle \sin\phi_{pq} \rangle_{-}$$

Subscripts - ϕ_{pq}. Superscripts - beam helicity.

- Analyze data from the E5 run period in Hall B.
  - Recorded about 2.3 billion triggers, $Q^2 = 0.2 - 5.0 (GeV/c)^2$.
  - Dual target cell with liquid hydrogen and deuterium.

Event Selection and Corrections

For 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 fi ducial	$\|dc\_ysc\| \leq 165(dc\_xsc - 80)/280$
	EC fi ducial	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 fi ducial	Same method as D. Protopopescu, *et al.*, CLAS-Note 2000-007.
	Quasi-elastic scattering	$0.92\, GeV \leq W \leq 1.0\, GeV$
	Select target	$-11.5\, cm < v_z < -8.0\, cm$
	Momentum corrections	Pitt (CLAS-Note 2001-018) and elastic-scattering methods
For protons:	Proton fi ducial cut	Same method as R. Nyazov and L.Weinstein, CLAS-NOTE 2001-013.
	ep vertex cut	$\|v_z(e) - v_z(proton)\| \leq 1.5\, cm$
	Momentum corrections	Pitt (CLAS-Note 2001-018) method
For neutrons:	Missing mass cut	$0.84\, GeV^2 \leq MM^2 \leq 0.92\, GeV^2$
Beam charge asymmetry:	2.6 GeV, reversed fi eld:	0.9936 ± 0.0007
	2.6 GeV, normal fi eld:	0.9944 ± 0.0007
	4.2 GeV, normal fi eld	0.9987 ± 0.0009
Radiative corrections:	EXCLURAD	Adding helicity dependent model
Beam polarization:	All Runs	0.736 ± 0.017

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

Recall

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

Let

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

For a sinusoidally-varying component to the acceptance

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

so

$$\langle \sin\phi_{pq} \rangle_{+} - \langle \sin\phi_{pq} \rangle_{-} = A'_{LT} \quad \text{and} \quad \langle \sin\phi_{pq} \rangle_{+} + \langle \sin\phi_{pq} \rangle_{-} = 2\alpha_{acc}$$

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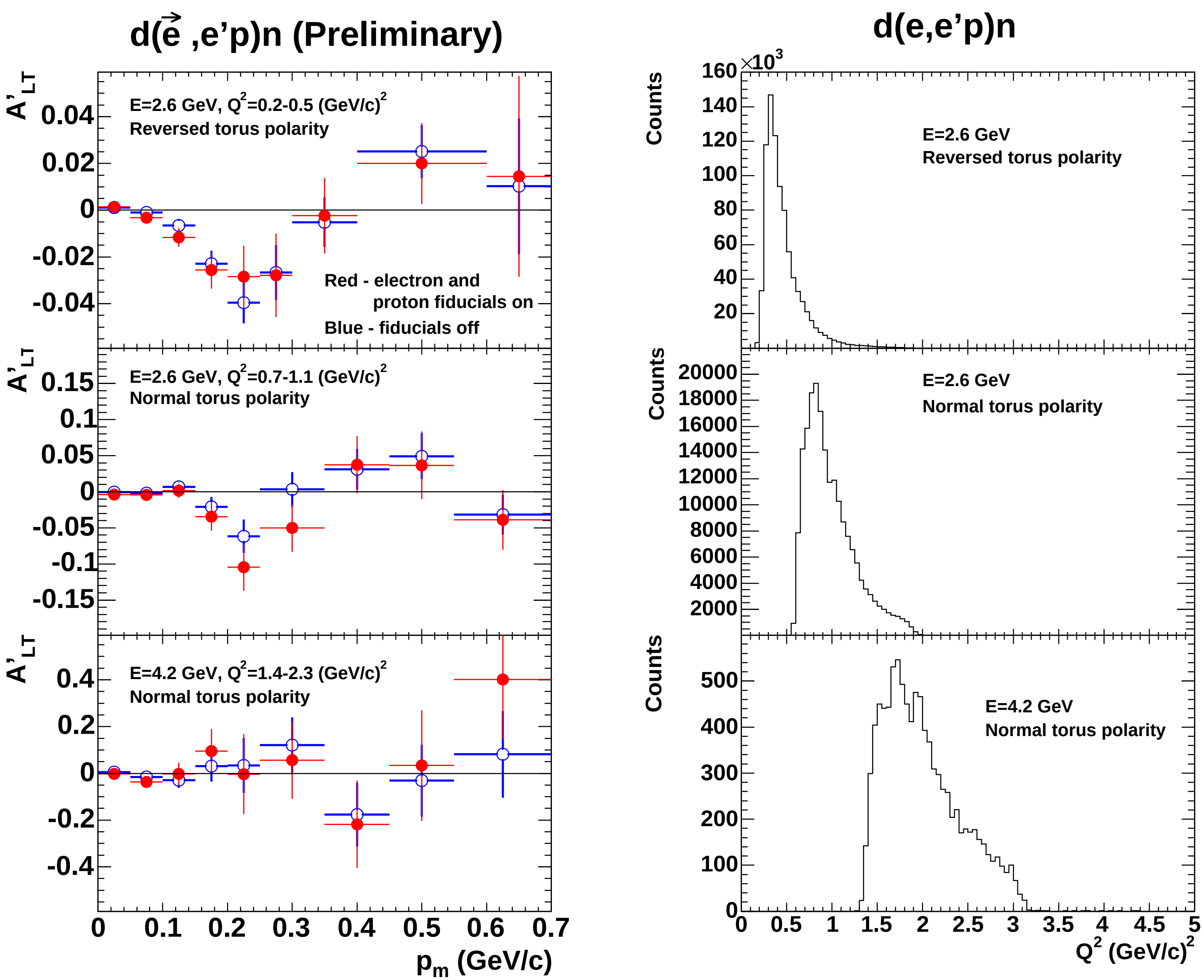
A'_{LT} Results for $d(\vec{e}, e'p)n$



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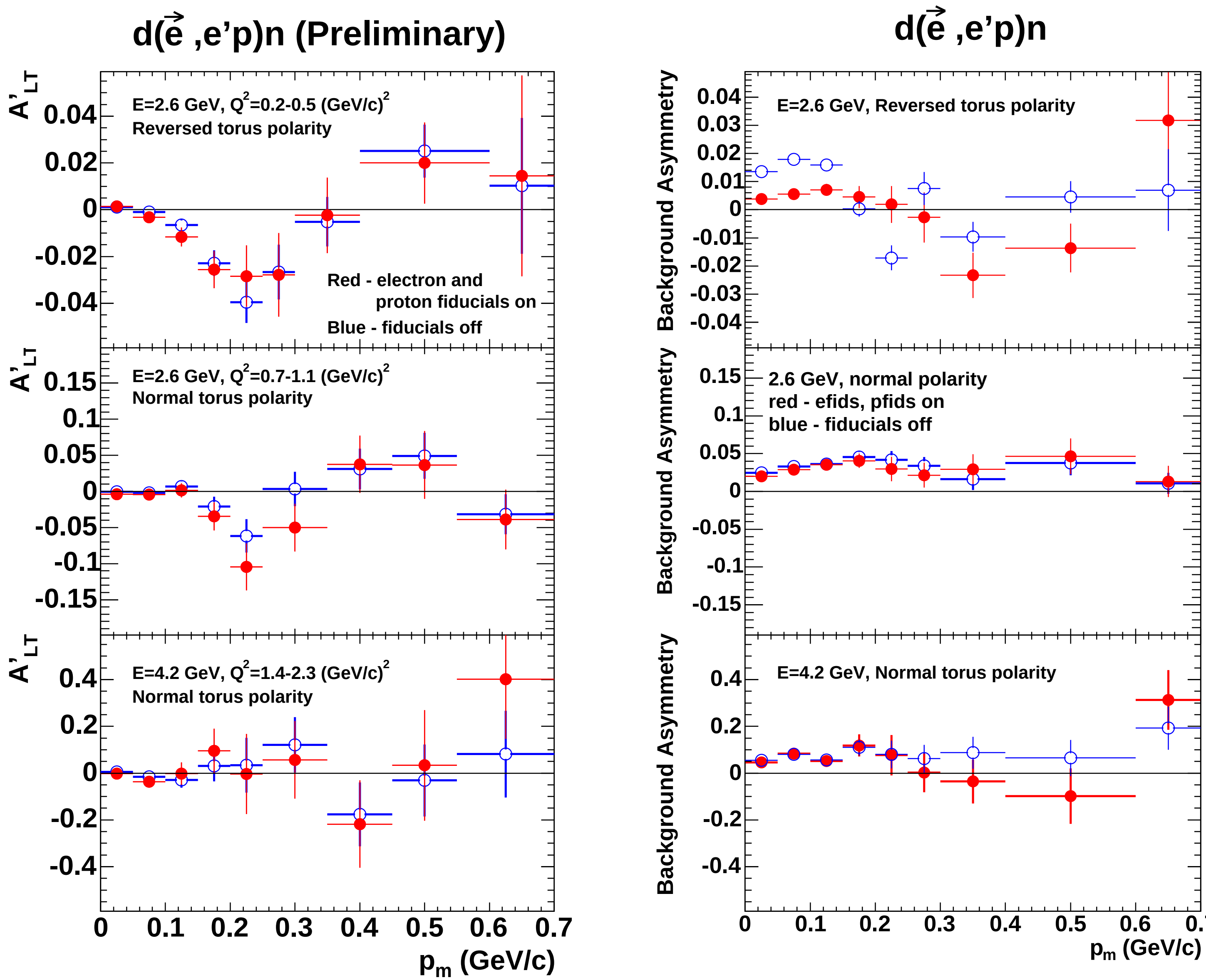
Asymmetry Background Results



Hartmuth Arenhoevel calculations of A'_{LT}

1. Numerical solution of the Schroedinger equation using some parameterization of the NN interaction like the Paris potential (NORMAL).

2. Additional components are then added to this starting point.

   (a) Meson exchange currents (MEC).

   (b) Isobar configurations (IC).

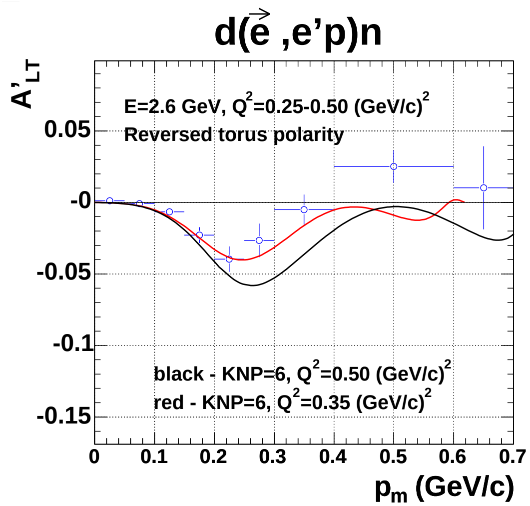
   (c) Final state interactions (FSI).

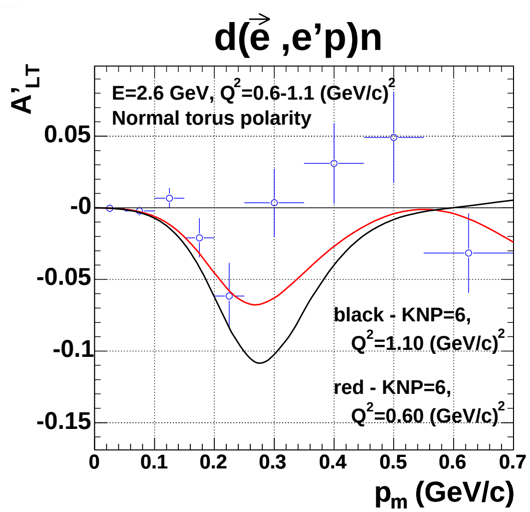
3. Relativistic corrections (RC) are also made to the nucleon charge and current densities.

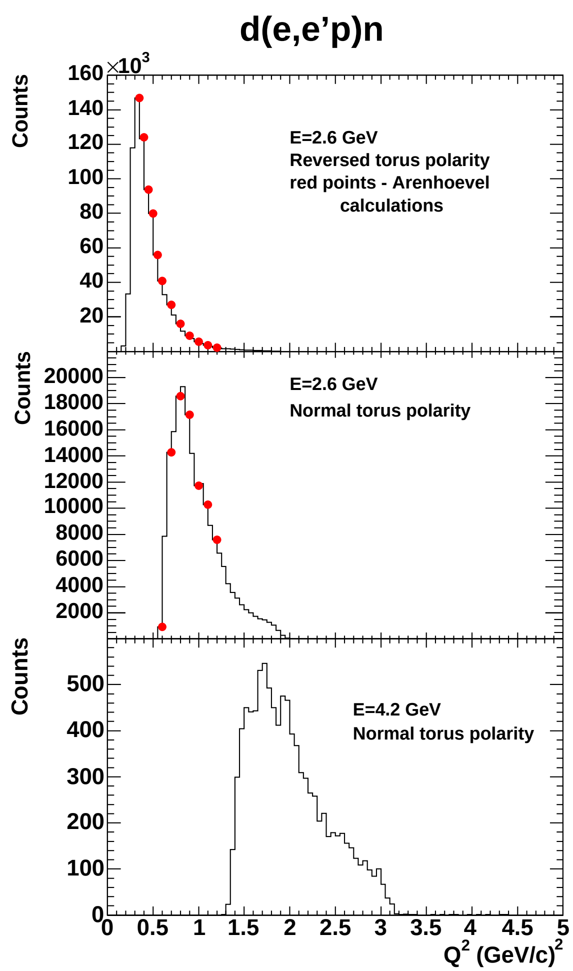
4. In the figures to follow, all of the ingredients listed above are included (KNP=6).

Comparison with Theory - Limiting Curves

Hartmuth Arenhoevel calculations

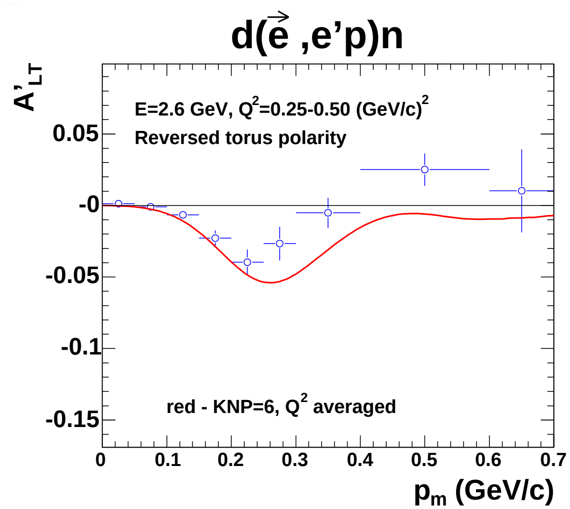


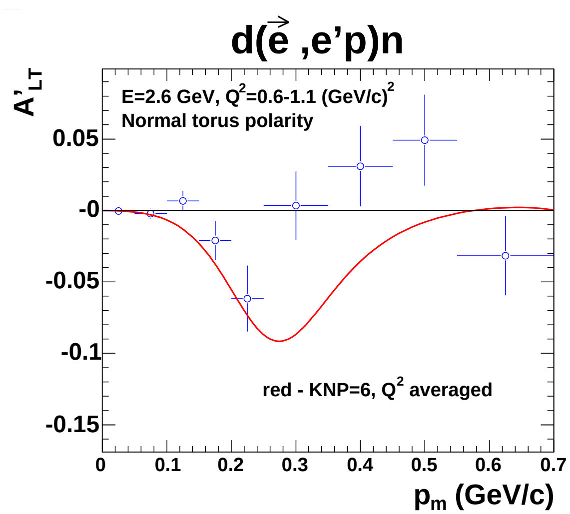


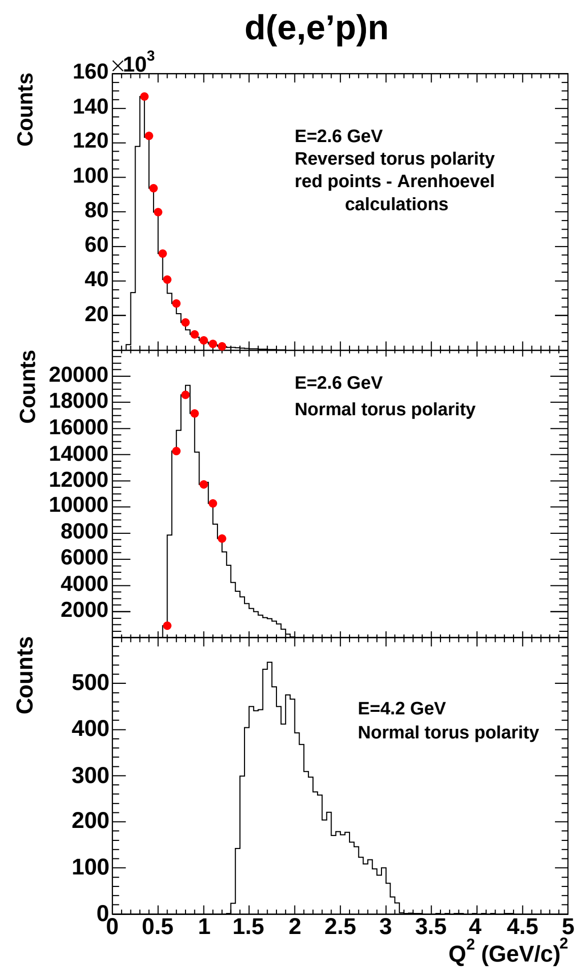


Comparison with Theory - Q^2-Averaged Curves

Hartmuth Arenhoevel calculations

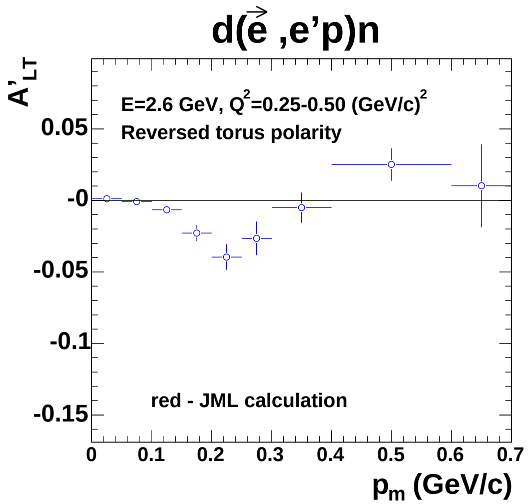


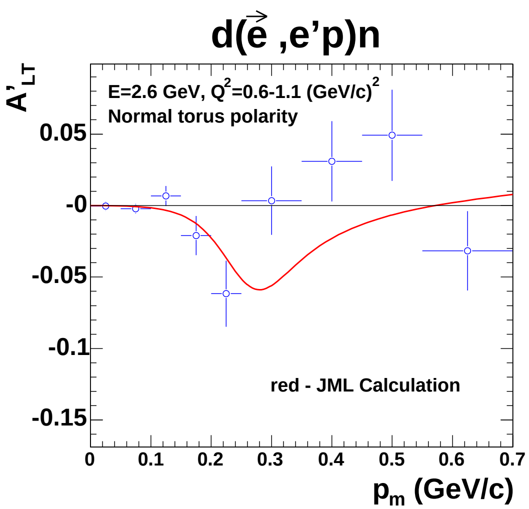


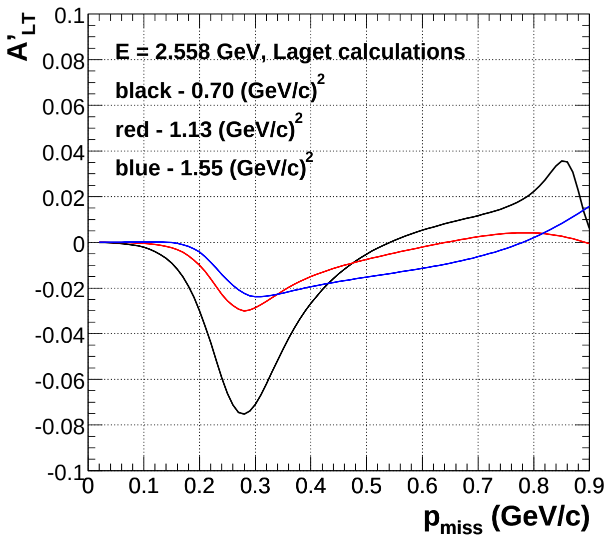


Comparison with Theory - Q^2-Averaged Curves

Jean-Marc Laget calculations



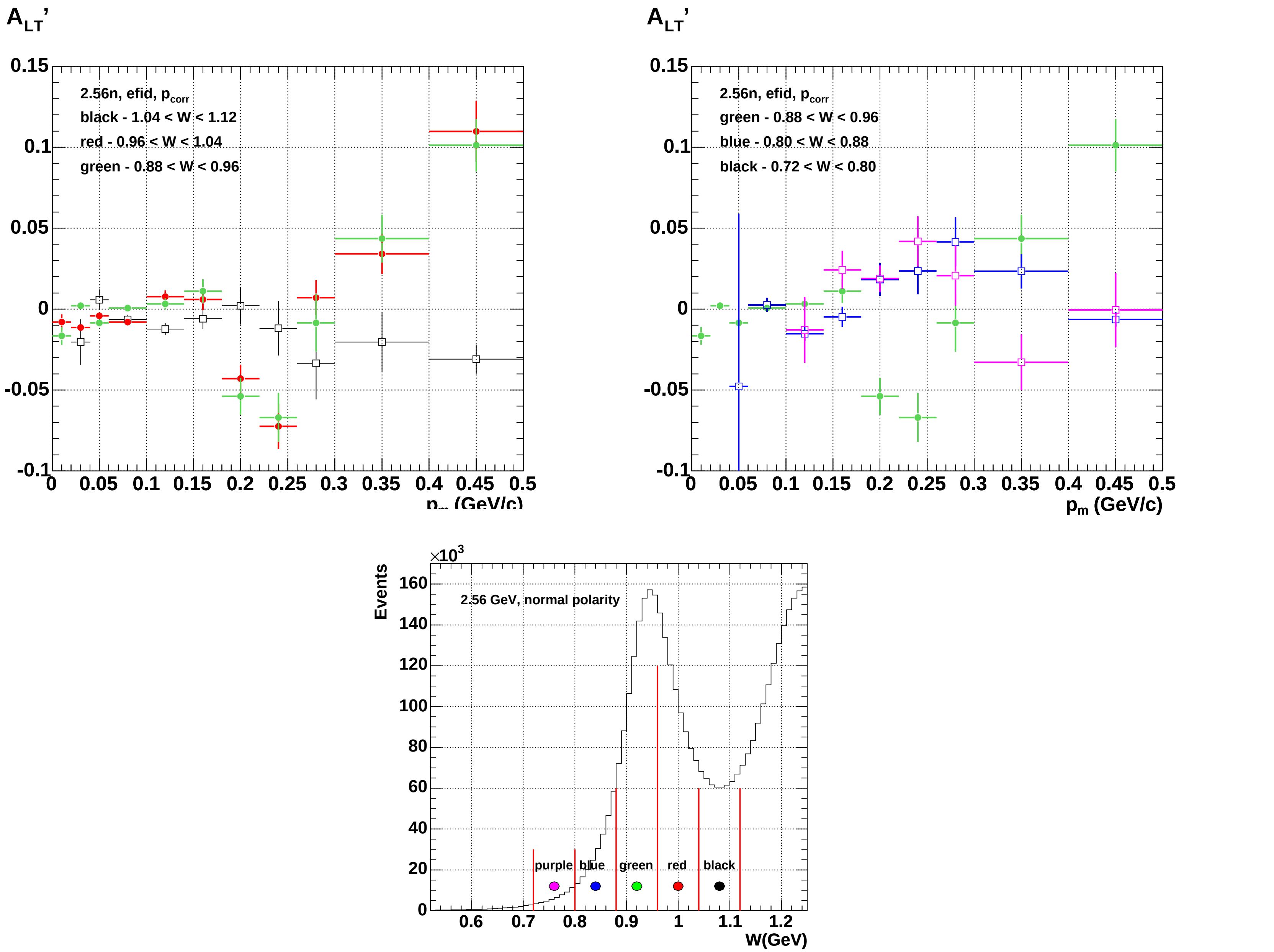




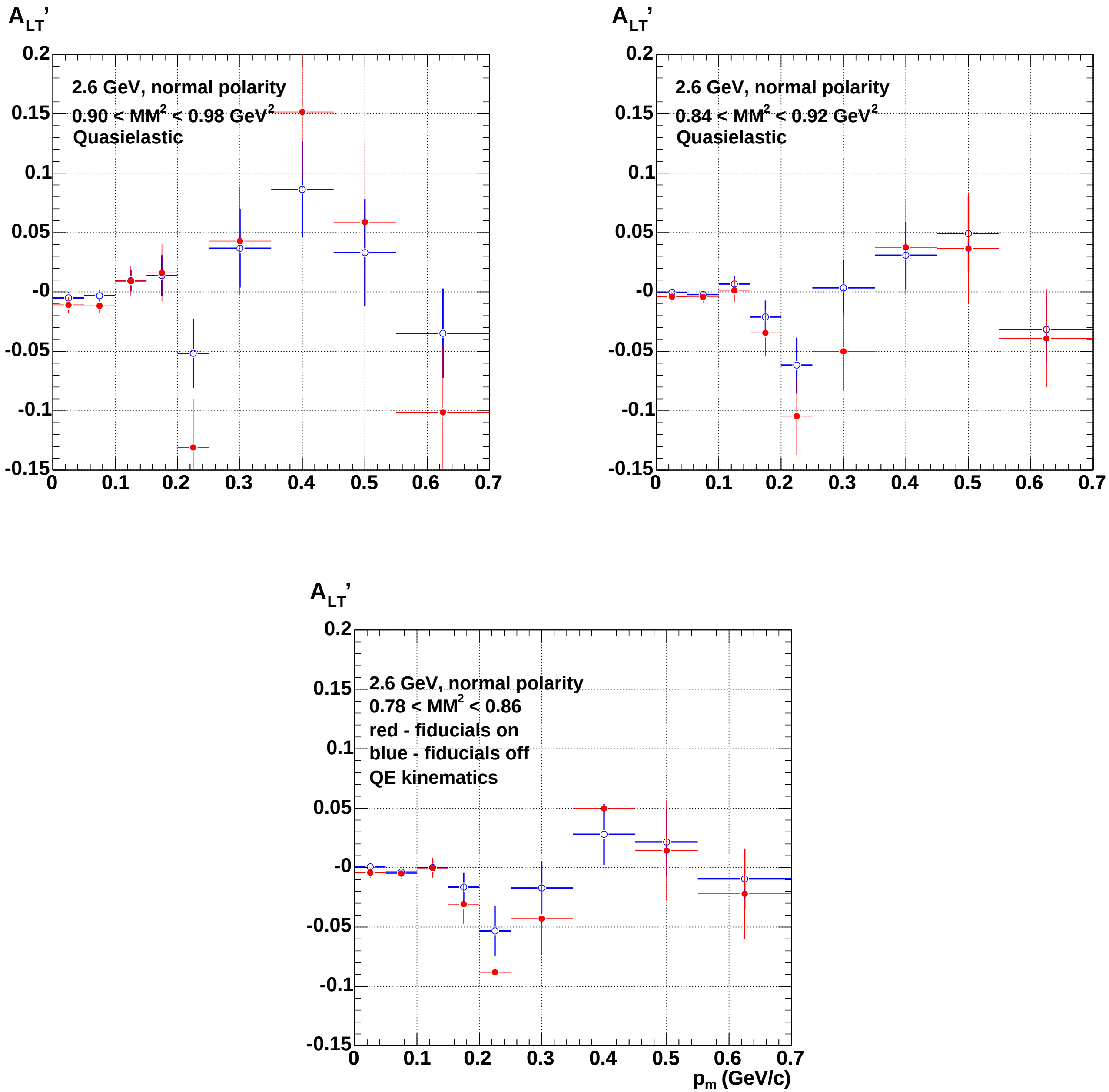
Conclusions

- We observe a 4-6% dip in A'_{LT} at $p_m \approx 220\ MeV/c$ in the lower Q^2 data sets. At higher energy, we can't draw conclusions because of the large statistical uncertainties.
- The $\langle \sin(\phi_{pq} \rangle$ technique works well including the subtraction of the two different beam helicities to eliminate acceptance effects.
- The background asymmetry is sensitive to the fiducial cuts for the reversed torus polarity running conditions, but not for the normal torus polarity running (within statistics).
- At low missing momentum p_m, the calculations by Arenhoevel and Laget reproduce the data, but diverge (they're too negative) above $p_m = 250\ MeV/c$. The dip we observe in A'_{LT} is not well understood.
- The source of the background asymmetry is under investigation.

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



MM^2 dependence of A'_{LT} at the Quasi-elastic Peak



Fifth Structure Function Asymmetry for $d(\vec{e}, e'p)n$

- Measured A'_{LT} for the $d(\vec{e}, e'p)n$ reaction for the E5 running period.
- See a dip in A'_{LT} at $p_m \approx 220\ MeV/c$ in the lower Q^2 data.
- Background asymmetry extracted for each set of running conditions. We see significant difference for reversed torus polarity running.
- Existing calculations from Arenhoevel and Laget diverge from the data at $p_m > 2$