Experimental Signatures of the Limits of the Hadronic Description of Nuclei

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- Introduction – pedagogy, things (I hope) we all agree on
- Inclusive (e,e') and NN scattering
- My bias – when hadronic theories break down
- Some experimental results and interpretation
- Summary

The Hadronic-Models-Can-Always-Work-in-Principle Principle

- We always measure hadrons (and leptons) in and out; they are the physical states; we never see individual quarks in our detectors.
- Since we measure matrix elements between hadronic states, hadronic theory always possible.
- Problem: standards are high; is the hadronic theory reasonable?
- Hadronic bias: need to ``prove'' no reasonable hadronic theory can work.

The Quark-Gluon-Models-Can-Always-Work-in-Principle Principle

- Hadrons are made of quarks and gluons.
- The hadrons in the theory can always in principle be replaced by a more detailed description using the underlying quark/gluon degrees of freedom.
- Quark bias: hadronic theories are approximate effective theories; of course quark theories can work. They are better since they provide a deeper understanding of the physics..

The What-Works-Most Conveniently Principle

- We can in principle use either hadrons or quarks and gluons in our theories.
- Perhaps an **acceptable** theory can be constructed with both, or one of the two, or neither of the two sets of degrees of freedom.
- Quarks vs. hadrons is a matter of practice, not a matter of principle.
- We wish to find rules that tell us which theory is likely most convenient.

Experimental Signatures ...

- If either quark or hadron degrees of freedom can be used ... then there are **no** clean experimental signatures of a limit.
- Disagreement between data and theory just means theorists have not managed to generate a sufficiently complete, consistent theory. It does not mean the theory cannot work.

Inclusive vs. Exclusive Scattering?

- Although much of the discussion of hadrons vs. quarks/gluons occurs in the context of exclusive reactions, there are similar issues in inclusive scattering
- In (e,e') at E = several GeV and Q^2 = several GeV^2, we know pQCD describes inclusive scattering, but not the exclusive final states that are summed over

What We Learn from Inclusive Scattering. I

- At large Q^2 and large W, we see deep inelastic scattering from quarks.
- At small Q^2 and large W, we see baryon resonances.
  - Duality: average over hadronic resonances = quarks.
- At $W=m_p$ we see the proton, but we generally use quark models to understand its properties.

What We Learn from Inclusive Scattering. II

- So we can always use some appropriate quark model to understand the p(e,e')X reaction... but at large Q^2 and large W, we **need** to use quarks.
- At smaller W, we see the proton / baryon resonances, and hadronic theories also are sensible.

Exclusive Reactions: NN Scattering

- We have good hadronic models of the NN interaction with both χPT at small energies, and conventional effective NN interactions over a wide range of energies.
- Modern (1990s+) NN forces are more phenomenological than the previous (1980s) generation, and provide much better, $\chi^2 \sim 1$/d.o.f., fits.

NN Scattering II

- Is the phenomenology:
- A) An acceptable cheat, to incorporate heavier meson exchanges, since the NN force is so complicated? A sum over an infinite set of meson exchanges should be equivalent to a sum over all possible quark exchanges.
- B) Or an indication that there are important quark effects, which will always be poorly modeled in any truncated hadronic theory?
- Or both or neither? I suspect B), but I don't think the answer is absolutely clear at present.

NN Scattering III

- Even if the NN phenomenology reflects quarks, rather than heavier mesons, the NN force provides a good description of nuclear properties – see recent calculations up to *A*=12.
- It will be difficult to come to the conclusion that hadronic theories break down, and quarks are needed, if quark effects are already largely/effectively included in the NN force.

NN Scattering IV

- Guichon and Thomas, PRL 93, 132502 (2004), conclude that the NN force arising from quark-meson coupling model is similar to the parameterized NN force used by conventional nuclear physicists.
- This observation again makes clear the difficulty of casting hadronic vs quark/gluon d.o.f. in opposing roles.

My Bias

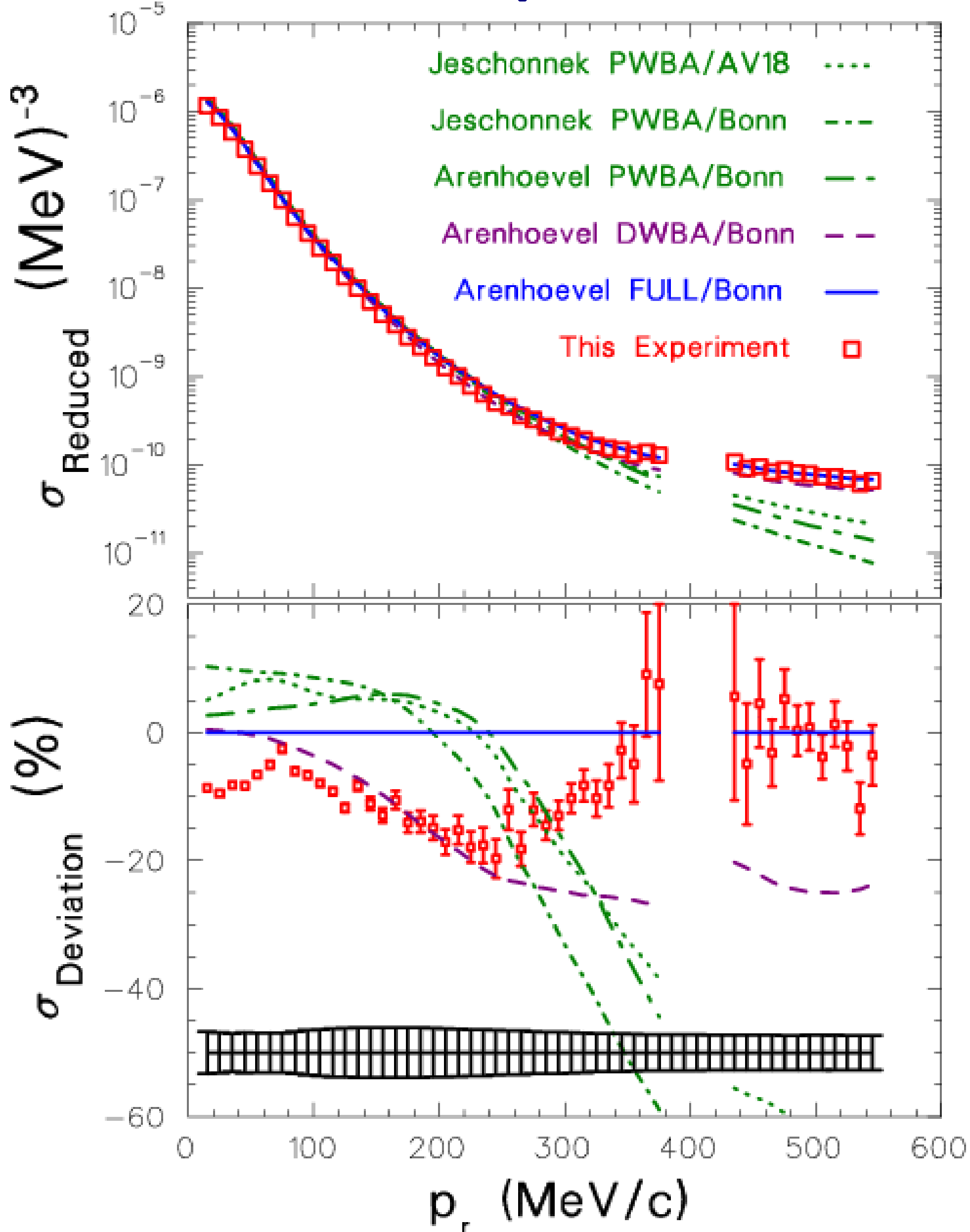
- At $W = m_p$, quasifree scattering, NN interaction already includes quark effects. Any residual quark signatures will be subtle, and conclusions about hadronic theory breakdowns will be difficult.
- If you believe that we must prove hadronic models do not work, details, like ratios or polarizations, are needed.
- At large s and t, it is inherently difficult to formulate good nuclear theory. Can we formulate a good quark theory?

Some data

- I focus on exclusive reactions. I assume QF (e,e') discussed in great detail elsewhere.
- d(e,e'p)
- ^{3}He(e,e'p)d and pn
- ^{4}He(e,e'p) polarization transfer
- elastic deuteron form factors
- d and ^{3}He photodisintegration

JLab E94-004 d(e,e'p)n

- Ulmer et al., PRL 89, 062301 (2002).
- QF ⊥ kinematics: x ~ 1, Q^2 ~ 0.7 GeV^2.
- At low p_r, ~5 % variation in PWBA, data off from full calculation ~10 %.
- Rescattering moves strength to high p_r.
- Theory not great, but no apparent **need** for quarks.

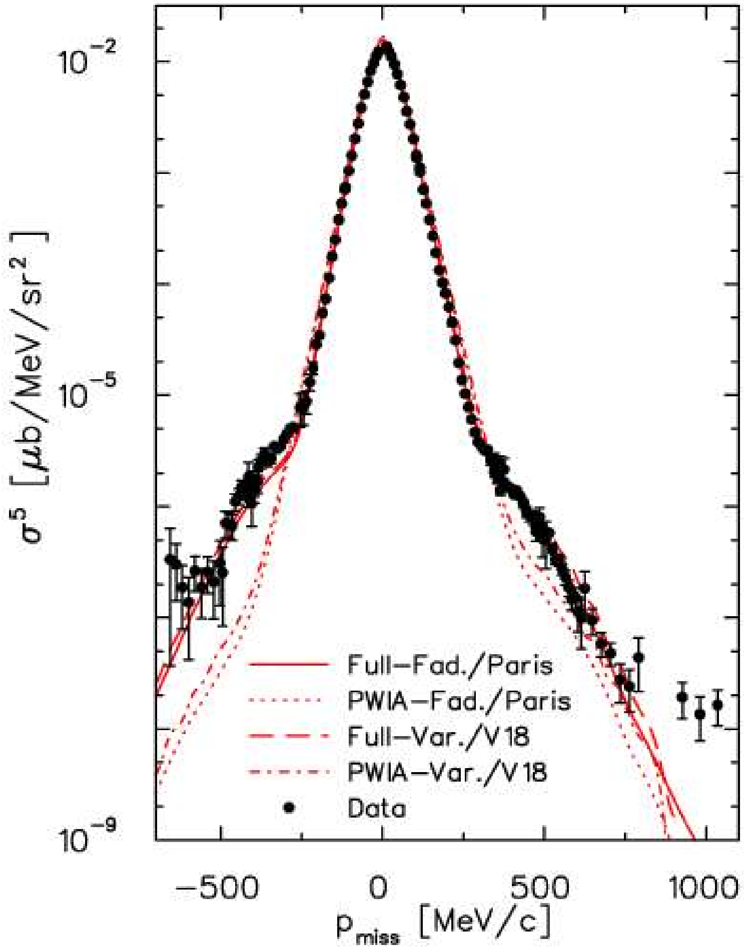


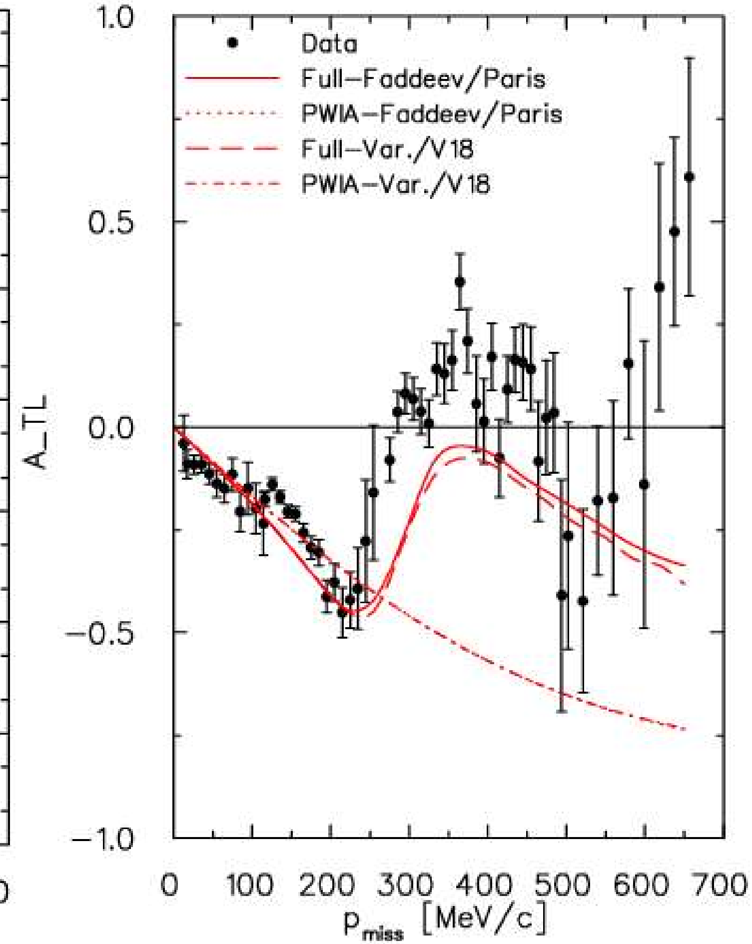
JLab E94-004 d(e,e'p)n

- General expectation: need high p_r (p_{miss}), or equivalently short range correlations, to see quark effects.
- More extensive d(e,e'p)n measurements have been run in both Halls A (E01-020) and B (E5); results soon.
- Perpendicular kinematics sensitive to FSI, leading to uncertainty and model dependence in the calculations.
- Parallel kinematics has less sensitive to FSI, but sensitive to the nucleon in-medium current. Additional form factors related to off-shell nucleon are uncertain and model dependent, except at $Q^2 = 0$.
- Meson exchange currents unimportant at high Q^2.

JLab E89-044 $^3He(e,e'p)d$

- Rvachev et al., submitted to PRL.
- QF ⊥ kinematics: x ~ 1, Q^2 ~ 1.55 GeV^2.
- Hadronic calculations reasonably reflect data.

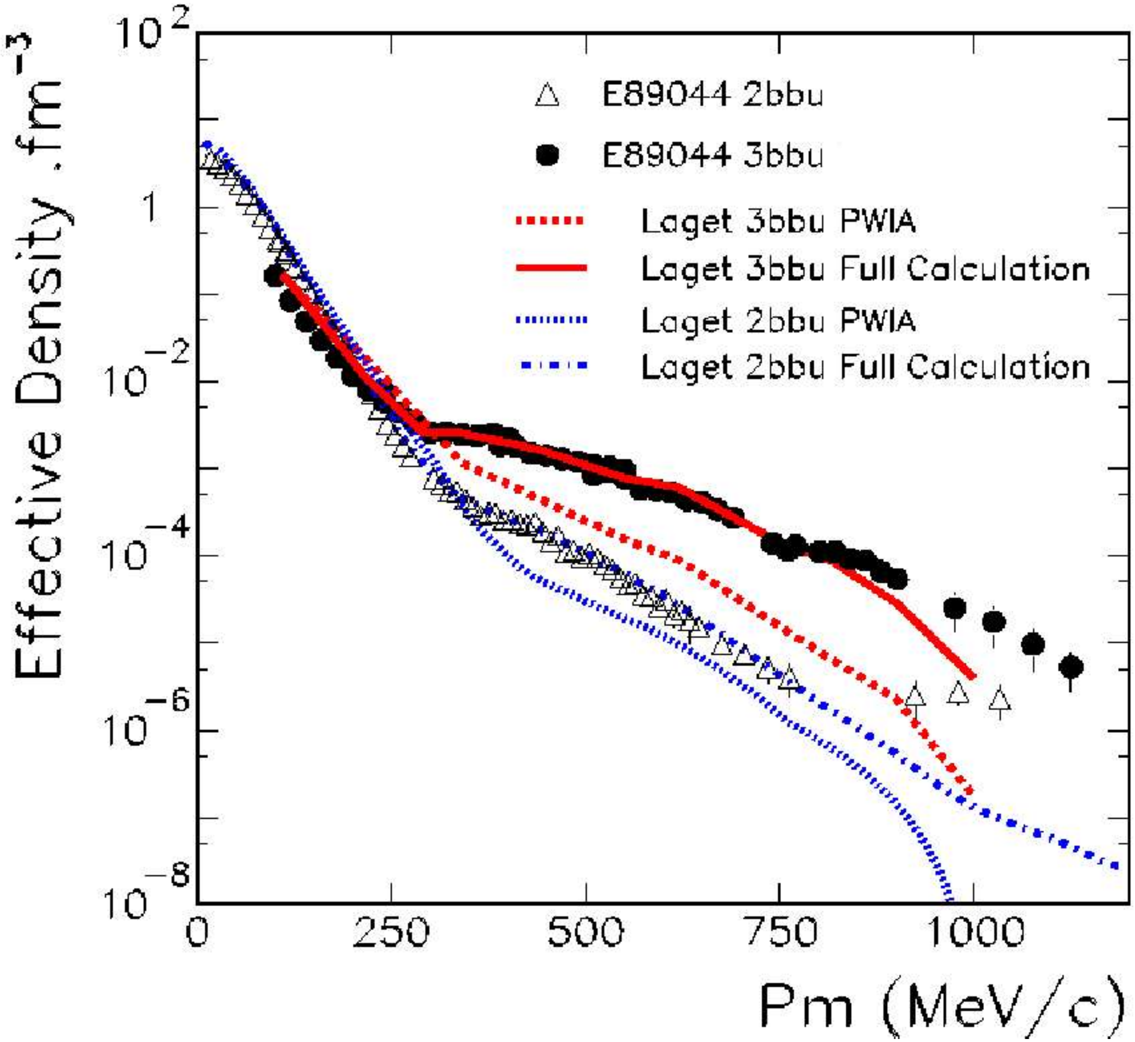




- 10 times too small at 1 GeV/c in σ
- 20 % offset at 10^{-4} level in A_{TL}

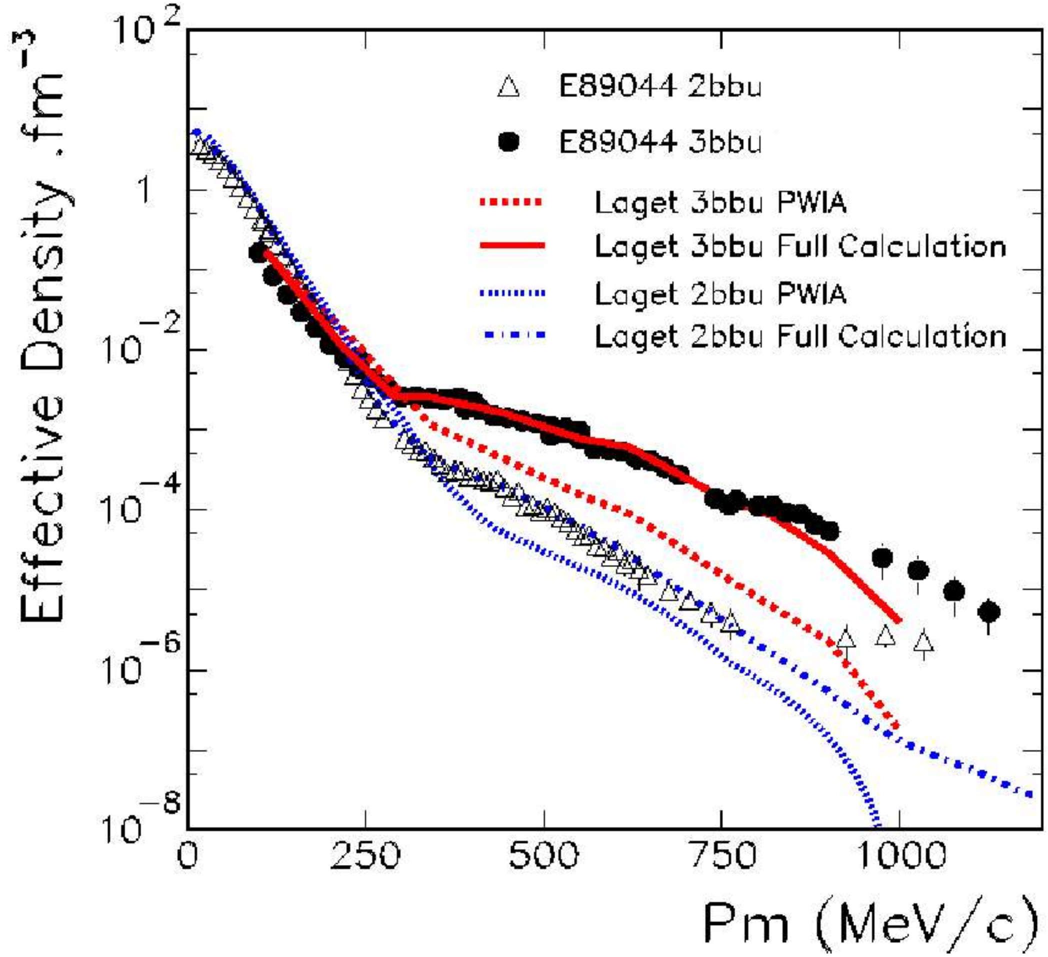
JLab E89-044 ^{3}He(e,e'p)pn

- Benmokhtar et al., submitted to PRL.
- QF ⊥ kinematics: x ~ 1, Q^2 ~ 1.55 GeV^2.
- Short-range NN correlations favor 3bbu, lead to most of high p_m strength
- FSI also move strength to high p_m.
- Can understand strength with hadronic calculation.



JLab E89-044 $^3He(e,e'p)$

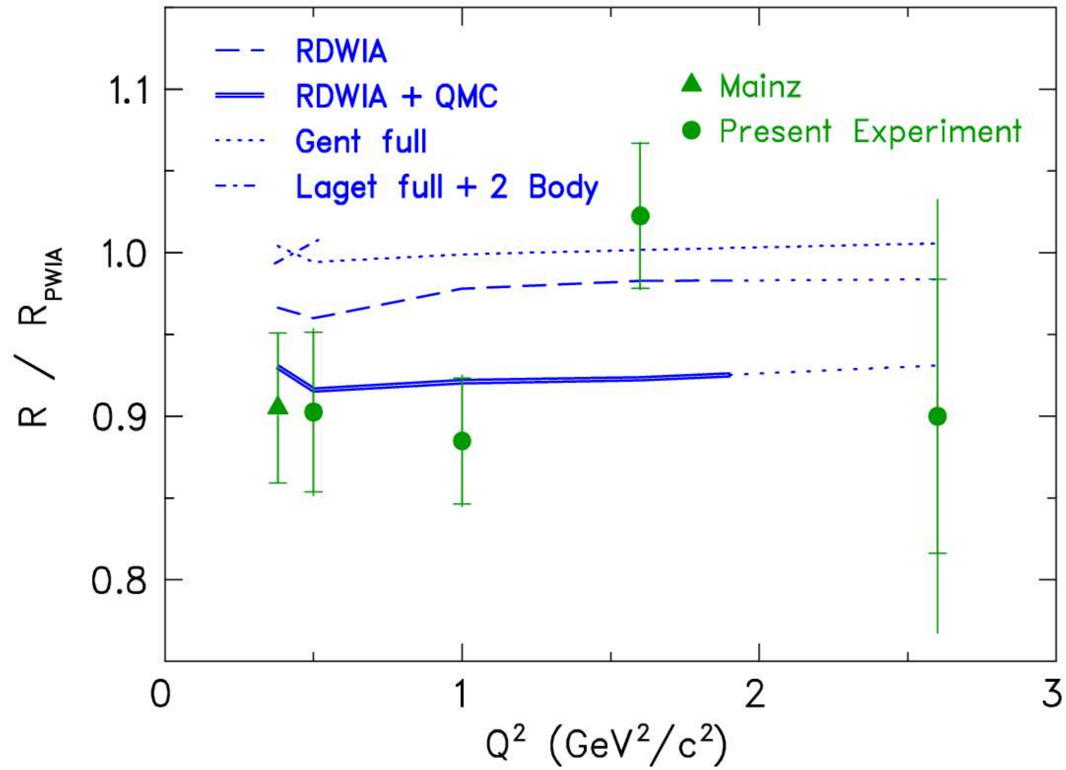
- What is happening near p_m ~ 1 GeV/c?
- 3bbu integration misses strength above pion threshold; simple estimate: 3bbu/2bbu ratio constant ~ 100.



JLab E89-044 $^4He(\mathbf{e},e'\mathbf{p})t$

- $x = 1$, low p_m
- $R = P_l/P_t$ is ratio of polarization transfers.
- Data are several % below best modern calculations.
- Data insensitive to conventional two-body currents.
- QMC effects, medium modified form factors, nicely explain data. (Lu, Thomas, Miller, ...)

- Follow-up experiment adds points at 0.8, 1.3 GeV^2 (Hall A, 2006?)

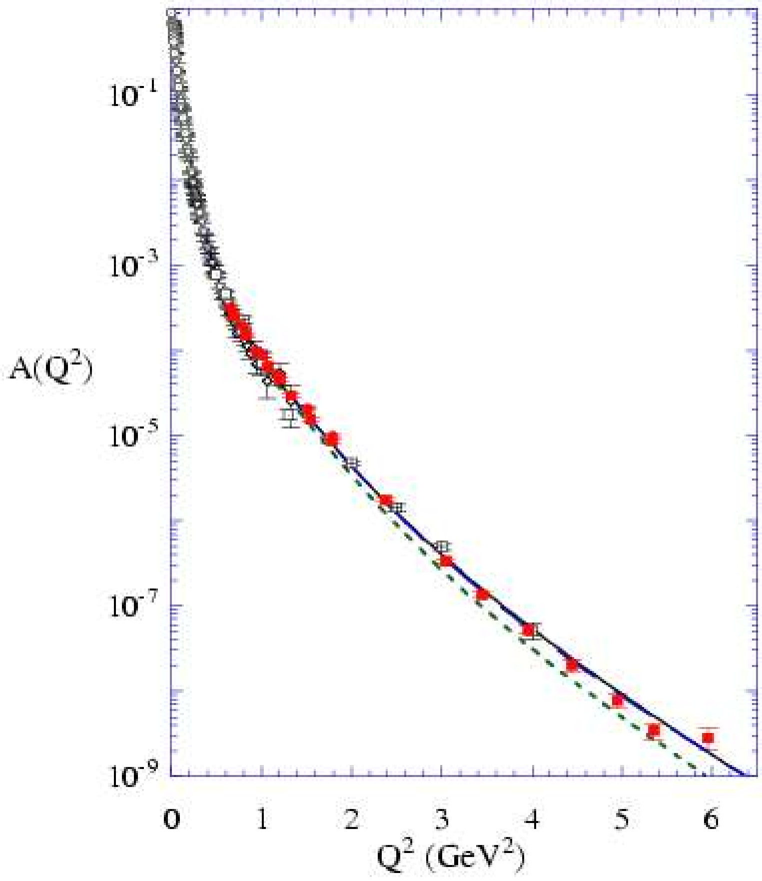


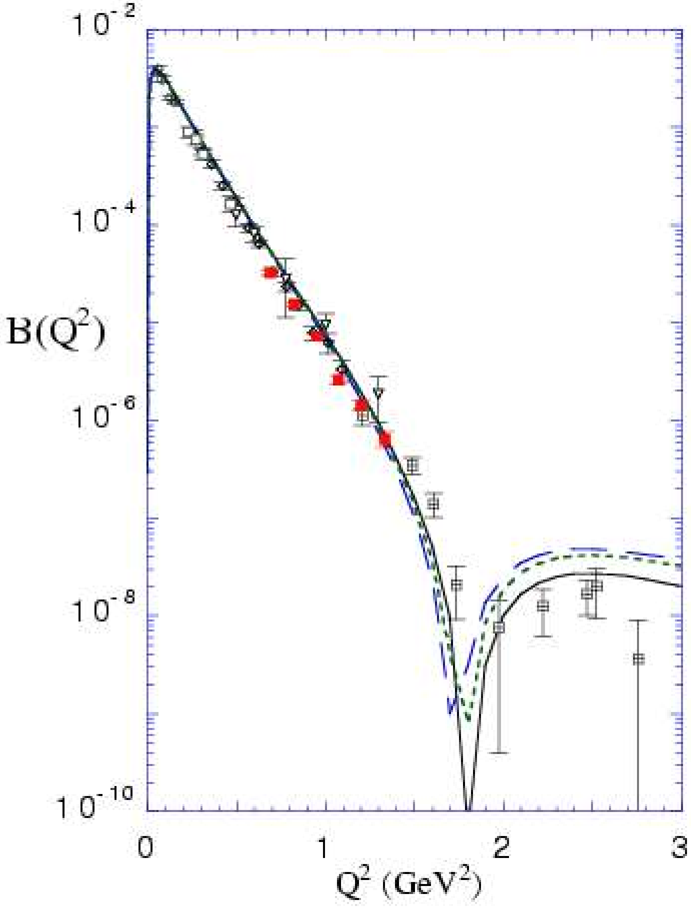
A(e,e'p) and 12 GeV Upgrade

- The experiments are generally at modest Q^2, so the 12 GeV upgrade is not needed, but offers some benefits
- Count rate increases at higher energy, higher ε kinematics for fixed Q^2.
- New spectrometer combinations, HRS + MAD / SHMS + HMS, offer improvements in coincidence efficiency for the higher beam energies.

Elastic ed Scattering

- From van Orden and Gross: conventional relativistic hadronic theory describes deuterium to highest Q^2
- B uses low energies at 180°, 12 GeV pushes A to 10 GeV^2





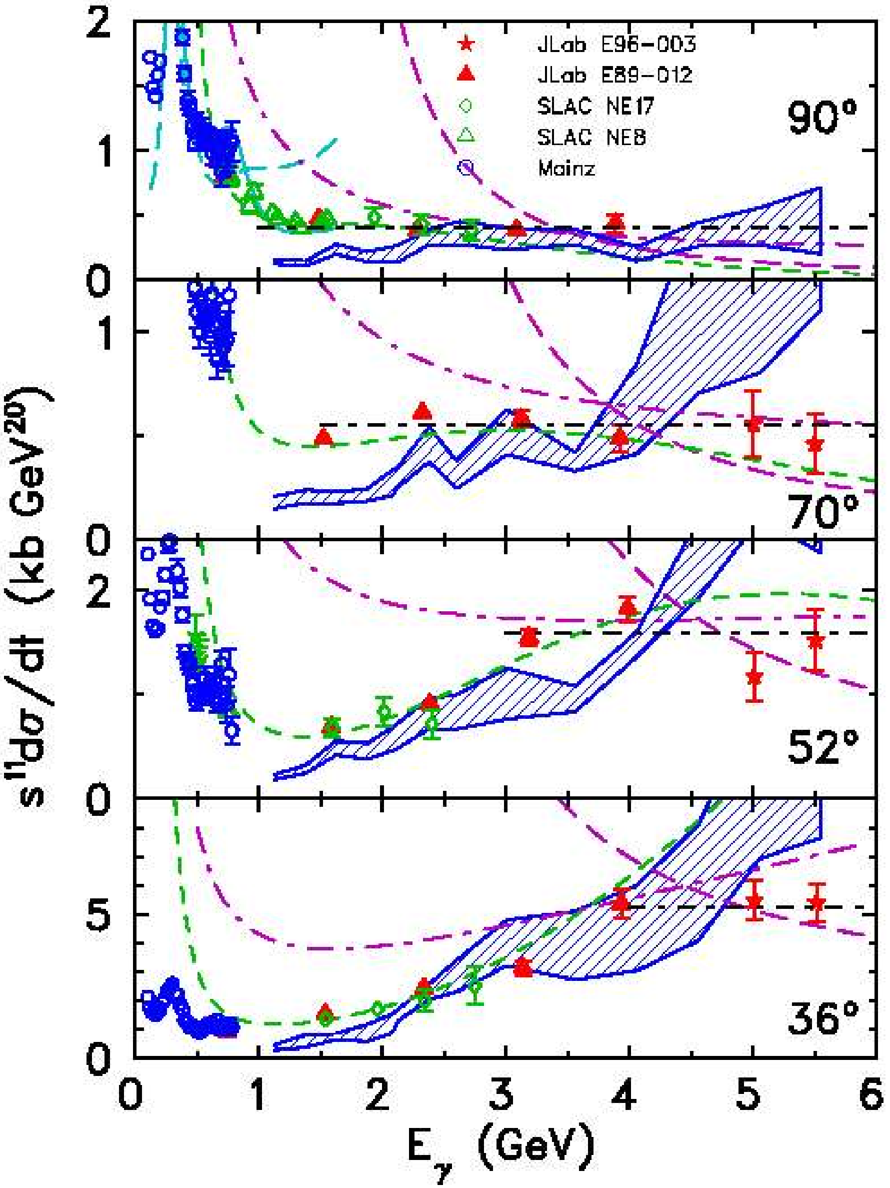
- ^3He also possible to 6 GeV^2
- ^3H and ^4He also of interest

Elastic ed Scattering versus d(g,p)n Photodisintegration

- Both reactions have been measured to large t (Q^2)
- But d(g,p)n has been measured to large $W^2 \sim (5\ GeV)^2$, while ed elastics are measured at fixed $W = m_d$.
- Photodisintegration requires summing over lots of resonances – quarks naturally do the summation.
- Intermediate state moves **away** from resonance region in ed elastic scattering. The resonances are far off-shell, and thus should contribute little. The nucleon states dominate and quarks are likely not needed.

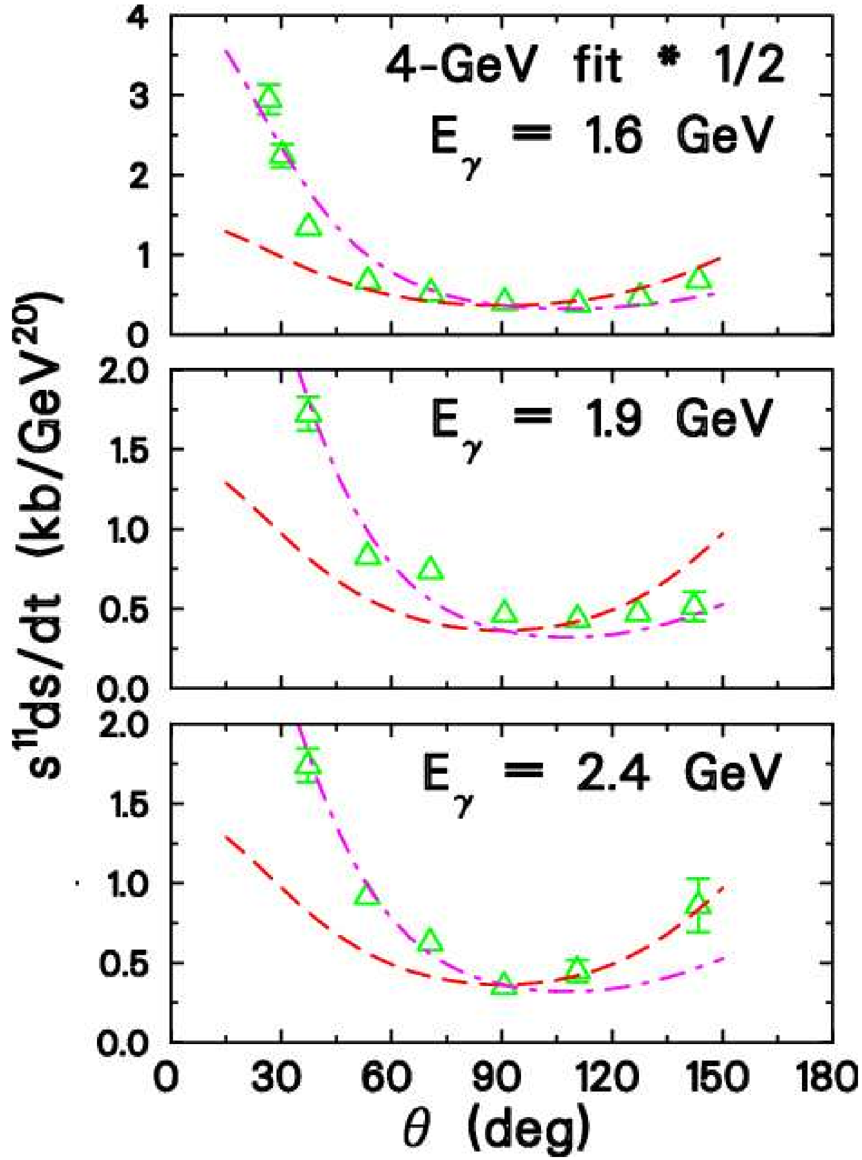
Deuteron Photodisintegration

- Highest energy data from JLab E96-003, Schulte et al., PRL 87, 102302 (2001).
- The onset of "pQCD-like" scaling at all angles corresponds to PT ~ 1.3 GeV.
- Why the precocious scaling? An indication of "quark effects", even if not pQCD?



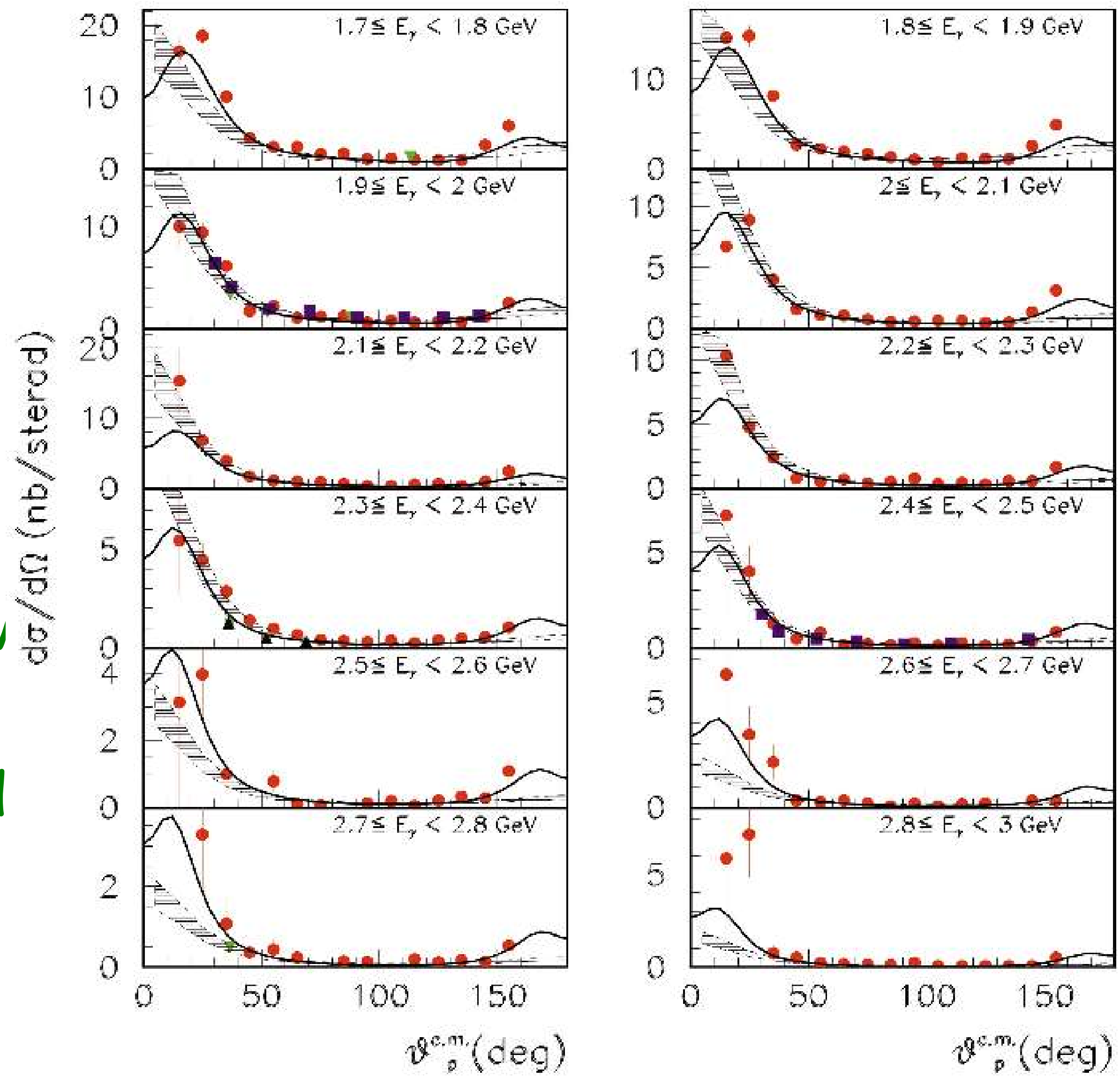
Angular Distributions

- Cross sections from Schulte et al., PRC 66, 042201R (2002).
- Simple parameterization suggested by Radyushkin reproduces shape of angular distributions as magnitude drops factor of ~1500
- Two parameters, one normalization (red dash) plus one asymmetry (magenta dot-dash).



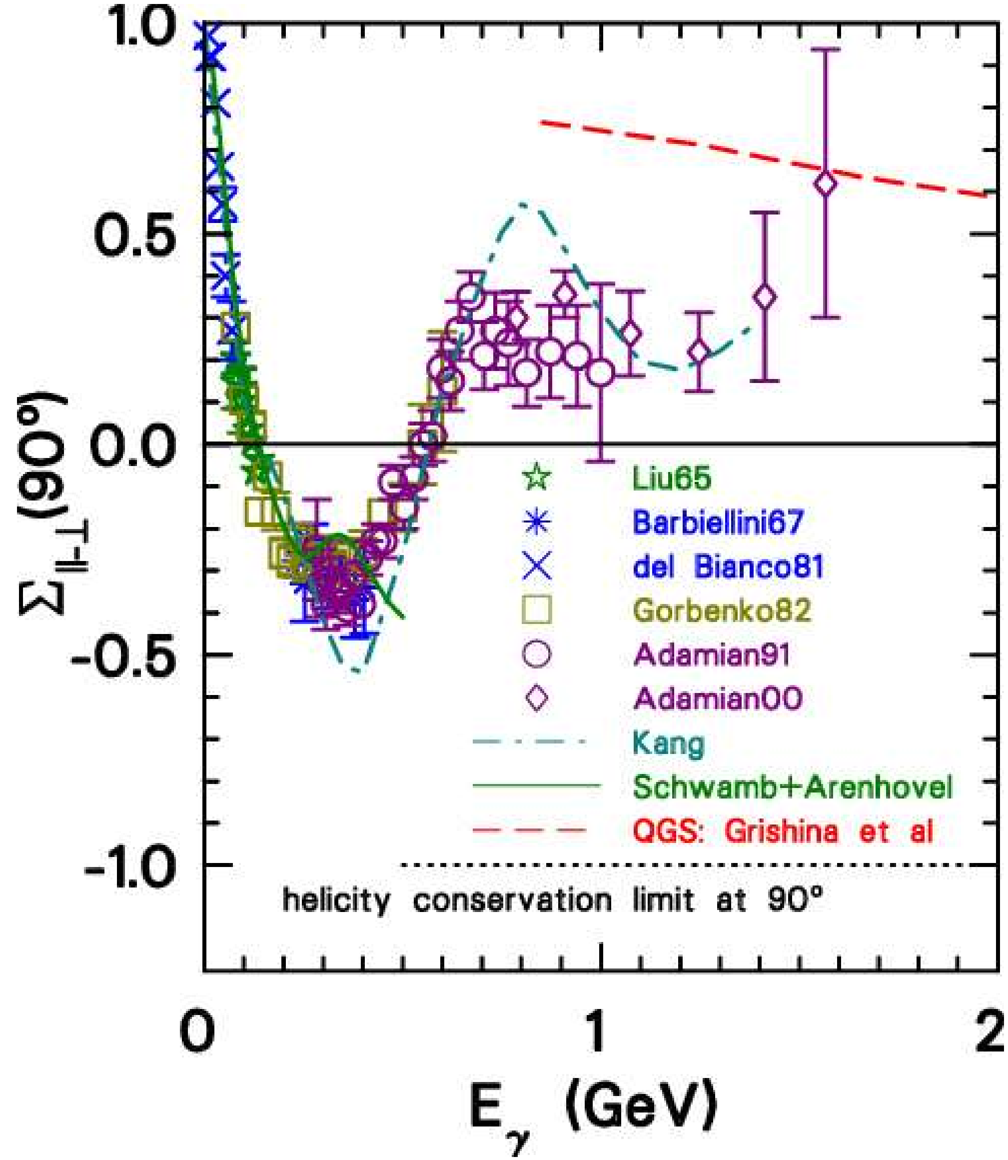
Hall B Angular Distributions

- Hall B CLAS data: M. Mirazita et al., PRC 70, 014005 (2004)
- Quark Gluon String Model (QGS) predicts data well; also predicts a forward minimum, from IS/IV interference. HRM also good.
- SPring-8/LEPS measured very forward-angle $d\sigma/d\Omega$ and Σ, for 1.5 - 2.4 GeV, $\theta \rightarrow 45^{\circ}_{cm}$.



The Σ Asymmetry

- The simple issue, for polarizations, is hadron helicity conservation (HHC), which is generally violated in high-energy reactions.
- Adamian et al., EPJA 8, 423 (2000), showed the Σ asymmetry, is about constant, or maybe heading away from the pQCD limit.
- Or does it?

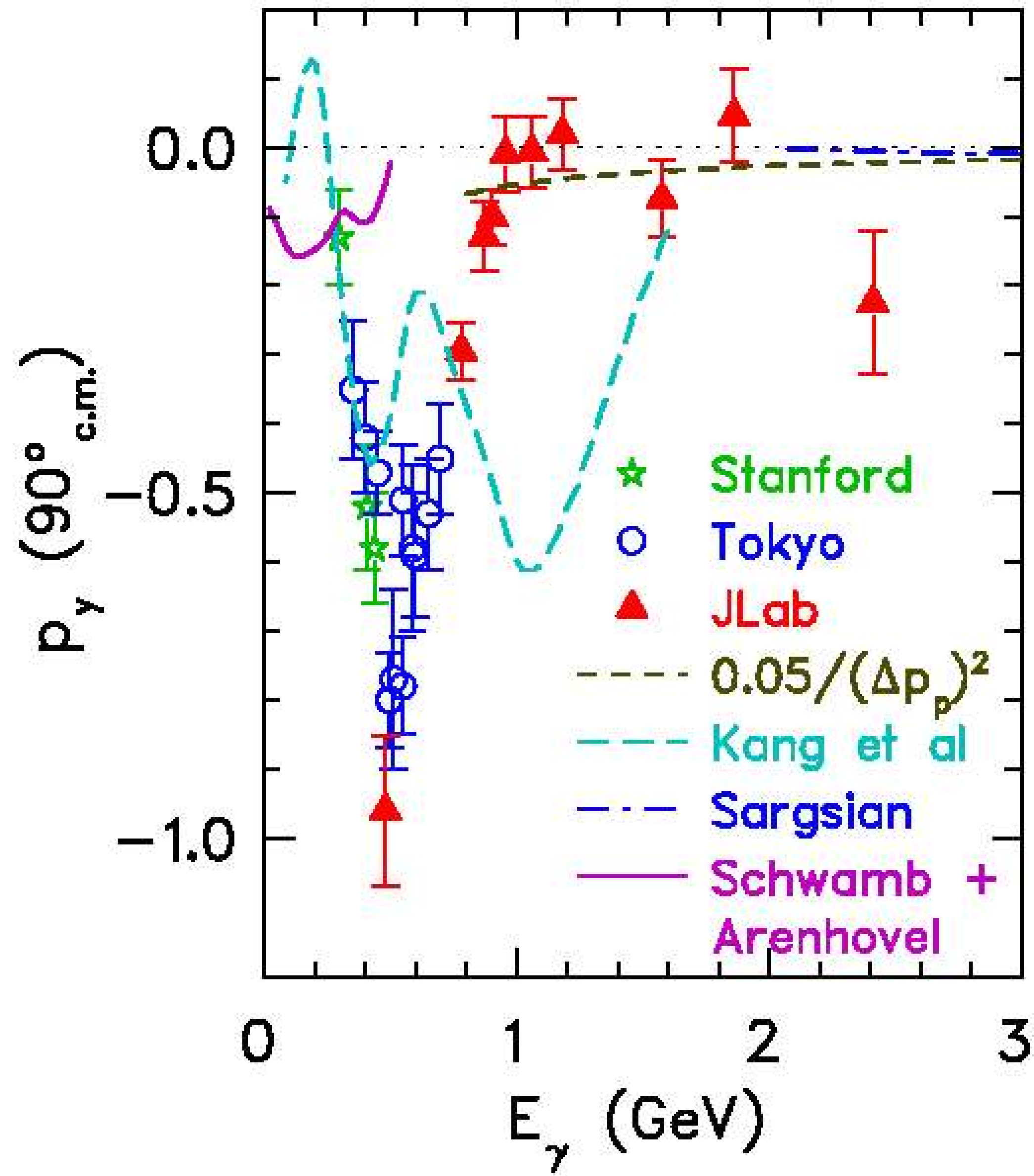


The Σ Asymmetry Limit

- Grishina et al., nucl-th/0209076, recently pointed out that the long accepted limit for $\Sigma(90^{\circ})$ from hadron helicity conservation is only correct for isoscalar photons.
- For isovector photons, some amplitudes change sign, and Σ goes to +1, not -1!
- Thus, if HHC were otherwise observed, it would be reasonable to determine from Σ the relative strength of the isovector vs. isoscalar photon couplings.
- So how strong is other evidence against HHC in $\gamma d \rightarrow pn$? (It is not seen in other reactions.)

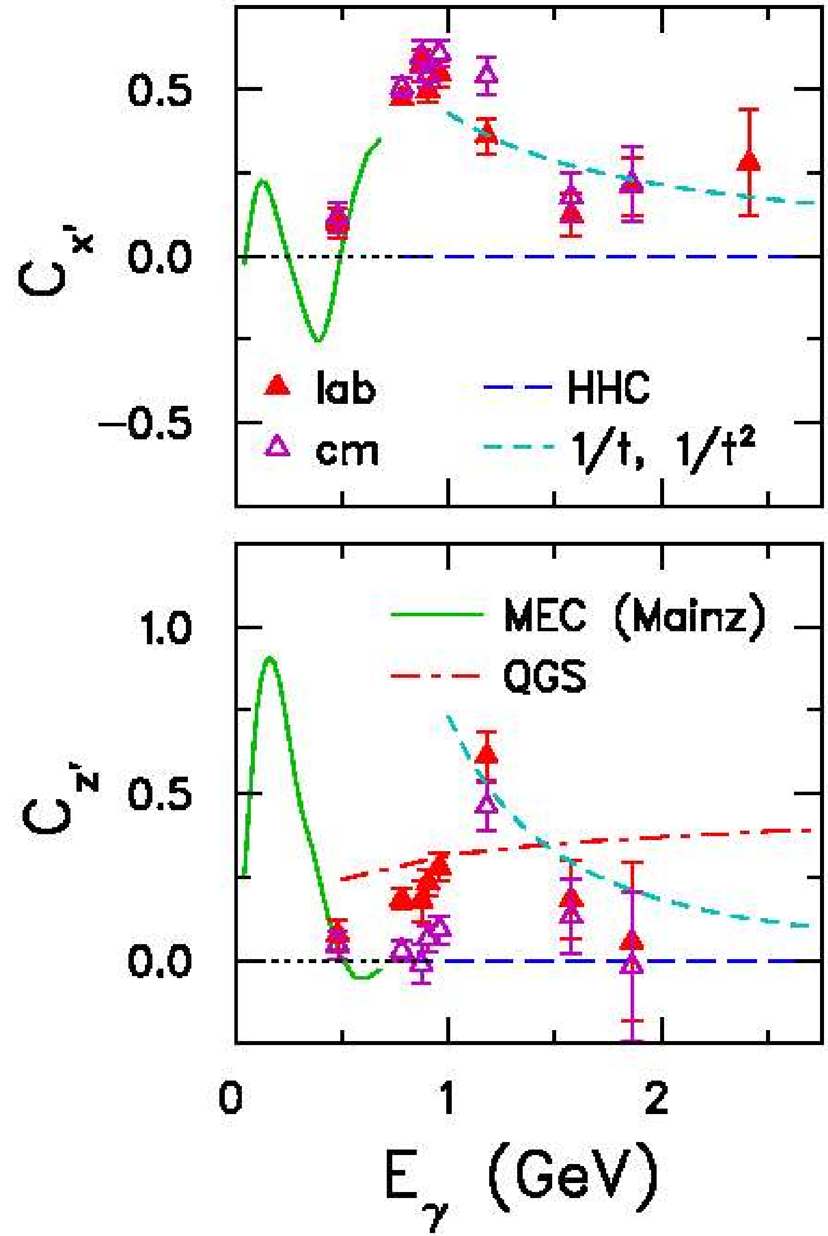
The Induced Polarization p_y

- Wijesooriya et al., PRL 86, 2975 (2001), showed p_y is consistent with vanishing above 1 GeV. One point of 6 is 2σ below 0. (The Kharkov data are suppressed here.)
- Sargsian (HRM) predicts p_y is small and negative, based on pn→pn.
- A 1/t approach to HHS is also fine above 1 GeV.



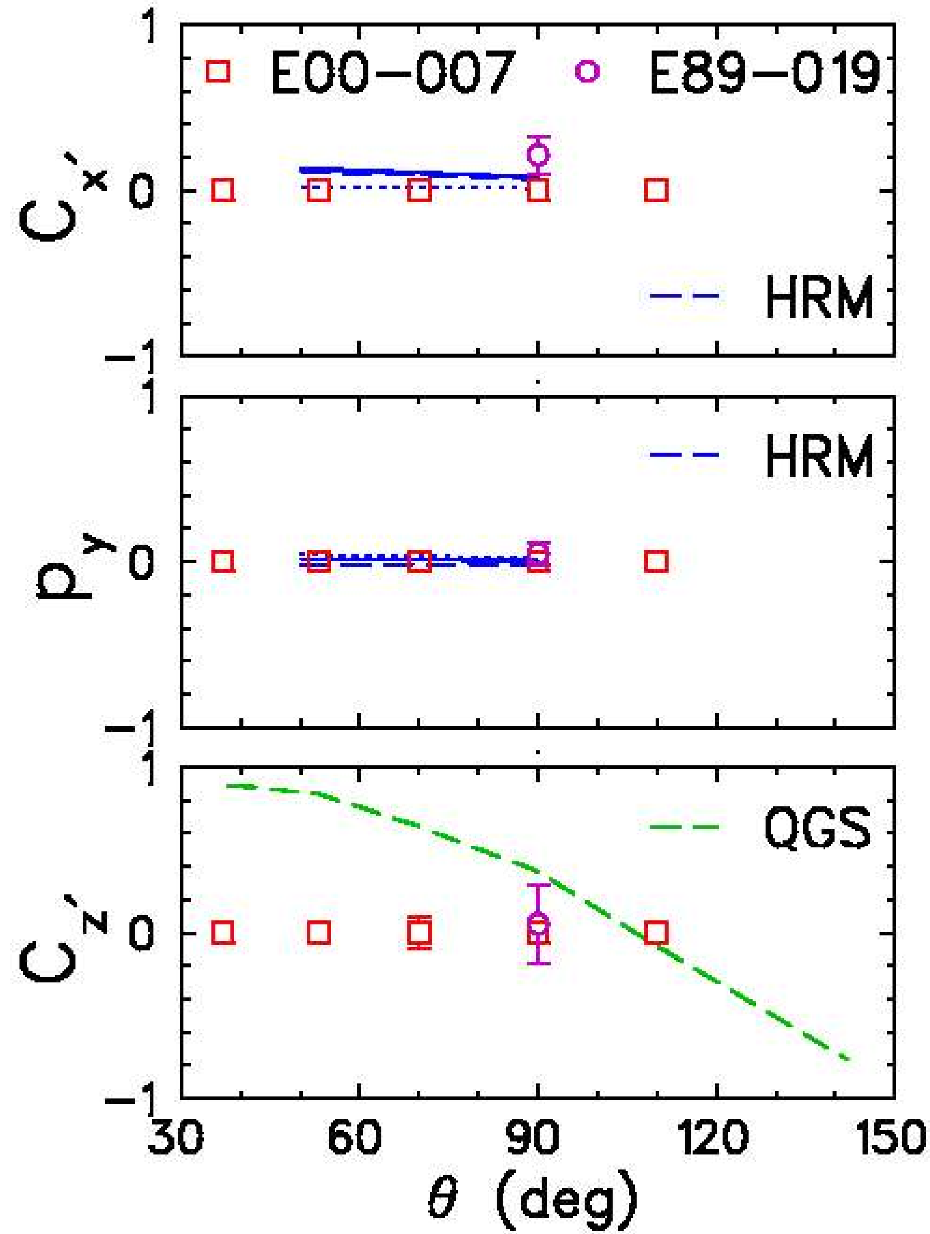
Polarization Transfers

- Also from Wijesooriya et al., PRL 86, 2975 (2001).
- Schwamb and Arenhövel have a good prediction for the 500-MeV point and the trend.
- QGS: ``simple'' model for $C_{z'}$. HRM: $C_{z'}$ similar to HRM, $C_{x'} > 0$ but small. I suggest better data are needed.
- Data not in disagreement with approach to HHC.



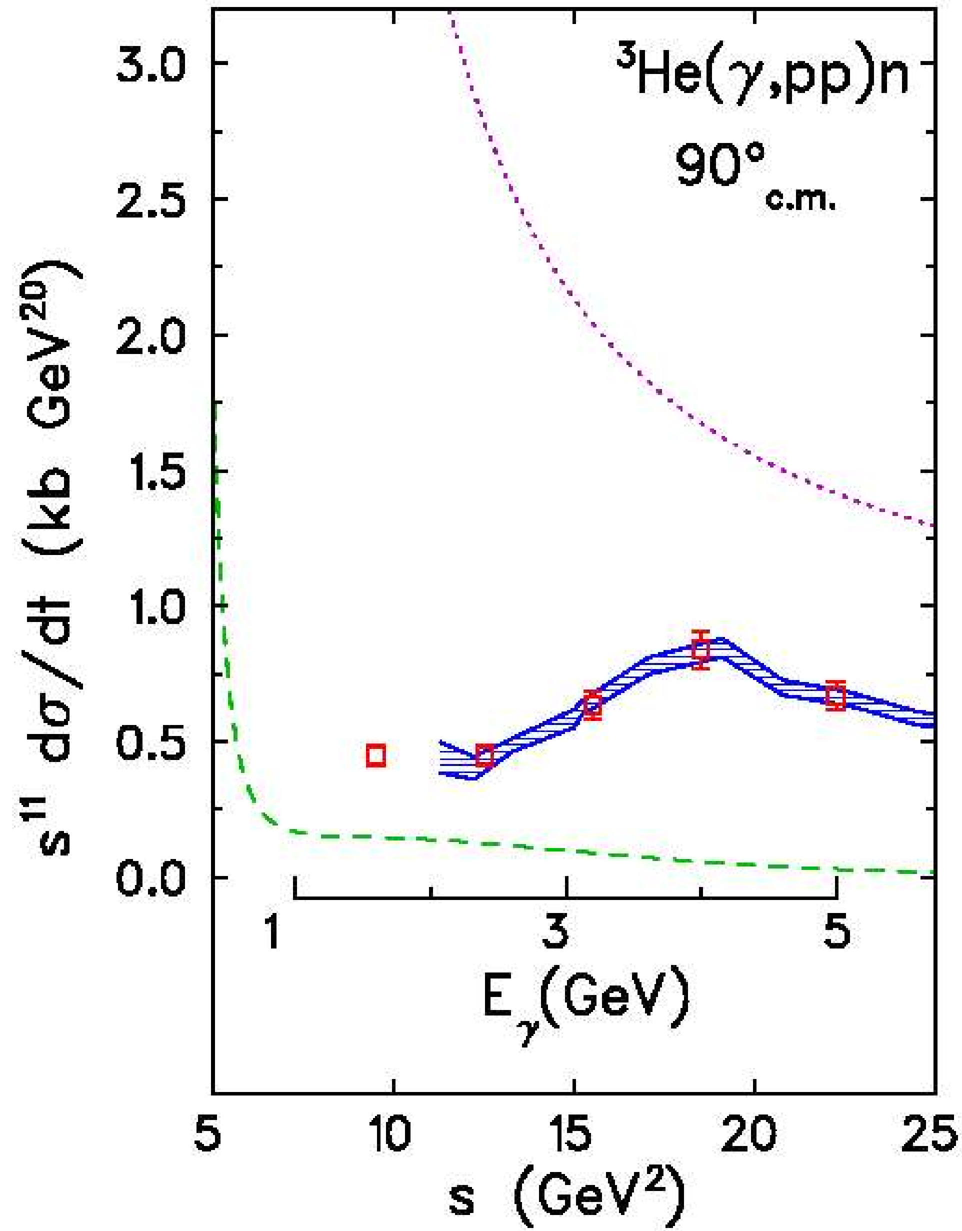
Jefferson Lab E00-007

- We measured a recoil polarization angular distribution at 2 GeV, in late 2002. Points are put at 0, with analysis underway.
- At limit of validity for HRM.
- $C_{z'}$ is good test for QGS, as interferences make $C_{x'}$ and p_y difficult to predict.



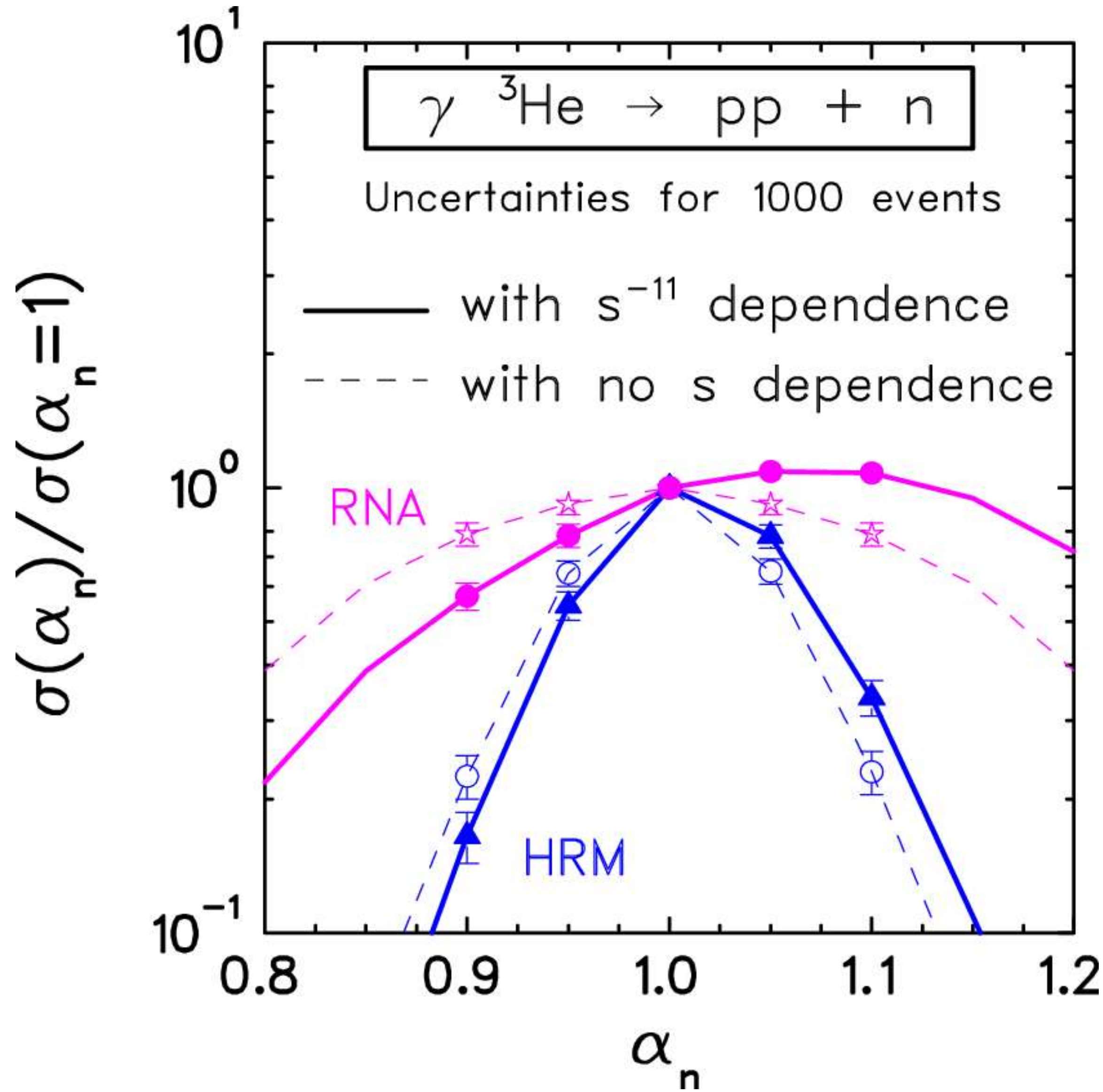
What Is Next?

- MAD allows cross section and polarization measurements to each be pushed 1-2 GeV higher.
- Brodsky et al., PLB 578, 69 (2003) discuss pp breakup using ^{3}He vs. pn breakup.
- At low energy, $\sigma_{pp} << \sigma_{pn}$, but quark models that roughly describe d(γ,p) vary widely for pp breakup
- Data already taken by CLAS up to ~1.5 GeV (S. Strauch, p.c., unpublished); Hall A E03-101



^{3}He and α

- α = (E-p_z)/m is light cone momentum fraction
- Re-scattering ~ conserves α
- The distribution is harder (flatter) if the reaction mechanism proceeds through the high-momentum, short-range tails of the wave function



Summary

- Quarks/gluons and hadrons are alternative basis states.
- If the effective hadronic interactions already include the quark effects, a major breakdown necessitating quark d.o.f. is unlikely.
- Hadronic models generally work well at $x=1$.
- At large W and Q^2, we either have to lower standards for hadronic theories, or develop good quark models – perhaps we already have!

Outlook – Personal Biases

- I have doubts that we will **need** quarks for the x ~ 1 (e,e'p) physics.
- I am very excited about new ^{3}He photodisintegration and ^{4}He(e,e'p) polarization transfer data.
- I do not expect a general paradigm shift to quarks to happen anytime soon, but ...