Hadrons in the Nuclear Medium

Rolf Ent
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Science & Technology Review
June 2004

- The Baryon-Meson versus Quark-Gluon Description
- Nuclear Effects in Structure Functions
- Tagged Structure Functions
- Using the Nucleus as a Laboratory
- Summary

Campaigns and Performance Measures

The Structure of the Nuclear Building Blocks

3) How does the NN Force arise from the underlying quark and gluon structure of hadronic matter?

The Structure of Nuclei

4) What is the structure of nuclear matter?
5) At what distance and energy scale does the underlying quark and gluon structure of nuclear matter become evident?

DOE Performance Measure:

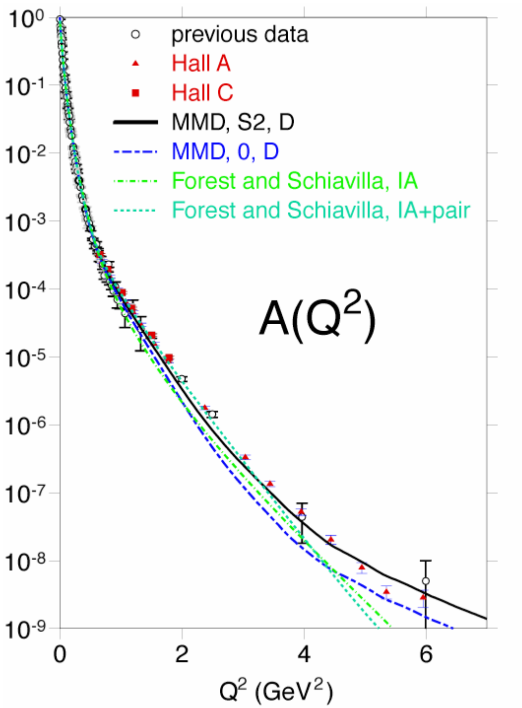
… and compare free proton and bound proton properties via measurement of polarization transfer in the $^4He(\vec{e},e'\vec{p})^3H$ reaction.

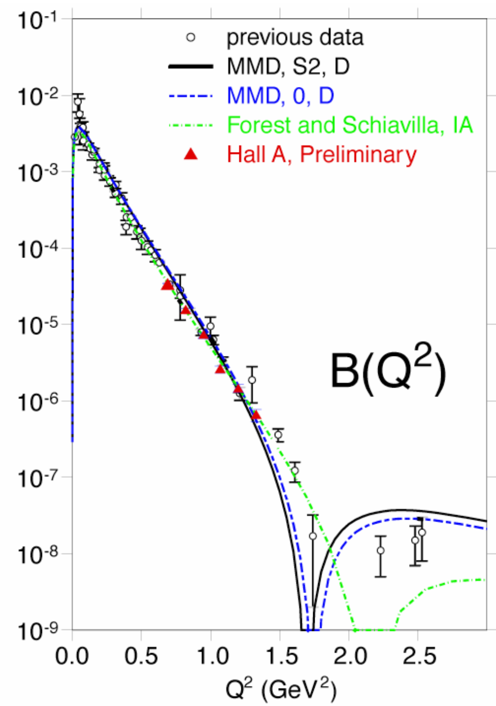
QCD Lagrangian: quarks and gluons

Nuclear Physics Model is an effective (but highly successful!) model using free nucleons and mesons as degrees of freedom.

Are these, under every circumstance, the best effective degrees of freedom to chose?

JLab Data Reveal Deuteron's Size and Shape





For elastic e-d scattering:

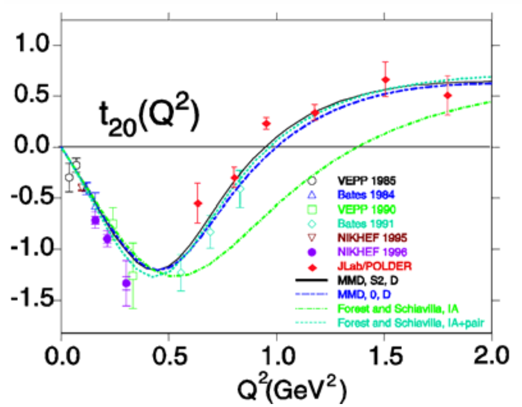
$$\frac{d\sigma}{d\Omega} = \sigma_M \left[A + B\tan^2\frac{\theta}{2}\right]$$

$$A(Q^2) = G_C^2 + \tfrac{8}{9}\tau^2 G_Q^2 + \tfrac{2}{3}\tau G$$

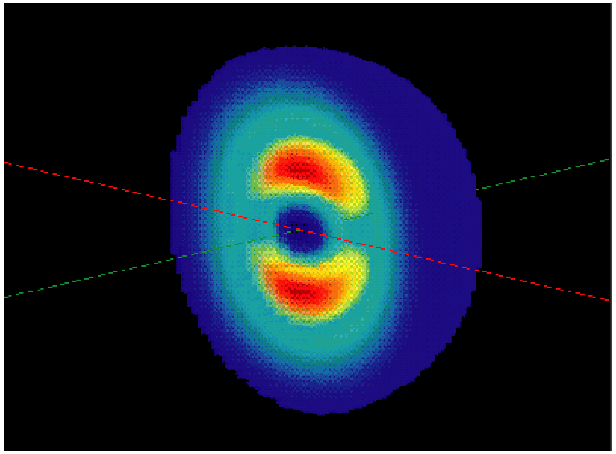
$$B(Q^2) = \tfrac{4}{3}\tau(1+\tau)G_M^2$$

- 3rd observable needed to separate G_C and G_Q

→ *tensor polarization t_{20}*



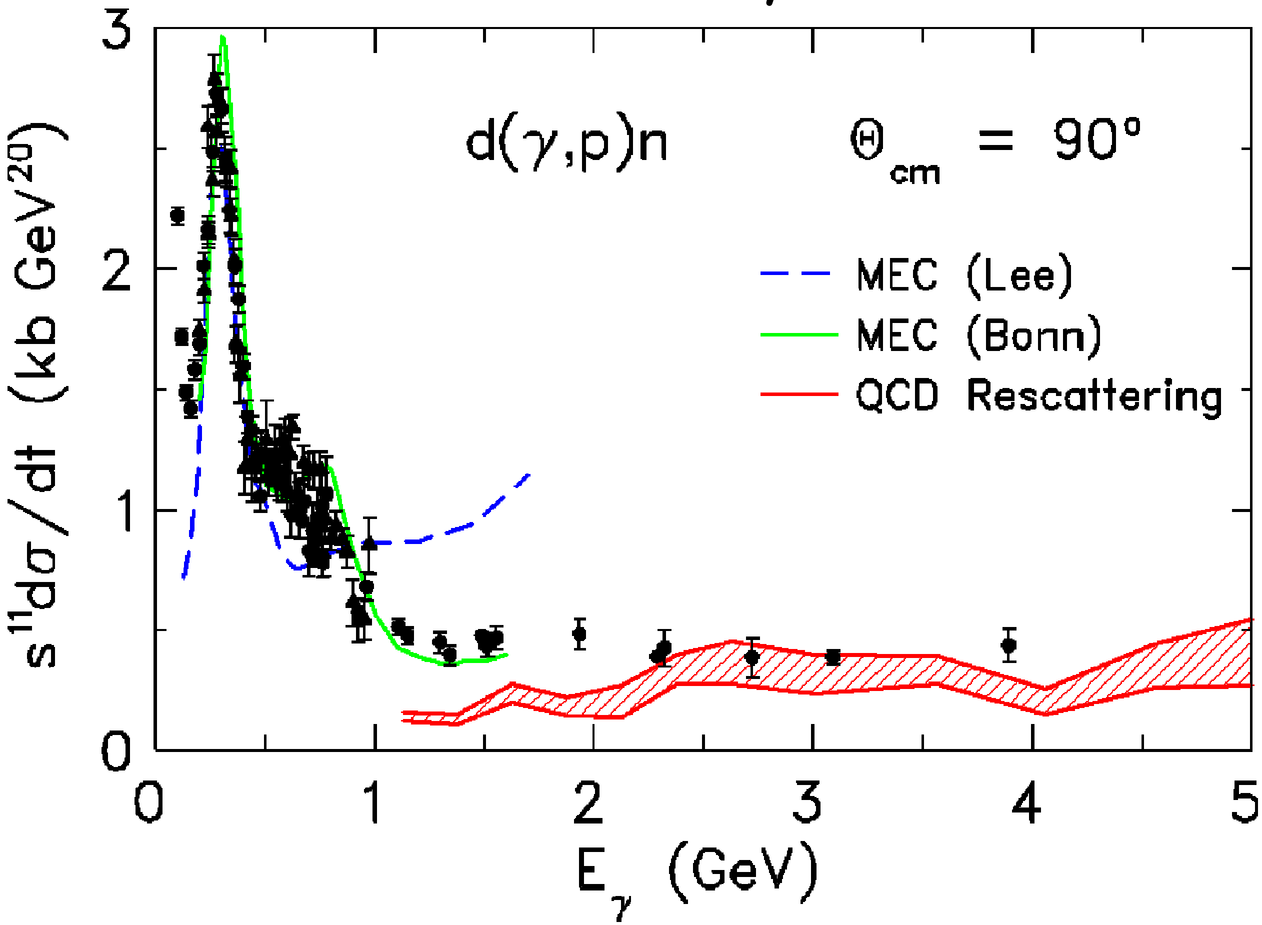
Combined Data ->
Deuteron's Intrinsic Shape



The nucleon-based description works down to < 0.5 fm

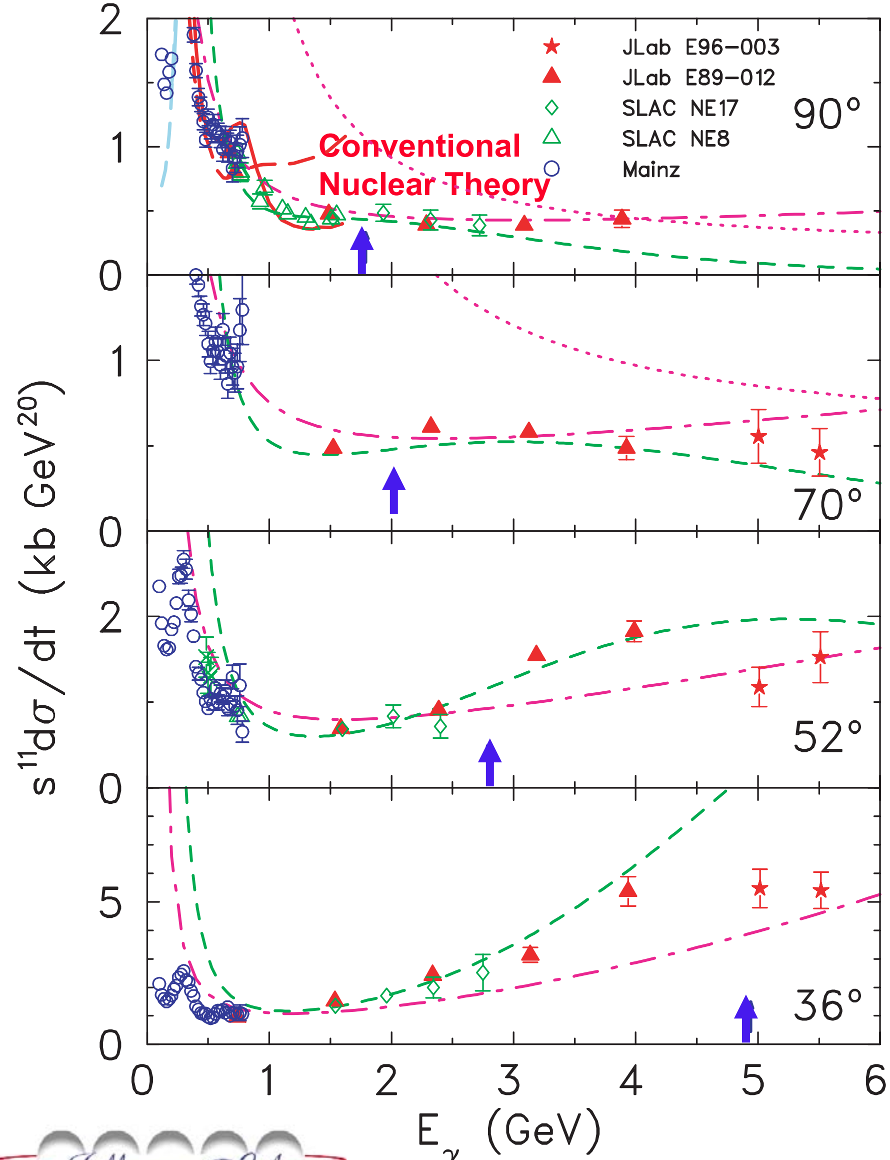
Is there a Limit for Meson-Baryon Models?

Not really but ...



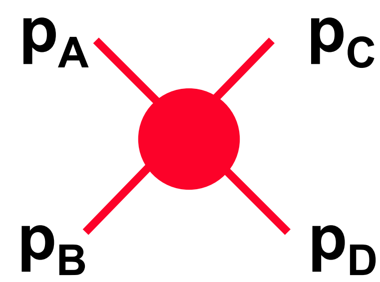
... there might be a more economical QCD description.

Transition to the Quark-Gluon Description



Scaling behavior ($d\sigma/dt \propto s^{-11}$)
for P_T > 1.2 GeV/c (see ↑)

⇒ quark-gluon description sets in at scales below ~0.1 fm



$d\sigma/dt \propto f(\theta_{cm})/s^{n-2}$

where $n = n_A + n_B + n_C + n_D$

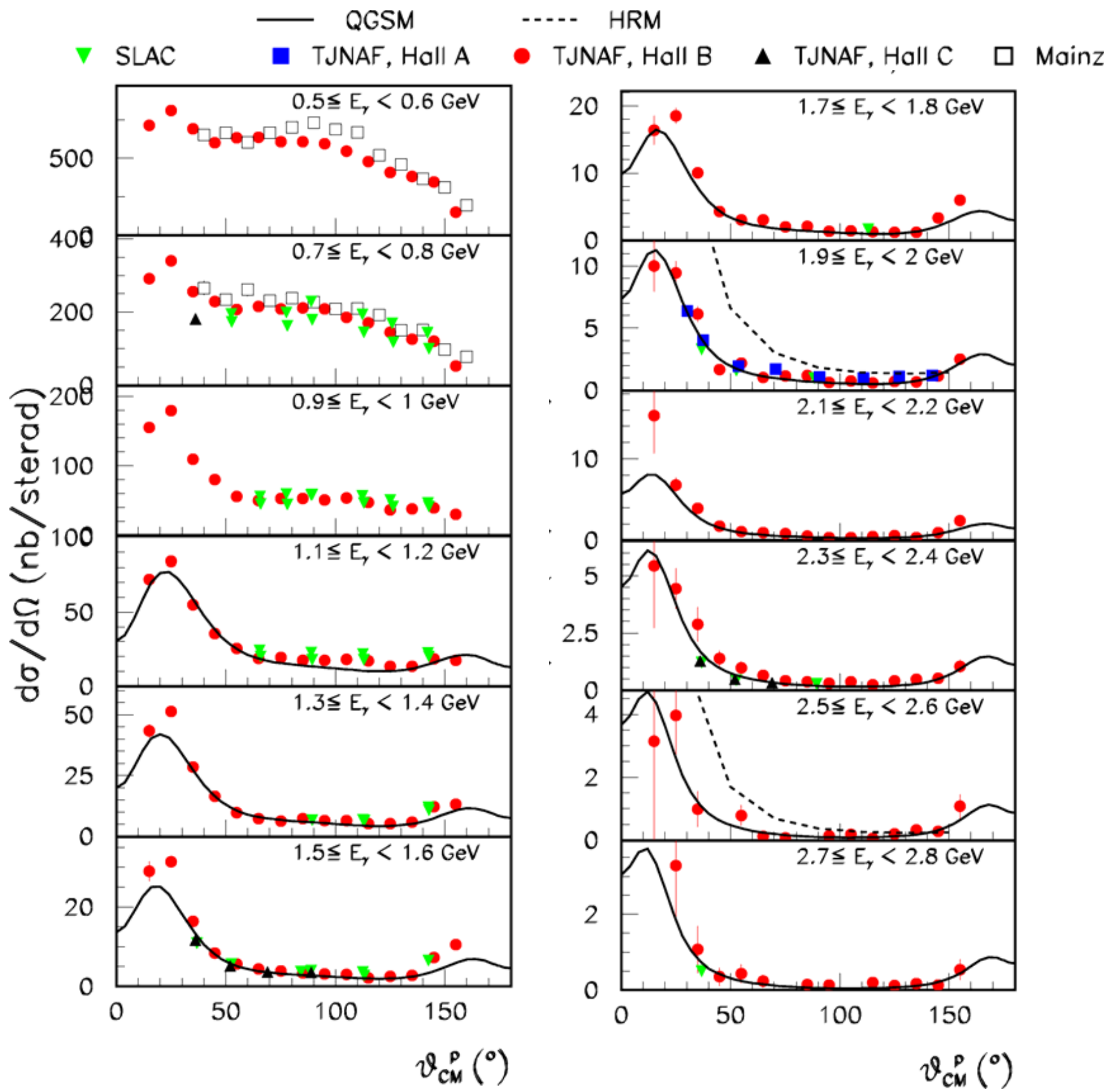
$s = (p_A+p_B)^2$, $t=(p_A-p_C)^2$

$\gamma d \rightarrow pn \Leftrightarrow n=13 \Leftrightarrow d\sigma/dt \propto s^{-11}$

Exploring the Transition Region

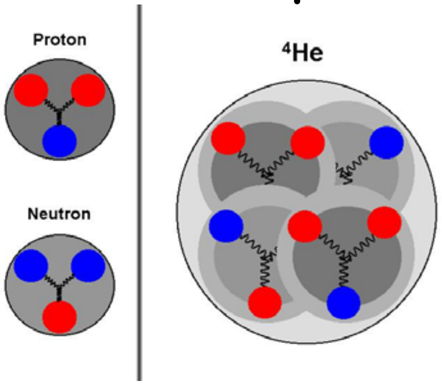
Now nearly complete angular distributions of D(γ,p)n up to E_γ = 3 GeV with CLAS →

Excellent fit of data with $d\sigma/dt \propto s^{-11}$ if starting fit at p_T ~ 1.0-1.3 GeV/c.



Hadrons in the Nuclear Medium

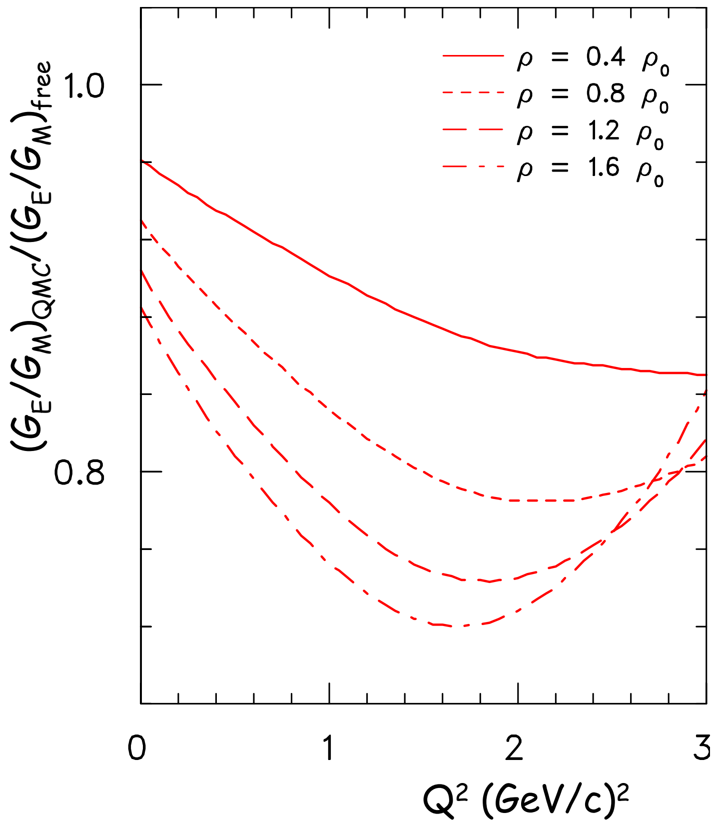
- Nucleons and Mesons are not the fundamental entities of the underlying theory.
- At high densities a phase transition must occur to a quark-gluon plasma.
- At nuclear matter densities of 0.17 nucleons/fm^3, nucleon wave functions overlap considerably.

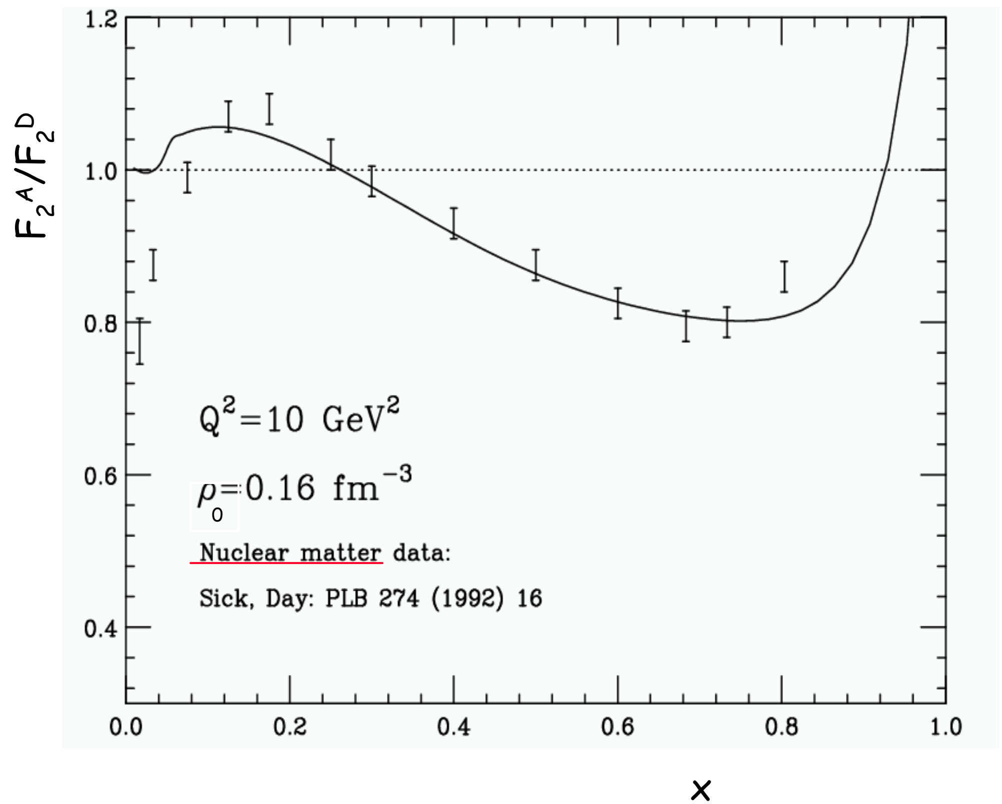


- EMC effect: Change in the inclusive deep-inelastic structure function of a nucleus relative to that of a free nucleon.

Quarks in Nuclear Physics

Quark-Meson Coupling (QMC) Model (Thomas et al.): quark's response to mean scalar and vector field (similar to quantum hadrodynamics for nucleon's response) → quark substructure of nucleon irrelevant for bulk properties of nucleus, but is relevant for form factor and structure functions

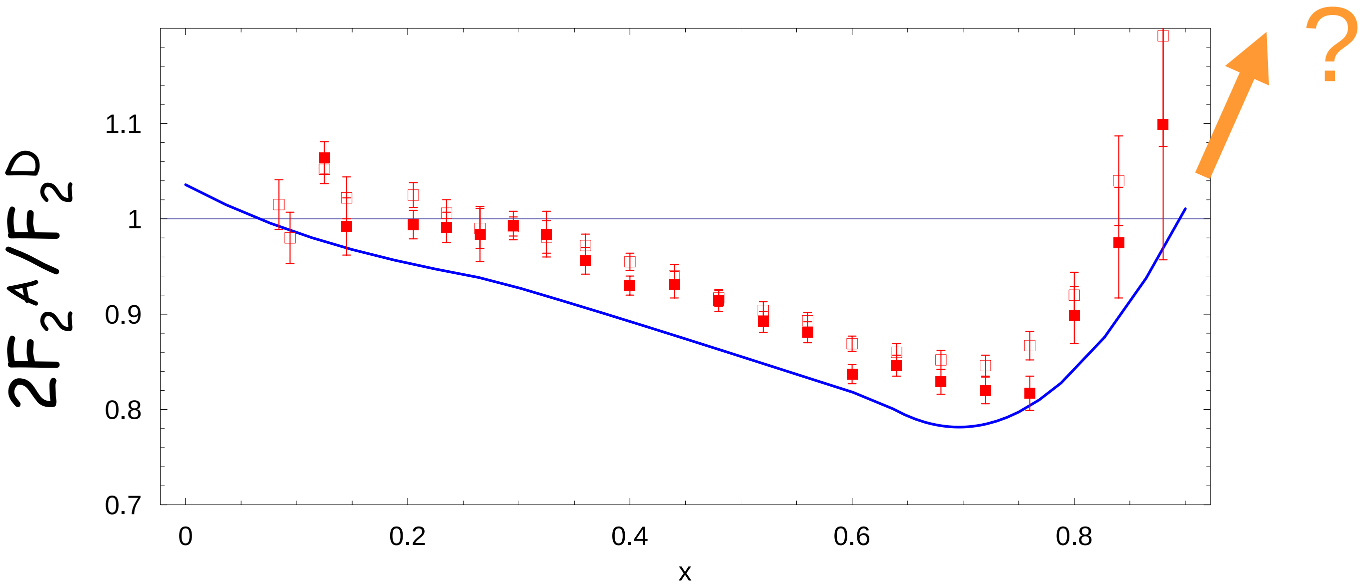




Effects are Precursor of Quark Gluon Plasma

The EMC Effect

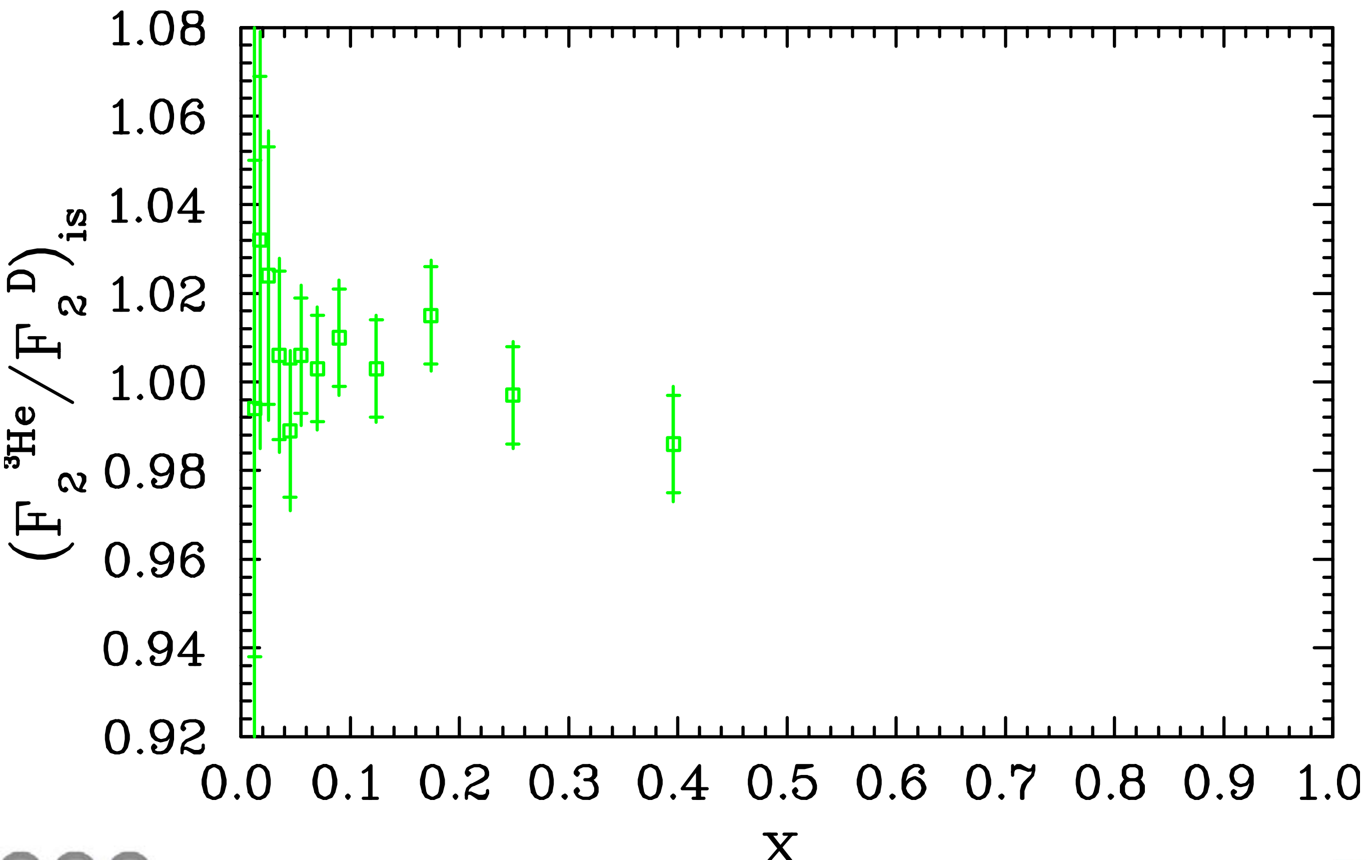
European Muon Collaboration: muon scattering to measure nuclear structure functions (1982)



- Depletion of the nuclear structure function $F_2^A(x)$ in the valence-quark regime $0.3 < x < 0.8$
- Specific cause for depletion remains unclear: conventional nuclear effects or nucleon swelling?
- J. Smith & G.A. Miller (2003): chiral quark soliton model of the nucleon
  claim: Conventional nuclear physics does not explain full EMC effect

EMC Effect in ^3He and ^4He

The Nuclear EMC effect shows that quarks behave differently in nuclear systems.
It has been extensively measured in A>8 nuclei.



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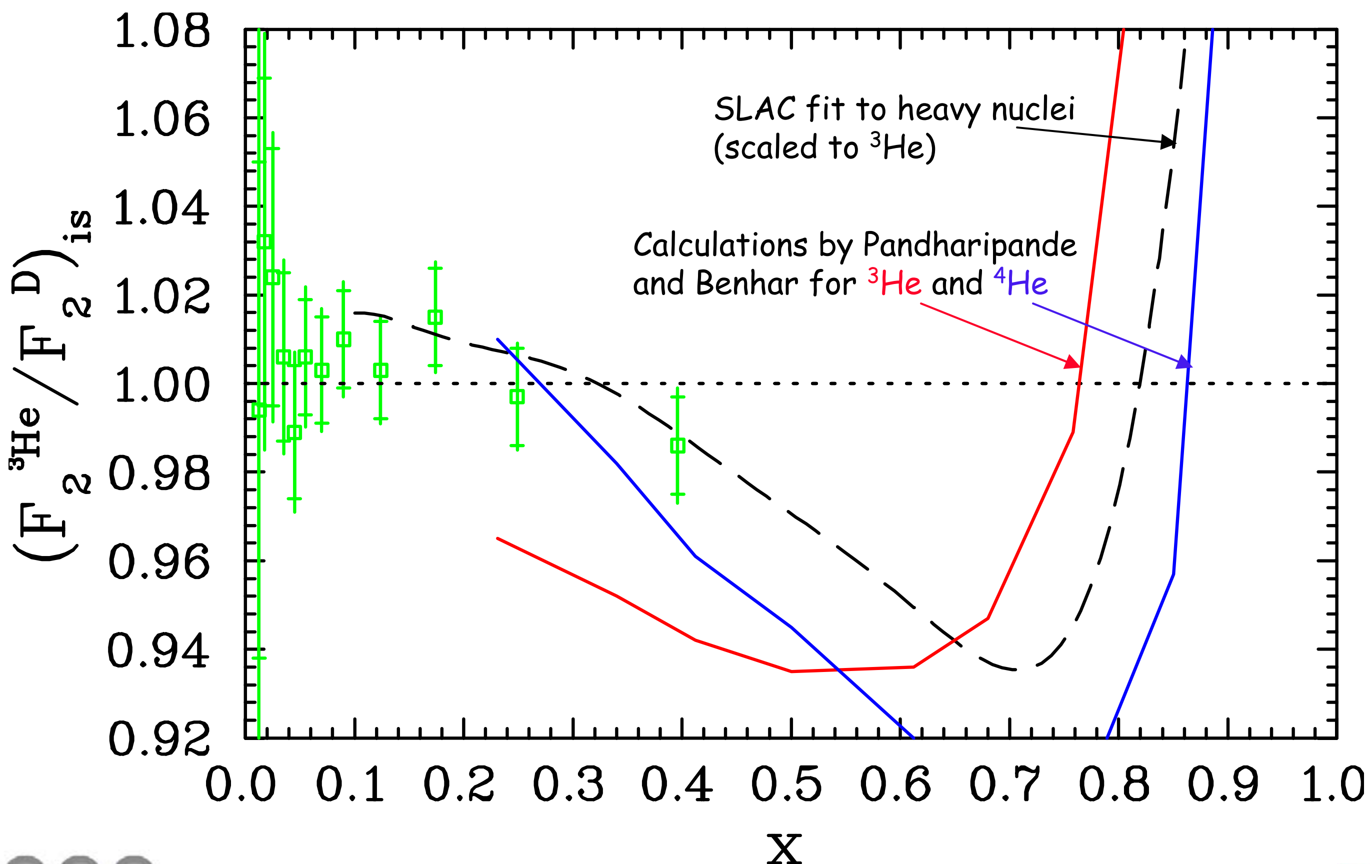
It has been extensively measured in A>8 nuclei, but current data do not differentiate between models with either an A-dependence or a ρ-dependence.

→ Measure the shape in very light nuclei to distinguish
→ Test models of the EMC effect in exact few-body calculations



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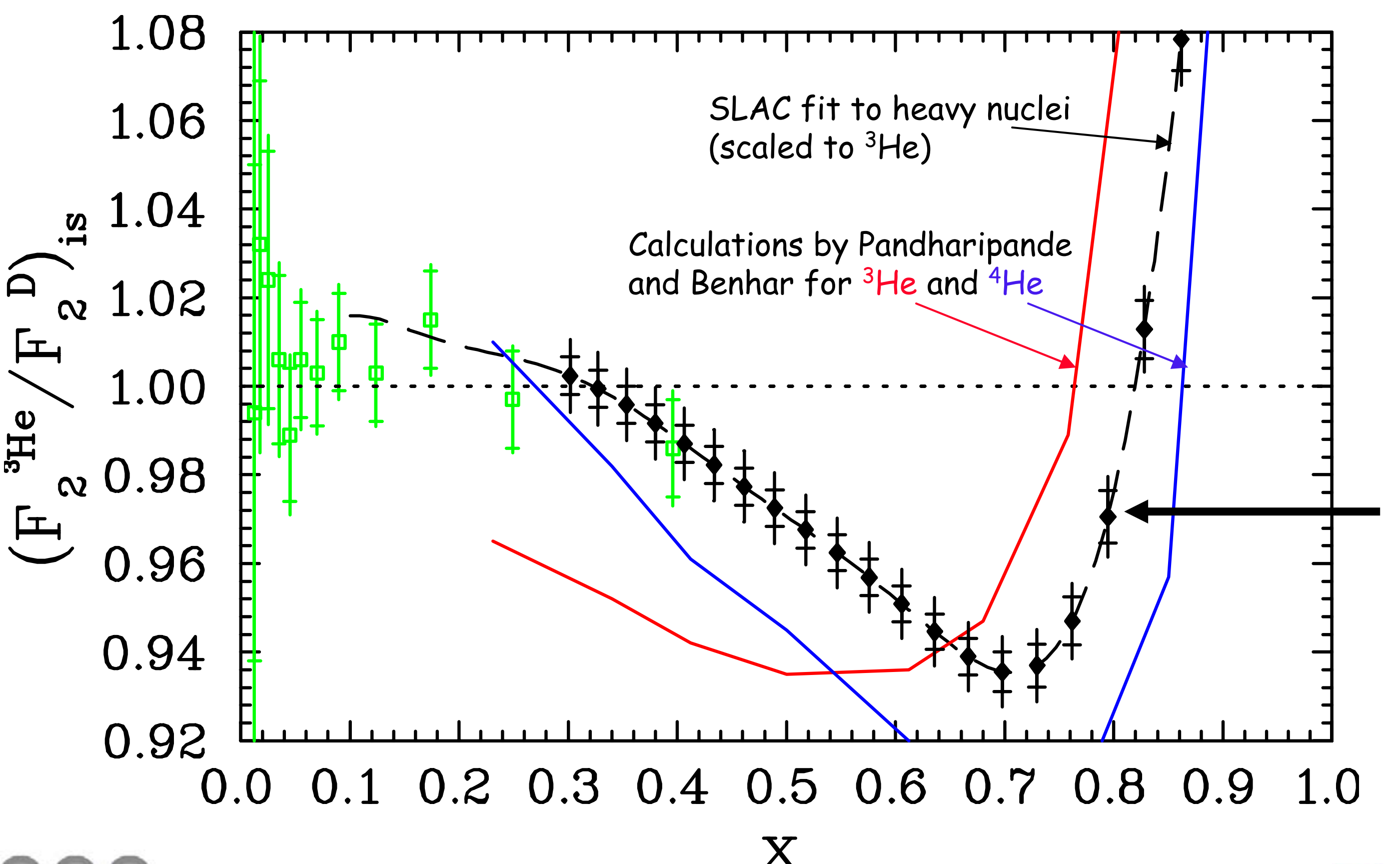
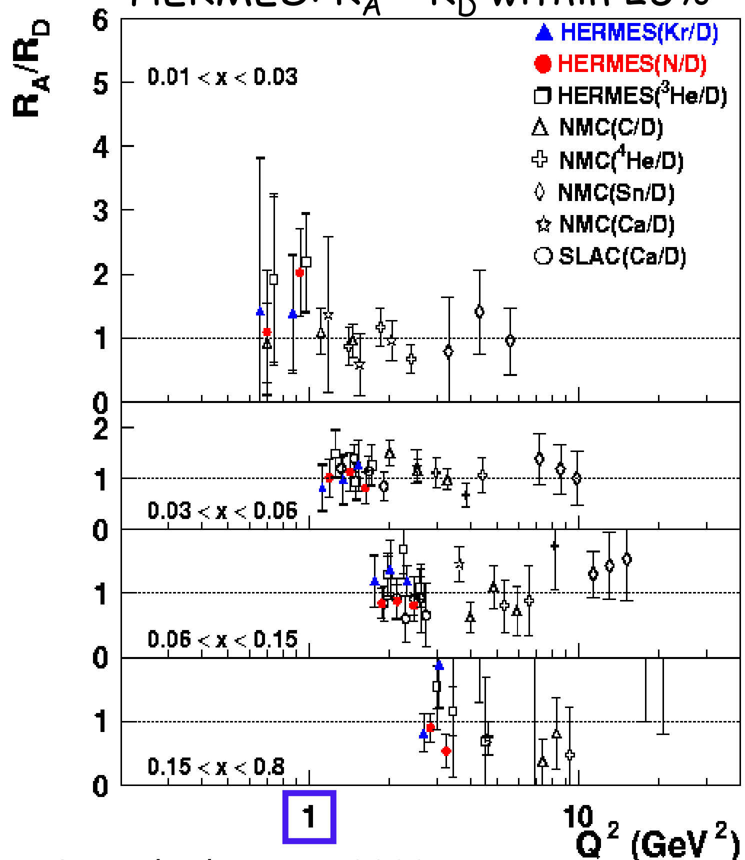


Projected uncertainties for an experiment to run this year (November)

EMC Effect in R = σ_L/σ_T

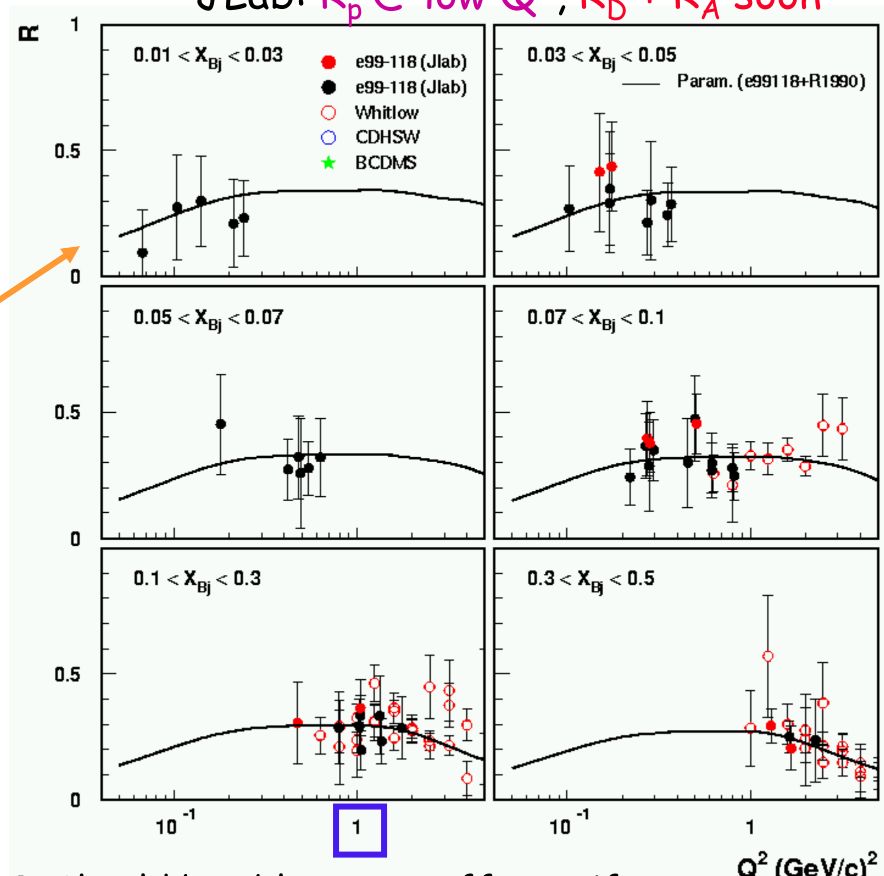
EMC Effect is measured as ratio of F_2^A/F_2^D
In Bjorken Limit: $F_2 = 2xF_1$ (transverse only)
There *should* be medium effects also in F_L, or in $R = \sigma_L/\sigma_T$!

HERMES: $R_A = R_D$ within 25%



E. Garutti, Ph.D UvA 2003,

JLab: R_p @ low Q^2, R_D + R_A soon



→ Should be able to see effects, if any.

R in Nuclei – Link with Neutrino Community

Mass difference between neutrino flavors: $\Delta M^2 \sim E/L$,
with E the ν energy and L the distance source-detector

L was fixed when ΔM^2 was thought to be larger →
ν energy of interest ~ few GeV ~ JLab energy!

ν physics derived from Monte Carlo models folding poorly known beam properties with the best known response of a detector to the creation of various particles in ν interactions → All conventional Nuclear Physics needs to be known for few-GeV probes and included, both for the axial and vector couplings

Approach I : High Luminosity few-GeV ν Experiments
Approach II : Electron scattering experiments to constrain Monte Carlo
Approach III: Do both to extract axial information from difference

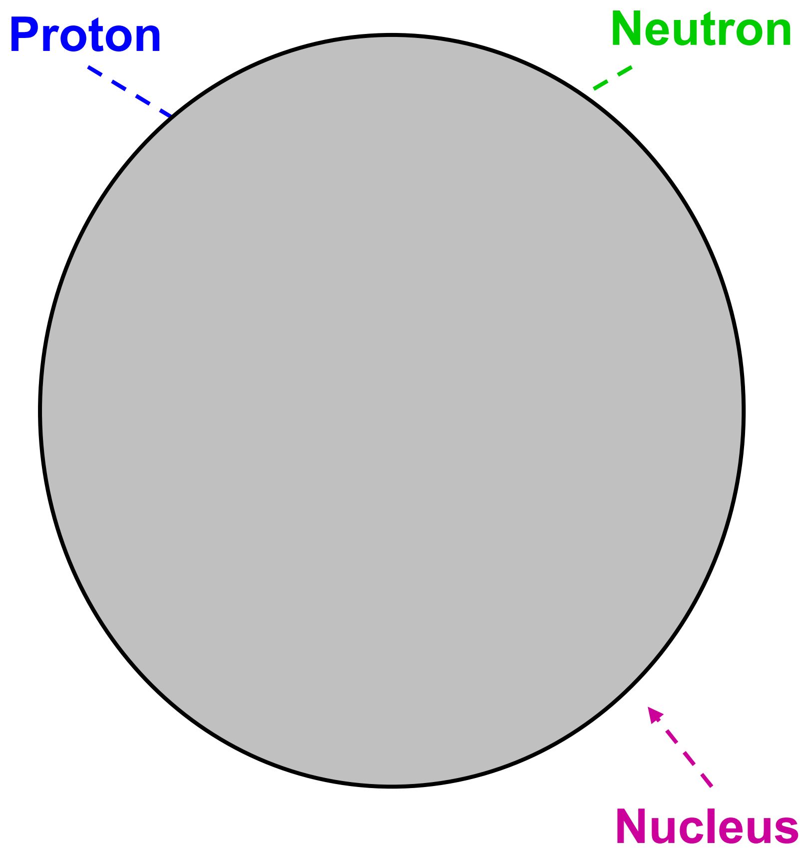
Neutrino community (Bodek et al.) involved in:

I) Approved experiment to measure $R = \sigma_L/\sigma_T$ in Nuclei in Hall C

II) Analysis of existing data on low-energy transparencies and multi-pion production in Hall B

EMC Effect at large x (> 1)

- A nuclear medium has an average density, ρ_o, of 0.17 GeV/fm^3.
- A typical distance for 2 nucleons participating in a short-range correlation (SRC) is ~1.0 fm → the local density can increase by a factor of ~4: this is comparable to the density of neutron stars.
- Nucleons participating in a SRC are deeply bound, i.e. their structure should be modified, like their shape or quark distributions.
- $x = Q^2/2M\nu > 1$ → can be used to select quarks inside nucleon participating in a SRC → superfast quarks!

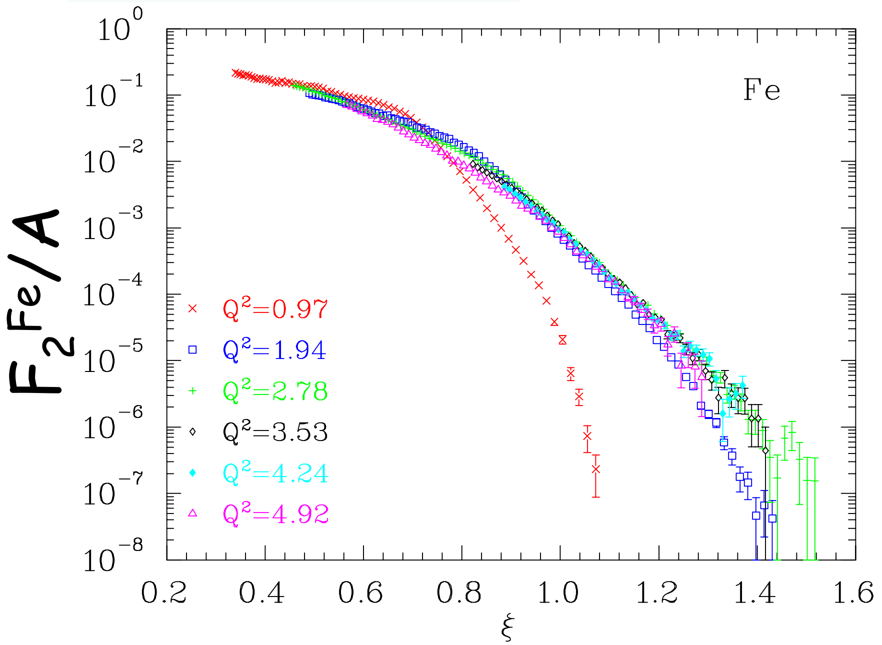


EMC Effect at large x (> 1)

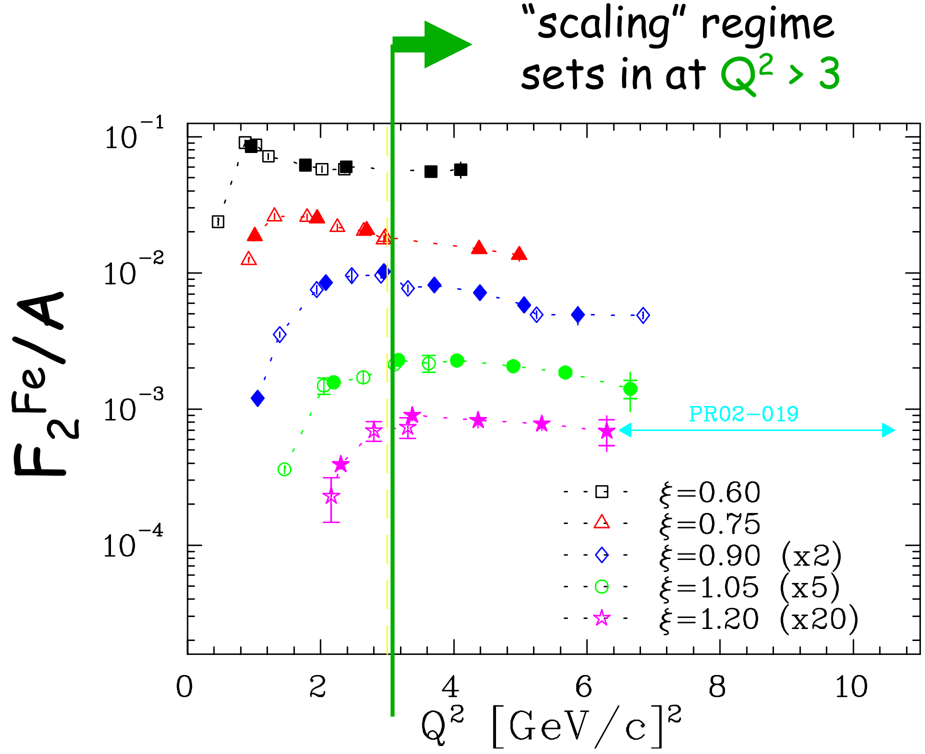
E89-008 @ 4 GeV:
Iron cross sections vs (ν,Q^2)
→Structure Functions vs ξ

$X = 1$, $Q^2 = 3$ } → $\xi = 0.80$

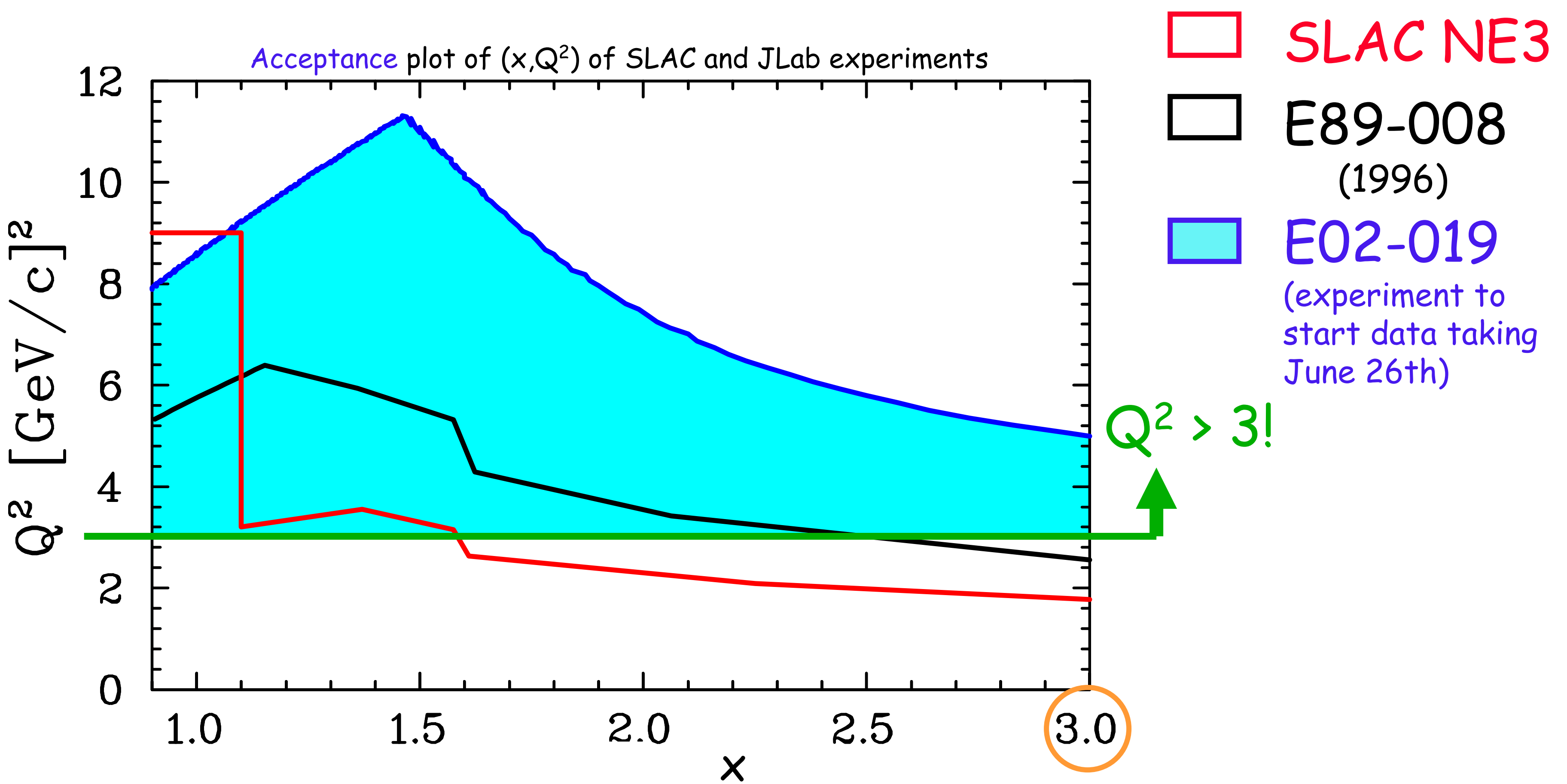
$$\xi = \frac{2x}{1+\sqrt{1+4m^2x^2/Q^2}} \longrightarrow x \text{ (as } Q^2 \to \infty\text{)}$$



"scaling" regime sets in at $Q^2 > 3$



EMC Effect at large x (> 1) - cont.



Note: $x = 3$, $Q^2 = 5$ → nucleon with 1.78+ GeV/c!

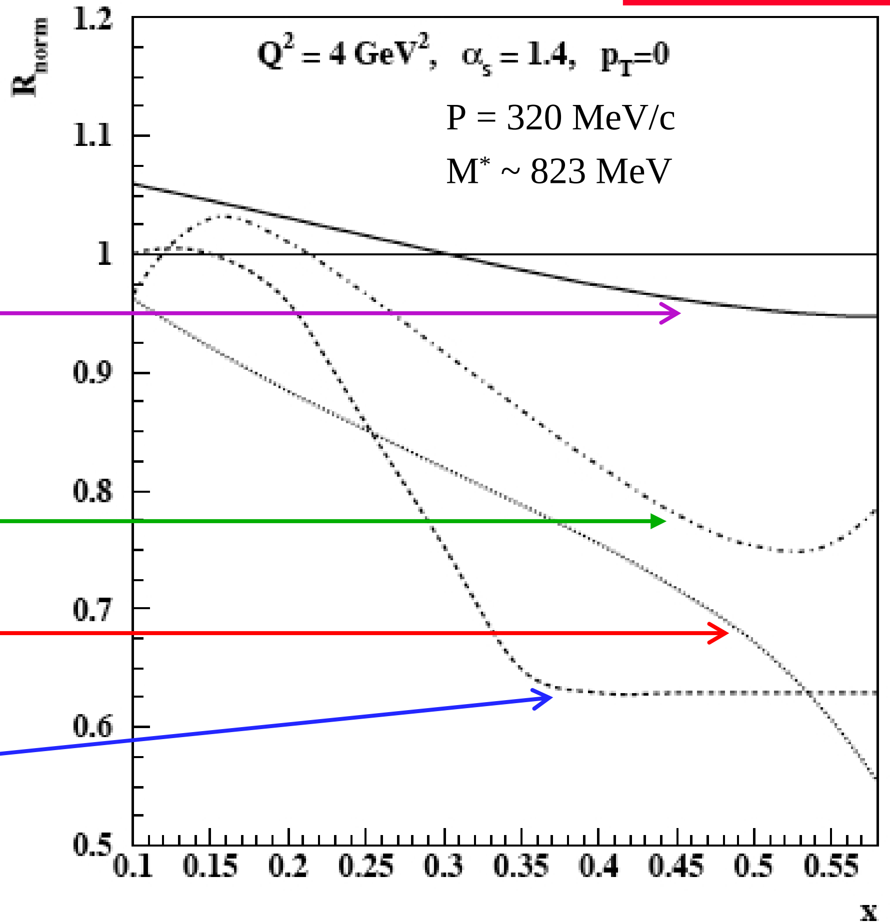
(similar for $x = 1.5$, $Q^2 = 10$)

Tagged Structure Functions

Goal: Tag nucleon (here, neutron) participating in SRC directly

$D(e,e'p_s)n$

$$\frac{F_{2N}^{eff}(x,Q^2,\alpha)}{F_{2N}^{free}(x,Q^2,\alpha)}$$



Modification of the off-shell scattering amplitude (Thomas, Melnitchouk)

6-quark bags (C. Carlson et al.)

Color delocalization

Suppression of "point-like configurations"

Already measured in CLAS for 300 < P < 600 MeV/c (proton angles > 107°)

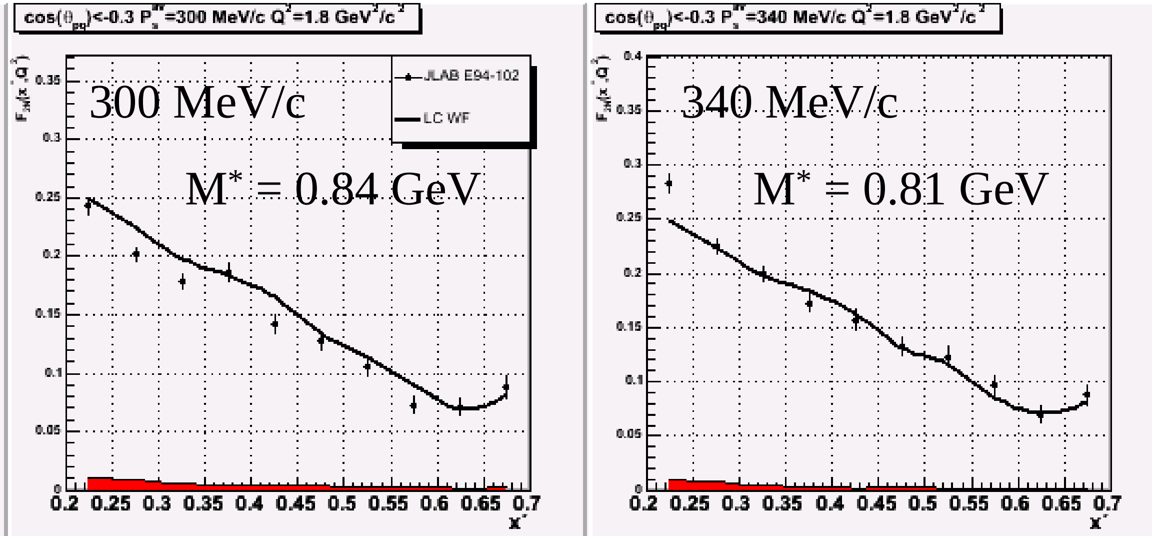
Preliminary Results: x^* (= $Q^2/2p^{\mu}_n q_{\mu}$) dependence

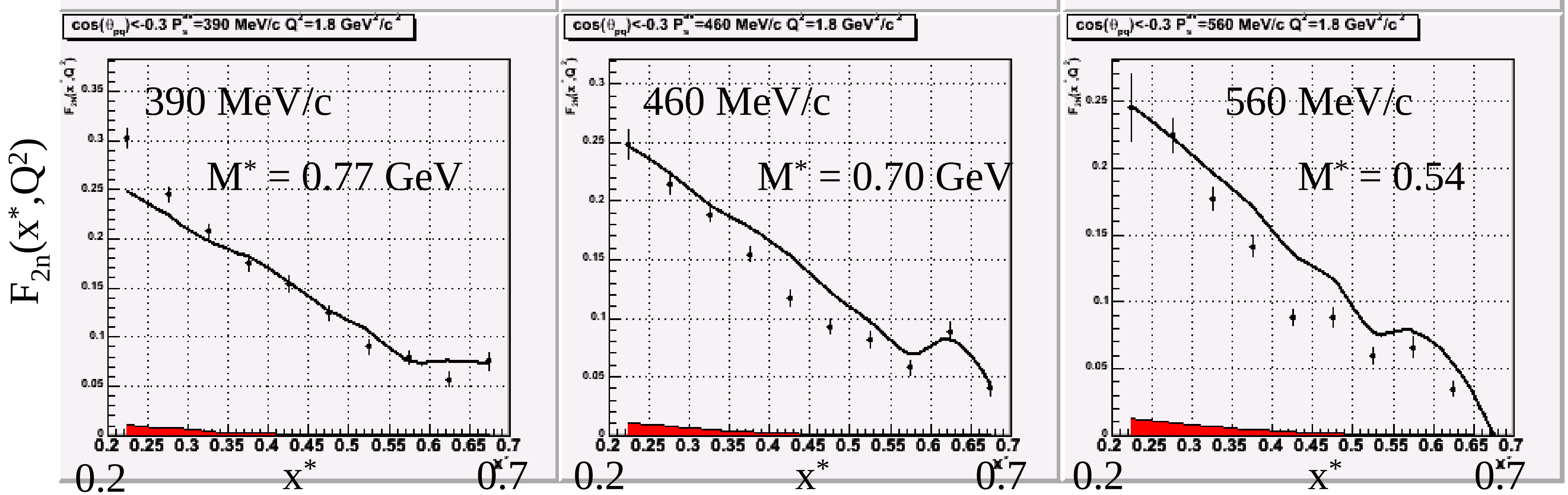
$Q^2 = 1.8$ GeV^2

Proton angles > 107.5^O

Several different proton momenta

Vertical axis: structure function $F_{2n}(x^*,Q^2)$





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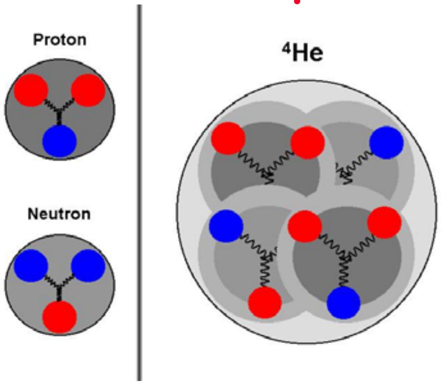


- EMC effect: Change in the inclusive deep-inelastic structure function of a nucleus relative to that of a free nucleon.

Polarization transfer in $^4He(\vec{e},e'\vec{p})^3H$

- E93-049 (Hall A): Measured $^4He(\vec{e},e'\vec{p})^3H$ in quasi-elastic kinematics for Q^2 = 0.5, 1.0, 1.6 and 2.6 $(GeV/c)^2$ using Focal Plane Polarimeter
- Extracted "Superratio": (P'_x/P'_z) in $^4He/(P'_x/P'_z)$ in ^1H

- Free electron-nucleon scattering

$$\frac{G_E}{G_M} = -\frac{P'_x}{P'_z}\frac{(E_i+E_f)}{2m}\tan\frac{\Theta_e}{2}$$

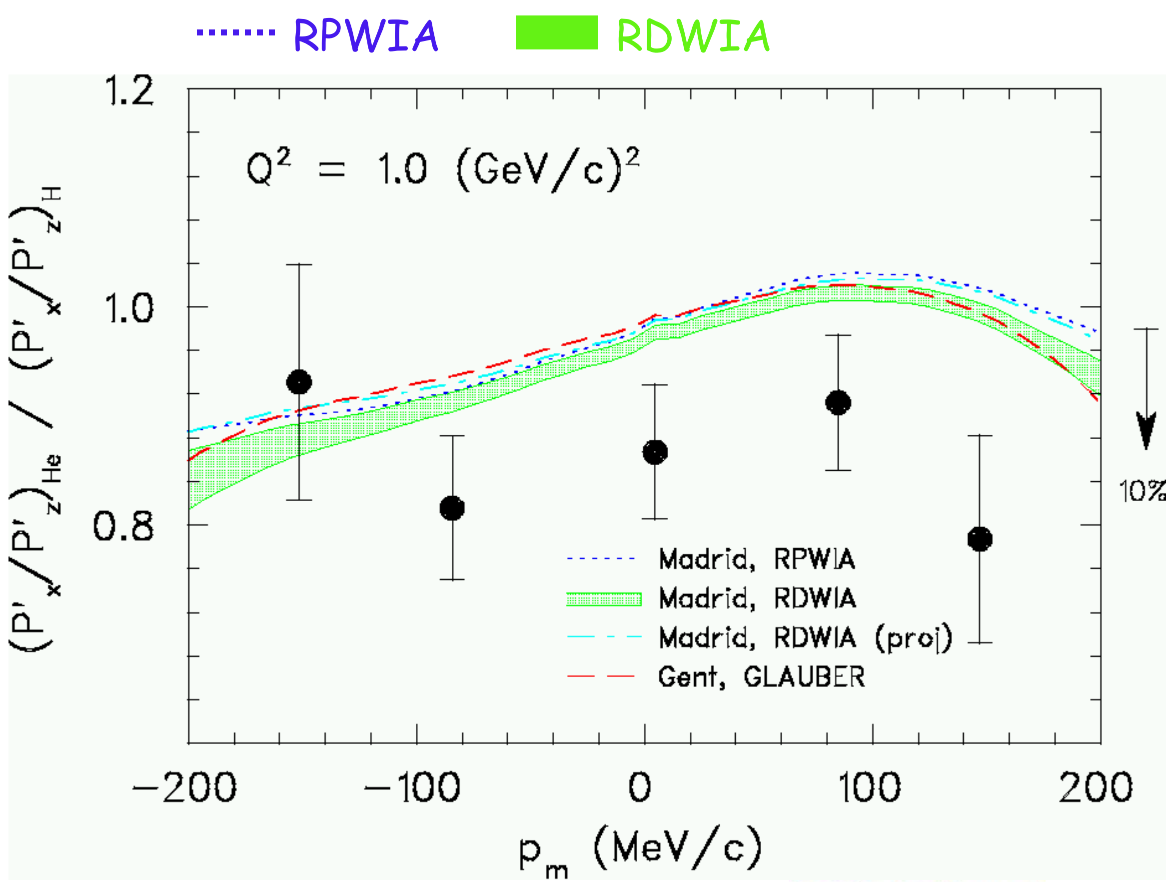
(see also talk by Kees de Jager)

- Bound nucleons → evaluation within model

- Reaction mechanism effects minimal for $A(\vec{e},e'\vec{p})$ about $P_m = 0$

$$\frac{\tilde{G}_E}{\tilde{G}_M} = -\frac{P'_x}{P'_z}\frac{(E_i+E_f)}{2m}\tan\frac{\Theta_e}{2}$$

→ Form Factors in the Nucleus



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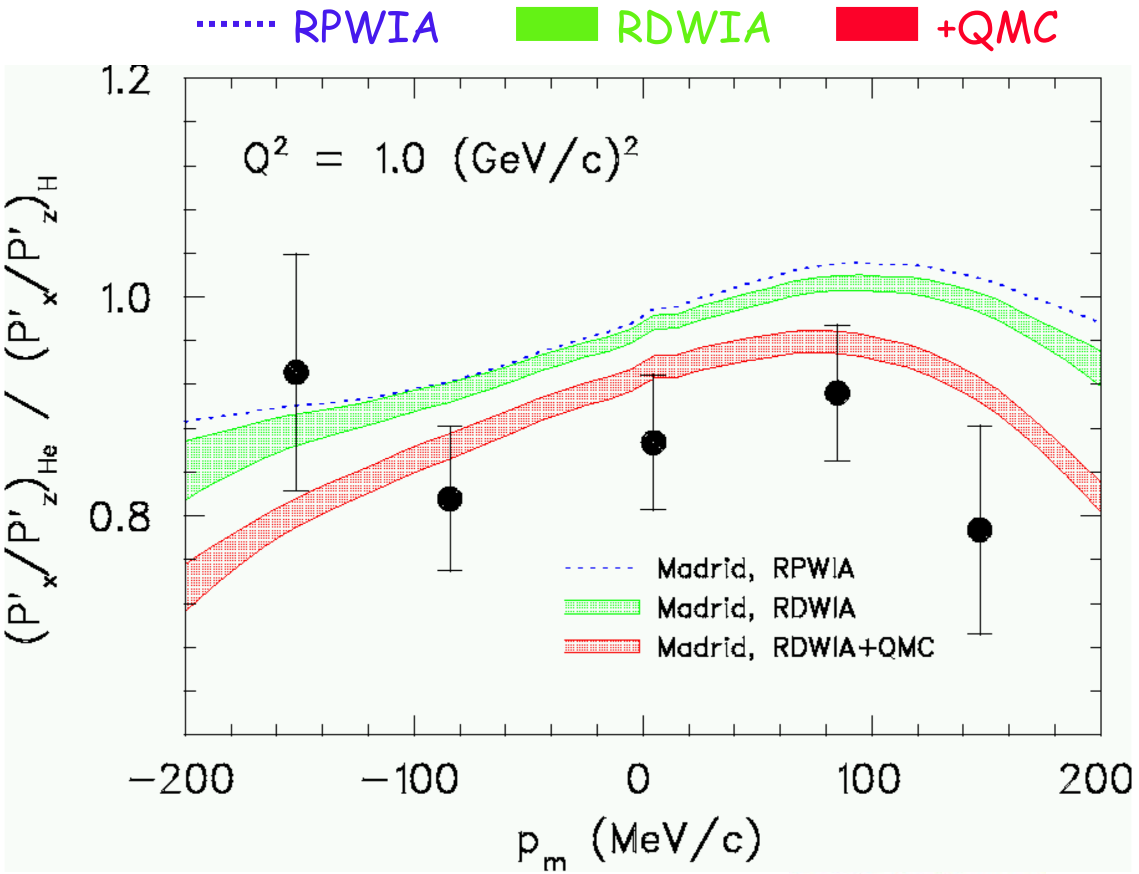
Medium Modifications of Nucleon Form Factor

- Compared to calculations by Udias without and with inclusion of medium effects predicted by Thomas *et al.* (Quark Meson Coupling model).



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- After corrections for FSI effects: deviation from 1 a measure of the medium dependence of G_E^p/G_M^p

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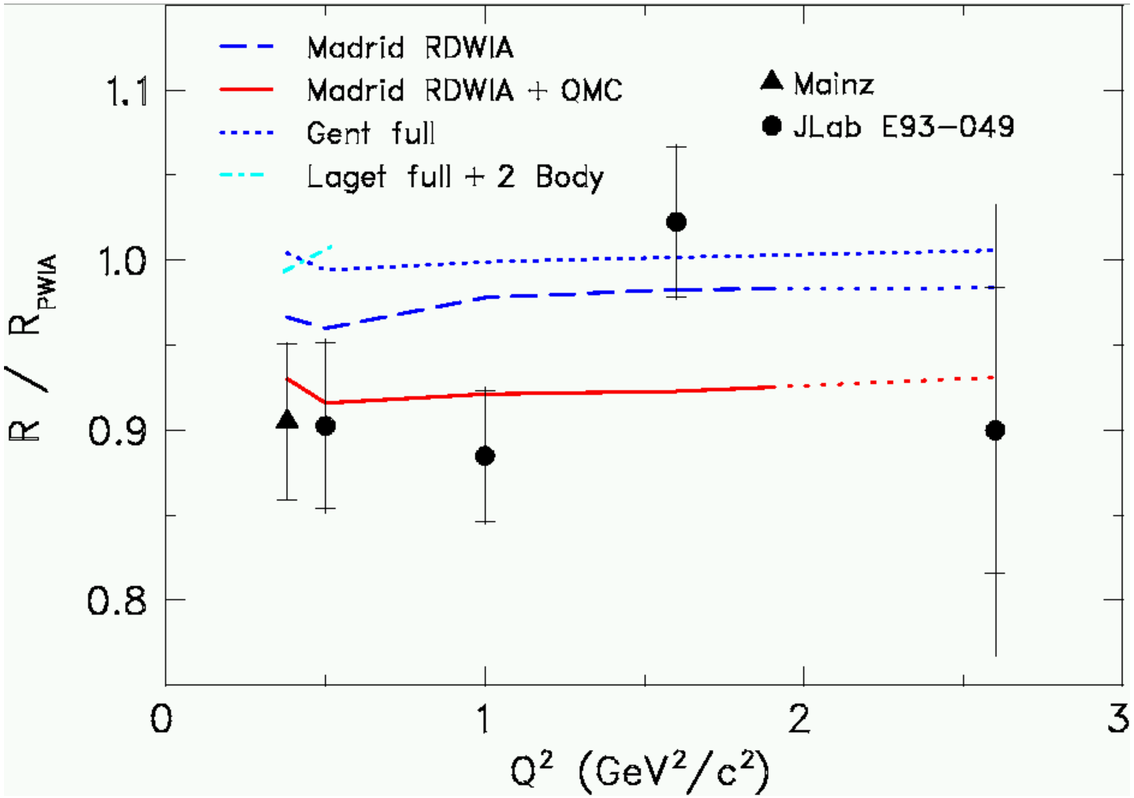

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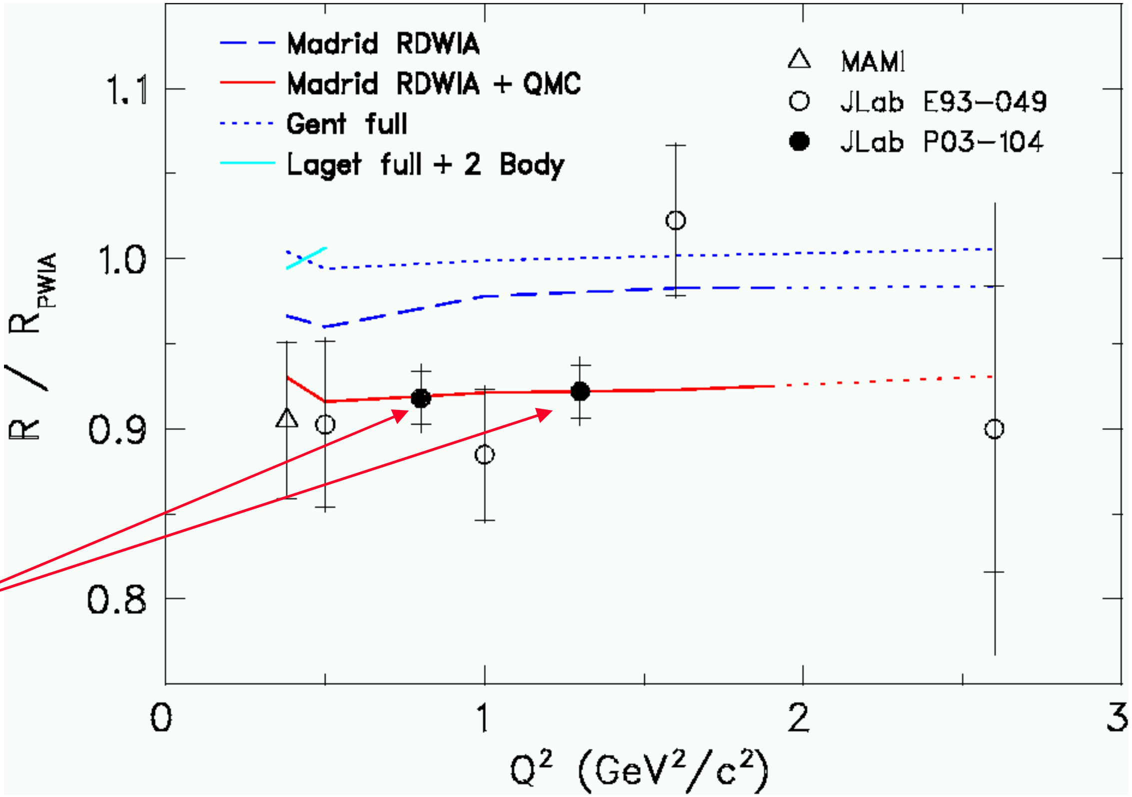
- New proposal approved by PAC24



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  Any signatures for the onset of non-hadronic degrees of freedom and QCD dynamics?

Nuclear Transparency

Exclusive Processes

Nucleons

$A + B \rightarrow C + D$

↓

N

Nuclei

$A + B' \rightarrow C + D + X$

↓

${}^{A}N_{Z}$

Ratio of cross-sections for exclusive processes from nuclei to nucleons is termed as Transparency

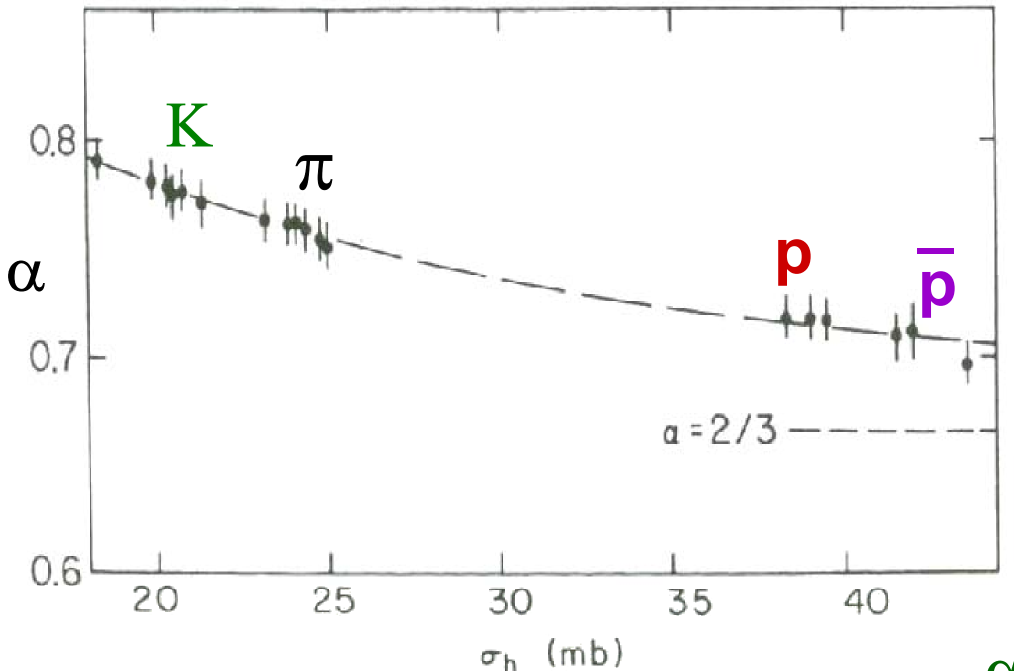
$$T = \frac{\sigma(A)}{A\sigma_o}$$

$\sigma(A)$ parameterized as = $\sigma_0 A^{\alpha}$

σ_o = free (nucleon) cross-section

Experimentally α = 0.72 – 0.78, for π, κ, p

Total Hadron-Nucleus Cross Sections



Hadron– Nucleus total cross section

Fit to $\sigma(A) = \sigma_0 A^{\alpha}$

Hadron momentum 60, 200, 250 GeV/c

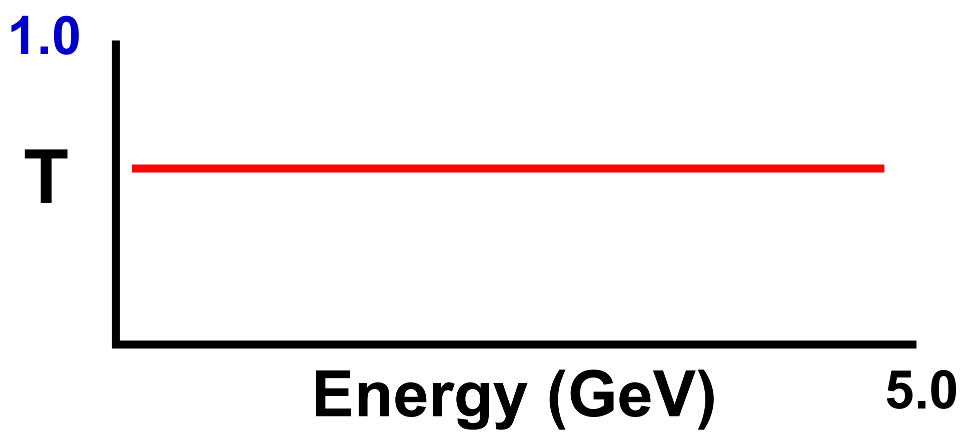
α **= 0.72 – 0.78, for p,** π**, k**

α **< 1 interpreted as due to the strongly interacting nature of the probe**

A. S. Carroll *et al.* Phys. Lett 80B 319 (1979)

Nuclear Transparency

Traditional nuclear physics calculations (Glauber calculations) predict transparency to be nearly energy independent .



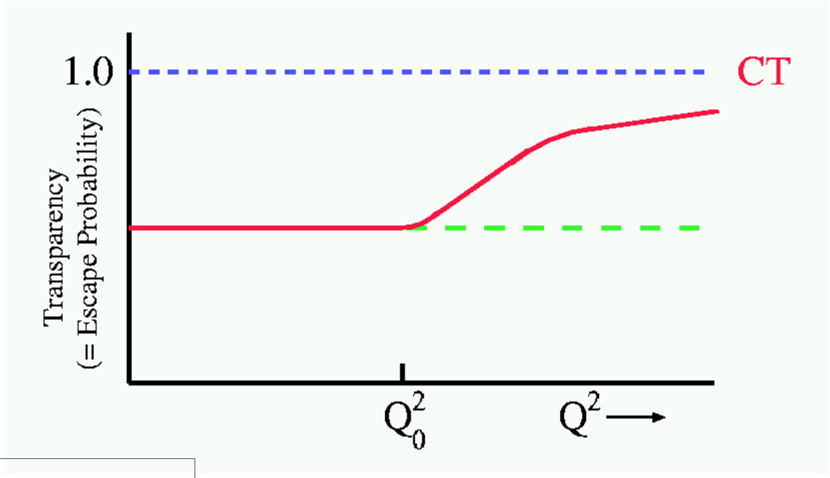
Ingredients

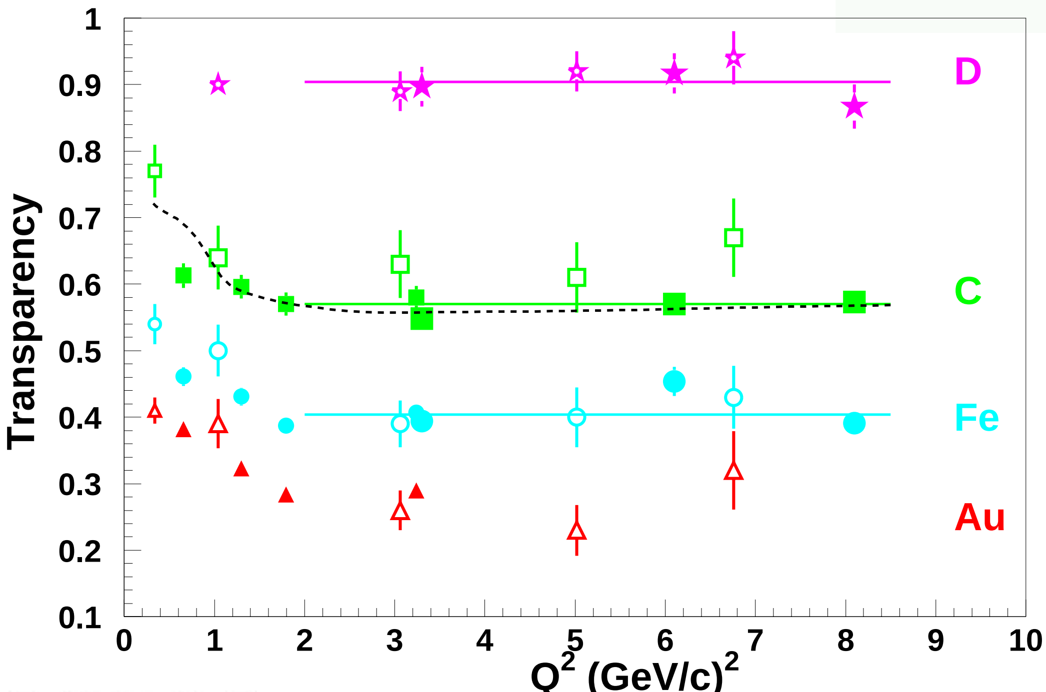
- σ_{hN} h-N cross-section
- Glauber multiple scattering approximation
- Correlations & FSI effects.

For light nuclei very precise calculations of T are possible.

Search for Color Transparency in Quasi-free A(e,e'p) Scattering

From fundamental considerations (quantum mechanics, relativity, nature of the strong interaction) it is predicted (Brodsky, Mueller) that fast protons scattered from the nucleus will have decreased final state interactions





Hall C – E94-139

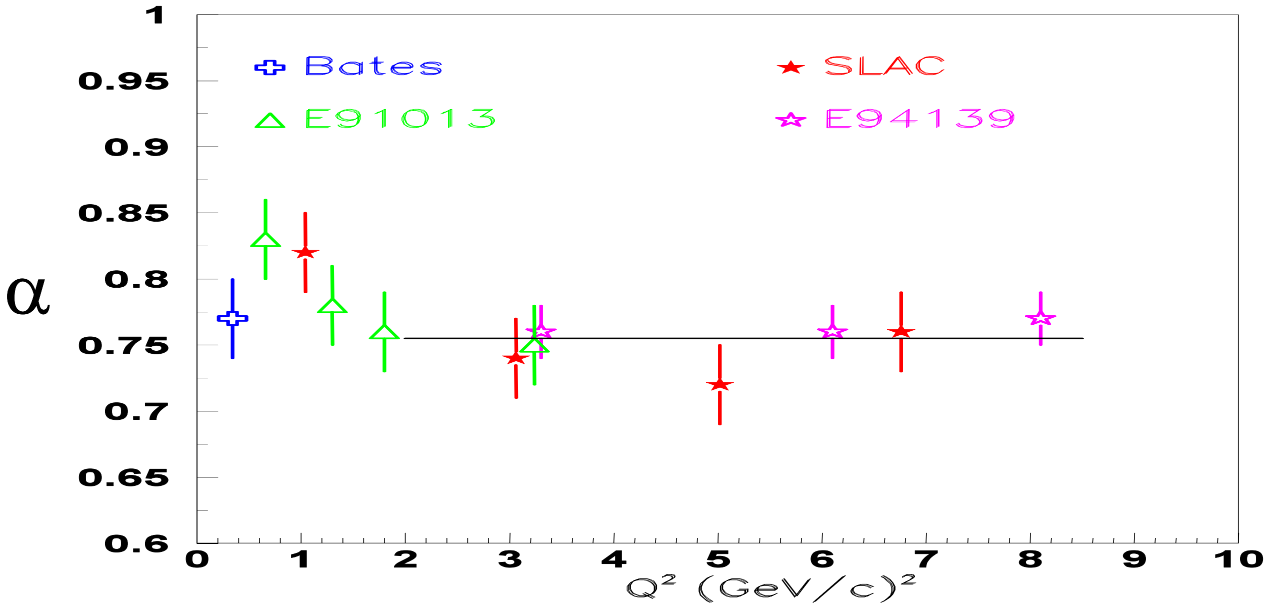
Constant value line fits give good description χ^2/df = 1

Conventional Nuclear Physics Calculation by Pandharipande *et al.* (dashed) also gives good description

→No sign of CT yet

A(e,e'p) Results -- A Dependence

Fit to $\sigma = \sigma_o A^{\alpha}$



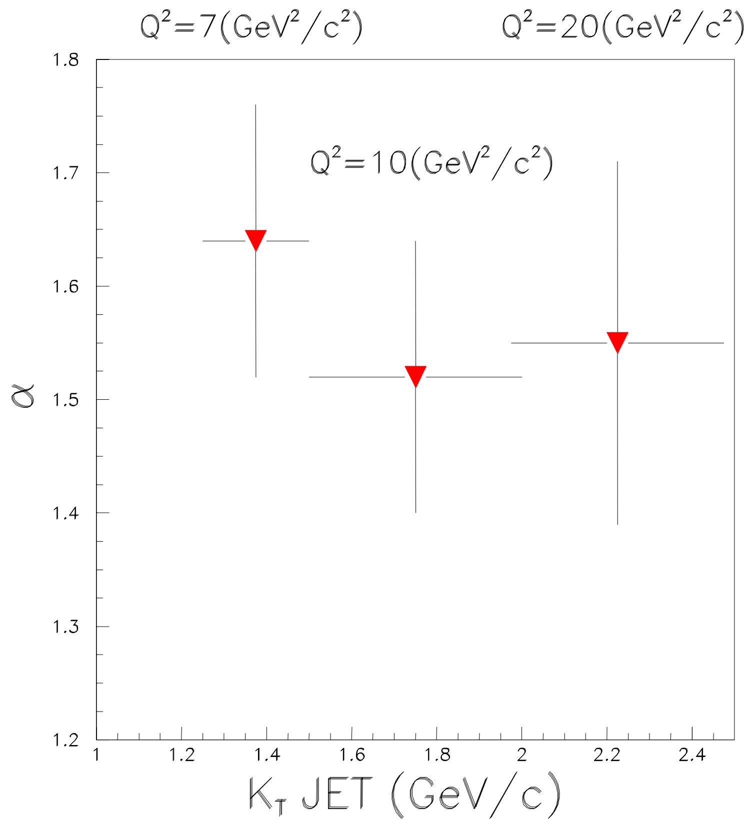
α = constant = 0.75 **for $Q^2 > 2$ (GeV/c)^2**

Close to proton-nucleus total cross section data!

qqq vs $q\bar{q}$ systems

- There is no unambiguous, model independent, evidence for CT in qqq systems.
- Small size is more probable in 2 quark system such as pions than in protons.
  (B. Blattel et al., PRL 70, 896 (1993)
- Onset of CT expected at lower Q^2 in $q\bar{q}$ system.
- Formation length is ~ 10 fm at moderate Q^2 in $q\bar{q}$ system (→ larger than nuclear radius)
- Onset of CT related to onset of factorization required for access to GPDs in deep exclusive $q\bar{q}$ production

$A(\pi,\text{dijet})$ Data from FNAL



Coherent π^+ diffractive dissociation with 500 GeV/c pions on Pt and C.

Fit to $\sigma = \sigma_0 A^\alpha$

α > 0.76 from pion-nucleus total cross-section.

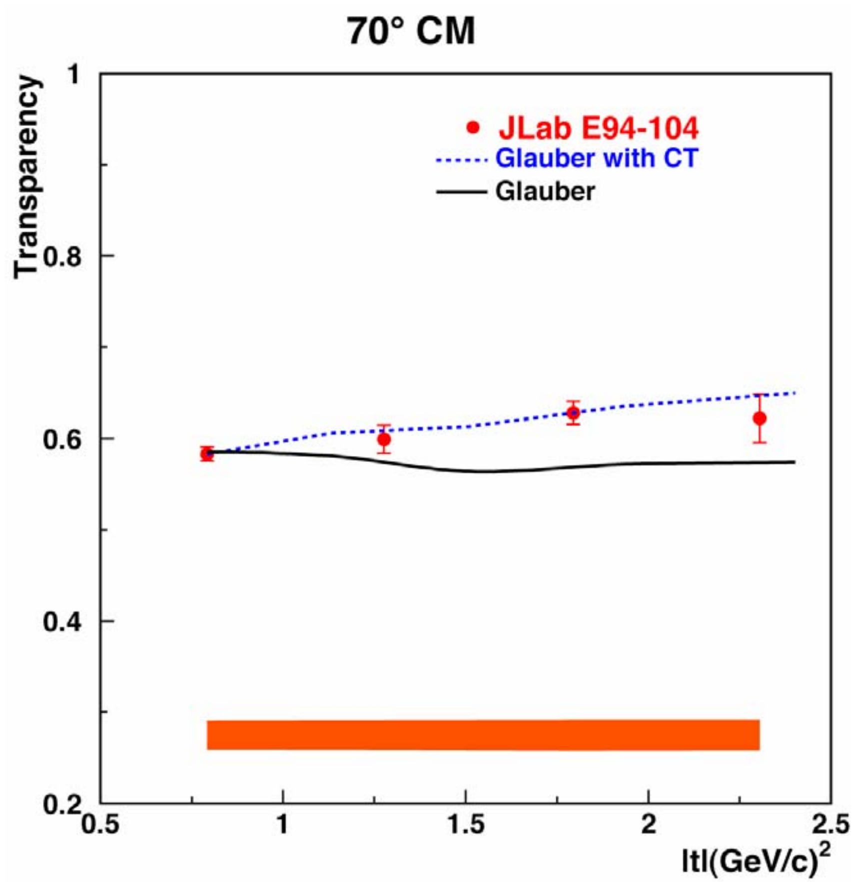
Aitala *et al.*, PRL **86** 4773 (2001)

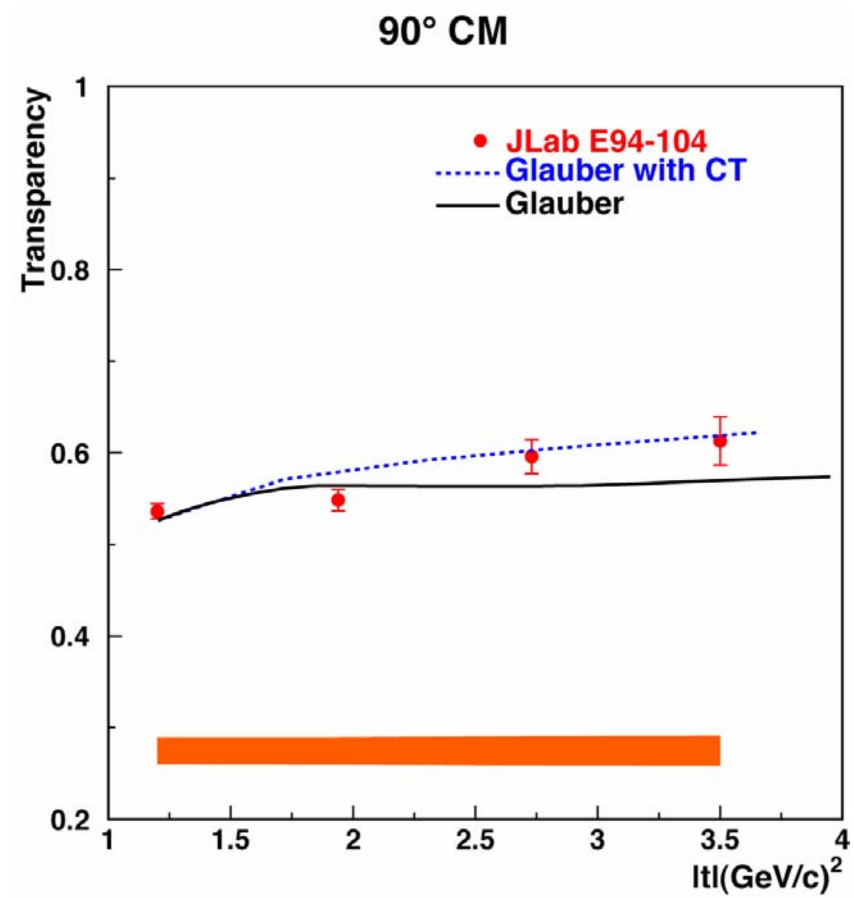
Claim: Full CT effect observed by $Q^2 \sim 10\ (GeV/c)^2$

→ $A(e,e'\pi)$ and $A(e,e'\rho)$ experiments at JLab pushing Q^2 range

→ $A(\gamma,\pi^- p)$ pushing t range

Results from E94-104 (γ n -> π^- p in ^{4}He)

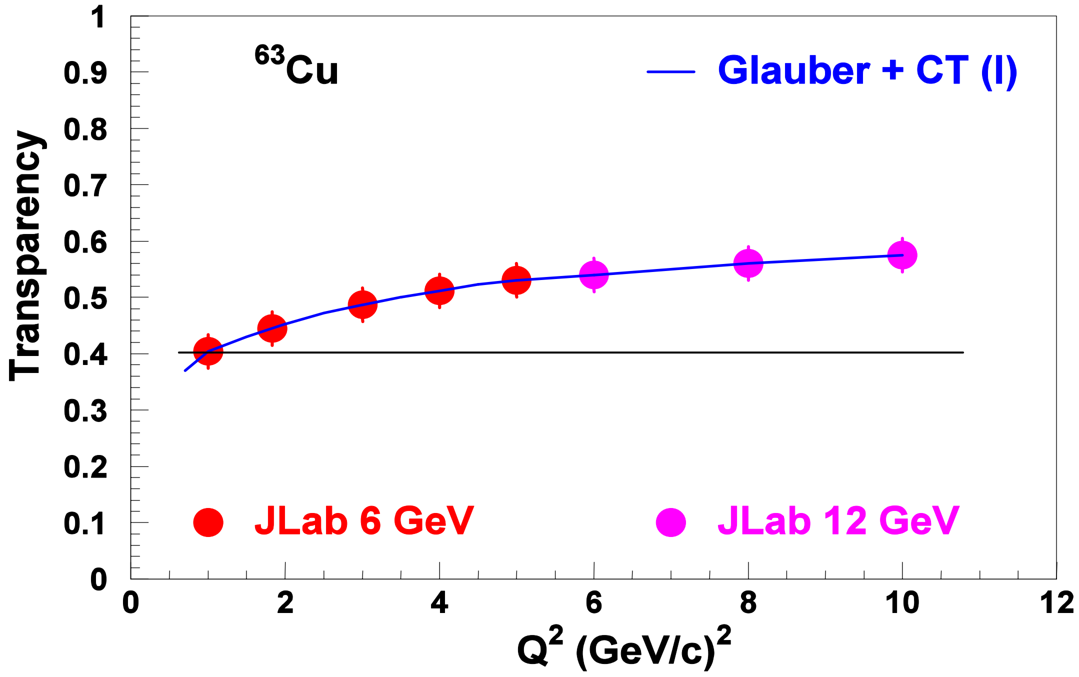




- Calculations use Glauber theory and correlations from Argonne v_{14} and Urbana VIII
- CT estimated from quantum diffusion model, normalization can be chosen arbitrarily
- Data show t-dependence seemingly at variance with traditional nuclear physics
- Clear need for extension to higher t-values

A Pion Transparency Experiment

JLab Experiment E01-107: A(e,e'π) on H, D, C, Cu, Au



Measurable effect predicted for $Q^2 < 5$ (GeV/c)^2 (Miller et al., Ralston et al.)

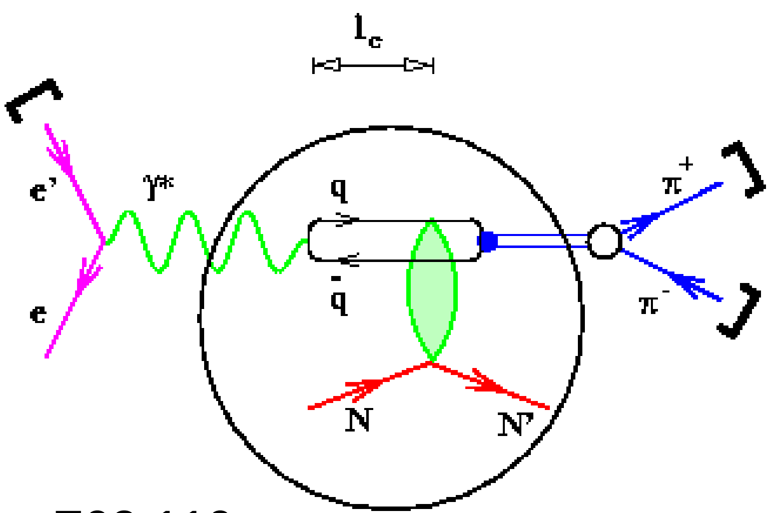
- Projected uncertainties for experiment to start this July (E = 5.75 GeV)

CT and Quark Propagation through Nuclei

Search for Color Transparency

Measure ρ absorption vs. Q^2 at fixed coherence length l_c

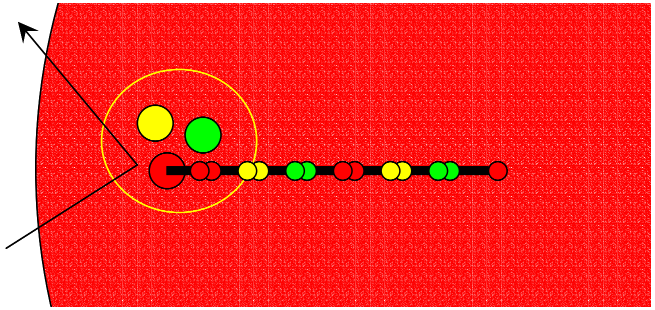
Compare absorption in deuterium, carbon, aluminum, and iron



Quark Propagation through Nuclei

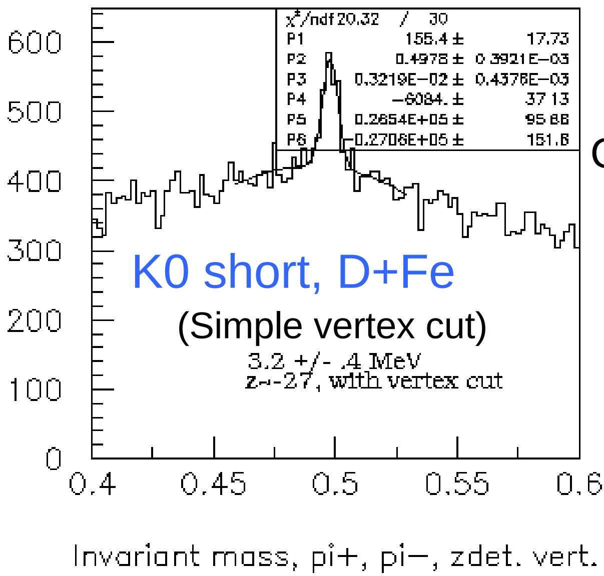
Measure attenuation and transverse momentum broadening of hadrons (p, K) in DIS kinematics

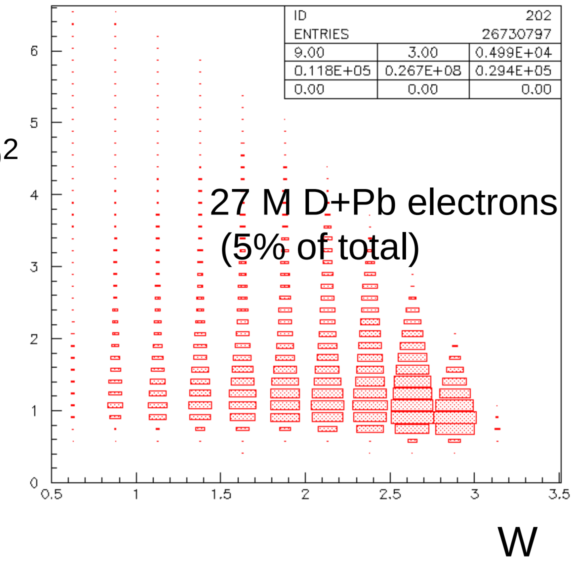
Compare absorption in deuterium, carbon, iron, tin, and lead

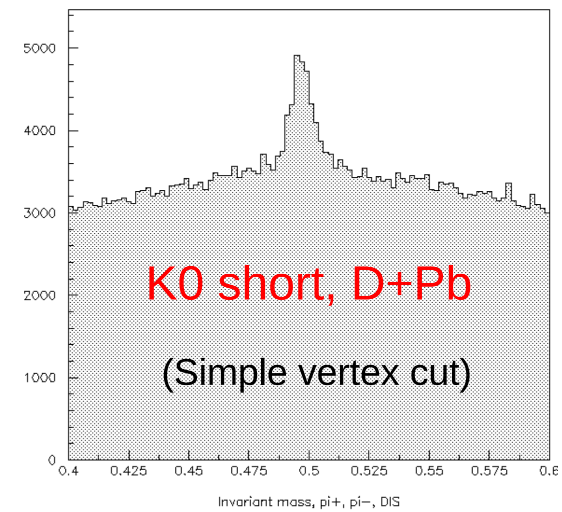


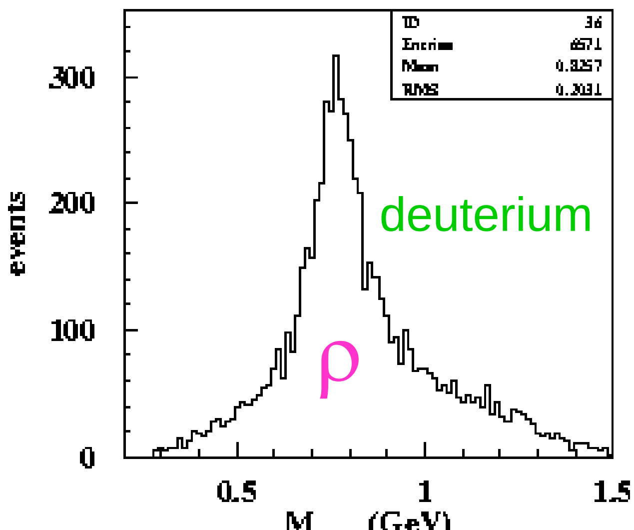
E02-110 → **EG2** ← E02-104

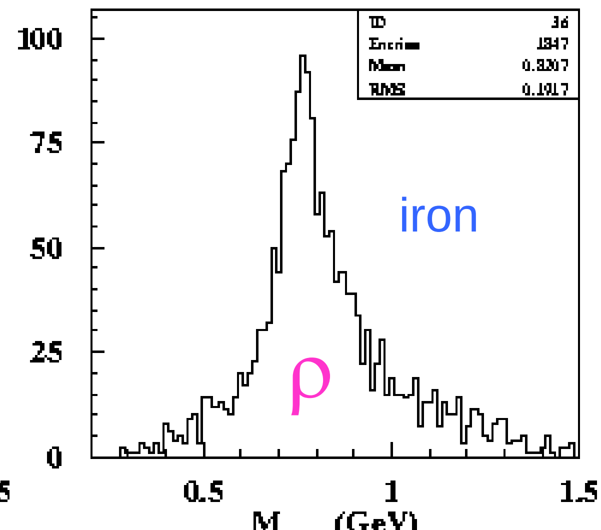
CLAS EG2 - Online Results (2003)

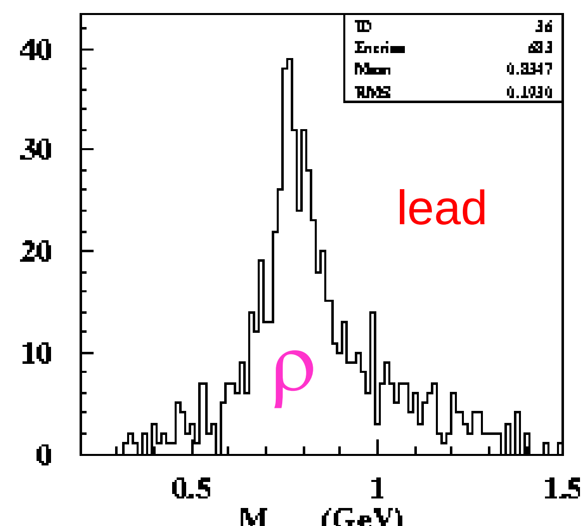












Summary

In principle both baryon-meson and quark-gluon descriptions of the nucleus should work, question is rather what is the most efficient description of observables?

JLab is pushing both descriptions to the limit:

1) A description of the deuteron elastic scattering data in terms of conventional nuclear physics works to much smaller distance scales (0.5 fm) than expected.
2) Deuteron photodisintegration experiments reveal the underlying quark-gluon degrees of freedom at a distance scale smaller than 0.1 fm.
3) First indication that a nucleus is not merely a set of nucleons, the nuclear EMC effect, is under scrutiny for cases where nucleons are strongly bound ($x > 1$, tagged structure functions). Can alternatively view this as scattering from superfast quarks.
4) A second indication is given by the observed medium dependence of proton form factors, considered a precursor of the onset of a quark gluon plasma.
5) Proton transparency data can be well described by conventional nuclear physics;
6) But have seen hints of QCD dynamics (Color Transparency) in meson production data. Full effects of CT may be anticipated at $Q^2 < 10$ here, presently under investigation.

Data show beautiful balance between conventional nuclear physics descriptions and QCD effects.

This topic: some experiments complete, many ran/to run in FY'03 and '04