Hadrons in the Nuclear Medium

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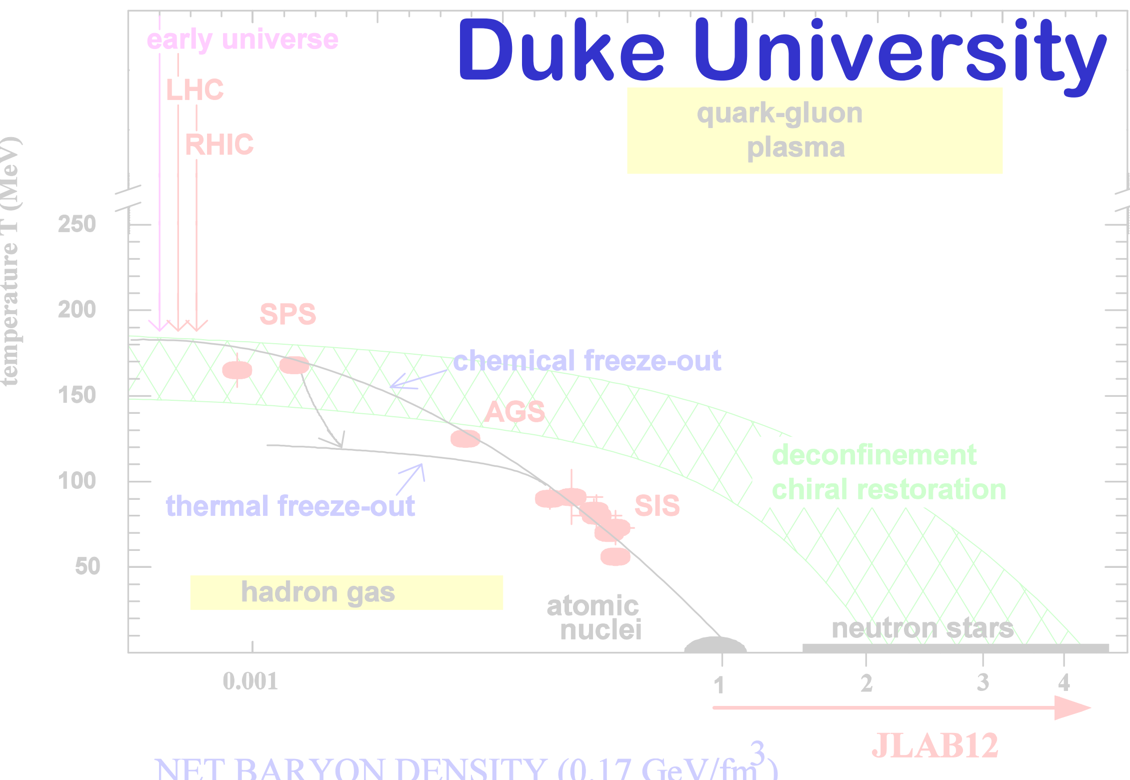


HUGS, June 2003

Lecture - 1

Outline

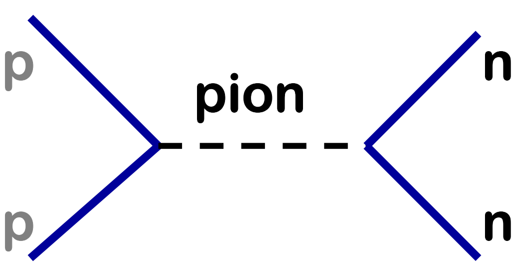
- Historical overview and Motivation
- Some Definitions
- Matter at high densities
- Exclusive processes at high momentum transfer
- Probing the limits of nucleon based description of nuclei

Historical Overview

The goal of Nuclear Physics is to understand the forces holding atomic nuclei together.

Modern era began in the 1930s with the discovery of the neutron

First attempt: Yukawa's original idea - nucleons interact by exchanging massive particles (mesons).



$$Range \approx c\Delta t \approx \frac{\hbar}{2mc} \Rightarrow m_\pi \approx 100 \text{ MeV}$$

The pion was discovered in 1947 by Cecil Powell

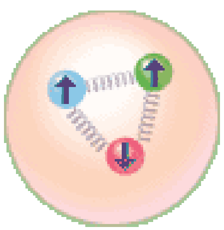
followed by

Explosion of particle discoveries (1947–1960s)

led

Gell-Mann and Zweig introduce quarks to organize the spectrum (particle zoo).

and



Δ^{++}(u,u,u) ⇨ additional quantum number (color).

eventually in the 1970s

At SLAC deep-inelastic electron-nucleon scattering results indicate point like constituents.

The Standard Model

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

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3

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

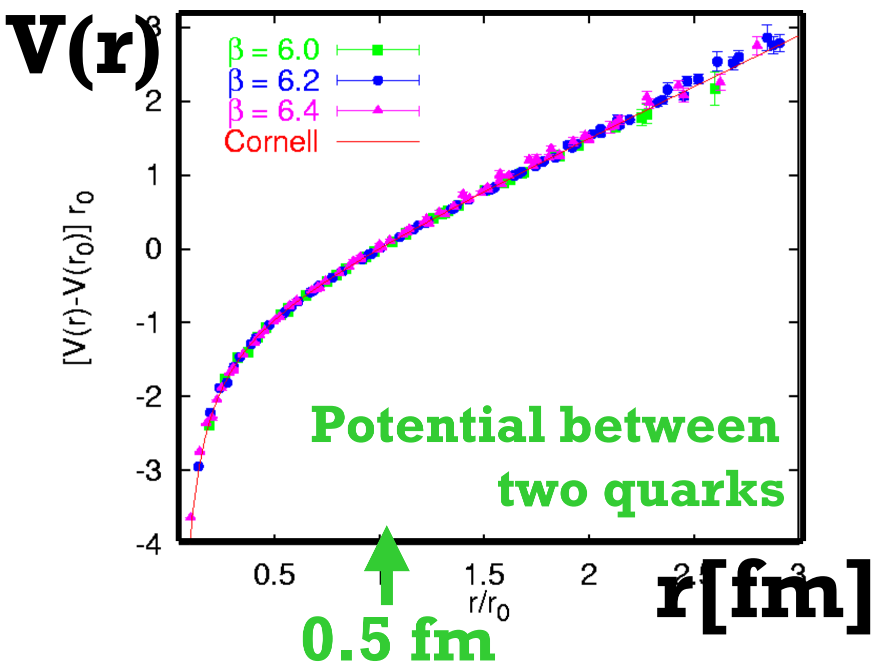
Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge	Name	Mass GeV/c^2	Electric charge
γ photon	0	0	g gluon	0	0
W^-	80.4	−1			
W^+	80.4	+1			
Z^0	91.187	0			

Introduction

Quantum Chromo Dynamics (QCD): The fundamental theory describing the strong force in terms of quarks and gluons carrying color charges.

Strongly attractive at all distances except at very short distances.

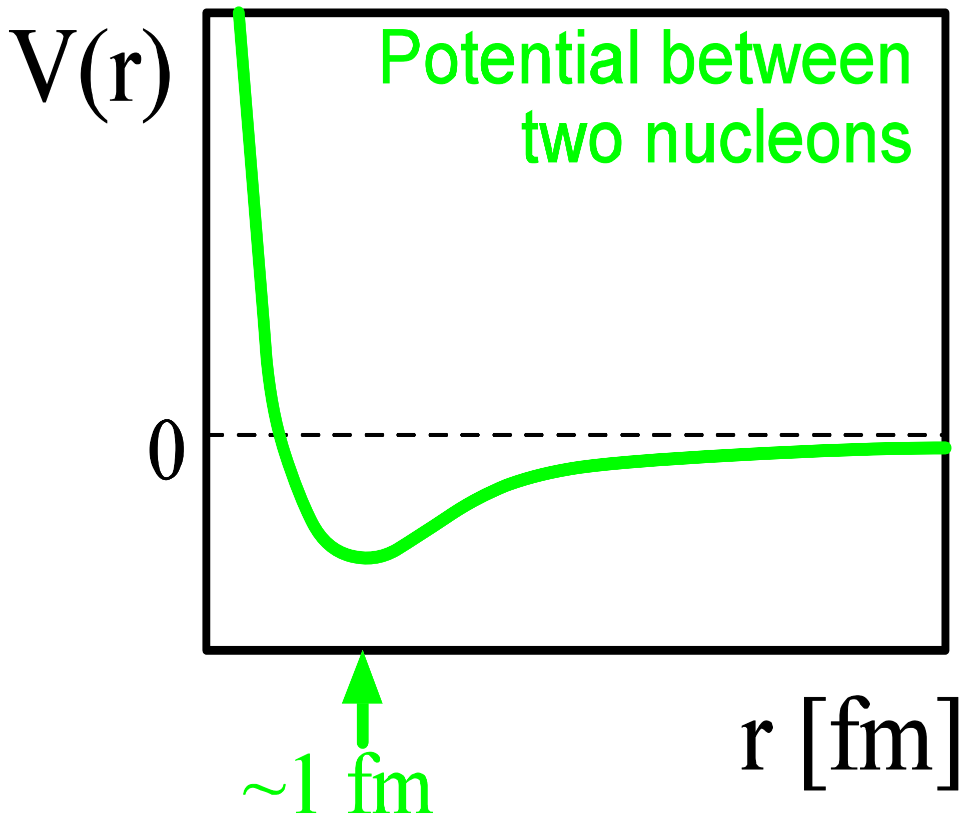
Force at distances
 > 1 fm = 18 tons



At short distances or high energies, QCD is asymptotically free ⇨ Perturbative methods can be applied

Introduction

"Real World":
nucleons + mesons + interactions

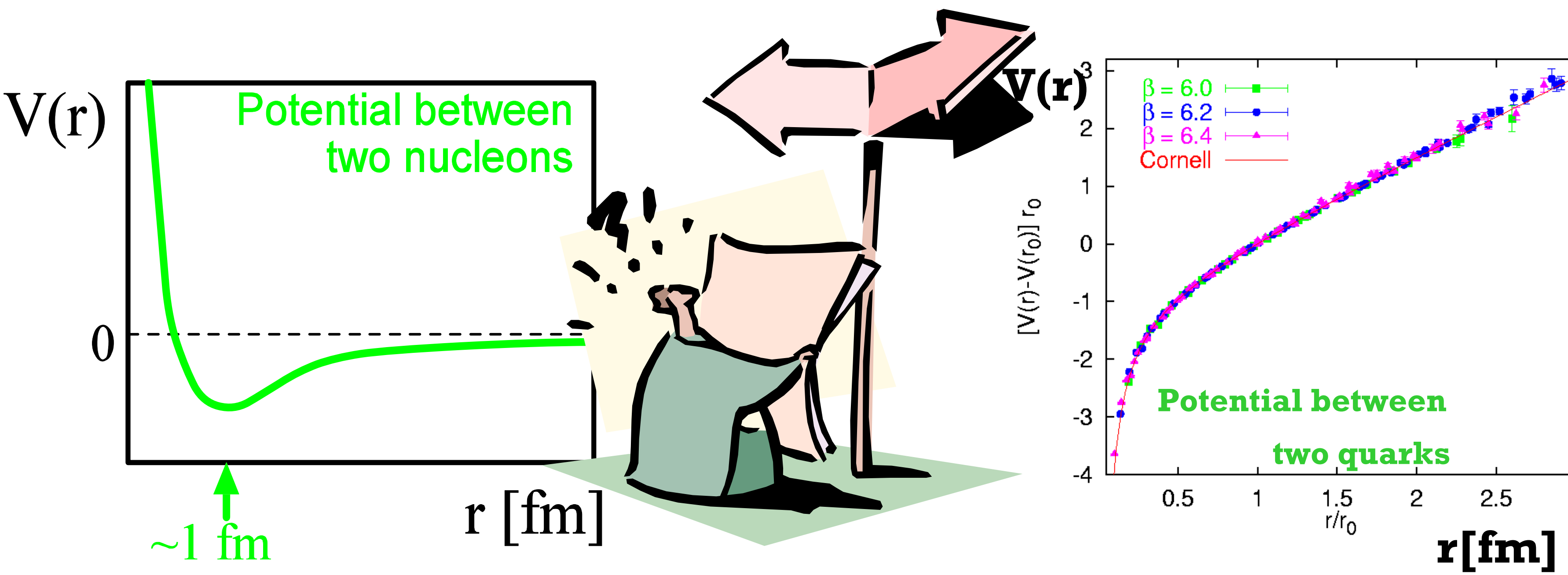


Matter is colorless

Quark interactions cancel at large distances making Hadronic interactions finite.

Two “Realms” of Nuclear Physics

Both realms are well described but there is no roadmap from QCD land to the “Real world.”



“Real World” **QCD Land**

Drawing the Roadmap

Understanding nucleons & nuclei in terms of quarks and gluons is the most important unsolved problem of the Standard Model of nuclear and particle physics.

in other words

We need data that will connect QCD land to real world

Unique opportunity exists in studying hadrons in nuclear matter and comparing them with hadrons in free space.

& Look for

Modifications in the structure and interactions of hadrons in the nucleus.	&	The transition from quark gluon to nucleon-meson degrees of freedom.

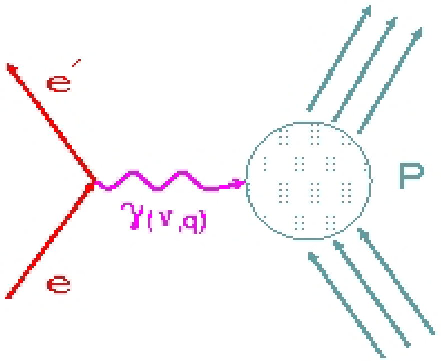
Drawing the Roadmap

- Matter at high densities
  - Modification of nuclear structure at high densities
  - High density fluctuations in nuclei
  - Deep inelastic scattering at $x > 1$
  - Tagged structure functions
- Exclusive processes at high momentum transfer
  - Color transparency
  - Nuclear Filtering
- Charm production in nuclei
- Probing the limits of nucleon based description of nuclei

Some Definitions

Exclusive vs Inclusive Scattering

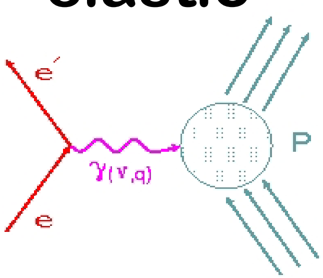
Exclusive : Completely determined initial and final states



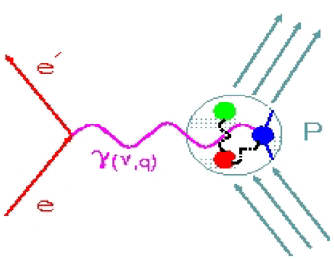
Eg. e + p → e' + p
all final states detected

Inclusive : all final states are not measured e + p → e' + X

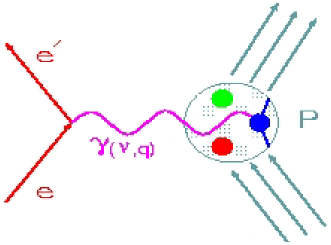
elastic



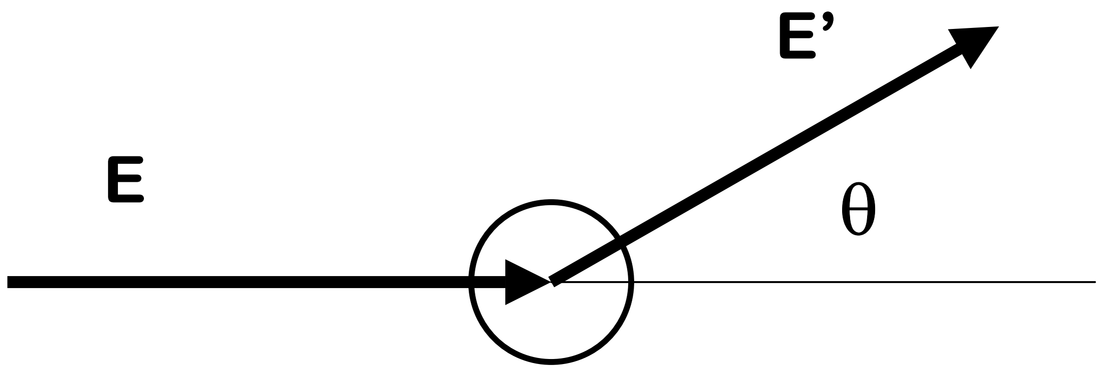
resonance



deep inelastic



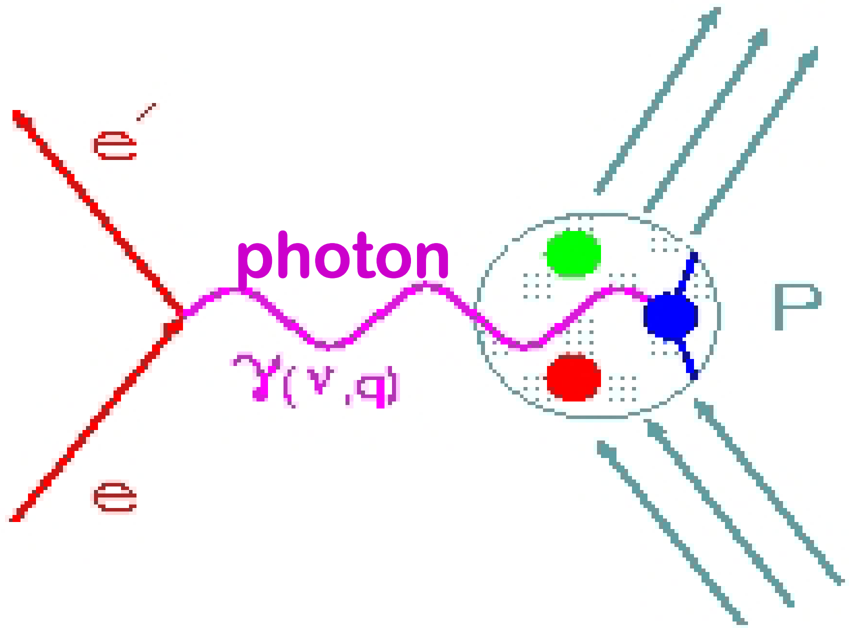
Scattering Kinematics



E
E'
θ

$\nu = E - E'$ (energy transferred by photon)
$X = Q^2 / 2M\nu$
$Q^2 = 4EE'\sin^2(\theta/2)$

X and Q^2

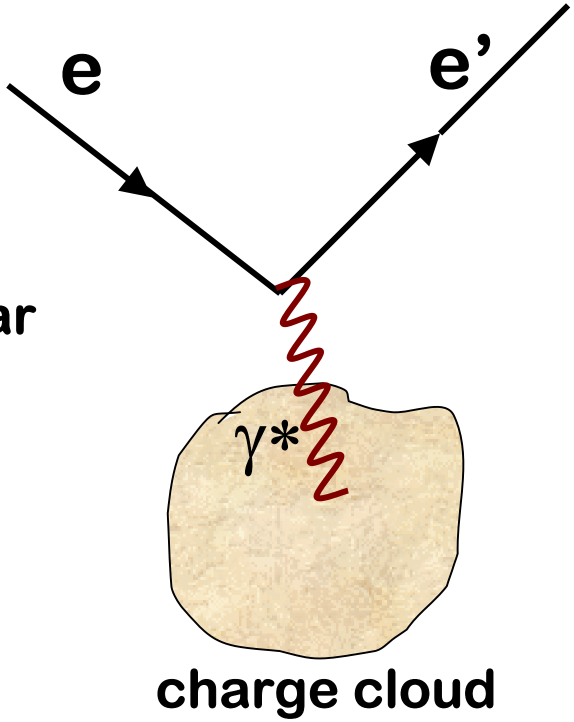


Q^2 : Square of four momentum of the virtual photon, or momentum transfer square (higher Q^2 probes shorter distances)

X : Fraction of nucleon momentum carried by the struck quark.

$$0 < X < 1$$

Form Factors

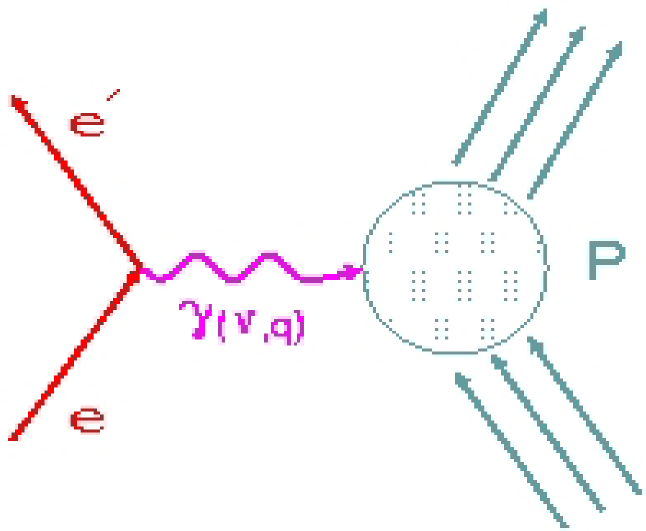


One can Image an object by scattering electrons off it and measuring the angular distribution of the scattered electrons.

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Point}} \left|F(q)\right|^2$$

For a static charge the Form factor $F(q)$ is the Fourier transform of the charge distribution

Elastic Scattering

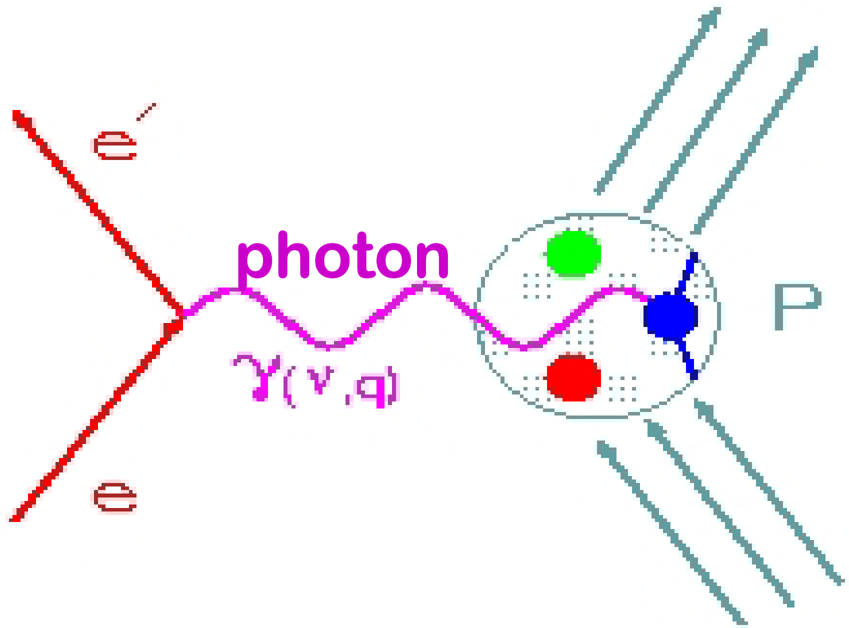


For e p → e' p' the cross-section can be written as

$$\frac{d\sigma}{d\Omega} = (K)[\frac{G_E^2 + \tau G_M^2}{1+\tau}\cos^2\frac{\theta}{2} + 2\tau G_M^2 \sin^2\frac{\theta}{2}]$$

G_E and G_M Related to the charge and magnetic moment distribution of the proton.

Deep Inelastic Scattering



For e p → e X the cross-section can be written as

$$\boxed{\frac{d\sigma}{dE'\,d\Omega} = (K)[2W_1(\nu,Q^2)\sin^2(\theta/2) + W_2(\nu,Q^2)\cos^2(\theta/2)]}$$

Structure Functions

$$\boxed{\frac{d\sigma}{dE'\,d\Omega} = (K)[2W_1(\nu,Q^2)\sin^2(\theta/2) + W_2(\nu,Q^2)\cos^2(\theta/2)]}$$

$W_1(\nu,Q^2), W_2(\nu,Q^2)$ **are the two structure functions which describes what's inside the proton.**

As Q^2 increases the structure functions simplify and depend only on the fraction of momentum carried by the partons.

at large Q^2

$$mW_1(\nu,Q^2) \rightarrow F_1(x)$$

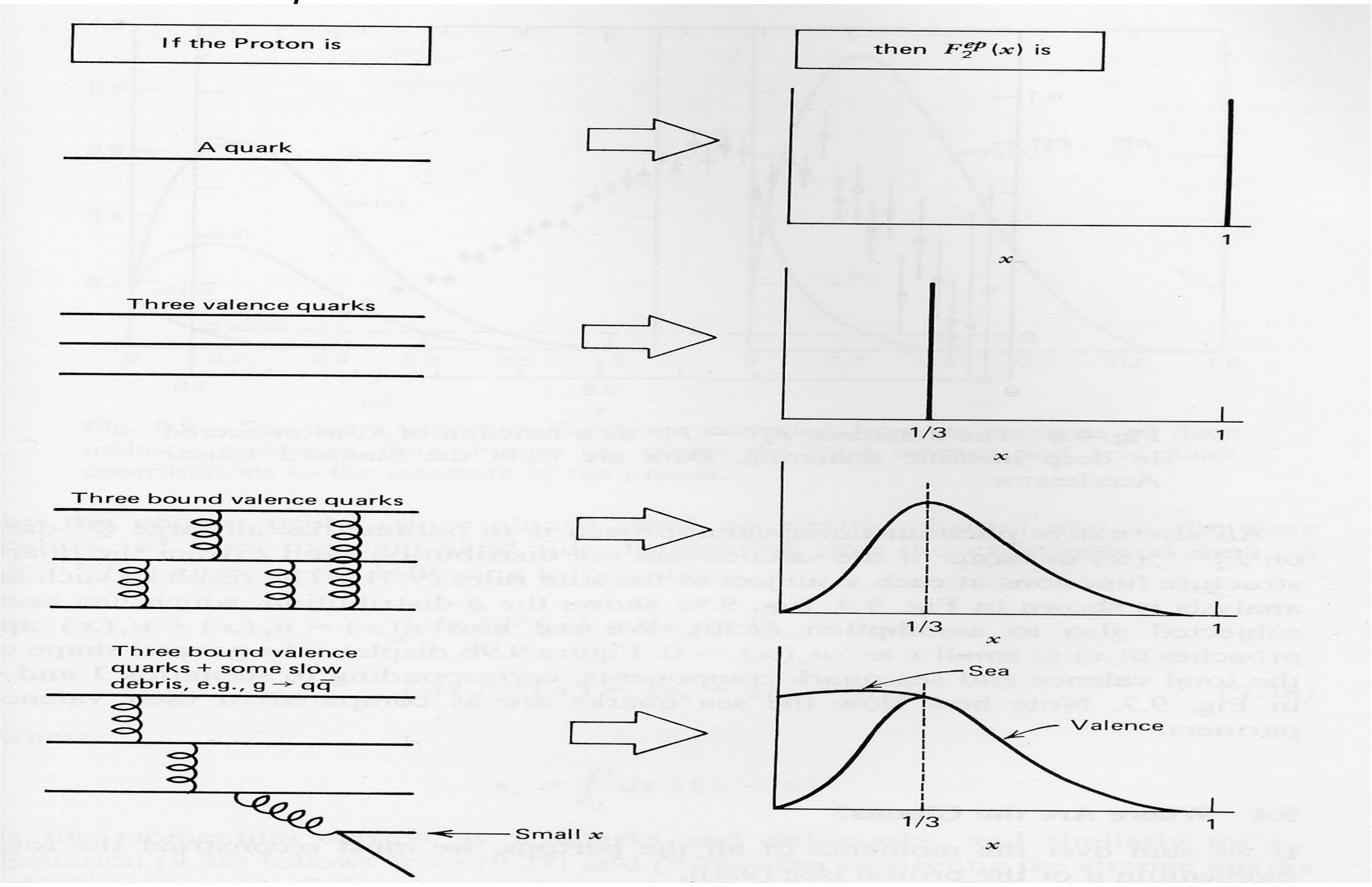
$$\nu W_2(\nu,Q^2) \rightarrow F_2(x)$$

$$2xF_1 = F_2$$

Structure Functions

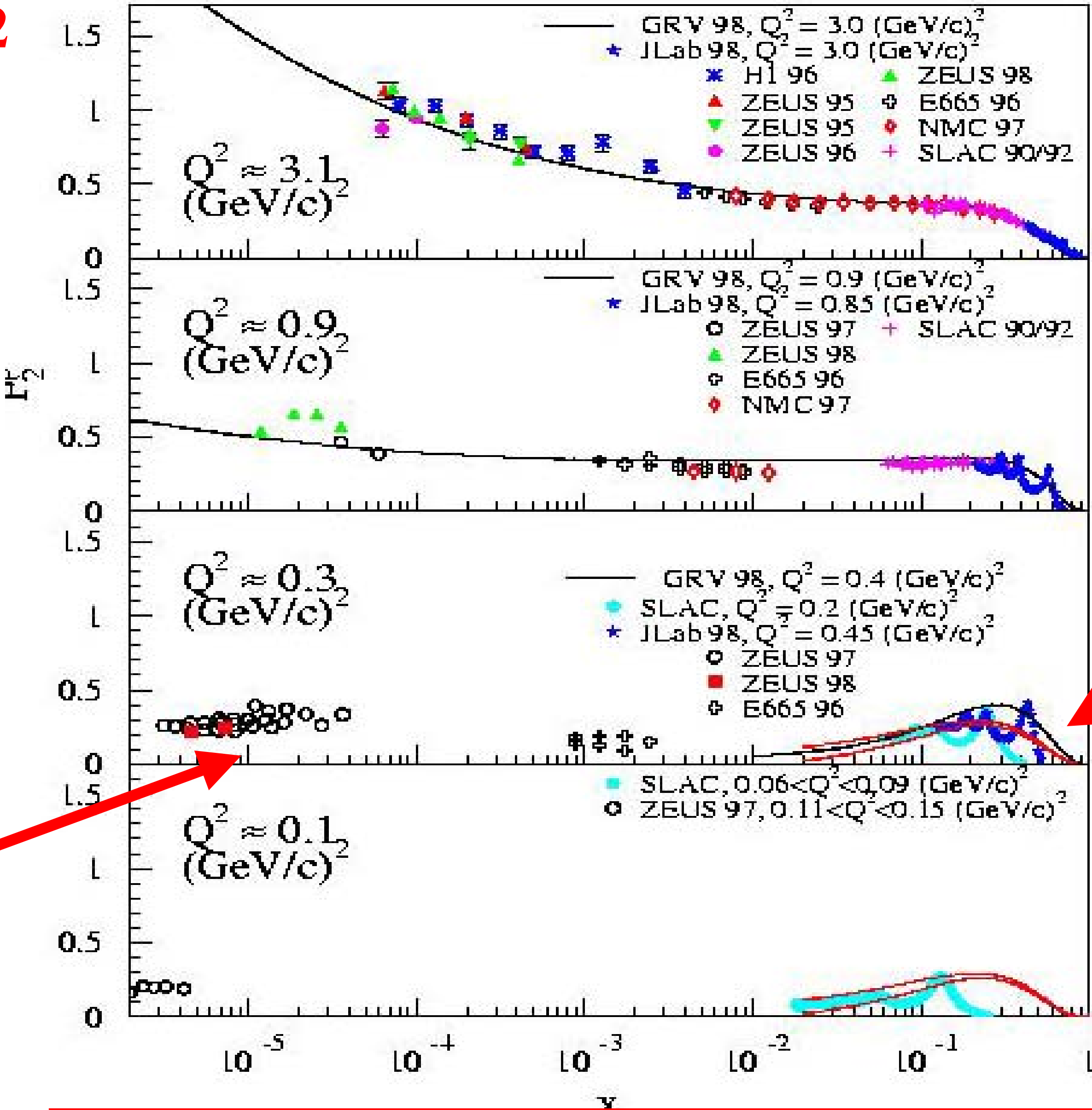
$$F_2(x) = \sum_i e_i^2 x f_i(x)$$

probability of finding a quark with a fraction x of the proton momentum.



F_2

$F_2 \sim$ probability of finding a quark with momentum fraction x

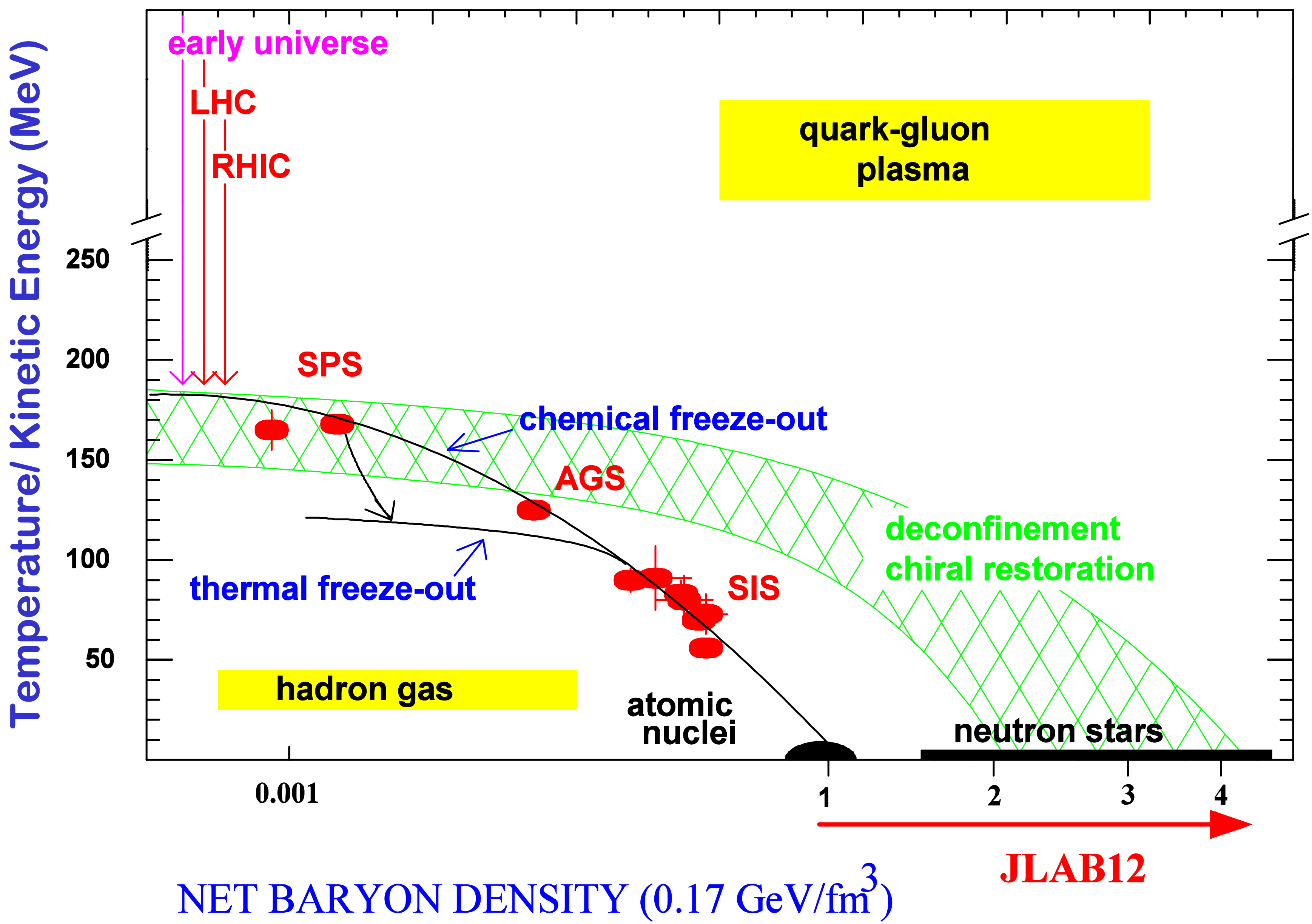


1/3, 3 quarks

Quark-antiquark pairs from the glue

x ~ momentum fraction carried by struck quark

Phases of Nuclear Matter



Drawing the Roadmap

- Matter at high densities

- Modification of nuclear structure at high densities
- High density fluctuations in nuclei
- Deep inelastic scattering at $x > 1$
- Tagged structure functions

Structure Functions at High Density

$$\boxed{AF_2^A = ZF_2^p + (A-Z)F_2^n}$$???

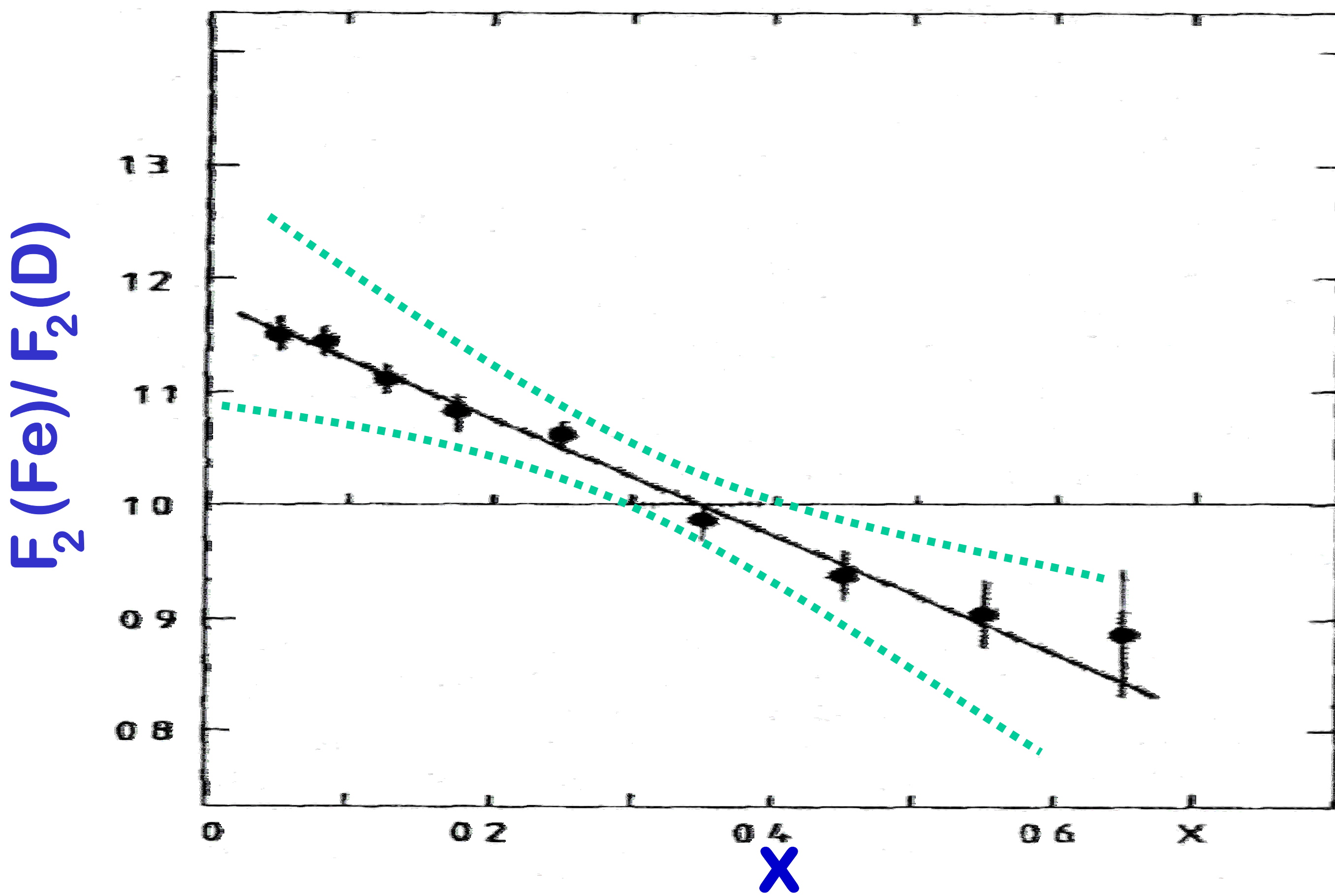
The European Muon Collaboration was the first experiment to measure the structure functions in iron and in deuterium from deep inelastic scattering of muons.

In 1983 they announced their first results as a ratio of $F_2(\mathrm{Fe})/F_2(\mathrm{D})$ as a function of x .

The EMC Effect

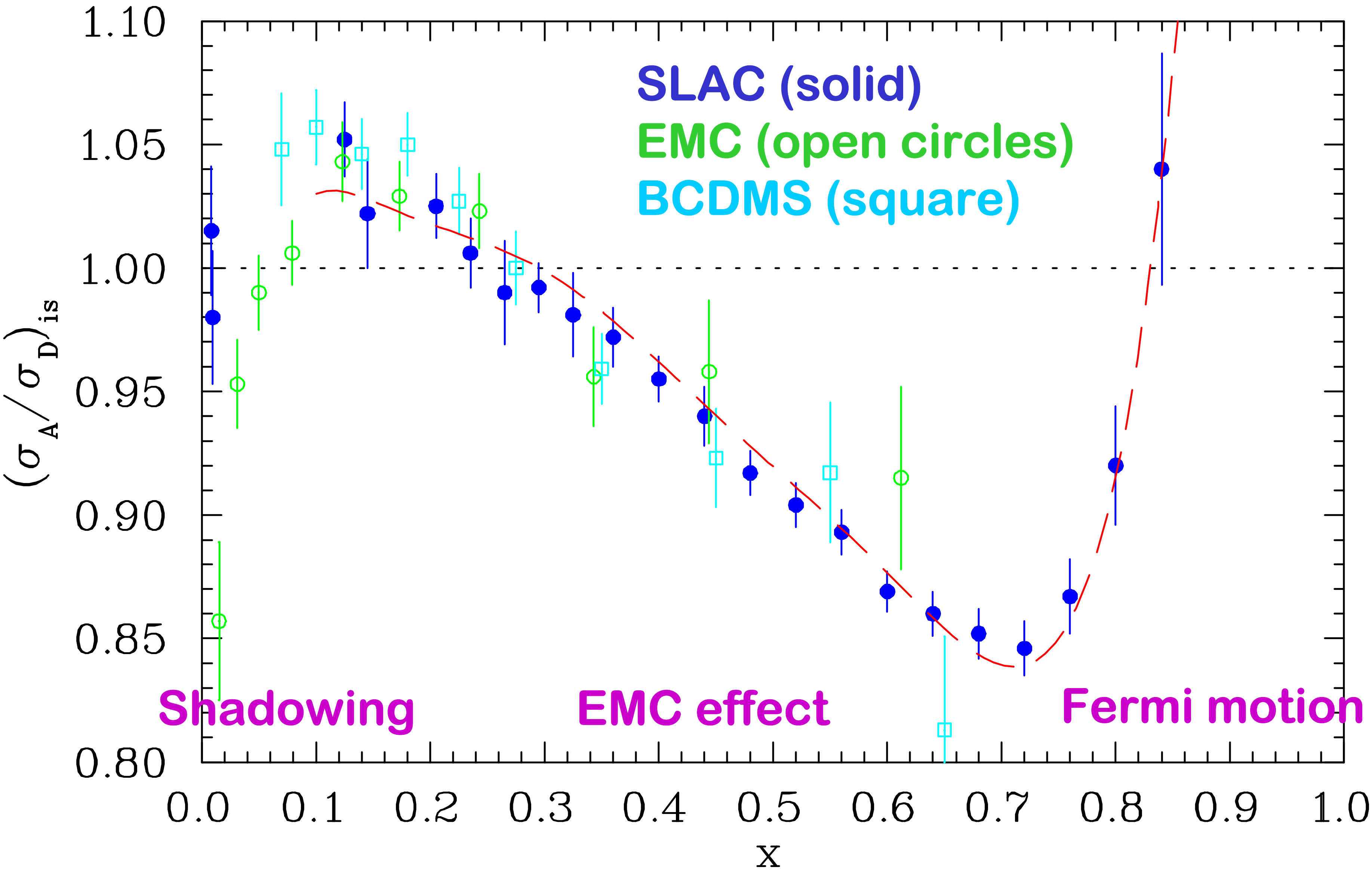
$$AF_2^A \neq ZF_2^p + (A-Z)F_2^n$$

F_2 ~ probability of finding a quark with momentum fraction x in iron vs deuterium



x ~ momentum fraction carried by struck quark

The EMC Effect



Nuclear Shadowing

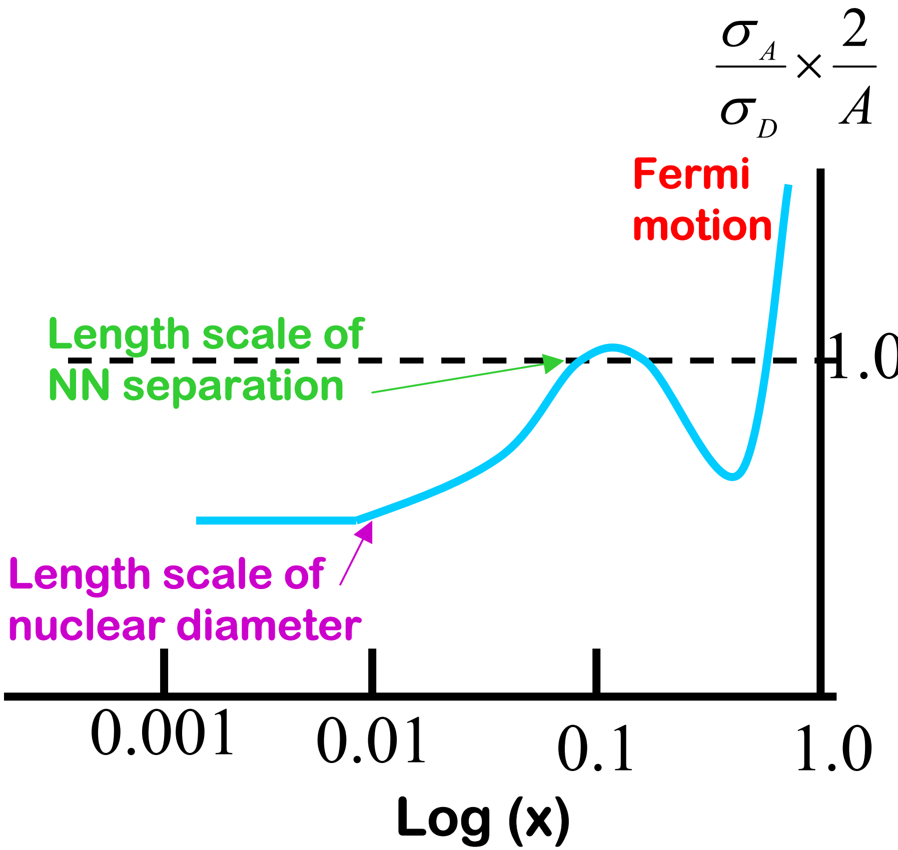
Length scales of the problem :

$$\Delta l = \frac{\hbar c}{\Delta E} = \frac{\hbar c}{xM} = \frac{0.2}{x}\text{fm}$$

Spacing between nucleons $\approx 2\text{fm} \Rightarrow x \approx 0.1$

Diameter of heavy nuclei $\approx 10\text{fm} \Rightarrow x \approx 0.02$

Average separation in deuterium $\approx 4\text{fm} \Rightarrow x \approx 0.05$



Models of the EMC Effect

Nucleon structure is modified in the nuclear medium

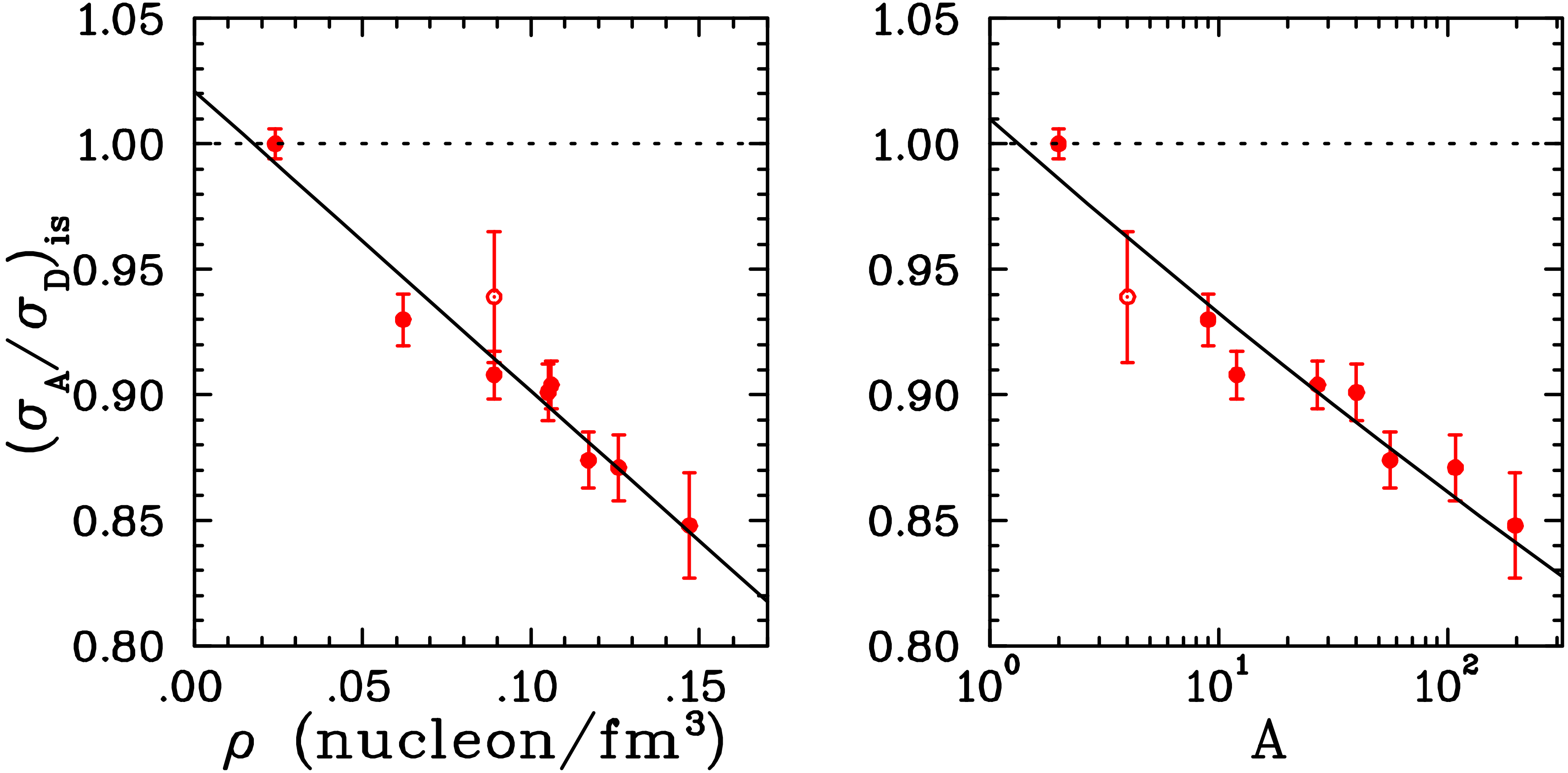
- Swollen nucleons
- parton recombination (multiquark clusters)
- Dynamical rescaling

or

Nuclear structure is modified in the convolution due to multinucleon effects.

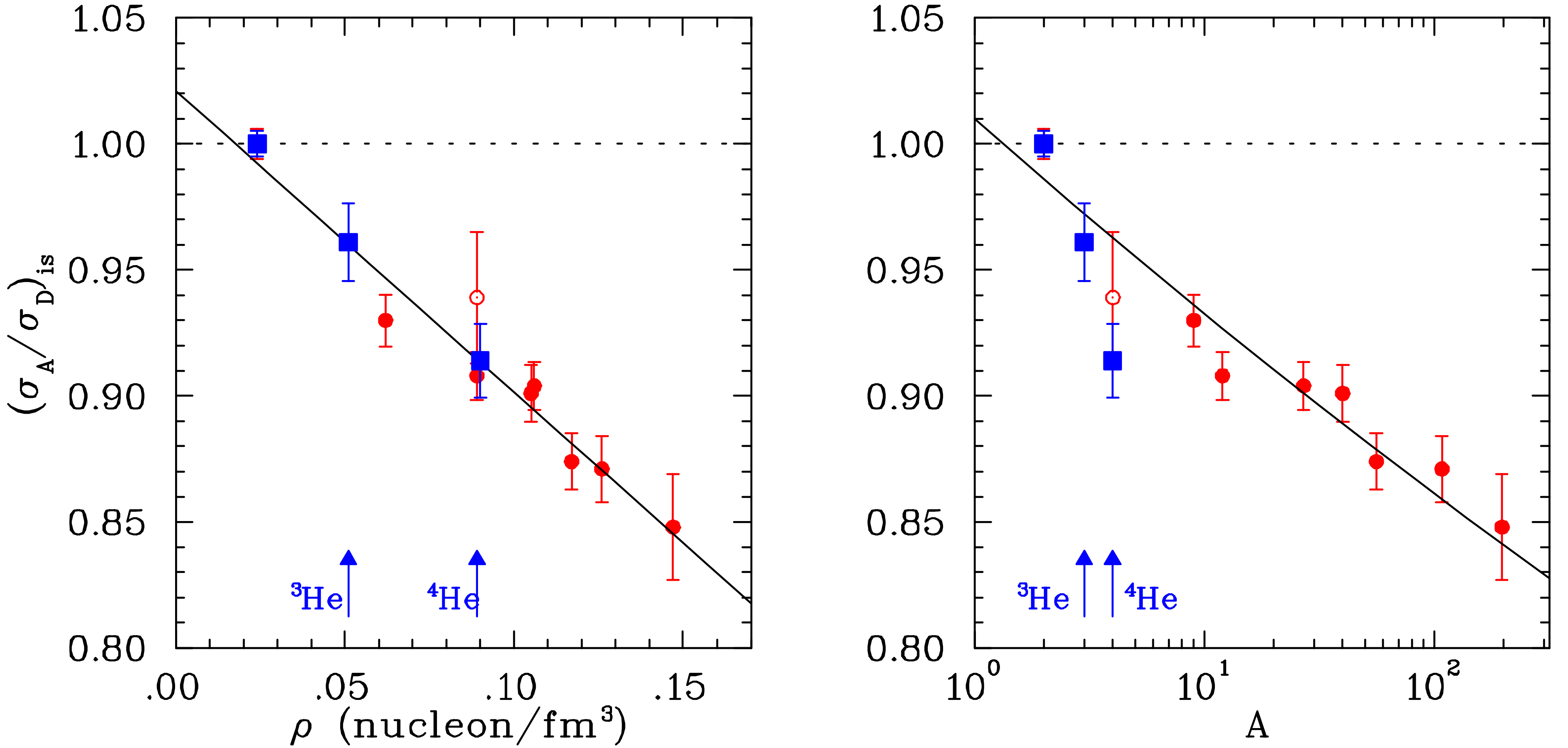
- Binding
- Nuclear pions
- N-N Correlations

Does EMC Effect Vary with ρ_A or A ?



$\boxed{\sigma_A/\sigma_D}$ **at x = 0.6**

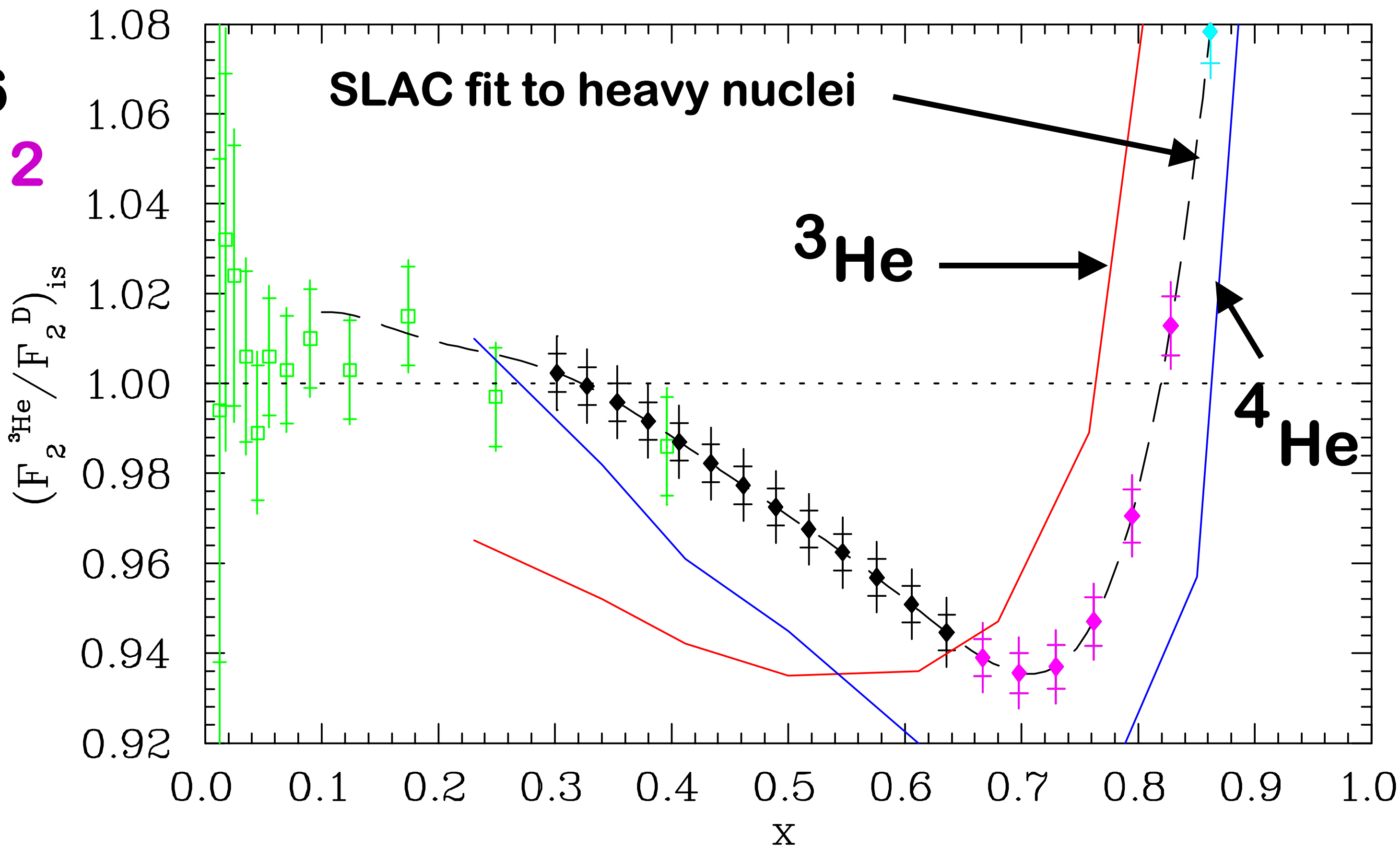
Does EMC Effect Vary with ρ_A or A ?



$\boxed{\sigma_A/\sigma_D}$ **at x = 0.6**

Plans to Measure EMC Effect at JLab

- JLab 6
- JLab 12



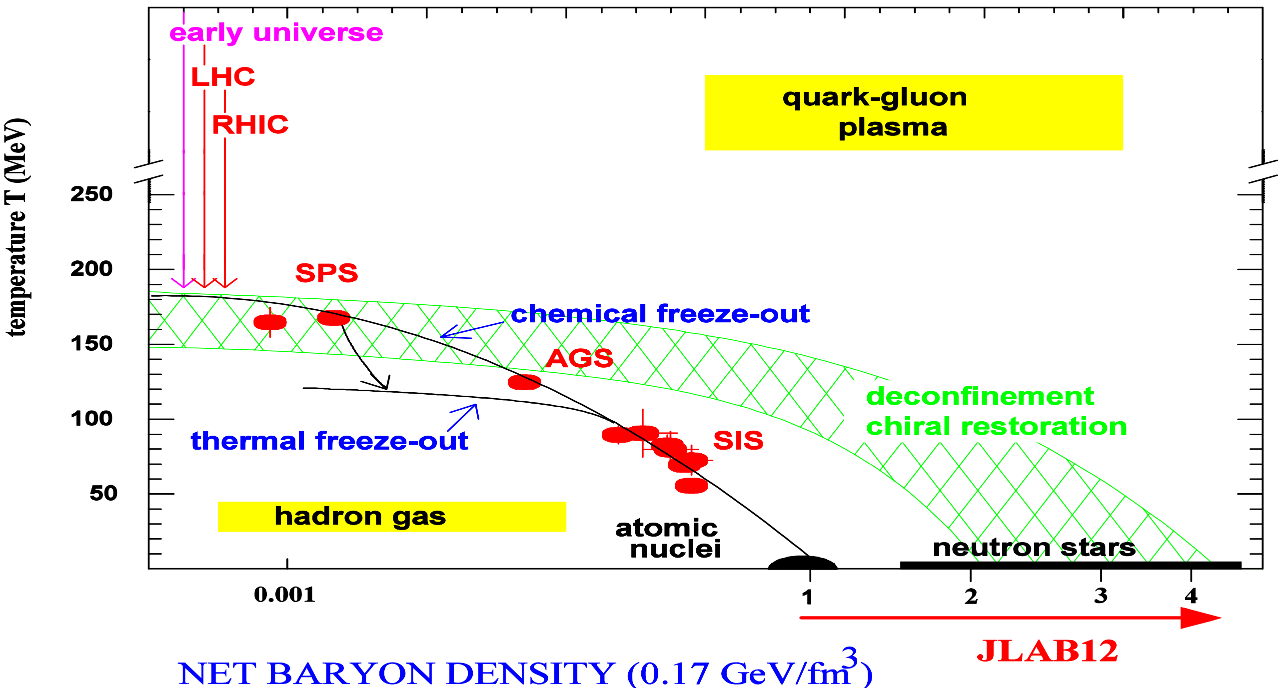
- determine the A and ρ dependence
- help evaluate models of EMC
- determine the nuclear effects in deuterium

What We Know So Far

- The nucleus is not just a collection of nucleons
- Deviations from the nucleonic model grows linearly with the nuclear density.

BUT

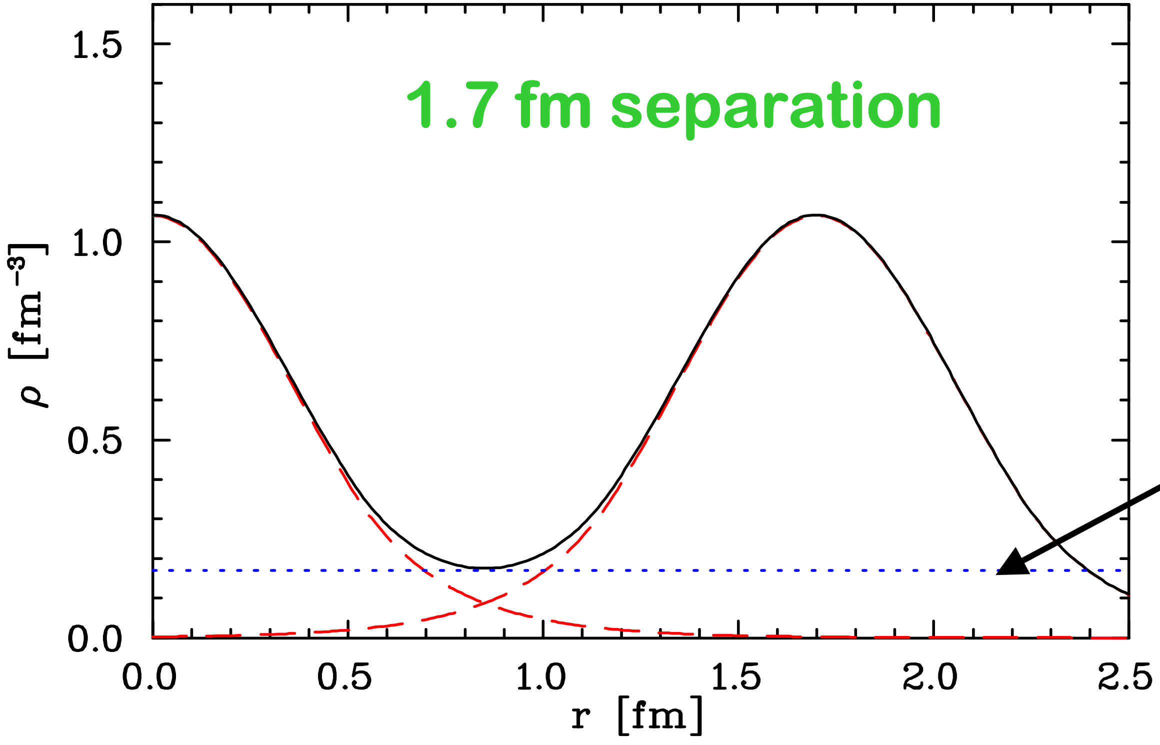
Average nuclear densities are well below phase transition



REALLY ?

Average Nuclear Density

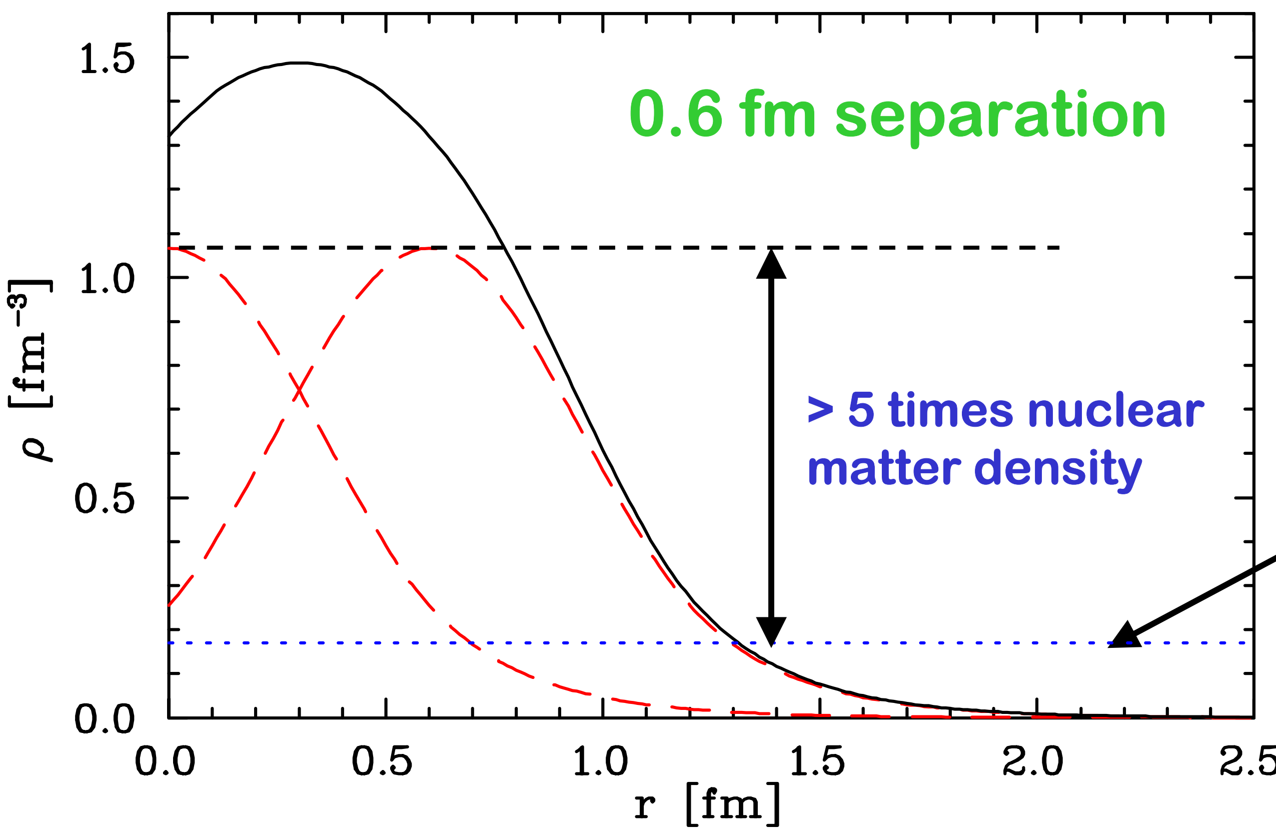
Nucleon charge radius ~ 0.86 fm , separation ~ 1.7 fm
Nucleons already closely packed in nuclei.

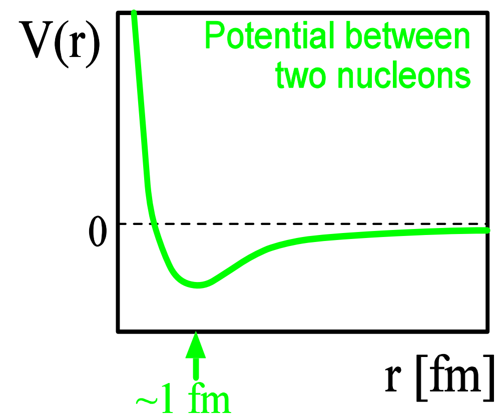


Average Nuclear density

Small Distance Fluctuations in Nuclei

Nucleon separation is only limited by the short range repulsive core ➡ 1 GeV at ~ 0.4 fm





Average Nuclear density

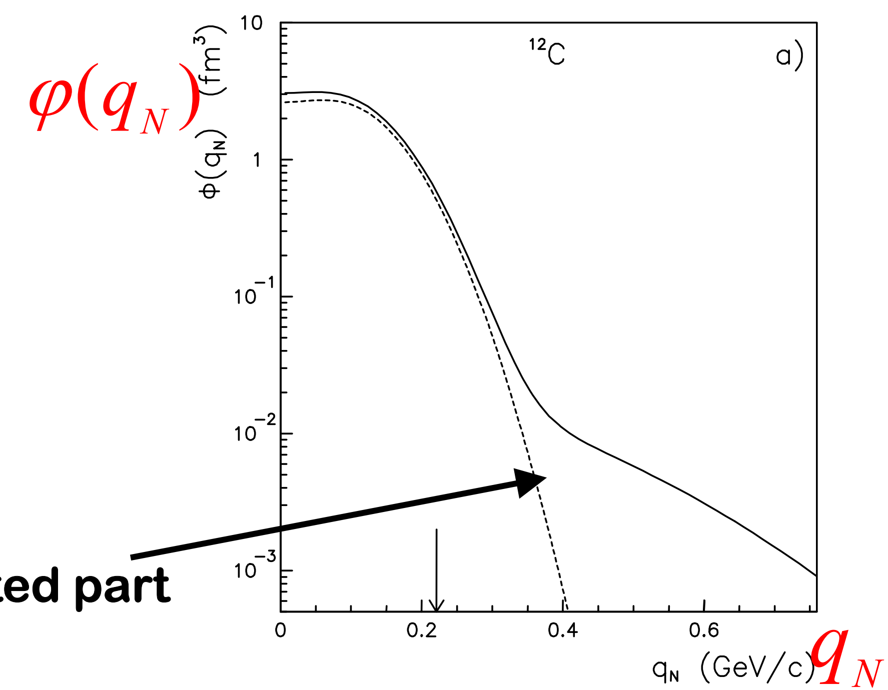
Short Range Correlations

Small distance fluctuations ⇨ **Short Range Correlations (SRC)**

Short range/distance ⇔ **High relative momentum**

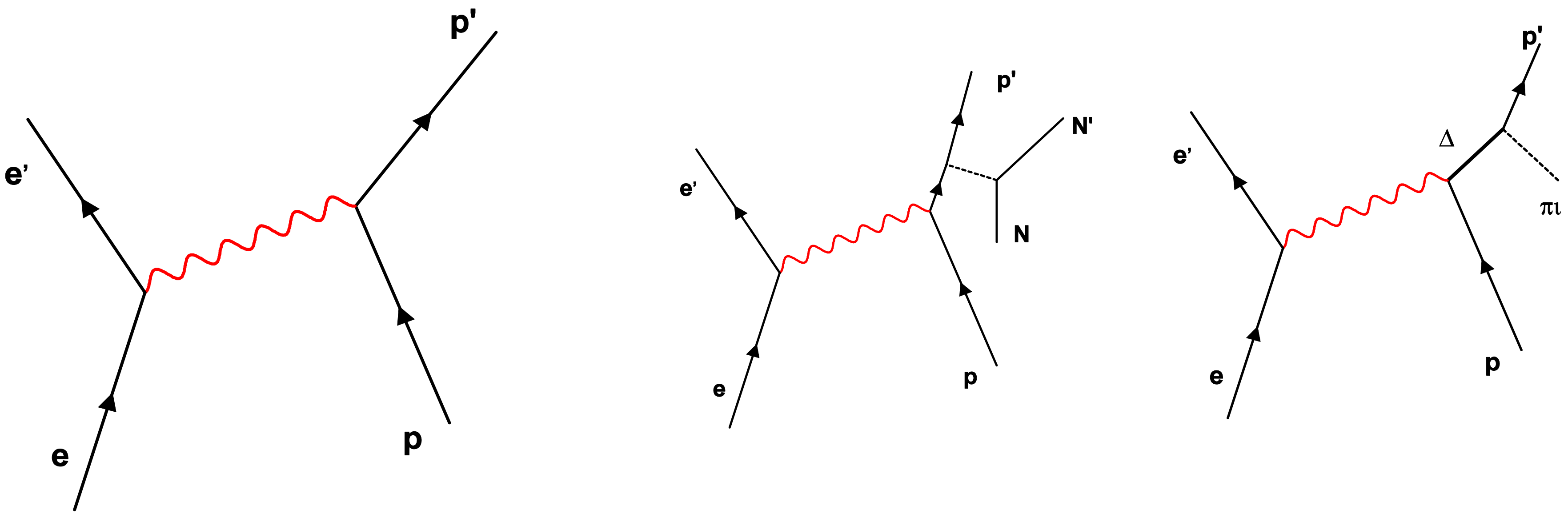
High momentum components of the nuclear wave function should be sensitive to correlated nucleons.

Uncorrelated part



SRC vs FSI & MEC

When using any scattering process to probe for SRC:
Have to distinguish from Final State Interactions and multi step processes.



The contributions from FSI and MEC decrease with increasing Q^2

How to Look for SRC?

- A(e,e') reaction at x > 1 (Can be used to measure probability of 2N, 3N corr)

- D(e,e'pn) with $p_m \geq 400(MeV/c)$

- A(e,e'N) and A(e,e'NN) for A > 2 (probe detailed structure of SRC)

- A(e,e' $N_f N_b$) reaction

A(e,e') Reactions at $x > 1$

$$x = \frac{Q^2}{2M_N \nu}$$

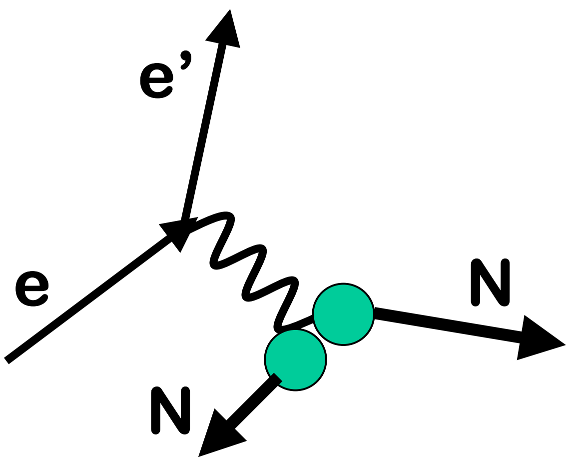
x is the fraction of the nucleon momentum carried by the struck quark in the large Q^2 and ν limit.

In the nucleus the nucleons share momentum, so x can vary between 0 and A (the total number of nucleons).

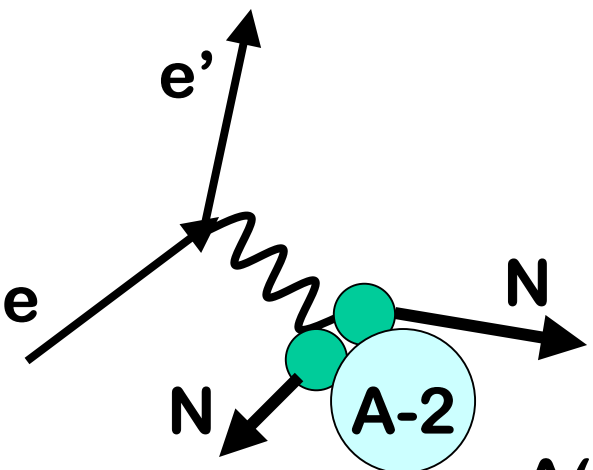
$x > 1$ corresponds to the quarks carrying momentum fraction larger than that of a nucleon at rest in the nucleus.

A(e,e') Reactions at $x > 1$

Measurements at $x > 1$ are sensitive to the high momentum nucleons in the nucleus.



d(e,e')



A(e,e')

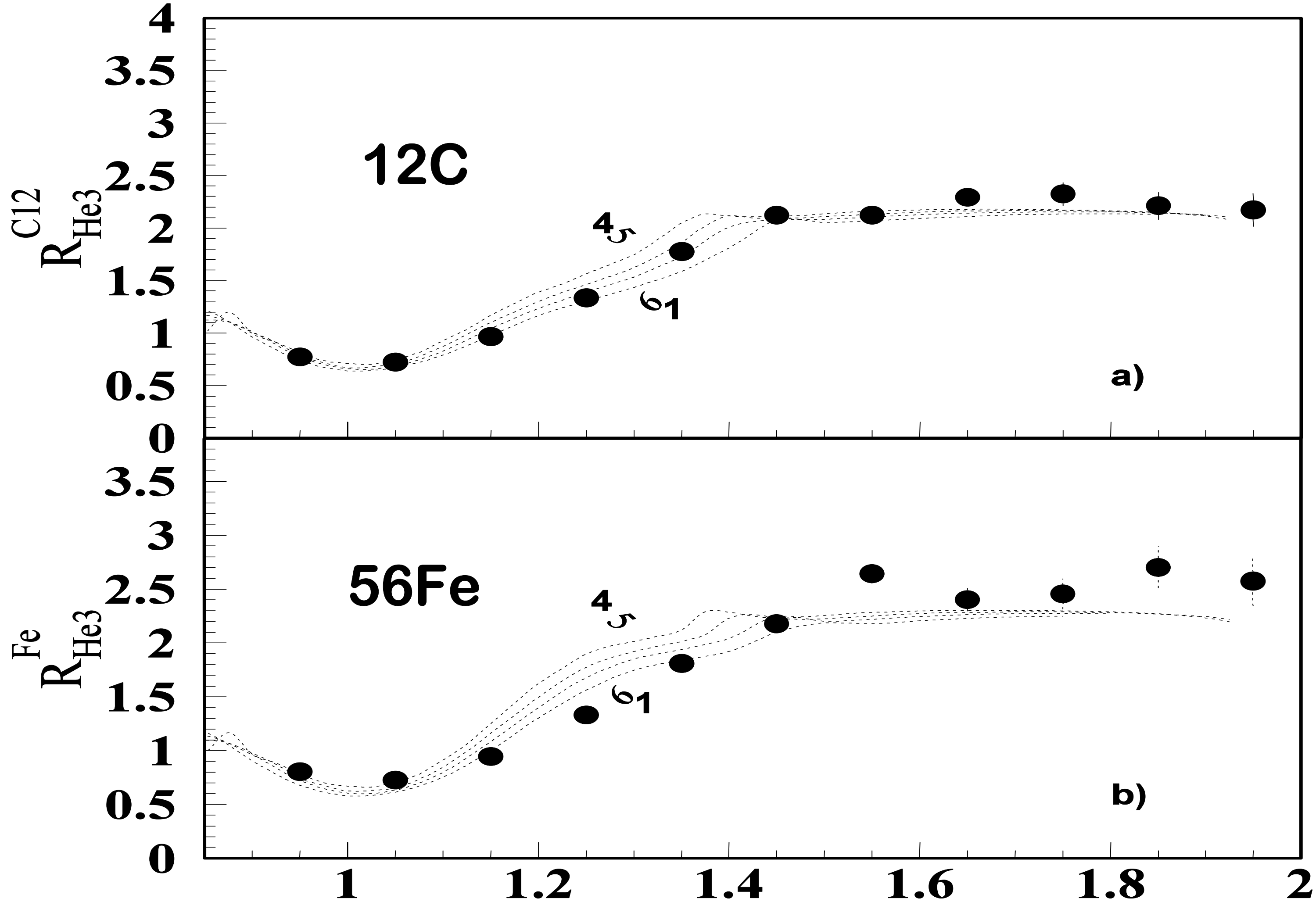
The ratio of (e,e') cross-sections should be independent of x and Q^2 (for $Q^2 > 1$ and $x >> 1$)

and

The ratio is related to the relative per –nucleon probability of SRC in nucleus A relative to d

A(e,e') Reactions at x > 1

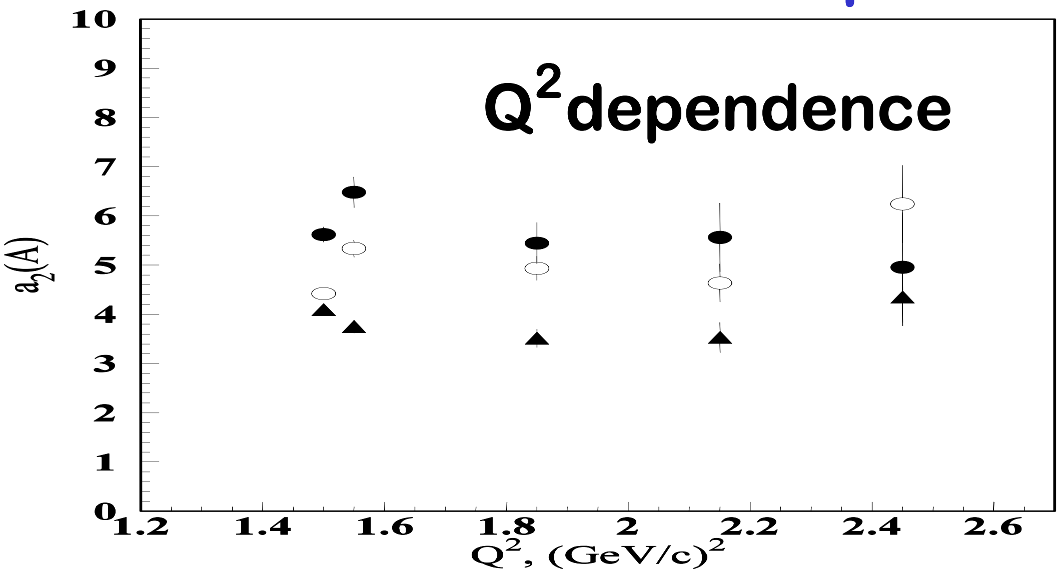
Ratio of cross-sections to 3He



Egiyan et al, Nucl-Ex/0301008

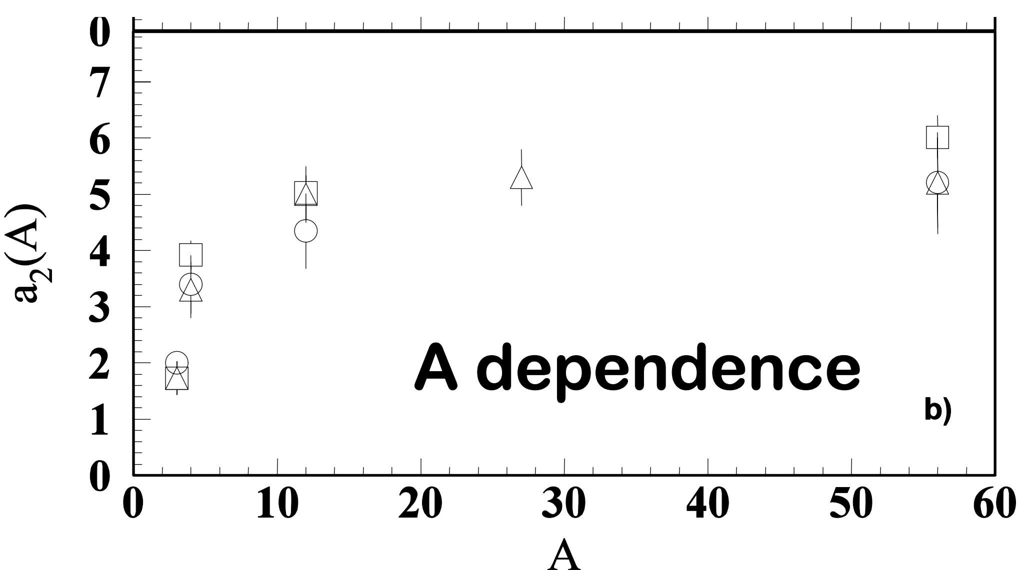
A(e,e') Reactions at $x > 1$

A and Q^2 dependence of ratios



No x or Q^2 dependence for $x > 1.5$

SRC model valid



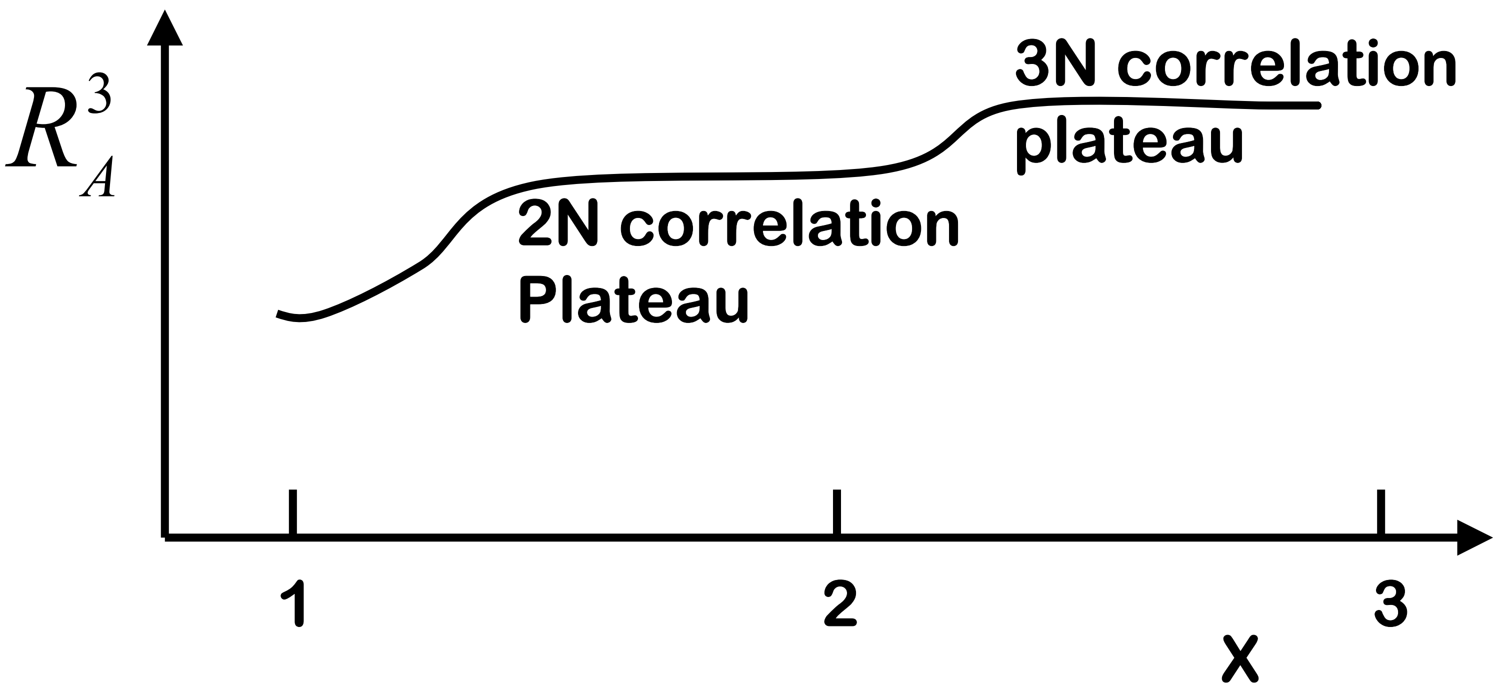
5 times more SRC for A > 10 than in deuterium

Egiyan et al, Nucl-Ex/0301008

Extension to 12 GeV

Look for 3N correlations at 2 < x < 3

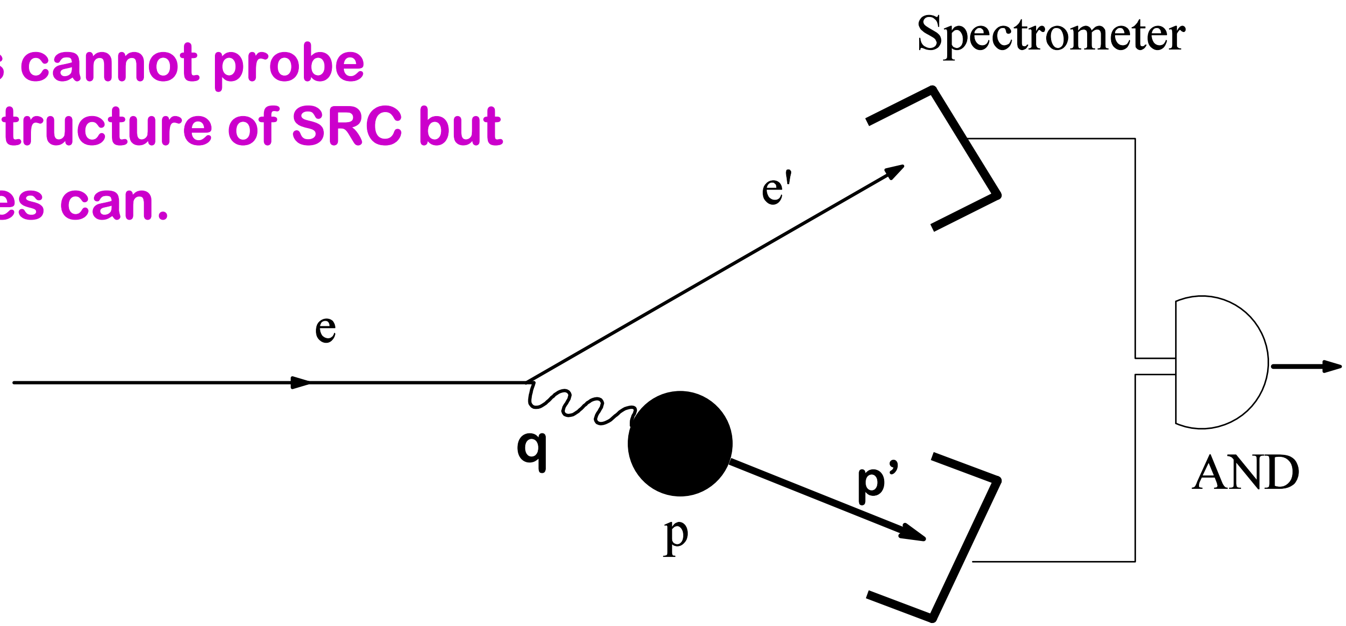
Relative probability of 3N correlations in A and in 3He



A(e,e'N) and A(e,e'NN)

The range of $\gamma*$ **is :** $\dfrac{\hbar}{2Q}$ **hence,** $1.5 \leq Q^2 \leq 4.0$ **is ideal range**

Inclusive reactions cannot probe the details of the structure of SRC but Exclusive processes can.



$$E_m = E_e - E_{e'} - T_{p'} - T_{A-1}$$

$$\vec{p}_m = \vec{p}_{p'} - \vec{q}$$

A(e,e'N) and A(e,e'NN)

d(e,e'pn) is the simplest of the exclusive processes,
the deuteron wavefunction is also reasonably well known
This process at $p_m \geq 400(MeV/c)$ will provide the ultimate test of our understanding of NN correlations.

For A(e,e'p) for A > 2 the $E_m - p_m$ correlations at high Q^2 will provide one of the signatures for scattering from SRC.

A(e,e' $N_f N_b$) reaction with one nucleon moving forward and one moving backward is expected to be dominated by NN correlations and can be used to compare pp, pn and nn correlations.

Quark Structure of SRC

In electron scattering from quarks at $x \geq 1 + {K_F}/{m_N} \approx 1.2$

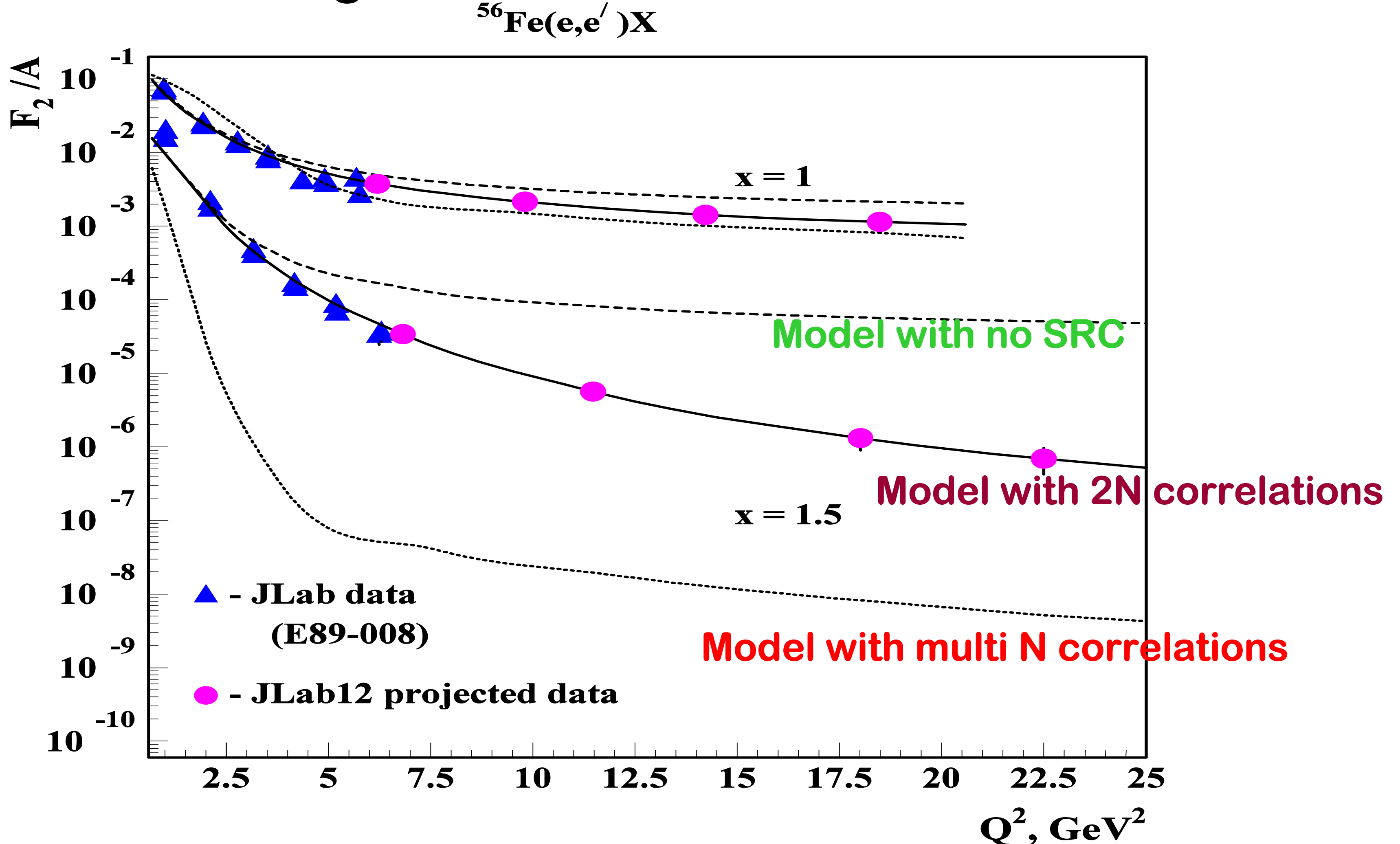
all quarks involved are from nucleons with momentum larger than the Fermi momentum of the nucleus.

At large Q^2 contribution from electrons scattering quasi-elastically from nucleons is very small.

These superfast quarks can only come from multiple nucleons with large relative momentum which are closer than the average inter-nucleon separation (i.e. a super dense configuration or some multi-quark configuration.

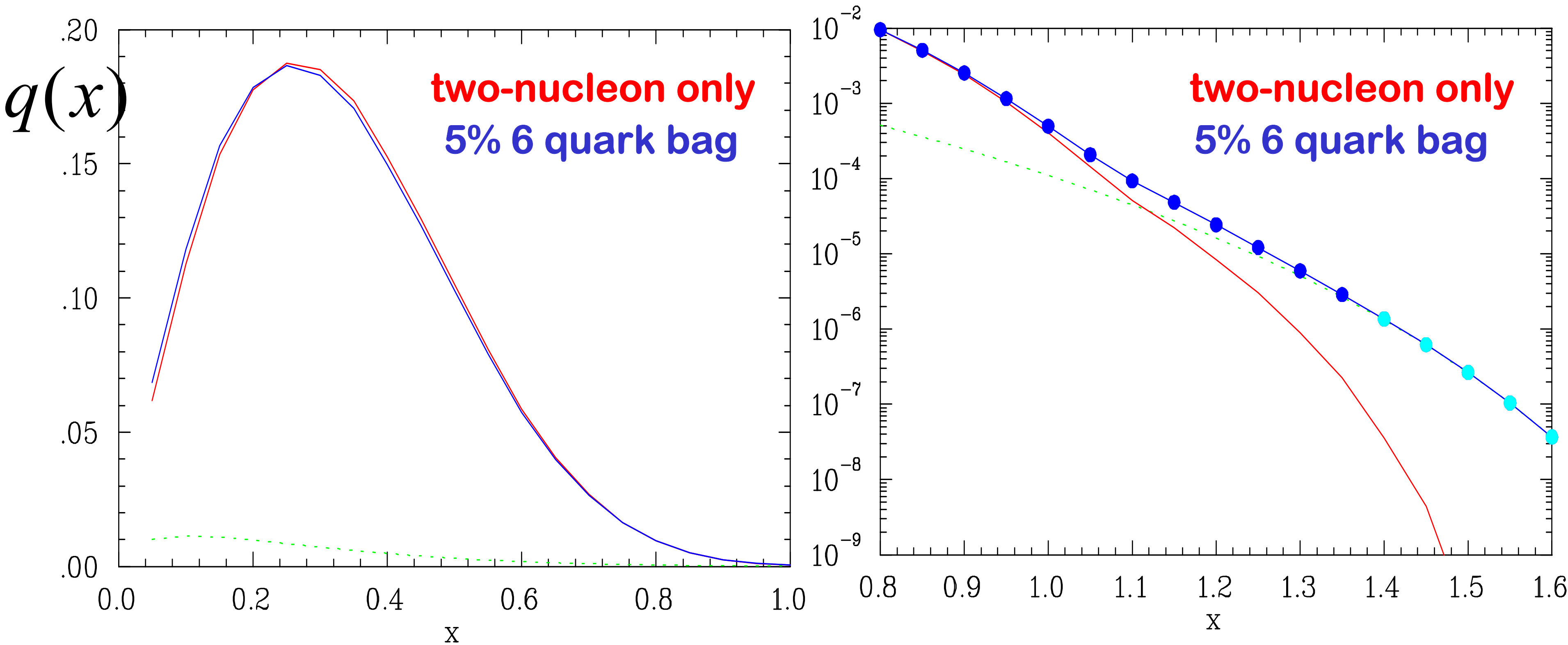
Superfast Quarks

Signature can be found by measuring $F_2(x,Q^2)$ in nuclei at large Q^2 and at $x > 1$



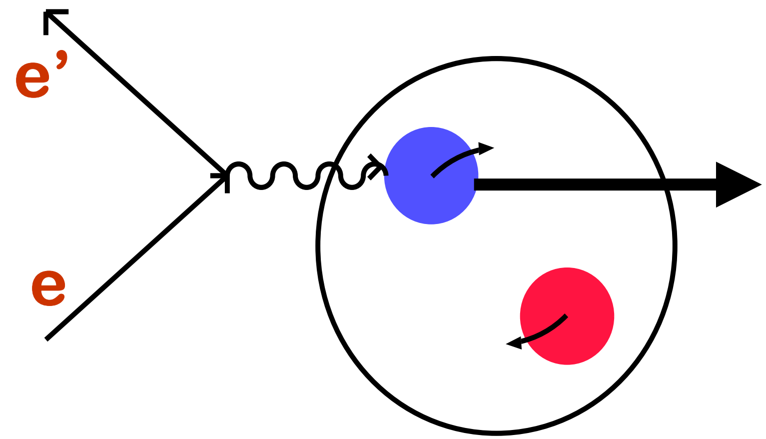
Quark Distribution of SRC

D(e,e') at very high Q^2 and $x > 1$ can provide a clear signature of exotic states in nuclei such as 6 quark bags



Modification of SRC Structure

e + d → e' + N + X



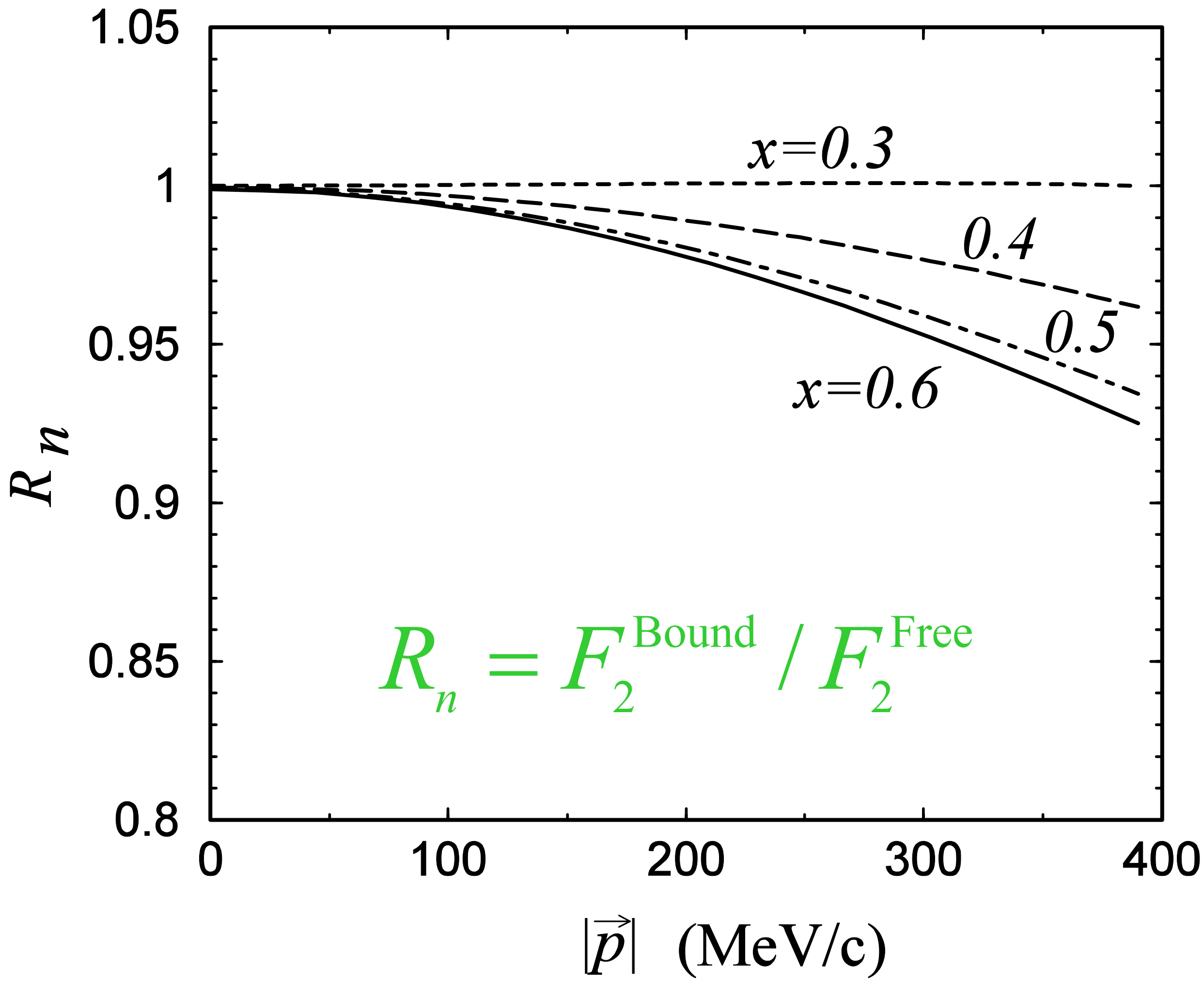
Detect backward proton (spectator proton)

Slow backward proton (P_s^{small}) tags free neutron

Fast backward proton (P_s^{large}) tags high density conf. (SRC)

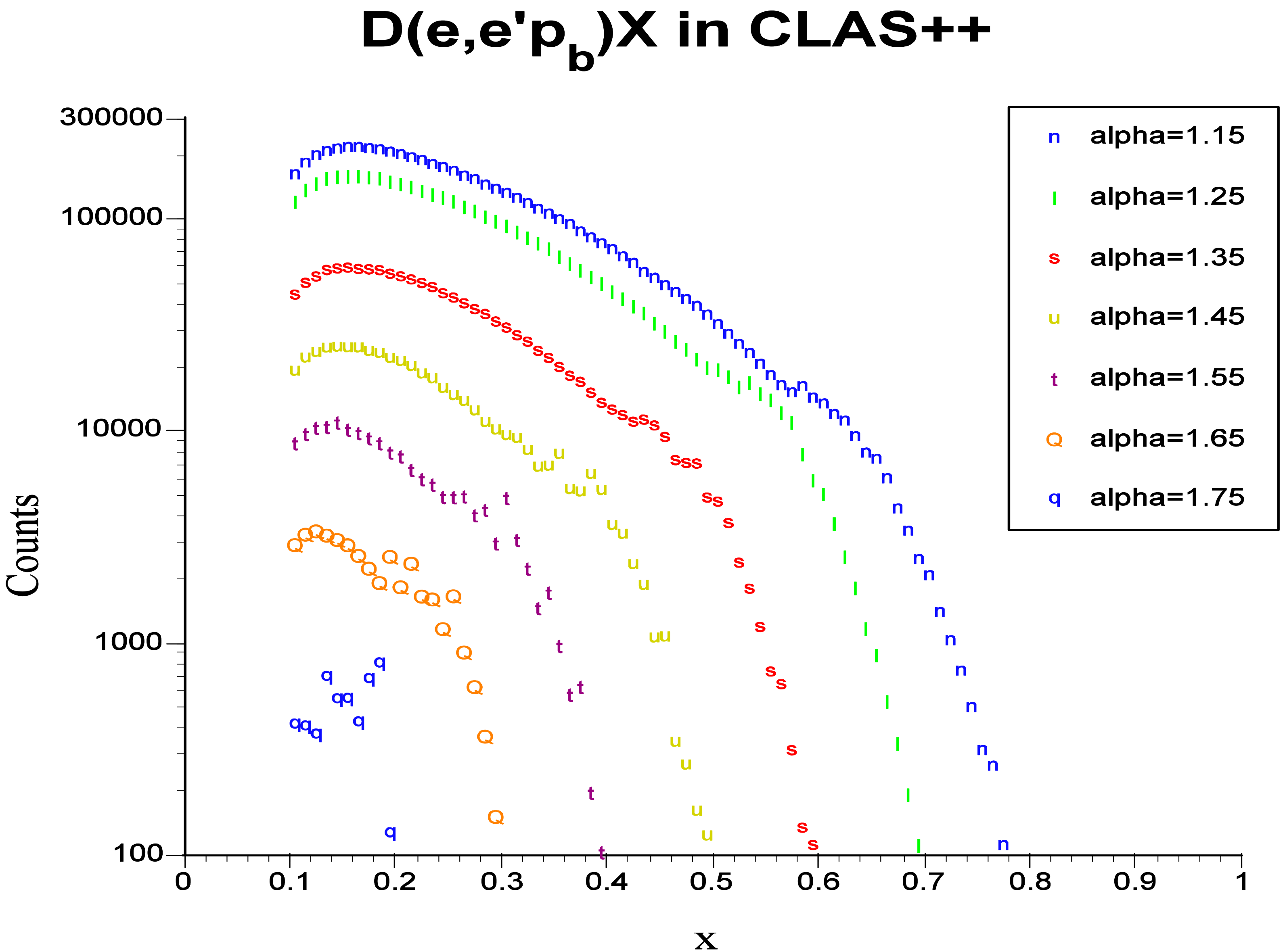
Measure F_2 for fast and slow spectator protons to form the ratio $F_2^n(P_s^{\mathrm{large}})/F_2^n(P_s^{\mathrm{small}})$

Tagged EMC Effect



Tagged EMC effect probes modification of SRC structure in the medium

$D(e,e'p_s)$ with CLAS



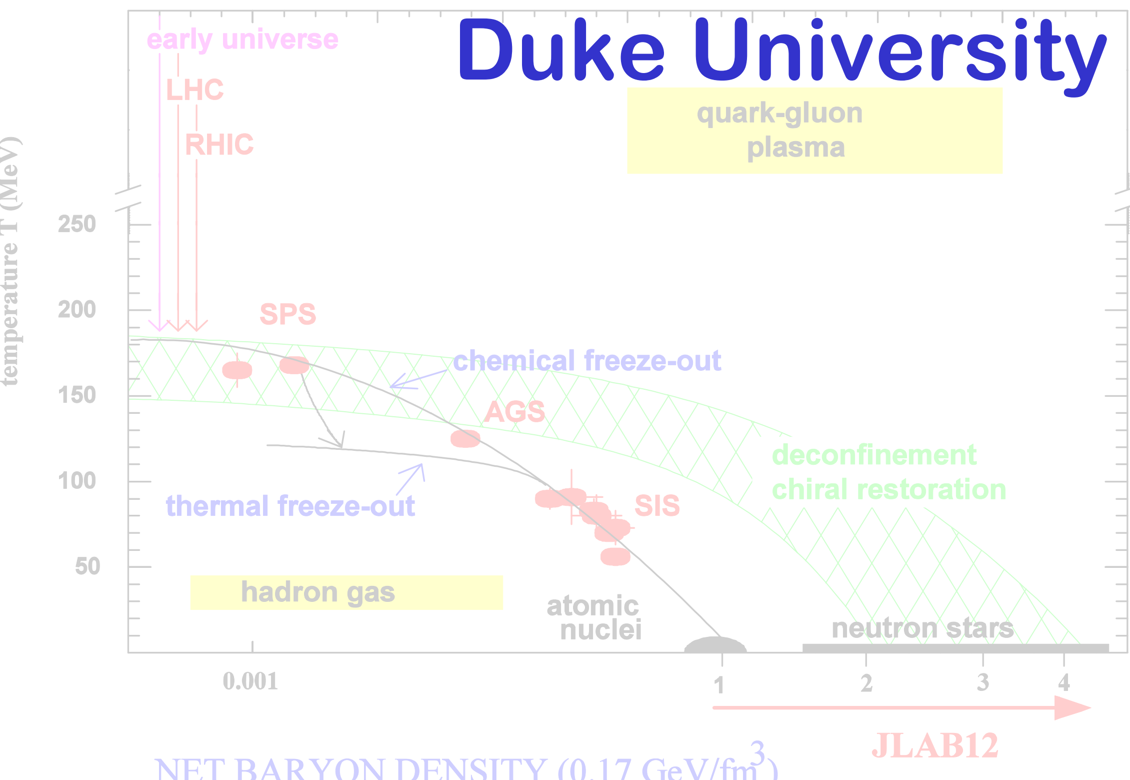
Summary

- Nuclear structure is modified in the nuclear medium
- One of the reasons could be SRC
- SRC can be studied in many different reactions
- SRC probability, SRC structure, SRC quark structure and modification of SRC structure all continue to be studied at Jlab.
- 12 GeV upgrade will allow even more extensive coverage.

Hadrons in the Nuclear Medium

Dipangkar Dutta

Duke University



HUGS, June 2003

Lecture - 2

Drawing the Roadmap

Understanding nucleons & nuclei in terms of quarks and gluons is the most important unsolved problem of the Standard Model of nuclear and particle physics.

in other words

We need data that will connect QCD land to real world

Unique opportunity exists in studying hadrons in nuclear matter and comparing them with hadrons in free space.

& Look for

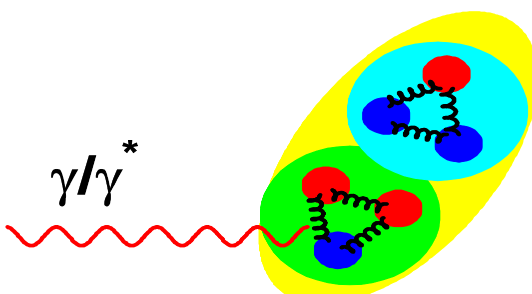
Modifications in the structure and interactions of hadrons in the nucleus.	&	The transition from quark gluon to nucleon-meson degrees of freedom.

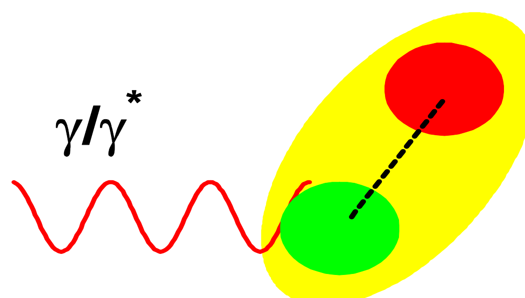
Drawing the Roadmap

- Matter at high densities
  - Modification of nuclear structure at high densities
  - High density fluctuations in nuclei
  - Deep inelastic scattering at $x > 1$
  - Tagged structure functions
- Exclusive processes at high momentum transfer
  - Color transparency
  - Nuclear Filtering
- Probing the limits of nucleon based description of nuclei

From Quarks to Nuclei

Quantum Chromo Dynamics (QCD) with quark-gluon degrees of freedom is very successful at the high energy, perturbative regime.





Nucleon-meson degrees of freedom work better at lower energies.

What Is the Energy Threshold for the Transition?

Exclusive processes (processes with completely determined initial and final states), are used to study the transition region.

Exclusive Processes

Nucleons

- Quark counting rules
- Hadron helicity conservation

Nuclei

- Color transparency
- Nuclear filtering

How Transparent is Your Nucleus?

Exclusive Processes

Nucleons

Nuclei

A + B → C + D

N

A + B → C + D + X

$^{A}N_{Z}$

Exclusive processes on nucleons and nuclei can be used to measure transparency of nuclei

Nuclear Transparency

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

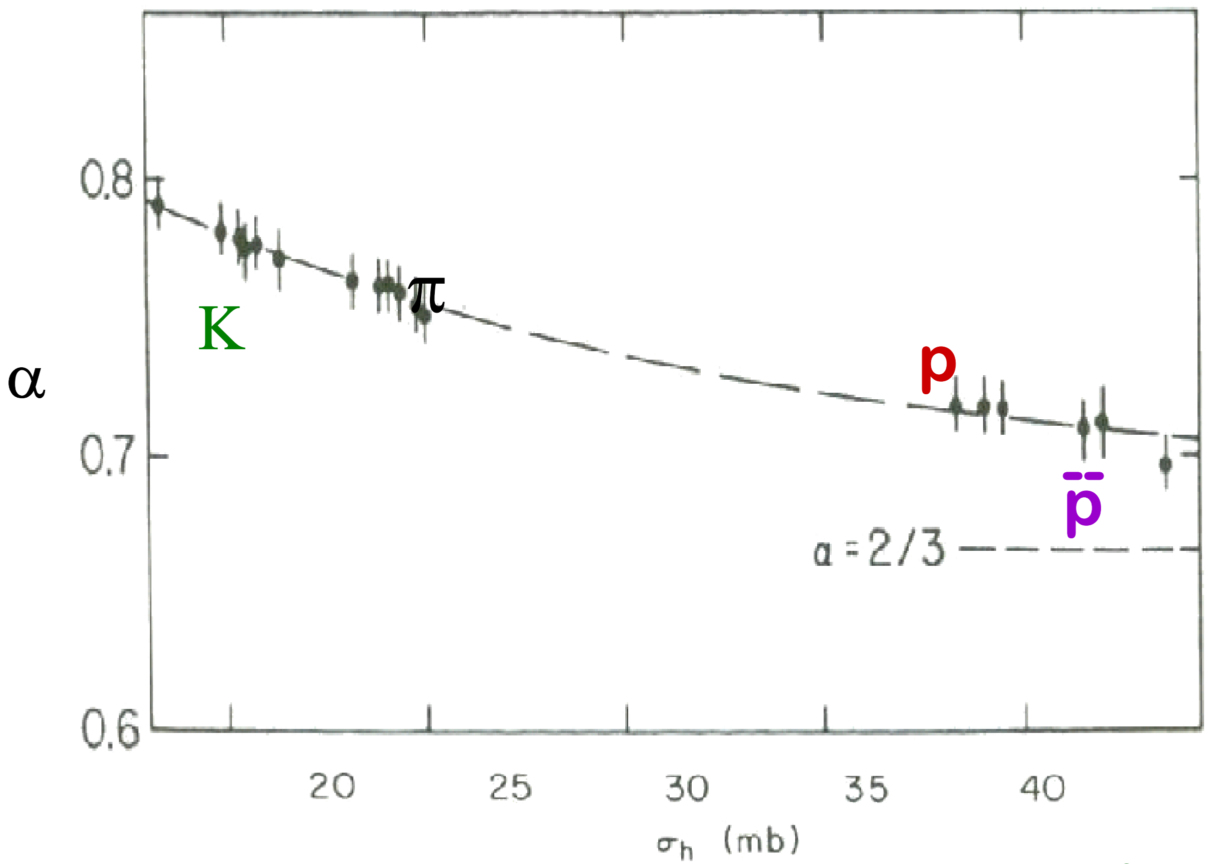
$$T = \frac{\sigma_N}{A\sigma_0}$$

σ_0 = free (nucleon) cross-section

σ_N parameterized as = $\sigma_0 A^{\alpha}$

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

Total Cross-sections



Hadron– Nucleus total cross-section

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

Hadron momentum 60, 200, 250 GeV/c

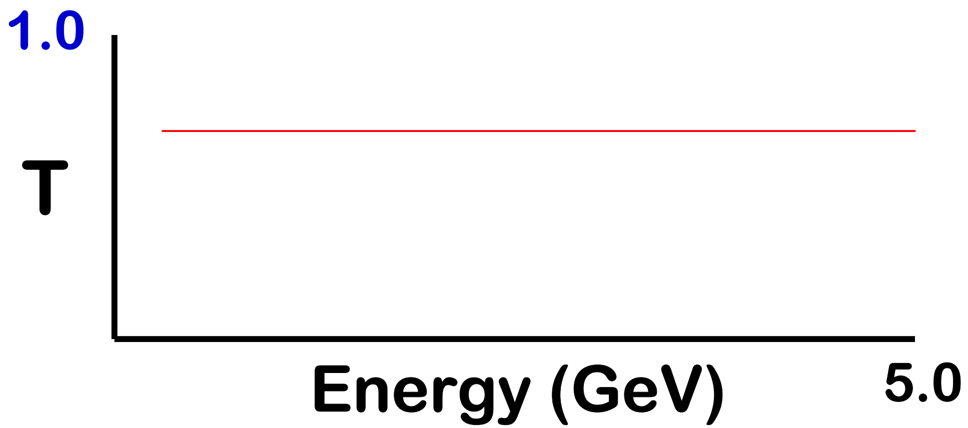
α **= 0.72 – 0.78, for** π, κ, **p**

α **< 1 interpreted as due to the strong interaction 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 energy independent .



Ingredients

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

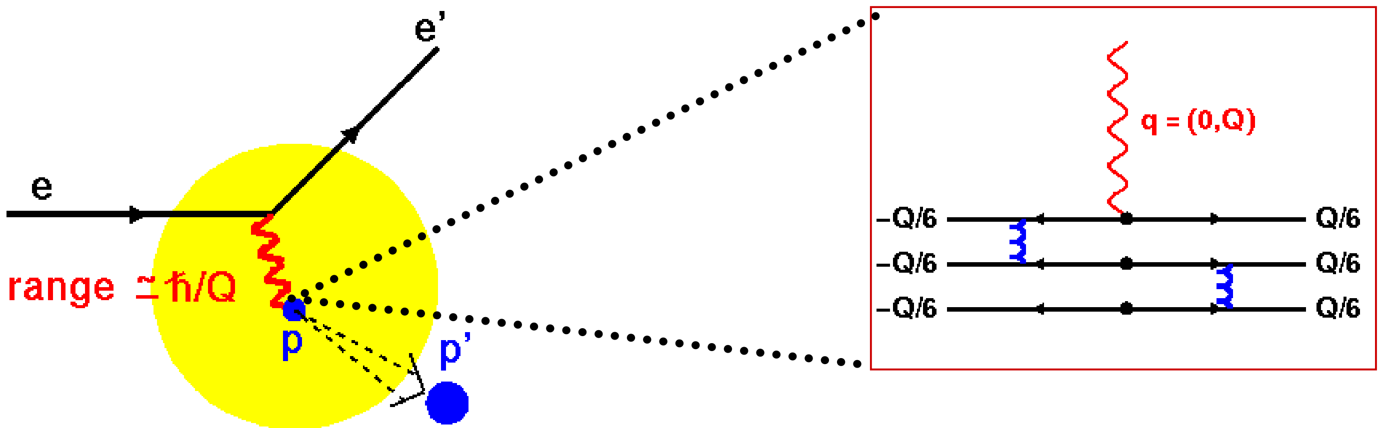
Glauber approx:
- Energy of particle much larger than interaction potential
- Particle wavelength larger than width of potential
- Scattering at small angles with respect to incident direction.

Color Transparency

CT refers to the vanishing of the h-N interaction for h produced in exclusive processes at high Q

- ❑ **At high Q , the hadron involved fluctuates to a small transverse size – called the PLC (quantum mechanics).**
- ❑ **The PLC experiences reduced interaction with the nucleus – it is color screened (nature of the strong force).**
- ❑ **The PLC remains small as it propagates out of the nucleus (relativity).**

Why is the PLC Selected Out?



Using e-p scattering as an example

- The momentum is distributed roughly equally among the quarks,

(for it to be elastic scattering) ⇨ lifetime $\simeq \hbar/cQ$

⇨ range $\simeq \hbar/Q$

- At high Q an elastic interaction can occur only if the transverse size of the hadron involved is smaller than the equilibrium size.

Color Screening of the PLC

The color field of a color neutral object vanishes with decreasing size of the object .

$$\boxed{\sigma_{PLC} \approx \sigma_{hN} \frac{b^2}{R^2{}_h}}$$

(Analogues to electric dipole in QED)

Lifetime of the PLC

In the frame of the nucleus the lifetime of the PLC is dilated.

$$\boxed{\gamma\, \boldsymbol{t}_{f} = \frac{E}{m}\boldsymbol{t}_{f}}$$

The PLC can propagate out of the nucleus before returning to its equilibrium size.

Color Transparency - Experimental Status

CT refers to the vanishing of the h-N interaction for h produced in exclusive processes at high Q

h can be : $q\bar{q}$ system ($e^{+}e^{-}$ in QED)
qqq system (unique to QCD)

- Color Transparency in A(p,2p) BNL
- Color Transparency in A(e,e'p) JLab,SLAC
- Color Transparency in A(ℓ,ℓ' ρ) FNAL, HERMES
- Color Transparency in di-jet production FNAL
- Color Transparency in A(e,e'π) JLab
- Color Transparency in A(γ,πp) JLab

Transparency in A(p,2p) Reaction

First experiment to look for color transparency

Experiment performed at Brookhaven

Proton knockout

Using:

$$p + A \rightarrow p + p + X$$

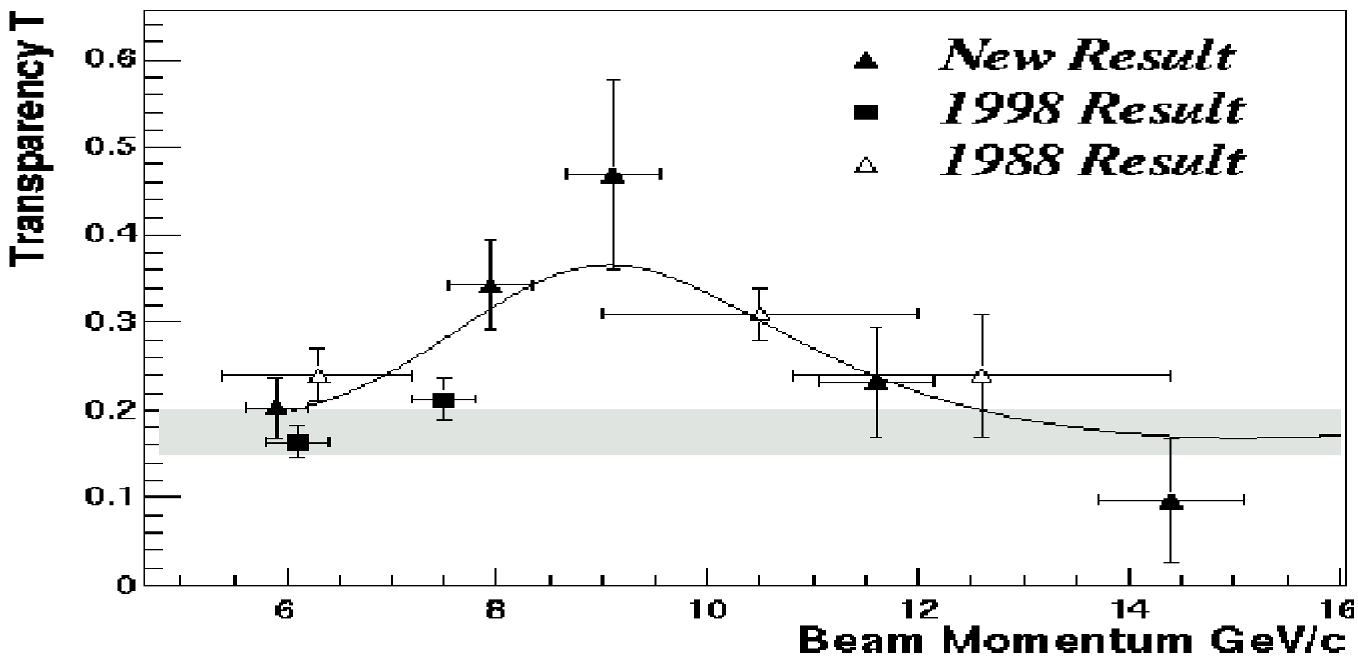
&

$$p + p \rightarrow p + p$$

$$\boxed{T = \frac{\sigma_{pA}}{A\,\sigma_{pp}}}$$

Transparency in A(p,2p) Reaction

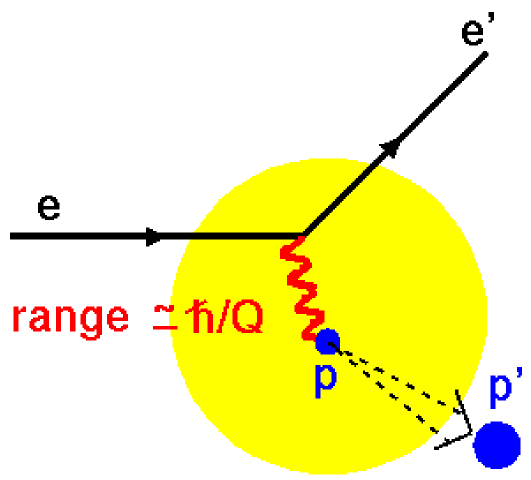
First experiment to look for color transparency



Results inconsistent with CT but explained in terms of nuclear filtering or charm resonance states.

Transparency in A(e,e'p) Reaction

The prediction of CT implies: Fast protons have reduced final state interactions.

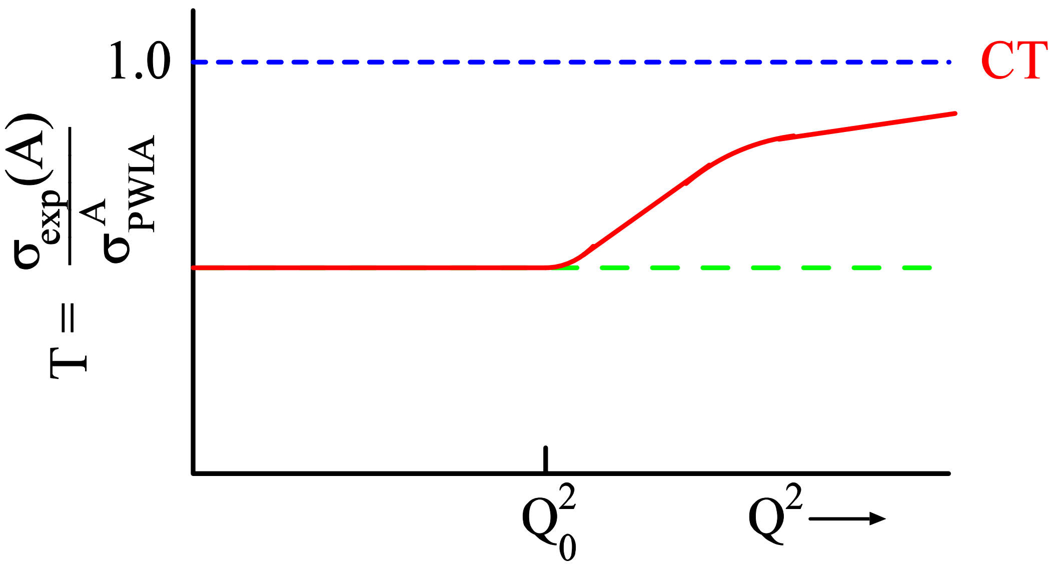


e + A → e' + p + X

At JLab search for CT focused on A(e,e'p)
E91-013 & E94-139

Transparency in A(e,e'p) Reaction

The prediction of CT implies: Fast protons have reduced final state interactions.



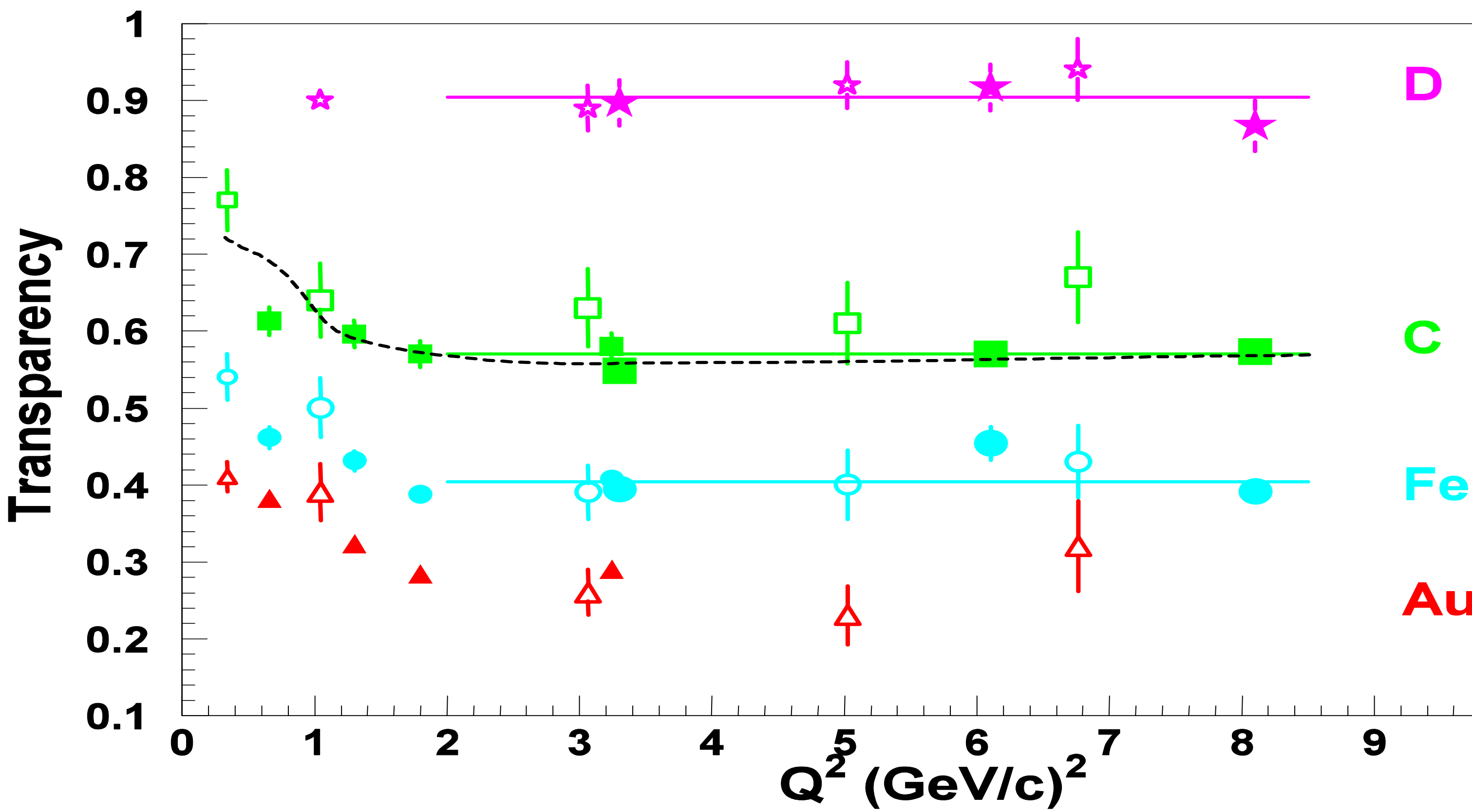
$e + A \rightarrow e' + p + X$

Q^2 is square of the momentum transfer

At JLab search for CT focused on A(e,e'p)
E91-013 & E94-139

A(e,e'p) Results

Q^2 dependence consistent with standard nuclear physics calculations

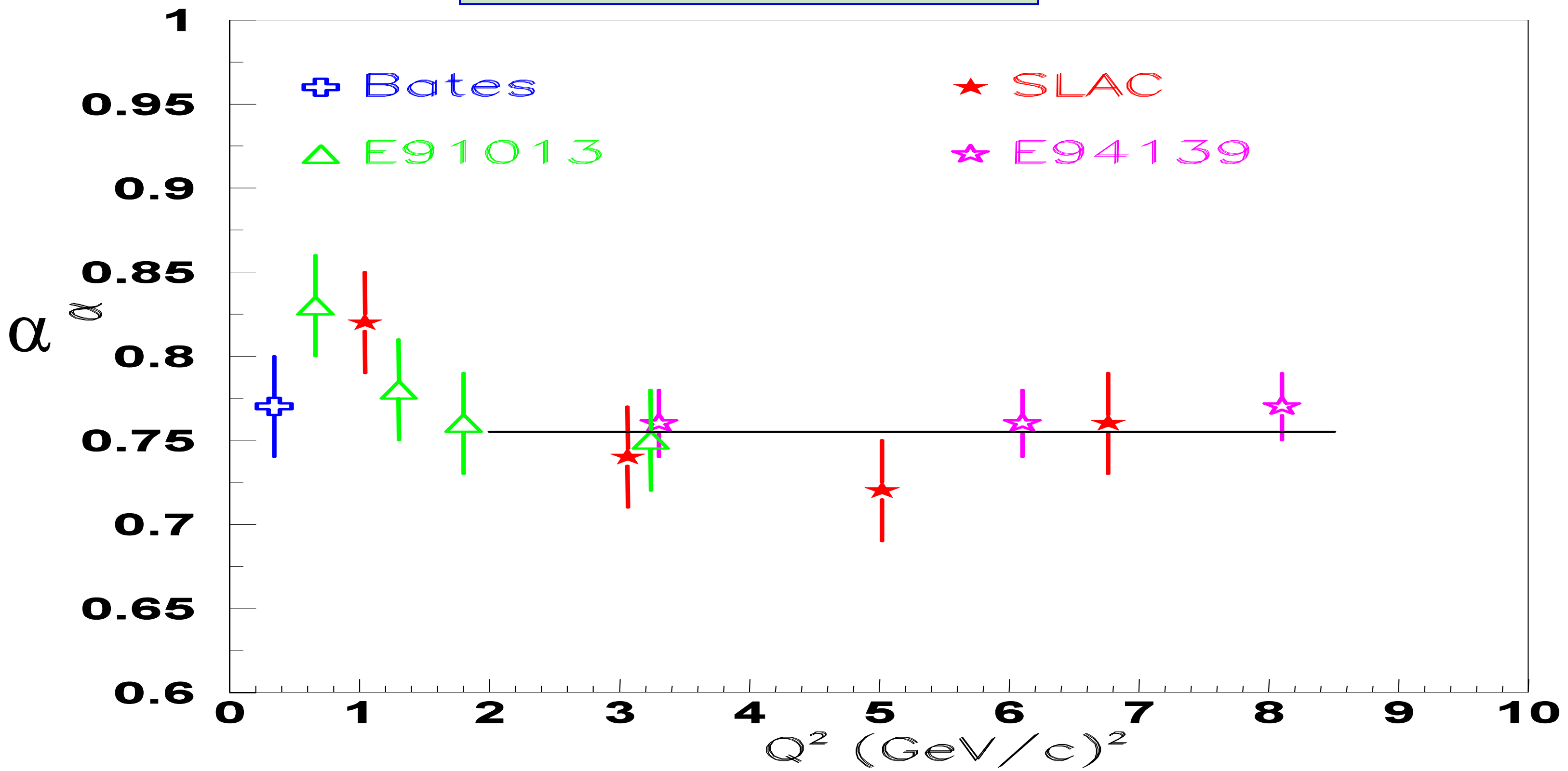


Constant value fit for $Q^2 > 2$ (GeV/c)^2 has $\chi^2/df \cong 1$

K. Garrow et al. PRC 66, 044613 (2000)

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

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



α = constant = 0.76

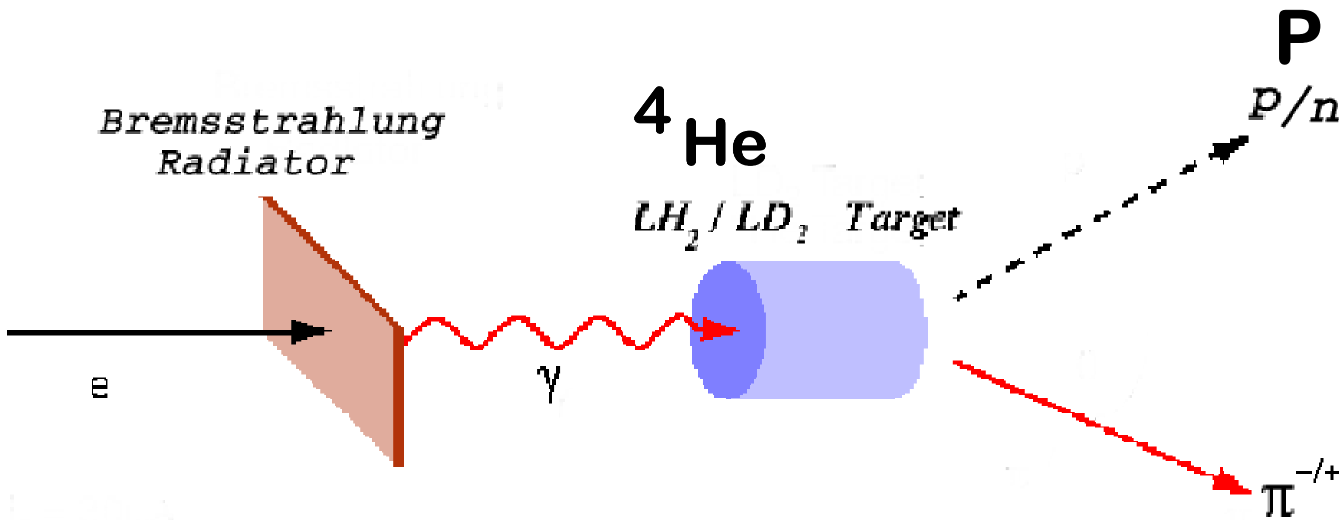
for $Q^2 > 2$ $(GeV/c)^2$

qqq vs $q\bar{q}$ systems

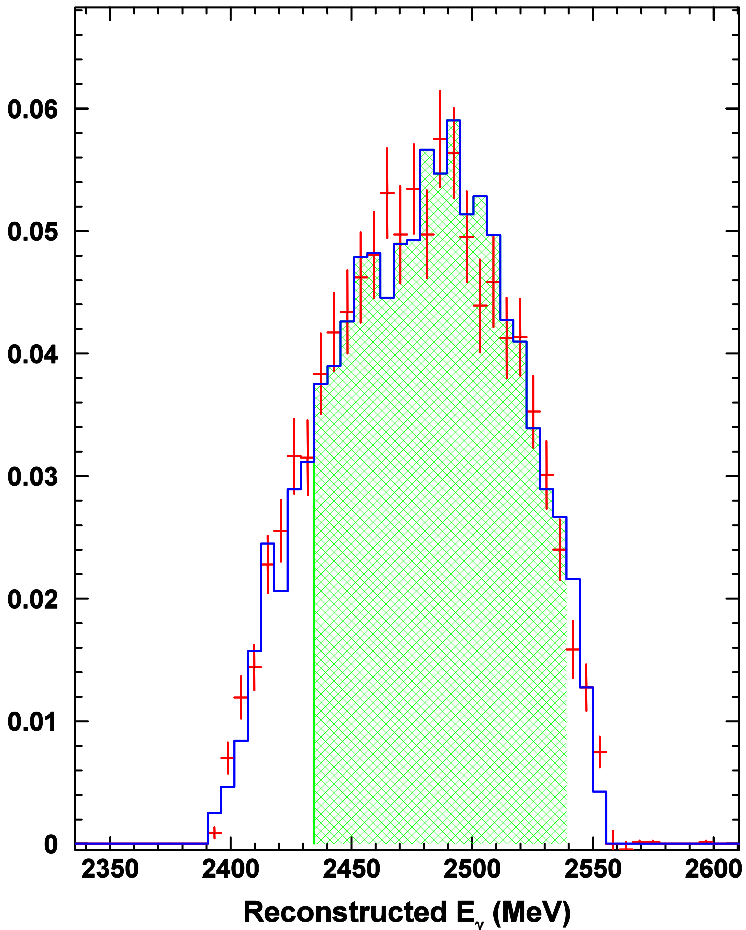
- There is no unambiguous, model independent, evidence for CT in qqq systems.
- Small size is more probable in 2 quark system such as pions than in protons.
- Onset of CT expected at lower Q^2 in $q\bar{q}$ system.
- Formation length is ~ 10 fm at moderate Q^2 in $q\bar{q}$ system.

Pion-photoproduction

$\gamma\ n \rightarrow \pi^{-} p$ in ^{4}He



Pion Photoproduction



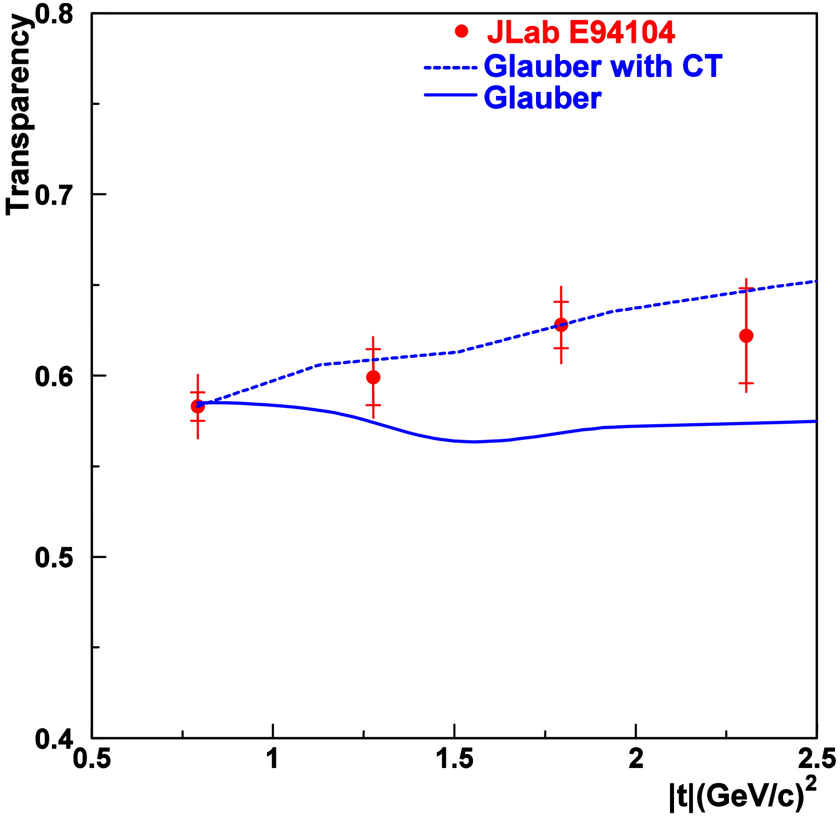
$$\gamma + {}^4\mathrm{He} \longrightarrow \pi^- + p + X$$

Assume X remains in the ground state

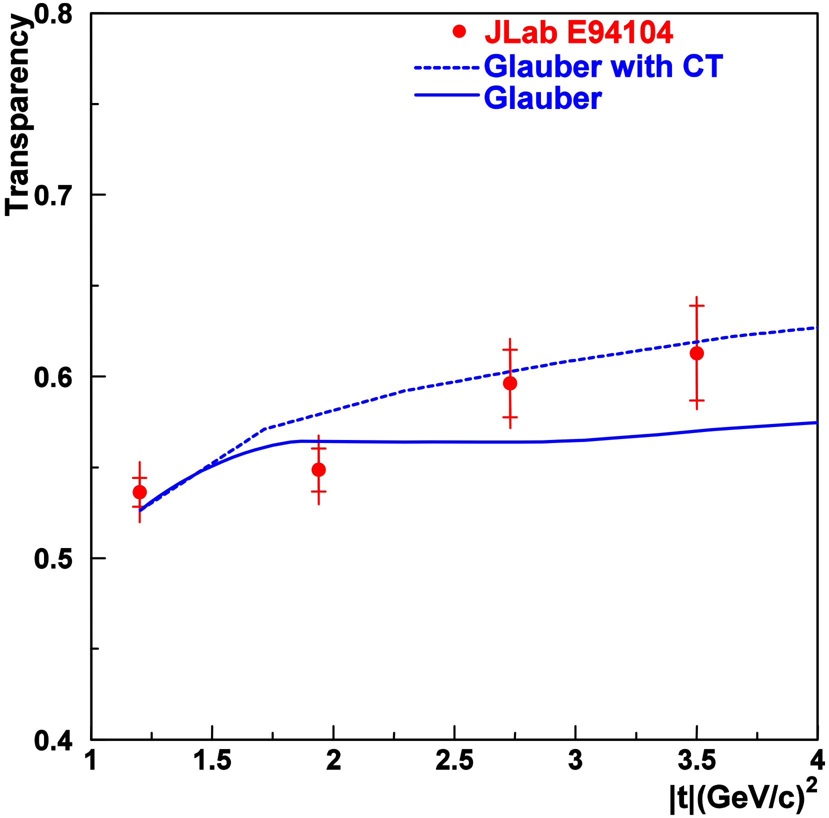
$$T \approx \frac{\gamma + {}^4\mathrm{He} \longrightarrow \pi^- + p + X}{\gamma + n \to \pi^- + p}$$

Results

70^0 pion C.M. angle

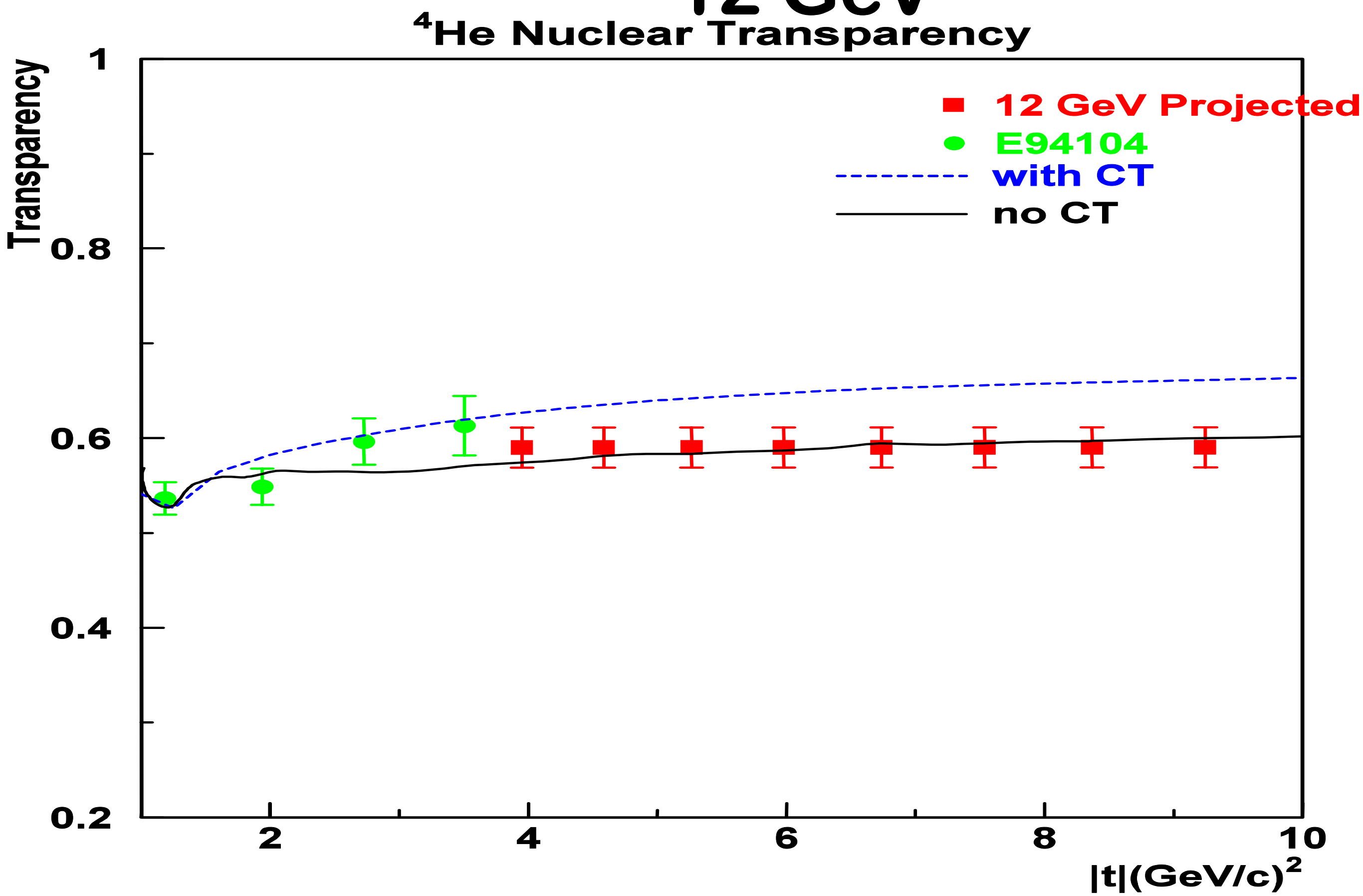


90^0 pion C.M. angle

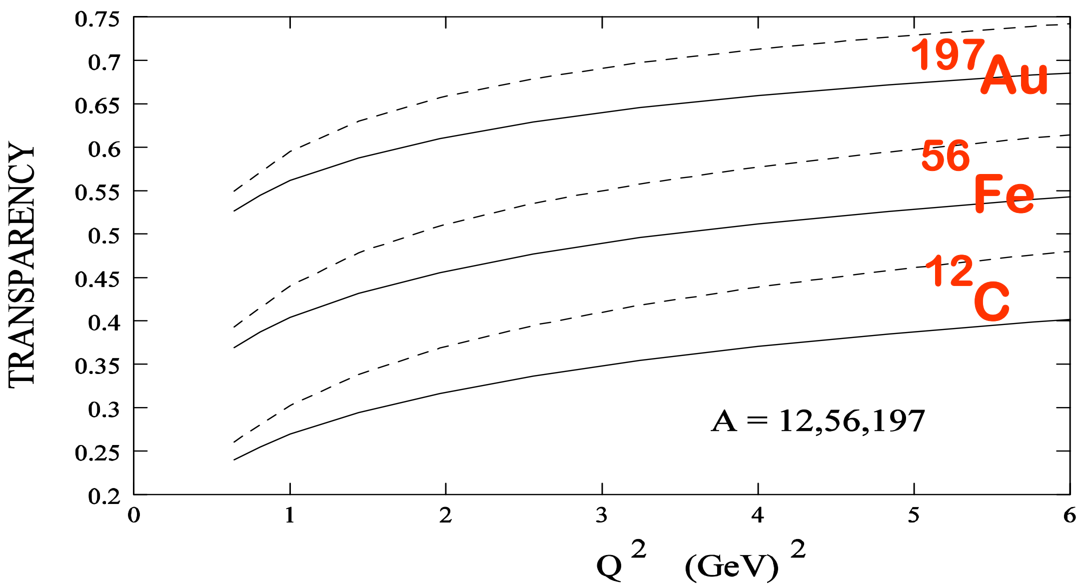


Future Searches: 12 GeV Upgrade of JLab

Projections for photo-pion production at 12 GeV



The A(e,e' π) Reaction



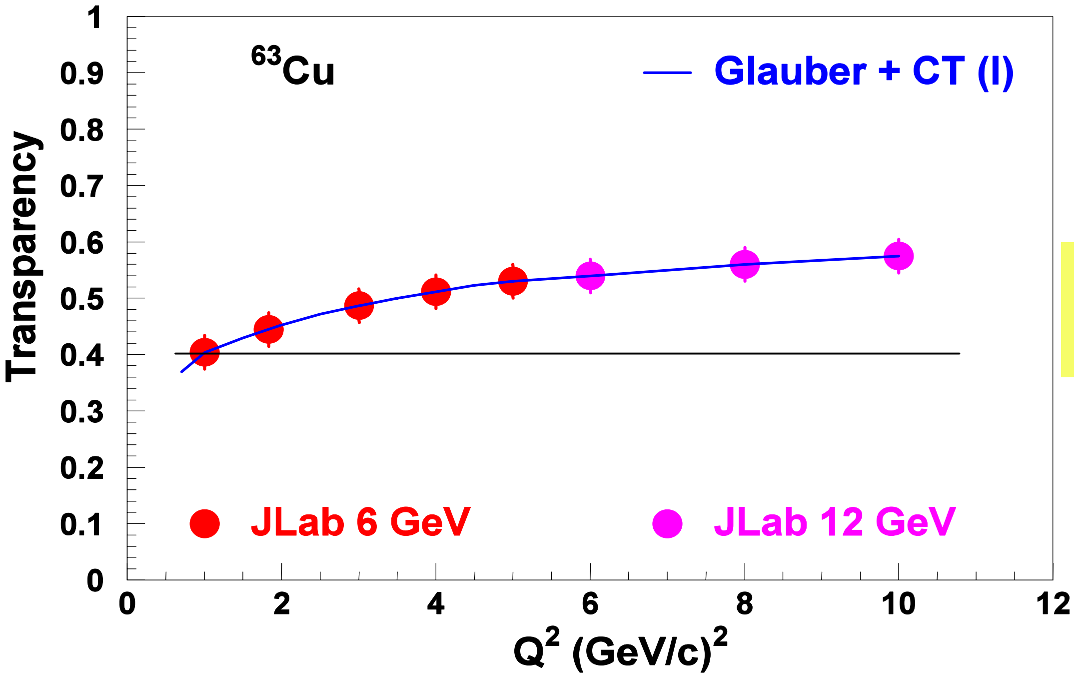
e + A → e + π + X

These predictions are consistent with existing data and independent calculations.

- Most of the CT effect is at $Q^2 > 10\ (GeV/c)^2$
- Two different quark distributions predict effects > 40 % at Q^2 between $1 – 5\ (GeV/c)^2$ for Gold nucleus.

A Pion Transparency Experiment

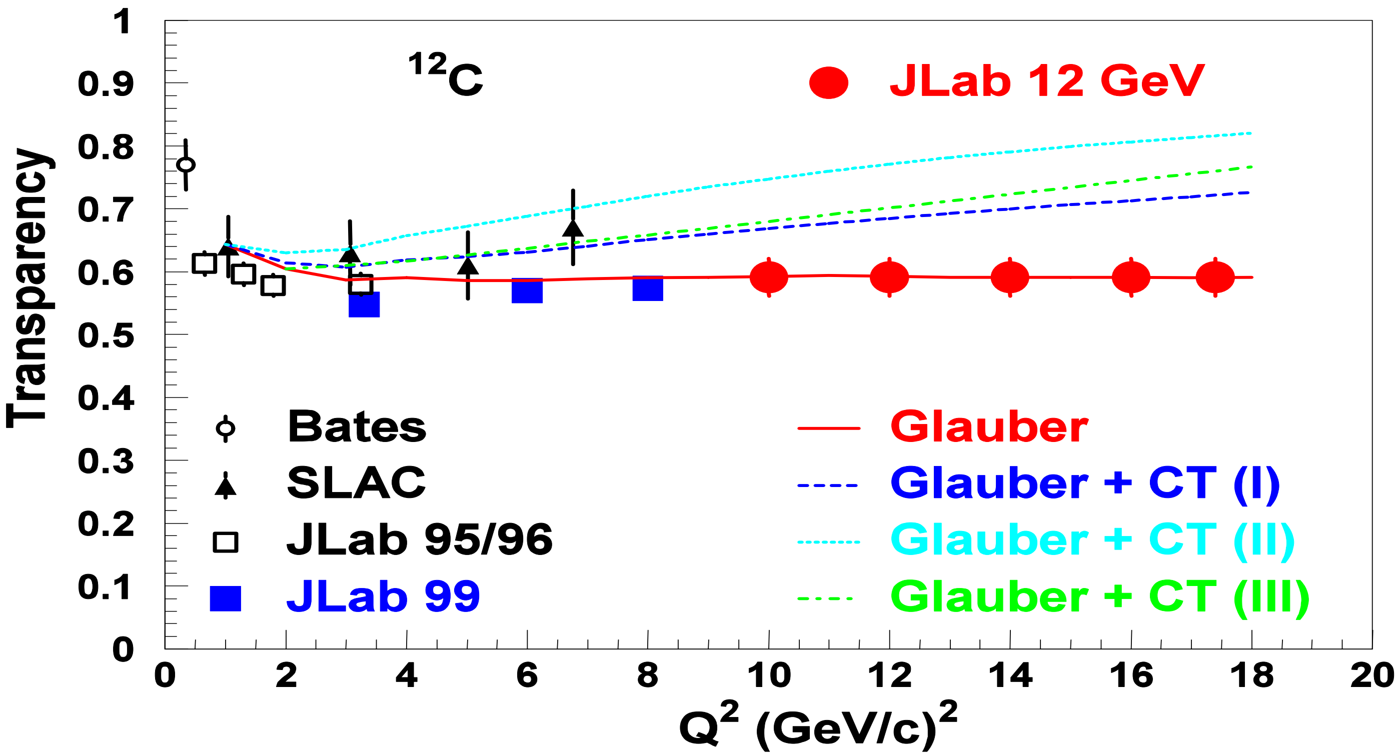
JLab Experiment E01-107: A(e,e' π) on H, D, C, Cu, Au



Measurable effect predicted for $Q^2 <$ 5 (GeV/c)^2

Projected combined statistical & systematic uncertainty of 5 – 10 % and the combined A & Q^2 effect measurable.

A(e,e'p) at 12 GeV



With HMS and SHMS @ 12 GeV

What Is the Energy Threshold for the Transition?

Exclusive processes (processes with completely determined initial and final states), are used to study the transition region.

Exclusive Processes

- **Nucleons**
  - Quark counting rules
  - Hadron helicity conservation
- **Nuclei**
  - Color transparency
  - Nuclear filtering

The Constituent Quark Counting Rule

Exclusive two body reactions (A+B →C+D) at large momentum transfers should scale as:

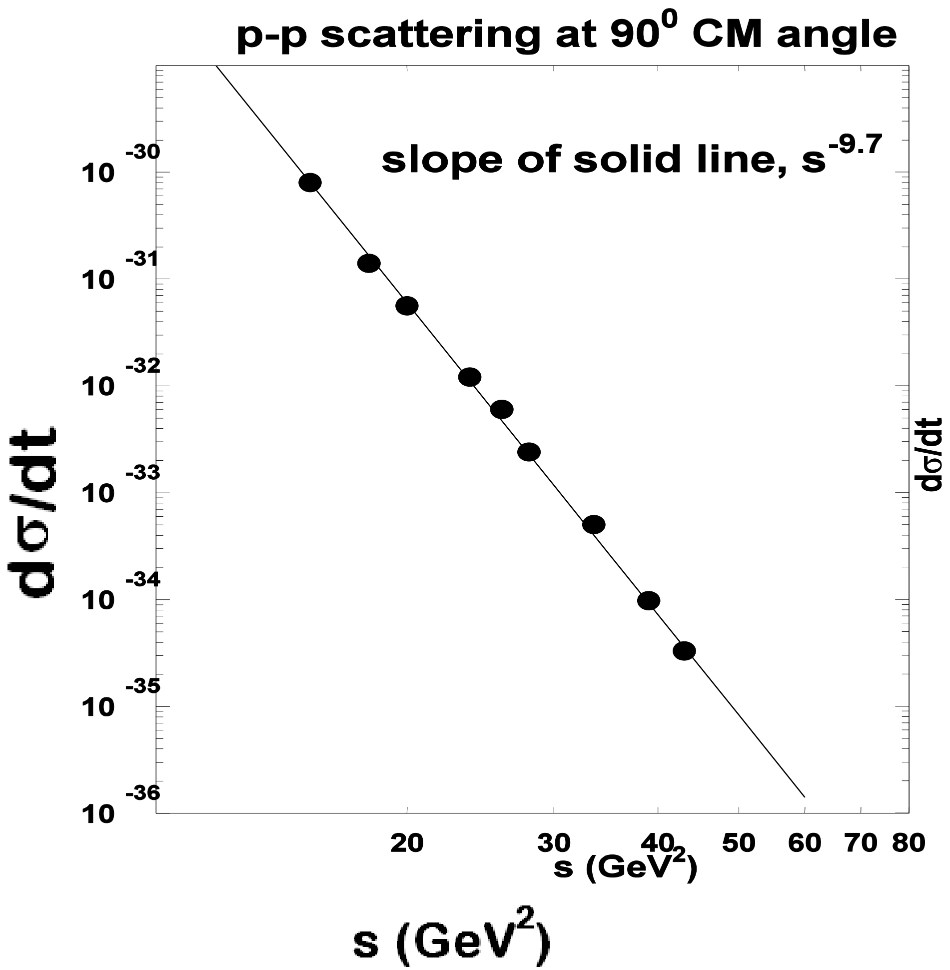
$$\boxed{\frac{d\sigma}{dt} = f(\theta_{CM}) \frac{1}{s^{n-2}}}$$

s = c.m. energy

n = # of fields

- **First derived based on dimensional analysis (Brodsky, Farrar,….)**
- **Confirmed within short distance pQCD framework (Brodsky, Le page)**
- **Many exclusive process seem to exhibit global quark counting rule behavior**

Elastic *p-p* Scattering



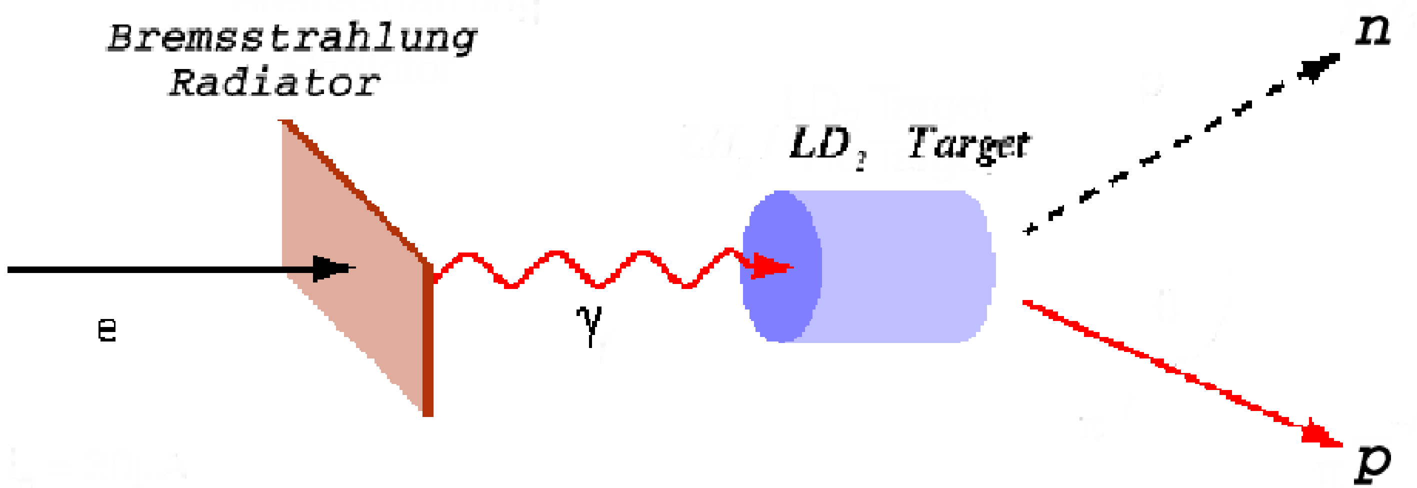
From data compilation of Landshoff and Polkinghorn

quark counting rule predicts

$$\frac{d\sigma}{dt} \propto s^{-10}$$

Deuteron Photo-disintegration

$\gamma + d \rightarrow p + n$



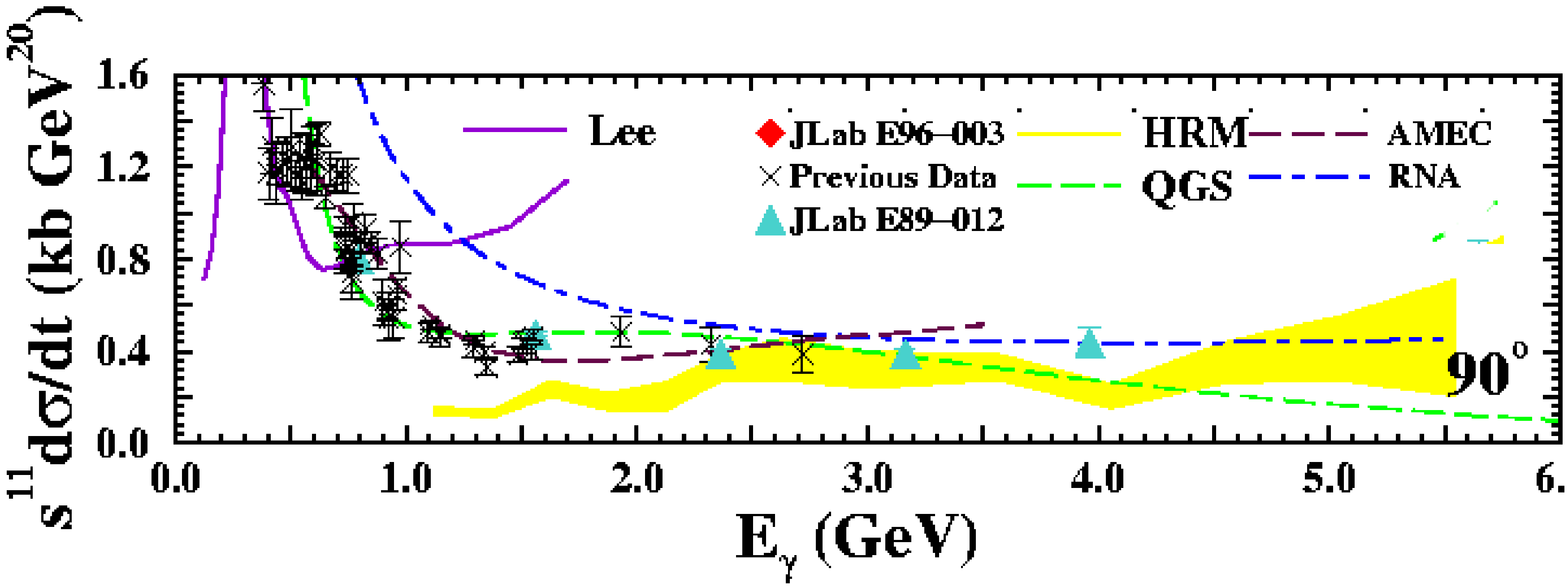
quark counting rule predicts $\frac{d\sigma}{dt} \propto s^{-11}$

Studied at SLAC, and most recently at JLab

Deuteron Photo-disintegration

$\gamma + d \rightarrow p + n$ @ 90 deg CM angle

JLab E89-012



C. Bochna *et al.*, PRL **81,** 4576 (1998)

Hadron Helicity Conservation

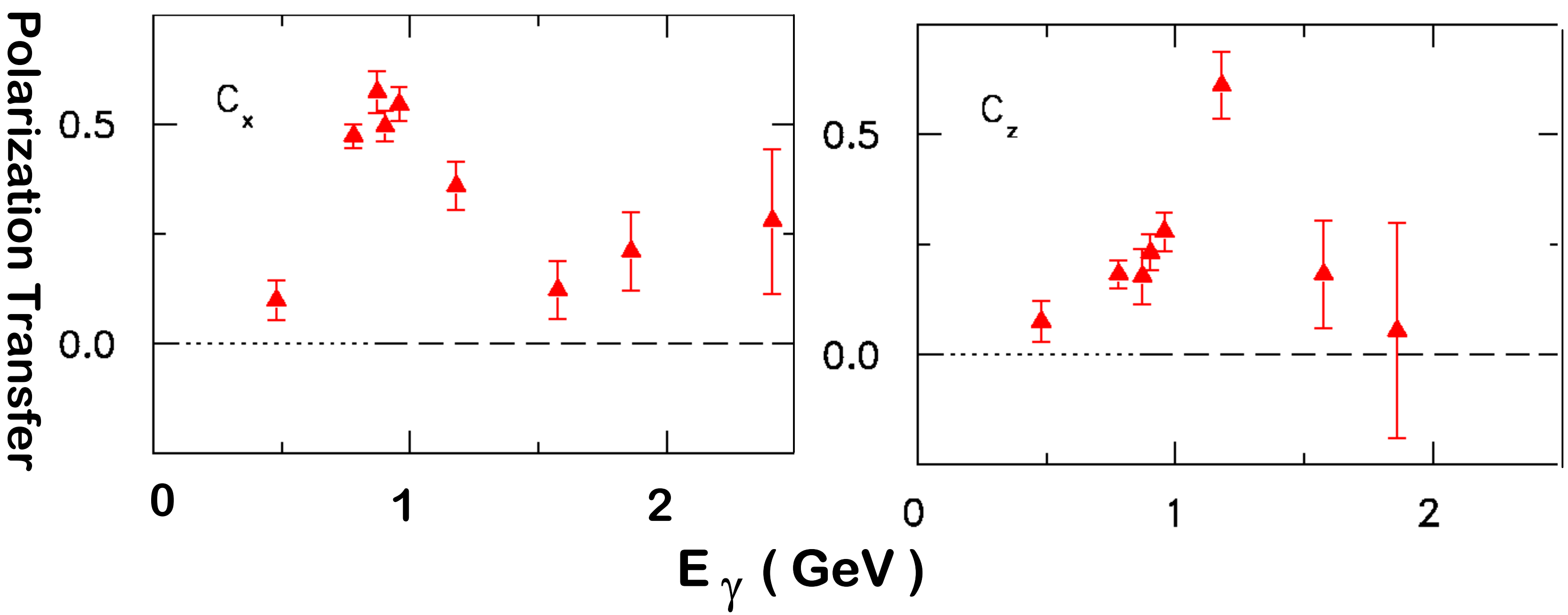
Short distance pQCD predicts helicity conservation in exclusive two-body processes ($A+B \rightarrow C+D$)

$$\lambda_A + \lambda_B = \lambda_C + \lambda_D$$

- Based on quark helicity conservation.
- Experimental data tends not to agree with HHC.

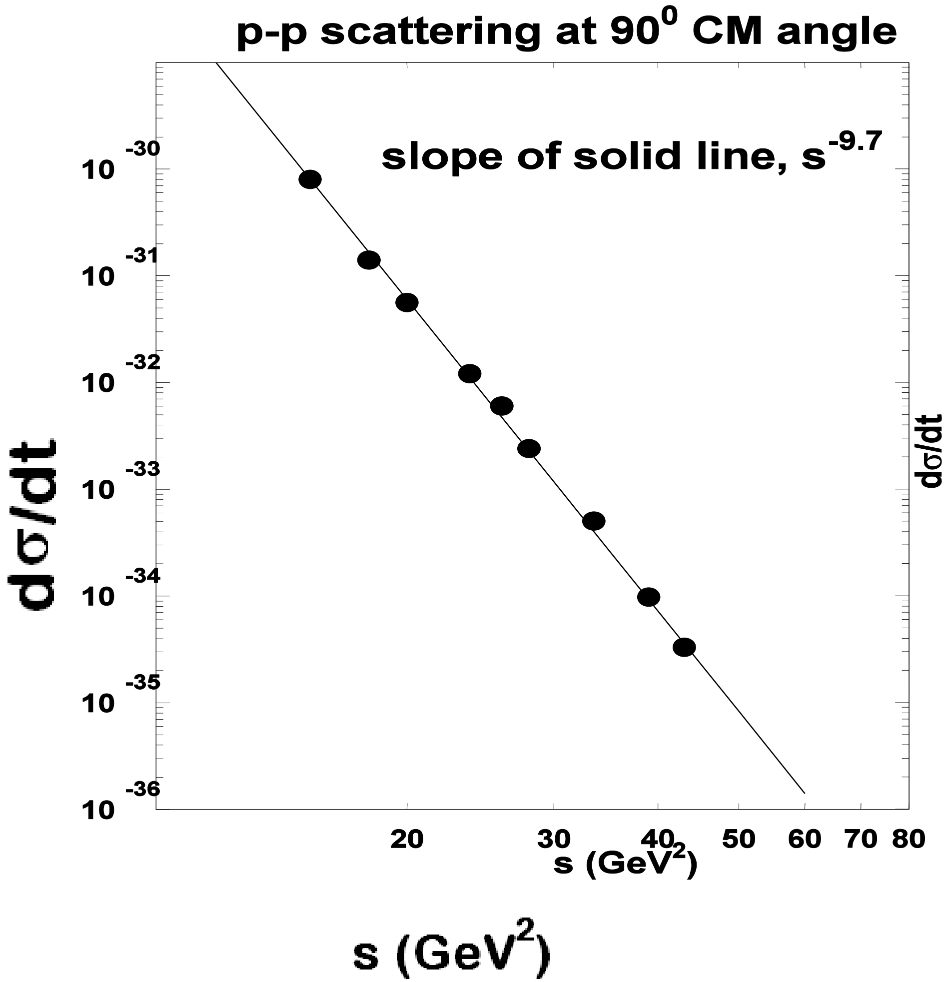
Hadron Helicity Conservation

$$\vec{\gamma} + \mathbf{d} \rightarrow \vec{\mathbf{p}} + \mathbf{n}$$



K. Wijesooriya *et al.*, PRL **86,** 2975 (2001)

Elastic *p-p* Scattering



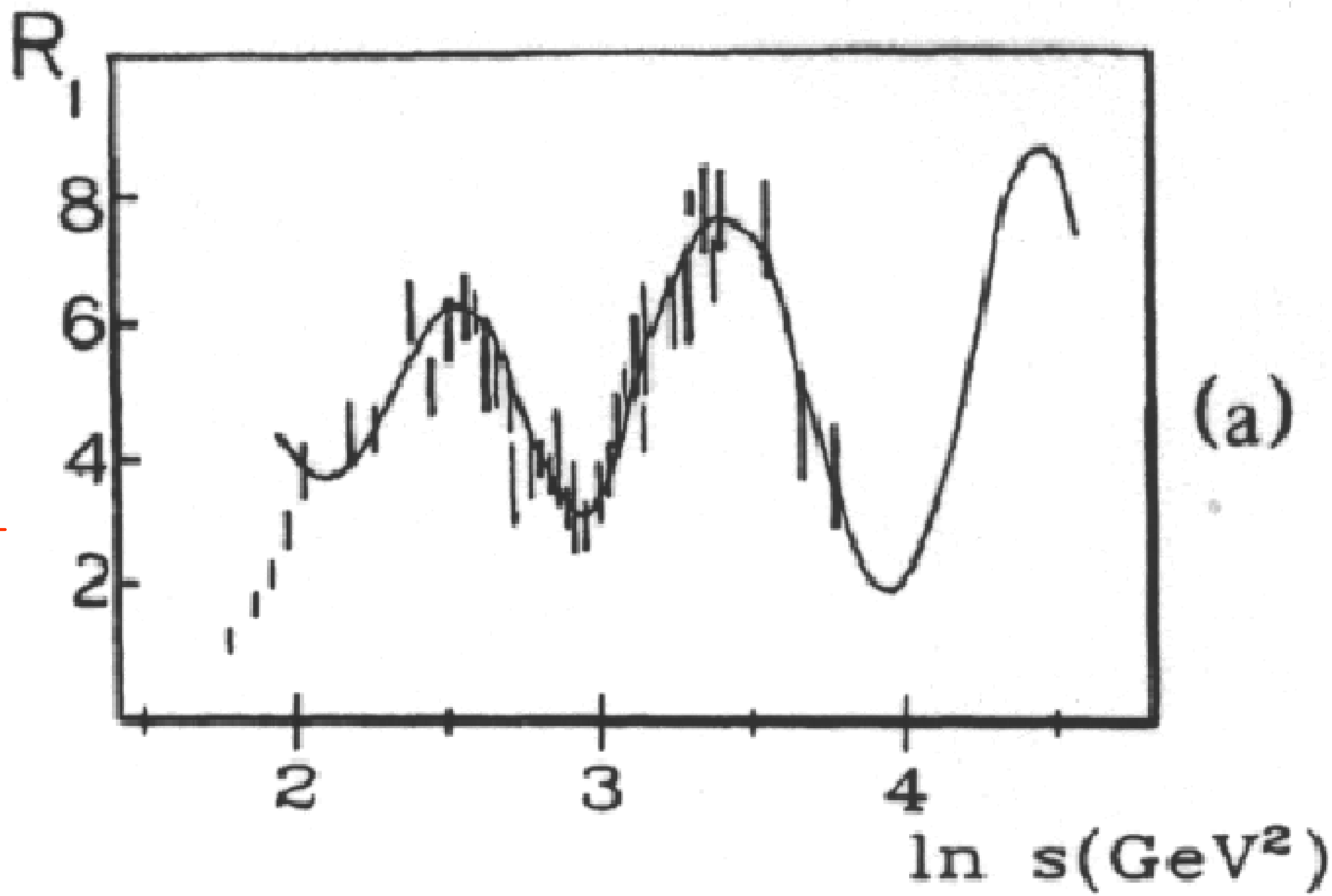
From data compilation of Landshoff and Polkinghorn

quark counting rule predicts

$$\frac{d\sigma}{dt} \propto s^{-10}$$

Elastic *p-p* Scattering

$$R_1 \propto s^{10} \frac{d\sigma}{dt}$$



J. P. Ralston and B. Pire, PRL 61, 1823 (1988)

Oscillatory Scaling Behavior

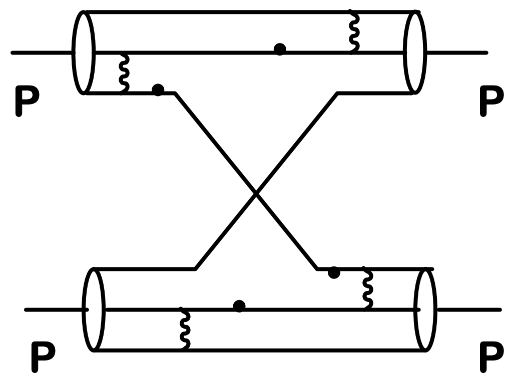
The oscillations in the scaled cross-section explained as:

- ❑ **Resonance state production near the charm threshold (Brodsky, Schmidt , …….).**

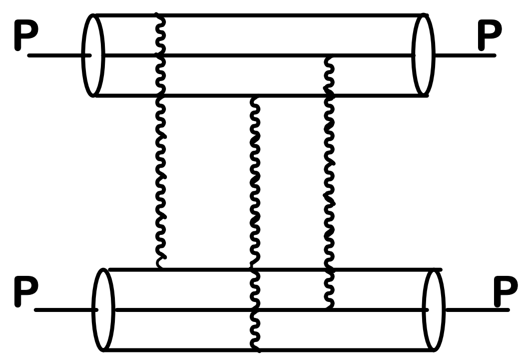
- ❑ **Interference between short distance (Born) and long distance (Landshoff) amplitudes, (Ralston & Pire and Carlson, Myhrer, …….)**

Born vs Independent Scattering Amplitude in *p-p* Scattering

- Born amplitude



- Independent scattering (Landshoff) amplitude



+ Corrections due to gluon radiation (Sudakov Effect)

Nuclear Filtering

What happens to the oscillatory scaling behavior in the nuclear medium ?

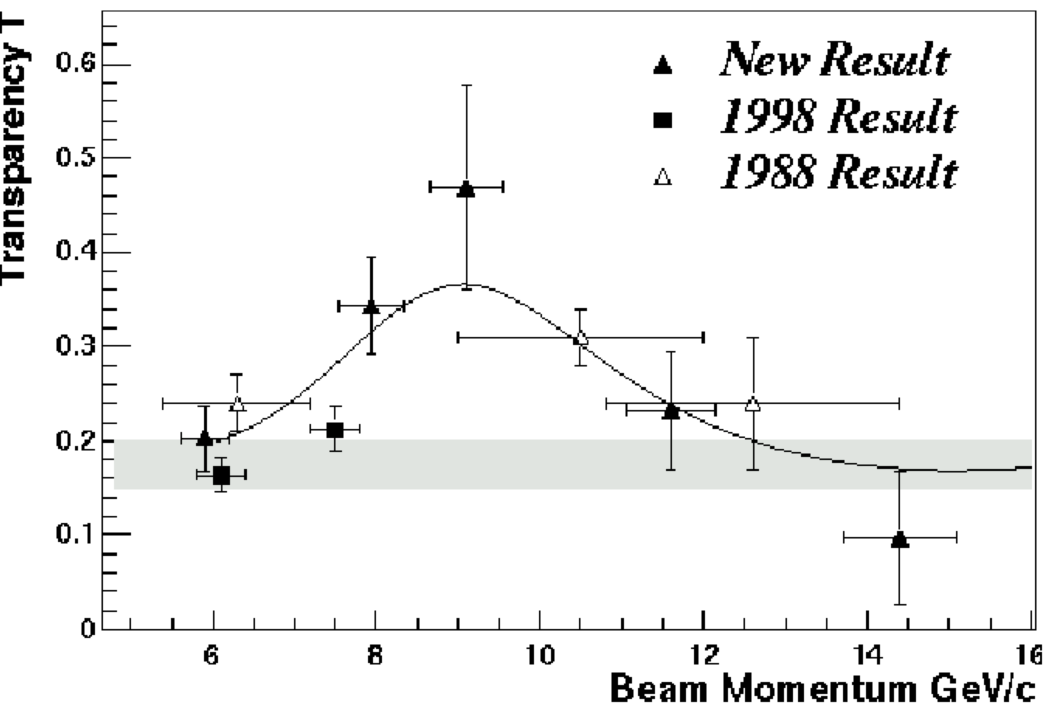
- It has been suggested that they are damped out because the long distance amplitude is suppressed in the nuclear medium.

- This is called “ Nuclear Filtering.”

- This implies there should be oscillations in nuclear transparency 180^{o} out-of-phase with the oscillations in the free cross-section.

Transparency in A(p,2p) Processes

p + $^{A}N_{Z}$ → p + p + X @ BNL

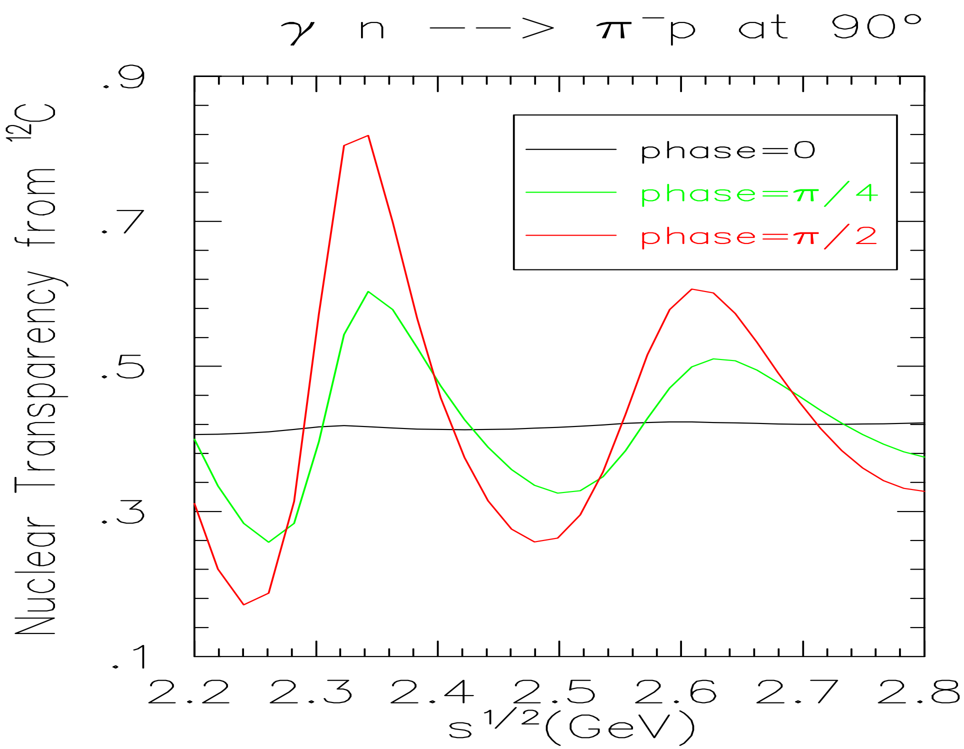


Shaded band is from a conventional nuclear physics calculation

Solid line is fit to 1/oscillation in p-p scattering data

- BNL results explained in terms of Nuclear Filtering (Ralston & Pire)
- In terms of charm resonance states (Brodsky & Le page).

Nuclear Filtering with Photo-pions



$$\gamma + {}^{12}C \rightarrow \pi^- + p + X$$

$$T \approx \frac{\gamma + {}^{12}C \rightarrow \pi^- + p + X}{\gamma + n \rightarrow \pi^- + p}$$

- **Large oscillations in photo-pion transparency predicted by Jain, Kundu and Ralston.**
- **Amplitude depends on an additional nuclear phase.**
- **Can be tested with photo-pion production from Carbon.**

Nuclear Filtering vs CT

- Nuclear filtering uses the medium actively to suppress the long-distance amplitude.
- In CT the large momentum transfer selects the short distance amplitude which is then free to propagate through the passive medium.
- The CT limit is $Q \rightarrow \infty$, and the onset of CT is expected to be sooner on lighter nuclei.
- The nuclear filtering limit is $A \gg 1$, and the effect bigger in heavier nuclei.

Drawing the Roadmap

- Matter at high densities
  - Modification of nuclear structure at high densities
  - High density fluctuations in nuclei
  - Deep inelastic scattering at $x > 1$
  - Tagged structure functions
- Exclusive processes at high momentum transfer
  - Color transparency
  - Nuclear Filtering
- Probing the limits of nucleon based description of nuclei

The Nucleon Meson Picture

Nucleus: made of individual nucleons interacting via 2 and 3 body potentials

Describes data from KeV (eg. Solar reactions) to GeV (eg. Deuteron form factors) range.

but

Short range interactions are poorly constrained

EM probe: Interacts via 1, 2 and many body currents

Questions:

- How do these potentials and currents arise from the underlying quark-gluon degrees of freedom?
- At what length scales (Q^2) does this model fail?

Probing the Limits of Nucleons in Nuclei

The existence of quarks in the nucleus will be shown by the failure of nucleon-meson models.

Possible measurements

- Few body elastic form factors at high Q^2
- Deuteron photodisintegration
- A(e,e')X ratios at $x > 1$ and $x > 2$
- He(e,e'pp)n to measure correlated pp pairs

Deuteron and Helium Form Factors

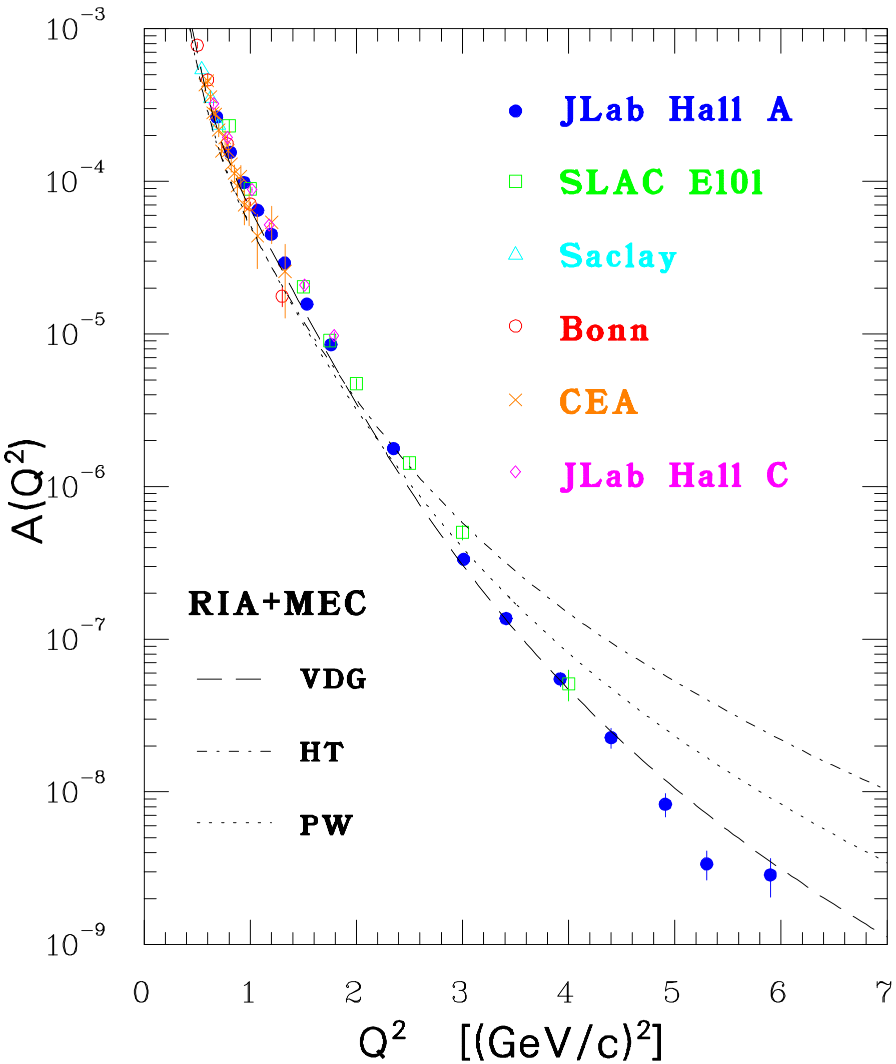
$$\frac{d\sigma}{d\Omega} = (K)[A(Q^2)\cos^2(\theta/2) + B(Q^2)\sin^2(\theta/2)]$$

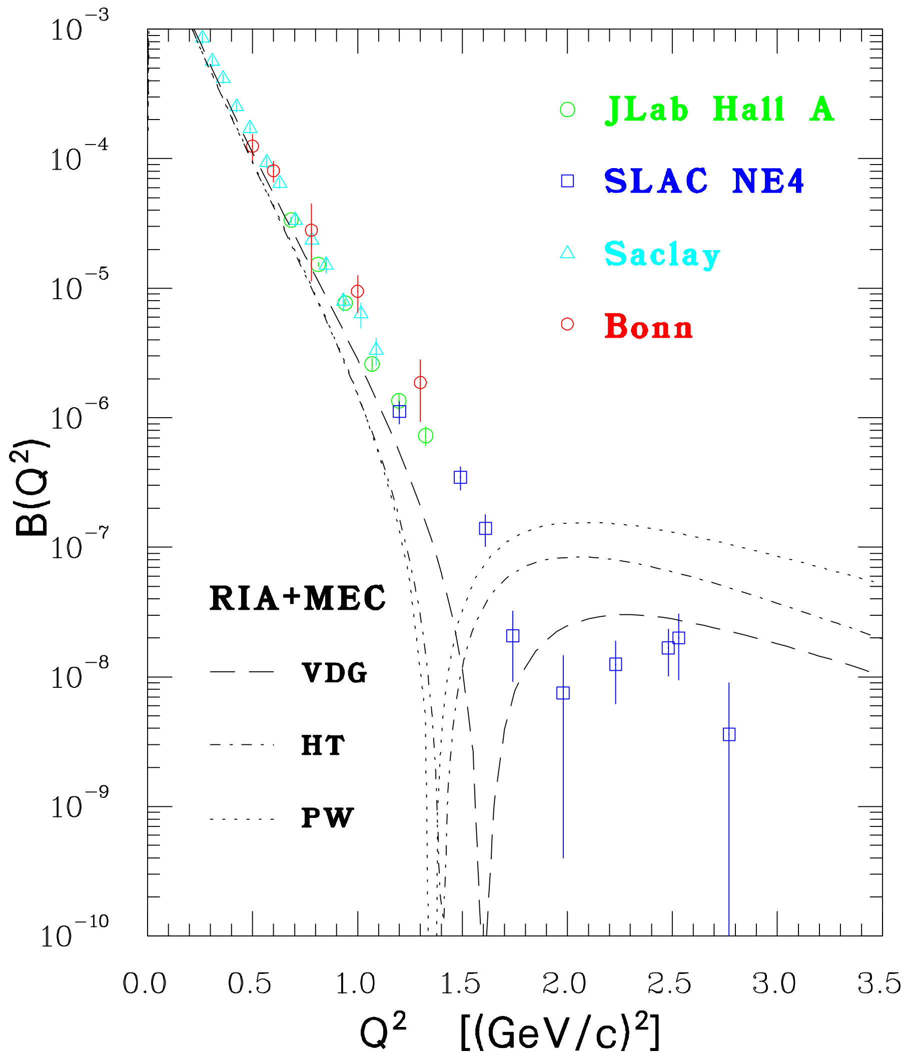
Forward angle scattering → A (Q^2)

Backward angle scattering → B (Q^2)

High precision measurements of formfactors at high Q^2 will test nucleonic vs quark-gluon models.

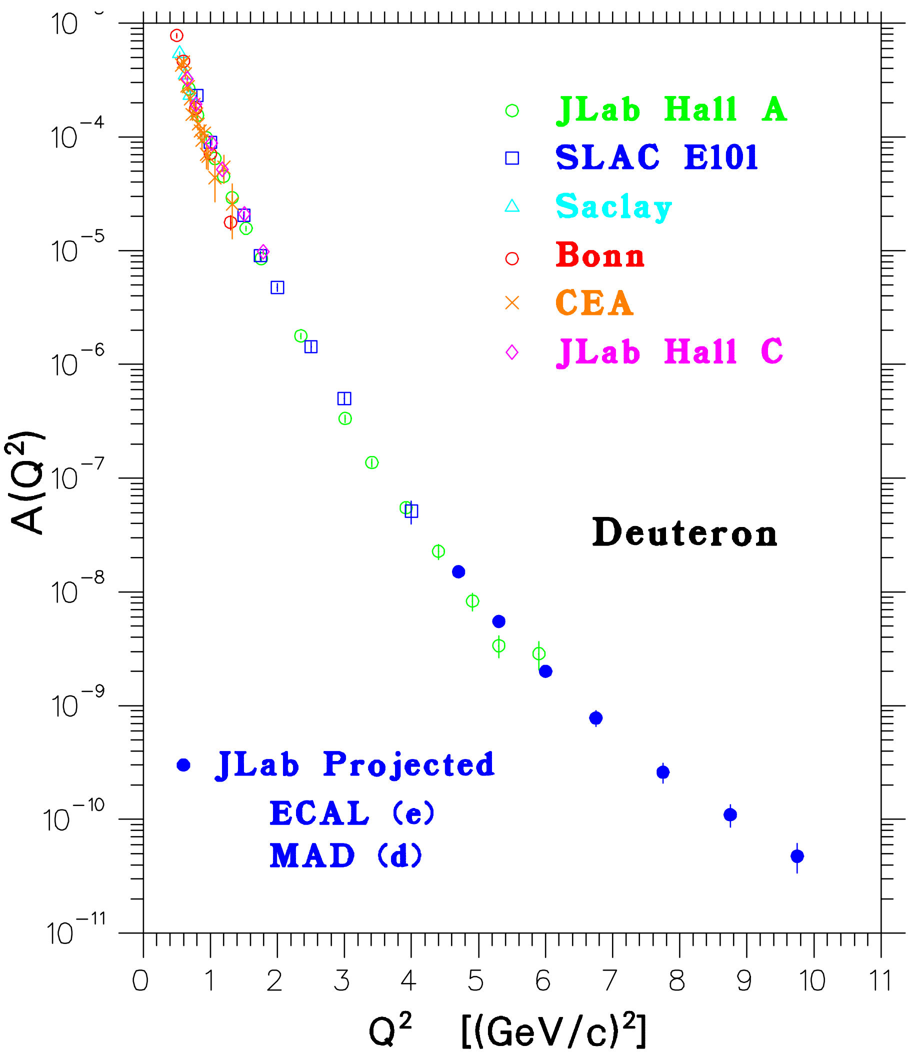
Deuteron Form Factors

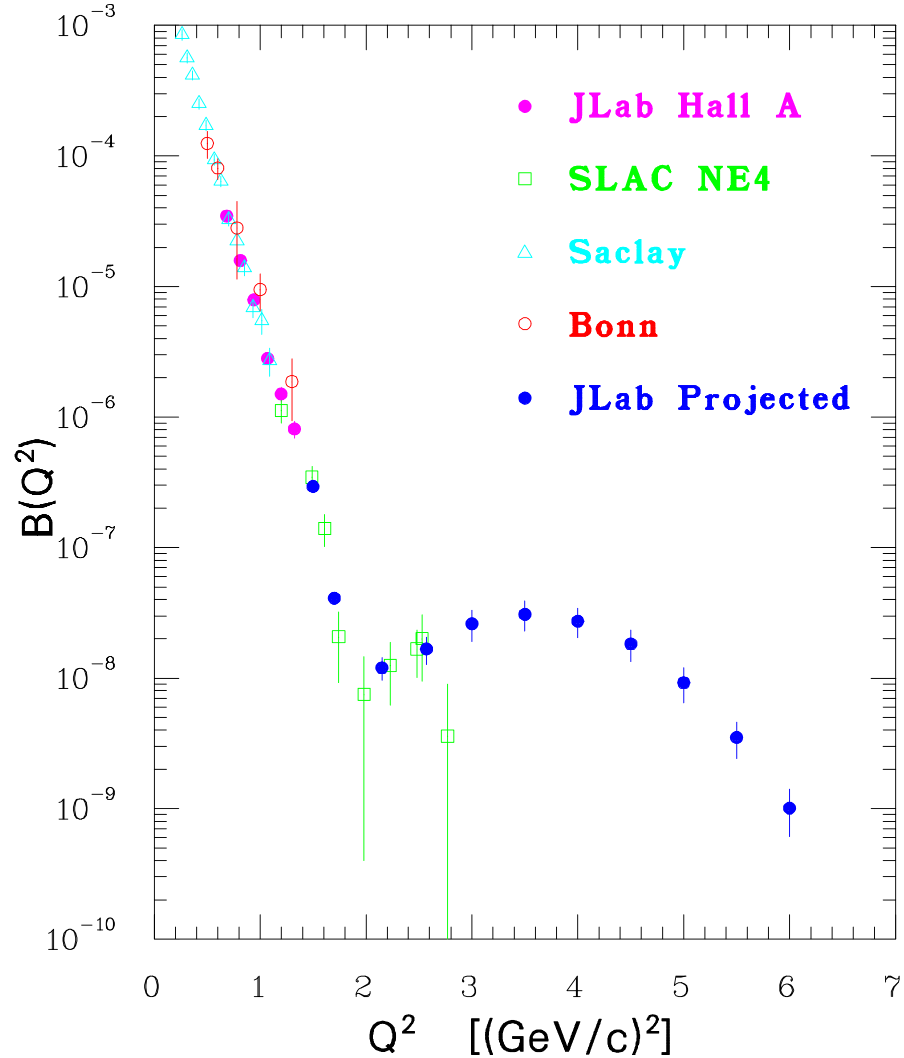




M Petratos

Deuteron Form Factors



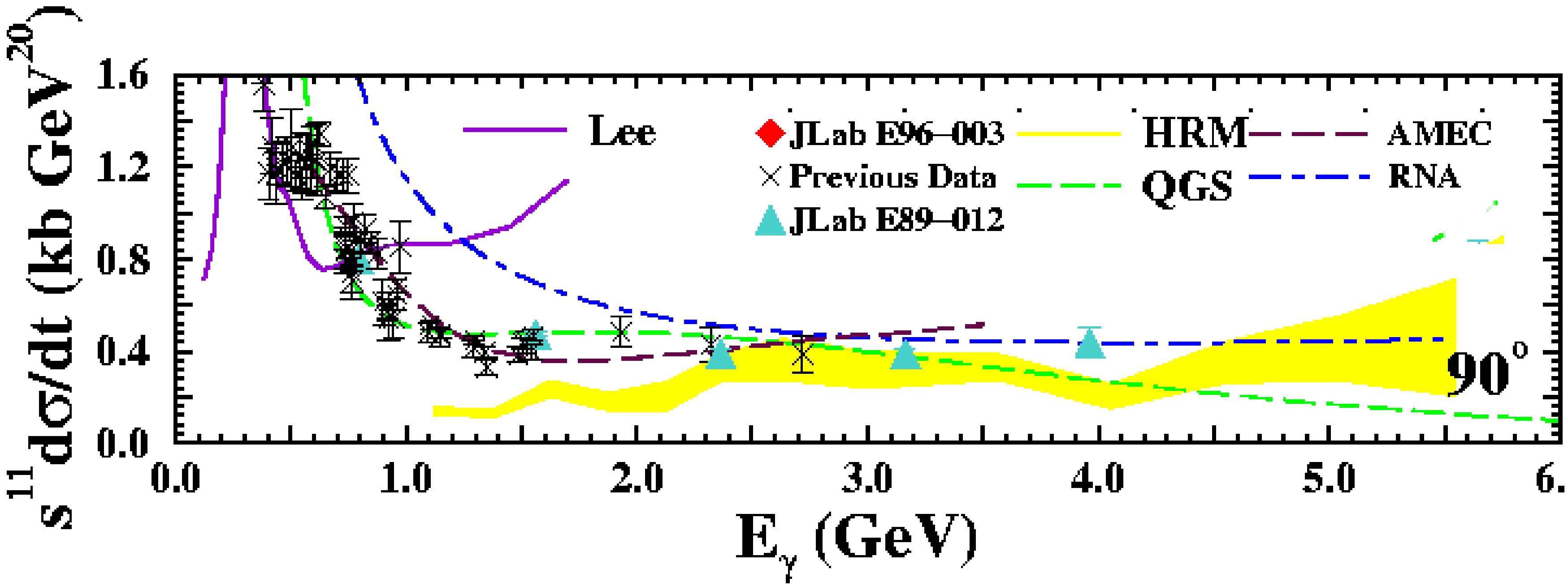


M Petratos

Deuteron Photo-disintegration

$\gamma + \mathbf{d} \rightarrow \mathbf{p} + \mathbf{n}$ **@ 90 deg CM angle**

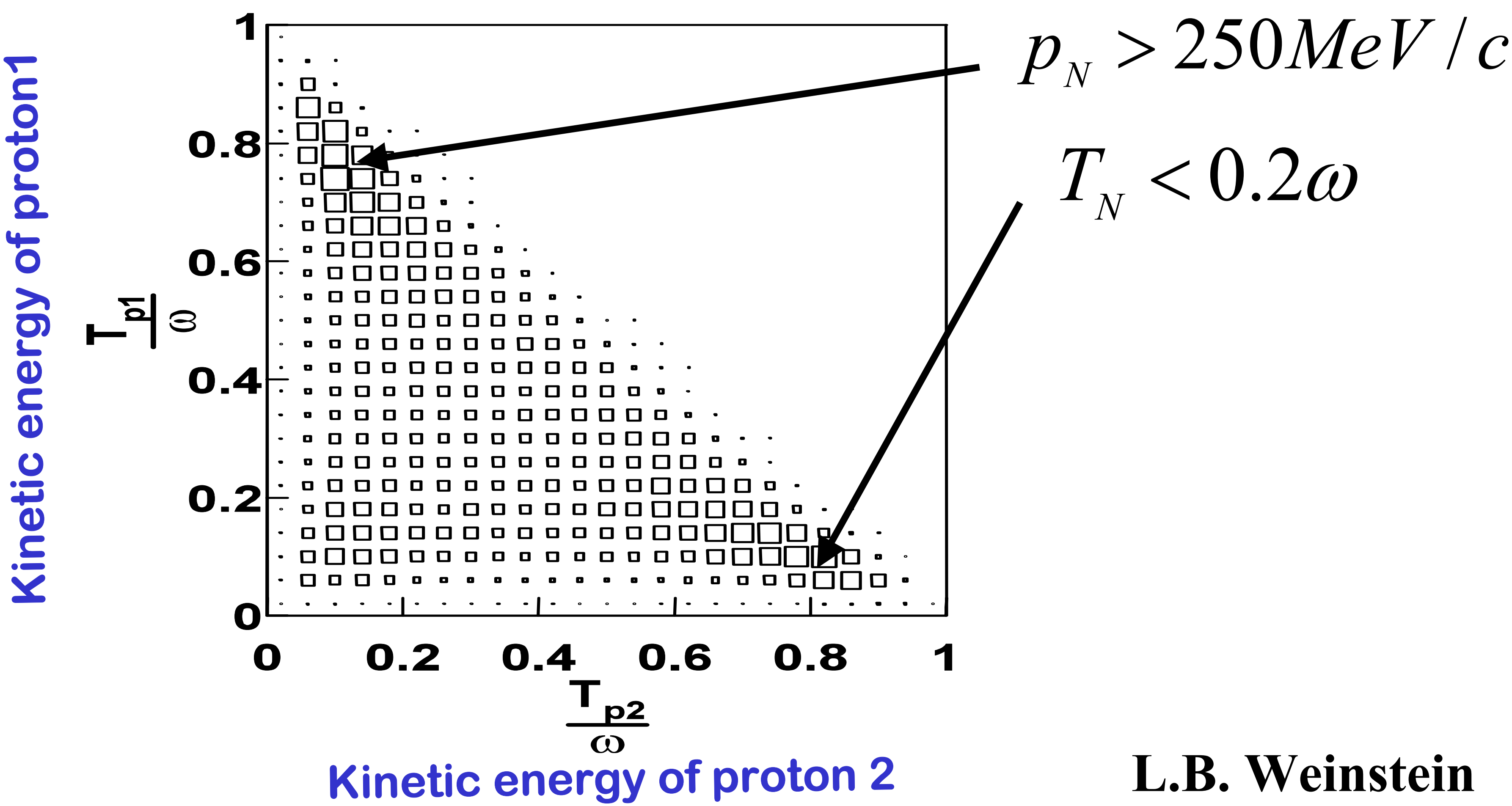
JLab E89-012



C. Bochna *et al.*, PRL **81,** 4576 (1998)

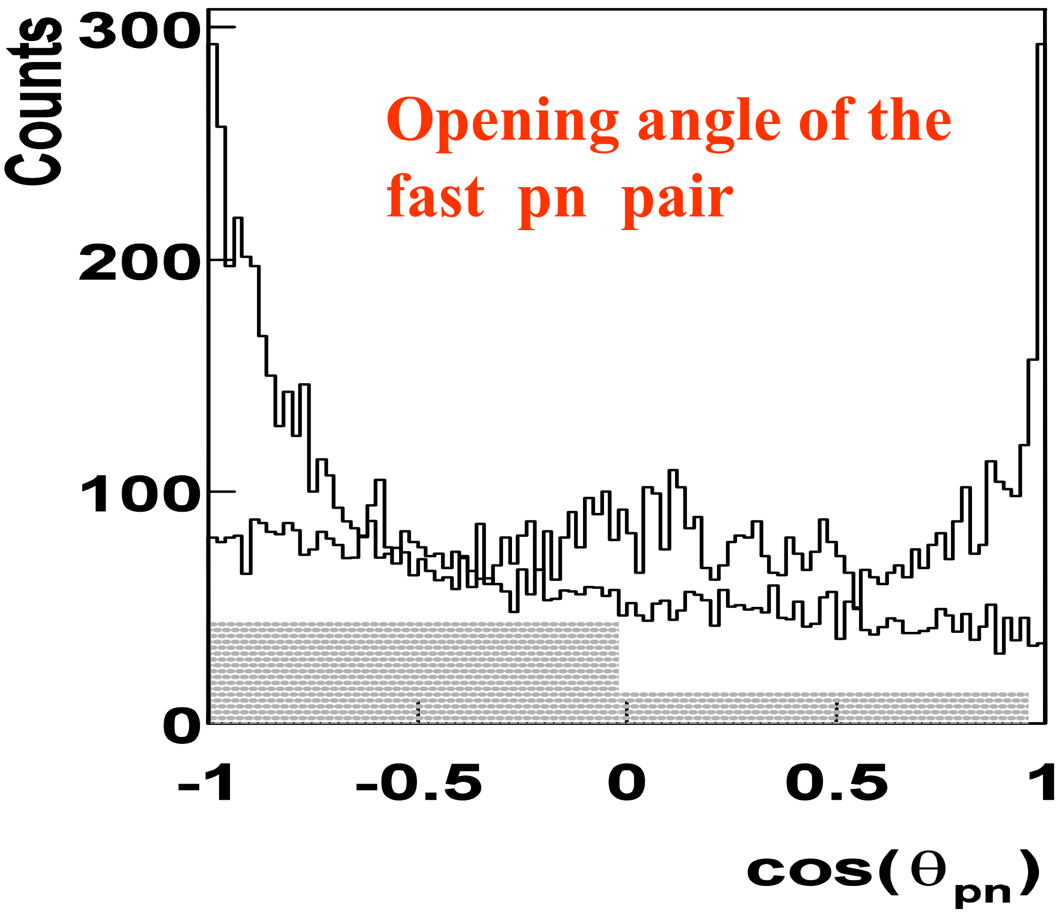
$^3He(e,e'pp)n$

Detect 3 fast nucleons (p > 250 MeV/c)



L.B. Weinstein

$^3He(e,e'pp)n$



When one nucleon has most of the energy, the other two are preferentially back to back.

Might be the first direct measurement of NN correlations.

Studies at higher Q^2 will be effective tests of nucleonic models.

Summary

- Studying hadrons in the nuclear medium and comparing them to free hadrons provides a unique opportunity for understanding nuleons and nuclei in terms of quarks and gluons

- One can look for modifications in the structure and interactions of hadrons in the nucleus.

- There are hints of such modifications from experiments, but precision experiments at JLab will provide a more Complete picture.

- One can also look for signatures of transition from the nucleon-meson to the quark-gluon picture, such as color transparency and nuclear filtering.

Summary

- So far there is no unambiguous evidence for color transparency but the program at JLab is likely to provide definitive answers.

- JLab also has a impressive array of experiments looking for the limits of the nucleon-meson description of nuclei.