Nuclear Physics with Electromagnetic Probes
Lectures 5

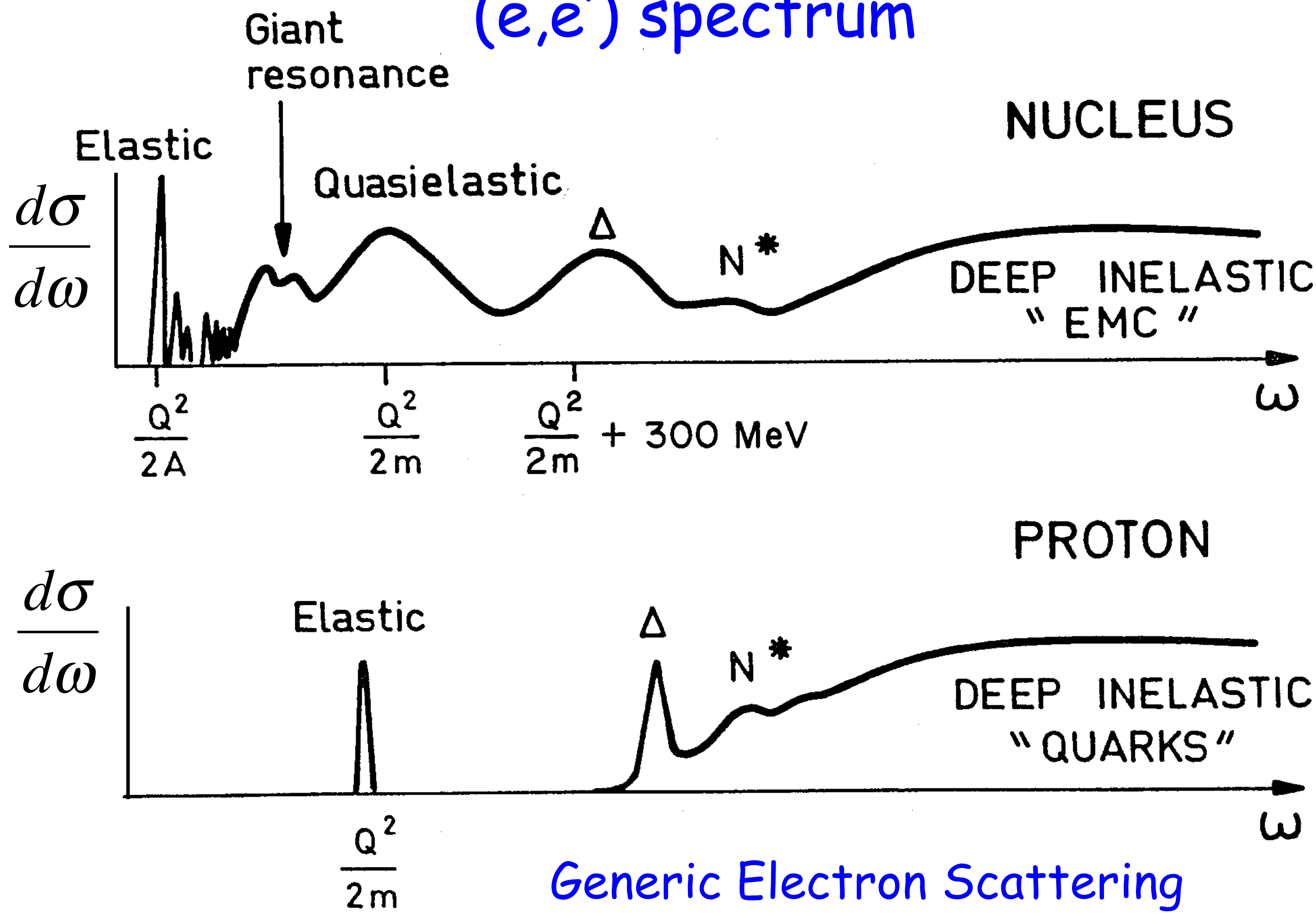
Lawrence Weinstein
Old Dominion University
Norfolk, VA USA

Hampton University Graduate School
2012

Course Outline

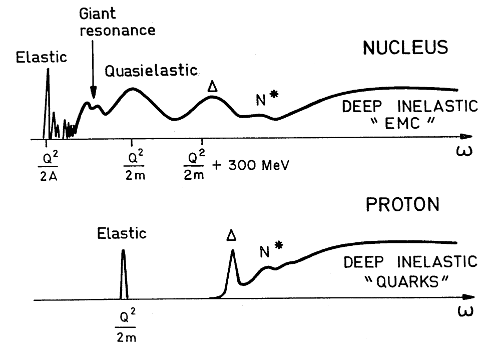
- Lecture 1: Beams and detectors
- Lecture 2: Elastic Scattering:
  - Charge and mass distributions
  - Deuteron form factors
- Lectures 3+4:
  - Single nucleon distributions in nuclei
    - Energy
    - Momentum
  - Correlated nucleon pairs.
- Lecture 5: Quarks in Nuclei
  - Nucleon modification in nuclei
  - Hadronization
  - Color transparency

(e,e') spectrum



Generic Electron Scattering
at fixed momentum transfer

Experimental goals:



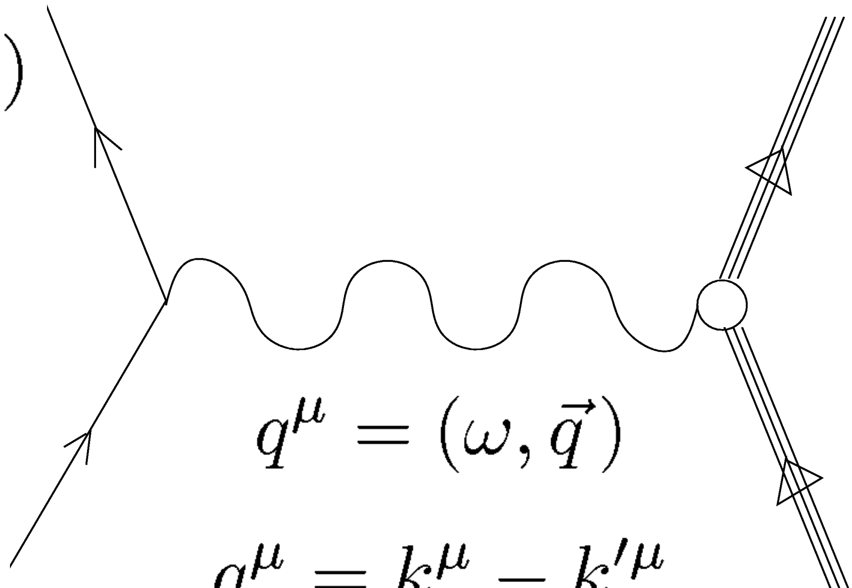
- Elastic scattering
  - structure of the nucleus
    - Form factors, charge distributions, spin dependent FF
- Quasielastic (QE) scattering
  - Shell structure
    - Momentum distributions
    - Occupancies
  - Short Range Correlated nucleon pairs
  - Nuclear transparency and color transparency
- Deep Inelastic Scattering (DIS)
  - The EMC Effect and Nucleon modification in nuclei
  - Quark hadronization in nuclei

Inclusive electron scattering (e,e')

$k'^{\mu} = (E', \vec{k}\,')$

$p'^{\mu} = (E_p, \vec{p}_p)$

(not detected)



Lab frame kinematics

$q^{\mu} = (\omega, \vec{q}\,)$

$k^{\mu} = (E, \vec{k}\,)$

$q^{\mu} = k^{\mu} - k'^{\mu}$

$p^{\mu} = (M, \vec{0}\,)$

Invariants:

$$p^{\mu} p_{\mu} = M^2 \qquad p_{\mu} q^{\mu} = M\omega$$

$$Q^2 = -q^{\mu} q_{\mu} = |\vec{q}\,|^2 - \omega^2 \qquad W^2 = (q^{\mu} + p^{\mu})^2 = p'_{\mu} p'^{\mu}$$

Short Range Correlations (SRC) Reminder

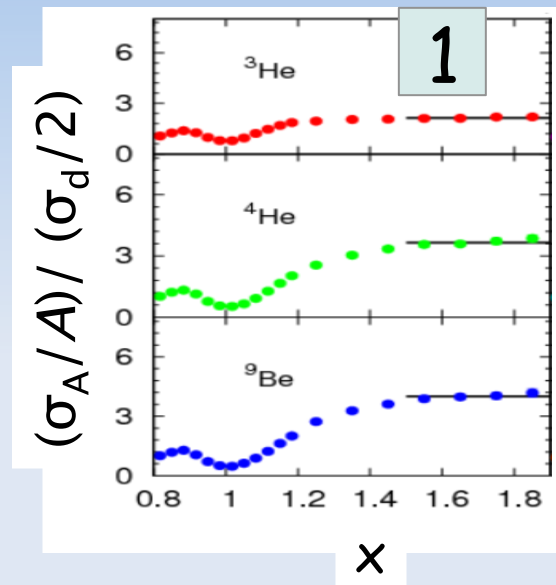
1 The probability for a nucleon to have p≥300 MeV/c in medium nuclei is 20-25%

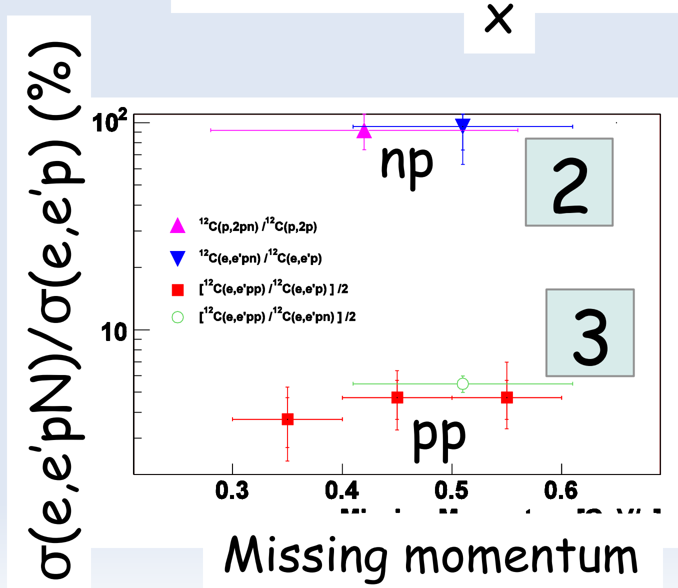
2 More than ~90% of these nucleons belong to 2N-SRC.

- 2N-SRC dominated by np pairs

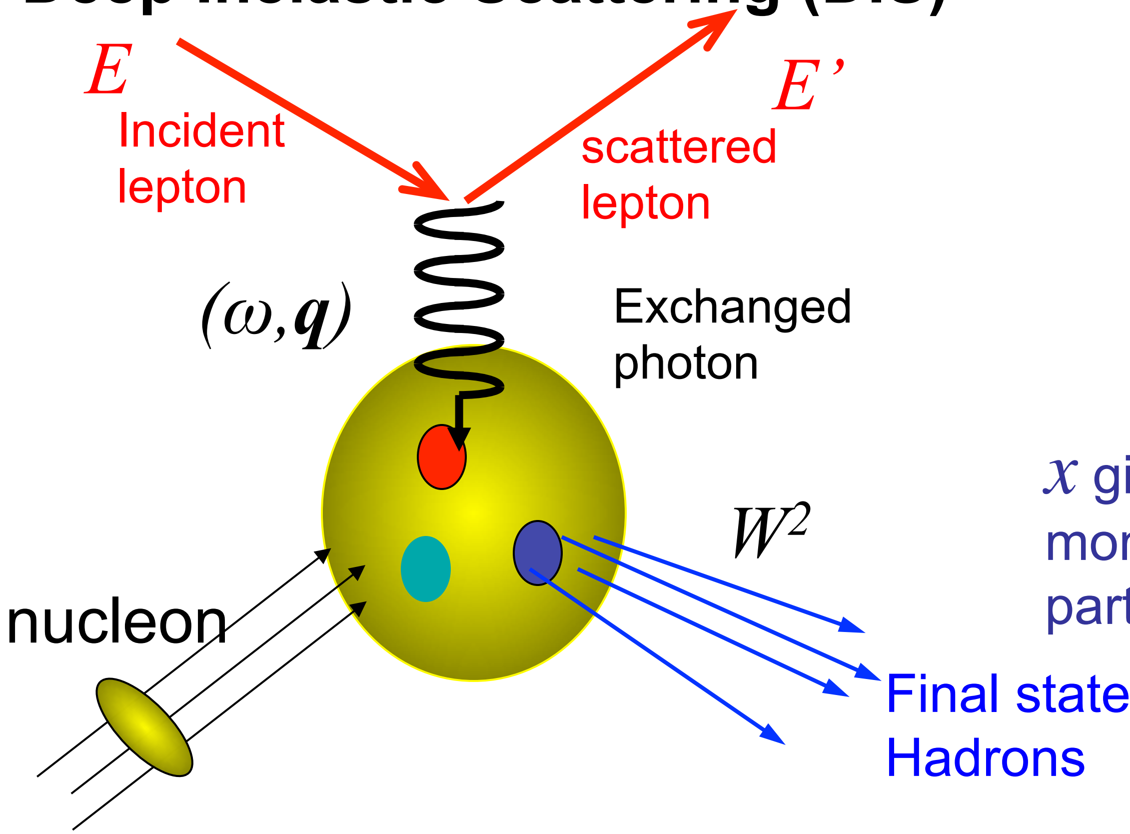
3 → **Tensor interaction**

1
2 ⇒ ~80% of kinetic energy of nucleon in nuclei is carried by nucleons in 2N-SRC.





Deep Inelastic Scattering (DIS)



$$Q^2 = -q_\mu q^\mu = q^2 - \omega^2$$

$$\omega = E' - E$$

$$x = \frac{Q^2}{2m\omega}$$

x gives the fraction of nucleon momentum carried by the struck parton

$$\frac{d^2\sigma}{dx\,dQ^2} = \frac{4\pi\alpha^2 (E')^2}{xQ^4}\frac{E'}{E}\left(F_2\cos^2\frac{\theta}{2} + 2\frac{\nu}{M}F_1\sin^2\frac{\theta}{2}\right)$$

Electrons, muons, neutrinos

E, E' : 5-500 GeV

Q^2: 5-50 GeV^2

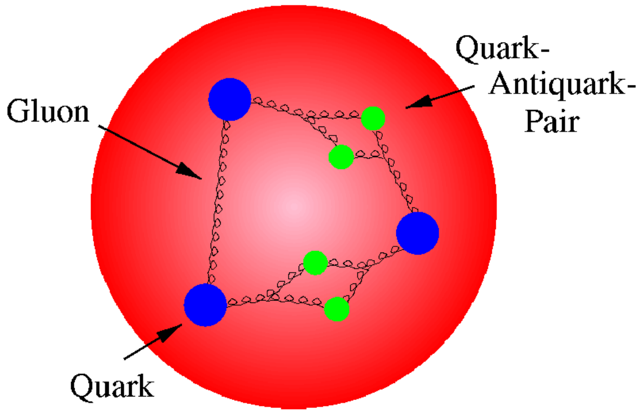
W^2 > 4 GeV^2

$0 \leq x \leq 1$

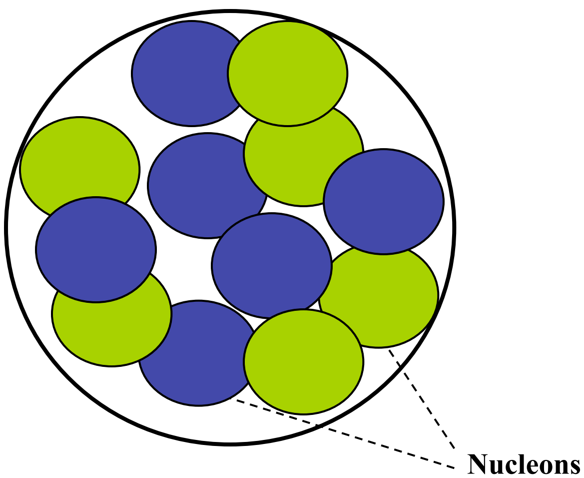
Information about the nucleon vertex is contained in $F_1(x,Q^2)$ and $F_2(x,Q^2)$, the unpolarized structure functions

W: invariant mass of final state

DIS and Nuclear Energy Scales



DIS Scale: tens of **GeV**
- incident energies
- energy transfers
- invariant masses



Nuclear scale: less than 10 MeV
- nucleon binding energy

Naive expectation :

DIS off a bound nucleon = DIS off a free nucleon

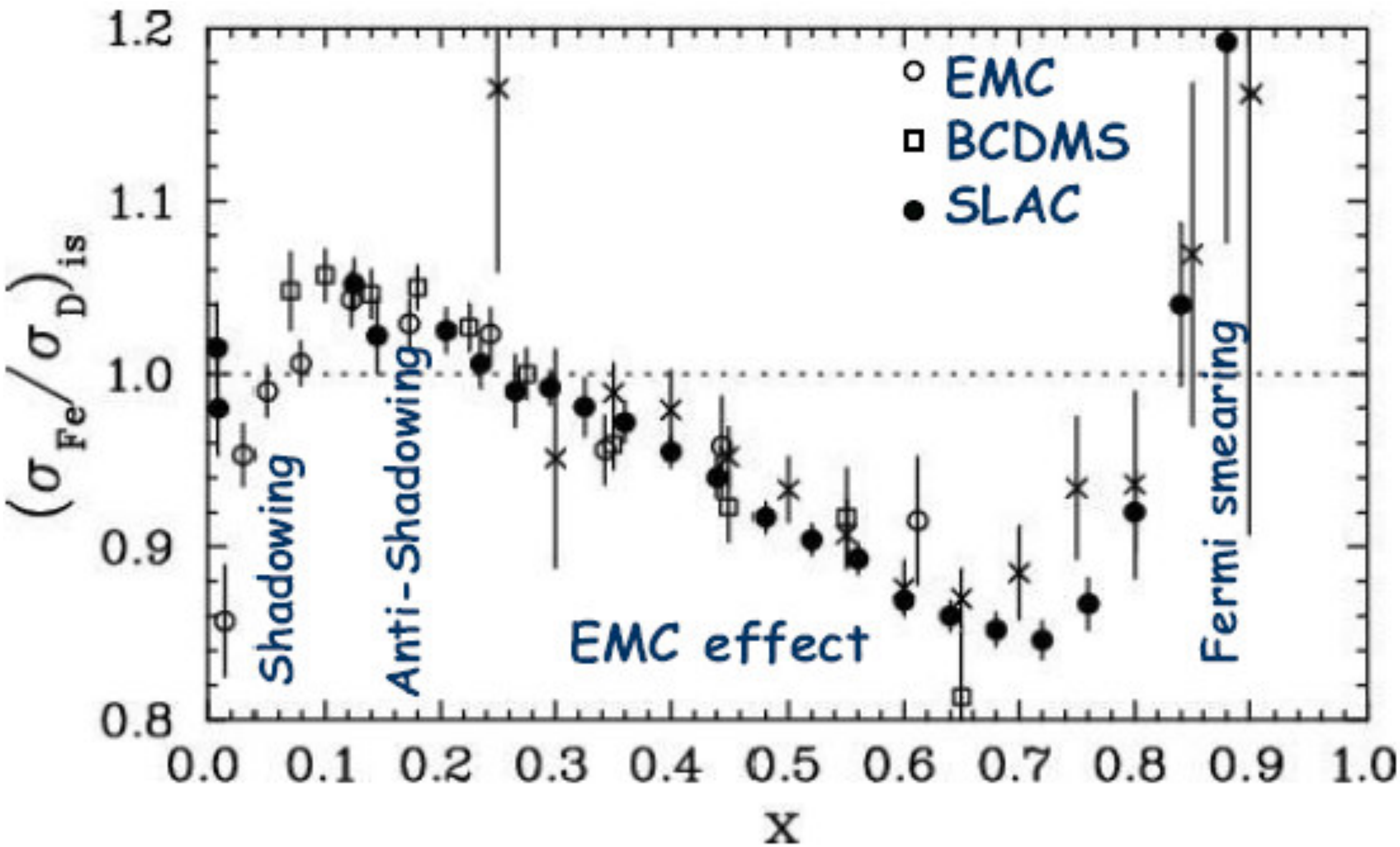
(Except some small Fermi motion correction)

MeV vs GeV

xkcd.com

The European Muon Collaboration (EMC) effect

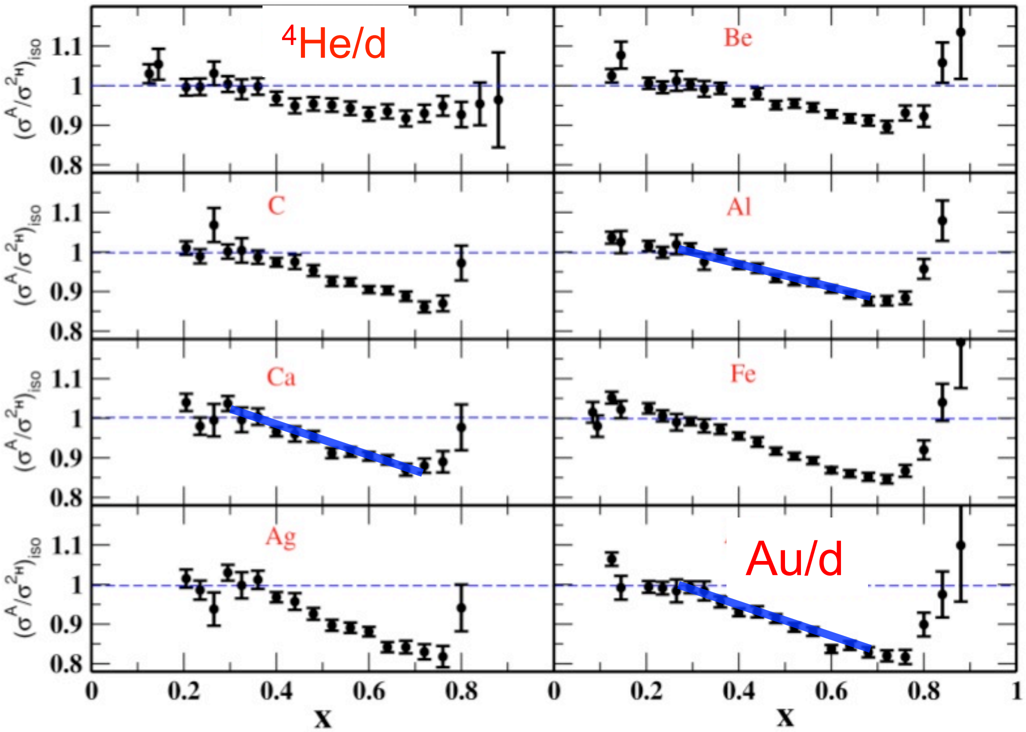
Ratio of Iron to deuterium cross section



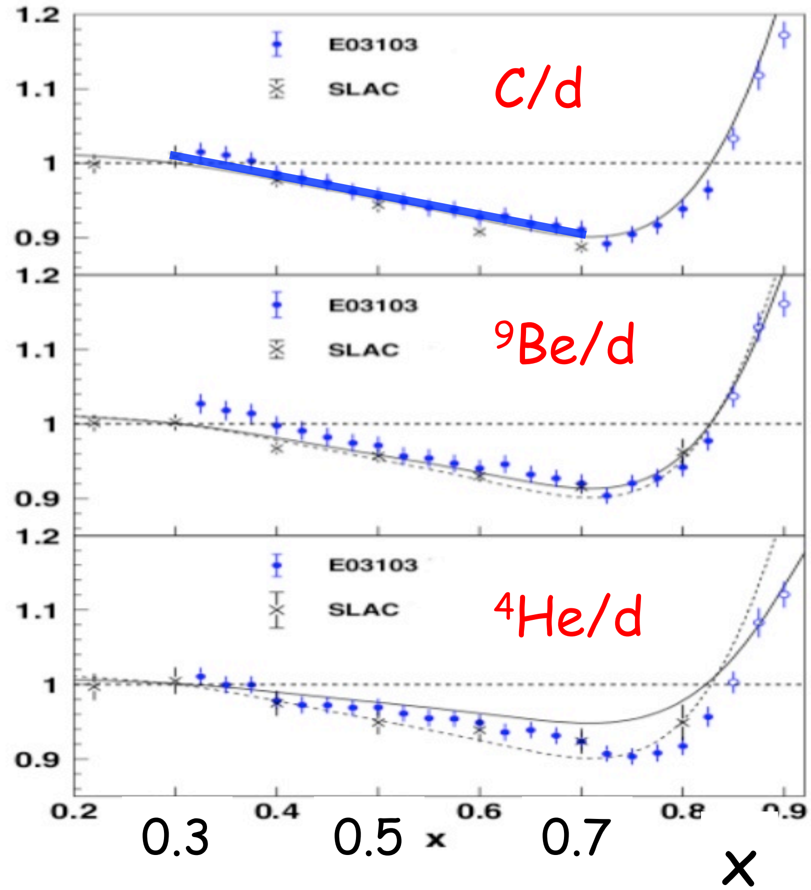
DIS cross section per nucleon in nuclei ≠ DIS off a free nucleon

EMC Data: nuclear DIS ≠ nucleon DIS

$$\frac{2}{A} \cdot \frac{\sigma^A}{\sigma^d}$$



J. Gomez, PRD **49**, 4348 (1994).



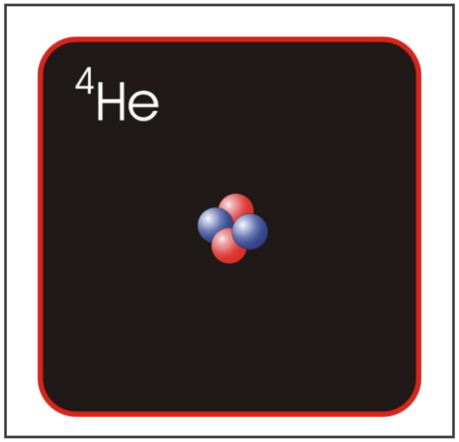
J. Seely, PRL 103, 202301 (2009)

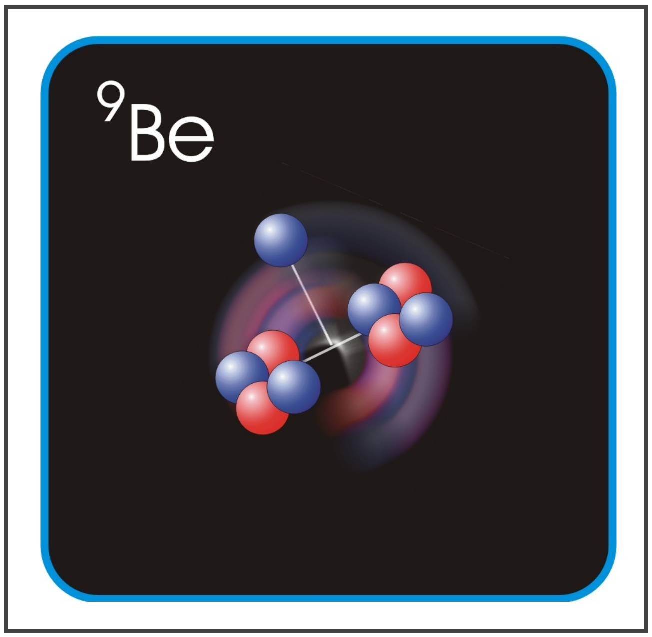
Very linear for 0.3 < x < 0.7

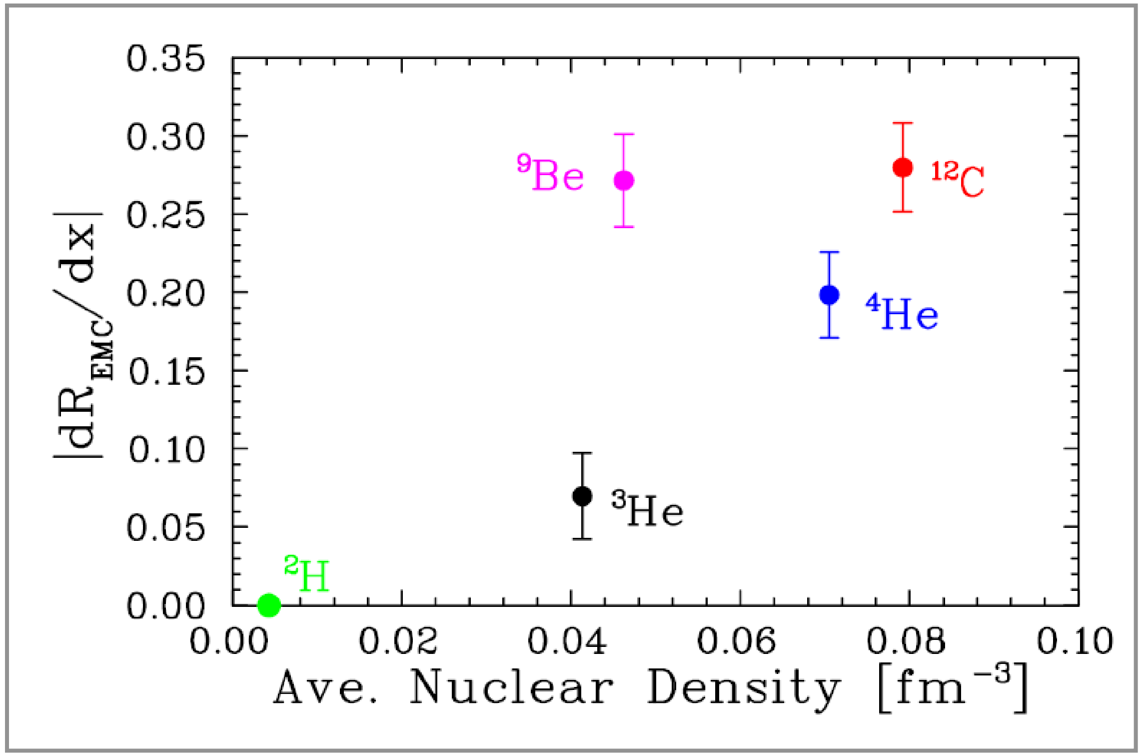
(the lines shown are not fits)

Characterize the EMC strength by its slope

EMC Effect does not scale with average density







EMC effect appears to follow "local" density

- connection to correlations?

Theory and the EMC Effect

IA = Impulse Approximation model:

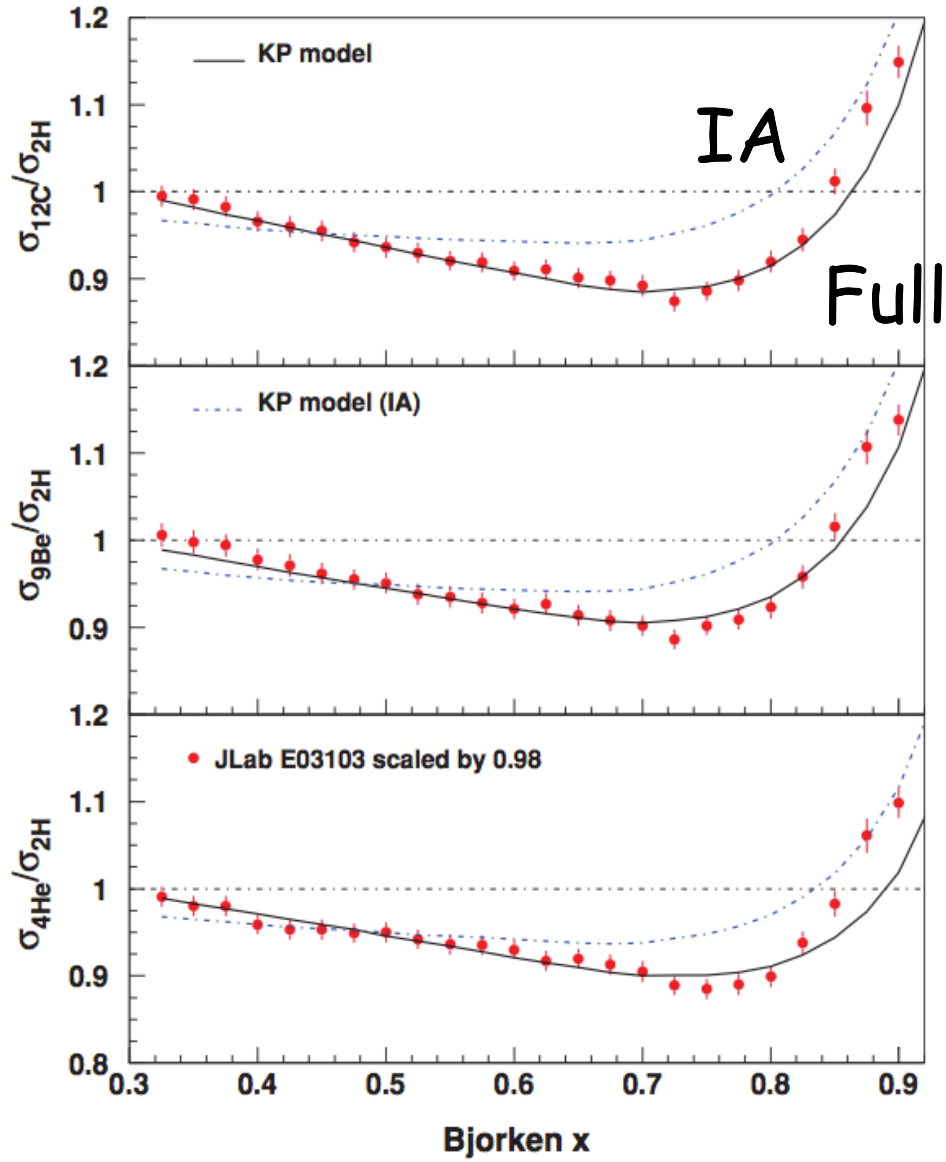
- incoherent scattering from bound nucleons
- includes nuclear binding and Fermi motion

Full:

- also includes pions in nuclei, coherent effects and
- Modification of bound nucleon structure
  - Proportional to p^2

Nucleon modification needed!

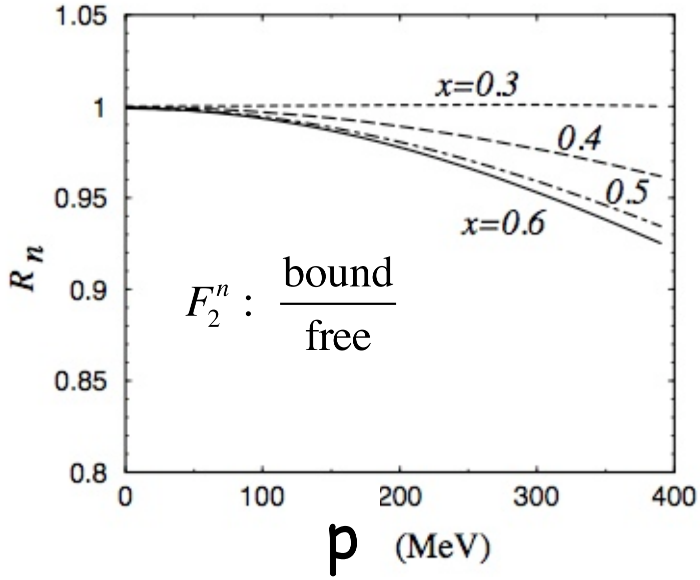
Kulagin and Petti, PRC **82** (2010) 054614



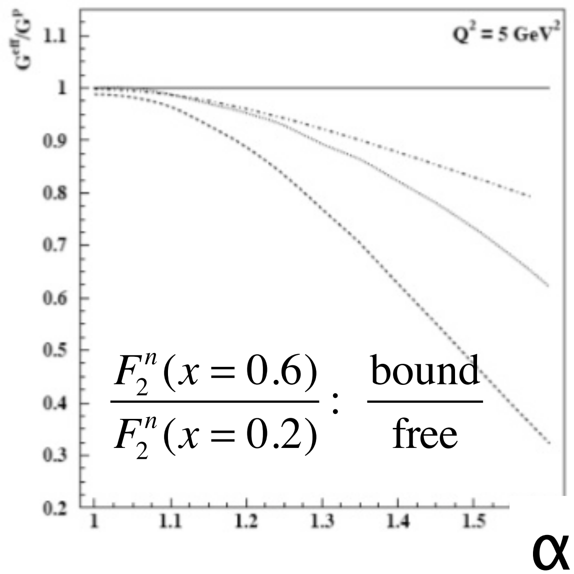
EMC Models ($0.3 < x_B < 0.7$)

- No generally accepted model
- Models need to include
  - Fermi motion
  - Binding energy
  - Some form of nucleon off-shell behavior (modification)

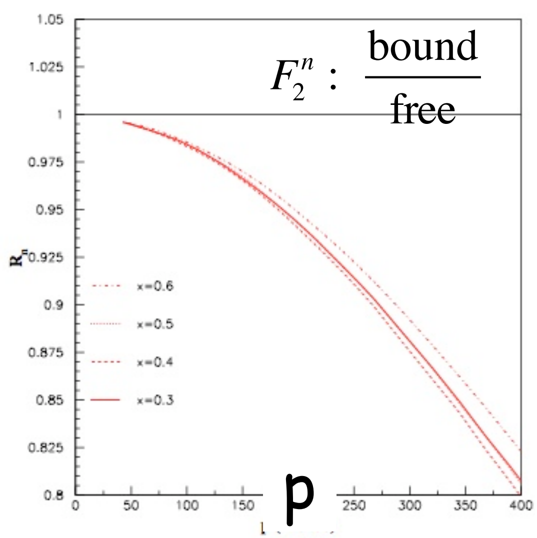
Lots of Nucleon Modification Models



Melnitchouk, Schreiber and Thomas, PLB335, 11 (1994)



Melnitchouk, Sargsian and Strikman, Z. Phys **A359** 99



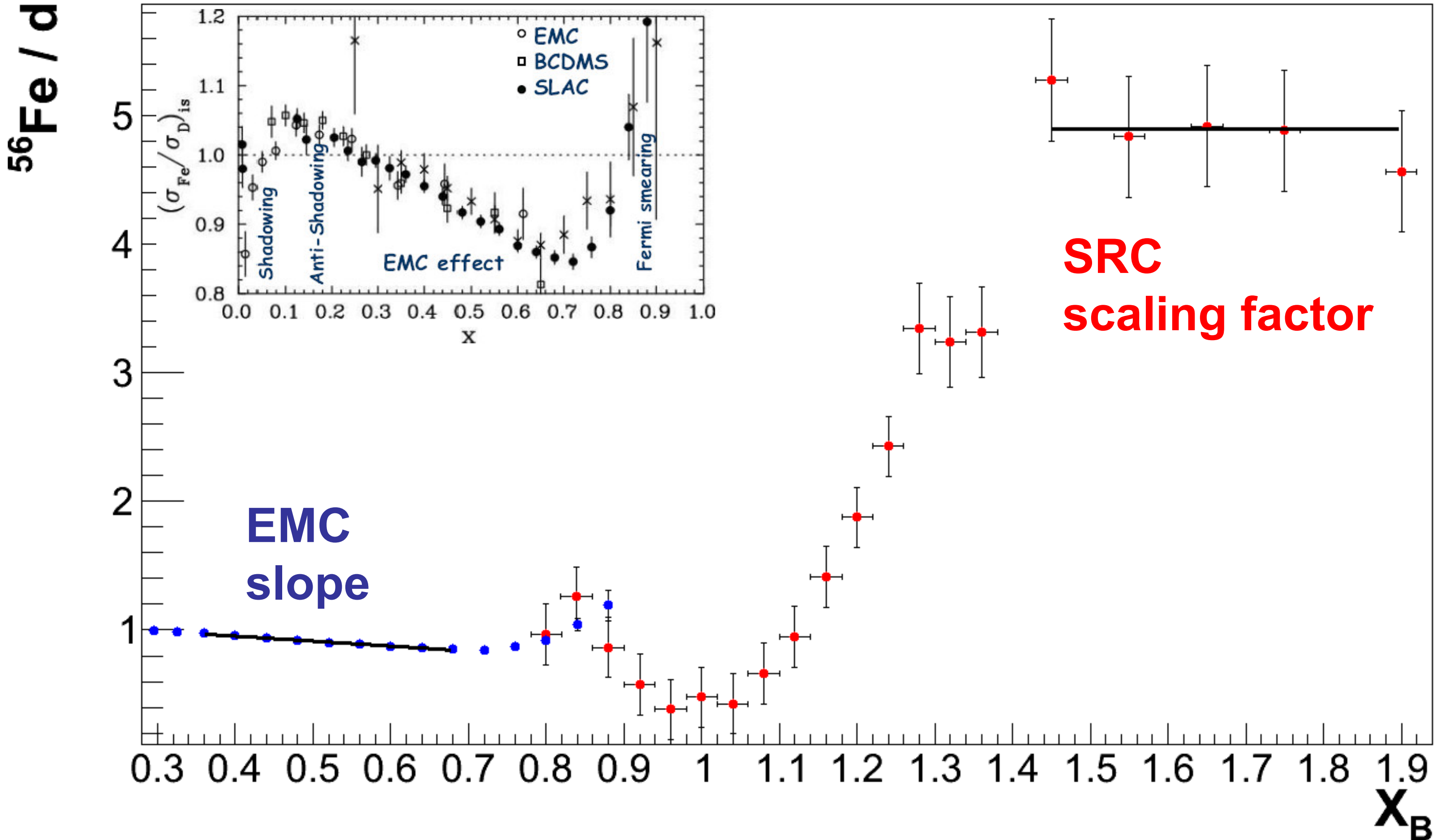
Liuti and Gross, PLB 356, 157 (1995).

Modifications increase with

- initial momentum
- nucleon virtuality
- nucleon offshell-ness

(same concept, different words)

EMC Effect and Correlations

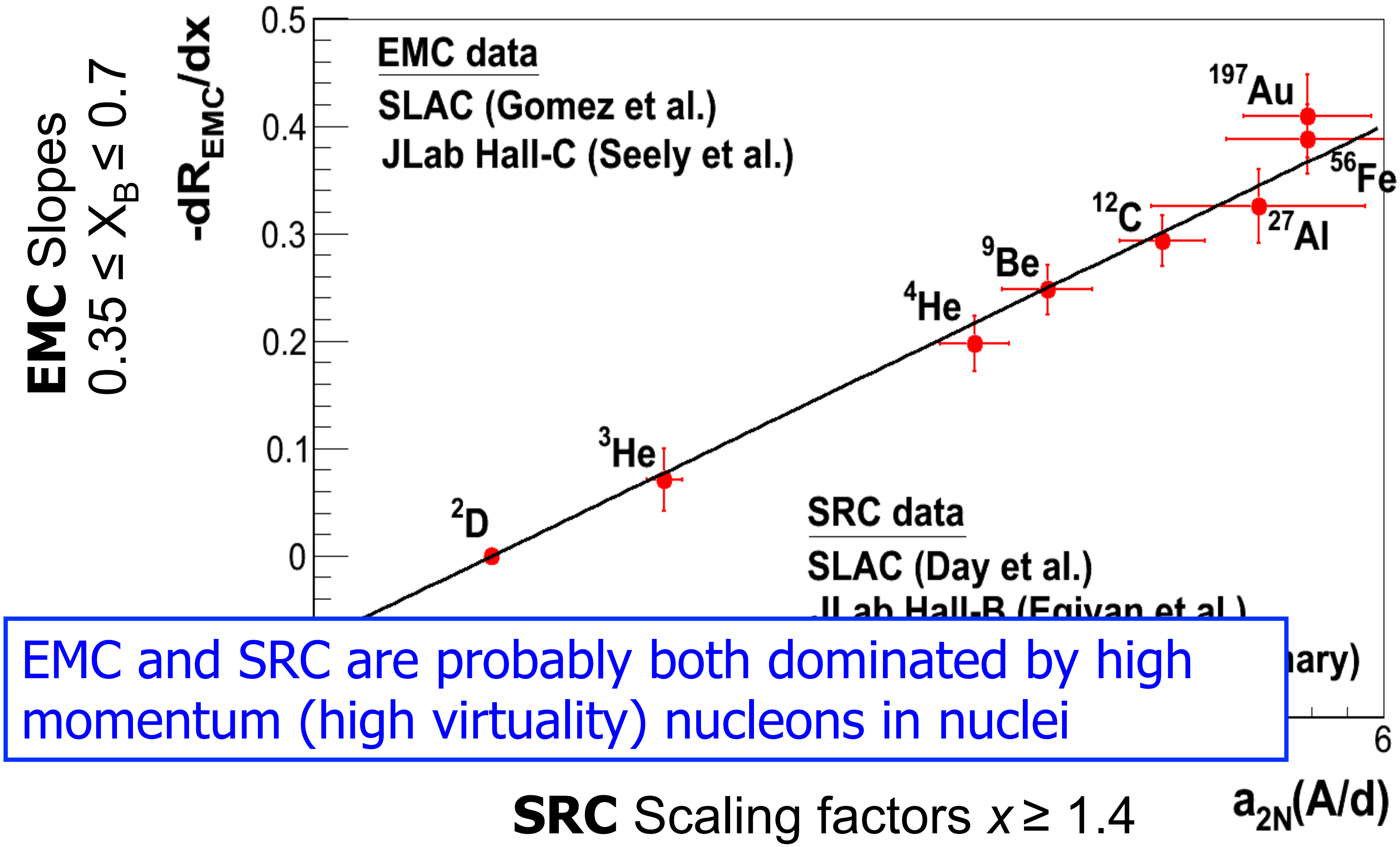


Is there a connection?

Frankfurt, Strikman, Day, Sargsyan, Phys. Rev. C48 (1993) 2451. Q^2 = 2.3 GeV^2

Gomez et al., Phys. Rev. D49, 4348 (1983). Q^2 = 2, 5, and 10 GeV^2 (avg)

EMC Effect and Correlations



EMC and SRC are probably both dominated by high momentum (high virtuality) nucleons in nuclei

SRC Scaling factors $x \geq 1.4$

Weinstein et al, PRL**106** 052301 (2011)

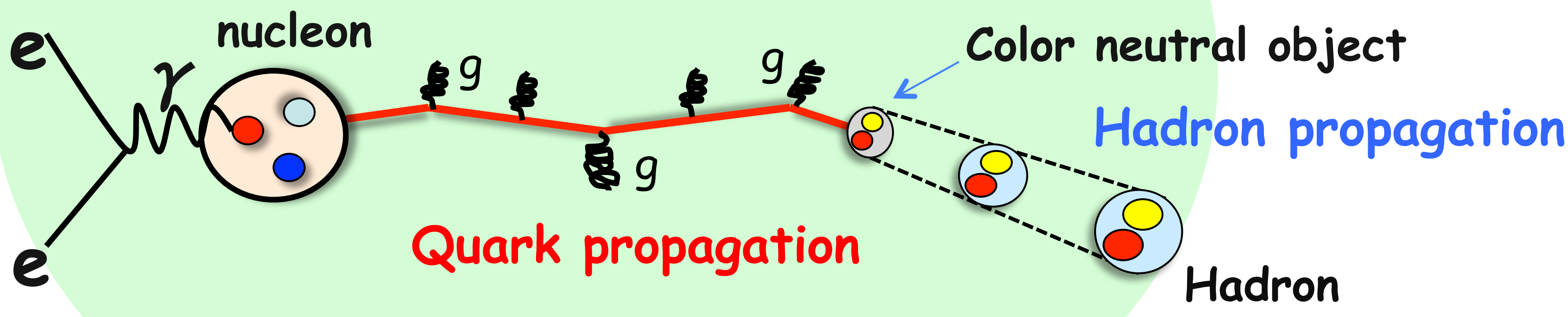
How do quarks traverse the nucleus?

1) Knock a quark out of a nucleon via deep inelastic scattering
2) ~~Detect the knocked-out quarks~~

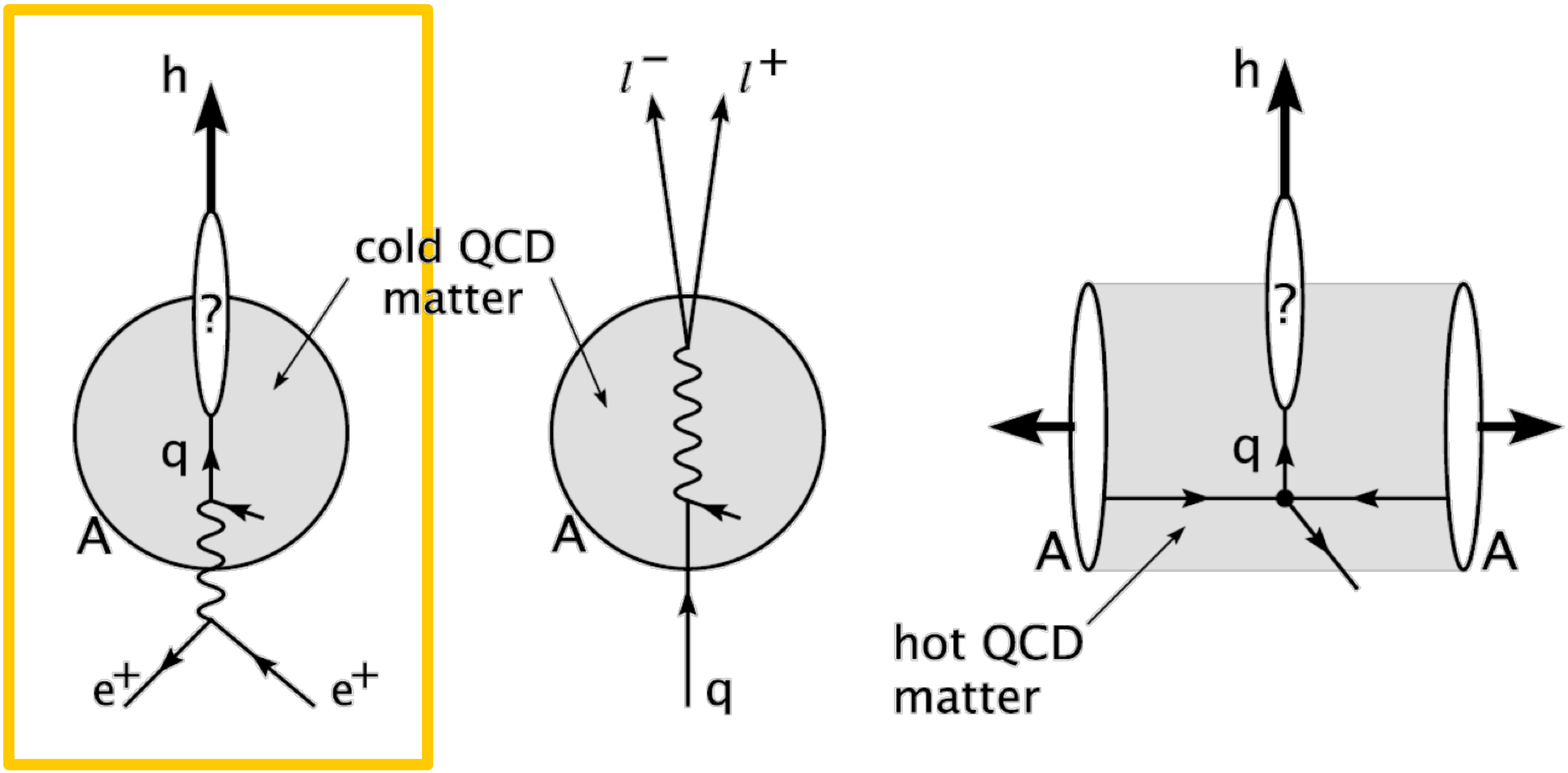
2) Detect the knocked-out hadrons
3) Figure out what happened

Big Picture

How do nuclei of different sizes change this process?



- What is the interaction of the struck quark before it neutralizes its color?
- How long does it take to form the color field of a hadron?
- What is the interaction of color neutral object while it evolves to a fully formed hadron?



DIS Electron scattering

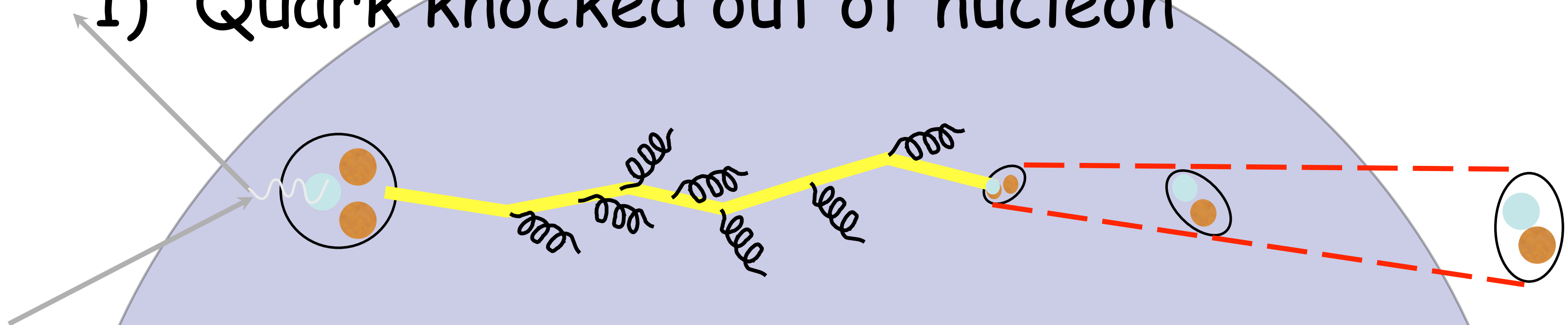
Drell-Yan (pp collisions)

Heavy Ion Collsions

Quark propagation in nuclear targets

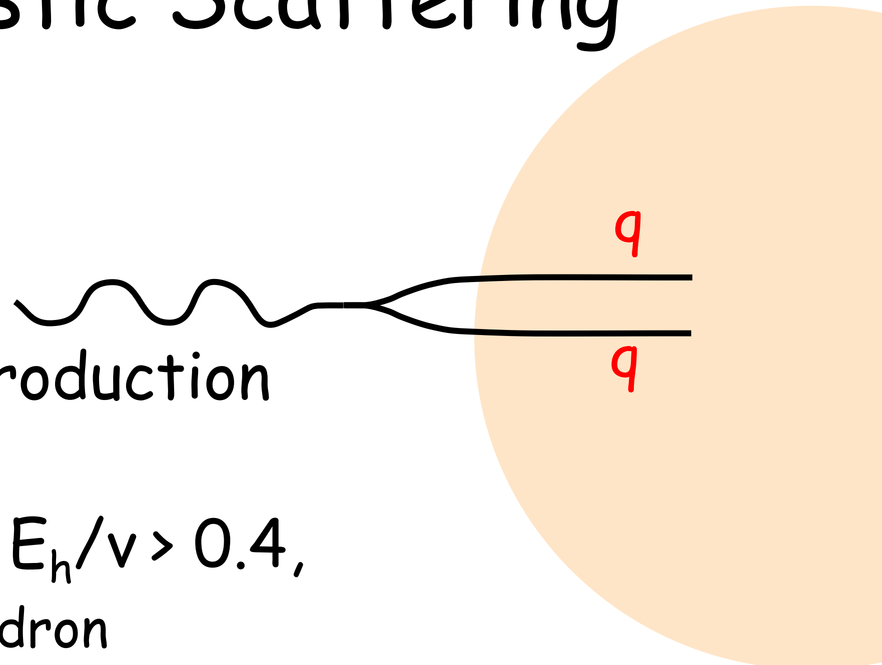
Deep Inelastic Scattering: In Nuclei

1) Quark knocked out of nucleon



2) Parton (quark) propagation phase
    1) Radiates gluons
    2) Loses energy
    3) Multiple scatters
3) Hadron formation phase
    1) Small pre-hadron (qqbar) system forms
    2) Expands to full size
    3) Interacts with medium

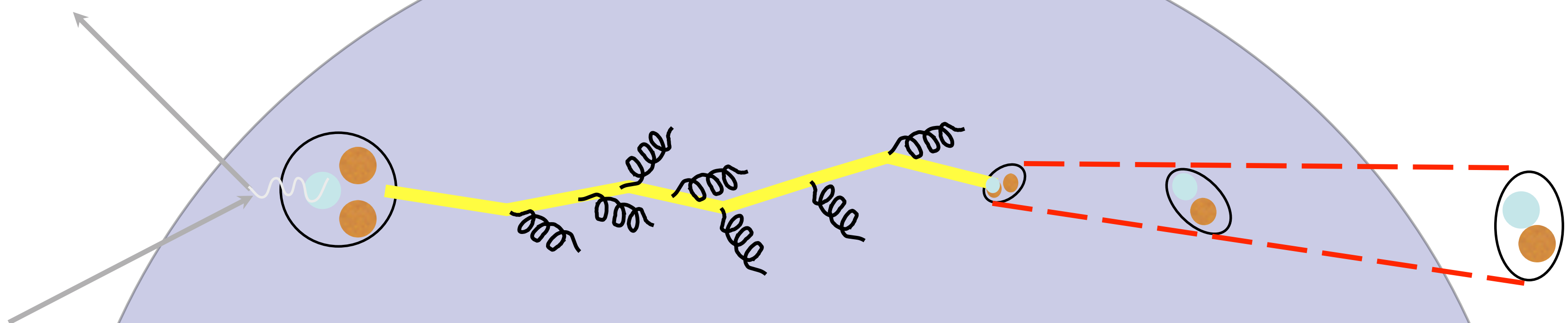
Select Deep Inelastic Scattering



- $Q^2 > 1\ GeV^2$
- $W > 2$ GeV (Deep Inelastic)
- $x > 0.1$ to avoid quark pair production
  - Far from real photon point
- Hadron energy fraction $z = E_h/\nu > 0.4$,
  - struck quark most likely in hadron

How to figure out what happened

Identify *parton propagation* phase by transverse momentum (p_T) broadening



Identify *hadron formation* phase by hadron attenuation

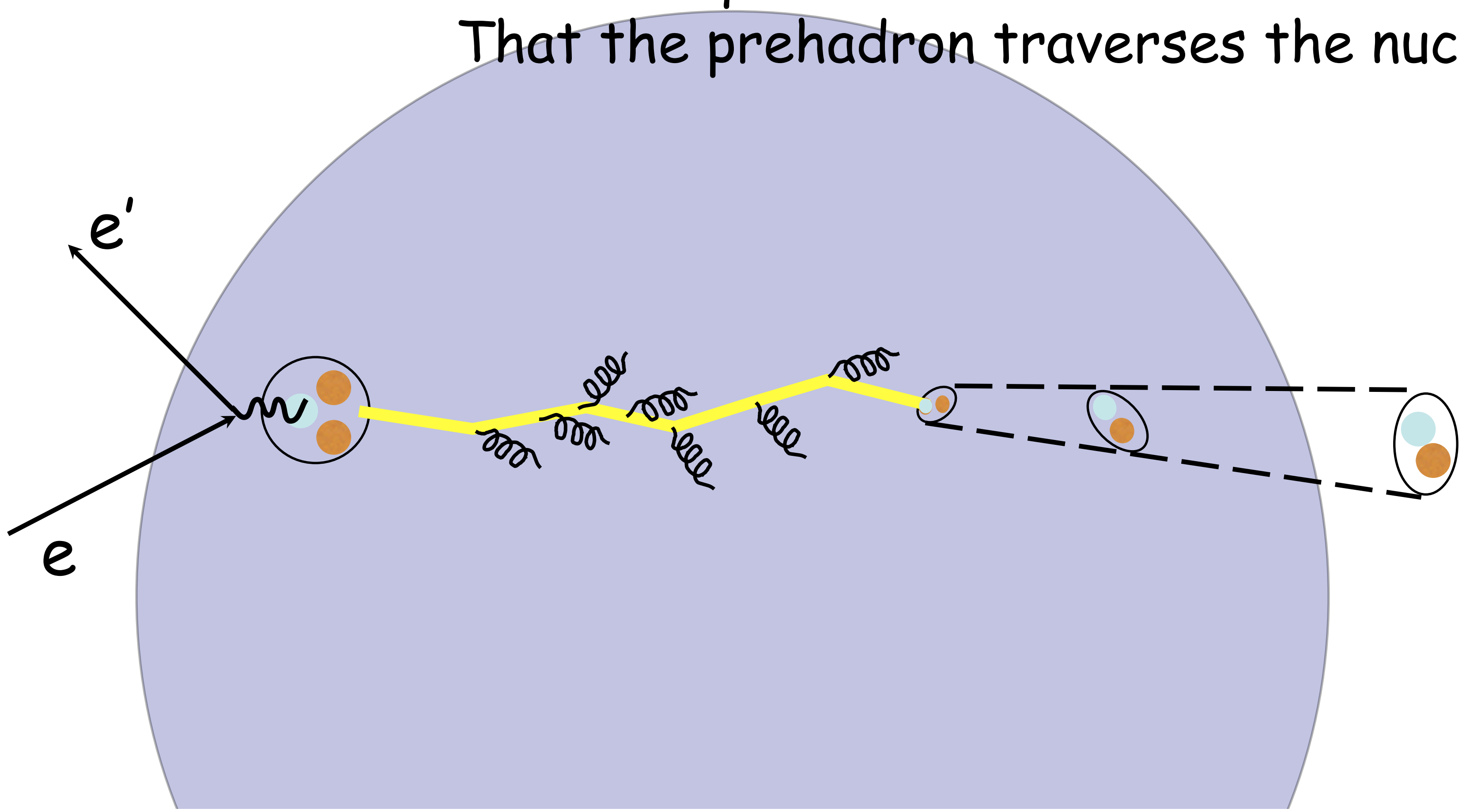
Vary the nuclear sizes and momenta to extract QCD characteristic times and reaction mechanisms

Apply: e.g., improve understanding of hot dense matter

Vary the nuclear size:

Vary the distances

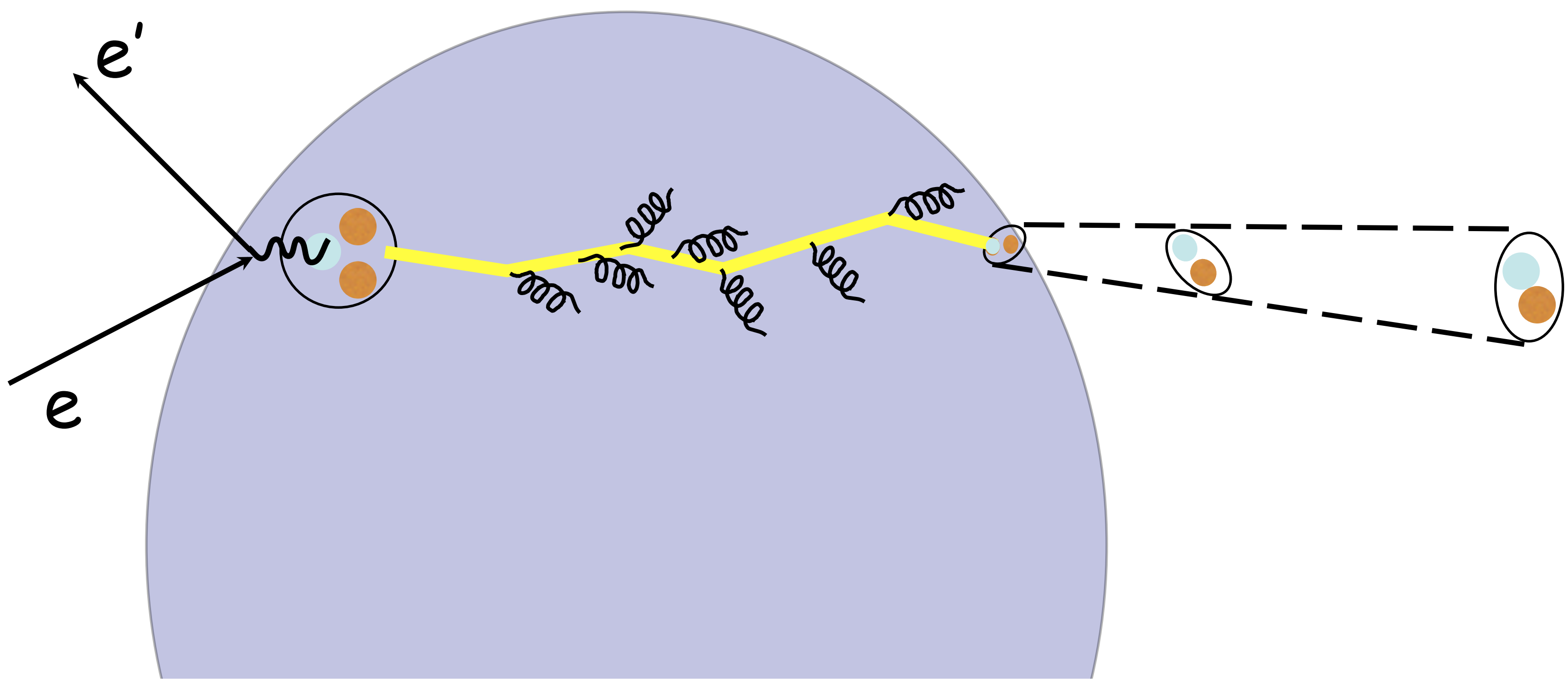
- That the quark traverses the nucleus
- That the prehadron traverses the nucleus



Vary the nuclear size:

Vary the distances

- That the quark traverses the nucleus
- That the prehadron traverses the nucleus

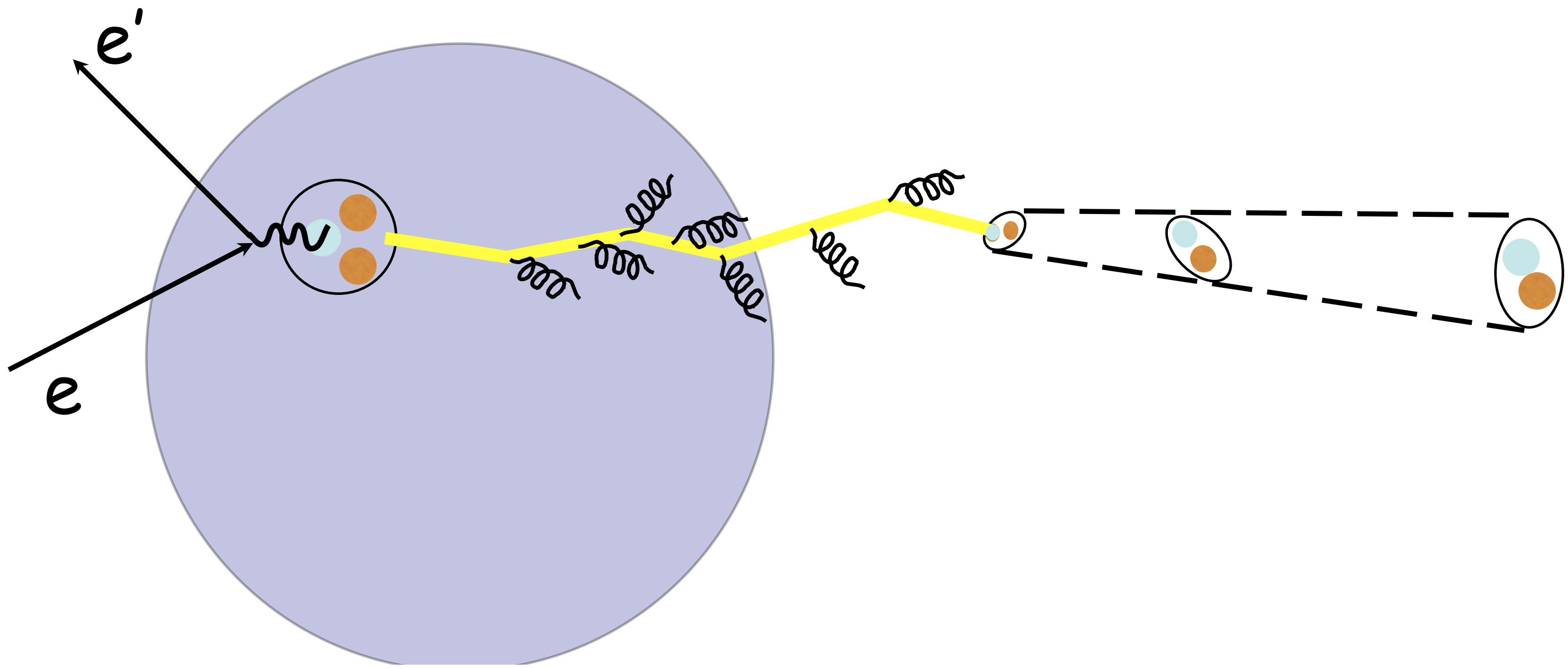


Vary the nuclear size:

Vary the distances

That the quark traverses the nucleus

That the prehadron traverses the nucleus



A(e,e'h) Variables and Observables

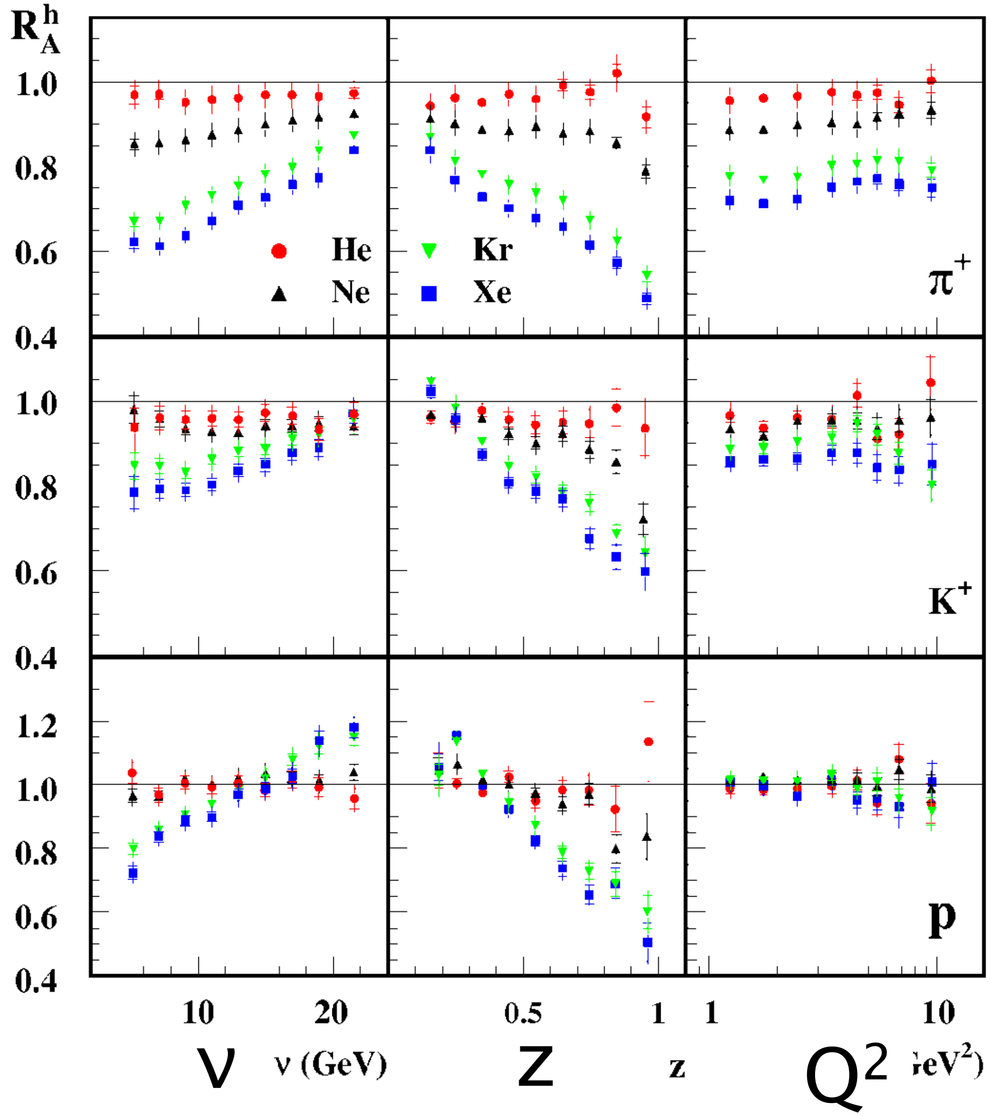
- Measure DIS hadron production on nucleus *A* compared to deuterium
- Four variables:
  - Momentum transfer $Q^2 > 1$ GeV^2
  - Energy transfer ν or $x = Q^2/2m\nu$
  - Hadron energy fraction $z = E_h/\nu$
  - Hadron transverse momentum (relative to q): p_T
- Two observables:
  - Multiplicity ratio $$R_A^h(Q^2,x,z,p_T) = \frac{N_A^h(Q^2,x,z,p_T)}{N_d^h(Q^2,x,z,p_T)} \frac{N_d^e(Q^2,x)}{N_A^e(Q^2,x)}$$
  - Transverse momentum broadening

$$\Delta p_T^2 = \ <p_T^2>_A - <p_T^2>_d$$

Hermes multiplicity ratios

Multiplicity
- decreases with
  - Hadron energy fraction z
  - Nuclear mass
- increases with
  - Energy transfer ν
- Independent of Q^2

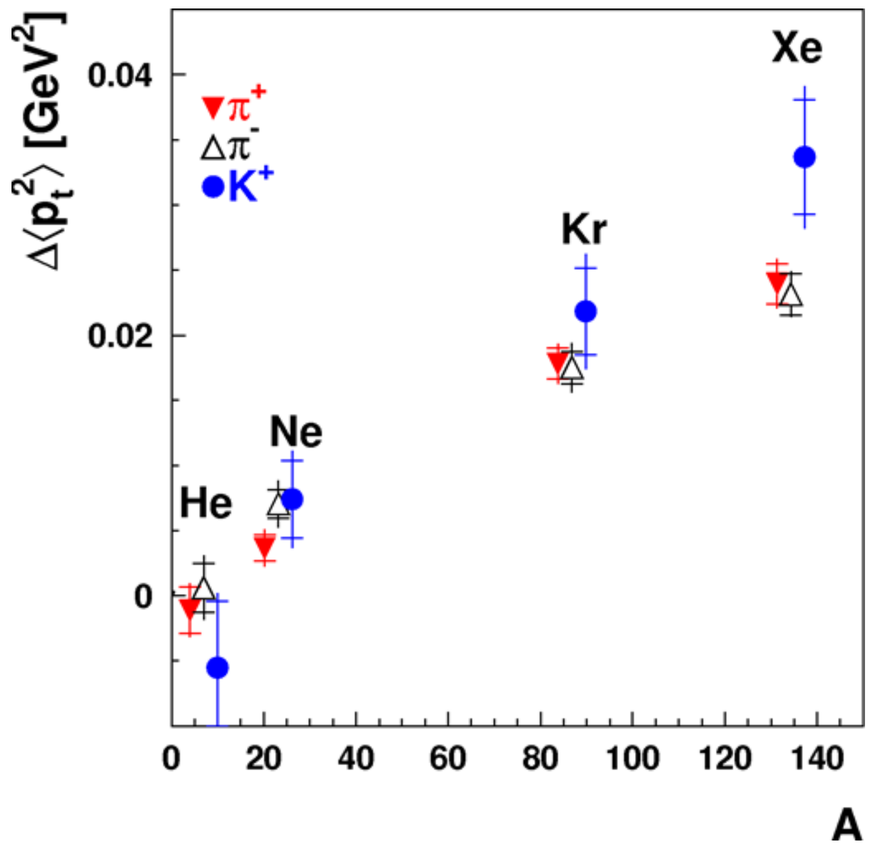
$$R_A^h(Q^2,x,z,p_T) = \frac{N_A^h(Q^2,x,z,p_T)}{N_d^h(Q^2,x,z,p_T)} \frac{N_d^e(Q^2,x)}{N_A^e(Q^2,x)}$$



Airapetian et al., Nucl. Phys. B780 (2007)

HERMES: p_T Broadening

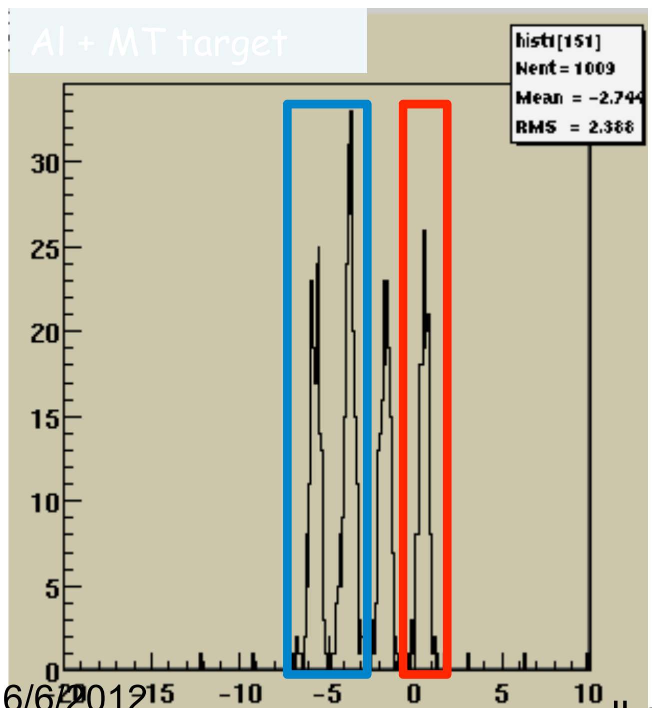
Airapetian et al., Phys.Lett. B684 (2010)



- Broadening increases with A.
  - Can't determine the functional form.
- No broadening when z=1 (not shown)
  - Therefore broadening due to quark, not prehadron

CLAS EG2 Run

- Electron Beam 5 GeV (50 days) & 4 GeV (7days)
- Targets: ^{2}H&Fe, ^{2}H&C, ^{2}H&Pb
- Luminosity ~ $2x10^{34}$ $cm^{-2}s^{-1}$

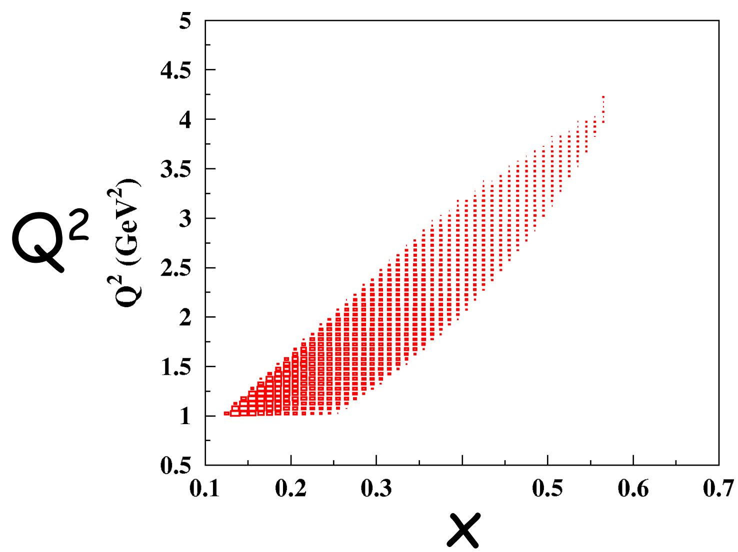


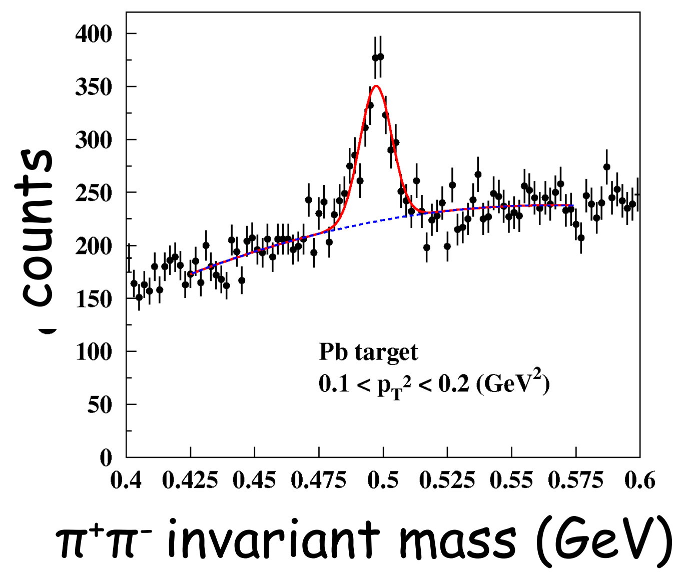
Hakobyan et al, NIM A592 (2008)

CLAS Hadronization

- $Q^2 > 1$ GeV^2, $W > 2$ GeV
  - to select DIS
- $y = \nu/E < 0.85$
  - to avoid regions with large Rad. Corrections.
- Detect $(e,e'\pi^+\pi^-)$ events.
  - Reconstruct K_S^0 from the $\pi^+\pi^-$
  - Fit the peak and background
- Also look at other hadrons
  - $(e,e'\pi^+)$ and $(e,e'\pi^-)$
  - $(e,e'K^+)$ and $(e,e'K^-)$
- Model the reaction and the detector to account for missing acceptance

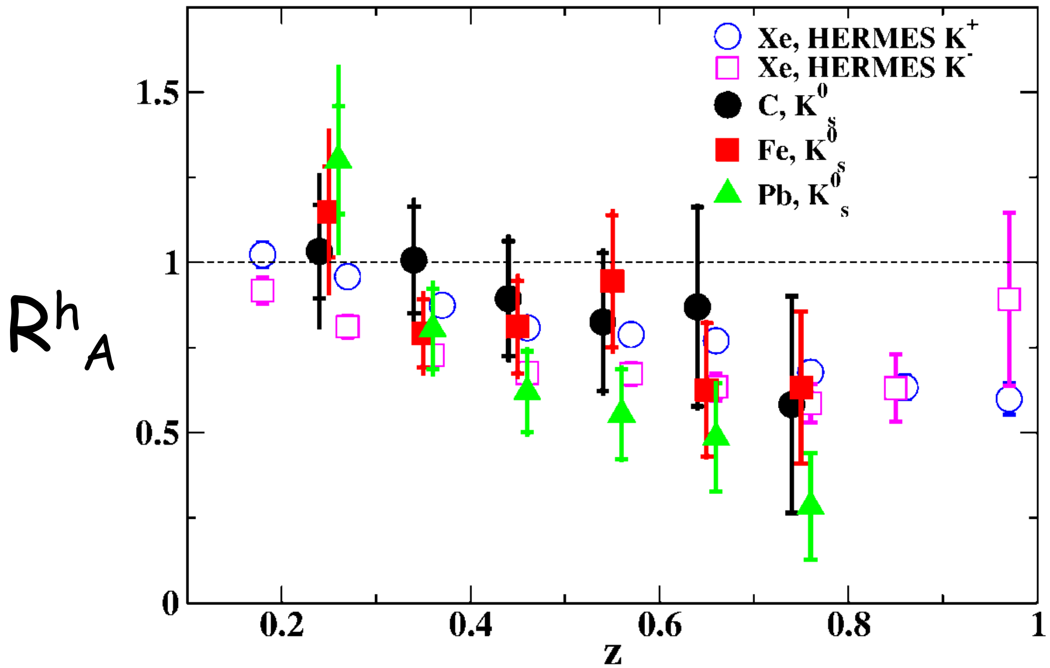
Daniel et al., **Phys.Lett. B706 (2011)**





CLAS K_S^0 Multiplicities

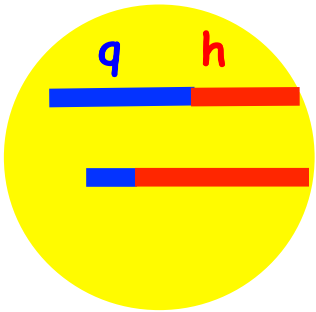
Daniel et al., **Phys.Lett. B706 (2011)**

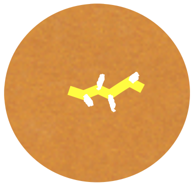


- Multiplicity ratio decreases with z and with target mass
- Good agreement with Hermes charged Kaon data

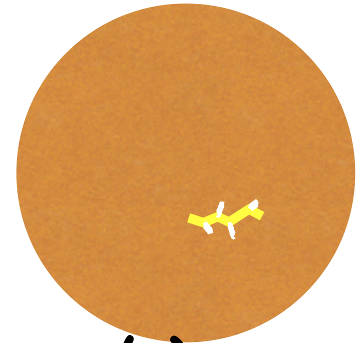
Geometrical model

- Three-parameter model:
  - scale factor (~proportional to transport coefficient)
  - production time (distributed exponentially)
  - effective absorption cross section
- Fourth parameter: quark dE/dx, also explored
- ***Simultaneous fit*** *of p_T broadening and multiplicity ratio in bins in Q^2, ν, and z*
- Realistic nuclear densities
  - » Path begins at point with probability proportional to density
  - » Part of path is quark, part of path is (pre-)hadron

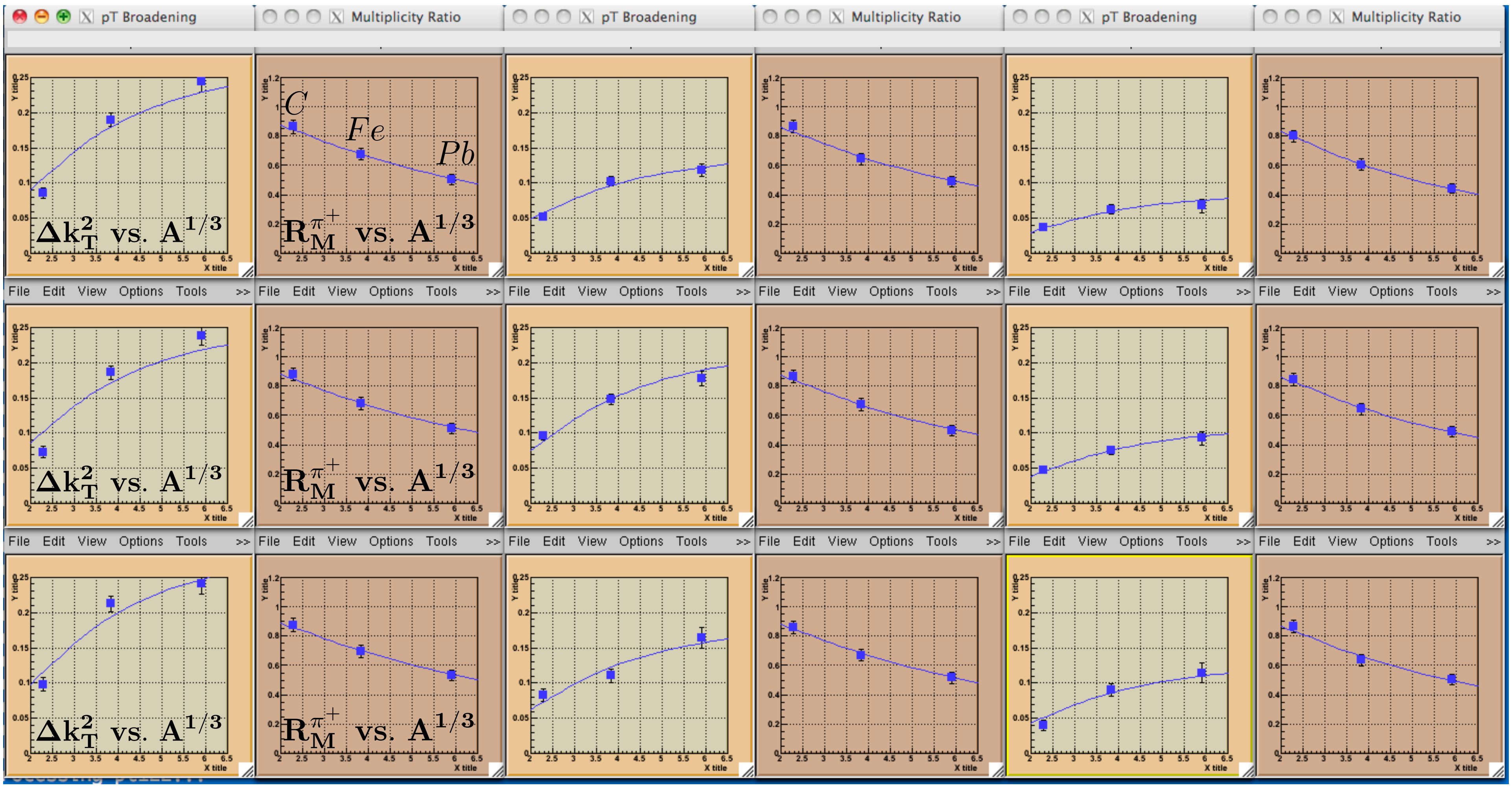




Results from combined fit to hadrons
3 or 4 parameter geometric model
various bins in Q^2, ν, and z



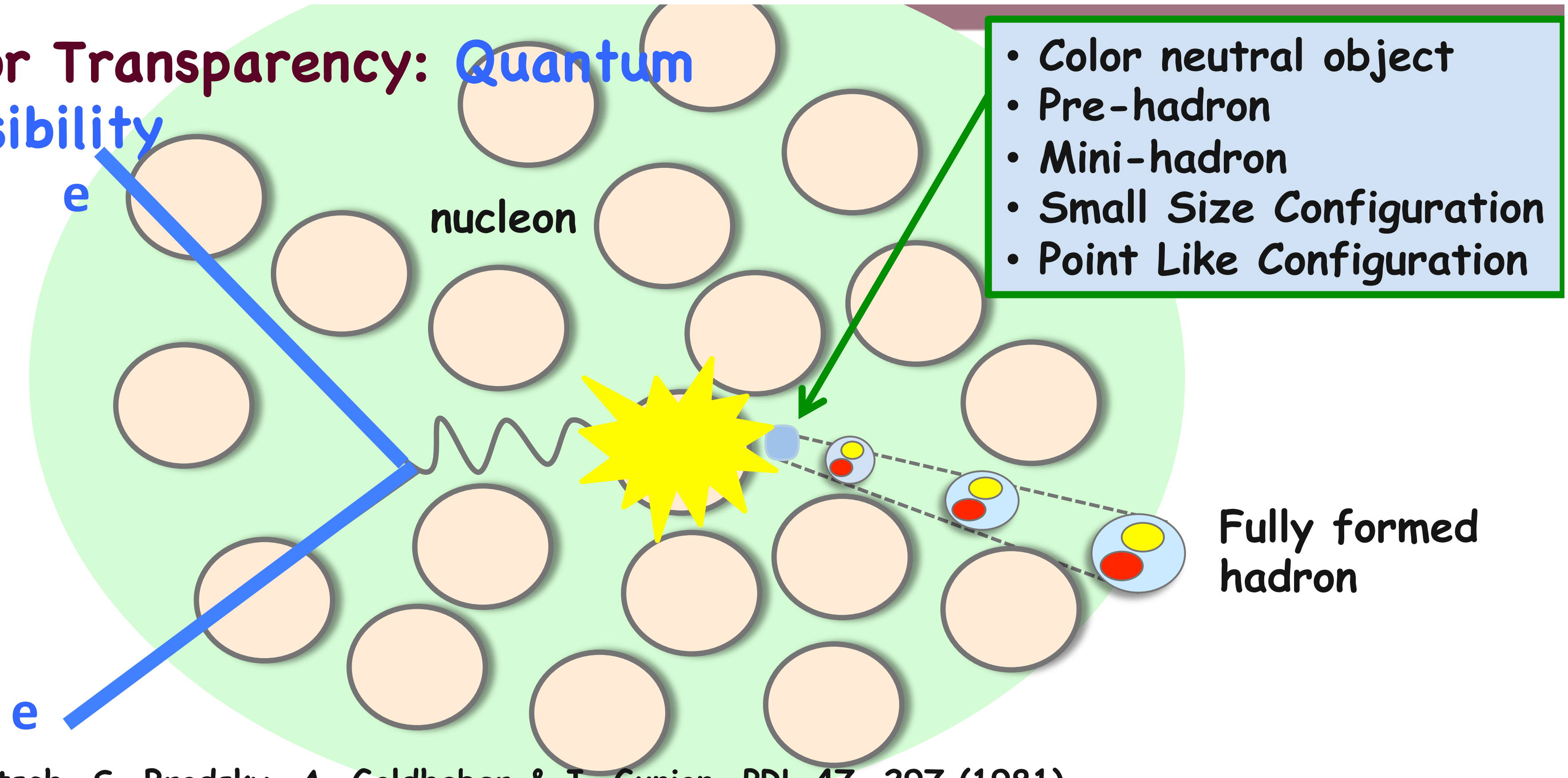
fits are consistent with **1.6 < τ_p < 2 fm/c** (<R_{carbon}/c)



Hadronization

- Collected lots of data and still analyzing it
- Hope to understand
  - Quark propagation lengths
  - Hadron propagation lengths
  - Quark multiple scattering and energy loss mechanisms
- Goal: To understand how a knocked out quark interacts with the nucleus as it evolves to become a colorless full-size hadron
- Lots more experiments to come at 12 GeV

Color Transparency: Quantum invisibility



G. Bertsch, S. Brodsky, A. Goldhaber & J. Gunion, PRL 47, 297 (1981)
A. Zamolodchikov, B. Kopeliovich and L. Lapidus, Pis'ma Zh.Teor. Fiz (1981);SPJETP Lett. (1981).
S. Brodsky & A. Mueller, Phys. Lett. B206, 685 (1988)

◆ QCD predicts the existence of small hadron-like configurations which will pass through nuclear matter with dramatically reduced interaction

◆ small size → small color dipole (or tripole) moment → reduced nuclear interaction

The 3 Pillars of Color Transparency "CT"

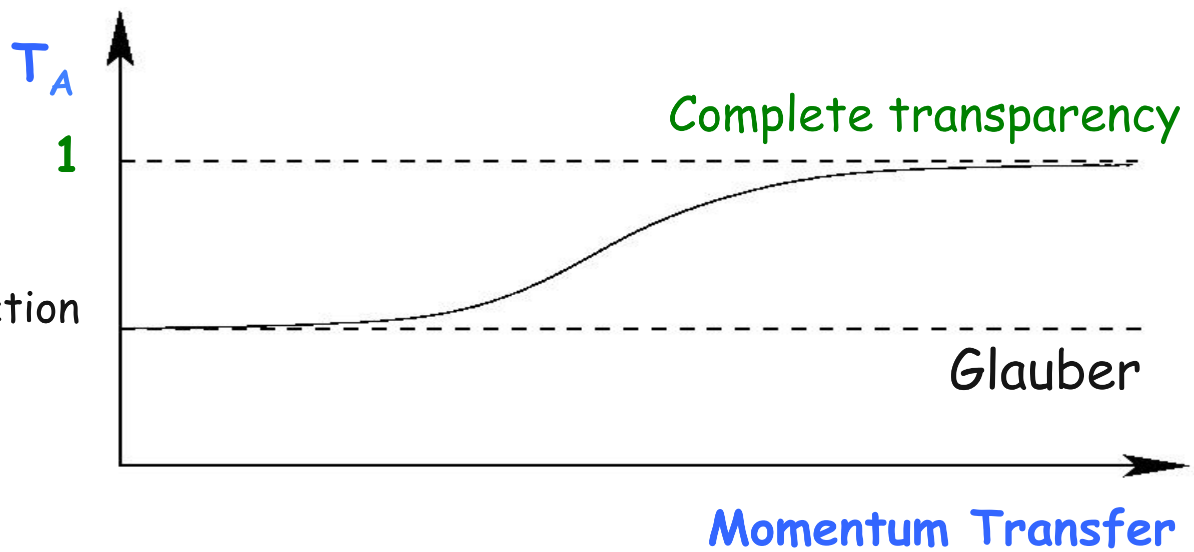
- ✓ Creation of Small Size Configurations (SSC)
- ✓ SSC experiences reduced interaction with the medium
- ✓ SSC does not expand fully until it leaves the nucleus

The signature of Color Transparency is the increase of the medium "nuclear" Transparency T_A as a function of the momentum transfer

$$T_A = \frac{\sigma_A}{A\sigma_N}$$

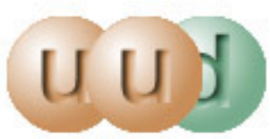
σ_N is the free (nucleon) cross section

σ_A is the nuclear cross section



Medium Energy search for Color Transparency

Baryons

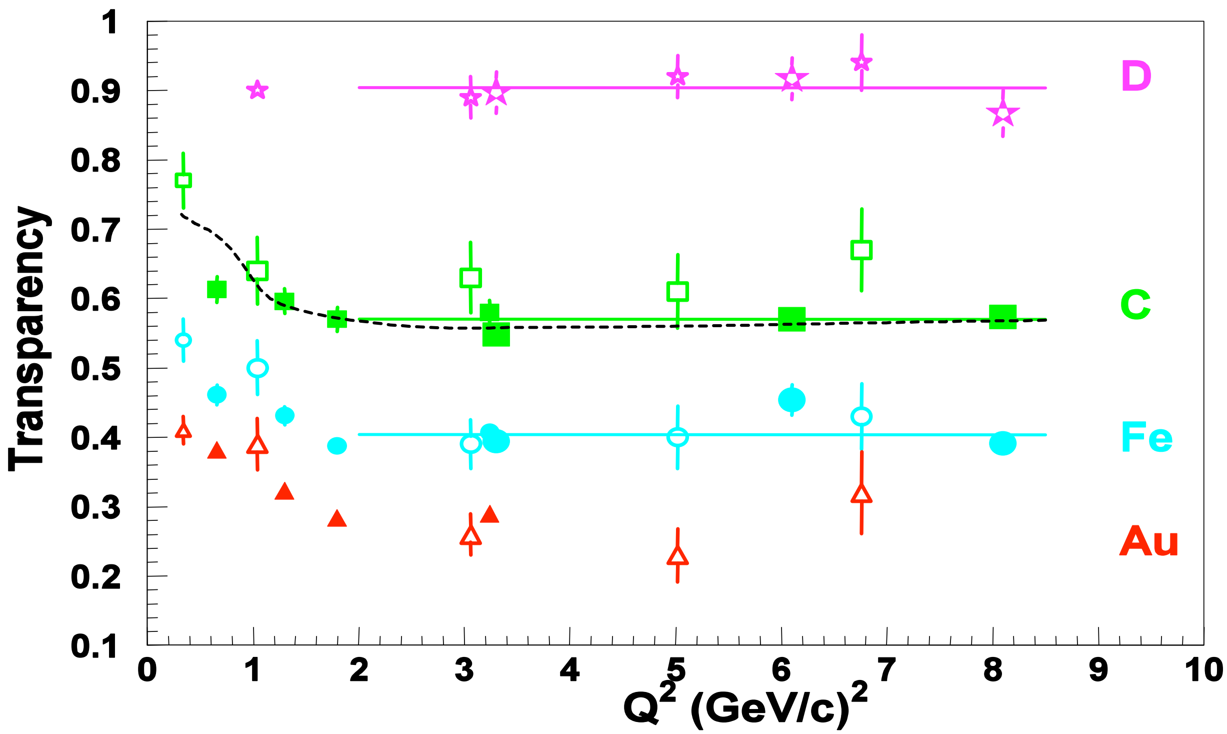


- ❑ A(p, 2p) BNL
- ❑ A(e, e′p) SLAC and JLab

Mesons

- ❑ A(γ, πp) JLab
- ❑ A(e, e′π) JLab
- ❑ A(e, e′ρ) Fermilab, DESY and JLab

Search for Color Transparency in A(e, e'p) reaction



N. C. R. Makins et al. PRL 72, 1986 (1994)
G. Garino et al. PRC 45, 780 (1992)

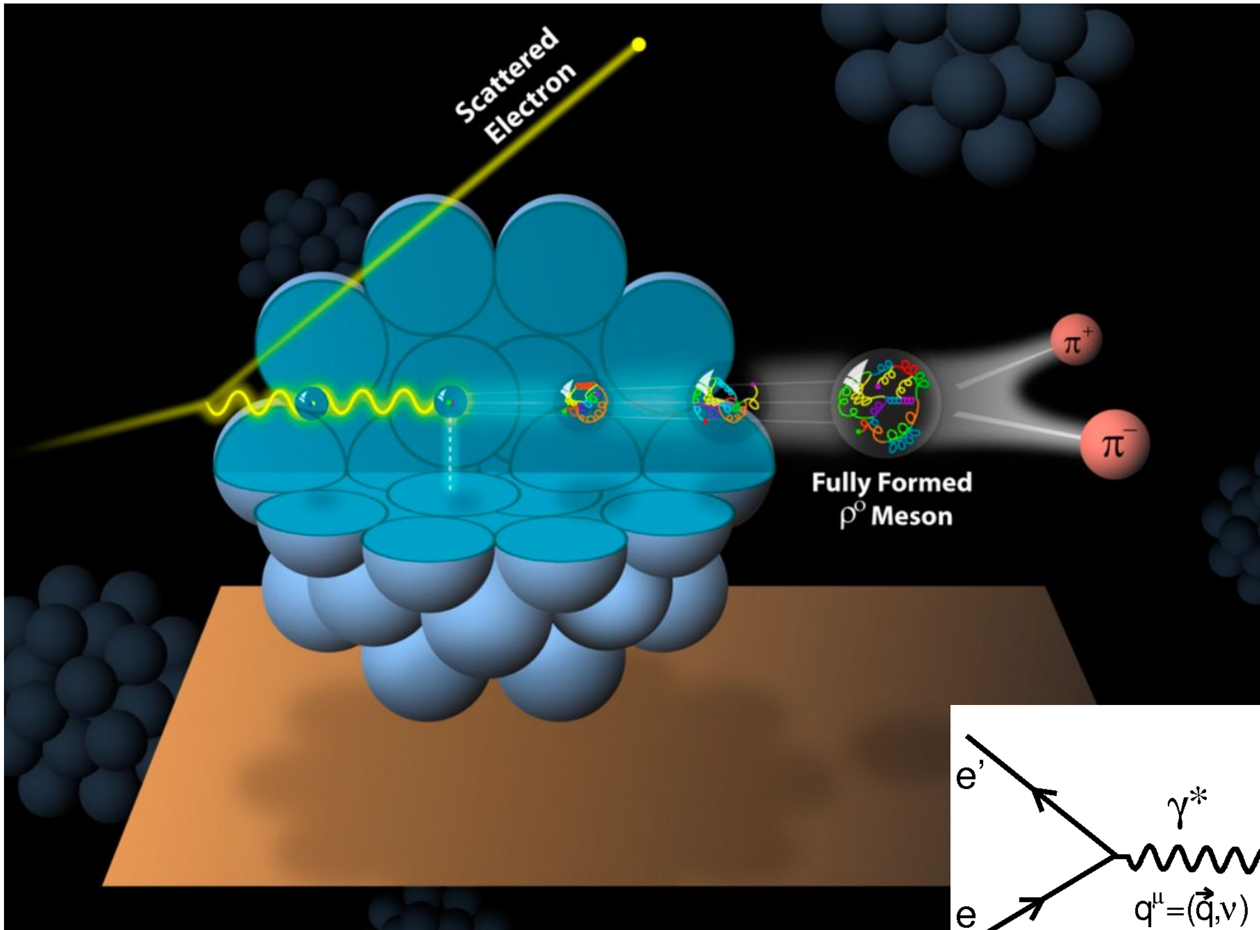
D. Abbott et al. PRL 80, 5072 (1998)
K. Garrow et al. PRC 66, 044613 (2002)

Solid Pts – JLab
Open Pts -- other

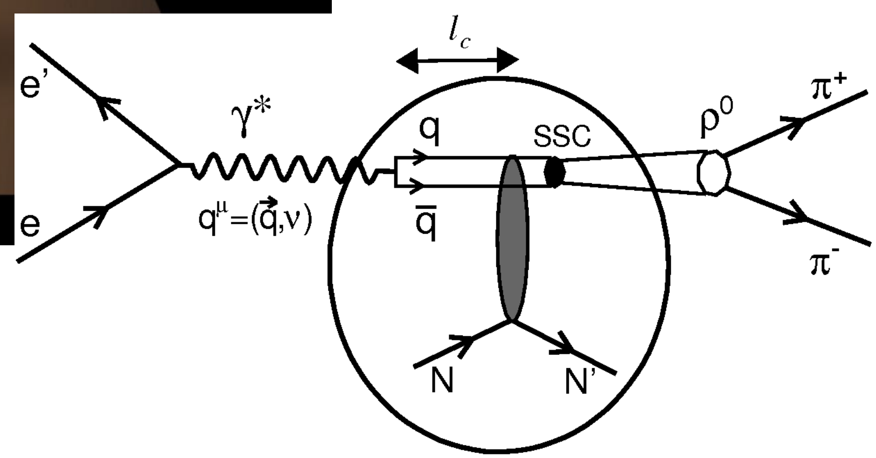
No increase in transparency seen. *Alas.*

Conventional Nuclear Physics "Glauber" Calculation gives good** description
(V. Pandharipande and S. Pieper PRC 1992)

CT with ρ^0 in CLAS



- ρ^0 has the same quantum numbers as γ
- It should be easier to form SSC with two quarks.
- VMD production mechanism is well understood



Coherence length is the fluctuation distance of the q-qbar

$$l_c = 2\nu / (Q^2 + M_\rho^2)$$

Event Selection

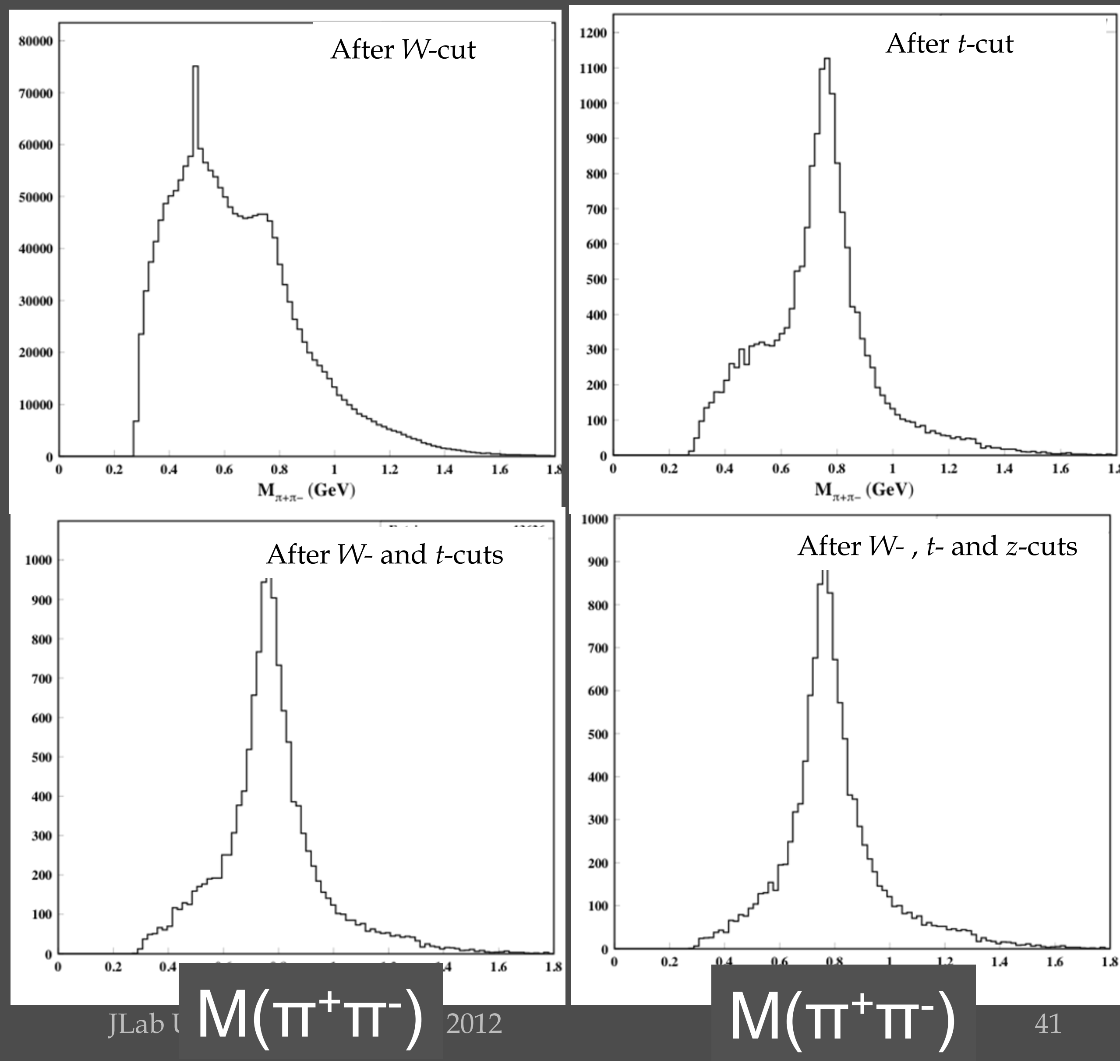
El Fassi et al. , Phys. Lett. B712 (2012)

Reaction of interest is:

$e + A \rightarrow e' + X + r^0$

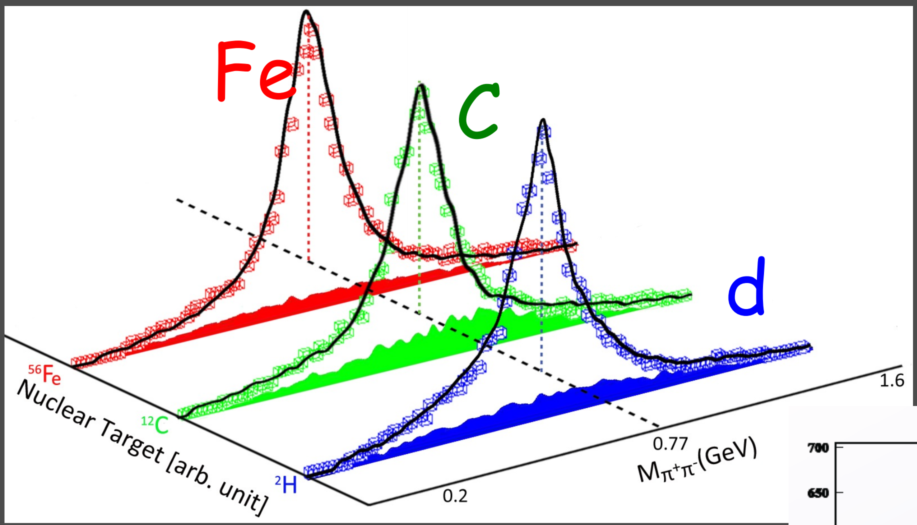
$\rightarrow e' + X +$ p$^+$ + p$^-$

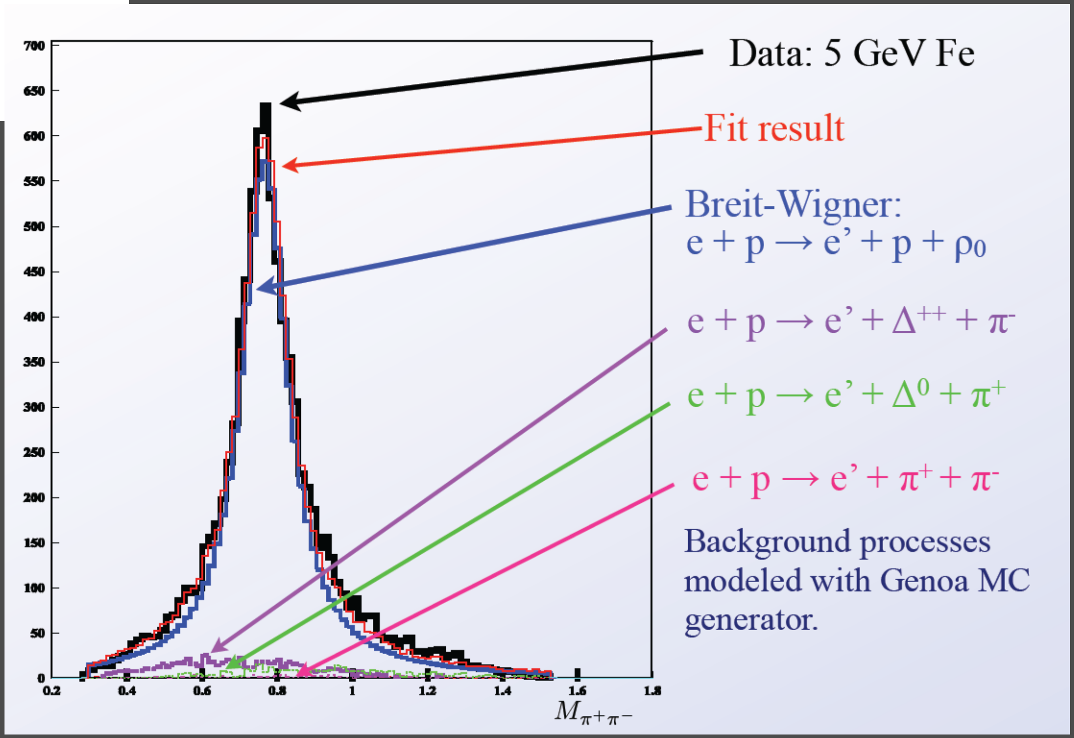
- Use EG2 data again
- W>2 GeV
  - To exclude the resonance region
- ***0.1 < -t < 0.4 GeV*** ^{2}
  - Selects diffractive, incoherent process.
- $z=E\rho/\upsilon>0.9$
  - selects elastically produced r-s.



$\pi + \pi -$ Invariant Mass

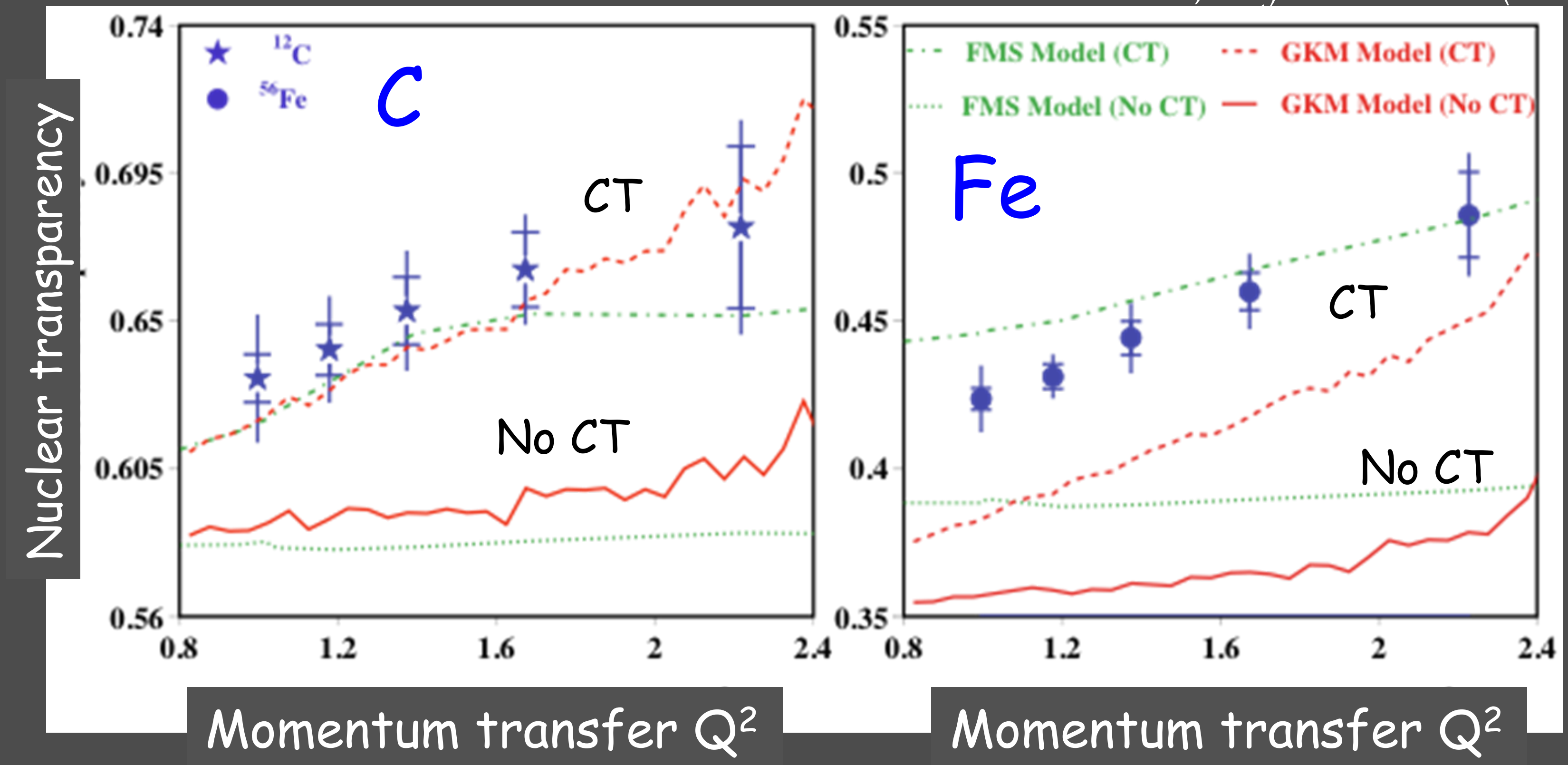
El Fassi et al. , Phys. Lett. B712 (2012)





Transparency vs Q^2

El Fassi et al. , Phys. Lett. B712 (2012)



Strong (but not definitive) evidence for color transparency
Extend this to higher Q^2 at 12 GeV

Quarks in nuclei

- Nucleon quark distributions are modified (by at least a few percent) in nuclei
- We are learning how bare quarks interact as they travel thru nuclei
- We are learning how bare quarks evolve to colorless hadrons
- Small size hadrons interact less as they travel thru nuclei (color transparency)

There is lots more to learn at 12 GeV about all of these topics.