QCD Dynamics in electron-nucleus collisions

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Jefferson Lab

Jefferson Lab

Course Overview

- Nuclear systems and the electron scattering probe
  - Elastic scattering
  - Quasielastic scattering
  - Deep inelastic scattering

- Hadrons in the nucleus
  - Short and long range dynamics
  - EMC effect
  - Hadronization and color transparency

- Implications and open questions

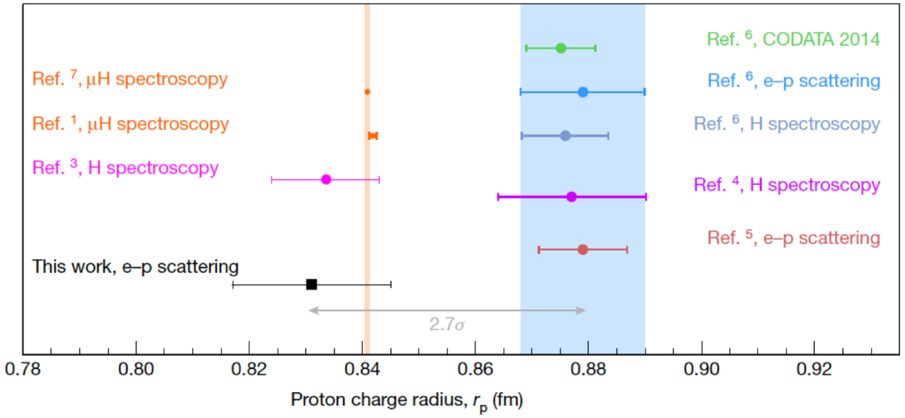
Review from yesterday

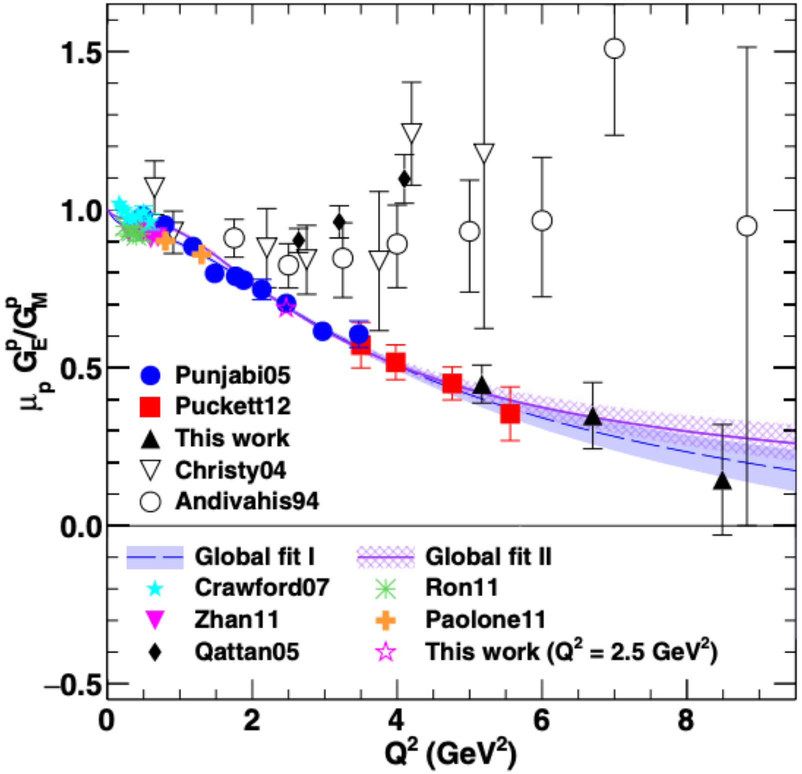
- Nuclear strong interaction that binds nuclei is the residual from the strong interaction between quarks.

- Elastic scattering:
  - Form factors describe the nuclear and nucleon structure in terms of charge and magnetic moment
- Quasielastic scattering:
  - Shell structure, momentum distributions, correlations
- Deep inelastic scattering:
  - Quark-parton picture, structure functions describe quark momentum distributions

Elastic scattering summary

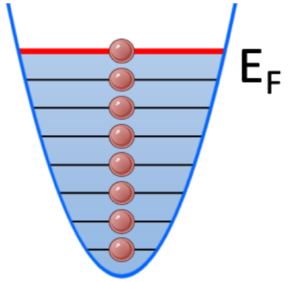
- We can measure things like the charge and magnetic moment distributions of the nucleons.
- These are described in terms of form factors (a Fourier transformation of the distributions).
- We can use form factors to extract the radius.
- This tells us about the structure of nucleons and nuclei.
- Nucleons are not point-like!



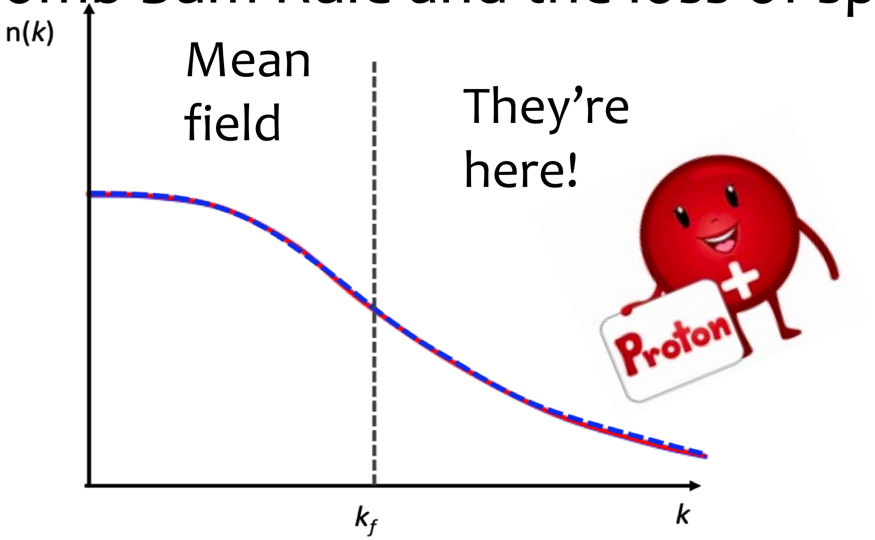


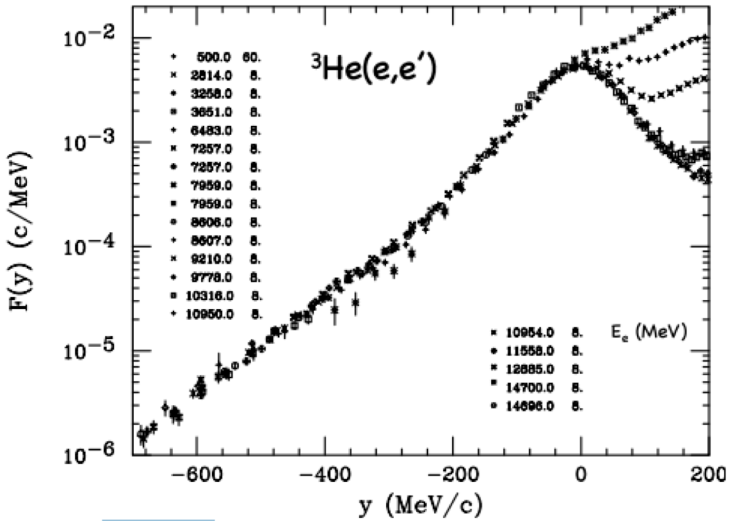
Quasielastic scattering summary

- Nuclei are complicated systems that we model with different assumptions.



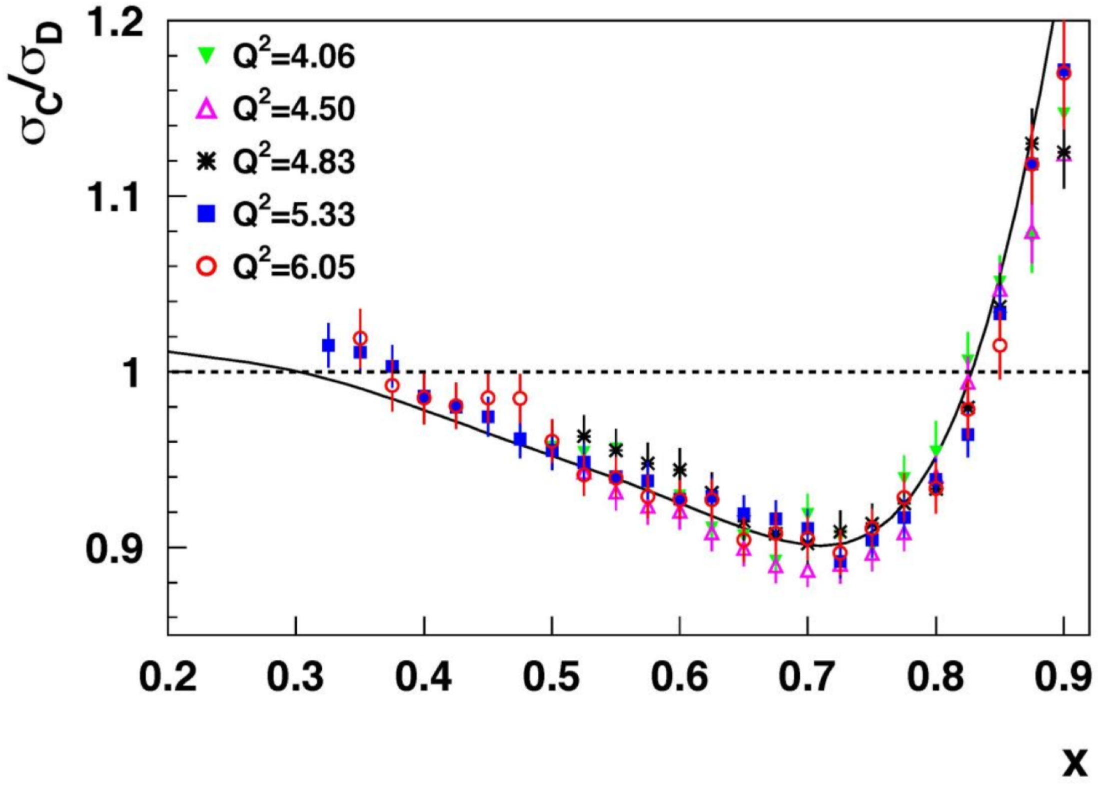
- Fermi gas model gives us a good idea about the cross section.
- Scaling refers to the dependence of a cross section on a single variable
  - y-scaling can tell us about the nucleon momentum distributions in the nucleus.
- Indications that nucleons are not truly quasifree (but modified in the nucleus) from the Coulomb Sum Rule and the loss of spectroscopic strength in orbitals.





Deep inelastic scattering summary

- Structure functions contain the quark momentum density information.
- In the quark-parton model, DIS is scattering from a quasi-free quark.
- EMC Effect: There's a loss of momentum carried by the valence quarks in a bound nucleon vs that of a free nucleon. Many models try to explain the data. Many experiments try to understand the problem.



Principles of experiments

Theory or Model

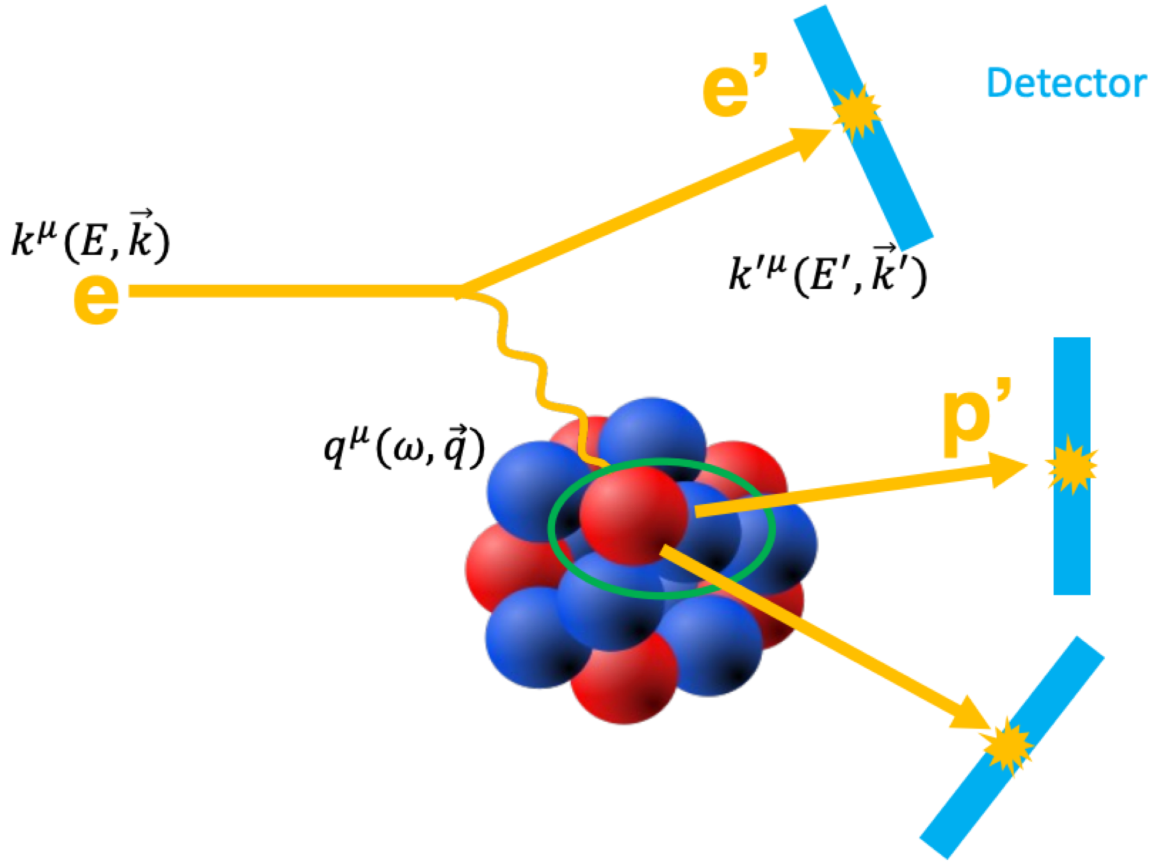
Design of experiment:
Determine beam energy, kinematics of the reaction

Measure things:
Count events (cross sections), detect particles

Reconstruct the event:
Reconstruct interaction point

Physics!
Interpret, how does this support the model and assumptions?

How experimentalists study the reactions



- **Inclusive (e,e'):** detect only the electron
- **Semi-inclusive**: detect the electron and a hadron
- **Exclusive**: detect all final state particles

Luminosity, defined

Electron beam luminosity

- Number of electrons per unit time
- $L_B[s^{-1}] = \frac{I_B}{q_e} = \frac{N_e}{s}$

Target luminosity (thickness)

- Number of particles (N=Nucleon/Nucleus) in a unit of area
- $L_T[cm^{-2}] = \rho \left[\frac{g}{cm^3}\right] \times \frac{l\,[cm]}{A} \times N_A = \frac{N_N}{cm^2}$

Total (integrated) luminosity:

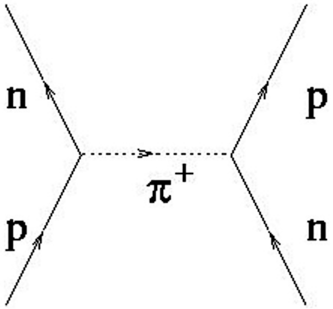
- Number of eN interactions per unit of time, per unit of area
- $L[s^{-1}cm^{-2}] = L_B \times L_T$

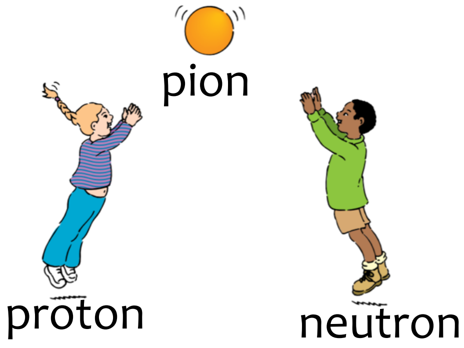
Event rate

- Events per time for a given cross section, $\sigma\ [cm^2]$
- $\frac{N_{ev}}{s} = L \times \sigma$

Nuclear physics

What holds the nucleus together?





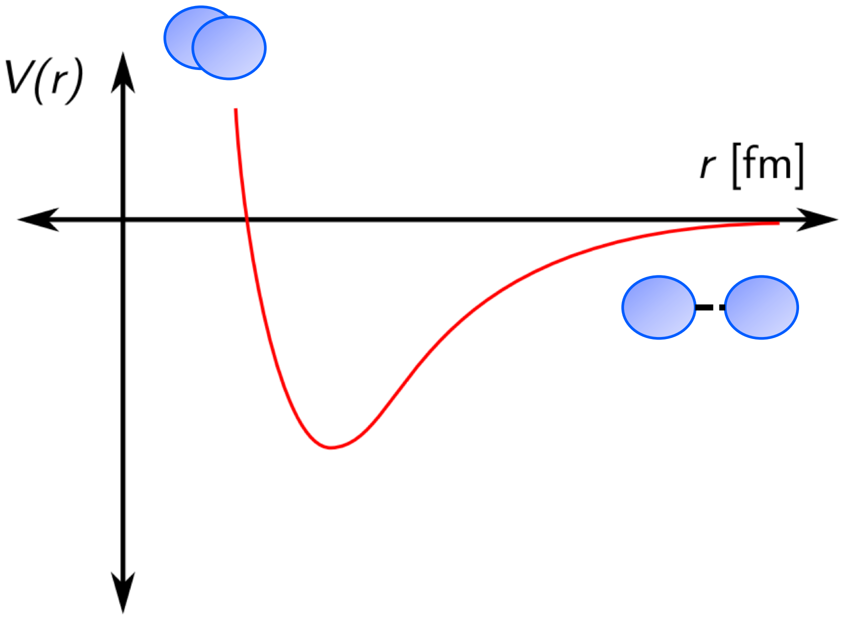
Began with the exchange of mesons via a Yukawa potential


quarks and gluons

Quantum Chromo Dynamics (QCD) is the leading theory of the strong force using quark and gluon degrees of freedom that carry color charge.

NN potential

Potential between nucleons

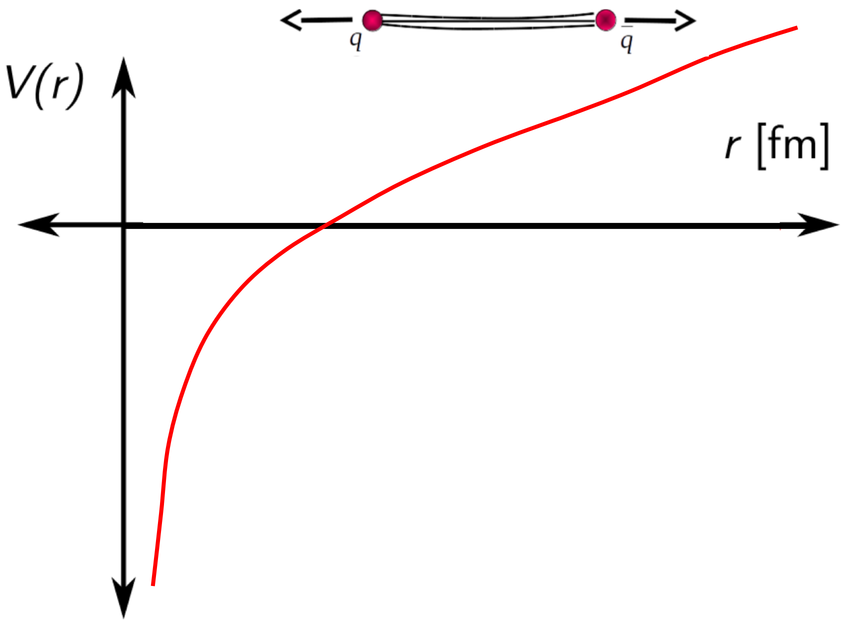


Characterized by:

- Repulsive core
- Attractive potential between nucleons
- Nucleons and mesons, interactions
- Colorless matter
- Quark interactions cancel at large distances making hadronic interactions finite

QCD potential

Potential between quarks

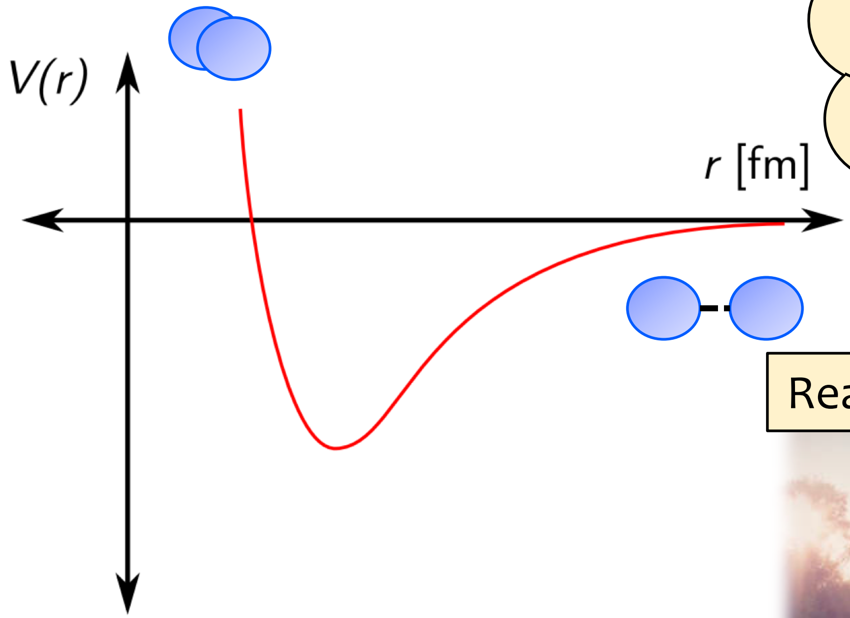


Characterized by:

- Strongly attractive
- At short distances or high energies, QCD is asymptotically free (pQCD works here)

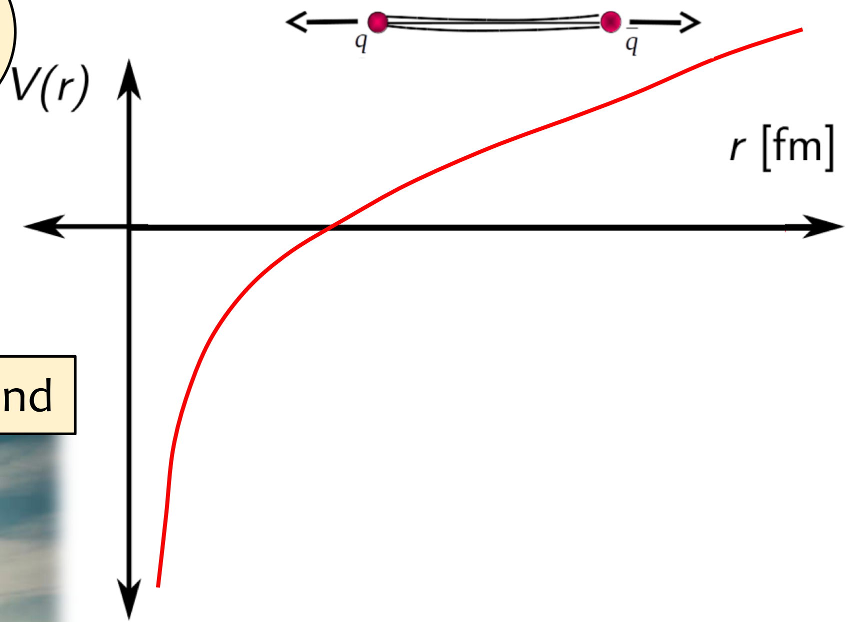
Two descriptions of nuclear physics

Potential between nucleons



What is the roadmap between these two regimes?

Potential between quarks



nucleons & mesons

quarks & gluons

Drawing the roadmap

QCD is the leading theory for the strong force interaction.

Yet, we are still trying to fully describe nucleons and nuclei in terms of quarks and gluons.

We have to connect the Real World to QCD Land using data.

Useful clues:

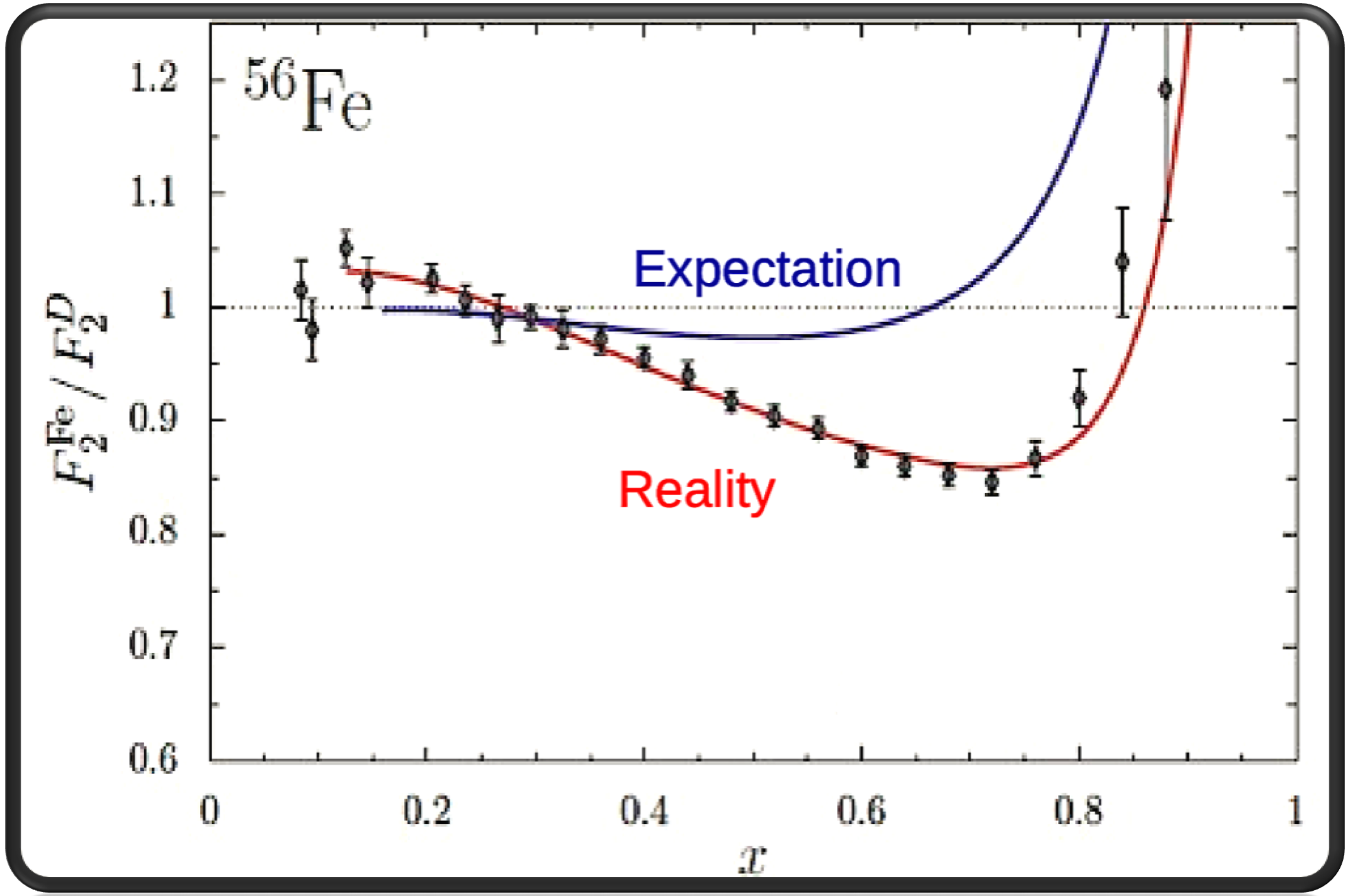
Modifications in the structure and interactions of hadrons in the nucleus.

The transition from quark-gluon to nucleon-meson degrees of freedom.

EMC Effect

Recall: observation in DIS

- The effect increases with A
- It's Q^2 independent
- Region is 0.3<x<0.7
- Universal x-dependence



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

Some models for the EMC Effect

Nucleon structure is modified in the nuclear medium

- Swollen nucleons
- Multiquark clusters
- Dynamical rescaling

~ or ~

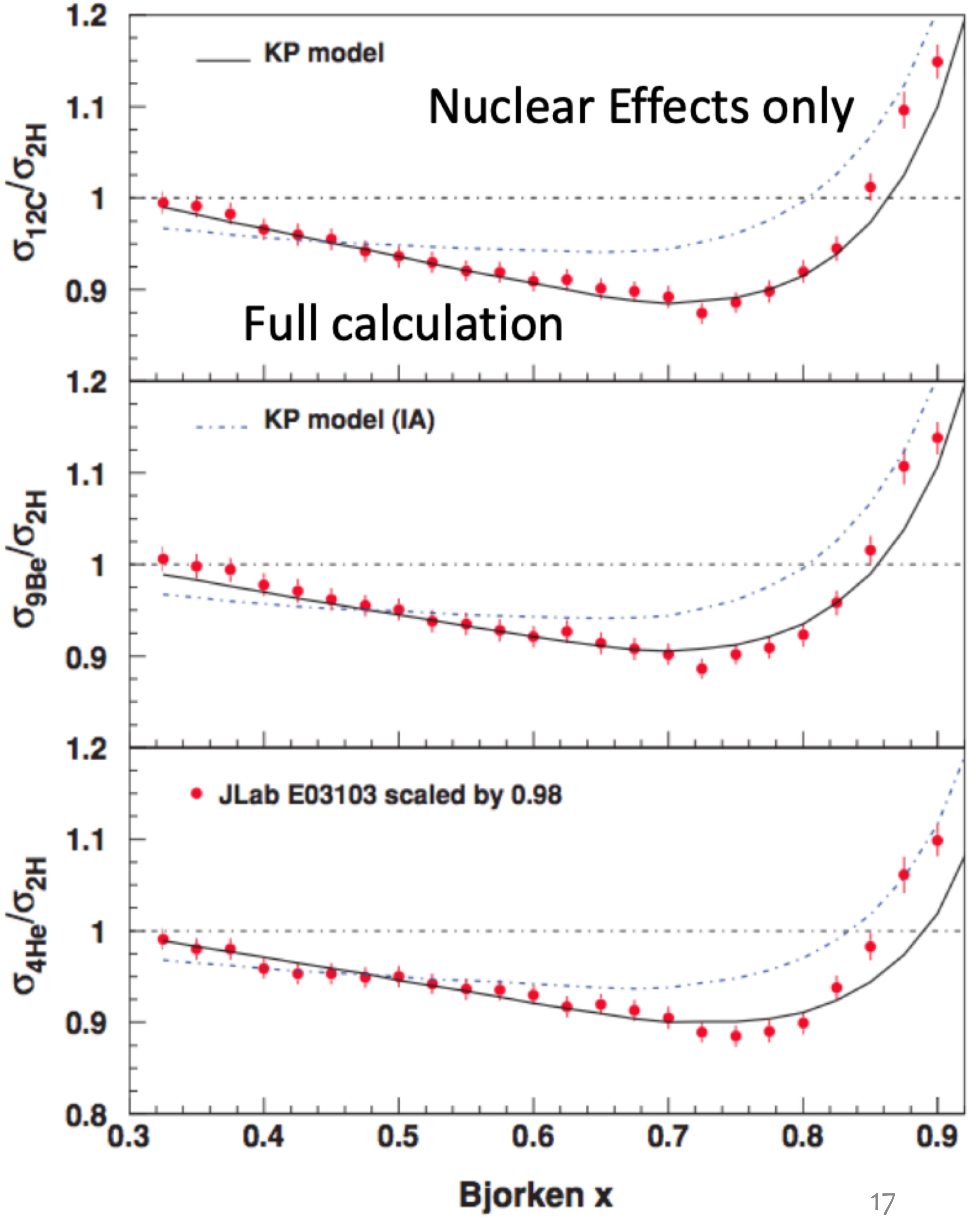
Nuclear structure is modified due to multi-nucleon effects

- Binding
- Nuclear pions
- NN short-range correlations

Nucleon modification needed to describe the data

Nuclear Effects:
- Fermi motion
- Binding energy

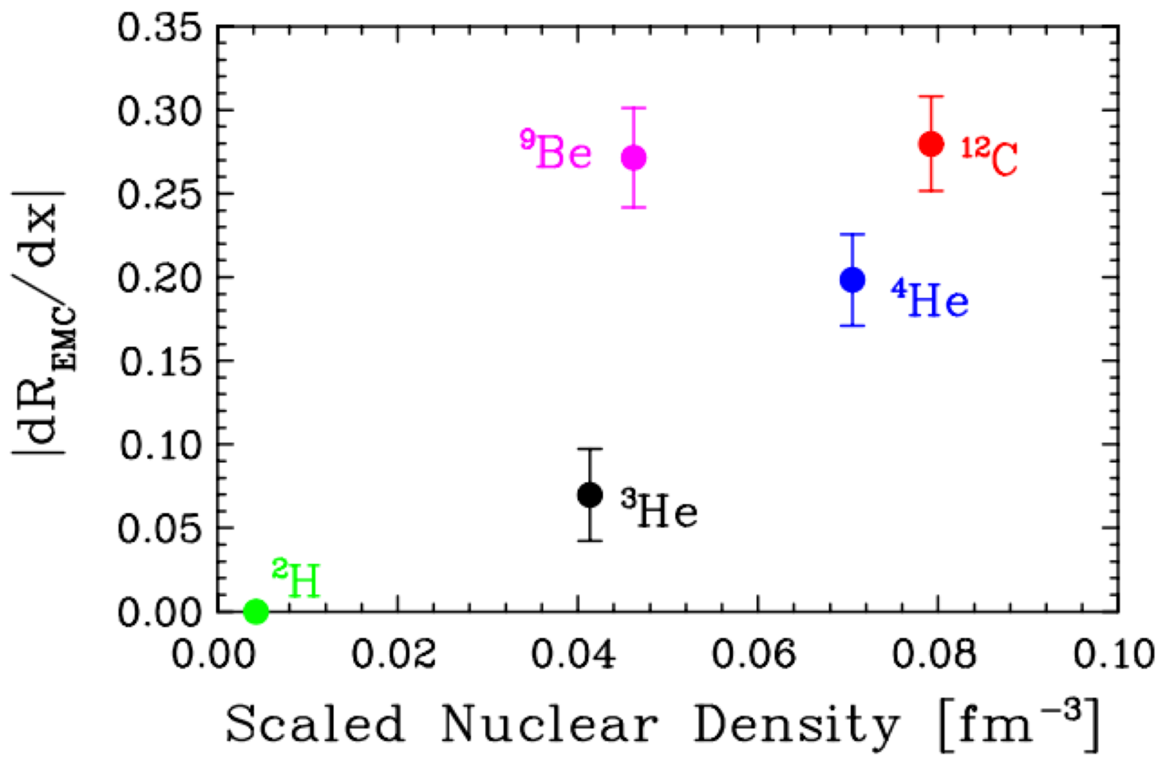
Full Calculation:
- Nucleon modification
- Phenomenological change to bound nucleon structure functions, proportional to virtuality (p^2)
- Nuclear pions
- Shadowing



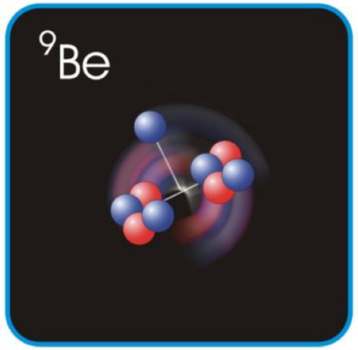
Kulagin and Petty, PRC 82, 054614 (2010)

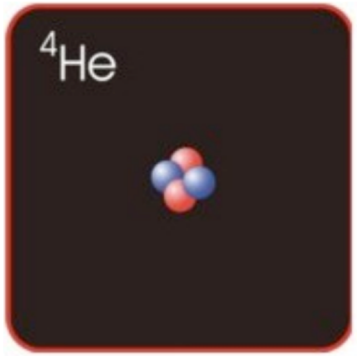
EMC Effect in light nuclei

(EMC Slope)



(average)





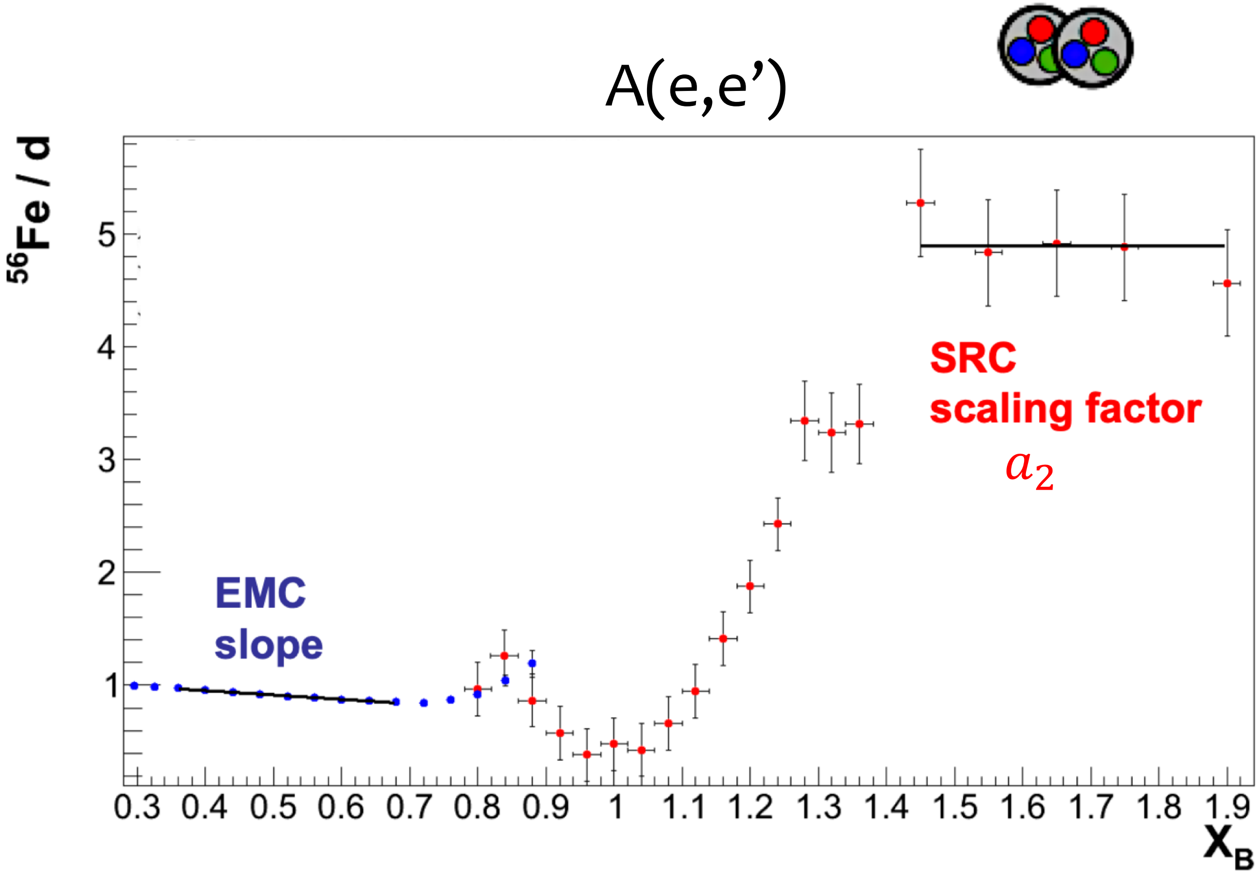
^{9}Be has a lower average density (2α+n)

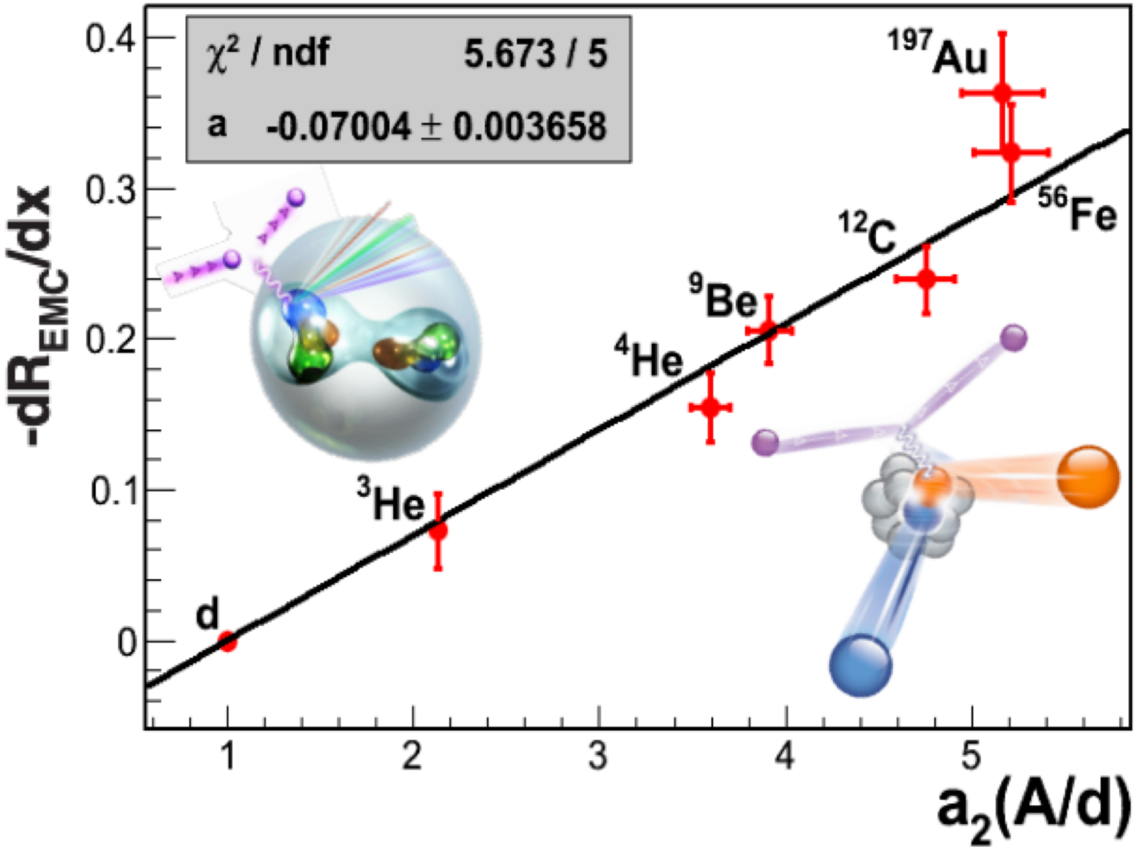
Local density important to the modification!

J. Seely et al., Phys. Rev. Lett. 103, 202301 (2009)

EMC Effect and SRCs

SRCs related to the local density.
EMC Effect seems to correlate well with local density and SRCs!





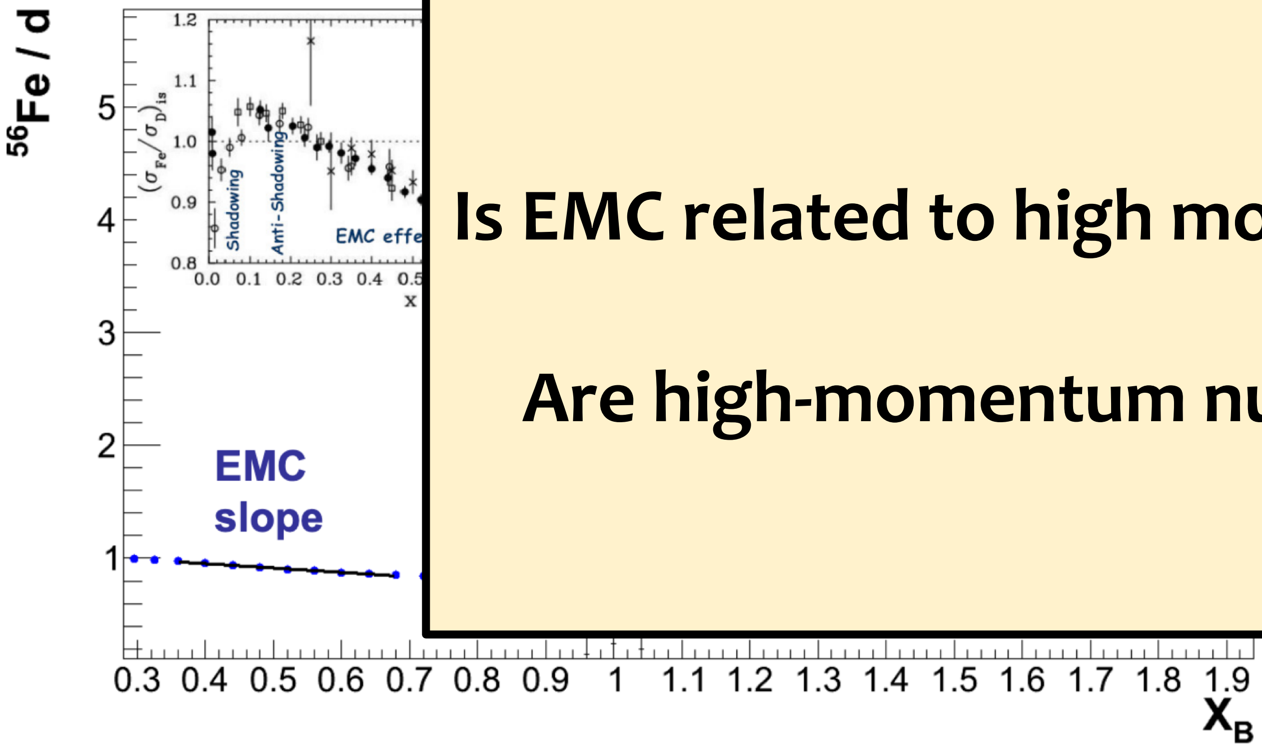
Frankfurt, Strikman, Day, Sargsyan, Phys. Rev. C48 (1993) 2451
Gomez et al., Phys. Rev. D49, 4348 (1983)

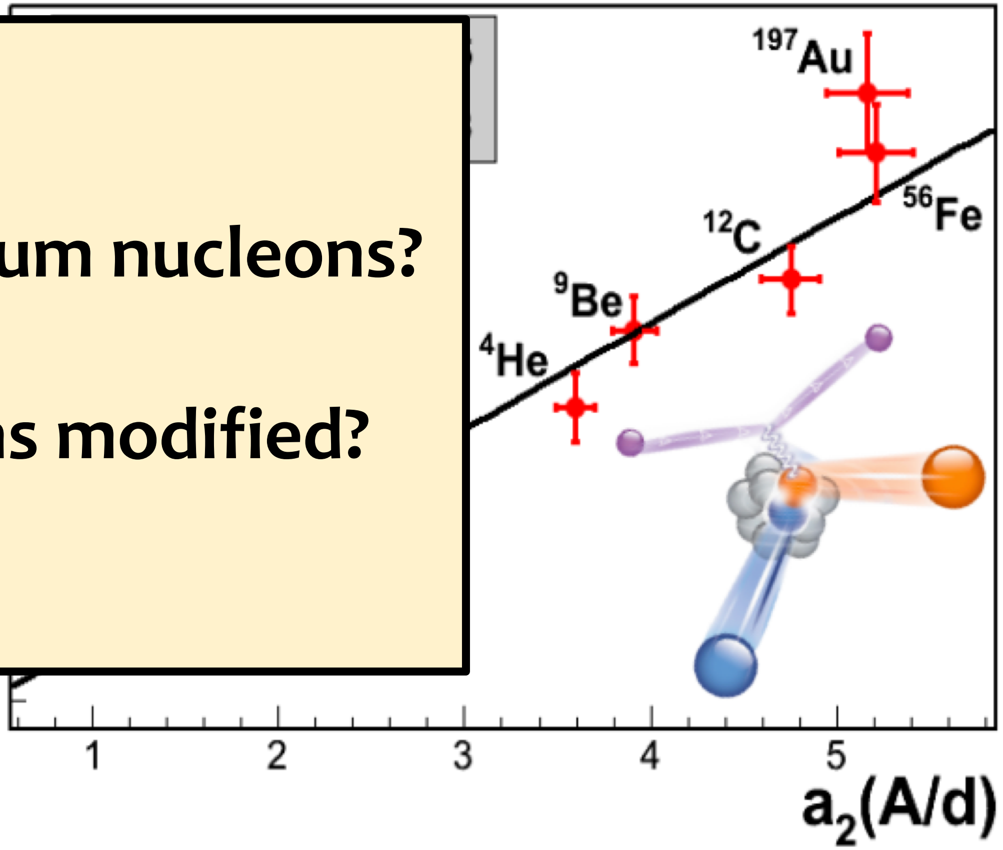
O.Hen et al, Phys. Rev. C **85**, 047301 (2012)
Weinstein et al, PRL106 052301 (2011)

EMC Effect and SRCs

SRCs related to the local density.
EMC Effect seems to correlate well with local density and SRCs!

A(e,e')





Is EMC related to high momentum nucleons?

Are high-momentum nucleons modified?

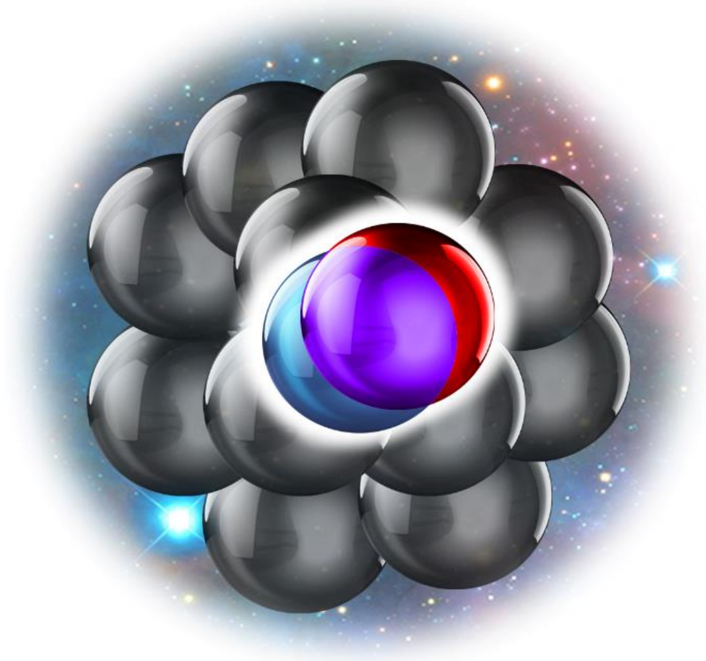
Frankfurt, Strikman, Day, Sargsyan, Phys. Rev. C48 (1993) 2451
Gomez et al., Phys. Rev. D49, 4348 (1983)

O.Hen et al, Phys. Rev. C **85**, 047301 (2012)
Weinstein et al, PRL106 052301 (2011)

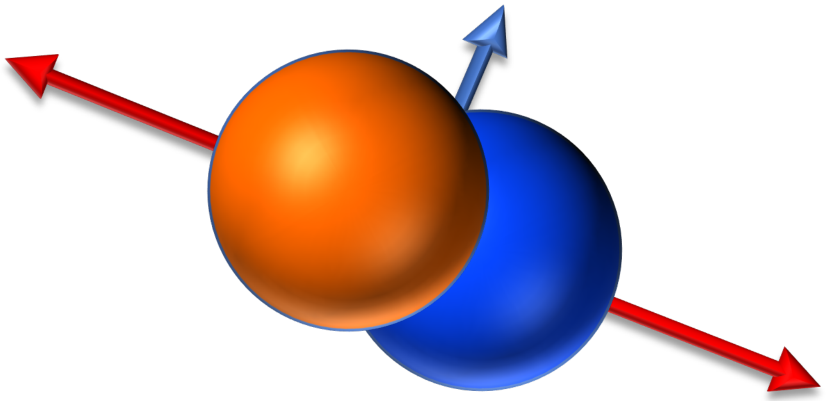
Revisiting NN short-range correlated pairs

Nucleon pairs that are close together (overlapping) in the nucleus

High relative momentum and low center of mass momentum (as compared to k_f)



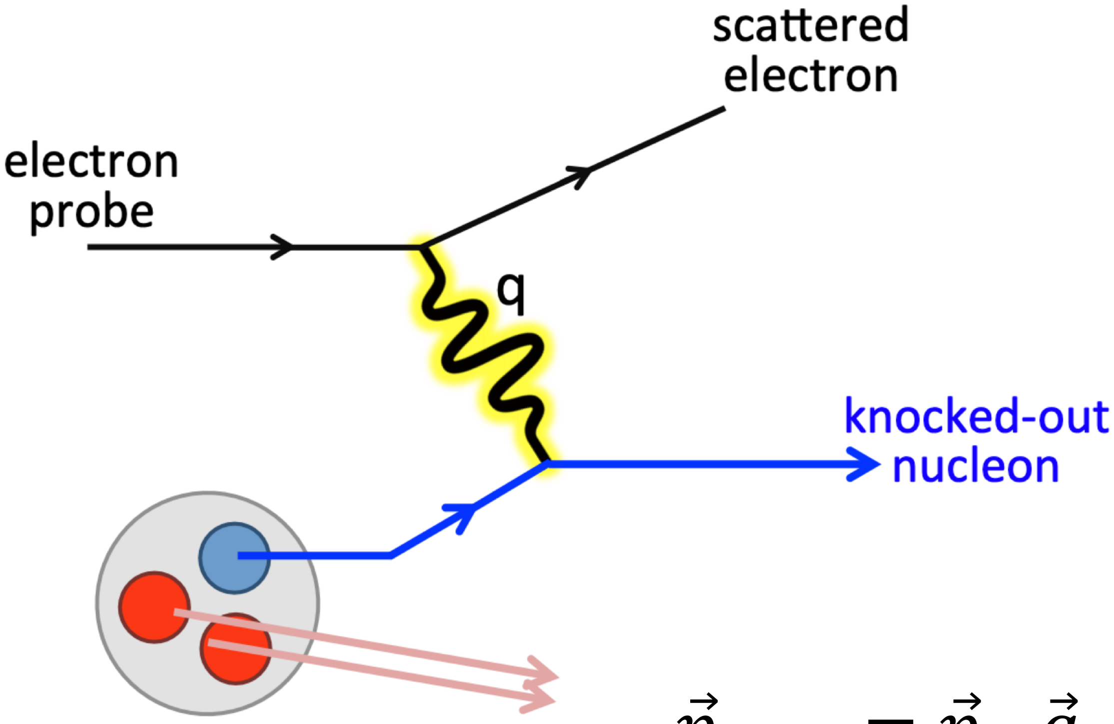
r-space



k-space

SRC measurements

$x_B > 1$ kinematics



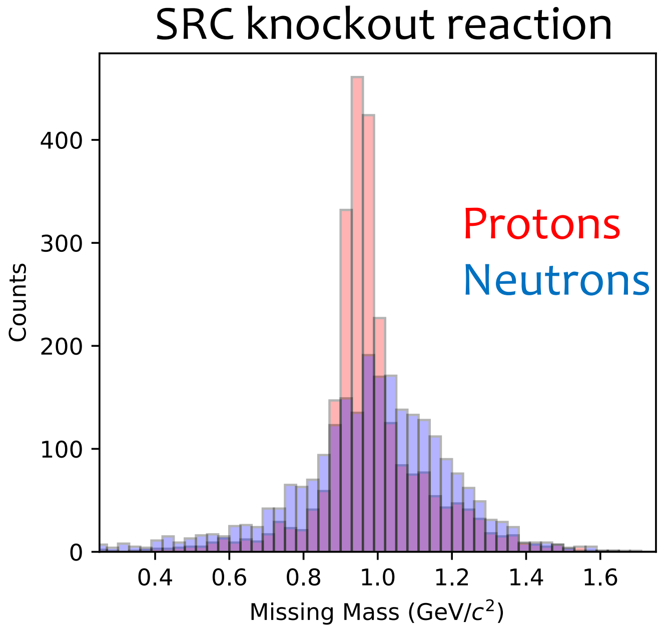
$$\vec{p}_{miss} = \vec{p} - \vec{q}$$

$$m_{miss}^2 = \left[(\vec{q},\omega) + (\vec{0},m_d) - (\vec{p},E_p)\right]^2$$

$$E_{miss} = \omega - T_N - T_{A-1}$$

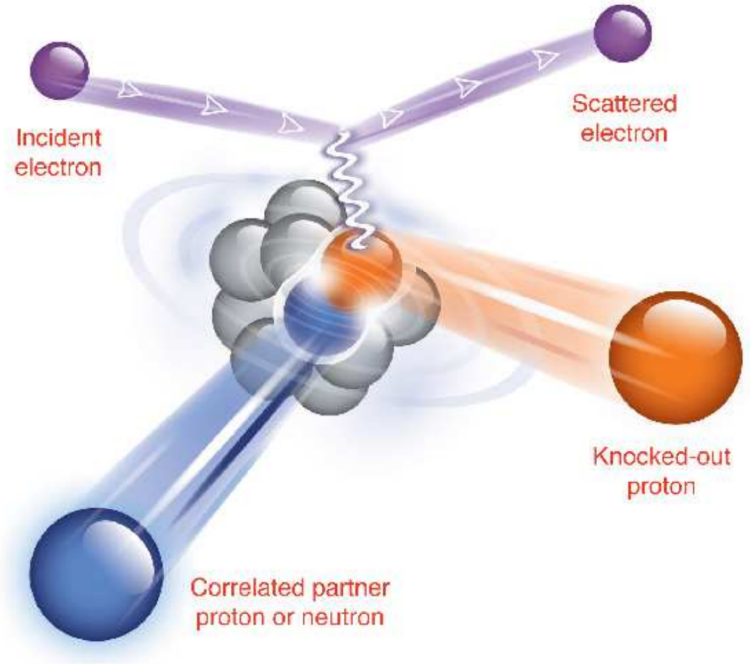
Reconstruct:

- scattered electron
- lead nucleon (p or n)
  - P_{miss}
  - M_{miss} (standing pair)
  - E_{miss}



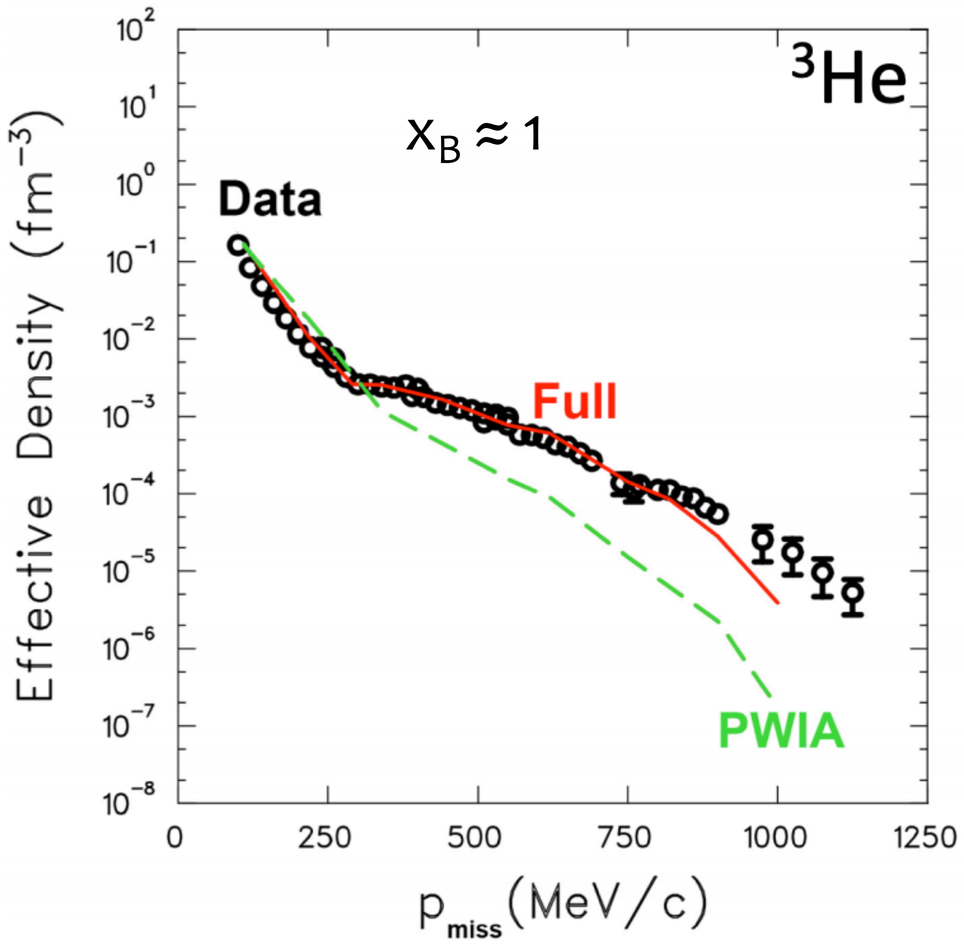
How do we look for SRCs?

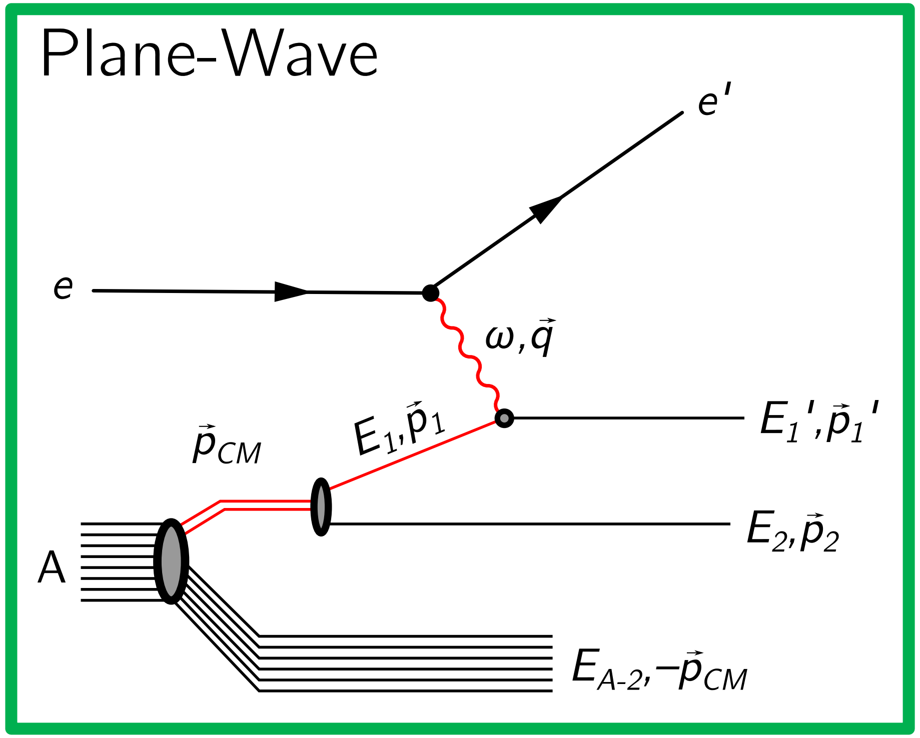
- A(e,e’) reaction at x>1: can inform us about the probability of 2N and 3N SRC
- D(e,e’pn): simplest nucleus with pairing
- A(e,e’N) and A(e,e’NN): probes the detailed structure of SRCs



Minimize competing processes

Perpendicular kinematics not sensitive to the momentum distribution

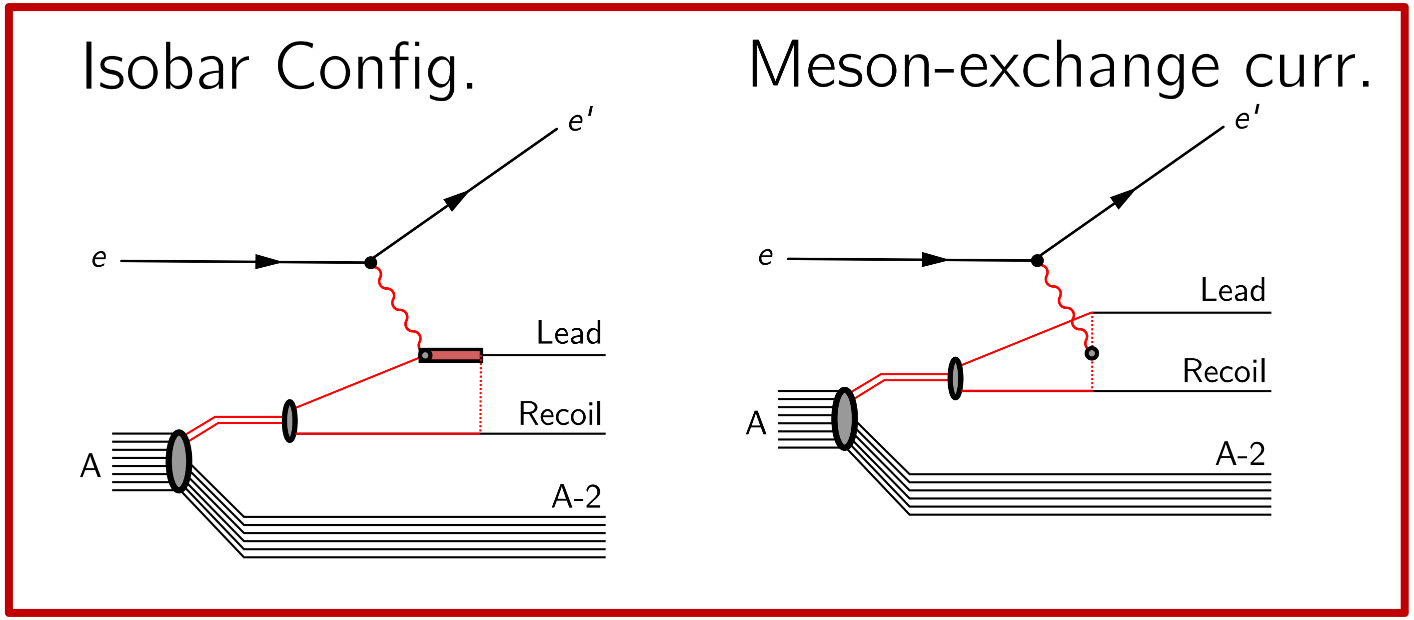


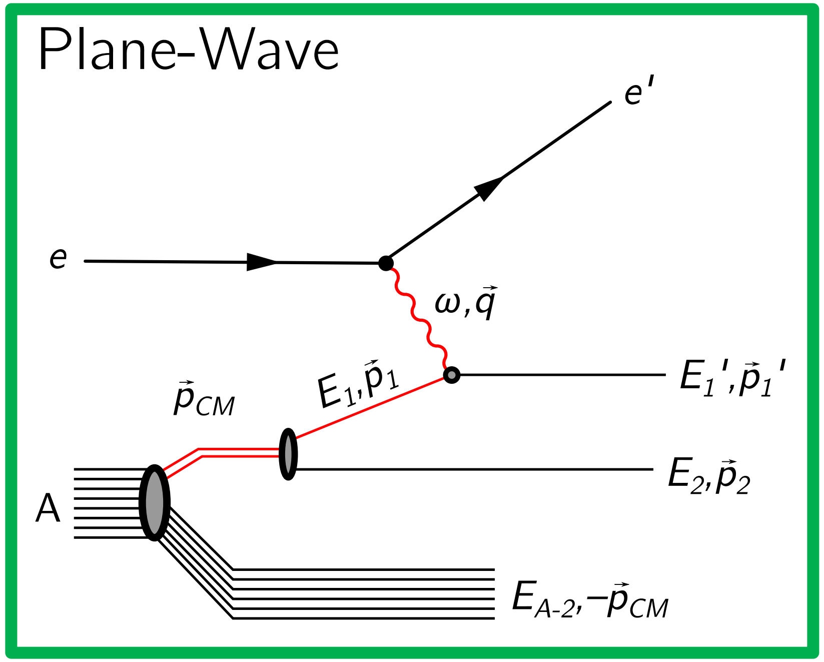


F. Benmokhtar et al., PRL 94, 082305 (2005)

Minimize competing processes

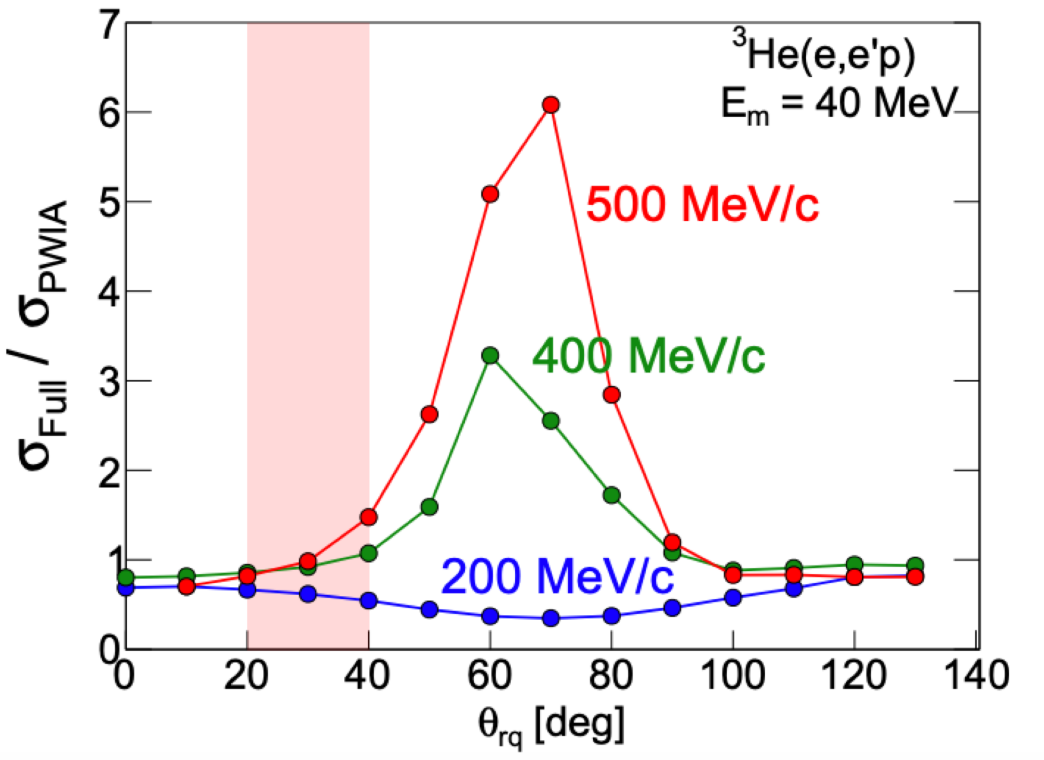
- $Q^2 > 1.8\ GeV^2/c^2$ (reduce MEC)
- $x_B > 1$ (anti-parallel), reduce IC



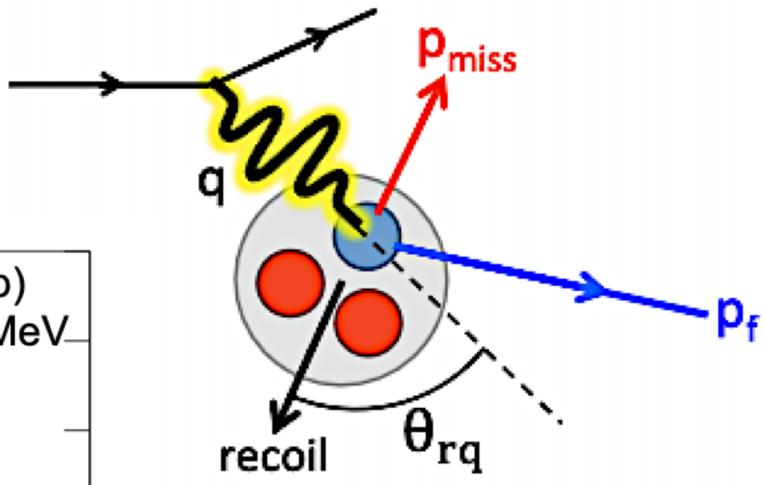


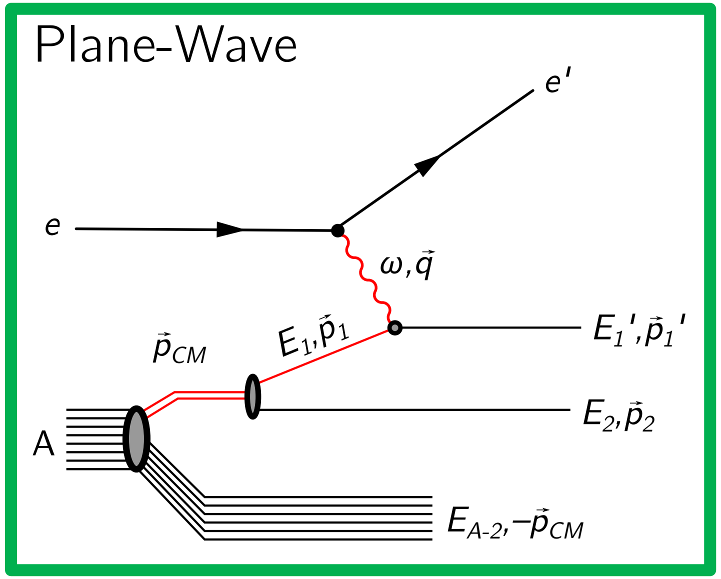
Minimize competing processes

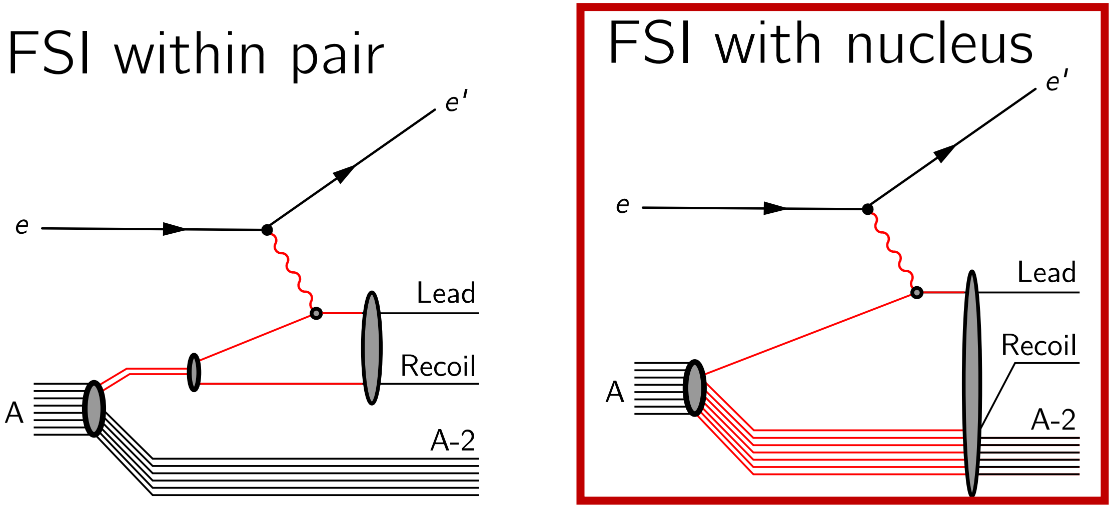
- $\Theta_{r,q} < 40°$



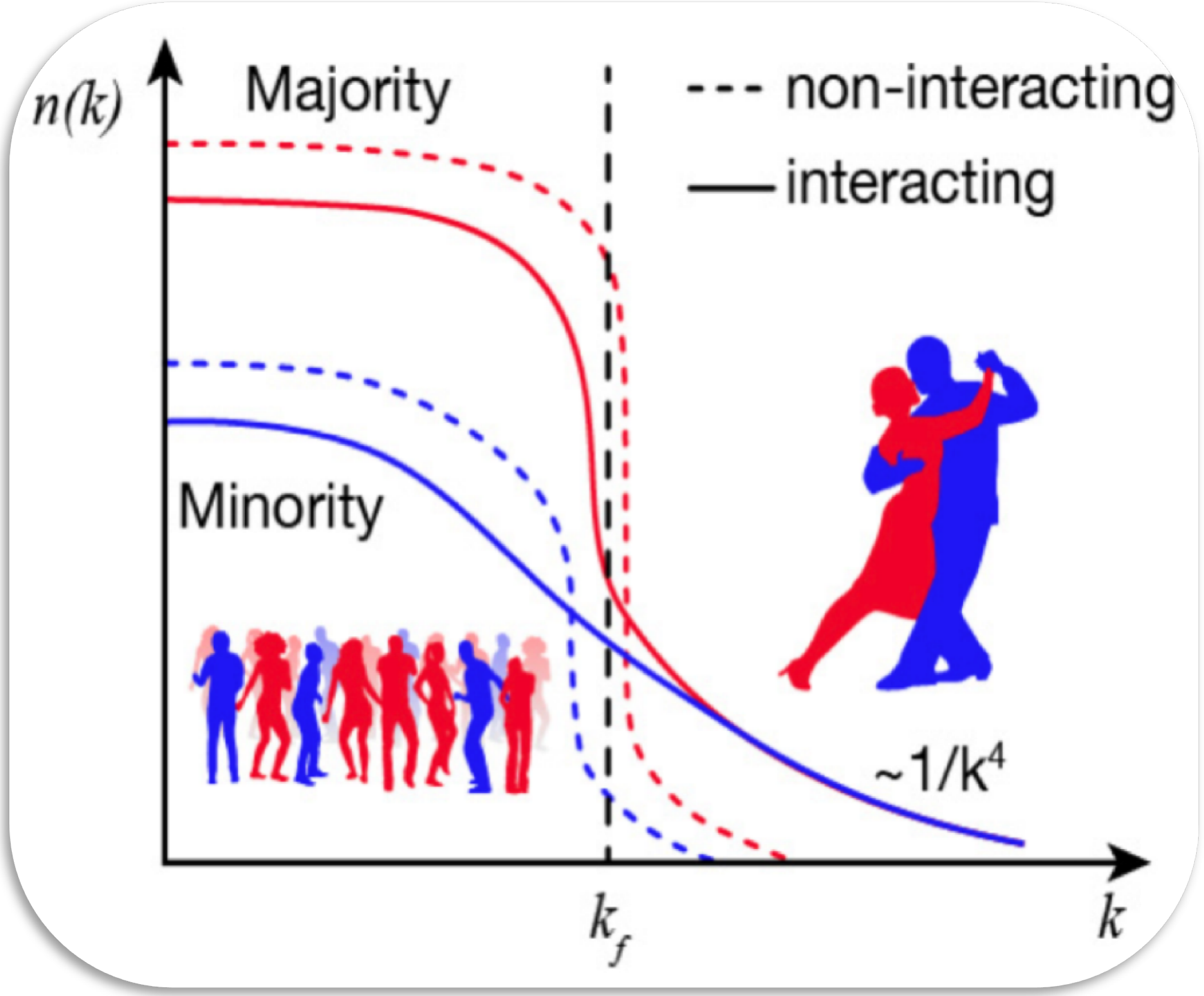
Calculation by M. Sargsian





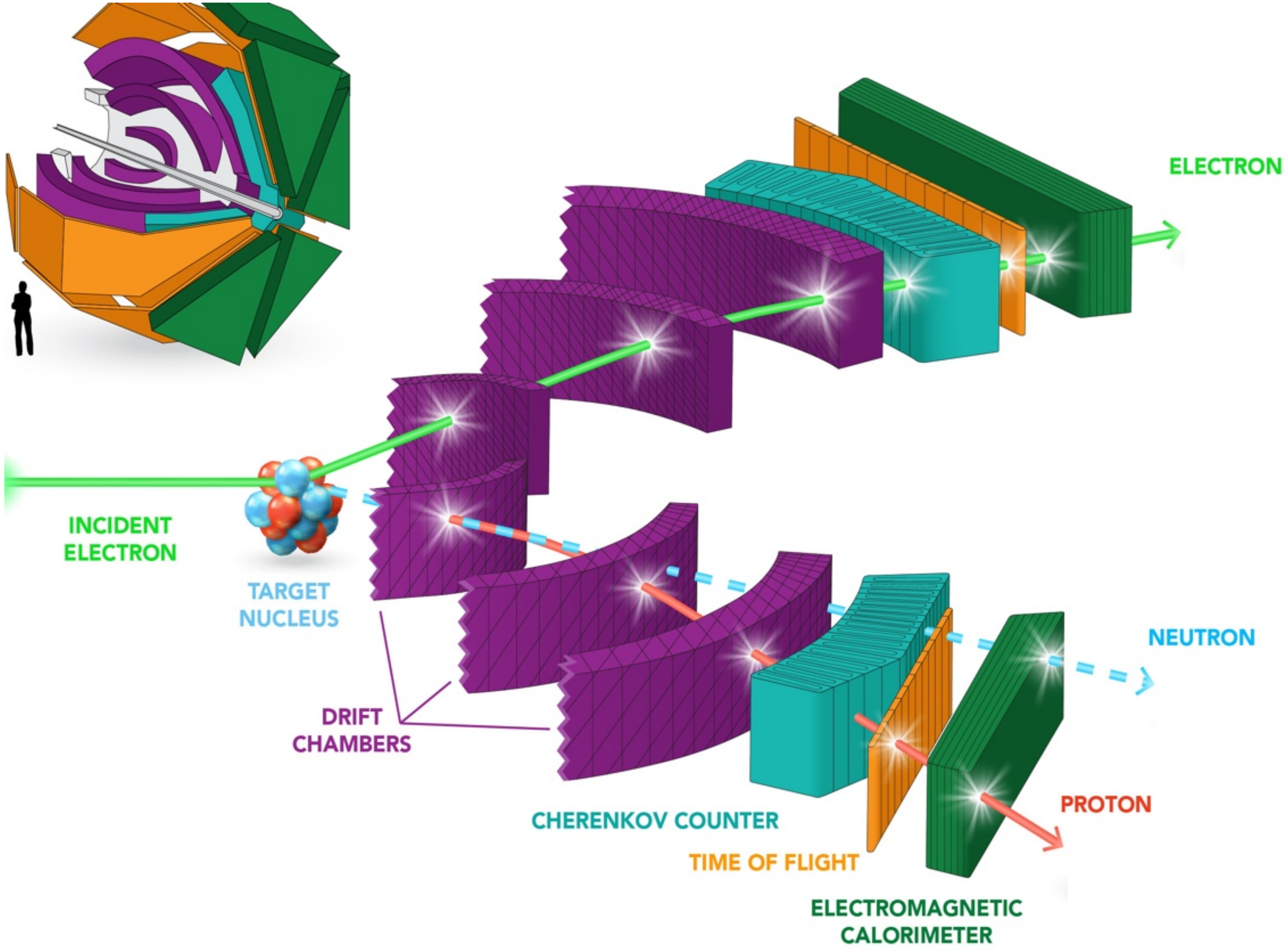


SRCs in the high momentum tail



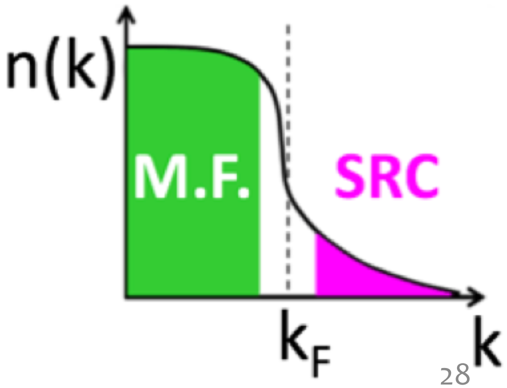
Knockout studies in CLAS (6 GeV era)

CLAS detector

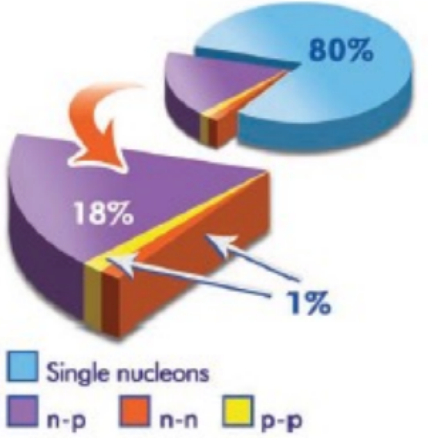


Low momentum
→ Mean field

High momentum
→ SRC pairs

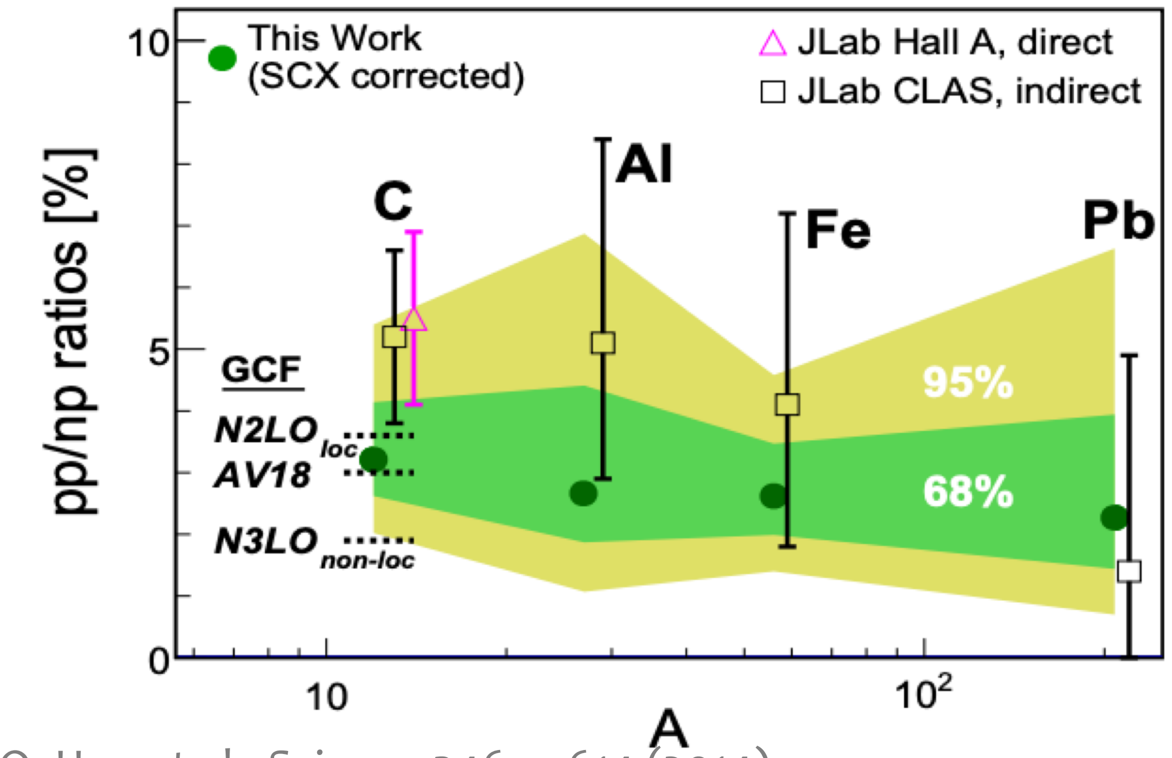


np-pairs dominant (tensor interaction)

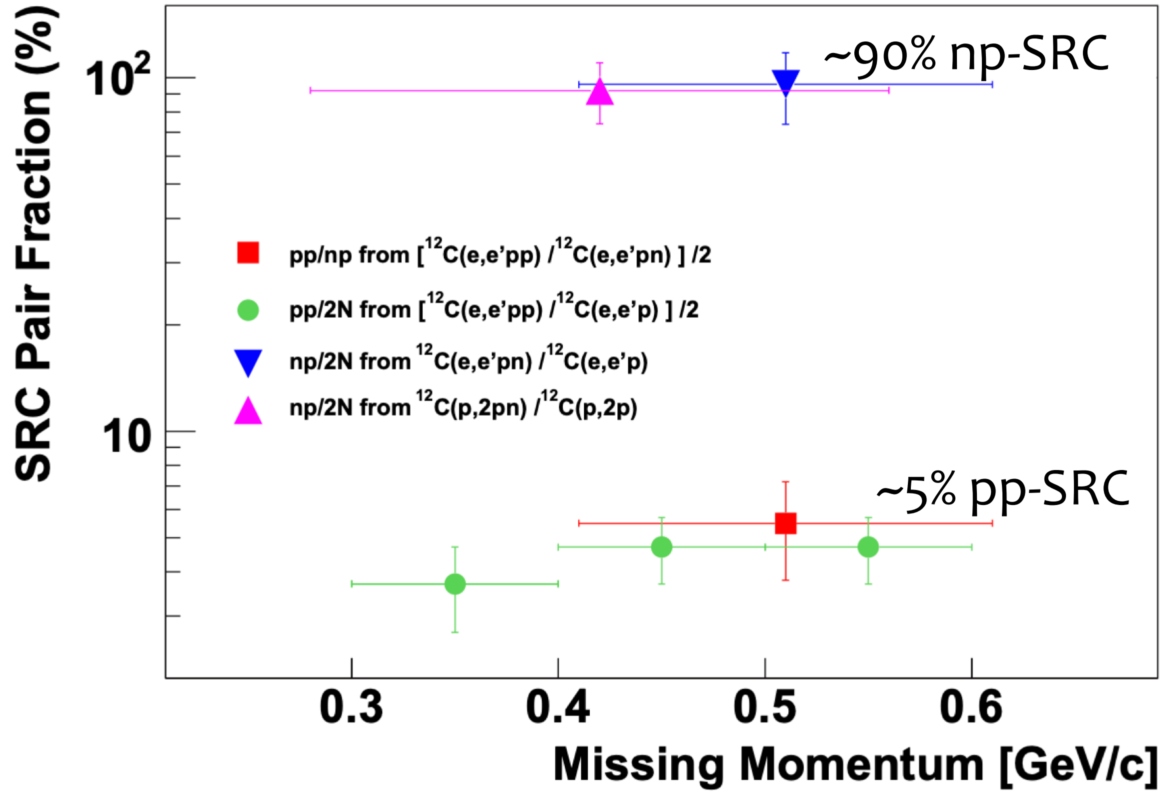


np pair dominate pp pairs by a factor of ~ 20 times

High momentum nucleons in nuclei

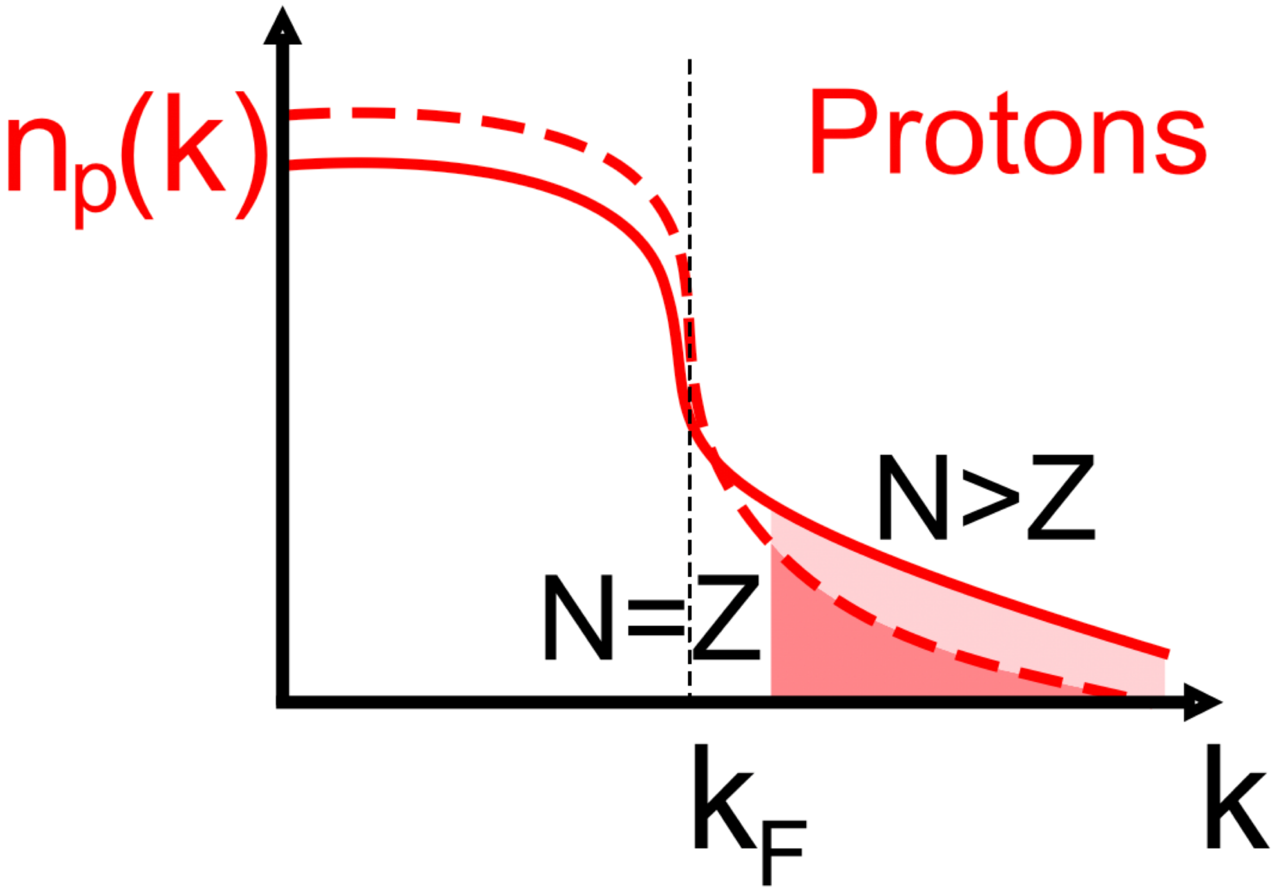


O. Hen et al., Science 346 p. 614 (2014)
M. Duer et al., PRL122, 172502 (2019)



R. Subedi et al, Science 320 (2008) 1476

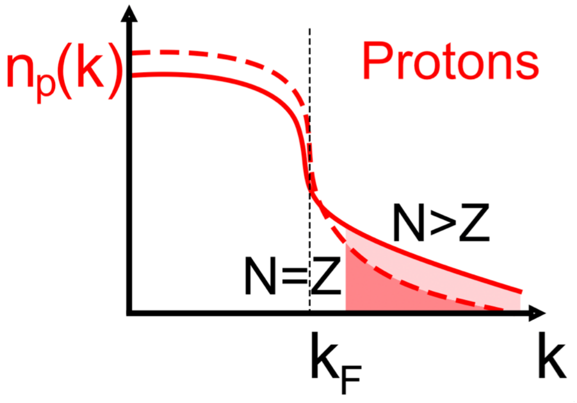
Protons “speed up” in neutron-rich nuclei



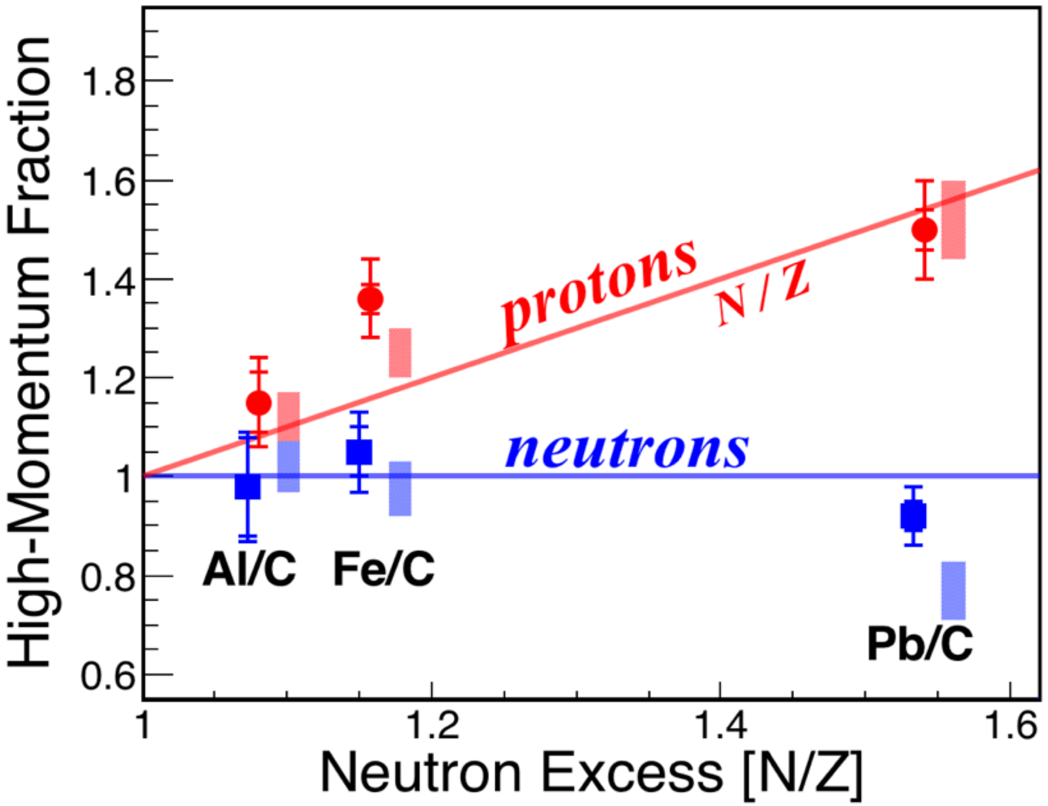
Duer et al. (CLAS collaboration), Nature 560, 617 (2018)

Protons "speed up" in neutron-rich nuclei

Minority (proton) moves faster than majority (neutron) in neutron-rich nuclei



$$\frac{{}^{27}Al(e,e'N_{high})/{}^{27}Al(e,e'N_{low})}{{}^{12}C(e,e'N_{high})/{}^{12}C(e,e'N_{low})}$$



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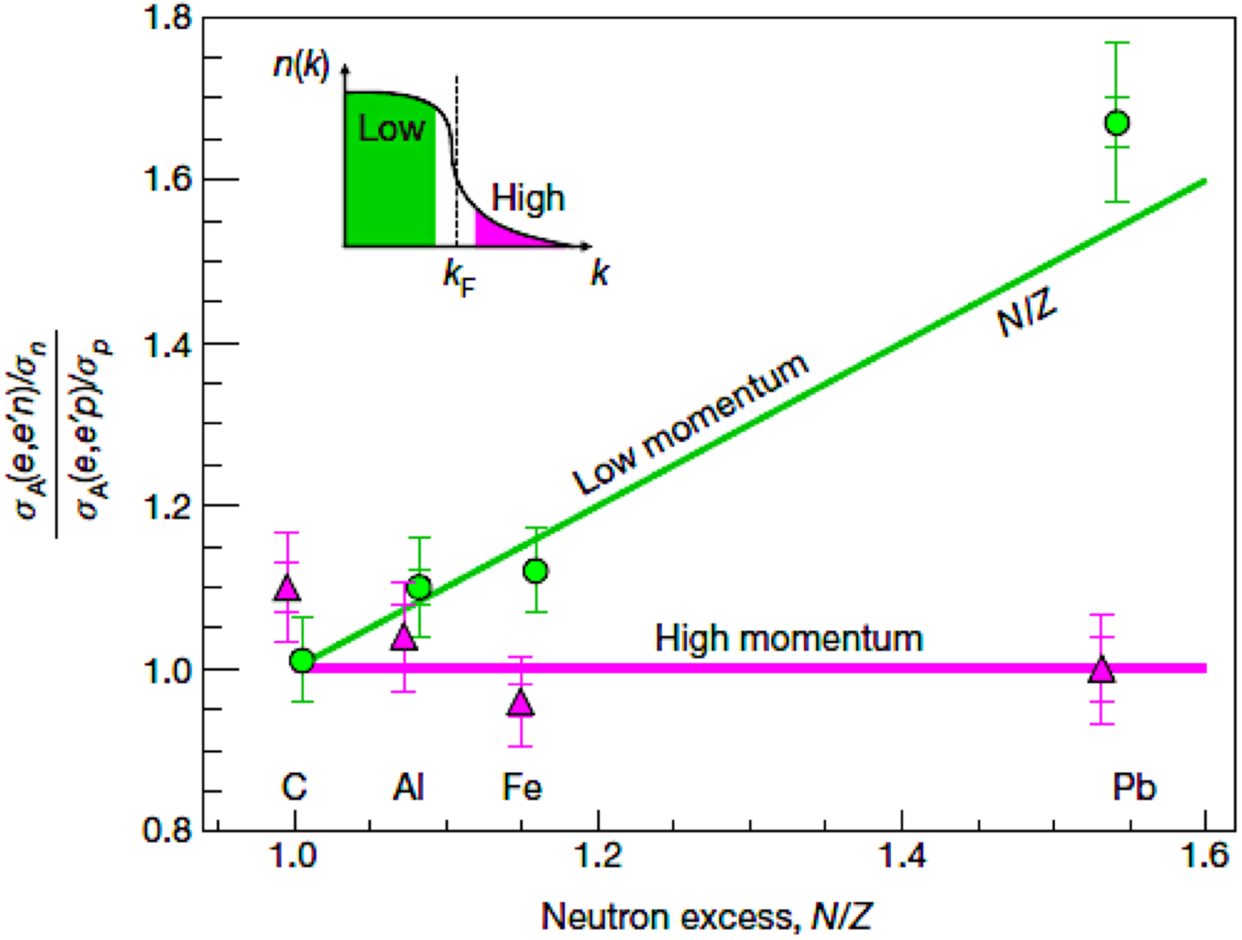
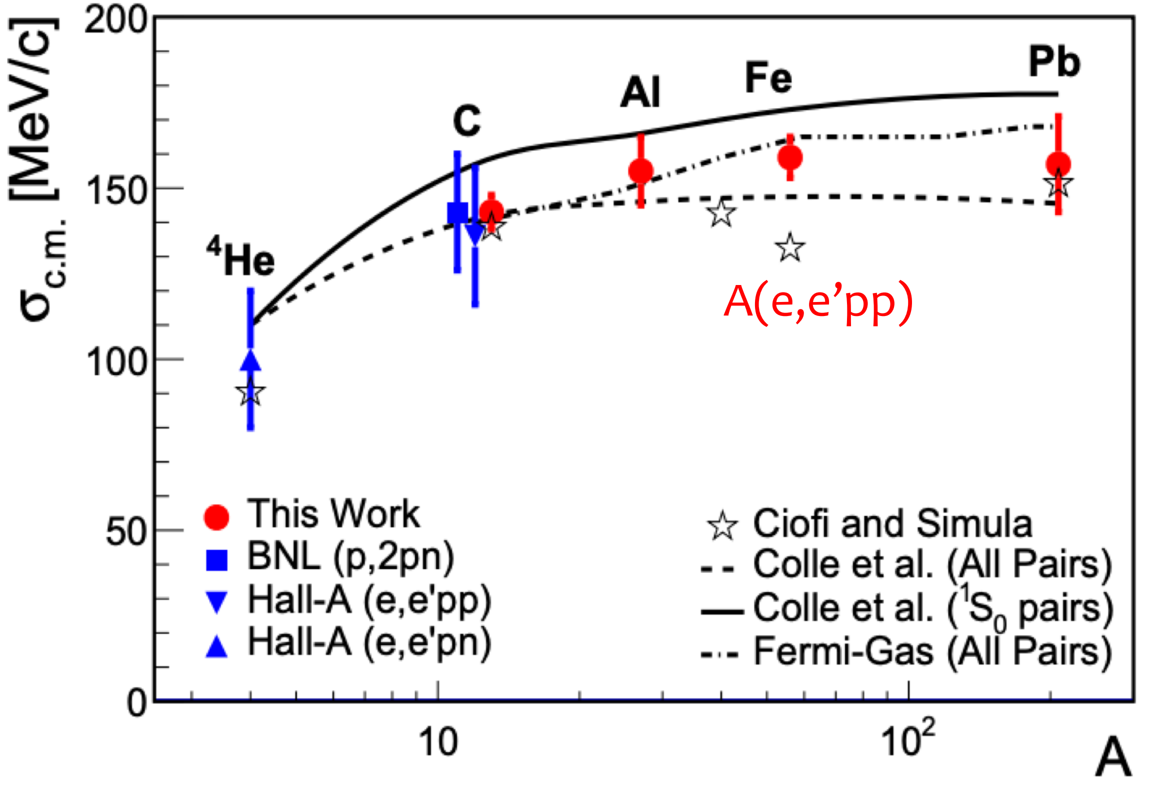
neutron: proton ratio

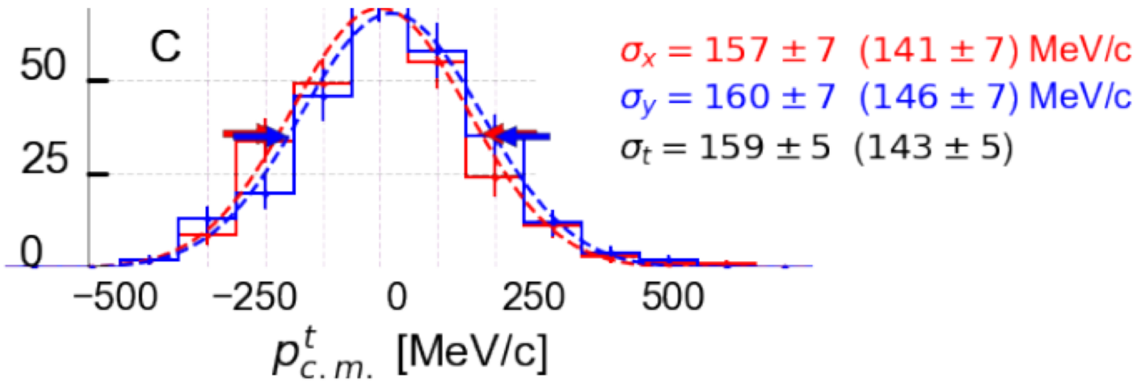


c.m. momentum



- Small c.m. -> small separation between the pairs
- 3D Gaussian -> consistent with the sum of 2 mean field nucleons
- SRC pairs formed from mean field nucleons in specific quantum states

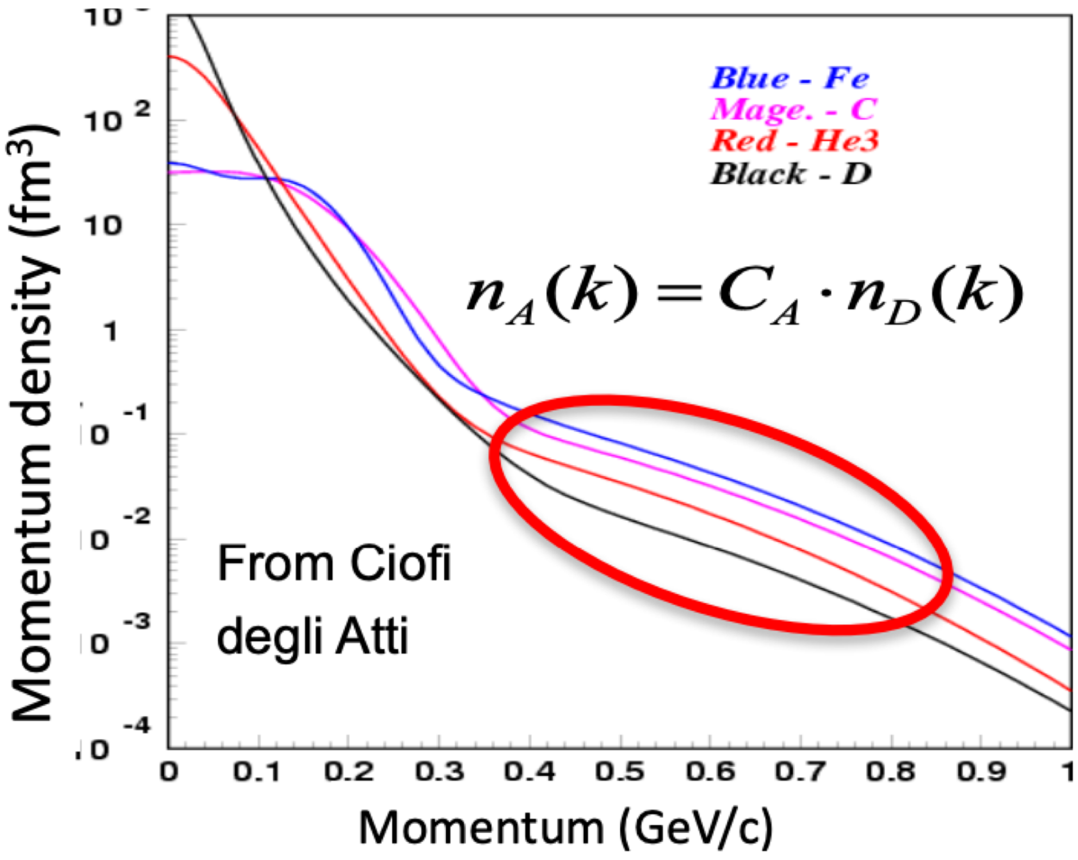
$$\vec{p}_{c.m.} = \vec{p}_{miss} + \vec{p}_{recoil} = \vec{p}_p - \vec{q} + \vec{p}_{recoil}$$

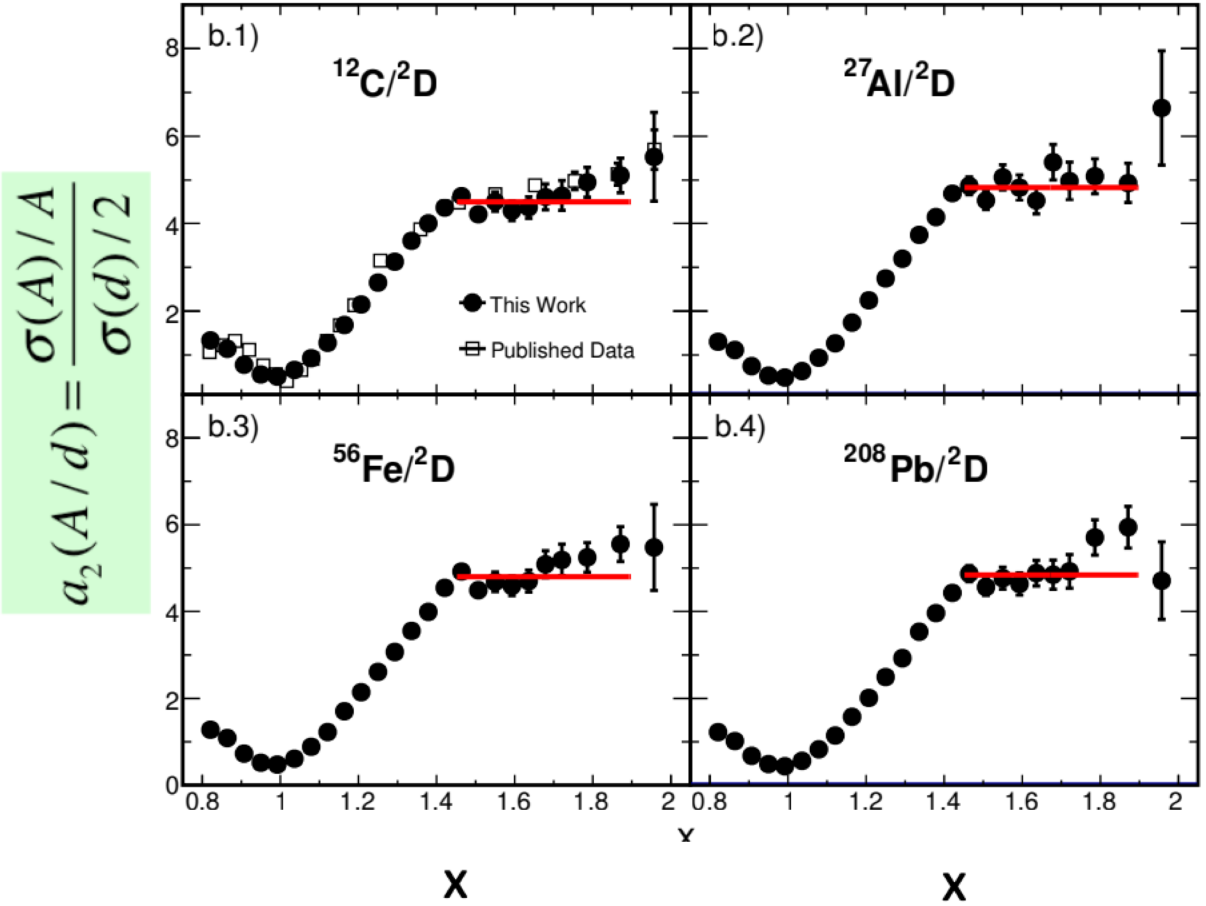


E. O. Cohen et al, Phys. Rev. Lett. 121, 092501 (2018)

SRC scaling

At high nucleon momenta, strength is different but shapes of distributions are similar
→ scaling!





B. Schmookler et al, Nature 566, 354 (2019)

Effective theory for SRCs

$$\Psi \xrightarrow{r_{ij} \to 0} \varphi(r_{ij}) \times A_{ij}(R_{ij}, \{r\}_{k \neq ij})$$

Many two body wave function

Two-body Wave function

A-2 Residual system

Generalized contact formalism: two body densities

$$\rho_A^{NN,\alpha}(r) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(r)|^2$$

Many body density

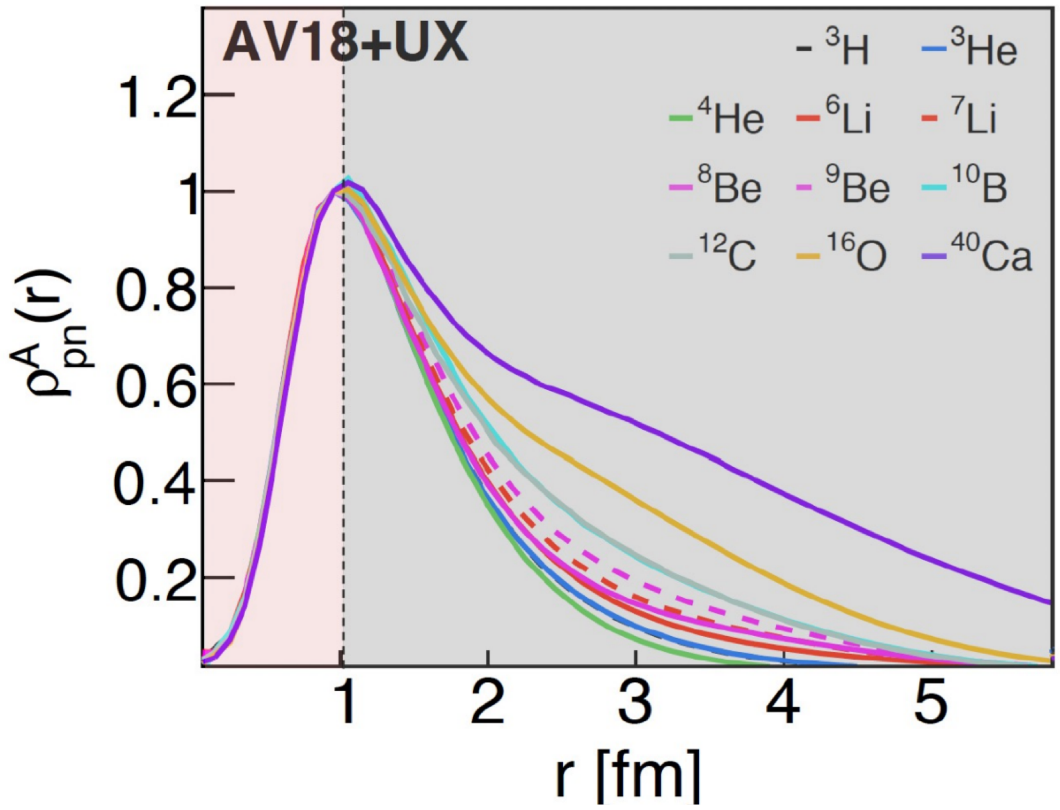
Nucleus-dependent contact

2-body density (universal)

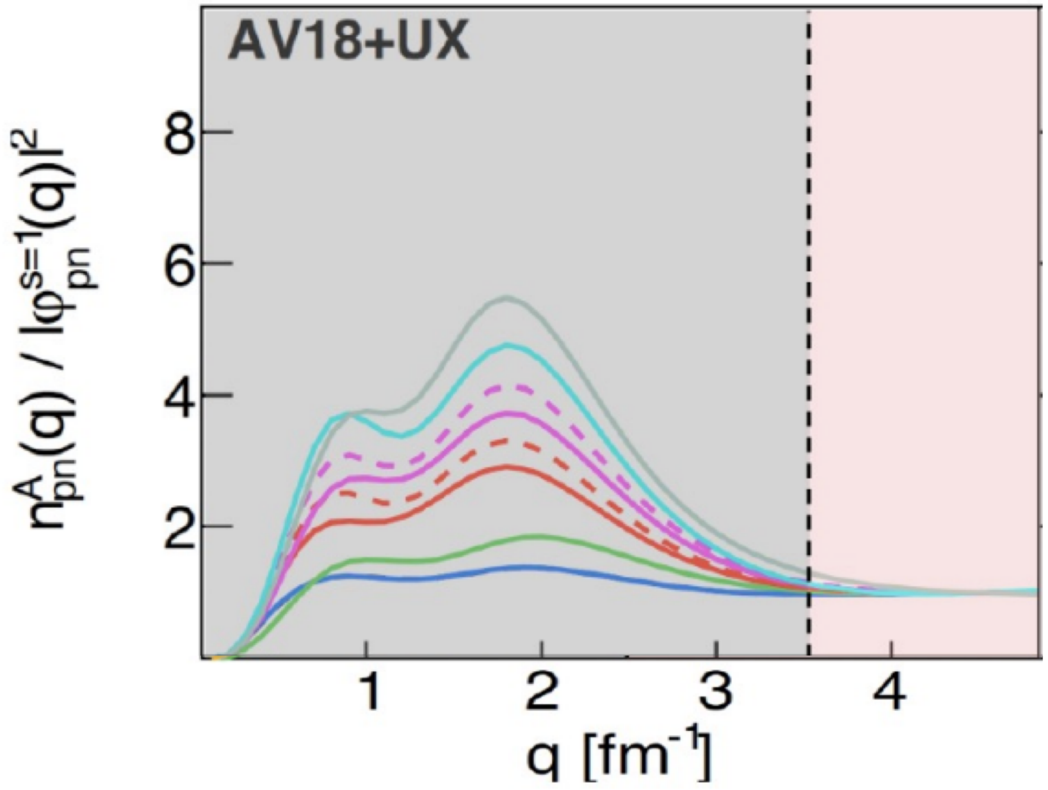
GCF: small r, high k scaling

$$\rho_A^{NN,\alpha}(r) = C_A^{NN,\alpha} \times |\varphi_{NN}^{\alpha}(r)|^2$$

Small r



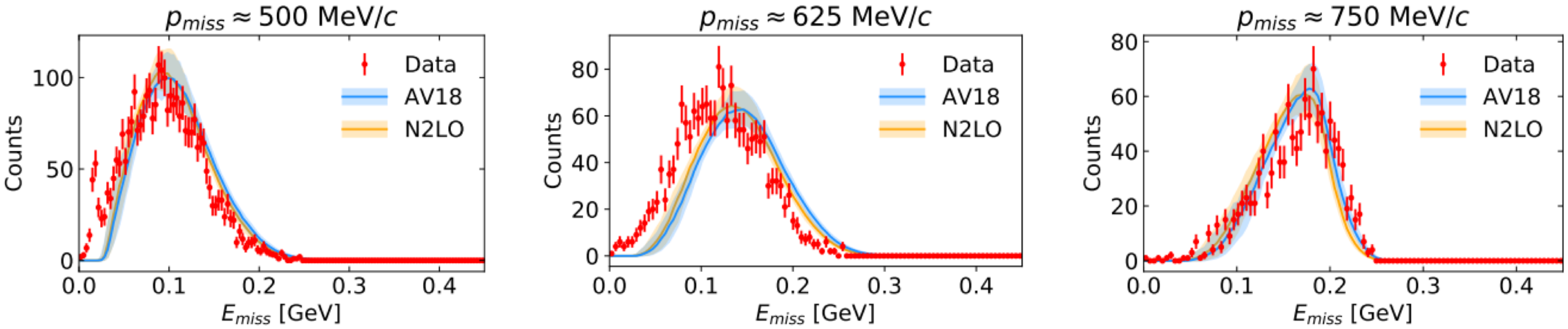
Large q (k)



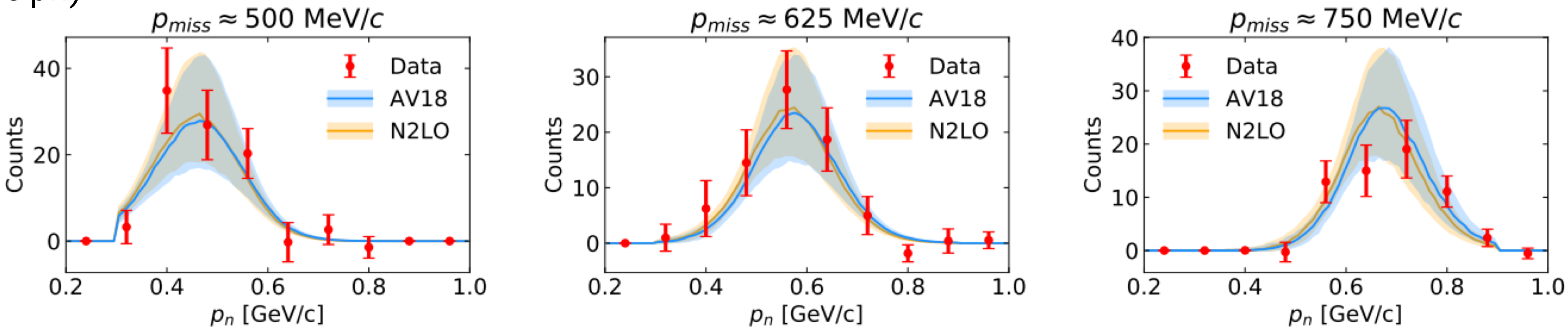
Cruz Torres and Lonardoni et al., Nature Physics (2020)

GCF compared to data

^{4}He(e,e'p) is well described using the GCF formalism!



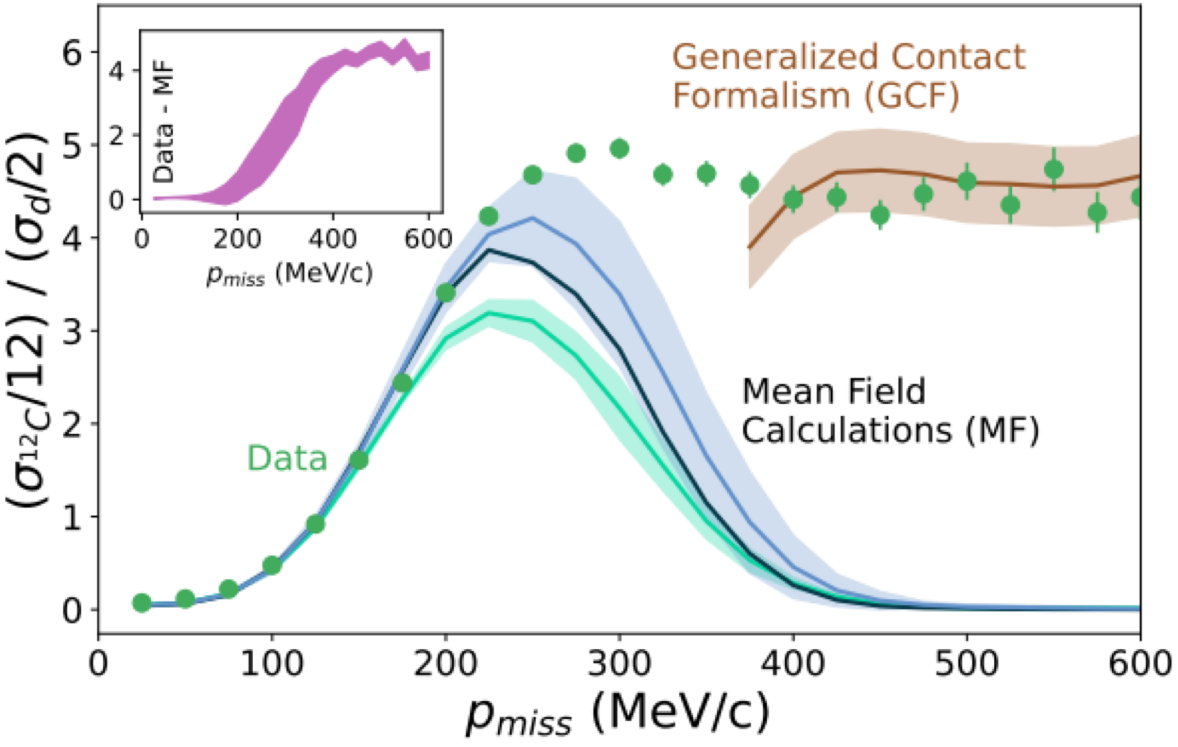
^{4}He(e,e'pn)

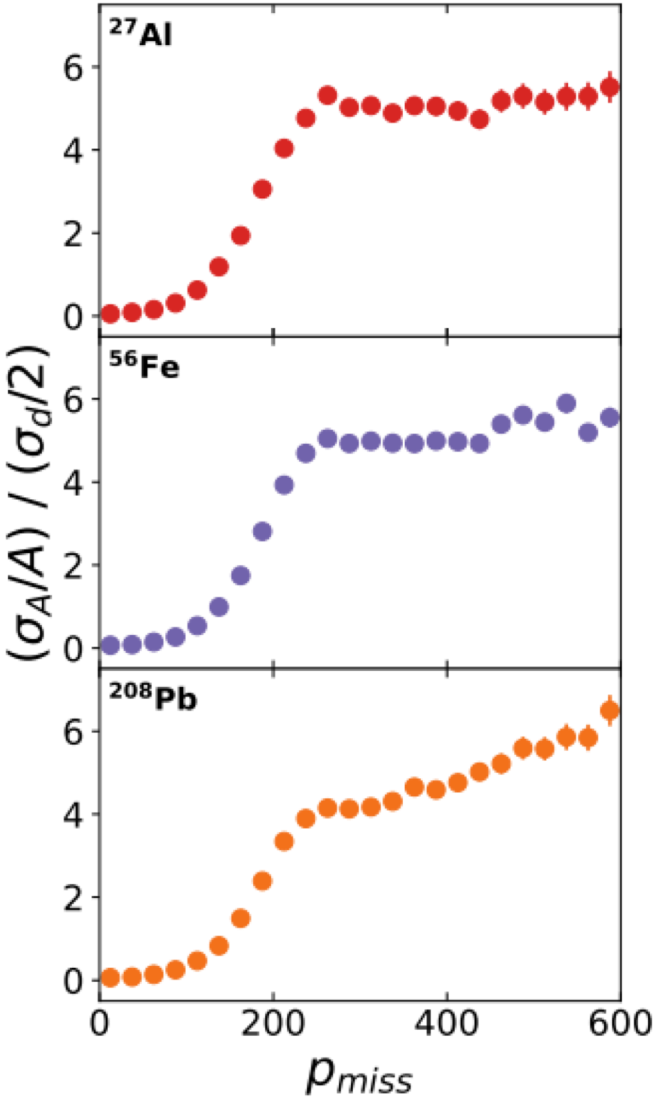


J.R. Pybus et al, Phys. Lett. B **805**, 135429 (2020)

Evidence of x-scaling

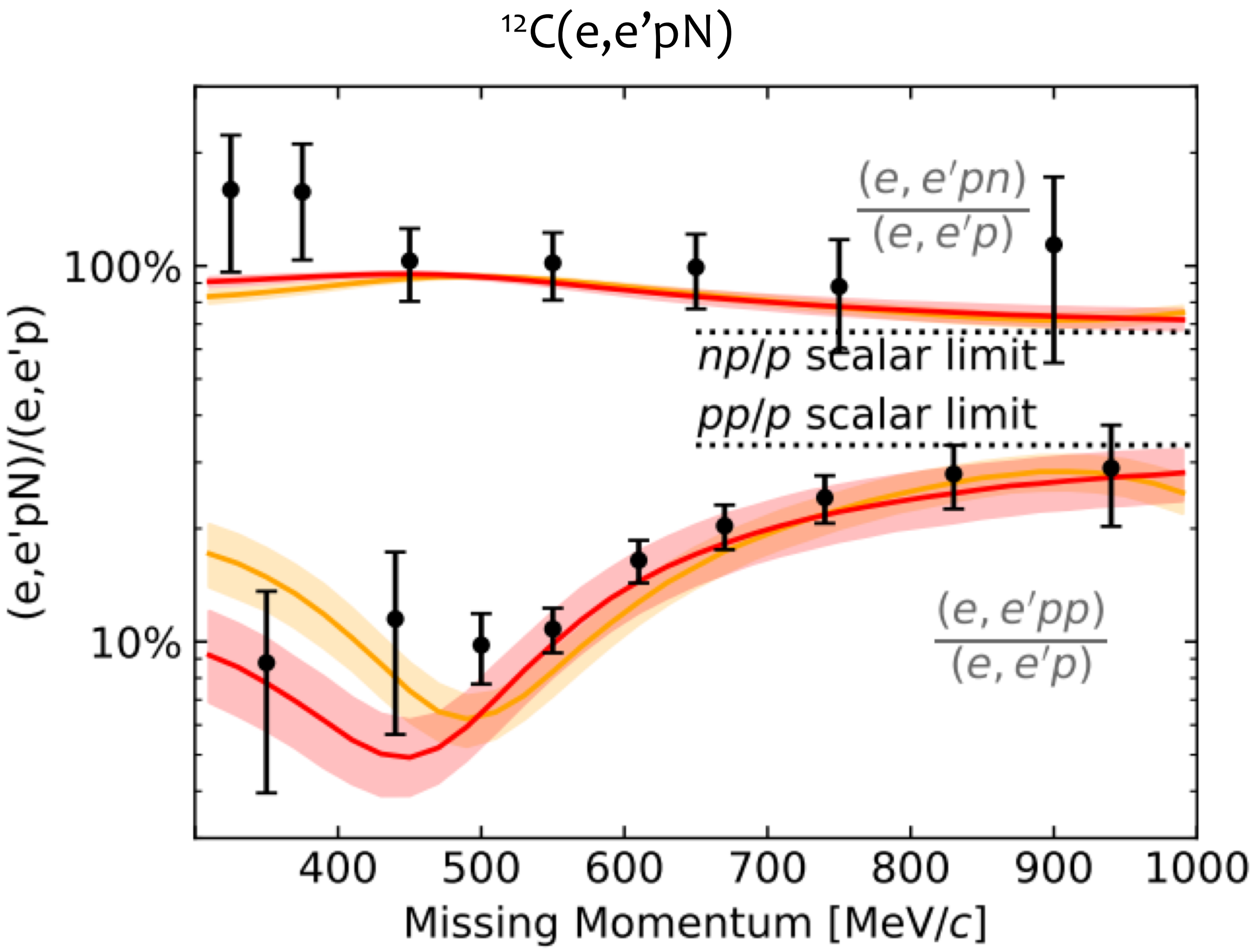
A(e,e'p), for x from 0.7-1.8





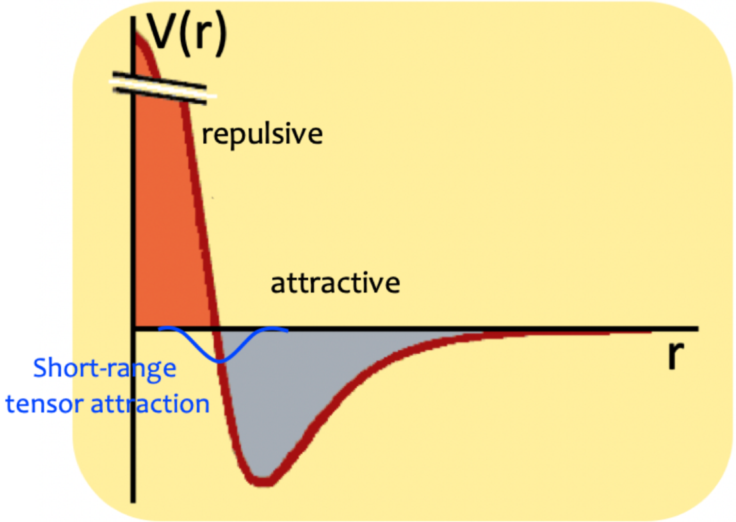
I. Korover et al, Phys. Rev. C, accepted (2023)

SRC in the tensor to scalar transition region



Data compared to GCF model (N2LO, AV18)

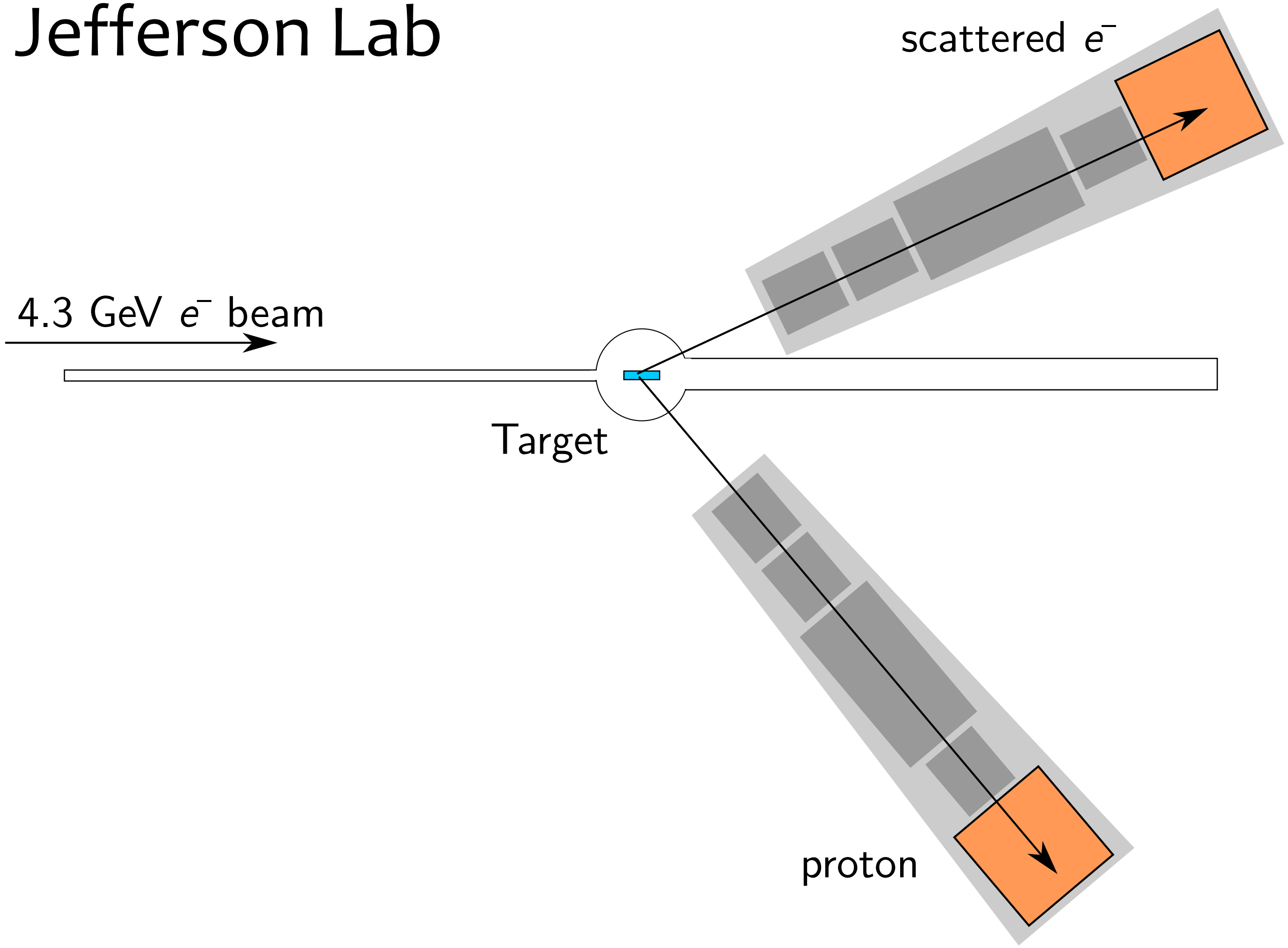
Transition from isospin-dependent tensor NN interaction (~400 MeV) to an isospin-independent scalar interaction (~800 MeV)

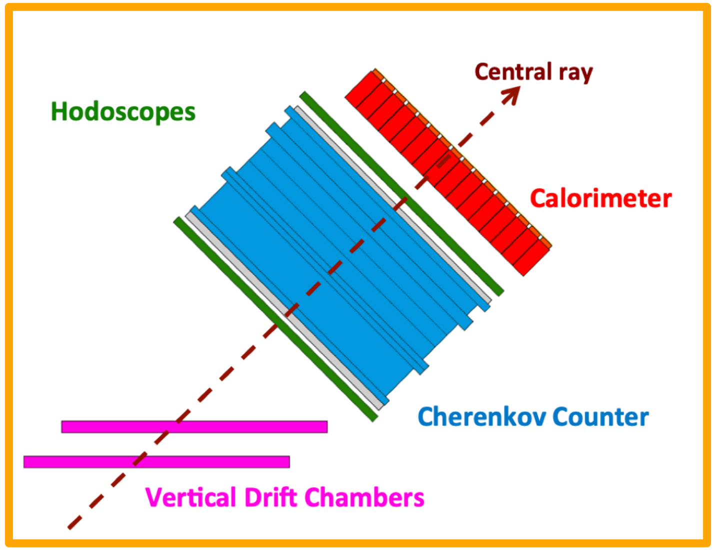


I. Korover et al, Phys. Lett. B **820**, 136523 (2021)

(e,e'p) to study the NN interaction

Hall A, Jefferson Lab





High p_{miss} setting ("high momentum")

Low p_{miss} setting ("low momentum")

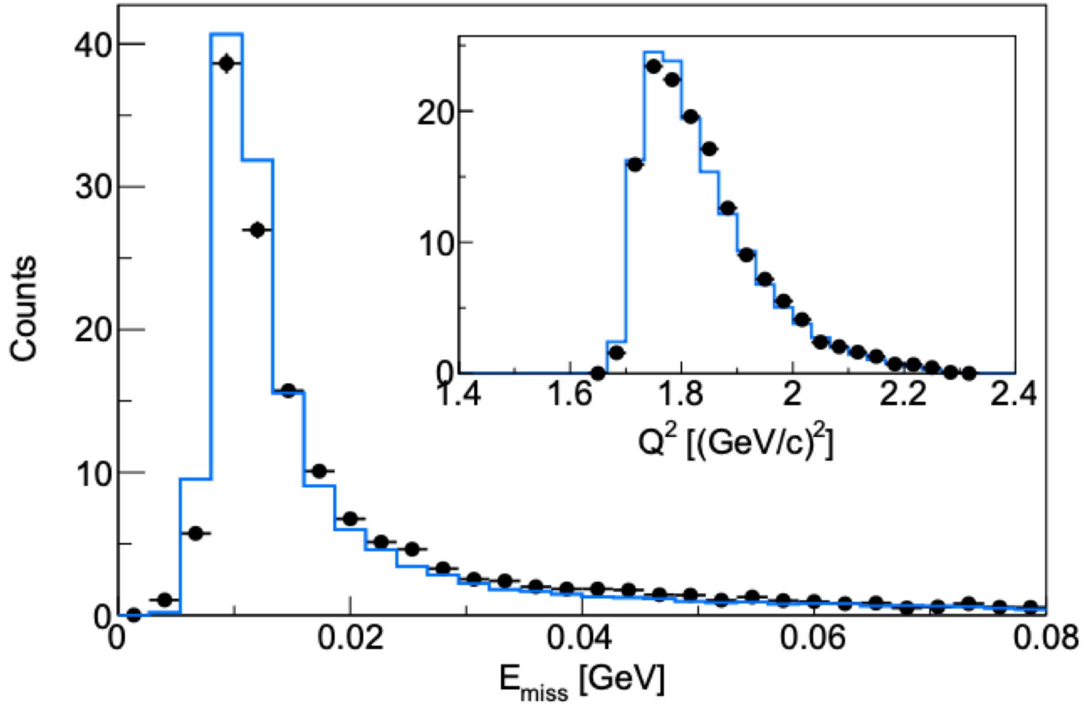
R. Cruz-Torres et al., PLB 797 134890 (2019)
R. Cruz-Torres, PRL 124 212501 (2020) [Editor Suggestion]

First simultaneous measurement on ^3He, ^3H, ^2H

$$\frac{^3He\,(p)}{^3H\,(p)} \cong \frac{^3He\,(p)}{^3He\,(n)}$$

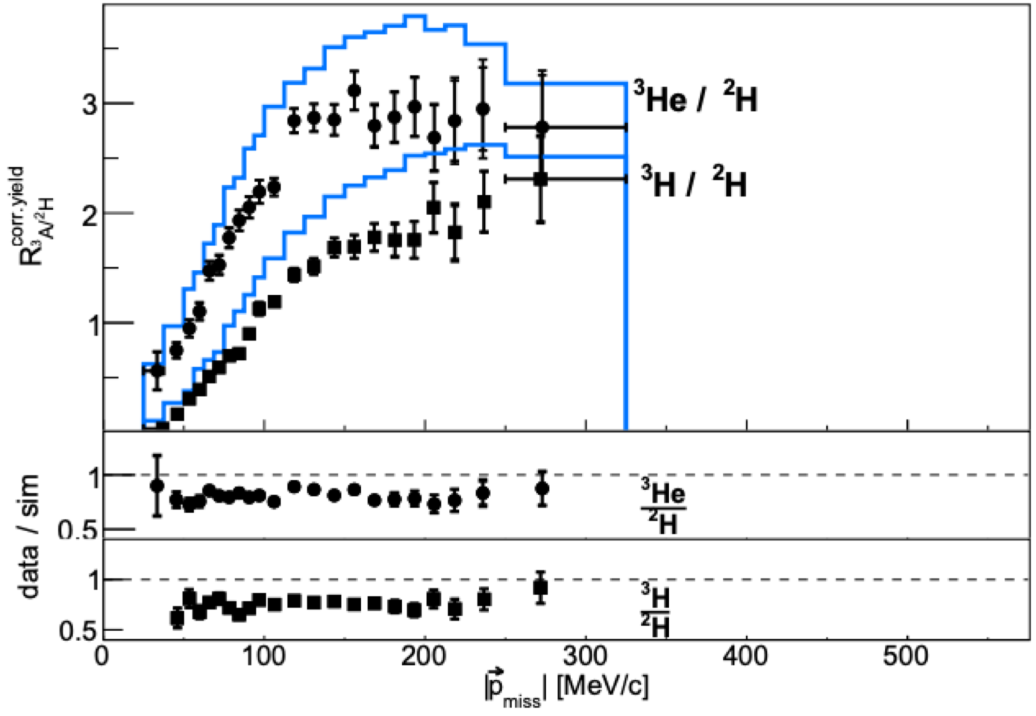
^3H: E_{miss} for low p_{miss},

Simulation of ^3He neutron spectral function



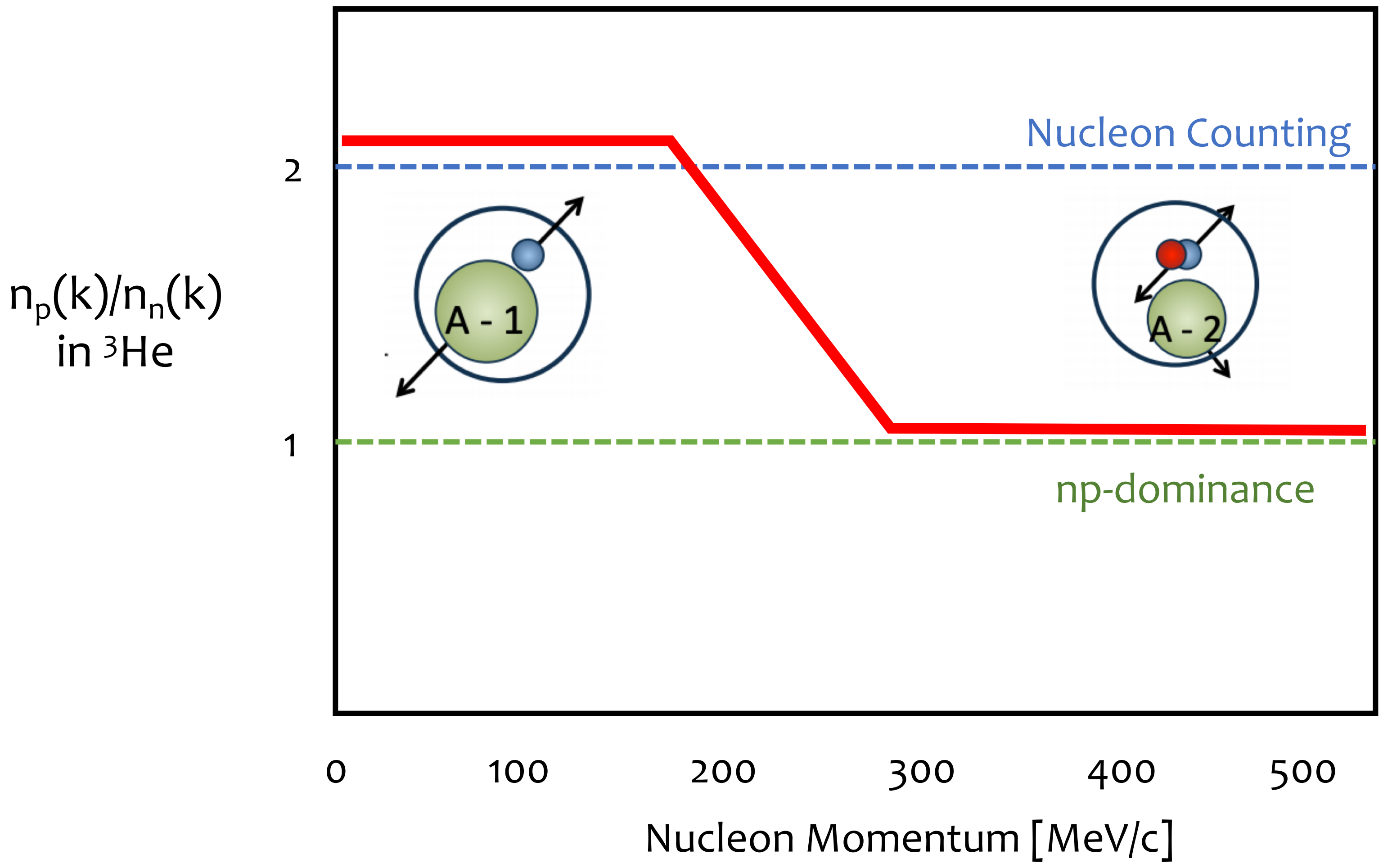
Ratios relative to deuterium

PWIA simulation

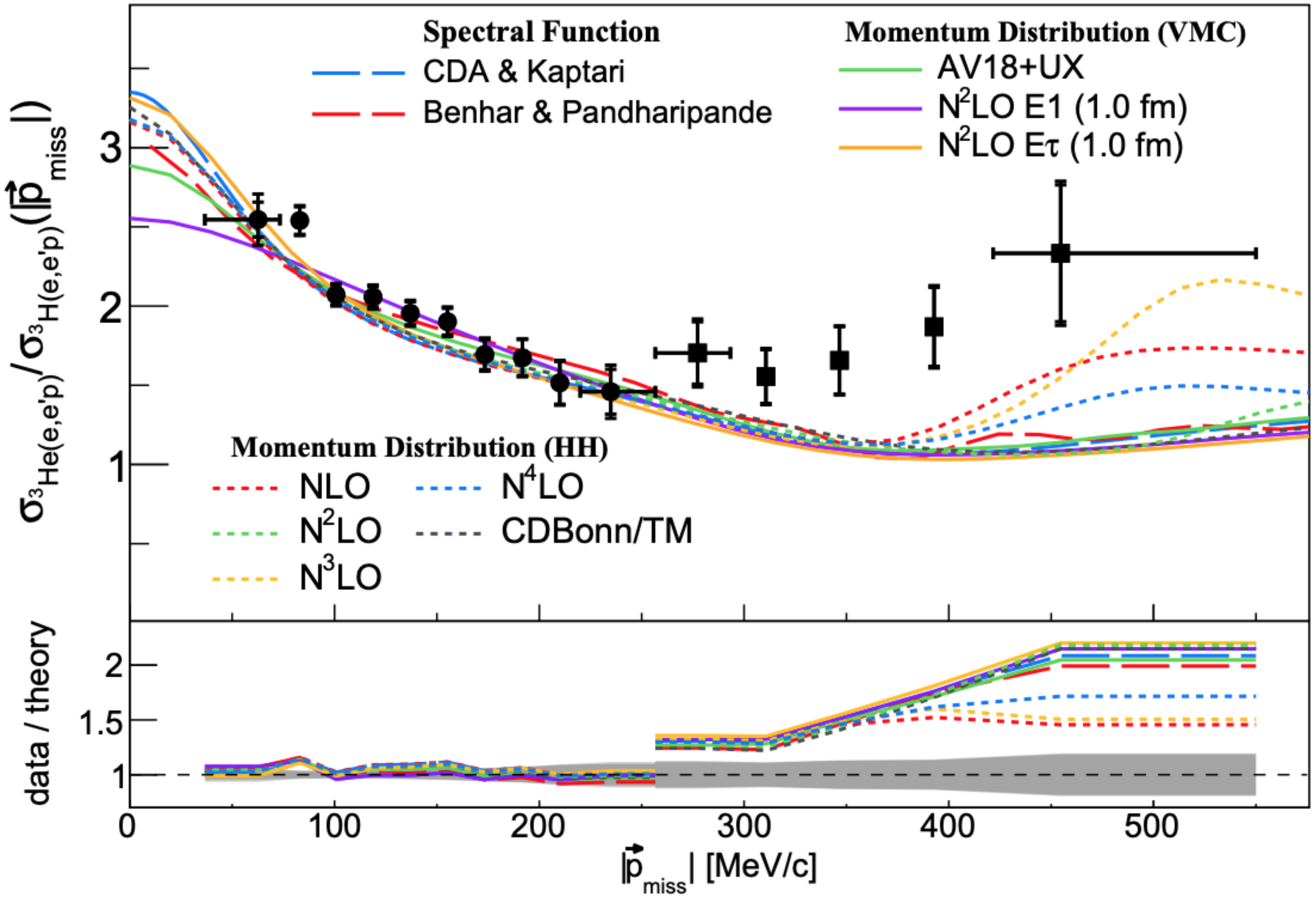


R. Cruz-Torres et al., PLB 797 134890 (2019)

Simple picture of the $^3He/^3H$ ratio



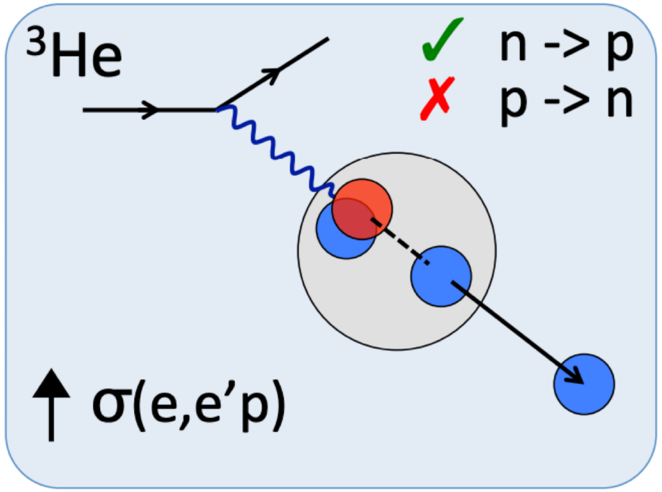
^{3}He/^{3}H ratio results

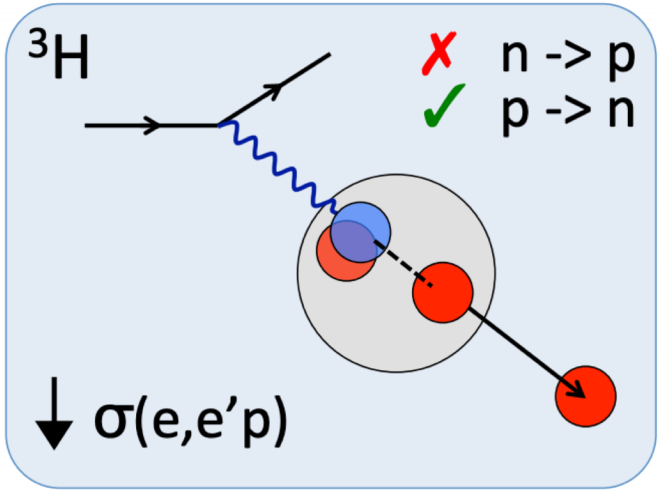


R. Cruz-Torres et al., PLB 797 134890 (2019)

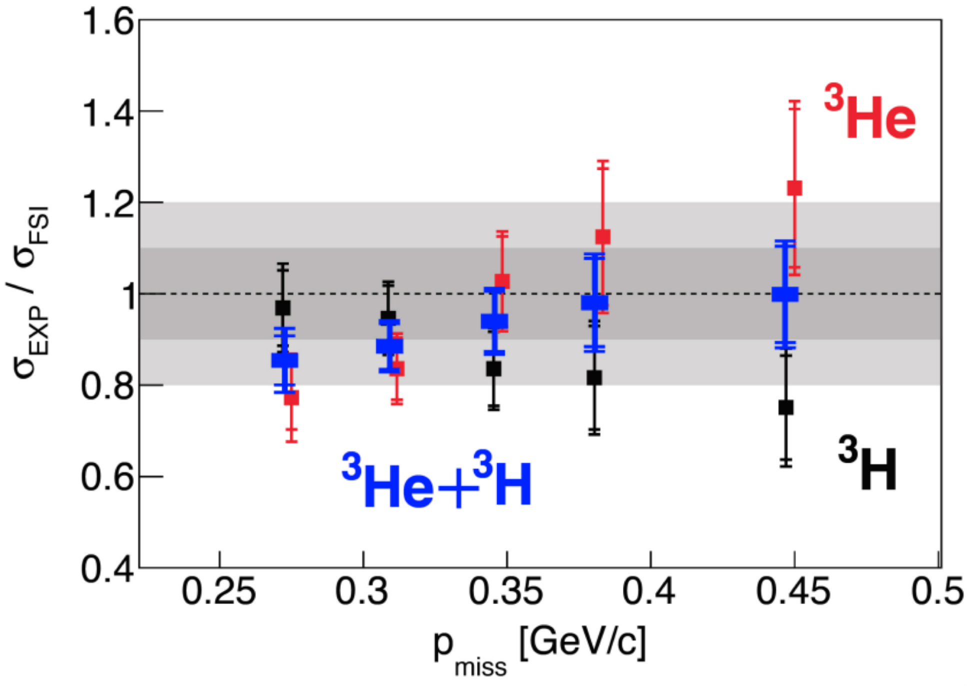
Iso-scalar sum

Iso-scalar sum insensitive to Single Charge Exchange (SCX)





Iso-scalar sum described by theory at higher p_{miss}



Planned experiment to explore higher momentum in CLAS12

*σ_{FSI} from M. Sargsian,
using Generalized Eikonal Approximation, excludes FSI_{23}

Re-visiting the EMC Effect with SRCs

Bound = **'quasi Free'** + **Modified SRCs**

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n)$$

$$\Delta F_2^N = F_2^{N*} - F_2^N$$

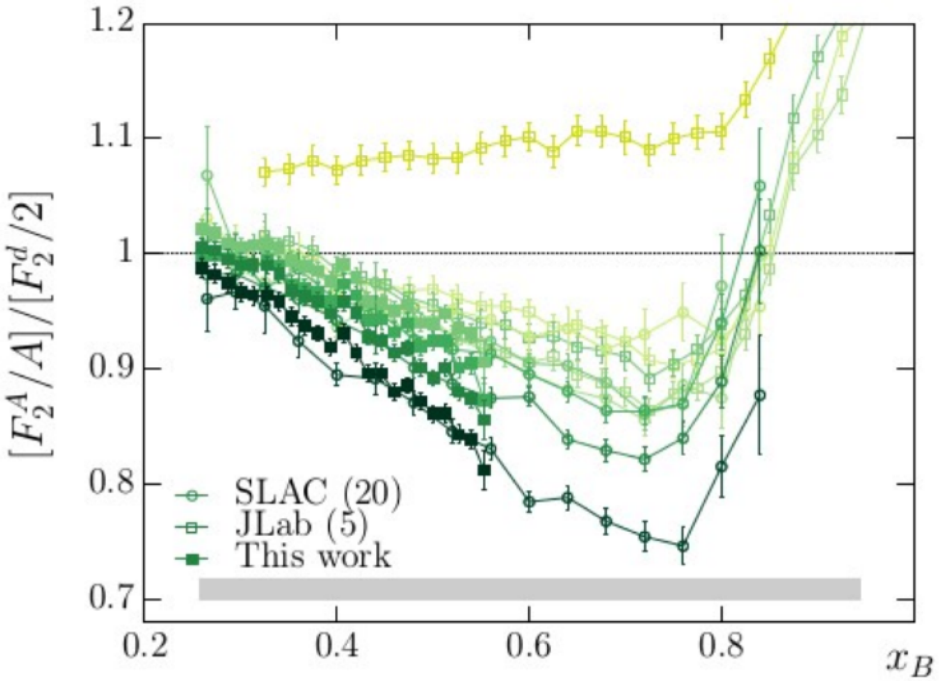
$$F_2^d = F_2^p + F_2^n + n_d^{SRC}(\Delta F_2^p + \Delta F_2^n)$$

$$a_2 \equiv \frac{2}{A} n_A^{SRC} / n_d^{SRC}$$

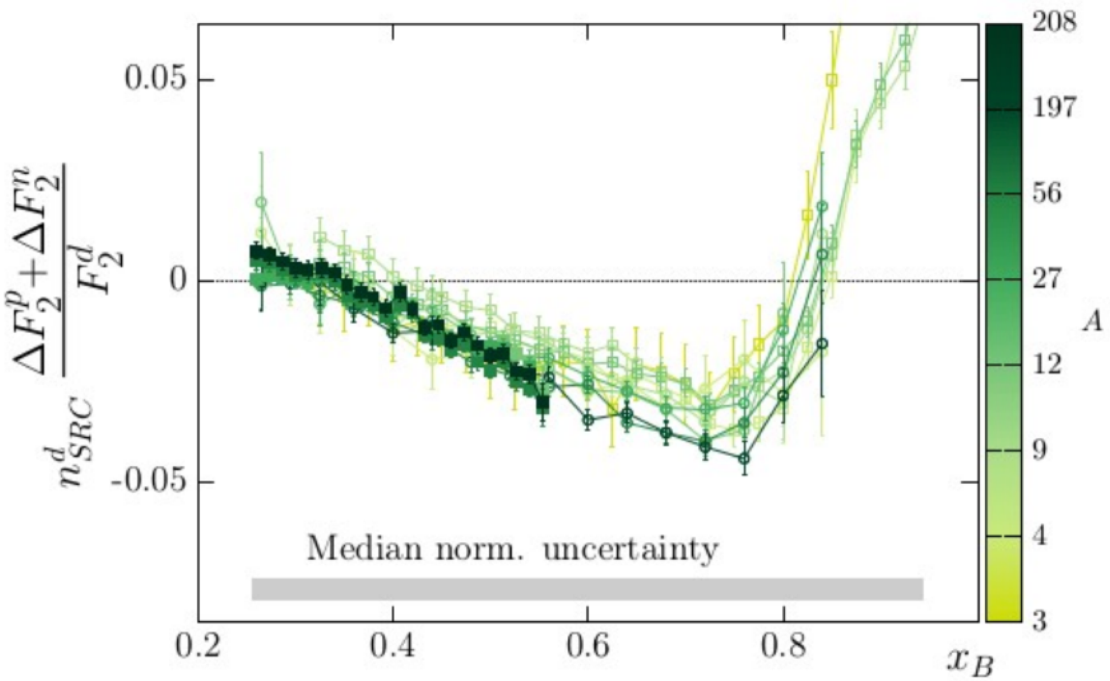
EMC Effect and SRC abundances

$$n_d^{SRC}\,\frac{\Delta F_2^p+\Delta F_2^n}{F_2^d}=\frac{\frac{F_2^A}{F_2^d}-(Z-N)\frac{F_2^p}{F_2^d}-N}{\frac{A}{2}a_2-N}$$

Universal???



Nucleus-Dependent

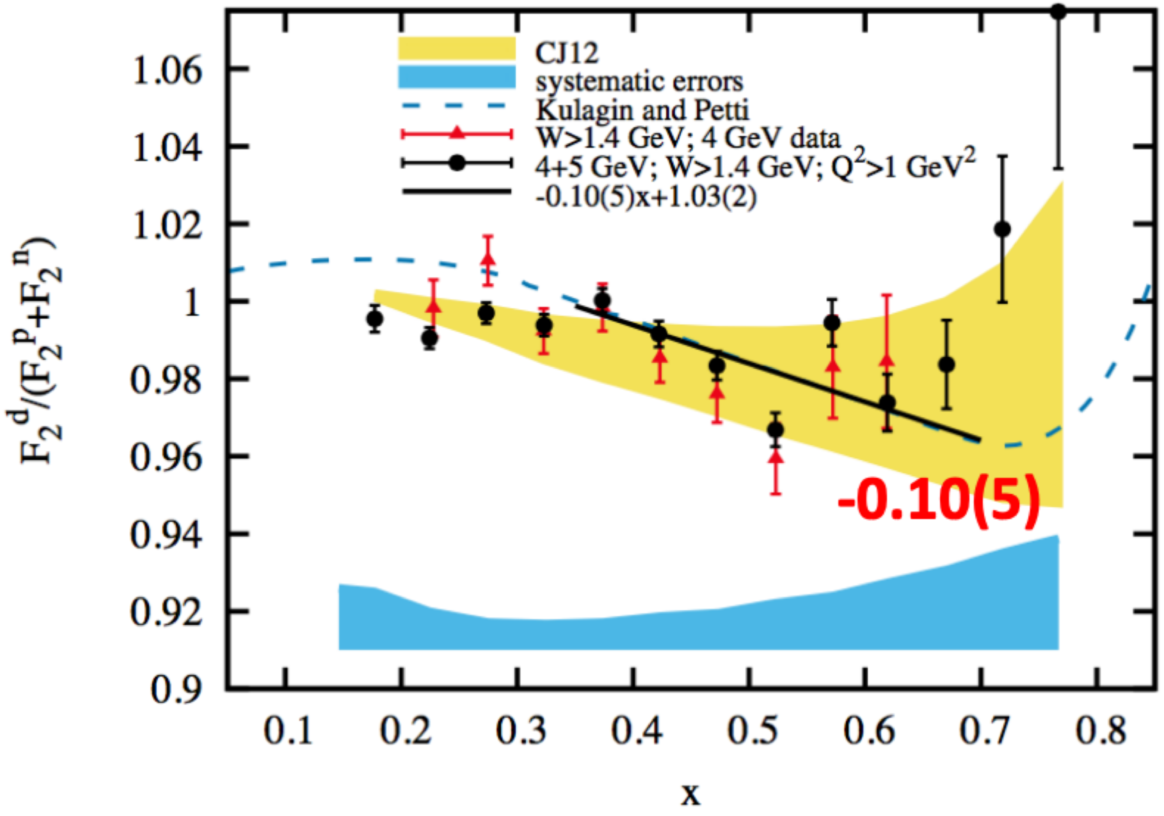


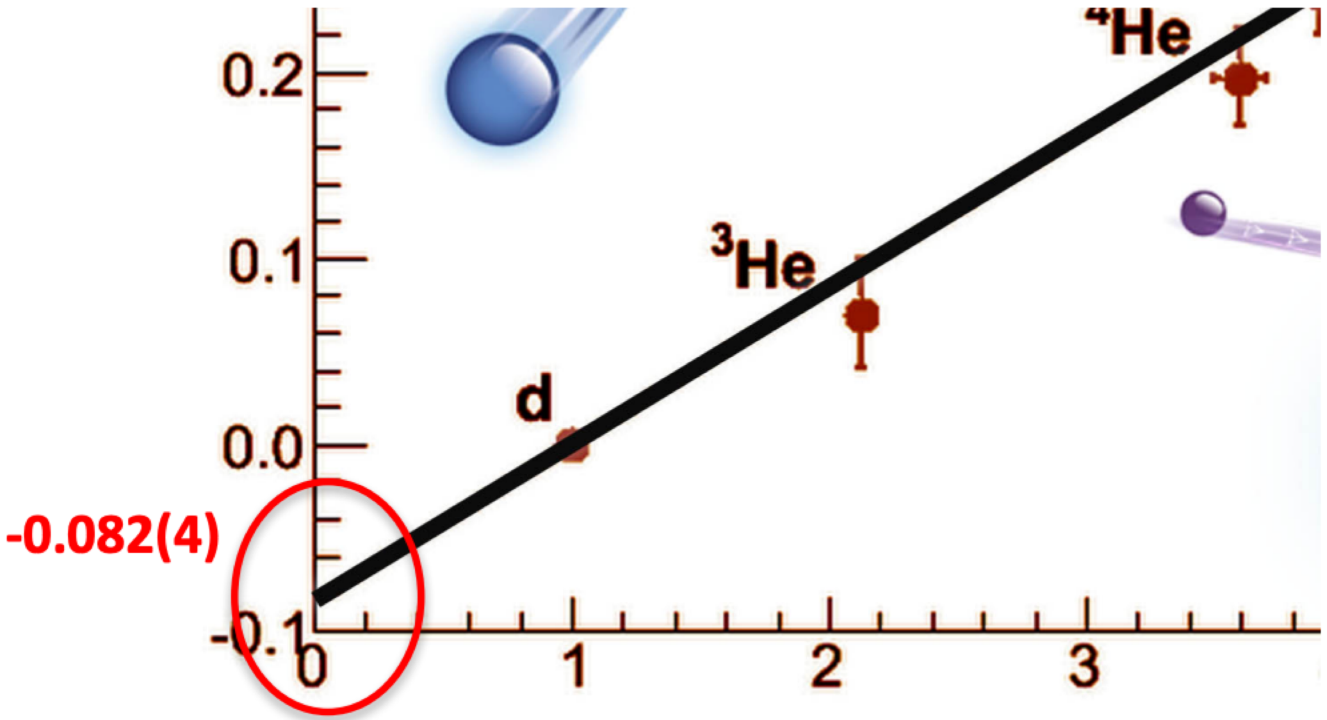
Implies heavier nuclei with many more neutrons than protons, each proton is more likely than each neutron to belong to an SRC pair and hence to have its quark structure distorted.

B. Schmookler et al, Nature **566**, 354 (2019)

Is there an EMC Effect in the deuteron?

$$\sigma_d^{DIS} \neq \sigma_p^{DIS} + \sigma_n^{DIS}$$





Slope is consistent with conventional nuclear physics models that include off-shell corrections, as well as with short-range-correlation models of the EMC effect

Griffioen et al, PRC 92, 015211 (2015)

The big EMC Effect question

Are all the nucleons each modified a little bit by the mean field?

or

Are the few high-momentum nucleons each modified a lot by the short range interaction?

How can we test the Big Question?

Measure the in-medium modified(?) structure function F_2 in DIS as a function of nucleon momentum:

$$\frac{d^3\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{1}{\omega}F_2(x_B,Q^2) + \frac{2}{M}F_1(x_B,Q^2)\cdot\tan^2\left(\frac{\theta_e}{2}\right)\right]$$

F_1 and F_2 are related by R, the measured ratio of longitudinal and transverse cross sections. Thus, the cross section yields F_2.

All nucleons modified

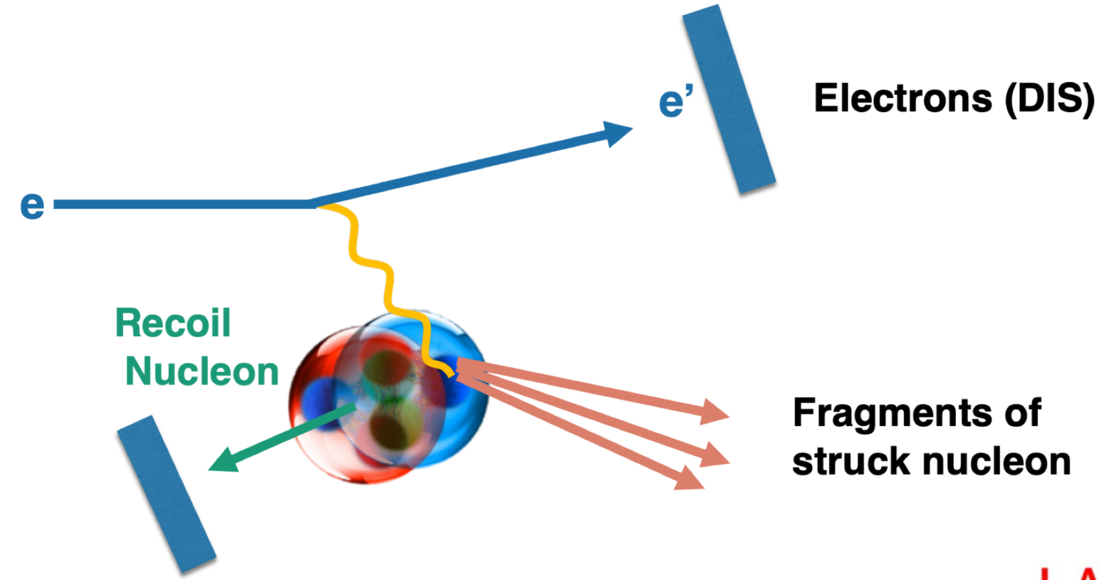
- F_2 independent of momentum
- $F_2 \neq$ free F_2 (small difference for all nucleons)

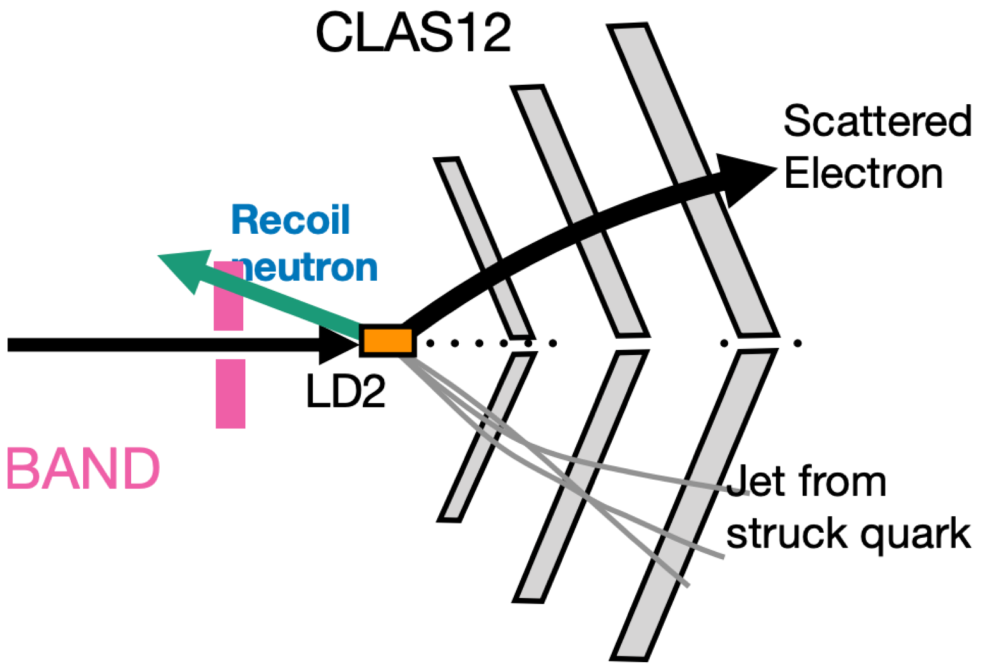
SRC nucleons modified

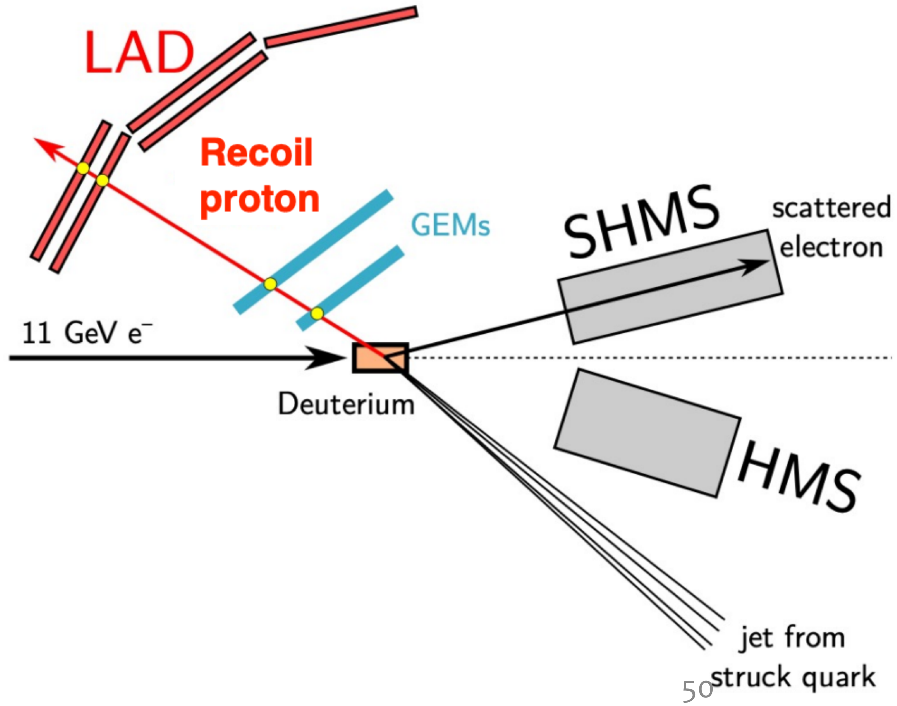
- F_2 varies with momentum
- $F_2 \neq$ free F_2 (big difference for high momentum nucleons)

Two experiments that test this:
BAND in Hall B (analyzing)
LAD in Hall C (runs in 2024)

On a quest – spectator tagging!







Exploring the QCD transition

Modifications in the structure and interactions of hadrons in the nucleus.

The transition from quark-gluon to nucleon-meson degrees of freedom.

Nuclear transparency
-> Color transparency

Nuclear transparency

Probability knocked out proton in scattering to be deflected or absorbed.

Ratio of cross-sections for exclusive processes from nuclei and nucleons is the Transparency.

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

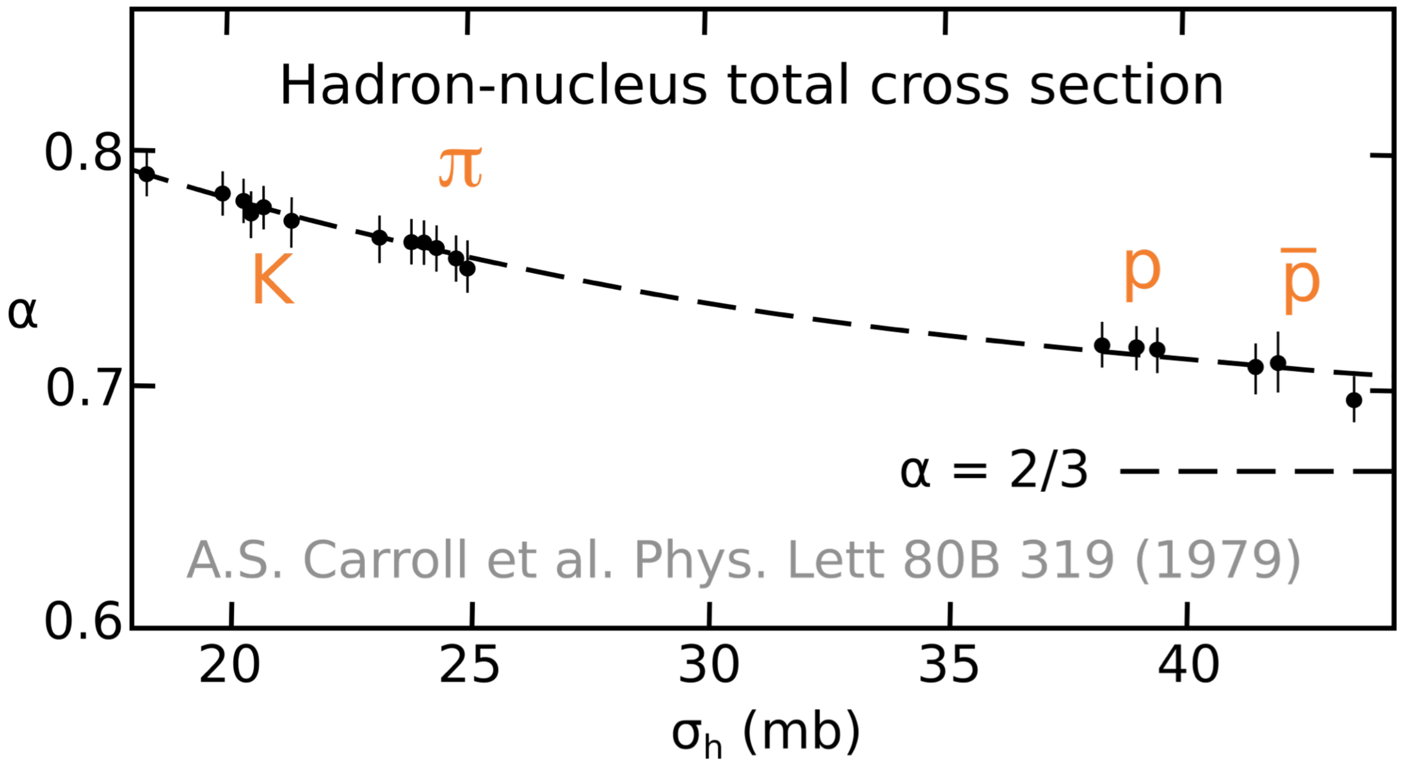
σ_A (nuclear cross section)

σ_N (free nucleon cross section)

$$\sigma_A = \sigma_N\, A^{\alpha}$$

Hadron-nucleus total cross section

Hadron momenta:
60, 200, 280 GeV/c



$$\sigma_A(A) = \sigma_N \, A^\alpha$$

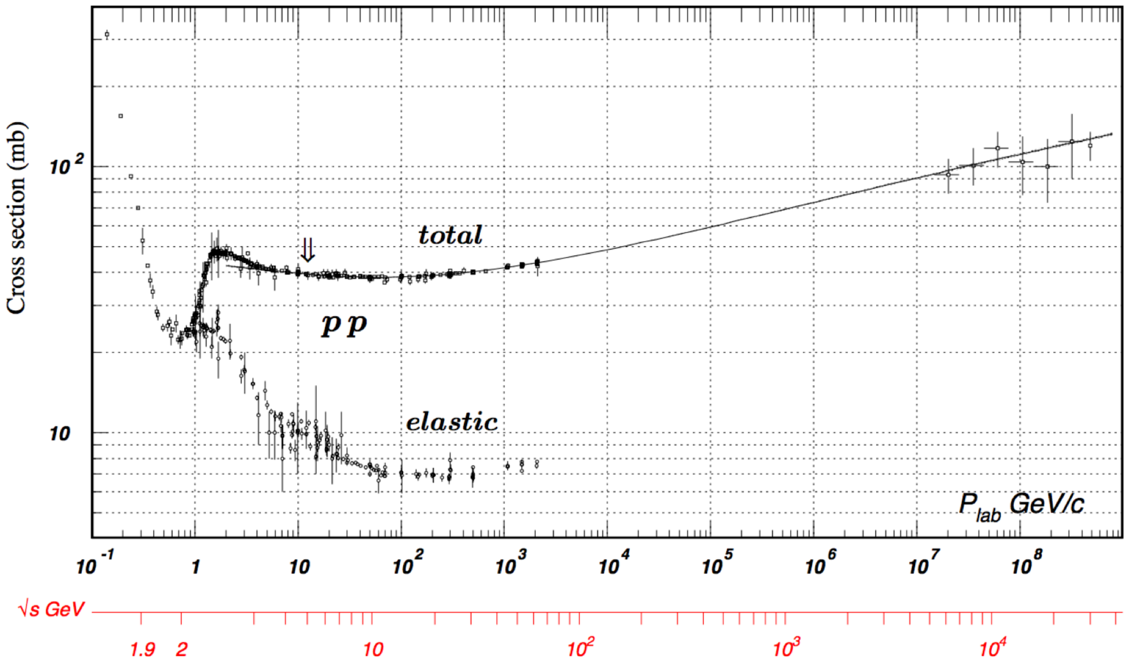
α <1 due to strong interaction nature of the probe

Absorption cross section momentum independent.
Tendency of ***α*** → 2/3 expected for opaque nucleus.

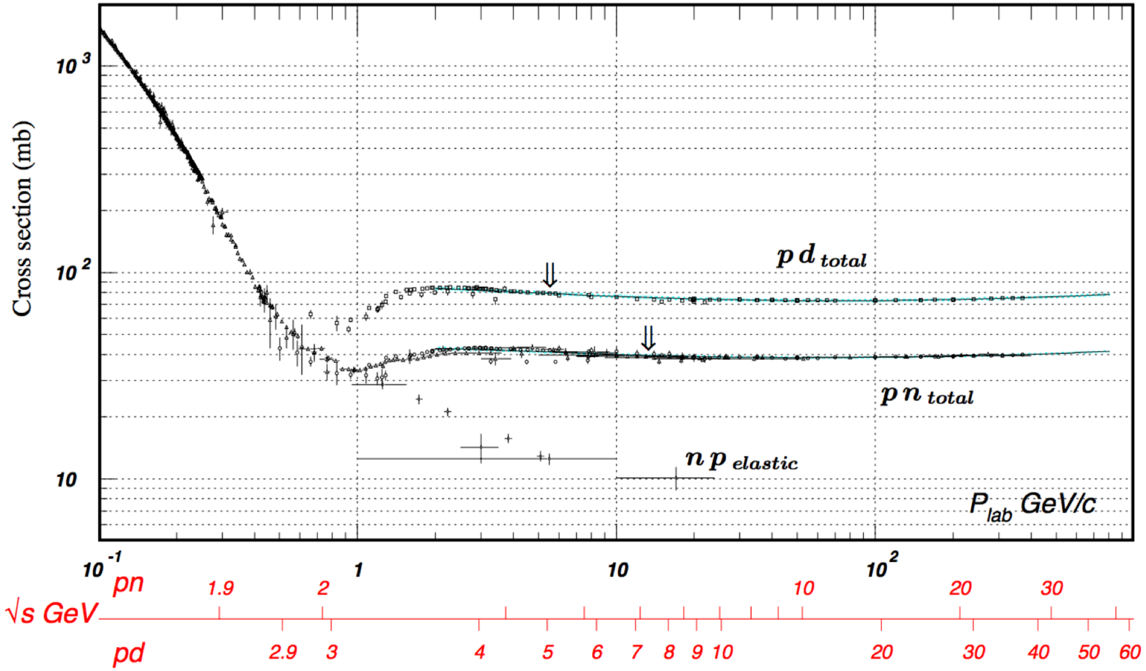
NN cross section

NN cross section is essentially energy independent

pp scattering cross section

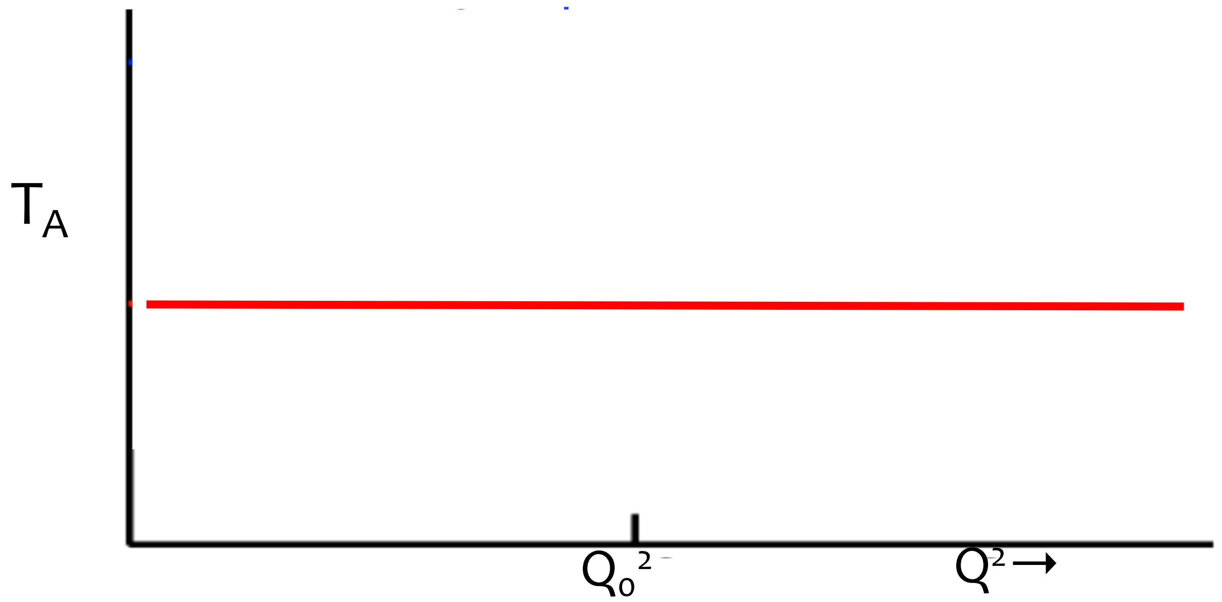


pn scattering cross section



Transparency ingredients

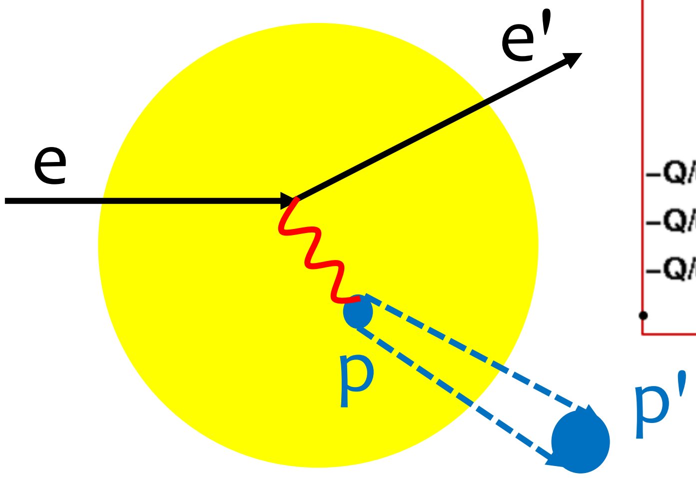
Traditional nuclear physics calculations (Glauber) predict energy independent transparency:

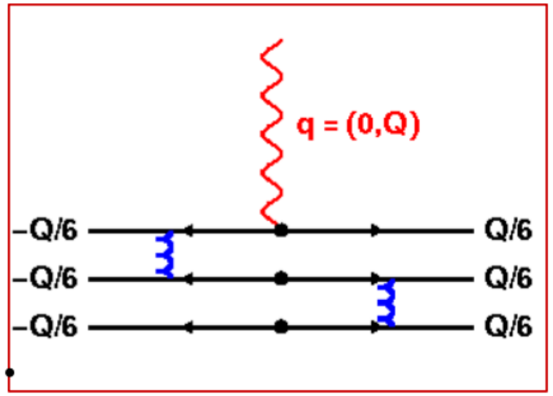


Measuring transparency:

- scattering cross section
- Glauber multiple scattering
- Correlations and Final State Interaction (FSI) effects

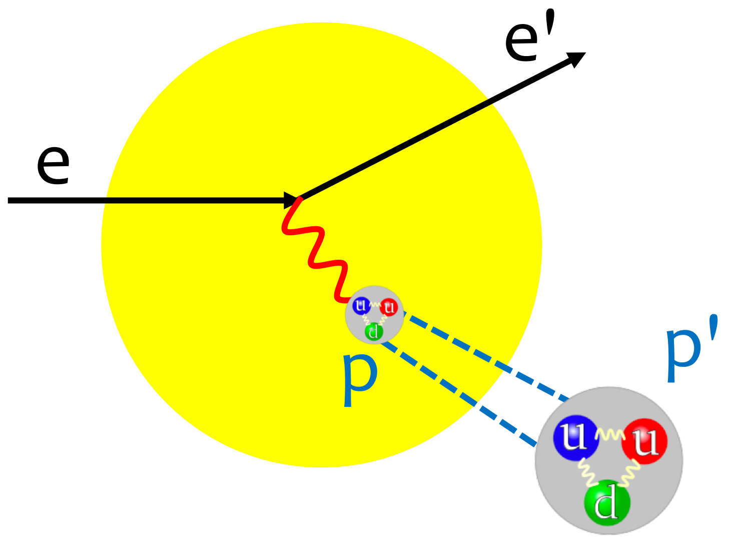
Color transparency





- Introduced by Mueller and Brodsky, 1982
- Vanishing of initial/final state interaction of hadrons with nuclear medium in exclusive processes at high momentum transfer

Color transparency is a fundamental prediction of QCD

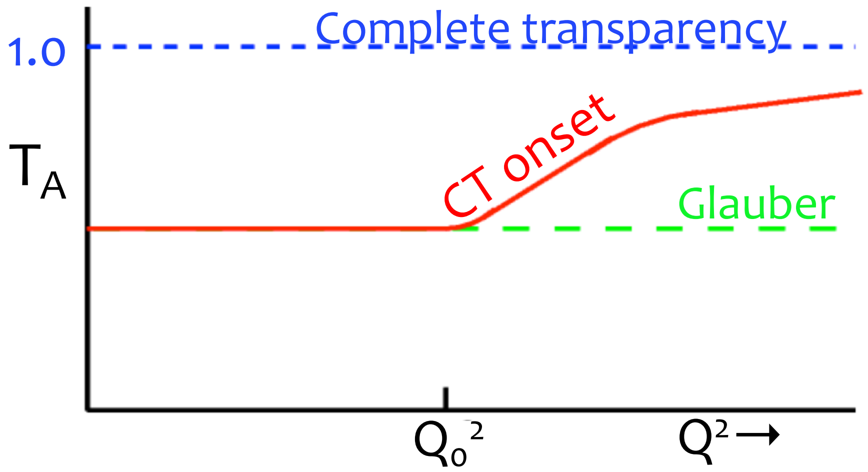


Quantum mechanics:
Hadrons fluctuate to small transverse size (*squeezing*, transferred momentum)

Relativity:
Maintains this small size as it propagates out of the nucleus (*freezing*, transferred energy)

Strong force:
Experience reduced attenuation in the nucleus, color screened

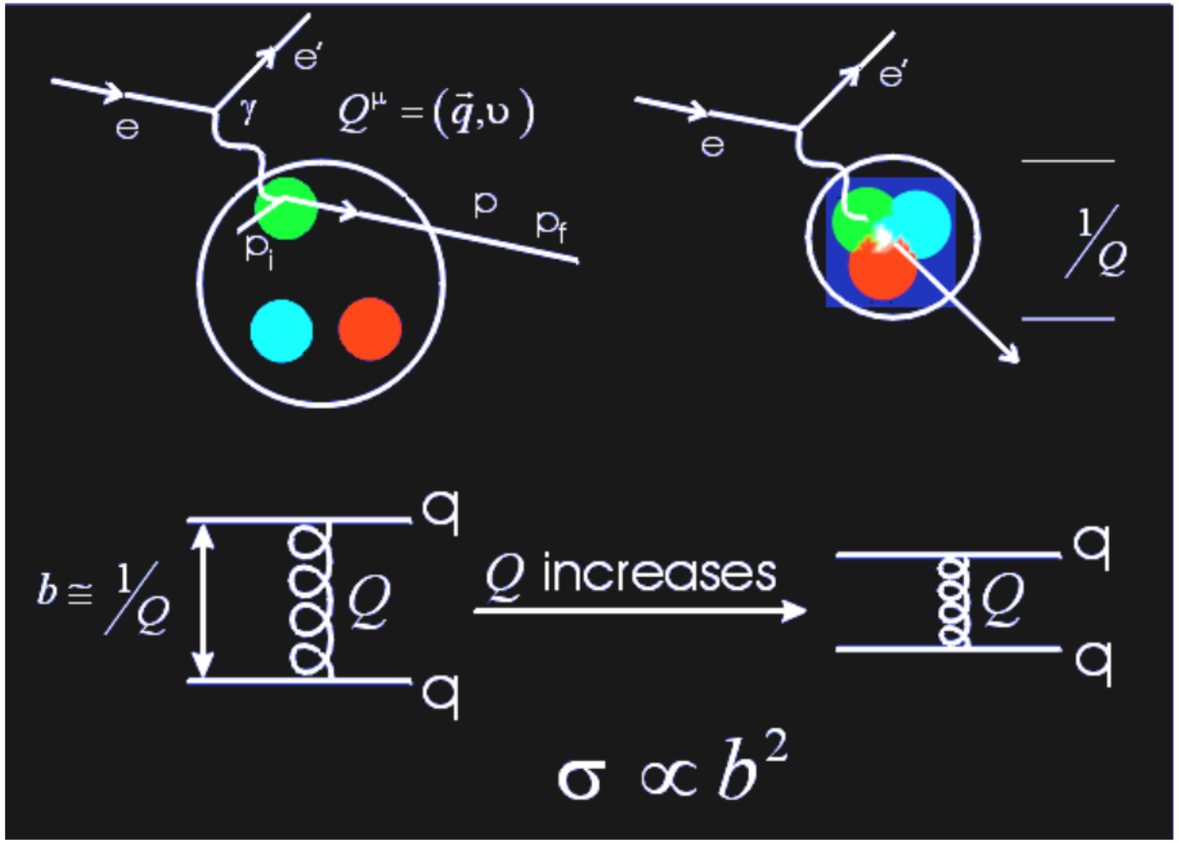
Onset of color transparency



- Not predicted by strongly interacting hadronic picture → arises in picture of quark-gluon interactions
- QCD: color field of singlet objects vanishes as size is reduced
- Signature is a rise in nuclear transparency, T_A, as a function of the momentum transfer, Q^2

Scales of color transparency

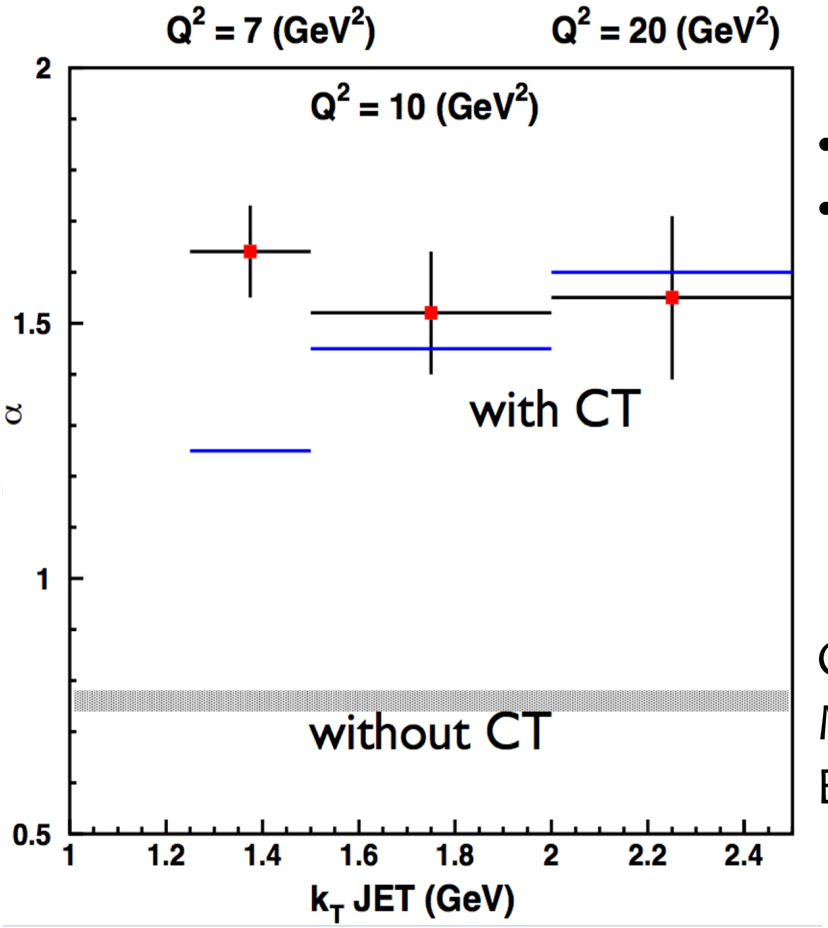
- Selection of the small size configuration ("squeezing", transferred momentum)
- At intermediate energies, expansion of of hadron also important ("freezing", transferred energy)
- Interplay between squeezing and freezing to determine the scale for onset of CT



CT at high energies

Coherent diffractive dissociation of 500 GeV/c pions on C and Pt

π + A → 2 jets + A'



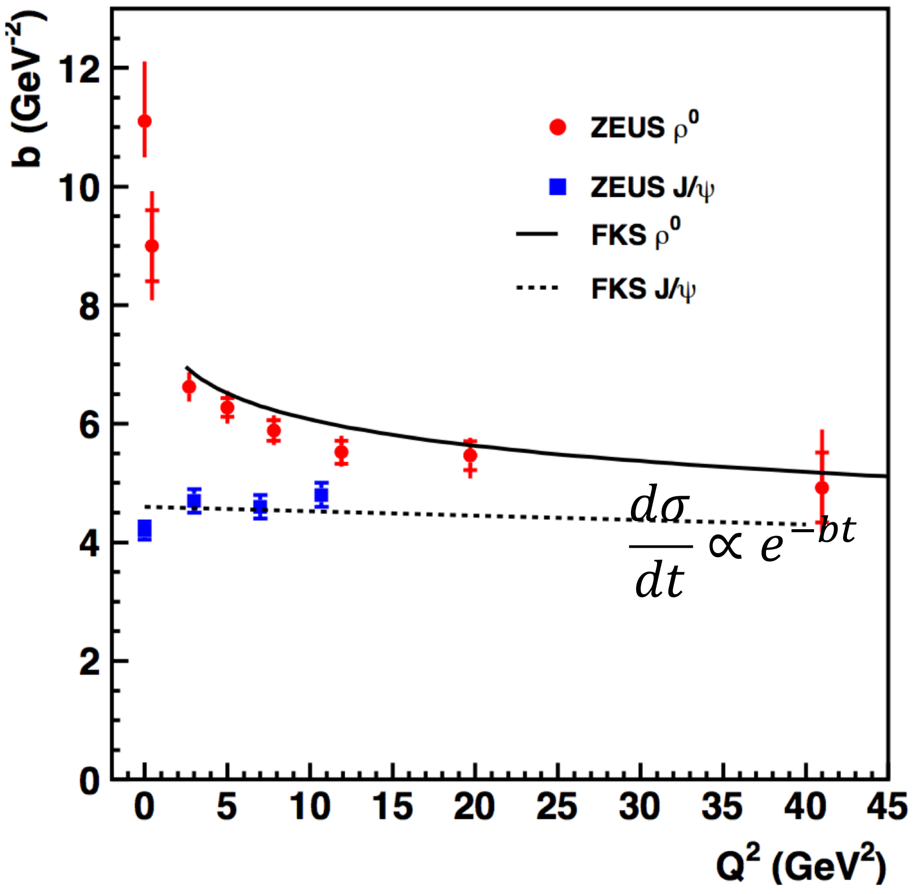
- Fit to $\sigma = \sigma_0 A^{\alpha}$
- Pion-nucleus total cross section, α=1.6

CT predictions by L. L. Frankfurt, G. A. Miller, and M. Strikman, Phys. Lett. B304, 1 (1993)

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

CT at high energies

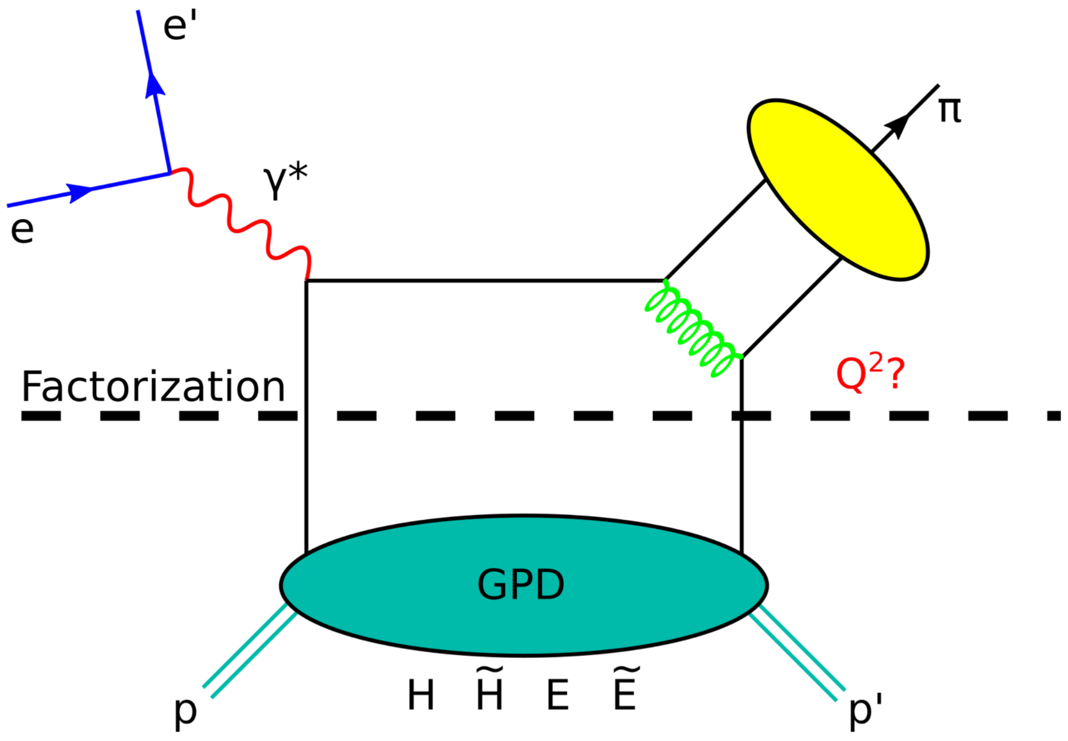
Vector meson production at HERA



$$\frac{d\sigma}{dt} \propto e^{-bt}$$

Convergence of t-slope at large Q^2 is seen to be related to presence of small configuration qq-bar

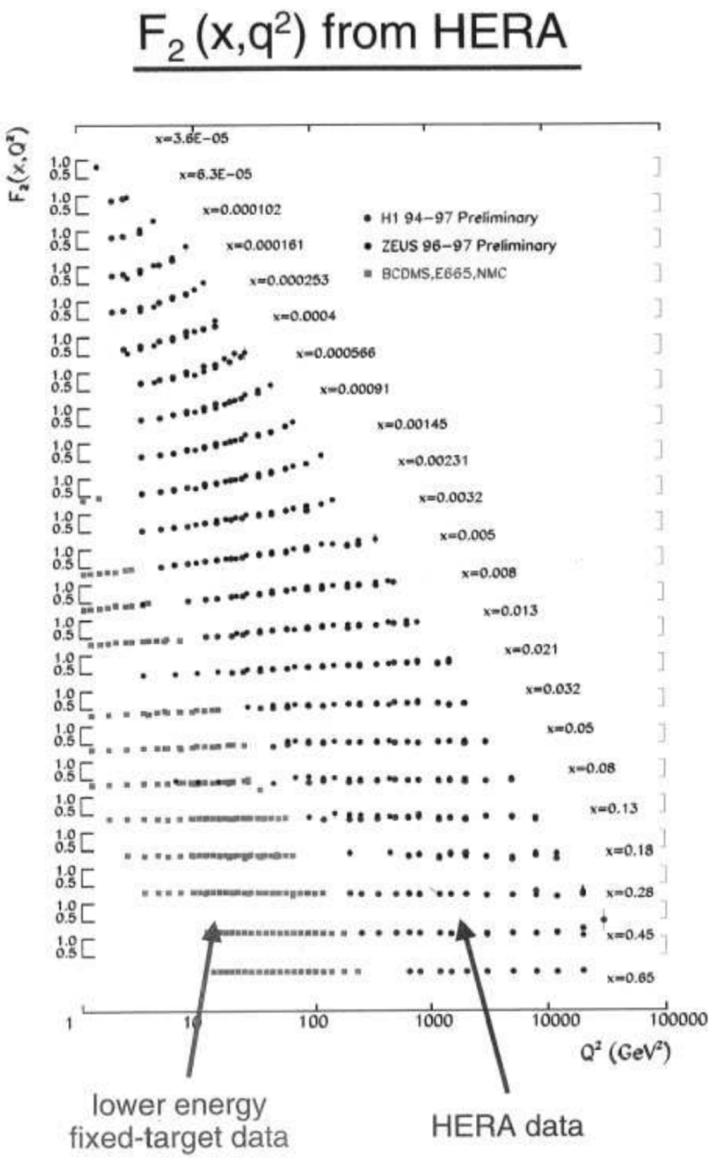
Relation to factorization



- Connection of GPDs to exclusive cross sections enable rigorous mapping of complete nucleon wave functions
- GPD framework assumes dominance of the handbag model
- Outgoing meson maintains small transverse size, suppressing soft interactions ➞ factorization
- Factorizes into a hard interaction with single quark and soft part (GPDs)

Color cancellation needed for factorization:
-> small objects
-> at high Q^2, small size object moves through nucleus

No FSIs in DIS

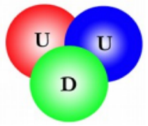


- DIS from heavy targets at high energies shows Bjorken scaling
- evidence of no FSI ➞ CT?

CT experiments

CT experiments

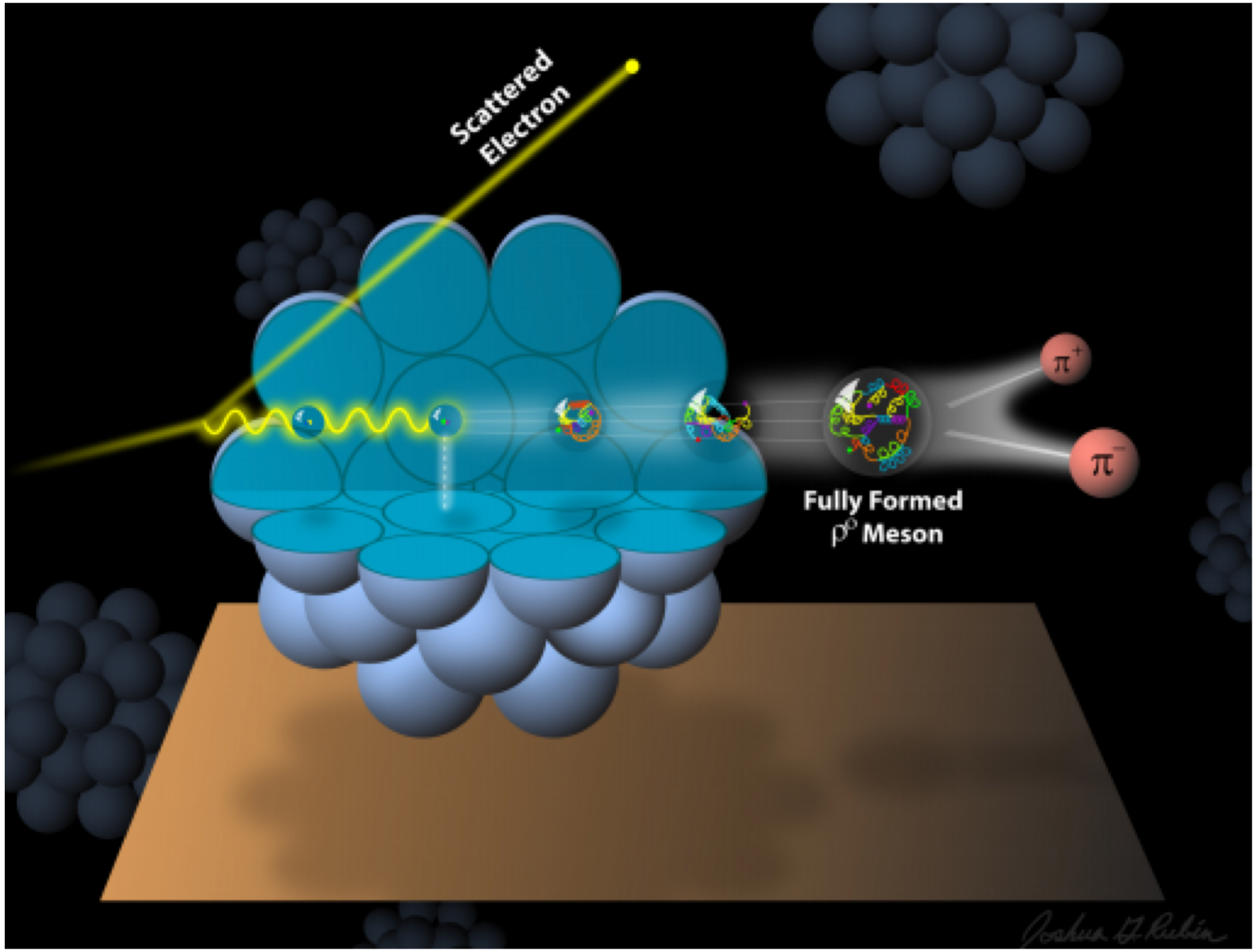
Baryon



A(p,2p): BNL
A(e,e'p): SLAC, JLab

Meson

A(π,di-jet): FNAL
A(γ, π^- p): JLab
A(e, e'π^+): JLab
A(e, e'ρ^0): DESY & JLab

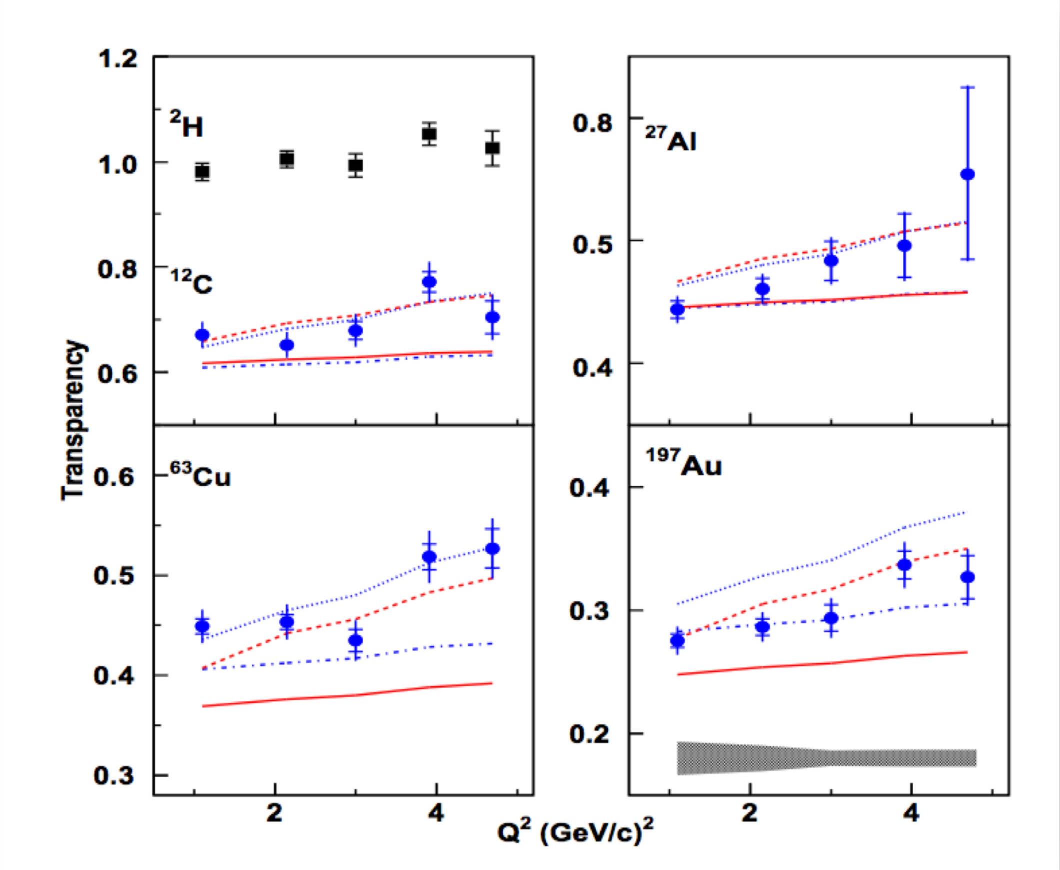


Previous measurements in mesons

Enhancements consistent with CT (increasing with Q^2 and A) observed

Hall C E01-107 pion electro-production

$A(e,e'\pi^+)$

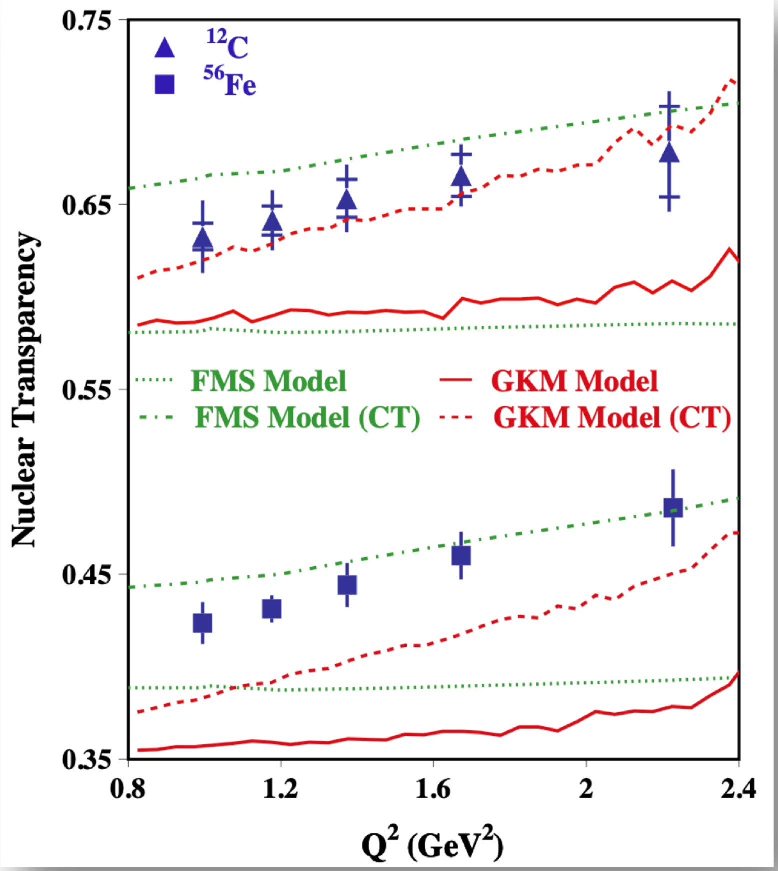


B.Clasie *et al.* PRL 99:242502 (2007)

X. Qian *et al.* PRC81:055209 (2010)

CLAS E02-110 rho electro-production

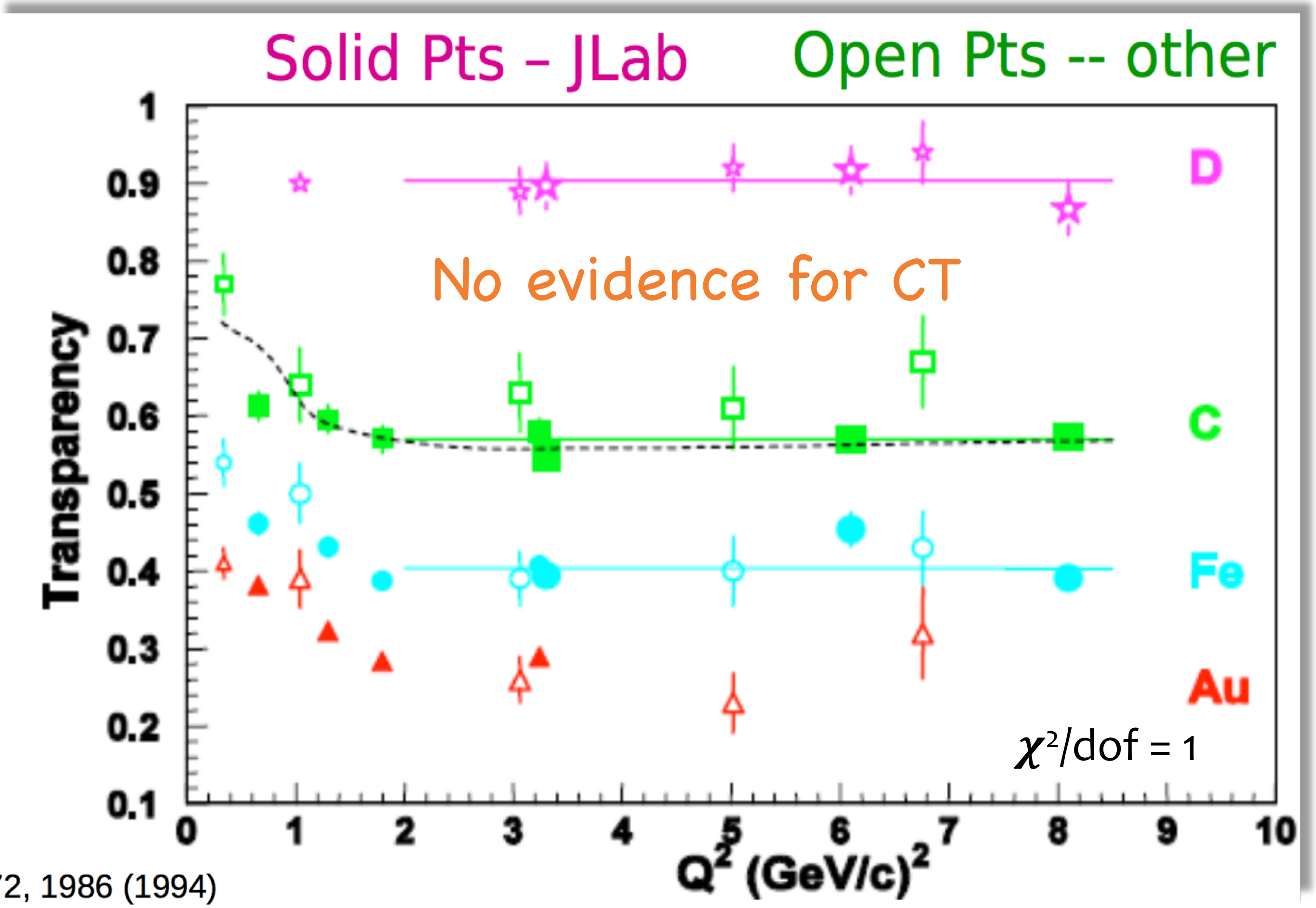
$A(e,e'\rho^0)$



L. El Fassi *et al.* PLB 712,326 (2012)

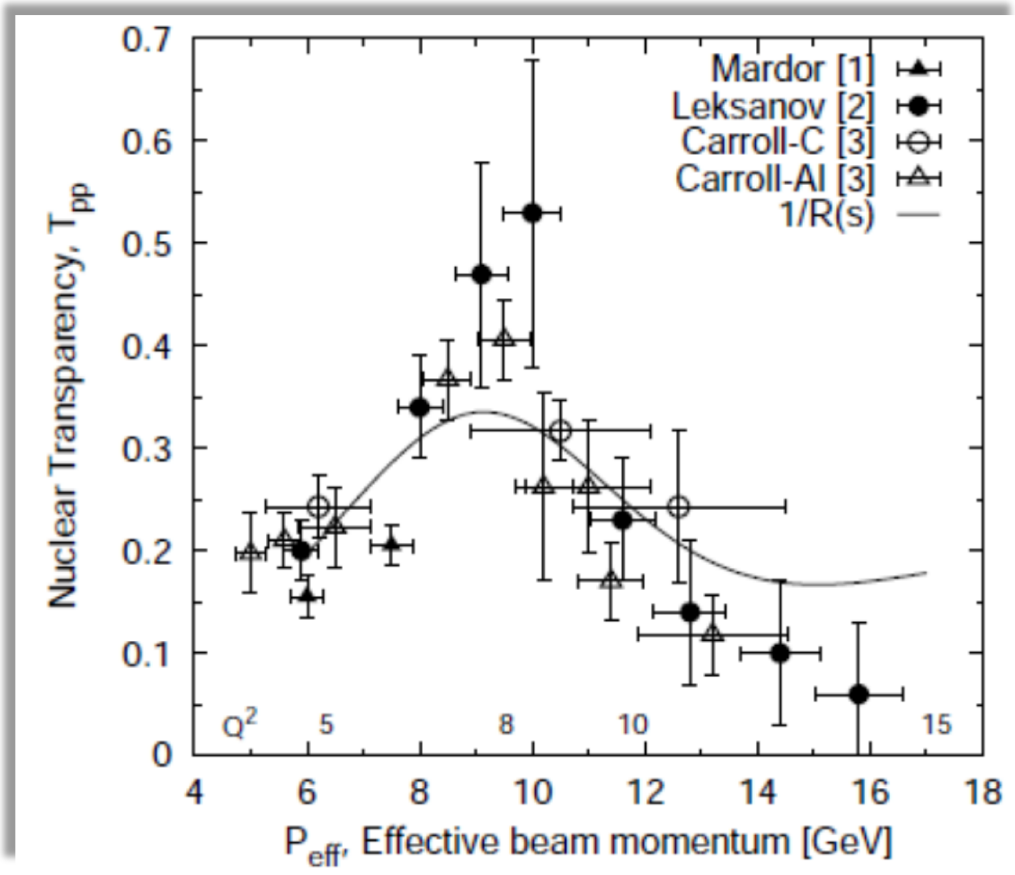
Previous measurements in baryons in 6 GeV era

A(e,e'p) results consistent with standard nuclear physics



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)

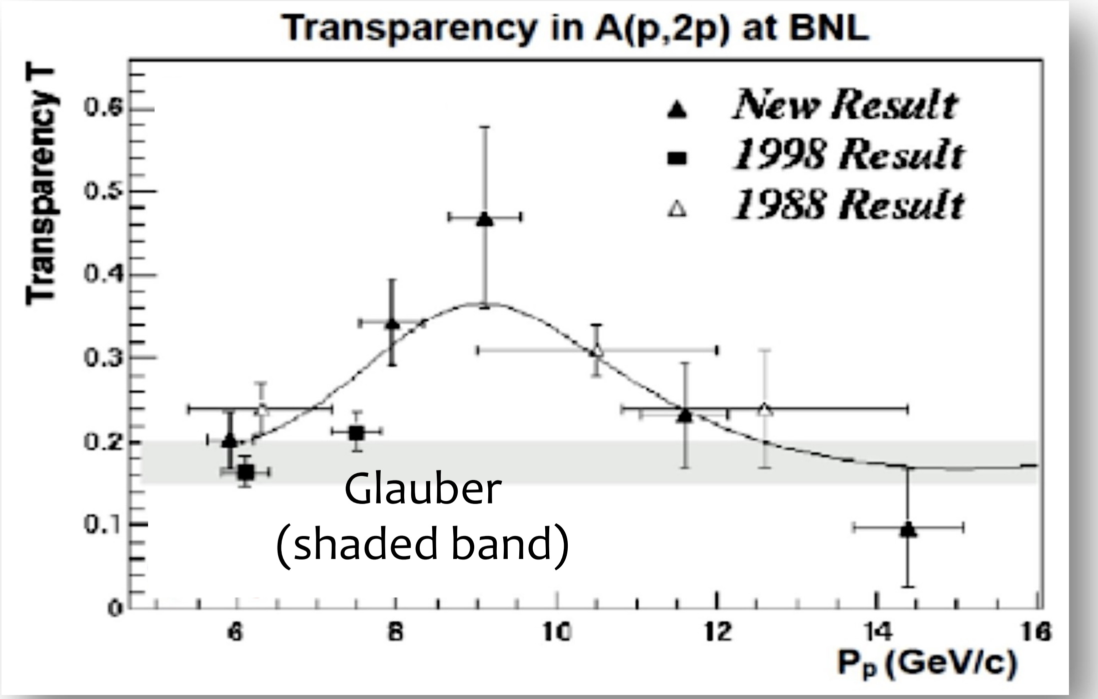
A(p,pp)



A. Leksanov et al. PRL 87 (2001)
J. L. S. Aclander et al., PRC 70 (2004)

Transparency in A(p,pp) experiment at Brookhaven:

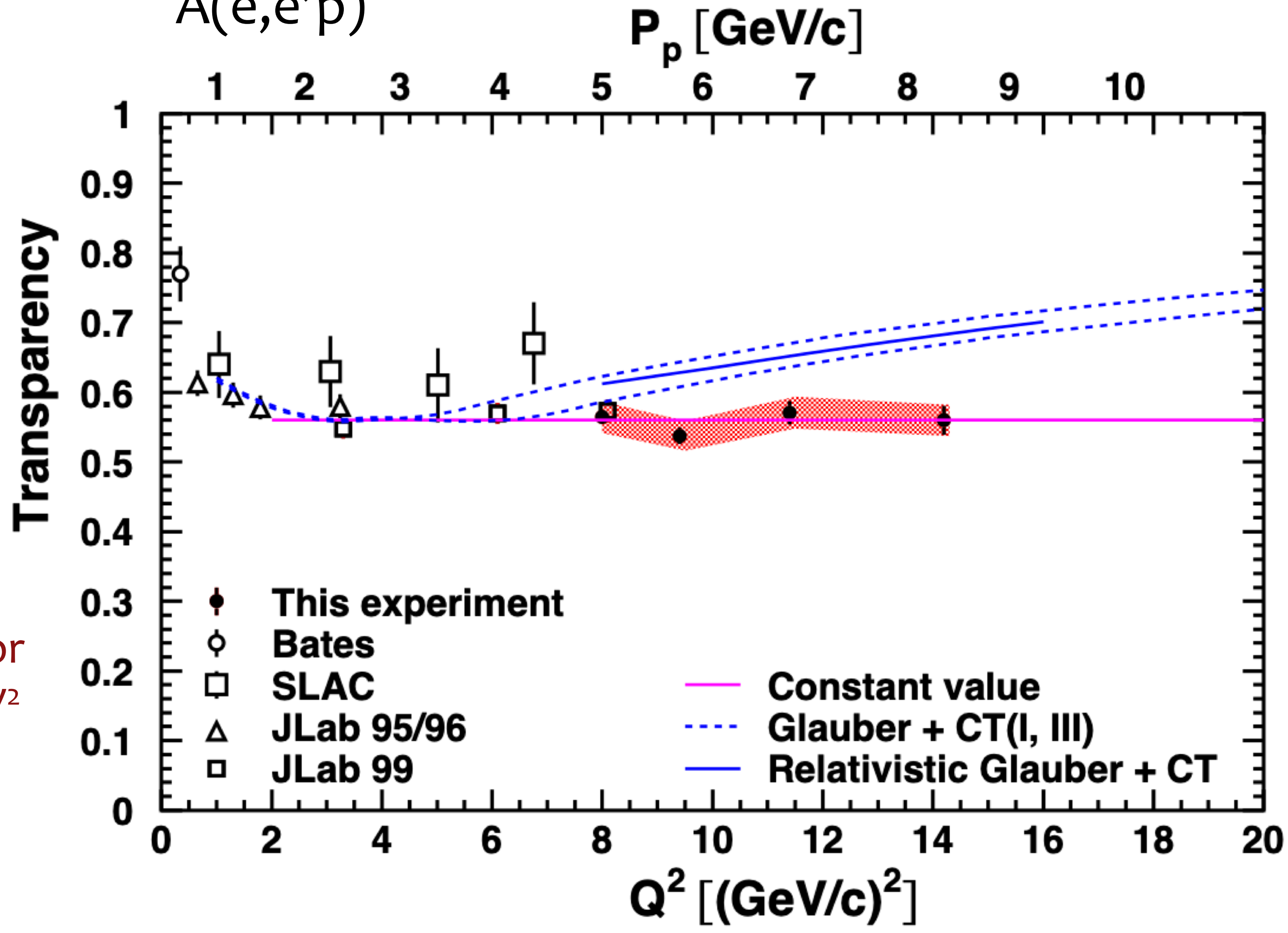
- observed enhancement in transparency
- inconsistent with CT only
- could be explained by including nuclear filtering or charm resonance



PRL 87, 212301 (2001)
PRL 81, 5085 (1998)
PRL 61, 1698 (1988)

JLab 12 GeV closes the loophole…

A(e,e'p)



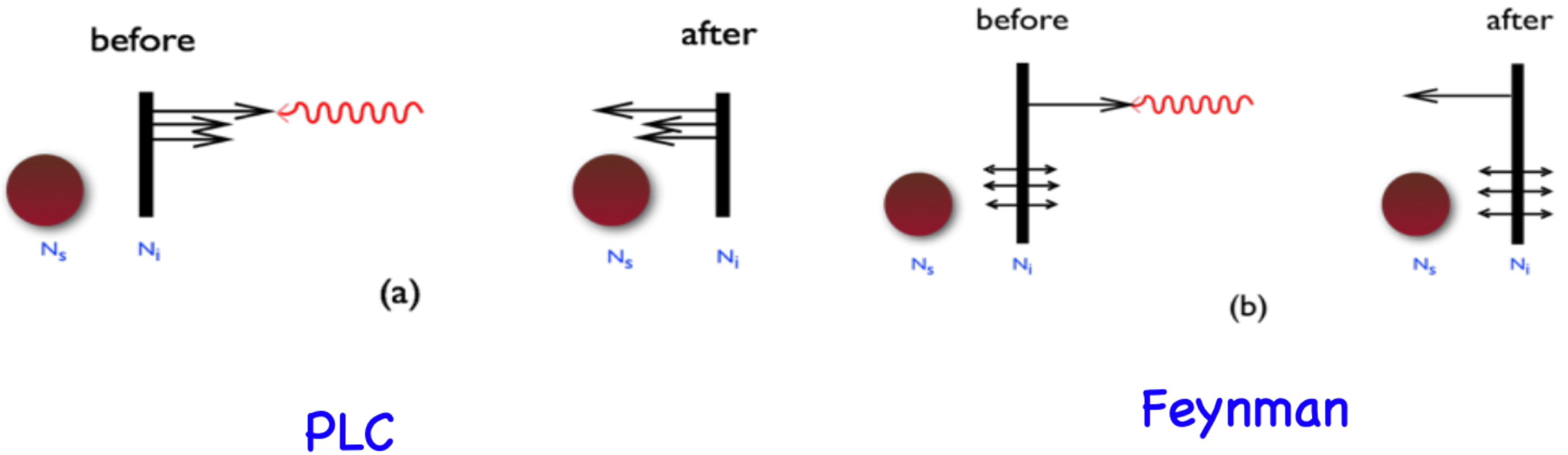
Onset not observed for protons at Q^2 = 14 GeV^2

Parallel kinematics: reduced FSIs, θ_{pq} = 0

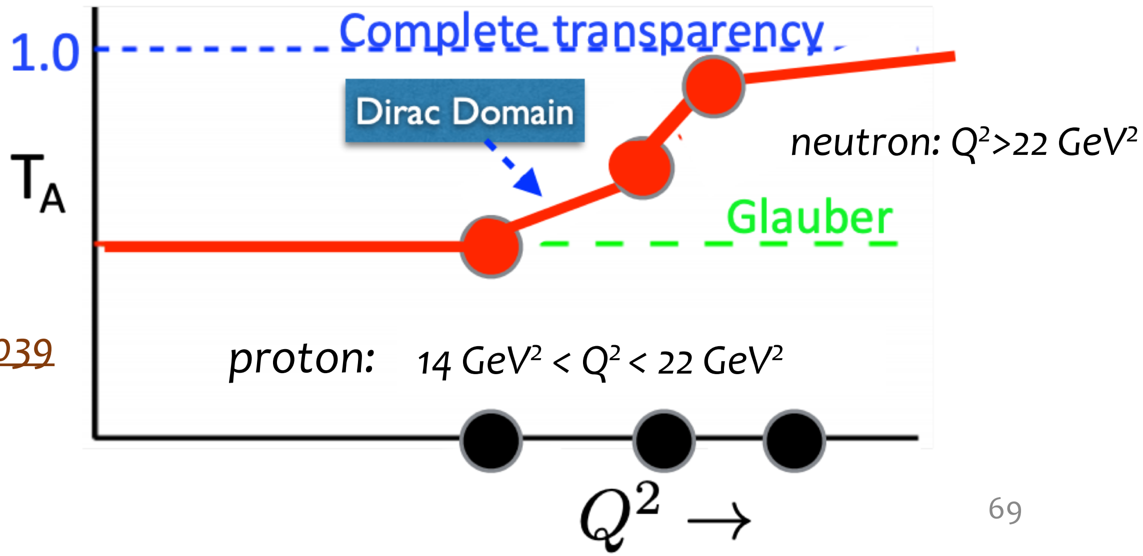
D. Bhetuwal et al, PRL126:082301 (2021)

Possible explanations

- No PLC was formed
(Feynman Mechanism)

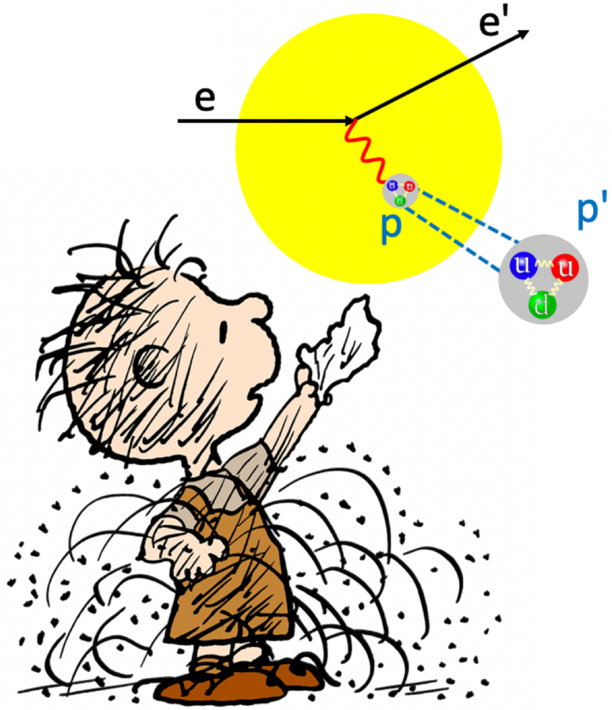


- Not high enough in Q^2
(Holographic light front QCD predictions)



G. Miller, Physics 2022, 4(2), 590-596; https://doi.org/10.3390/physics4020039
O. Caplow-Munro and G. Miller, PRC 104, L012201 (2021)
S. Brodsky and G. de Téramond, Physics 2022, 4(2), 633-646; https://doi.org/10.3390/physics4020042

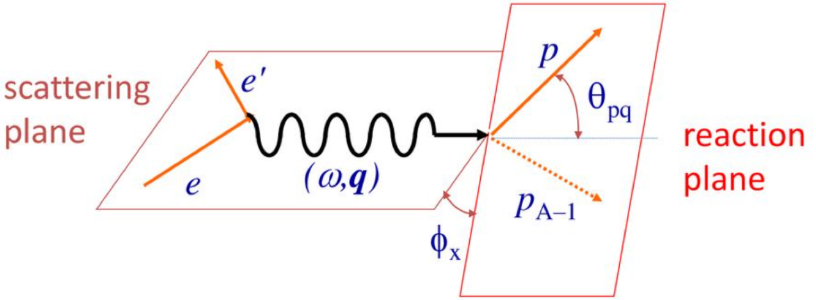
Time to re-think our approach



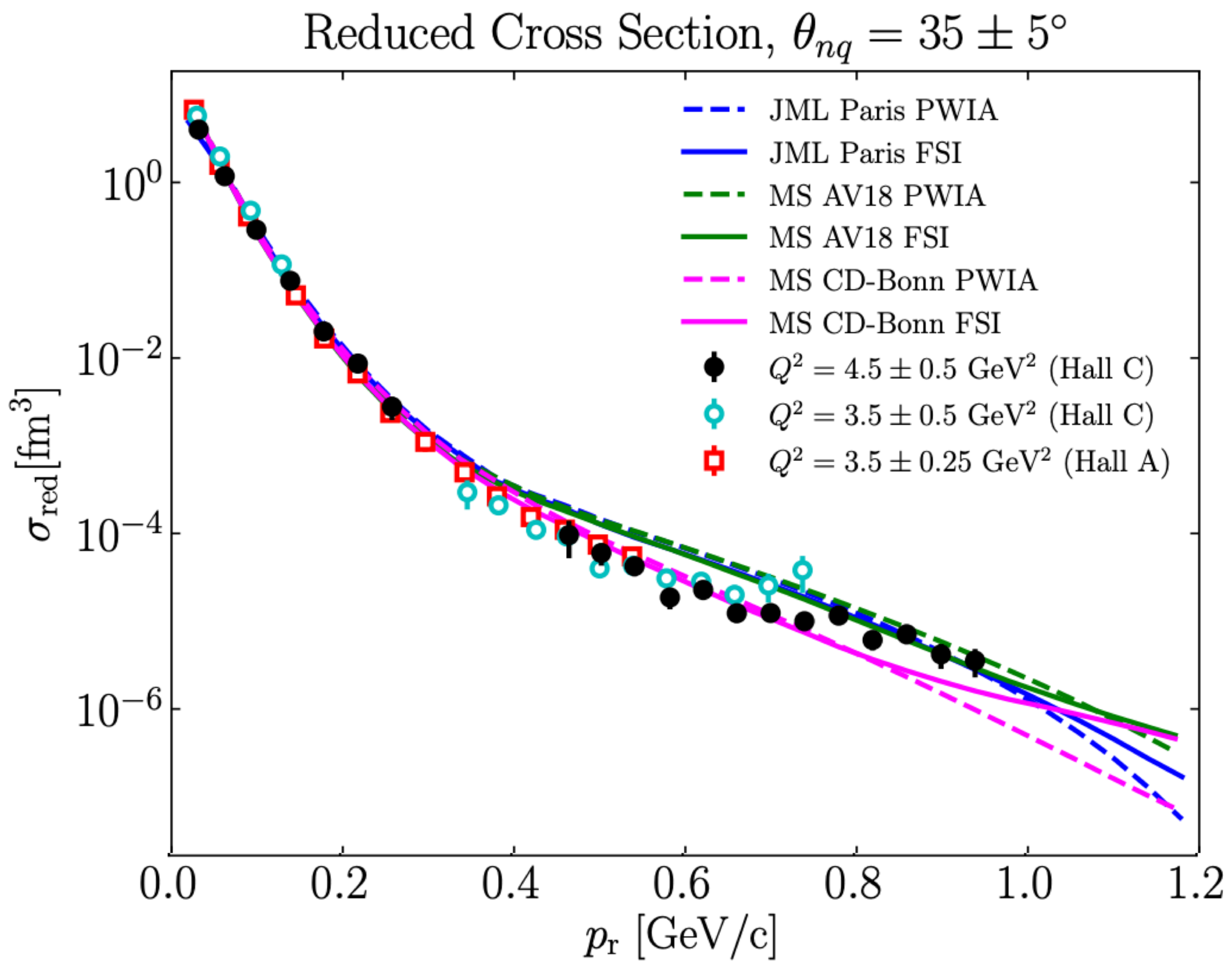
Traditionally looked in regions with already reduced FSIs (parallel kinematics)

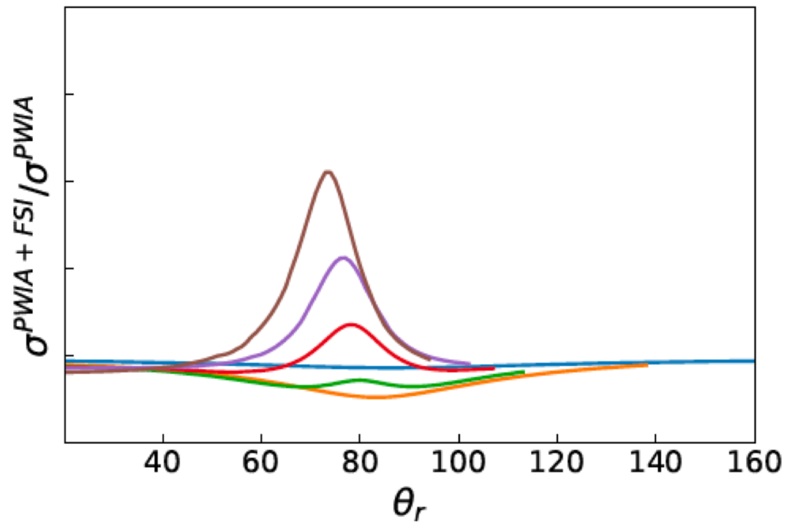
New approach to choose kinematics with large FSIs and compare with kinematics with low FSIs and map the Q^2 dependence

Parallel kinematics -> high rates, small FSI
proton initial momentum parallel to q-vector



Deuteron electrodisintegration





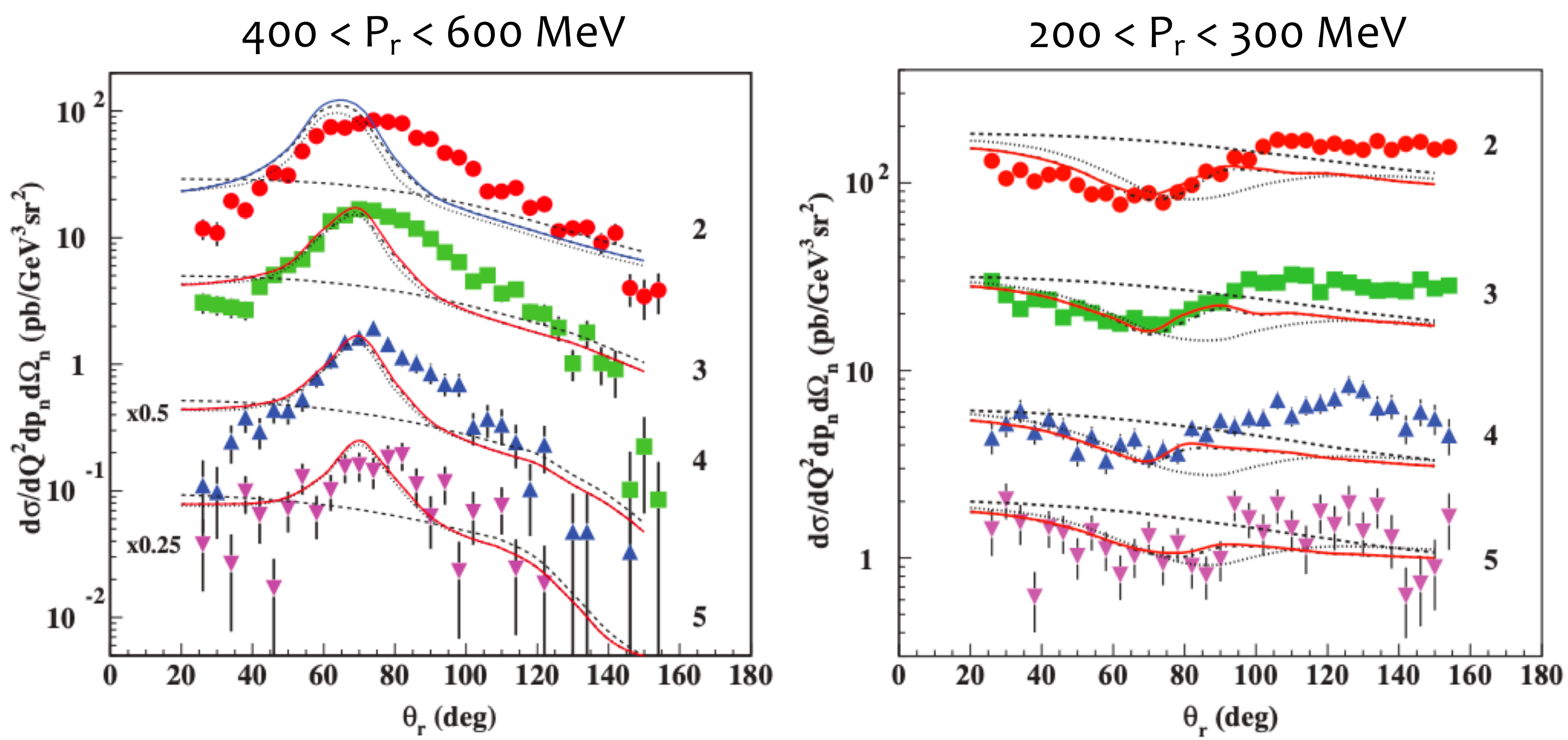
- Region at p_r<250 MeV corresponds to OPEP well known (long range, common to all potentials)
- Dominated by PWIA up to different p_r

Rescattering kinematics

Deuteron has well known FSI contributions from double scattering

Double-scattering is the square of re-scattering amplitude of knocked out nucleon

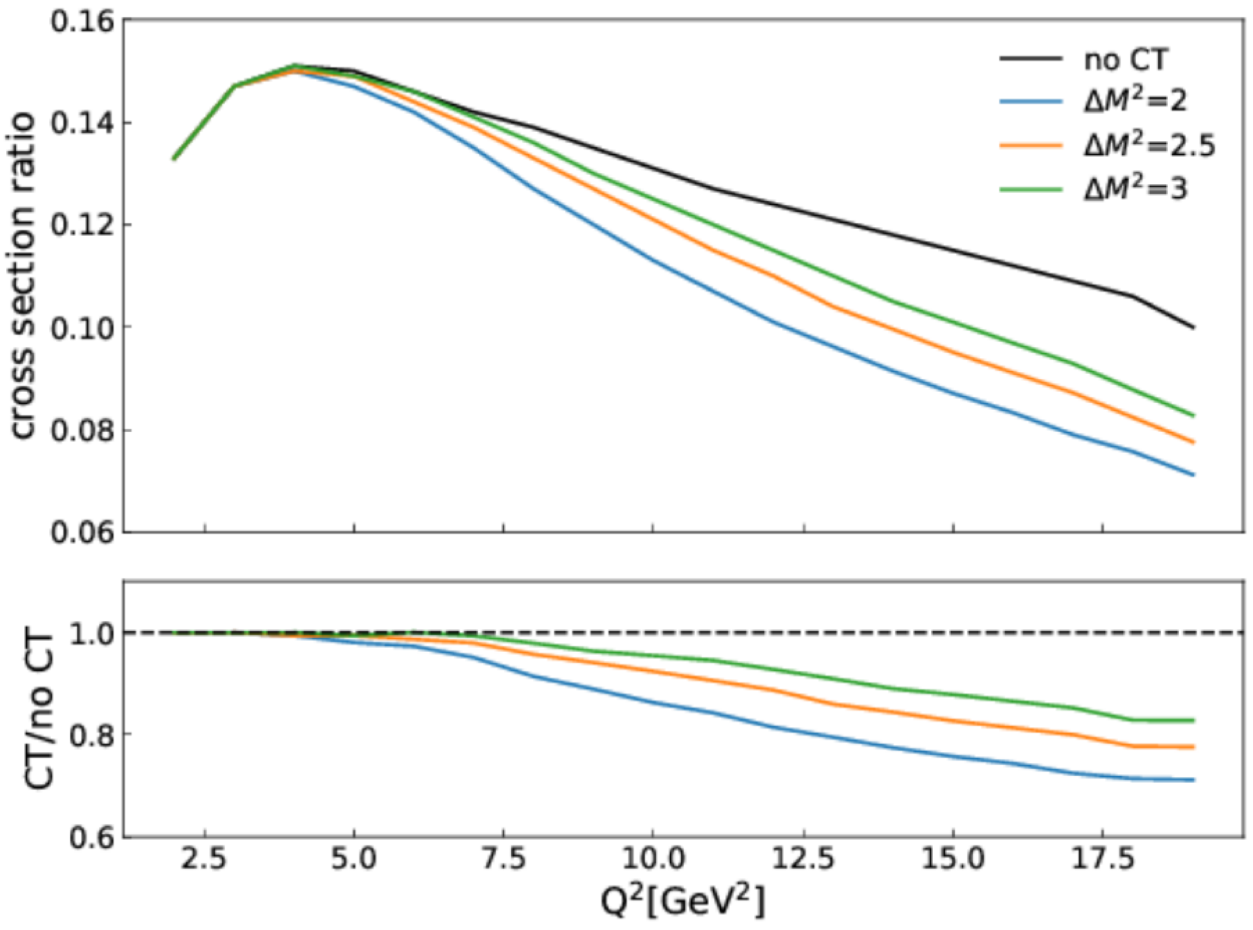
Can construct the ratio, R = XS high FSI / XS low FSI – varied by P_r or angle

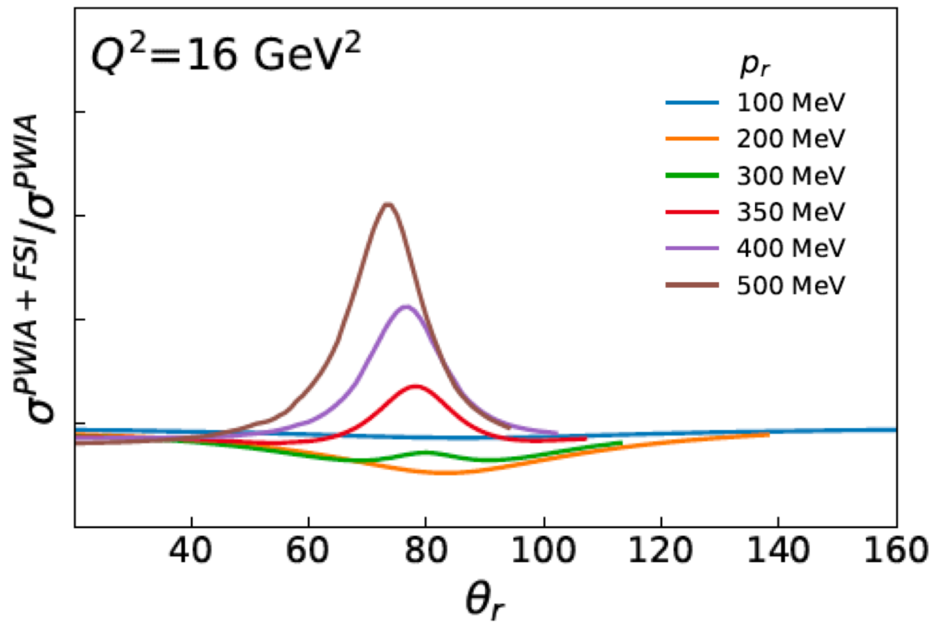


K. S. Egiyan et al., PRL 98:262502 (2007)

Sensitivity to CT

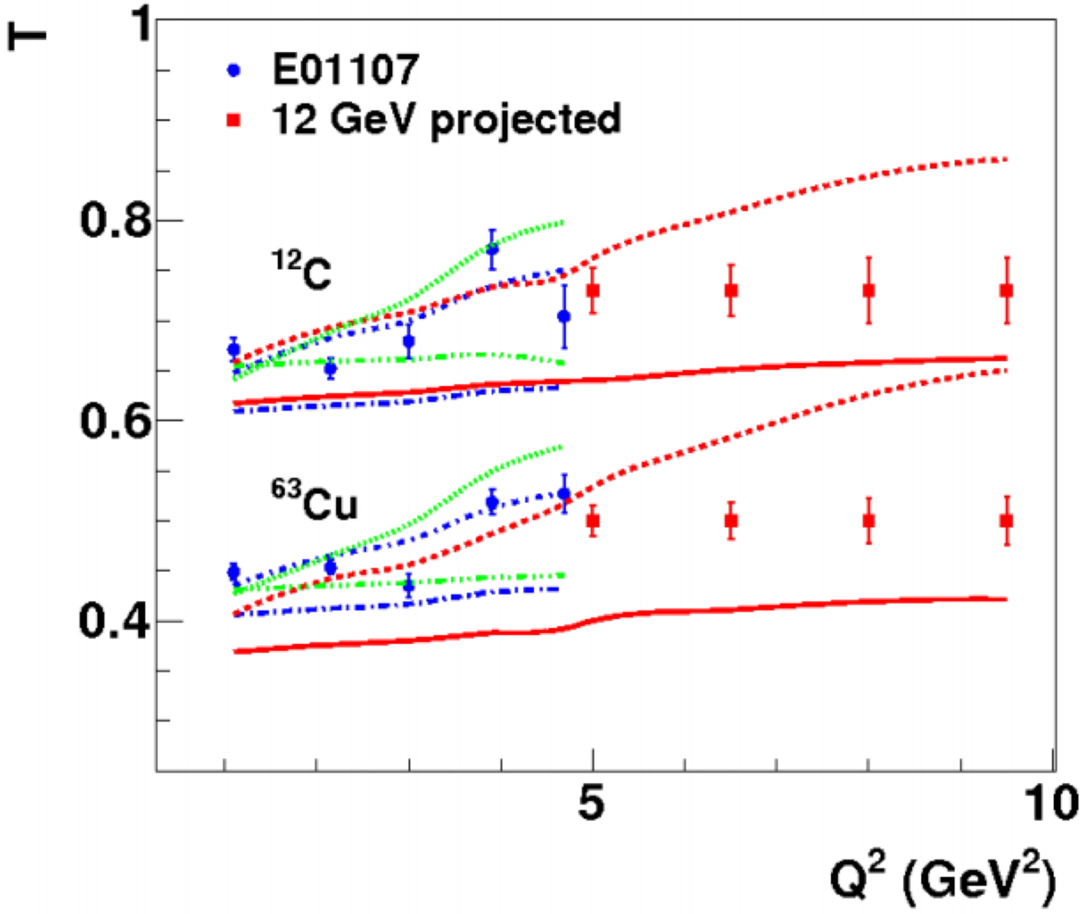
Well-described by GEA (more realistic at higher Q^2)

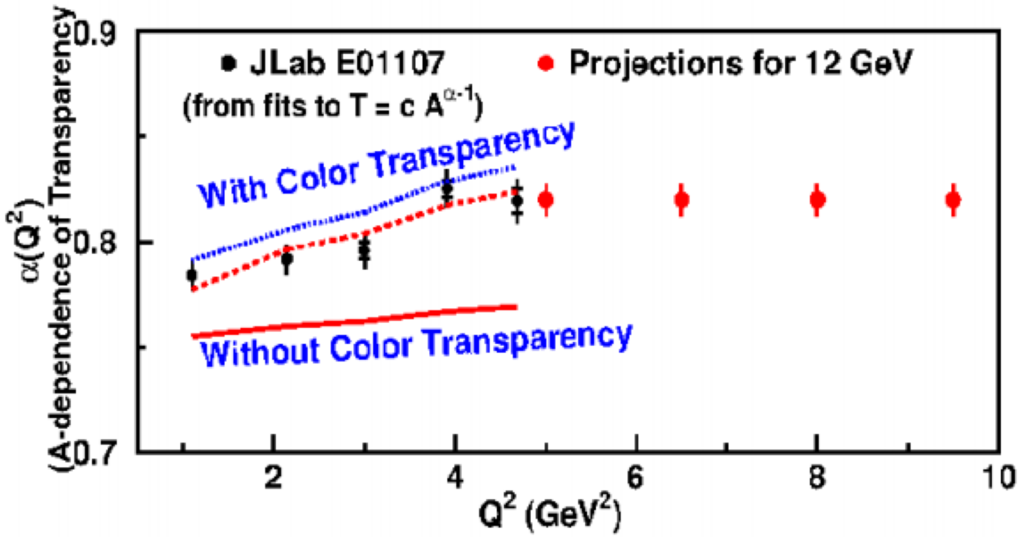




Imminent experiments examining the onset of CT in mesons

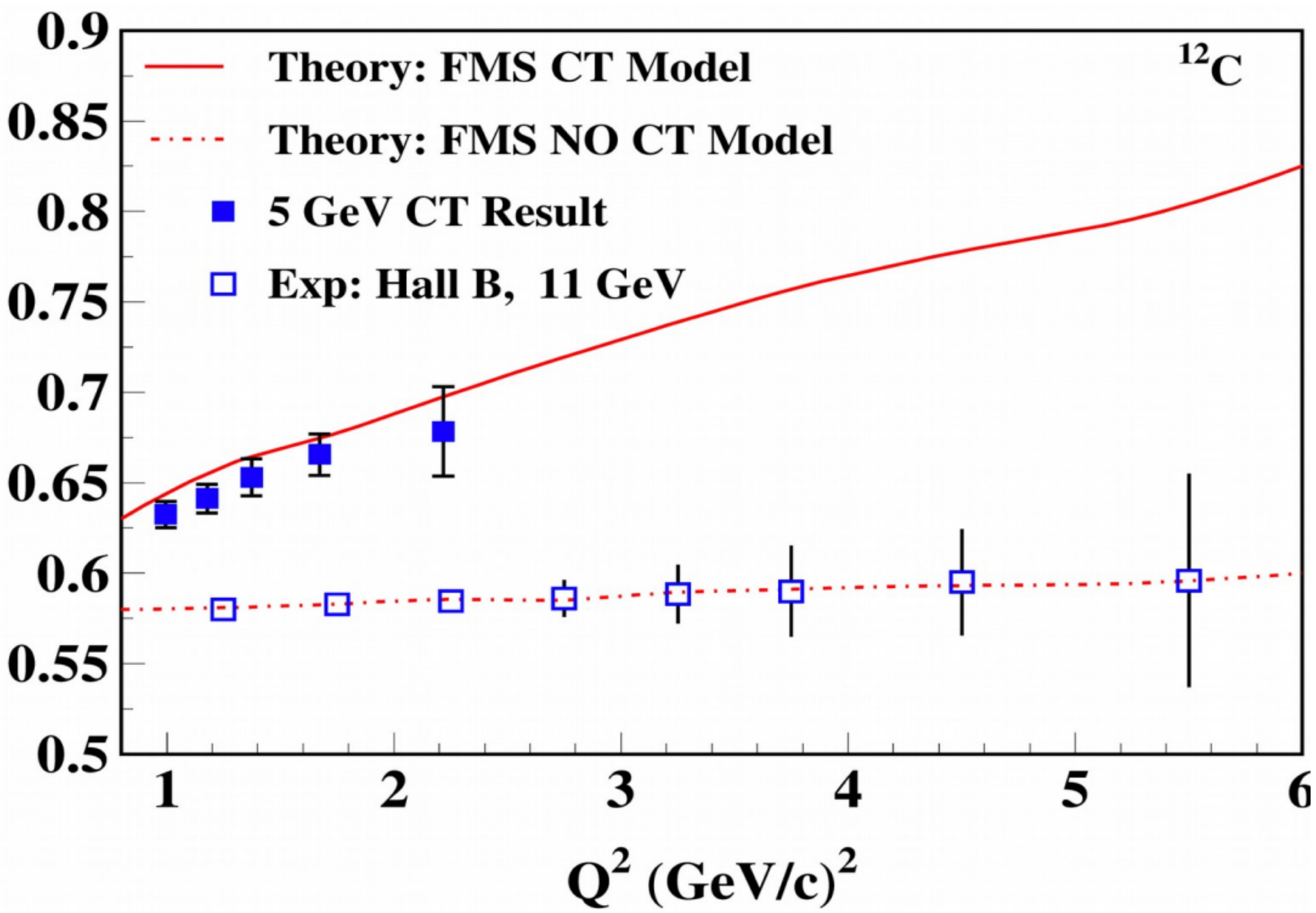
Measure the onset in pion electro-production over large momentum range in Hall C

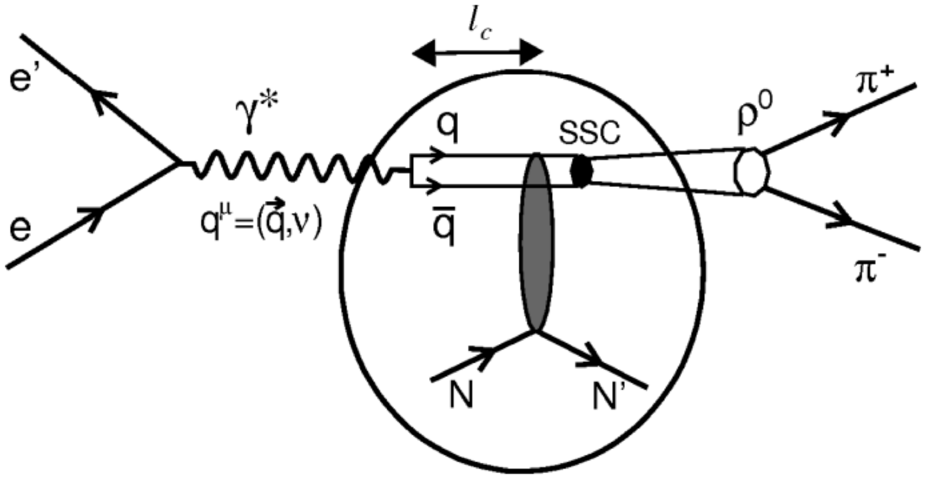




Onset of CT in the rho-meson

Rho transparency measurements will be extended to highest Q^2 in Hall B





Review

Different avenues to better bridge the gap between the observances in the real world and QCD dynamics

SRCs provide a unique insight in QCD dynamics in the nucleus:

- Related to local density (as is the EMC Effect)
- Universal to all nuclei
- Dominated the high momentum tail
- Tensor dominated
- Further studies in this area using spectator tagging will give us better clues on the relation to the EMC Effect

Review

Different avenues to better bridge the gap between the observances in the real world and QCD dynamics

Onset of Color Transparency is important:

- Direct link from quark-gluon d.o.f. to the nucleonic picture
- Tells us where factorization theorems are relevant (essential for GPDs)
- Assumed in high energy reactions
- Onset but not the plateau is generally observed for mesons and will be explored further in the 12 GeV program
- Onset in protons is not yet established

Hadronization

DIS:

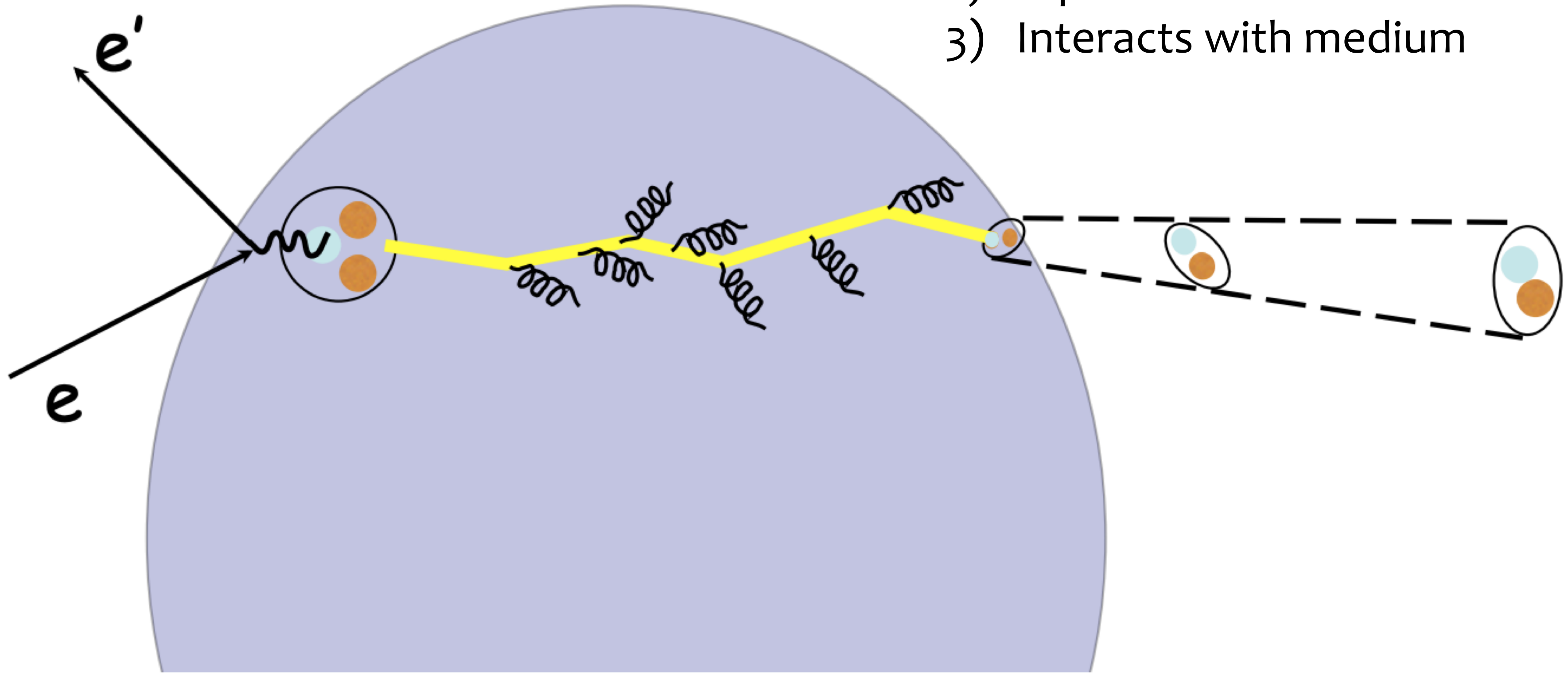
- $Q^2 > 1$ GeV^2
- W > 2 GeV (DIS)
- x > 0.1 (decreases contribution from quark pair production
- $Z=E_h/\nu > 0.4$ (quark in the hadron)

Parton (quark) propagation phase

1) Radiates gluons
2) Loses energy
3) Multiple scatters

Hadron formation phase

1) Small pre-hadron (qqbar) system forms
2) Expands to full size
3) Interacts with medium

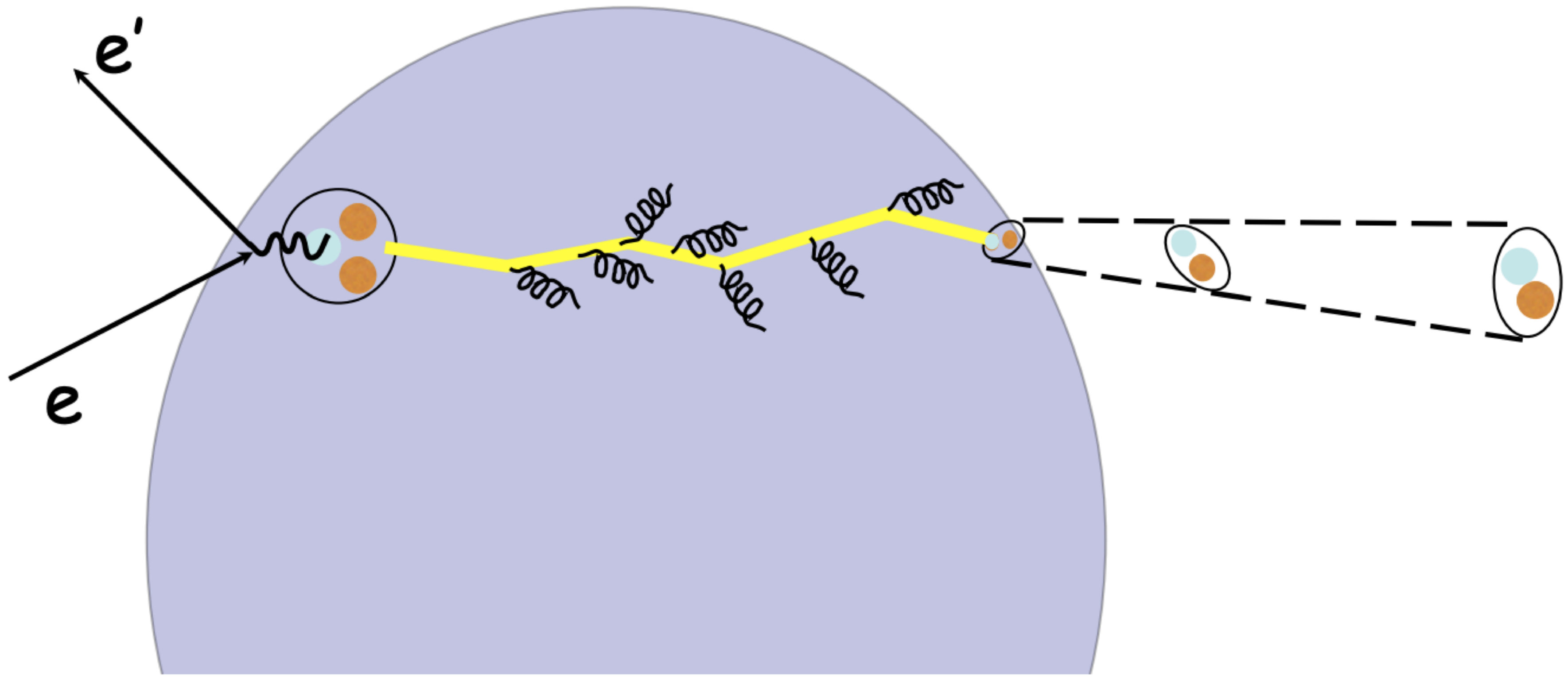


Hadronization

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

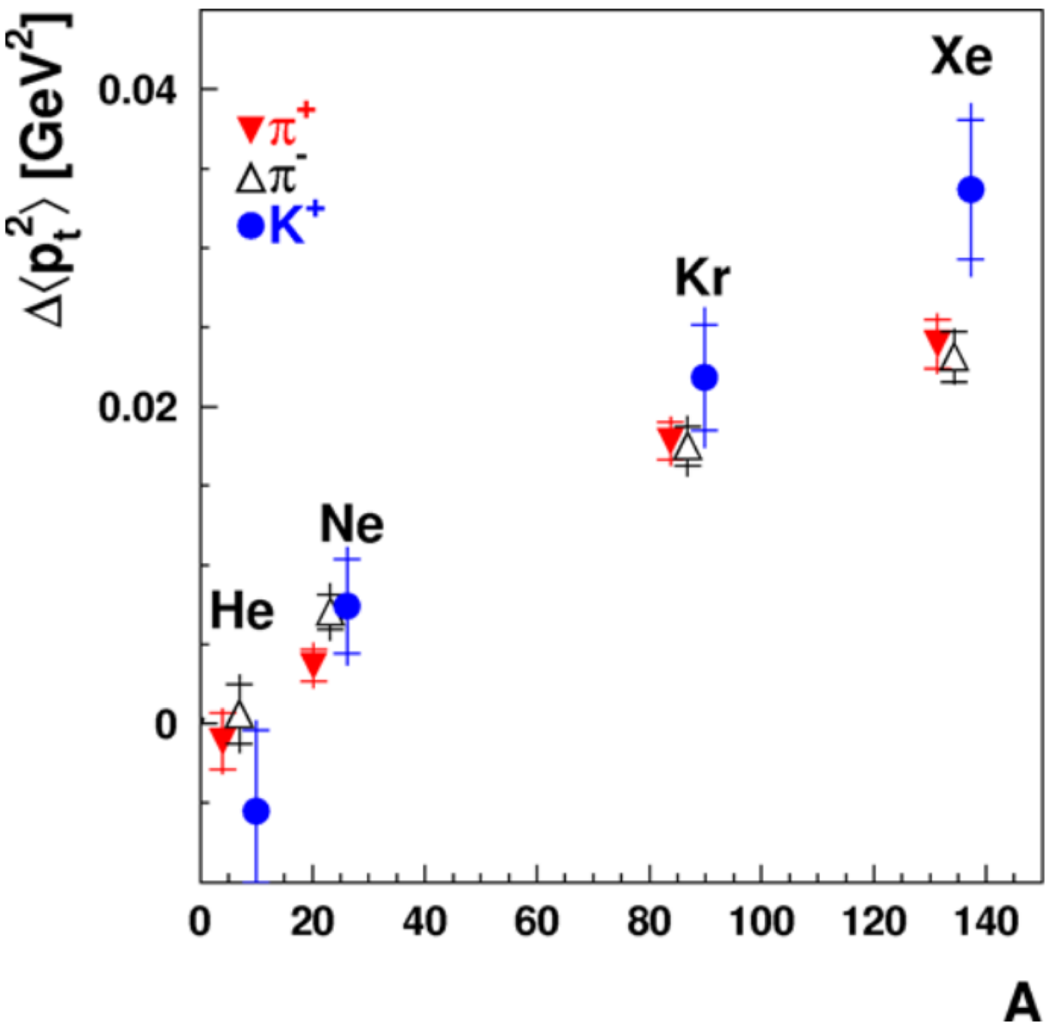
Parton (quark) propagation phase:
Identified by pT broadening

Hadron formation phase:
Identified by hadron attenuation



pT broadening

Hermes experiment



Broadening increases with A.

No broadening when z=1 (not shown).

Therefore broadening due to quark, not prehadron!

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