An experimentalist's approach to hadronic physics (Days 2 & 3)

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Course Overview

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

- Hadrons in the nucleus
  - Short and long range dynamics
  - EMC effect
  - Transparency

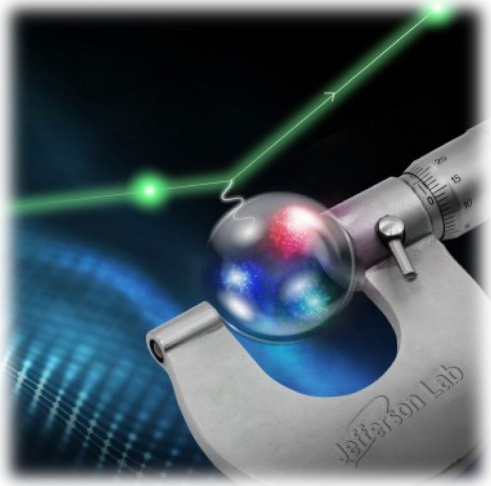
Review from yesterday

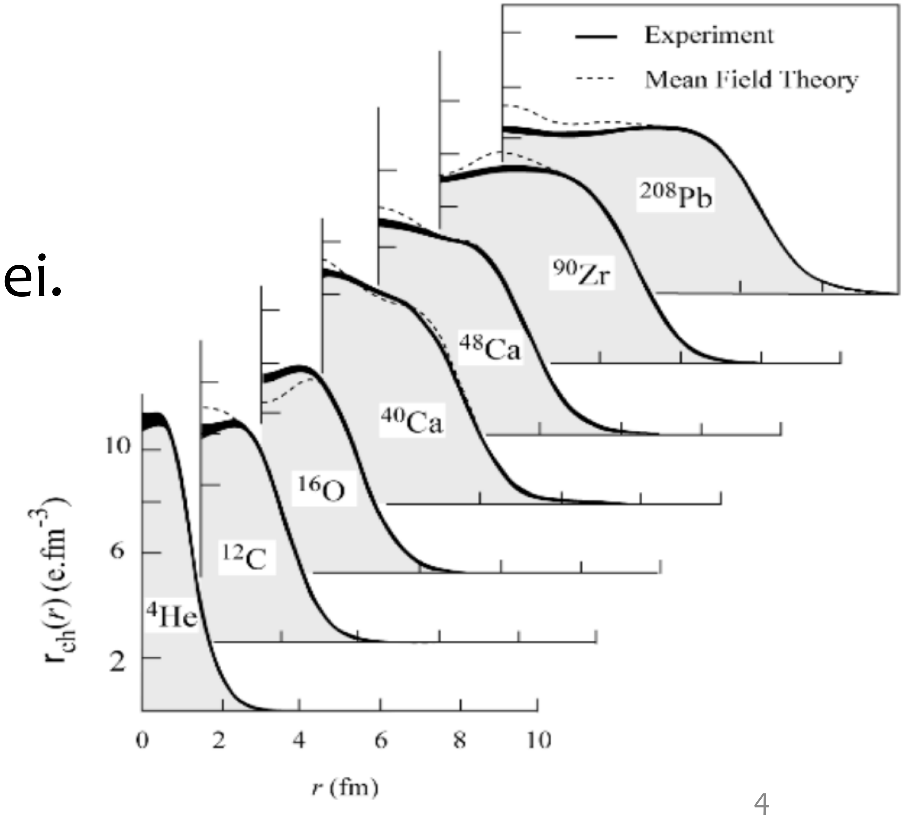
- Nuclear strong interaction that binds nuclei is the residual from the strong interaction between quarks!

- 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

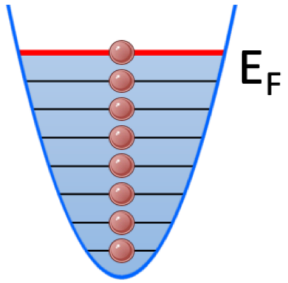
Elastic scattering summary

- 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!

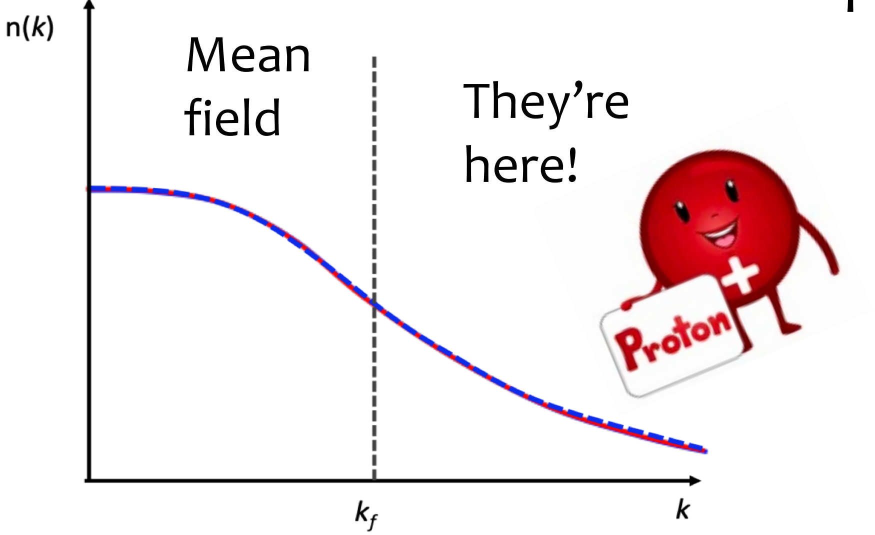


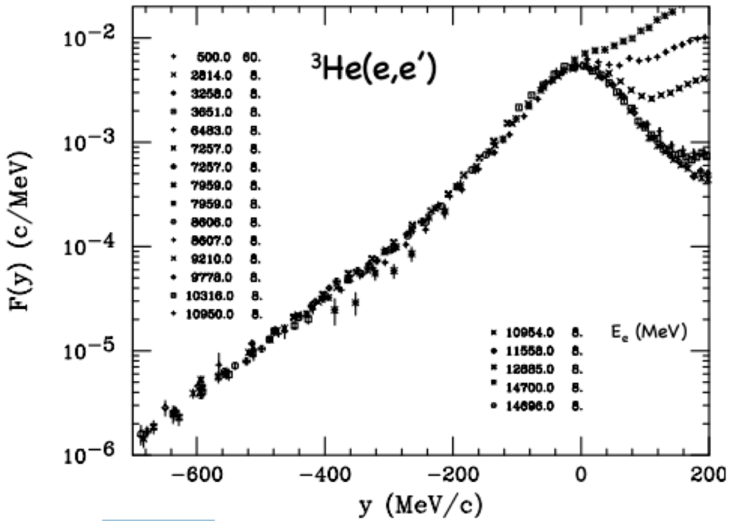


Quasielastic scattering summary



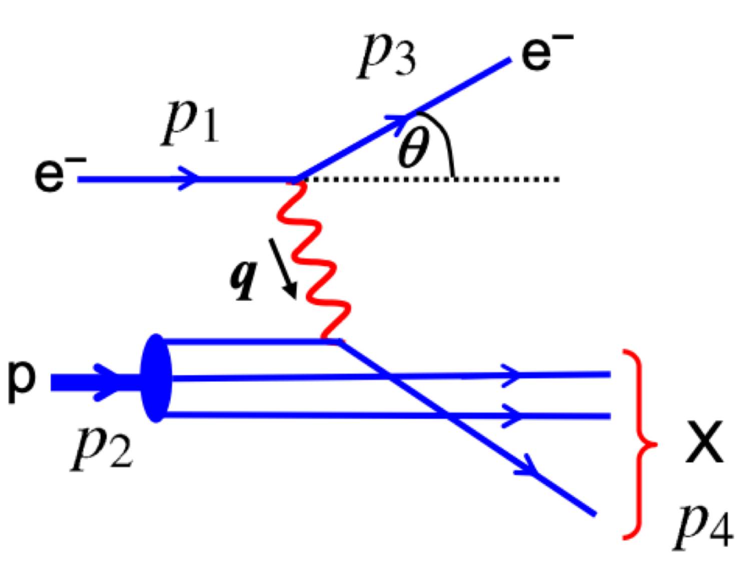
- Nuclei are complicated systems that we model with different assumptions.
- Fermi gas model gives us a good idea about the cross section.
- Scaling refers to the dependence of a cross section on a single variable
  - y-scaling can tell us about the nucleon momentum distributions in the nucleus.
- Indications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

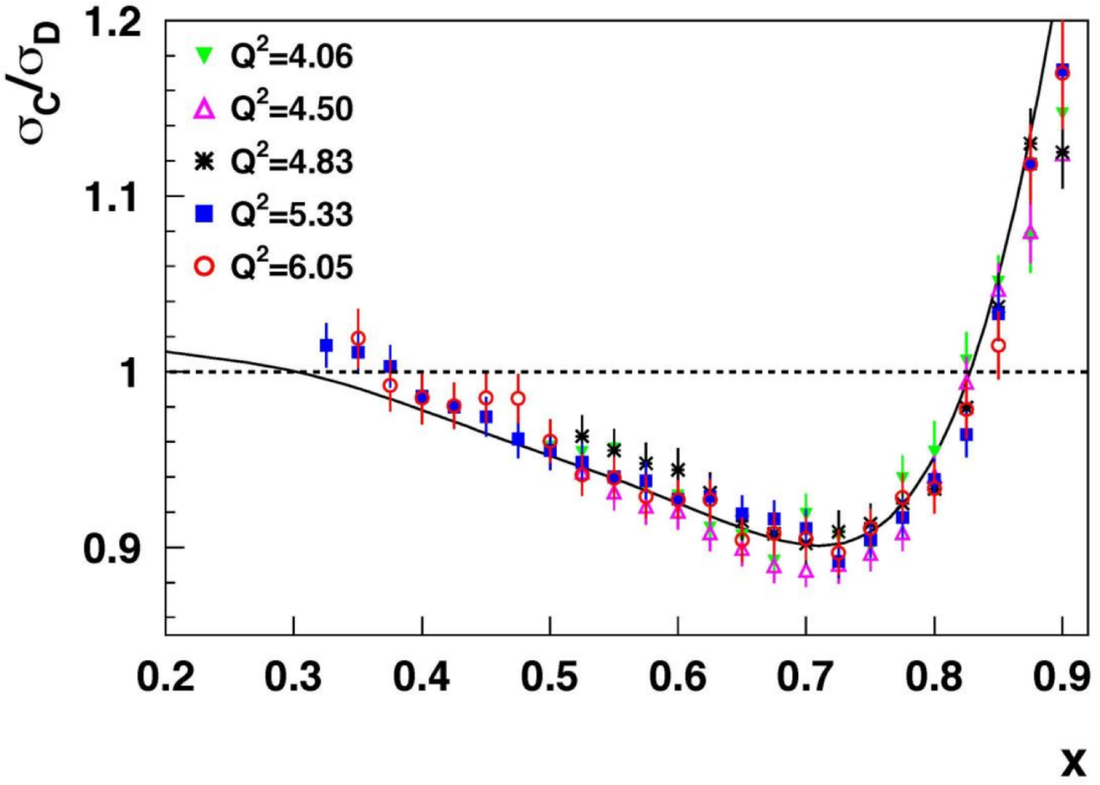




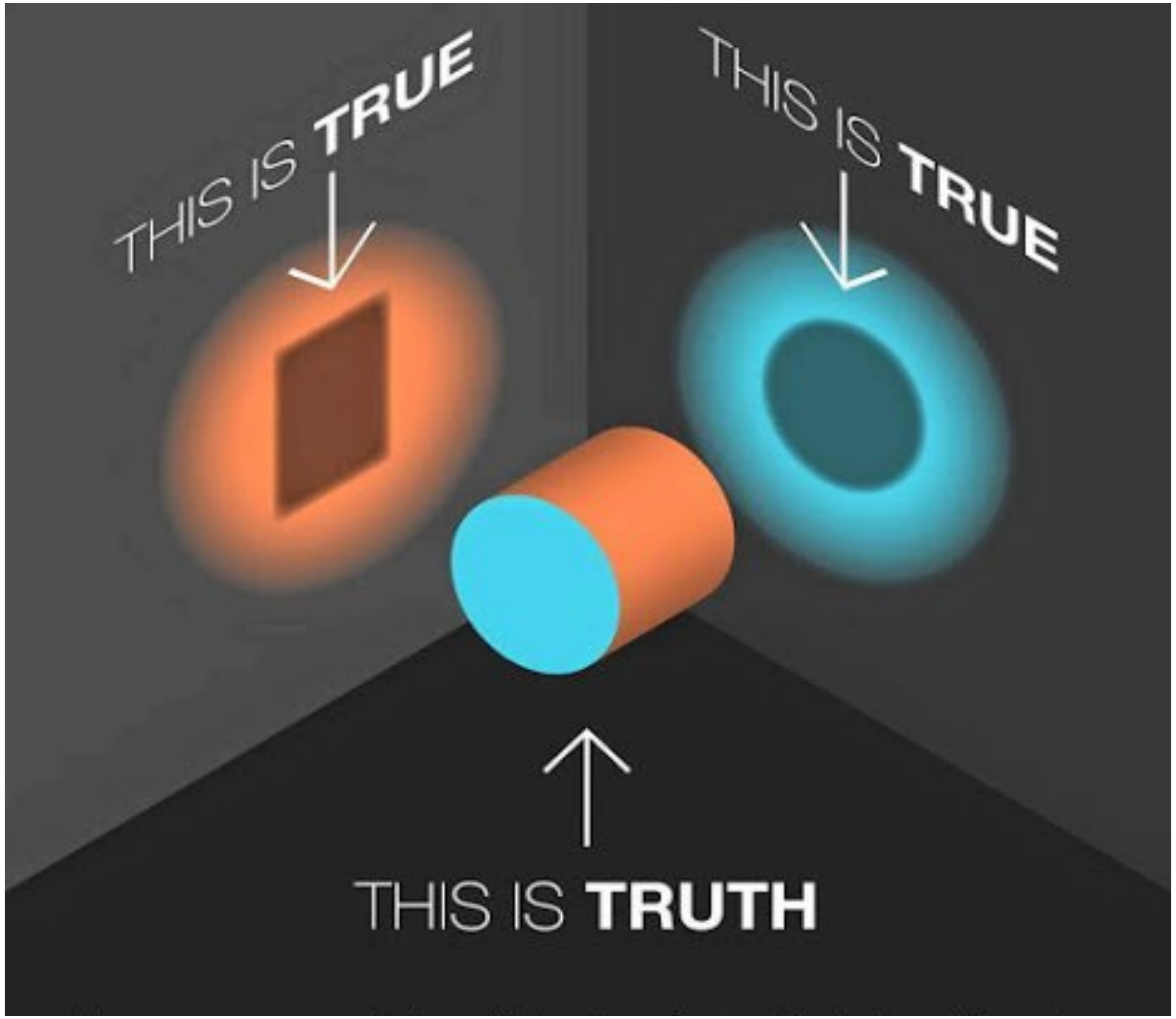
Deep inelastic scattering summary

- 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.

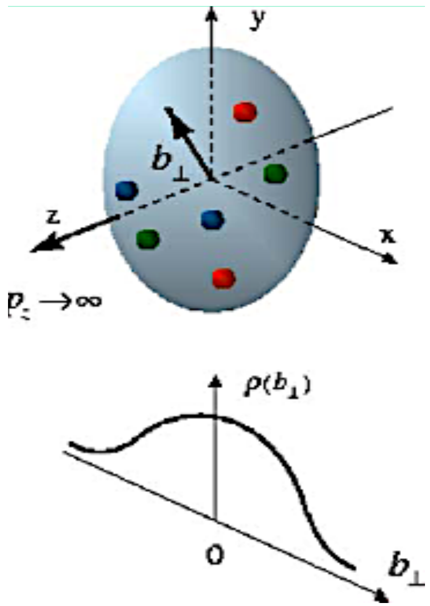


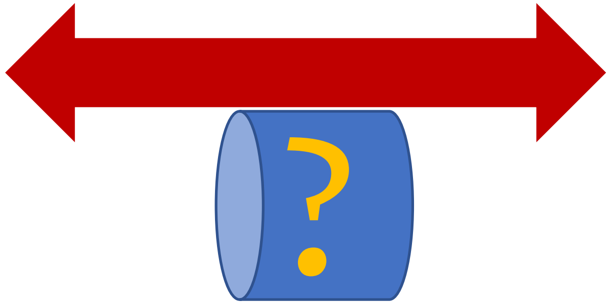


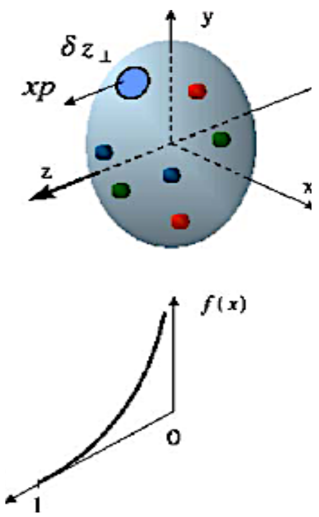
Completing the structure picture



Descriptions from e-p scattering

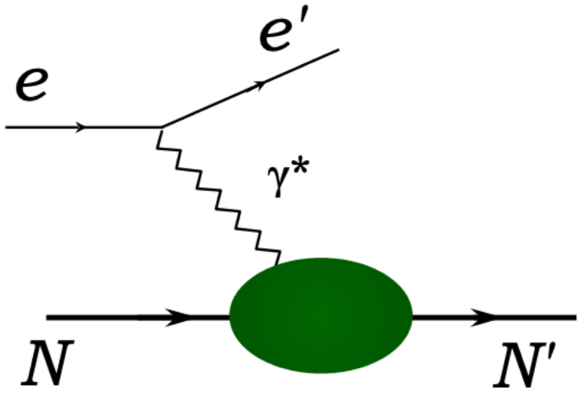






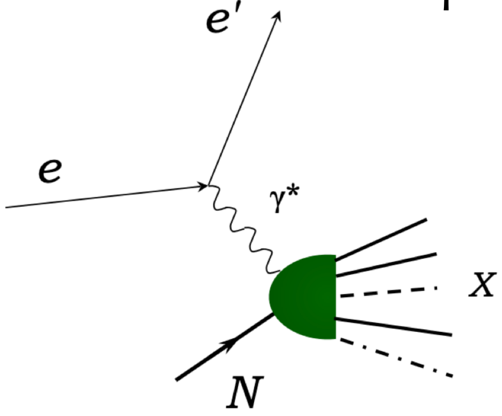
Elastic scattering:

Form factors describe the transverse quark distribution in coordinate space

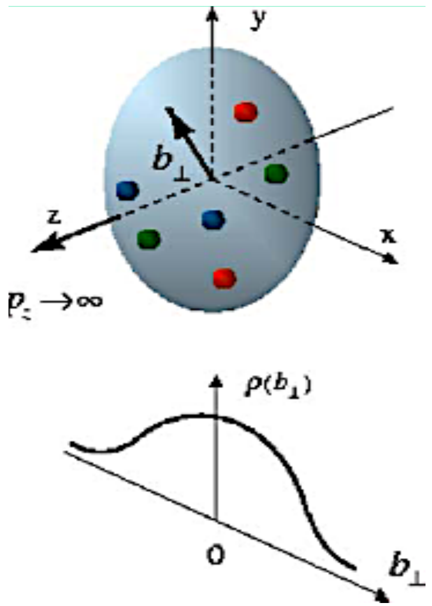


Deep inelastic scattering:

Parton distributions describe the longitudinal quark distribution in momentum space



Descriptions from e-p scattering



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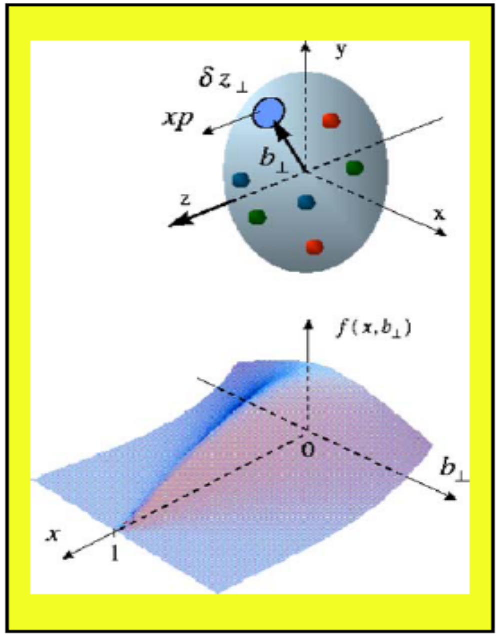
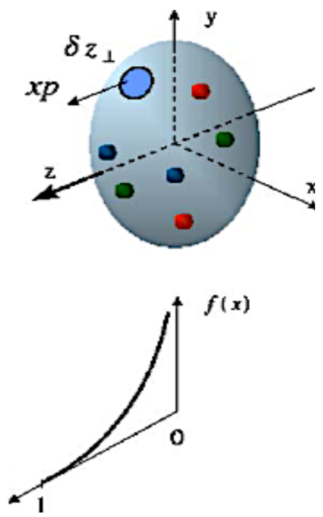


Generalized Parton Distributions

GPDs: H, E, $\tilde{H}$, $\tilde{E}$

Connect the charge and parton distributions
→ coordinated quark distributions in both coordinate and momentum space!

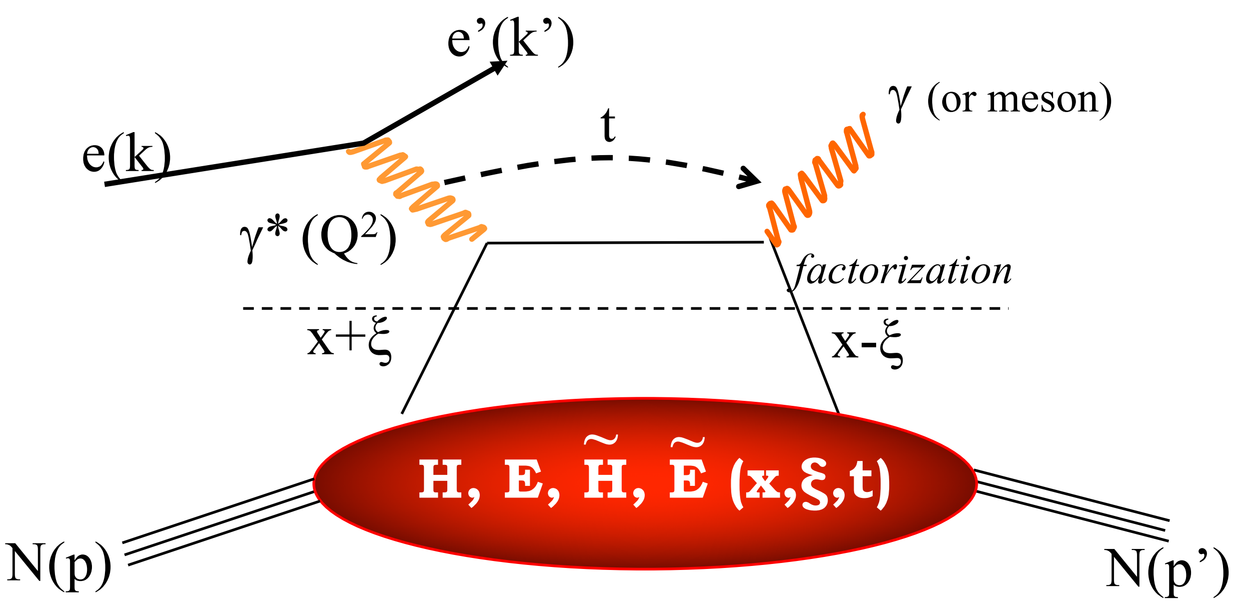


Deep inelastic scattering:

Parton distributions describe the longitudinal quark distribution in momentum space

Accessing GPDs

"Handbag" diagram



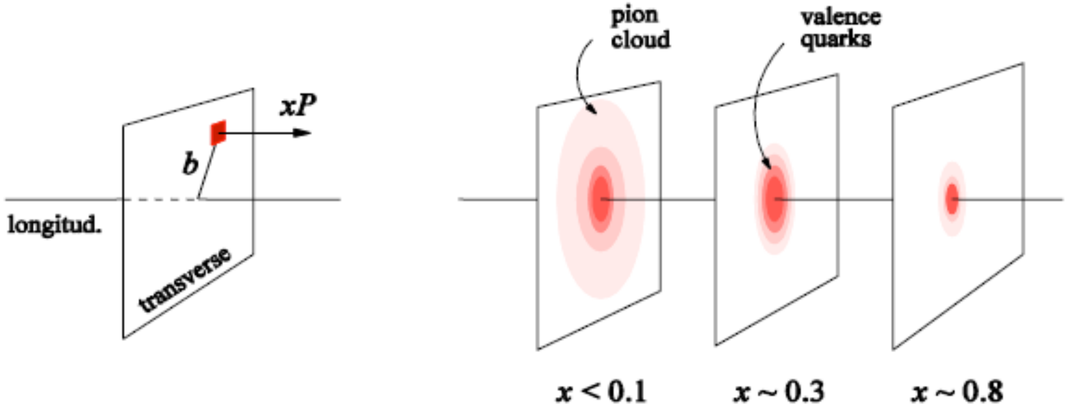
4 GPDs in LO in QCD (quark-helicity conserving)

x ≡ momentum fraction carried by struck quark
ξ ≡ difference of the quark momentum from initial to final state
t ≡ the momentum transferred to the proton

- Factorization of the hard interaction with a single quark and the soft part (characterized by the GPDs)
- Factorization only holds in the Bjorken regime (high Q^2 and ω)

What do we learn?

Nucleon tomography
M. Burkardt, PRD 62, 71503 (2000)



Probability to find a quark of a given momentum fraction at a given position in the transverse plane

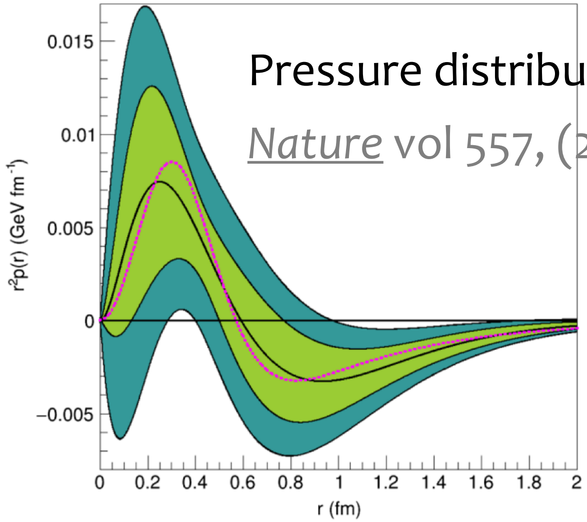
Quark angular momentum (Ji's sum rule)
X. Ji, Phy.Rev.Lett.78 (1997)

$$\frac{1}{2}\int_{-1}^{1} xdx(H(x,\xi,t=0)+E(x,\xi,t=0)) = J = \frac{1}{2}\Delta\Sigma + \Delta L$$

Nucleon spin: $\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + \Delta L}_{\mathbf{J}} + J_G$

Gravitational form factor → shear forces and pressure

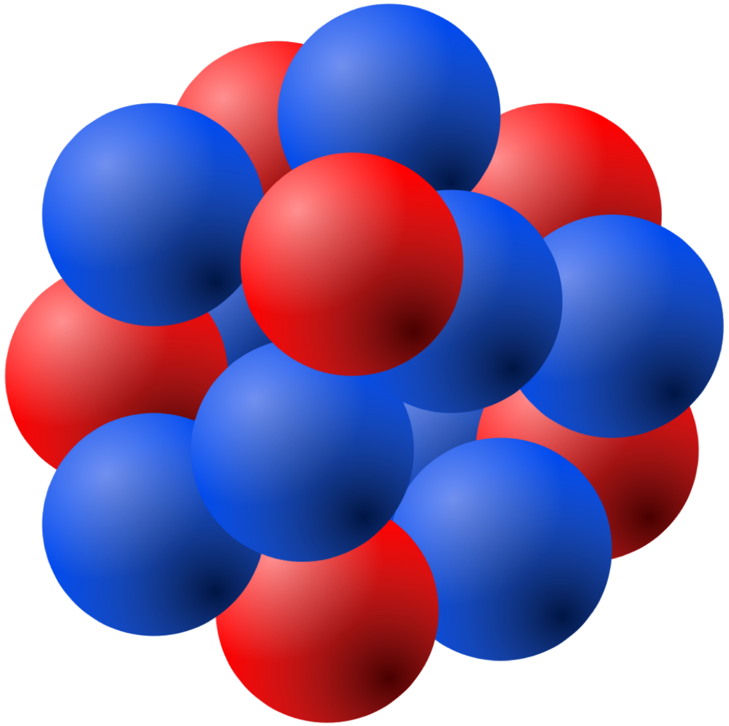
$$\int_{-1}^{1} xH(x,\xi,t)dx = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$



Pressure distribution in proton

Nature vol 557, (2018)

Taking a step back from structure…



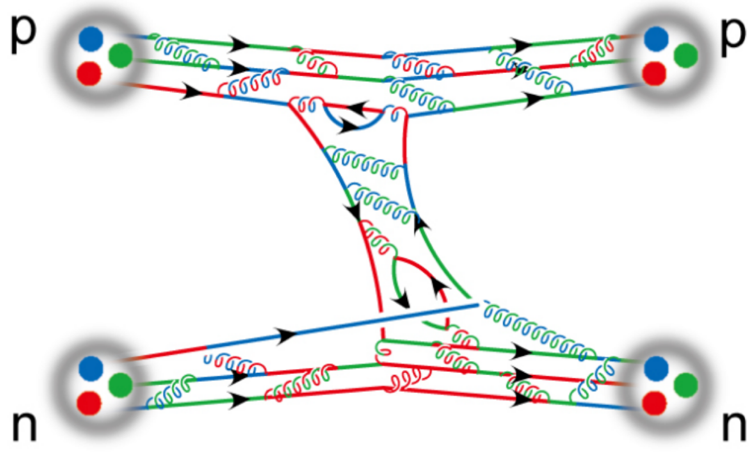
What happens when we put the nucleons in a nucleus?

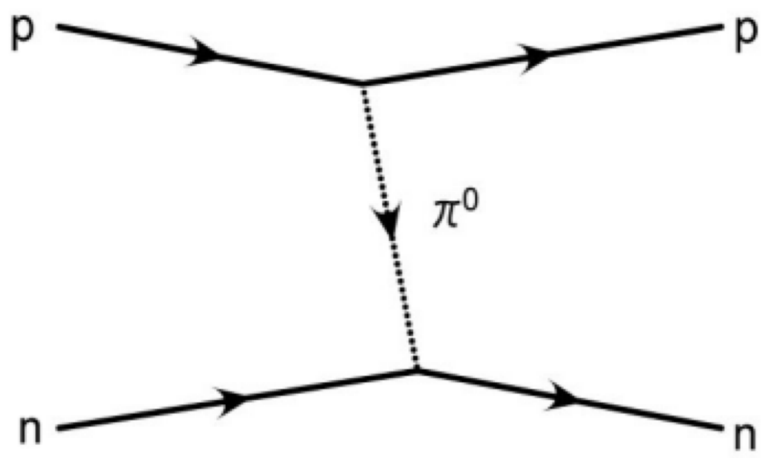
Nuclear picture is a many body problem

$$\sum_i \left\{ -\frac{\hbar^2}{2m_i} \nabla_i^2 \Psi(\vec{r}_1, \dots, \vec{r}_N, t) \right\} + U(\vec{r}_1, \dots, \vec{r}_N)\Psi(\vec{r}_1, \dots, \vec{r}_N, t) = i\hbar \frac{\partial}{\partial t} \Psi(\vec{r}_1, \dots, \vec{r}_N, t)$$

From elastic scattering, we already know that quarks and gluons compose the nucleons…

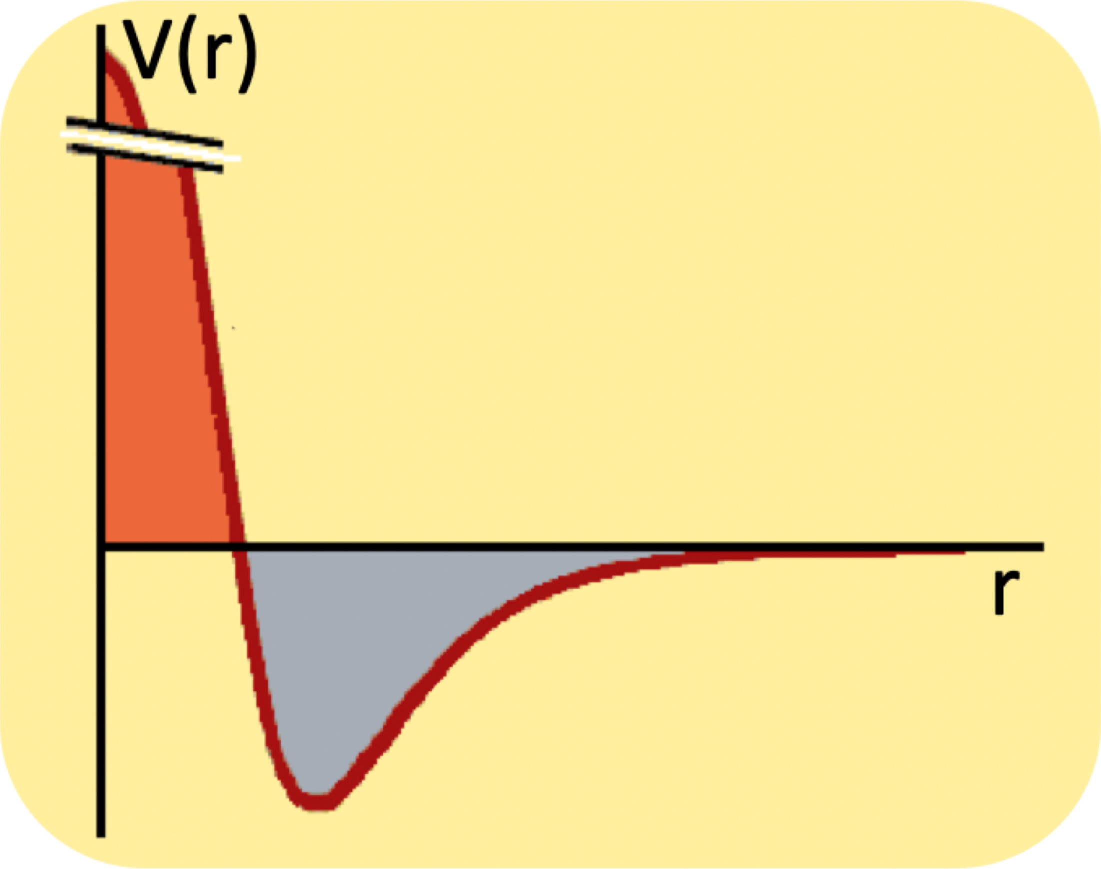
We simplify by describing the effective NN interaction as:



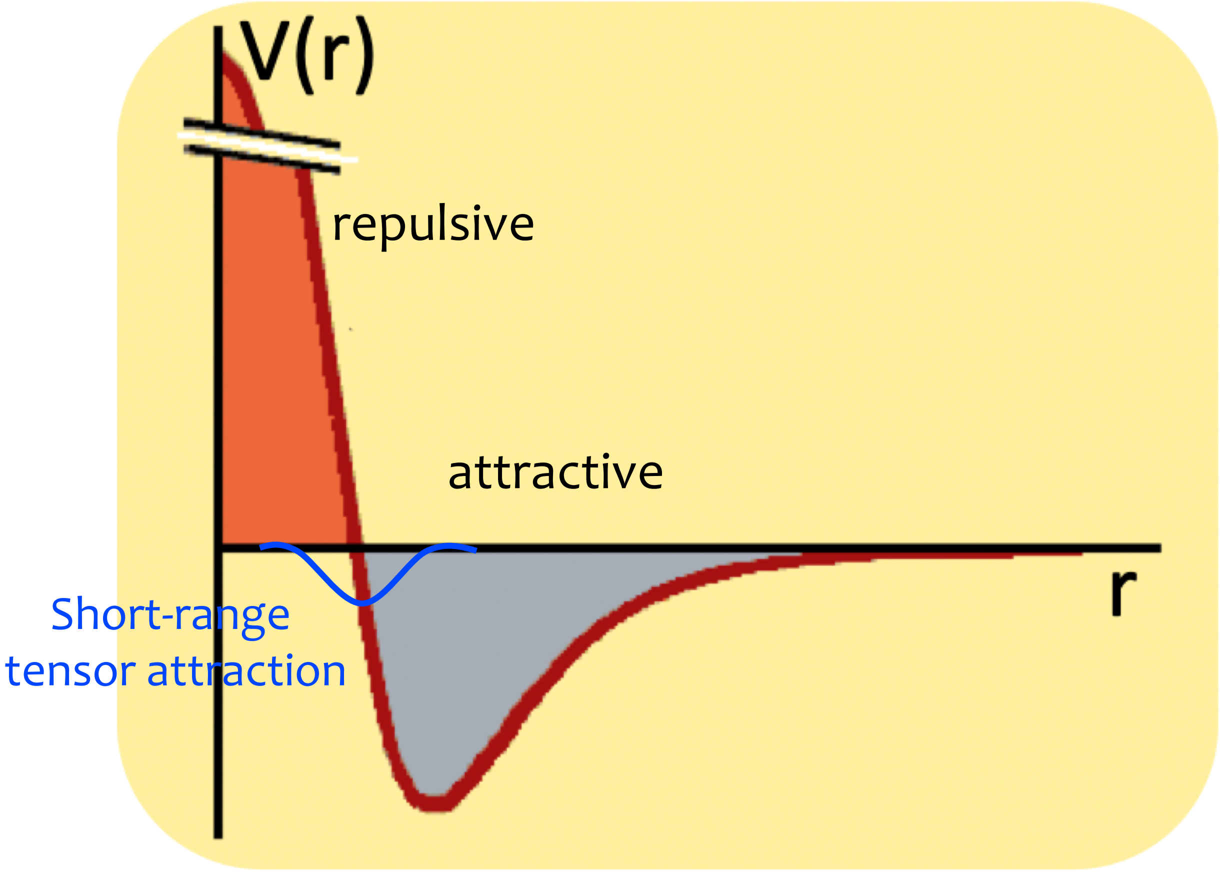


What holds the nucleus together?

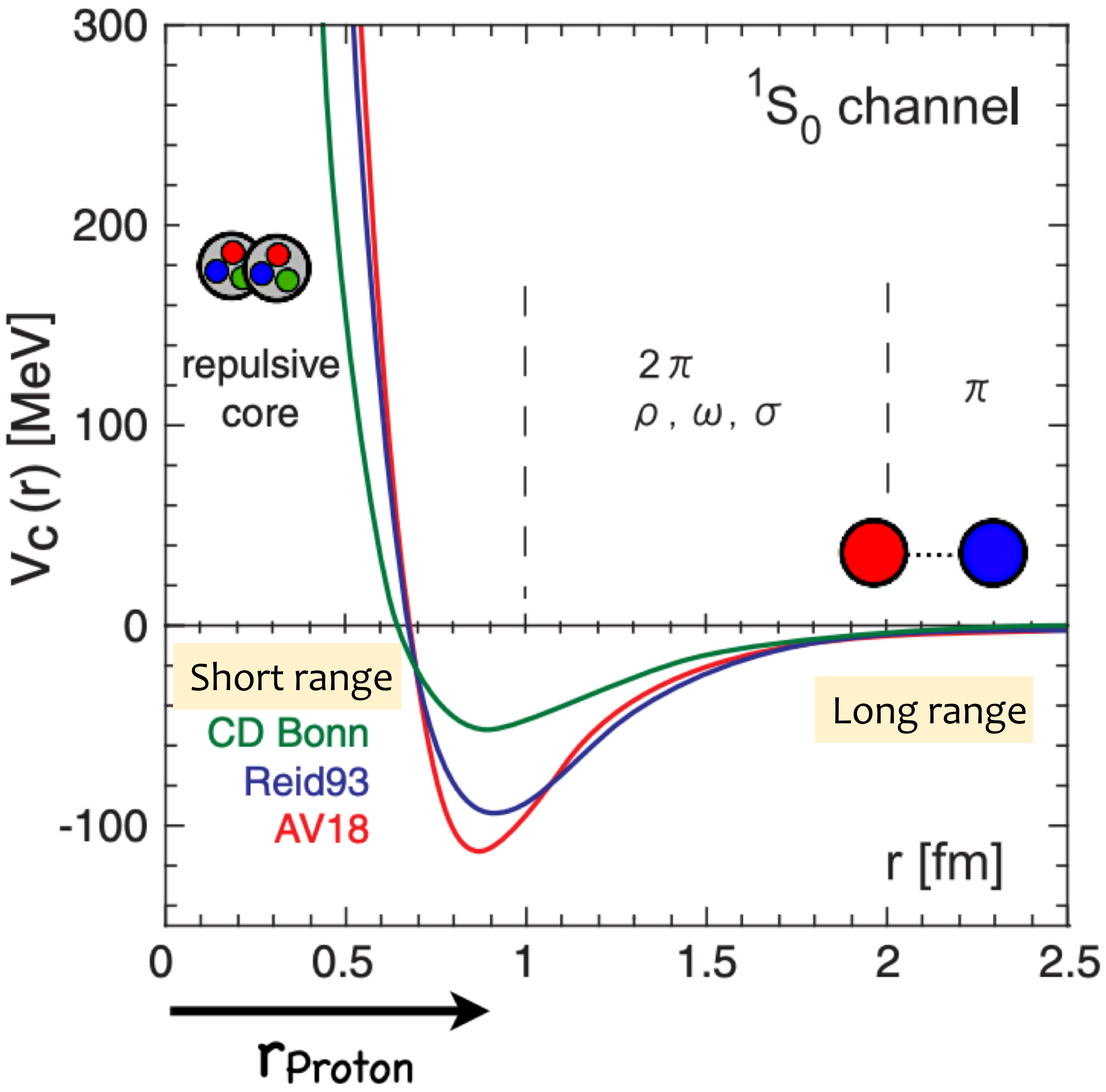
NN potential



NN potential

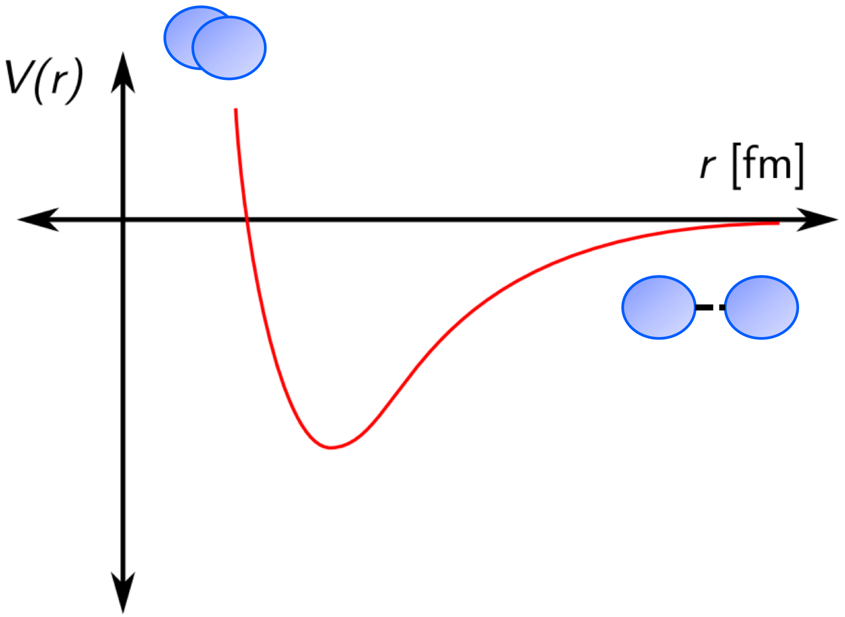


NN interaction



NN potential

Potential between nucleons

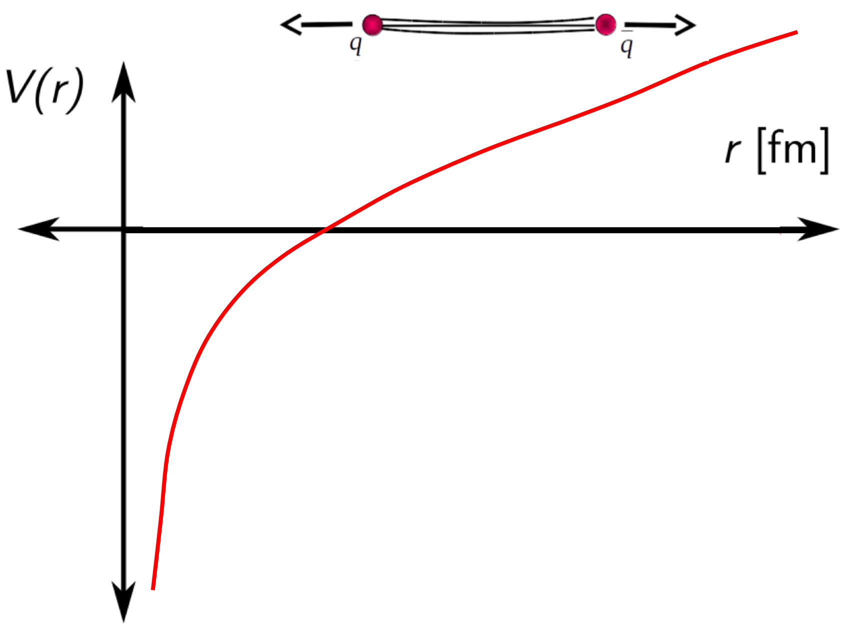


Characterized by:

- 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:

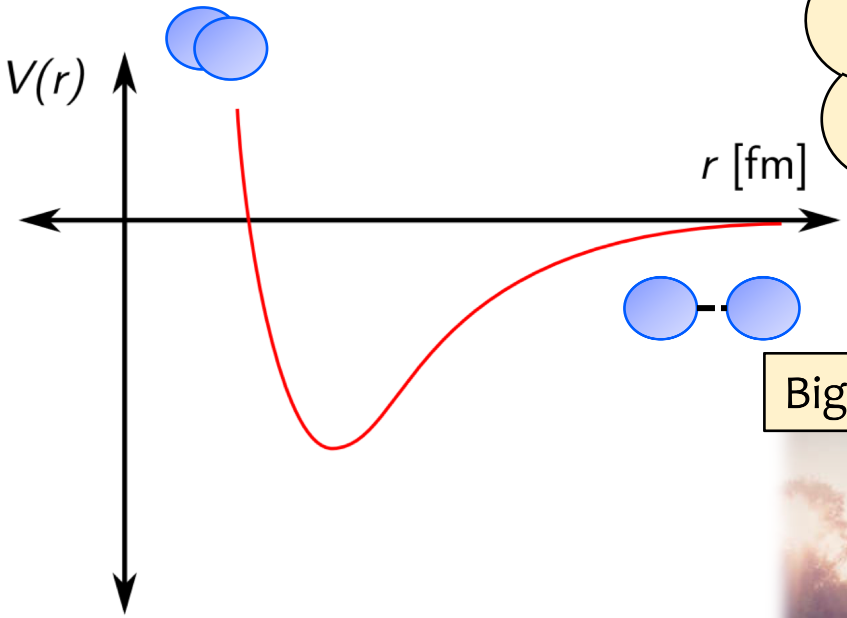
- Strongly attractive
- At short distances or high energies, QCD is asymptotically free (pQCD works here)

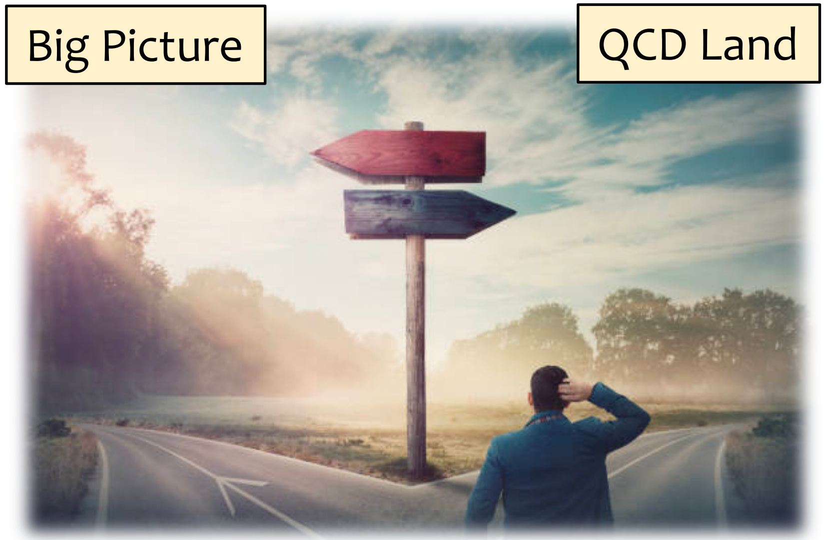
Two descriptions of nuclear physics

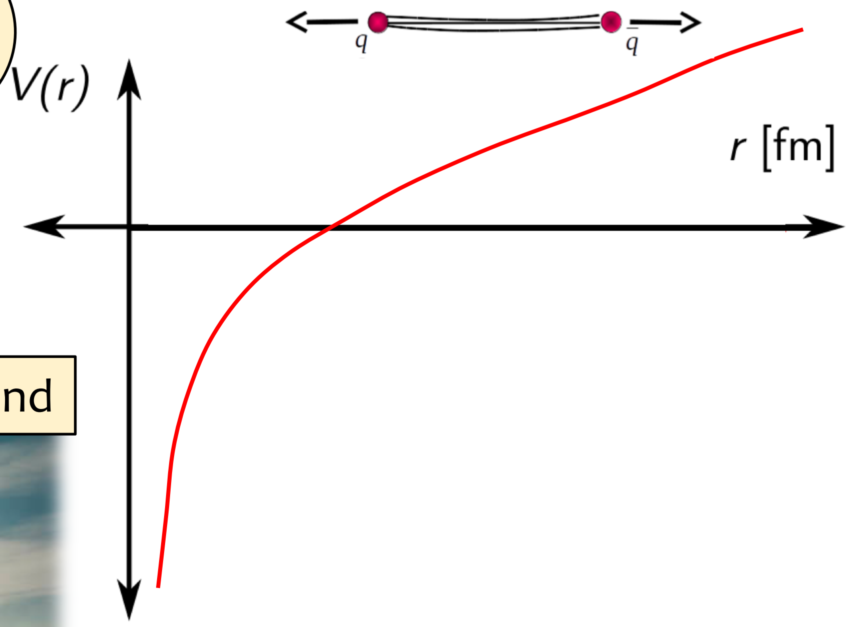
Potential between nucleons

What is the roadmap between these two regimes?

Potential between quarks







nucleons & mesons

quarks & gluons

Drawing the roadmap

QCD is the leading description for the strong force.

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

We have to connect the Big Picture to QCD Land using data.

Useful clues:

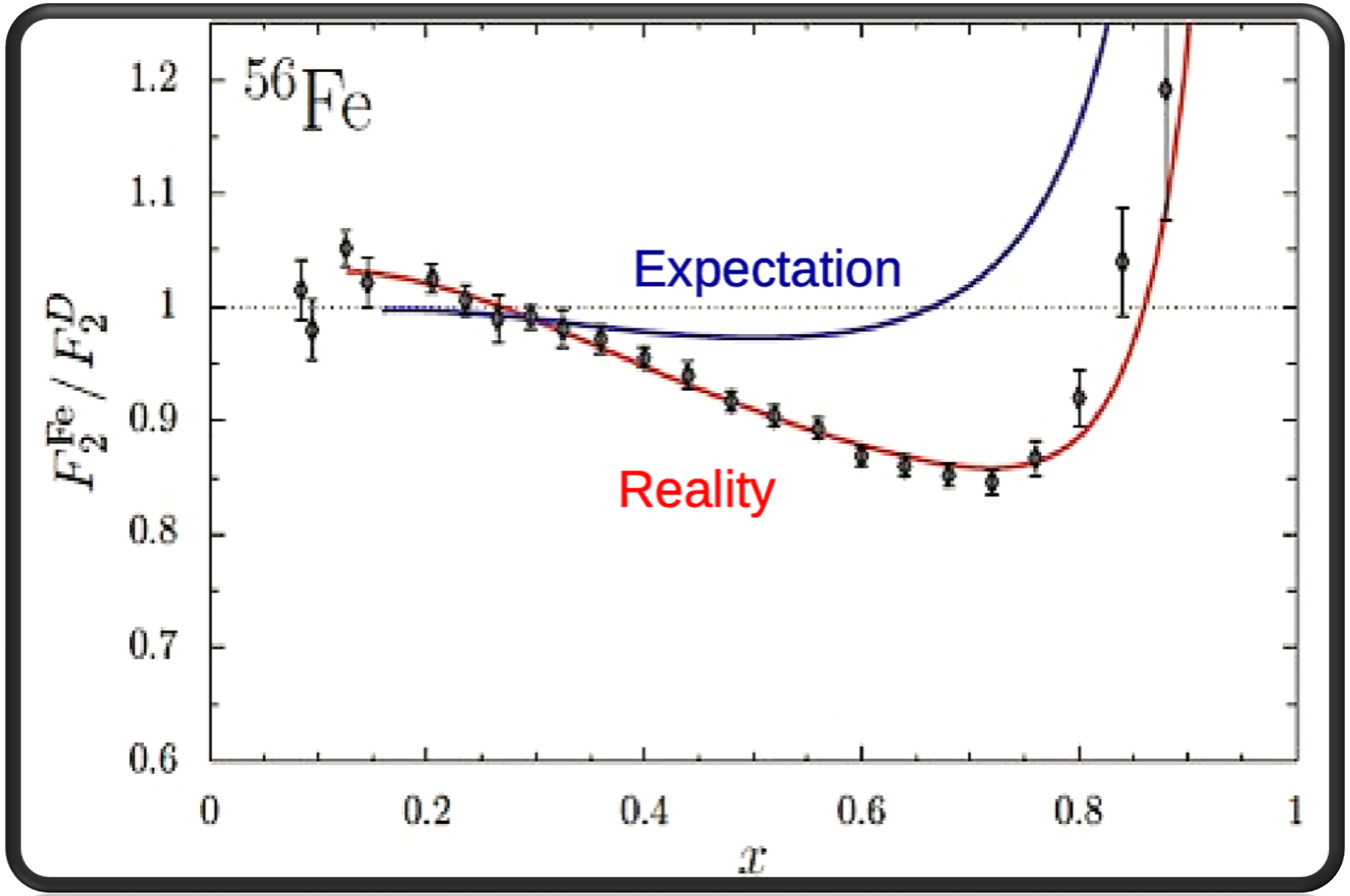
Modifications in the structure and interactions of hadrons in the nucleus.

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

Hypothesis: Nucleon structure is modified in the nuclear medium

- Swollen nucleons: confinement size related to nuclear density
- Multiquark clusters: color singlet states (6+) quarks form when nucleon wave functions overlap
- Dynamical rescaling: quark distributions in bound nucleon look like those in the free nucleon at higher Q^2

Hypothesis: Nuclear structure is modified due to multi-nucleon effects

- Binding and Fermi motion are leading order effects
- Contribution from nuclear pions
- NN short-range correlations

EMC ⟶ Everyone's Model is Cool 😎

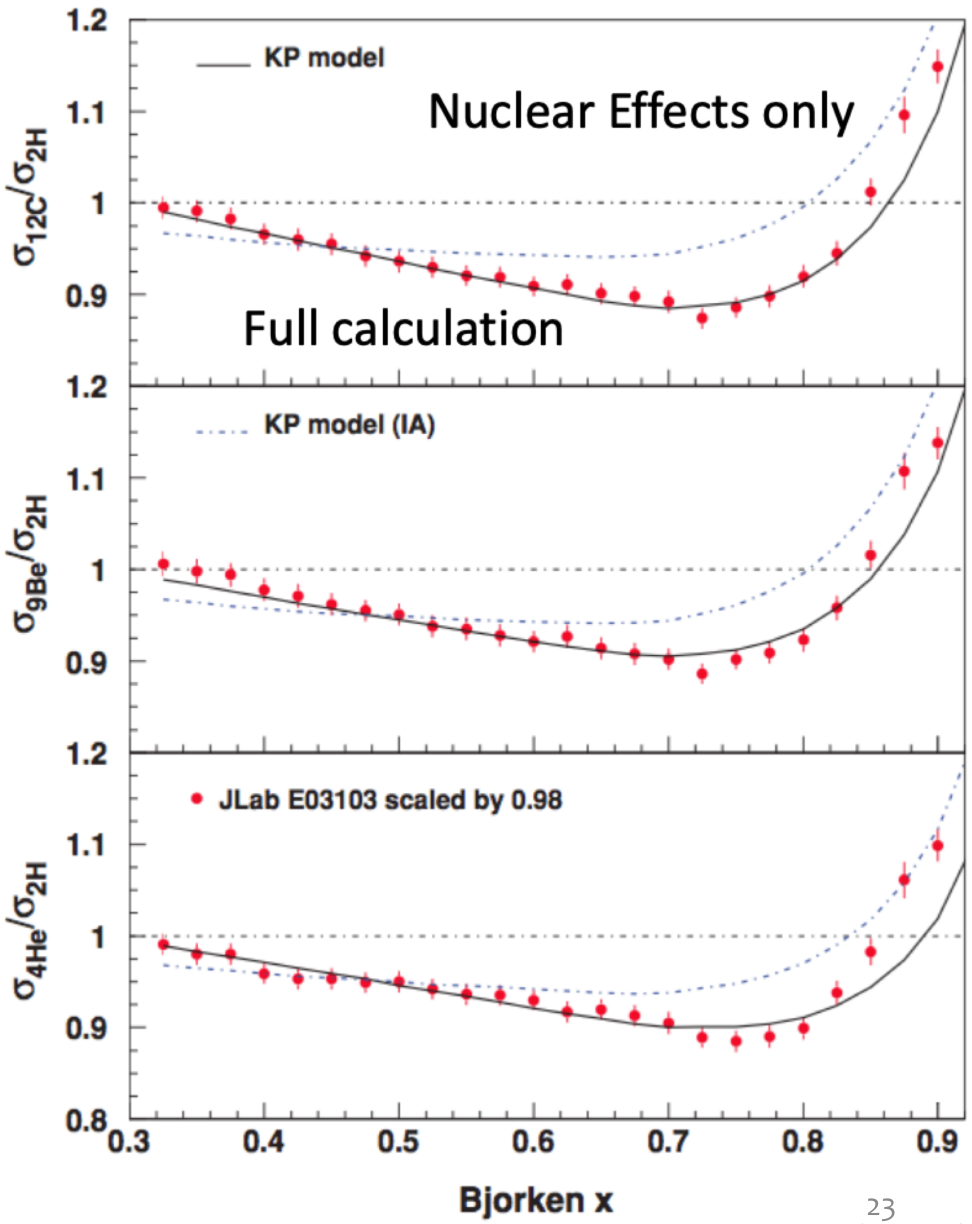
Nucleon modification needed to describe the data

Nuclear Effects:

- Fermi motion
- Binding energy

Full Calculation:

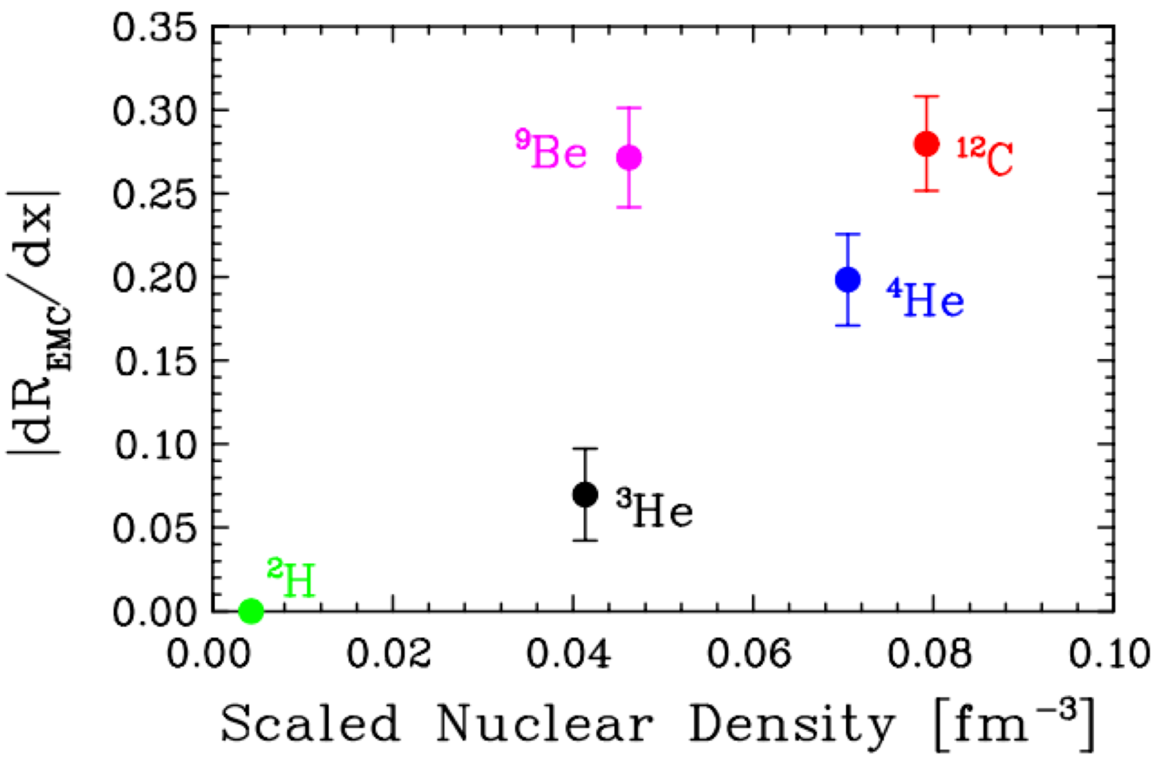
- Nucleon modification
- Phenomenological change to bound nucleon structure functions, proportional to virtuality (p^2)
- Nuclear pions
- Shadowing



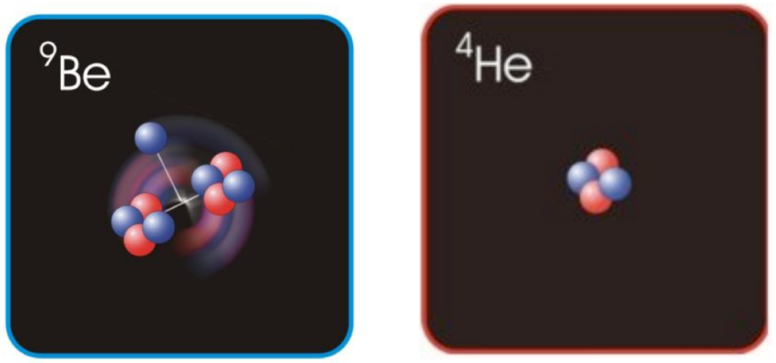
Kulagin and Petty, PRC 82, 054614 (2010)

EMC Effect in light nuclei

(EMC Slope)



(average)



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

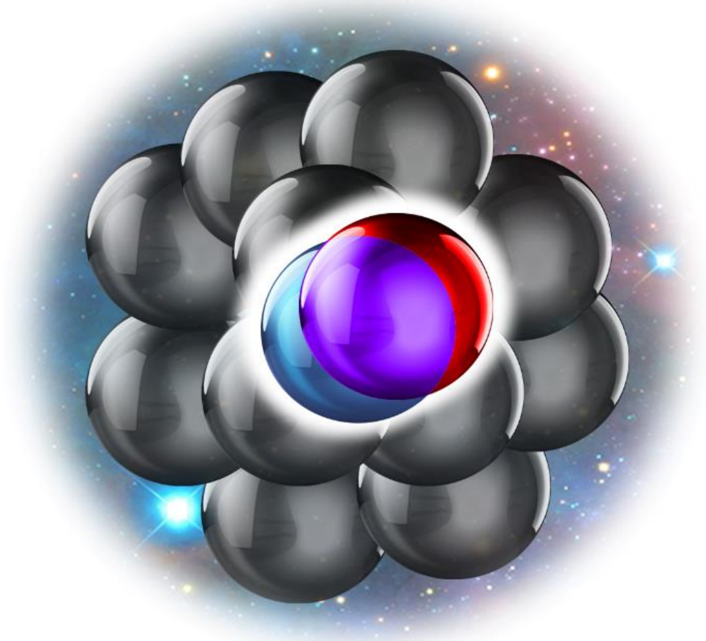
Local density important to the modification!

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

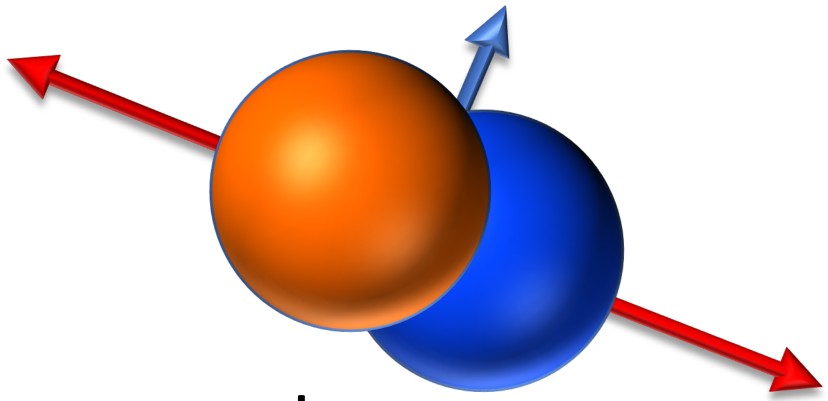
Other local density effects: NN short-range correlated pairs

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

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

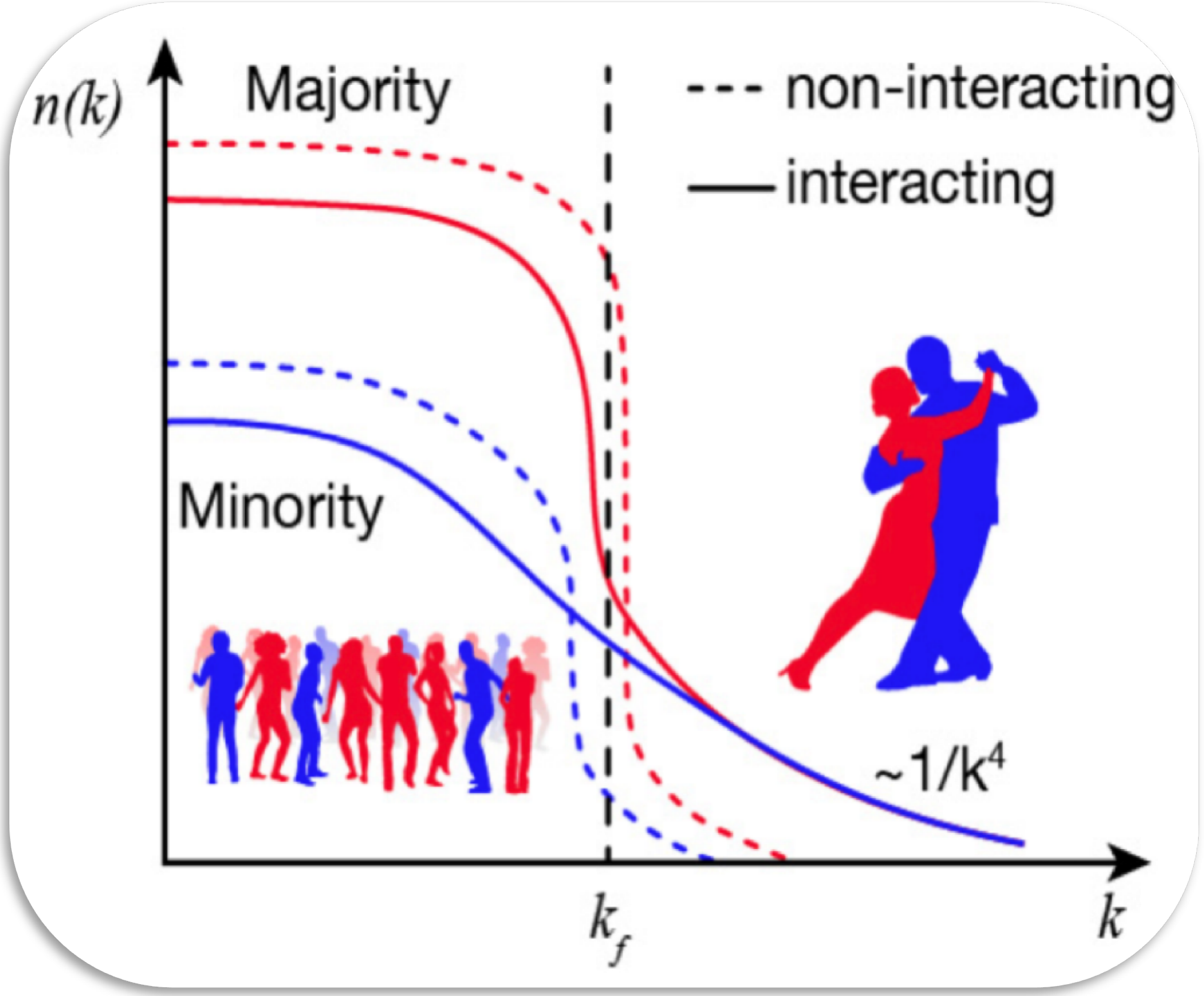


r-space



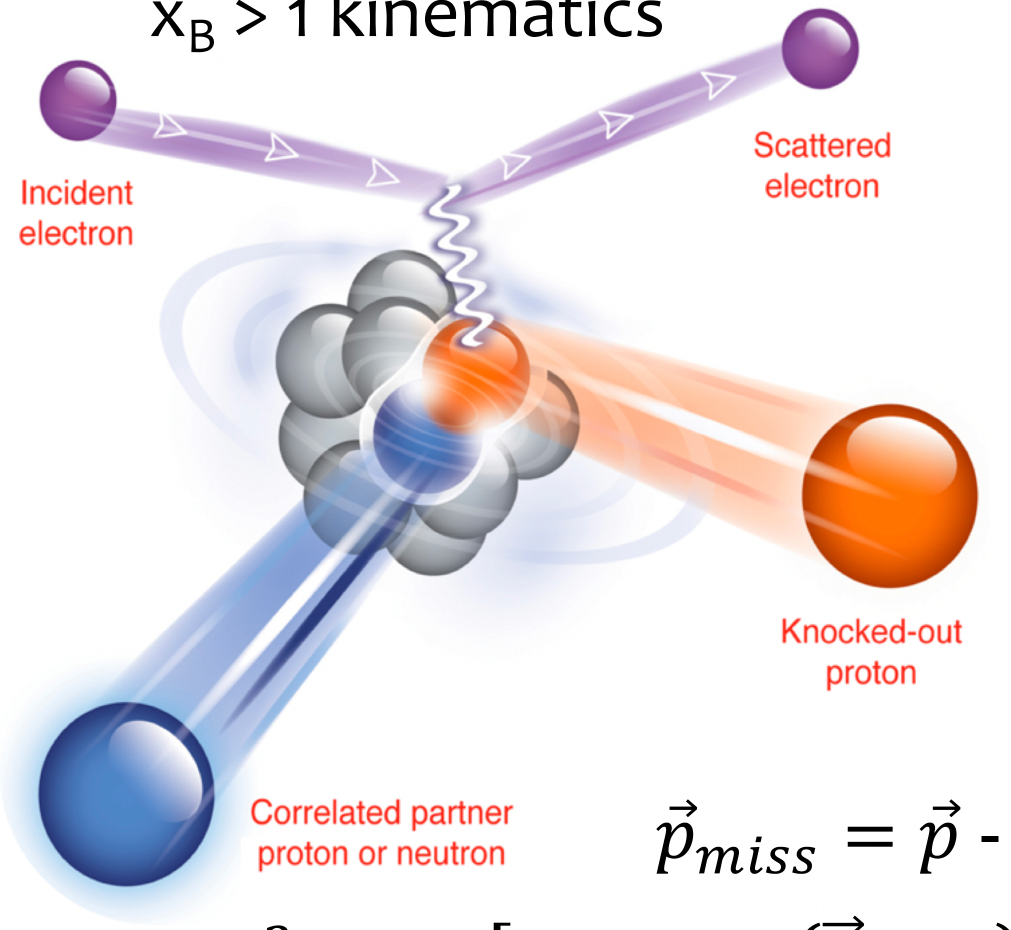
k-space

SRCs in the high momentum tail



How do we look for SRCs?

$x_B > 1$ kinematics



Reconstruct:

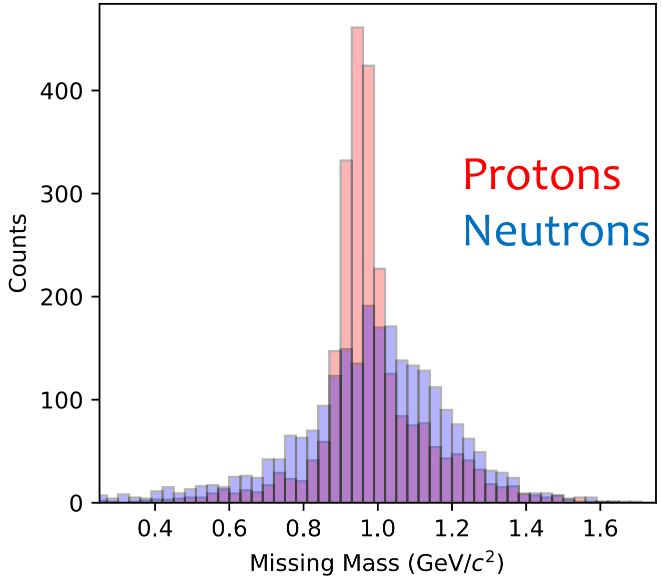
- scattered electron
- Detect a nucleon (p or n)
  - P_{miss}
  - M_{miss} (standing pair)
  - E_{miss}

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

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

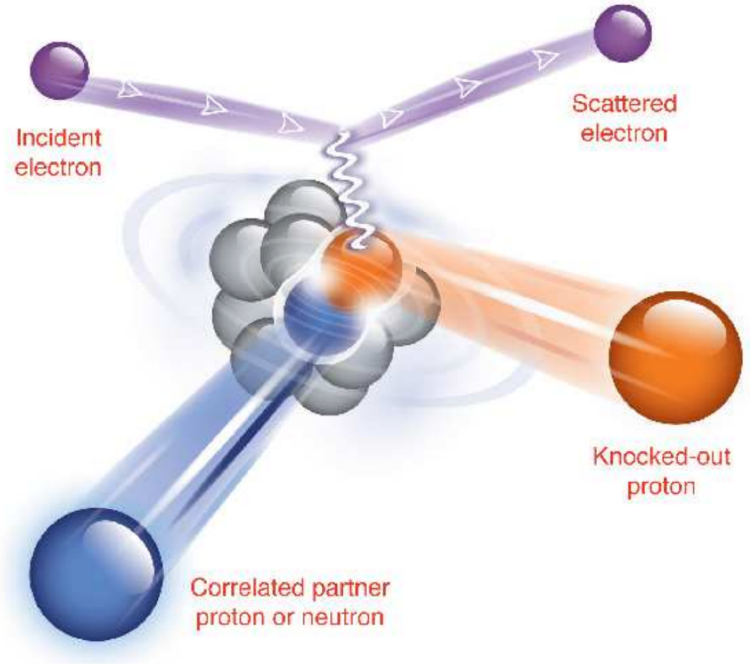
$$E_{miss} = \omega - T_N - T_{A-1}$$

SRC knockout reaction



How do we look for SRCs?

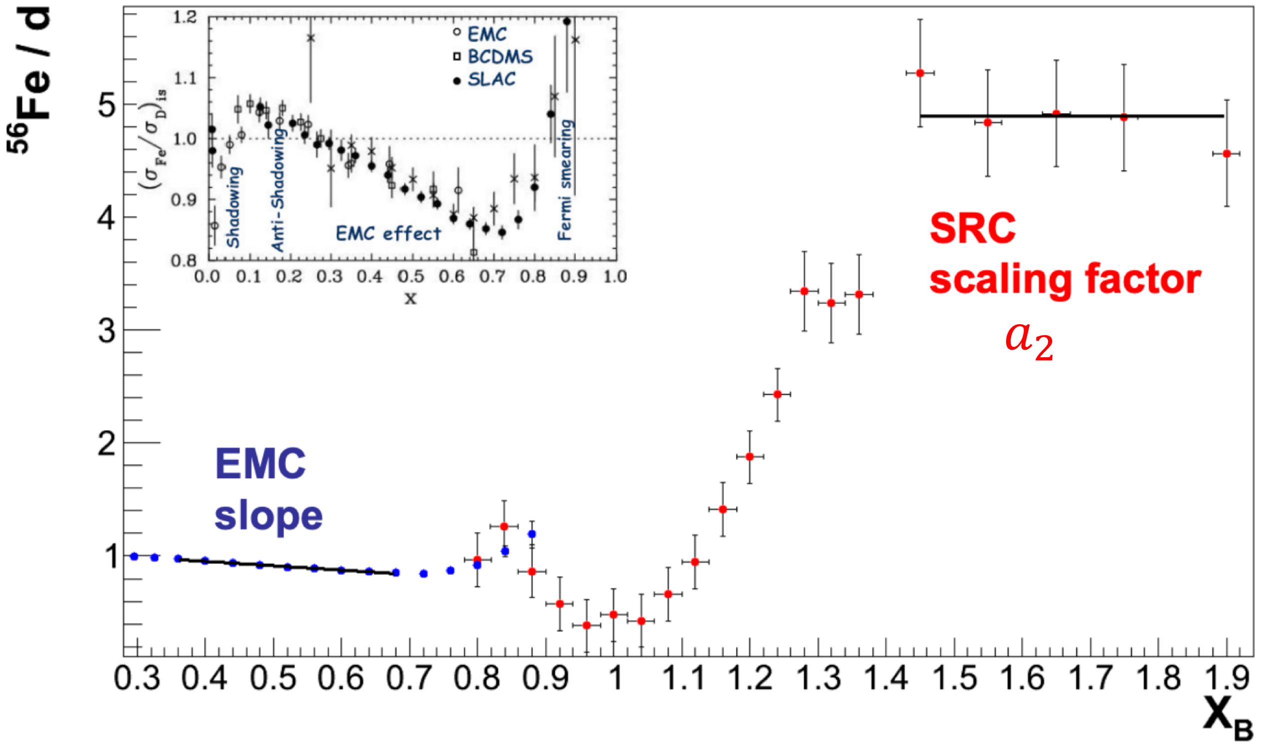
- A(e,e’) reaction at x>1: can inform us about the probability of 2N and 3N SRC
- D(e,e’pn): simplest nucleus with pairing
- A(e,e’N) and A(e,e’NN): probes the detailed structure of SRCs

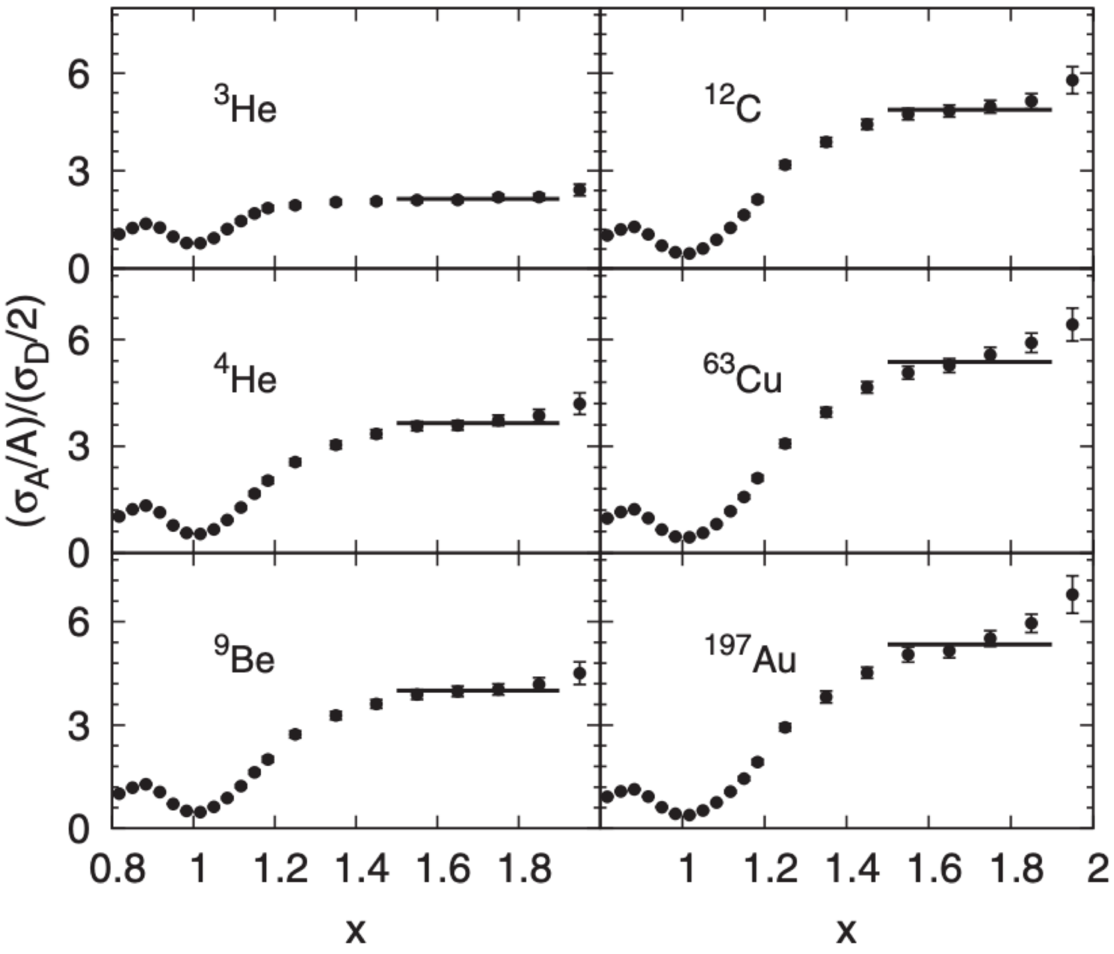


SRC scaling plateau

SRCs related to the local density.

A(e,e')



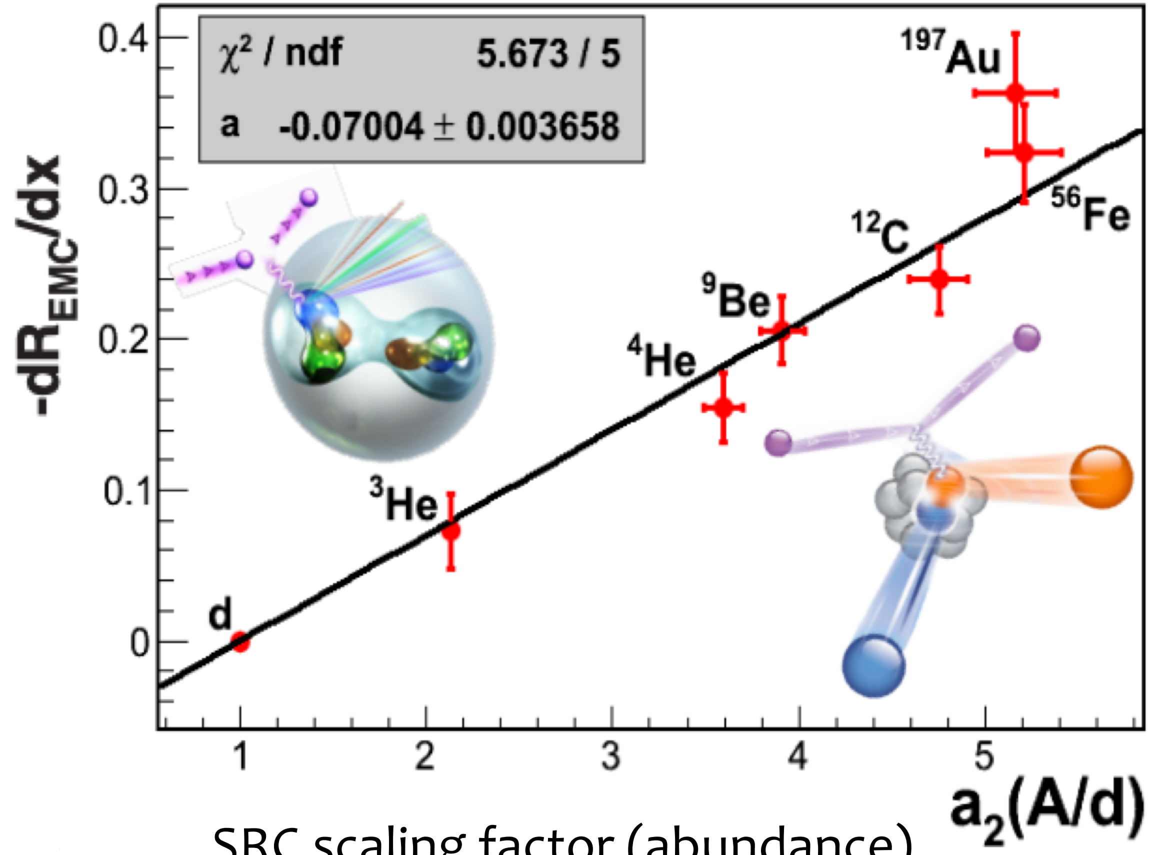


Frankfurt, Strikman, Day, Sargsyan, Phys. Rev. C48 (1993) 2451
Gomez et al., Phys. Rev. D49, 4348 (1983)

N. Fomin et al., PRL 108, 092502 (2012)

EMC Effect and SRCs

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



SRC scaling factor (abundance)

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

Re-visiting the EMC Effect with SRCs

Bound = 'quasi Free' + Modified SRCs

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

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

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

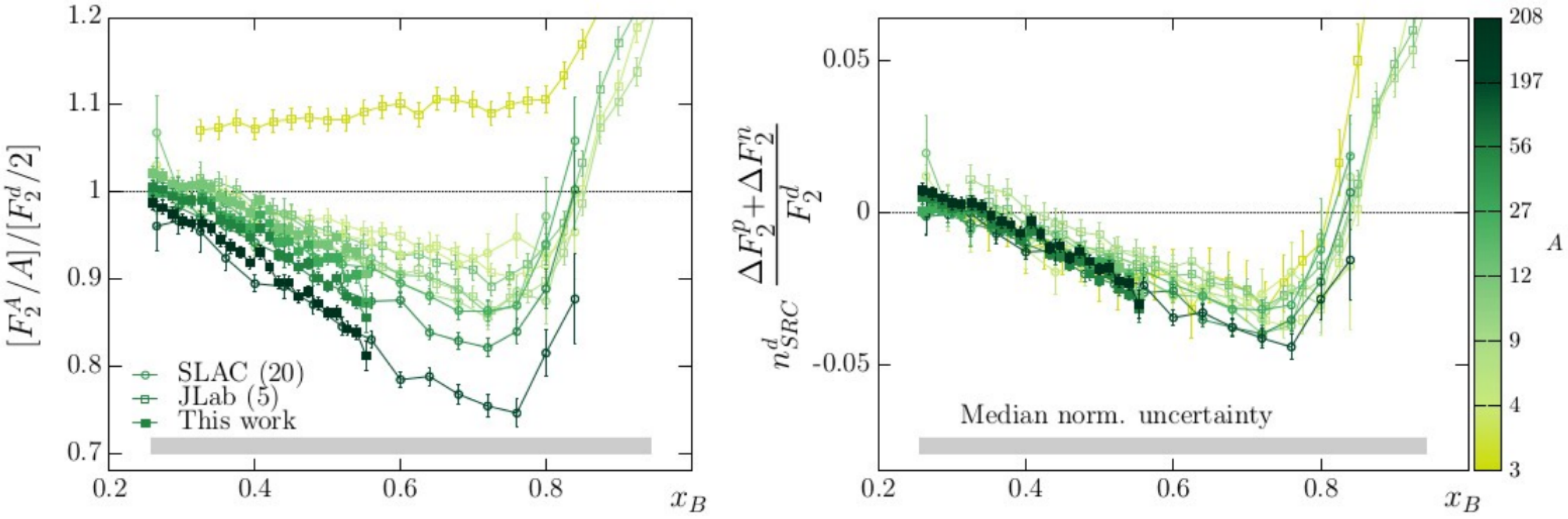
$$a_2 \equiv \frac{2}{A} n_A^{SRC} / n_d^{SRC}$$

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

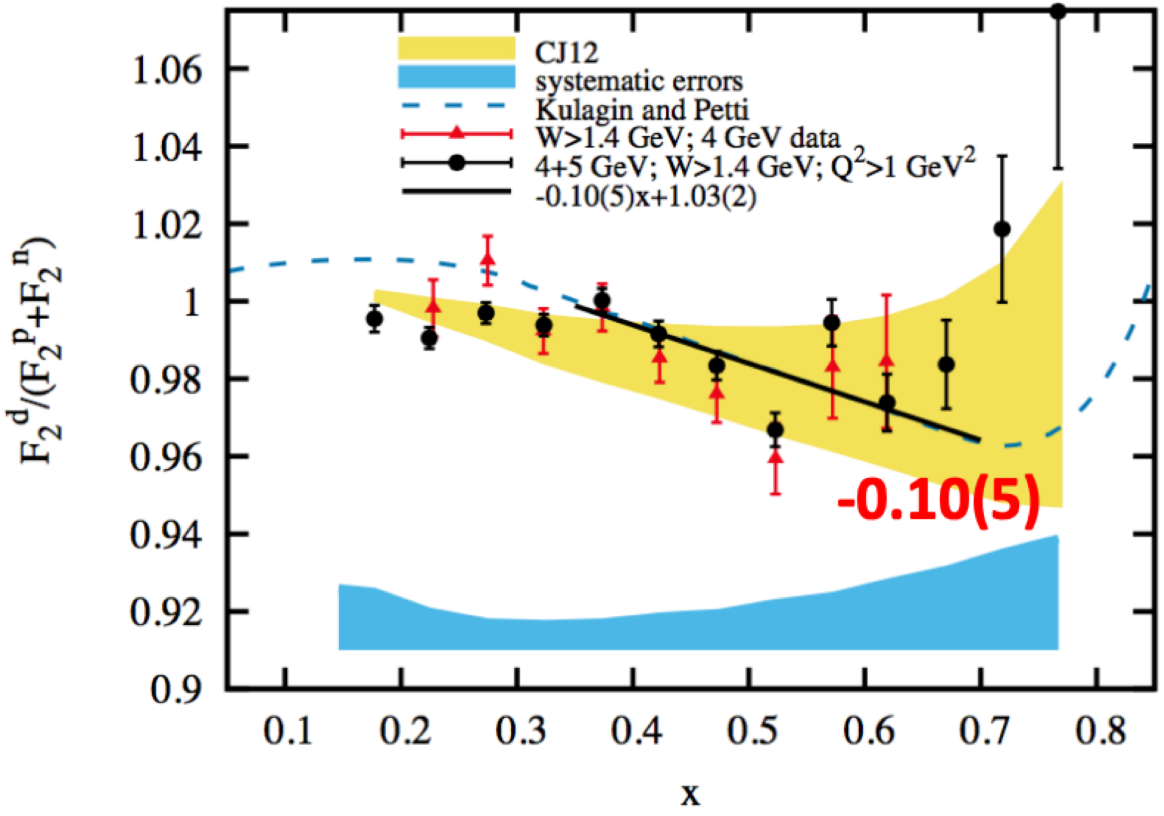


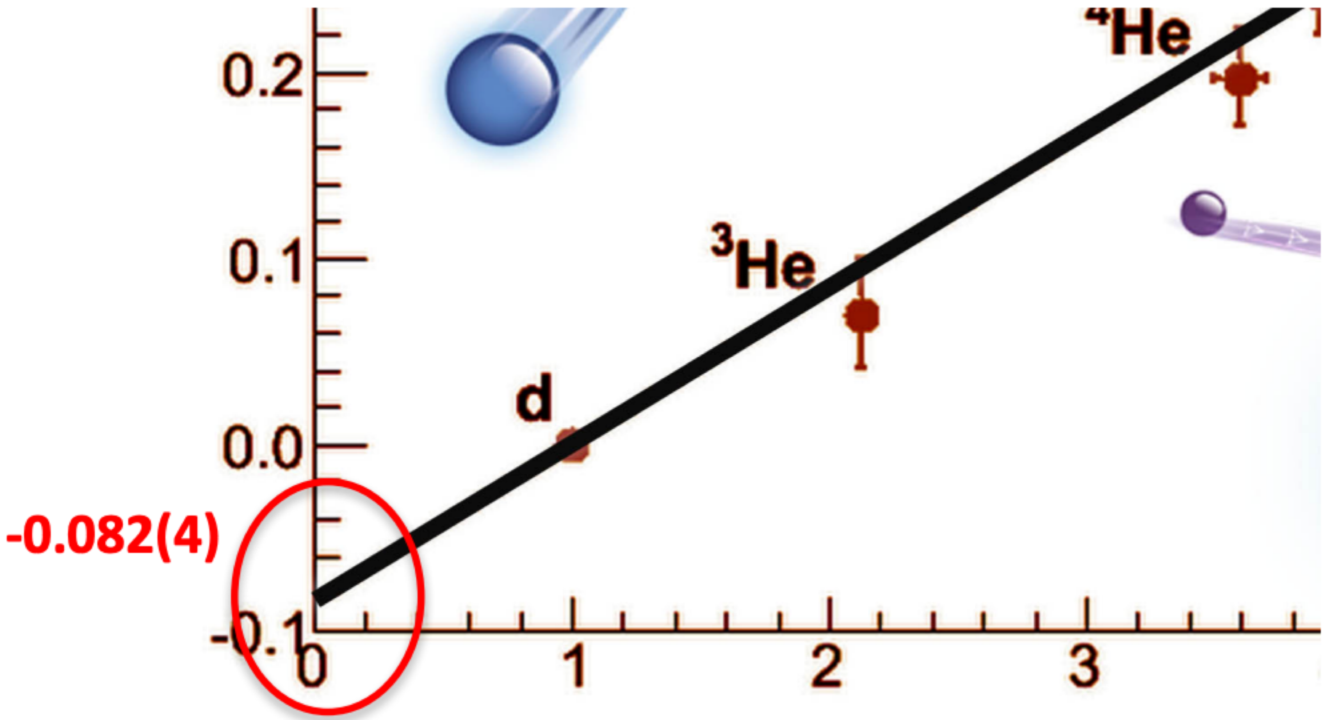
Implies heavier nuclei with many more neutrons than protons, each proton is more likely than each neutron to belong to an SRC pair and hence to have its quark structure distorted.

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 SRC-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

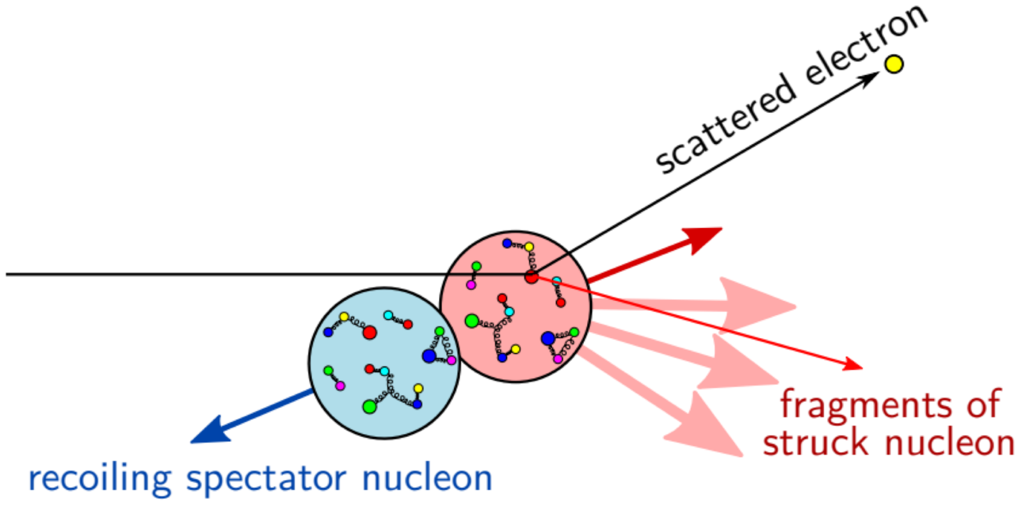
- F_2 independent of momentum
- $F_2 \neq$ free F_2 (small difference for all nucleons)

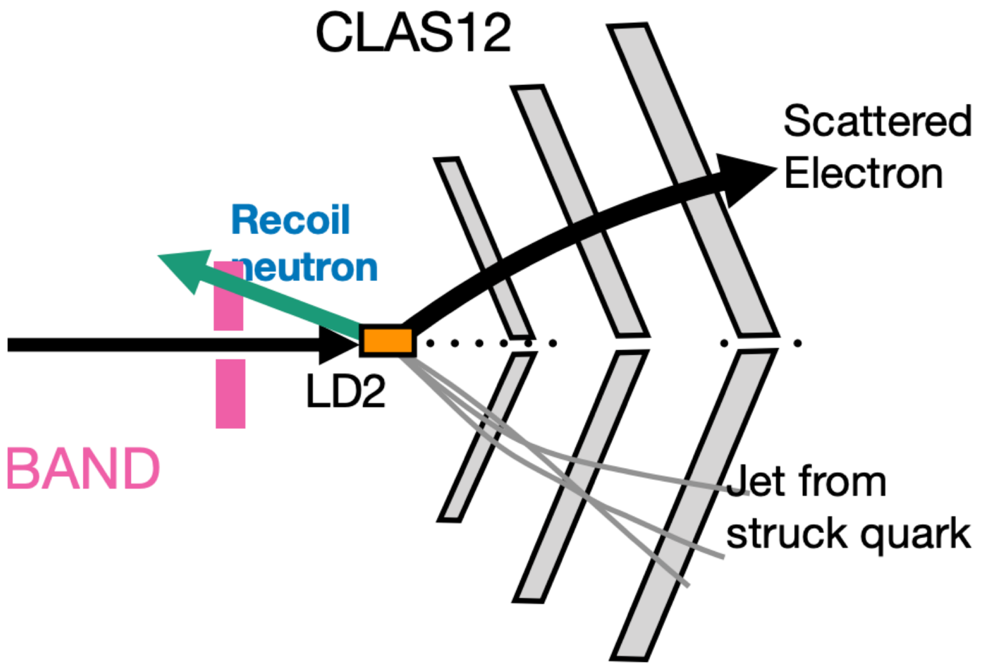
Two experiments that test this:
BAND in Hall B (analyzing)
LAD in Hall C (runs in 2025)

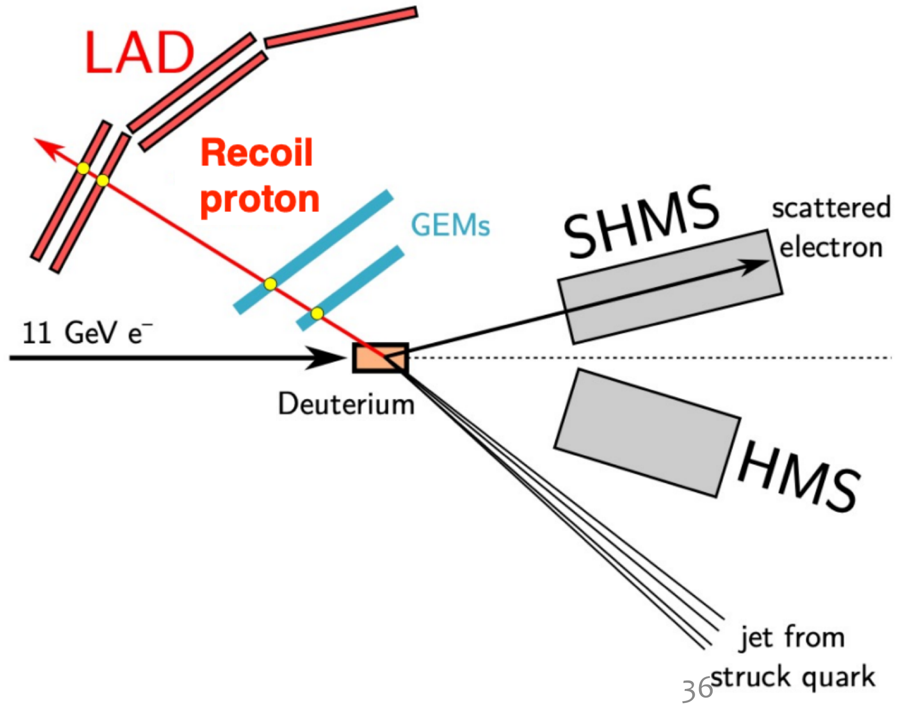
SRC nucleons modified

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

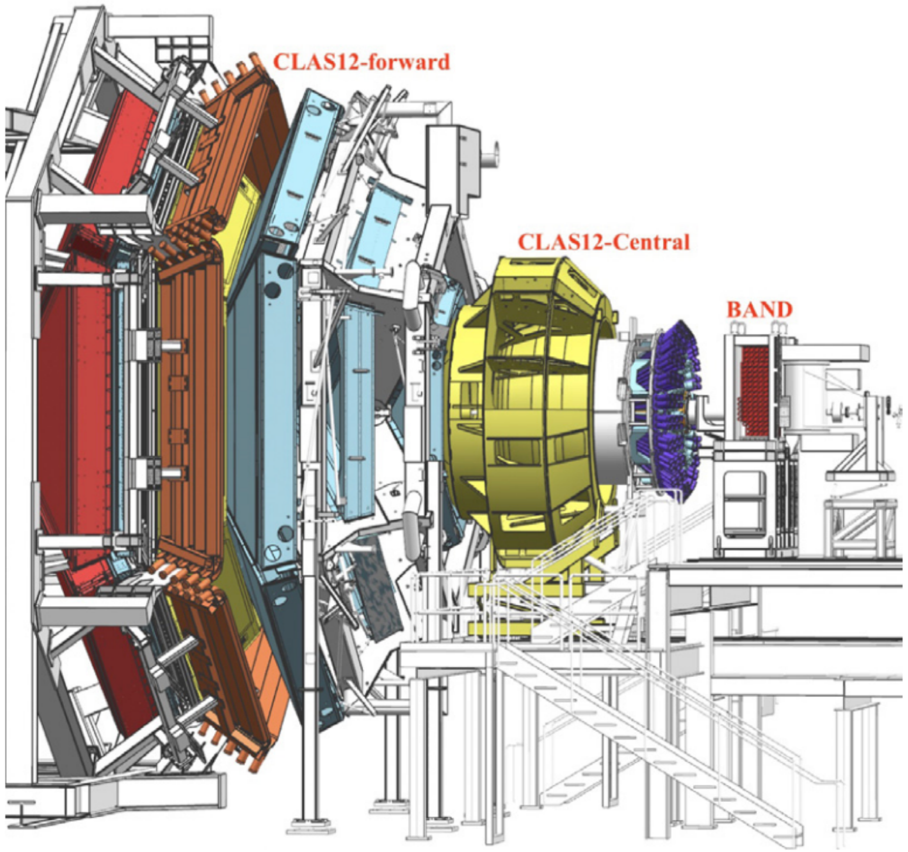
On a quest – spectator tagging!

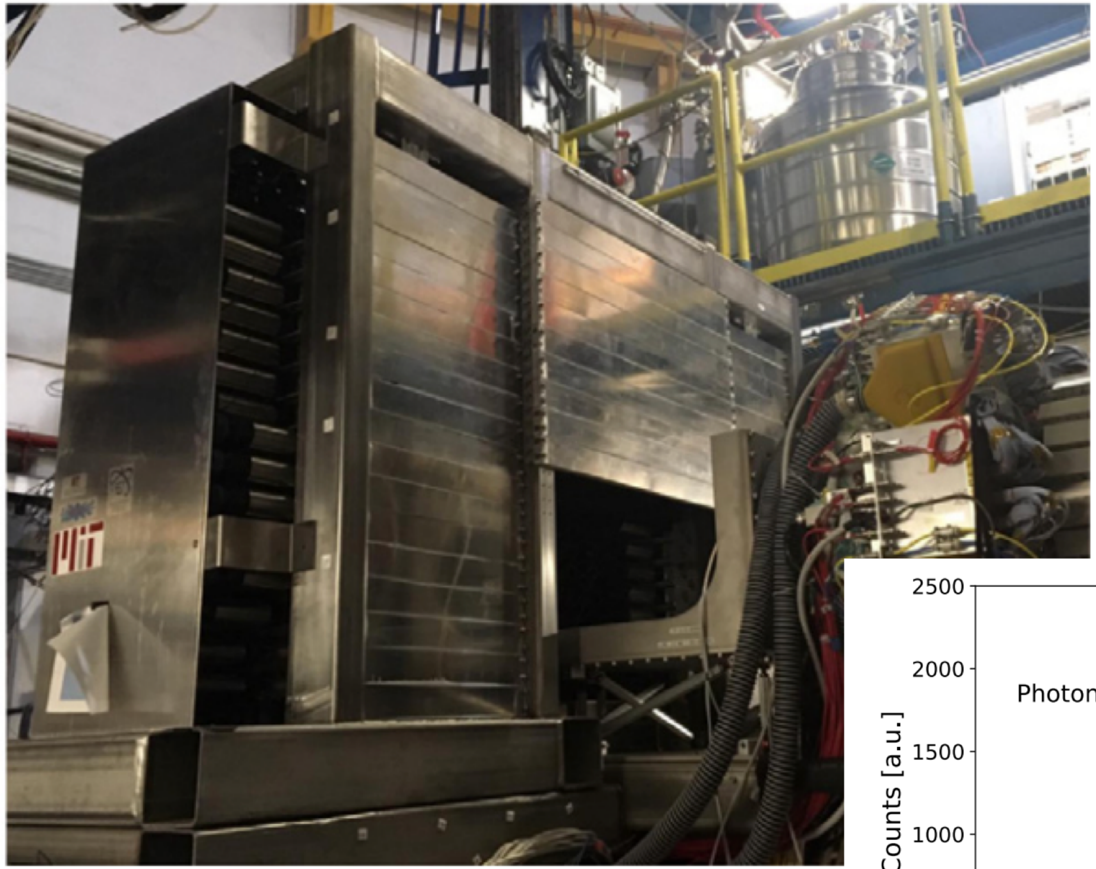


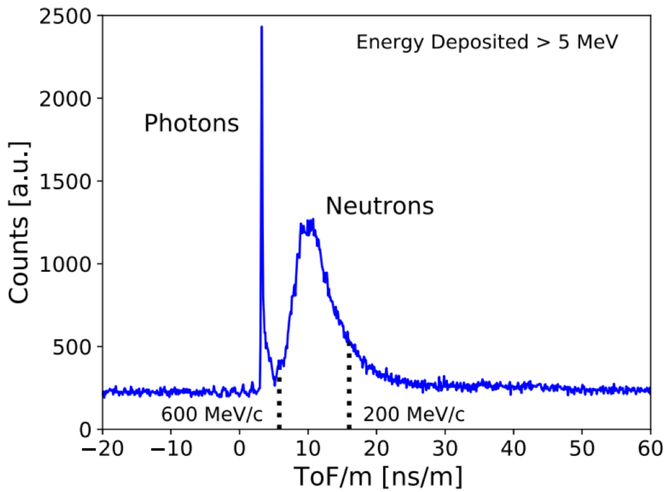




Back-angle neutron detector (BAND) in Hall B

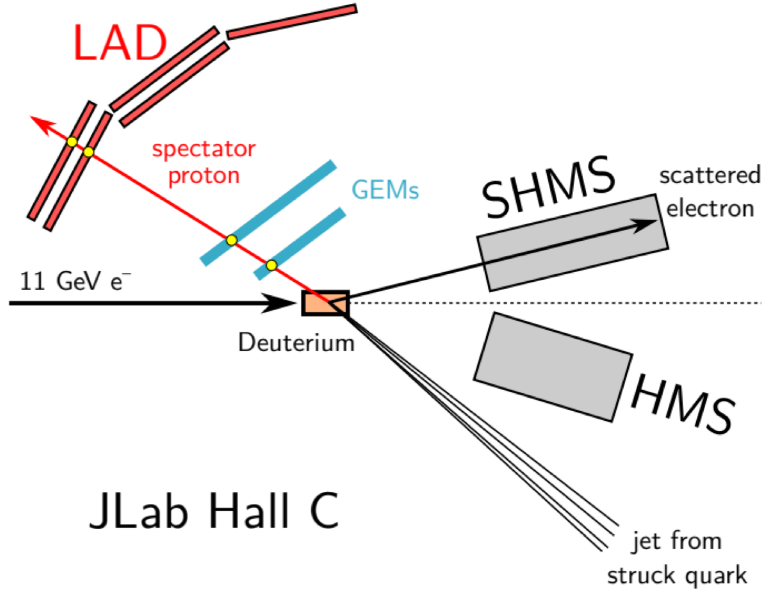


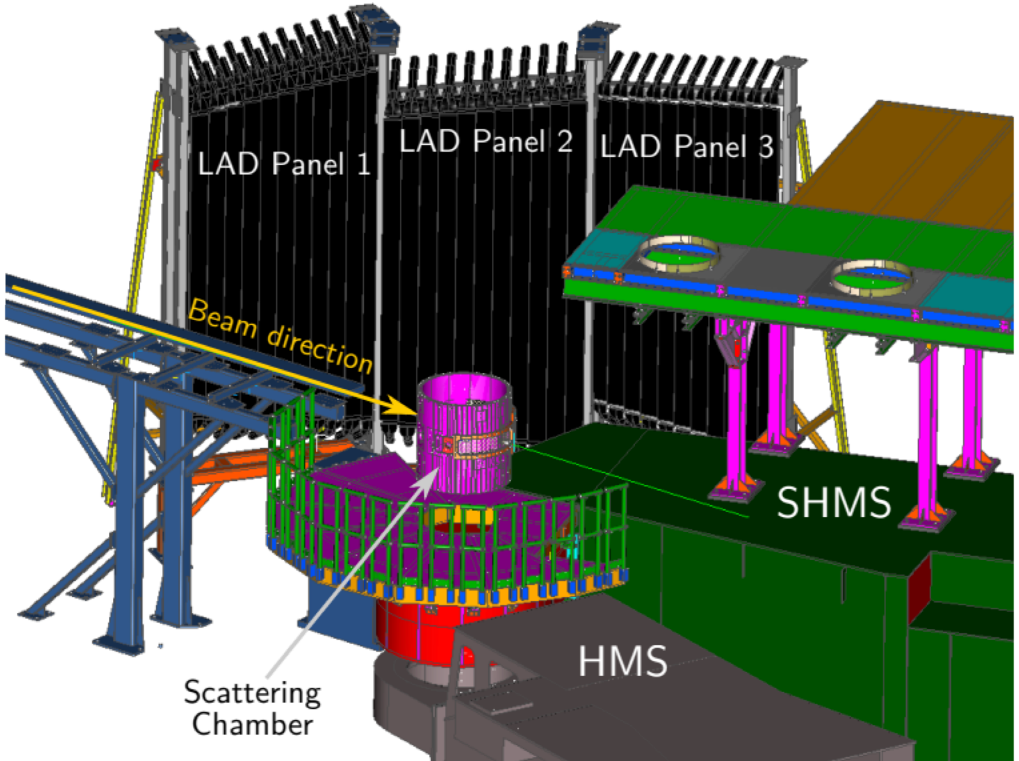




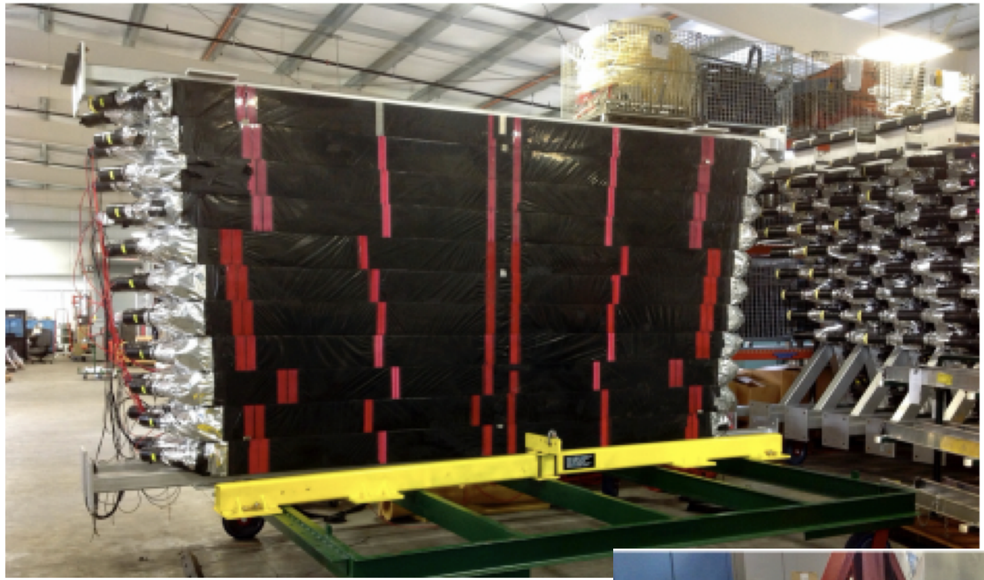
Nucl. Instrum. Meth. A **978**, 164356 (2020). arXiv: 2004.10339

Large-angle detector (LAD) in Hall C (detects protons)



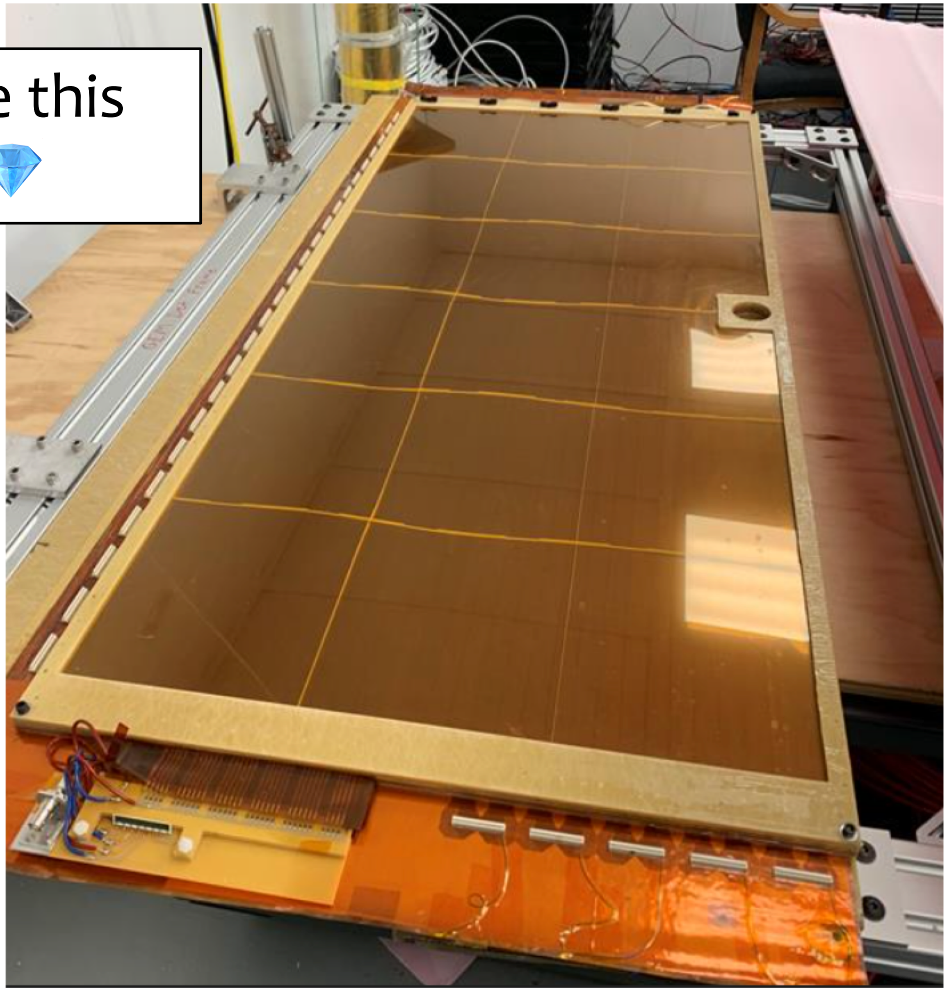


LAD experiment detectors

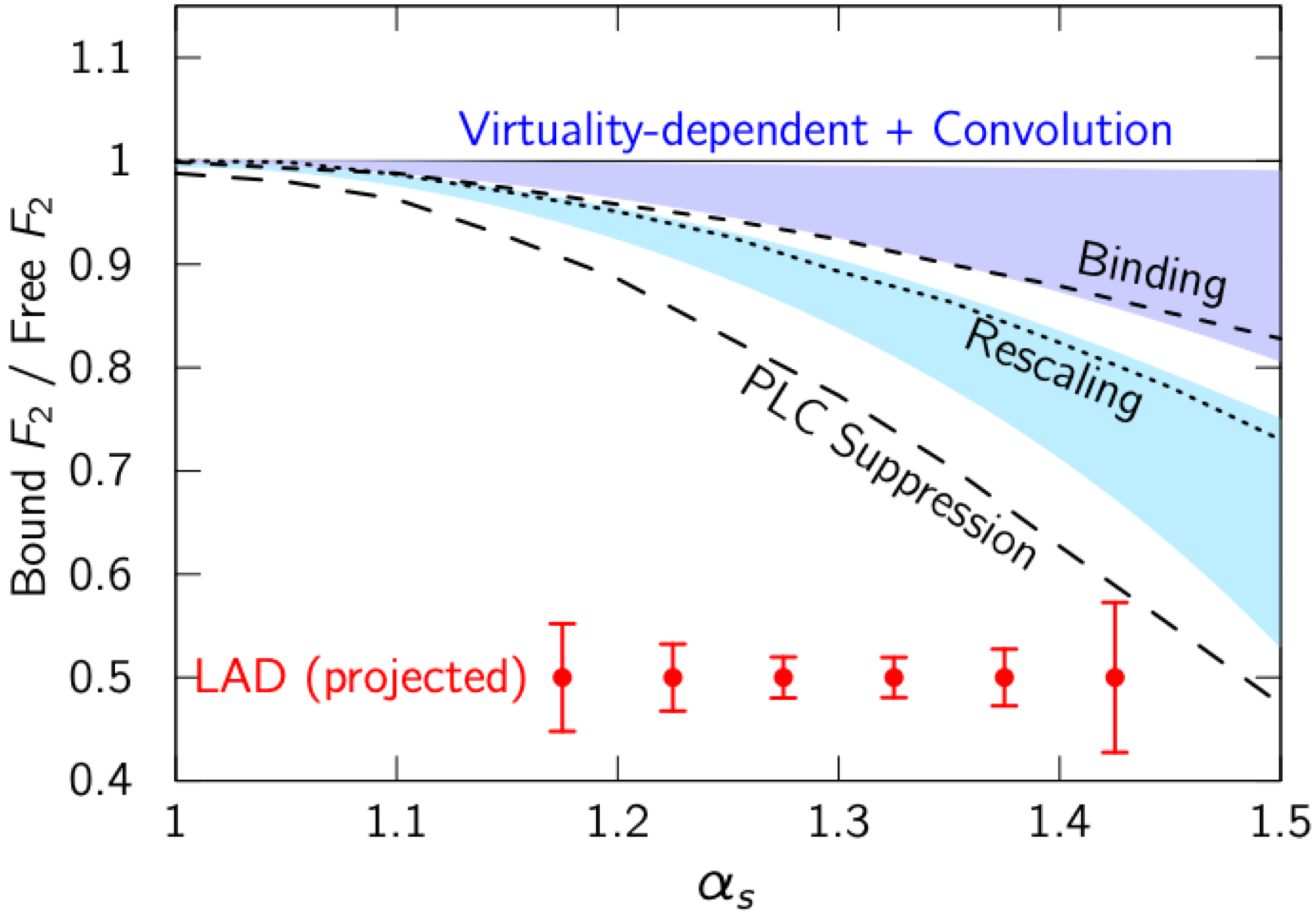


Repurpose large scintillators from Hall B (CLAS 6)

Recognize this GEM? 💎



LAD will distinguish between modification models

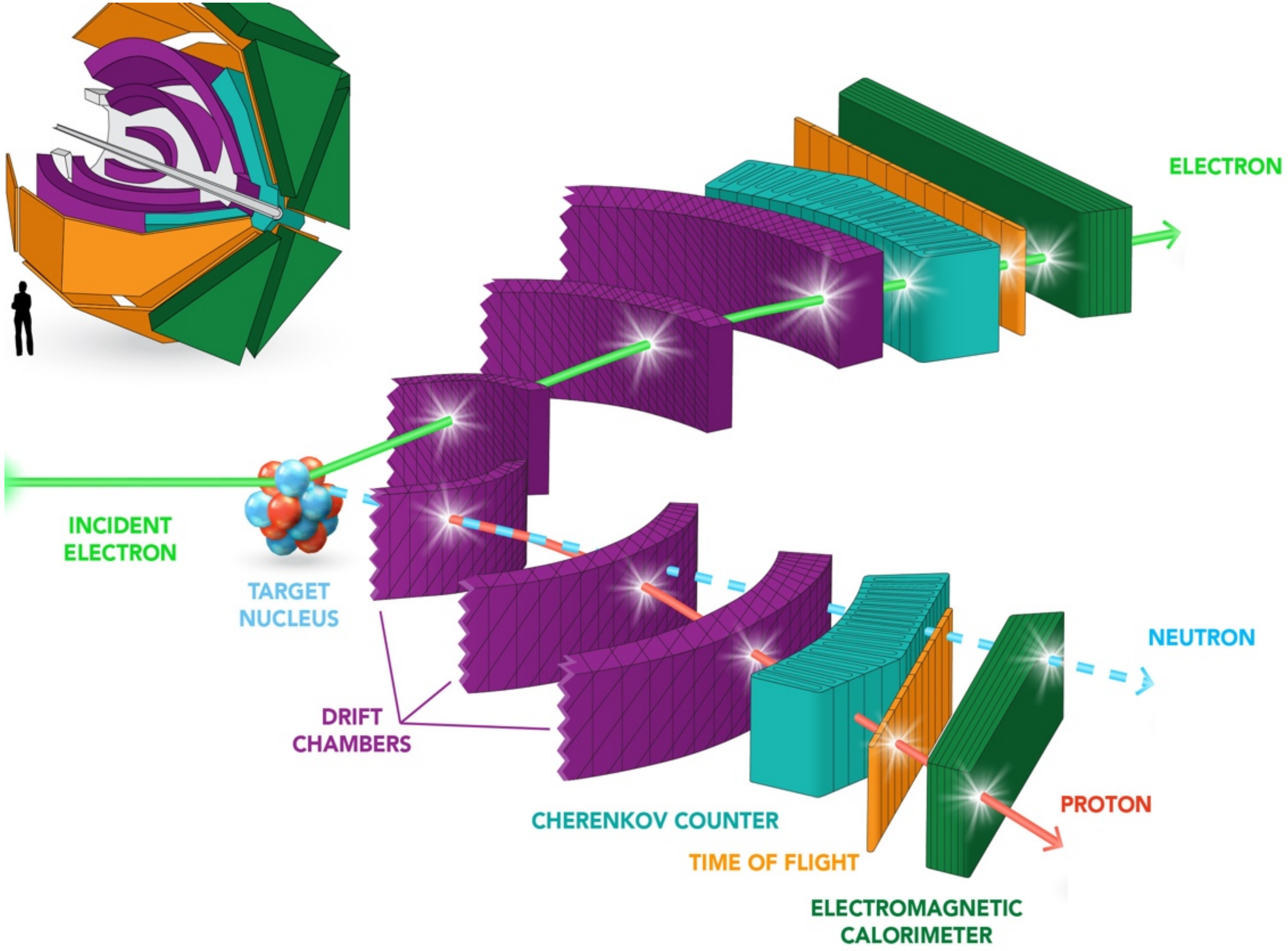


Melnitchouk, Sargsian, Strikman, Z. Phys. A 359, p. 99 (1997)
E. P. Segarra et al., Phys. Rev. Research 3, 023240 (2021)

What else do we learn from NN SRCs about nucleons?

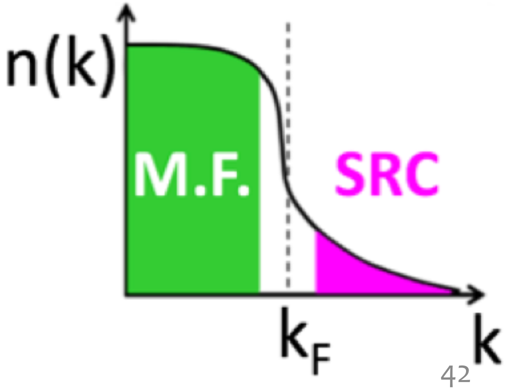
Knockout studies in CLAS (6 GeV era)

CLAS detector



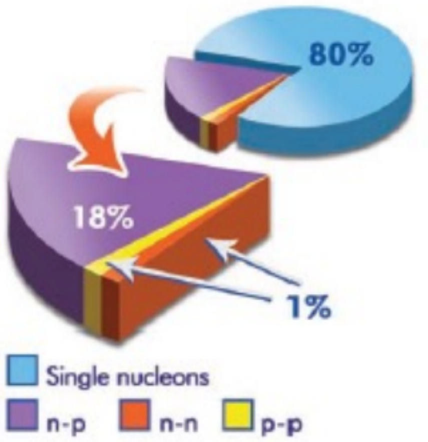
Low momentum
→ Mean field

High momentum
→ SRC pairs



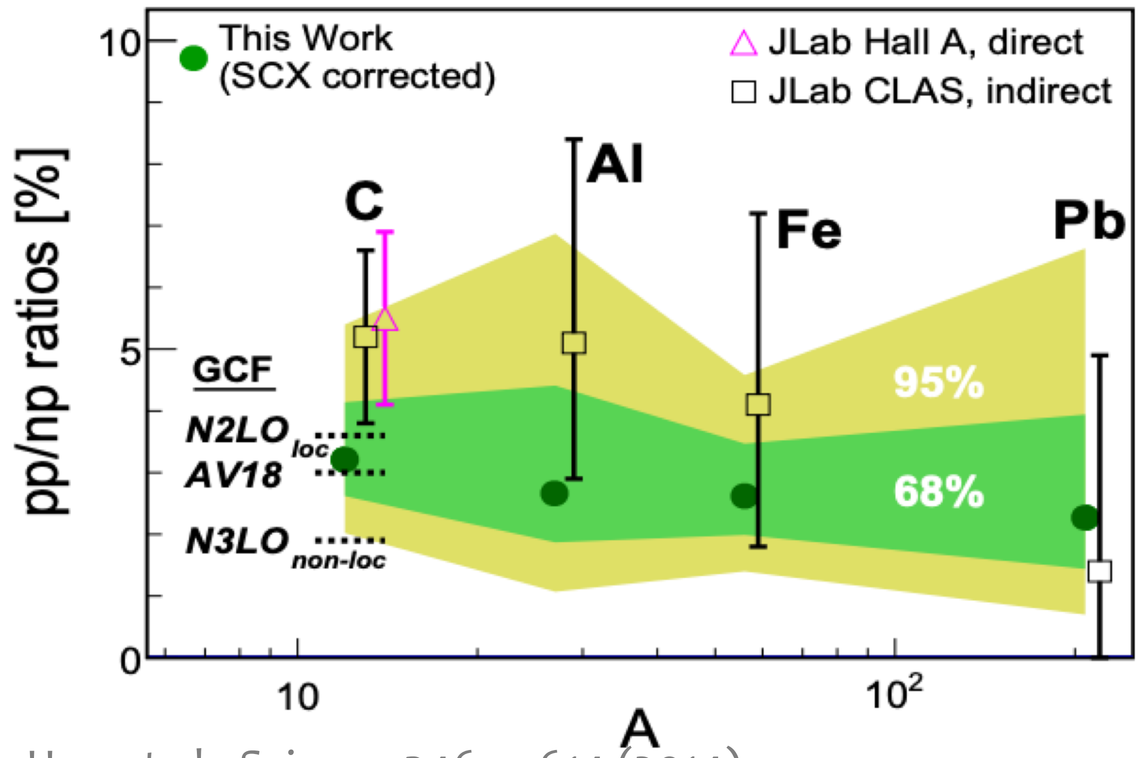
Picture of CLAS detector (Hall B)

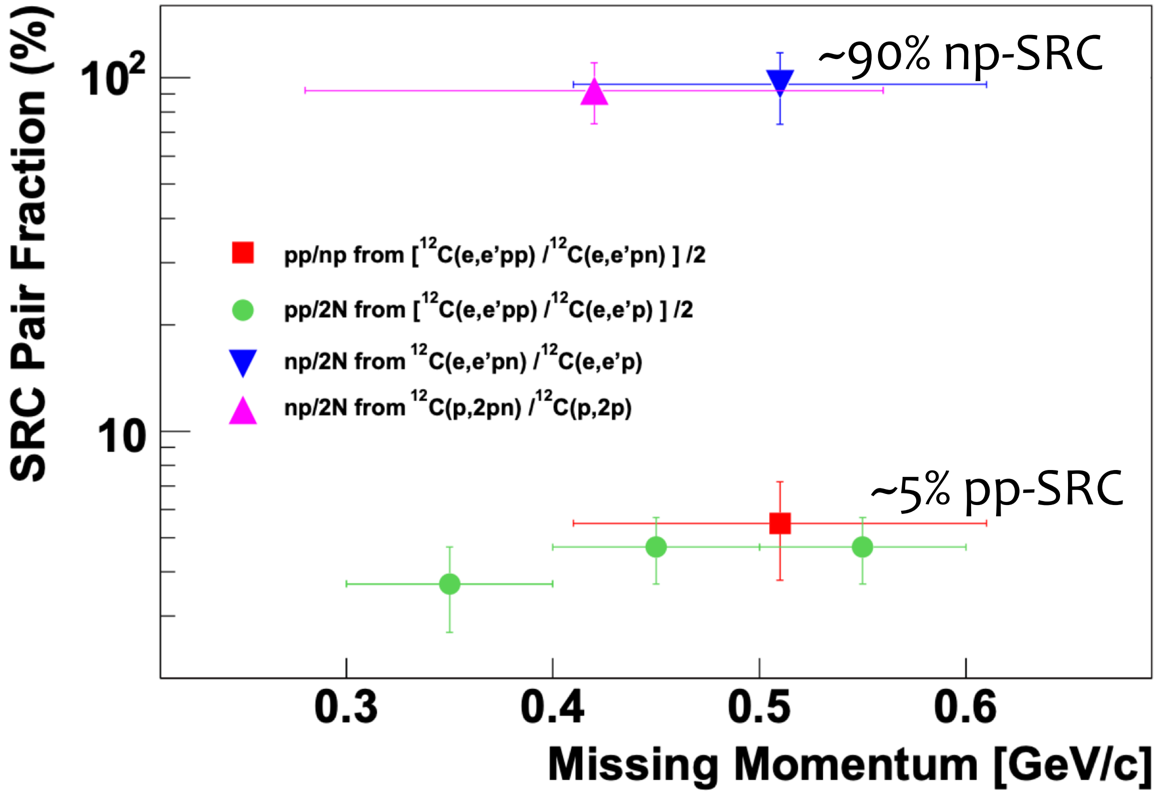
np-pairs dominant (tensor interaction)



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

High momentum nucleons in nuclei

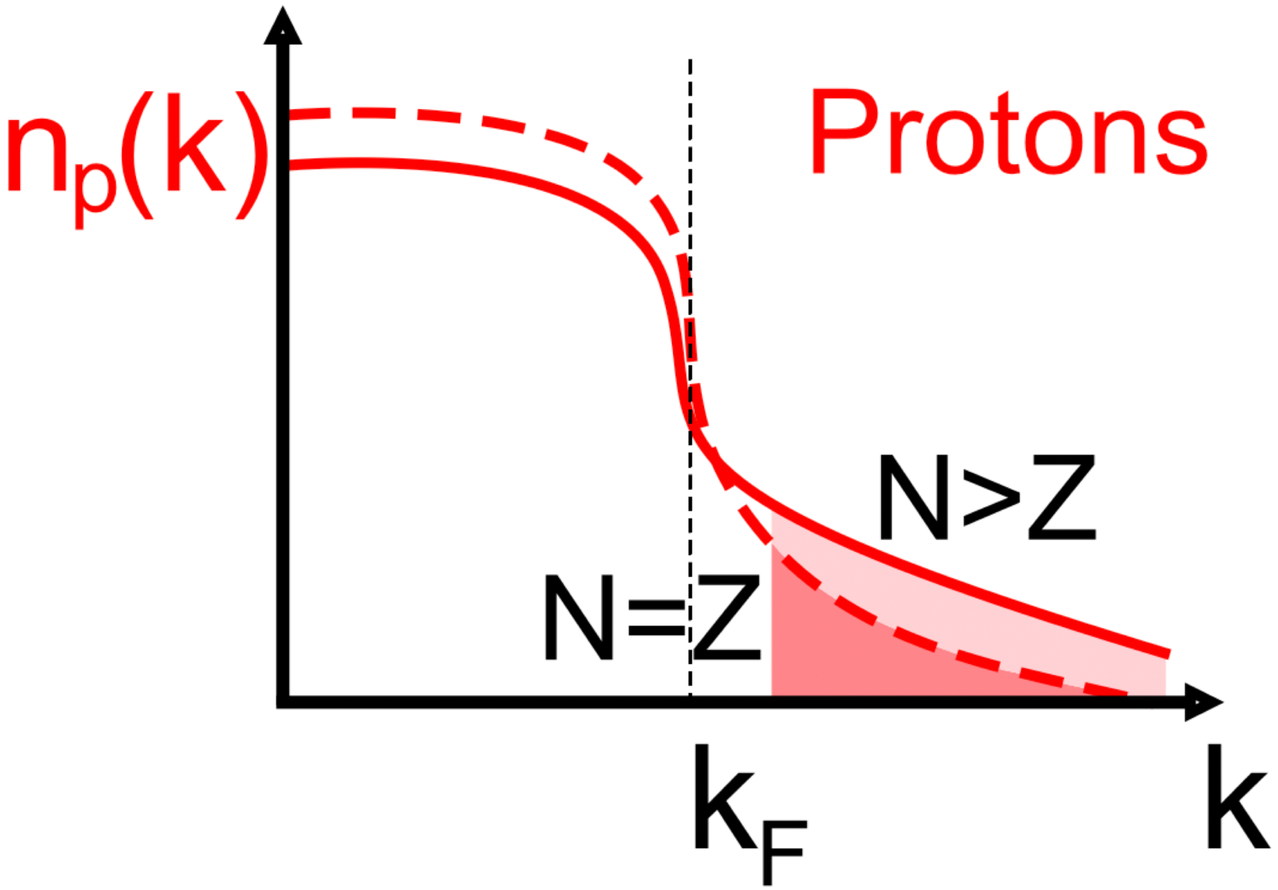




O. Hen et al., Science 346 p. 614 (2014)
M. Duer et al., PRL122, 172502 (2019)

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

Protons "speed up" in neutron-rich nuclei

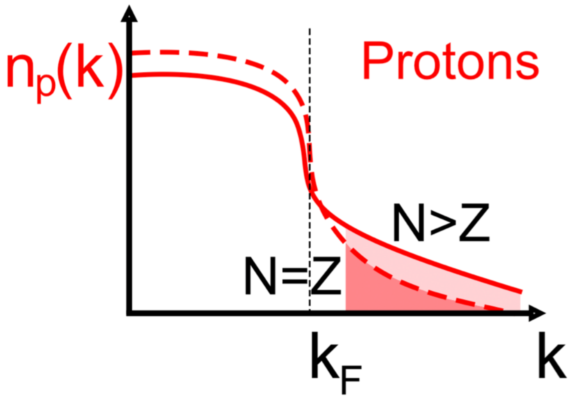


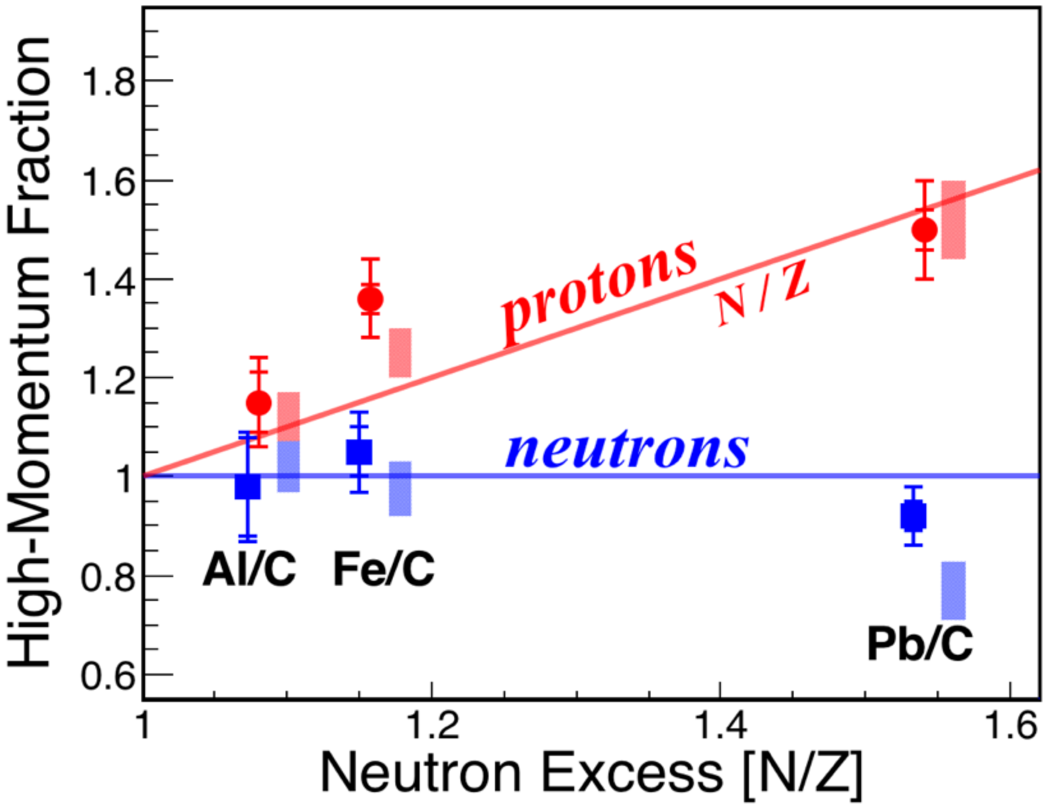
Duer et al. (CLAS collaboration), Nature 560, 617 (2018)

Protons "speed up" in neutron-rich nuclei

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

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



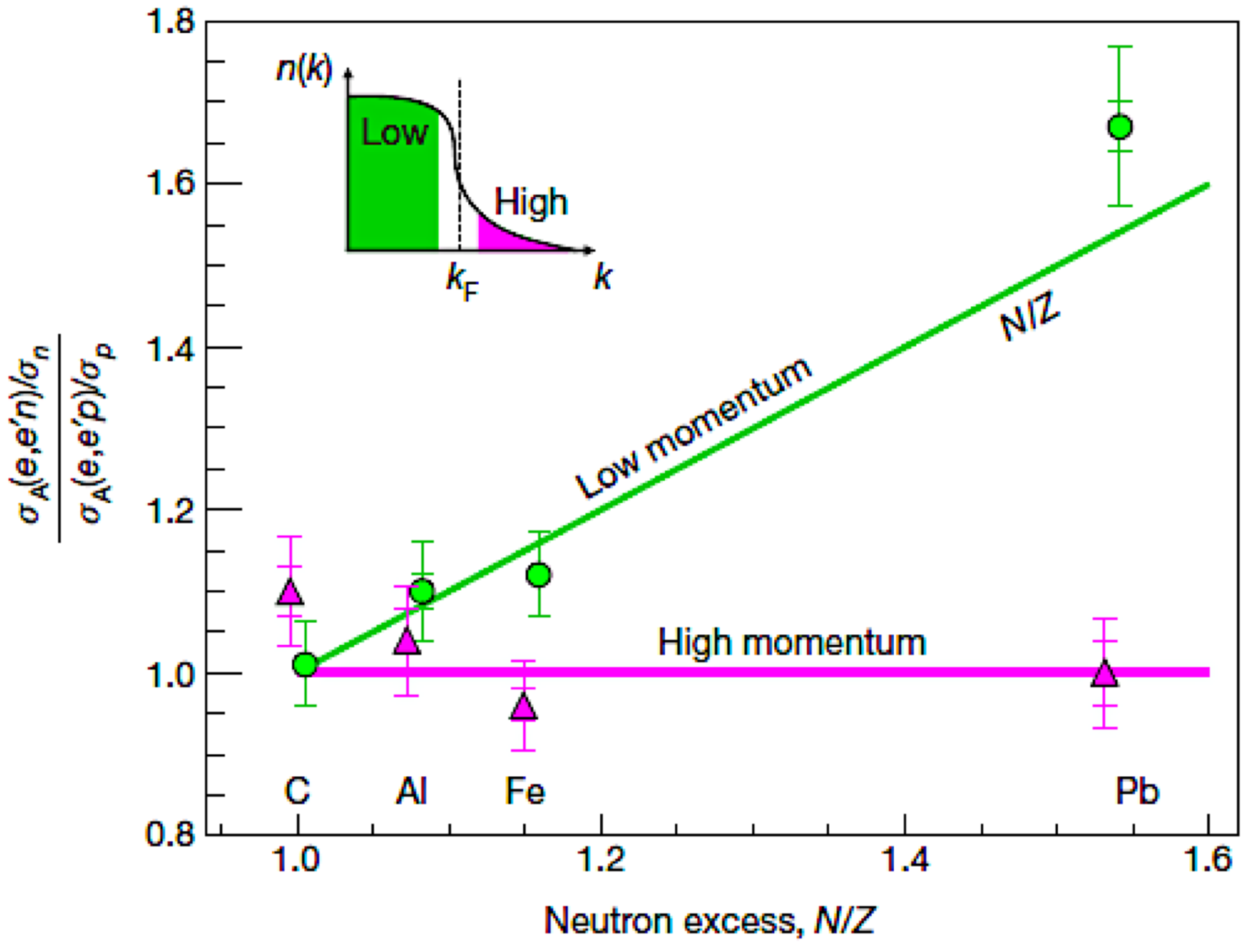


Duer et al. (CLAS collaboration), Nature 560, 617 (2018)

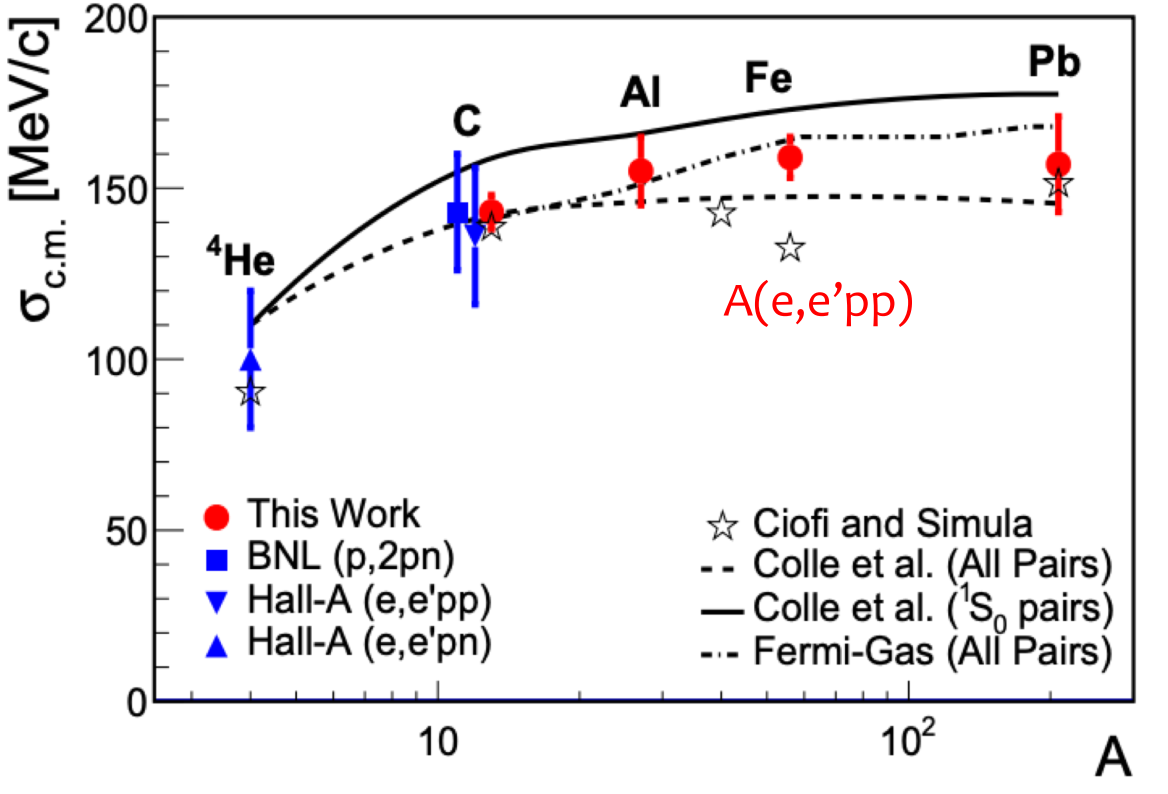
Protons "speed up" in neutron-rich nuclei

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

neutron: proton ratio

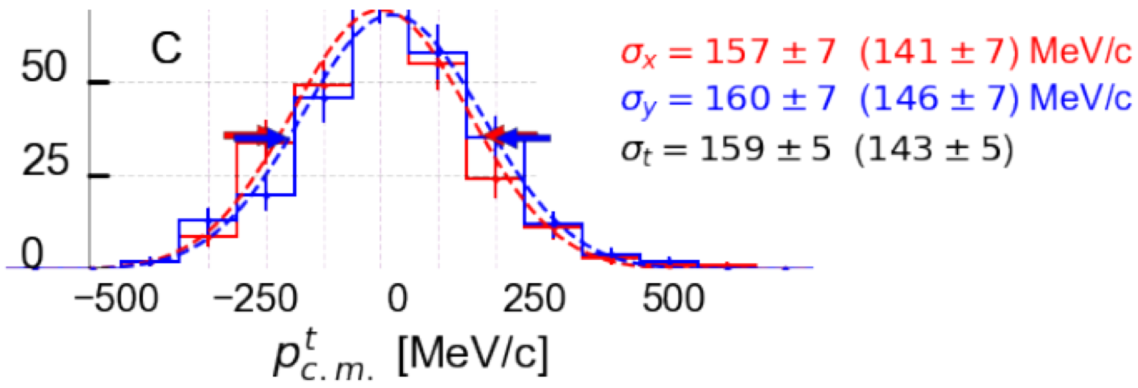


Center of mass momentum



- Small c.m. -> small separation between the pairs
- 3D Gaussian -> consistent with the sum of 2 mean field nucleons

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



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

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

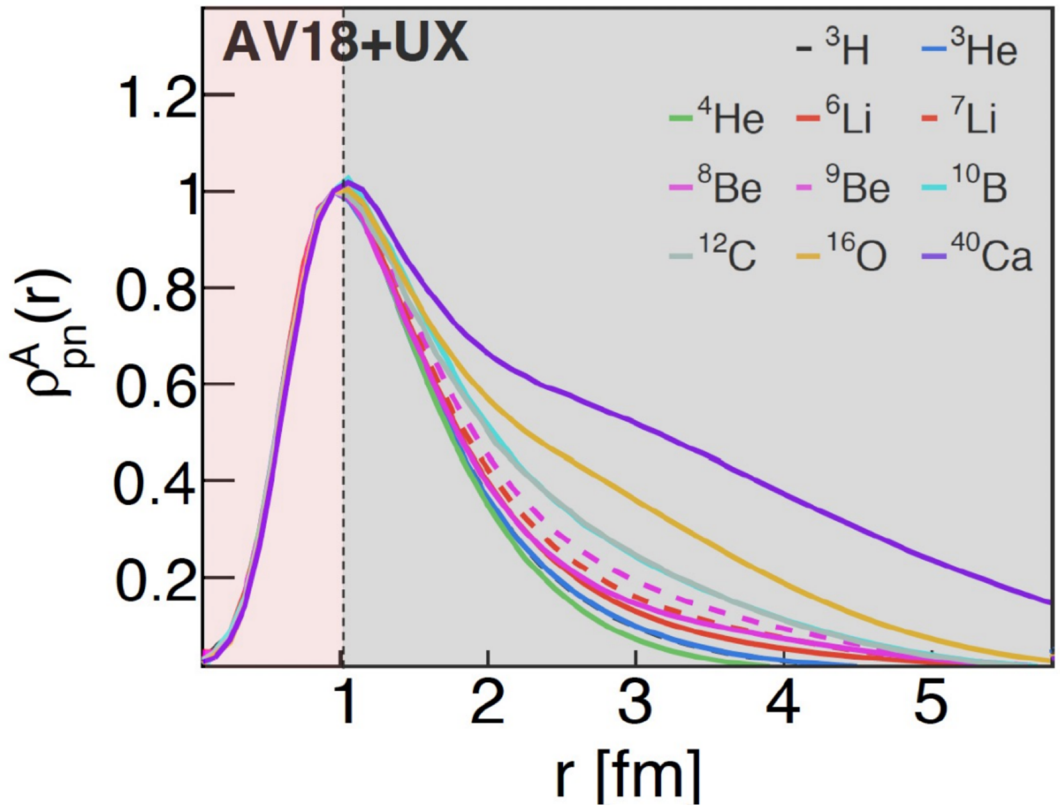
Nucleus-dependent contact

2-body density (universal)

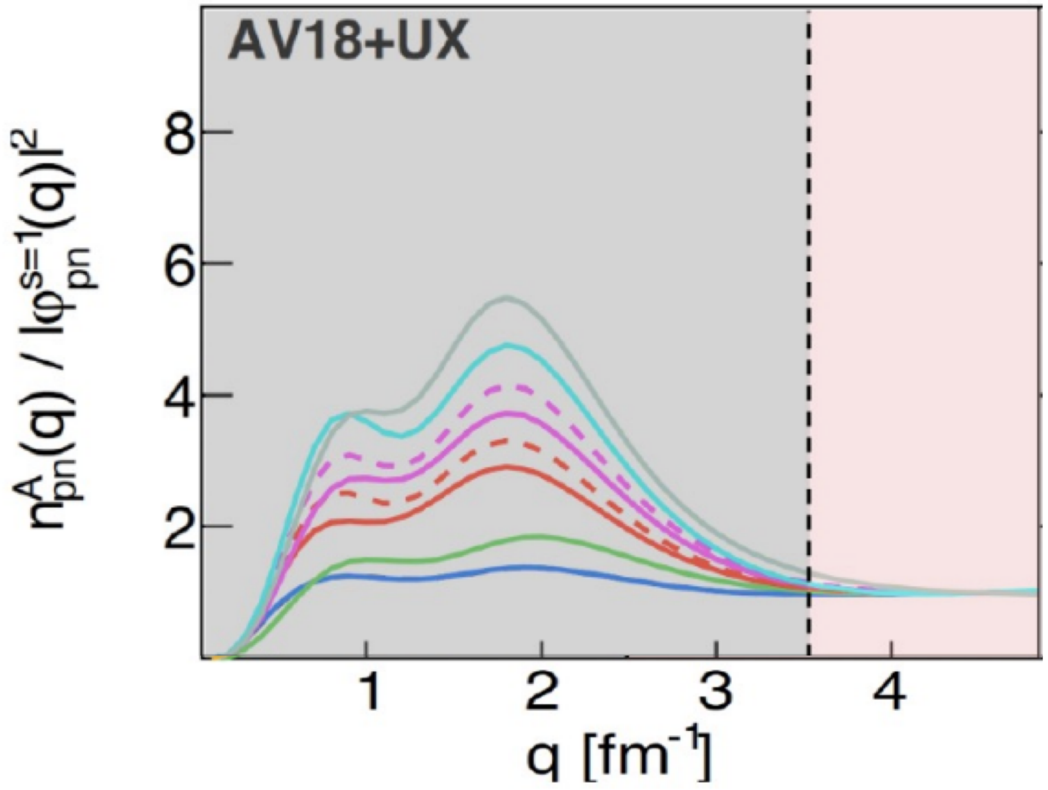
GCF: small r, high k scaling

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

Small r



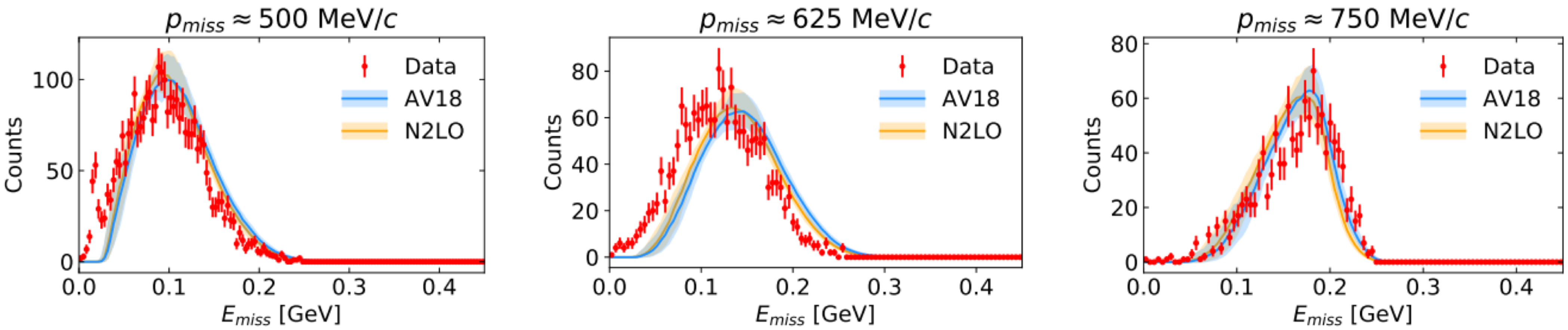
Large q (k)



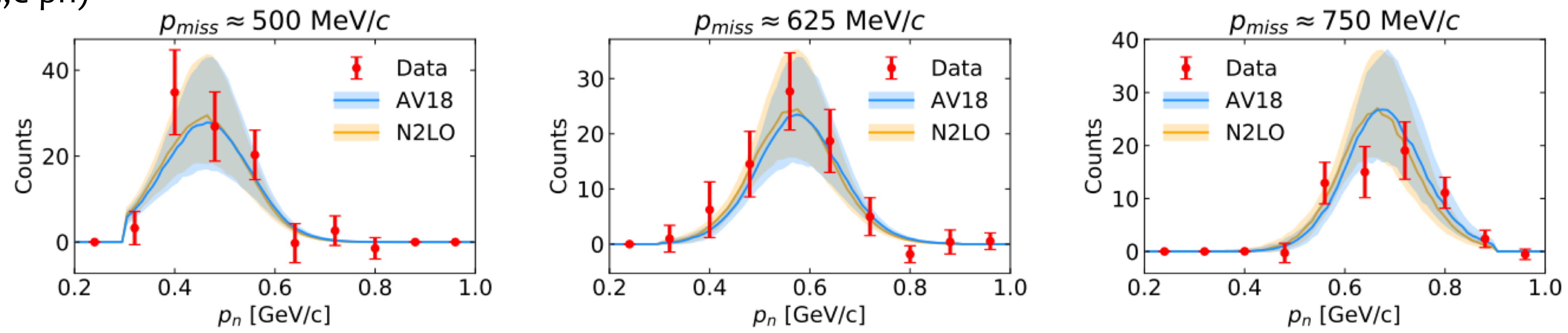
Cruz Torres and Lonardoni et al., Nature Physics (2020)

GCF compared to data

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



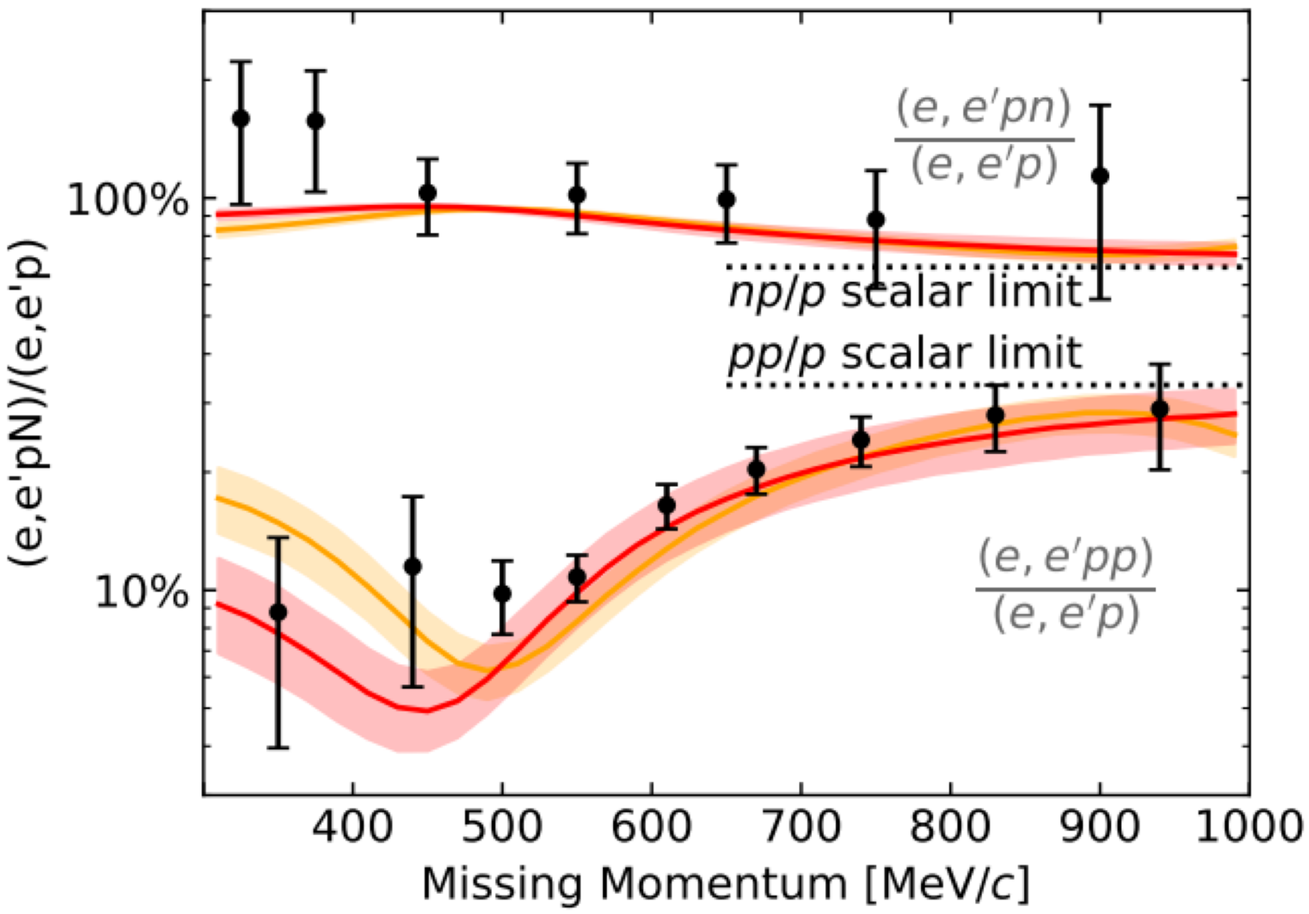
^{4}He(e,e'pn)



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

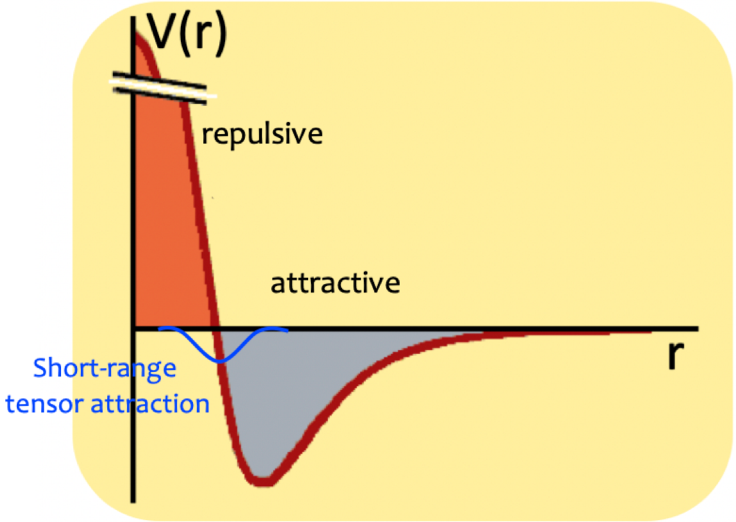
SRC in the tensor to scalar transition region

^{12}C(e,e'pN)



Data compared to GCF model (N2LO, AV18)

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



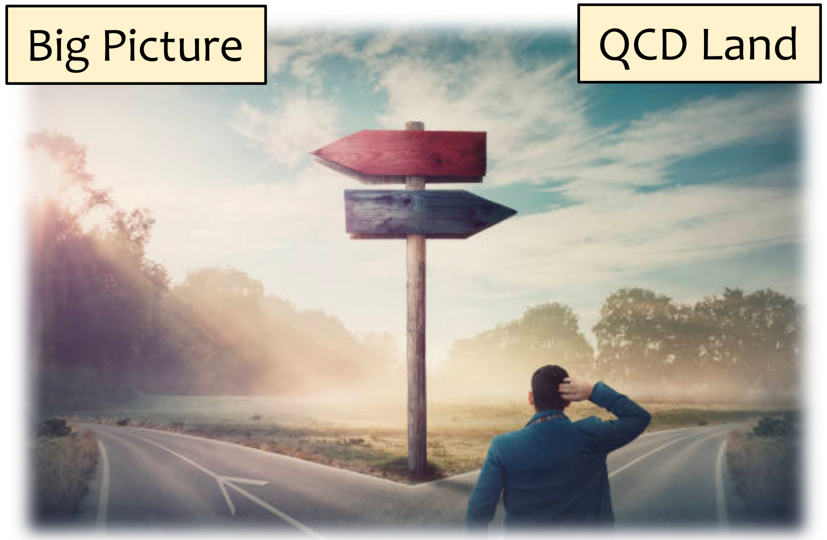
I. Korover et al, Phys. Lett. B **820**, 136523 (2021)

An experimentalist's approach to hadronic physics (Day 3)

Holly Szumila-Vance
Assistant Professor, Florida International University

2024 STFC Nuclear Physics Summer School
Durham University
August 2024

FLORIDA INTERNATIONAL UNIVERSITY



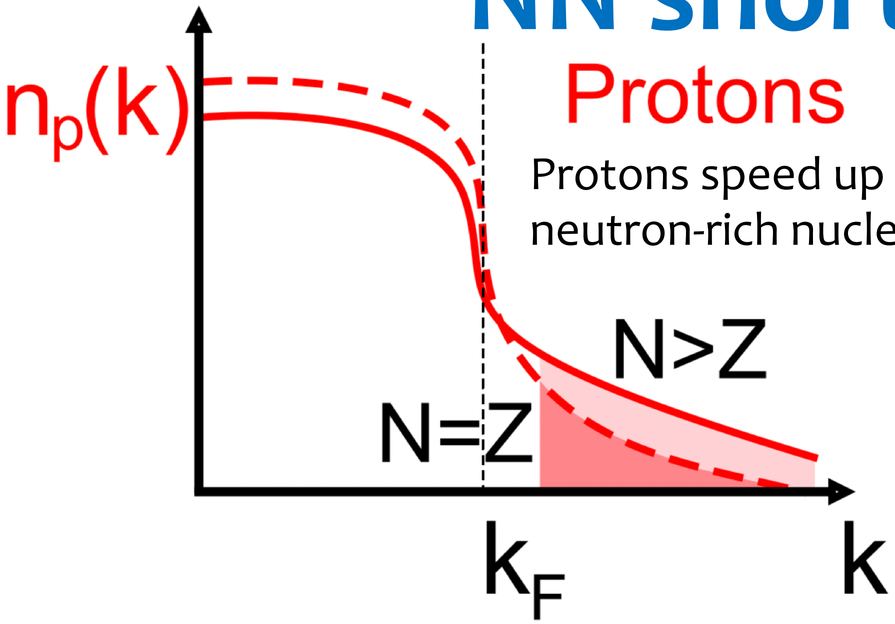
Review

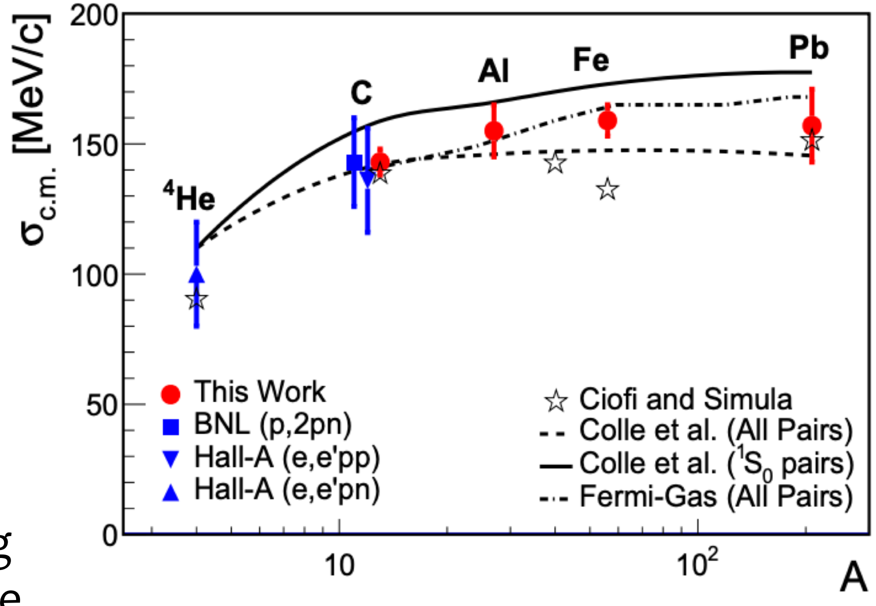
Different avenues to better bridge the gap between the observances in the Big Picture and QCD dynamics

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
- The future of SRC studies depends on observations in other processes such as real photoproduction to establish universality.
- Future studies also search for 3N SRCs

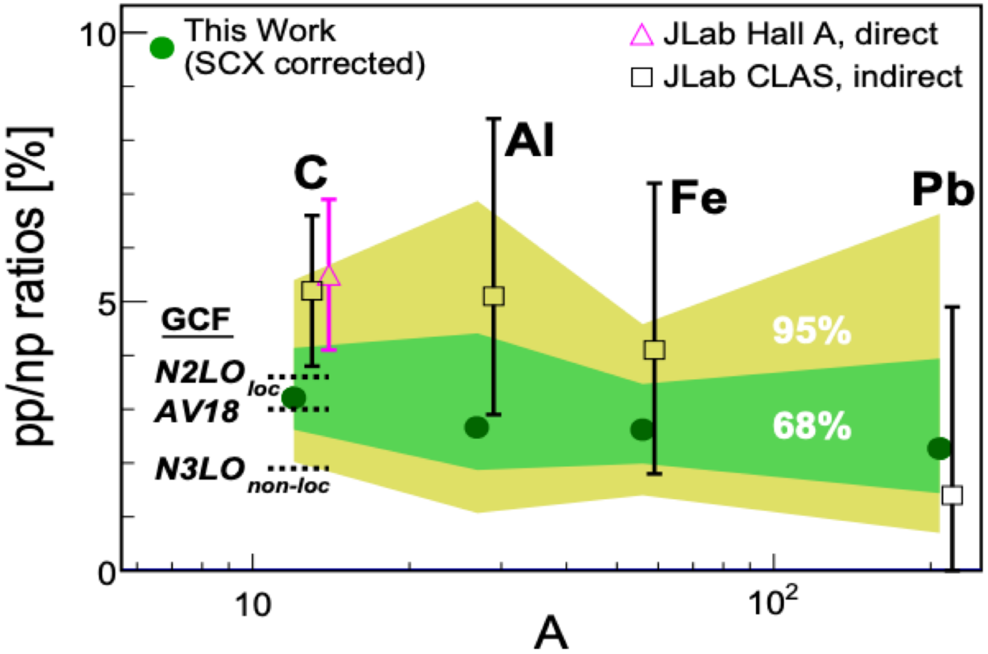
NN short range correlated pairs

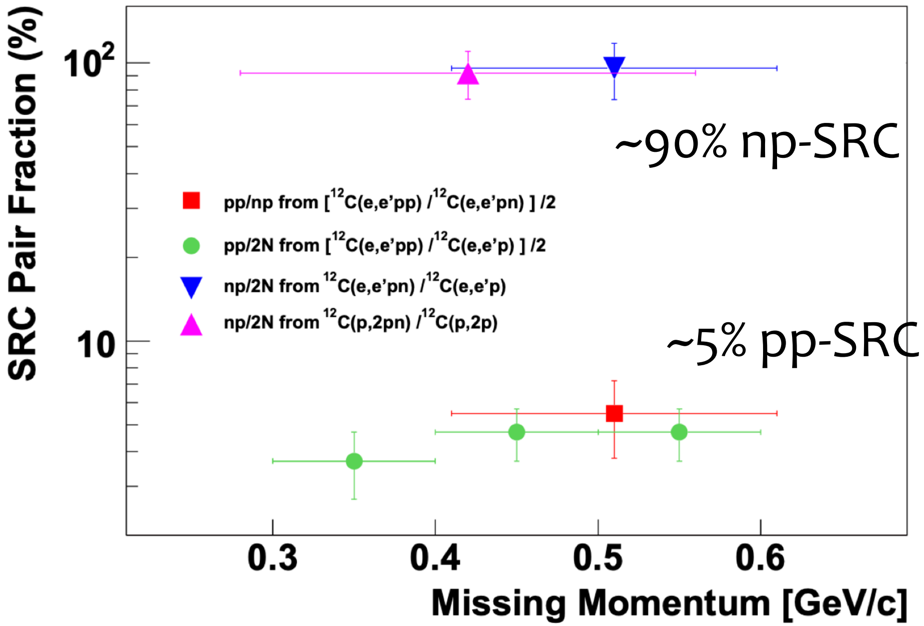




c.m. consistent with 2N

np-pairing dominance



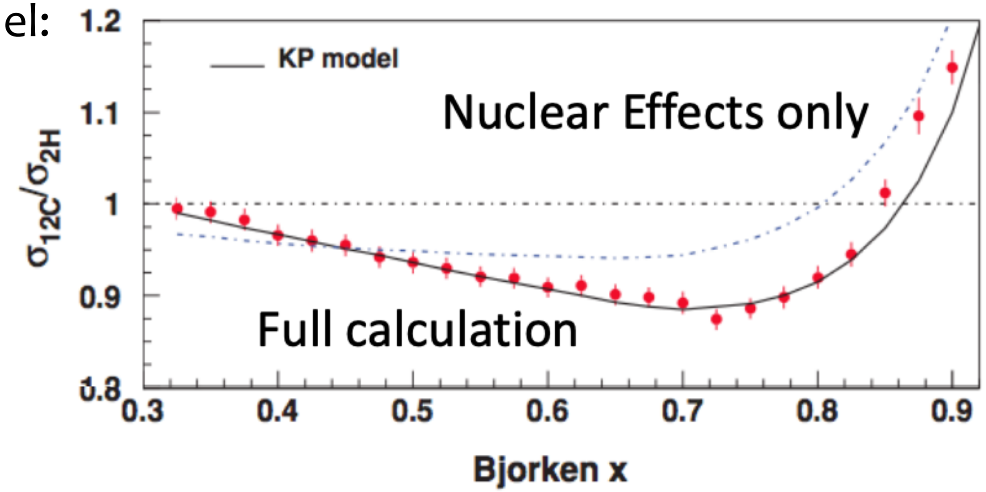


EMC Effect

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

EMC Effect cannot be fully accounted for in one model:

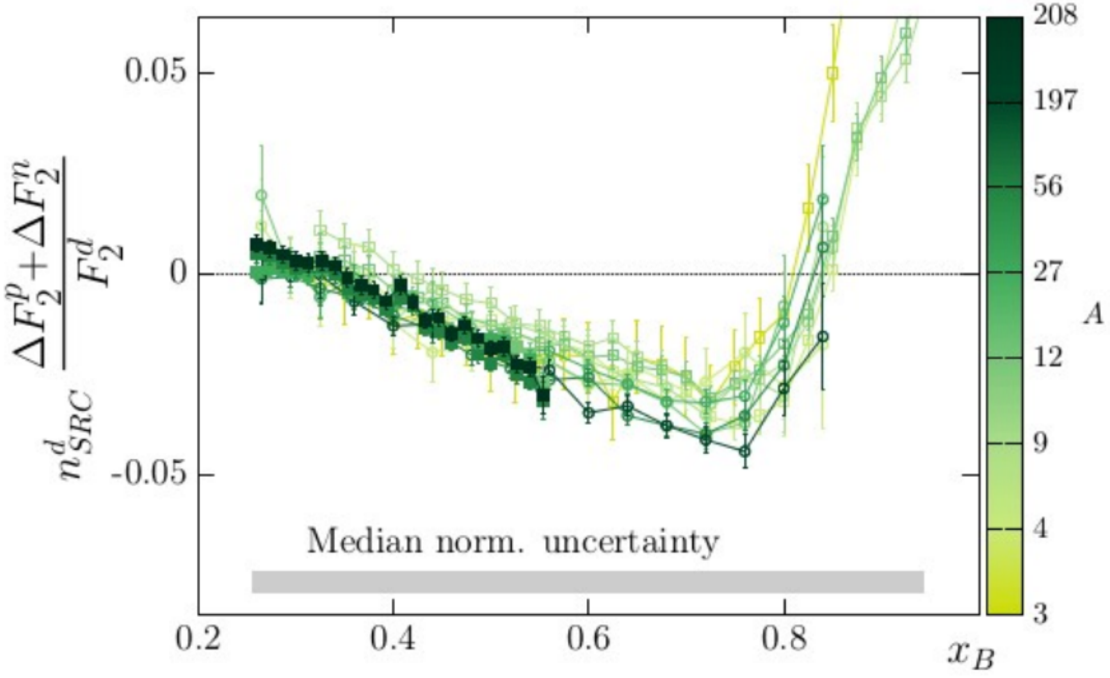
Are the few high-momentum nucleons each modified a lot by the short range interaction?

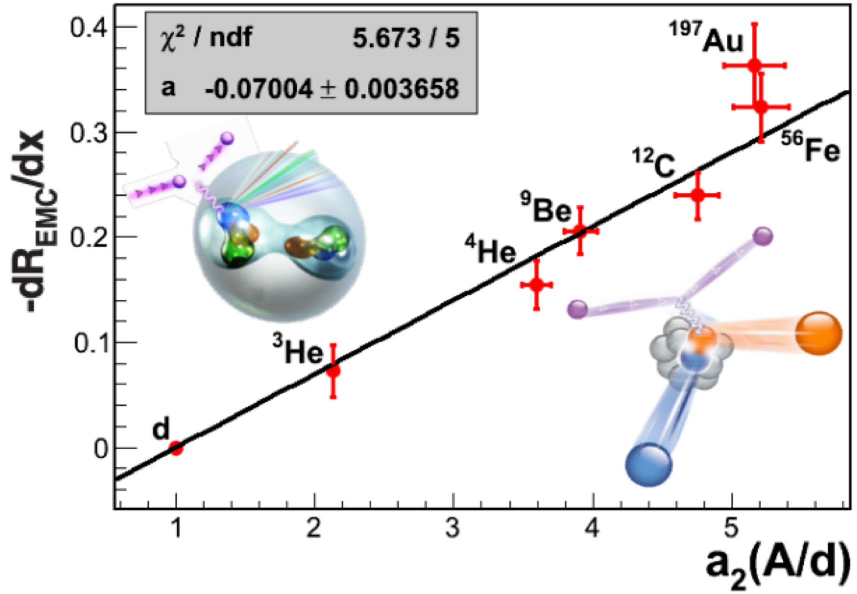


Strongly linked to local density, and correlates with SRCs:

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

Universal??? Nucleus-Dependent





Exploring the QCD transition

Big Picture

QCD Land

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

If we are going to learn anything about nucleons in the nucleus, we have to know something about transparency

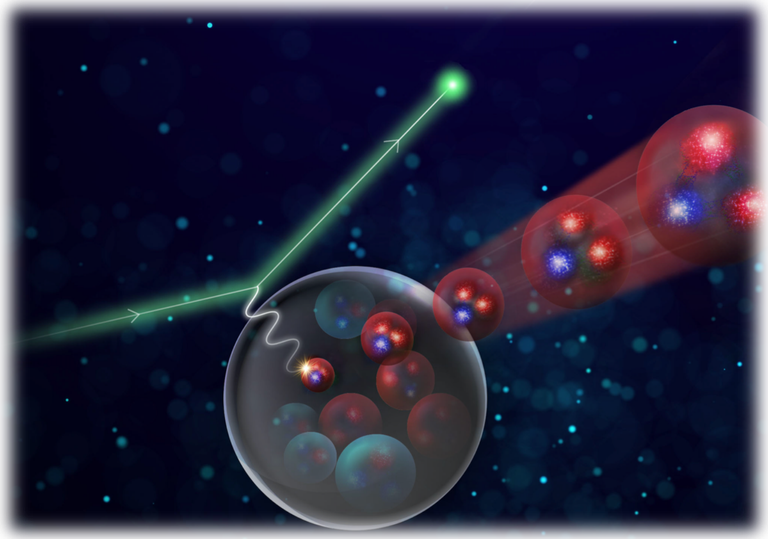
Transparency refers to the probability that a knocked out nucleon is deflected or absorbed.

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)

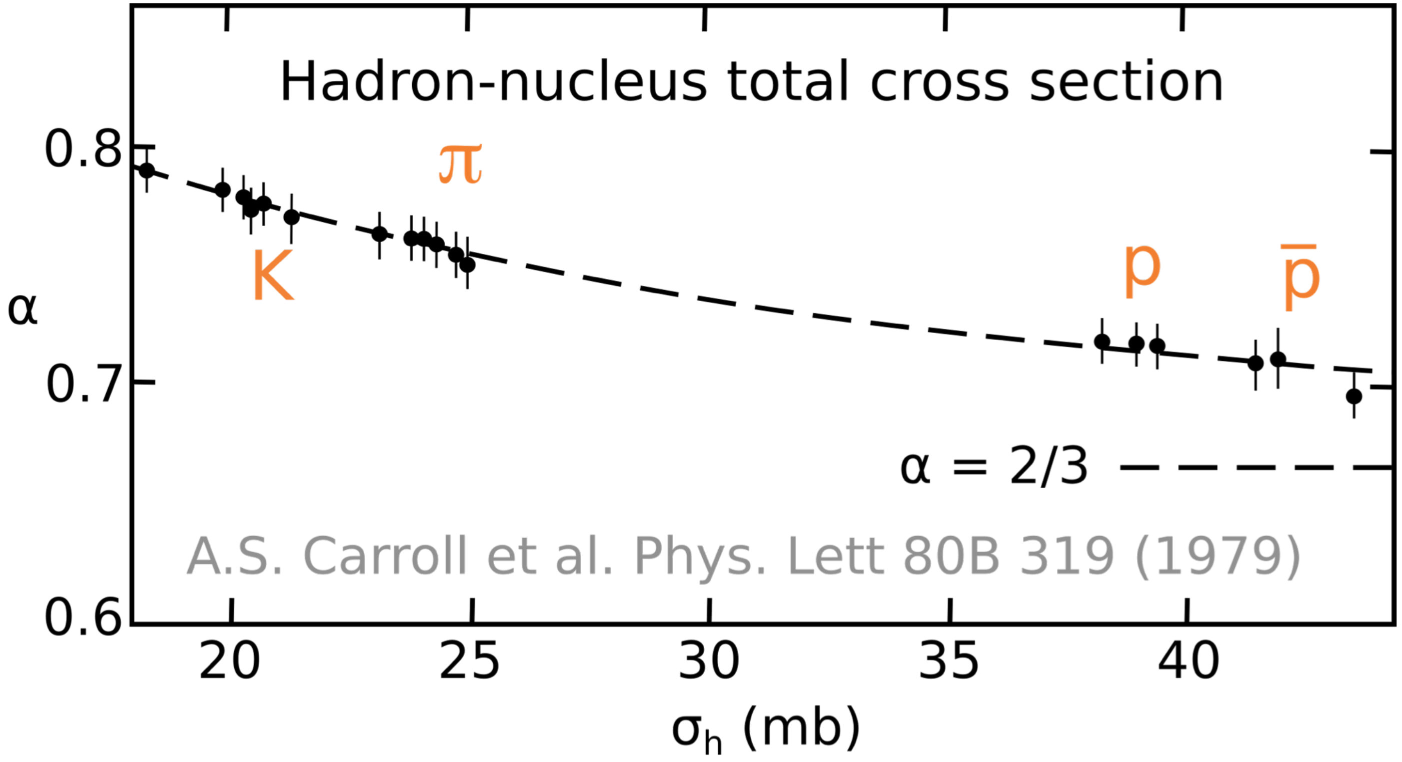
σ_N (free nucleon cross section)



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

Hadron-nucleus total cross section

Hadron momenta: 60, 200, 280 GeV/c



Targets of Li, C, Al, Cu, Sn and Pb

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

$\boldsymbol{\alpha}$ <1 due to strong interaction nature of the probe

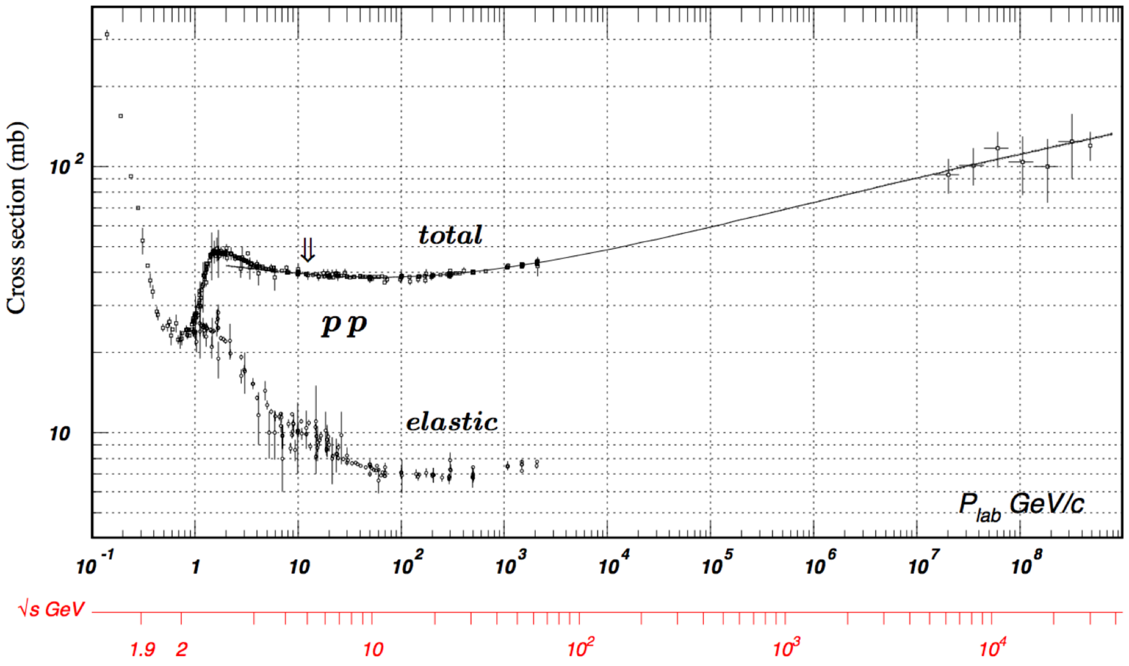
Absorption cross section momentum independent.
Tendency of $\boldsymbol{\alpha} \rightarrow 2/3$ expected for opaque nucleus.

Recall nuclear radius:
$r = r_0 A^{\frac{1}{3}}$

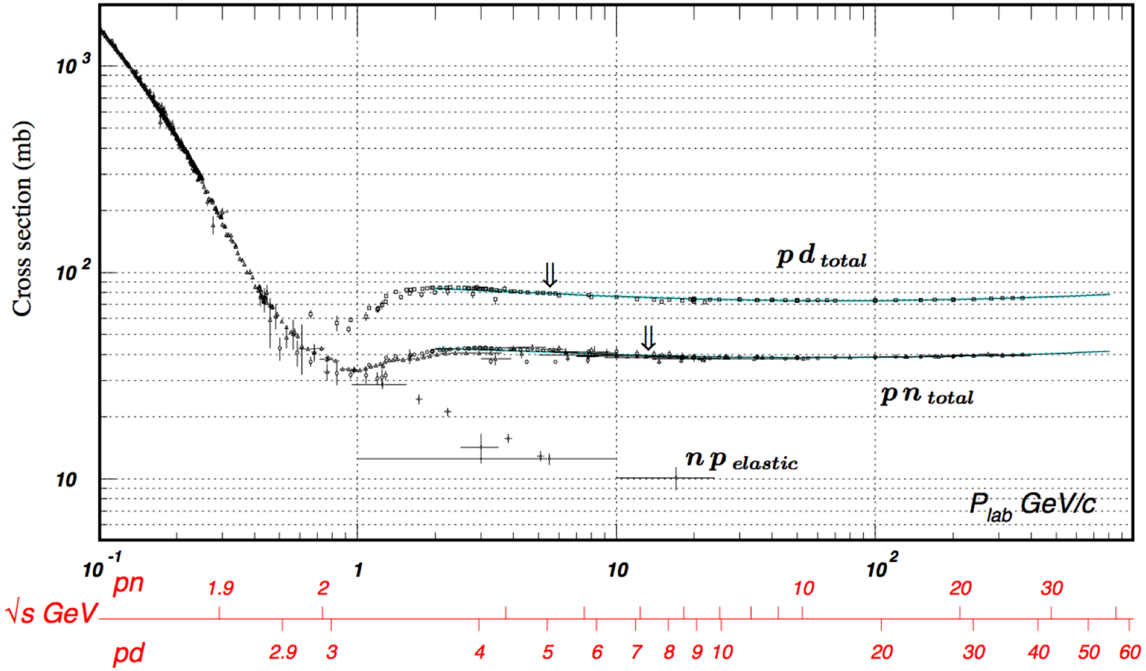
NN cross section

NN cross section is essentially energy independent

pp scattering cross section

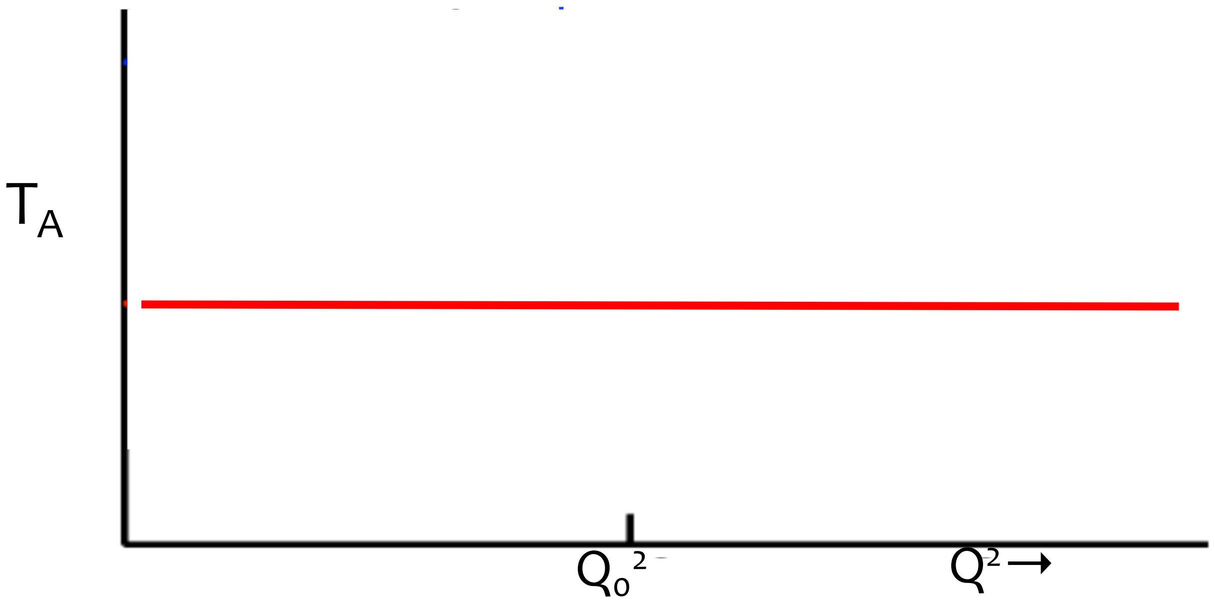


pn scattering cross section



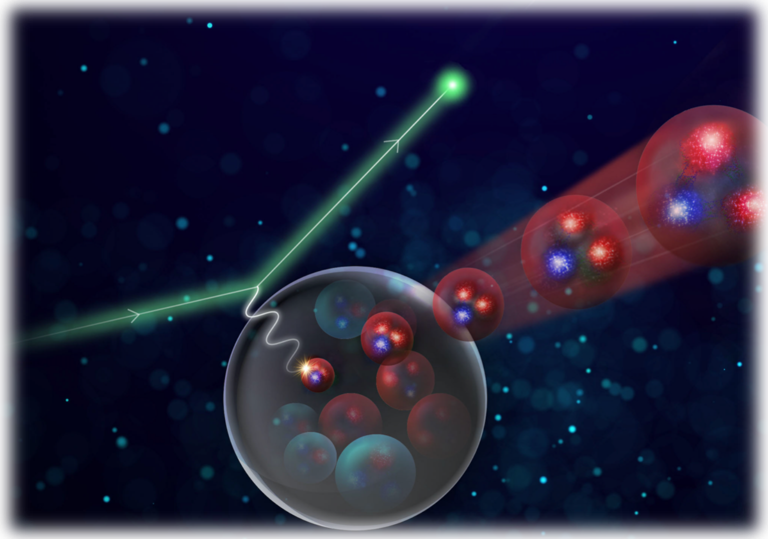
Transparency ingredients

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



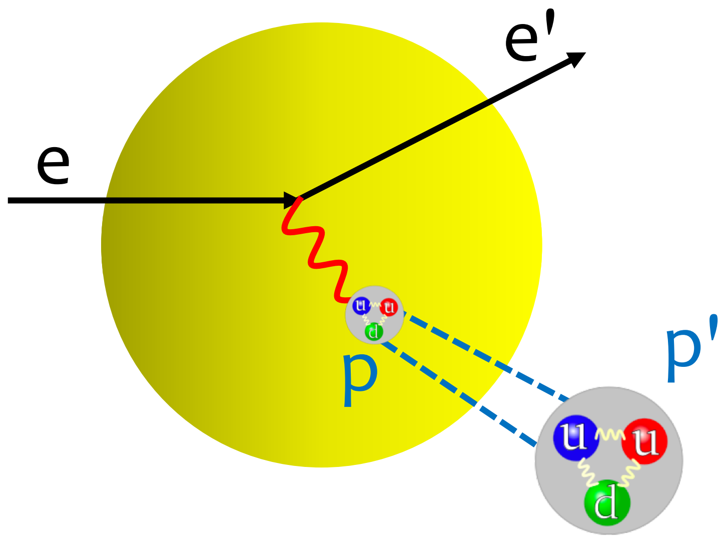
Measuring transparency:

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



Color transparency is a fundamental prediction of QCD

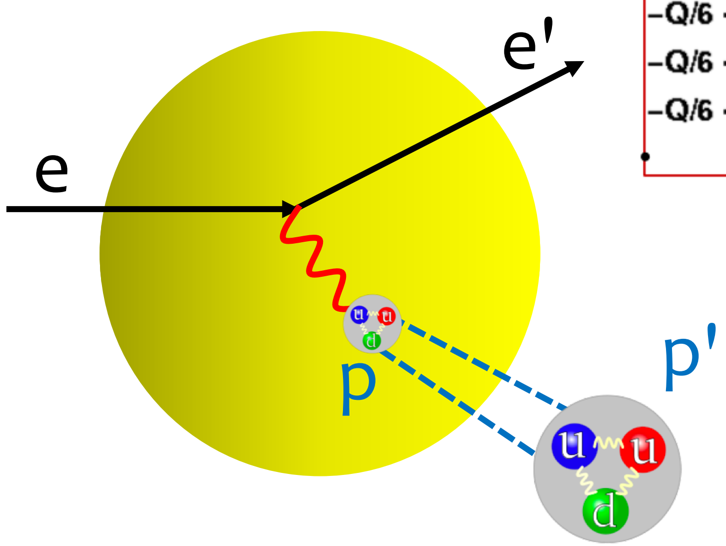
Quantum mechanics:
Hadrons fluctuate to small transverse size (*squeezing*, transferred momentum)

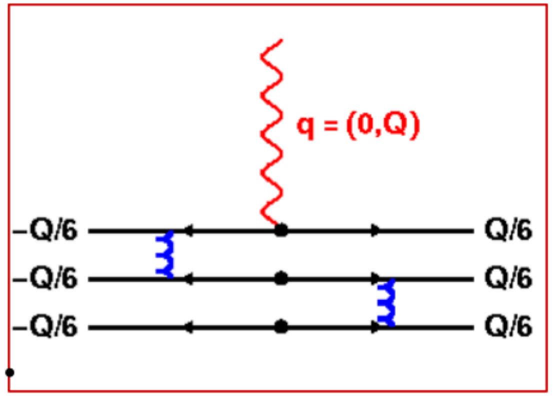


Relativity:
Maintains this small size as it propagates out of the nucleus (*freezing*, transferred energy)

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

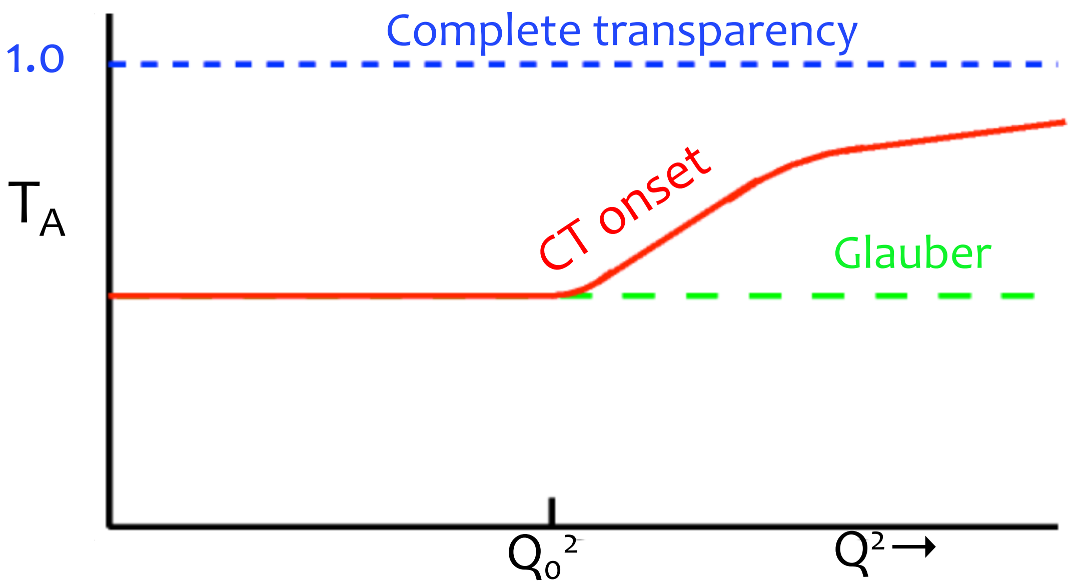
Color transparency



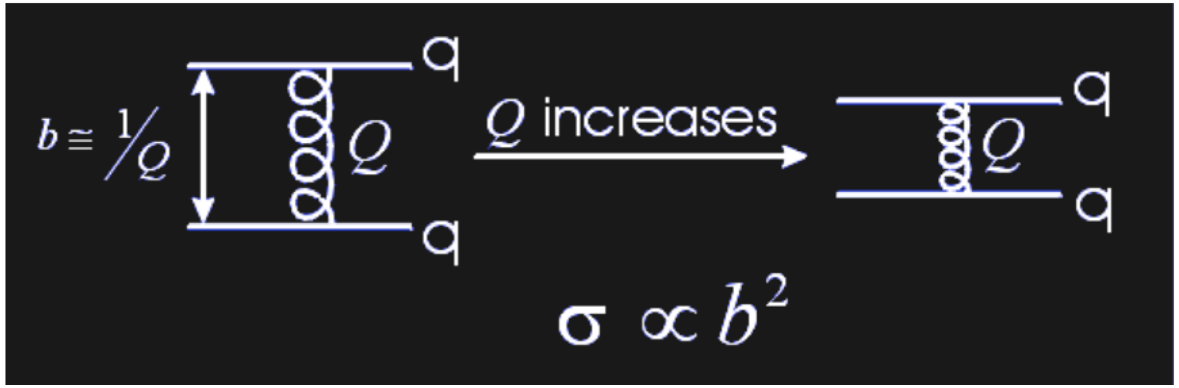


- Introduced by Mueller and Brodsky, 1982
- Vanishing of initial/final state interaction of hadrons with nuclear medium in exclusive processes at high momentum transfer

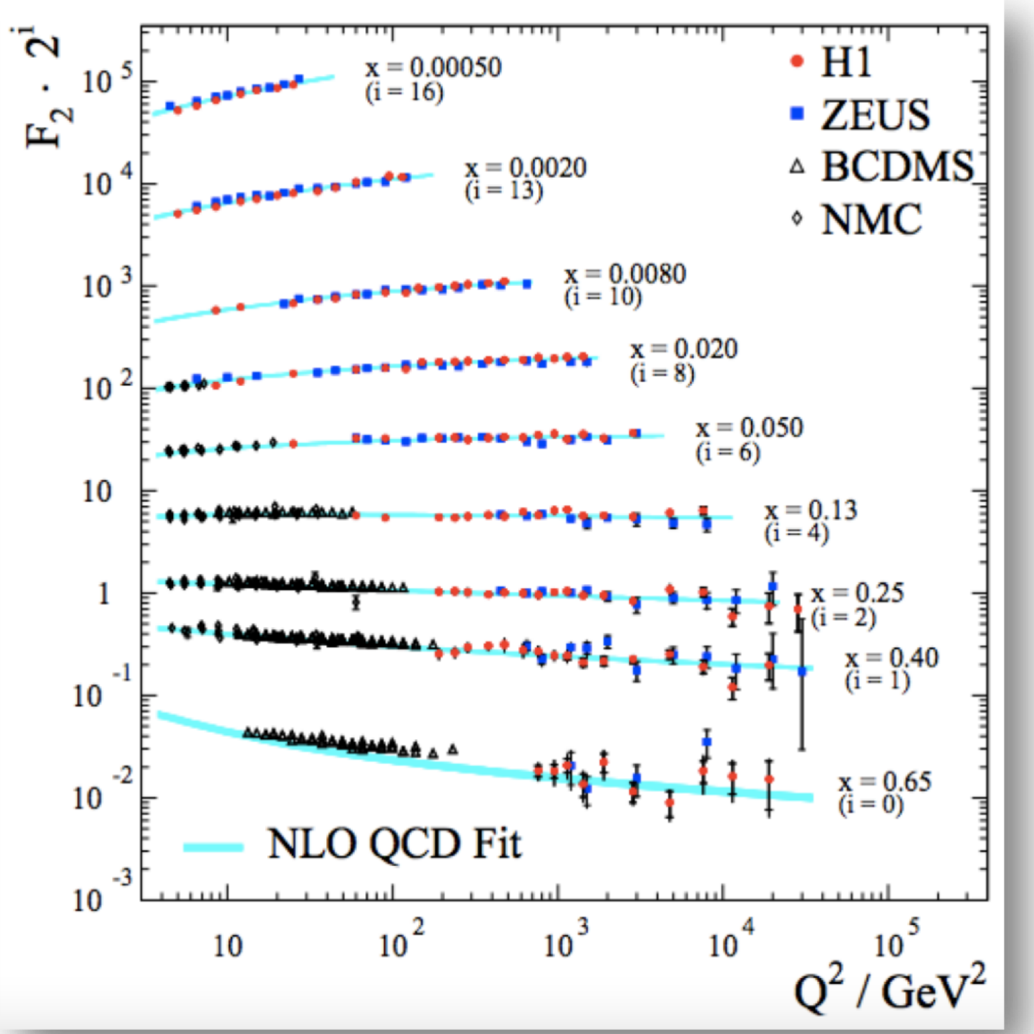
Onset of color transparency



- 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

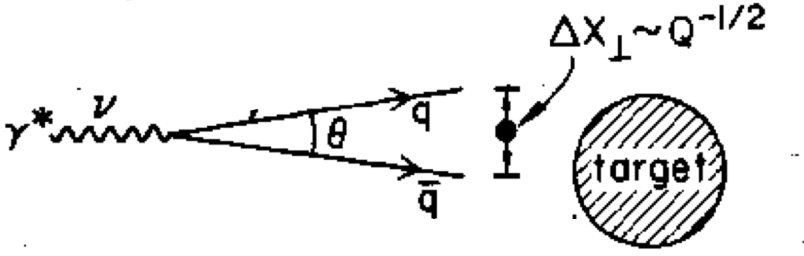


First indirect evidence of CT from DIS: Bjorken scaling at small x



Small x ($\leq 10^{-2}$) → long longitudinal distances

Virtual photon fluctuates into a $q\bar{q}$ pair



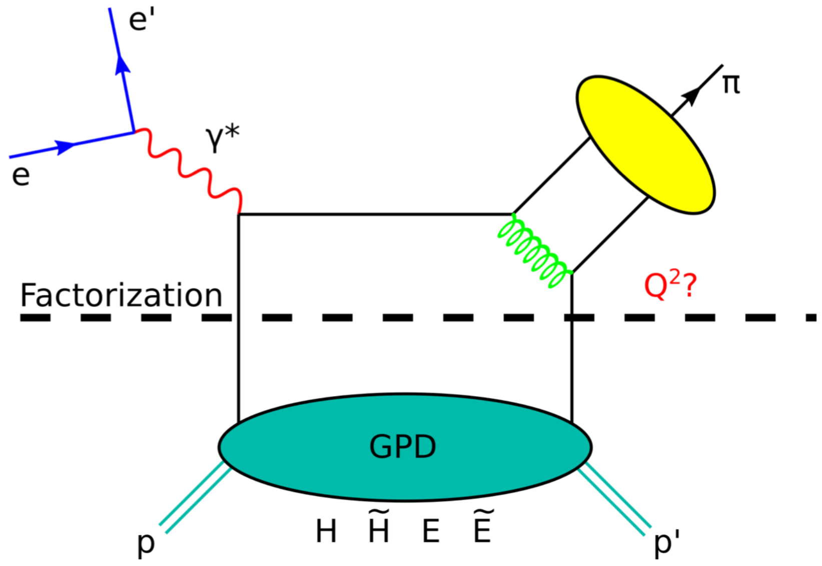
Scaling shows no evidence of this interaction

Bjorken, SLAC-PUB-1756

Frankfurt and Strikman, Phys Rep 160, 235 (1988)

CT is connected to other physics interpretations

GPD framework requires factorization into a hard interaction with single quark and soft part (GPDs).



Color cancellation required for factorization:

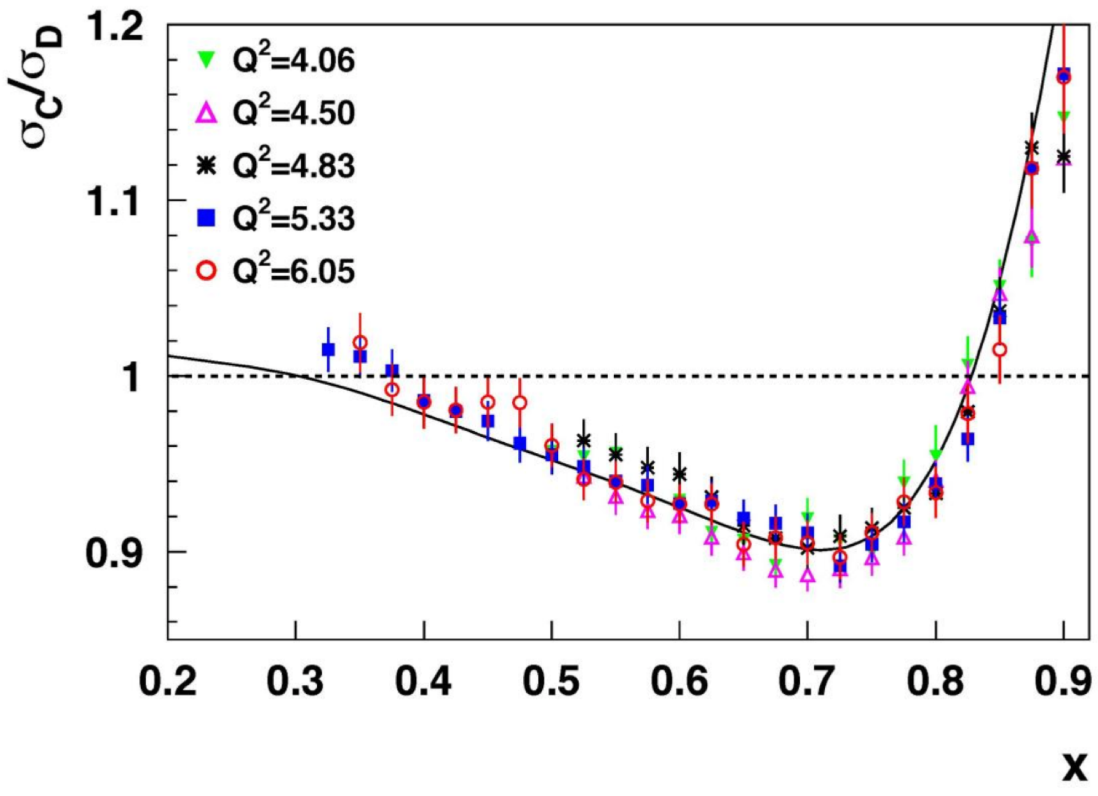
-> small size configurations

-> at high Q^2 , small size object moves through nucleus with no further interactions

L. Frankfurt and M. Strikman, Phys Rep. 160, 235 (1988).

CT could be connected to the EMC Effect

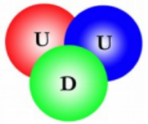
Is EMC Effect related to a suppression of nucleons in point-like configurations?



CT experiments

CT onset experiments

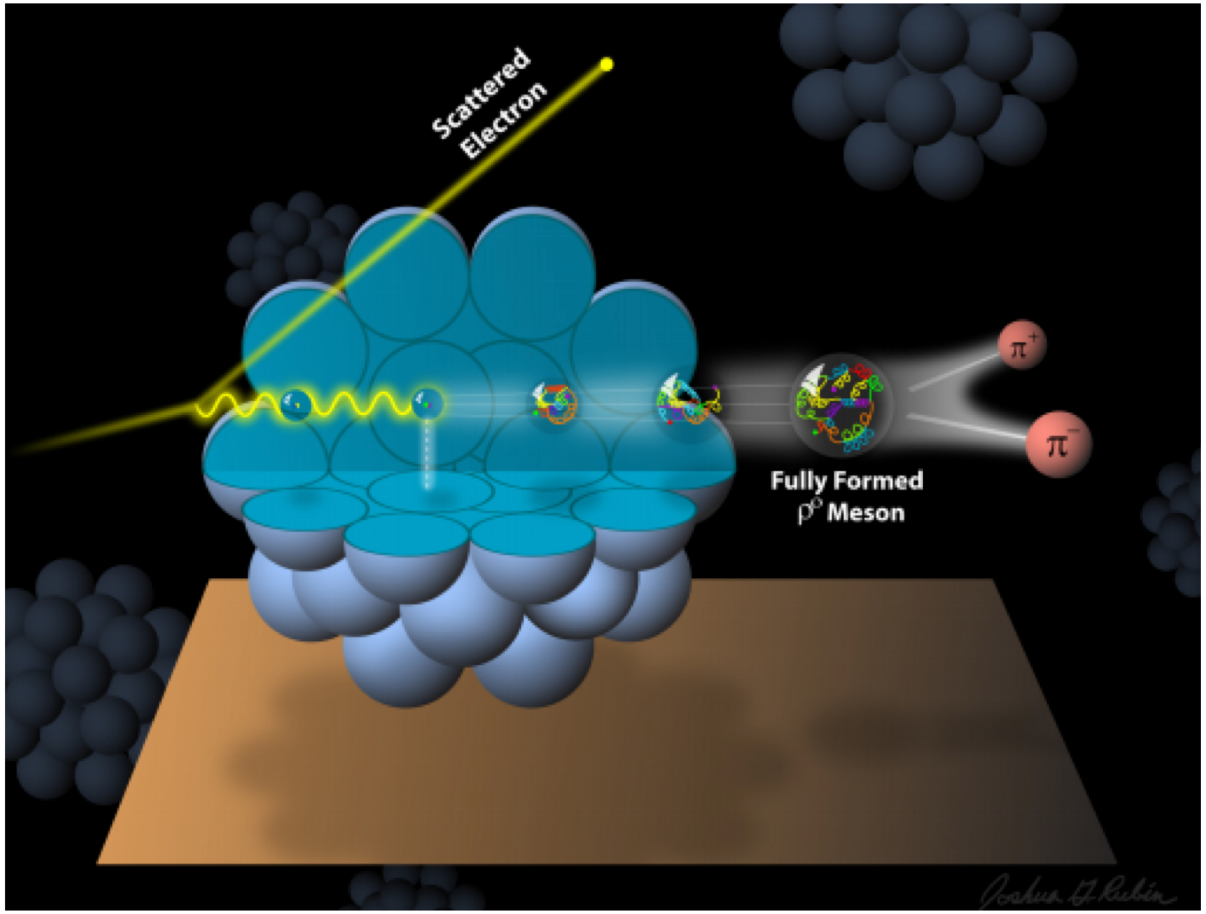
Baryon



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

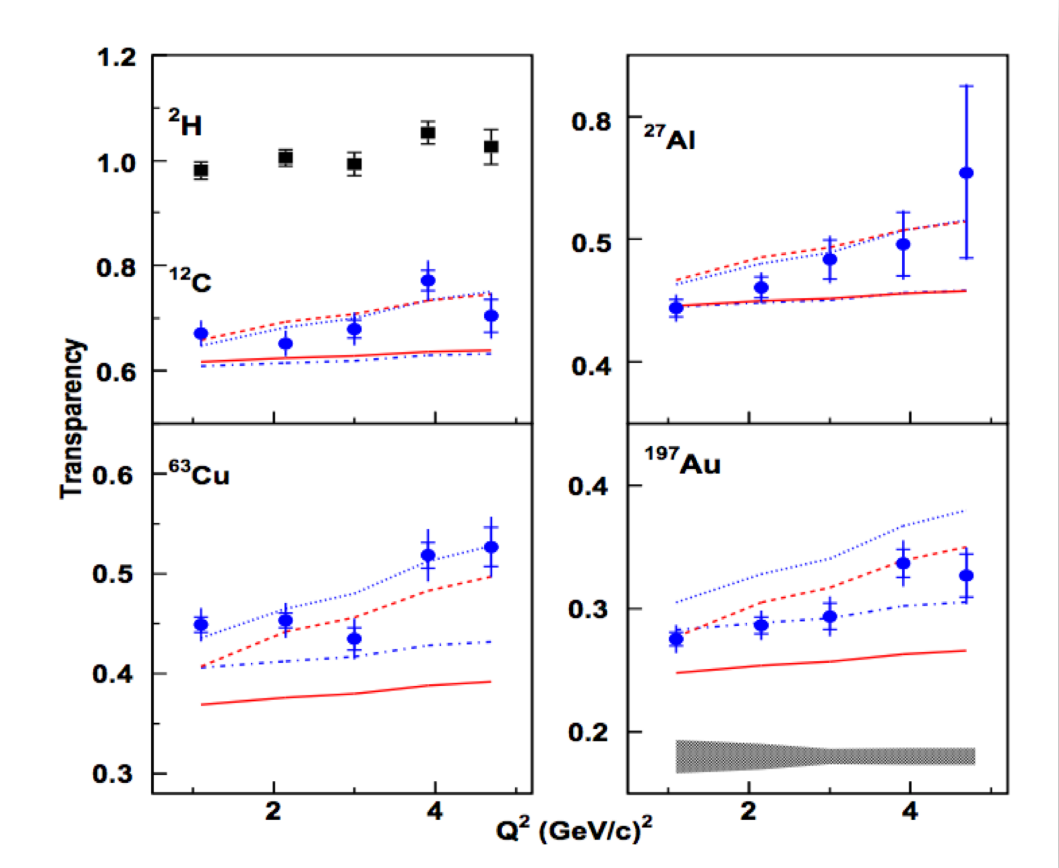


Previous measurements in mesons

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

Hall C E01-107 pion electro-production

A(e,e’π^+)

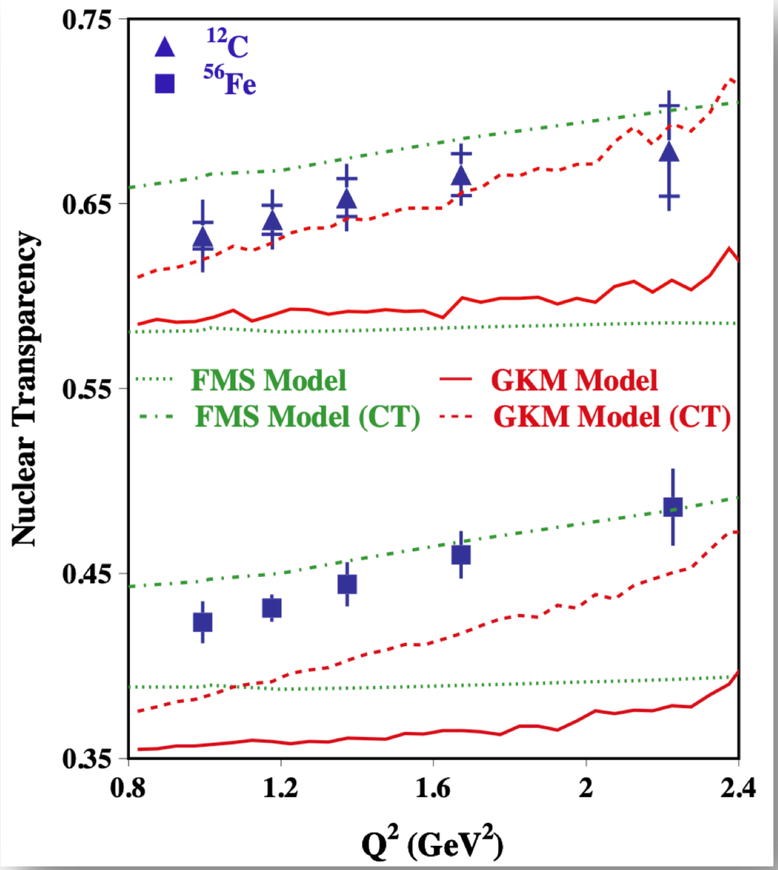


B.Clasie *et al.* PRL 99:242502 (2007)

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

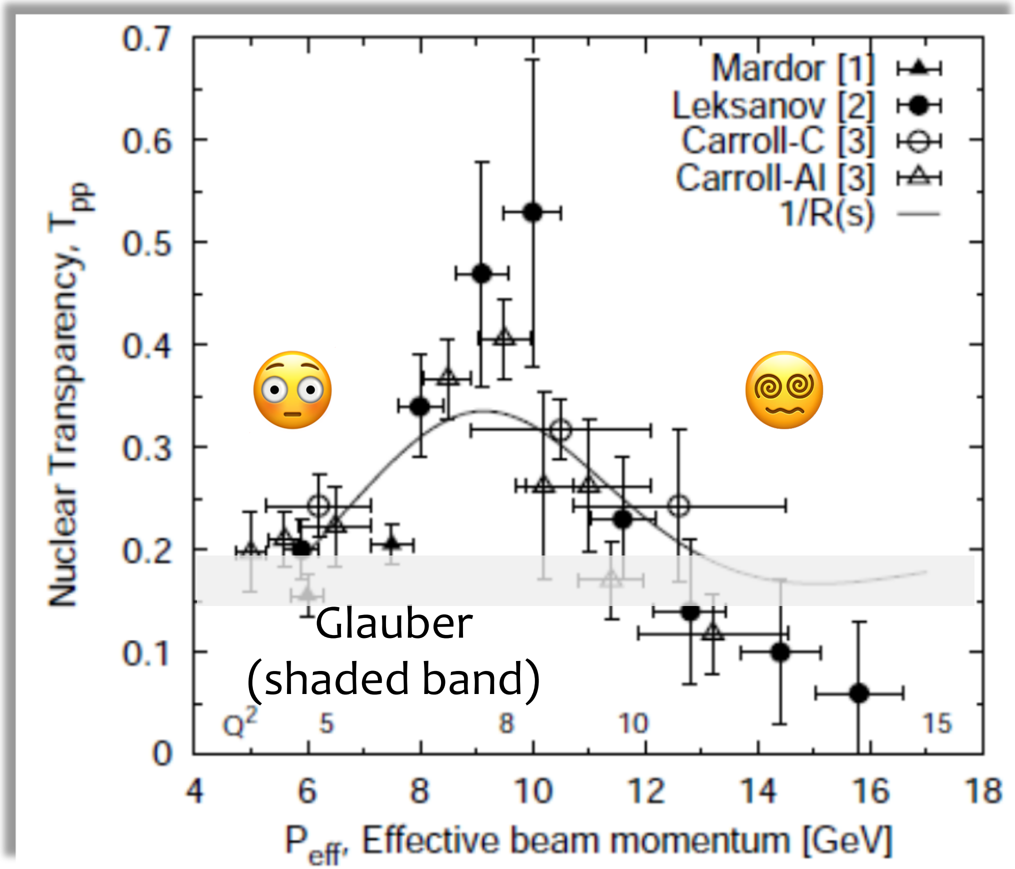
CLAS E02-110 rho electro-production

A(e,e’ρ^0)



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

A(p,pp)



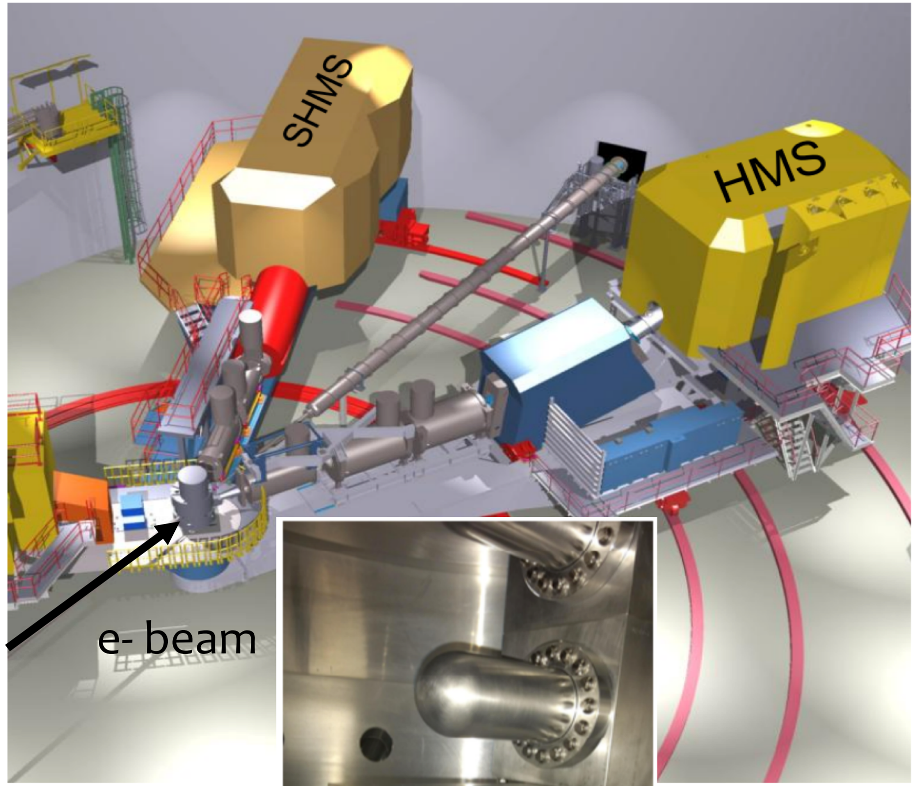
A. Leksanov et al. PRL 87 (2001)
J. L. S. Aclander et al., PRC 70 (2004)

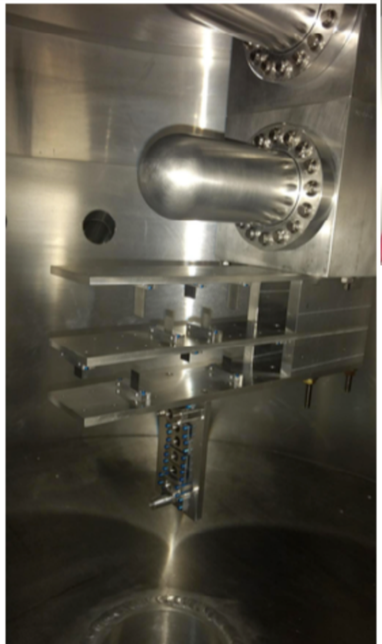
Transparency in A(p,pp) experiment at Brookhaven:

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

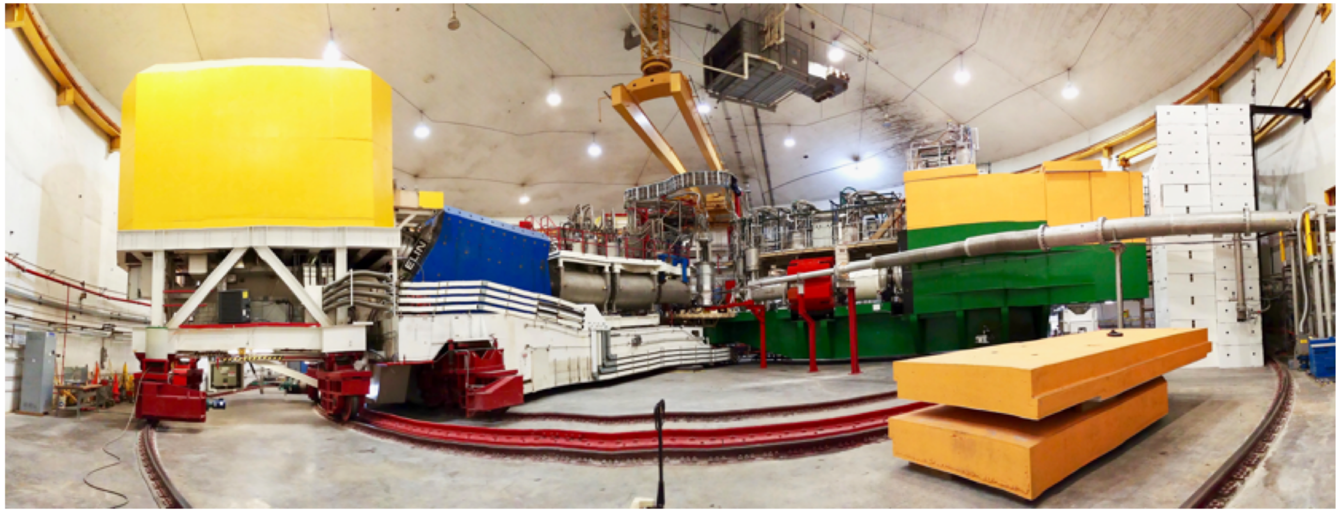
PRL 87, 212301 (2001), PRL 81, 5085 (1998), PRL 61, 1698 (1988)

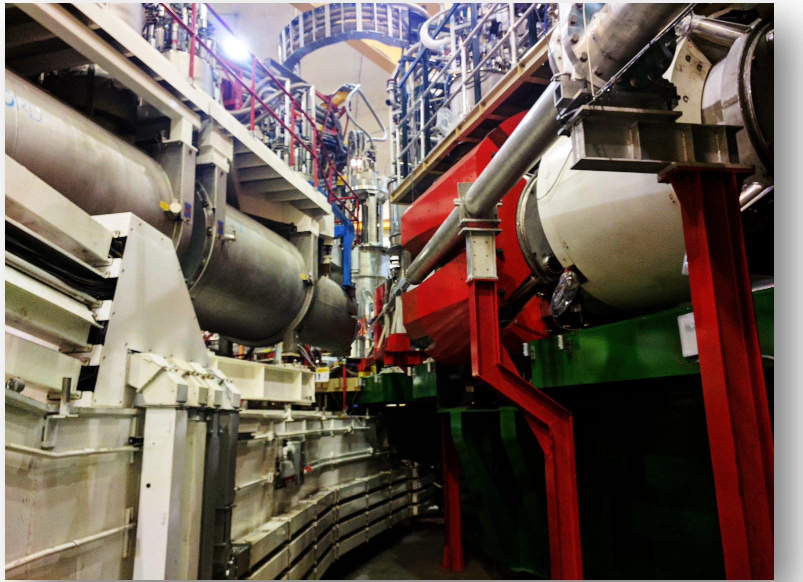
New spectrometer needed to measure protons at highest momenta!





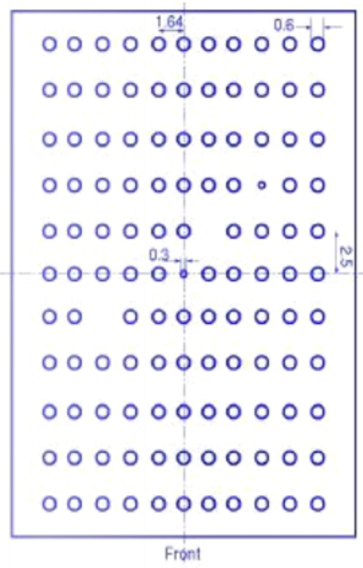
Target ladder picture

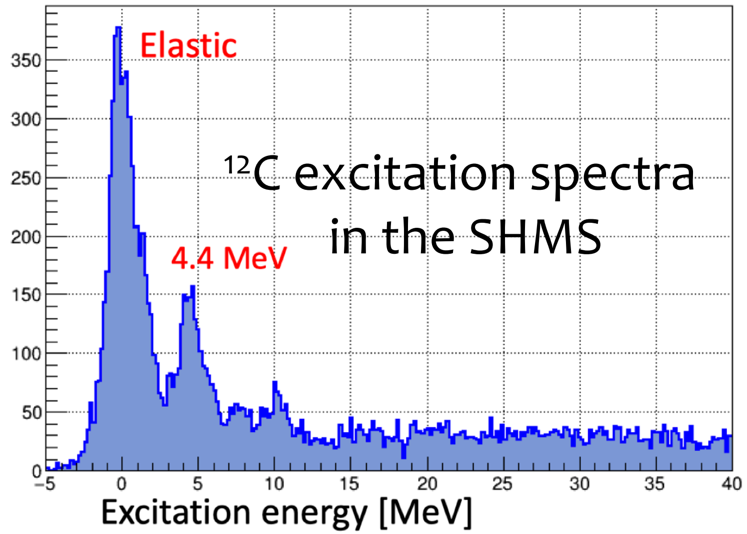


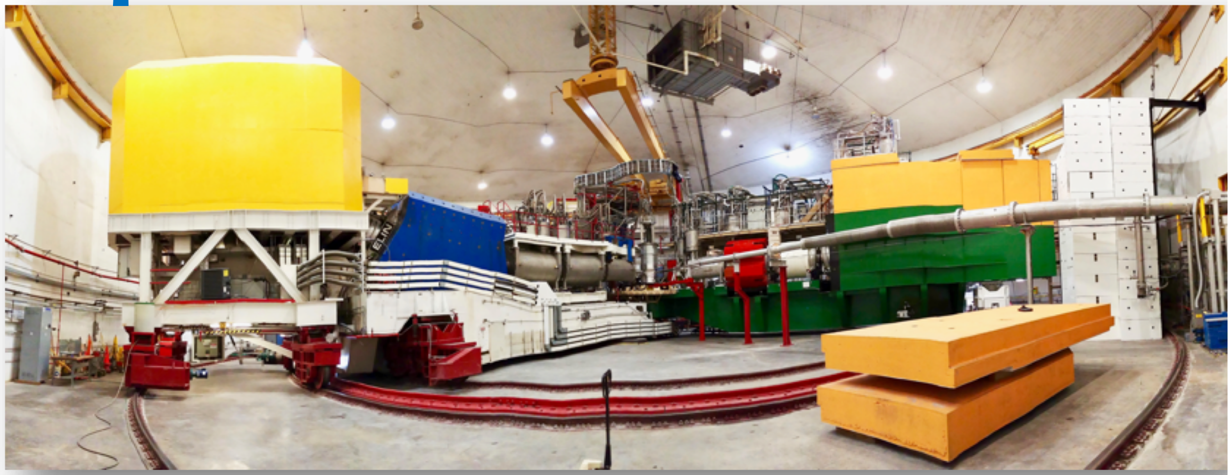


Commissioning a spectrometer

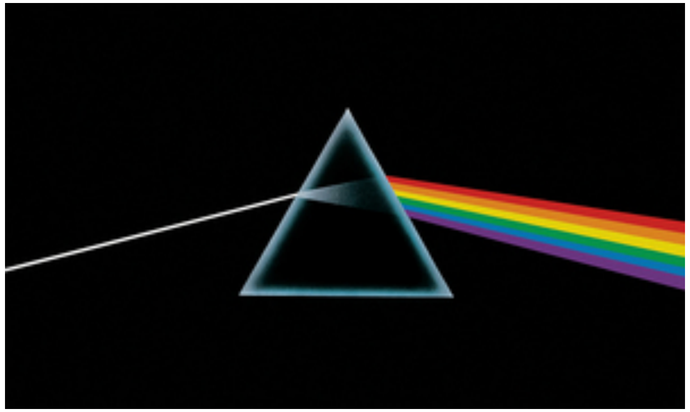
Insert sieve to trace particle trajectories



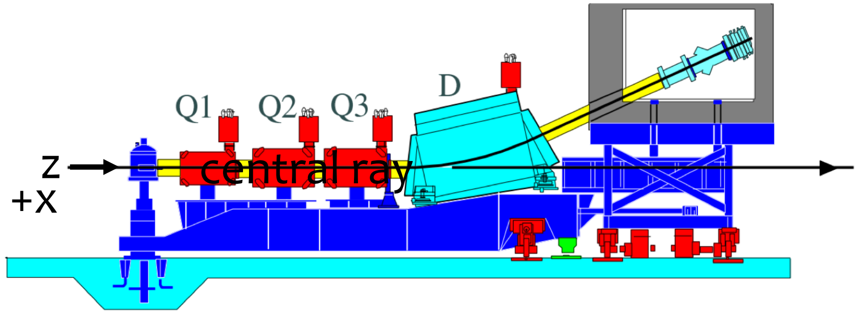




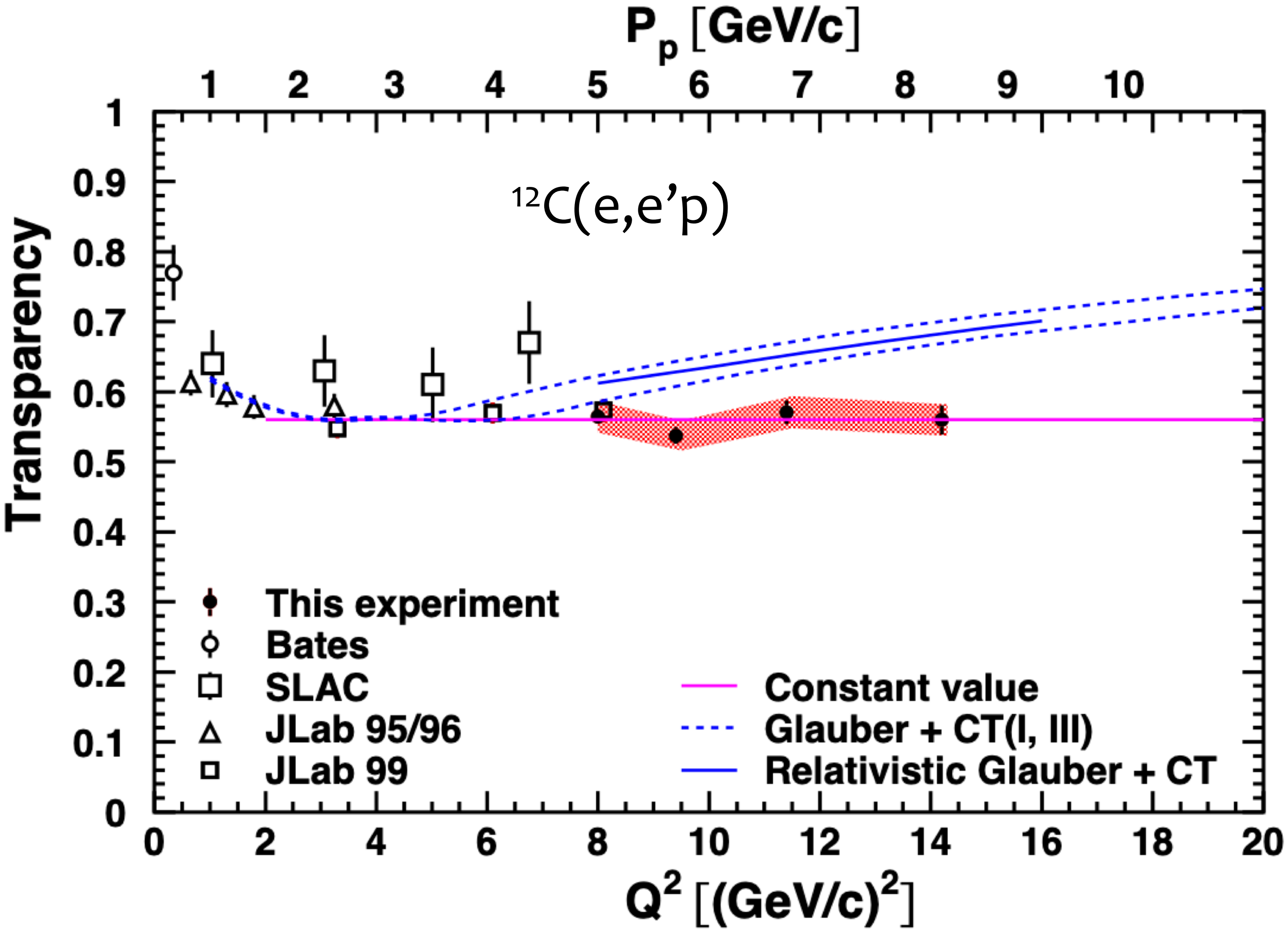
The new SHMS ran for the first time in the proton CT experiment in Hall C (enabling higher proton momenta)



Focusing spectrometers are like prisms, separating particles by momenta instead of frequency



No CT observed! 🤯

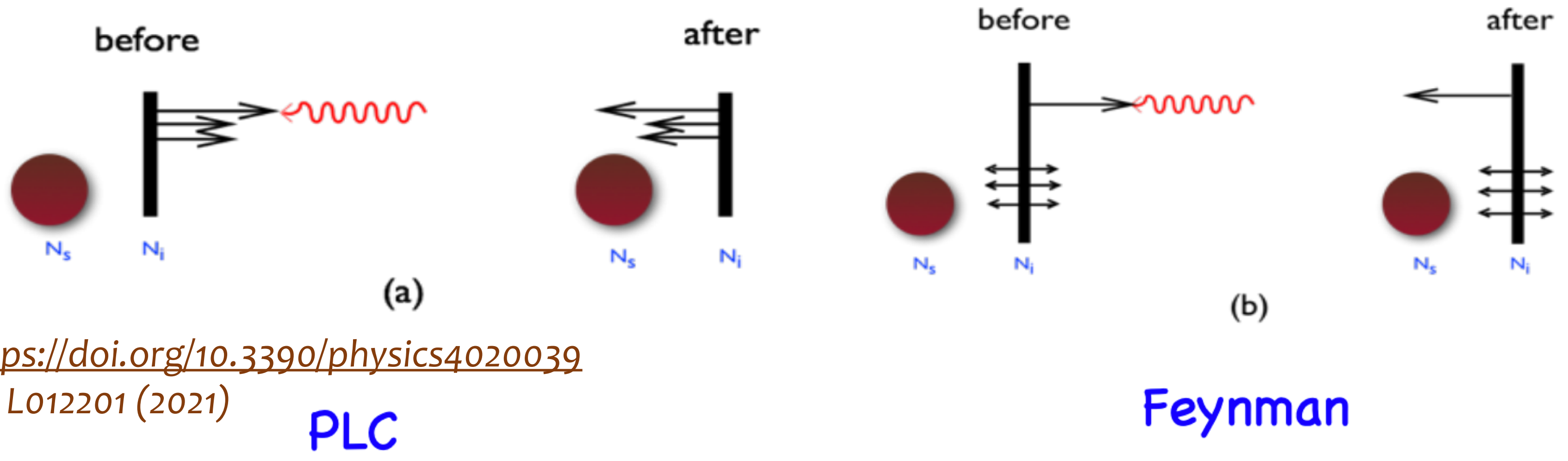


Parallel kinematics: reduced FSIs, θ_{pq} = 0

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

Possible explanations

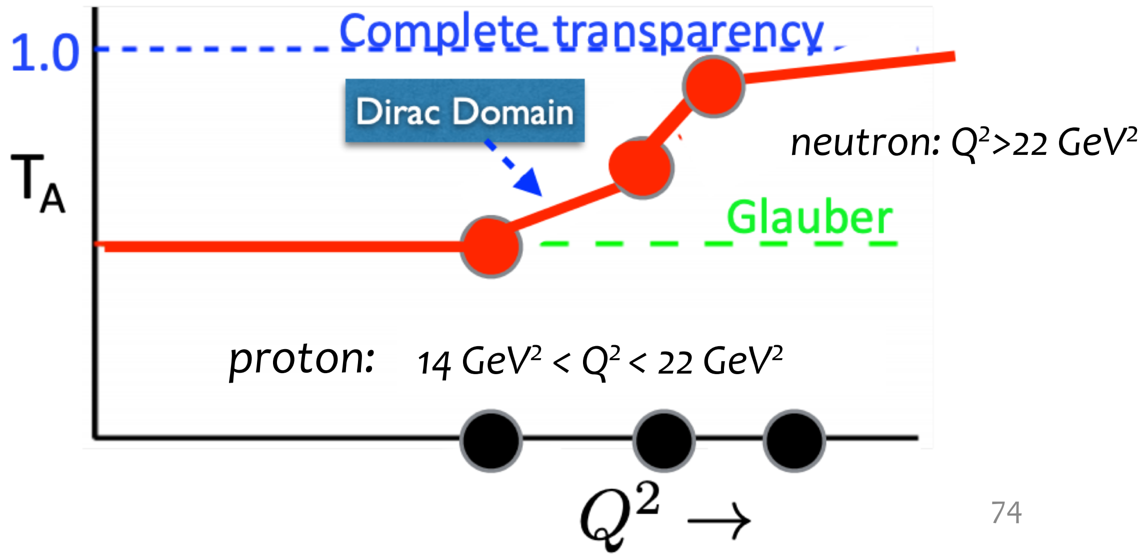
No PLC was formed
(Feynman Mechanism)



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

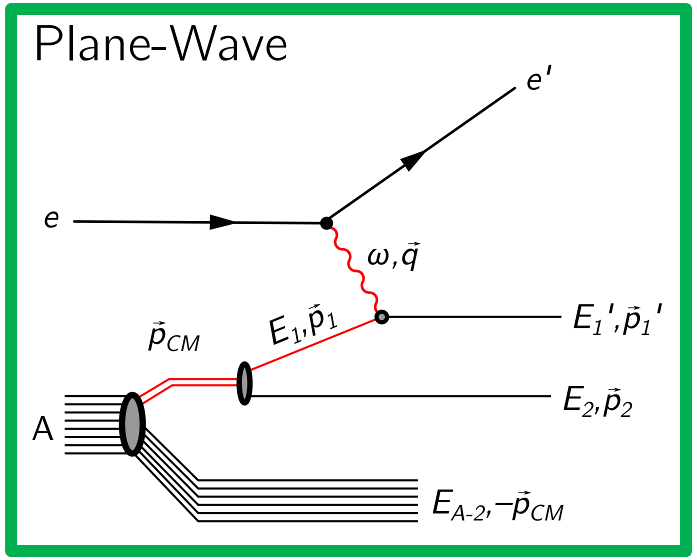
Not high enough in Q^2
(Holographic light front QCD predictions)

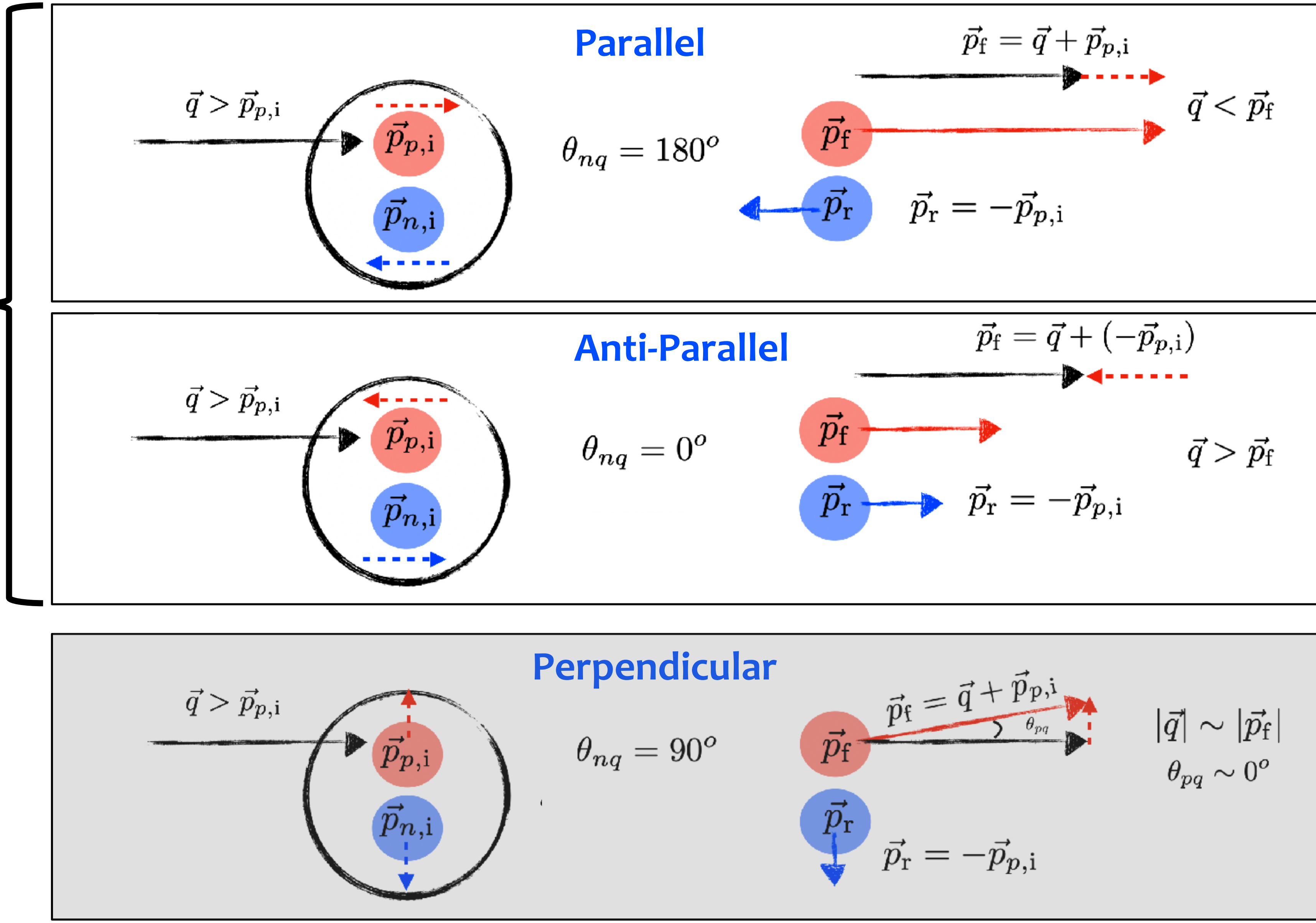
S. Brodsky and G. de Téramond, Physics 2022, 4(2), 633-646; https://doi.org/10.3390/physics4020042



Interlude here: Let's revisit the kinematics

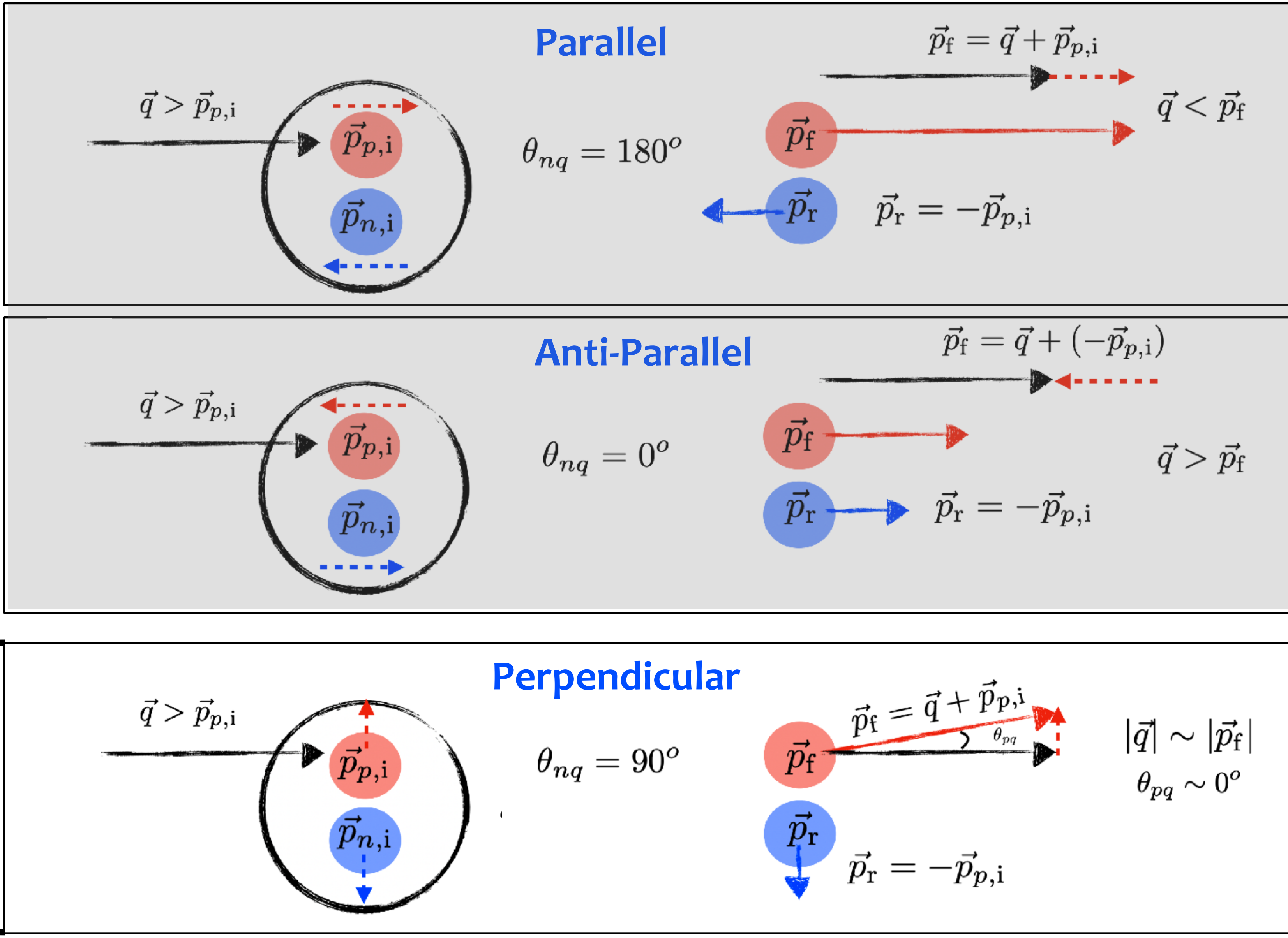
Characterized by low final state interactions: → sensitive to the momentum distribution & SRC structure





Yero, C., (2020). FIU Electronic Theses and Dissertations. 4479. https://digitalcommons.fiu.edu/etd/4479

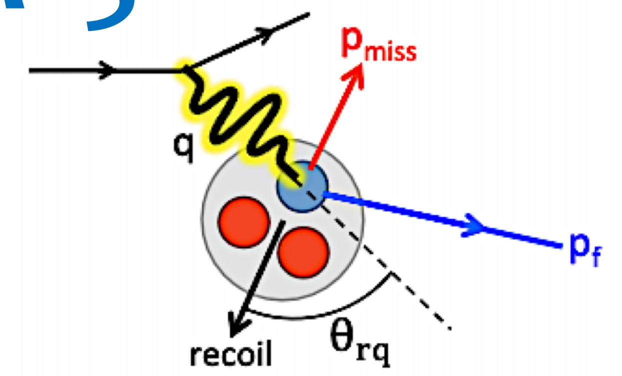
Let's revisit the kinematics



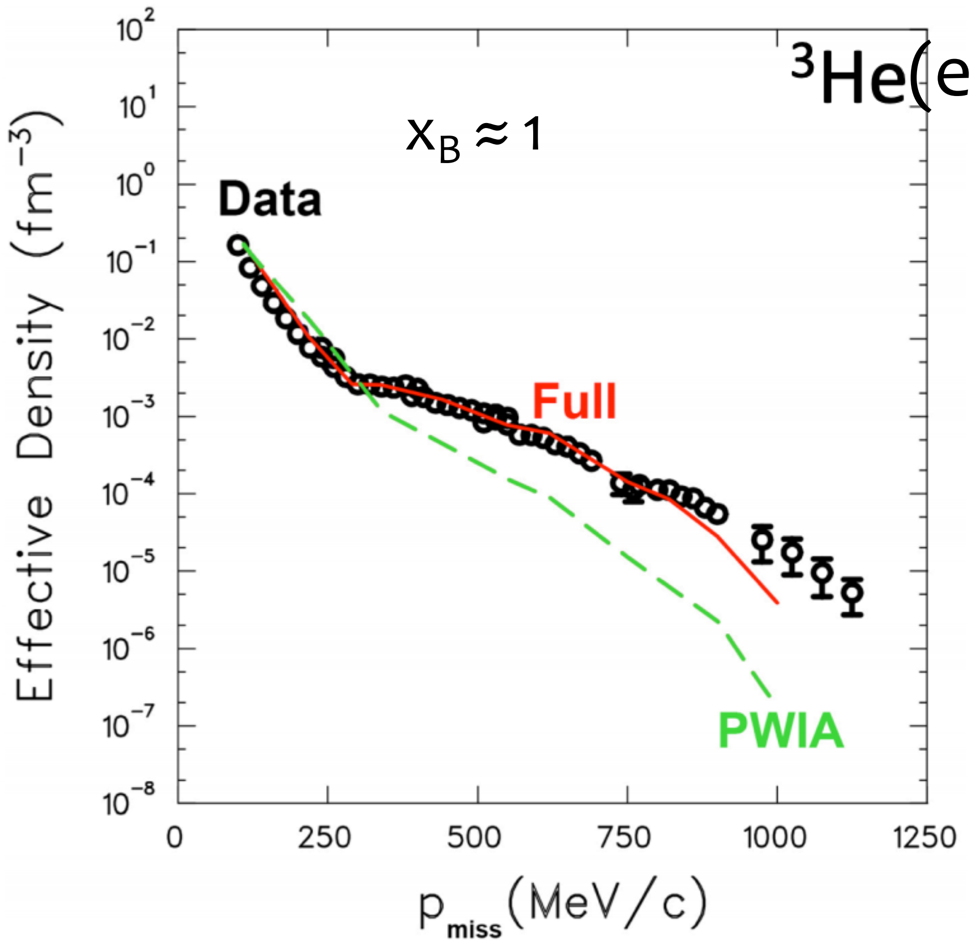
Can be characterized by high final state interactions

Yero, C., (2020). FIU Electronic Theses and Dissertations. 4479. https://digitalcommons.fiu.edu/etd/4479

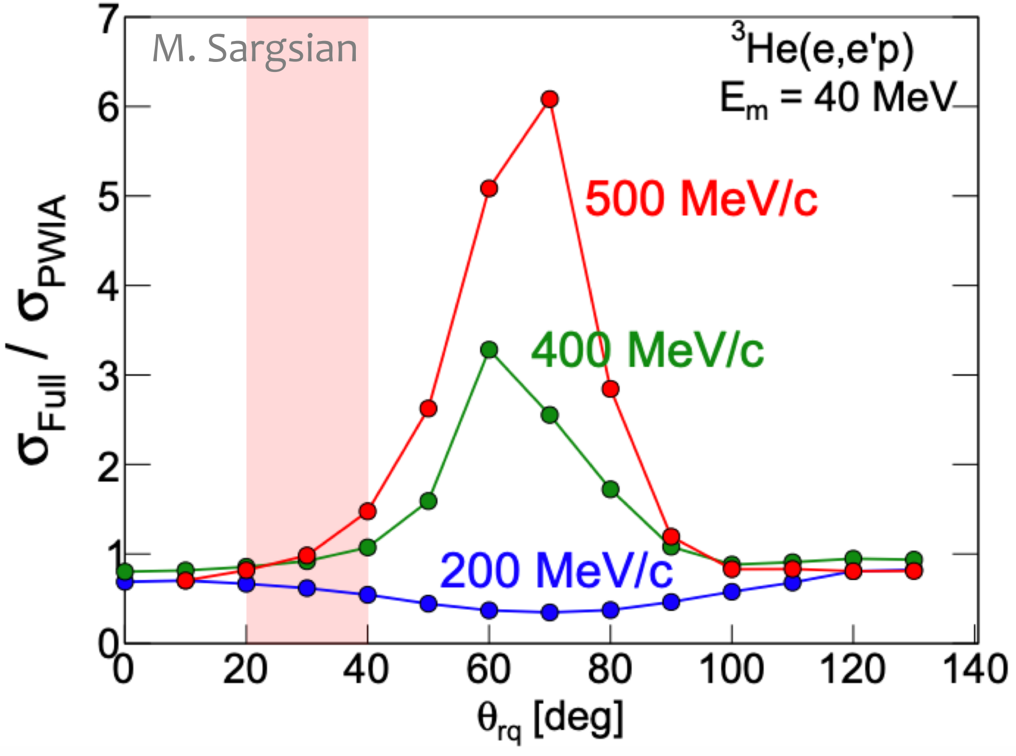
Perpendicular kinematics in A=3



Perpendicular kinematics not sensitive to the momentum distribution



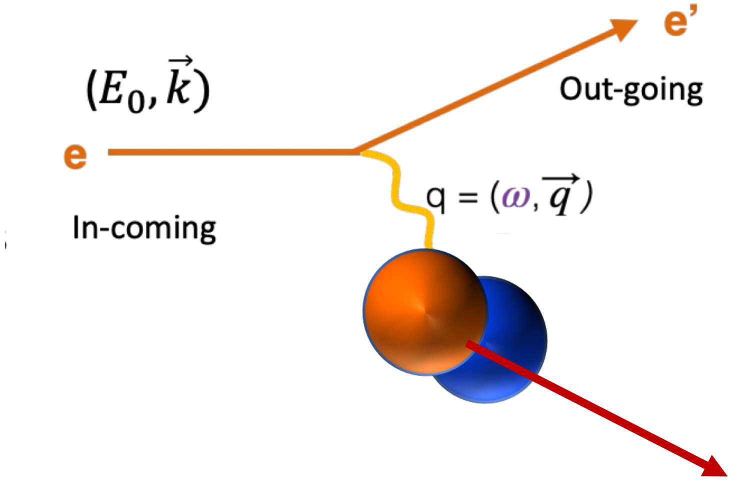
F. Benmokhtar et al., PRL 94, 082305 (2005)



Where "Full" includes final state interactions

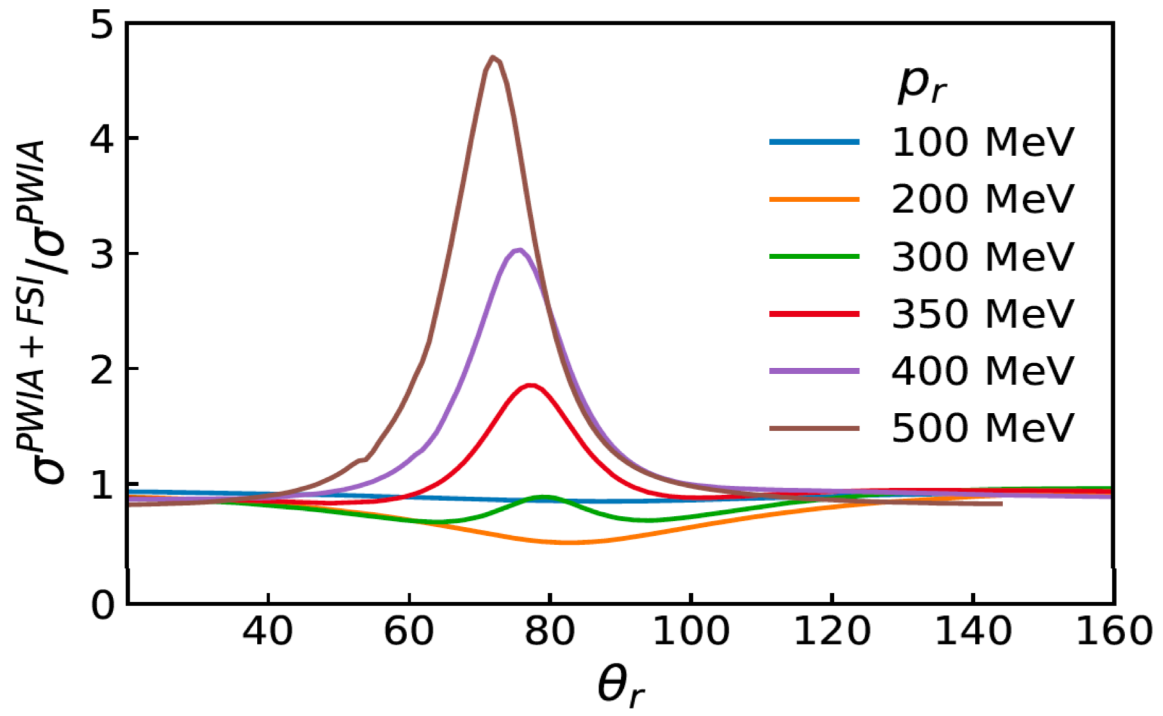
Deuteron kinematics are well-described

$$e + d \;\rightarrow e' + p + n$$



$p_m = q - p_{f,p}$ "recoil" momentum

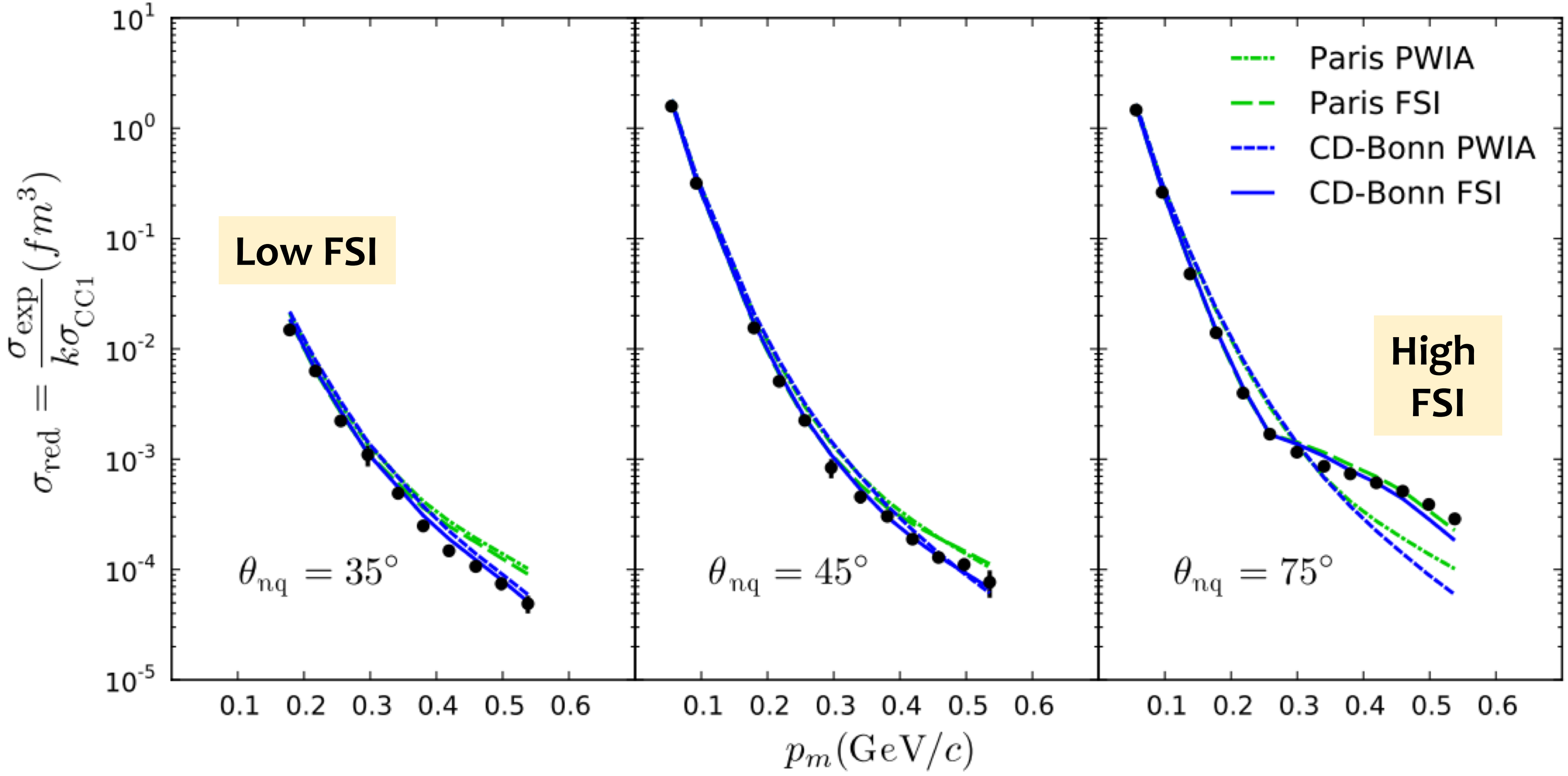
θ_{nq} "recoil" angle



Generalized Eikonal Approximation (GEA) accurate description involving final state interaction (re-scattering) contributions

Deuteron kinematics with enhanced FSI are well-known

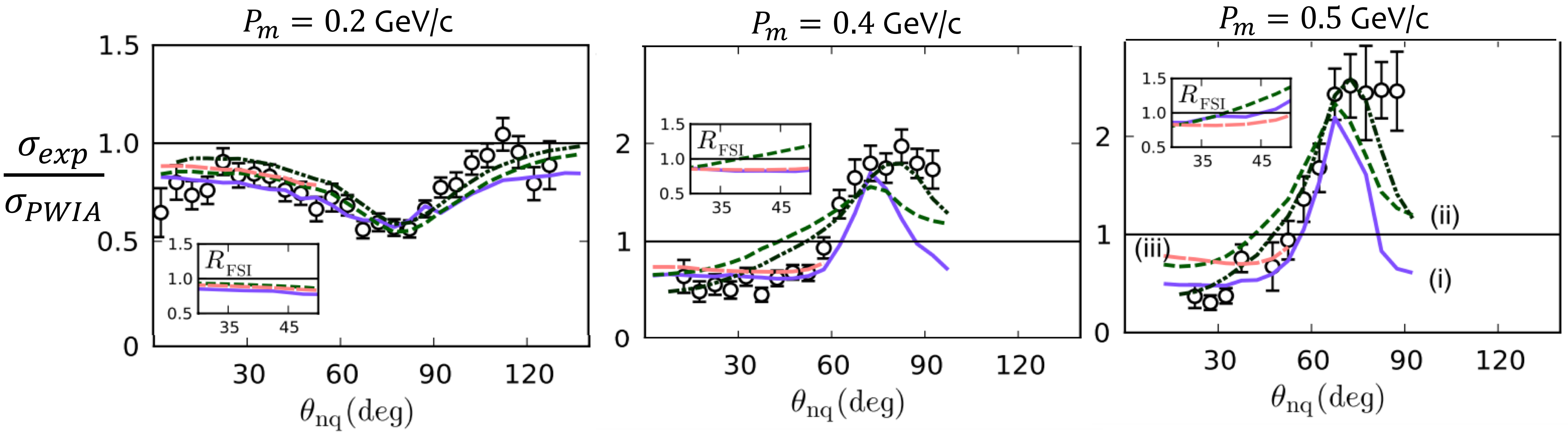
$Q^2 = 3.5$ (GeV/c)²



W. Boeglin et al., PRL (2011)

Larger missing momentum increases the sensitivity to FSIs

$Q^2 = 3.5\ (\text{GeV/c})^2$

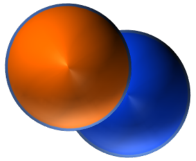


W. Boeglin et al., PRL (2011)

Deuteron is the simplest example of the nuclear interaction affecting partonic properties!

- The nuclear interaction that binds the deuteron also makes the neutron stable.

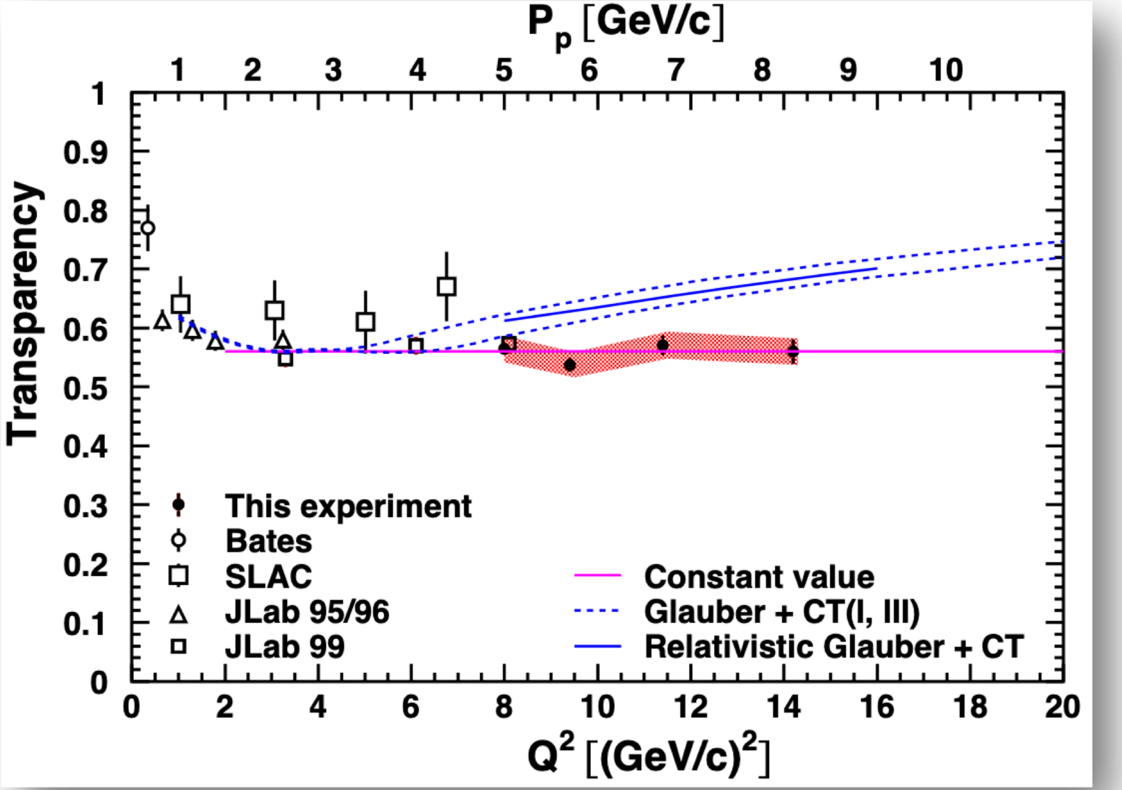
- Simplest nuclear system = Deuteron



- Free neutron is unstable: decays in ~ 10 minutes

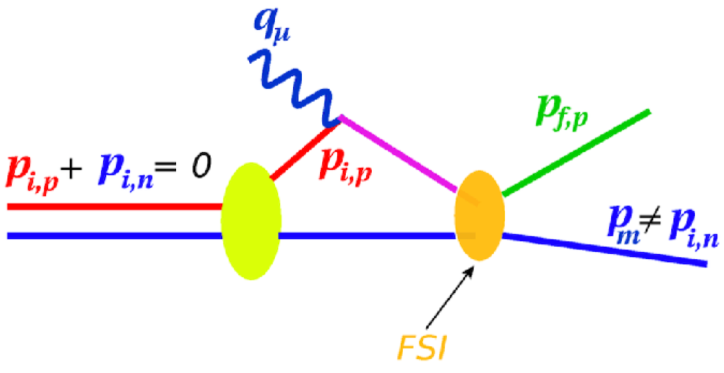
- Bound in the Deuteron, a neutron can live forever

New idea:
Enhance the signal by searching in regime of high FSIs



All previous proton CT experiments used **parallel** kinematics!
→ Looking for a reduction in FSIs where FSIs are already small

We can instead look for a change in the FSI contributions in the deuteron



Final State Interactions (FSI)

Look for a decrease in the re-scattered protons instead of an increase in the non re-scattered ones!

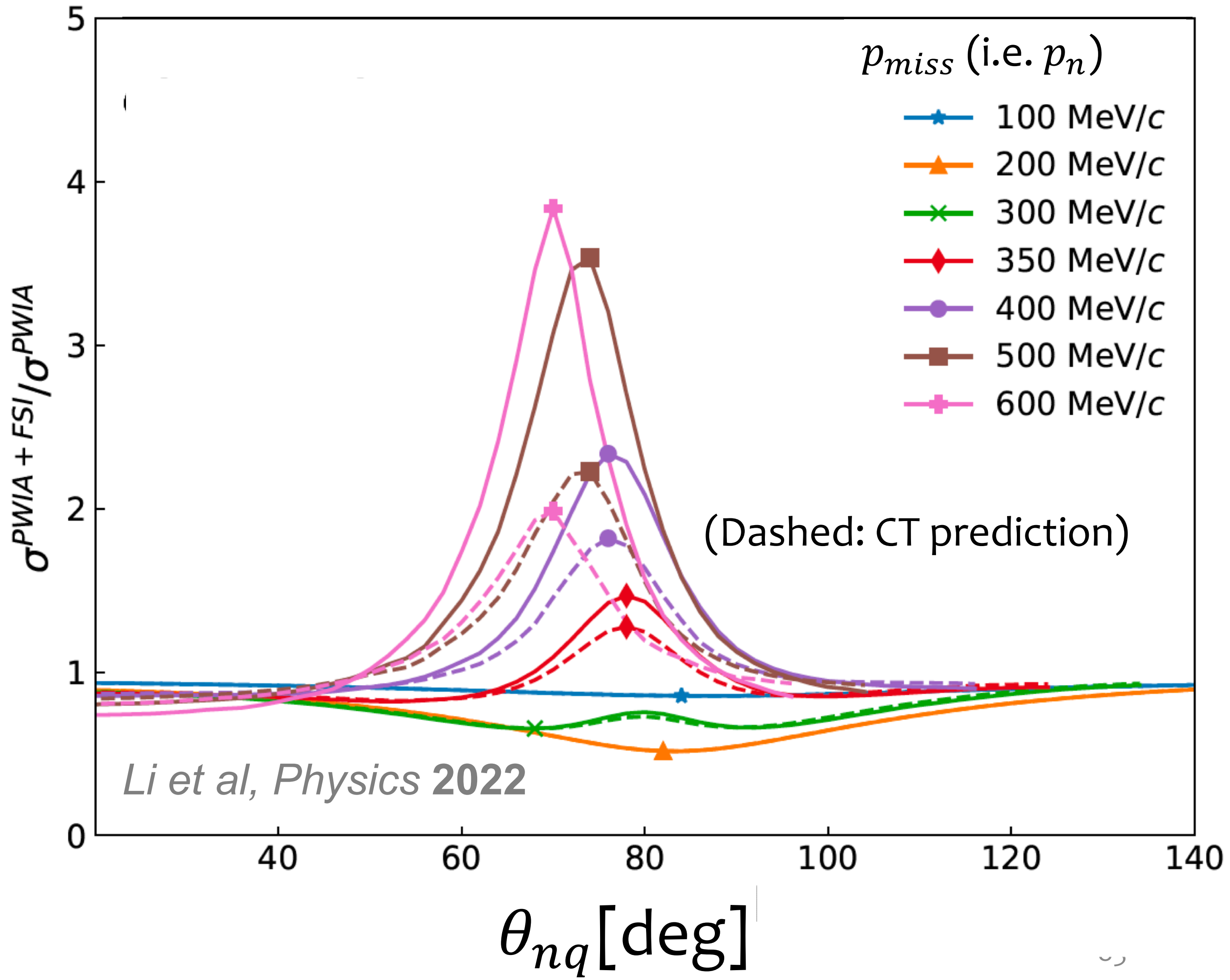
Looking in the region of high FSIs for CT

Specific choice of kinematics → large FSIs from double scattering

Measure the ratio of of counts in high/low FSIs:

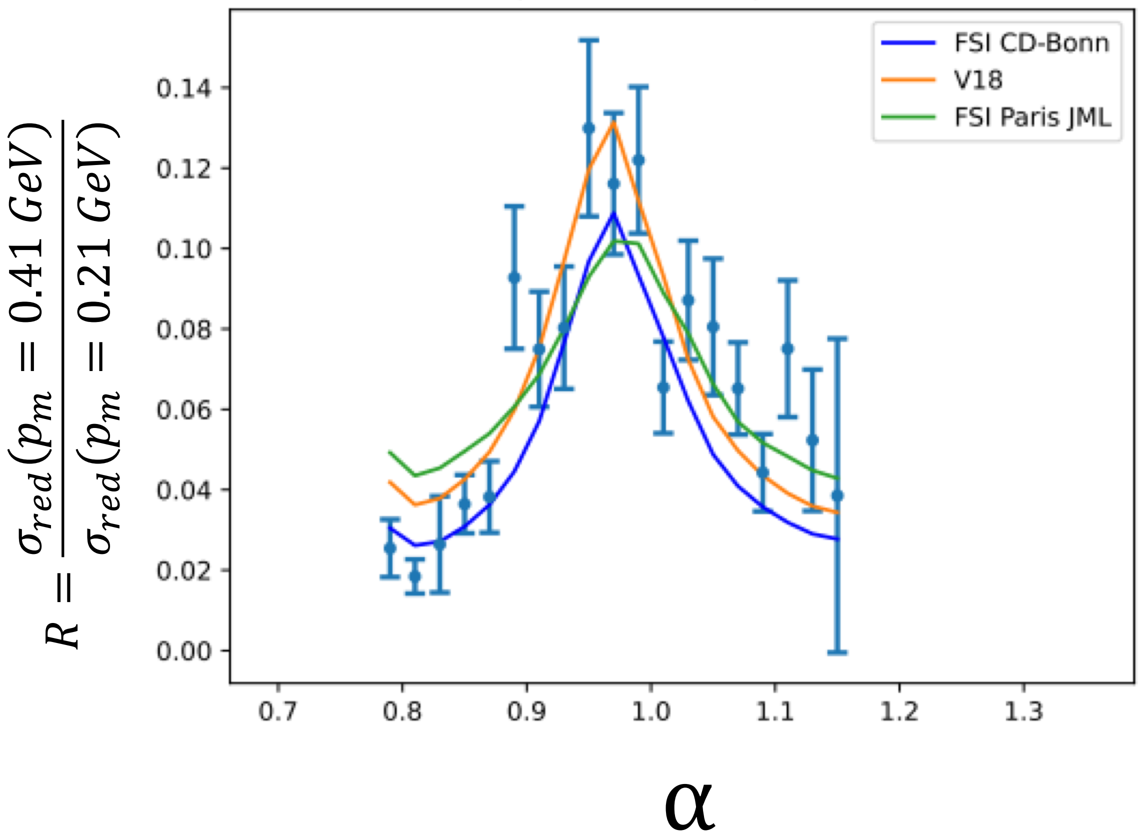
$$\downarrow R = \frac{\sigma(p_r = 400\ MeV) \downarrow}{\sigma(p_r = 200\ MeV) \uparrow}$$

CT: reduction of FSI → reduction of R



Ratio is established in previous data

Q^2 = 3.5 (GeV/c)²

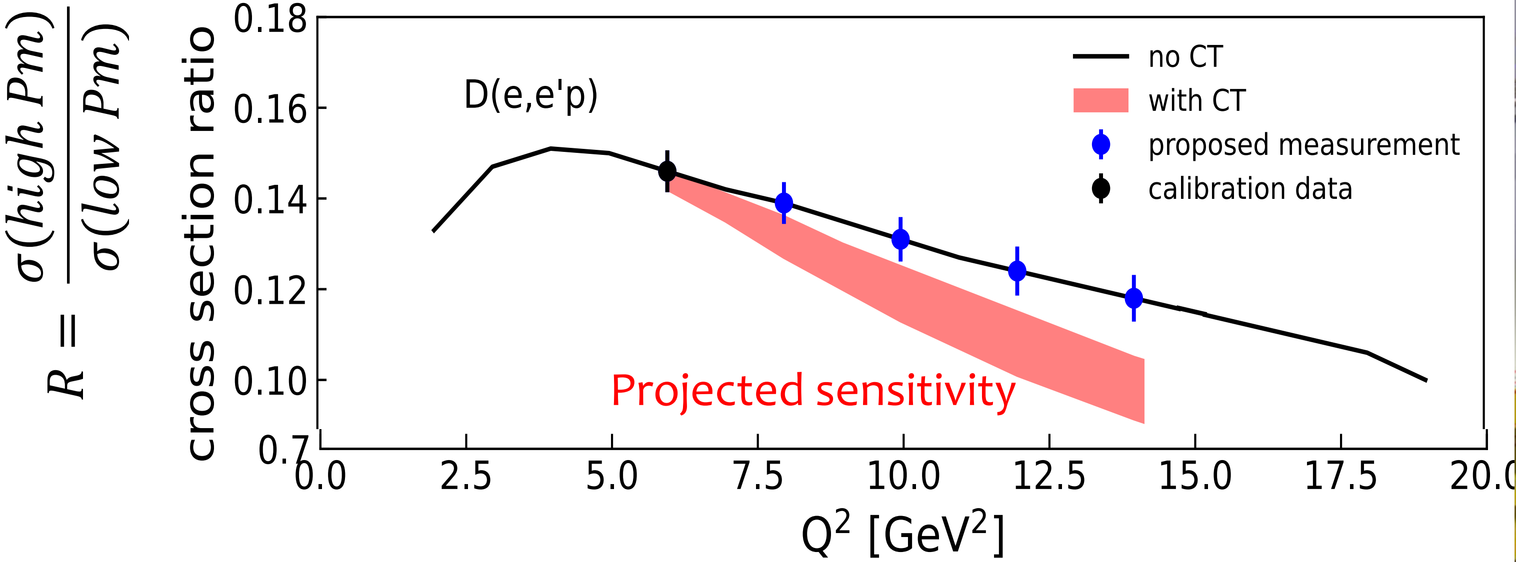


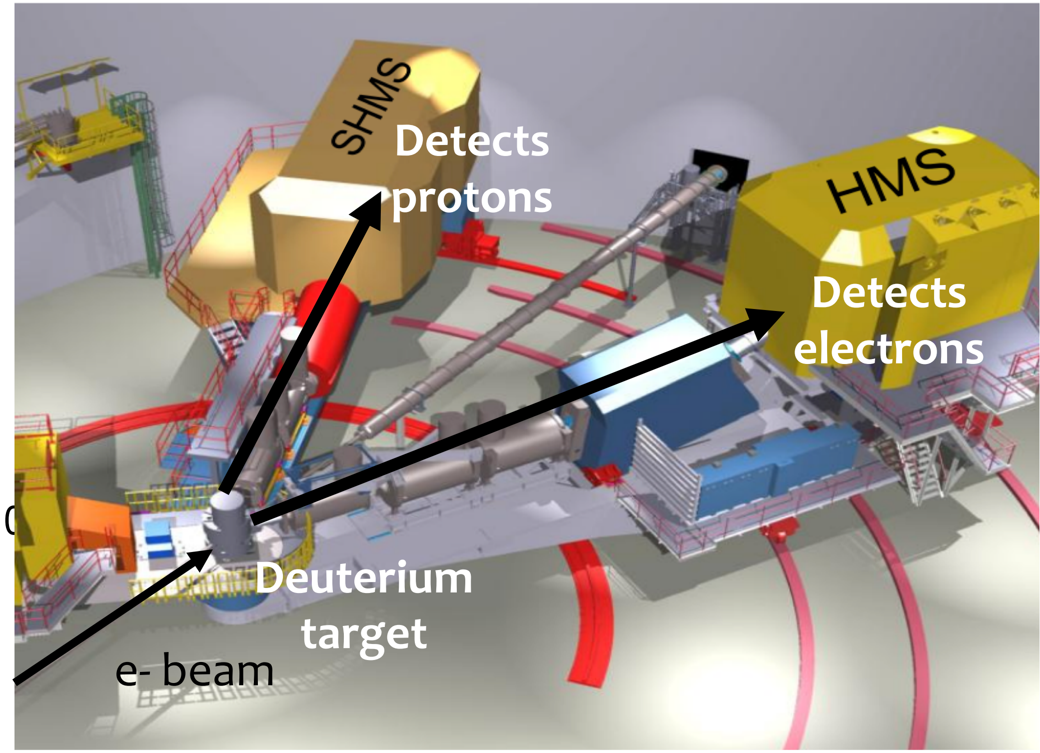
Light cone momentum fraction optimal near 1: $\alpha = (E_n - p_n cos\theta_{\gamma n})/m_n$

W. Boeglin, M. Sargsian https://arxiv.org/abs/2402.13411

Enhanced sensitivity for detecting proton CT

Approved future experiment





Sensitive to shorter PLC lifetime (or rapid expansion)

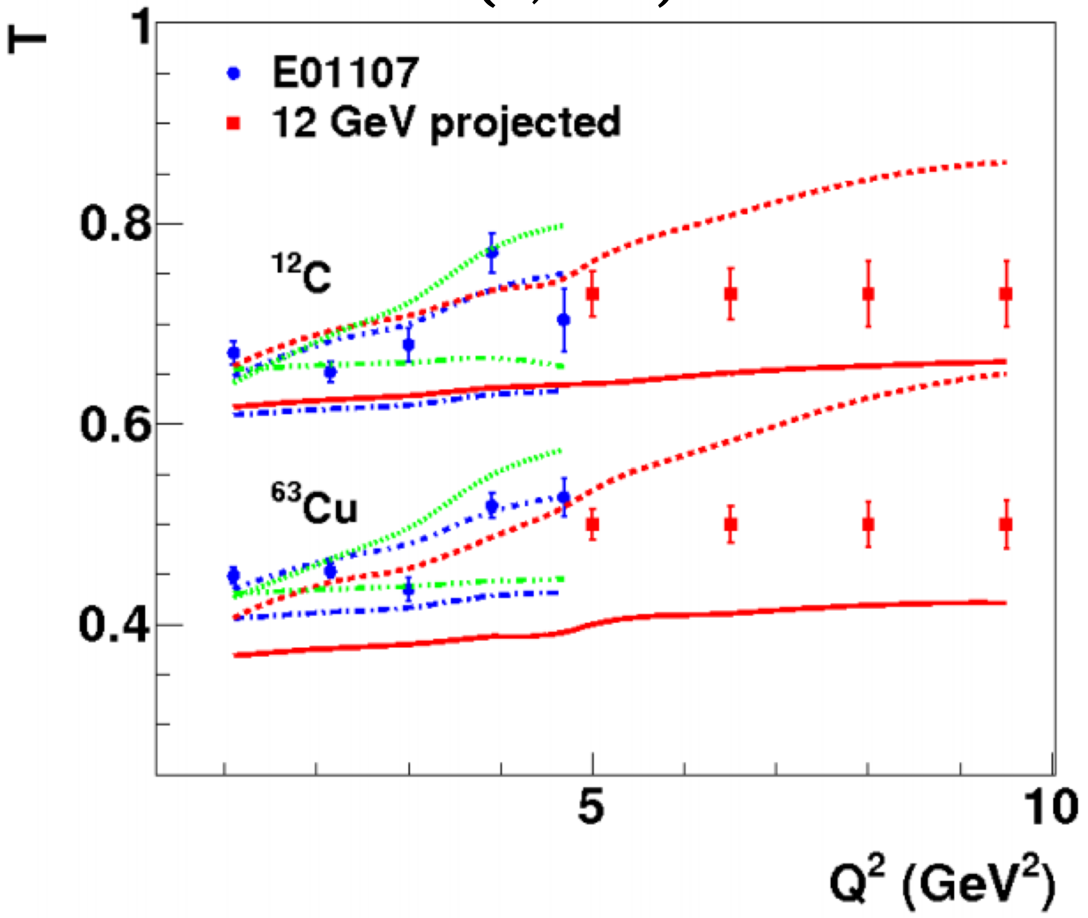
The larger spectator momentum →
smaller distances between the production and rescattering vertices

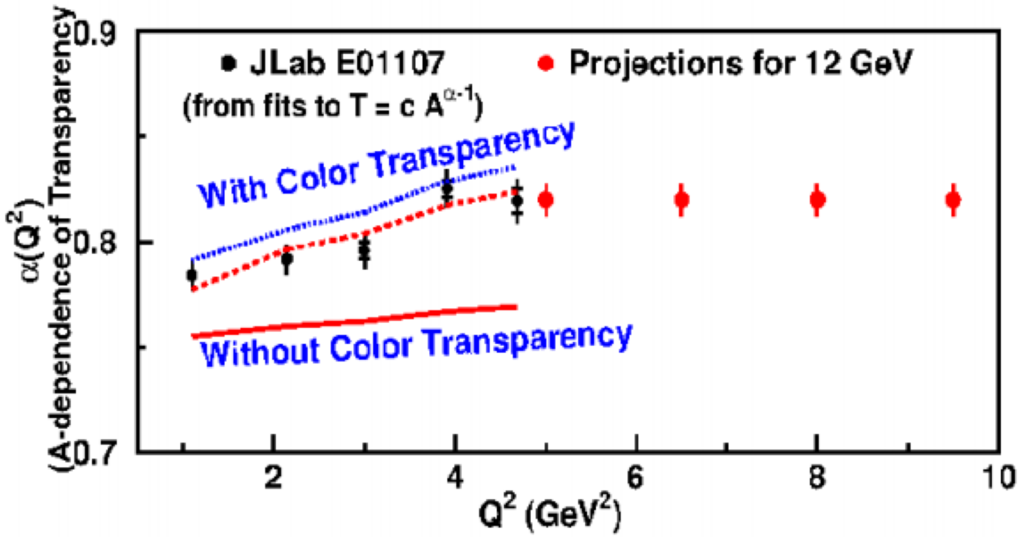
This measurement could help estimate the energies needed in heavy ion collisions to produce a weakly interacting quark-gluon plasma

Imminent experiments examining the onset of CT in mesons

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

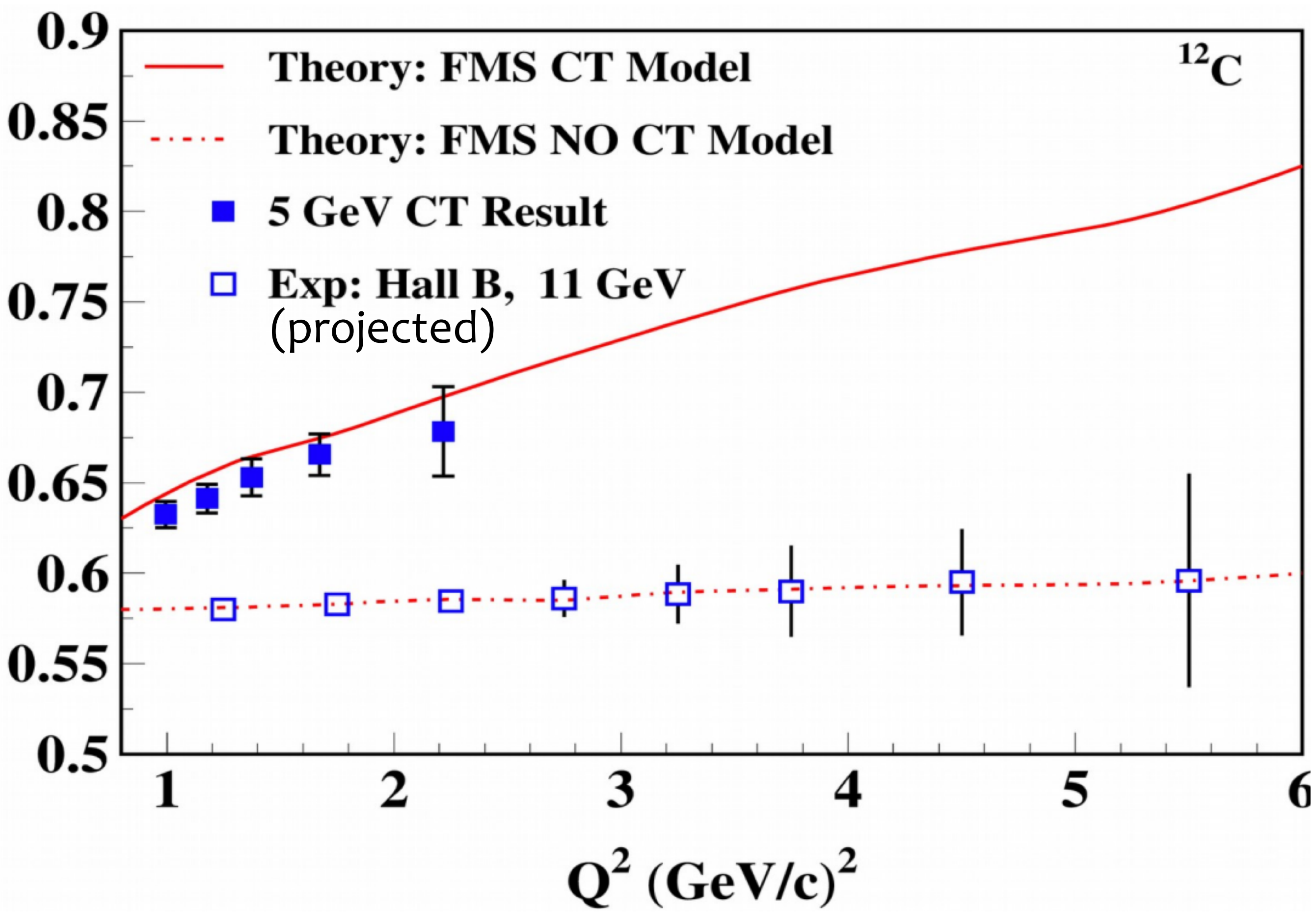
A(e,e'π^+)

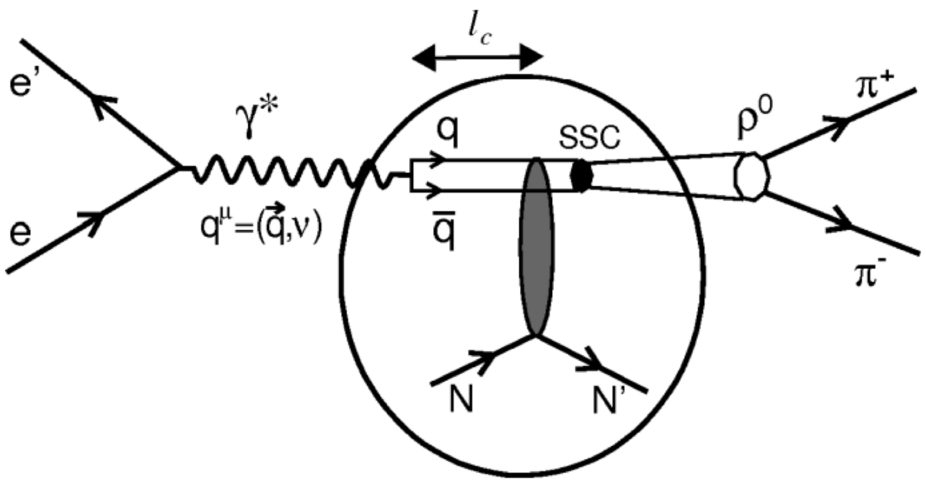


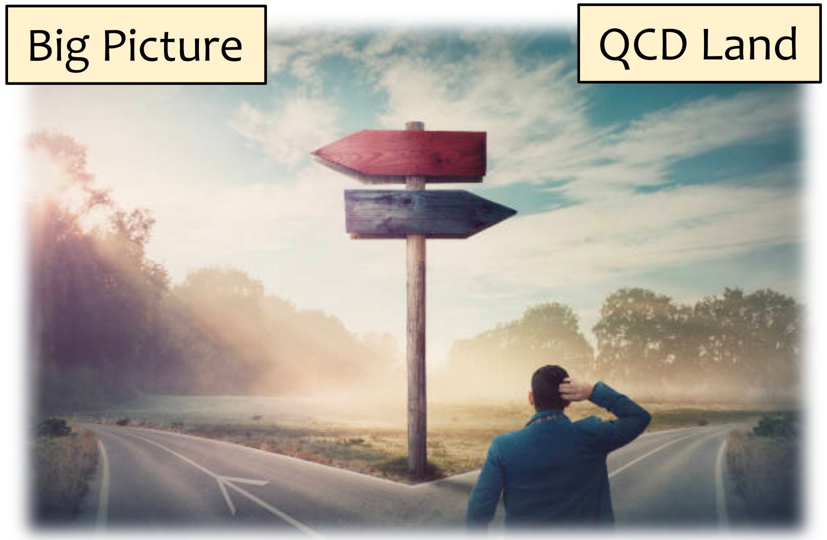


Onset of CT in the rho-meson

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 Big Picture and QCD dynamics

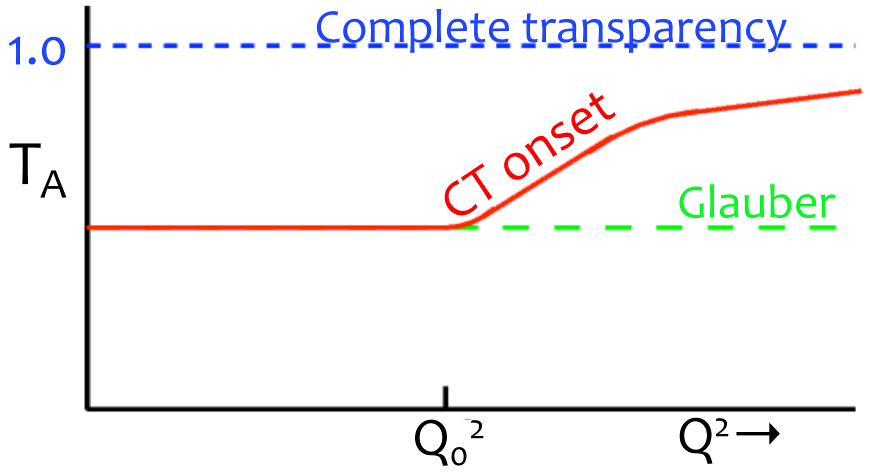
Onset of Color Transparency is important:

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

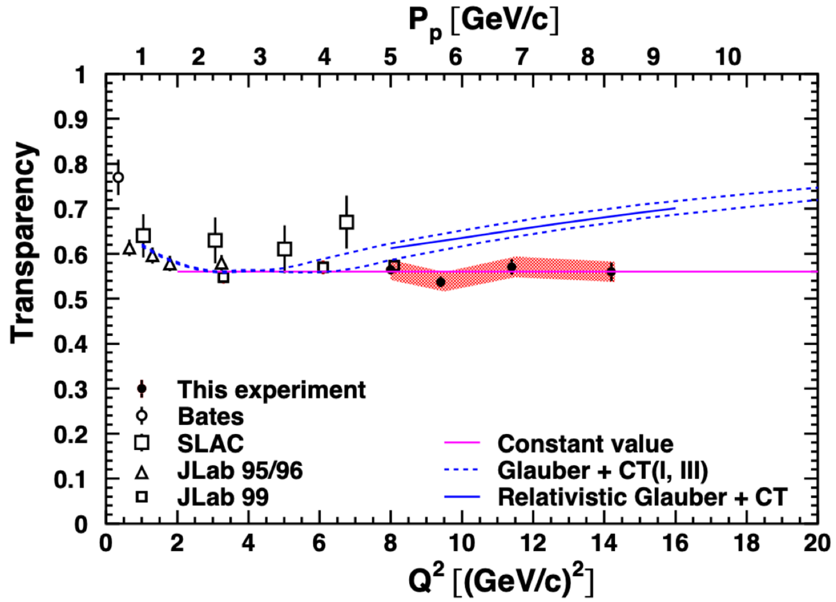
Nuclear transparency must be included in any calculation when knocking out a nucleon

Color transparency

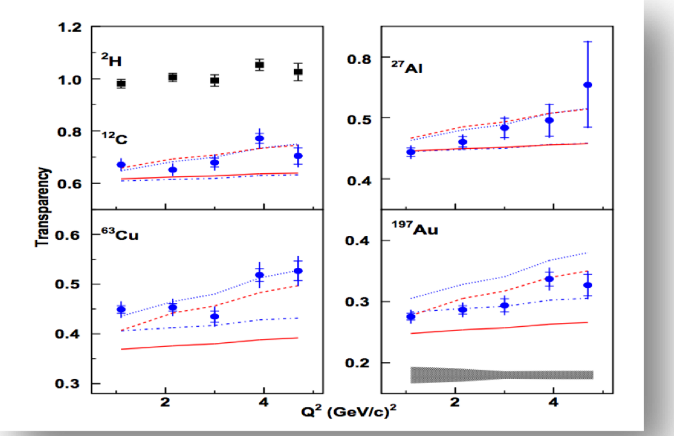
Predicted by QCD:
Observation of transition from q-g d.o.f.



Not seen in protons:

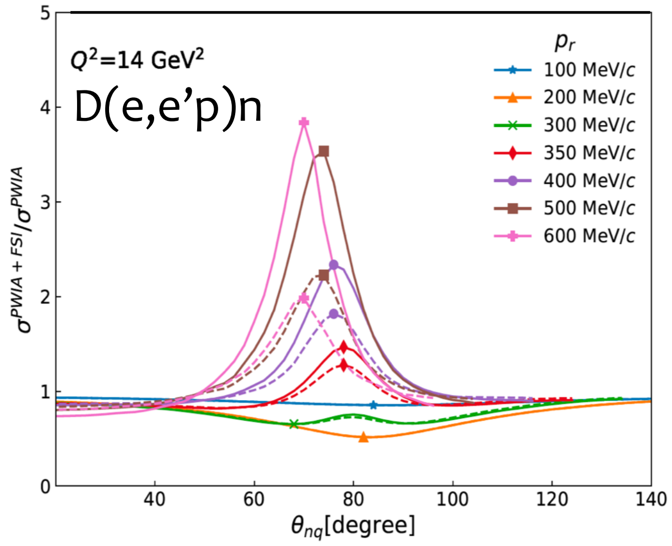


Hints from mesons:

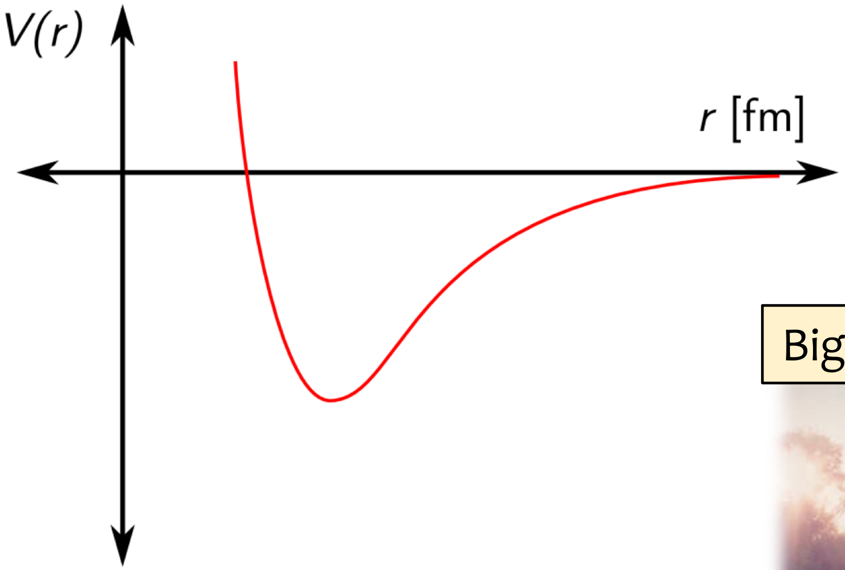


B.Clasie *et al.* PRL 99:242502 (2007)

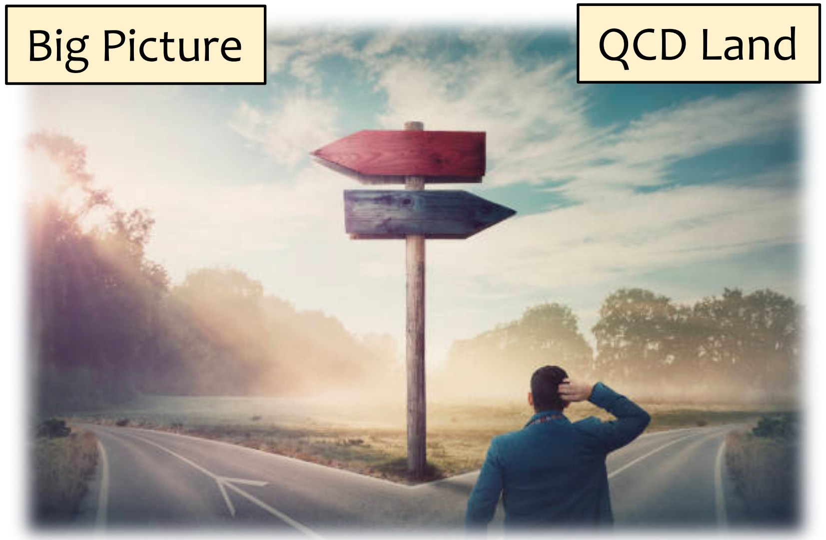
New kinematics seems promising:

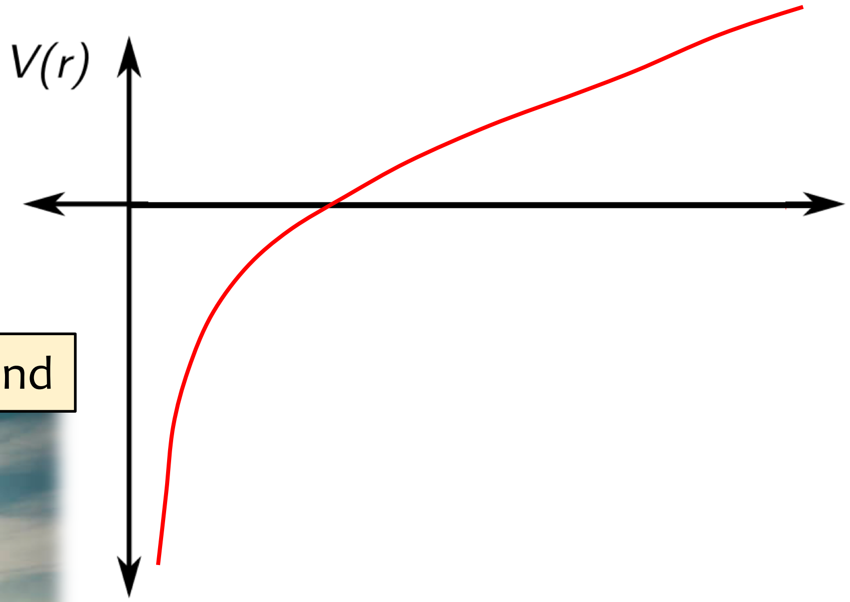


Examining another connection between QCD Land and the Big Picture



nucleons & mesons

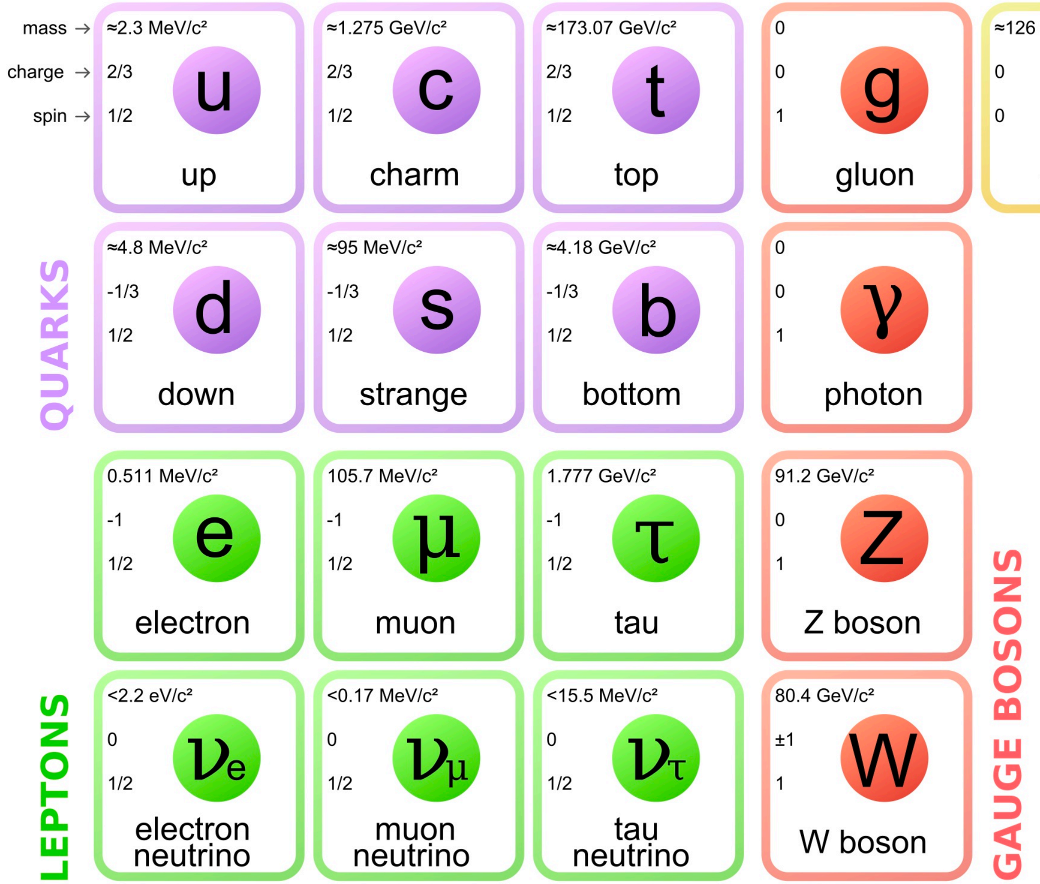




quarks & gluons

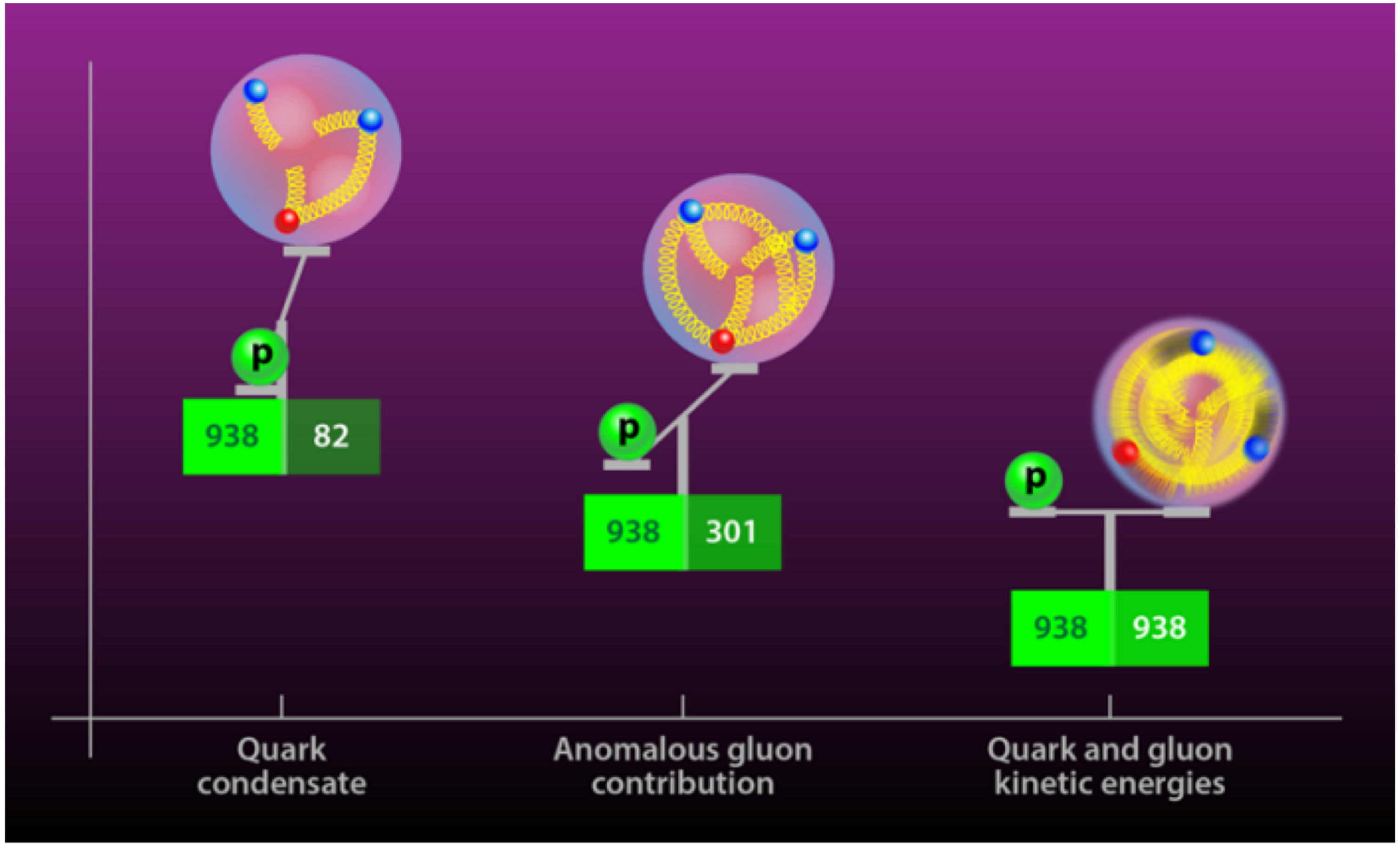
Where does the proton get its mass?

Mass emerges out of the complex structure of the proton



Mass of the proton > 100x the sum of the constituent quark masses!

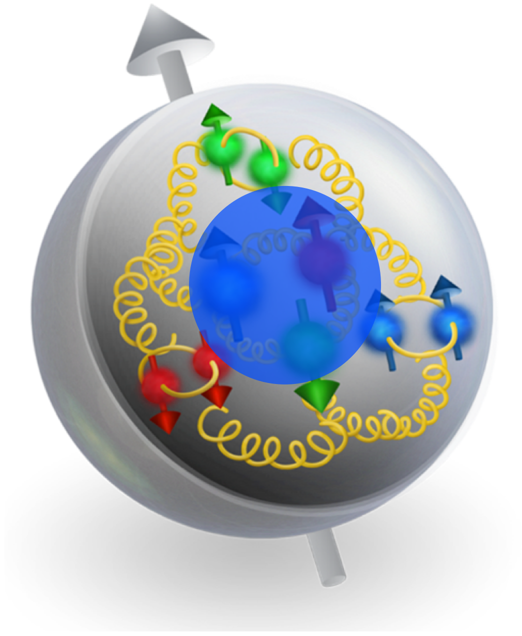
90% from the dynamics of quarks and gluons



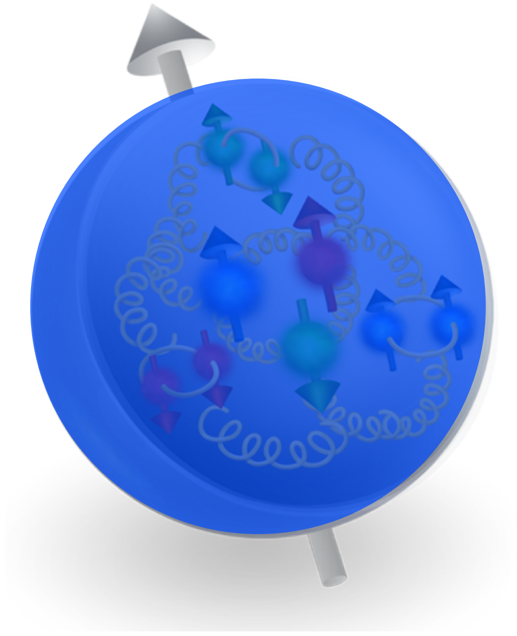
A. Walker-Loud, https://physics.aps.org/articles/pdf/10.1103/Physics.11.118
Y.-B. Yang et al, Phys. Rev. Lett. 121, 212001 (2018).

How does the mass radius compare to the charge radius?

Where is the energy inside the proton?



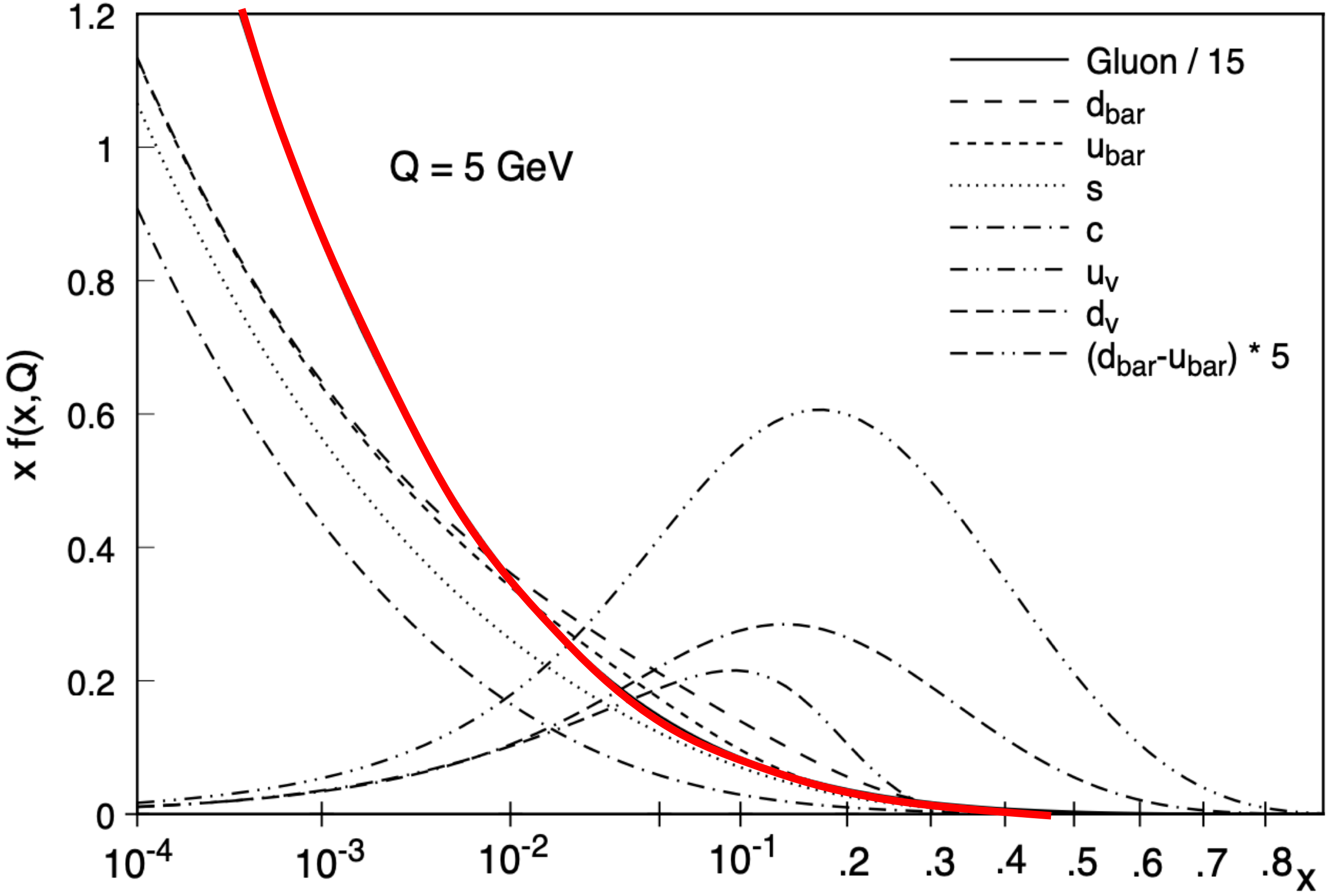
Dense, energetic core?



Same as the charge radius?

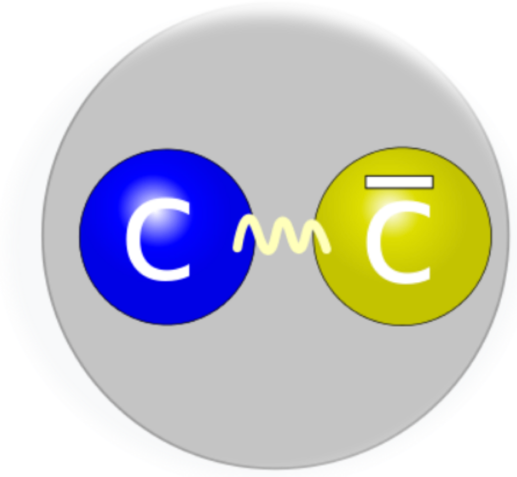
Halo beyond the charge radius?

Recall the enormous gluonic contribution!



How do we learn about the gluonic part?

Hints from quarkonium: J/ψ



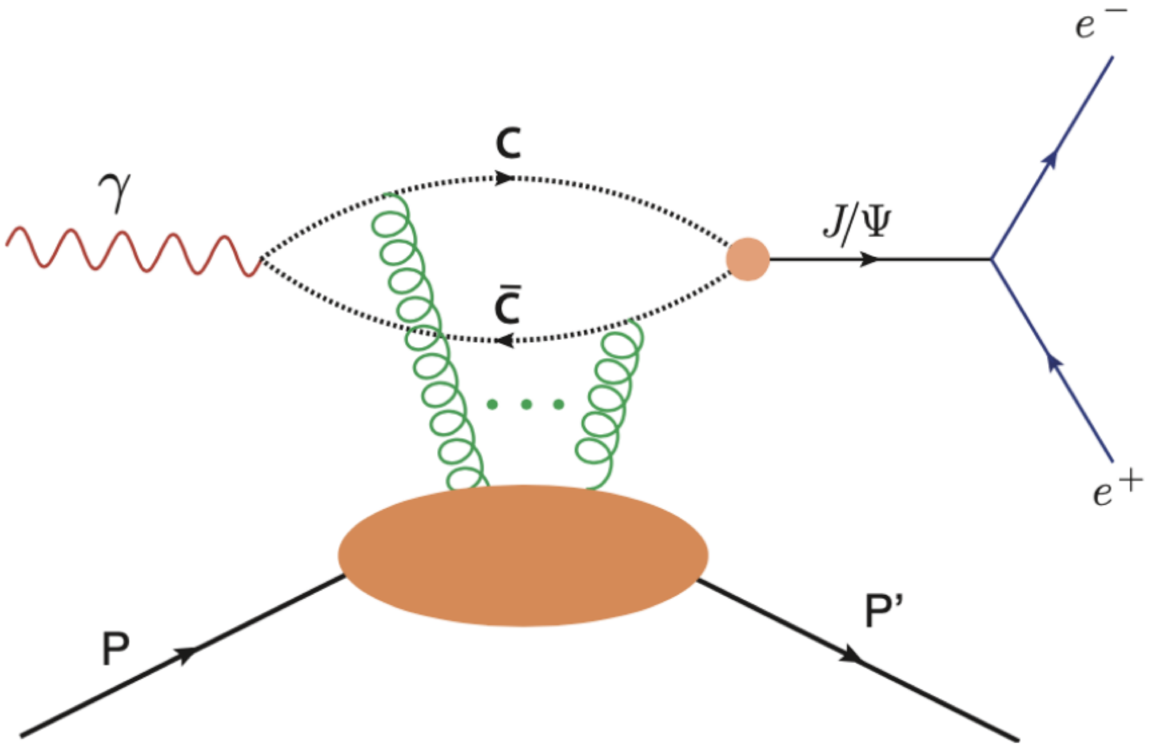
Discovered separately (simultaneously) by groups at SLAC and BNL

J/ψ only couple to gluons, not light quarks

Near threshold cross section provides direct insight to gluons

Branching ratios to leptons

$J/\psi(1S) \to e^- e^+/\mu^- \mu^+$ 6.0%



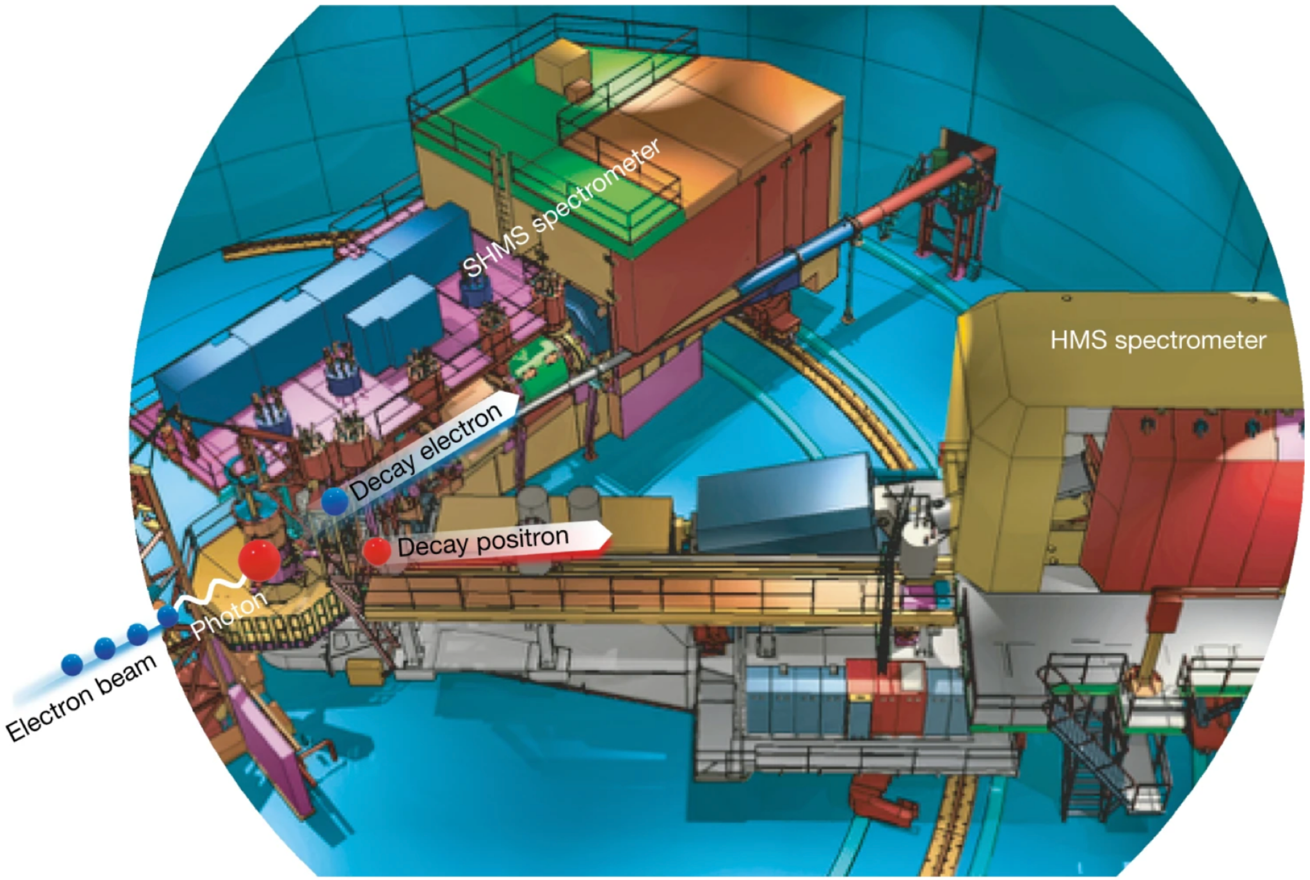
Gravitational Form Factors (GFF)

QCD Energy-Momentum Tensor (EMT): describes the distribution of energy, momentum and stress associated with quarks and gluons

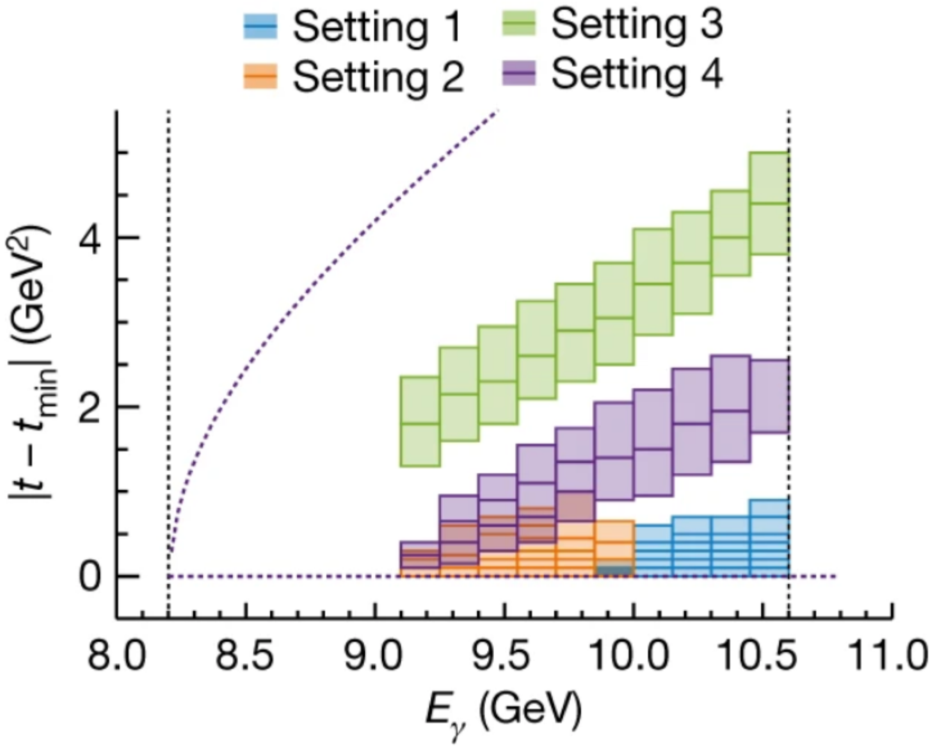
$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N \rangle = \bar{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}(t)\frac{iP^{\{\mu}\sigma^{\nu\}}\rho\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \bar{C}_{g,q}(t)Mg^{\mu\nu} \right) u(N)$$

- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g} \rangle$
- $J_{g,q}(t) = 1/2\left(A_{g,q}(t) + B_{g,q}(t)\right)$: Related to angular momentum, $J_{\text{tot}}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$: Related to pressure and shear forces

Hall C experiment reconstructing J/ψ

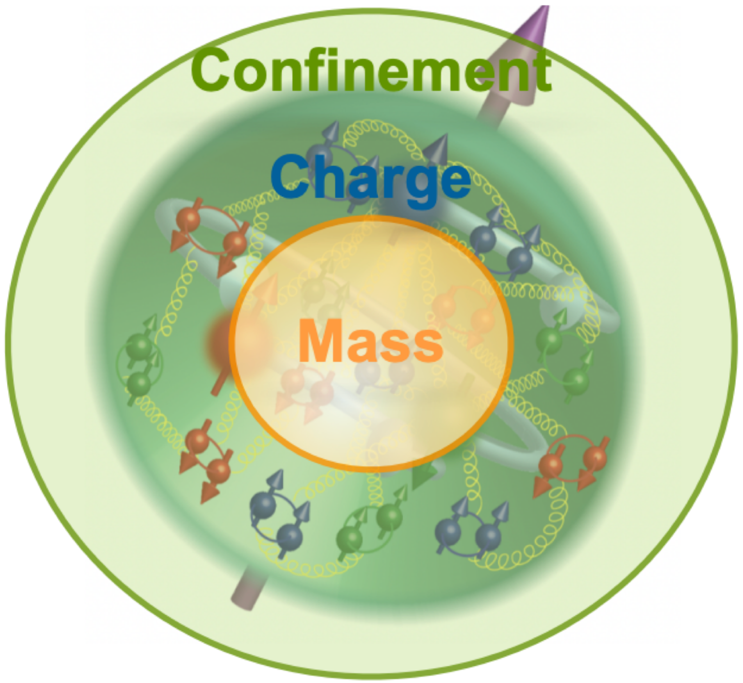


$$\sigma_{\text{tot}}^{\gamma_p} = \int_{t_{\min}}^{t_{\max}} dt \frac{d\sigma}{dt}$$



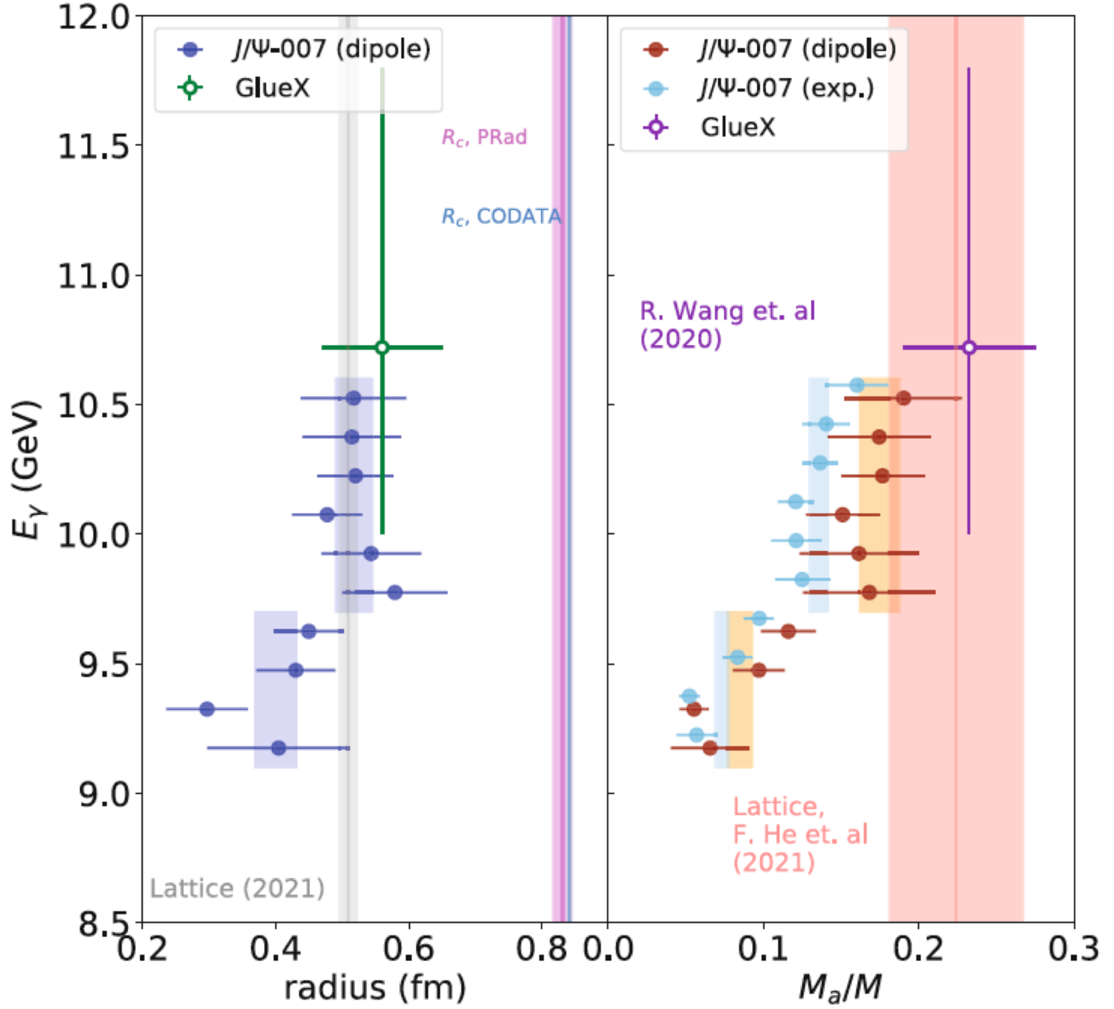
B. Duran et al, Nature volume 615, pages813–816 (2023)

Mass radius < charge radius



Inner core, dominated by tensor gluonic fields

Confining scalar gluon density (> charge radius)



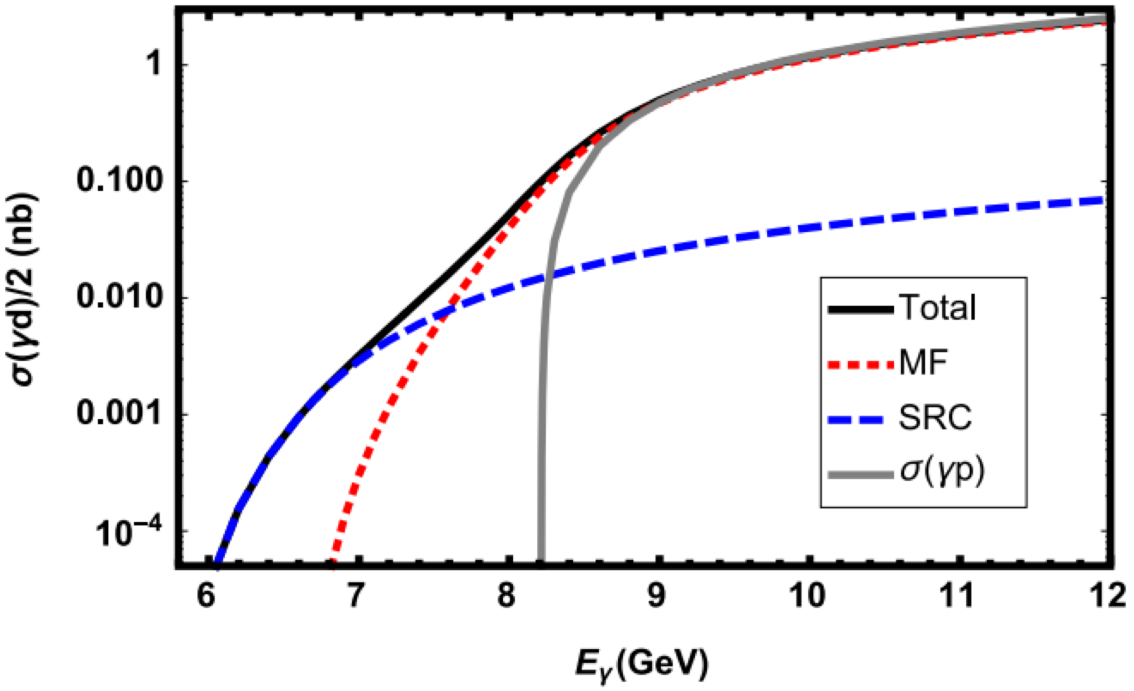
Extended Data Fig. 2 | Mass radius and trace anomaly. Left panel: The extracted radius as a function of the photon energy according to ref.[9] together with the GlueX result. Both our and the GlueX extractions used a dipole fit of the form factor. The charge radius from CODATA and the latest electron scattering[6] (labeled PRad) are plotted as lines with error bands. The lattice result[12] is plotted as a grey line with grey error band. Right panel: The extracted M_a/M according to Ji's mass decomposition[40] following[32] along with a recent direct lattice calculation of the same quantity[41].

B. Duran et al, <u>Nature</u> volume 615, pages813–816 (2023)

Lots of possibilities with J/ψ

Is there a gluonic analogue to the EMC Effect? Near threshold could tell us …

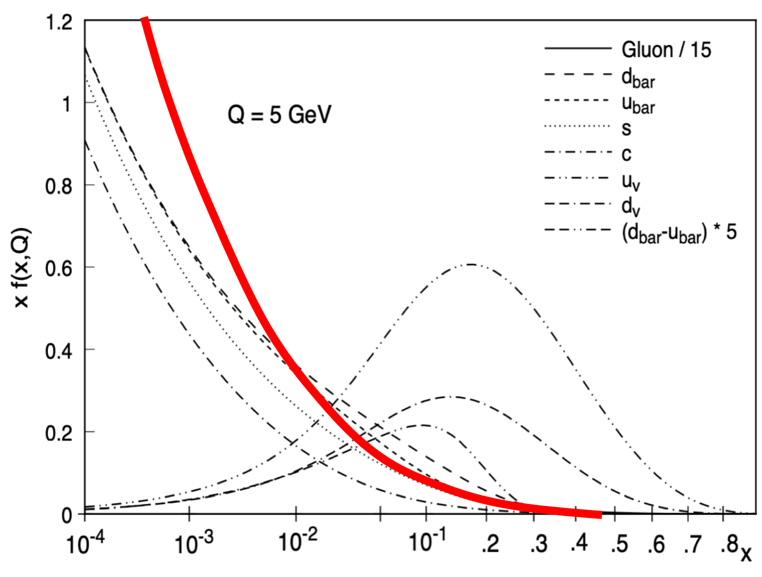
Can we study SRCs? Theory says yes! Could be a gluonic probe of SRCs



Test of SRC Universality:
i.e. SRCs are responsible for the EMC Effect across all different nuclei in the same manner?

Y. Hatta et al, Physics Letters B, vol. 803, p. 135321, (2020).

Outlook



Future machines (like the EIC) and physics processes (like J/ψ) can help us access information from the gluons in nucleons.

Form Factor studies will push to higher Q2 to make improved descriptions and improve our understanding of the quark dynamics.

SRC studies have given us many new insights over the past decade. The future will seek to establish universality amongst reaction mechanisms and observation of 3N SRC.

CT is direct connection between the QCD and hadronic descriptions of matter. Future experiments will possibly fully confirm this.

Visualizing the proton

Check out the video here: https://arts.mit.edu/visualizing-the-proton/