From Quarks to Nuclei: new results from the upgraded Jefferson Lab.

MISSISSIPPI STATE

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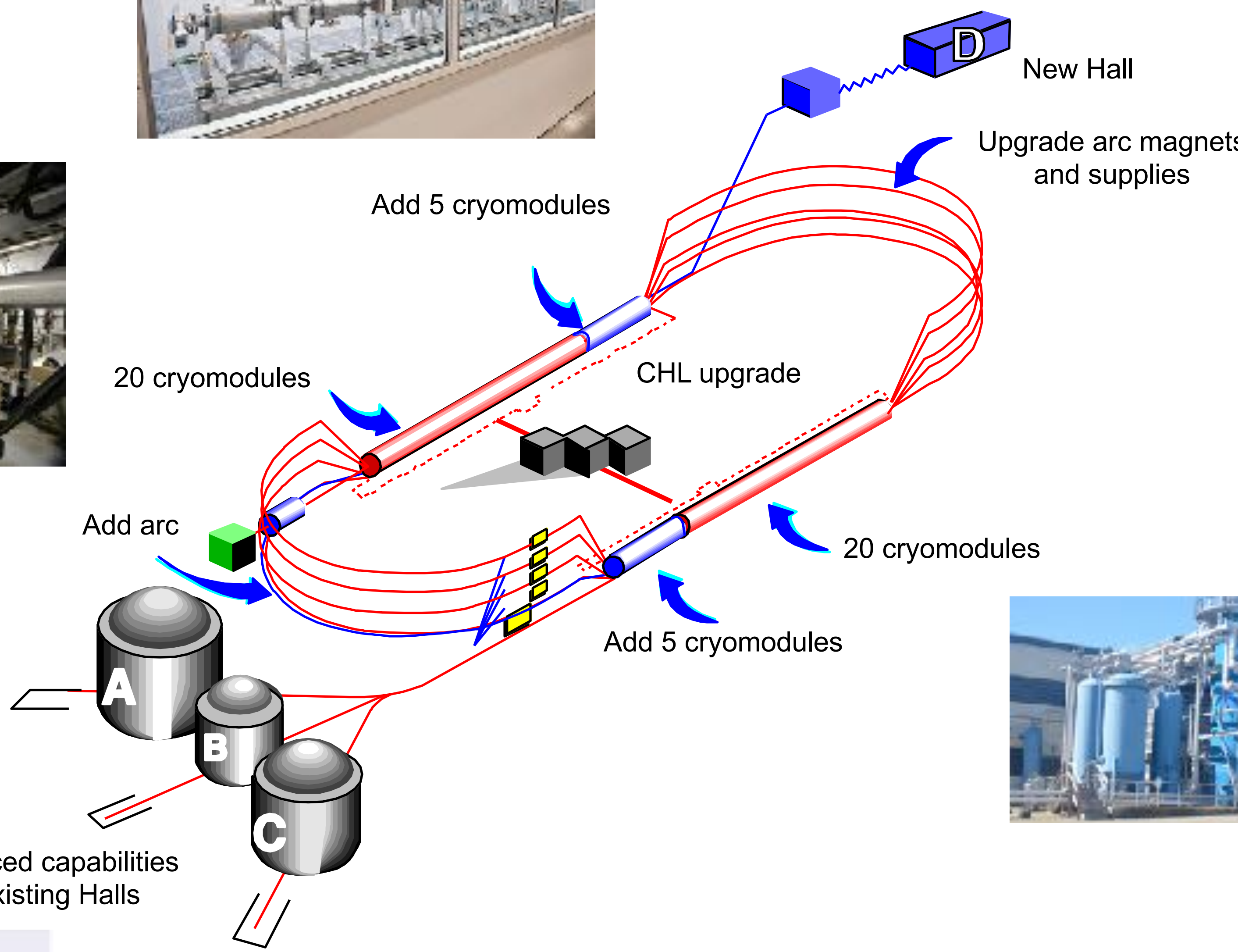
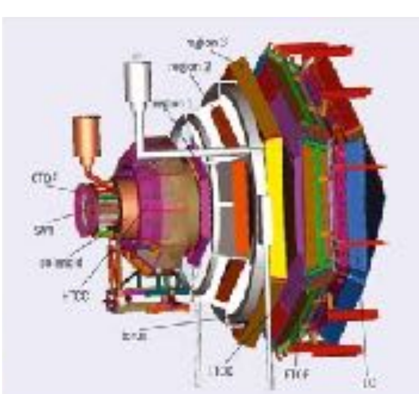
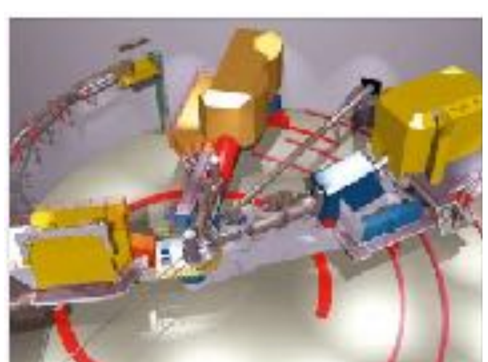
Jefferson Lab
Exploring the Nature of Matter

GHP 2021
April 13-15, 2021

The Jefferson Lab 12 GeV upgrade project was declared completed on September 27, 2017.







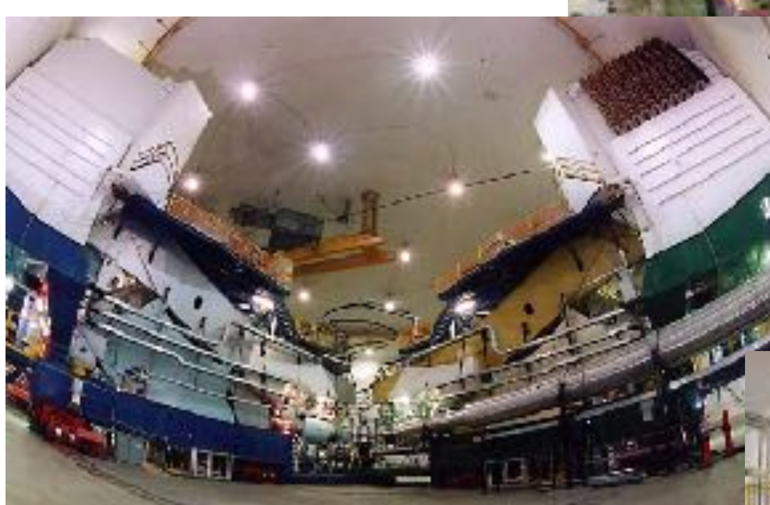
The last 6 GeV era experiments completed in May 2012.

To date, over 27 experiments (~1/3) have already been completed using the upgraded JLab.

Hall-D

First beam May 2014,
2 experiments completed

4-Hall operation since Jan. 2018



Hall-A

First beam April 2014,
9 experiments completed

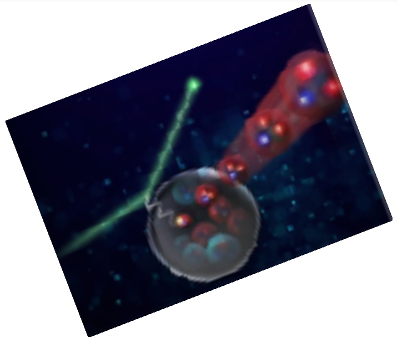
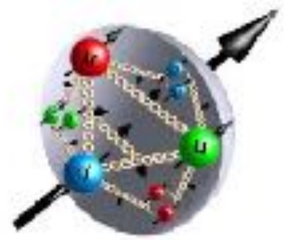
Hall-B

First beam Dec. 2014,
9 experiments completed

Hall-C

First beam Sept. 2017,
7 experiments completed

These early experiments address a wide range of basic nuclear physics questions.


1. **How do we reveal the quark structure of nuclei?**
2. **Why & how are the quark distributions inside nuclei modified?**
3. **What is the nature of short range forces in nuclei?**
4. What NP phenomena are critical for neutrino experiment?
5. How do we reveal the quark structure of nucleons and their excited states?
6. What is the neutron density in heavy nuclei?
7. How do quarks and gluons create nucleon structure and properties?
8. What does the quark/gluon orbital angular momentum contribute to the proton's spin?
9. What is the role of glue in the spectroscopy of light mesons and baryons?
10. Is there evidence for physics beyond the standard model of particle physics at low energies?

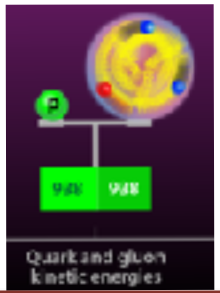
hadrons and cold nuclear matter

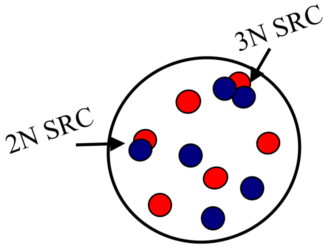
transv. & long. hadron structure

3D structure of hadrons

hadron spectra

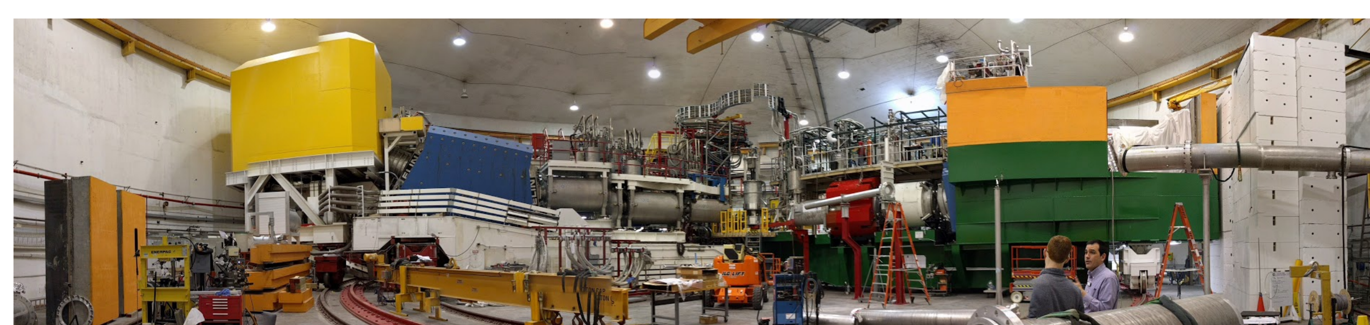
SM tests & fund. symmetries



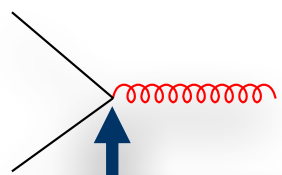
Outline

1. Introduction
2. Early results from
   - Experiments probing short distance structure in light nuclei.
   - Experiments studying hadron propagation in nuclei.
   - Experiments looking at short range correlations and the EMC effect
3. Summary



The role of quarks and gluons in nuclei is still one of the important unsolved and much debated problems.

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

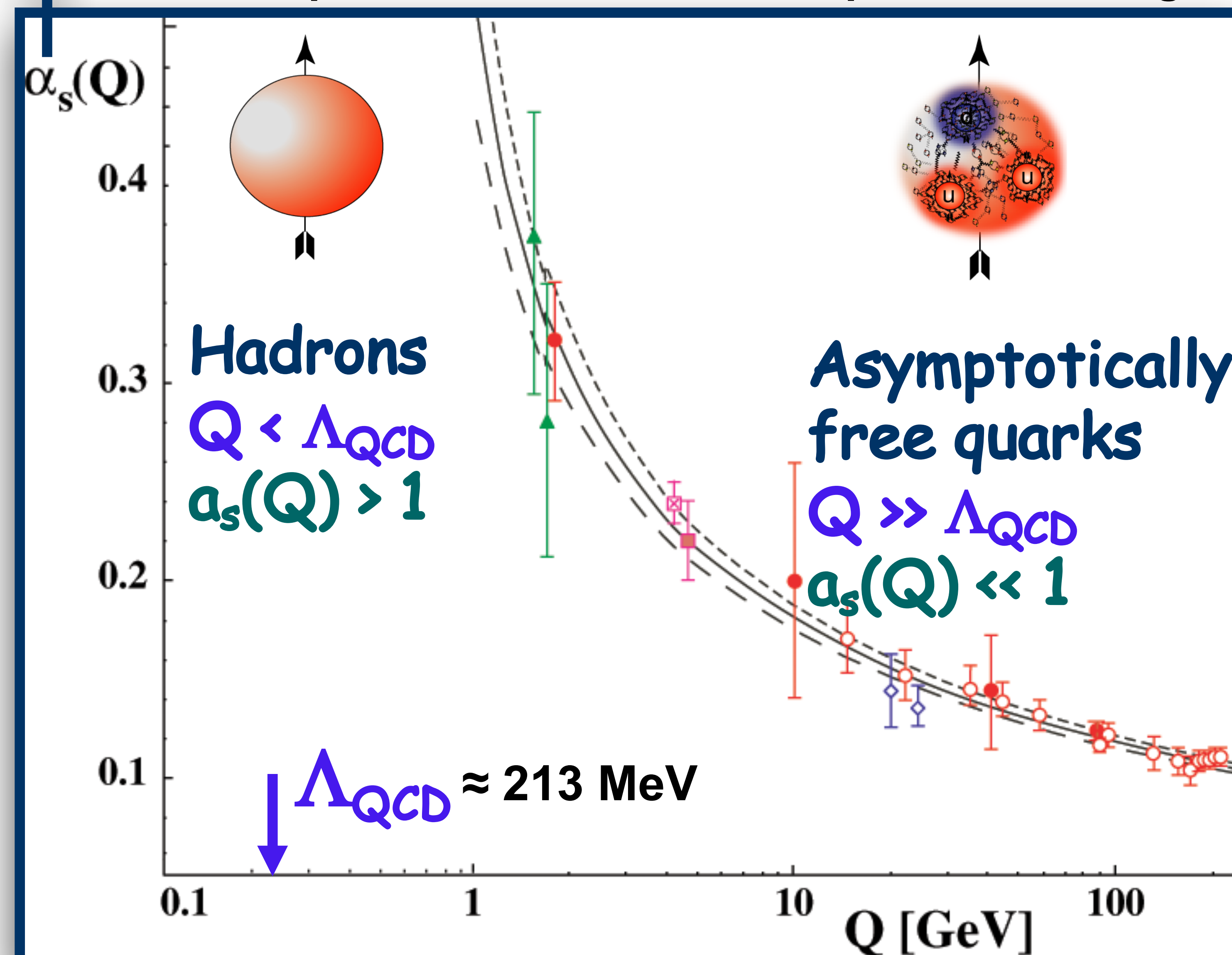


Λ_{QCD} ~ mass or (distance)$^{-1}$ scale where $\alpha_S = 1$; separates confinement and perturbative regions

Nuclei as stable systems made of quarks & gluons should be excellent testing ground for QCD.

quarks and gluons in nucleons + nuclei are non-perturbative (hidden)

Hadrons in nuclei are strongly interacting.



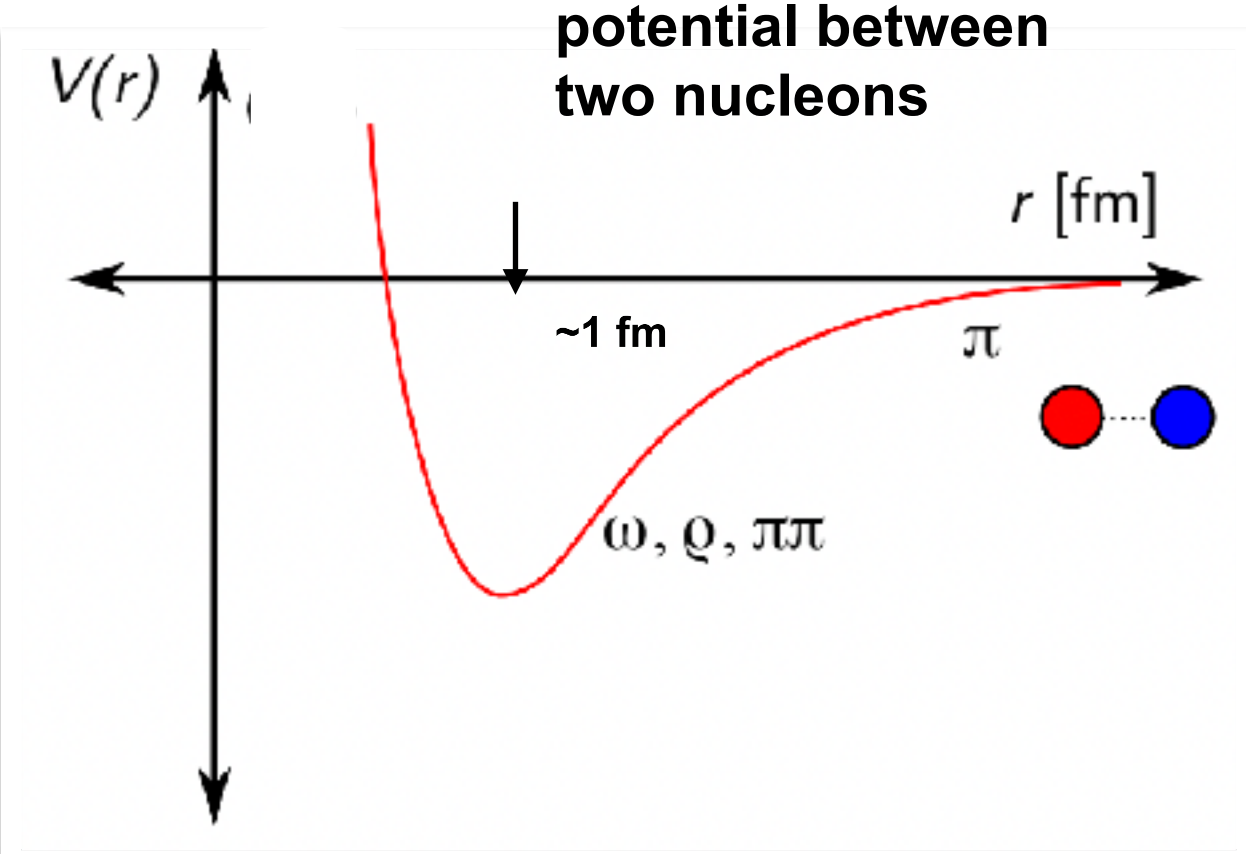
pQCD mechanisms dominate at high energies or short distances

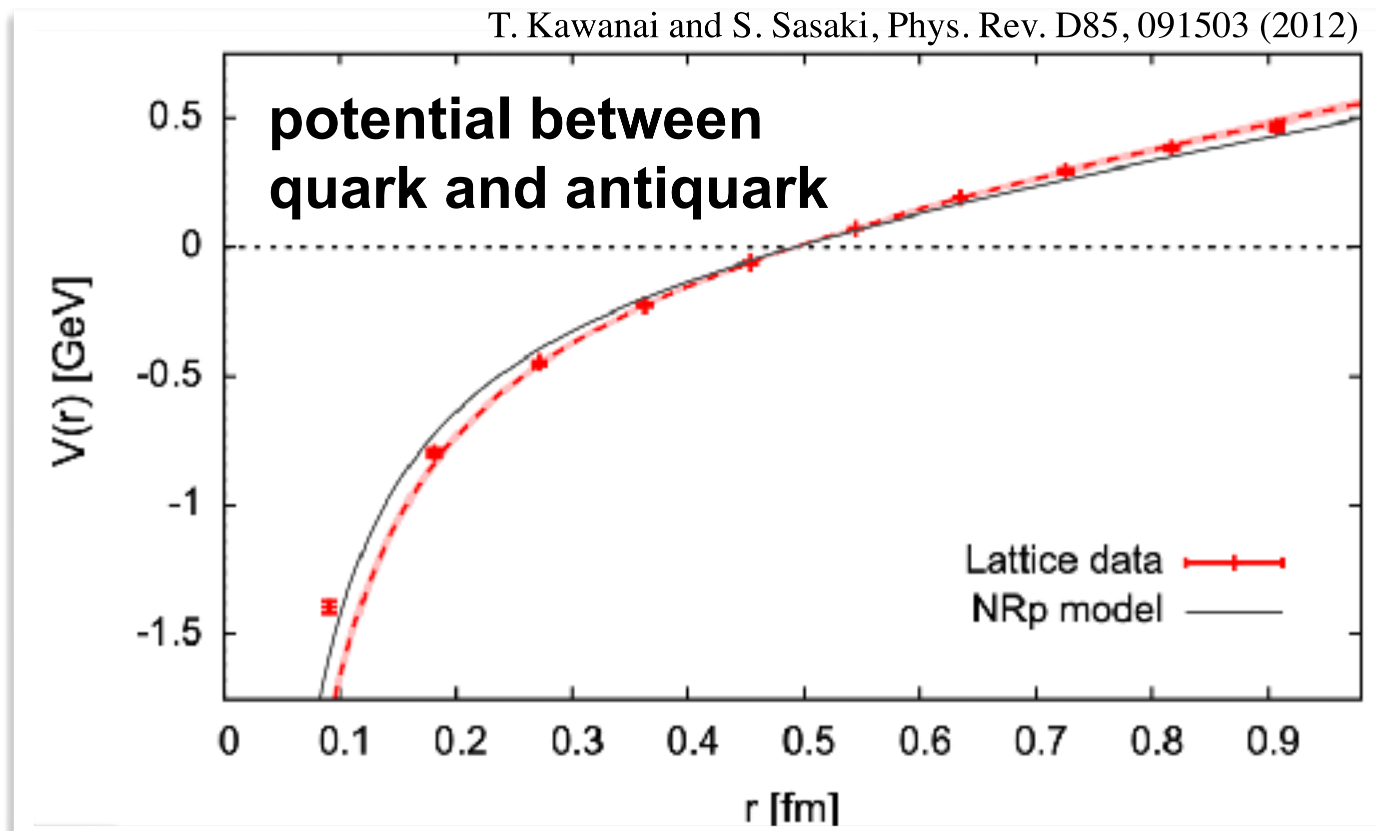
Unclear what energy is high enough for pQCD to be un-ambiguously applicable

Matter is colorless

Traditional nuclear physics: nucleons + mesons

QCD: quarks + gluons with linear confining potential for r > 0.5 fm



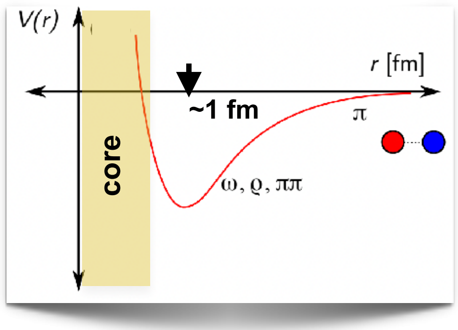


How to describe nuclei in terms of quarks & gluons of QCD?
What is the energy threshold for the transition?

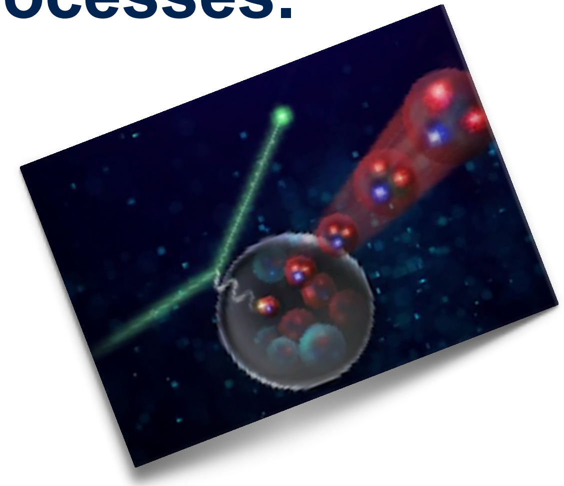
Tuesday 13 April 2021			
Unraveling the Nucleon's Collinear Structure (13:30-15:30)	14:50	[136] Residual Mean Field Model of Valence Quarks in the Nucleon	SARGSIAN, Misak

JLab 12 GeV program has a wide ranging program to address these very questions.

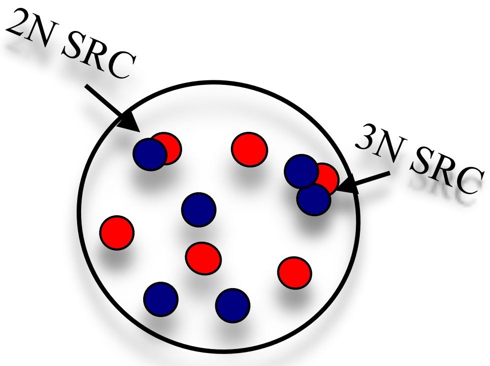
Examine nuclear structure at short distance scales to reveal QCD as the ultimate source of the strong interaction.



Understand the role of color in nuclei by studying the propagation of hadrons through nuclei with exclusive processes.

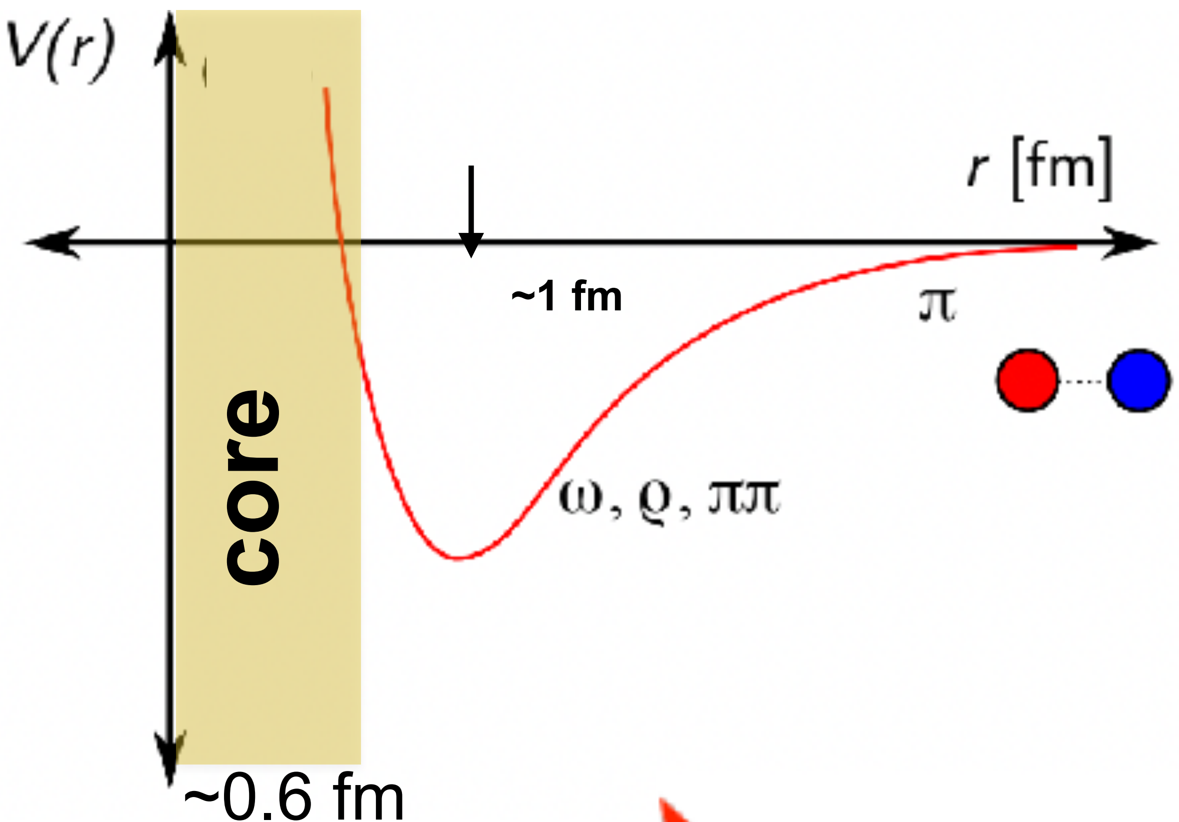


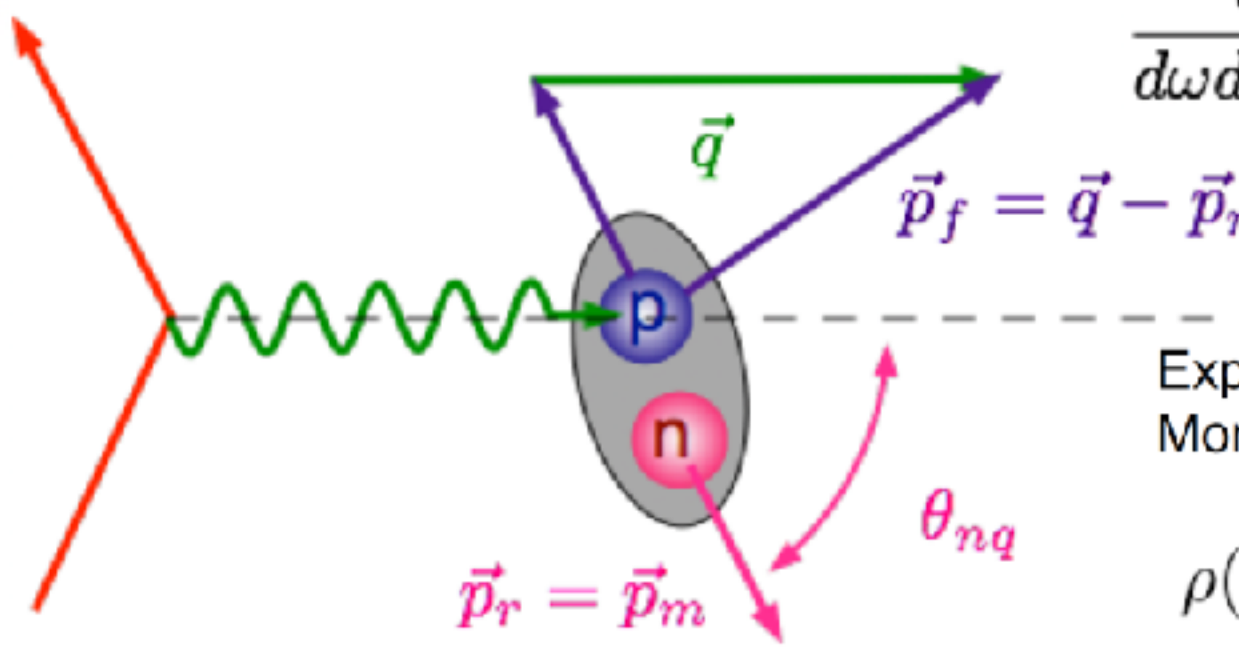
Probe the properties of superdense fluctuations of nuclear matter and their correlation to the modification of quark distributions in nuclei.



Study nuclear structure at short distance scales to reveal the ultimate source of the strong interaction.

D(e,e'p)n **provides details about the high-momentum or short distance structure**





$$\frac{d^5\sigma}{d\omega d\Omega_e d\Omega_p} = k\sigma_{ep}\rho(p_r)$$

Experimental Momentum distributions:

$$\rho(p_r)_{exp} = \sigma_{red} = \frac{\sigma_{exp}}{k\sigma_{ep}}$$

One of the commissioning experiments in Hall-C examined the short distance structure (core).

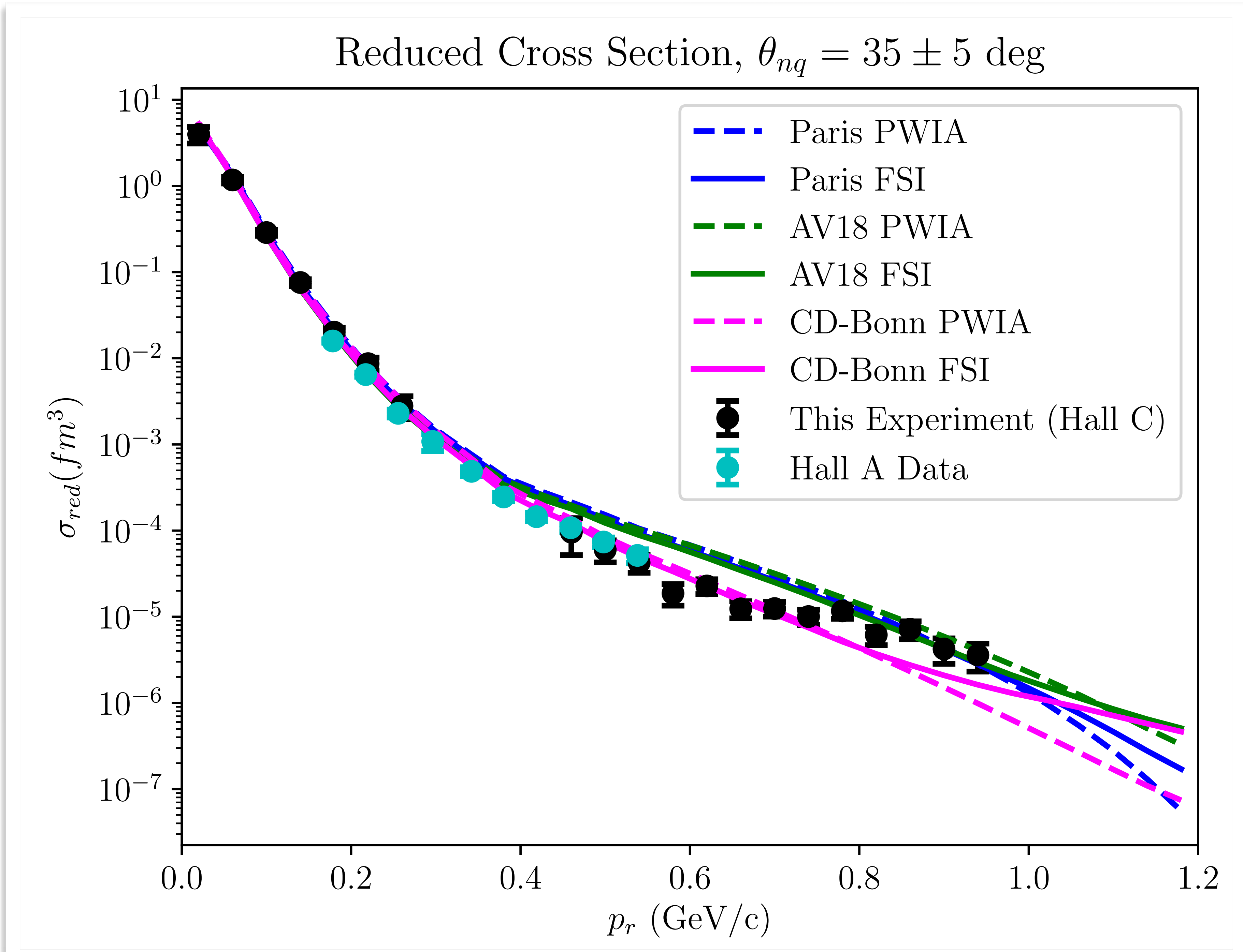
D(e,e'p)n **provides details about the high-momentum or short distance structure**

The Hall C experiment extends the reach to the highest $|P_m|$ to date.
$|P_m|$ ~ 1 GeV/c

Theory input was crucial for this experiment to help select the kinematics with small FSI

Results show deviations from current models above |Pm| > 700 MeV/c

Future: new improved calculations and explore inelastic channels at JLab & EIC



C. Yero et al., Phys. Rev. Lett., 125, 262501 (2020).

Plot courtesy Carlos Yero

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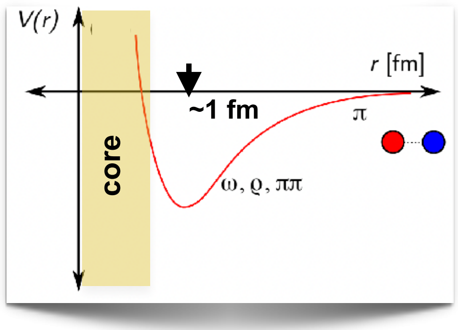
Examine nuclear structure at short distance scales to reveal QCD as the ultimate source of the strong interaction.

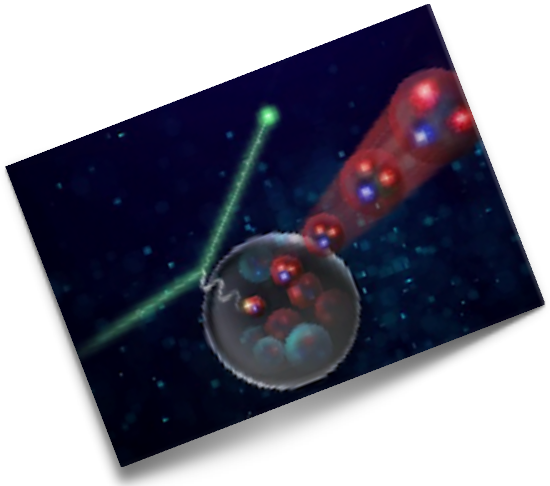


Understand the role of color in nuclei by studying the propagation of hadrons through nuclei with exclusive processes.

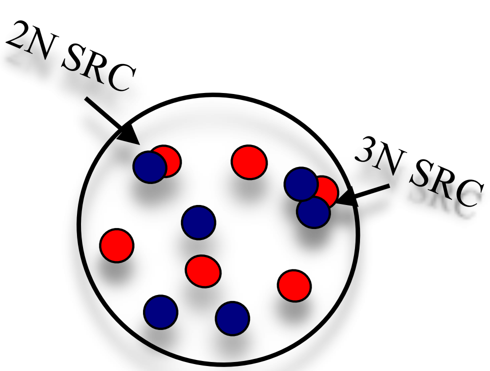
Wednesday 14 April 2021

Hadrons in Nuclei (13:30-15:30)

14:30	[73] Onset of Color Transparency in Protons at JLab	BHETUWAL, Deepak



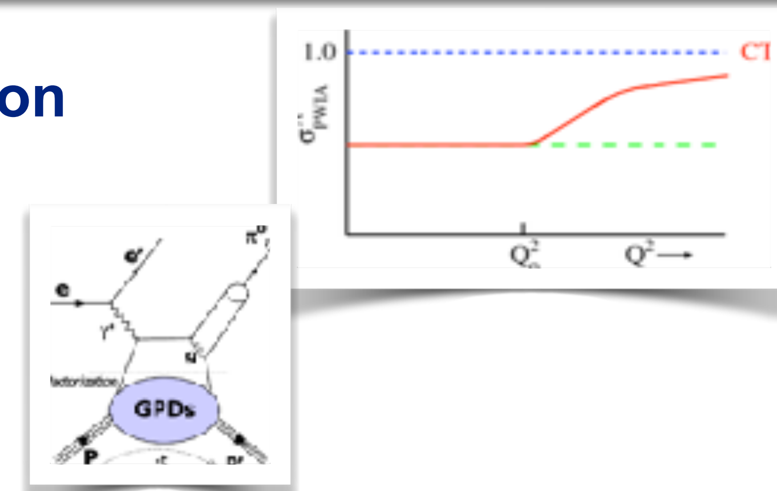
Probe the properties of superdense fluctuations of nuclear matter and their correlation to the modification of quark distributions in nuclei.



Study the propagation of hadrons through nuclei with exclusive processes.

Look for the onset of QCD predictions associated with hadron propagation in nuclei.

Establish connections with the alternative framework which advocates the dominance of the handbag mechanism

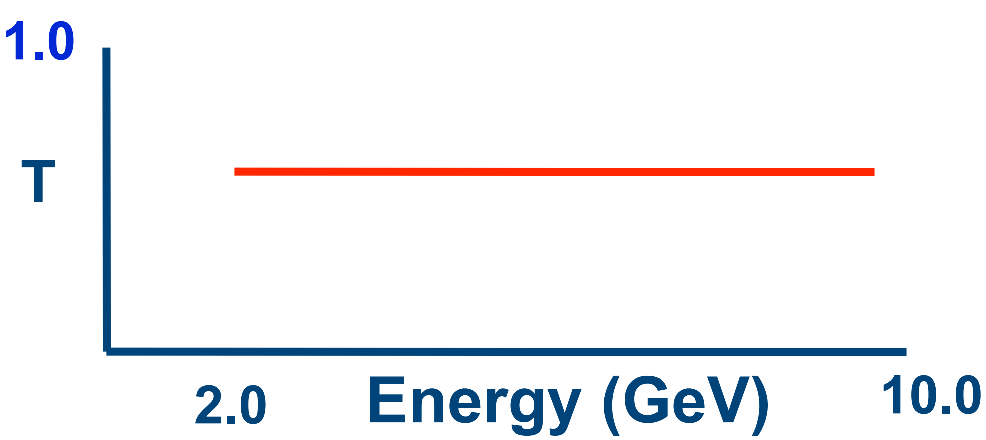


At high energies hadron propagation is dominated by **reduction of flux**, which is quantified by **Nuclear Transparency**.

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

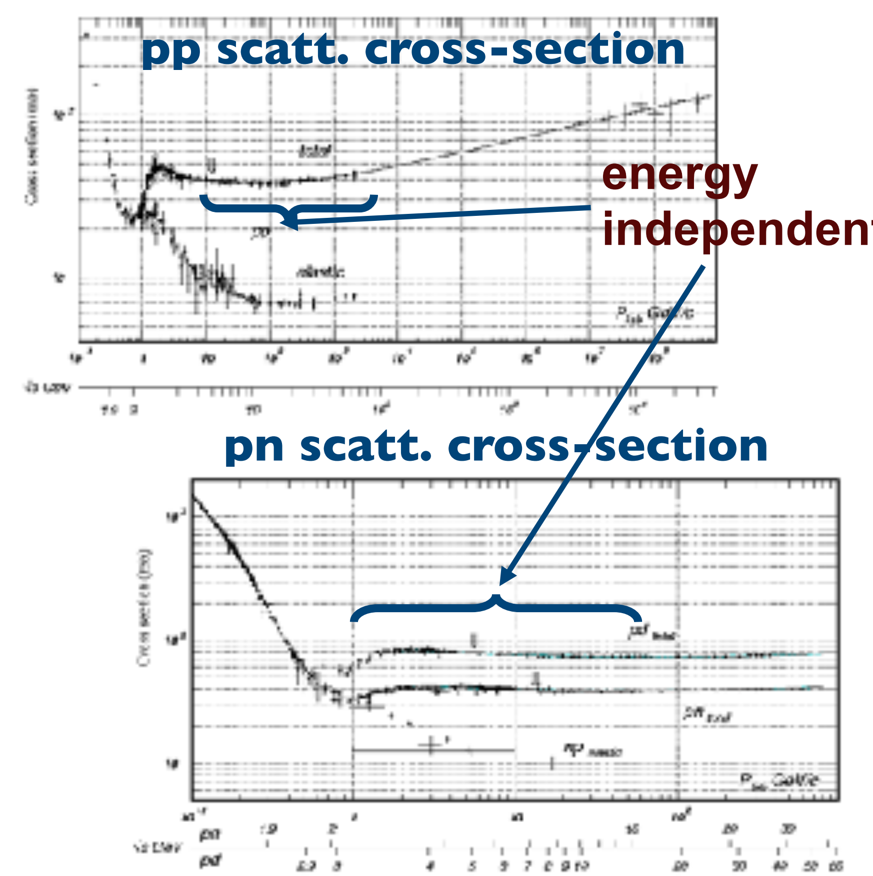
σ_N = nuclear cross section parameterized as $\sigma_0 A^{\alpha}$
σ_0 = free (nucleon) cross-section

Traditional NP calculations



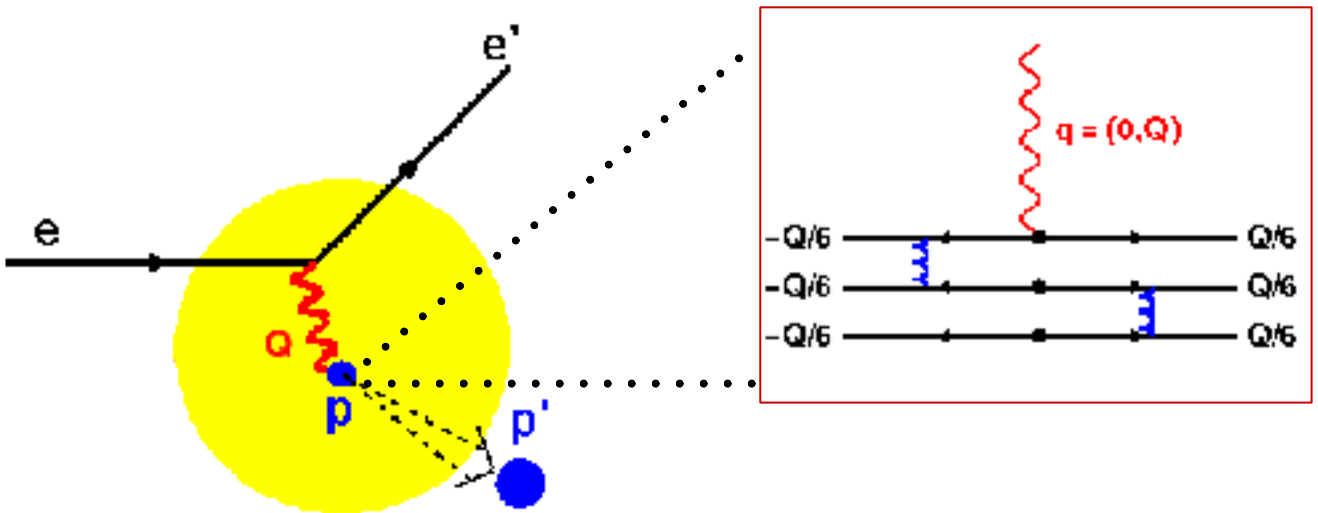
Ingredients

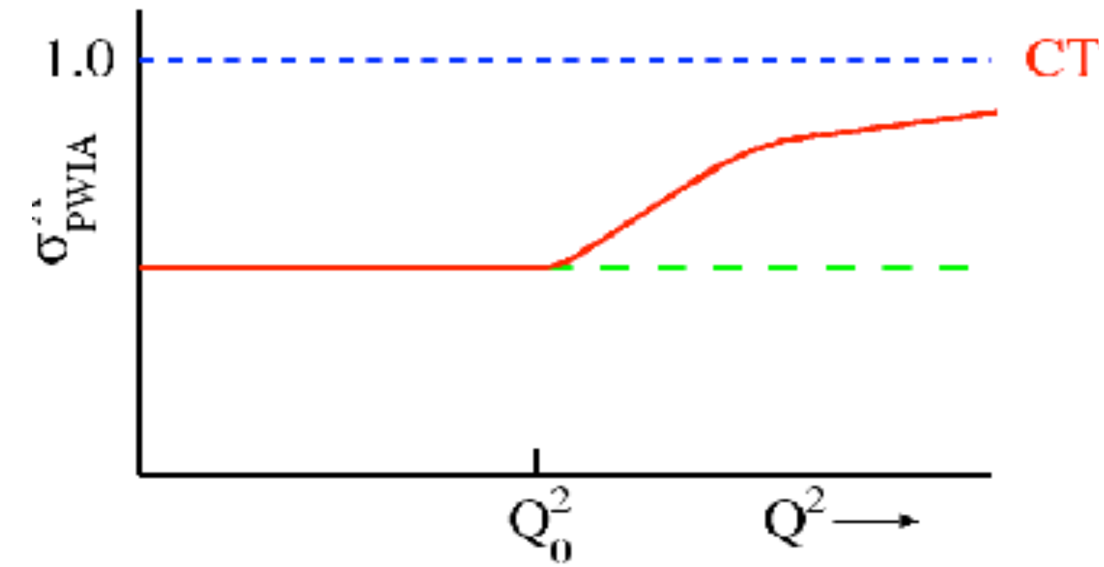
- σ_{hN} h-N cross-section
- Glauber multiple scattering approximation
- Correlations & FSI effects.



For light nuclei very precise calculations of are possible.

QCD predicts that h-N interaction for hadrons produced in exclusive processes at high Q should vanish.





At high momentum transfers, scattering takes place via selection of amplitudes characterized by small transverse size (PLC) - "squeezing"

The compact size is maintained while traversing the nuclear medium - "freezing".

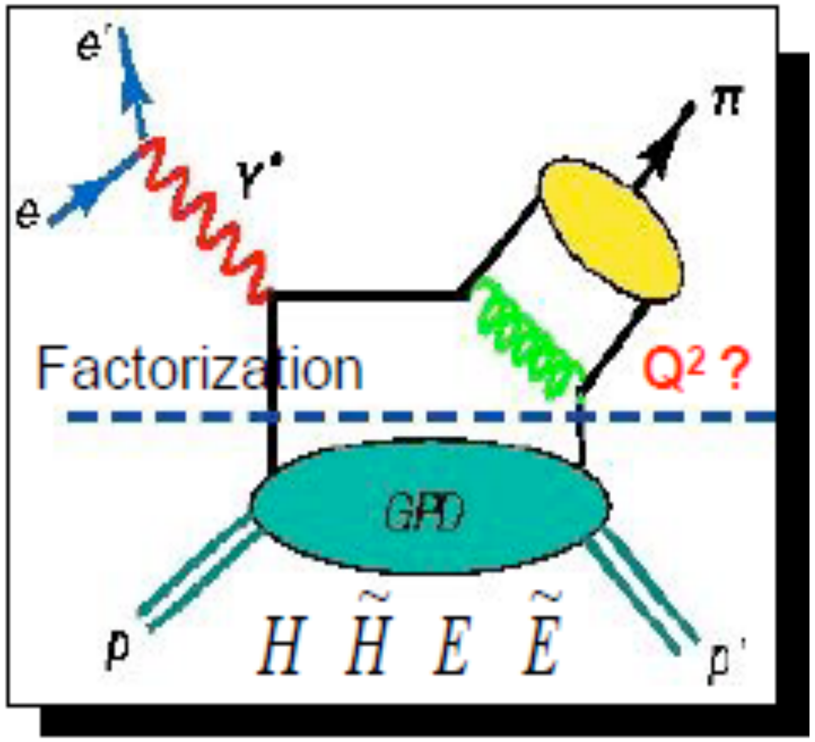
The PLC is 'color screened' - it passes undisturbed through the nuclear medium.

$$\sigma_{PLC} \approx \sigma_{hN} \frac{b^2}{R_h^2}$$

CT is unexpected in a strongly interacting hadronic picture, but it is natural in a quark-gluon framework.

Onset of CT would be a signature of the onset of QCD degrees of freedom in nuclei

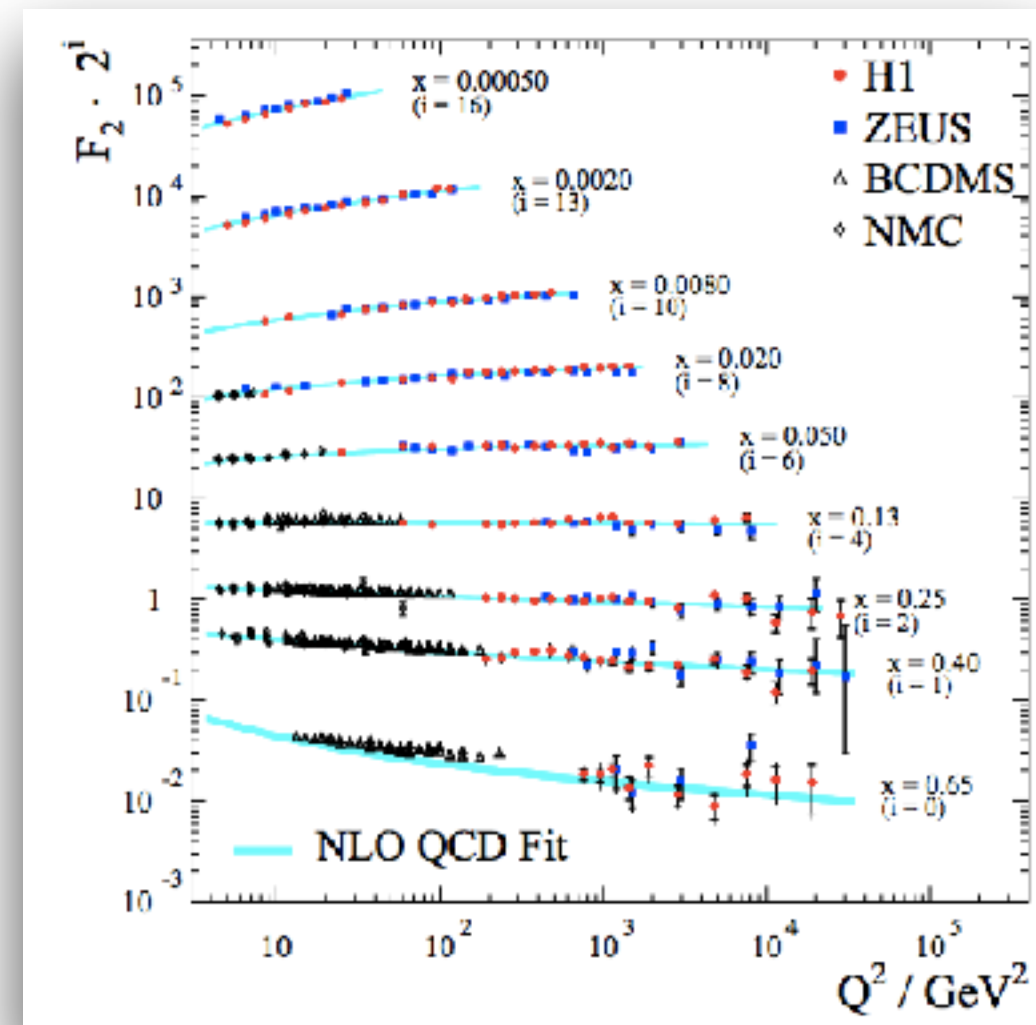
CT is also connected to the framework of GPDs and essential to account for Bjorken scaling in DIS at small x.



The onset of CT is a necessary (but not sufficient) conditions for factorization.

-Strikman, Frankfurt, Miller and Sargsian

- small size configurations (SSC/PLC) needed for factorization
- It is still uncertain what Q^2 value reaches the factorization regime



Reduced interaction at high energies due to "squeezing and freezing"(i.e. due to CT) is assumed in calculations of structure functions.

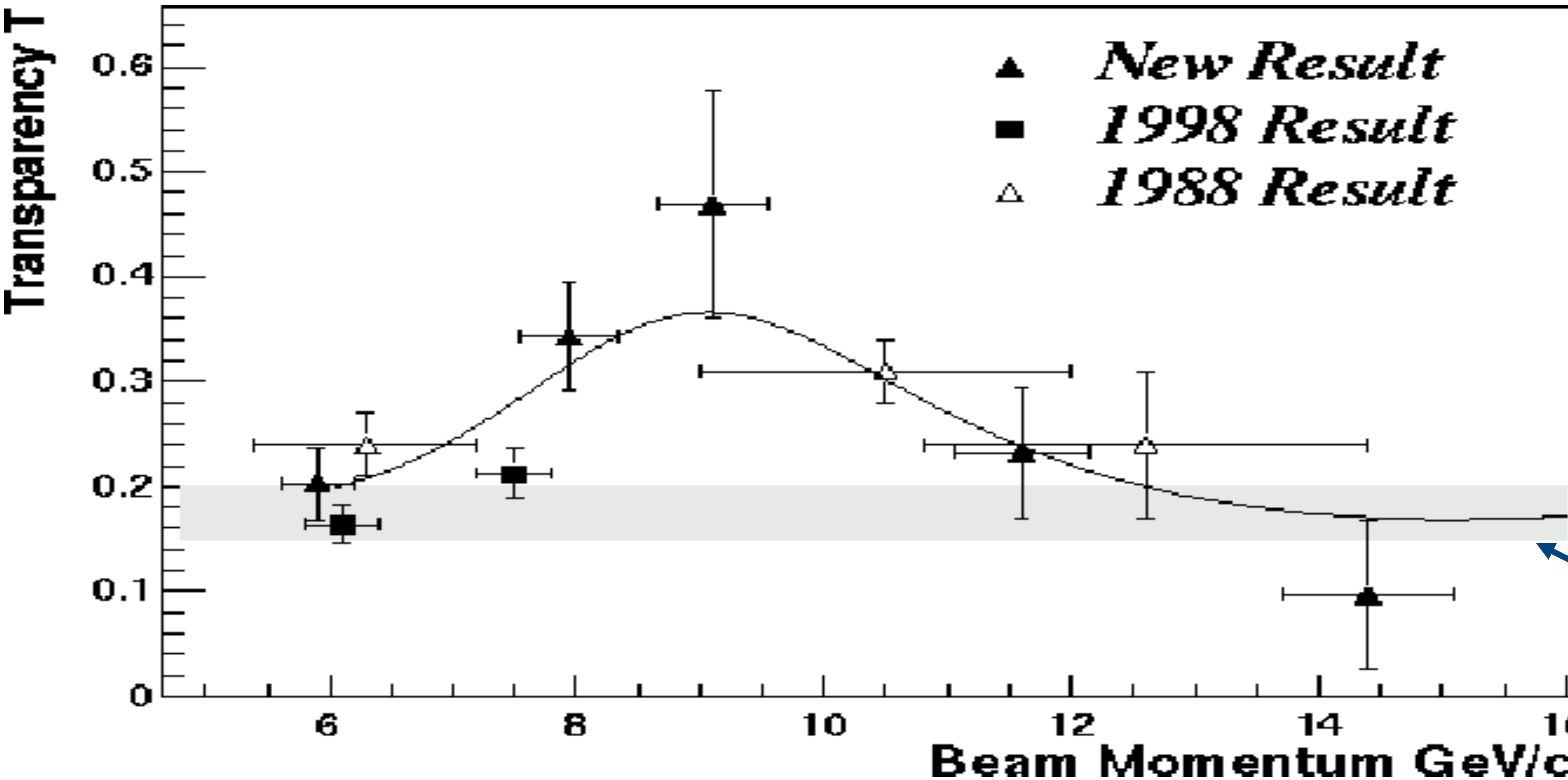
L. Frankfurt and M. Strikman, Phys Rep. 160, 235 (1988).

CT is implied by the successful description of DIS.

Although CT is well established at high energies the evidence at intermediate energies is lacking for baryons.

First direct search for the onset of CT

Transparency in A(p,2p) Reaction at BNL



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

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

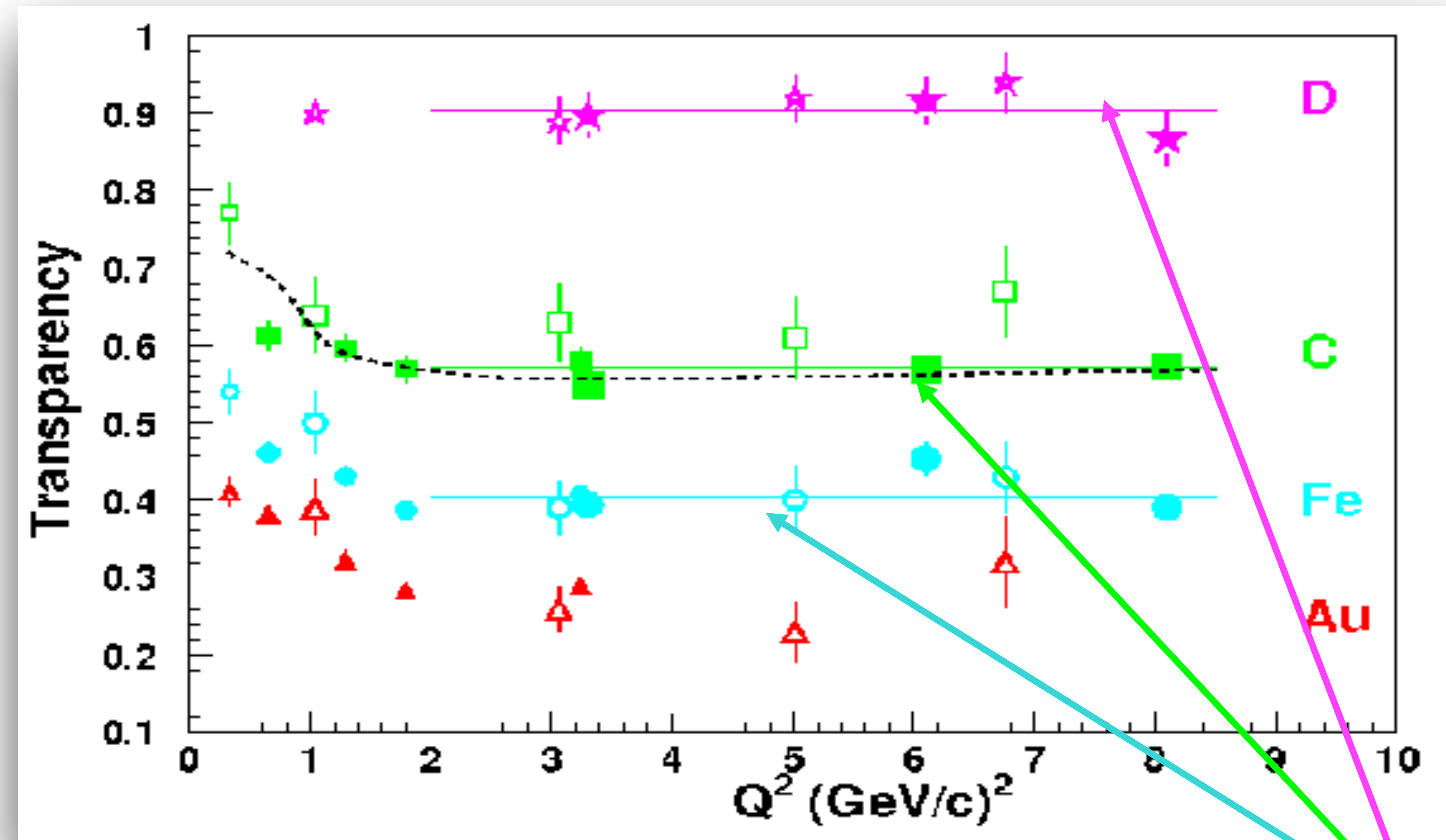
Shaded band Glauber calculation

Results inconsistent with CT only. But can be explained by including additional mechanisms such as nuclear filtering or charm resonance states.

There has a been a long ongoing effort to measure CT in protons using the A(e,e'p) reaction.

A(e,e'p) results

Q² dependence consistent with standard nuclear physics calculations



Solid Pts – JLab

Open Pts -- other

Constant value fit for Q^2 > 2 (GeV/c)^2 has $\chi^2 / \mathrm{df} \sim 1$

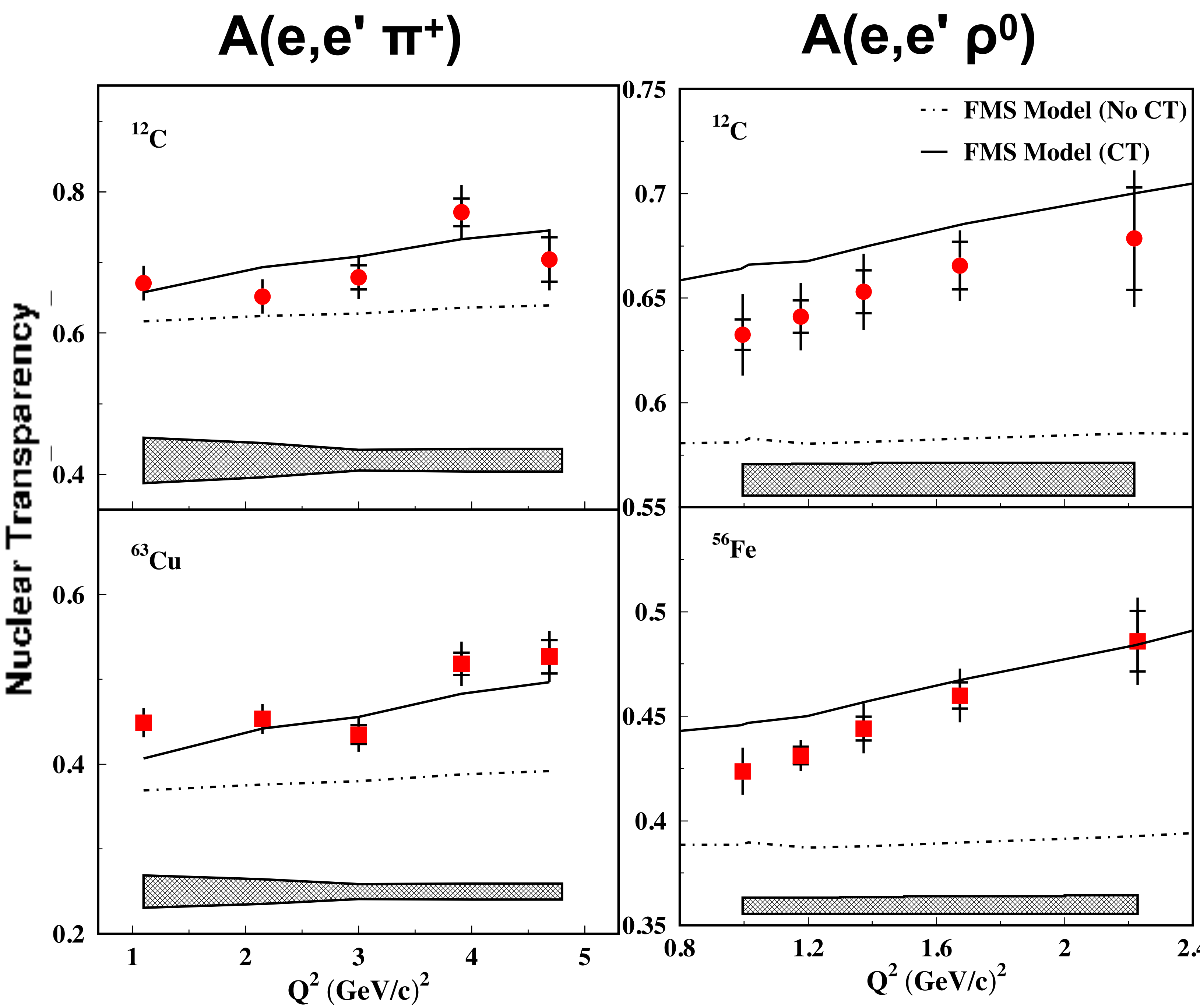
N. C. R. Makins et al. PRL 72, 1986 (1994)

G. Garino et al. PRC 45, 780 (1992)

D. Abbott et al. PRL 80, 5072 (1998)

K. Garrow et al. PRC 66, 044613 (2002)

But, JLab experiments from the 6-GeV era have conclusively observed the onset of CT in mesons.



·**Hall-C Experiment E01-107 pion electroproduction from nuclei found an enhancement in transparency with increasing Q^2 & A, consistent with the prediction of CT.**
(X. Qian et al., PRC81:055209 (2010), B. Clasie et al, PRL99:242502 (2007))

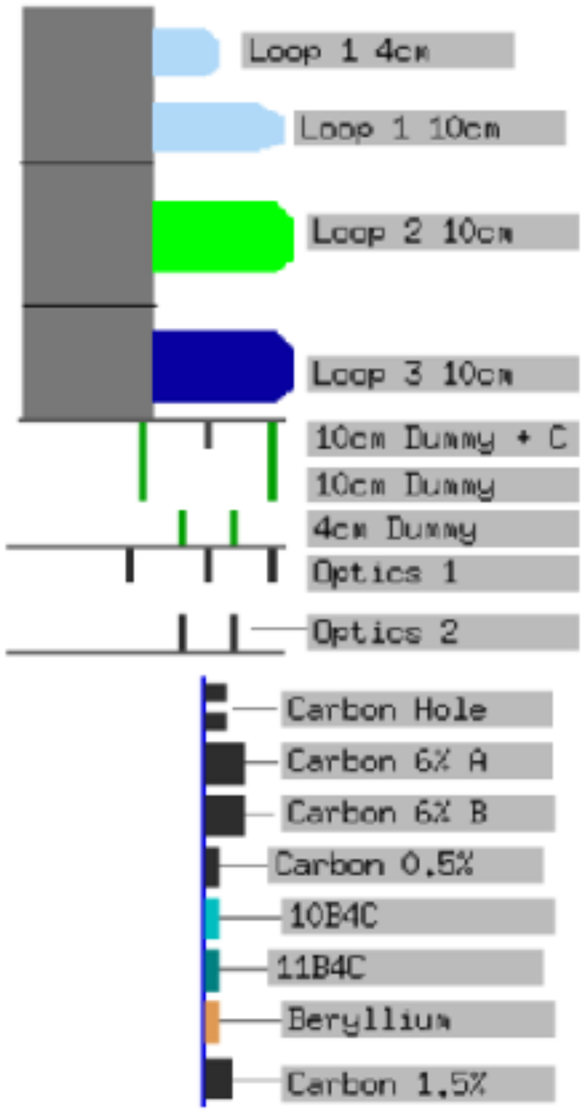
·**CLAS Experiment E02-110 rho electroproduction from nuclei found a similar enhancement, consistent with the same predictions**
(L. El-Fassi, et al., PLB 712, 326 (2012))

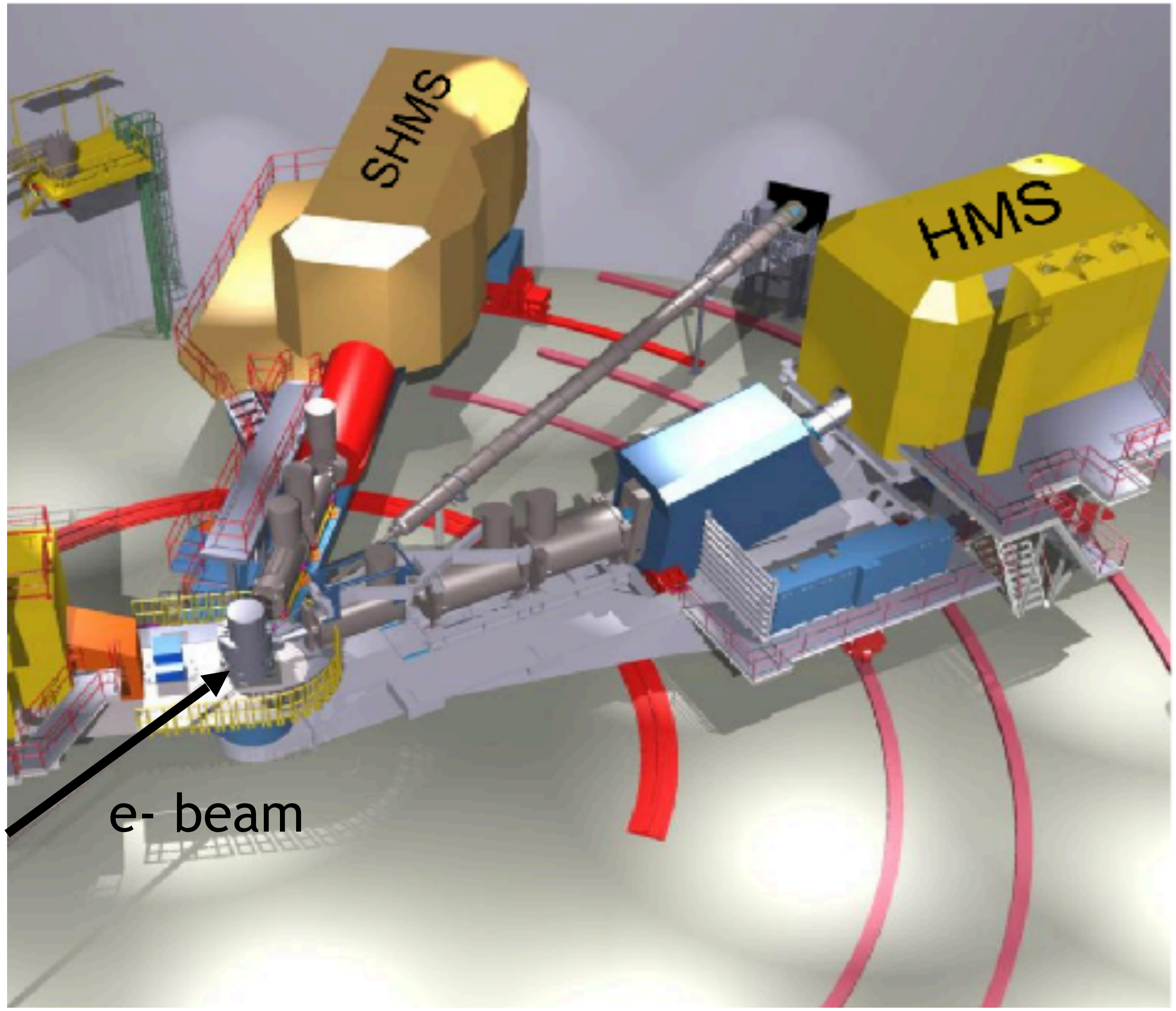
.

FMS: Frankfurt, Miller and Strikman, Phys. Rev., C78: 015208, 2008

The first experiment to run in JLab Hall C in the 12 GeV era, was a search for the onset of CT in protons.

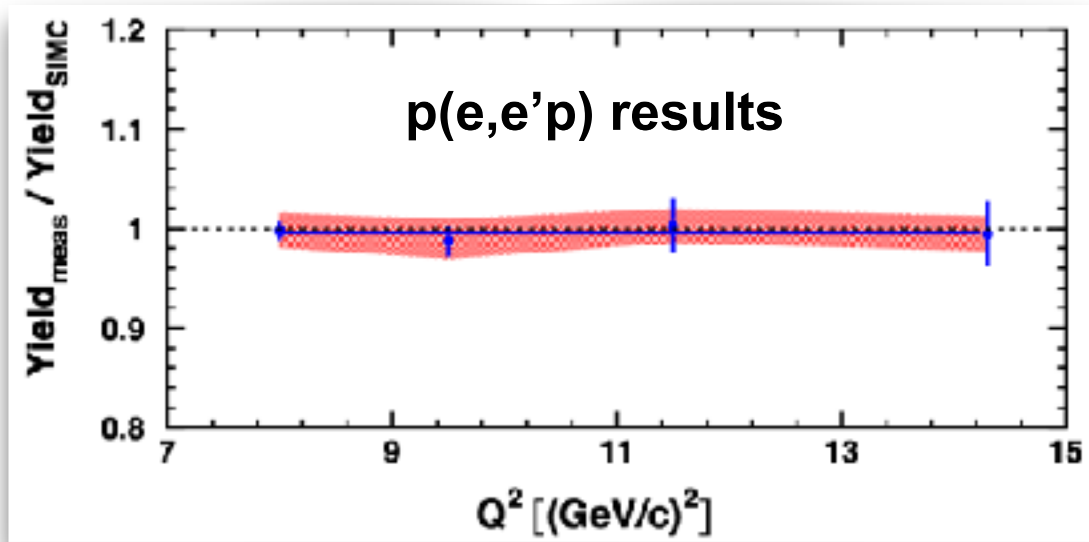
- Coincidence trigger: SHMS measures protons, HMS measures electrons
- Targets: 10 cm LH_2 (H(e,e'p) normalization),
- 6% ^{12}C (production),
- Al dummy (background)





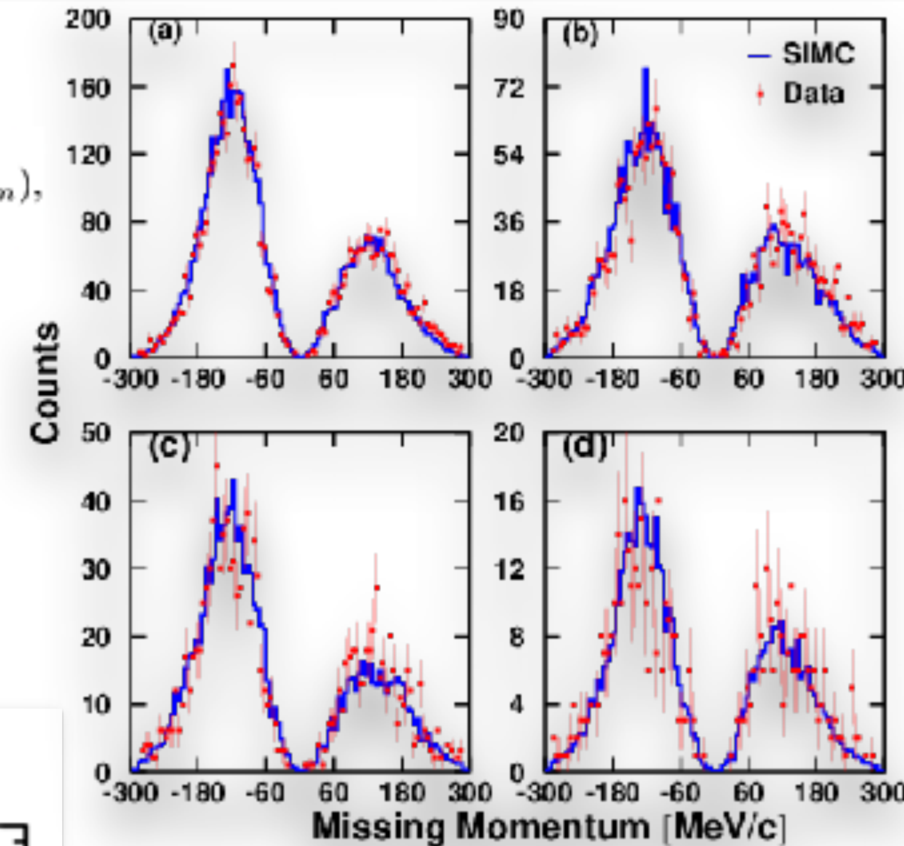
The results from the first Hall C experiment rule out the onset of CT in (e,e’p) up to Q^2 = 14.3 GeV^2

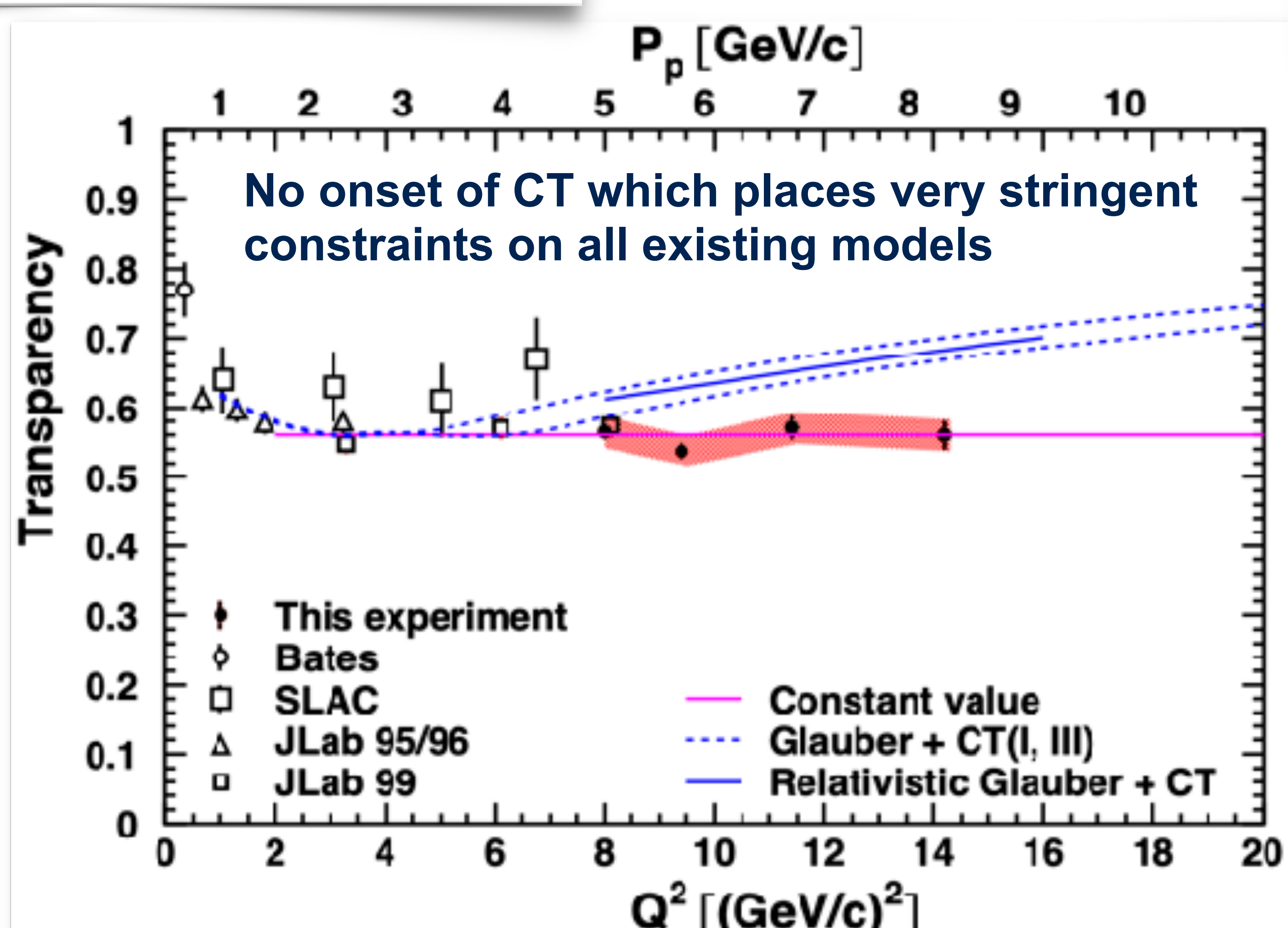
agrees with parametrization of known
ep elastic data & simulation of experiment



$$\frac{d^5\sigma}{dE_{e'}d\Omega_{e'}dE_{p'}d\Omega_{p'}} = E_{p'}|p_{p'}|\sigma_{ep}S(E_m, \vec{p}_m),$$

spectral functions agree with PWIA reaction mechanism.

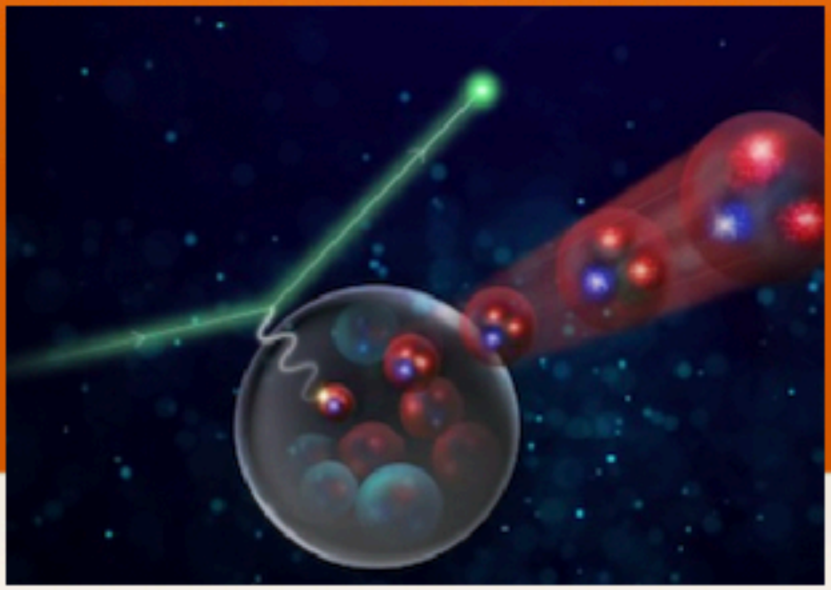




BNL observations unlikely to be because of CT

D. Bhetuwal et al.,
Phys. Rev. Lett., 126, 082301 (2021)

https://indico.jlab.org/event/437/



The Future of Color Transparency and Hadronization Studies at Jefferson Lab and Beyond

7-8 June 2021
Online
US/Eastern timezone

- Code of Conduct
- Overview
- Timetable
- Registration
- Participant List

Contact

d.dutta@msstate.edu
662 617 5366

This workshop will explore the options for new theoretical and experimental efforts towards resolving the puzzling lack of color transparency in protons as reported by a new A(e,e'p) experiment at the recently upgraded Jefferson Lab. The objectives of the workshop are to stimulate new theoretical and experimental work towards understanding the origins of the apparent reaction dependence of this fundamental prediction of QCD, and/or the differences between three-quark and quark-antiquark states.

The connection of color transparency/coherence phenomenon with final state interactions in deep inelastic scattering, hadronization in the nuclear medium, heavy-ion collisions, and quantum entanglement will be examined. The possibility for new experimental searches including at future facilities such as the EIC will also be discussed. The results of the workshop will be summarized in a report that can serve as a roadmap for the future developments and a guide to areas for possible collaboration.

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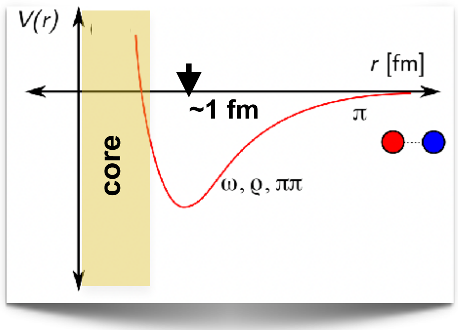

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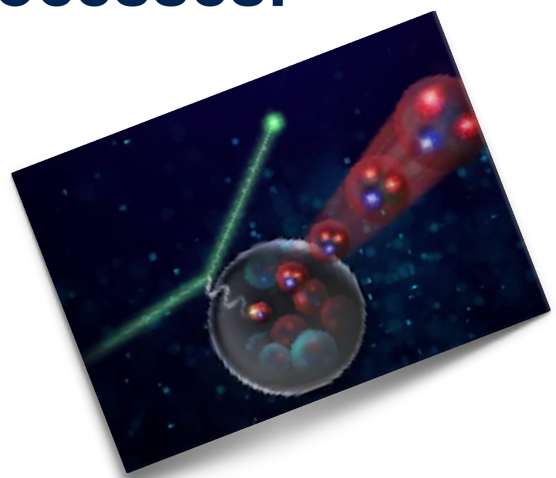


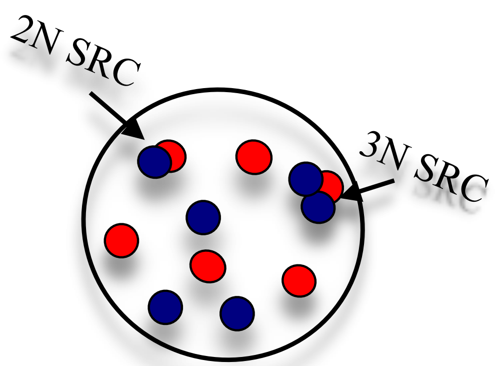
Probe the properties of superdense fluctuations of nuclear matter and their correlation to the modification of quark distributions in nuclei.

Wednesday 14 April 2021 Hadrons in Nuclei (13:30-15:30)

14:50	[160] Elastic Electron Scattering from 3He and 3H Mirror Nuclei	KURBANY, Leiqaa

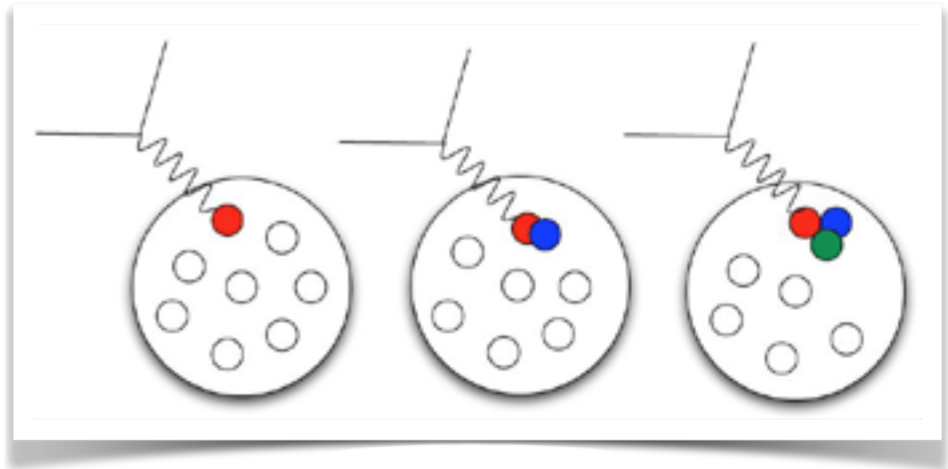
Thursday 15 April 2021 Nuclear PDFs (13:30-15:30)

14:50	[172] Determing the isospin Dependence of short-range correlations in Tritium and Helium-3 at Jefferson Lab	LI, Shujie



Examine what happens during the brief intervals when two or more nucleons overlap in space (Short Range Correlations).

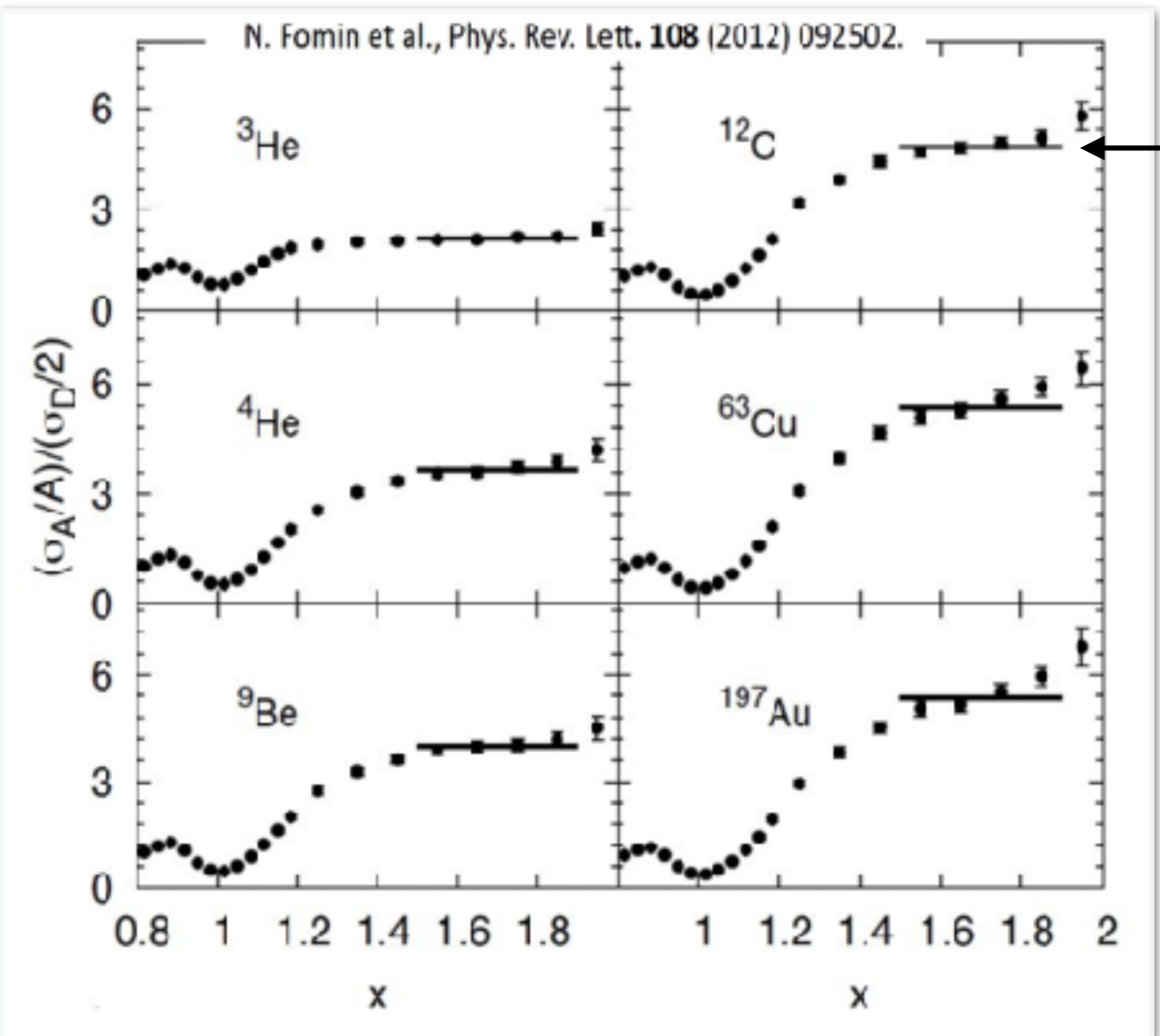
In inclusive quasi-elastic (QE) scattering high momentum nucleons dominate at $x > 1$



$$\sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3$$

probability of finding 2N SRC in nucleus A

If SRC is dominant the per nucleon ratio of $x > 1$ yields should be constant $\frac{\sigma_A}{\sigma_{^2H}} \approx \frac{a_2(A)}{a_2(^2H)}$



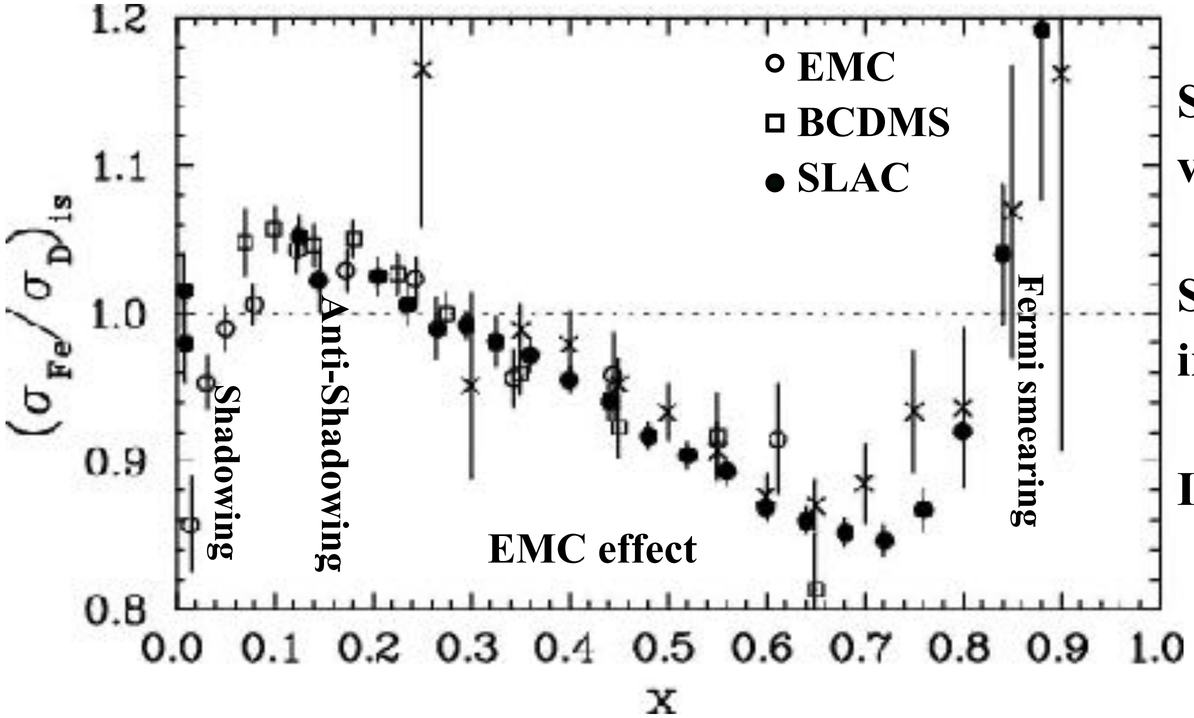
number of deuteron like high momentum pairs in the nucleus (w/o corrections for center-of-mass motion).

do we need quark exchanges between nucleons and the kneading of the nucleon constituents into six- or nine-quark bags?

DIS at $x > 1$ ⇒ access to super-fast quarks

(quarks that carry light-cone momentum fraction > that of a nucleon at rest)?

40 years ago the discovery of the EMC effect brought quarks into nuclear physics.

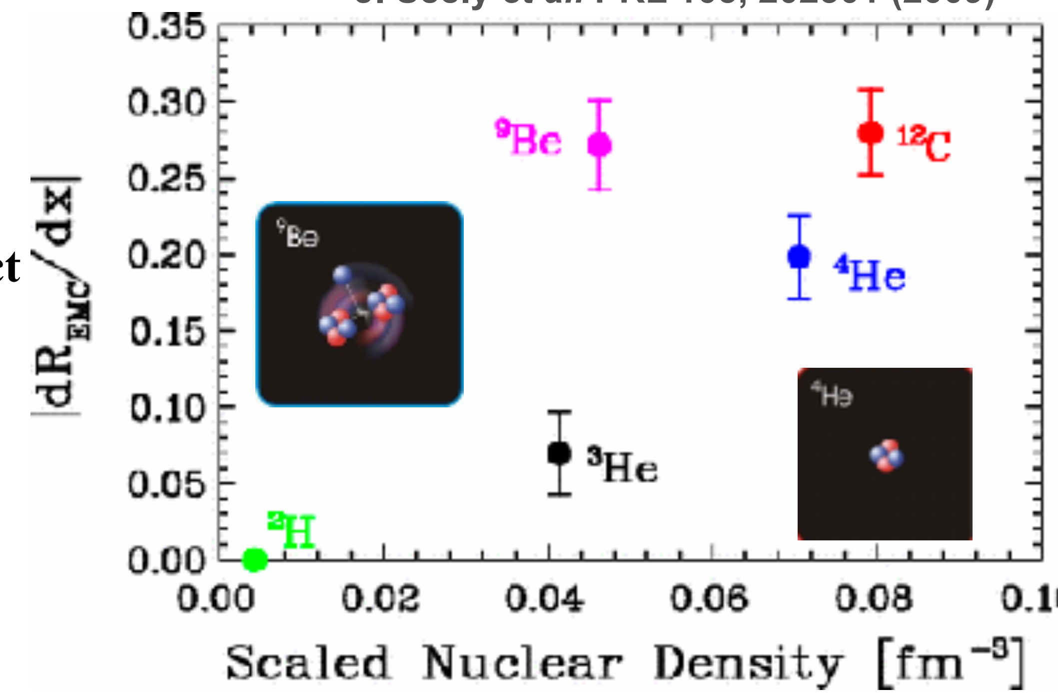


Size of EMC effect varies with A

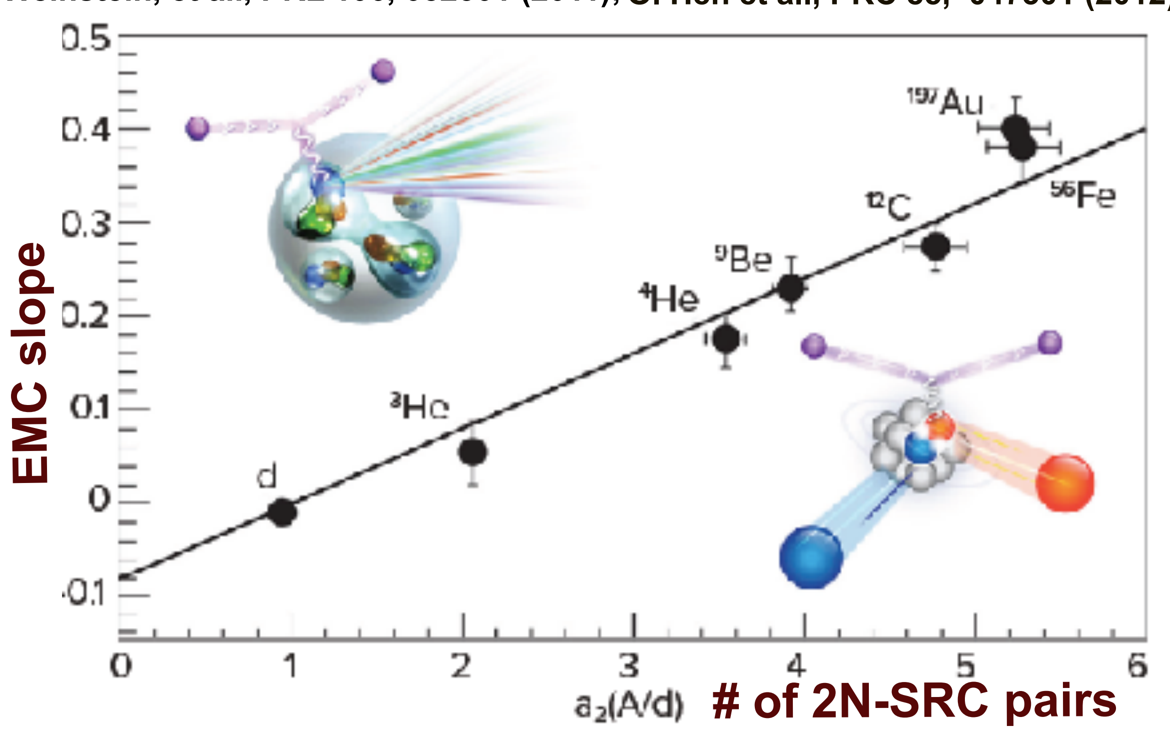
Shape of EMC effect independent of A

Independent of Q^2

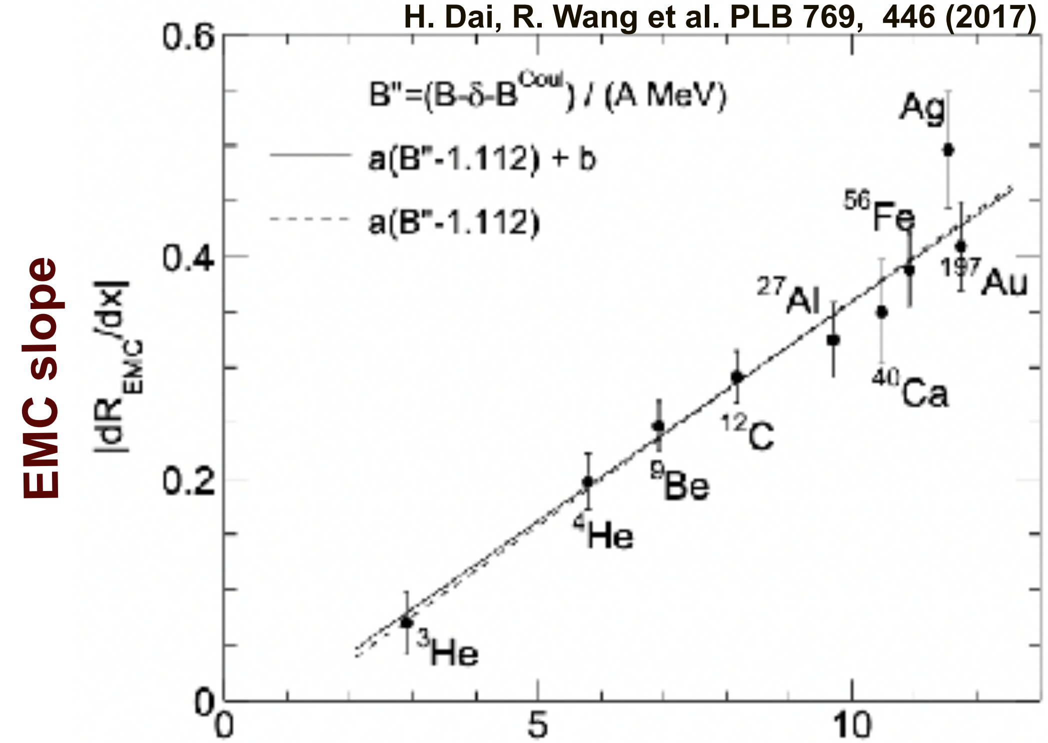
J. Seely *et al.* PRL 103, 202301 (2009)



L. Weinstein, et al., PRL 106, 052301 (2011); O. Hen et al., PRC 85, 047301 (2012)

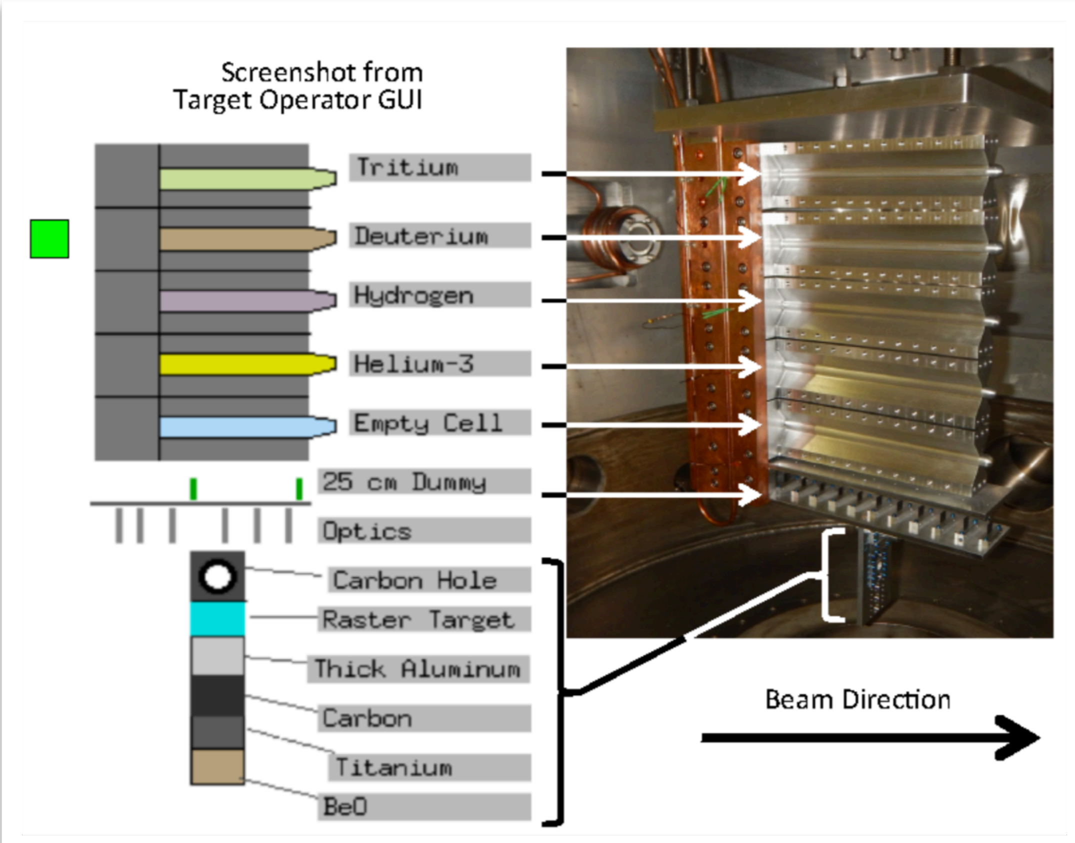


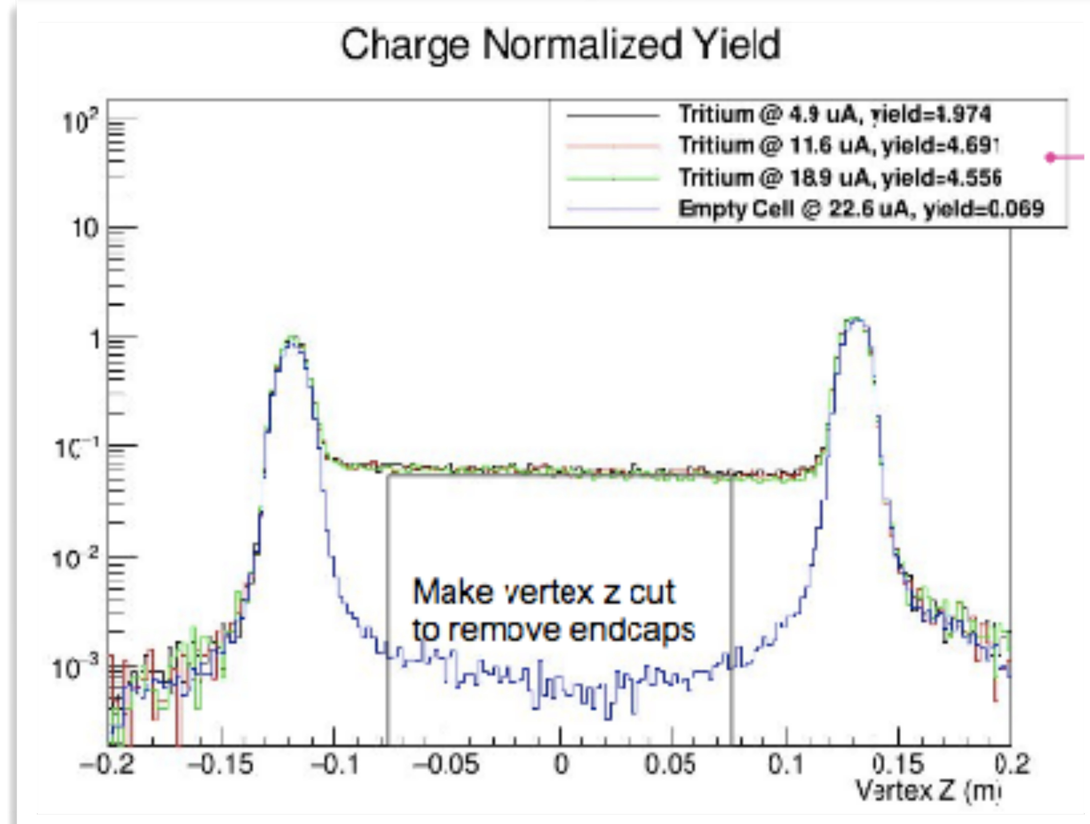
H. Dai, R. Wang et al. PLB 769, 446 (2017)



A large campaign underway at JLab to study SRC and EMC effect

A unique Tritium program in Hall A included studies of superdense fluctuations in nuclei.

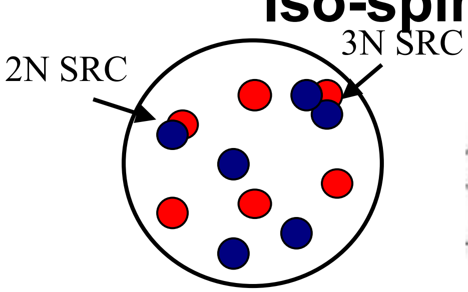




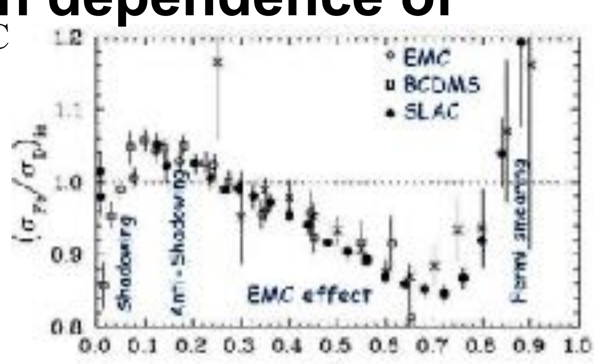
Low activity (~ 1 kCi); High-pressure sealed cell @ 40K; Beam current < 22.5μA

<u>Used for a broad physics program with mirror nuclei (^{3}H, ^{3}He)</u>

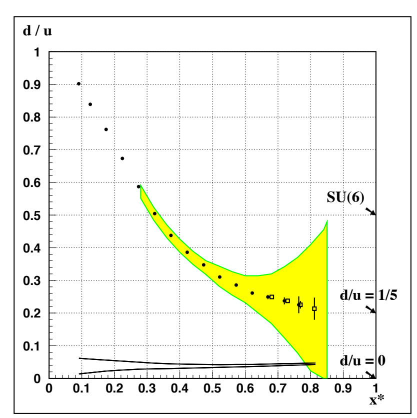
Iso-spin dependence of



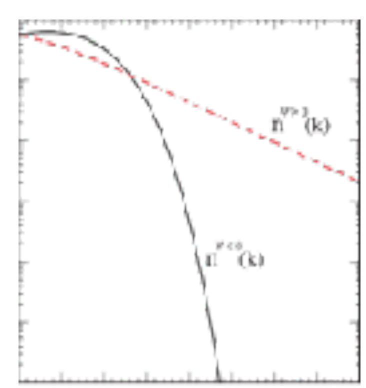
Short range correlations,



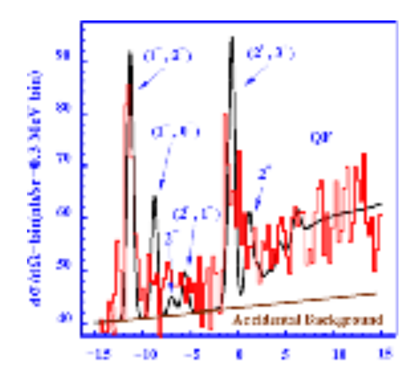
EMC effect,



$F_2^n/F_2^p \rightarrow$ d/u,



p & n momentum distributions,

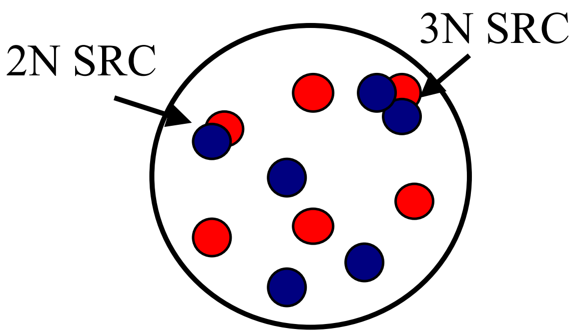


Λ hypernuclear spectroscopy,

+ form factors

+ …..

The Tritium program includes studies of short range correlations with inclusive scattering from ^{3}H/^{3}He.

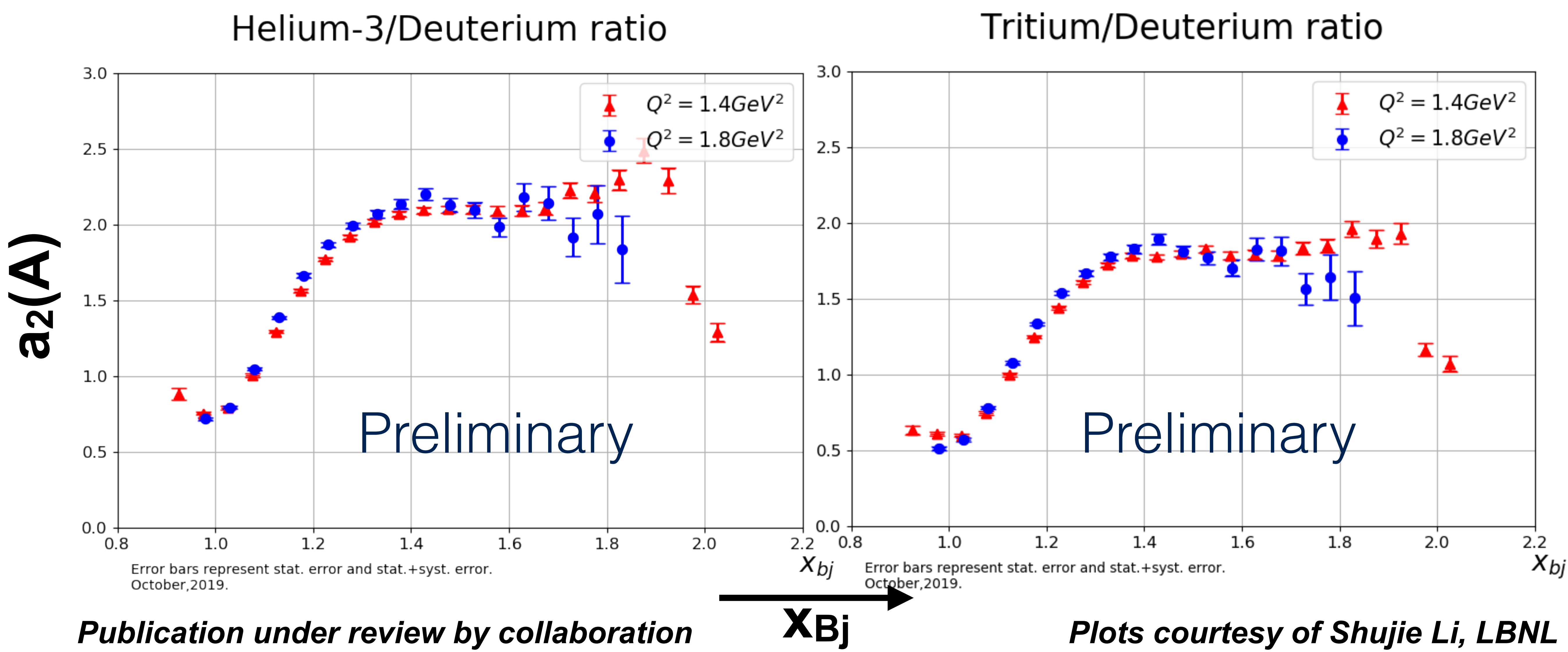


$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A)$$

(A/D) ratio of inclusive cross section at *x>1*

$\propto$ probability of scattering from a SRC pair

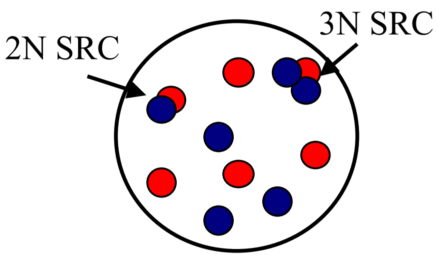
Compare ^{3}He to ^{3}H to study the composition of SRCs



Publication under review by collaboration

Plots courtesy of Shujie Li, LBNL

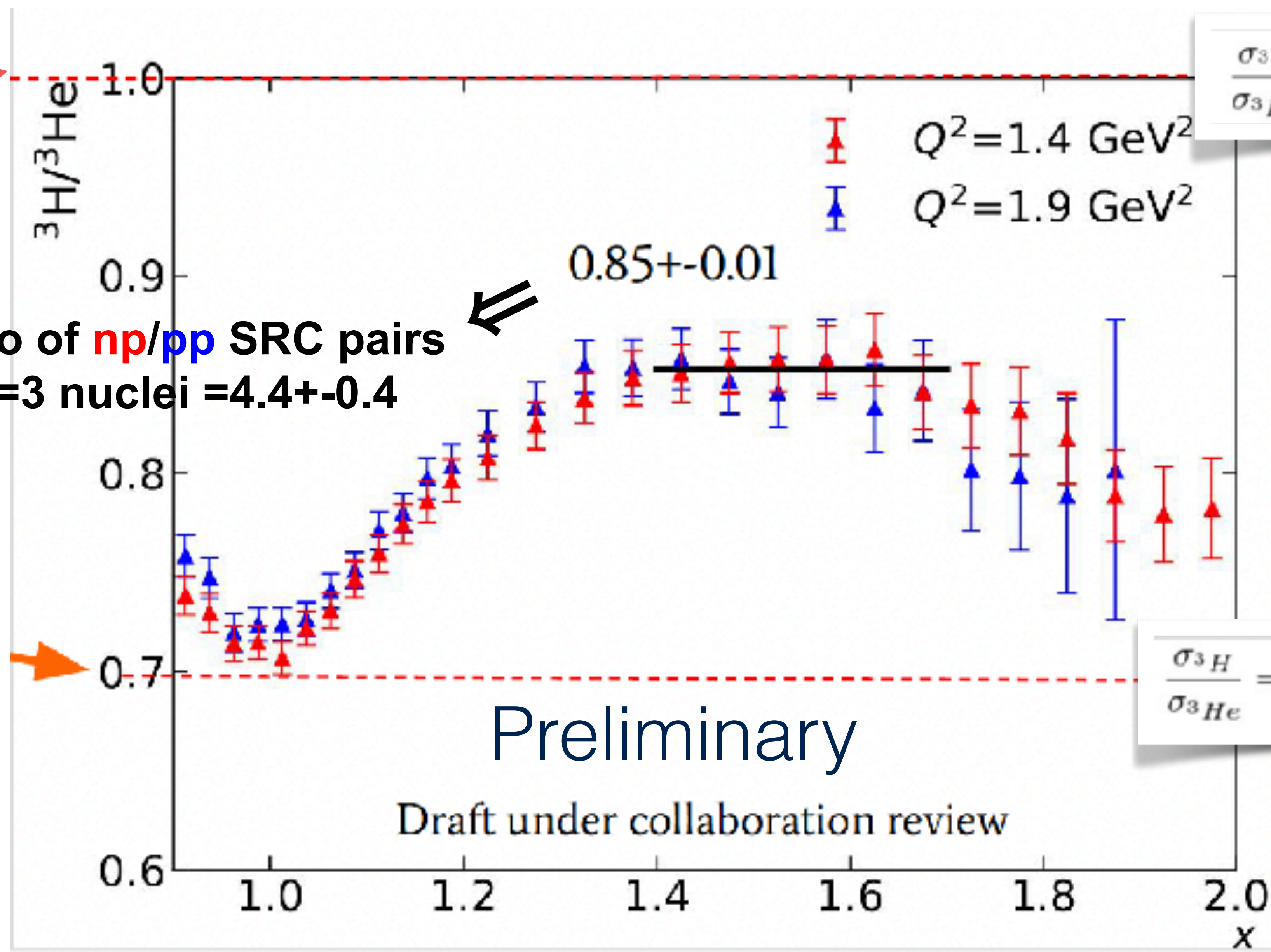
The Tritium program includes studies of short range correlations with inclusive scattering from $^3H/^3He$.



Compare ^3He to ^3H to study the composition of SRCs

complete np dominance

$$\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{\sigma_{np}+\sigma_n}{\sigma_{np}+\sigma_p} \simeq \frac{\sigma_{np}}{\sigma_{np}} = 1$$



Ratio of np/pp SRC pairs in A=3 nuclei =4.4+-0.4

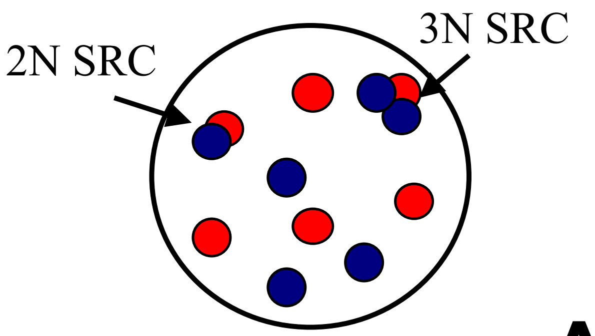
no isospin dependence

$$\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{2\sigma_{nn}+\sigma_{pp}}{\sigma_{nn}+2\sigma_{pp}} \xrightarrow{\sigma_p \sim 3\sigma_n} 0.7$$

x_{Bj}

Plots courtesy of Shujie Li, LBNL

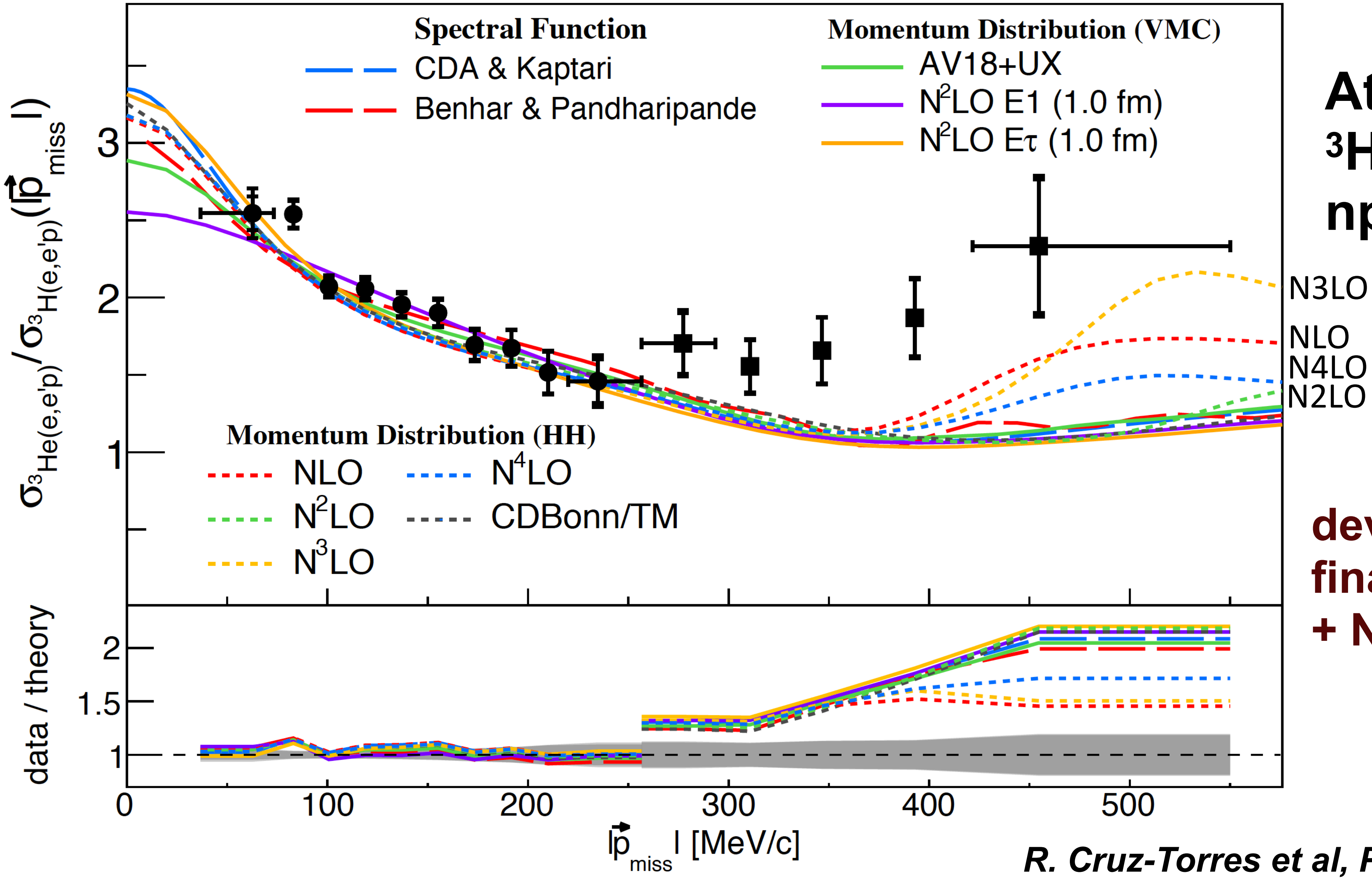
A study of short range correlations with exclusive scattering from $^3H/^3He$ was the first publication from the Tritium program in Hall A.



Short Range Correlations in $^3H/^3He$

using proton and neutron momentum distributions in A = 3 asymmetric nuclei

A(e,e'p) yields at x>1 vs Missing Momentum $|P_m|$

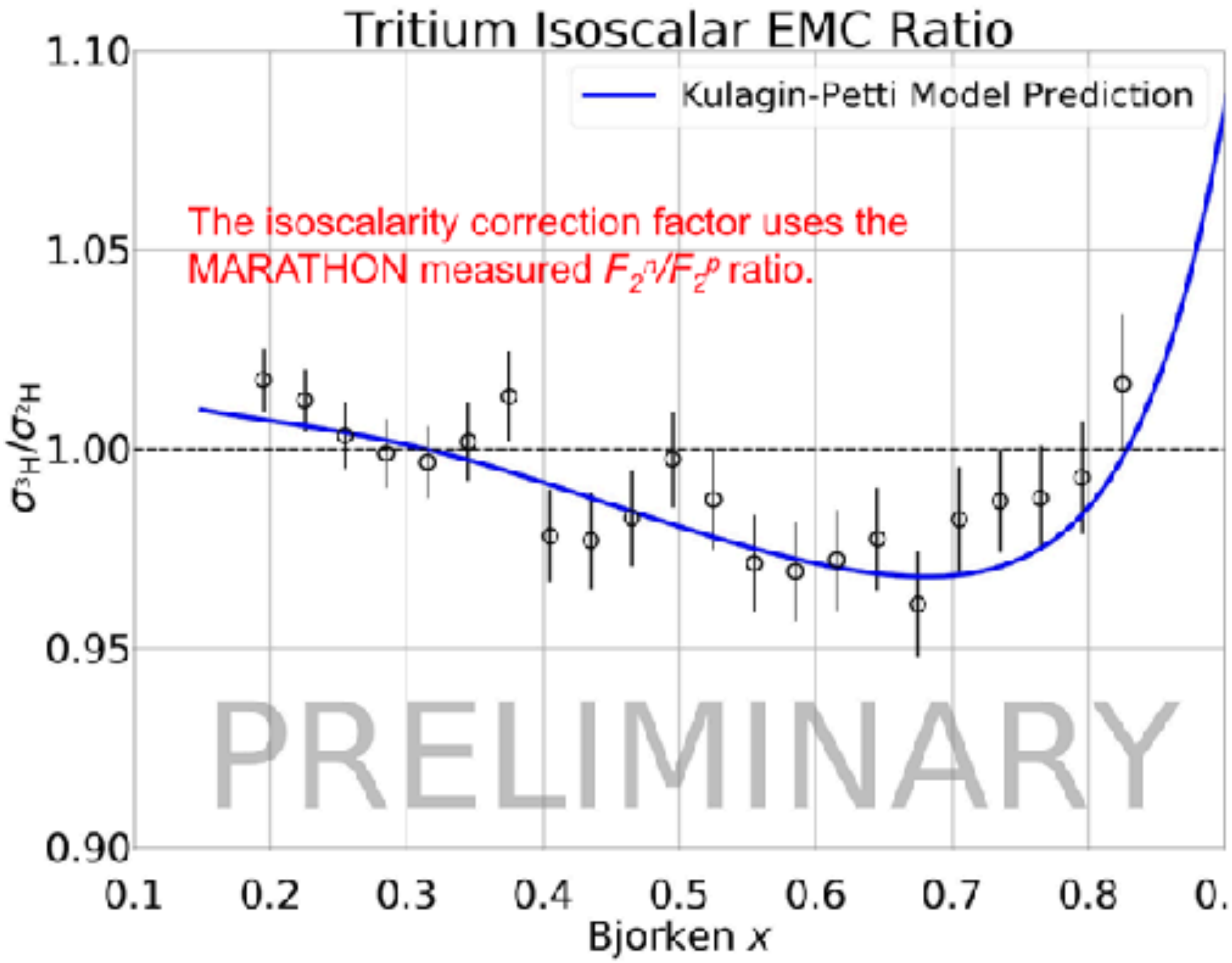


At large $|P_m|$, $^3He/^3H$ ratio ~ 1 in np dominance picture

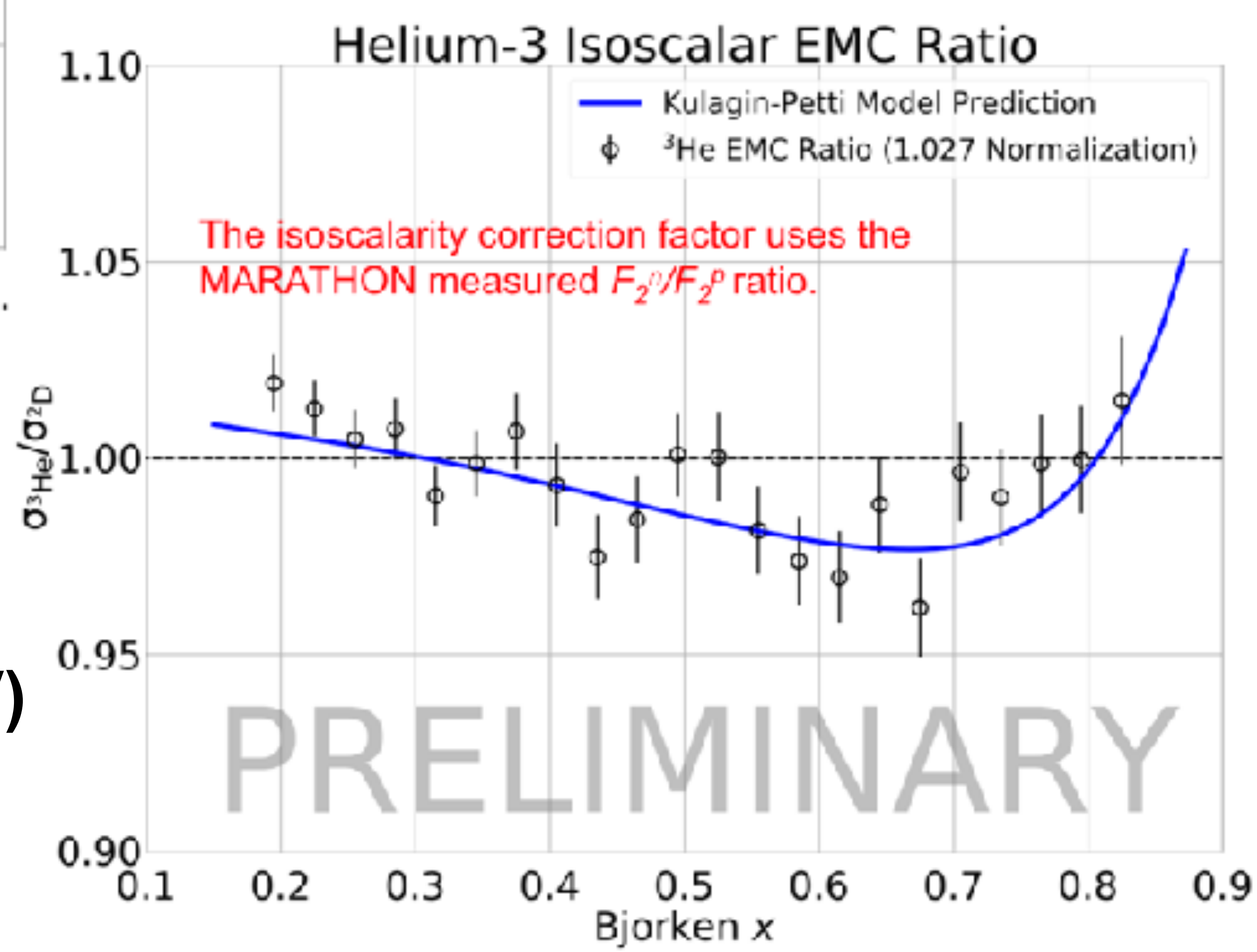
deviations due to final state interactions (FSI) + NN potential?

R. Cruz-Torres et al, Phys.Lett. B797 (2019) 134890

EMC effect in Tritium and Helium-3 was also measured



The First measurement of EMC Effect in Tritium

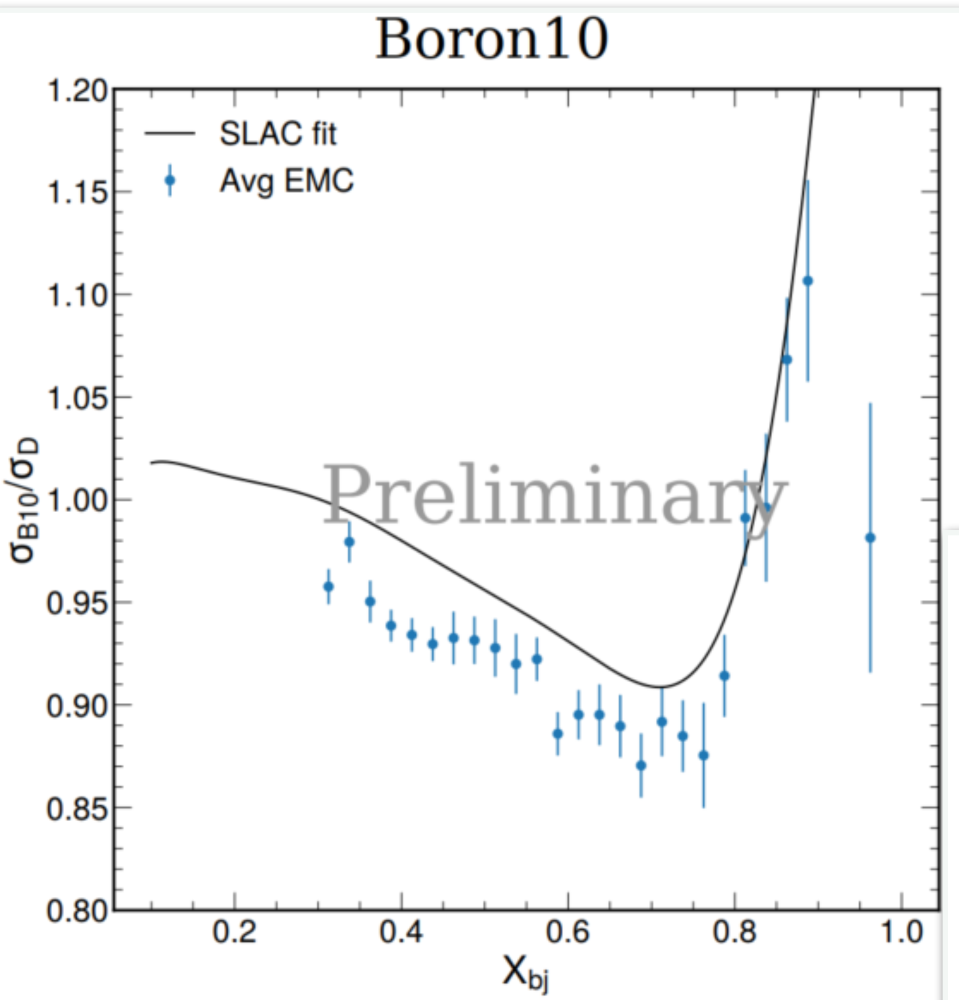


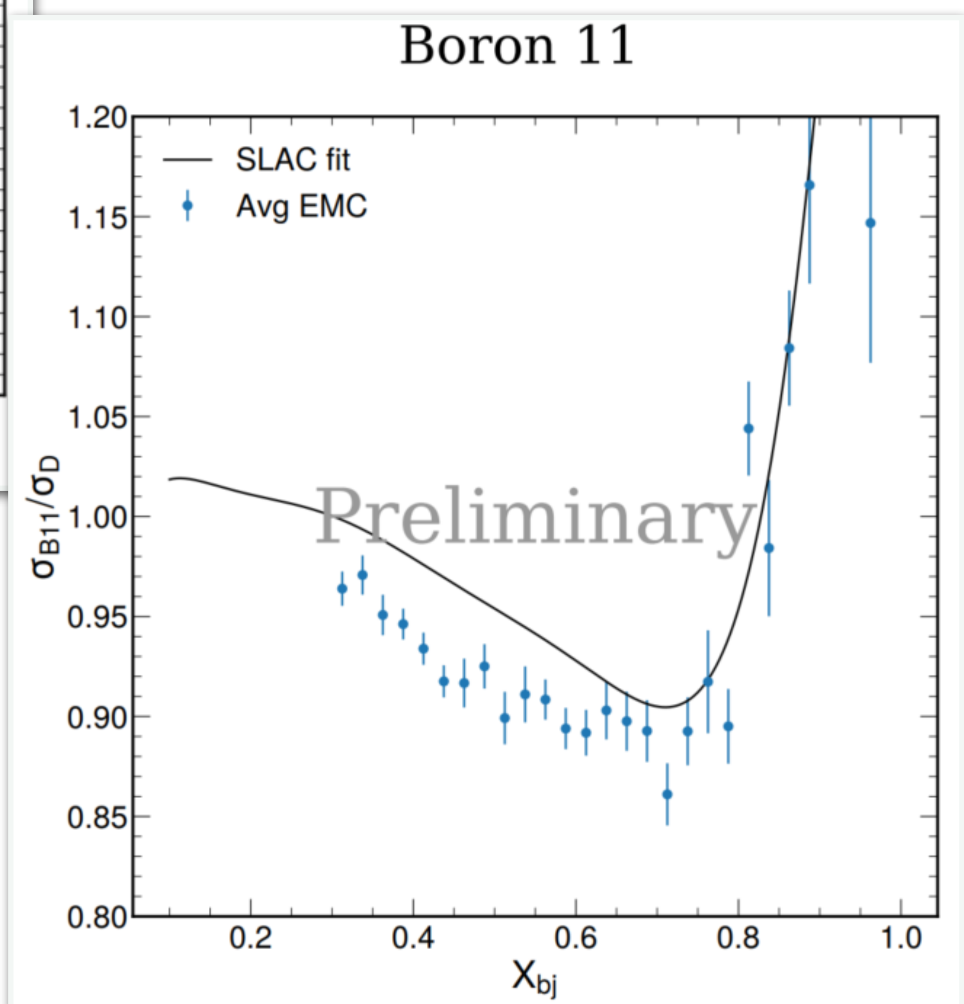
^{3}He result agrees with 6 GeV measurement in DIS region (W>2 GeV)

Plots courtesy of Makis Petratos

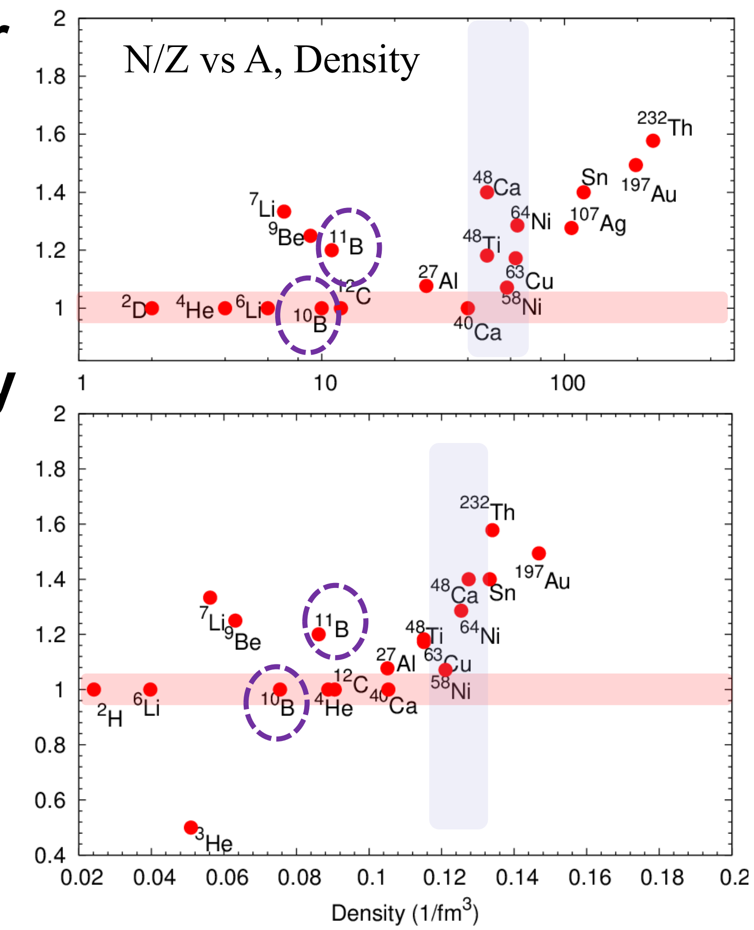
Another experiment in Hall C has measured the EMC effect and 2N-SRC (at x >1) in ^{10}B & ^{9}B.

The First measurement of EMC Effect in Boron





- **Additional light nuclei to further investigate cluster structure will run in summer 2022.**
- **Scans over a wide range of N/Z for medium/heavy nuclei to study isospin dependence**

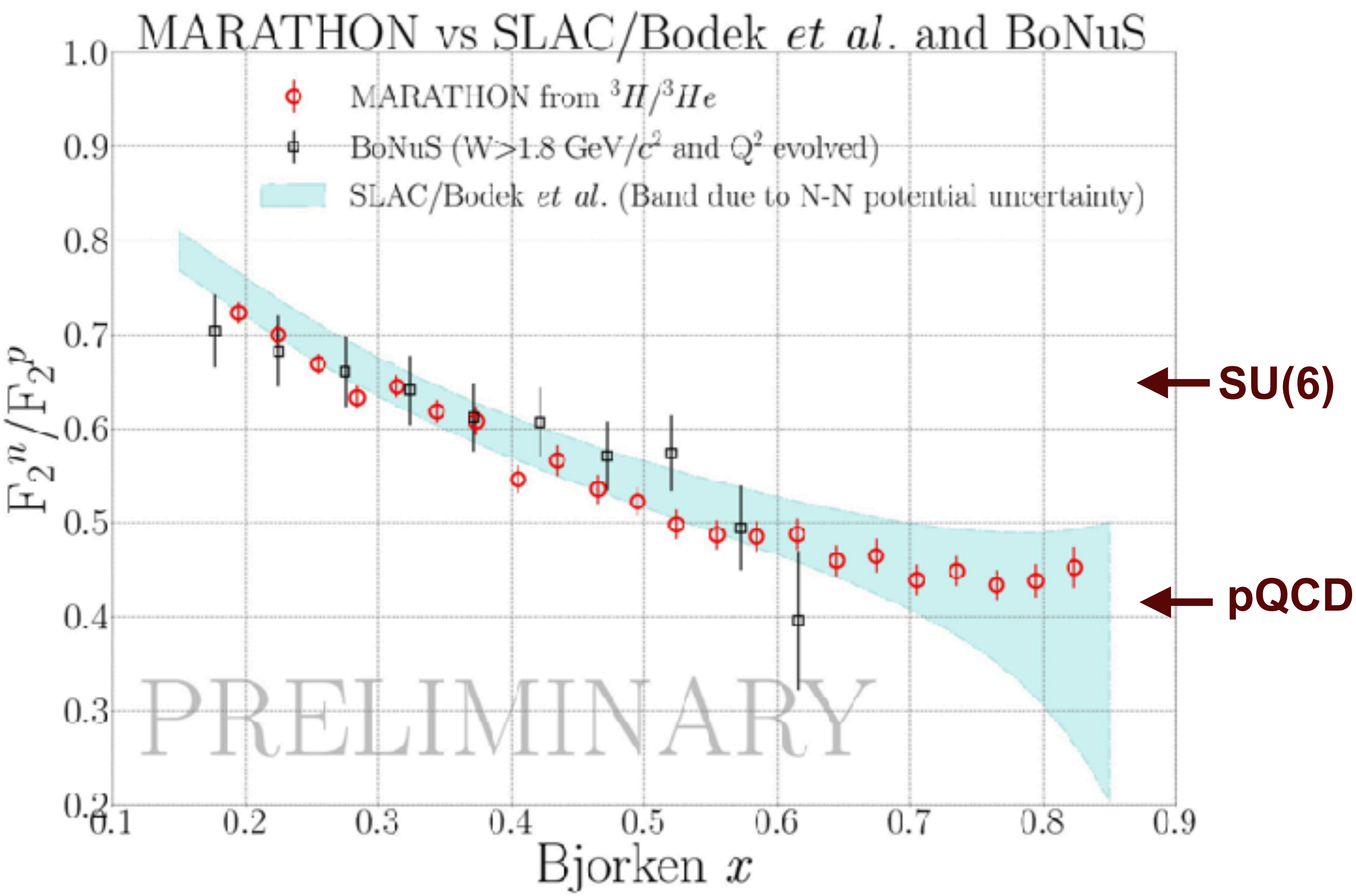


- **Measure 2N SRCs concurrently for same nuclei to further illuminate the SRC/ EMC connection**

Plots courtesy of A. Karki

The Tritium program also measured F_2^n/F_2^p & d/u, using ^3H & ^3He.

MeAsurement of the F_2^n/F_2^p, d/u RAtios and A=3 EMC Effect in Deep Inelastic Electron Scattering Off the Tritium and Helium MirrOr Nuclei (MARATHON).



F_2^n/F_2^p is extracted from the ^3H and ^3He cross sections using the knowledge of the difference in their nuclear effects

$$\frac{F_2^n}{F_2^p} = \frac{2R^* - \sigma^{^3He}/\sigma^{^3H}}{2\sigma^{^3He}/\sigma^{^3H} - R^*}$$

where

$$R^* = \frac{R(^3He)}{R(^3H)}$$

and

$$R(^3He) = \frac{F_2^{^3He}}{2F_2^p + F_2^n}$$

$$R(^3H) = \frac{F_2^{^3H}}{F_2^p + 2F_2^n}$$

Submitted to PRL *Plot courtesy of Makis Petratos*

Incomplete list of other completed experiments that will have results soon.

Charge symmetry violation in quark distributions:
Measured SIDIS ratio of π^+/π^- on Deuterium, data collected in 2018 and 2019 in Hall C.

SIDIS pion electroproduction scans in (x, z, P_T) and Q^2 at fixed x, data collected in 2018 and 2019 in Hall C.

L-T separated cross sections for exclusive kaon electroproduction at high Q^2, data collected in 2018 and 2019 in Hall C.

Determining the Λ-n interaction via study of Λ-nn resonance, data collected as part of the Tritium program in 2018 in Hall A.

Measurement of the neutron distribution in ^{208}Pb using parity violating electron scattering, data collected in Fall 2019 and 2020. Results to appear in PRL soon.

Measurement of Bound Neutron Structure (BoNuS-12) in Hall-B completed in 2020.

Summary

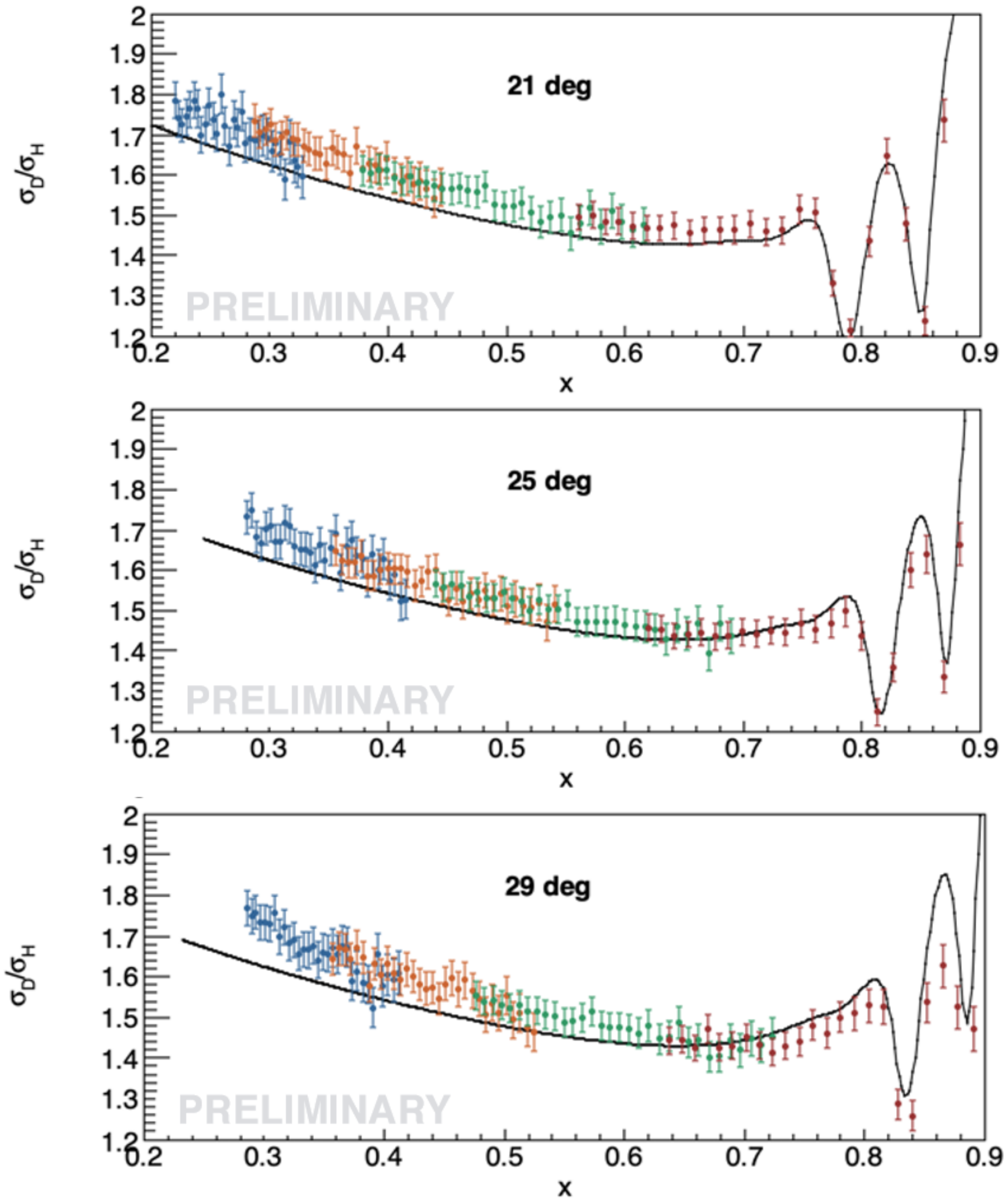
- The upgraded accelerator at JLab is fully operational and the extensive experimental program is underway in earnest.
- Over 30% of the approved experiments have already been completed.
- Exciting new results on the role of quarks in nuclei are trickling in and some have already been published.
- Some of these results are very puzzling.
- Look out for the deluge about to come, and move us closer to an eventual resolution to the problem of quarks in nuclei.

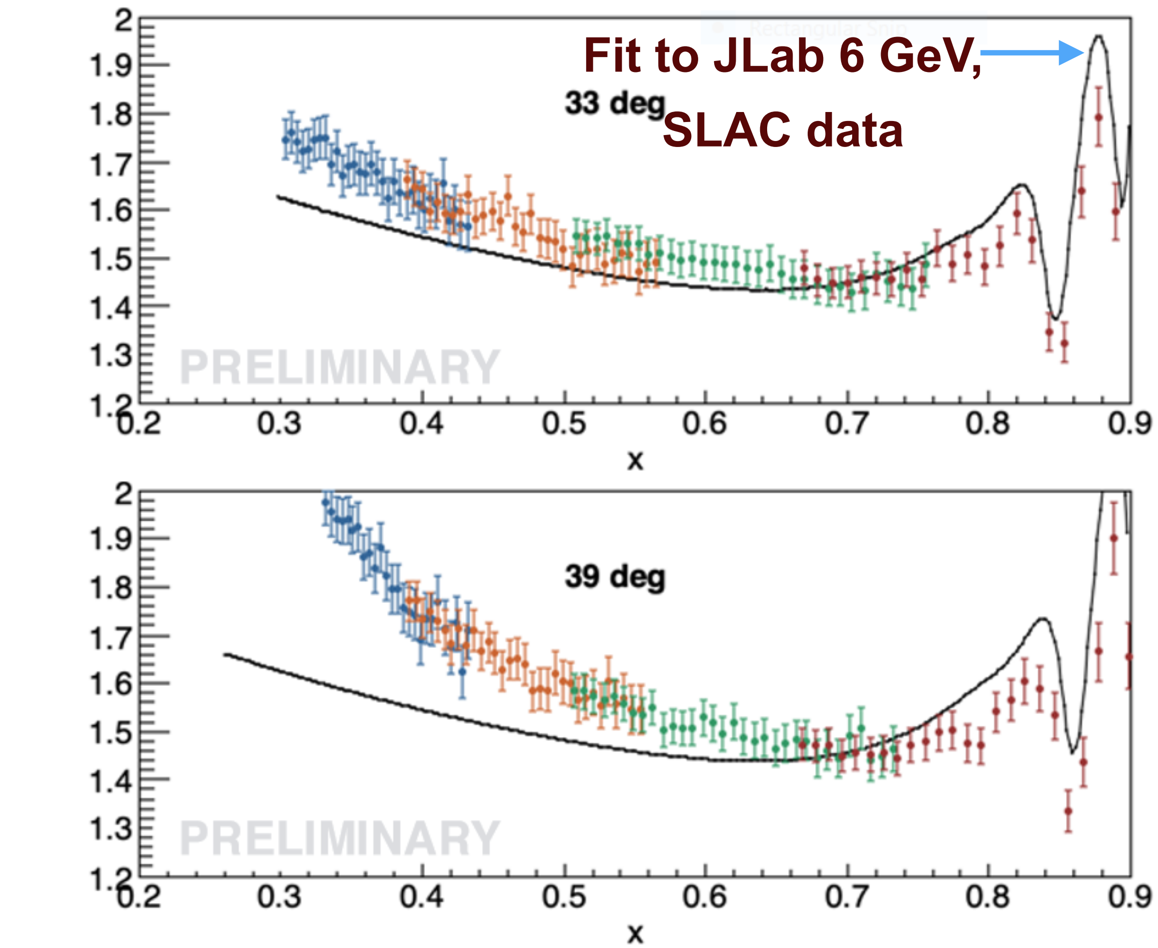
This work is supported by US DOE under contract #DE-FG02-07ER41528

A big shout out to the army of graduate students and post docs working on these experiments.

Among the completed experiments several conducted extensive measurements of structure functions and PDFs.

One of the Hall-C commissioning experiments measured H(e,e') and D(e,e') cross section to: i) study quark-hadron duality, and ii) compare moments of the F_2 structure function to Lattice calculations





Preliminary D/H ratios (not yet corrected for charge symmetric backgrounds)

Plots courtesy Abel Sun