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U.S. DEPARTMENT OF ENERGY
Office of Science

From THREE to INFINITY

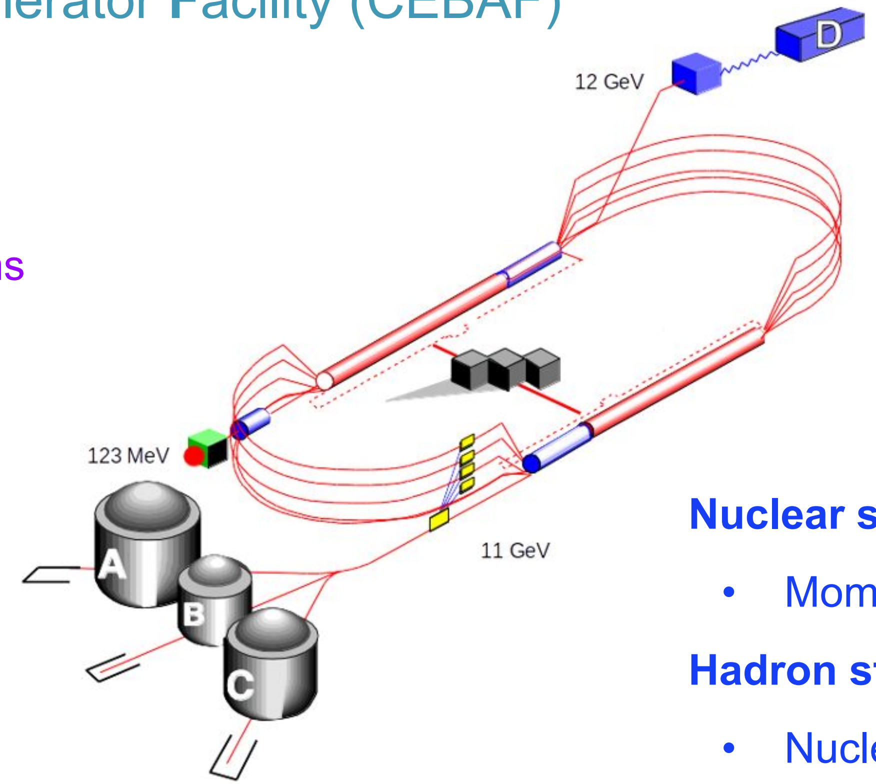
the asymmetric nuclei study at Jefferson Lab

Shujie Li, Berkeley Lab, August 30, 2022

Jefferson Lab as the "Intensity Frontier"

Continuous **E**lectron **B**eam **A**ccelerator **F**acility (CEBAF)

- High luminosity: up to $10^{38}/cm^2/s$
- Electron as the clean probe
- Fixed targets
- 4 experimental halls, diverse programs



Nuclear structure

- Momentum distribution, charge radii,...

Hadron structure

- Nucleons, resonances, mesons
- 1D and 3D imaging

Hadron spectroscopy

Fundamental symmetries

- Dark matter, BSM physics,...

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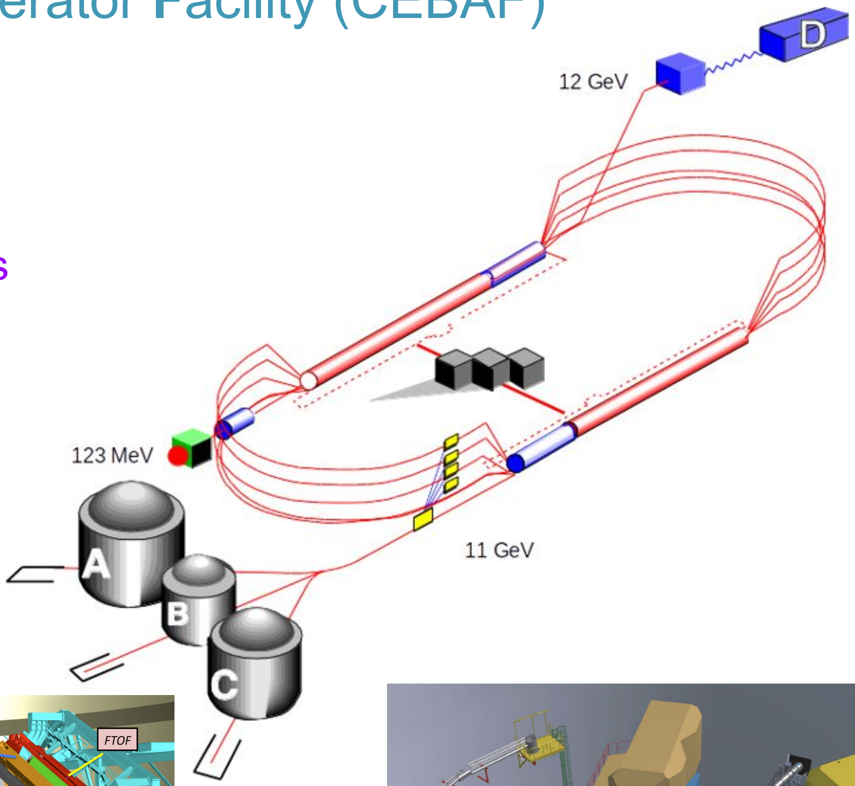
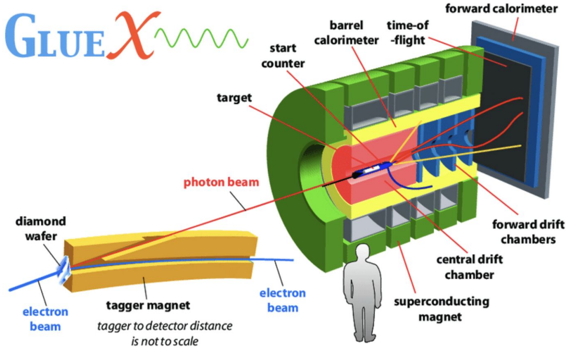
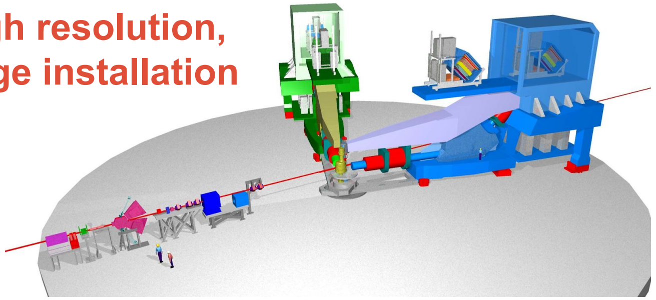
Photon beam
-exotic mesons

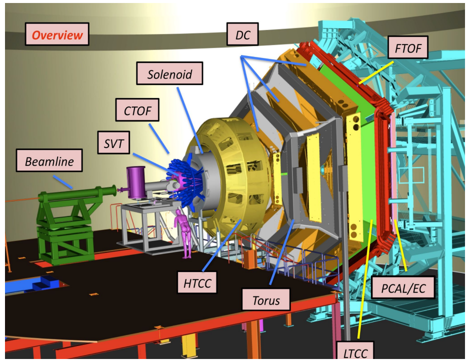


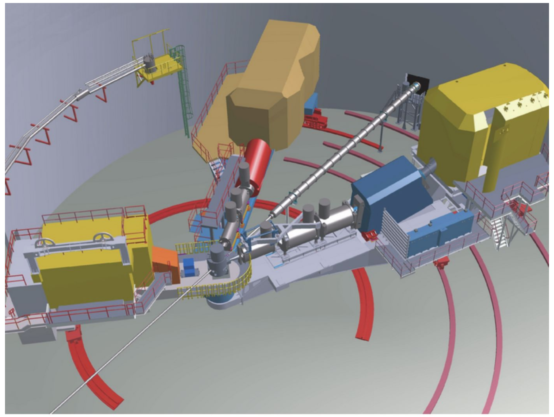


High resolution,
large installation



Large Acceptance,
-3D imaging





High momentum,
-precision cross sections

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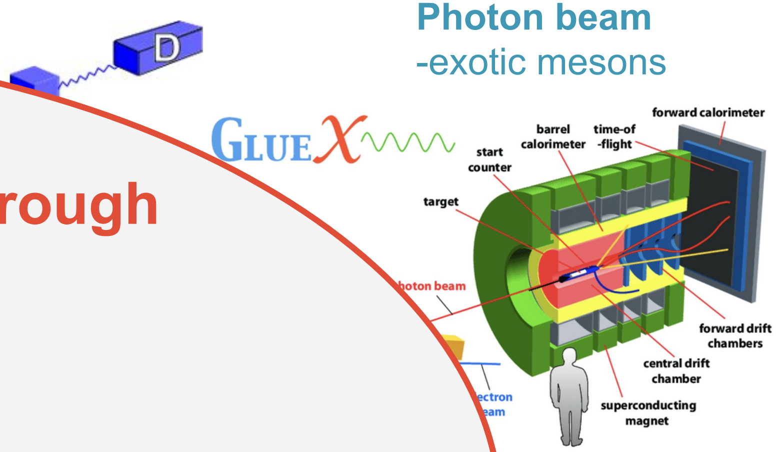
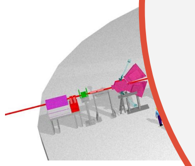
- 4 experimental h

Photon beam
-exotic mesons



High resoluti
large install



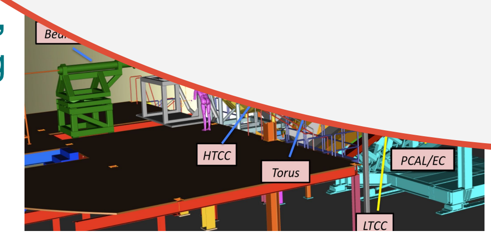
Isospin Asymmetry Study Through Asymmetric Nuclei

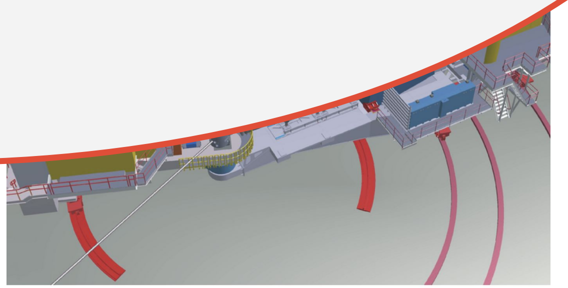
^{3}H, ^{3}He, …, ^{48}Ca, …, ^{208}Pb, ...

- Partonic structure, and in-medium modifications → u vs. d quarks
- Nucleon-nucleon interactions, nucleon momentum distribution → proton vs. neutron
- Charge radii → proton, neutron radii

omentum,
sion cross sections

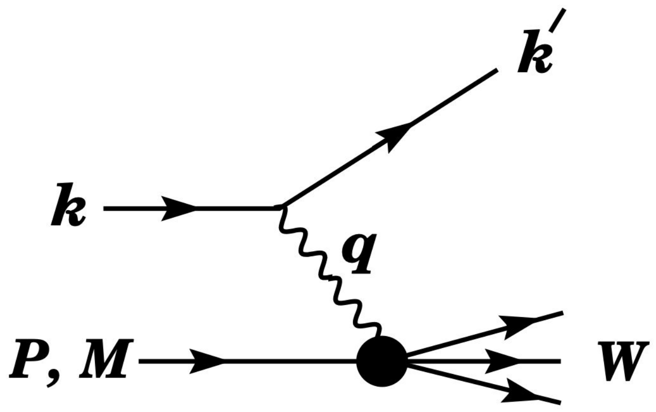
Large Acceptance,
-3D imaging





1, 2, 3 …

Deep inelastic scattering on A=1



Leptonic tensor

hadronic tensor

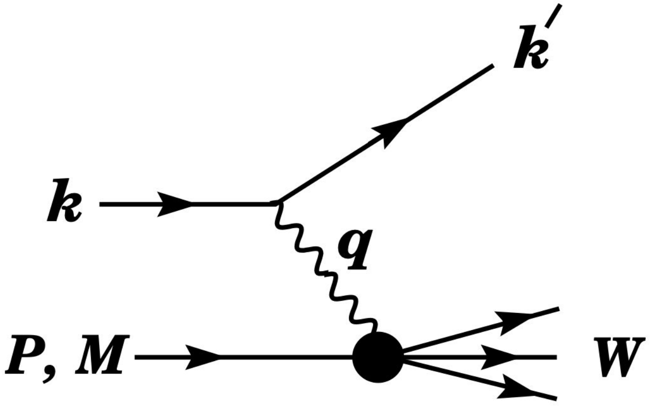
$$\frac{d^2\sigma}{dxdy} = \frac{2\pi y\alpha^2}{Q^4}\sum_j \eta_j \, L_j^{\mu\nu} W_{\mu\nu}^j$$

$Q^2 = -q^2$ four-momentum transfer

$x = \dfrac{Q^2}{2M\nu}$ fraction of nucleon momentum carried by the struck quark in parton model.

1, 2, 3 …

Deep inelastic scattering on A=1



Leptonic tensor

$$\frac{d^2\sigma}{dxdy} = \frac{2\pi y \alpha^2}{Q^4} \sum_j \eta_j \, L_j^{\mu\nu} W^j_{\mu\nu}$$

hadronic tensor
→ Partonic structure in terms of structure function F_1, F_2, …

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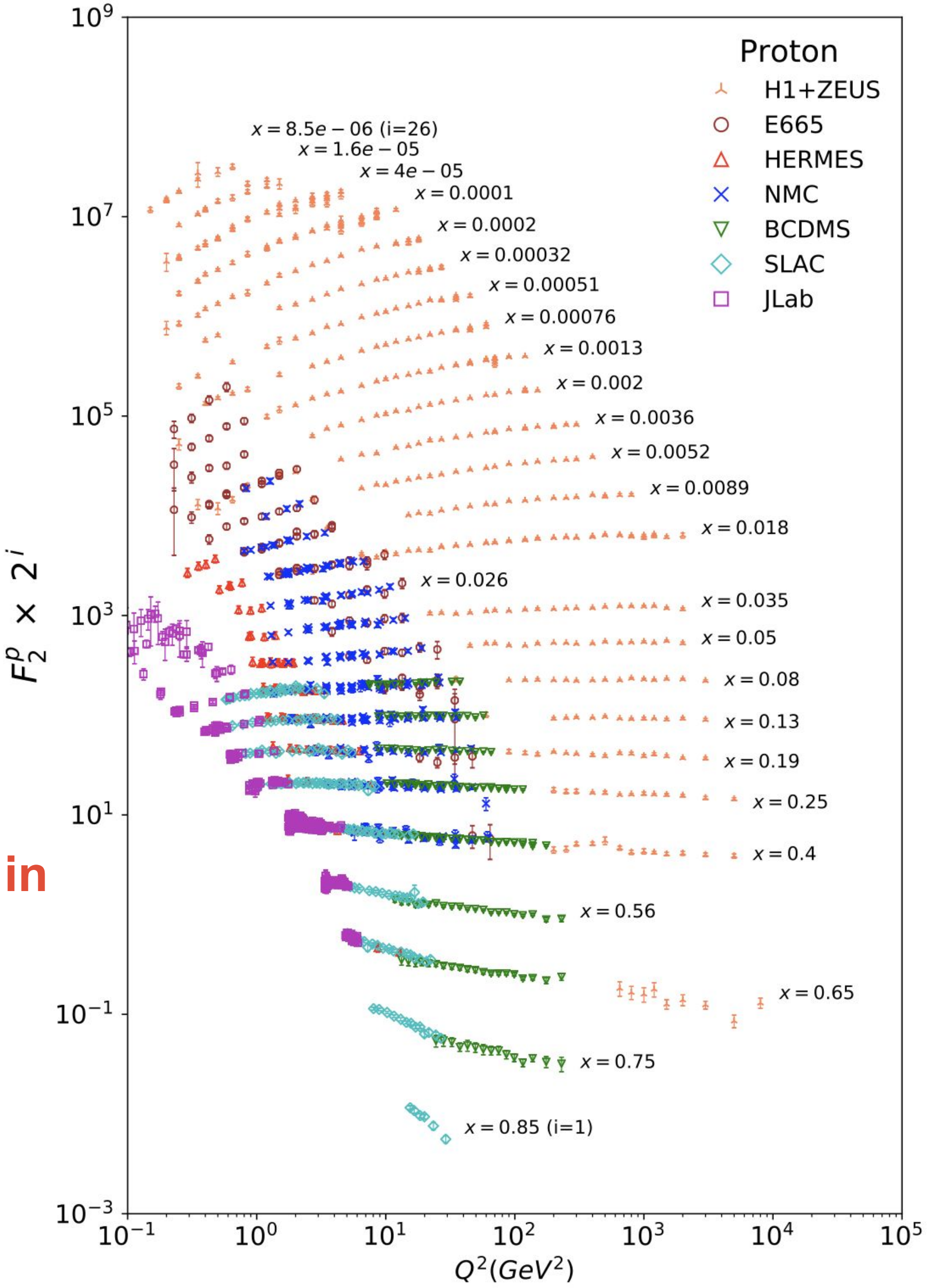

1, 2, 3 …

F_2 n/p → d/u at large x

- d/u at x→1: a crucial test of valence quark models and pQCD.

Nucleon Model	F_2^n/F_2^p x→1	d/u x→1
SU(6) Symmetry	2/3	0.5
Scalar diquark	1/4	0
DSE contact interaction	0.41	0.18
DSE realistic interaction	0.49	0.28
pQCD (helicity conservation)	3/7	0.2

Courtesy of S. Kuhn, JLab PR12-06-113

1, 2, 3 …

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- Access d/u through F_2 n/p

At leading order, assuming charge symmetry

$$F_2^p = x\left[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s})\right]$$

$$F_2^n = x\left[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})\right]$$

Ignore sea quarks and strange quark contributions at x>0.3

$$\boxed{\frac{F_2^n}{F_2^p} \approx \frac{u+4d}{4u+d} \Rightarrow \frac{d}{u} \approx \frac{4F_2^{n/p}-1}{4-F_2^{n/p}}}$$

1, 2, 3 …

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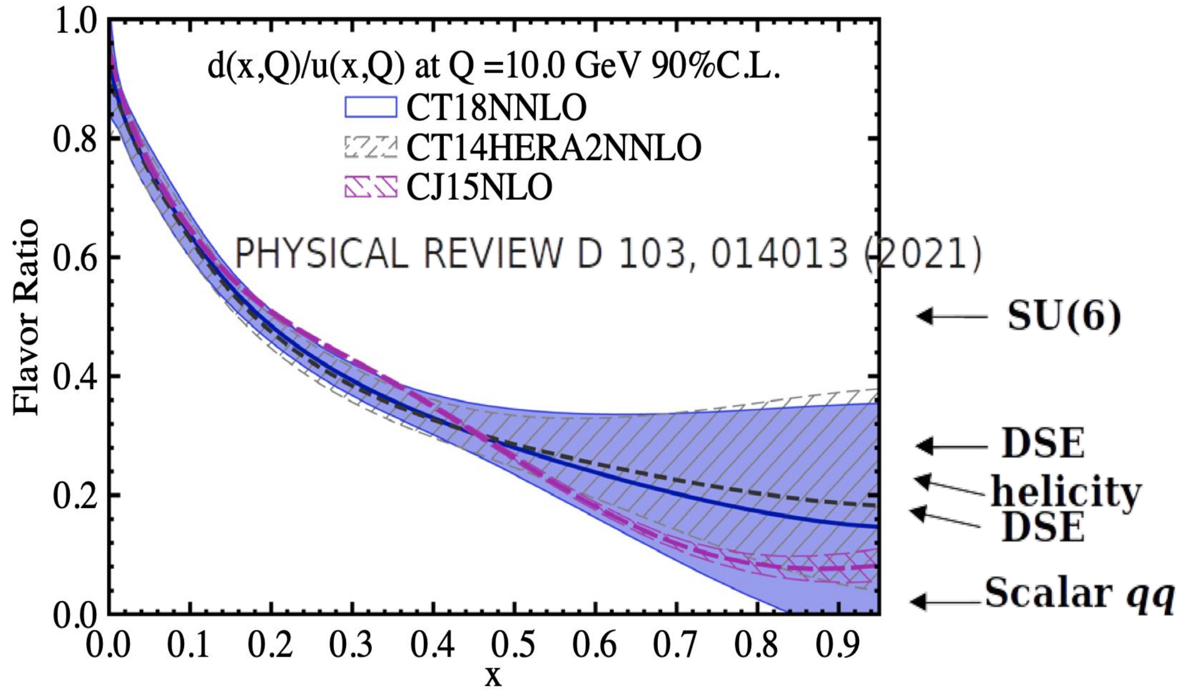
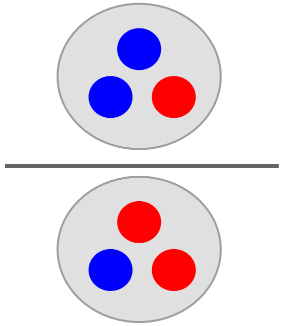
- Realistic d/u extraction at x→1 from global QCD analysis
  - lack of constraints from data
  - **NO** free neutron target:
    - n = D - p with nuclear correction
    - large uncertainty as x→ 1



1, 2, 3 …

The JLab Hall A Tritium experiments



Tritium v.s. Helium-3:

- Large isospin (neutron-proton) asymmetry
- Similar separation energy: 6.26 MeV v.s. 5.49 MeV
- Small Coulomb effect: V_eff = 0.66 MeV v.s. 0

$$^3H = 2n + p$$
$$^3He = 2p + n$$
$$\Rightarrow {}^3H/{}^3He = (2n/p+1)/(2+n/p)$$
$$\Rightarrow n/p$$

1, 2, 3 …

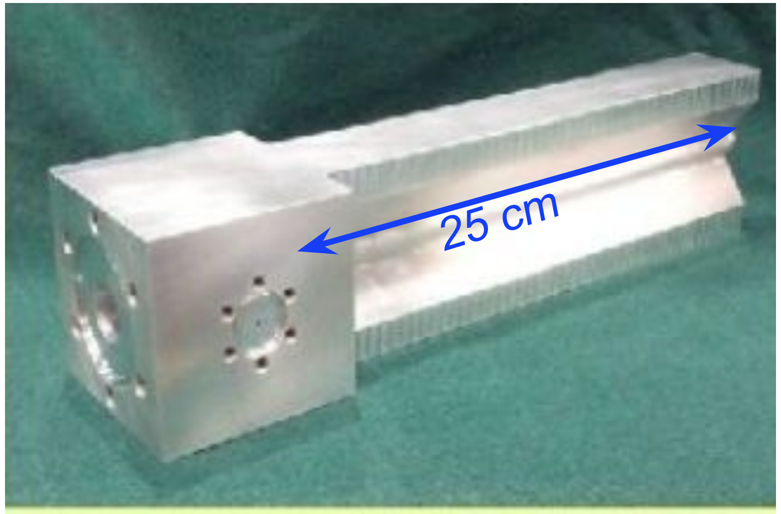
The JLab Hall A Tritium experiments

a collective efforts of many students and postdocs, Hall A staff, engineers, target experts, etc.

Measurement of the Nucleon F_2^n/F_2^p Structure Function Ratio by the Jefferson Lab MARATHON Tritium/Helium-3 Deep Inelastic Scattering Experiment

D. Abrams,[1] H. Albataineh,[2] B. S. Aljawrneh,[3] S. Alsalmi,[4,5] D. Androic,[6] K. Aniol,[7] W. Armstrong,[8] J. Arrington,[8,9] H. Atac,[10] T. Averett,[11] C. Ayerbe Gayoso,[11] X. Bai,[1] J. Bane,[12] S. Barcus,[11] A. Beck,[13] V. Bellini,[14] H. Bhatt,[15] D. Bhetuwal,[15] D. Biswas,[16] D. Blyth,[8] W. Boeglin,[17] D. Bulumulla,[18] J. Butler,[19] A. Camsonne,[19] M. Carmignotto,[19] J. Castellanos,[17] J.-P. Chen,[19] E. O. Cohen,[20] S. Covrig,[19] K. Craycraft,[11] R. Cruz-Torres,[13] B. Dongwi,[14] B. Duran,[10] D. Dutta,[15] E. Fuchey,[21] C. Gal,[1] T. N. Gautam,[16] S. Gilad,[13] K. Gnanvo,[1] T. Gogami,[22] J. Gomez,[19] C. Gu,[1] A. Habarakada,[16] T. Hague,[4] J.-O. Hansen,[19] M. Hattawy,[8] F. Hauenstein,[18] D. W. Higinbotham,[19] R. J. Holt,[8,*] E. W. Hughes,[23] C. Hyde,[18] H. Ibrahim,[24] S. Jian,[1] S. Joosten,[10] A. Karki,[15] B. Karki,[25] A. T. Katramatou,[4] C. Keith,[19] C. Keppel,[19] M. Khachatryan,[18] V. Khachatryan,[26] A. Khanal,[17] A. Kievsky,[27] D. King,[28] P. M. King,[25] I. Korover,[29] S. A. Kulagin,[30] K. S. Kumar,[26] T. Kutz,[26] N. Lashley-Colthirst,[16] S. Li,[31] W. Li,[32] H. Liu,[23] S. Liuti,[1] N. Liyanage,[1] P. Markowitz,[17] R. E. McClellan,[19] D. Meekins,[19] S. Mey-Tal Beck,[13] Z.-E. Meziani,[10] R. Michaels,[19] M. Mihovilovic,[33,34,35] V. Nelyubin,[1] D. Nguyen,[1] Nuruzzaman,[36] M. Nycz,[4] R. Obrecht,[21] M. Olson,[37] V. F. Owen,[11] E. Pace,[38] B. Pandey,[16] V. Pandey,[39] M. Paolone,[10] A. Papadopoulou,[13] S. Park,[26] S. Paul,[11] G. G. Petratos,[4] R. Petti,[40] E. Piasetzky,[20] R. Pomatsalyuk,[41] S. Premathilake,[1] A. J. R. Puckett,[21] V. Punjabi,[42] R. D. Ransome,[36] M. N. H. Rashad,[18] P. E. Reimer,[8] S. Riordan,[8] J. Roche,[25] G. Salmè,[43] N. Santiesteban,[31] B. Sawatzky,[19] S. Scopetta,[44] A. Schmidt,[13] B. Schmookler,[13] J. Segal,[19] E. P. Segarra,[13] A. Shahinyan,[45] S. Širca,[33,34] N. Sparveris,[10] T. Su,[4,46] R. Suleiman,[19] H. Szumila-Vance,[19] A. S. Tadepalli,[36] L. Tang,[16,19] W. Tireman,[47] F. Tortorici,[14] G. M. Urciuoli,[43] B. Wojtsekhowski,[19] S. Wood,[19] Z. H. Ye,[8,†] Z. Y. Ye,[48] and J. Zhang[26]

(Jefferson Lab Hall A Tritium Collaboration)

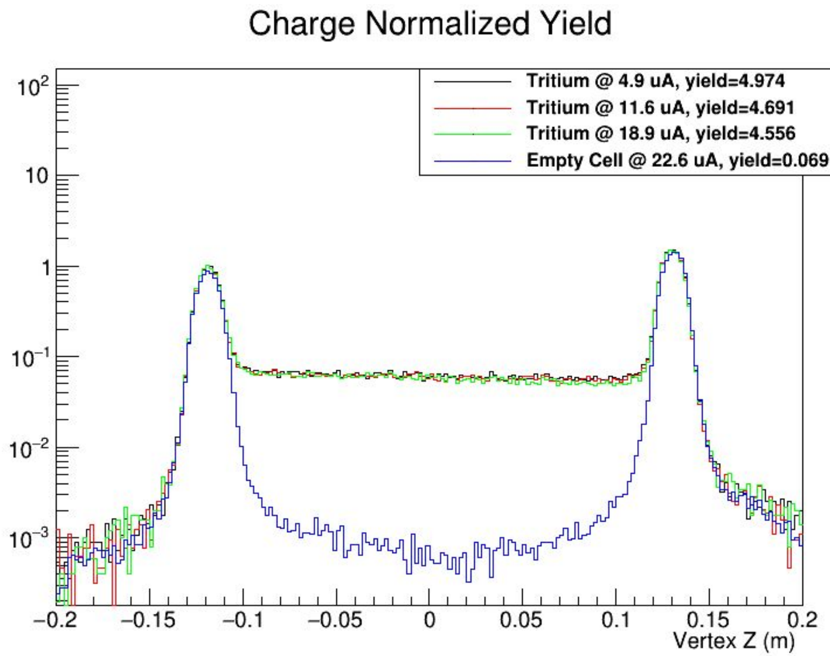


- Low-density, room temperature gas target system
- 25 cm alloy target cell
- 1000 Ci of tritium gas (safe to ship with FedEx)

1, 2, 3 …

The JLab Hall A Tritium experiments

a collective efforts of many students and postdocs, Hall A staff, engineers, target experts, etc.



E12-11-103 "MARATHON" F2n/p, EMC
10.1103/PhysRevLett.128.132003

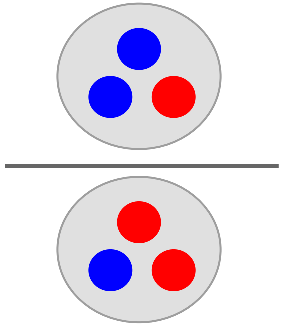
E12-14-011 high momentum nucleon distribution
10.1016/j.physletb.2019.134890, 10.1103/PhysRevLett.124.212501

E12-11-112 isospin dependence of SRC
10.1038/s41586-022-05007-2

E12-17-003 nnL hypernuclei
10.1103/PhysRevC.105.L051001

1, 2, 3 …

F_2 n/p from A=3 system



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- Large isospin (neutron-proton) asymmetry
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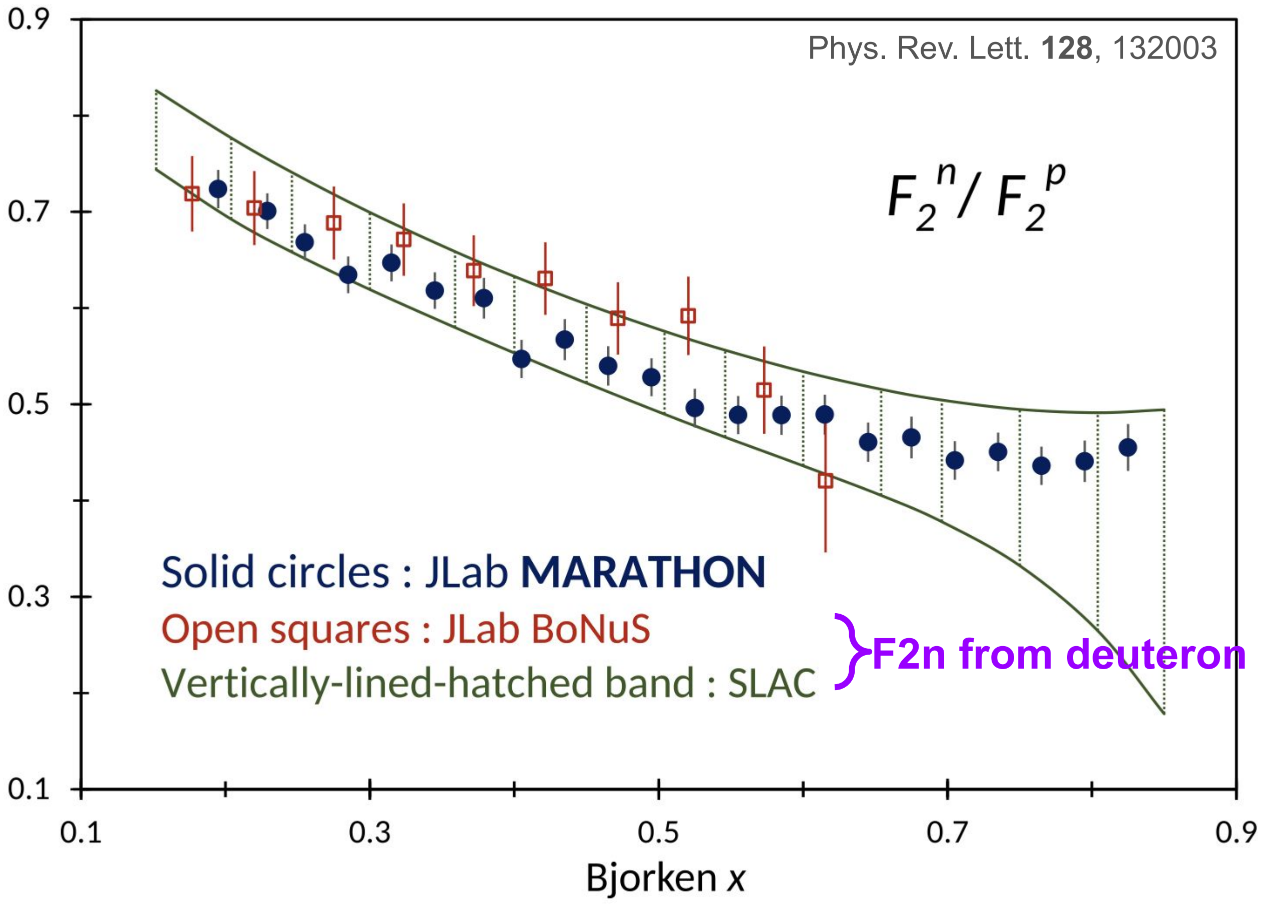
$$R(^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n}, \quad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n}$$

model dependence?
isospin-dependent nuclear effect?
C. Cocuzza et. al., arXiv:2104.06946

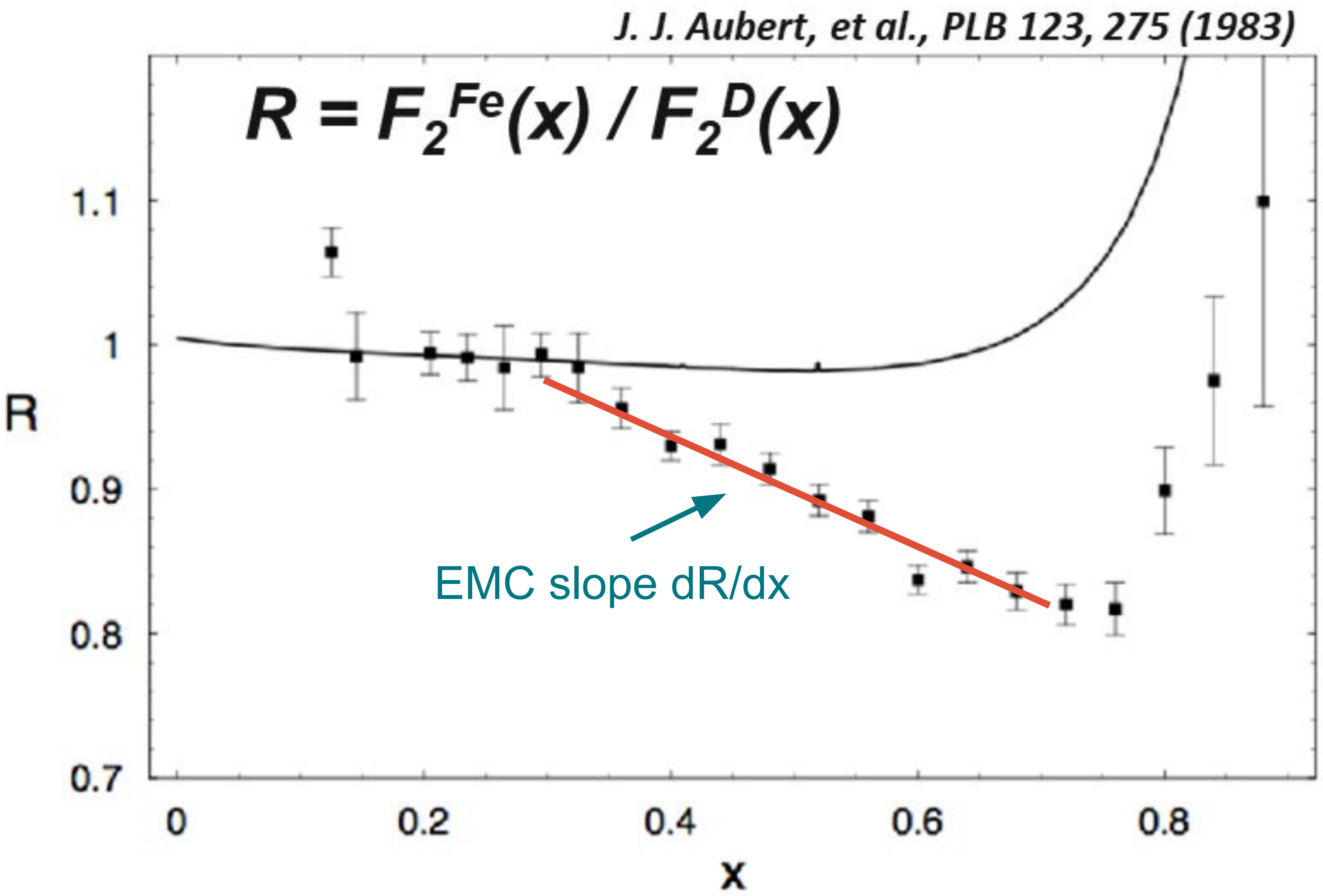
$$\boxed{\mathcal{R} = \frac{R(^3\mathrm{He})}{R(^3\mathrm{H})}}$$

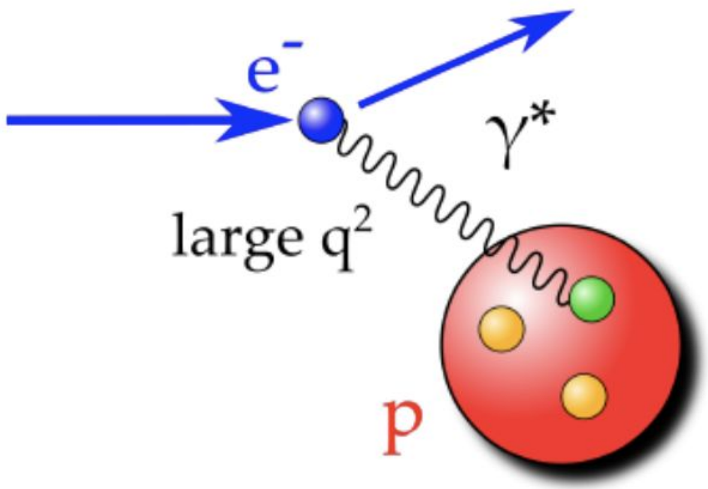
$$\boxed{\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}}}$$



The European Muon Collaboration Effect

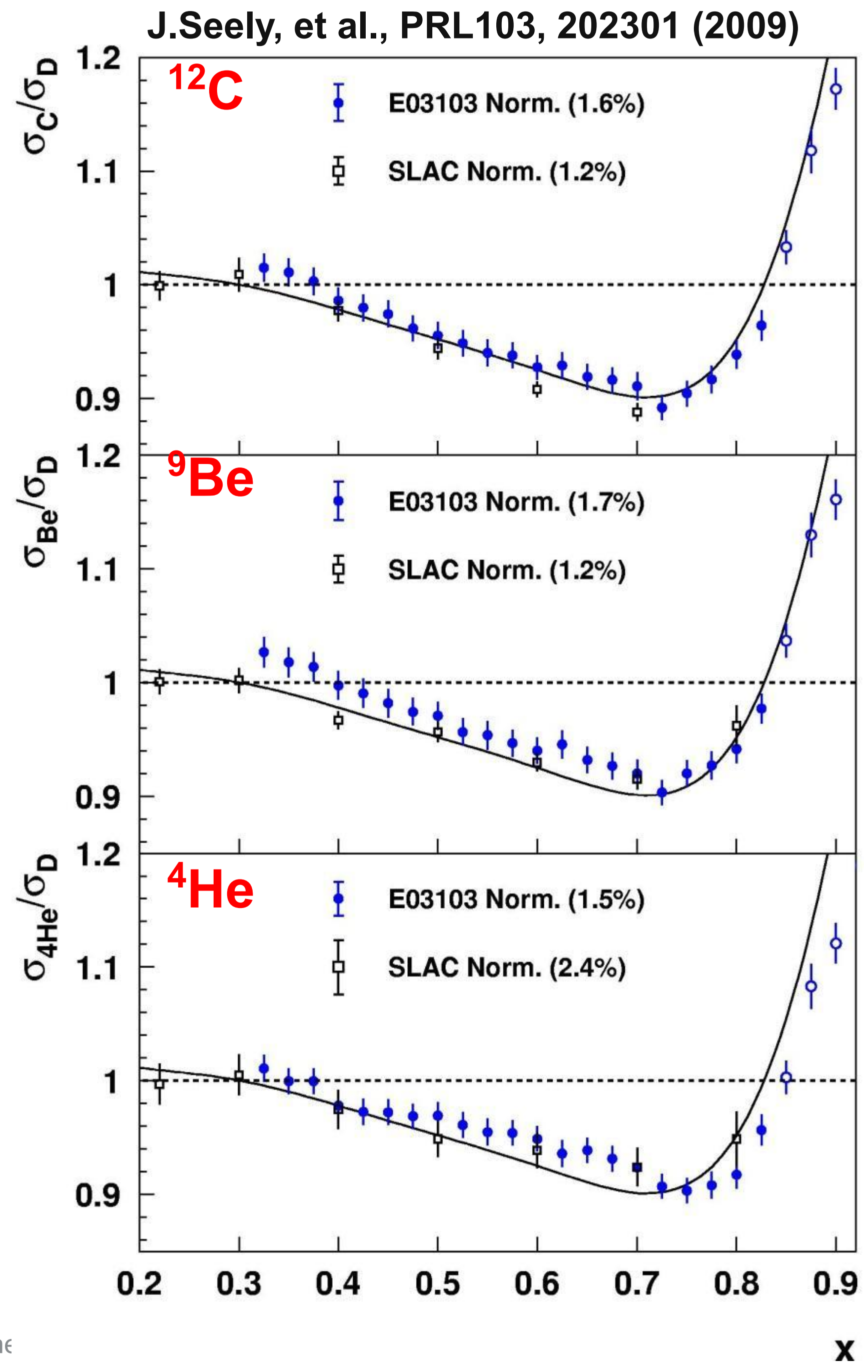
In-medium modification of parton distributions

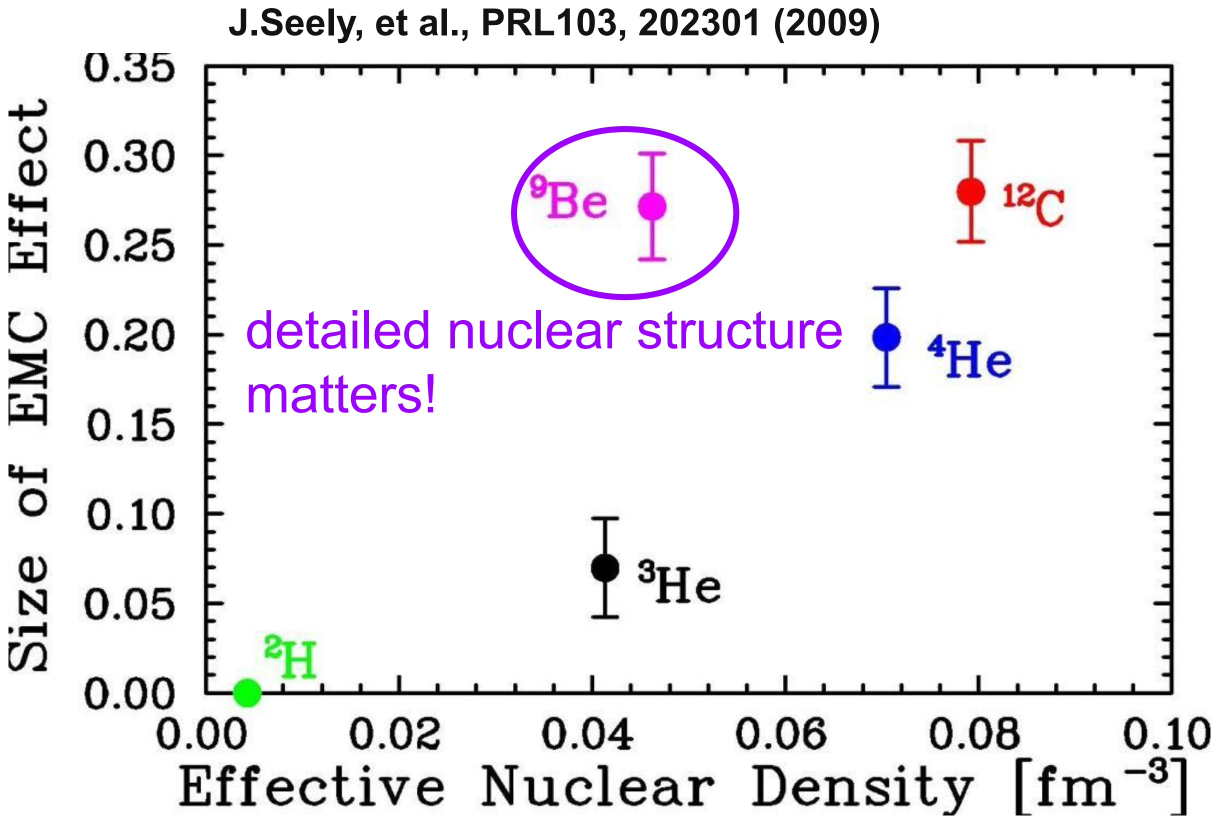




Nucleus binding energy: O(10) MeV
DIS momentum transfer: O(10) GeV

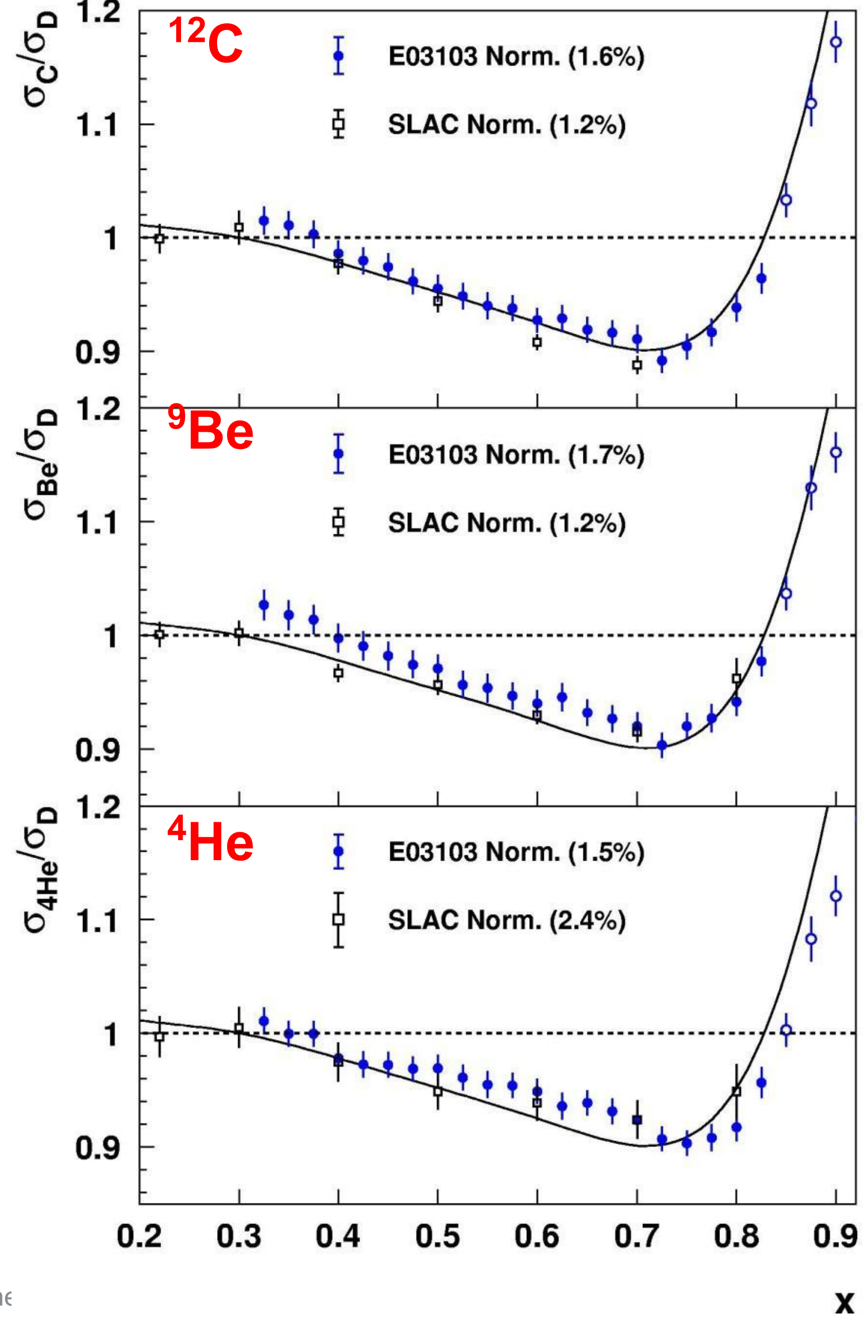
The EMC Effect



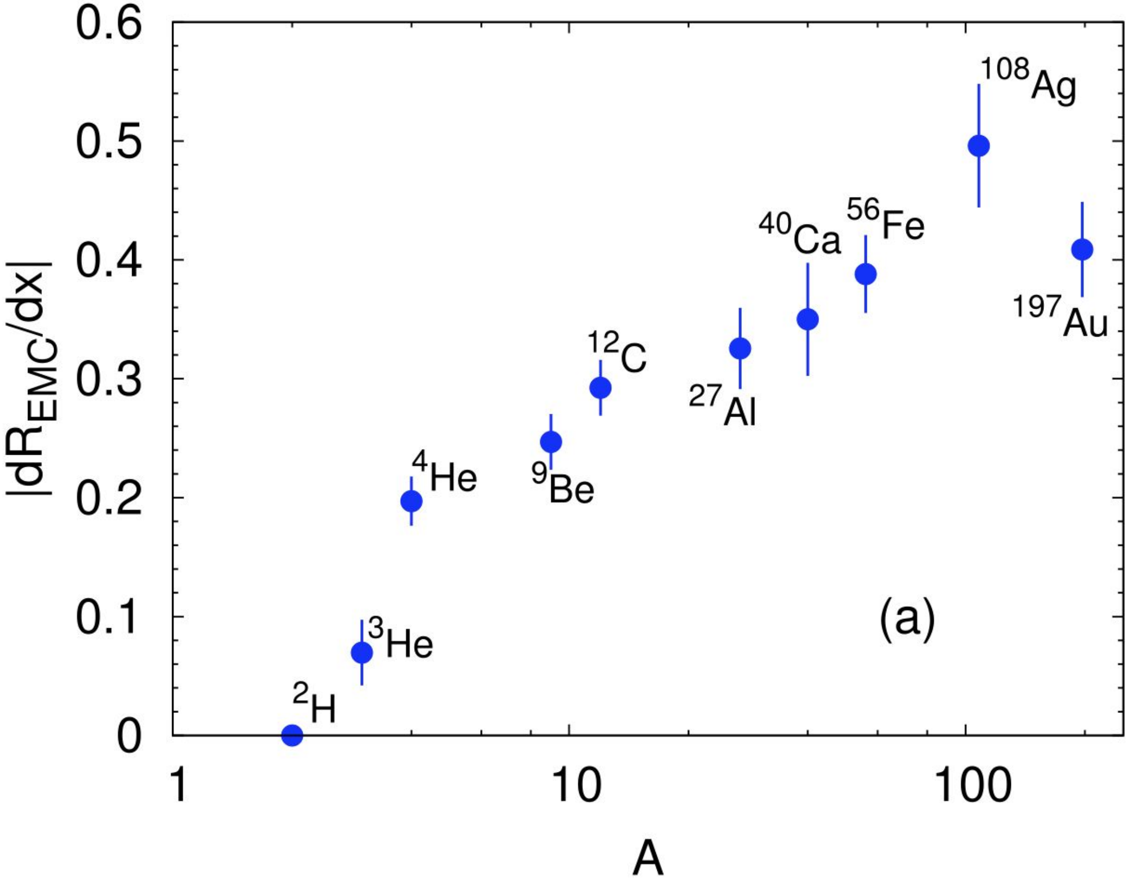


The EMC Effect

J.Seely, et al., PRL103, 202301 (2009)

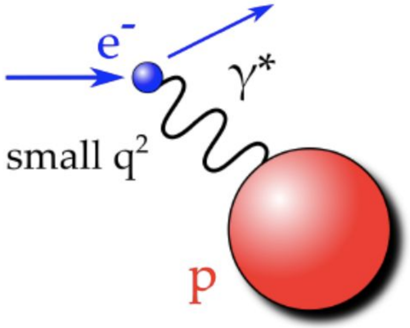


J. Arrington et. al, 10.1103/PhysRevC.86.065204



1, 2, 3 …

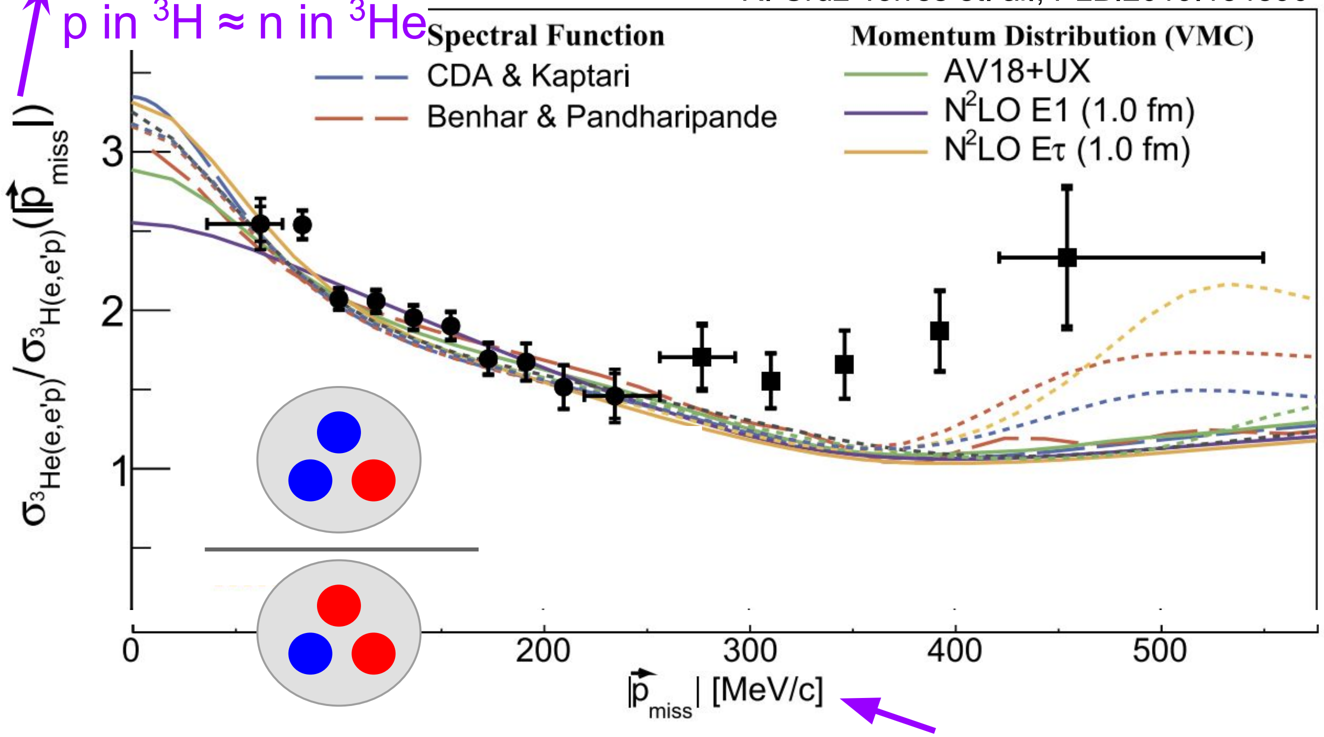
Quasi-elastic scattering to probe high momentum nucleons



p/n momentum distribution in ^{3}He

p in ^{3}H ≈ n in ^{3}He

R. Cruz-Torres et. al., PLB.2019.134890



~ nucleon initial momentum in PWIA

1, 2, 3 …

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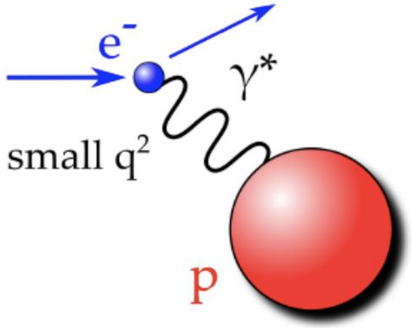

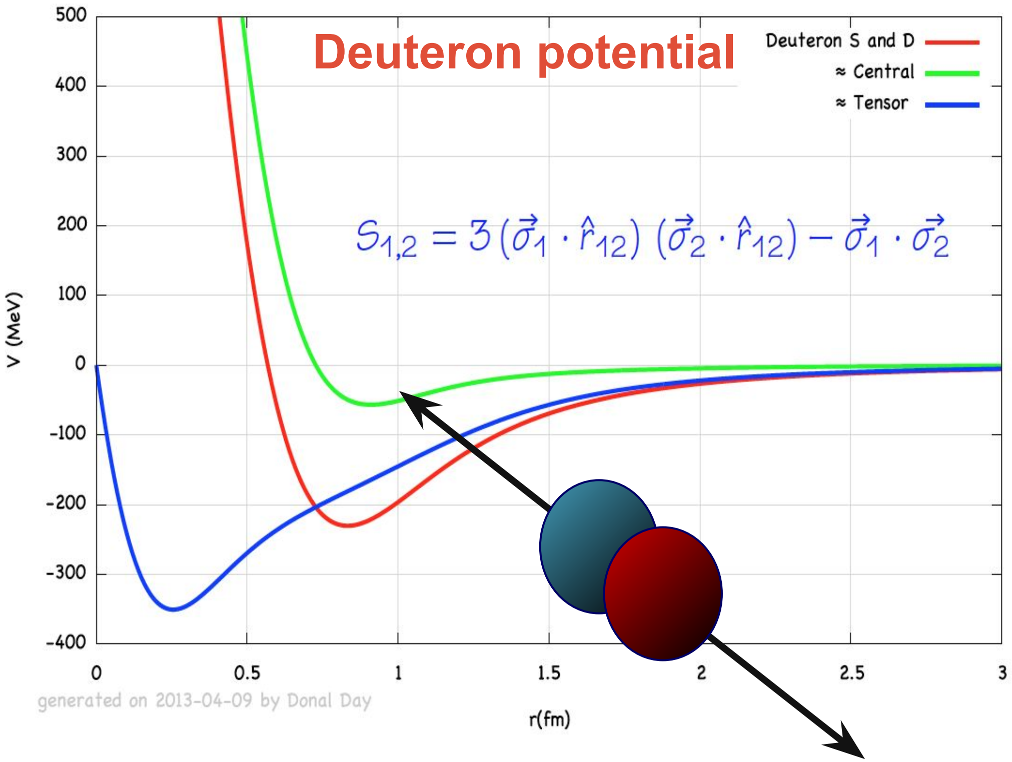

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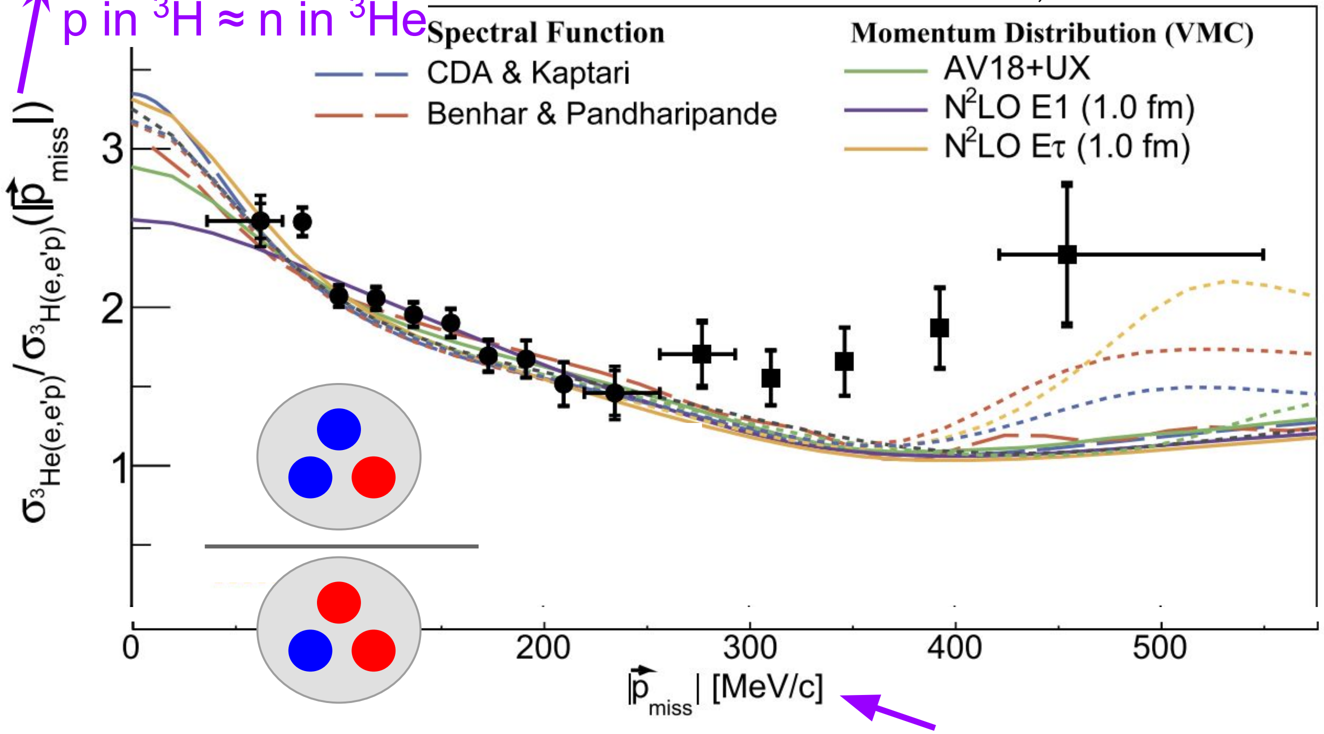


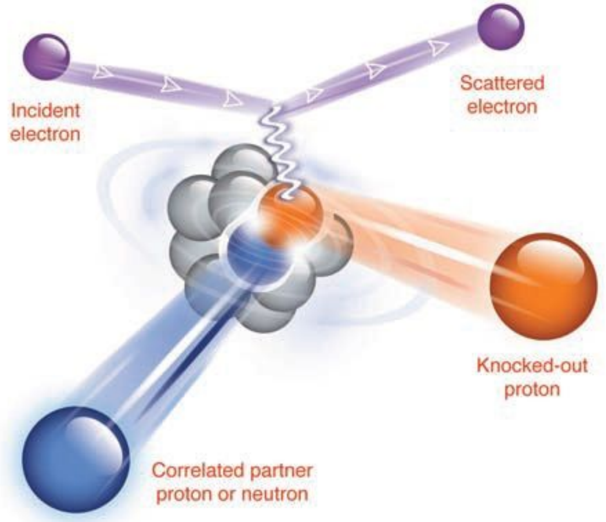
~ nucleon initial momentum in PWIA

Short-range correlated (SRC) N-N pair in nuclei:

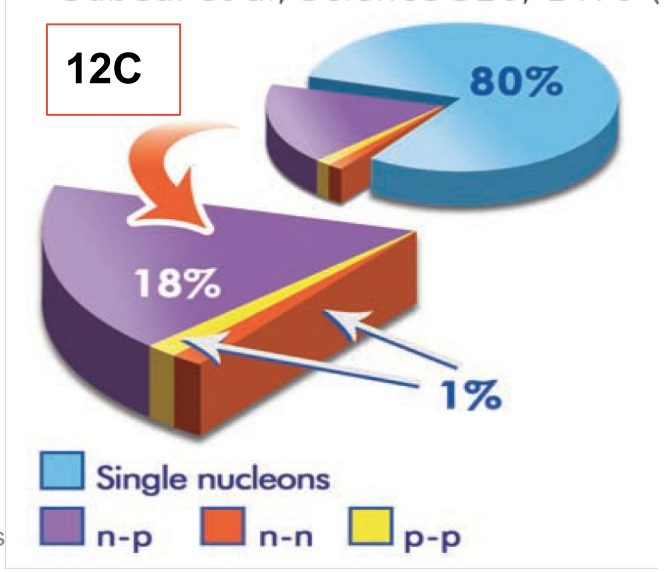
- large back-to-back momentum, low excitation state
- mainly n-p pairs (isospin=0)

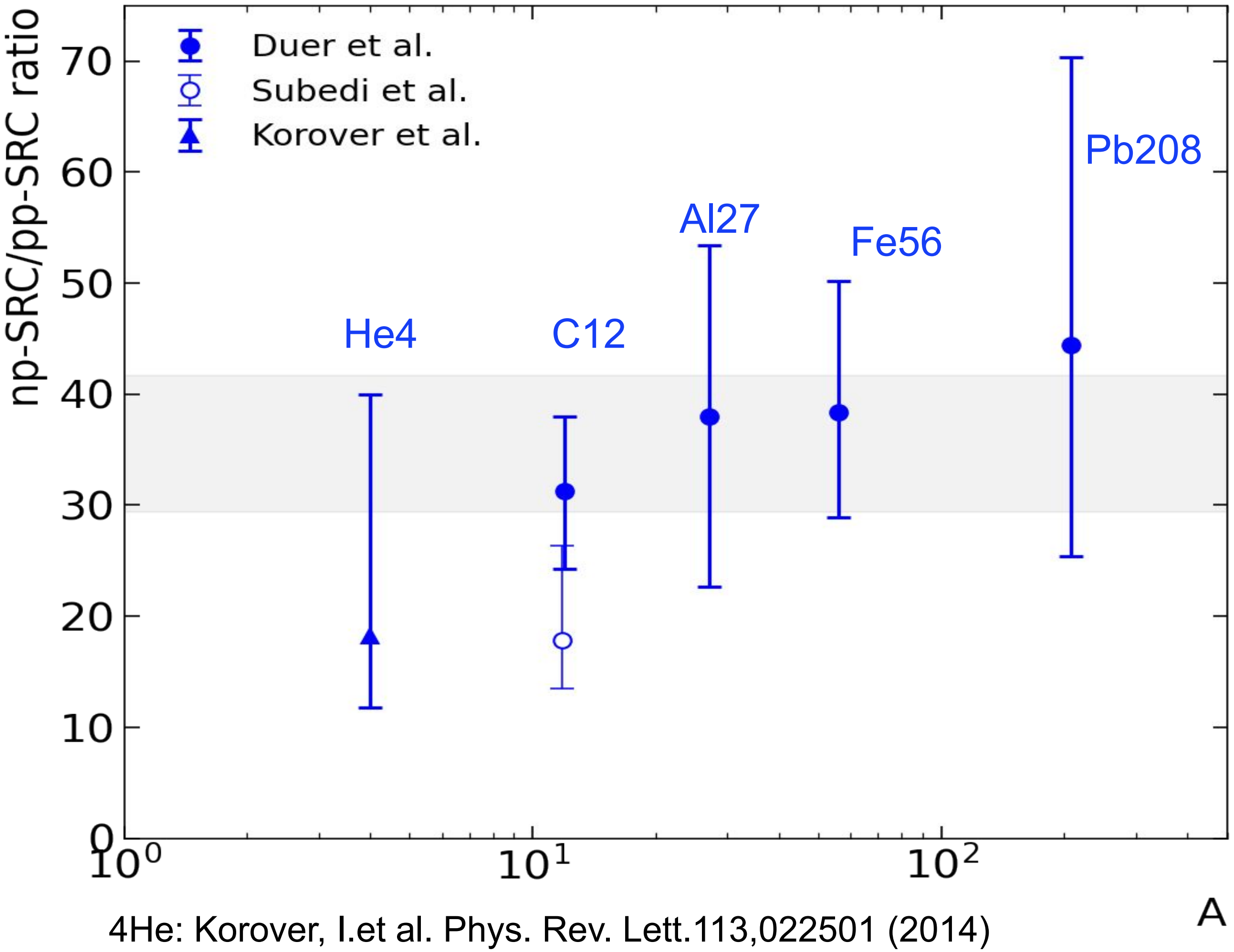
Short-range Correlations in Coincidence Measurements

Count high momentum triple-coincidence pairs



Subedi et al, Science 320, 1476 (2008)





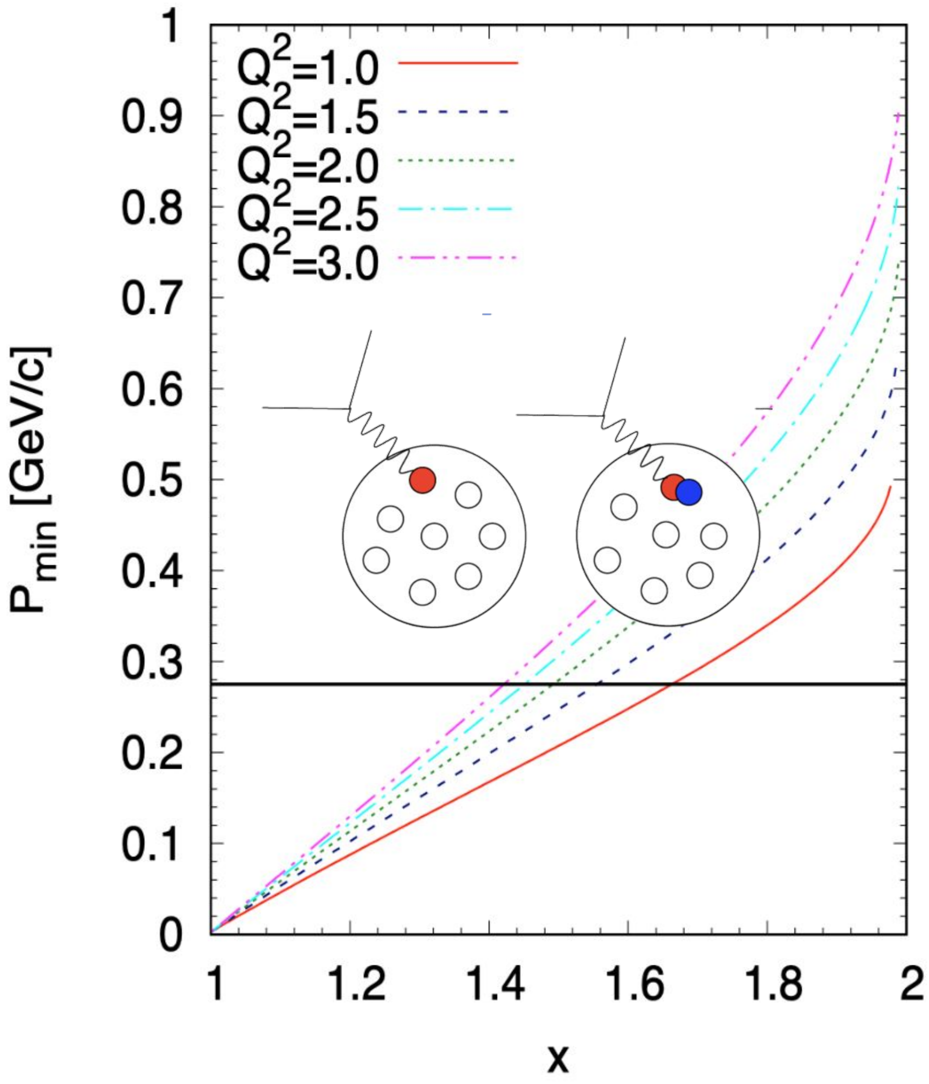
4He: Korover, I.et al. Phys. Rev. Lett.113,022501 (2014)
12C (open circle): Subedi, R. et al. Science, 320, 1476–1478 (2008).
e'pN in Solid blue: Duer, M. et al. Phys. Rev. Lett.122, 172502 (2019)

The as

Short-range Correlations in (e, e')

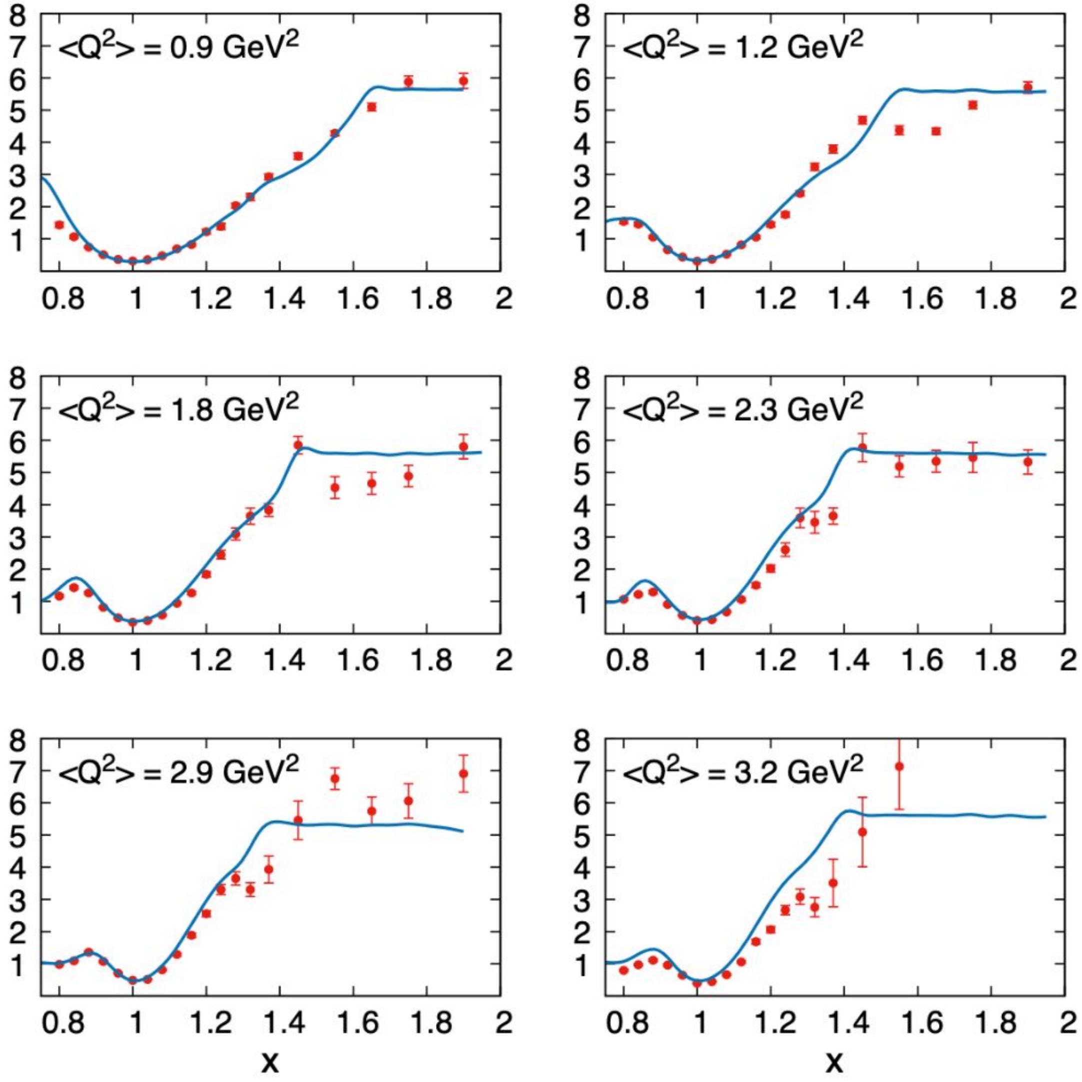
n-p pair dominance → A/D cross section

plateau → scaling above Fermi momentum



Fe/D cross section ratio from SLAC

Phys. Rev. C 48:2451 (1993)



10.1146/annurev-nucl-102020-022253

Short-range Correlations in (e, e')

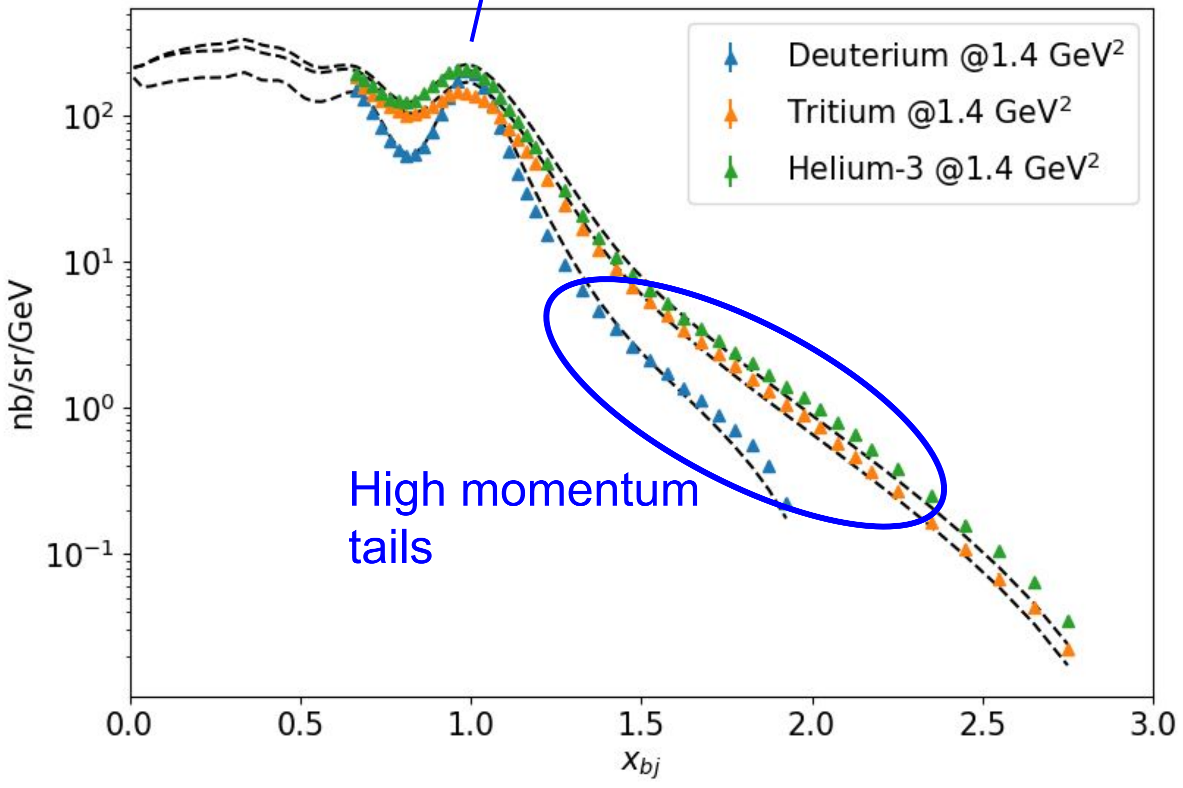
Probability to find 2N SRC in nucleus A

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

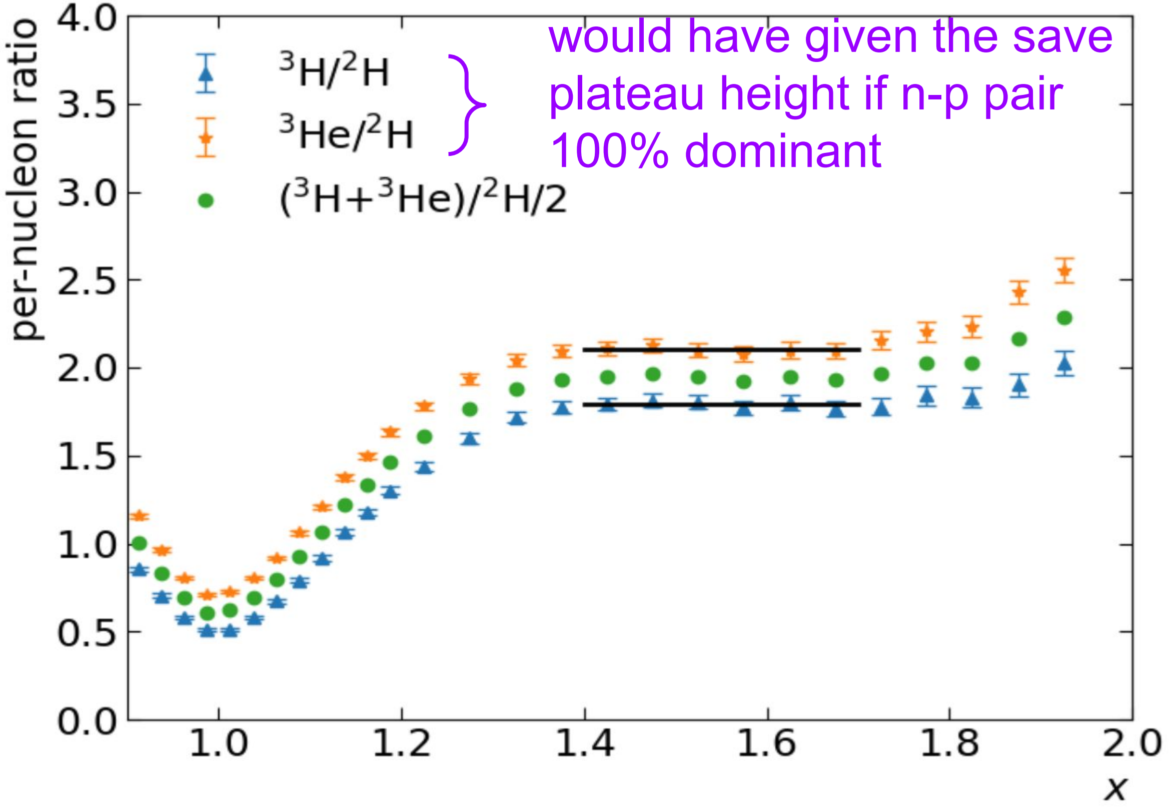
Cross section from 2N SRC

QE peak

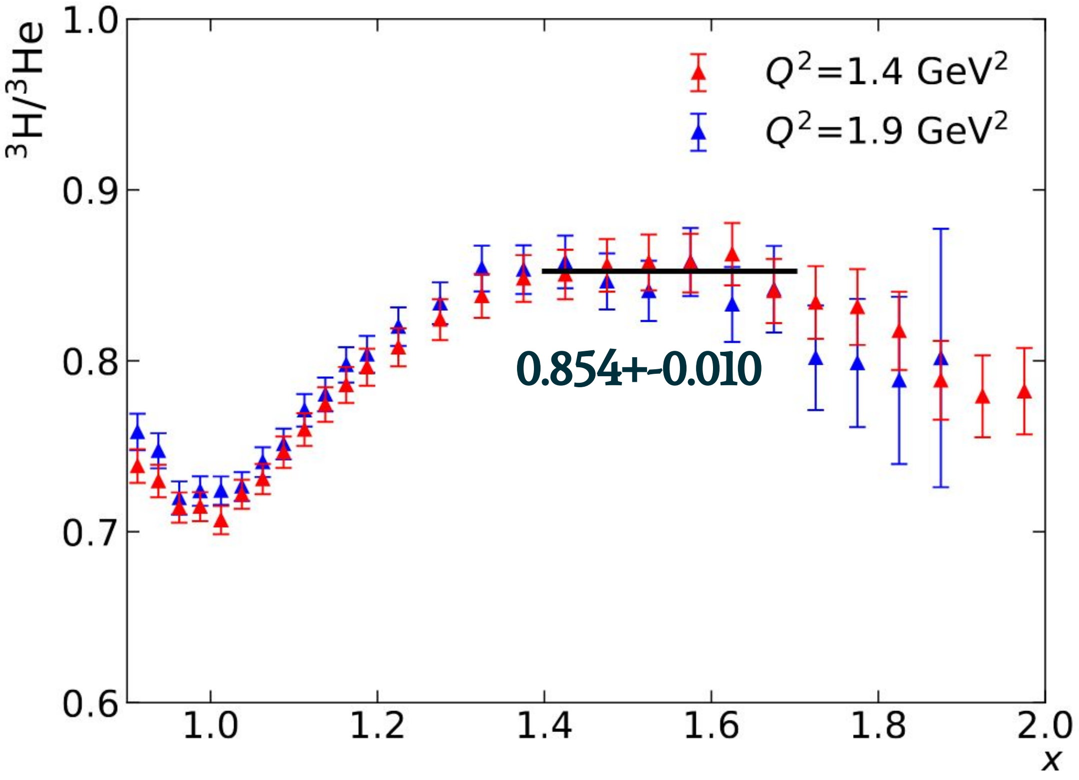
Absolute cross section



A/D ratio



Extract np/pp SRC Pair Ratio From $^3H/^3He$ Ratio:



$$\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{N_{np}\sigma_{np} + N_{pp}\sigma_{nn}}{N_{np}\sigma_{np} + N_{pp}\sigma_{pp}}$$

Offshell elastic xsection (de Forest "cc1")

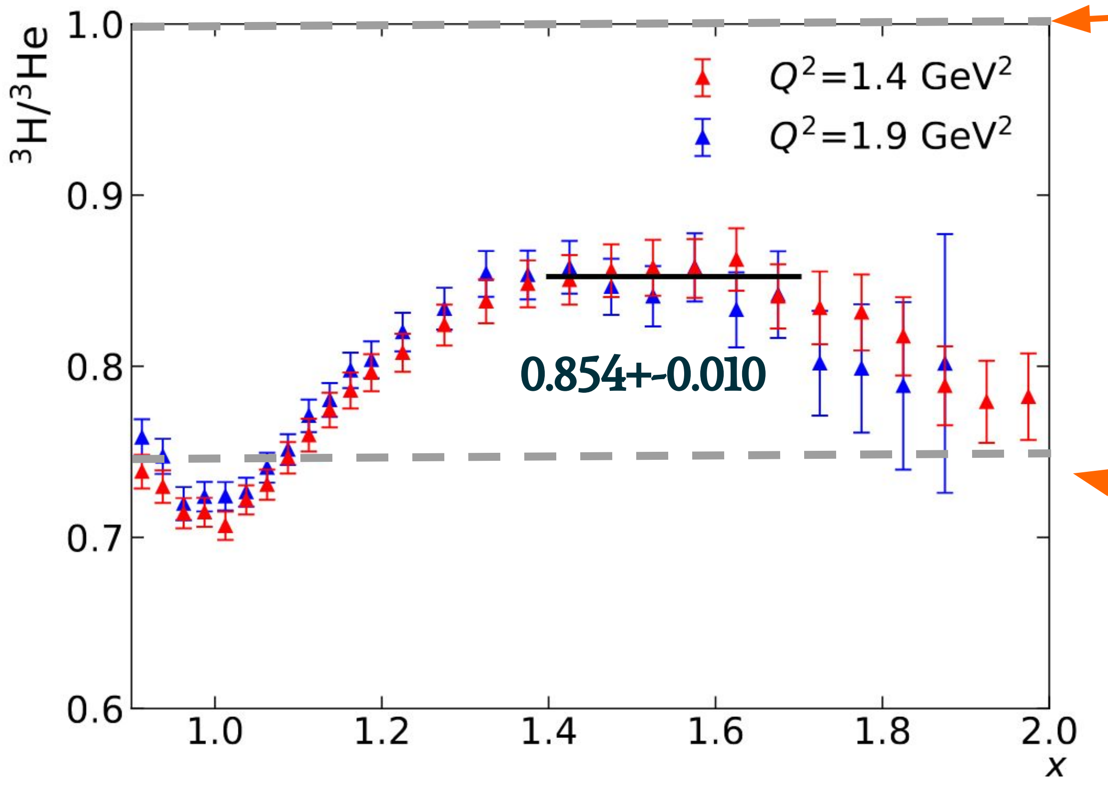
$$\sigma_{np} = \sigma_{ep} + \sigma_{en}, \sigma_{pp} = 2\sigma_{ep}$$

number of pp to np pairs ratio (assume the same in A=3)

$$R_{pp/np} = N_{pp}/N_{np}$$

$$\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{1 + \sigma_{p/n} + 2R_{pp/np}}{1 + \sigma_{p/n}(1 + 2R_{pp/np})}$$

Extract np/pp SRC Pair Ratio From $^3H/^3He$ Ratio:



If np dominant:

$$R_{pp/np} = 0 \rightarrow \frac{\sigma_{^3H}}{\sigma_{^3He}} = 1$$

If no isospin preference:

1 pp and 2 np pairs in ^{3}He from pair counting

$$R_{pp/np} = 0.5, \sigma_{p/n} = 2.55 \rightarrow \frac{\sigma_{^3H}}{\sigma_{^3He}} = 0.75$$

Extract np/pp SRC Pair Ratio From ^{3}H/^{3}He Ratio:

$$\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{1+\sigma_{p/n}+2R_{pp/np}}{1+\sigma_{p/n}(1+2R_{pp/np})}$$

correction due to **center-of-mass** motion difference: 2MeV b/w 3H and 3He, 12 MeV b/w pp and np
(Ciofi degli Atti, Claudio and Morita, Hiko, 2017)

Ratio of np/pp SRC pairs in A=3 nuclei:

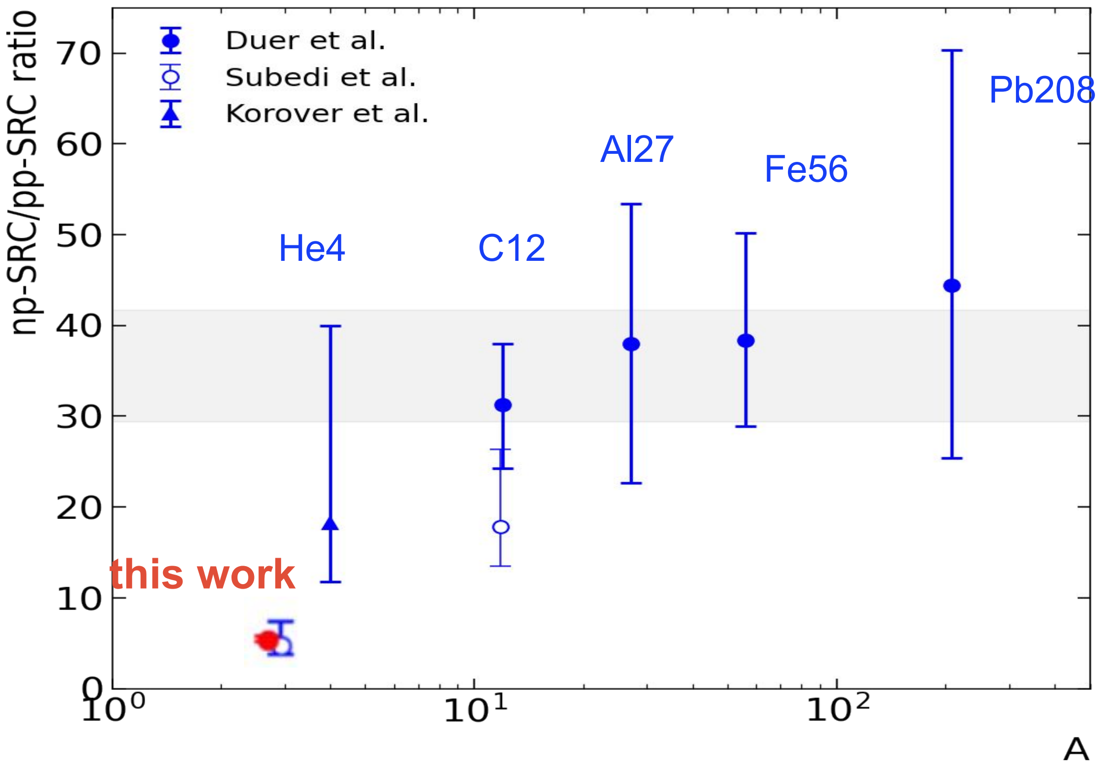
$R_{np/pp}$ =4.2+-0.4

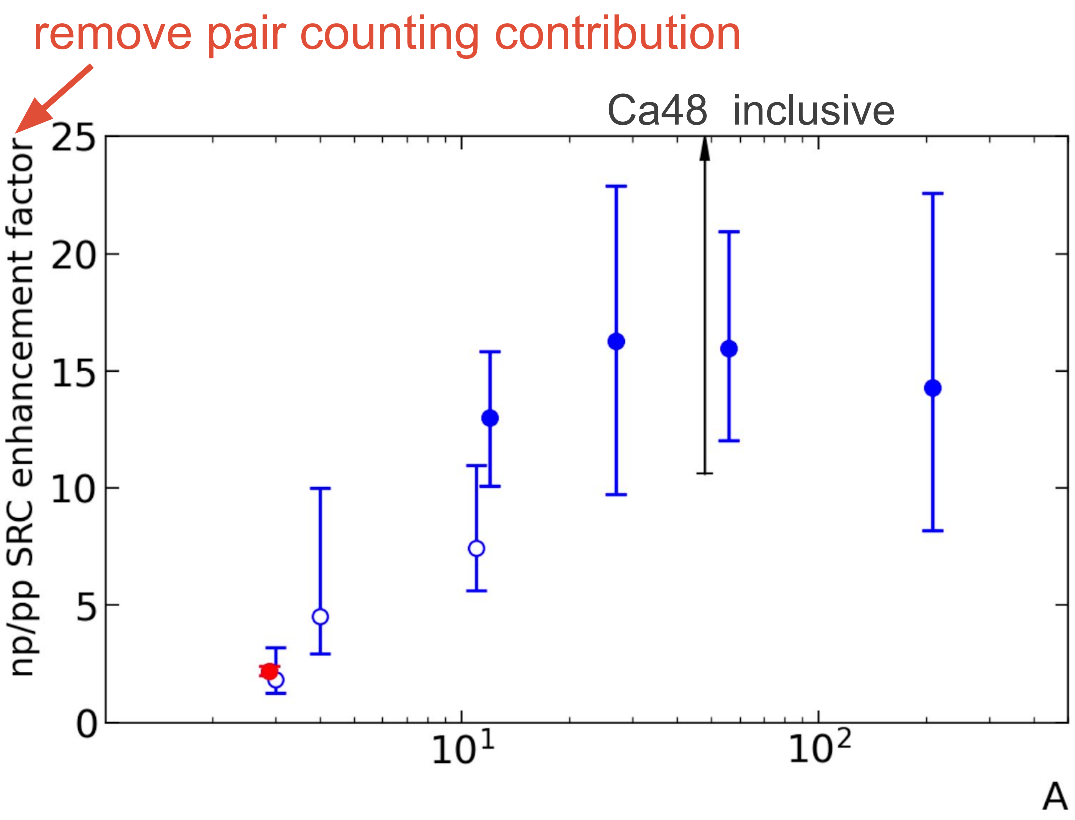
Remove contribution from pair counting:
2 np pairs v.s. 1 pp(nn) pair

np/pp “**enhancement factor**” = 2.1+-0.2

To be appeared on Nature
SL et. al,
10.1038/s41586-022-05007-2

A-dependance of np SRC

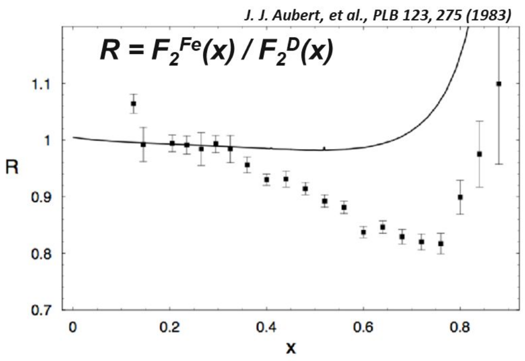


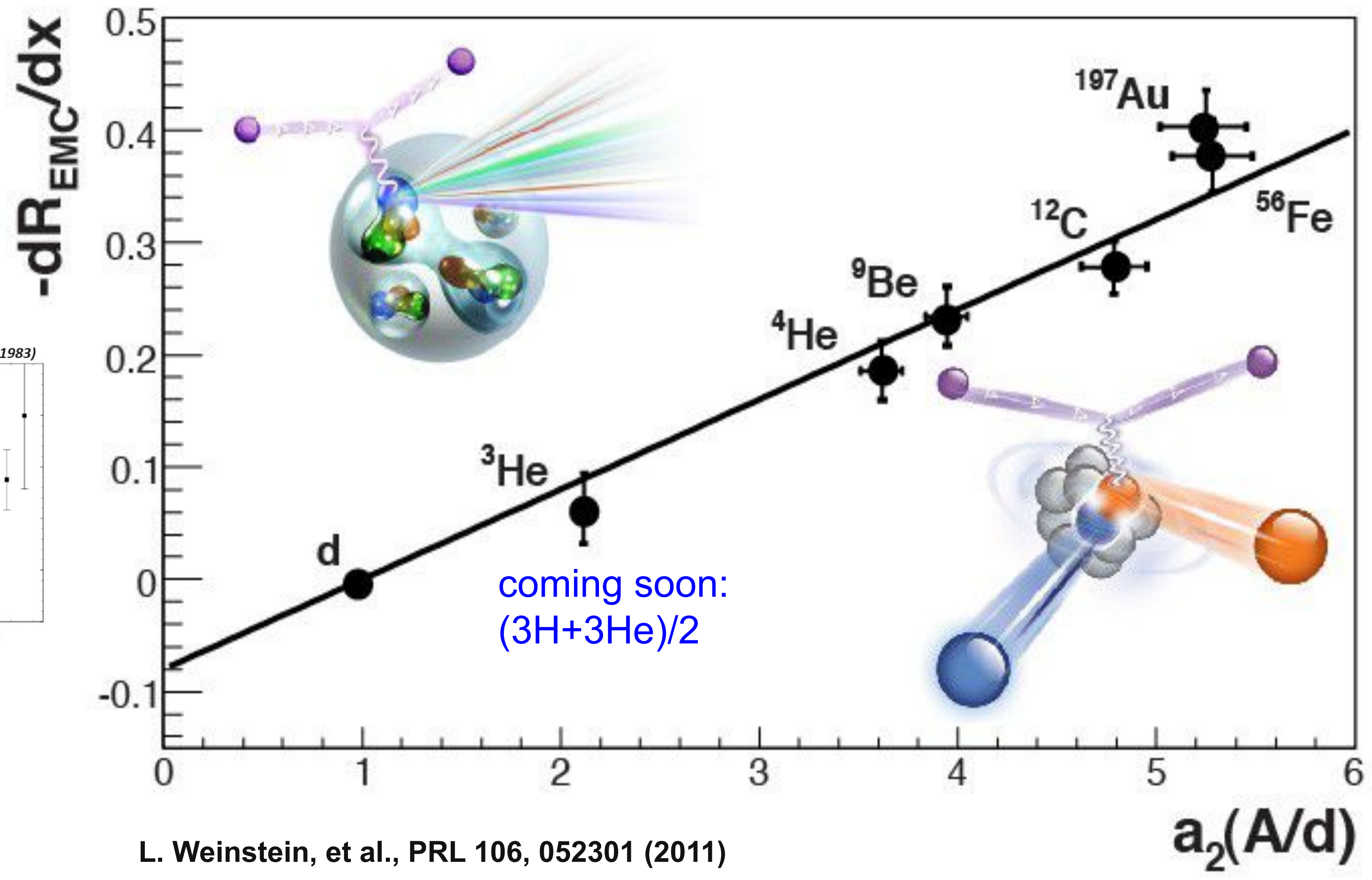


Ca48: Nguyen, D. et al. Phys. Rev. C, 102, 064004 (2020)

SRC-EMC Relations

EMC slope



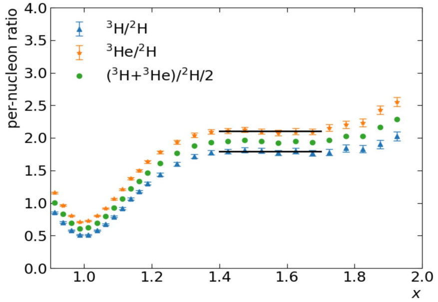


L. Weinstein, et al., PRL 106, 052301 (2011)

O. Hen, et al, PRC 85, 047301 (2012)

J. Arrington, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86, 065204 (2012)

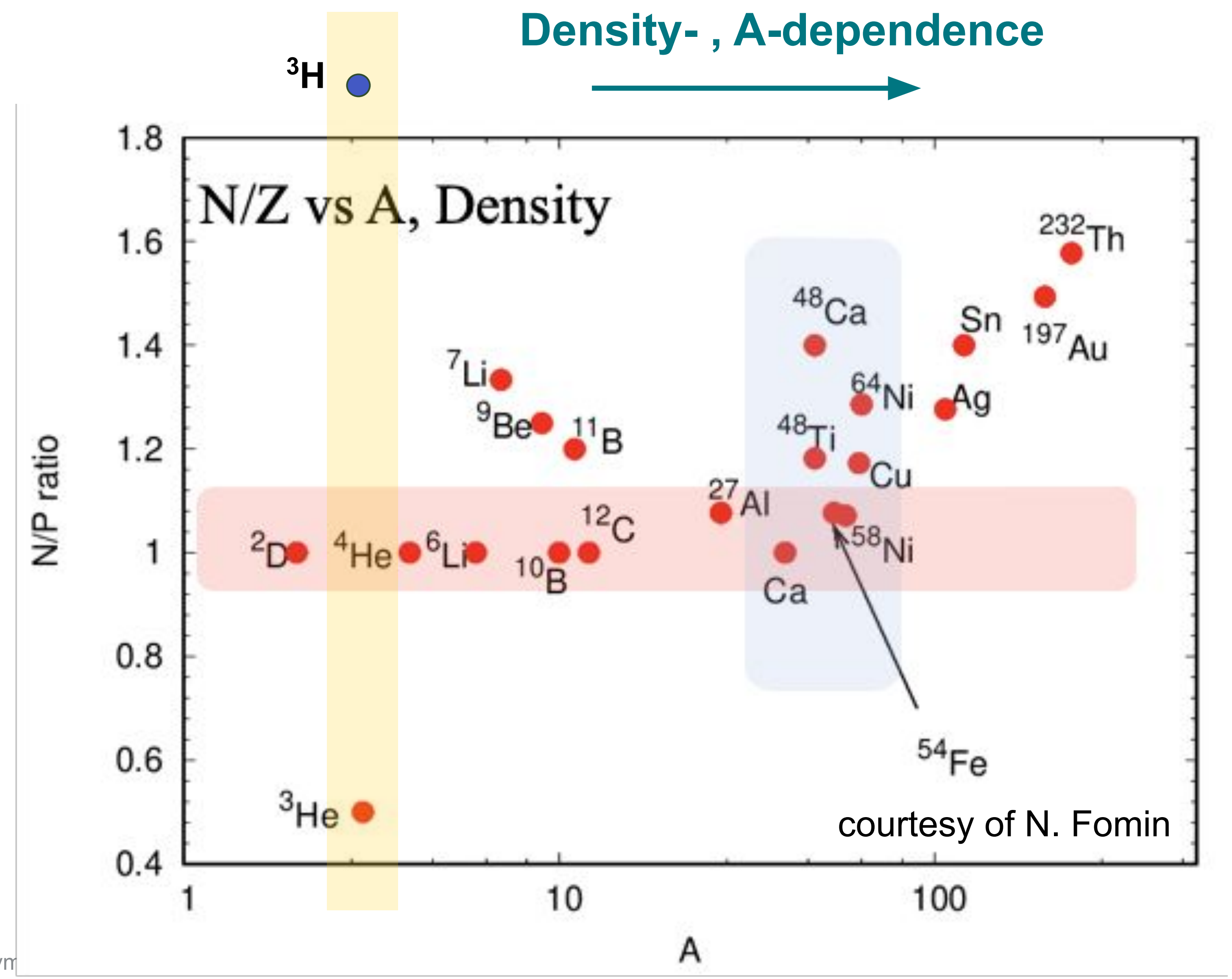
SRC plateau height



SRC-EMC Relations

A road map to infinity

See talks from D. Higinbotham, N. Fomin, J. Arrington, F. Hauenstein, **Thursday afternoon**@Camelia/Dogwood

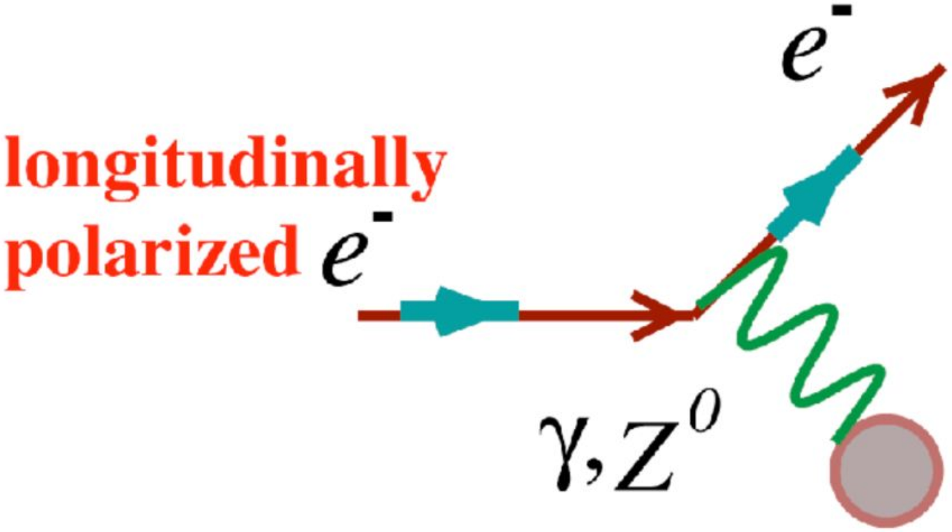


Nuclear Matter

- equation of state (see C. Drischler's talk)
- symmetric vs. neutron excess

Parity Violating Electron Scattering

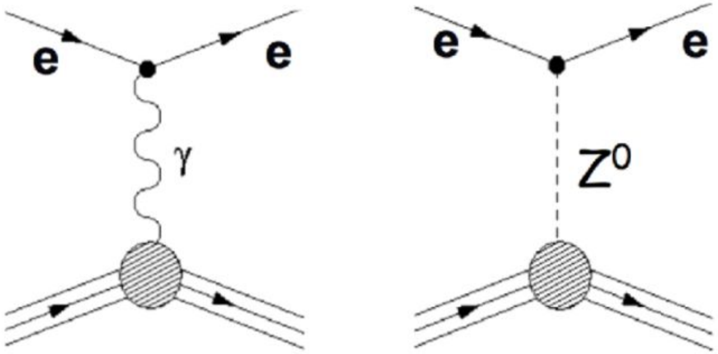
The power of weak



Proton weak charge ~ 0.07
Neutron weak charge ~ -1

In elastic e+N scattering ($Q^2 << M^Z$):

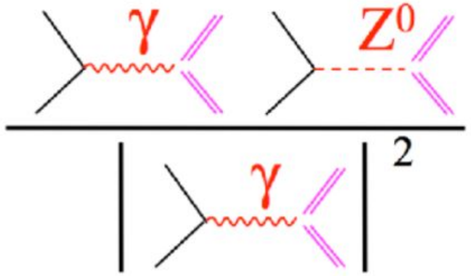
$$\sigma \propto |M_\gamma + M_{weak}|^2$$



dominant

Z^0 primarily couples to neutrons

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$

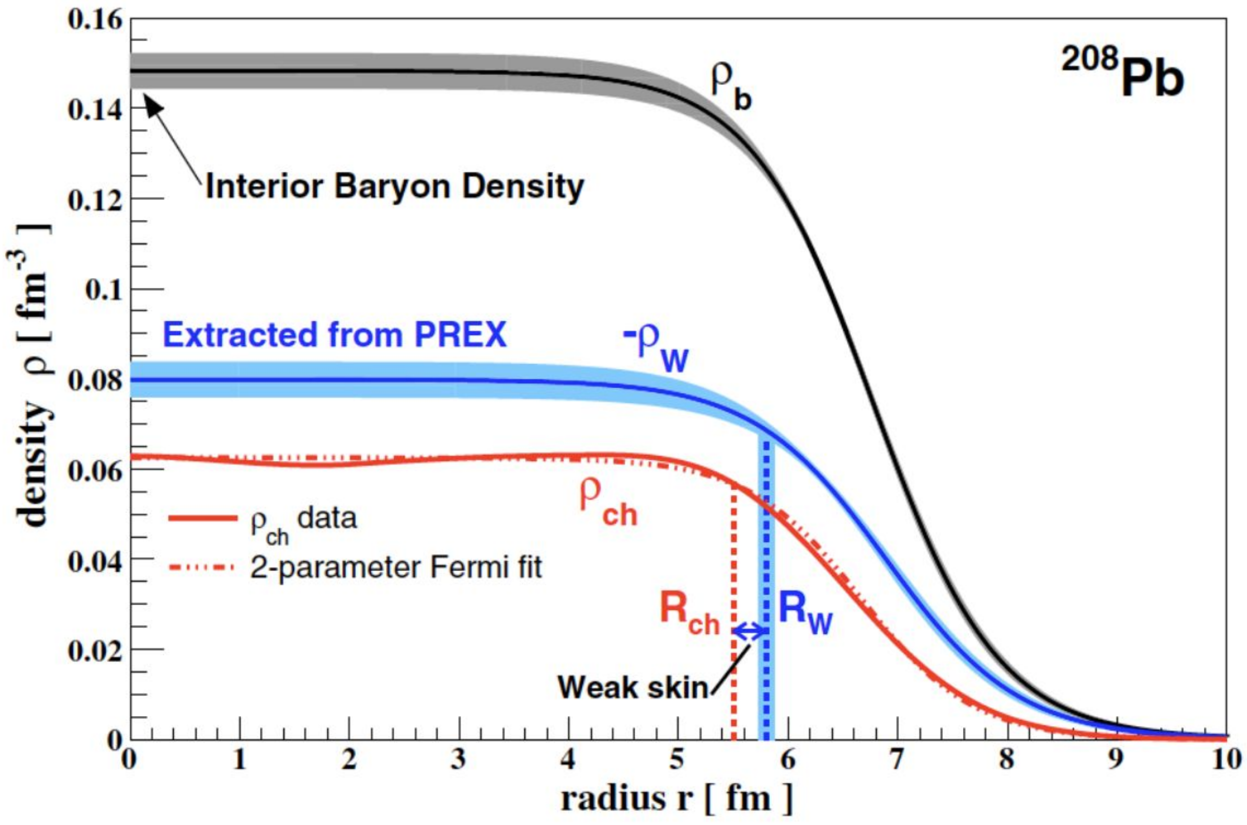


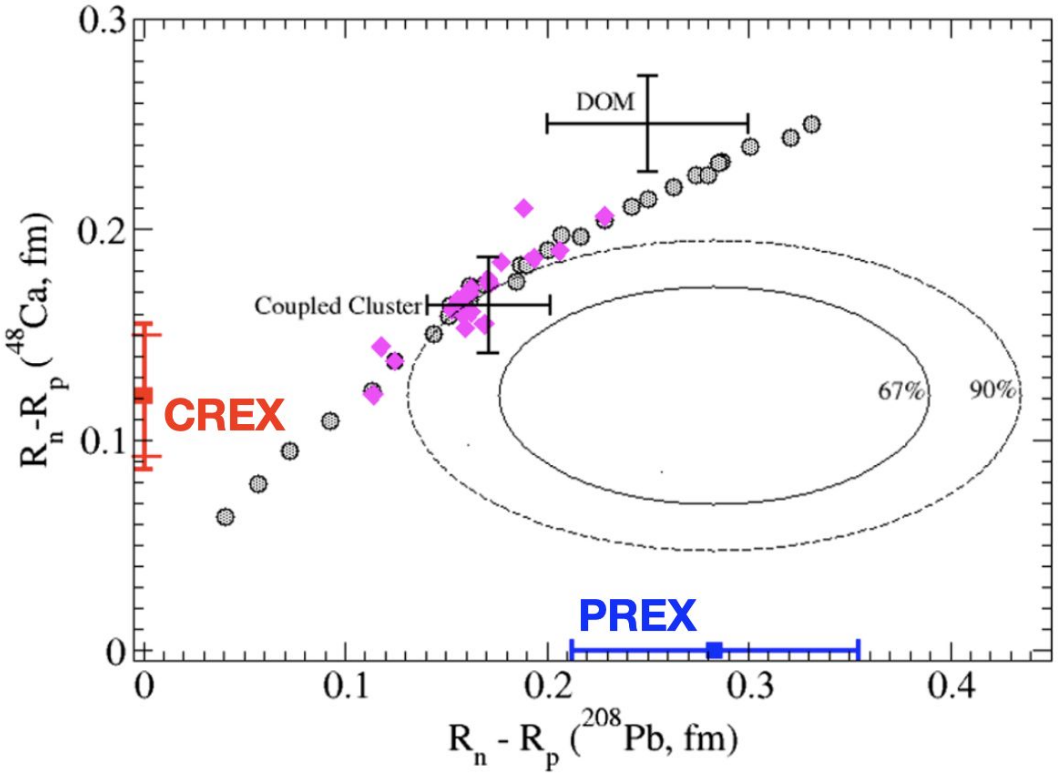
$$\propto \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|} \sim 10^{-4} \cdot Q^2$$

Courtesy of S. Park

From Neutron Skin to Neutron Stars

see J. Mammei's talk





Phys. Rev. Lett. 126, 172502 (2021)
Phys. Rev. Lett. 129, 042501 (2022)

Summary

- Electron scattering has unique sensitivity to important nuclear properties. Careful choice of asymmetric targets provides insight into both general nuclear structure and isospin/flavor dependence

- The recent tritium experiments at Jefferson provide high impact results on
  - F_2 n/p at large x
  - n/p momentum distributions and np/pp SRC ratio in A=3 system
  - The combined MARATHON and SRC results will provide unique information to understand the SRC-EMC relation.

- Starting Fall 2022, experiments at Hall C, JLab will map out the EMC-SRC relation in various light and heavy nuclei to disentangle the A vs. N/Z dependence. Also, following the success of Hall A tritium program ("once in a generation"), a broad CLAS program with tritium has been approved by JLab.

- Parity-violation electron scattering provide unique access to neutron skin thickness on heavy nuclei. That will also be used to determine the flavor-dependence in EMC effect with the future SoLID project.

THANK YOU!

From Neutron Skin to Neutron Stars

Elastic Scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp.} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{F_{ch}^2+\tau F_M^2}{1+\tau} + 2\tau F_M^2 tan^2(\frac{\theta}{2})\right].$$

$$\langle r^2\rangle \equiv -6\hbar^2 \frac{dF(q^2)}{dq^2}\bigg|_{q^2=0}$$

$$\frac{\sigma\ {}^3H}{\sigma\ {}^3He} \rightarrow \frac{F_{ch}\ {}^3H}{F_{ch}\ {}^3He} \rightarrow \Delta R_{RMS}$$

Ref.	^{3}H	^{3}He
SACLAY	1.76 ± 0.09	1.96 ± 0.03
Bates	1.68 ± 0.03	1.97 ± 0.03
GFMC	1.77 ± 0.01	1.97 ± 0.01
χEFT	1.756 ± 0.006	1.962 ± 0.004

$\rightarrow \Delta R_{RMS} = 0.20 \pm 0.1$

$\rightarrow \Delta R_{RMS} = 0.29 \pm 0.04$

Jefferson Lab Experiment E1214009

Approved but not scheduled

Ratio of the electric form factor in the mirror nuclei 3He and 3H

Spokespersons:

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Jefferson Lab
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Myers, Luke
Bluffton University
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Data taken during beam study

- Beam current: 5μA
- Beam energy: 1.171 GeV
- Momentum: 1.128 GeV
- Angle: 17 degree
- $Q^2 = 0.11\ GeV^2$

Quasi-elastic Scattering

to access the initial state of correlated nucleons

Inclusive measurement:

- Calculate the nucleon initial momentum **range** from electron kinematics

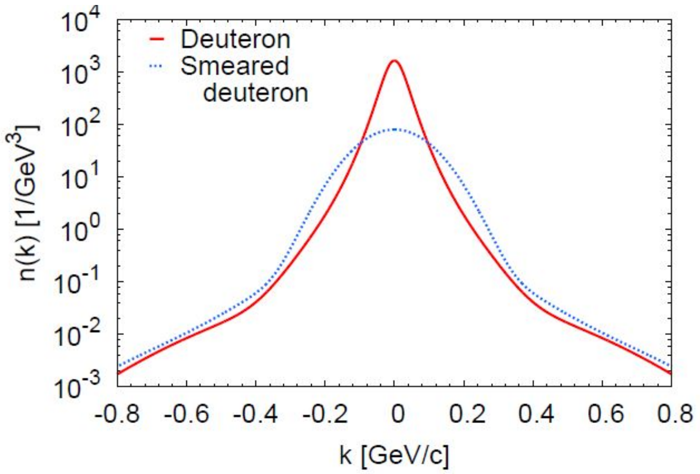
- High statistics
- Need high x, high Q2
- Competing process e.g. meson exchange current

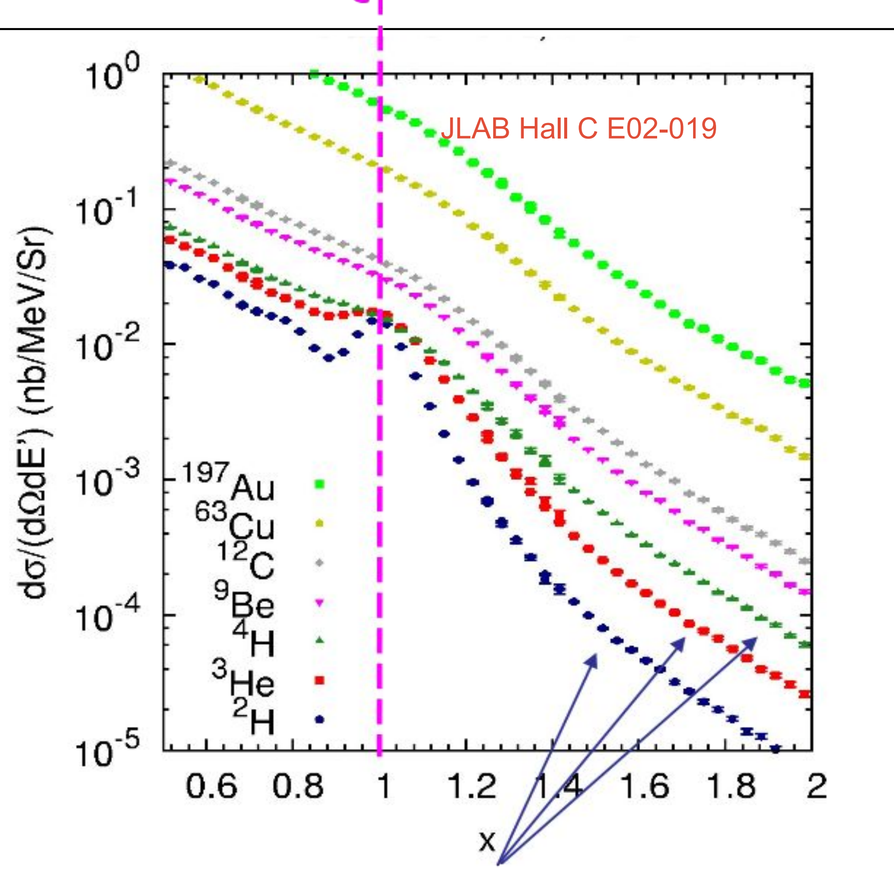
At 1.4<x<2:

Probability to find 2N SRC in nucleus A

$$\sigma_A = \cancelto{0}{\sigma_{QE}} + a_2(A)\sigma_2 + \cancelto{0}{a_3(A)\sigma_3} + \ldots$$

Cross section from 2N SRC





High momentum tails should yield constant ratio if SRC-dominated

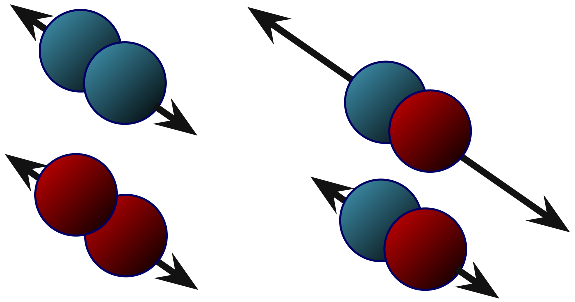
N. Fomin, et al., PRL 108 (2012) 092052

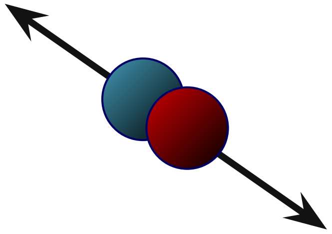
Short-distance behavior and the EMC effect

~~1. EMC effect driven by **average density** of the nucleus~~
~~[J. Gomez, et al., PRD 94, 4348 (1994), Frankfurt and Strikman, Phys. Rept. 160 (1988) 235]~~

2. EMC effect is driven by **Local Density (LD)** – overlap of nucleons
[J. Seely et al., PRL 103, 202301, 2009]
SRCs generated by interactions in short-distance (high-density) np pairs
EMC effect driven by high-density nucleon configurations (pairs, clusters)

3. EMC effect driven by **High Virtuality (HV)** of the nucleons
[L. Weinstein et al, PRL 106, 052301,2011]
SRC measurements directly probe high-momentum nucleons
EMC effect driven by off-shell effects in high-momentum nucleons

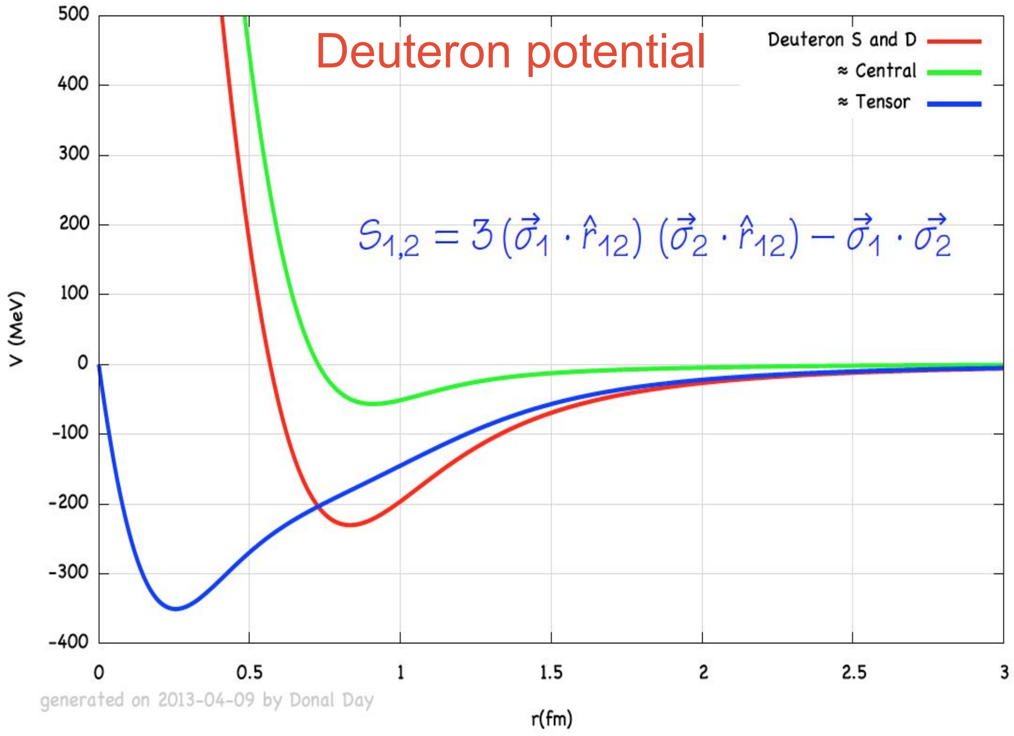


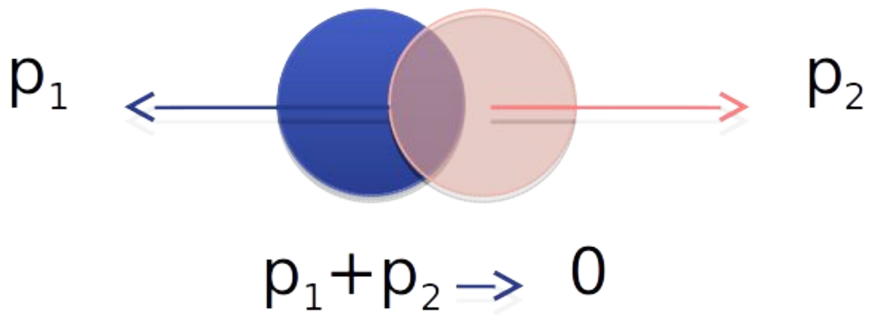


First comparison of HV/LD explanations of EMC-SRC correlation:
JA, A. Daniel, D. Day, N. Fomin, D. Gaskell, P. Solvignon, PRC 86 (2012) 065204

Nucleon-Nucleon Short Range Correlation (SRC)

Free nucleon-nucleon potential = **Repulsive core+ attractive tensor force**
T = 1, S = 0 :np, pp, nn pairs. The tensor operator $S_{1,2}$= 0 , no attractive tensor force
T = 0, S = 1: Deuteron-like np pair.

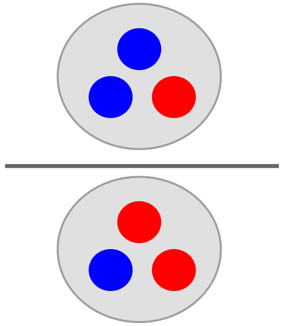




N-N SRC pair in nuclei:

- large back-to-back momentum, low excitation state
- fraction of SRC pairs in nuclei ?
- in which T and S configuration ?

1, 2, 3 …



Tritium v.s. Helium-3:

- Large isospin (neutron-proton) asymmetry
- Similar separation energy: 6.26 MeV v.s. 5.49 MeV
- Small Coulomb effect: V_eff = 0.66 MeV v.s. 0

Tritium experiments at JLab

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

$$\boxed{\mathcal{R} = \frac{R(^3\mathrm{He})}{R(^3\mathrm{H})}}$$

model dependence?
isospin-dependent
nuclear effect?
C. Cocuzza et. al., arXiv:2104.06946

$$\boxed{\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}}}$$

Phys. Rev. Lett. **128**, 132003