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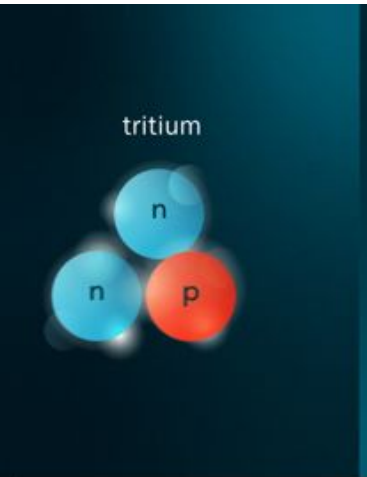
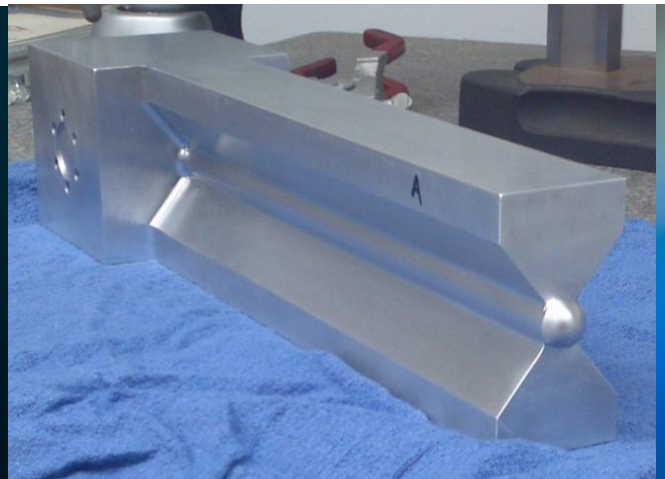
U.S. DEPARTMENT OF ENERGY
Office of Science

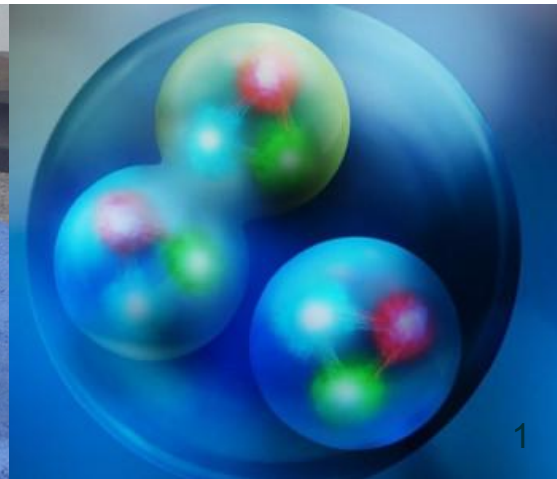
Scaling behaviors of Short-range Correlations in A=3 Systems

Shujie Li, Lawrence Berkeley National Lab

Nuclear Physics Seminar @ BNL
June 17, 2024

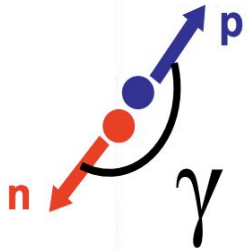


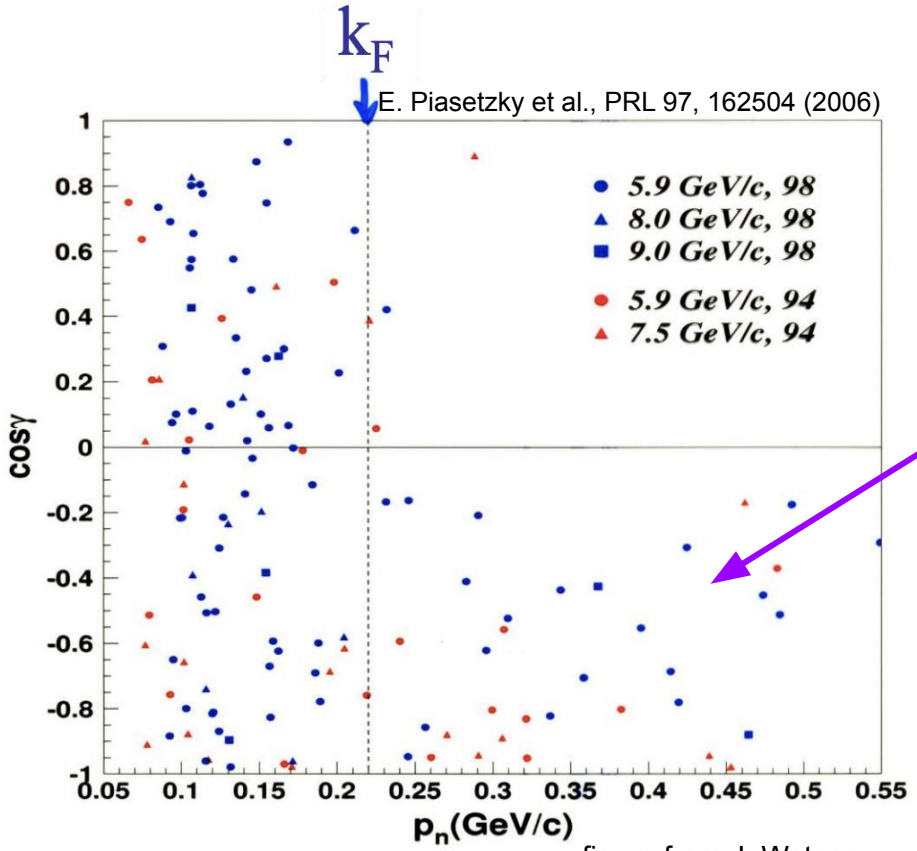




SRC @ BNL

C(p,p'pn)X with EVA spectrometer at AGS





most **high momentum** nucleon pairs have strong **back-to-back** initial angle correlation.

figure from J. Watson

SRC @ BNL

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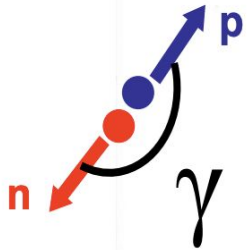
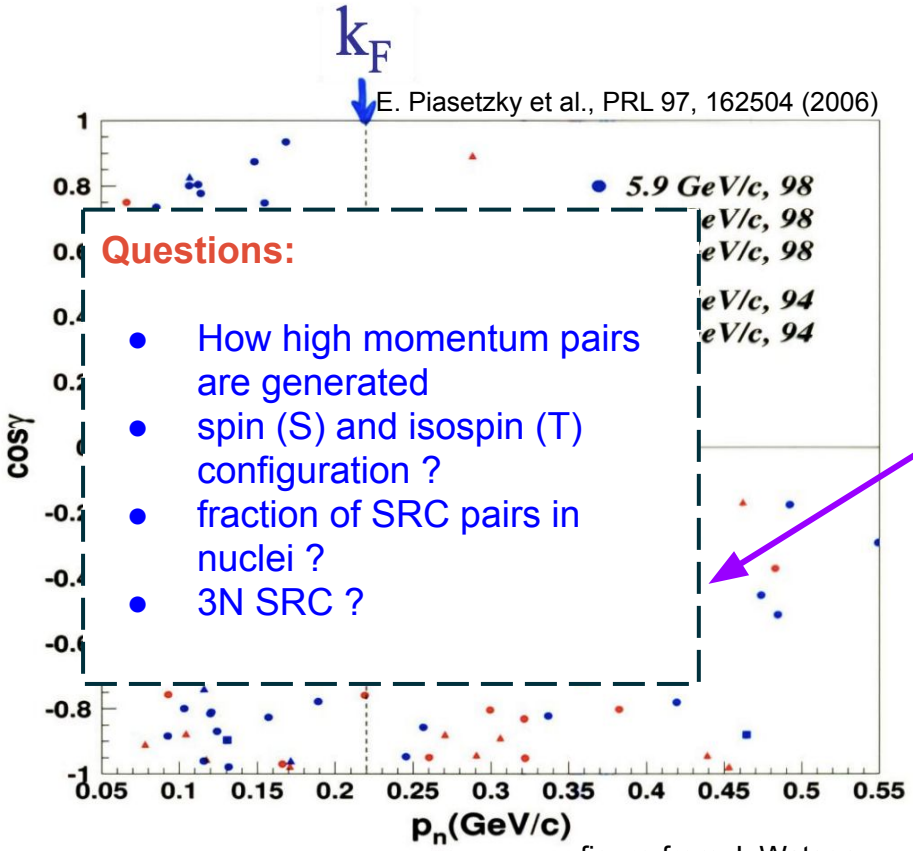




Questions:

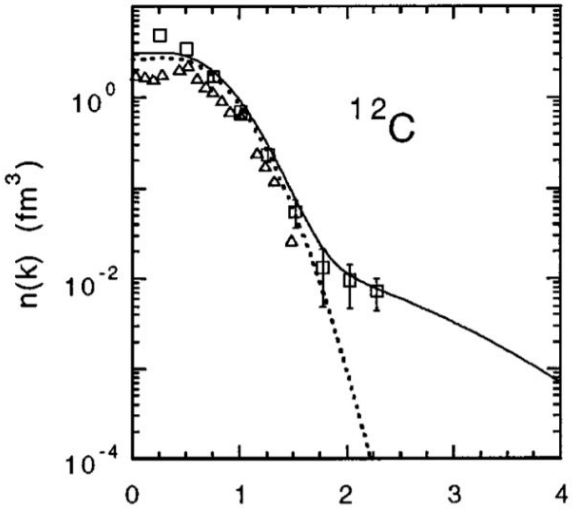
- How high momentum pairs are generated
- spin (S) and isospin (T) configuration ?
- fraction of SRC pairs in nuclei ?
- 3N SRC ?

most **high momentum** nucleon pairs have strong **back-to-back** initial angle correlation.

figure from J. Watson

Nucleon momentum and interactions

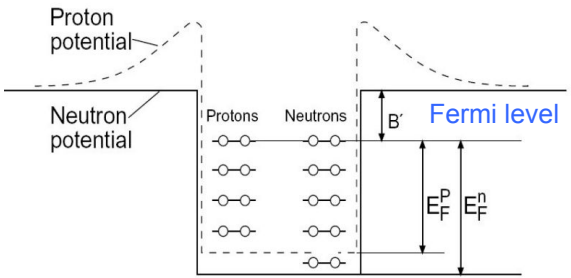
Cioffi Degli Atti. et al. PRC53. 1689 (1996)



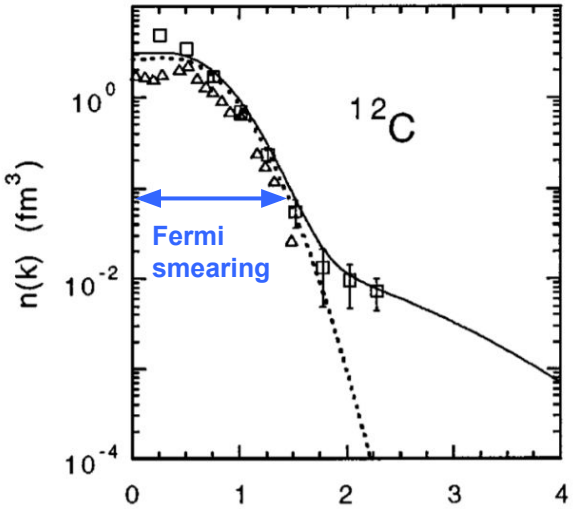
Nucleon momentum and interactions

- **Independent particle shell model ("Mean field"):**
  nucleons move independently in an averaged potential induced by the rest of the nucleus system:

$$\left[-\frac{\hbar^2}{2m_N}\nabla_i^2 + U(\boldsymbol{x})\right]\phi_\alpha(\boldsymbol{x}_i) = \epsilon_\alpha\phi_\alpha(\boldsymbol{x}_i)$$



Cioffi Degli Atti. et al. PRC53. 1689 (1996)



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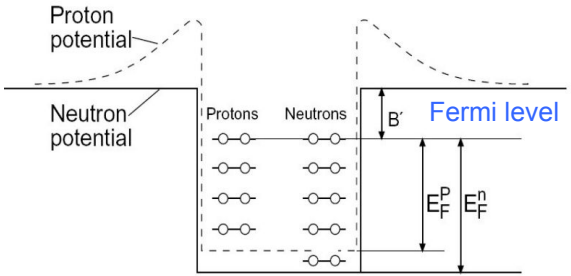

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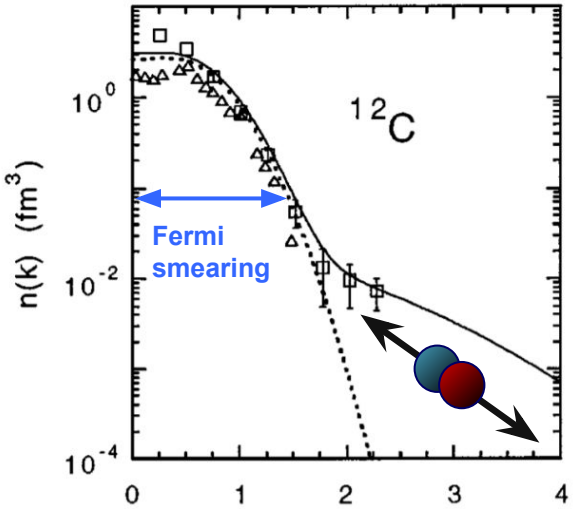
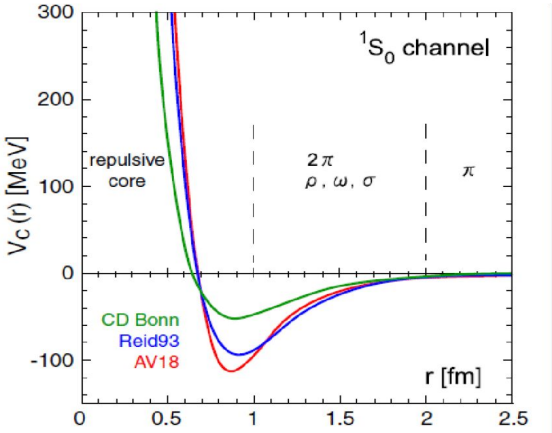


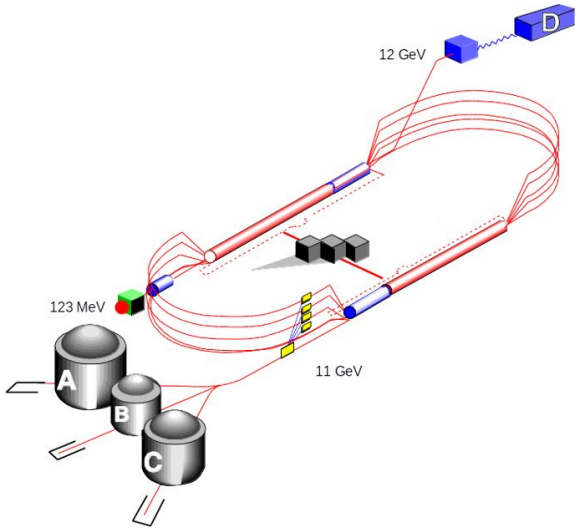


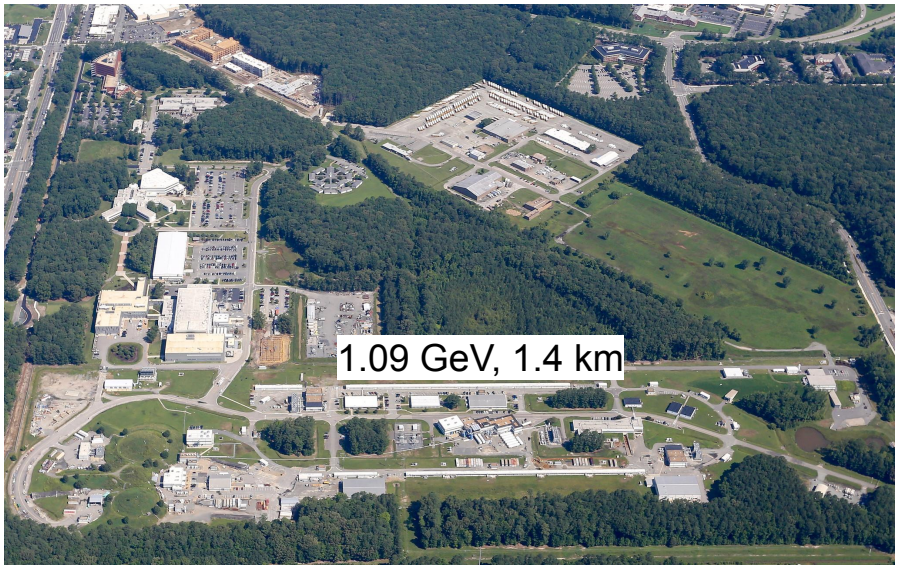
- **Nucleon-nucleon short-range correlations:**
  - NN pairs with large back-to-back momentum, while total → 0
  - T=0 deuteron-like np pair dominants due to tensor force.

Jefferson Lab as the “Intensity Frontier”

Continuous Electron Beam Accelerator Facility (CEBAF)

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





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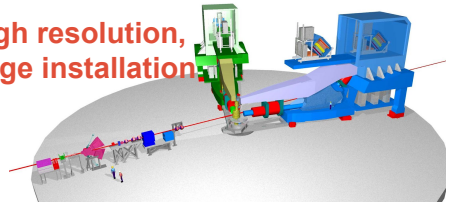
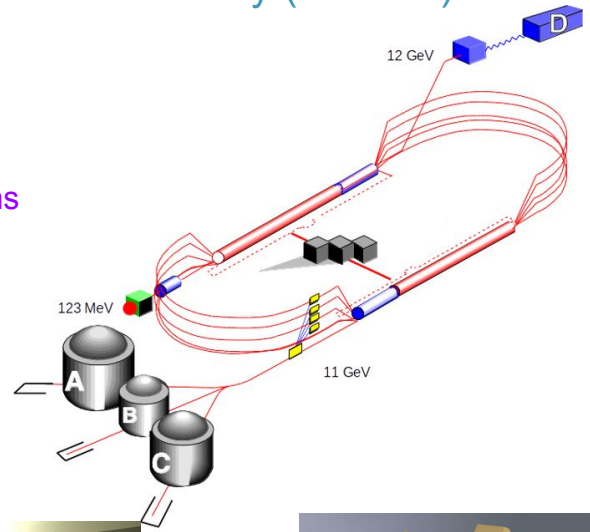
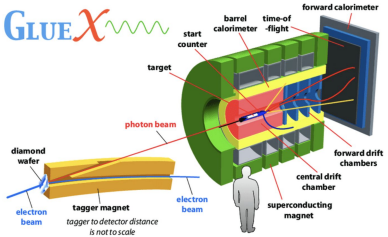
High resolution, large installation

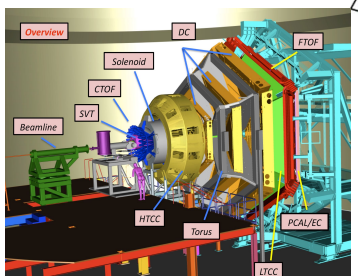


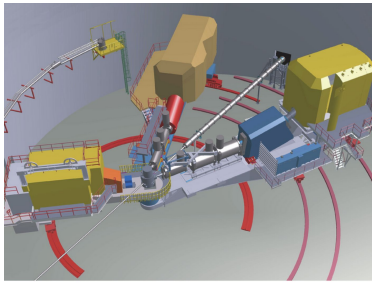


Photon beam



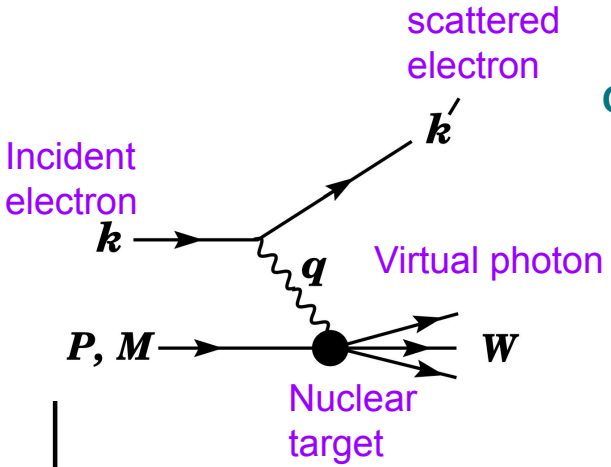
Large Acceptance





High momentum,
-precision cross sections

Electron Scattering

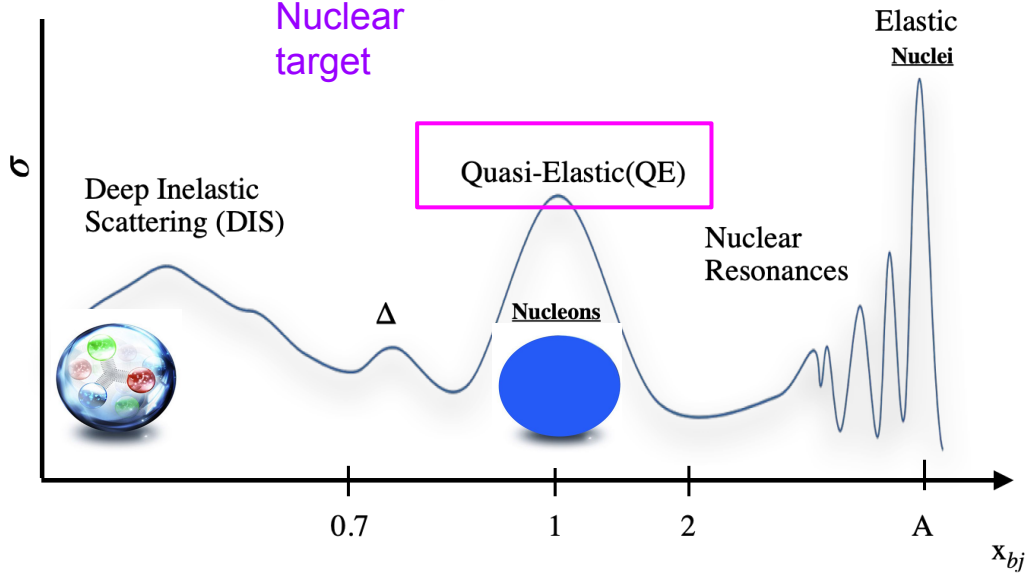


Cross section ~ probability of scattering

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

Leptonic tensor (QED)
Point-like electron

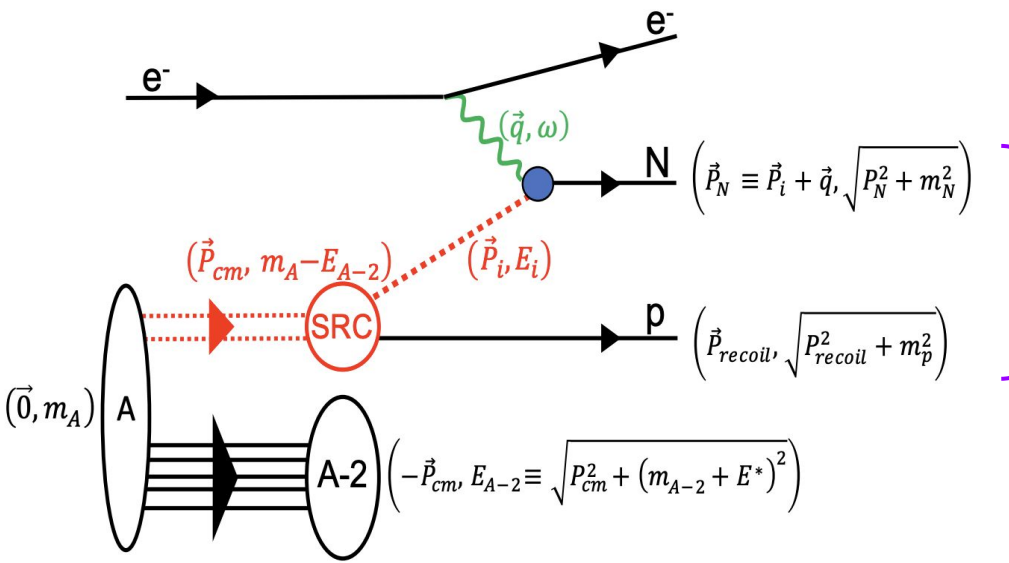
hadronic tensor
Nuclear structure:
(nucleonic / partonic)



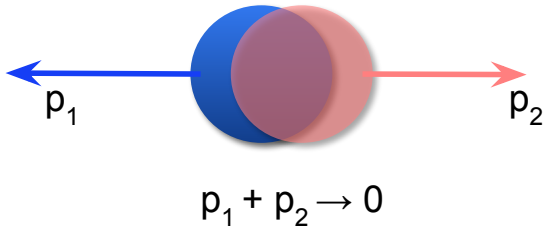
$Q^2 = -q^2$ four-momentum transfer squared

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

Probing SRC in Electron QE Scattering



Large back-to-back momentum (>k_F)

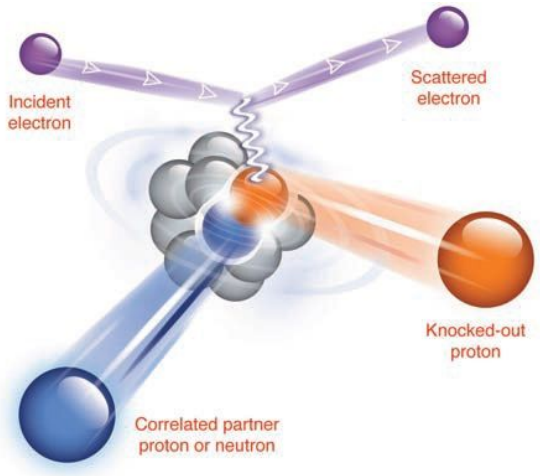


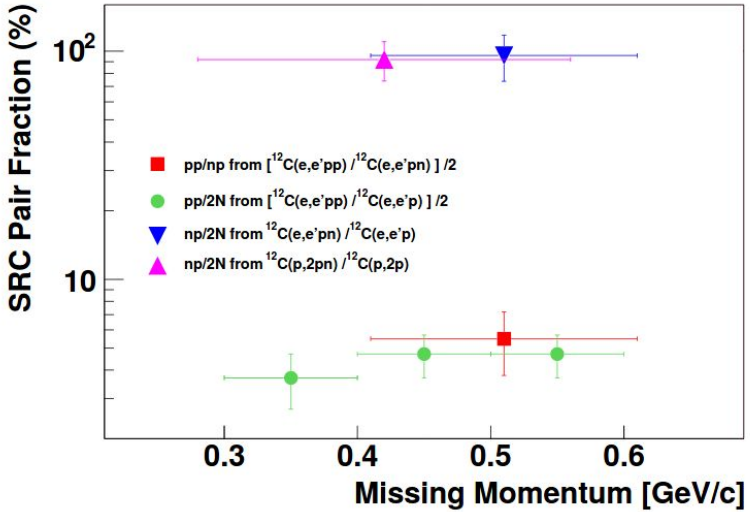
SRC in Exclusive Quasi-elastic Scattering

to access the initial state of correlated nucleons, low stats, large contaminations

JLab E01-015:

Probing the tensor force dominant region with missing momentum 300~600 MeV





Subedi et al, Science 320, 1476 (2008)

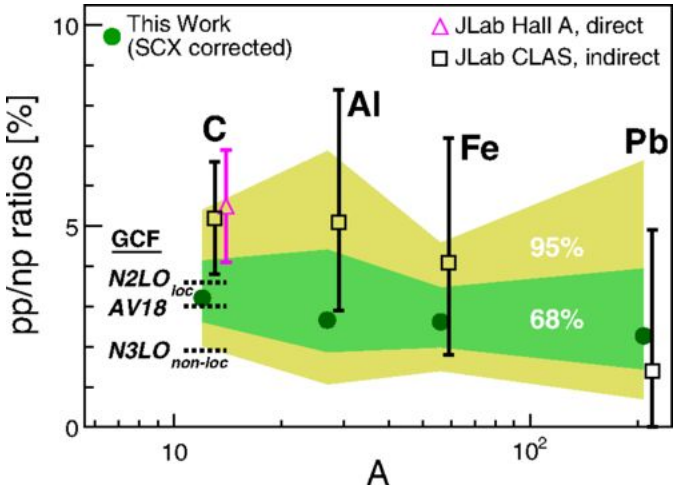
- **Almost all high momentum nucleons appear in pairs**
- **more than 90% of SRC pairs are n-p pairs**
  ⇒ isospin 0, np pairs dominate

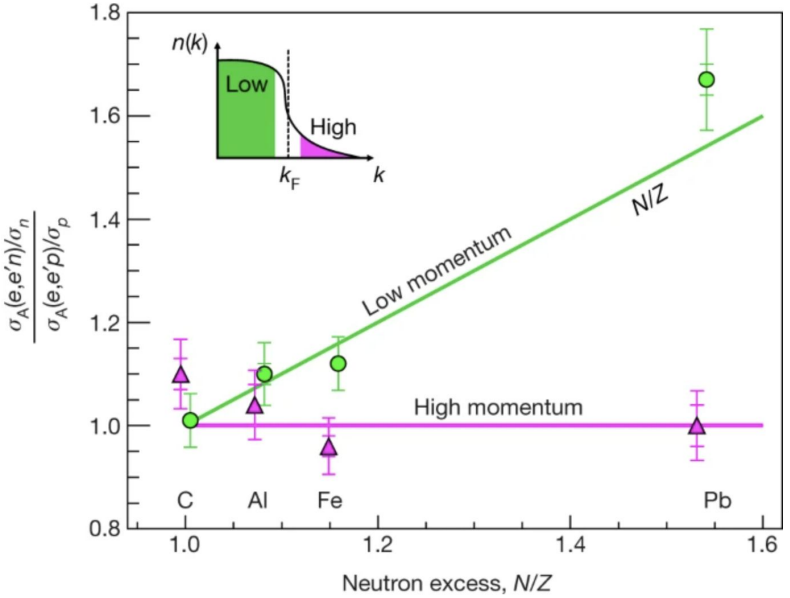
SRC in Exclusive Quasi-elastic Scattering

to access the initial state of correlated nucleons, low stats, large contaminations

A(e,e'np)/A(e,e'pp) from CLAS6 data mining

M. Duer *et al.* (CLAS Collaboration), Phys. Rev. Lett. 122, 172502



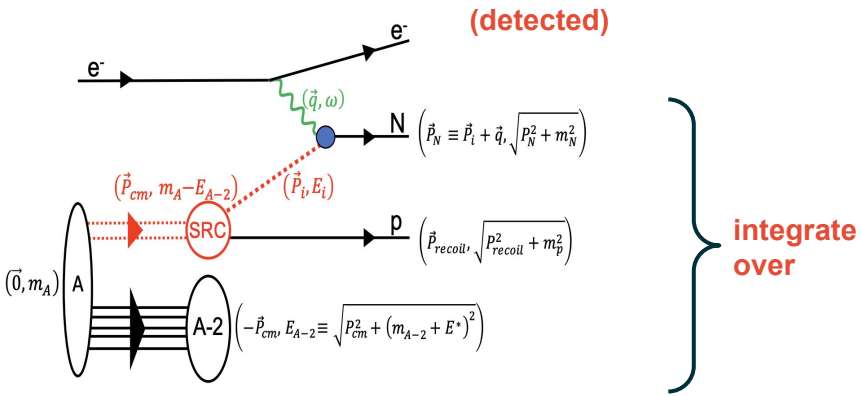


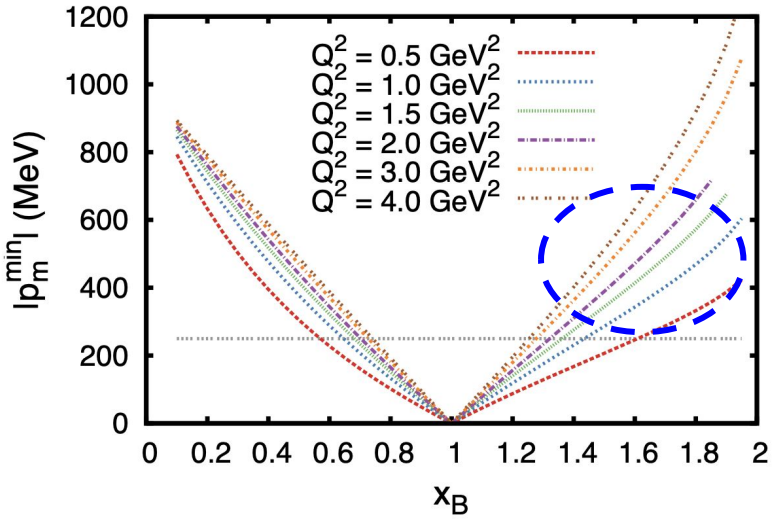
- **large n-p enhancement of SRC in heavy nuclei**

SRC in Inclusive Quasi-elastic Scattering

Inclusive (e,e') scattering:

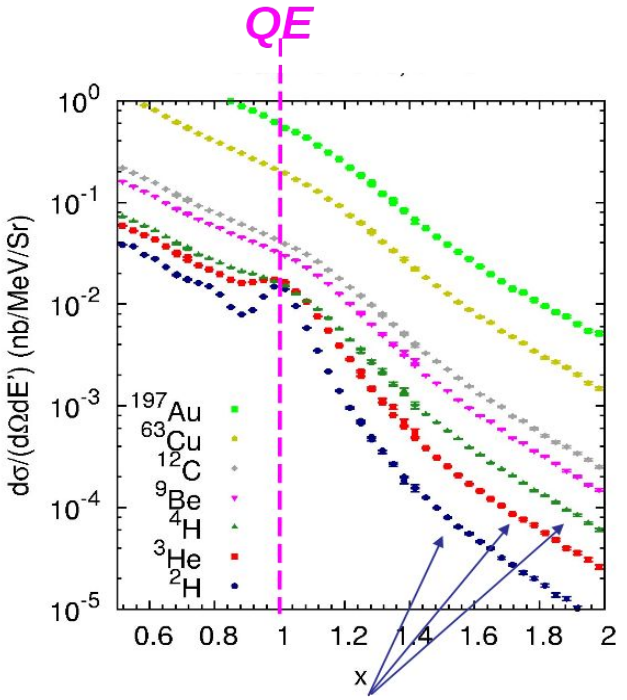
- high statistics
- background suppressed at high Q^2
- No **direct** access to initial nucleon momentum
- high x and Q^2 → high nucleon momentum





Q2>1.4 GeV2, 1.4<x<2 (high momentum, low energy transfer):
minimum initial momentum of the struck nucleon > k_F
⇒ 2N SRC dominant

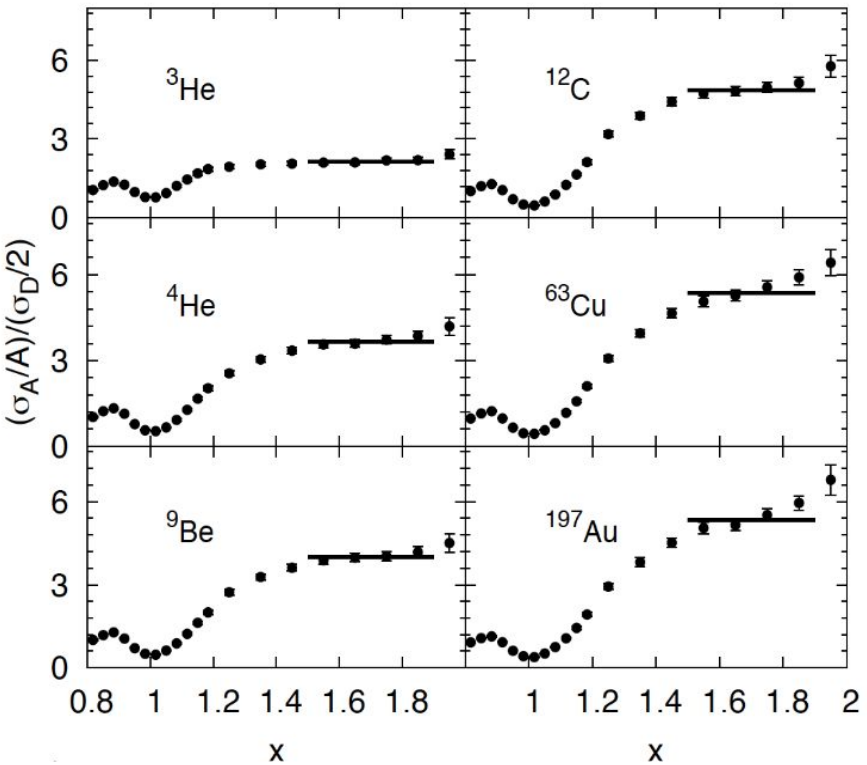
Onset of 2N SRC scaling at x>1



High momentum tails should yield constant ratio if SRC-dominated

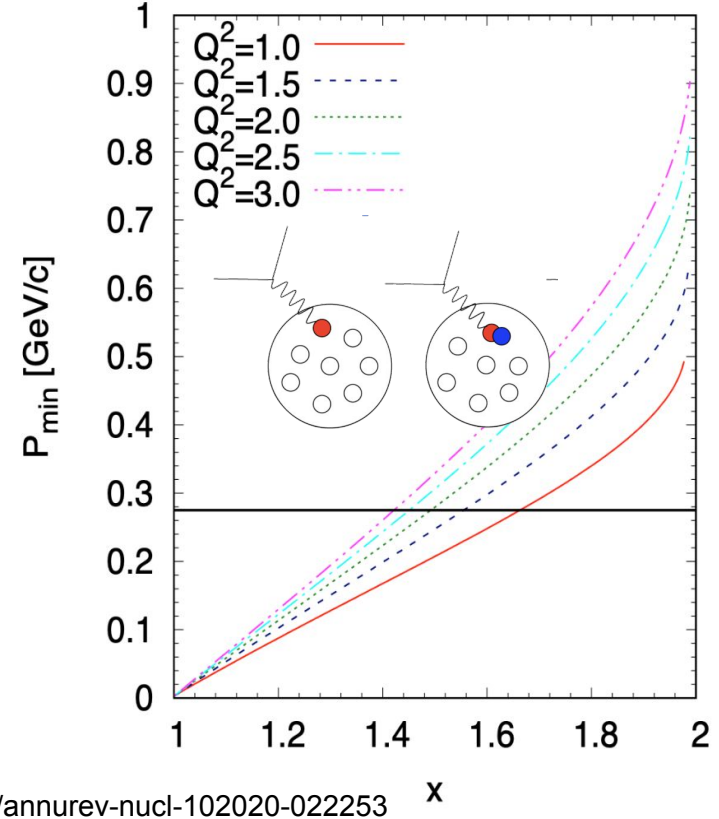
N. Fomin, et al., PRL 108 (2012) 092052

JLAB Hall C E02-019



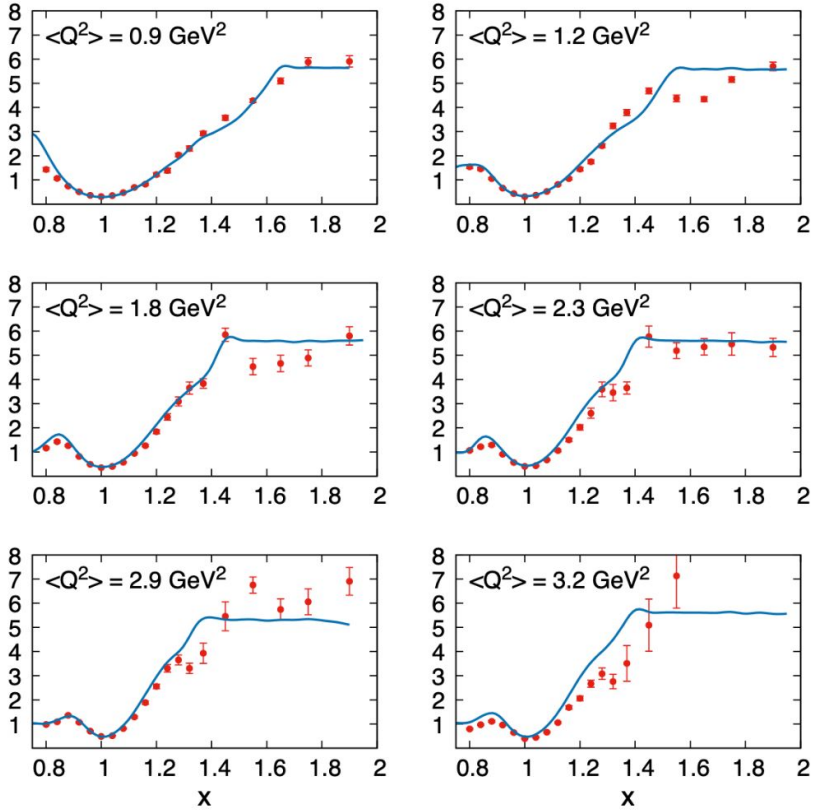
SRC in Inclusive Quasi-elastic Scattering

Q^2-scaling



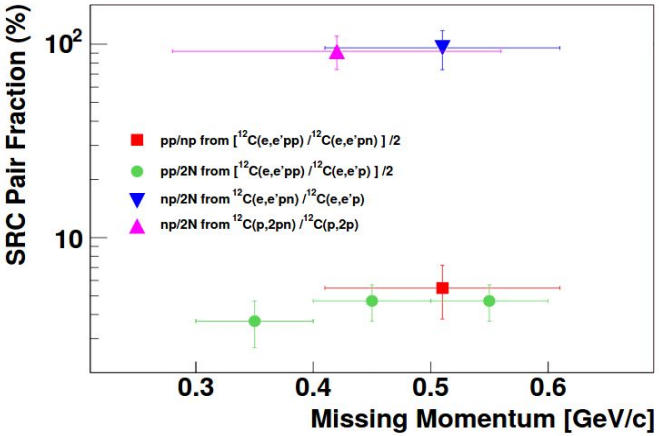
Fe/D cross section ratio from SLAC

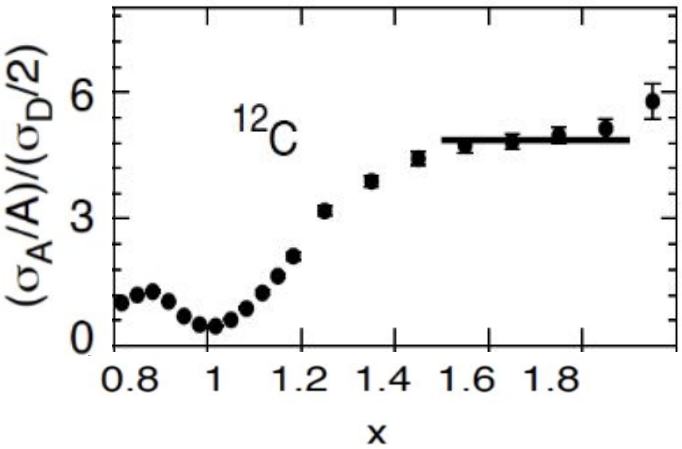
Phys. Rev. C 48:2451 (**1993**)

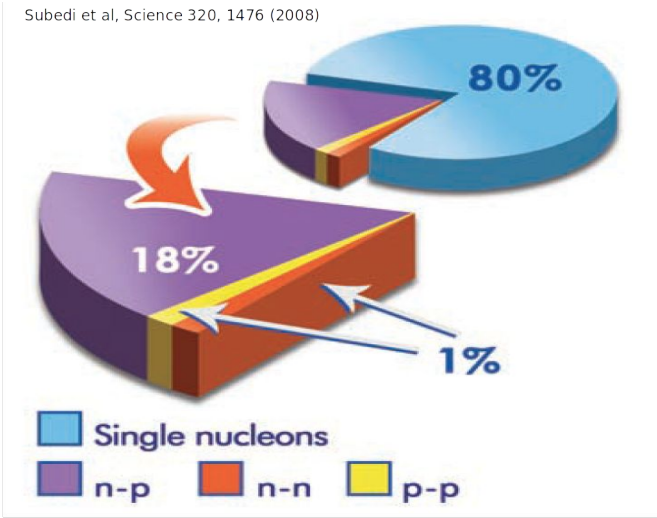


10.1146/annurev-nucl-102020-022253

Inclusive + exclusive scattering for SRC







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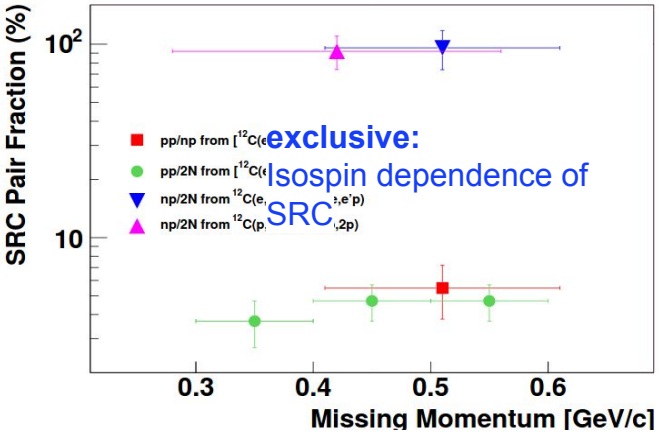
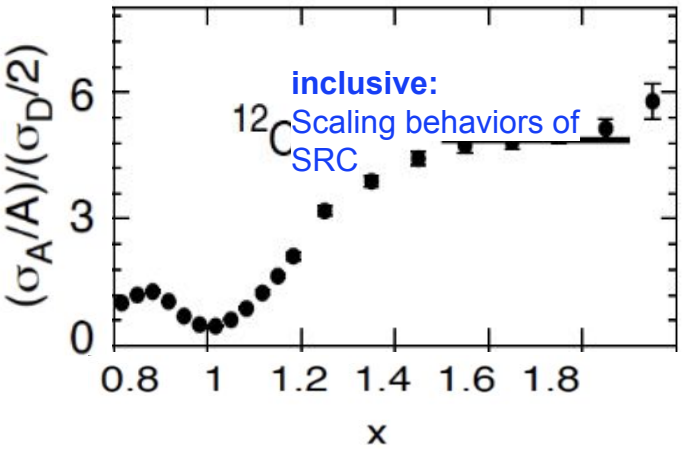
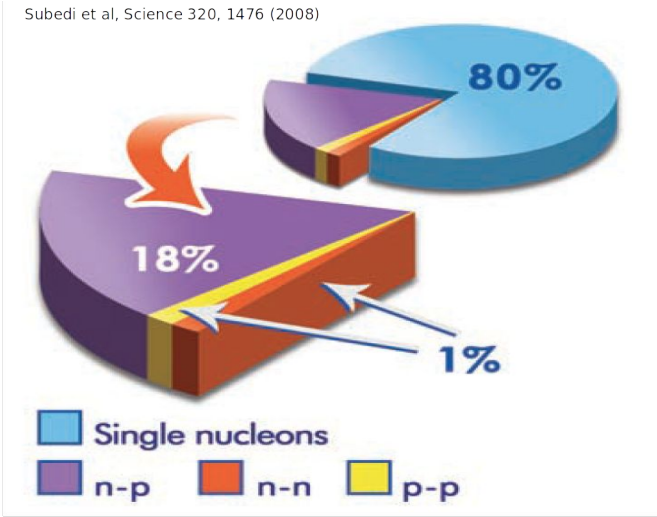


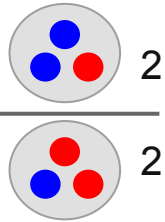
exclusive:
Isospin dependence of SRC



inclusive:
^{12}C Scaling behaviors of SRC



Inclusive Scattering on A=3 Nuclei



2 np + 1 nn pairs

2 np + 1 pp pairs

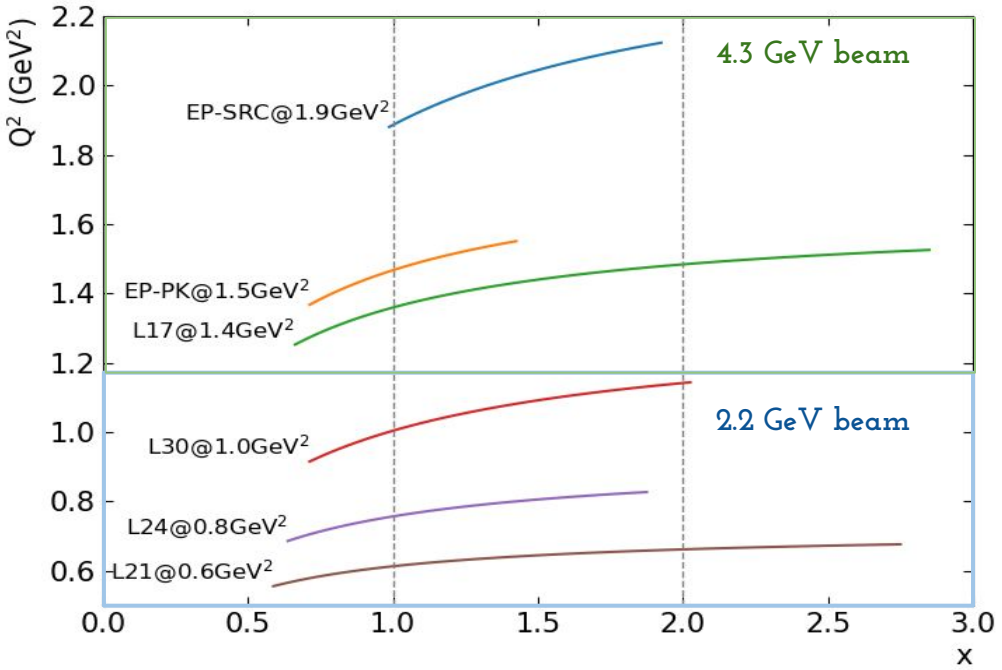
Tritium v.s. Helium-3:

- 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

High statistics

Calculable* few body systems

Systematic uncertainties canceled in the ratio



SRC SL et al, Nature 609, 41-45 (2022)
GMn: N. Santiesteban et al, Phys.Rev.Lett. 132 (2024) 16, 162501

E12-11-112: Precision Measurement of the Isospin Dependence in the 2N and 3N Short-range Correlation Region

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

2N SRC: SL et al, Nature 609, 41-45 (2022)
GMn: N. Santiesteban et al, Phys.Rev.Lett. 132 (2024) 16, 162501

E12-17-003 nnL hypernuclei

Experiment Configuration

Hall A @ JLab

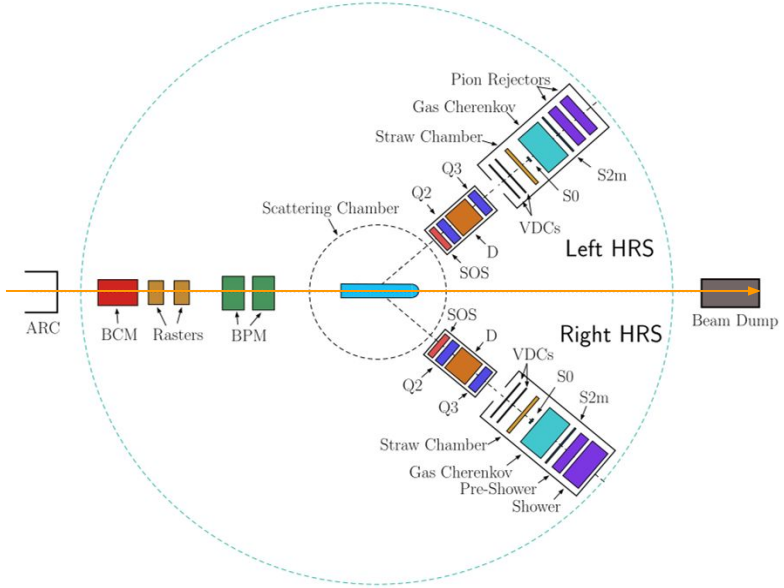
Primary Kinematics:

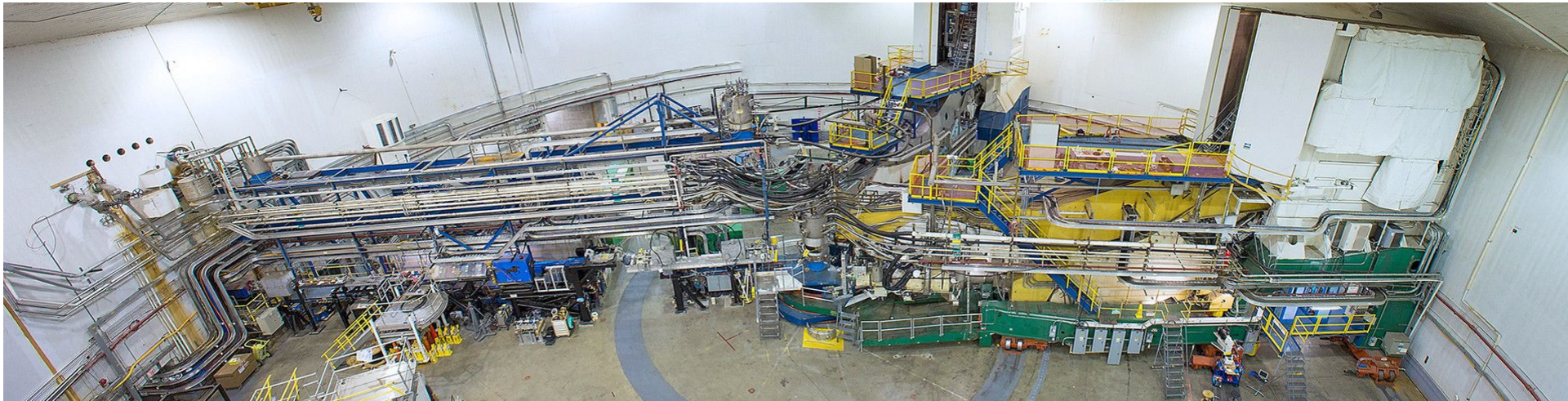
Beam energy: 4.3 GeV

Momentum : 3.54, 3.82 GeV

Angle : 20.88, 17 degree

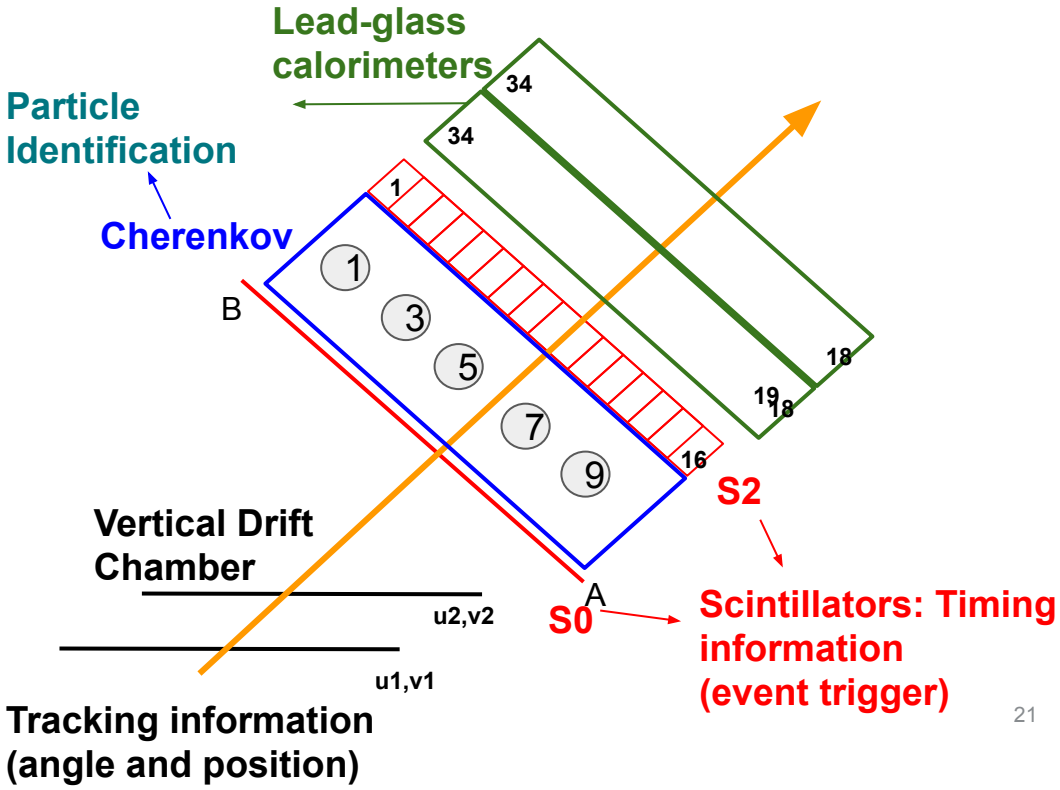
Q^2 : 1.8, 1.4 GeV^2





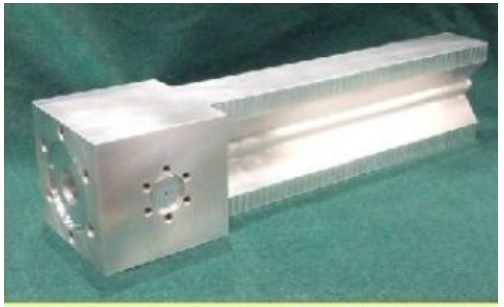
Detector Package

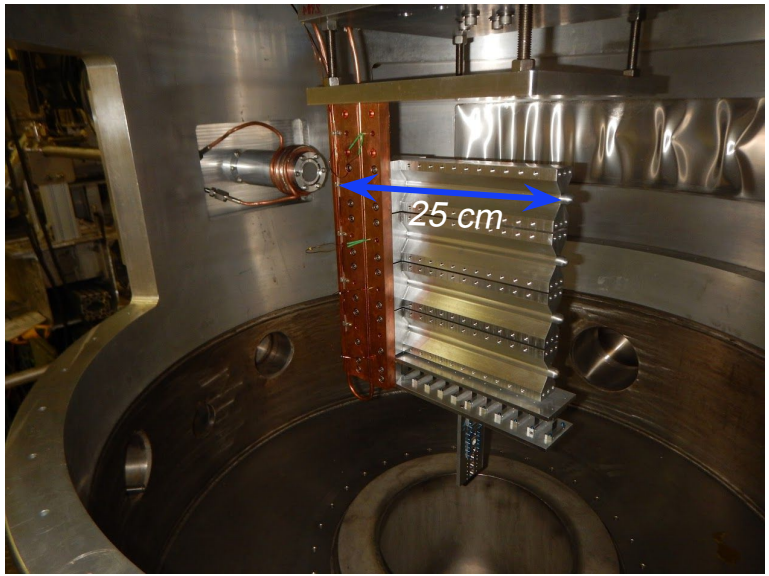
Hall A @ JLab

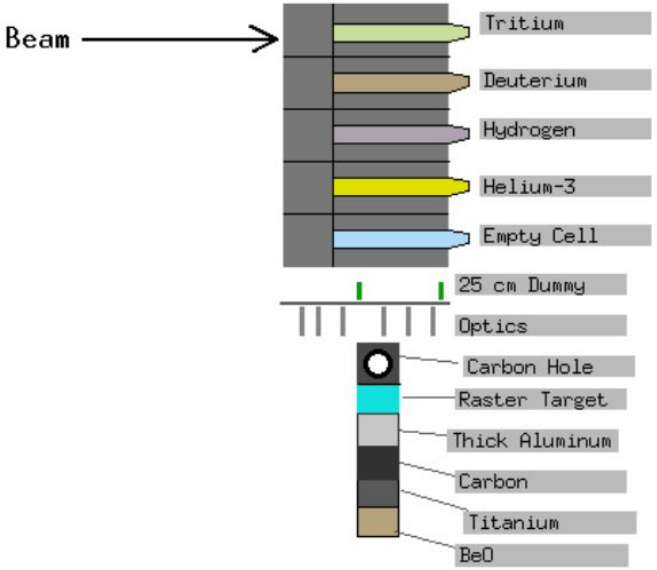


The Gas Target System

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

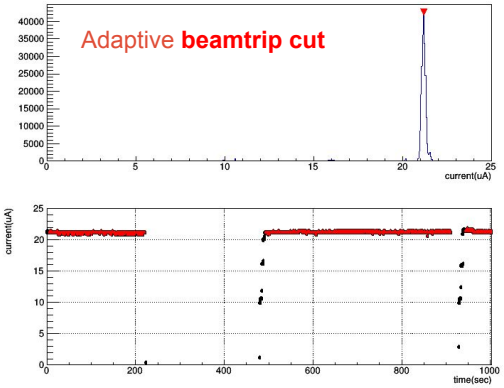


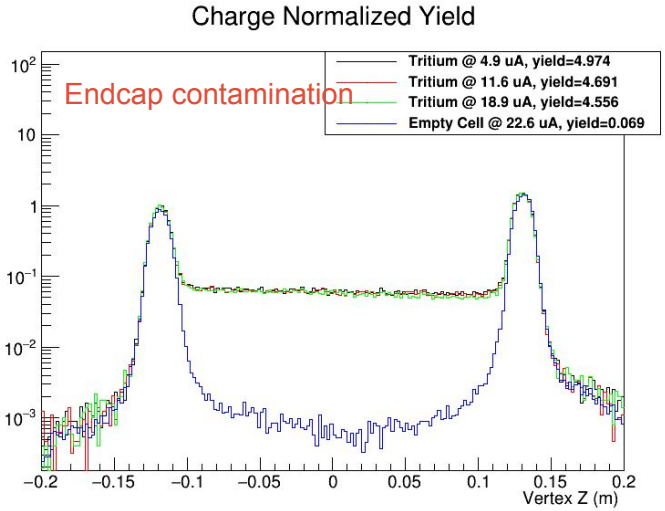




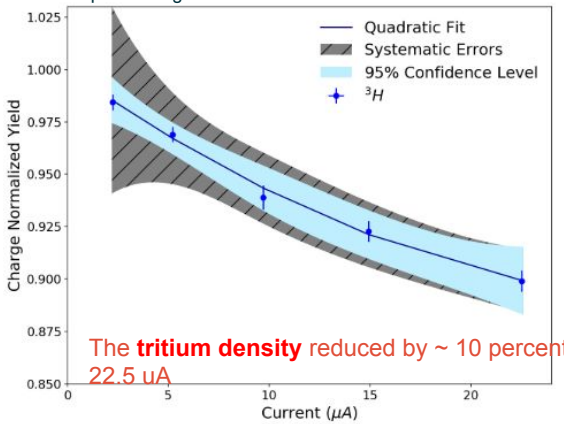
The Gas Target System: special handling

- Maximum current = 22.5 uA on gas cells to minimize the risk of gas leak.
- Endcap (75mg/cm2 Aluminum) being mis-reconstructed into thin gas body (77mg/cm2 Tritium)
- “Boiling”: gas density change along beam path
- Tritium decay correction
- Hydrogen contamination.

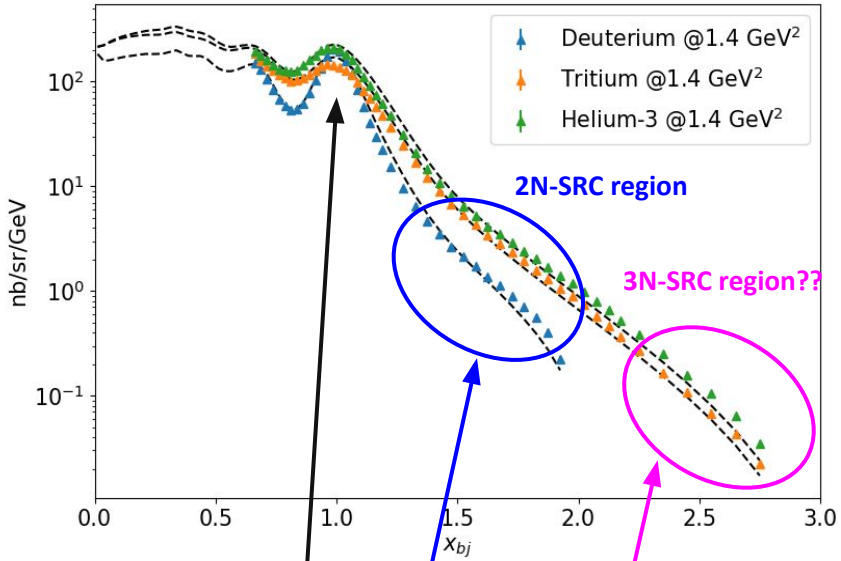




S. Santiesteban et al. ,
https://doi.org/10.1016/J.NIMA.2019.06.025



QE Cross sections



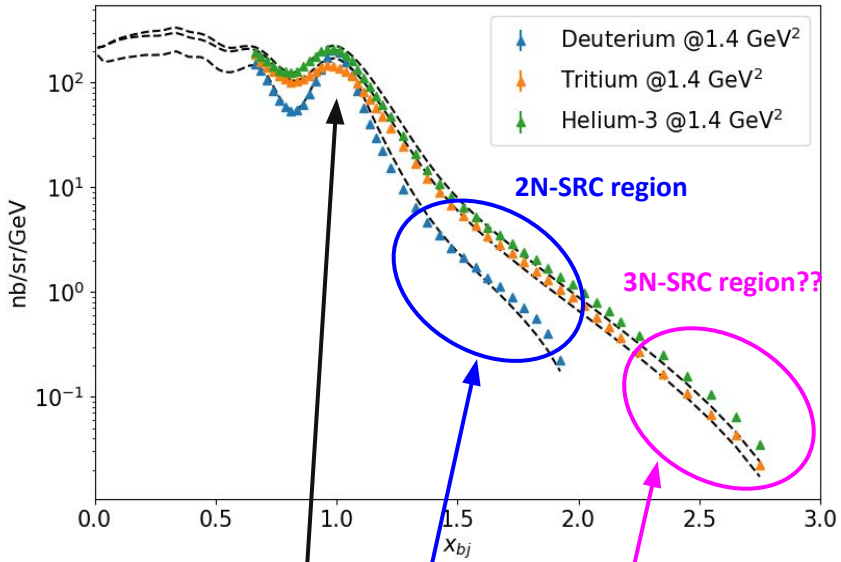
too small

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

Vanishes quickly at x>1

e'N contribution dominants by np pairs

Onset of 2N SRC scaling at x>1



too small

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

Vanishes quickly at x>1

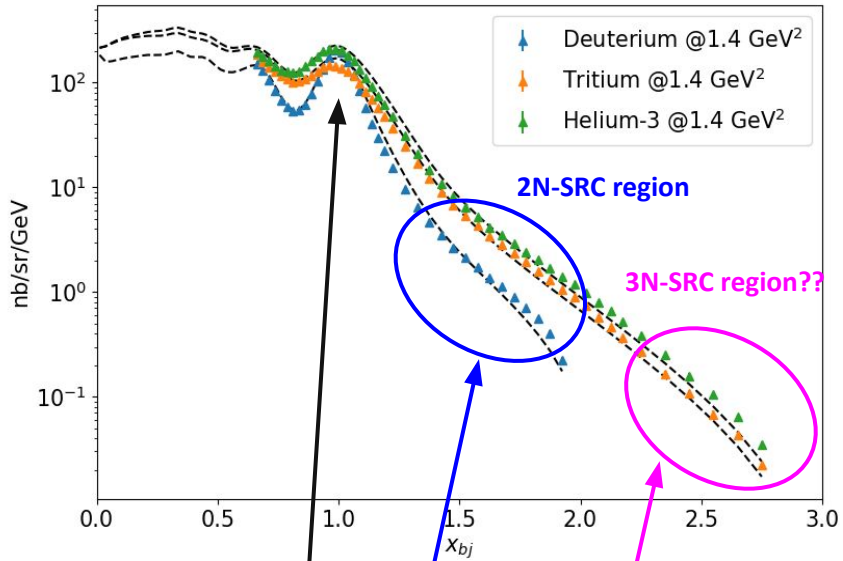
e'N contribution dominants by np pairs

Suppression of scaling-violating behaviors:

- Meson-exchange current (MEC):
  - $1/Q^2$ suppression
- Isobar Current (IC):
  - $1/Q^2$ and x>1 suppression
- Final State Interactions (FSI):
  - **exclusive**: kinematics (recoil angle etc.) pre-selection, model-dependent corrections
  - **inclusive**: contained within the SRC pair at large Q^2

$$\frac{\sigma_A}{\sigma_{^2H}} \approx \frac{a_2(A)}{a_2(^2H)} = const$$

Onset of 2N SRC scaling at x>1



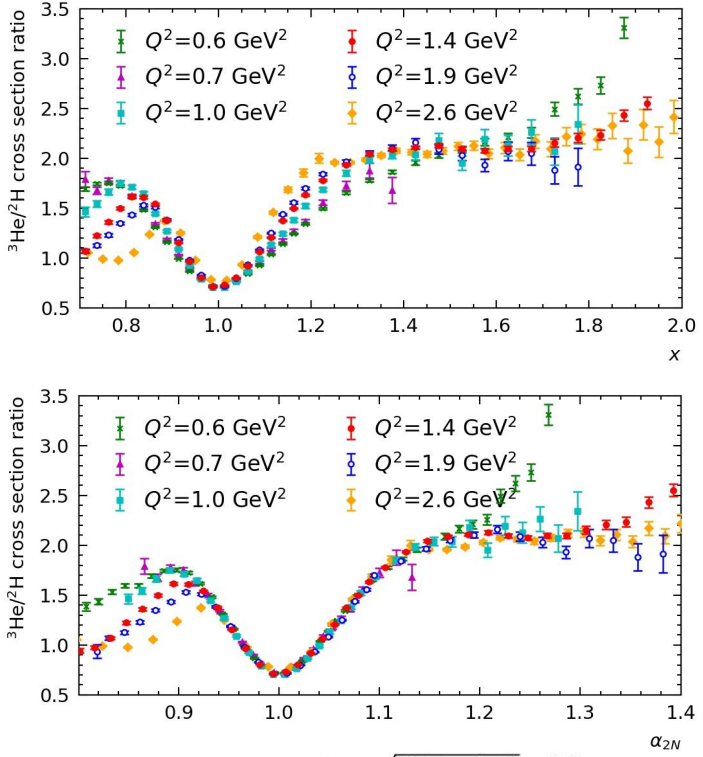
too small

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

Vanishes quickly at x>1

e'N contribution dominants by np pairs

3He/2H



$$\alpha_{2N} = 2 - \frac{q_- + 2m}{2m}\,\frac{\sqrt{W^2 - 4m^2} + W}{W}$$

Not-so-strong Isospin dependence in A=3 nuclei

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

= 0.854±0.010

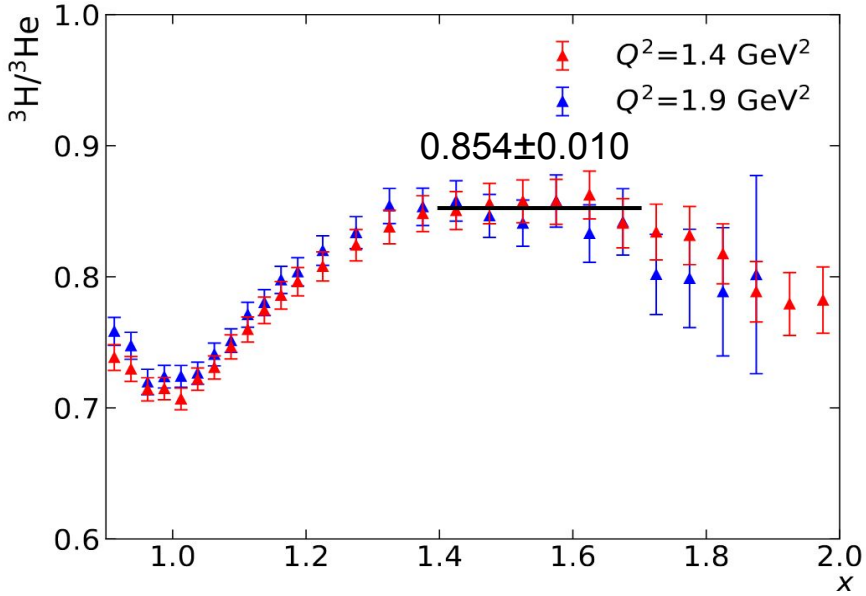
Offshell elastic xsection (de Forest "cc1")

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

number of pp to np pairs ratio in A=3

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

Apply corrections due to **center-of-mass motion** differences between np, pp in ^{3}H and ^{3}He (Ciofi degli Atti, Claudio and Morita, Hiko, 2017)



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

$R_{np/pp}$ =4.3 ± 0.4

SL et al, Nature 609, 41-45 (2022)

Not-so-strong Isospin dependence in A=3 nuclei

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

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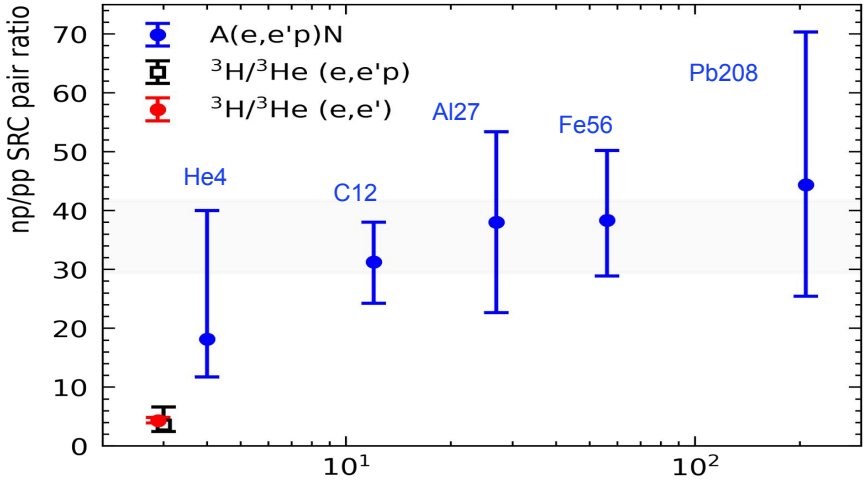
np/pp pair ratio v.s.A



References:

inclusive:

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

exclusive:

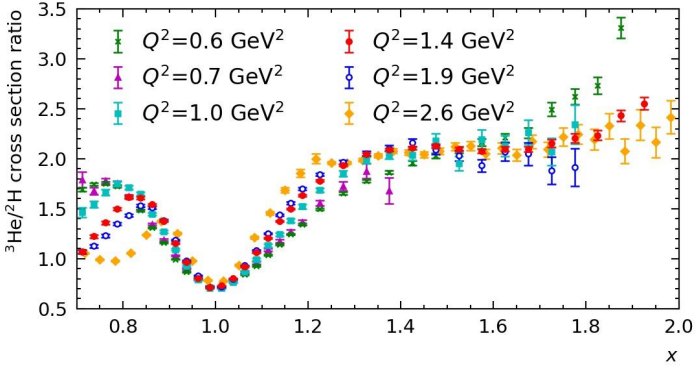
H3/He3 e'p; Cruz-Torres, R.et al. Phys. Lett. B797,134890 (2019)

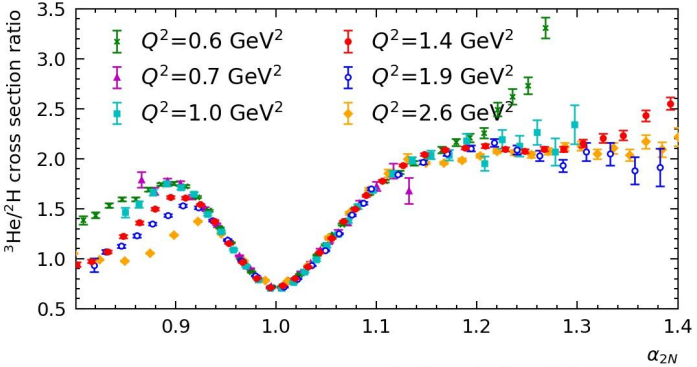
He4: Korover, I.et al. Phys. Rev. Lett.113,022501 (2014)

e'pN in Solid blue: Duer, M.et al.Phys. Rev. Lett.122, 172502 (2019)

Early onset of SRC scaling

3He/2H





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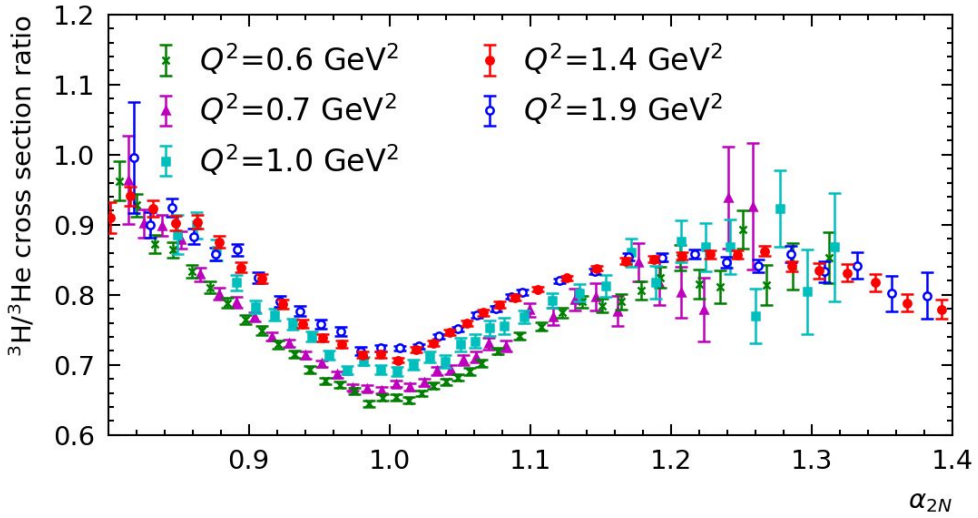
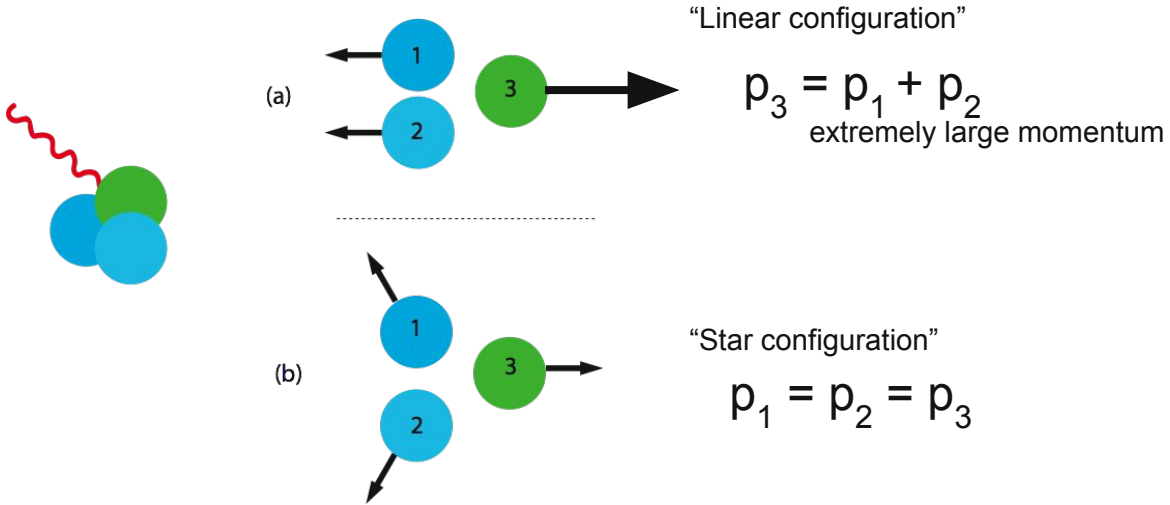
3H/3He



Momentum-isospin correlations in A=3 systems



"Linear configuration"

$p_3 = p_1 + p_2$

extremely large momentum

"Star configuration"

$p_1 = p_2 = p_3$

(a) yields $R(^3H/^3He) \approx \sigma_p/\sigma_n \approx 2.5$ if nucleon #3 is always the singly-occurring nucleon

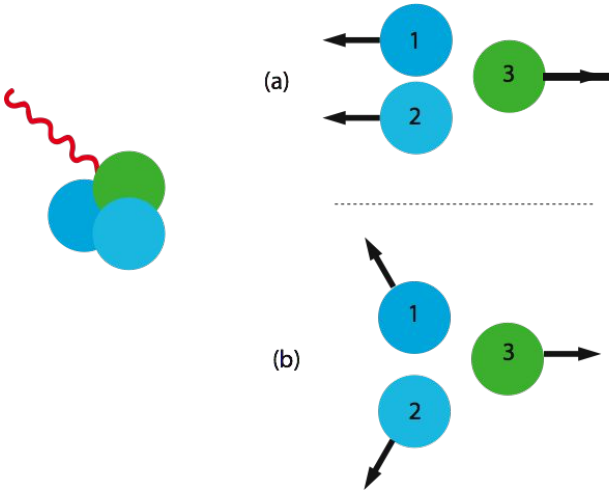
(a) yields $R(^3H/^3He) \approx \sigma_n/\sigma_p \approx 0.4$ if nucleon #3 is always the doubly-occurring nucleon

(a) yields $R(^3H/^3He) \approx 0.7$ if configuration is isospin-independent

(b) yields $R(^3H/^3He) \approx 0.7$ since all nucleons have same contribution to high-momentum component

$R \neq 0.7$ implies isospin dependence AND non-symmetric momentum sharing

3N SRC in Nuclei?



"Linear configuration"

$p_3 = p_1 + p_2$

extremely large momentum

3N SRC = (2N SRC) **2

Pmin > 2x onset of 2N SRC

"Star configuration"

$p_1 = p_2 = p_3$

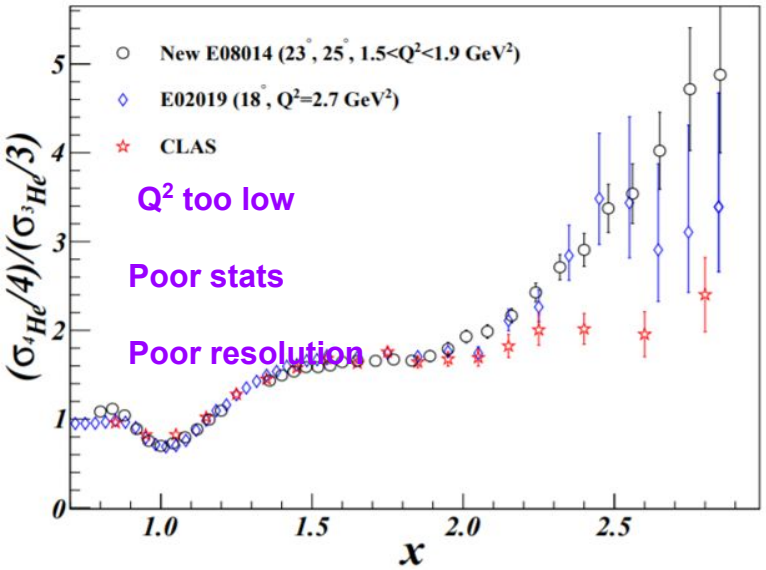
Irreducible 3N SRC

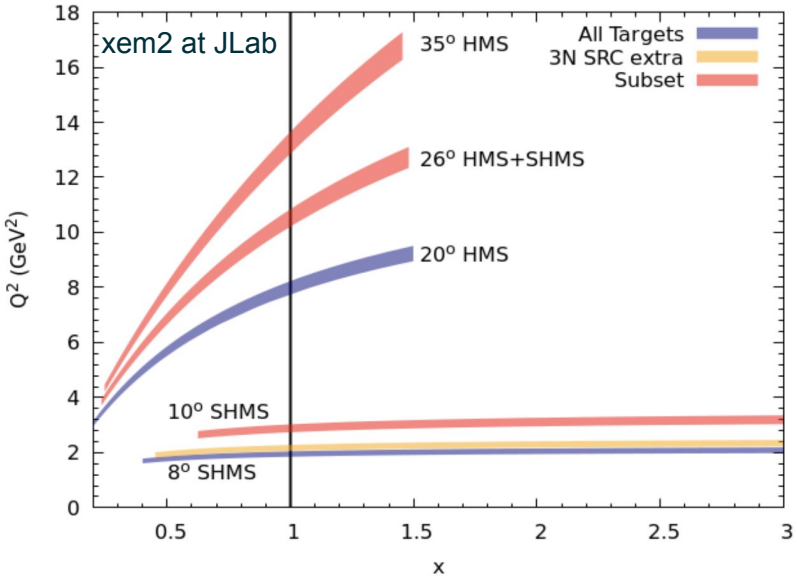
Extreme large pmin

$$\left[\sum_i -\frac{\hbar^2}{2m_N}\nabla_i^2 + \sum_{i<j} v_2(\boldsymbol{x}_i, \boldsymbol{x}_j) + \sum_{i<j<k} v_3(\boldsymbol{x}_i, \boldsymbol{x}_j, \boldsymbol{x}_k) + \ldots\right]\Psi_A = E_A\Psi_A$$

Cross Section beyond x=2: three-nucleon SRCs?

Previous A/^{3}He ratio:





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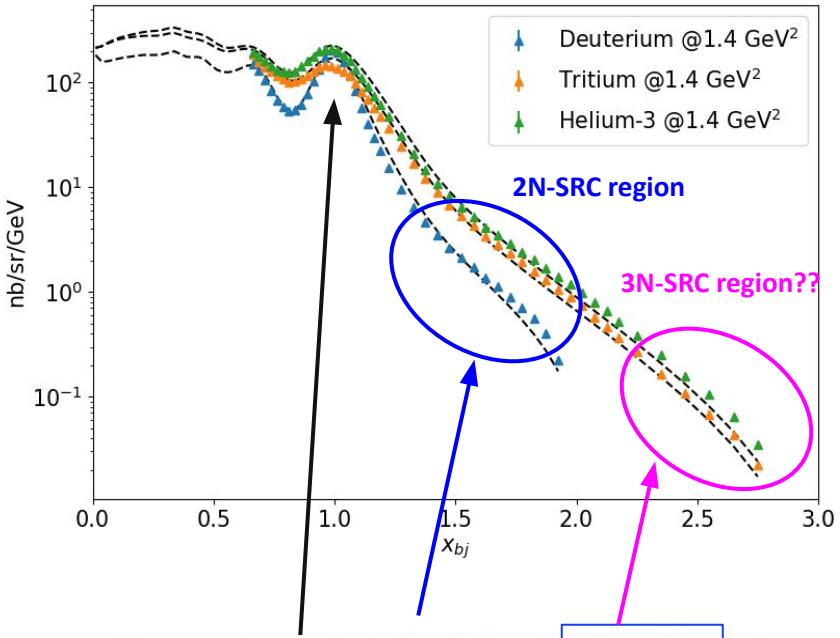


$$\sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \ldots$$

Calculations using realistic decay function predict R=0.7

Scaling in A/^{3}He predicted to be valid for $\alpha > 1.6$ in all nuclei*

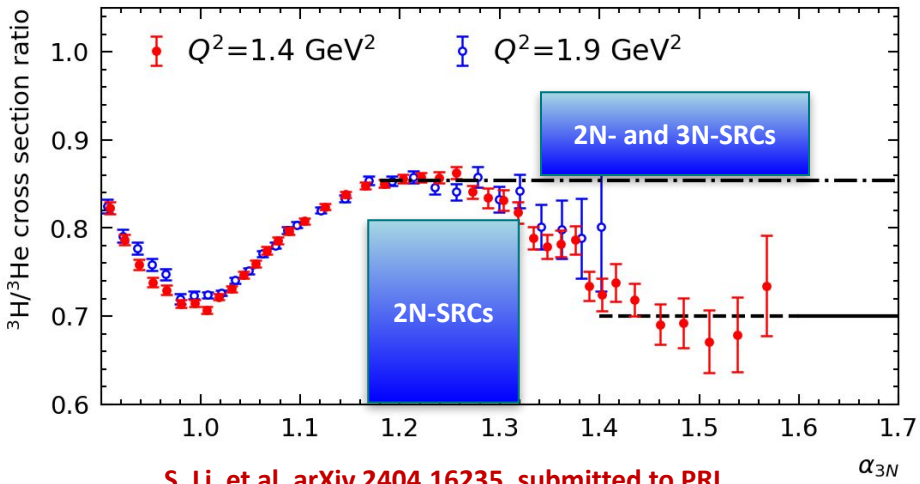
*$\alpha > 1.4$ using the same criteria for A=3

D. Day, L. Frankfurt, M. Sargsian, and M. Strikman, PRC 107 (2023) 014319

Beyond x=2 both 2N and 3N-SRCs can contribute

- A/^{3}He ratio examined for 3N-SRC dominance: plateau at x>2
- No clear observation of 3N-SRCs; "need higher Q^2 values"

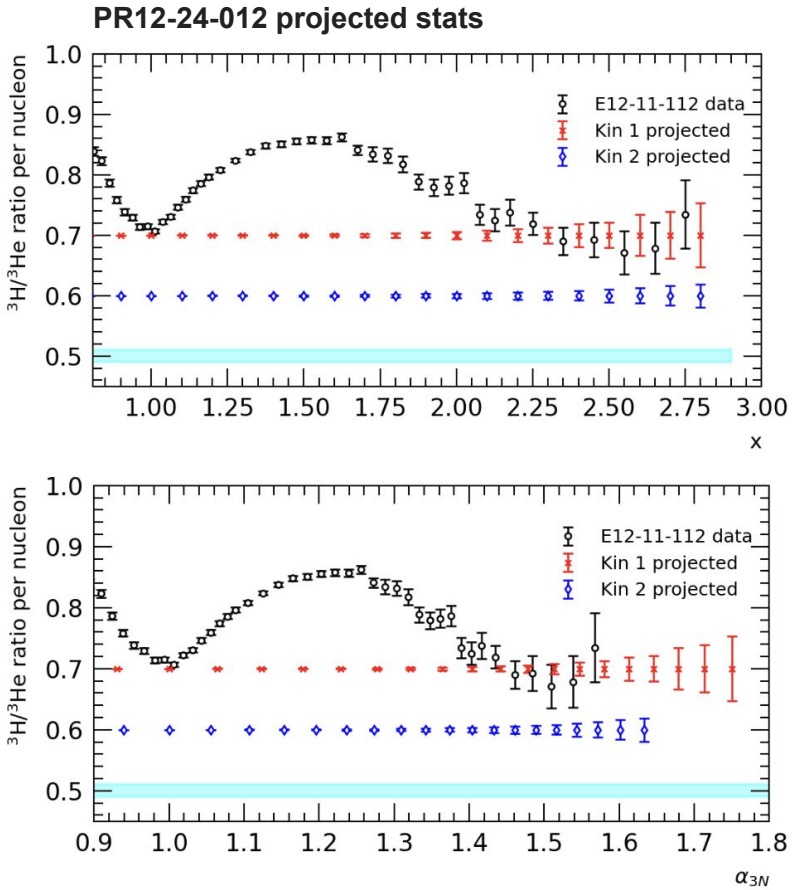
3H/3He ratios show early onset of scaling in α_{2N} (x), and



S. Li, et al. arXiv 2404.16235, submitted to PRL

33

New JLab proposal to study 3N SRC with Tritium



- Bring tritium target to Hall C
- 53 PAC days
- Higher momentum, smaller angle with SHMS
- higher Q^2 → larger α
- more DIS (n/p) measurements at large x, and more potentials…

Isospin structure of 3N short-range correlations and the nucleon structure functions in ^{3}H and ^{3}He

A Proposal to PAC 52

May 1, 2024

B. Duran (co-spokesperson), N. Fomin (co-spokesperson)
University of Tennessee, Knoxville, TN

J. Arrington (co-spokesperson), T. J. Hague (co-spokesperson), S. Li (co-spokesperson and contact)
Lawrence Berkeley National Laboratory, Berkeley, CA

D. Gaskell, F. Hauenstein, D. Higinbotham(co-spokesperson), D. Meekins(co-spokesperson)
Thomas Jefferson National Accelerator Facility, Newport News, VA

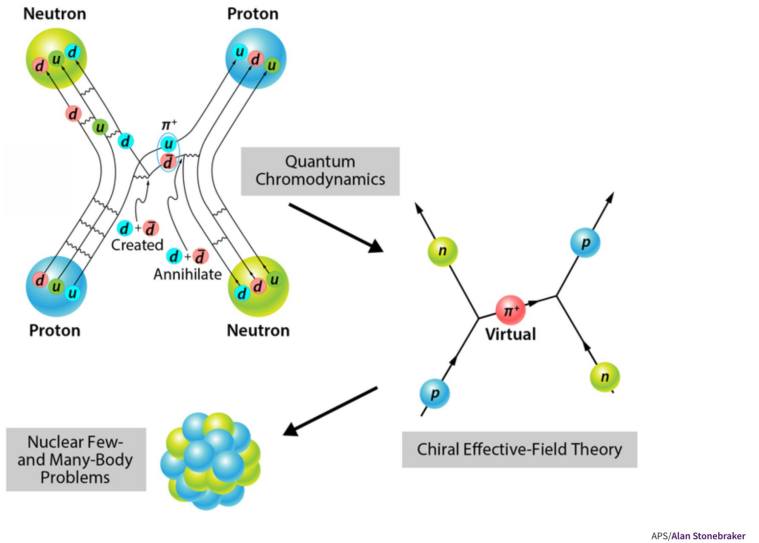
H. Chinchay, O. Olokunboyo, D. Ruth, N. Santiesteban, Z. Wolters
University of New Hampshire, Durham, NH

S. Bera, C. Cotton, M. Nycz, H. Presley, R. Trotta, X. Zheng
University of Virginia, Charlottesville, VA

B. Schmookler
University of California, Riverside, CA

M. Sargsian
Florida International University, Miami, FL

SRC in Two Scales



Proton radius ~ **0.84** fm

Inter-nucleon separation in heavy nuclei and nuclear matter (A->inf)
~ 1.7 fm

at short distances

- Largely overlapped wave functions
- In-medium modification of nucleon wave function
- In-medium modification of quark and gluon?
- quark/gluon interaction between two nucleons??

SRC in Two Scales

Inclusive x>1 xsection:

a2 plateau:

$$\sigma_A \approx a_2(A) \cdot \sigma_{^2H}$$

np enhancement factor:

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

factorization with xEFT

J-W Chen, 10.1103/PhysRevLett.119.262502

$$\sigma_A/A \simeq \sigma_N + g_2(A,\Lambda)\sigma_2(\Lambda)$$

Exclusive xsection:

Generalized Contact Formalism

R. Weiss, PRC 103, L031301 (2021)

$$\frac{d^8\sigma_A}{dE_e d\Omega_e d^3\vec{p}_{\text{c.m.}} d\Omega_{\text{rel}}}$$

$$= \kappa_{\text{IF}} \sum_{N_1N_2,\beta} s\sigma_{eN_1} C^{A,\beta}_{N_1N_2} \left|\tilde{\varphi}^{\beta}_{N_1N_2}(\vec{p}_{\text{rel}})\right|^2 n^{A,\beta}_{N_1N_2}(\vec{p}_{\text{c.m.}})$$

$$\equiv \sum_{N_1N_2,\beta} C^{A,\beta}_{N_1N_2} \times \sigma^{\beta}_{N_1N_2,\text{IF}},$$

SRC in Two Scales

Inclusive x>1 xsection:

a2 plateau: $\sigma_A \approx a_2(A) \cdot \sigma_{^2H}$

np enhancement factor:

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Scale Separation:

Impact of SRC

=

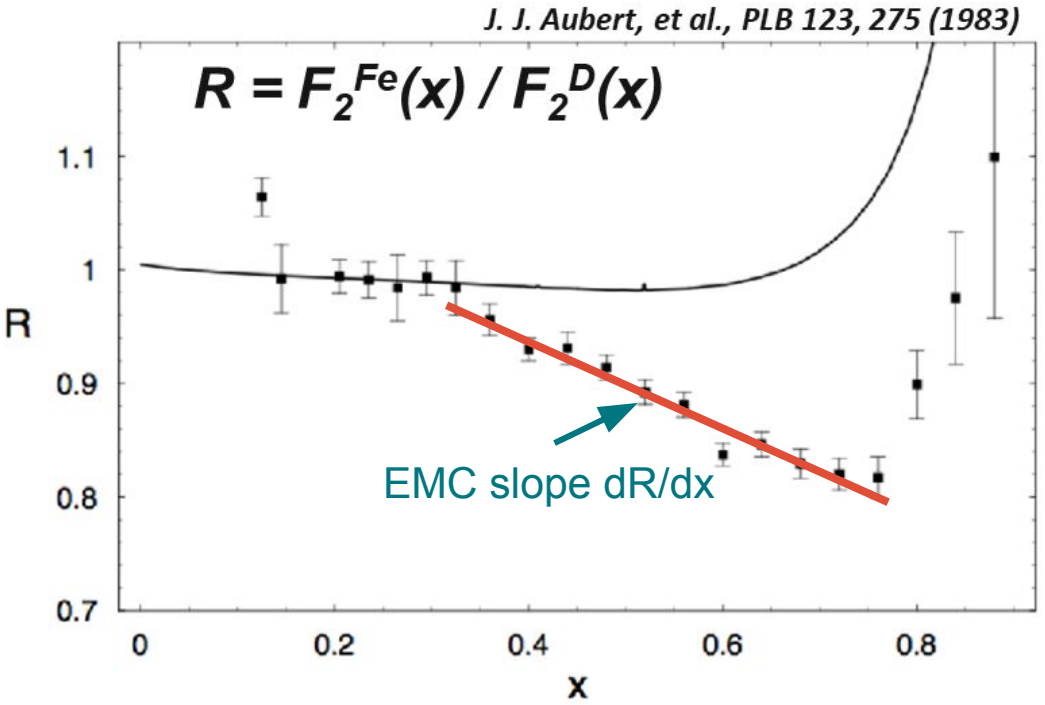
nuclear modifications → SRC-EMC relation

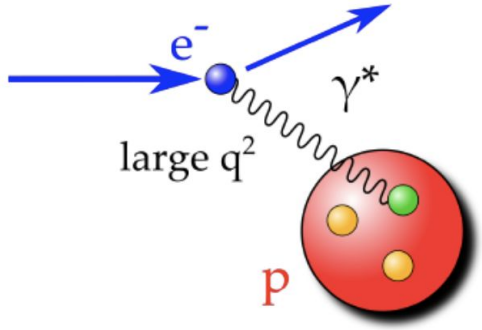
x

NN interaction → More deuteron study

The European Muon Collaboration Effect

In-medium modification of parton distributions

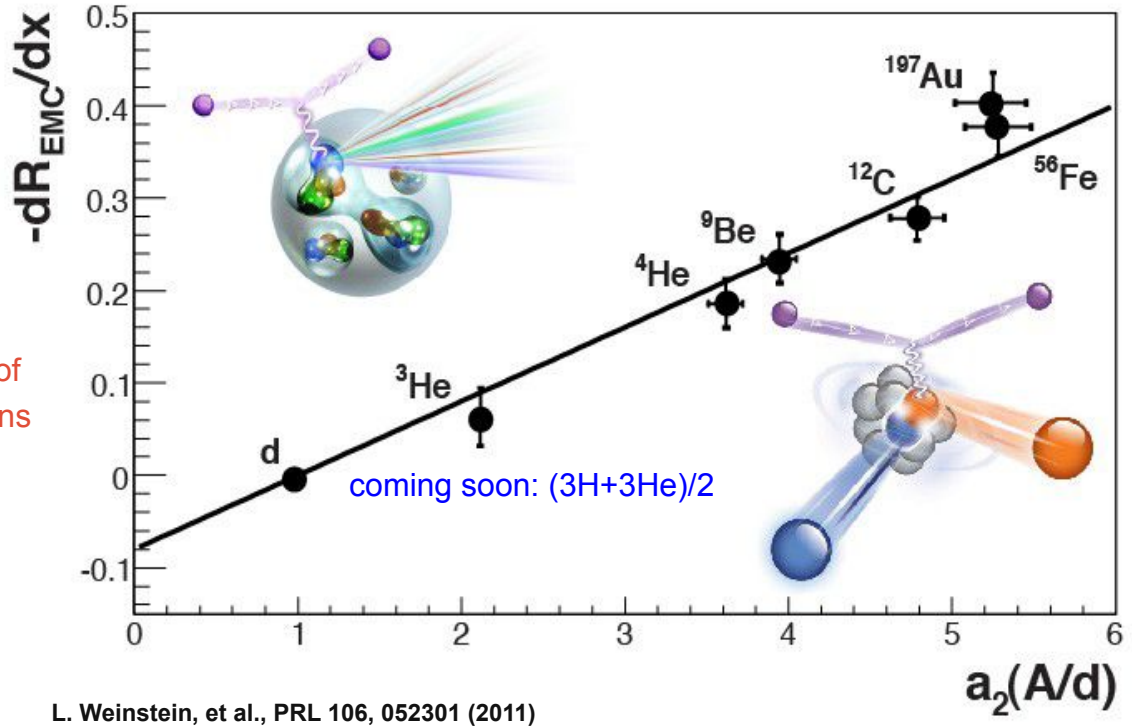




Nucleus binding energy: O(10) MeV
DIS momentum transfer: O(10) GeV

SRC-EMC

EMC slope:
in-medium modifications of parton distribution functions



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

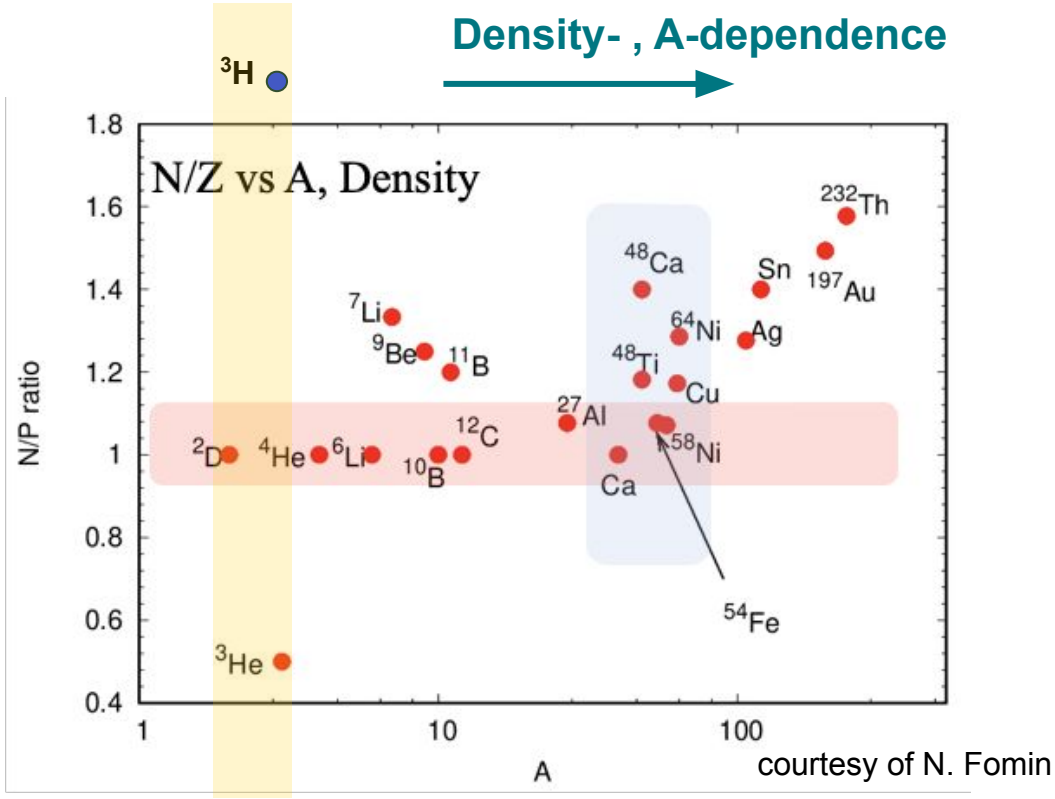
O. Hen, et al, PRC 85, 047301 (2012)

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

SRC plateau height:
Fraction of high-momentum NN pairs

SRC-EMC

JLab Hall C experiments E12-10-008 and E12-06-105
Results coming soon!

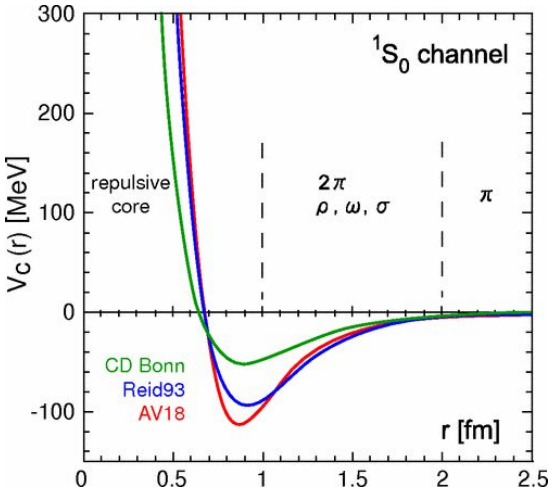


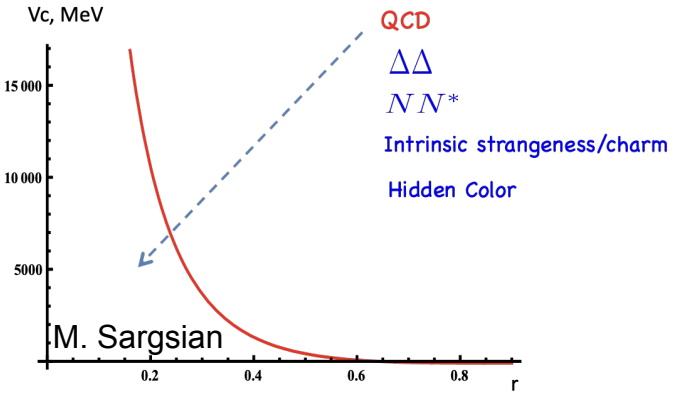
courtesy of N. Fomin

Isospin effect and flavor dependence
(next: PVEMC with SoLID)

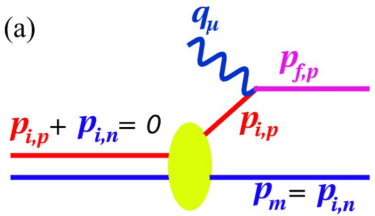
Deuteron Repulsive Core

Probing the deuteron repulsive core at short-distance, large Q2

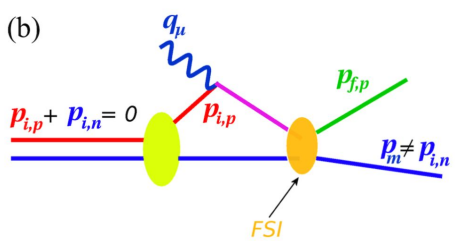




JLab E12-23-010, approved for 50 PAC days



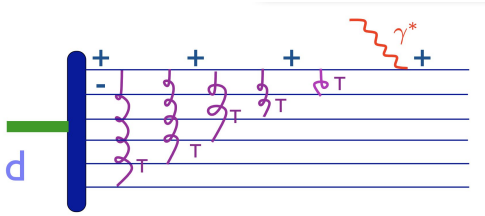
Plane Wave Impulse Approximation (PWIA)

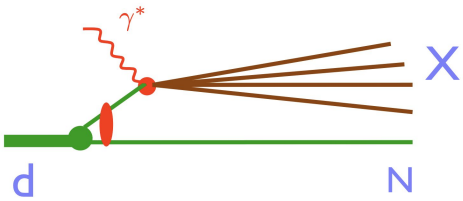


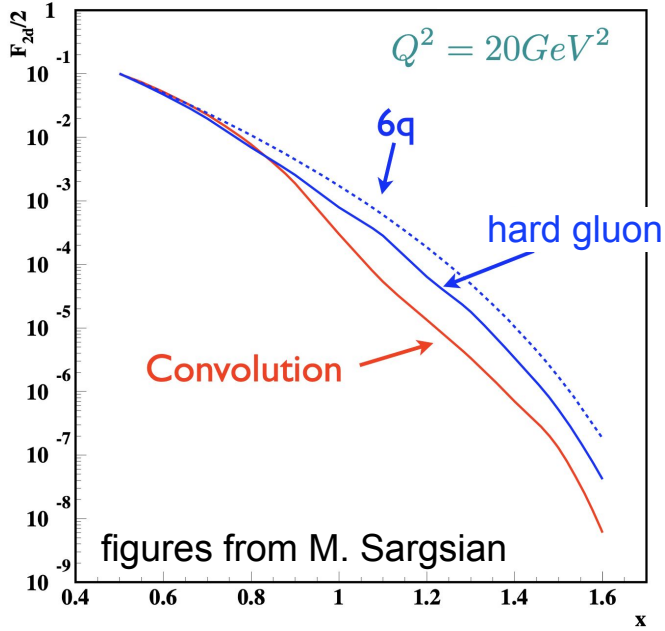
Final State Interactions (FSI)

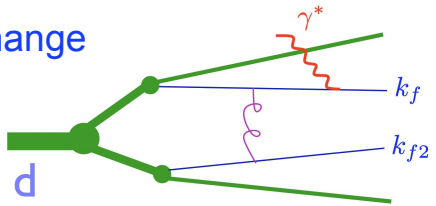
Super-fast Quarks at x>1

Part of E12-06-105 data on tape!



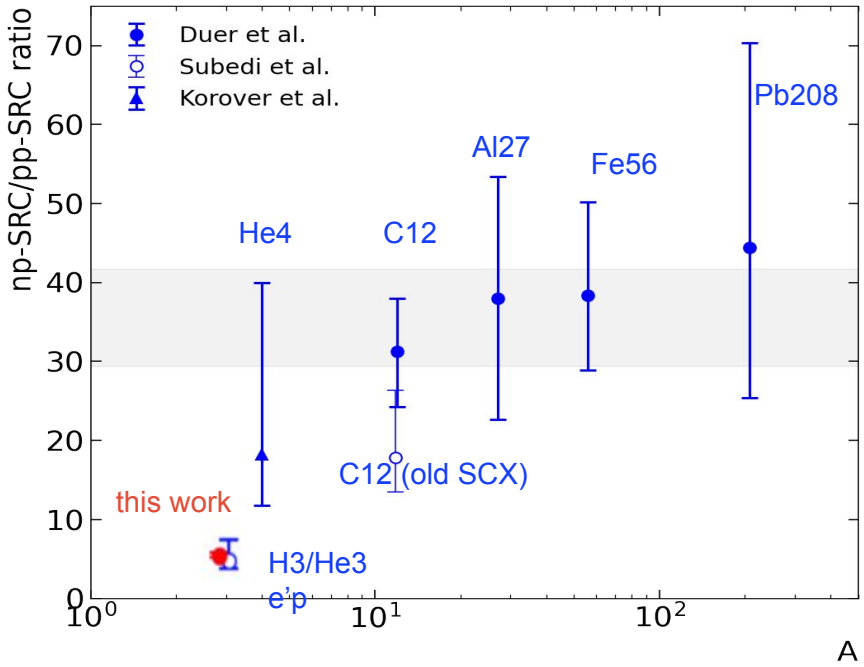






Thank you!

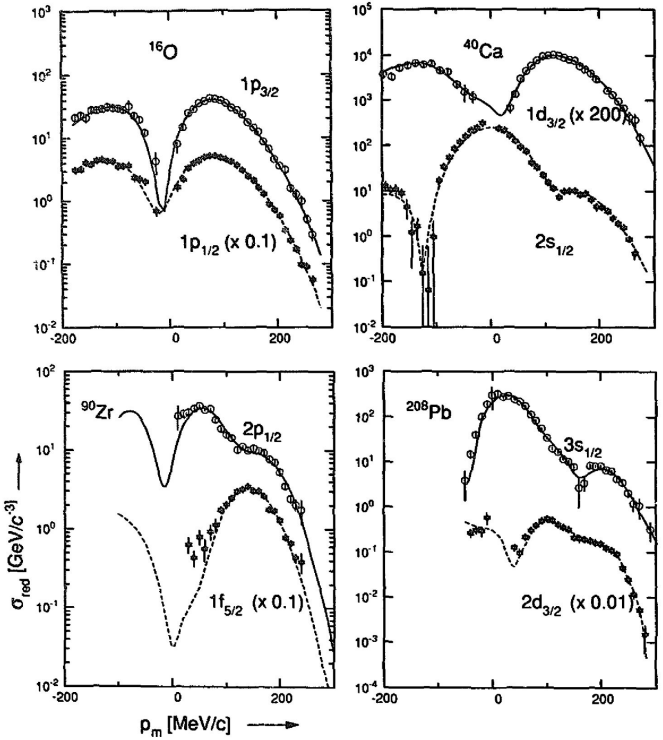
np/pp pair ratio v.s.A



Nucleons in Nuclei:

Independent Particle Shell Model(IPSM)

Lapikas1993 @ NIKHEF: (e,e'p)



→ **valence (outmost) shell**

→ **next deeper shell**

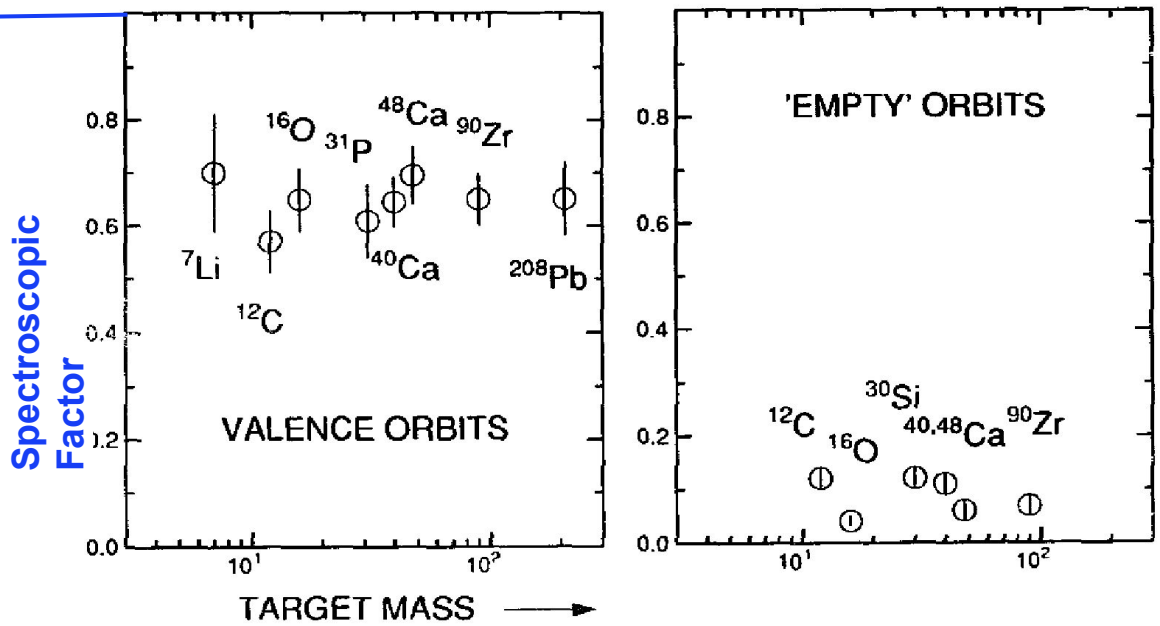
Curves: Distorted Wave Impulse Approximation (DWIA) Calculation with **fitted** spectroscopic strength

Nucleons in Nuclei:

Independent Particle Shell Model(IPSM)

Lapikas1993 @ NIKHEF: (e,e'p)

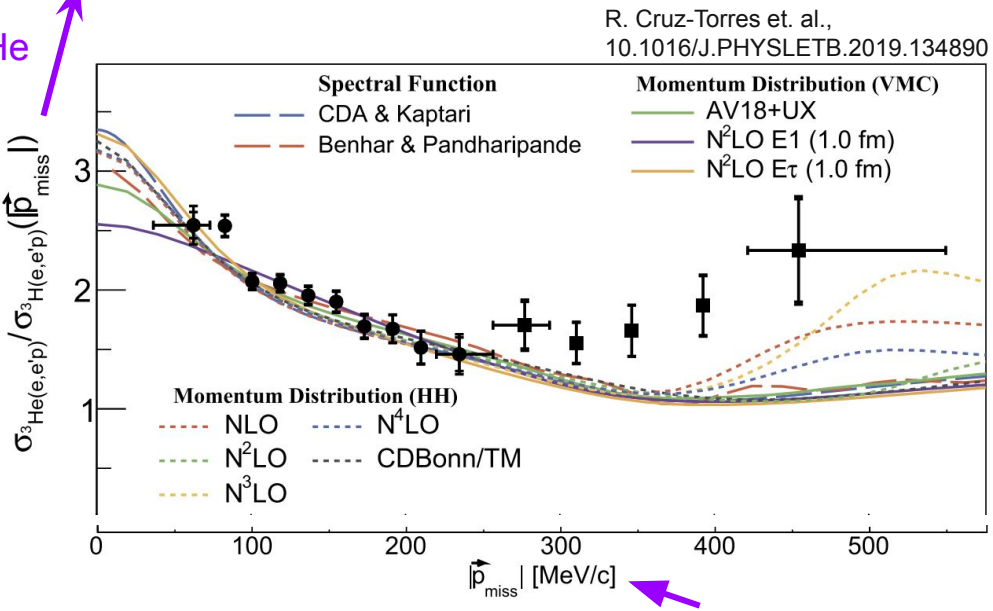
1 if the orbit is fully occupied



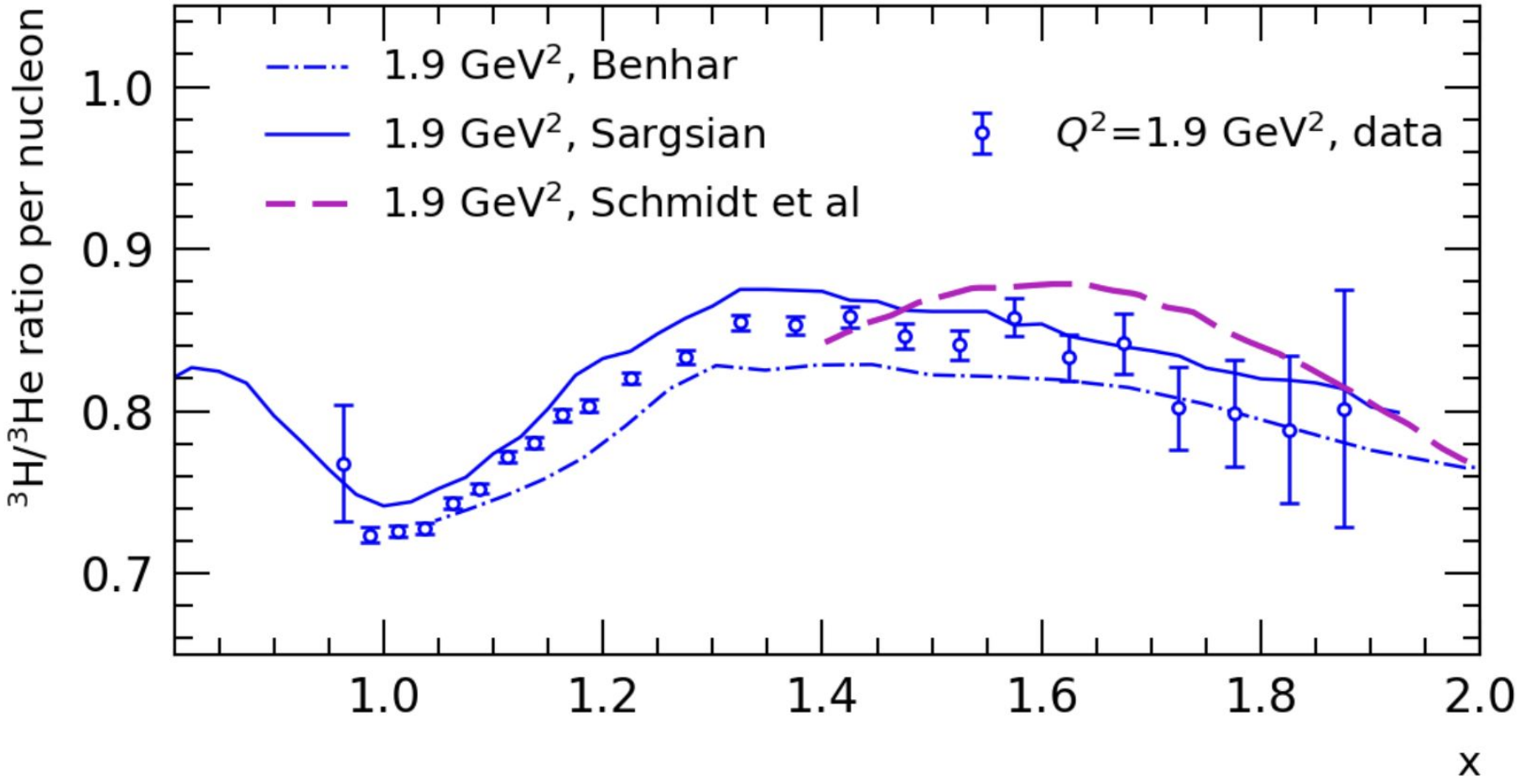
3H/3He (e,e'p) Ratios

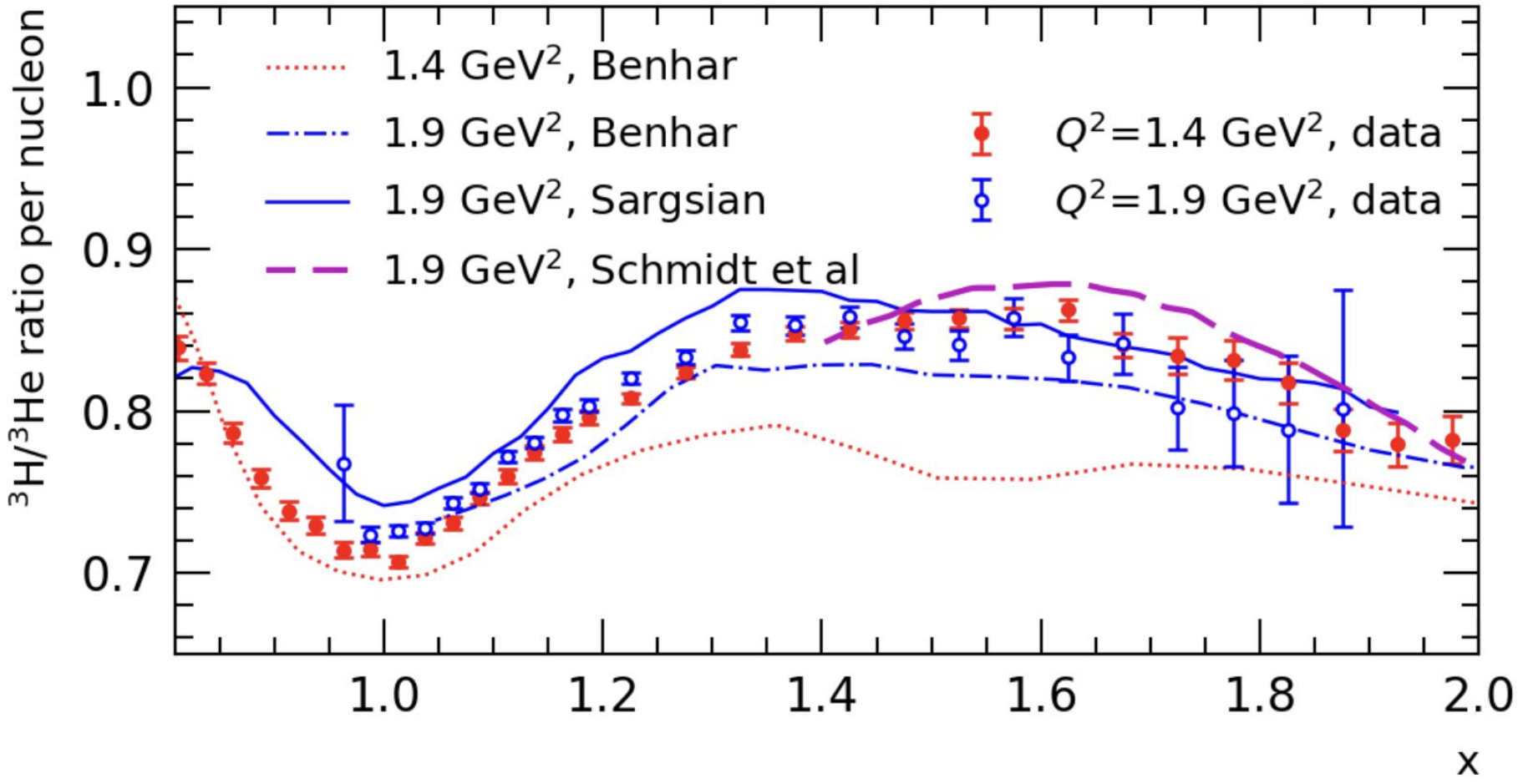
p/n momentum distribution in ^{3}He

p in ^{3}H ≈ n in ^{3}He



~ nucleon initial momentum in PWIA


1.9 GeV², Benhar
1.9 GeV², Sargsian
1.9 GeV², Schmidt et al
Q²=1.9 GeV², data
³H/³He ratio per nucleon
1.0
0.9
0.8
0.7
1.0
1.2
1.4
1.6
1.8
2.0
x


1.4 GeV², Benhar
1.9 GeV², Benhar
1.9 GeV², Sargsian
1.9 GeV², Schmidt et al
Q²=1.4 GeV², data
Q²=1.9 GeV², data
³H/³He ratio per nucleon
1.0
0.9
0.8
0.7
1.0
1.2
1.4
1.6
1.8
2.0
x