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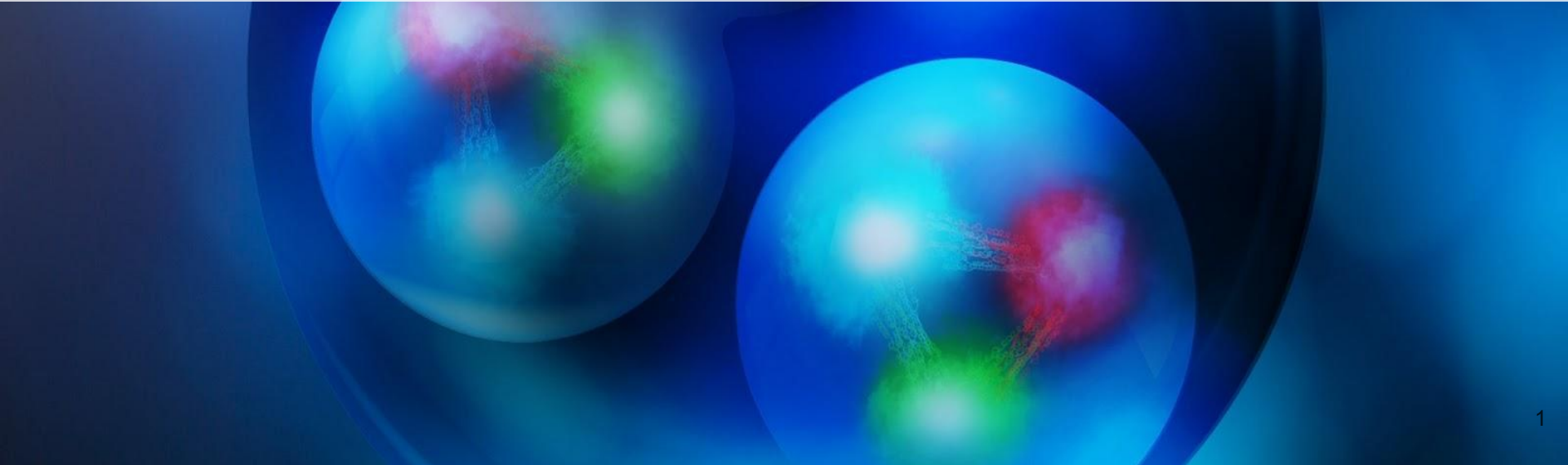
U.S. DEPARTMENT OF ENERGY
Office of Science

Short-range Correlations in A=3 Systems

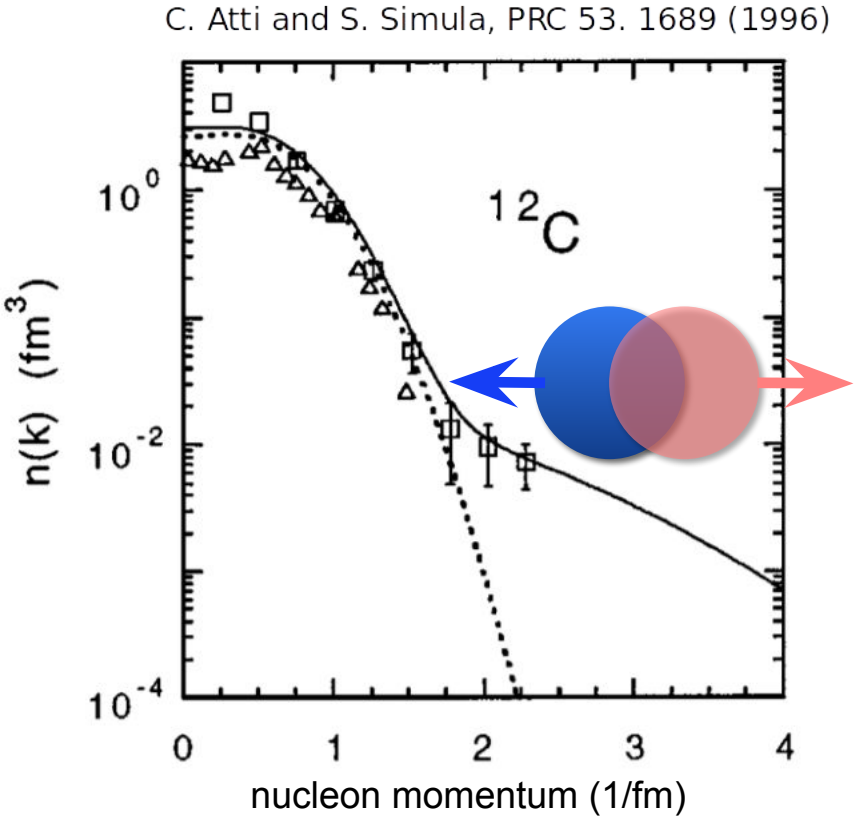
Shujie Li

ECT* workshop on short-distance nuclear structure and PDFs

Jul 17, 2023

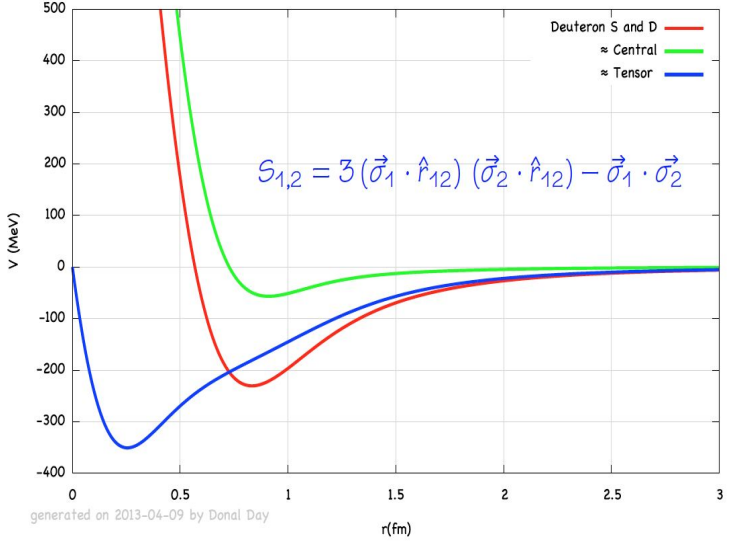


Nucleon-nucleon interactions at short distances

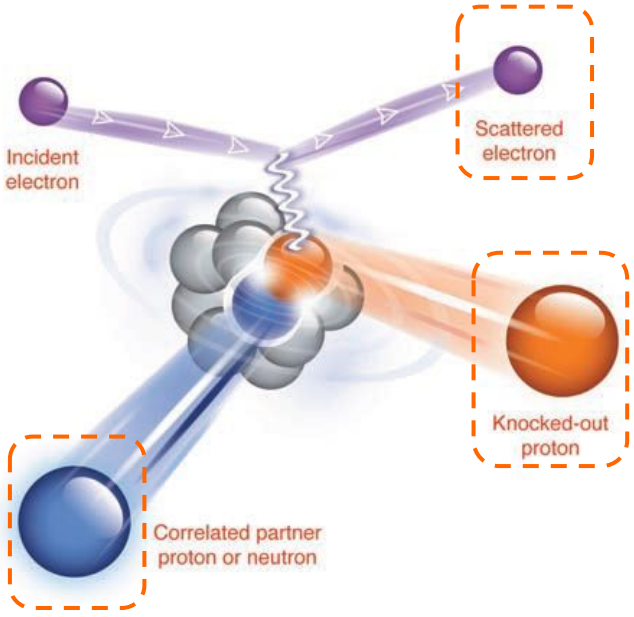


High momentum pair:

- Large back-to-back momentum, total → 0
- Isospin T=0 (np singlet) dominates



Probing SRC in Quasi-elastic Scattering (e,e'pN)

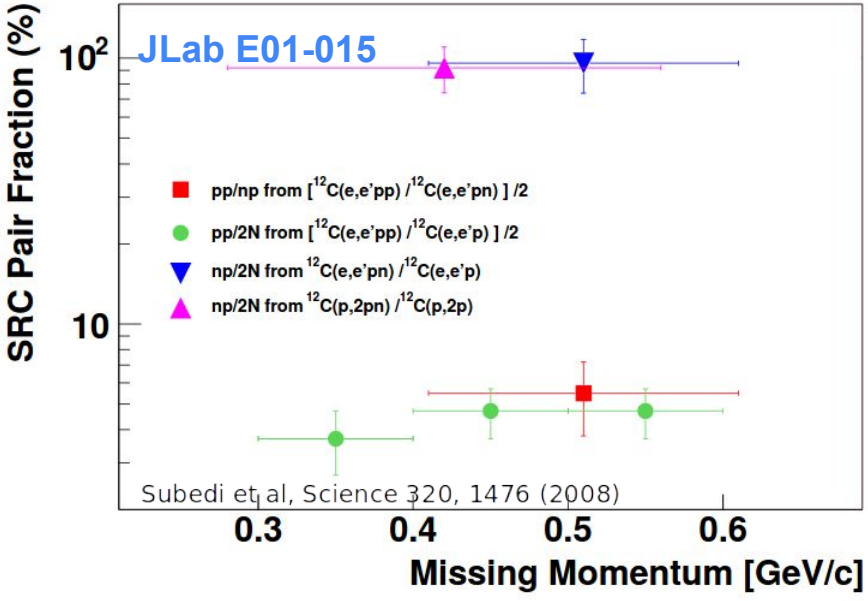


~90% of high momentum nucleon pairs in ^{12}**C** are np pairs:

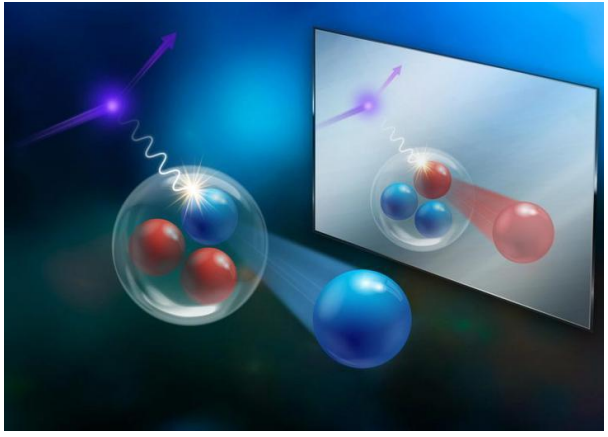
np:pp:nn=18:1:1

Exclusive measurement:

- Measure the scattered nucleon (and the paired one), **direct** knowledge of the final state particle information (momentum, angle, etc)
- Subject to re-scattering and charge exchange
- Low statistics



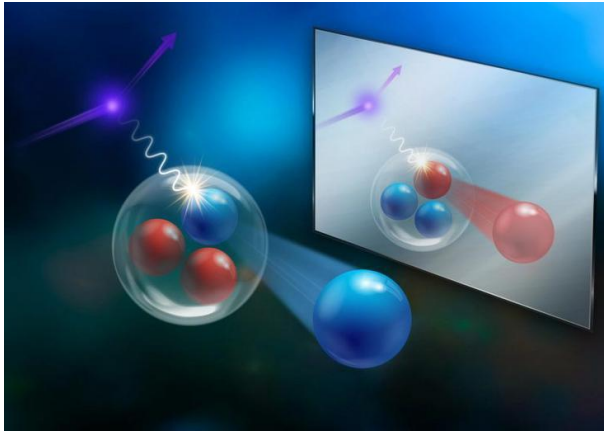
Probing SRC in A=3 Systems

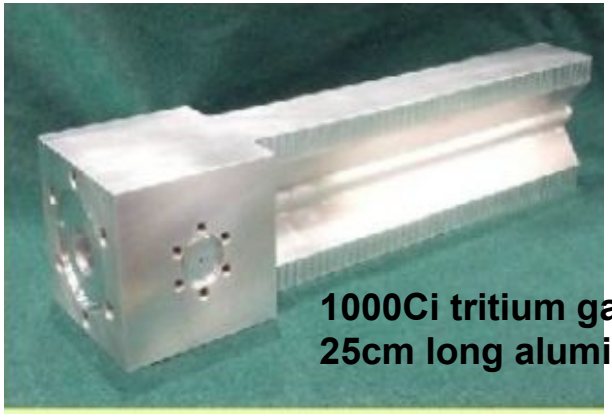


Tritium v.s. Helium-3:

- Large isospin (n/p, d/u) asymmetry
- Similar separation energy: 6.26 MeV v.s. 5.49 MeV
- Similar center-of-mass motion of the pair
- Similar FSI
- Calculable* few-body systems

Probing SRC in A=3 Systems





1000Ci tritium gas sealed in 25cm long aluminum cell

Tritium v.s. Helium-3:

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- Similar center-of-mass motion of the pair
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Hall A Tritium Experiments (2018):

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

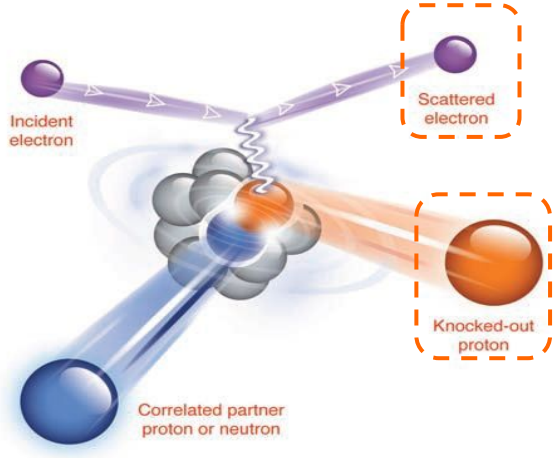
E12-11-103 “MARATHON” F2n/p, EMC
10.1103/PhysRevLett.128.132003

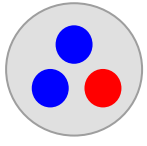
E12-14-011 high momentum nucleon distribution
10.1016/j.physletb.2019.134890,
10.1103/PhysRevLett.124.212501

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

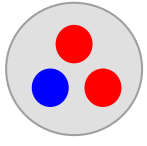
E12-17-003 nnL hypernuclei
10.1103/PhysRevC.105.L051001

Probing SRC in A=3 Systems (e,e'p)



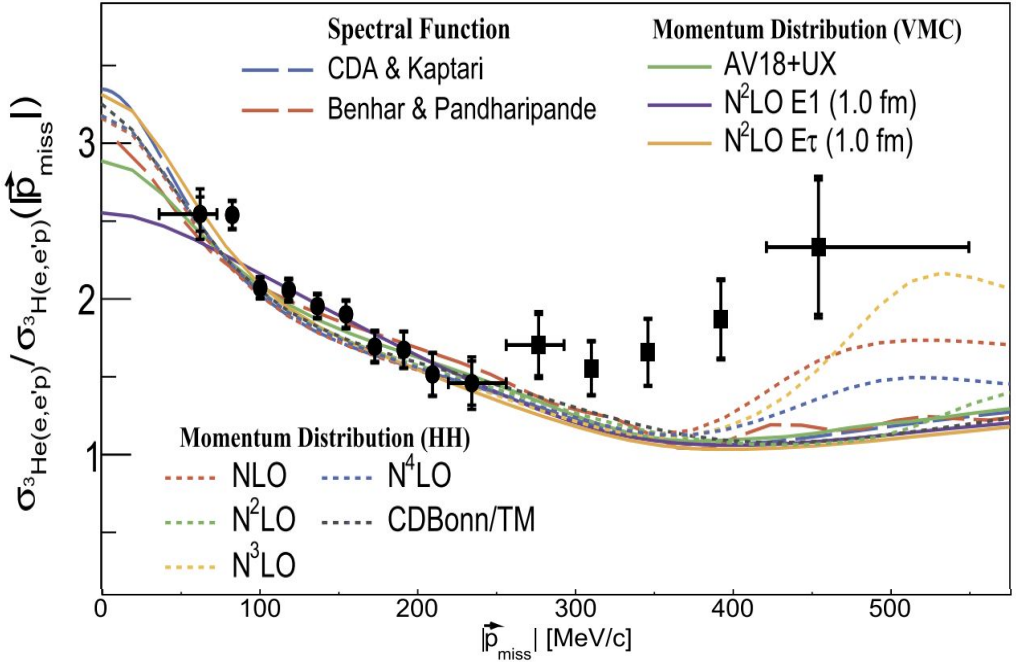


p in ^{3}H ≈ n in ^{3}He



N(p) in ^{3}He ≈ N(np) in ^{3}He

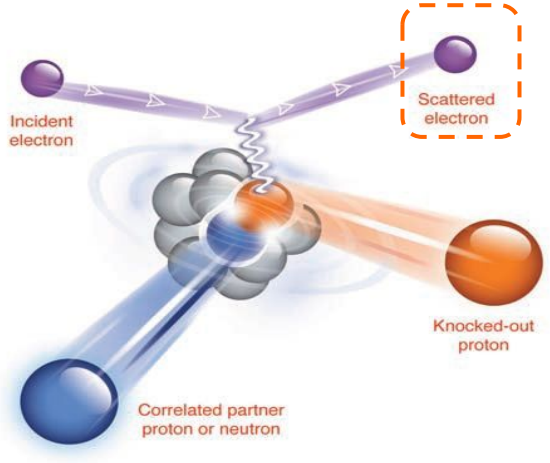
R. Cruz-Torres et. al., 10.1016/J.PHYSLETB.2019.134890

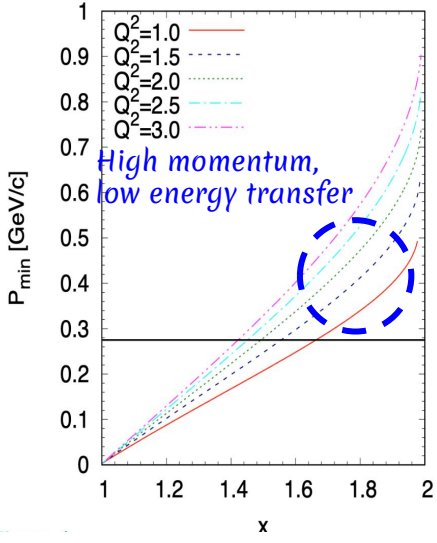


$$\frac{\sigma_{^3\mathrm{H}(e,e'p)}}{\sigma_{^3\mathrm{He}(e,e'p)}} = \frac{N_{np}\sigma_{np}}{N_{np}\sigma_{np} + N_{pp}\sigma_{pp}}$$

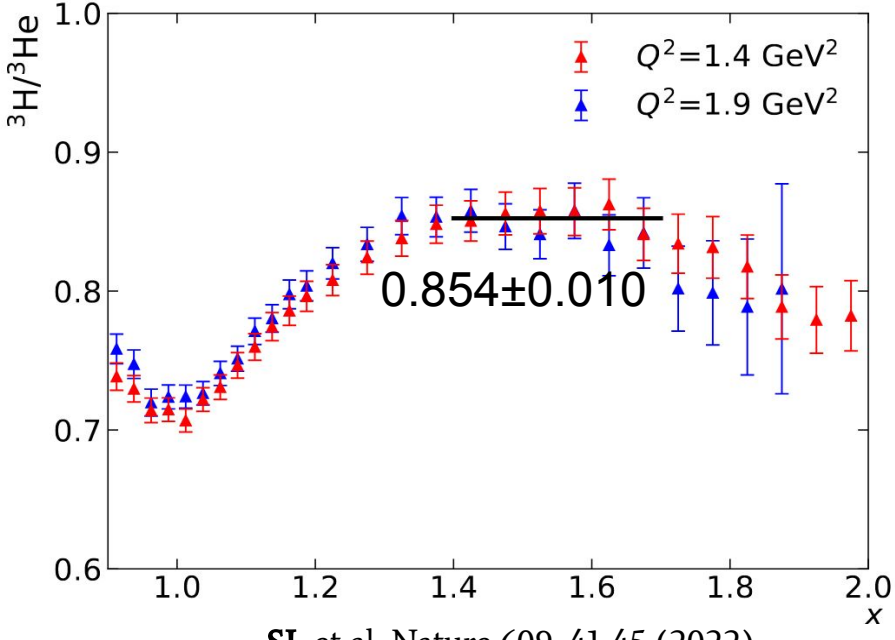
⇒ $N_{np/pp}$ =3.6 (+ 3.0 - 1.1)

Probing SRC in A=3 Systems (e,e')





Q^2>1.4 GeV2, 1.4<x<2: minimum initial momentum of the struck nucleon > k_F ⇒ Deuteron-like 2N SRC dominant



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

Inclusive measurement:

- High statistics
- Integrated nucleon momentum
- Deuteron-like pairs → scaling in x and Q^2

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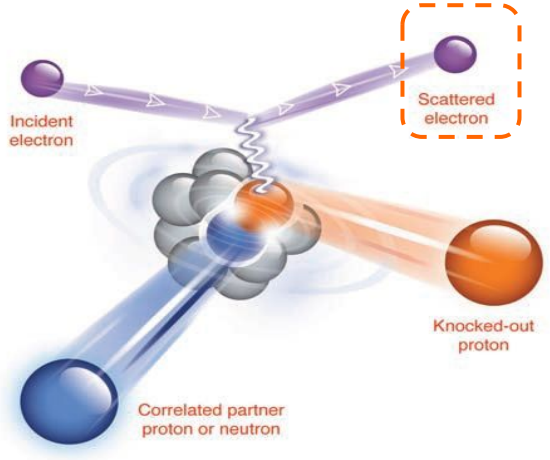

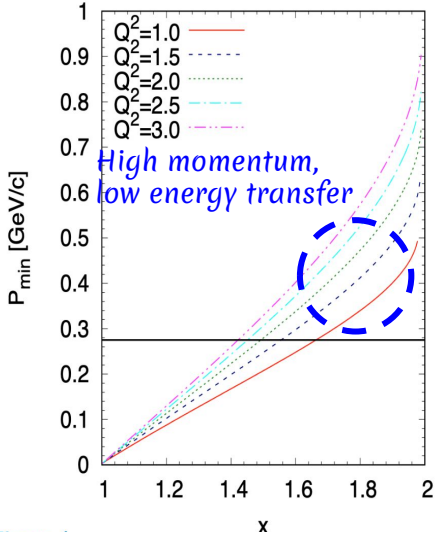

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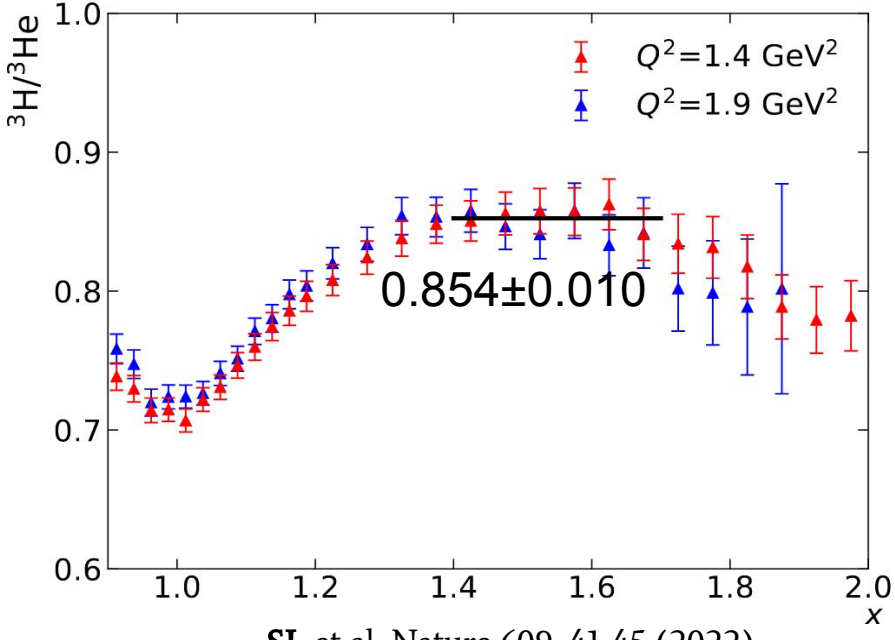

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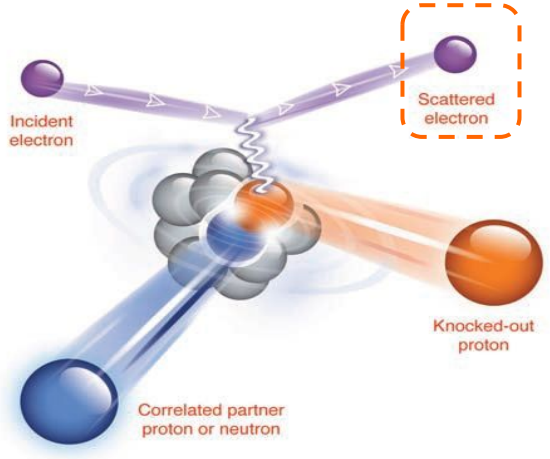
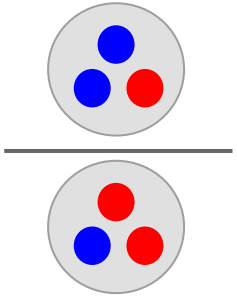
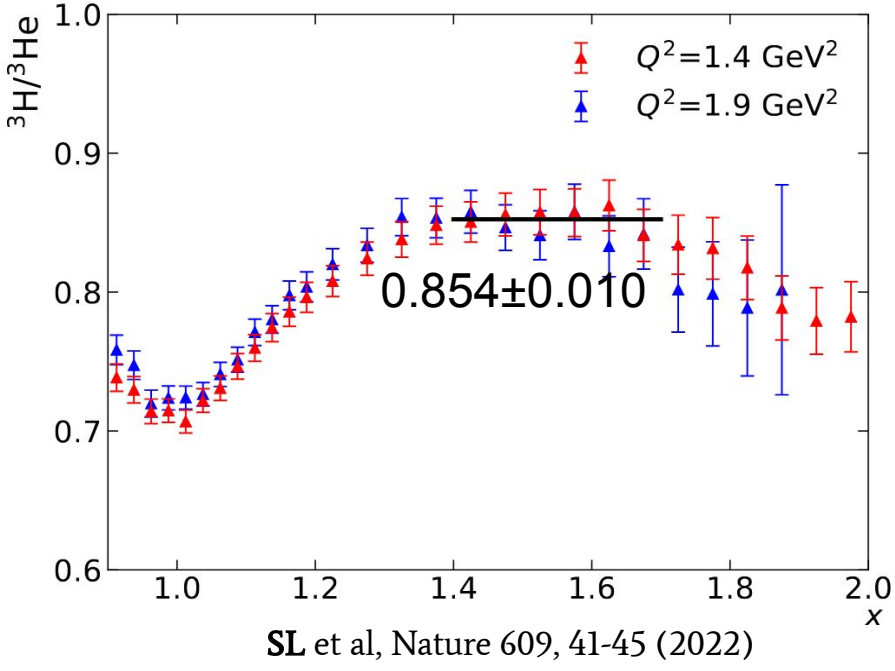




^3H = 2np + 1nn

^3He = 2np + 1pp

nn in ^3H ≈ pp in ^3He

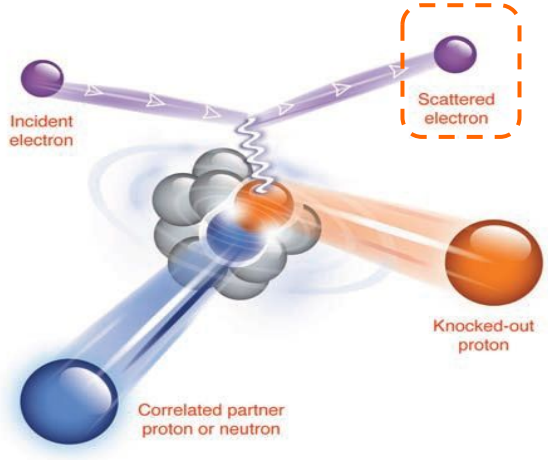


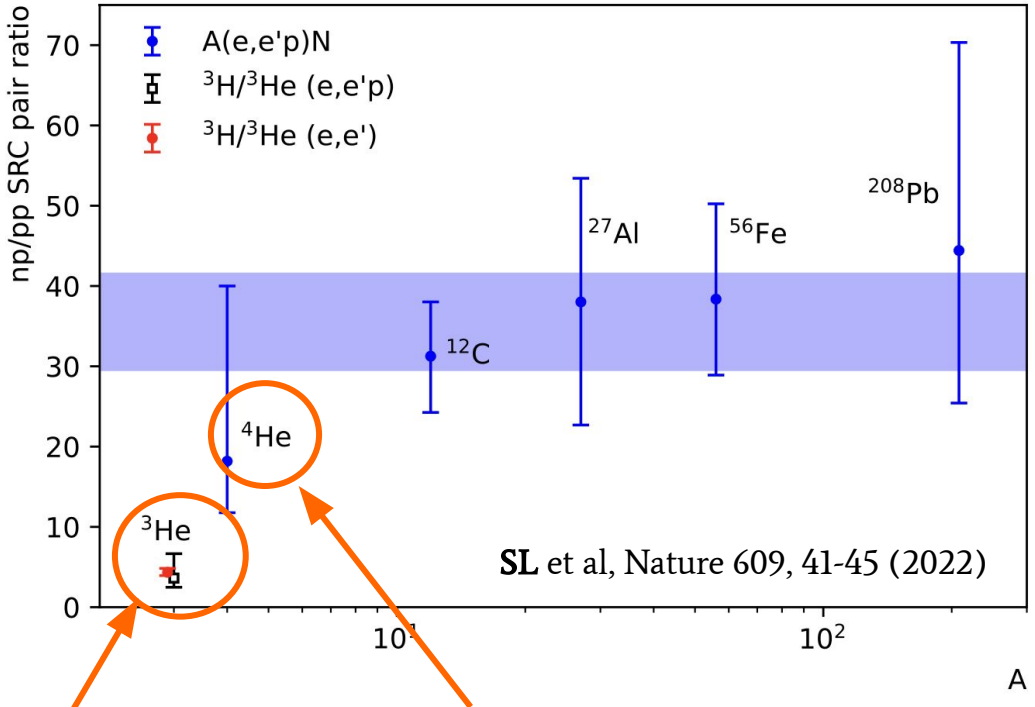
SL et al, Nature 609, 41-45 (2022)

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

$N_{np/pp}$ =4.3 ± 0.4

Probing SRC in A=3 Systems (e,e')





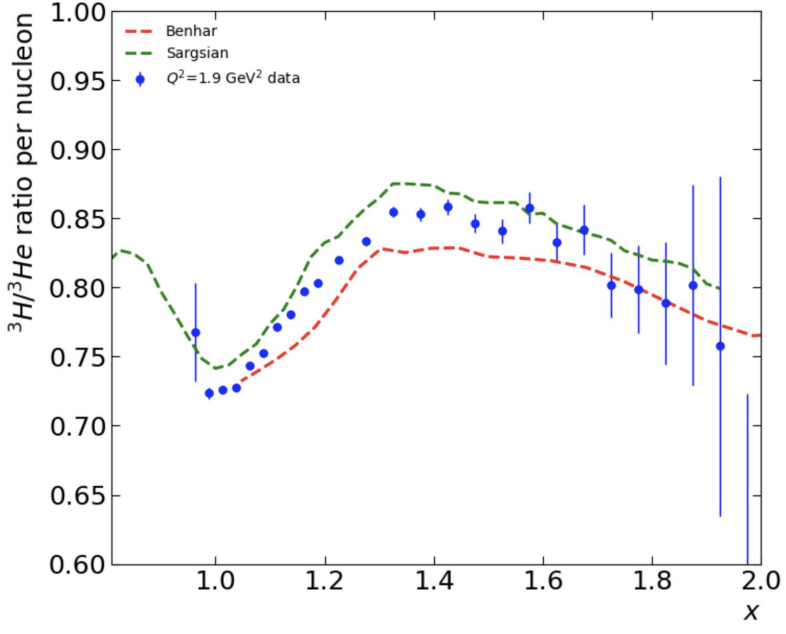
Why np is less dominant in A=3?

Better He4 measurements?

Status of Calculations?

SRC ratio

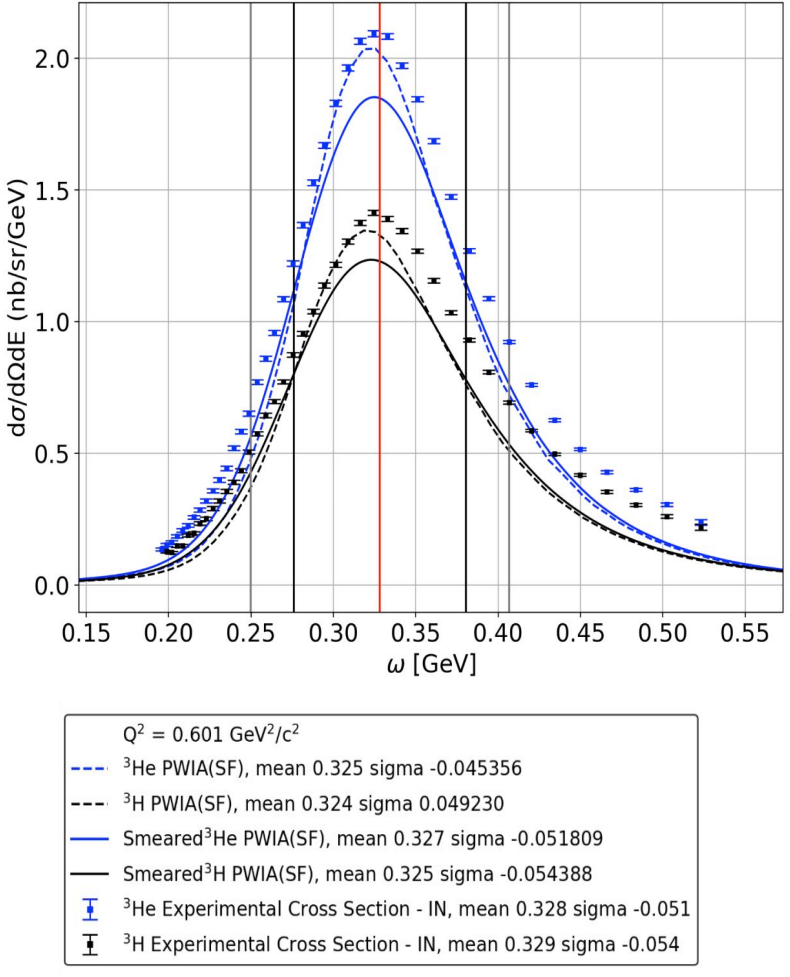
- Calculations from Misak and Omar
- Works at high Q^2, how about scaling at lower Q^2?



Inclusive xsection data vs. calculation

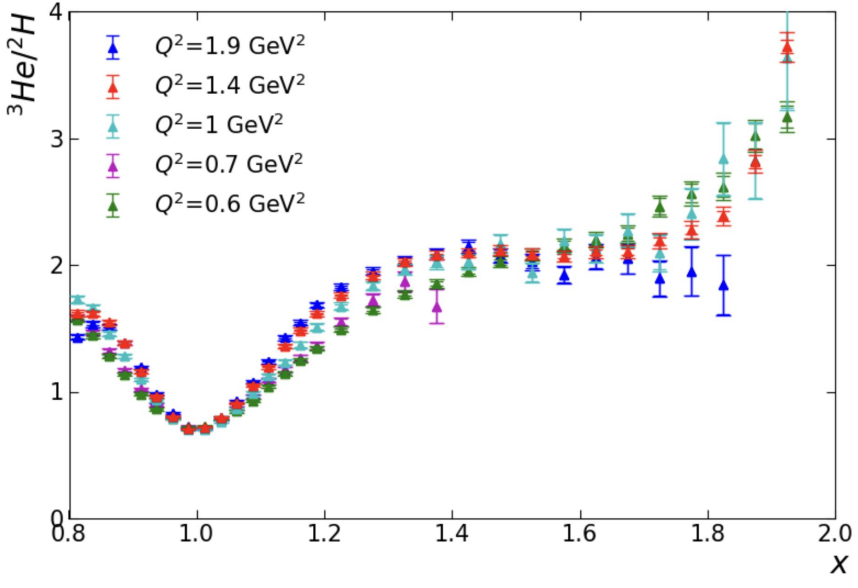
spectral function / GFMC + FSI

Noemi Rocco et al.



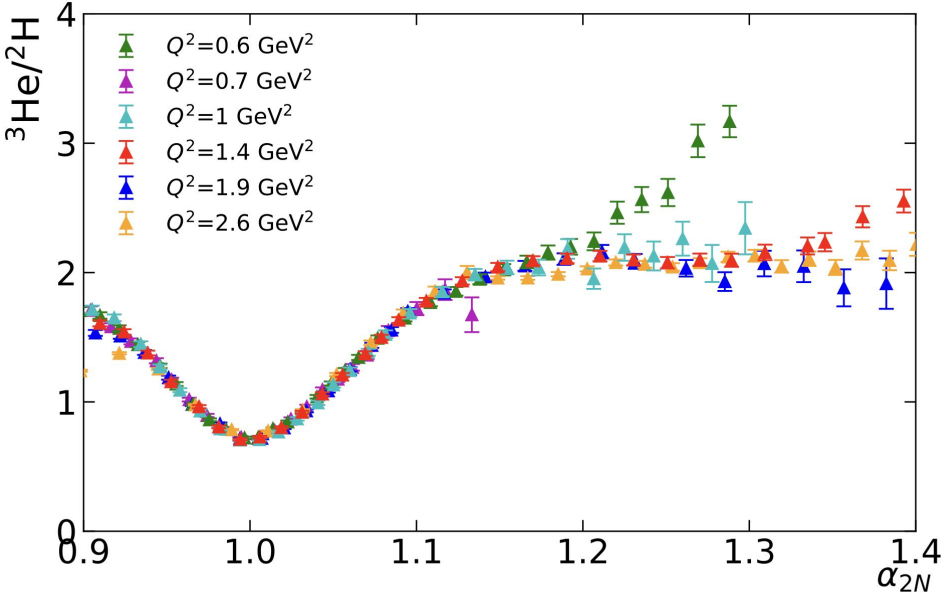
Q^2 Scaling

Plateau starting from 1 GeV^2



light-cone variable

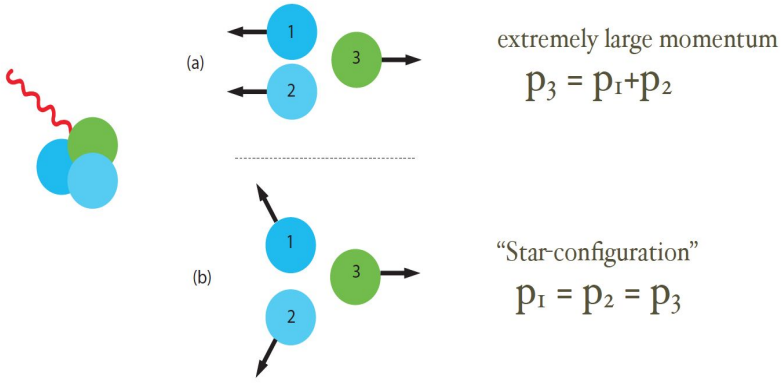
$$\alpha_{2N} = 2 - \frac{q_- + 2m}{2m} \frac{\sqrt{W^2 - 4m^2} + W}{W}$$



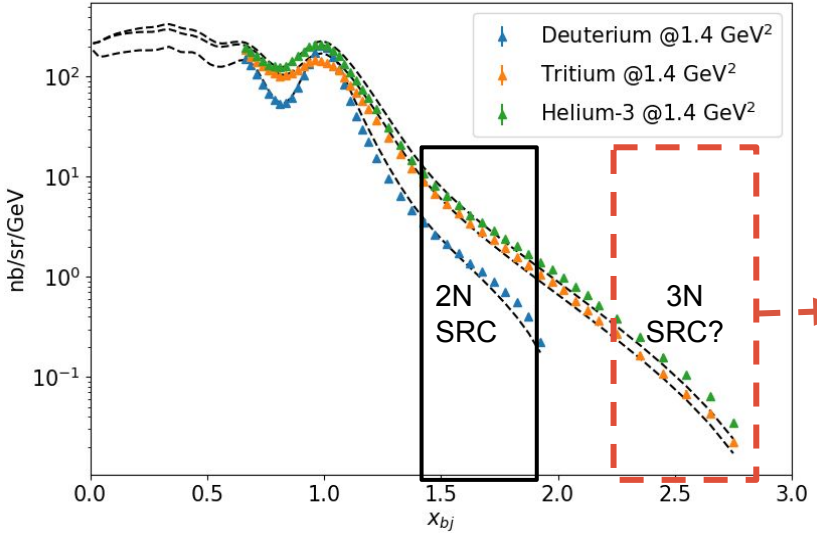
3N SRC ?

Ideal: Q^2>5 GeV^2 , x>2 to isolate 3N SRC contribution:

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

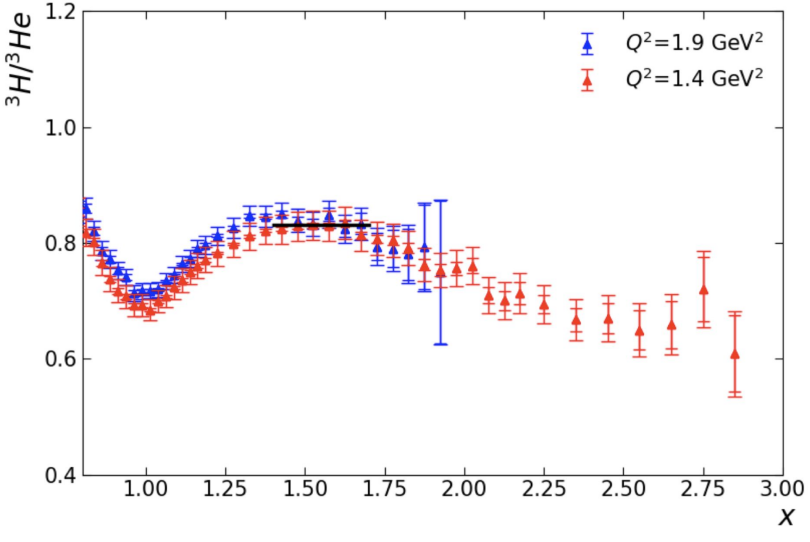


Data from this work:



Q2 may be too small to isolate 3N-SRC, but can still provide info on 3N momentum sharing

publication in preparation



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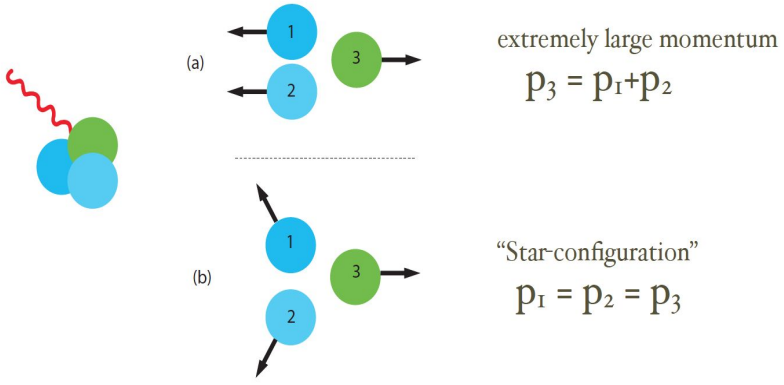

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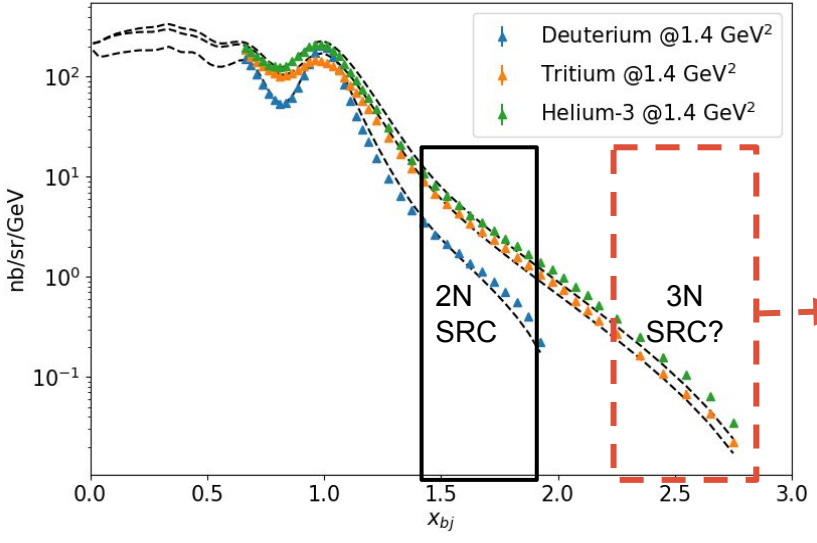

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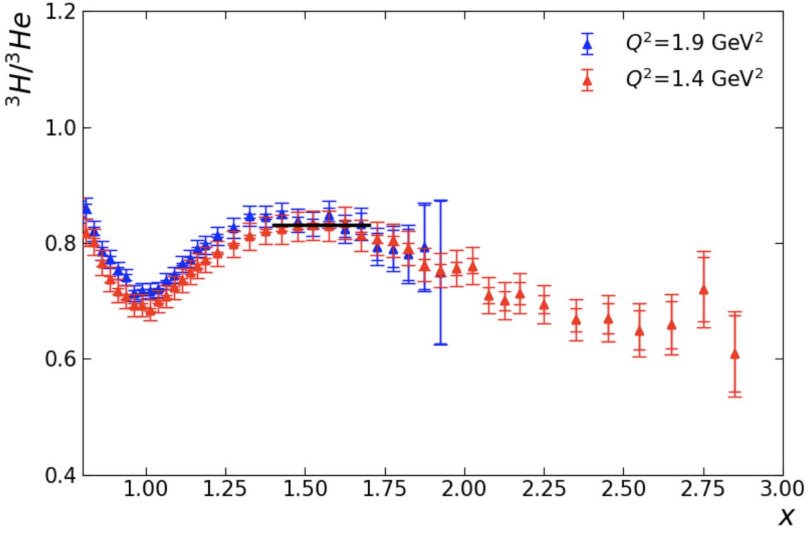
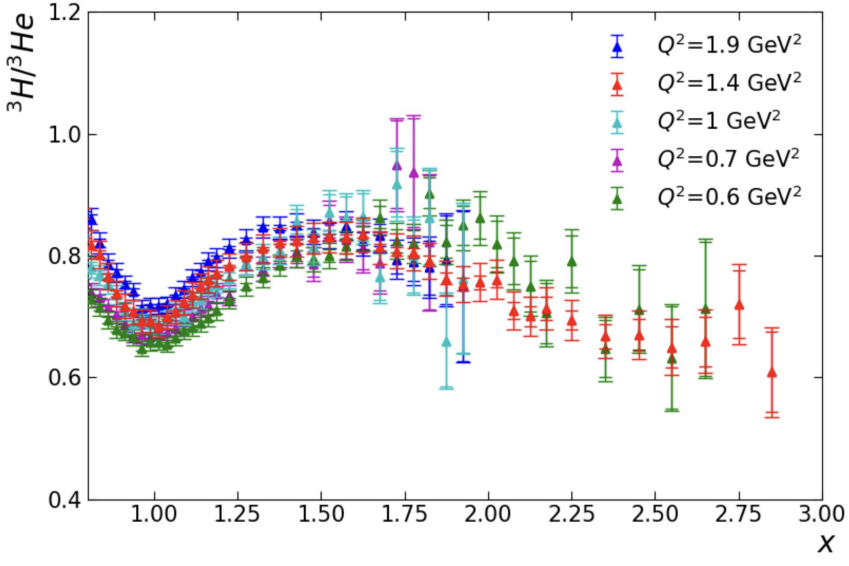
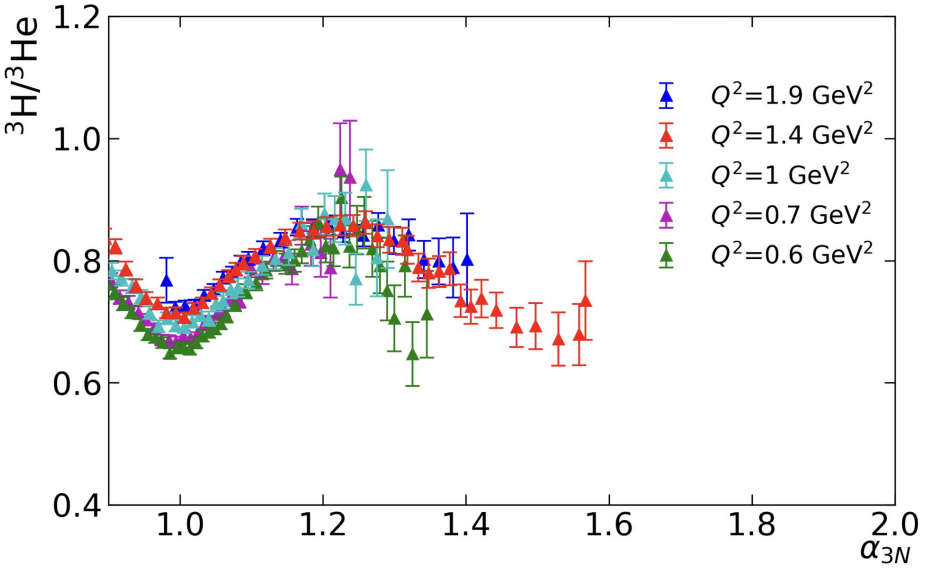


3N SRC ?

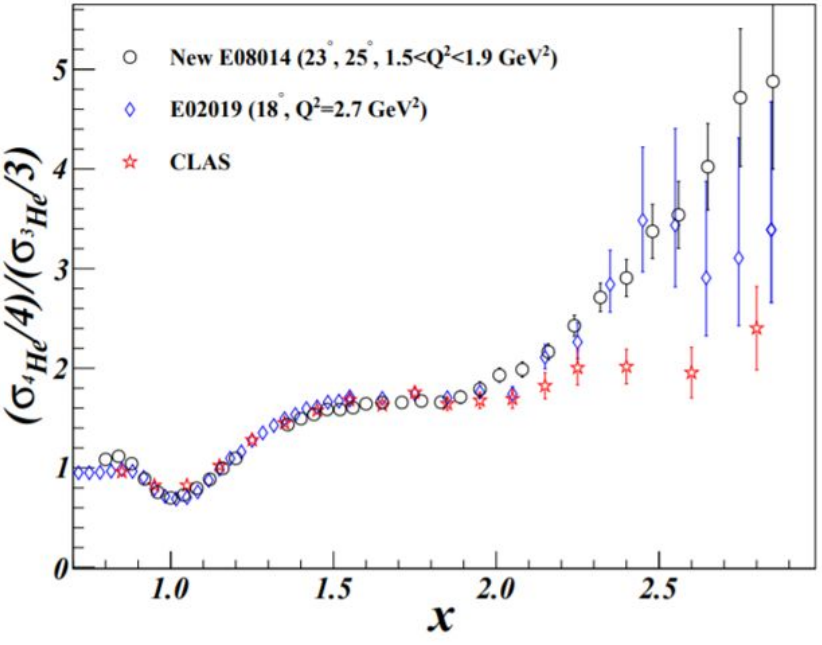




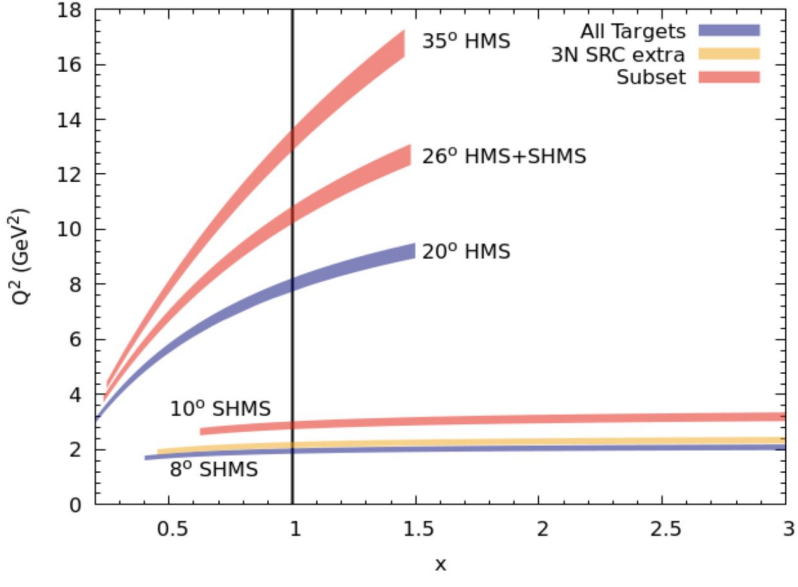
See predictions by Misak (10.1103/PhysRevC.107.014319) and Ronen (https://arxiv.org/abs/2301.09605)

3N SRC ?

Past: inconsistent results



Present: XEM2 @ Hall C: A/^{3}He ratio

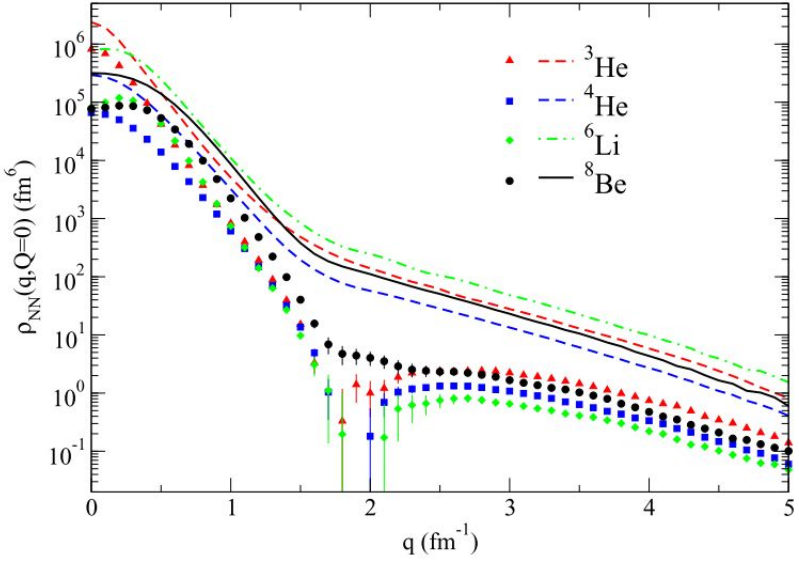


Future:
LOI 12-21-001 A/(3H+3He) @ Hall C
(with N. Fomin and J. Arrington)

Isospin Dependence in Calculations

VMC with AV18 + UX

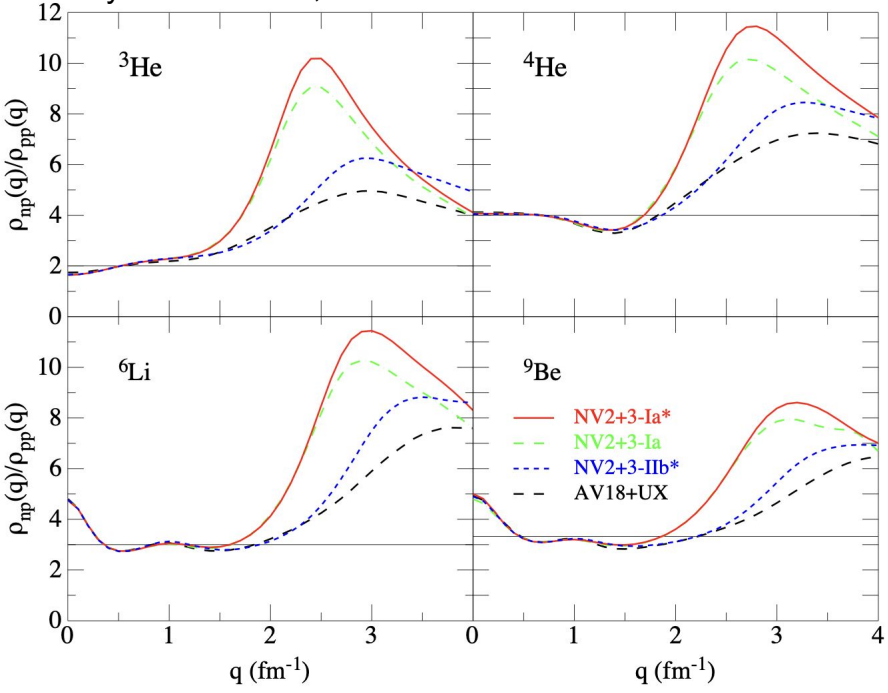
R. Schiavilla, R. B. Wiringa, S. C. Pieper, and J. Carlson, Phys. Rev. Lett. 98, 132501



Relative momentum

VMC with xEFT

M. Piarulli, S. Pastore, R. B. Wiringa, S. Brusilow, and R. Lim Phys. Rev. C 107, 014314



SRC-EMC?

- **Jiunn-Wei Chen**, William Detmold, Joel E. Lynn, and Achim Schwenk, Phys. Rev. Lett. 119, 262502
- J E Lynn et al 2020 J. Phys. G: Nucl. Part. Phys. 47 045109

EMC

Isoscalar operator

$$F_2^A(x,Q^2)/A \simeq F_2^N(x,Q^2) + g_2(A,\Lambda) f_2(x,Q^2,\Lambda)$$

$$g_2(A,\Lambda) = \frac{1}{2A}\langle A| : (N^\dagger N)^2 : |A\rangle_\Lambda$$

Matrix element from EFT corresponds to nuclear modification from < 0.5 GeV

Unknown function independent of A from>0.5 GeV, need Lattice calculation

Factorized A and x dependence:

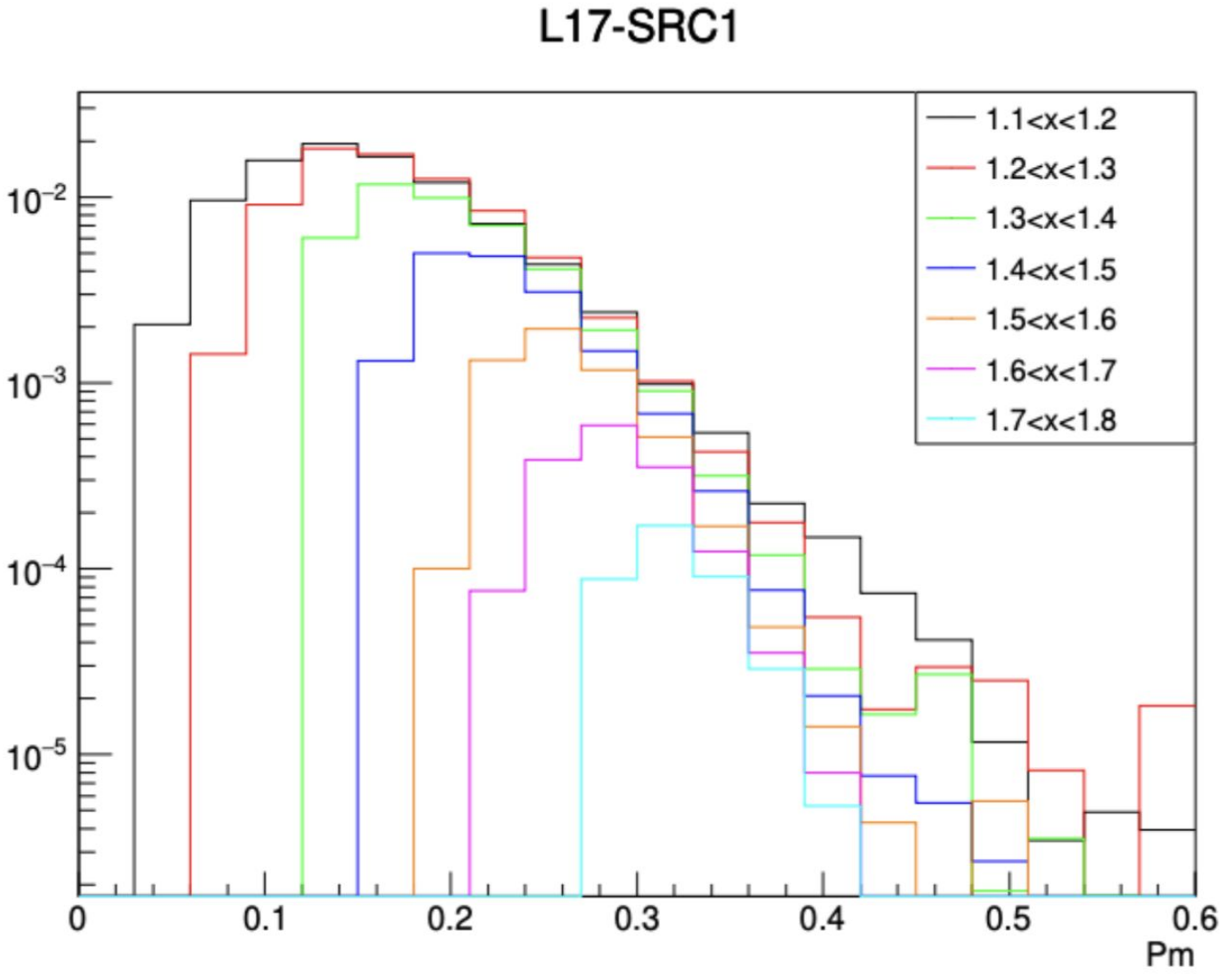
$$R_{EMC}(A,x) - 1 = \frac{2}{A}\frac{F_2^Q}{F_{2d}} - 1$$

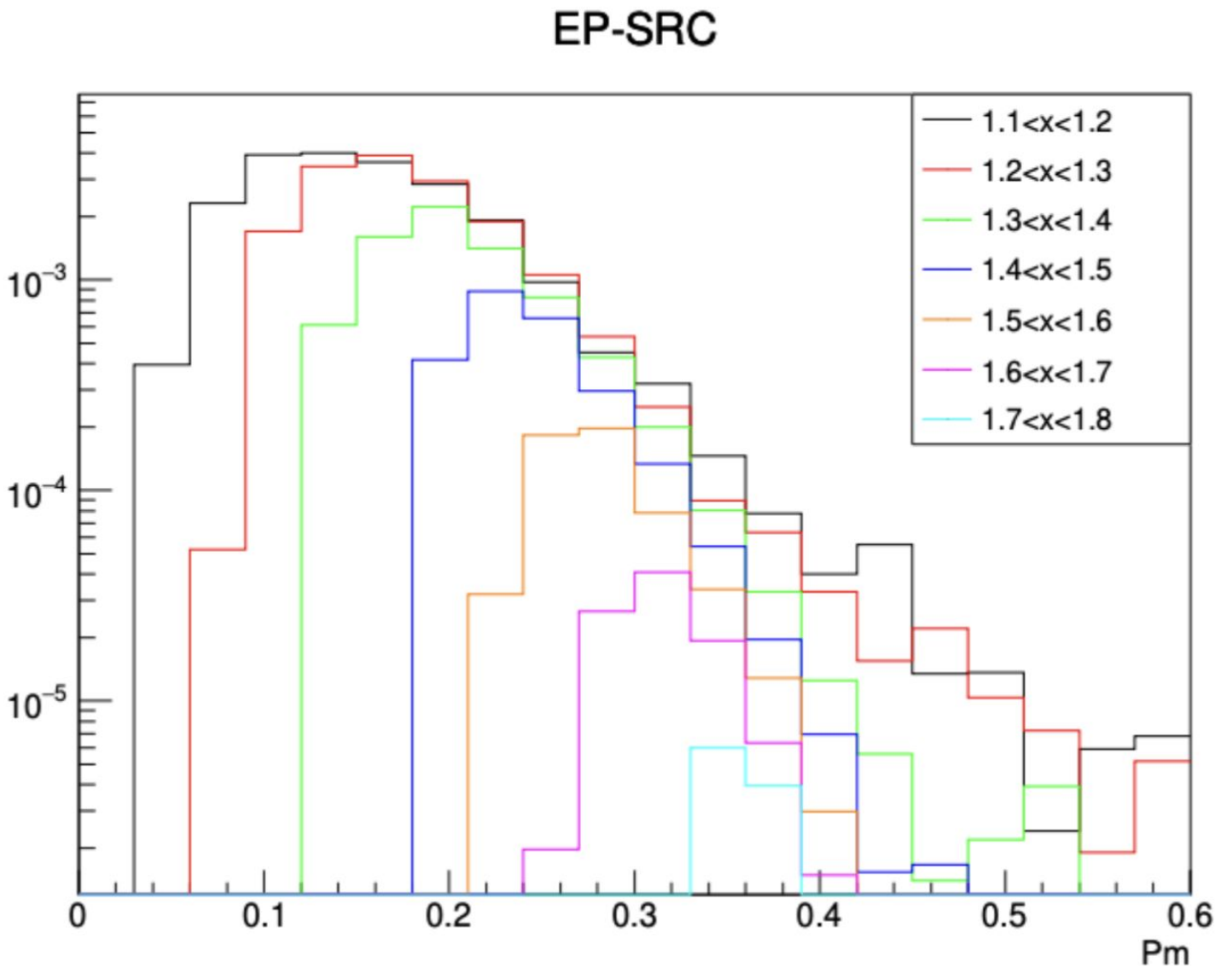
$$= (1 - \frac{F_2^N(x)}{F_2^d(x)})(\frac{g_2^A}{g_2^d} - 1)$$

SRC

$$\sigma_A/A \simeq \sigma_N + g_2(A,\Lambda)\sigma_2(\Lambda) \Rightarrow a_2(A,x>1) \simeq \frac{g_2(A,\Lambda)}{g_2(2,\Lambda)}$$

Thank you!

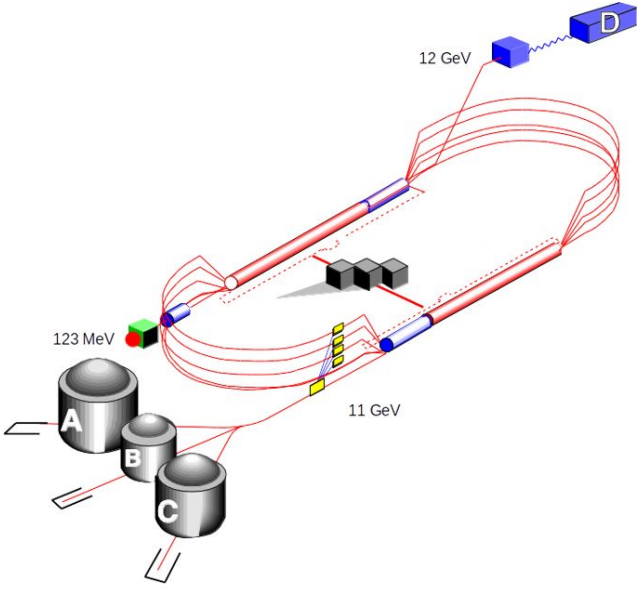

L17-SRC1
1.1<x<1.2
1.2<x<1.3
1.3<x<1.4
1.4<x<1.5
1.5<x<1.6
1.6<x<1.7
1.7<x<1.8
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
0.1
0.2
0.3
0.4
0.5
0.6
Pm

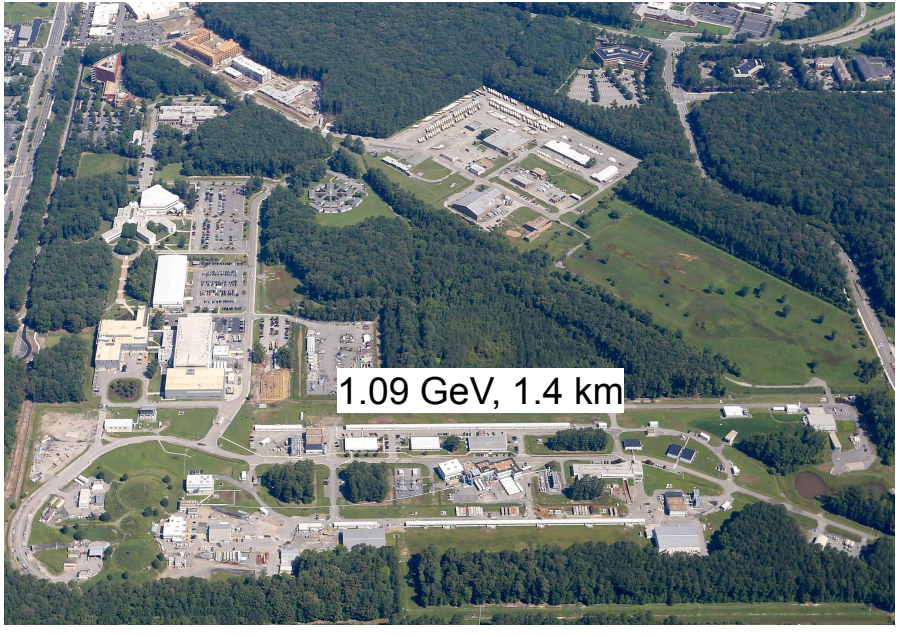

EP-SRC
1.1<x<1.2
1.2<x<1.3
1.3<x<1.4
1.4<x<1.5
1.5<x<1.6
1.6<x<1.7
1.7<x<1.8
10^{-3}
10^{-4}
10^{-5}
0
0.1
0.2
0.3
0.4
0.5
0.6
Pm

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
- Upto 12 GeV electrons scattering off fixed targets
- 4 experimental halls, diverse programs





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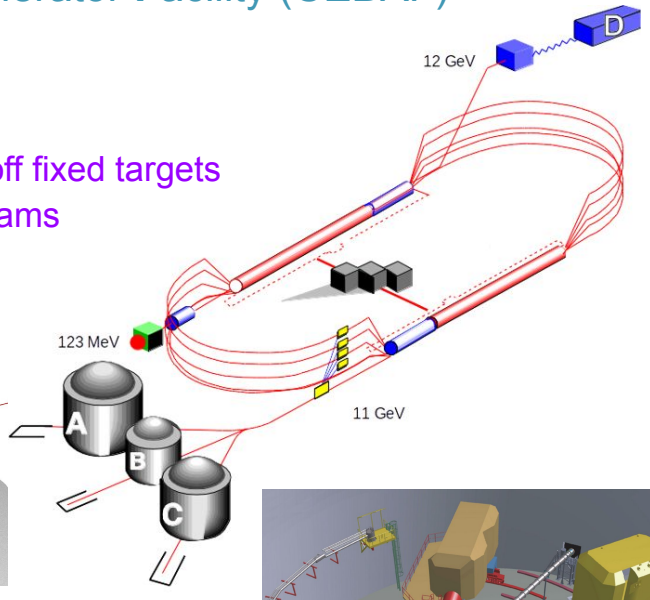
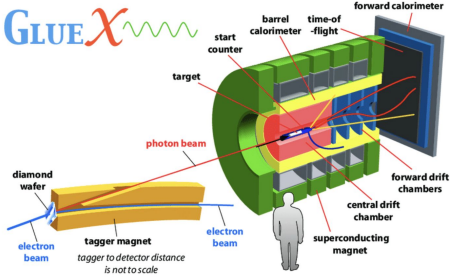
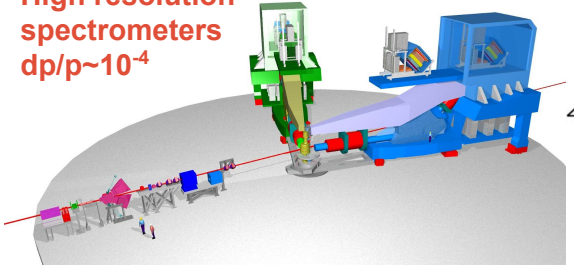
- Upto 12 GeV electrons scattering off fixed targets
- 4 experimental halls, diverse programs

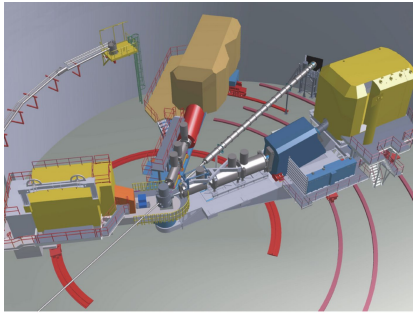


Real photon beam



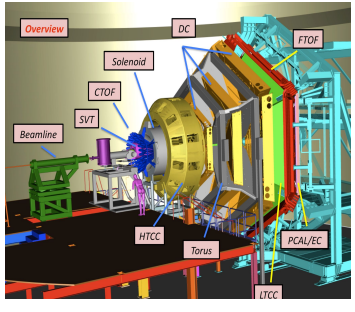
High resolution spectrometers dp/p~10^{-4}



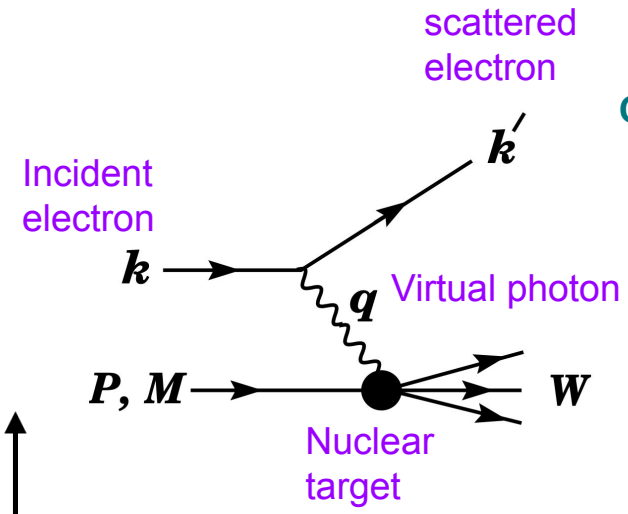


High momentum spectrometer,
-precision cross sections

The CEBAF Large Acceptance Spectrometer (CLAS)



Electron Scattering

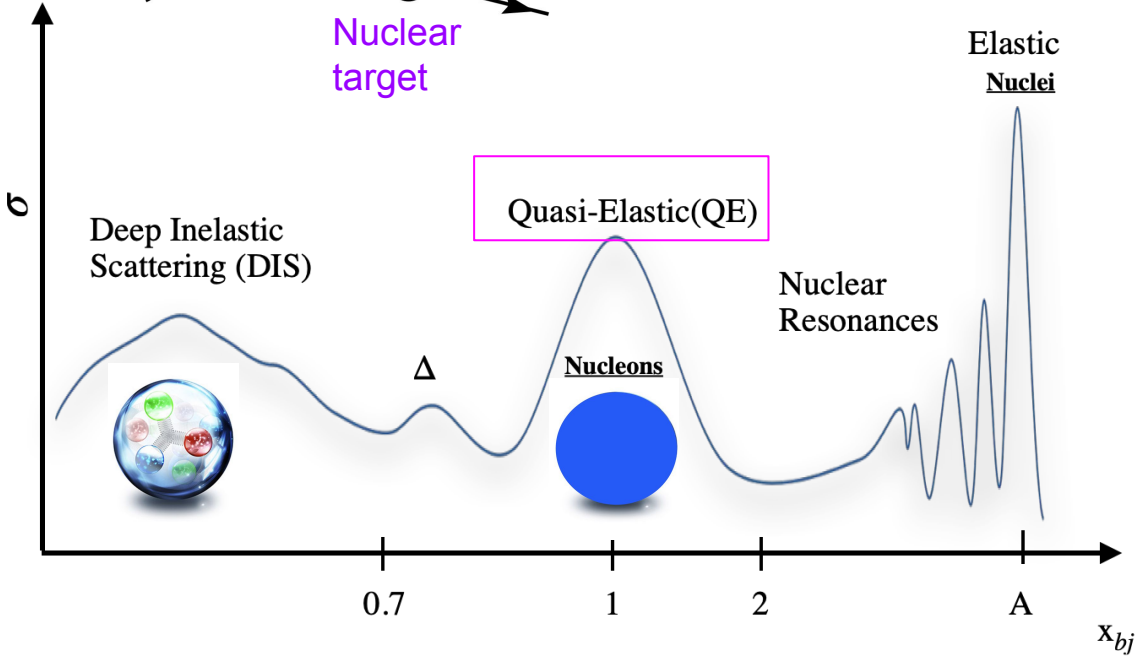


Cross section ~ probability of scattering

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

Leptonic tensor (QED)
Point-like electron

hadronic tensor
Nuclear structure:
(nucleonic / partonic)



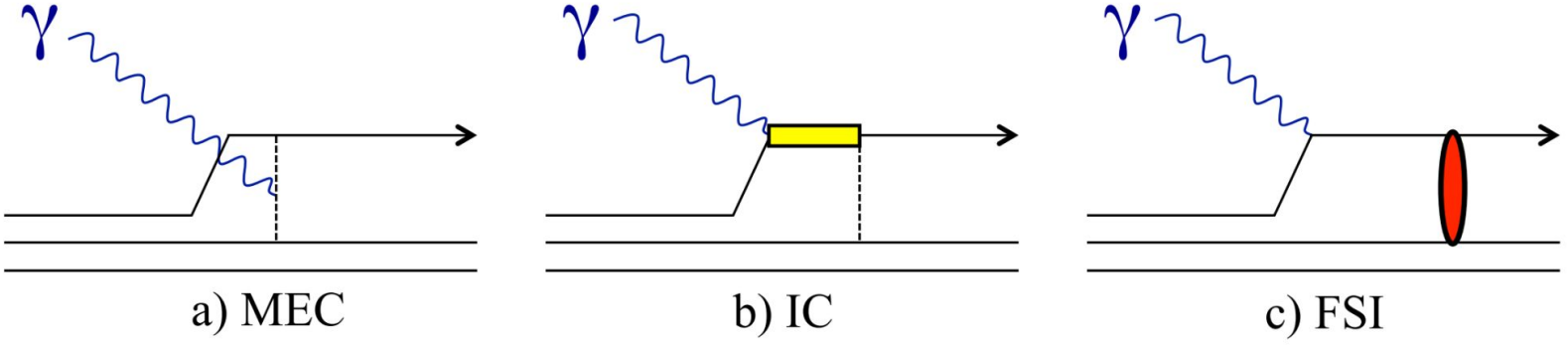
$Q^2 = -q^2$ four-momentum transfer squared

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

Probing SRC in Quasi-elastic Scattering

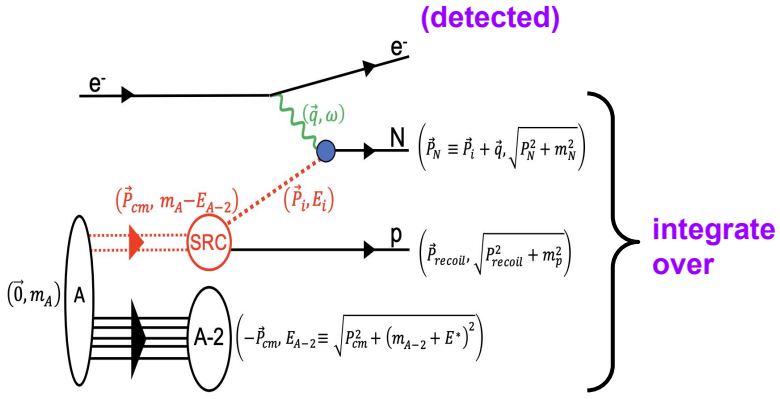
Competing processes:

- 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



a) MEC b) IC c) FSI

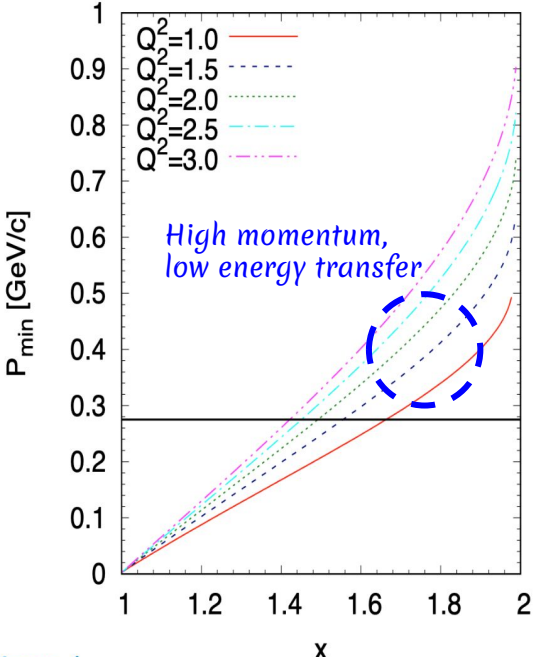
Probing SRC in Quasi-elastic Scattering



Inclusive measurement:

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

- High statistics
- Need high x, high Q2 to
  - Suppress competing process e.g. meson exchange current
  - Ensure p_min > k_F



Q2>1.4 GeV2, 1.4<x<2:
minimum initial momentum of the struck nucleon > k_F
⇒ Deuteron-like 2N SRC dominant

prob. of finding 2N SRC in nucleus A

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

(0 over σ_{QE}, 0 over σ_3)

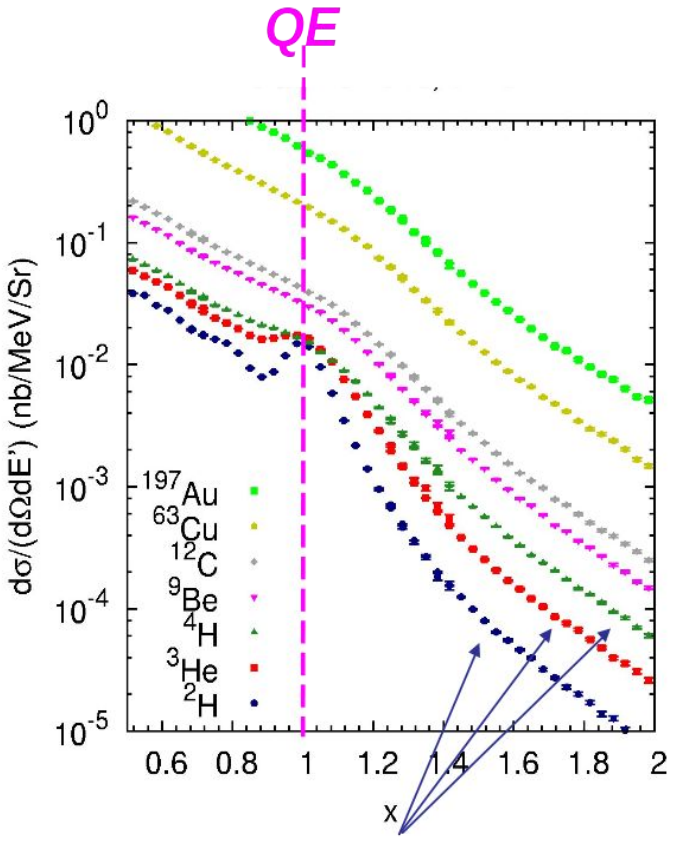
cross section from 2N SRC

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

** up to center-of-mass motion corrections

4% high momentum component in deuteron wave function

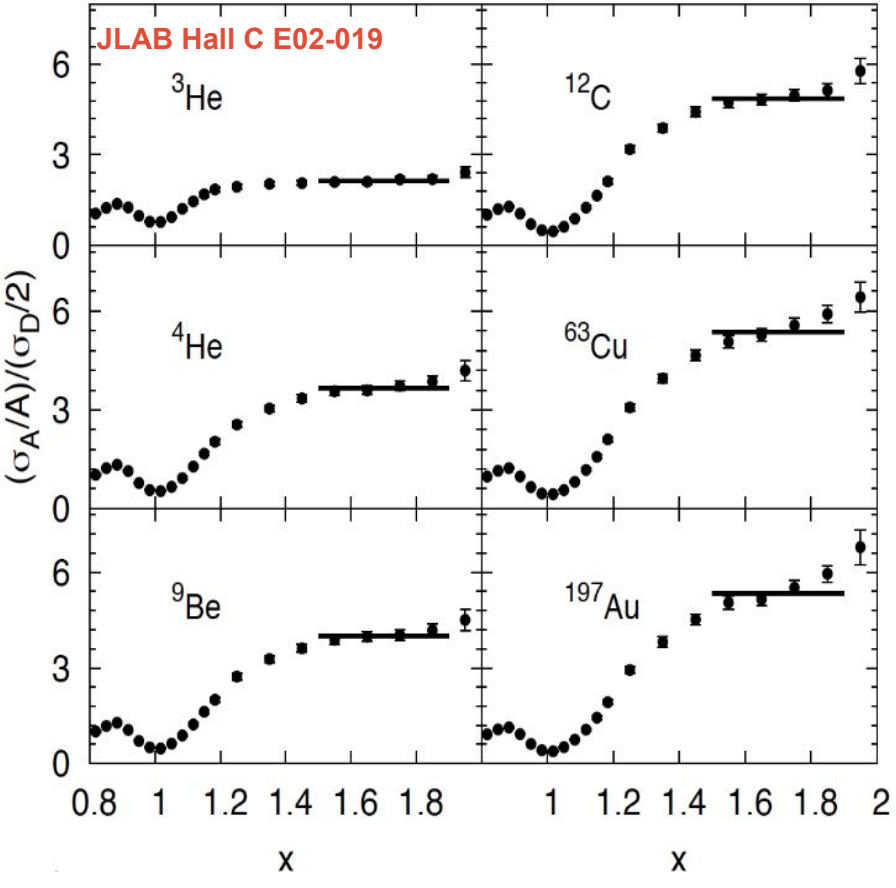
SRC Plateau / Bjorken x-scaling



High momentum tails should yield constant ratio if SRC-dominated

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

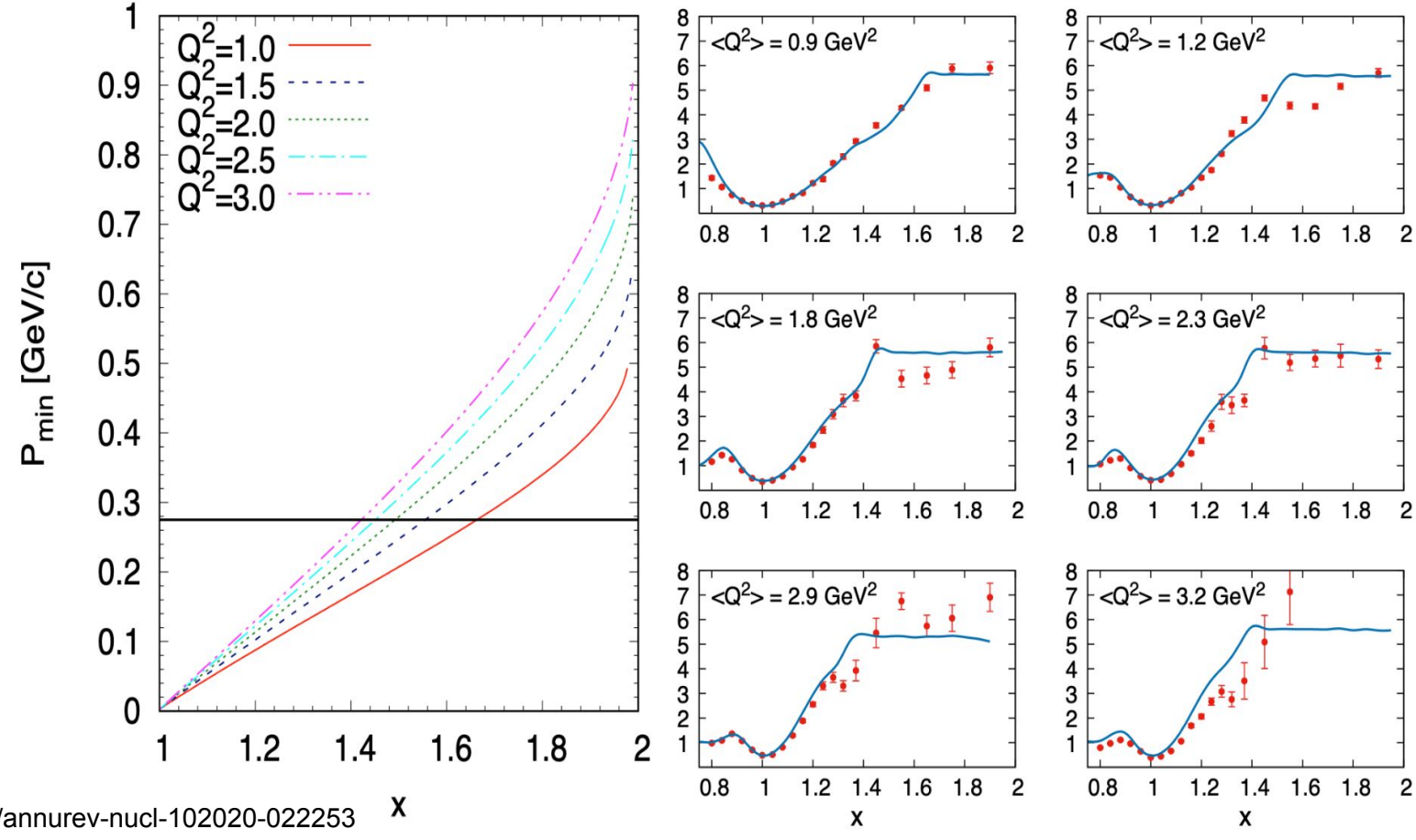
Plateaus in A/D cross section ratio



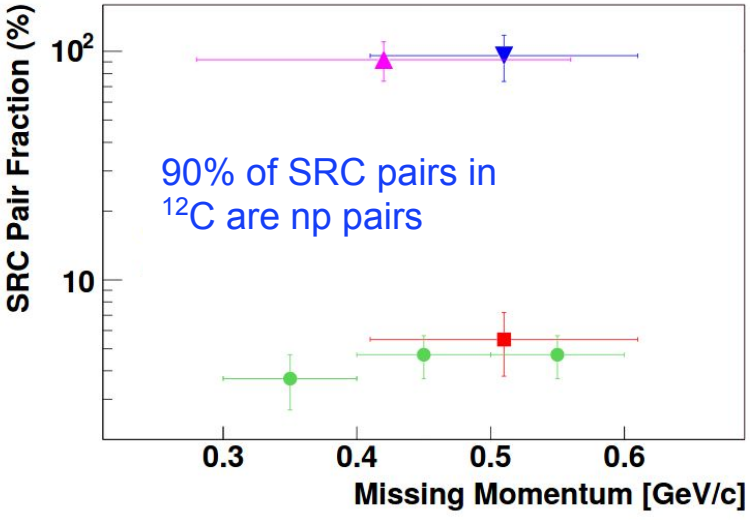
SRC Plateau / Q^2-scaling

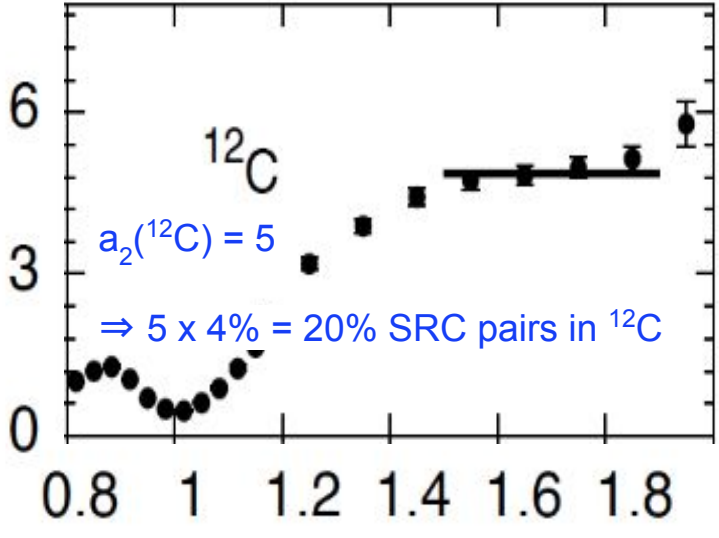
Fe/D cross section ratio from SLAC

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

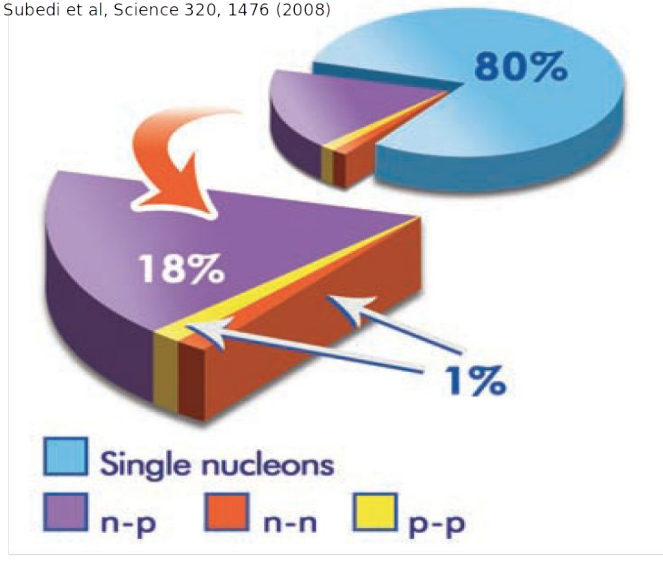


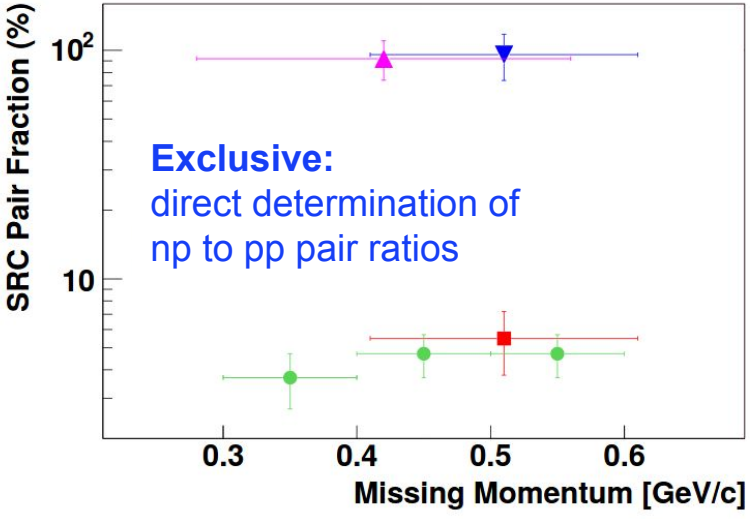
10.1146/annurev-nucl-102020-022253

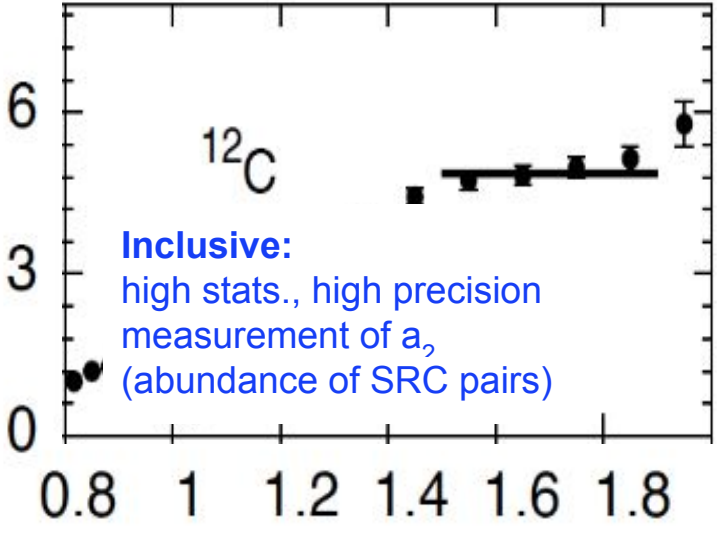




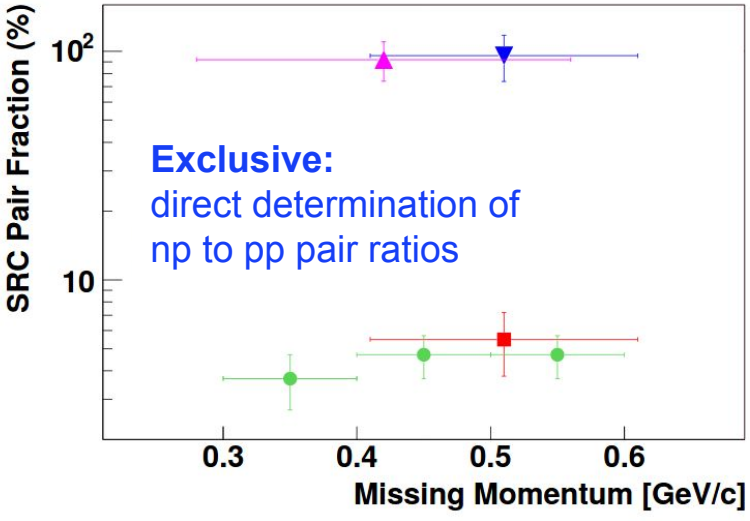
Subedi et al, Science 320, 1476 (2008)

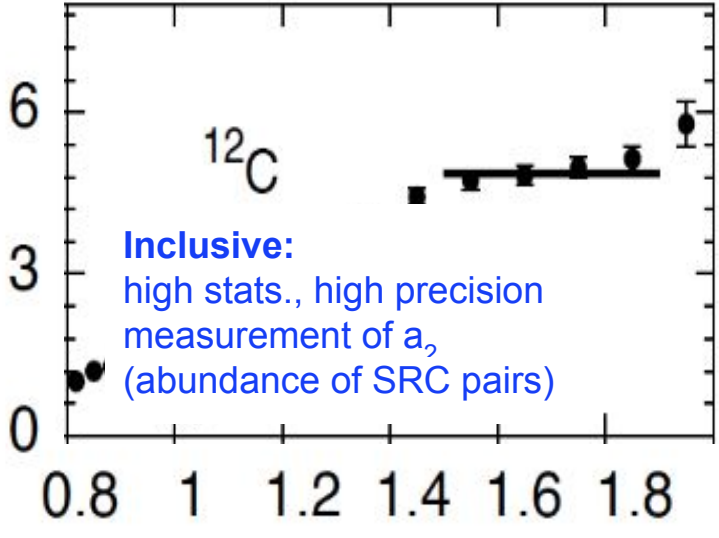


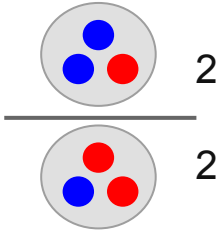

SRC Pair Fraction (%)
10^2
10
0.3
0.4
0.5
0.6
Missing Momentum [GeV/c]
Exclusive:
direct determination of
np to pp pair ratios


^{12}C
6
3
0
0.8
1
1.2
1.4
1.6
1.8
Inclusive:
high stats., high precision
measurement of a_2
(abundance of SRC pairs)

Inclusive Scattering with A=3 nuclei







2 np + 1 nn pairs

2 np + 1 pp pairs

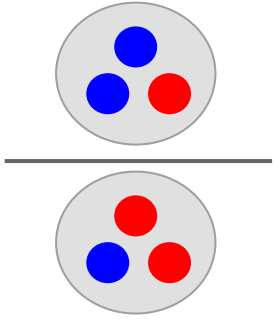
Tritium v.s. Helium-3:

- Large isospin (neutron-proton) asymmetry
- Similar separation energy: 6.26 MeV v.s. 5.49 MeV
- Similar center-of-mass motion of the pair
- Similar FSI
- Calculable* few-body systems

Inclusive cross section ratio:

- High statistics
- Systematic uncertainties canceled in the ratio

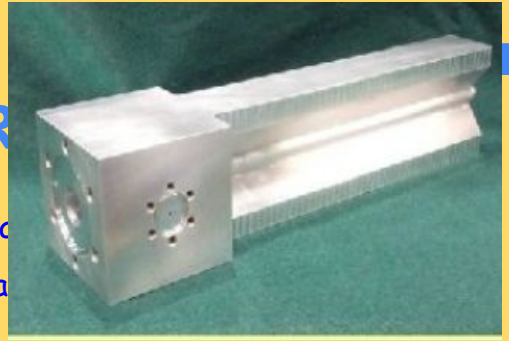
The isospin structure of SRC pairs in A=3



2 np + 1 nn pairs

2 np + 1 pp pairs

E12-11-112: Precision Measurement of the nce in the 2N and 3N Short-range Correlation R



Spokespersons: Patricia Solvignon, John Arrington, Donal Day, Doug

Students: Leiqaa Kurbany (elastic form factor) , Shujie Li (SRC), Na

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

Experiment Configuration

Hall A @ JLab

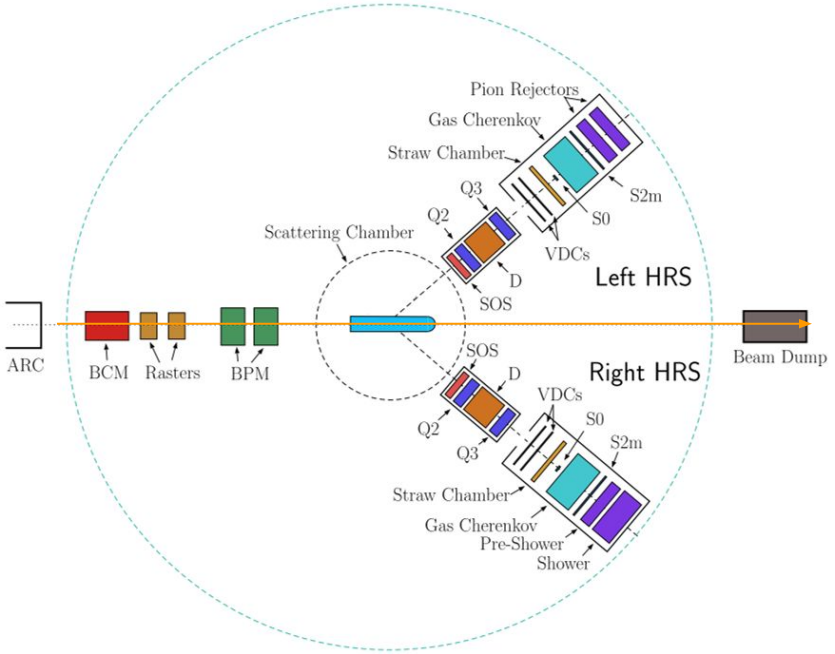
Primary Kinematics:

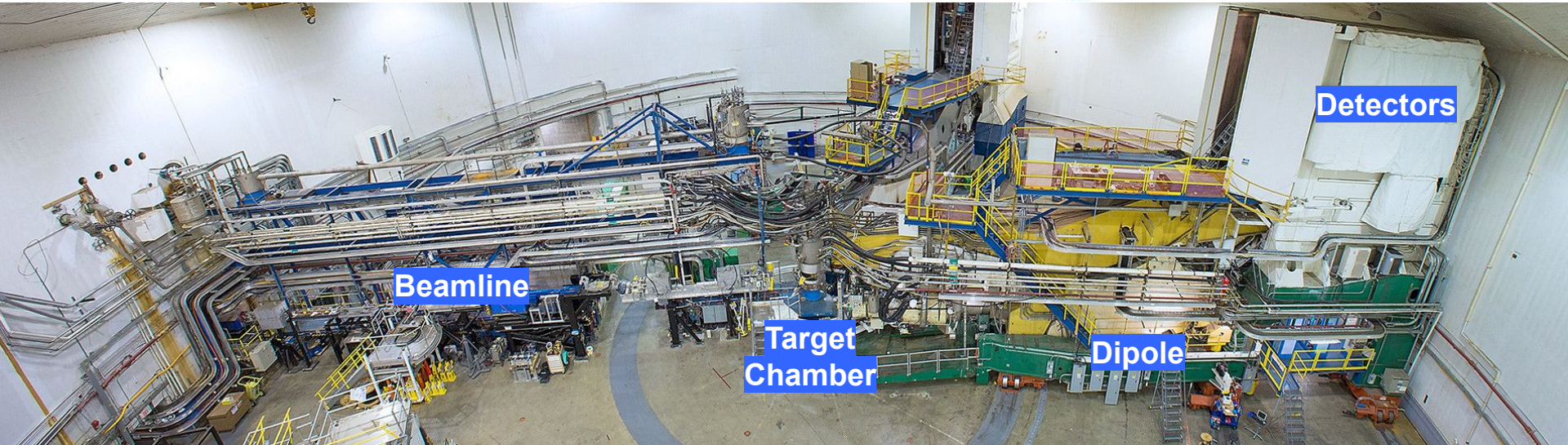
Beam energy: 4.3 GeV

Momentum : 3.54, 3.82 GeV

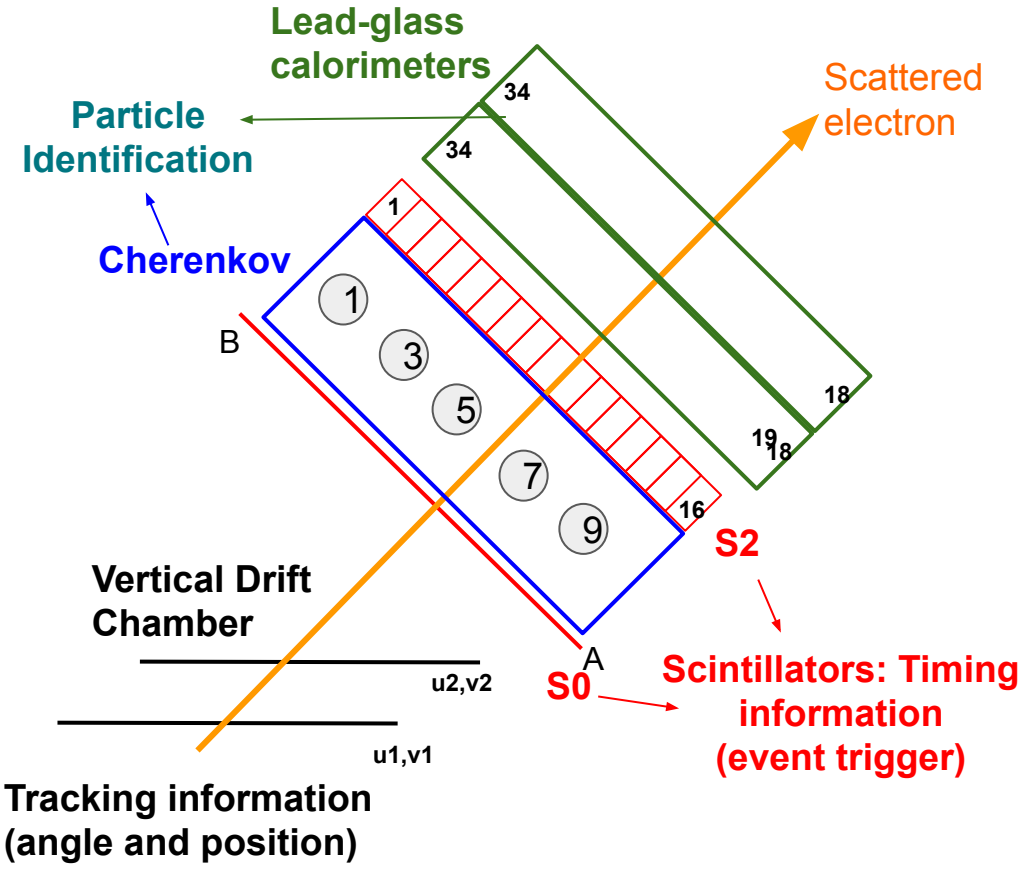
Angle : 20.88, 17 degree

Q^2 : 1.8, 1.4 GeV^2



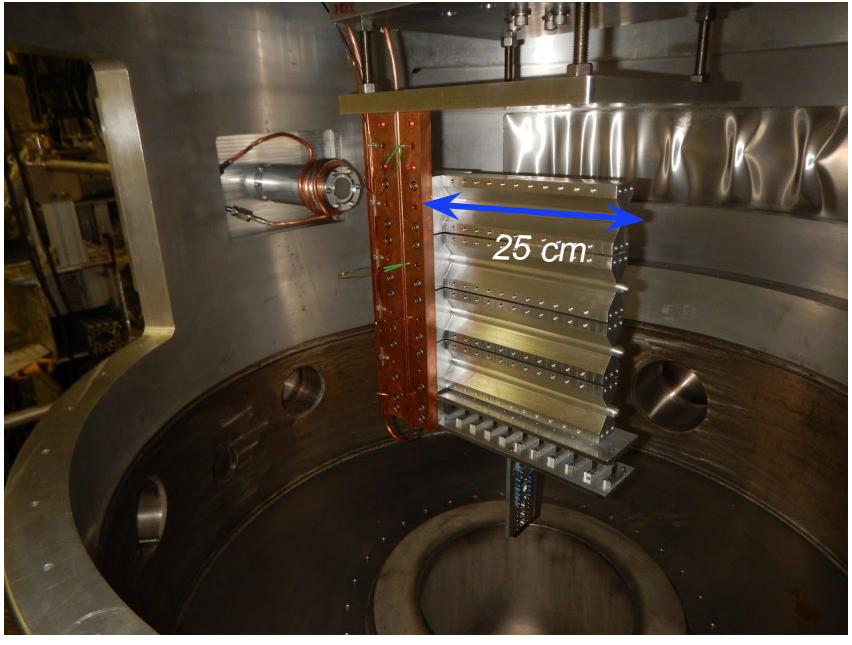


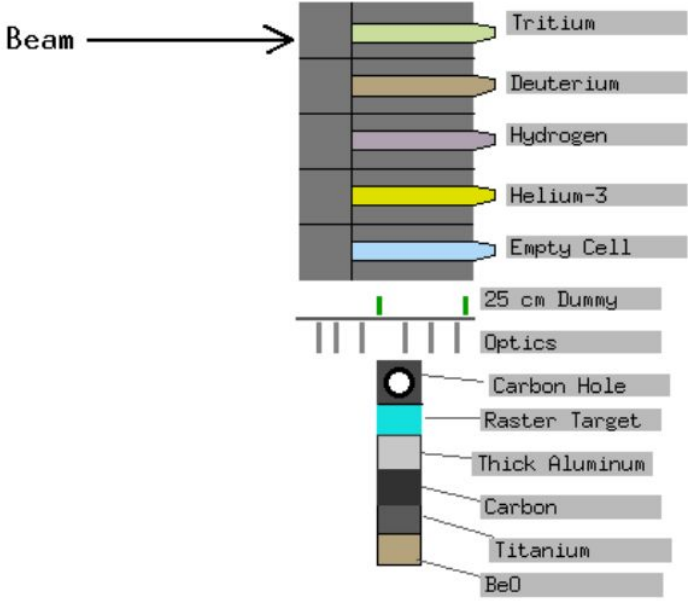
Detecting Electrons



The Gas Target System

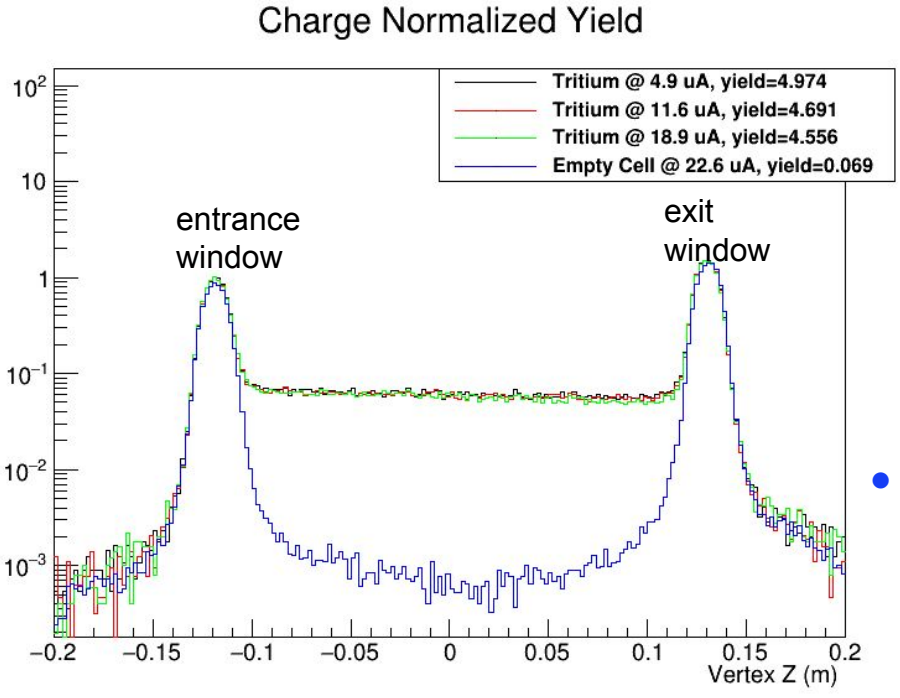
- Only tritium target for high energy electron scattering in the past 30 years
- Low-density, high pressure, room temperature gas target system
- 25 cm sealed alloy target cell
- 1000 Ci of tritium gas (safe to ship with FedEx)



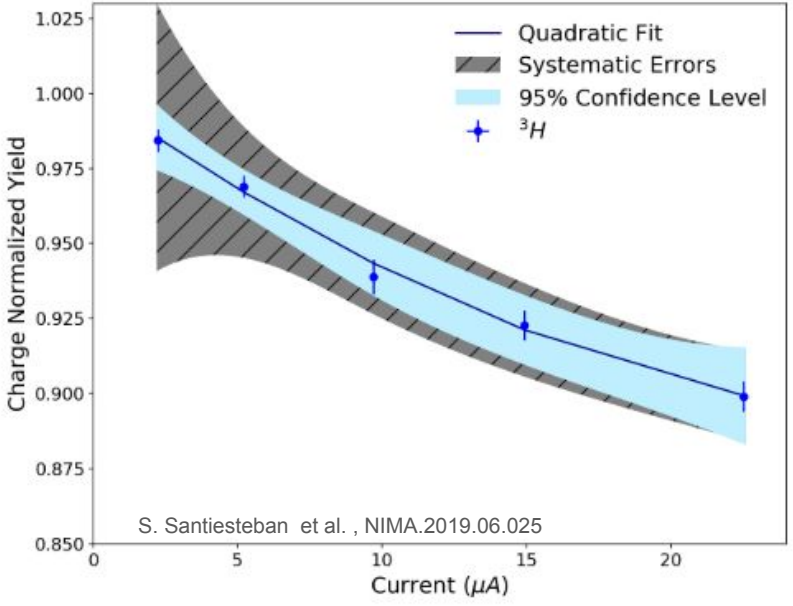


The Gas Target System

- Maximum current = 22.5 uA on target windows to minimize the risk of gas leak
- Tritium decay correction
- Hydrogen contamination correction



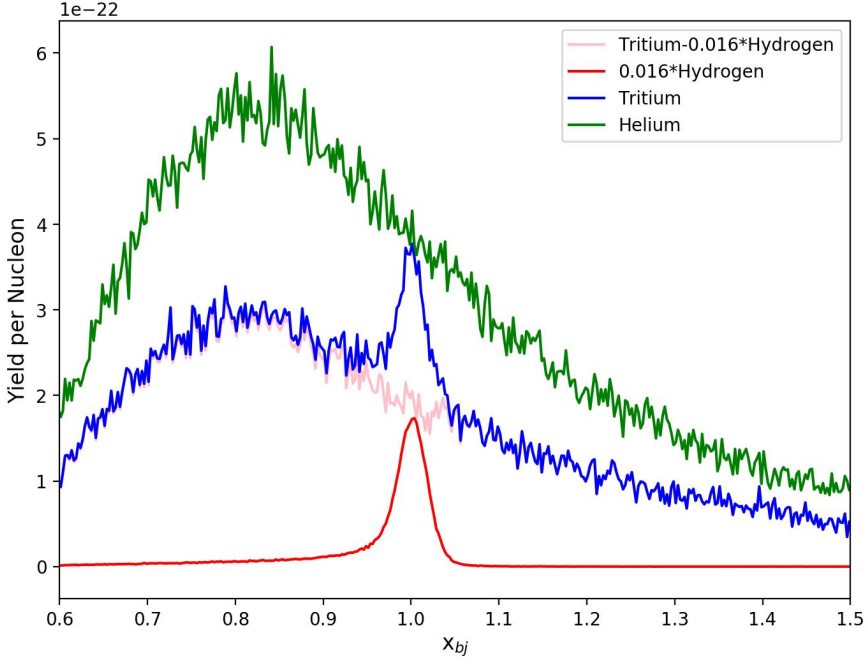
- **"Boiling" effect**:
  - The tritium areal density along the beam path reduced by ~ 10% at 22.5 uA

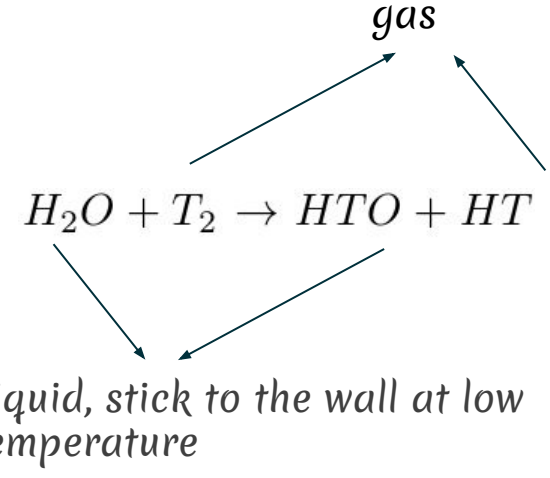


- **Endcap contamination**:
  - Endcap windows (75mg/cm^2 Aluminum) being mis-reconstructed into thin gas body (77mg/cm^2 Tritium)

The Gas Target System: Hydrogen contamination

Hydrogen in the 2nd Tritium cell (used in the fall 2018)

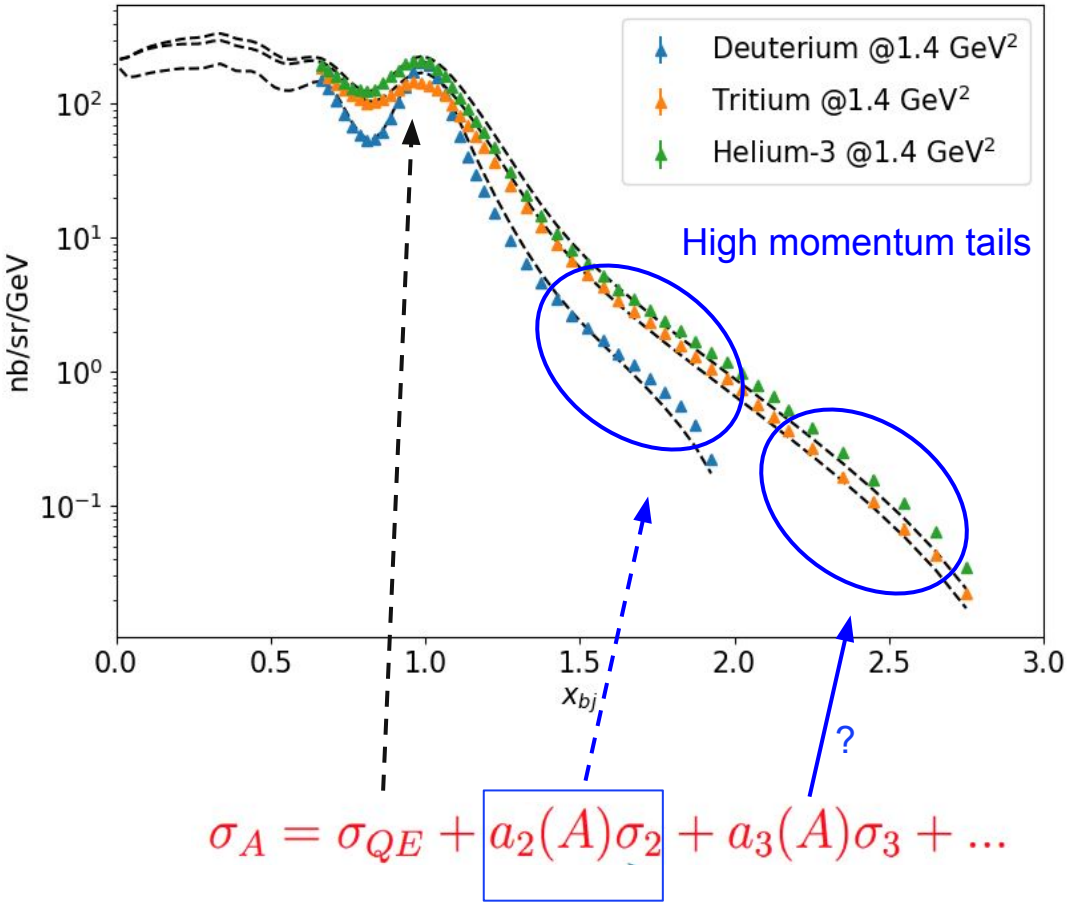




1.6% * rho_hyd * 3 / rho_tri ⇒ 4.1% density loss in tritium cell

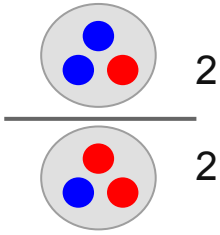
Absolute Cross Sections

Absolute cross section



Plateaus in A/D (e,e') Ratios

** Yield ratio to cancel systematic uncertainties!

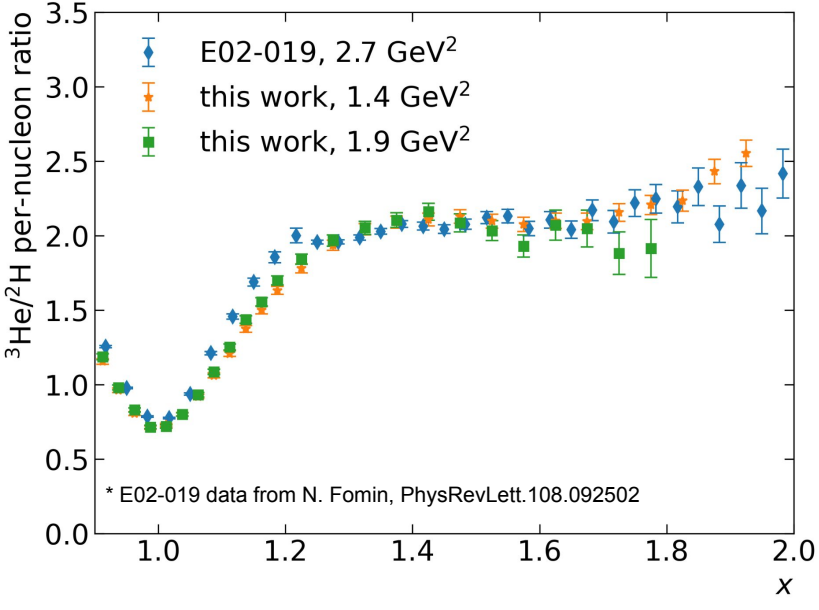


2 np + 1 nn pairs

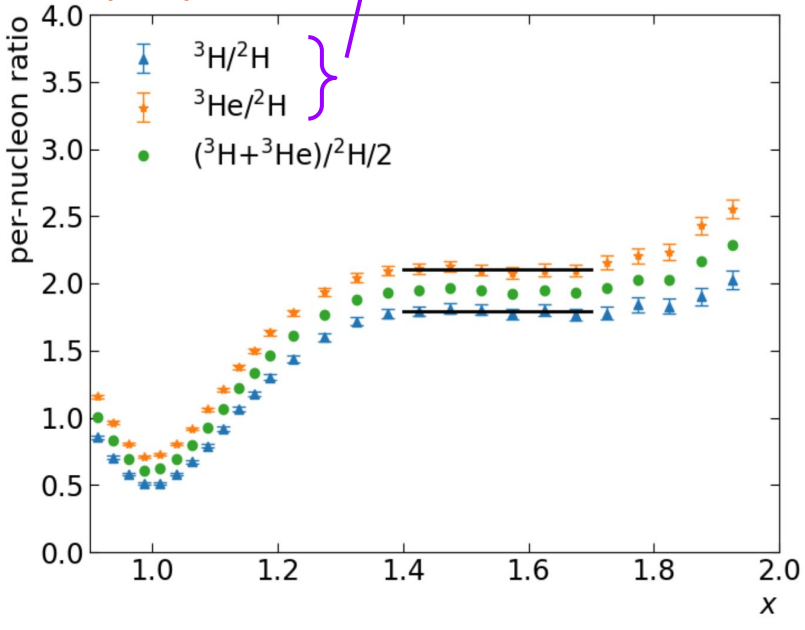
2 np + 1 pp pairs

would have given the same plateau height if 100% np dominant

^{3}He/D ratio



(A=3)/D ratio



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

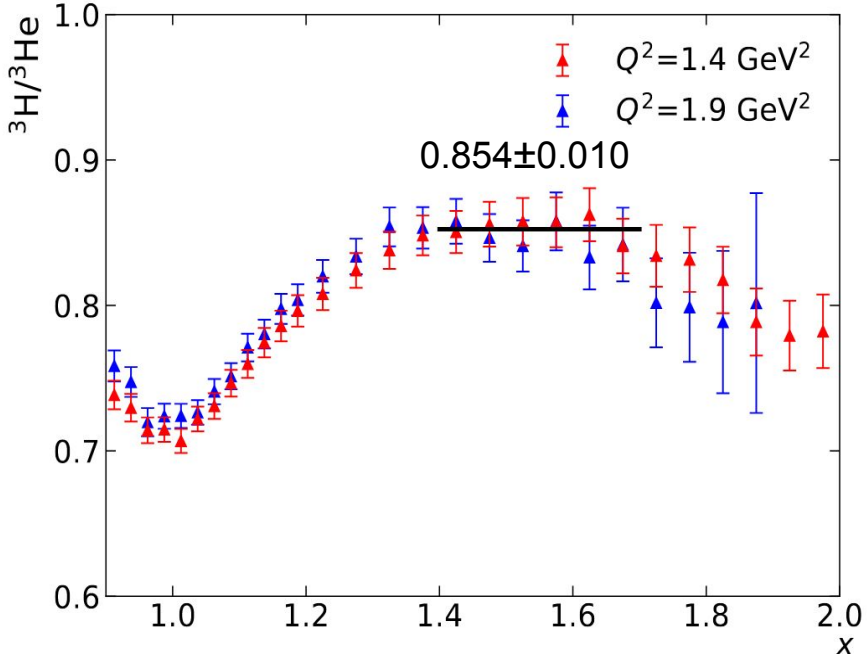
Offshell elastic xsection (de Forest "cc1")

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

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)