PR12-14-012

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

A proposal to PAC52

Spokespersons:

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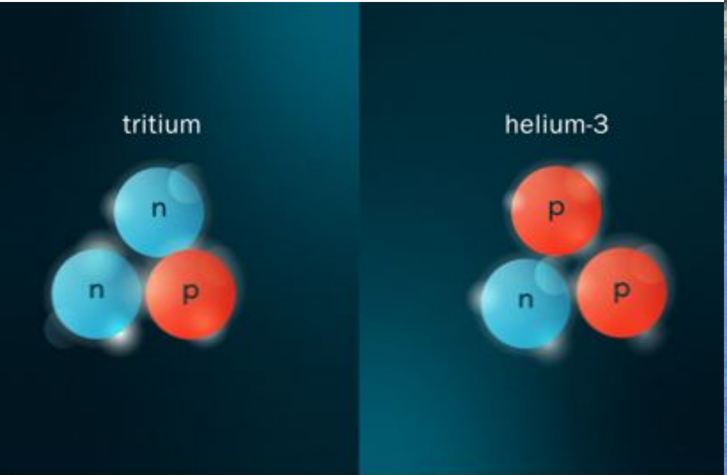
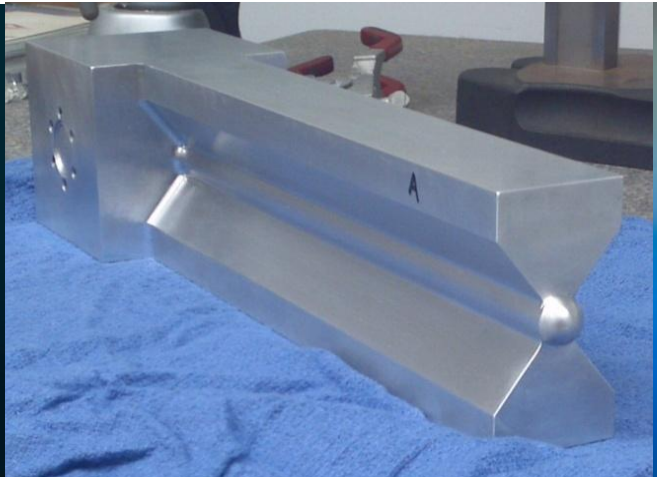
PAC52@JLab

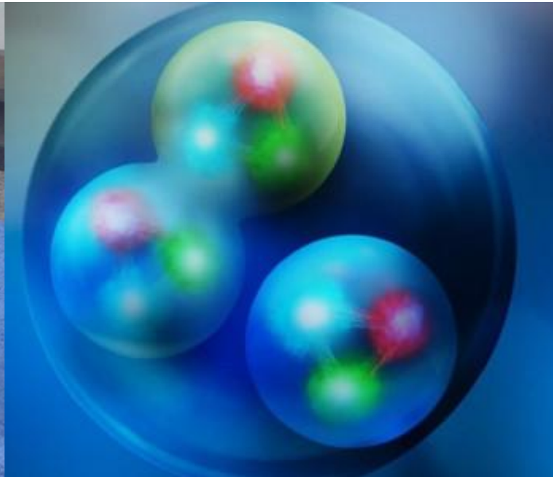
July 9, 2024

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

- Use (e,e’) inclusive QE scattering to isolate the high-momentum nucleons in nuclei
- Compare the momentum and isospin configuration in ^{3}H and ^{3}He
- Great kinematic reach with Hall C SHMS
- Parallel F_2 n/p study with HMS







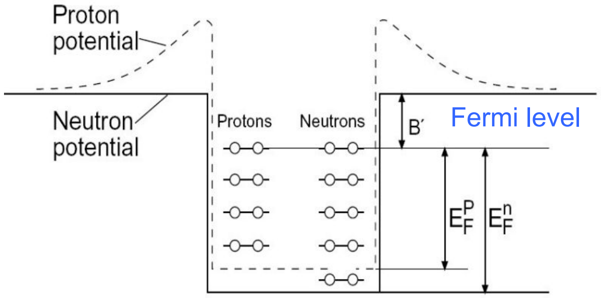
How nucleons move in nuclei and interact with each other?

Schrödinger equation:

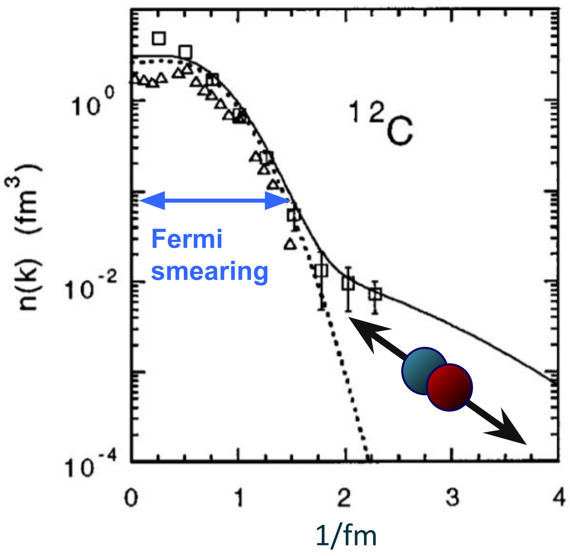
$$[\sum_i -\frac{\hbar^2}{2m_N}\nabla_i^2 + \sum_{i<j} v_2(\boldsymbol{x}_i, \boldsymbol{x}_j) + \sum_{i<j<k} v_3(\boldsymbol{x}_i, \boldsymbol{x}_j, \boldsymbol{x}_k) + ...]\Psi_A = E_A\Psi_A$$

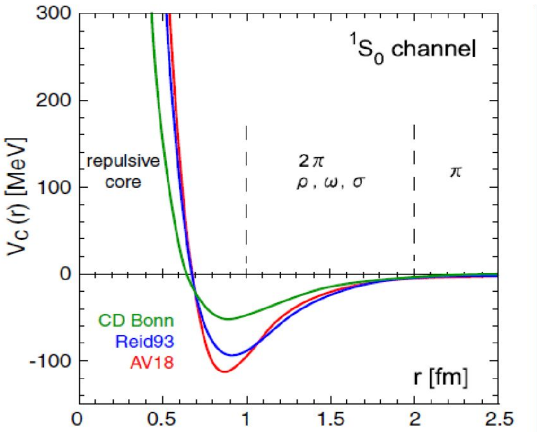
- **Independent particle shell model ("Mean field"):**

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



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



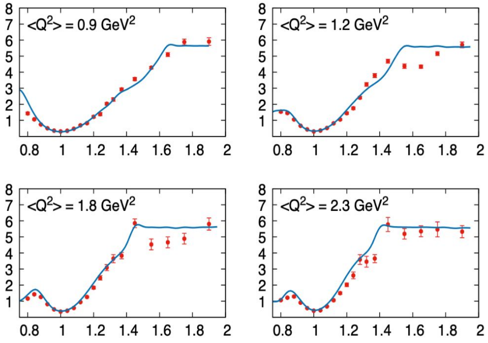


"The main effects of NN correlations is to generate high momentum and high removal energy components"

Decades of 2-nucleon Short-Range Correlation studies

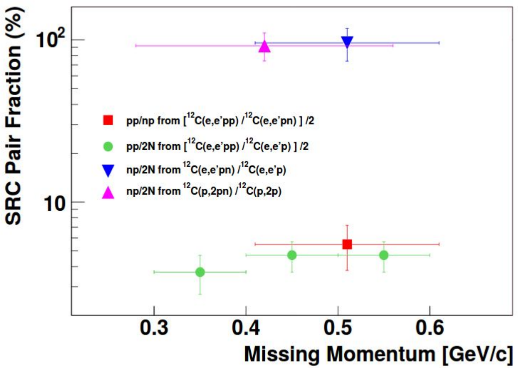
Fe/D (e,e') @SLAC

L. Frankfurt et al, Phys. Rev. C 48:2451 (**1993**)



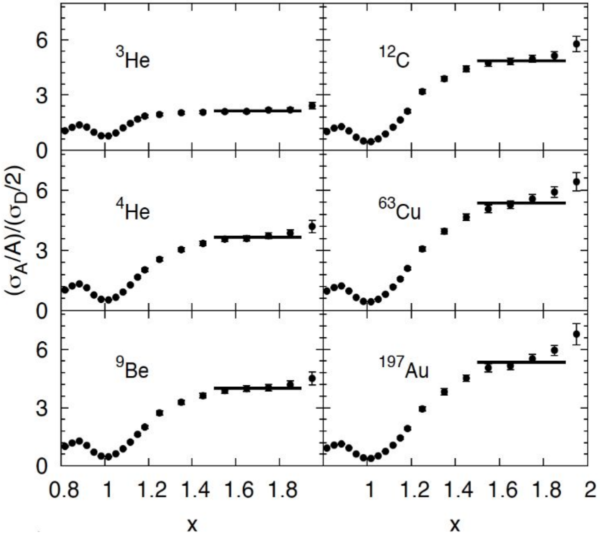
^{12}C(e,e'pN)@JLab

Subedi et al, Science 320, 1476 (2008)



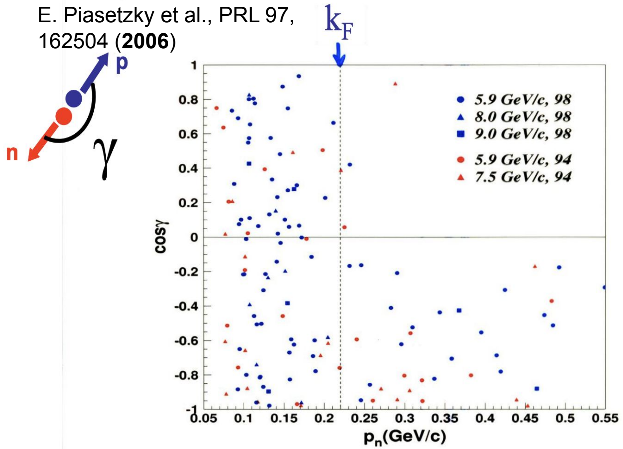
A/D (e,e') @JLab

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



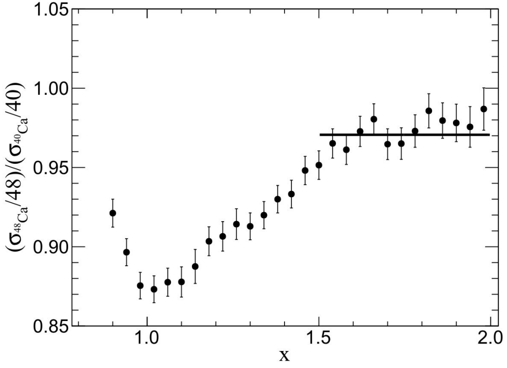
^{12}C(p,p'pn)X@BNL

E. Piasetzky et al., PRL 97, 162504 (**2006**)



^{48}Ca/^{40}Ca (e,e') @JLab

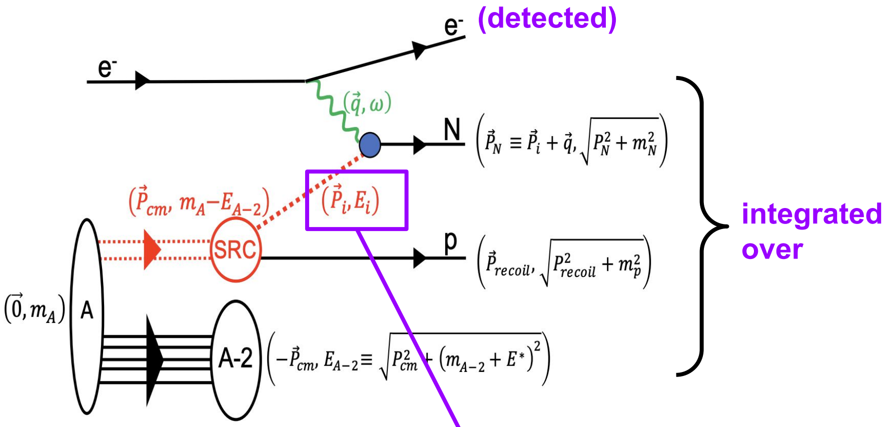
D. Nguyen *et al.* Phys. Rev. C **102**, 064004



- NN pairs with **large back-to-back** momentum and total → 0
- Up to **20%** of nucleons
- Isospin **T=0 deuteron-like np** pair dominate due to tensor force.

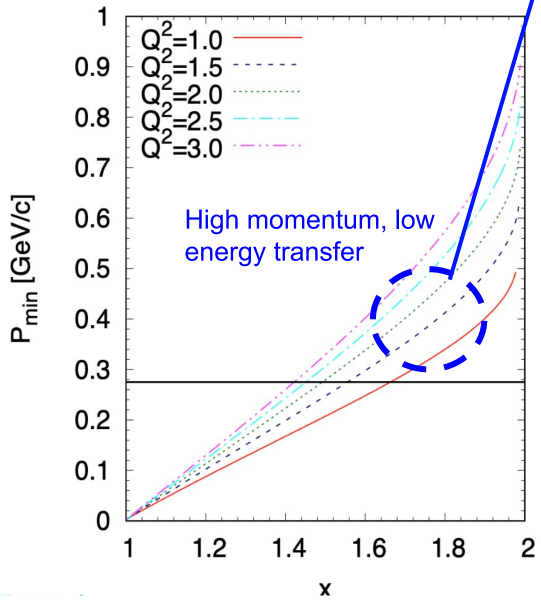
Our approach: probing high momentum nucleons in (e,e')

Inclusive QE scattering on 2N SRC:



Kinematic constraints on the minimum initial momentum

Experimental cut:
$Q^2 > 1.4$ GeV^2, $x > 1.4$ ⇒
$p_{min} > k_F$ ⇒ 2N SRC dominant



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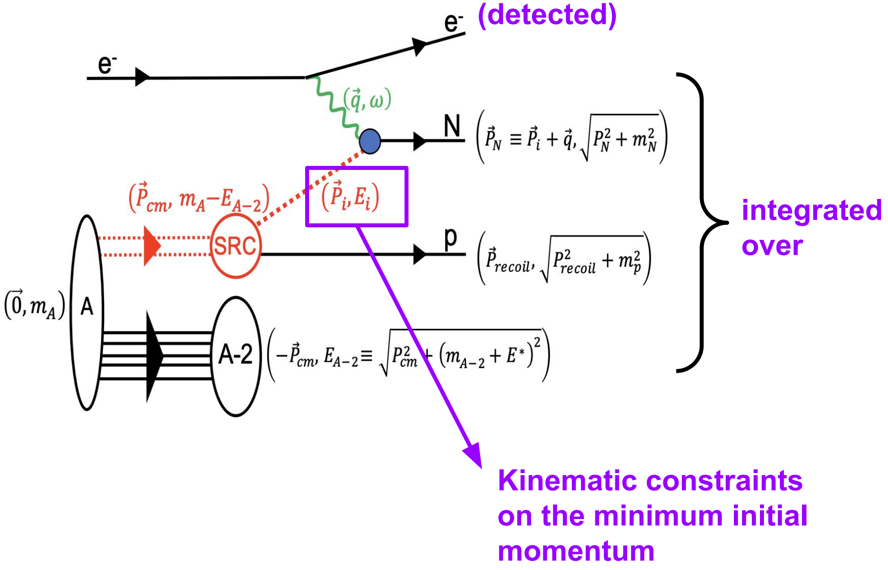
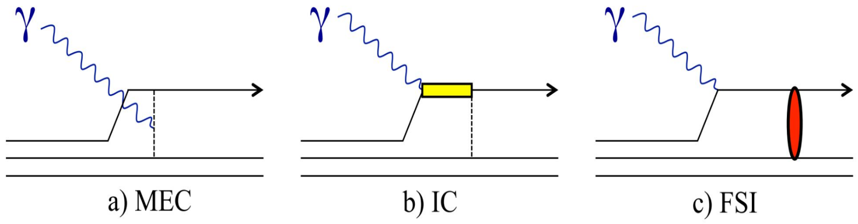
Inclusive QE scattering on 2N SRC:



Competing processes:

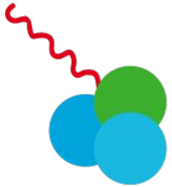
- Meson-exchange current (MEC):
  - $1/Q^2$ suppression
- Isobar Current (IC):
  - $1/Q^2$ and x>1 suppression
- Final State Interactions (FSI):
  - contained within the SRC pair at large Q^2

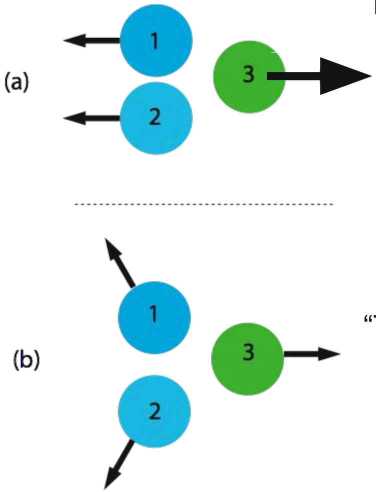


This proposal: 3N SRC study with A=3 mirror nuclei

- Searching for 3N configurations in which **all 3 nucleons has momenta above Fermi momentum**

- Understanding momentum-isospin configurations in A=3 systems



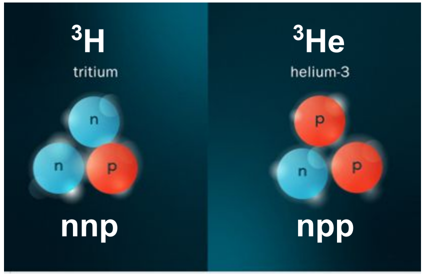


“Line” configuration

$$p_3 = p_1 + p_2$$

“Triangle” configuration

$$p_1 = p_2 = p_3$$



- **Cleanest and minimum nuclear systems to study 3N SRC**
- **Similar separation energy:**
  - 6.26 MeV v.s. 5.49 MeV
- **Small Coulomb effect:**
  - V_eff = 0.66 MeV v.s. 0
- **Small Fermi momentum:**
  - < 100 MeV

The previous (and first) tritium project @ JLab

Hall A Tritium Experiments in 2018

E12-10-103 “MARATHON” F2n/p, EMC
10.1103/PhysRevLett.128.132003

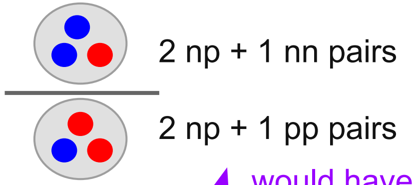
E12-14-011 SRC with (e,e’p)
10.1016/j.physletb.2019.134890,
10.1103/PhysRevLett.124.212501

E12-11-112 SRC with (e,e’)
2N SRC: SL et al, Nature 609, 41-45 (2022)
GMn: N. Santiesteban et al, Phys.Rev.Lett. 132 (2024) 16, 162501
3N SRC: SL et al, arXiv:2404.16235, submitted to PRL

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

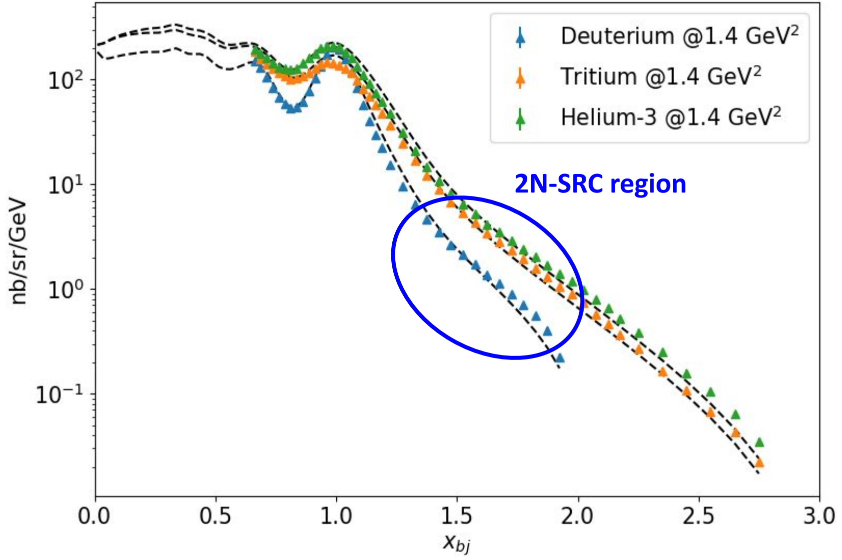
Dec. 2017, first beam on tritium target

E12-11-112: Study 2N SRC isospin with A=3

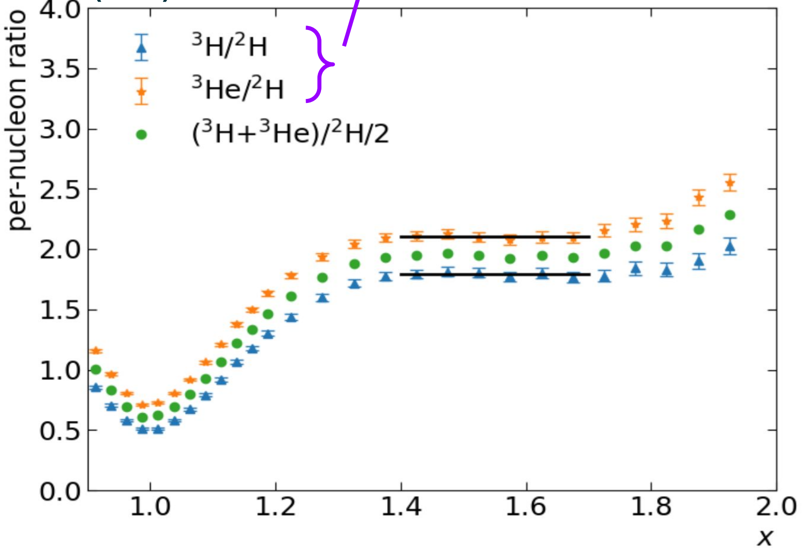


would have given the same plateau height if 100% np dominant

(e,e') cross section from E12-11-112@Hall A

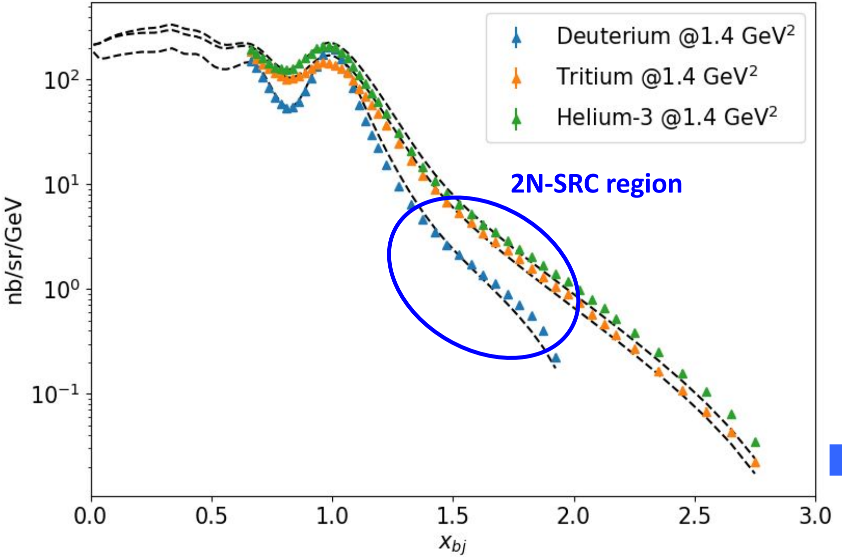


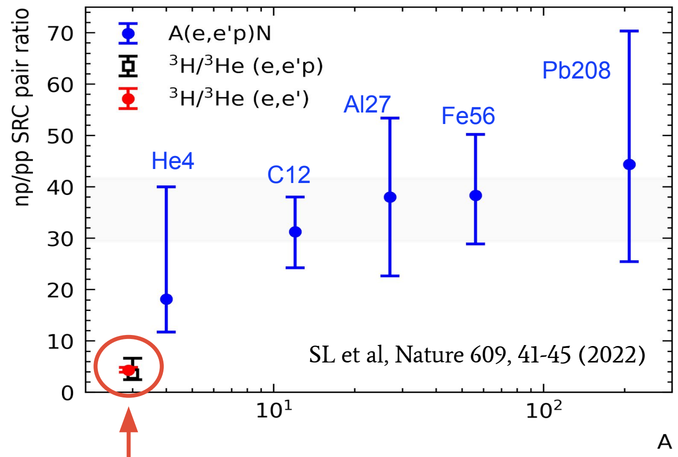
(A=3)/D ratio

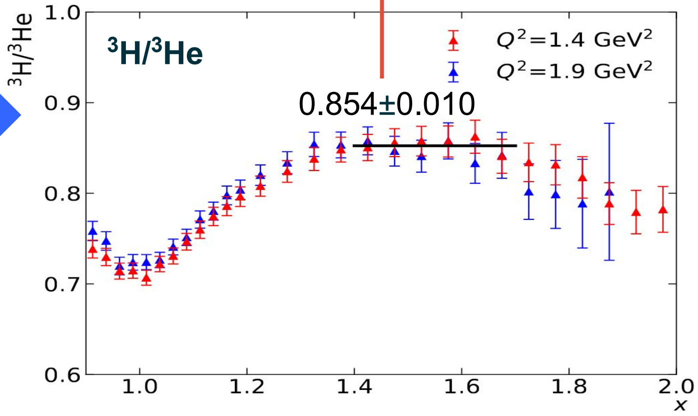


E12-11-112: Study 2N SRC isospin with A=3

(e,e') cross section from E12-11-112@Hall A

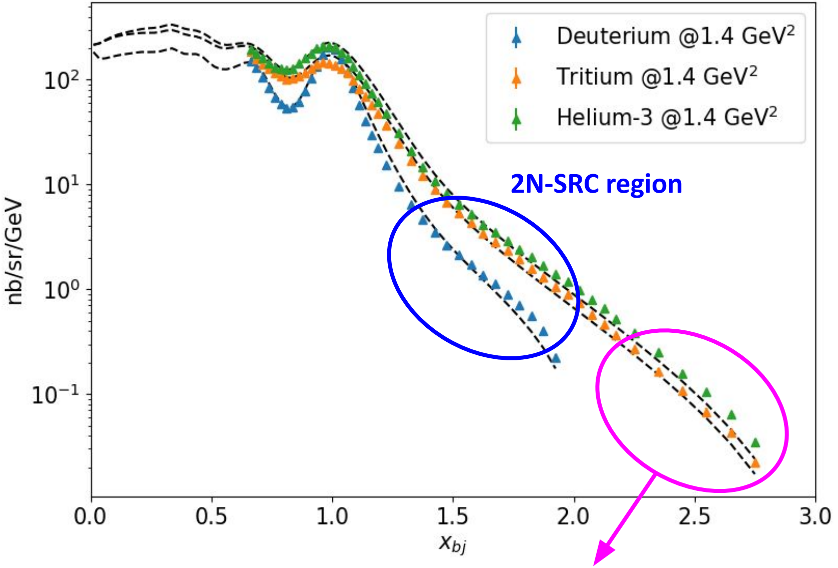


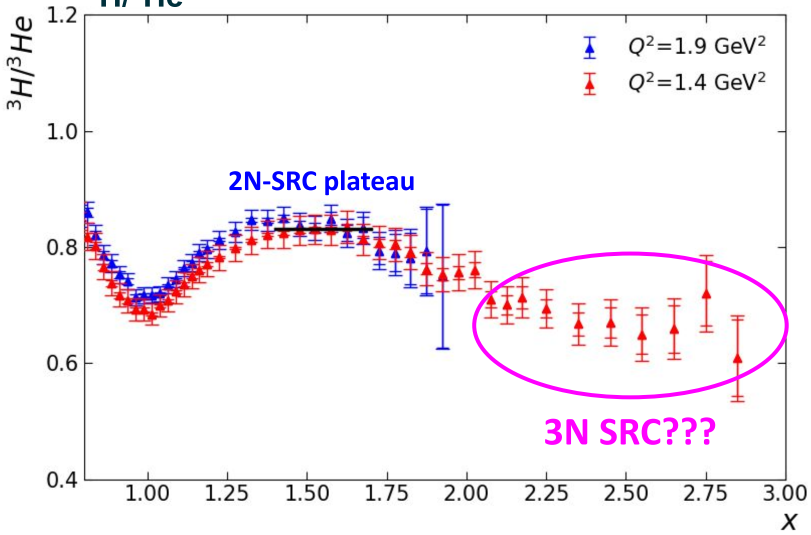




E12-11-112: hint of 3N SRC scaling?

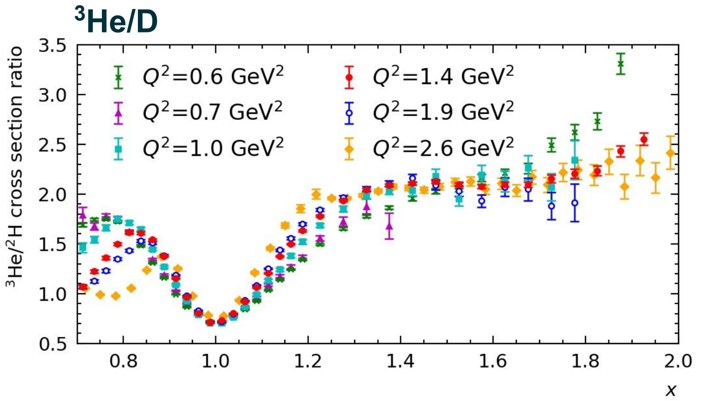
(e,e') cross section from E12-11-112@Hall A





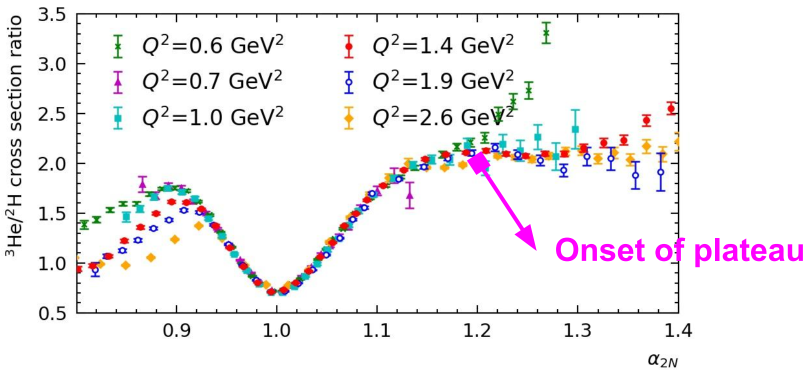
larger x → larger momentum → 2N+3N SRC?

E12-11-112: check onset of SRC scaling

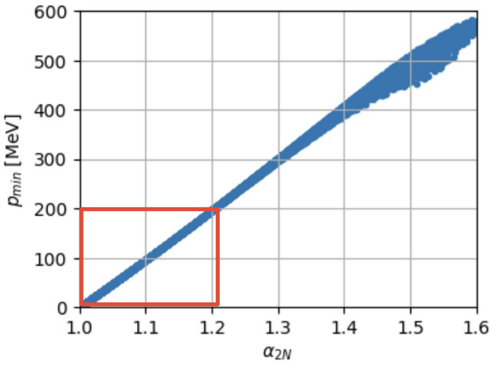


Light-cone variable

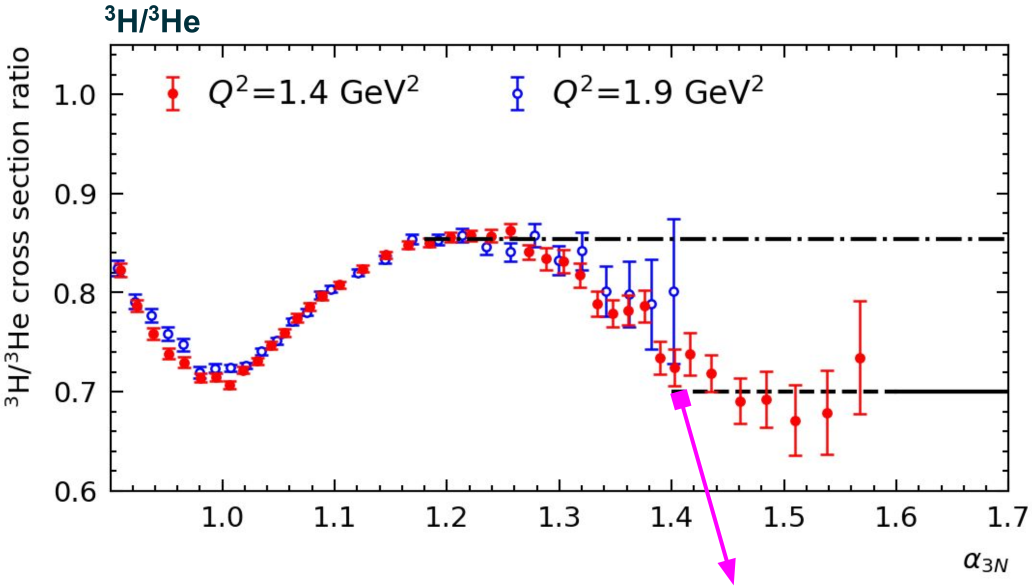
$$\alpha_{2N} = 2 - \frac{q_- + 2m}{2m} \frac{\sqrt{W^2 - 4m^2} + W}{W}$$

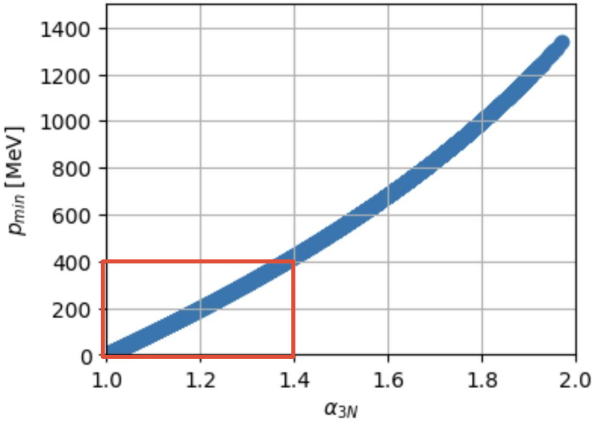


- **Scaling down to Q^2 = 1 GeV^2 :**
  - More cancellation between FSI, CM motion
  - Cancellations should be nearly complete in ^{3}H/^{3}He
- **Onset at $\alpha_{2N} < 1.2 \rightarrow$ pmin ~ 200 MeV**
  - Earlier onset in α_{2N} due to lower mean-field momenta: **k_F <100 MeV in A=3**
  - Same for ^{3}H/^{3}He, plus expect cancellation between MF contributions where it's small but not negligible



E12-11-112: check onset of SRC scaling



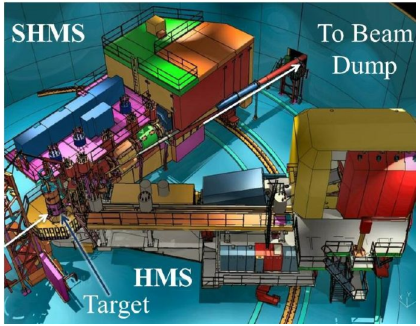


α_{3N} = 1.4 → pmin ~ 400 MeV = 2 x (2N SRC onset)

- Possible onset of 3N plateau?
- Still need
  - more statistics
  - Q^2 - scaling (higher α_{3N})

PR12-24-012: proposed kinematics

	E12-11-112 (E12-14-011)	PR12-24-012	
		kin1	kin2
Beam Energy	4.3 GeV	11 GeV	8.8 GeV
Spectrometer	HRS@Hall A	SHMS@Hall C	SHMS@Hall C
Angle	17.0 - 20.88	9	9
Central momentum	3.54 - 3.94 GeV	9.8 GeV	8.2 GeV
Q2	1.4 - 1.9	2.8	1.8



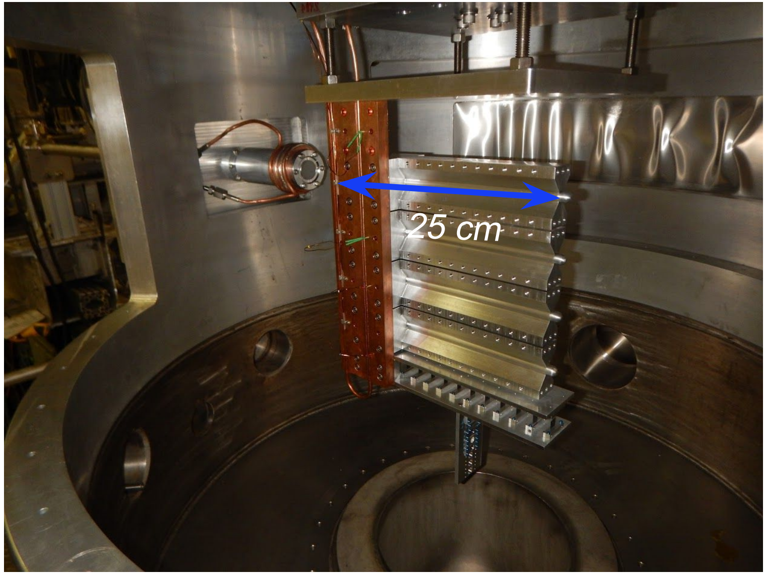
SHMS in standard configuration to detect scattered electrons

- Good momentum resolution (v.s. Hall B)
- Higher central momentum range, smaller angle (v.s. Hall A) → higher rates
- Large momentum acceptance

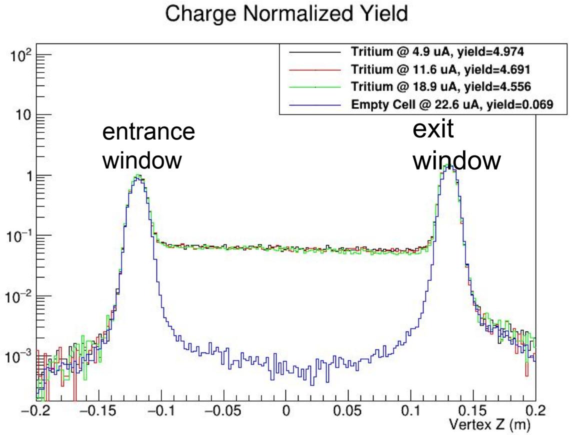
PR12-24-012: target system

Exactly the same target cell design from Hall A:

- 25cm long **sealed** Alloy cell, hold **1000 Ci** tritium
- Well-understood target properties: density fluctuation, decay etc
- Beam current < 25uA and other **safety** measures
- Successful cooperation with Savannah River Site



- Use **collimator** (tungsten bricks) to block endcaps
  - Remove contamination and reduce rates
  - Similar to A1n/D2n design
  - Effective target length -5.5<z<9cm



PR12-24-012: beam time estimations

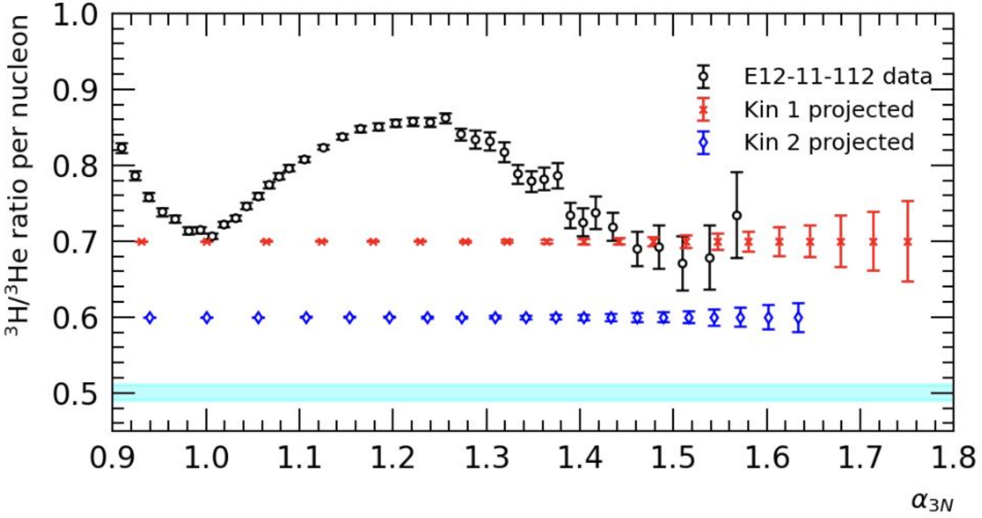
- ❖ Optics, target "boiling", and background studies
- ❖ Deuteron data for cross check

Items	PAC Days
Kin 1 production	34
Kin 1 calibration	5
Kin 2 production	10
Kin 2 calibration	2
Installations and configuration changes	2
Total	53

5k events on ^{3}H and ^{3}He (prescaled)

10k events on ^{3}H and ^{3}He

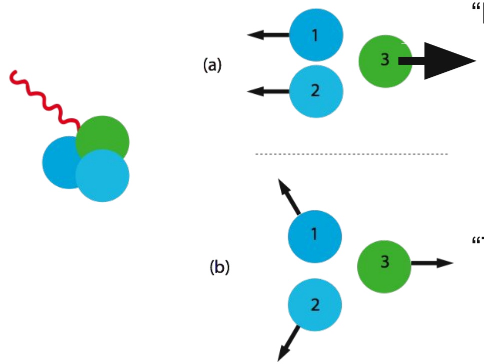
- ❖ Hall C single arm simulation
- ❖ DIS+QE+elastic cross section model fitted to tritium data
- ❖ Radiative correction included
- ❖ 90% efficiency, 14.5cm effective target length, 10% density reduction with beam



Searching for 3N SRC plateau:

- Reach α_{3N}= 1.75 → pmin=800 MeV
- Two Q^2 settings to confirm **scaling**
- Measure the expected 3N SRC plateau in high **precision**
- 2% systematics in ratio

PR12-24-012: sensitivities



"Line" configuration

$p_3 = p_1 + p_2$

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

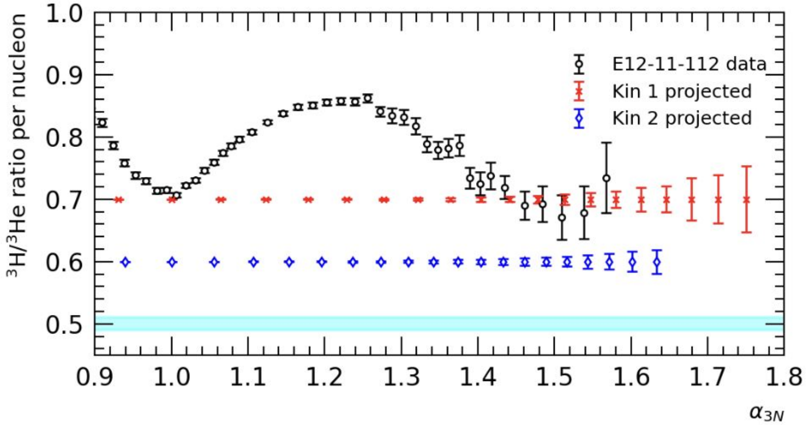
$R(^3H/^3He) \approx \sigma_n/\sigma_p \approx 0.4$ if nucleon #3 is always the doubly-occurring nucleon

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

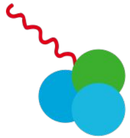
"Triangle" configuration

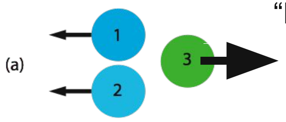
$p_1 = p_2 = p_3$

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



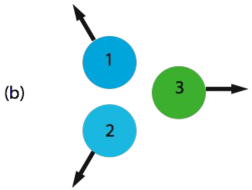
PR12-24-012: theory predictions





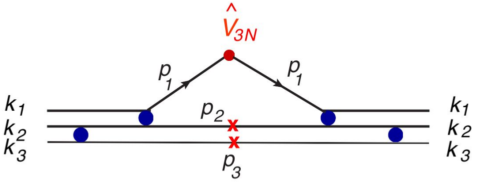
"Line" configuration

$p_3 = p_1 + p_2$



"Triangle" configuration

$p_1 = p_2 = p_3$



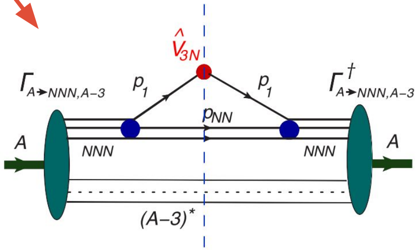
Convolution of 2N SRCs:

$R(^3H/^3He)_{3N} \approx [R(^3H/^3He)_{2N}]^2$

$= 0.854^2$

≈ 0.7

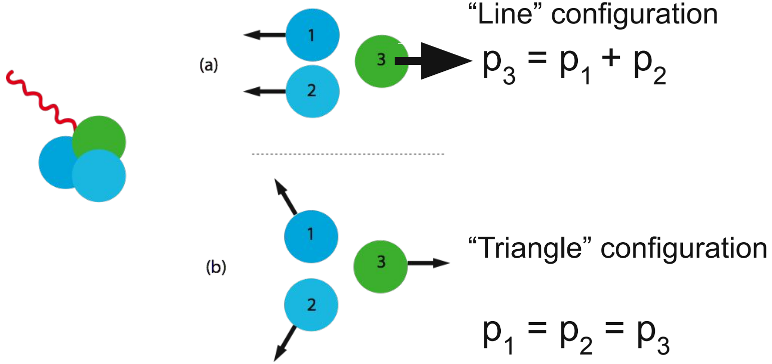
D. Day, L. Frankfurt, M. Sargsian, and M. Strikman, PRC 107 (2023) 014319



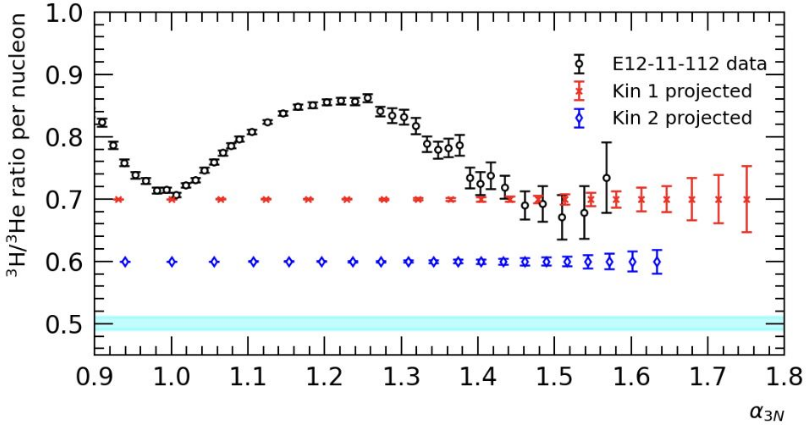
Irreducible 3N SRC:

- Involves inelastic transition
- Extremely high momentum

Summary



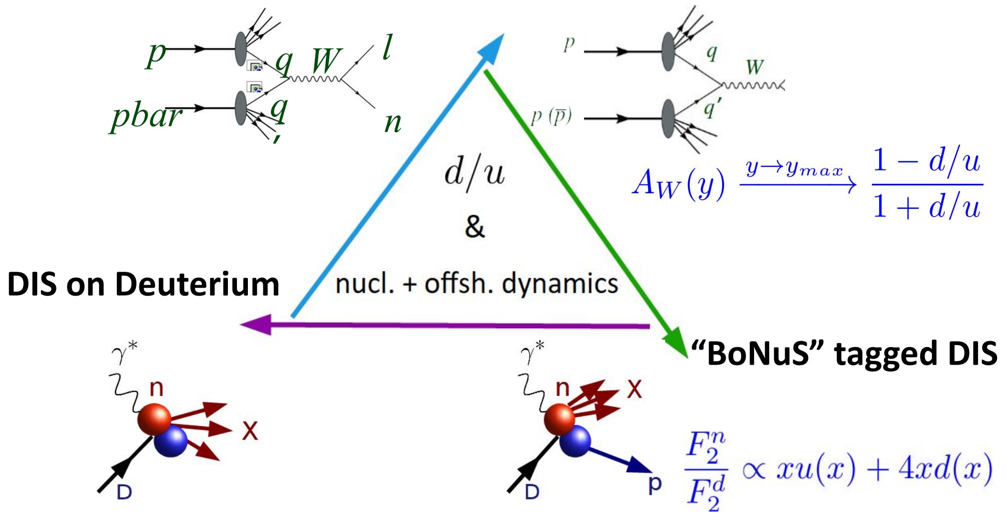
- 53 PAC days to search for 3N configurations in which all 3 nucleons has momenta above Fermi momentum
- Developed upon the success of 2018 tritium experiments at JLab, with improved kinematics @ SHMS
- Unique A=3 mirror nuclei comparison to understand momentum-isospin correlations in 3N
- Combined analysis of A/(^{3}H+^{3}He)



Parallel measurement: ^{3}H/^{3}He → F_2 n/p

Motivation: d/u at large x → 1

D0, CDF asymmetries

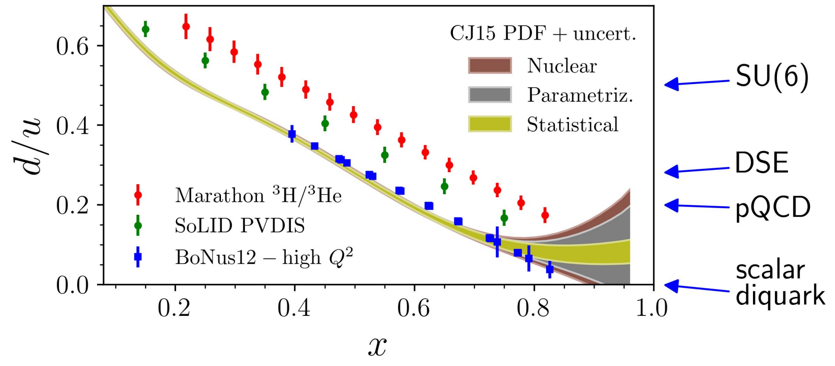


$A_W(y) \xrightarrow{y \to y_{max}} \dfrac{1-d/u}{1+d/u}$

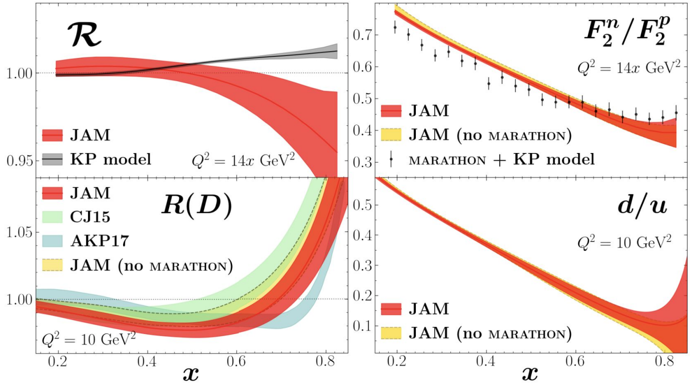
$\dfrac{F_2^n}{F_2^d} \propto xu(x) + 4xd(x)$

$F_2^d \propto S_D \otimes [xu_{\text{off}}(x) + xd_{\text{off}}(x)]$

Pre-MARATHOn



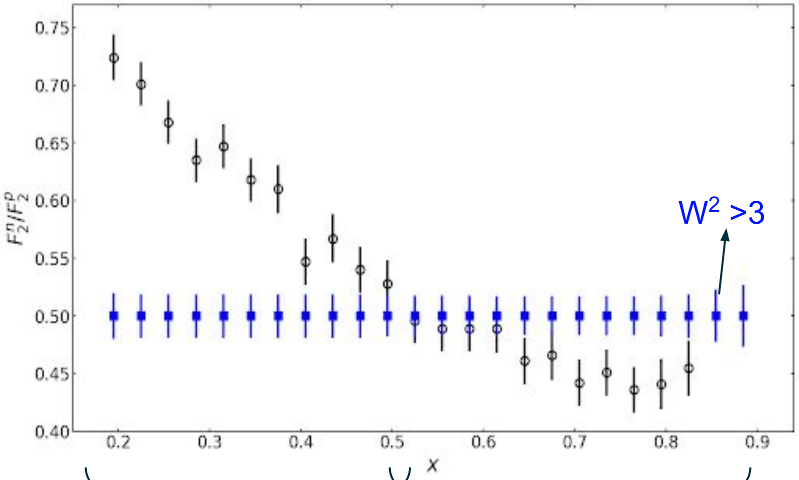
Now?



C. Cocuzza et. al., Phys. Rev. Lett. **127**, 242001

Parallel measurement: ^{3}H/^{3}He → F_2 n/p

PR12-24-012 Projection



- ebeam=8.8 GeV 11 GeV
- HMS from 18 to 40 degrees

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

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

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

- Parallel DIS data-taking with HMS
- Up to 50% more stats than MARATHOn at large x
- Independent check of normalization
- Double the ^{3}H/^{3}He data for global fit

Thank you!

SRC kinematics

Kinematics	Ebeam (GeV)	Momentum (GeV)	Angle (Degree)	Total Rate (kHz)	at x=2.5 Events (per hour)	at x=2.5 Q^2 (GeV^2)	at x=2.5 α_{3N}
Kin1	11.0	9.8	9.0	2.8	12	2.8	1.6
Kin2	8.8	8.2	9.0	7.0	200	1.8	1.5

Table 1: Proposed kinematic settings for tritium and helium-3 measurements. The estimated total rates have no acceptance cuts, and include no contribution from entrance/exit aluminum window because the assumed use of tungsten block as collimator.

SRC kinematics

Items	PAC Days
Kin 1 production	34
Kin 1 calibration	5
Kin 2 production	10
Kin 2 calibration	2
Installations and configuration changes	2
Total	53

Table 2: Requested number of PAC days. The production includes tritium and helium-3 data taking. Calibration includes optics, endcap contamination study, boiling study, and other installation/adjustment time.

The statistics goal for this experiment is to reach 5k events per target at x=2.5 with Kin 1, and 10k events for Kin 2 (after prescale). That corresponds to 17 days, and 6 days of beam, respectively. 90% overall efficiency is assumed, as well as a 10% target density reduction due to the beam induced target gas density change [44]. Table 2 shows the requested 53 PAC days. The production days include tritium and helium-3 data taking. Calibration includes optics, endcap contamination study, boiling study, and other installation/adjustment tasks. It also includes deuterium data taking to allow for a cross check of the ^{3}H/^{2}H and ^{3}He/^{2}H ratios at $x < 2$, and studies of the acceptance for a well studied nucleus near the QE peak and the 2N-SRC tail. The projected ^{3}H/^{3}He statistics is shown in Figure 10.

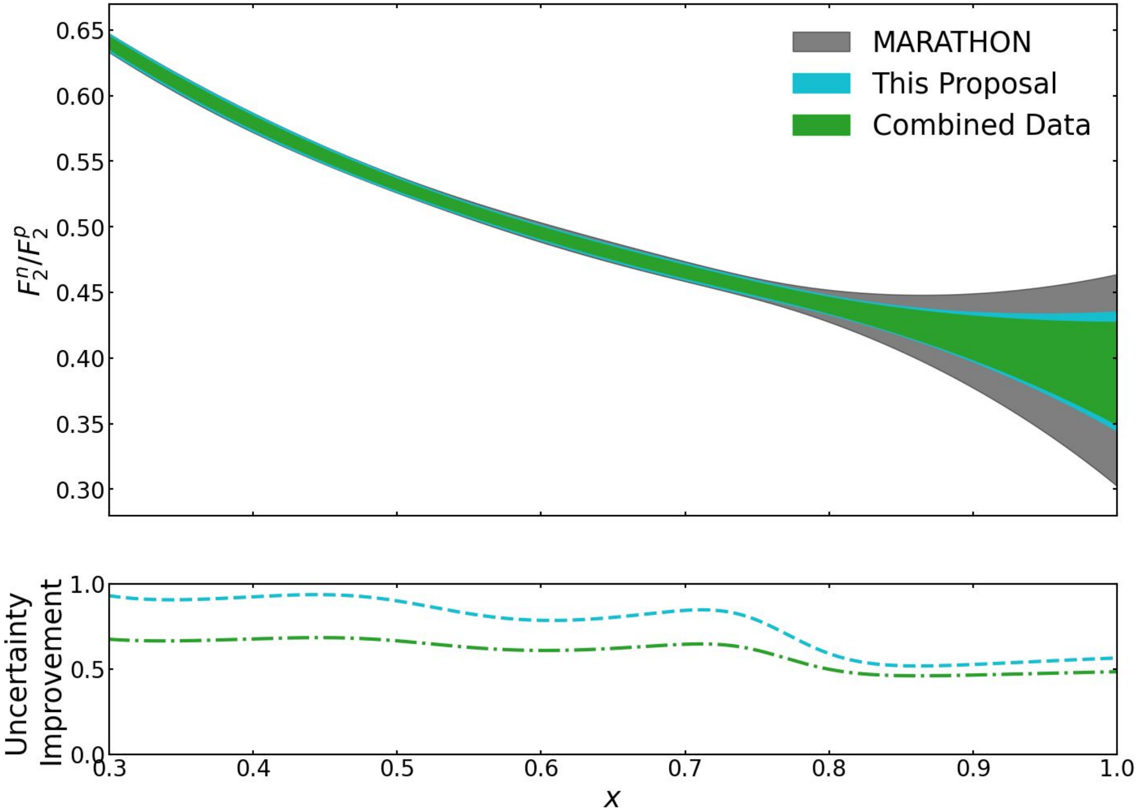
F2 kinematics

Ebeam	theta	E'	xbj
			0.195
8.8	18	2.759	0.225
			0.255
8.8	20	2.841	0.285
			0.315
8.8	22	2.866	0.345
			0.375
8.8	25	2.774	0.405
			0.435
			0.465
8.8	30	2.486	0.495
			0.525

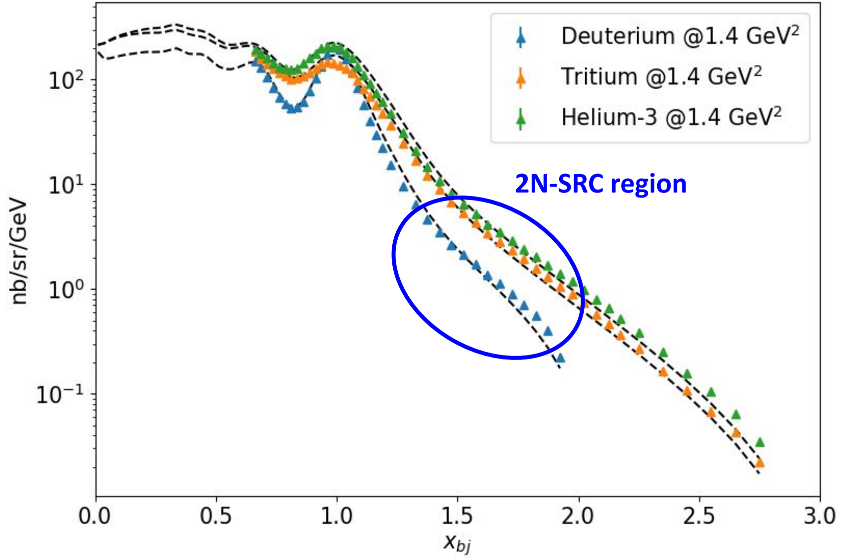
Ebeam	theta	E'	xbj
			0.465
11	22	4.035	0.495
			0.525
			0.555
11	25	3.883	0.585
			0.615
			0.645
			0.675
11	30	3.456	0.705
			0.735
			0.765
			0.795
11	40	2.578	0.825
			0.855
			0.885

F2 impact study

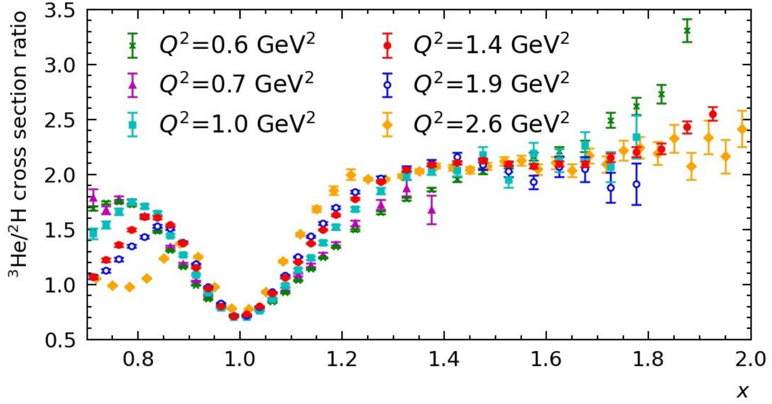
Cubit fit for illustration



2N SRC scaling at x>1



3He/2H



prob. of finding 2N SRC in nucleus A

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

0 0

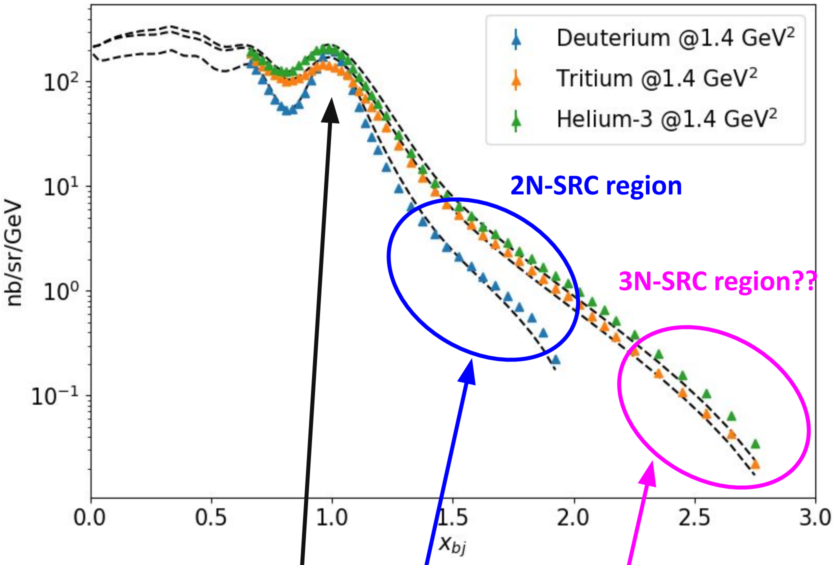
cross section from 2N SRC

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

** up to center-of-mass motion corrections

4% high momentum component in deuteron wave function

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



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

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*

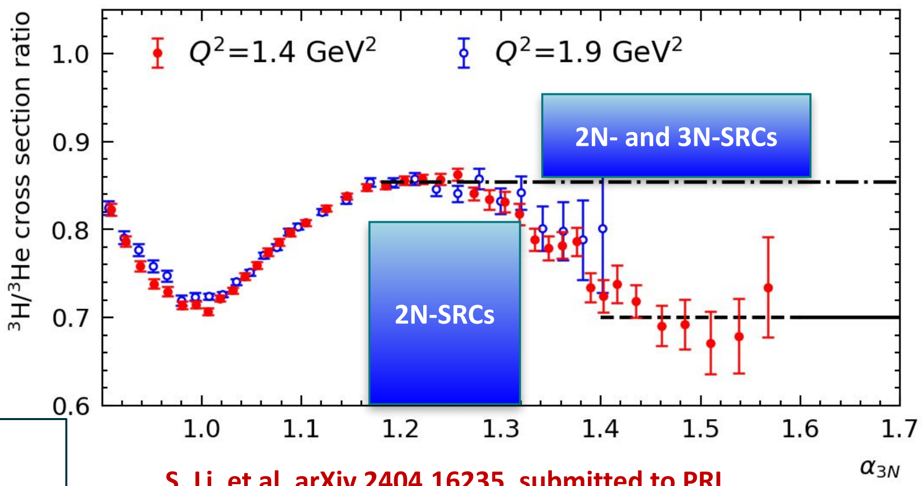
*$\alpha > 1.4$ using the same criteria for A=3

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_{3N} (x), and



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

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

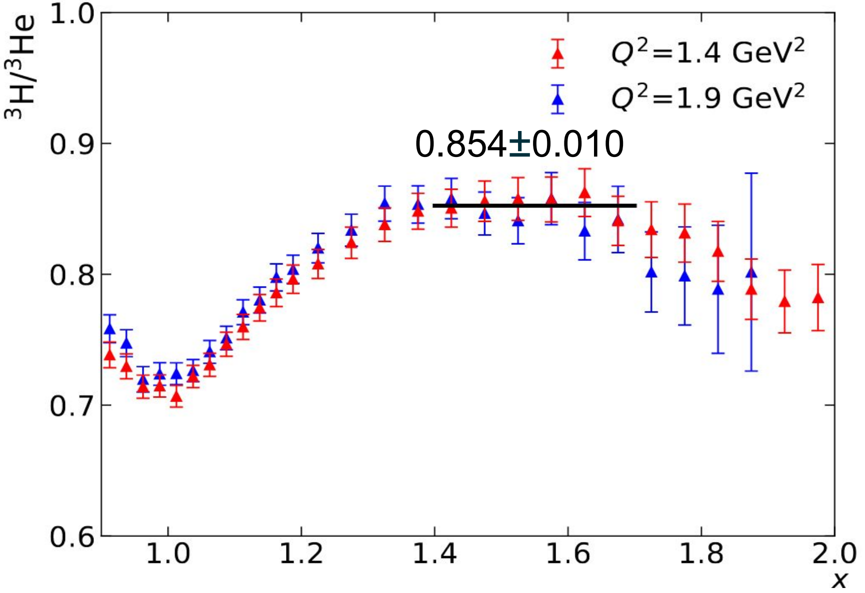
Offshell elastic xsection (de Forest "cc1")

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

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 ^3H and ^3He (Ciofi degli Atti, Claudio and Morita, Hiko, 2017)

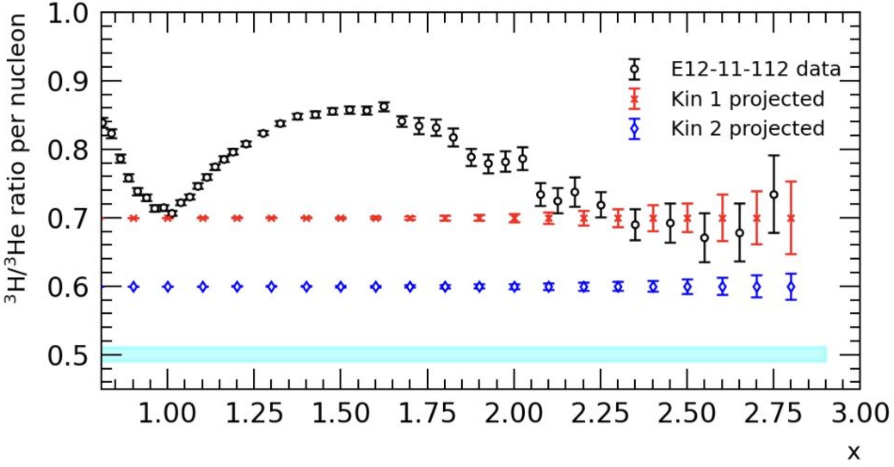


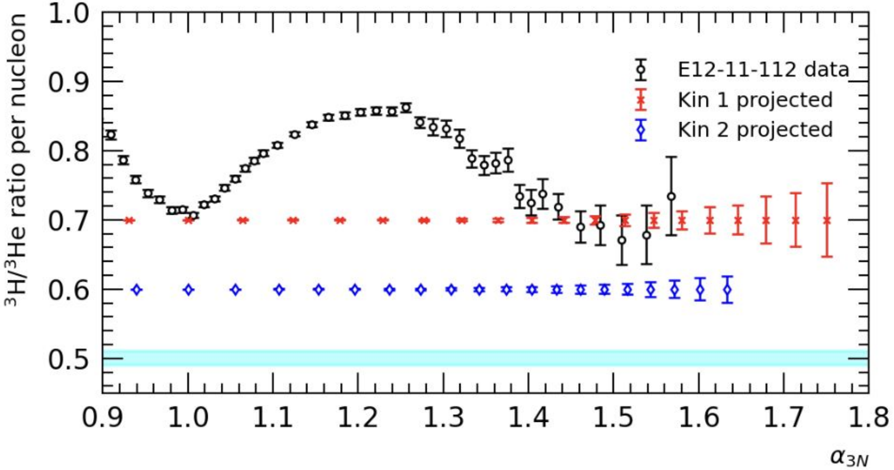
Ratio of np/pp SRC pairs in A=3 nuclei:

$R_{np/pp}$ =4.3 ± 0.4

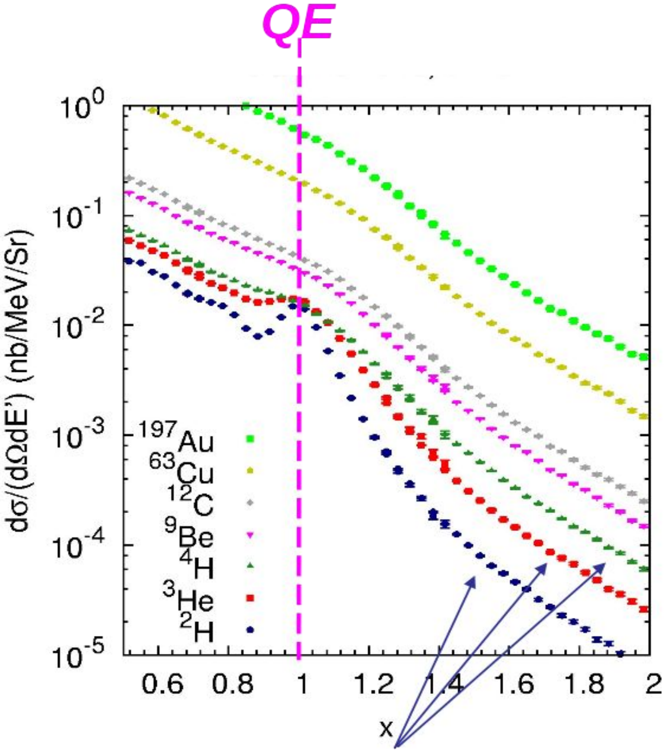
SL et al, Nature 609, 41-45 (2022)

PR12-24-012 projected stats



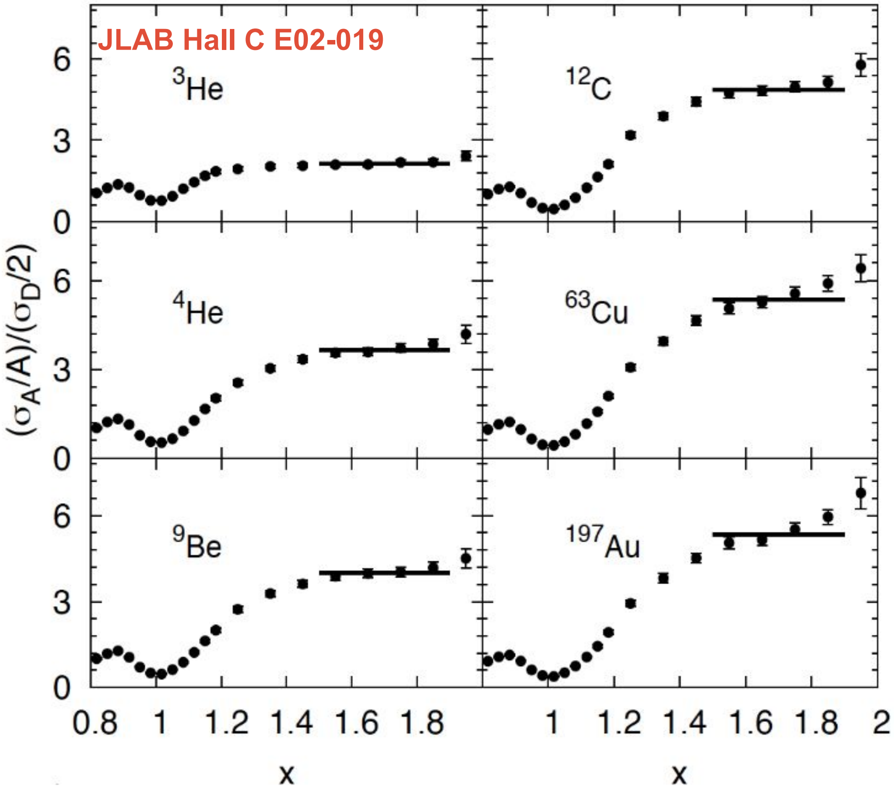


SRC Plateau / Bjorken x-scaling



High momentum tails should yield constant ratio if SRC-dominated

Plateaus in A/D cross section ratio



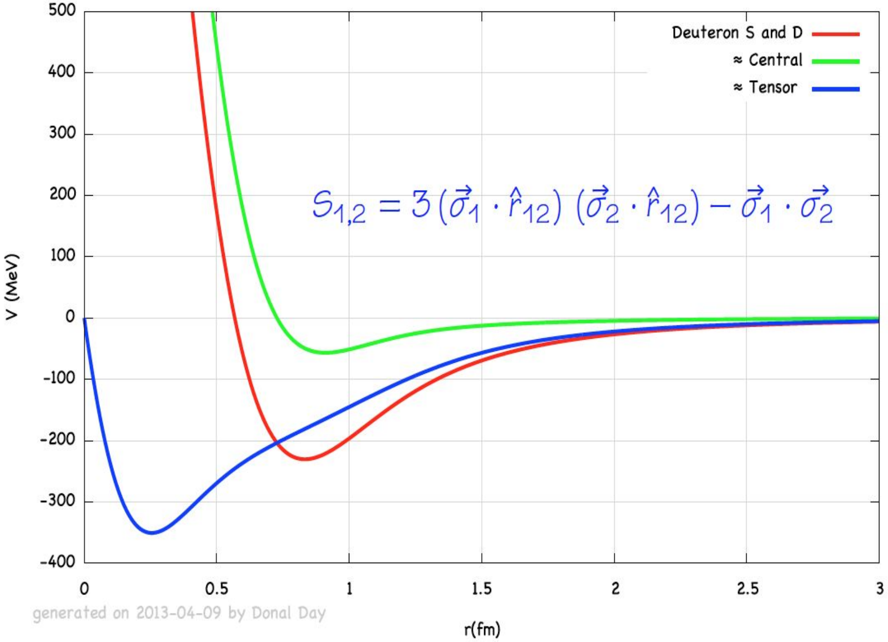
N. Fomin, et al., PRL 108 (2012) 092052

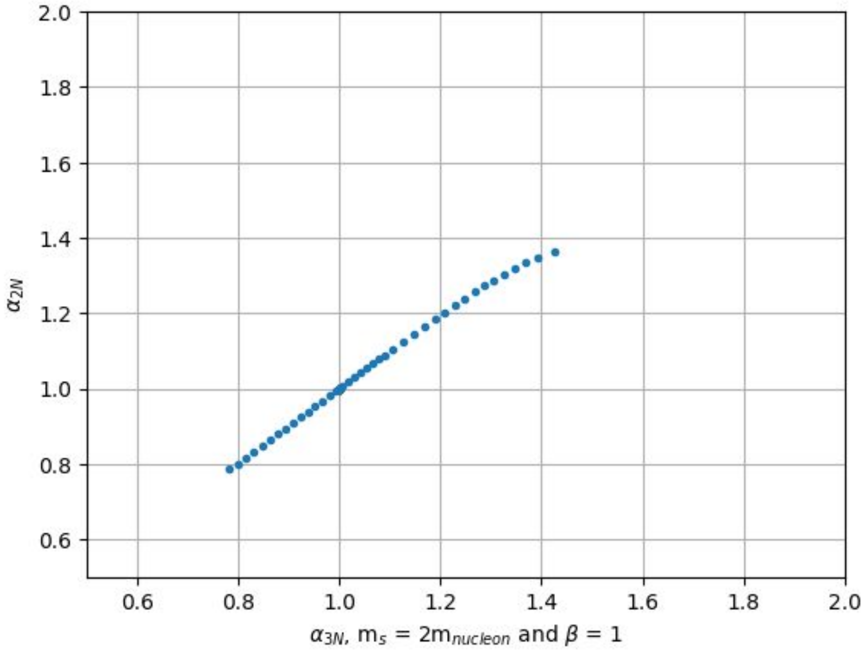
Nucleon-Nucleon Potentials

Free nucleon-nucleon potential = **Repulsive core** + **attractive tensor force**

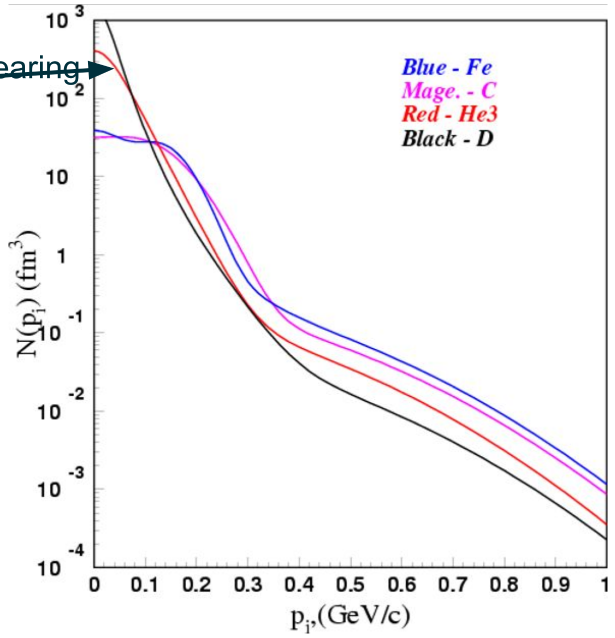
S (spin) = 0, T (isospin) = 1: np, pp, nn pairs. The **tensor operator** $S_{1,2} = 0$, no attractive tensor force

S (spin) =1, T (isospin) = 0: Deuteron-like np pair.



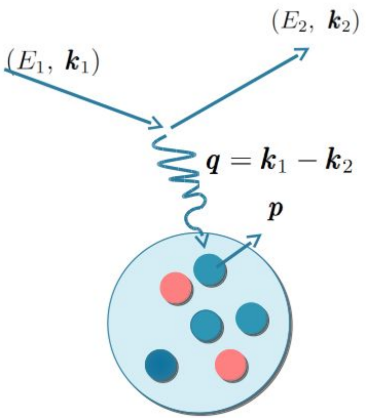


Narrower smearing in light nuclei



(e,e') x>1 data from 2018

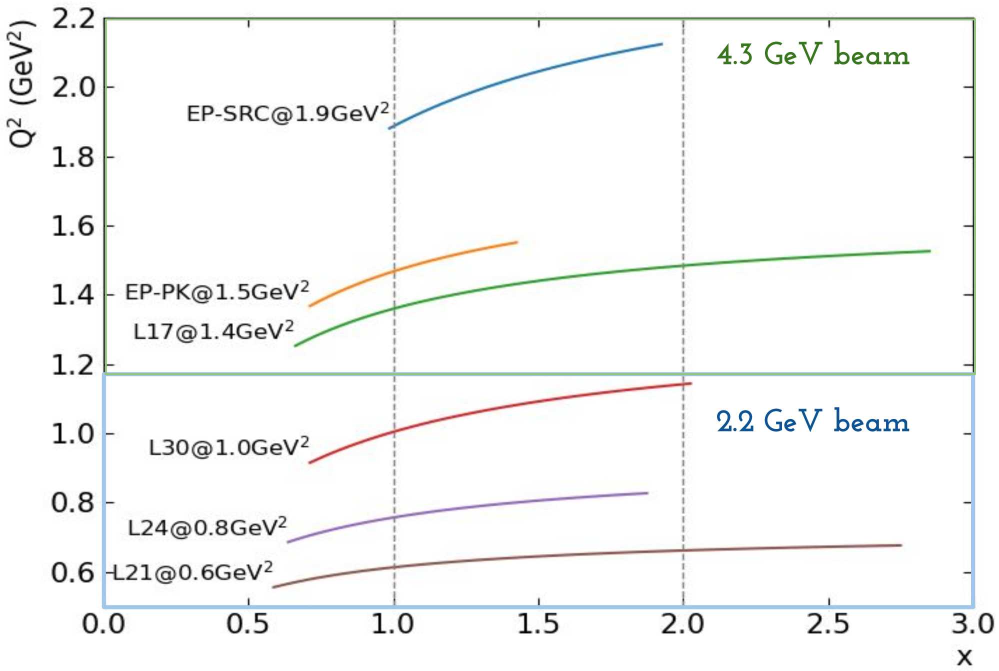
4-momentum transfer $Q^2=-q^2$
Bjorken $x = Q^2/2m(E_1-E_2)$



x>1: SL et al, Nature 609, 41-45 (2022)
GMn (see [Nathaly's talk]on Tuesday): N. Santiesteban et al, Phys.Rev.Lett. 132 (2024) 16, 162501

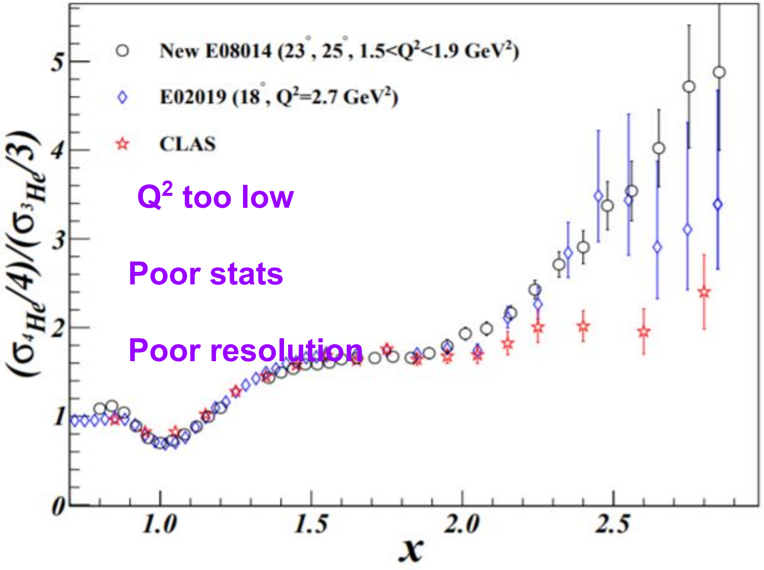
LHRS@Hall A:

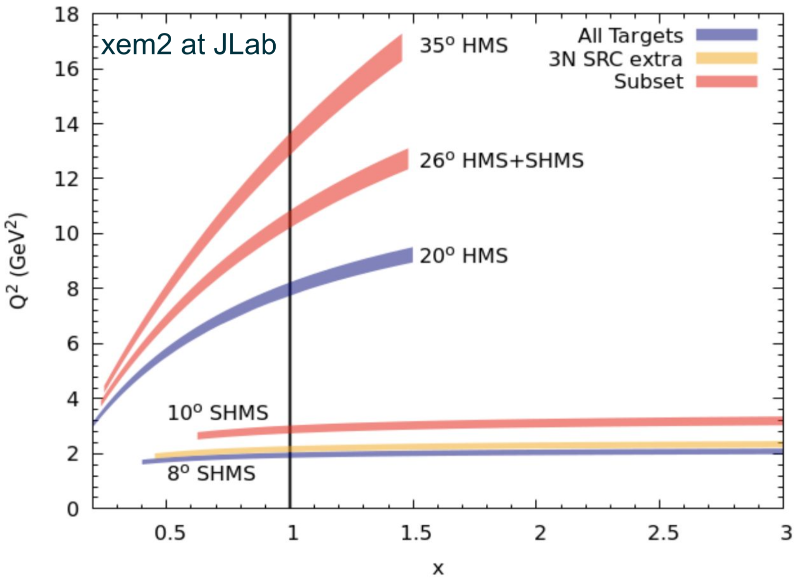
Deuterium, tritium and helium-3 targets
E12-11-112 and E12-14-011

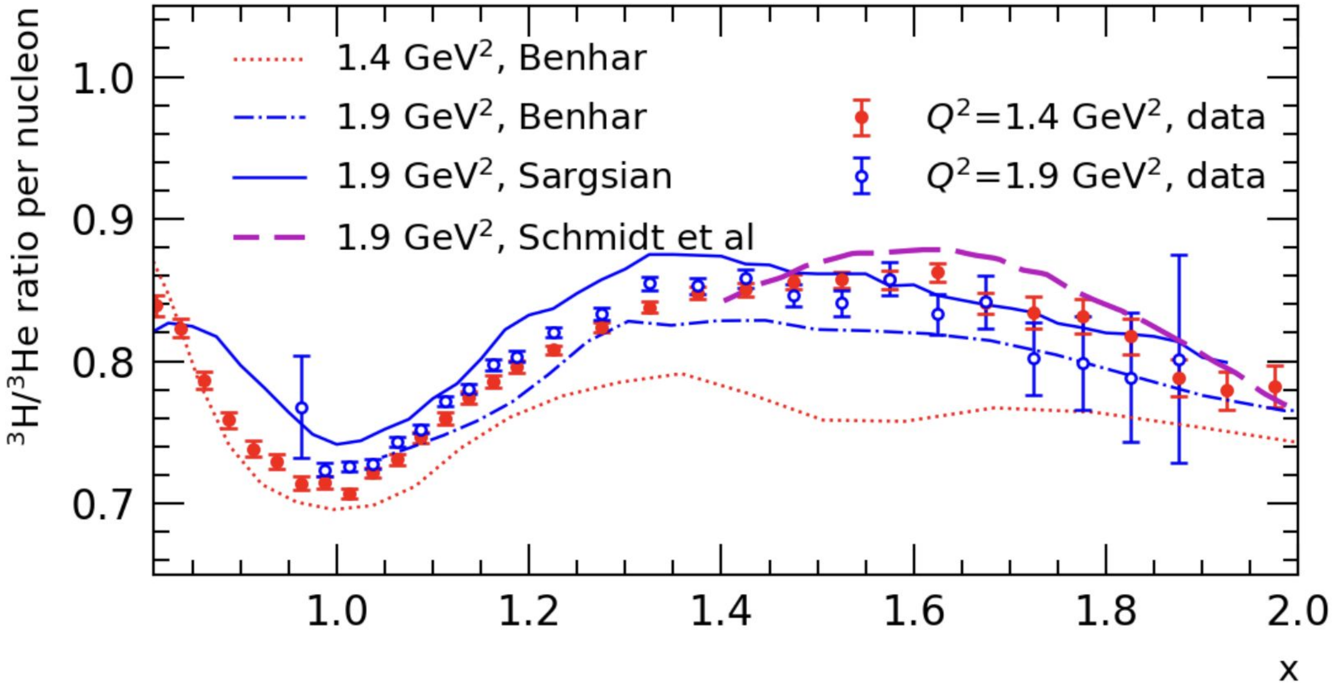


Cross Section beyond x=2: three-nucleon SRCs?

Previous A/^{3}He ratio:







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