



BERKELEY LAB

Bringing Science Solutions to the World

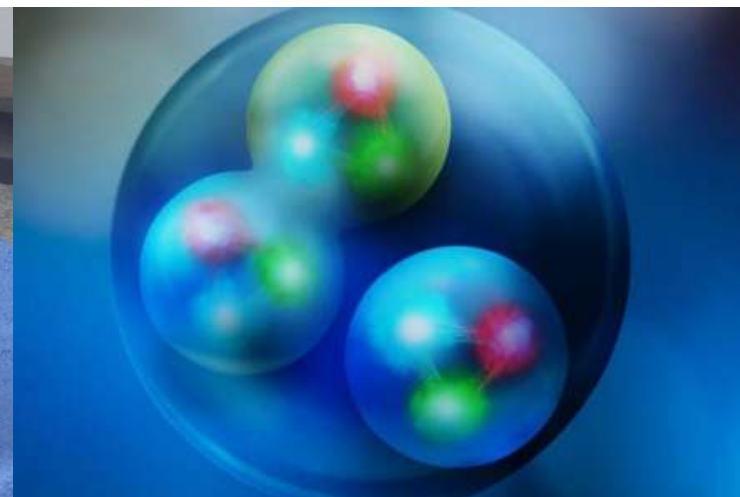
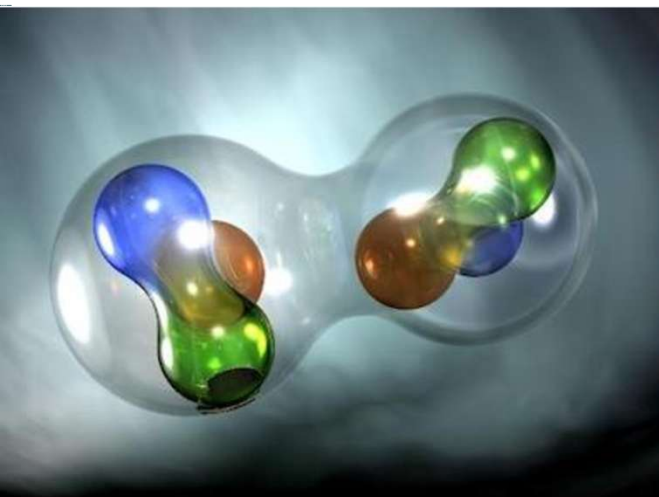


Office of Science

Mirror nuclei rungroun proposal for Hall C

John Arrington, Lawrence Berkeley National Lab

Hall A/C Summer Meeting, 2026



Two main physics topics

E12-26-011: “Constraining the flavor content of the nucleon and flavor-dependent nuclear effects in the mirror nuclei ${}^3\text{H}$ and ${}^3\text{He}$ ” [T.Hague, JA, D. Meekins, S. Li, M. Nycz]

- **Leading-order:** extension of the MARATHON experiment
 - Aim for factor 2 improvement in F_{2n}/F_{2p} over full x range (MARATHON + HallC vs just MARATHON)
- **Higher-order:** Dedicated studies to constrain effects limiting extractions of F_{2n}/F_{2p} and $d(x)/u(x)$
 - Isospin dependence of $R=\sigma_L/\sigma_T$ at $x=0.3$ (impact of flavor-dependent nuclear corrections on normalization)
 - Constrain isospin-dependence of Higher Twist corrections at large x (for MARATHON and D/p)

E12-26-012: “Probing the isospin and momentum structure of three-nucleon short-range correlations in the ${}^3\text{H}/{}^3\text{He}$ mirror system” [S. Li, JA]

- Search for expected early onset of 3N-SRC dominance in $A=3$ nuclei
- **Study momentum, isospin structure of high- p nucleon distribution** (whether or not 3N-SRCs dominate)
 - Direct, model-independent comparison of isospin structure in large- x scattering (high- p nucleons)
 - Absolute cross sections and precise ratios for comparison to *ab initio* calculations at very large x
 - If 3N-SRCs dominate, the isospin structure information translates into a statement of 3N-SRC structure

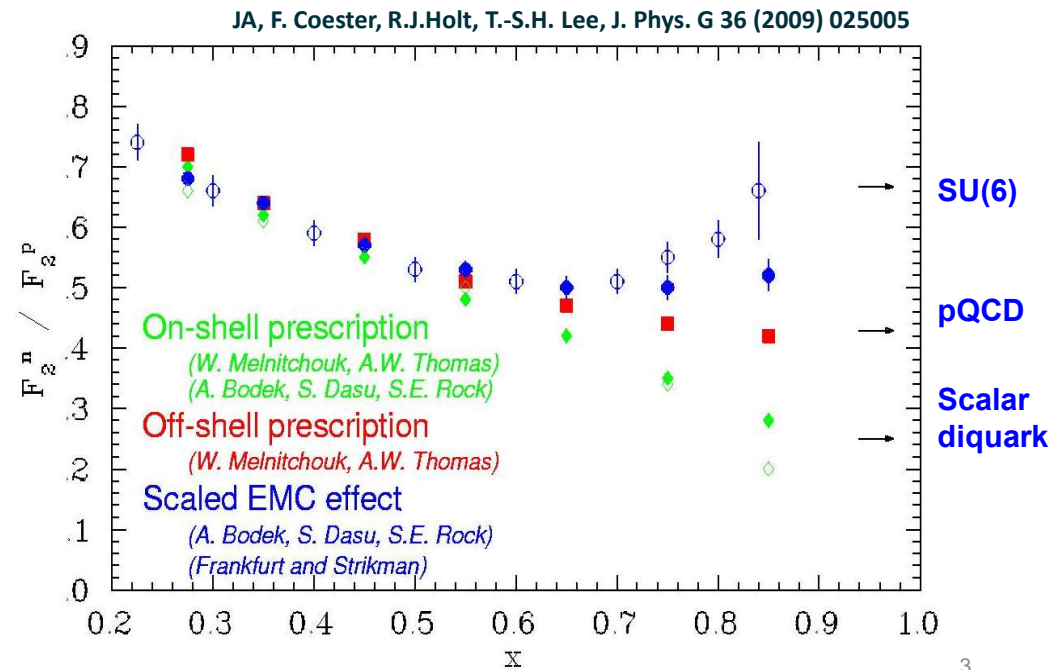
Neutron structure function

No free neutron targets – typical approach is to use the deuteron

- Main approach: $F_{2n}(x) \approx F_{2d}(x) - F_{2p}(x)$
- Nuclear effects lead to $F_{2n}(x)$ extraction with large model-dependent uncertainties, **especially at large x**

Very large model dependence for $x > 0.6$

- Errors enhanced by large proton subtraction
- **On-shell** and **off-shell** calculations of deuteron structure
- “**Scaled EMC effect**”: Extrapolate nuclear effects in F_{2A}/F_{2D} to obtain F_{2D}/F_{2N}



The MARATHON experiment

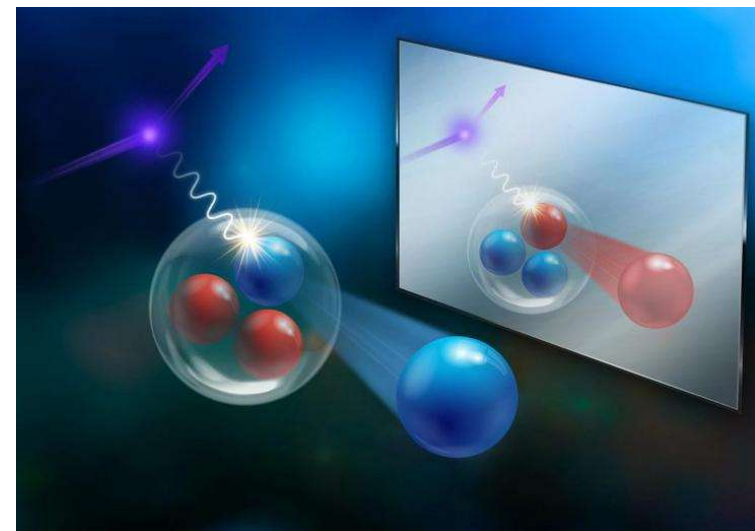
Triton (${}^3\text{H}$) – Helion (${}^3\text{He}$) comparisons

- Few-body nuclei: that allow for precise *ab initio* calculations
- Mirror nuclei: Isospin symmetry connects proton distributions in one nucleus to neutrons in the other
- Nuclear effects are larger than for deuteron, but *cancel in ${}^3\text{H}/{}^3\text{He}$ ratio*

Mirror nuclei: isospin/flavor structure

- ${}^3\text{He}/{}^3\text{H} \approx (p+p+n) / (p+n+n) = (2 + n/p) / (1 + 2 n/p)$
- $n/p \approx (d+d+u) / (d+u+u) = (2 + d/u) / (1 + 2 d/u)$ (+ charge or cross-section weighting)

*Goal of MARATHON: extract neutron structure and $d(x)/u(x)$ while **avoiding questions of nuclear effects***



MARATHON: n/p extraction

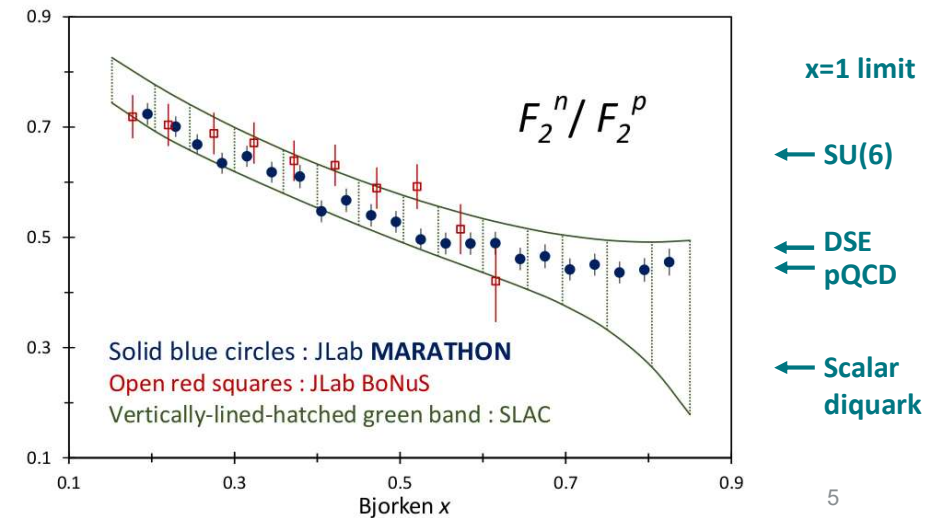
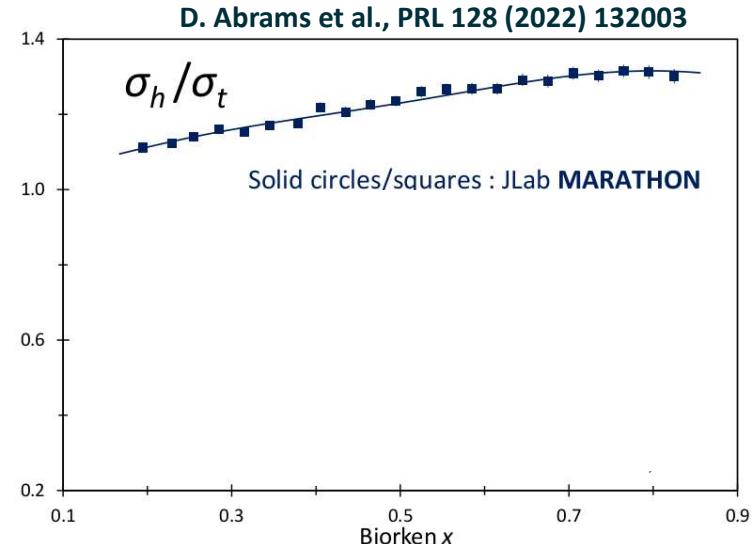
JLab E12-10-103: G.Petratos, JA, M. Katramatou, D. Meekins, R. Ransome

Measure σ_h/σ_t ratio with 1-1.5% uncertainties

- Large cancellation of systematic uncertainties
- Extract F_{2n}/F_{2p} using Kulagin-Petti model and uncertainties
- Ratio normalized down 2.5% to reproduce F_{2n}/F_{2p} at $x=0.3$

F_{2n}/F_{2p} extracted with much smaller model uncertainty
Disfavors SU(6) and scalar diquark

Kulagin-Petti model and quoted uncertainties used for nuclear correction and to determine 3H/3He normalization



Different conclusions you may have heard

MARATHON: Dramatic decrease in uncertainty of F_{2n}/F_{2p} at large x

Global pdf analyses: minimal impact on pdfs

This isn't just the difference between structure functions and pdfs

- Uncertainties on F_{2n}/F_{2p} are significantly decreased. The improvement is less, but still significant, if you take a more conservative approach to normalization and model-dependence uncertainties

T. J. Hague, JA, S. Li, S. N. Santiesteban, PRC 110 (2022) L041302

- Global pdf analyses: extraction of $d(x)/u(x)$ is improved noticeably **IF everything else is kept the same**
 - Details depend on the fit – selection of data, flexibility of off-shell effects, etc... can have a large impact on the final uncertainties
- Global pdf analyses that allow for flavor-dependent nuclear effects lead to much smaller changes in $d(x)/u(x)$, but **provide much stronger constraints on flavor-dependent nuclear effects**
 - Details depend on the fit – form and flexibility of off-shell effects, higher-twist effects, etc... can have a large impact on the final uncertainties

MARATHON 'vs' D/p extractions

What does it tell us about nuclear effects, and is it sensitive to the assumptions made in the MARATHON extraction?

Modified approach - more conservative - to estimating the model dependence of the MARATHON n/p extraction

- Examine range of model with a variety of ingredients; use the central value and spread for the correction and uncertainty

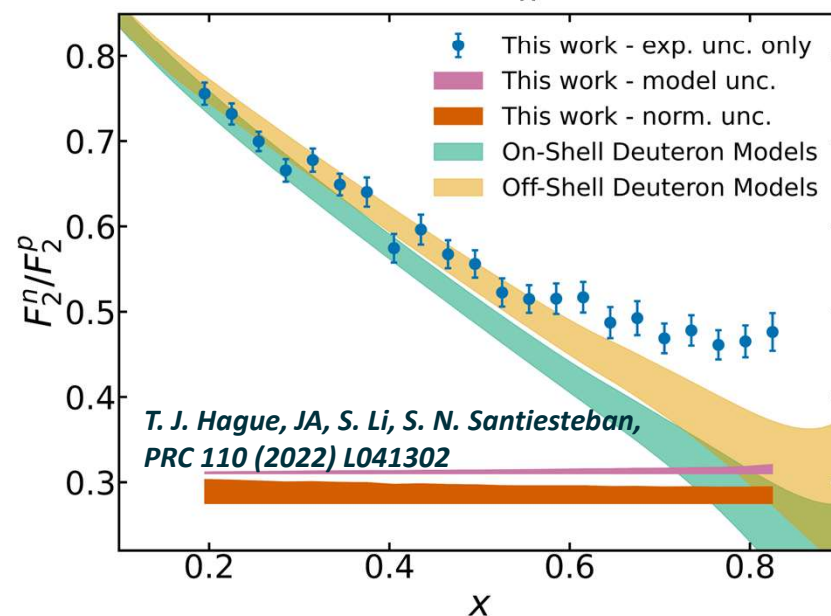
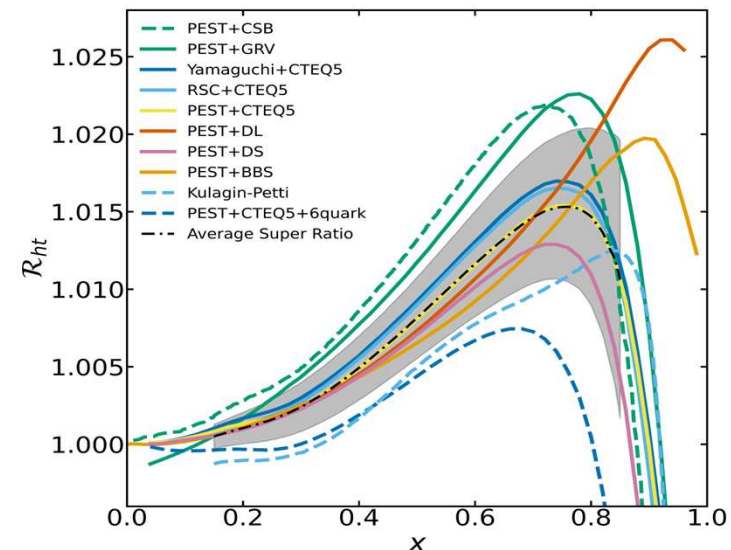
Take a more conservative uncertainty on the normalization

- Based on target thickness estimates, know to +/-1.2%
- MARATHON applied (2.5+/-0.7)% shift – based on KP model
- A global pdf analysis found (0.7+/-0.6)% – different model

→ Apply (1.25+/-1.25)% normalization – cover full range of estimates

Even with this very conservative approach:

- n/p uncertainties are still much smaller than for d/p extractions
- Normalization uncertainty more important than model dependence (in this analysis)
- Consistency requires larger off-shell (or more exotic) effects in the deuteron OR isospin-dependent nuclear effects in A=3

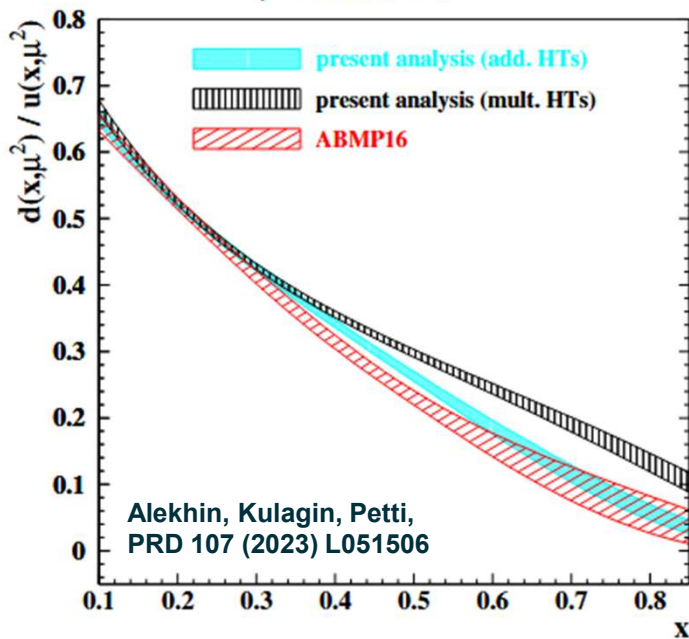


Global pdf fit including MARATHON (no other changes)

Simply adding MARATHON data to an existing fit improves high- x uncertainties

- Modest in this analysis, as it uses a model for nuclear effects with a small model dependence.
- New feature: Higher twist corrections for p , n cancel if applied as multiplicative corrections, but not if treated as additive corrections.

$$\mu^2 = 14x \text{ (GeV}^2\text{)}$$

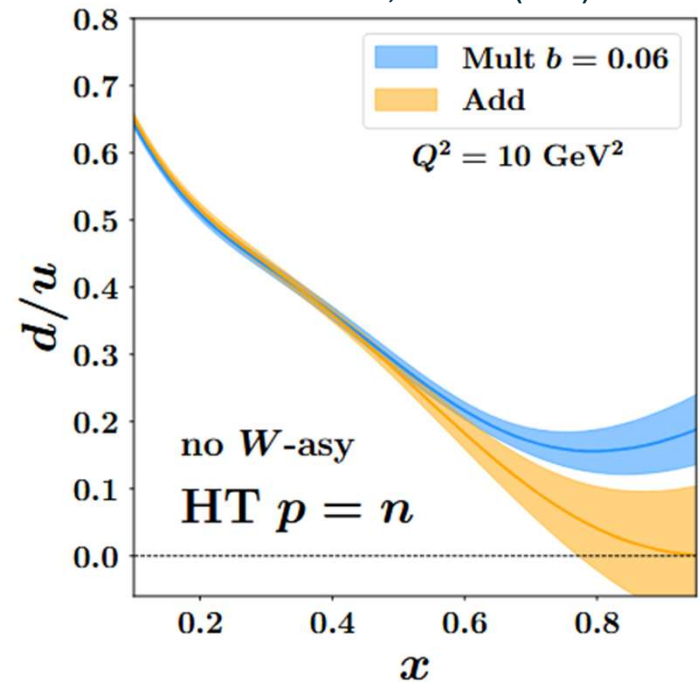


Additive vs multiplicative
difference is larger than
the fit uncertainties

Important for BOTH D/p
and $3H/3He$ extractions

Flavor-dependent effects
are especially important
for MARATHON data

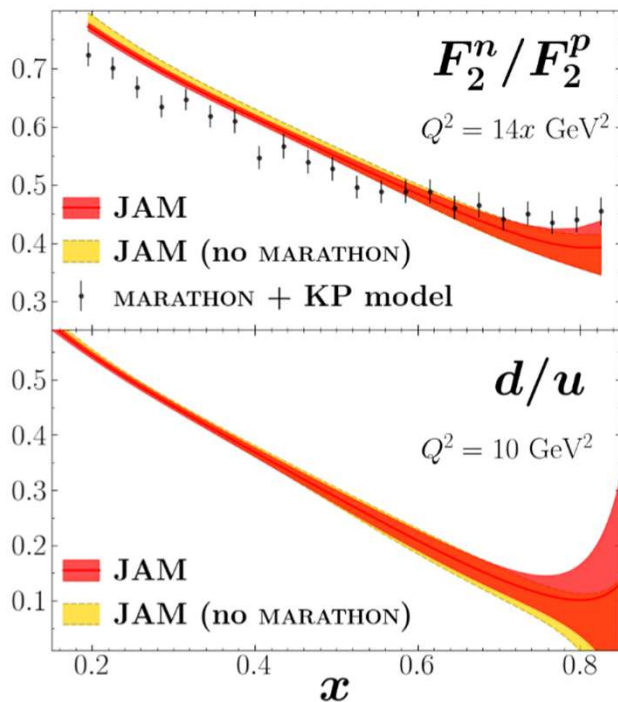
M. Cerutti et al., PRD 111 (2025) 9



Global pdf fit including MARATHON (fitting flavor dependence)

Given the sensitivity to flavor-dependent nuclear effects many analysis fit proton vs neutron (or up vs down) off-shell effects

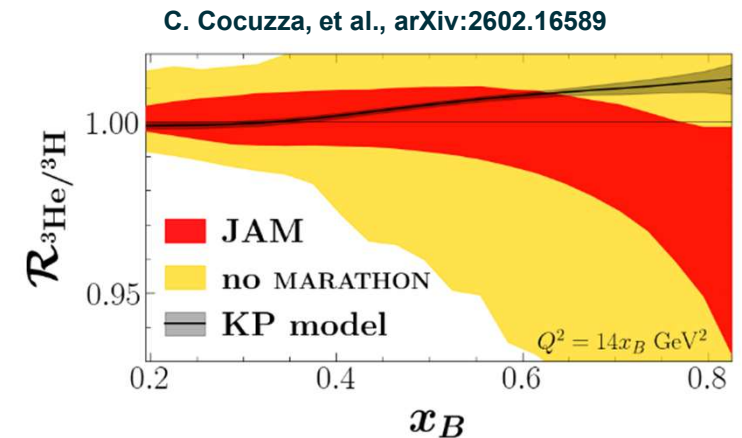
- Extraction of $d(x)/u(x)$ is comparable to precision of non-MARATHON fits with a single off-shell correction
- Allows for constraint of flavor-dependent nuclear corrections



JAM21 analysis:
 F_2^n/F_2^p and $d(x)/u(x)$
 extractions not very
 different w/MARATHON

Values disagree with
 MARATHON extraction
 (different corrections)

C. Cocuzza, et al., PRL
 127 (2021) 074301



JAM26: Significant reduction in the
 range of nuclear effects: MARATHON \rightarrow
 constraints on proton vs neutron effects

Questions raised by PDF analyses?

- Best way to normalize the 3H/3He ratio
 - Estimated target thickness: (0.0+/-1.2)%
 - KP model comparison: (2.5+/-0.7)%
 - JAM21 global pdf analysis: (0.7+/-0.6)%
- Model dependence of the nuclear corrections
- Isospin dependence effects beyond that of typical models

MARATHON vs D/p only or QCD fits w/o A=3

Extraction	F_{2n}/F_{2p} at $x \approx 0.85$	d/u at $x \approx 0.85$
MARATHON [1]	0.43–0.48	0.20–0.26*
Arrington [6]	0.18–0.35	< 0.1*
Accardi [9]	-	< 0.21
JAM [36]	-	< 0.15
CJ21 [35]	-	0.05–0.15
AKP [37]	-	< 0.1

What else can we do?

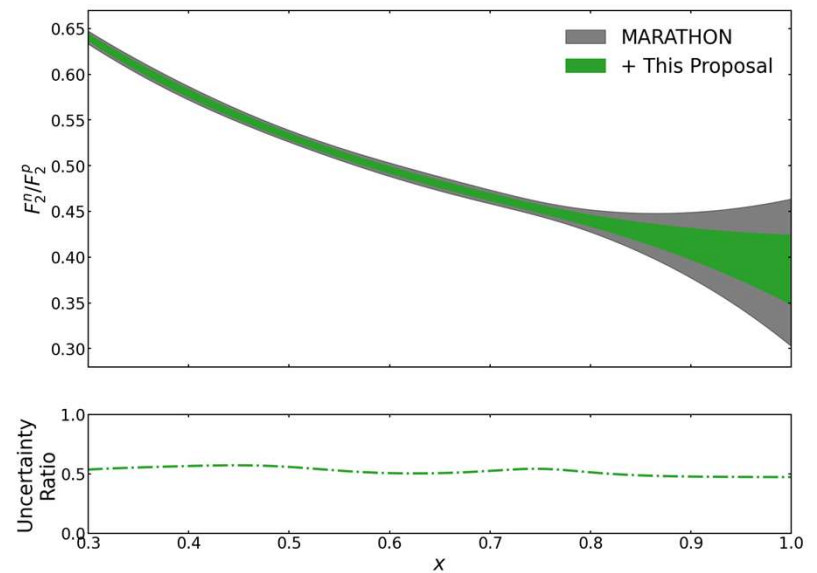
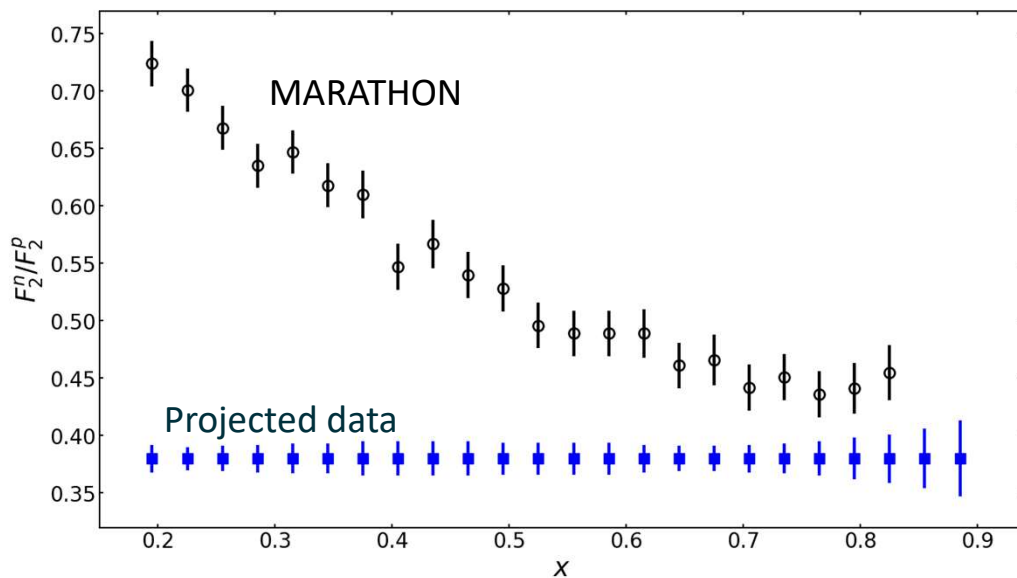
Multiple groups are examining/comparing global fits to identify assumptions that lead to inconsistent results

What can new experiments do?

- Better precision and larger x range on 3H/3He
- Study flavor dependence of higher-twist effects at large x
- Check on at least some effects that could impact the normalization procedure

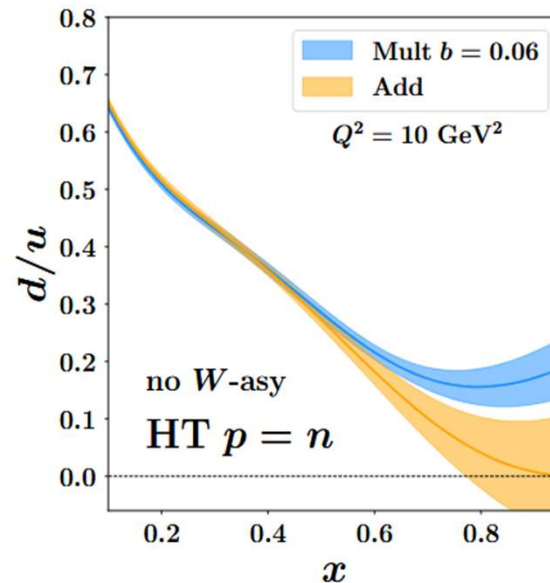
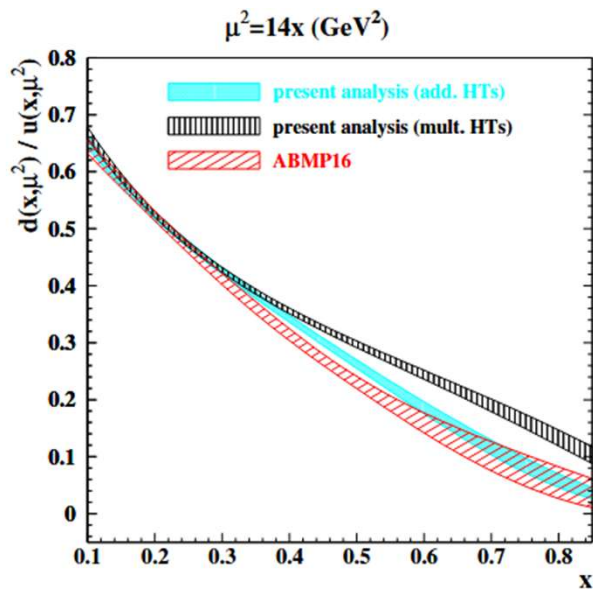
New DIS tritium measurements in Hall C

- Larger solid angle and momentum acceptance of HMS compared to HRS allows better statistics, higher x range, larger W^2 (in general)
 - New measurement provides cross check of normalization (before applying bootstrapping procedure)
 - Combined result gives factor ~ 2 improvement over measured range and extrapolation to $x=1$



New DIS tritium measurements in Hall C

- Larger solid angle and momentum acceptance of HMS compared to HRS allows better statistics, higher x range, larger W^2 (in general)
- Measure Q^2 dependence for $0.55 < x < 0.75$ (Q^2 from 4.7-9 GeV^2 at $x=0.65$)
 - Contribution from $d(x)/u(x)$ should have minimal Q^2 dependence
 - Higher twist should have much larger Q^2 dependence
- Important for understanding extractions for $3\text{H}/3\text{He}$ AND $2\text{H}/1\text{H}$



Q^2 range and precision are more than enough to make a clear observation of HT

Need to evaluate one of these fits to determine expected size of flavor-dependent component

New DIS tritium measurements in Hall C

- Larger solid angle and momentum acceptance of HMS compared to HRS allows better statistics, higher x range, larger W^2 (in general)
- Measure Q^2 dependence for $0.55 < x < 0.75$ (Q^2 from 4.7-9 GeV^2 at $x=0.65$)
- Measure A-dependence (isospin dependence) of R at $x=0.3$, where ratio normalized against calculations
 - $R=\sigma_L/\sigma_T$ is assumed to be A independent to extract F2 ratio from cross section ratio
 - A single L/T separation (6.6, 8.8, 11 GeV) to constrain this potential flavor-dependent correction at $x=0.3$

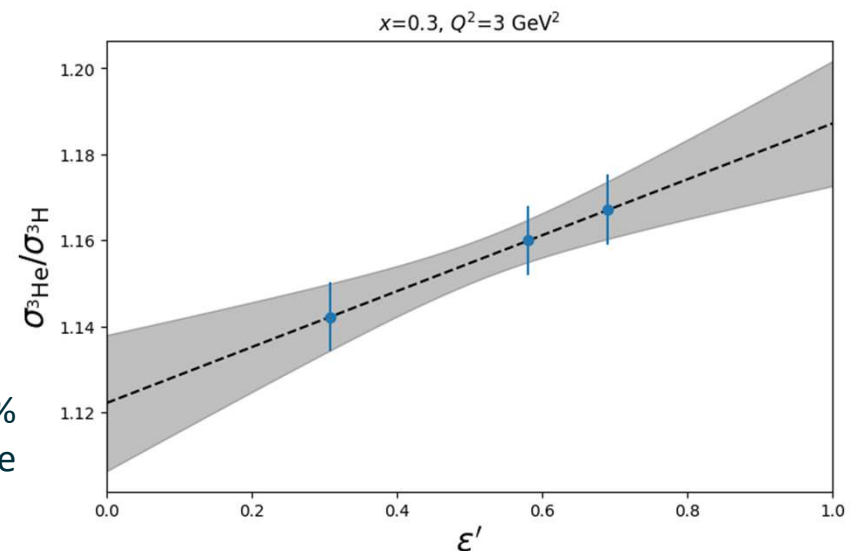
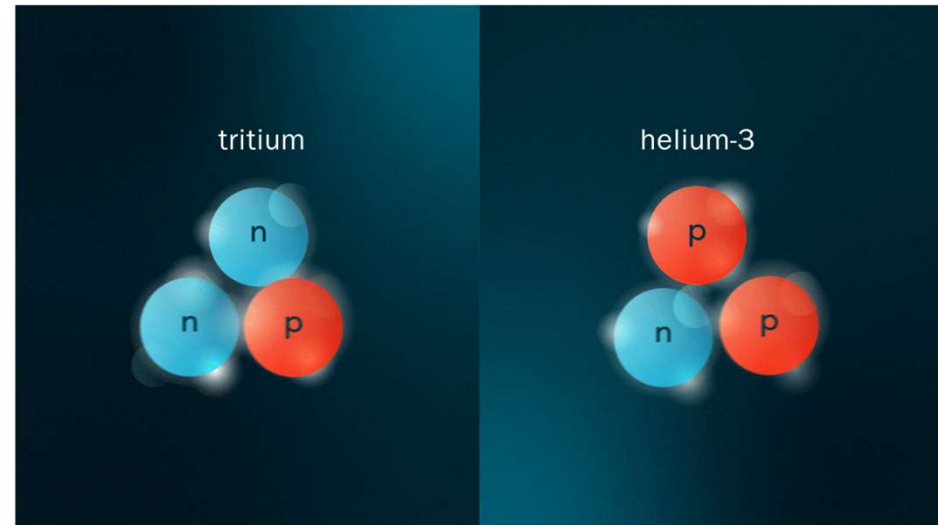


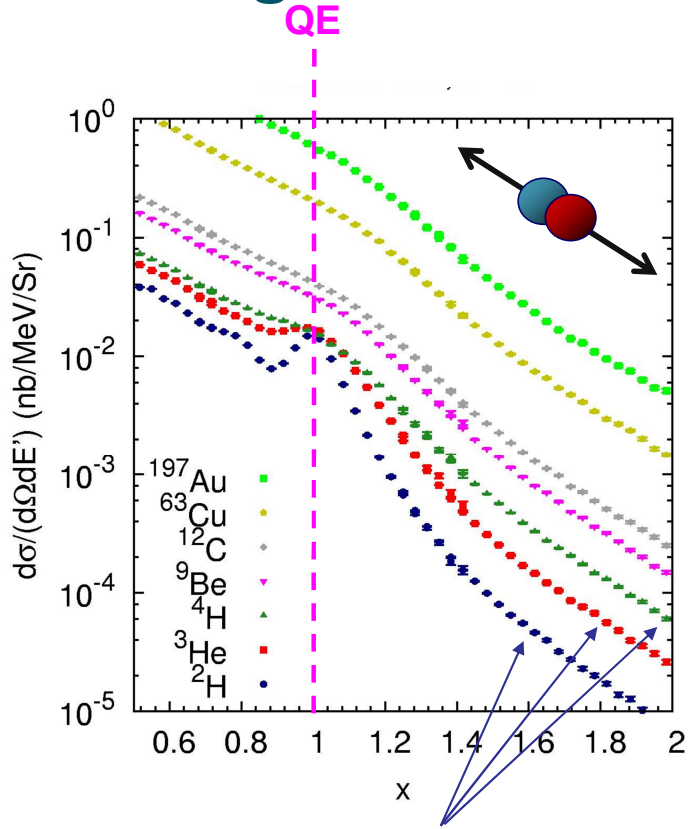
Figure shows impact of 30% difference for R in 3H and 3He

Proposal #2: Short-range correlations

- Hall A tritium SRC focused on isospin-structure of 2N-SRCs
- Data also taken to demonstrate **early onset of SRCs dominance in A=3 nuclei**
- Some exploratory data at $x > 2$ provided insight into isospin structure for high-momentum nucleons, and **showed signs of 3N-SRC dominance**

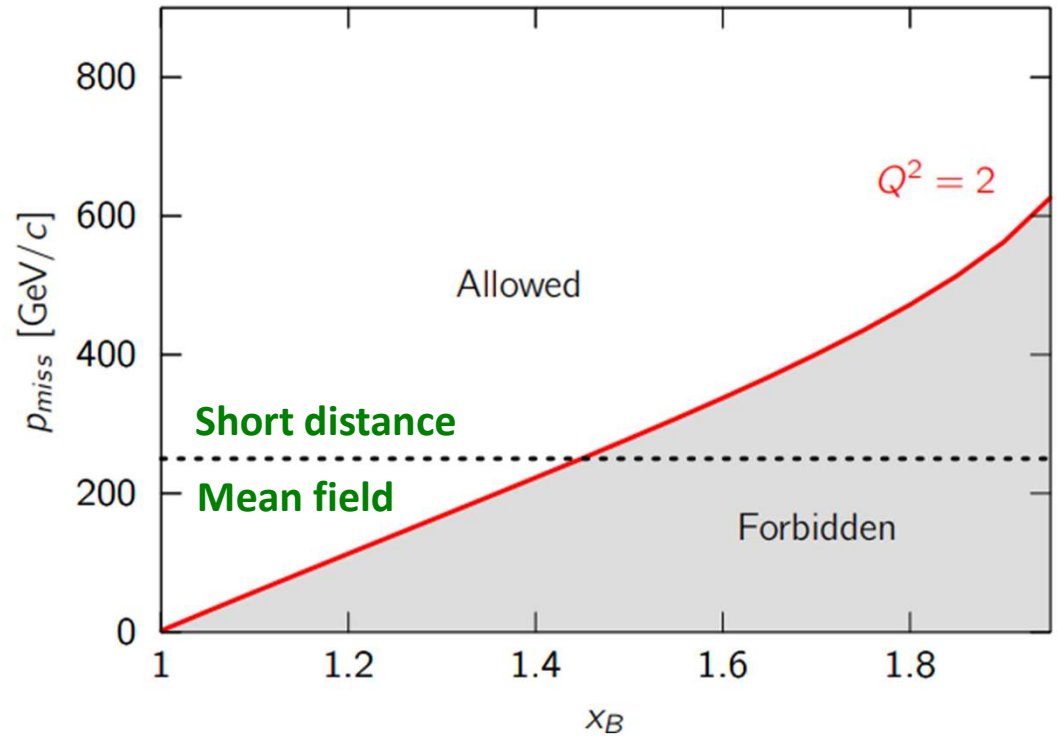


Isolating SRCs in inclusive scattering



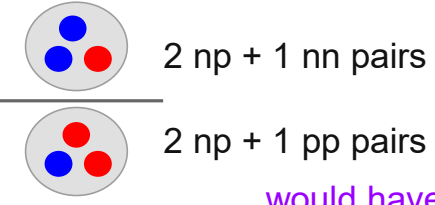
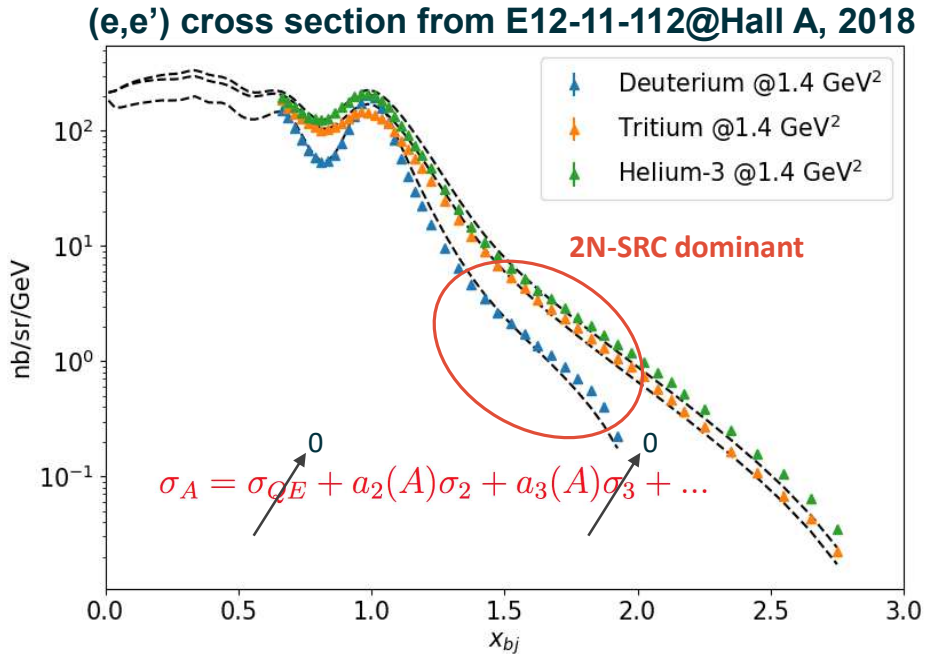
High momentum tails should yield **constant ratio** if SRC-dominated (beyond MF region)

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

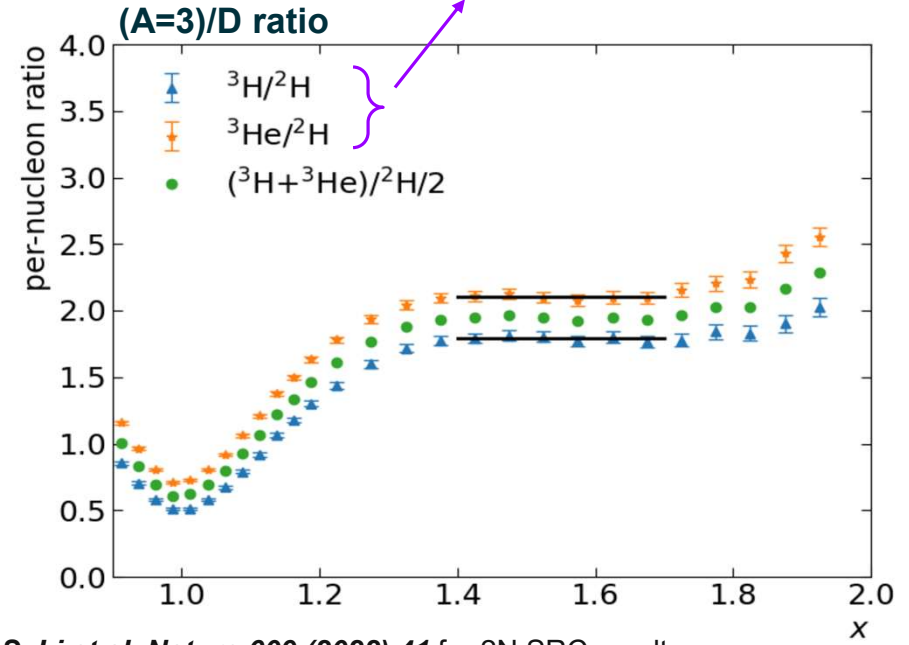


At large x , mean-field region excluded, should see **universal behavior from 2N-SRCs**: Cross section identical in all targets, A/D ratio independent of x and Q^2 (**SRC cross section scaling**)

Hall A Tritium: 2N- and 3N-SRCs in A=3

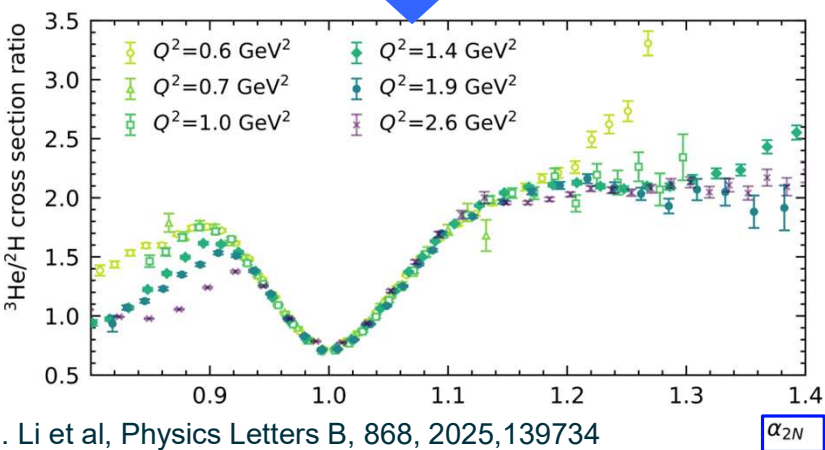
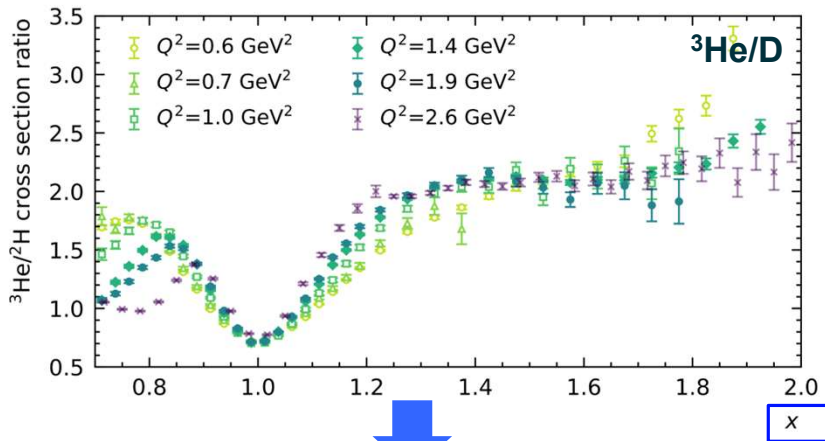


would have given identical plateaus if 100% np-SRCs

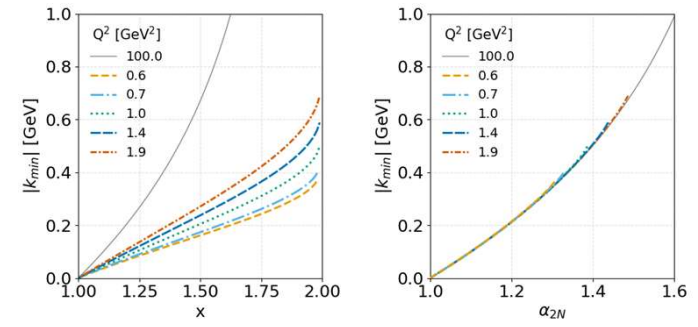


S. Li et al, Nature 609 (2022) 41 for 2N SRC results.

Early onset of 2N SRC scaling in A=3



S. Li et al, Physics Letters B, 868, 2025, 139734



- x used as surrogate for struck nucleon momentum
- Large Q^2 dependence in mapping x to k_{init} → Light-cone α
- Much better scaling near QE peak

A=3 nuclei have smaller shell-model momenta

- 2N-SRC scaling onset at $\alpha \approx 1.15$ for A=3 (1.3-1.4 for $A \geq 12$)

Few body nuclei have smaller scaling violations, e.g. FSI

- 2N-SRC scaling onset at $Q^2 = 1$ for A=3 (~1.4 GeV^2 for $A \geq 12$)

2N-SRC scaling seen much earlier in A=3

Can we also expect onset of 3N SRC scaling at lower Q^2 ?

- 2N- and 3N-SRCs both contribute at all x values.
- More about where 2N-SRCs are small than where 3N-SRCs are large

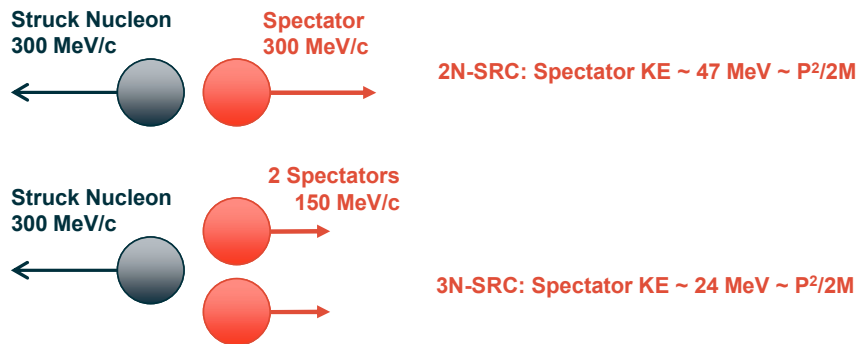
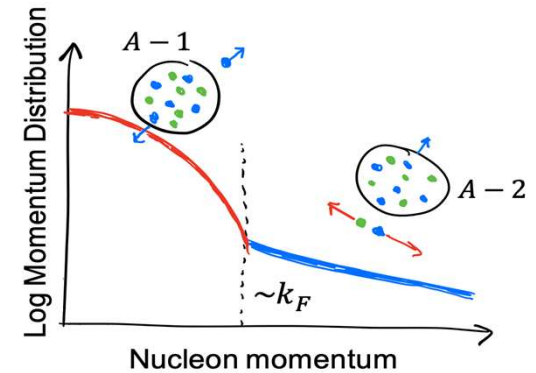
Early onset of 3N SRC scaling in A=3?

Scattering for $x \approx 1$: mean-field (MF), 2N-SRCs, 3N-SRCs can contribute...

- Taking SRCs to be a set of nucleons with large relative, small total momentum
- MF contribution is largest near $x=1$
- Mix of MF and SRCs as we go to larger x

MF distribution drops rapidly above $k_{\text{Fermi}} \rightarrow$ 2N- and 3N-SRCs above $\alpha(k_{\text{Fermi}})$

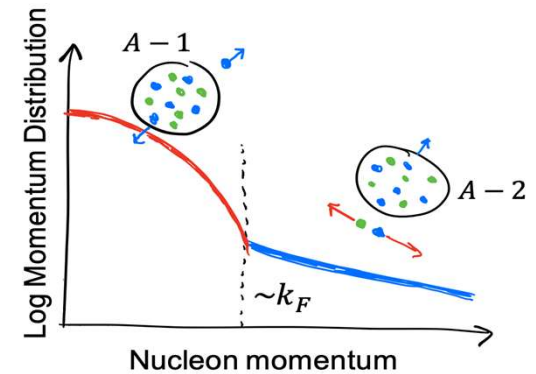
- 3N-SRCs assumed to be much smaller contribution, so expect 2N-SRCs to dominate
- Larger α probes larger k_{init} ; plateau suggests 3N-SRC/2N-SRC ratio stays small
- At large enough k_{init} (large enough α), 3N-SRC is lower energy state and 2N-SRCs suppressed – what value of α ?



Early onset of 3N SRC scaling in A=3?

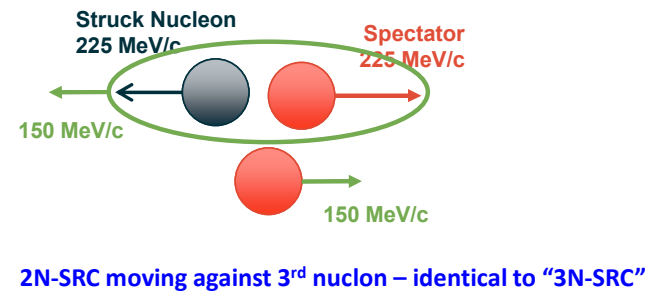
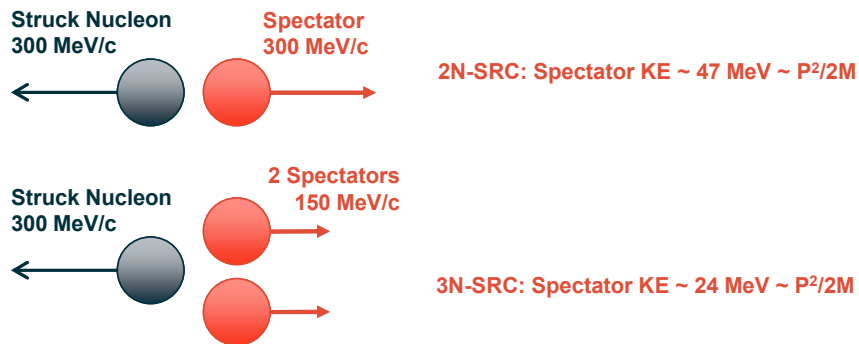
Scattering for $x \approx 1$: mean-field (MF), 2N-SRCs, 3N-SRCs can contribute...

- Taking SRCs to be a set of nucleons with large relative, small total momentum
- MF contribution is largest near $x=1$
- Mix of MF and SRCs as we go to larger x



MF distribution drops rapidly above $k_{\text{Fermi}} \rightarrow$ 2N- and 3N-SRCs above $\alpha(k_{\text{Fermi}})$

- 3N-SRCs assumed to be much smaller contribution, so expect 2N-SRCs to dominate
- Larger α probes larger k_{init} ; plateau suggests 3N-SRC/2N-SRC ratio stays small
- At large enough k_{init} (large enough α), 3N-SRC is lower energy state and 2N-SRCs suppressed – what value of α ?
 - 2N-SRC with CM motion in the nucleus can look like 3N-SRC; **Can't exclude 2N-SRCs even if it looks like 3N**
 - Sargsian proposed requiring all three nucleons to be above k_f to suppress 2N-SRCs



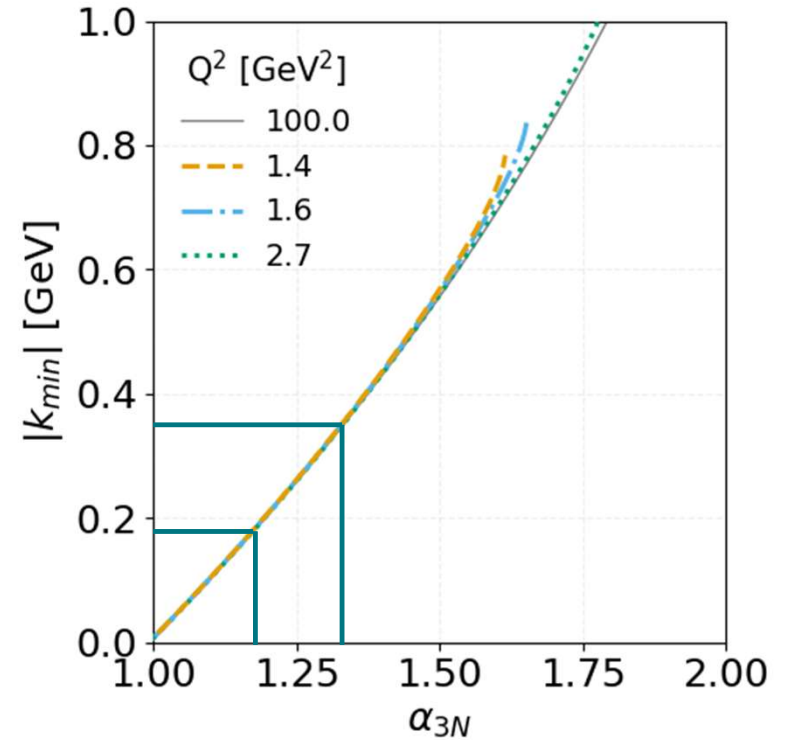
3N-SRC dominance

2N-SRCs dominate at $\alpha \approx 1.15 \rightarrow k_{\text{init}} > 180 \text{ MeV}/c$

Two recoil nucleons with $k > 180 \text{ MeV}/c \rightarrow \alpha > 1.35$

Expect 3N-SRC may start to dominate in this region

Note: lower than predicted α threshold to isolate 3N-SRCs in heavy nuclei \rightarrow accessible at lower Q^2 , realistic with low-density tritium target.

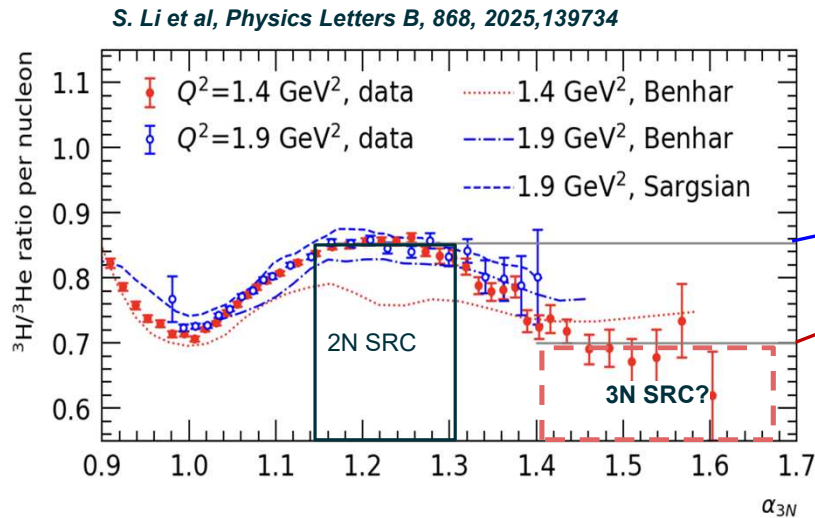


3N-SRC dominance

2N-SRCs dominate at $\alpha \approx 1.15 \rightarrow k_{\text{init}} > 180 \text{ MeV}/c$

Two recoil nucleons with $k > 180 \text{ MeV}/c \rightarrow \alpha > 1.3-1.35$

Expect 3N-SRC may start to dominate in this region

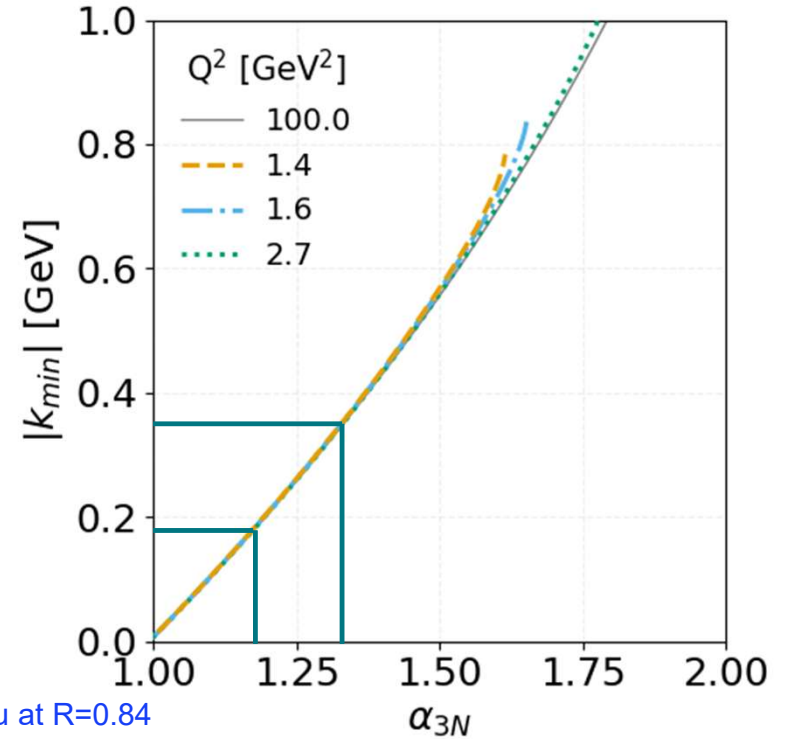


2N-SRC plateau at $R=0.84$

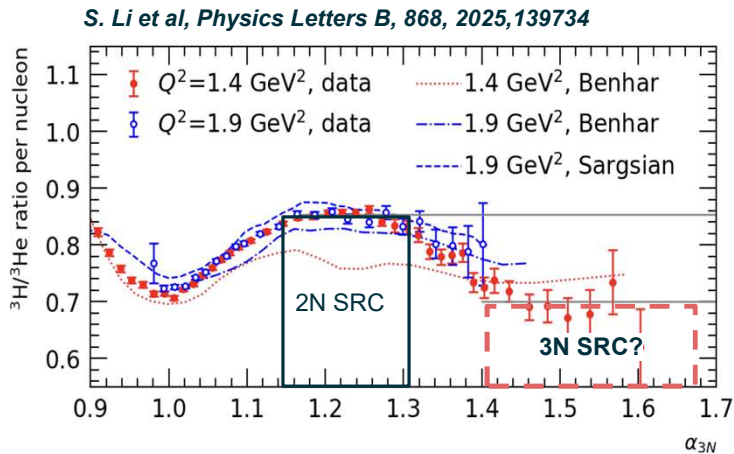
Possible 3N-SRC plateau above $a=1.4$
 Ratio ≈ 0.7 , consistent with 2N-SRC ratio squared $(0.84)^2$

Prediction assuming that consecutive NN interactions dominate over 3N for

Hall A data hints at 3N-SRC dominance



3N-SRC dominance



Ratio sensitive to relative proton, neutron contribution:

- Proton/neutron ratio = Z/N for target $\rightarrow R=0.7$
- Equal proton and neutron contributions $\rightarrow R=1$
- $R=0.84$ implies that singly-occurring nucleon has enhanced

${}^3\text{H}/{}^3\text{He}$ ratio sensitive to relative proton and neutron contribution - independent of whether 2N or 3N SRCs dominate a region

- For $\alpha > 1.3$, the decrease in the ratio suggests that the contribution from protons vs neutrons scales with content of the nucleus
- Want to determine if the ratio stays at $R \approx 0.7$ or continues to decrease, suggesting dominance of doubly-occurring nucleon

If $\alpha > 1.4$ is dominated by 3N-SRCs, then the highest-momentum nucleon is equally sampled between all protons, neutrons in the nucleus

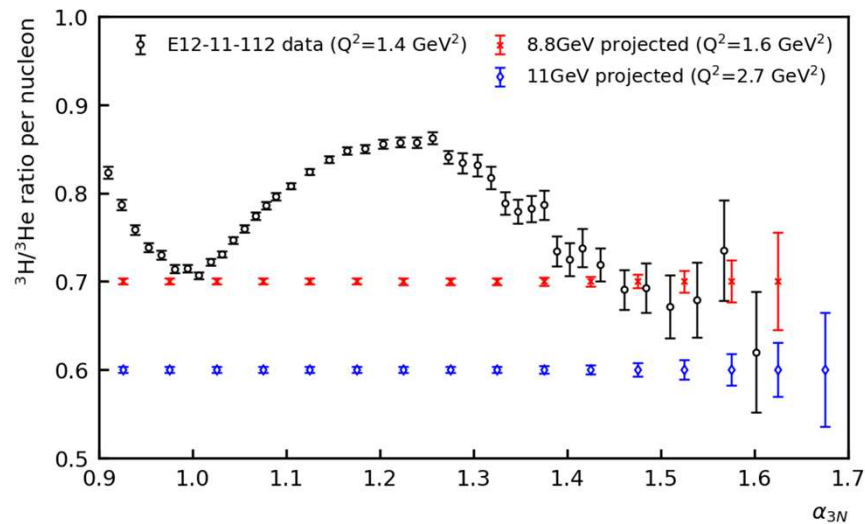
To claim isolation of 3N-SRCs:

Would like better statistics to **clearly demonstrate plateau in α**

Second Q^2 value to **confirm constant cross section ratio for all kinematics where all initial nucleons have $k > k_F$**

New Proposal: Kinematics

	E12-11-112	This Proposal	
Kinematics	L17	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	8.5	8.5
Central momentum	3.54 - 3.94 GeV	9.8 GeV	8.2 GeV
Q²	1.4	2.7	1.6



- 60 PAC days including calibrations
- <3% uncertainties up to $\alpha=1.7$
- 2 settings to confirm the plateau, establish scaling
- Unique chance to probe high-momentum structure in $A=3$ providing constraints to *ab initio* calculations

Summary: Back to the first slide

E12-26-011: “Constraining the flavor content of the nucleon and flavor-dependent nuclear effects in the mirror nuclei ^3H and ^3He ” [T.Hague, JA, D. Meekins, S. Li, M. Nycz]

- **Leading-order:** extension of the MARATHON experiment
 - Aim for factor 2 improvement in F_{2n}/F_{2p} over full x range (MARATHON + HallC vs just MARATHON)
- **Higher-order:** Dedicated studies to constrain effects limiting extractions of F_{2n}/F_{2p} and $d(x)/u(x)$
 - Isospin dependence of $R=\sigma_L/\sigma_T$ at $x=0.3$ (impact of flavor-dependent nuclear corrections on normalization)
 - Constrain isospin-dependence of Higher Twist corrections at large x (for MARATHON and D/p)

E12-26-012: “Probing the isospin and momentum structure of three-nucleon short-range correlations in the $^3\text{H}/^3\text{He}$ mirror system” [S. Li, JA]

- Search for expected early onset of 3N-SRC dominance in $A=3$ nuclei
- **Study momentum, isospin structure of high- p nucleon distribution** (whether or not 3N-SRCs dominate)
 - Direct, model-independent comparison of isospin structure in large- x scattering (high- p nucleons)
 - Absolute cross sections and precise ratios for comparison to *ab initio* calculations at very large x
 - If 3N-SRCs dominate, the isospin structure information translates into a statement of 3N-SRC structure