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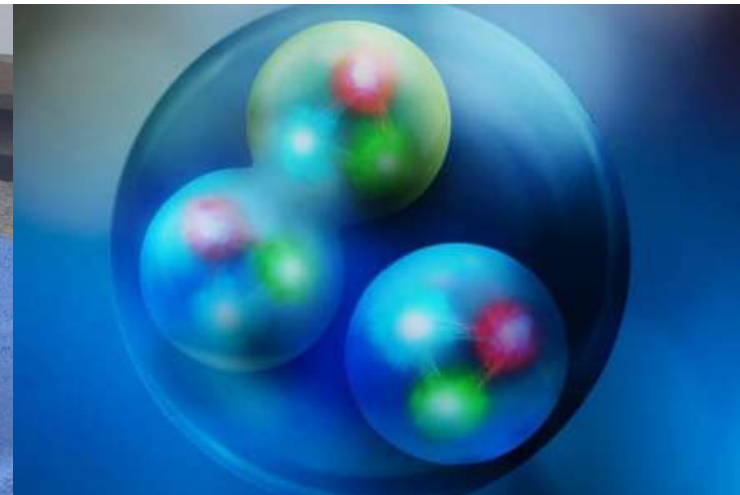
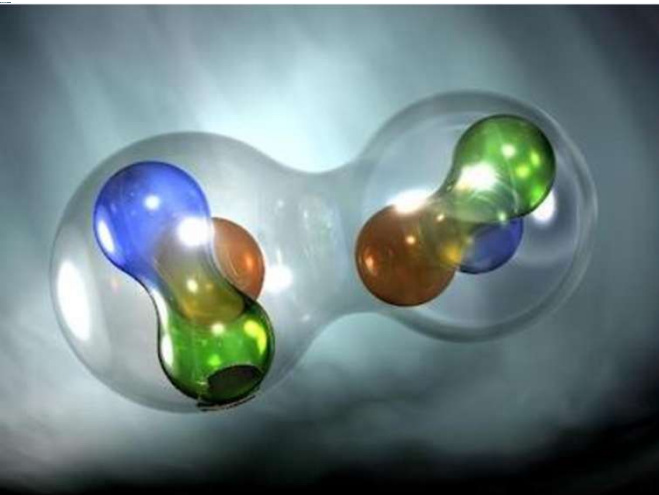
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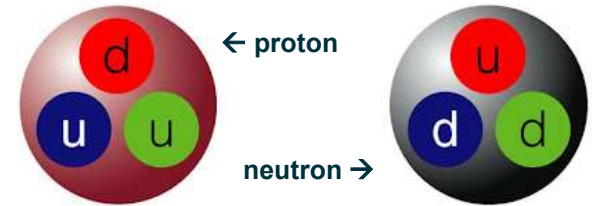
Impact of the MARATHON experiment

John Arrington, Lawrence Berkeley National Lab

Qualitative Challenges in SRC/EMC Physics, June 12, 2026



Nucleon pdfs: the importance of the neutron



Deep-inelastic scattering (DIS) allows for e structure function $F_2(x)$

- x = quark longitudinal momentum fraction
- $F_2(x)$ related to parton momentum distributions (pdfs)

$$F_2(x) \sim \sum e_i^2 q_i(x) \quad i=up, \text{down, strange...}$$

Proton: $F_2(x) \propto 8u(x) + d(x)$

$u(x), d(x)$ defined as the quark distributions in the proton

Neutron: $F_2(x) \propto 2u(x) + 4d(x)$

isospin symmetry \rightarrow d-quark distribution for neutron = $u(x)$, u-quark = $d(x)$

- $u(x)$ already well constrained by the proton data
- $d(x)$ extraction requires neutron structure function
- d/u in the valence region sensitive to properties of the nucleon wavefunction
- Several predictions for d/u as $x \rightarrow 1$.

$$p^\uparrow = -\frac{1}{3}d^\uparrow(uu)_1 - \frac{\sqrt{2}}{3}d^\downarrow(uu)_1 + \frac{\sqrt{2}}{6}u^\uparrow(ud)_1 - \frac{1}{3}u^\downarrow(ud)_1 + \frac{1}{\sqrt{2}}u^\uparrow(ud)_0$$

interacting quark
spectator diquark
diquark spin

	$\frac{F_2^n}{F_2^p}$	$\frac{d}{u}$	$\frac{\Delta d}{\Delta u}$	$\frac{\Delta u}{u}$	$\frac{\Delta d}{d}$	A_1^n	A_1^p
DSE-1	0.49	0.28	-0.11	0.65	-0.26	0.17	0.59
DSE-2	0.41	0.18	-0.07	0.88	-0.33	0.34	0.88
$0_{[ud]}^+$	$\frac{1}{4}$	0	0	1	0	1	1
NJL	0.43	0.20	-0.06	0.80	-0.25	0.35	0.77
SU(6)	$\frac{2}{3}$	$\frac{1}{2}$	$-\frac{1}{4}$	$\frac{2}{3}$	$-\frac{1}{3}$	0	$\frac{5}{9}$
CQM	$\frac{1}{4}$	0	0	1	$-\frac{1}{3}$	1	1
pQCD	$\frac{3}{7}$	$\frac{1}{5}$	$\frac{1}{5}$	1	1	1	1

R. J. Holt and C. D. Roberts, Rev. Mod. Phys. 82 (2010) 2911

C. D. Roberts, R. J. Holt, and S. M. Schmidt, Phys. Lett. B727 (2013) 249

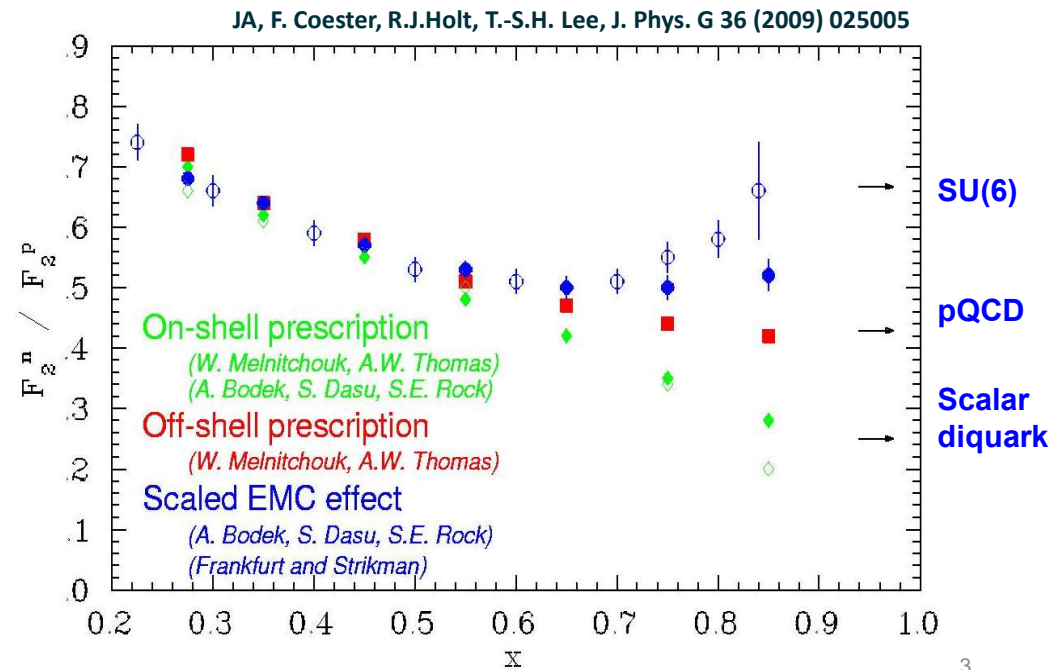
Neutron structure function

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 (^3H) – Helion (^3He) comparisons

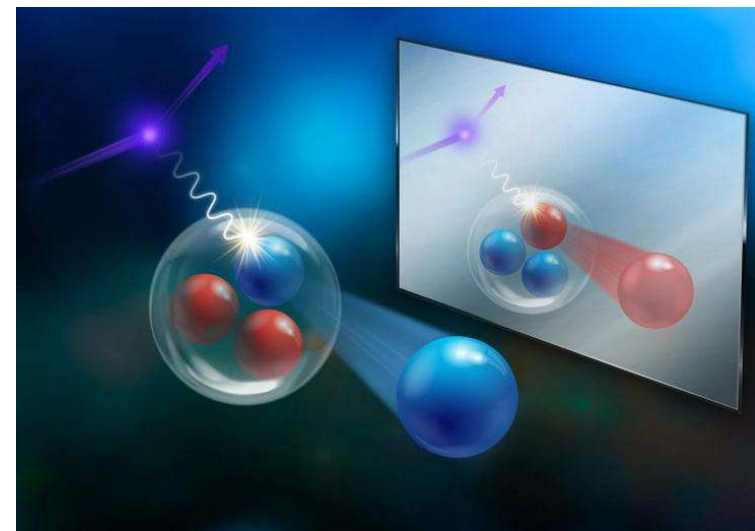
- Few-body nuclei: that allow for precise *ab initio* calculations
- Mirror nuclei: Isospin symmetry connects proton distributions in one nucleus to neutrons in the other
- Nuclear effects are larger than for deuteron, but *cancel in $^3\text{H}/^3\text{He}$ ratio*

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***

*Goal of this talk: **focus on the questions MARATHON raised about nuclear effects***



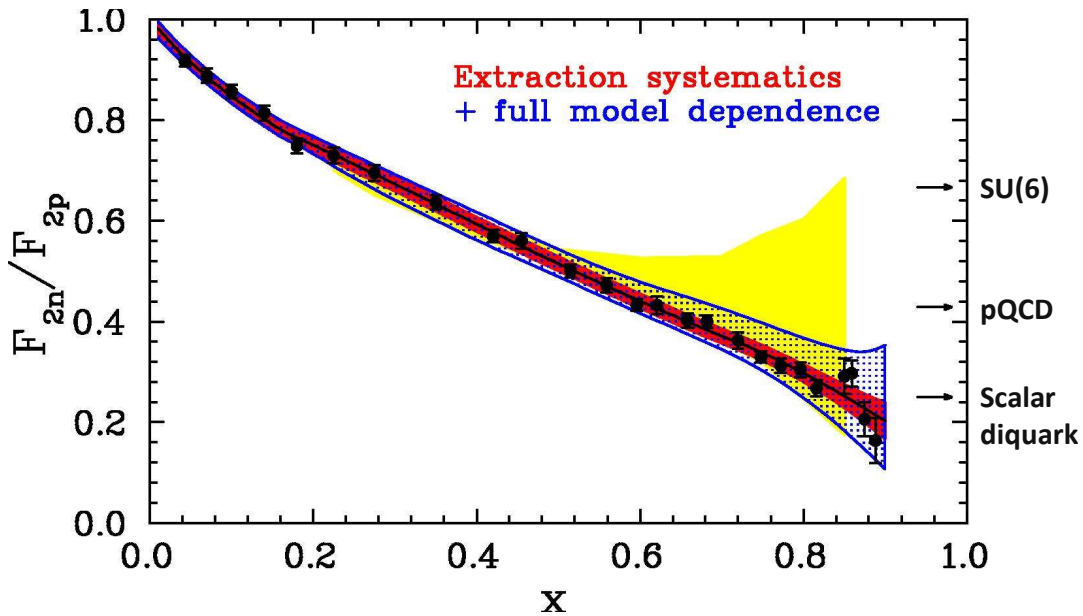
#1: Neutron structure function

Several n/p extractions w/estimated experimental, **model-dependence**, wavefunction uncertainties

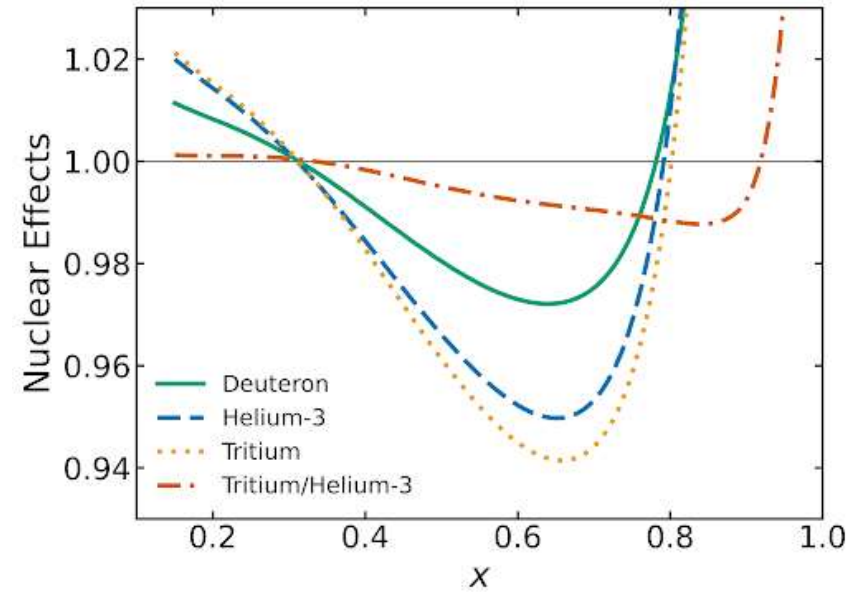
JA, F. Coester, R.J.Holt, T.-S.H. Lee, *J. Phys. G* 36 (2009) 025005

A. Accardi, et al., *PRD84* (2011) 014008 [CJ12 pdf analysis]

JA, J. G. Rubin, W. Melnitchouk, *PRL* 108 (2012) 252001



Improvement possible with 3H, 3He



T.J.Hague, JA, S. Li, S. N. Santiesteban, *PRC* 110 (2024) L041302

MARATHON: n/p extraction

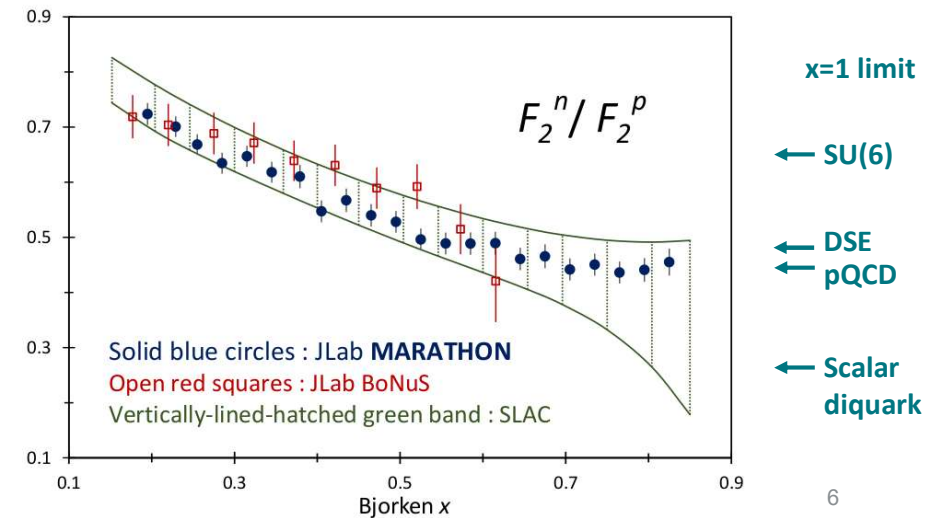
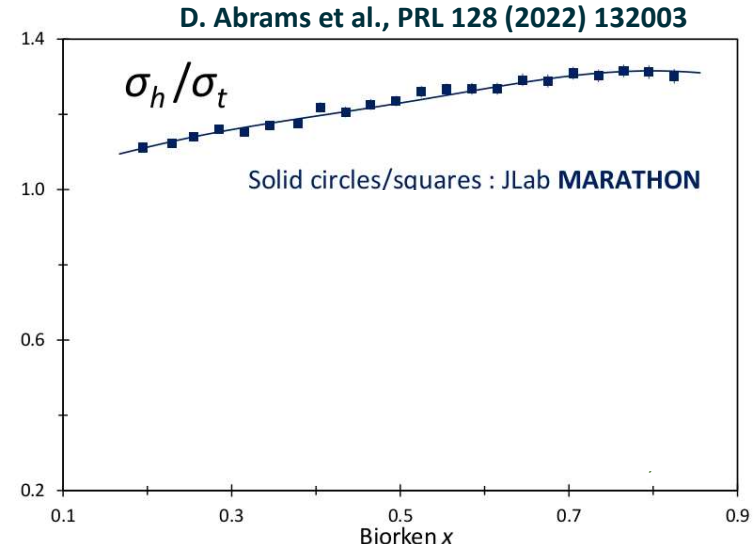
JLab E12-10-103: G.Petratos, JA, M. Katramatou, D. Meekins, R. Ransome

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 $x=0.3$

3H/3He ratio: nuclear effects largely cancel and the result is mainly sensitive to F_{2n}/F_{2p}

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



MARATHON: A=3 EMC effect

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 $x=0.3$

3H/3He ratio: nuclear effects largely cancel and the result is mainly sensitive to F_{2n}/F_{2p}

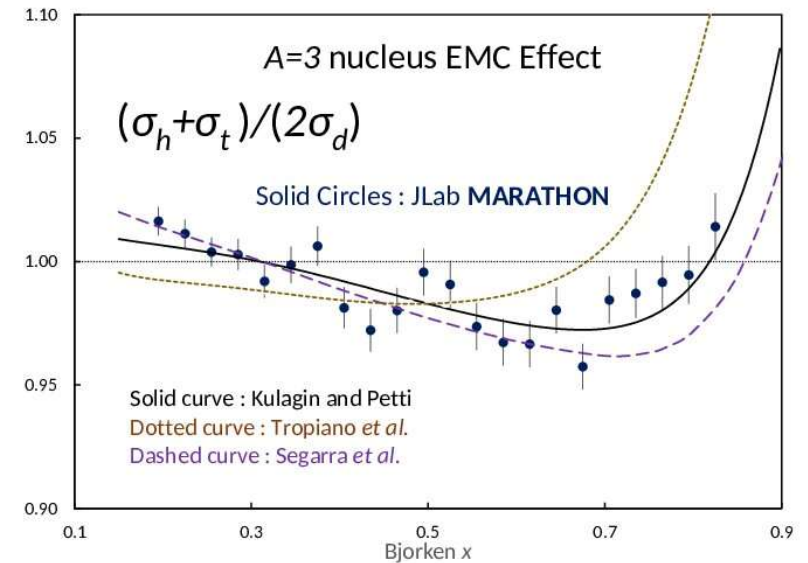
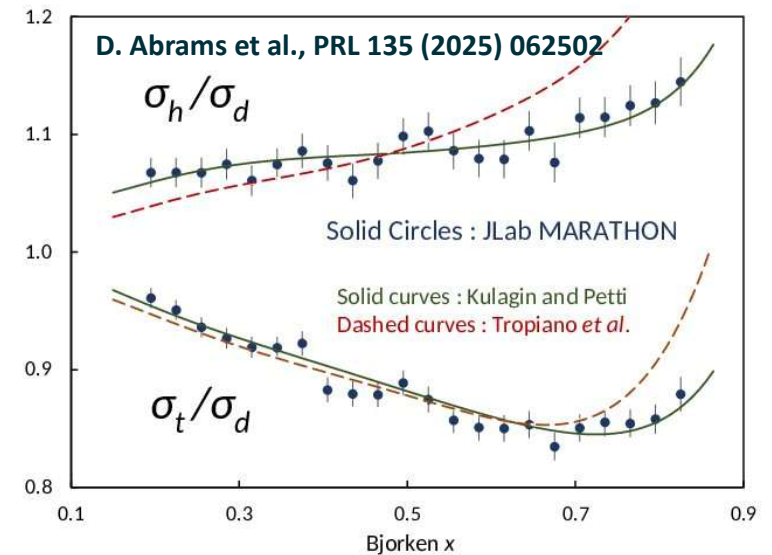
- F_{2n}/F_{2p} extracted with much smaller model dependence
- Disfavors SU(6) and scalar diquark

3H-3He average: isospin effects largely cancel, ratio to deuteron is sensitive to nuclear effects for "isoscalar" A=3 nucleus

- MARATHON ${}^3\text{H}/{}^2\text{H}$, ${}^3\text{He}/{}^2\text{H}$ ratios provide direct measure of nuclear effects for "isoscalar" A=3

NOTE: KP model (+quoted uncertainty) used for 3H/3He nuclear correction to extract n/p, and normalize target ratios

MARATHON agreed with E03-103 (6 GeV EMC) data for 3He/2H – KP model claimed that both expts required 2-2.5% normalization shifts



Different conclusions you may have heard

1. MARATHON: Dramatic decrease in uncertainty of F_{2n}/F_{2p} at large x
2. Global pdf analyses: minimal impact on pdfs

My personal take: not quite as simple as these make it sound

1. 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
2. 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
3. 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
4. The apparent inconsistency is not JUST F_{2n}/F_{2p} vs $d(x)/u(x)$, but that difference is very important

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

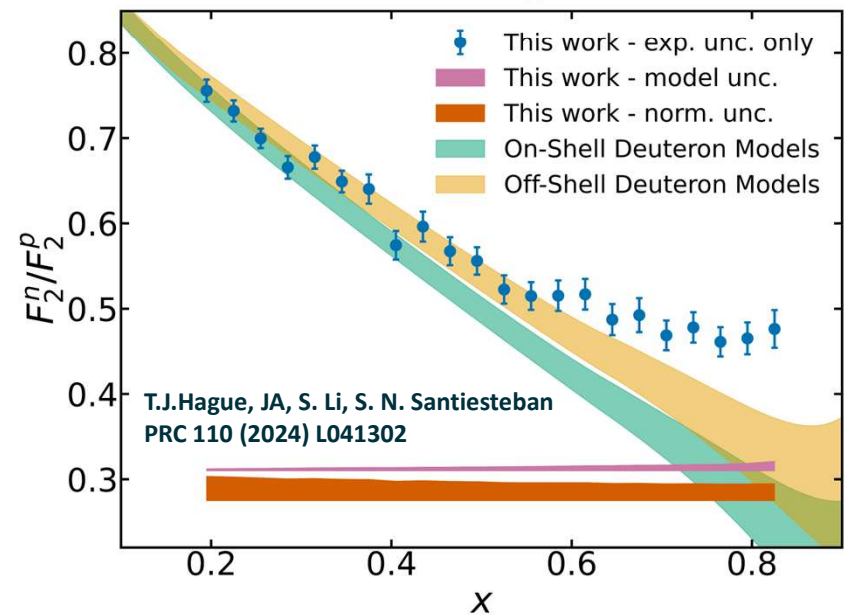
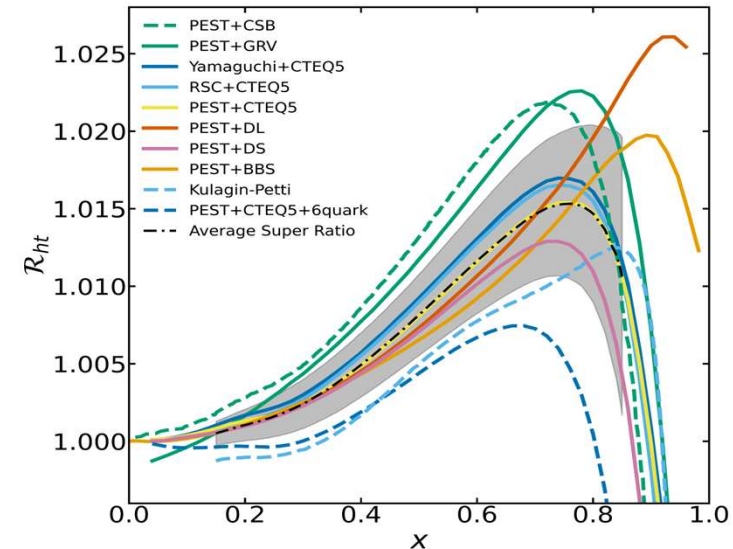
Take a more conservative uncertainty on the normalization

- 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

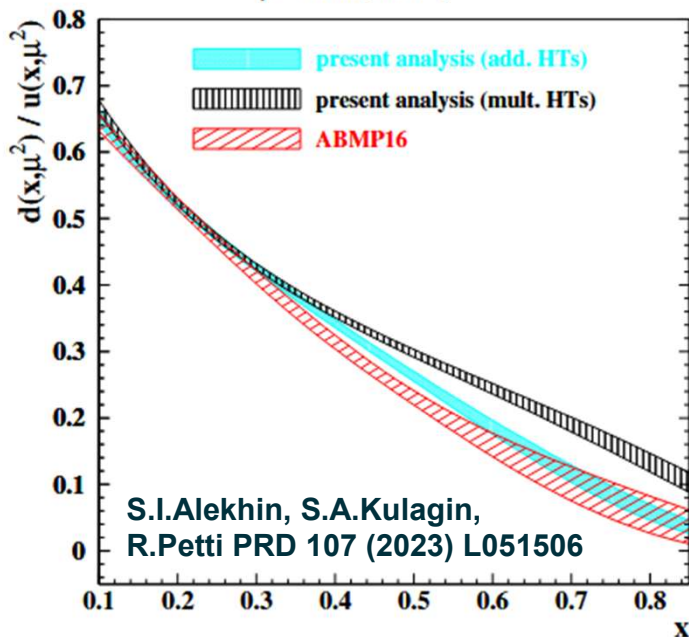


Global pdf fit including MARATHON (no other changes)

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.

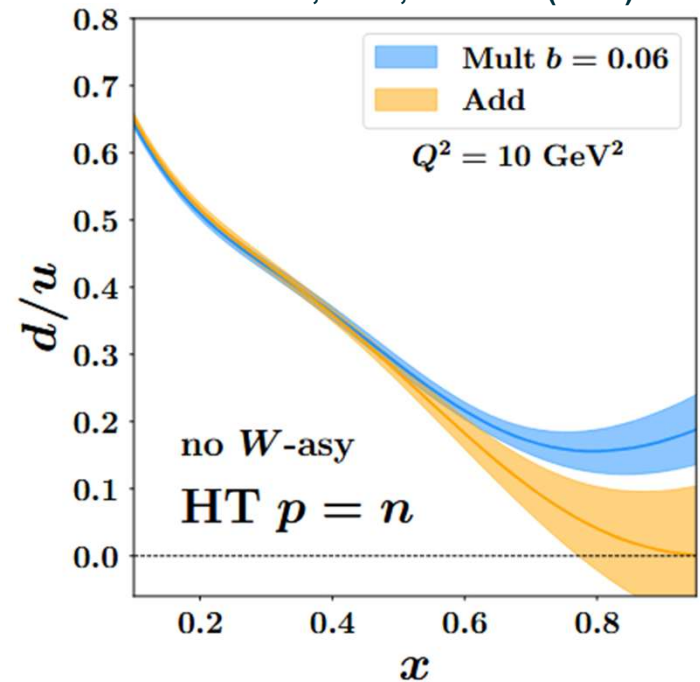
$$\mu^2 = 14x \text{ (GeV}^2\text{)}$$



Additive vs multiplicative
difference is larger than
the fit uncertainties

Flavor-dependent effects
are especially important
for MARATHON data

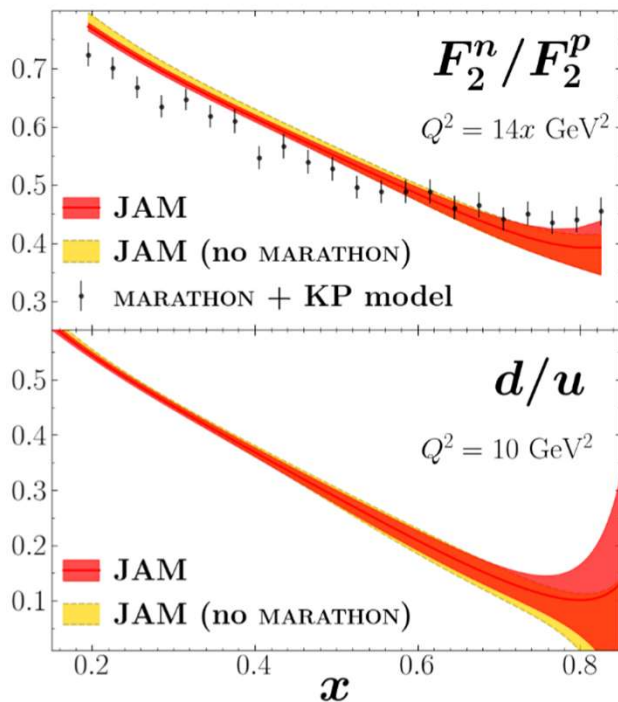
M. Cerutti, et al., PRD 111 (2025) 9



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

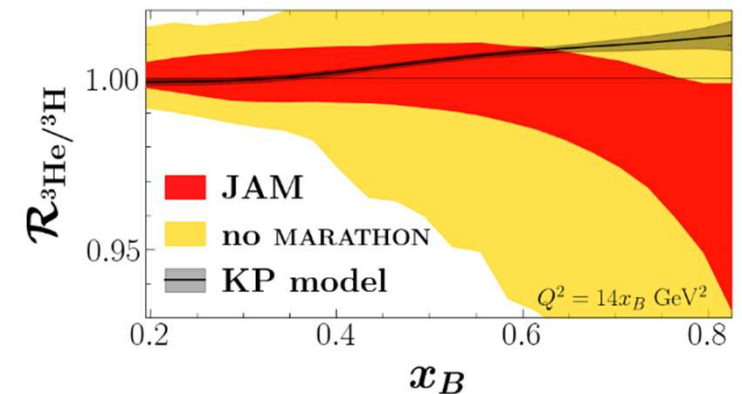


JAM21 analysis:
 F_2^n/F_2^p and $d(x)/u(x)$
 extractions not very
 different w/MARATHON

Values disagree with
 MARATHON extraction
 (different corrections)

C. Cocuzza, et al., PRL 127 (2021) 242001

C. Cocuzza, et al, arXiv:2602.16589



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

Analysis including MARATHON raise questions

- Best way to normalize the 3H/3He ratio
- Model dependence of the 3H/3He \rightarrow n/p correction
- 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 next?

Several 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

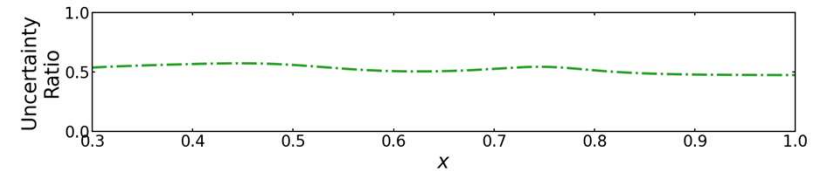
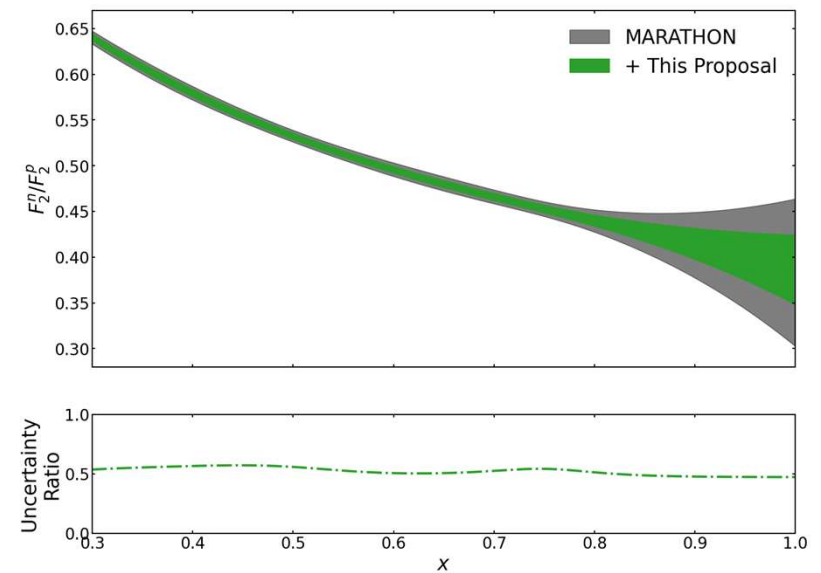
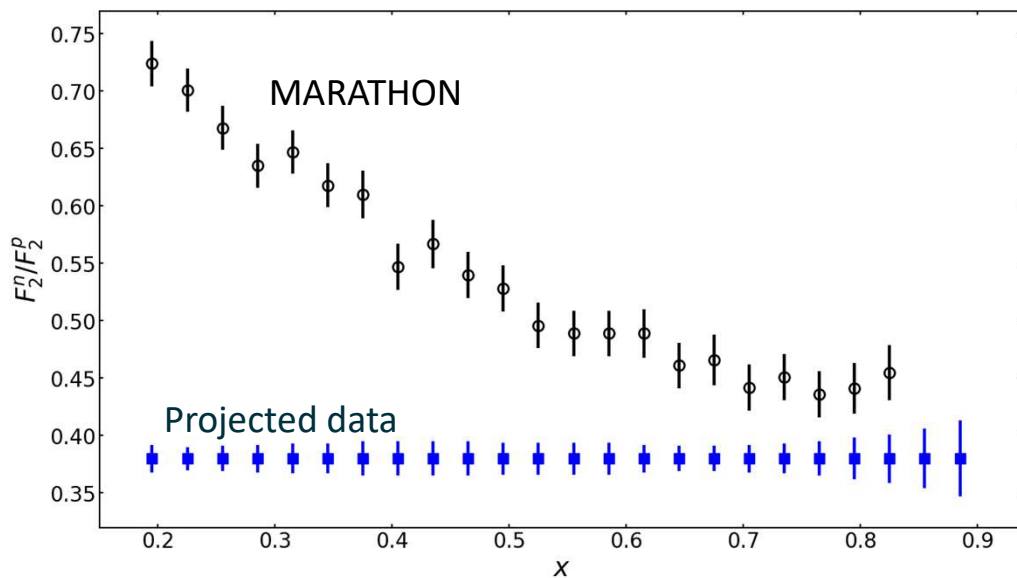
New tritium proposal in Hall C

- PR12-26-011: T. Hague, JA, S. Li, D. Meekins, M. Nycz
- Run group proposal with 3N-SRC (using SHMS)
- We will use the HMS to measure $^3\text{H}/^3\text{He}$ ratios, as MARATHON did, but add additional tests related to the questions raised in the analysis of the MARATHON data.

Constraining the flavor content of the nucleon and flavor-dependent nuclear effects in the mirror nuclei ^3H and ^3He .
(PAC54)

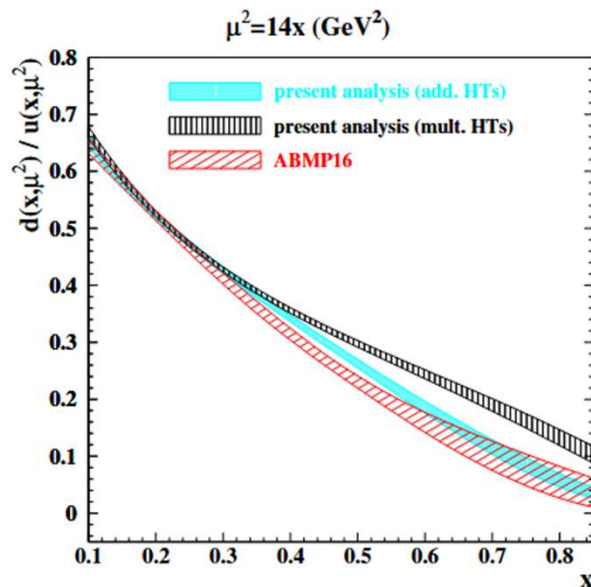
New tritium proposal in Hall C

- 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 $x=1$

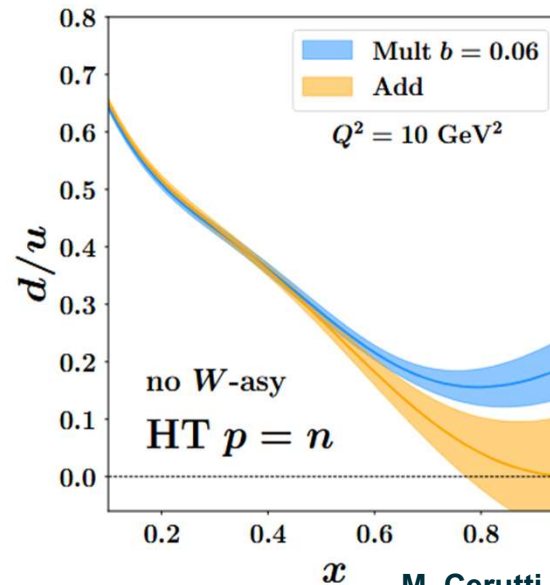


New tritium proposal in Hall C

- 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



S.I.Alekhin, S.A.Kulagin,
R.Petti PRD 107 (2023) L051506



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

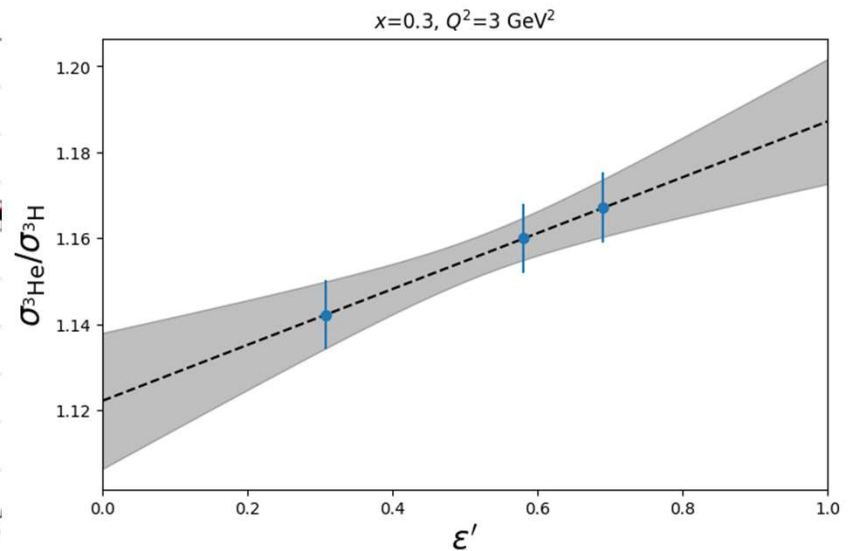
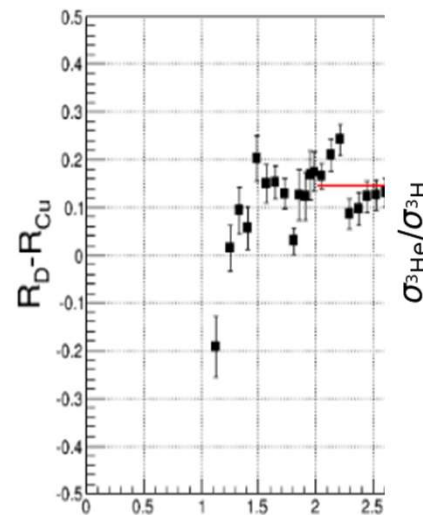
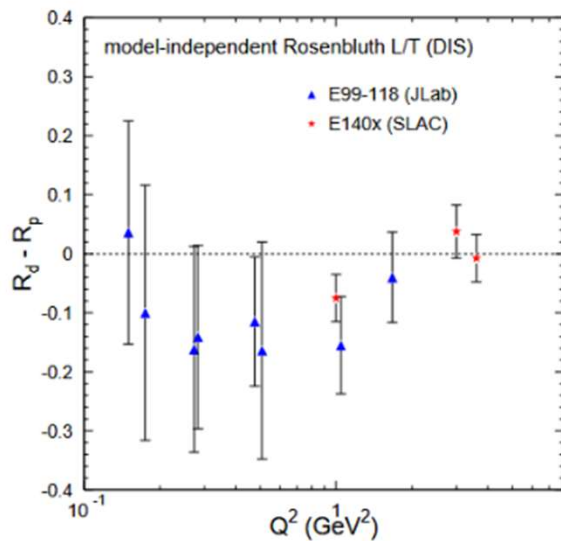
Q^2 range and precision are more than enough to make a clear observation of HT

Need to evaluate specific fits to determine the size of their flavor-dependent component

Additive HT would impact both MARATHON and D/p extractions

New tritium proposal 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 F_2 ratio from cross section ratio
 - A single L/T separation (6.6, 8.8, 11 GeV) to constrain this potential flavor-dependent correction at $x=0.3$



Summary

MARATHON made precise measurements of the $3\text{H}/3\text{He}$ (and $A=3$ EMC ratios) up to $x=0.84$

Extractions of n/p structure function ratios based on a specific model (or range of models) yield improved uncertainties

MARATHON data allows for constraints on flavor-dependent nuclear effects

- Flavor-dependent EMC effect
- Isospin-dependent higher-twist effects

New experiment proposed to improve on MARATHON precision and x range, and to directly constrain isospin-dependence of HT, and (some) potential flavor-dependent nuclear effects.