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U.S. DEPARTMENT OF ENERGY
Office of Science

Inclusive Scattering with Tritium at x>1

Shujie Li
on behalf of the E12-11-112 Collaboration

Hall A Winter Meeting
Feb 11, 2022

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

Spokespersons: Patricia Solvignon, John Arrington, Donal Day, Douglas Higinbotham, Zhihong Ye

Students: Leiqaa Kurbany, Shujie Li, Nathaly Santiesteban

Hall A Tritium Experiments:

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

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2017.12: Commissioning

2018.2-2018.5: E12-11-103 MARATHON

2018.4 E12-14-011 exclusive SRC

2018.5 : E12-11-112 x>1 (inclusive SRC) 2.2 GeV beam, 5 days

2018.9-11 : E12-11-112 x>1 (inclusive SRC) 4.3 GeV beam, 33 days

2018.11: E12-17-003 e'K

Summary of Data Taking

Fall 2018

LHRS: Dedicated NN and 3N SRC study (1<xbj<3) with 4.3 GeV beam

RHRS: QE scan

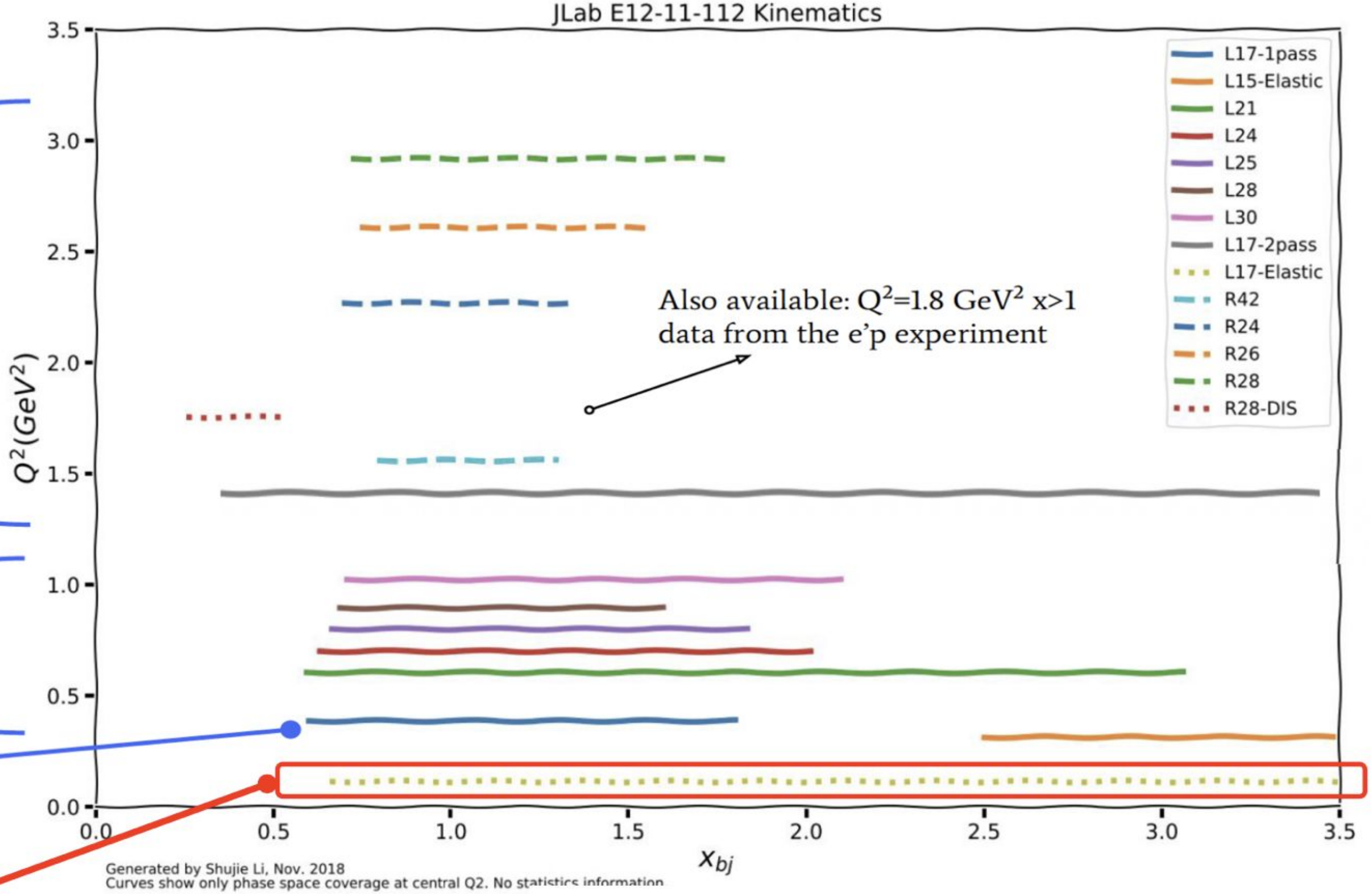
May 2018:

QE scan with 2.2 GeV beam

Dec 2017:

Commissioning

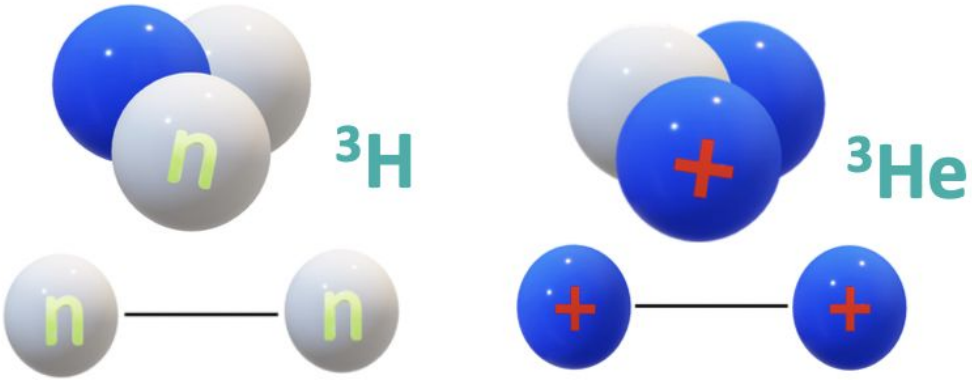
Target "boiling" study (also QE data at Q2=0.4 GeV2)

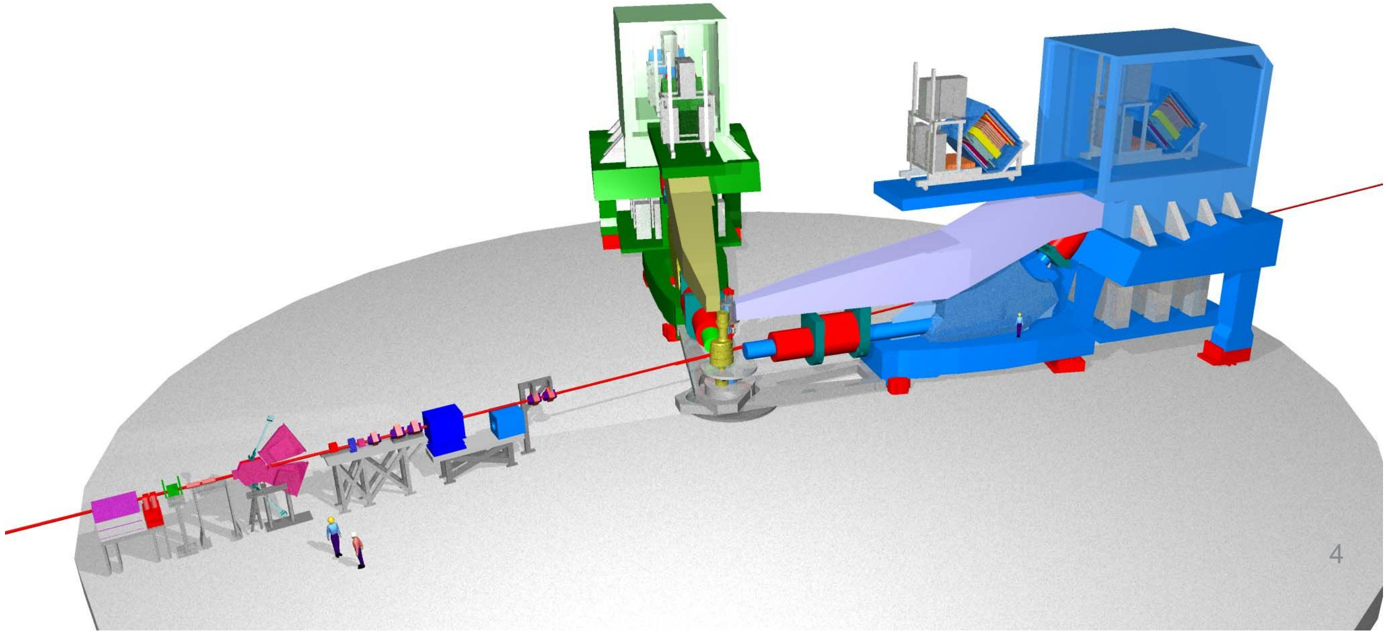


October 2018: Elastic scattering with 1.171 GeV beam

Inclusive Scattering on the A=3 Mirror Nuclei

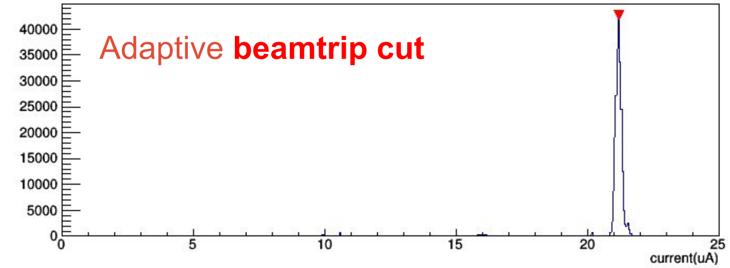
- High statistics
- Calculable* few body system
- Small relative nuclear correction
- Systematic uncertainties canceled in the ratio

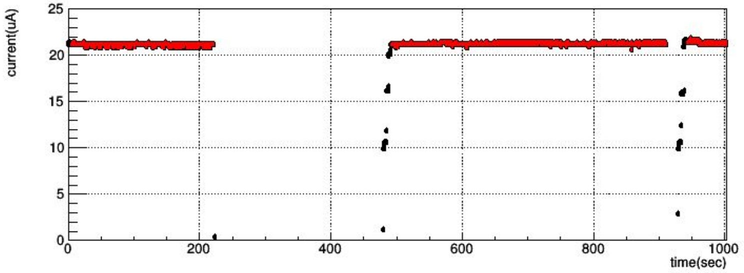


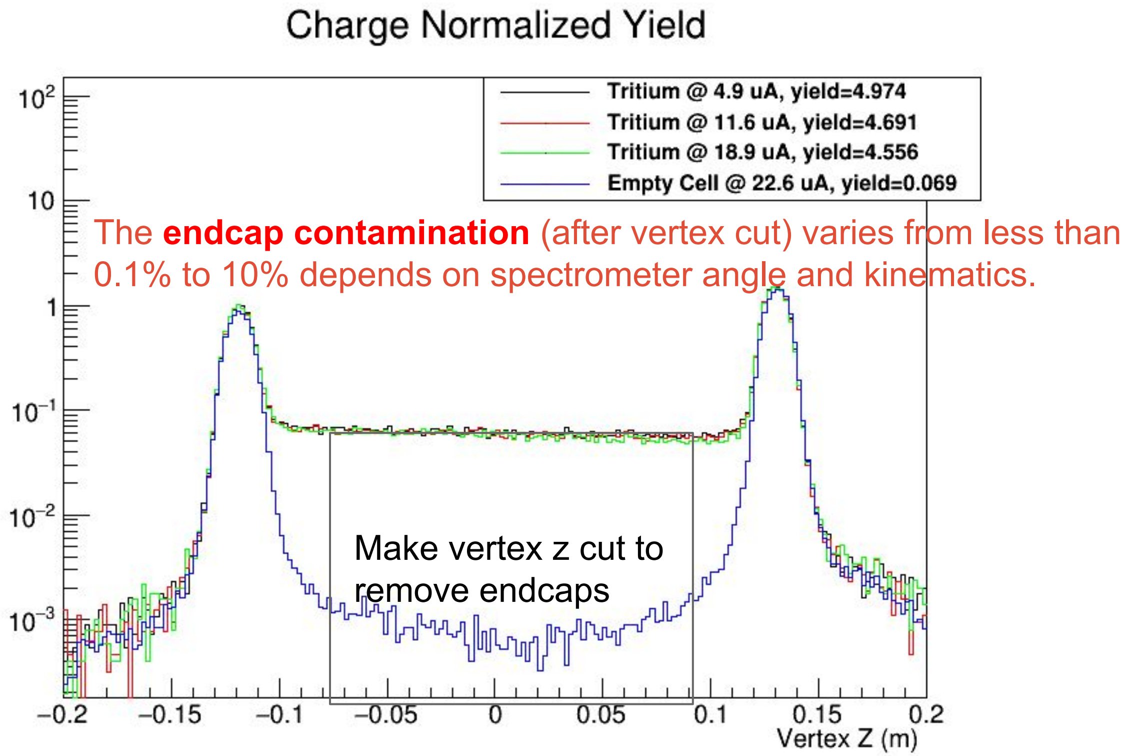


The Gas Target System: special handling

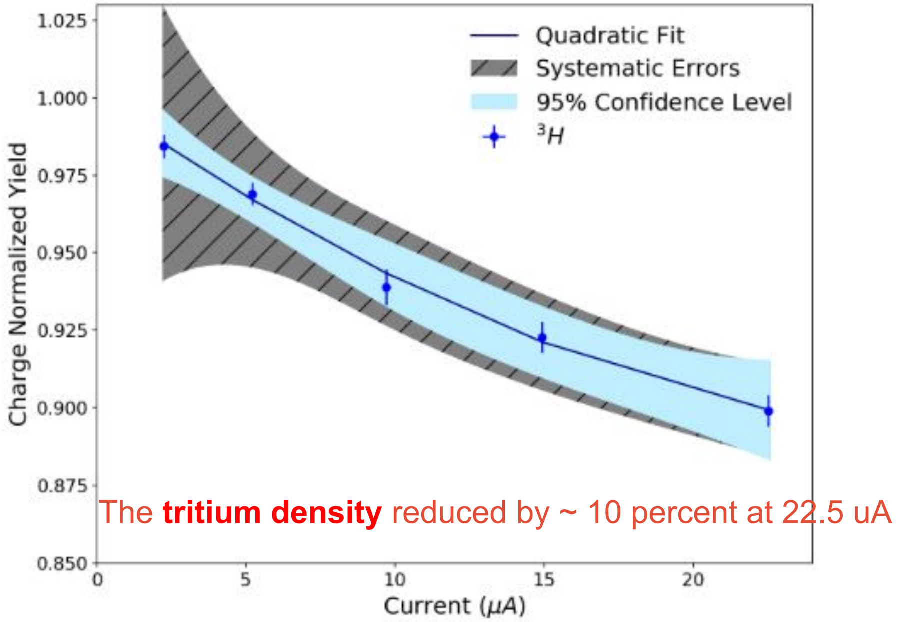
- Maximum current = 22.5 uA on gas cells to minimize the risk of gas leak.
- Endcap (75mg/cm2 Aluminum) being mis-reconstructed into thin gas body (77mg/cm2 Tritium)
- "Boiling": gas density change along beam path
- Tritium decay correction
- Hydrogen contamination.







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

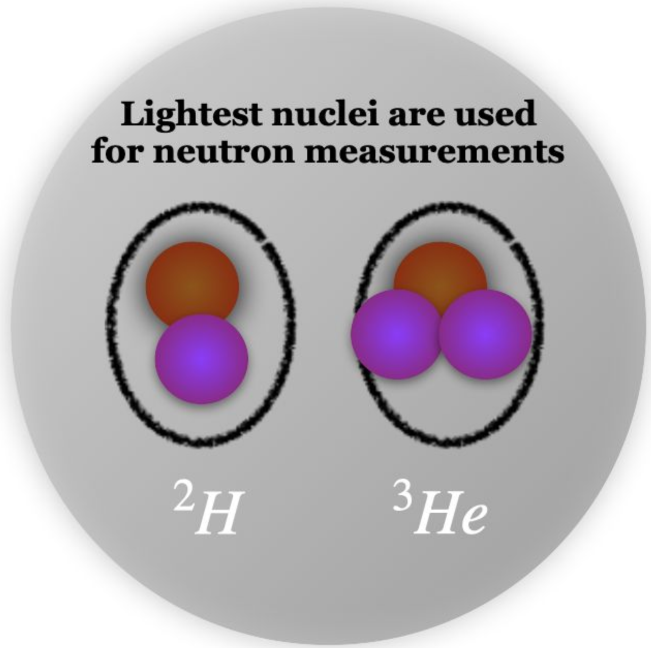


x=1: GMn Analysis

by Nathaly Santiesteban (UNH)

Accessing to neutrons

$$\left(\frac{d\sigma}{d\Omega}\right)_n = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{1+\tau}\left((G_E^n(Q^2))^2 + \frac{\tau}{\varepsilon}(G_M^n(Q^2))^2\right)$$



Neutron measurements include:

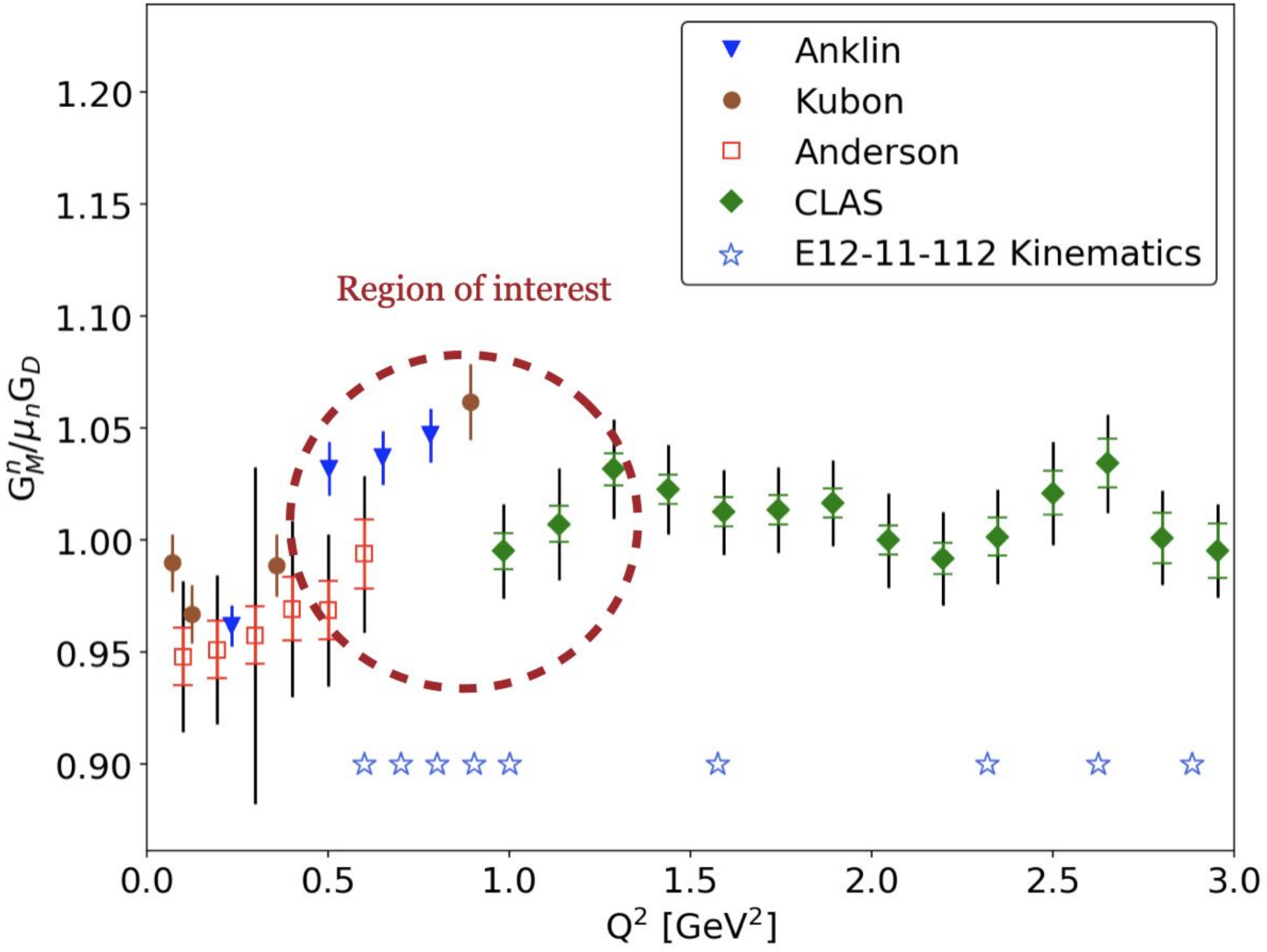
$^3\vec{He}(\vec{e}, e')$ QE
polarization experiments

$\frac{^2H(e, e'p)}{^2H(e, e'n)}$ QE ratio

$^2\vec{H}(\vec{e}, e')$ QE
Vector-polarized deuterium

$^2H(e, e') - p(e, e')$
$^2H(e, e'p)$, $^2H(e, e'n)$

E12-11-112 Goal



Measure the neutron magnetic form factor using the $^3H/^3He$ cross-section ratios

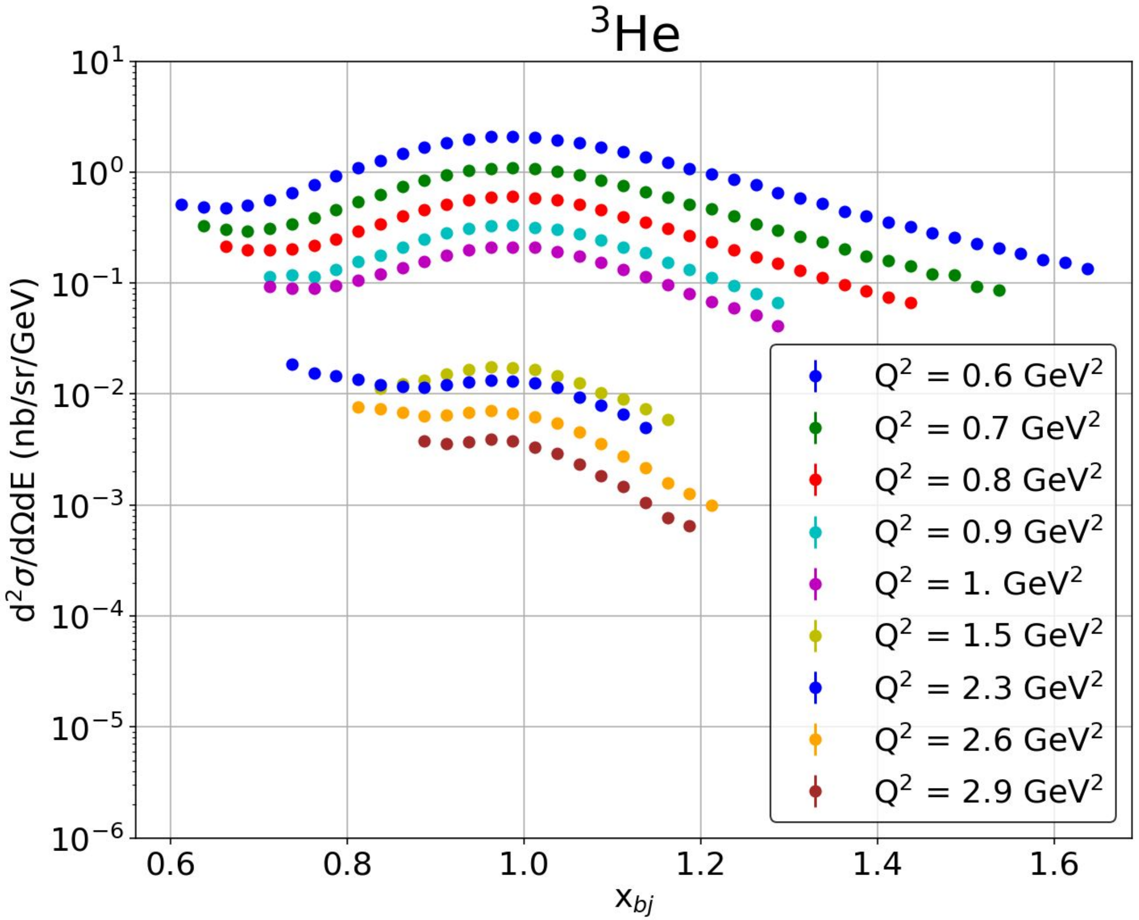
$$\sigma_{3H} \sim 2\sigma_n + \sigma_p \qquad \sigma_{3He} \sim \sigma_n + 2\sigma_p$$

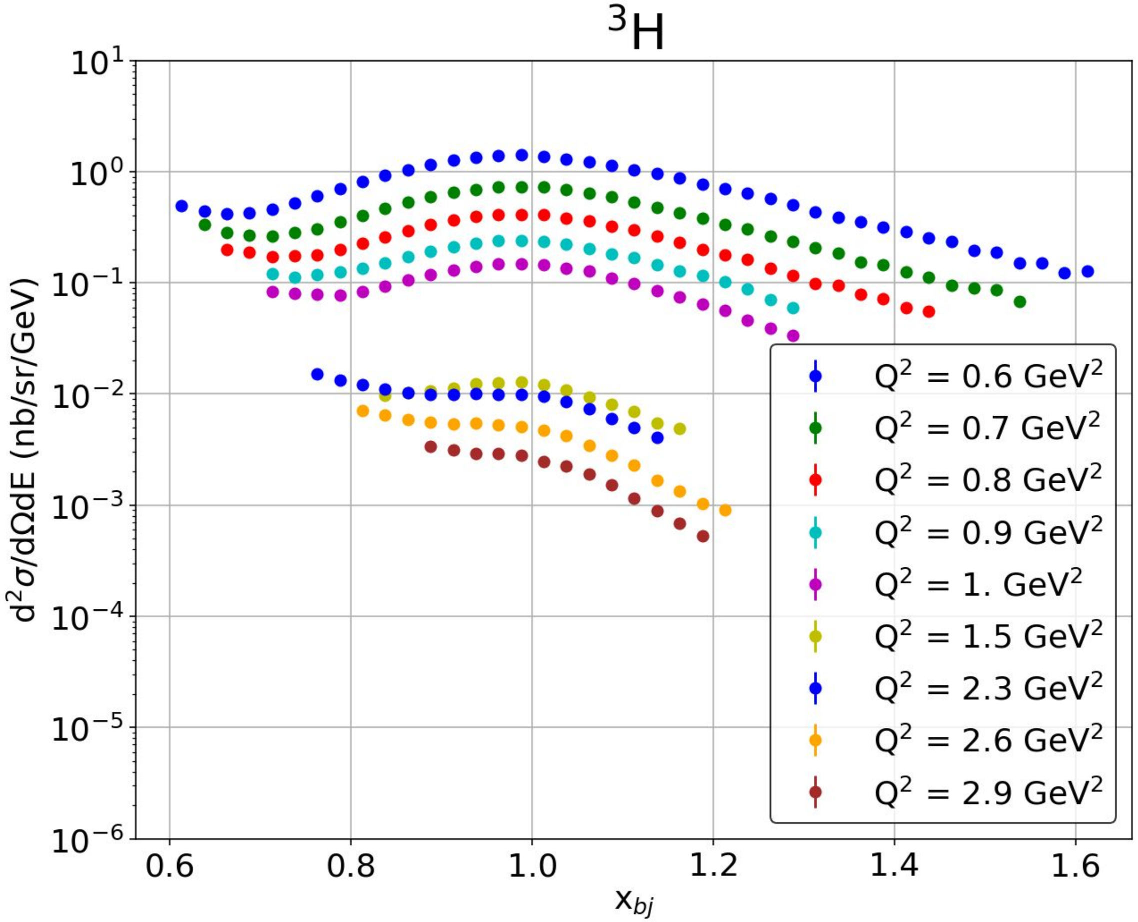
$$R = \frac{\sigma_{3H}}{\sigma_{3He}} \sim \frac{2\sigma_n + \sigma_p}{\sigma_n + 2\sigma_p}$$

$$(G_M^n)^2 \sim \frac{\epsilon}{\tau}[\frac{1-2R}{R-2}\sigma_p \frac{1+\tau}{\sigma_{mott}} - (G_E^n)^2]$$

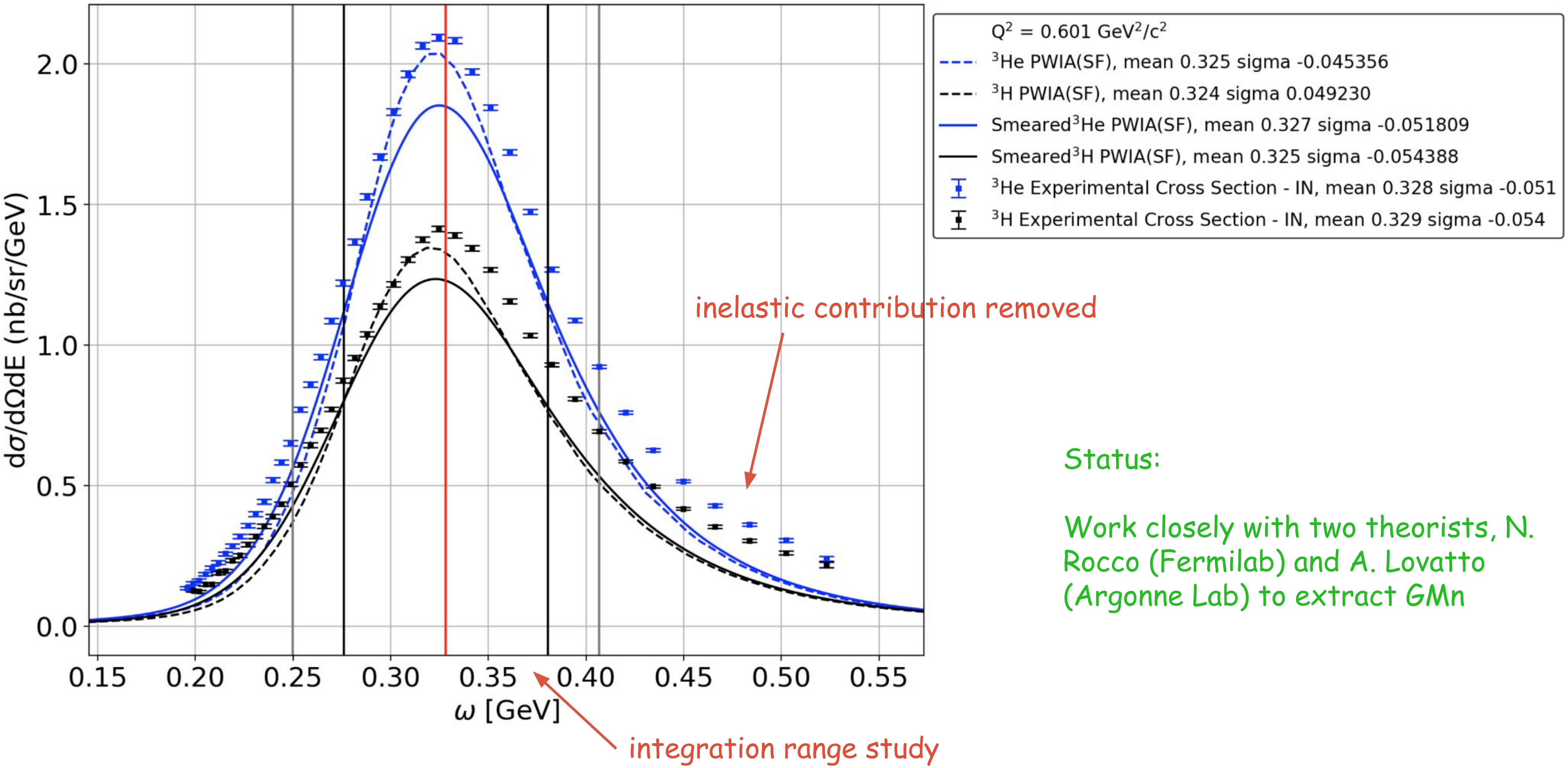
- Clean QE channel
- high stat.
- no need to measure neutron directly
- nuclear corrections
- model of eN cross section

Extracting QE cross sections





Extracting QE cross sections



Status:

Work closely with two theorists, N. Rocco (Fermilab) and A. Lovatto (Argonne Lab) to extract GMn

x>1: Isospin-dependence of SRC

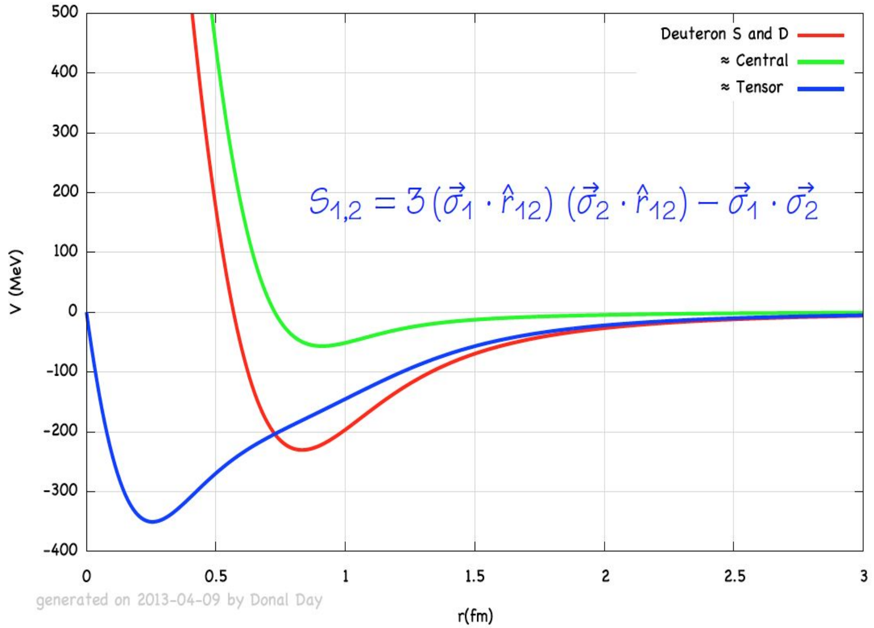
by Shujie Li (LBL)

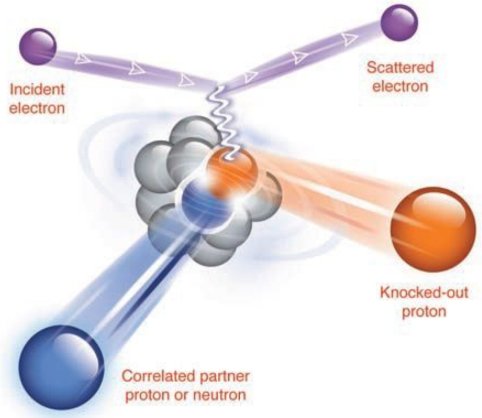
Nucleon-Nucleon Short Range Correlation (SRC)

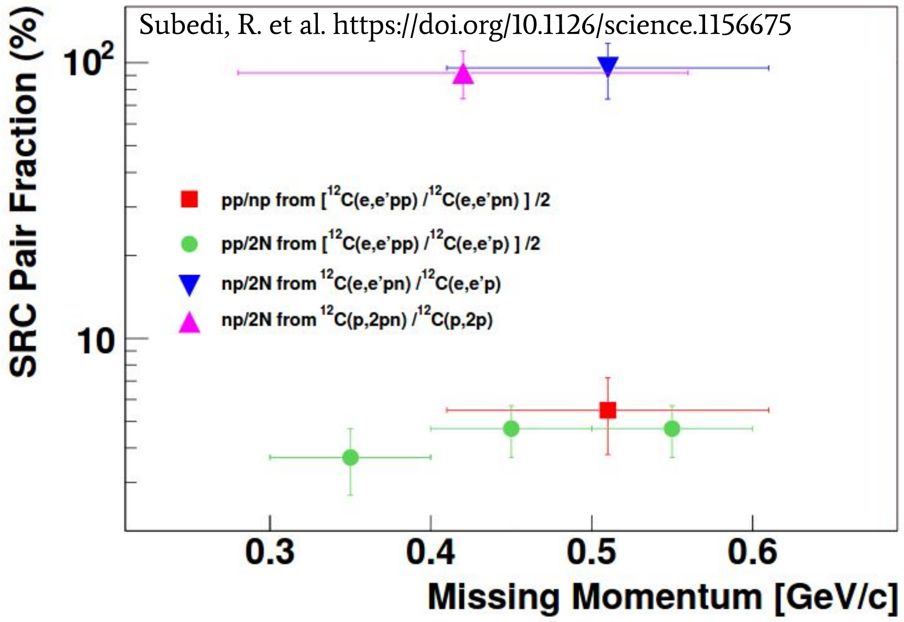
Free nucleon-nucleon potential = **Repulsive core** + **attractive tensor force**

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

T = 0, S = 1: Deuteron-like np pair.





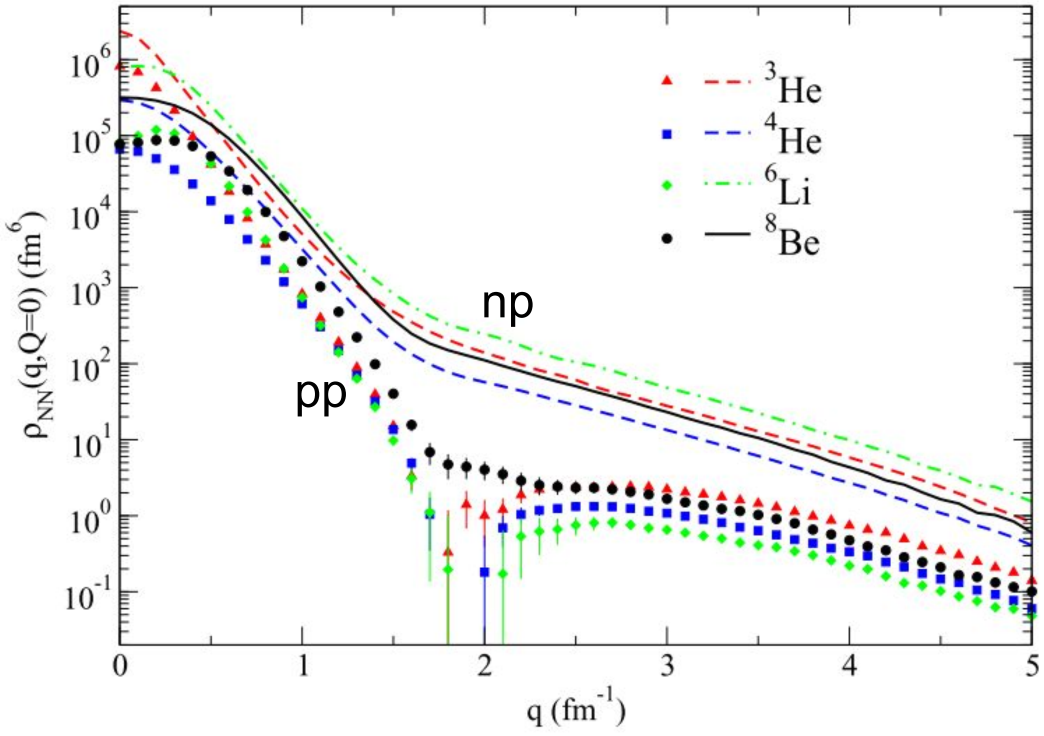


large back-to-back momentum
center-of-mass motion → 0

Strong evidence of np dominance from the Hall A triple-coincidence experiment.

Isospin-dependence of 2N SRC

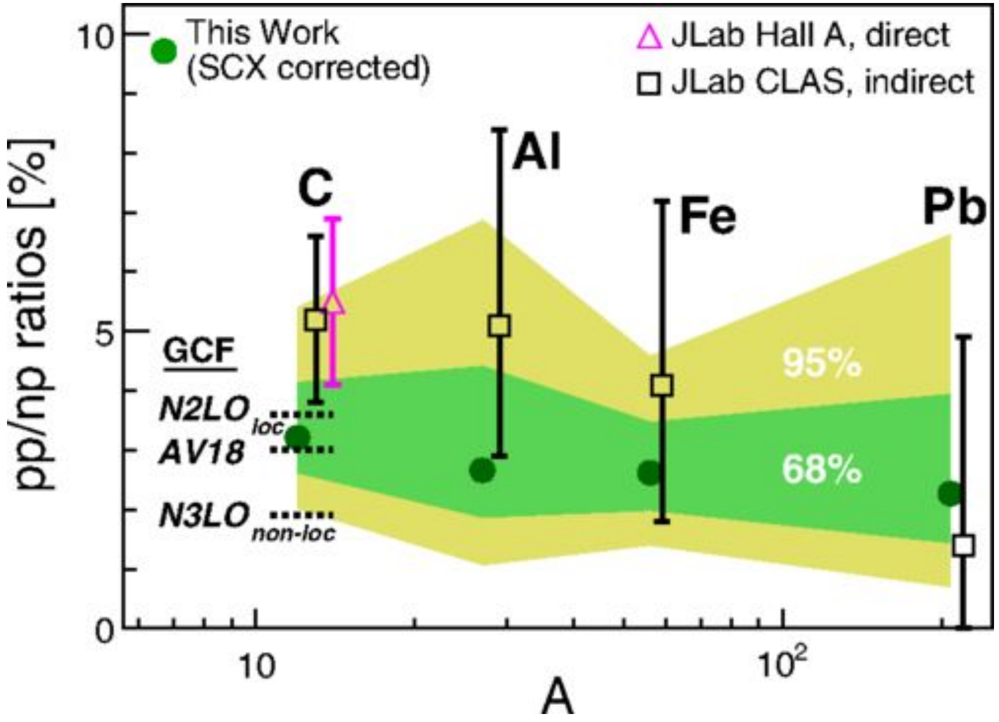
np-dominance from VMC calculations



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

np-dominance in exclusive measurements

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



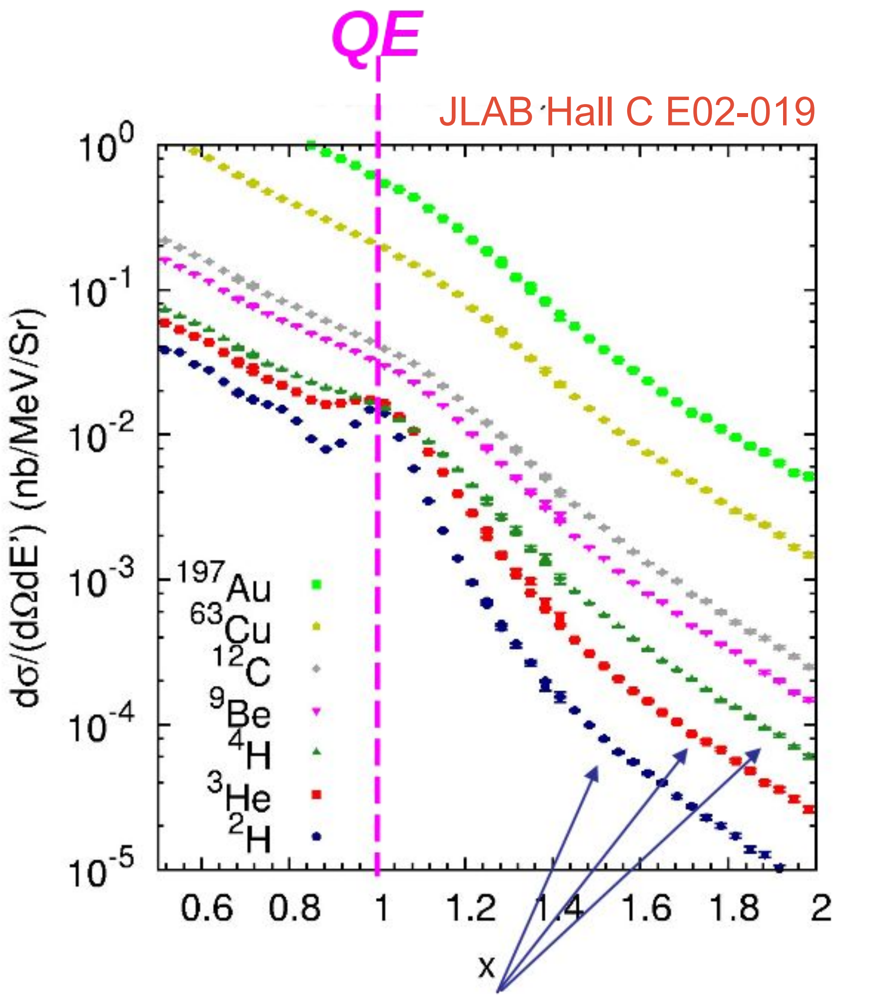
np-dominance in inclusive Tritium SRC:

- **A=3 nuclei have largest isospin-asymmetry**
- **high statistics**
- **take ratios between mirror nuclei to cancel competing processes.**
- **compare to *ab initio* calculations**

Probing 2N SRC at x>1

Inclusive electron scattering:

- high statistics
- background suppressed at high Q2

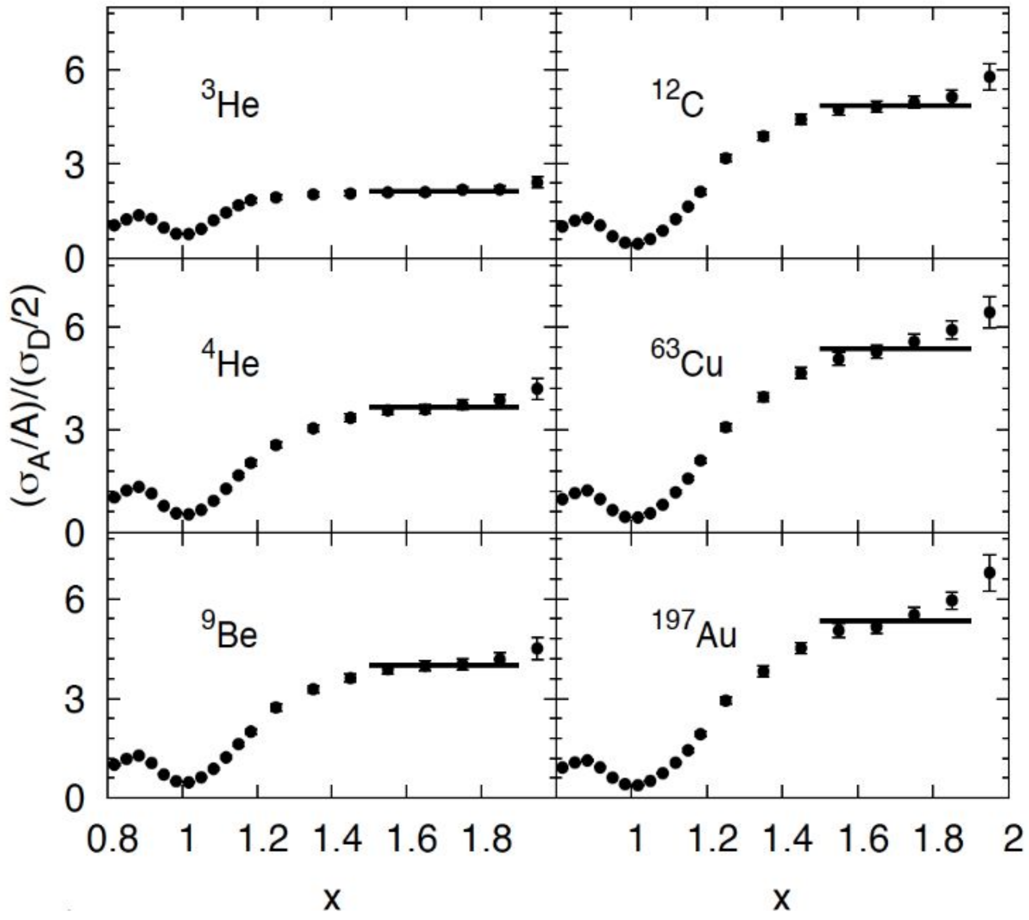


High momentum tails should yield constant ratio if SRC-dominated

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

Plateaus in Cross section ratio b/w 1.3< xbj <2:

N. Fomin et al., Phys. Rev. Lett. **108** (2012) 092502.

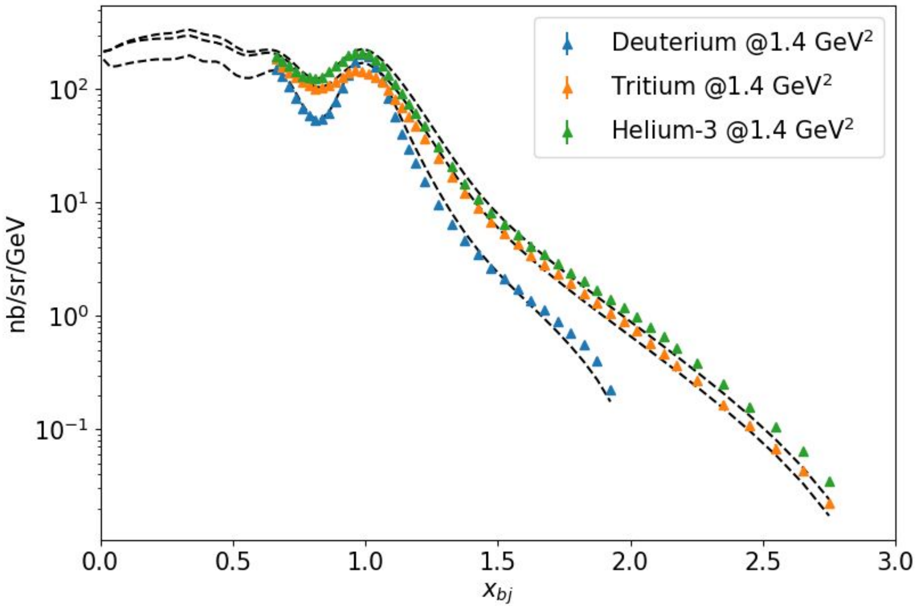


x>1 cross section ratio (from yield ratio):

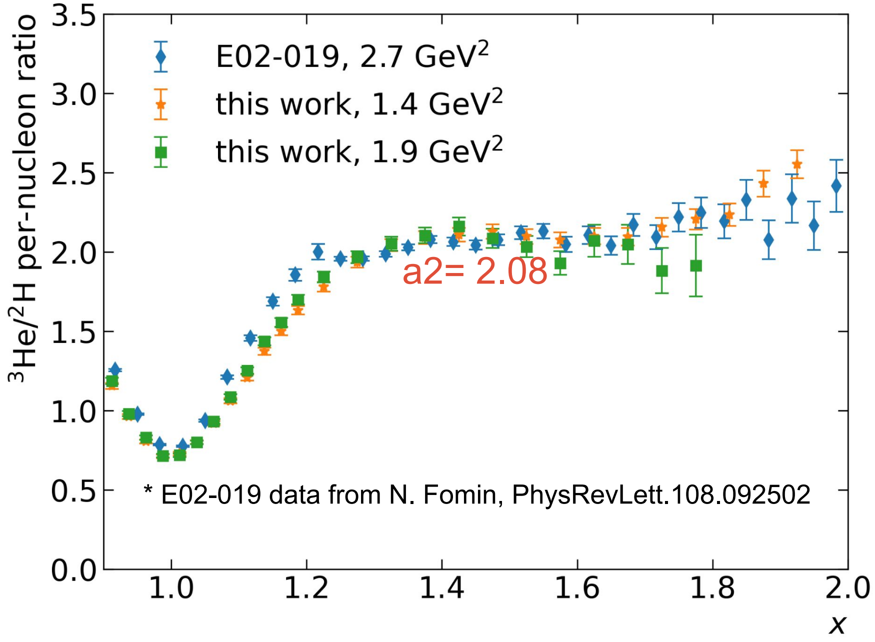
Kinematic Settings:

Beam energy:	4.3 GeV
HRS Momentum:	3.5 to 3.9 GeV
Angle:	17 to 23 degree
Q2:	1.4 to 1.9 GeV2
Targets:	H, 2H, 3H, 3He, C12, Ti48

Raw cross sections

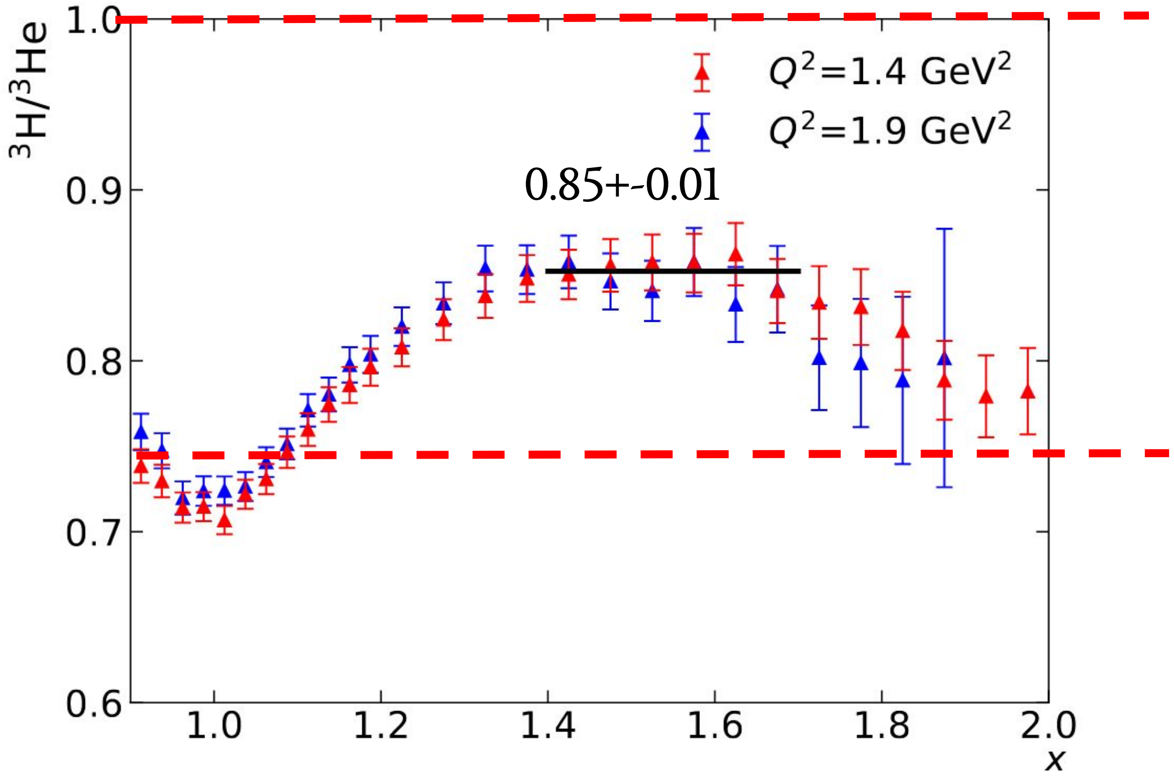


Calibration Check: 3He/2H ratio



x>1 cross section ratio (from yield ratio):

Manuscript under review



Predicted range of 3H/3He ratio

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

Offshell elastic xsection (de Forest "cc1")

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

number of pp to np pairs ratio

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

$$\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{1 + \sigma_{p/n} + 2R_{pp/np}}{1 + \sigma_{p/n}(1 + 2R_{pp/np})}$$

if np dominance:

$$R_{pp/np} = 0 \rightarrow \frac{\sigma_{^3H}}{\sigma_{^3He}} = 1$$

if no isospin preference: 1 pp and n np pairs in He3 from pair counting

$$R_{pp/np} = 0.5, \sigma_{p/n} = 2.55 \rightarrow \frac{\sigma_{^3H}}{\sigma_{^3He}} = 0.75$$

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

$$\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{1+\sigma_{p/n}+2R_{pp/np}}{1+\sigma_{p/n}(1+2R_{pp/np})} = 0.85\text{+-}0.01$$

correction due to center-of-mass motion difference:
2MeV b/w 3H and 3He, 12 MeV b/w pp and np
(Ciofi degli Atti, Claudio and Morita, Hiko, 2017)

Ratio of np/pp SRC pairs in A=3 nuclei:
$R_{np/pp}$ =4.2+-0.4

Remove contribution from pair counting:
2 np pairs v.s. 1 pp(nn) pair

np/pp "**enhancement factor**" = 2.1+-0.2

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

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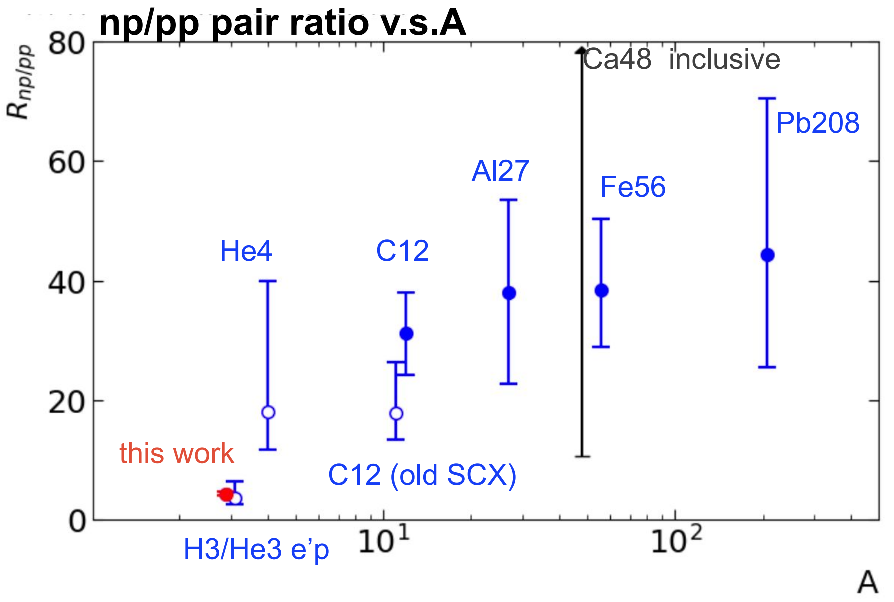

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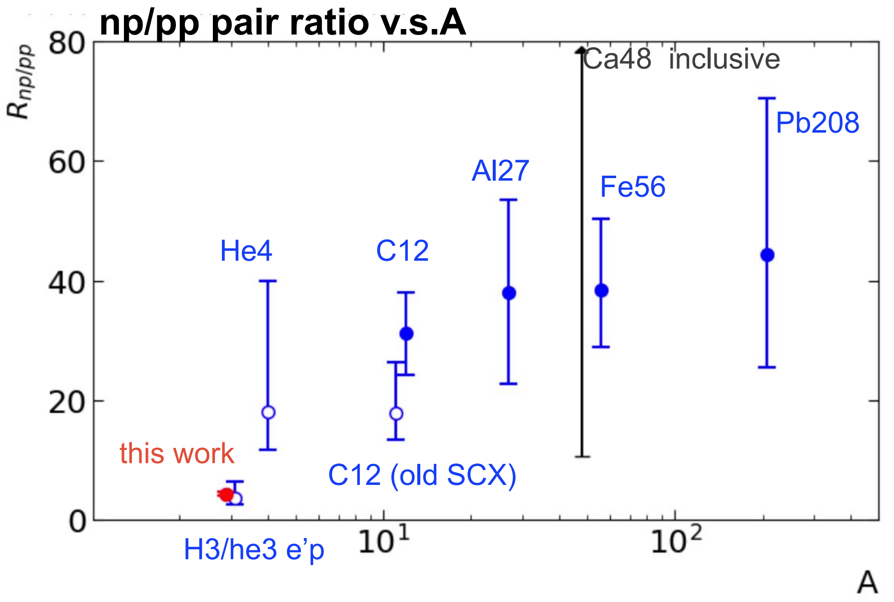
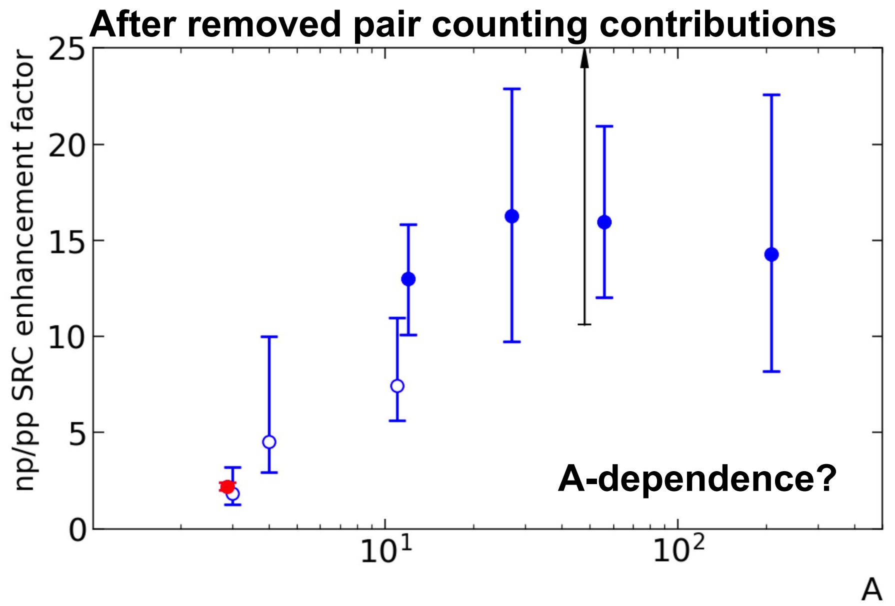




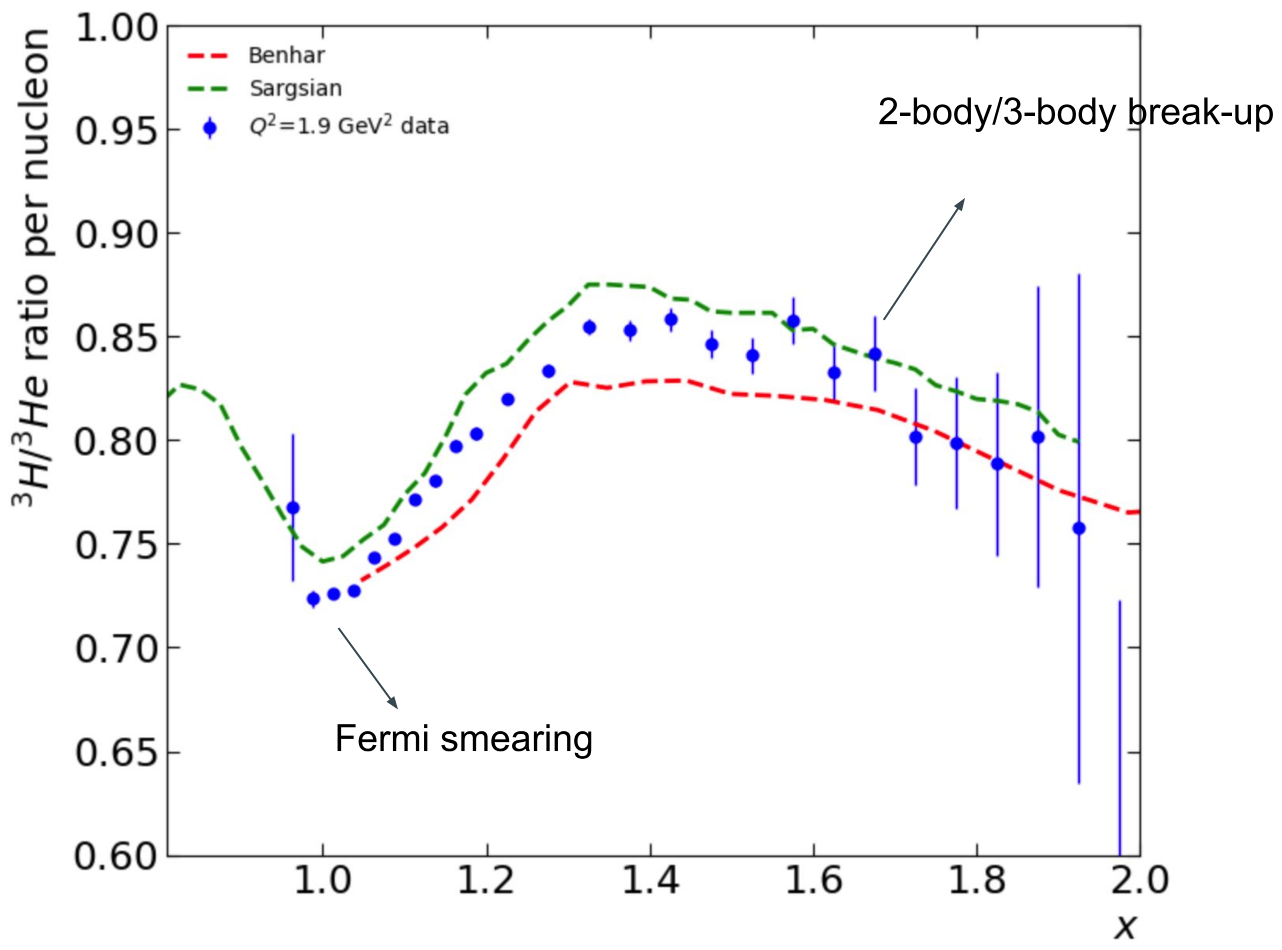
References:

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

exclusive:
H3/He3 e'p; Cruz-Torres, R.et al. Phys. Lett. B797,134890 (2019)
He4: Korover, I.et al. Phys. Rev. Lett.113,022501 (2014)
C12(old SCX): Subedi, R.et al. Science, 320, 1476–1478 (2008).
e'pN in Solid blue: Duer, M.et al.Phys. Rev. Lett.122, 172502 (2019)

Data to Calculation Comparison:

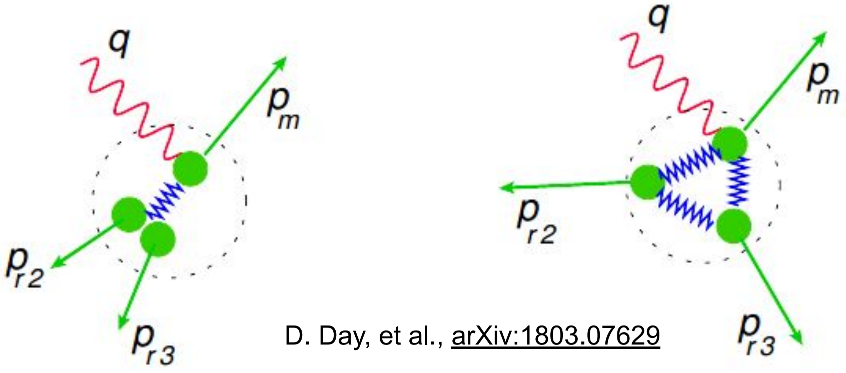
work in-progress with 3 theory groups



Things to explore:

- ~5% overall difference b/w data and calculated ratio
- Q2 dependence in calculation
- build xsection from GFMC NN momentum

Towards 3N SRC

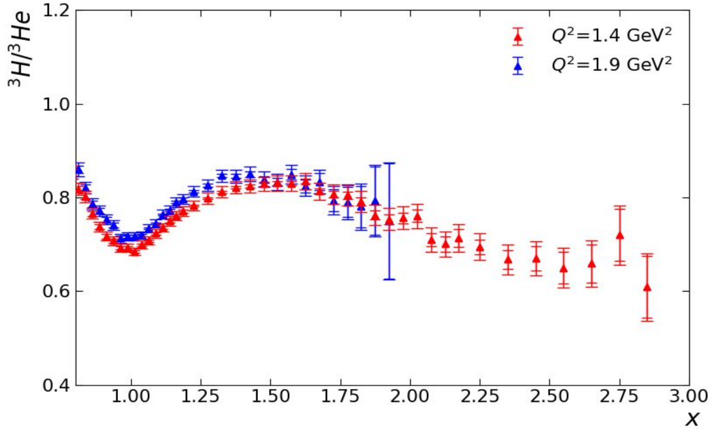


D. Day, et al., arXiv:1803.07629

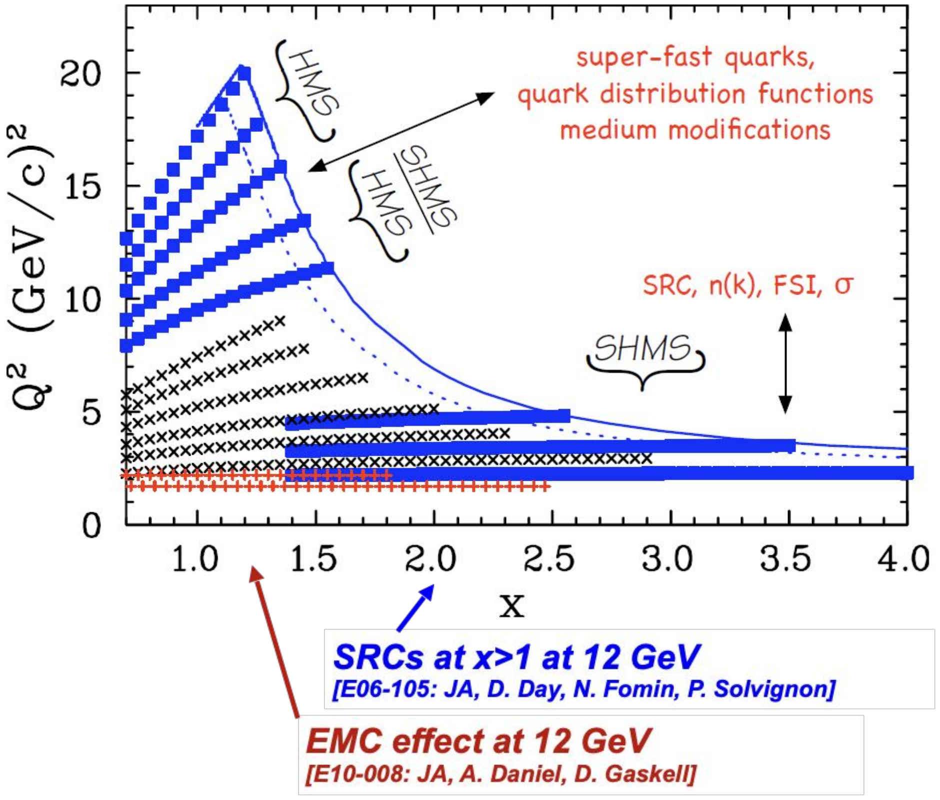
(a) Dominant channel: (b)

$$\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{2\sigma_{nn}+\sigma_{pp}}{\sigma_{nn}+2\sigma_{pp}} \xrightarrow{\sigma_p\sim 3\sigma_n} 0.7$$

Hall A Tritium: downward going trend but Q2 too low



Hall C x>1: 3N SRC with higher Q2 and various nuclei (2H, 3He, 4He, 9Be, C, …, Ca48, Cu, Au), and SRC-EMC connection



Hall C Tritium SRC LOI: 3N SRC with tritium and helium-3

x=3: ^{3}H Charge Form Factor

By Leiqaa Kurbany (UNH, Advisor: Elena Long)

Motivation

Elastic Scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp.} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{F_{ch}^2+\tau F_M^2}{1+\tau}+2\tau F_M^2 tan^2(\frac{\theta}{2})\right].$$

$$\langle r^2\rangle \equiv -6\hbar^2\frac{dF(q^2)}{dq^2}\Bigg|_{q^2=0}$$

$$\frac{\sigma\ {}^3H}{\sigma\ {}^3He} \rightarrow \frac{F_{ch}\ {}^3H}{F_{ch}\ {}^3He} \rightarrow \Delta R_{RMS}$$

Ref.	^{3}H	^{3}He
SACLAY	1.76 ± 0.09	1.96 ± 0.03
Bates	1.68 ± 0.03	1.97 ± 0.03
GFMC	1.77 ± 0.01	1.97 ± 0.01
χEFT	1.756 ± 0.006	1.962 ± 0.004

SACLAY → $\Delta R_{RMS} = 0.20 \pm 0.1$

Bates → $\Delta R_{RMS} = 0.29 \pm 0.04$

- First measurement at SLAC (Collard 1965)
- Large systematic uncertainty (especially from target density)
- Discrepancy between experiments

Motivation

Approved but not scheduled

Jefferson Lab Experiment E1214009

Ratio of the electric form factor in the mirror nuclei 3He and 3H

Spokespersons:

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Elastic Scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp.} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{F_{ch}^2 + \tau F_M^2}{1+\tau} + 2\tau F_M^2 tan^2(\frac{\theta}{2})\right].$$

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→ $\Delta R_{RMS} = 0.20 \pm 0.1$ (SACLAY)

→ $\Delta R_{RMS} = 0.29 \pm 0.04$ (Bates)

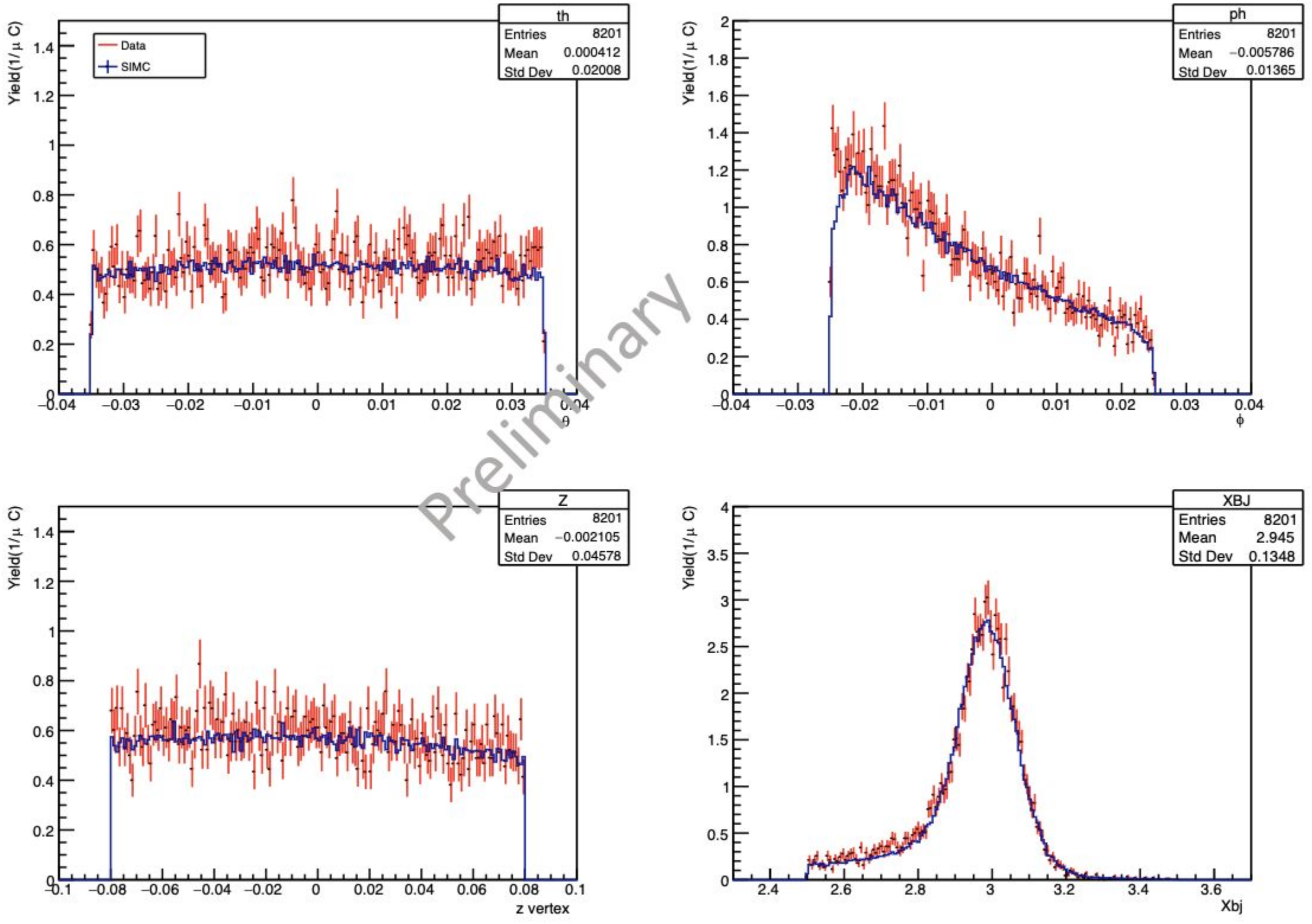
Data taken during beam study

- Beam current: 5μA
- Beam energy: 1.171 GeV
- Momentum: 1.128 GeV
- Angle: 17 degree
- Q^2 = 0.11 GeV^2

Cross Section Extraction with SIMC

Agreement between the data and SIMC for ^3H target

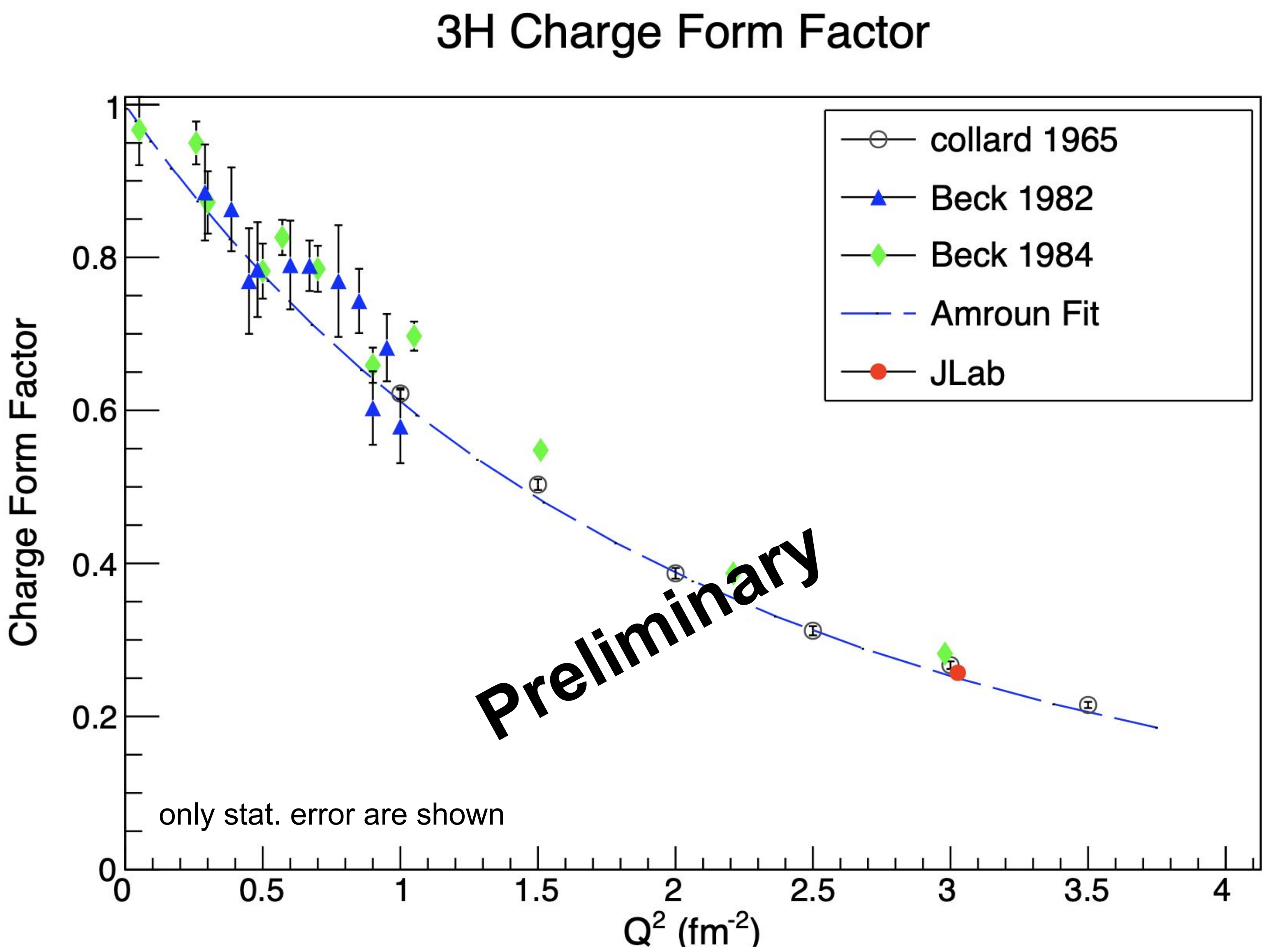
- Shape agreement is good
- The data Yield is 96 % of the SIMC Yield for 2.5< xbj< 3.5



Uncertainties

Source	Relative per Target (%)	Ratio
Beam Energy	0.3%	0.05%
Scattering Angle	0.9%	0.1%
Trigger + PID	0.10%	0.05%
Acceptance	2%	0.2%
Endcaps contamination	0.1%	0.05%
Radiative correction	1.5%	0.3%
Tracking Efficiency	0.20%	0.05%
Charge	3%	0.2%
Boiling	0.5%	0.1%
TGT THICKNESS*	0.4% for 3H 1% for 3He	1.06%
Hydrogen contamination	0.2%	0.2%
3He contamination	0.1% conservative	0.1%
Total	**4.20%**	**1.17%**

Projected Results and Outlook



Analysis status:

- Obtained one data point at 0.11 GeV2 with small uncertainties that can be used as a reference point to normalize old data
- F_{Ch}(3H) will be extracted from absolute cross section and the ratio (with a model of 3He).
- Will perform a new global fit to extract charge radius

Summary

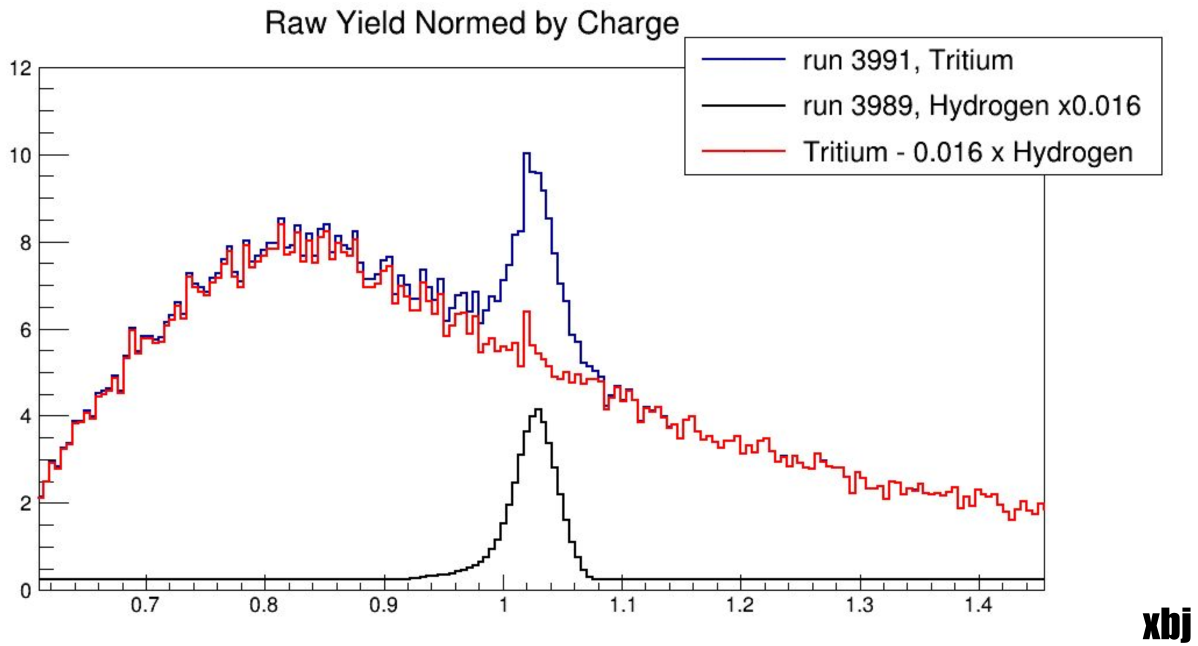
- E12-11-112 experiment took inclusive electron scattering data with tritium and helium-3 to study three physics topics
  - x=1: GMn
  - x>1: SRC
  - x=3: Fch
- Data analysis involves three Ph.D. students (two graduated, one is writing thesis).
- 3H and 3He cross section (and ratios) have been extracted from all three xbj ranges. Physics extractions are on the way

Thank you!

Backups

The Gas Target System: surprise (>﹏<)

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

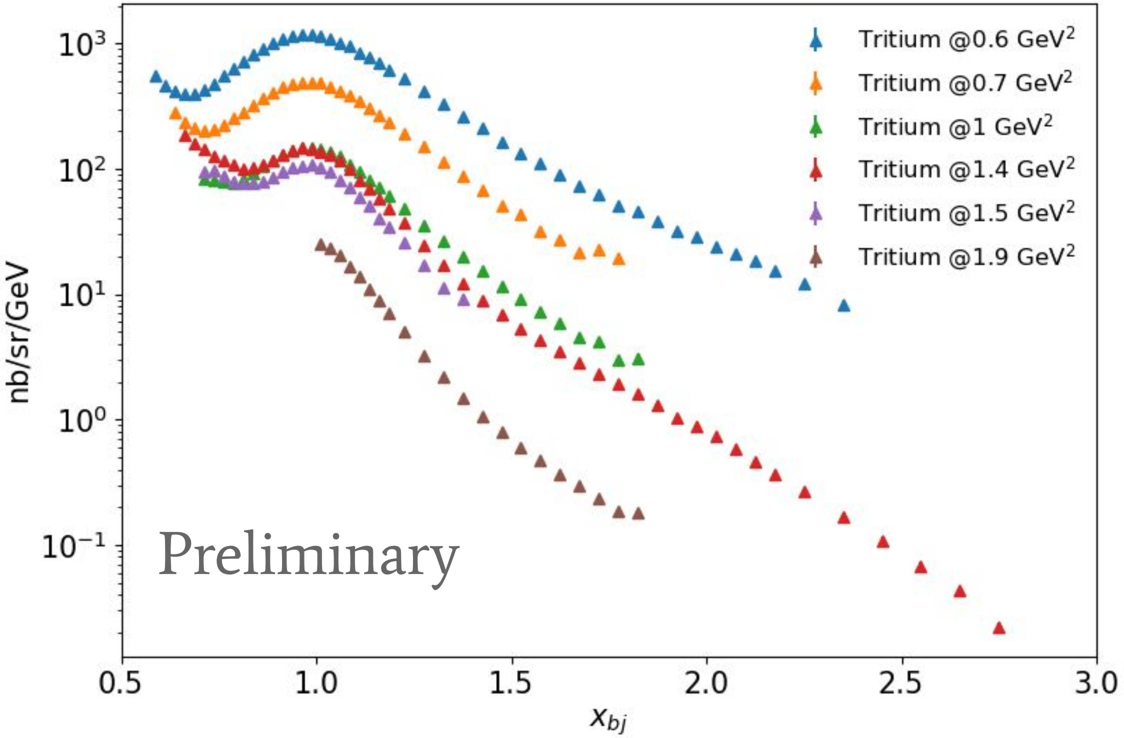


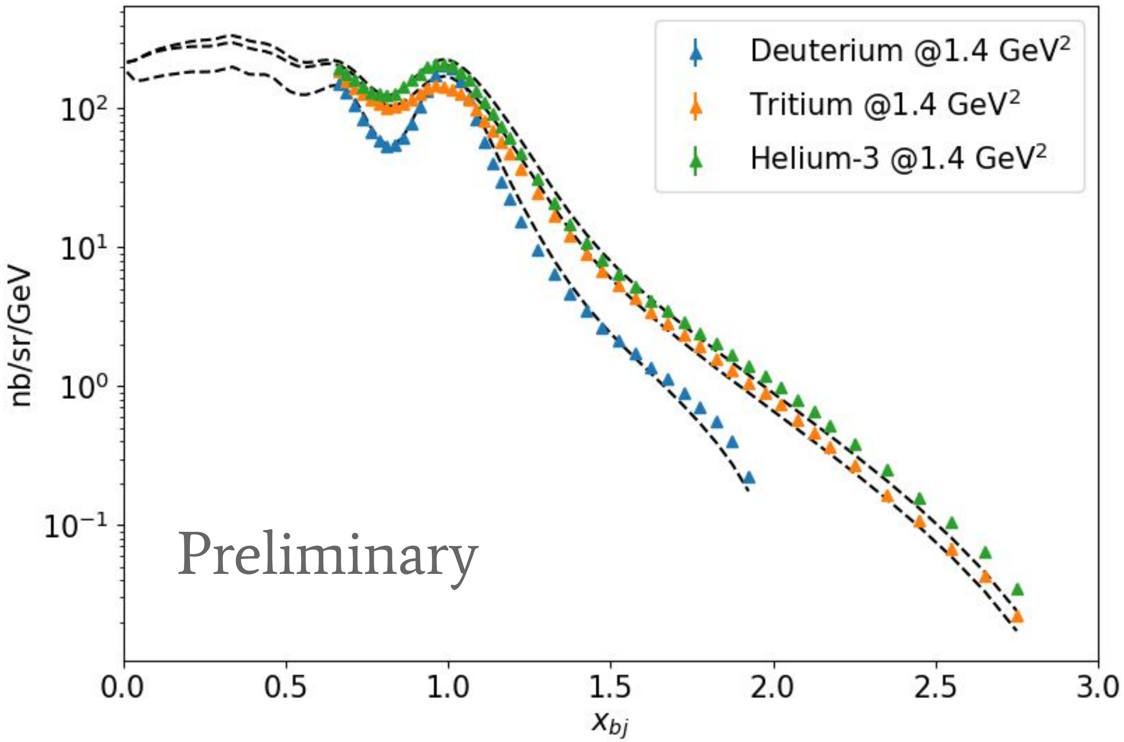
gas

$$H_2O + T_2 \rightarrow HTO + HT$$

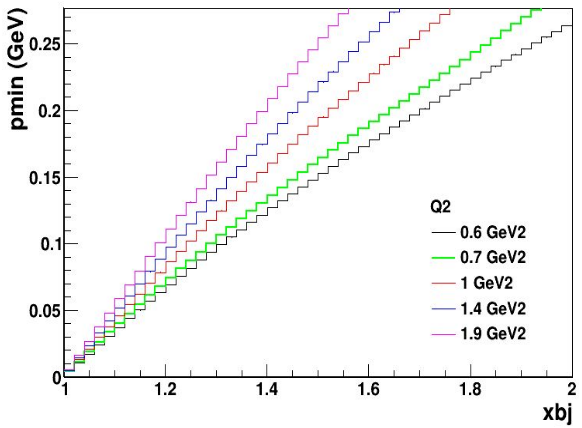
Liquid, stick to the wall at low temperature

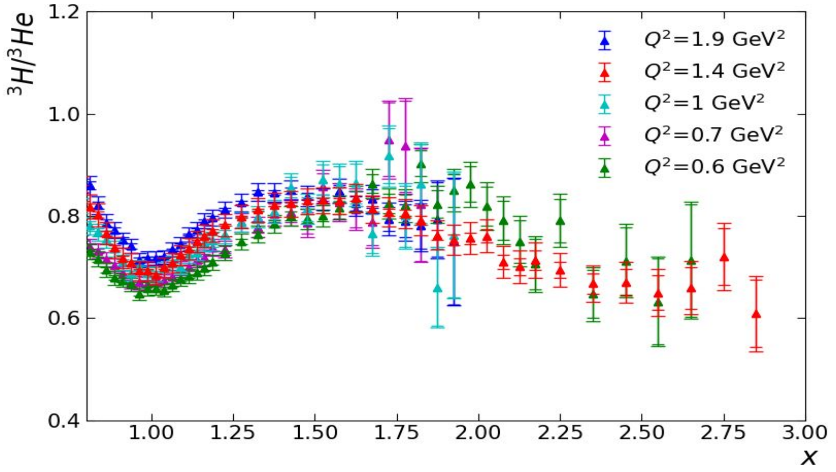
Absolute Cross Sections and Momentum Distribution

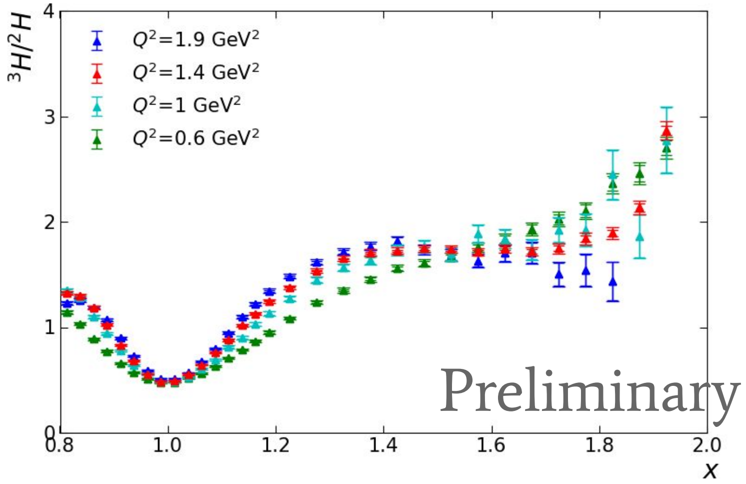


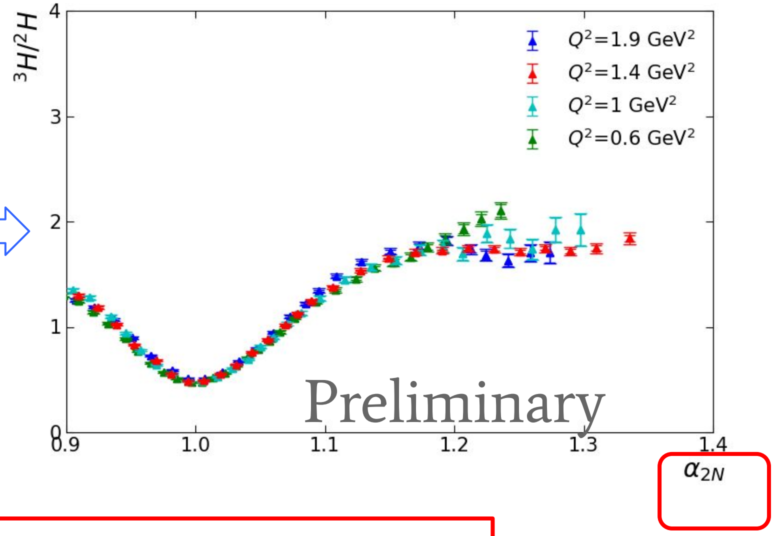


Mean-field to SRC transition









Light cone variable:

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

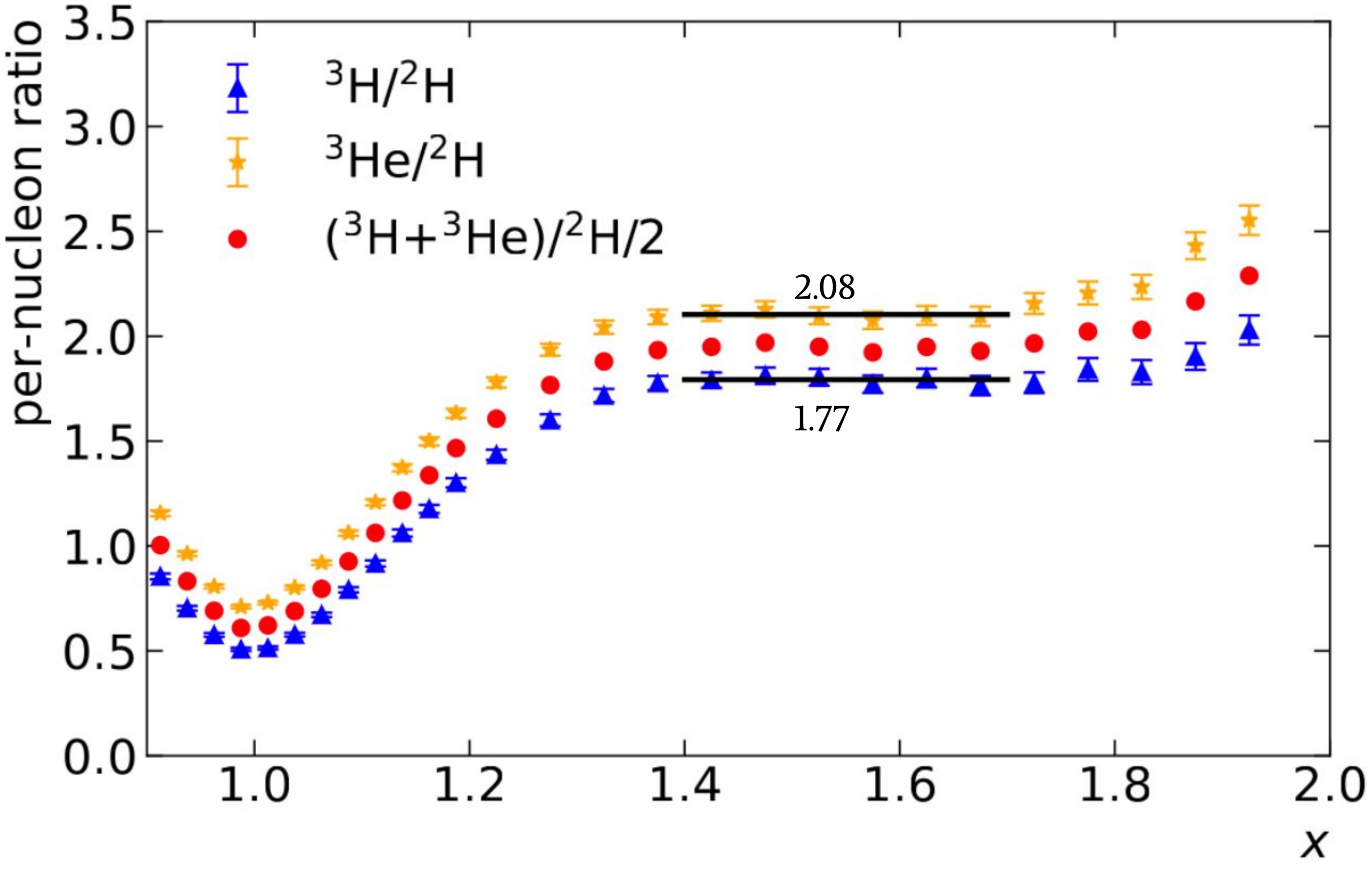


FIG. 2. A/^{2}H per-nucleon cross section ratios for A = ^{3}H, ^{3}He, and (^{3}H+^{3}He)/2 from the $Q^2 = 1.4$ GeV^2 data. The solid lines indicate the combined a_2 value from the $Q^2 = 1.4$ and 1.9 GeV^2 data sets. Error bars for the ^{3}H and ^{3}He ratios represent the combined statistical and uncorrelated systematic uncertainty.