How we learned to stop worrying and love tritium

Nathaly Santiesteban

On behalf of the E12-11-112 collaboration

Hall A/C Summer Collaboration Meeting
July 8, 2021

University of New Hampshire

Jefferson Lab
Thomas Jefferson National Accelerator Facility

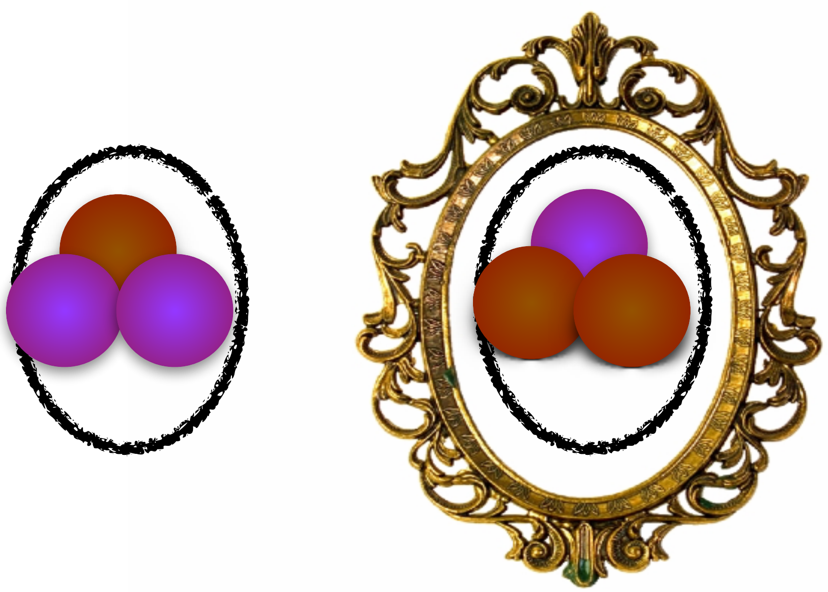
E12-11-112 workforce

Shujie Li

Leiqaa Kurbani

Nathaly Santiesteban

$^3H/^3He$ motivation

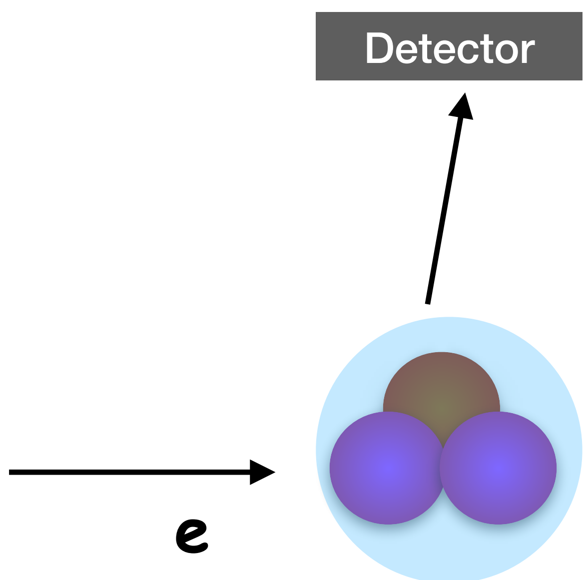


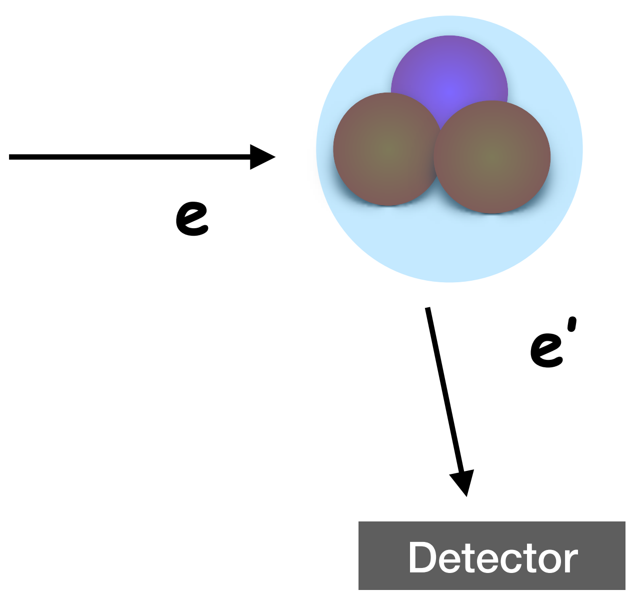
^3He and ^3H mirror nuclei:

^3He (protons) ⟷ ^3H(neutrons)

- ✦ Few-body nuclei
- ✦ Benchmark data
- ✦ cancellation of experimental systematics, nuclear effects

$^3H/^3He$ motivation





^3He and ^3H mirror nuclei:

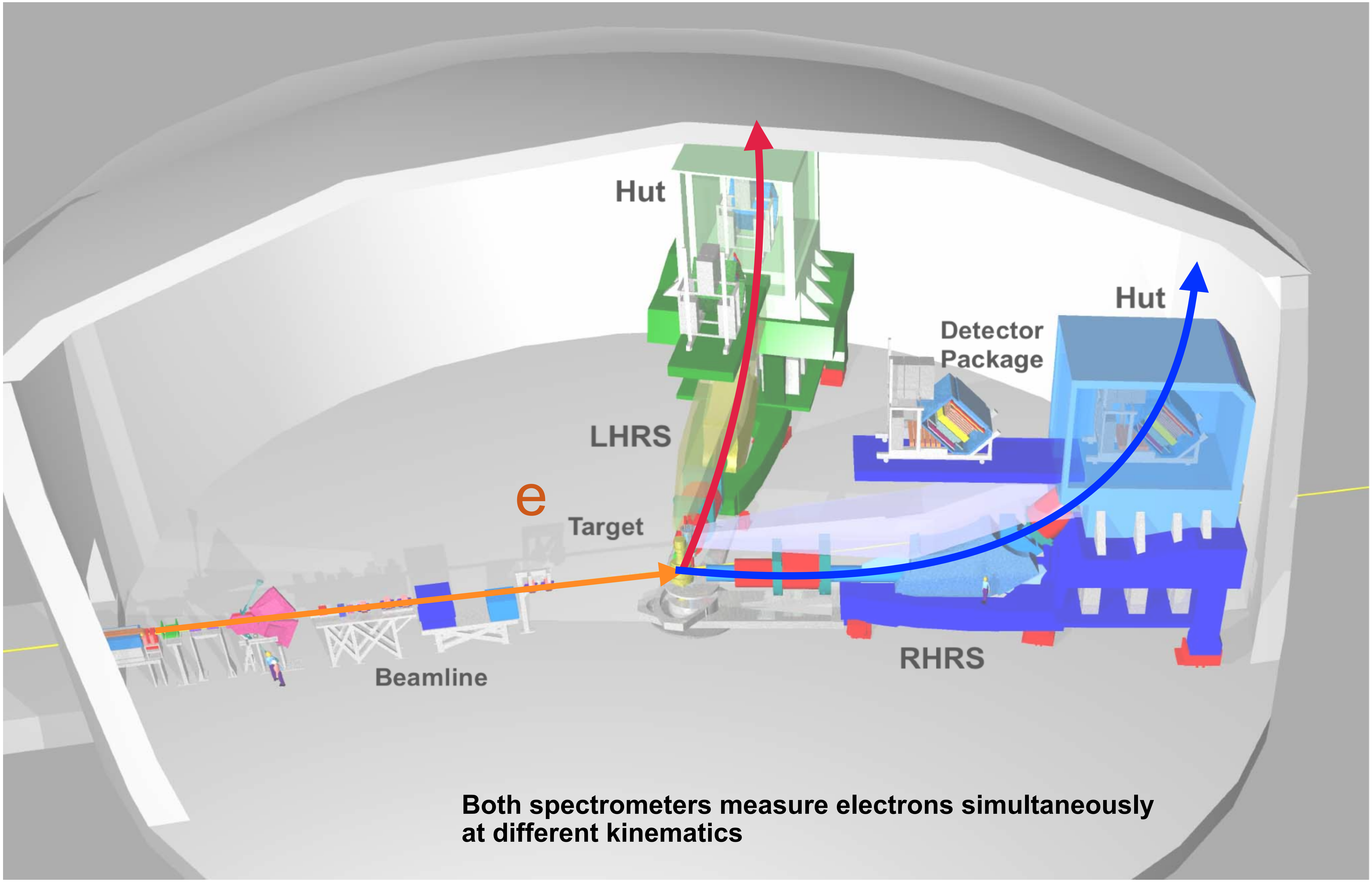
^3He (protons) $\leftrightarrow$ ^3H(neutrons)

- ✦ Few-body nuclei
- ✦ Benchmark data
- ✦ cancellation of experimental systematics, nuclear effects

Inclusive Measurements

- ✦ Sum of Short-range correlations:
  3He/3H (2pn + pp)/(2pn + nn) (x>1)
  Ratio of pp to pn pairs assuming isospin symmetry
- ✦ Access G_M^n: Effective neutron target (x=1)
- ✦ Charge radius of 3H vs 3He (x=3)

Hall A configuration



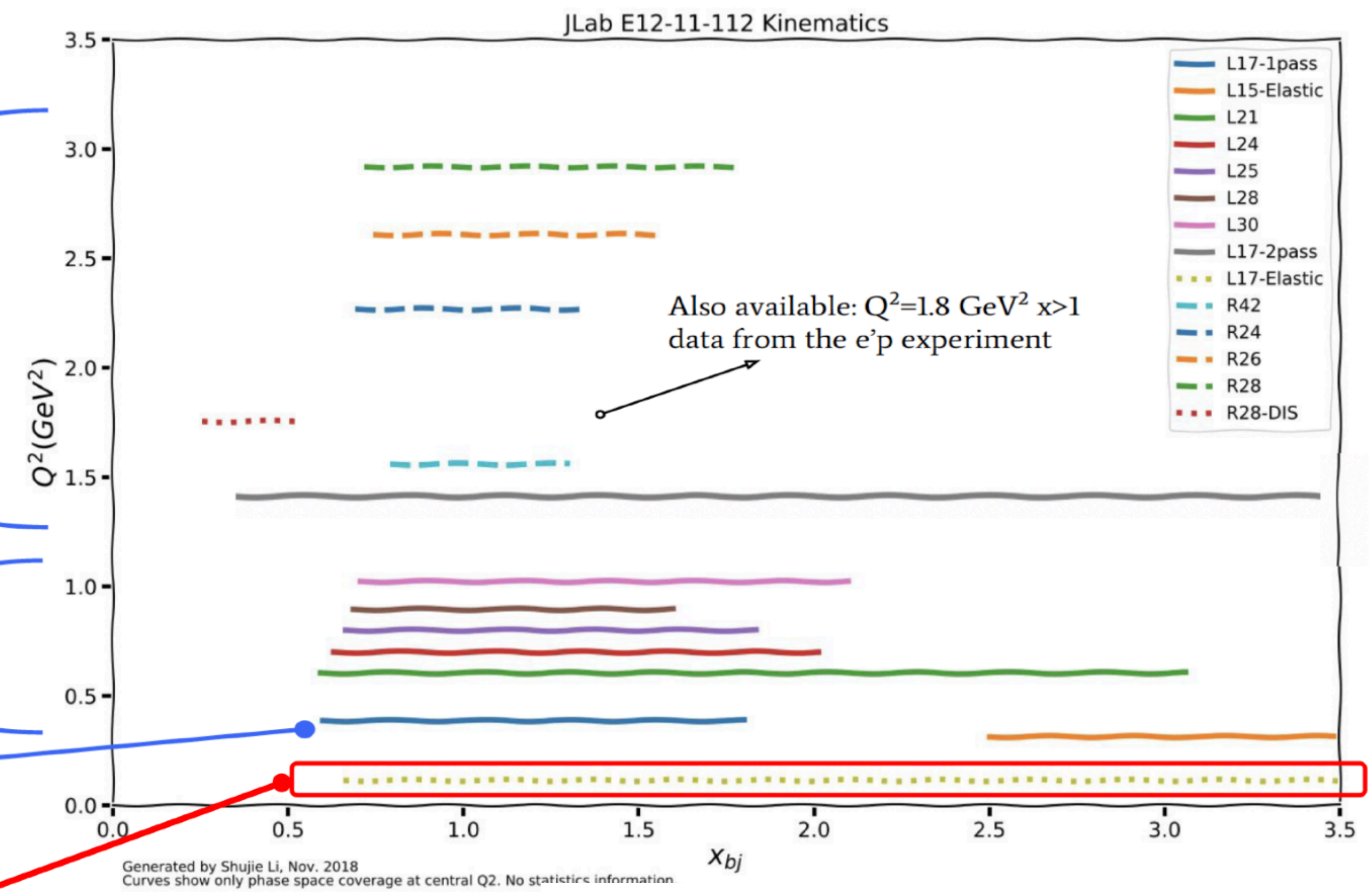
Kinematics coverage

P. Solvignon, J.Arrington, D.B.Day, D. Higinbotham, Z. Ye (Spokepeople)

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

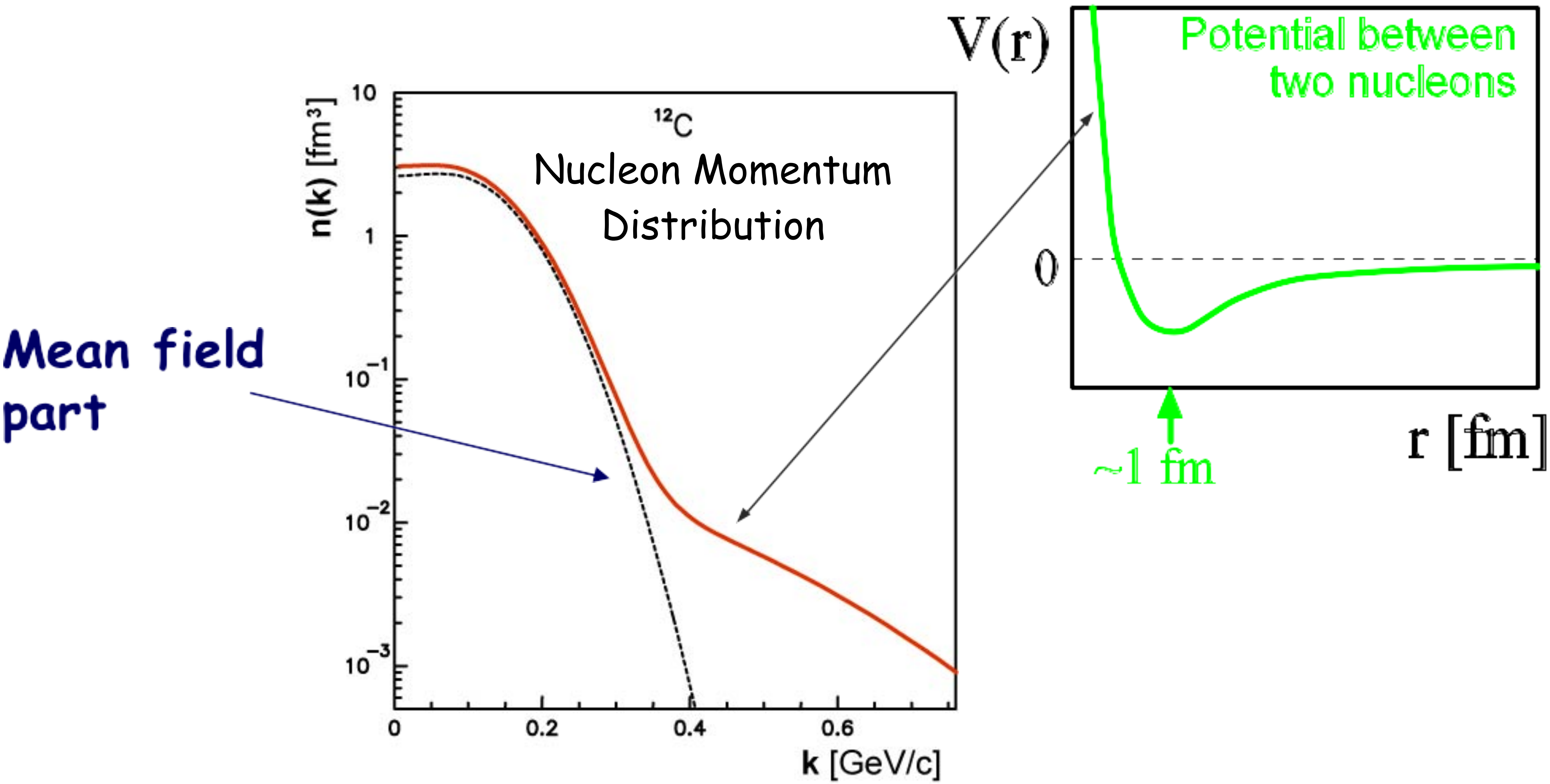
Dec 2017:
Commissioning
Target "boiling" study (also QE data at Q2=0.4 GeV2)



October 2018: Elastic scattering with 1.171 GeV beam

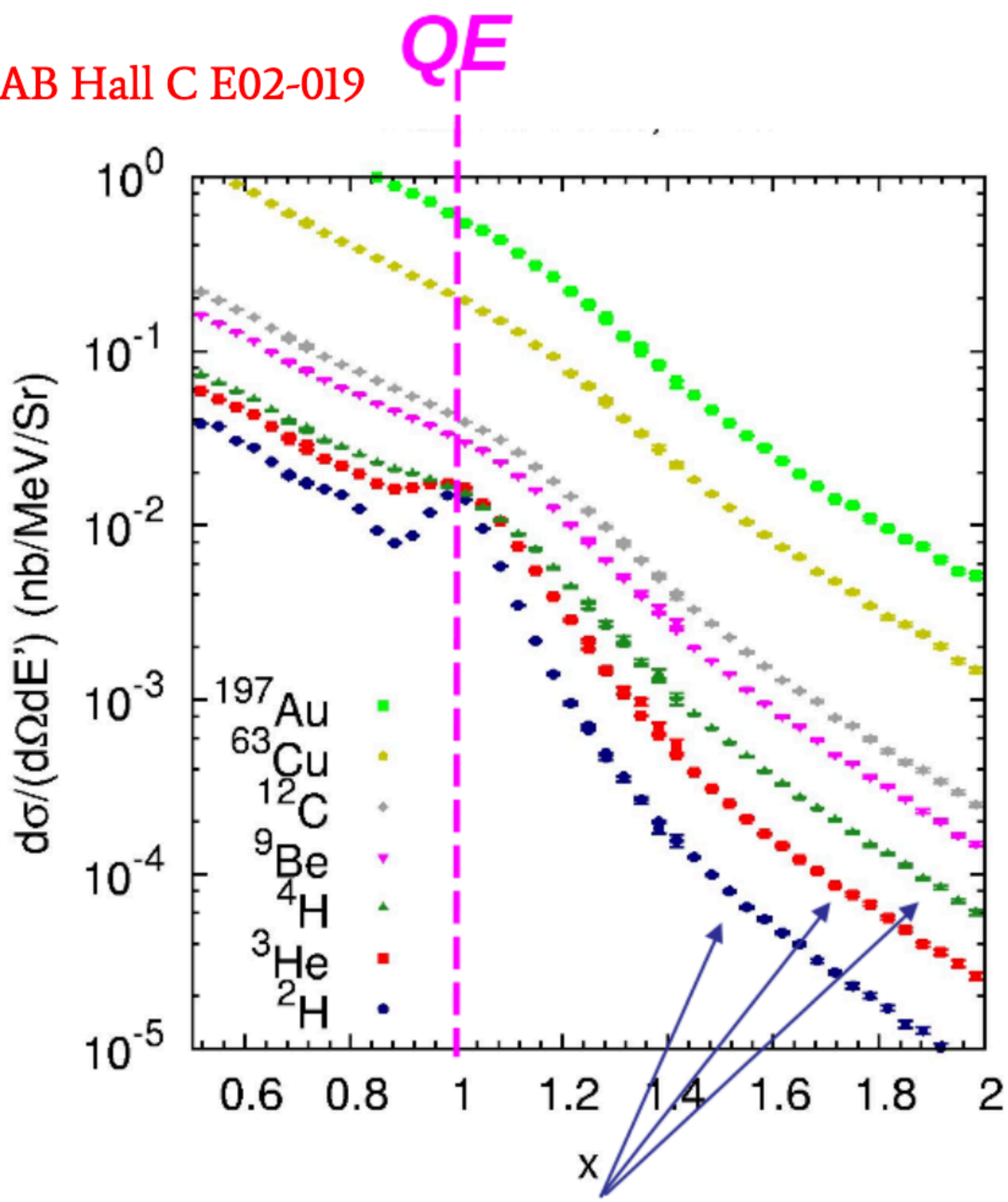
X>1 Physics Analysis

Short Range Correlations



Probing 2N SRC at x>1

JLAB Hall C E02-019



High momentum tails should yield constant ratio if SRC-dominated

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

Probing 2N SRC at x>1

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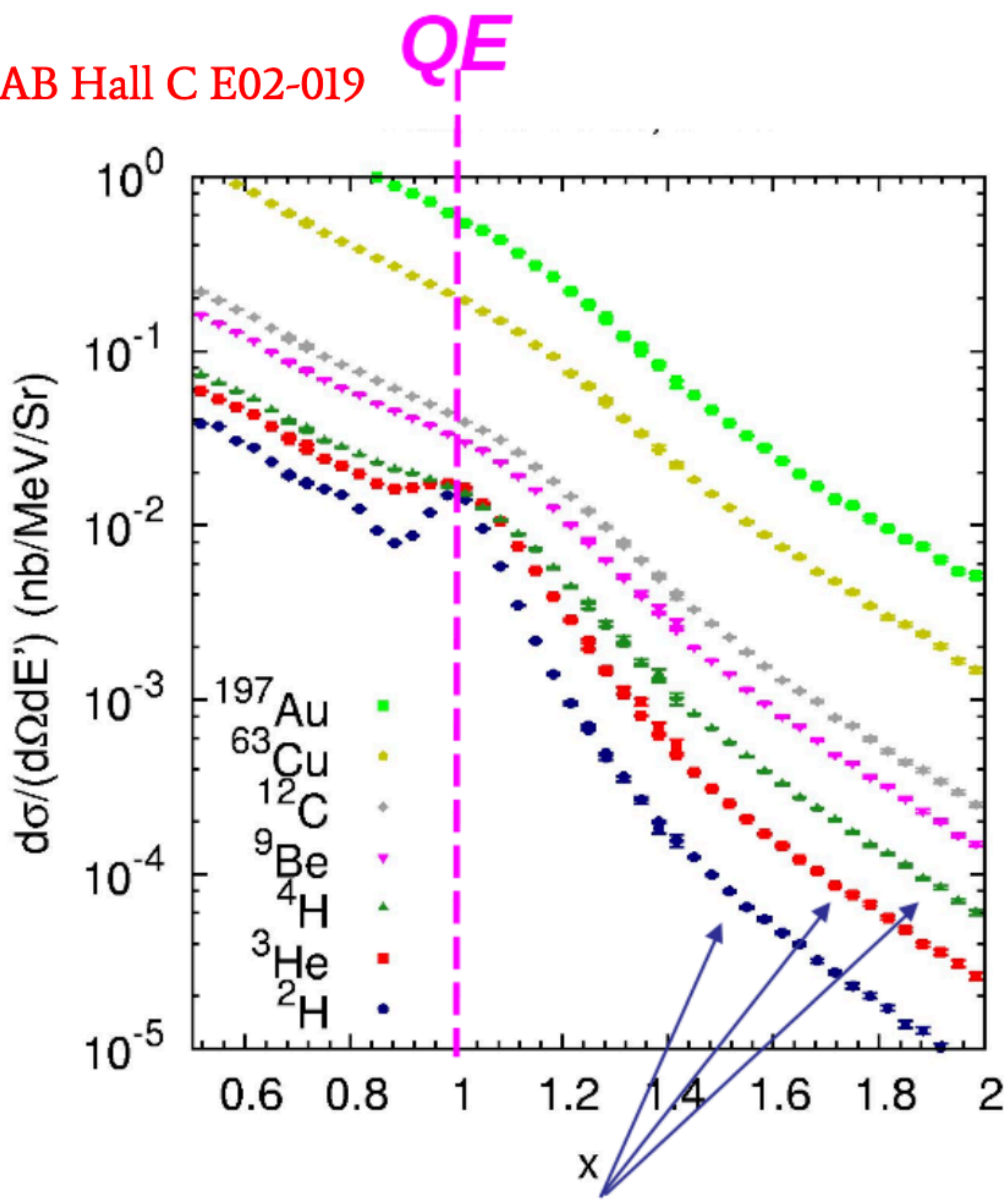


High momentum tails should yield* constant ratio *if SRC-dominated

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

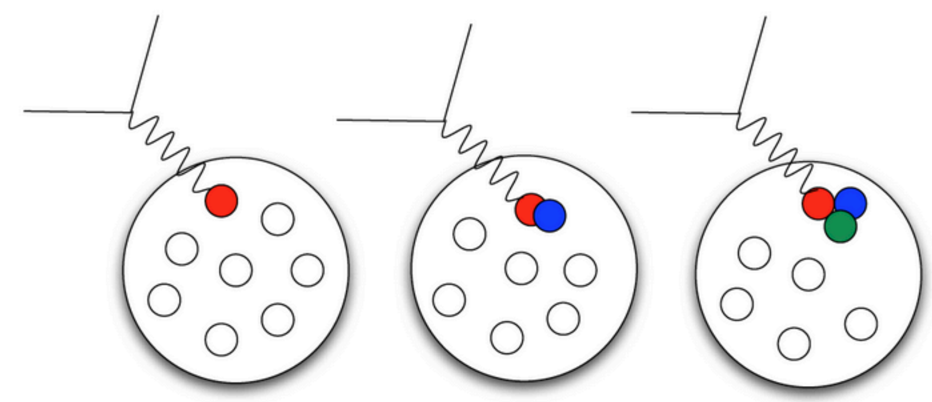
Inclusive electron scattering:

- high statistics
- background suppressed at high Q2

Probability to find 2N SRC in nucleus A

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

Cross section from 2N SRC



Previous Experiments

Plateaus in Cross section ratio

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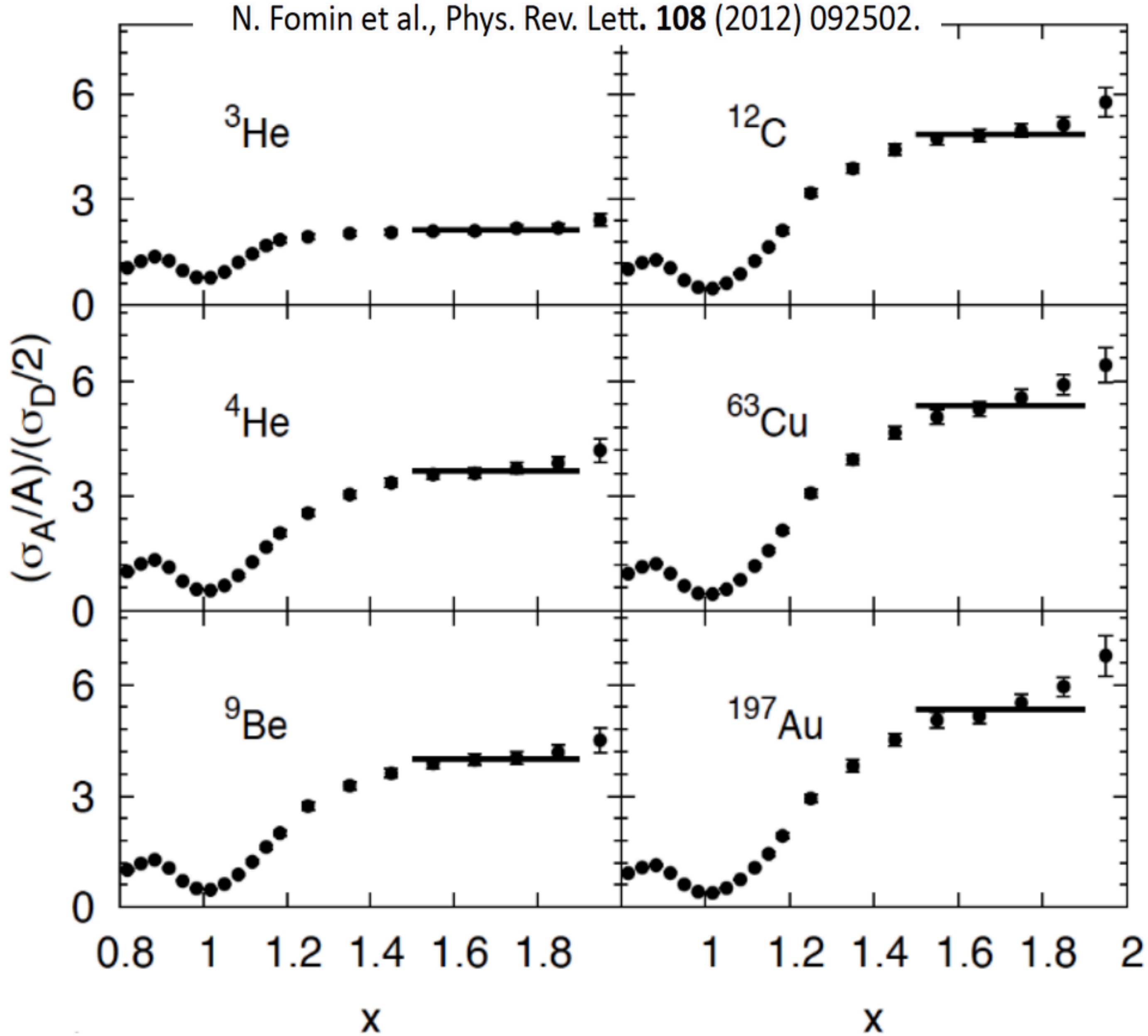
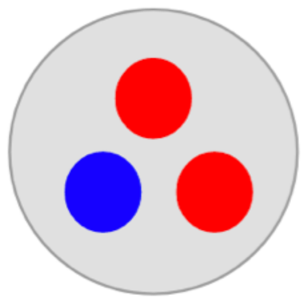
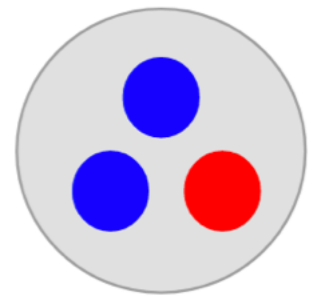
$$\frac{\sigma_A}{\sigma_{^2H}} \approx \frac{a_2(A)}{a_2(^2H)} = const$$



Precision Measurement of the Isospin Dependence in the 2N Short Range Correlation Region





Check the 2N SRC isospin dependence at 1<x<2, and also 3N momentum sharing configuration.

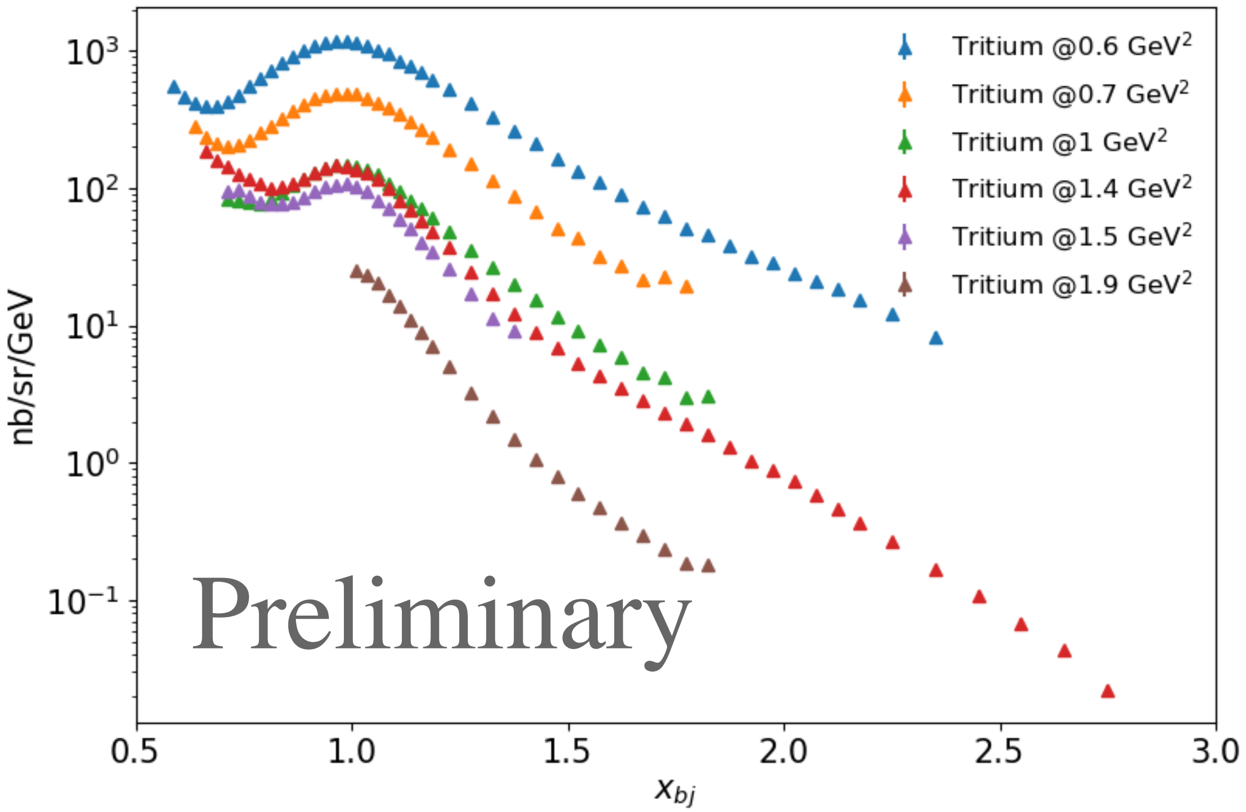
np pair dominates: $$\frac{\sigma_{^3H}}{\sigma_{^3He}} \approx \frac{2\sigma_{np}}{2\sigma_{np}} = 1$$

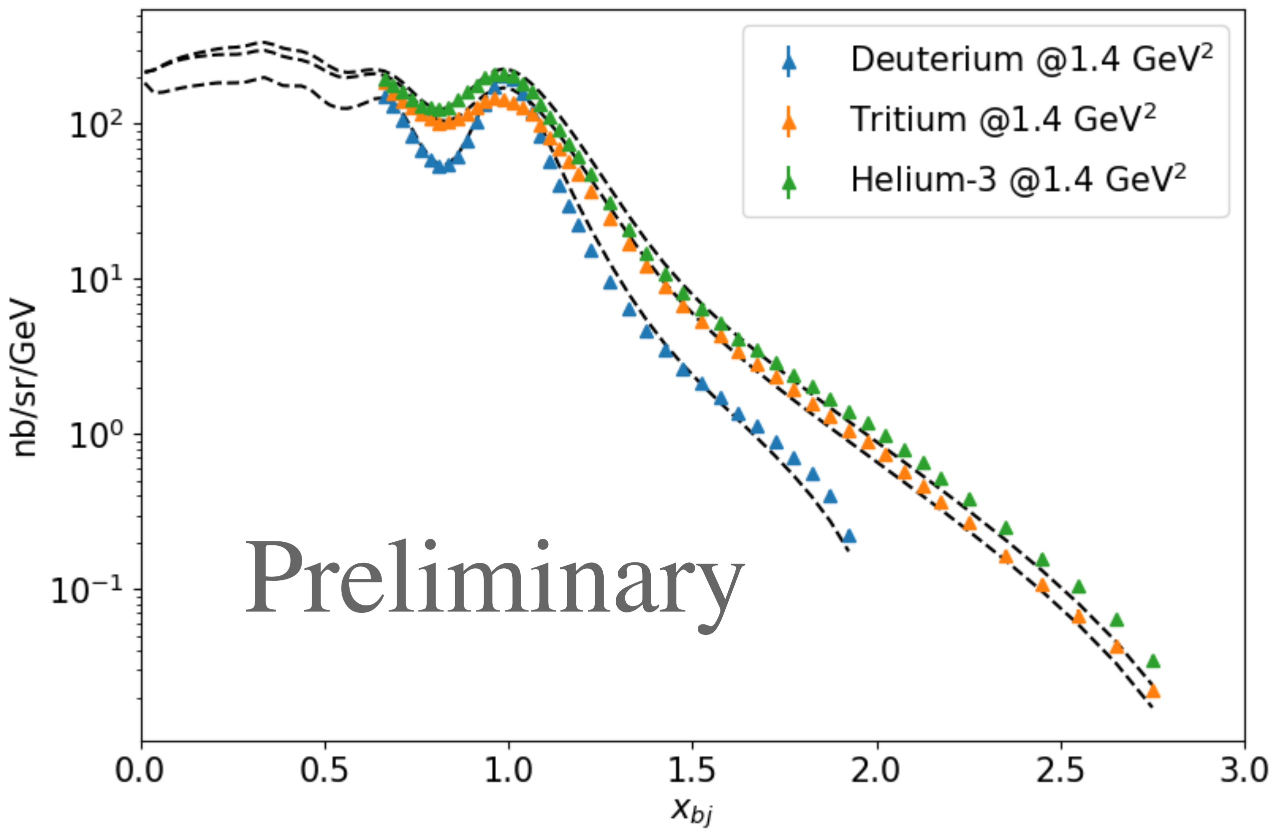
where $\sigma_{np} = \sigma_n + \sigma_p$

no isospin preference: $$\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{2\sigma_{np} + \sigma_{nn}}{2\sigma_{np} + \sigma_{pp}} \rightarrow 0.74$$

$\sigma_p \approx 2.43\sigma_n$

Preliminary Cross-Sections (x>1)

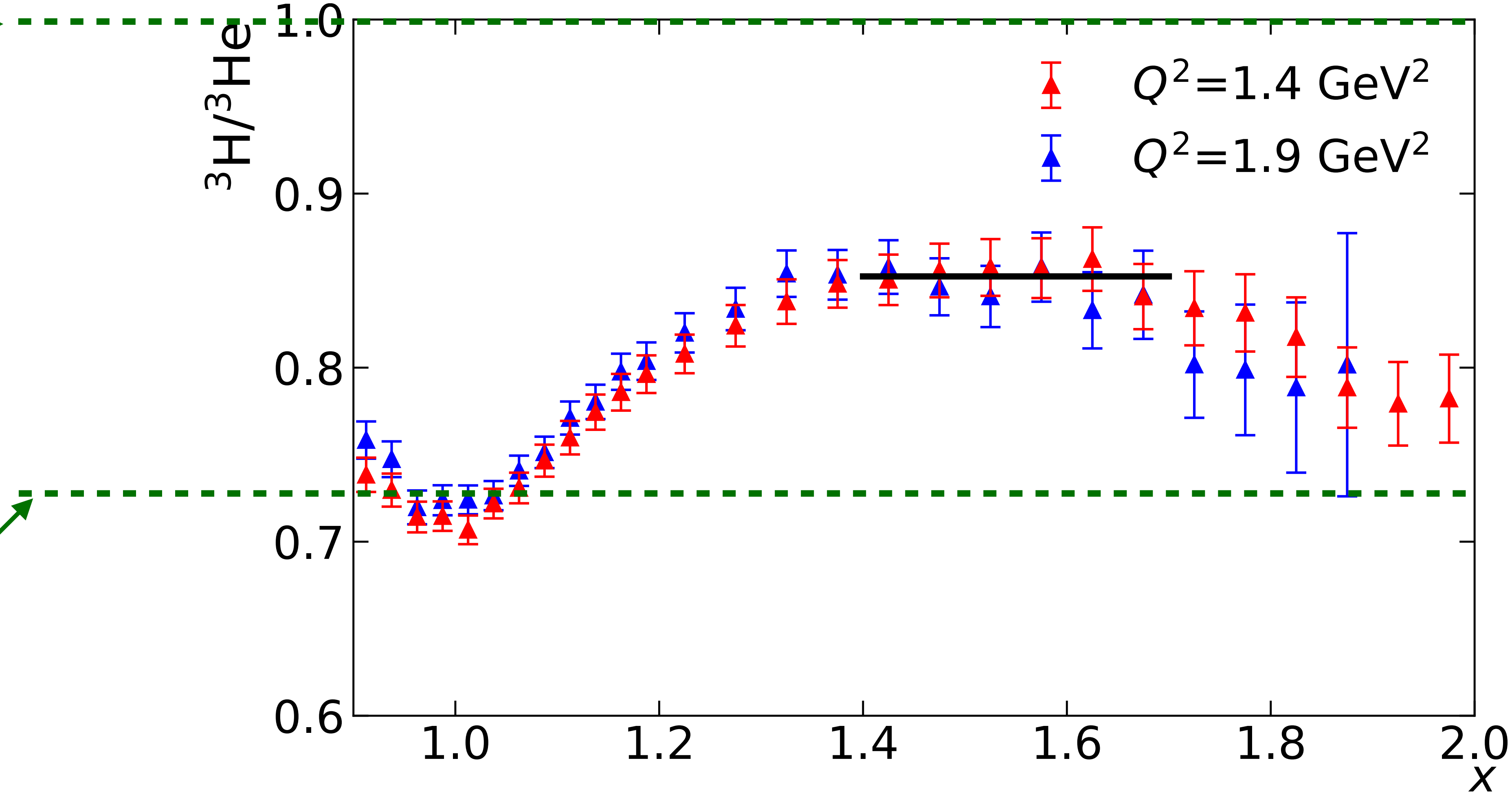




^{3}H/^{3}He Cross Section Ratio

$$\frac{\sigma_{^3H}}{\sigma_{^3He}} \approx \frac{2\sigma_{np}}{\sigma_{np}} = 1$$

$$\frac{\sigma_{^3H}}{\sigma_{^3He}} = \frac{2\sigma_{np} + \sigma_{pp}}{2\sigma_{np} + \sigma_{pp}} \rightarrow 0.74$$



^{3}H/^{3}He Interpretation

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

➡ where: $\sigma_{np} = \sigma_n + \sigma_p$

➡ Off-shell deForest cross section:

$$\sigma_p / \sigma_n \approx 2.43$$

➡ Experimental Cross section ratio:

$$\frac{\sigma_{^3H}}{\sigma_{^3He}} = 0.85$$

➡ Assuming $N_{nn}(^3H) = N_{pp}(^3He)$

$^3H/^3He$ Interpretation

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

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$$\frac{\sigma_{^3H}}{\sigma_{^3He}} = 0.85$$

➡ Assuming $N_{nn}(^3H) = N_{pp}(^3He)$

From the cross section ratio:

$$\frac{N_{np}}{N_{pp}} = 4.23$$

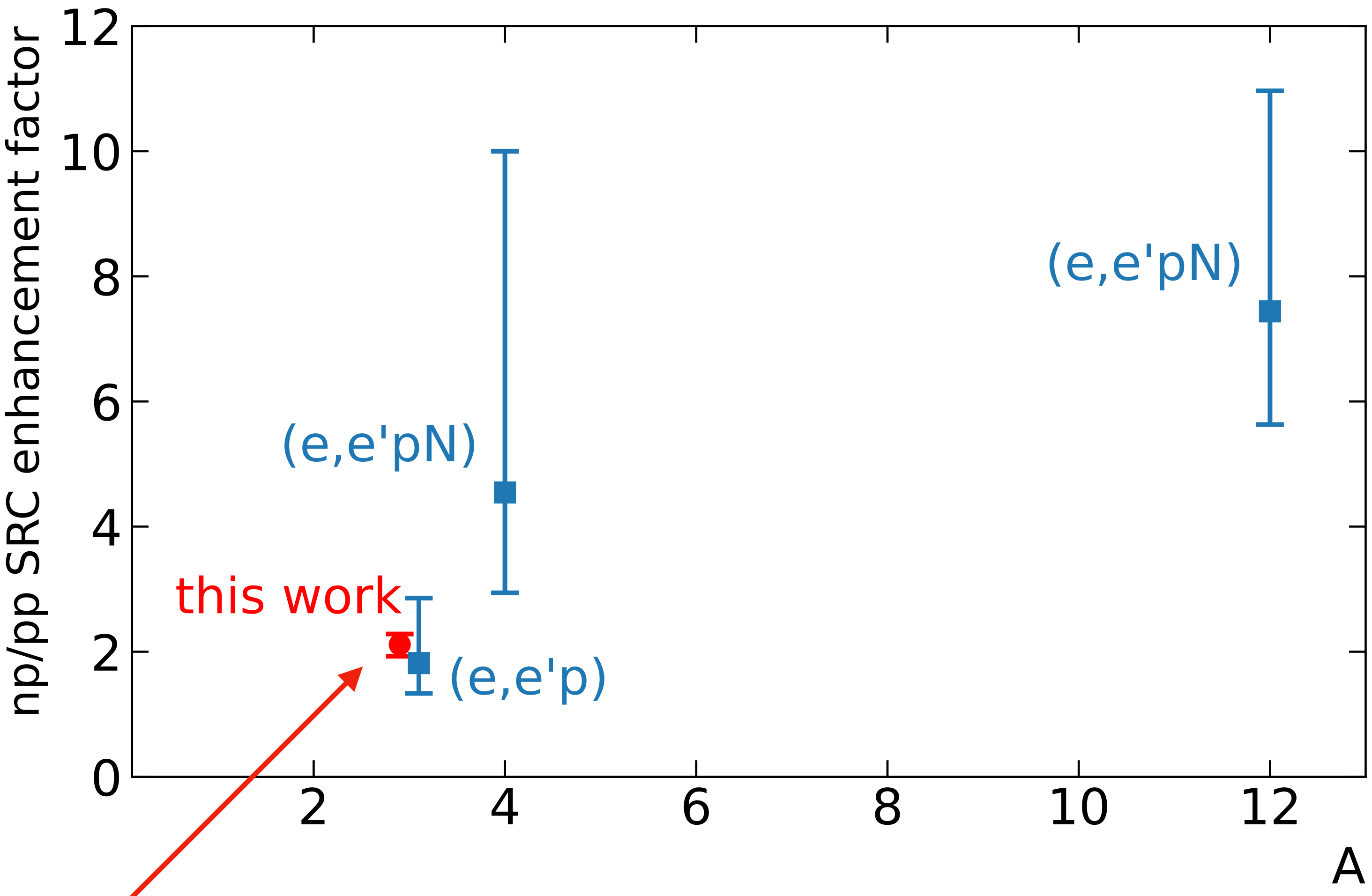
From pair counting in ^{3}He:

$$P_{np/pp} = 2$$

2.1 enhancement from simple np pair counting

$^3H/^3He$ Interpretation

Phys. Rev. Lett. 124, 212501 (2020)
I. Korover et al., Phys. Rev. Lett.113, 022501 (2014)
R. Shneoret al., Phys. Rev. Lett.99, 072501 (2007)



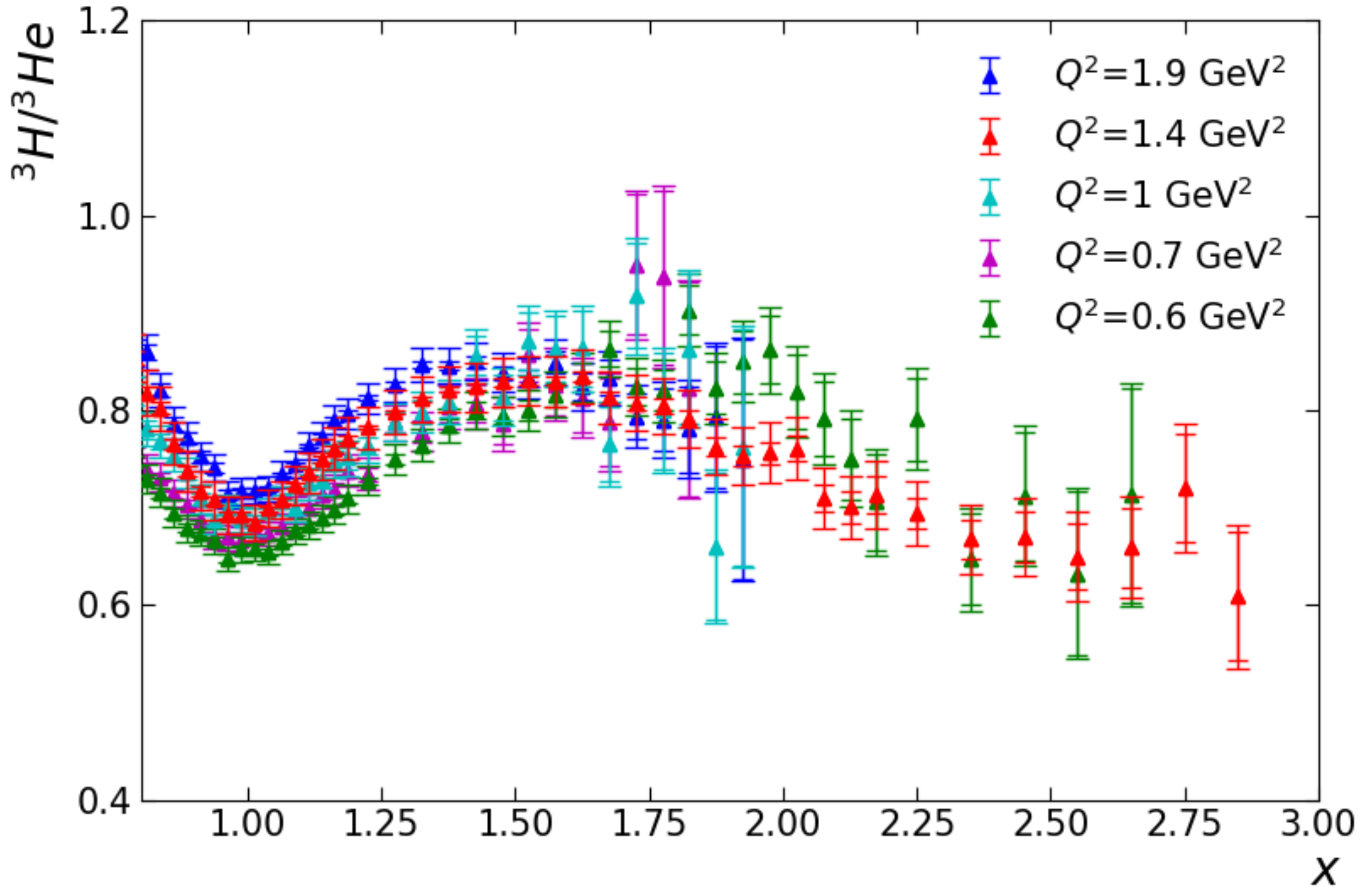
2.1 enhancement from simple np pair counting

The isospin structure of short-range correlations in the mirror nuclei ^3H and ^3He

S. Li,[1,2] R. Cruz-Torres,[3,2] N. Santiesteban,[1,3] D. Abrams,[4] S. Alsalmi,[5] D. Androic,[6] K. Aniol,[7] J. Arrington,[2,8] T. Averett,[9] C. Ayerbe Gayoso,[9] J. Bane,[10] S. Barcus,[9] J. Barrow,[10] A. Beck,[3] V. Bellini,[11] H. Bhatt,[12] D. Bhetuwal,[12] D. Biswas,[13] D. Bulumulla,[14] A. Camsonne,[15] J. Castellanos,[16] J. Chen,[9] J-P. Chen,[15] D. Chrisman,[17] M. E. Christy,[13] C. Clarke,[18] S. Covrig,[15] K. Craycraft,[10] D. Day,[4] D. Dutta,[12] E. Fuchey,[19] C. Gal,[4] F. Garibaldi,[20] T. N. Gautam,[13] T. Gogami,[21] J. Gomez,[15] P. Guéye,[13,17] A. Habarakada,[13] T. Hague,[5] O. Hansen,[15] F. Hauenstein,[14] W. Henry,[22] D. W. Higinbotham,[15] R. J. Holt,[8] C. Hyde,[14] K. Itabashi,[21] M. Kaneta,[21] A. Karki,[12] A. T. Katramatou,[5] C. E. Keppel,[15] M. Khachatryan,[14] V. Khachatryan,[18] P. M. King,[23] I. Korover,[24] L. Kurbany,[1] T. Kutz,[18] N. Lashley-Colthirst,[13] W. B. Li,[9] H. Liu,[25] N. Liyanage,[4] E. Long,[1] J. Mammei,[26] P. Markowitz,[16] R. E. McClellan,[15] F. Meddi,[20] D. Meekins,[15] S. Mey-Tal Beck,[3] R. Michaels,[15] M. Mihovilovič,[27,28,29] A. Moyer,[30] S. Nagao,[21] V. Nelyubin,[4] D. Nguyen,[4] M. Nycz,[5] M. Olson,[31] L. Ou,[3] V. Owen,[9] C. Palatchi,[4] B. Pandey,[13] A. Papadopoulou,[3] S. Park,[18] S. Paul,[9] T. Petkovic,[6] R. Pomatsalyuk,[32] S. Premathilake,[4] V. Punjabi,[33] R. D. Ransome,[34] P. E. Reimer,[8] J. Reinhold,[16] S. Riordan,[8] J. Roche,[23] V. M. Rodriguez,[35] A. Schmidt,[3] B. Schmookler,[3] E. P. Segarra,[3] A. Shahinyan,[36] K. Slifer,[1] P. Solvignon,[1] S. Širca,[27,28] T. Su,[5] R. Suleiman,[15] H. Szumila-Vance,[15] L. Tang,[15] Y. Tian,[37] W. Tireman,[38] F. Tortorici,[11] Y. Toyama,[21] K. Uehara,[21] G. Urciuoli,[20] D. Votaw,[17] J. Williamson,[39] B. Wojtsekhowski,[15] S. Wood,[15] Z. H. Ye,[8,*] J. Zhang,[4] and X. Zheng[4]
(Thomas Jefferson National Accelerator Facility Hall A Tritium Collaboration)

Currently under review by PRL

Future Work

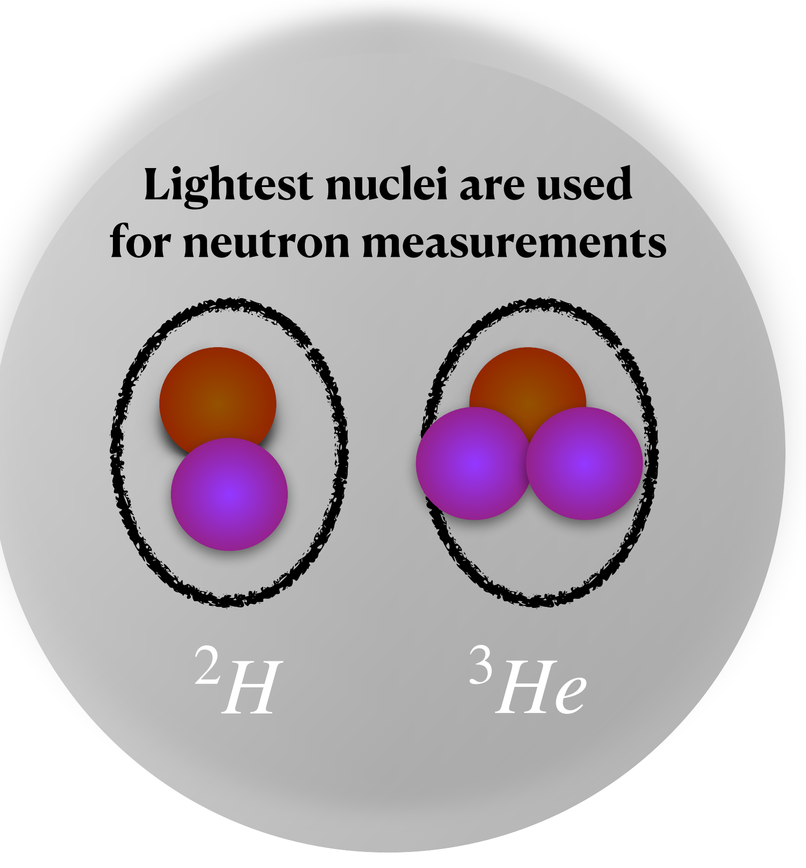


- Additional data at low Q2
- Additional data at x>2
- Theoretical calculations are underway
  Noemi Rocco (Fermilab)
  Alessandro Lovato (Argonne Lab)
  Misak Sargsian (FIU)

Expectations
1+ Publication of the theoretical interpretation.
1 arXiv paper with extracted cross sections

X=1 Physics Analysis

Accessing to neutrons



Neutron measurements include:

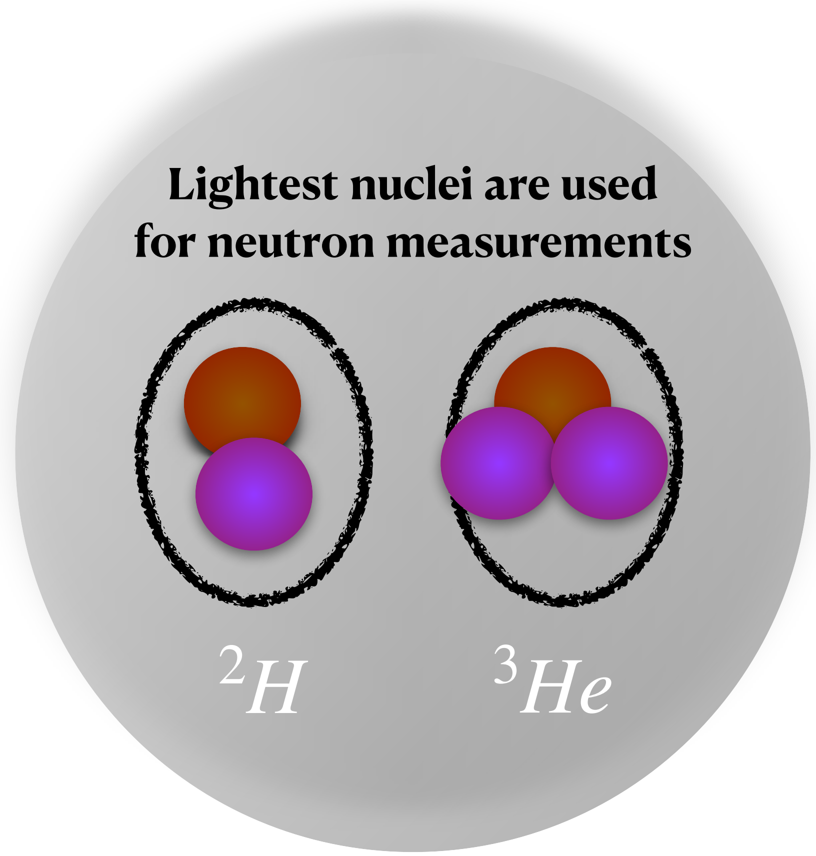
$^3\overrightarrow{He}(\vec{e}, e')$ QE
polarization experiments

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

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

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

Accessing to neutrons



If measuring neutrons (no charge):

- Energy information from time of flight
- Requires precise measurement of neutron detection efficiencies

Measurement Corrections:

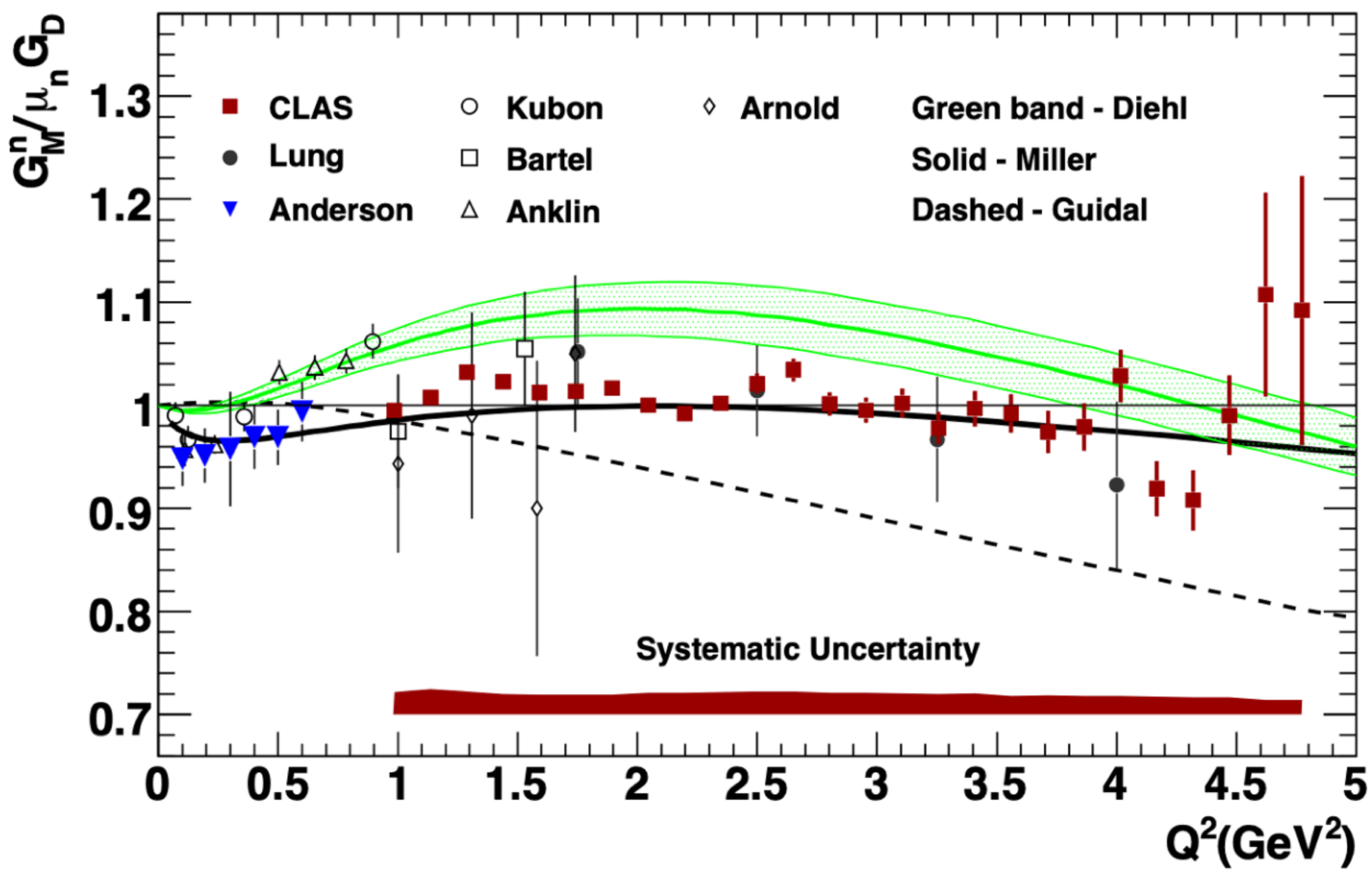
- Reaction mechanisms FSI and MEC
- Nuclear structure

Neutron cross section

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

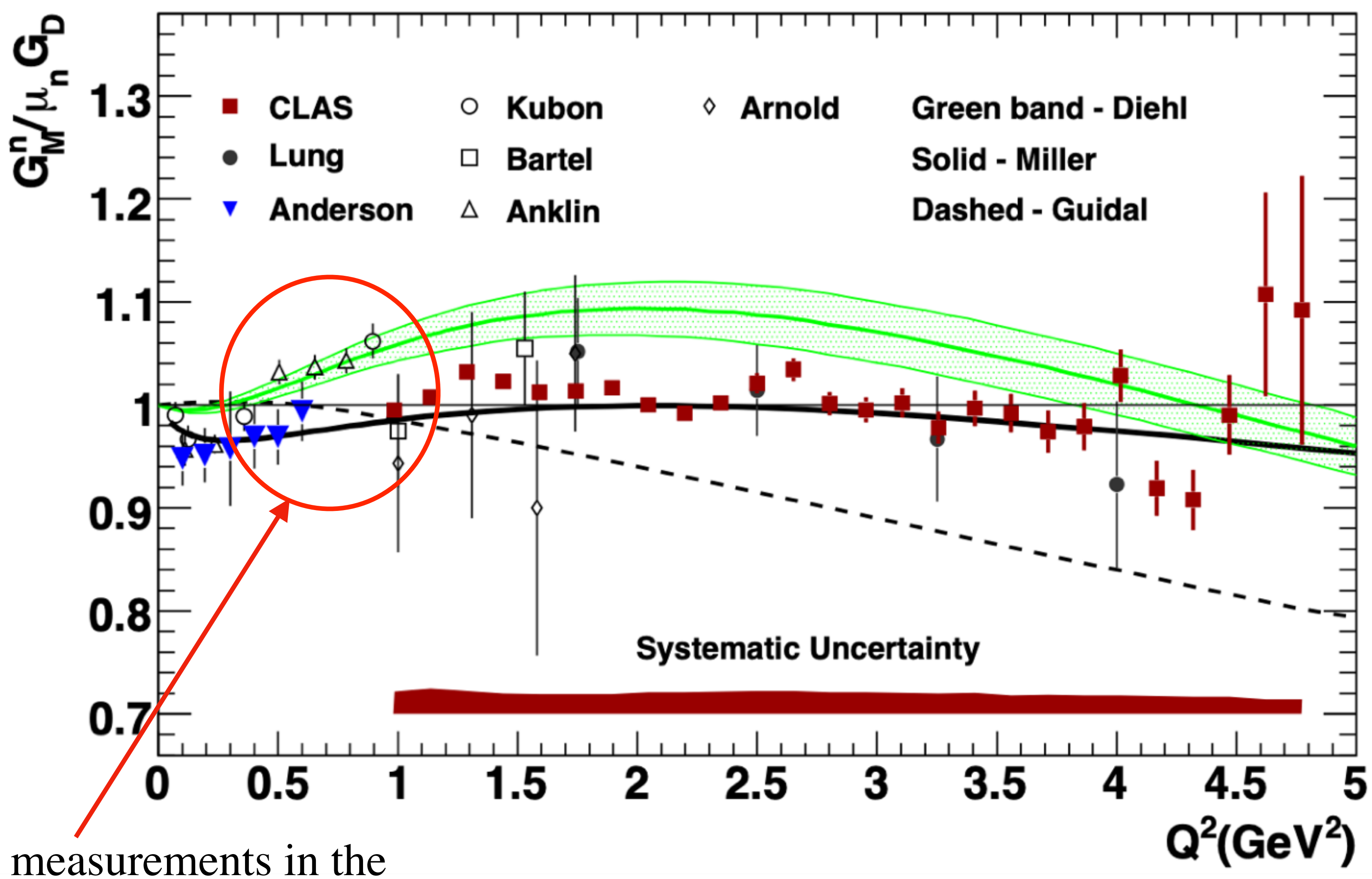
How well do we know the magnetic form factor?

Current Status of G_M^n



CLAS Collaboration. Phys.Rev.Lett. **102** (2009)

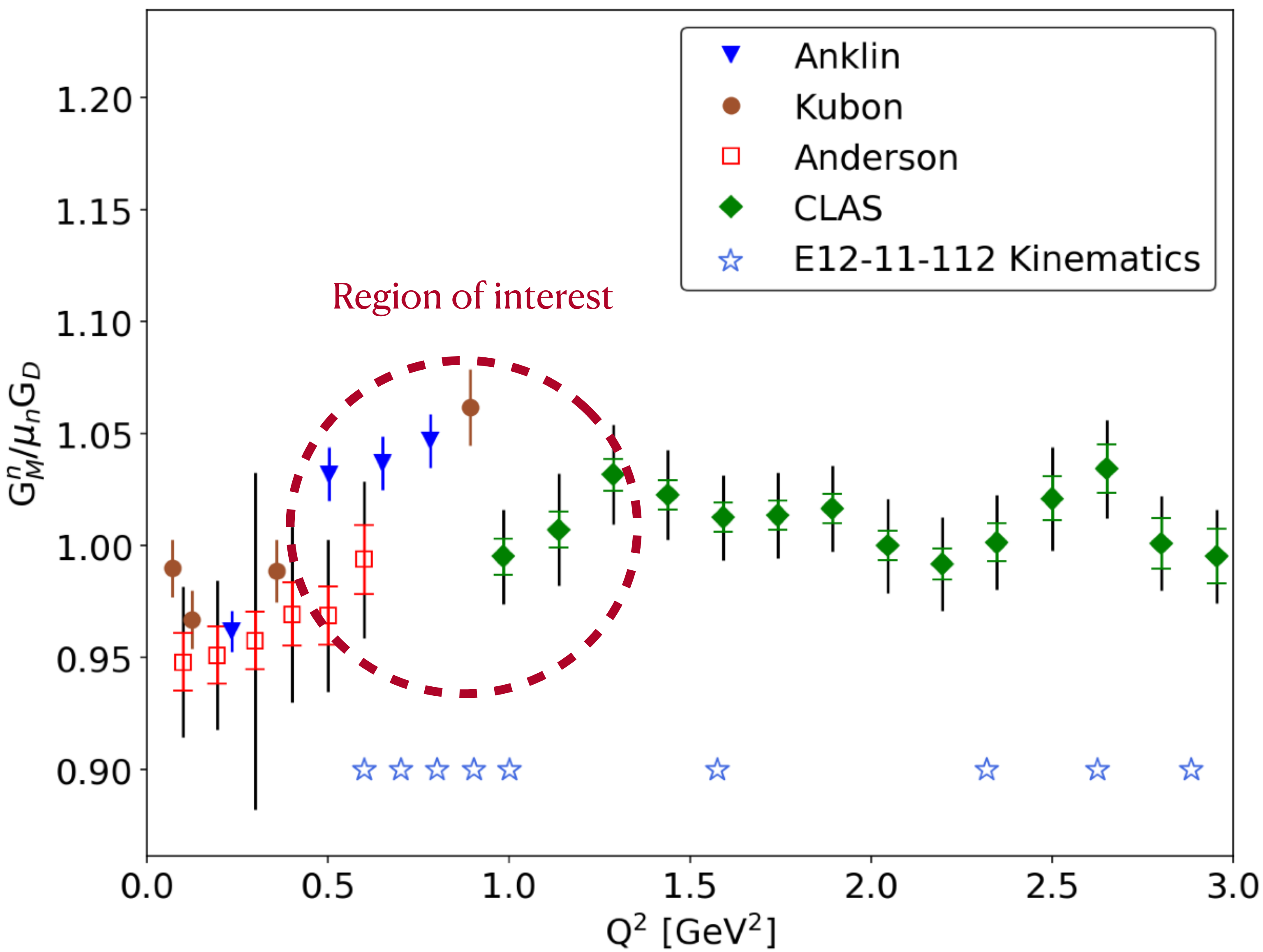
Current Status of G_M^n



High precision measurements in the $0.5 < Q^2 < 1$ region have ~8% discrepancy

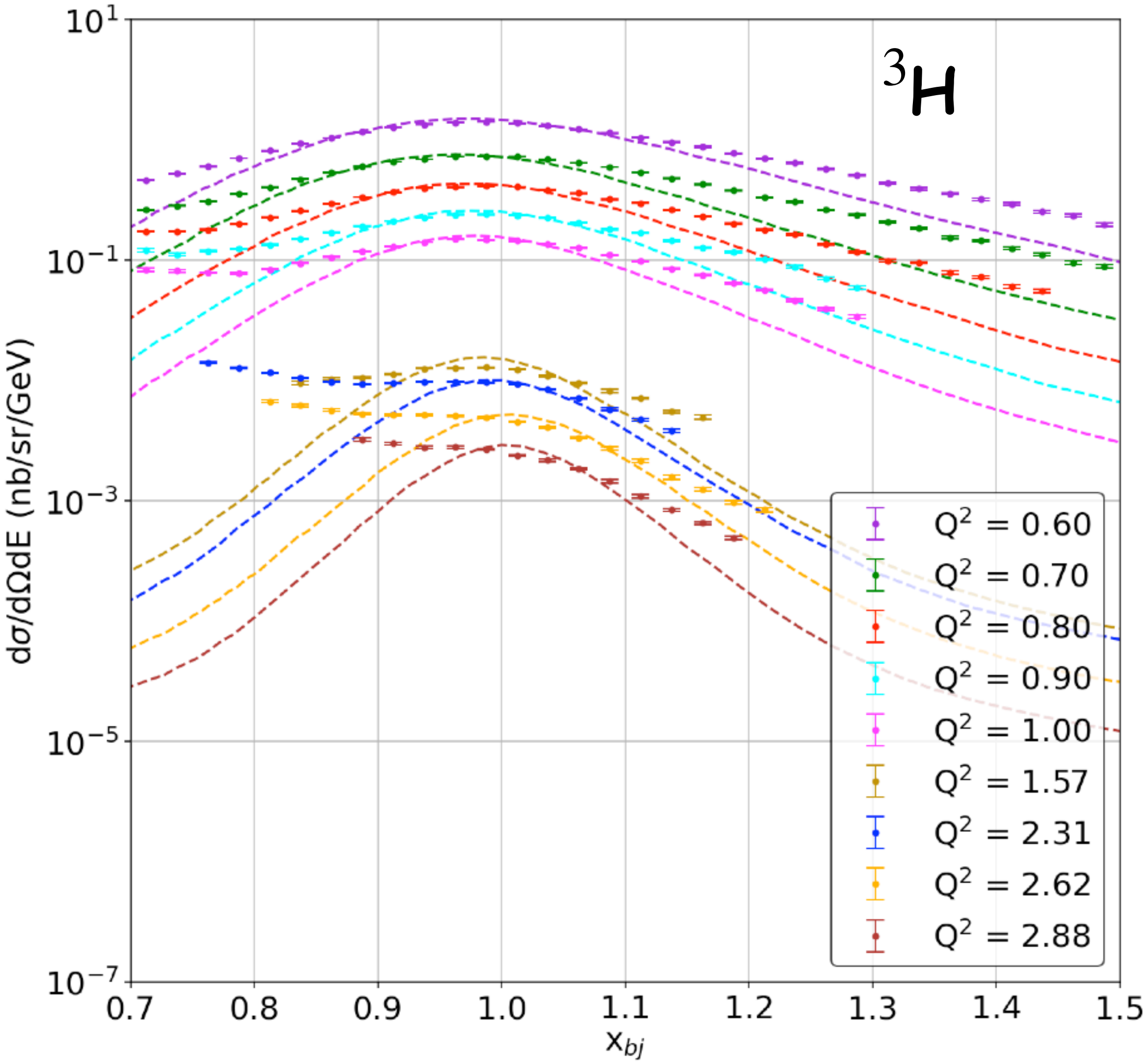
CLAS Collaboration. Phys.Rev.Lett. **102** (2009)

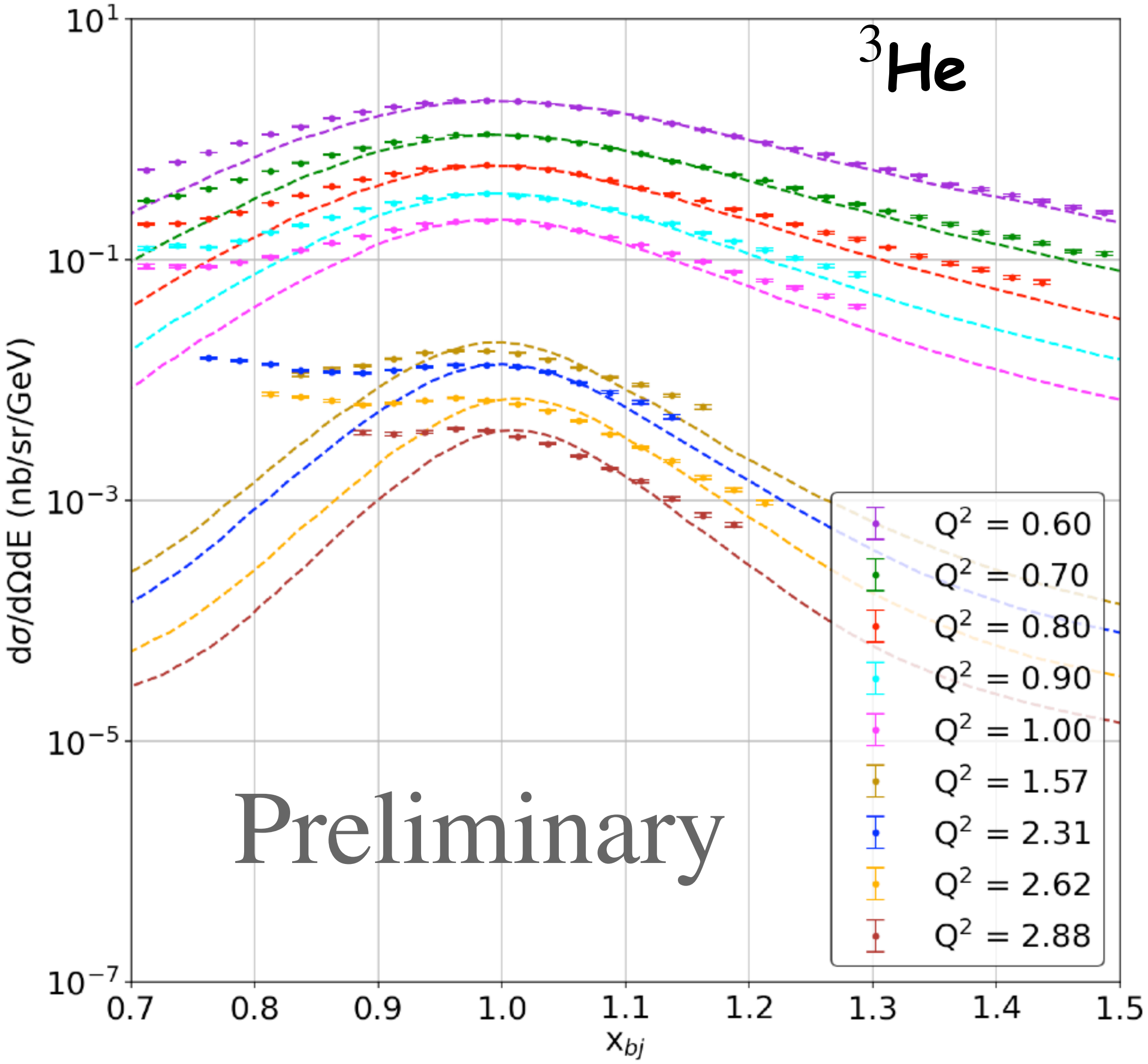
E12-11-112 Goal



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

Preliminary Cross Sections





Theory calculations courtesy of N. Rocco (Fermilab) and A. Lovatto (Argonne Lab)

G_M^n extraction without medium corrections

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

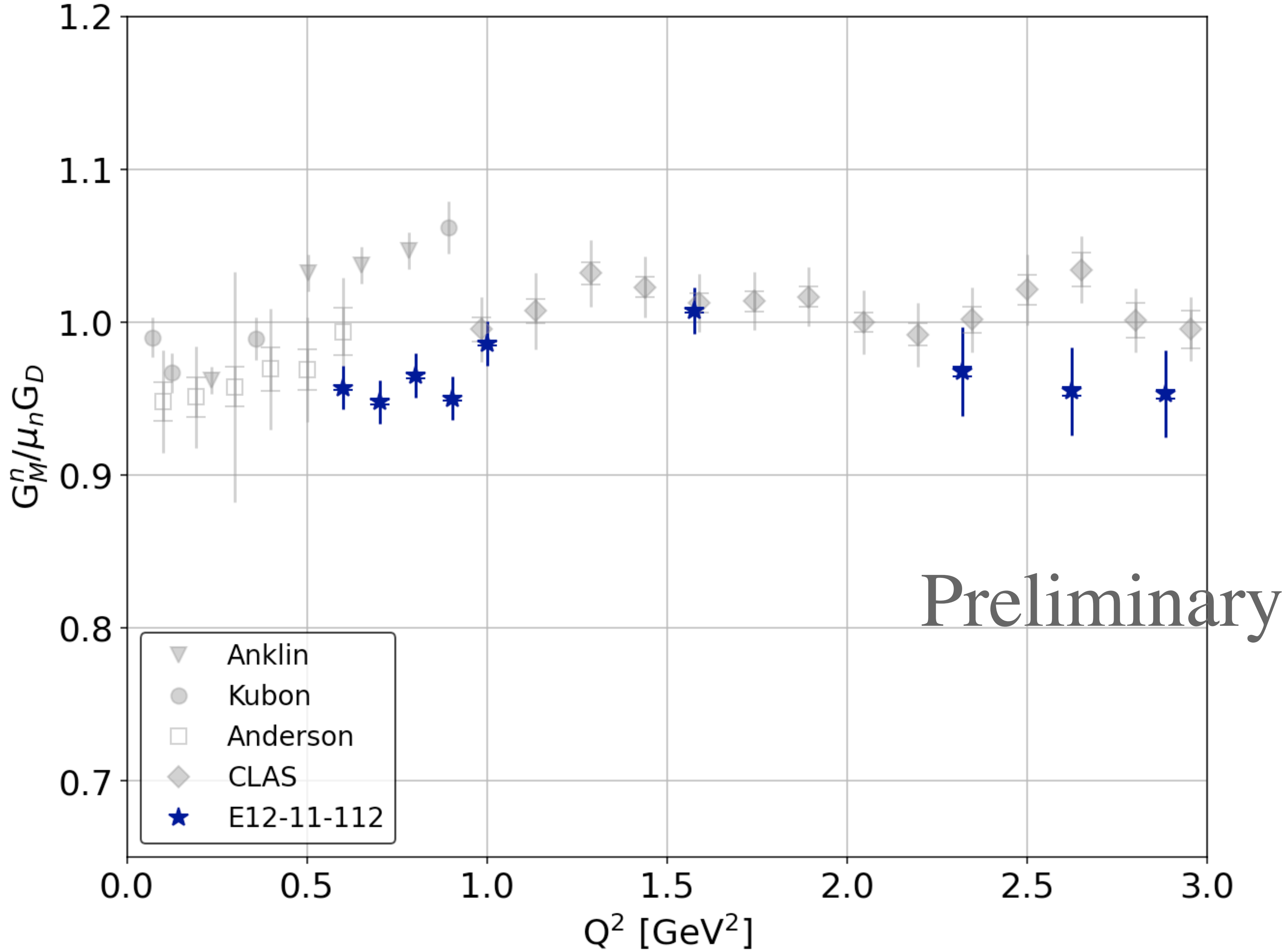
$$R = \frac{\sigma_{3H}}{\sigma_{3He}} \sim \frac{2\sigma_n + \sigma_p}{\sigma_n + 2\sigma_p}$$

$$\sigma_n \sim \frac{1-2R}{R-2}\sigma_p$$

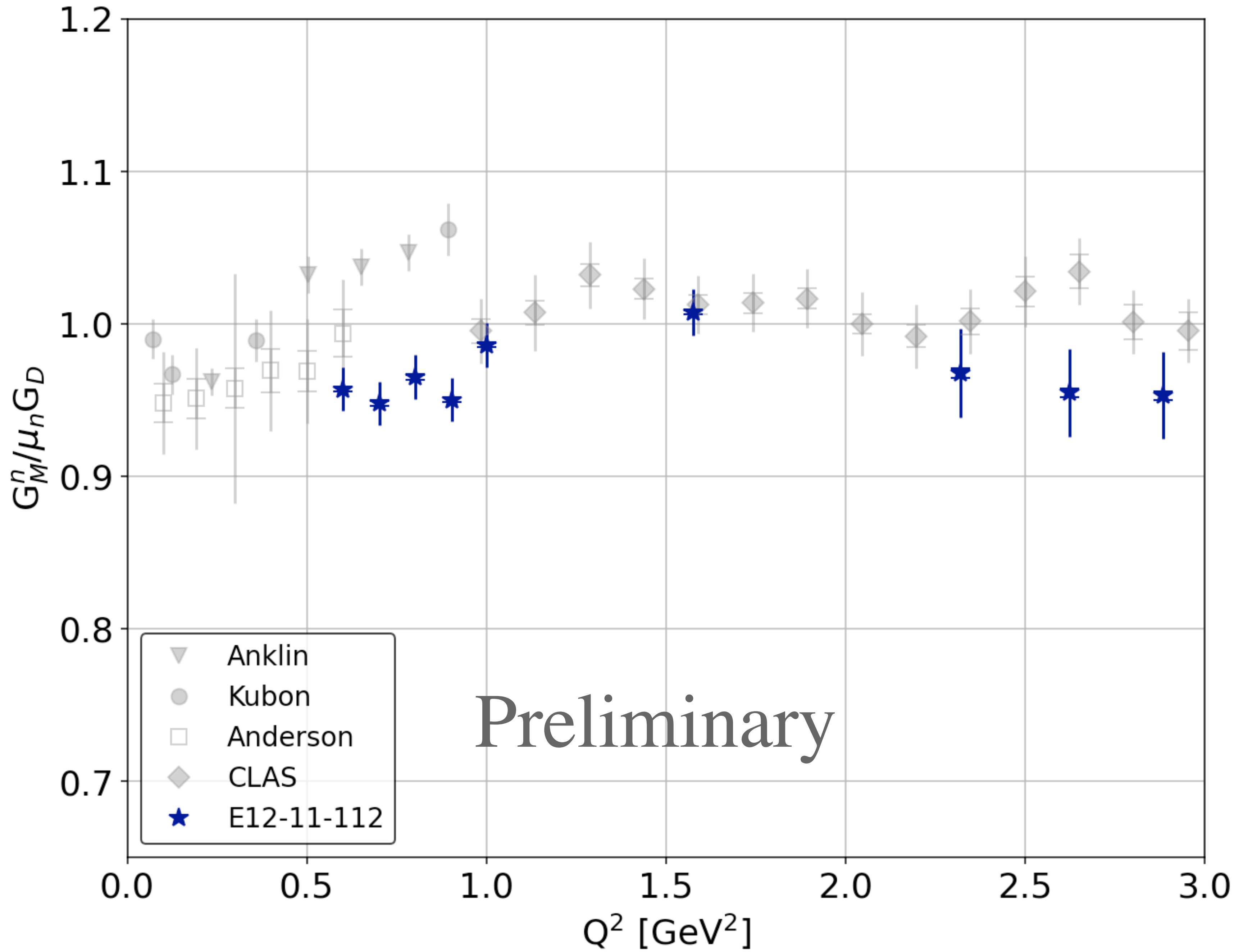
$$(G_M^n)^2 \sim \frac{\epsilon}{\tau}\left[\frac{1-2R}{R-2}\sigma_p\frac{1+\tau}{\sigma_{mott}} - (G_E^n)^2\right]$$

G_M^n extraction without medium corrections

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



Current Work



Finalize the final version of this plot after medium corrections.

Expectations

1 form factor publication

1 arXiv paper with extracted cross sections

Uncertainties

$1 \leq x \leq 2$

Sources	Cross-Section Normalization (%)	Cross-Section Point-to-Point (%)	Ratios Normalization (%)	Ratios Point-to-Point (%)
Beam Energy	—-	0.5 - 1	—-	—-
Scattering Angle	0.6	0.2	—-	—-
Momentum		1-3	—-	—-
Tracking Efficiency	0.2	0.1	—-	—-
Acceptance	—-	0.1-1.5	—-	—-
Efficiencies/Trigger/ Livetime	—-	0.01-0.1	—-	—-
^{3}He contamination		<0.3		<0.3
Radiative Corrections	1	0.4-0.4	—-	—-
Endcap Contamination	0.07	0.1-0.3	0.1	0.1-0.3
Charge	0.5	—-	0.1	—-
Boiling	0.3, 0.4	—-	0.2	—-
Target Thickness	0.3-1	—-	1.04	—-
Hydrogen Contamination**	0.2	—-	0.2	—-

Total ~ 1.15

** Only in the Fall kinematics

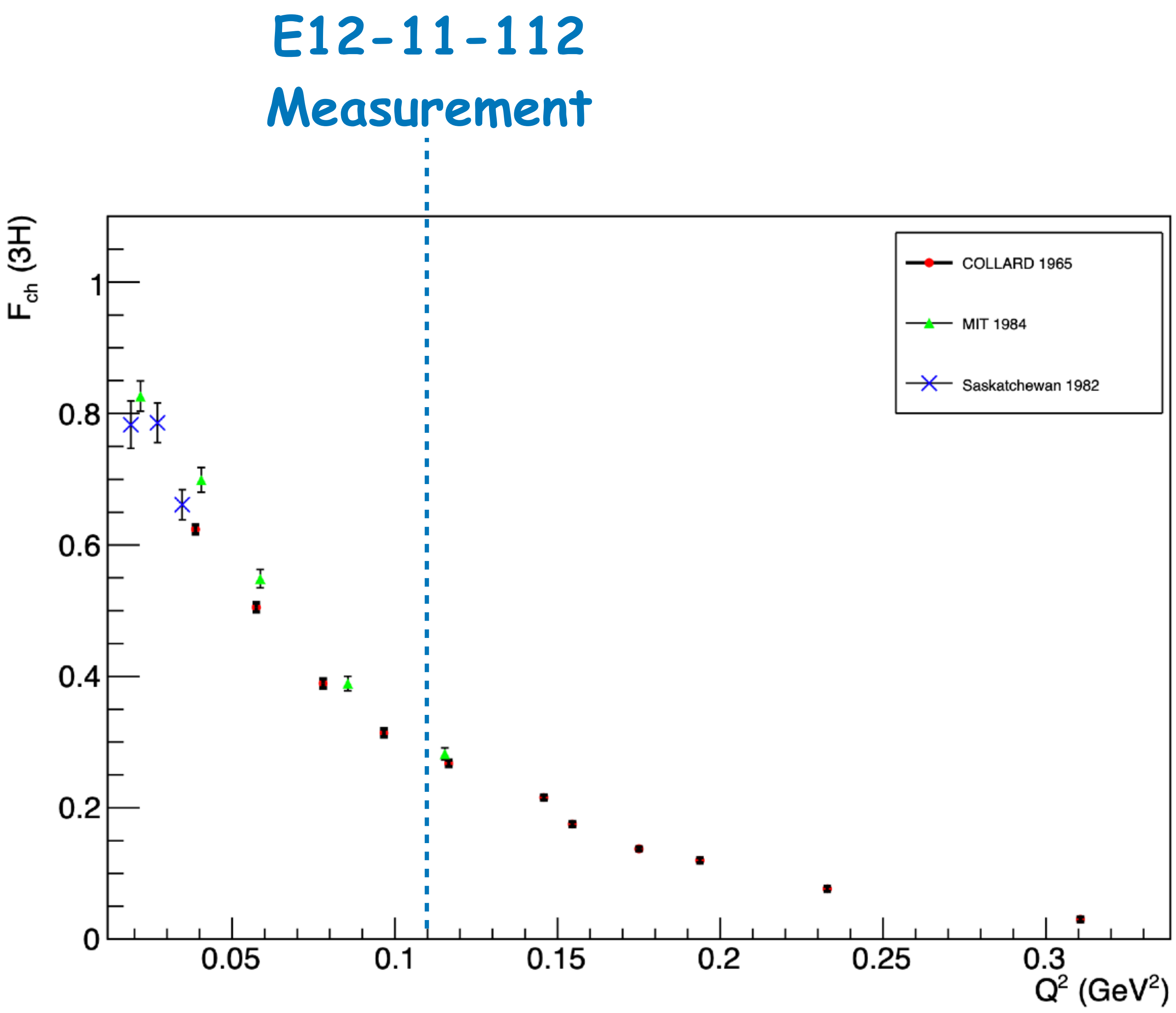
X=3 Physics Analysis

Elastic Scattering

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

Elastic Scattering

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



The charge form factor can be described by :

$$F(q^2) = \int e^{\frac{iq\cdot x}{\hbar}} \rho(x) d^3x \xrightarrow{x\to r} 4\pi \int \rho(r) \frac{\sin(|q|r/\hbar)}{|q|r/\hbar} r^2 dr$$

Extracting the charge radius in the limit $q^2 \to 0$:

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

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

Goal: Extract the ^{3}H charge radius

Current experimental results: large uncertainties, discrepancies

	$<r^2_{rms}>_{3H}$	$<r^2_{rms}>_{3He}$	
GFMC	1.77(1)	1.97(1)	
χEFT	1.756(6)	1.962(4)	
SACLAY	1.76(9)	1.96(3)	→ $\Delta R_{RMS} = 0.20(10)$
BATES	1.68(3)	1.97(3)	→ $\Delta R_{RMS} = 0.29(04)$
Atomic	--------	1.959(4)	

Extracting the ^{3}H Charge Radius

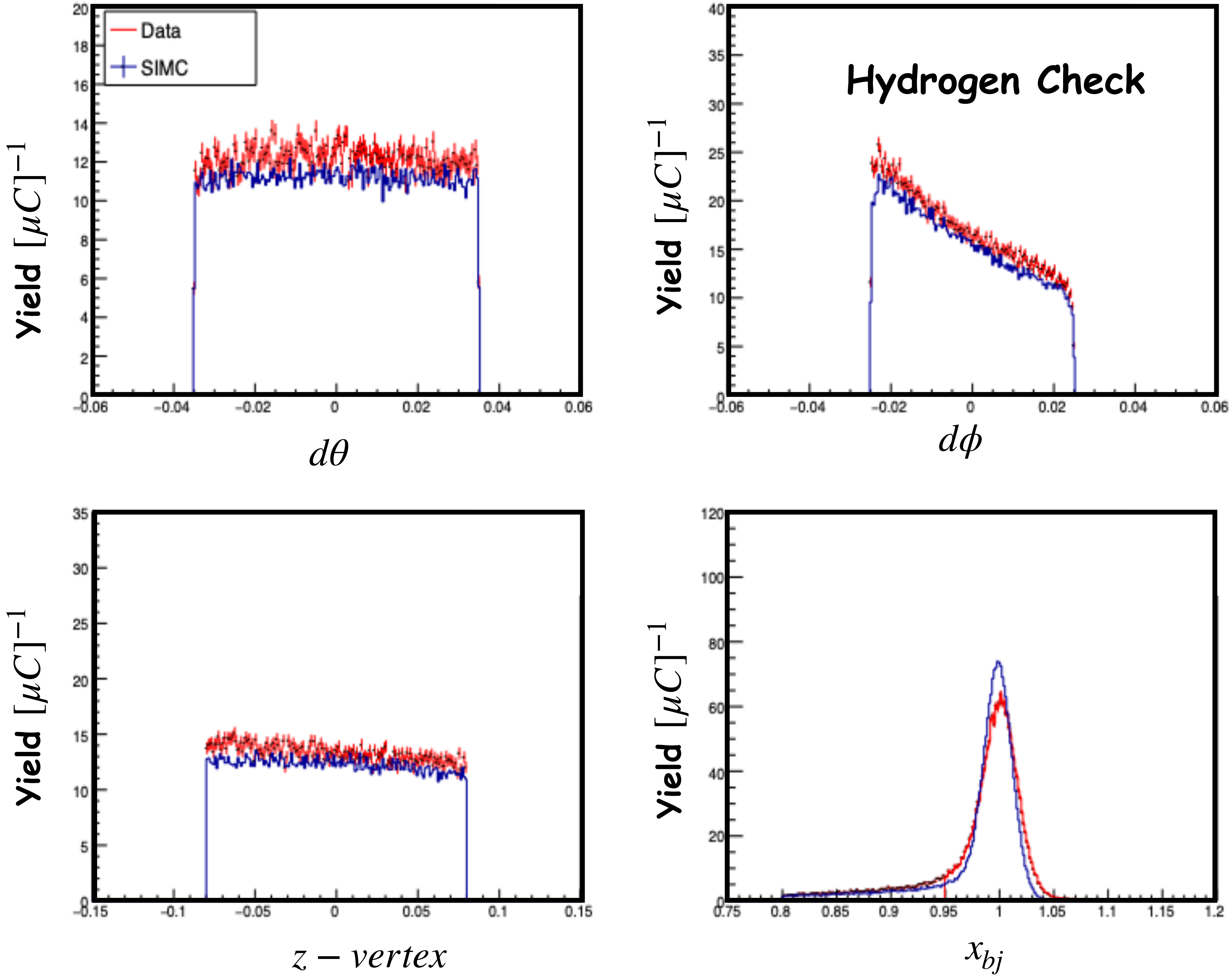
Q^2 = 0.11 GeV^2

$\sigma(^3He)$ will be compared with world data.

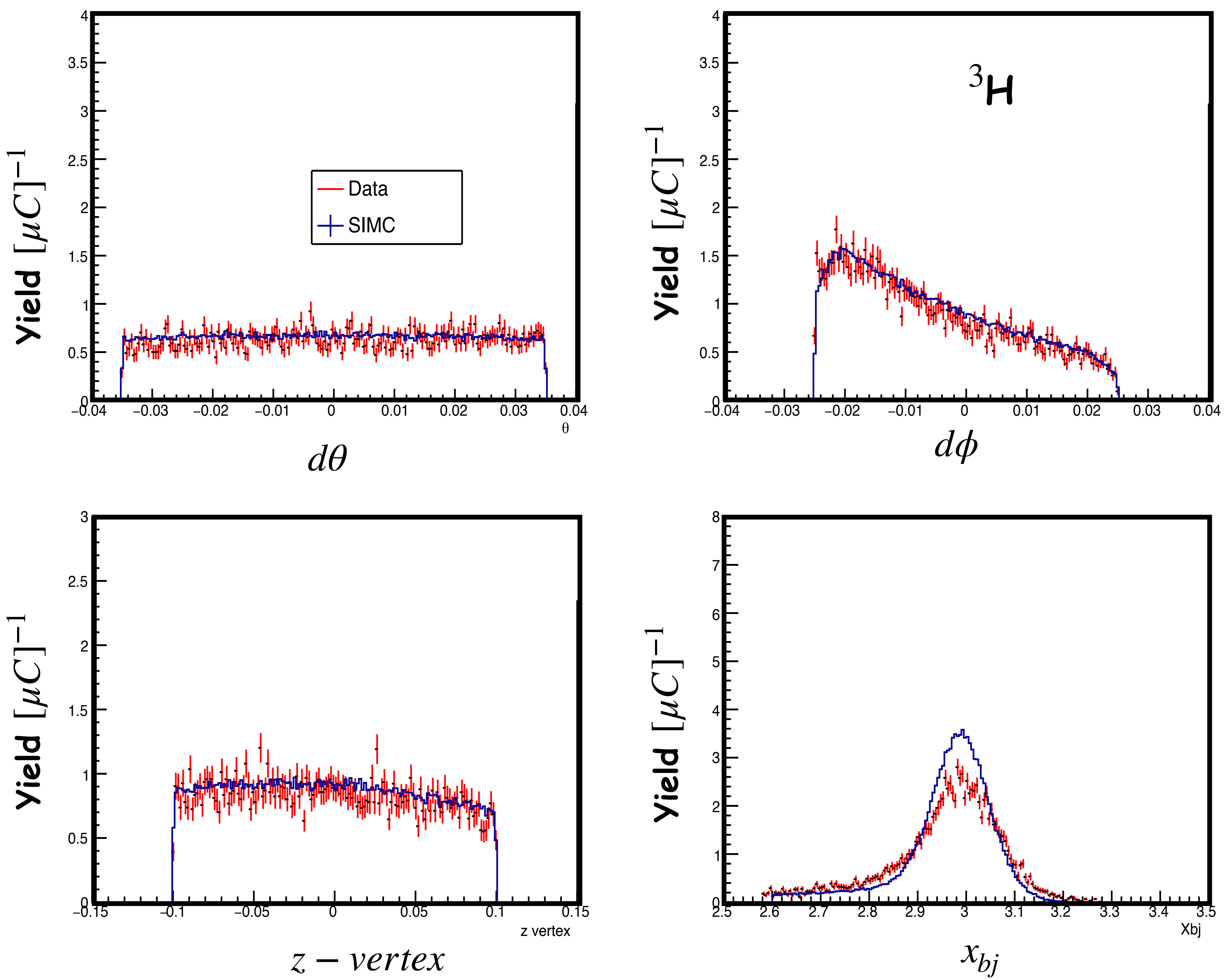
3H/3He ratio will be used to normalize $\sigma(^3H)$ with smaller normalization uncertainty (expected ~1.5%)

Perform a Global fit to the world ^{3}H data after including the Q^2 = 0.11 GeV^2 point and extrapolate to $q^2 \rightarrow 0$.

<u>Data vs SIMC</u>



Data vs SIMC



Data
SIMC
^{3}H
Yield $[\mu C]^{-1}$
θ
$d\theta$
$d\phi$
z vertex
$z - vertex$
Xbj
x_{bj}

Status and Future Work

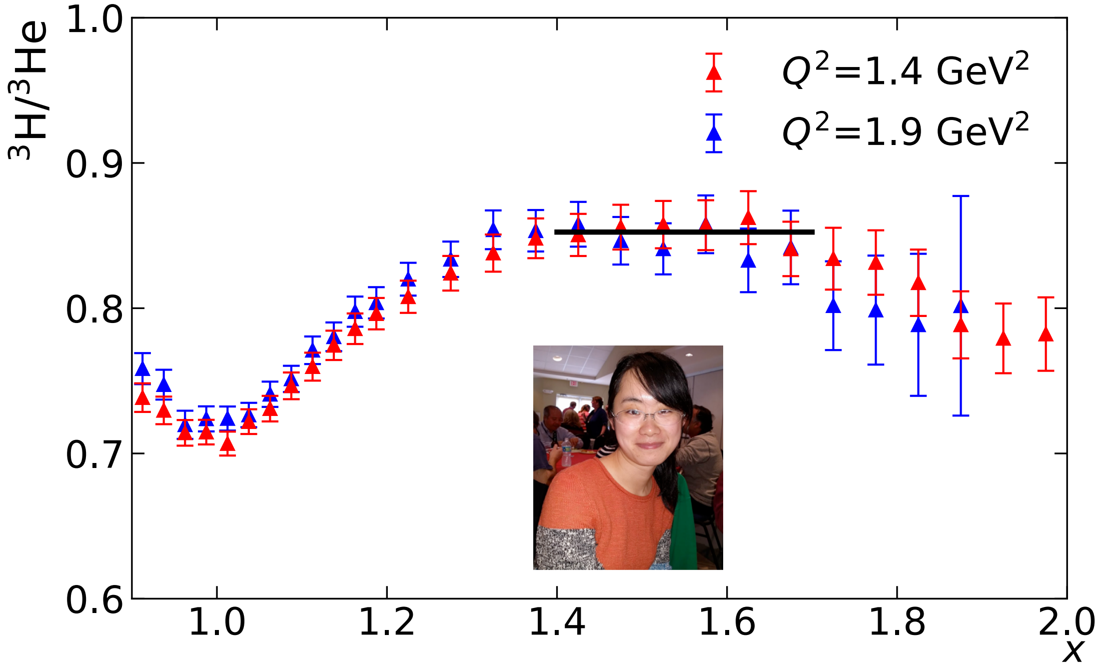
- Data is calibrated and Yields were extracted successfully.
- Simulation and Data comparisons are being optimized.
- Systematic uncertainties are under review.

Next…

- Cross section ratios extraction
- Global fit analysis

Expectations: 1 ^{3}H charge radius
Publication

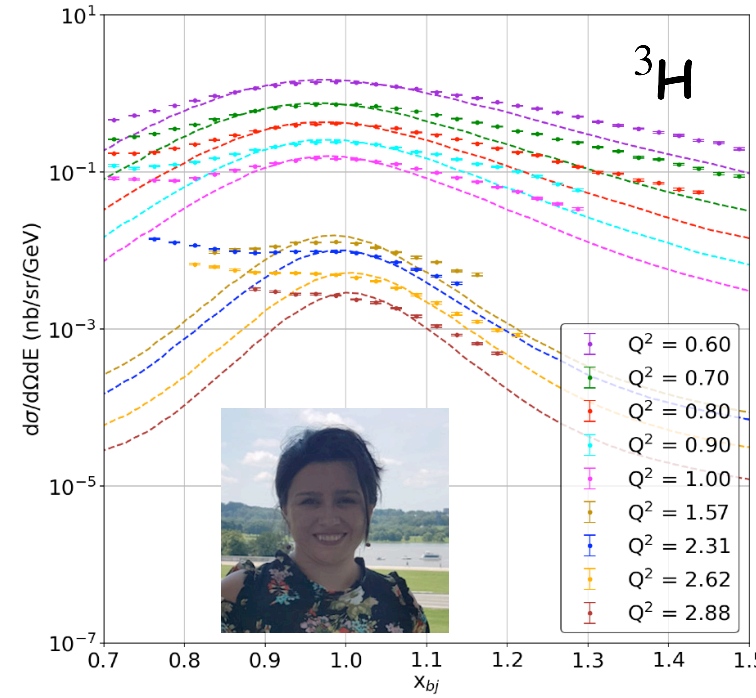
Summary



1 Submitted publication

1+ Publication of the theoretical interpretation + x>2 data.

1 arXiv paper with extracted cross sections



1 Form factor publication

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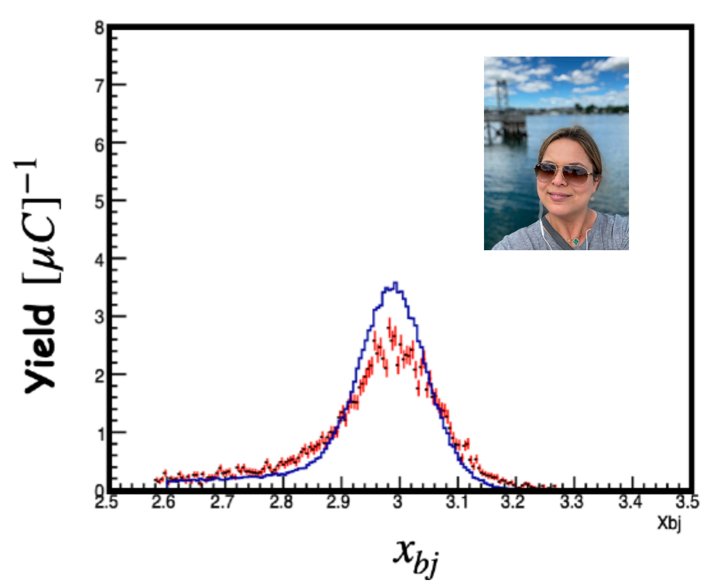

1 ^{3}H charge radius Publication

Thank you!

Special thanks to:
Shujie Li, Leiqaa Kurbani, John Arrington,
Douglas Higginbotham, Elena Long, Karl Slifer, Zhihong Ye
E12-11-112 collaboration
Tritium collaboration
Target group
Hall A staff and collaborators