# Tritium (e,e’) Analysis updates

**Shujie Li**
**on behalf of the E12-11-112 collaboration**

**June 16, 2022 @ JLab Hall A/C Summer Meeting**

# 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 (elastic form factor) , Shujie Li (SRC), Nathaly Santiesteban (GMn)

## Hall A Tritium Experiments:

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

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

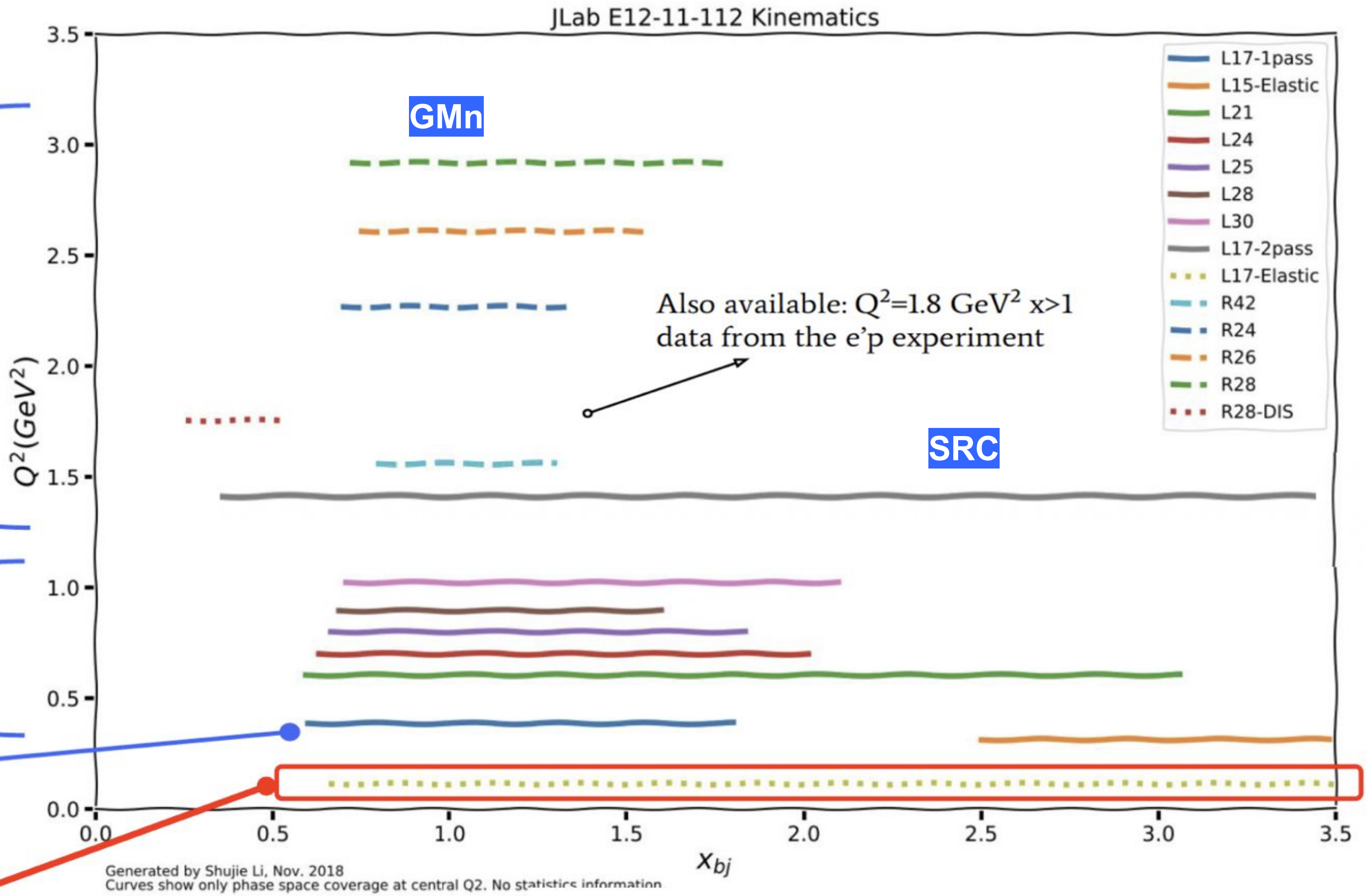
May 2018:

QE scan with 2.2 GeV beam

Dec 2017:

Commissioning

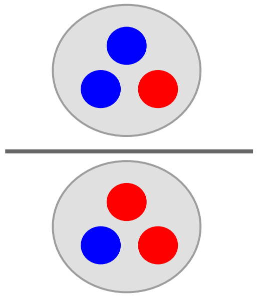
Target "boiling" study ( also QE data at Q2=0.4 GeV2)




**October 2018: Elastic scattering with 1.171 GeV beam**

Elastic form factor

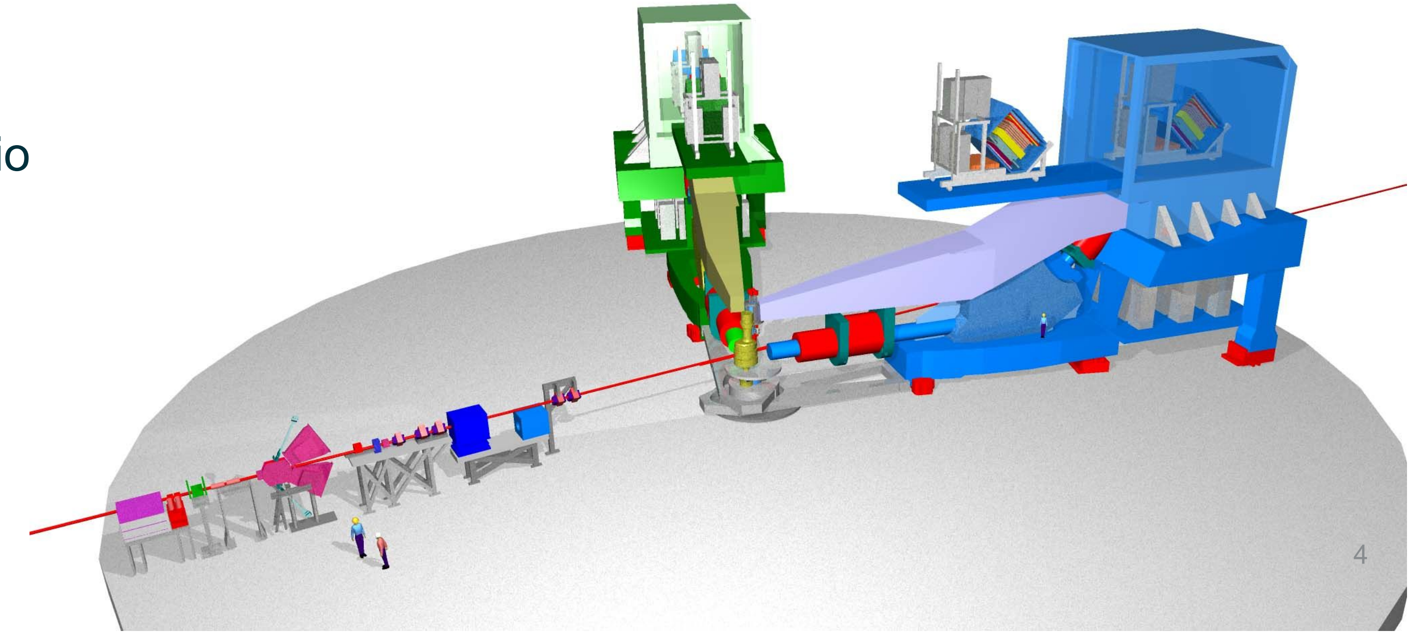
# Inclusive Scattering on the A=3 Mirror Nuclei



Tritium v.s. Helium-3:

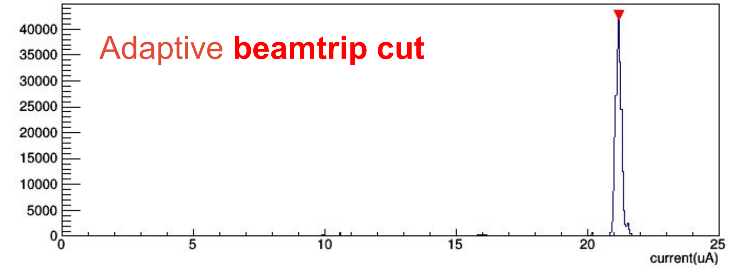
- Large isospin (neutron-proton) asymmetry
- Similar separation energy:  6.26 MeV v.s. 5.49 MeV
- Small Coulomb effect:  V_eff = 0.66 MeV  v.s. 0

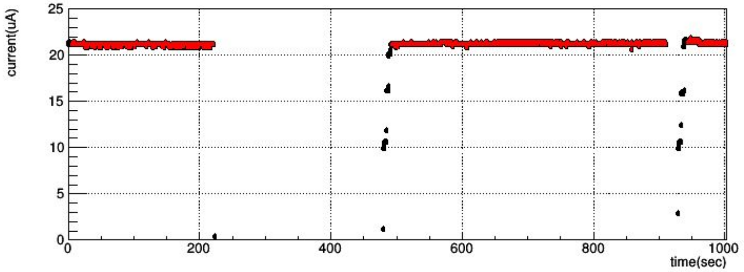
- High statistics
- Calculable* few body system
- Systematic uncertainties canceled in the ratio

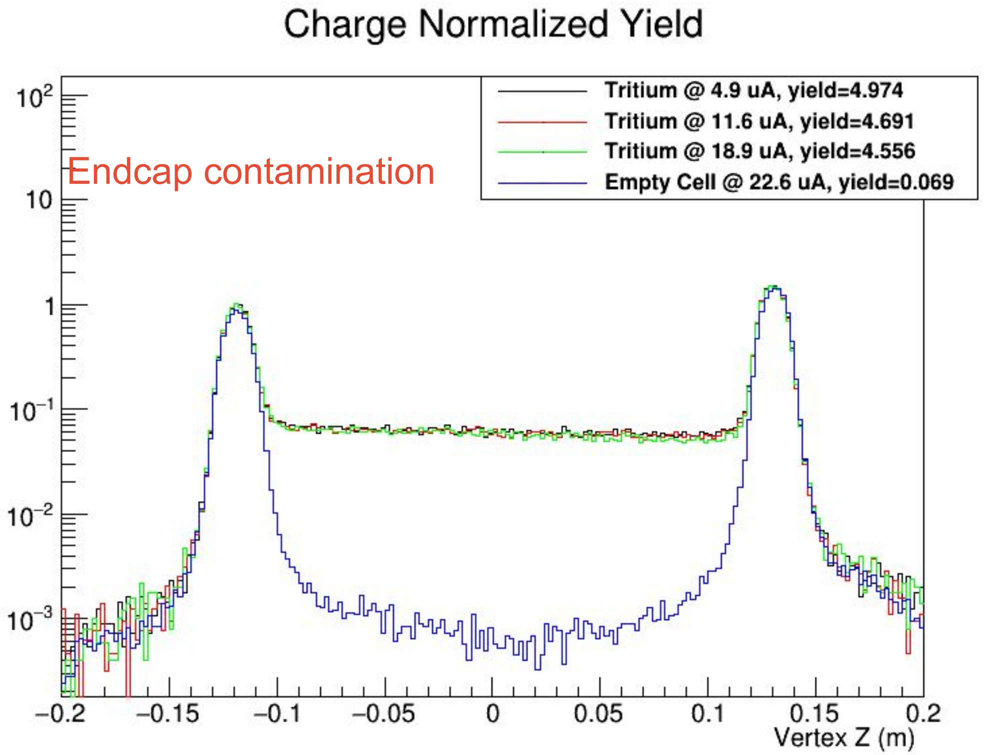


# The Gas Target System: special handling

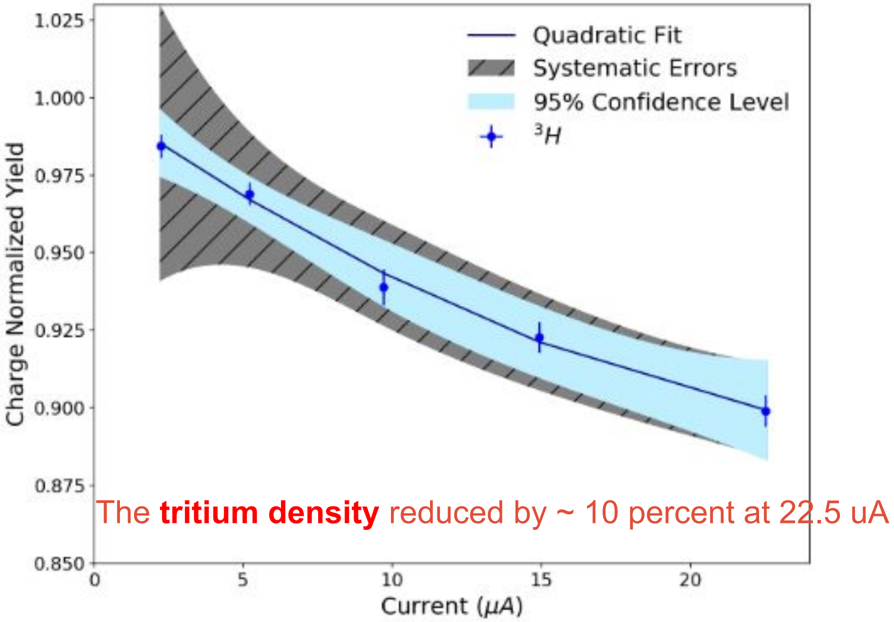
- Maximum current = 22.5 uA on gas cells to minimize the risk of gas leak.
- Endcap (75mg/cm2 Aluminum) being mis-reconstructed into thin gas body (77mg/cm2 Tritium)
- “Boiling”: gas density change along beam path
- Tritium decay correction
- Hydrogen contamination.



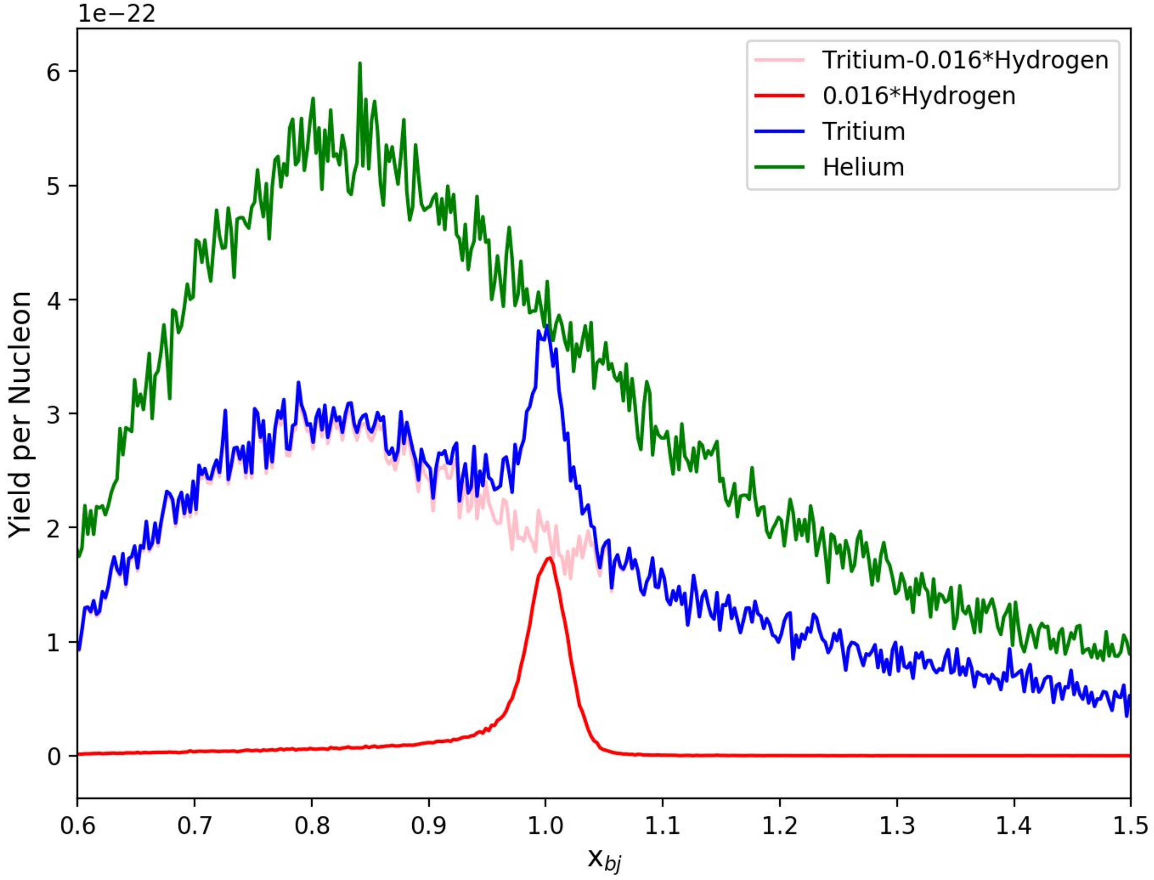




S. Santiesteban et al., https://doi.org/10.1016/J.NIMA.2019.06.025



# The Gas Target System: Hydrogen contamination

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




*gas*

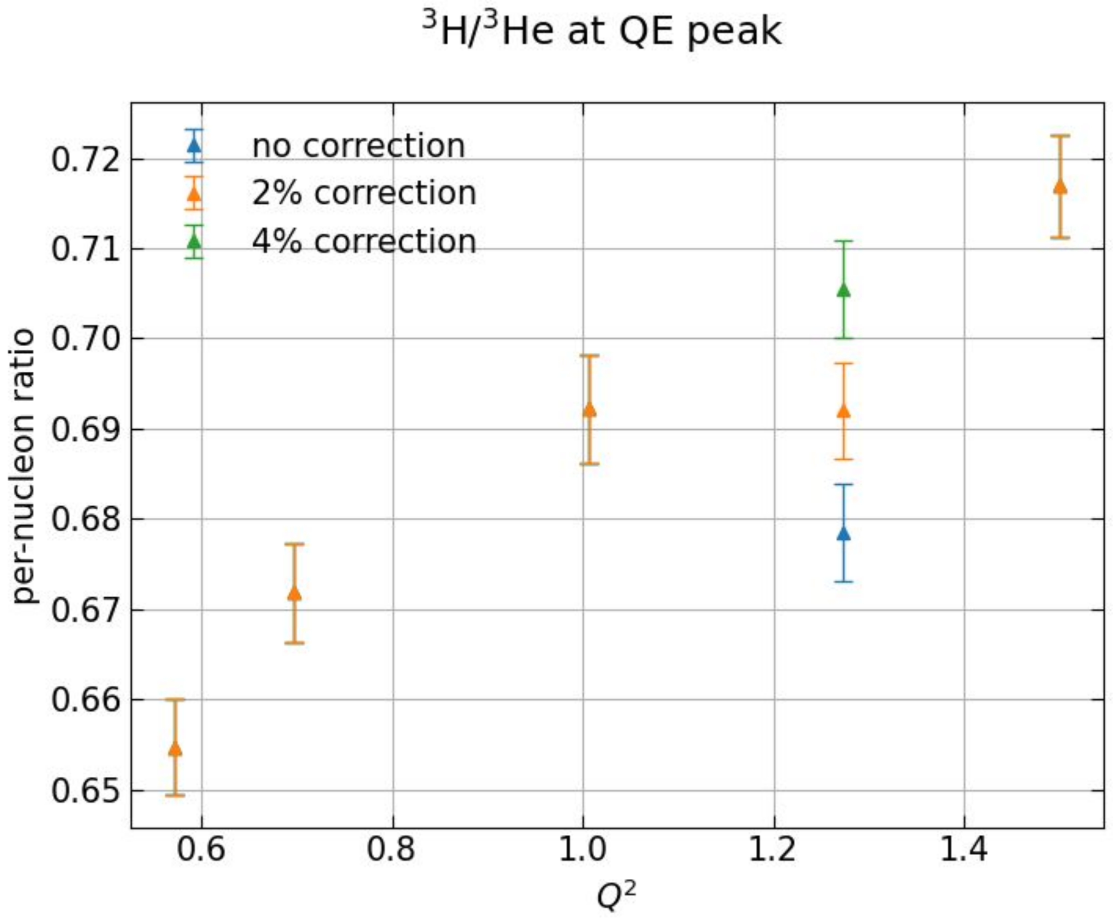
$$H_2O + T_2 \rightarrow HTO + HT$$

*Liquid, stick to the wall at low temperature*

1.6% * rho_hyd * 3 / rho_tri ⇒ 4.1% density loss in tritium cell

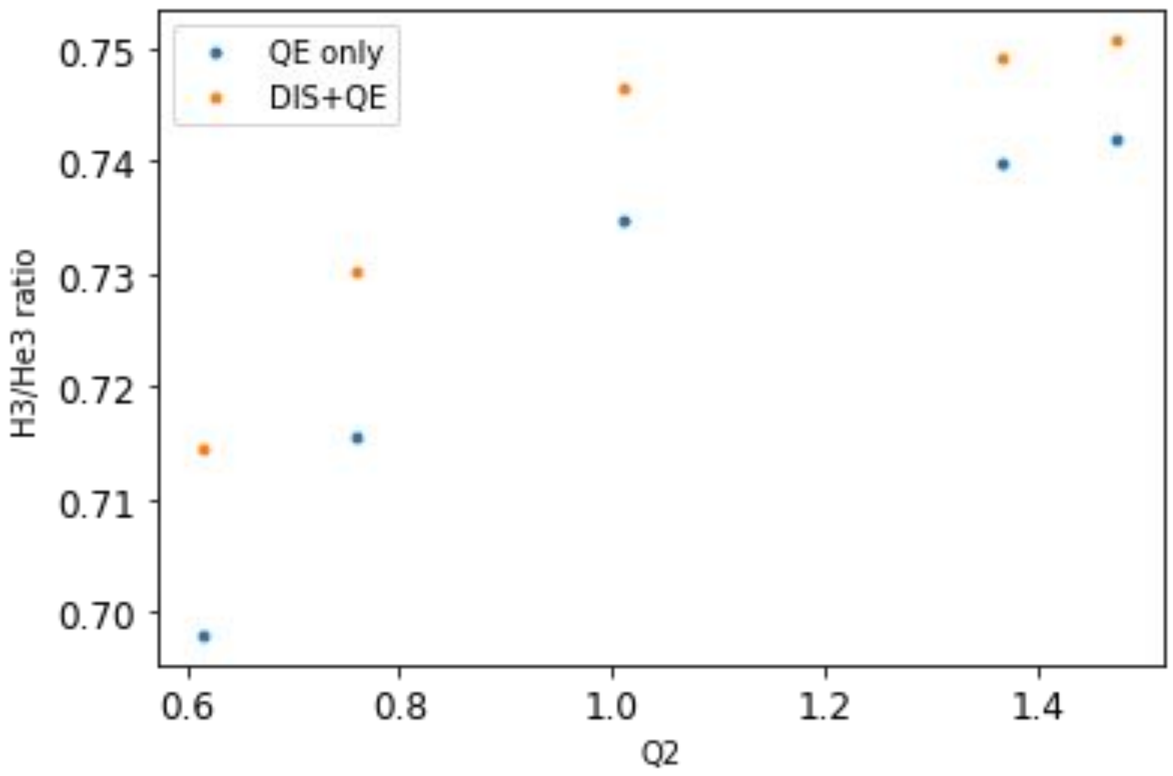
# The Gas Target System: Hydrogen contamination

## Check Tritium Normalization (due to hydrogen contamination) with QE ratios

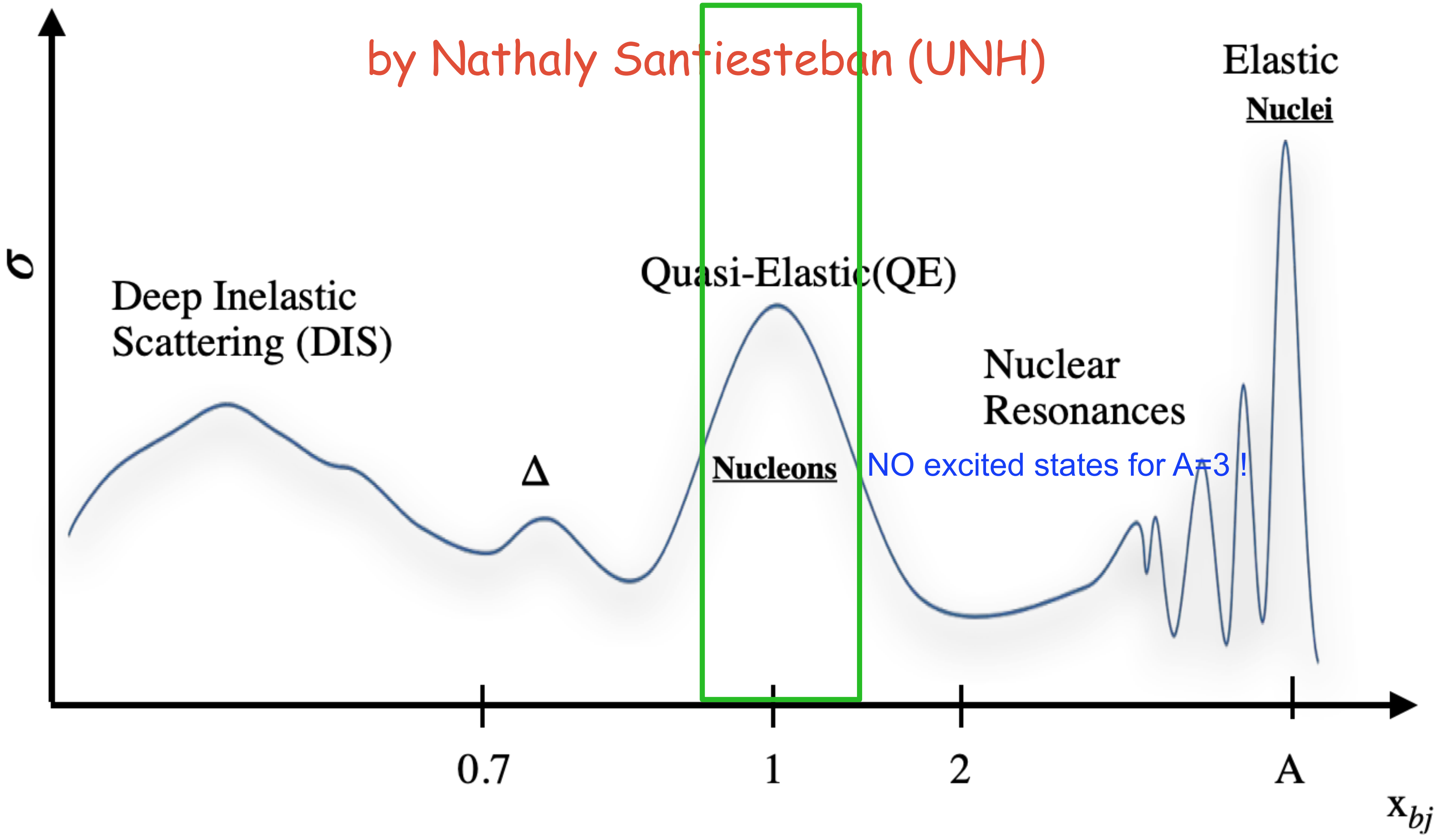



*Weighted average of 4 points bw 0.96 and 1.03, with ptp errors

XEMC model

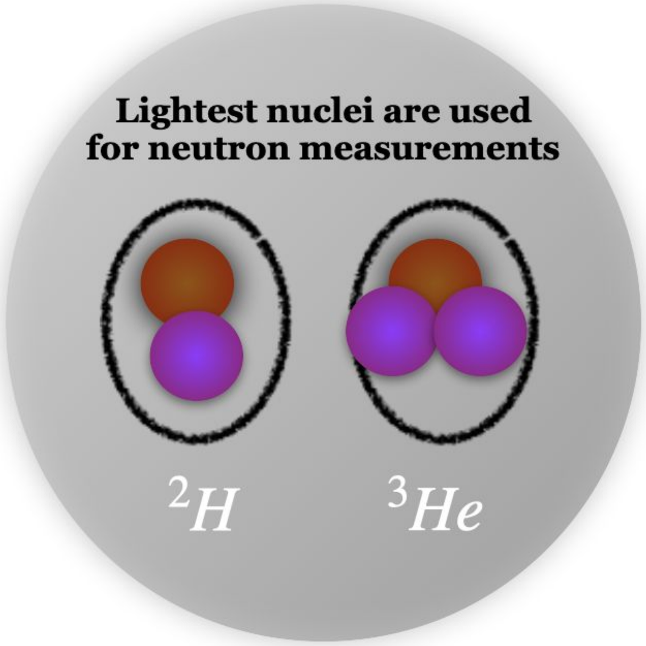


# x=1: GMn Analysis



# Accessing to neutrons

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




**Neutron measurements include:**

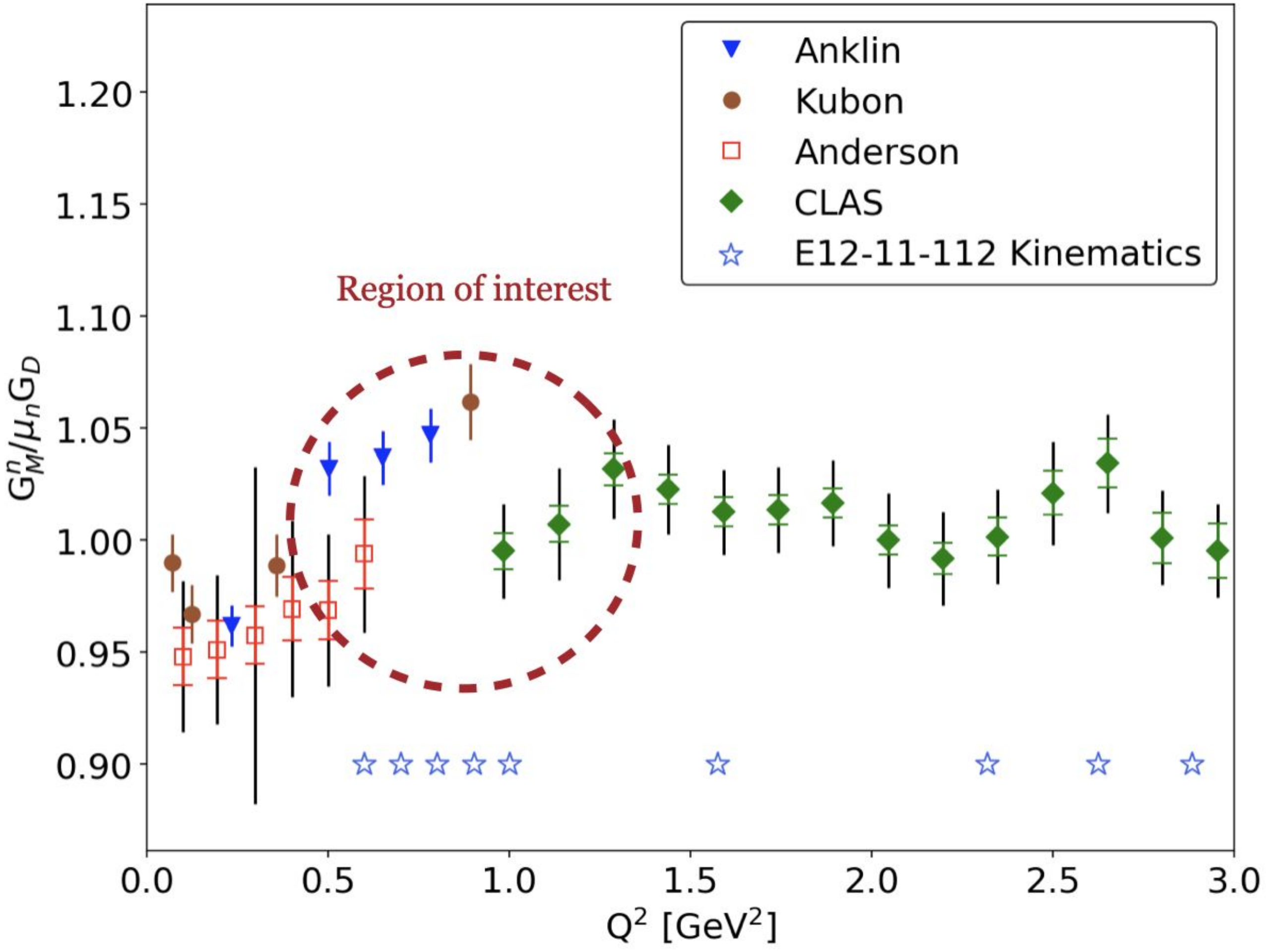
$^3\vec{He}(\vec{e},e')$ QE
polarization experiments

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

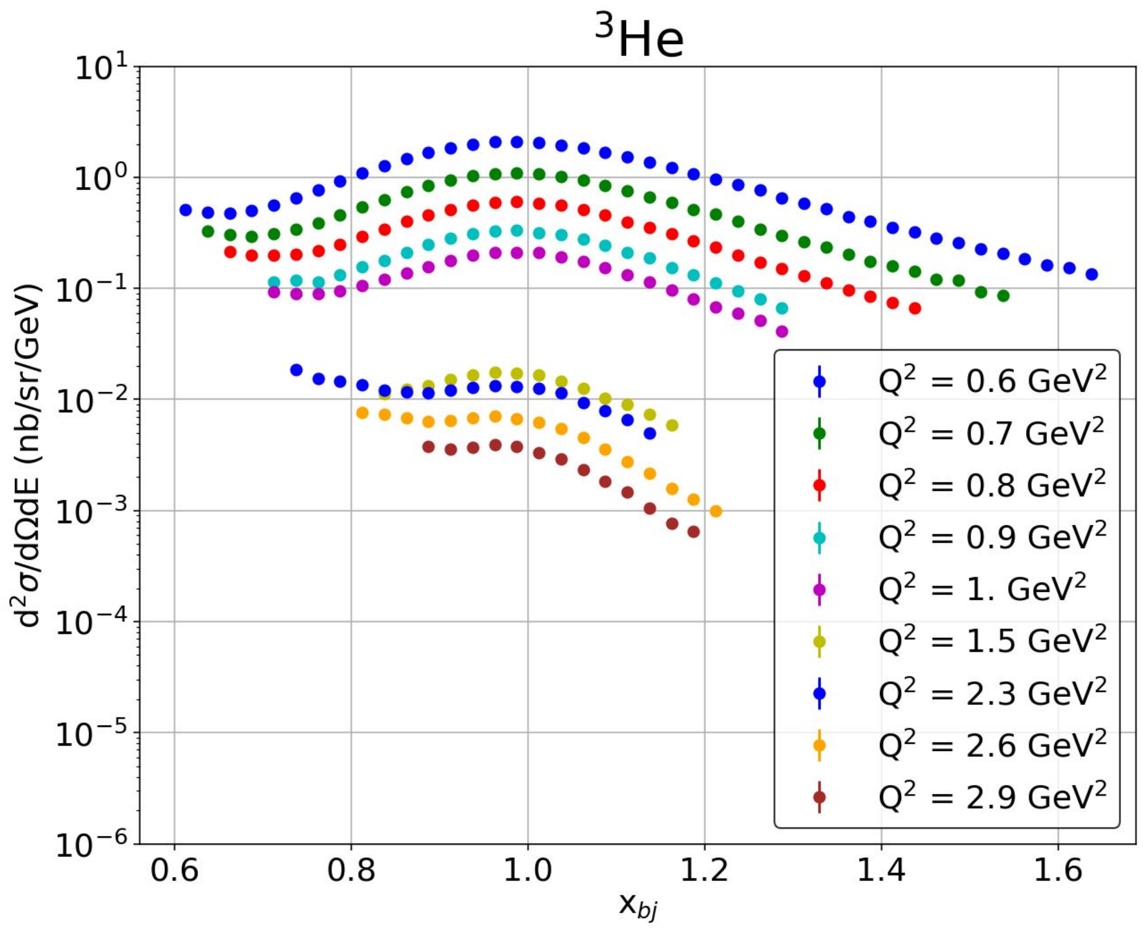
$$\sigma_{3H} \sim 2\sigma_n + \sigma_p \qquad \sigma_{3He} \sim \sigma_n + 2\sigma_p$$

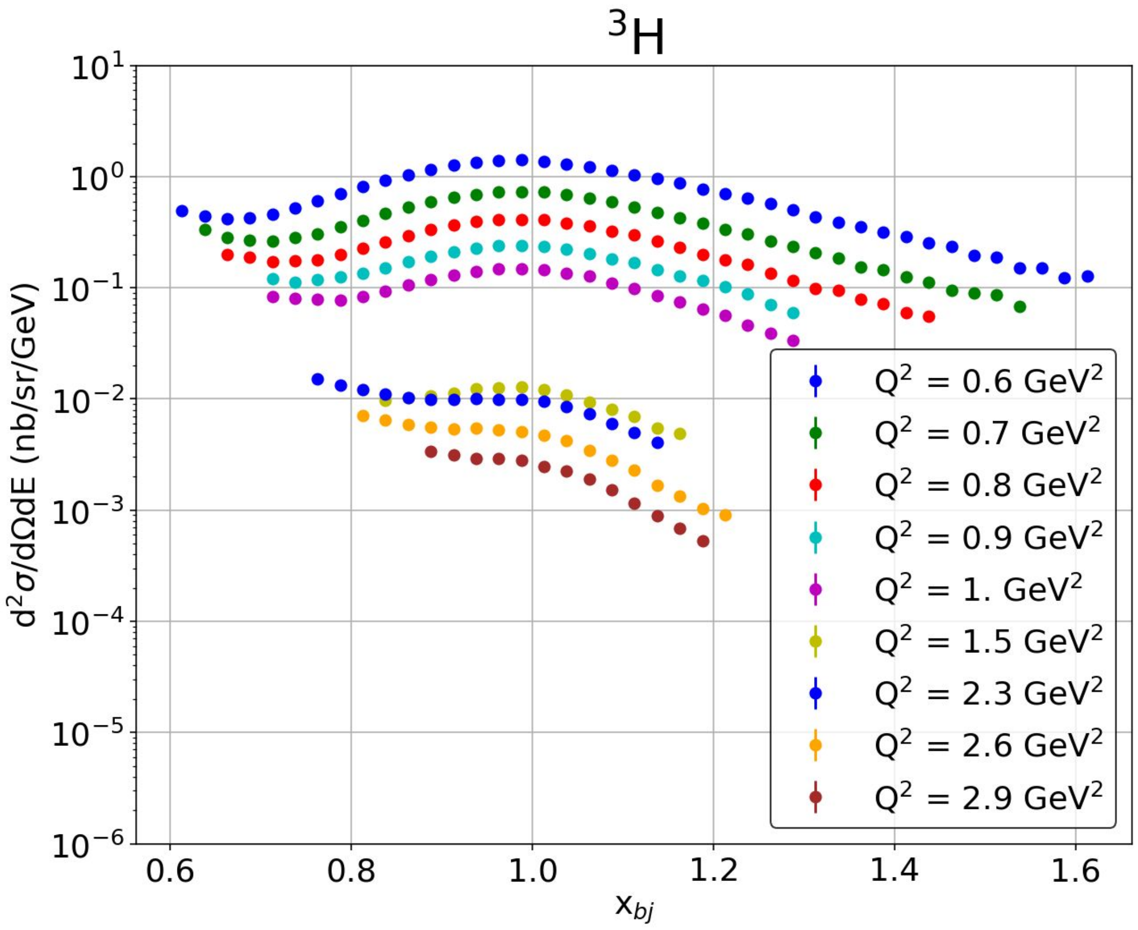
$$R = \frac{\sigma_{3H}}{\sigma_{3He}} \sim \frac{2\sigma_n + \sigma_p}{\sigma_n + 2\sigma_p}$$

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

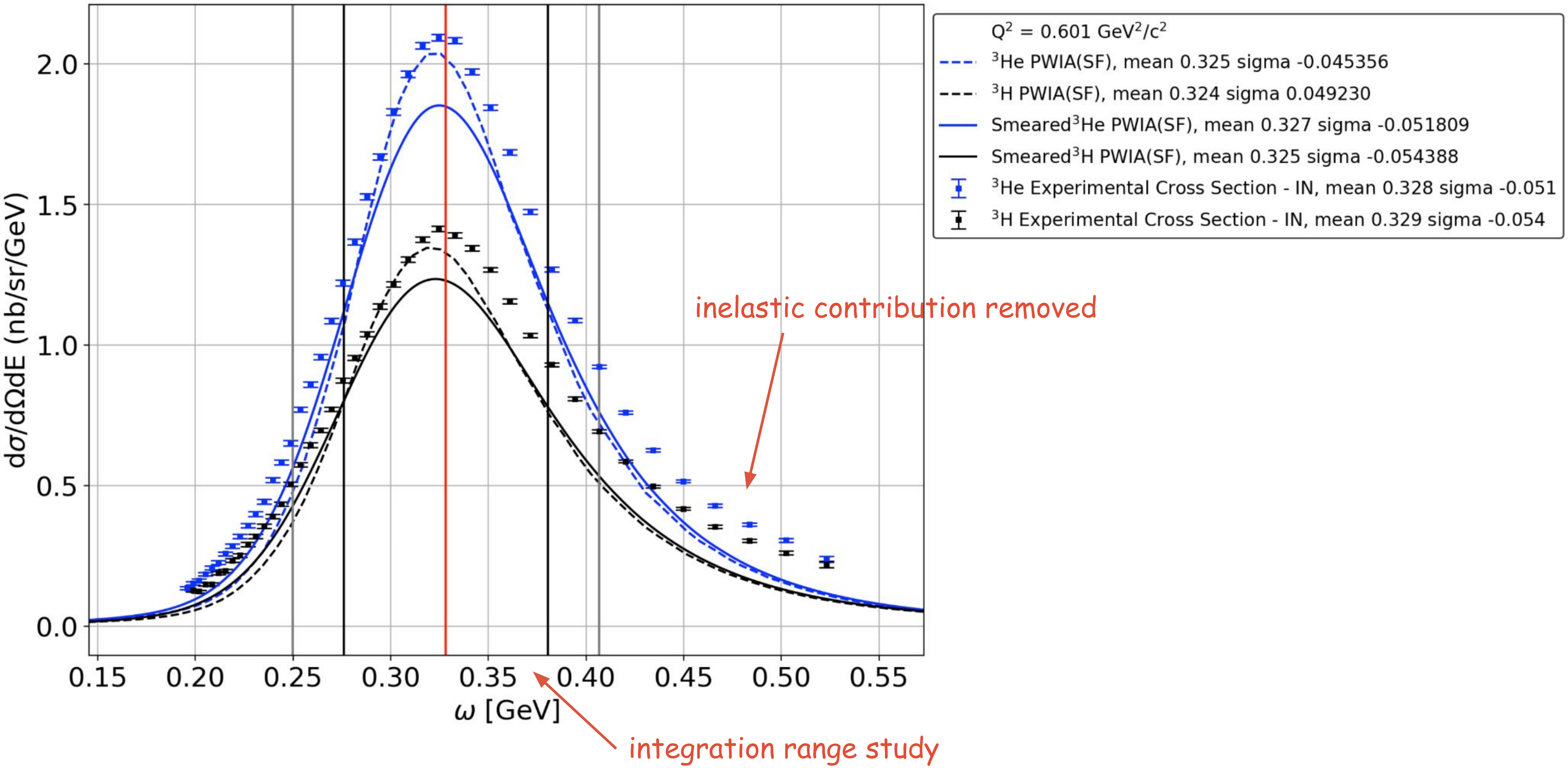
- Clean QE channel
- high stat.
- no need to measure neutron directly
- nuclear corrections
- model of eN cross section

# Extracting QE cross sections

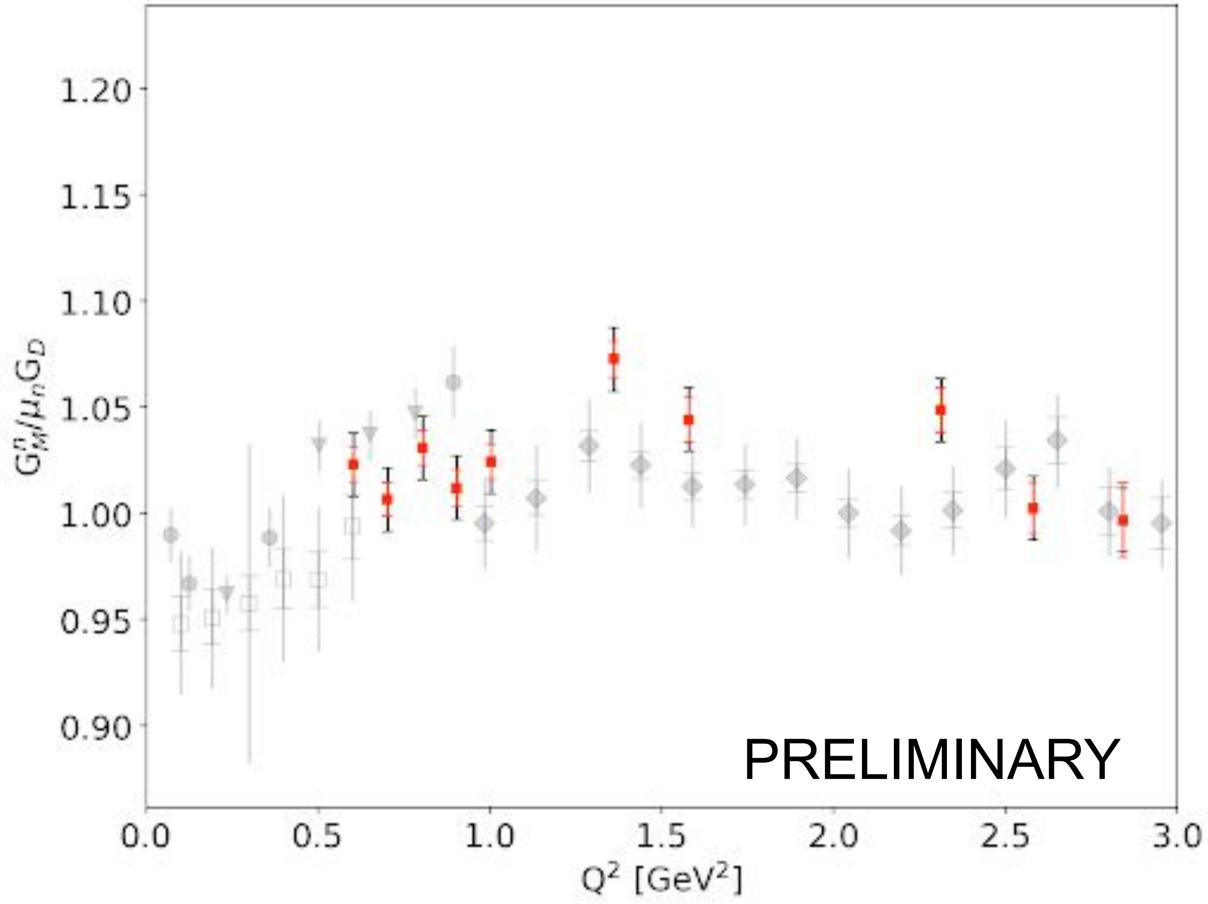


# Extracting QE cross sections



# Preliminary Results



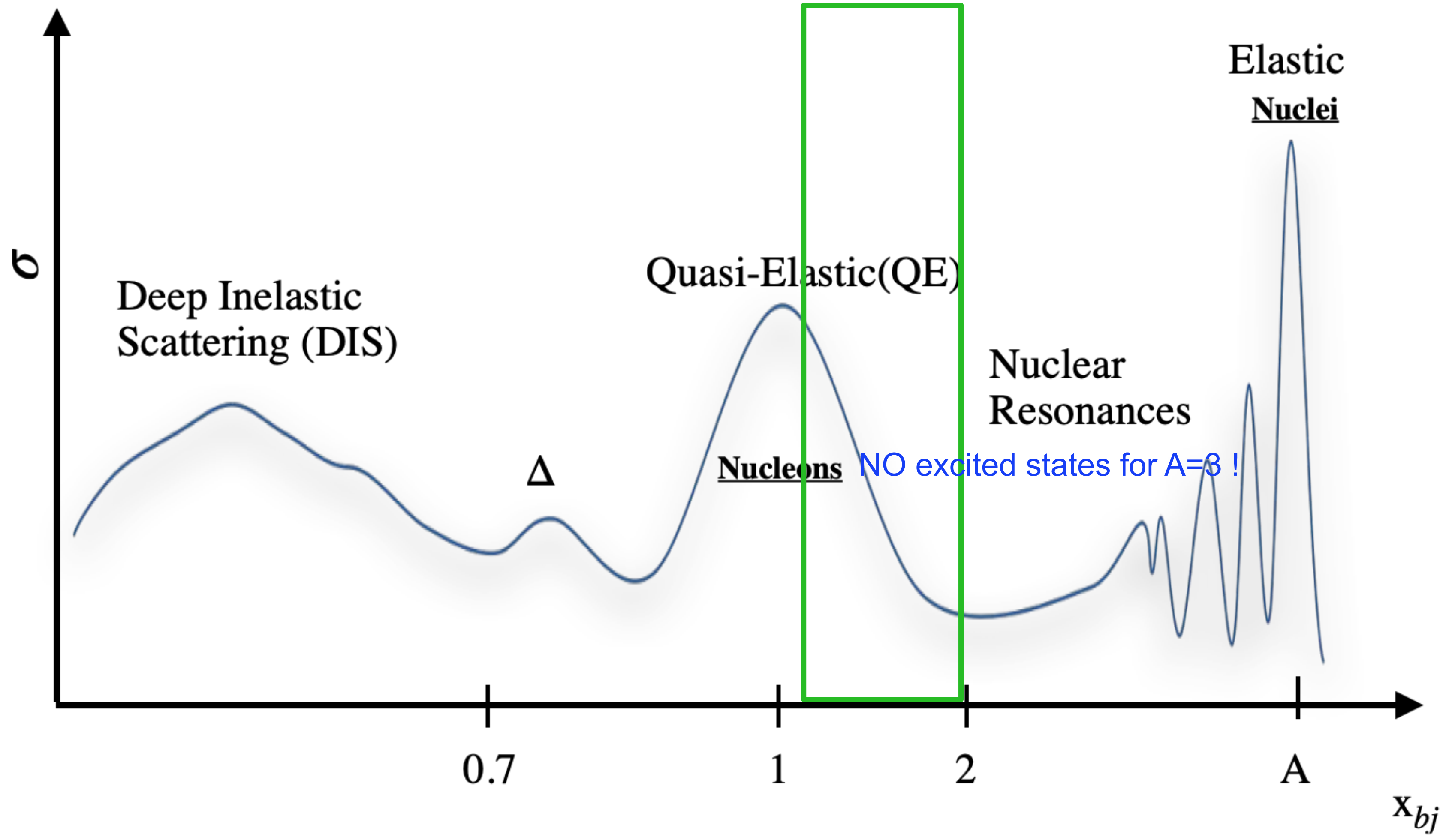

Error bars: red: stat, black: normalization uncertainties

**Status:**

- Looking into details of inelastic subtraction
- Work closely with two theorists, N. Rocco (Fermilab) and A. Lovatto (Argonne Lab) to understand model-dependence

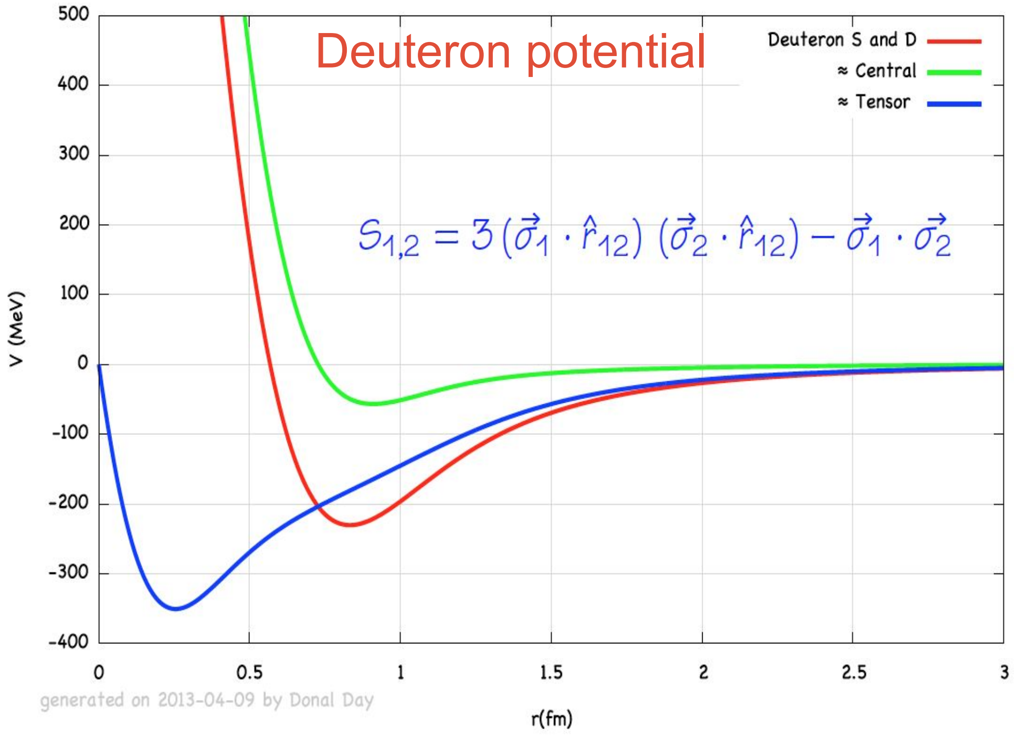
# x>1: Isospin-dependence of SRC

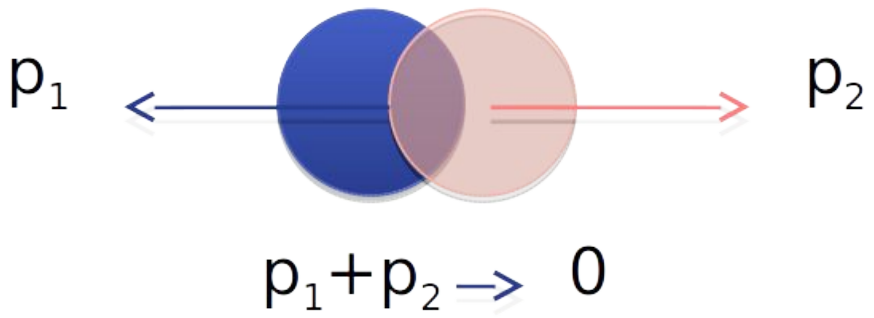
by Shujie Li (LBL)



# 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.



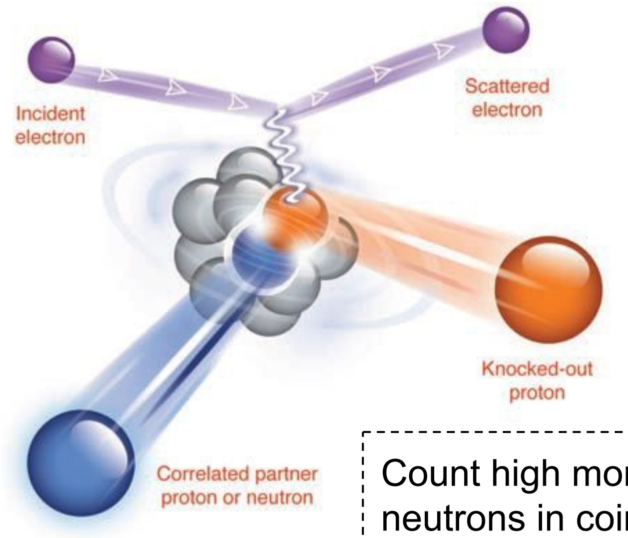




**N-N SRC pair in nuclei:**

- large back-to-back momentum, low excitation state
- fraction of SRC pairs in nuclei ?
- in which T and S configuration ?

# Quasi-elastic Scattering

to access the initial state of correlated nucleons




Count high momentum proton and neutrons in coincidence

**Exclusive measurement:**

- Measure the scattered nucleon (and the paired one), **direct** knowledge of the final state particle information ( momentum, angle, etc)
- Subject to re-scattering and charge exchange
- Low statistics

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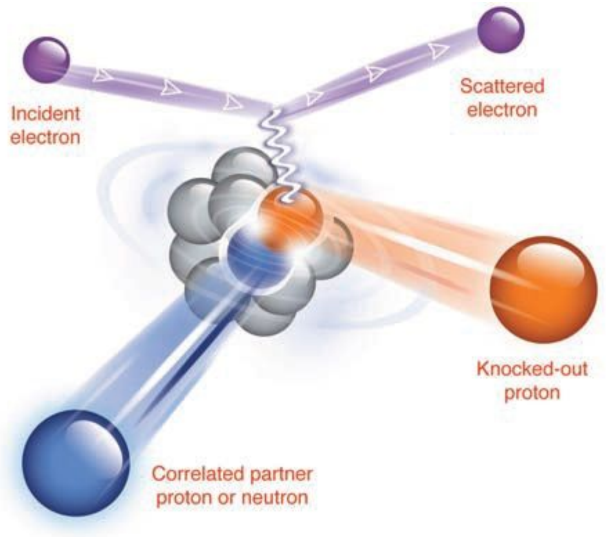


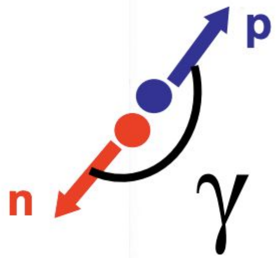


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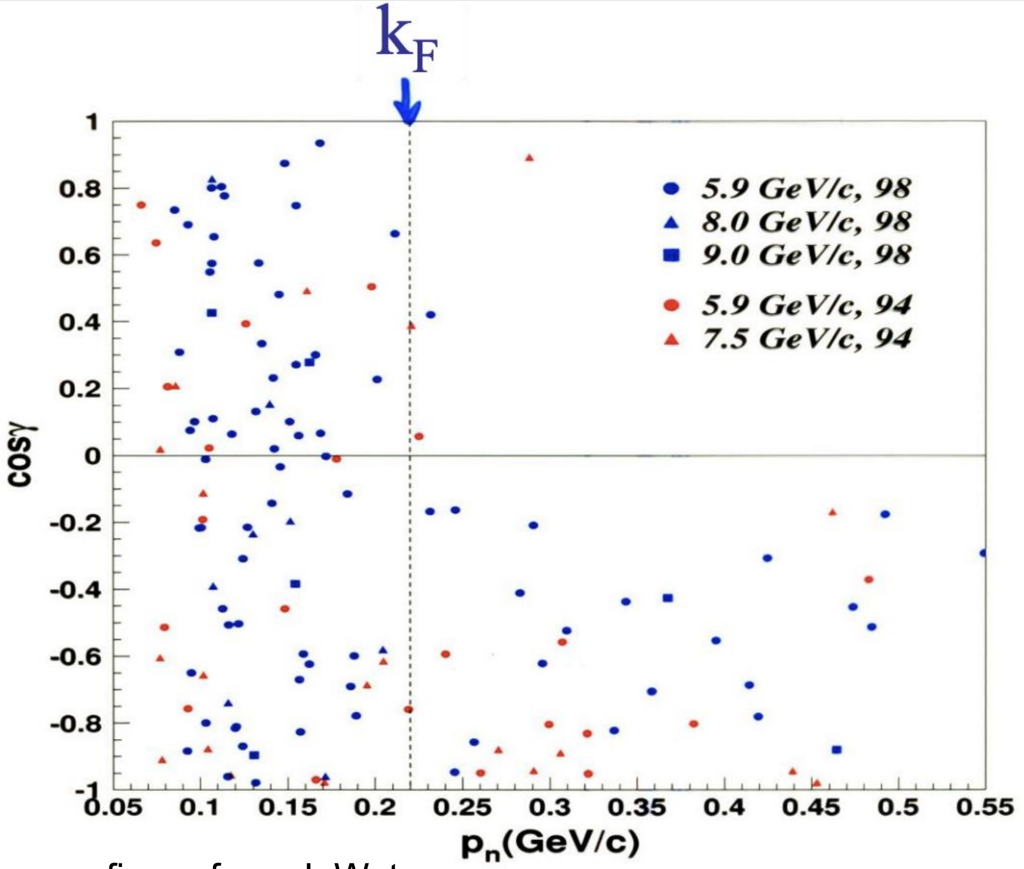


figure from J. Watson

**C(p,p'pn)X at BNL**: most high momentum nucleon pairs have strong **back-to-back** initial angle correlation.

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

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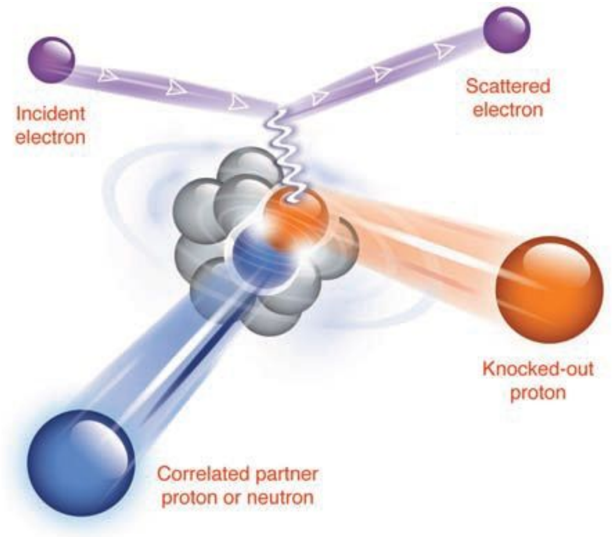


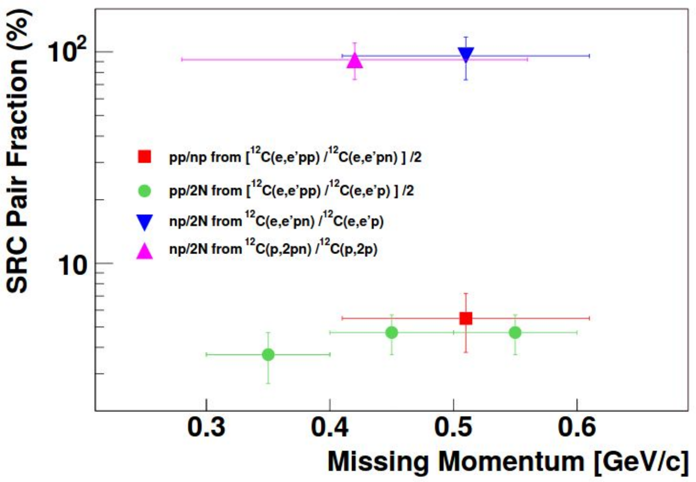


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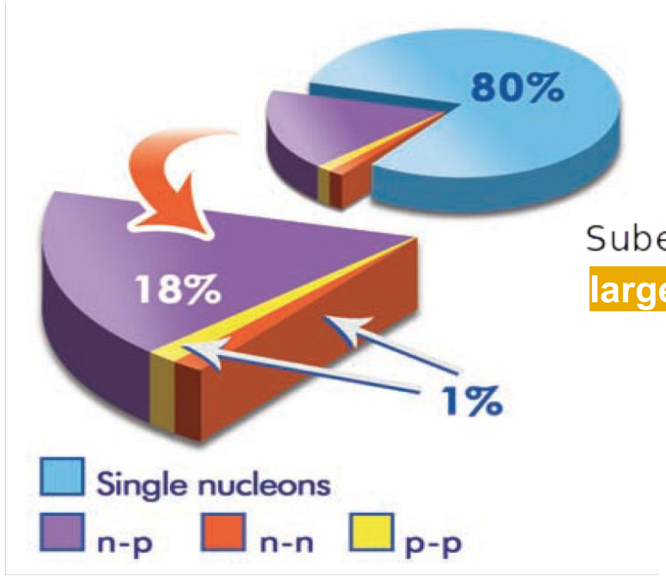


Subedi et al, Science 320, 1476 (2008)

large n-p dominance of SRC in C12

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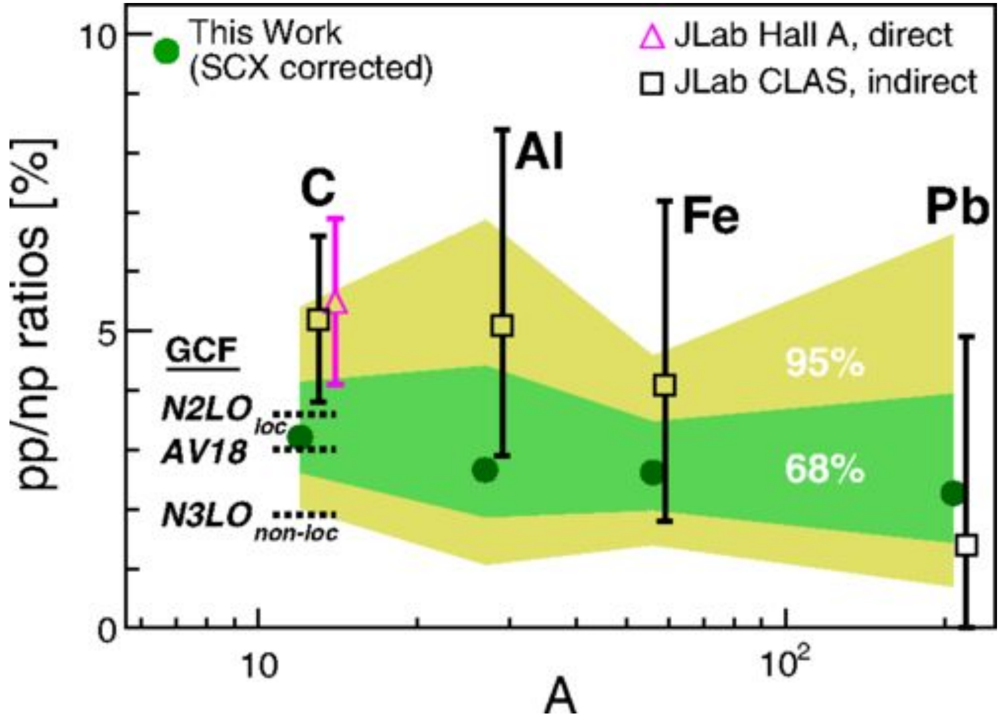
to access the initial state of correlated nucleons

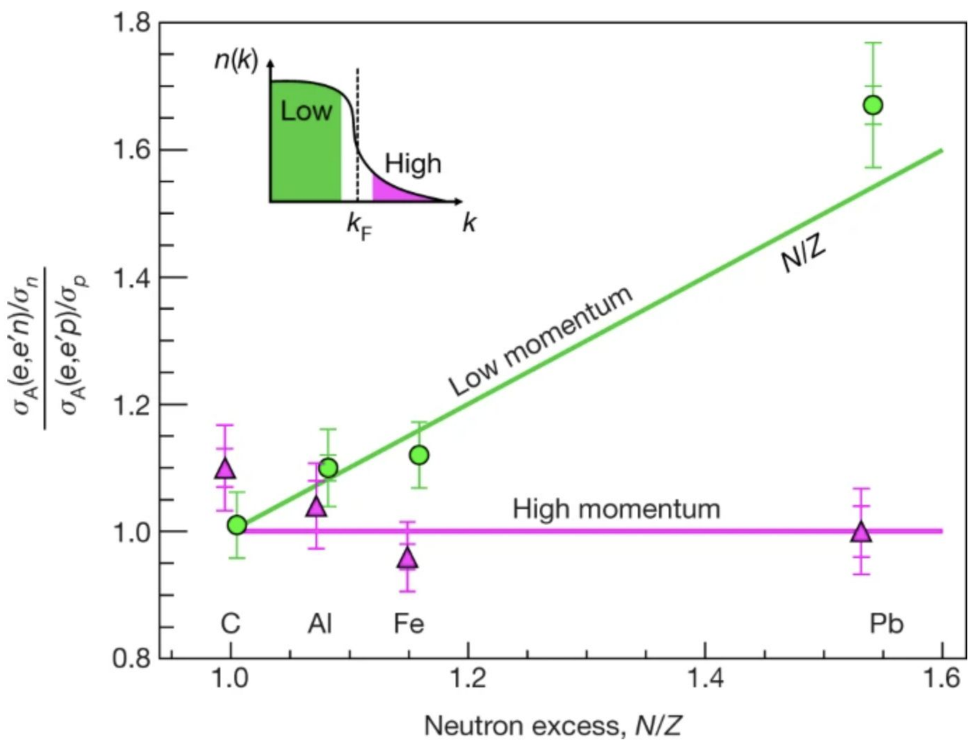
**Exclusive measurement:**

- Measure the scattered nucleon (and the paired one), **direct** knowledge of the final state particle information ( momentum, angle, etc)
- Subject to re-scattering and charge exchange
- Low statistics, large uncertainties

large n-p dominance of SRC in heavy nuclei

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



# Quasi-elastic Scattering

to access the initial state of correlated nucleons

**Inclusive measurement:**

- Calculate the nucleon initial momentum **range** from electron kinematics

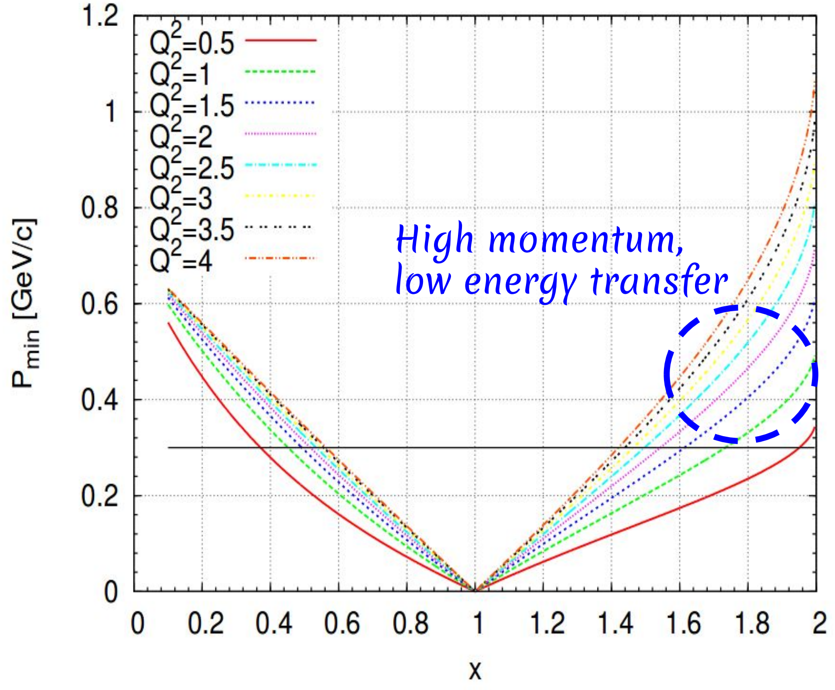
- High statistics
- Need high x, high Q2
- Competing process e.g. meson exchange current

Probability to find 2N SRC in nucleus A

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

Cross section from 2N SRC

N. Fomin et al, Annual Review of Nuclear and Particle Science 2017 67:1, 129-159



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**At 1.4<x<2:**

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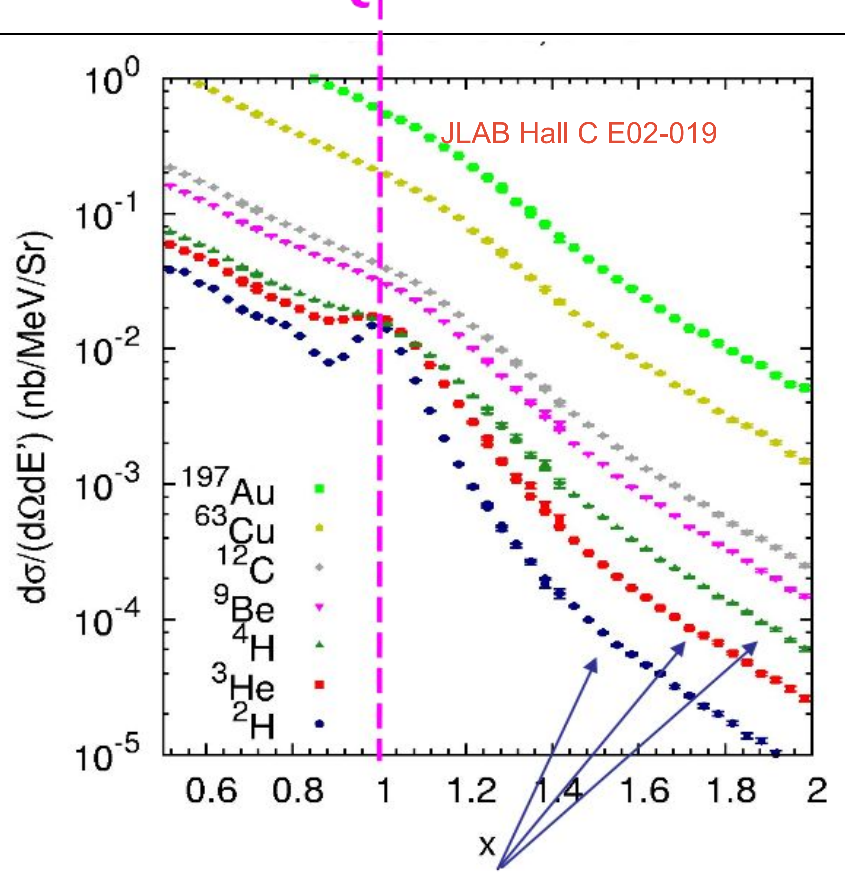
Cross section from 2N SRC




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

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

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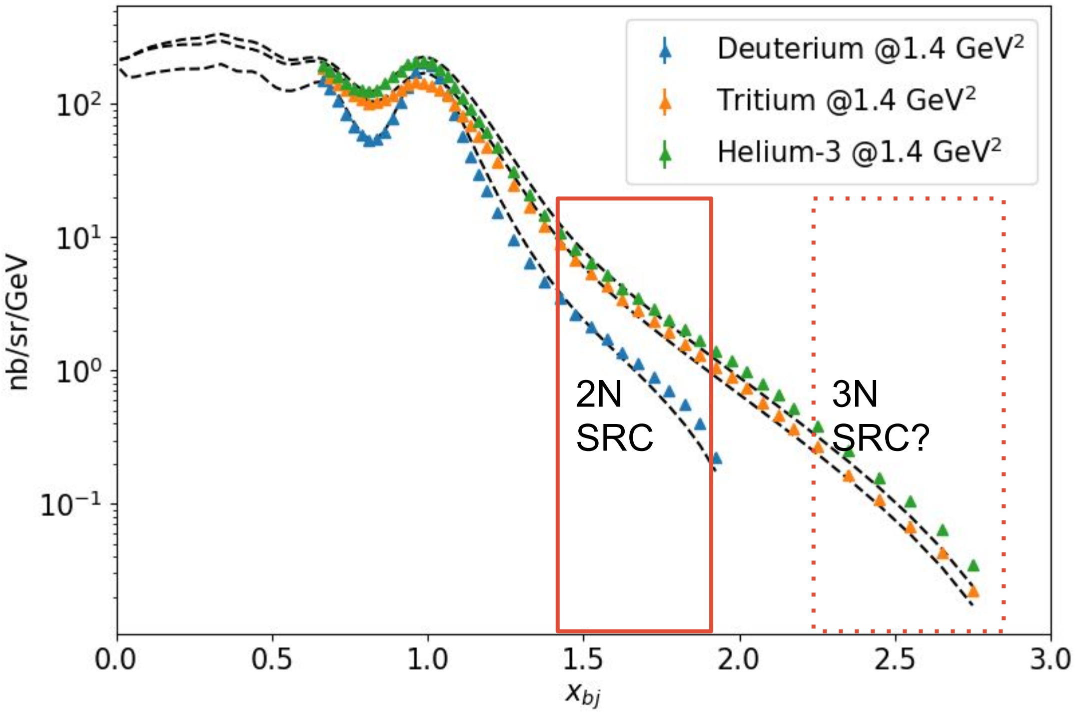
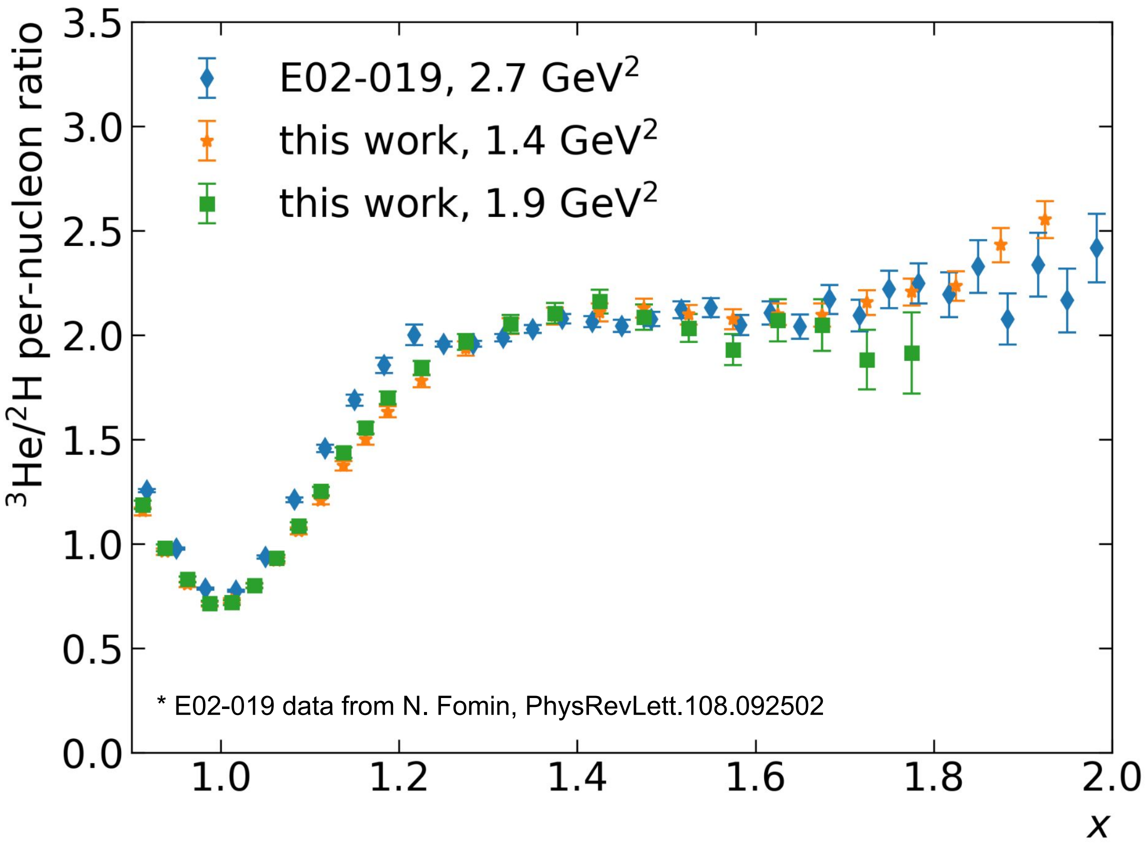
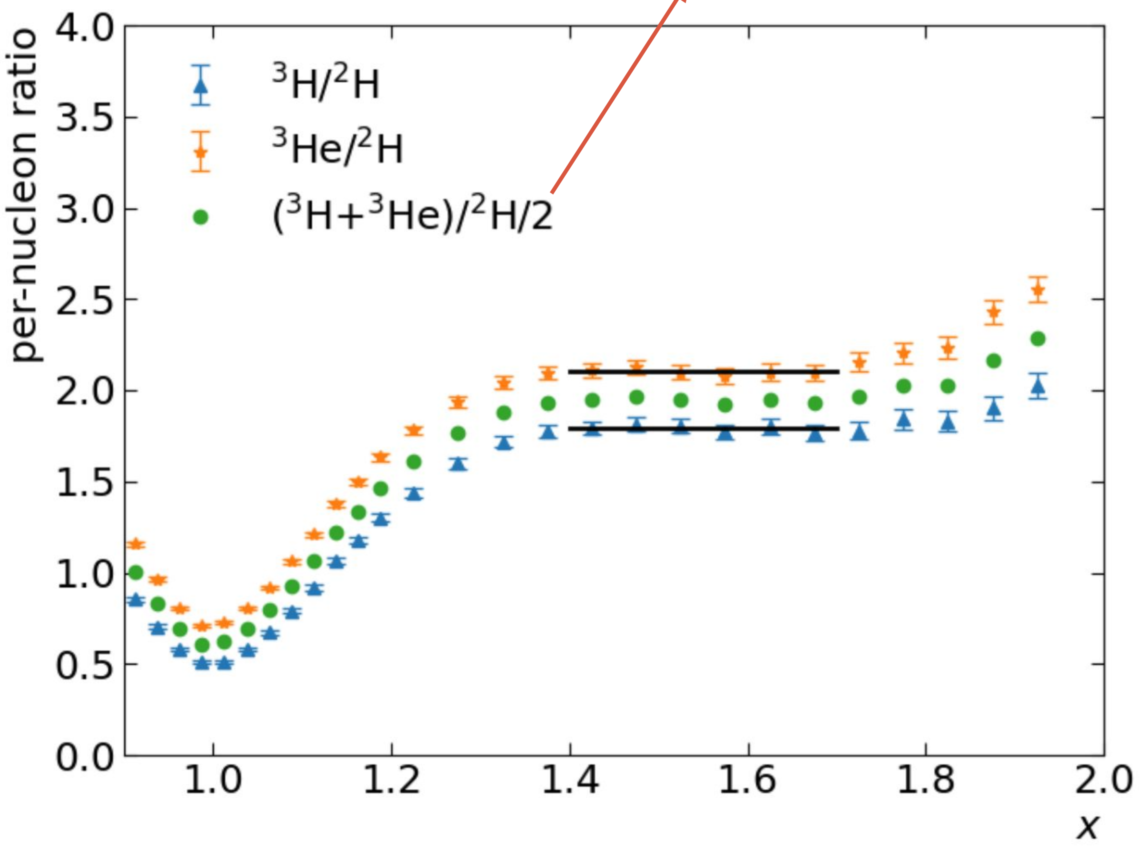



High momentum tails (x>1.4) yield constant cross section ratio if np-SRC dominates

# Plateaus in A/D ratios

will be combined with MARATHON EMC results to study EMC-SRC relation



# Extract np/pp SRC fraction from tritium/helium-3 ratio:

not always possible from inclusive data

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

Offshell elastic xsection (de Forest “cc1”)

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

number of pp to np pairs ratio（Assume the same in tritium and helium-3)

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

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

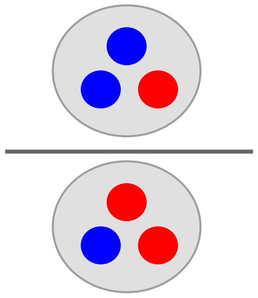
**if np dominance:**

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

**if no isospin preference:**

1 pp and 2 np pairs in He3 from pair counting

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



2 np + 1 nn pairs

2 np + 1 pp pairs

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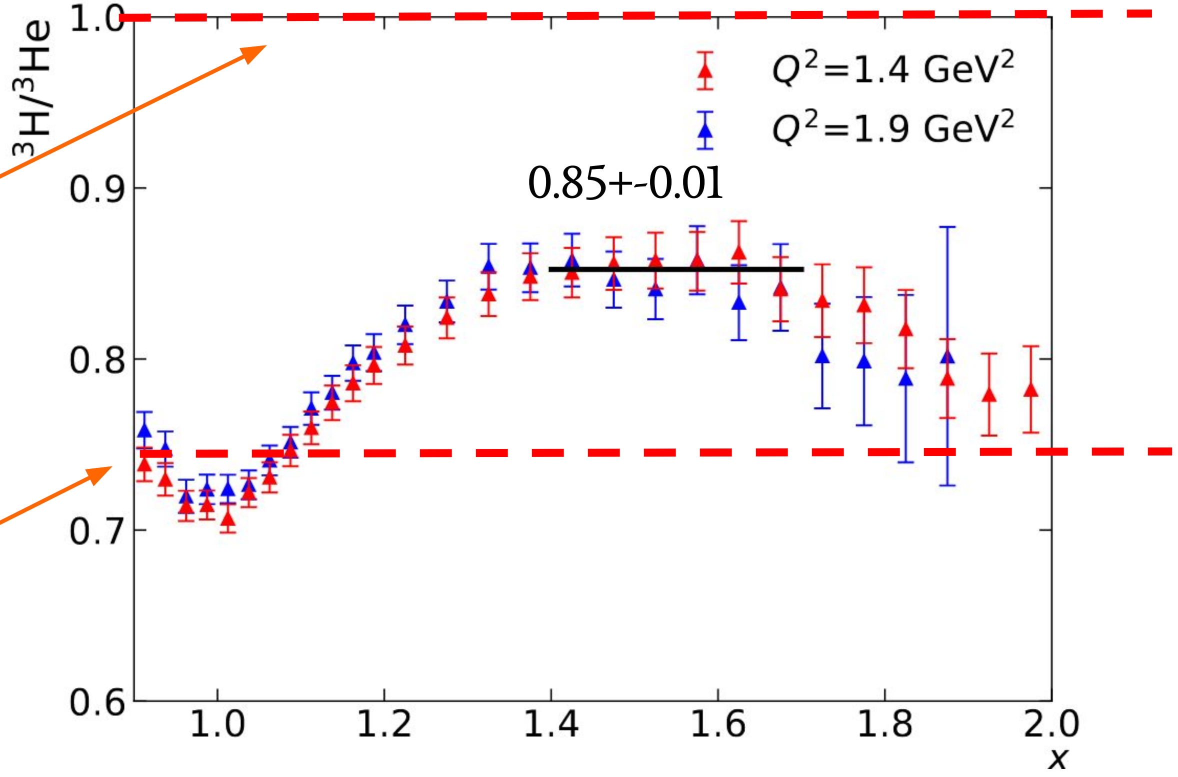


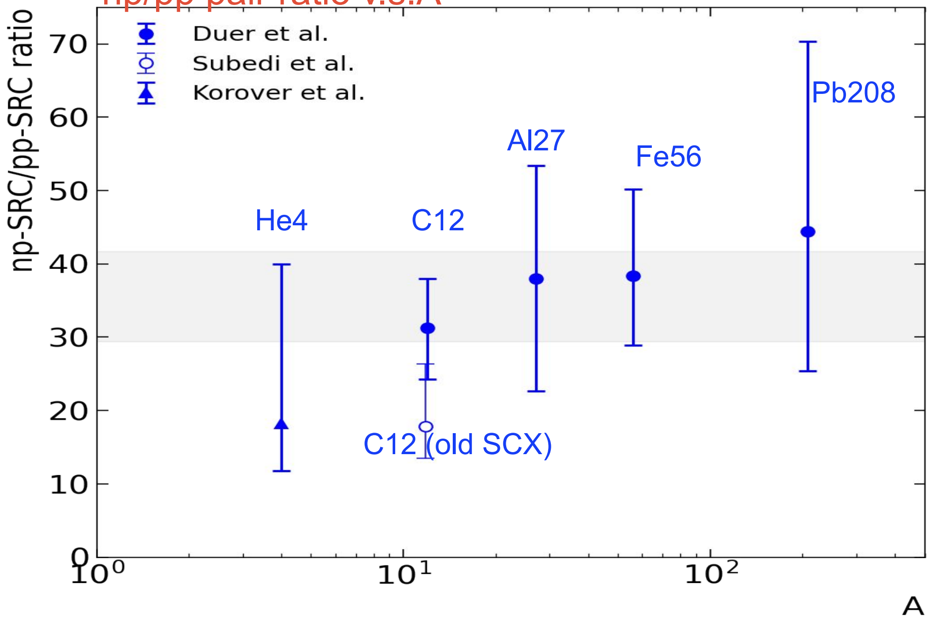
# Not-so-strong Isospin dependence in A=3 nuclei

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

correction due to center-of-mass motion difference:
2MeV b/w 3H and 3He, 12 MeV b/w pp and np

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

np/pp pair ratio v.s.A





References:

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

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e'pN in Solid blue: Duer, M.et al.Phys. Rev. Lett.122, 172502 (2019)

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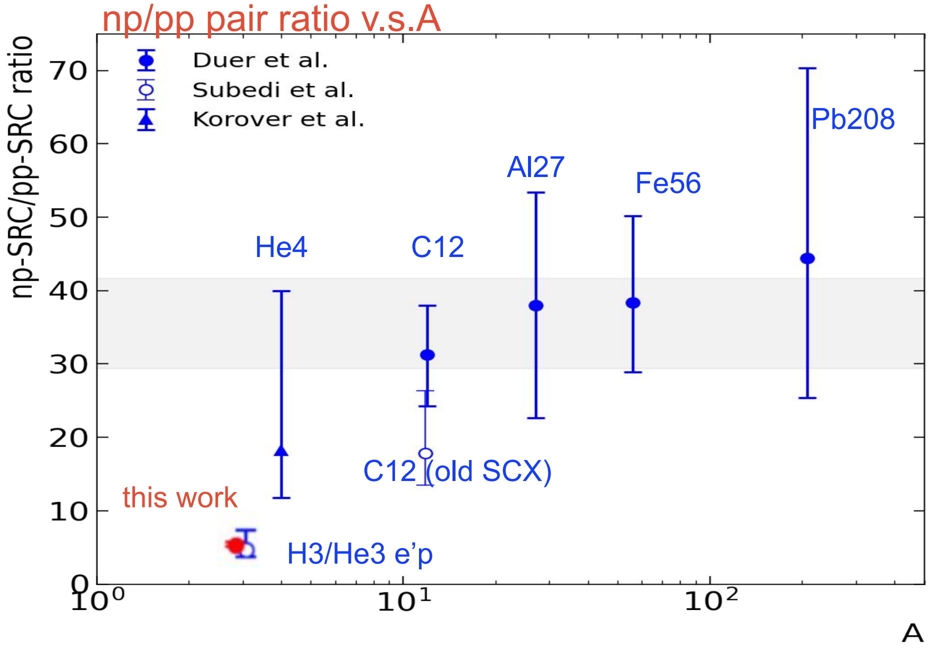


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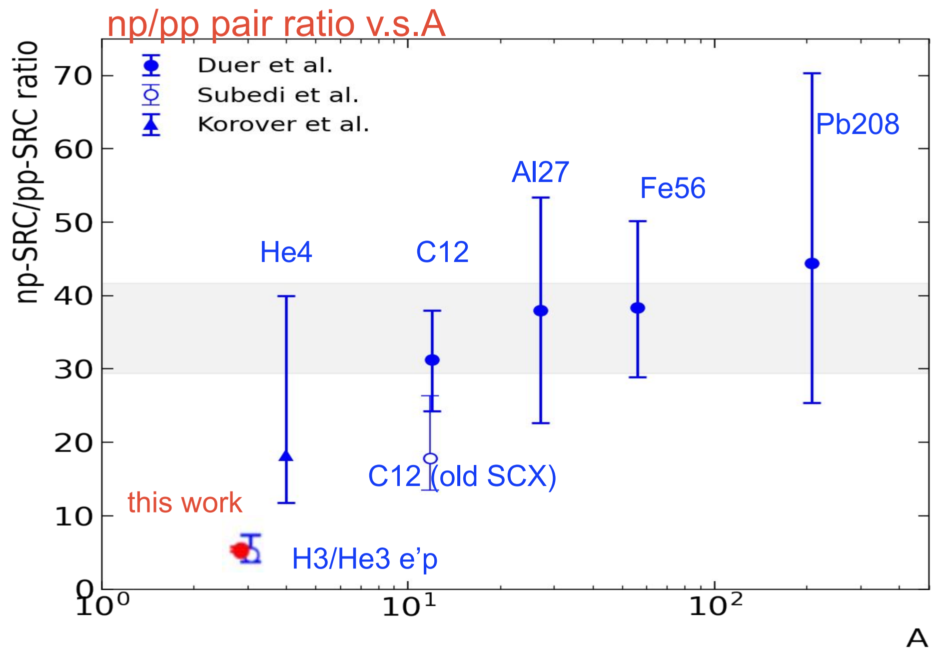
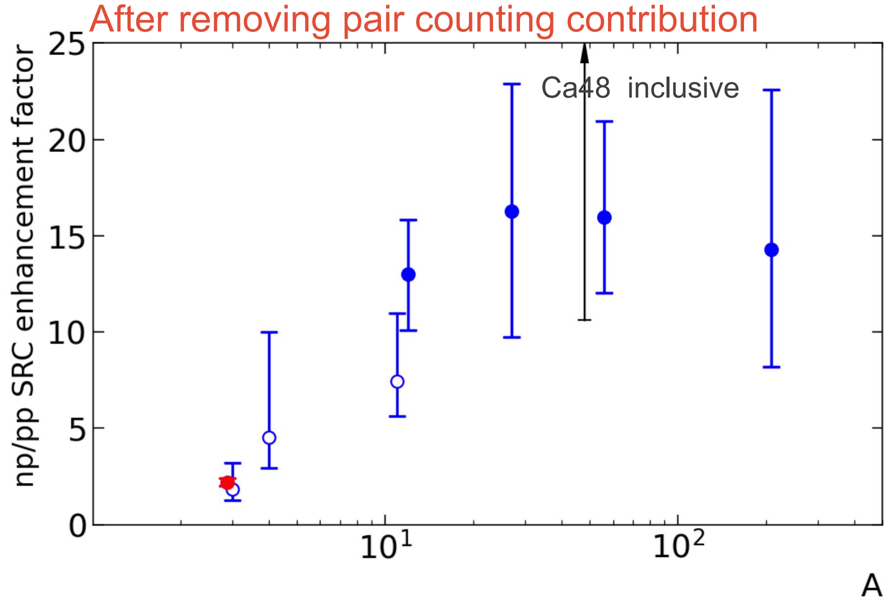
2MeV b/w 3H and 3He, 12 MeV b/w pp and np
(Ciofi degli Atti, Claudio and Morita, Hiko, 2017)

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
to be published on Nature




References:

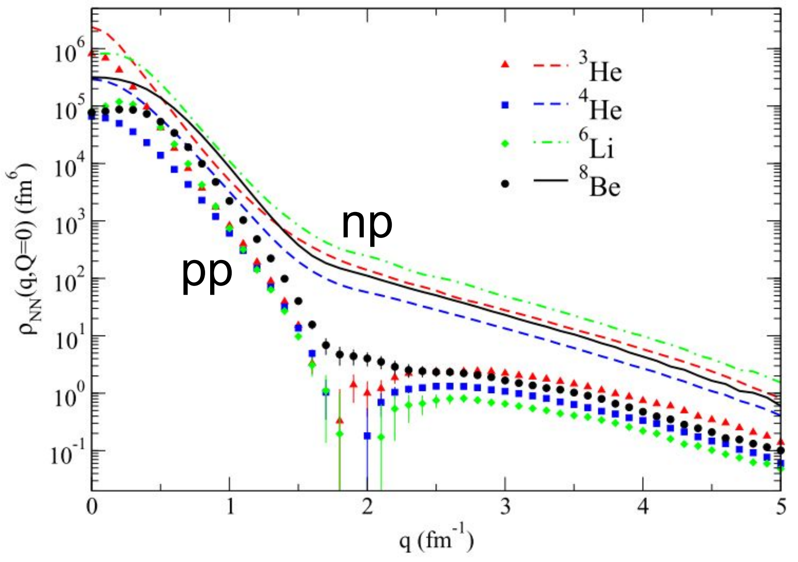

inclusive:
Ca48: Nguyen, D. et al. Phys. Rev. C, 102, 064004 (2020)

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)

# Towards a full calculation

**np-dominance from VMC calculations**

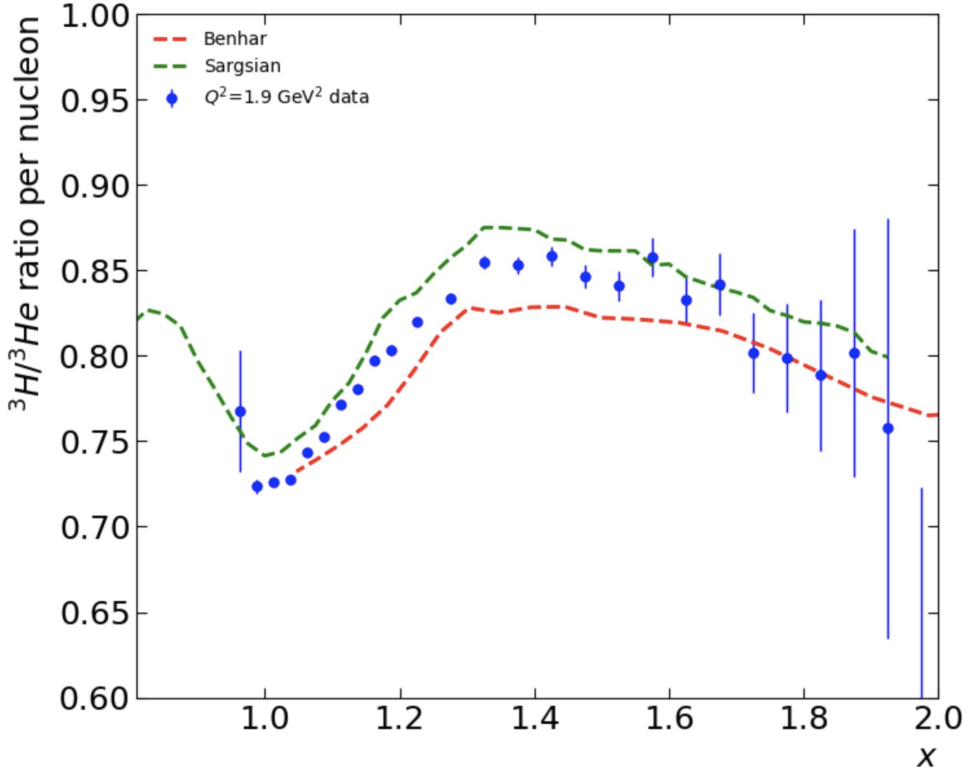
a momentum-dependent np/pp ratio is expected but not enough to explain the difference between A=3 and heavier nuclei




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

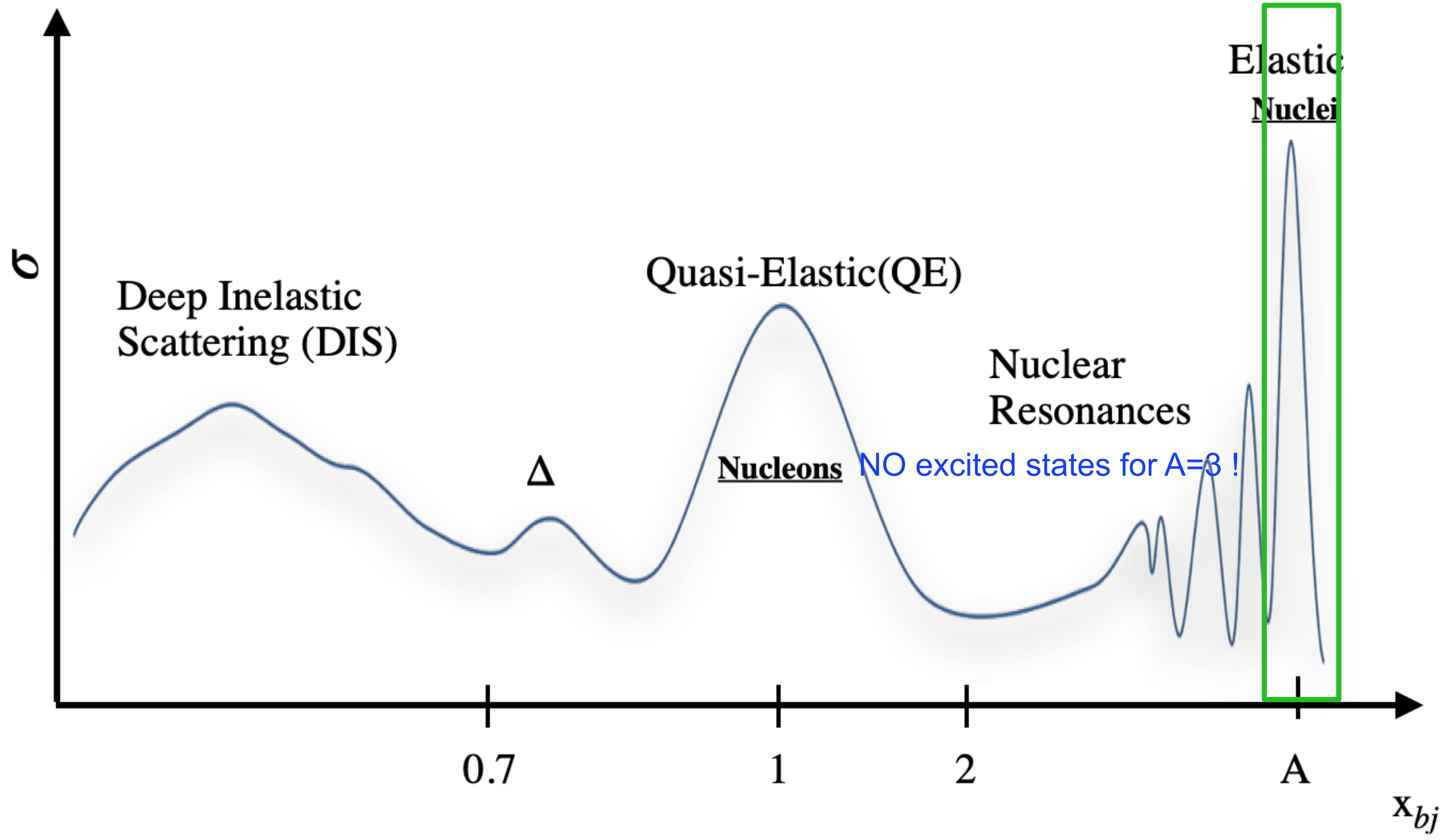
**1.9GeV2 data compared with calculations:**

- ~5% normalization difference?
- difference at QE peak
- can not describe lower Q2 data well



# x=3: $^3$H Charge Form Factor

By Leiqaa Kurbany (UNH, Advisor: Elena Long)



# Motivation

Elastic Scattering

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

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

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

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

| Ref. | $^3$H | $^3$He |
|---|---|---|
| SACLAY | $1.76 \pm 0.09$ | $1.96 \pm 0.03$ |
| Bates | $1.68 \pm 0.03$ | $1.97 \pm 0.03$ |
| GFMC | $1.77 \pm 0.01$ | $1.97 \pm 0.01$ |
| $\chi$EFT | $1.756 \pm 0.006$ | $1.962 \pm 0.004$ |

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

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

Approved but not scheduled

# Motivation

Elastic Scattering

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

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

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

**Jefferson Lab Experiment E1214009**

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

**Spokespersons:**


**Arrington, John**
Lawrence Berkeley Laboratory, Berkeley, CA
johna@jlab.org
**Averett, Todd**
The College of William and Mary
averett@jlab.org
**Higinbotham, Douglas**
Jefferson Lab
doug@jlab.org
**Myers, Luke**
Bluffton University
lmyers@jlab.org

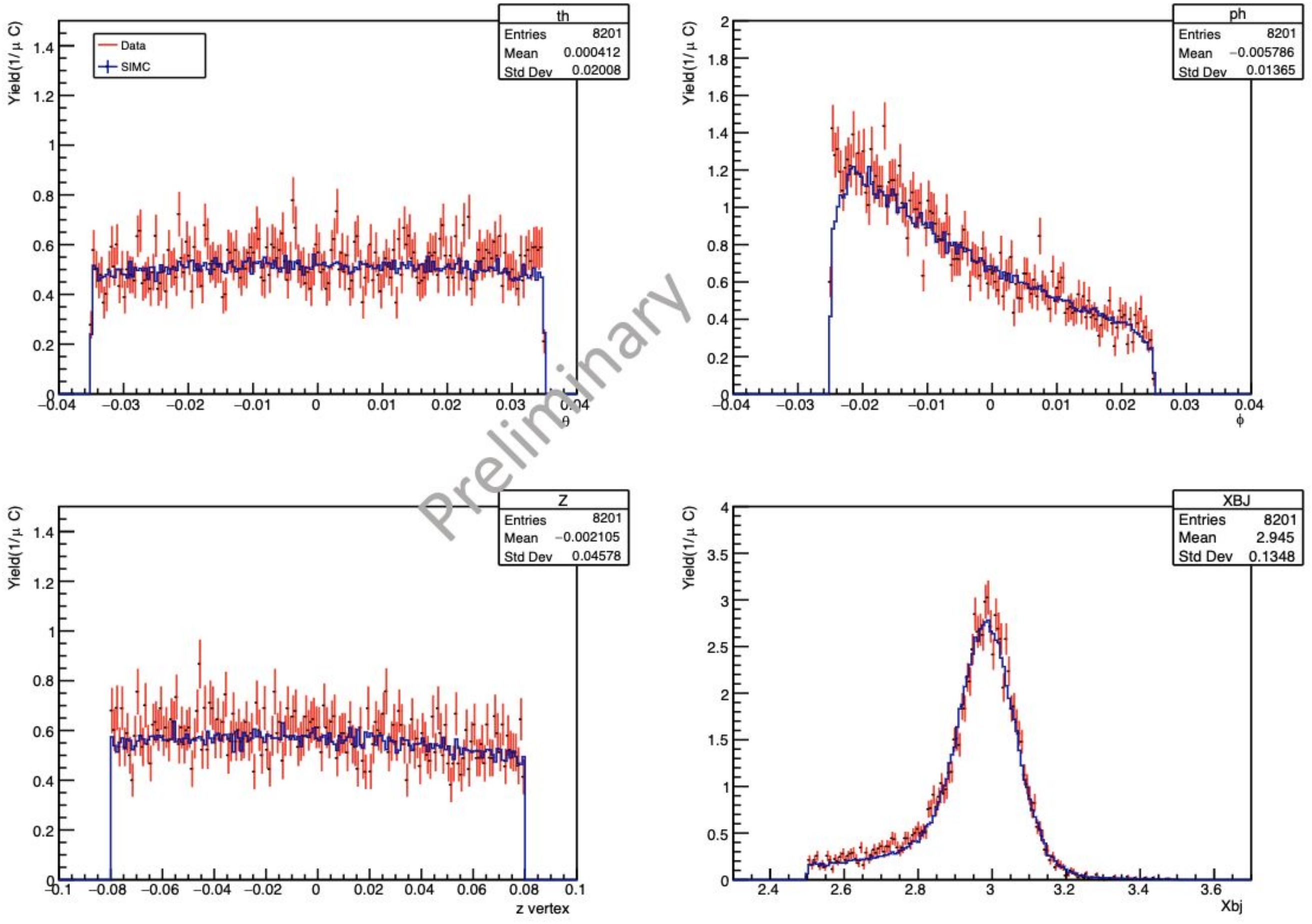

Data taken during beam study

- 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 $^3$H target

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

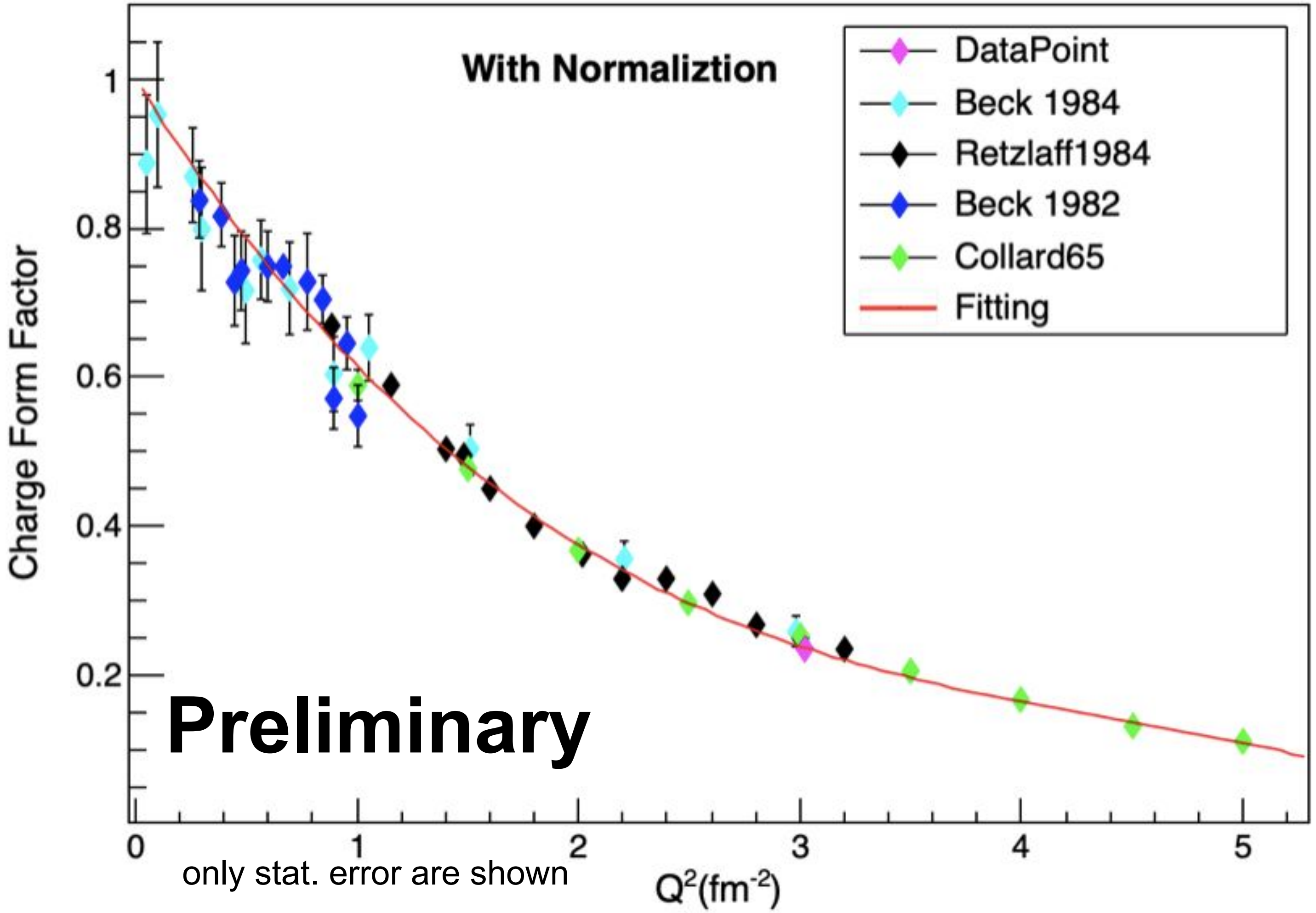


# Uncertainties

| Systematic | | |
|---|---|---|
| **Source** | **Relative per Target** | **Ratio** |
| Charge | 3% | 0.2% |
| Acceptance | 2% | 0.2% |
| Radiative correction | 1.5% | 0.3% |
| TGT THICKNESS | 0.4% for 3H , 1% for 3He | 1.06% |
| Scattering Angle | 0.9% | 0.1% |
| Boiling | 0.5% | 0.1% |
| Beam Energy | 0.3% | 0.05% |
| Tracking Efficiency | 0.2% | 0.05% |
| Hydrogen contamination | 0.2% | 0.2% |
| 3He contamination | 0.1% conservative | 0.1% |
| Trigger + PID | 0.1% | 0.05% |
| Endcaps contamination | 0.1% | 0.05% |
| Total | 4.20% | 1.17% |
| Statistical | | |
| Total | 1.14% for 3H , 0.89% for 3He | 1.44% |

Preliminary

# Preliminary Results




*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).
- 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

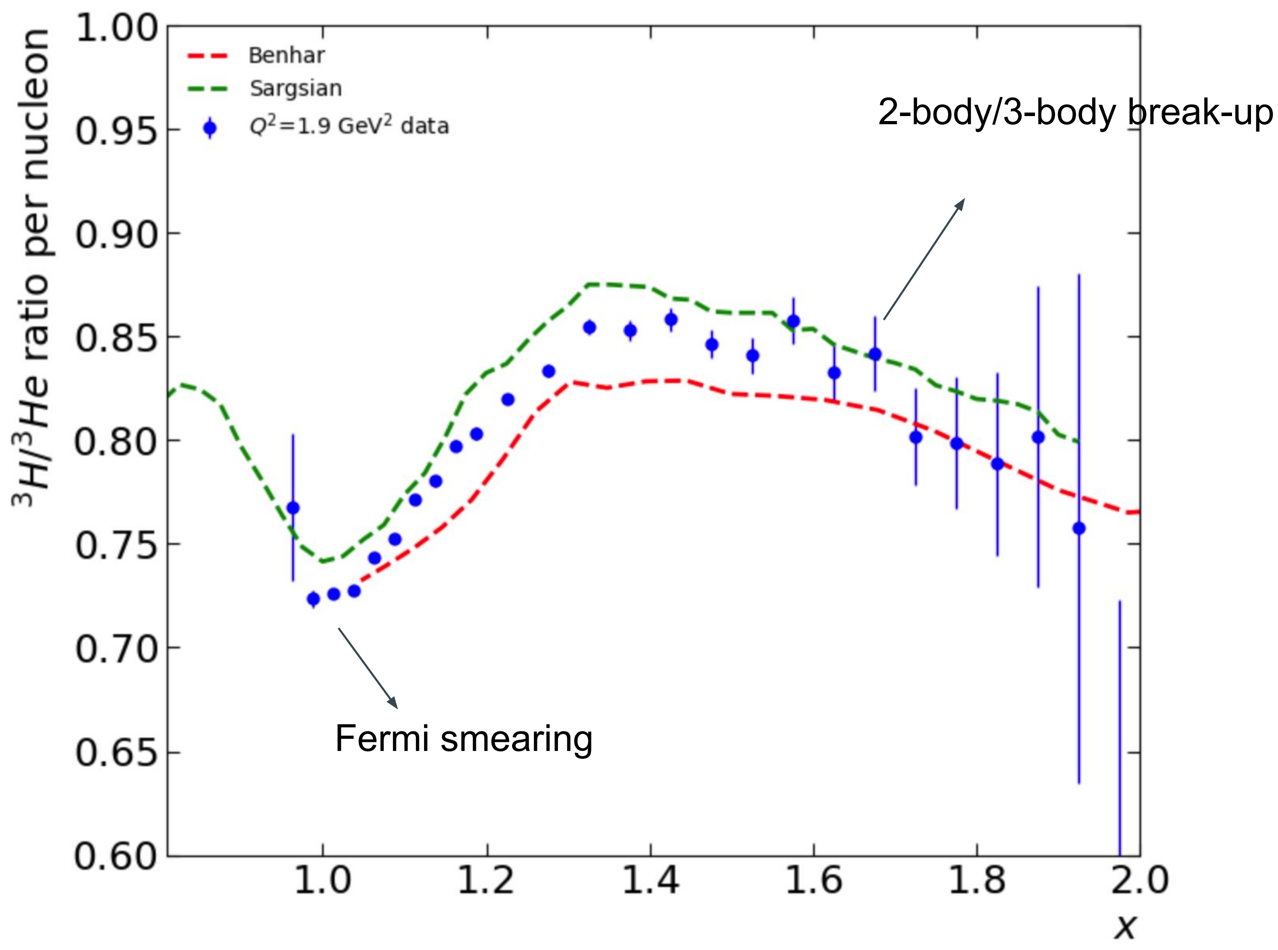
** more Tritium result:
1pm today by Dien Nguyen on n-n bound state in tritium https://doi.org/10.1016/j.physletb.2022.137165

Thank you!

# Backups

# Data to Calculation Comparison:

work in-progress with 3 theory groups

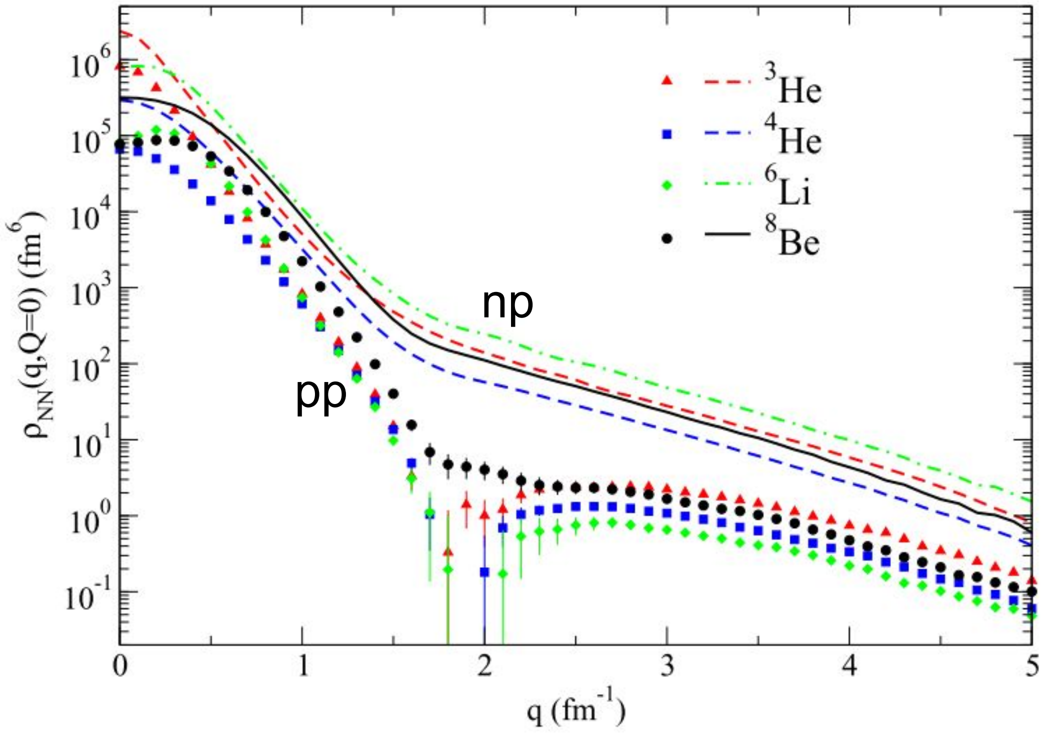



things to explore:

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

# Isospin-dependence of 2N SRC

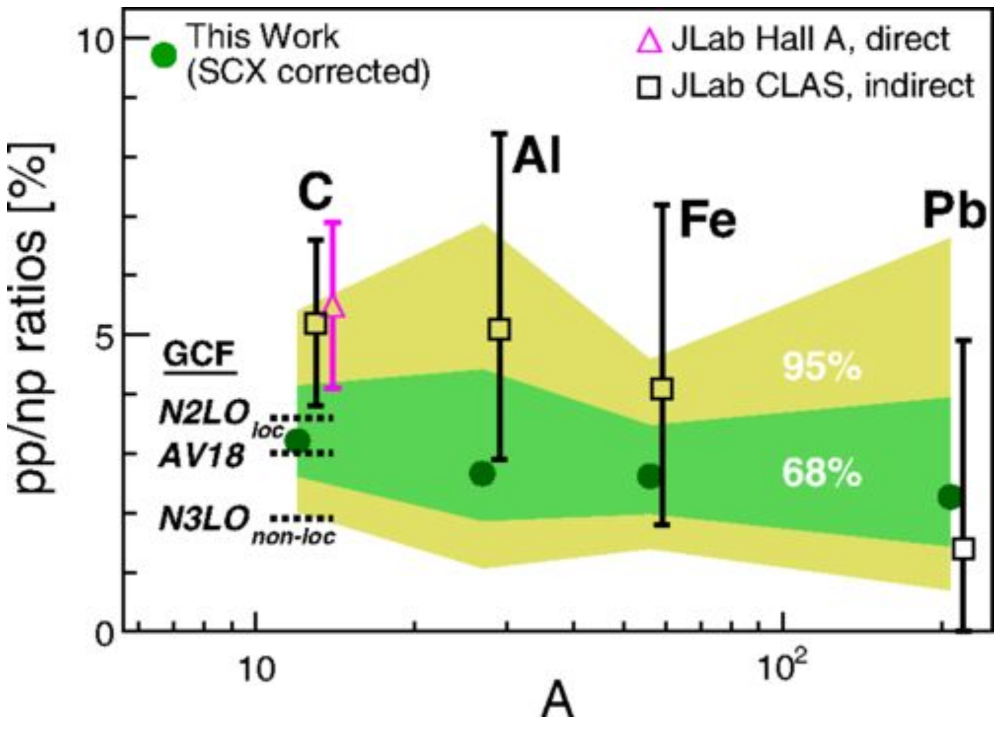
## np-dominance from VMC calculations




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

## np-dominance in exclusive measurements

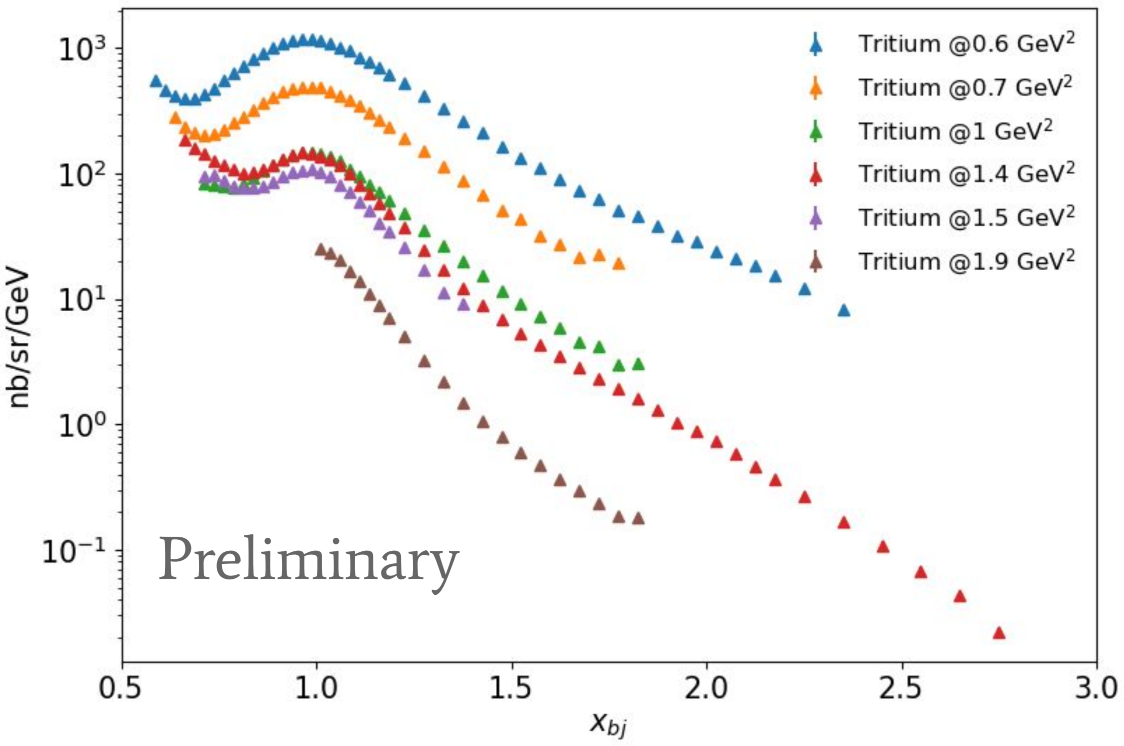
M. Duer *et al.* (CLAS Collaboration), Phys. Rev. Lett. 122, 172502

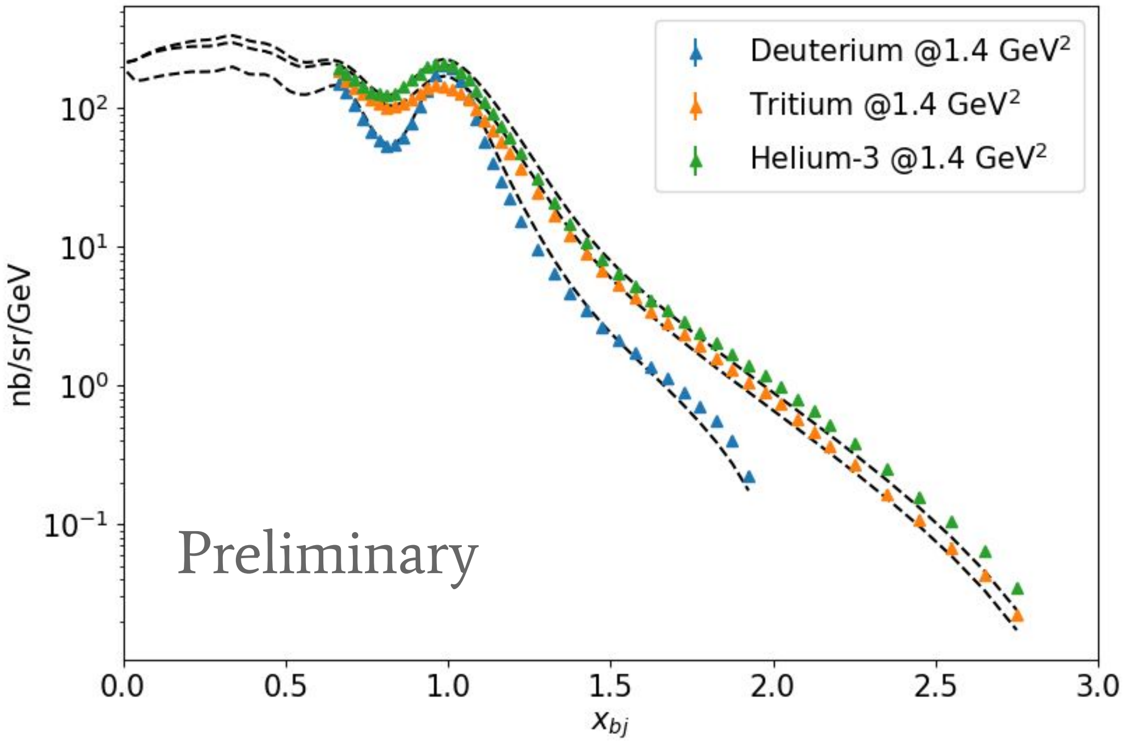



use figure 1 from draft instead

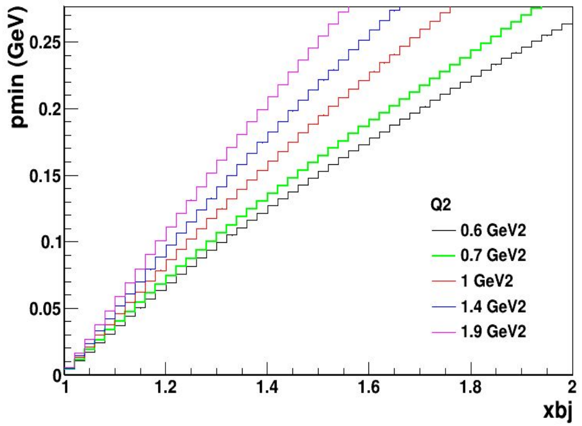
check the new review article

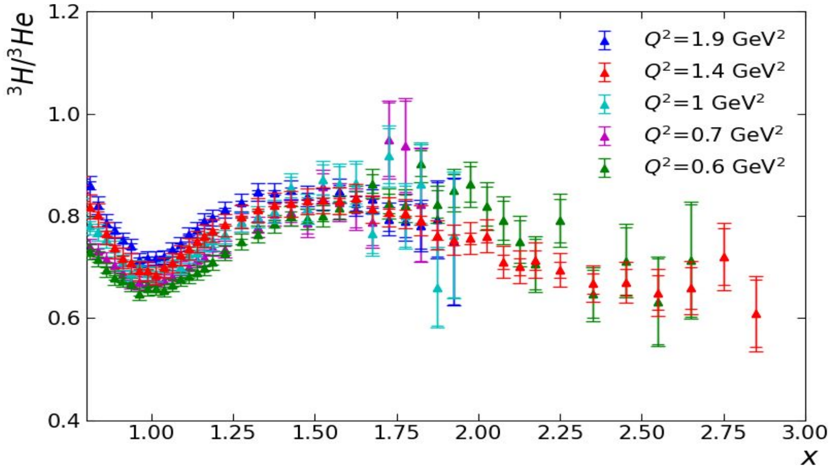
# Absolute Cross Sections and Momentum Distribution

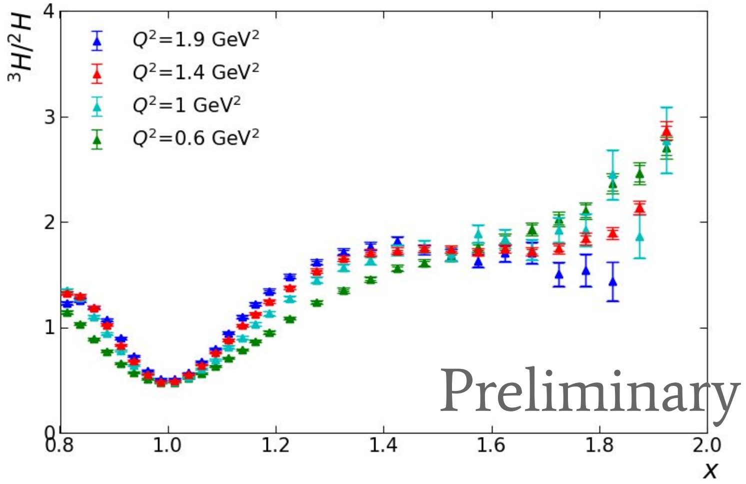


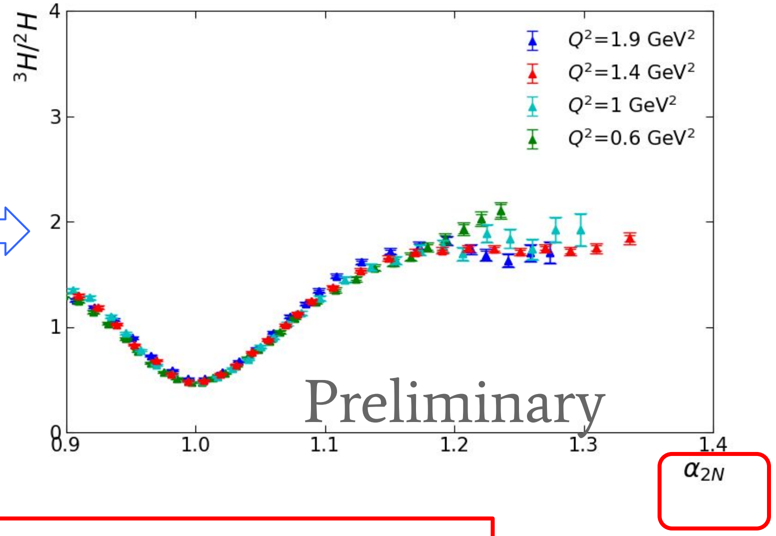



# Mean-field to SRC transition



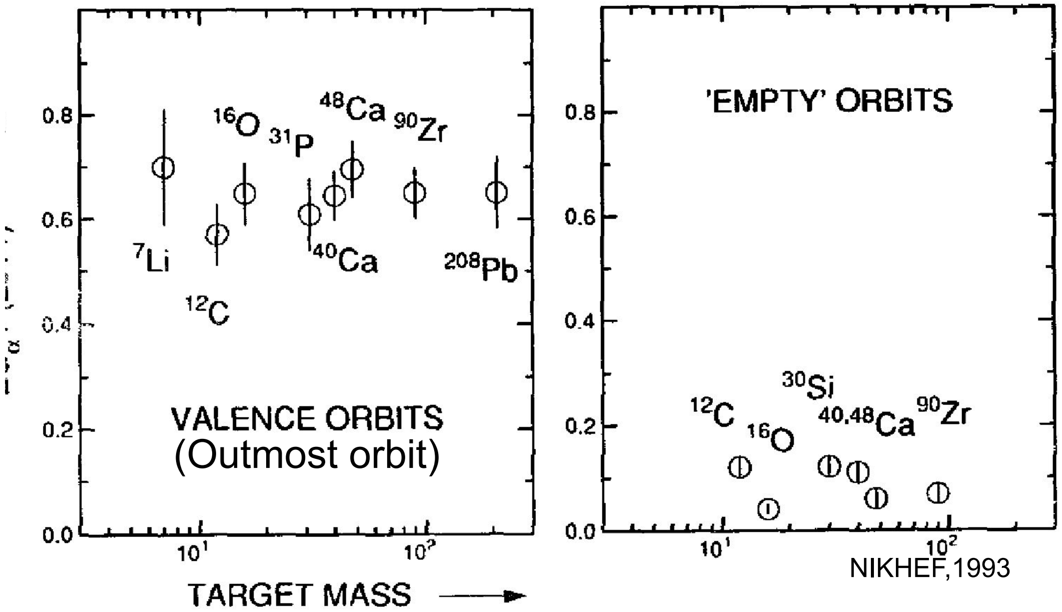




**Light cone variable:**

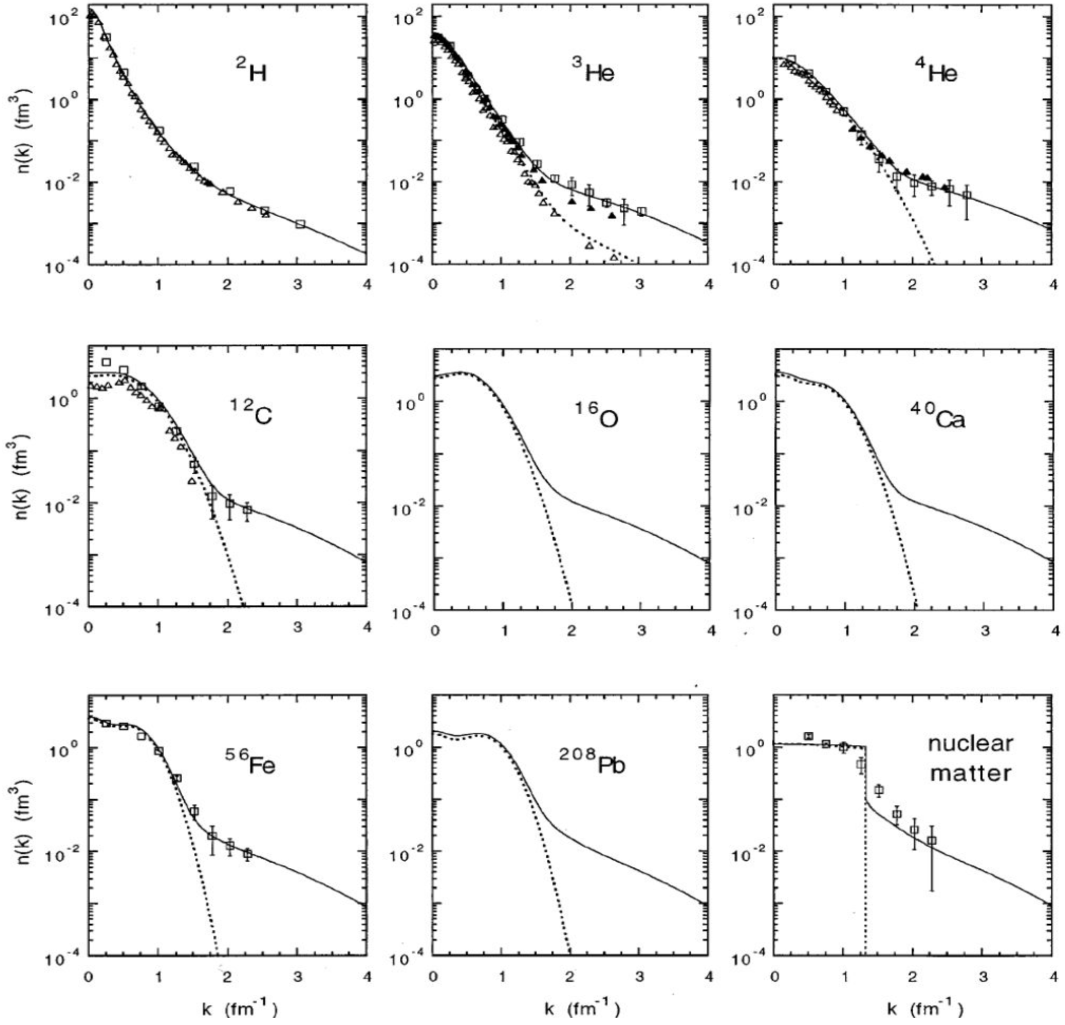
$$\alpha_{2N} = 2 - \frac{q_- + 2m}{2m}\,\frac{\sqrt{W^2 - 4m^2} + W}{W}$$

# High Momentum Nucleons in Various Nuclei:

- Spectroscopic strength from low energy e'p: the closed orbits are NOT fully occupied.




- High momentum tails in nucleon momentum distribution




C. Atti and S. Simula, PRC 53. 1689 (1996)

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

# Quasi-elastic Scattering

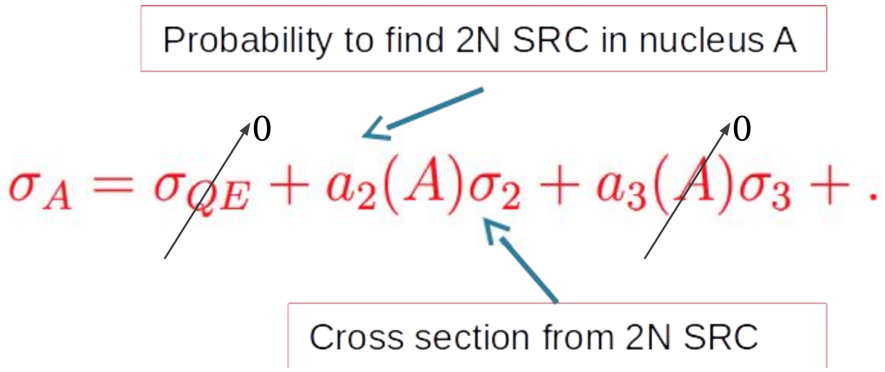
to access the initial state of correlated nucleons

**Inclusive measurement:**

- Calculate the nucleon initial momentum **range** from electron kinematics

- High statistics
- Need high x, high Q2
- Competing process e.g. meson exchange current

**At 1.4<x<2:**




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

**Plateaus in Cross section ratio b/w 1.4< xbj <2:**

**Deuteron-like np pairs dominate**

JLAB Hall C E02-019