$^{3}H/^{3}He$ inclusive measurements in the $x \geq 1$ region

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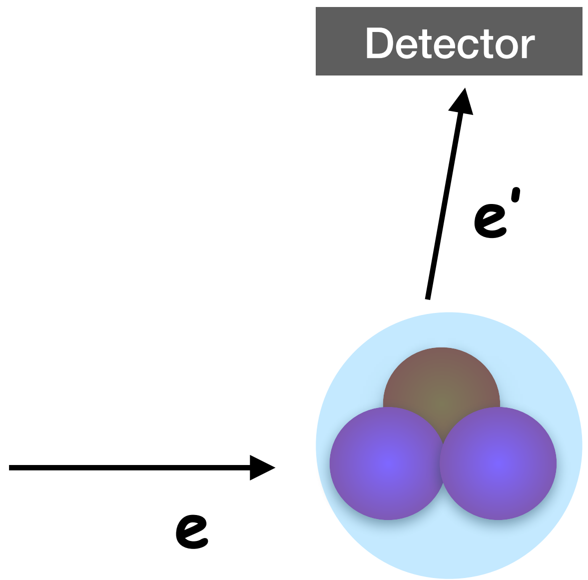
On behalf of the E12-11-112 collaboration

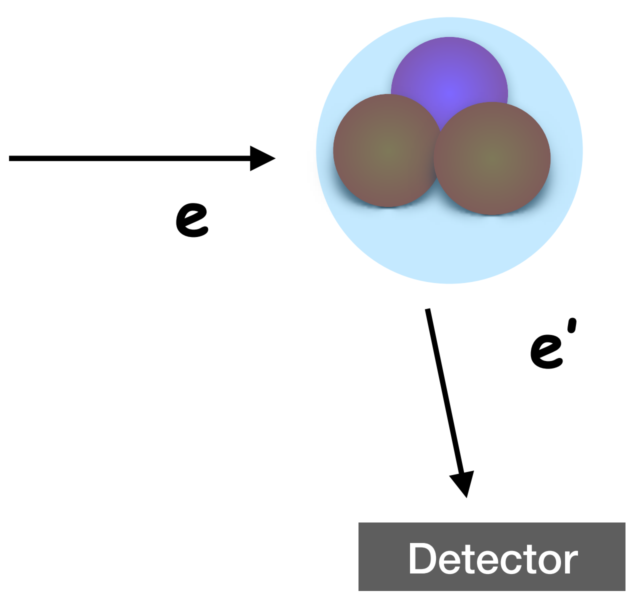
Hall A Collaboration Meeting
January 27, 2023

University of New Hampshire

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Motivation





^{3}He and ^{3}H mirror nuclei:

^{3}He (protons) ⟷ ^{3}H(neutrons)

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

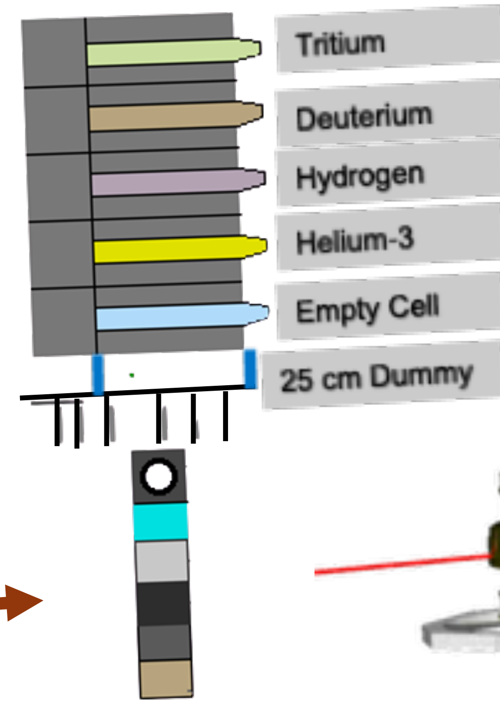
Inclusive Measurements

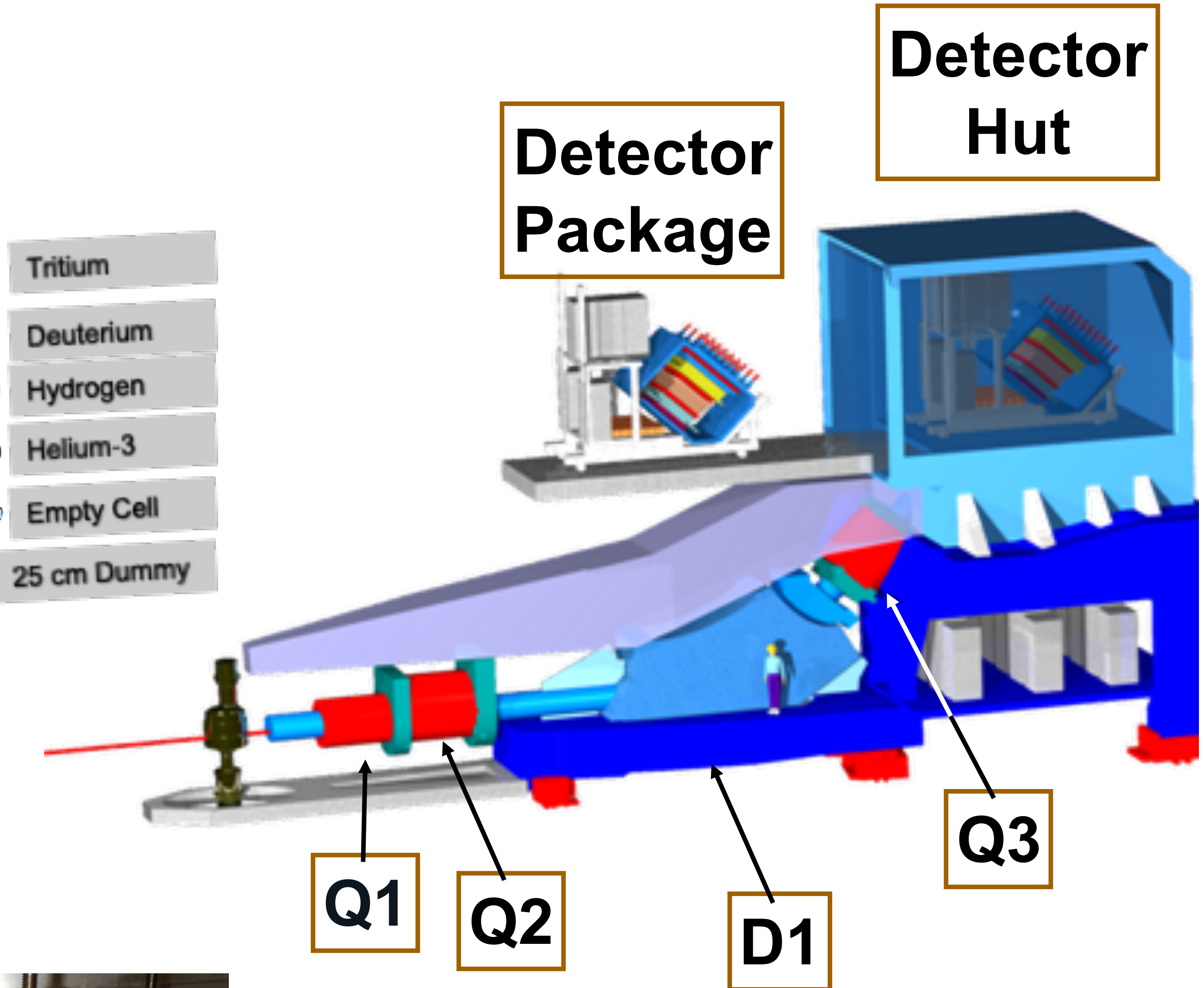
- ✦ Sum of Short-range correlations:
  3He/3H (2pn + pp)/(2pn + nn) (x>1)
  Ratio of pp to pn pairs assuming isospin symmetry
- ✦ Access G_M^n: Effective neutron target (x=1)
- ✦ Charge radius of 3H vs 3He (x=3)

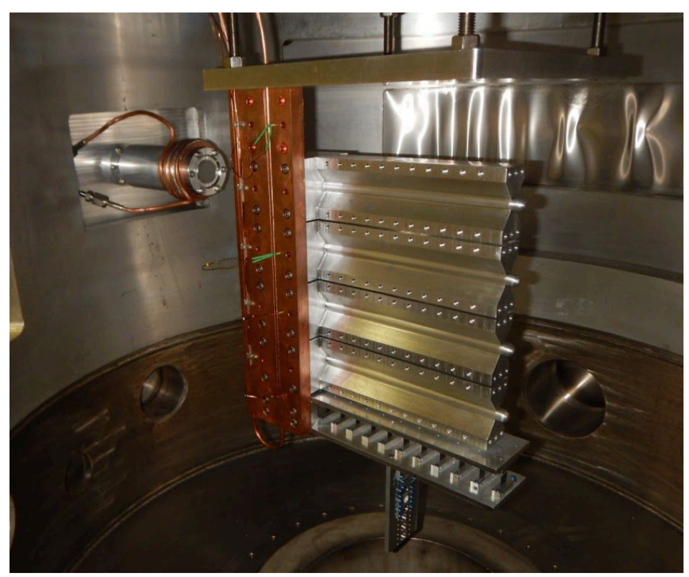
Hall A

$E = 2.2$ Gev
$E = 4.3$ Gev

Electron
Beam



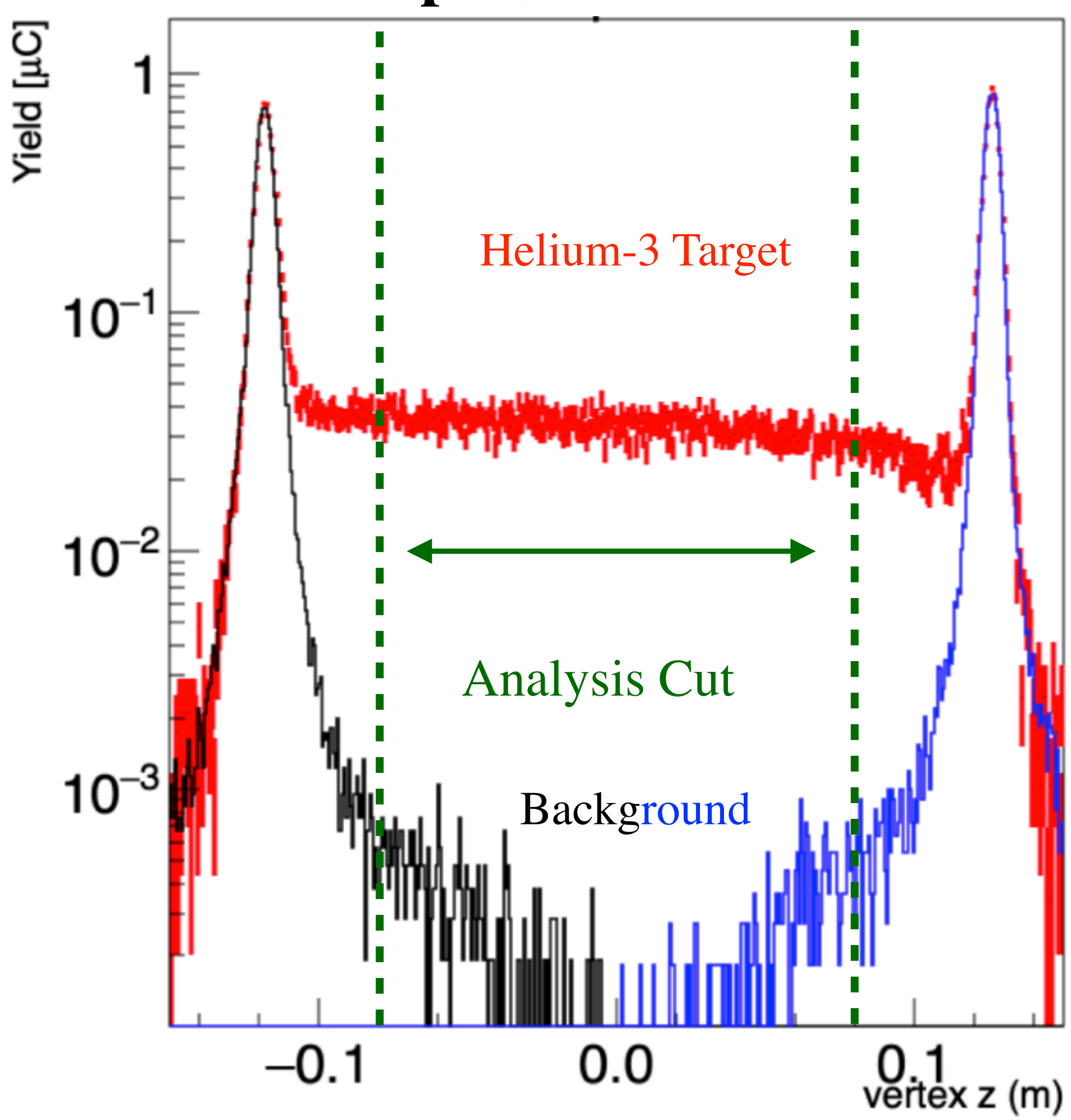


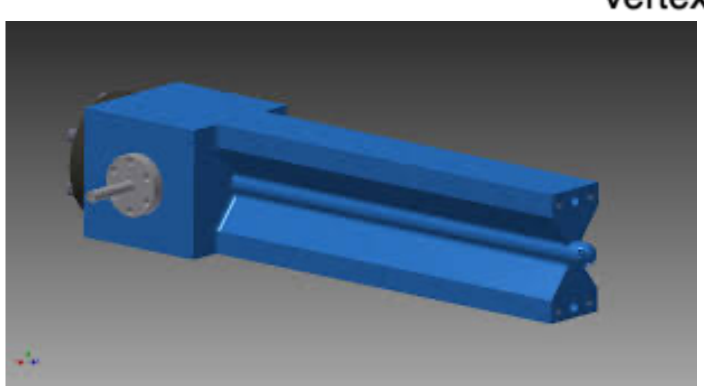


Target System

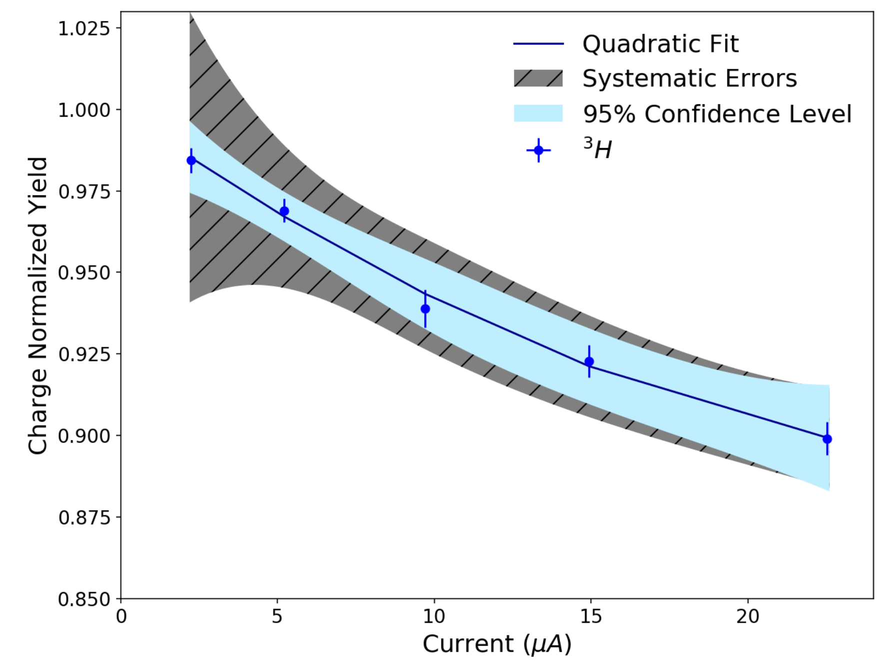
Data Analysis Particularities

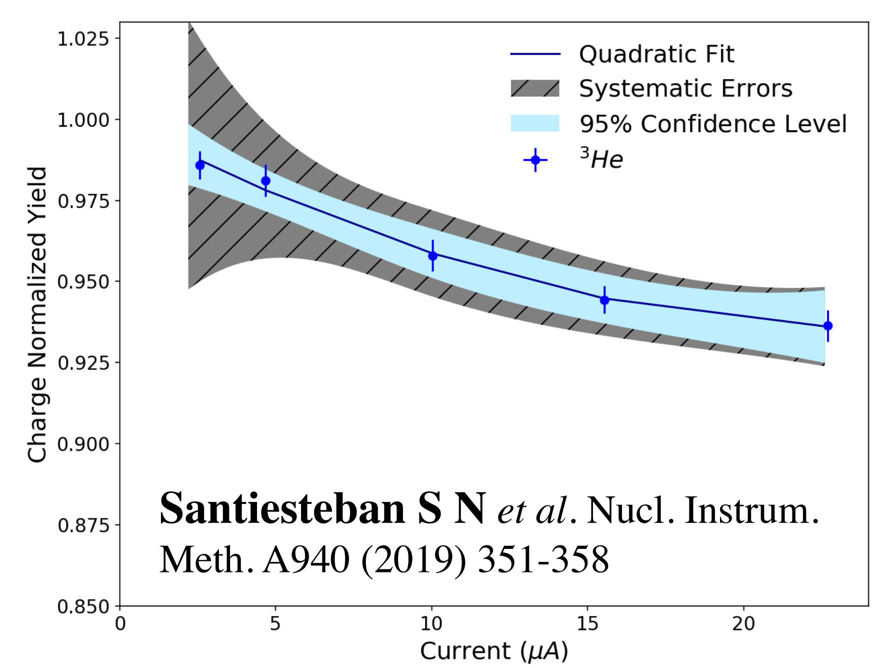
Endcap Contamination





Gas Density Correction



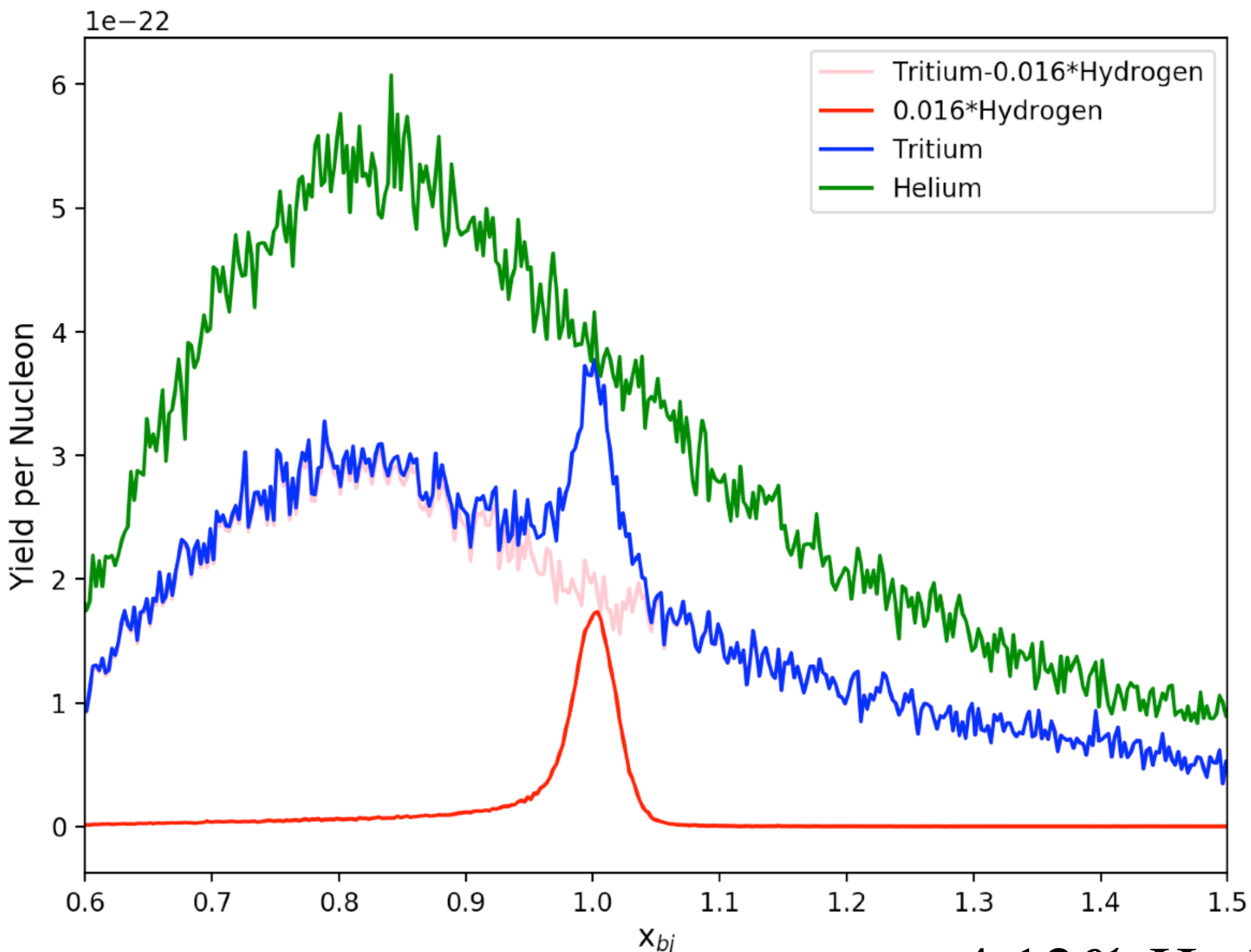


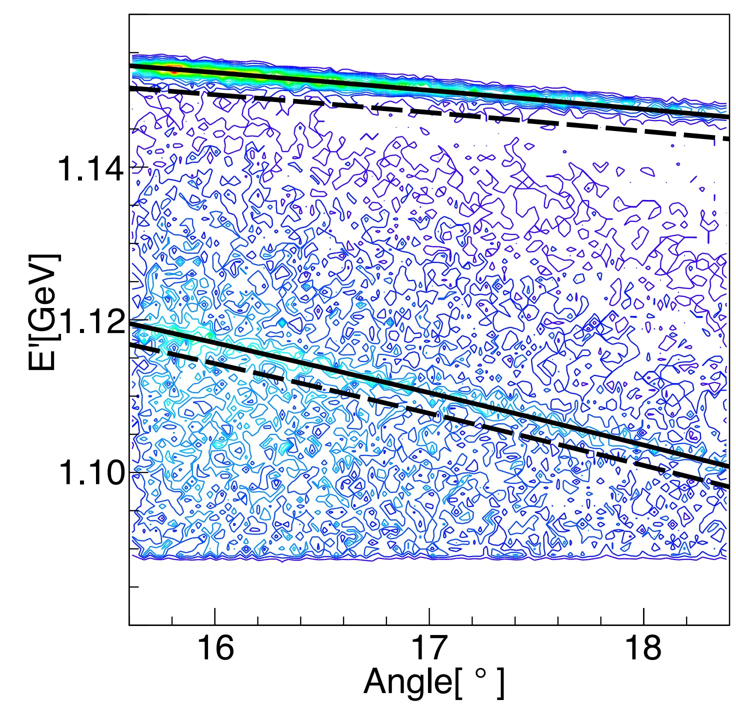
Santiesteban S N *et al*. Nucl. Instrum. Meth. A940 (2019) 351-358

Density Reduction in the targets for $22\mu A$:

^3He~ 6% ^3H~ 10 %

Hydrogen Contamination in the Tritium Second Cell



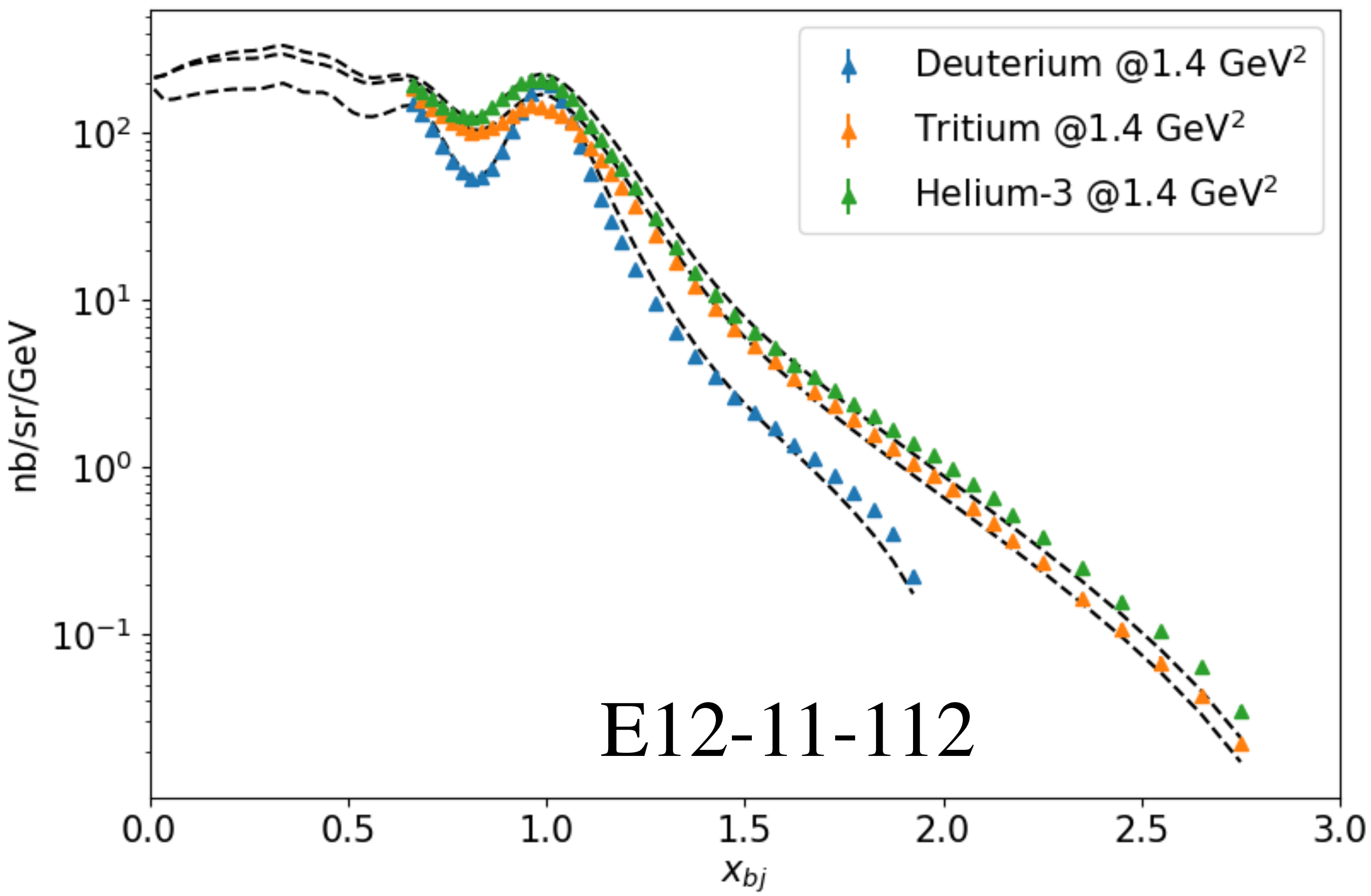


$$H_2O + T_2 \rightarrow HTO + HT$$

4.12% Hydrogen Contamination

The kinematics with hydrogen contamination were corrected with simulation or data when available.

1. Isospin-dependence of SRC

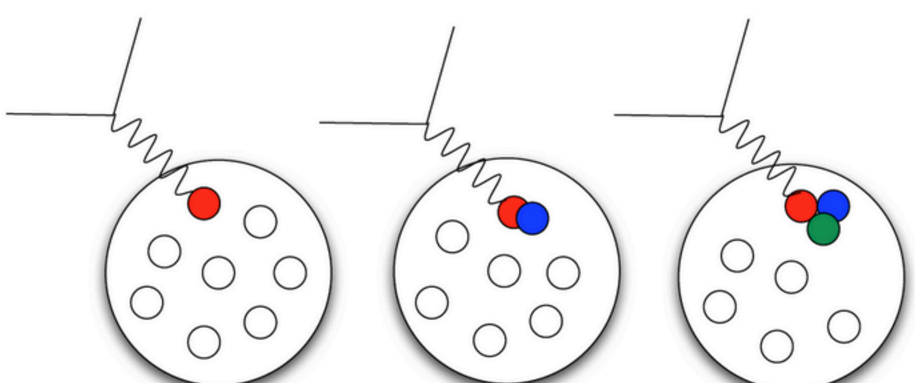


At 1.4<x<2
Dominates

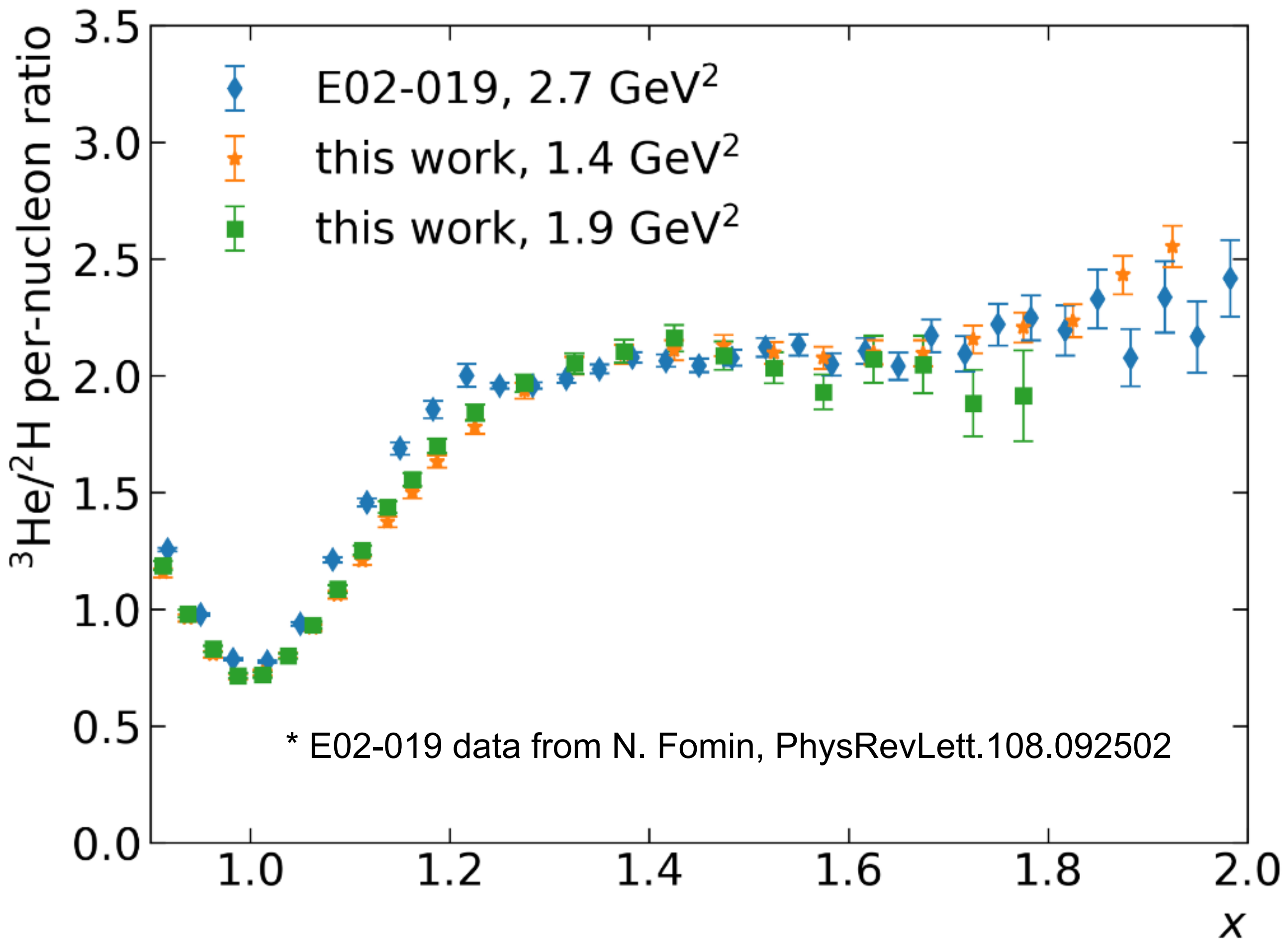
Probability to find 2N SRC in nucleus A

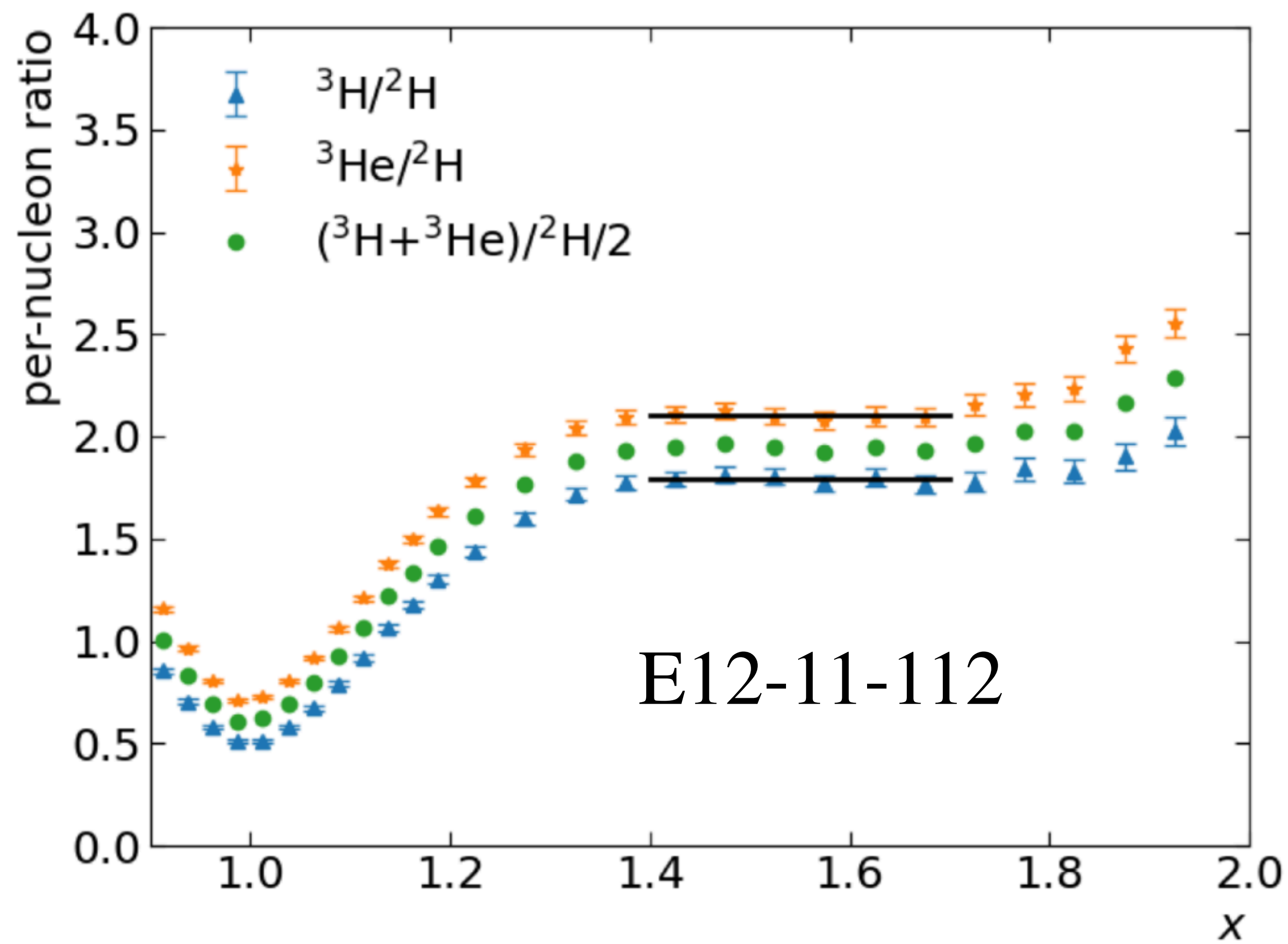
$$\sigma_A = \sigma_{QE} + a_2(A)\sigma_2 + a_3(A)\sigma_3 + \ldots$$

Cross section from 2N SRC



E12-11-112 Results





What did we expect?

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

Off shell cross sections:

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

number of pp to np pairs in ^3He: $R_{pp/np} = \hat{N}_{pp}/N_{np}$

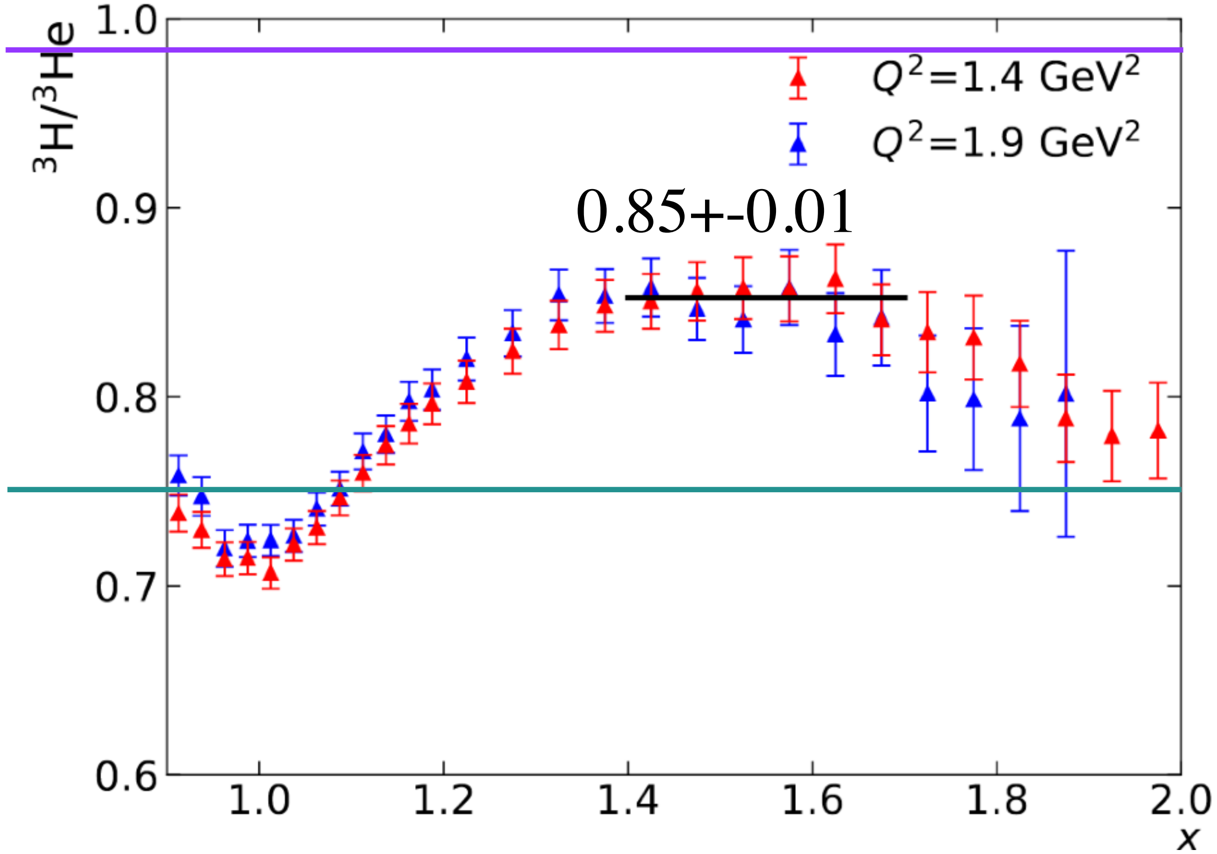
Assuming the same for the mirror nuclei ^3H

np dominance:

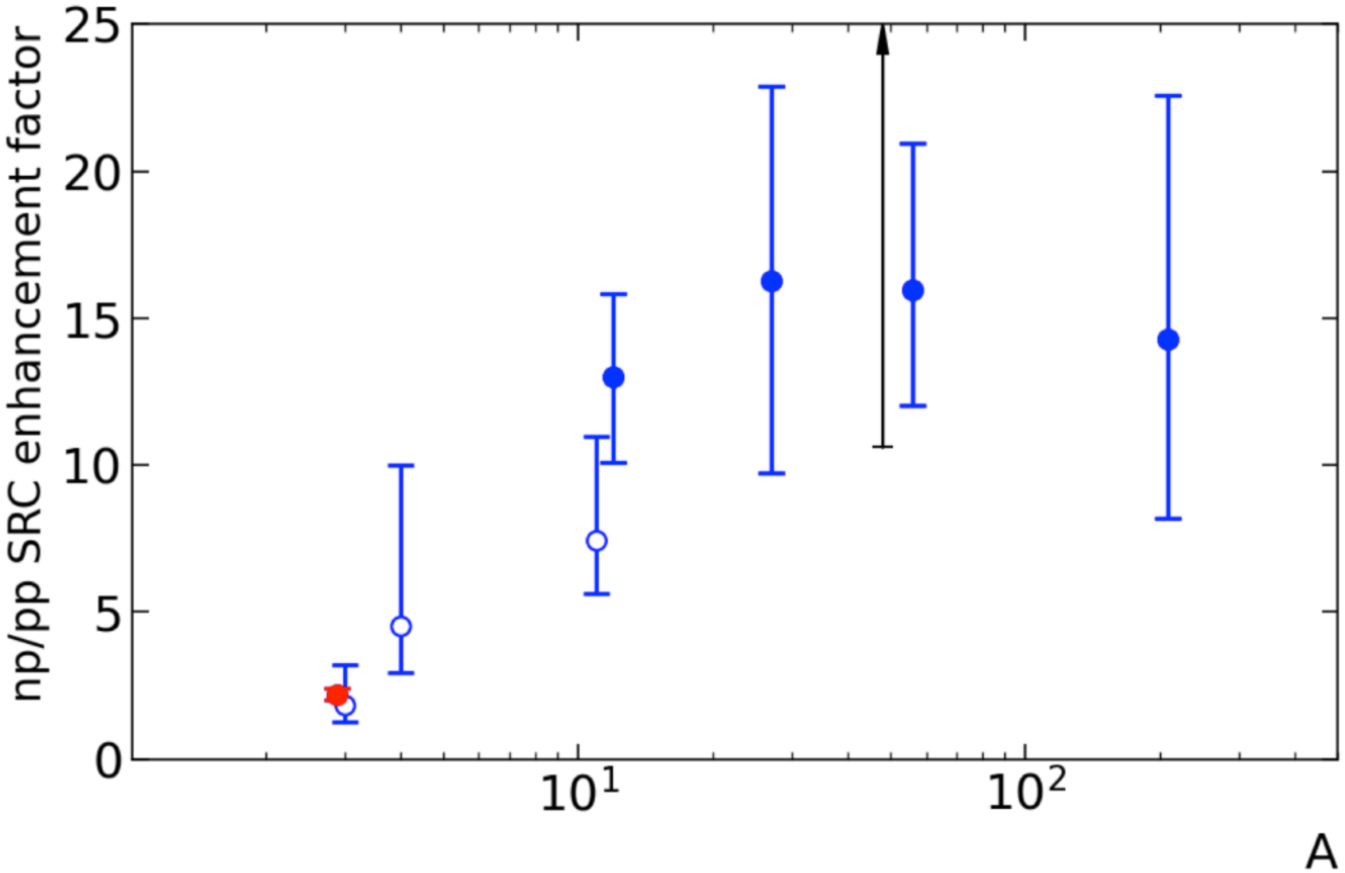
$$R_{pp/np} = 0 \rightarrow \frac{\sigma_{^3H}}{\sigma_{^3He}} = 1$$

pp dominance:

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



What does this mean?



Ratio of np/pp SRC pairs in A=3 nuclei:

$$R_{np} = 4.2 \pm 0.4$$

Removing contribution from pair counting, 2 np pairs vs 1 np pair

$$R_{np} = 2.1 \pm 0.2$$

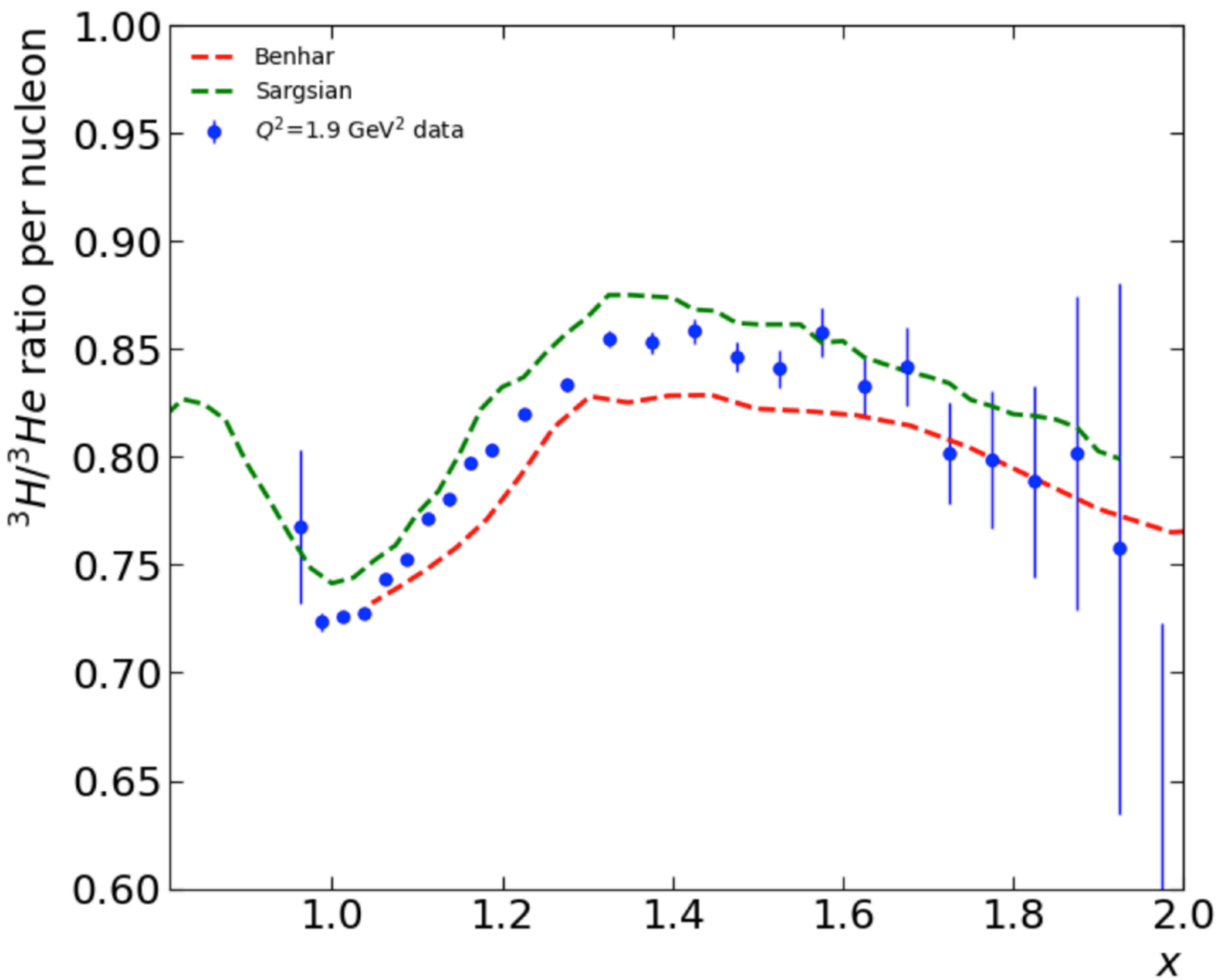
References:

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)

Published in: Nature 609 (2022) 7925, 41-45

Next Studies



1.9 GeV^2 data compared with calculations:

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

Focus in the 3N SRC

- Inclusive cross section (and ratios)
- Compare with calculations

2. Elastic Measurement

	$<r^2_{rms}>_{3H}$	$<r^2_{rms}>_{3He}$
GFMC	1.77(1)	1.97(1)
χEFT	1.756(6)	1.962(4)
SACLAY	1.76(9)	1.96(3)
BATES	1.68(3)	1.97(3)

$\Delta R_{RMS} = 0.20(10)$

$\Delta R_{RMS} = 0.29(04)$

Goal: Extract the charge radius

Current experimental results: large uncertainties, discrepancies

Jefferson Lab Experiment E1214009

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

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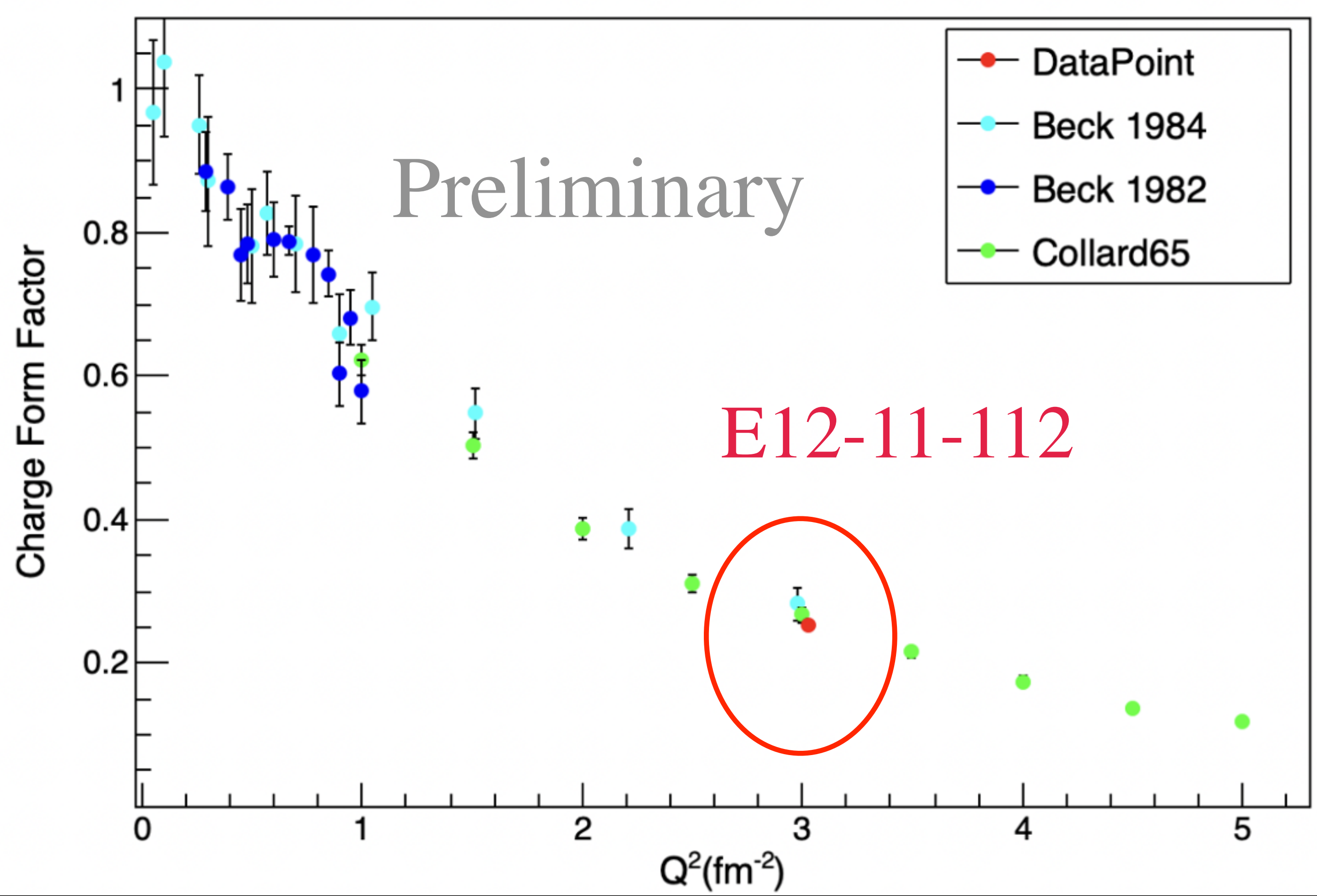
Motivated by the E12-14-009 experiment.
Never scheduled

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

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

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



Experiment Configuration

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

Q^2 not as low as we would like

We make it work
with what we have!

Normalization Uncertainties

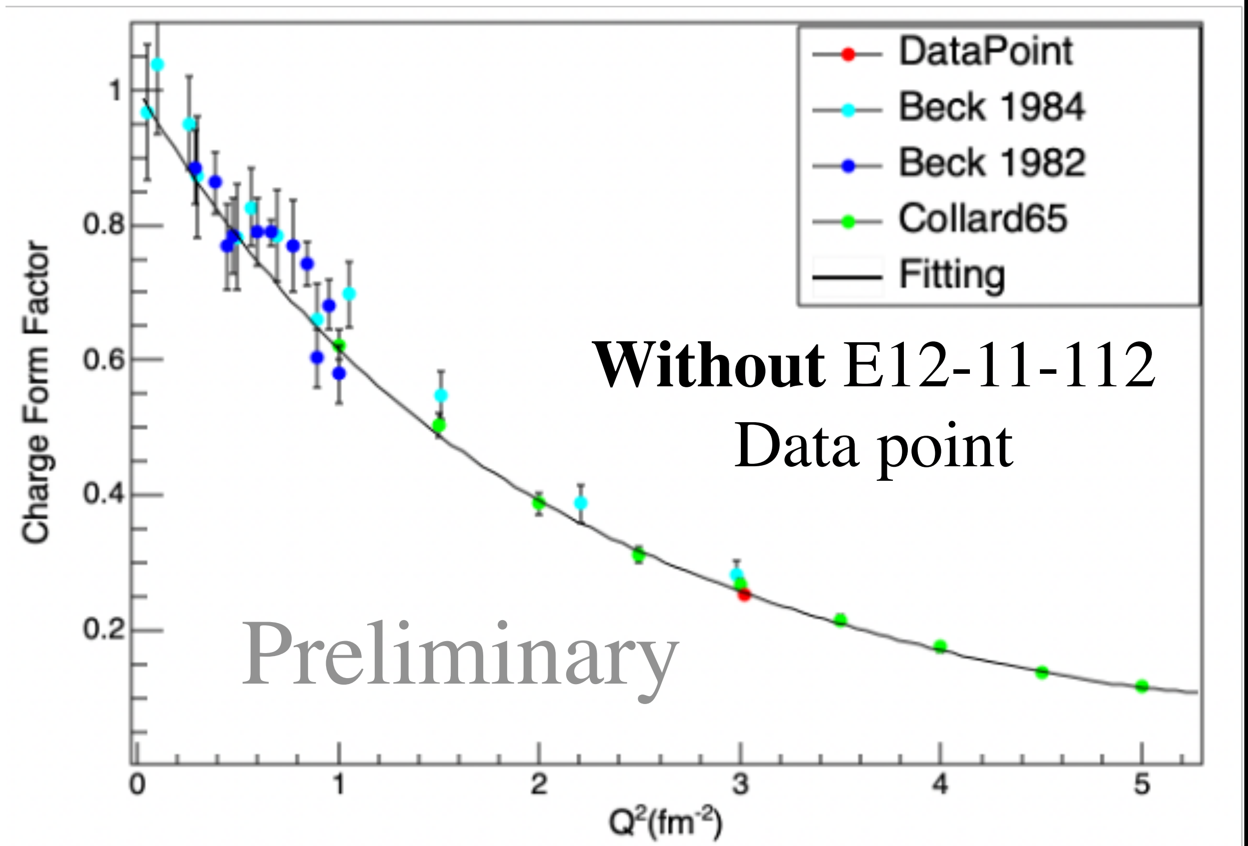
Systematic		
Source	Relative per Target	$^3H/^3He$ ratio
Charge	3%	0.2%
Acceptance	2%	0.2%
Radiative Correction	1.5%	0.3%
Target Thickness	0.4% for ^3H , 1% for ^3He	1.06%
Scattering Angle	0.9%	0.1%
Boiling	0.5%	0.1%
Beam Energy	0.3%	0.05%
Tracking Efficiency	0.2%	0.05%
Hydrogen contamination	0.2%	0.2%
^3He contamination	0.1% conservative	0.1%
(Trigger + PID) cuts	0.1%	0.05%
Endcaps contamination	0.1%	0.05%
Total Systematic	4.35% for^3H , 4.29% for ^3He	1.17%
Statistical		
Total Statistical	1.14% for ^3H , 0.89% for ^3He	1.44%

Target	Total Uncertainty
^3H	4.35%
^3He	4.29%
$^3H/\ ^3He$ Ratio	1.85%

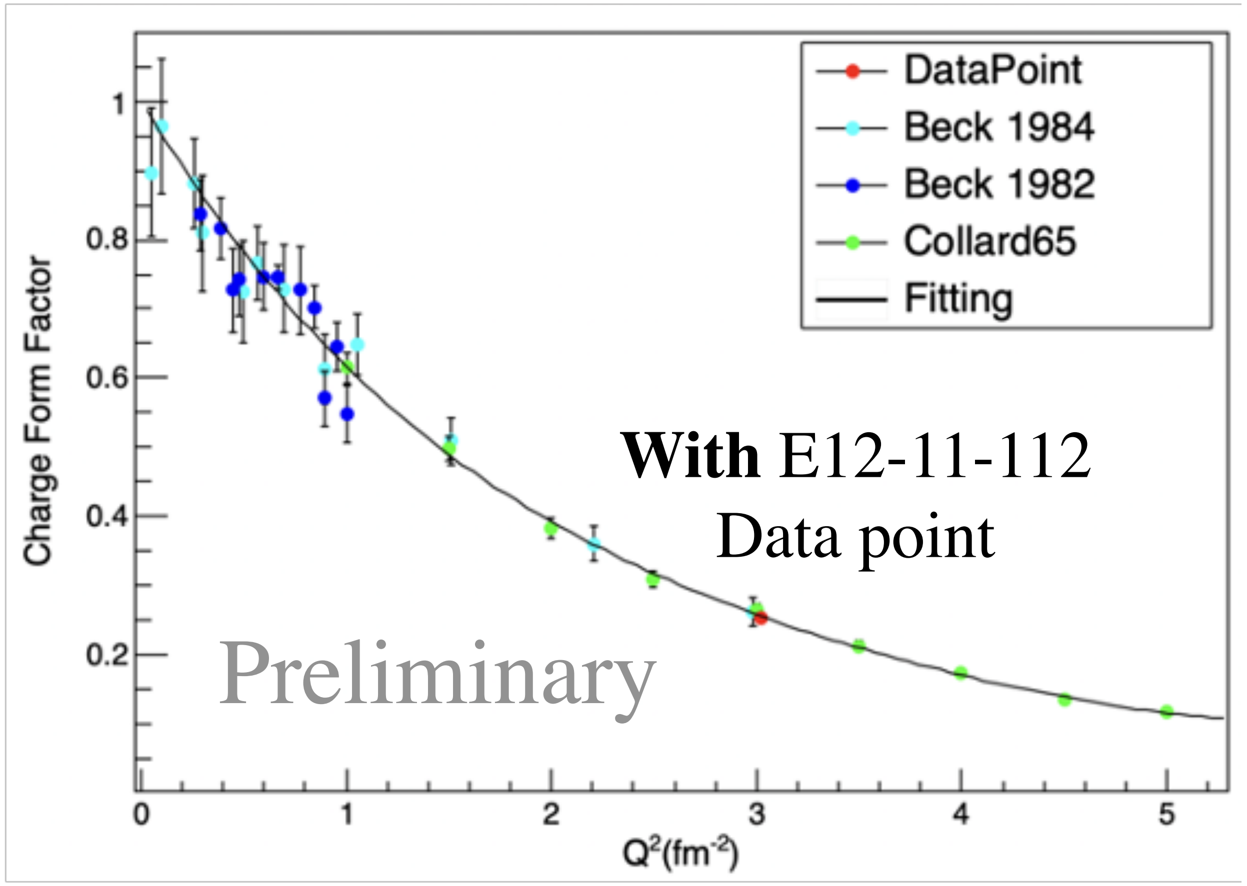
Impact in the world ^{3}H data normalization

$$\chi^2 = \sum_{i=1}^{1=N} \left(\sum_{j=1}^{j=j_{max}} \frac{(n_i\sigma_{ij} - F(\vec{a}, Q_j^2))^2}{(\Delta\sigma_{ij})^2} \right) + \frac{(n_i - 1)^2}{\Delta n_i}$$

Earlier data had questions about the normalization (density of the targets).

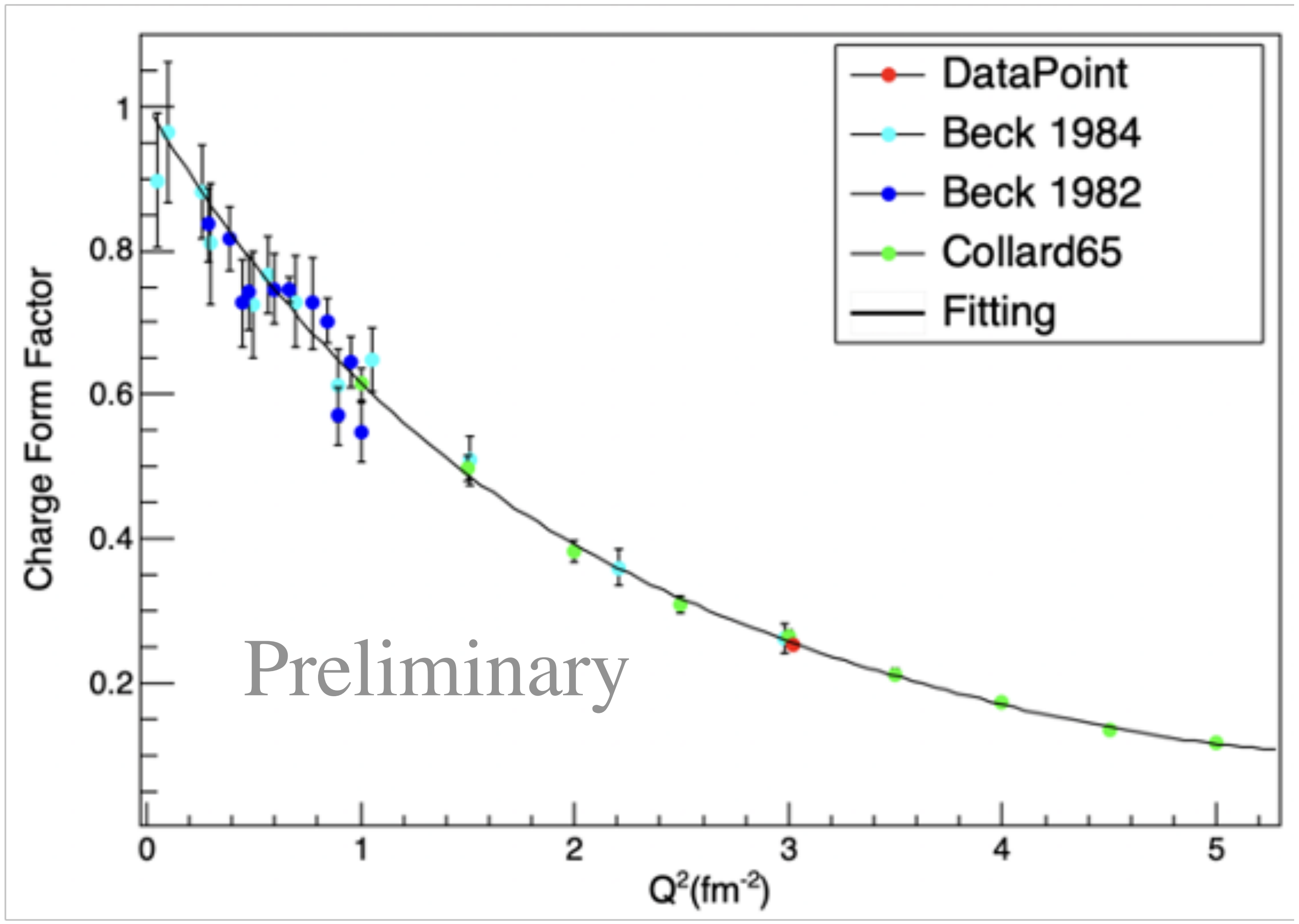


Fitting parameters	Value	Uncertainty	Uncertainty%
a_0	1.000e00	-	-
a_1	-4.595e-01	6.502e-02	14.14
a_2	1.070e-01	4.752e-02	44.39
a_3	-1.422e-02	1.222e-02	85.91
a_4	8.303e-04	1.059e-03	127.51
$n_{Beck1984}$	1.052e00	4.379e-02	4.16
$n_{collard}$	9.738e-01	5.061e-02	5.19
$n_{Beck1982}$	1.036e00	3.901e-02	3.76



Fitting parameters	Value	Uncertainty	Uncertainty%
a_0	1.000e00	-	-
a_1	-4.926e-01	4.839e-02	9.82
a_2	1.262e-01	3.938e-02	31.18
a_3	-1.824e-02	1.071e-02	58.69
a_4	1.121e-03	9.559e-04	85.22
$n_{Beck1984}$	1.077e00	3.287e-02	3.05
$n_{collard}$	1.012e00	2.731e-02	2.69
$n_{Beck1982}$	1.057e00	3.012e-02	2.84

Current Status



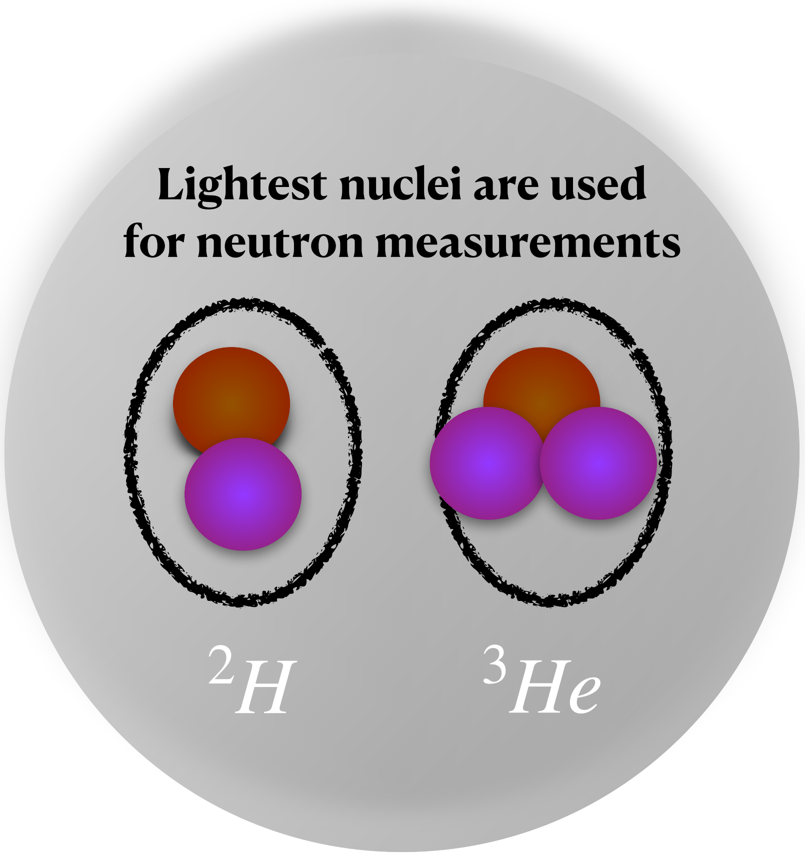
Sensitivity study is done

Δn_i Normalization for:
Beck(1984) data set is 2.25%
Beck(1982) data set is 7% and for
Collard(1965) data set is 2%.

.

Next Step:
Formalize normalization mechanism.
Estimate the charge radius.

3. G_M^n measurement



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

Ideally, but not possible.

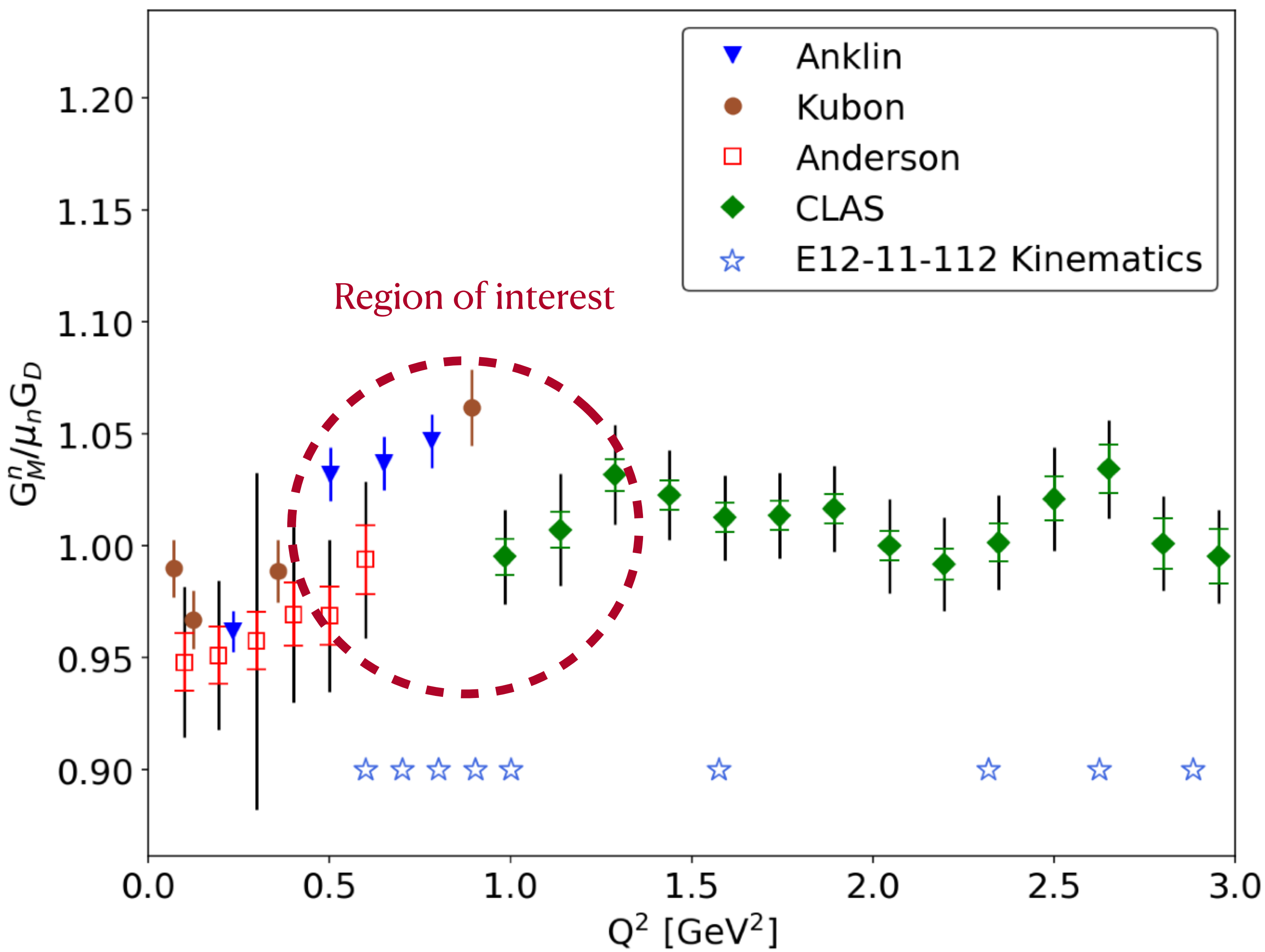
If measuring neutrons (no charge):

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

Measurement Corrections:

- Reaction mechanisms FSI and MEC
- Nuclear structure

E12-11-112 Goal

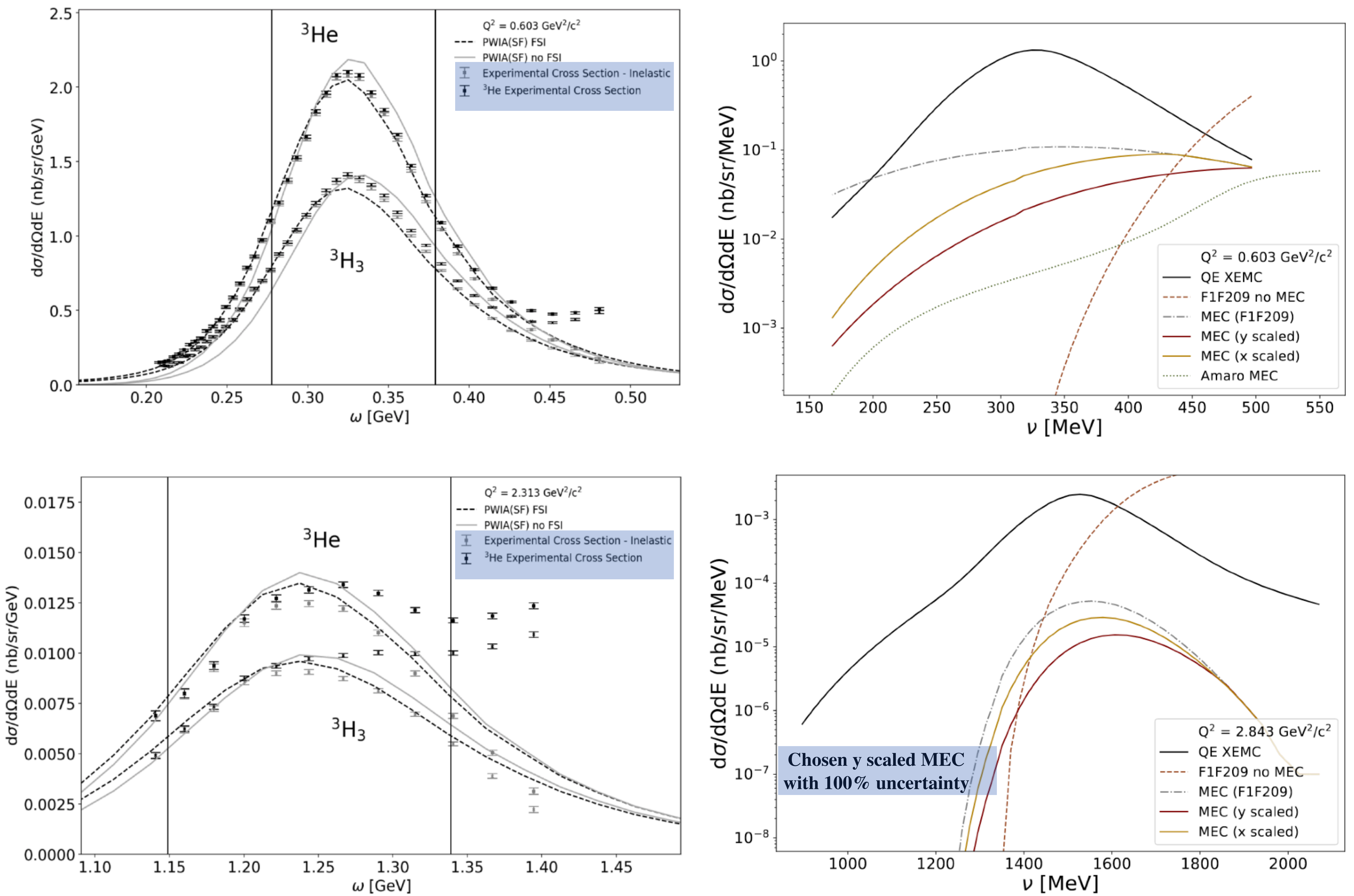


Measure the neutron magnetic form factor using the $^3H/^3He$ cross-section ratios

We have shown extracted Cross sections in the past let's see how we get to G_M^n

Some steps to get to G_M^n:

1. Remove the inelastic distribution from the cross sections



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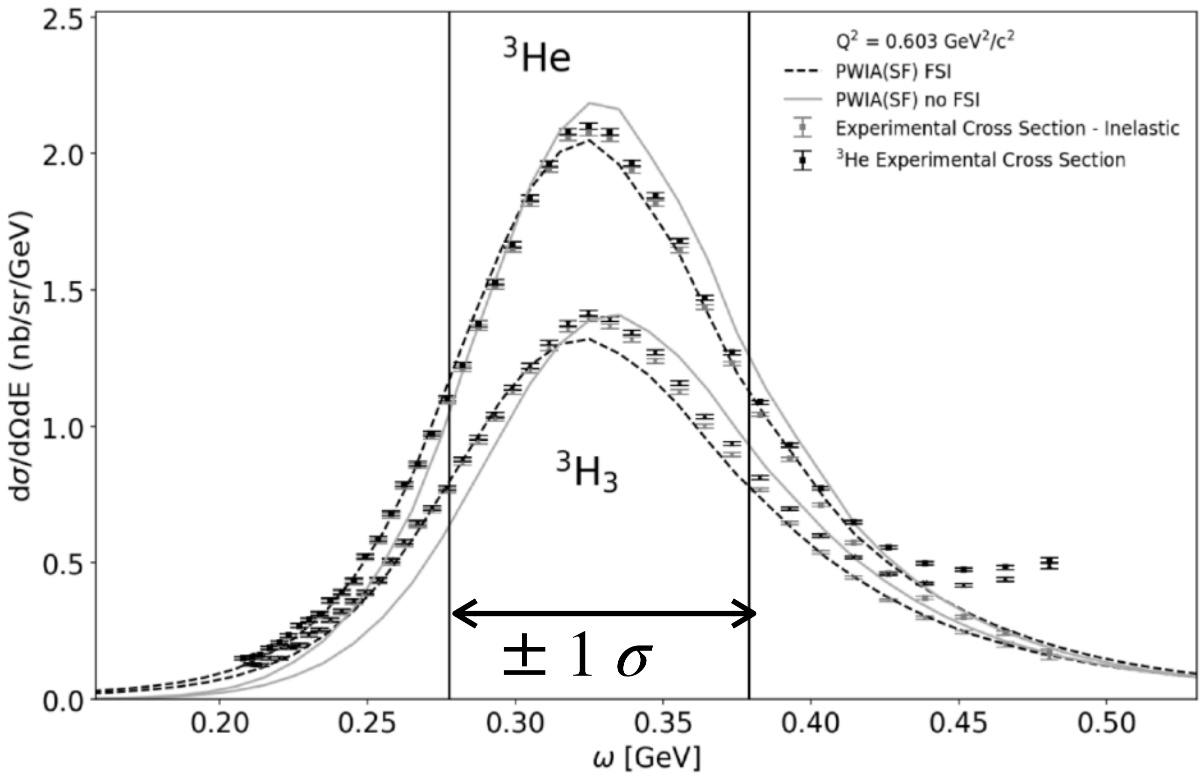

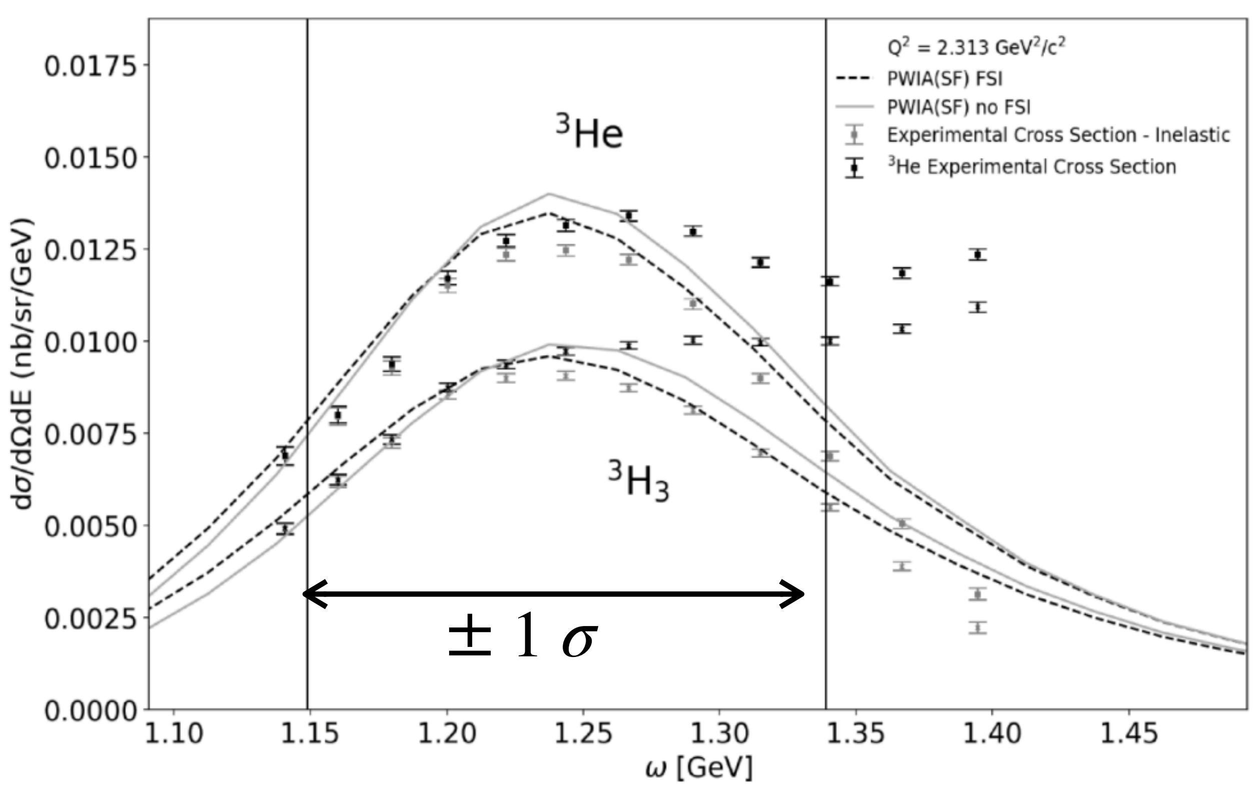

1. Remove the inelastic distribution from the cross sections
2. Integrate the $\pm 1\ \sigma$ region (in both the model and the data), and calculate the ratio $R =^3 H/^3He$

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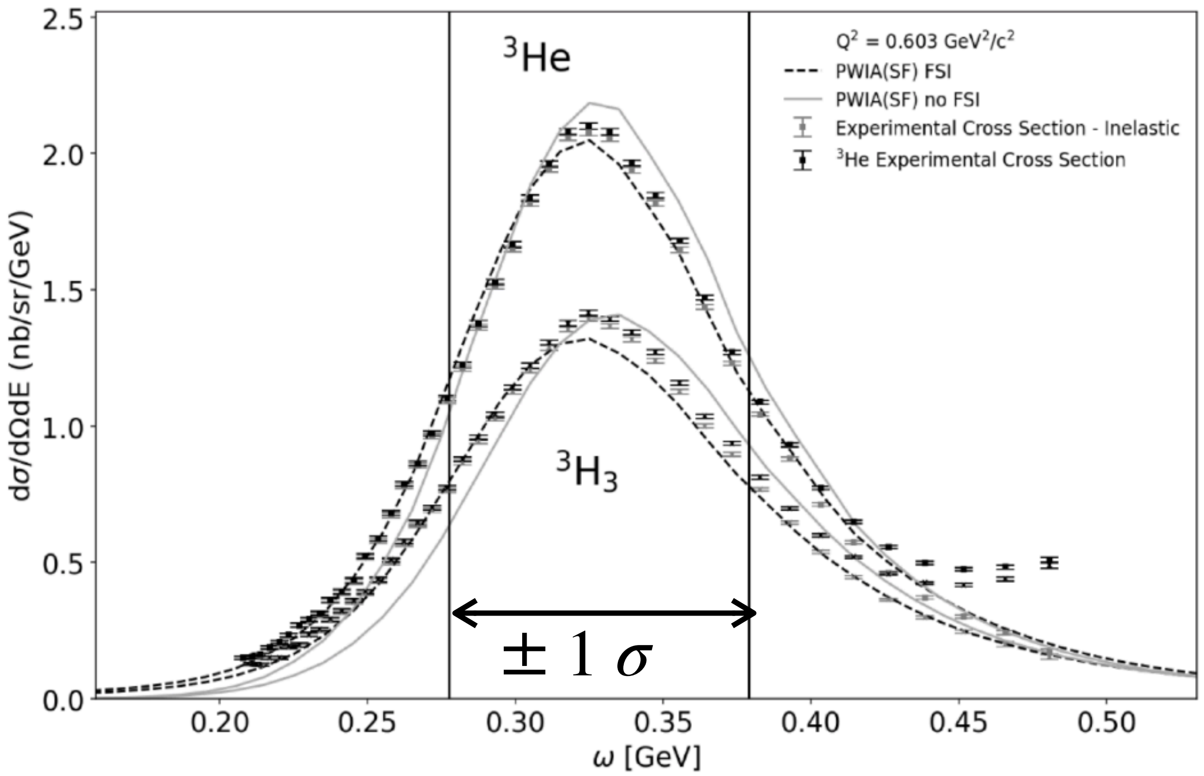
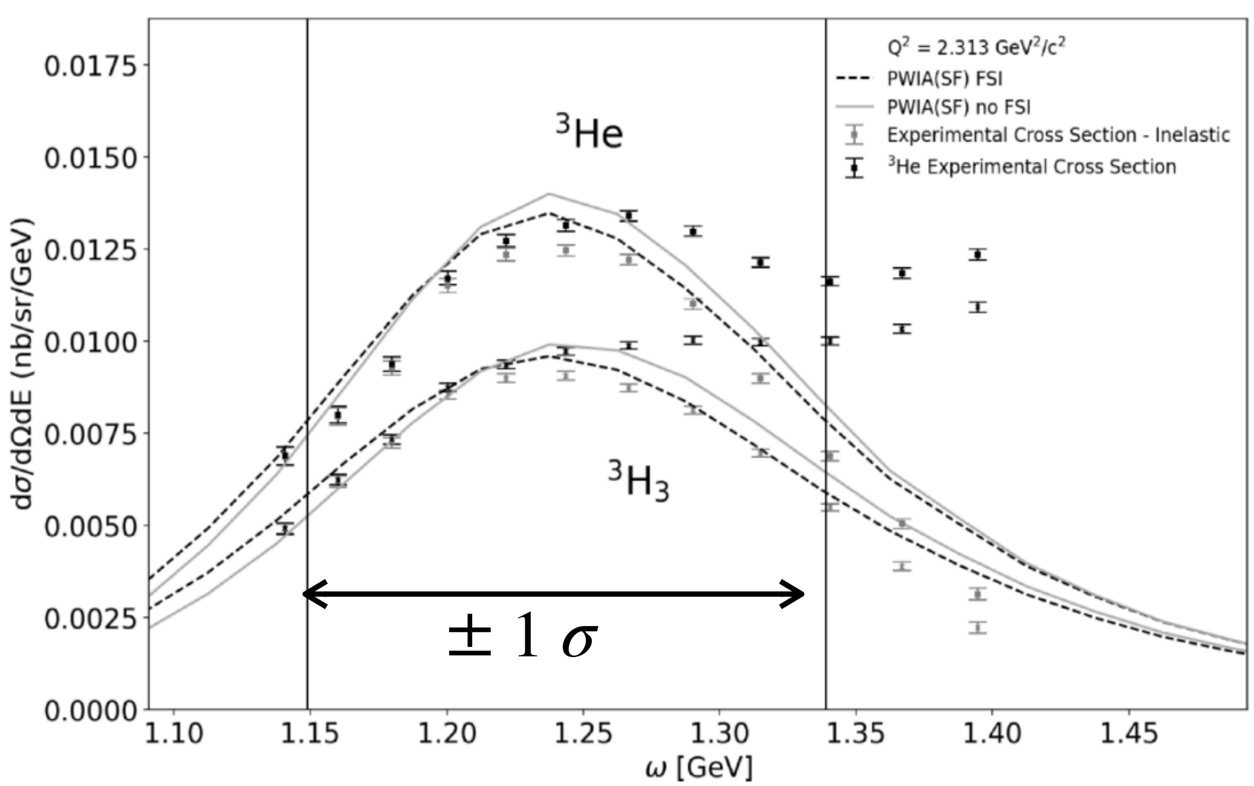


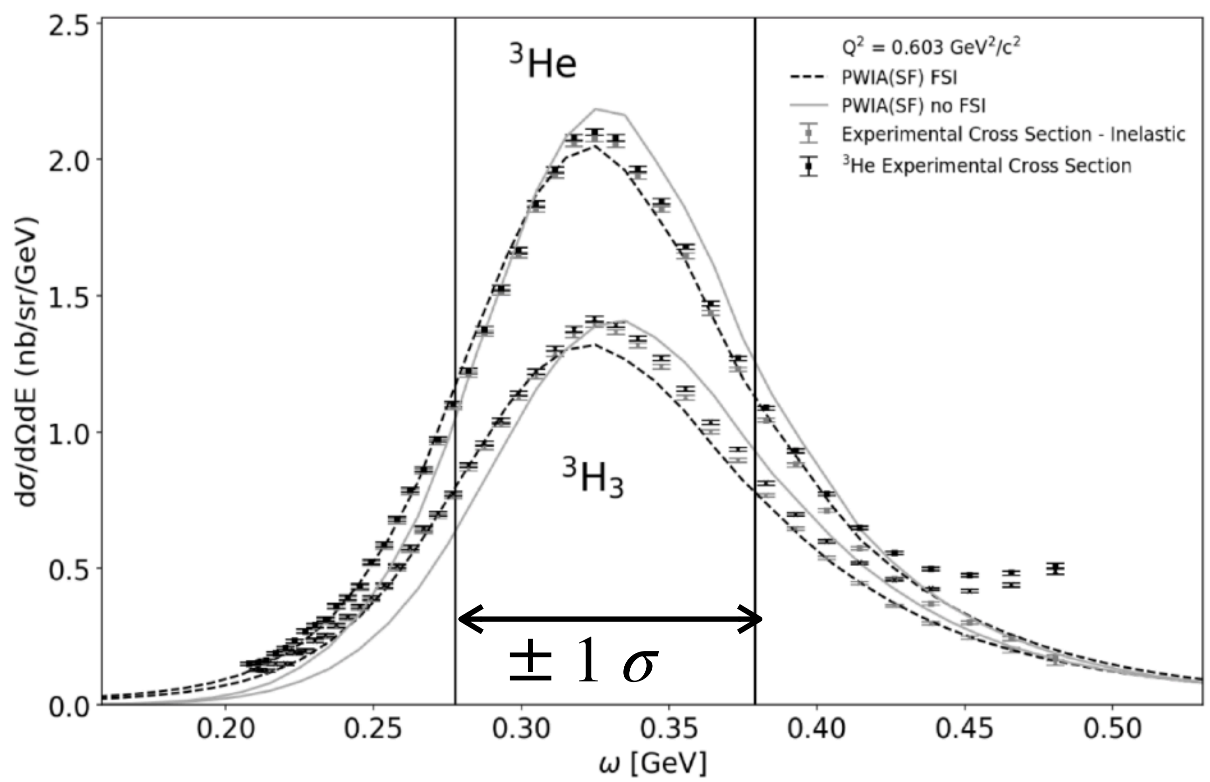


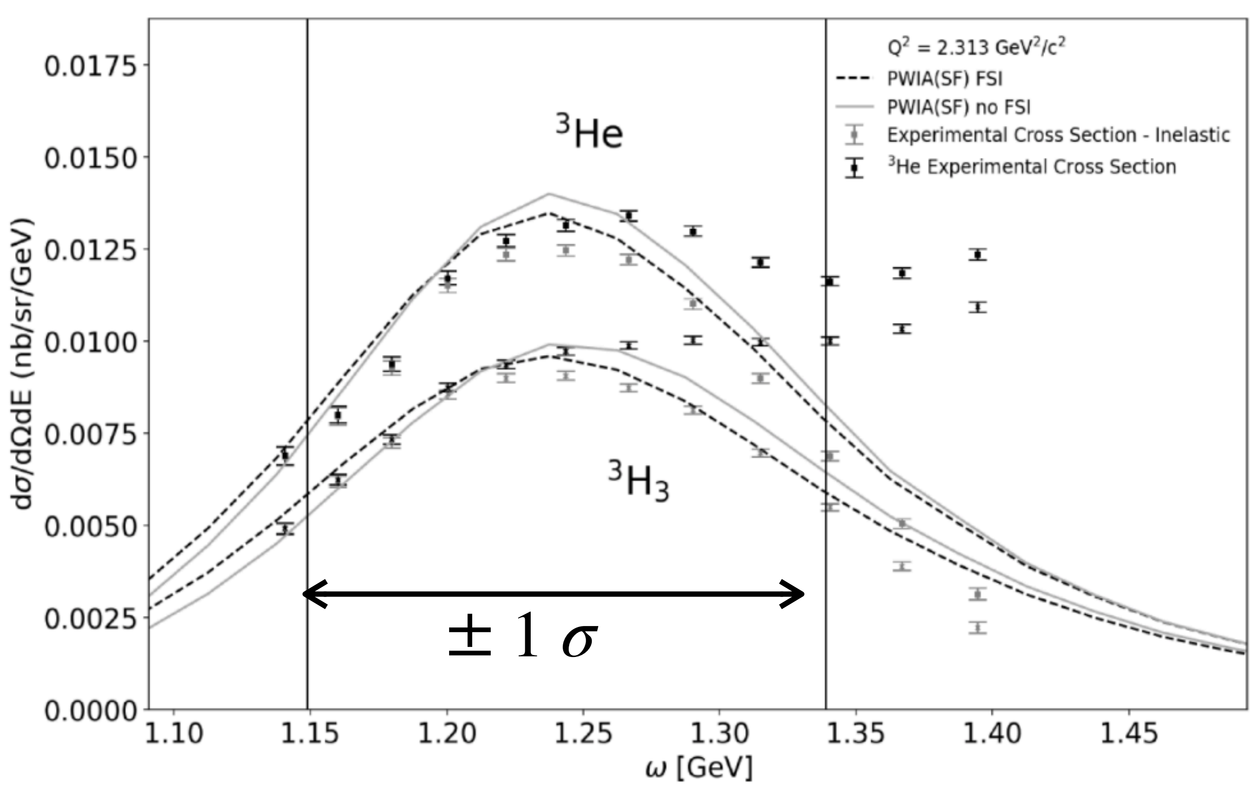
1. Remove the inelastic distribution from the cross sections
2. Integrate the $\pm$ 1 σ region (in both the model and the data), and calculate the ratio $R =^3 H/^3He$
3. Estimate the medium effects (α) from the model ratio:

$$R^{Model} = \alpha\frac{2\sigma_n + \sigma_p}{\sigma_n + 2\sigma_p}$$

The nucleon cross sections are calculated with the from factors from Z. Ye, J. Arrington, R. J. Hill, and G. Lee, Physics Letters B 777, 8 (2018).

Some steps to get to G_M^n:





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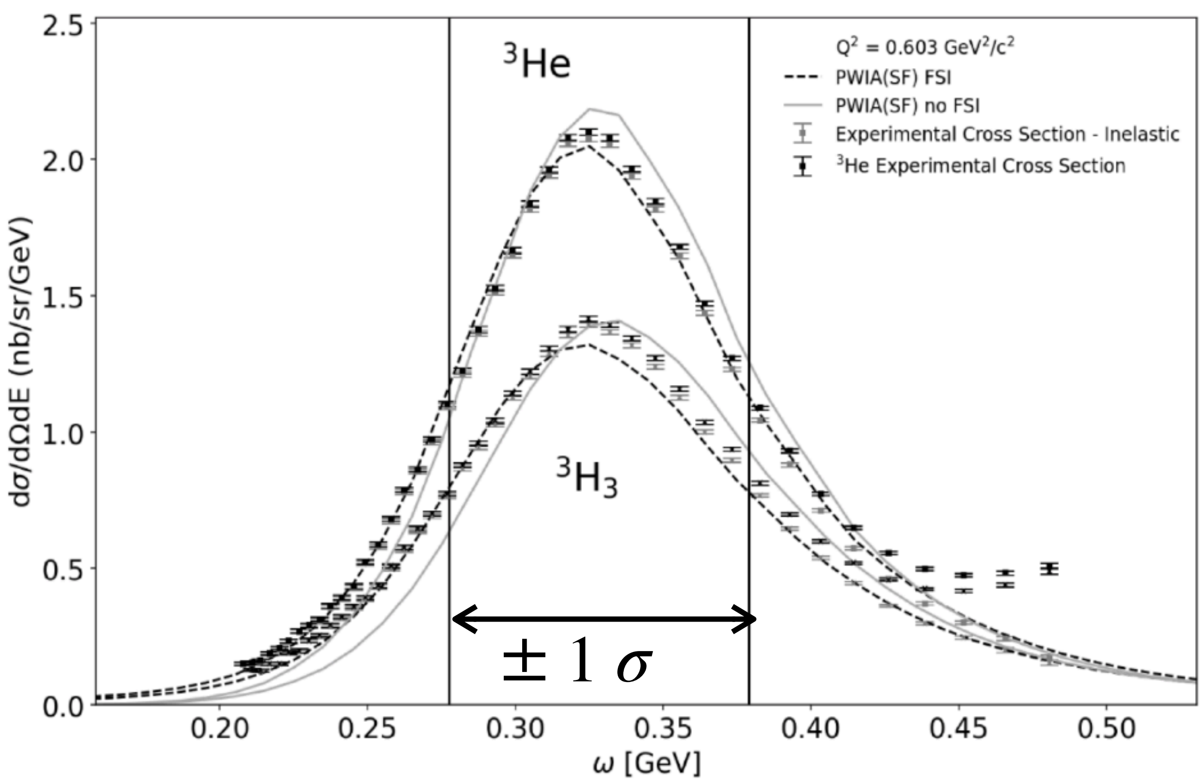
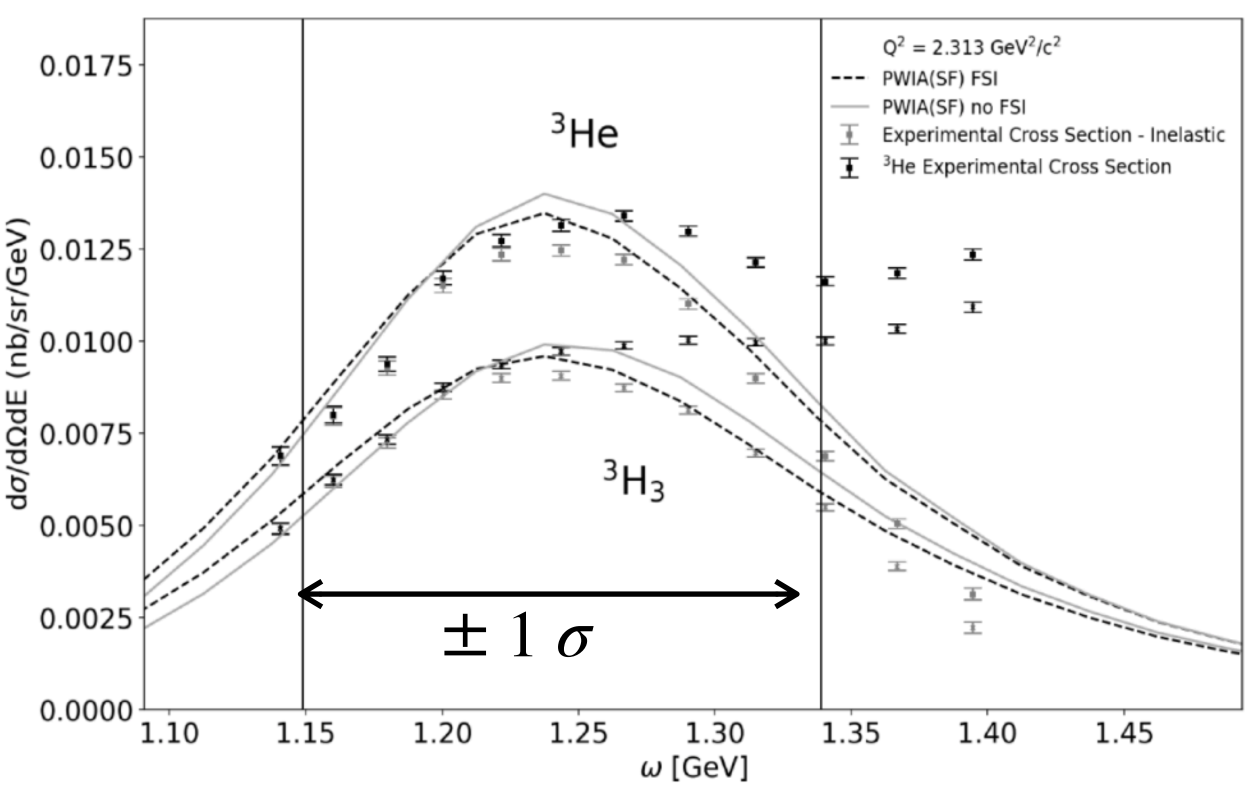
2. Integrate the $\pm 1\ \sigma$ region (in both the model and the data), and calculate the ratio $R = ^3H/^3He$
3. Estimate the medium effects (α) from the model ratio.
4. The magnetic form factor is calculated from the data .
5. Calculate the σ_n/σ_p from the data ratio using the medium effects:

$$(\sigma_n/\sigma_p)^{Data} = \frac{\alpha - 2R^{Data}}{R^{Data} - 2\alpha}$$

Some steps to get to G_M^n:





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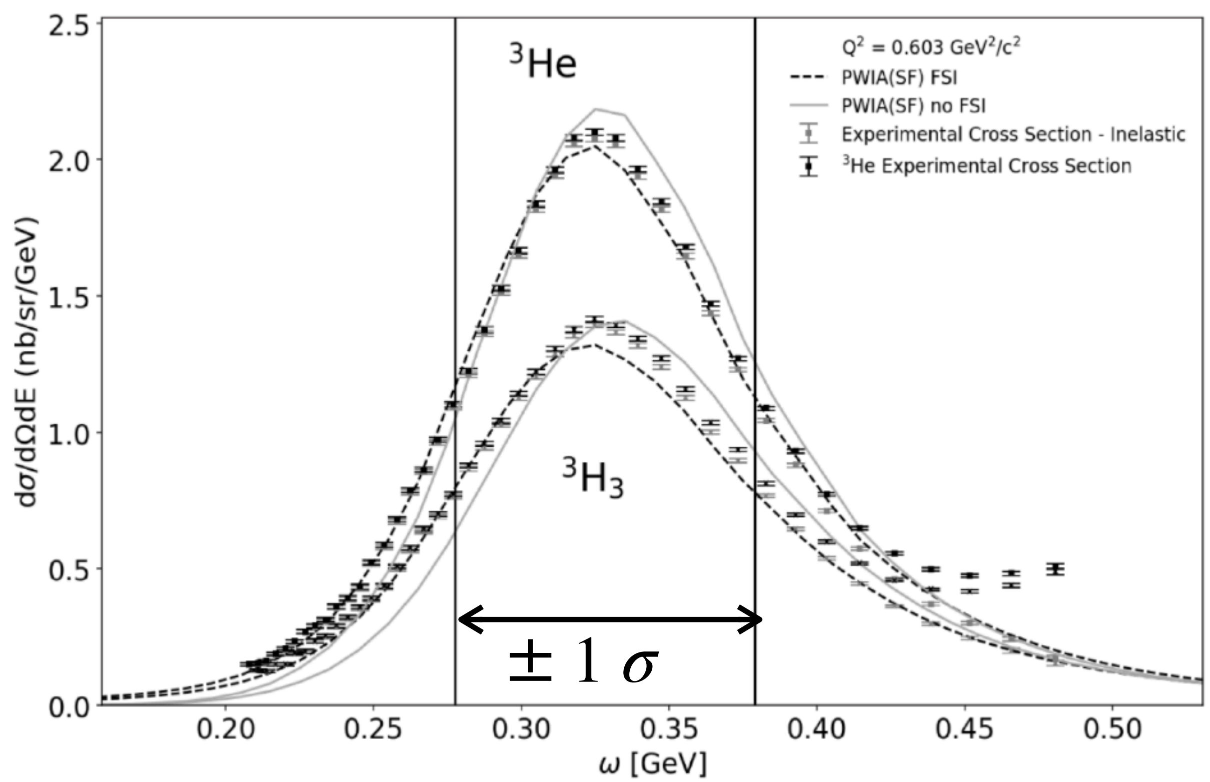
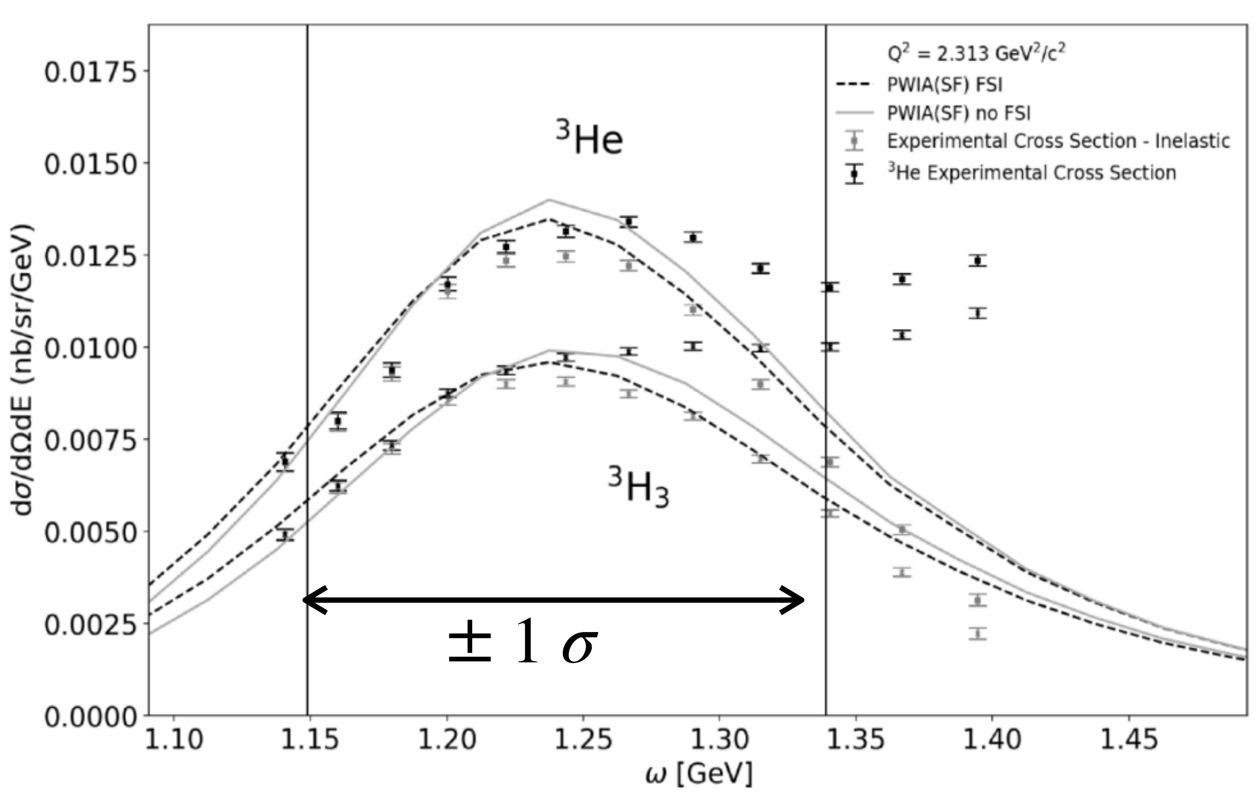
6. Estimate $\sigma_n^{Data-(Born+TPE)}$

$$\sigma_n^{Data-(Born+TPE)} = (\sigma_n/\sigma_p)^{Data}\sigma_p^{Fit-(Born+TPE)}$$

Using $\sigma_p^{Fit-(Born+TPE)}$ from direct fit to measured cross sections with no TPE correction J. Arrington, W. Melnitchouk, and J. A. Tjon, Phys. Rev. C 76, 035205 (2007).

Some steps to get to G_M^n:





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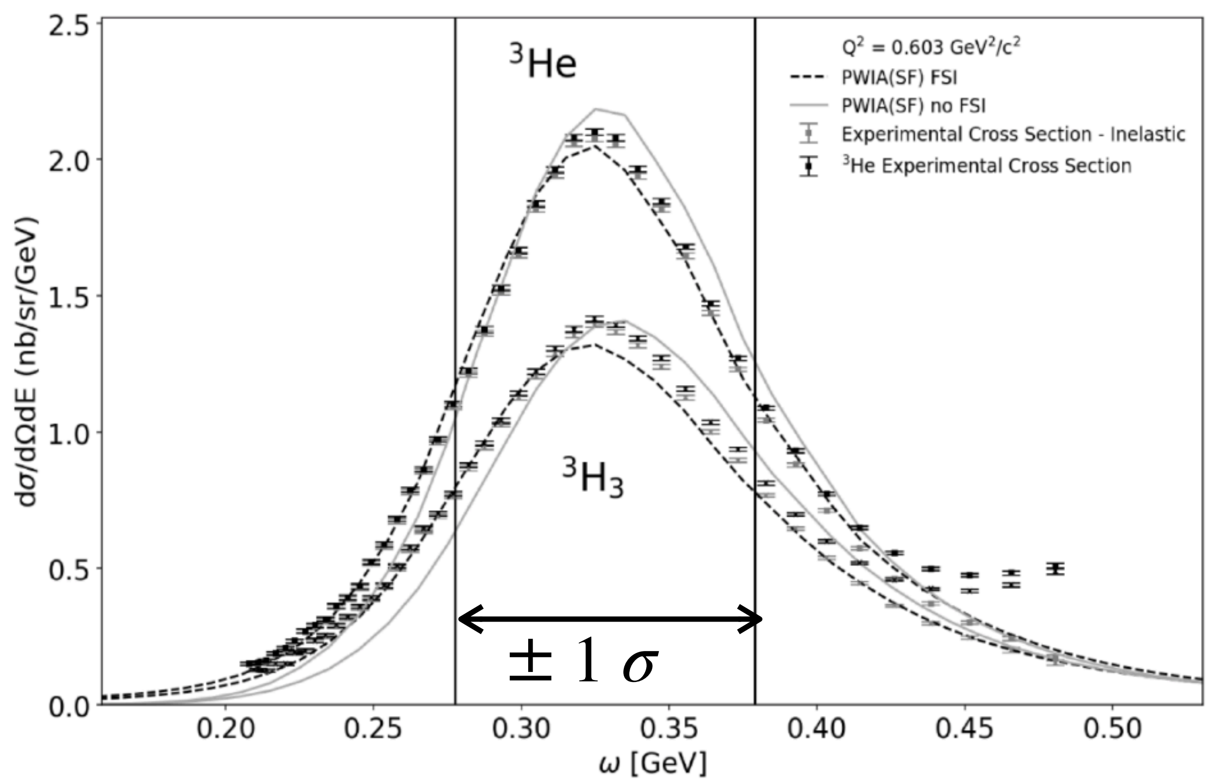
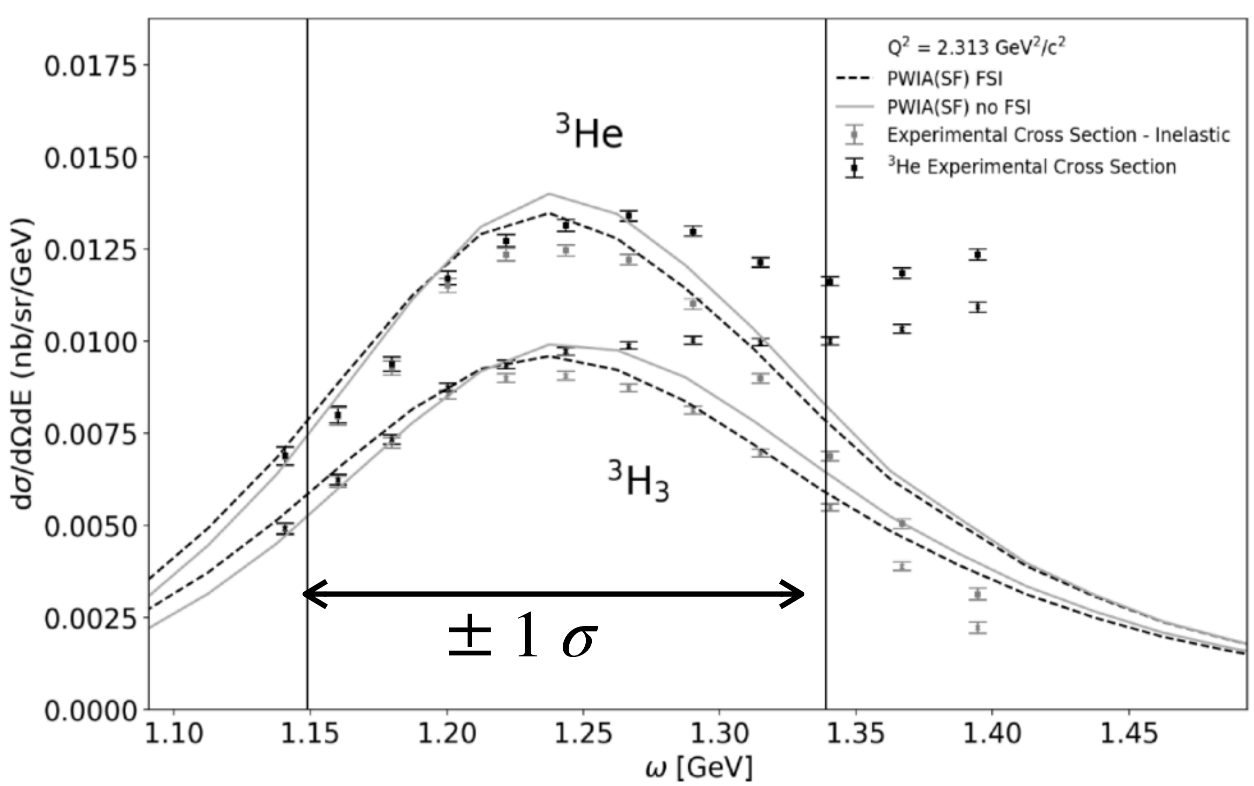
5. Calculate the σ_n/σ_p from the data ratio using the medium effects.
6. Estimate $\sigma_n^{Data-(Born+TPE)}$
7. Extract the born cross section (σ_n^{Born}), after correcting for the TPE.

$$\sigma_n^{Born} = \sigma_n^{Data-(Born+TPE)} C_{TPE}^{e-n}$$

Some steps to get to G_M^n:





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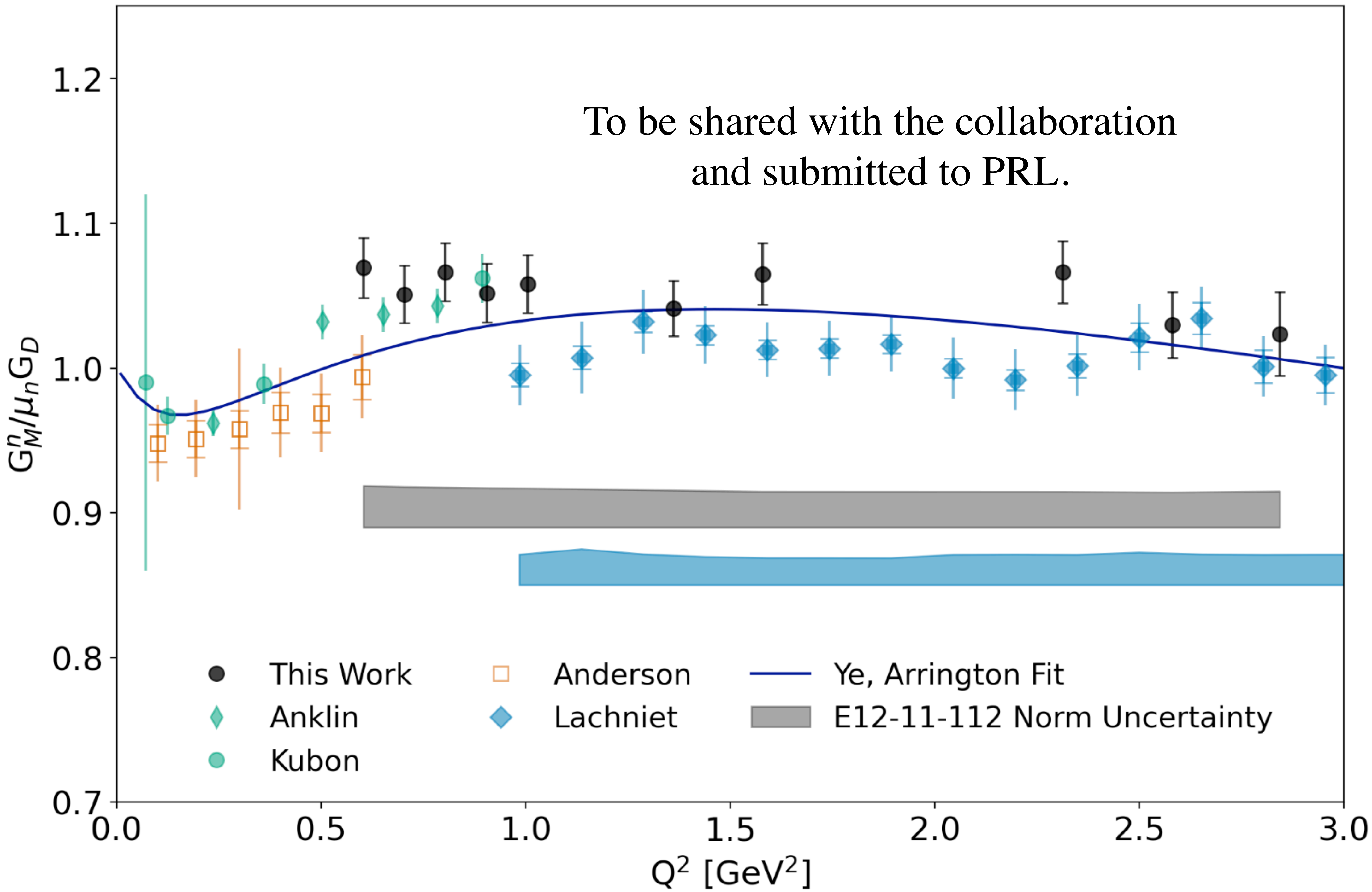
4. The magnetic form factor is calculated from the data .
5. Calculate the σ_n/σ_p from the data ratio using the medium effects.
6. Estimate $\sigma_n^{Data-(Born+TPE)}$
7. Extract the born cross section (σ_n^{Born}), after correcting for the TPE.
8. Extract the form factor:

$$G_M^n = \left(\left[\sigma_n^{Born} - \frac{\epsilon}{\tau}(G_E^n)^2\right]\right)^{1/2}$$

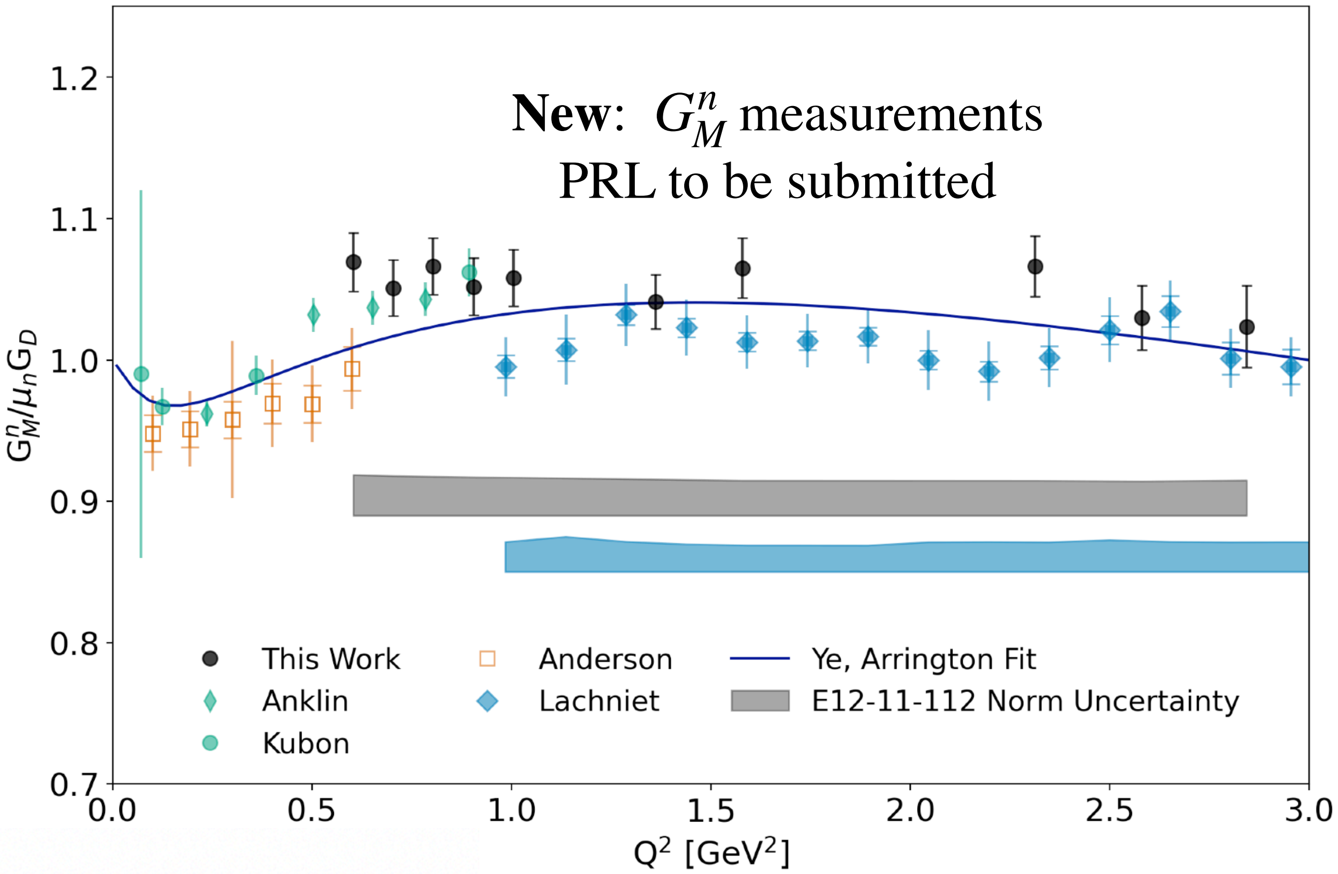
with G_E^n from Z. Ye, J. Arrington, R. J. Hill, and G. Lee, Physics Letters B 777, 8 (2018).

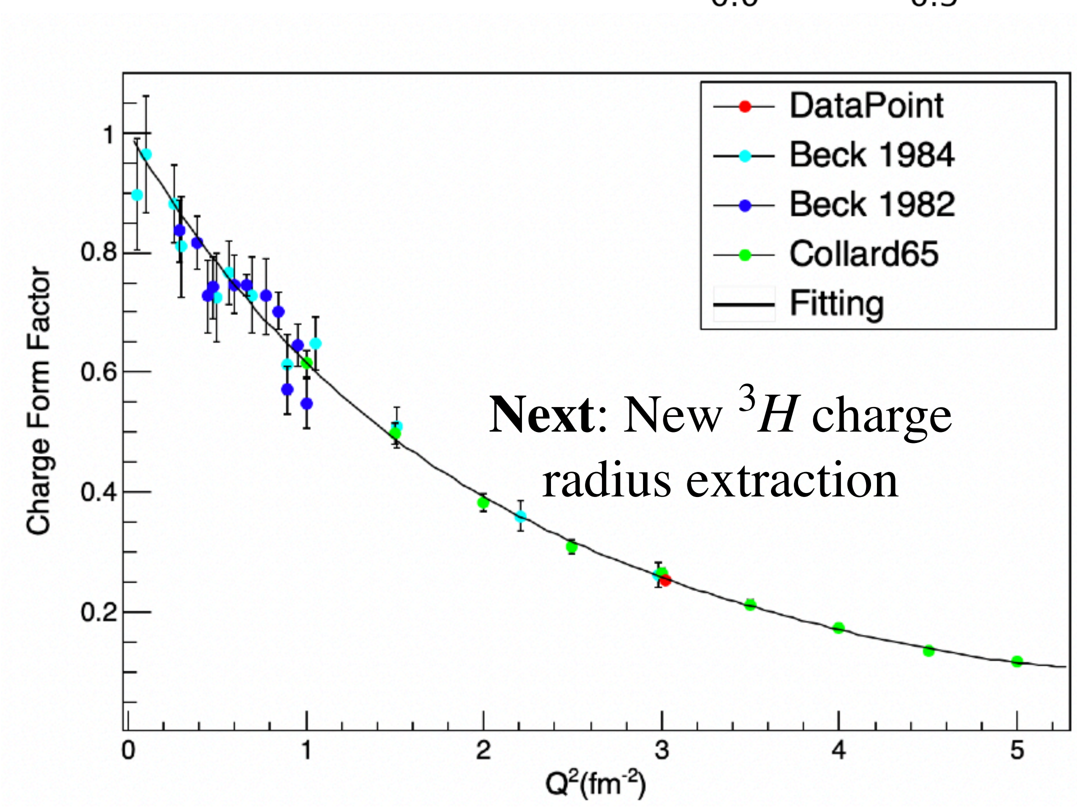
G_M^n results

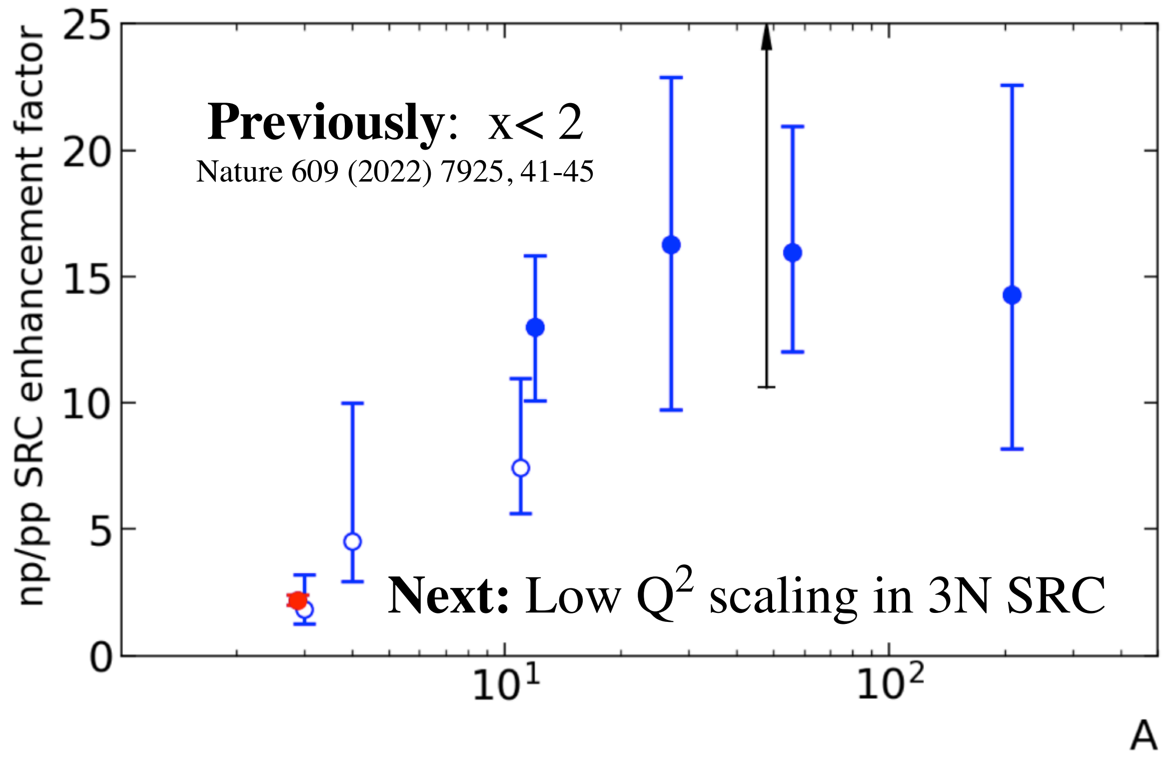


To be shared with the collaboration and submitted to PRL.
1.2
1.1
1.0
0.9
0.8
0.7
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$G_M^n/\mu_n G_D$
Q^2 [GeV^2]
This Work
Anklin
Kubon
Anderson
Lachniet
Ye, Arrington Fit
E12-11-112 Norm Uncertainty

Summary


New: G_M^n measurements
PRL to be submitted
$G_M^n/\mu_n G_D$
Q^2 [GeV^2]
This Work
Anklin
Kubon
Anderson
Lachniet
Ye, Arrington Fit
E12-11-112 Norm Uncertainty


Charge Form Factor
Q^2(fm^{-2})
DataPoint
Beck 1984
Beck 1982
Collard65
Fitting
Next: New ^3H charge radius extraction


np/pp SRC enhancement factor
A
Previously: x< 2
Nature 609 (2022) 7925, 41-45
Next: Low Q^2 scaling in 3N SRC