A novel measurement of the neutron magnetic form factor from A=3 mirror nuclei

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On behalf of the E12-11-112 collaboration

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2024

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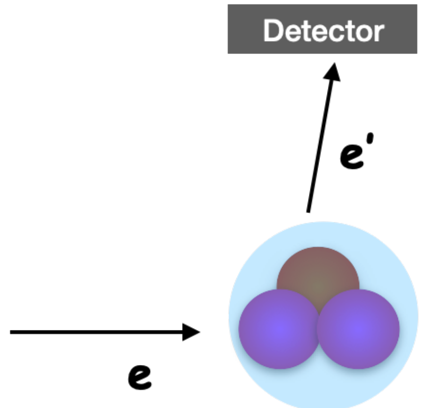
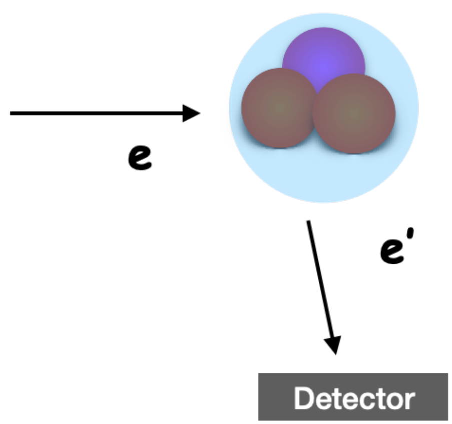
University of New Hampshire

U.S. DEPARTMENT OF ENERGY

E12-11-112 Experiment





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

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

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

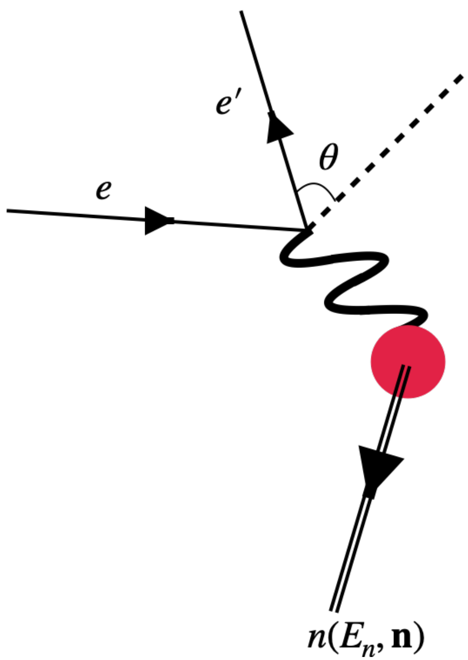
Inclusive Measurements

- ✦ Sum of Short-range correlations (See Shujie's talk tomorrow)
  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) **(This talk)**
- ✦ Charge radius of 3H vs 3He (x=3) (In progress)

X

Understanding neutron form factors

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



$G_E^n(Q^2)$: Electric form factor

$G_M^n(Q^2)$: Magnetic form factor

Encode information on the spatial distribution of charge and magnetization

In the center of mass of the electron-Nucleon system (Breit frame) no energy transfer ($\omega_{CM} = 0 \rightarrow |q|^2 = |\mathbf{q}|$)

$\rho(\mathbf{r}) \rightarrow$ charge distribution $\quad\quad \mu(\mathbf{r}) \rightarrow$ Magnetization distribution

$G_E = \int \rho(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}} d^3\mathbf{r} \quad\quad G_M = \int \mu(\mathbf{r}) e^{i\mathbf{q}\cdot\mathbf{r}} d^3\mathbf{r}$

Static limit: $Q^2 \rightarrow 0$

$G_E^n(0) = 0 \quad\quad G_M^n(0) = \mu_n$

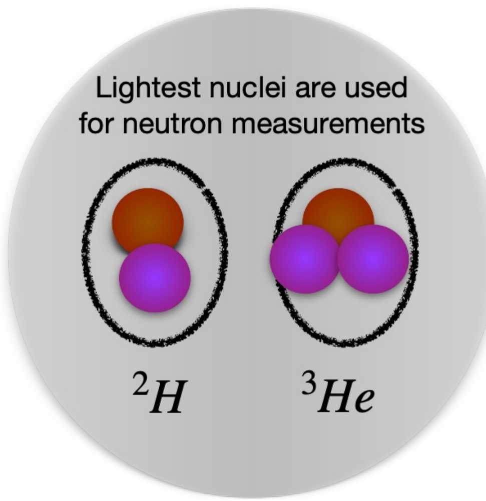
No free neutron target

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.



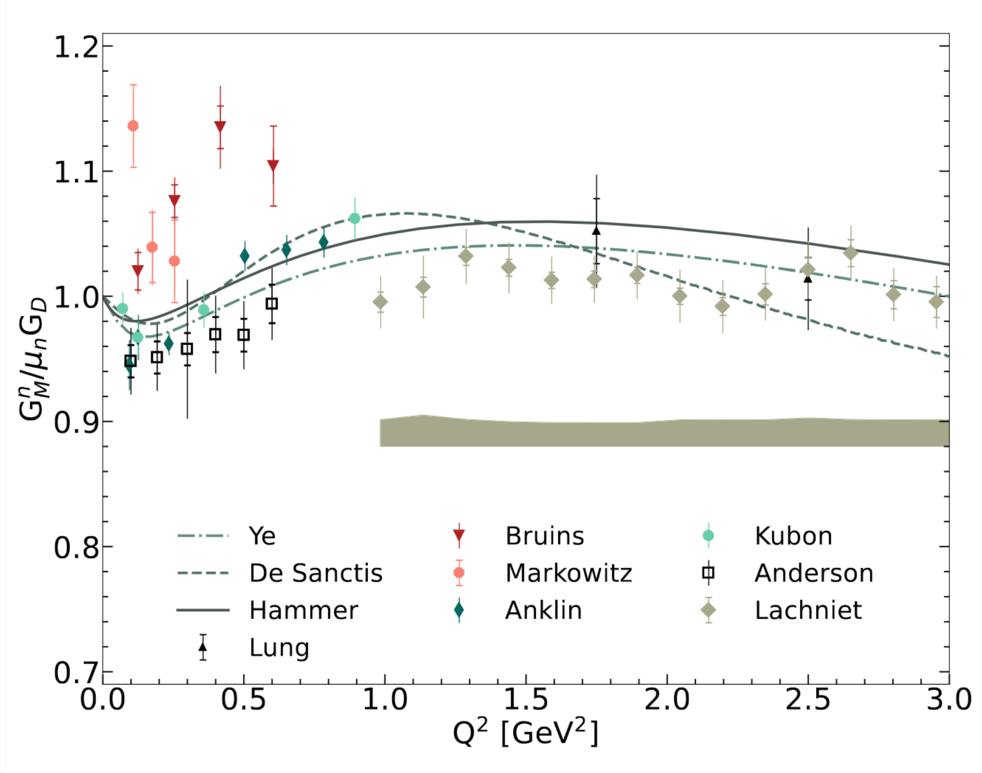
Neutron measurements include:

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

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

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

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



Previous measurements

Inclusive: d(e,e')

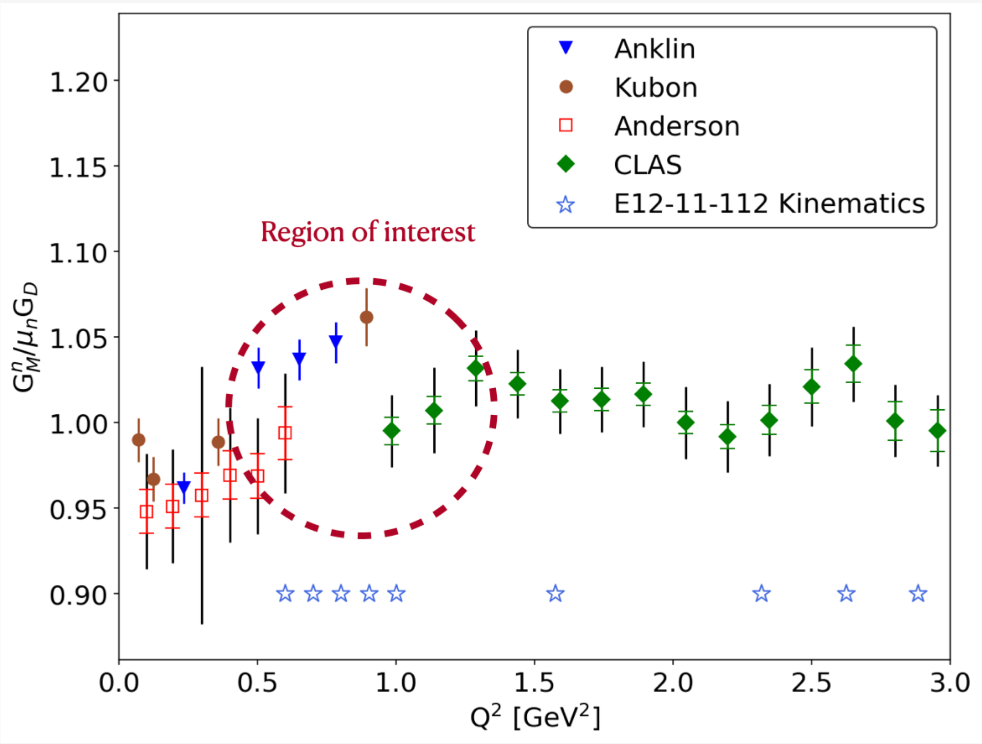
- Subtract proton, correct for Fermi motion
- Large subtraction enhances statistical, expt. systematic, and model uncertainties

Exclusive: ratio of d(e,e'n)/d(e,e'p)

- No proton 'subtraction'
- Low (uncertain) neutron detection efficiency
- Smaller correction for motion in deuteron

Polarized ^{3}He

- Corrections are well understood at low Q^2
- Larger overall uncertainties



Motivation

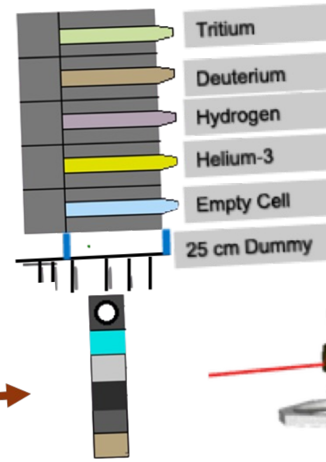
- Of particular interest is the region $0.5<Q^2<1$ GeV^2 , where the differences are most pronounced
- E12-11-112 covered QE peak for $0.6<Q^2<2.8$
- Goal of providing new data in this region to help understand the discrepancy using the A=3 targets – very different corrections, systematic uncertainties.

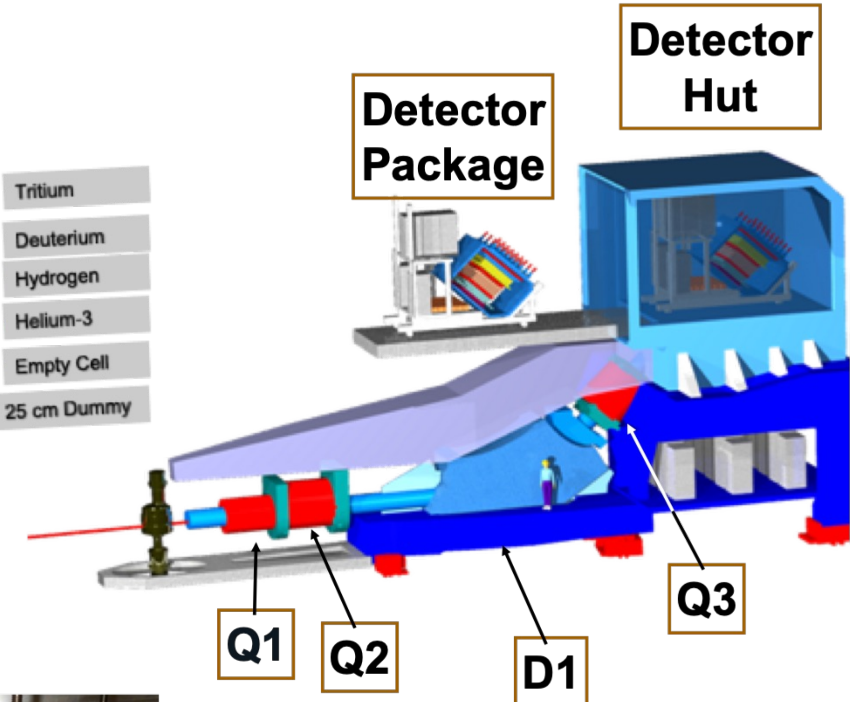
Experimental Setup

Hall A

E = 2.2 Gev
E = 4.3 Gev

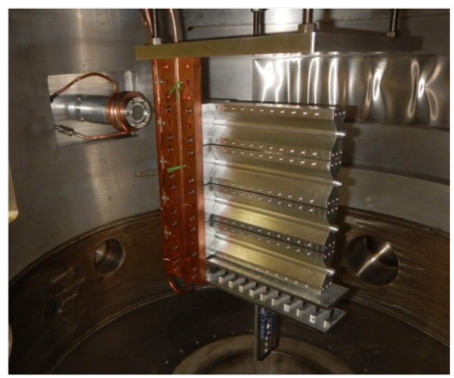
Electron Beam



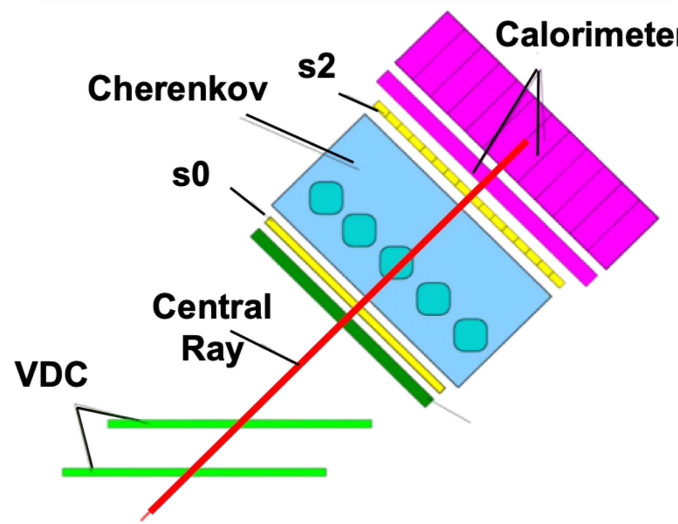


LHRS and RHRS

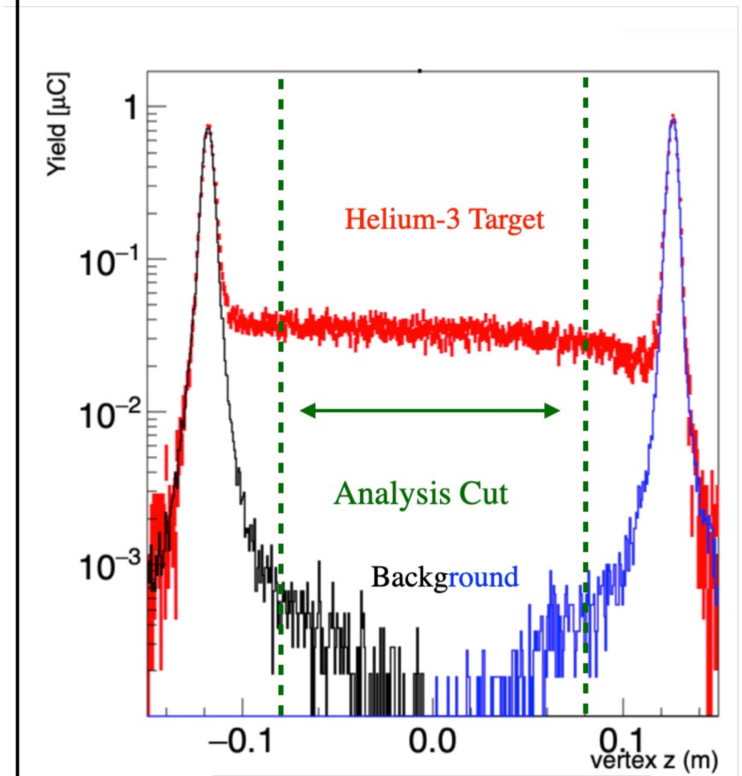
*10 different Q^2 Points
*2-3 Kinematics Settings per Q^2 point.
*3 run periods.
*2 Tritium Cells

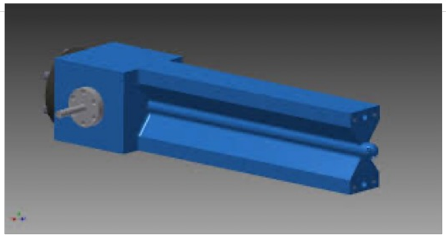


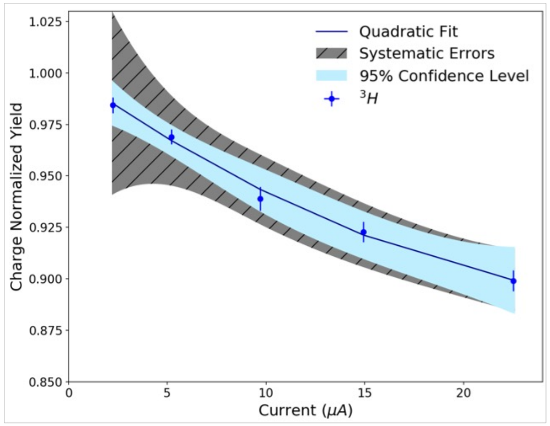
Target System

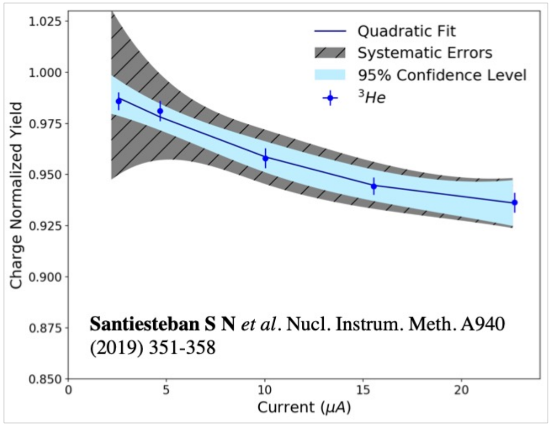


A few analysis remarks







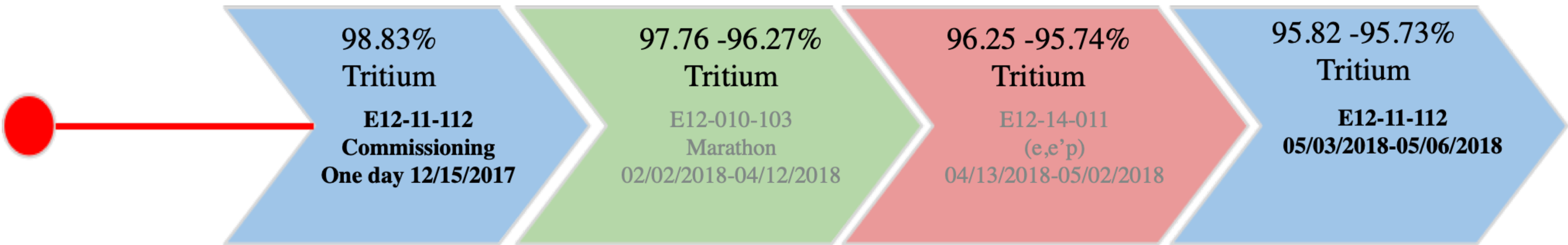


Density Reduction in the targets for $22\mu A$:

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

Helium contamination in the tritium cell

First Cell:



Second Cell:

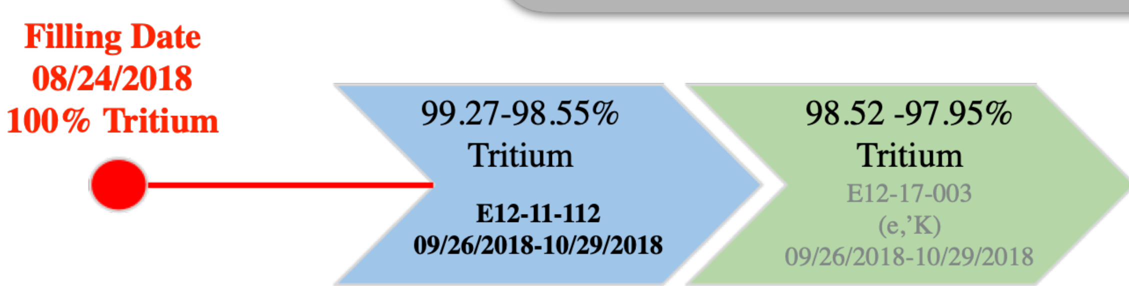
Tritium ($\tau = 4500 \pm 8$ days): $n_{^3H}(t) = n_0 e^{-t/\tau}$

What is measured: $\sigma^{measured} = \sigma^{^3H} e^{-t/\tau} + \sigma^{^3He}(1 - e^{-t/\tau})$

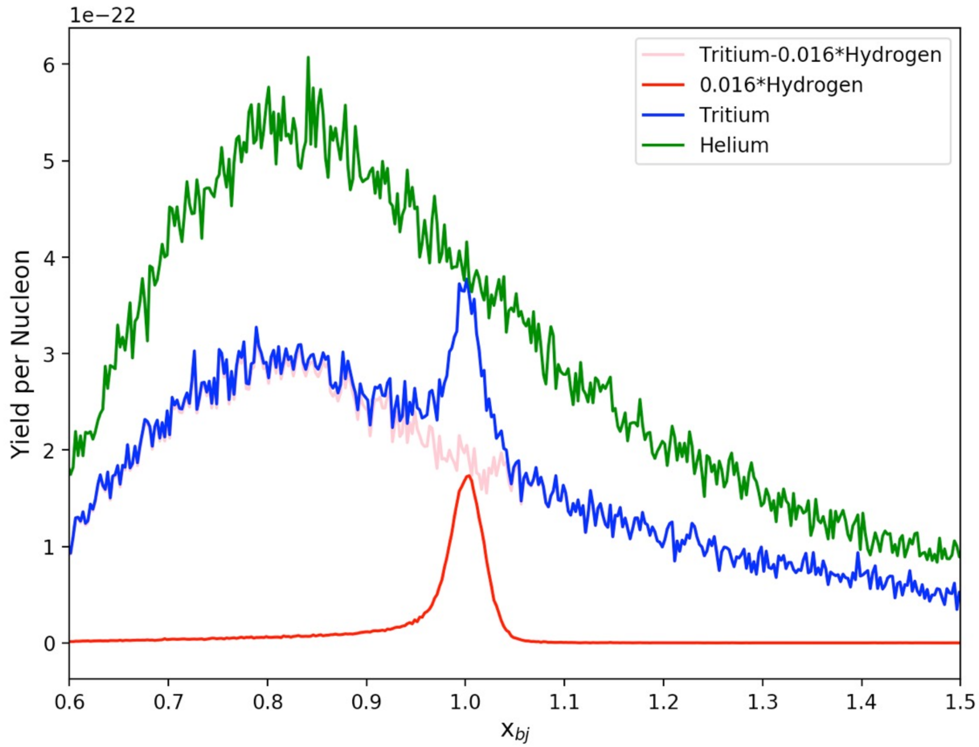
What is wanted:

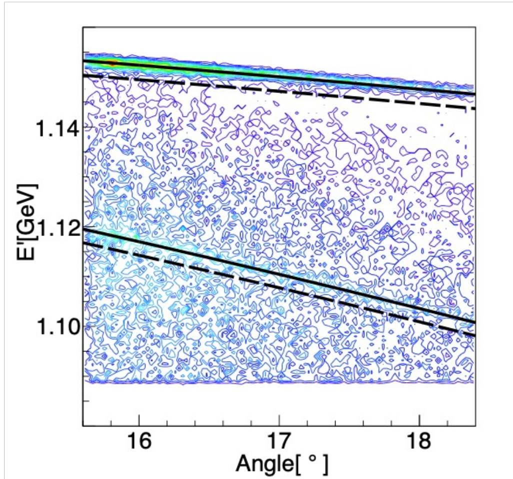
if $f(t) = \frac{n_{^3H}(t)}{n_0} = 1 - e^{-t/\tau}$

$$Y^{^3H} = \frac{Y^{measured}}{1 - f(t)} - Y^{^3He} \frac{f(t)}{1 - f(t)}$$



Hydrogen contamination in the second tritium cell



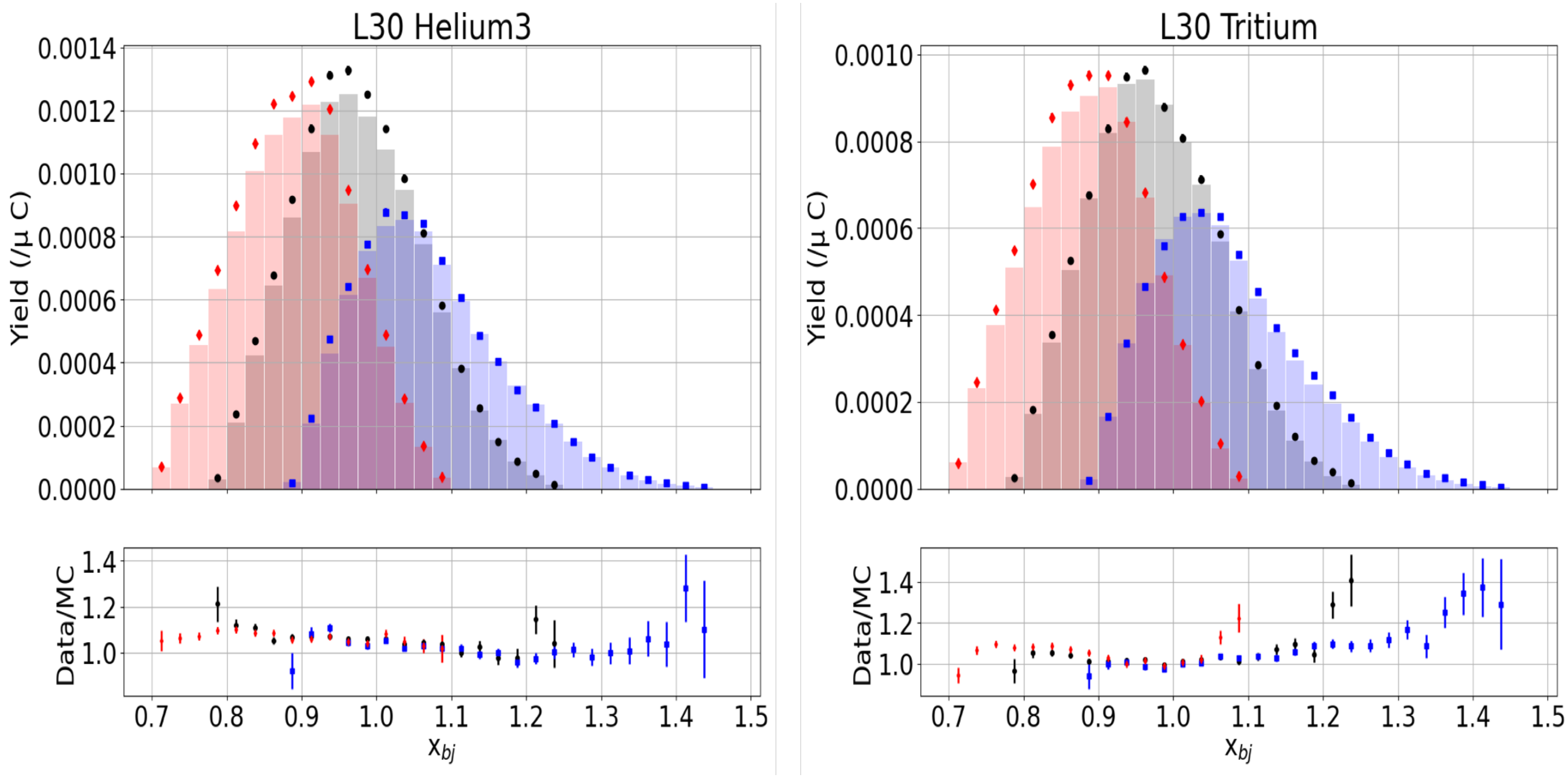


$$H_2O + T_2 \rightarrow HTO + HT$$

4.12% Hydrogen Contamination

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

Data/MC Sample



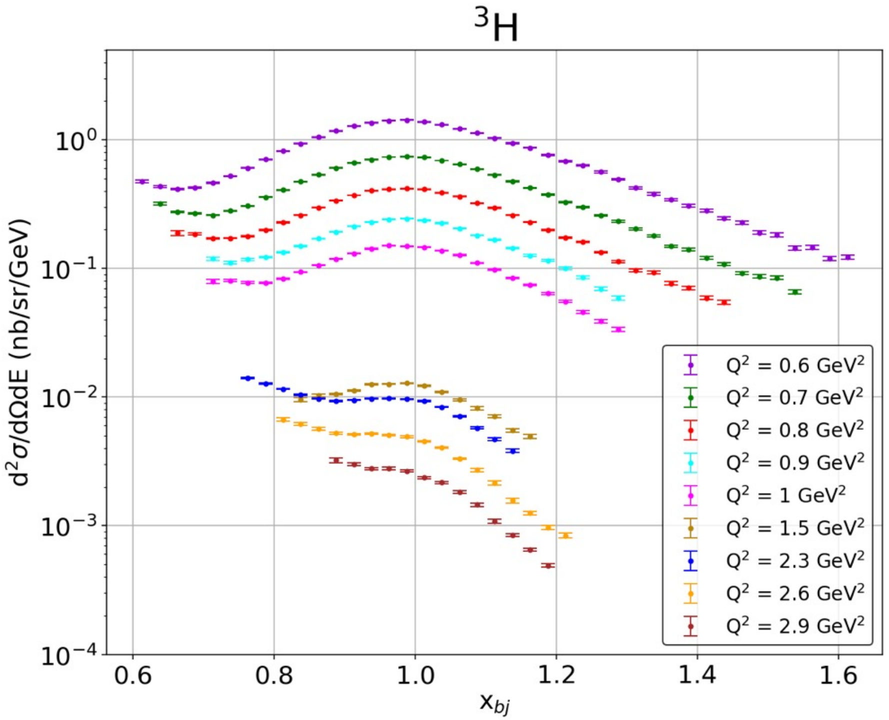
LS: Low Side of the QE peak

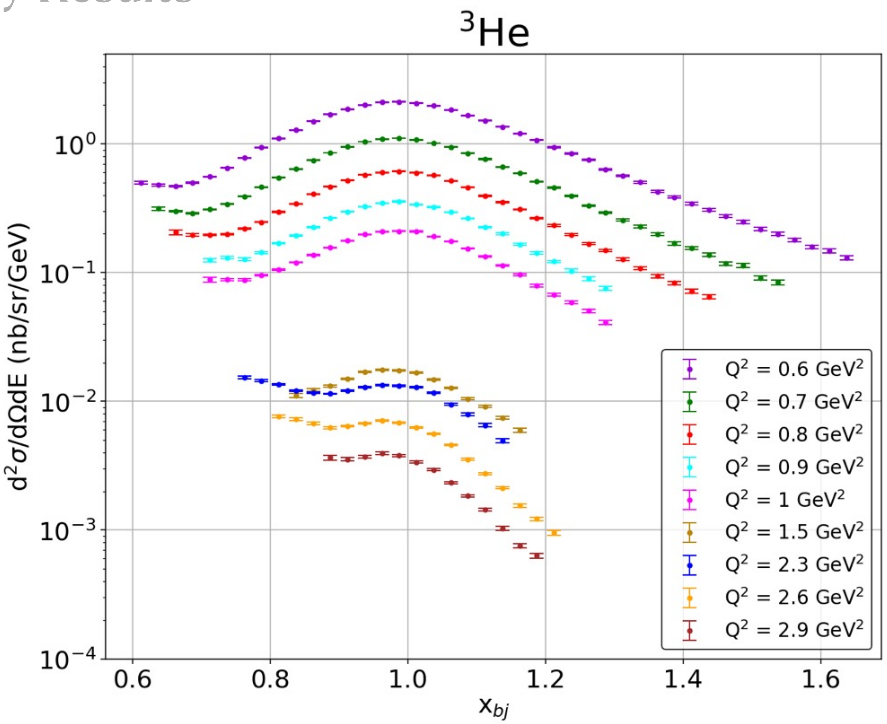
PK: Centered at the QE peak

HS: High side of the QE peak

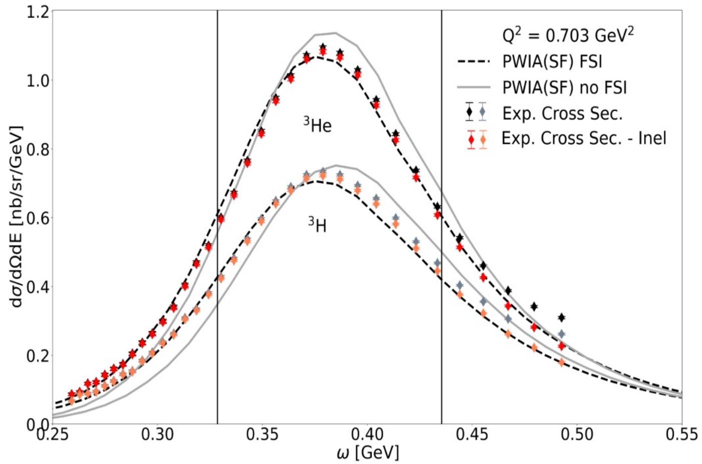
Cross-Sections

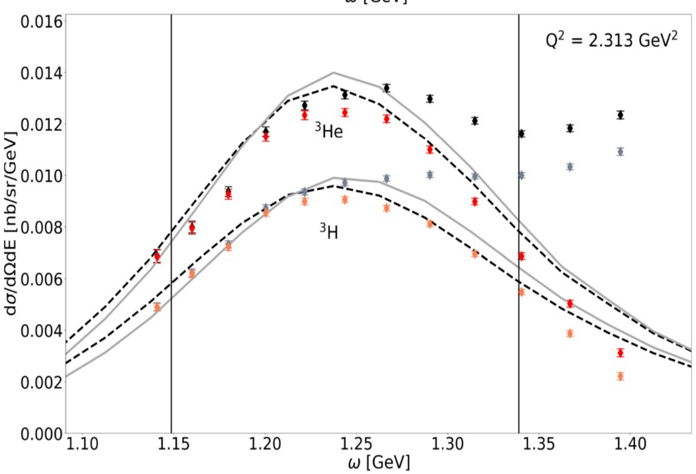
Preliminary Results





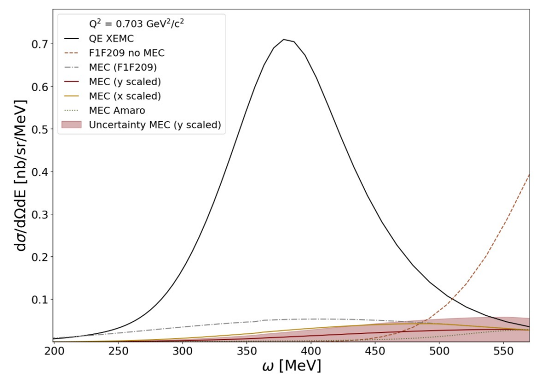
From Cross-Sections to G^n_M

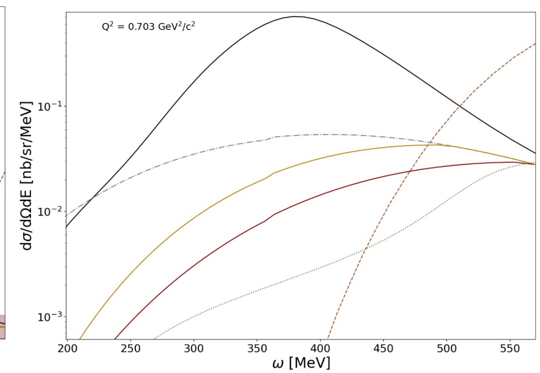




Calculations from Rocco and Lovatto
Phys. Rev. C 105, 014002 (2022)

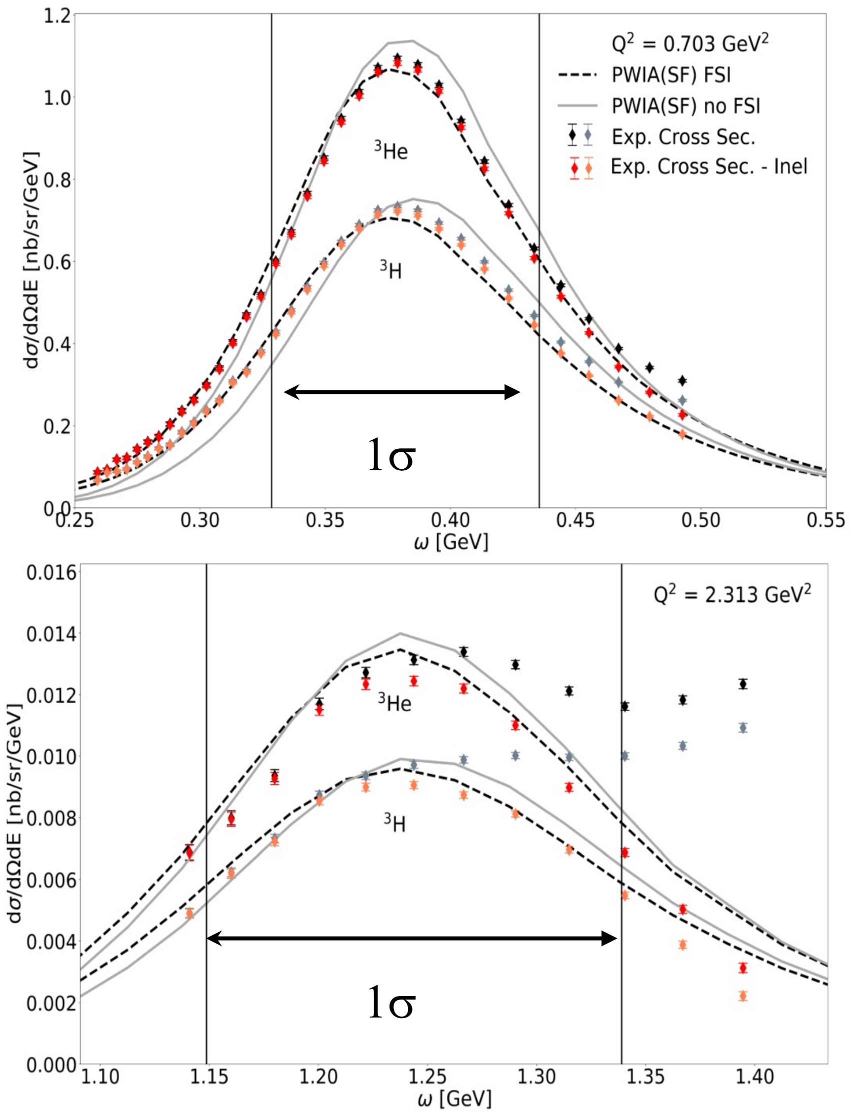
1. Remove the inelastic distribution from the cross sections





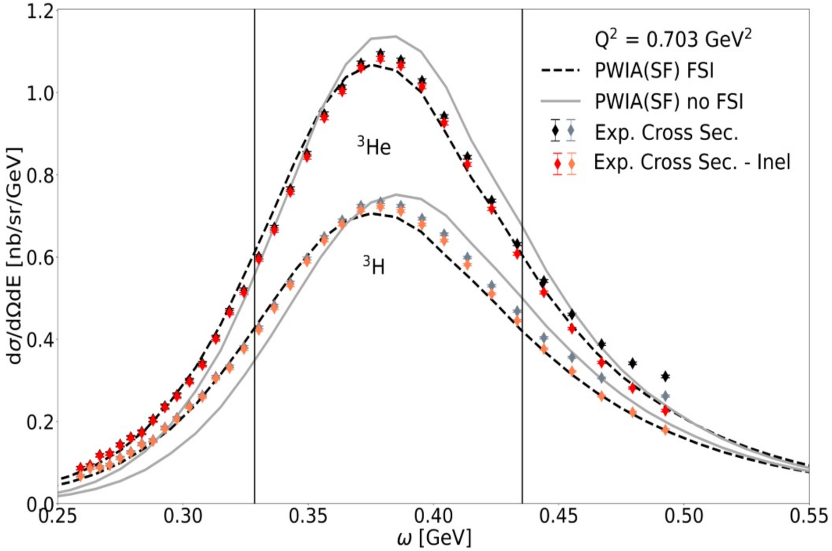
MEC100% uncertainty

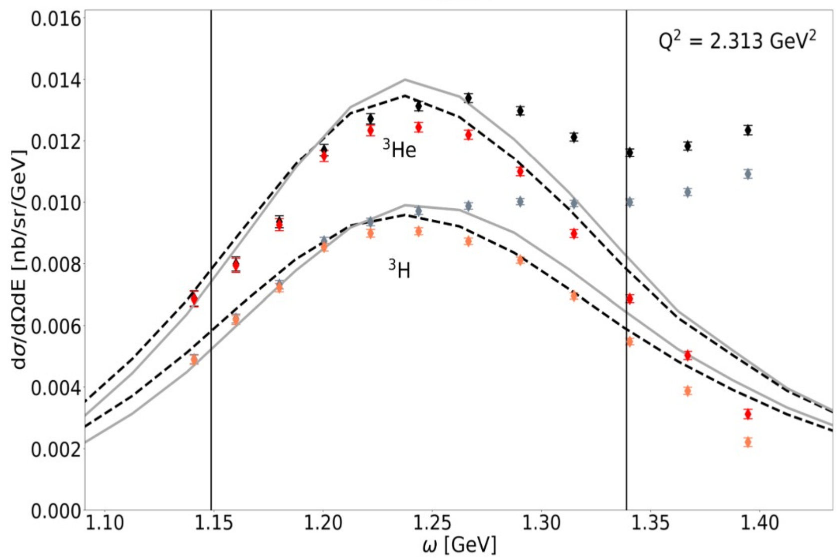
From Cross-Sections to G^n_M



1. Remove the inelastic distribution from the cross sections
2. Integrate the 1σ region (in both the model and the data) and calculate the ratio R = ^{3}H/^{3}He.

From Cross-Sections to G^n_M

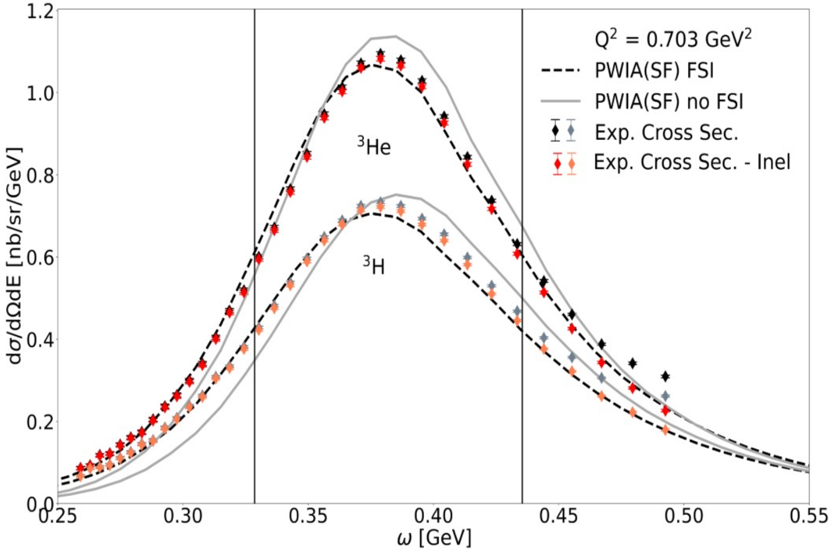


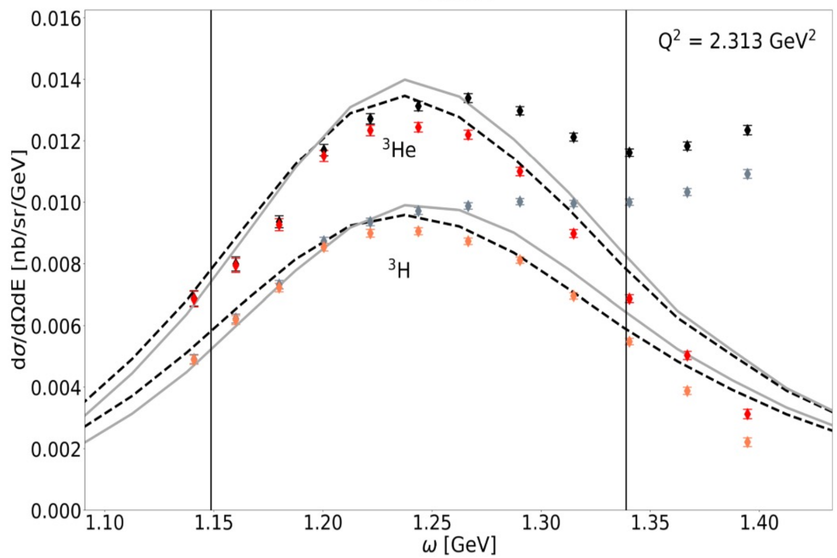


1. Remove the inelastic distribution from the cross sections
2. Integrate the 1σ region (in both the model and the data) and calculate the ratio R = ^{3}H/^{3}He.
3. Estimate the medium effects from the model (calculations).

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

From Cross-Sections to G^n_M





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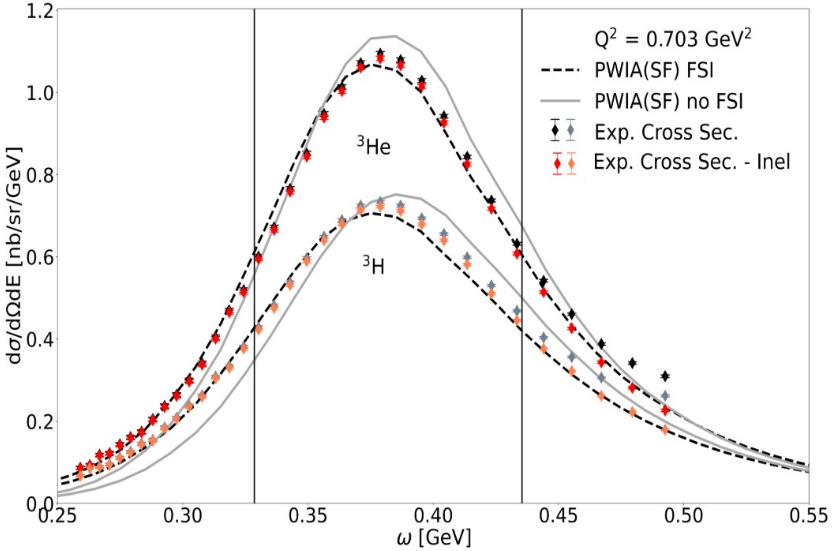
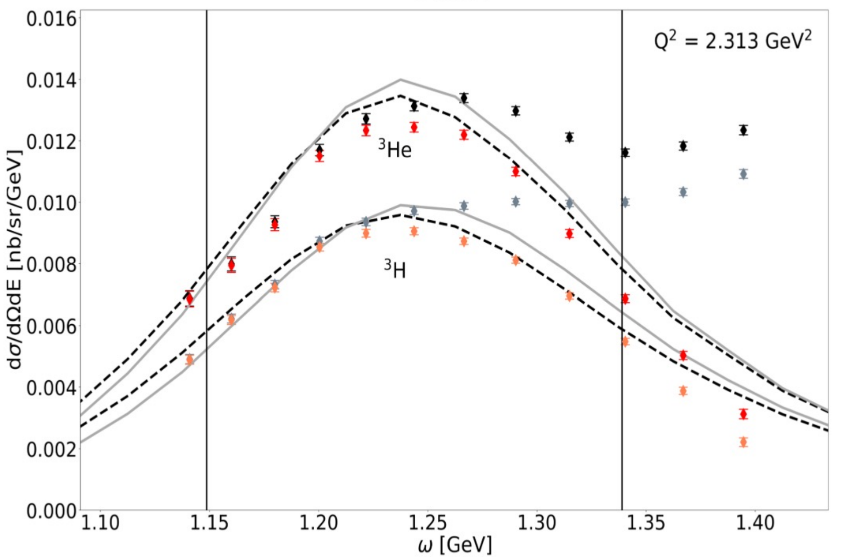
4. Calculate the σ_n/σ_p from the data ratio using the medium effects.

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

From Cross-Sections to G^n_M





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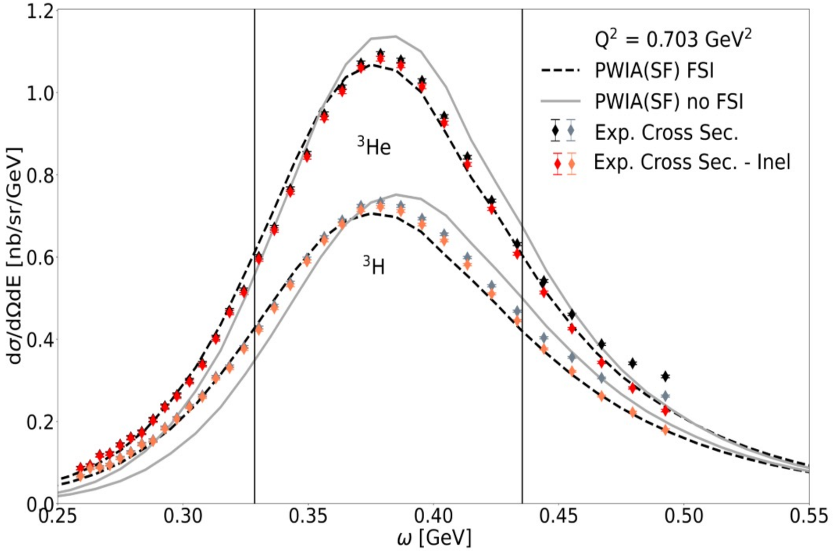
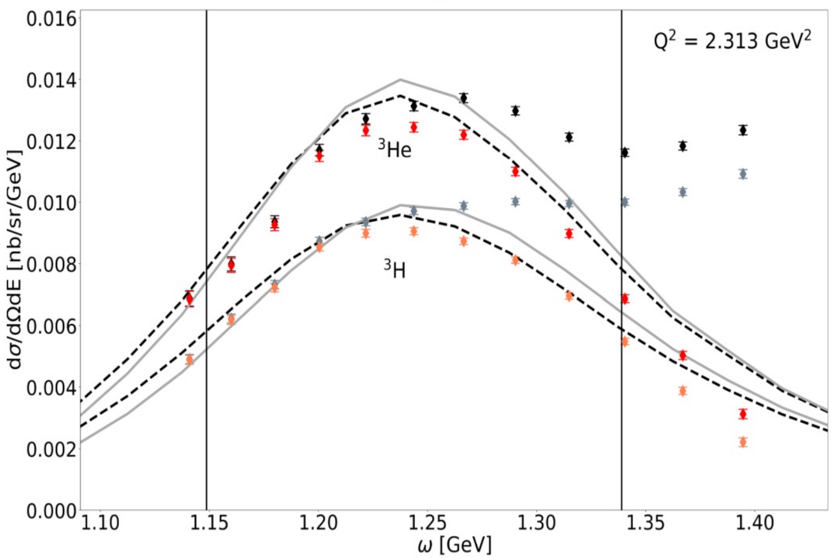
4. Calculate the σ_n/σ_p from the data ratio using the medium effects.
5. Extract the born cross section, after correcting for the TPE.

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

$\sigma_p^{Fit-(Born+TPE)}$ 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).

From Cross-Sections to G^n_M





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4. Calculate the σ_n/σ_p from the data ratio using the medium effects.
5. Extract the born cross section, after correcting for the TPE.
6. Extract the form factor:

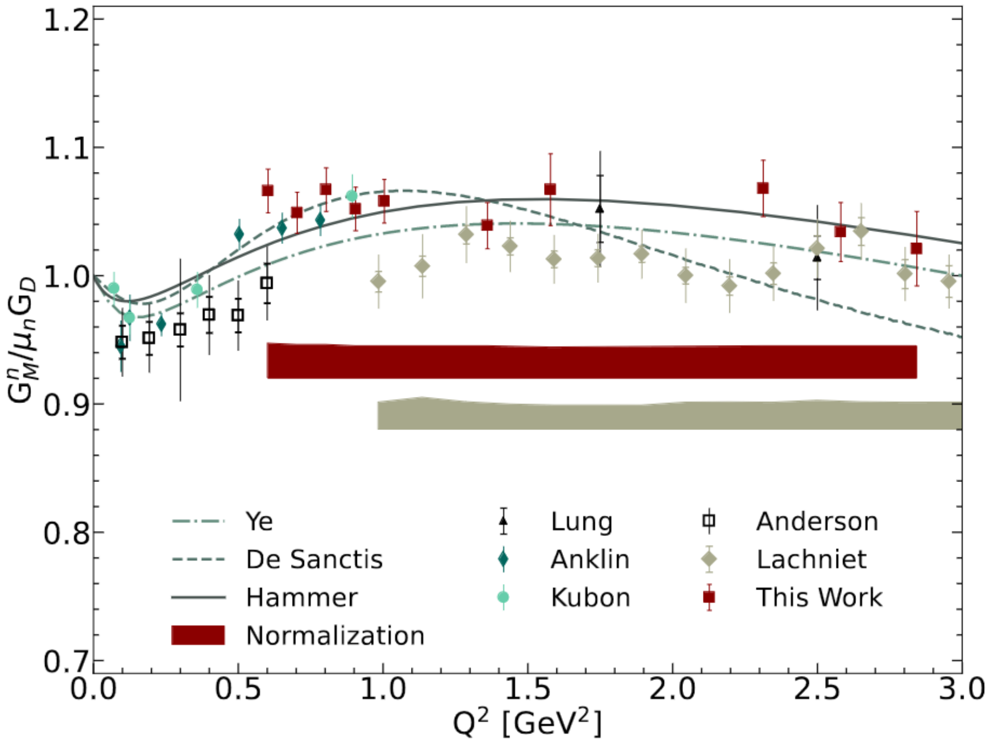
$$G_M^n = \left(\left[\sigma_n^{Born} - \frac{\epsilon}{\tau}(G_E^n)^2\right]\right)^{1/2}$$

Subtract G^n_E contribution to get G^n_M from Z. Ye, J. Arrington, R. J. Hill, and G. Lee, Physics Letters B 777, 8 (2018).

Leading systematic contributions

Source	Normalization %	Point-to-Point for the Cross-sections %
Background Contamination (endcaps)	0.1	0.15 (QE)
Target Thickness	1.08	0
Charge	0	0.1
3He contamination	0	0.35
Model Dependence	0.2	0.5
Radiative corrections	0.3	0.4
cut dependence/shape imperfections	0.3	0.3
MEC subtraction	L(0.4) and R(0.2)	L(0.3) and R(0.2)
FSI	0.3	0.2
SF vs nk estimate	0.2	0.2

This work



Some experiments did not separate out scale uncertainties from point-to-point systematics

Tritium results cover Q2 range of multiple experiments – useful in constraining relative normalizations

Are the data consistent when accounting for scale uncertainties?

Our new results along with a subset of previous measurement

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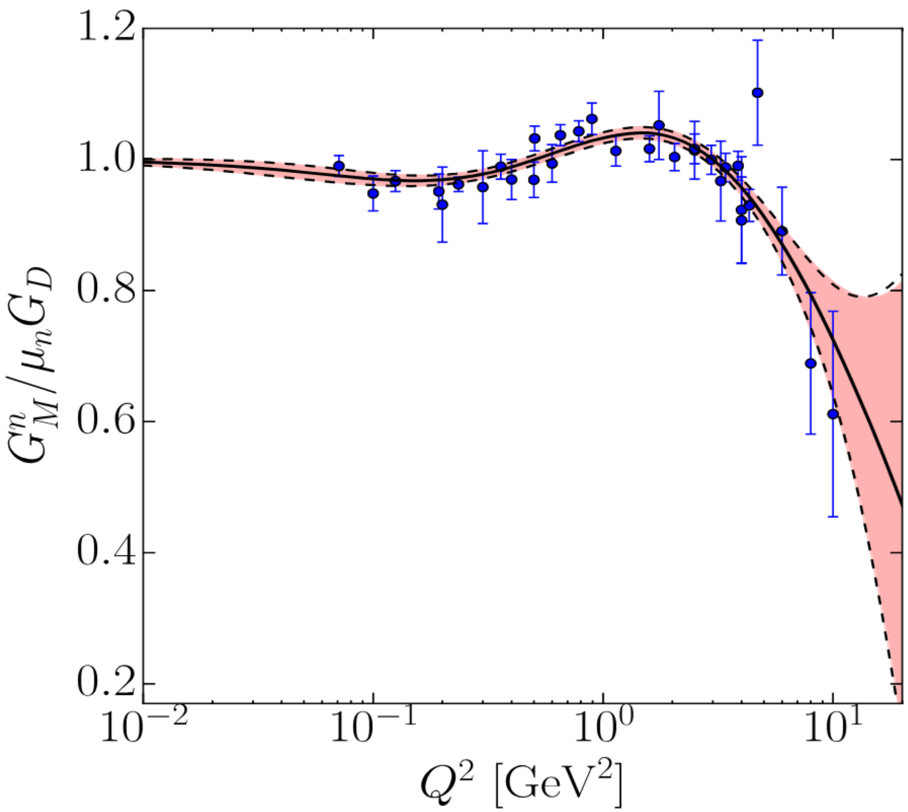


$$G(Q^2) = \sum_{k=0}^{k_{\max}} a_k z^k , \quad z = \frac{\sqrt{t_{\text{cut}} + Q^2} - \sqrt{t_{\text{cut}} - t_0}}{\sqrt{t_{\text{cut}} + Q^2} + \sqrt{t_{\text{cut}} - t_0}}$$

$$t_{\text{cut}} = 4m_\pi^2 \qquad t_0 = -0.7 \text{ GeV}^2$$

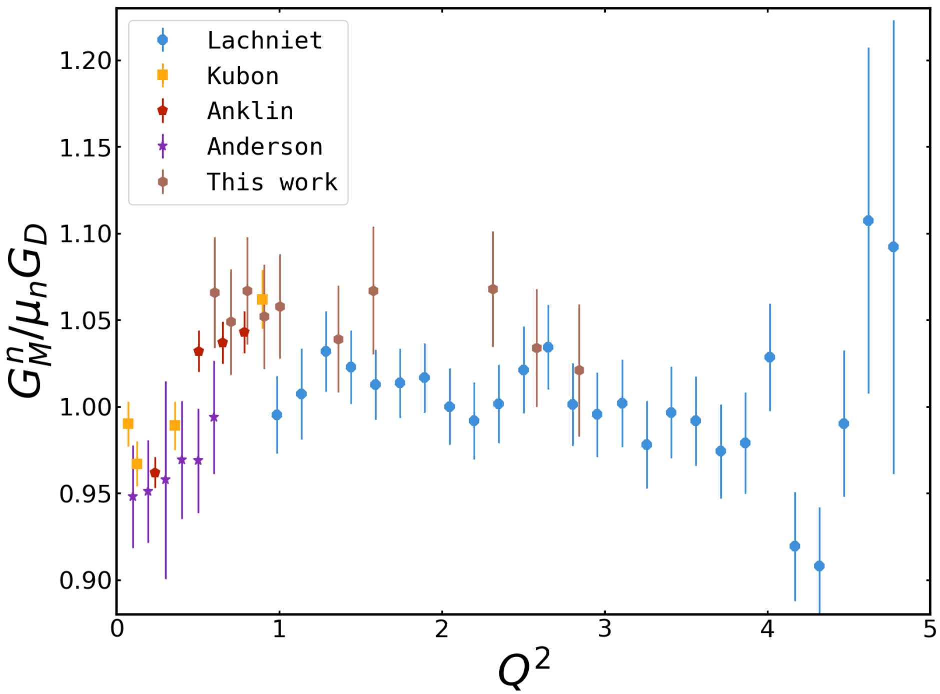
Some additional steps

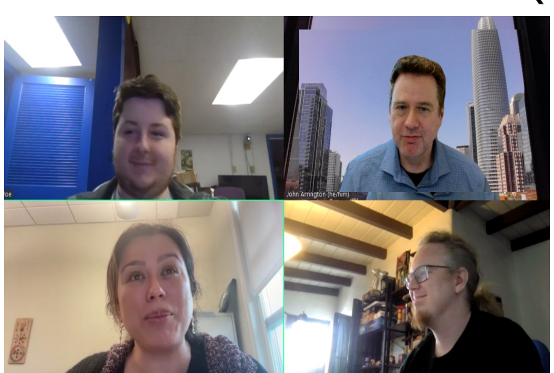
- Z. Ye *et al.* performed global fit. For GMn, increased uncertainties on data sets in region where results were inconsistent – all experiments given reduced weight

- Updating the global fit from this work using the exact same fit approach, but given more detailed estimate of scale uncertainty for each experiment (and reduced point-to-point uncertainties when something already included shifted to scale)

- Addl. Uncertainties associated with impact of TPE on previous measurements.

Global fit analysis





Examine each experimental paper individually:

- Add additional sources of uncertainties: e.g. TPE (not included in original work).

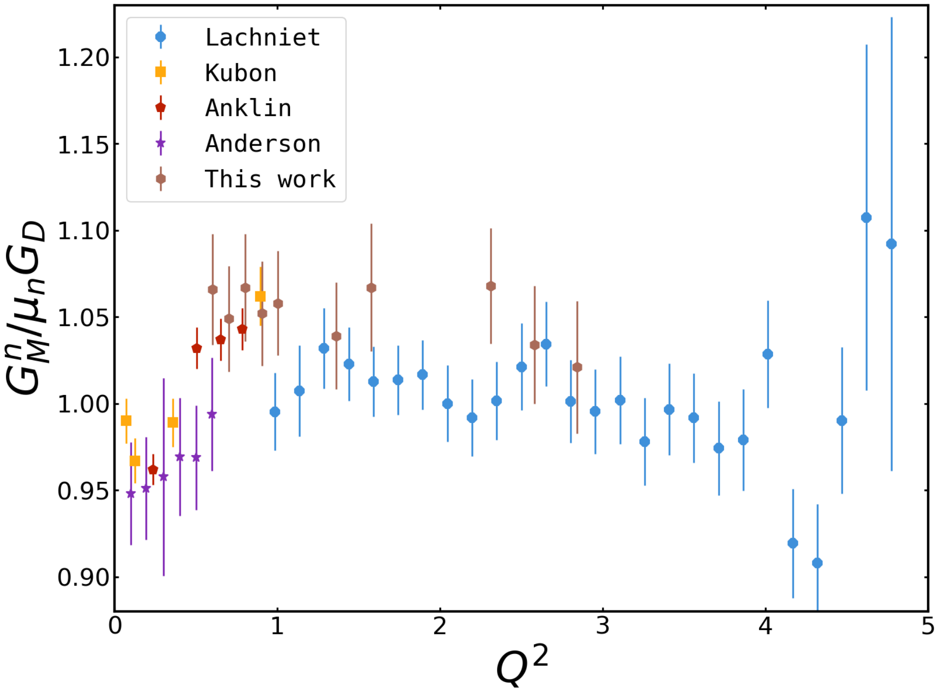
- In a few cases, enhance uncertainties (typically RC and proton FF uncertainty for older experiments).

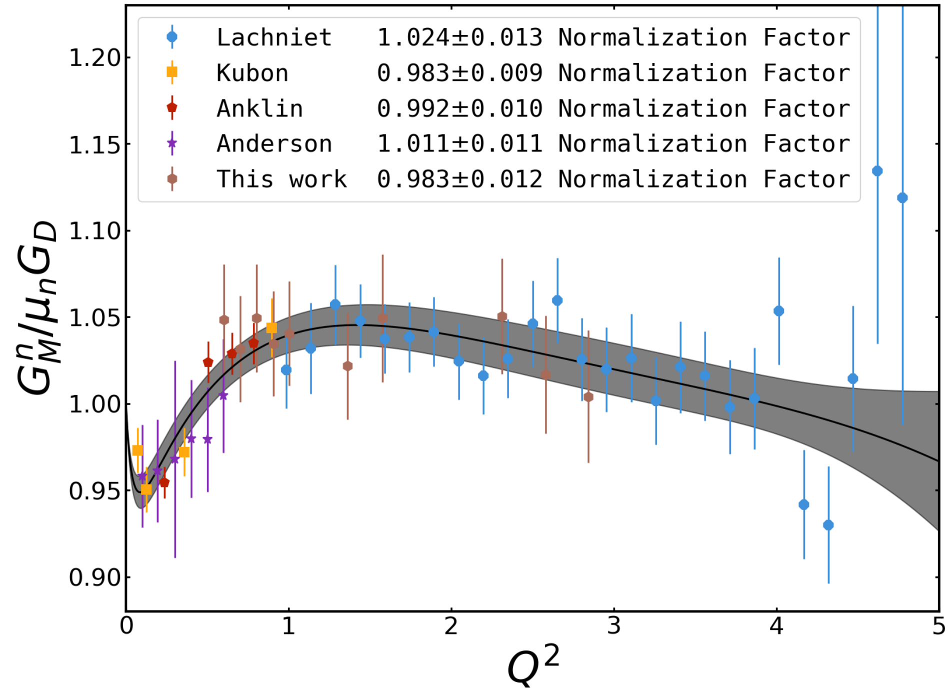
- Identify highly-correlated uncertainties (neutron efficiency, nuclear models); add scale uncertainty and remove some/all of this uncorrelated uncertainty.

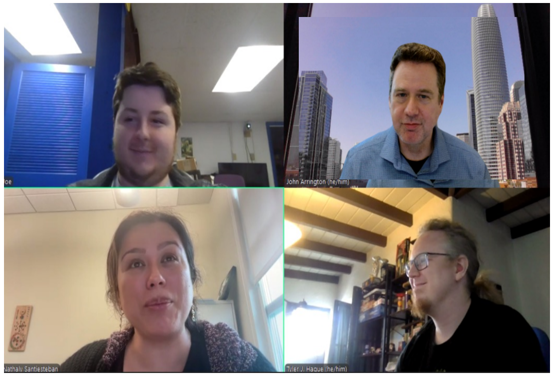
- 1-2% scale uncertainties for most experiments; larger for Rock, Lung (inclusive from proton and deuteron).

Courtesy of J. Jane (UNH) and T. Hague (LBNL)

Global fit analysis





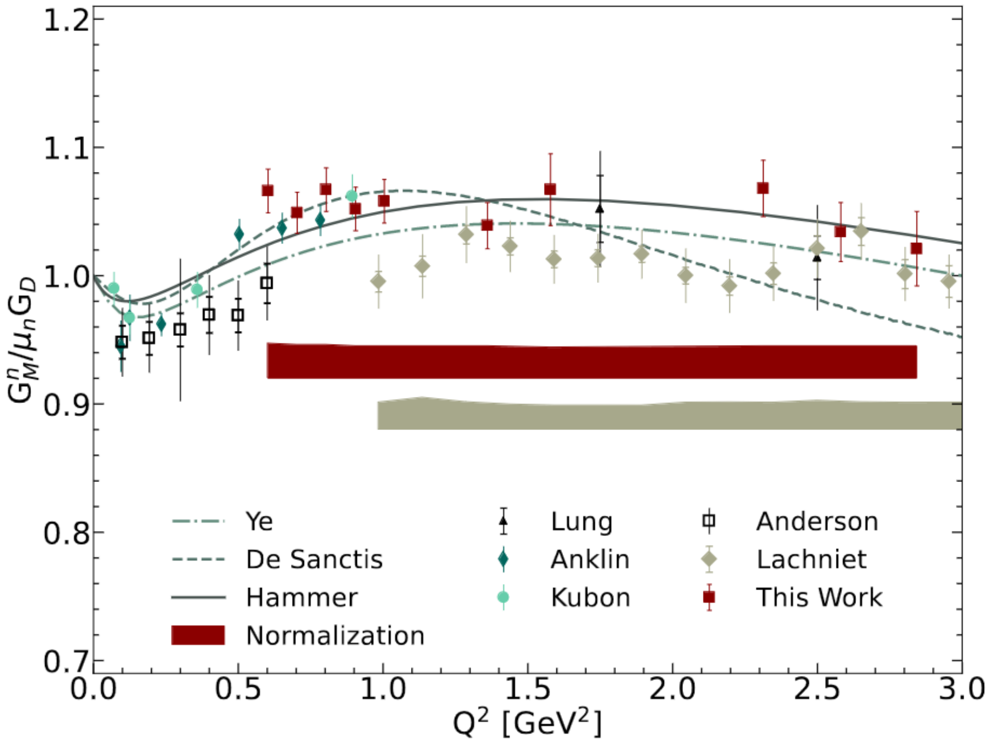


Global data in agreement...

Work in progress

Courtesy of J. Jane (UNH) and T. Hague (LBNL)

Summary



Our new results along with a subset of previous measurement

A deep study of the uncertainties could lead to reach consistency in the world's data.

This data help tie together normalizations of different data sets due to overlapping multiple measurements

Thank you!

Acknowledgment to everyone who worked on the experiment