# Potential to Measure a Neutron Form Factor with Neutrino-Nucleus Elastic Scattering

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# Outline

- Why do we want to measure the neutron form factor of a nucleus?
- How could this be done with neutrino-nucleus elastic scattering?
- What are the prospects?

Work done in collaboration with Gail McLaughlin at NC State

# Why measure the neutron form factor?

- We do not have accurate knowledge of the size of medium to heavy nuclei
- Charge radii are well known from electron scattering
- Neutron radii are probed with hadronic (proton, pion) scattering but interpretation of experiments suffers from uncertainty in theory (for example: corrections from multiple scattering, medium modifications to nucleon-nucleon interaction)
- Nuclear structure calculations (mean field models, Skyrme interactions) to predict neutron radii disagree
- Figure of merit in literature: Uncertainty on $R_n$ is ~ %10

Horowitz, Pollock, Souder, Michaels, Phys Rev C, 63, 025501 (2001)

## Why measure the neutron form factor?
## *Part II*

- Neutron form factor, density distribution, radius are all related
- HPSM suggest applications of a better knowledge of neutron density distribution in nuclei
- Saturation density of nuclear matter
- May impact: nuclear structure, atomic PNC experiments, neutron rich radioactive beams, neutron stars

Horowitz, Pollock, Souder, Michaels, Phys Rev C, 63, 025501 (2001)

# How could a neutron form factor be measured?

- HPSM propose parity violating electron scattering on $^{208}Pb$ (asymmetry depends on neutron form factor)
- Experiment tentatively scheduled at JLAB for 2008 (see http://hallaweb.jlab.org/parity/)
- Claim: extract $R_n$ to %1 for lead
- Will this accuracy be achieved? Will experiment take place?

$$A_{LR} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$A_{LR} = \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \left[ 4\sin^2\theta_W - 1 + \frac{F_n(Q^2)}{F_p(Q^2)} \right]$$

Horowitz, Pollock, Souder, Michaels, Phys Rev C, 63, 025501 (2001)

## How could a neutron form factor be measured with neutrino-nucleus elastic scattering?

- Need neutrino source
- Need nuclear recoil detector
- Need to detect elastic scattering events
- Fit measured events to calculated events (obtained using different models to predict neutron form factor)
- If calculated events from different nuclear models are outside error bars on measured events then fitting a model is possible

# Example of experimental setup

- Neutrinos from Spallation Neutron Source at Oak Ridge
- Cryogenic Low Energy Astrophysics with Noble Gases

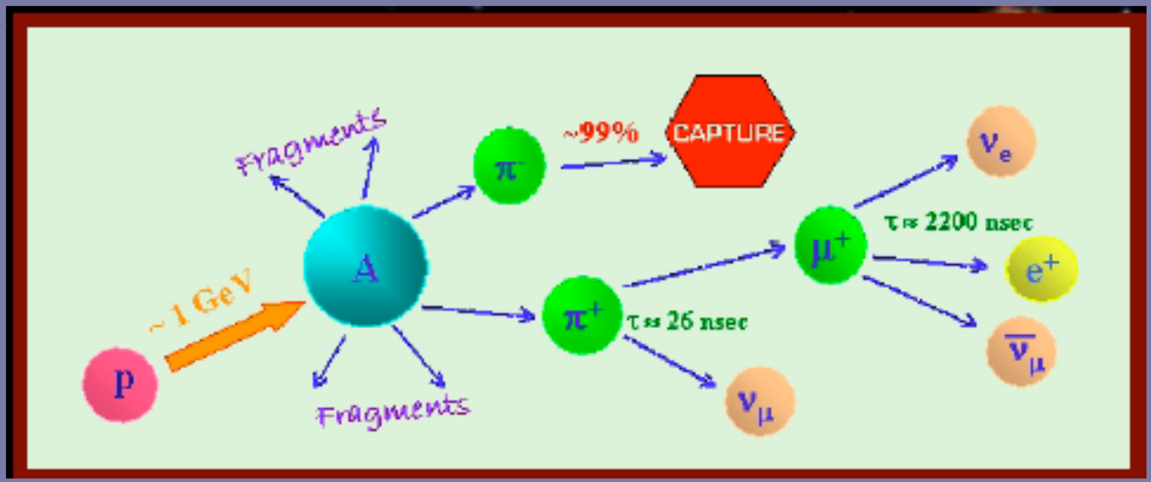
K. Scholberg, Phys Rev D, 73, 033005 (2006)

- Detect neutrino-nucleus elastic scattering
- considered: search/constrain beyond Standard Model neutrino interactions, neutrino magnetic moment, $\sin^2\theta_W$ at low energy

This experimental setup also considered by
J. Barranco, O.G. Miranda, T.I. Rashba, hep-ph/0702175
"…sensitivity to extra neutral gauge bosons, leptoquarks and R-parity breaking interactions…"

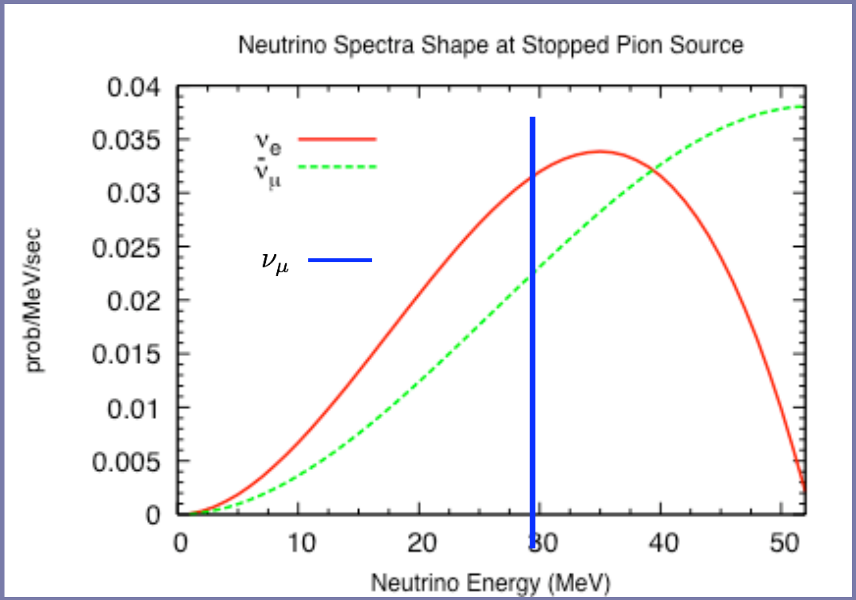
# Stopped-Pion Neutrino Source

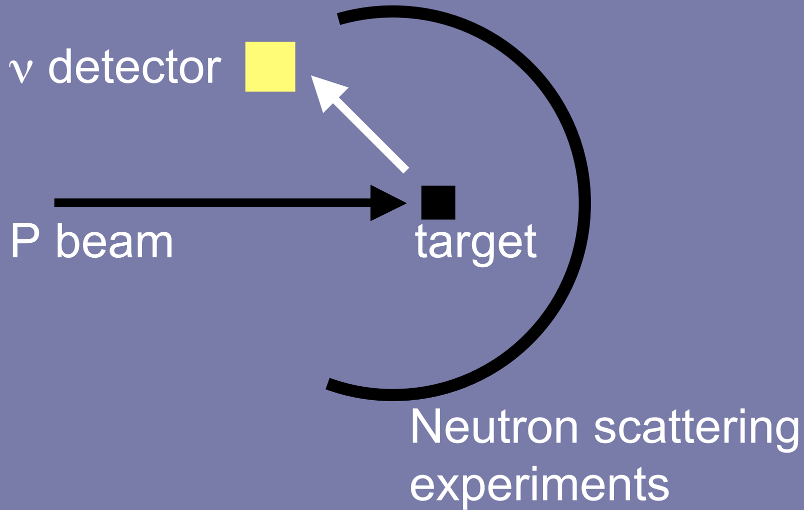
- Spallation Neutron Source at Oak Ridge National Lab
- http://neutrons.ornl.gov/
- Contructed to produce neutrons for material science research
- side effect: **neutrino source** - $10^{15}$ neutrinos/sec emitted




http://www.phy.ornl.gov/nusns/

# Stopped-Pion Neutrino Source
## *Part II*




- Decay at rest, well known spectra
- neutrinos are FREE
- Detector ~ 20m from target
- flux ~$1 \times 10^7$ ν / s $cm^2$ of each flavor at detector
- pulsed beam - useful for reducing backgrounds
- neutron background (in addition to beam, cosmic ray, internal detector, other experiments instruments, etc)

http://www.phy.ornl.gov/nusns/

# CLEAN

- Purpose: detect Dark Matter; Low Energy Neutrinos
- neutrino-electron and neutrino-nucleus elastic scattering

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- Liquid noble gases scintillate in the UV
- Thin wavelength shifting film on photomultiplier tubes to convert UV to visible

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- Measure solar pp neutrino flux
- neutrino & anti neutrino magnetic moment (using reactor neutrinos and solar neutrinos) sensitive to $10^{-11}$ $\mu_B$
- Supernova neutrinos (Total spectra because flavor blind)

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D. N. McKinsey, K. J. Coakley, Astroparticle Physics, 22, 355 (2005)
C. J. Horowitz, K. J. Coakley, D. N. McKinsey, Phys Rev D 68, 23005 (2003)
Also see http://mckinseygroup.physics.yale.edu/publications/

# CLEAN
## *Part II*

- Prototypes with Liquid Neon and Liquid Argon
- 10 kg mass tested, next 30 kg mass
- Full sized detector 10-100 tons liquid Ne or Ar; thousands of photomultipliers (1 ton can also provide useful measurements)
- Position resolution of events, enery resolution better than 10 keV
- Other noble elements could be used - helium, xenon

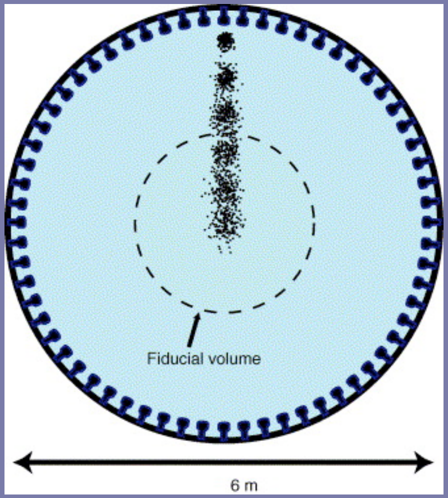


Fig. 2. Illustration of the position resolution expected in the full-size CLEAN. In a Monte Carlo simulation, 200 keV events are placed at r = 50, 100, 150, 200, and 250 cm. The dots surrounding these points indicate the estimated position of these events, calculated using a spatial estimation algorithm.


D. N. McKinsey, K. J. Coakley, Astroparticle Physics, 22, 355 (2005)
C. J. Horowitz, K. J. Coakley, D. N. McKinsey, Phys Rev D 68, 23005 (2003)
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# Status of idea to put CLEAN detector at SNS

- K. Scholberg (Duke) & R. Henning (UNC Chapel Hill) are doing a simulation of neutron background at location of detector (this summer)
- Evaluate shielding required to reduce neutron background
- Submit proposal in Fall for funding: shielding, putting the prototype CLEAN detector to oak ridge, doing the measurement
- D. McKinsey is at Duke talking about this yesterday and today!

# How can detecting neutrino-nucleus elastic scattering provide information on the neutron distribution?

- review neutrino-nucleus elastic scattering
- example of events in detector
- consider predictions for events from different nuclear models

# Neutrino-Nucleus Elastic Scattering (spin 0 nucleus)

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

$$F(Q^2) = \frac{1}{Q_W} \int [\rho_n(r) - (1 - 4\sin^2\theta_W)\rho_p(r)] \frac{\sin(Qr)}{Qr} r^2 dr$$

$$\sin^2\theta_W \approx 0.231$$

- Form factor is Fourier transform of density distribution
- Nu-Nuc elastic scattering couples mostly to neutrons
- Clean measurement of neutron distribution

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- For low energy $\nu$'s with $\lambda_\nu \sim R$ scattering will be coherent:
- $\nu$ "sees" all nucleons in nucleus
- to get matrix element sum amplitudes then square

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- as $E_\nu$ increases $\lambda_\nu$ decreases, $\nu$ sees less of nucleus
- FF accounts for reduction in $\sigma$ as $E_\nu$ increases

# Form Factor

- Nuclear structure calculation to get wavefunctions
- Density is: $\rho(r) = \sum_i < \psi_i^\dagger(r)\psi_i(r) >$
- Mean field models, nucleon-nucleon interactions, various operators, etc

- Use analytic expression to model form factor that depends on $R_n$ since this is the parameter we want to measure
- Qualitatively: ρ(r) = (constant density) x (Gaussian density dist.)

$$F(Q^2) = \frac{3j_1(QR_0)}{QR_0}\exp[-\tfrac{1}{2}(Qs)^2]$$
$$R_0^2 = R^2 - 5s^2$$

*R* is radius of density distribution
*s* = surface thickness --- measure of length over which ρ goes from central value to a specified smaller value

J. Engel, Phys Lett B 264, 114 (1991)

# Form Factor
## *Part II*

$$F(Q^2) = \frac{1}{Q_W}[NF_n(Q^2) - Z(1 - 4\sin^2\theta_W)F_p(Q^2)]$$

$F_n(Q^2)$ and $F_p(Q^2)$ *are evaluated at* $R_n$ and $R_p$ respectively

Consider the detector filled with argon isotope $^{39}$Ar
Z = 18, N = 22

From experiment: $< R_p^2 > \approx 11.75$
K. Blaum et. al., Hyperfine Interactions 162, 101 (2005)
Use $R_p = 3.43$

To represent neutron Form Factors from different nuclear structure calculations, modify $R_n$

- Start with $R_n = R_p$ (a good guess)
- Then consider $R_n = R_p \pm \%10$ and $R_n = R_p \pm \%1$

# <u>Form Factor</u>

## *Part III*

## Some additional comments:

- Why consider $R_n = R_p$ + and - modification?
- Z ~ N nucleus might expect $R_n \sim R_p$
- But Coulomb repulsion could give $R_p > R_n$
- For N >> Z nucleus, expect $R_n > R_p$

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- For both $F_n(Q^2)$ and $F_p(Q^2)$ use $s$ ~ 0.5 fm
- Modified $s$ but found conclusions do not change

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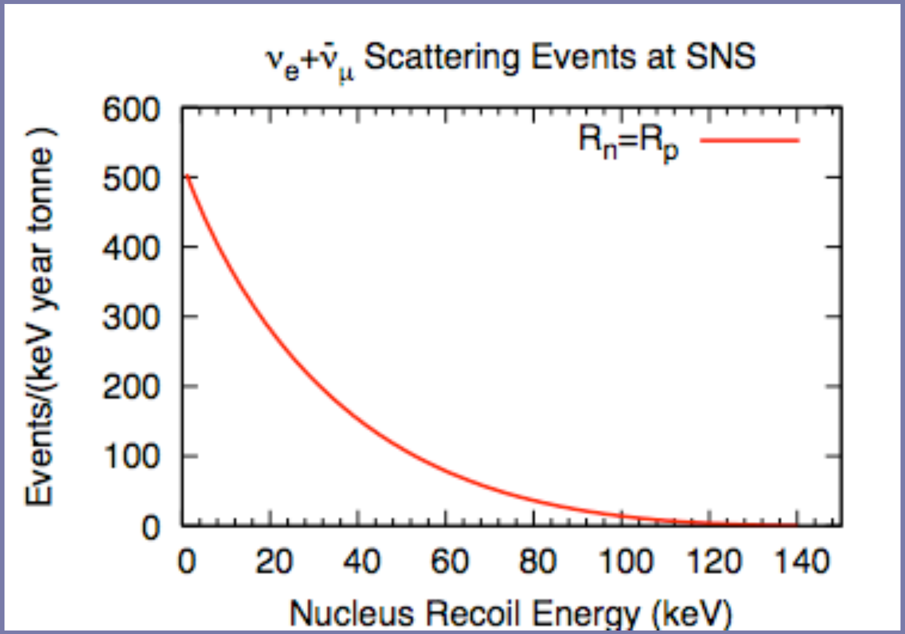
- If the experiment were performed, when analyzing the data one would use a single nuclear model to compute all parameters and do the fit self consistently

## Predictions of Events

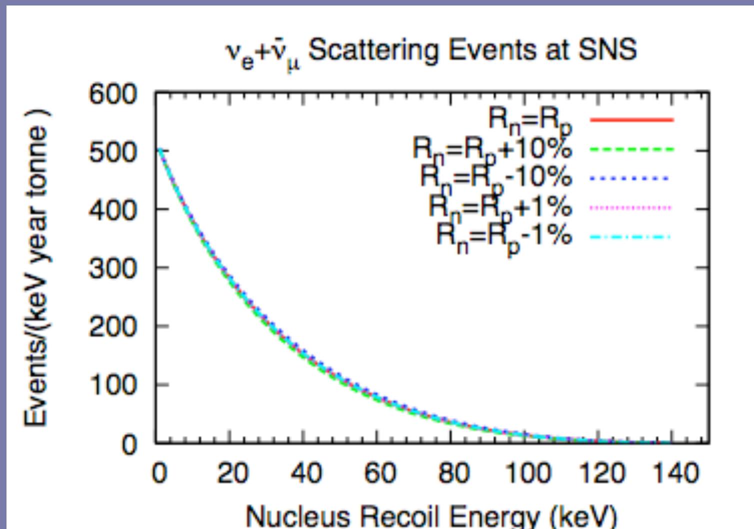
$$\frac{dN}{dT}(T) = N_t \int_{E_{\min}(T)}^{m_\mu/2} f(E)\, \frac{d\sigma}{dT}(E,T)\; dE$$

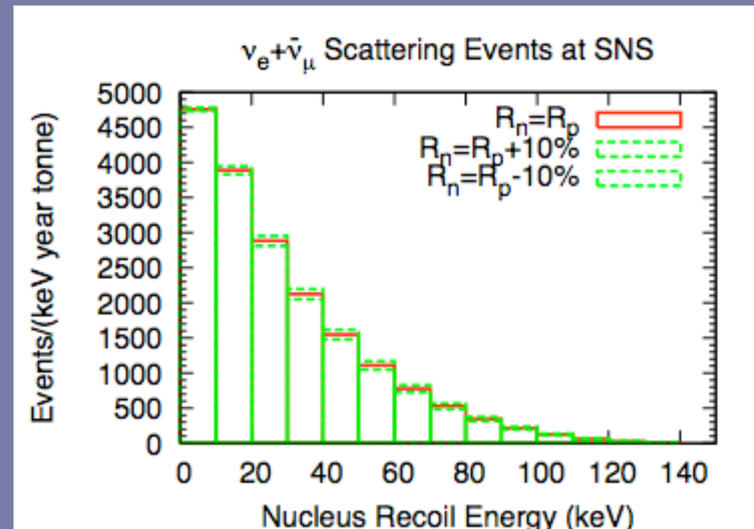



Total events for 1 year run time, in 1 tonne liquid argon detector, per nuclear recoil energy v.s. nuclear recoil energy in keV

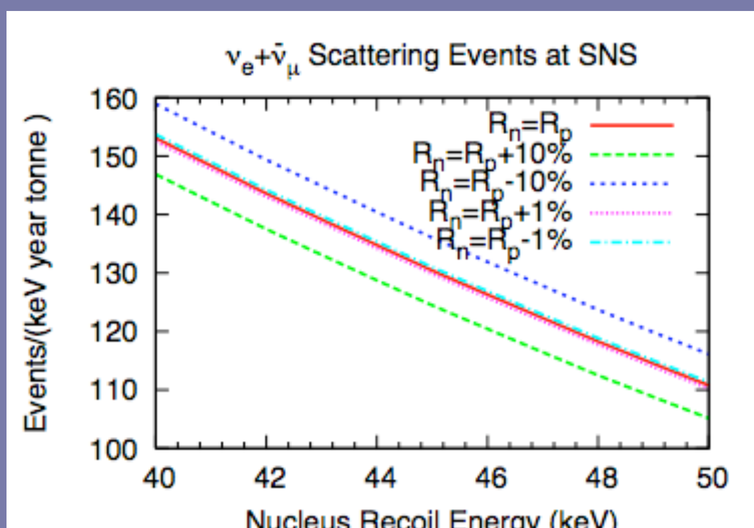
For case $R_n = R_p$

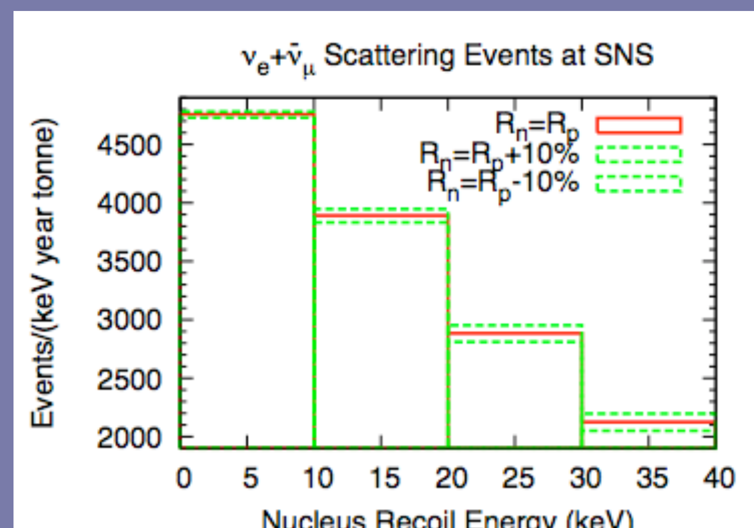
# Events predicted by different nuclear models




zoom



## Do predictions from different theories lie outside error bars?

- Consider systematic uncertainty of %10

  K. Scholberg, Phys Rev D, 73, 033005 (2006)
- Accounts for beam, neutrino flux reaching detector, detector uncertainties
- Background? Detector efficiency? Statistical uncertainty?
- Consider again different theory predictions relative to %10 systematic uncertainty…

# Binned events over total range of nuclear recoil energy

| Bin Range(keV) | $R_n = R_p$ | $R_n = R_p + 10\%$ | % diff. | $R_n = R_p - 10\%$ | % diff. | $R_n = R_p + 1\%$ | % diff. | $R_n = R_p - 1\%$ | % diff. |
|---|---|---|---|---|---|---|---|---|---|
| 0-10 | 4756 | 4729 | -1 | 4781 | 1 | 4754 | -0 | 4759 | 0 |
| 10-20 | 3891 | 3832 | -2 | 3946 | 1 | 3885 | -0 | 3897 | 0 |
| 20-30 | 2884 | 2811 | -3 | 2952 | 2 | 2877 | -0 | 2891 | 0 |
| 30-40 | 2126 | 2050 | -4 | 2196 | 3 | 2118 | -0 | 2133 | 0 |
| 40-50 | 1549 | 1478 | -5 | 1616 | 4 | 1542 | -0 | 1556 | 0 |
| 50-60 | 1110 | 1048 | -6 | 1169 | 5 | 1104 | -1 | 1116 | 1 |
| 60-70 | 778 | 726 | -7 | 827 | 6 | 773 | -1 | 783 | 1 |
| 70-80 | 529 | 489 | -8 | 568 | 7 | 525 | -1 | 533 | 1 |
| 80-90 | 347 | 316 | -9 | 376 | 8 | 344 | -1 | 350 | 1 |
| 90-100 | 215 | 194 | -10 | 236 | 10 | 213 | -1 | 217 | 1 |
| 100-110 | 124 | 111 | -11 | 137 | 11 | 123 | -1 | 125 | 1 |
| 110-120 | 64 | 56 | -12 | 71 | 12 | 63 | -1 | 65 | 1 |
| 120-130 | 27 | 23 | -13 | 30 | 13 | 27 | -1 | 27 | 1 |
| 130-140 | 8 | 6 | -14 | 9 | 14 | 7 | -1 | 8 | 1 |

1. $R_n$ to %1 --- not possible
2. $R_n$ to %10 --- will depend on background, efficiency, statistics
3. Potential to distinguish models that are equivalent to $R_n = R_p$ + %10 from those that are equivalent to $R_n = R_p$ - %10. Such fitting could provide useful experimental input for nuclear structure by ruling out some nuclear models.

# Conclusions

- Analyzed prospects to measure the neutron form factor of a nucleus by detecting neutrino-nucleus elastic scattering.
- This appears to be difficult, but some useful information may be obtainable.
- This analysis is still preliminary.  Systematic uncertainties, detector efficiency, and background are not known.
- We do not know what accuracy the JLAB measurement will ultimately achieve.
- A positive note - this analysis shows that nuclear physics uncertainties should not interfere with Beyond Standard Model physics interaction searches.