Form Factor in Coherent Elastic Neutrino Nucleus Scattering

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Basic cross section

Coherent elastic neutrino nucleus scattering cross section

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

- E : neutrino energy, T : nuclear recoil
- $Q^2 = \frac{2E^2TM}{(E^2 - ET)}$: squared momentum transfer
- $Q_W = N - Z(1 - 4\sin^2\theta_W)$: weak charge
- F(Q^2): form factor - largest uncertainty in cross section

Assumes a spin zero nucleus, no non-standard model interactions

Making a theoretical prediction

Fold cross section (previous slide) with incoming neutrino spectrum (e.g. left figure) to find nuclear recoil spectrum (right figure)

νs from π/μ decay at rest

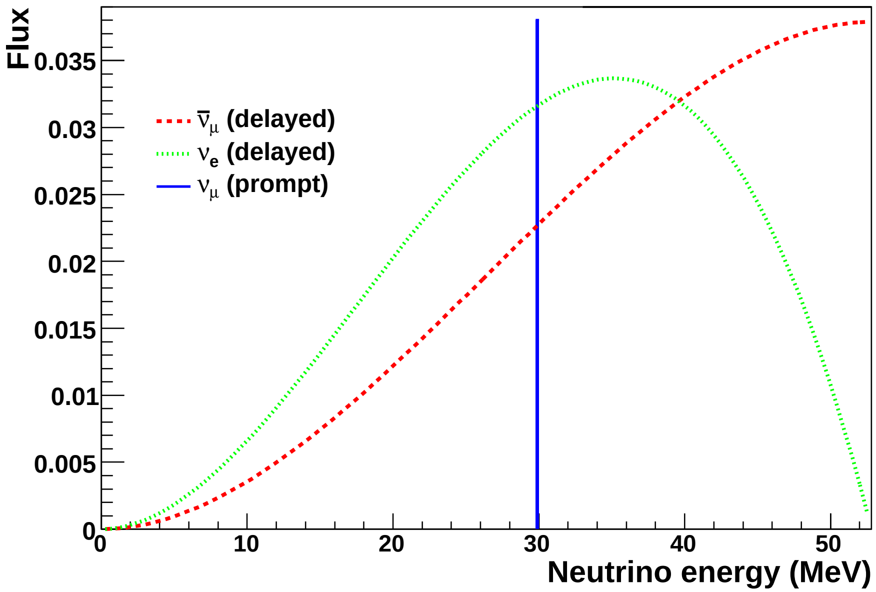


Fig. from Scholberg 2006

Spectrum of nuclear recoils

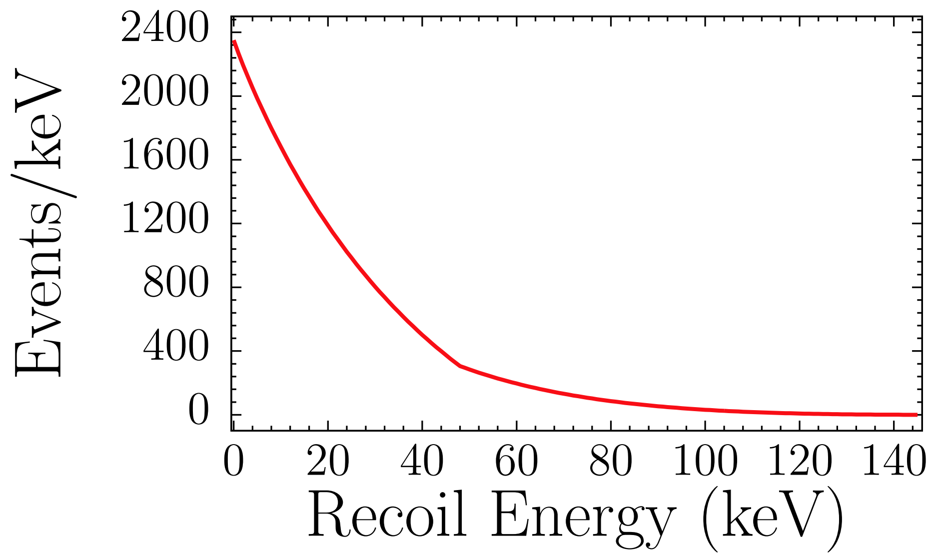
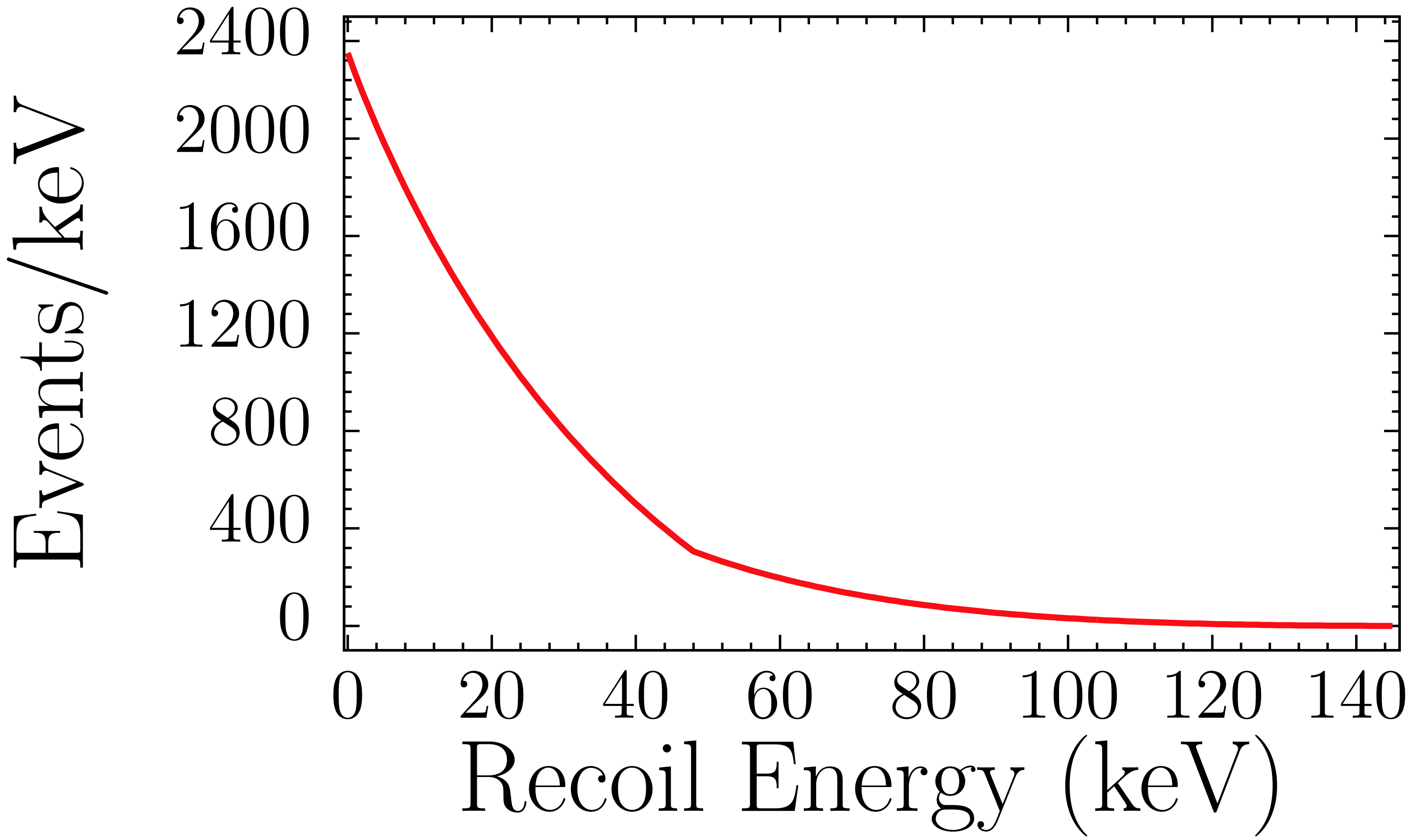


Fig. from Patton et al 2012

Beyond First Detection of CEνNS



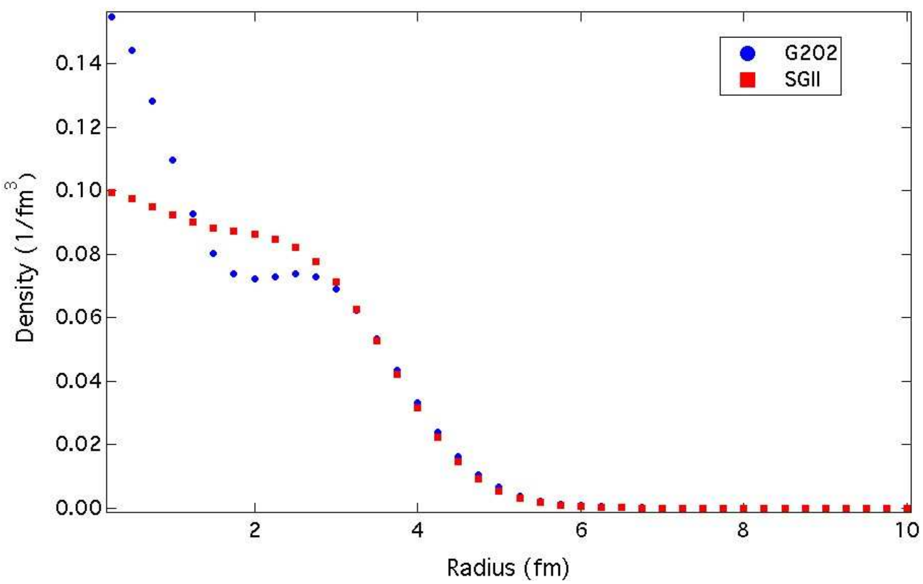
Use deviations in the shape of this curve to understand the form factor.

Form factor

Understanding the structure of the nucleus

Form factor, $F(Q^2)$ is the Fourier transform of the density distributions of protons and neutrons in the nucleus.

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



density distributions

$$\langle R^2 \rangle^{1/2}_{SGII} = 3.405 \text{ fm}$$
$$\langle R^2 \rangle^{1/2}_{G202} = 3.454 \text{ fm}$$

Form factor

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- Proton form factor term is suppressed by $1 - 4\sin^2(\theta_W)$
- Neutron form factor is not suppressed

CEνNS can be used to determine the neutron form factor Amanik et al 2009

Form factor

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

- Proton form factor can be measured by electromagnetic probes.
- Neutron form factor is less well known:
- Neutron scattering - many measurements - requires theory to go from cross section to form factor
- Parity violating electron scattering - PREX at Jlab Pb at one Q^2, extract $A_{PV} \sim 0.65 \times 10^{-6}$ then determine neutron radius, now also CREX at Jlab on Ca

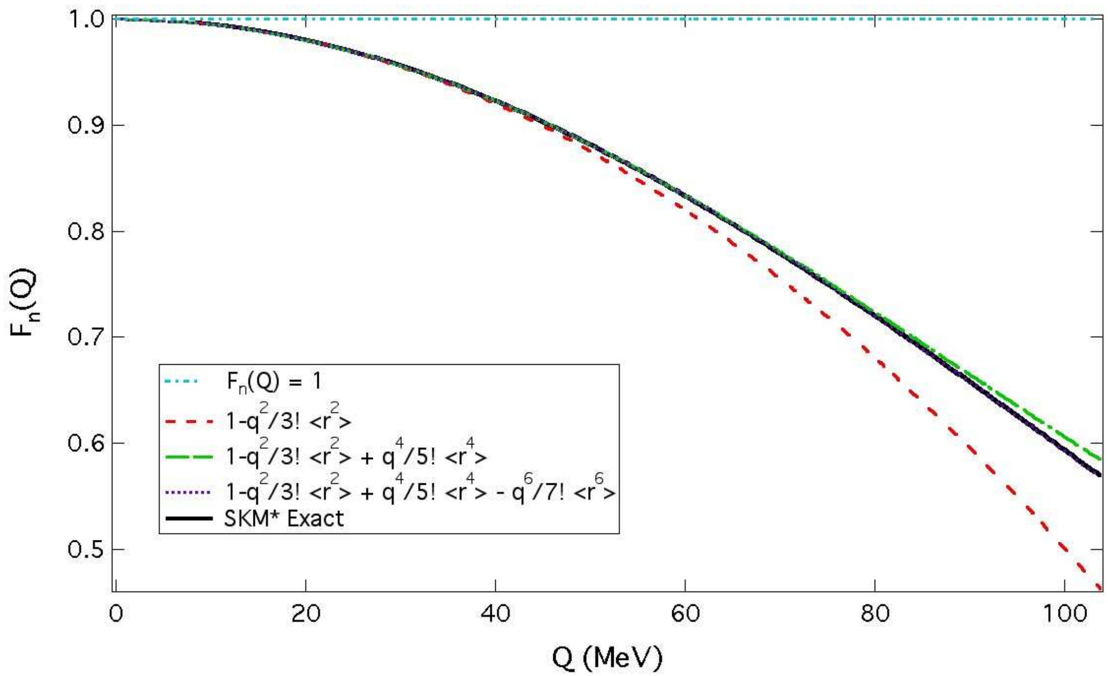
CEνNS recoil curve can be fit: neutron radius and higher moments

Nuclear-Neutron form factor from CEνNS

Taylor expand the $\sin(Qr)$ form factor:

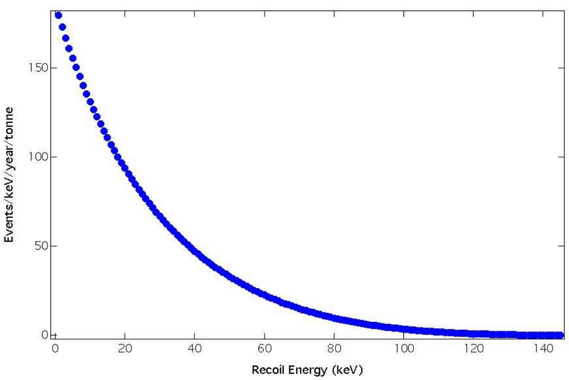
$$F_n(Q^2) = \frac{1}{Q_W}\int \rho_n(r)\frac{\sin(Qr)}{Qr}r^2 dr \approx \frac{N}{Q_W}\left(1 - \frac{Q^2}{3!}\langle R_n^2\rangle + \frac{Q^4}{5!}\langle R_n^4\rangle - ...\right)$$

Moments of the density distribution, $\langle R_n^2\rangle$, $\langle R_n^4\rangle$ characterize the form factor. Patton et al 2012, 2013

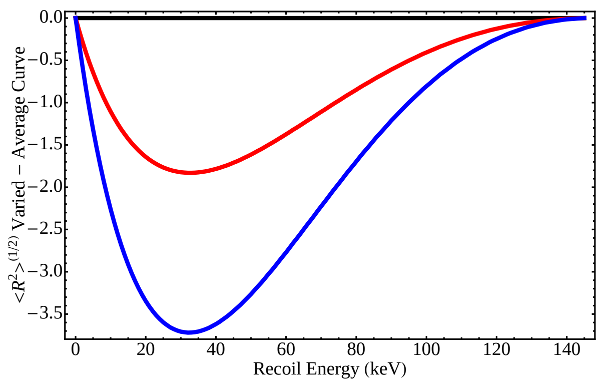


The moments, $\langle R^2 \rangle^{1/2}$, $\langle R^4 \rangle^{1/4}$, change the event curve

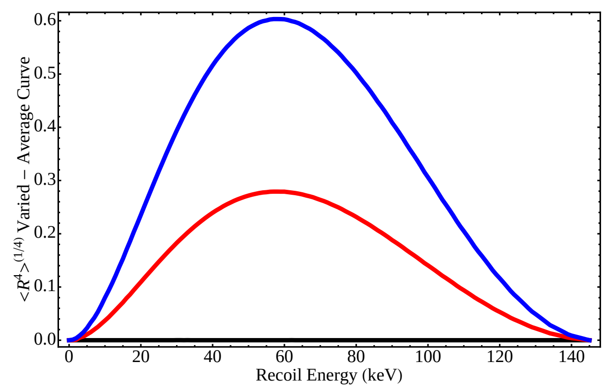
$$F_n(Q^2) \approx \frac{N}{Q_W}(1 - \frac{Q^2}{3!}\langle R_n^2 \rangle + \frac{Q^4}{5!}\langle R_n^4 \rangle - ...)$$



original event curve



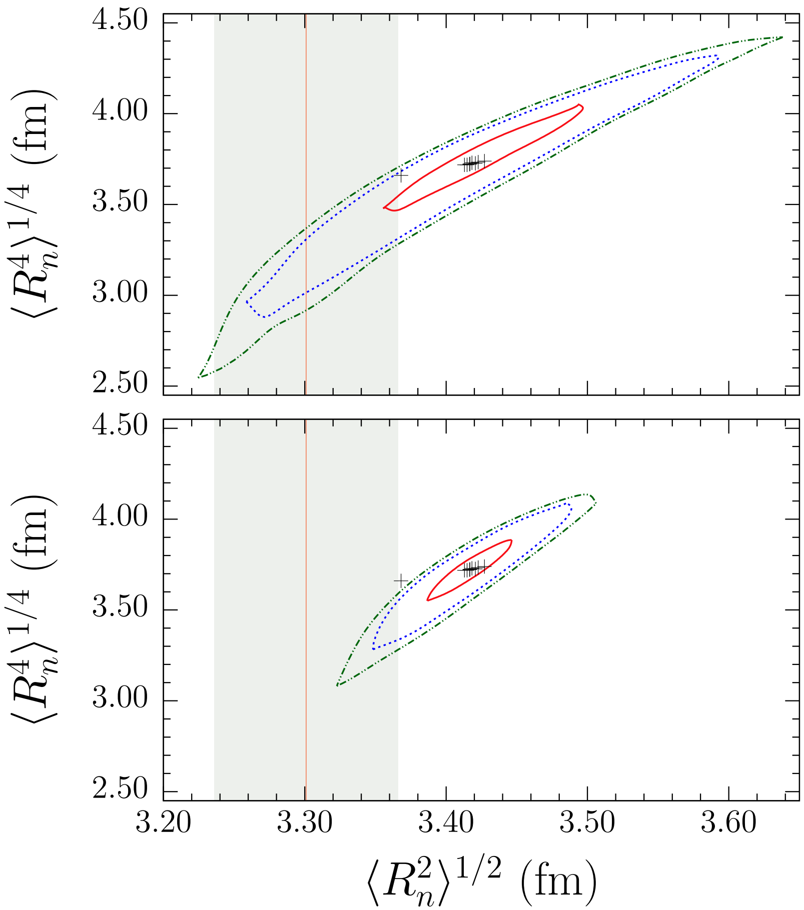
increase in $\langle R^2 \rangle^{1/2}$



increase $\langle R^4 \rangle^{1/4}$

Look at differences in event curves with increased neutron radius and fourth moment for muon decay at rest neutrinos on argon.

Liquid argon scenario



3.5 tonnes argon 16m from SNS, 18m from Daeδalus, 30m from ESS for one year. Shows 40%, 91% and 97% confidence contours. Crosses are theory predictions.

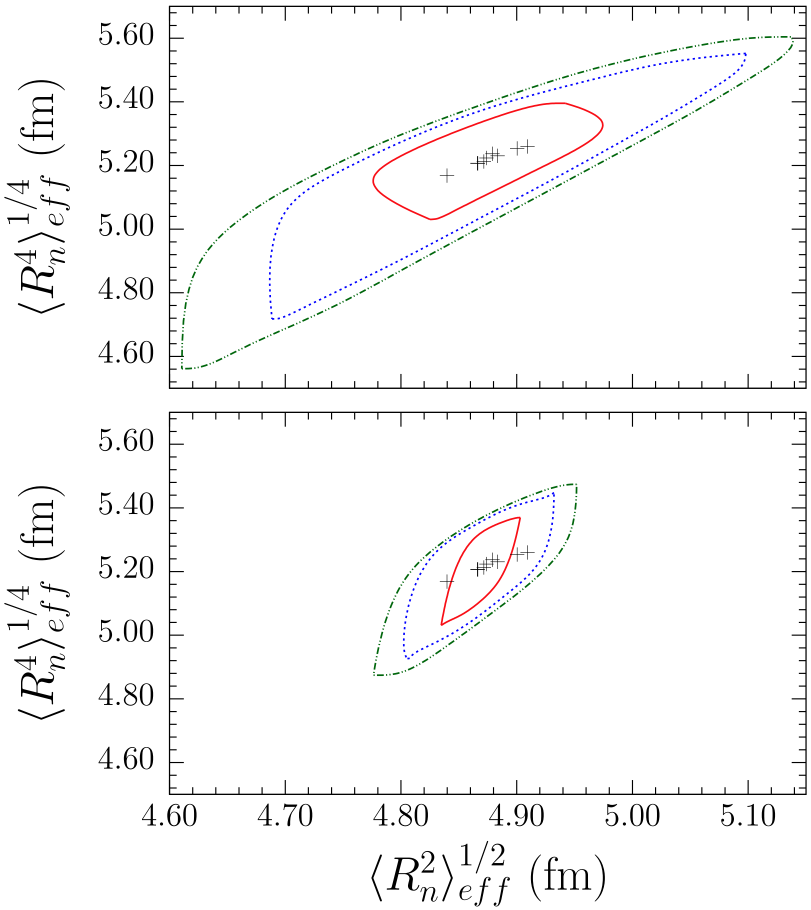
Fig. from Patton et al 2012

Band is measurement from neutron scattering. Top plot: normalization of neutrino flux not known, bottom plot normalization of neutrino flux known.

Xenon requires a weighted sum of isotopes

$$\langle R^2 \rangle_{eff}^{1/2} = \left(\frac{\sum_i N_i^2 X_i M_i \langle R_i^2 \rangle}{\sum_i N_i^2 X_i M_i} \right)^{1/2} \tag{1}$$

Xenon is more constraining

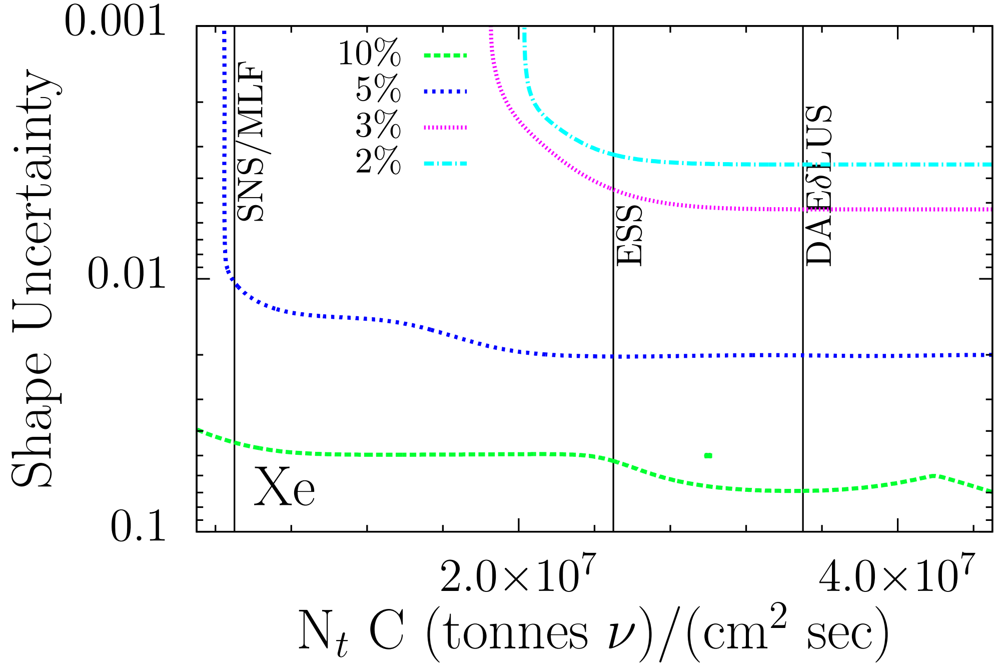


300 kg Xenon 16m from SNS, 18m from Daeδalus, 30m from ESS for one year. Shows 40%, 91% and 97% confidence contours. Crosses are theory predictions.

fig. from Patton et al 2012

Top plot: normalization of neutrino flux not known, bottom plot normalization of neutrino flux known.

Shape uncertainty and sensitivity to the neutron radius



500 kg Xenon 20m from the source.

fig. from Patton et al 2014

Vertical axis is uncorrelated error on each 10keV bin. Horizontal axis is a measure of the number of recoils in the detector. Curves show the sensitvity for the nuclear-neutron radius.

Summary

- CEνNS provides an alternative, complementary method for studying the nuclear-neutron distribution
- the neutron radius pulls the event curve down at lower recoil energy
- the fourth moment pulls it up at higher recoil energy
- fitting the event curve to these two parameters provides a measurement of the these moments
- understanding the (experimental) shape uncertainty is a crucial
- to determine the neutron radius to 2%, the uncorrelated shape uncertainty has to be understood at tenths of a percent