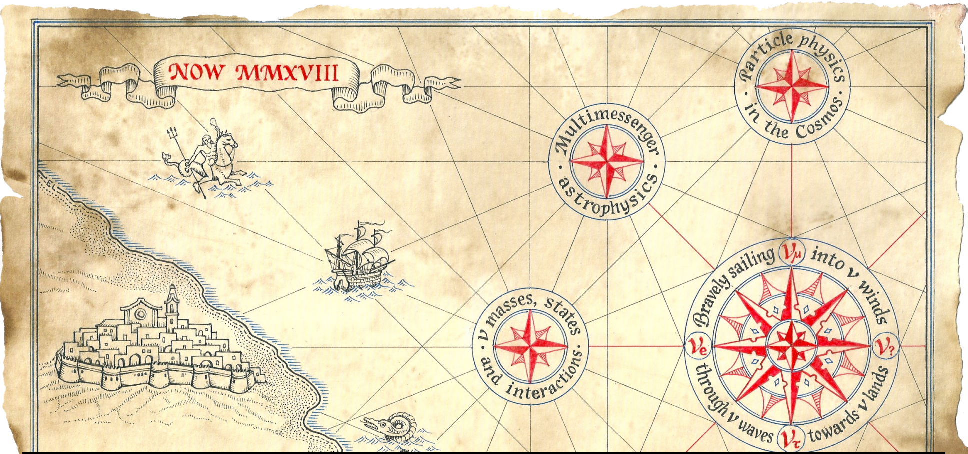

Neutrino Charge Radii from Coherent Elastic ν-Nucleus Scattering

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Neutrino Oscillation Workshop 2018

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Coherent Elastic Neutrino-Nucleus Scattering

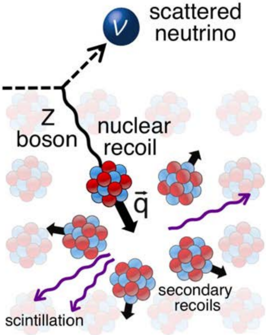
- Predicted in 1974 for $qR \lesssim 1$

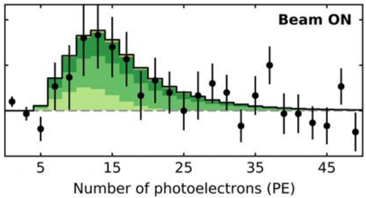
  [Freedman, Phys. Rev. D9 (1974) 1389]

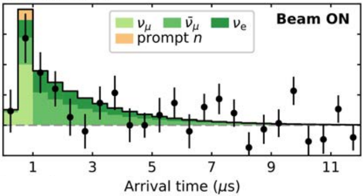
- $$\frac{d\sigma}{dT}(E,T) \simeq \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E^2}\right) N^2 F_N^2(q^2)$$

- Observed in 2017 in the COHERENT experiment at the Oak Ridge Spallation Neutron Source with CsI ($N_{Cs} = 78$, $N_I = 74$) [G. Rich talk]

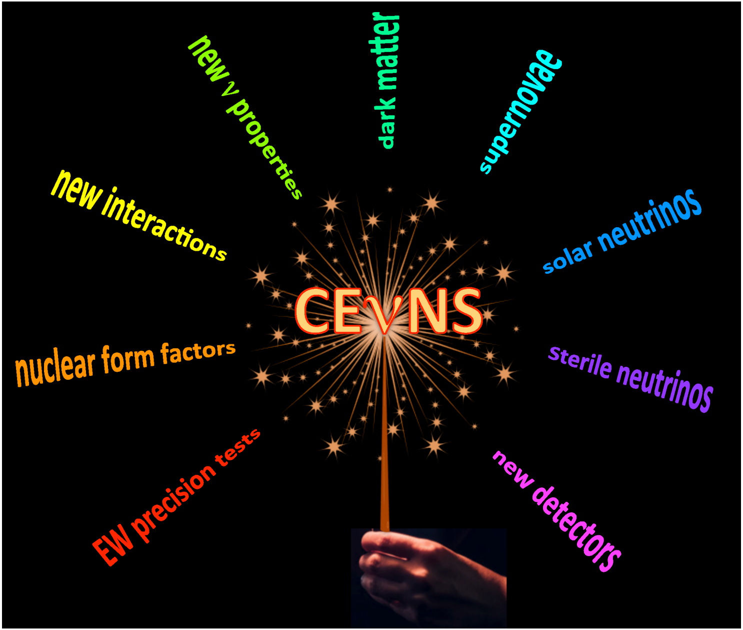
  [Science 357 (2017) 1123, arXiv:1708.01294]







Several oncoming new experiments: CONUS [M. Lindner talk], CONNIE, NU-CLEUS [J. Rothe talk], MINER, Ricochet, TEXONO, νGEN



[E. Lisi, Neutrino 2018]

- Taking into account interactions with both neutrons and protons

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E^2}\right)\left[g_V^n N F_N(q^2) + g_V^p Z F_Z(q^2)\right]^2$$

$$g_V^n = -\frac{1}{2} \qquad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W = 0.0227 \pm 0.0002$$

The neutron contribution is dominant! $\Longrightarrow$ $\dfrac{d\sigma}{dT} \sim N^2 F_N^2(q^2)$

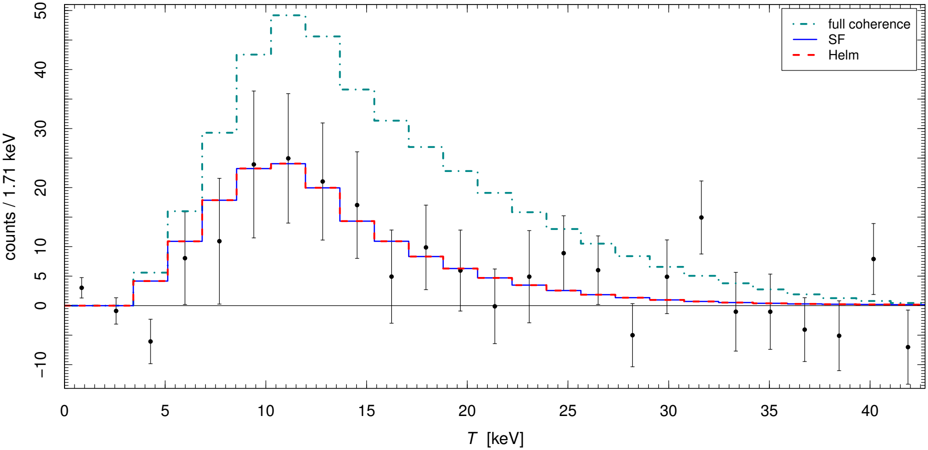
- The form factors $F_N(q^2)$ and $F_Z(q^2)$ describe the loss of coherence for $qR \gtrsim 1$. [see: Bednyakov, Naumov, arXiv:1806.08768]

- Coherence requires very small values of the nuclear kinetic recoil energy $T \simeq q^2/2M$:

$$qR \lesssim 1 \quad \Longleftrightarrow \quad T \lesssim \frac{1}{2MR^2}$$

$$M \approx 100\,\text{GeV}, \quad R \approx 5\,\text{fm} \quad \Longrightarrow \quad T \lesssim 10\,\text{keV}$$

- In the COHERENT experiment neutrino-nucleus scattering is not completely coherent:



[Cadeddu, CG, Y.F. Li, Y.Y. Zhang, PRL 120 (2018) 072501, arXiv:1710.02730]

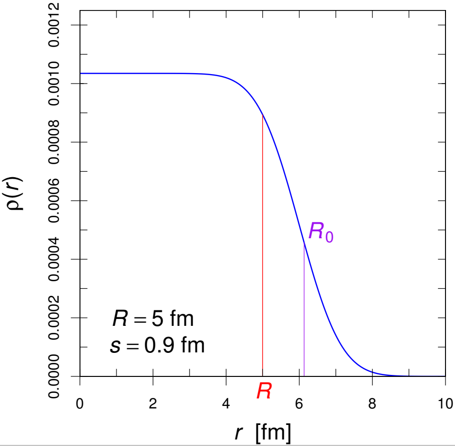
- Partial coherency gives information on the nuclear neutron form factor $F_N(q^2)$, which is the Fourier transform of the neutron distribution in the nucleus.

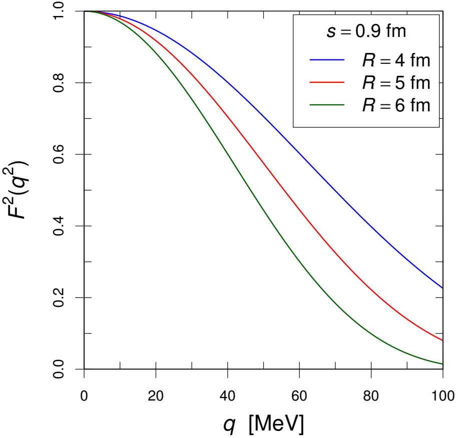
Helm form factor: $F_N^{\text{Helm}}(q^2) = 3\,\frac{j_1(qR_0)}{qR_0}\,e^{-q^2 s^2/2}$

Spherical Bessel function of order one: $j_1(x) = \sin(x)/x^2 - \cos(x)/x$

Obtained from the convolution of a sphere with constant density and radius R_0 (bulk radius) and a gaussian density with standard deviation s

Rms radius: $R^2 = \frac{3}{5}\,R_0^2 + 3s^2$ Surface thickness: $s \simeq 0.9\,\text{fm}$





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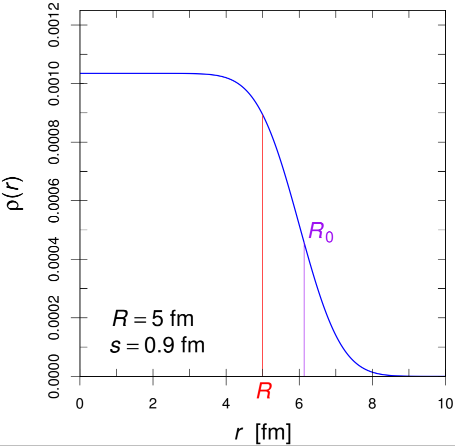
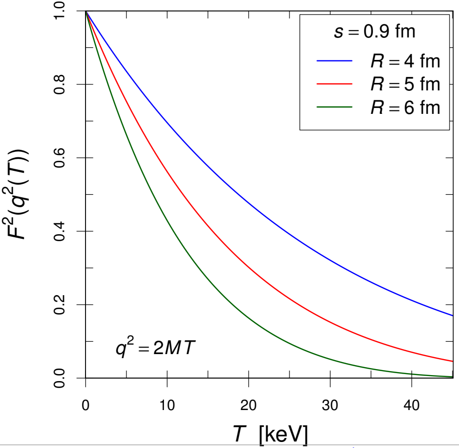


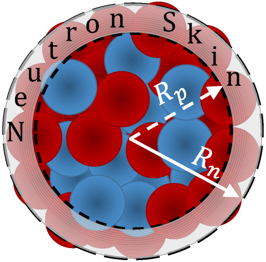


The Nuclear Proton and Neutron Distributions

- The nuclear proton distribution (charge density) is probed with electromagnetic interactions.
- Most sensitive are electron-nucleus elastic scattering and muonic atom spectroscopy.
- Hadron scattering experiments give information on the nuclear neutron distribution, but their interpretation depends on the model used to describe non-perturbative strong interactions.
- More reliable are neutral current weak interaction measurements.
  But they are more difficult.
- Before 2017 there was only one measurement of R_n with neutral-current weak interactions through parity-violating electron scattering:

$$R_n(^{208}\text{Pb}) = 5.78^{+0.16}_{-0.18}\,\text{fm}$$

[PREX, PRL 108 (2012) 112502]



- The rms radii of the proton distributions of ^{133}Cs and ^{127}I have been determined with muonic atom spectroscopy: [Fricke et al, ADNDT 60 (1995) 177]

$$R_p^{(\mu)}(^{133}\text{Cs}) = 4.804\,\text{fm} \qquad R_p^{(\mu)}(^{127}\text{I}) = 4.749\,\text{fm}$$

- Fit of the COHERENT data: [Cadeddu, CG, Li, Zhang, PRL 120 (2018) 072501, arXiv:1710.02730]

$$R_n(^{133}\text{Cs}) \simeq R_n(^{127}\text{I}) = 5.5^{+0.9}_{-1.1}\,\text{fm}$$

- This is the first determination of R_n with neutrino-nucleus scattering.

- The uncertainty is large, but it can be improved in future experiments.

- Relativistic mean field nuclear model:

$$R_p(^{133}\text{Cs}) = 4.79\,\text{fm} \qquad R_p(^{127}\text{I}) = 4.73\,\text{fm}$$

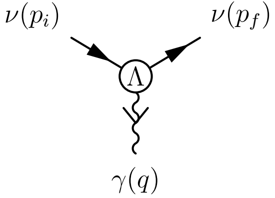
$$R_n(^{133}\text{Cs}) = 5.01\,\text{fm} \qquad R_n(^{127}\text{I}) = 4.94\,\text{fm}$$

Neutrino Charge Radii

- In the Standard Model neutrinos are neutral and there are no electromagnetic interactions at the tree-level.

- Radiative corrections generate an effective electromagnetic interaction vertex

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) F(q^2)$$



- $F(q^2) = \cancel{F(0)} + q^2 \left. \frac{dF(q^2)}{dq^2} \right|_{q^2=0} + \ldots = q^2 \, \frac{\langle r^2 \rangle}{6} + \ldots$

- In the Standard Model: [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = \frac{G_{\text{F}}}{4\sqrt{2}\pi^2} \left[3 - 2 \log\left(\frac{m_\ell^2}{m_W^2} \right) \right]$$

[see the review CG, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]

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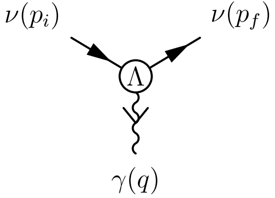

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- In the Standard Model: [Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_e} \rangle_{\text{SM}} = 4.1 \times 10^{-33}\,\text{cm}^2 \quad \langle r^2_{\nu_\mu} \rangle_{\text{SM}} = 2.4 \times 10^{-33}\,\text{cm}^2 \quad \langle r^2_{\nu_\tau} \rangle_{\text{SM}} = 1.5 \times 10^{-33}\,\text{cm}^2$$

[see the review CG, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]

Experimental Bounds

Method	Experiment	Limit [cm^2]	CL	Year
Reactor $\bar{\nu}_e$-e^-	Krasnoyarsk	$\lvert\langle r^2_{\nu_e}\rangle\rvert < 7.3 \times 10^{-32}$	90%	1992
	TEXONO	$-4.2 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 6.6 \times 10^{-32}$	90%	2009
Accelerator ν_e-e^-	LAMPF	$-7.12 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 10.88 \times 10^{-32}$	90%	1992
	LSND	$-5.94 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 8.28 \times 10^{-32}$	90%	2001
Accelerator ν_μ-e^-	BNL-E734	$-4.22 \times 10^{-32} < \langle r^2_{\nu_\mu}\rangle < 0.48 \times 10^{-32}$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu}\rangle\rvert < 1.2 \times 10^{-32}$	90%	1994

Phenomenological Bounds

- From a combined fit of $\nu_e e^-$ and $\bar{\nu}_e e^-$ data: [Barranco, Miranda, Rashba, PLB 662 (2008) 431]

$$-0.26 \times 10^{-32} < \langle r^2_{\nu_e}\rangle < 6.64 \times 10^{-32}\,\mathrm{cm}^2 \quad (90\%\ \mathrm{CL})$$

- From CHARM-II and CCFR data: [Hirsch, Nardi, Restrepo, PRD 67 (2003) 033005]

$$-0.52 \times 10^{-32} < \langle r^2_{\nu_\mu}\rangle < 0.68 \times 10^{-32}\,\mathrm{cm}^2 \quad (90\%\ \mathrm{CL})$$

[see the review CG, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]

- Neutrino charge radii contributions to CEνNS $\nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$:

$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT}(E,T) = \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E^2}\right)\Bigg\{\Bigg[g_V^n N F_N(q^2) + \left(g_V^p - \frac{2}{3}\,m_W^2 \sin^2\vartheta_W \langle r_\nu^2\rangle_{\ell\ell}\right) Z F_Z(q^2)\Bigg]^2 + \frac{4}{9}\,m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(q^2) \sum_{\ell'\neq\ell} |\langle r_\nu^2\rangle_{\ell'\ell}|^2\Bigg\}$$

- In the Standard Model there are only diagonal charge radii $\langle r_{\nu_\ell}^2\rangle \equiv \langle r_\nu^2\rangle_{\ell\ell}$ because lepton numbers are conserved.
- Since $g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W$, diagonal charge radii generate the coherent shifts

$$\sin^2\vartheta_W \to \sin^2\vartheta_W\left(1+\frac{1}{3}m_W^2\langle r_{\nu_\ell}^2\rangle\right)$$

- In general, the neutrino charge radius matrix $\langle r_\nu^2\rangle$ can be non-diagonal and the transition charge radii generate the incoherent contribution

$$\frac{4}{9}\,m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(q^2) \sum_{\ell'\neq\ell} |\langle r_\nu^2\rangle_{\ell'\ell}|^2 \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \nu_{\ell'\neq\ell} + \mathcal{N}$$

[Kouzakov, Studenikin, PRD 95 (2017) 055013, arXiv:1703.00401]

COHERENT Neutrino Spectra

Neutrinos at the Oak Ridge Spallation Neutron Source are produced by a pulsed proton beam striking a mercury target.

- Prompt monochromatic ν_μ from stopped pion decays:

$$\pi^+ \to \mu^+ + \nu_\mu$$

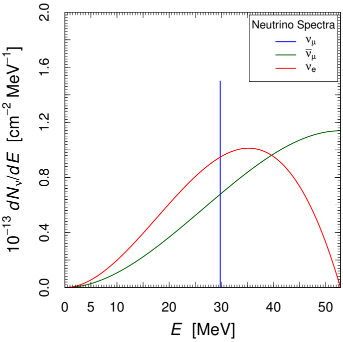
$$\frac{dN_{\nu_\mu}}{dE} = \eta\, \delta\left(E - \frac{m_\pi^2 - m_\mu^2}{2m_\pi}\right)$$

- Delayed $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays:

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

$$\frac{dN_{\nu_{\bar{\mu}}}}{dE} = \eta\, \frac{64E^2}{m_\mu^3}\left(\frac{3}{4} - \frac{E}{m_\mu}\right)$$

$$\frac{dN_{\nu_e}}{dE} = \eta\, \frac{192E^2}{m_\mu^3}\left(\frac{1}{2} - \frac{E}{m_\mu}\right)$$



- The spectrum is especially sensitive to the difference of the properties of ν_μ and those of $\bar{\nu}_\mu$ and ν_e.
- Note that $\langle r_{\bar{\nu}}^2 \rangle_{\ell\ell'} = -\langle r_\nu^2 \rangle_{\ell\ell'}$.

Fit without transition charge radii

[Cadeddu, CG, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, in preparation]

Time-integrated COHERENT data

- Fixed neutron distribution radii:

  $R_n(^{133}\mathrm{Cs}) = 5.01\,\mathrm{fm} \quad R_n(^{127}\mathrm{I}) = 4.94\,\mathrm{fm}$

  $\chi^2_{\min} = 2.7 \quad \mathrm{NDF} = 10 \quad \mathrm{GoF} = 99\%$

  Marginal 90% CL bounds $[10^{-32}\,\mathrm{cm}^2]$:

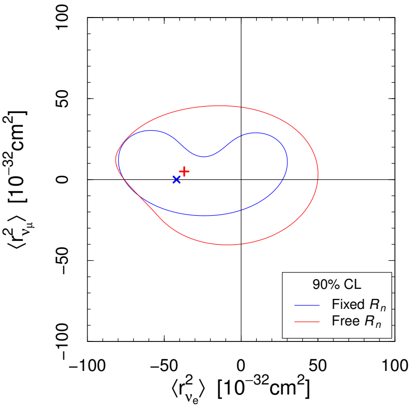
  $-69 < \langle r^2_{\nu_e} \rangle < 19 \quad -15 < \langle r^2_{\nu_\mu} \rangle < 21$

- Free neutron distribution radii:

  $\chi^2_{\min} = 2.5 \quad \mathrm{NDF} = 8 \quad \mathrm{GoF} = 96\%$

  Marginal 90% CL bounds $[10^{-32}\,\mathrm{cm}^2]$:

  $-69 < \langle r^2_{\nu_e} \rangle < 40 \quad -33 < \langle r^2_{\nu_\mu} \rangle < 38$



Fit with transition charge radii

[Cadeddu, CG, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, in preparation]

Time-integrated COHERENT data

- Fixed neutron distribution radii:

$R_n(^{133}\mathrm{Cs}) = 5.01\,\mathrm{fm} \quad R_n(^{127}\mathrm{I}) = 4.94\,\mathrm{fm}$

$\chi^2_{\min} = 2.6 \quad \mathrm{NDF} = 7 \quad \mathrm{GoF} = 92\%$

Marginal 90% CL bounds $[10^{-32}\,\mathrm{cm}^2]$:

$-69 < \langle r^2_{\nu_e} \rangle < 19 \quad -15 < \langle r^2_{\nu_\mu} \rangle < 22$

$|\langle r^2_\nu \rangle_{e\mu}| < 25 \quad |\langle r^2_\nu \rangle_{e\tau}| < 44 \quad |\langle r^2_\nu \rangle_{\mu\tau}| < 31$

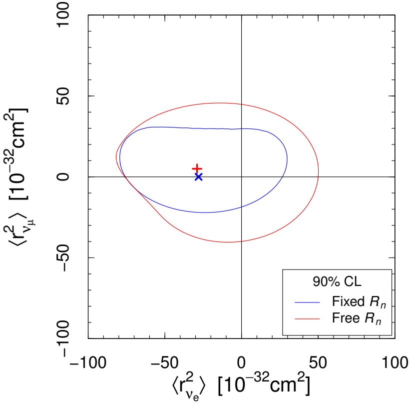
- Free neutron distribution radii:

$\chi^2_{\min} = 2.5 \quad \mathrm{NDF} = 5 \quad \mathrm{GoF} = 77\%$

Marginal 90% CL bounds $[10^{-32}\,\mathrm{cm}^2]$:

$-69 < \langle r^2_{\nu_e} \rangle < 40 \quad -33 < \langle r^2_{\nu_\mu} \rangle < 38$

$|\langle r^2_\nu \rangle_{e\mu}| < 29 \quad |\langle r^2_\nu \rangle_{e\tau}| < 49 \quad |\langle r^2_\nu \rangle_{\mu\tau}| < 35$



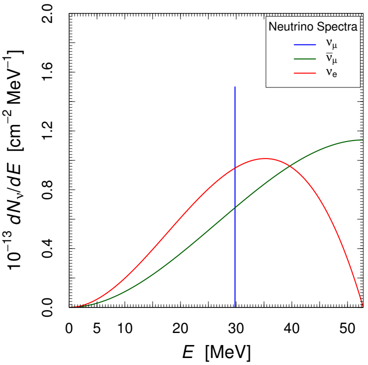
COHERENT Time Distribution

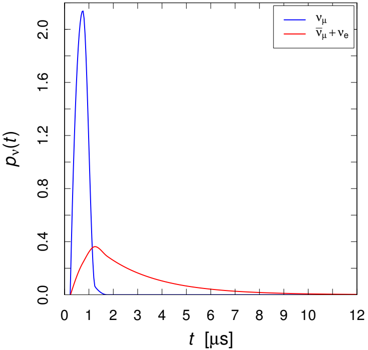
- Prompt monochromatic ν_μ from stopped pion decays:

$$\pi^+ \to \mu^+ + \nu_\mu$$

- Delayed $\bar{\nu}_\mu$ and ν_e from the subsequent muon decays:

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$





The time distribution of the data increases the information on the difference between the properties of ν_μ and those of $\bar{\nu}_\mu$ and ν_e.

Fit of Time-dependent COHERENT data

[Cadeddu, CG, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, in preparation]

- Fixed neutron distribution radii:

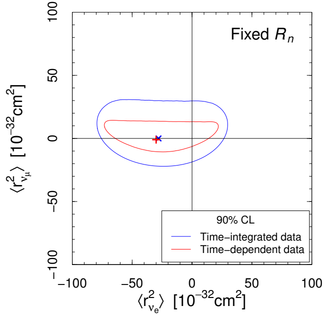
  $R_n(^{133}\text{Cs}) = 5.01\,\text{fm} \quad R_n(^{127}\text{I}) = 4.94\,\text{fm}$

  $\chi^2_{\text{min}} = 154.2 \quad \text{NDF} = 139 \quad \text{GoF} = 18\%$

  Marginal 90% CL bounds $[10^{-32}\,\text{cm}^2]$:

  $-63 < \langle r^2_{\nu_e} \rangle < 12 \quad -7 < \langle r^2_{\nu_\mu} \rangle < 9$

  $|\langle r^2_\nu \rangle_{e\mu}| < 22 \quad |\langle r^2_\nu \rangle_{e\tau}| < 37 \quad |\langle r^2_\nu \rangle_{\mu\tau}| < 26$



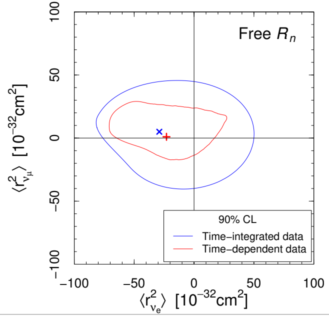
- Free neutron distribution radii:

  $\chi^2_{\text{min}} = 153.7 \quad \text{NDF} = 137 \quad \text{GoF} = 16\%$

  Marginal 90% CL bounds $[10^{-32}\,\text{cm}^2]$:

  $-61 < \langle r^2_{\nu_e} \rangle < 16 \quad -11 < \langle r^2_{\nu_\mu} \rangle < 23$

  $|\langle r^2_\nu \rangle_{e\mu}| < 26 \quad |\langle r^2_\nu \rangle_{e\tau}| < 40 \quad |\langle r^2_\nu \rangle_{\mu\tau}| < 30$



Conclusions

- The observation of CEνNS in the COHERENT experiment opened the way for new powerful measurements of the properties of nuclei and neutrinos.
- First determination of R_n with ν-nucleus scattering:

$$R_n(^{133}\mathrm{Cs}) \simeq R_n(^{127}\mathrm{I}) = 5.5^{+0.9}_{-1.1}\,\mathrm{fm}$$

- The time-dependent spectral data of the COHERENT experiment constrain (at 90% CL with a free average neutron distribution radius)

$$-61 < \langle r^2_{\nu_e} \rangle < 16 \qquad -11 < \langle r^2_{\nu_\mu} \rangle < 23 \qquad (90\%\ \mathrm{CL})$$

- First constraints on transition charge radii: $[10^{-32}\,\mathrm{cm}^2]$

$$|\langle r^2_{\nu} \rangle_{e\mu}| < 26 \qquad |\langle r^2_{\nu} \rangle_{e\tau}| < 40 \qquad |\langle r^2_{\nu} \rangle_{\mu\tau}| < 30 \qquad (90\%\ \mathrm{CL})$$

- An improvement of about 1 order of magnitude is necessary to be competitive with the current limits of the order of few $\times\, 10^{-32}\,\mathrm{cm}^2$.
- An improvement of about 2 orders of magnitude is necessary to reach the Standard Model values

$$\langle r^2_{\nu_e} \rangle_{\mathrm{SM}} = 4.1 \times 10^{-33}\,\mathrm{cm}^2 \qquad \langle r^2_{\nu_\mu} \rangle_{\mathrm{SM}} = 2.4 \times 10^{-33}\,\mathrm{cm}^2$$

- The new CEνNS experiments may allow to approach these values.