Harvesting the Data of the COHERENT Experiment

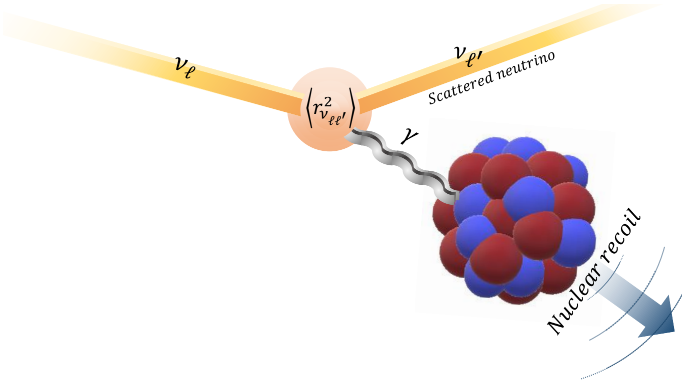
Carlo Giunti and **Matteo Cadeddu**

Torino, Italy   Cagliari, Italy

WIN 2019

XXVII International Workshop on Weak Interactions and Neutrinos

3-8 June 2019, Bari, Italy



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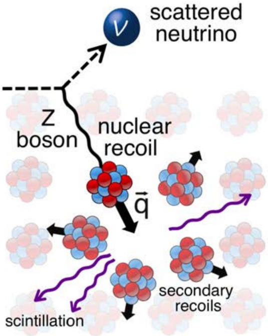
Based on:

- Cadeddu, Giunti, Y.F. Li, Y.Y. Zhang, Average CsI neutron density distribution from COHERENT data, PRL 120 (2018) 072501, arXiv:1710.02730
- Cadeddu, Dordei, Reinterpreting the weak mixing angle from atomic parity violation in view of the Cs neutron rms radius measurement from COHERENT, PRD 99 (2019) 033010, arXiv:1808.10202
- Cadeddu, Giunti, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, Neutrino Charge Radii from COHERENT Elastic Neutrino-Nucleus Scattering, PRD 98 (2018) 113010, arXiv:1810.05606

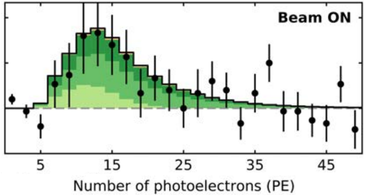
Coherent Elastic Neutrino-Nucleus Scattering

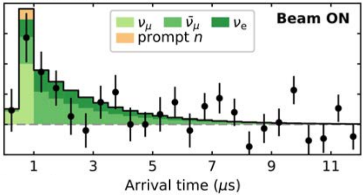


- Predicted in 1974 for $|\vec{q}|R \lesssim 1$
  [Freedman, PRD 9 (1974) 1389]

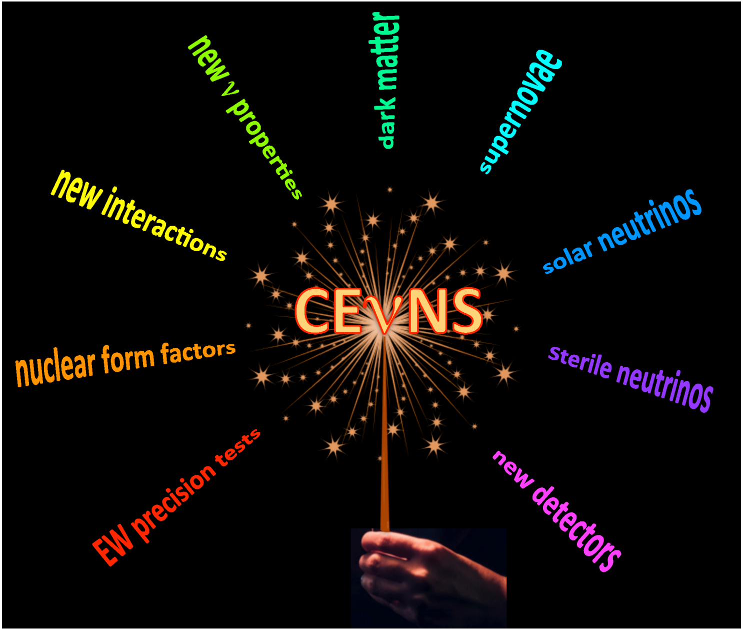
- $$\frac{d\sigma}{dT}(E_\nu, T) \simeq \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) N^2 F_N^2(|\vec{q}|^2)$$
  [Drukier, Stodolski, PRD (1984) 2295]

- Observed in 2017 in the COHERENT experiment at the Oak Ridge Spallation Neutron Source with CsI ($N_{Cs} = 78$, $N_I = 74$)
  [Science 357 (2017) 1123, arXiv:1708.01294]





- Several oncoming new experiments: CONUS, CONNIE, NU-CLEUS, MINER, Ricochet, TEXONO, νGEN



[E. Lisi, Neutrino 2018]

- Taking into account interactions with both neutrons and protons

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

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

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

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

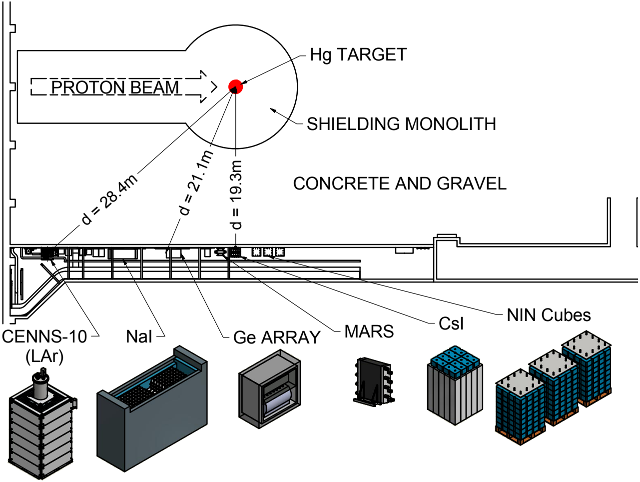
- Coherence requires very small values of the nuclear kinetic recoil energy $T \simeq |\vec{q}|^2/2M$:

$$|\vec{q}|R \lesssim 1 \quad \Longleftrightarrow \quad T \lesssim \frac{1}{2MR^2}$$

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

The COHERENT Experiment

Oak Ridge Spallation Neutron Source



14.6 kg CsI
scintillating crystal

[COHERENT, arXiv:1803.09183]

COHERENT Neutrino Spectrum and Time

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

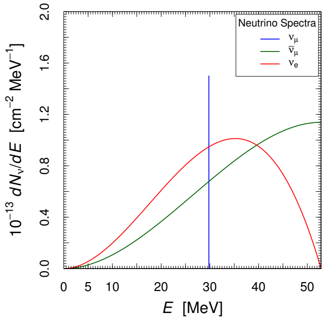
- Prompt monochromatic ν_μ from stopped pion decays:

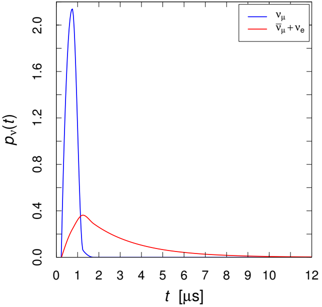
$$\pi^+ \to \mu^+ + \nu_\mu$$

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

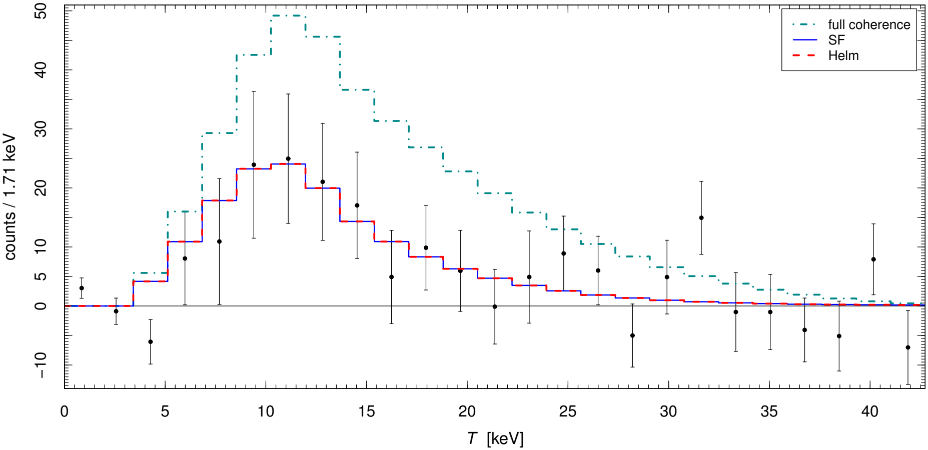
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

- The COHERENT energy and time information allow us to distinguish the interactions of ν_e, ν_μ, and $\bar{\nu}_\mu$.





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



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

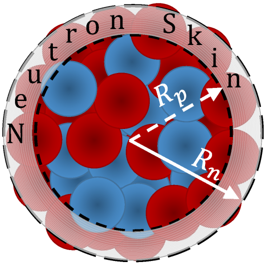
- Partial coherency gives information on the nuclear neutron form factor $F_N(|\vec{q}|^2)$, which is the Fourier transform of the neutron distribution in the nucleus.

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:

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

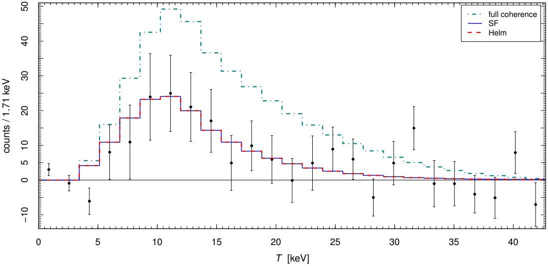
[PREX, PRL 108 (2012) 112502]

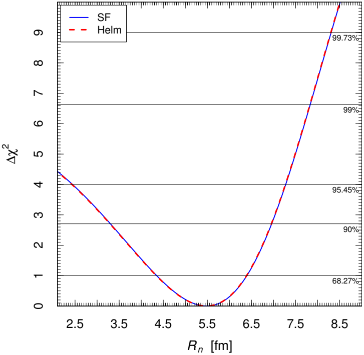


- The rms radii of the proton distributions of ^{133}Cs and ^{127}I have been determined with muonic atom spectroscopy: [Fricke et al, ADNDT 60 (1995) 177]

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

- Fit of the COHERENT data to get $R_n(^{133}\text{Cs}) \simeq R_n(^{127}\text{I})$:





[Cadeddu, Giunti, Li, Zhang, PRL 120 (2018) 072501, arXiv:1710.02730]

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

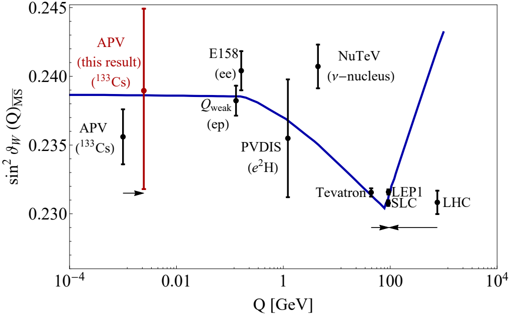
[Cadeddu, Giunti, Li, Zhang, PRL 120 (2018) 072501, arXiv:1710.02730]

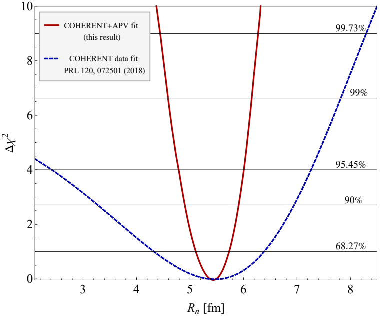
- This is the first determination of R_n with neutrino-nucleus scattering.
- The uncertainty is large, but it can be improved in future experiments.
- Predictions of nonrelativistic Skyrme-Hartree-Fock (SHF) and relativistic mean field (RMF) nuclear models:

	^{133}Cs		^{127}I	
	R_p	R_n	R_p	R_n
SHF SkM*	4.76	4.90	4.71	4.84
SHF SkP	4.79	4.91	4.72	4.84
SHF SkI4	4.73	4.88	4.67	4.81
SHF Sly4	4.78	4.90	4.71	4.84
SHF UNEDF1	4.76	4.90	4.68	4.83
RMF NL-SH	4.74	4.93	4.68	4.86
RMF NL3	4.75	4.95	4.69	4.89
RMF NL-Z2	4.79	5.01	4.73	4.94
Exp. (μ-atom spect.)	4.804		4.749	

Weak Mixing Angle from Atomic Parity Violation

[Cadeddu, Dordei, PRD 99 (2019) 033010, arXiv:1808.10202]





$$Q_W \simeq q_p Z \left(1 - 4\sin^2\vartheta_W\right) - q_n N$$

COHERENT + APV $\Longrightarrow$

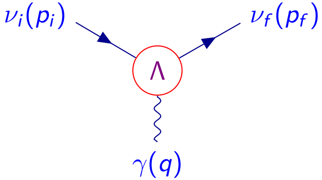
$$\begin{cases} R_n = 5.42 \pm 0.31\,\text{fm} \\ \Delta R_{np} = 0.62 \pm 0.31\,\text{fm} \end{cases}$$

neutron skin

Electromagnetic Interactions

- Effective Hamiltonian: $\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_\mu^{(\nu)}(x) A^\mu(x) = \sum_{k,j=1} \overline{\nu_k}(x) \Lambda_\mu^{kj} \nu_j(x) A^\mu(x)$

- Effective electromagnetic vertex:



$$\langle \nu_f(p_f) | j_\mu^{(\nu)}(0) | \nu_i(p_i) \rangle = \overline{u_f}(p_f) \Lambda_\mu^{fi}(q) u_i(p_i)$$

$$q = p_i - p_f$$

- Vertex function:

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) \left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i\sigma_{\mu\nu} q^\nu \left[F_M(q^2) + i F_E(q^2) \gamma_5\right]$$

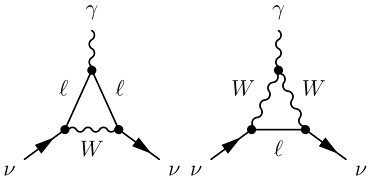
Lorentz-invariant form factors:	charge	anapole	magnetic	electric
$q^2 = 0 \quad \Longrightarrow$	$\mathfrak{q}$	a	μ	ε

Neutrino Charge Radius

- 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

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



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

- In the Standard Model:

[Bernabeu et al, PRD 62 (2000) 113012, NPB 680 (2004) 450]

$$\langle r^2_{\nu_\ell} \rangle_{\text{SM}} = -\frac{G_F}{2\sqrt{2}\pi^2}\left[3 - 2\log\left(\frac{m^2_\ell}{m^2_W}\right)\right]$$

$$\langle r^2_{\nu_e} \rangle_{\text{SM}} = -8.2 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\mu} \rangle_{\text{SM}} = -4.8 \times 10^{-33}\,\text{cm}^2$$
$$\langle r^2_{\nu_\tau} \rangle_{\text{SM}} = -3.0 \times 10^{-33}\,\text{cm}^2$$

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 $\nu_e \, e^-$	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 $\nu_\mu \, e^-$	BNL-E734	$-5.7 \times 10^{-32} < \langle r^2_{\nu_\mu} \rangle < 1.1 \times 10^{-32}$	90%	1990
	CHARM-II	$\lvert\langle r^2_{\nu_\mu} \rangle\rvert < 1.2 \times 10^{-32}$	90%	1994

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

and the update in Cadeddu, Giunti, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, PRD 98 (2018) 113010, arXiv:1810.05606]

- Neutrino charge radii contributions to ν_ℓ–$\mathcal{N}$ CEνNS:

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

- In the Standard Model there are only diagonal charge radii $\langle r^2_{\nu_\ell}\rangle \equiv \langle r^2_{\nu_{\ell\ell}}\rangle$ because lepton numbers are conserved.

- Diagonal charge radii generate the coherent shifts

$$\sin^2\vartheta_W \to \sin^2\vartheta_W\left(1 + \frac{1}{3} m_W^2 \langle r^2_{\nu_\ell}\rangle\right) \quad \Longleftrightarrow \quad \nu_\ell + \mathcal{N} \to \nu_\ell + \mathcal{N}$$

- Transition charge radii generate the incoherent contribution

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

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

Fit of COHERENT data

[Cadeddu, Giunti, Kouzakov, Y.F. Li, Studenikin, Y.Y. Zhang, PRD 98 (2018) 113010, arXiv:1810.05606]

- Fixed neutron distribution radii (RMF NL-Z2):

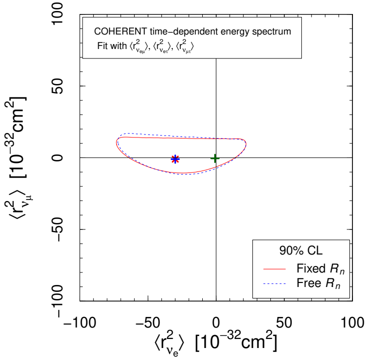
  $R_n(^{133}\text{Cs}) = 5.01\,\text{fm} \quad R_n(^{127}\text{I}) = 4.94\,\text{fm}$

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

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

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

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



- Free neutron distribution radii:

  $\chi^2_{\text{min}} = 154.2 \quad \text{NDF} = 137 \quad \text{GoF} = 15\%$

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

  $-63 < \langle r^2_{\nu_e} \rangle < 12 \quad -8 < \langle r^2_{\nu_\mu} \rangle < 11$

  $|\langle r^2_{\nu_{e\mu}} \rangle| < 22 \quad |\langle r^2_{\nu_{e\tau}} \rangle| < 38 \quad |\langle r^2_{\nu_{\mu\tau}} \rangle| < 27$

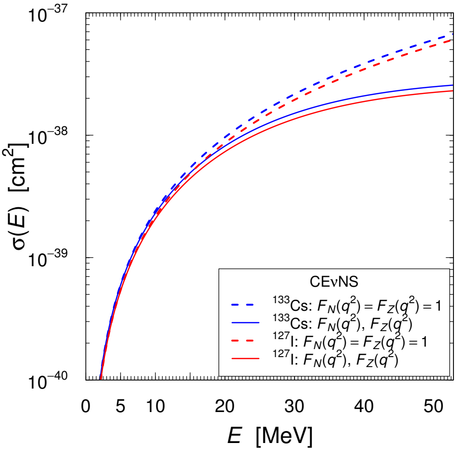
- The COHERENT energy and time information allow us to distinguish the charge radii of ν_e and ν_μ.

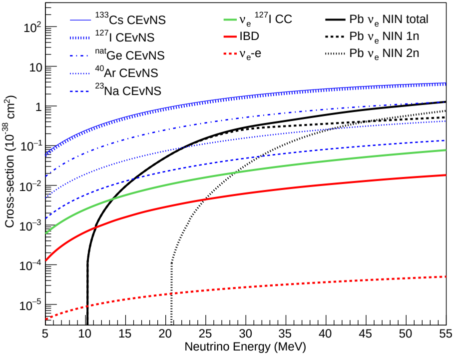
Conclusions

- The observation of CEνNS in the COHERENT experiment opened the way for new powerful measurements of the properties of nuclei and neutrinos.
- We obtained the first determination of R_n with ν-nucleus scattering.
- We constrained the neutrino charge radii and obtained the first constraints on the transition charge radii.
- An improvement of about 1 order of magnitude is necessary to be competitive with the current limits on $\langle r^2_{\nu_e} \rangle$ and $\langle r^2_{\nu_\mu} \rangle$.
- An improvement of about 2 orders of magnitude is necessary to reach the Standard Model values of $\langle r^2_{\nu_e} \rangle$ and $\langle r^2_{\nu_\mu} \rangle$.
- The new CEνNS experiments may allow to approach this goal.

Backup Slides

Cross Section





[COHERENT, arXiv:1803.09183]

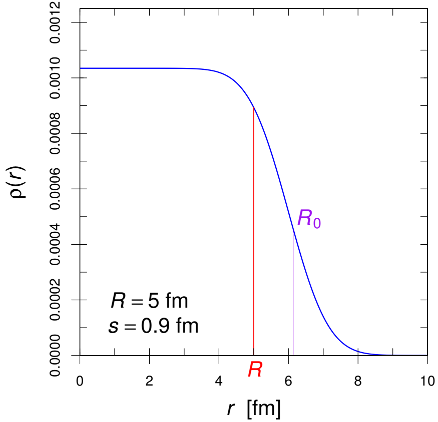
Helm form factor: $F_N^{\text{Helm}}(|\vec{q}|^2) = 3\,\frac{j_1(|\vec{q}|R_0)}{|\vec{q}|R_0}\,e^{-|\vec{q}|^2 s^2/2}$

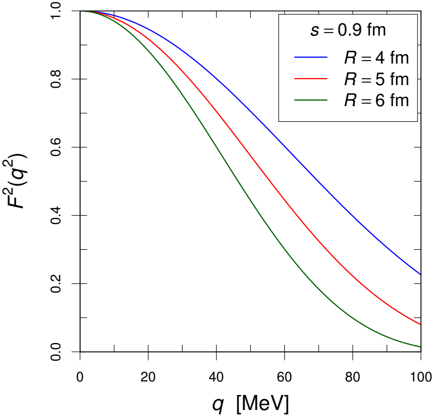
Spherical Bessel function of order one: $j_1(x) = \sin(x)/x^2 - \cos(x)/x$

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

Rms radius: $R^2 = \langle r^2 \rangle = \frac{3}{5}\,R_0^2 + 3s^2$

Surface thickness: $s \simeq 0.9\,\text{fm}$





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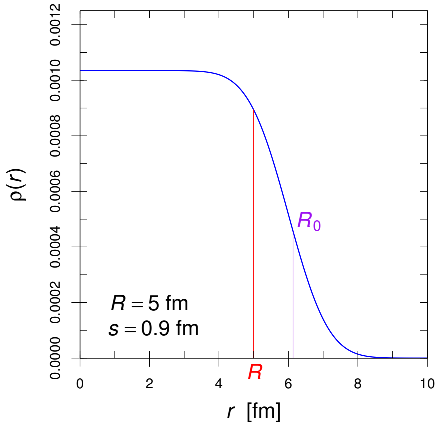

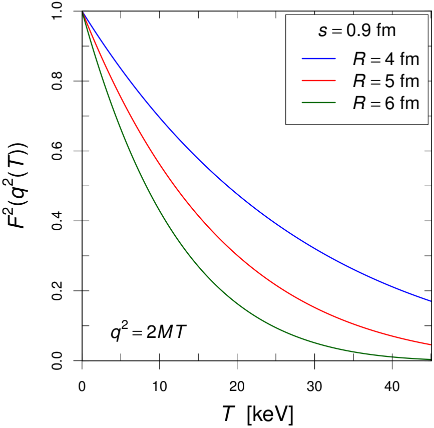

Electromagnetic Vertex Function

$$\Lambda_\mu(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right)\left[F_Q(q^2) + F_A(q^2) q^2 \gamma_5\right] - i\sigma_{\mu\nu} q^\nu \left[F_M(q^2) + i F_E(q^2)\gamma_5\right]$$

Lorentz-invariant form factors: charge, anapole, magnetic, electric

$q^2 = 0 \implies$ $\mathbb{q}$, a, μ, ε

- Hermitian form factors: $F_Q = F_Q^\dagger$, $F_A = F_A^\dagger$, $F_M = F_M^\dagger$, $F_E = F_E^\dagger$
- Majorana neutrinos: $F_Q = -F_Q^T$, $F_A = F_A^T$, $F_M = -F_M^T$, $F_E = -F_E^T$

  no diagonal charges and electric and magnetic moments
- For ultrarelativistic neutrinos $\gamma_5 \to -1 \Rightarrow$ The phenomenology of the charge and anapole moments are similar and the phenomenology of the magnetic and electric moments are similar.
- For ultrarelativistic neutrinos the charge and anapole terms conserve helicity, whereas the magnetic and electric terms invert helicity.