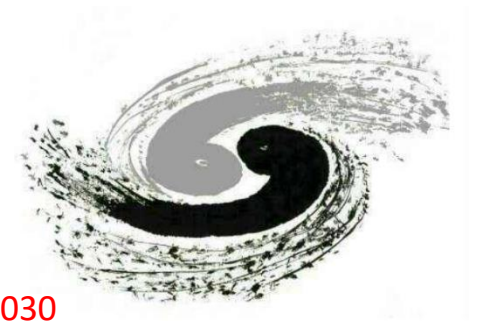


# Constraints on neutrino electromagnetic properties from COHERENT elastic neutrino-nucleus scattering

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*M. Cadeddu et al. Phys.Rev.D 102 (2020) 1, 015030*

Based on a work in collaboration with M. Cadeddu, N. Cargioli, F. Dordei, C. Giunti, E. Picciau, Y. F. Li, Y. Y. Zhang.

# Coherent Elastic Neutrino-Nucleus Scattering

- Predicted in 1974 for  $|\vec{q}|R \ll 1$  [Freedman, Physical Review D, 1974, 9(5): 1389]

- Taking into account interactions with both neutrons and protons

[P.A. Zyla et al., Prog. Theor. Exp. Phys. 2020, 083C01 (2020)]

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

Tree Level

$$g_V^n = -\frac{1}{2} \quad g_V^p = \frac{1}{2} - 2\sin^2\theta_W$$

The neutron contribution is dominant!



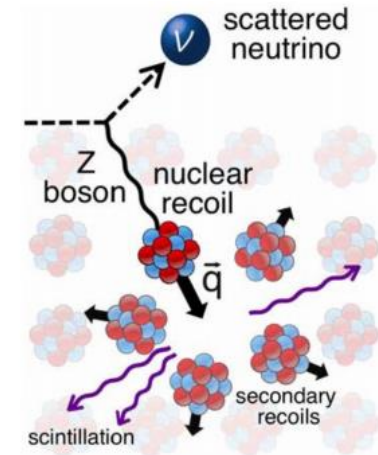
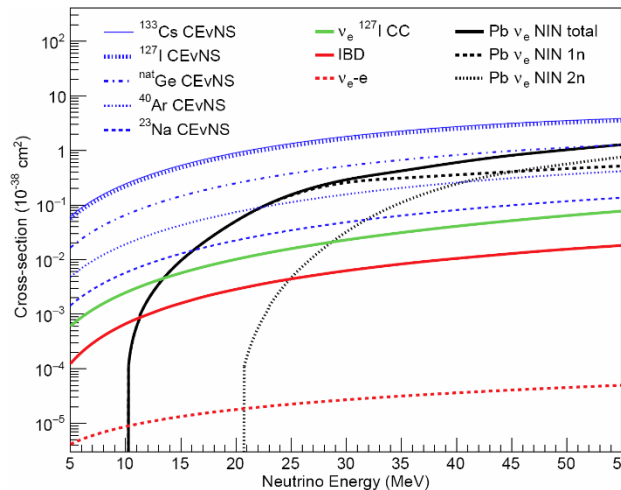
$$\frac{d\sigma}{dT} \sim N^2 F_N^2(q^2)$$

- The form factors  $F_N(|\vec{q}|^2)$  and  $F_Z(|\vec{q}|^2)$  describe the loss of coherence for  $|\vec{q}|R \gtrsim 1$ .

$$T \approx |\vec{q}|^2 / 2M$$

$$M \sim 100 \text{ GeV}, R \sim 5 \text{ fm}$$

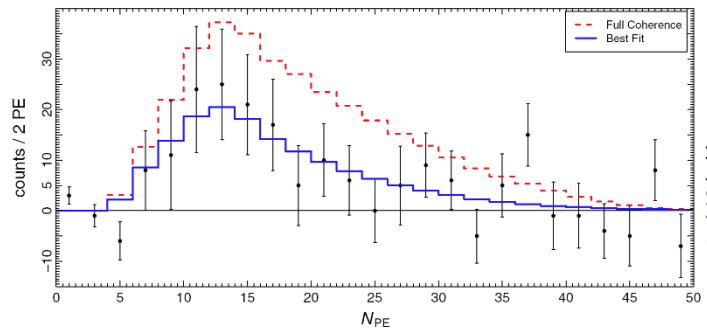
$$\rightarrow T \lesssim 10 \text{ keV}$$



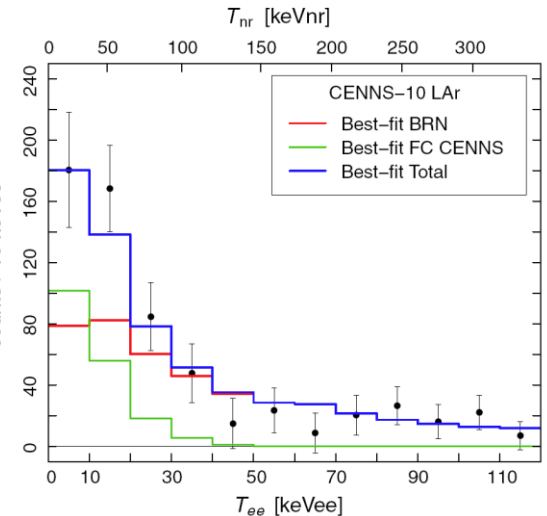
# The COHERENT experiment



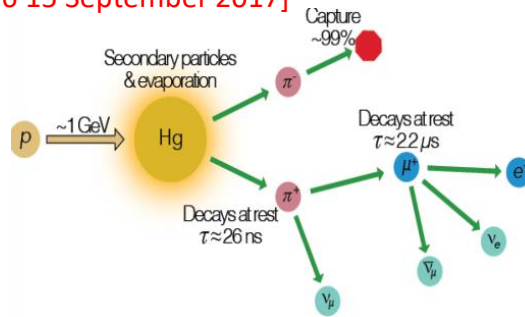
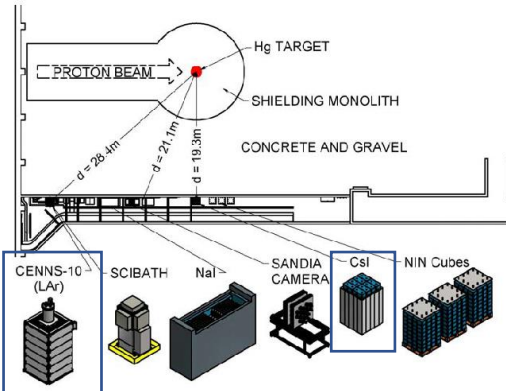
14.6 kg CsI(2017)



24 kg LAr(2020)



[Akimov et al. *Science* Vol 357, Issue 6356 15 September 2017]



- Prompt monochromatic  $\nu_\mu$ :  
 $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- Delayed  $\bar{\nu}_\mu$  and  $\nu_e$ :  
 $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- The COHERENT energy and time information allow us to distinguish the interactions of  $\nu_e$ ,  $\nu_\mu$  and  $\bar{\nu}_\mu$

[COHERENT, arXiv:1803.09183, arXiv:2003.10630]

# Neutrino electromagnetic properties

- Effective electromagnetic Hamiltonian: [Giunti, Studenikin, RMP 87 (2015) 531, arXiv:1403.6344]

$$\mathcal{H}_{\text{em}}^{(\nu)} = j_{\mu}^{(\nu)}(x) A^{\mu}(x) = \sum_{k,j=1}^N \bar{\nu}_k(x) \Lambda_{\mu}^{kj} \nu_j(x) A^{\mu}(x)$$

- Vertex function:

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

Lorentz-invariant form factors:

charge

anapole

magnetic

electric

$\gamma(q)$

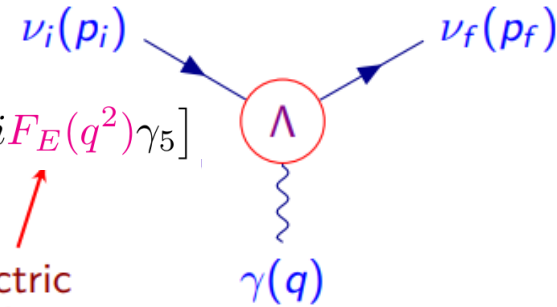
$$q^2 = 0 \implies$$

$q$

$a$

$\mu$

$\epsilon$



$$F_Q(q^2) = F_Q(0) + q^2 \frac{dF_Q(q^2)}{dq^2} \Big|_{q^2=0} + \dots = q_{\nu} + \frac{q^2}{6} \langle r_{\nu}^2 \rangle \dots$$

In the Standard Model:

$$F_Q(q^2) \approx \frac{q^2}{6} \langle r_{\nu}^2 \rangle$$

Beyond the Standard Model:  $F_Q(q^2) \approx q_{\nu}$

$$\frac{d\sigma_{\nu\ell-N}}{dT}(E, T) = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E^2}\right) \left\{ \left[ \left( g_V^p - \tilde{Q}_{\ell\ell} \right) Z F_Z(|\vec{q}|^2) + g_V^n N F_N(|\vec{q}|^2) \right]^2 + Z^2 F_Z^2(|\vec{q}|^2) \sum_{\ell' \neq \ell} |\tilde{Q}_{\ell'\ell}|^2 \right\}$$

$$\frac{d\sigma_{\nu\ell-N}^{\text{mag}}}{dT_{\text{nr}}}(E, T_{\text{nr}}) = \frac{\pi \alpha^2}{m_e^2} \left( \frac{1}{T_{\text{nr}}} - \frac{1}{E} \right) Z^2 F_Z^2(|\vec{q}|^2) \left| \frac{\mu_{\nu\ell}}{\mu_B} \right|^2$$

$\nu$  magnetic moments

$$\frac{\sqrt{2}\pi\alpha}{3G_F} \langle r_{\nu\ell\ell'}^2 \rangle$$

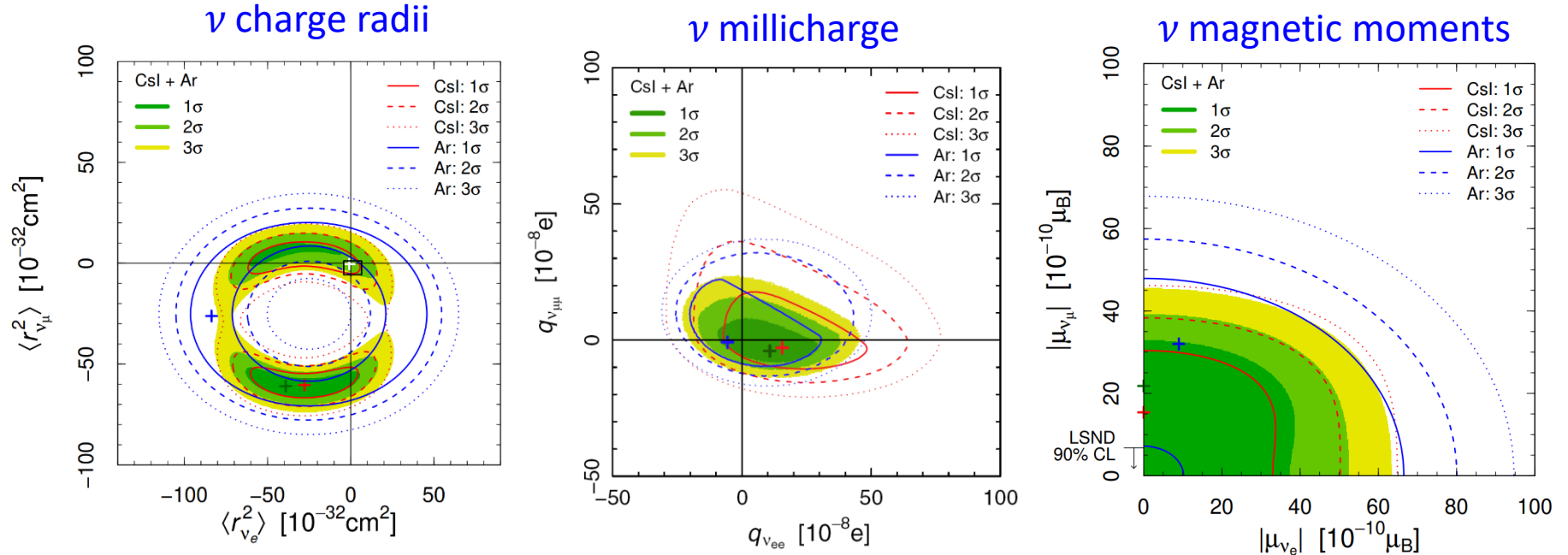
$\nu$  charge radii

$$\frac{2\sqrt{2}\pi\alpha}{G_F q^2} q_{\nu\ell\ell'}$$

$\nu$  millicharge

# Fit of COHERENT data: neutrino electromagnetic properties

[M. Cadeddu et al. *Phys.Rev.D* 102 (2020) 1, 015030]



- constraints on the neutrino charge radii:
 
$$-78 < \langle r_{\nu_e}^2 \rangle < 22, -71 < \langle r_{\nu_\mu}^2 \rangle < 17 \quad [10^{-32} \text{cm}^2].$$
- constraints on the neutrino millicharge:
 
$$-20 < q_{\nu_e} < 42, -12 < q_{\nu_\mu} < 20 \quad [10^{-8} e].$$
- constraints on the effective neutrino magnetic moment:
 
$$|\mu_{\nu_e}| < 56, |\mu_{\nu_\mu}| < 41 \quad [10^{-10} \mu_B].$$
- neutrino charge radii, 100 higher than SM
- Improvement of the **only existing laboratory** bound of  $q_{\nu_{\mu\mu}}$ .
- Muon neutrino magnetic moment only about five times larger than the best current laboratory limit.

# Summary

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- CE $\nu$ NS: unique process to explore the neutrino electromagnetic properties.
- The combined fit of the COHERENT CsI and Ar: improvement of constraints on neutrino electromagnetic properties.
- CE $\nu$ NS: a new way to explore the nuclear and neutrino physics
  - Electroweak precision tests:
    - [M. Cadeddu et al. Phys.Rev.D 101 \(2020\) 3, 033004](#)
    - O. Tomalak et al. *JHEP* 02 (2021) 097
  - NSI:
    - B. Dutta et al. *JHEP* 09 (2020) 106
    - C. Giunti, *Phys.Rev.D* 101 (2020) 3, 035039
  - light vector mediators
    - O.G. Miranda et al. *JHEP* 05 (2020) 130
    - [M. Cadeddu et al. JHEP 01 \(2021\) 116](#)
  - Nuclear structure:
    - [M. Cadeddu et al. Phys.Rev.Lett.120.072501](#)
    - [M. Cadeddu et al. arXiv: 2102.06153](#)
    - D. K. Papoulias, *Phys.Rev.D* 102 (2020) 113004
    - P. Coloma et al. *JHEP* 08 (2020) 08, 030
  - ...

# Thanks