

Theoretical Overview on Coherent Elastic Neutrino-Nucleus Scattering

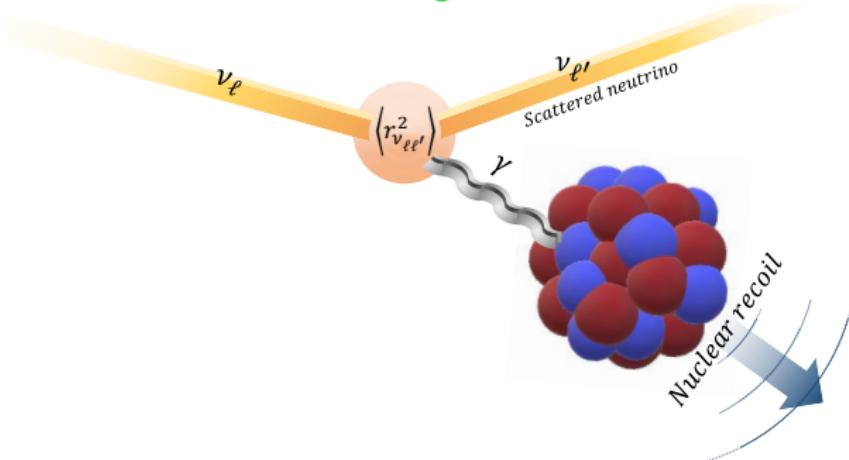
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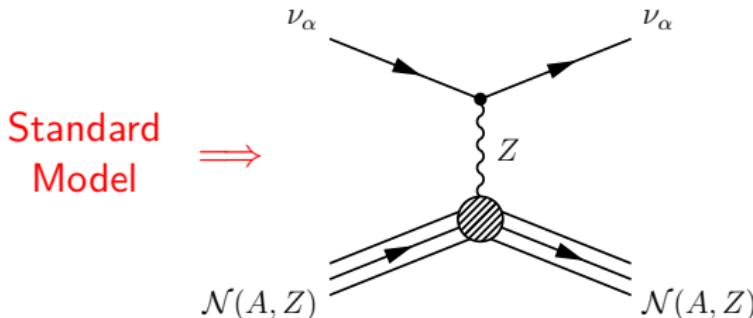
19–25 August 2021



Coherent Elastic Neutrino-Nucleus Scattering

- CE ν NS: pronounced “sevens”
- Neutral-Current (NC) interaction:

$$\nu + \mathcal{N}(A, Z) \rightarrow \nu + \mathcal{N}(A, Z)$$



- The nucleus $\mathcal{N}(A, Z)$ recoils without any internal change of state!
- CE ν NS was predicted in 1974! [Freedman, PRD 9 (1974) 1389]
- Experimental difficulty: low nuclear recoil kinetic energy $T \lesssim 10 \text{ keV}$
- CE ν NS was observed for the first time 43 years later, in 2017 by the COHERENT experiment at the Oak Ridge Spallation Neutron Source with CsI ($^{133}_{55}\text{Cs}_{78}$, $^{127}_{53}\text{I}_{74}$) [COHERENT, arXiv:1708.01294]
- Second observation in 2020 by the COHERENT experiment with a LAr detector ($^{40}_{18}\text{Ar}_{22}$) [COHERENT, arXiv:2003.10630]

CE ν NS Cross Section

Standard Model:

$$\frac{d\sigma_{CE\nu NS}}{dT}(E_\nu, T) = \frac{G_F^2 M}{4\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) [Q_W(Q^2)]^2$$

- Weak charge of the nucleus \mathcal{N} :

$$|\vec{q}| = \sqrt{2 M T}$$

$$Q_W(Q^2) = g_V^n N F_N(|\vec{q}|) + g_V^p Z F_Z(|\vec{q}|)$$

$$g_V^n = -\frac{1}{2} \quad g_V^p = \frac{1}{2} - 2 \sin^2 \vartheta_W (Q^2 \simeq 0) = 0.0227 \pm 0.0002$$

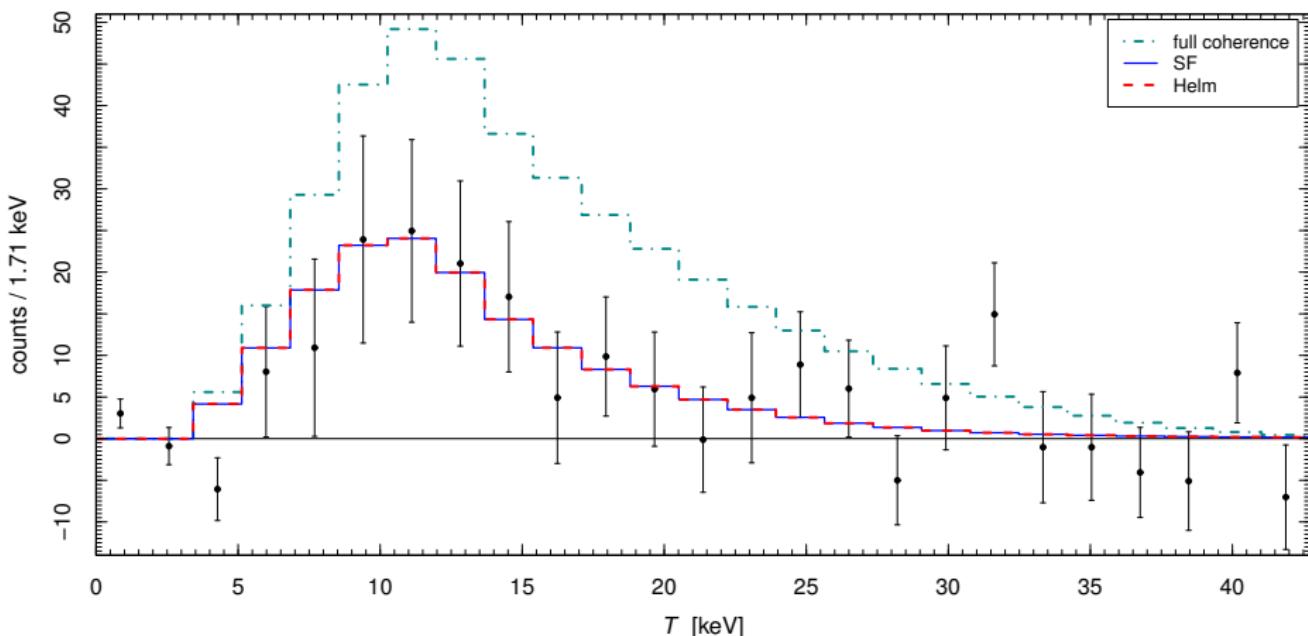
The neutron contribution is dominant! $\implies \frac{d\sigma_{CE\nu NS}}{dT} \propto N^2$

[Freedman, PRD 9 (1974) 1389; Drukier, Stodolsky, PRD 30 (1984) 2295; Barranco, Miranda, Rashba, hep-ph/0508299]

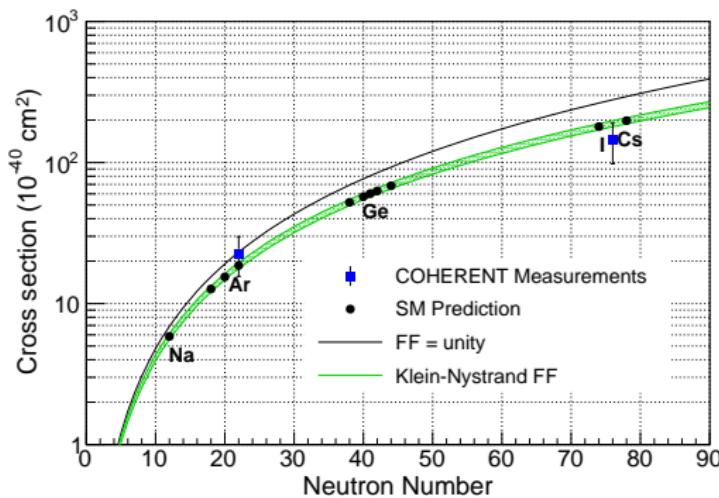
- The coherent nuclear recoil gives a big cross section enhancement for heavy nuclei: $\sigma_{NC}^{incoherent} \propto N \implies \sigma_{CE\nu NS}/\sigma_{NC}^{incoherent} \propto N$
- The nuclear form factors $F_N(|\vec{q}|)$ and $F_Z(|\vec{q}|)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$. [Patton et al, arXiv:1207.0693; Bednyakov, Naumov, arXiv:1806.08768; Papoulias et al, arXiv:1903.03722; Ciuffoli et al, arXiv:1801.02166; Canas et al, arXiv:1911.09831; Van Dessel et al, arXiv:2007.03658]

- In the COHERENT experiment the scattering is **not completely coherent**

$$\text{CsI: } \left\{ \begin{array}{l} |\vec{q}| \sim 30 - 80 \text{ MeV} \sim 0.1 - 0.4 \text{ fm}^{-1} \\ R \approx 1.2 A^{1/3} \text{ fm} \approx 5 \text{ fm} \end{array} \right\} \Rightarrow |\vec{q}|R \sim 0.5 - 2$$



[Cadeddu, CG, Li, Zhang, arXiv:1710.02730]

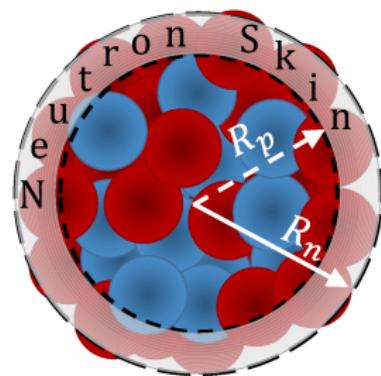


[COHERENT, arXiv:2003.10630]

- ▶ Partial coherency is described by the **nuclear neutron form factor** $F_N(|\vec{q}|)$
- ▶ Fourier transform of the **neutron distribution in the nucleus** $\rho_N(r)$:
$$F_N(|\vec{q}|) = \int e^{-i\vec{q}\cdot\vec{r}} \rho_N(r) d^3r$$
- ▶ Measurable parameter: **the radius R_n of the nuclear neutron distribution**

The Nuclear Proton and Neutron Distributions

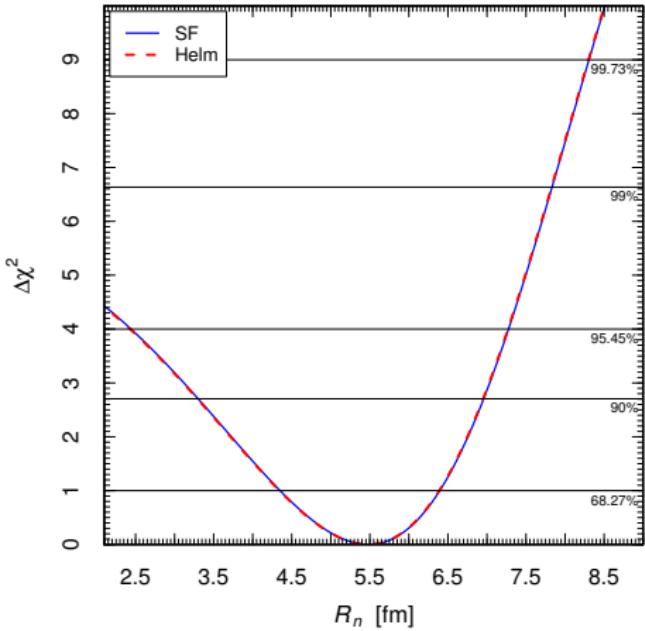
- The nuclear proton distribution (charge density) is probed with electromagnetic interactions.
 - Most sensitive are electron-nucleus elastic scattering and muonic atom spectroscopy.
 - Hadron scattering experiments give information on the nuclear neutron distribution, but their interpretation depends 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, arXiv:1201.2568]
- Larger than $R_p(^{208}\text{Pb}) = 5.5028 \pm 0.0013 \text{ fm} \implies \text{Neutron Skin}$



- ▶ Fit of the 2017 COHERENT CsI data:

$$R_n(\text{CsI}) = 5.5^{+0.9}_{-1.1} \text{ fm}$$

[Cadeddu, CG, Li, Zhang, arXiv:1710.02730]



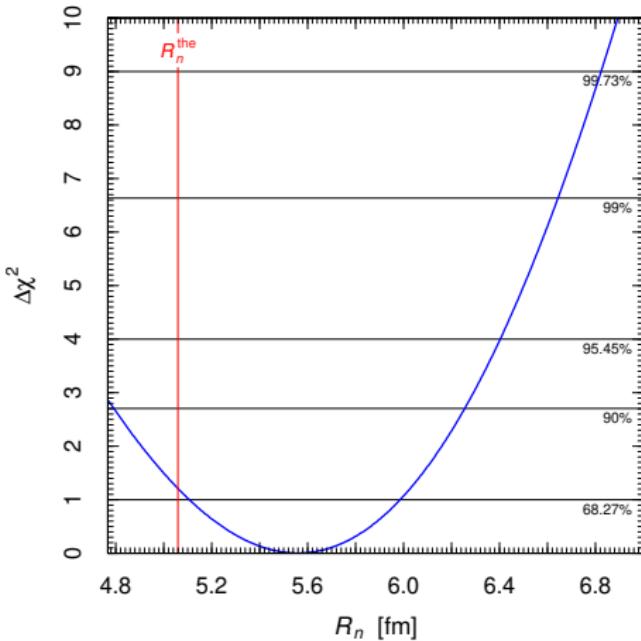
- ▶ $R_n(\text{CsI}) \simeq R_n(^{133}\text{Cs}) \simeq R_n(^{127}\text{I})$
- ▶ First determination of R_n with neutrino-nucleus scattering.
- ▶ Best fit larger than

$$R_p(^{133}\text{Cs}) = 4.821 \pm 0.005 \text{ fm}$$

$$R_p(^{127}\text{I}) = 4.766 \pm 0.008 \text{ fm}$$

Indicates a sizable **neutron skin**

[see also: Papoulias, Kosmas, Sahu, Kota, Hota, arXiv:1903.03722; Papoulias, arXiv:1907.11644; Khan, Rodejohann, arXiv:1907.12444; Coloma, Esteban, Gonzalez-Garcia, Menendez, arXiv:2006.08624]



- With new 2020 COHERENT CsI data:

[Pershey @ Magnificent CE ν NS 2020]

$$R_n(\text{CsI}) = 5.55 \pm 0.44 \text{ fm}$$

[Cadeddu et al, arXiv:2102.06153]

- Neutron skin:

$$\Delta R_{np}(\text{CsI}) = 0.76 \pm 0.44 \text{ fm}$$

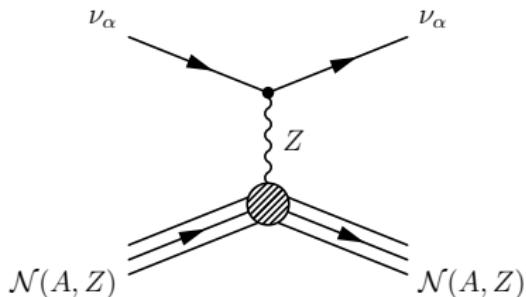
- Predictions of nuclear models:

$$\Delta R_{np}(\text{CsI}) \approx 0.1 - 0.3 \text{ fm}$$

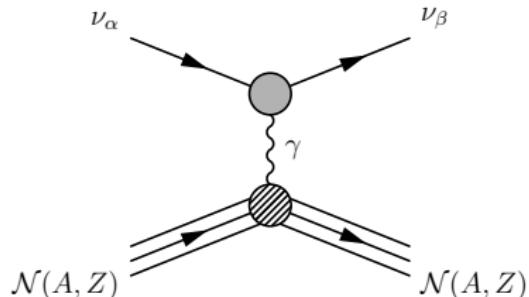
- A large neutron skin has important implications for:
 - Nuclear physics: a larger pressure of neutrons
 - Astrophysics: a larger size of neutron stars

SM and BSM CE ν NS Neutrino Interactions

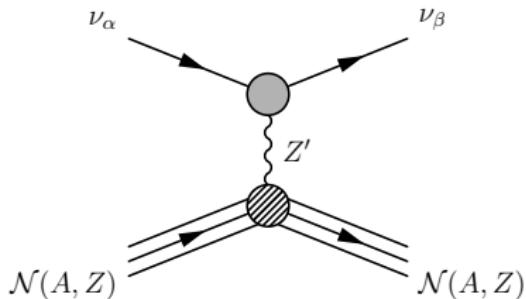
Standard Model NC



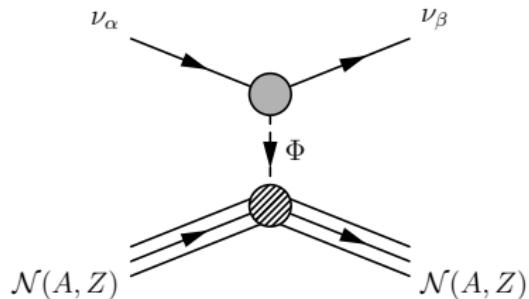
Electromagnetic Interactions



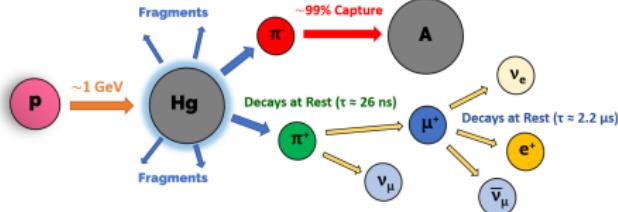
BSM Vector Mediator



BSM Scalar Mediator



COHERENT Stopped-Pion Neutrino Source



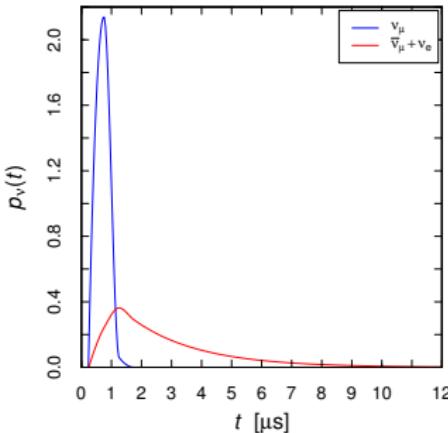
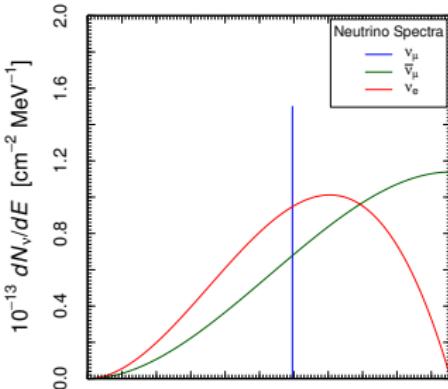
- ▶ Prompt monochromatic ν_μ from stopped pion decays:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

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

- ▶ Allows to probe SM and BSM neutral current ν_e and ν_μ interactions, that are distinguished by different energy and time distributions



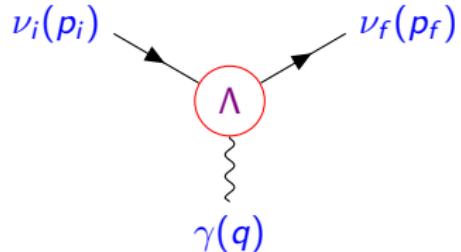
Neutrino Electromagnetic Interactions

- 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:

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

Lorentz-invariant form factors:

$$q^2 = 0 \implies$$

$$\begin{array}{cc} \uparrow & \uparrow \\ \text{charge} & \text{anapole} \\ \downarrow & \downarrow \\ q & a \end{array}$$

helicity-conserving

$$\begin{array}{cc} \uparrow & \uparrow \\ \text{magnetic} & \text{electric} \\ \downarrow & \downarrow \\ \mu & \varepsilon \end{array}$$

helicity-flipping

Electromagnetic Vertex Function

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

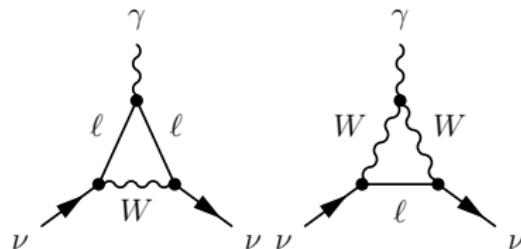
Lorentz-invariant form factors: charge anapole magnetic electric
 $q^2 = 0 \implies q \quad a \quad \mu \quad \varepsilon$

- ▶ 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 in the mass basis
- ▶ For left-handed ultrarelativistic neutrinos $\gamma_5 \rightarrow -1 \Rightarrow$ The phenomenology of the charge and anapole 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.

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

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



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

- In the Standard Model:

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

$$\langle r_{\nu_\ell}^2 \rangle_{\text{SM}} = -\frac{G_F}{2\sqrt{2}\pi^2} \left[3 - 2 \log \left(\frac{m_\ell^2}{m_W^2} \right) \right]$$

$$\begin{aligned}\langle r_{\nu_e}^2 \rangle_{\text{SM}} &= -8.2 \times 10^{-33} \text{ cm}^2 \\ \langle r_{\nu_\mu}^2 \rangle_{\text{SM}} &= -4.8 \times 10^{-33} \text{ cm}^2 \\ \langle r_{\nu_\tau}^2 \rangle_{\text{SM}} &= -3.0 \times 10^{-33} \text{ cm}^2\end{aligned}$$

Experimental Bounds

Method	Experiment	Limit [cm ²]	CL	Year
Reactor $\bar{\nu}_e e^-$	Krasnoyarsk	$ \langle r_{\nu_e}^2 \rangle < 7.3 \times 10^{-32}$	90%	1992
	TEXONO	$-4.2 \times 10^{-32} < \langle r_{\nu_e}^2 \rangle < 6.6 \times 10^{-32}$	90%	2009
Accelerator $\nu_e e^-$	LAMPF	$-7.12 \times 10^{-32} < \langle r_{\nu_e}^2 \rangle < 10.88 \times 10^{-32}$	90%	1992
	LSND	$-5.94 \times 10^{-32} < \langle r_{\nu_e}^2 \rangle < 8.28 \times 10^{-32}$	90%	2001
Accelerator $\nu_\mu e^-$	BNL-E734	$-5.7 \times 10^{-32} < \langle r_{\nu_\mu}^2 \rangle < 1.1 \times 10^{-32}$	90%	1990
	CHARM-II	$ \langle r_{\nu_\mu}^2 \rangle < 1.2 \times 10^{-32}$	90%	1994

[see the review CG, Studenikin, arXiv:1403.6344

and the update in Cadeddu, CG, Kouzakov, Li, Studenikin, Zhang, arXiv:1810.05606]

- Neutrino charge radii contributions to $\nu_\ell - \mathcal{N}$ CE ν NS:

$$\frac{d\sigma_{\nu_\ell - \mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) \left\{ \left[-\frac{1}{2} NF_N(|\vec{q}|) \underbrace{g_V^\eta}_{g_V^\eta} + \left(\underbrace{\frac{1}{2} - 2\sin^2\vartheta_W - \frac{2}{3} m_W^2 \sin^2\vartheta_W \langle r_{\nu\ell\ell}^2 \rangle}_{g_V^p \simeq 0.023} \right) ZF_Z(|\vec{q}|) \right]^2 + \frac{4}{9} m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(|\vec{q}|) \sum_{\ell' \neq \ell} |\langle r_{\nu\ell'\ell}^2 \rangle|^2 \right\}$$

- In the Standard Model there are only diagonal charge radii $\langle r_{\nu_\ell}^2 \rangle \equiv \langle r_{\nu\ell\ell}^2 \rangle$ because lepton numbers are conserved.
- Diagonal charge radii generate the coherent shifts

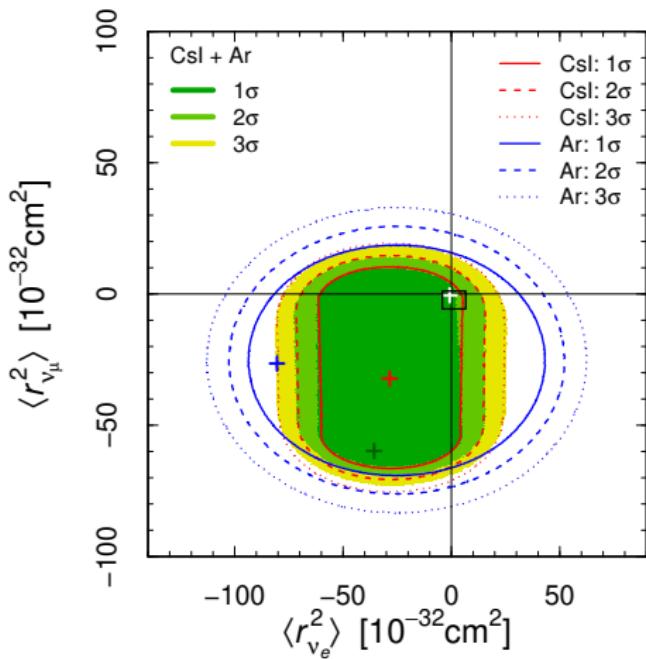
$$\sin^2\vartheta_W \rightarrow \sin^2\vartheta_W \left(1 + \frac{1}{3} m_W^2 \langle r_{\nu_\ell}^2 \rangle\right) \iff \nu_\ell + \mathcal{N} \rightarrow \nu_\ell + \mathcal{N}$$

- Transition charge radii generate the incoherent contribution

$$\frac{4}{9} m_W^4 \sin^4\vartheta_W Z^2 F_Z^2(|\vec{q}|) \sum_{\ell' \neq \ell} |\langle r_{\nu\ell'\ell}^2 \rangle|^2 \iff \nu_\ell + \mathcal{N} \rightarrow \sum_{\ell' \neq \ell} \nu_{\ell' \neq \ell} + \mathcal{N}$$

[Kouzakov, Studenikin, arXiv:1703.00401]

COHERENT constraints on neutrino charge radii



$$\begin{aligned} |\langle r_{\nu_{e\mu}}^2 \rangle| &< 36 \times 10^{-32} \text{ cm}^2 \\ |\langle r_{\nu_{e\tau}}^2 \rangle| &< 50 \times 10^{-32} \text{ cm}^2 \quad (3\sigma) \\ |\langle r_{\nu_{\mu\tau}}^2 \rangle| &< 44 \times 10^{-32} \text{ cm}^2 \end{aligned}$$

[Cadeddu, Dordei, CG, Li, Picciano, Zhang, arXiv:2005.01645]

Effective charge radii
in the flavor basis:

$$\langle r_{\nu_{\ell\ell'}}^2 \rangle = \sum_{j,k} U_{\ell j}^* U_{\ell' k} \langle r_{\nu_{jk}}^2 \rangle$$

[see also: Papoulias, Kosmas, arXiv:1711.09773; Cadeddu, CG, Kouzakov, Li, Studenikin, Zhang, arXiv:1810.05606;
Papoulias, arXiv:1907.11644; Khan, Rodejohann, arXiv:1907.12444; Cadeddu, Dordei, CG, Li, Zhang, arXiv:1908.06045;
Miranda, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, arXiv:2003.12050]

Neutrino Electric Charges

- Neutrinos can be **millicharged particles** in theories beyond the Standard Model.
- Neutrino charge contributions to $\nu_\ell - \mathcal{N}$ CE ν NS:

$$\frac{d\sigma_{\nu_\ell - \mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) \left\{ \left[-\frac{1}{2} \underbrace{NF_N(|\vec{q}|)}_{g_V^n} \right. \right. \\ \left. \left. + \left(\underbrace{\frac{1}{2} - 2 \sin^2 \vartheta_W}_{g_V^p \simeq 0.023} + \frac{2m_W^2 \sin^2 \vartheta_W}{MT} q_{\nu \ell e} \right) ZF_Z(|\vec{q}|) \right]^2 \right. \\ \left. + \frac{4m_W^4 \sin^4 \vartheta_W}{M^2 T^2} Z^2 F_Z^2(|\vec{q}|) \sum_{\ell' \neq \ell} |q_{\nu \ell' e'}|^2 \right\}$$

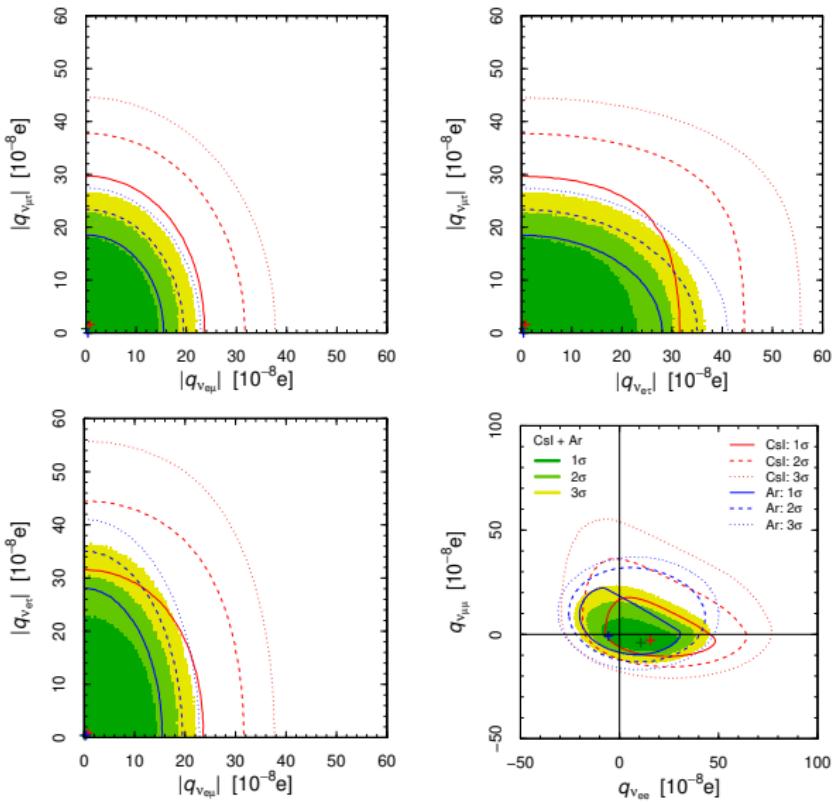
- $q_{\bar{\nu}_{\ell \ell'}} = -q_{\nu_{\ell \ell'}}$, but also $g_V^{p,n}(\bar{\nu}) = -g_V^{p,n}(\nu)$.

Limits on neutrino millicharges

Limit	Method	Reference
$ q_{\nu_e} \lesssim 3 \times 10^{-21} e$	Neutrality of matter	Raffelt (1999)
$ q_{\nu_e} \lesssim 3.7 \times 10^{-12} e$	Nuclear reactor	Gninenko et al (2006)
$ q_{\nu_e} \lesssim 1.5 \times 10^{-12} e$	Nuclear reactor	Studenikin (2013)
$ q_{\nu_e} \lesssim 1.0 \times 10^{-12} e$	Nuclear reactors	Chen et al (2014)
$ q_{\nu_\mu} \lesssim 3 \times 10^{-8} e$	COHERENT CE ν NS	Cadeddu et al (2020)
$ q_{\nu_{\mu\tau}} \lesssim 2 \times 10^{-8} e$	COHERENT CE ν NS	Cadeddu et al (2020)
$ q_{\nu_\mu} \lesssim 3 \times 10^{-9} e$	LSND	Das et al (2020)
$ q_{\nu_\tau} \lesssim 4 \times 10^{-6} e$	DONUT	Das et al (2020)
$ q_{\nu_\tau} \lesssim 4 \times 10^{-4} e$	BEBC beam dump	Babu et al (1993)
$ q_\nu \lesssim 3 \times 10^{-4} e$	SLAC e ⁻ beam dump	Davidson et al (1991)
$ q_\nu \lesssim 6 \times 10^{-14} e$	Solar cooling (plasmon decay)	Raffelt (1999)
$ q_\nu \lesssim 2 \times 10^{-14} e$	Red giant cooling (plasmon decay)	Raffelt (1999)
$ q_\nu \lesssim 2 \times 10^{-14} e$	Red giant cooling (plasmon decay)	Raffelt (1999)
$ q_\nu \lesssim 4 \times 10^{-35} e$	Neutrality of Universe	Caprini, Ferreira (2003)

COHERENT constraints on neutrino millicharges

[Cadeddu, Dordei, CG, Li, Picciano, Zhang, arXiv:2005.01645]



[future prospects: Parada, arXiv:1907.04942]

- Effective charges in the flavor basis:
$$q_{\nu_{\ell\ell'}} = \sum_{j,k} U_{\ell j}^* U_{\ell' k} q_{\nu_{jk}}$$
- The bounds on the charges involving the electron neutrino flavor
 $q_{\nu_{ee}} \quad q_{\nu_{e\mu}} \quad q_{\nu_{e\tau}}$ are not competitive with respect to those obtained in reactor neutrino experiments, that are at the level of $10^{-12} e$ in neutrino-electron elastic scattering experiments.
- The bounds on
 $q_{\nu_{\mu\mu}} \quad q_{\nu_{\mu\tau}}$ are the first ones obtained from laboratory data.

Neutrino Magnetic and Electric Moments

- Extended Standard Model with **Dirac** massive neutrinos ($\Delta L = 0$):

$$\begin{aligned} \mu_{kk}^D &\simeq 3.2 \times 10^{-19} \mu_B \left(\frac{m_k}{\text{eV}} \right) \quad \varepsilon_{kk}^D = 0 \\ \mu_{kj}^D \\ i\varepsilon_{kj}^D \end{aligned} \left\{ \right. \simeq -3.9 \times 10^{-23} \mu_B \left(\frac{m_k \pm m_j}{\text{eV}} \right) \sum_{\ell=e,\mu,\tau} U_{\ell k}^* U_{\ell j} \left(\frac{m_\ell}{m_\tau} \right)^2$$

off-diagonal moments are GIM-suppressed

[Fujikawa, Shrock, PRL 45 (1980) 963; Pal, Wolfenstein, PRD 25 (1982) 766; Shrock, NPB 206 (1982) 359;
Dvornikov, Studenikin, hep-ph/0305206]

- Extended Standard Model with **Majorana** massive neutrinos ($|\Delta L| = 2$):

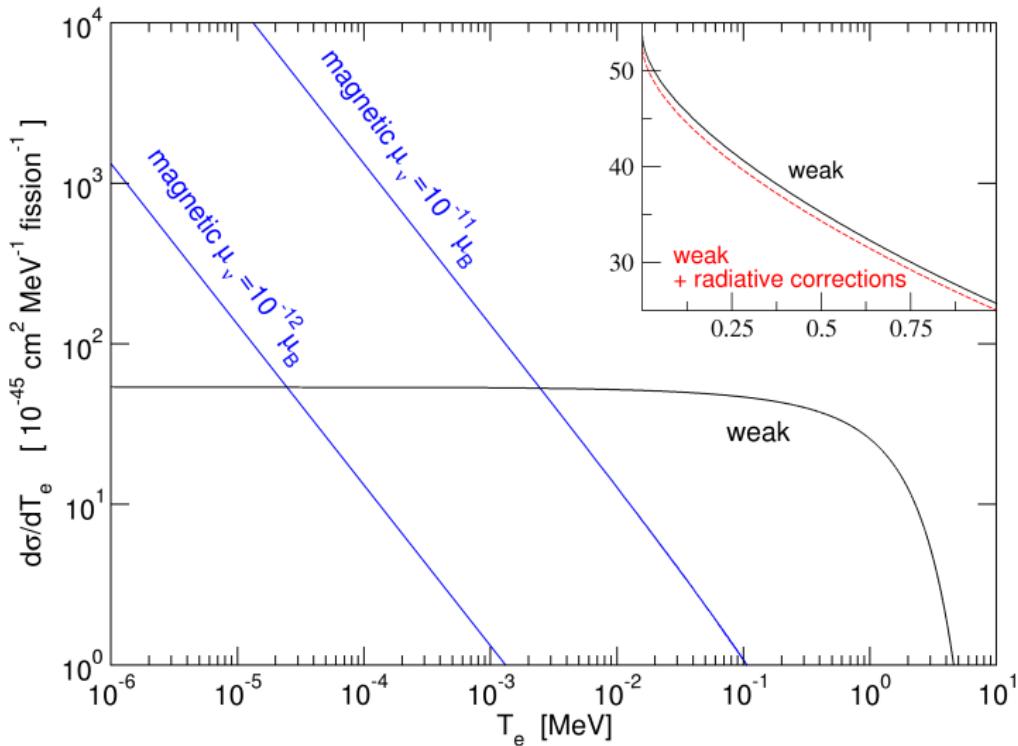
$$\begin{aligned} \mu_{kj}^M &\simeq -7.8 \times 10^{-23} \mu_B i (m_k + m_j) \sum_{\ell=e,\mu,\tau} \text{Im} [U_{\ell k}^* U_{\ell j}] \frac{m_\ell^2}{m_W^2} \\ \varepsilon_{kj}^M &\simeq 7.8 \times 10^{-23} \mu_B i (m_k - m_j) \sum_{\ell=e,\mu,\tau} \text{Re} [U_{\ell k}^* U_{\ell j}] \frac{m_\ell^2}{m_W^2} \end{aligned}$$

[Shrock, NPB 206 (1982) 359]

GIM-suppressed, but additional model-dependent contributions of the scalar sector can enhance the Majorana transition dipole moments

[Pal, Wolfenstein, PRD 25 (1982) 766; Barr, Freire, Zee, PRL 65 (1990) 2626; Pal, PRD 44 (1991) 2261]

$$\left(\frac{d\sigma_{\nu e^-}}{dT_e} \right)_{\text{mag}} = \frac{\pi \alpha^2}{m_e^2} \left(\frac{1}{T_e} - \frac{1}{E_\nu} \right) \left(\frac{\mu_\nu}{\mu_B} \right)^2$$



[Balantekin, Vassh, arXiv:1312.6858]

Method	Experiment	Limit [μ_B]	CL	Year
Reactor $\bar{\nu}_e e^-$	Krasnoyarsk	$\mu_{\nu_e} < 2.4 \times 10^{-10}$	90%	1992
	Rovno	$\mu_{\nu_e} < 1.9 \times 10^{-10}$	95%	1993
	MUNU	$\mu_{\nu_e} < 9 \times 10^{-11}$	90%	2005
	TEXONO	$\mu_{\nu_e} < 7.4 \times 10^{-11}$	90%	2006
	GEMMA	$\mu_{\nu_e} < 2.9 \times 10^{-11}$	90%	2012
Accelerator $\nu_e e^-$	LAMPF	$\mu_{\nu_e} < 1.1 \times 10^{-9}$	90%	1992
Accelerator $(\nu_\mu, \bar{\nu}_\mu) e^-$	BNL-E734	$\mu_{\nu_\mu} < 8.5 \times 10^{-10}$	90%	1990
	LAMPF	$\mu_{\nu_\mu} < 7.4 \times 10^{-10}$	90%	1992
	LSND	$\mu_{\nu_\mu} < 6.8 \times 10^{-10}$	90%	2001
Accelerator $(\nu_\tau, \bar{\nu}_\tau) e^-$	DONUT	$\mu_{\nu_\tau} < 3.9 \times 10^{-7}$	90%	2001
Solar $\nu_e e^-$	Super-Kamiokande	$\mu_S(E_\nu \gtrsim 5 \text{ MeV}) < 1.1 \times 10^{-10}$	90%	2004
	Borexino	$\mu_S(E_\nu \lesssim 1 \text{ MeV}) < 2.8 \times 10^{-11}$	90%	2017

[see the review CG, Studenikin, arXiv:1403.6344]

- ▶ Gap of about 8 orders of magnitude between the experimental limits and the $\lesssim 10^{-19} \mu_B$ prediction of the minimal Standard Model extensions.
- ▶ $\mu_\nu \gg 10^{-19} \mu_B$ discovery \Rightarrow non-minimal new physics beyond the SM.
- ▶ Neutrino spin-flavor precession in a magnetic field

[Lim, Marciano, PRD 37 (1988) 1368; Akhmedov, PLB 213 (1988) 64]

- Neutrino magnetic (and electric) moment contributions to CE ν NS:

$$\frac{d\sigma_{\nu_\ell \text{-} \mathcal{N}}}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi} \left(1 - \frac{MT}{2E_\nu^2}\right) [g_V^n N F_N(|\vec{q}|) + g_V^p Z F_Z(|\vec{q}|)]^2 \\ + \frac{\pi\alpha^2}{m_e^2} \left(\frac{1}{T} - \frac{1}{E_\nu}\right) Z^2 F_Z^2(|\vec{q}|) \frac{\mu_{\nu_\ell}^2}{\mu_B^2}$$

- The magnetic moment interaction adds **incoherently** to the weak interaction because it **flips helicity**.
- Effective magnetic moment of flavor neutrinos:

$$\mu_{\nu_\ell}^2 = \sum_j \left| \sum_k U_{\ell k}^* (\mu_{jk} - i\varepsilon_{jk}) \right|^2$$

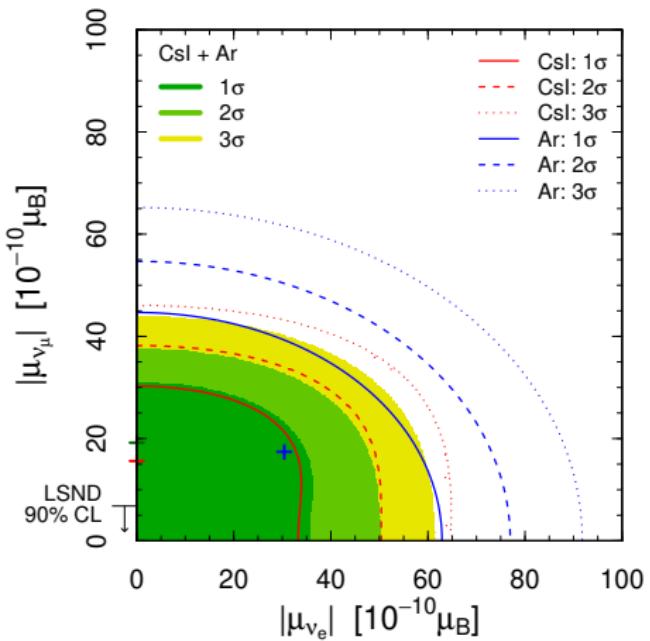
[Grimus, Stockinger, hep-ph/9708279;
Beacom, Vogel, hep-ph/9907383;
CG, Studenikin, arXiv:1403.6344]

- Neglecting the electric moments:

$$\mu_{\nu_\ell}^2 = \sum_{i,j} U_{\ell i} (\mu^2)_{ij} U_{\ell j}^* \quad \text{with} \quad (\mu^2)_{ij} = \sum_k \mu_{ik} \mu_{kj}$$

COHERENT constraints on ν magnetic moments

[Cadeddu, Dordei, CG, Li, Picciano, Zhang, arXiv:2005.01645]



- The sensitivity to $|\mu_{\nu_e}|$ is not competitive with that of reactor experiments:

$$|\mu_{\nu_e}| < 2.9 \times 10^{-11} \mu_B \quad (90\% \text{ CL})$$

[GEMMA, AHEP 2012 (2012) 350150]

- The constraint on $|\mu_{\nu_\mu}|$ is not too far from the best current laboratory limit:

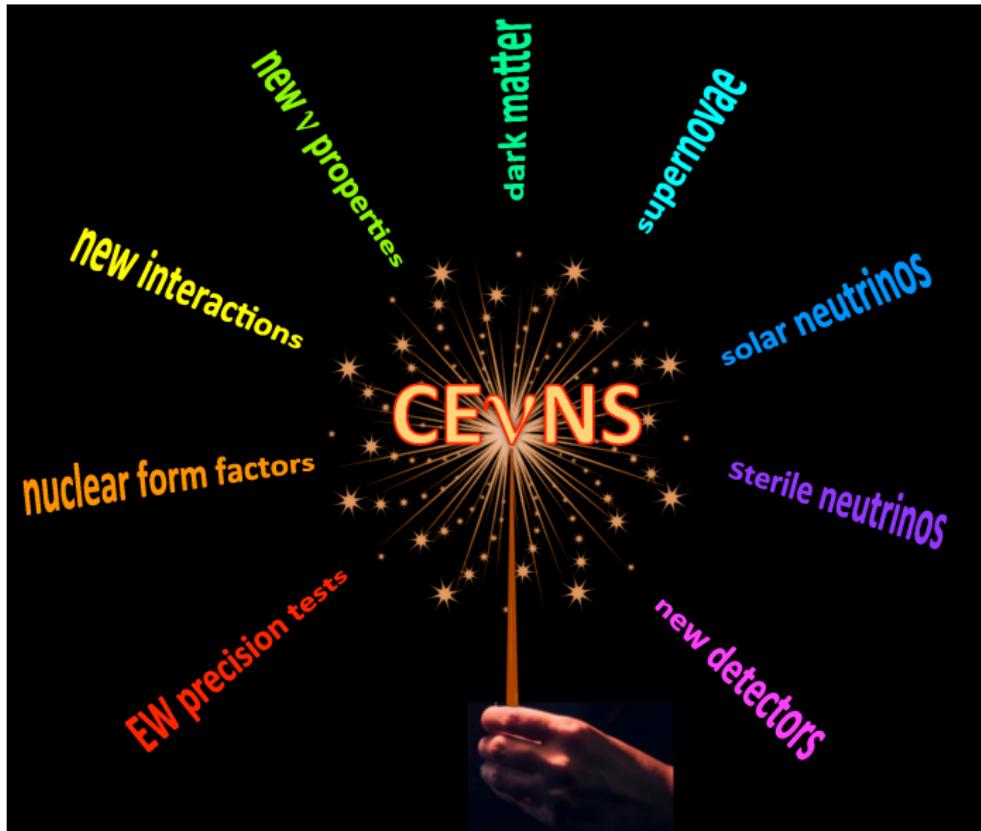
$$|\mu_{\nu_\mu}| < 6.8 \times 10^{-10} \mu_B \quad (90\% \text{ CL})$$

[LSND, hep-ex/0101039]

[see also: Papoulias, Kosmas, arXiv:1711.09773; Papoulias, arXiv:1907.11644; Khan, Rodejohann, arXiv:1907.12444;
Cadeddu, Dordei, CG, Li, Zhang, arXiv:1908.06045;
Miranda, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, arXiv:2003.12050]

[future prospects: Miranda, Papoulias, Tortola, Valle, arXiv:1905.03750]

Conclusions



[E. Lisi, Neutrino 2018]