CEvNS phenomenology with reactors

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Outline

1. Non-standard interactions
2. Testing the Standard Model with CEνNS
3. Neutrino electromagnetic properties
4. Sterile neutrinos
5. Conclusions

CEνNS experiments at reactors

	Dresden II	Ge	
	CONUS	HPGe	
	νGEN	HPGe	
	TEXONO	HPGe	
	CONNIE	Si	
	vIOLETA	Si	

	RED-100	Xe	
	RELICS	Xe	
	SBC	Ar	
	NEON	NaI(Tl)	
	MINER	Si-Ge	
	RICOCHET	Si-Ge	
	NUCLEUS	$CaWO_4$	

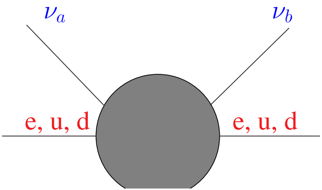
Non-standard interactions (NSI)

Non-standard interactions NSI

Most extensions of the SM predict neutral current non-standard interactions (NSI) of neutrinos which can be either flavor preserving (FD or NU) or flavor-changing (FC).

NSI effective Lagragian form:

$$\mathcal{L}_{eff}^{NSI} = -\sum_{\alpha\beta fP} \varepsilon_{\alpha\beta}^{fP} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f}\gamma^\rho P f)$$



Here $\alpha, \beta = e, \mu, \tau$; $f = e, u, d$; $P = L, R$; $L = (1-\gamma_5)/2$; $R = (1+\gamma_5)/2$

NSI degeneracies

$$H_{\rm NSI} = \sqrt{2} G_F N_f \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix} .$$

Mixing angle in matter + NSI

$$\tan 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E}\right) \sin 2\theta + 2\sqrt{2} G_F \varepsilon N_d}{\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}\, G_F\, N_e + \sqrt{2}\, G_F \varepsilon'\, N_d} .$$

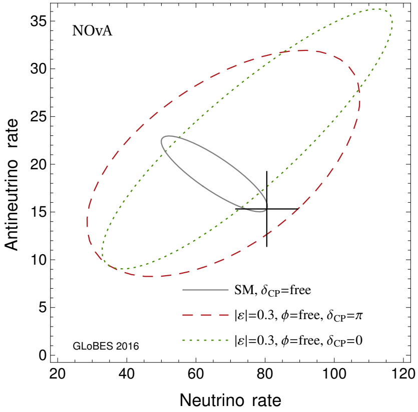
Resonance $\quad \frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}\, G_F\, N_e + \sqrt{2}\, G_F\, \varepsilon'\, N_d = 0 .$

$$\varepsilon' > \frac{N_e}{N_d}$$

OGM, M. Tortola, J. W. F. Valle, JHEP 0610:008 (2006) hep-ph/0406280

P. Coloma, T. Schwetz, Phys.Rev. D94 (2016) 055005

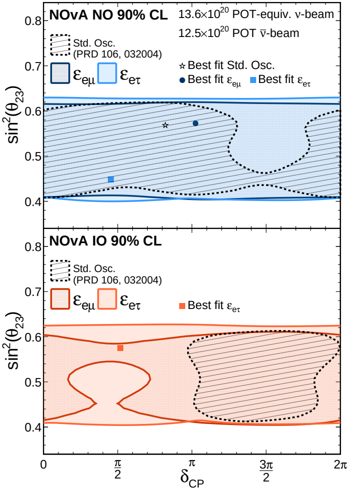
NSI degeneracies



P. Huber, D. V. Forero Phys.Rev.Lett. 117 (2016) no.3, 031801

see OGM, Tortola, Valle PRL 117 061804 for the case of non-unitarity

NSI degeneracies



NOvA coll. arXiv:2403.07266

see also S. S. Chatterjee and A. Palazzo, Phys. Rev. Lett. 126, 051802 (2021), 2008.04161
see also P. B. Denton, J. Gehrlein, and R. Pestes, Phys. Rev. Lett. 126, 051801 (2021), 2008.01110

NSI and CEνNS

$$G_V = \left[\left(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}\right) Z + \left(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}\right) N\right] F_{nucl}^V(Q^2) \quad (1)$$

$$\begin{aligned}\frac{d\sigma}{dT}(E_\nu, T) &= \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \\ &\times \left\{\left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})\right]^2 + \right. \\ &+ \left.\sum_{\alpha=\mu,\tau}\left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV})\right]^2\right\}\end{aligned}$$

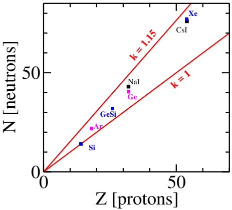
J. Barranco, OGM, T. I. Rashba JHEP 0512 (2005) 021

K. Scholberg PRD **73** (2007) 033005

$$\left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})\right]^2 = \left[Zg_V^p + Ng_V^n\right]^2$$

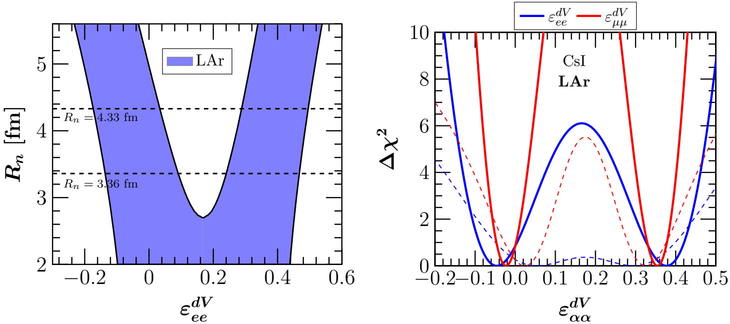
$$\varepsilon_{ee}^{uV}(2Z+N) + \varepsilon_{ee}^{dV}(Z+2N) = \text{const}\,.$$

Solution: take two targets with **maximally different** $k = (A+N)/(A+Z)$



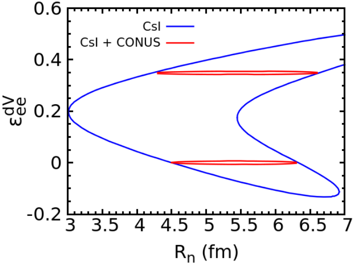
Nucleus	N/Z
Si	1.0
Ar	1.22
Ge	1.25
I	1.40
CS	1.42
Xe	1.44

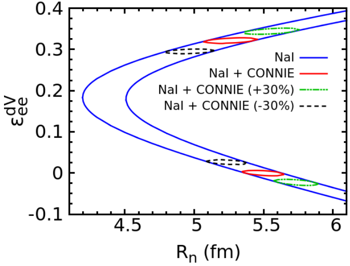
NSI vs R_n



OGM, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, JHEP 05(2020)130 2003.12050

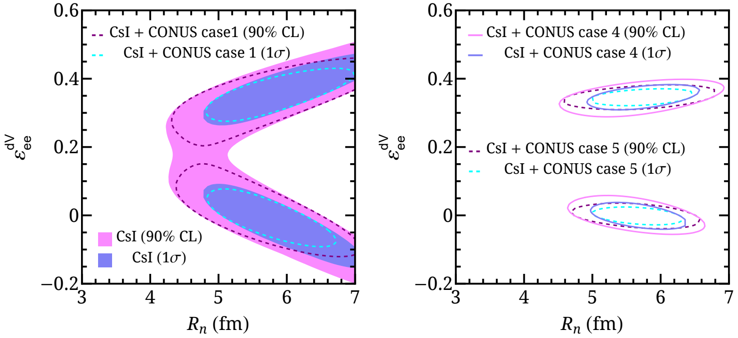
NSI vs R_n





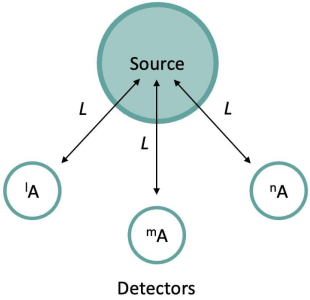
Canas, Garces, OGM, Parada, Sanchez Garcia Phys. Rev. D **101** (2020) 035012

NSI vs R_n



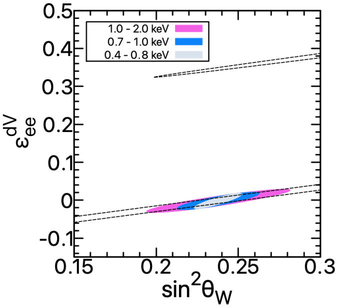
Rossi, Sanchez Garcia, Tortola Phys.Rev.D 109 (2024) 9, 095044

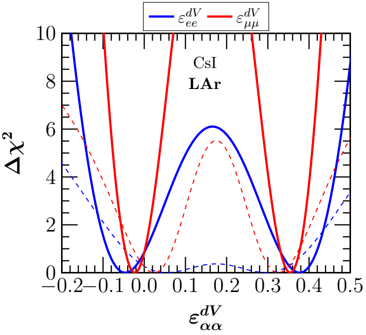
Using isotopes of the same element



Galindo-Uribarri, OGM, Sanchez Garcia Phys Rev D **105** 033001 (2022) ArXiv:2011.10230

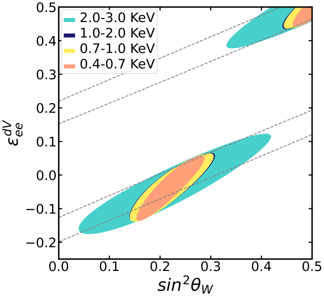
Using three germanium isotopes

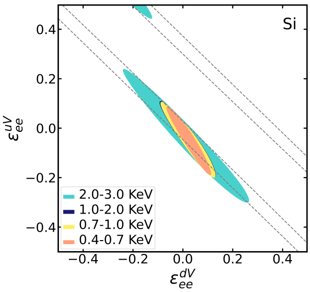




Galindo-Uribarri, OGM, Sanchez Garcia Phys Rev D **105** 033001 (2022) ArXiv:2011.10230

Using two silicon isotopes

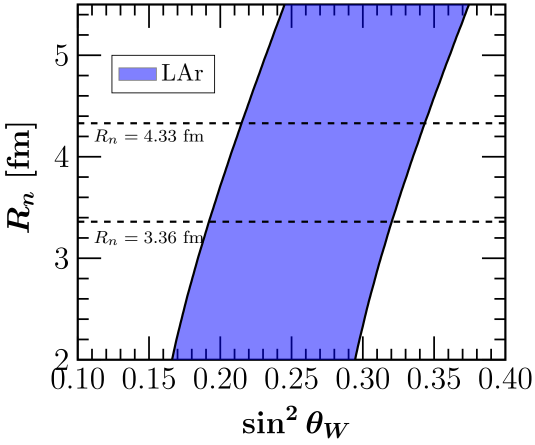




Laura Duque, work in progress

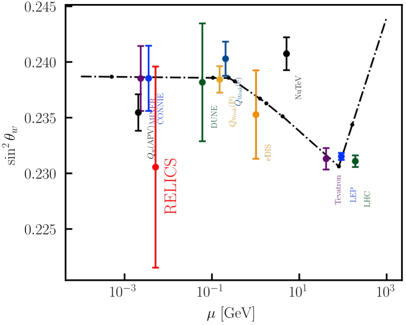
Testing Standard Model with Ceνns.

$\sin\theta_W$ vs R_n

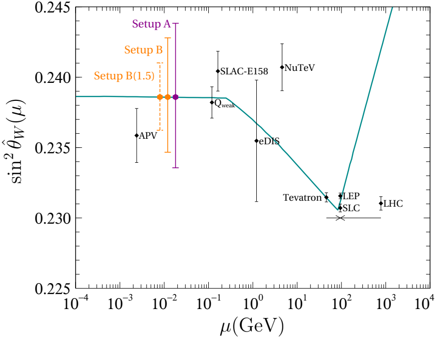


OGM, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, JHEP 05(2020)130 2003.12050

Future sensitivity for $\sin^2\theta_W$



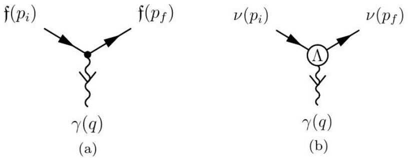
RELICS Coll. arXiv:2405.05554



SBC Coll. Flores et. al. Phys. Rev. D103 (2021) L091301

Electromagnetic interactions

$$\mathcal{H}_{em}^{f}(x) = j_{\mu}^{f}(x)A^{\mu}(x) = \mathfrak{q}_f \bar{f}(x)\gamma_{\mu} f(x)A^{\mu}(x),$$



* For neutrinos: $q_{\nu} = 0 \rightarrow$ there are no electromagnetic interactions at tree level.

* However, such interactions can arise from loop diagrams at higher order in the perturbative expansion.

$$\mathcal{H}_{eff}(x) = j_{\mu}^{eff}(x)A^{\mu}(x) = \sum_{k,j=1}^{3} \overline{\nu_k}(x)\Lambda_{\mu}^{kj}\nu_j(x)A^{\mu}(x)$$

C. Giunti, A. Studenikin RMP **87** (2015) 531

Limits on the effective NMM from reactor and accelerator data

Experiment	Bounds	
CONUS	$\mu_{\bar{\nu}_e} \leq 7.5 \times 10^{-11} \mu_B$	CONUS Eur. Phys. J. **82** (2022) 813
Dresden II	$\mu_{\bar{\nu}_e} \leq 2.13 \times 10^{-10} \mu_B$	Atzori Corona et al JHEP09(2022) 164
COHERENT	$\mu_{\nu_e} \leq 3.8 \times 10^{-9} \mu_B$	de Romeri et al JHEP 04(2023) 035
COHERENT	$\mu_{\nu_\mu} \leq 2.6 \times 10^{-9} \mu_B$	de Romeri et al JHEP 04(2023) 035
GEMMA	$\mu_{\bar{\nu}_e} \leq 2.9 \times 10^{-11} \mu_B$	GEMMA Adv.High Energy Phys. 2012 (2012) 350150
MUNU	$\mu_{\bar{\nu}_e} \leq 9 \times 10^{-11} \mu_B$	MUNU Phys.Lett.B 615 (2005) 153
TEXONO	$\mu_{\bar{\nu}_e} \leq 2.2 \times 10^{-10} \mu_B$	TEXONO Phys.Rev.D 81 (2010) 072001
TEXONO	$\mu_{\bar{\nu}_e} \leq 7.4 \times 10^{-11} \mu_B$	TEXONO Phys Rev. D75 012001 (2007)
LUX-ZEPLIN	$\mu_{\bar{\nu}_\odot} \leq 1.1 \times 10^{-11} \mu_B$	Atzori Corona et al Phys Rev. D107 (2023) 053001

The effective neutrino magnetic moment

The effective neutrino magnetic moment can be described with more detail in a phenomenological approach in which the NMM is described by a complex matrix $\lambda = \mu - id$ ($\tilde{\lambda}$) in the flavor (mass) basis, that for the Majorana case takes the form

$$\lambda = \begin{pmatrix} 0 & \Lambda_\tau & -\Lambda_\mu \\ -\Lambda_\tau & 0 & \Lambda_e \\ \Lambda_\mu & -\Lambda_e & 0 \end{pmatrix}, \qquad \tilde{\lambda} = \begin{pmatrix} 0 & \Lambda_3 & -\Lambda_2 \\ -\Lambda_3 & 0 & \Lambda_1 \\ \Lambda_2 & -\Lambda_1 & 0 \end{pmatrix},$$

where $\lambda_{\alpha\beta} = \varepsilon_{\alpha\beta\gamma}\Lambda_\gamma$.

The transition magnetic moments Λ_α and Λ_i are complex parameters:

$$\Lambda_\alpha = |\Lambda_\alpha| e^{i\zeta_\alpha}, \qquad \Lambda_i = |\Lambda_i| e^{i\zeta_i}.$$

W. Grimus, T. Schwetz, NPB **587** 45 (2000)

Neutrino electron scattering

$$\lambda\lambda^\dagger = \begin{pmatrix} |\Lambda_\mu|^2 + |\Lambda_\tau|^2 & -\Lambda_\mu\Lambda_e^* & -\Lambda_\tau\Lambda_3^* \\ -\Lambda_e\Lambda_\mu^* & |\Lambda_e|^2 + |\Lambda_\tau|^2 & -\Lambda_\tau\Lambda_\mu^* \\ -\Lambda_e\Lambda_\tau^* & -\Lambda_\mu\Lambda_\tau^* & |\Lambda_e|^2 + |\Lambda_\mu|^2 \end{pmatrix}$$

W. Grimus, T. Schwetz, NPB **587** 45 (2000)

Effective NMM at reactor experiments.

In the mass basis

$$(\mu_\nu^M)^2 = \tilde{a}_-^\dagger \tilde{\lambda}^\dagger \tilde{\lambda} \tilde{a}_- + \tilde{a}_+^\dagger \tilde{\lambda} \tilde{\lambda}^\dagger \tilde{a}_+,$$

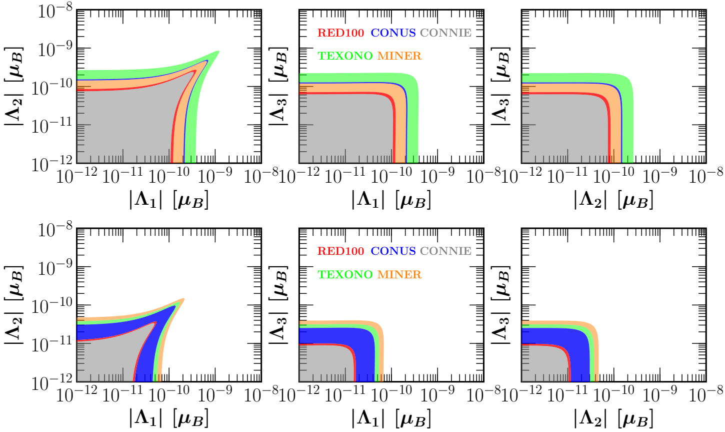
where $\tilde{a}_- = U^\dagger a_- \to \tilde{a}_-^\dagger = a_-^\dagger U, \qquad \tilde{a}_+ = U^T a_+ \to \tilde{a}_+^\dagger = a_+^\dagger U^*.$

$$\begin{aligned}(\mu_R^M)^2 &= |\Lambda|^2 - s_{12}^2 c_{13}^2 |\Lambda_2|^2 - c_{12}^2 c_{13}^2 |\Lambda_1|^2 - s_{13}^2 |\Lambda_3|^2 \\ &- 2 s_{12} c_{12} c_{13}^2 |\Lambda_1||\Lambda_2| \cos\delta_{12} - 2 c_{12} c_{13} s_{13} |\Lambda_1||\Lambda_3| \cos\delta_{13} \\ &- 2 s_{12} c_{13} s_{13} |\Lambda_2||\Lambda_3| \cos\delta_{23}, \qquad \theta_{13} \neq 0\end{aligned}$$

$\delta_{12} = \xi_3$, $\delta_{23} = \xi_2 - \delta$, and $\delta_{13} = \delta_{12} - \delta_{23}$.

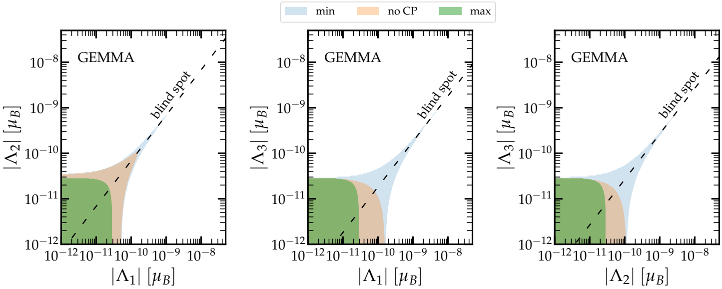
Canas, OGM, Parada, Tortola, Valle PLB **753** 191 (2016).

Effective NMM at reactor experiments.



[OGM, Papoulias, Tórtola, Valle, JHEP 1907 (2019) 103]

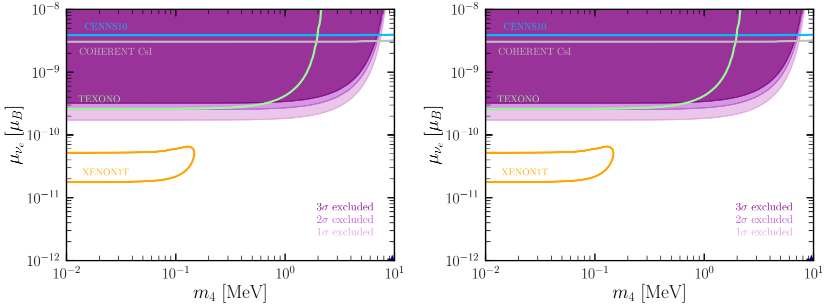
Effective NMM at reactor experiments.



Aristizabal Sierra, O. G. Miranda, D. K. Papoulias, G. Sanchez Garcia
Phys.Rev.D 105 (2022) 3, 035027

A transition into a massive neutrino state

Sterile neutrino transition magnetic moment



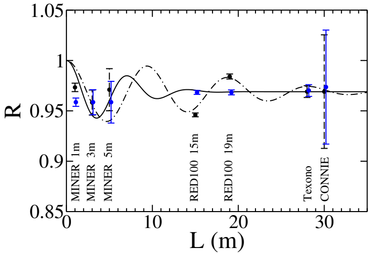
Aristizabal Sierra, De Romeri, Papoulias JHEP 09(2022) 076 arXiv:2203.02414

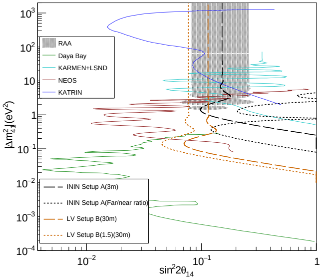
OGM, Papoulias, Sanders, Tórtola, Valle, JHEP 12(2021) 191 arXiv:2109.09545

P D Bolton, F F Deppisch, K Fridell, et al Phys.Rev.D **106** (2022) 035036 arXiv:2110.02233

Sterile neutrino and CEνNS

Sterile neutrino

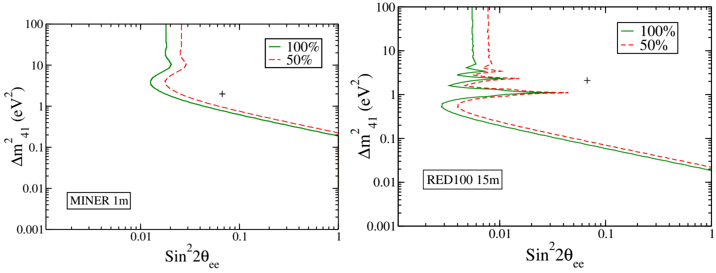




Canas, Garces, OGM, Parada, Phys. Lett. B **776** 451 (2018)

E. Alfonso-Pita, L. J. Flores, E. Peinado, E. Vázquez-Jáuregui Phys.Rev.D 105 (2022) 113005 arXiv:2203.05982

Sterile neutrino



Canas, Garces, OGM, Parada, Phys. Lett. B **776** 451 (2018)

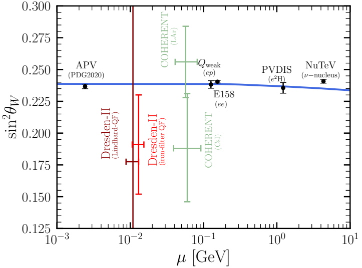
Conclusions

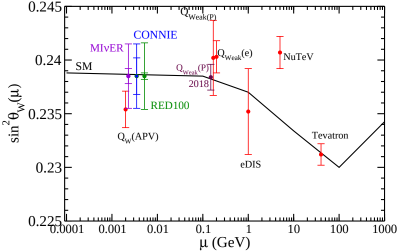
- ✓ COHERENT measurements inaugurated a new period where different experiments will measure CEνNS reaction with good accuracy.
- ✓ Different experiments will complement each other to have better a better knowledge on different aspects on neutrino physics, particle physics, and nuclear physics.
- ✓ Reactor measurements will be of great interest as they are complementary to those comming from π-DAR neutrino sources

Thanks

Work supported by CONAHCYT grant 23238

Future sensitivity for $\sin^2 \theta_W$

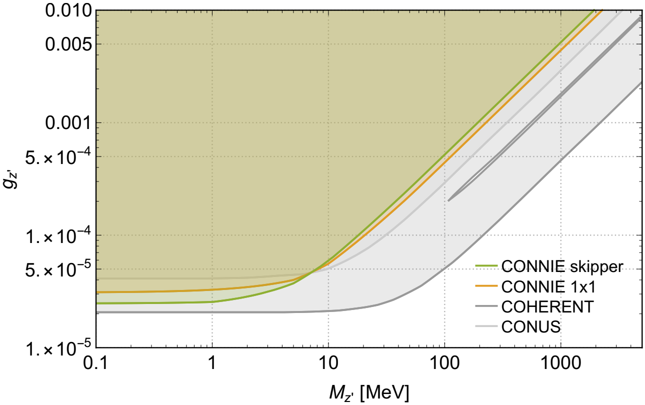




Aristizabal Sierra, De Romeri, Papoulias JHEP 09(2022) 076 arXiv:2203.02414

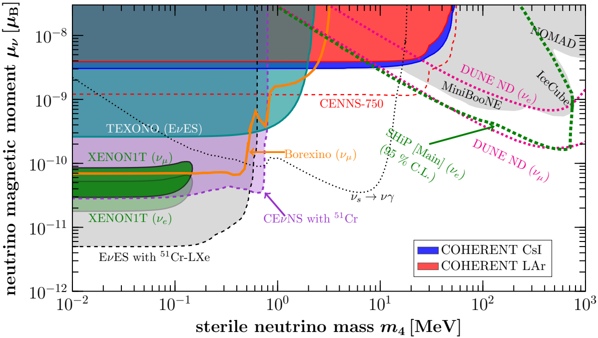
Canas, Garces, OGM, Parada Phys. Lett. B784 (2018) 159 arXiv:1806.01310

Light mediators



CONNIE arXiv:2403.15976

Sterile neutrino transition magnetic moment



OGM, Papoulias, Sanders, Tórtola, Valle, JHEP 12(2021) 191 arXiv:2109.09545

See also P D Bolton, F F Deppisch, K Fridell, et al Phys.Rev.D **106** (2022) 035036 arXiv:2110.02233