Studying neutrino physics in the low energy regime, the CEvNS case

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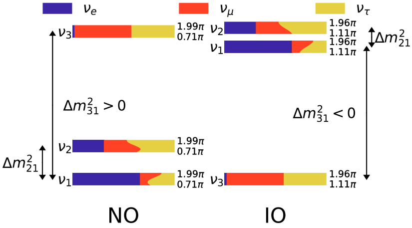
Outline

1. Introduction
2. Some new physics scenarios (NSI)
3. Coherent Elastic Neutrino-Nucleus Scattering
4. Conclusions

Introduction



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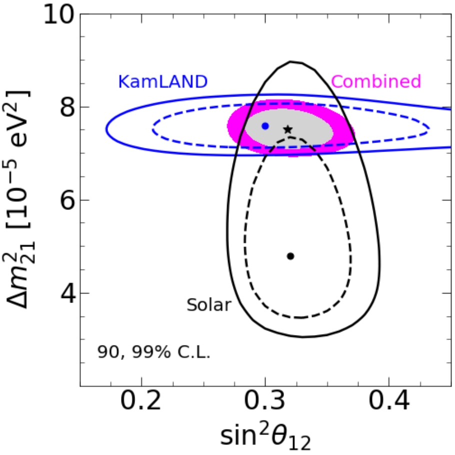

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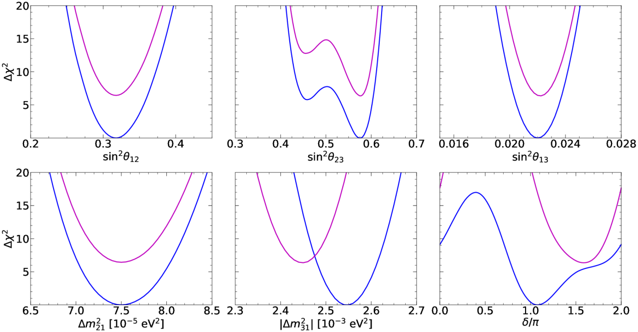
Introduction



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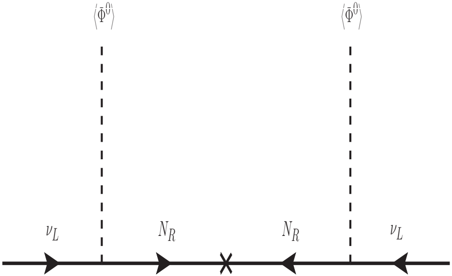
Why to go beyond the Standard Model?

Neutral heavy leptons and seesaw schemes



Minkowski 1977, Gell-Mann Ramond Slanski 1979, Yanagida 1979, Mohapatra Senjanovic 80, Schechter Valle 1980.

Neutral heavy leptons and seesaw schemes

Massive neutrinos and physics beyond the Standard Model.

$$\begin{bmatrix} M_L & D \\ D^T & M_R \end{bmatrix}$$

Minkowski; Gell-mann, Ramond, Slansky; Yanagida; Mohapatra, Senjanovic; Schechter, Valle

$$M_{\nu\,\mathrm{eff}} = M_L - DM_R^{-1}D^T$$

$$K = (K_L, K_H)$$

$$\mathcal{L} = \frac{ig'}{2\sin\theta_W} Z_\mu \bar{\nu}_L \gamma_\mu K^\dagger K \nu_L \,.$$

Seesaw schemes

$$\begin{bmatrix} M_L & D \\ D^T & M_R \end{bmatrix}$$

$$\begin{bmatrix} 0 & D & 0 \\ D^T & 0 & M \\ 0 & M^T & \mu \end{bmatrix}$$

$\frac{n(n-1)}{2}$ mixing angles

$\frac{(n-1)(n-2)}{2}$ phases

Minkowski 1977, Gell-Mann Ramond Slanski 1979, Yanagida 1979, Mohapatra Senjanovic 80, Schechter Valle 1980.

Mixing matrix

$$U^{NP} = \omega_{n-1\,n}\omega_{n-2\,n}\dots\omega_{2\,n}\omega_{1\,n}\omega_{n-2\,n-1}\dots\omega_{2\,n-1}\omega_{1\,n-1}\dots\omega_{3\,4}\,\omega_{2\,4}\omega_{1\,4}\,,$$

$$U^{3\times 3} = \omega_{2\,3}\,\omega_{1\,3}\,\omega_{1\,2}\,.$$

$$\omega_{13} = \begin{pmatrix} c_{13} & 0 & e^{-i\phi_{13}}s_{13} & \\ 0 & 1 & 0 & \vdots \\ -e^{i\phi_{13}}s_{13} & 0 & c_{13} & \\ & \dots & & 1 \end{pmatrix}$$

with $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, $\eta_{ij} = e^{-i\phi_{ij}}\,\sin\theta_{ij}$, and $\bar{\eta}_{ij} = -e^{i\phi_{ij}}\,\sin\theta_{ij}$

Mixing matrix

$$U_{\alpha i}^{n\times n} = \begin{pmatrix} N & S \\ V & T \end{pmatrix}$$

$$NN^\dagger + SS^\dagger = I,$$

$$N^\dagger N + V^\dagger V = I.$$

Mixing matrix

$$N = N^{NP}\, U^{3\times 3} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times 3}$$

$$\begin{aligned} \alpha_{11} &= c_{1\,n}\, c_{1 n-1} c_{1\,n-2} \ldots c_{14}, \\ \alpha_{22} &= c_{2\,n}\, c_{2 n-1} c_{2\,n-2} \ldots c_{24}, \\ \alpha_{33} &= c_{3\,n}\, c_{3 n-1} c_{3\,n-2} \ldots c_{34}, \end{aligned}$$

Escrihuela, Forero, OGM, Tortola, Valle **PRD 93** 053009 (2015)

Extended gauge models

$SU(2)_L \otimes U(1)_Y \otimes SU(2)_R \otimes U(1)'_Y$ String inspired theories

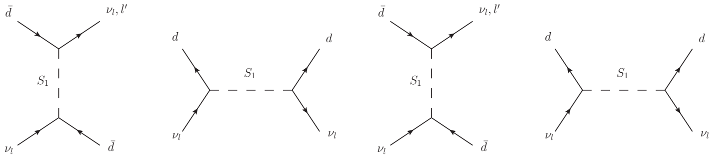
$$\mathcal{L}_{\nu N}^{NC} = -\frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left[\bar{\nu}_e \gamma^\mu (1-\gamma^5)\nu_e\right] \left\{\varepsilon^{qL}\left[\bar{q}\gamma_\mu(1-\gamma^5)q\right] + \varepsilon^{qR}\left[\bar{q}\gamma_\mu(1+\gamma^5)q\right]\right\},$$

$$\begin{aligned}
\varepsilon^{uL} &= -4\frac{M_Z^2}{M_{Z'}^2}\sin^2\theta_W \rho_{\nu N}^{NC}\left(\frac{\cos\beta}{\sqrt{24}} - \frac{\sin\beta}{3}\sqrt{\frac{5}{8}}\right)\left(\frac{3\cos\beta}{2\sqrt{24}} + \frac{\sin\beta}{6}\sqrt{\frac{5}{8}}\right) \\
\varepsilon^{dR} &= -8\frac{M_Z^2}{M_{Z'}^2}\sin^2\theta_W \rho_{\nu N}^{NC}\left(\frac{3\cos\beta}{2\sqrt{24}} + \frac{\sin\beta}{6}\sqrt{\frac{5}{8}}\right)^2, \\
\varepsilon^{dL} &= \varepsilon^{uL} = -\varepsilon^{uR},
\end{aligned} \quad (1)$$

Leptoquarks

$$\mathcal{L} \supset + y_{3\,ij}^{LL} \bar{Q}_L^{C\,i,a} \epsilon^{ab} (\tau^k S_3^k)^{bc} L_L^{j,c} - y_{2\,ij}^{RL} \bar{u}_R^i R_2^a \epsilon^{ab} L_L^{j,b} -$$
$$- \tilde{y}_{2\,ij}^{RL} \bar{d}_R^i \tilde{R}_2^a \epsilon^{ab} L_L^{j,b} + y_{1\,ij}^{LL} \bar{Q}_L^{C\,i,a} S_1 \epsilon^{ab} L_L^{j,b} + + \ldots$$

Scalar leptoquarks



See e.g. I. Dorsner et. al. Phys. Rept. 641 (2016) 1

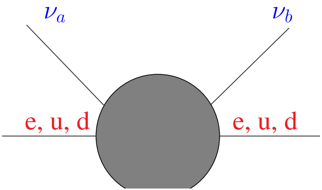
Non-standard interactions (NSI)

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).

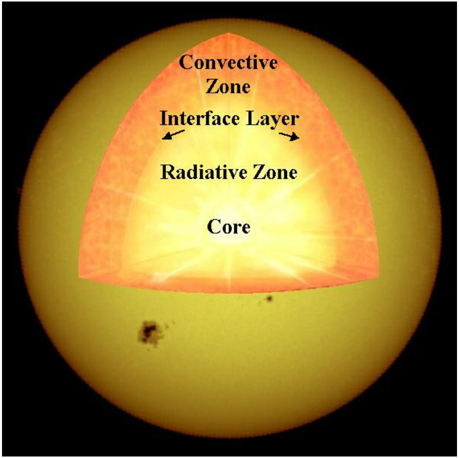
NSI effective Lagragian form:

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



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

NSI in Solar neutrino data



Neutrino oscillations

Massive ν's:
the neutrino mass states ν_i (i=1,2,3) are different from the flavor states (weak interaction) ν_α (e, μ, τ)

$$|\nu_\alpha\rangle = \sum_i U_{ai} |\nu_i\rangle$$

$$\text{Time: } t = 0 \quad |\nu_\alpha(x, t=0)\rangle = \sum_i U_{\alpha i} e^{ip_i x} |\nu_i\rangle$$

$$\text{Time: } t > 0 \quad |\nu_\alpha(x, t)\rangle = \sum_i U_{\alpha i} e^{ip_i x - iE_i t} |\nu_i\rangle$$

$$\text{Ultrarelativistic } \nu\text{-s } m_i \ll p_i \qquad E_i = \sqrt{m_i^2 + p_i^2} \approx p_i + \frac{m_i^2}{2p_i}$$

$$\text{and } x \approx t \quad |\nu_\alpha(x, t)\rangle = \sum_i U_{\alpha i} e^{-i\frac{m_i^2}{2p_i} t} |\nu_i\rangle$$

Neutrino oscillations

$$
\begin{pmatrix}
c_{12}c_{13} & s_{12}c_{13} & s_{13}\,e^{-i\delta} \\
-(s_{12}c_{23} + c_{12}s_{23}s_{13}\,e^{i\delta}) & (c_{12}c_{23} - s_{12}s_{23}s_{13}\,e^{i\delta}) & s_{23}c_{13} \\
(s_{12}s_{23} - c_{12}c_{23}s_{13}\,e^{i\delta}) & -(c_{12}s_{23} + s_{12}c_{23}s_{13}\,e^{i\delta}) & c_{23}c_{13}
\end{pmatrix}
$$

$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta) &= \left| \sum_j U^*_{\alpha j} U_{\beta j}\, e^{-i\frac{m_j^2}{2E}L} \right|^2 = \\
\delta_{\alpha\beta} &- 4\sum_{i>j} \Re\left\{ U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j} \right\} \sin^2\left(\frac{\Delta m^2_{ij}}{4E} L \right) \\
&+ 2\sum_{i>j} \Im\left\{ U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j} \right\} \sin\left(\frac{\Delta m^2_{ij}}{2E} L \right)
\end{aligned}
$$

Neutrino oscillations

Wolfenstein 1978

- Neutral currents (NC): Z_0
- Charged currents (CC): $W_\pm$

$$V_e = \sqrt{2}\, G_F \left(N_e - \frac{N_n}{2} \right) , \qquad V_\mu = V_\tau = \sqrt{2}\, G_F \left(-\frac{N_n}{2} \right) .$$

Evolution ecuation

$$i \frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}\, G_F N_e & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} .$$

Constant density case

Conversion probability $\nu_e \leftrightarrow \nu_\mu$:

$$P(\nu_e \to \nu_\mu;\, L) = \sin^2 2\theta_m\, \sin^2\left(\pi \frac{L}{l_m}\right)\,,$$

Matter mixing angle

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

Resonance $\quad \sqrt{2}\, G_F\, N_e = \dfrac{\Delta m^2}{2E}\cos 2\theta$

Wolfenstein 1978, Mikheev & Smirnov 1985

Non Standard Interactions in the Sun

$$H_{\rm NSI} = \sqrt{2} G_F N_f \left(\begin{array}{cc} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{array} \right) .$$

Mixing angle in matter + NSI

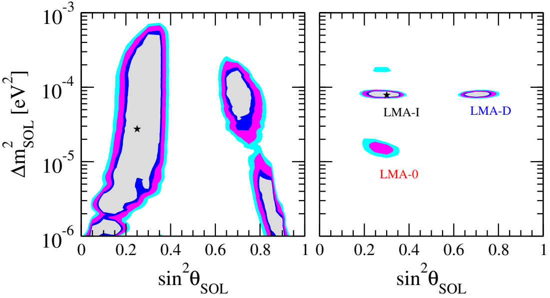
$$\tan 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E}\right) \sin 2\theta + 2\sqrt{2} G_F \varepsilon N_d}{\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2}\, G_F\, N_e + \sqrt{2}\, G_F \varepsilon'\, N_d} .$$

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

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

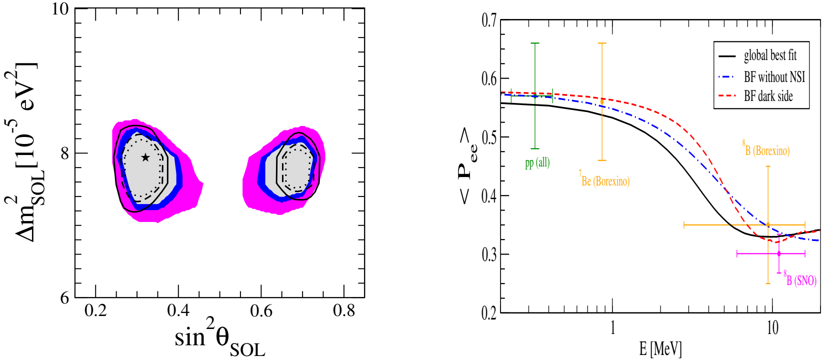
OGM, M. Tortola, J. W. F. Valle, JHEP 0610:008 (2006) hep-ph/0406280

Solar + KamLAND without and with NSI



OGM, M. Tortola, J. W. F. Valle, JHEP 0610:008 (2006)

LMA-Dark solution



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

F. J. Escrihuela, OGM, M. Tortola, J. W. F. Valle, Phys. Rev. D **80** 105009 (2009)

M. C. Gonzalez-Garcia, M. Maltoni, JHEP **1309** 152 (2013)

M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz Nucl. Phys. B **908** 199 (2016)

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

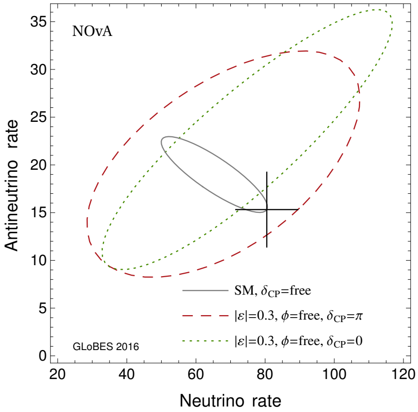
NSI degeneracy

$$
\begin{aligned}
\varepsilon_{ee} \rightarrow &\quad - \quad \varepsilon_{ee} - 2 \\
\varepsilon_{\alpha\beta} \rightarrow &\quad - \quad \varepsilon^*_{\alpha\beta} \quad (\alpha\beta \neq ee)
\end{aligned}
$$

$$
H_{mat} \rightarrow \quad - \quad H^*_{mat}
$$

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

CP violation degeneracy



P. Huber, D. V. Forero Phys.Rev. D94 (2016) 055005

NSI and CP violation

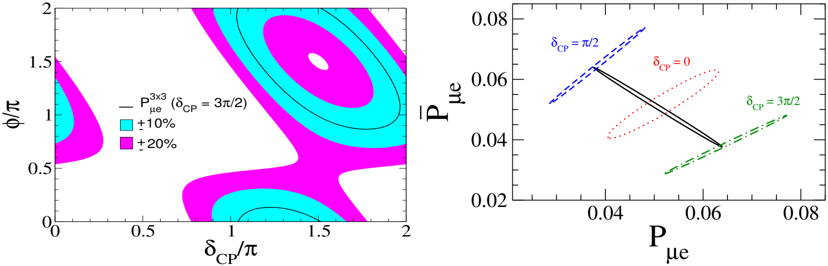
$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P^{3\times 3}_{\mu e} + \alpha^2_{11}\alpha_{22}|\alpha_{21}|P^I_{\mu e} + \alpha^2_{11}|\alpha_{21}|^2,$$

$$\begin{aligned} P^I_{\mu e} &= -2\left[\sin(2\theta_{13})\sin\theta_{23}\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{31}L}{4E_\nu}+\phi+\delta_{CP}\right)\right] \\ &- \cos\theta_{13}\cos\theta_{23}\sin(2\theta_{12})\sin\left(\frac{\Delta m^2_{21}L}{2E_\nu}\right)\sin(\phi), \end{aligned}$$

with $-\delta_{CP} = \phi_{12} - \phi_{13} + \phi_{23}$ and $\phi = \mathrm{I}_{\mathrm{NP}} = \phi_{12} - \mathrm{Arg}(\alpha_{21})$.

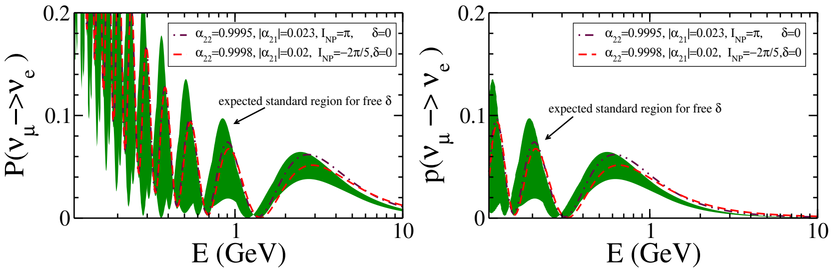
M. A. Tortola, OGM, J W F Valle, Phys.Rev.Lett. **117** (2016) 061804

NSI and CP violation



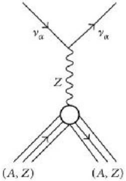
M. A. Tortola, OGM, J W F Valle, Phys.Rev.Lett. **117** (2016) 061804

NSI and CP violation



OGM, J W F Valle, Nucl. Phys. **B908** (2016) 436

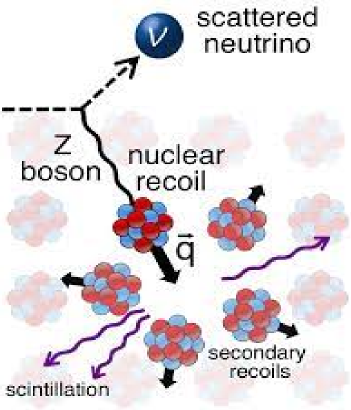
Coherent elastic neutrino-nucleus scattering

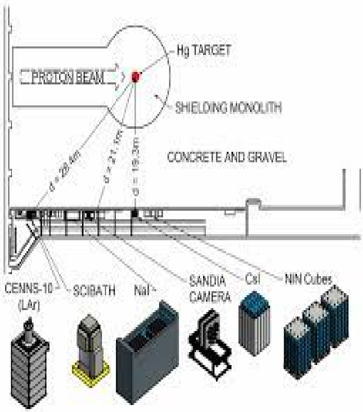


$$\left(\frac{d\sigma}{dT}\right) \approx \frac{G_F^2 M}{4\pi}\left[1 - \frac{MT}{2E_\nu^2}\right]\left[N F_N(q^2) + Z(1 - 4\sin^2\theta_W) F_Z(q^2)\right]^2$$

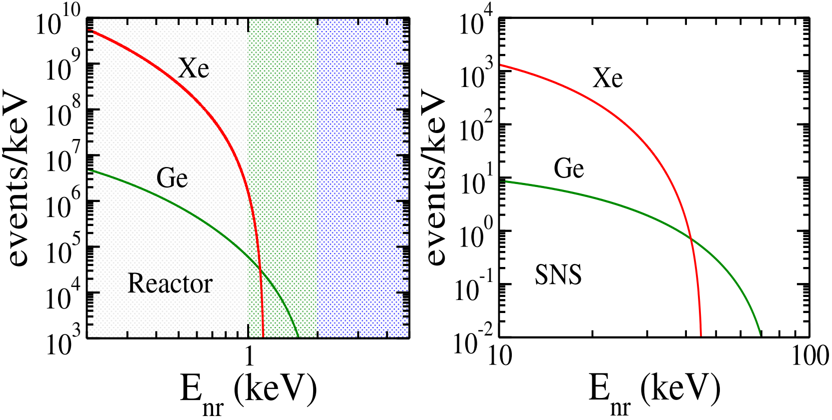
M is the nucleus mass;
T recoil nucleus energy (from 0 to $T_{max} = 2E_\nu^2/(M + 2E_\nu)$);
E_ν neutrino energy;
$qR << 1$, $q \simeq \sqrt{2MT}$;
D. Freedman Phys. Rev. D9 1389 (1974)

CEνNS





COHERENT Coll. Science 357 (2017) 1123



events/keV
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
Xe
Ge
Reactor
1
E_nr (keV)
events/keV
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
Xe
Ge
SNS
10
100
E_nr (keV)

CEνNS experiments at π-DAR and reactors

COHERENT	CsI	2017
COHERENT	LAr	2020
COHERENT	CsI	2021
COHERENT	Ge	
COHERENT	NaI	
ESS	Xe	
ESS	CsI	
ESS	Ge	
CCM	LAr	

For LBL: Aristizabal-Sierra, Dutta, Kim, Snowden-Ifft, Strigari Phys. Rev. **D104** (2021) 033004

CONUS	HPGe	
νGEN	HPGe	
TEXONO	HPGe	
CONNIE	Si	
vIOLETA	Si	
RED-100	Xe	
NEON	NaI(Tl)	
SBC	Ar	
MINER	Si-Ge	
NUCLEUS	$CaWO_4$	

For ANS: Bellengghi, Chiesa, Di Noto, Pallavicini, Previtali, Eur. Phys. J **C79** (2019) 727

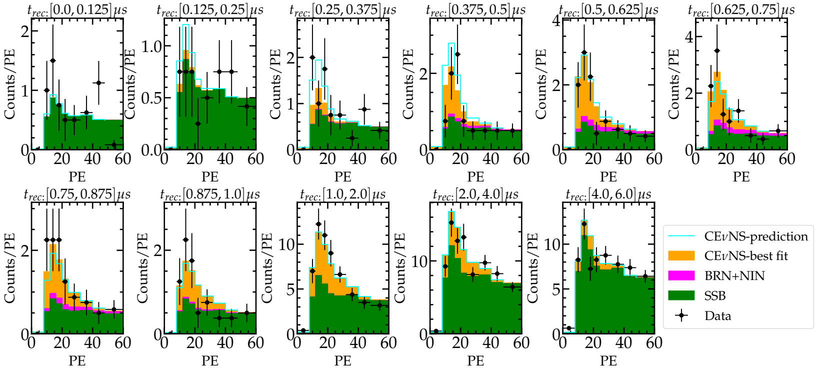
CEνNS CsI detector

$$N_{i,n}^{\mathrm{CE}\nu\mathrm{NS},\mathcal{N}} = N_{\mathrm{target}} \int_{E_{\mathrm{nr}}^{i}}^{E_{\mathrm{nr}}^{i+1}} dE_{\mathrm{nr}}\, \epsilon_E(E_{\mathrm{nr}}) \int_0^{E_{\mathrm{nr}}^{\prime\,\max}} dE'_{\mathrm{nr}}\, P(E_{\mathrm{nr}}, E'_{\mathrm{nr}}) \times$$
$$\int_{E_\nu^{\min}(E'_{\mathrm{nr}})}^{E_\nu^{\max}} dE_\nu \frac{dN_n}{dE_\nu}(E_\nu) \frac{d\sigma_{\nu_\ell \mathcal{N}}}{dE'_{\mathrm{nr}}}\Big|_{\mathrm{CE}\nu\mathrm{NS}}(E_\nu, E'_{\mathrm{nr}}),$$

De Romeri, OMG, Papoulias, Sanchez Garcia, Tortola, Valle arXiv:2211.11905

based on COHERENT Coll. D. Akimov et al. Phys. Rev. Lett. **129 (2022) 081801, arXiv:2110.07730**

CEνNS CsI detector



De Romeri, OMG, Papoulias, Sanchez Garcia, Tortola, Valle arXiv:2211.11905

in agreement with D. Pershey, talk at Magnificent CEvNS, 2020
https://indico.cern.ch/event/943069/contributions/4066386/

CEνNS CsI detector

$$\chi^2_{\rm CsI}\Big|_{\rm CE\nu NS(+ES)} = 2\sum_{i=1}^{9}\sum_{j=1}^{11}\left[N_{\rm th}^{\rm CsI} - N_{ij}^{\rm exp} + N_{ij}^{\rm exp}\ln\left(\frac{N_{ij}^{\rm exp}}{N_{\rm th}^{\rm CsI}}\right)\right] + \sum_{k=0}^{4(5)}\left(\frac{\alpha_k}{\sigma_k}\right)^2 .$$

$$N_{\rm th}^{\rm CsI, CE\nu NS+ES} = (1+\alpha_0+\alpha_5)N_{ij}^{\rm CE\nu NS}(\alpha_4,\alpha_6,\alpha_7) + (1+\alpha_0)N_{ij}^{\rm ES}(\alpha_6,\alpha_7) + (1+\alpha_1)N_{ij}^{\rm BRN}(\alpha_6) + (1+\alpha_2)N_{ij}^{\rm NIN}(\alpha_6) + (1+\alpha_3)N_{ij}^{\rm SSB} .$$

De Romeri, OMG, Papoulias, Sanchez Garcia, Tortola, Valle arXiv:2211.11905

based on COHERENT Coll. D. Akimov et al. Phys. Rev. Lett. **129 (2022) 081801, arXiv:2110.07730**

CEνNS CsI detector

- α_0 efficiency and flux 11 %
- α_1 Beam related neutrons 25 %
- α_2 Neutrino induced neutrons 35 %
- α_3 Steady state background 2.1 %
- α_4 nuclear root mean square radius 5 %
- α_5 Quenching factor 3.8 %
- α_6 Beam timing
- α_7 Uncertainty in the CEνNS efficiency

De Romeri, OMG, Papoulias, Sanchez Garcia, Tortola, Valle arXiv:2211.11905

based on COHERENT Coll. D. Akimov et al. Phys. Rev. Lett. **129 (2022) 081801, arXiv:2110.07730**

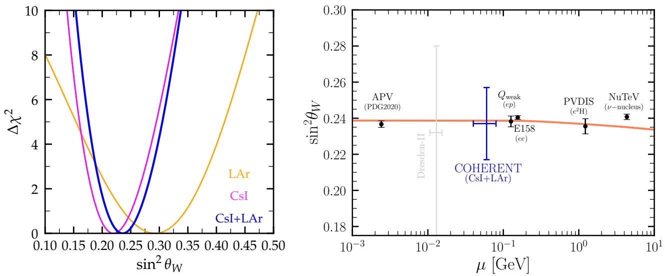
CEνNS LAr detector

$$
\begin{aligned}
\chi^2_{\mathrm{LAr}} = \sum_{i=1}^{12}\sum_{j=1}^{10}\frac{1}{\sigma_{ij}^2}\Big[&(1+\beta_0+\beta_1\Delta^{F_{90+}}_{\mathrm{CE}\nu\mathrm{NS}}+\beta_1\Delta^{F_{90-}}_{\mathrm{CE}\nu\mathrm{NS}}+\beta_2\Delta^{t_{\mathrm{trig}}}_{\mathrm{CE}\nu\mathrm{NS}})N_{ij}^{\mathrm{CE}\nu\mathrm{NS}}\\
&+(1+\beta_3)N_{ij}^{\mathrm{SSB}}\\
&+(1+\beta_4+\beta_5\Delta^{E_+}_{\mathrm{pBRN}}+\beta_5\Delta^{E_-}_{\mathrm{pBRN}}+\beta_6\Delta^{t^+_{\mathrm{trig}}}_{\mathrm{pBRN}}+\beta_6\Delta^{t^-_{\mathrm{trig}}}_{\mathrm{pBRN}}+\beta_7\Delta^{t^{\mathrm{w}}_{\mathrm{trig}}}_{\mathrm{pBRN}})N_{ij}^{\mathrm{pBRN}}\\
&+(1+\beta_8)N_{ij}^{\mathrm{dBRN}}-N_{ij}^{\mathrm{exp}}\Big]^2\\
&+\sum_{k=0,3,4,8}\left(\frac{\beta_k}{\sigma_k}\right)^2+\sum_{k=1,2,5,6,7}(\beta_k)^2\ ,
\end{aligned}
$$

De Romeri, OMG, Papoulias, Sanchez Garcia, Tortola, Valle arXiv:2211.11905

Testing Standard Model with CEνNS.

Current test for $\sin^2\theta_W$



- $\sin^2\theta_W = 0.237 \pm 0.029$
- $\sin^2\theta_W = 0.258^{+0.048}_{-0.050}$ LAr
- $\sin^2\theta_W = 0.209^{+0.072}_{-0.069}$ CsI

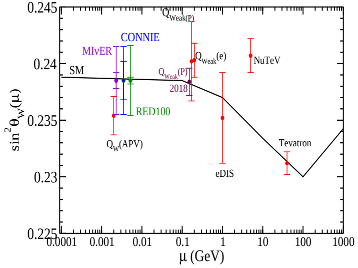
De Romeri, OGM, Papoulias, Sanchez Garcia, Tortola, Valle, 2211.11905

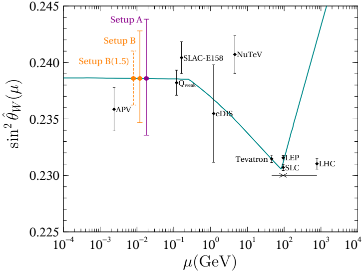
OGM, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, JHEP 05(2020) 130 2003.12050

Papoulias Phys. Rev. **D102** (2020) 113004

See also Cadeddu, Dordei, Giunti, Li, Picciau et al Phys. Rev. **D102** (2020) 015030

Future sensitivity for $\sin^2\theta_W$



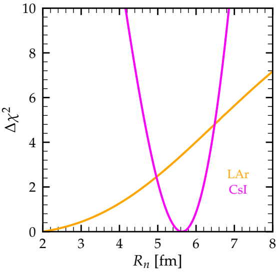


Canas, Garces, OGM, Parada Phys. Lett. B784 (2018) 159

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

See also: Fernandez-Moroni, Machado, Martinez-Soler, Perez-Gonzalez, Rodriguez, Rosauro-Alcaraz, JHEP **03(2021)** 186

Curren result for R_n



- $R_n(\mathrm{Ar})[0.00, 3.72] fm$
- $R_n(\mathrm{CsI})[5.22, 6.03] fm$

De Romeri, OGM, Papoulias, Sanchez Garcia, Tortola, Valle, 2211.11905

Phys. Rev. **D102** (2020) 015030

CEνNS and NSI

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

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

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

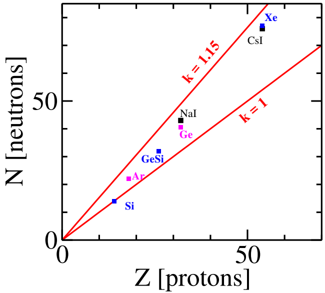
J. Barranco, OGM, T. I. Rashba PRD **73** (2007) 033005

CENNS + NSI

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

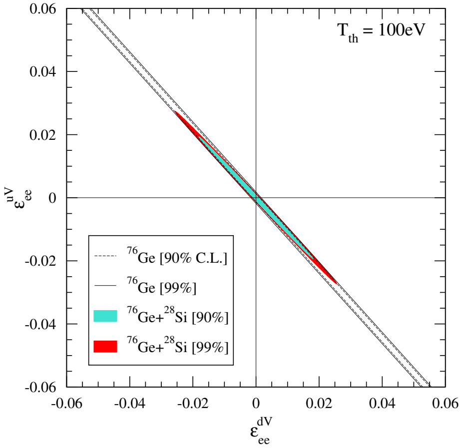
$$\varepsilon_{ee}^{uV}(2Z+N) + \varepsilon_{ee}^{dV}(Z+2N) = \text{const}\,.$$

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



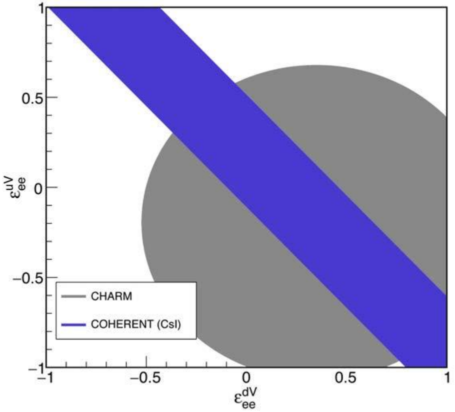
updated from J. Barranco, OGM, T.I. Rashba JHEP 0512:021 (2005)

Estimated bounds on NSI for TEXONO (Ge+Si)



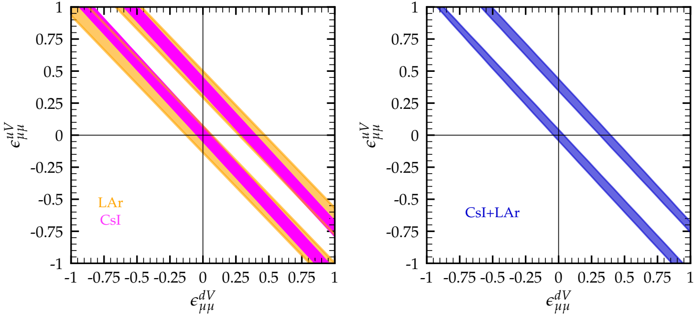
J. Barranco, OGM, T.I. Rashba JHEP 0512:021 (2005)

First bound from COHERENT



COHERENT Coll. Science 357 (2017) 1123

Combined analysis of CEνNS CsI and LAr

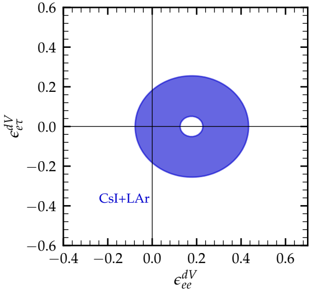


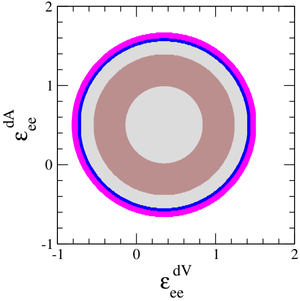
De Romeri, OGM, Papoulias, Sanchez Garcia, Tortola, Valle, 2211.11905

See also COHERENT Coll. Phys. Rev. Lett. **D129** (2022) 081801

COHERENT Coll. Phys. Rev. Lett. **D126** (2021) 012002

Combined analysis of CEνNS CsI and LAr





De Romeri, OGM, Papoulias, Sanchez Garcia, Tortola, Valle, 2211.11905

OGM, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, JHEP 01(2021)067 2003.12050

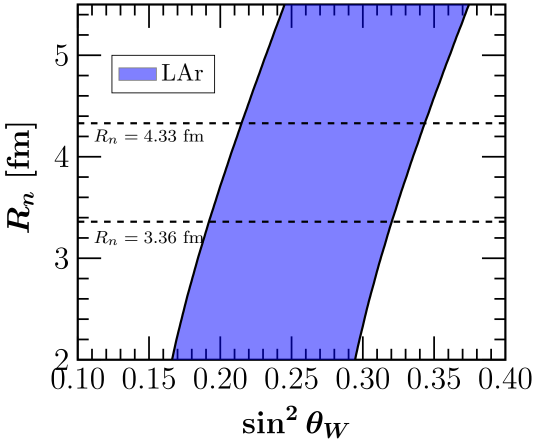
Papoulias Phys. Rev. **D102** (2020) 113004

See also Giunti Phys. Rev. **D101** (2020) 035039

ϵ_{ee}^{dV} from CHARM data

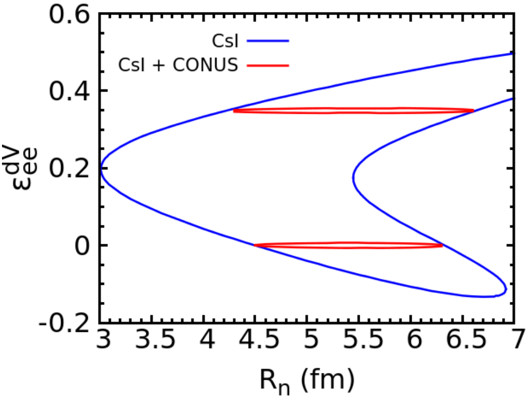
Interplay between different observables

NSI vs R_n



OGM, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, JHEP 01(2021)067 2003.12050

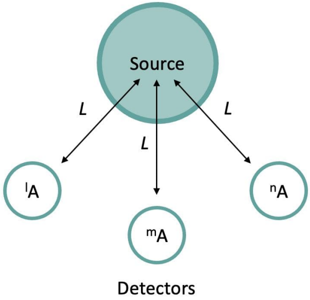
NSI vs R_n



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

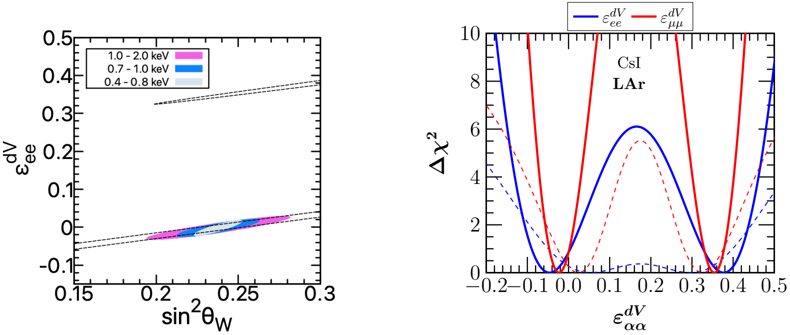
Future CEνENS tests

Using three isotopes of the same element



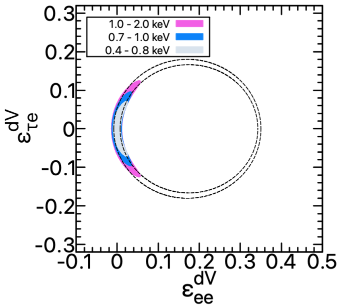
Galindo-Uribarri, OGM, Sanchez Garcia Phys Rev D **105** 033001 (2022) ArXiv:2011.10230

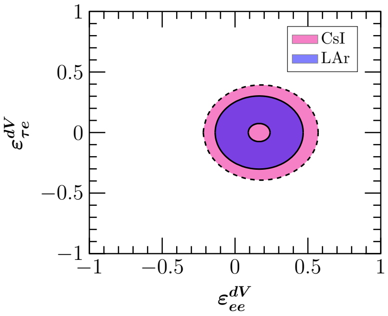
Using three isotopes of the same element



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

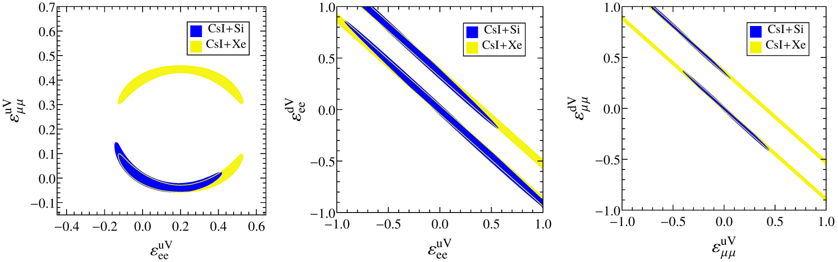
Using three isotopes of the same element





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

The European Spallation Source



Chatterjee, Lavignac, OGM, Sanchez Garcia, ArXiv:2208.11771

Generalized ν interactions

Generalized neutrino interactions

$$\mathcal{L}_{eff}^{NC} = -\frac{G_F}{\sqrt{2}} \sum_j \epsilon_{\alpha\beta}^{f,j} (\bar{\nu}_\alpha \mathcal{O}_j \nu_\beta)(\bar{f} \mathcal{O}_j^{'} f)\,,$$

ϵ	$\mathcal{O}_j$	$\mathcal{O}_j^{'}$
$\epsilon^{f,L}$	$\gamma_\mu(1-\gamma^5)$	$\gamma^\mu(1-\gamma^5)$
$\epsilon^{f,R}$	$\gamma_\mu(1-\gamma^5)$	$\gamma^\mu(1+\gamma^5)$
$\epsilon^{f,S}$	$(1-\gamma^5)$	1
$-\epsilon^{f,P}$	$(1-\gamma^5)$	γ^5
$\epsilon^{f,T}$	$\sigma_{\mu\nu}(1-\gamma^5)$	$\sigma^{\mu\nu}(1-\gamma^5)$

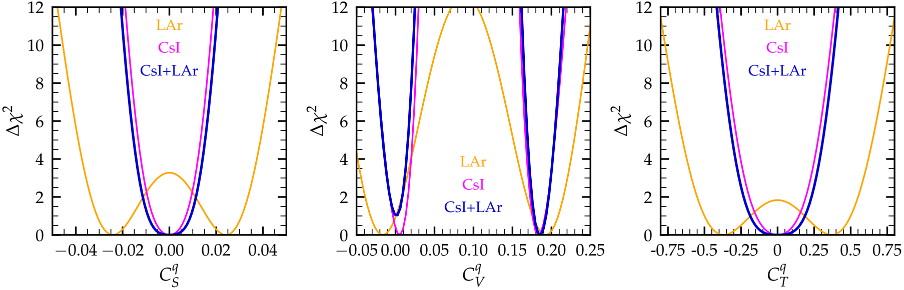
Table: Effective operators and effective couplings.

Bischer and W. Rodejohann, Phys. Rev. D 99, 036006 (2019), arXiv:1810.02220

Han, J. Liao, H. Liu, and D. Marfatia, JHEP 07, 207 (2020), arXiv:2004.13869

D. Aristizabal Sierra, V. De Romeri, and N. Rojas, Phys. Rev. D 98, 075018 (2018), arXiv:1806.07424

Bounds on GNI from CEνNS



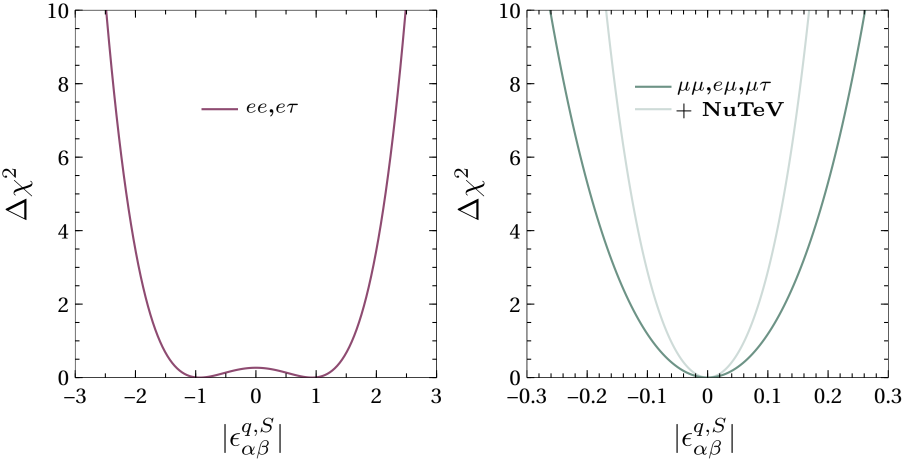
De Romeri, OGM, Papoulias, Sanchez Garcia, Tortola, Valle, 2211.11905

OGM, Papoulias, Sanchez Garcia, Sanders, Tortola, Valle, JHEP 01(2021)067 2003.12050

Papoulias Phys. Rev. **D102** (2020) 113004

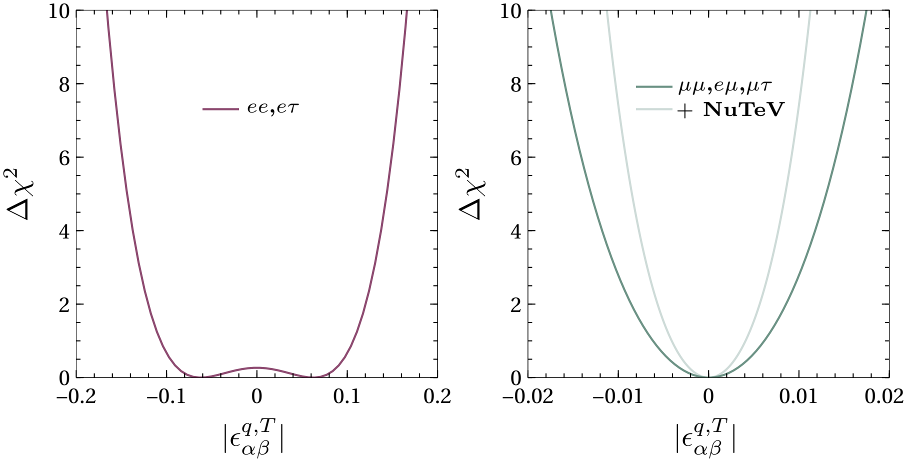
See also Giunti Phys. Rev. **D101** (2020) 035039

Bounds on scalar GNI for neutrino-quark



F. J. Escrihuela, L. J. Flores, OGM, J. Rendon, JHEP 07 (2021) 061 arXiv:2105.06484

Bounds on tensor GNI for neutrino-quark



F. J. Escrihuela, L. J. Flores, OGM, J. Rendon, JHEP 07 (2021) 061 arXiv:2105.06484

Bounds on tensor GNI for neutrino-quark

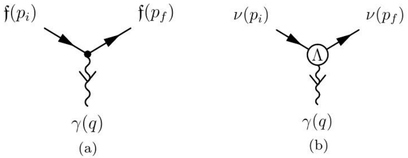
Experiments	Scalar	Pseudoscalar	Tensor
CHARM$-e$	$\lvert\epsilon^{q,X}_{ee}\rvert < 1.9$		$\lvert\epsilon^{q,T}_{ee}\rvert < 0.13$
CHARM + CDHS (+ NuTeV)	$\lvert\epsilon^{q,X}_{\mu\mu}\rvert < 0.15\,(0.1)$		$\lvert\epsilon^{q,T}_{\mu\mu}\rvert < 0.01\,(0.006)$
CHARM$-e$ + CHARM + CDHS (+ NuTeV)	$\lvert\epsilon^{q,X}_{e\mu}\rvert < 0.15\,(0.1)$		$\lvert\epsilon^{q,T}_{e\mu}\rvert < 0.01\,(0.006)$
CHARM$-e$	$\lvert\epsilon^{q,X}_{e\tau}\rvert < 1.9$		$\lvert\epsilon^{q,T}_{e\tau}\rvert < 0.13$
CHARM + CDHS (+ NuTeV)	$\lvert\epsilon^{q,X}_{\mu\tau}\rvert < 0.15\,(0.1)$		$\lvert\epsilon^{q,T}_{\mu\tau}\rvert < 0.01\,(0.006)$

Table: Combined 90% C.L. limits on the different scalar, pseudoscalar, and tensor neutrino interaction parameters, with $X = S, P$. For each suitable parameter, we also show in brackets the corresponding limits including the NuTeV measurements.

F. J. Escrihuela, L. J. Flores, OGM, J. Rendon, JHEP 07 (2021) 061 arXiv:2105.06484

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

Neutrino magnetic in the "Standard Model"

In a minimal extension of the Standard Model

$$\mu_{ij} = \frac{3eG_F}{16\pi^2\sqrt{2}}(m_{\nu i} + m_{\nu j}) \sum_{\alpha=e}^{\tau} i\,\mathcal{I}m \left[U^*_{\alpha i} U_{\alpha j} \left(\frac{m_{l\alpha}}{M_{\mathrm{W}}} \right)^2 \right].$$

Robert E. Shrock NPB **206** (1982) 359
P. B. Pal and L. Wolfenstein, Phys. Rev. D25, 766 (1982)

Neutrino magnetic in the "Standard Model"

In the minimal SM extension with light neutrino mass, the neutrino magnetic moment is expected to be very small:

$$\mu_\nu = 3.2 \times 10^{-19} \left(\frac{m_\nu}{1eV} \right) \mu_B$$

Robert E. Shrock NPB **206** (1982) 359
W. Marciano, A. I. Sanda PLB **67** 303 (1977)

Majorana neutrinos

$$\mathcal{H}_{em}^{M} = -\frac{1}{4}\nu_L^T C^{-1}\left(\mu - i d\gamma_5\right)\sigma^{\alpha\beta}\nu_L F_{\alpha\beta} = -\frac{1}{4}\nu_L^T C^{-1}\,\lambda\,\sigma^{\alpha\beta}\nu_L F_{\alpha\beta} + h.c.,$$

$$\mu^T = -\mu, \qquad d^T = -d$$

Majorana case:

The MM and EDM matrices are antisymmetric and hermitian, and, therefore, imaginary. λ is an antisymmetric matrix.

J. Schechter and J. W. F. Valle, PRD **24** 1883 (1981)

P. B. Pal and L. Wolfenstein, Phys. Rev. D25, 766 (1982)

B. Kayser, Phys.Rev. D26, 1662 (1982)

J. F. Nieves, Phys. Rev. D26, 3152 (1982)

The effective neutrino magnetic moment

The discussion could be translated into a more 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

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

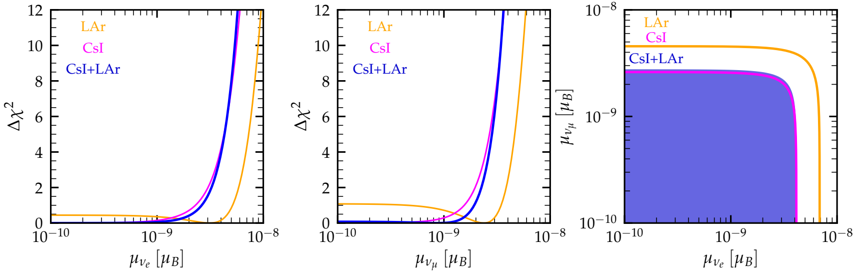
where $\lambda_{\alpha\beta} = \varepsilon_{\alpha\beta\gamma}\Lambda_\gamma$.

The transition magnetic moments Λ_α and Λ_i are complex parameters:

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

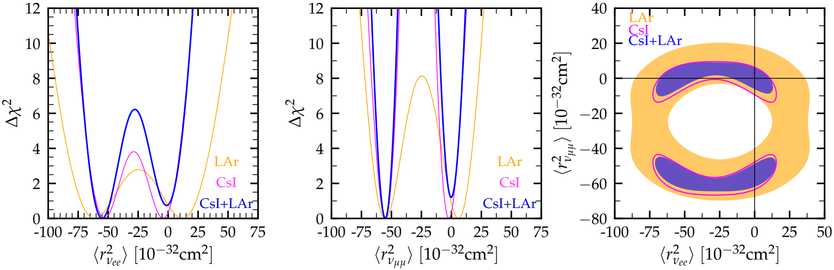
W. Grimus, T. Schwetz, NPB **587** 45 (2000)

Neutrino electromagnetic properties



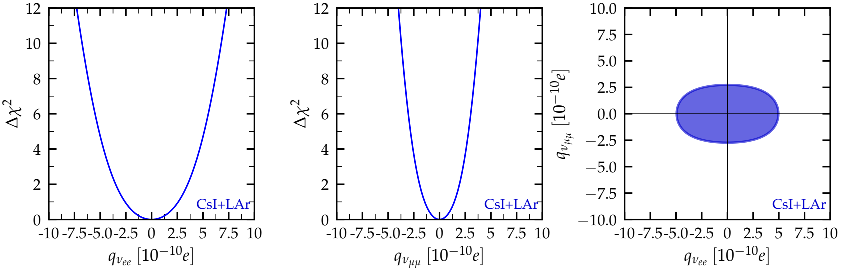
De Romeri, OGM, Papoulias, Sanchez Garcia, Tortola, Valle, 2211.11905

Neutrino electromagnetic properties



De Romeri, OGM, Papoulias, Sanchez Garcia, Tortola, Valle, 2211.11905

Neutrino electromagnetic properties



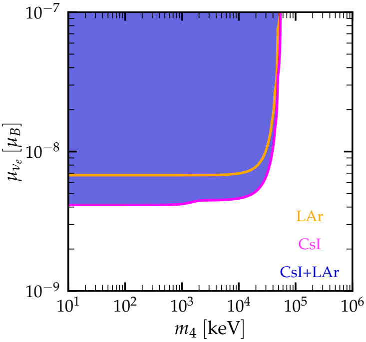
De Romeri, OGM, Papoulias, Sanchez Garcia, Tortola, Valle, 2211.11905

A transition into a massive neutrino state

If a fourth neutrino exists, the complete expression for the effective solar neutrino magnetic moment would be:

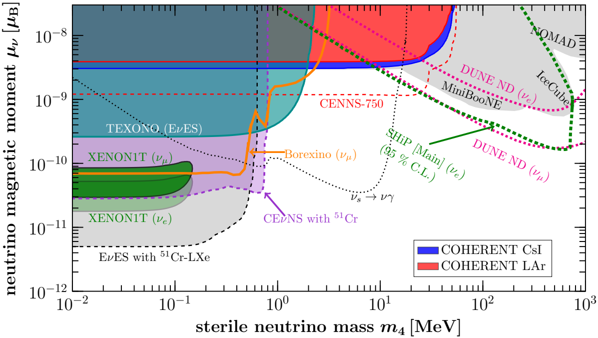
$$
\begin{aligned}
(\mu^{M}_{\nu,\,\mathrm{sol}})^2 &= P_{e1}(|\tilde{\lambda}_{12}|^2 + |\tilde{\lambda}_{13}|^2 + |\tilde{\lambda}_{14}|^2) + P_{e2}(|\tilde{\lambda}_{12}|^2 + |\tilde{\lambda}_{23}|^2 + |\tilde{\lambda}_{24}|^2) \\
&+ P_{e3}(|\tilde{\lambda}_{13}|^2 + |\tilde{\lambda}_{23}|^2 + |\tilde{\lambda}_{34}|^2) + P_{e4}(|\tilde{\lambda}_{14}|^2 + |\tilde{\lambda}_{24}|^2 + |\tilde{\lambda}_{34}|^2)
\end{aligned}
$$

Massive neutrino state



De Romeri, OGM, Papoulias, Sanchez Garcia, Tortola, Valle, 2211.11905

Massive neutrino state



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

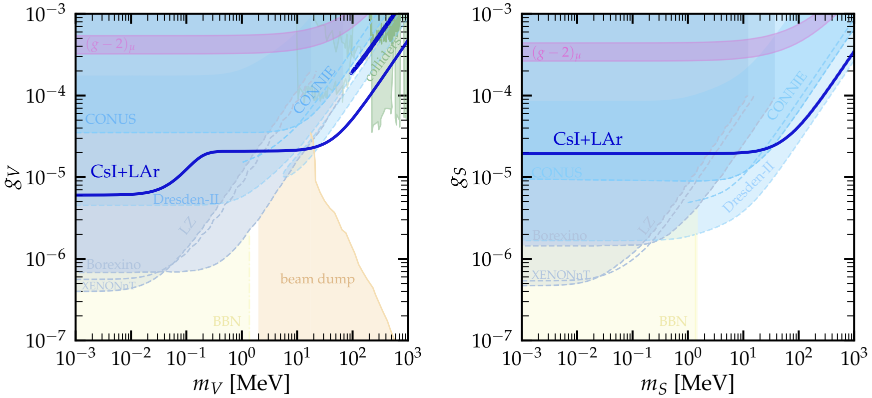
P D Bolton, F F Deppisch, K Fridell, et al Phys.Rev.D **106** (2022) 035036 arXiv:2110.02233

Conclusions

- ✓ Neutrino physics is living in a precision era, with a lot of experimental results and many others to come.
- ✓ Neutrino oscillation experiments are fundamental, but there are other experiments that play an important complementary role.
- ✓ With the detection of CEνNS a new window to test for standard and non-standard particle physics is open.
- ✓ The systematic study of the results to come may lead us to new physics beyond the Standard Model that could explain the neutrino mass pattern.

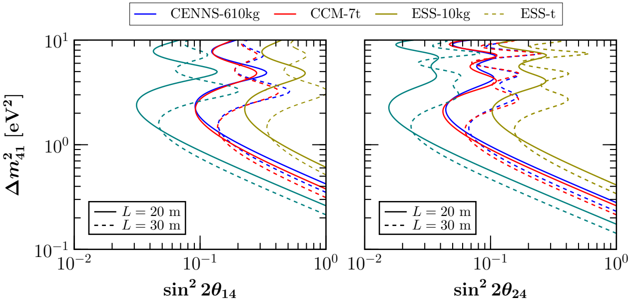
Thanks

Light vector mediators



De Romeri, OGM, Papoulias, Sanchez Garcia, Tortola, Valle, 2211.11905

Sterile neutrino



OGM, Papoulias, Sanders, Tortola, Valle Phys. Rev. D102 (2020) 113014

See also B Dutta et al, Phys. Rev. D **94** 093003 (2016)

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

Non-unitarity and CEνNS

Non unitarity

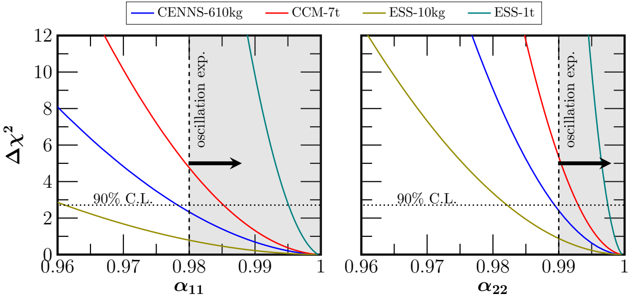
Neutral heavy leptons are a common feature of many extensions of the SM and play and important role in models for neutrino mass generation. The seesaw mechanism is perhaps the most representative example.

$$U_{\alpha i}^{n\times n} = \begin{pmatrix} N & S \\ V & T \end{pmatrix}$$

$$NN^\dagger + SS^\dagger = I,$$

- S Antusch, O Fischer, JHEP 10(2014) 094
- Escriuela, Forero, OGM, Tortola, Valle, Phys. Rev. **D92** 119905 (2015)
- S Parke, M Ross-Lonergan, Physical Review, **D93** 113009 (2016)
- C S Fong, H Minakata, H Nunokawa, JHEP 02(2017) 114
- M Blennow, P Coloma, E Fernandez-Martinez, J Hernandez-Garcia, J Lopez-Pavon, JHEP 02(2019) 015
- S A Ellis, K Kelly, S W Li JHEP 12(2020) 068
- Forero, Giunti, Ternes, Tortola, arXiv: 2103.01998

Non unitarity



OGM, Papoulias, Sanders, Tortola, Valle Phys. Rev. D102 (2020) 113014

Other experimental observables

NSI-d constraints for ν_μ

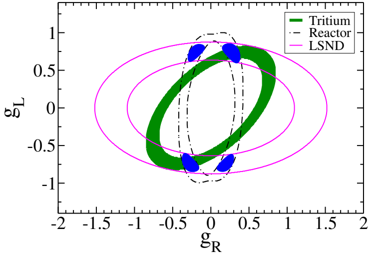
Global with NuTeV reanalysis	NSI with down	NSI with up
	NU	NU
NNPDF	$-0.042 < \epsilon_{\mu\mu}^{dV} < 0.042$	$-0.044 < \epsilon_{\mu\mu}^{uV} < -0.044$
	$-0.091 < \epsilon_{\mu\mu}^{dA} < 0.091$	$-0.15 < \epsilon_{\mu\mu}^{uA} < 0.18$
Bentz at al.	$-0.042 < \epsilon_{\mu\mu}^{dV} < 0.042$	$-0.044 < \epsilon_{\mu\mu}^{uV} < -0.044$
	$-0.072 < \epsilon_{\mu\mu}^{dA} < 0.057$	$-0.094 < \epsilon_{\mu\mu}^{uA} < 0.14$
	FC	FC
NNPDF/Bentz et al.	$-0.007 < \epsilon_{\mu\tau}^{dV} < 0.007$	$-0.007 < \epsilon_{\mu\tau}^{uV} < 0.007$
	$-0.039 < \epsilon_{\mu\tau}^{dA} < 0.039$	$-0.039 < \epsilon_{\mu\tau}^{uA} < 0.039$

Escrihuela, Miranda, Tortola, Valle, PRD **83** 093002 (2011)

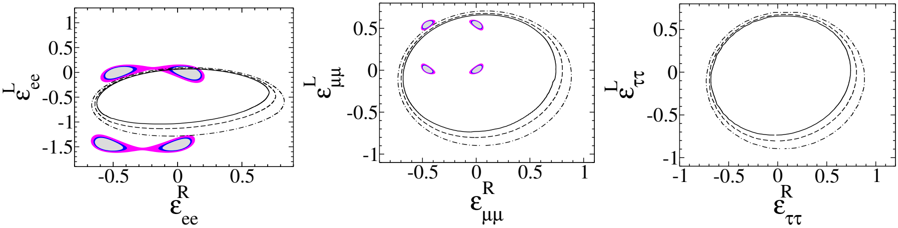
NSI for ν interactions with electrons

The $\nu_e e$ interaction

Experiment	Energy (MeV)	events	measurement
LSND $\nu_e e$	10-50	191	$\sigma = [10.1 \pm 1.5] \times E_{\nu_e}(\mathrm{MeV}) \times 10^{-45}\mathrm{cm}^2$
Irvine $\bar{\nu}_e - e$	1.5 - 3.0	381	$\sigma = [0.86 \pm 0.25] \times \sigma_{V-A}$
Irvine $\bar{\nu}_e - e$	3.0 - 4.5	77	$\sigma = [1.7 \pm 0.44] \times \sigma_{V-A}$
Rovno $\bar{\nu}_e - e$	0.6 - 2.0	41	$\sigma = (1.26 \pm 0.62) \times 10^{-44}\mathrm{cm}^2/\mathrm{fission}$
MUNU $\bar{\nu}_e - e$	0.7 - 2.0	68	1.07 ± 0.34 events day $^{-1}$

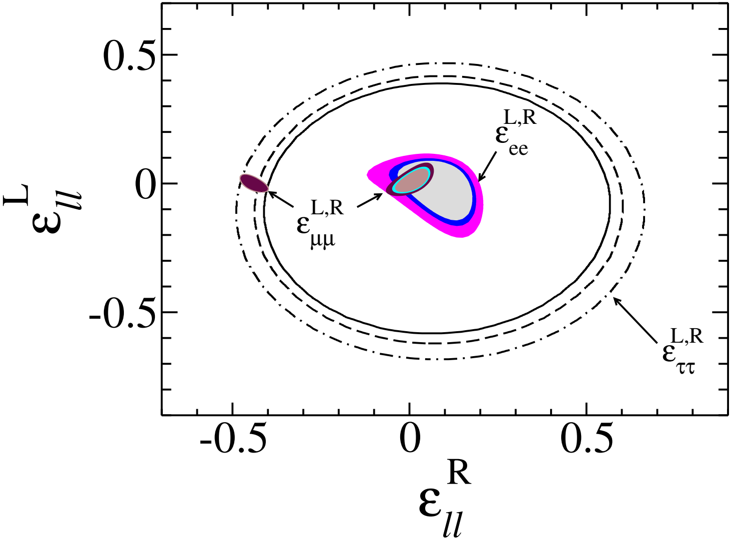


Laboratory constraints



Barranco, Miranda, Moura, Valle PRD **77** 093014 '08

Laboratory constraints



Laboratory constraints

	Region at 90% C. L.	one parameter
ε^L_{ee}	$-0.14 < \varepsilon^L_{ee} < 0.09$	$-0.03 < \varepsilon^L_{ee} < 0.08$
ε^R_{ee}	$-0.03 < \varepsilon^R_{ee} < 0.18$	$0.004 < \varepsilon^R_{ee} < 0.15$
$\varepsilon^L_{\mu\mu}$	$-0.033 < \varepsilon^L_{\mu\mu} < 0.055$	$\lvert\varepsilon^L_{\mu\mu}\rvert < 0.03$
$\varepsilon^R_{\mu\mu}$	$-0.040 < \varepsilon^R_{\mu\mu} < 0.053$	$\lvert\varepsilon^R_{\mu\mu}\rvert < 0.03$
$\varepsilon^L_{\tau\tau}$	$-0.6 < \varepsilon^L_{\tau\tau} < 0.4$	$-0.5 < \varepsilon^L_{\tau\tau} < 0.2$
$\varepsilon^R_{\tau\tau}$	$-0.4 < \varepsilon^R_{\tau\tau} < 0.6$	$-0.3 < \varepsilon^R_{\tau\tau} < 0.4$

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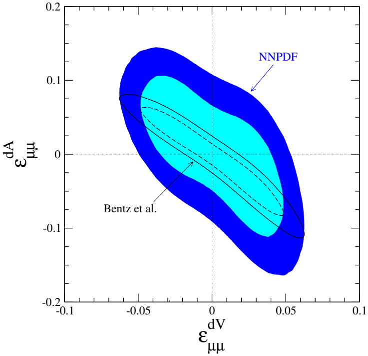
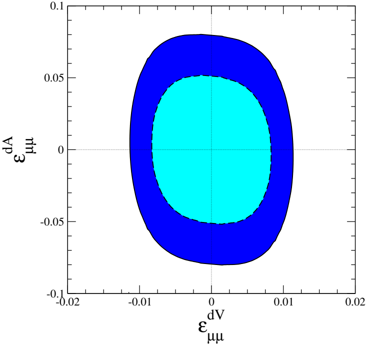
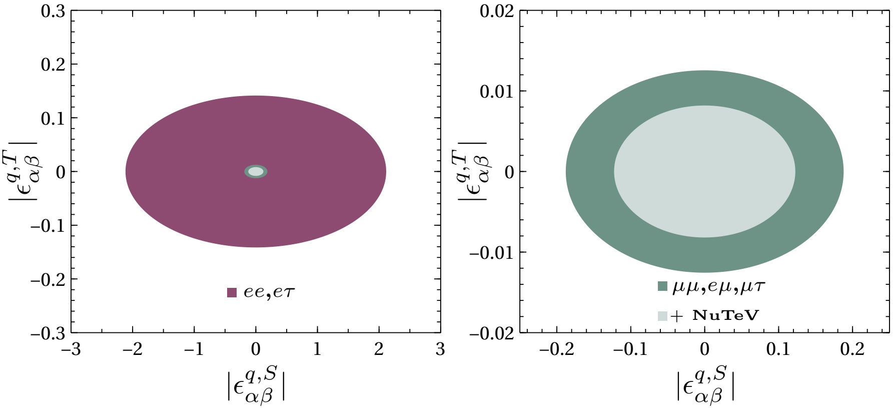
NSI-d constraints for ν_μ





Global constraints on GNI for neutrino-quark



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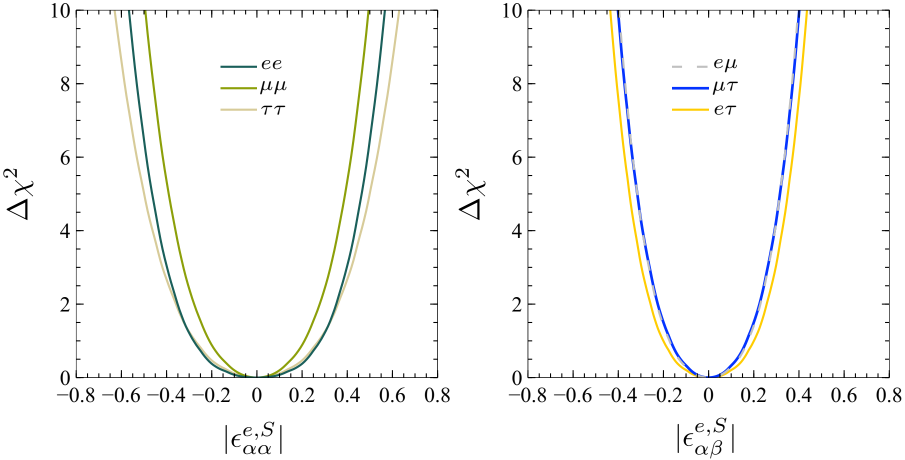
Bounds on scalar GNI for neutrino-electron



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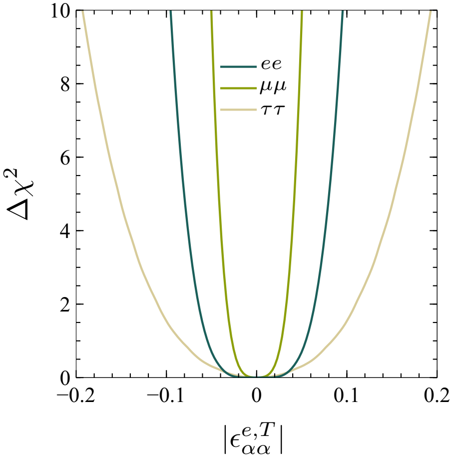
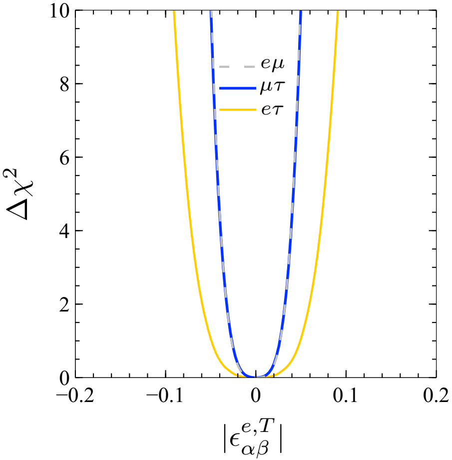
Bounds on tensor GNI for neutrino-electron





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Bounds on tensor GNI for neutrino-electron

Experiments	Scalar	Pseudoscalar	Tensor
$e^- e^+$ + TEXONO	$\lvert\epsilon_{ee}^{e,S}\rvert < 0.38$	$\lvert\epsilon_{ee}^{e,P}\rvert < 0.40$	$\lvert\epsilon_{ee}^{e,T}\rvert < 0.07$
$e^- e^+$ + CHARM-II	$\lvert\epsilon_{\mu\mu}^{e,X}\rvert < 0.31$		$\lvert\epsilon_{\mu\mu}^{e,T}\rvert < 0.03$
$e^- e^+$	$\lvert\epsilon_{\tau\tau}^{e,X}\rvert < 0.40$		$\lvert\epsilon_{\tau\tau}^{e,T}\rvert < 0.12$
$e^- e^+$ + TEXONO + CHARM-II	$\lvert\epsilon_{e\mu}^{e,S}\rvert < 0.25$	$\lvert\epsilon_{e\mu}^{e,P}\rvert < 0.25$	$\lvert\epsilon_{e\mu}^{e,T}\rvert < 0.03$
$e^- e^+$ + TEXONO	$\lvert\epsilon_{e\tau}^{e,S}\rvert < 0.28$	$\lvert\epsilon_{e\tau}^{e,P}\rvert < 0.29$	$\lvert\epsilon_{e\tau}^{e,T}\rvert < 0.07$
$e^- e^+$ + CHARM-II	$\lvert\epsilon_{\mu\tau}^{e,X}\rvert < 0.25$		$\lvert\epsilon_{\mu\tau}^{e,T}\rvert < 0.03$

Table: Combined 90% C.L. limits on the different scalar, pseudoscalar, and tensor neutrino interaction parameters, with $X = S, P$. For each suitable parameter, we also show in brackets the corresponding limits including the NuTeV measurements.

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Massive neutrino state