Neutrino transition magnetic moments and sterile neutrinos from CEνNS

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Outline

1. Electromagnetic neutrino vertex
   - neutrino transition magnetic moments (TMMs)
     - TMMs for reactor/SNS/solar neutrinos
   - sensitivity at CEνNS experiments
     - TMMs
     - impact of CP violating phases
     - comparison with Borexino
2. Sterile neutrinos
   - sensitivity on the mixing parameters
     - SNS neutrinos
     - reactor neutrinos
3. Summary

Electromagnetic contribution to CEνNS cross section

The Electromagnetic CEνNS cross section reads [Vogel, Engel.: PRD 39 [1989] 3378

$$\left(\frac{d\sigma}{dT_A}\right)_{\mathrm{EM}} = \frac{\pi a_{\mathrm{EM}}^2 \mu_\nu^2 Z^2}{m_e^2}\left(\frac{1 - T_A/E_\nu}{T_A}\right) F^2(Q^2)\,.$$

- can be dominant for sub-keV threshold experiments
- may lead to detectable distortions of the recoil spectrum

The helicity preserving SM cross section adds incoherently with the helicity-violating EM cross section

$$\left(\frac{d\sigma}{dT_A}\right)_{\mathrm{tot}} = \left(\frac{d\sigma}{dT_A}\right)_{\mathrm{SM}} + \left(\frac{d\sigma}{dT_A}\right)_{\mathrm{EM}}$$

μ_ν^2 is the effective neutrino magnetic moment in the mass basis relevant to a given neutrino beam (reactor, SNS, etc.)

- Experimental measurements usually constrain some process-dependent effective parameter combination
- needs to be expressed in terms of fundamental parameters (TMMs + CP phases + mixing-angles)
- Even in the case of laboratory neutrino experiments, where the initial neutrino flux is fixed to have a well determined given flavor, there is no sensitivity to the final neutrino state

Electromagnetic neutrino vertex (spin component)

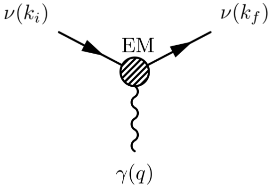
Dirac neutrinos: $H_{\mathsf{EM}}^{\mathrm{D}} = \frac{1}{2}\bar{\nu}_R \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + \mathrm{h.c.}$

- $\lambda = \mu - i\epsilon$ is an arbitrary complex matrix
- $\mu = \mu^\dagger$ and $\epsilon = \epsilon^\dagger$.

Majorana neutrinos: $H_{\mathsf{EM}}^{\mathrm{M}} = -\frac{1}{4}\nu_L^{\mathsf{T}} C^{-1} \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + \mathrm{h.c.}$

- $\lambda = \mu - i\epsilon$: antisymmetric complex matrix ($\lambda_{\alpha\beta} = -\lambda_{\beta\alpha}$)
- $\mu^{\mathsf{T}} = -\mu$ and $\epsilon^{\mathsf{T}} = -\epsilon$ are two imaginary matrices.
- three complex or six real parameters are required

In contrast to the Dirac case, vanishing diagonal moments are implied for Majorana neutrinos, $\mu_{ii}^{\mathrm{M}} = \epsilon_{ii}^{\mathrm{M}} = 0$.



[Schechter, Valle: PRD 24 (1981), PRD 25 (1982)]

The neutrino transition magnetic moment (TMM) matrix

The magnetic moment matrix λ ($\tilde{\lambda}$) in the flavor (mass) basis reads

[Tórtola: PoS AHEP 2003 (2003)]

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

- the definition $\lambda_{\alpha\beta} = \varepsilon_{\alpha\beta\gamma}\Lambda_\gamma$ has been introduced,
- the neutrino TMMs are represented by the complex parameters

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

three complex or six real parameters (3 moduli + 3 phases)

Effective neutrino magnetic moment @ experiments

Is expressed in terms of the neutrino magnetic moment matrix and the amplitudes of positive and negative helicity states 3−vectors $\mathfrak{a}_+$ and $\mathfrak{a}_-$,

- In the flavor basis one finds [Grimus, Schwetz: Nucl. Phys. B587 (2000)]

$$\left(\mu_\nu^F\right)^2 = \mathfrak{a}_-^\dagger \lambda^\dagger \lambda \mathfrak{a}_- + \mathfrak{a}_+^\dagger \lambda \lambda^\dagger \mathfrak{a}_+ \,,$$

Introducing the transformations (U is the lepton mixing matrix)

$$\tilde{\mathfrak{a}}_- = U^\dagger \mathfrak{a}_-, \qquad \tilde{\mathfrak{a}}_+ = U^\mathsf{T} \mathfrak{a}_+, \qquad \tilde{\lambda} = U^\mathsf{T} \lambda U \,,$$

- In the mass basis reads

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

TMMs in flavor & mass basis @ reactor facilities

Reactor antineutrinos: $\bar{\nu}_e$ (with $\mathfrak{a}_+^1 = 1$)

- flavor basis

$$\left(\mu^F_{\bar{\nu}_e,\,\text{reactor}}\right)^2 = |\Lambda_\mu|^2 + |\Lambda_\tau|^2$$

where $|\Lambda_\mu|$ and $|\Lambda_\tau|$ are the elements of the neutrino TMM matrix λ describing the corresponding conversions from the electron antineutrino to the muon and tau neutrino states

- mass basis [Cañas et al.: PLB 753 (2016)]

$$\begin{aligned}\left(\mu^M_{\bar{\nu}_e,\,\text{reactor}}\right)^2 =& |\boldsymbol{\Lambda}|^2 - c_{12}^2 c_{13}^2 |\Lambda_1|^2 - s_{12}^2 c_{13}^2 |\Lambda_2|^2 - s_{13}^2 |\Lambda_3|^2 \\ & - c_{13}^2 \sin 2\theta_{12} |\Lambda_1||\Lambda_2| \cos\xi_3 \\ & - c_{12} \sin 2\theta_{13} |\Lambda_1||\Lambda_3| \cos(\delta_{\text{CP}} - \xi_2) \\ & - s_{12} \sin 2\theta_{13} |\Lambda_2||\Lambda_3| \cos(\delta_{\text{CP}} - \xi_1)\,,\end{aligned}$$

with $|\boldsymbol{\Lambda}|^2 = |\Lambda_1|^2 + |\Lambda_2|^2 + |\Lambda_3|^2$ and

phase redefinition: $\xi_1 = \zeta_3 - \zeta_2$, $\xi_2 = \zeta_3 - \zeta_1$ and $\xi_3 = \zeta_1 - \zeta_2$

TMMs in flavor & mass basis @ SNS facilities (prompt)

Prompt beam: $\underline{\nu_\mu \text{ (with } \mathfrak{a}_-^2 = 1)}$

- flavor basis

$$\left(\mu^F_{\nu_\mu,\,\text{prompt}}\right)^2 = |\Lambda_e|^2 + |\Lambda_\tau|^2$$

- mass basis

$$\begin{aligned}\left(\mu^M_{\nu_\mu,\,\text{prompt}}\right)^2 = & |\Lambda_1|^2 \left[-2 c_{12} c_{23} s_{12} s_{13} s_{23} \cos\delta_{\text{CP}} \right. \\ & \qquad \left. + s_{23}^2 \left(c_{13}^2 + s_{12}^2 s_{13}^2\right) + c_{12}^2 c_{23}^2\right] \\ & + |\Lambda_2|^2 \left[2 c_{12} c_{23} s_{13} s_{23} s_{12} \cos\delta_{\text{CP}} + c_{23}^2 s_{12}^2 + s_{23}^2 \left(c_{12}^2 s_{13}^2 + c_{13}^2\right)\right] \\ & + |\Lambda_3|^2 \left[c_{23}^2 + s_{13}^2 s_{23}^2\right] \\ & + 2\,|\Lambda_1 \Lambda_2| \left[c_{23} c_{12}^2 s_{13} s_{23} \cos\left(\delta_{\text{CP}} + \xi_3\right) - c_{23} s_{12}^2 s_{13} s_{23} \cos\left(\delta_{\text{CP}} - \xi_3\right) \right. \\ & \qquad \left. + c_{12} s_{12} \left(c_{23}^2 - s_{13}^2 s_{23}^2\right) \cos\xi_3\right] \\ & + 2\,|\Lambda_1 \Lambda_3| \left[c_{13} s_{23} \left(c_{12} s_{13} s_{23} \cos\left(\delta_{\text{CP}} - \xi_2\right) + c_{23} s_{12} \cos\xi_2\right)\right] \\ & + 2\,|\Lambda_2 \Lambda_3| \left[c_{13} s_{23} \left(s_{12} s_{13} s_{23} \cos\left(\delta_{\text{CP}} - \xi_1\right) - c_{12} c_{23} \cos\xi_1\right)\right] .\end{aligned}$$

[Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]

TMMs in flavor & mass basis @ SNS facilities (delayed ν_e)

Delayed beam: (i) ν_e (with $\mathfrak{a}_-^1 = 1$) and (ii) $\bar{\nu}_\mu$ (with $\mathfrak{a}_+^2 = 1$)

ν_e component

- flavor basis

$$\left(\mu^F_{\nu_e,\,\text{delayed}}\right)^2 = |\Lambda_\mu|^2 + |\Lambda_\tau|^2$$

- mass basis

$$\begin{aligned}\left(\mu^M_{\nu_e,\,\text{delayed}}\right)^2 &= |\Lambda_1|^2\left[c_{13}^2 s_{12}^2 + s_{13}^2\right] + |\Lambda_2|^2\left[c_{12}^2 c_{13}^2 + s_{13}^2\right] + |\Lambda_3|^2\, c_{13}^2 \\ &- |\Lambda_1\Lambda_2|\left[c_{13}^2 \sin(2\theta_{12}) \cos\xi_3\right] - |\Lambda_1\Lambda_3|\left[c_{12}\sin(2\theta_{13})\cos(\delta_{\text{CP}} - \xi_2)\right] \\ &- |\Lambda_2\Lambda_3|\left[s_{12}\sin(2\theta_{13})\cos(\delta_{\text{CP}} - \xi_1)\right] ,\end{aligned}$$

[Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]

TMMs in flavor & mass basis @ SNS facilities (delayed $\bar{\nu}_\mu$)

Delayed beam: (i) ν_e (with $\mathfrak{a}_-^1 = 1$) and (ii) $\bar{\nu}_\mu$ (with $\mathfrak{a}_+^2 = 1$)

$\bar{\nu}_\mu$ component

- flavor basis

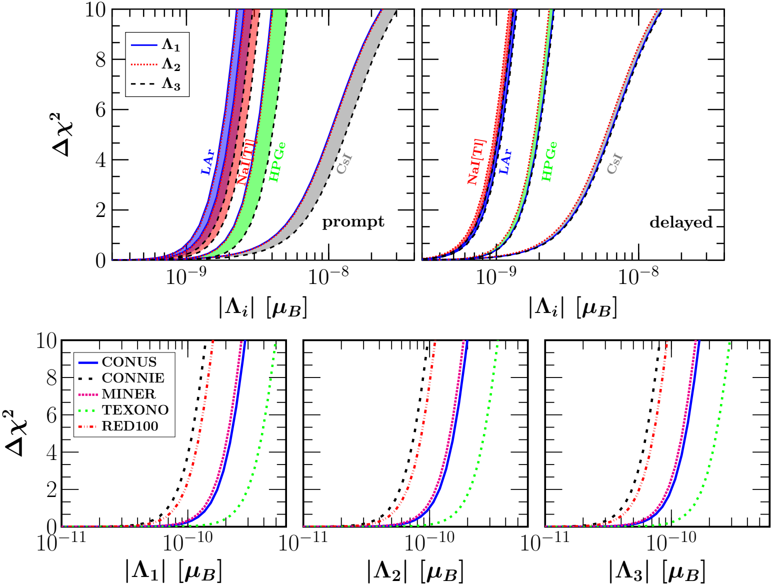
$$\left(\mu^F_{\bar{\nu}_\mu,\,\text{delayed}}\right)^2 = |\Lambda_e|^2 + |\Lambda_\tau|^2$$

- mass basis

$$\begin{aligned}
\left(\mu^M_{\bar{\nu}_\mu,\,\text{delayed}}\right)^2 &= |\Lambda_1|^2 \left[-2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta_{\text{CP}} + s_{23}^2\left(c_{13}^2 + s_{12}^2 s_{13}^2\right) + c_{12}^2 c_{23}^2\right] \\
&+ |\Lambda_2|^2 \left[2c_{12}c_{23}s_{12}s_{13}s_{23}\cos\delta_{\text{CP}} + s_{23}^2\left(c_{13}^2 + c_{12}^2 s_{13}^2\right) + s_{12}^2 c_{23}^2\right] \\
&+ |\Lambda_3|^2 \left[\frac{1}{4}\left(2c_{13}^2\cos(2\theta_{23}) - \cos(2\theta_{13}) + 3\right)\right] \\
&+ 2\,|\Lambda_1\Lambda_2| \left[c_{23}s_{13}s_{23}\left(c_{12}^2\cos\left(\delta_{\text{CP}} + \xi_3\right) - s_{12}^2\cos\left(\delta_{\text{CP}} - \xi_3\right)\right)\right. \\
&\left. + c_{12}c_{23}^2 s_{12}\cos\xi_3 - c_{12}s_{12}s_{13}^2 s_{23}^2\cos\xi_3\right] \\
&+ 2\,|\Lambda_1\Lambda_3| \left[c_{13}s_{23}\left(c_{12}s_{13}s_{23}\cos\left(\delta_{\text{CP}} - \xi_2\right) + c_{23}s_{12}\cos\xi_2\right)\right] \\
&+ 2\,|\Lambda_2\Lambda_3| \left[c_{13}s_{23}\left(s_{12}s_{13}s_{23}\cos\left(\delta_{\text{CP}} - \xi_1\right) - c_{12}c_{23}\cos\xi_1\right)\right]
\end{aligned}$$

[Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]

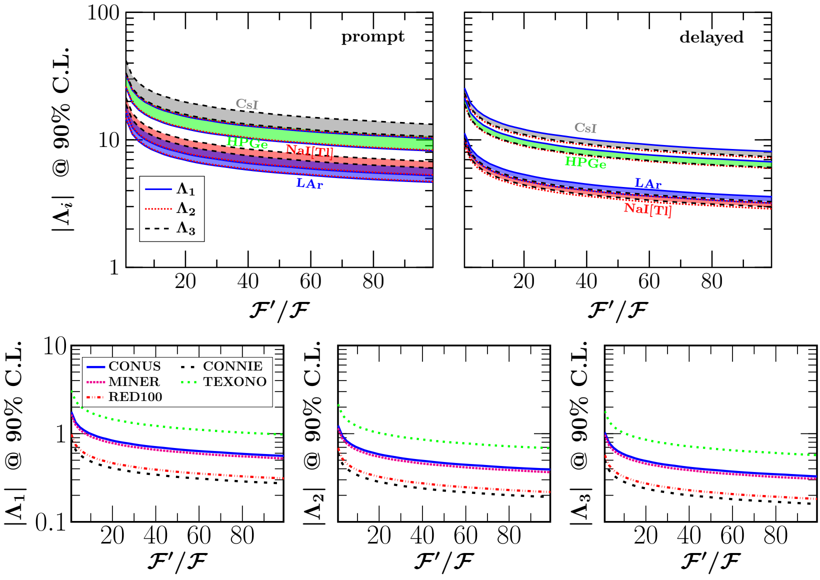
Analysis of CEνNS data: sensitivity to $|\Lambda_i|$



all results in units $10^{-10}\mu_B$

[Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]

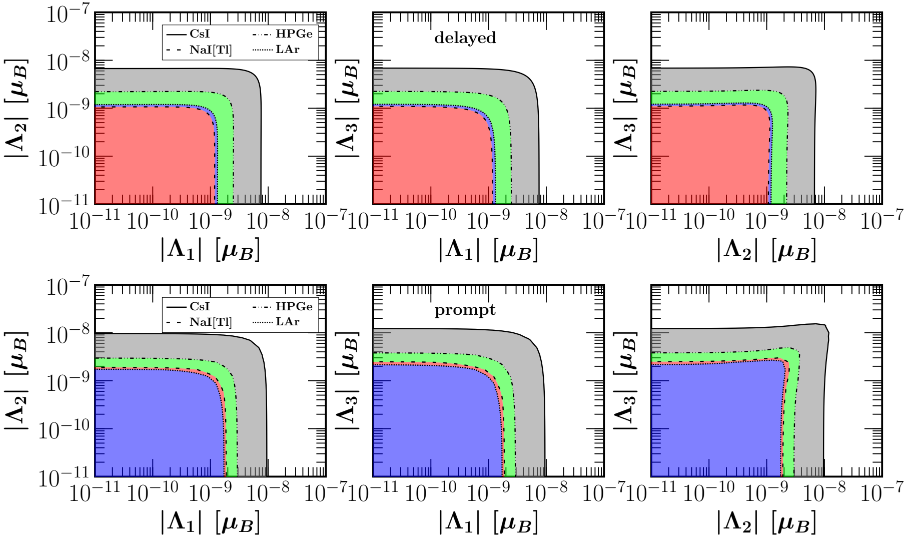
Estimating the future prospects: luminosity factor variation



all results in units $10^{-10}\mu_B$

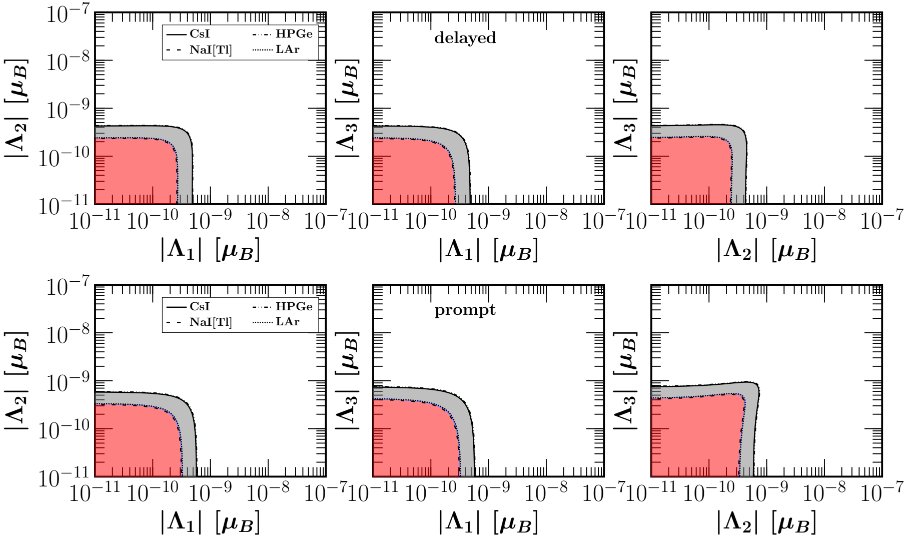
[Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]

Current COHERENT setup: combined constraints



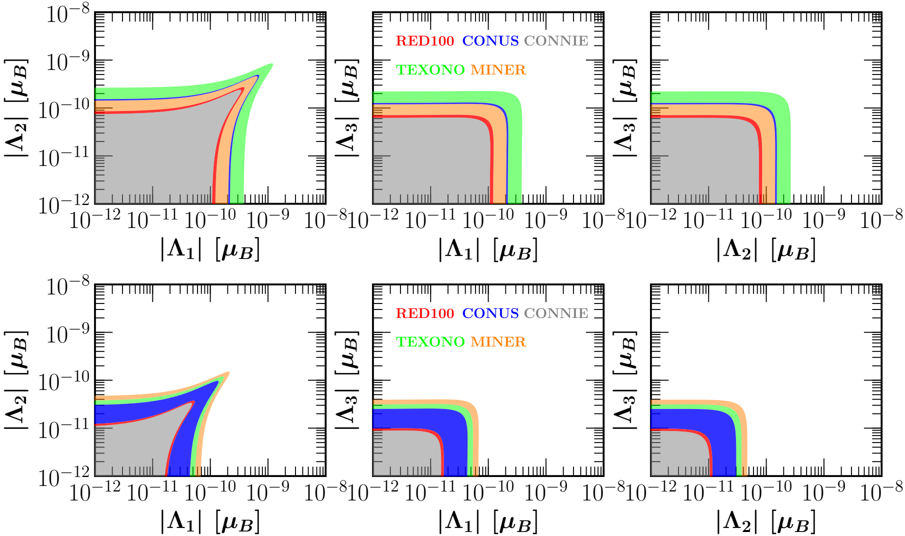
[Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]

Future COHERENT setup: combined constraints



[Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]

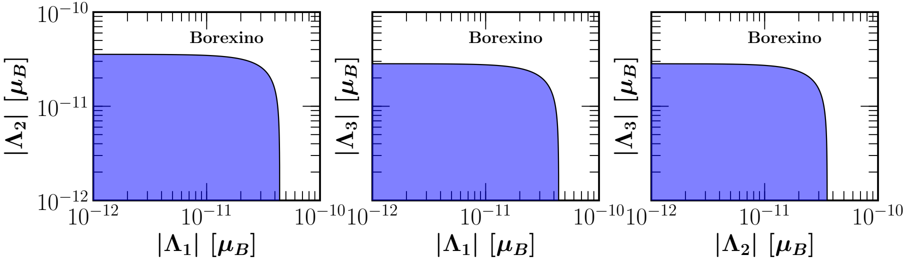
Current & Future Reactor experiments: combined constraints



[Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]

Solar neutrinos from Borexino

[Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]



- solar electron neutrinos undergo flavor oscillations arriving to the detector as an incoherent admixture of mass eigenstates (no phase dependence)
- dependence on neutrino mixing and oscillation factor between the source and detection is considered $\left(\mu^M_{\nu,\text{eff}}\right)^2 (L, E_\nu) = \sum_j \left| \sum_i U^*_{\alpha i} e^{-i\,\Delta m^2_{ij} L/2E_\nu}\, \tilde{\lambda}_{ij} \right|^2$
- the oscillation probabilities from ν_e to mass eigenstates ν_i are approximated

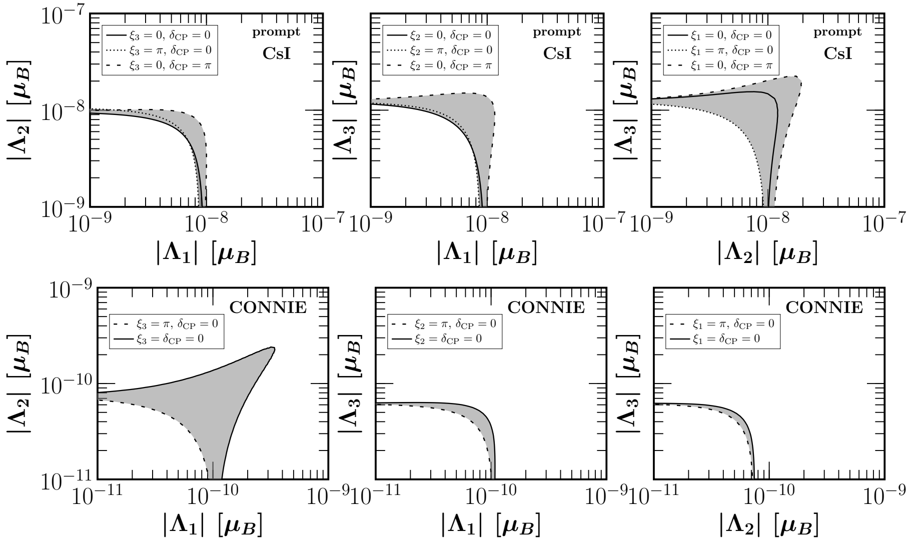
$$P^{3\nu}_{e3} = \sin^2\theta_{13}, \quad P^{3\nu}_{e1} = \cos^2\theta_{13} P^{2\nu}_{e1}, \quad P^{3\nu}_{e2} = \cos^2\theta_{13} P^{2\nu}_{e2},$$

  and the unitarity condition, $P^{2\nu}_{e1} + P^{2\nu}_{e2} = 1$
- eff. neutrino magnetic moment for solar neutrinos in mass basis [Cañas et al.: PLB 753 (2016)]

$$(\mu^M_{\nu,\,\text{sol}})^2 = |\mathbf{\Lambda}|^2 - c^2_{13}|\Lambda_2|^2 + (c^2_{13} - 1)|\Lambda_3|^2 + c^2_{13} P^{2\nu}_{e1}(|\Lambda_2|^2 - |\Lambda_1|^2)$$

- Recall Borexino phase-II limit $\mu_\nu < 2.8 \times 10^{-11} \mu_B$ [Borexino Collab., Agostini et al.:PRD 96 (2017)]

Impact of CP phases



explore the robustness of TMMs limits [Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]

Sensitivity to the sterile mixing parameters (COHERENT)

- **Matrix elements in the (3+1) scheme**

  $|U_{e4}|^2 = s_{14}^2,\ |U_{\mu 4}|^2 = s_{24}^2 c_{14}^2,$

  $s_{ij} \equiv \sin\phi_{ij}$ and $c_{ij} \equiv \cos\phi_{ij}$

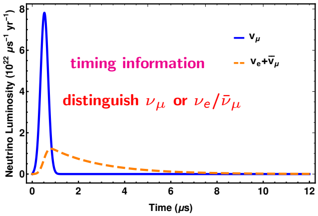
- **Mixing angles**

$$\sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)$$
$$\sin^2 2\theta_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$$

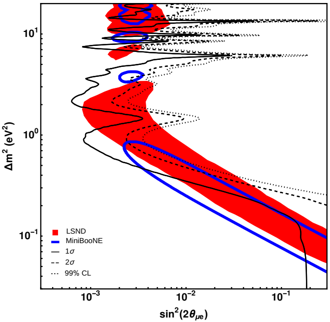
- **Oscillation probability**

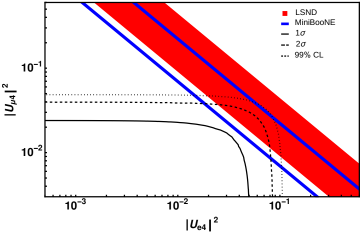
$$P_{\alpha\beta} \approx = \begin{cases} 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2 \frac{\Delta_{41}}{2} & (\alpha = \beta) \\ \sin^2 2\theta_{\alpha\beta} \sin^2 \frac{\Delta_{41}}{2} & (\alpha \neq \beta) \end{cases},$$

$\Delta_{ij} \equiv 2.54 \left(\Delta m_{ij}^2/\mathrm{eV}^2\right)(L/\mathrm{km})(\mathrm{GeV}/E_\nu),$
where $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$



- **exclusion curves: 100 kg CsI, 3 years**
  [Blanco, Hooper, Machado arXiv:1901.08094]





Sensitivity to the sterile mixing parameters (reactors)

- **Matrix elements in the (3+1) scheme**

  $|U_{e4}|^2 = s_{14}^2,\ |U_{\mu 4}|^2 = s_{24}^2 c_{14}^2,$
  $s_{ij} \equiv \sin\phi_{ij}$ and $c_{ij} \equiv \cos\phi_{ij}$

- **Mixing angles**

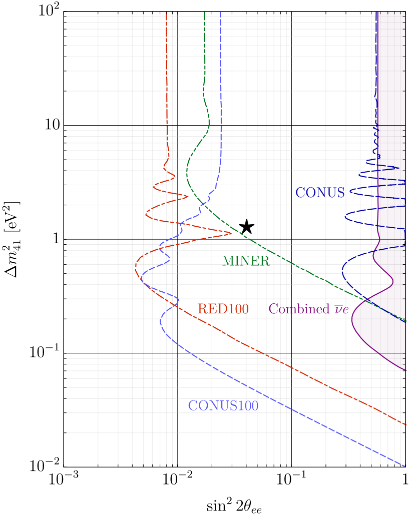
$$\sin^2 2\theta_{\alpha\alpha} = 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)$$
$$\sin^2 2\theta_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$$

- **Oscillation probability**

$$P_{\alpha\beta} \approx= \begin{cases} 1-\sin^2 2\theta_{\alpha\alpha}\sin^2\frac{\Delta_{41}}{2} & (\alpha=\beta) \\ \sin^2 2\theta_{\alpha\beta}\sin^2\frac{\Delta_{41}}{2} & (\alpha\neq\beta) \end{cases},$$

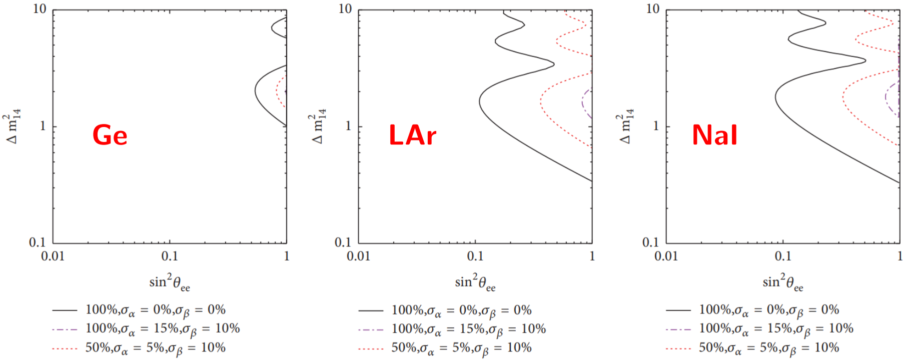
$\Delta_{ij} \equiv 2.54\left(\Delta m_{ij}^2/\text{eV}^2\right)(L/\text{km})(\text{GeV}/E_\nu)$,
where $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$

- **exclusion curves: reactor CEνNS experiments**
  [Berryman PRD D100 (2019) 023540]



Sterile neutrinos @ COHERENT (probing $\sin^2 2\theta_{ee}$)

[Miranda, Sanchez-Garcia, Sanders, Adv.High Energy Phys. 2019 (2019) 3902819]

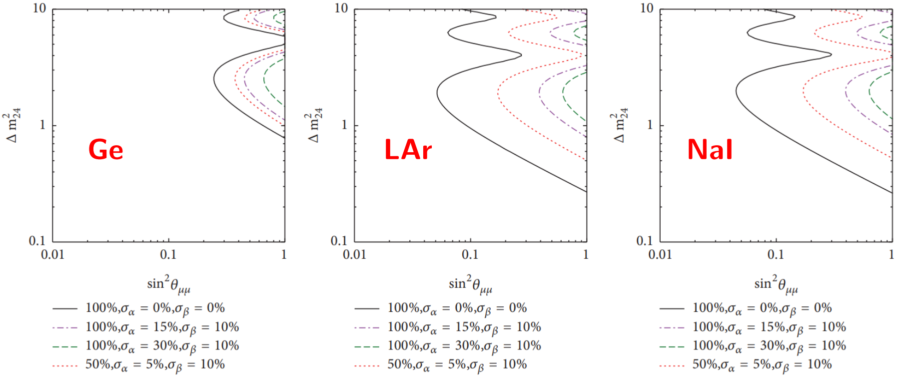


	T_{thres}	Baseline	Det. Tec.	Fid. Mass
^{133}Cs^{127}I	5 keV	19.3 m	Scintillator	14.6 kg
^{72}Ge	5 keV	22 m	HPGe PPC	10 kg
^{23}Na^{127}I	13 keV	28 m	Scintillator	2000 kg
^{40}Ar	20 keV	29 m	Liquid scintillator	1000 kg

Current and future experimental setups for the COHERENT collaboration detectors

Sterile neutrinos @ COHERENT (probing $\sin^2 2\theta_{\mu\mu}$)

[Miranda, Sanchez-Garcia, Sanders, Adv.High Energy Phys. 2019 (2019) 3902819]



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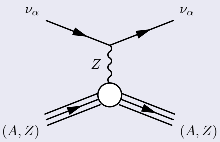
Current and future experimental setups for the COHERENT collaboration detectors

Summary

SM CEνNS reaction (conventional)

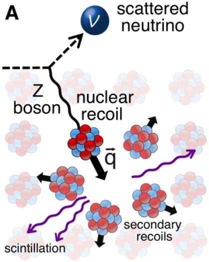
$$\nu_\alpha + (A, Z) \to \nu_\alpha + (A, Z), \quad \alpha = (e, \mu, \tau)$$



- Finally observed by COHERENT in August 2017
  (other: MINER, TEXONO, CONNIE, Ricochet, νGEN, ν-cleus etc.)
- COHERENT (LAr), CONNIE, CONUS (hints)
- Very high experimental sensitivity (low detector threshold) is required

Electromagnetic neutrinos

- presented the effective μ_ν formalism in terms of fundamental parameters relevant to terrestrial neutrino experiments
- current and future limits on $|\Lambda_i|$ from low-energy CEνNS experiments (of the order of $10^{-11}\mu_B$ at least)
- demonstrated that CEνNS experiments can be competitive to large-scale ones e.g. with Borexino



Sterile neutrinos

- favorable facilities for sterile neutrino searches
- future CEνNS experiments are complementary to the LSND, MiniBooNE, MINOS+, JUNO, Daya Bay, etc. sensitivities

... *much more to expect*

Thank you for your attention !

Extras

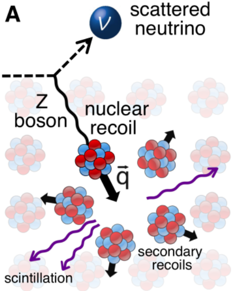
Standard Model CEνNS cross section

CEνNS cross section expressed through the nuclear recoil energy T_A

$$\left(\frac{d\sigma}{dT_A}\right)_{\text{SM}} = \frac{G_F^2 m_A}{\pi}\left[\mathcal{Q}_V^2\left(1-\frac{m_A T_A}{2E_\nu^2}\right)+\mathcal{Q}_A^2\left(1+\frac{m_A T_A}{2E_\nu^2}\right)\right]F^2(Q^2)$$

[DKP, Kosmas: PRD 97 (2018)]

- E_ν: is the incident neutrino energy
- m_A: the nuclear mass of the detector material
- Z protons and $N = A - Z$ neutrons
- vector $\mathcal{Q}_V$ and axial vector $\mathcal{Q}_A$ contributions
- $F(Q^2)$: is the nuclear form factor



$$\mathcal{Q}_V = \left[2(g_u^L+g_u^R)+(g_d^L+g_d^R)\right]Z+\left[(g_u^L+g_u^R)+2(g_d^L+g_d^R)\right]N\,,$$

$$\mathcal{Q}_A = \left[2(g_u^L-g_u^R)+(g_d^L-g_d^R)\right](\delta Z)+\left[(g_u^L-g_u^R)+2(g_d^L-g_d^R)\right](\delta N)\,,$$

- $(\delta Z) = Z_+ - Z_-$ and $(\delta N) = N_+ - N_-$, where Z_+ (N_+) and Z_- (N_-) refers to total number of protons (neutrons) with spin up or down [Barranco et al.: JHEP 0512 (2005)]

Experimental configuration

[Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]

Experiment	detector	mass	threshold	efficiency	exposure	baseline (m)
			SNS			
COHERENT	CsI[Na]	14.57 kg [100 kg]	5 keV [1 keV]	Eq. (**??**) [100%]	308.1 days [10 yr]	19.3
COHERENT	HPGe	15 kg [100 kg]	5 keV [1 keV]	50% [100%]	308.1 days [10 yr]	22
COHERENT	LAr	1 ton [10 ton]	20 keV [10 keV]	50% [100%]	308.1 days [10 yr]	29
COHERENT	NaI[Tl]	2 ton [10 ton]	13 keV [5 keV]	50% [100%]	308.1 days [10 yr]	28
			Reactor			
CONUS	Ge	3.85 kg [100 kg]	100 eV	50% [100%]	1 yr [10 yr]	17
CONNIE	Si	1 kg [100 kg]	28 eV	50% [100%]	1 yr [10 yr]	30
MINER	2Ge:1Si	1 kg [100 kg]	100 eV	50% [100%]	1 yr [10 yr]	2
TEXONO	Ge	1 kg [100 kg]	100 eV	50% [100%]	1 yr [10 yr]	28
RED100	Xe	100 kg [100 kg]	500 eV	50% [100%]	1 yr [10 yr]	19

Calculation of the number of events above threshold

$$N_{\rm theor} = \sum_{\nu_\alpha} \sum_{x=\rm isotope} \mathcal{F}_x \int_{T_{\rm th}}^{T_A^{\rm max}} \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} f_{\nu_\alpha}(E_\nu) \mathcal{A}(T_A) \left(\frac{d\sigma_x}{dT_A}(E_\nu, T_A) \right)_{\rm tot} dE_\nu dT_A \,,$$

- luminosity for a detector with target material x: $\mathcal{F}_x = N_{\rm targ}^x \Phi_\nu$
- $E_\nu^{\rm min} = \sqrt{m_A T_A/2}$: the minimum incident neutrino energy to produce a nuclear recoil

Statistical analysis

First phase of COHERENT (with a CsI detector)

$$\chi^2(\mathcal{S}) = \min_{\mathrm{a}_1,\mathrm{a}_2}\left[\frac{(N_{\rm meas} - N_{\rm theor}(\mathcal{S})[1+\mathrm{a}_1] - B_{0n}[1+\mathrm{a}_2])^2}{(\sigma_{\rm stat})^2} + \left(\frac{\mathrm{a}_1}{\sigma_{\mathrm{a}_1}}\right)^2 + \left(\frac{\mathrm{a}_2}{\sigma_{\mathrm{a}_2}}\right)^2\right].$$

- measured number of events is $N_{\rm meas} = 142$,
- a_1 and a_2 are the systematic uncertainties (signal and background rates), with $\sigma_{\mathrm{a}_1} = 0.28$ and $\sigma_{\mathrm{a}_2} = 0.25$.
- Statistical uncertainty $\sigma_{\rm stat} = \sqrt{N_{\rm meas} + B_{0n} + 2B_{ss}}$, where the quantities $B_{0n} = 6$ and $B_{ss} = 405$ denote the beam-on prompt neutron and the steady-state background events respectively.

Reactor experiments and next generation of COHERENT

$$\chi^2(\mathcal{S}) = \min_{\mathrm{a}}\left[\frac{(N_{\rm meas} - N_{\rm theor}(\mathcal{S})[1+\mathrm{a}])^2}{(1+\sigma_{\rm stat})N_{\rm meas}} + \left(\frac{\mathrm{a}}{\sigma_{\rm sys}}\right)^2\right],$$

- with $\sigma_{stat} = \sigma_{\rm sys} = 0.2$ (0.1) for the current (future) setups.

Probe TMMs through minimization over the nuisance parameter a and calculate $\Delta\chi^2(\mathcal{S}) = \chi^2(\mathcal{S}) - \chi^2_{\rm min}(\mathcal{S})$, with $\mathcal{S} \equiv \{|\Lambda_i|, \xi_i, \delta_{\rm CP}\}$

Constraints on TMMs from CEvNS experiments

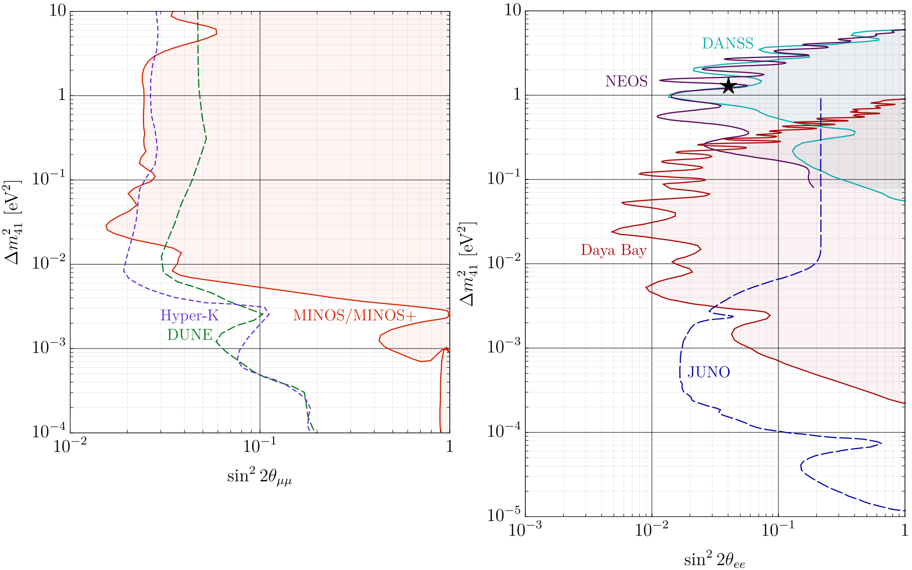
Experiment	$\|\Lambda_1\|$	$\|\Lambda_2\|$	$\|\Lambda_3\|$
	SNS prompt		
CsI[Na]	69.2 [5.0]	70.2 [5.1]	89.6 [6.4]
HPGe	25.9 [5.1]	26.2 [5.2]	33.5 [6.6]
LAr	14.7 [2.9]	14.9 [2.9]	19.1 [3.7]
NaI[Tl]	16.6 [2.8]	16.8 [2.8]	21.5 [3.6]
	SNS delayed		
CsI[Na]	54.5 [4.2]	48.7 [3.7]	49.8 [3.7]
HPGe	21.3 [4.2]	18.9 [3.8]	19.1 [3.8]
LAr	11.3 [2.3]	10.1 [2.1]	10.4 [2.1]
NaI[Tl]	10.0 [2.3]	9.1 [2.0]	9.4 [2.0]
	Reactor		
CONUS	1.9 [0.37]	1.3 [0.26]	1.1 [0.22]
CONNIE	0.90 [0.13]	0.63 [0.09]	0.53 [0.08]
MINER	1.7 [0.58]	1.2 [0.41]	1.0 [0.34]
TEXONO	3.2 [0.46]	2.3 [0.32]	1.9 [0.27]
RED100	1.0 [0.14]	0.72 [0.10]	0.61 [0.08]
	Solar		
Borexino	0.44	0.36	0.28

90% C.L. limits on TMM elements $|\Lambda_i|$, in units of 10^{-10} μ_B, from current and future CEνNS experiments. The numbers in square brackets indicate the attainable sensitivities in the future setups.

- CEνNS experiments are sensitive to EM neutrino properties
- can probe TMMs at $10^{-11}\mu_B$ at least
- competitive with large-scale solar neutrino experiments

[Miranda, DKP, Tórtola, Valle, JHEP 1907 (2019) 103]

Exclusion curves to sterile neutrinos



taken from

[Berryman PRD D100 (2019) 023540]