NON-STANDARD NEUTRIINO INTERACTIONS (NSI)

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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Non-Standard neutrino Interactions

- Neutral current Non-Standard Interaction (NSI): propagation of neutrinos in matter

$$\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{fX}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)$$

$$\text{matter field } f \in \{e,u,d\} \text{ (for NC-NSI)}$$

- Charged current Non-Standard Interaction (NSI): production and detection

$$\mathcal{L}_{\mathrm{CC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{ff'X}\,(\bar{\nu}_\alpha\gamma^\mu P_L\ell_\beta)\left(\bar{f}'\gamma_\mu P_X f\right)$$

$$f \neq f' \in \{u,d\} \text{ (for CC-NSI).}$$

Neutral current NSI

$$\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{fX}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)$$

$\epsilon_{\alpha\beta}^{fX} \to 0$ ⇒ Standard Model

$$P_{R,L} = (1 \pm \gamma_5)/2.$$

matter field $f \in \{e, u, d\}$ (for NC-NSI)

Vector NSI $\boxed{\epsilon_{\alpha\beta}^{fV} = \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}}$

Axial NSI $\boxed{\epsilon_{\alpha\beta}^{fA} = \epsilon_{\alpha\beta}^{fR} - \epsilon_{\alpha\beta}^{fL}}$

Phenomenological consequences of vector NSI

$$\boxed{\epsilon^{fV}_{\alpha\beta} = \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}}$$

- Neutrino propagation in matter
- Coherent Elastic neutrino Nucleus Scattering $(\mathrm{CE}\nu\mathrm{NS})$: for coupling to u and d quarks

  $$\boxed{\epsilon^{uL}_{\alpha\beta} + \epsilon^{uR}_{\alpha\beta}} \qquad \boxed{\epsilon^{dL}_{\alpha\beta} + \epsilon^{dR}_{\alpha\beta}}$$

- Scattering of neutrinos off electron at BOREXINO $\nu + e \to \nu + e$

  $$\boxed{\epsilon^{eL}_{\alpha\beta} + \epsilon^{eR}_{\alpha\beta}}$$

- High energy neutrino scattering experiments (CHARM and NuTeV)
- ~~Neutral current scattering off deuterium at SNO~~ $\boxed{\nu + D \to \nu + n + p}$

Phenomenological consequences of axial vector NSI $\boxed{\epsilon^{fA}_{\alpha\beta} = \epsilon^{fR}_{\alpha\beta} - \epsilon^{fL}_{\alpha\beta}}$

- ~~Neutrino propagation in matter~~
- ~~Coherent Elastic neutrino Nucleus Scattering (CEνNS) : for coupling to u and d~~
- Scattering of neutrinos off electron $\nu + e \to \nu + e$

$$\boxed{\epsilon^{eA}_{\alpha\beta} = \epsilon^{eR}_{\alpha\beta} - \epsilon^{eL}_{\alpha\beta}}$$

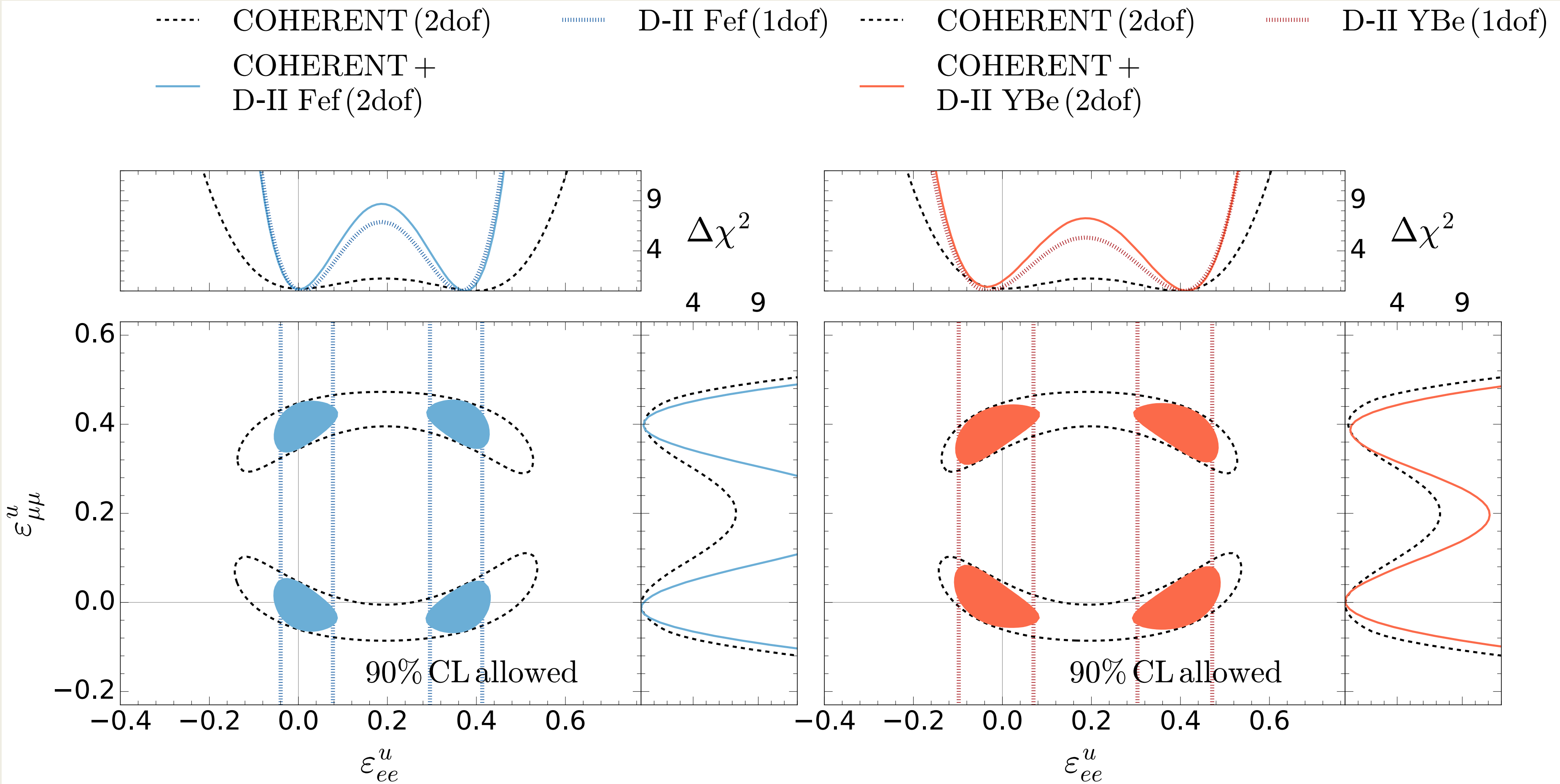
- High energy neutrino scattering experiments (CHARM and NuTeV)
- Neutral current scattering off deuterium at SNO $\boxed{\nu + D \to \nu + n + p}$

	Allowed regions at 90% CL ($\Delta\chi^2 = 2.71$)			
	Vector		Axial Vector	
	1 Parameter	Marginalized	1 Parameter	Marginalized
ε_{ee}	$[-0.09, +0.14]$	$[-1.05, +0.17]$	$[-0.05, +0.10]$	$[-0.38, +0.24]$
$\varepsilon_{\mu\mu}$	$[-0.51, +0.35]$	$[-2.38, +1.54]$	$[-0.29, +0.19] \oplus [+0.68, +1.45]$	$[-1.47, +2.37]$
$\varepsilon_{\tau\tau}$	$[-0.66, +0.52]$	$[-2.85, +2.04]$	$[-0.40, +0.36] \oplus [+0.69, +1.44]$	$[-1.82, +2.81]$
$\varepsilon_{e\mu}$	$[-0.34, +0.61]$	$[-0.83, +0.84]$	$[-0.30, +0.43]$	$[-0.79, +0.76]$
$\varepsilon_{e\tau}$	$[-0.48, +0.47]$	$[-0.90, +0.85]$	$[-0.40, +0.38]$	$[-0.81, +0.78]$
$\varepsilon_{\mu\tau}$	$[-0.25, +0.36]$	$[-2.07, +2.06]$	$[-1.10, -0.75] \oplus [-0.13, +0.22]$	$[-1.95, +1.91]$

Table 2. 90% CL bounds (1 d.o.f., 2-sided) on the coefficients of NSI operators with electrons, for the vector (ε^V) and axial vector (ε^A) scenarios. Results are provided separately for two cases: when only one NSI operator is included at at time ("1 Parameter") or when the remaining NSI coefficients are allowed to float freely in the fit ("Marginalized").

$$\nu + e \to \nu + e$$

P. Coloma et al.,
"Constraining New Physics with Borexino Phase-II spectral data," [arXiv:2204.03011 [hep-ph]].



$$\left[\mathcal{Q}_W + (2\,Z + N)\ \varepsilon^u_{ee}\right]^2 + 2\left[\mathcal{Q}_W + (2\,Z + N)\ \varepsilon^u_{\mu\mu}\right]^2 = \text{constant}$$

P. Coloma et al., "Bounds on new physics with data of the Dresden-II reactor experiment and COHERENT," JHEP **05** (2022), 037

Oscillation in matter in presence of NSI

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H^\nu \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$H^\nu = H_{\rm vac} + H_{\rm mat} \quad \text{and} \quad H^{\bar\nu} = (H_{\rm vac} - H_{\rm mat})^*$$

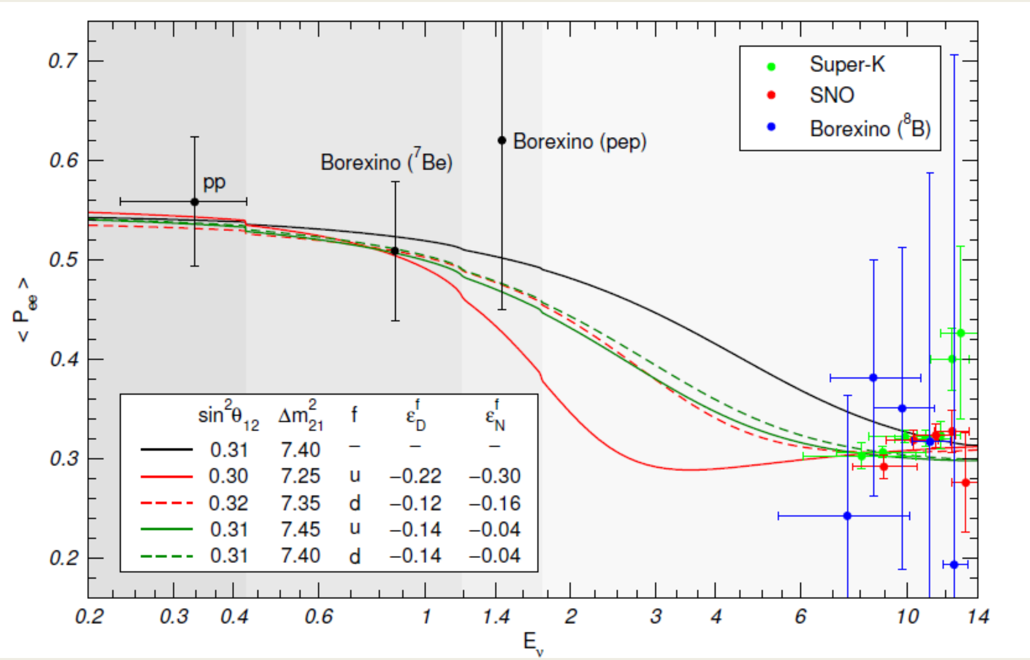
$$\epsilon^f_{\alpha\beta} = \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}$$

$$H_{\rm mat} = \sqrt{2}G_F N_e(r)\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix} + \sqrt{2}G_F \sum_{f=e,u,d} N_f(r)\begin{pmatrix}\varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau}\\ \varepsilon^{f*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau}\\ \varepsilon^{f*}_{e\tau} & \varepsilon^{f*}_{\mu\tau} & \varepsilon^f_{\tau\tau}\end{pmatrix}$$

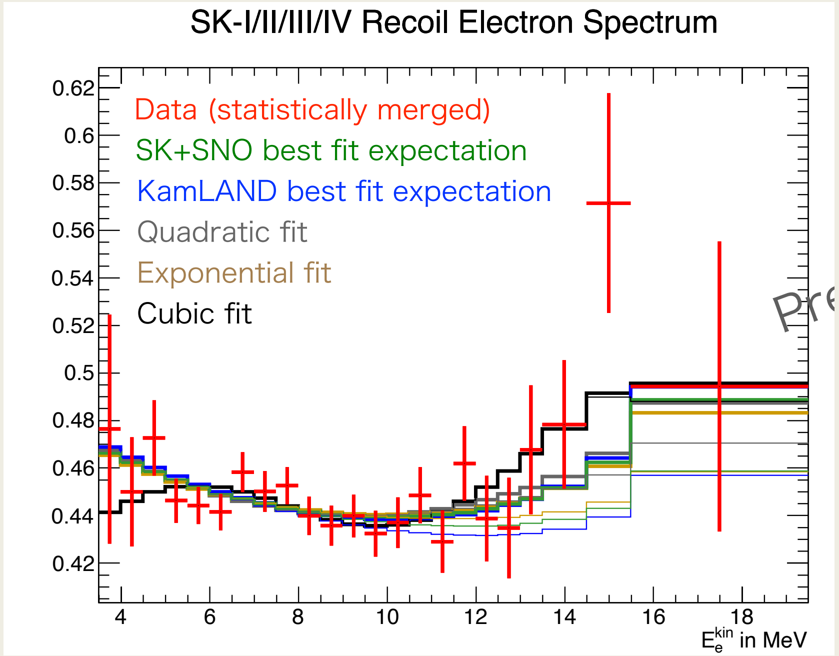
$$H_{\rm mat} = \sqrt{2} G_F N_e(r) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2} G_F \sum_{f=e,u,d} N_f(r) \begin{pmatrix} \varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau} \\ \varepsilon^{f*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau} \\ \varepsilon^{f*}_{e\tau} & \varepsilon^{f*}_{\mu\tau} & \varepsilon^f_{\tau\tau} \end{pmatrix}$$

Oscillation is senstive to $\left\{ \begin{array}{l} \epsilon_{\alpha\beta} \quad \alpha \neq \beta \\ \epsilon_{\alpha\alpha} - \epsilon_{\beta\beta} \end{array} \right.$

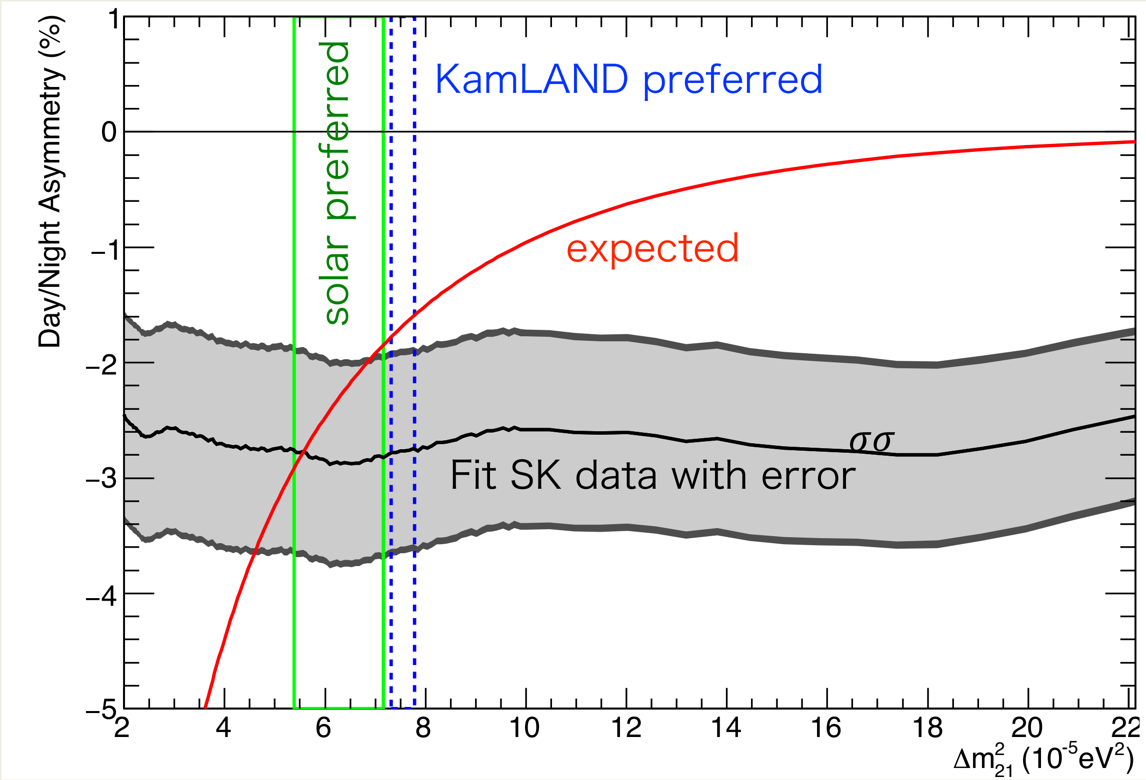
Just like sensitivity to $m_i^2 - m_j^2$ rather than to $m_i^2,\ m_j^2$



Maltoni and Gonzalez-Garcia, JHEP 2013



Y. Koshio's talk on Thursday
Poster T10-583 by Y. Nakano



Y. Koshio's talk on Thursday
Poster T10-583 by Y. Nakano

1.5 sigma discrepancy between KamLAND and SK from D/N asymmetry

Global neutrino oscillation analysis plus COHERENT

	Total Rate	Data Release t+E
ε^u_{ee}	$[-0.012, +0.621]$	$[+0.043, +0.384]$
$\varepsilon^u_{\mu\mu}$	$[-0.115, +0.405]$	$[-0.050, +0.062]$
$\varepsilon^u_{\tau\tau}$	$[-0.116, +0.406]$	$[-0.050, +0.065]$
$\varepsilon^u_{e\mu}$	$[-0.059, +0.033]$	$[-0.055, +0.027]$
$\varepsilon^u_{e\tau}$	$[-0.250, +0.110]$	$[-0.141, +0.090]$
$\varepsilon^u_{\mu\tau}$	$[-0.012, +0.008]$	$[-0.006, +0.006]$
ε^d_{ee}	$[-0.015, +0.566]$	$[+0.036, +0.354]$
$\varepsilon^d_{\mu\mu}$	$[-0.104, +0.363]$	$[-0.046, +0.057]$
$\varepsilon^d_{\tau\tau}$	$[-0.104, +0.363]$	$[-0.046, +0.059]$
$\varepsilon^d_{e\mu}$	$[-0.058, +0.032]$	$[-0.052, +0.024]$
$\varepsilon^d_{e\tau}$	$[-0.198, +0.103]$	$[-0.106, +0.082]$
$\varepsilon^d_{\mu\tau}$	$[-0.008, +0.008]$	$[-0.005, +0.005]$
ε^p_{ee}	$[-0.035, +2.056]$	$[+0.142, +1.239]$
$\varepsilon^p_{\mu\mu}$	$[-0.379, +1.402]$	$[-0.166, +0.204]$
$\varepsilon^p_{\tau\tau}$	$[-0.379, +1.409]$	$[-0.168, +0.257]$
$\varepsilon^p_{e\mu}$	$[-0.179, +0.112]$	$[-0.174, +0.086]$
$\varepsilon^p_{e\tau}$	$[-0.877, +0.340]$	$[-0.503, +0.295]$
$\varepsilon^p_{\mu\tau}$	$[-0.041, +0.025]$	$[-0.020, +0.019]$

P. Coloma, et al, "Improved global fit to Non-Standard neutrino Interactions using COHERENT energy and timing data," JHEP **02** (2020), 023

What is the underlying model for the effective four-fermion Lagrangian?

- Integrating out Z' with mass $m_{Z'}$ and coupling $g_{Z'}$

$$\boxed{-2\sqrt{2}G_F\, \epsilon_{\alpha\beta}^{fX}\, (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)}$$

$$\epsilon = \left(\frac{g_{Z'}^2}{m_{Z'}^2}\right) G_F^{-1}$$

Underlying theory for NSI

$$\boxed{\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\, \epsilon_{\alpha\beta}^{f\,X}\, (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)}$$

Integrating out a heavy intermediate state

Neutral U(1) gauge boson as mediator

$$\boxed{Z'_\mu \bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta} \qquad \boxed{Z'_\mu \bar{f} \gamma^\mu P_X f}$$

Underlying theory for NSI

$$\boxed{\mathcal{L}_{\rm NC-NSI} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{f\,X}\left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right)\left(\bar{f}\gamma_\mu P_X f\right)}$$

Integrating out a heavy intermediate state

Neutral U(1) gauge boson as mediator

$$\boxed{Z'_\mu\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta} \qquad \boxed{Z'_\mu\bar{f}\gamma^\mu P_X f}$$

Charged scalar (a la Fierz transformation)

$$\boxed{\overline{\psi_1}P_L\psi_2\overline{\psi_3}P_R\psi_4 = \overline{\psi_{1R}}\psi_{2L}\overline{\psi_{3L}}\psi_{4R} = -\frac{1}{2}\overline{\psi_1}\gamma^\mu P_R\psi_4\overline{\psi_3}\gamma_\mu P_L\psi_2}$$

Forero and Huang, JHEP 1703 (2017); Bischer, Rodejohann and Xu, JHEP 1810 (2018) 096, arXiv:1807.08102

Underlying theory for NSI

$$\boxed{\mathcal{L}_{\rm NC-NSI} = -2\sqrt{2}G_F\, \epsilon_{\alpha\beta}^{f\,X} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f}\gamma_\mu P_X f\right)}$$

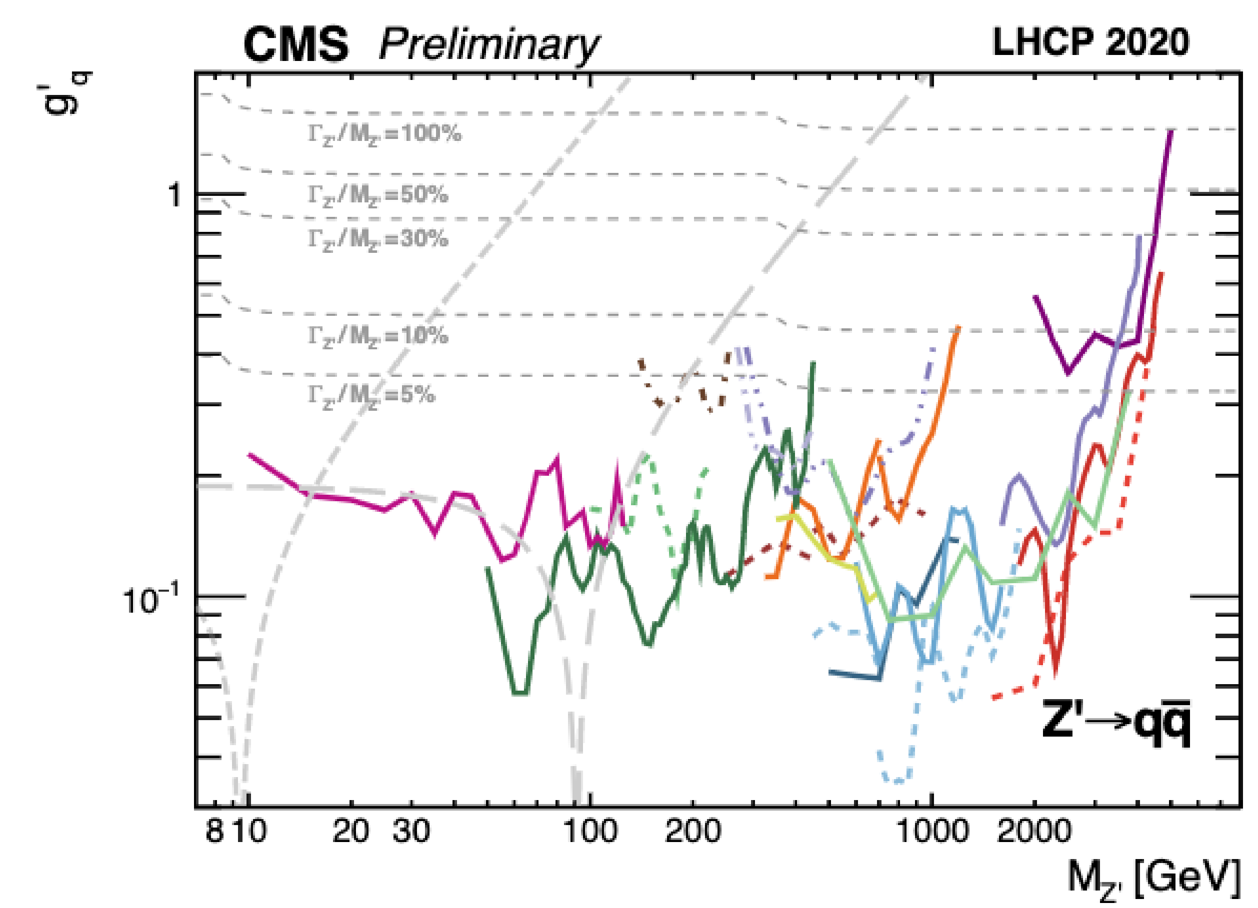
Integrating out a heavy intermediate state

Our Focus

Neutral U(1) gauge boson as mediator

$\boxed{Z'_\mu \bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta}$

$\boxed{Z'_\mu \bar{f} \gamma^\mu P_X f}$



PDG

ATLAS, CMS, CDF, and UA2 experiments

Too small NSI

$$\boxed{-2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{fX}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)}$$

$$\boxed{\epsilon_{\alpha\beta}^{f}\equiv\epsilon_{\alpha\beta}^{fL}+\epsilon_{\alpha\beta}^{fR}.}$$

$$\epsilon=\left(\frac{g_{Z'}^2}{m_{Z'}^2}\right)G_F^{-1}$$

For $m_{Z'}>100\ \mathrm{GeV}$, $\epsilon\ll 1$

Can we make a viable model for $\epsilon \sim 1$?

Motivation: LMA-Dark solution for solar neutrino

Oscillation in matter in presence of NSI

$$\boxed{i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H^\nu \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}$$

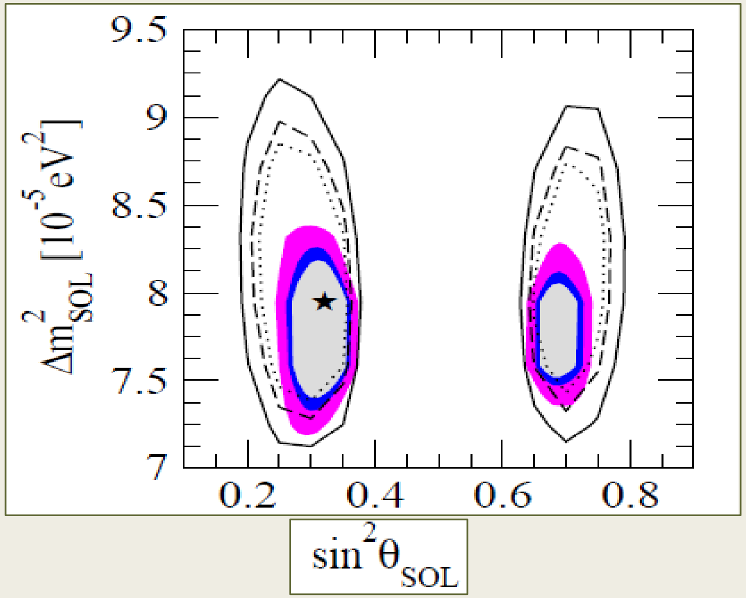
$$\epsilon^f_{\alpha\beta} = \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}$$

$$\boxed{H^\nu = H_{\rm vac} + H_{\rm mat} \quad \text{and} \quad H^{\bar\nu} = (H_{\rm vac} - H_{\rm mat})^*}$$

$$\boxed{H_{\rm mat} = \sqrt{2}G_F N_e(r)\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix} + \sqrt{2}G_F \sum_{f=e,u,d} N_f(r)\begin{pmatrix}\varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau}\\ \varepsilon^{f*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau}\\ \varepsilon^{f*}_{e\tau} & \varepsilon^{f*}_{\mu\tau} & \varepsilon^f_{\tau\tau}\end{pmatrix}}$$

LMA-Dark solution

- Miranda, Tortola and Valle, JHEP 2006; Escrihuela et al., PRD 2009



$\theta_{12} > \pi/4$

$$-1.40 < \epsilon^u_{ee} - \epsilon^u_{\mu\mu} < -0.68 \quad \text{and} \quad -1.44 < \epsilon^d_{ee} - \epsilon^d_{\mu\mu} < -0.87 \quad \text{at } 3\sigma \text{ C.L.}$$

Generalized mass ordering degeneracy

$$\boxed{\theta_{12} \to \frac{\pi}{2} - \theta_{12},\ \delta \to \pi - \delta,\ \Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21},\ \text{and}\ V_{eff} \to -S \cdot V^*_{eff} \cdot S}$$

$$S = \mathrm{Diag}(1, -1, -1)\ \text{and}\ (V_{eff})_{\alpha\beta} = \sqrt{2} G_F N_e [(\delta_{\alpha 1}\delta_{\beta 1}) + \epsilon_{\alpha\beta}]$$

$$\boxed{\epsilon_{\alpha\beta} = \sum_{f\in\{e,u,d\}} (N_f/N_e)\epsilon^f_{\alpha\beta}}$$

By carrying out long baseline neutrino experiments on Earth with different baseline and beam energy configurations, this degeneracy cannot be resolved.

ALMOST CONSTANT THROUGOUT THE EARTH CRUST AND MANTLE

$$N_n/N_p = N_n/N_e \qquad\qquad N_u/N_e \quad N_d/N_e$$

Generalized mass ordering degeneracy

$$\theta_{12} \to \frac{\pi}{2} - \theta_{12},\ \delta \to \pi - \delta,\ \Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21},\ \text{and}\ V_{eff} \to -S \cdot V^*_{eff} \cdot S$$

where $S = \text{Diag}(1, -1, -1)$ and $(V_{eff})_{\alpha\beta} = \sqrt{2} G_F N_e [(\delta_{\alpha 1}\delta_{\beta 1}) + \epsilon_{\alpha\beta}]$ in which $\epsilon_{\alpha\beta} = \sum_{f\in\{e,u,d\}} (N_f/N_e)\epsilon^f_{\alpha\beta}$

Combining the solar data with long baseline or atmosheric neutrino data

$$\boxed{N_u/N_d|_{sun} \neq N_u/N_d|_{Earth}}$$

Generalized mass ordering degeneracy

$$\theta_{12} \to \frac{\pi}{2} - \theta_{12},\ \delta \to \pi - \delta,\ \Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21},\ \text{and}\ V_{eff} \to -S \cdot V^*_{eff} \cdot S$$

where $S = \mathrm{Diag}(1, -1, -1)$ and $(V_{eff})_{\alpha\beta} = \sqrt{2} G_F N_e [(\delta_{\alpha 1}\delta_{\beta 1}) + \epsilon_{\alpha\beta}]$ in which $\epsilon_{\alpha\beta} = \sum_{f\in\{e,u,d\}} (N_f/N_e)\epsilon^f_{\alpha\beta}$

Scattering experiments can break the degeneracy

Too small NSI

$$\boxed{-2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{fX}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)}$$

$$\boxed{\epsilon_{\alpha\beta}^{f} \equiv \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}.}$$

$$\epsilon = \left(\frac{g_{Z'}^2}{m_{Z'}^2}\right) G_F^{-1}$$

For $m_{Z'} > 100 \text{ GeV}$, $\epsilon \ll 1$

Suggestion

- What if $m_{Z'} \sim 10 \text{ MeV}$

YF, "A model for large non-standard interactions leading to LMA-Dark solution," Phys. Lett. B748 (2015) 311-315; YF and J Heeck, "Neutrinophilic nonstandard interactions," PRD 94 (2016) 53010; YF and I Shoemaker, "lepton flavor violating NSI via light mediator," JHEP 1607 (2016) 33.
YF and M Tortola, "neutrino oscillations and non-standard interactions," *Front.in Phys.* 6 (2018) 10; P.B.Denton, Y.F. and I.M.Shoemaker, "Activating the fourth neutrino of the 3+1 scheme,'' Phys. Rev. D 99 (2019) no.3, 035003; Y.F., "A model for lepton flavor violating non-standard neutrino interactions,'' Phys. Lett. B **803** (2020), 135349

Suggestion

- What if $m_{Z'} \sim 10\ \mathrm{MeV}$

$\epsilon \sim 1$ $\Rightarrow$ $g_{Z'} \sim 10^{-5} - 10^{-4}$

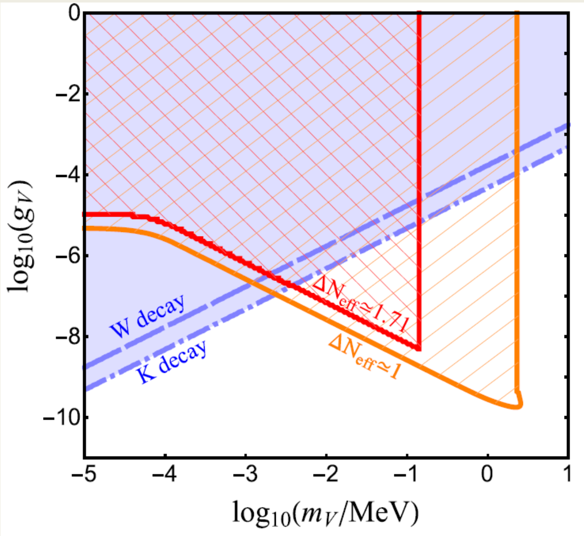
- Bounds can be avoided not because the mass of the intermediate state is high

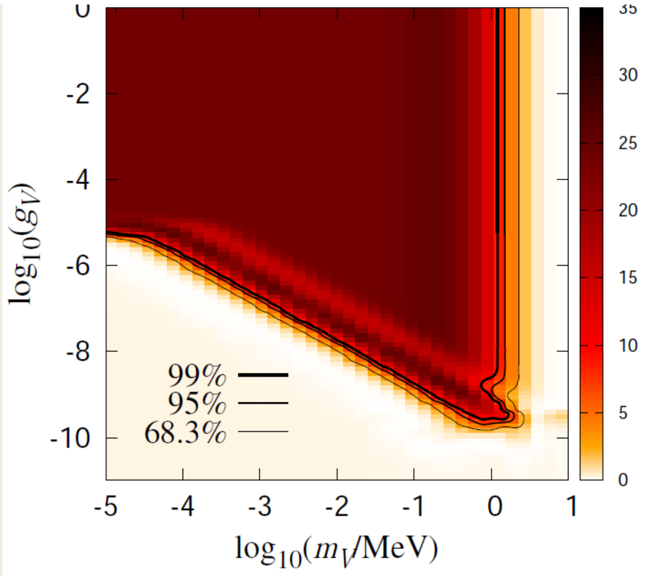
But because coupling is small!

Cosmological bounds on extra relativistic degrees of freedom

- Huang, Ohlsson and Zhou, PRD 97 (2018) 75009

The contour plot and density map of the χ^2 function



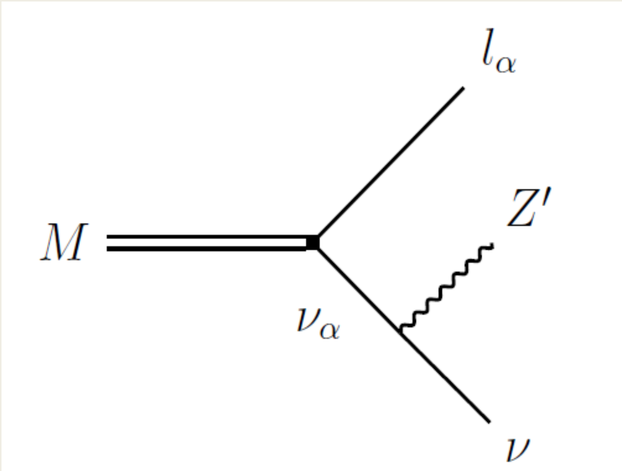


$$m_{Z'} \lesssim 5\ \text{MeV}$$

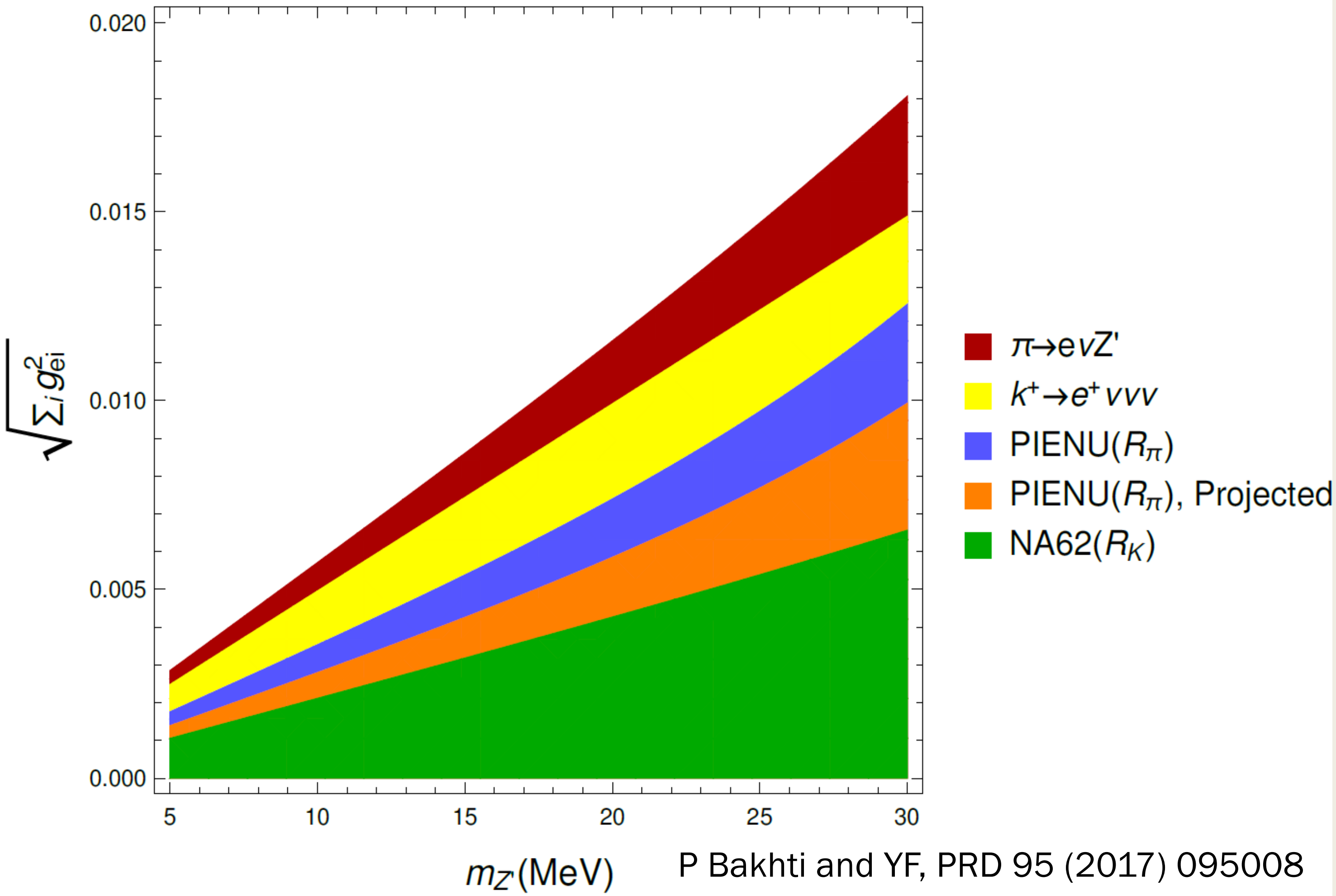
$$Y_p = 0.2449 \pm 0.0040$$

$$D/H|_p = (2.53 \pm 0.04) \times 10^{-5}$$

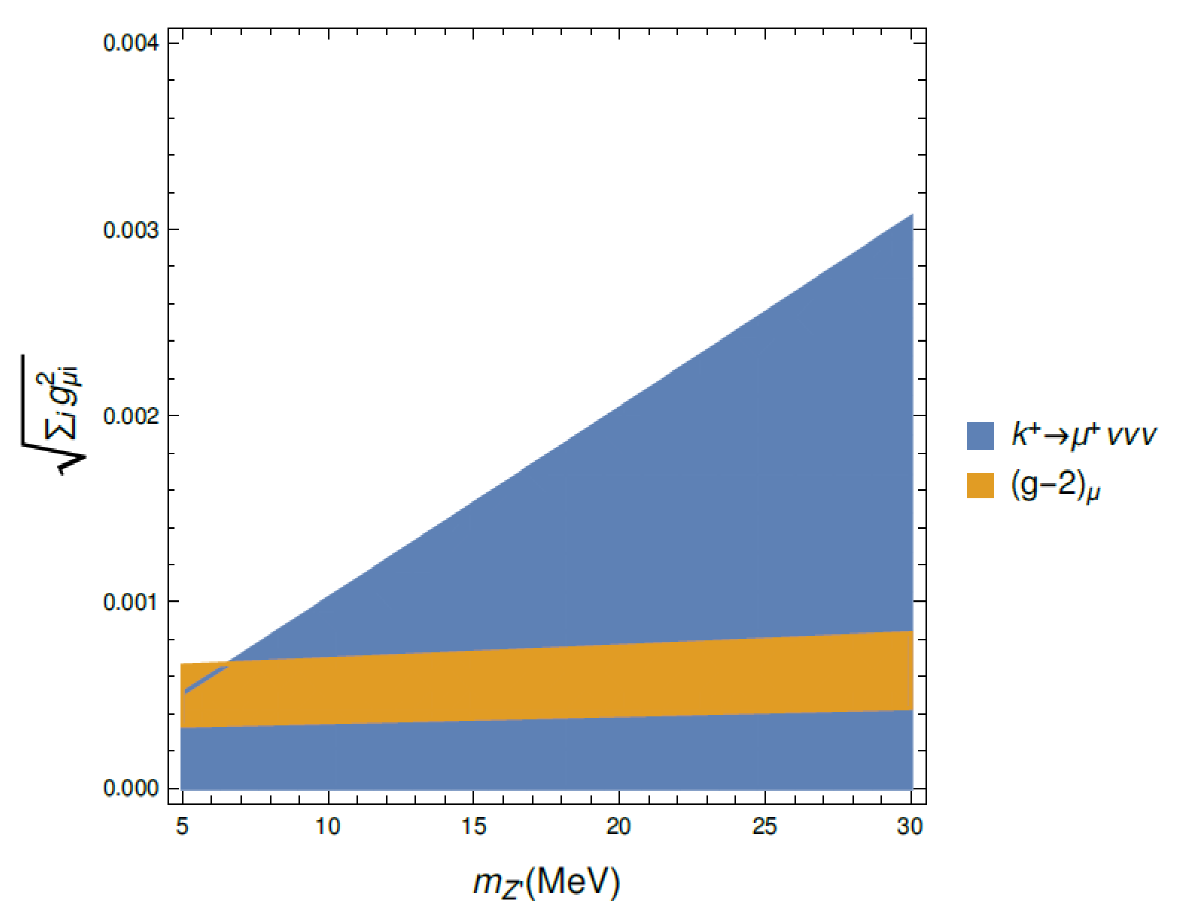
Bounds on Couplings of neutrinos



$$R_M \equiv \frac{Br(M^+ \to e^+ + \text{missing energy})}{Br(M^+ \to \mu^+ + \text{missing energy})} \qquad M^+ = \pi^+, K^+$$



P Bakhti and YF, PRD 95 (2017) 095008



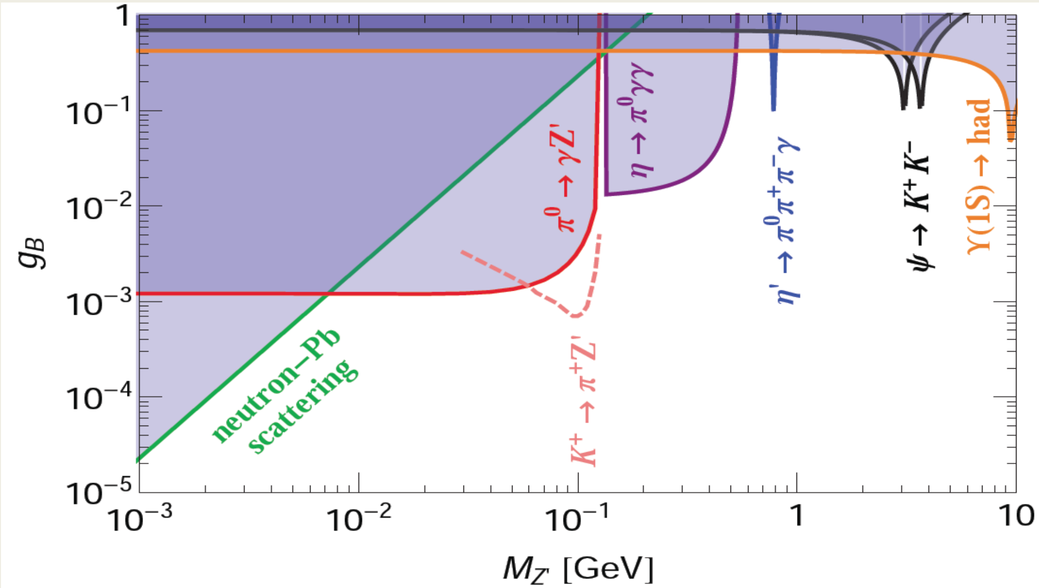
$$\Gamma(K^+ \to \mu^+ \nu \bar{\nu} \nu) < 2.4 \times 10^{-6} \Gamma(K^+ \to \text{all}) \text{ at } 90\% \text{ confidence level}$$

Artamonov et al.,
BNL-E494 collaboration,
PRD 79 (2009) 092004

P Bakhti and YF, PRD 95 (2017) 095008

Coupling to quarks

- Non-chiral couplings: No impact on total measurement at SNO
- Flavor universal: Going to mass basis $q_i \not\to q_j Z'$



$$\pi^0 \to \gamma Z'$$

Y.F. and J Heeck, PRD 94 (2016) 053010

Coupling to neutrinos

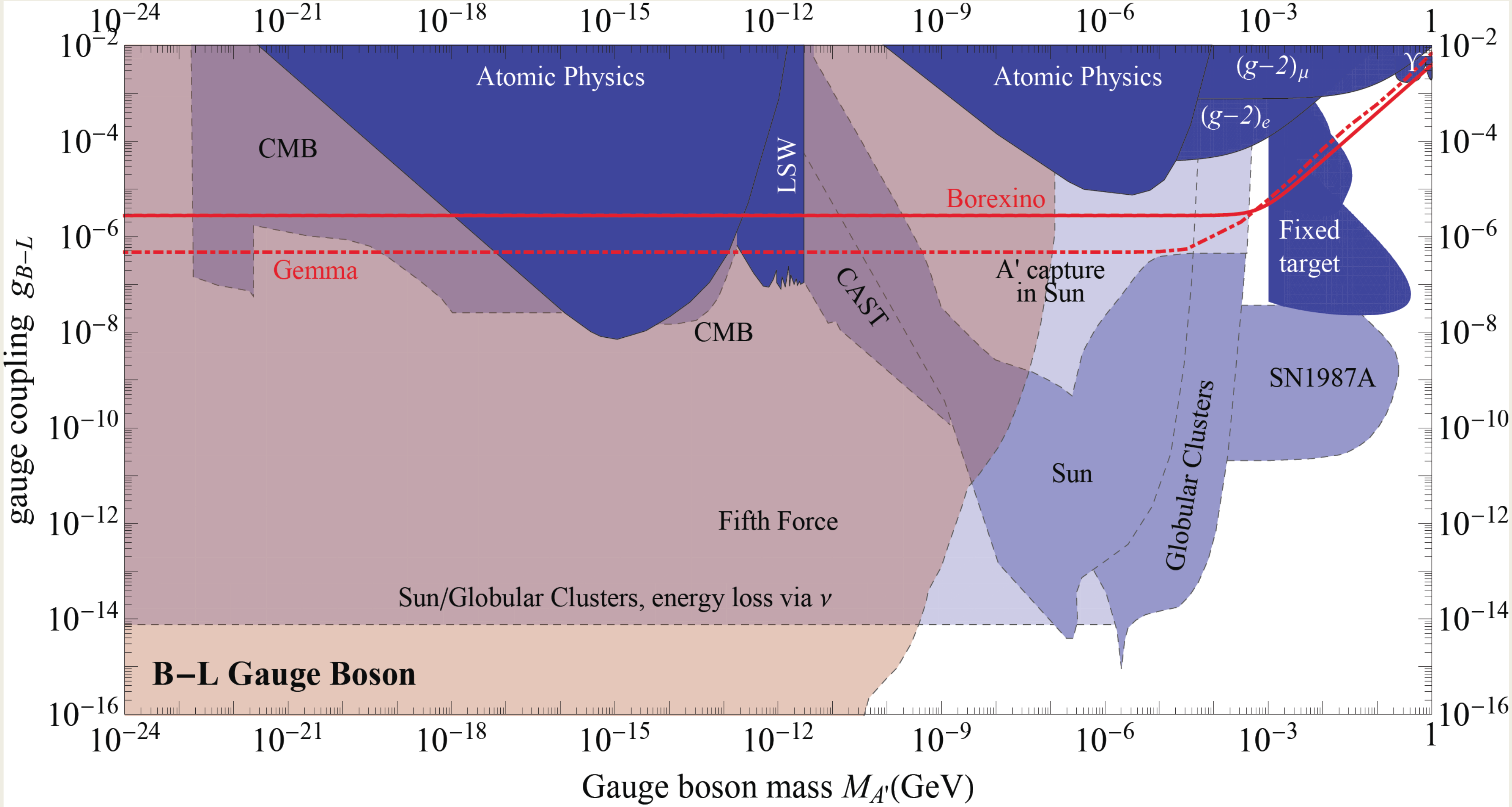
- Direct coupling to neutrinos

Gauge symmetry:

$$a_e L_e + a_\mu L_\mu + a_\tau L_\tau + B$$

$$\epsilon^u_{\alpha\alpha} = \epsilon^d_{\alpha\alpha} = \frac{g'^2 a_\alpha}{6\sqrt{2} G_F m^2_{Z'}} \quad \text{and} \quad \epsilon^u_{\alpha\beta} = 0|_{\alpha\neq\beta}$$

Charged leptons including the electron obtain NSI.



$\boxed{g' a_e < 3 \times 10^{-11}}$

Harnik, Kopp and Machado, JCAP 1207 (2012) 026

$$a_e = 0 \quad \Longrightarrow \quad \epsilon_{ee} = 0$$

$$a_\mu, a_\tau \neq 0 \quad \Longrightarrow \quad \epsilon_{\mu\mu}, \epsilon_{\tau\tau} \neq 0$$

Oscillation is sensitive to $\epsilon_{\alpha\alpha} - \epsilon_{\beta\beta}$

Can we build a model for nonzero ee and off-diagonal elements?

$$\begin{pmatrix} \epsilon_{ee}^{fV} & \epsilon_{e\mu}^{fV} & \epsilon_{e\tau}^{fV} \\ \epsilon_{e\mu}^{fV*} & \epsilon_{\mu\mu}^{fV} & \epsilon_{\mu\tau}^{fV} \\ \epsilon_{e\tau}^{fV*} & \epsilon_{\mu\tau}^{fV*} & \epsilon_{\tau\tau}^{fV} \end{pmatrix}$$

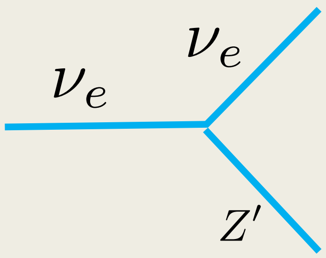
NSI for neutrinos but not for charged leptons

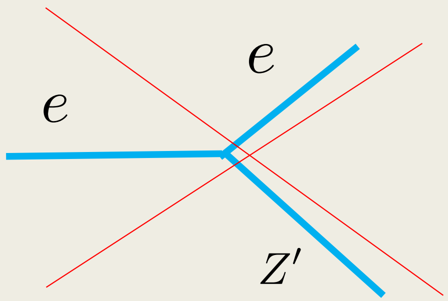
$\boxed{a_\psi L_\psi + B}$

Mixing with ψ : $\boxed{\begin{array}{c} \nu_\alpha + \kappa_\alpha \psi \\ -\kappa_\alpha \nu_\alpha + \psi \end{array}}$ $\boxed{\begin{array}{c} \nu_\beta + \kappa_\beta \psi \\ -\kappa_\beta \nu_\beta + \psi \end{array}}$

$$\boxed{g' a_\Psi Z'_\mu \left(\sum_{\alpha,\beta} \kappa^*_\alpha \kappa_\beta \bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta - \kappa^*_\alpha \bar{\nu}_\alpha \gamma^\mu P_L \Psi - \kappa_\alpha \bar{\Psi} \gamma^\mu P_L \nu_\alpha \right)}$$

$\kappa_e \neq 0$





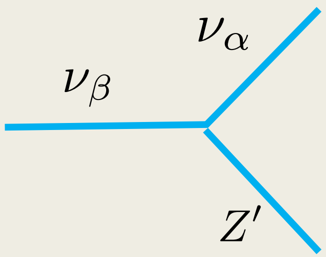
$|\epsilon_{ee}| \sim 1$

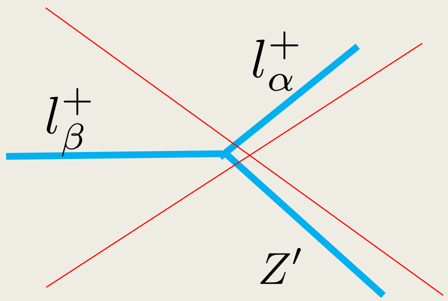
LFV NSI for neutrinos but not for charged leptons

$$\boxed{a_\psi L_\psi + B}$$

Mixing with ψ : $\boxed{\begin{array}{c} \nu_\alpha + \kappa_\alpha \psi \\ -\kappa_\alpha \nu_\alpha + \psi \end{array}}$ $\boxed{\begin{array}{c} \nu_\beta + \kappa_\beta \psi \\ -\kappa_\beta \nu_\beta + \psi \end{array}}$

$$\boxed{g' a_\Psi Z'_\mu \left(\sum_{\alpha,\beta} \kappa_\alpha^* \kappa_\beta \bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta - \kappa_\alpha^* \bar{\nu}_\alpha \gamma^\mu P_L \Psi - \kappa_\alpha \bar{\Psi} \gamma^\mu P_L \nu_\alpha \right)}$$





Enhanced by $m_{l_\beta}^2 / m_{Z'}^2$

$$Br(\tau^- \to e^- Z') < 2.7 \times 10^{-3}$$

$$Br(\tau^- \to \mu^- Z') < 5 \times 10^{-3}$$

$$Br(\mu \to e Z') < 10^{-5}$$

Coupling of neutrinos through mixing

$$g' a_\Psi Z'_\mu \left(\sum_{\alpha,\beta} \kappa^*_\alpha \kappa_\beta \bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta - \kappa^*_\alpha \bar{\nu}_\alpha \gamma^\mu P_L \Psi - \kappa_\alpha \bar{\Psi} \gamma^\mu P_L \nu_\alpha \right)$$

$$\epsilon^u_{\alpha\beta} = \epsilon^d_{\alpha\beta} = \frac{g'^2 a_\Psi \kappa^*_\alpha \kappa_\beta}{6\sqrt{2} G_F m^2_{Z'}}$$

$$\epsilon^{u(d)}_{\alpha\alpha} \epsilon^{u(d)}_{\beta\beta} = |\epsilon^{u(d)}_{\alpha\beta}|^2$$

$$|\kappa_e|^2 < 2.5 \times 10^{-3} \quad |\kappa_e|^2 < 4.4 \times 10^{-4} \quad \text{and} \quad |\kappa_\tau|^2 < 5.6 \times 10^{-3} \text{ at } 2\sigma$$

Fernandez-Martinez et al., JHEP 08 (2016) 033

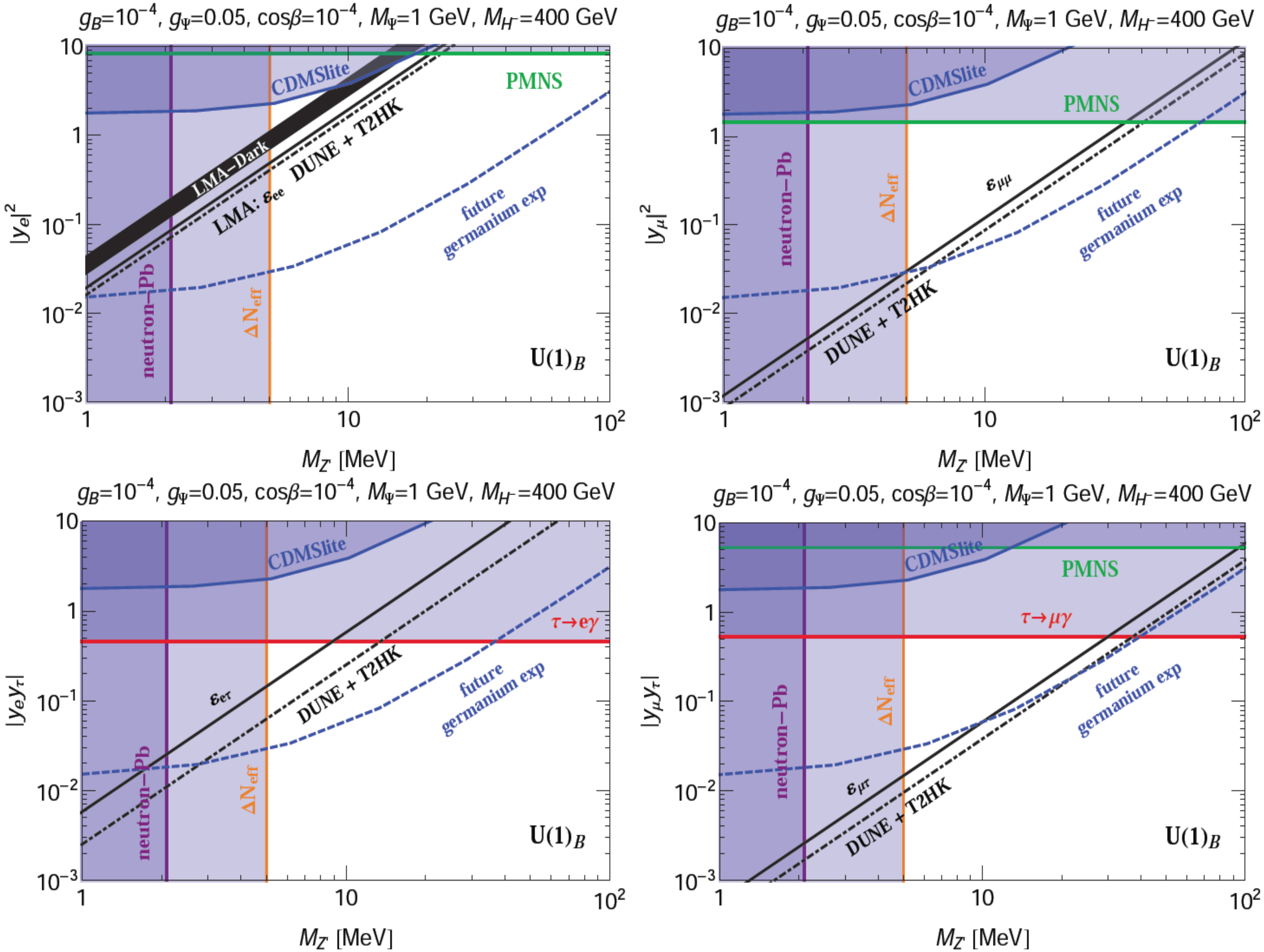
Coupling of neutrinos through mixing

$$g' a_\Psi Z'_\mu \left(\sum_{\alpha,\beta} \kappa_\alpha^* \kappa_\beta \bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta - \kappa_\alpha^* \bar{\nu}_\alpha \gamma^\mu P_L \Psi - \kappa_\alpha \bar{\Psi} \gamma^\mu P_L \nu_\alpha \right)$$

$$\epsilon^u_{\alpha\beta} = \epsilon^d_{\alpha\beta} = \frac{g'^2 a_\Psi \kappa_\alpha^* \kappa_\beta}{6\sqrt{2} G_F m_{Z'}^2}$$

$$\epsilon^{u(d)}_{\alpha\alpha} \epsilon^{u(d)}_{\beta\beta} = |\epsilon^{u(d)}_{\alpha\beta}|^2$$

$$\epsilon^u_{\alpha\beta} = \epsilon^d_{\alpha\beta} = 1 \left(\frac{g'}{10^{-5}} \right) \left(\frac{g' a_\Psi}{1} \right) \frac{\kappa_\alpha^* \kappa_\beta}{10^{-3}} \left(\frac{10 \text{ MeV}}{m_{Z'}} \right)^2$$



Y.F. and J. Heeck,
PRD94 (2016)

$$y_\alpha \bar{L}_\alpha \tilde{H}' \psi_R$$

Solar neutrino coherent
Interaction in future direct
dark matter search experiments

$$\kappa_\alpha = \frac{y_\alpha \langle H' \rangle}{m_\psi}$$

Credibility limit of four Fermi effective interaction

- For neutrino oscillation,

(forward scattering).

$$m_{Z'}^{-1} \sim 10 \text{ Fermi} \ll \text{size of medium}$$

A. Yu. Smirnov and X-J Xu, JHEP 2 (2019) 046

High energy neutrino scattering experiments

$$q^2 \gg m_{Z'}^2$$

$$\cancel{\mathcal{L}_{NSI} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}^{fP}(\bar{\nu}_\alpha\gamma^\mu L\nu_\beta)(\bar{f}\gamma_\mu P\ f)}$$

Suppression factor $m_{Z'}^2/(q^2 - m_{Z'}^2)$

Bounds from CHARM II and NuTeV are relaxed

Coherent Elastic neutrino Nucleus Scattering (CEνNS)

$$N_\alpha = N_t \Delta t \frac{G_F^2}{2\pi} M_t \int_{E_{r,\mathrm{tr}}} dE_r \int dE_\nu \phi_\alpha(E_\nu) \frac{Q_{w\alpha}^2(\sqrt{2M_t E_r})}{4} F^2(2M_t E_r) \left(2 - \frac{M_t E_r}{E_\nu^2}\right)$$

Recoil energy

$$\frac{Q_{w\alpha}^2(q)}{4} = \left[Z g_p^V + N g_n^V + 3(Z+N)\epsilon_{\alpha\alpha}^{q,V}(q)\right]^2 + 9(Z+N)^2 \sum_{\beta \neq \alpha} \left[\epsilon_{\alpha\beta}^{q,V}(q)\right]^2$$

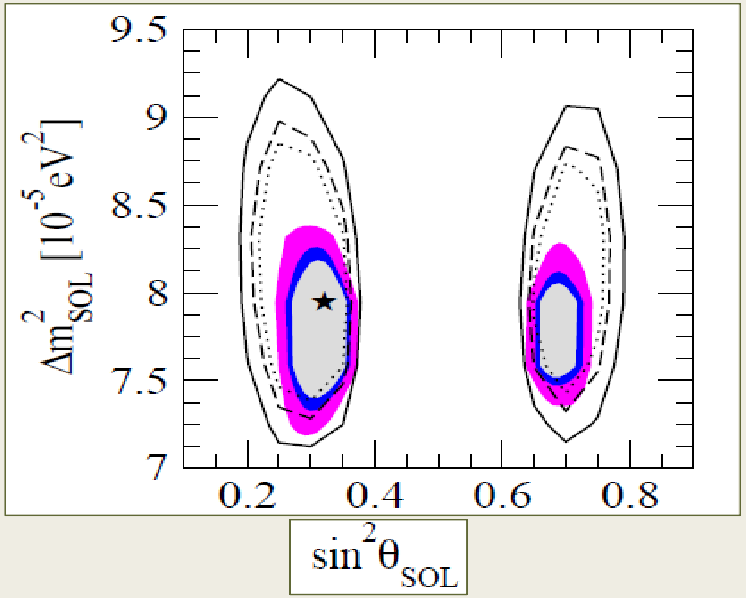
$$\epsilon_{\alpha\beta}^{f,V}(q) \equiv \frac{(g_\nu)_{\alpha\beta} g_f}{2\sqrt{2} G_F (q^2 + M_{Z'}^2)} = \epsilon_{\alpha\beta}^{f,V}(0) \frac{M_{Z'}^2}{q^2 + M_{Z'}^2},$$

$$\boxed{q^2 \sim m_{Z'}^2}$$

Denton, YF, Shoemaker, JHEP 07 (2018) 037

LMA-Dark solution

- Miranda, Tortola and Valle, JHEP 2006; Escrihuela et al., PRD 2009



$\theta_{12} > \pi/4$

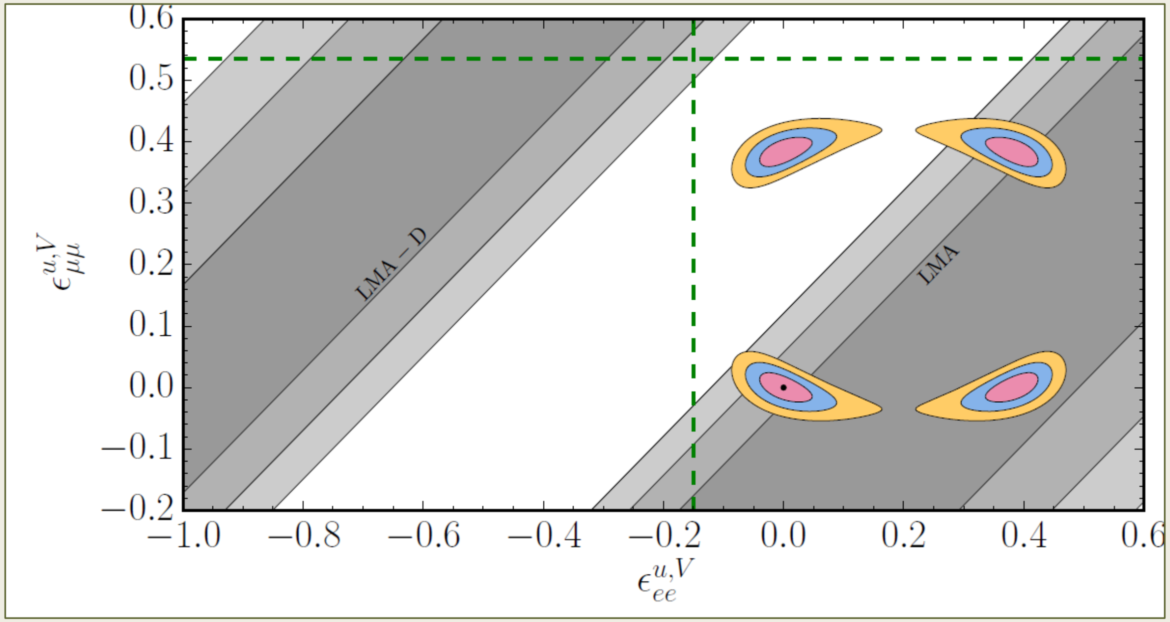
$$-1.40 < \epsilon^u_{ee} - \epsilon^u_{\mu\mu} < -0.68 \quad \text{and} \quad -1.44 < \epsilon^d_{ee} - \epsilon^d_{\mu\mu} < -0.87 \quad \text{at } 3\sigma \text{ C.L.}$$

IS LMA-Dark ruled out?

Coherent Elastic neutrino Nucleus Scattering experiments can probe this solution.

P. Coloma, M.C. Gonzalez-Garcia, M. Maltoni and T. Schwetz,, Phys. Rev. D 96 (2017) 115007, J. Liao and D. Marfatia,, Phys. Lett. B 775 (2017) 54, P.B. Denton, Y. Farzan and I.M. Shoemaker, JHEP 07 (2018) 037, C. Giunti, Phys.Rev. D 101 (2020) 035039, P. Coloma, I. Esteban, M.C. Gonzalez-Garcia and M. Maltoni, JHEP 02 (2020) 023, O.G. Miranda, D.K. Papoulias, G. Sanchez Garcia, O. Sanders, M. Tórtola and J.W.F. Valle, JHEP 05 (2020) 130, B. Dutta, R.F. Lang, S. Liao, S. Sinha, L. Strigari and A. Thompson, JHEP 09 (2020) 106, M Chaves and T. Schwetz, JHEP 05 (2021) 042; P. B. Denton and J Gehrlein, arXiv:2204.09060

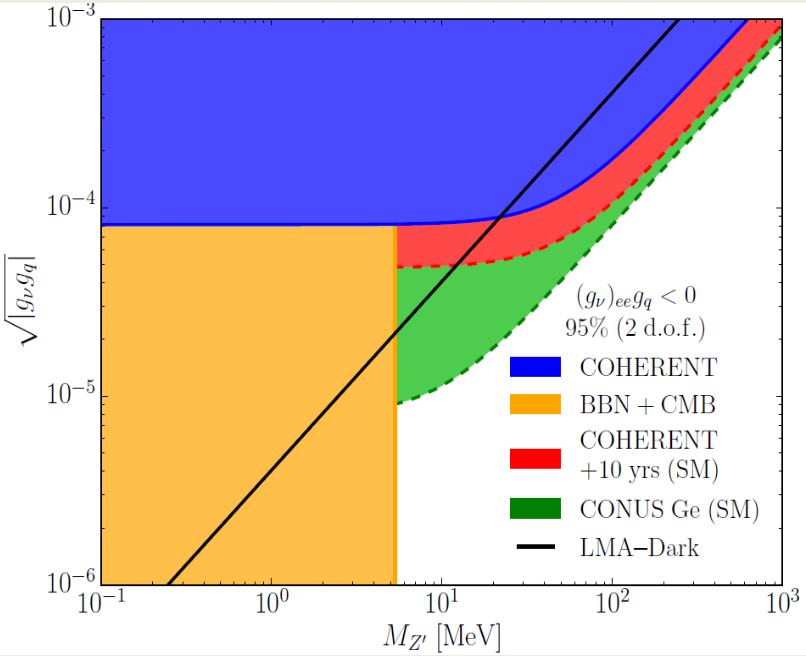
COHERENT experiment

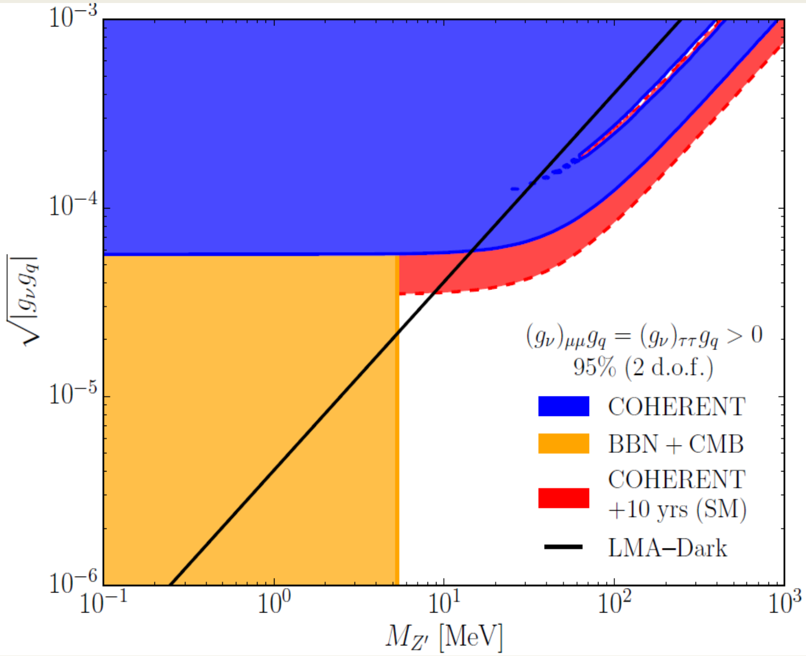


Coloma et al, JHEP 1704 (2017) 116

Neutrino source: Pion decay at rest

Arbitrary $\epsilon^{uV}/\epsilon^{dV}$ FOR HEAVY MEDIATOR





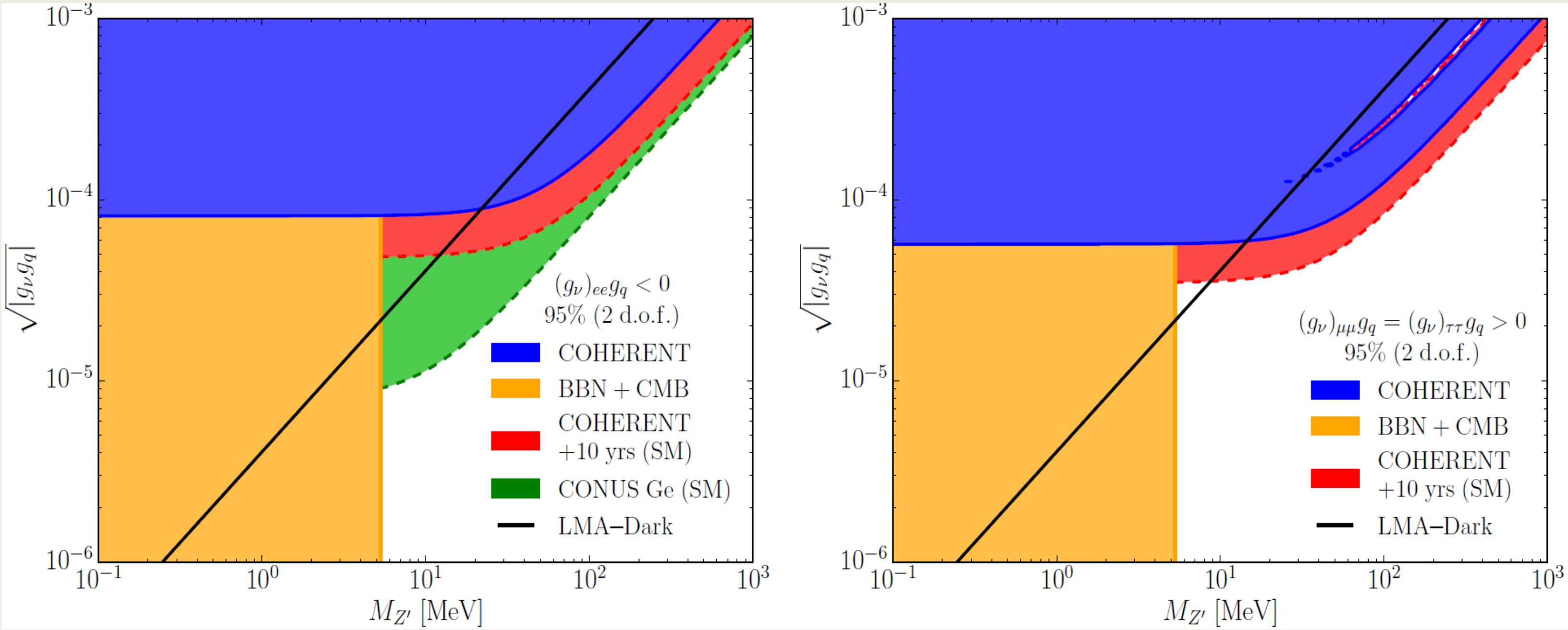
Denton, YF and Shoemaker, JHEP 1807 (2018) 037; arXiv:1804.03660.

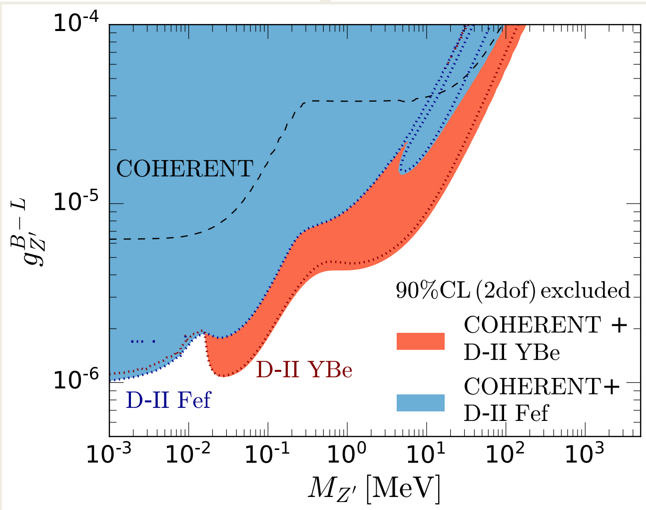
$$\eta = 45^\circ$$

COherent NeUtrino Scattering experiment (CONUS)

$$\epsilon^u = \epsilon^d$$

Germanium detector with detection threshold of 0.1 keV located 17 m away from a nuclear power plant 3.9 GW in Brokdorf, Germany



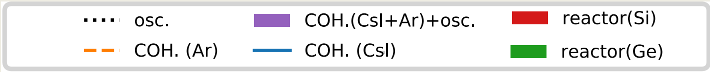


Coloma et al., arXiv:2202.10829

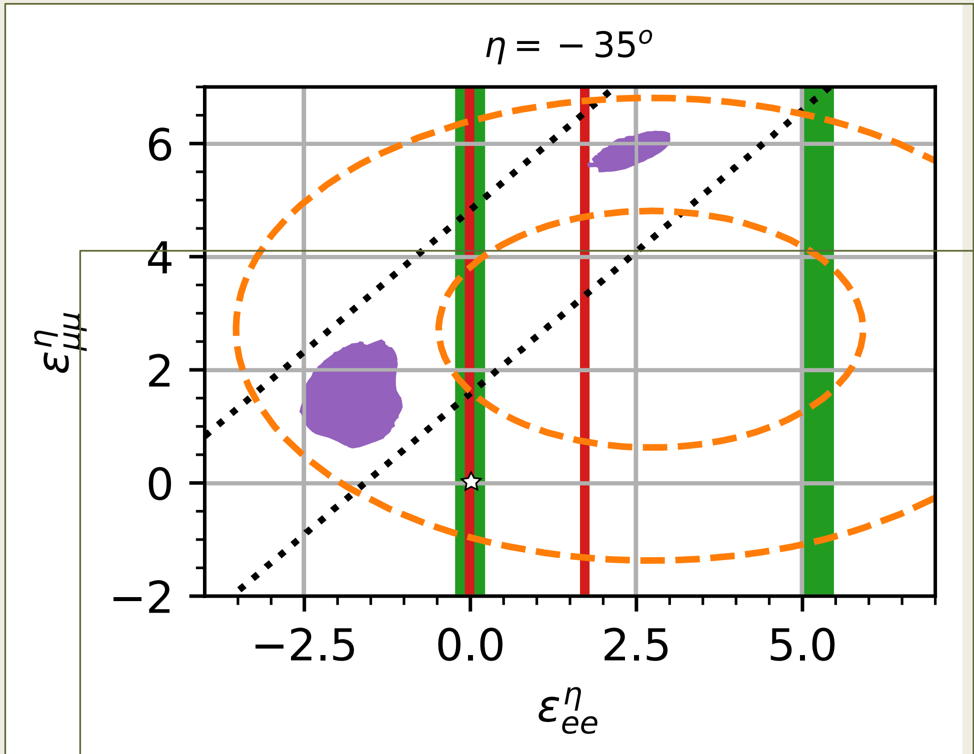
- CAN WE SAY THAT LMA-DARK SOLUTION HAS COMPLETELY DIED?

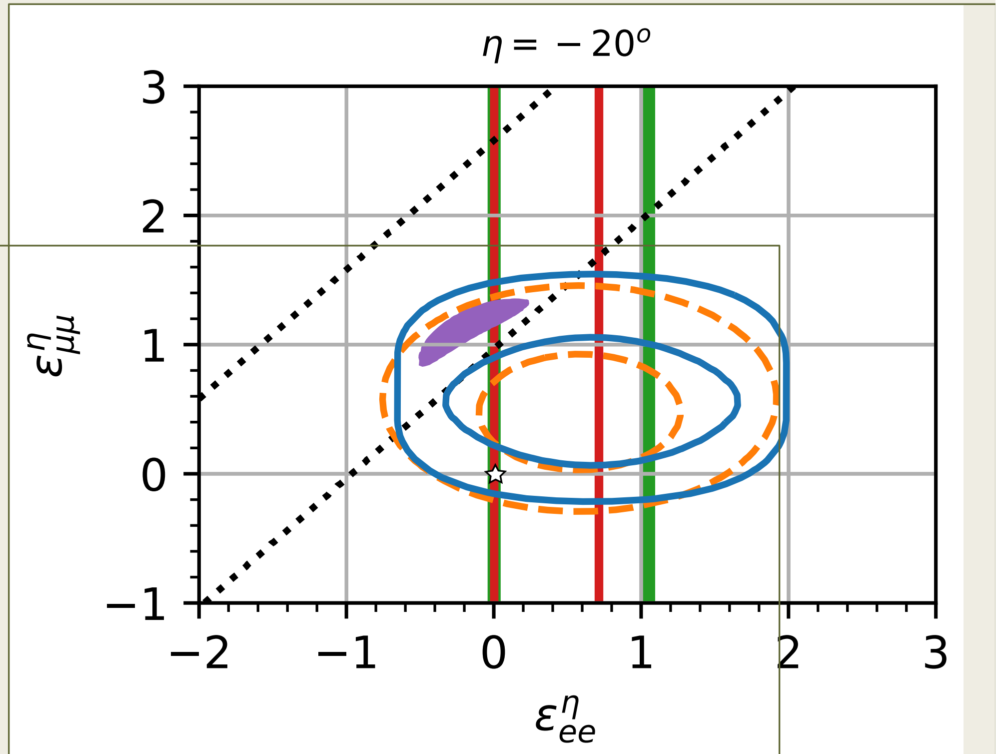
- NO

- IN OUR MODEL, $\epsilon^u = \epsilon^d$ but if we allow for $\epsilon^u \neq \epsilon^d$



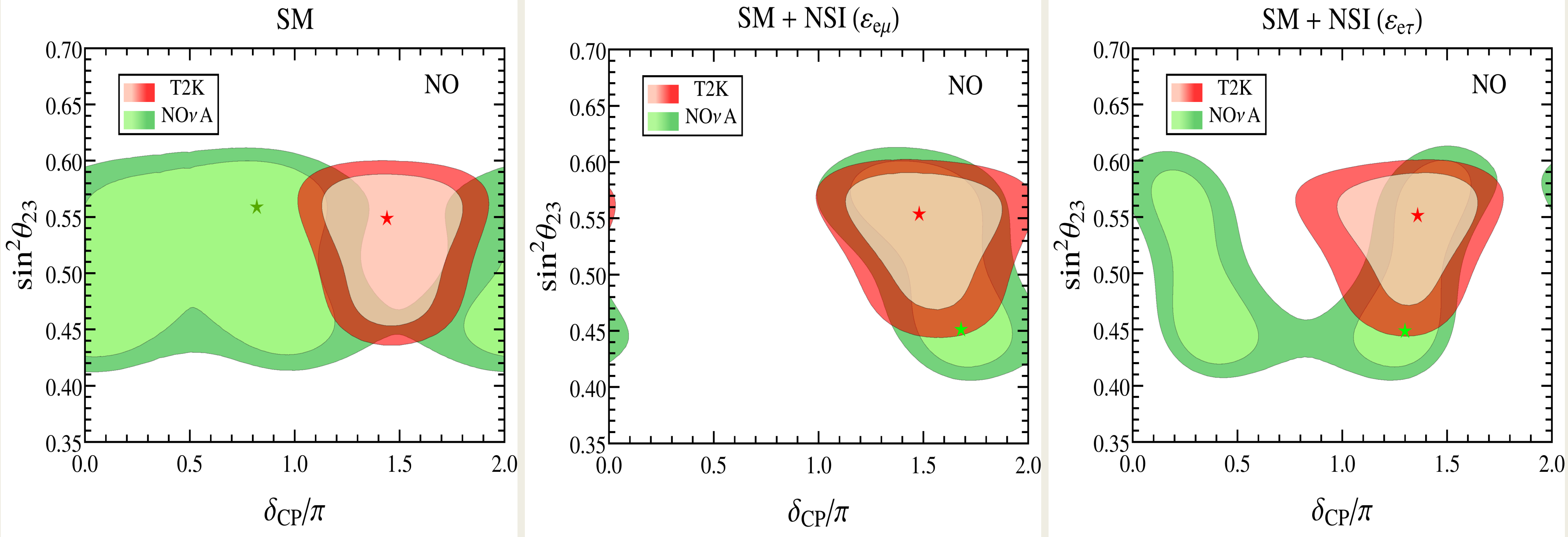
$$\tan\eta = \epsilon^{n}_{\alpha\beta}/\epsilon^{p}_{\alpha\beta}$$





$$\epsilon^{p}_{\alpha\beta} = 2\epsilon^{u}_{\alpha\beta} + \epsilon^{d}_{\alpha\beta} = \sqrt{5}\epsilon^{\eta}_{\alpha\beta}\cos\eta\,, \qquad \epsilon^{n}_{\alpha\beta} = 2\epsilon^{d}_{\alpha\beta} + \epsilon^{u}_{\alpha\beta} = \sqrt{5}\epsilon^{\eta}_{\alpha\beta}\sin\eta\,.$$

M Chaves and T. Schwetz, JHEP 05 (2021) 042



$(|\varepsilon_{e\mu}| = 0.15, \phi_{e\mu} = 1.38\pi)$. $|\varepsilon_{e\tau}| = 0.275, \phi_{e\tau} = 1.62\pi$

$$\varepsilon_{\alpha\beta} \equiv \sum_{f,C} \varepsilon_{\alpha\beta}^{fC} \frac{N_f}{N_e} \equiv \sum_{f=e,u,d} \left(\varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR}\right) \frac{N_f}{N_e},$$

$$N_u \simeq N_d \simeq 3N_e$$

S. S. Chatterjee and A Palazzo, arXiv:2201.10412; PRL 126 (2021) 5, 051802

What we need

$$g_f(\bar{f}\gamma^\mu f)Z'_\mu$$

$$(g_\nu)_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu\nu_\beta)Z'_\mu \qquad \alpha\neq\beta.$$

$$\Rightarrow \quad \epsilon^f_{\alpha\beta} = \frac{g_f(g_\nu)_{\alpha\beta}}{2\sqrt{2}G_F m^2_{Z'}}$$

Coupling to neutrinos

new gauge $U'(1)$

$\psi_1 \to e^{i\alpha}\psi_1$ and $\psi_2 \to e^{-i\alpha}\psi_2$.

$$\psi_1 \equiv \frac{N_1 + N_2}{\sqrt{2}} \quad \text{and} \quad \psi_2 \equiv \frac{N_1 - N_2}{\sqrt{2}},$$

$$g_\psi(\bar{\psi}_1\gamma^\mu\psi_1 - \bar{\psi}_2\gamma^\mu\psi_2)Z'_\mu = g_\psi(\bar{N}_1\gamma^\mu N_2 + \bar{N}_2\gamma^\mu N_1)Z'_\mu.$$

$$\frac{M_N}{2}(\psi_1^T c\psi_2 + \psi_2^T c\psi_1) + H.c. = \frac{M_N}{2}(N_1^T cN_1 - N_2^T cN_2) + H.c.$$

Y.F., “A model for lepton flavor violating non-standard neutrino interactions," Phys. Lett. B **803** (2020), 135349

Trick!

$$g_\psi(\bar{\psi}_1\gamma^\mu\psi_1 - \bar{\psi}_2\gamma^\mu\psi_2)Z'_\mu = g_\psi(\bar{N}_1\gamma^\mu N_2 + \bar{N}_2\gamma^\mu N_1)Z'_\mu.$$

Mixed with ν_α

$\sin\alpha$

Mixed with ν_β

$\sin\beta$

$$(g_\nu)_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu\nu_\beta)Z'_\mu \qquad \alpha \neq \beta.$$

$$(g_\nu)_{\alpha\beta} = g_\psi \sin\alpha \sin\beta.$$

How to obtain the mixing?

$U'(1)$, $\phi \to e^{i\alpha}\phi$.

Z_2 symmetry

$$\psi_1 \leftrightarrow \psi_2, \qquad \phi \leftrightarrow \phi^* \qquad \text{and} \qquad Z' \to -Z'.$$

$$L_\alpha \to L_\alpha \qquad L_\beta \to -L_\beta$$

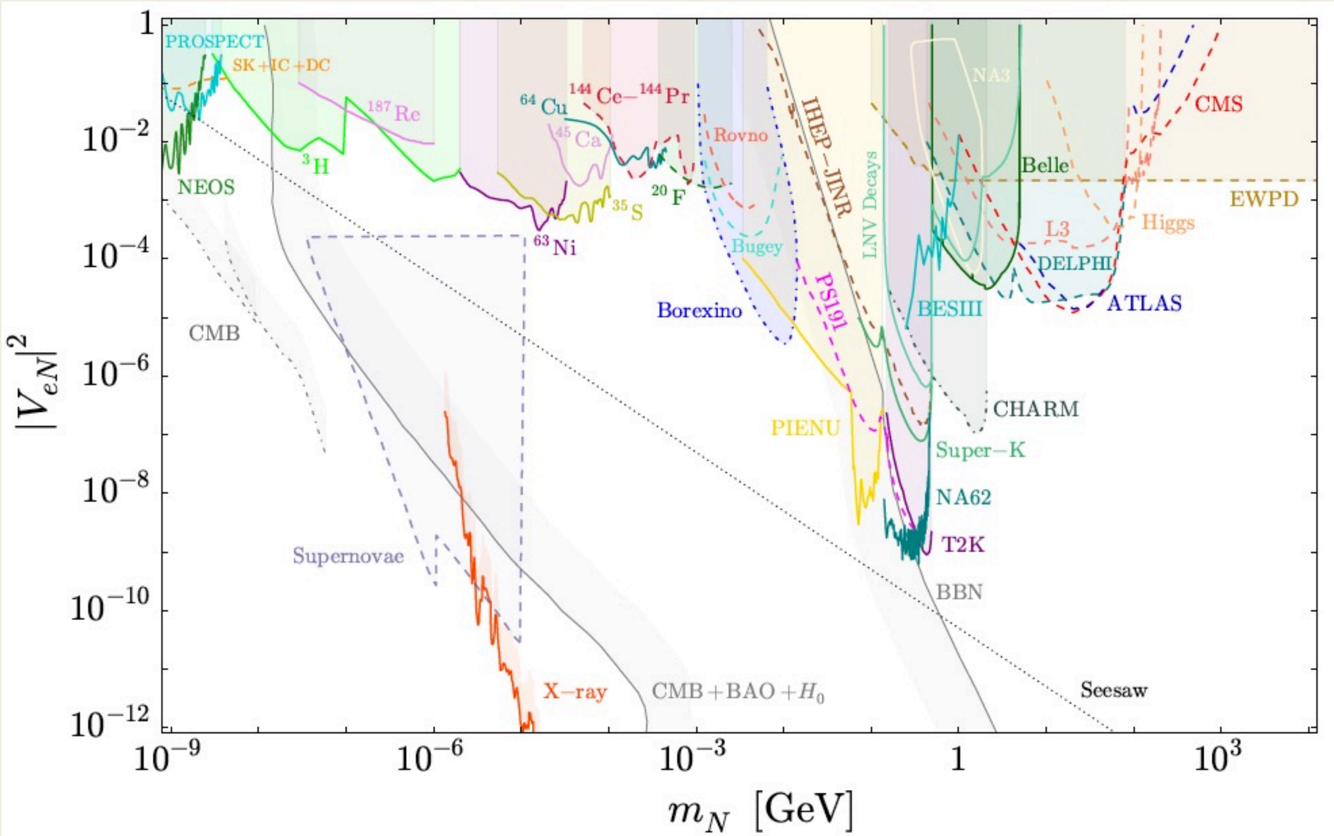
Even odd

$$\psi_1 \equiv \frac{N_1 + N_2}{\sqrt{2}} \qquad \text{and} \qquad \psi_2 \equiv \frac{N_1 - N_2}{\sqrt{2}},$$

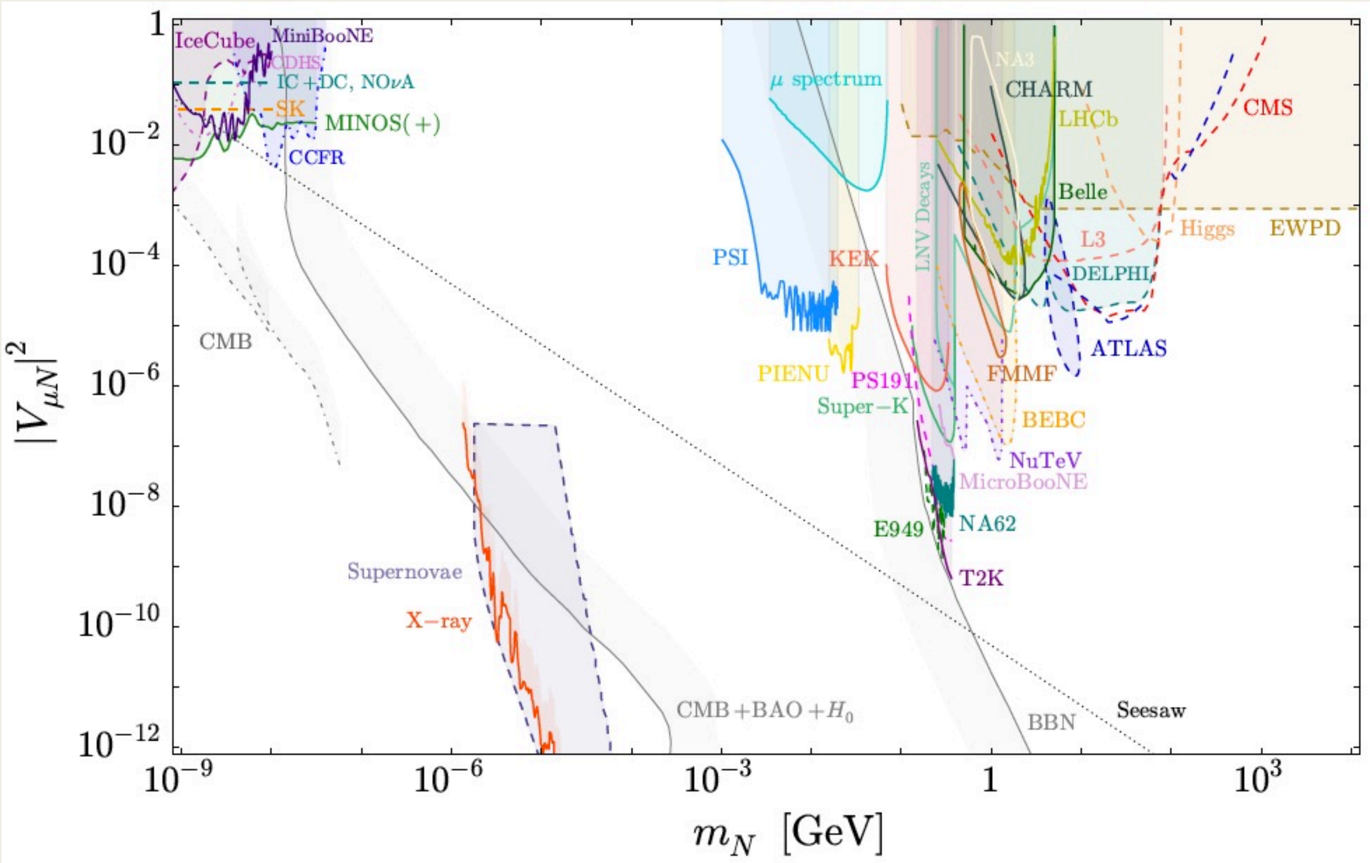
Flavor structure of NSI

$$(g_\nu)_{\alpha\beta} = g_\psi \sin\alpha \sin\beta.$$

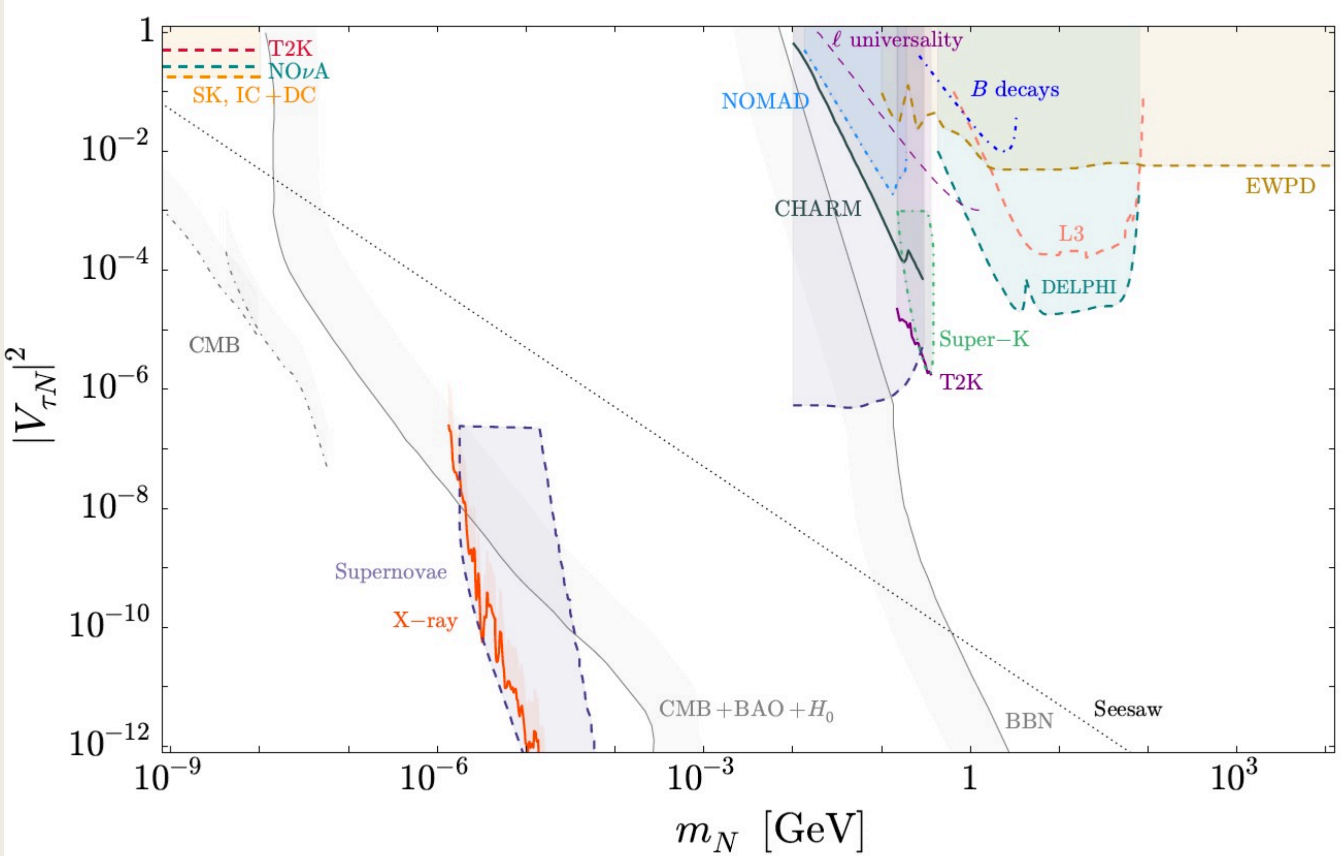
$$(g_\nu)_{\alpha\alpha} = 0$$
$$(g_\nu)_{\beta\beta} = 0 \quad \Longrightarrow \quad \cancel{|\epsilon_{\alpha\beta}|^2 < \epsilon_{\alpha\alpha}\epsilon_{\beta\beta}}$$
$$(g_\nu)_{\alpha\beta} \neq 0$$



P Bolton, F. Deppisch, B Dev, JHEP 2003 (2020) 170, arXiv"1912.03058



P Bolton, F. Deppisch, B Dev, JHEP 2003 (2020) 170, arXiv"1912.03058



P Bolton, F. Deppisch, B Dev, JHEP 2003 (2020) 170, arXiv"1912.03058

Can we escape the bounds?

Let us take $m_N > m_K$

Most of the bounds come from searching the last charged leptons.

- Electroweak interactions:

$$N \to l_\alpha \bar{l}_\beta \nu$$

- The dominant decay mode in our model:

$$N \to Z'\nu \qquad Z' \to \nu\bar{\nu}$$

Lepton flavor violating process

- Violation of unitarity: $\boxed{(U^\dagger_{PMNS} \cdot U_{PMNS})_{\alpha\beta}|_{\alpha\neq\beta}}$

$$l^-_\alpha \cancel{\rightarrow} l^-_\beta \gamma$$

$$\nu_\alpha + N_1 \sin\alpha$$

$$\nu_\beta + N_2 \sin\beta$$

Violation of unitarity of the mixing matrix

$\boxed{Z \to \text{invisibles}}$

$\boxed{W \to l + \text{missing energy}}$

Deviation from SM is
Suppressed both by $\sin^2\alpha$ or $\sin^2\beta$ and $O\left(\frac{m_N^2}{m_W^2}\right)$

$\boxed{m_N > m_K,}$

$\boxed{K^+(\pi^+) \to l_\alpha^+ \nu}$ $\cos^2\alpha$

$\boxed{K^+(\pi^+) \to l_\beta^+ \nu}$ $\cos^2\beta$

EWPD $\Rightarrow$ $\boxed{\sin\alpha \sin\beta < 10^{-3}}$

$\boxed{(g_\nu)_{\alpha\beta}|_{\alpha\neq\beta} < 10^{-3} g_\psi}$

LFV charged lepton decay

$\cancel{l_\alpha \to l_\beta \gamma}$

two-loop suppressed

$\boxed{l_\alpha \to l_\beta Z'}$

One-loop effect

$$\frac{m_\alpha}{4\pi}\left(\frac{m_\psi^2}{m_W^2}\frac{g_\nu}{16\pi^2}\right)^2 g_{SU(2)}^4\frac{m_\alpha^2}{m_{Z'}^2}$$

GIM suppression

LFV charged lepton decay

$\cancel{l_\alpha \to l_\beta \gamma}$ $\boxed{\text{two-loop suppressed}}$

$l_\alpha \to l_\beta Z'$ One-loop effect

PDG: $\mathrm{Br}(\tau \to e Z') < 2.7 \times 10^{-3} \quad \text{and} \quad \mathrm{Br}(\tau \to \mu Z') < 5 \times 10^{-3}$

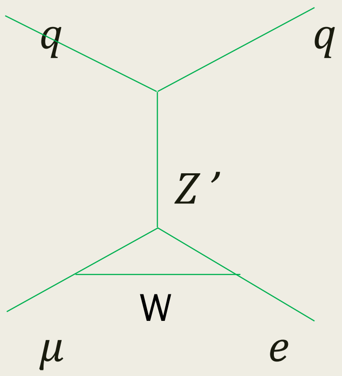
These bounds can be easily satisfied for $g_\nu < 10^{-3}$ and $m_{Z'} > 10$ MeV.

Heeck and Rodehohann, PLB776 (2018) 385

$Br(\mu \to e Z') < 10^{-5}$

$(g_\nu)_{\mu e} < 10^{-3}$, $m_\psi \sim$ GeV and $m_{Z'} \sim 10$ MeV,

muon to electron conversion



SINDRUM II collaboration
Bertl et al., Eur Phys J C 47 (2006) 337

$$R < 7 \times 10^{-13}$$

$$\boxed{R = \frac{\Gamma(\mu + N \to e + N)}{\Gamma(\mu + N \to \nu_\mu + N')} \sim \frac{(g_\nu)^2_{e\mu} g_q^2}{(16\pi^2)^2} \left(\frac{m_\psi^2}{m_\mu^2 + m_{Z'}^2} \right)^2 = 5 \times 10^{-15} \left(\frac{g_\nu}{10^{-3}}\right)^2 \left(\frac{g_q}{10^{-4}}\right)^2 \left(\frac{m_\psi}{1\ \mathrm{GeV}}\right)^4}$$

Mu2e, COMET

$$R \sim 5 \times 10^{-17}$$

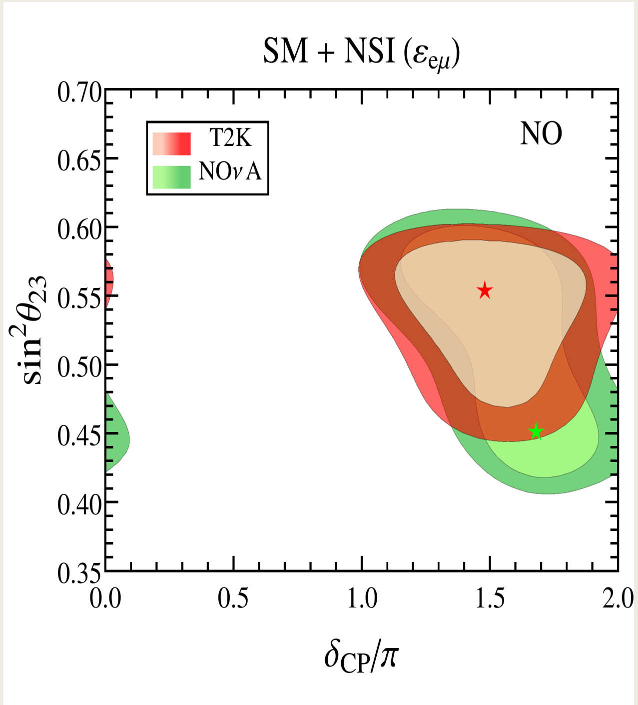
Smoking gun of the model for discernible $\epsilon^f_{e\mu}$

1) Muon to e conversion but $\mu^- \cancel{\to} e^-\gamma$

2) $\mu^- \to e^- Z'$

3) $K^+(\pi^+) \to l^- + \text{missing energy}$

4) Invisible Higgs decay mode



$$|\epsilon_{e\mu}| \sim 0.15$$

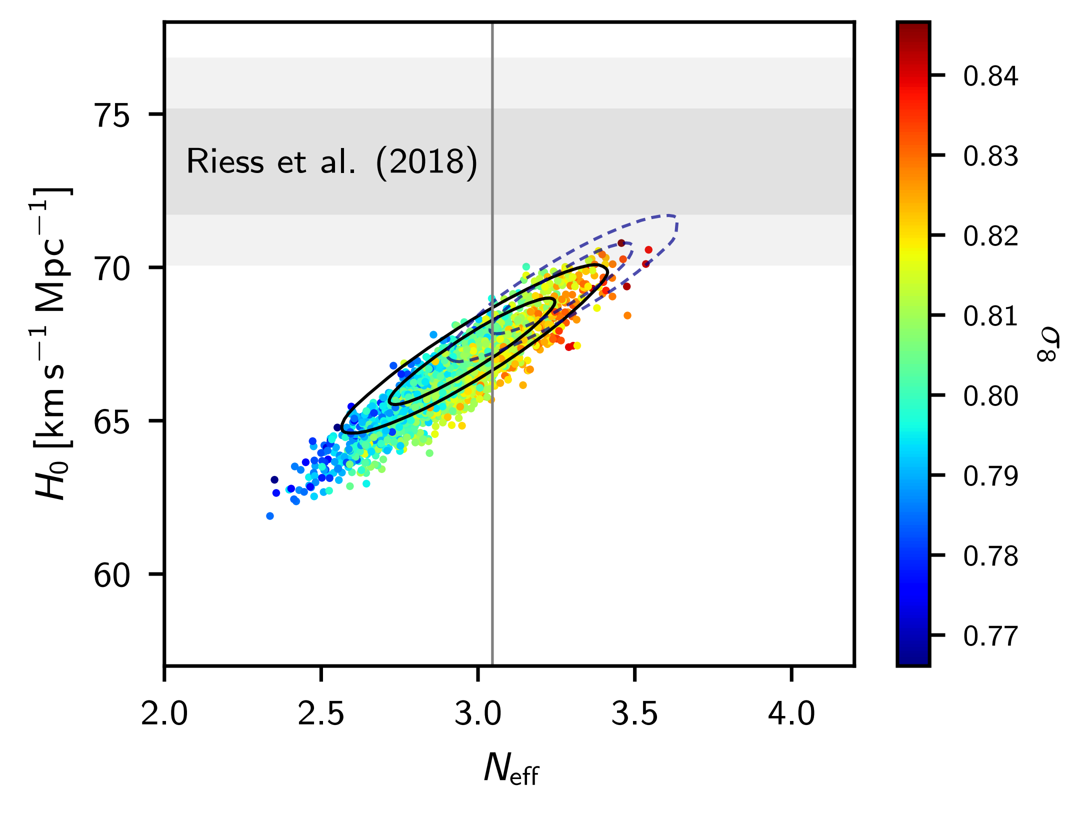
S. S. Chatterjee and A Palazzo, PRL 126 (2021) 5, 051802

Summary

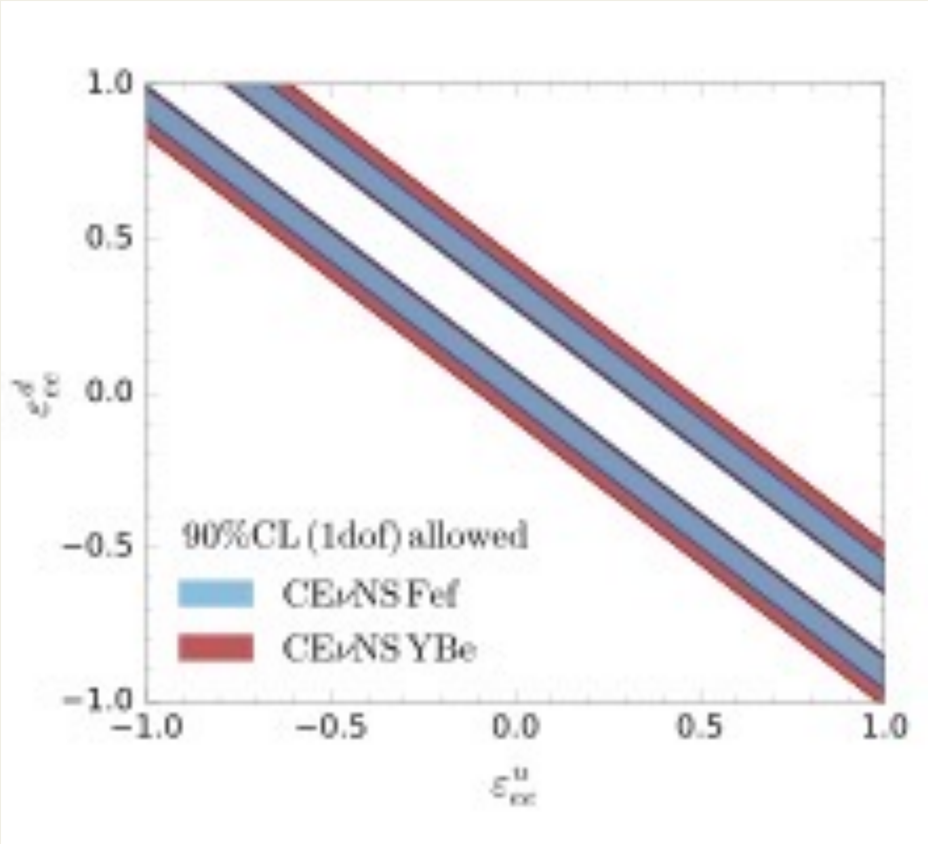
- In the neutrino precision era, we should take possibility of NSI more serious.
- New U(1): Light mediator, small coupling ⇒ large NSI
- Mixing of neutrinos with fermions charged under new U(1) ⇒ NSI for neutrinos

  No NSI for charged leptons
- Models for arbitrary flavor structure: $\epsilon_{\alpha\alpha}\epsilon_{\beta\beta} > |\epsilon_{\alpha\beta}|^2$ or $\epsilon_{\alpha\alpha}\epsilon_{\beta\beta} < |\epsilon_{\alpha\beta}|^2$

Backup slides



Riess et al. (2018)
H_0 [km s^{-1} Mpc^{-1}]
75
70
65
60
2.0
2.5
3.0
3.5
4.0
$N_{\rm eff}$
0.84
0.83
0.82
0.81
0.80
0.79
0.78
0.77
σ_8



$$\left[\mathcal{Q}_W + (2\,Z + N)\,\varepsilon^u_{ee} + (2\,N + Z)\,\varepsilon^d_{ee}\right]^2 = \text{constant}\ ,$$

P. Coloma et al., "Bounds on new physics with data of the Dresden-II reactor experiment and COHERENT," JHEP 05 (2022), 037

Blind region in parameter space

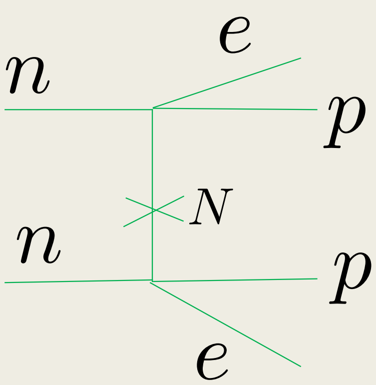
$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} Q^2 F^2(q^2) M \left(2 - \frac{MT}{E_\nu^2}\right).$$

$$Q_\alpha^2 = \left[Z(g_p^V + \epsilon_{\alpha\alpha}^p) + N(g_n^V + \epsilon_{\alpha\alpha}^n)\right]^2 + \sum_{\beta\neq\alpha}\left[Z\epsilon_{\alpha\beta}^p + N\epsilon_{\alpha\beta}^n\right]^2$$

$$= \left(Q_{\rm SM} + Z\epsilon_{\alpha\alpha}^{Y,\eta}\right)^2 + Z^2\sum_{\beta\neq\alpha}\left(\epsilon_{\alpha\beta}^{Y,\eta}\right)^2,$$

Target	Z	Y	$\eta_{\rm blind}$
C_3F_8	8.2	1.081	$-42.8°$
Si	14	1.006	$-44.8°$
Ar	18	1.235	$-39.0°$
Ge	32	1.270	$-38.2°$
CsI	54	1.405	$-35.4°$
Xe	54	1.431	$-35.0°$

Lepton number violation



$$B^- \to \pi^+ \mu^- \mu^-$$

Majorana mass

$$m_N N^T c N$$

Dirac mass

$$m_N \bar{N} N$$

$$\boxed{\frac{M_N}{2}(\psi_1^T c \psi_2 + \psi_2^T c \psi_1) + H.c. = \frac{M_N}{2}(N_1^T c N_1 - N_2^T c N_2) + H.c.}$$

Z′ coupling to matter fields

1 Gauging a linear combination of Baryon number and lepton numbers

$$B-(a_eL_e+a_\mu L_\mu+a_\tau L_\tau)$$

$$a_e+a_\mu+a_\tau=3$$

$$g_q=g_B/3 \text{ and } g_\alpha=a_\alpha g_B \text{ where } \alpha\in\{e,\mu,\tau\}$$

2 Kinetic mixing with hypercharge gauge boson

$$\delta Z'_{\mu\nu}B^{\mu\nu}$$

Photon component

$$g_f=(Q_f e)\cos\theta_W\delta.$$

Z component

Coupling suppressed by $(m_{Z'}^2/m_Z^2)\delta\sin\theta_W$

Z′ coupling to matter fields

1 Gauging a linear combination of Baryon number and lepton numbers

$$B - (a_e L_e + a_\mu L_\mu + a_\tau L_\tau)$$

$$a_e + a_\mu + a_\tau = 3$$

$$g_q = g_B/3 \text{ and } g_\alpha = a_\alpha g_B \text{ where } \alpha \in \{e, \mu, \tau\}$$

2 Kinetic mixing with hypercharge gauge boson

$$\delta Z'_{\mu\nu} B^{\mu\nu} \xrightarrow{\text{Photon component}} g_f = (Q_f e) \cos\theta_W \delta.$$

$$\epsilon^p_{\alpha\beta} = -\epsilon^e_{\alpha\beta}$$

NSI in CEνNS CONUS, COHERENT

NO NSI in neutrino oscillation

Gauging $B-(a_eL_e+a_\mu L_\mu+a_\tau L_\tau)$

$\boxed{a_e=0}$

$\boxed{130 \text{ MeV} > m_{Z'} > 10 \text{ MeV}}$ $\boxed{g_q \sim g_\tau \sim g_\mu \sim g_\nu < 10^{-3}}$

$\boxed{Z' \to \nu\bar{\nu}}$

$$\boxed{(g_\nu)_{\alpha\beta} = 10^{-3} g_\psi \text{ and } m_{Z'} \sim 500 \text{ MeV} g_\psi}$$

$$\boxed{\epsilon^q_{\alpha\beta} = \frac{0.12}{g_\psi}\frac{g_q}{10^{-3}}}$$

Flavor conserving NSI

$$\boxed{\epsilon^q_{\mu\mu} = -3\frac{a_\mu g_q}{(g_\nu)_{\alpha\beta}}\epsilon^q_{\alpha\beta} \quad \text{and} \quad \epsilon^q_{\tau\tau} = -3\frac{a_\tau g_q}{(g_\nu)_{\alpha\beta}}\epsilon^q_{\alpha\beta}}$$

Anomaly cancelation: $\boxed{a_\mu + a_\tau = 3}$

Proper choice of g_ψ/g_q $\Rightarrow$ $\boxed{\alpha \neq \beta,\ |\epsilon^q_{\alpha\beta}|^2 > |\epsilon^q_{\alpha\alpha}\epsilon^q_{\beta\beta}|}$

Strong bounds on $\epsilon^q_{\mu\mu}$ from CEνNS $\Rightarrow$ $a_\mu = 0,\ a_\tau = 3$