Models for non-standard neutrino interactions

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Effects of NSI on neutrinos

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

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

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

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

Effects of NSI on neutrinos

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

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

Focus of this talk

Non-standard neutral current interaction

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

Projection matrix

Matter field

Neutrino propagation: $\epsilon_{\alpha\beta}^{f} \equiv \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}.$

Hamiltonian of neutrinos

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

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

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \cos\theta_{12} & & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$H_{vac} = U \cdot {\rm Diag}(m_1^2/2E_\nu, m_2^2/2E_\nu, m_3^2/2E_\nu) \cdot U^\dagger$$

Matter effects in presence of NSI

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

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

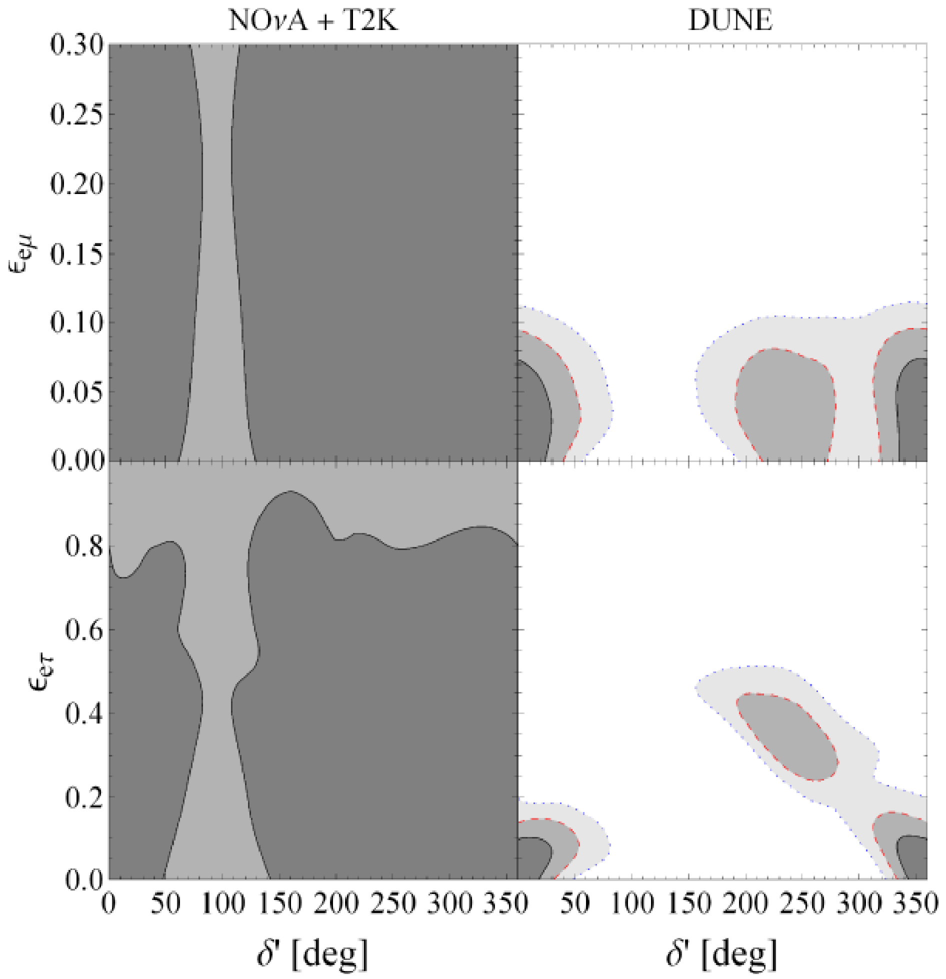
$$H_{\rm mat} = \sqrt{2} G_F N_e(r) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2} G_F \sum_{f=e,u,d} N_f(r) \begin{pmatrix} \varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau} \\ \varepsilon^{f*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau} \\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

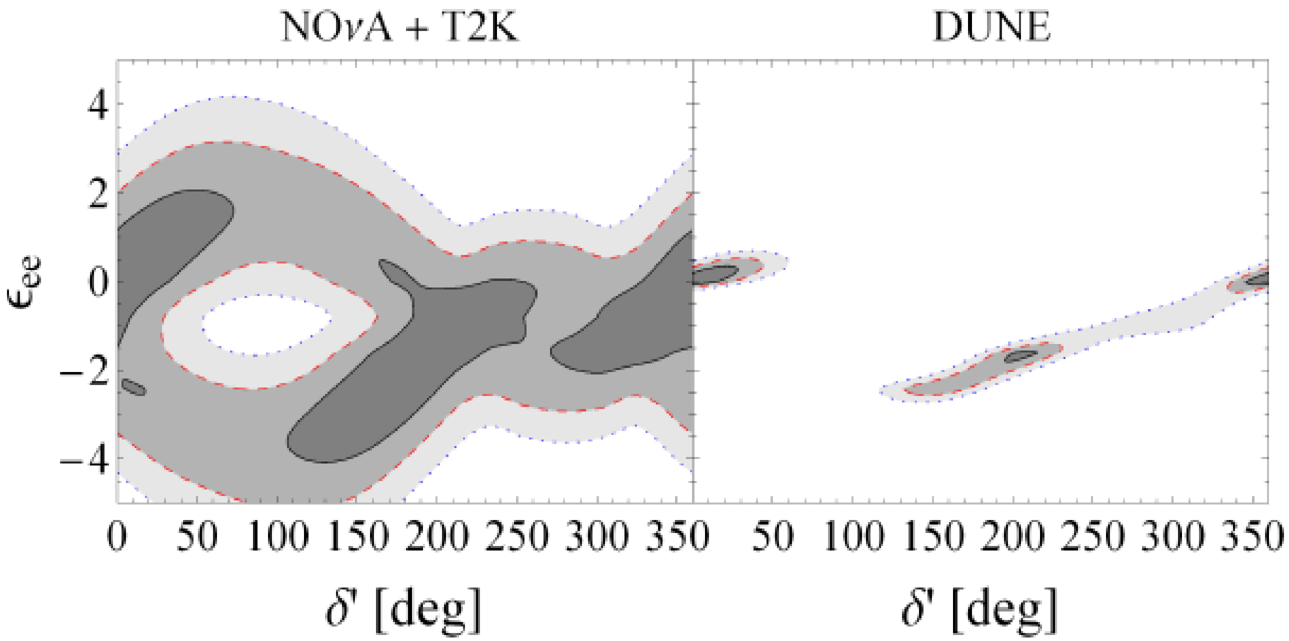
Effects of NSI in long baseline experiments

Renewed interest in NSI

NSI can fake CP-violation and lead to wrong determination of θ_{23} octant and mass ordering

Masud and Mehta, PRD 94(2016); Forero and Huber, PLB 117 (2016); Liao, Marfatia and Whistnant PRD 93 (2016); JHEP 1701 (2017) 071; Agarwalla, Chatterjee and Palazzo, PLB 762 (2016); Verma and Bhardwaj, 1808.04263; Flore, Garces, Miranda, Phys Rev D98 (2018)35030;Wang and Zhou, 1801.05656; Deepath, Goswami and Nath, 1711.04840; 1612.00784; Fukasawa, Ghosh, Yasuda, PRD 95 (2017);Forero and Huang, JHEP 1703 (2017); Ge and Smirnov, JHEP 1610; A. de Gouvea and K Kelly, 1605.09376; Coloma, Schwetz, PRD 94 (2016)

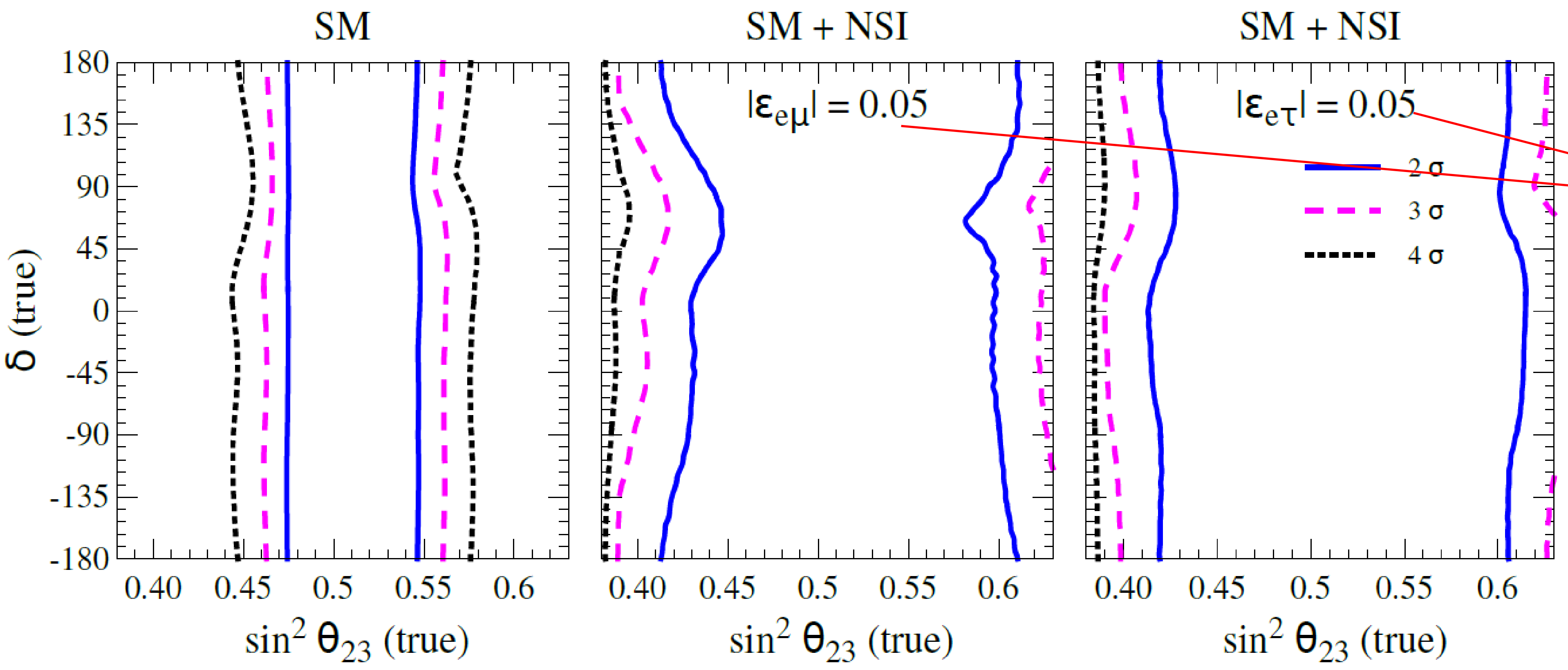




Liao Marfatia Whisnant, PRD93 (2016)

SM with $\delta = 0$

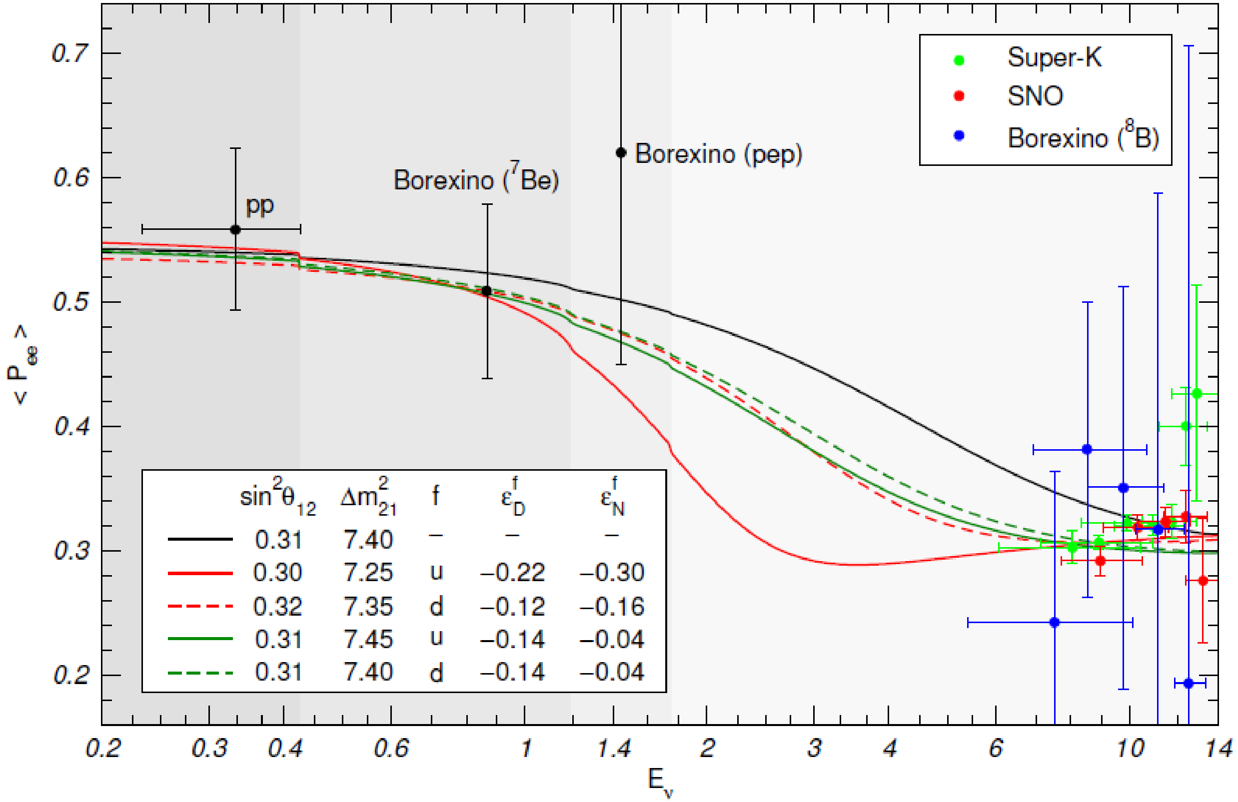
Octant discovery potential of DUNE



Accepted within
Present uncertainties

Agarwalla, Chatterjee and Palazzo, PLB 762 (2016)

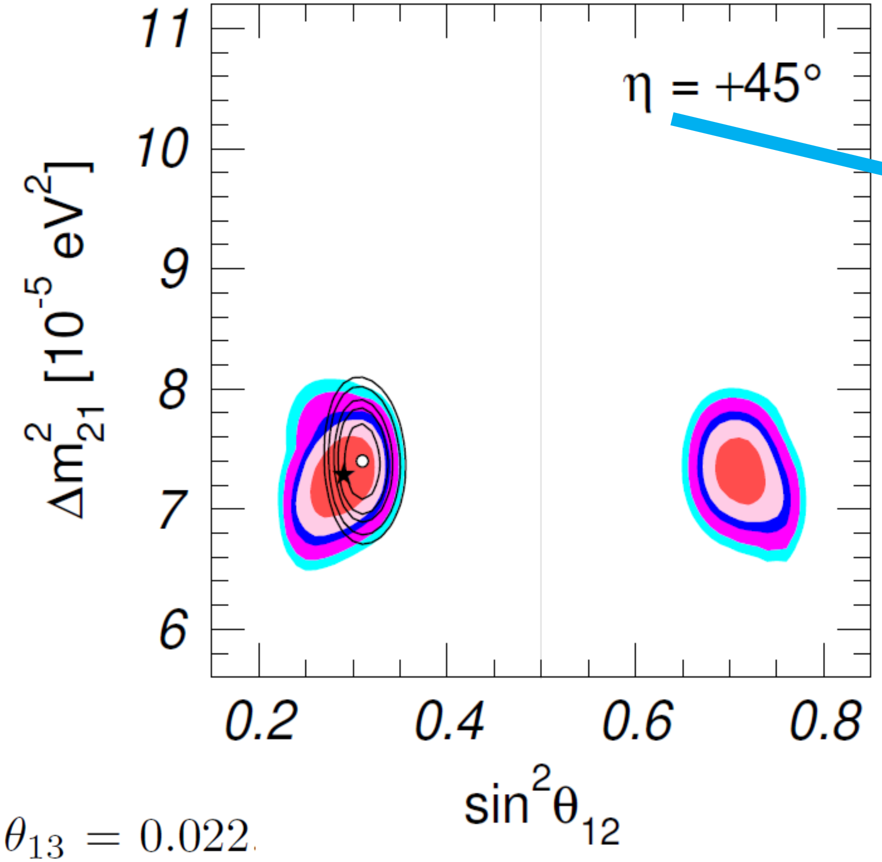
Solving solar and KamLAND tension



Maltoni and Gonzalez-Garcia, JHEP 2013

Fit to solar and KamLAND data

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



$\epsilon^u = \epsilon^d$

Esteban, Gonzalez-Garcia, M. Maltoni, Martinez-Soler and J Salvado, JHEP 1808 (2018) 180, arXiv:1805.04530

Solar+KamLAND

$\sin^2\theta_{13} = 0.022$

LMA-Dark solution

LMA-Dark solution provides even a better fit. (suppression of low energy upturn)

$$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu} \qquad [-1.192, -0.802]$$

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

Scattering experiments

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

NuTeV and CHARM rule out a large part (but not all) of parameter space of LMA-Dark solution.

Davidson, Pena-Garay, Rius, SantaMaria, JHEP 2003

COHERENT experiment (a CEνNS setup) also rules out LMA-Dark solution.

P. Coloma, M.C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, PRD 94 (2017) 115007;

P. Coloma, P. Denton, M.C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, JHEP1704 (2017) 116

Scattering experiments

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

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P. Coloma, P. Denton, M.C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, JHEP1704 (2017) 116

But not in the model that we shall present

Underlying theory for NSI

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

Integrating out a heavy intermediate state

Neutral U(1) gauge boson as mediator

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

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

Charged scalar (a la Fierz transformation)

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

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

Underlying theory for NSI

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

Integrating out a heavy intermediate state

Our Focus

Neutral U(1) gauge boson as mediator

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

Charged scalar (a la Fierz transformation)

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

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

Too small NSI

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

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

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

$$m_{Z'} \gg 100\ \mathrm{GeV} \quad \Longrightarrow \quad \epsilon \ll 1$$

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,” Frontiers in Physics 6 (2018) 10; Y. Farzan, “A model for lepton flavor violating non-standard neutrino interactions,” PLB (2020 135349; P. Denton, Y.F. and I Shoemaker, “Activating the fourth neutrino of the 3+1 scheme,” PRD 99 (2019) 035003

Suggestion

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

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

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

But because coupling is small!

Neutral current Non-Standard Interactions

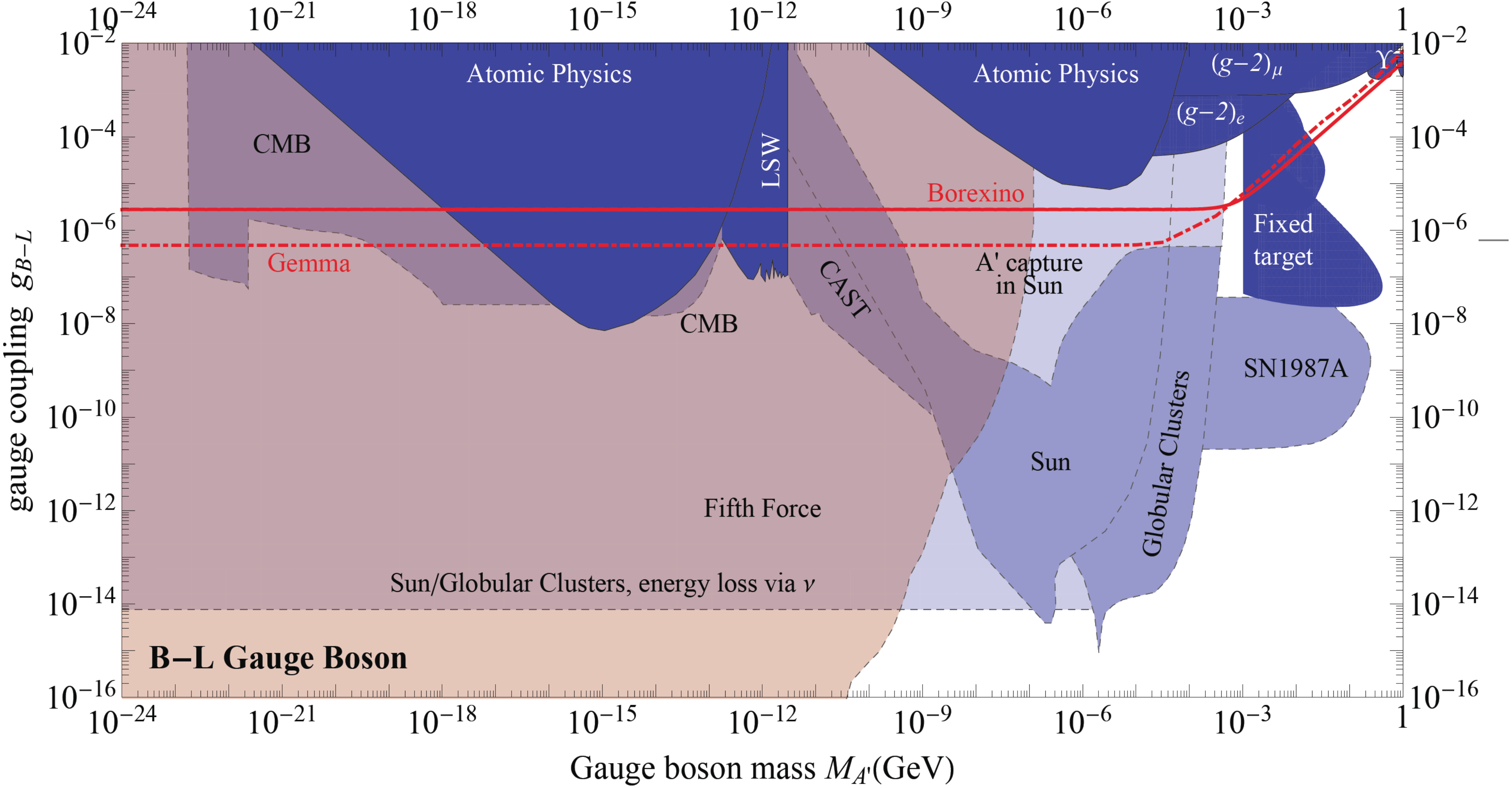
NSI $$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\,\varepsilon^{fX}_{\alpha\beta}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_X f)$$

Y.F. and J. Heeck, PRD94 (2016); Y.F. and Shoemaker, JHEP 1607 (2016); YF, PLB 748 (2015)

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

$$\boxed{\epsilon^u_{\alpha\beta} = \epsilon^d_{\alpha\beta} = \frac{g_B(g_\nu)_{\alpha\beta}}{\sqrt{2}G_F M^2_{Z'}}}$$

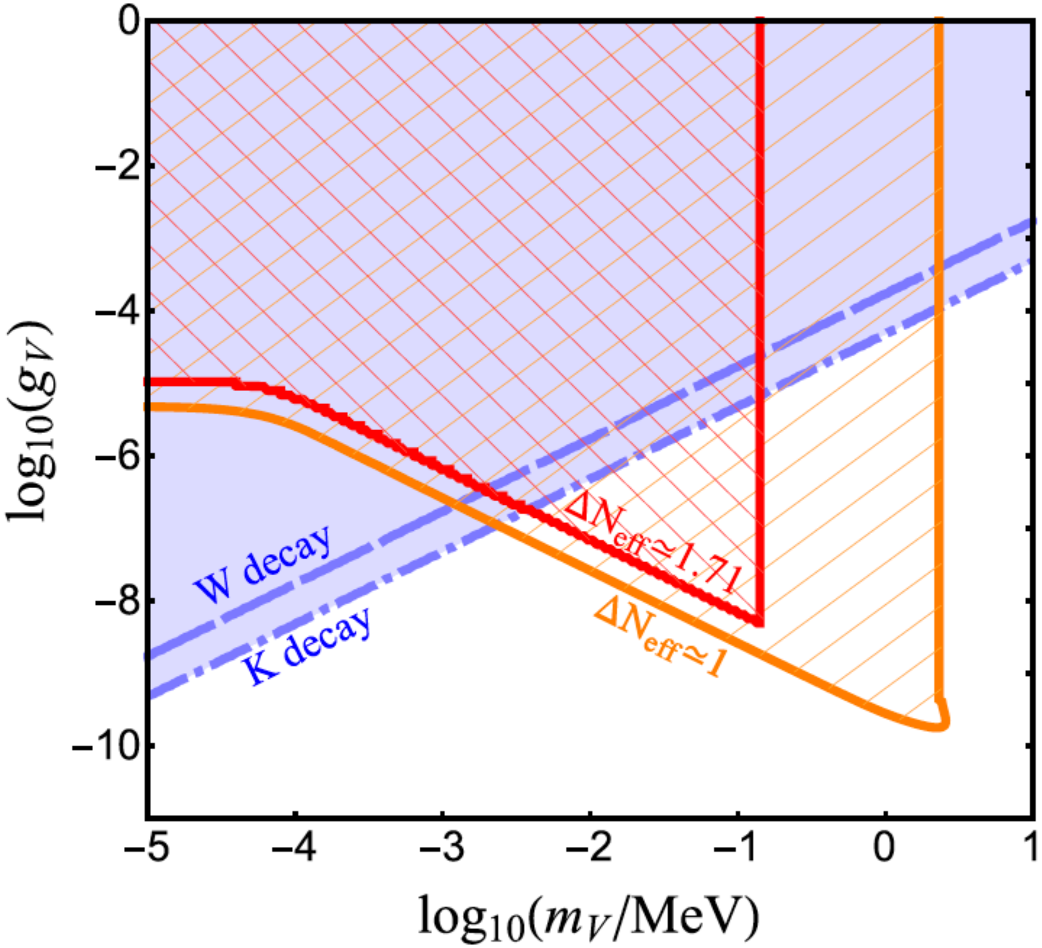
$$\boxed{\sqrt{g_\nu g_B} \sim 7\times 10^{-5}\frac{m_{Z'}}{10\ \rm MeV}} \quad \Longleftrightarrow \quad \boxed{\epsilon^u_{\alpha\beta} = \epsilon^d_{\alpha\beta} \sim 1}$$



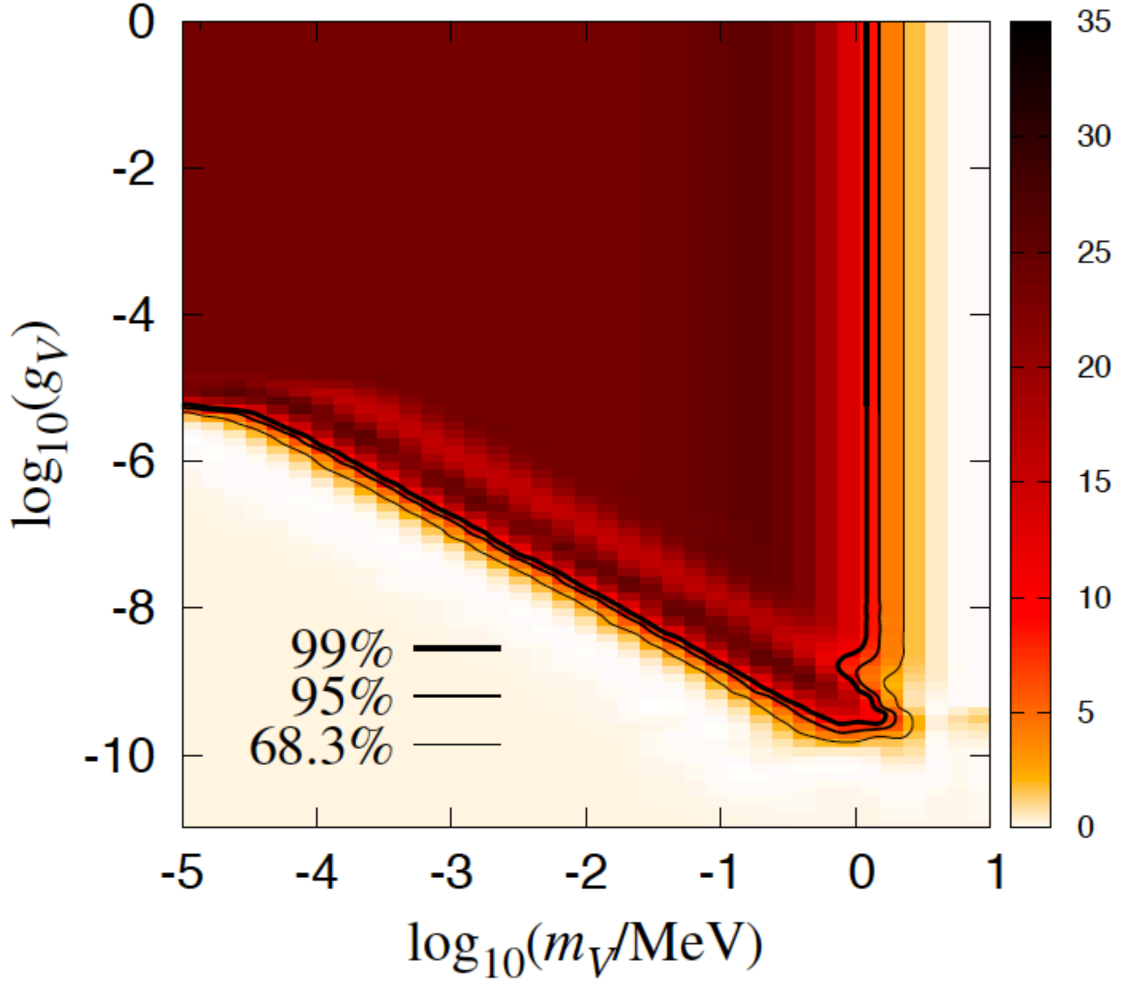
$g'a_e < 3 \times 10^{-11}$

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

Effect in early universe



Huang, Ohlsson, Zhou,
PRD 97 (2018) 075009



$$Y_{\mathrm{p}} = 0.2449 \pm 0.0040$$

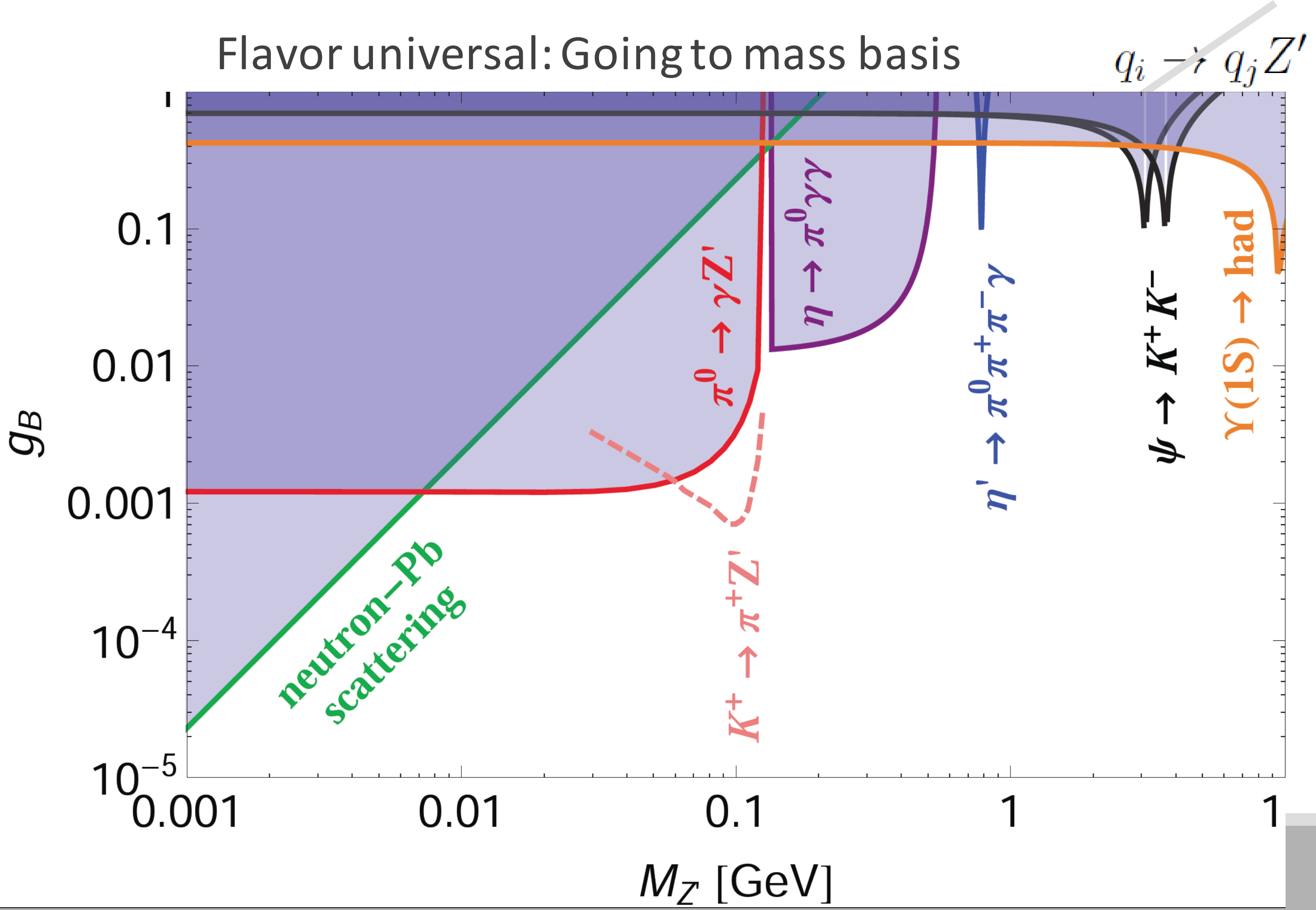
$$\mathrm{D/H}|_{\mathrm{p}} = (2.53 \pm 0.04) \times 10^{-5}$$

Huang, Ohlsson, Zhou, PRD 97 (2018) 075009

Coupling to quarks

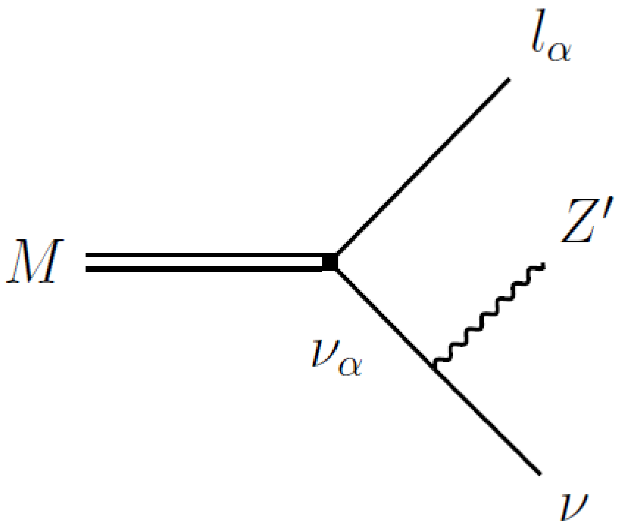
Non-chiral couplings: No impact on total measurement at SNO

Flavor universal: Going to mass basis

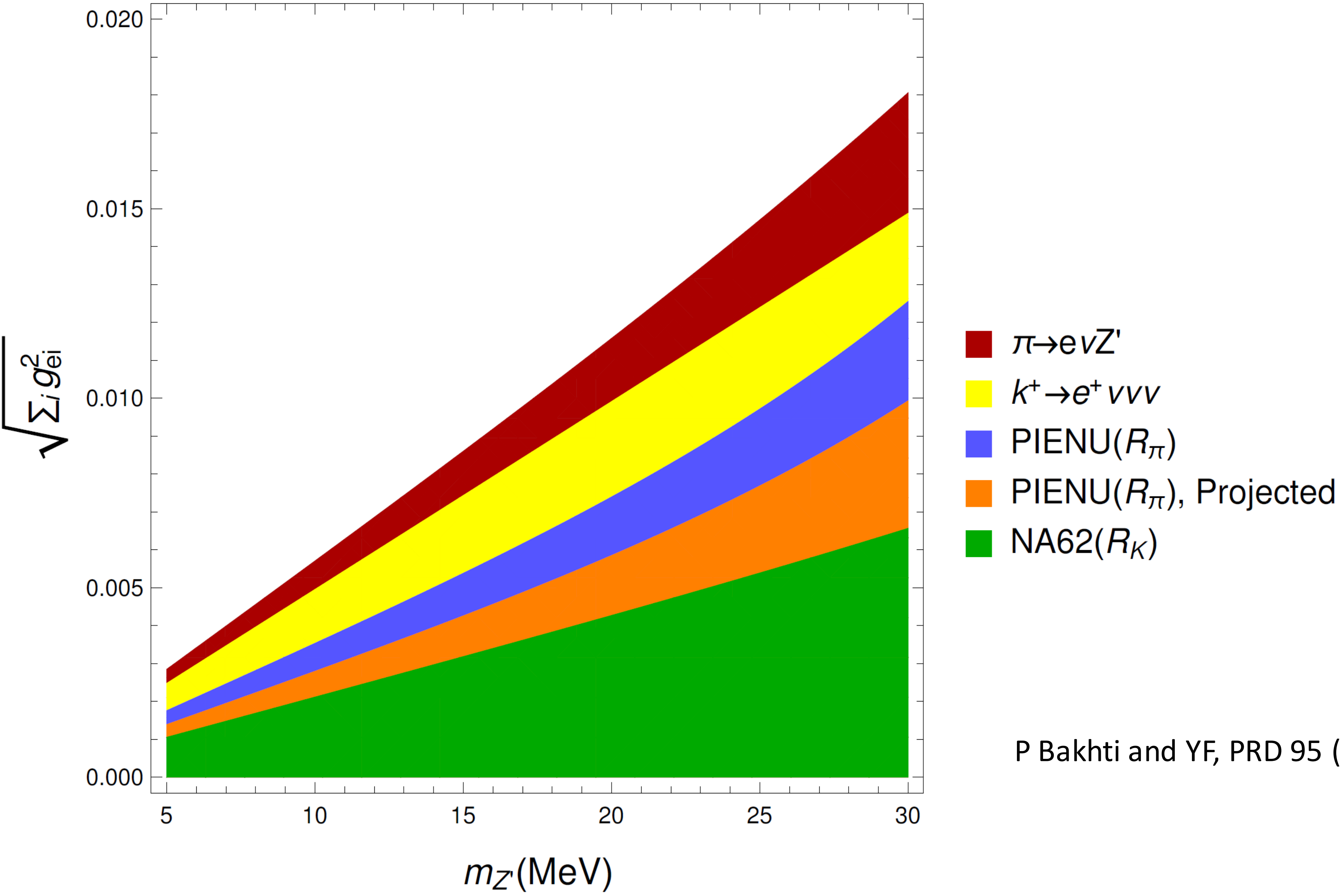


Y.F. and Heeck, *Phys.Rev.D* 94 (2016) 5, 053010

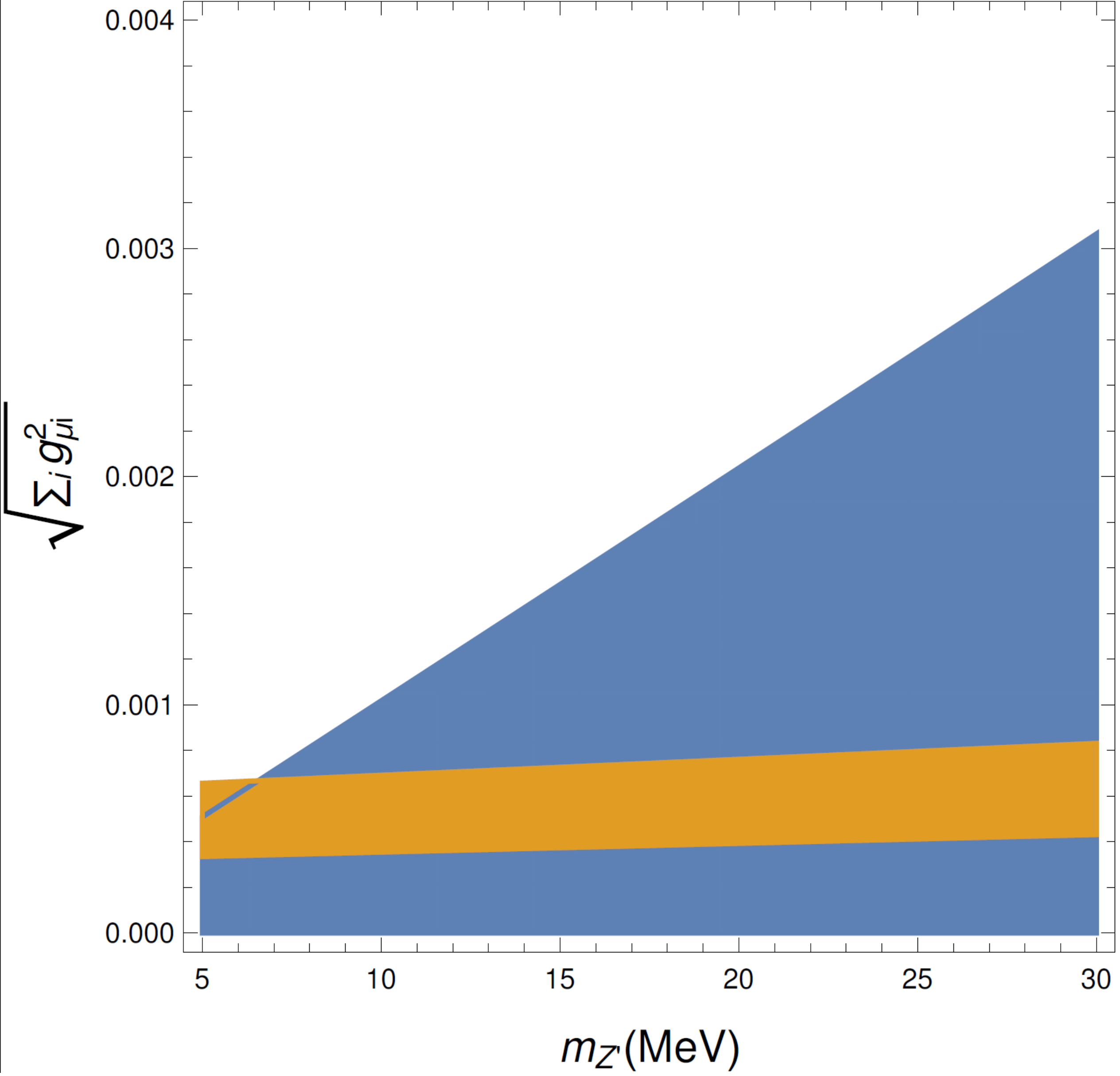
Bounds on Couplings of neutrinos



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



P Bakhti and YF, PRD 95 (2017) 095008



Artamonov et al.,
BNL-E949 collaboration,
PRD 79 (2009) 092004

P Bakhti and YF, PRD 95 (2017) 095008

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

Neutrino scattering experiments

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

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

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

Neutrino scattering experiments

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

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

$$\boxed{10\ \mathrm{MeV} \lesssim m_{Z'} \ll 1\ \mathrm{GeV}}$$

Relaxing bounds from scattering experiments, NuTeV and CHARM

New U(1) gauge symmetry

Direct coupling to neutrinos

Gauge symmetry:

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

Coupling to neutrinos through mixing with ψ: κ_α

Gauge symmetry: $a_\psi L_\psi + B$

New U(1) gauge symmetry

Direct coupling to neutrinos

Gauge symmetry:

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

⇒ Charged leptons couple to Z’

Coupling to neutrinos through mixing with ψ: κ_α

Gauge symmetry: $a_\psi L_\psi + B$

⇒ Charged leptons do not couple

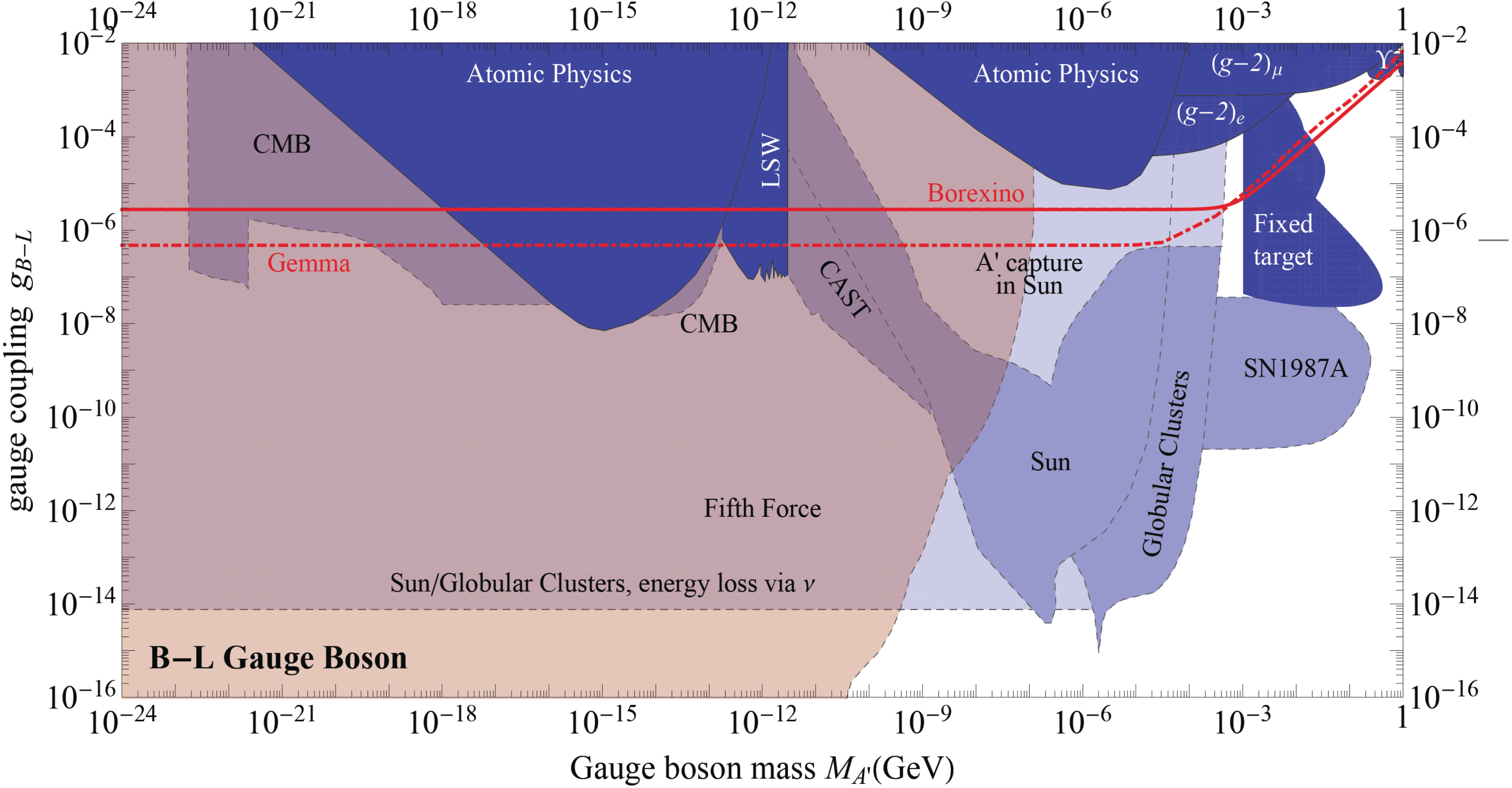
Coupling to neutrinos

Direct coupling to neutrinos

Gauge symmetry:

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

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



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

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

$$\boxed{a_e L_e + a_\mu L_\mu + a_\tau L_\tau + B}$$

$$\boxed{a_e = 0}$$

Anomaly cancelation: $\boxed{a_\mu = a_\tau = -3/2}$

Reproducing best fit $$\boxed{g' = 4 \times 10^{-5} \frac{m_{Z'}}{10 \text{ MeV}} \left(\frac{\epsilon_{ee} - \epsilon_{\mu\mu}}{0.3} \right)^{1/2}}$$

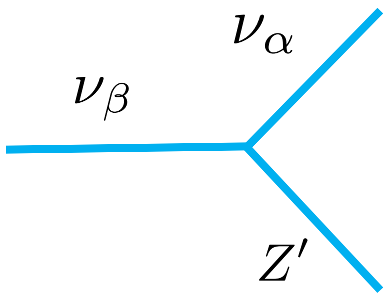
$\epsilon_{ee} - \epsilon_{\mu\mu} = 0.3$ Best fit reconciling KamLAND and solar neutrino data Miranda, Tortola, Valle, JHEP 10 (2006) 8

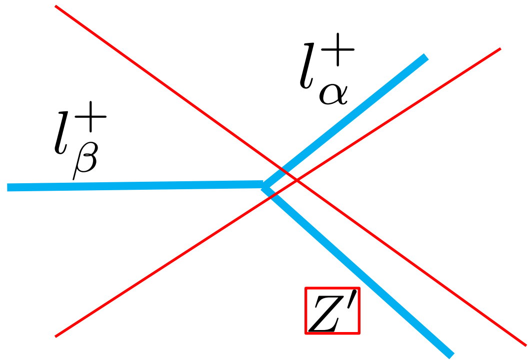
LFV NSI for neutrinos but not for charged leptons

$$a_\psi L_\psi + B$$

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

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





Coupling of neutrinos through mixing

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

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

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

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

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

Coupling of neutrinos through mixing

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

$$\epsilon_{\alpha\beta}^u = \epsilon_{\alpha\beta}^d = \frac{g'^2 a_\Psi \kappa_\alpha^* \kappa_\beta}{6\sqrt{2} G_F m_{Z'}^2}$$

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

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

Flavor structure of NSI

$$a_\psi L_\psi + B \xrightarrow{\kappa_\alpha, \kappa_\beta} \epsilon^f_{\alpha\beta}\epsilon^f_{\beta\alpha} = \epsilon^f_{\alpha\alpha}\epsilon^f_{\beta\beta}.$$

More than one ψ $\longrightarrow$ $\left|\epsilon^f_{\alpha\beta}\right|^2 < |\epsilon^f_{\alpha\alpha}\epsilon^f_{\beta\beta}|$

Y.F. and J. Heeck, "Neutrinophilic Nonstandard interactions," PRD 94 (2016) 053010

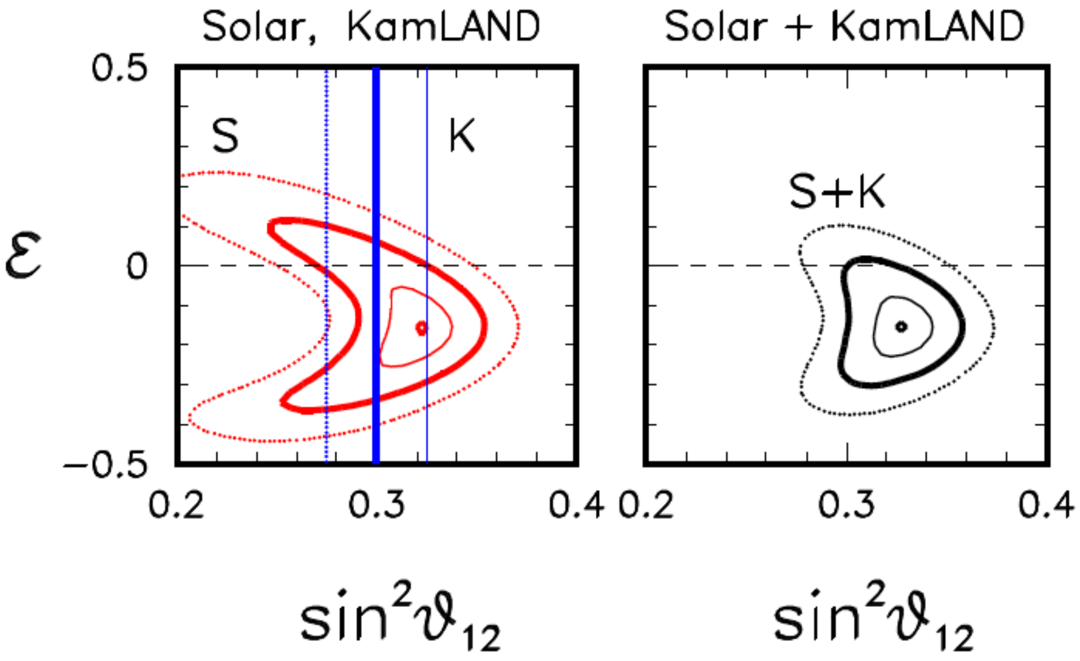
How can we obtain the opposite relation?

$$|\epsilon^f_{\alpha\beta}| > |\epsilon^f_{\alpha\alpha}\epsilon^f_{\beta\beta}|^{1/2}$$

Y.F., "A model for lepton flavor violating Non-standard neutrino interactions," PLB (2020) 135349

Hint from solar neutrinos

$$\epsilon = \epsilon_{e\mu}^{dV} \cos\theta_{23} - \epsilon_{e\tau}^{dV} \sin\theta_{23}$$

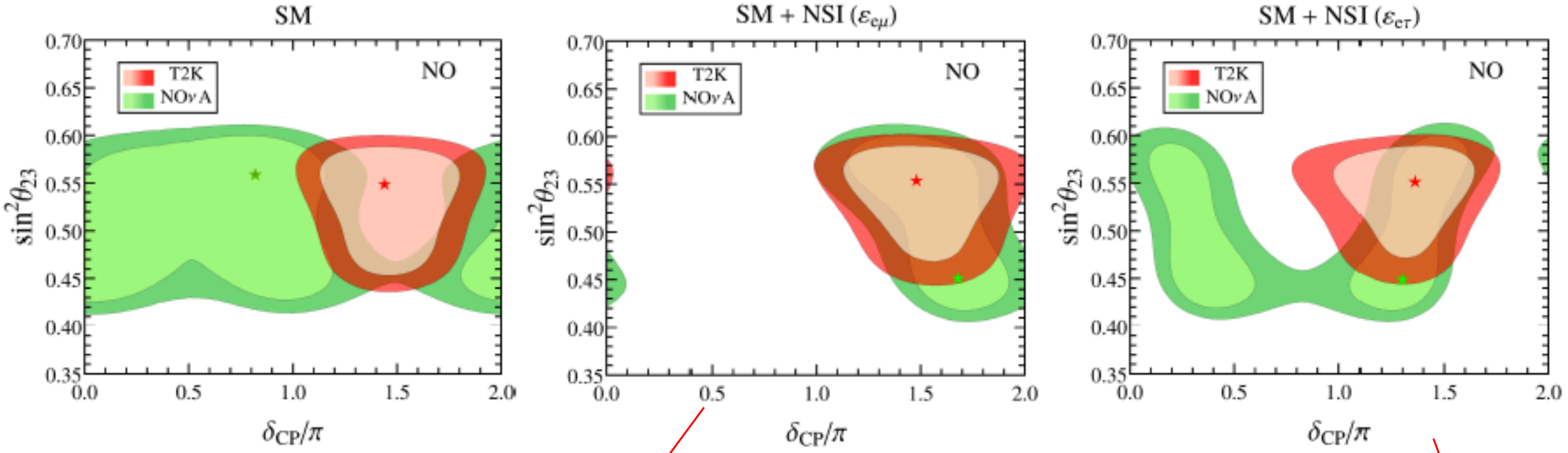


$$|\epsilon_{\alpha\beta}^{f}| > |\epsilon_{\alpha\alpha}^{f}\epsilon_{\beta\beta}^{f}|^{1/2}$$

Palazzo, PRD 83 (2011)

NSI as solution to Nova and T2K discrepancy

Chatterjee and Palazzo, 2008.014161



68%
90%

$$|\varepsilon_{e\mu}| = 0.15, \phi_{e\mu} = 1.38\pi$$

$$|\varepsilon_{e\tau}| = 0.275, \phi_{e\tau} = 1.62\pi.$$

What we need

$$\left\{\begin{array}{l} g_f(\bar{f}\gamma^\mu f)Z'_\mu \\ (g_\nu)_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu\nu_\beta)Z'_\mu \qquad \alpha \neq \beta. \end{array}\right. \Rightarrow \epsilon^f_{\alpha\beta} = \frac{g_f(g_\nu)_{\alpha\beta}}{2\sqrt{2}G_F m^2_{Z'}}$$

Y.F., “A model for lepton flavor violating Non-standard neutrino interactions,” PLB (2020) 135349

Coupling to neutrinos

new gauge $U'(1)$

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

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

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

Y.F., “A model for lepton flavor violating Non-standard neutrino interactions,”PLB (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

$\sin\beta$

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

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

How to obtain the mixing?

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

Z_2 symmetry

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

$$\boxed{L_\alpha \to L_\alpha \quad L_\beta \to -L_\beta}$$

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

$$\phi\psi_1 - \phi^*\psi_2$$

$$\phi\psi_1 + \phi^*\psi_2$$

$\boxed{Z_2}$

Even

Odd

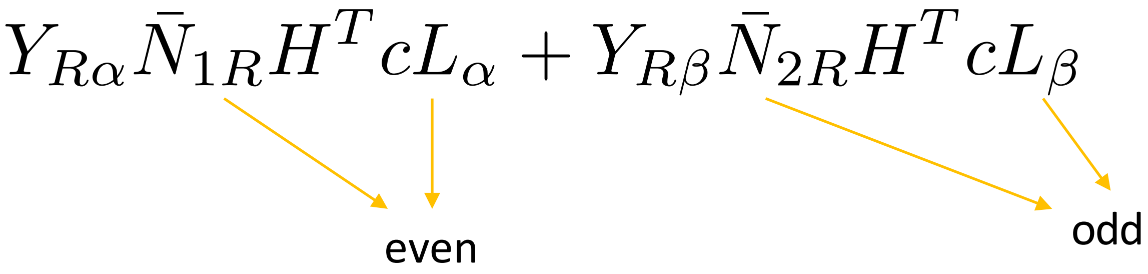
$$\boxed{Y_1 \bar{N}_{R1}(\phi\psi_1 + \phi^*\psi_2) + Y_2 \bar{N}_{R2}(\phi\psi_1 - \phi^*\psi_2)}$$

$$\Downarrow$$

$$\boxed{m_{N_1} \bar{N}_{R1} N_1 + m_{N_2} \bar{N}_{R2} N_2}$$

$$\boxed{m_{N_1} = Y_1 v_\phi \quad m_{N_2} = Y_2 v_\phi}$$

$$Y_{R\alpha}\bar{N}_{1R}H^T cL_\alpha + Y_{R\beta}\bar{N}_{2R}H^T cL_\beta$$



even

odd

$$Y_{R\alpha}\bar{N}_{1R}H^T cL_\alpha + Y_{R\beta}\bar{N}_{2R}H^T cL_\beta$$

$$m_{N_1} = Y_1 v_\phi$$

$$[\nu_\alpha^T \;\; N_1^T \;\; N_{1R}^\dagger c]c \begin{bmatrix} 0 & 0 & Y_{R\alpha}\langle H\rangle \\ 0 & 0 & m_{N_1} \\ Y_{R\alpha}\langle H\rangle & m_{N_1} & 0 \end{bmatrix} \begin{bmatrix} \nu_\alpha \\ N_1 \\ cN_{1R}^* \end{bmatrix}$$

Inverse seesaw

$$\begin{bmatrix} 1 & -\frac{Y_{R\alpha}\langle H\rangle}{m_{N_1}} & 0 \\ \frac{Y_{R\alpha}\langle H\rangle}{m_{N_1}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{Y_{R\alpha}\langle H\rangle}{m_{N_1}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

$$\sin\alpha = -\frac{Y_{R\alpha}\langle H\rangle}{m_{N_1}}$$

$$\boxed{Y_{R\alpha}\bar{N}_{1R}H^T cL_\alpha + Y_{R\beta}\bar{N}_{2R}H^T cL_\beta}$$

$$\boxed{m_{N_1} = Y_1 v_\phi}$$

$$\boxed{[\nu_\alpha^T \;\; N_1^T \;\; N_{1R}^\dagger c]c \begin{bmatrix} 0 & 0 & Y_{R\alpha}\langle H\rangle \\ 0 & 0 & m_{N_1} \\ Y_{R\alpha}\langle H\rangle & m_{N_1} & 0 \end{bmatrix} \begin{bmatrix} \nu_\alpha \\ N_1 \\ cN_{1R}^* \end{bmatrix}}$$

Inverse seesaw

$$\begin{bmatrix} 1 & -\frac{Y_{R\alpha}\langle H\rangle}{m_{N_1}} & 0 \\ \frac{Y_{R\alpha}\langle H\rangle}{m_{N_1}} & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{Y_{R\alpha}\langle H\rangle}{m_{N_1}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

Similarly for $\nu_\alpha \to \nu_\beta,$

$$Y_{R\alpha} \to Y_{R\beta},$$

$$m_{N_1} \to m_{N_2}$$

$$\boxed{\sin\beta = -\frac{Y_{R\beta}\langle H\rangle}{m_{N_2}}}$$

Flavor structure of NSI

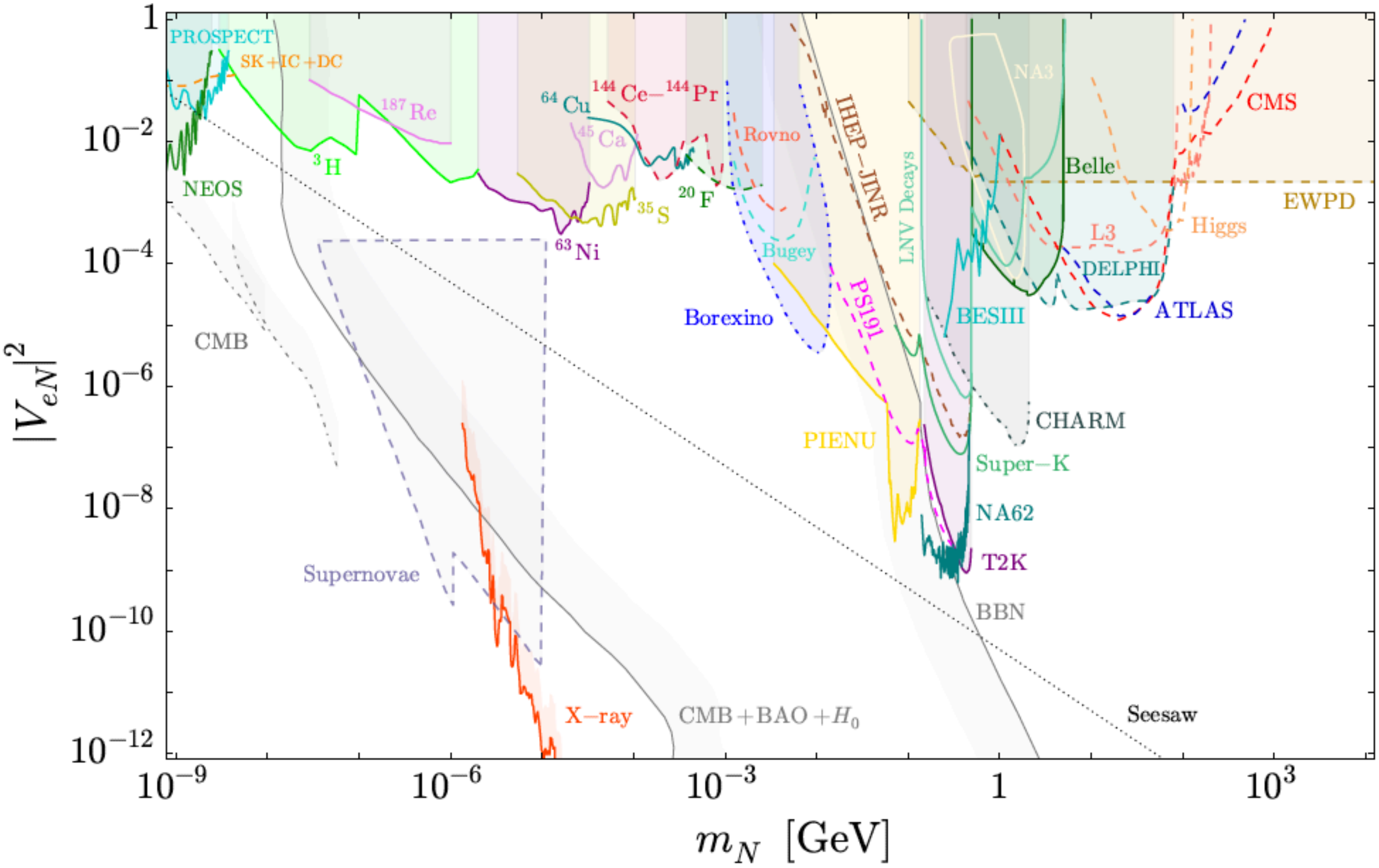
$$(g_\nu)_{\alpha\beta} = g_\psi \sin\alpha \sin\beta.$$

$$\begin{array}{l} (g_\nu)_{\alpha\alpha} = 0 \\ (g_\nu)_{\beta\beta} = 0 \\ (g_\nu)_{\alpha\beta} \neq 0 \end{array} \quad \Longrightarrow \quad \begin{array}{l} \epsilon_{\alpha\alpha} = 0 \\ \epsilon_{\beta\beta} = 0 \\ \epsilon_{\alpha\beta} \neq 0 \end{array}$$

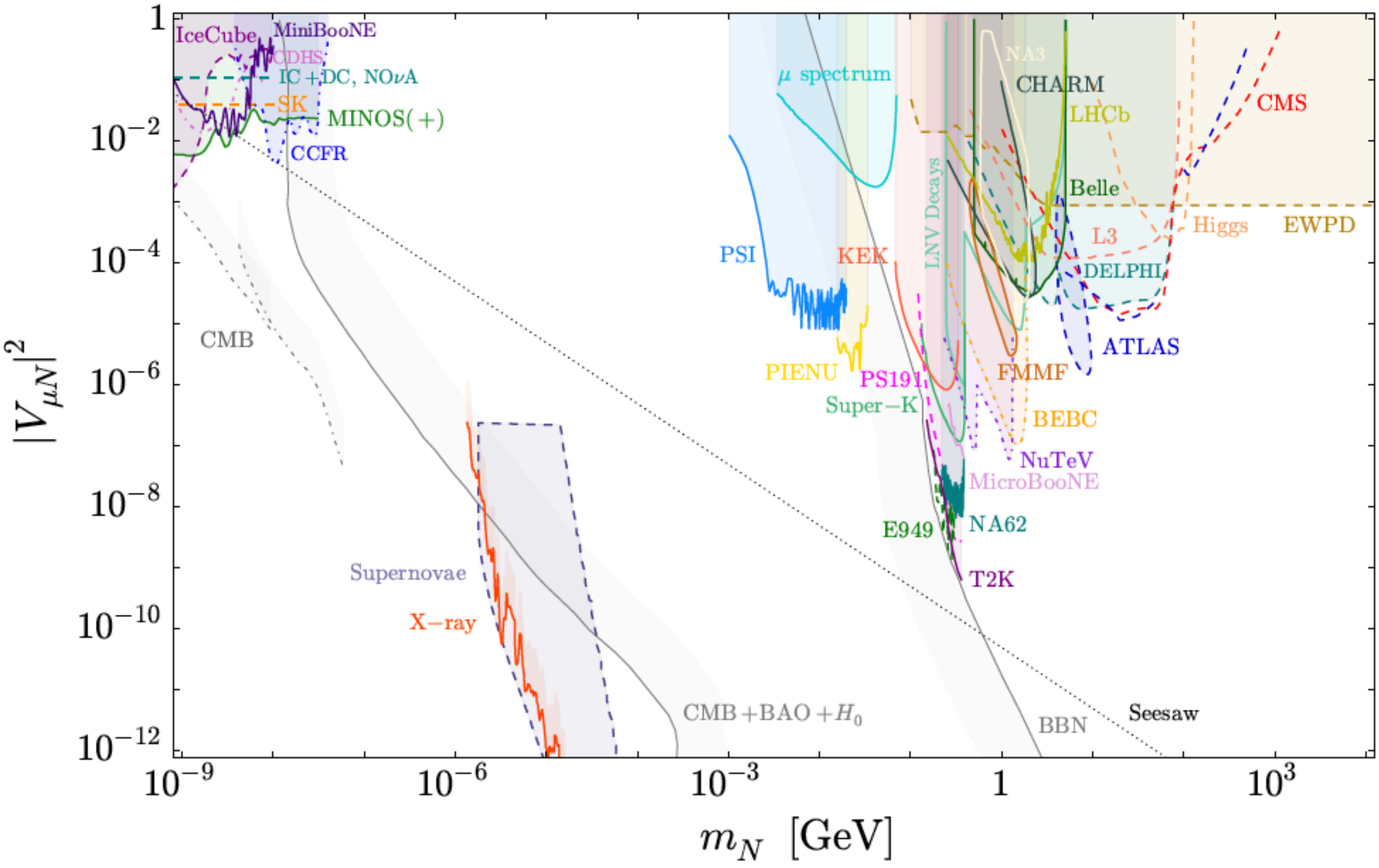
Bounds on the mixing of N_1 and N_2 with active neutrinos

I.e., Bounds on

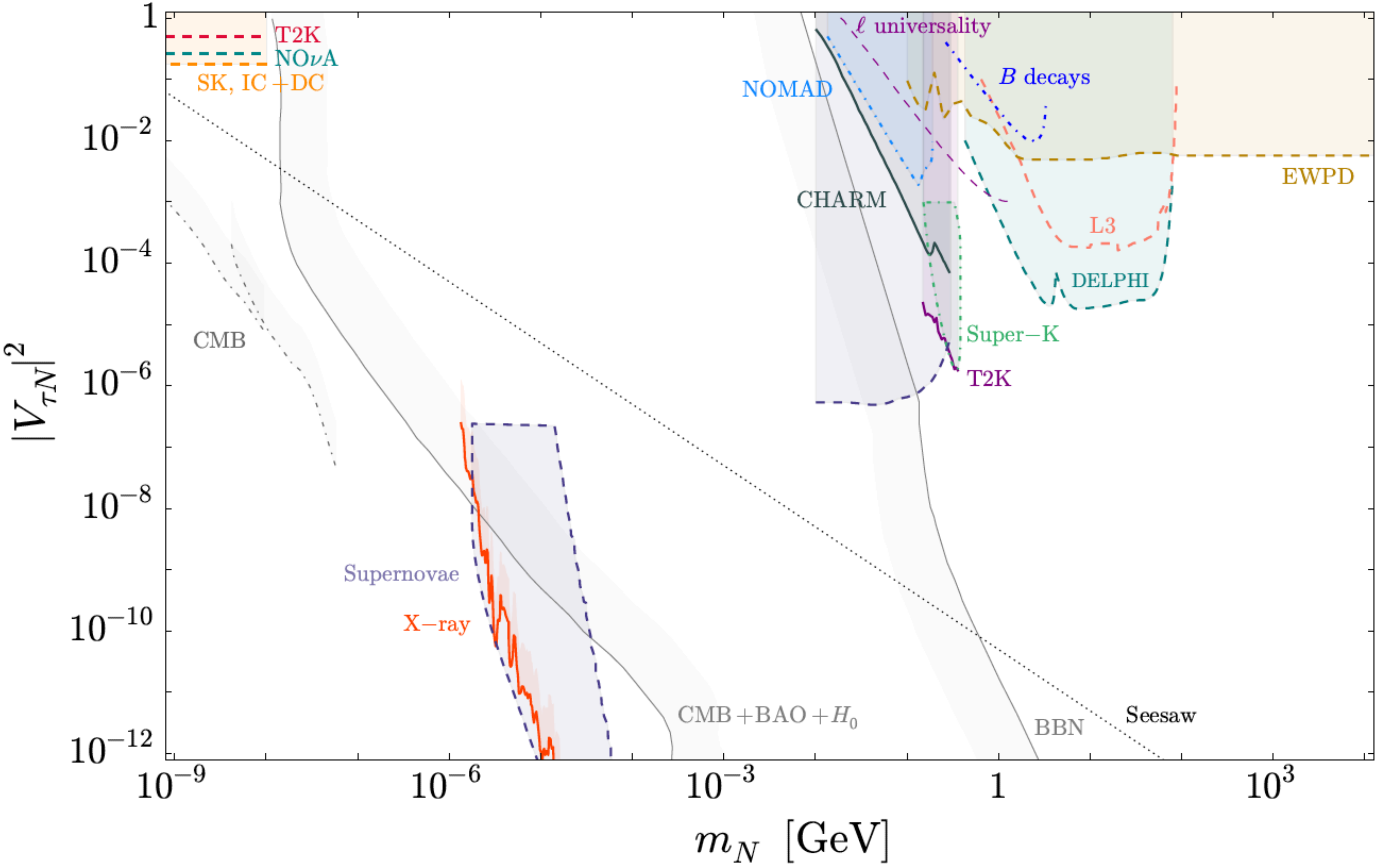
$$\boxed{\sin\alpha \text{ and } \sin\beta}$$



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

$$m_{N_1}, m_{N_2} > 500 \text{ MeV}$$ → No bound from supernova and BBN or Kaon decay

$$\boxed{m_{N_1} = Y_1 v_\phi \quad m_{N_2} = Y_2 v_\phi}$$

$$m_{Z'} = g_\psi v_\phi/\sqrt{2} > (g_\psi/Y_{1,2})500 \text{ MeV}$$

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

Can we escape the bounds?

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:

$$(U^\dagger_{PMNS} \cdot U_{PMNS})_{\alpha\beta}|_{\alpha\neq\beta}$$

$$\xcancel{l_\alpha^- \to l_\beta^- \gamma}$$

$$\boxed{\nu_\alpha \text{ mixes with } N_1}$$

$$\boxed{\nu_\beta \text{ mixes with } N_2}$$

$$\boxed{\text{two-loop suppressed}}$$

Violation of unitarity of the mixing matrix

$Z \to \text{invisibles}$

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

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

$m_N > m_K,$

$K^+(\pi^+) \to l_\alpha^+ \nu$

$K^+(\pi^+) \to l_\beta^+ \nu$

$\sin\alpha, \sin\beta < 0.03$

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

LFV charged lepton decay

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

$\boxed{\text{two-loop suppressed}}$

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

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

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

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

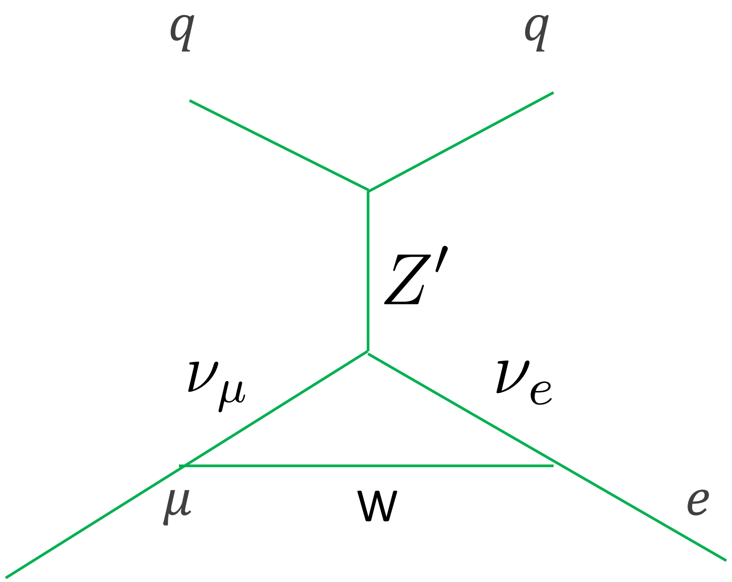
PDG: $\boxed{\mathrm{Br}(\tau \to e Z') < 2.7 \times 10^{-3} \quad \text{and} \quad \mathrm{Br}(\tau \to \mu Z') < 5 \times 10^{-3}}$

Heeck and Rodejohann,
PLB776 (2018) 385

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

Close to the prediction for $(g_\nu)_{\mu e} \sim 10^{-3}$ and $m_{Z'} \sim 10 \text{ MeV}$

muon to electron conversion



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

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

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

Mu2e, COMET

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

Smoking gun of the model

1) $\epsilon_{e\mu} \sim 0.1$

2) Muon to e conversion on nuclei but $\mu^- \cancel{\to e^-} \gamma$

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

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

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) ⇒ LFV NSI for neutrinos

No LFV 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

Higgs invisible decay mode

$$Y_{R\alpha}\bar{N}_{1R}H^T c L_\alpha + Y_{R\beta}\bar{N}_{2R}H^T c L_\beta$$

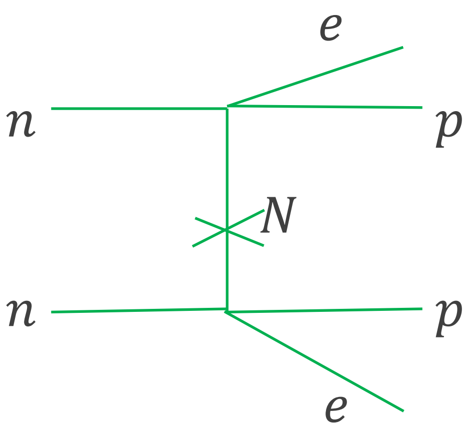
$$\boxed{H \to \bar{\nu}_\alpha N_1} \qquad \boxed{H \to \bar{\nu}_\beta N_2}$$

$$\boxed{Y_{R\alpha}^2 m_H/(4\pi)} \qquad \boxed{Y_{R\beta}^2 m_H/(4\pi)}$$

PDG $\mathrm{Br}(H \to \text{invisibles}) < 0.2 \Rightarrow Y_{R\alpha,\beta}\langle H\rangle < 2\ \text{GeV}$

In our model: $Y_{R\alpha,\beta}\langle H\rangle \sim 15\ \text{MeV}$

Lepton number violation



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

Majorana mass

$$m_N N^T c N$$

Dirac mass

$$m_N \bar{N} N$$

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

z' coupling to matter fields

1 Gauging a linear combination of Baryon number and lepton numbers

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

$$\boxed{a_e + a_\mu + a_\tau = 3}$$

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

2 Kinetic mixing with hypercharge gauge boson

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

Z component → Coupling suppressed by $(m^2_{Z'}/m^2_Z)\delta \sin\theta_W$

z' coupling to matter fields

1 Gauging a linear combination of Baryon number and lepton numbers

$$\boxed{B-(a_eL_e+a_\mu L_\mu+a_\tau L_\tau)} \qquad \boxed{a_e+a_\mu+a_\tau=3}$$

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

2 Kinetic mixing with hypercharge gauge boson

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

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

NSI in CEνNS CONUS, COHERENT

NO NSI in neutrino oscillation

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

$$\boxed{a_e=0}$$

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

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

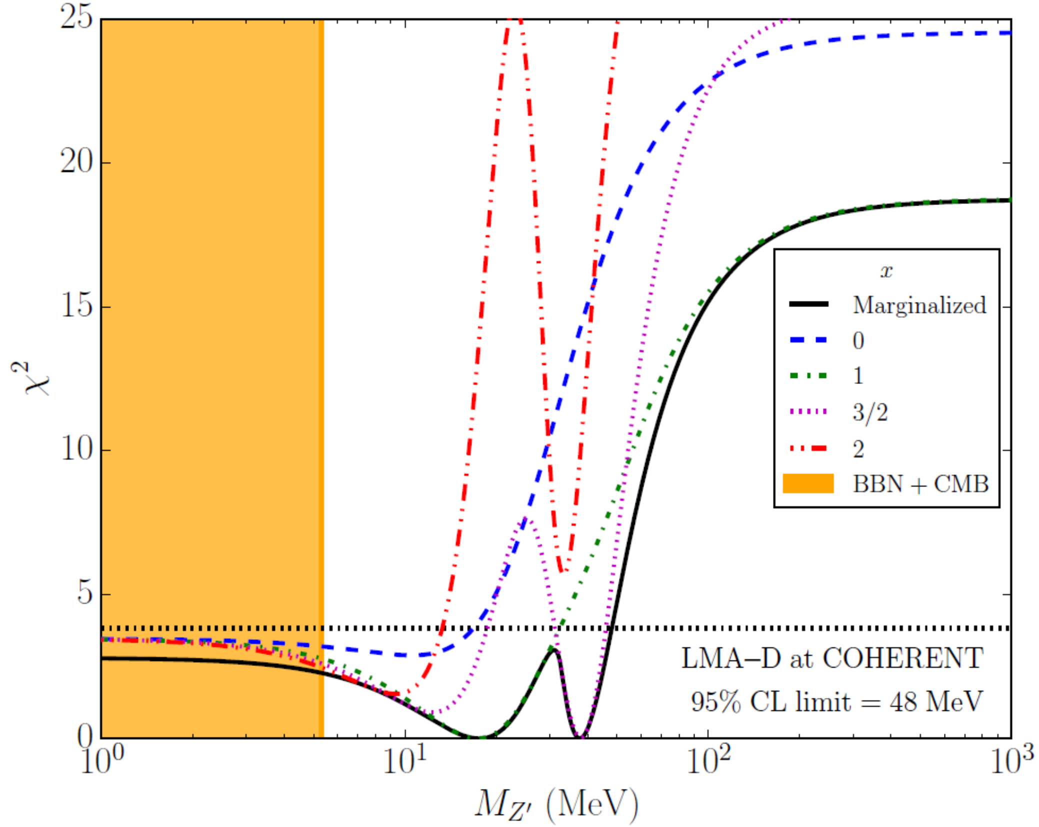
$$(g_\nu)_{\alpha\beta} = 10^{-3} g_\psi \text{ and } m_{Z'} \sim 500 \text{ MeV} g_\psi$$

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

LMA-Dark after COHERENT data

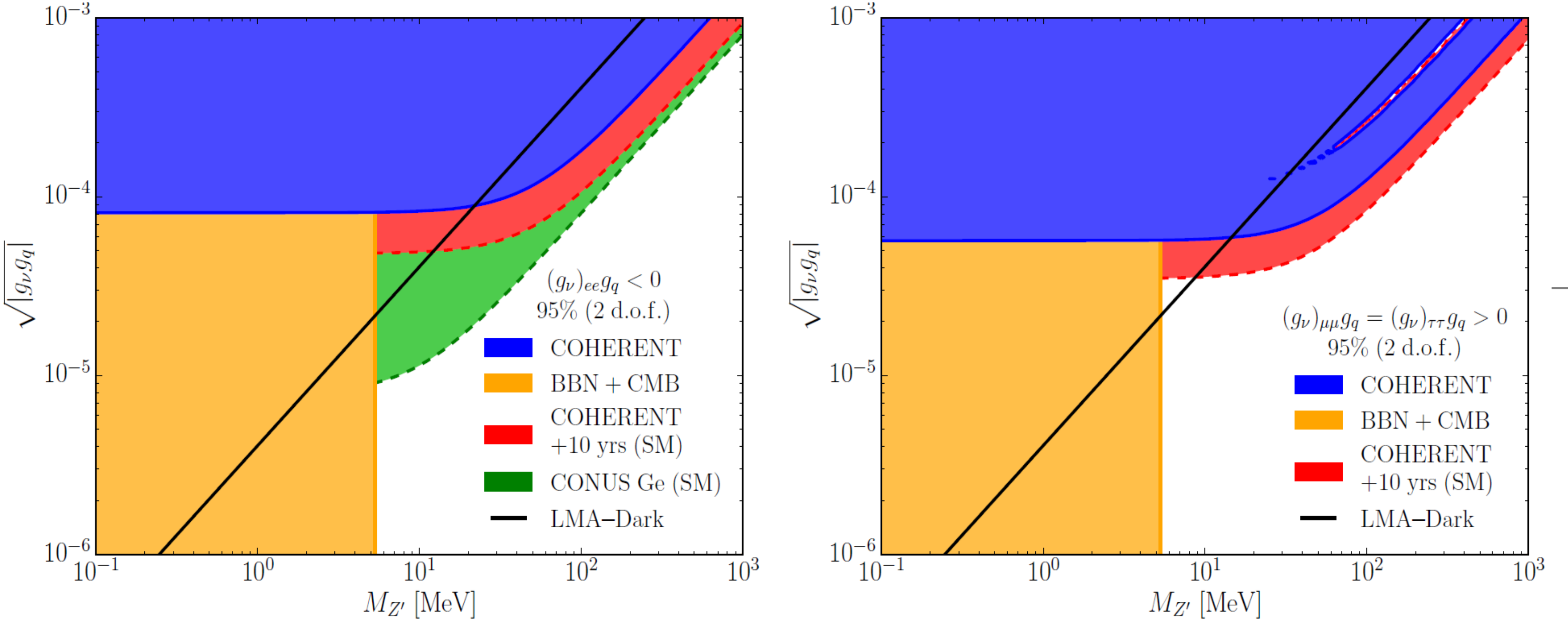
$$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (x-2, x, x)$$

$$\epsilon_{ee}^{u,V} = \epsilon_{ee}^{d,V} = \frac{x}{4} - \frac{1}{2}$$



$M_{Z'} > 48$ MeV at 95% C.L. (1 d.o.f.)

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

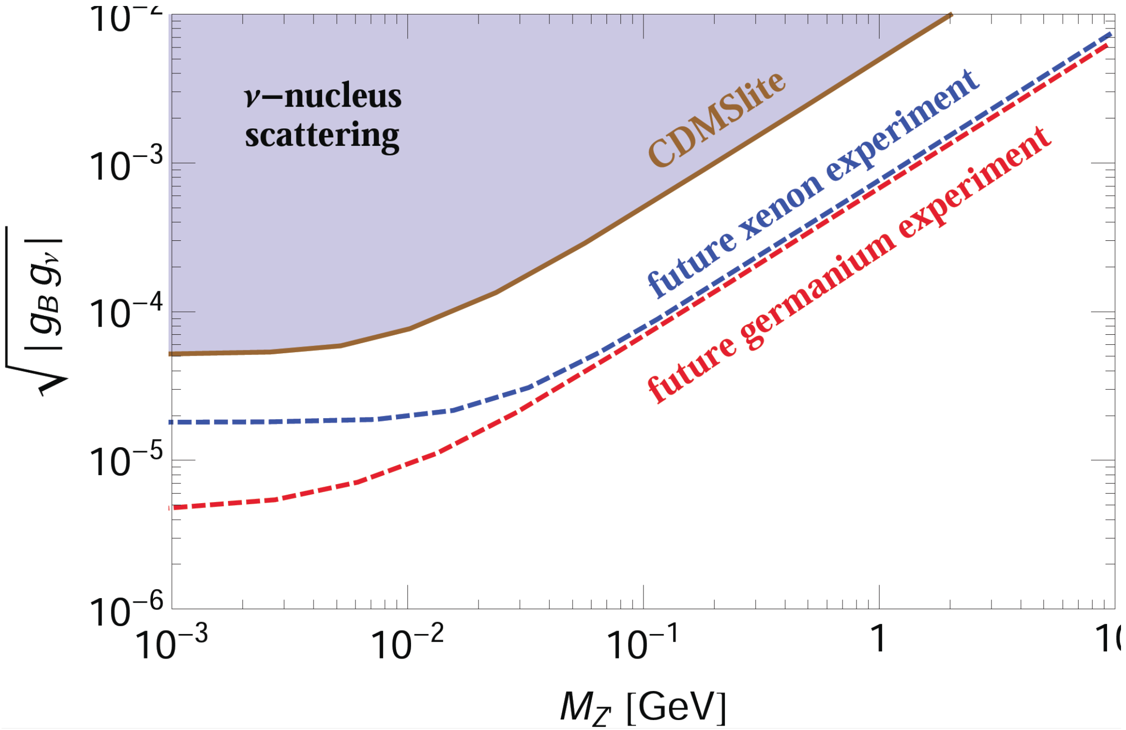


Denton, YF and Shoemaker, JHEP 1807 (2018) 037; arXiv:1804.03660.

COherent NeUtrino Scattering experiment (CONUS)

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

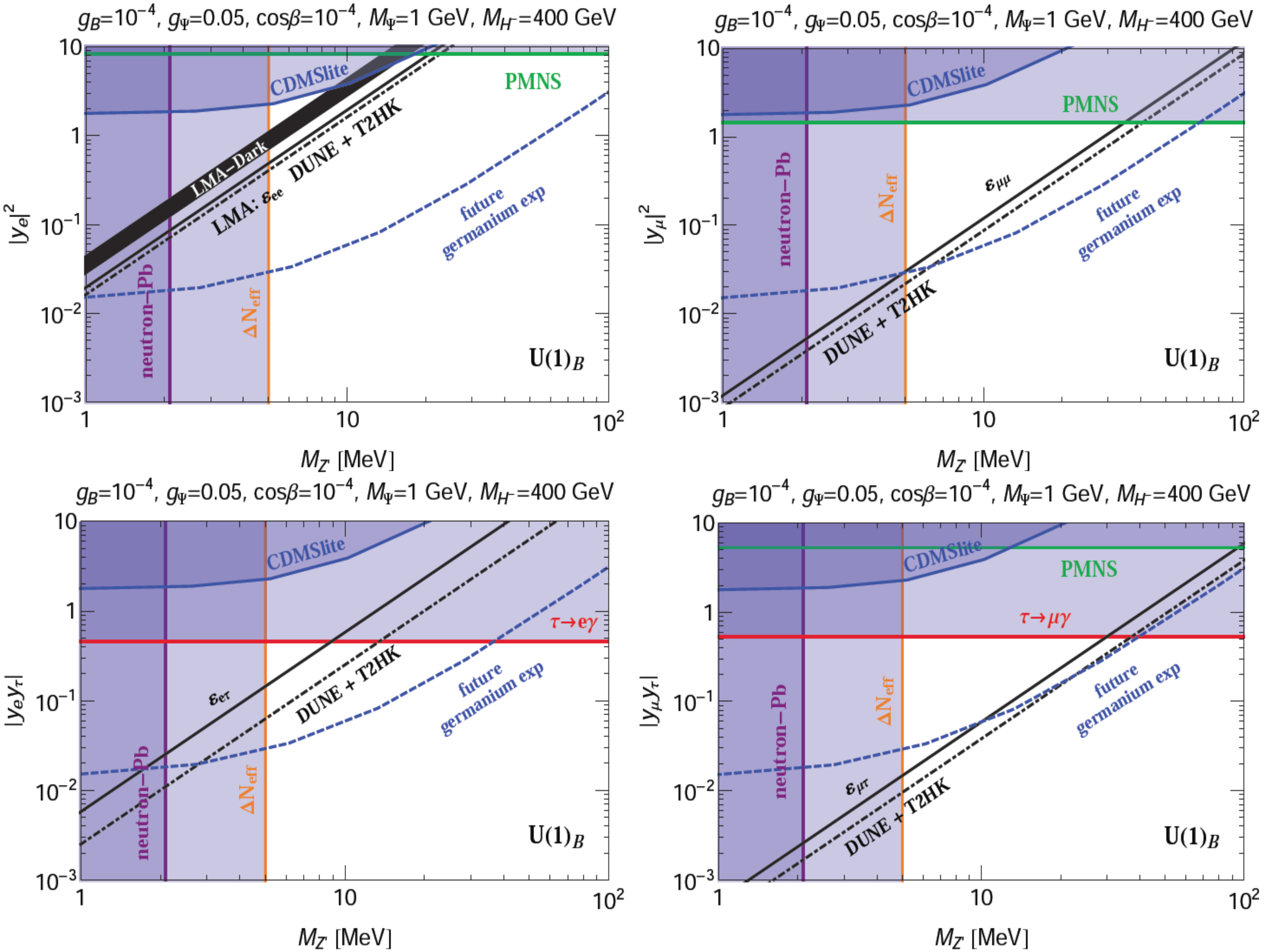
Solar neutrino interaction at DM direct detection experiments



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

Cerdeno et al,JHEP 05 (2016) 118

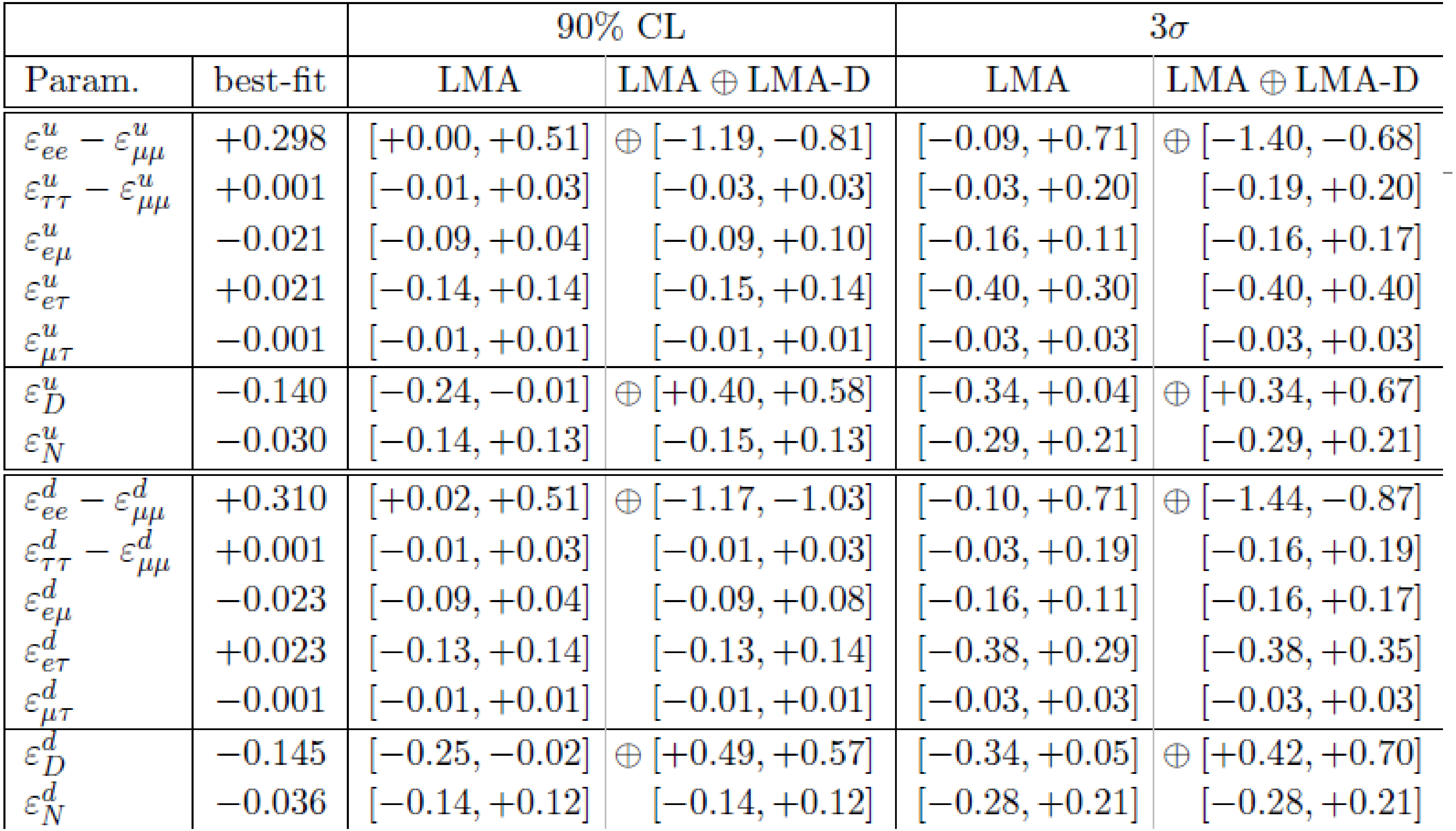
SuperCDMS SNOLAB LUX–ZEPLIN



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

Solar neutrino coherent Interaction in future direct dark matter search experiments

$$\kappa_\alpha = \frac{y_\alpha \langle H' \rangle}{M_\Psi} = \frac{y_\alpha v \cos\beta}{\sqrt{2} M_\Psi}$$



		90% CL		3σ	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus\ [-1.19, -0.81]$	$[-0.09, +0.71]$	$\oplus\ [-1.40, -0.68]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$	$[-0.03, +0.20]$	$[-0.19, +0.20]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$	$[-0.40, +0.30]$	$[-0.40, +0.40]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^u_D	-0.140	$[-0.24, -0.01]$	$\oplus\ [+0.40, +0.58]$	$[-0.34, +0.04]$	$\oplus\ [+0.34, +0.67]$
ε^u_N	-0.030	$[-0.14, +0.13]$	$[-0.15, +0.13]$	$[-0.29, +0.21]$	$[-0.29, +0.21]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus\ [-1.17, -1.03]$	$[-0.10, +0.71]$	$\oplus\ [-1.44, -0.87]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$	$[-0.03, +0.19]$	$[-0.16, +0.19]$
$\varepsilon^d_{e\mu}$	-0.023	$[-0.09, +0.04]$	$[-0.09, +0.08]$	$[-0.16, +0.11]$	$[-0.16, +0.17]$
$\varepsilon^d_{e\tau}$	$+0.023$	$[-0.13, +0.14]$	$[-0.13, +0.14]$	$[-0.38, +0.29]$	$[-0.38, +0.35]$
$\varepsilon^d_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$	$[-0.03, +0.03]$	$[-0.03, +0.03]$
ε^d_D	-0.145	$[-0.25, -0.02]$	$\oplus\ [+0.49, +0.57]$	$[-0.34, +0.05]$	$\oplus\ [+0.42, +0.70]$
ε^d_N	-0.036	$[-0.14, +0.12]$	$[-0.14, +0.12]$	$[-0.28, +0.21]$	$[-0.28, +0.21]$

Maltoni and Gonzalez-Garcia, JHEP 2013