Non-standard interactions of neutrinos

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IPM, TEHRAN

elusives
neutrinos, dark matter & dark energy physics

Different kinds of coupling to a new scalar

Yukawa interaction: $\phi \bar{N} \nu$

Gauge coupling: $\bar{\nu}\gamma^{\mu}\nu Z'_{\mu}$

Coupling to higher spin particles?

Higher dimension operators?

Different kinds of coupling to a new scalar

Yukawa interaction: $\phi \bar{N} \nu$

Gauge coupling: $\bar{\nu} \gamma^\mu \nu Z'_\mu$ ⇐ Focus of this talk

Coupling to higher spin particles?

Higher dimension operators?

Effects of NSI on neutrinos

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

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

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

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

Effects of NSI on neutrinos

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

Focus of this talk

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

Outline

Impact on propagation of neutrinos in matter and consequences for neutrino experiments

Underlying models

Bounds from various experiments with focus on CEνNS

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

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

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

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

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

Matter effects in presence of NSI

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

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

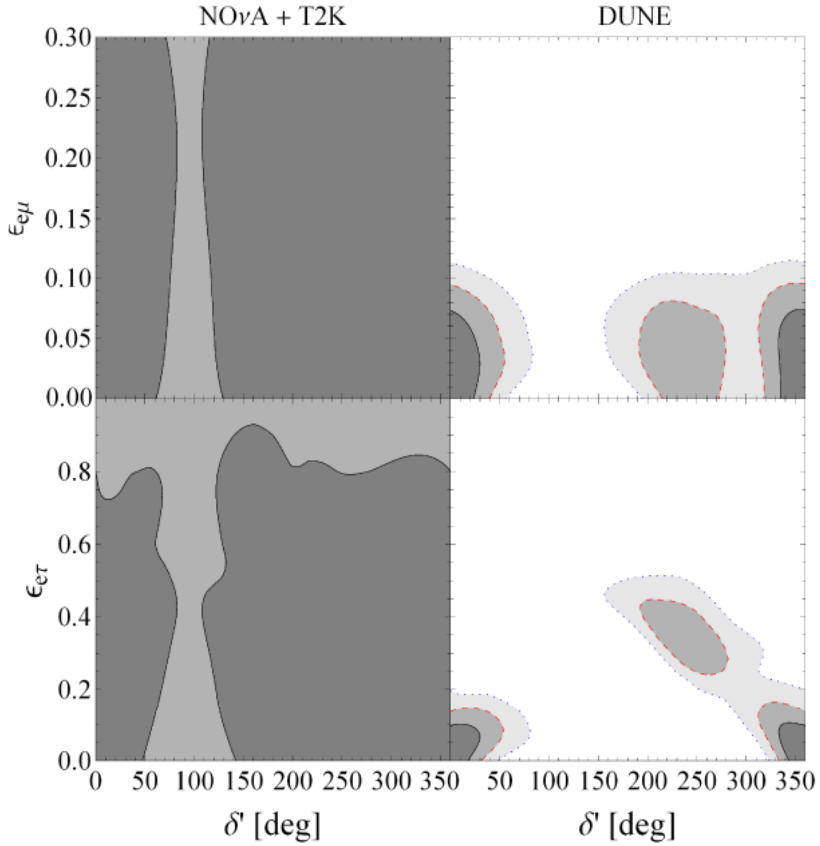
$$H_{\text{mat}} = \sqrt{2}G_F N_e(r)\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix} + \sqrt{2}G_F \sum_{f=e,u,d} N_f(r)\begin{pmatrix}\varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau}\\ \varepsilon^{f*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau}\\ \varepsilon^{f*}_{e\tau}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

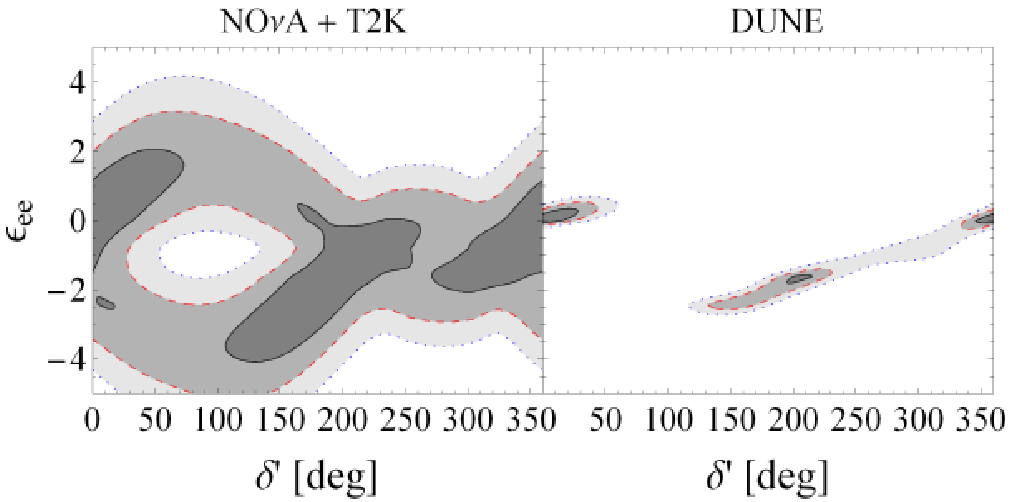
Effects of NSI in long baseline experiments

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)

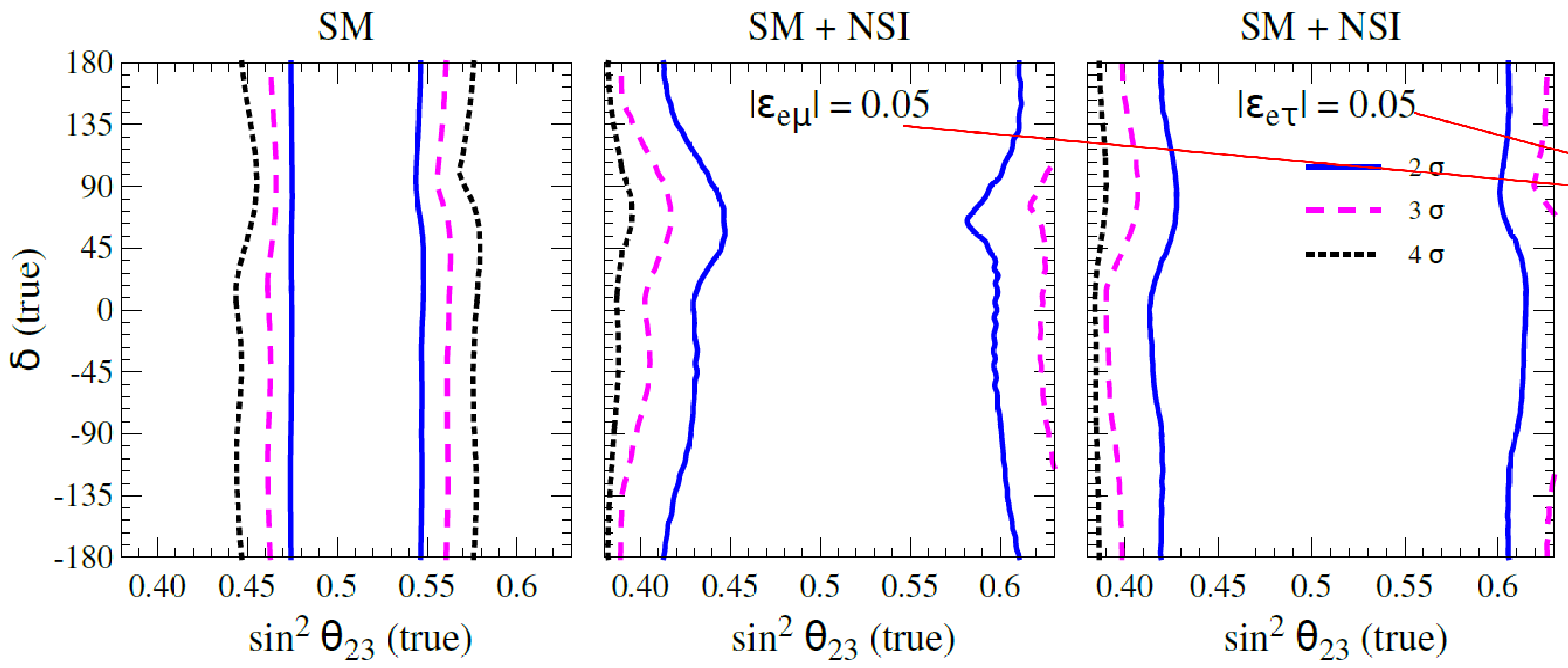




Liao Marfatia Whisnant, PRD93 (2016)

$\mathrm{SM\ with\ } \delta = 0$

Octant discovery potential of DUNE

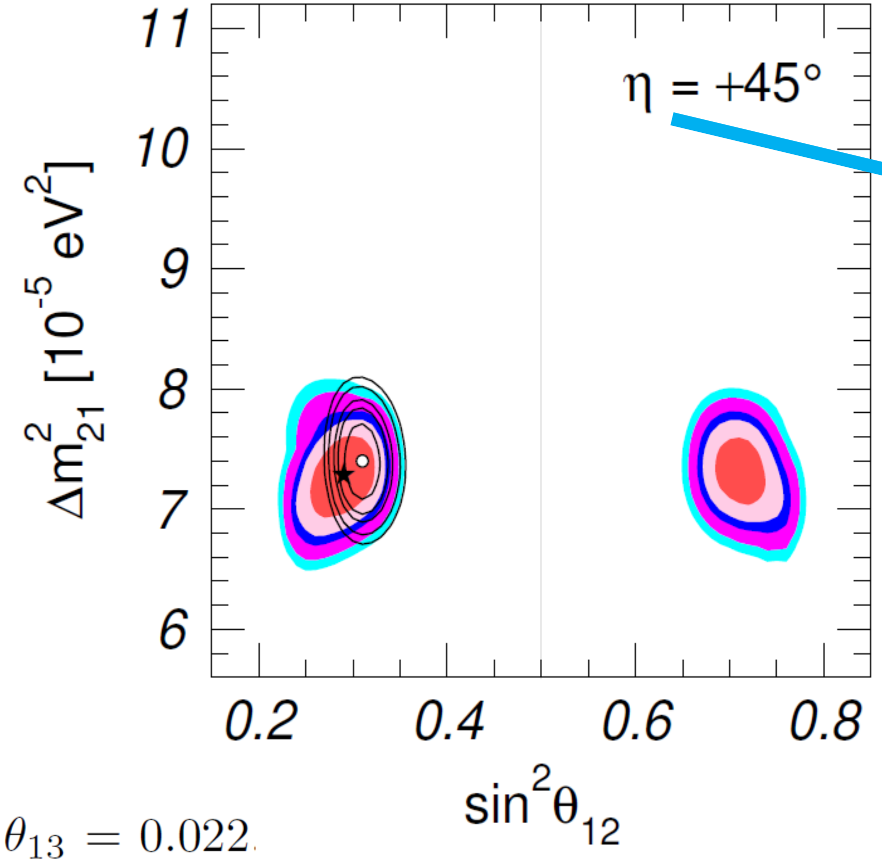


Accepted within
Present uncertainties

Agarwalla, Chatterjee and Palazzo, PLB 762 (2016)

Fit to solar and KamLand data

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

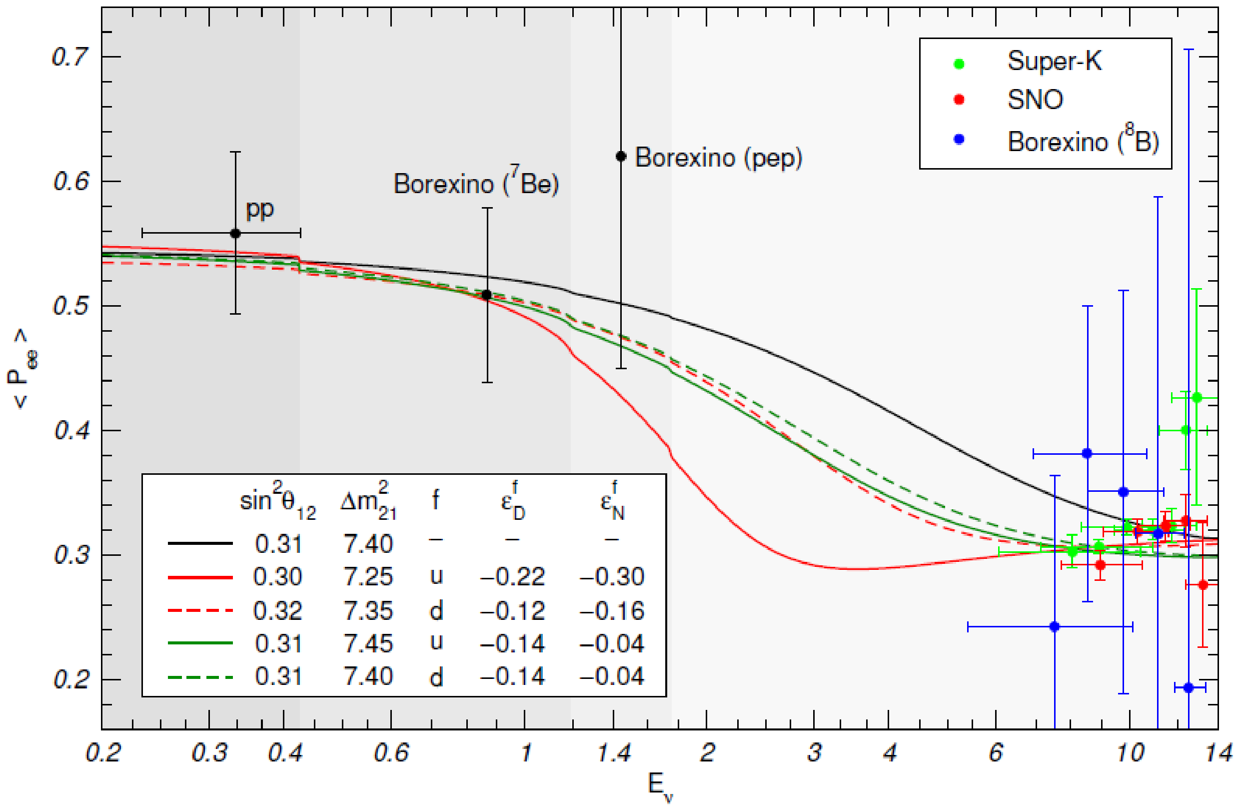


$\epsilon^u = \epsilon^d$

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

Esteban, Gonzalez-Garcia, M. Maltoni, Martinez-Soler and J Salvado, arXiv:1805.04530

Solar+KamLAND



Maltoni and Gonzalez-Garcia, JHEP 2013

LMA-Dark solution

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

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

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

Total flux measurement at SNO

Neutral current

Deuteron dissociation

$$D + \nu \rightarrow p + n + \nu$$

Gamow-Teller transition

Sensitive only to axial-vector interaction

No effect from $\epsilon^{f}_{\alpha\beta} \equiv \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}$

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

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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

Determining 12 octant

Shedding light on LMA-Dark solar neutrino solution by medium baseline reactor experiments: JUNO and RENO-50

YF and Bakhti, JHEP 2014

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \left| |U_{e1}|^2 + |U_{e2}|^2 e^{i\Delta_{21}} + |U_{e3}|^2 e^{i\Delta_{31}} \right|^2 = \left| c_{12}^2 c_{13}^2 + s_{12}^2 c_{13}^2 e^{i\Delta_{21}} + s_{13}^2 e^{i\Delta_{31}} \right|^2 =$$

$$c_{13}^4 (1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta_{21}}{2}) + s_{13}^4 + 2 s_{13}^2 c_{13}^2 [\cos \Delta_{31} (c_{12}^2 + s_{12}^2 \cos \Delta_{21}) + s_{12}^2 \sin \Delta_{31} \sin \Delta_{21}]$$

Medium Baseline reactor experiments

DAYA BAY in CHINA → JUNO

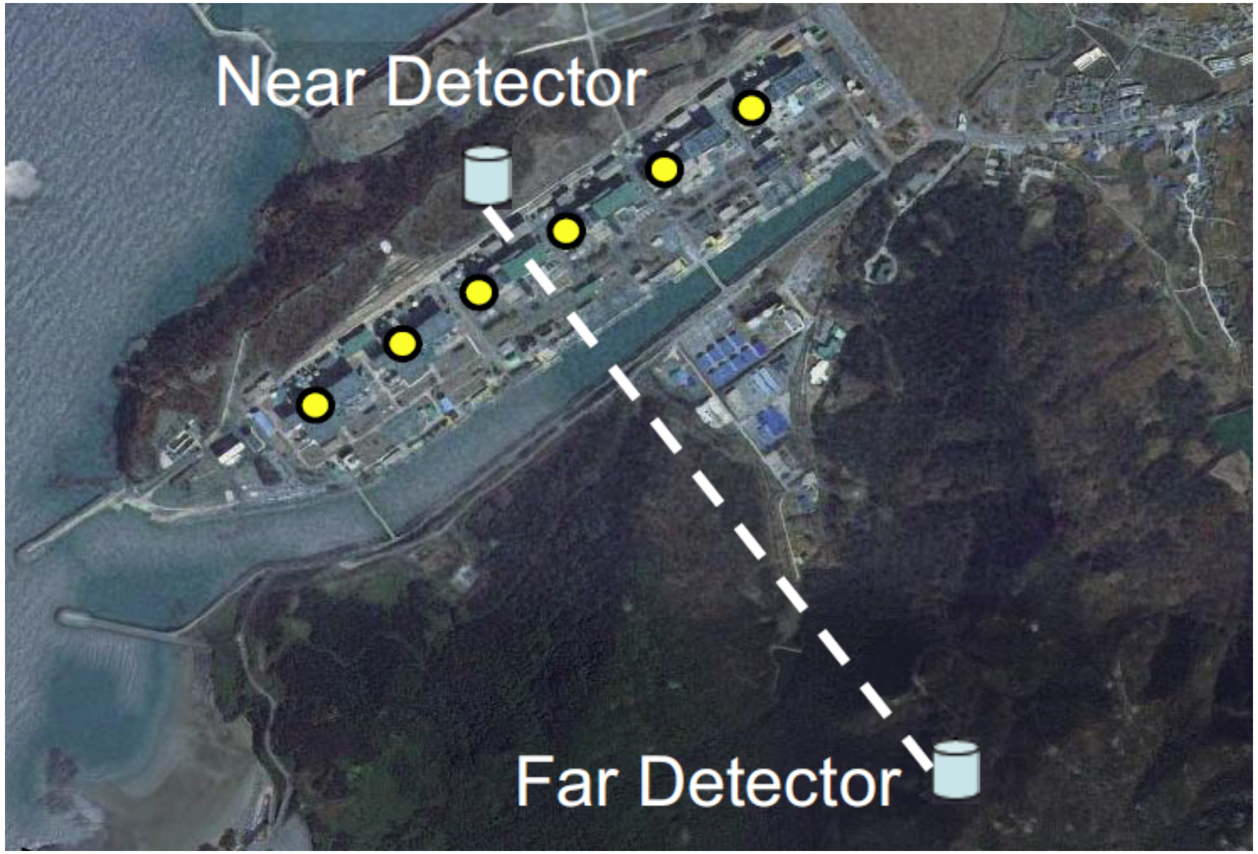
RENO in South Korea → RENO-50

Ready for data taking in 2020.

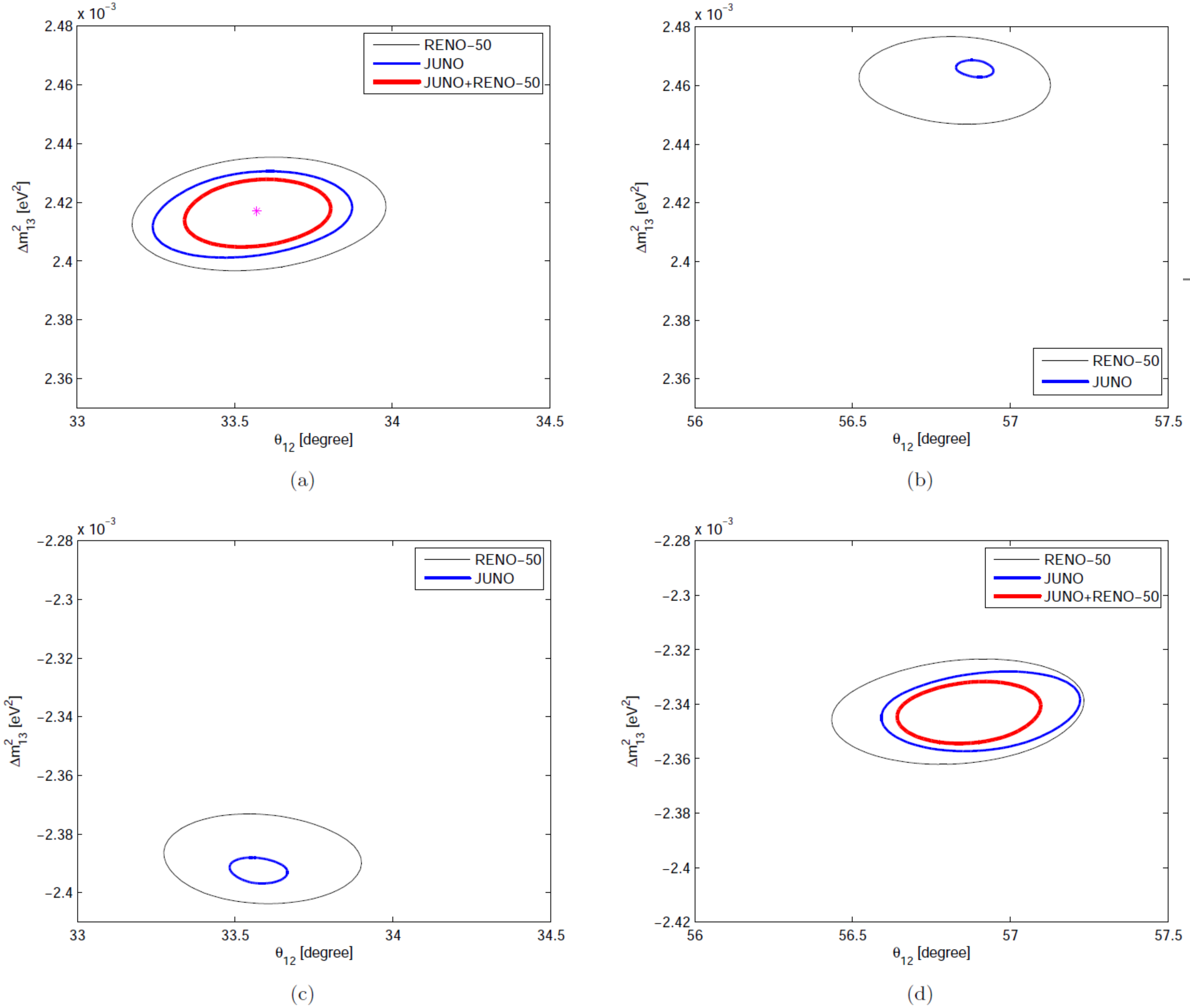
Baseline ~ 50 km

Main goal determination of $\mathrm{sgn}(\Delta m^2_{31})$

RENO-50 in South Korea



Daya Bay and Juno



$$\frac{\delta E_\nu}{E_\nu} \simeq 3\% \times (\frac{E_\nu}{\text{MeV}})^{1/2}$$

YF and Bakhti, JHEP 2014

Allowed region at 3 σ C.L. after 5 years of data taking by RENO-50 and JUNO.

Generalized mass ordering degeneracy

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

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

$$\epsilon_{\alpha\beta} = \sum\nolimits_{f \in \{e,u,d\}} (N_f / N_e) \epsilon_{\alpha\beta}^f$$

Generalized mass ordering degeneracy

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No dependence on energy and baseline

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

Degeneracy cannot be solved by changing baseline/beam energy.

Generalized mass ordering degeneracy

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

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

Variation of N_n/N_e can solve the degeneracy.

Across the Earth radius: $N_n/N_e \simeq 1$ Sun center: $N_n/N_e \simeq 1/2$ Sun surface: $N_n/N_e \simeq 1/6$

Global analysis of oscillation data

	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.005, +0.130]$	$[-0.152, +0.130]$
$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.067]$
$\varepsilon^u_{e\tau}$	$[-0.292, +0.119]$	$[-0.292, +0.336]$
$\varepsilon^u_{\mu\tau}$	$[-0.013, +0.010]$	$[-0.013, +0.014]$

Esteban, Gonzalez-Garcia, M. Maltoni, Martinez-Soler and J Salvado, arXiv:1805.04530

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

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 transforamation)

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

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

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

Neutral U(1) gauge boson as mediator

Our Focus

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

Charged scalar (a la Fierz trasnforamation)

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

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

Underlying theory for LMA-Dark?

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

Various model with heavy intermediate particle
For a review see:

T. Ohlsson, "Status of non-standard neutrino interactions," Rept. Prog. Phys. **76** (2013) 044201 [arXiv:1209.2710 [hep-ph]].

Too small NSI

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

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

$$\epsilon \sim \left(\frac{g_X^2}{m_X^2}\right) G_F^{-1}$$

$m_X \gg 100\ \mathrm{GeV}$ → $\epsilon \ll 1$

Suggestion

What if $m_X \sim 10 \text{ MeV}$

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” to appear in Frontiers in physics

Suggestion

What if

$$m_X \sim 10 \text{ MeV}$$

$$\epsilon \sim 1 \quad \Rightarrow \quad g_X \sim 10^{-4} - 10^{-5}$$

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

But because coupling is small!

Neutral current Non-Standard Interactions

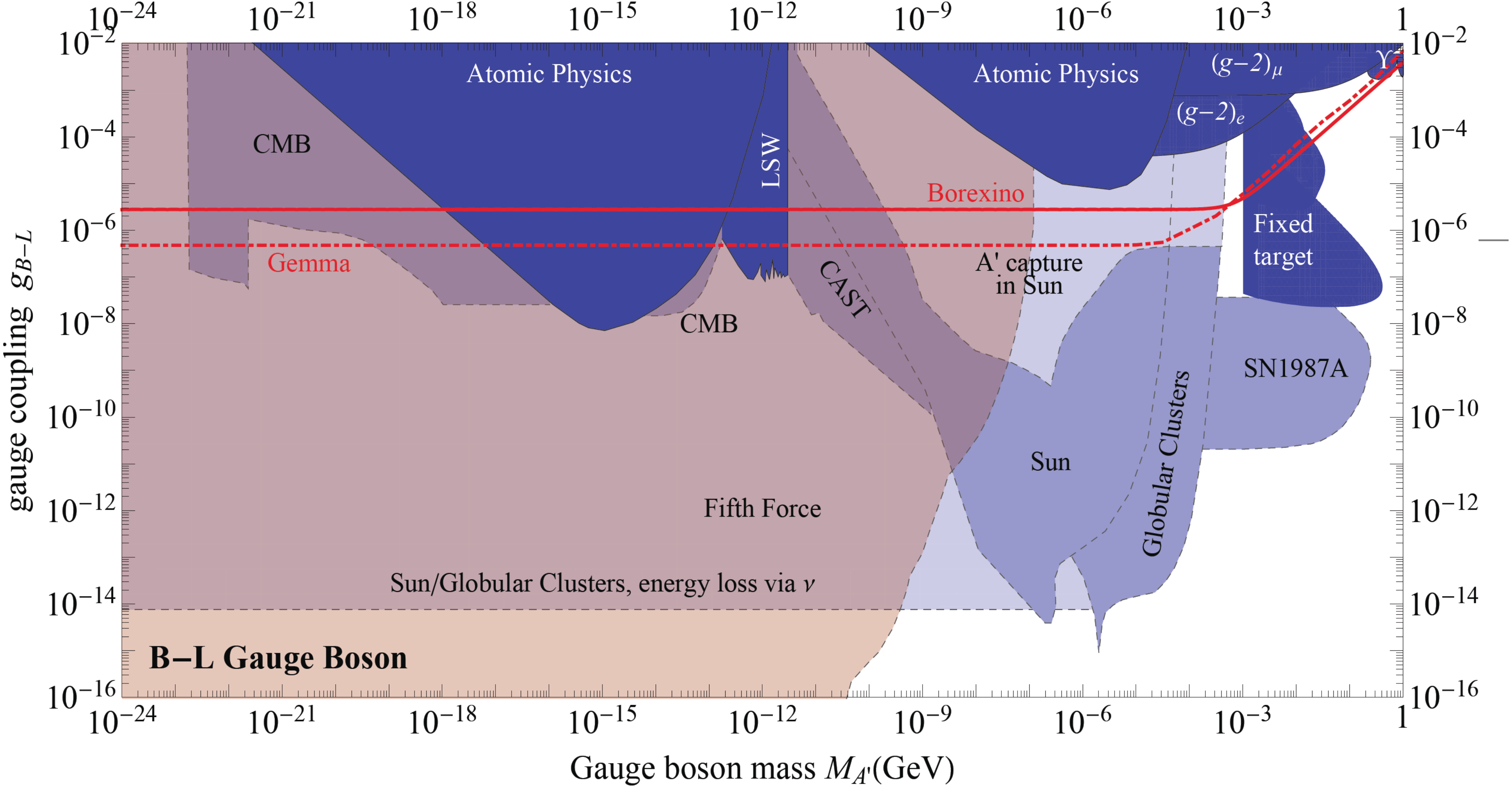
NSI $$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\,\varepsilon_{\alpha\beta}^{fX}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_X f)$$

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

$$g_\nu\bar{\nu}\gamma^\mu\nu Z'_\mu \qquad g_B\bar{q}\gamma^\mu q Z'_\mu$$

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

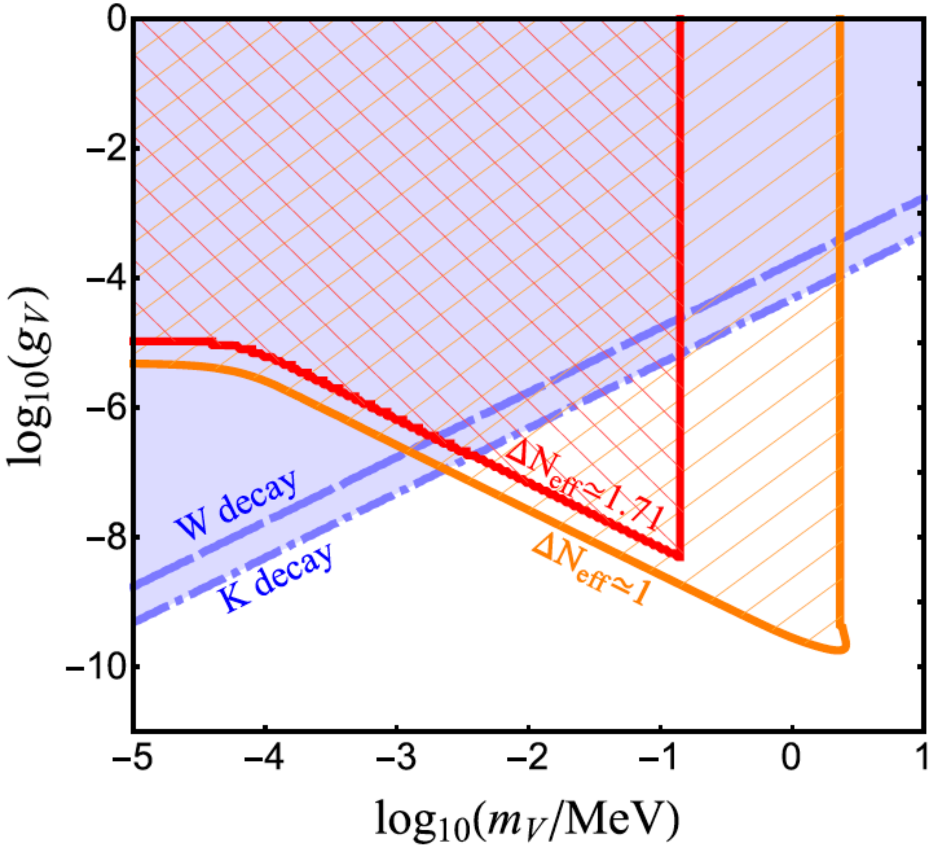
$$\sqrt{g_\nu g_B} \sim 7\times 10^{-5}\frac{m_{Z'}}{10\ \mathrm{MeV}} \quad \Longleftrightarrow \quad \epsilon^u_{\alpha\beta} = \epsilon^d_{\alpha\beta} \sim 1$$



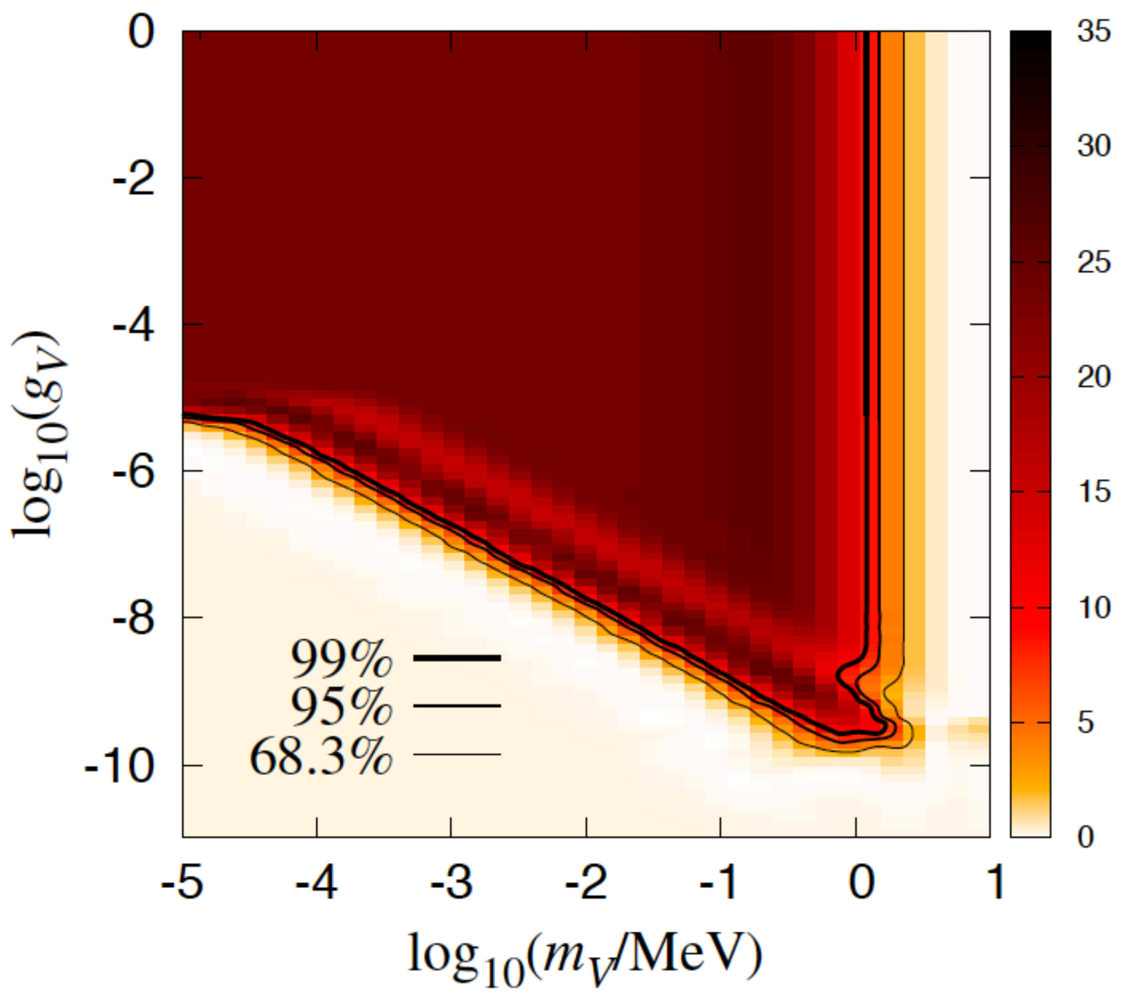
$g' a_e < 3 \times 10^{-11}$

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

Effect in early universe



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



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

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

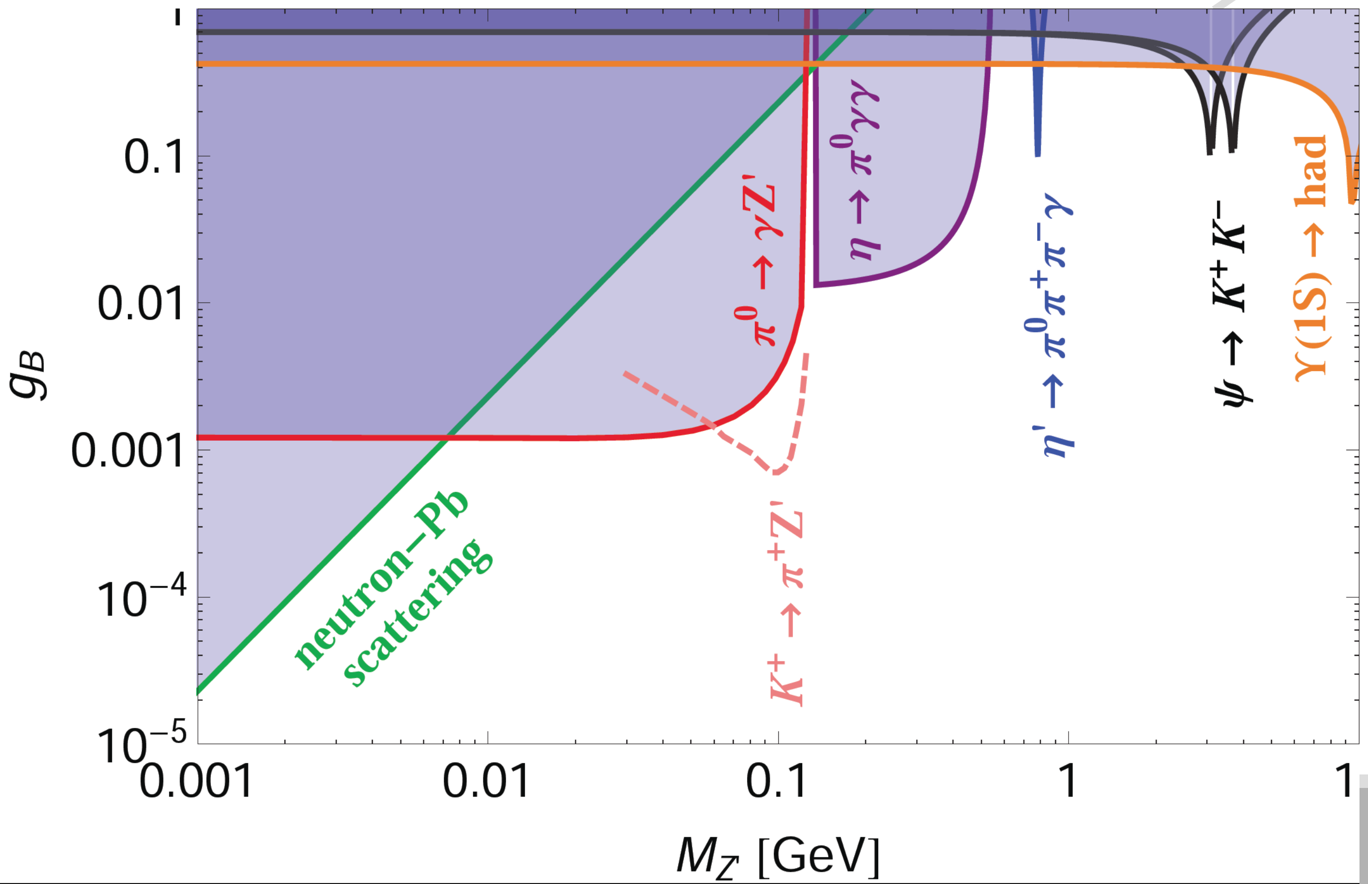
Huang, Ohlsson, Zhou, PRD 97 (2018) 075009

Coupling to quarks

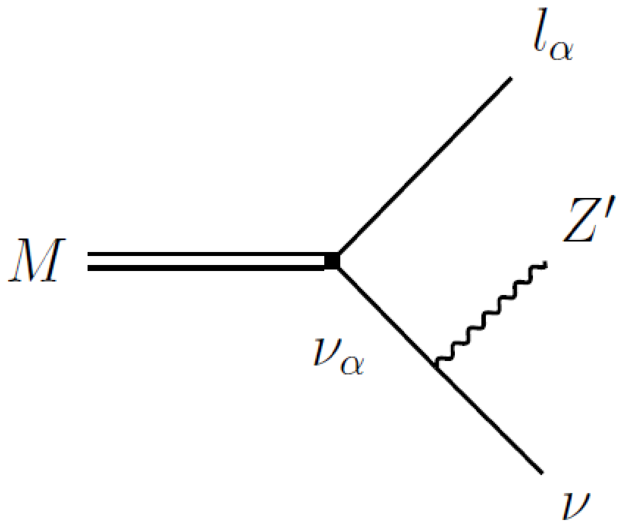
Non-chiral couplings: No impact on total measurement at SNO

Flavor universal: Going to mass basis

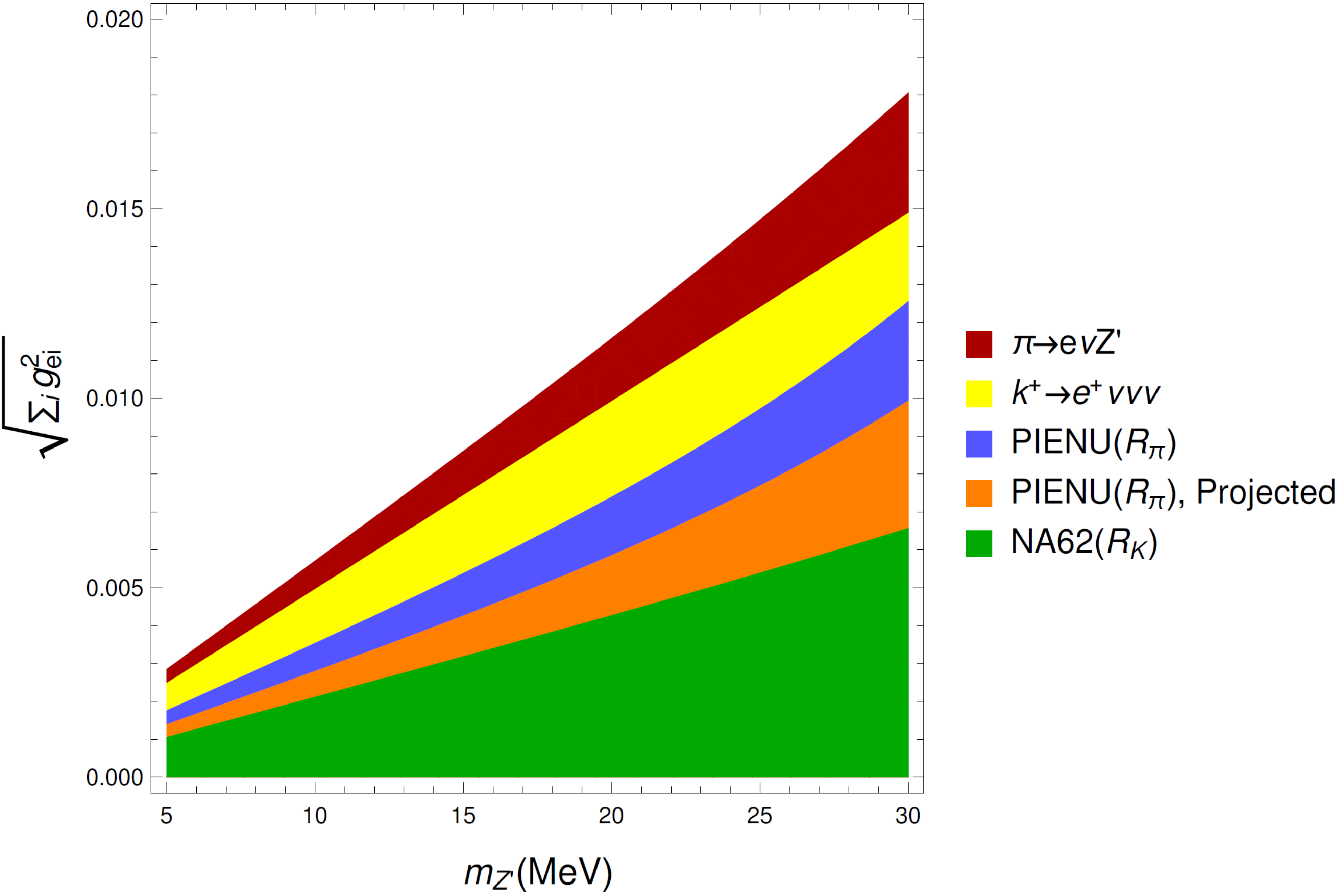
$q_i \to q_j Z'$



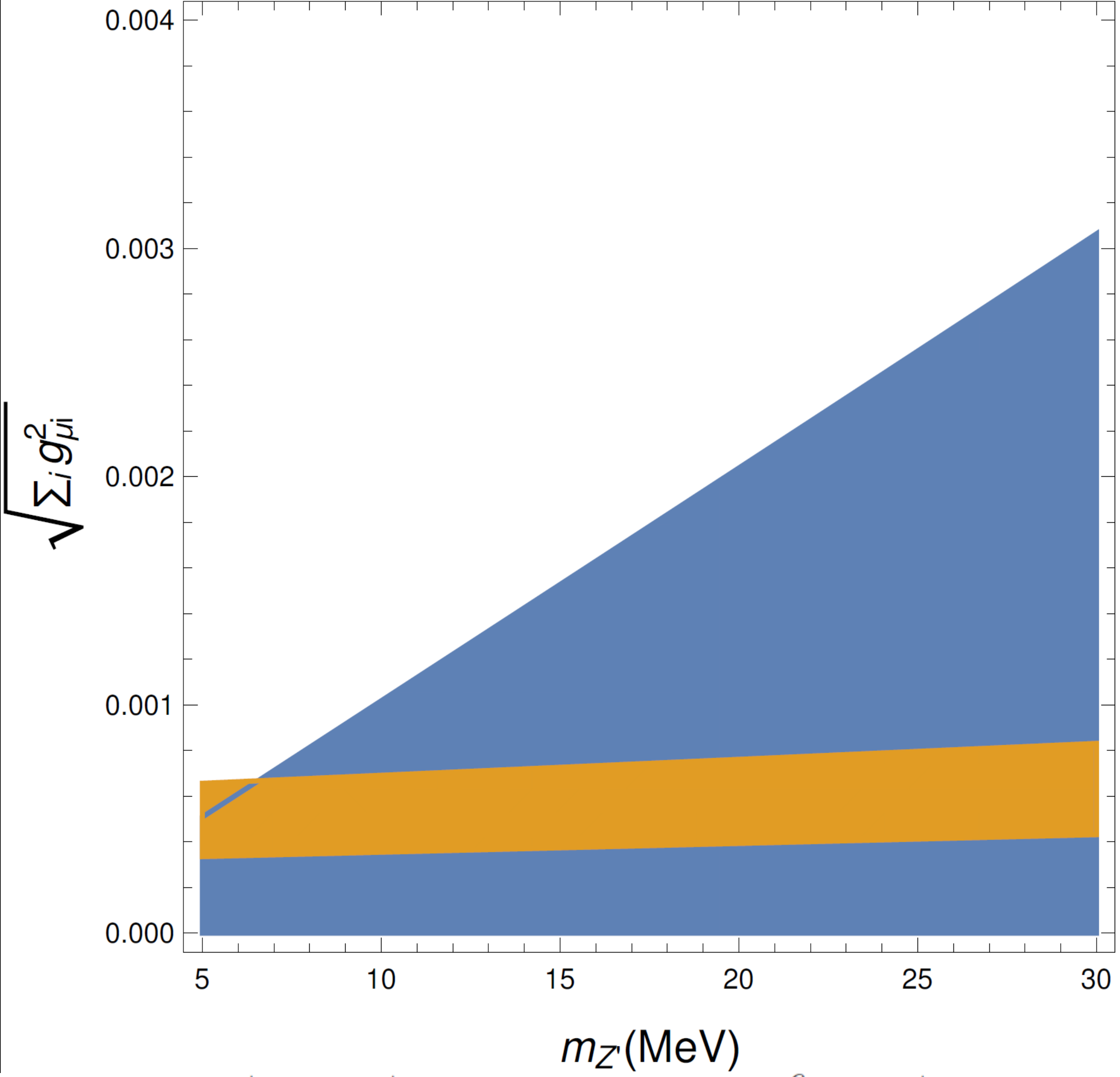
Bounds on Couplings of neutrinos



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



P Bakhti and YF, PRD 95 (2017) 095008



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

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

P Bakhti and YF, PRD 95 (2017) 095008

Coupling to neutrinos

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: $a_\psi L_\psi + B$

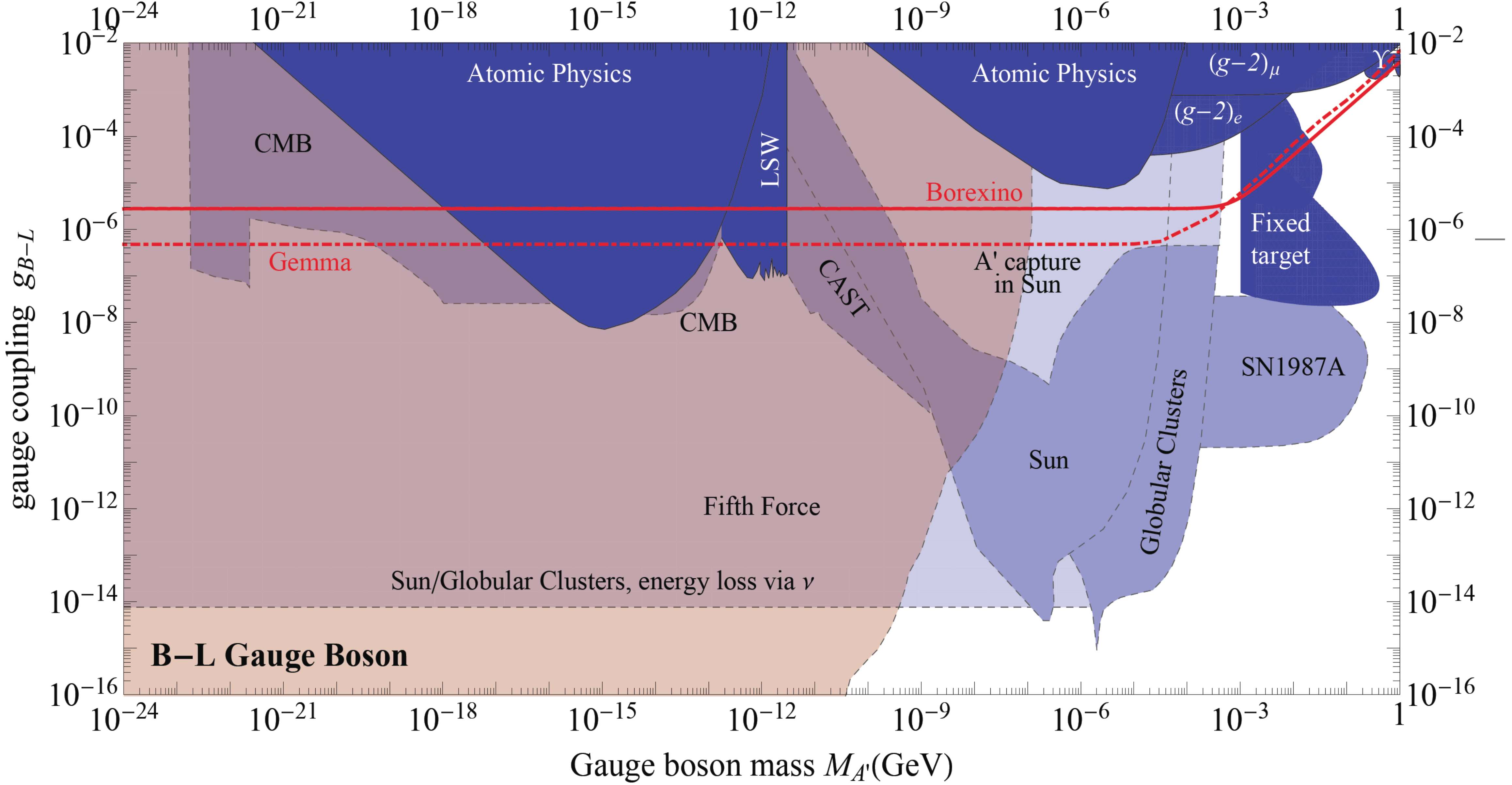
Coupling to neutrinos

Direct coupling to neutrinos

Gauge symmetry:

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

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



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

$$a_e = 0$$

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

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

$$c\tau_{Z'} \sim 10^{-9} \text{ km} \left(\frac{7 \times 10^{-5}}{g'} \right)^2 \left(\frac{10 \text{ MeV}}{m_{Z'}} \right) \frac{1}{a_\mu^2 + a_\tau^2}$$

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

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

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

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

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

Neutrino scattering experiments

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

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

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

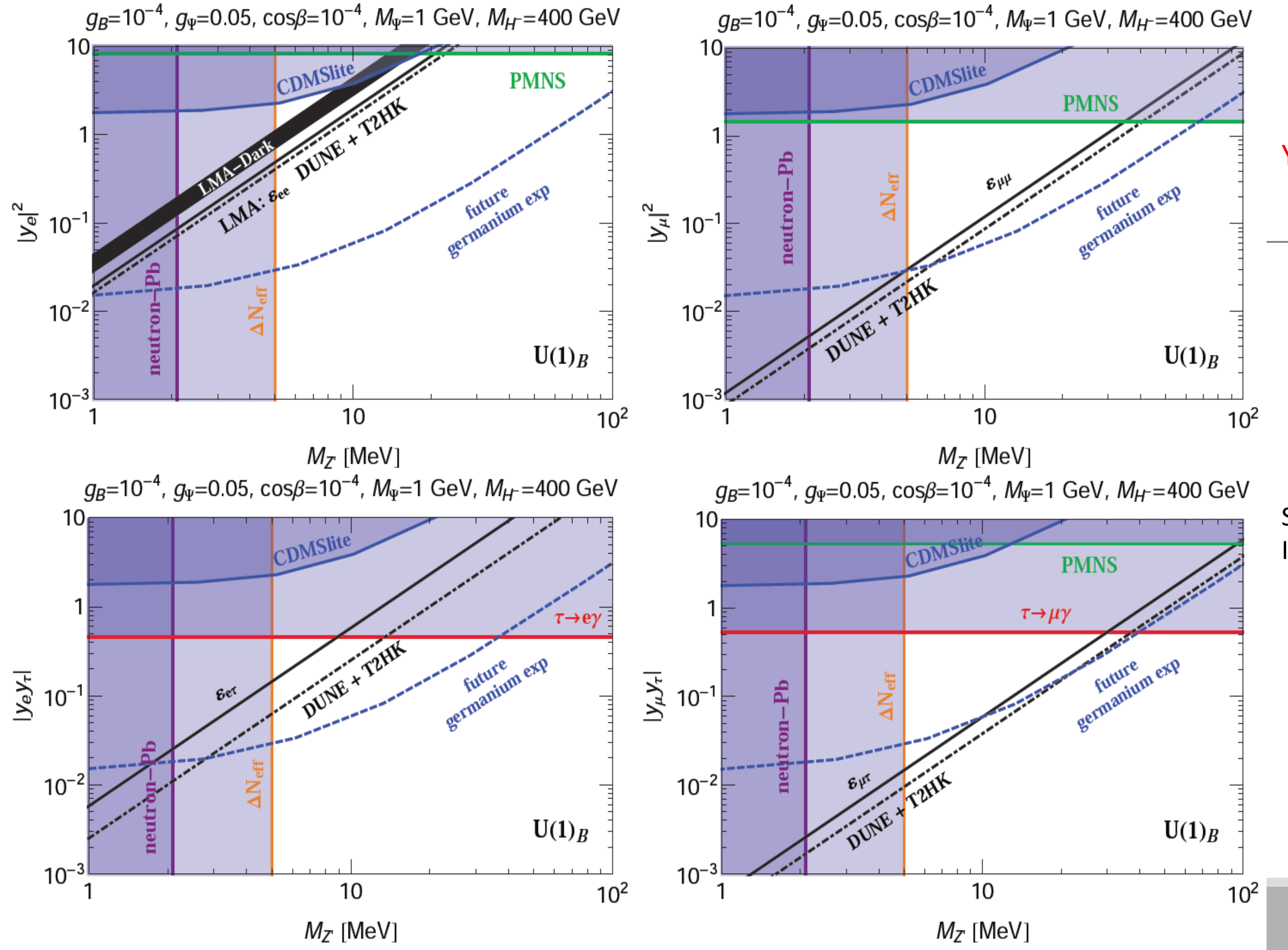
Neutrino scattering experiments

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

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

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

Relaxing bounds from scattering experiments, NuTeV and CHARM



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

Solar neutrino coherent Interaction in future direct dark matter search experiments

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

Set-up of the COHERENT experiment

Detector: 14.6 kg CsI scintillator

Source: Spallation Neutron Source (SNS) at Oak Ridge National Lab

$$\pi^+ \to \mu^+ + \nu_\mu$$

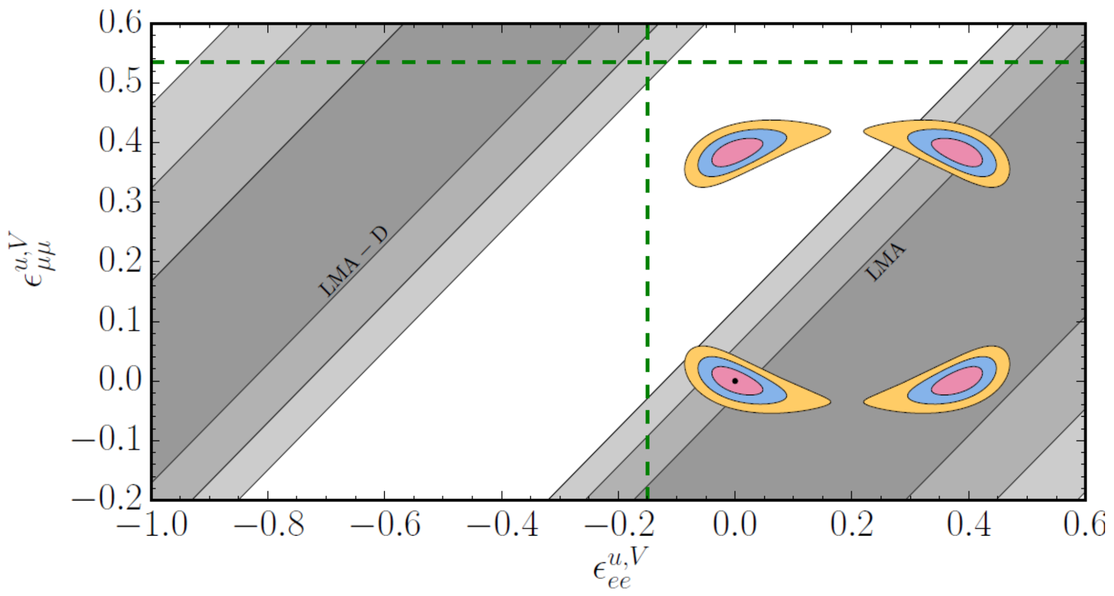
$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$

$$N_{\mathrm{POT}} = 1.76 \times 10^{23}$$

$$L = 19.3 \mathrm{~m}$$

Akimov et al., Science 357 (2017) No 6356, 1123

COHERENT experiment

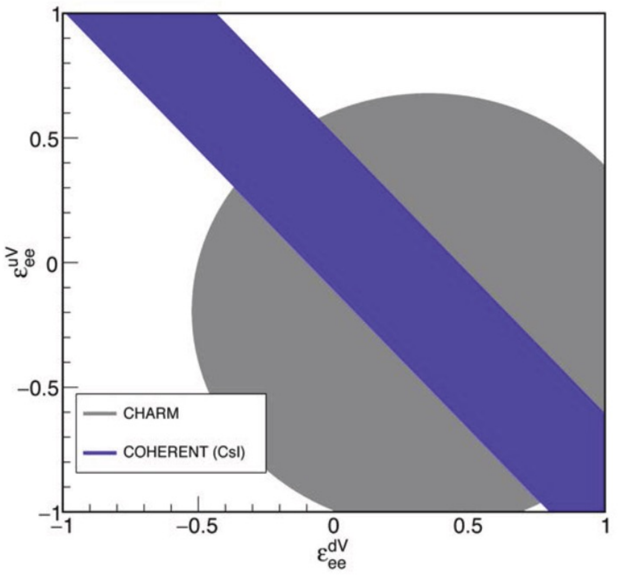


Coloma et al, JHEP 1704 (2017) 116

Neutrino source: Pion decay at rest

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

JHEP 1704 (2017) 116



P. Coloma, P. Denton, Gonzalez-Garcia, Maltoni and Schwetz, "curtailing the dark Side in non-standard neutrino interaction," JHEP 1704 (2017) 116

Akimov et al., Science 357 (2017) No 6356, 1123

Standard coherent interaction

$$\frac{d\sigma_\alpha}{dE_r} = \frac{G_F^2}{2\pi} Q_\alpha^2 F^2(2ME_r) M \left(2 - \frac{ME_r}{E_\nu^2}\right)$$

$$Q_{\alpha,\mathrm{SM}}^2 = \left(Z g_p^V + N g_n^V\right)^2$$

$$g_p^V = \tfrac{1}{2} - 2\sin^2\theta_W \qquad g_n^V = -\tfrac{1}{2}$$

Liao and Marfatia, Phys Lett B775 (2017) 54

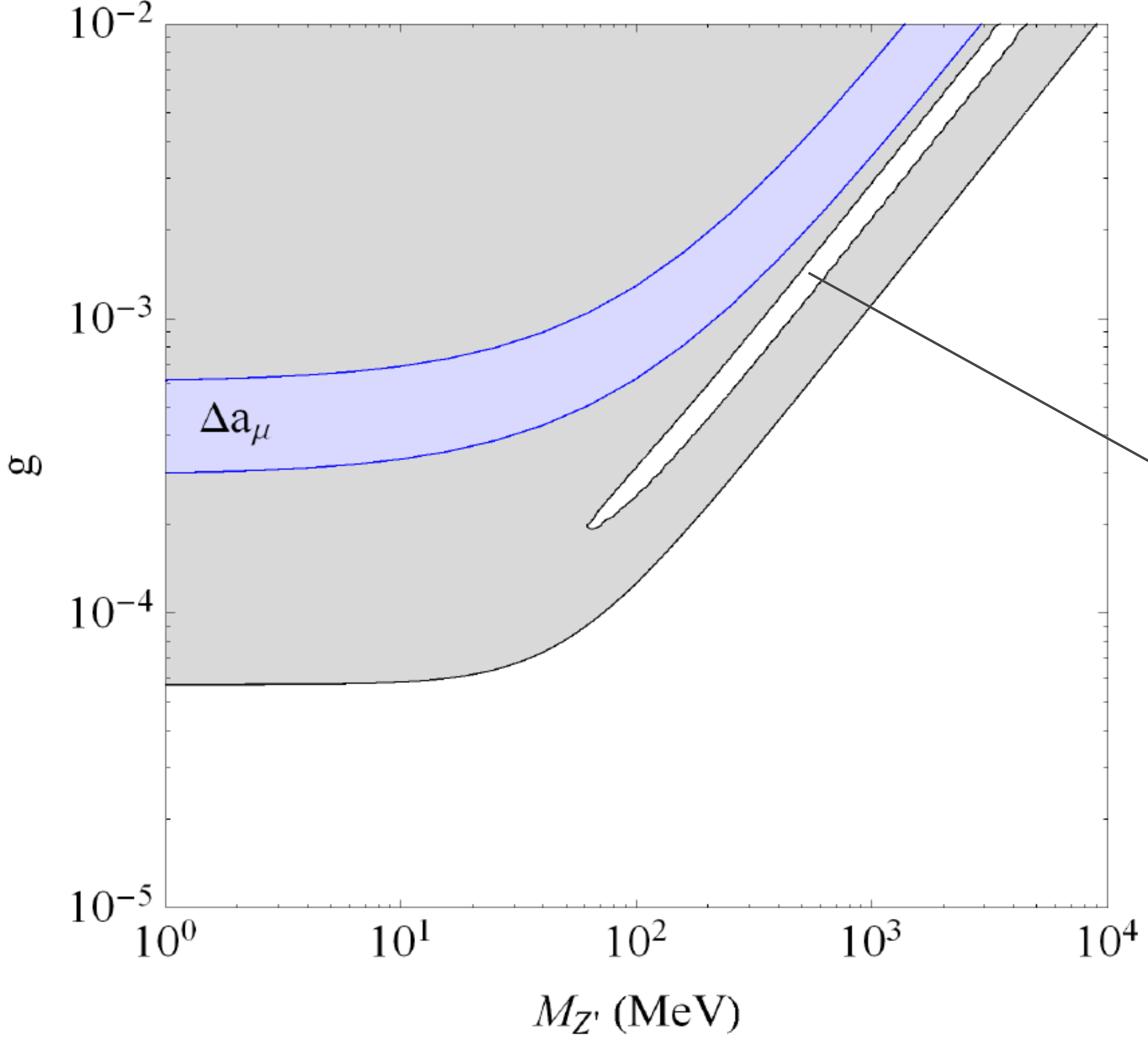
Coherent interaction with light mediator

$$\frac{d\sigma_\alpha}{dE_r} = \frac{G_F^2}{2\pi} Q_\alpha^2 F^2(2ME_r) M \left(2 - \frac{ME_r}{E_\nu^2}\right)$$

$$Q_{\alpha,\mathrm{NSI}}^2 = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)}\right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)}\right)\right]^2$$

$$Q^2 = 2ME_r$$

Liao and Marfatia, Phys Lett B775 (2017) 54



$$Q_{\alpha,\mathrm{NSI}} = -Q_{\alpha,\mathrm{SM}},$$

$\updownarrow$

$$\frac{g^2}{M_{Z'}^2} = -\frac{4\sqrt{2}(Zg_p^V + Ng_n^V)}{3(Z+N)} G_F$$

$\updownarrow$

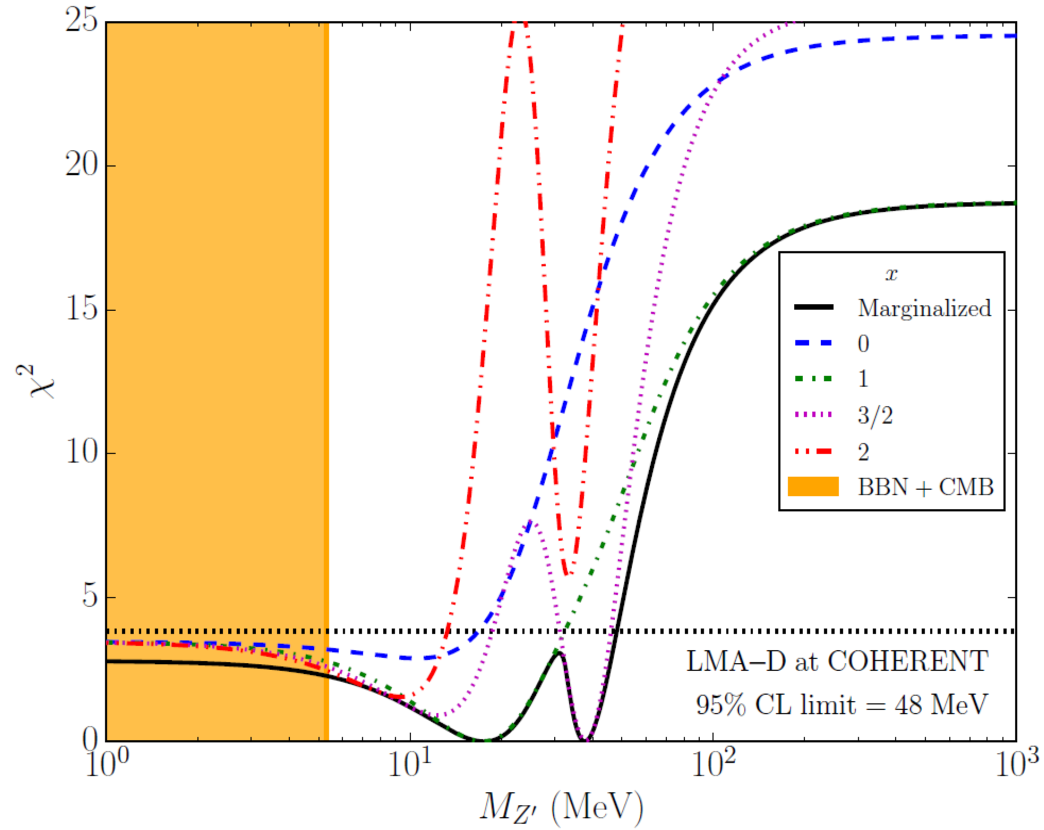
$$M_{Z'} \gg \sqrt{2ME_r}.$$

Liao and Marfatia, Phys Lett B775 (2017) 54

LMA-Dark after COHERENT data

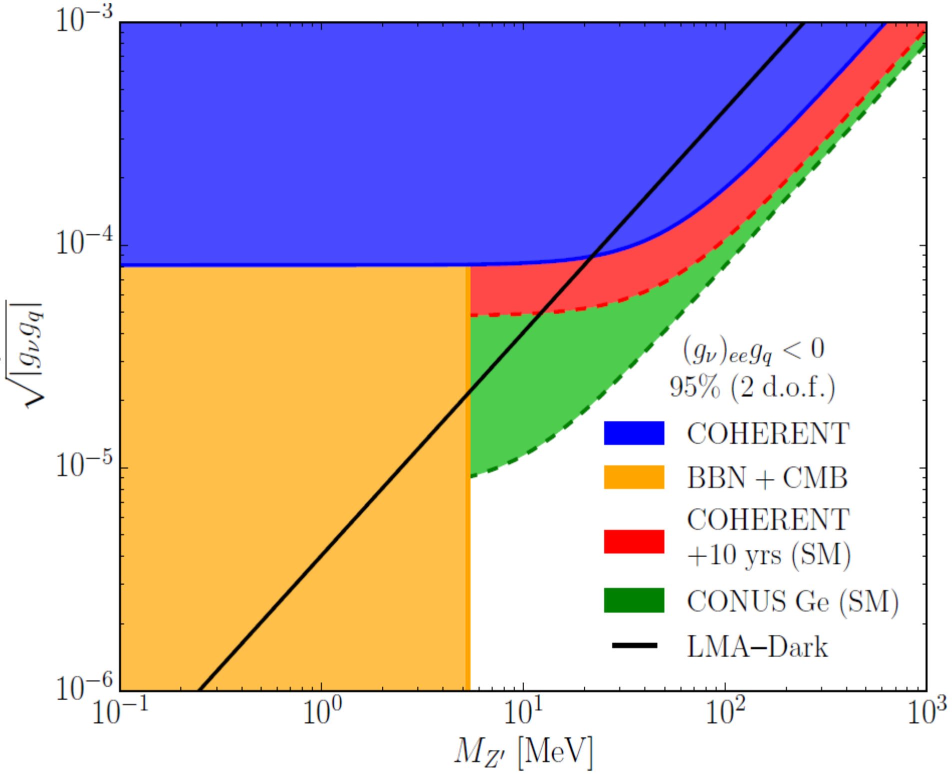
$$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (x-2, x, x)$$

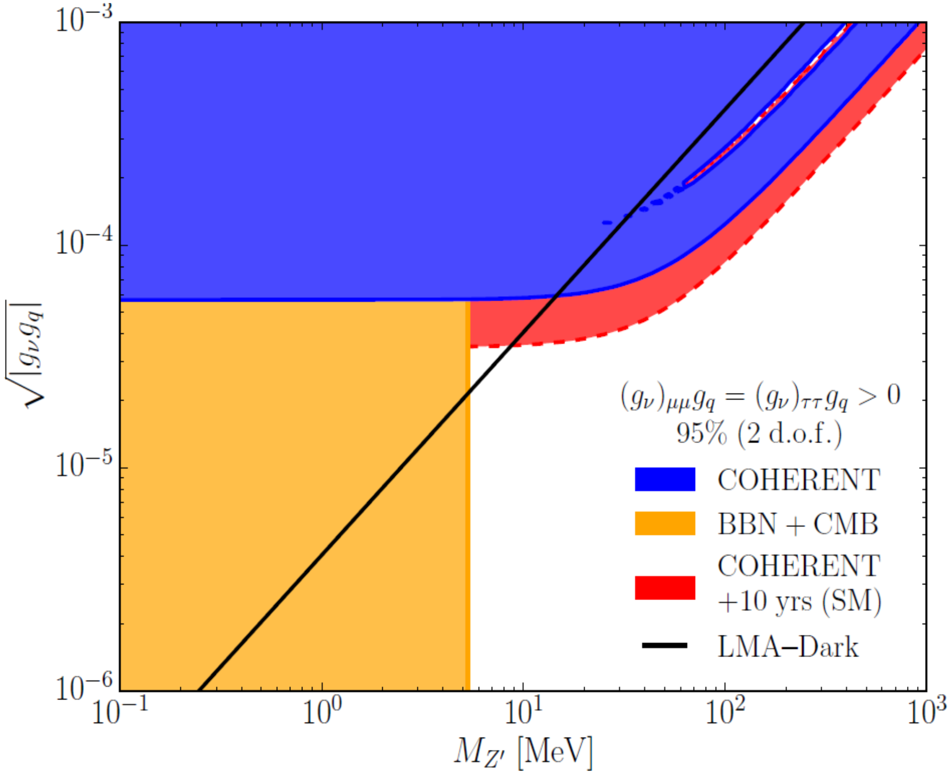
$$\epsilon_{ee}^{u,V} = \epsilon_{ee}^{d,V} = \frac{x}{4} - \frac{1}{2}$$



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

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



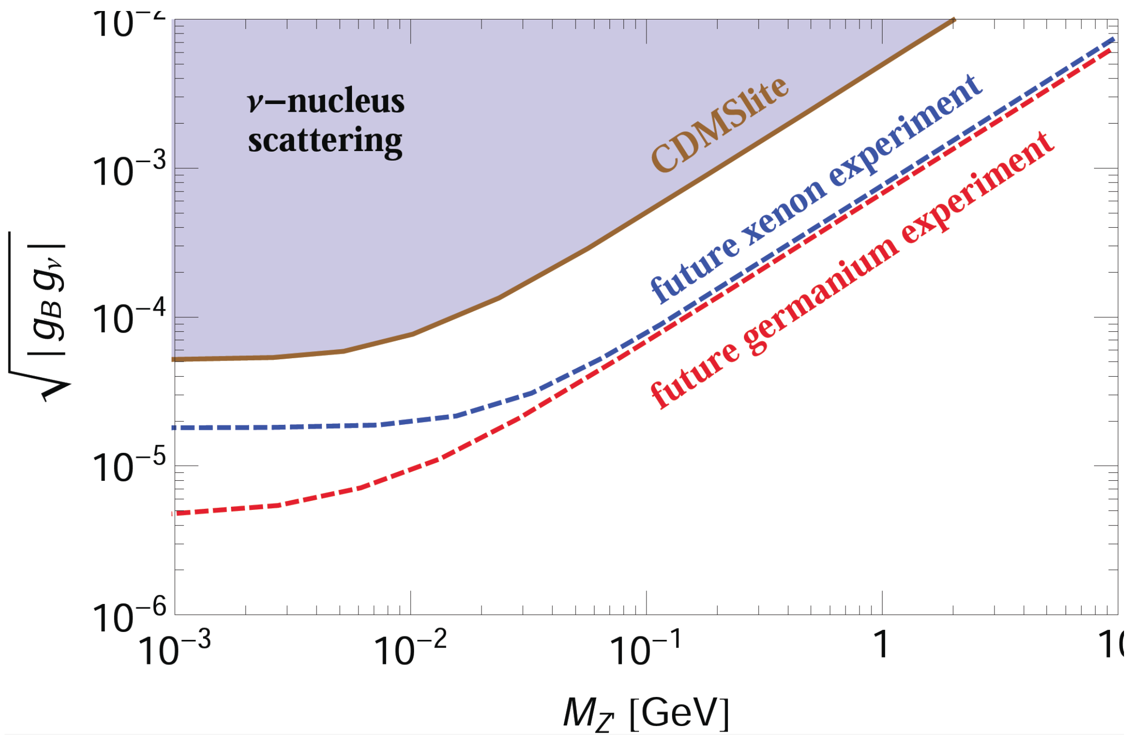


Denton, YF and Shoemaker, JHEP 1807 (2018) 037; arXiv:1804.03660.

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

LMA-DARK solution

BBN+CMB

No Dip is cosmic
neutrino spectrum

Viable Z' mass range

$(\mathrm{CE}\nu\mathrm{NS})$

CONUS,
COHERENT
Future solar

Summary

In the neutrino precision era, NSI should be taken seriously. LMA-Dark solution is still alive.

Neutrino coupling with light particles can be embedded in electroweak symmetric models.

Information can be found from low energy experiments: CONUS, COHERENT, NA62 and etc.

Backup slides

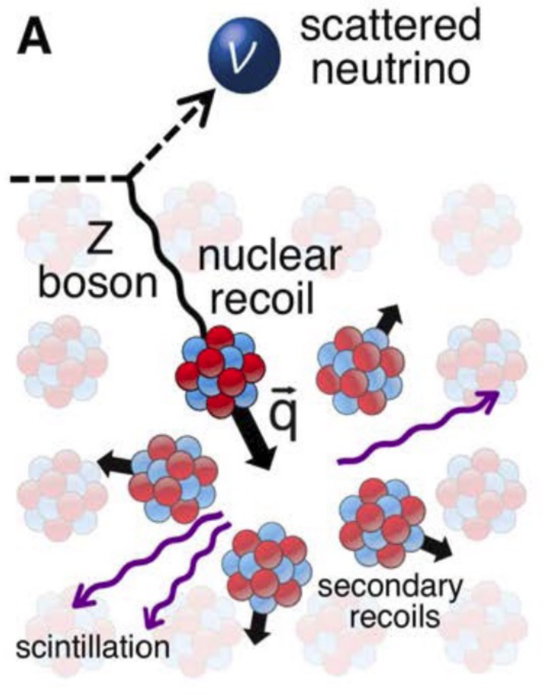
COHERENT experiment

Akimov et al., “Observation of Coherent Elastic neutrino Nucleus Scattering,” science 357 (2017) No 6356, 1123

(CEνNS)

Freedman, PRD 9 (1974) 1389.

$$QR \lesssim 1$$



They find 6.7σ CL evidence for CEνNS

Observational consequences

Emission in Supernova

Similar to

$$\mathcal{L}_\mu - \mathcal{L}_\tau$$

Kamada and Yu, arXiv:1504.00711

$$c\tau_{Z'} \sim 10^{-9}\text{km}(g'/7\times10^{-5})^{-2}(T/10\text{ MeV})(10\text{ MeV}/m_{Z'})^2$$

Reduced mean free path for ν_μ and ν_τ

prolong the diffusion time

High energy cosmic neutrino

Kamada and Yu, arXiv:1504.00711

$$\mathcal{L}_\mu - \mathcal{L}_\tau$$

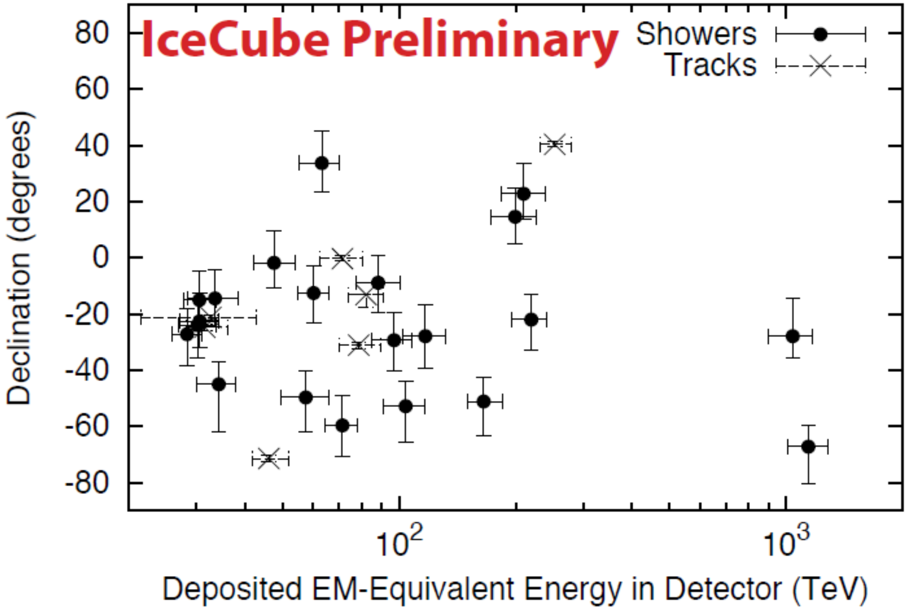
$$\nu\nu \to Z' \to \nu\nu$$

Background neutrino at rest

$$400 \text{ TeV to PeV}$$

Dip or gap in ICECUBE spectrum

Results of Contained Vertex Event Search (4.3σ)



28 events (7 with visible muons, 21 without) on background of $10.6^{+4.5}_{-3.9}$ (12.1 ± 3.4 with reference charm model)

N. Whitehorn, UW Madison

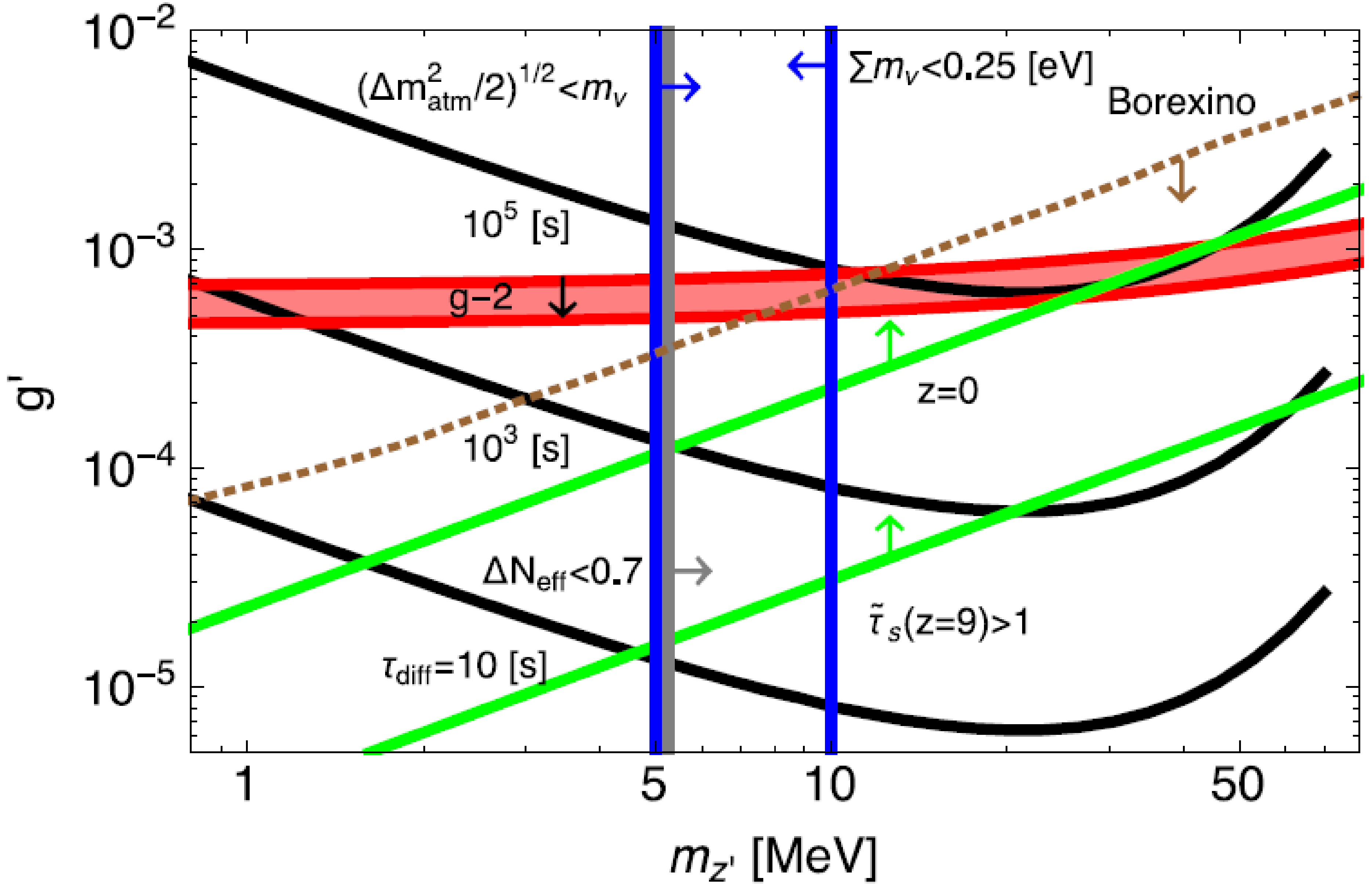
Theoretical prediction of dip in 400 TeV to PeV is robust!

↓

Testing model

		90% CL		3σ	
Param.	best-fit	LMA	LMA ⊕ LMA-D	LMA	LMA ⊕ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	+0.298	[+0.00, +0.51]	⊕ [−1.19, −0.81]	[−0.09, +0.71]	⊕ [−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]	⊕ [+0.40, +0.58]	[−0.34, +0.04]	⊕ [+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]	⊕ [−1.17, −1.03]	[−0.10, +0.71]	⊕ [−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]	⊕ [+0.49, +0.57]	[−0.34, +0.05]	⊕ [+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



Kamada and Yu, 1504.00711

Yukawa coupling of neutrinos

$$\lambda_1 \bar{N}_1 H^T c L_e + \lambda_2 \bar{N}_2 H^T c L_\mu + \lambda_3 \bar{N}_3 H^T c L_\tau + \lambda_4 \bar{N}_2 H^T c L_\tau + \lambda_5 \bar{N}_3 H^T c L_\mu + \text{H.c.}$$

Basis change: $\lambda_4 = 0 \text{ or } \lambda_5 = 0$

Mix: $\nu_\mu \text{ and } \nu_\tau$

No mixing: $\nu_e \text{ and } \nu_\mu$ $\nu_e \text{ and } \nu_\tau$

Majorana masses

If there is no Majorana mass for right-handed neutrinos:

1) $m_{N_i} \sim m_\nu$ (ΔN_{eff})

2) Smallness of neutrino mass

Majorana masses

$$M_1 N_1^T c N_1 +$$
$$S_1(A_2 N_2^T c N_2 + A_3 N_3^T c N_3 + A_{23} N_2^T c N_3) +$$
$$S_2(B_2 N_1^T c N_2 + B_3 N_1^T c N_3) + \mathrm{H.c.}$$

Neutrino trident scattering

$$\nu + A \to \nu + A + \mu^+ + \mu^-$$

CCFR collaboration:

$$\text{scattering of} \sim 160 \text{ GeV neutrino beam off an iron target}$$

PRL66 (1991)

CHARM II collaboration

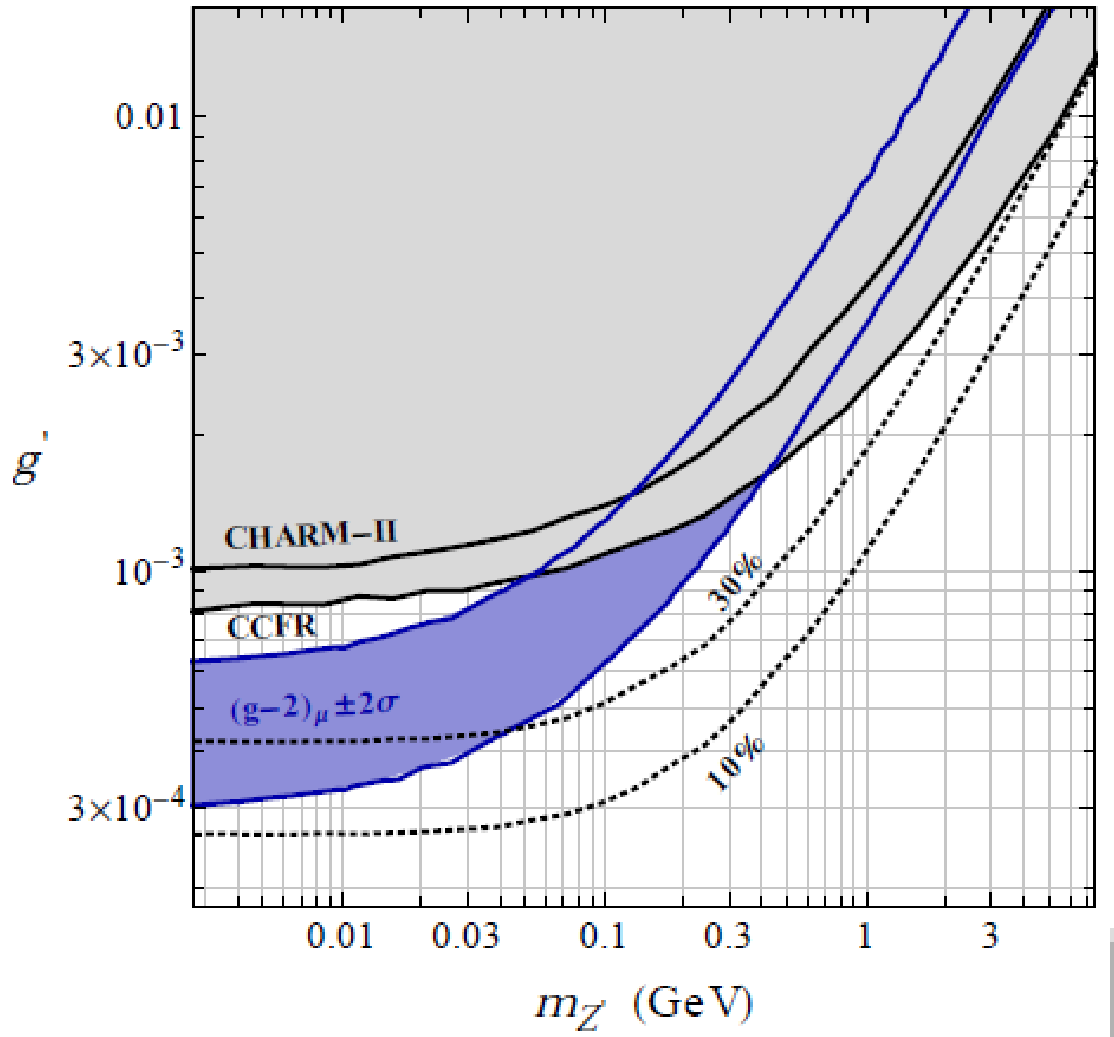
$$\text{scattering of} \sim 20 \text{ GeV neutrino beam off a glass target}$$

PLB 245 (1990)

Neutrino trident scattering

Altmannshofer et al., PRL113 (2014)

$$\nu + A \to \nu + A + \mu^+ + \mu^-$$



$(\bar{u}\gamma^\rho P u)(\bar{\nu}_\mu \gamma_\rho L \nu_\mu)$	$\lvert\varepsilon^{uL}_{\mu\mu}\rvert < 0.003$ $-0.008 < \varepsilon^{uR}_{\mu\mu} < 0.003$ NuTeV	$\lvert\varepsilon^{uL}_{\mu\mu}\rvert < 0.001$ $\lvert\varepsilon^{uR}_{\mu\mu}\rvert < 0.002$ s^2_W in DIS at nufact
$(\bar{d}\gamma^\rho P d)(\bar{\nu}_\mu \gamma_\rho L \nu_\mu)$	$\lvert\varepsilon^{dL}_{\mu\mu}\rvert < 0.003$ $-0.008 < \varepsilon^{dR}_{\mu\mu} < 0.015$ NuTeV	$\lvert\varepsilon^{dL}_{\mu\mu}\rvert < 0.0009$ $\lvert\varepsilon^{dR}_{\mu\mu}\rvert < 0.005$ s^2_W in DIS at nufact

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

NuTeV: Muon neutrino energy~75 GeV

$(\bar{u}\gamma^\rho P u)(\bar{\nu}_e \gamma_\rho L \nu_e)$	$-1 < \varepsilon_{ee}^{uL} < 0.3$	$\lvert\varepsilon_{ee}^{uL}\rvert < 0.001$
	$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	$\lvert\varepsilon_{ee}^{uR}\rvert < 0.002$
	CHARM	s_W^2 in DIS at nufact
$(\bar{d}\gamma^\rho P d)(\bar{\nu}_e \gamma_\rho L \nu_e)$	$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	$\lvert\varepsilon_{ee}^{dL}\rvert < 0.0009$
	$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	$\lvert\varepsilon_{ee}^{dR}\rvert < 0.005$
	CHARM	s_W^2 in DIS at nufact

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

$\nu_e q \to \nu q$ scattering