Viable models for large Non-Standard neutrino Interactions (NSI)

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Effects of NSI on neutrinos

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

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

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

Non-standard neutral current interaction

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

Chirality Projection matrix

Matter field

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

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

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

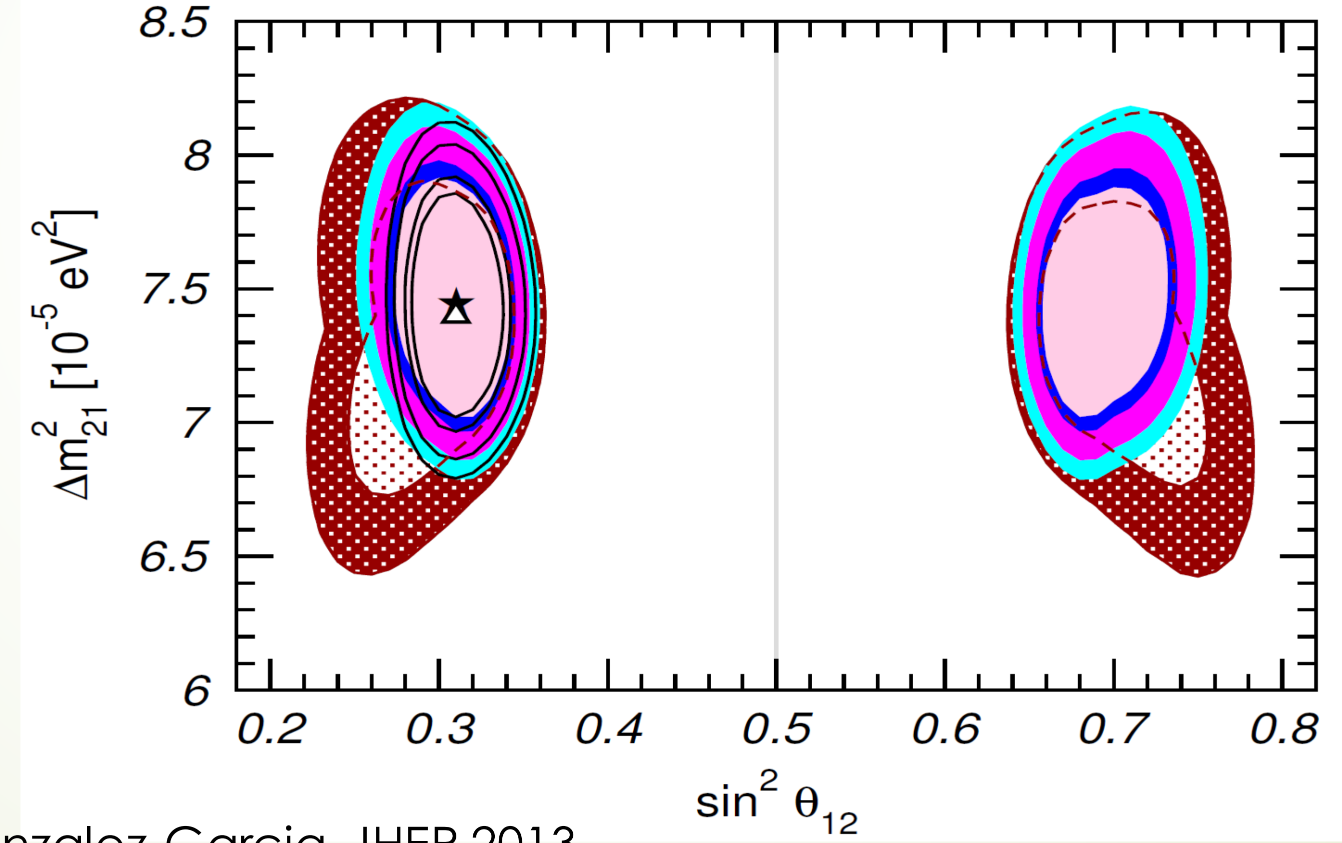
$$H_{mat} = \sqrt{2}G_F \left[N_e \begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix} + \sum_{f=e,u,d} N_f \begin{pmatrix}\epsilon^f_{ee} & \epsilon^f_{e\mu} & \epsilon^f_{e\tau}\\ \epsilon^{f*}_{e\mu} & \epsilon^f_{\mu\mu} & \epsilon^f_{\mu\tau}\\ \epsilon^{f*}_{e\tau} & \epsilon^{f*}_{\mu\tau} & \epsilon^f_{\tau\tau}\end{pmatrix} \right]$$

		90% CL	
Param.	best-fit	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$+0.298$	$[+0.00, +0.51]$	$\oplus$ $[-1.19, -0.81]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.03, +0.03]$
$\varepsilon^u_{e\mu}$	-0.021	$[-0.09, +0.04]$	$[-0.09, +0.10]$
$\varepsilon^u_{e\tau}$	$+0.021$	$[-0.14, +0.14]$	$[-0.15, +0.14]$
$\varepsilon^u_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$
ε^u_D	-0.140	$[-0.24, -0.01]$	$\oplus$ $[+0.40, +0.58]$
ε^u_N	-0.030	$[-0.14, +0.13]$	$[-0.15, +0.13]$
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	$+0.310$	$[+0.02, +0.51]$	$\oplus$ $[-1.17, -1.03]$
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	$+0.001$	$[-0.01, +0.03]$	$[-0.01, +0.03]$
$\varepsilon^d_{e\mu}$	-0.023	$[-0.09, +0.04]$	$[-0.09, +0.08]$
$\varepsilon^d_{e\tau}$	$+0.023$	$[-0.13, +0.14]$	$[-0.13, +0.14]$
$\varepsilon^d_{\mu\tau}$	-0.001	$[-0.01, +0.01]$	$[-0.01, +0.01]$
ε^d_D	-0.145	$[-0.25, -0.02]$	$\oplus$ $[+0.49, +0.57]$
ε^d_N	-0.036	$[-0.14, +0.12]$	$[-0.14, +0.12]$

Maltoni and Gonzalez-Garcia, JHEP 2013

LMA-Dark solution

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



Maltoni and Gonzalez-Garcia, JHEP 2013

LMA-Dark solution

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

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

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

Total flux measurement at SNO

- Neutral current
- Deuteron dissociation

$$\nu + D \to \nu + p + n$$

- 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

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But not in the model that we shall present

Underlying theory ?

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

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

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

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

Underlying theory

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

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

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

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

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

$$-1.40 < \epsilon_{ee}^{u} - \epsilon_{\mu\mu}^{u} < -0.68 \ \text{ and } \ -1.44 < \epsilon_{ee}^{d} - \epsilon_{\mu\mu}^{d} < -0.87 \ \text{ at } 3\sigma \text{ C.L.}$$

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

$m_X \gg 100 \text{ GeV}$ $\Rightarrow$ $\epsilon \ll 1$

ATLAS $\sqrt{s} = 8\ \mathrm{TeV}$ bound

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

Aad et al., PRD90 (2014) 52005

$$m_{Z'_{SM}} > 2900\ \mathrm{GeV}$$

$$\Downarrow$$

$$\epsilon < 10^{-3}$$

Suggestion

- What if $m_X \sim 10\ \mathrm{MeV}$

YF, A model for large non-standard interactions leading to LMA-Dark solution, Phys. Lett. B748 (2015) 311-315;
YF and Shoemaker, Lepton flavor violating non-standard interactions, JHEP 1607 (2016) 033.
YF and Heeck, Neutrinophilic non-standard interactions, 1607.07616

Suggestion

- What if $m_X \sim 10\ \mathrm{MeV}$

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

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

But because coupling is small!

Suggestion

- What if $m_X \sim 10\ \mathrm{MeV}$

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

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

But because coupling is small!

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

For forward scattering we can still use the effective Lagrangian.

Model for LMA-Dark with $\epsilon_{\mu\mu} = \epsilon_{\tau\tau} \sim 1$

$$-g'\left(Y_L \sum_{\alpha\in\{\mu,\tau\}} \bar{L}_\alpha\gamma^\mu L_\alpha + Y_{Q_1}\bar{Q}_1\gamma^\mu Q_1 + Y_{u_1}\bar{u}_R\gamma^\mu u_R + Y_{d_1}\bar{d}_R\gamma^\mu d_R\right) Z'_\mu \in \mathcal{L}$$

$$\mathcal{L}_{NSI} = -\frac{g'^2 Y_L}{m_{Z'}^2}\left(\sum_{\alpha\in\{\mu,\tau\}} \bar{L}_\alpha\gamma^\mu L_\alpha\right)\left(Y_{Q_1}\bar{Q}_1\gamma_\mu Q_1 + Y_{u_1}\bar{u}_R\gamma_\mu u_R + Y_{d_1}\bar{d}_R\gamma_\mu d_R\right)$$

YF PLB 748 (2015) 311

$$-g'\left(Y_L\sum_{\alpha\in\{\mu,\tau\}}\bar{L}_\alpha\gamma^\mu L_\alpha+Y_{Q_1}\bar{Q}_1\gamma^\mu Q_1+Y_{u_1}\bar{u}_R\gamma^\mu u_R+Y_{d_1}\bar{d}_R\gamma^\mu d_R\right)Z'_\mu\in\mathcal{L}$$

NO coupling to the electron

$$\mathcal{L}_{NSI}=-\frac{g'^2Y_L}{m_{Z'}^2}\Big(\sum_{\alpha\in\{\mu,\tau\}}\bar{L}_\alpha\gamma^\mu L_\alpha\Big)\left(Y_{Q_1}\bar{Q}_1\gamma_\mu Q_1+Y_{u_1}\bar{u}_R\gamma_\mu u_R+Y_{d_1}\bar{d}_R\gamma_\mu d_R\right)$$

$$\epsilon^u_{\tau\tau} = \epsilon^u_{\mu\mu} = \frac{g'^2}{m^2_{Z'}} \frac{Y_L(Y_{Q_1} + Y_{u_1})}{2\sqrt{2}G_F}$$

$$\epsilon^u_{ee} = \epsilon^d_{ee} = 0$$

$$\epsilon^d_{\tau\tau} = \epsilon^d_{\mu\mu} = \frac{g'^2}{m^2_{Z'}} \frac{Y_L(Y_{Q_1} + Y_{d_1})}{2\sqrt{2}G_F}$$

$$\epsilon^u_{\alpha\beta} = \epsilon^d_{\alpha\beta} = 0 \quad \alpha \neq \beta$$

Why not to couple to electron

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

LMA-Dark solution

$$\epsilon_{\mu\mu}^{u,d} \sim 1$$

$$\epsilon_{\tau\tau}^{u} = \epsilon_{\mu\mu}^{u} = \frac{g'^2}{m_{Z'}^2} \frac{Y_L(Y_{Q_1} + Y_{u_1})}{2\sqrt{2}G_F}$$

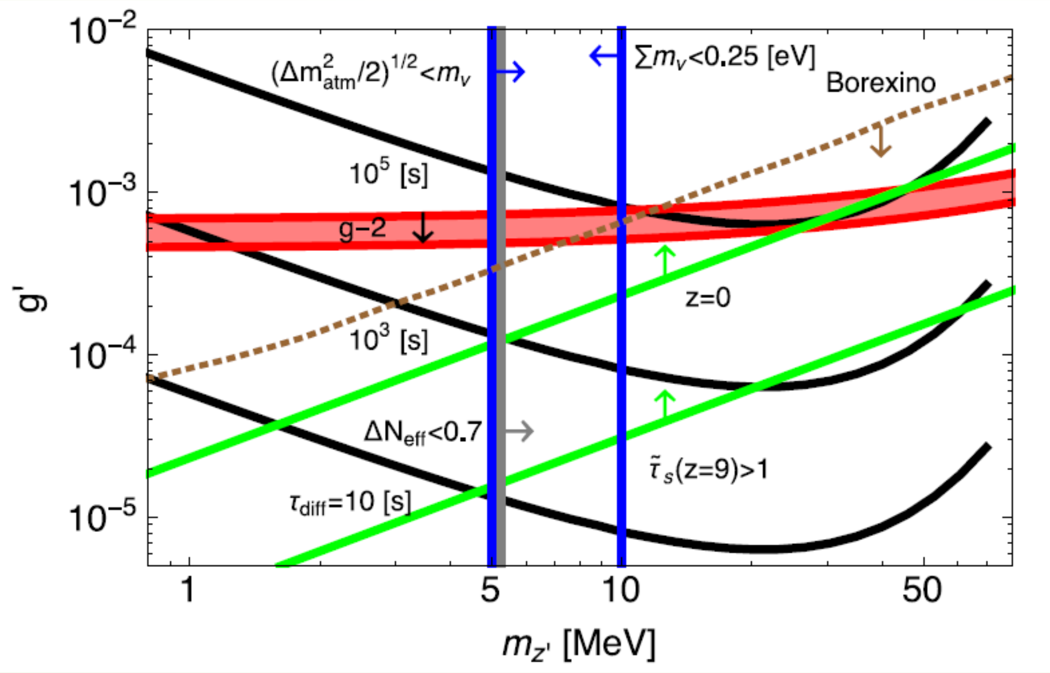
$$\epsilon_{\tau\tau}^{d} = \epsilon_{\mu\mu}^{d} = \frac{g'^2}{m_{Z'}^2} \frac{Y_L(Y_{Q_1} + Y_{d_1})}{2\sqrt{2}G_F}$$

$$g' \sim 7 \times 10^{-5} \frac{m_{Z'}}{10\ \text{MeV}}$$

Big Bang Nucleosynthesis

- Kamada and Yu, PRD 92 (2015)

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



$$\Delta N_{\text{eff}} < 0.7$$

Neutrino scattering experiments

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

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

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

Neutrino scattering experiments

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

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

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

Relaxing bounds from scattering experiments, NuTeV and CHARM

Gauging $U(1)'$

$$\epsilon^u_{\tau\tau} = \epsilon^u_{\mu\mu} = \frac{g'^2}{m^2_{Z'}} \frac{Y_L(Y_{Q_1} + Y_{u_1})}{2\sqrt{2}G_F}$$

$$\epsilon^d_{\tau\tau} = \epsilon^d_{\mu\mu} = \frac{g'^2}{m^2_{Z'}} \frac{Y_L(Y_{Q_1} + Y_{d_1})}{2\sqrt{2}G_F}$$

$$\epsilon^{u,d}_{\mu\mu} \simeq \epsilon^{u,d}_{\tau\tau} \sim 1$$

Gauging $U(1)'$

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$$\epsilon^{u,d}_{\mu\mu} \simeq \epsilon^{u,d}_{\tau\tau} \sim 1$$

$\cancel{\mathcal{B} - \mathcal{L}}$

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

$U(1)'$

$$\mathcal{L}_\mu + \mathcal{L}_\tau + \mathcal{B}_1 - a\mathcal{B}_2 - (3-a)\mathcal{B}_3$$

$$Y_{Q_1} = Y_{u_1} = Y_{d_1} = 1/3\ , \quad Y_{Q_2} = Y_{u_2} = Y_{d_2} = -a/3$$

$$Y_{Q_3} = Y_{u_3} = Y_{d_3} = -1 + a/3$$

$$U(1)'$$

$$\mathcal{L}_\mu + \mathcal{L}_\tau + \mathcal{B}_1 - a\mathcal{B}_2 - (3-a)\mathcal{B}_3$$

$$Y_e = Y_{L_e} = 0 \quad \text{and} \quad Y_\mu = Y_\tau = Y_{L_\mu} = Y_{L_\tau} = 1$$

MODEL FOR LMA-DARK

- Desired sign and magnitude

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

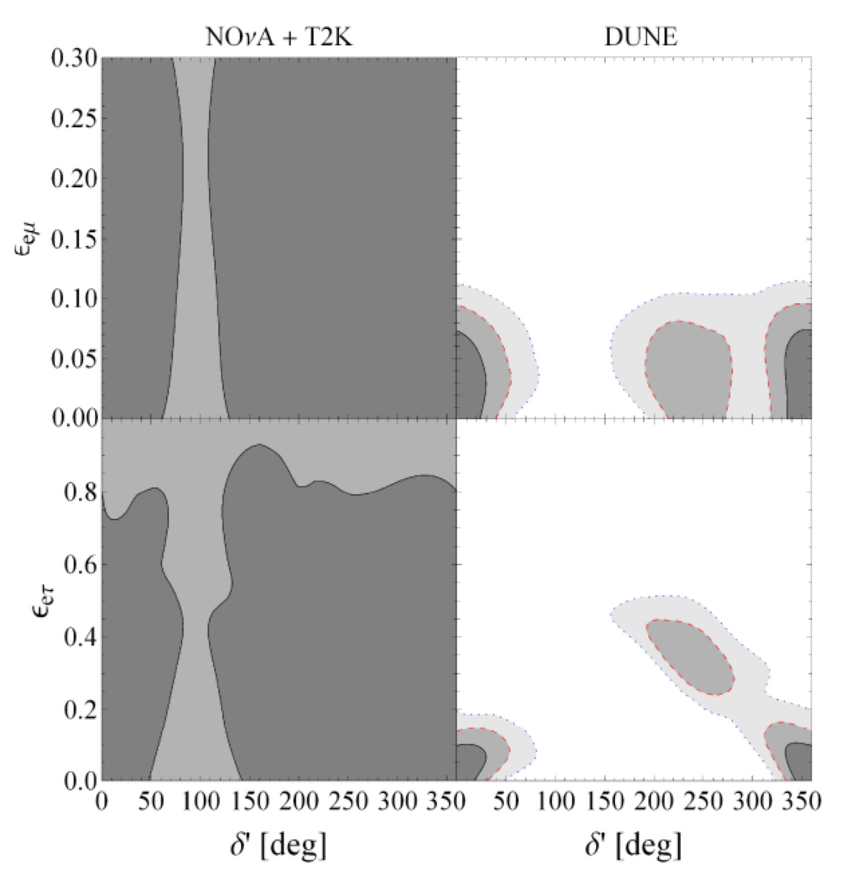
YF, A model for large non-standard interactions leading to LMA-Dark solution, Phys. Lett. B748 (2015) 311-315;

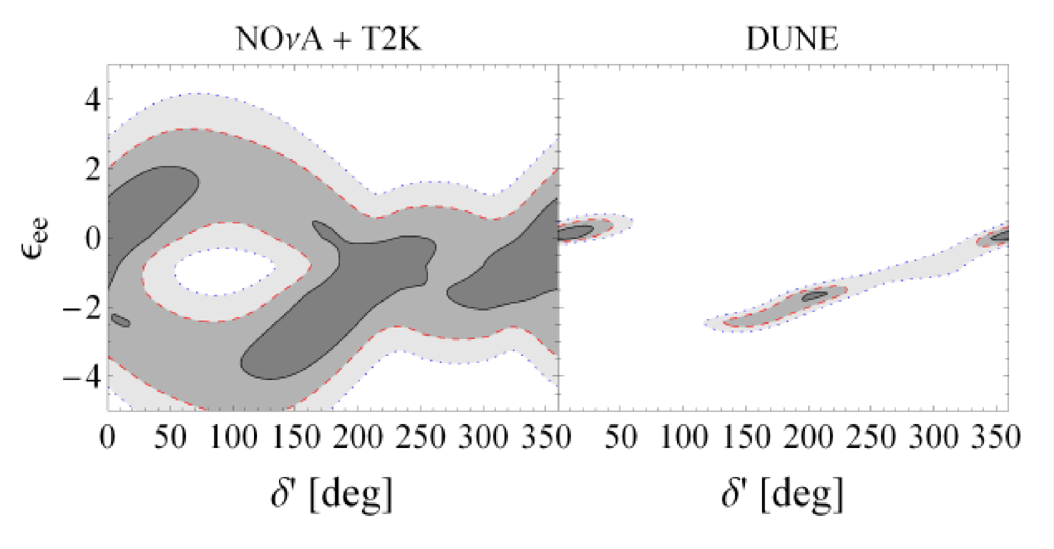
Effects of NSI in long baseline experiments

- Renewed interest in NSI

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

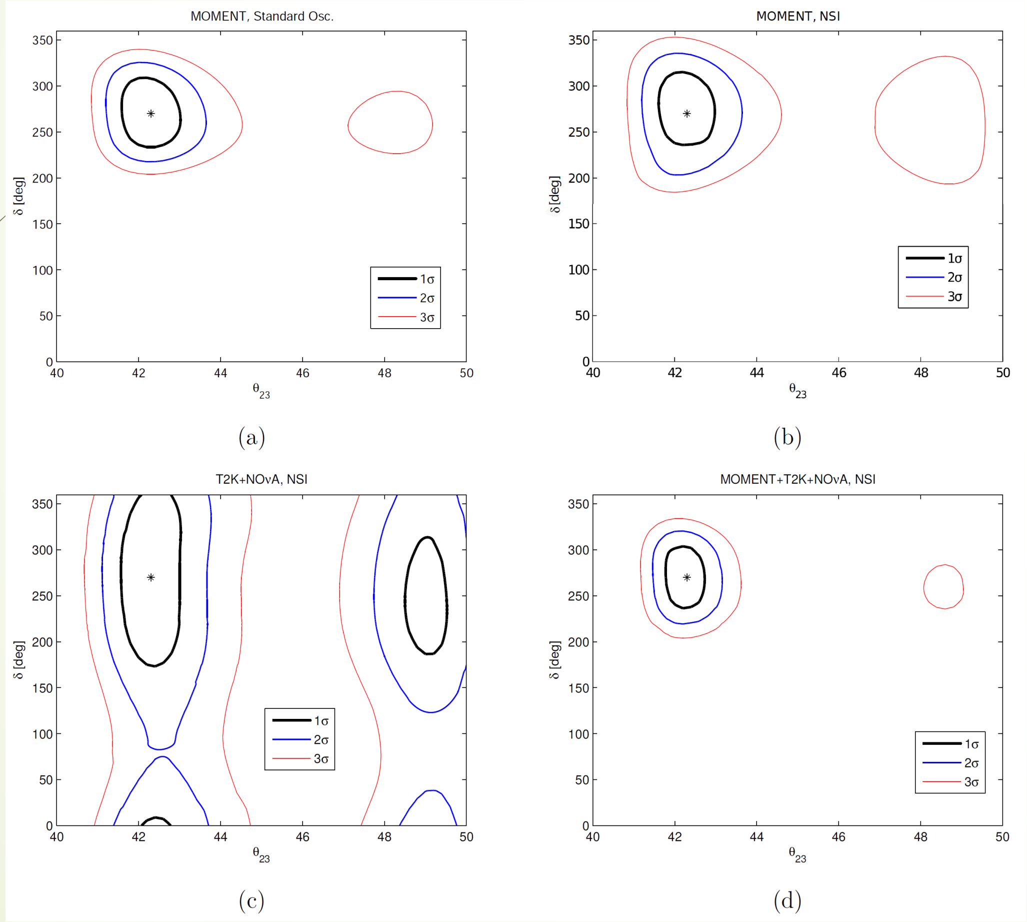
Masud and Mehta, PRD 94(2016); Forero and Huber, PLB 117 (2016); Liao, Marfatia and Whistnant PRD 93 (2016); Agarwalla, Chatterjee and Palazzo, 1607.01745, ….





- Liao Marfatia Whisnant, PRD93 (2016)

MuOn decay MEdium baseline NeuTrino beam (MOMENT)



Bakhti and YF, JHEP 1607 (2016) 109

Lepton flavor violating NSI

$$\tilde{L} \equiv \begin{pmatrix} \tilde{L}_\alpha \\ \tilde{L}_\beta \end{pmatrix} \xrightarrow{U(1)'} e^{i\zeta g' \sigma_1 \alpha} \tilde{L},$$

Charged lepton mass basis

$$L \equiv \begin{pmatrix} L_\alpha \\ L_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta_L & -\sin\theta_L \\ \sin\theta_L & \cos\theta_L \end{pmatrix} \tilde{L}$$

Lepton flavor violating NSI

$$\tilde{L} \equiv \begin{pmatrix} \tilde{L}_\alpha \\ \tilde{L}_\beta \end{pmatrix} \xrightarrow{U(1)'} e^{i\zeta g' \sigma_1 \alpha} \tilde{L},$$

$$\frac{\tilde{L}_\alpha + \tilde{L}_\beta}{\sqrt{2}} \to e^{i\alpha\zeta g'} \frac{\tilde{L}_\alpha + \tilde{L}_\beta}{\sqrt{2}} \quad \text{and} \quad \frac{\tilde{L}_\alpha - \tilde{L}_\beta}{\sqrt{2}} \to e^{-i\alpha\zeta g'} \frac{\tilde{L}_\alpha - \tilde{L}_\beta}{\sqrt{2}}$$

Lepton flavor violating NSI

$$\tilde{L} \equiv \begin{pmatrix} \tilde{L}_\alpha \\ \tilde{L}_\beta \end{pmatrix} \xrightarrow{U(1)'} e^{i\zeta g' \sigma_1 \alpha} \tilde{L},$$

$$\tilde{R} \equiv \begin{pmatrix} \tilde{l}^-_{R\alpha} \\ \tilde{l}^-_{R\beta} \end{pmatrix} \xrightarrow{U(1)'} e^{i\zeta g' \sigma_1 \alpha} \tilde{R}.$$

Yukawa coupling with SM Higgs

$$b_0 \tilde{R}^\dagger H^\dagger \tilde{L} + b_1 \tilde{R}^\dagger \sigma_1 H^\dagger \tilde{L},$$

Charges of baryons under new U(1)’

$$\eta_1 B_1 + \eta_2 B_2 + \eta_3 B_3$$

Flavor structure of NSI

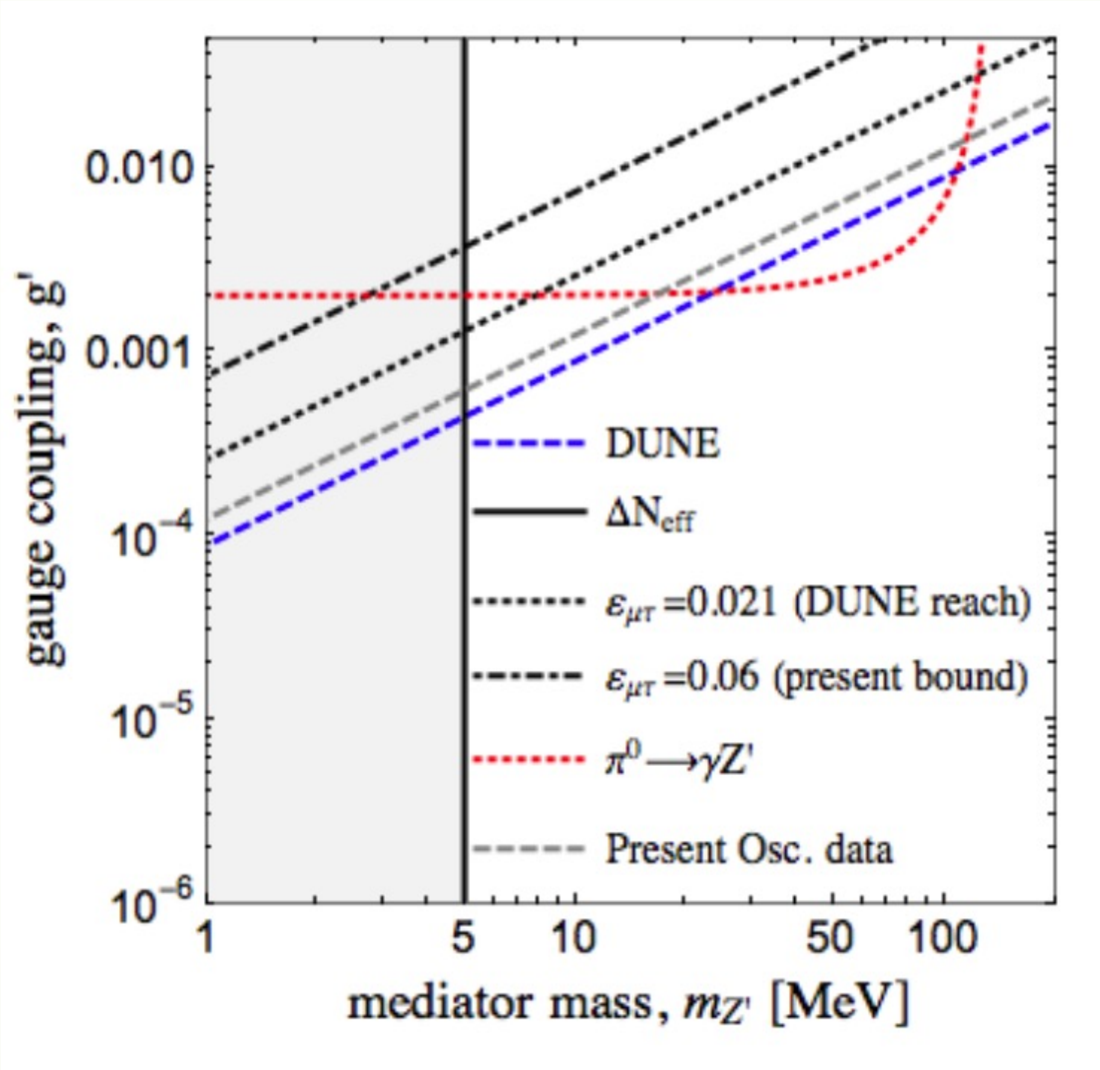
$$\epsilon^{uL} = \epsilon^{uR} = \epsilon^{dL} = \epsilon^{dR} = \frac{\zeta \eta_1 (g')^2}{m_{Z'}^2} \frac{1}{2\sqrt{2} G_F} \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\sin 2\theta_L & \cos 2\theta_L \\ 0 & \cos 2\theta_L & \sin 2\theta_L \end{pmatrix}$$

LFV rare decay

$$\Gamma(l_\beta^- \to Z' l_\alpha^-) = \frac{(g')^2 \zeta^2}{32\pi} \frac{m_{l_\beta}^3}{m_{Z'}^2} (\cos^2 2\theta_L + \cos^2 2\theta_R)$$

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

$$\zeta(\cos^2 2\theta_L + \cos^2 2\theta_R)^{1/2} < 3 \times 10^{-9} (\frac{1}{g'})(\frac{m_{Z'}}{10 \text{ MeV}})$$



gauge coupling, g'
0.010
0.001
10^{-4}
10^{-5}
10^{-6}
1
5
10
50
100
mediator mass, $m_{Z'}$ [MeV]
DUNE
ΔN_{eff}
$\varepsilon_{\mu\tau}$ =0.021 (DUNE reach)
$\varepsilon_{\mu\tau}$ =0.06 (present bound)
$\pi^0 \longrightarrow \gamma Z'$
Present Osc. data

$$b_0\tilde{R}^\dagger H^\dagger \tilde{L} + b_1\tilde{R}^\dagger \sigma_1 H^\dagger \tilde{L},$$

$$\mathrm{Br}(H \to \tau\mu) > \frac{\mathrm{Br}(H \to \tau\tau)}{2}\left(\frac{\cos 2\theta_L}{1+\sin 2\theta_L}\right)^2.$$

$$\tan 2\theta_L = (-\epsilon_{\mu\mu} + \epsilon_{\tau\tau})/(2\epsilon_{\mu\tau}).$$

Neutrinophilic Non-Standard Interaction

YF and J Heeck, 1607.07616

Neutrinophilic Non-Standard Interaction

Benefits: We do not need to worry about the interactions of charged lepton.

Especially $l_\alpha^- \to l_\beta^- + Z'$

Neutrinophilic Non-Standard Interaction

Q: How?   A: Mixing with a sterile Dirac fermion charged under new $U(1)$

Neutrinophilic Non-Standard Interaction

Q: How? A: Mixing with a sterile Dirac fermion charged under new U(1)

Ψ

New U(1)

- New Dirac fermion: $\Psi \to e^{ig_\Psi \alpha}\Psi$
- New scalar electroweak doublet: $H' \to e^{ig_\Psi \alpha} H'$

$$\mathcal{L} = -\sum_\alpha y_\alpha \overline{L}_\alpha \tilde{H}' P_R \Psi + \text{h.c.},$$

$$\mathcal{L} = \frac{1}{2}(\bar{\nu}^c, \bar{\Psi}_L^c, \bar{\Psi}_R) \begin{pmatrix} \mathcal{M}_\nu & 0 & y\langle H'\rangle \\ 0 & 0 & M_\Psi \\ y\langle H'\rangle & M_\Psi & 0 \end{pmatrix} \begin{pmatrix} \nu \\ \Psi_L \\ \Psi_R^c \end{pmatrix} + \text{h.c.},$$

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

$$\tan\beta \equiv \langle H\rangle / \langle H'\rangle, \text{ and } v \simeq 246\,\text{GeV}.$$

$$g_\Psi \kappa_\alpha^* \kappa_\beta Z'_\mu \bar{\nu}_\alpha \gamma^\mu \nu_\beta$$

- Standard Quarks: $q \to e^{ig_B \alpha/3} q$

Non-standard Interaction

$$\varepsilon^{u}_{\alpha\beta} = \varepsilon^{d}_{\alpha\beta} \simeq \frac{g_B g_\Psi \kappa^*_\alpha \kappa_\beta}{6\sqrt{2} G_F M^2_{Z'}} ,$$

$$|\varepsilon_{\alpha\beta}| = \sqrt{\varepsilon_{\alpha\alpha}\varepsilon_{\beta\beta}}.$$

Schwartz inequality:

$$g_\Psi \kappa^* \kappa^T \rightarrow \sum_j g_{\Psi_j} \kappa^*_{\Psi_j} \kappa^T_{\Psi_j}$$

$$|\varepsilon_{\alpha\beta}| \leq \sqrt{\varepsilon_{\alpha\alpha}\varepsilon_{\beta\beta}}$$

Some bounds

$\tan\beta \equiv \langle H\rangle/\langle H'\rangle$, and $v \simeq 246\,\mathrm{GeV}$.

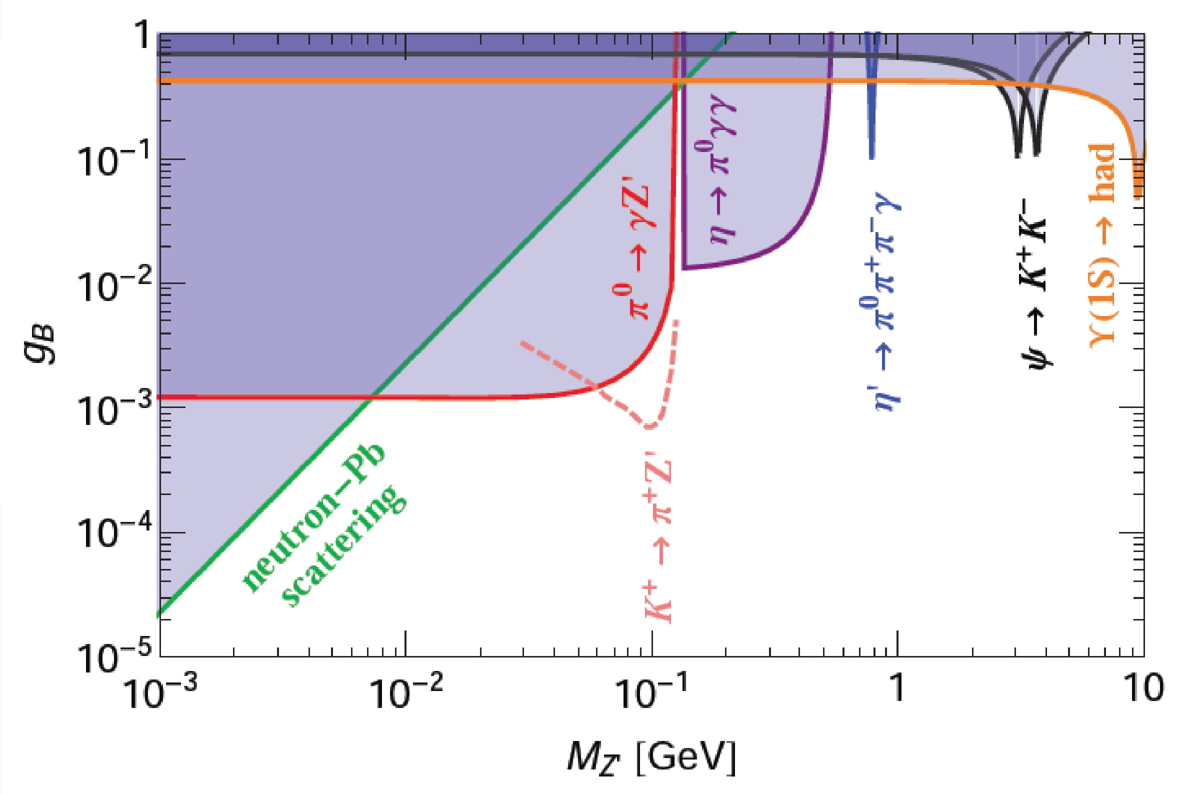
Contribution to gauge boson mass

$$\cos\beta \leq 4\times 10^{-4}\left(\frac{M_{Z'}}{10\ \mathrm{MeV}}\right)\left(\frac{0.1}{g_\Psi}\right)$$

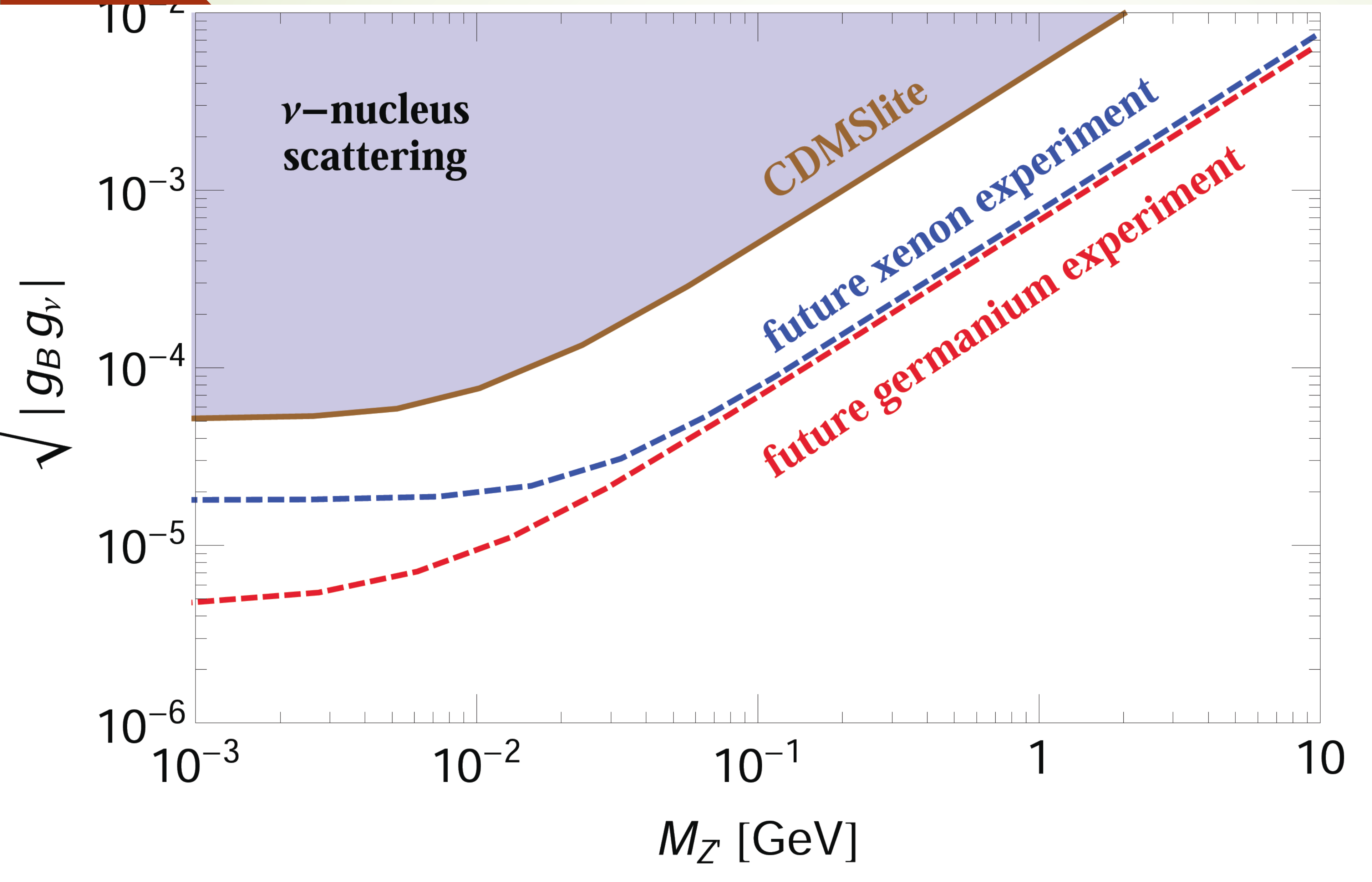
$$\kappa_\alpha = \frac{y_\alpha\langle H'\rangle}{M_\Psi} = \frac{y_\alpha v\cos\beta}{\sqrt{2}M_\Psi}$$

$$\varepsilon^u_{\alpha\beta} = \varepsilon^d_{\alpha\beta} \simeq \frac{g_B g_\Psi \kappa^*_\alpha \kappa_\beta}{6\sqrt{2}G_F M^2_{Z'}},$$

$$M_\Psi < \text{few GeV}\left(\frac{M_{Z'}}{10\,\mathrm{MeV}}\right)\left(\frac{0.2}{g_\Psi}\right)\left(\frac{0.03}{\kappa}\right)$$



No beam dump bound: $Z' \to \nu\bar{\nu}$ $Z' \to \pi^0\gamma \;(\pi^+\pi^-\pi^0)$



Credeno et al,
JHEP 05 (2016)

LUX-ZEPLIN

SuperCDMS

Violation of the unitarity of the PMNS matrix

Muon decay and tests of lepton flavor universality

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

Fernandez-Martinez, Hernandez-Garcia and Lopez-Pavon, JHEP 1608 (2016)

$$|\kappa_\mu \kappa_e| < 10^{-3}\ ,\ |\kappa_\mu \kappa_\tau| < 1.6 \times 10^{-3},\ \text{and } |\kappa_e \kappa_\tau| < 3.7 \times 10^{-3}$$

Bounds from $l_\alpha \to l_\beta \gamma$ and $l_\alpha \to Z' l_\beta$ are weaker.

UV completion

- Anomaly cancelation
- One example: Two generation of colorless fermions with opposite chiralities and U(1)' charges $B_1 \text{ and } B_2,$

$B_1 - B_2 = -3$

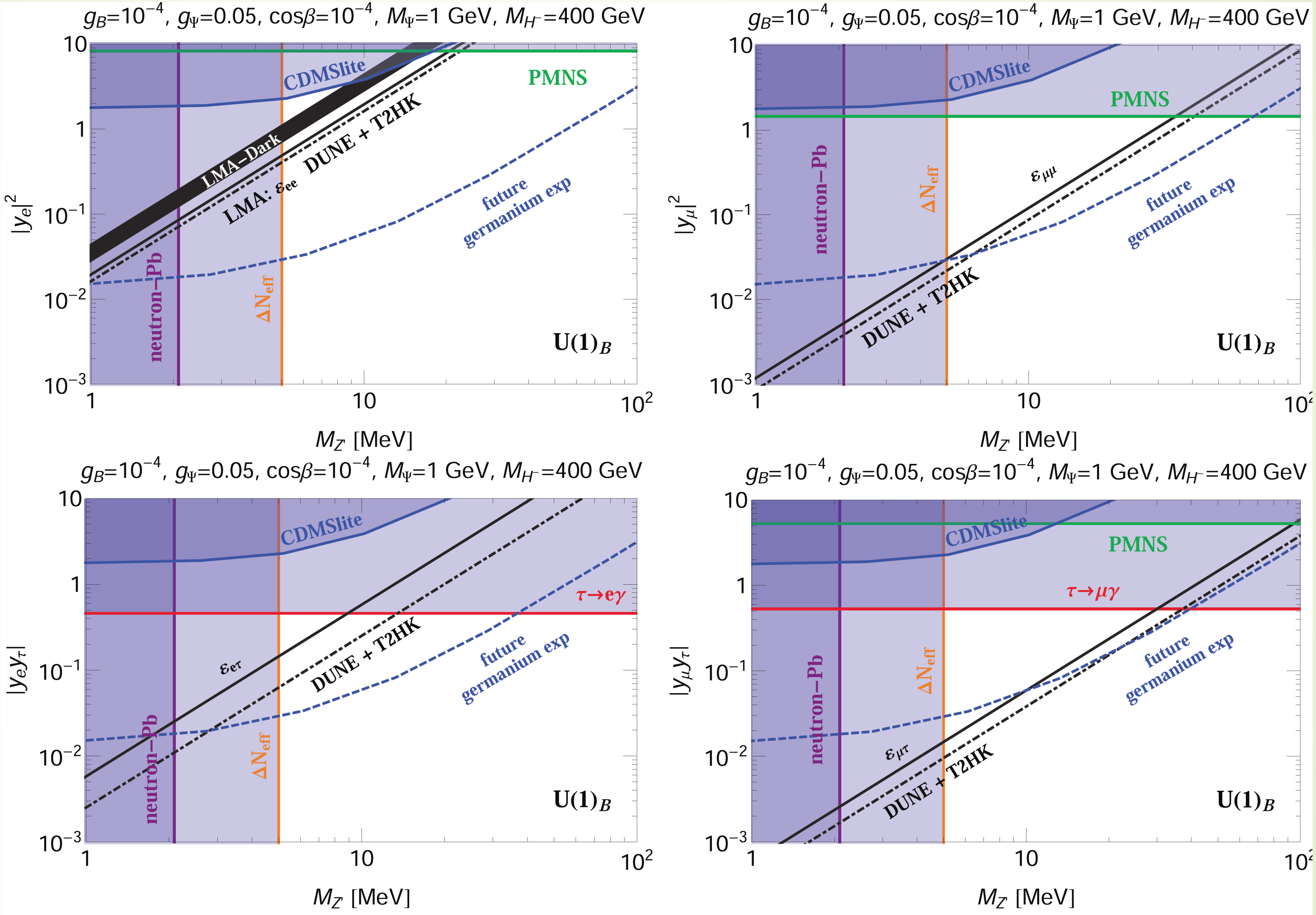
Duerr et al., PRL 110 (2013); PRD 91 (2015)

$M_{Z'} \text{ given by } g_B \langle S_B \rangle$

Electroweak singlet giving mass to new fermions

$\text{Taking } \langle S_B \rangle \gtrsim 1\,\text{TeV}$

$$g_B \lesssim 10^{-4} \left(\frac{M_{Z'}}{100\,\text{MeV}} \right)$$



$g_B=10^{-4}$, $g_\Psi=0.05$, $\cos\beta=10^{-4}$, $M_\Psi=1$ GeV, $M_{H^-}=400$ GeV
$|y_e|^2$
$M_{Z'}$ [MeV]
CDMSlite
PMNS
LMA–Dark
LMA: ε_{ee}
DUNE + T2HK
future germanium exp
neutron–Pb
$\Delta N_{\rm eff}$
$\mathbf{U(1)}_B$
$|y_\mu|^2$
$\varepsilon_{\mu\mu}$
$|y_e y_\tau|$
$\tau\to e\gamma$
$\varepsilon_{e\tau}$
$|y_\mu y_\tau|$
$\tau\to\mu\gamma$
$\varepsilon_{\mu\tau}$

Collider phenomenology

LEP+LHC $$M_{H^-} > 275\,\mathrm{GeV}$$

CMS Khachatryan et al., Eur Phys J C74 (2014) no 9, 3036

$$L = 19.5\,\mathrm{fb}^{-1} \text{ and } \sqrt{s} = 8\,\mathrm{TeV}$$

$$\frac{\mathrm{Br}(H^- \to \ell_\alpha \Psi)}{\mathrm{Br}(H^- \to \ell_\beta \Psi)} \simeq \frac{|y_\alpha|^2}{|y_\beta|^2} \simeq \frac{\varepsilon_{\alpha\alpha}}{\varepsilon_{\beta\beta}}$$

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

- Observational consequences

Emission in Supernova

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

Kamada and Yu, PRD 92 (2015)

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

- Reduced mean free path for neutrinos

prolong the diffusion time

High energy cosmic neutrino

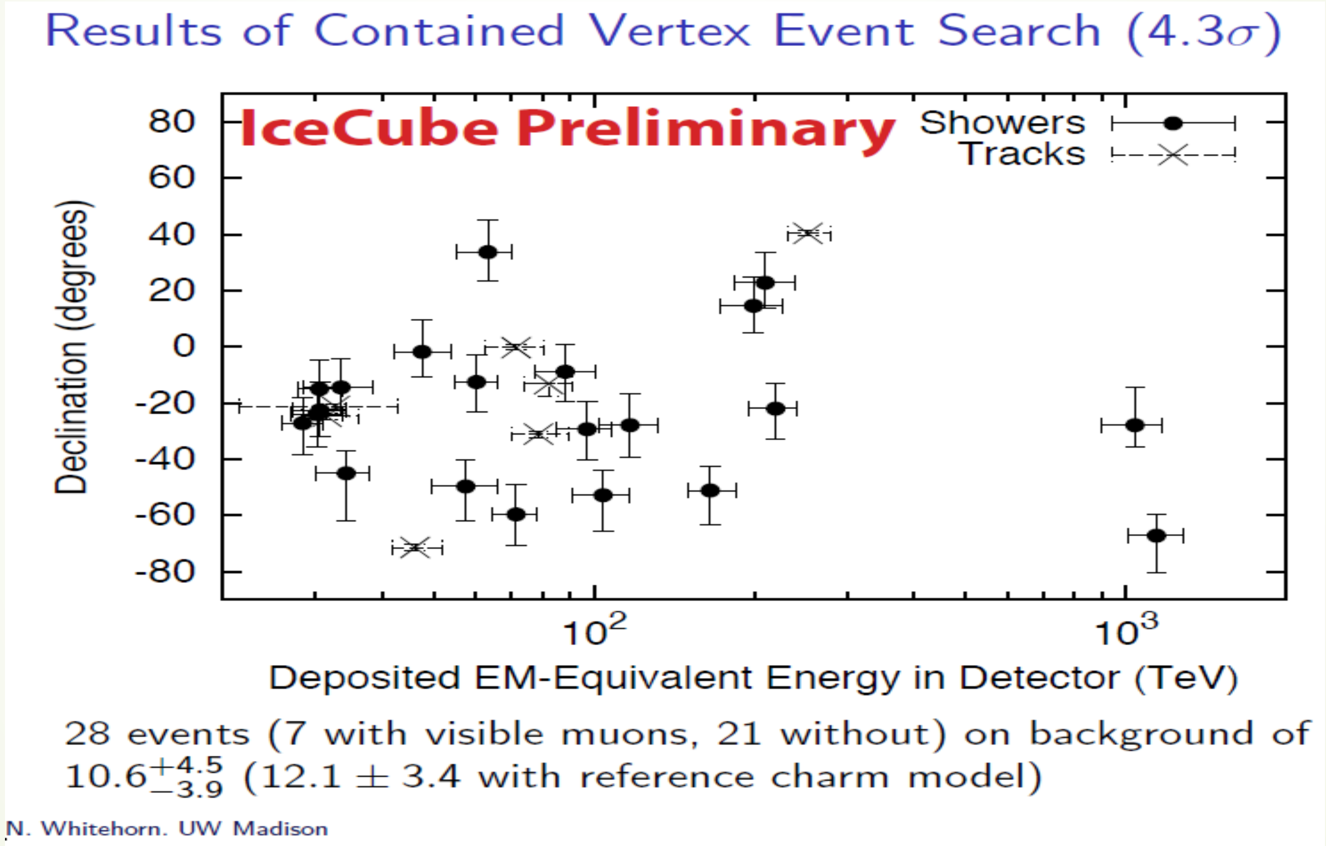
- Kamada and Yu, PRD 92 (2015) $\mathcal{L}_\mu - \mathcal{L}_\tau$

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

Background neutrino at rest

400 TeV to PeV

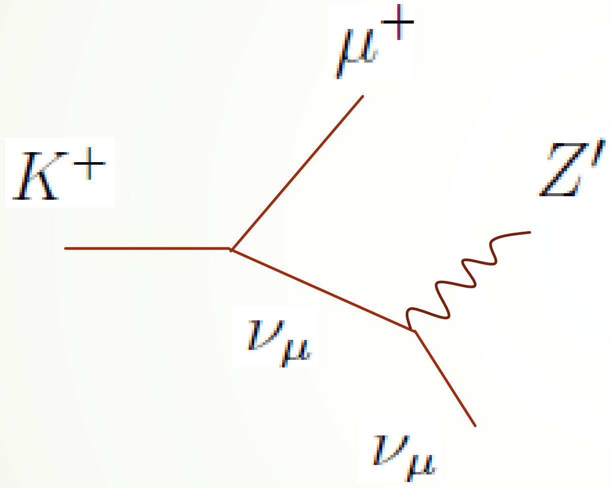
Dip or gap in ICECUBE spectrum



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

- Testing model

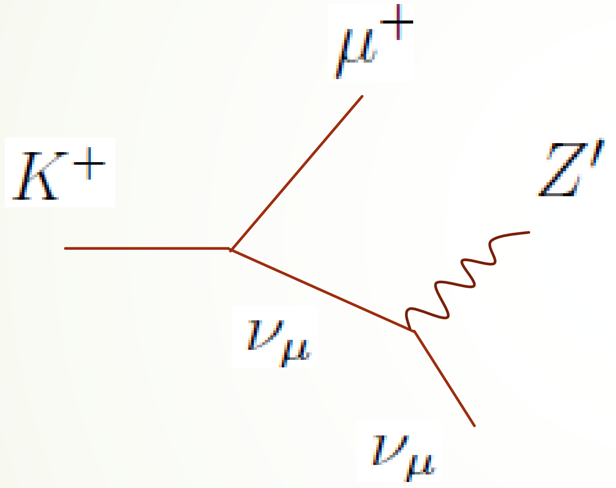
Meson decay



$$g' < 10^{-3}$$

Lessa and Peres, PRD 75 (2007)

Meson decay



$$m_{Z'} \sim 10 \text{ MeV and } g' \sim 7 \times 10^{-5}$$

$$g' < 10^{-3}$$

Lessa and Peres, PRD 75 (2007)

Summary

- Viable models for sizeable neutral current NSI based on $U(1)'$

$$\sqrt{g_\nu g_B} \sim 7 \times 10^{-5} \frac{m_{Z'}}{10 \ \mathrm{MeV}}$$

- Rich phenomenology: Prospect of testing via

1) SN neutrino
2) Dip below PeV in the spectrum of cosmic neutrinos
3) Rare meson decay
4) Interaction rate of solar neutrinos at dark matter direct detection experiments

Backup slides

Present 90% C.L. COLOMA, JHEP 03 (2016)

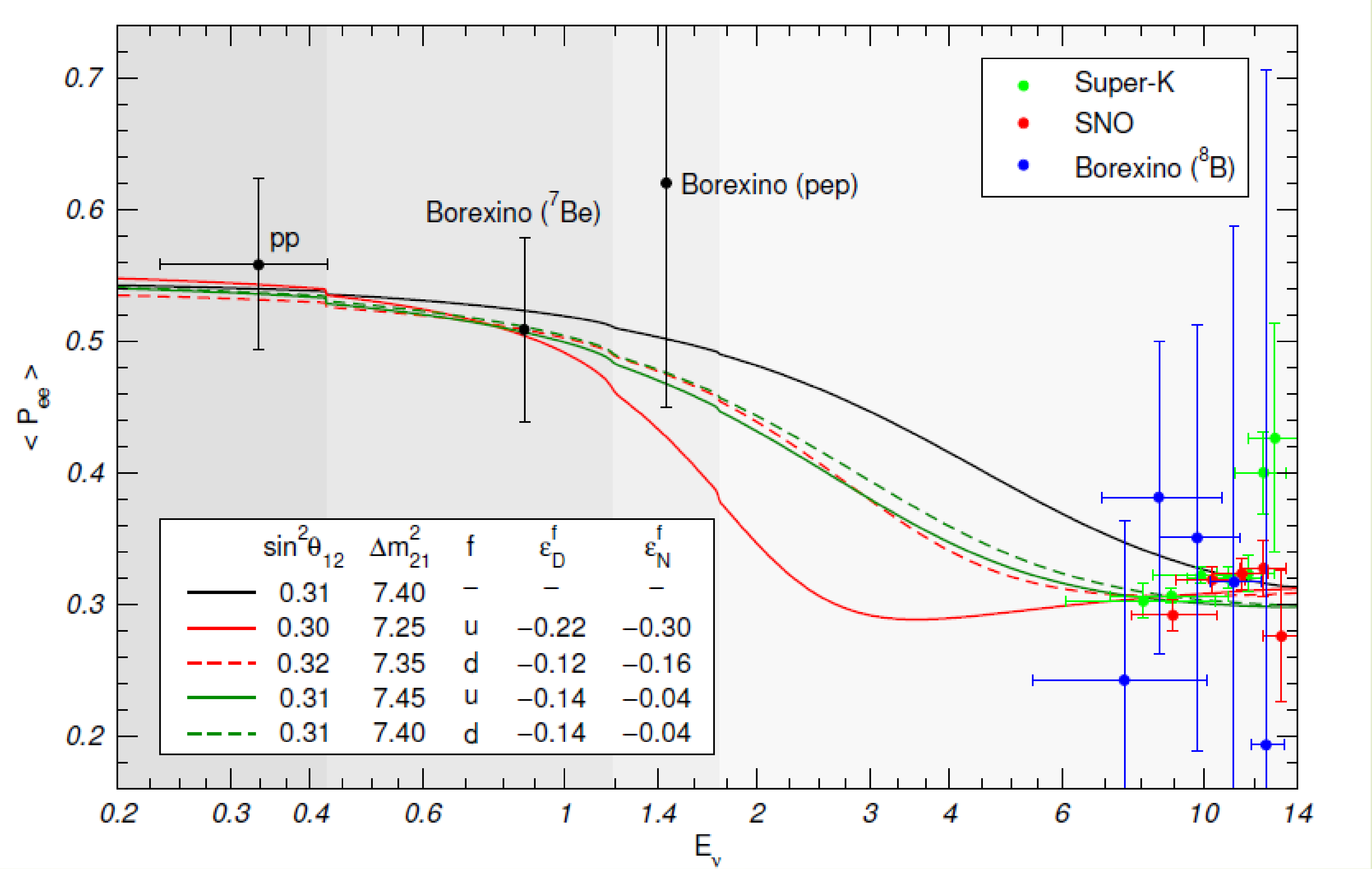
$$|\varepsilon^u_{e\mu} + \varepsilon^d_{e\mu}| < 0.12\,, \qquad |\varepsilon^u_{e\tau} + \varepsilon^d_{e\tau}| < 0.18\,, \qquad |\varepsilon^u_{\mu\tau} + \varepsilon^d_{\mu\tau}| < 0.018$$

$$0.11 < \varepsilon^u_{ee} + \varepsilon^d_{ee} - \varepsilon^u_{\tau\tau} - \varepsilon^d_{\tau\tau} < 0.60\,, \quad \text{and} \quad -0.04 < \varepsilon^u_{\mu\mu} + \varepsilon^d_{\mu\mu} - \varepsilon^u_{\tau\tau} - \varepsilon^d_{\tau\tau} < 0.037$$

DUNE 90 % C.L.

$$|\varepsilon^u_{e\mu} + \varepsilon^d_{e\mu}| < 0.024\,, \qquad |\varepsilon^u_{e\tau} + \varepsilon^d_{e\tau}| < 0.08\,, \qquad |\varepsilon^u_{\mu\tau} + \varepsilon^d_{\mu\tau}| < 0.012\,,$$

$$0.017 < \varepsilon^u_{ee} + \varepsilon^d_{ee} - \varepsilon^u_{\tau\tau} - \varepsilon^d_{\tau\tau} < 0.43\,, \quad \text{and} \quad -0.027 < \varepsilon^u_{\mu\mu} + \varepsilon^d_{\mu\mu} - \varepsilon^u_{\tau\tau} - \varepsilon^d_{\tau\tau} < 0.025\,.$$



Maltoni and Gonzalez-Garcia, JHEP 2013

Gauging $U(1)'$

$$\epsilon^u_{\tau\tau} = \epsilon^u_{\mu\mu} = \frac{g'^2}{m^2_{Z'}} \frac{Y_L(Y_{Q_1} + Y_{u_1})}{2\sqrt{2}G_F}$$

$$\epsilon^d_{\tau\tau} = \epsilon^d_{\mu\mu} = \frac{g'^2}{m^2_{Z'}} \frac{Y_L(Y_{Q_1} + Y_{d_1})}{2\sqrt{2}G_F}.$$

$$\epsilon^{u,d}_{\mu\mu} \simeq \epsilon^{u,d}_{\tau\tau} \sim 1$$

$\mathcal{B} - \mathcal{L}$

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

Flavor physics in quark sector

- Diagonal in flavor basis
- Non universal

Mixing in mass basis

- Universal coupling of first and second generations

Avoiding large contribution to $K\text{–}\overline{K}$ or $D\text{–}\overline{D}$ mixing,

Quark mixing

$$\boxed{\mathcal{L}_\mu + \mathcal{L}_\tau + \mathcal{B}_1 - a\mathcal{B}_2 - (3-a)\mathcal{B}_3}$$

$$\boxed{a = -1}$$

Mixing between first and second generations

No mixing between third generation and the rest

$$H'^\dagger c\bar{Q}_3 u_{1,2} \qquad \bar{d}_3 H'^\dagger Q_{1,2}$$

Flavor physics in quark sector

- Diagonal in flavor basis
- Non universal

Mixing in mass basis

- Universal coupling of first and second generations

Avoiding large contribution to $K\text{–}\overline{K}$ or $D\text{–}\overline{D}$ mixing,

- Crivellini, D'Amrosio and Heeck, PRD 91 (2015) 075006

$$O_9^{\ell\ell} = \frac{\alpha_{\rm EM}}{4\pi}\left[\bar{s}\gamma^\mu P_L b\right]\left[\bar{\ell}\gamma_\mu \ell\right],$$

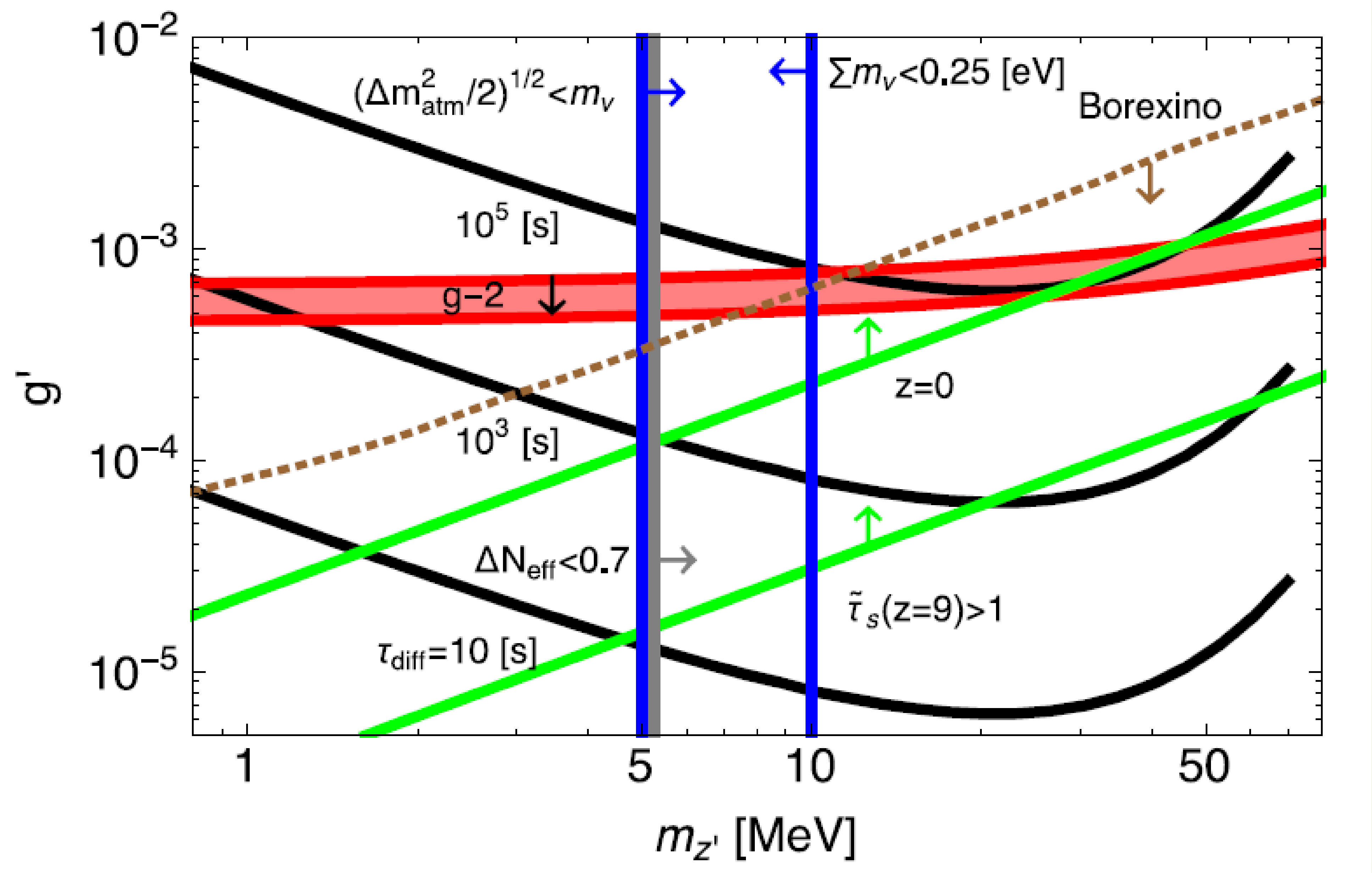
$$O_9^{\prime\ell\ell} = \frac{\alpha_{\rm EM}}{4\pi}\left[\bar{s}\gamma^\mu P_R b\right]\left[\bar{\ell}\gamma_\mu \ell\right],$$

$$C_9^{\mu\mu} \simeq \frac{-g'^2}{\sqrt{2}m_{Z'}^2}\frac{\pi}{\alpha_{\rm EM}}\frac{1}{G_F}a \simeq -\left(\frac{a}{1/3}\right)\left(\frac{3\,\mathrm{TeV}}{m_{Z'}/g'}\right)^2,$$

Global fit $R(K)$ and $B \to K^*\mu^+\mu^-$

$$R(K) = \frac{B \to K\mu^+\mu^-}{B \to Ke^+e^-} = 0.745^{+0.090}_{-0.074} \pm 0.036,$$

$$-0.60\,(-0.95) \geq C_9^{\mu\mu} \geq (-1.65)\; -2.00.$$



Kamada and Yu, 1504.00711

Determining

- 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

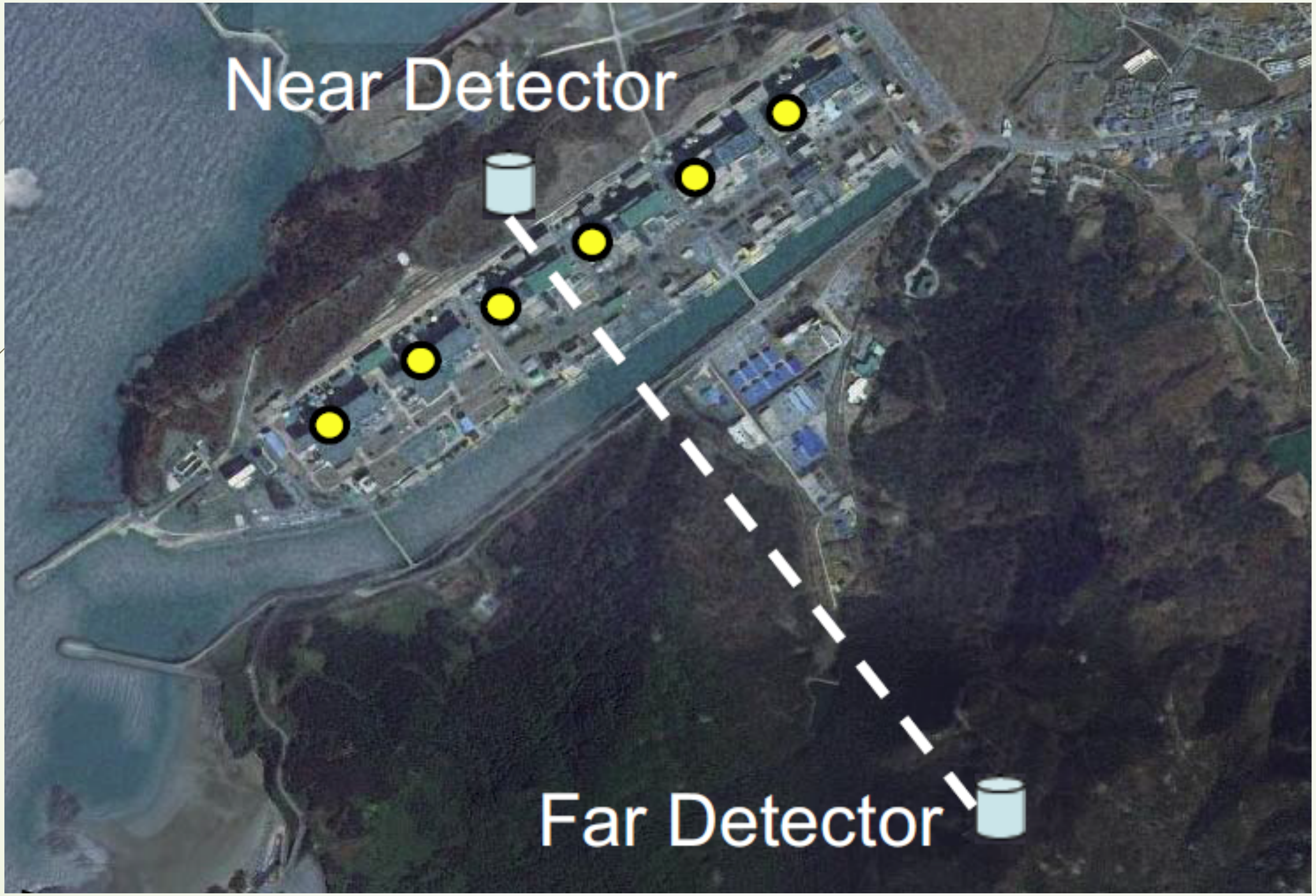
Ready for data taking in 2020.

- Baseline ~ 50 km

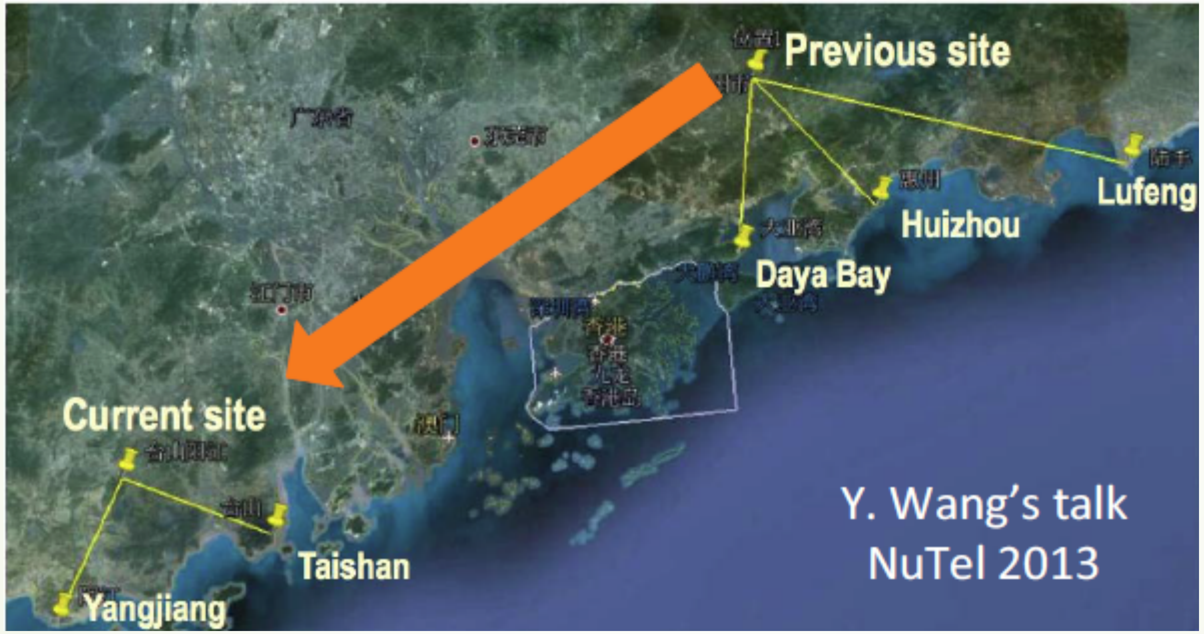
$$\frac{\Delta m_{01}^2 L}{2E_\nu} \sim 0.4 \frac{\Delta m_{01}^2}{10^{-5}\ \mathrm{eV}^2} \frac{L}{50\ \mathrm{km}} \frac{3\ \mathrm{MeV}}{E_\nu}$$

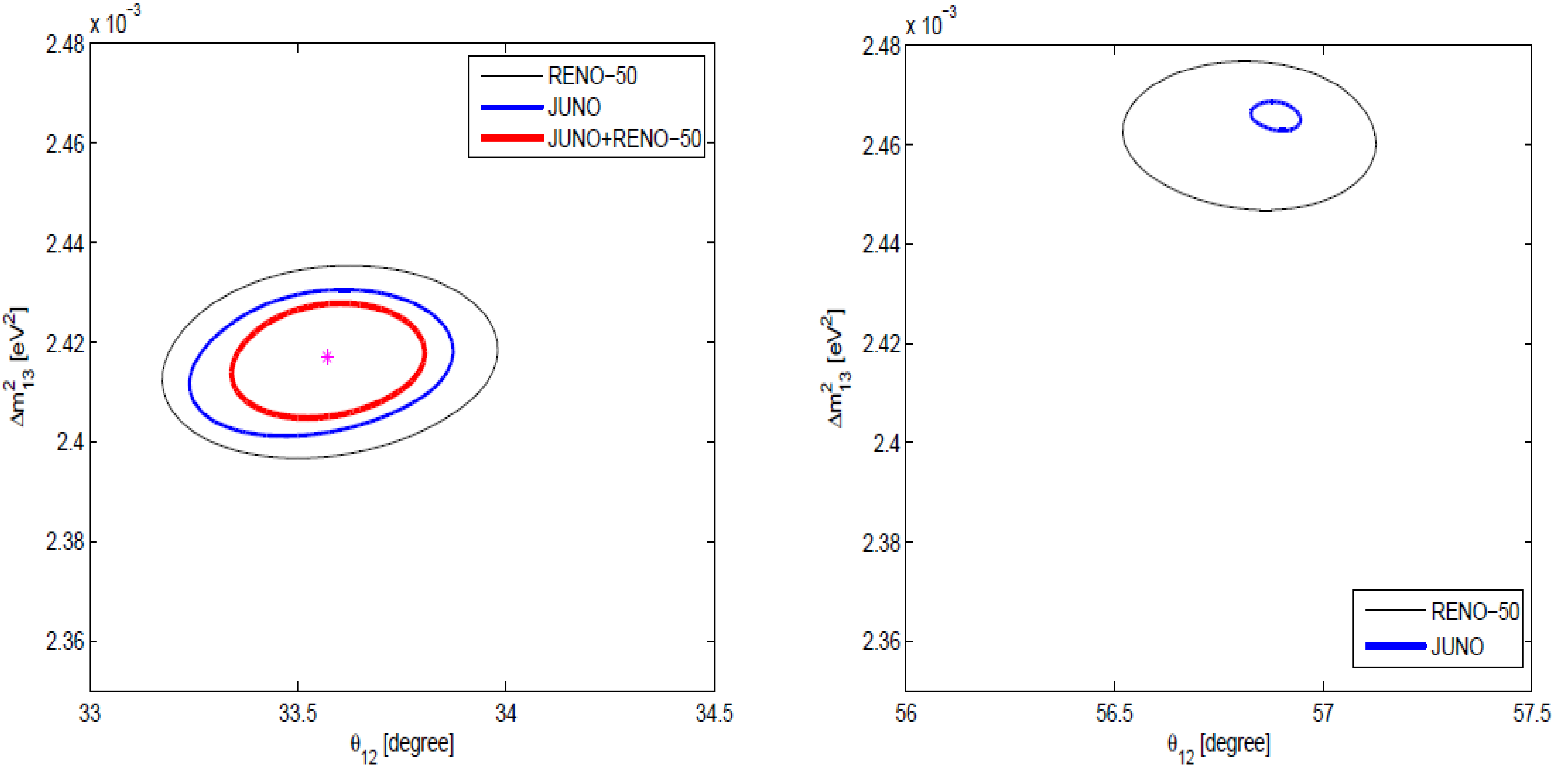
- Main goal determination of $\mathrm{sgn}(\Delta m_{31}^2)$

RENO-50 in South Korea



Daya Bay and Juno





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

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

Quark mixing

$$\mathcal{L}_\mu + \mathcal{L}_\tau + \mathcal{B}_1 - a\mathcal{B}_2 - (3-a)\mathcal{B}_3$$

$$\boxed{a = -1}$$

Mixing between first and second generations

No mixing between third generation and the rest

$$H'^\dagger c\bar{Q}_3 u_{1,2} \qquad \bar{d}_3 H'^\dagger Q_{1,2}$$

Flavor violation

$$H'^{\dagger} c \bar{Q}_3 u_{1,2} \qquad \bar{d}_3 H'^{\dagger} Q_{1,2}$$

$$\boxed{m_{H'} \gg 100\ \text{GeV}}$$

$$\langle H' \rangle \lesssim m_{EW}$$

Small VEV

$$-m_S^2|S|^2+\lambda_S|S|^4+m_{SHH'}SH^\dagger H'+m_{H'}^2 H'^\dagger H'$$

$$0<m_S^2\ll m_{H'}^2 \text{ and } m_{EW}^2<m_{H'}^2$$

$$\boxed{\langle S\rangle=\left(\frac{m_S^2}{2\lambda_S}\right)^{1/2},\quad \langle H'\rangle=-m_{SHH'}\frac{\langle H\rangle\langle S\rangle}{2m_{H'}^2}.}$$

Small VEV

$$-m_S^2|S|^2+\lambda_S|S|^4+m_{SHH'}SH^\dagger H'+m_{H'}^2H'^\dagger H'$$

$$0<m_S^2\ll m_{H'}^2 \text{ and } m_{EW}^2<m_{H'}^2$$

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$$m_{SHH'},\langle H\rangle \ll m_{H'} \text{ and } \langle S\rangle \lesssim \langle H\rangle$$

Small VEV

$$-m_S^2|S|^2+\lambda_S|S|^4+m_{SHH'}SH^\dagger H'+m_{H'}^2 H'^\dagger H'$$

$$0<m_S^2\ll m_{H'}^2 \text{ and } m_{EW}^2<m_{H'}^2$$

$$\boxed{\langle S\rangle=\left(\frac{m_S^2}{2\lambda_S}\right)^{1/2}, \quad \langle H'\rangle=-m_{SHH'}\frac{\langle H\rangle\langle S\rangle}{2m_{H'}^2}.}$$

$$m_{SHH'},\langle H\rangle \ll m_{H'} \text{ and } \langle S\rangle \lesssim \langle H\rangle$$

$$\Rightarrow \langle H'\rangle \ll m_{H'}, m_{EW}, \langle S\rangle$$

Mass of new gauge boson

$$m_{Z'} = g' \left(Y_{S_1}^2 \langle S_1 \rangle^2 + Y_{S_2}^2 \langle S_2 \rangle^2 + Y_S^2 \langle S \rangle^2 + Y_{H'}^2 \langle H' \rangle^2 \right)^{1/2}$$

$m_{Z'} \sim 10$ MeV and $g' \sim 7 \times 10^{-5}$

$$\langle S_1 \rangle \sim \langle S_2 \rangle \sim 100 \text{ GeV}$$

Proposal

$$\mu + A \to \mu + A + Z', \; Z' \to \nu\bar{\nu}$$

muon beam with energy of 150 GeV

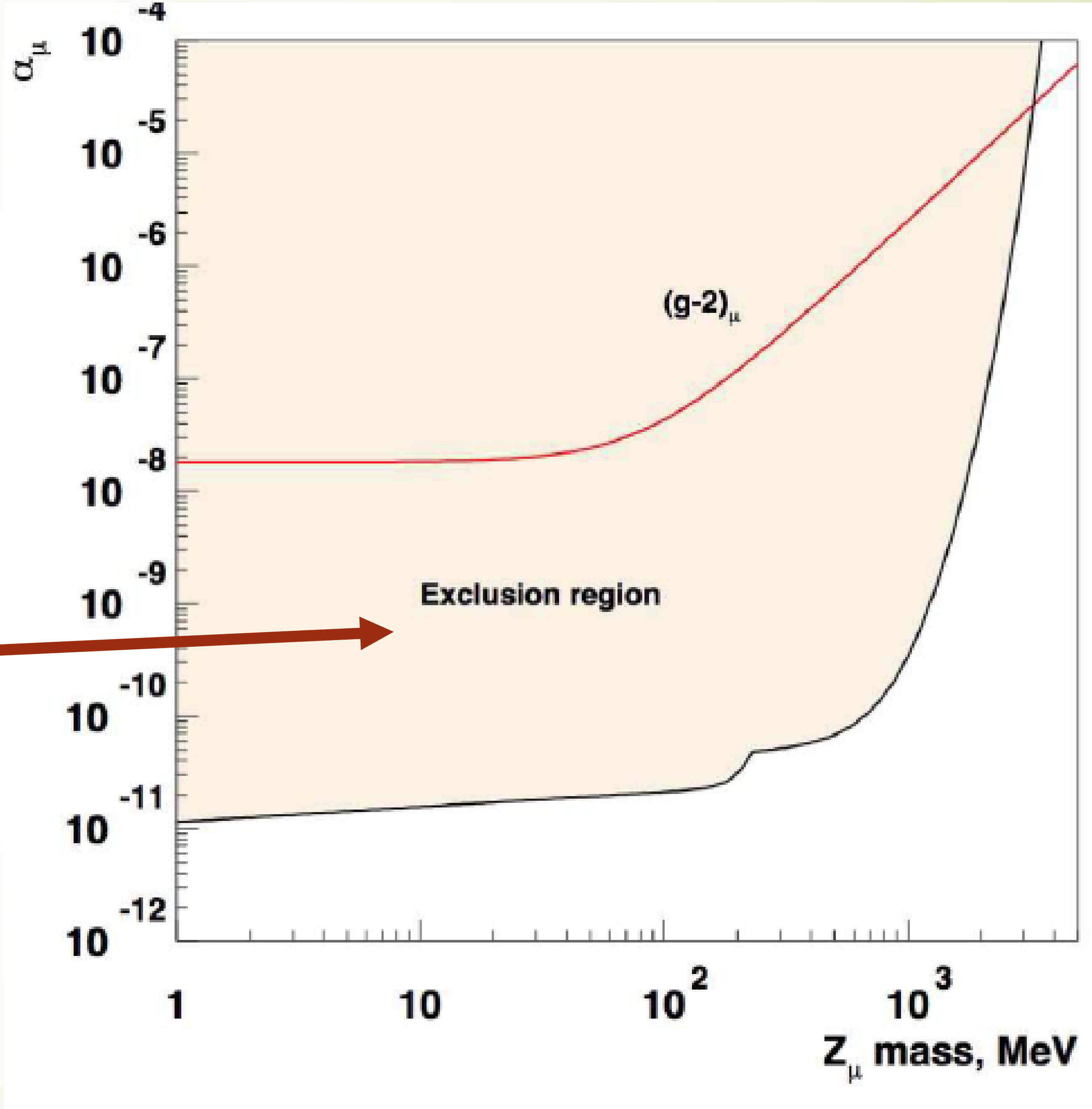
CERN SPS

Gninenko, Krasnikov and Matveev PRD 91 (2015)

- Gninenko, Krasnikov

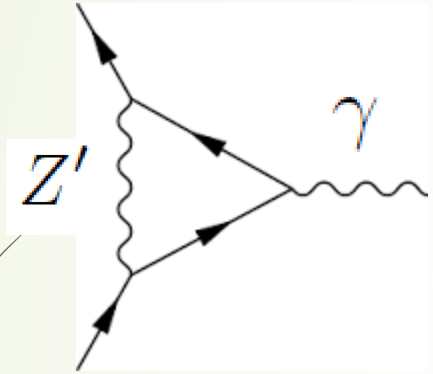
And Matveev, PRD 91 (2015)

$$g' \sim 7 \times 10^{-5}$$



$$10^{12} \text{ incident muons}$$

Muon magnetic dipole moment



$$\Delta(g-2)_\mu/2 = g'^2/8\pi^2$$

$$(g-2)_\mu/2 \sim 5\times 10^{-11}$$

Neutrino trident scattering

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

- CCFR collaboration:

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

PRL66 (1991)

- CHARM II collaboration

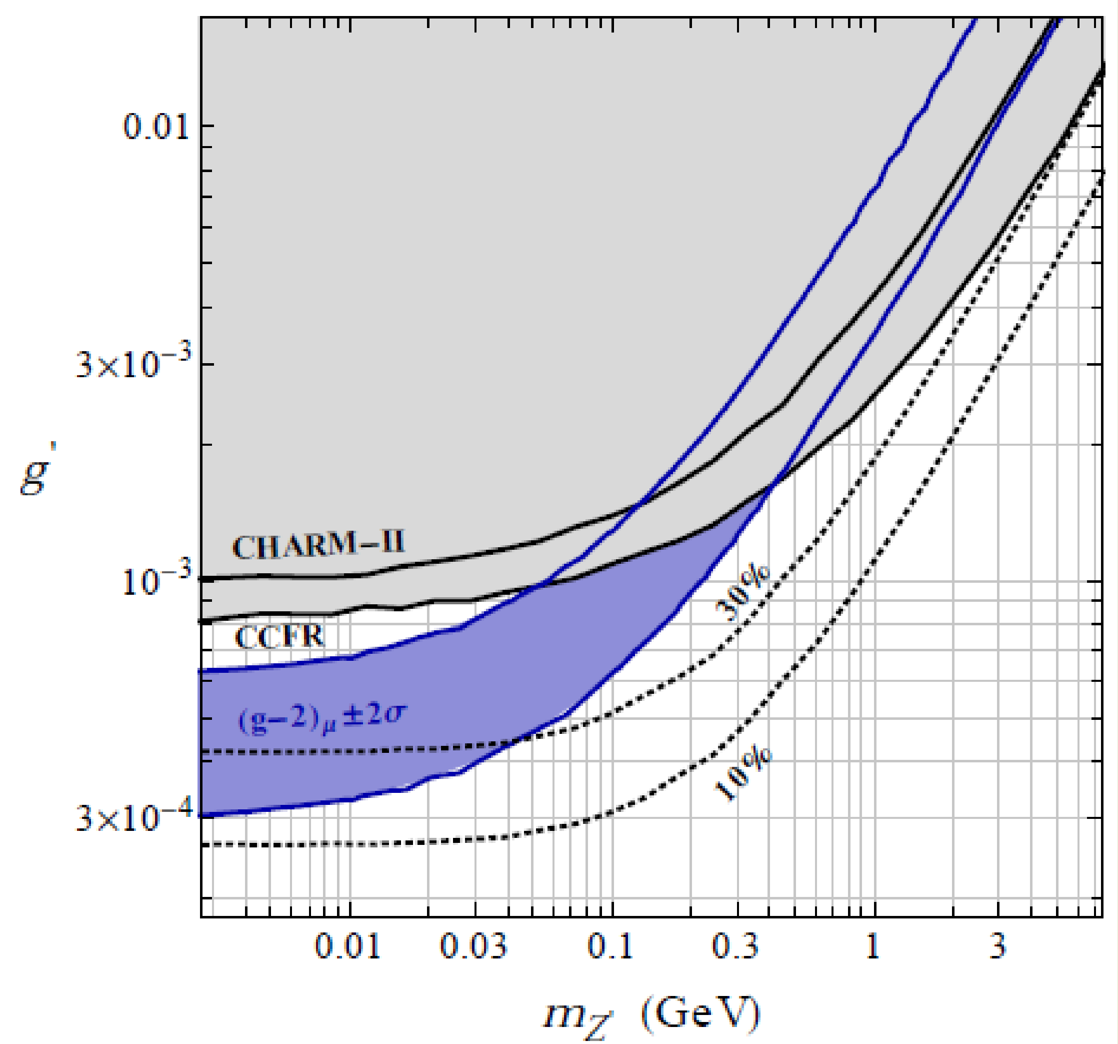
scattering of $\sim$ 20 GeV neutrino beam off a glass target

PLB 245 (1990)

Neutrino trident scattering

Altmannshofer et al., PRL113 (2014)

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



Yukawa coupling of neutrinos

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

$$Y_{N_2} = Y_{N_3} = Y_{L_\mu} = Y_{L_\tau} = 1$$

$$Y_{N_1} = 0$$

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: $\cancel{\nu_e \text{ and } \nu_\mu}$ $\cancel{\nu_e \text{ and } \nu_\tau}$

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

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