Non-Standard Interactions with light mediators

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elusives
neutrinos, dark matter & dark energy physics

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

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

Projection matrix

Matter field

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

Standard Oscillation

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

$$H^\nu = H_{vac} + H_{matt}$$

$$H_{vac} = U \cdot \text{Diag}\left(\frac{m_1^2}{2E}, \frac{m_2^2}{2E}, \frac{m_3^2}{2E}\right) \cdot U^\dagger$$

$$H_m = \begin{pmatrix} \sqrt{2}G_F N_e - \frac{\sqrt{2}}{2}G_F N_n & 0 & 0 \\ 0 & -\frac{\sqrt{2}}{2}G_F N_n & 0 \\ 0 & 0 & -\frac{\sqrt{2}}{2}G_F N_n \end{pmatrix}$$

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

Non-Standard matter effects

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

$$H^\nu = H_{vac} + H_{matt}$$

$$H_{vac} = U \cdot \mathrm{Diag}\left(\frac{m_1^2}{2E}, \frac{m_2^2}{2E}, \frac{m_3^2}{2E}\right) \cdot U^\dagger$$

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

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

Masud and Mehta, PRD 94(2016); Forero and Huber, PLB 117 (2016); Liao, Marfatia and Whistnant PRD 93 (2016); Agarwalla, Chatterjee and Palazzo, PLB 762 (2016)

Underlying models for NSI with light mediators

Y.F., PLB 748 (2015) 311; Y.F. and I. Shoemaker, JHEP 1607 (2016) 033; Y.F. and J. Heeck, PRD94 (2016) no 5, 53010, Y.F. and M. Tortola, Front. In Phys 6 (2018) 10

LMA-Dark solution

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

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

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

Total flux measurement at SNO

- Neutral current
- Deuteron dissociation

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

- Gamow-Teller transition
- Sensitive only to axial-vector interaction
- No effect from

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

Scattering experiments

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

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

Scattering experiments

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

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

But not in the model that we shall present

Underlying theory for LMA-Dark?

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

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

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

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

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

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

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

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 $m_X \sim 10 \text{ MeV}$

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

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

But because coupling is small!

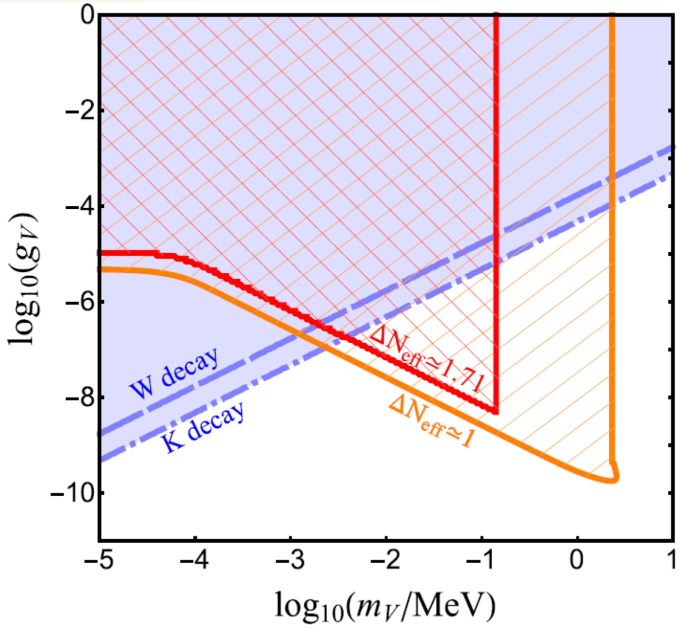
$$g_\nu \bar{\nu}_\alpha \gamma^\mu \nu_\beta Z'_\mu$$

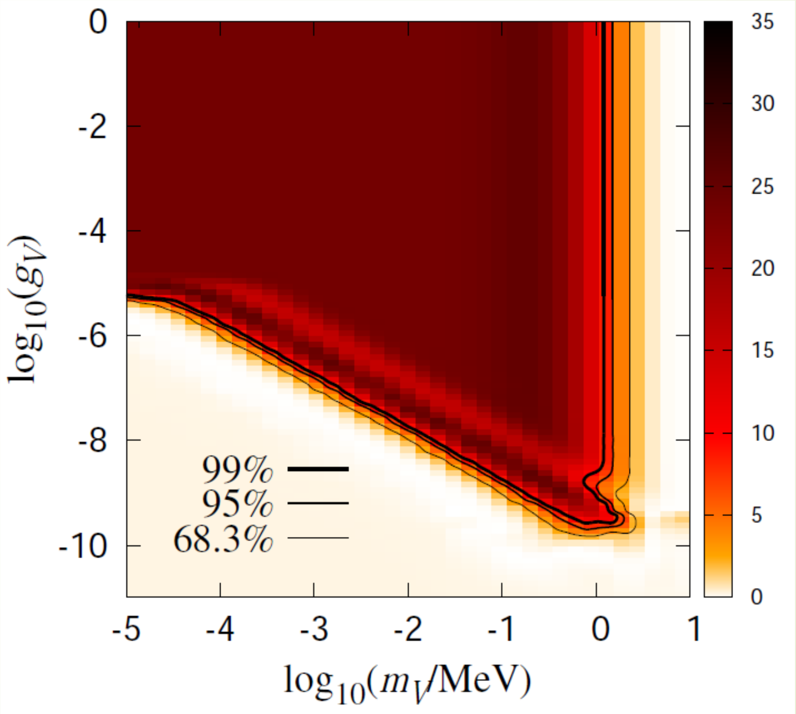
$$\frac{g_B}{3} \bar{q} \gamma^\mu q Z'_\mu$$

$$\epsilon^u_{\alpha\beta} = \epsilon^d_{\alpha\beta} = \frac{g_\nu g_B}{6\sqrt{2} G_F m^2_{Z'}}$$

Big Bang Nucleosynthesis

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



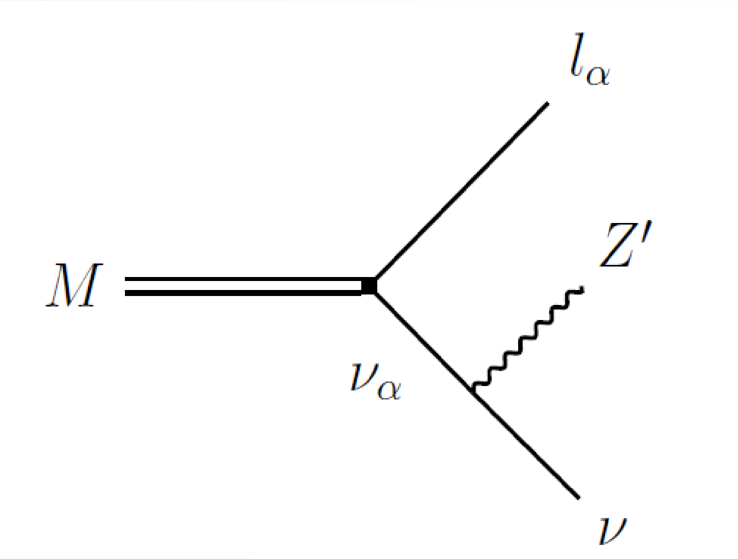


The contour plot and density map of the χ^2 function

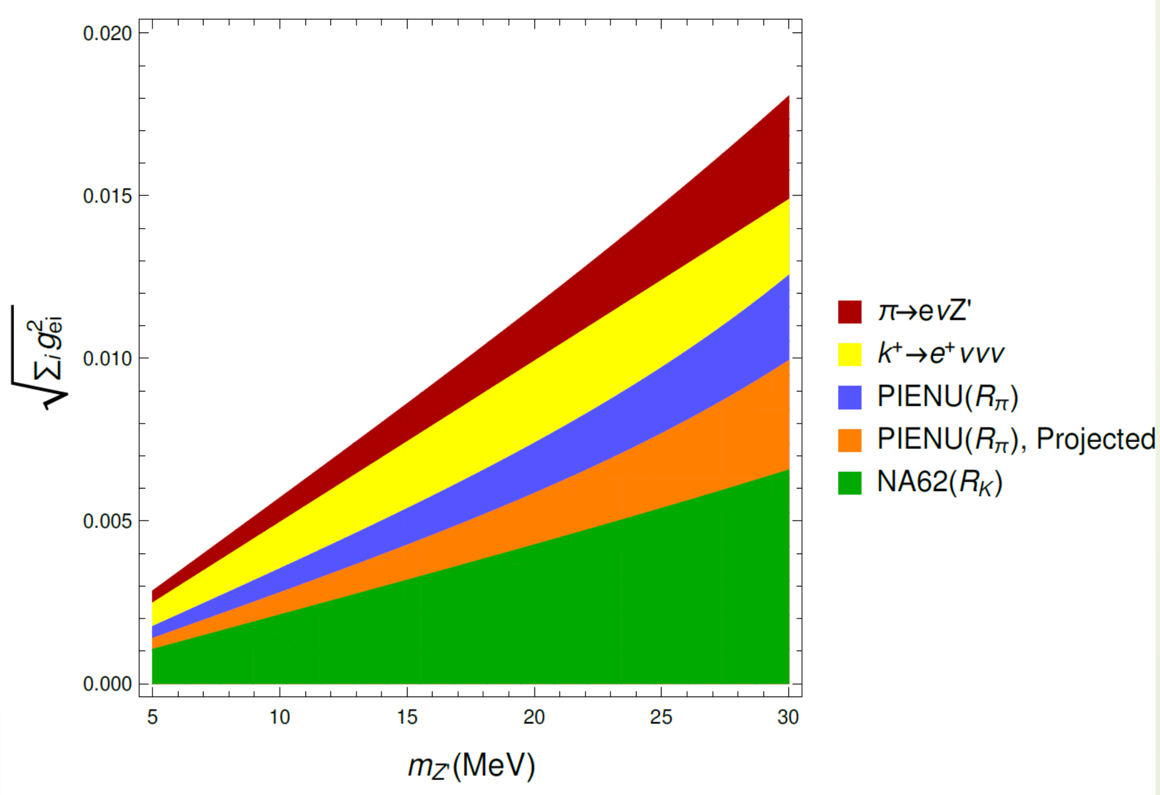
$$m_{Z'} \lesssim 5\ \mathrm{MeV}$$

$$Y_p = 0.2449 \pm 0.0040 \qquad D/H|_p = (2.53 \pm 0.04) \times 10^{-5}$$

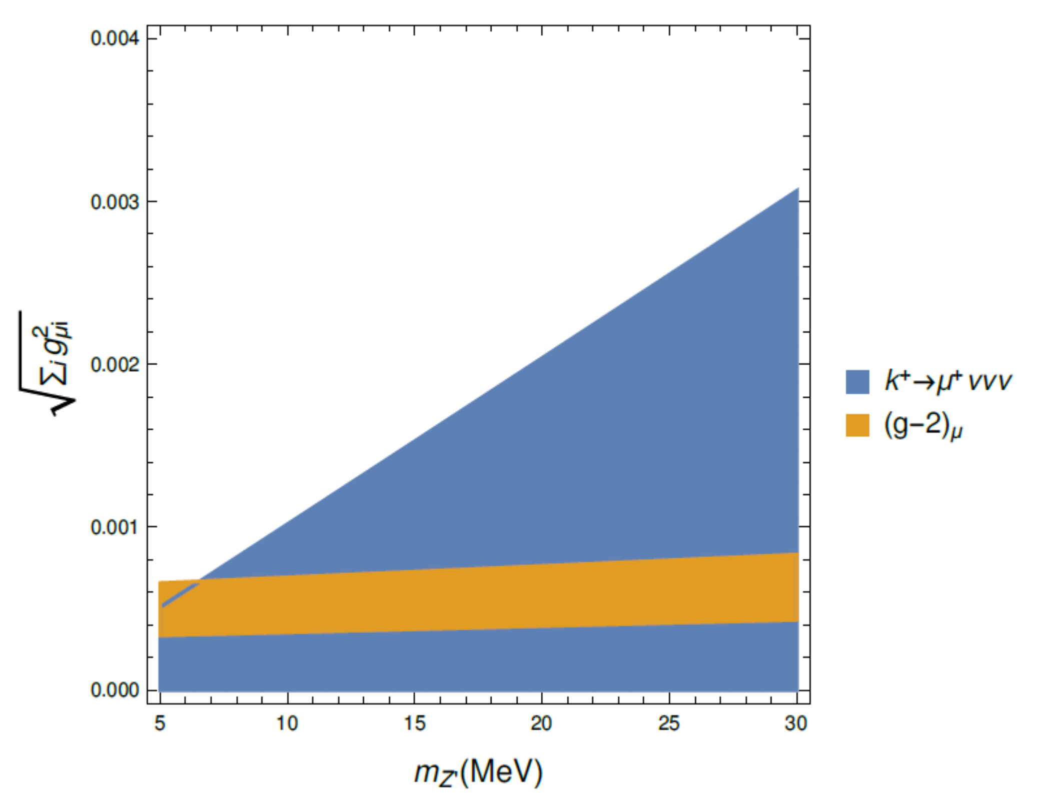
Bounds on Couplings of neutrinos



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



P Bakhti and YF, PRD 95 (2017) 095008



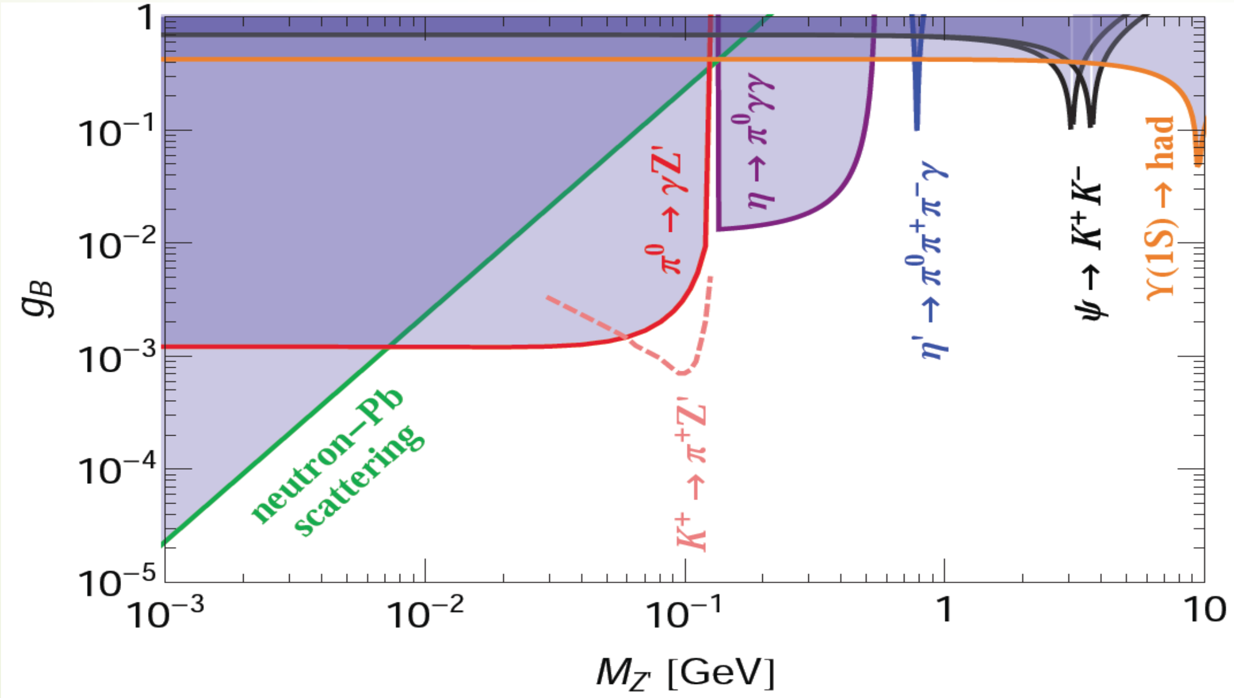
Artamonov et al.,
BNL-E494 collaboration,
PRD 79 (2009) 092004

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

P Bakhti and YF, PRD 95 (2017) 095008

Coupling to quarks

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



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

Coupling to neutrinos

Direct coupling to neutrinos

Gauge symmetry:

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

Coupling to neutrinos through mixing with ψ : κ_α

Gauge symmetry:

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

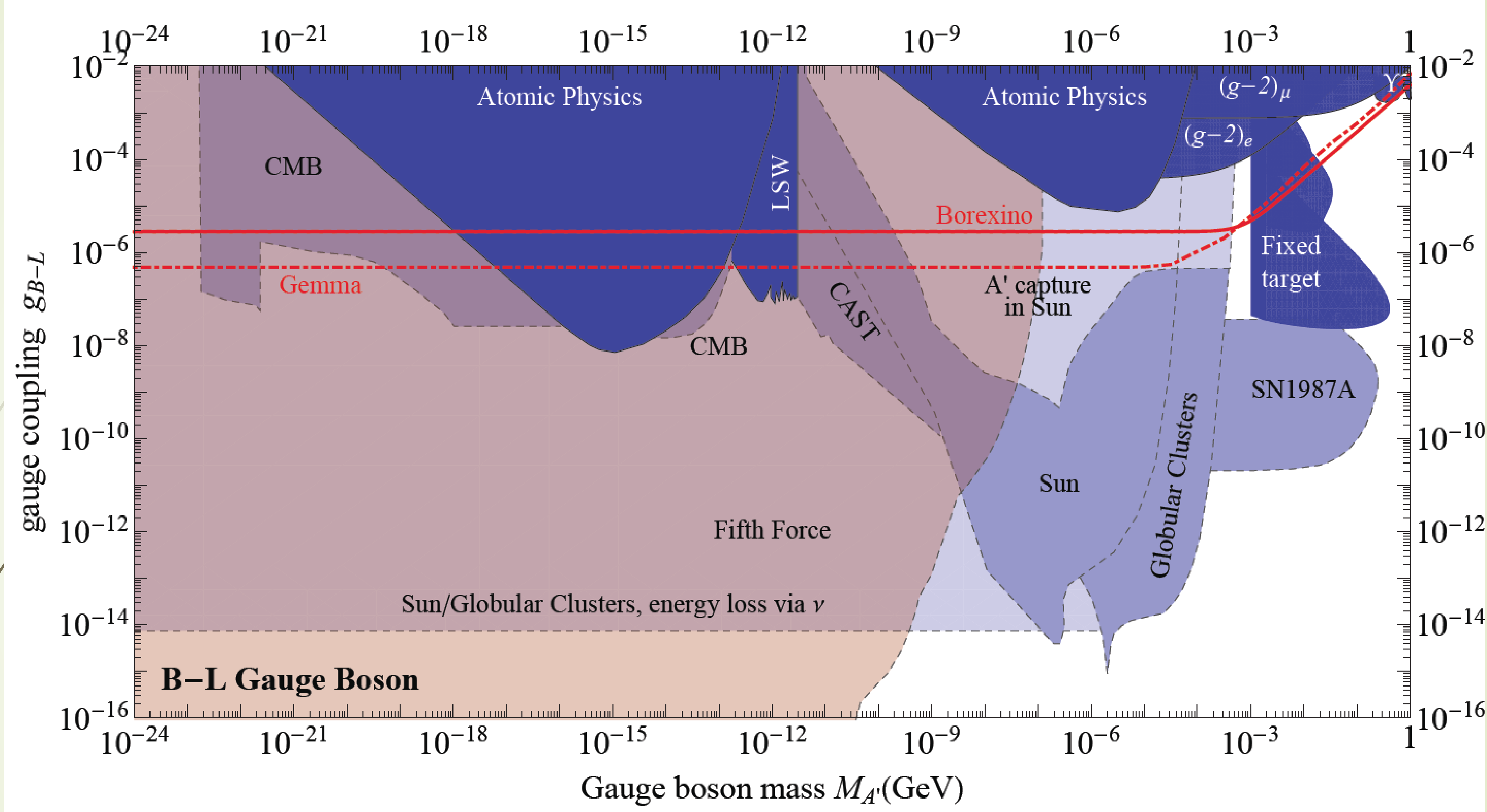
Coupling to neutrinos

- Direct coupling to neutrinos

Gauge symmetry:

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

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



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

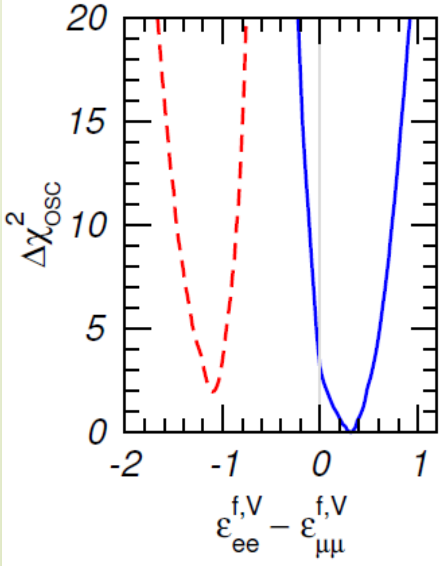
Harnik, Kopp and Machado, JCAP 1207 (2012) 026

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

$$a_e = 0$$

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

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



Anomaly cancelation

$$3 + a_e + a_\mu + a_\tau \neq 0$$

Adding a new generation of leptons (quarks)

Non-perturbative Yukawa coupling

Adding a pair of fermions with opposite hypercharges

$$Y_1 S e_{R4}^T c e_{5R} + Y_2 S L_4^T c L_5 + \text{H.c.}$$

$$g' \lesssim \frac{5\ \text{TeV}}{M_{4,5}} \frac{2\times10^{-6}}{3+a_\mu+a_\tau} \frac{m_{Z'}}{10\ \text{MeV}}$$

$$e^-_{4(5)} \to \nu_{4(5)} l \nu, \nu_{4(5)} q' \bar{q}$$

Coupling of neutrinos through mixing

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

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

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

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

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

Coupling of neutrinos through mixing

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

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

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

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

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

Neutrino scattering experiments

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

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

Suppression factor

$$\frac{m_{Z'}^2}{q^2 - m_{Z'}^2} \ll 1$$

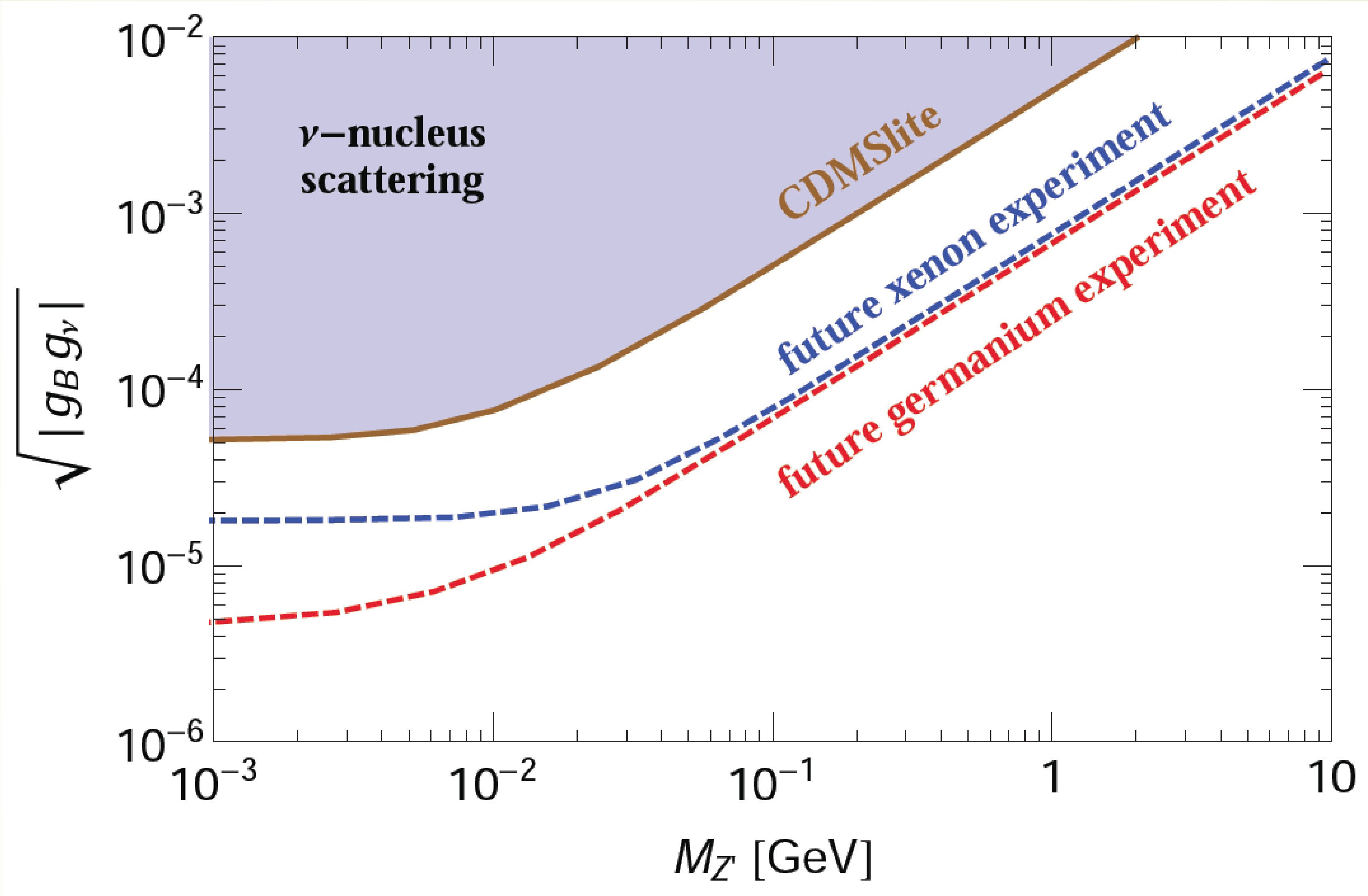
Neutrino scattering experiments

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

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

$$5\ \mathrm{MeV} \lesssim m_{Z'} \ll 1\ \mathrm{GeV}$$

Relaxing bounds from scattering experiments, NuTeV and CHARM

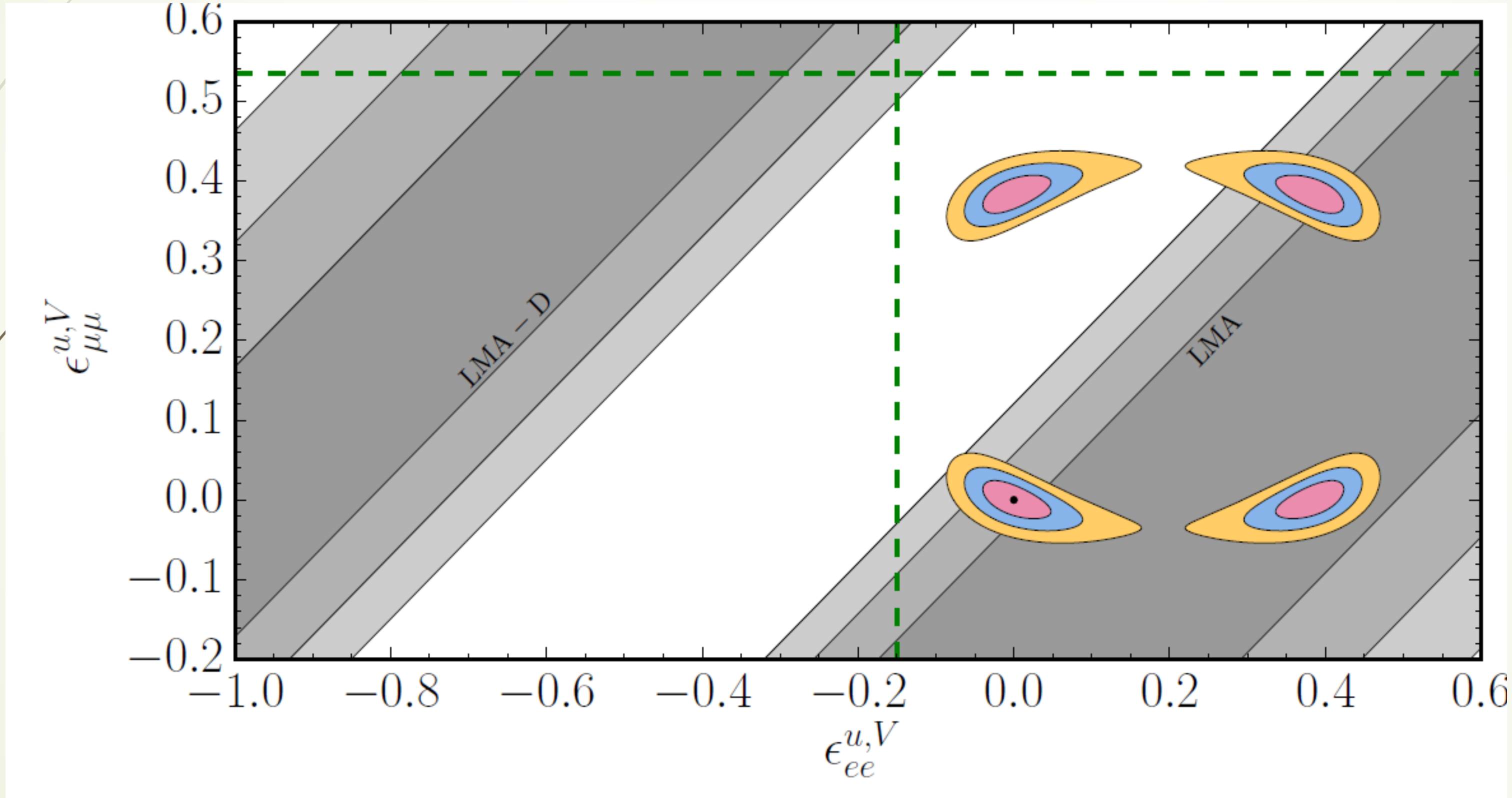


YF and J Heeck, PRD94 (2016) 053010

LUX-Zeplin

SuperCDMS SNOLAB

COHERENT experiment



Coloma et al, JHEP 1704 (2017) 116

Neutrino source: Pion decay at rest

COHERENT experiment

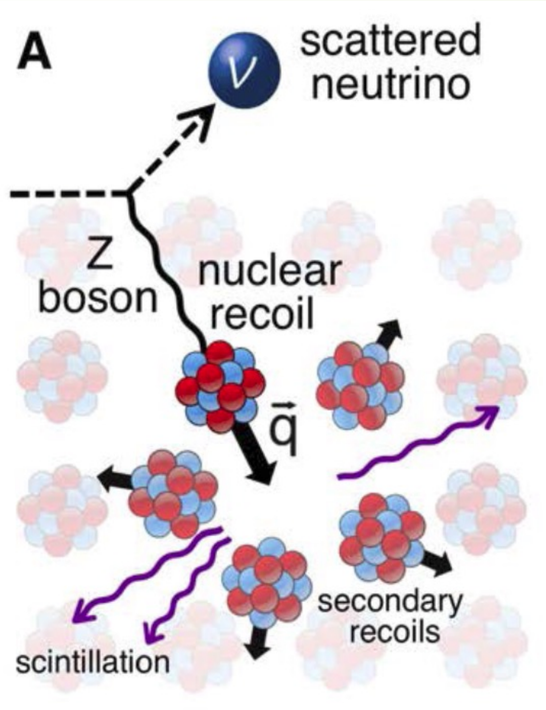
- Akimov et al., "Observation of Coherent Elastic neutrino Nucleus Scattering," science 357 (2017) No 6356, 1123

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

Freedman, PRD 9 (1974) 1389.

$QR \lesssim 1$

They find 6.7σ CL evidence for $\mathrm{CE}\nu\mathrm{NS}$



Set-up of the COHERENT experiment

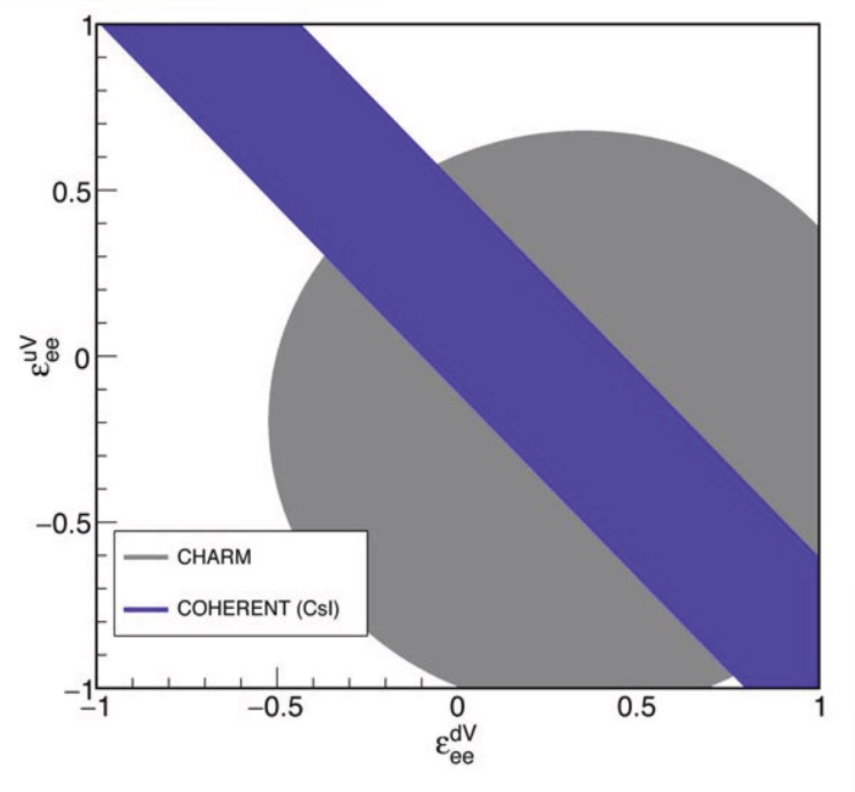
- Detector: 14.6 kg CsI scintillator
- Source: Spallation Neutron Source (SNS) at Oak Ridge National Lab

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

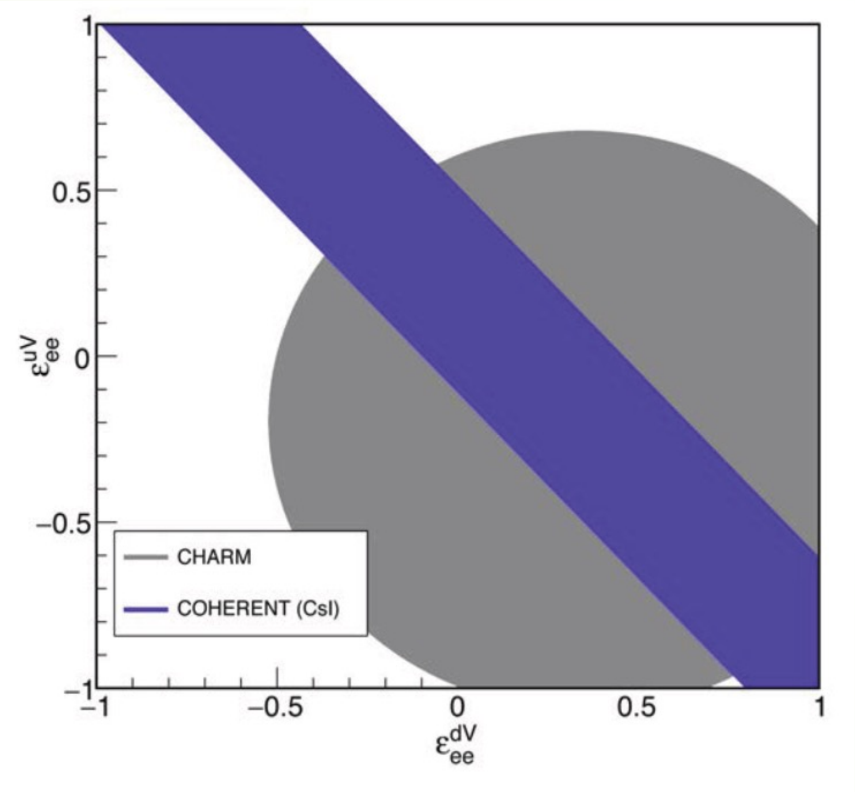
$$N_{\mathrm{POT}} = 1.76 \times 10^{23}$$

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



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

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

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

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

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

$$g_n^V = -\tfrac{1}{2}$$

Liao and Marfatia, Phys Lett B775 (2017) 54

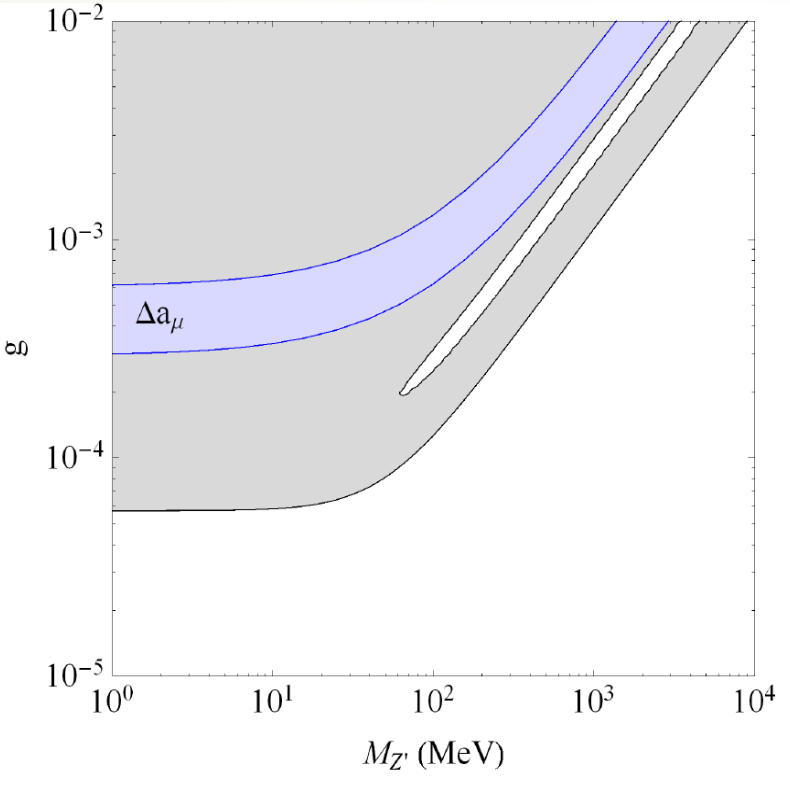
Coherent interaction with light mediator

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

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

$$Q^2 = 2ME_r$$

Liao and Marfatia, Phys Lett B775 (2017) 54



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

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

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

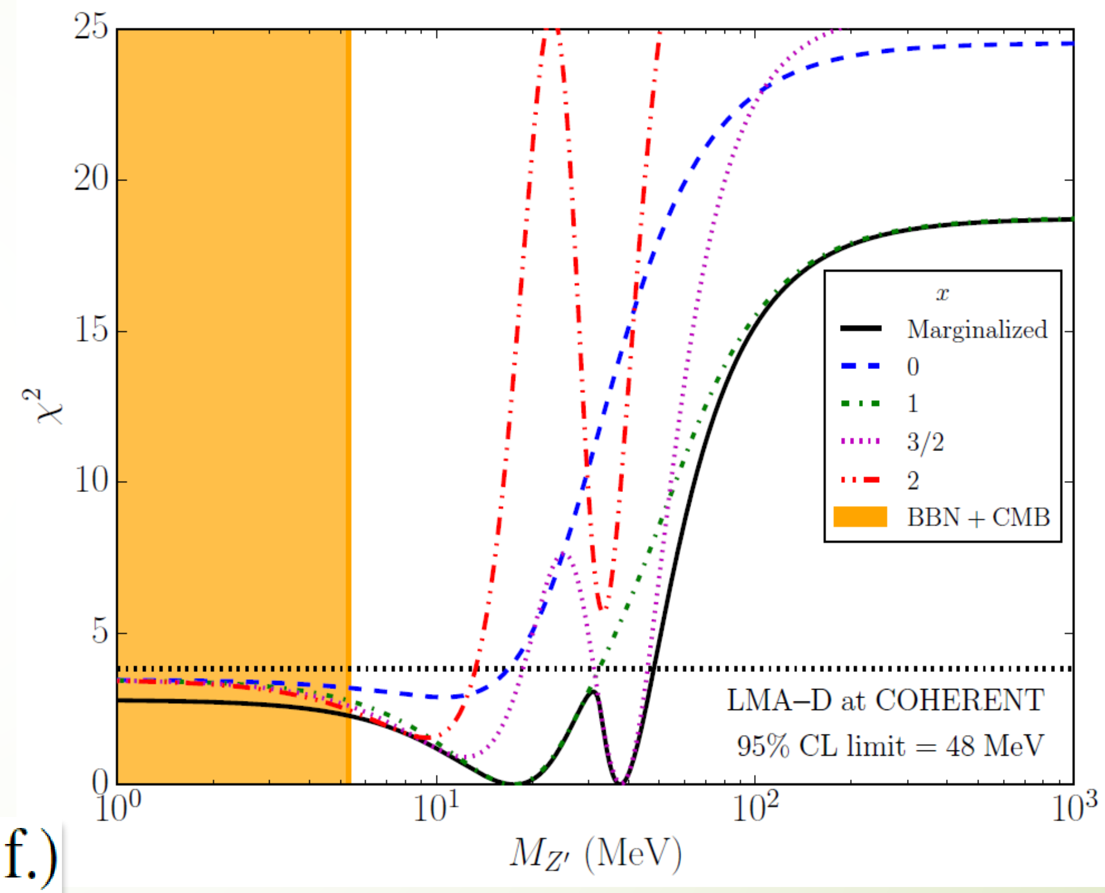
Liao and Marfatia, Phys Lett B775 (2017) 54

LMA-Dark after COHERENT data

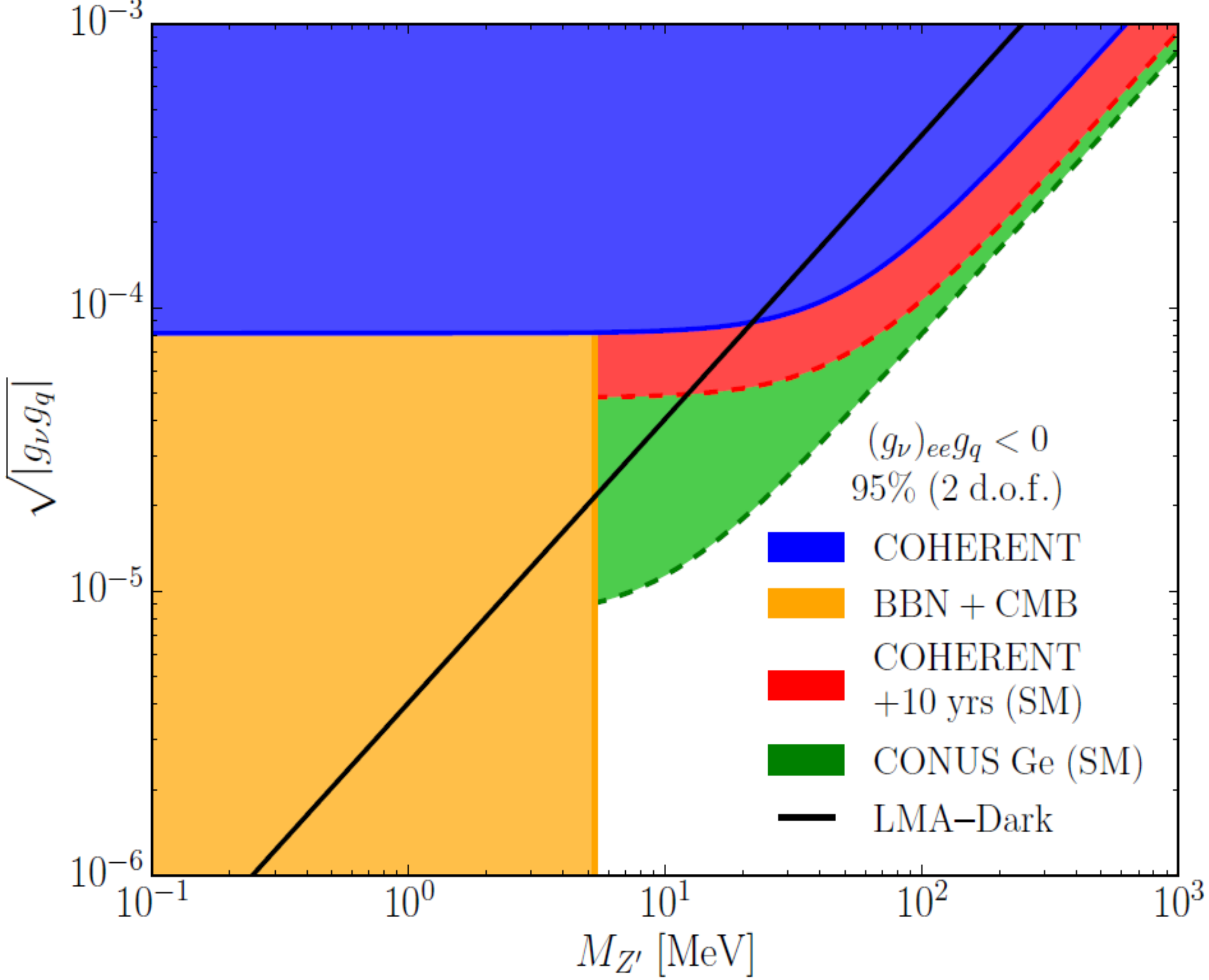
$$(\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}) = (x-2, x, x)$$

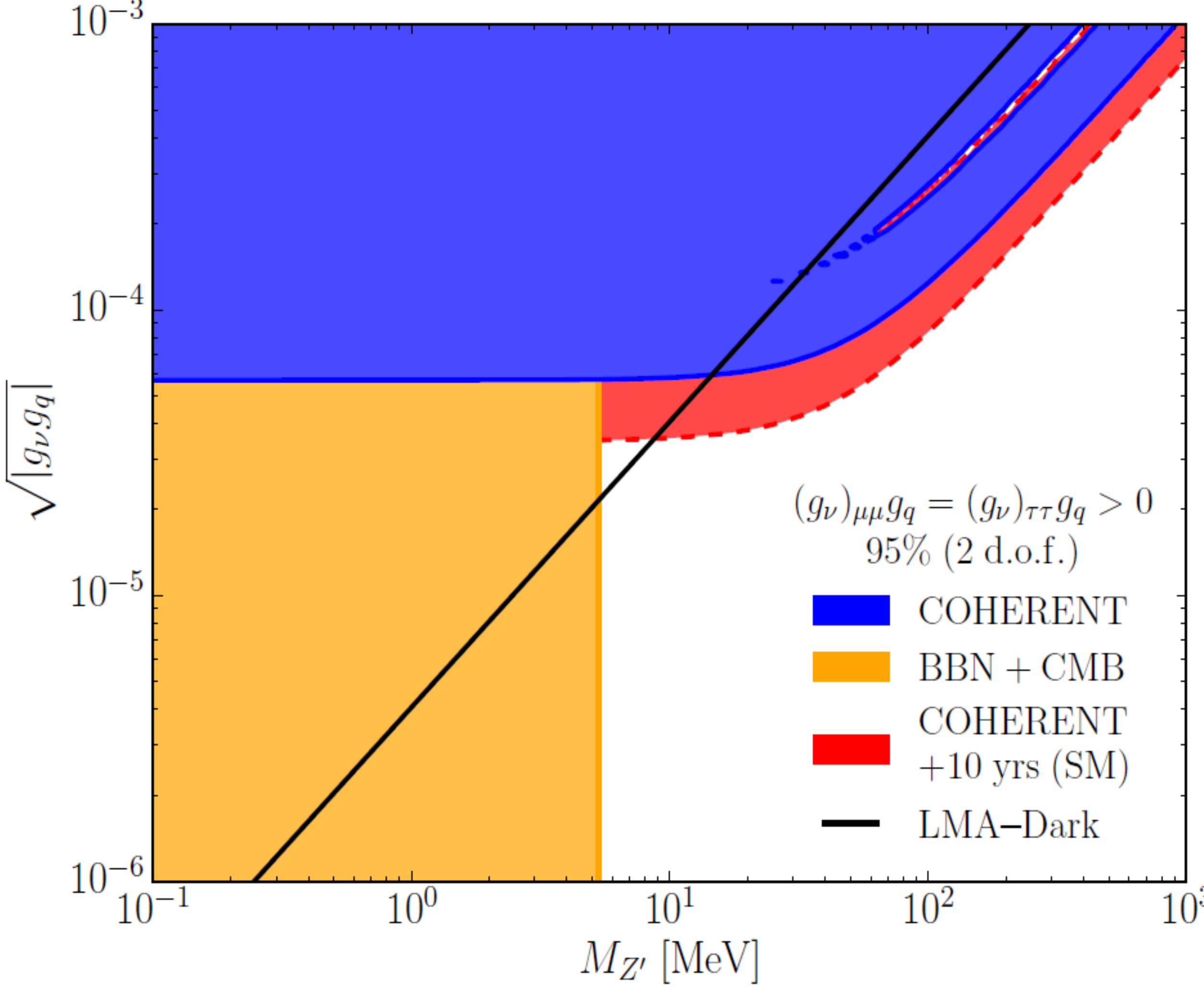
$$\epsilon_{ee}^{u,V} = \epsilon_{ee}^{d,V} = \frac{x}{4} - \frac{1}{2}$$

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



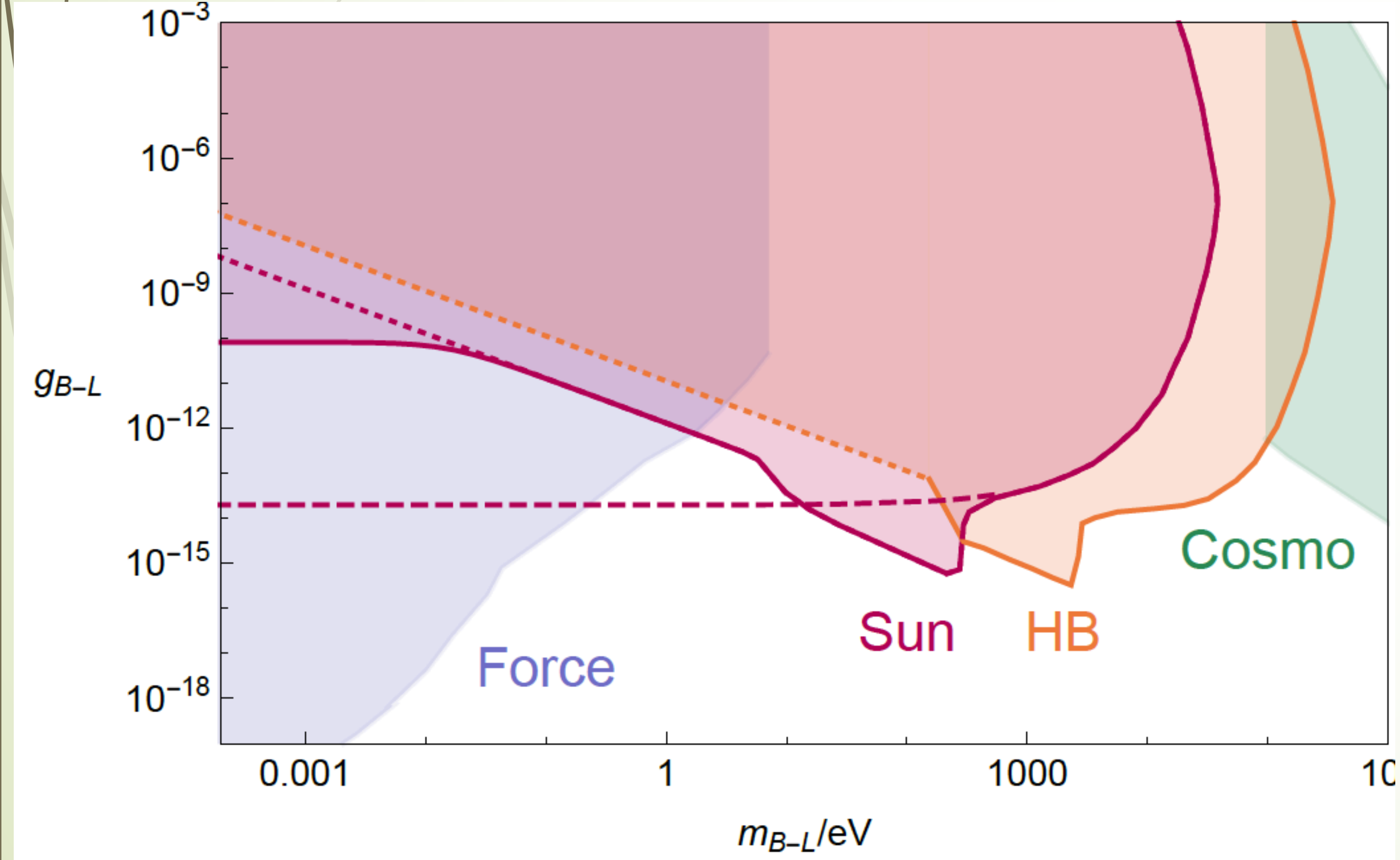
Denton, YF Shoemaker, arXiv:1804.03660, to appear in JHEP





Denton, YF Shoemaker, arXiv:1804.03660, to appear in JHEP

Even lighter mediator



Hardy and Lasenby,JHEP 1702 (2017) 33

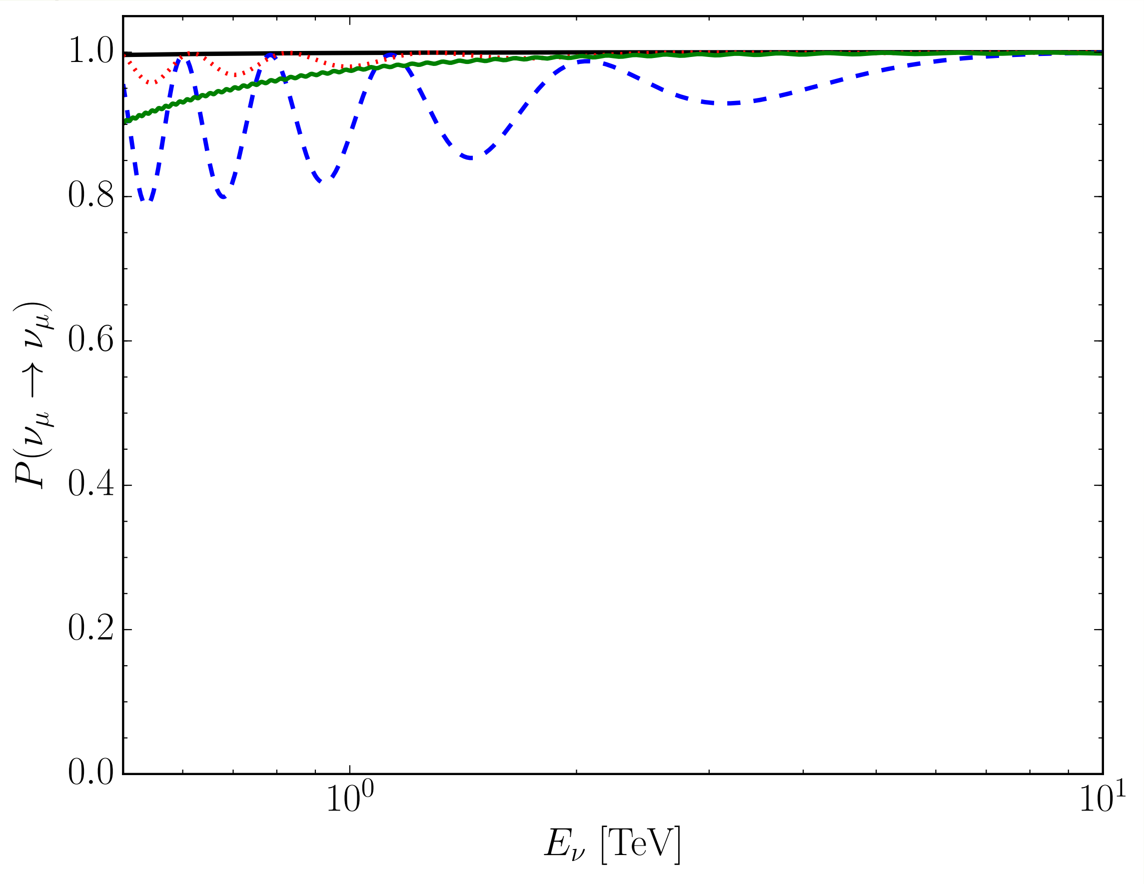
Free streaming at recombination:

$$g_\nu < 5 \times 10^{-5} \frac{m_{Z'}}{10\ eV}$$

Cherry, Denton, YF and Shoemaker,
Work in progress

$$g_{\nu_s} \sim 10^{-2}$$

$$\mathcal{L} = -2\sqrt{2}\epsilon G_F (\bar{\nu}_s \gamma^\mu \nu_s)(\bar{f}\gamma_\mu f)$$



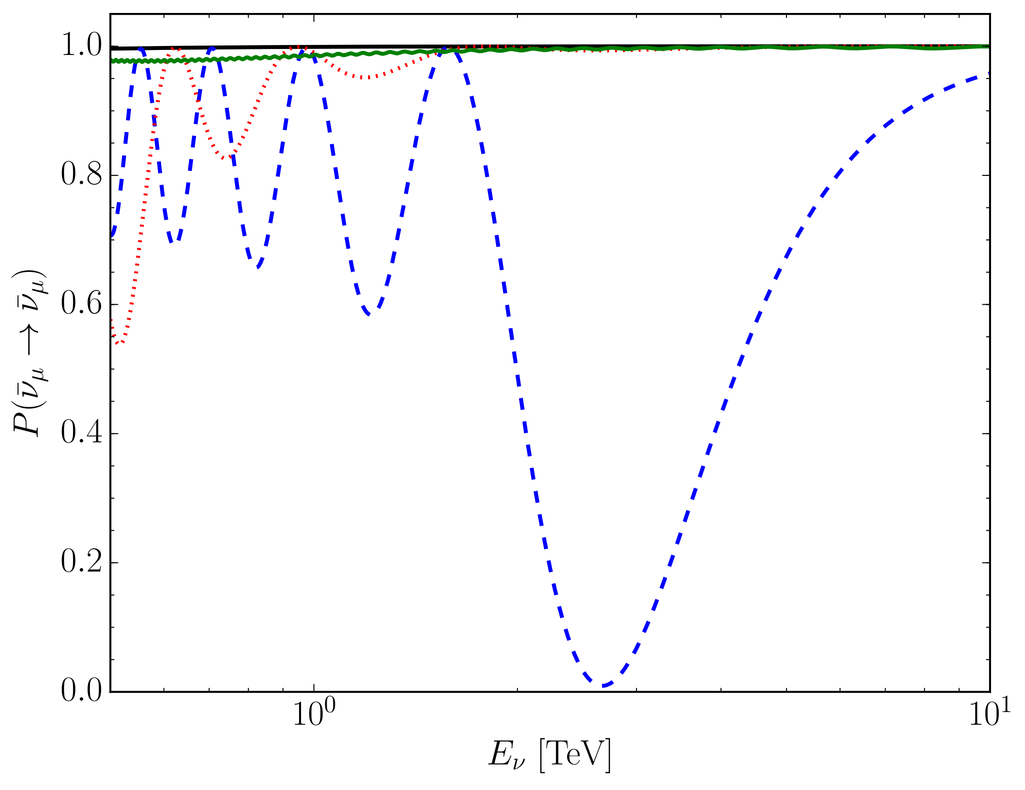
$\cos\theta_z = -0.8$

Cherry, Denton, Y.F. and shoemaker,
Work in progress

$\epsilon_{ss} = 6$

Liao and Marfatia, PRL 117 (2016) 71802

$\epsilon_{\mu\mu} = -6.26 \quad \epsilon_{\tau\tau} = -6.26$



Cherry, Denton, Y.F. and shoemaker,
Work in progress

$$\epsilon_{ss} = 6$$

Liao and Marfatia, PRL 117 (2016) 71802

$$\epsilon_{\mu\mu} = -6.26 \qquad \epsilon_{\tau\tau} = -6.26$$

$$\cos\theta_z = -0.8$$

Summary

- $U(1)'$ gauge boson with $m_{Z'} \sim 10\ \mathrm{MeV}$ and $\sqrt{g_\nu g_B} = 10^{-4} - 10^{-5}$ can lead to sizeable NSI.

- COHERENT has not ruled out LMA-Dark yet!

- Upcoming CEvNS experiments can test this scenario

Backup slides

- Observational consequences

Emission in Supernova

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

Kamada and Yu, arXiv:1504.00711

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

- Reduced mean free path for ν_μ and ν_τ

prolong the diffusion time

High energy cosmic neutrino

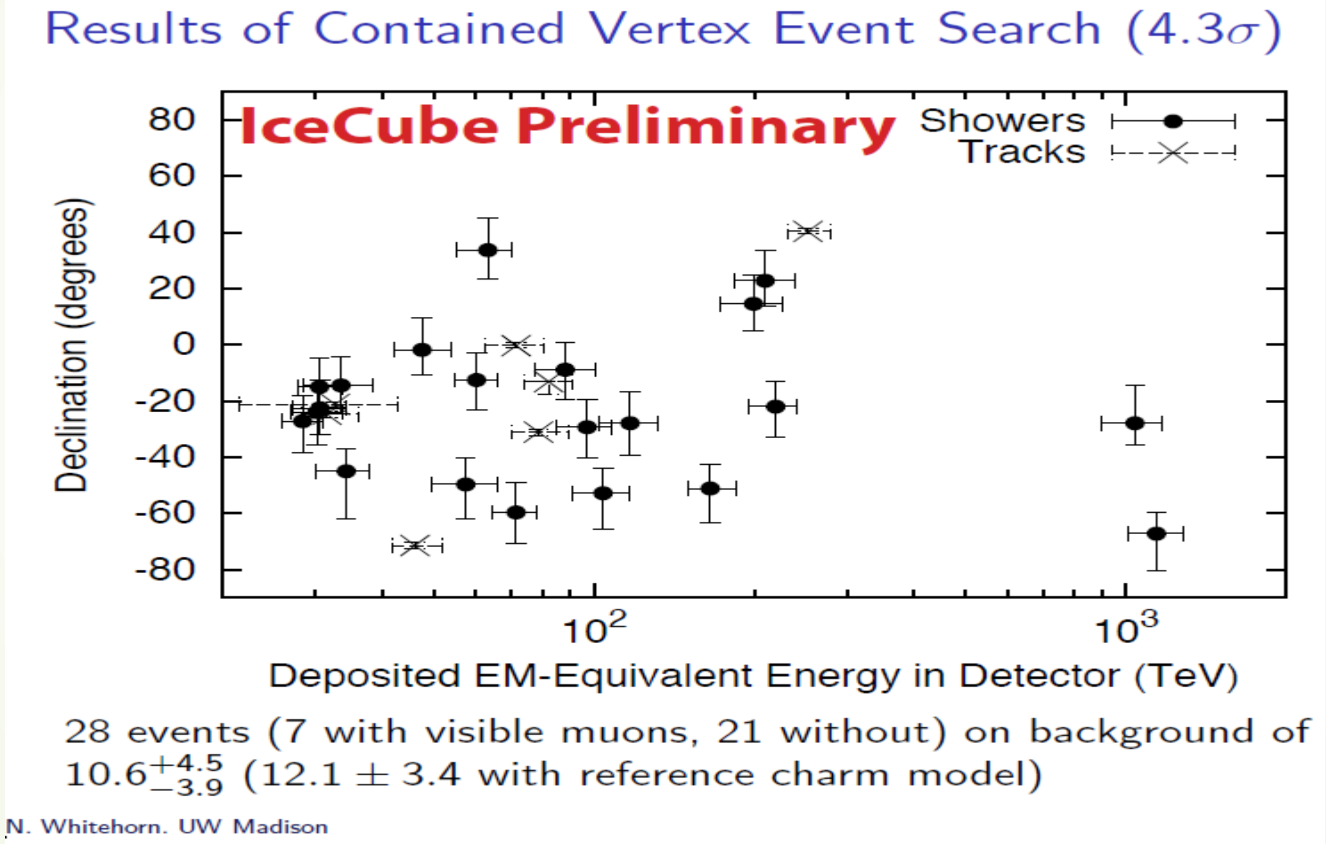
- Kamada and Yu, arXiv:1504.00711 $\mathcal{L}_\mu - \mathcal{L}_\tau$

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

Background neutrino at rest

400 TeV to PeV

Dip or gap in ICECUBE spectrum



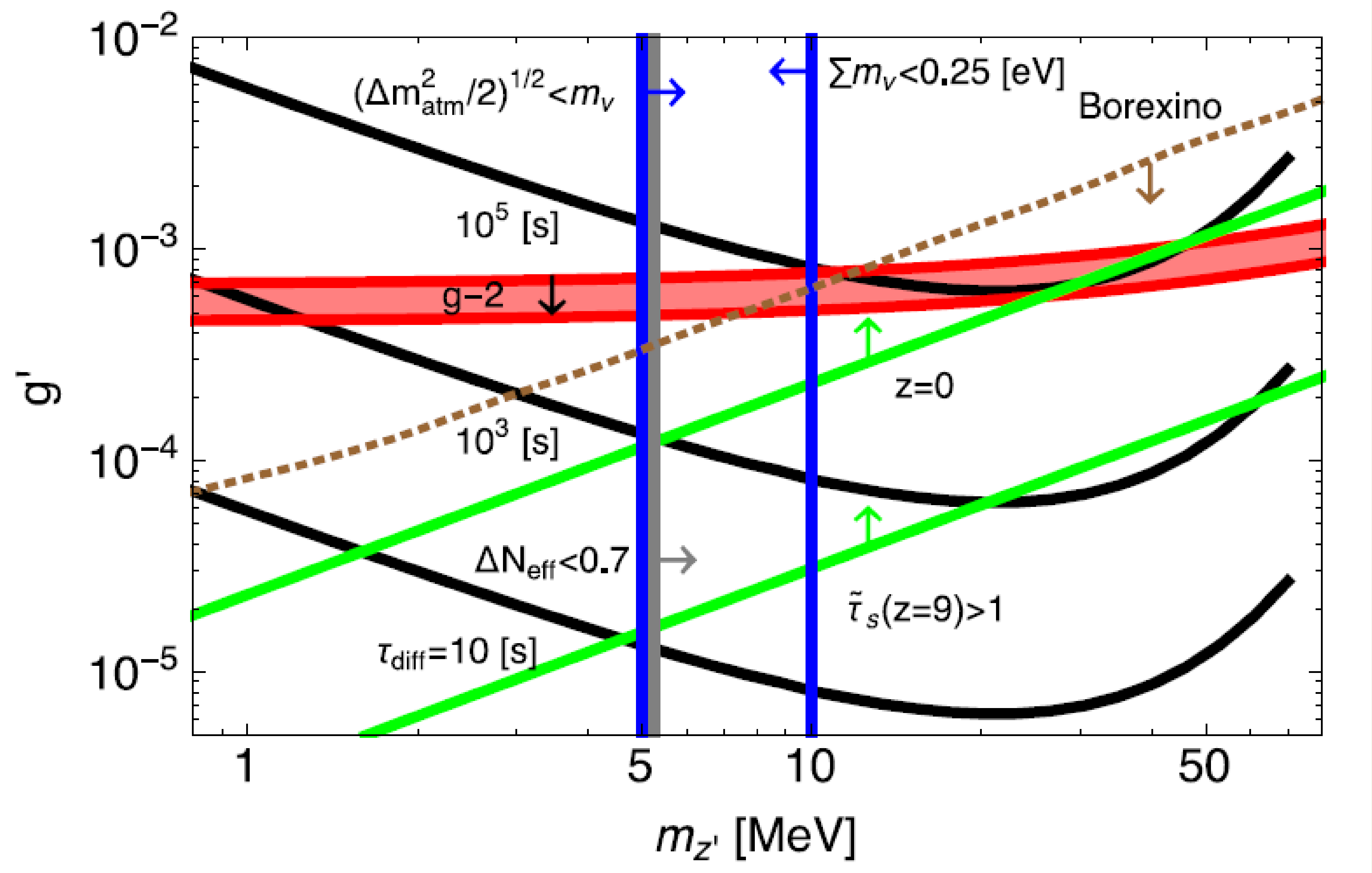
- Theoretical prediction of dip in 400 TeV to PeV is robust!

↓

- 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:

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

PRL66 (1991)

- CHARM II collaboration

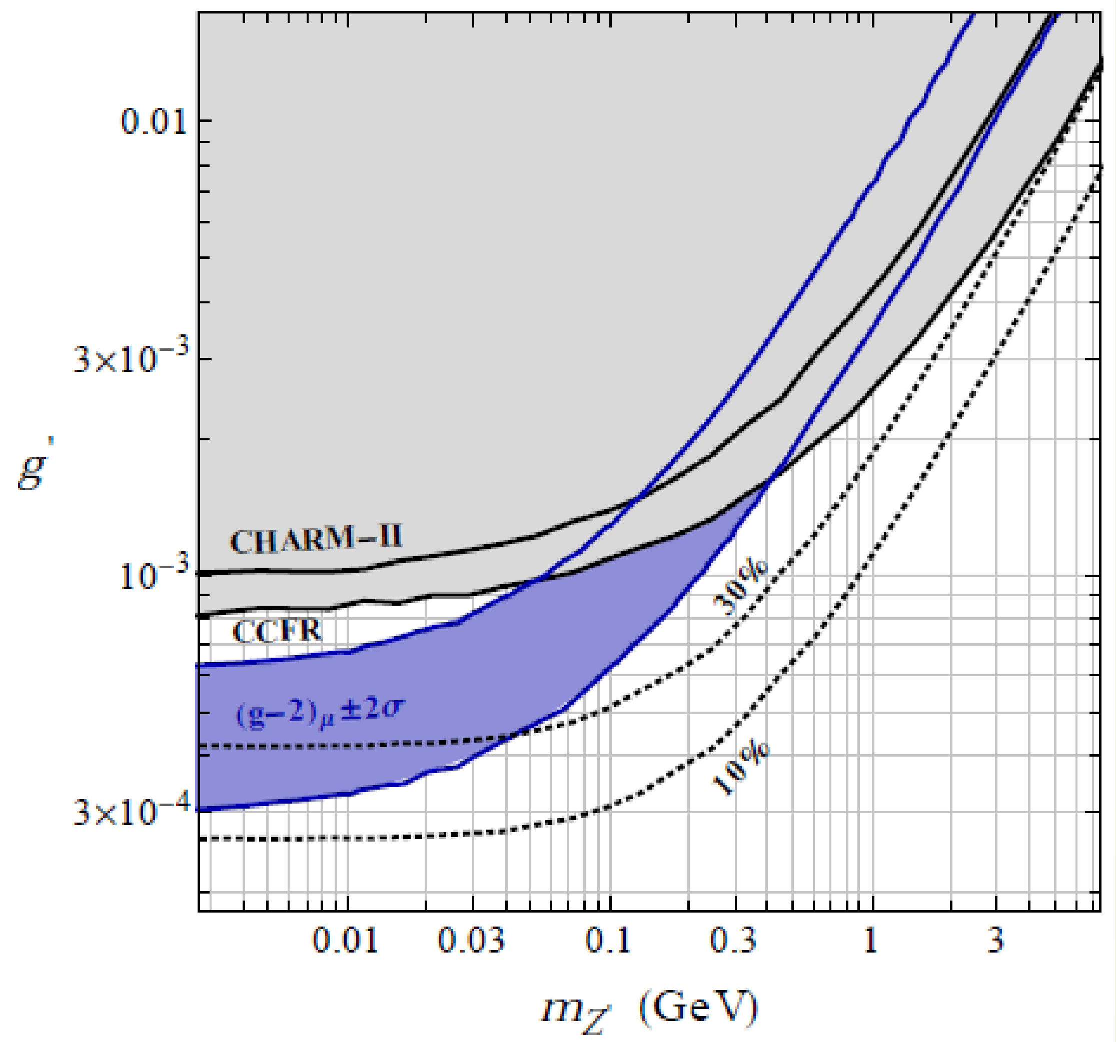
scattering of $\sim$ 20 GeV neutrino beam off a glass target

PLB 245 (1990)

Neutrino trident scattering

Altmannshofer et al., PRL113 (2014)

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



$(\bar{u}\gamma^\rho P u)(\bar{\nu}_\mu \gamma_\rho L \nu_\mu)$	$\lvert\varepsilon^{uL}_{\mu\mu}\rvert < 0.003$ $-0.008 < \varepsilon^{uR}_{\mu\mu} < 0.003$ 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

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

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

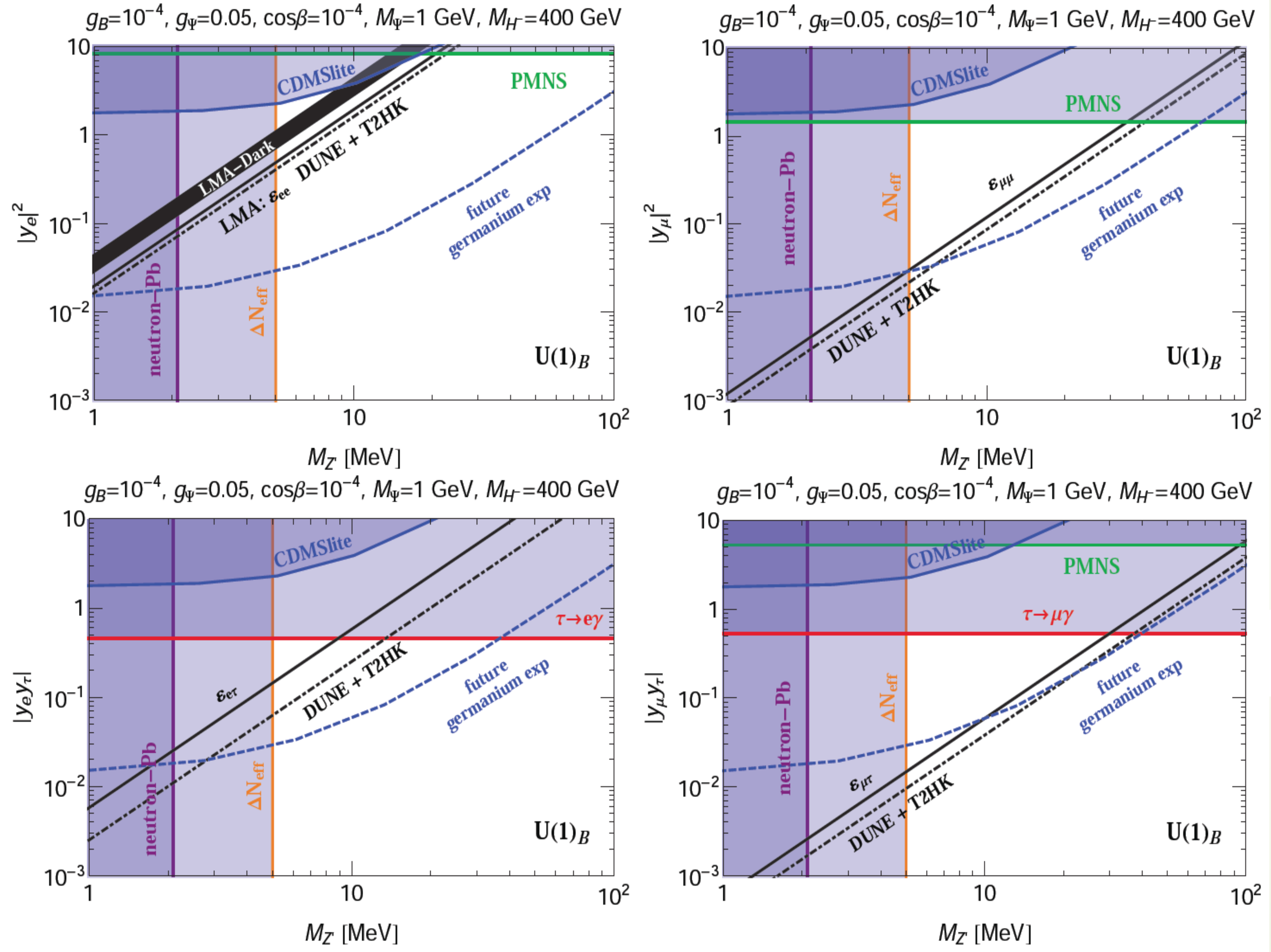
$$\nu_e q \to \nu q \text{ scattering}$$

Standard coherent interaction

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

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

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



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

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