Non-Standard Interactions in the neutrino sector

Pilar Coloma
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Neutrino Seminar
Fermilab
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One-slide summary for this talk

- Part I: introduction to Non-Standard neutrino Interactions (NSI)

- Part II: NSI in propagation, the LMA-dark solution and the neutrino mass ordering

- Part III: NSI vs oscillation+scattering data

Introduction to Non-Standard neutrino Interactions

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Neutrino masses

Neutrinos are special. Their masses can receive two different types of contributions:

1) Dirac mass: as for the rest of fermions in the SM

$$Y_\nu \overline{L}_L \widetilde{\phi} \nu_R \to m_\nu \bar{\nu}_L \nu_R$$

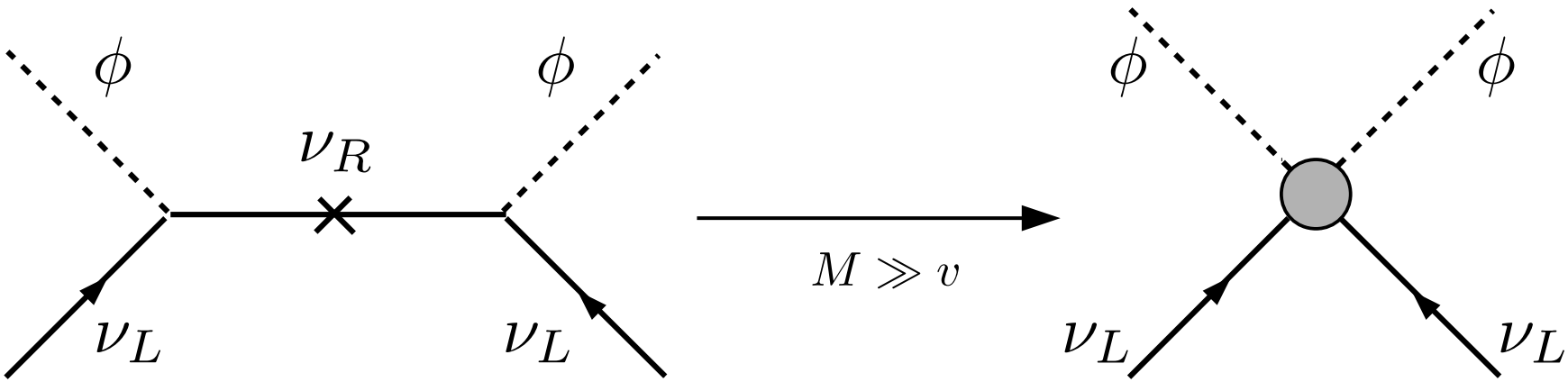
$$Y_\nu \lesssim 10^{-12}$$

2) A Majorana mass. For example:

$$Y_\nu \bar{L}_L \widetilde{\phi} \nu_R + \frac{1}{2} M \overline{\nu}_R^c \nu_R$$

$$(\not{L})$$

Neutrino masses



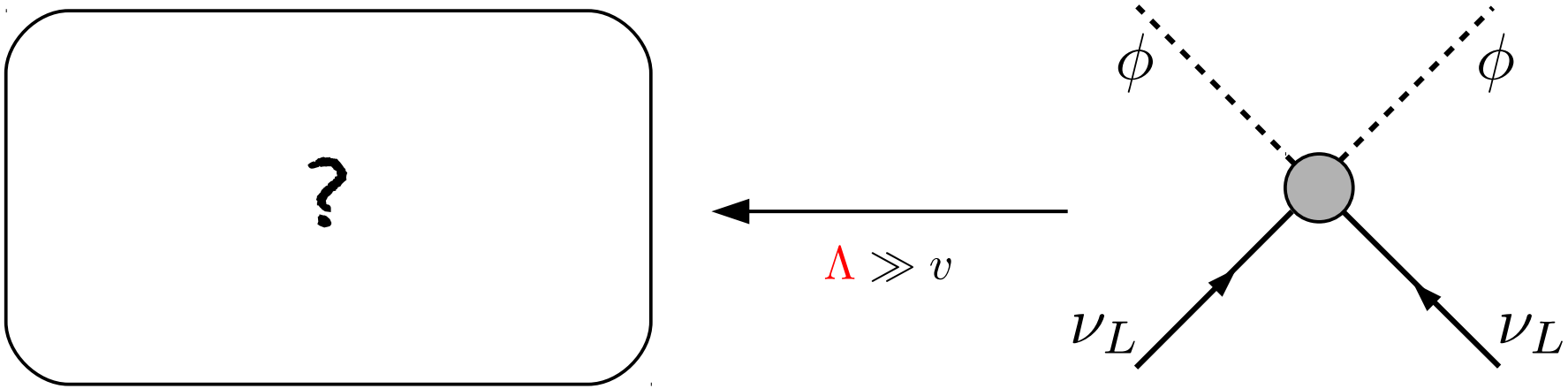
See-Saw type I

$$\propto \frac{1}{M}(\overline{L}_L\widetilde{\phi})(\widetilde{\phi}^t L_L^c)$$

Weinberg, 1979

$$m_\nu \propto \frac{v^2}{M}$$

Neutrino masses



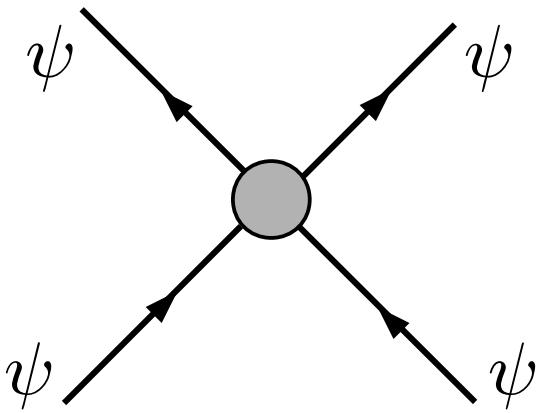
$$\propto \frac{1}{\Lambda}(\overline{L}_L\widetilde{\phi})(\widetilde{\phi}^t L_L^c)$$

Weinberg, 1979

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\,\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\,\delta\mathcal{L}^{d=6} + \ldots$$

Non-Standard Interactions

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\,\delta\mathcal{L}^{d=5} + \boxed{\frac{1}{\Lambda^2}\,\delta\mathcal{L}^{d=6}} + \ldots$$

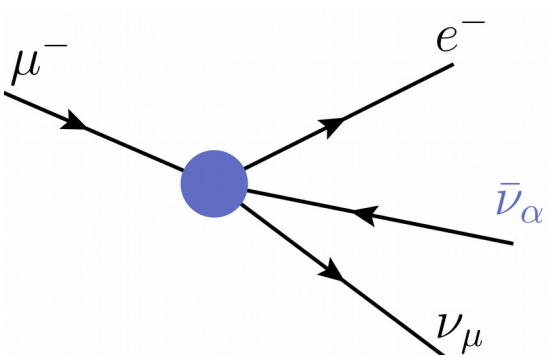


$$G_x \sim \frac{g^2}{\Lambda^2}$$

Non-Standard Interactions

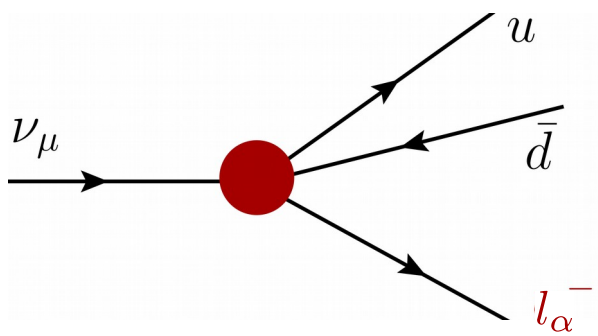
$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\,\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\,\delta\mathcal{L}^{d=6} + \ldots$$

NSI affecting
production



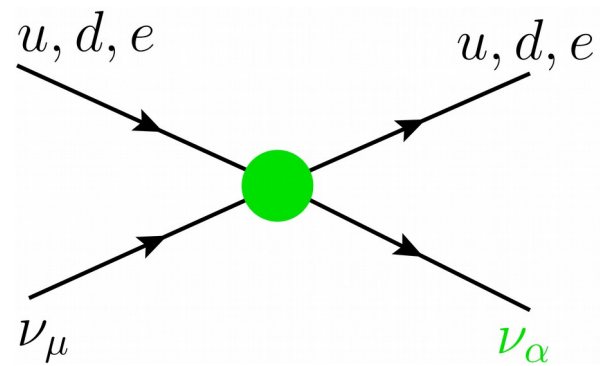
$$\varepsilon^{e\mu,P}_{\mu\alpha}\,(\overline{e}\gamma^\rho P\mu)\,(\overline{\nu}_\mu\gamma_\rho P_L\nu_\alpha)$$

NSI affecting
detection



$$\varepsilon^{ud,P}_{\mu\alpha}\,(\overline{d}\gamma^\rho Pu)\,(\overline{\nu}_\mu\gamma_\rho P_L l_\alpha)$$

NSI affecting
propagation



$$\varepsilon^{f,P}_{\mu\alpha}\,(\overline{f}\gamma^\rho Pf)\,(\overline{\nu}_\mu\gamma_\rho P_L\nu_\alpha)$$

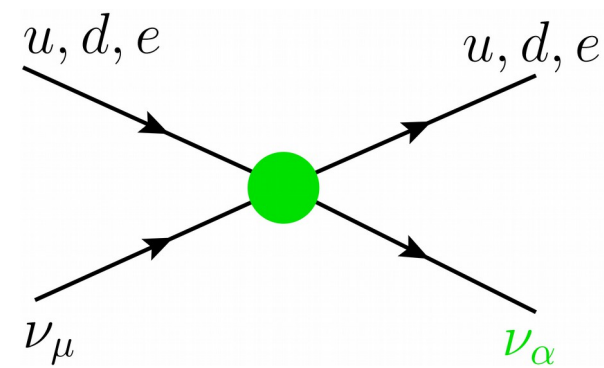
$$\varepsilon \sim \mathcal{O}(G_x/G_F)$$

Non-Standard Interactions

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\,\delta\mathcal{L}^{d=5} + \frac{1}{\Lambda^2}\,\delta\mathcal{L}^{d=6} + \ldots$$

THIS TALK

NSI affecting propagation



$$\varepsilon^{f,P}_{\mu\alpha}\left(\overline{f}\gamma^\rho P f\right)\left(\overline{\nu}_\mu\gamma_\rho P_L \nu_\alpha\right)$$

$$\varepsilon \sim \mathcal{O}(G_x/G_F)$$

NSI in propagation

NSI in propagation will lead to a generalized matter potential affecting neutrino oscillations:

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left[U\mathcal{H}_0 U^\dagger + A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} \right] \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$$A = \sqrt{2} G_F N_e$$

Oscillations are only sensitive to vector NSI in the form:

$$\epsilon_{\alpha\beta} \equiv \sum_{f,P} \frac{n_f}{n_e} \varepsilon^{fP}_{\alpha\beta} \qquad \text{(f = u,d,e; P = L,R)}$$

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$$\downarrow$$

$$\begin{pmatrix} 1+(\epsilon_{ee}-\epsilon_{\mu\mu}) & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & 0 & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & (\epsilon_{\tau\tau}-\epsilon_{\mu\mu}) \end{pmatrix}$$

Models for NSI

Model-independent bounds are rather weak for some parameters. However,

- It is expected that any model giving NSI would produce small effects at low energies, since they are (at least) quadratically suppressed

- Gauge invariance $\rightarrow$ typically imposes strong bounds coming from charged lepton processes (at least, $<10^{-2}$)

Antusch, Baumann, Fernandez-Martinez, 0807.1003 [hep-ph]
Gavela, Hernandez, Ota, Winter, 0809.3451 [hep-ph]

- Possible way out? New Physics way below the electroweak scale

(see e.g., Farzan 1505.06906,
Farzan and Shoemaker, 1512.09147,
Farzan and Heeck, 1607.07616)

Scattering constraints on NSI

Current bounds on neutral-current NSI with quarks:

- CHARM (nue) Phys. Lett. B180 no.3 (1986) 303
- CHARM (numu) Z.Phys.C36 (1987) 611
- NuTeV (numu) hep-ex/0110059 (see also Sam Zeller's thesis)
- CDHS (numu) Z.Phys.C45 (1990) 361
- CCFR (numu) Z. Phys. C45 (1990) 539

$\rightarrow$ No direct constraints on NSI-NC with tau neutrinos...

Davidson, Peña-Garay, Rius, Santamaria, hep-ph/0302093
Biggio, Blennow, Fernandez-Martinez, 0907.0097

Current bounds: scattering

Bounds on NC-NSI from scattering data (only one parameter at a time):

$$|\varepsilon^u_{\alpha\beta}| < \begin{pmatrix} \begin{matrix}1.0\\0.7\end{matrix} & 0.05 & 0.5 \\ 0.05 & \begin{matrix}0.003\\0.008\end{matrix} & 0.05 \\ 0.5 & 0.05 & \begin{matrix}1.4\\3\end{matrix} \end{pmatrix} \qquad |\varepsilon^d_{\alpha\beta}| < \begin{pmatrix} \begin{matrix}0.3\\0.6\end{matrix} & 0.05 & 0.5 \\ 0.05 & \begin{matrix}0.003\\0.015\end{matrix} & 0.05 \\ 0.5 & 0.05 & \begin{matrix}1.1\\6\end{matrix} \end{pmatrix}$$

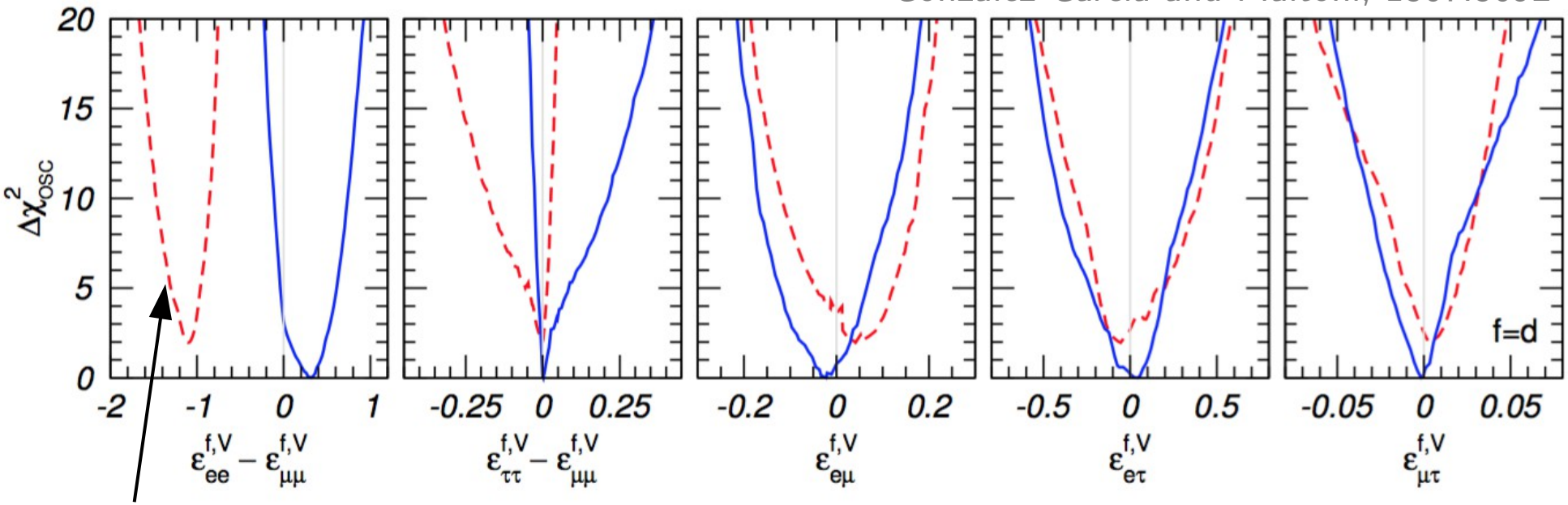
Davidson, Peña-Garay, Rius, Santamaria, hep-ph/0506143
Biggio, Blennow, Fernandez-Martinez, 0907.0097

$$\epsilon^{\oplus}_{\alpha\beta} \sim 3\,\varepsilon^u_{\alpha\beta} + 3\,\varepsilon^d_{\alpha\beta} + \varepsilon^e_{\alpha\beta}$$
$$\epsilon^{\odot}_{\alpha\beta} \sim 2\,\varepsilon^u_{\alpha\beta} + \varepsilon^d_{\alpha\beta} + \varepsilon^e_{\alpha\beta}$$

Current bounds: oscillations

Results from a global analysis of neutrino oscillation data (all parameters simultaneously, either for f=u or f=d):

Gonzalez-Garcia and Maltoni, 1307.3092



LMA-Dark solution

Miranda, Tortola, Valle, hep-ph/0406280

$$\epsilon^{\oplus}_{\alpha\beta} \sim 3\,\varepsilon^{u}_{\alpha\beta} + 3\,\varepsilon^{d}_{\alpha\beta} + \varepsilon^{e}_{\alpha\beta}$$

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The LMA-dark solution
and
the neutrino mass ordering

The LMA-dark solution

For solar neutrinos in the adiabatic regime:

$$P_{ee} = \frac{1}{2}\left[1 + \cos 2\theta \cos 2\theta_m\right]$$ Parke, 1986

Effective mixing angle at neutrino production point inside the Sun:

$$\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F N_e}{\Delta m_m^2}$$

The LMA-dark solution

For solar neutrinos in the adiabatic regime:

$$P_{ee} = \frac{1}{2}\left[1 + \cos 2\theta \cos 2\theta_m\right]$$ Parke, 1986

Effective mixing angle at neutrino production point inside the Sun, in presence of NSI:

$$\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F (N_e - \epsilon' N_d)}{\Delta m_m^2(\epsilon)}$$

Bottom line: One can obtain P $<$ 0.5 even for cos2θ $<$ 0, as long as ε' is large enough $\rightarrow$ solar mixing angle in the upper octant!

Miranda, Tortola, Valle, hep-ph/0406280

The LMA-dark solution

For KamLAND, in the two-family approximation:

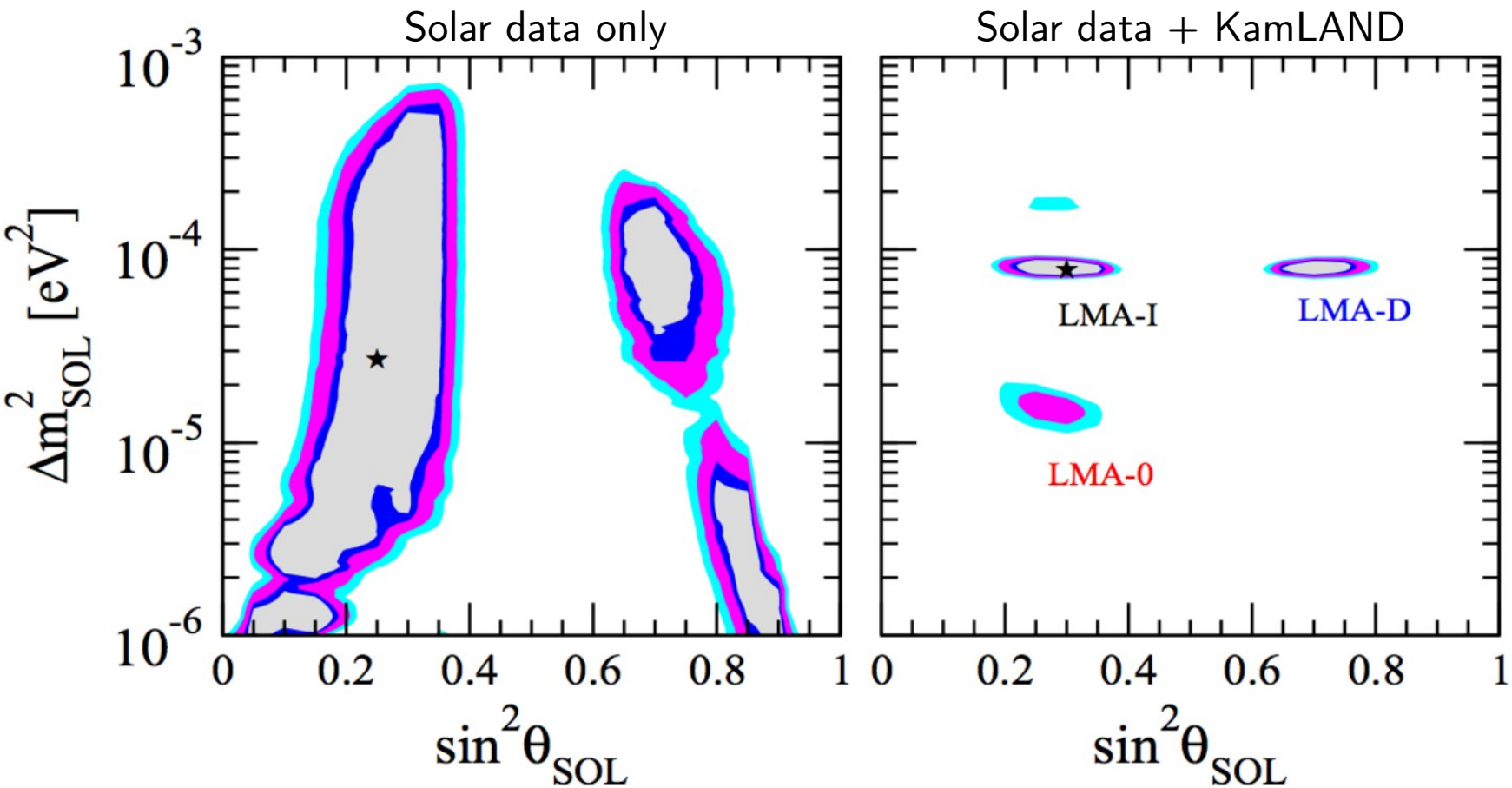
$$P_{ee} \simeq 1 - \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{21} L}{4E} \right)$$

KamLAND results invariant under

$$\theta_{12} \leftrightarrow \pi/2 - \theta_{12}$$

Miranda, Tortola, Valle, hep-ph/0406280

The LMA-dark solution



Miranda, Tortola, Valle, hep-ph/0406280

Generalized mass ordering degeneracy

Using $U = O_{23} O_{13} V_{12}$

The vacuum Hamiltonian can be rewritten as:

$$H_{\rm vac} = O_{23} O_{13} \begin{pmatrix} H^{(2)} & 0 \\ 0 & \Delta_{31} - \frac{\Delta_{21}}{2} \end{pmatrix} O_{13}^T O_{23}^T$$

$$H^{(2)} = \frac{\Delta_{21}}{2} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} e^{i\delta} \\ \sin 2\theta_{12} e^{-i\delta} & \cos 2\theta_{12} \end{pmatrix}$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E}$$

Generalized mass ordering degeneracy

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Invariant under:

$$\boxed{\begin{array}{l} \Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21} \\ \sin\theta_{12} \leftrightarrow \cos\theta_{12} \\ \delta \to \pi - \delta \end{array}}$$

$$H \to -H^*$$

(see e.g., Gonzalez-Garcia, Maltoni, Salvado, 1103.4365)

Minakata, Nunokawa, hep-ph/0108085
Bakhti and Farzan, 1403.0744

Generalized mass ordering degeneracy

In the SM, the matter potential can break the sign degeneracy:

$$H = H_0 + H_{\rm mat}$$

However, in presence of NSI:

$$H_{\rm mat} = \sqrt{2} G_F N_e(x) \begin{pmatrix} 1 + (\epsilon_{ee} - \epsilon_{\mu\mu}) & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & 0 & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & (\epsilon_{\tau\tau} - \epsilon_{\mu\mu}) \end{pmatrix}$$

$$\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21}$$
$$\sin\theta_{12} \leftrightarrow \cos\theta_{12}$$
$$\delta \to \pi - \delta$$

$$\epsilon_{ee} - \epsilon_{\mu\mu} \to -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2$$
$$\epsilon_{\tau\tau} - \epsilon_{\mu\mu} \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu})$$
$$\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha \neq \beta)$$

$$H \to -H^*$$

The LMA-dark solution reappears here

PC and Schwetz, 1604.05772
Bakhti and Farzan, 1403.0744

Combination of experiments

The effective NSI depend on the density of fermions:

$$\epsilon_{\alpha\beta} \equiv \sum_{f=u,d,e} Y_f(x)\varepsilon^{fV}_{\alpha\beta} \qquad Y_f \equiv N_f/N_e$$

$Y_u(x) = 2 + Y_n(x)$	$Y_n^{\oplus} \sim 1.05$
$Y_d(x) = 1 + 2Y_n(x)$	$Y_n^{\odot} \sim 1/2 \to 1/6$

This means that the degeneracy cannot be fulfilled simultaneously in Earth and Sun

PC and Schwetz, 1604.05772
(see also Escrihuela et al, 0907.2630)

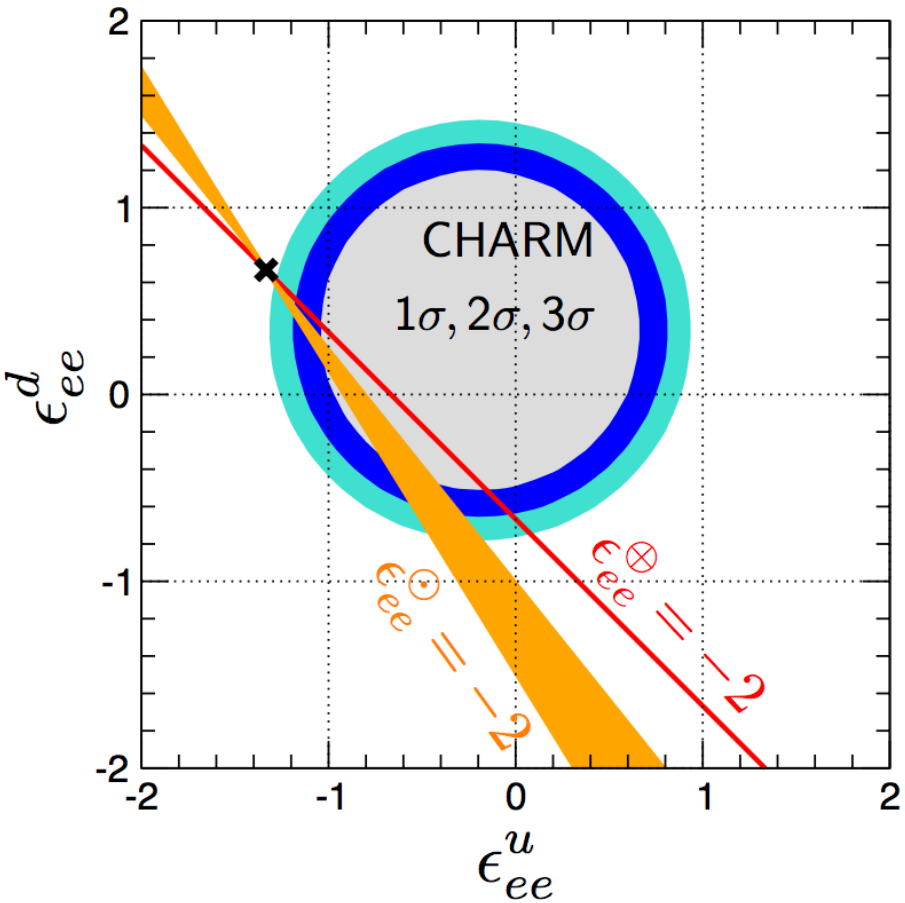
Combination of experiments

The effective NSI depend on the density of fermions:

$$\epsilon_{\alpha\beta} \equiv \sum_{f=u,d,e} Y_f(x)\varepsilon^{fV}_{\alpha\beta} \qquad Y_f \equiv N_f/N_e$$

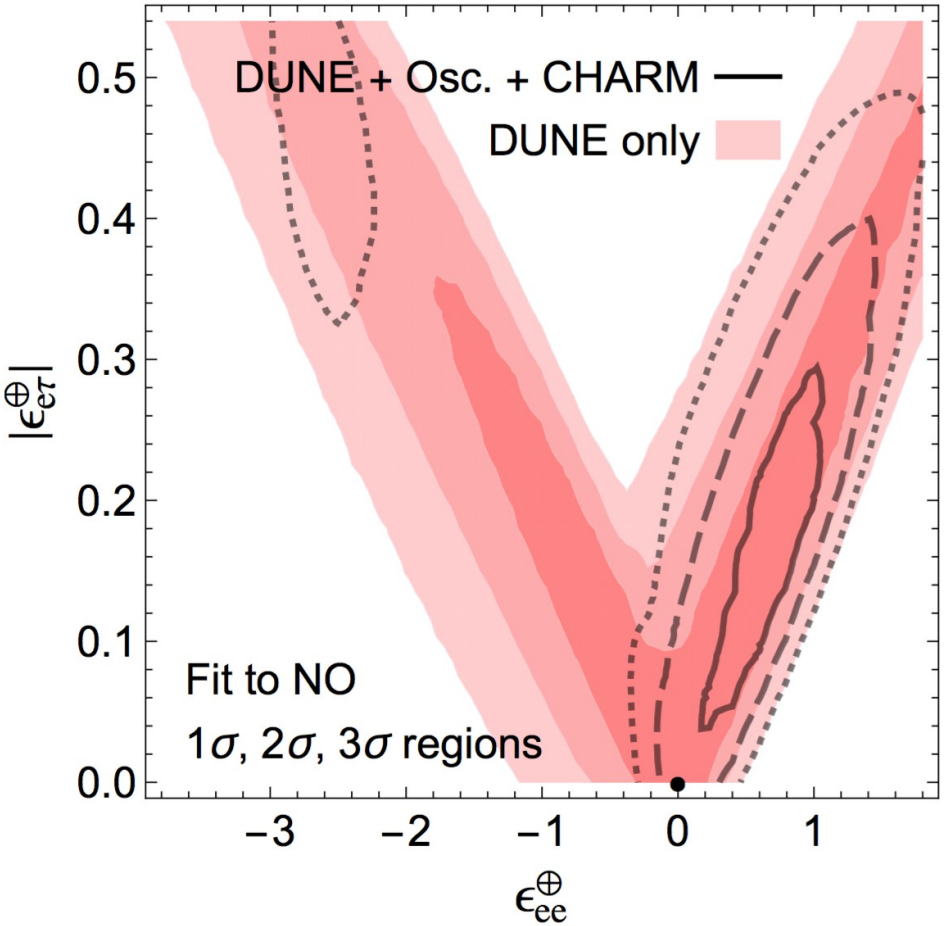
Scattering experiments are sensitive to the couplings <u>in the Lagrangian.</u>
For example, for only diagonal vector couplings in nue scattering on nuclei:

$$\sum_q \left(g^q_L + \frac{\varepsilon^{q,V}_{ee}}{2}\right)^2 + \left(g^q_R + \frac{\varepsilon^{q,V}_{ee}}{2}\right)^2$$



PC and Schwetz, 1604.05772
(see also Escrihuela et al, 0907.2630)

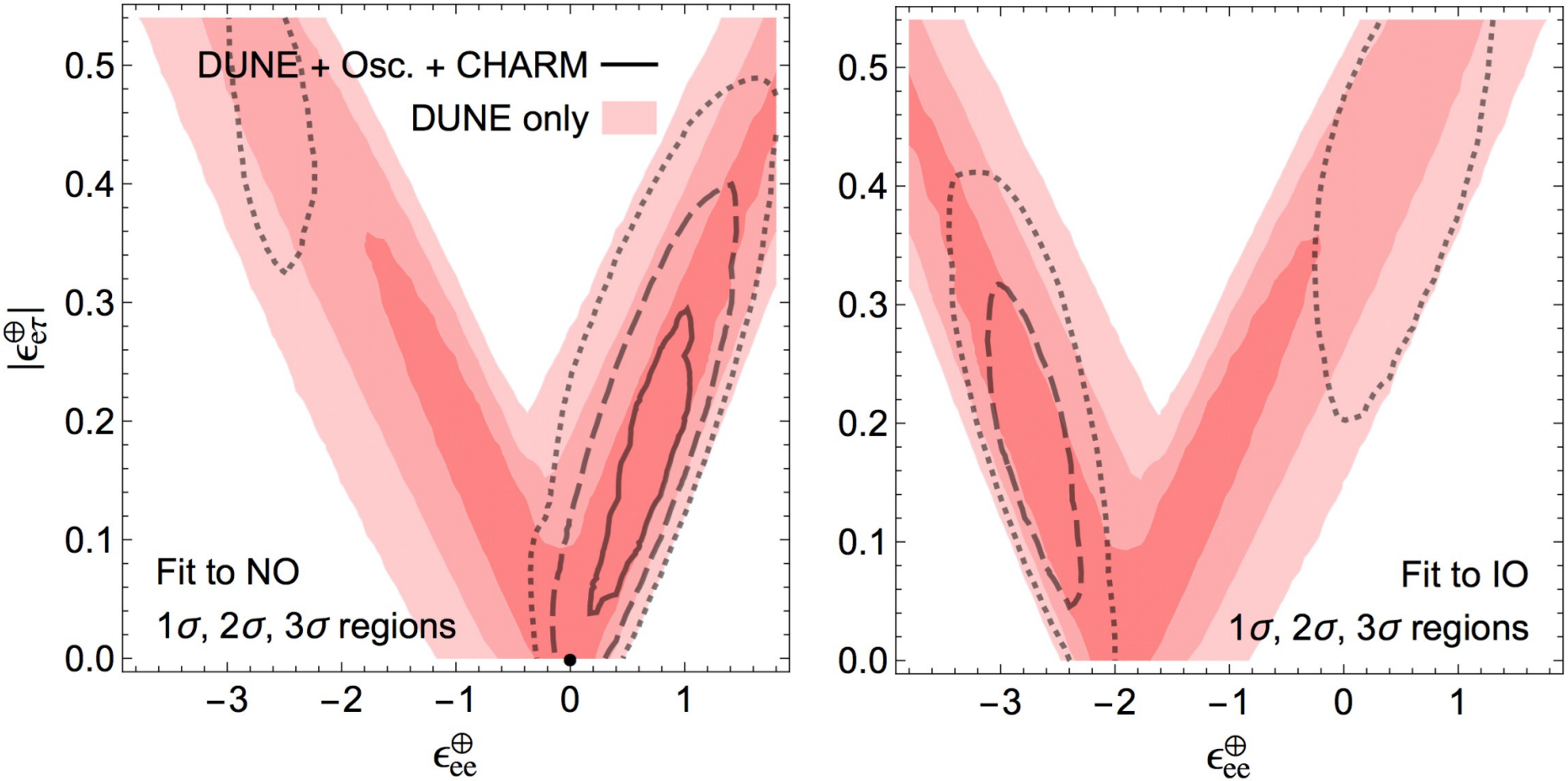
Combination of experiments



Solar prior from Gonzalez-Garcia and Maltoni, 1307.3092,
CHARM prior taken from Phys. Lett. B180, 303 (1986)

PC and Schwetz, 1604.05772

Combination of experiments



Solar prior from Gonzalez-Garcia and Maltoni, 1307.3092,
CHARM prior taken from Phys. Lett. B180, 303 (1986)

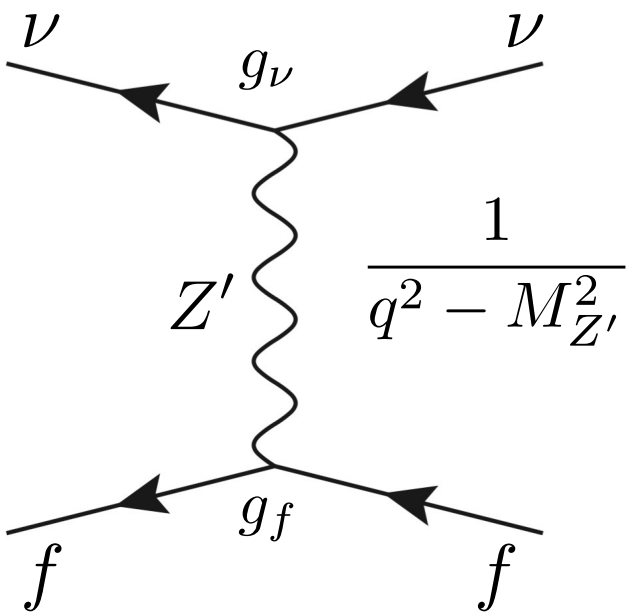
PC and Schwetz, 1604.05772

NSI

vs

oscillations + scattering

Models for NSI: heavy vs light mediators



$q^2 \sim 0$ → $\sigma \propto \epsilon \sim \frac{g_f g_\nu}{M_{Z'}^2}$

$q^2 \gg M_{Z'}^2$ → $\sigma \propto \frac{g_f g_\nu}{q^2} \sim \epsilon \frac{M_{Z'}^2}{q^2}$

→ In the rest of the talk, I will distinguish between "heavy" mediators (above 1 GeV) and "light" mediators (between 50 MeV and 1 GeV)

CHARM

The CHARM experiment was a proton fixed target experiment which used 400 GeV protons from the CERN SPS:

$$R_e = \frac{\sigma(\nu_e N \to \nu_e X) + \sigma(\bar{\nu}_e N \to \bar{\nu}_e X)}{\sigma(\nu_e N \to e X) + \sigma(\bar{\nu}_e N \to \bar{e} X)} = (\tilde{g}_e^L)^2 + (\tilde{g}_e^R)^2 = 0.406 \pm 0.140$$

CHARM coll., Phys. Lett. B180, 303 (1986)

$$(\tilde{g}_e^P)^2 = \sum_{q=u,d} \left[(g_q^P + \epsilon_{ee}^{q,P})^2 + \sum_{\alpha \neq e} |\epsilon_{e\alpha}^{q,P}|^2 \right]$$

SM couplings of the Z boson to quarks

NuTeV

The NuTeV experiment used 800 GeV protons. They reported measurements of numu – N and numubar – N in the deep-inelastic regime as well:

$$\underbrace{\begin{aligned} R_\mu^\nu &= \frac{\sigma_{\rm NC}(\nu_\mu)}{\sigma_{\rm CC}(\nu_\mu)} = (\tilde{g}_\mu^L)^2 + r(\tilde{g}_\mu^R)^2 \\ R_\mu^{\bar{\nu}} &= \frac{\sigma_{\rm NC}(\bar{\nu}_\mu)}{\sigma_{\rm CC}(\bar{\nu}_\mu)} = (\tilde{g}_\mu^L)^2 + \frac{1}{r}(\tilde{g}_\mu^R)^2 \end{aligned}} \qquad r = \frac{\sigma_{\rm CC}(\bar{\nu}_\mu)}{\sigma_{\rm CC}(\nu_\mu)}$$

$$(g^L_{\rm eff,exp})^2 = 0.30005 \pm 0.00137\,, \quad (g^R_{\rm eff,exp})^2 = 0.03076 \pm 0.00110$$

$\rightarrow$ These results show a significant tension (99%) with the SM values:

$$(g^L_{\rm eff,SM})^2 = 0.3042, \quad (g^R_{\rm eff,SM})^2 = 0.0301$$

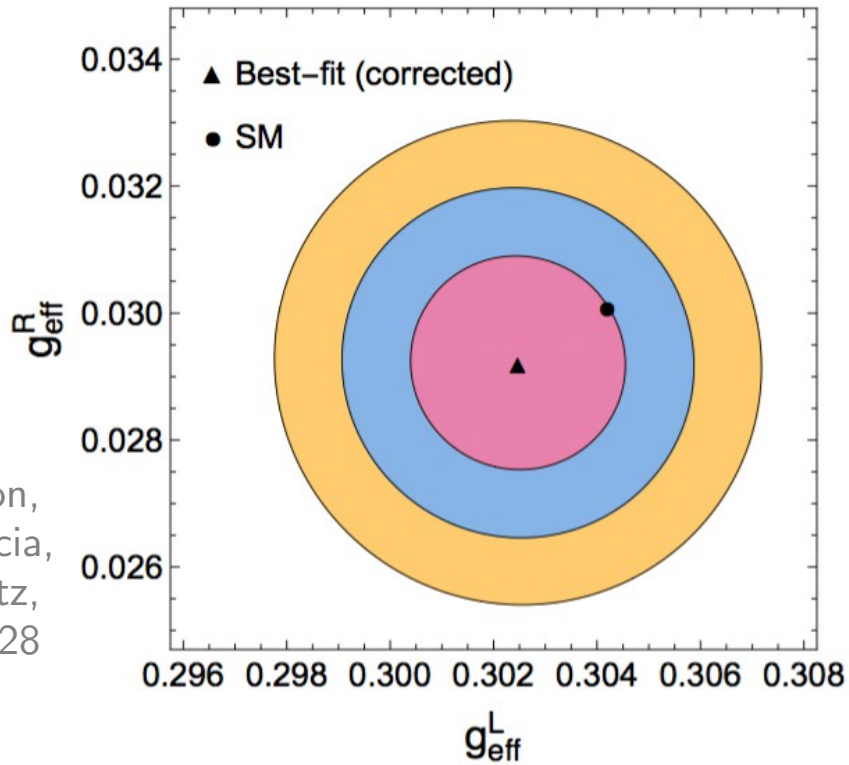
NuTeV coll., hep-ex/0110059
Zeller, FERMILAB-THESIS-2002-34

Corrections to the NuTeV anomaly

In 2009, Bentz et al pointed out the need to include several corrections to the NuTeV result (nuclear effects, Fe not isoscalar, PDF of the strange quark)

Bentz, Cloet, Londergan and Thomas, 0908.3198

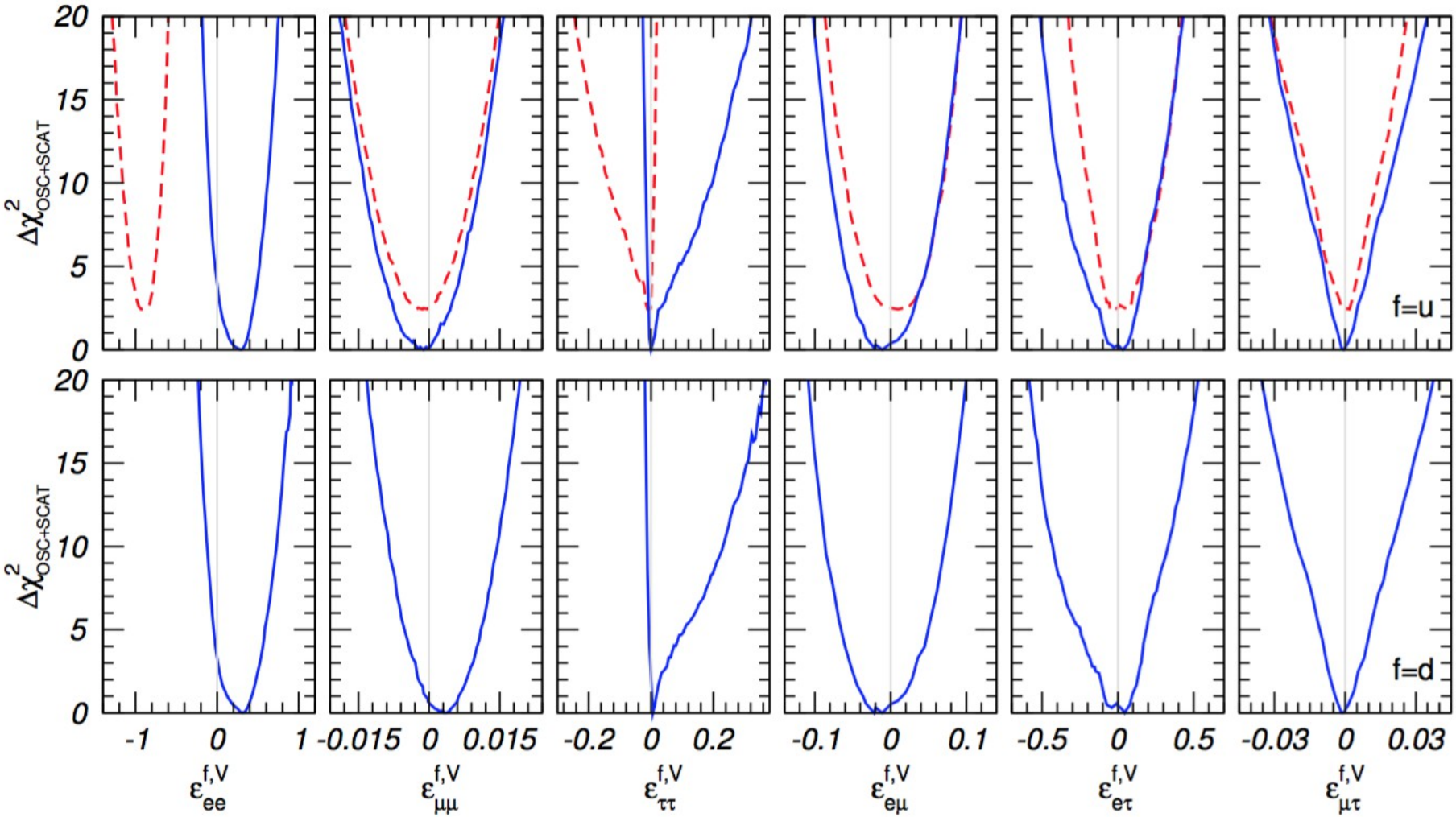
NuTeV after Bentz corrections:



PC, Denton, Gonzalez-Garcia, Maltoni, Schwetz, 1701.04828

Current combination: heavy regime

Oscillations + NuTeV (Bentz-et-al-corrected) + CHARM:



PC, Denton, Gonzalez-Garcia, Maltoni, Schwetz, 1701.04828
(see also Miranda, Tortola, Valle, hep-ph/0406280)

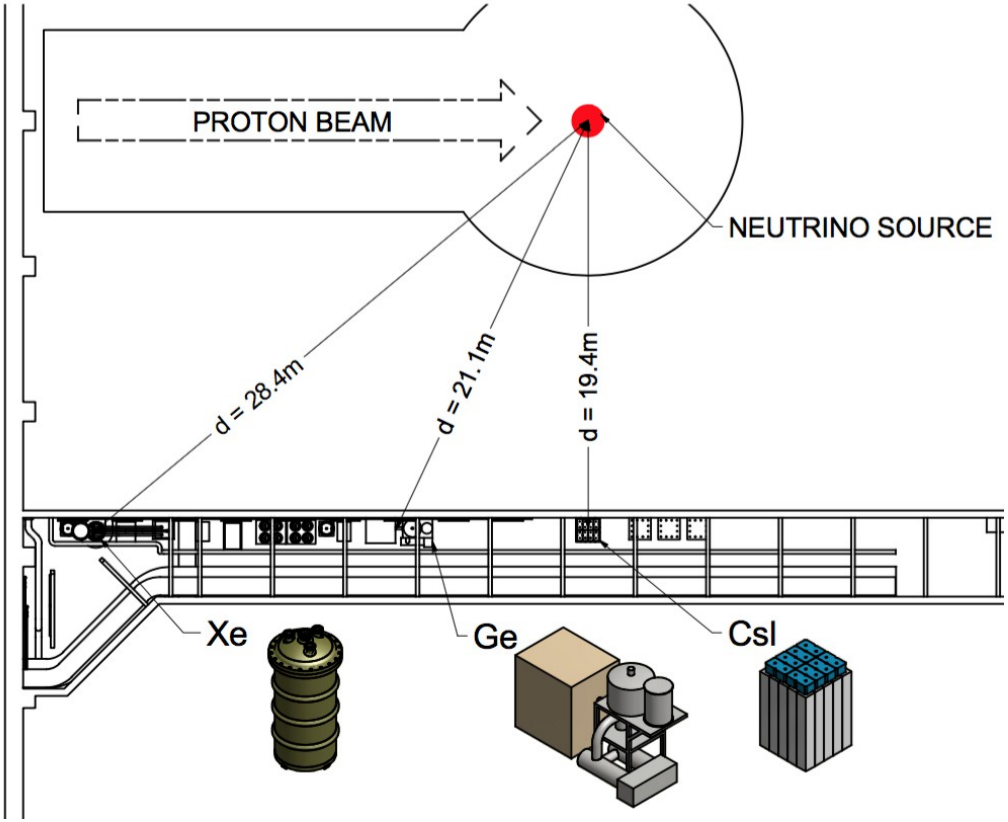
Future experiments?

Future proposals for coherent neutrino-nucleus scattering experiments:

- COHERENT COHERENT coll., 1509.08702 and Scholberg, hep-ex/0511042
- TEXONO see e.g., 0803.0033
- CONNIE see e.g., 1608.01565
- MINER MINER coll., 1609.02066 and Dent et al, 1612.06350

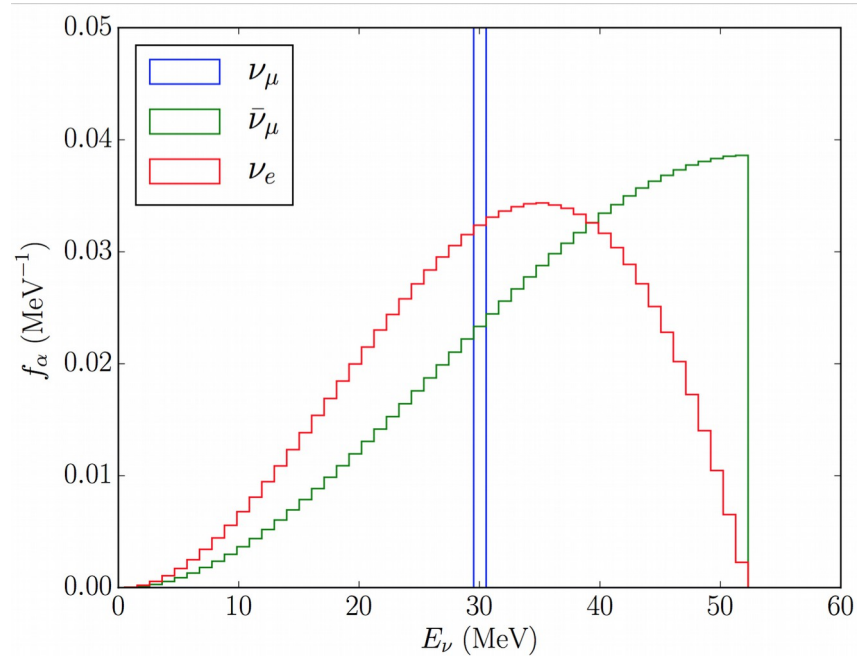
(See also Anderson et al, 1103.4894, Horowitz et al, astro-ph/0302071 and Lindner, Rodejohann and Xu, 1612.04150)

COHERENT



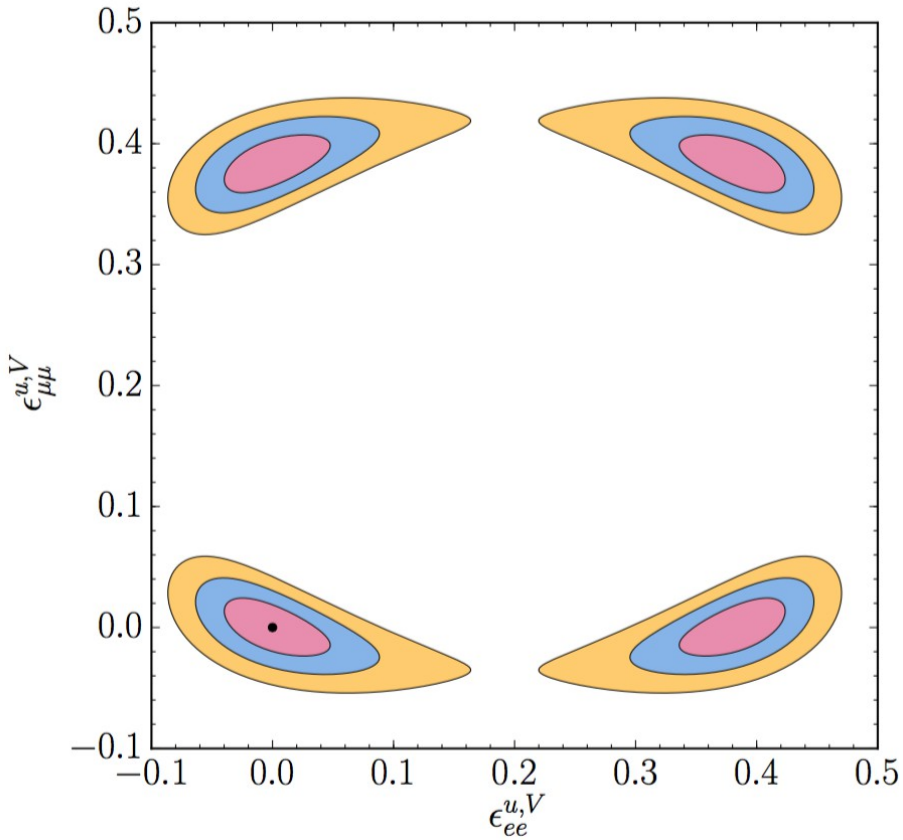
COHERENT coll., 1509.08702

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



$$\frac{d\sigma_\alpha}{dE_r} = \frac{G_F^2}{2\pi} \frac{Q_{w\alpha}^2}{4} F^2(2ME_r) M \left(2 - \frac{ME_r}{E_\nu^2}\right)$$

COHERENT



Results for Ge detector 10kg yr, 5 keV threshold

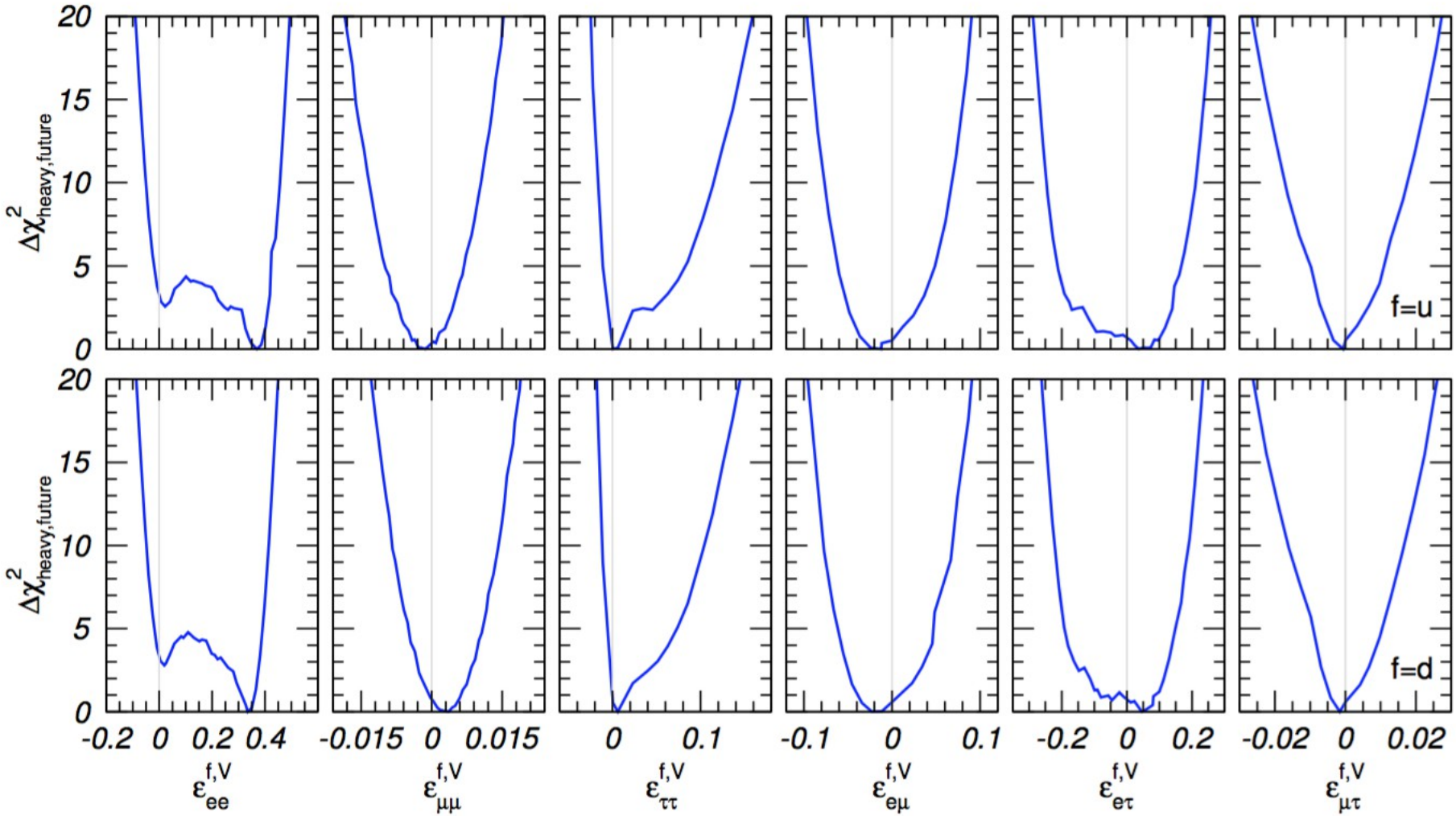
PC, Denton, Gonzalez-Garcia, Maltoni, Schwetz, 1701.04828

$$\frac{1}{4}Q_{w\alpha}^2 = \left[Z(g_p^V + 2\epsilon_{\alpha\alpha}^{u,V} + \epsilon_{\alpha\alpha}^{d,V}) + N(g_n^V + \epsilon_{\alpha\alpha}^{u,V} + 2\epsilon_{\alpha\alpha}^{d,V})\right]^2 +$$

$$+ \sum_{\beta\neq\alpha} \left[Z(2\epsilon_{\alpha\beta}^{u,V} + \epsilon_{\alpha\beta}^{d,V}) + N(\epsilon_{\alpha\beta}^{u,V} + 2\epsilon_{\alpha\beta}^{d,V})\right]^2$$

Future constraints: heavy regime

Oscillations+NuTeV+CHARM + COHERENT (generated using SM as input):

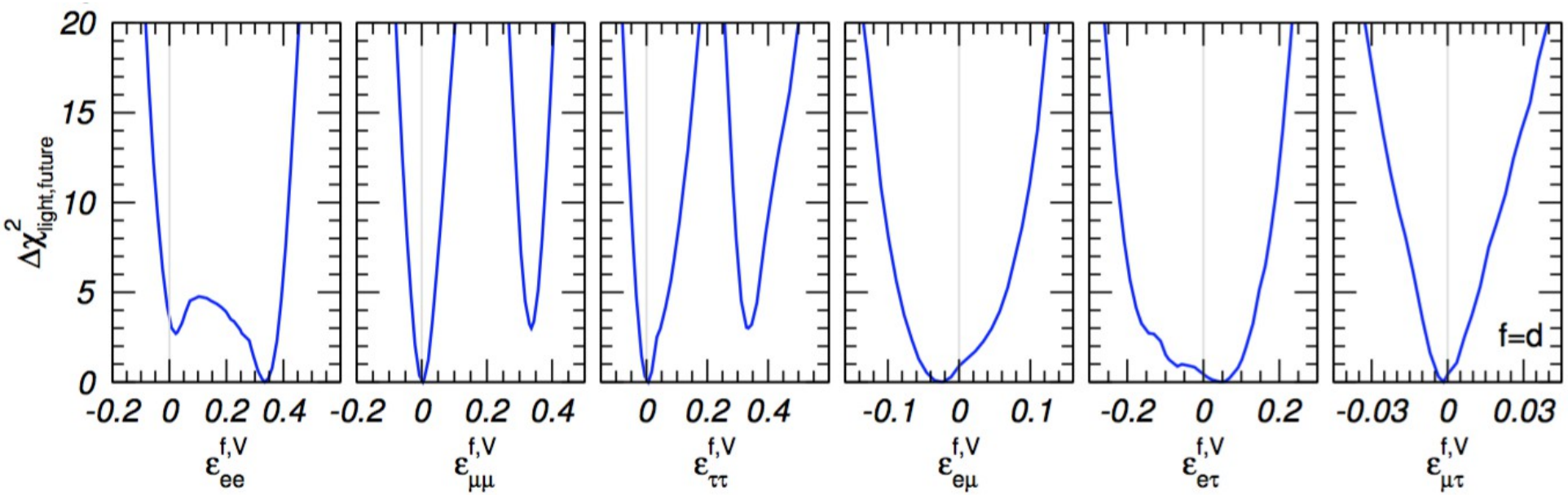


PC, Denton, Gonzalez-Garcia, Maltoni, Schwetz, 1701.04828

NSI from light mediators

For NSI models with mediators below ~ 1 GeV, NuTeV and CHARM constraints fade away. Only oscillations+COHERENT would apply in this case.

Oscillations (current data) + COHERENT (generated using SM as input):

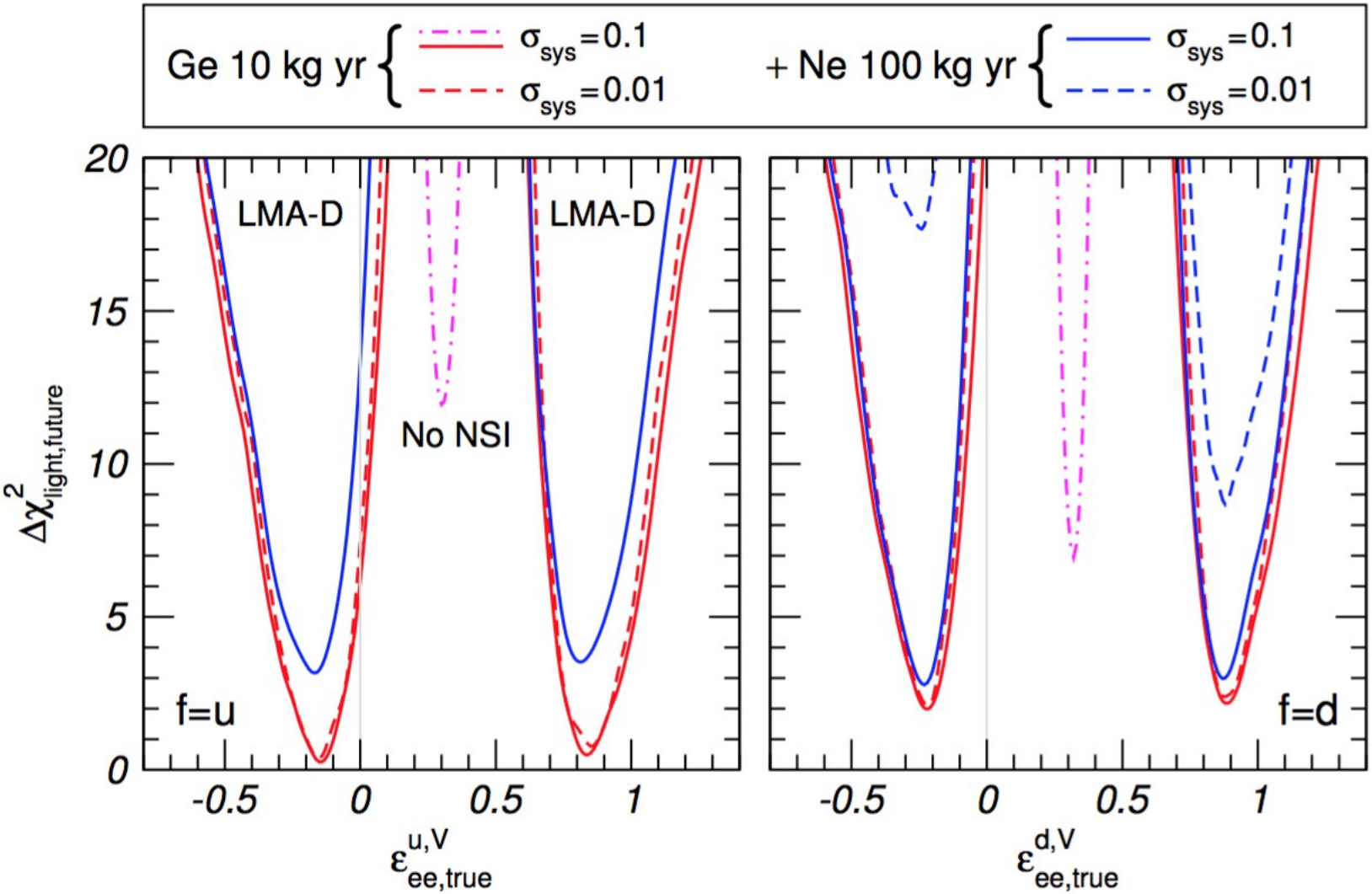


$\rightarrow$ VERY similar results obtained for f=u

PC, Denton, Gonzalez-Garcia, Maltoni, Schwetz, 1701.04828

What happens if we relax the SM assumption when simulating COHERENT data?

Degeneracies for COHERENT



PC, Denton, Gonzalez-Garcia, Maltoni, Schwetz, 1701.04828

Summary and conclusions

Non-Standard neutrino Interactions are expected in extensions Beyond the Standard Model.

- Models with light mediators can give rise to large NSI
- Dangerous degeneracies can take place in presence of NSI
- Further combination between scattering and oscillation data will be needed to rule out the LMA-dark solution
  - For models with heavy mediators and NSI with f=d, NuTeV+CHARM+oscillations are enough
  - For f =u, or for models with light mediators, coherent neutrino nucleus scattering experiments will be needed
  - In scenarios with nonzero NSI parameters, a combination of different targets at COHERENT may be needed to reject the LMA-dark solution.

Thank you!!