New physics searches in oscillations

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Fermilab

BLV2017
Case Western Reserve University, Cleveland
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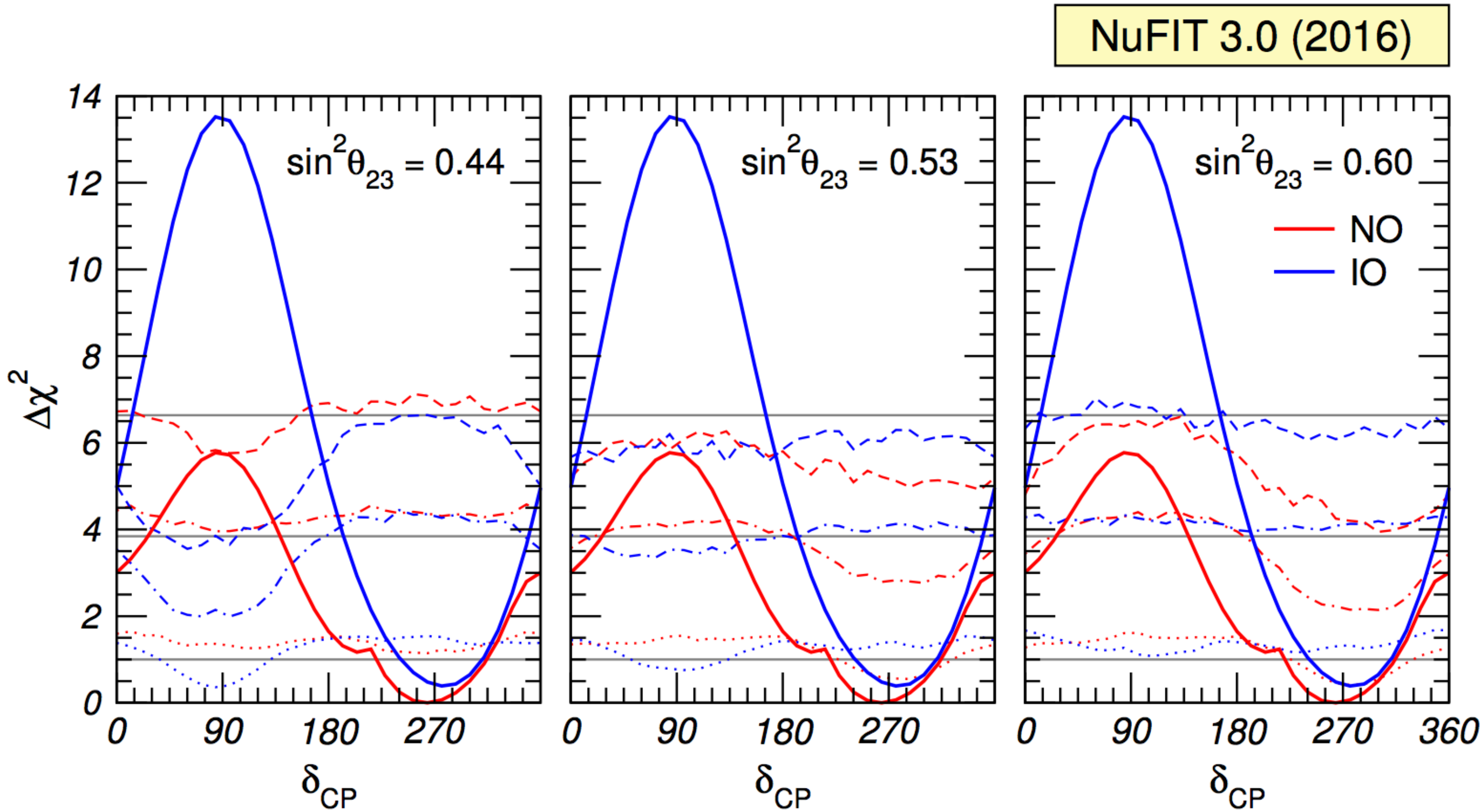
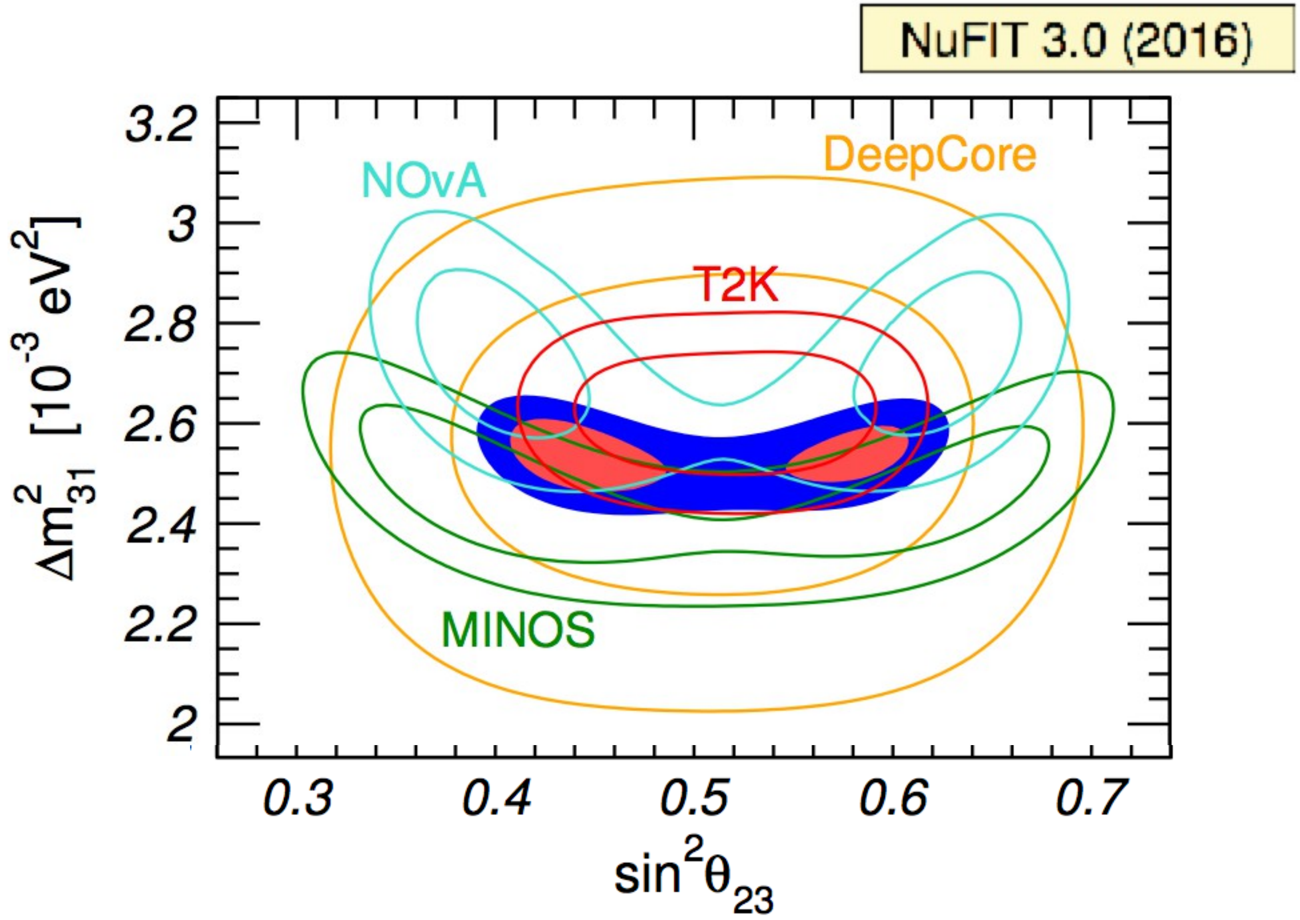
Hints for CP violation?



Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Schwetz, 1611.01514
(see also Capozzi, Lisi, Marrone, Montanino, Palazzo, 1601.07777)

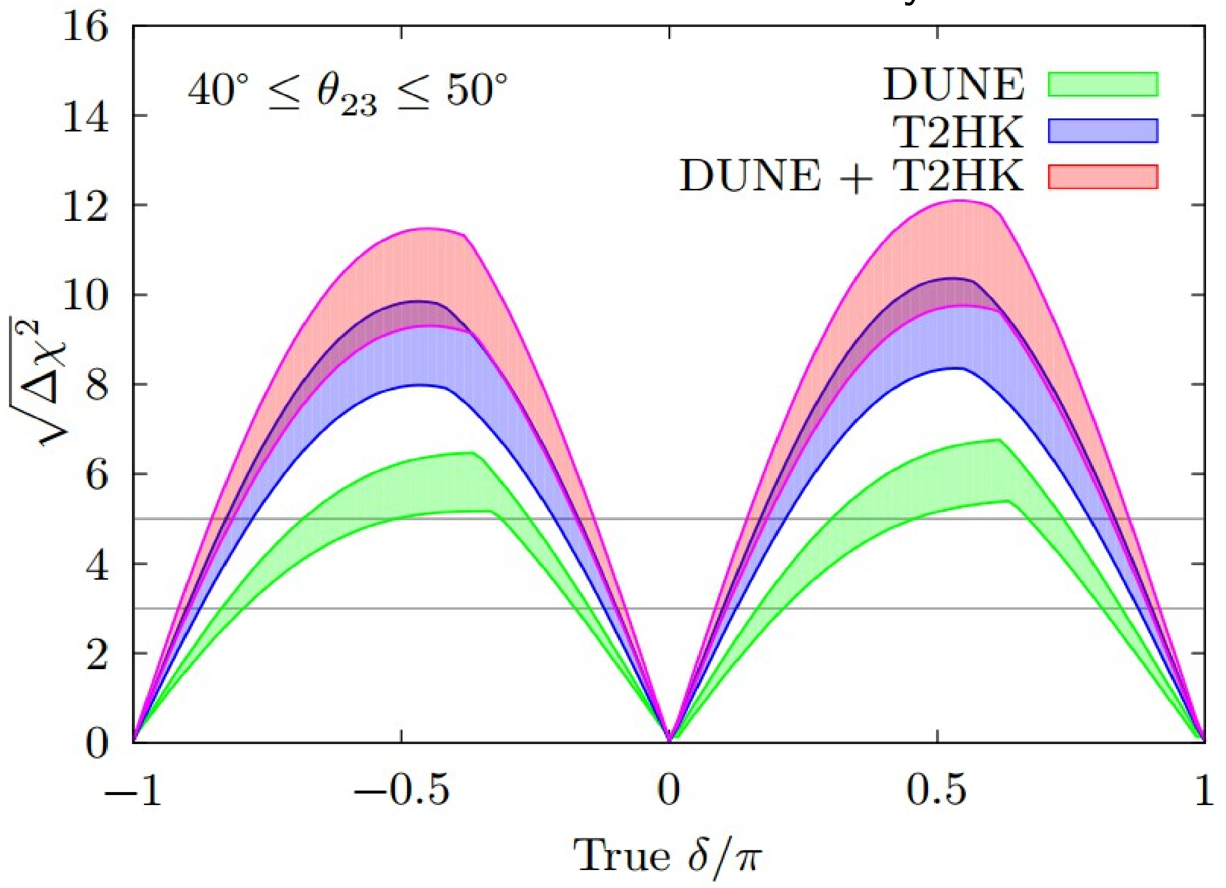
Atmospheric sector



Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Schwetz, 1611.01514
(see also Capozzi, Lisi, Marrone, Montanino, Palazzo, 1601.07777)

Future prospects

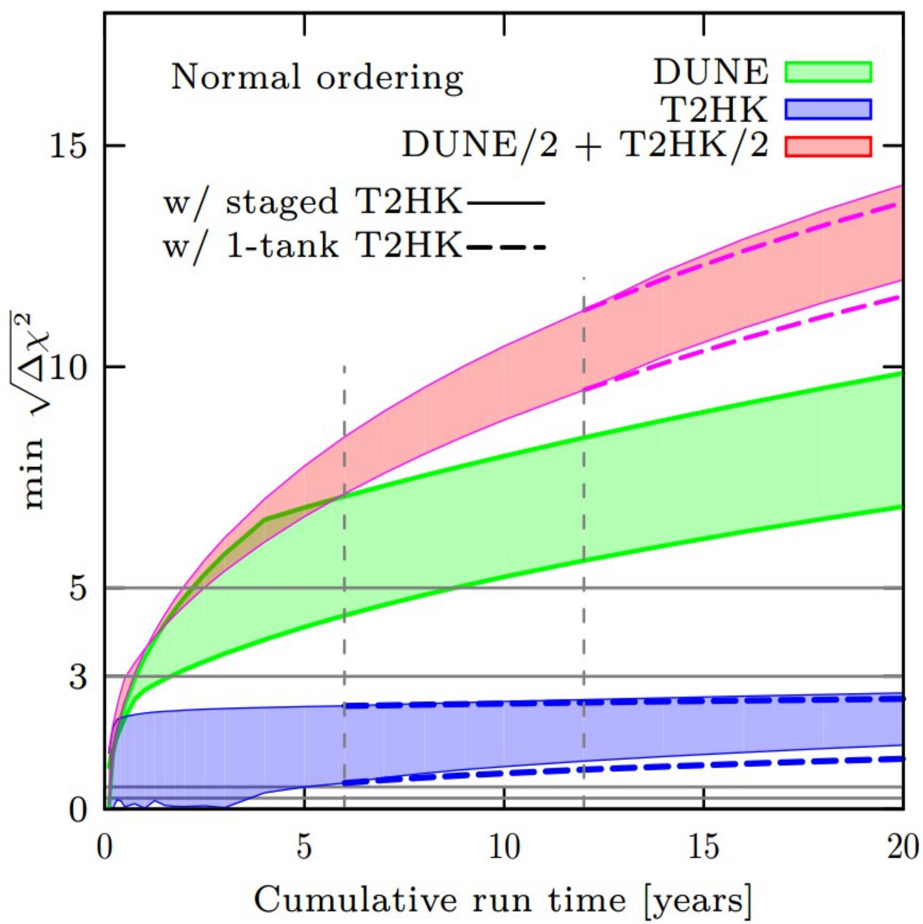
CP violation sensitivity



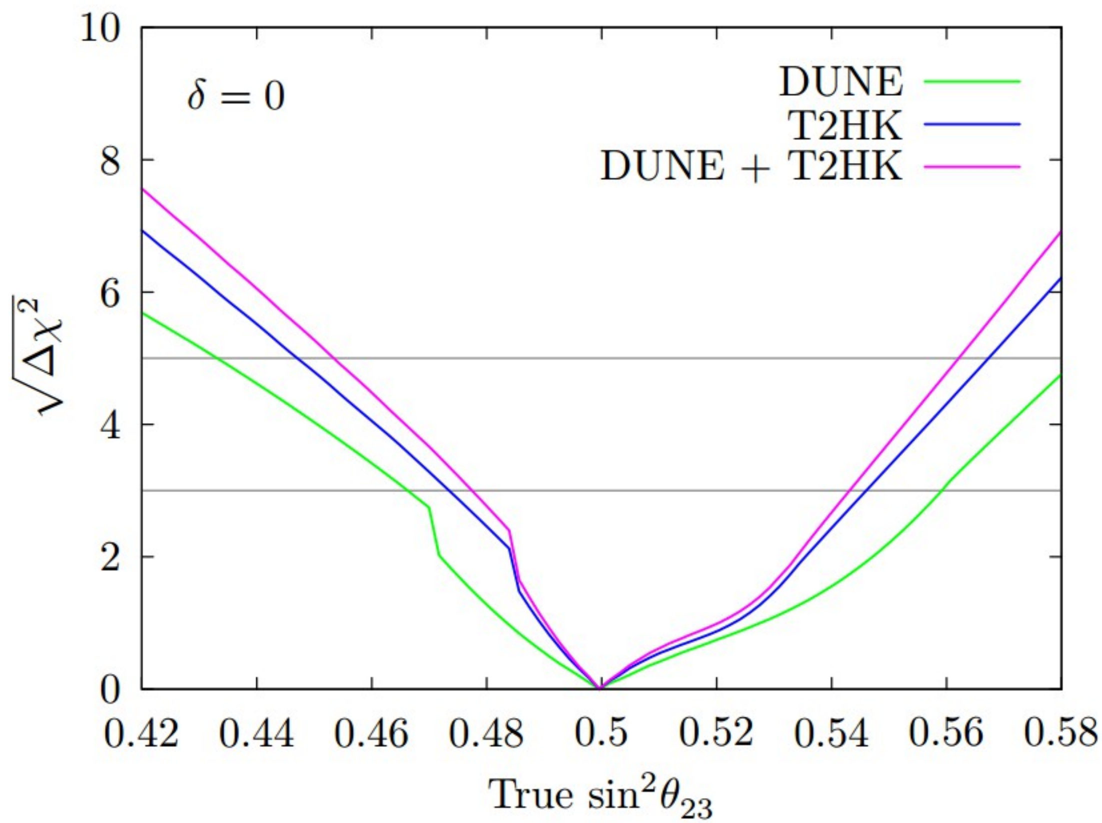
Ballett, King, Pascoli, Prouse, Wang, 1612.07275

Future prospects

Mass ordering sensitivity



Octant sensitivity



Ballett, King, Pascoli, Prouse, Wang, 1612.07275

Moving forward...

Neutrino masses

New particles are needed to generate neutrino masses. The simplest example is to add right-handed neutrinos:

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

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

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

2) A Majorana mass. For example:

$$Y_\nu \bar{L}_L \widetilde{\phi} \nu_R + \frac{1}{2} M_R \overline{\nu}^c_R \nu_R$$

$$\boxed{(\not{L})}$$

Non-Unitarity

$$\mathcal{M}_\nu = U^\dagger \begin{pmatrix} 0 & m_D \\ m_D^\dagger & M_R \end{pmatrix} U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

The full matrix is unitary,
but the 3x3 block is not:

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix} \qquad \mathcal{O}\left(\frac{m}{M}\right) \text{ naively}$$

Non-Unitarity

$$\mathcal{M}_\nu = U^\dagger \begin{pmatrix} 0 & m_D \\ m_D^\dagger & M_R \end{pmatrix} U = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

In principle, this scale can be either above or below EW scale.

The phenomenology will be very different, though!

Non-unitarity in oscillations

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

Heavy steriles
(not kinematically accessible)

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

Light steriles
(kinematically accessible)

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$
$$+ \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{-i\frac{\Delta m^2_{IJ} L}{2E}}$$
$$+ \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{-i\frac{\Delta m^2_{iJ} L}{2E}}$$

Non-unitarity in oscillations

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

Heavy steriles
(not kinematically accessible)

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

Light steriles
(kinematically accessible)

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

$$+ \sum_{I,J} \Theta_{\beta I} \Theta^*_{\alpha I} \Theta_{\alpha J} \Theta^*_{\beta J} e^{-i\frac{\Delta m^2_{IJ} L}{2E}}$$

If the new splitting is much
larger than the atmospheric one

$$\cancel{+ \sum_{i,J} N_{\beta i} N^*_{\alpha i} \Theta_{\alpha J} \Theta^*_{\beta J} e^{-i\frac{\Delta m^2_{iJ} L}{2E}}}$$

Non-unitarity in oscillations

$$U = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

Heavy steriles
(not kinematically accessible)

$$P_{\alpha\beta} = \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}}$$

Light steriles
(kinematically accessible)

$$P_{\alpha\beta} \simeq \sum_{i,j} N_{\beta i} N^*_{\alpha i} N_{\alpha j} N^*_{\beta j} e^{-i\frac{\Delta m^2_{ij} L}{2E}} + \mathcal{O}(\Theta^4)$$

$\rightarrow$ <u>Same observable effects in oscillations (at leading order)</u>

Blennow, PC, Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, 1609.08637
(see also Fong, Minakata, Nunokawa, 1609.08623)

Non-unitarity in oscillations

A convenient parametrization uses a lower triangular matrix:

$$N = (I - \alpha) U \qquad\qquad \alpha = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{e\mu} & \alpha_{\mu\mu} & 0 \\ \alpha_{e\tau} & \alpha_{\mu\tau} & \alpha_{\tau\tau} \end{pmatrix}$$

Xing, 0709.2220, and 1110.0083, Escrihuela et al, 1503.08879

The standard parametrization of eV-steriles with three new mixing angles is equivalent:

$$I - \alpha = U_{36} U_{26} U_{16} U_{35} U_{25} U_{15} U_{34} U_{24} U_{14}$$

$$\alpha \simeq \begin{pmatrix} \frac{1}{2}\left(s_{14}^2 + s_{15}^2 + s_{16}^2\right) & 0 & 0 \\ \hat{s}_{14}\hat{s}_{24}^* + \hat{s}_{15}\hat{s}_{25}^* + \hat{s}_{16}\hat{s}_{26}^* & \frac{1}{2}\left(s_{24}^2 + s_{25}^2 + s_{26}^2\right) & 0 \\ \hat{s}_{14}\hat{s}_{34}^* + \hat{s}_{15}\hat{s}_{35}^* + \hat{s}_{16}\hat{s}_{36}^* & \hat{s}_{24}\hat{s}_{34}^* + \hat{s}_{25}\hat{s}_{35}^* + \hat{s}_{26}\hat{s}_{36}^* & \frac{1}{2}\left(s_{34}^2 + s_{35}^2 + s_{36}^2\right) \end{pmatrix}$$

Non-unitarity in oscillations

Oscillation probabilities in disappearance experiments mostly unaffected:

$$\mathcal{P}_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31} + \mathcal{O}(\alpha^2)$$

Larger effects <u>could</u> be observed in the appearance channels:

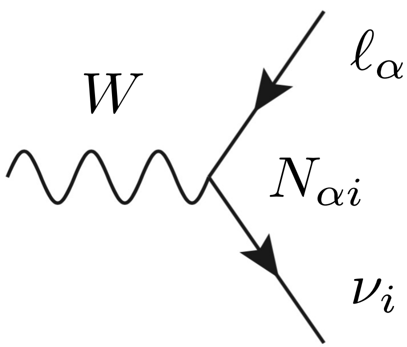
$$P_{\mu e} = P_{\mu e}^{3\times 3} + \alpha_{21} P_{\mu e}^{I} + \mathcal{O}(\alpha^2)$$

$$\left[P_{\mu e} = P_{\mu e}^{3\times 3} + s_{14}s_{24}(\ldots)\sin(\Delta \pm \delta \mp \delta_{NP}) + \mathcal{O}(s_{i4}^4)\right]$$

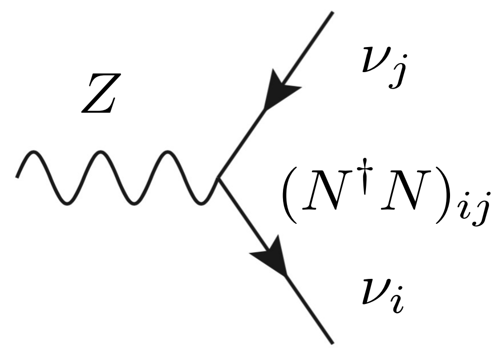
Escrihuela et al, 1503.08879
Blennow, PC, Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, 1609.08637
Fong, Minakata, Nunokawa, 1609.08623
Dutta, Gandhi, Kayser, Masud, Prakash, 1607.02152
Agarwalla, Chatterjee, Palazzo, 1605.04299

Current bounds

If the new states are above EW scale, weak processes get affected right away!



$$\Gamma = \Gamma_{SM} (N N^\dagger)_{\alpha\alpha}$$

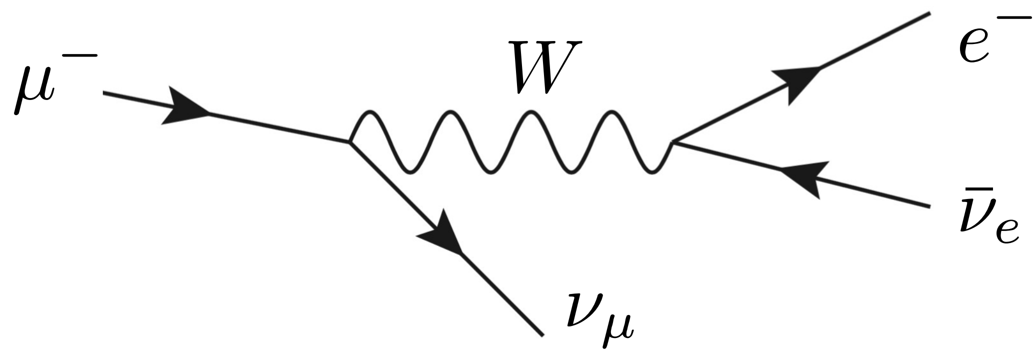


$$\Gamma = \Gamma_{SM} \sum_{ij} |(N^\dagger N)_{ij}|^2$$

Schechter and Valle, '80, Langacker and London '88, Gonzalez-Garcia and Valle '89, Branco, Rebelo, Valle '89, Bilenky and Giunti '93, Nardi, Roulet and Tommasini '94, Tommasini, Barenboim, Bernabeu and Jarlskog '95, ...

Current bounds

If the new states are above EW scale, weak processes get affected right away!



$$G_\mu = G_{SM}(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}$$

See e.g., Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, hep-ph/0607020
Fernandez-Martinez, Hernandez-Garcia and Lopez-Pavon, 1605.08774

Current bounds

	$(m > \mathrm{EW})$
α_{ee}	$1.3 \cdot 10^{-3}$
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$

EW observables

$\mu \to e\gamma$

Fernandez-Martinez, Hernandez-Garcia and Lopez-Pavon, 1605.08774
(see also Antusch and Fischer, 1407.6607)

(at 95% CL)

Current bounds

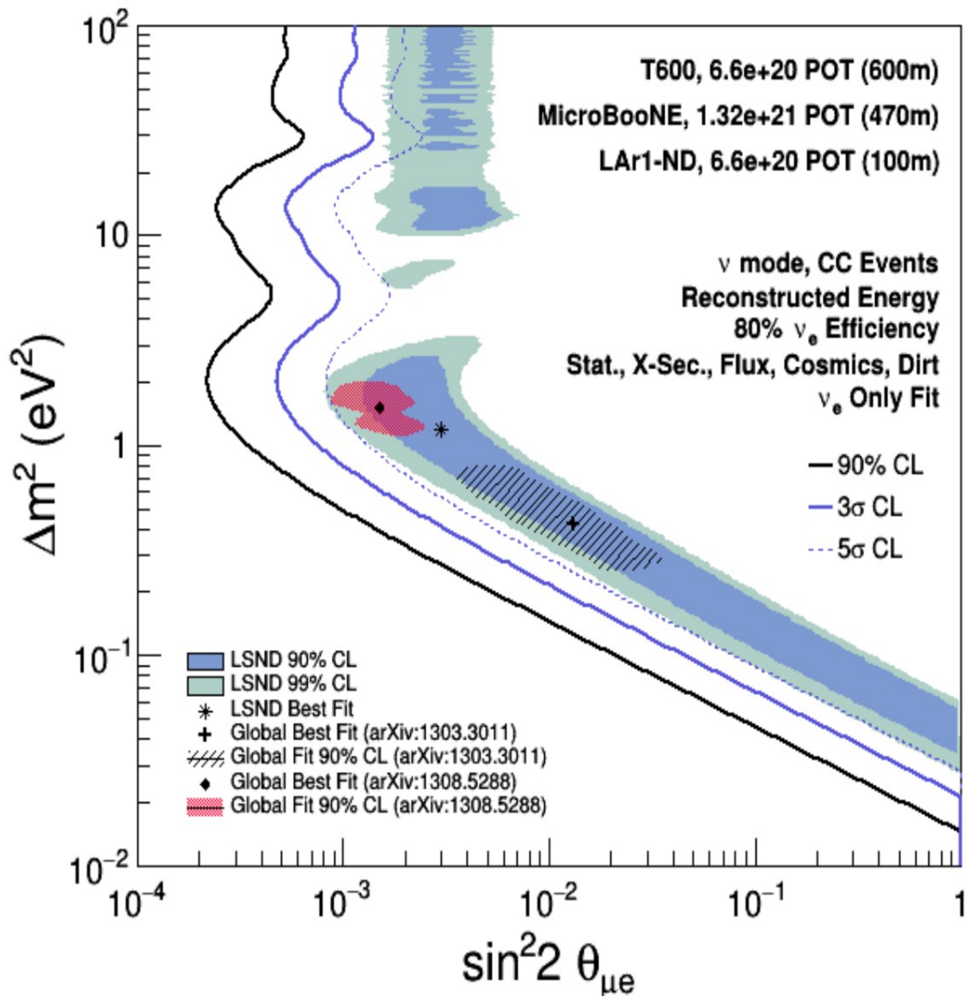
	$(m > \text{EW})$	$\Delta m^2 \gtrsim 100 \text{ eV}^2$
α_{ee}	$1.3 \cdot 10^{-3}$	$2.4 \cdot 10^{-2}$
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-2}$
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$	$1.0 \cdot 10^{-1}$
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$	$2.5 \cdot 10^{-2}$
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$	$6.9 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$

Oscillations
(short-baseline
& atmosph.)

Fernandez-Martinez, Hernandez-Garcia and Lopez-Pavon, 1605.08774
Blennow, PC, Fernandez-Martinez, Hernandez-Garcia and Lopez-Pavon, 1609.08637

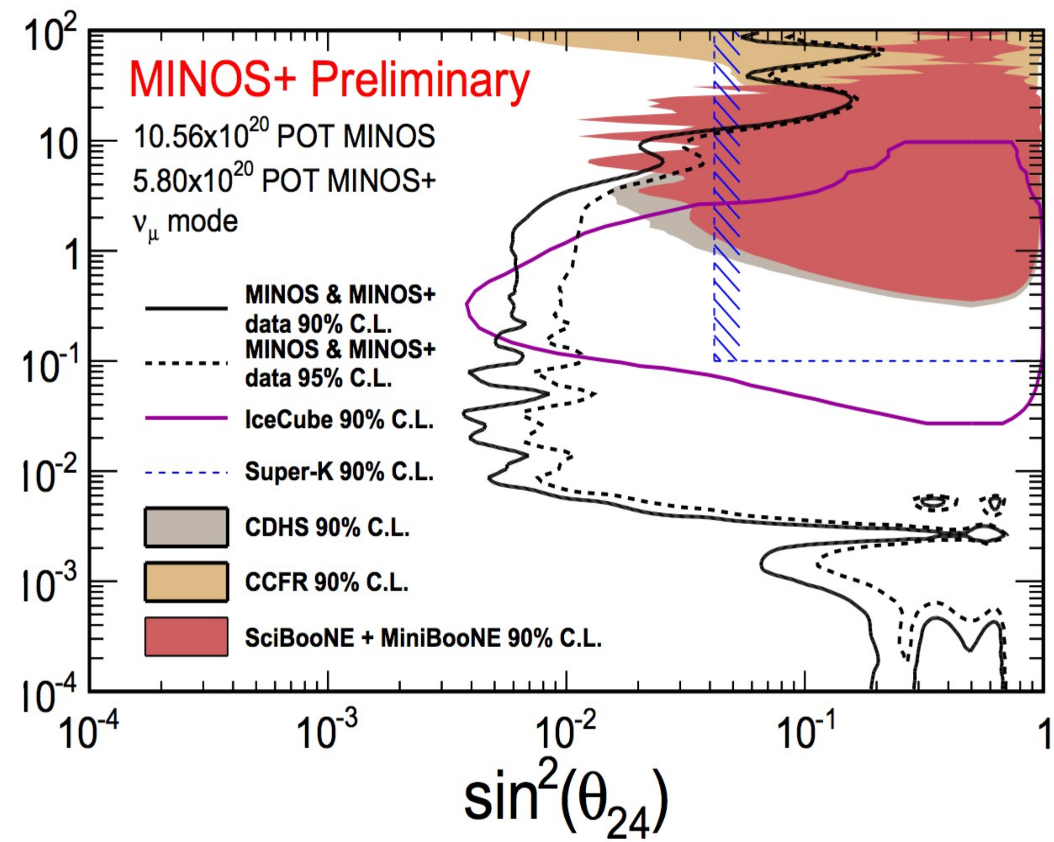
(at 95% CL)

Light steriles – not averaged out



Fermilab SBN program, 1503.01520

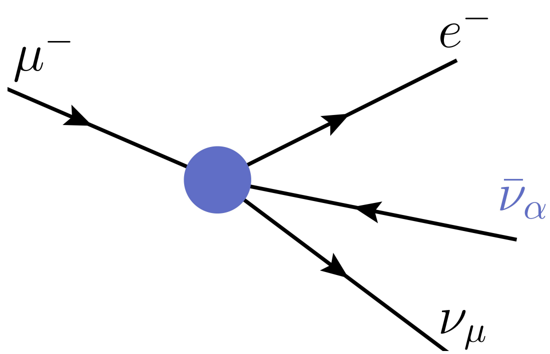
http://www-numi.fnal.gov/PublicInfo/forscientists.html



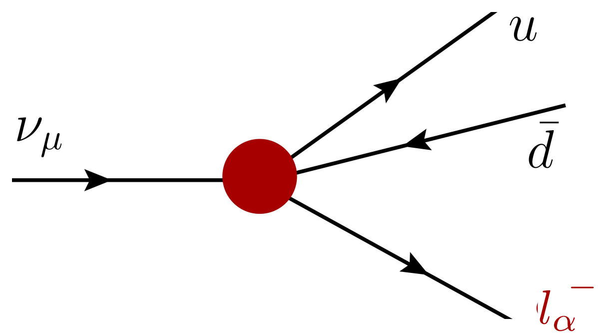
New physics searches:
Non-Standard Interactions

Non-Standard Interactions

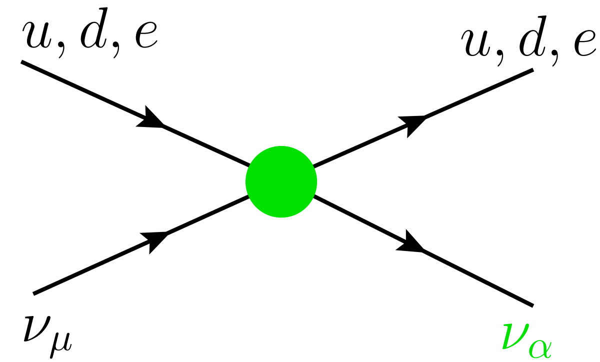
NSI affecting
production



NSI affecting
detection



NSI affecting
propagation



$$\varepsilon_{\mu\alpha}^{e\mu,P}\left(\overline{e}\gamma^\rho P\mu\right)\left(\overline{\nu}_\mu\gamma_\rho P_L\nu_\alpha\right) \qquad \varepsilon_{\mu\alpha}^{ud,P}\left(\overline{d}\gamma^\rho Pu\right)\left(\overline{\nu}_\mu\gamma_\rho P_L l_\alpha\right) \qquad \varepsilon_{\mu\alpha}^{f,P}\left(\overline{f}\gamma^\rho Pf\right)\left(\overline{\nu}_\mu\gamma_\rho P_L\nu_\alpha\right)$$

Quite constrained from EW processes
(meson and lepton decays, etc)

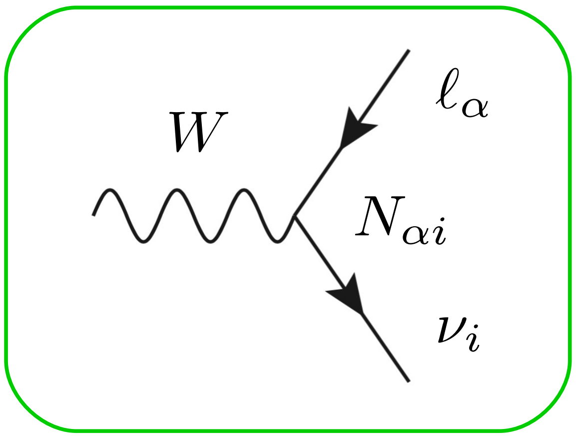
Constrained from neutrino
scattering and oscillations

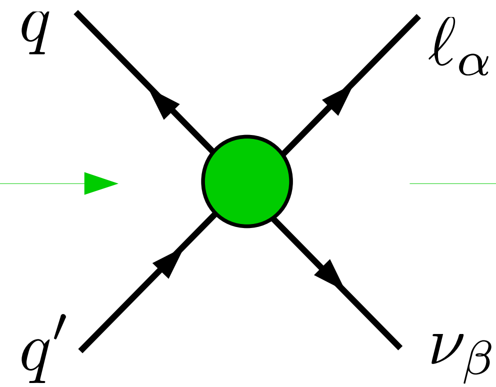
Biggio, Blennow, Fernandez-Martinez,
0907.0097

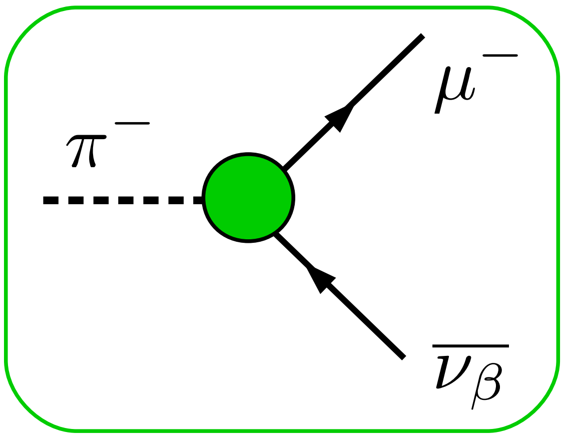
Davidson et al, hep-ph/0302093
Gonzalez-Garcia and Maltoni, 1307.3092
Denton et al, 1701.04828

NSI from non-unitarity

Non-unitarity automatically generates new interactions at low energies. For example:







Effects in detection, production and propagation are <u>correlated</u> and <u>simultaneously</u> generated:

$$\epsilon^{s*}_{\alpha\beta} = \epsilon^{d}_{\alpha\beta} = -\alpha_{\alpha\beta}$$

$$\epsilon^m_{ee} = -\alpha_{ee}$$
$$\epsilon^m_{\mu\mu} = \alpha_{\mu\mu}$$
$$\epsilon^m_{\tau\tau} = \alpha_{\tau\tau}$$

$$\epsilon^m_{\alpha\beta} = \frac{1}{2}\alpha^*_{\beta\alpha}$$

Blennow, PC, Fernandez-Martinez, Hernandez-Garcia, Lopez-Pavon, 1609.08637

Models for NSI

Can we get large NSI in the neutrino sector without entering in conflict with other bounds?

- 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 below the electroweak scale

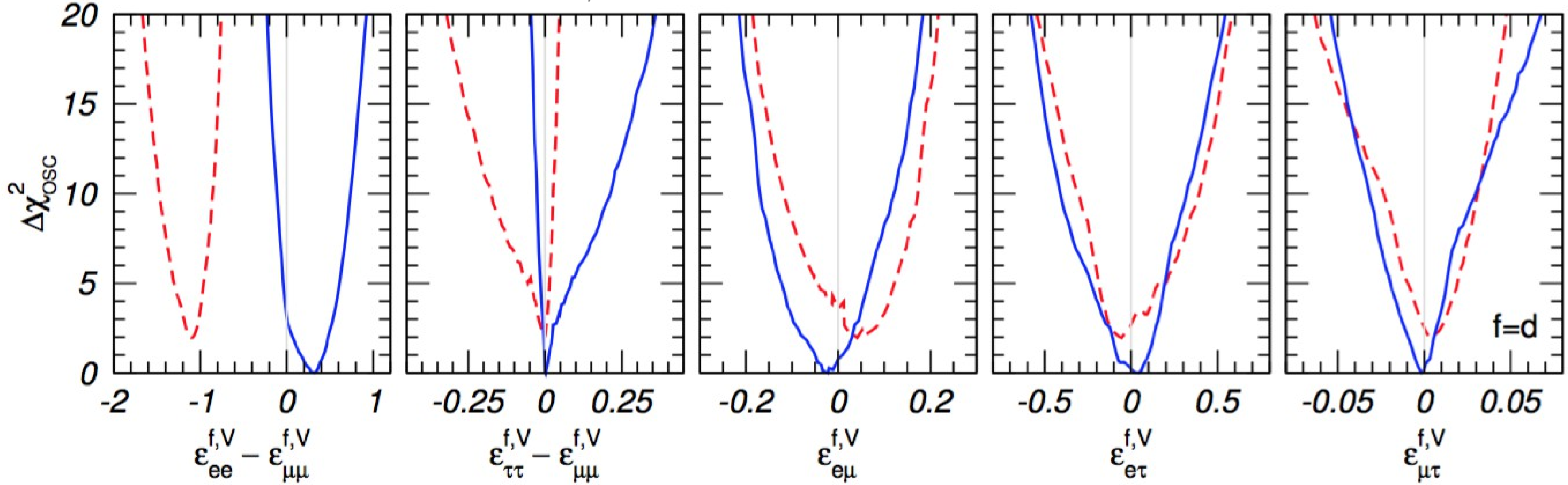
Farzan, 1505.06906
Farzan and Shoemaker, 1512.09147
Farzan and Heeck, 1607.07616
Capozzi, Shoemaker, Vecchi, 1702.08464
Babu, Friedland, Machado, Mocioiu, 1705.01822

(See also talks by Takeuchi and Capozzi)

Current bounds on NSI in propagation

From a global analysis of neutrino oscillation data:

Gonzalez-Garcia and Maltoni, 1307.3092



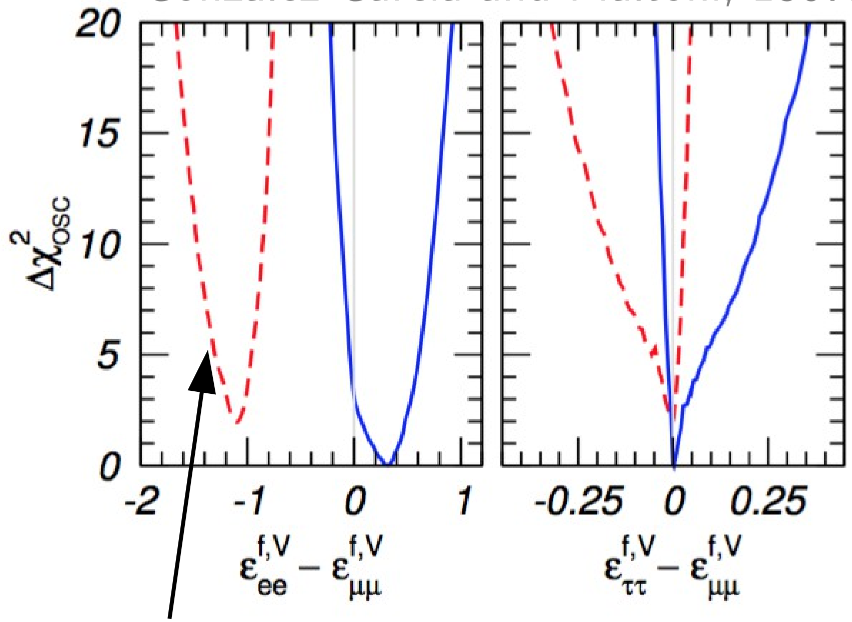
$$\epsilon^{\oplus}_{\alpha\beta} \sim 3\,\varepsilon^{u}_{\alpha\beta} + 3\,\varepsilon^{d}_{\alpha\beta} + \varepsilon^{e}_{\alpha\beta}$$

$$\epsilon^{\odot}_{\alpha\beta} \sim 2\,\varepsilon^{u}_{\alpha\beta} + \varepsilon^{d}_{\alpha\beta} + \varepsilon^{e}_{\alpha\beta}$$

Current bounds on NSI in propagation

From a global analysis of neutrino oscillation data:

Gonzalez-Garcia and Maltoni, 1307.3092



LMA-Dark solution

Miranda, Tortola, Valle, hep-ph/0406280

For solar neutrinos (adiabatic regime):

$$P_{ee} = \frac{1}{2}\left[1 + \cos 2\theta \cos 2\theta_m\right]$$ Parke'86

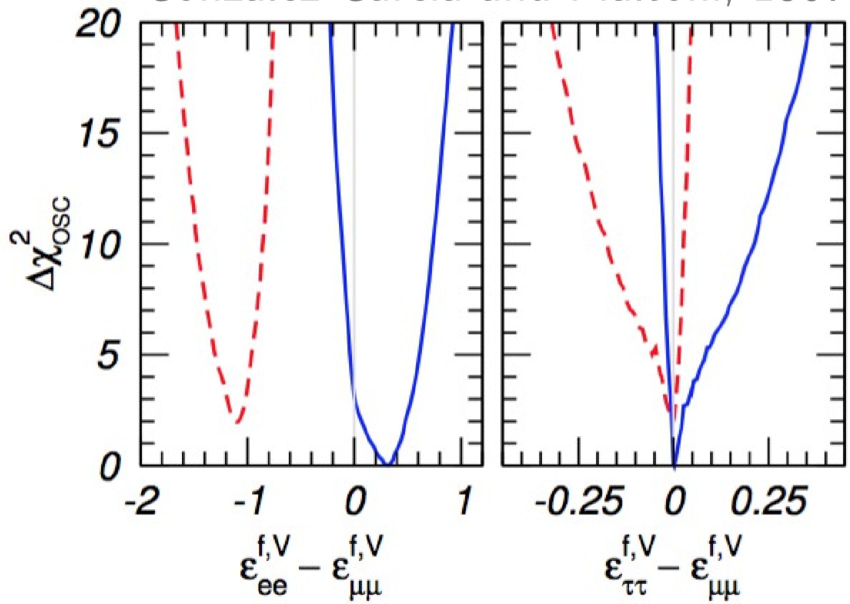
Effective mixing angle inside the Sun, in presence of NSI:

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

Current bounds on NSI in propagation

From a global analysis of neutrino oscillation data:

Gonzalez-Garcia and Maltoni, 1307.3092



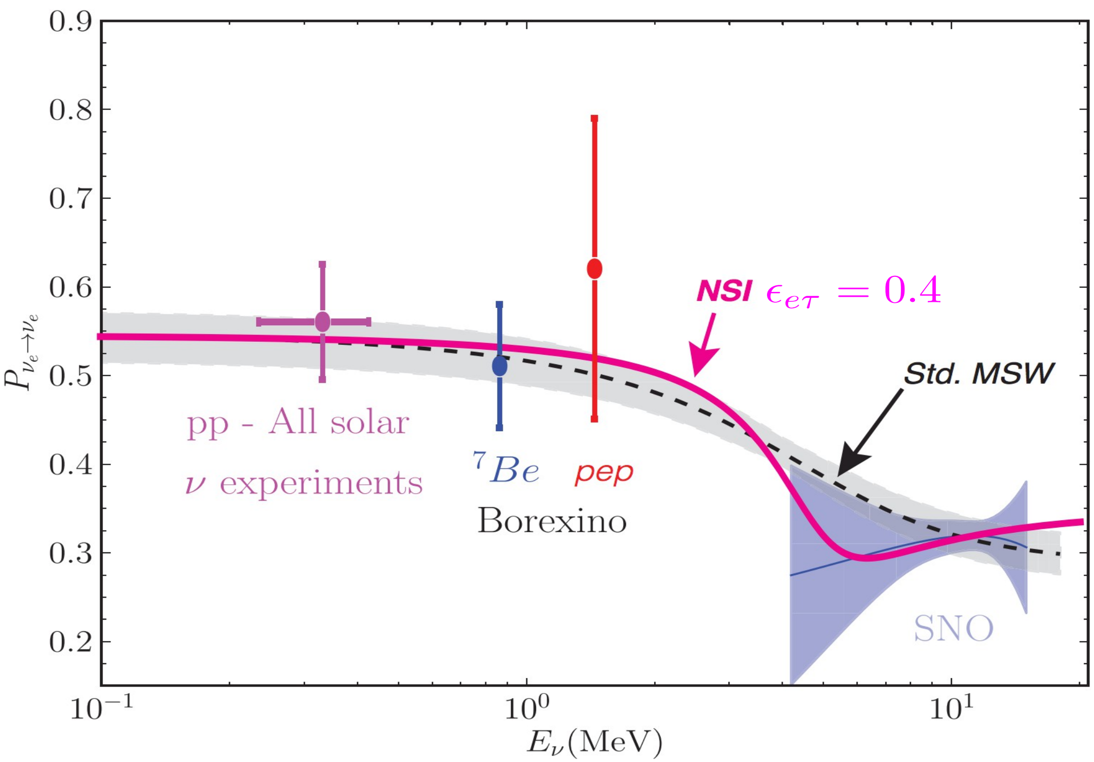
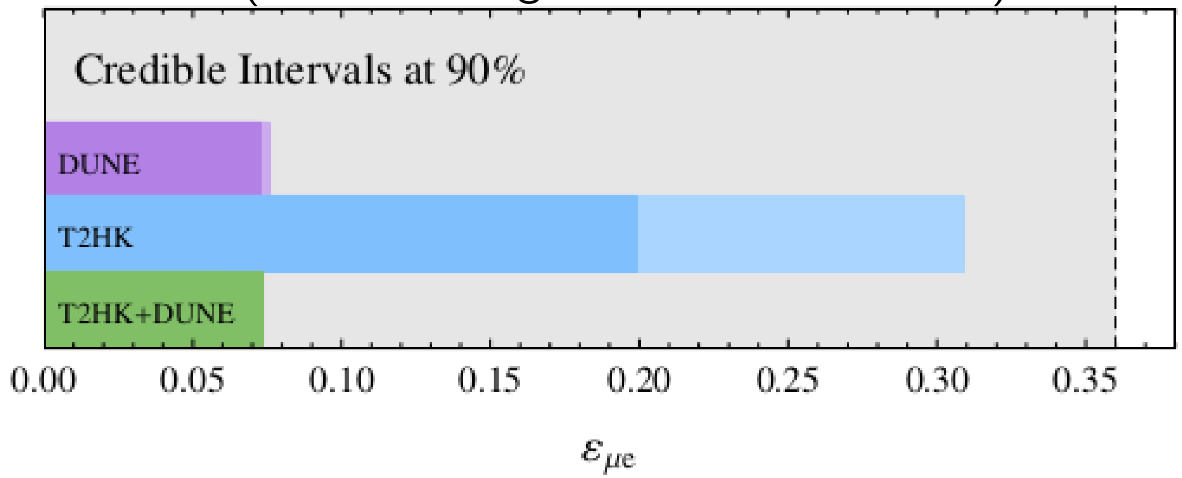
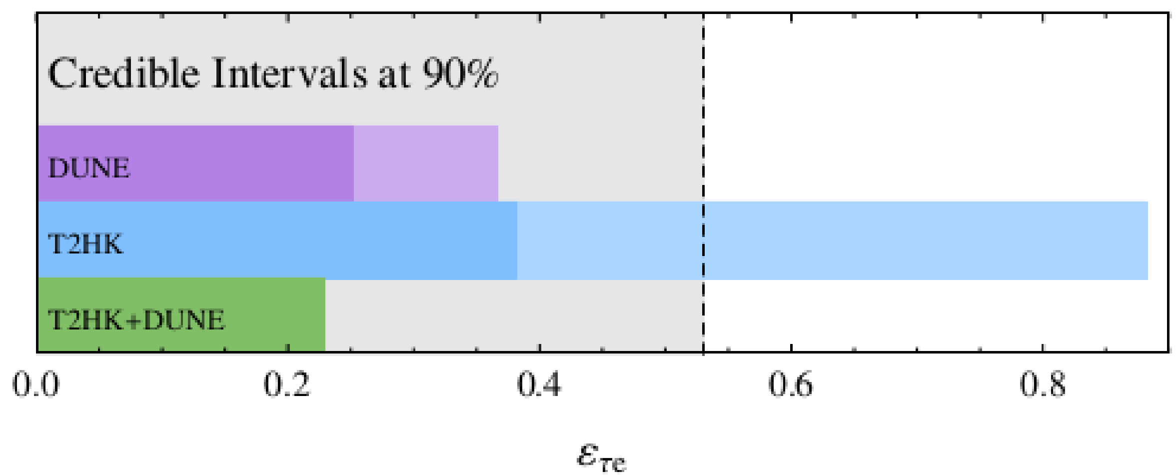


Figure from Friedland, Shoemaker, 1207.6642

DUNE sensitivities to NSI

(Mass ordering assumed to be known)





PC, 1511.06357

Generalized mass ordering degeneracy

Matter potential in presence of NSI:

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

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

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

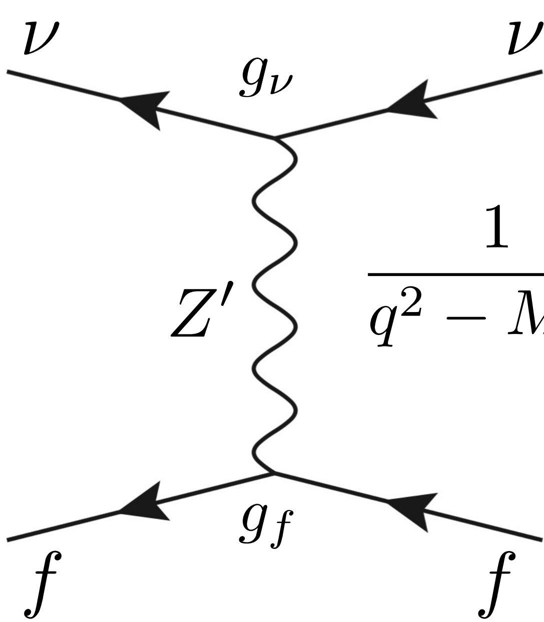
$$\epsilon_{ee} - \epsilon_{\mu\mu} \to -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2$$
$$\epsilon_{\tau\tau} - \epsilon_{\mu\mu} \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu})$$
$$\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha \neq \beta)$$

$$H \to -H^*$$

PC and Schwetz, 1604.05772
Bakhti and Farzan, 1403.0744

What about scattering data?

Heavy vs light mediators



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

$q^2 \sim 0$ — Oscillations:

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

Scattering — $q^2 \gg M_{Z'}^2$:

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

$\rightarrow$ We can distinguish between two very different classes of NSI models: "heavy" mediators (above 1 GeV) and "light" mediators (above 10 MeV)

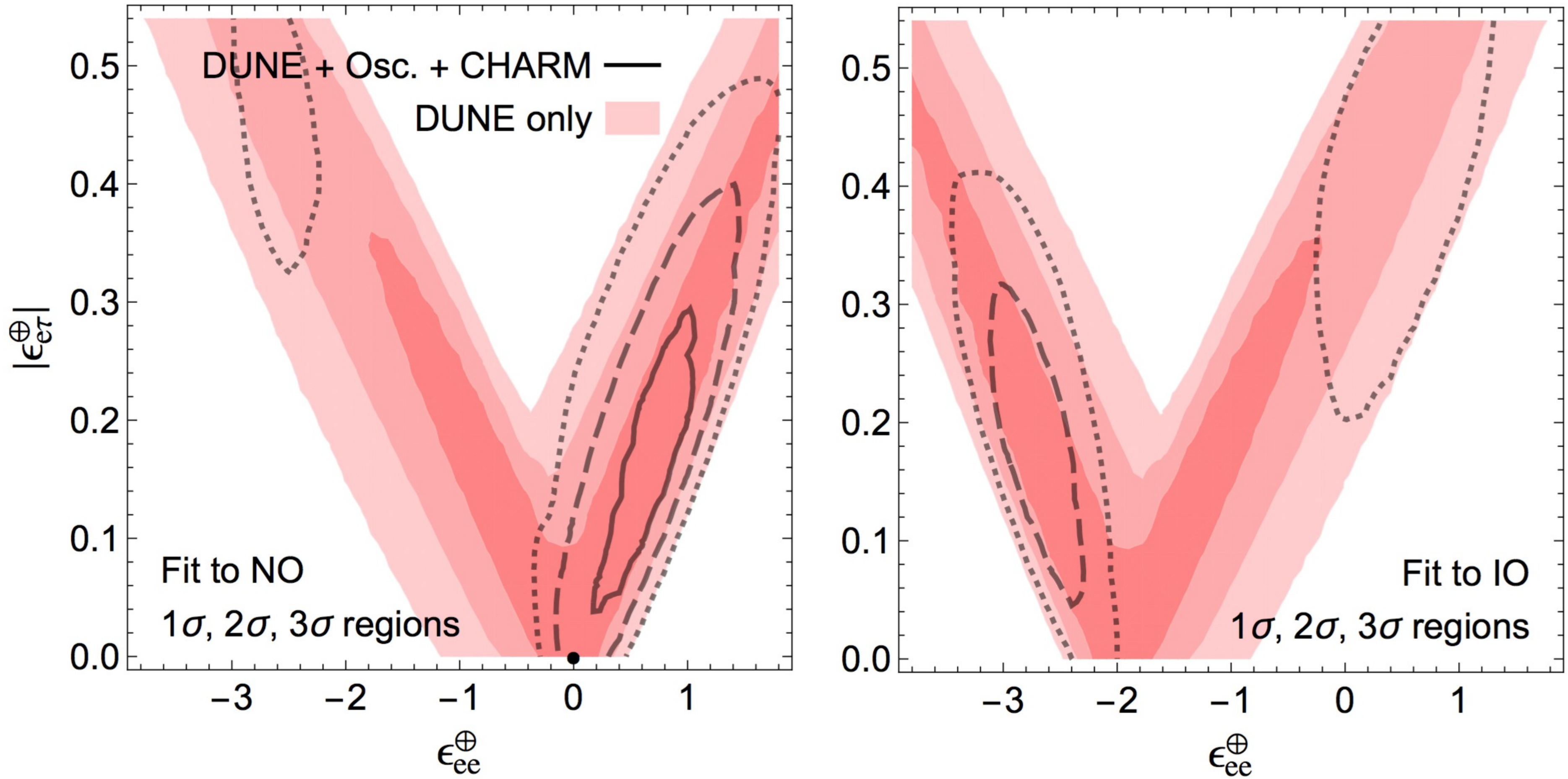
Including scattering data

Both CHARM and NuTeV measured a ratio of NC to CC events:

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

NuTeV coll., hep-ex/0110059
Zeller, FERMILAB-THESIS-2002-34
CHARM coll., Phys. Lett. B180, 303 (1986)

Future prospects: DUNE

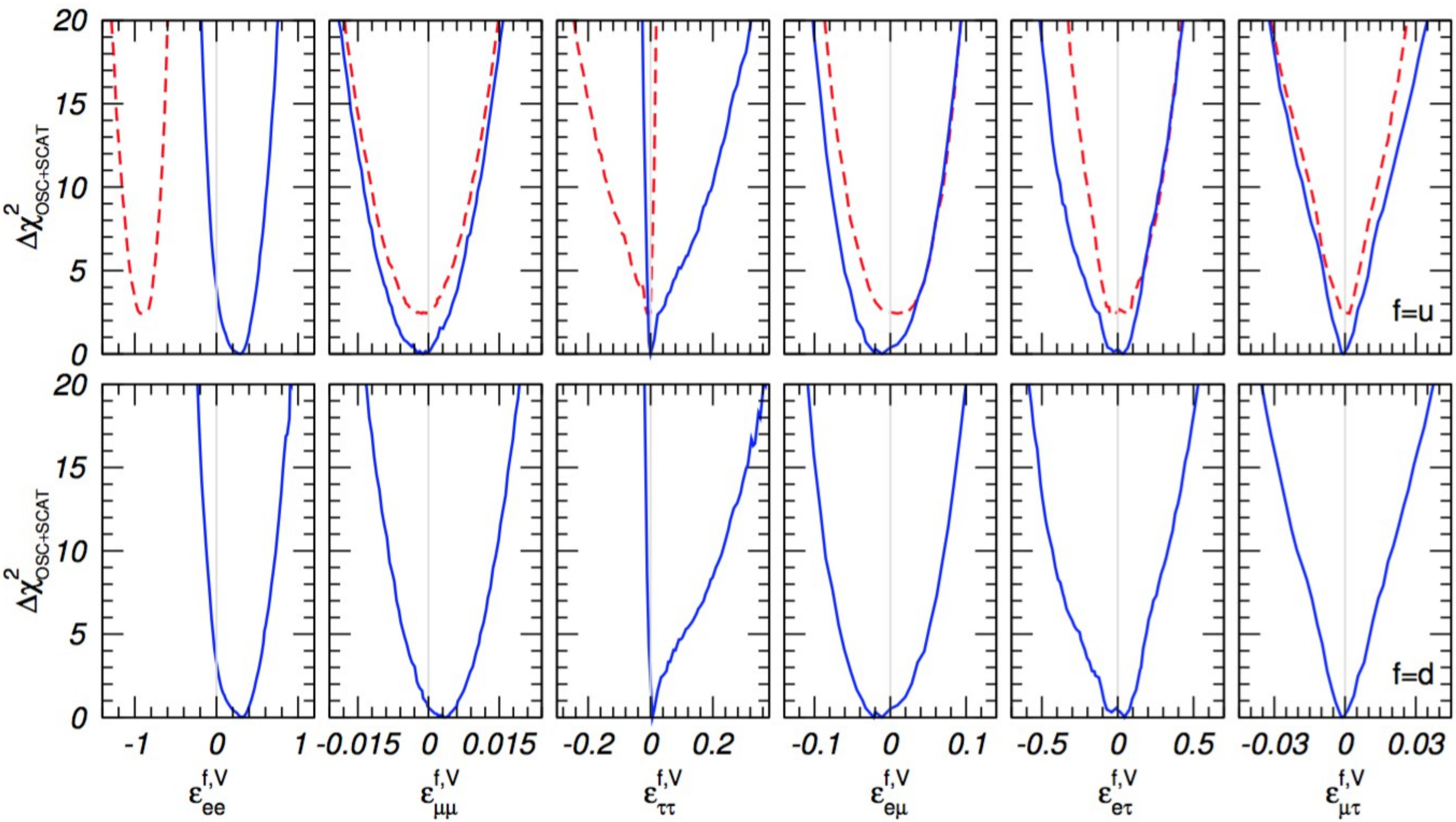


Osc. prior from Gonzalez-Garcia and Maltoni, 1307.3092,
CHARM prior taken from Phys. Lett. B180, 303 (1986)

PC and Schwetz, 1604.05772

Oscillations + scattering data

Oscillations + NuTeV (according to Bentz-et-al) + CHARM:



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

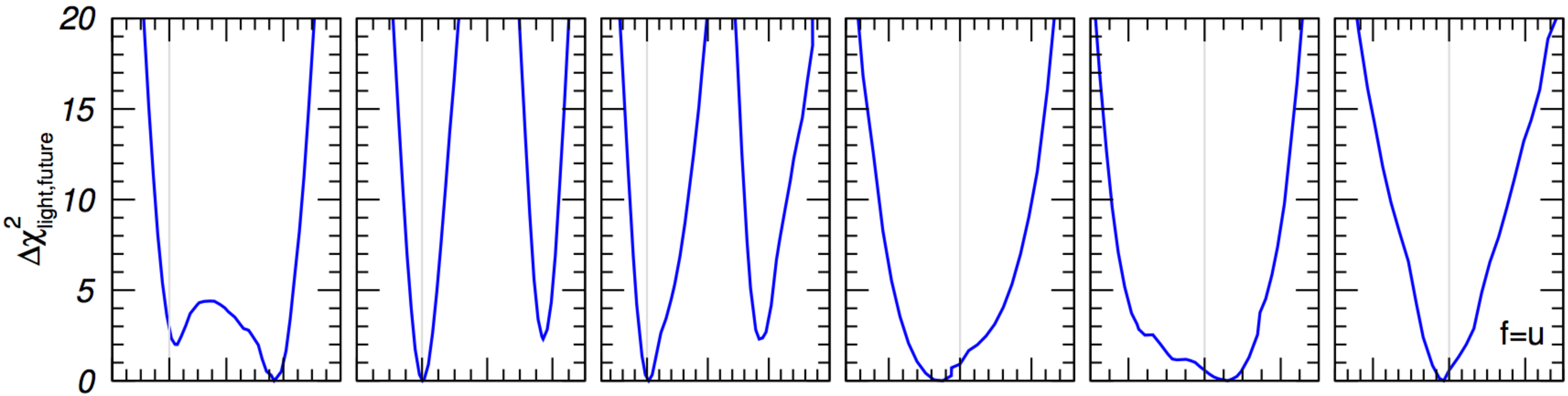
COHERENT

The future COHERENT experiment would measure a different combination of parameters:

$$Q^2_{w\alpha} \propto \left[Z(g_p^V + 2\epsilon^{u,V}_{\alpha\alpha} + \epsilon^{d,V}_{\alpha\alpha}) + N(g_n^V + \epsilon^{u,V}_{\alpha\alpha} + 2\epsilon^{d,V}_{\alpha\alpha})\right]^2 + \\ + \sum_{\beta\neq\alpha}\left[Z(2\epsilon^{u,V}_{\alpha\beta} + \epsilon^{d,V}_{\alpha\beta}) + N(\epsilon^{u,V}_{\alpha\beta} + 2\epsilon^{d,V}_{\alpha\beta})\right]^2$$

Scholberg,hep-ex/0511042

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



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

Summary and conclusions

Current data is already giving the first hints for the missing parameters in the neutrino sector.

Thinking ahead:

- Non-unitarity generally expected due to neutrino masses
  - If averaged-out, oscillation effects are the same regardless of scale
  - Very strong bounds if it comes from high energies
- Non-Standard Interactions:
  - Model building is challenging. Way out? $\rightarrow$ low scales
  - NSI can induce new dangerous degeneracies
  - Scattering experiments can help

Thank you!!