New Physics affecting neutrino propagation at DUNE

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Fermilab

Based on
PC arXiv:1511.06357 and PC and Schwetz arXiv:1604.05772

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Non-Standard Interactions

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

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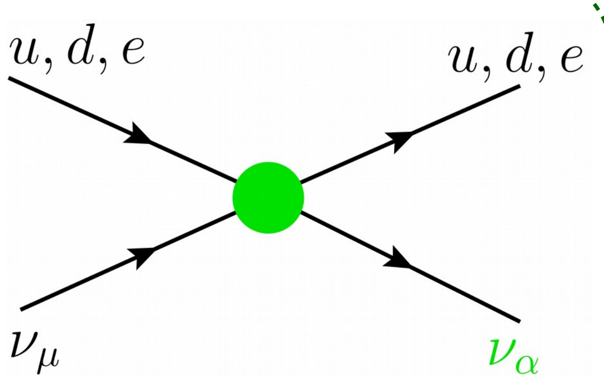
NSI can affect neutrinos in propagation through matter, e.g.:

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

Wolfenstein, '78, Valle '87, Guzzo et al '91



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

Models for NSI

Model-independent bounds are still weak for some parameters.
However, if the new scale is assumed to be large, then:

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Possible way out: New Physics stands below EWSB

Farzan 1505.06906
Farzan and Shoemaker, 1512.09147
Farzan and Heeck, 1607.07616

NSI in propagation

$$\varepsilon_{\alpha\beta} \equiv \sum_{f,P} \frac{n_f}{n_e} \epsilon_{\alpha\beta}^{fP} \sim 3\epsilon_{\alpha\beta}^{u,V} + 3\epsilon_{\alpha\beta}^{d,V} + \epsilon_{\alpha\beta}^{e,V}$$

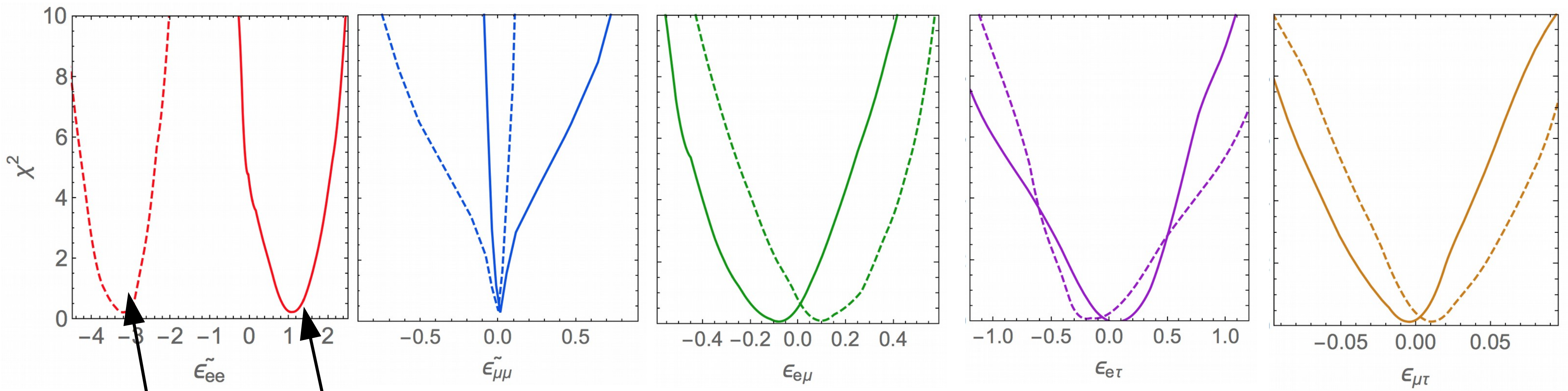
Effectively, NSI in propagation act as a generalized matter potential. Oscillation experiments will only be sensitive to two of the off-diagonal entries, e.g.:

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

$$\epsilon_{\alpha\alpha}^{\sim} \equiv \epsilon_{\alpha\alpha} - \epsilon_{\tau\tau}$$

All (std+NSI) parameters included at once in the simulations: completely model-independent!

Current constraints on NSI



LMA solution (SM)

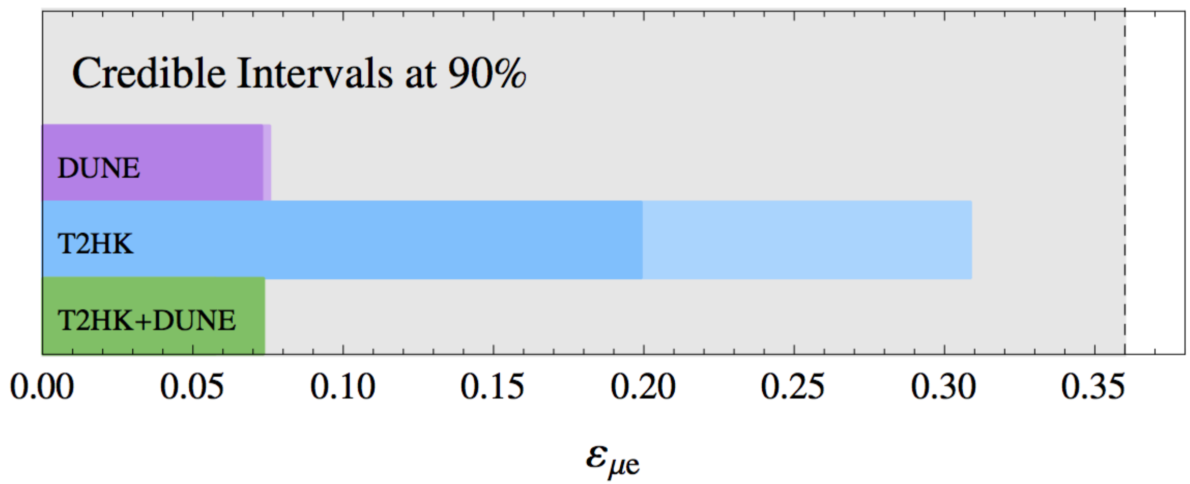
LMA-Dark solution

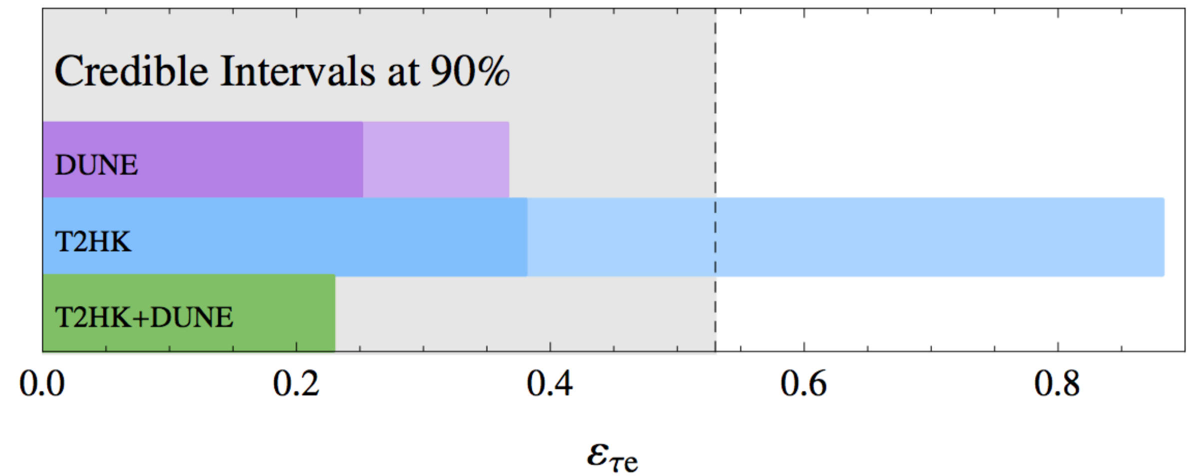
Miranda, Tortola, Valle, hep-ph/0406280

Bounds adapted from Gonzalez-Garcia and Maltoni, 1307.3092, for NSI affecting up-quarks only

(see also Davidson et al,hep-ph/0302093 and Biggio et al, 0907.0097)

DUNE sensitivities to NSI





PC, 1511.06357

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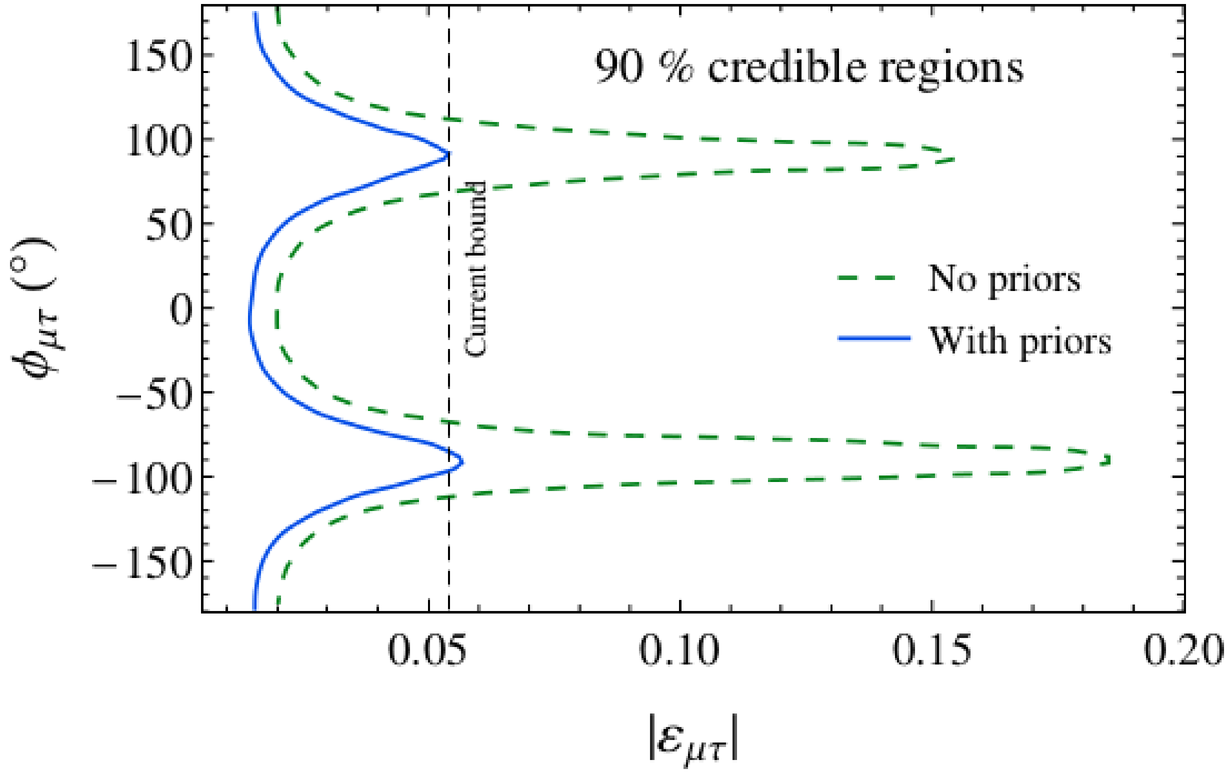
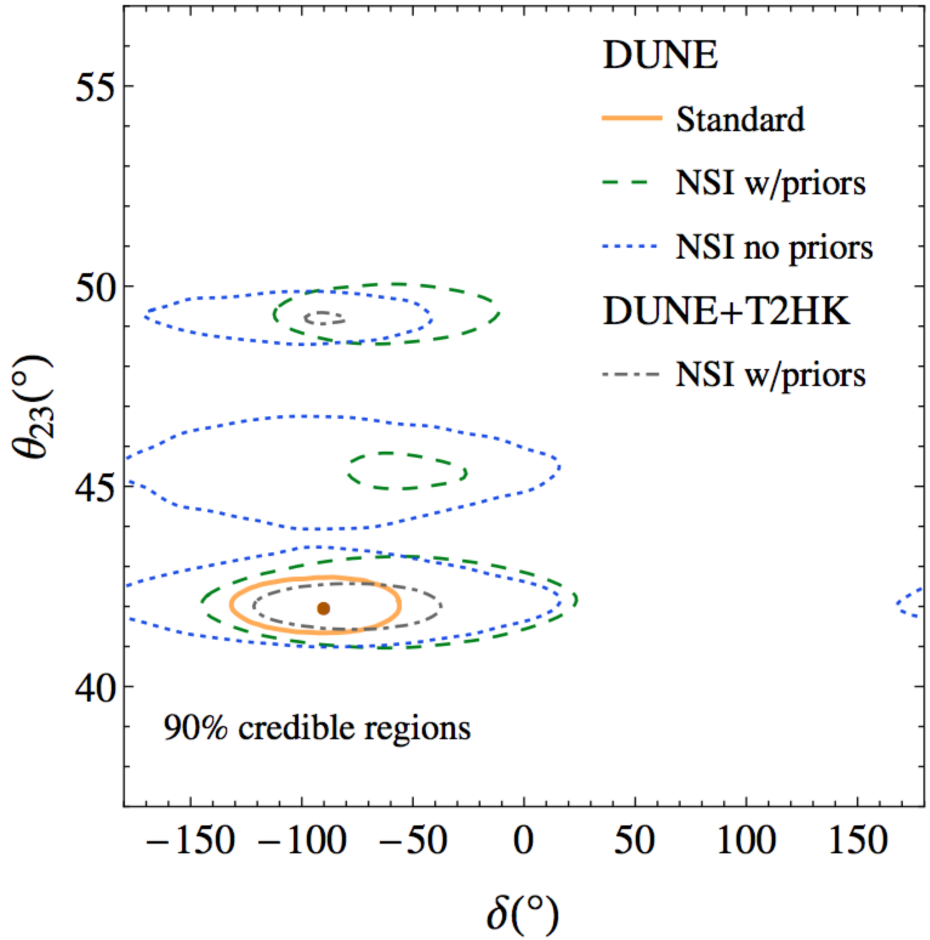


Some sensitivities show a strong dependence with the new CP-violating phases!

PC, 1511.06357

Potential issues: degeneracies



PC, 1511.06357
(See also talk by Poonam Mehta)

Generalized mass ordering degeneracy

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

The vacuum Hamiltonian can be rewritten as:

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

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

Invariant under:

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

$$H_{vac} \to -H^*_{vac}$$

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

Generalized mass ordering degeneracy

In the SM, the matter potential will break this degeneracy, as

$$H = H_{\mathrm{vac}} + H_{\mathrm{mat}}$$

PC and Schwetz, 1604.05772
Bakhti and Farzan, 1403.0744
(see also Garcia, Maltoni, Salvado, 1103.4365)

Generalized mass ordering degeneracy

In the SM, the matter potential will break this degeneracy, as

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

In presence of NSI, however:

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

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

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

$$H \to -H^*$$

The LMA-dark solution reappears here

PC and Schwetz, 1604.05772
Bakhti and Farzan, 1403.0744
(see also Garcia, Maltoni, Salvado, 1103.4365)

Combination of experiments

The NSI couplings depend on the density of neutrons in matter:

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

$$\boxed{\begin{aligned} Y_u(x) &= 2 + Y_n(x) \\ Y_d(x) &= 1 + 2Y_n(x) \end{aligned}}$$

$$Y_n^{\oplus} \sim 1.05$$
$$Y_n^{\odot} \sim 1/2 \to 1/6$$

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

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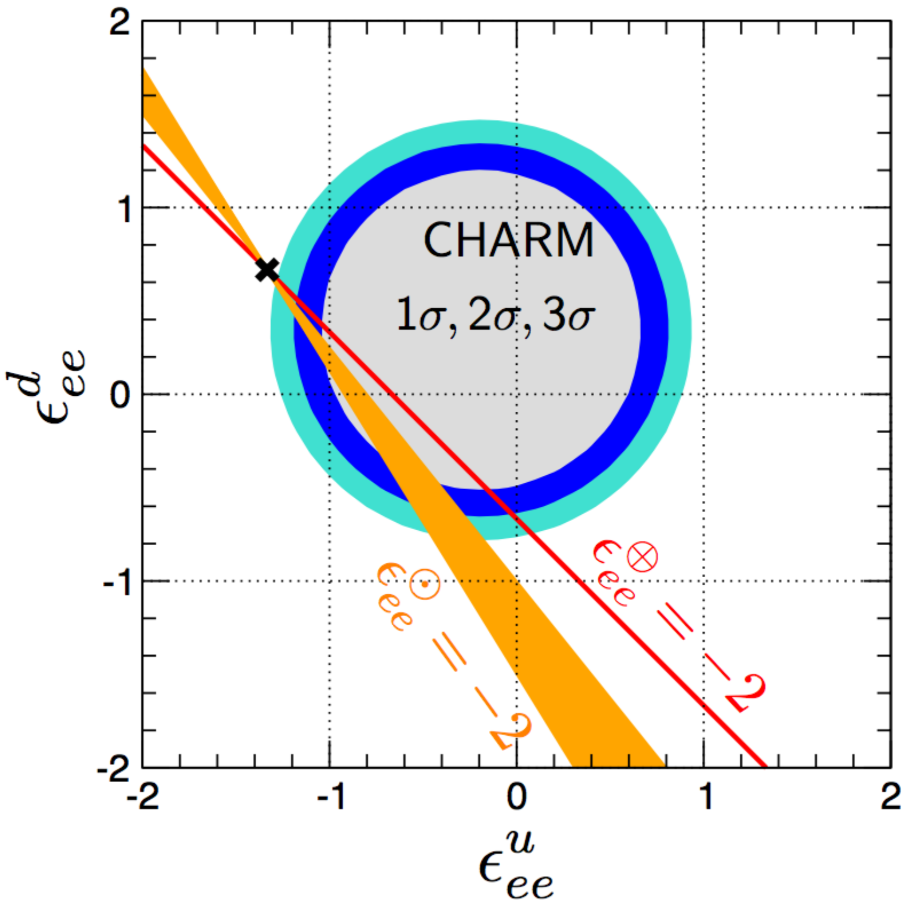

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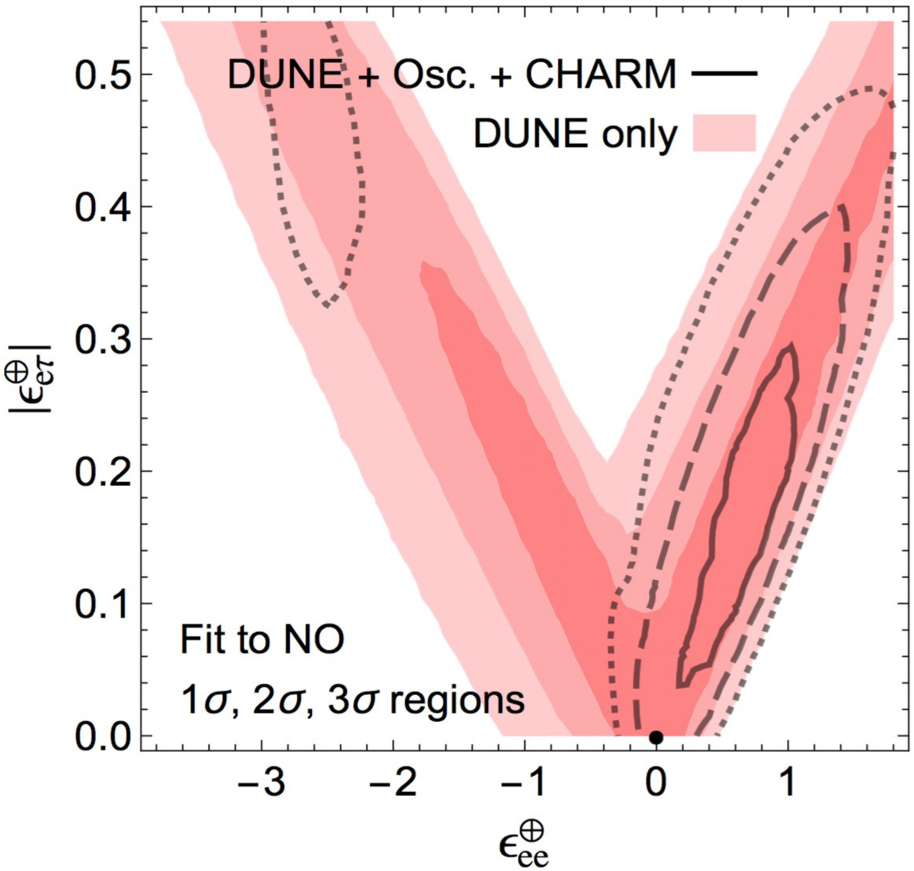
Results for NSI on up-quarks only



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

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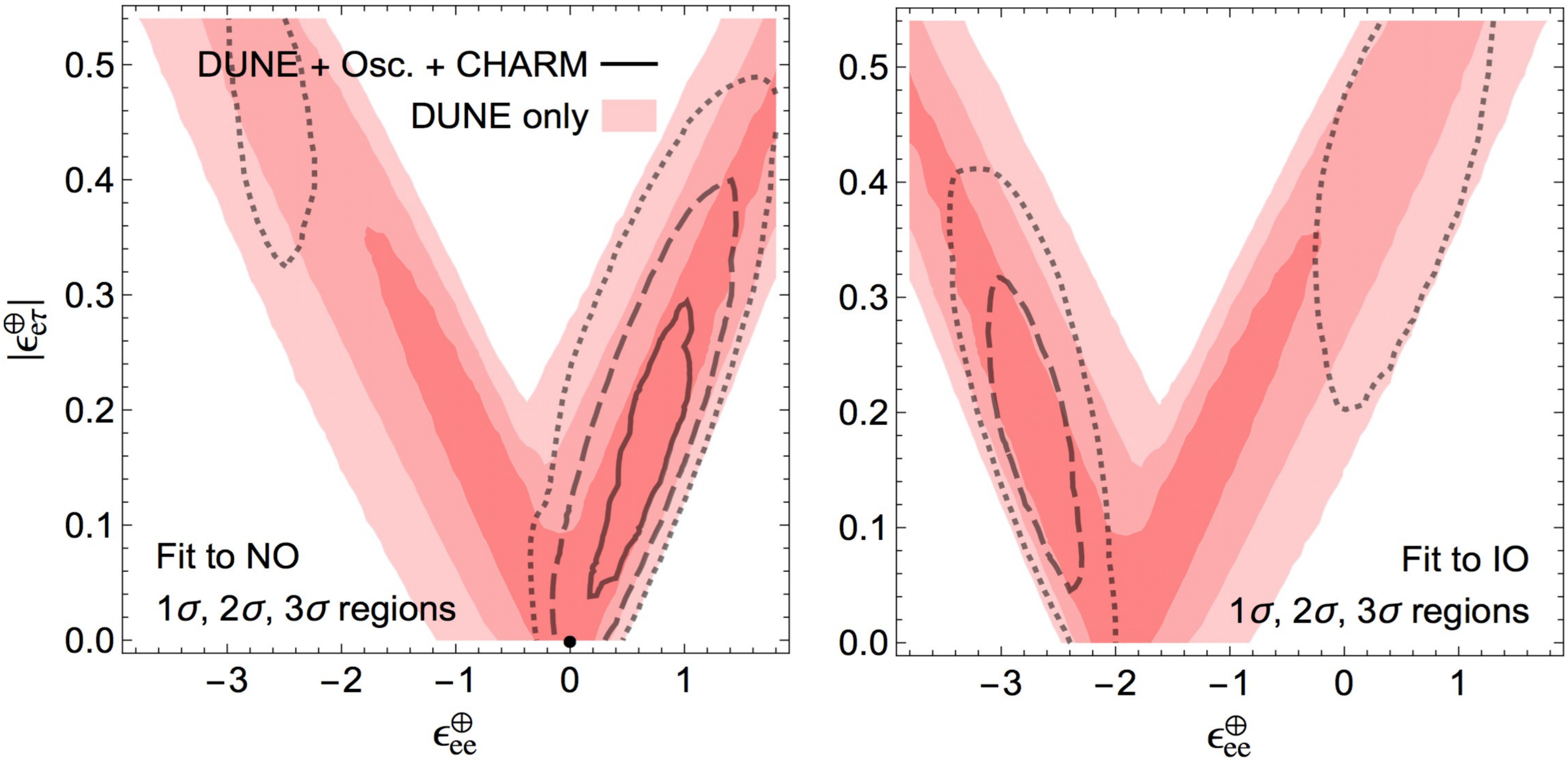

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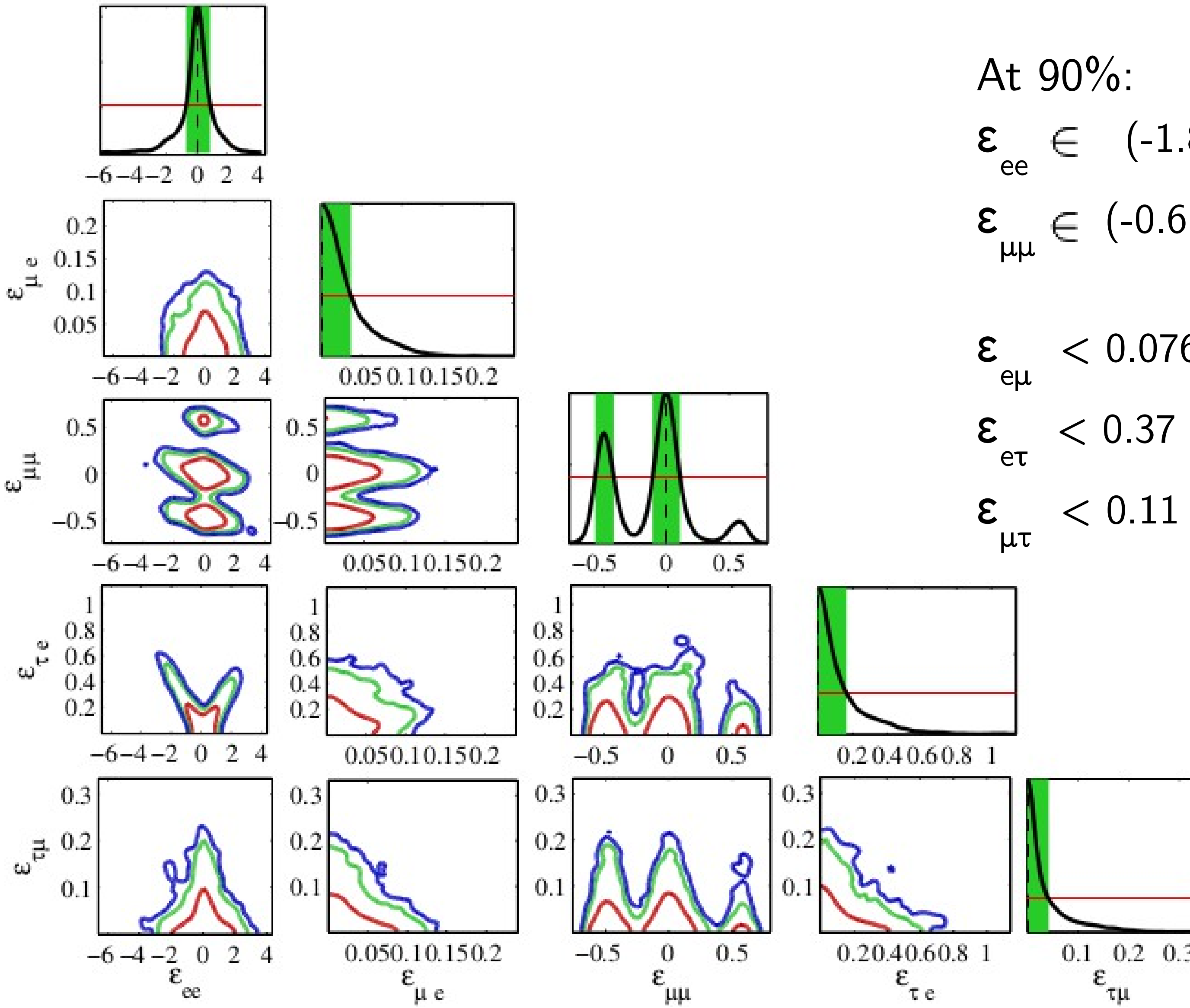
Summary and conclusions

- Model-independent sensitivities of DUNE to NSI in propagation have been evaluated including <u>all possible parameters at once:</u>
  - DUNE will significantly improve over current constraints for $\varepsilon_{e\mu}$, $\varepsilon_{e\tau}$ (and possibly $\varepsilon_{\mu\tau}$)
  - NSI could affect the determination of θ_{23} and δ
  - Important correlations take place among different NSI parameters, e.g., $\varepsilon_{e\tau}$ and ε_{ee}
- The LMA-dark solution is a manifestation of a more profound problem $\rightarrow$ a generalized mass ordering degeneracy!
  - It makes it <u>impossible</u> to determine the mass ordering for any oscillation experiment.

Thank you!!

DUNE sensitivities to NSI



At 90%:

$\varepsilon_{ee} \in$ (-1.89, 1.65)

$\varepsilon_{\mu\mu} \in$ (-0.6, -0.33) $\cup$ (-0.17, 0.19) $\cup$ (0.53,0.63)

$\varepsilon_{e\mu} < 0.076$

$\varepsilon_{e\tau} < 0.37$

$\varepsilon_{\mu\tau} < 0.11$

PC, 1511.06357

The LMA-dark solution

For solar neutrinos in the adiabatic regime:

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

Parke, 1986

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

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

$$\epsilon' = \sin^2\theta_{23}{}^{dV}_{\tau\tau} - \epsilon^{dV}_{ee}$$

Bottom line: One can obtain P < 0.5 even for cos2θ < 0, as long as ε' is large enough!

Miranda, Tortola, Valle, hep-ph/0406280

Medium baseline reactor experiments

Medium baseline reactor experiments are not affected by NSI as they are performed in vacuum. They are also sensitive to additional terms in the probability:

$$\begin{aligned} P_{ee} &= c_{13}^4\left(1-\sin^2 2\theta_{12}\sin^2\Delta_{21}\right)+s_{13}^4 \\ &+ 2s_{13}^2c_{13}^2[\cos 2\Delta_{31}(c_{12}^2+s_{12}^2\cos 2\Delta_{21})+s_{12}^2\sin 2\Delta_{31}\sin 2\Delta_{21}] \end{aligned}$$

$$\Delta_{ij}\equiv\frac{\Delta m_{ij}^2 L}{4E}$$

There is some sensitivity to both s_{12} and c_{12}!

This probability is invariant under the following transformation:

$$\boxed{\begin{aligned} & s_{12}\leftrightarrow c_{12}\quad\left(i.e., \theta_{12}\to\frac{\pi}{2}-\theta_{12}\right) \\ & \Delta_{31}\to-\Delta_{31}+\Delta_{21} \end{aligned}}$$

Bakhti and Farzan, 1403.0744