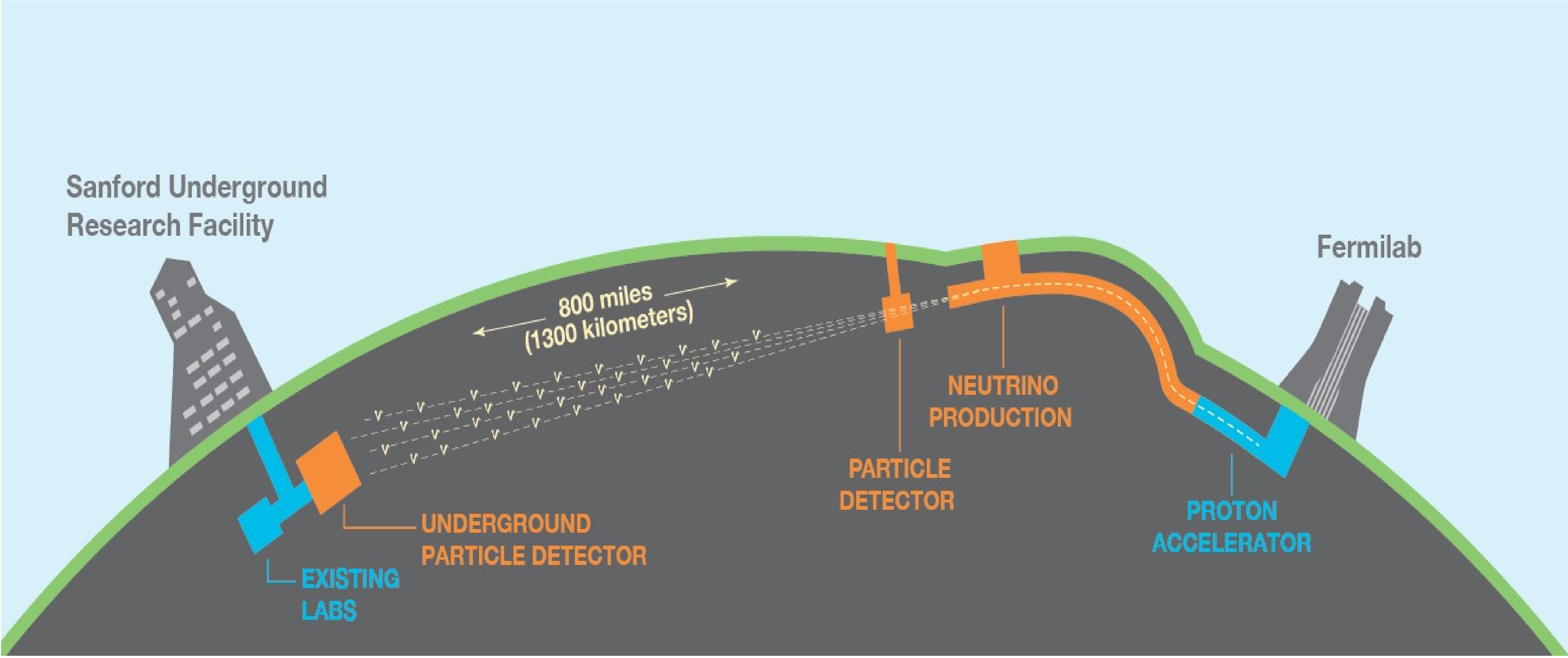
Constraining New Physics in the Neutrino Sector with the Near and Far DUNE detector

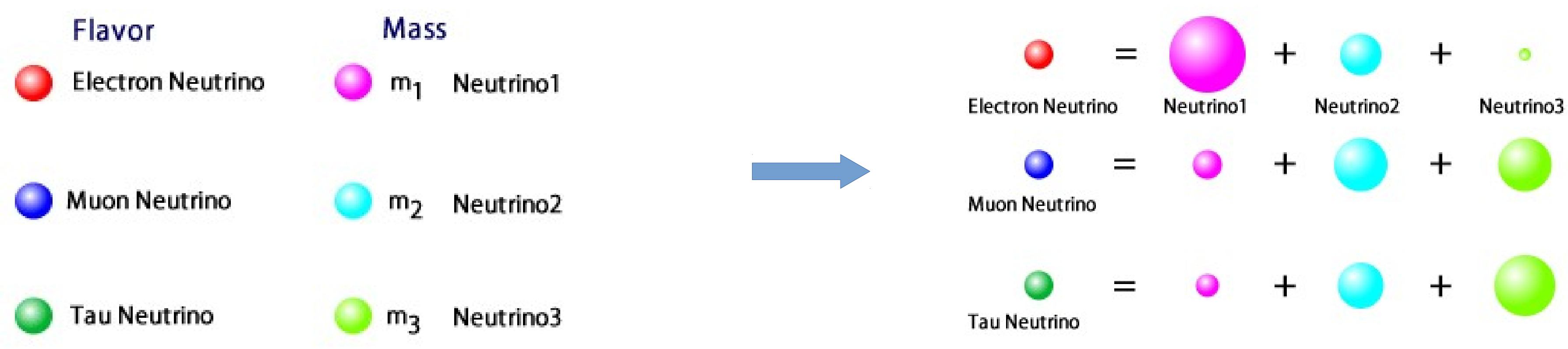


Davide Meloni
Dipartimento di Matematica e Fisica
Roma Tre

The Physics of Neutrino Oscillation

- flavor and mass eigenstates are different objects

SK web pages



- combination described by the PMNS unitary matrix...

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

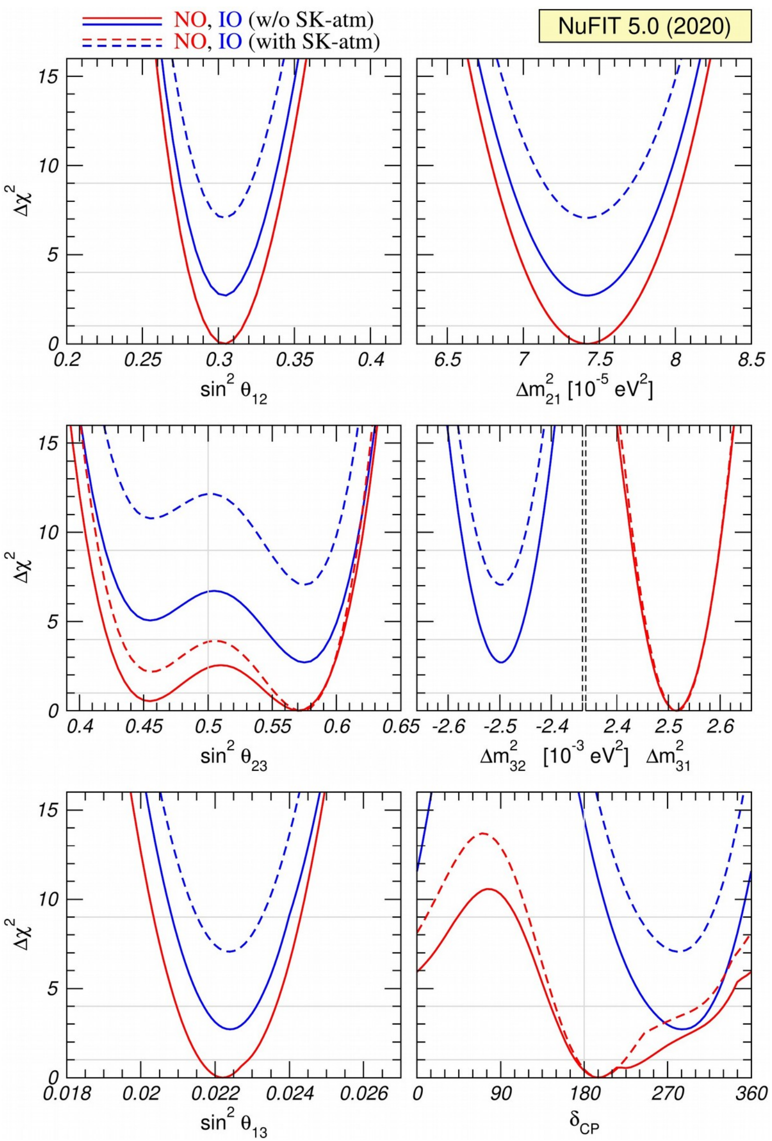
- ...governing transition probabilities

$$P_{\nu_\alpha \to \nu_\beta}(t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right),$$

Current situation

- standard 3-ν paradigm well established

http://www.nu-fit.org



NuFIT 5.0 (2020)

without SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

Only a few remaining questions:

- is there CP violation in the lepton sector?
- what is the neutrino mass ordering?
- is θ_{23} larger or smaller than 45°?

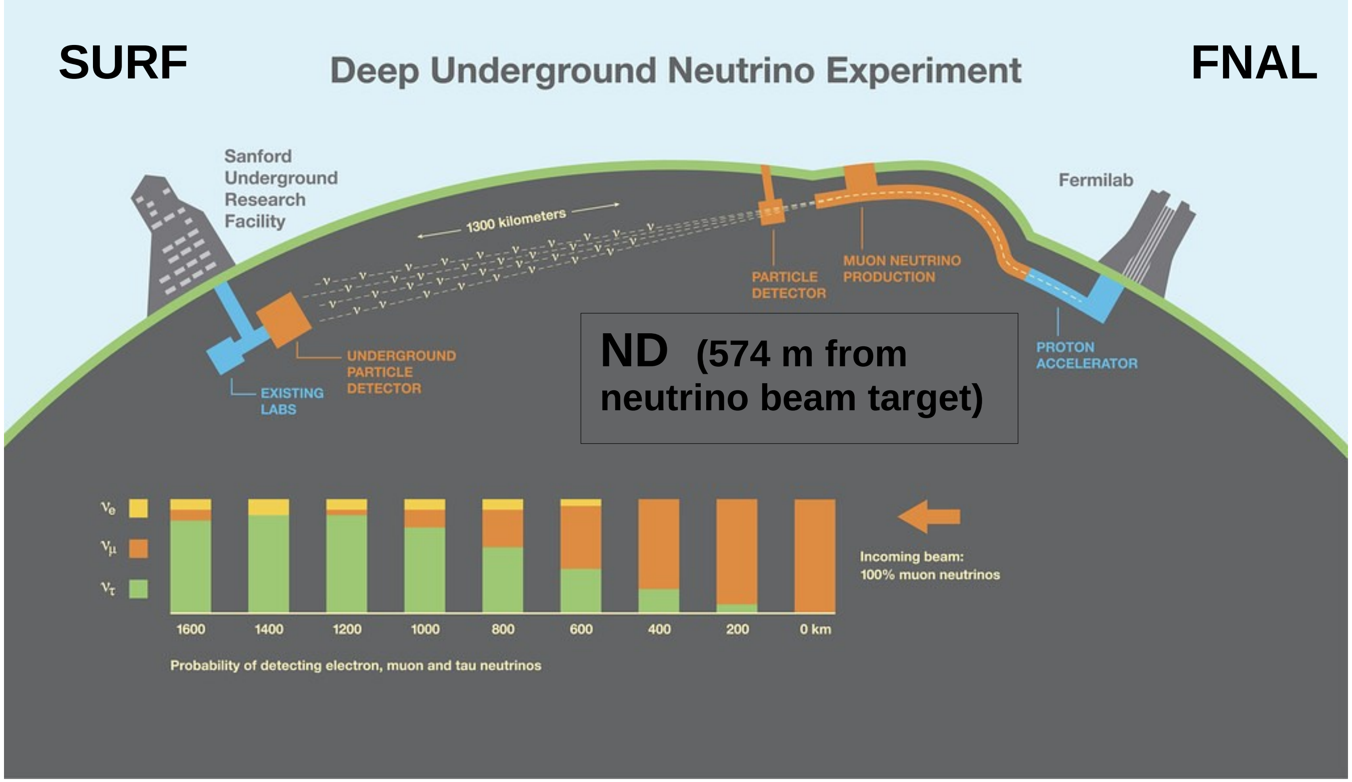
Introducing DUNE

“Deep Underground Neutrino Experiment”

- 1300 km baseline
- Large (70 kt) LArTPC far detector
- 1.5 km underground
- Near Detector (ND) w/LAr component

“Physics goals”

- ν and $\bar{\nu}$ oscillations (δ_{CP}, θ_{13}, θ_{23}, ordering of nu masses)
- Supernova burst neutrinos
- Beyond Standard Model processes



New Physics in the Neutrino Sector

- going beyond standard physics looking at $\nu_\mu \to \nu_\tau$ transition

A.Ghoshal, A.Giarnetti and D.M., JHEP **12** (2019), 126

- less studied transition channel

- some new physics appears at first order in terms quantifying the size of the new interaction relative to the weak scale (ε)

Example 1: ***sterile neutrino states***

$$U_{PMNS} = R(\theta_{34})\,R(\theta_{24})\,R(\theta_{23},\delta_2)\,R(\theta_{14})\,R(\theta_{13},\delta_3)\,R(\theta_{12},\delta_1)$$

three more angles

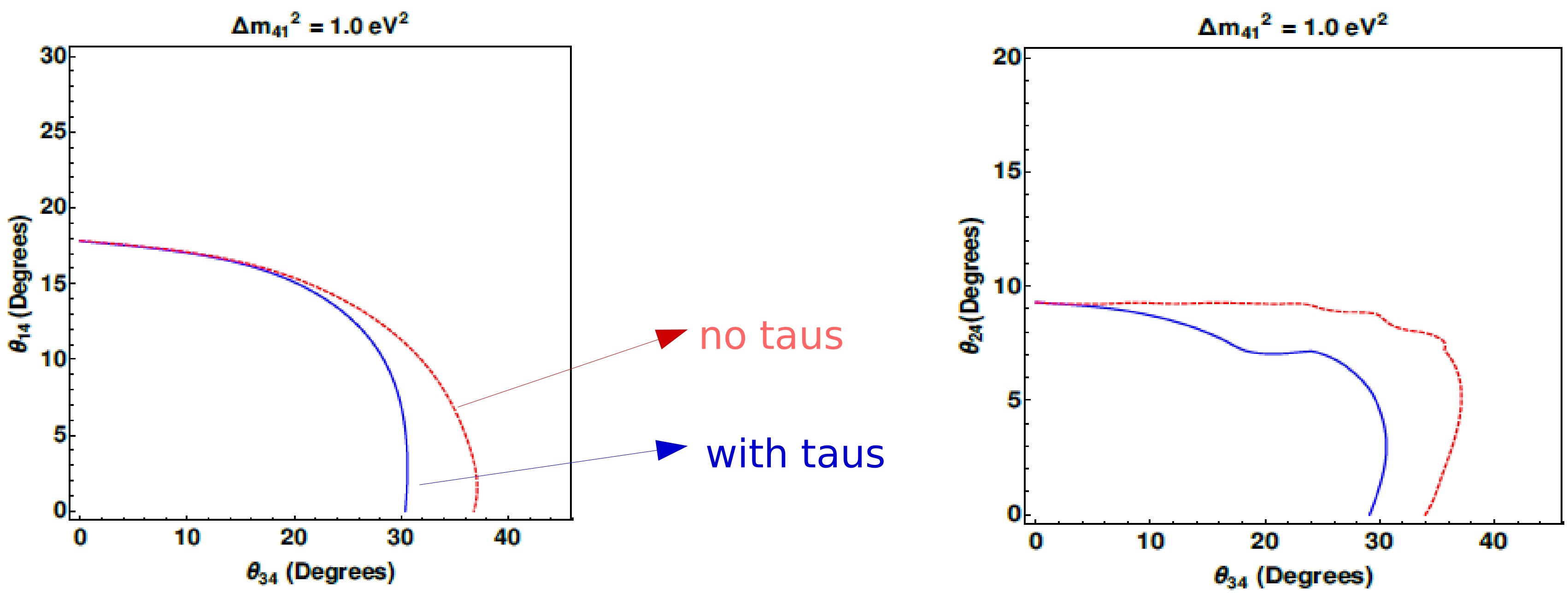
two more CP-phases

one more independent mass differences: Δm^2_{14}

Example 1: ***sterile neutrino states***

$\nu_\mu \rightarrow \nu_\tau$ sensitive to the combination: $$U^*_{\mu 4} U_{\tau 4} = \frac{1}{2}\cos^2\theta_{14}\sin\theta_{34}\sin 2\theta_{24}$$

$|U_{\mu 4}{}^* U_{\tau 4}| <\sim 0.04$
JHEP **08** (2018), 010



- increase in sensitivity for θ_{34} of about 20% compared to the case where τ signal events are not considered
- Good sensitivity to the other mixing angles at the level of 10-20 degrees

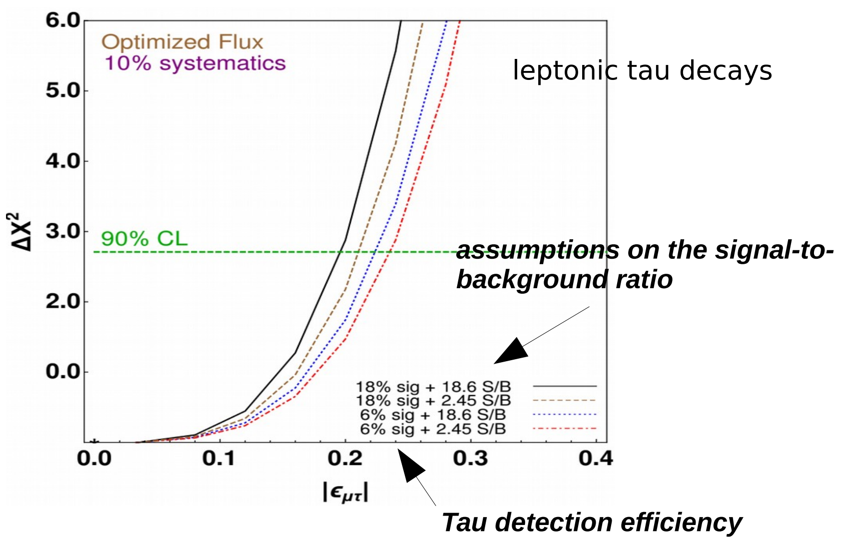
Example 2: ***Non-Standard Neutrino Interactions***

- Modified matter effects

$$L^{NSI} \propto G_F\, \epsilon_{\alpha\beta}\, [\bar{f}\,\gamma_\mu(1+a\,\gamma_5)f][\overline{\nu_\alpha}\,\gamma_\mu(1-\gamma_5)\,\nu_\beta]$$

$$P_{\nu_\mu \to \nu_\tau} = P^{standard}_{\nu_\mu \to \nu_\tau} + O(1) \times \epsilon_{\mu\tau}$$

A.Ghoshal, A.Giarnetti and D.M., JHEP 12 (2019)



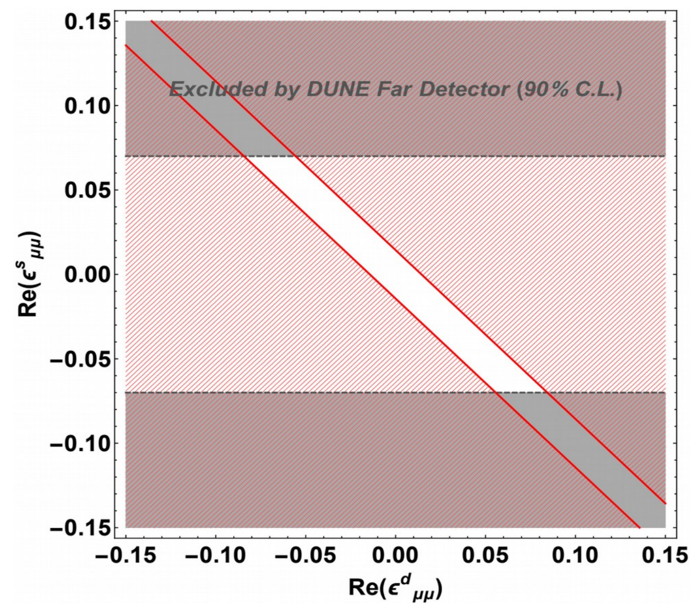
- Source and detector NSI (@ ND)

$$|\nu^s_\alpha\rangle = |\nu_\alpha\rangle + \sum_{flavors} \varepsilon^s_{\alpha\gamma}\,|\nu_\gamma\rangle$$

$$P_{\alpha\beta} = |[(1+\varepsilon^d)^T(1+\varepsilon^s)^T]_{\beta\alpha}|^2$$

$$\langle\nu^d_\beta| = \langle\nu_\beta| + \sum_{flavors} \varepsilon^d_{\gamma\beta}\,\langle\nu_\gamma|$$

A.Giarnetti and D.M., 2005.10272



Conclusions

- New neutrino experiments will probe the PMNS with huge precision
- Possibility to investigate New Physics effects in Neutrino oscillations
- The DUNE near and far detectors have the capabilities to probe several "beyond the standard model" scenarios, including sterile neutrinos and Non-Standard Interactions (NSI)
- Our studies show that DUNE can strongly constrain new mixing angles in the 3+1 scheme and some of the effective parameters of the NSI scenarios