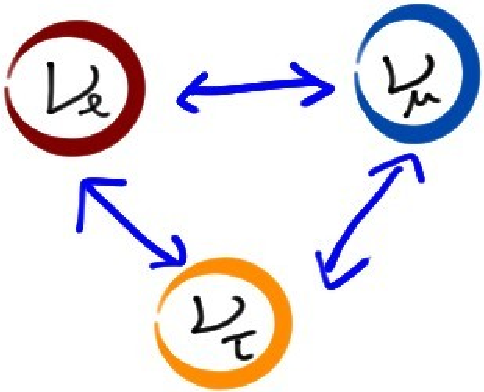
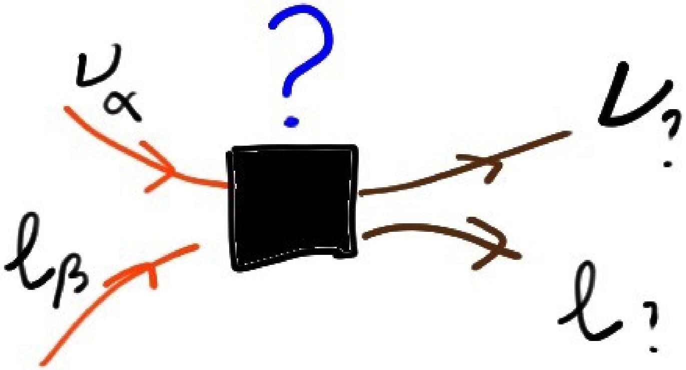
New Physics in the Lepton sector from future Neutrino Experiments





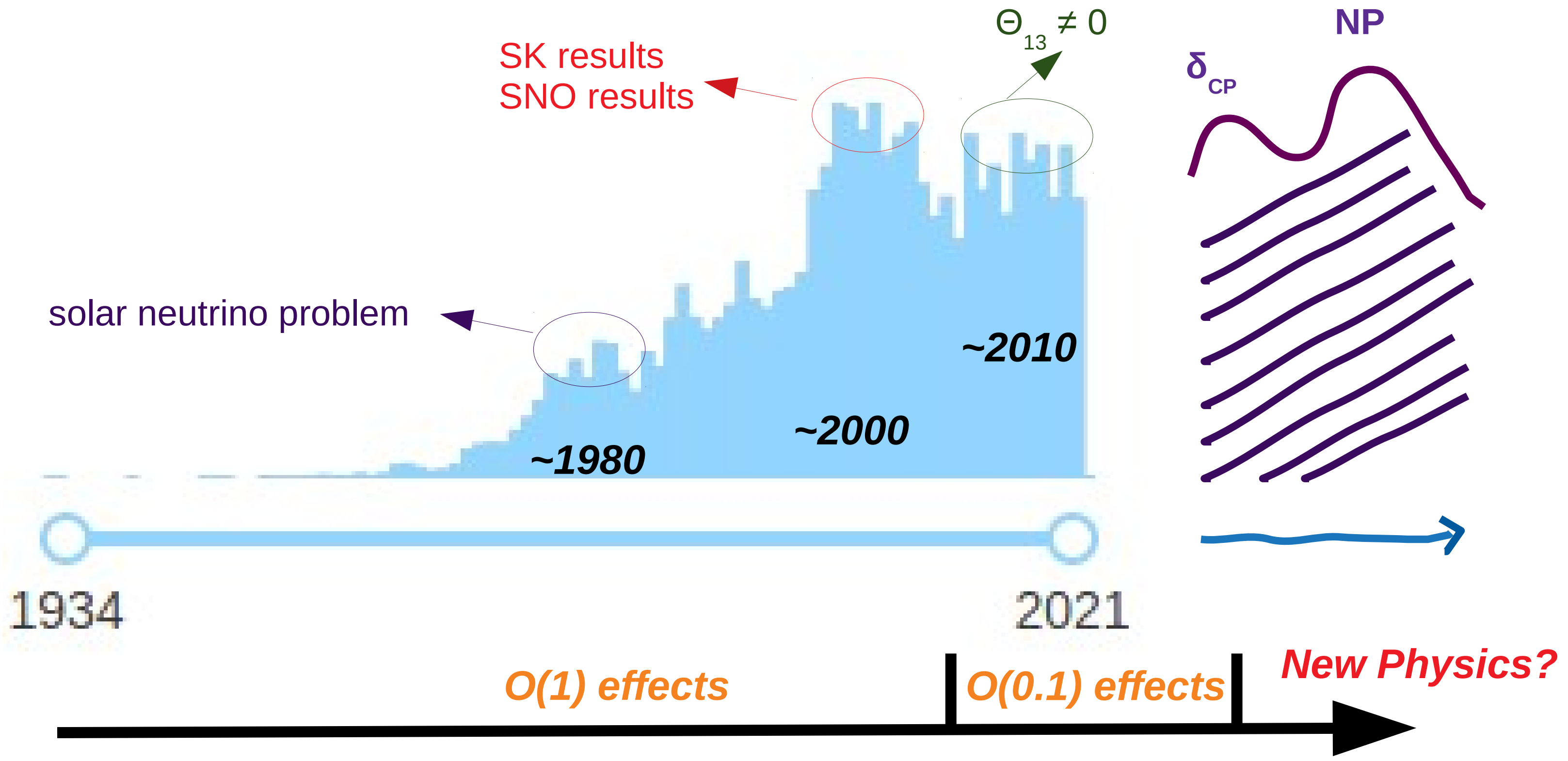

Neutrino Telescopes 2021

Chair of Galileo, from which, according to tradition, he gave lectures - Credits: Univ. of Padova - M. Pistore

Davide Meloni
Dipartimento di Matematica e Fisica
Roma Tre

Neutrino Physics and the Precision Era

around 36000 paper with the word “neutrino” in the title (Inspirehep.net)



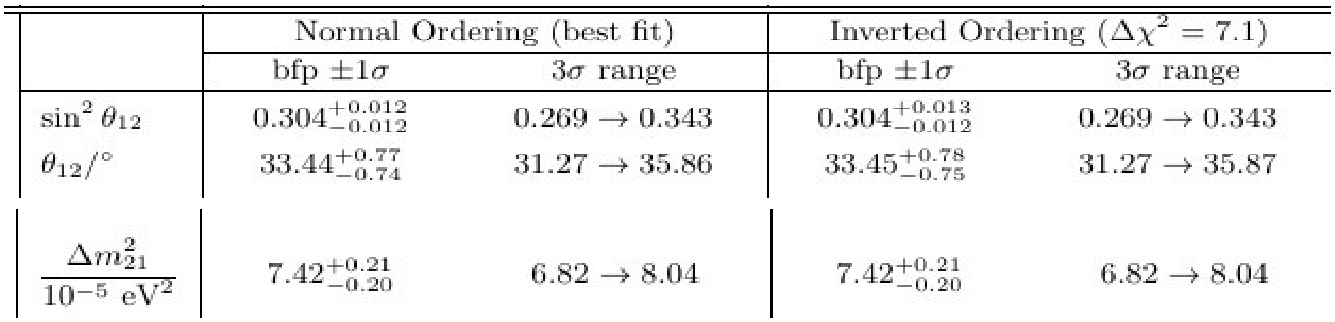
Current experimental situation

- standard 3-ν paradigm (well) established

solar sector

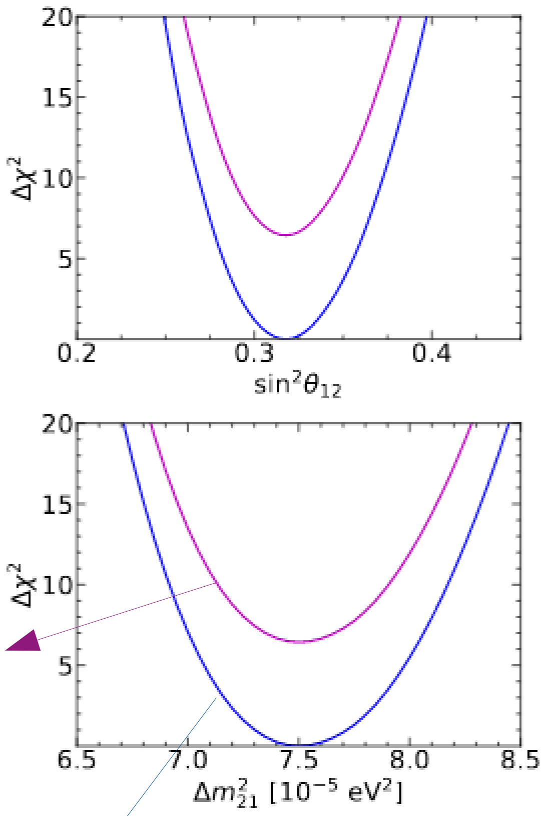
Salas, Forero, Gariazzo, Martinez-Mirave', Mena, Ternes, Tortola and Valle, JHEP02 (2021), 071

http://www.nu-fit.org



	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$

Erros at the level of 3-4 %



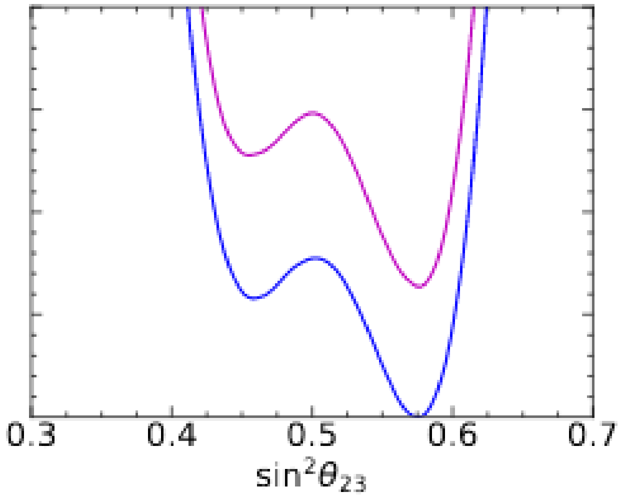
Inverted ordering

Normal ordering

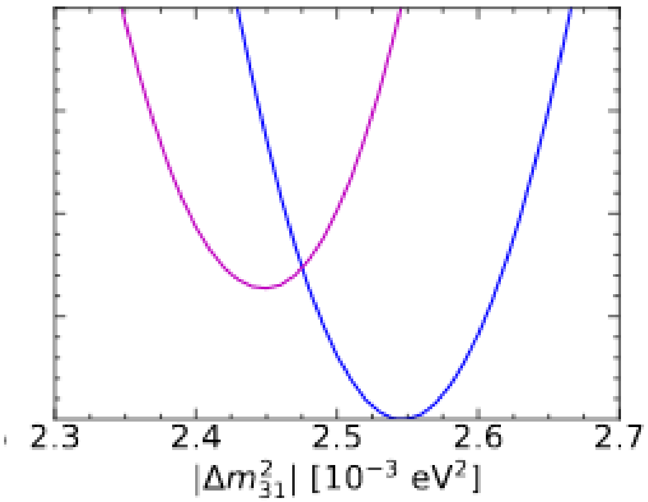
Current experimental situation

- standard 3-ν paradigm (well) established

atmospheric sector

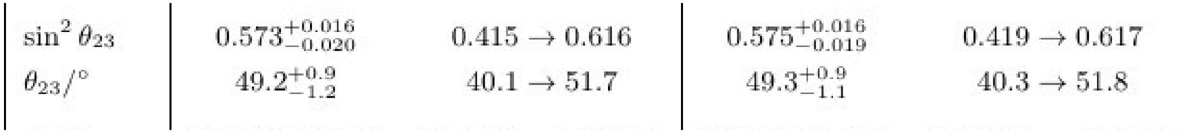


problem of the θ_{23} octant

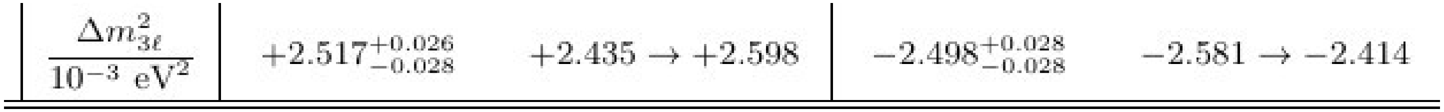


problem of the mass ordering

NO slighlty preferred



$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$

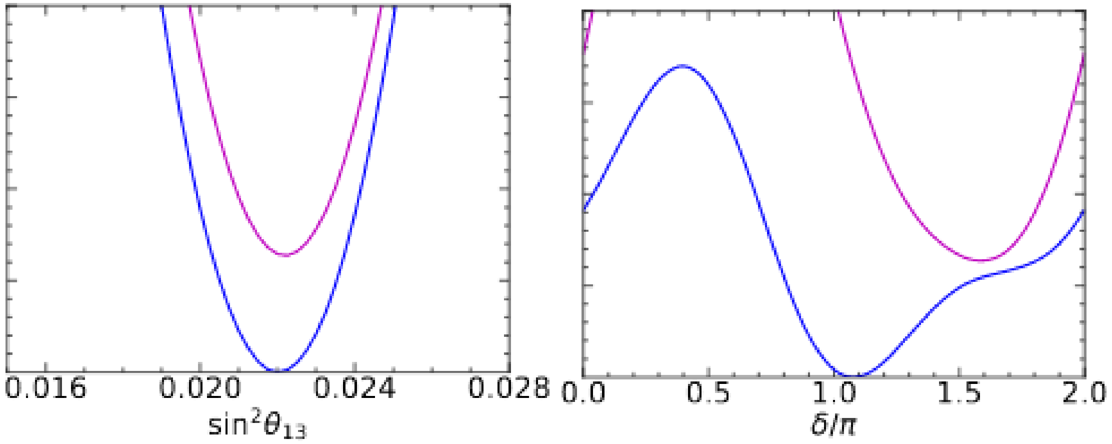


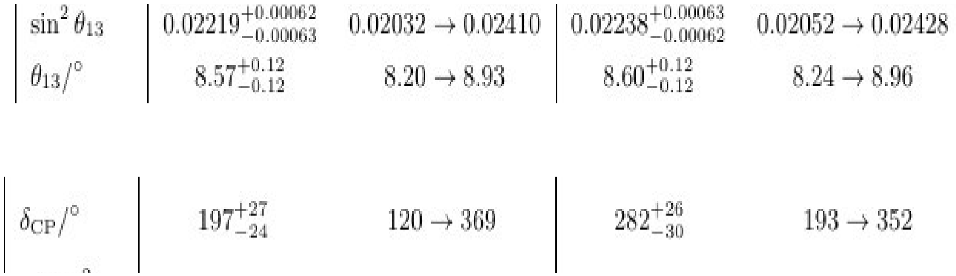
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

Current experimental situation

- standard 3-ν paradigm (well) established

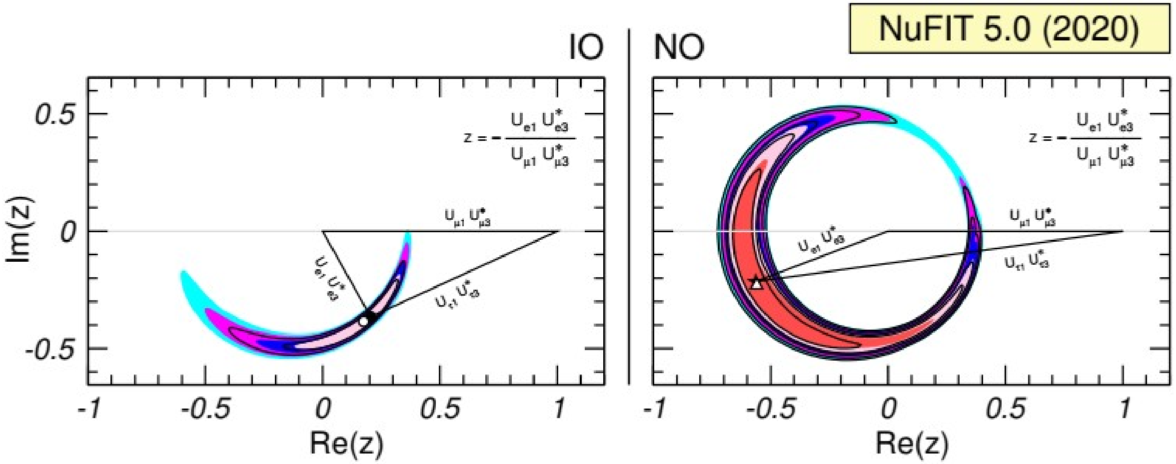
reactor sector





$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$

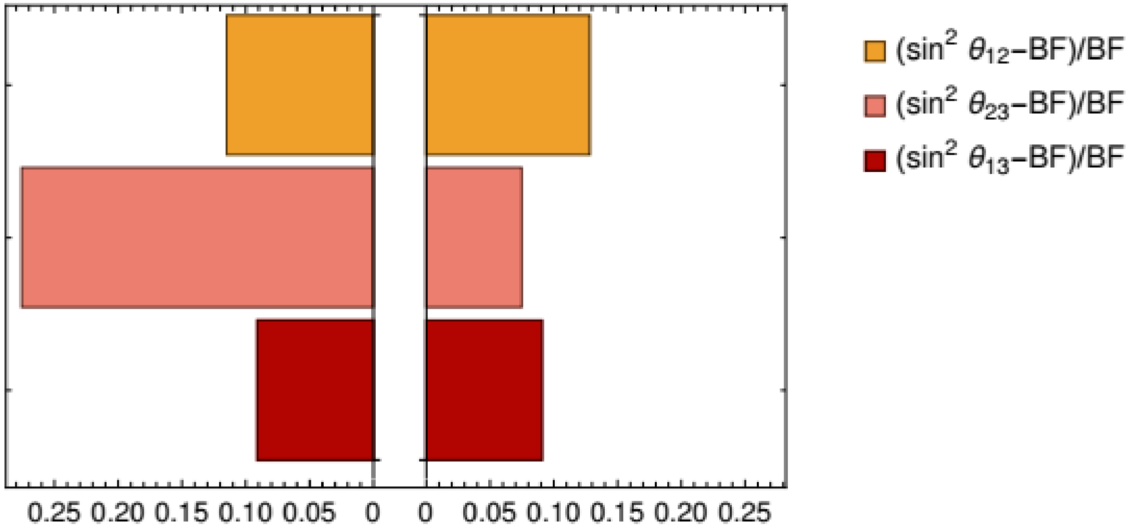
Existence of CP violation in the lepton sector (?)



Where is New Physics (in neutrino oscillations) ?

$$P \sim \left|A^{SM} + \epsilon A^{NP}\right|^2 \sim P^{SM} + 2\epsilon \Re\left(A^{SM} A^{NP}\right)$$

in the standard 3-ν paradigm



- in the absence of correlation between NP and standard parameters, strong constraints

- if correlation is strong, thus bounds can be (partially) relaxed

New Physics in Neutrino Oscillationss

Neutrino mass models

- scenarios where neutrinos new interactions:

“interdisciplinar” NP

neutrino decay

imprint on laboratory experiments

imprint on “*astrophysical*” neutrinos

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also Palazzo’s Talk

modified interactions with detector atoms

modified interactions with matter

- scenarios where the number of neutrino species is larger than 3

imprint on “*astrophysical*” neutrinos

sterile neutrino models – loss of unitarity

also Joaquim and Saviano’s Talks

- imprint on short-baseline experiments

- imprint on cosmological observables such as the cosmic microwave background and the distribution of matter at large scale

- ….

Future Experimental Alternatives

(some of them)

Accelerator-based long-baseline experiments
- Hyper-Kamiokande, DUNE

Accelerator-based short-baseline experiments
- MINERvA, MicroBooNE, SHiP
- COHERENT

Reactor neutrino experiments
- JUNO
- PROSPECT, SoLid, Watchman
- SOX

Astrophysical neutrino measurements
- PINGU, ORCA
- Hyper-Kamiokande, Jinping
- Super-Kamiokande-Gd
- IceCube-Gen2, KM3NeT, ARA
- PTOLEMY

Goals

- measure of δ_{CP}
- determination of mass hierarchy

Δm^2_{12}	~3%	~0.6%
Δm^2_{23}	~5%	~0.6%
$\sin^2\theta_{12}$	~6%	~0.7%
$\sin^2\theta_{23}$	~20%	N/A
$\sin^2\theta_{13}$	~14% → ~4%	~ 15%

- New Physics

Neutrino Decay

- Neutrino decay

G. B. Gelmini and M. Roncadelli, Phys. Lett.99B, 411 (1981)

J.Schechter, J.W.F.Valle,Phys.Rev.D25,774(1982)

G. B. Gelmini, J. W. F. Valle, Phys. Lett.142B, 181 (1984)

massless scalar field:
Majoron

$$\mathcal{L}_{\rm int} = \frac{(g_s)_{ij}}{2}\bar{\nu}_i\nu_j S + i\frac{(g_p)_{ij}}{2}\bar{\nu}_i\gamma_5\nu_j S$$

neutrino decay

$$\nu_i \to \nu + S$$

visible decay: active neutrinos

invisible decay (either because it is sterile or because its energy is too low to produce a signal through scattering)

Relevant parameter for phenomenology: ***depletion factor*** ***($m_i \to m_i - i\,\Gamma/2$)***

$$D_i = e^{-t/\tau_i} = e^{-\frac{m_i}{\tau_i}\frac{L}{E}} = e^{-\frac{1}{\beta_i}\frac{L}{E}} = e^{-\alpha_i\frac{L}{E}}$$

decay is relevant when $L/(E\,\beta_i) \gg 1$

Neutrino Decay

- Simplified 2-flavor approach

One unstable neutrino:

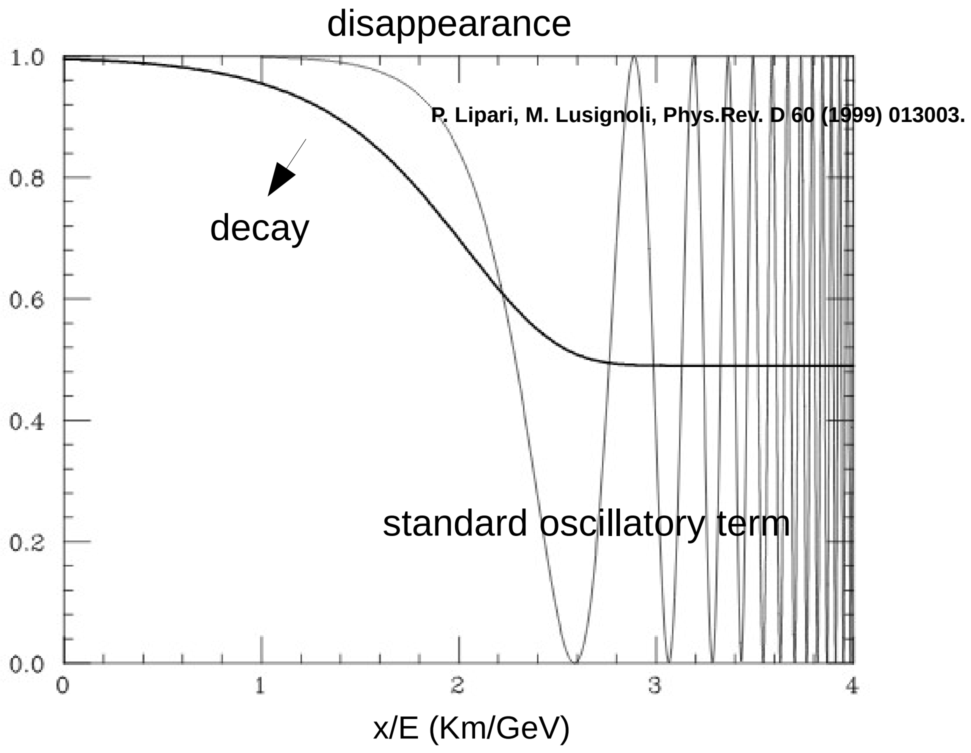
$$i\frac{d}{dx}\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix}=U\left[\frac{\Delta m^2}{2E}\begin{pmatrix}0&0\\0&1\end{pmatrix}-i\frac{\alpha}{2E}\begin{pmatrix}0&0\\0&1\end{pmatrix}\right]U^+\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix}\qquad \alpha=\frac{m}{\tau}\qquad U=\begin{pmatrix}\cos\theta&\sin\theta\\-\sin\theta&\cos\theta\end{pmatrix}$$

$$P(\nu_\alpha\rightarrow\nu_\alpha)=\cos^4\theta+\frac{1}{2}\sin^2(2\theta)e^{-\frac{\alpha x}{2E_\nu}}\cos\left(\frac{\Delta m^2 x}{2E_\nu}\right)+e^{-\frac{\alpha x}{E_\nu}}\sin^4\theta$$

$$P(\nu_\alpha\rightarrow\nu_\beta)=\frac{1}{2}\sin^2(2\theta)e^{-\frac{\alpha x}{E_\nu}}\left[1+e^{\frac{\alpha x}{E_\nu}}-2e^{\frac{\alpha x}{2E_\nu}}\cos\left(\frac{\Delta m^2 x}{2E_\nu}\right)\right]$$

⬇

$$P(\nu_\alpha\rightarrow\nu_\alpha)+P(\nu_\alpha\rightarrow\nu_\beta)=\cos^2\theta+e^{-\frac{\alpha x}{E_\nu}}\sin^2\theta\neq 1$$



P. Lipari, M. Lusignoli, Phys.Rev. D 60 (1999) 013003.

Neutrino Decay – <u>The Future</u>

- $\nu_3 \rightarrow \nu_4 + S$, 3-flavor effects taken into account

$$H = U\left[\frac{1}{2E}\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix} - i\frac{1}{2\beta_3 E}\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 1\end{pmatrix}\right]U^\dagger + \begin{pmatrix}A & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

$$\begin{pmatrix}\nu_\alpha\\ \nu_s\end{pmatrix} = \begin{pmatrix}U_{PMNS} & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}\nu_i\\ \nu_4\end{pmatrix}$$

unstable third mass eigenstates

standard matter effects

No active-sterile mixing

- At ***very*** long-baseline accelerator experiments:

damping factor

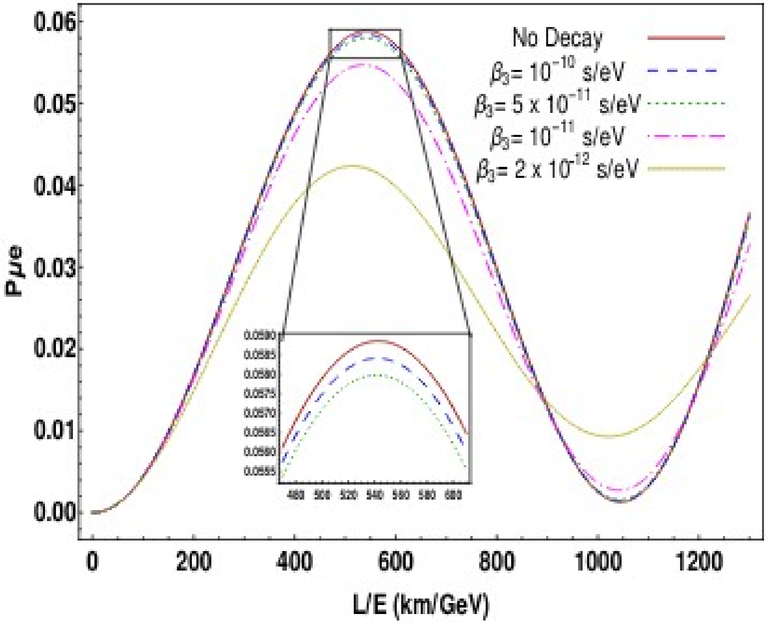
"constant term"

$$P^{(0)}_{\mu e} = \sin^2 2\theta_{13}\sin^2\theta_{23}\left[\boxed{e^{-\frac{1}{\beta_3}\frac{L}{2E}}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \boxed{\left(\frac{1-e^{-\frac{1}{\beta_3}\frac{L}{2E}}}{2}\right)^2}\right]$$

$$P^{(0)}_{\mu\tau} = \cos^4\theta_{13}\sin^2 2\theta_{23}\left[e^{-\frac{1}{\beta_3}\frac{L}{2E}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \left(\frac{1-e^{-\frac{1}{\beta_3}\frac{L}{2E}}}{2}\right)^2\right]$$

$$P^{(0)}_{\mu\mu} = 1 + 2\left(e^{-\frac{1}{\beta_3}\frac{L}{2E}} - 1\right)\cos^2\theta_{13}\sin^2\theta_{23} + \left(e^{-\frac{1}{\beta_3}\frac{L}{2E}} - 1\right)^2\cos^4\theta_{13}\sin^4\theta_{23}$$
$$- e^{-\frac{1}{\beta_3}\frac{L}{2E}}\left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right).$$

Ghoshal, Giarnetti, Meloni, 2003.09012,
accepted in Journal of Physics G



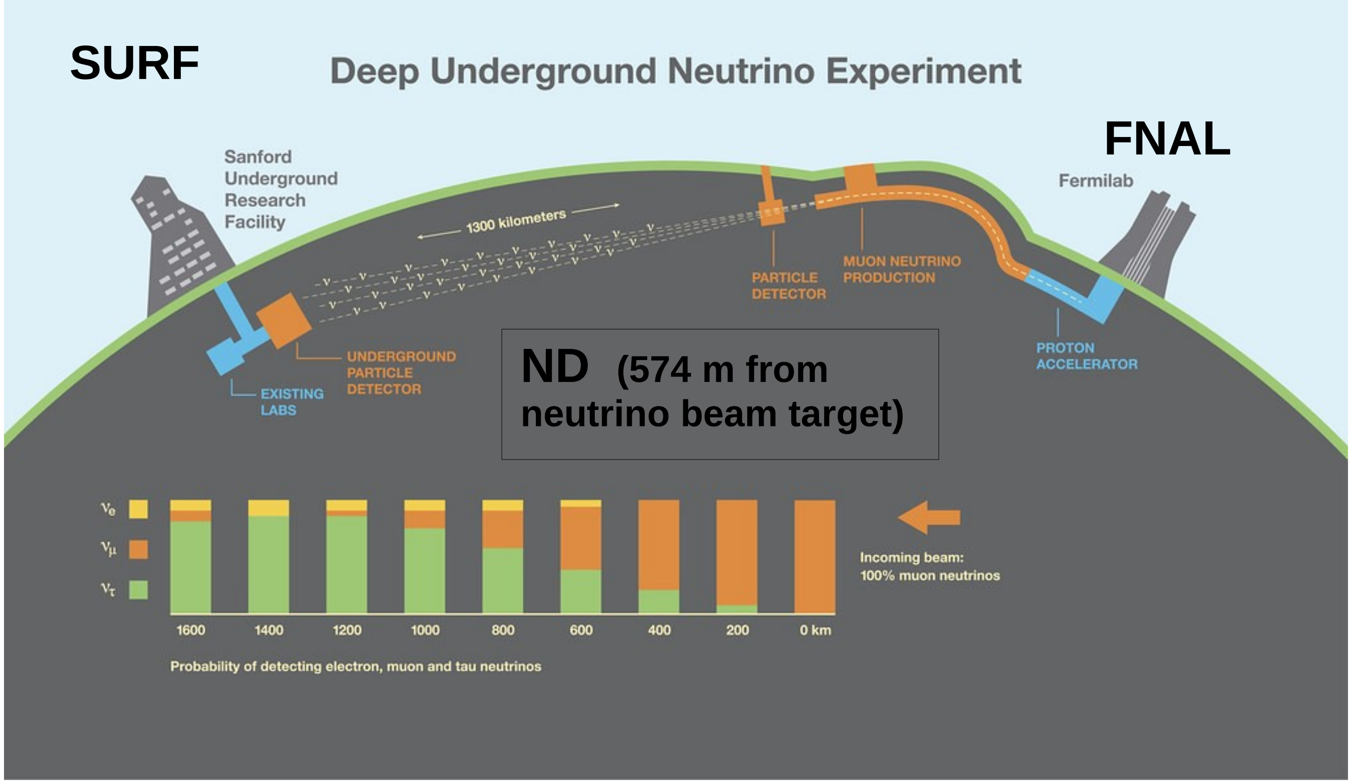
Introducing DUNE

“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



SURF

FNAL

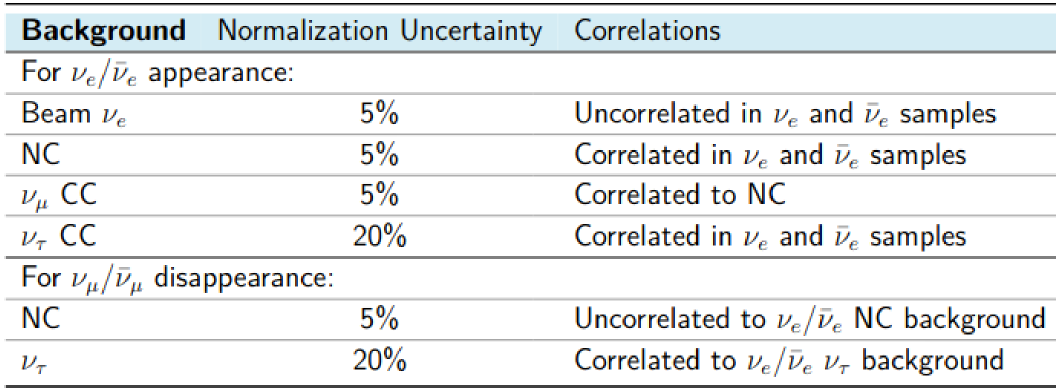
ND (574 m from neutrino beam target)

DUNE events

- neutrino signal channels:

- ν_e appearance and ν_μ disappearance channels
  (2% and 5% systematic normalization errors)

T. Alionet al[DUNE Collaboration], arXiv:1606.09550 [physics.ins-det]



Background	Normalization Uncertainty	Correlations
For $\nu_e/\bar{\nu}_e$ appearance:		
Beam ν_e	5%	Uncorrelated in ν_e and $\bar{\nu}_e$ samples
NC	5%	Correlated in ν_e and $\bar{\nu}_e$ samples
ν_μ CC	5%	Correlated to NC
ν_τ CC	20%	Correlated in ν_e and $\bar{\nu}_e$ samples
For $\nu_\mu/\bar{\nu}_\mu$ disappearance:		
NC	5%	Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background
ν_τ	20%	Correlated to $\nu_e/\bar{\nu}_e$ ν_τ background

- ν_τ appearance channel

electron mode

- 6% overall detection efficiency for the signal
- signal-to-background ratio of 2.45
- signal systematic uncertainty of 20%

hadronic mode

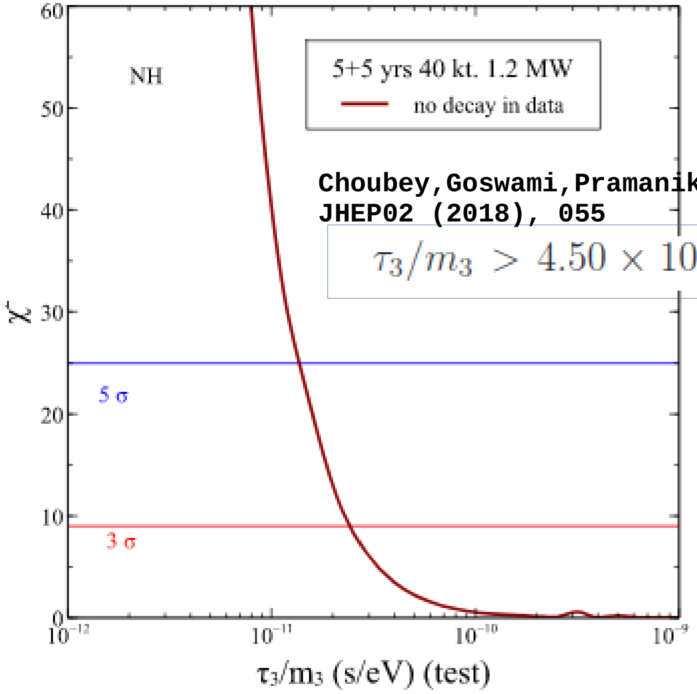
- we take into account that only 30% of the τ-s are detected
- 0.5% of the NC events as a background

- neutral current events
  (hadronic shower with a certain visible energy)

- overall 90% signal detection efficiency
- systematic uncertainty at 10%
- backgrounds come from the mis-identification of CC events (mainly a conservative 10% of the ν_μ and ν_e^{CC} events)

Latest sensitivities to nu lifetime

- sensitivity



Choubey,Goswami,Pramanik
JHEP02 (2018), 055

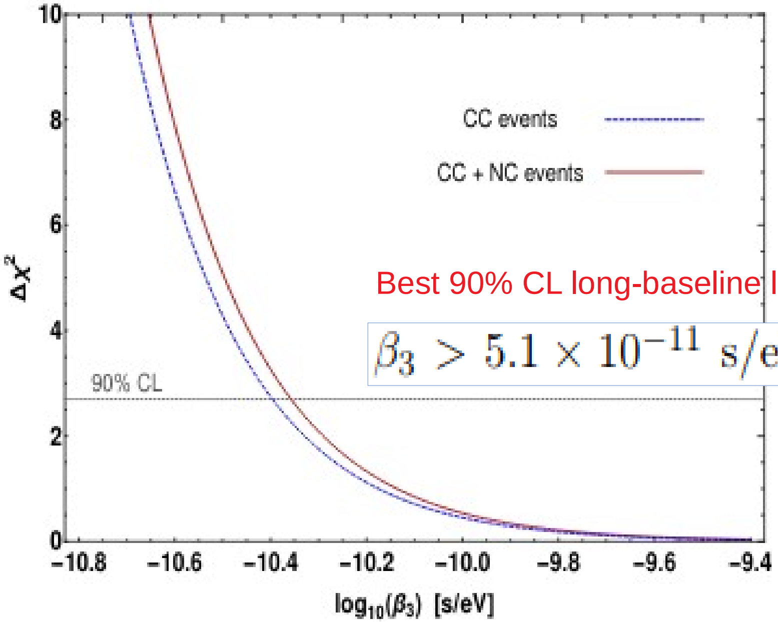
$$\tau_3/m_3 > 4.50 \times 10^{-11}\ \mathrm{s/eV}$$

DUNE

results from other future experiments

MOMENT	$2.8\ (1.6) \times 10^{-11}$	a muon-decay medium-baseline neutrino beam facility
ESSnuSB (540 km)	$4.22\ (1.68) \times 10^{-11}$	Neutrino Super Beam Experiment
ESSnuSB (360 km)	$4.95\ (2.64) \times 10^{-11}$	
JUNO	$9.3\ (4.7) \times 10^{-11}$	reactor neutrinos
INO	$1.51\ (0.566) \times 10^{-10}$	atmospheric neutrinos
KM3NeT-ORCA	$2.5\ (1.4) \times 10^{-10}$	atmospheric neutrinos

Ghoshal, Giarnetti, Meloni, 2003.09012,
accepted in Journal of Physics G



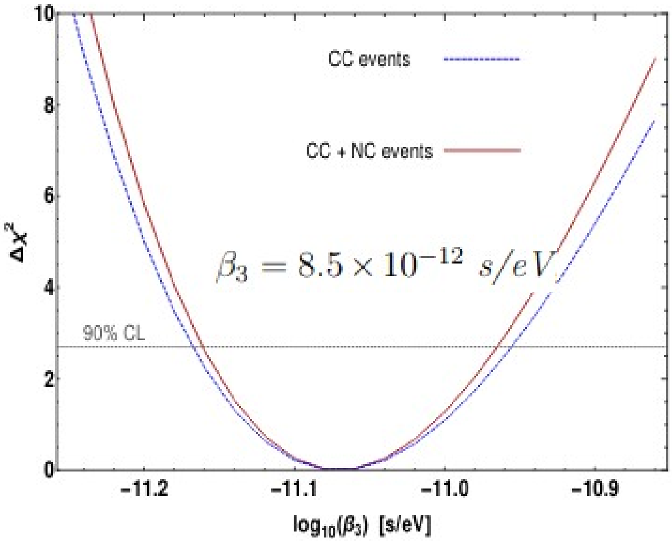
Best 90% CL long-baseline limit

$$\beta_3 > 5.1 \times 10^{-11}\ \mathrm{s/eV}$$

Latest sensitivities to nu lifetime

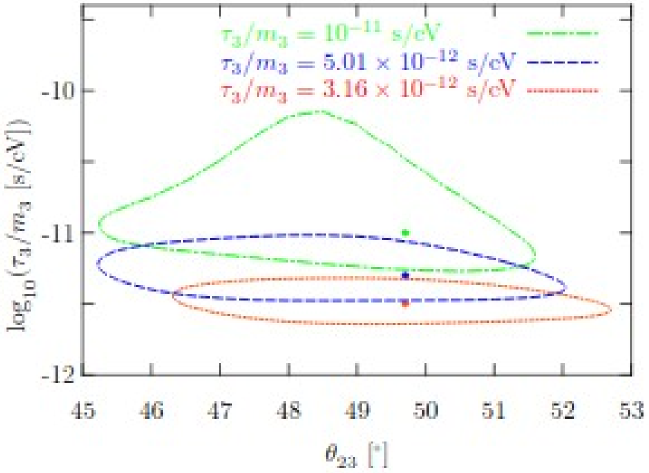
- precision measurement in DUNE

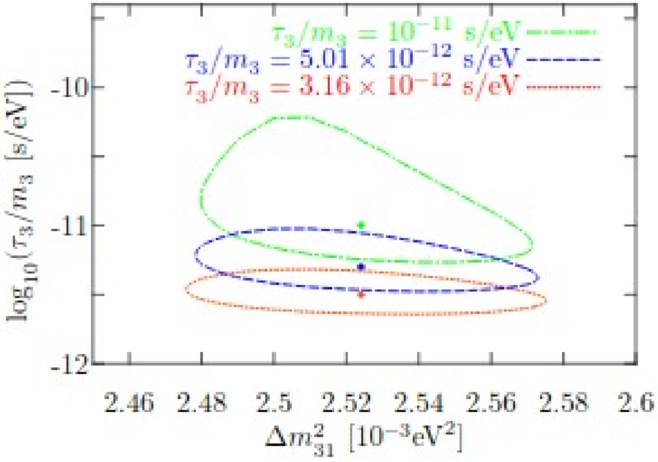
assuming $\beta_3 \neq 0$, uncertainty of about [10−30]% can be set at 90% CL, depending on the central value used.



- Impact on measurements in MOMENT

Tang, Wang and Zhang, JHEP02 (2018), 055





little correlations between θ_{23} and Δm^2_{31} at 3σ confidence level

Non-standard Neutrino Interactions (NSI)

- in the low energy regime, weak neutrino interactions can be described by effective four-fermion operators

$$\mathcal{L}_\nu = \frac{G_F}{\sqrt{2}} \left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5)\ell_\alpha\right] \left[\bar{f}' \gamma_\rho (1-\gamma^5) f\right]$$

$$\mathcal{L}_{\rm MSW} = \frac{G_F}{\sqrt{2}} \left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5)\nu_\alpha\right] \left[\bar{f} \gamma_\rho (1-\gamma^5) f\right]$$

lɑ = lepton doublet

f= components of an arbitrary weak doublet

- low-energy fingerprint of many “new physics” scenarios (similar structure as above)

$$\mathcal{L}_{\rm NSI} = \mathcal{L}_{V\pm A} + \mathcal{L}_{S\pm P} + \mathcal{L}_T,$$

ε represents the strength of the new interaction compared to G_F

source and detector interactions

$$\frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\varepsilon}_{\alpha\beta}^{s,f,f',V\pm A} \left[\bar{\nu}_\beta \gamma^\rho (1-\gamma^5)\ell_\alpha\right]\left[\bar{f}' \gamma_\rho (1\pm\gamma^5) f\right] + \frac{G_F}{\sqrt{2}} \sum_{f} \tilde{\varepsilon}_{\alpha\beta}^{m,f,V\pm A} \left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5)\nu_\beta\right]\left[\bar{f} \gamma_\rho (1\pm\gamma^5) f\right] + \text{h.c.},$$

non-standard matter effects

$$\mathcal{L}_{S\pm P} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\varepsilon}_{\alpha\beta}^{s,f,f',S\pm P} \left[\bar{\nu}_\beta (1+\gamma^5)\ell_\alpha\right]\left[\bar{f}' (1\pm\gamma^5) f\right]$$

$$\mathcal{L}_T = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\varepsilon}_{\alpha\beta}^{s,f,f',T} \left[\bar{\nu}_\beta \sigma^{\rho\tau} \ell_\alpha\right]\left[\bar{f}' \sigma_{\rho\tau} f\right]$$

Modified Oscillation Probabilities

- Standard oscillations:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \langle \nu_\beta | e^{-iHL} | \nu_\alpha \rangle^2 \right|$$

- Oscillations with Neutral Current NSI:

$$|\nu^s_\alpha\rangle = |\nu_\alpha\rangle + \sum_{\beta=e,\mu,\tau} \varepsilon^s_{\alpha\beta} |\nu_\beta\rangle$$

$$\langle \nu^d_\beta| = \langle \nu_\beta| + \sum_{\alpha=e,\mu,\tau} \varepsilon^d_{\alpha\beta} \langle \nu_\alpha|.$$

$$P(\nu^s_\alpha \rightarrow \nu^d_\beta) = \left| \langle \nu^d_\beta | e^{-i(H+V_{NSI})L} | \nu^s_\alpha \rangle \right|^2$$

$$\epsilon_{\alpha\beta} \equiv \epsilon^{eV}_{\alpha\beta} + \frac{N_u}{N_e} \epsilon^{uV}_{\alpha\beta} + \frac{N_d}{N_e} \epsilon^{dV}_{\alpha\beta}$$

$$V_{\text{NSI}} = \sqrt{2} G_F N_e \begin{pmatrix} \varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} \end{pmatrix}$$

$$\boxed{P(\nu^s_\alpha \rightarrow \nu^d_\beta) = \left| \left[(1+\epsilon^d)^T e^{-i(H+V_{NSI})L} (1+\epsilon^s)^T \right]_{\beta\alpha} \right|^2}$$

Modified Oscillation Probabilities

- Existing bounds

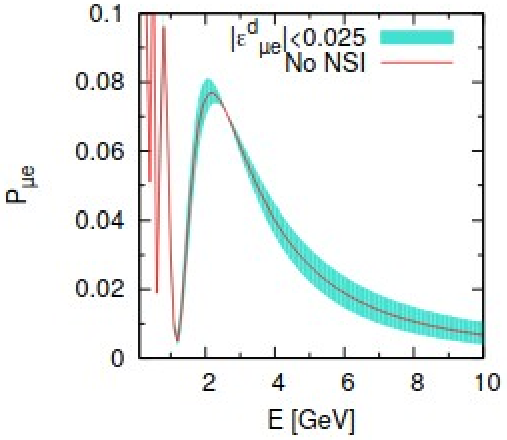
Blennow, Choubey, Ohlsson, Pramanik and Raut, JHEP08 (2016), 090
Biggio, Blennow, and Fernandez-Martinez, JHEP08, 090 (2009), 0907.0097

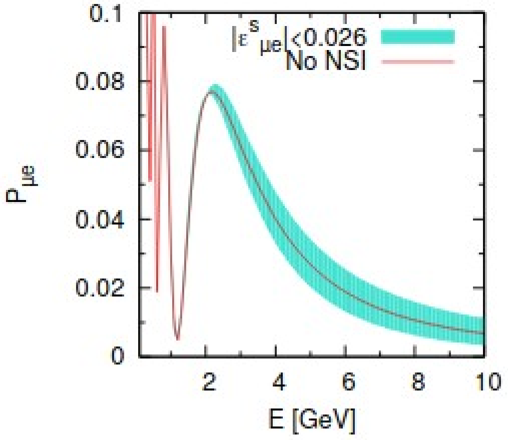
from G_F , pion decay, unitarity of CKM, oscillation experiments

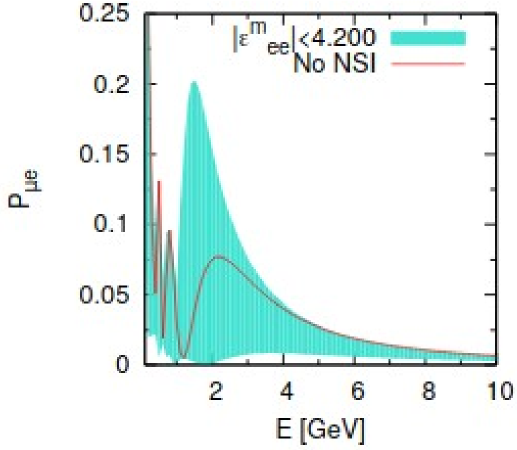
$$|\varepsilon^{s/d}_{\alpha\beta}| < \begin{bmatrix} 0.041 & 0.025 & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.12 & 0.018 & 0.13 \end{bmatrix}$$

mainly from neutrino-electron scattering and neutrino oscillations

$$|\varepsilon^{m}_{\alpha\beta}| < \begin{bmatrix} 4.2 & 0.3 & 3.0 \\ 0.3 & - & 0.04 \\ 3.0 & 0.04 & 0.15 \end{bmatrix}$$







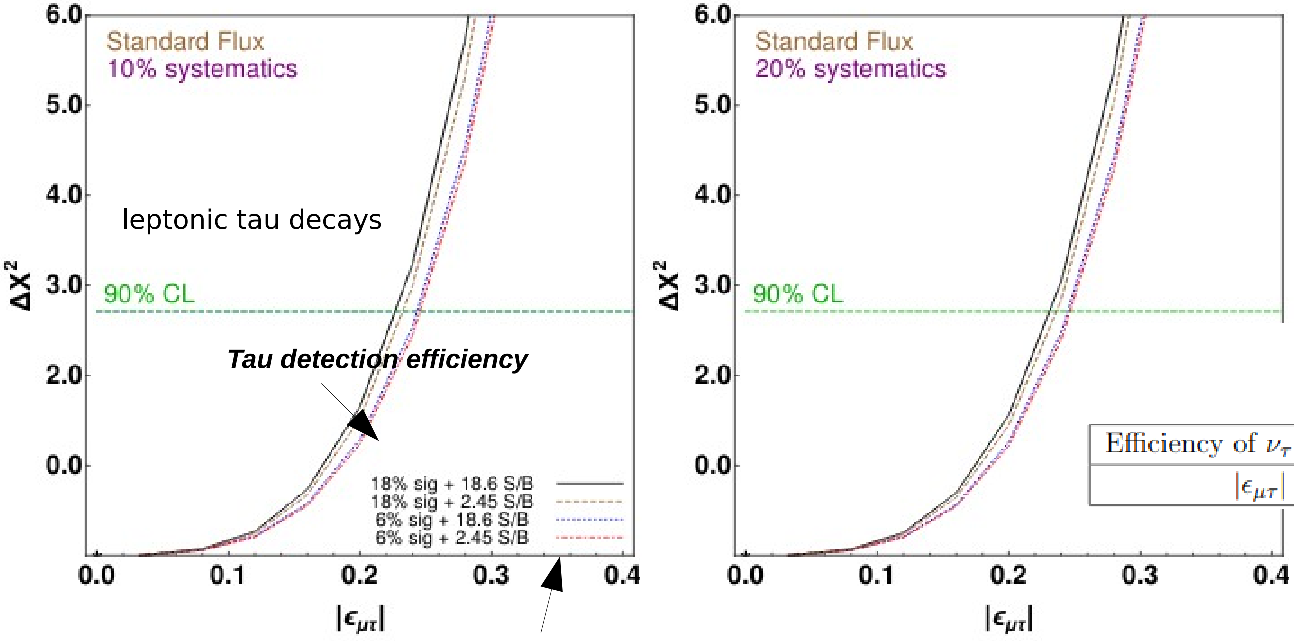
since the existing bounds on matter NSIs are weaker, they affect the probability more

The Future: signals at the DUNE Far Detector

- Introducing tau neutrinos into the game

Machado, Schulz and Turner, Phys. Rev. D102 (2020) no.5, 053010
Ghoshal, Giarnetti and Meloni, JHEP12 (2019), 126
de Gouvea and Kelly,Nucl. Phys. B908 (2016), 318-335

$$P_{\mu\tau} = P_{\mu\tau}^{SM} + \left(\frac{1}{2}\epsilon_{\tau\tau}\cos^2(2\theta_{23}) + 2\cos(2\theta_{23})\mathrm{Re}\{\epsilon_{\mu\tau}\}\right)(AL)\sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) + \mathcal{O}(\epsilon^2)$$



leptonic tau decays

Tau detection efficiency

assumptions on the signal-to-background ratio

	Standard Flux (10% sys)			
	S/B = 2.45		S/B = 18.6	
Efficiency of ν_τ detection	6%	18%	6%	18%
$\lvert\epsilon_{\mu\tau}\rvert$	[0,0.2452]	[0,0.2320]	[0,0.2431]	[0,0.2264]

limits approximately 35% smaller than those set by DUNE using only ν_e appearance and ν_μ disappearance channels with standard flux, $|\epsilon_{\mu\tau}|<0.32$

The future: signals at the DUNE Near Detector

- Source and detecton NSI

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$$P(\nu^s_\alpha \to \nu^d_\beta) = \left|\left[(1+\epsilon^d)^T e^{-i(H+V_{NSI})L}(1+\epsilon^s)^T\right]_{\beta\alpha}\right|^2 \xrightarrow{L=0} \boxed{P_{\alpha\beta} = |[(1+\varepsilon^d)^T(1+\varepsilon^s)^T]_{\beta\alpha}|^2}$$

Perturbation theory

$$P_{\alpha\alpha} = 1 + 2|\varepsilon^s_{\alpha\alpha}|\cos\Phi^s_{\alpha\alpha} + 2|\varepsilon^d_{\alpha\alpha}|\cos\Phi^d_{\alpha\alpha}$$

- dependence on the diagonal NSI parameters appears already at the first order

$$P_{\alpha\beta} = |\varepsilon^s_{\alpha\beta}|^2 + |\varepsilon^d_{\alpha\beta}|^2 + 2|\varepsilon^s_{\alpha\beta}||\varepsilon^d_{\alpha\beta}|\cos(\Phi^s_{\alpha\beta} - \Phi^d_{\alpha\beta})$$

- main dependence on ε with the same flavor indeces

The future: signals at the DUNE Near Detector

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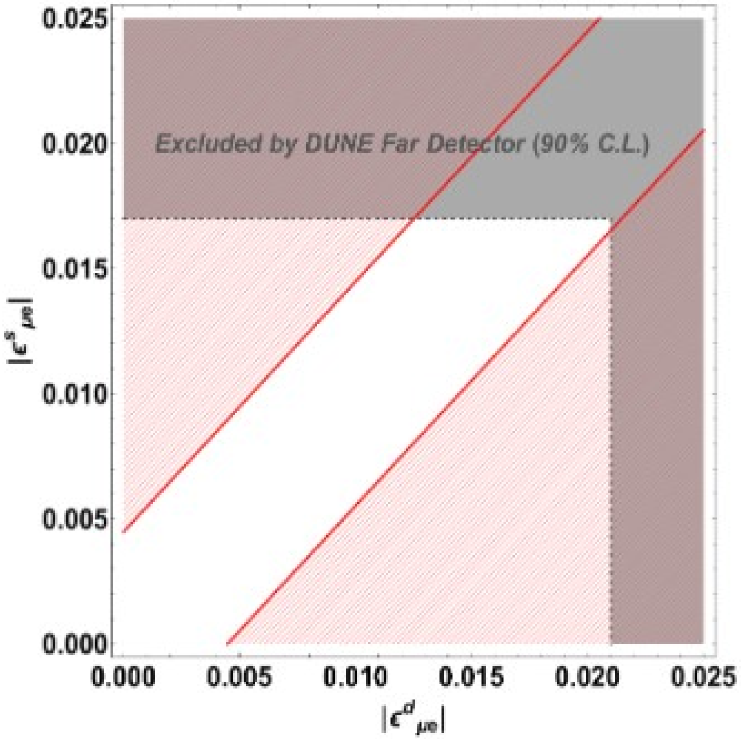
- overall systematic normalization uncertainty of 10% for the ν_μ disappearance, ν_e disappearance and ν_e appearance channels signals

- 25% for the ν_τ appearance signal

- for the NC background we considered a 15% uncertainty



Investigation of parameter space complementary to Far Detector studies

$$|\varepsilon^{s/d}_{\mu e}| < 0.0046 \qquad |\varepsilon^{s/d}_{\mu\tau}| < 0.0018$$

Very competitive bounds!

Conclusions

- On-going and planned neutrino experiments will probe the PMNS with huge precision
- Good chance to investigate New Physics effects in Neutrino oscillations:

  several "Beyond the Standard Model" scenarios, including Neutrino Decay and Non-Standard Interactions
- For the latter, interesting synergy between FD and ND