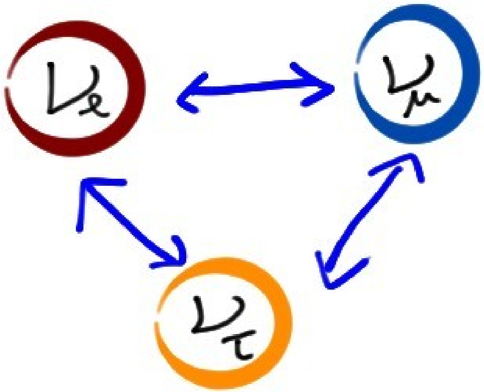
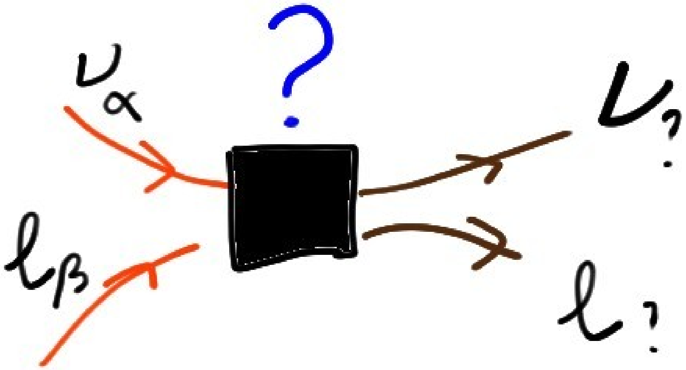
New Physics in the Lepton sector from future Neutrino Experiments





Davide Meloni
Dipartimento di Matematica e Fisica
Roma Tre

Beyond Standard Model:
From Theory to Experiment
(BSM- 2021)

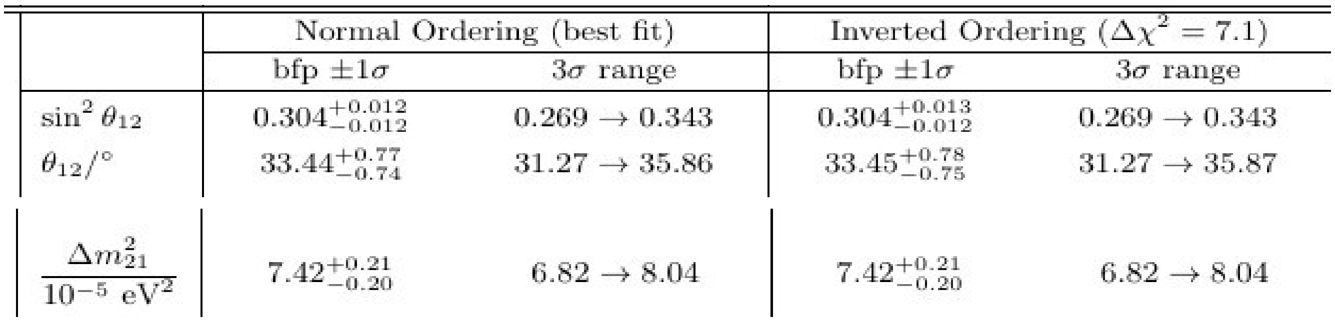
Current experimental situation

- standard 3-ν paradigm (well) established

solar sector

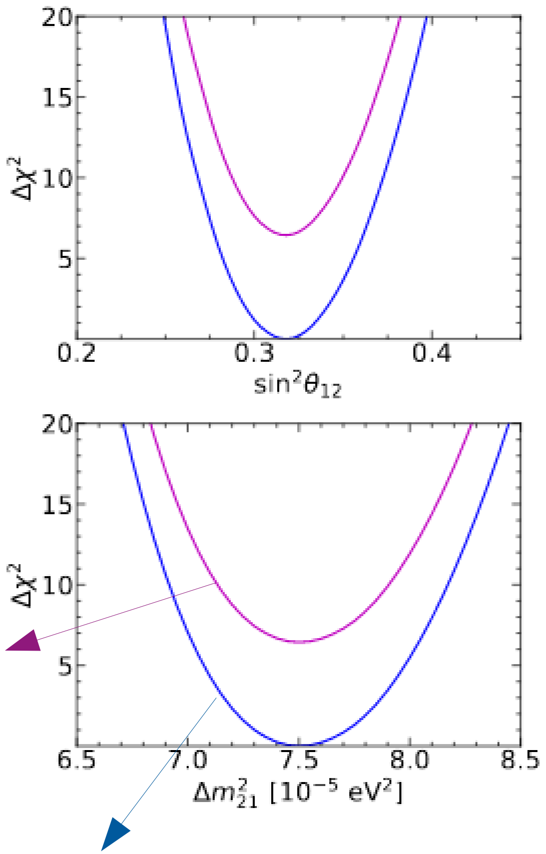
**Salas, Forero, Gariazzo, Martinez-Mirave’,
Mena, Ternes, Tortola and Valle,
JHEP02 (2021), 071**

http://www.nu-fit.org



	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$

Erros at the level of 3-4 %



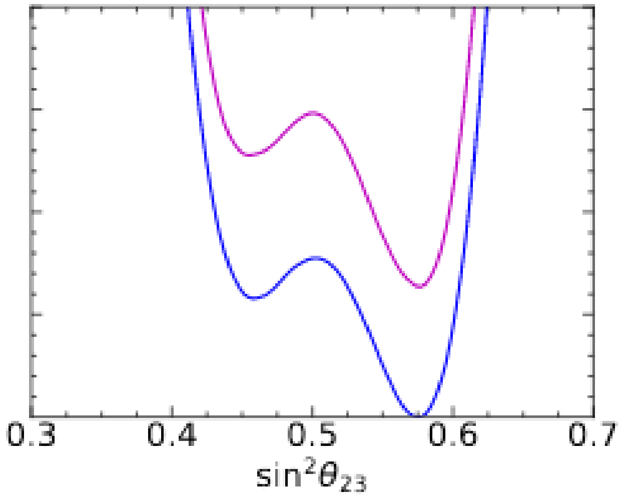
Inverted ordering

Normal ordering

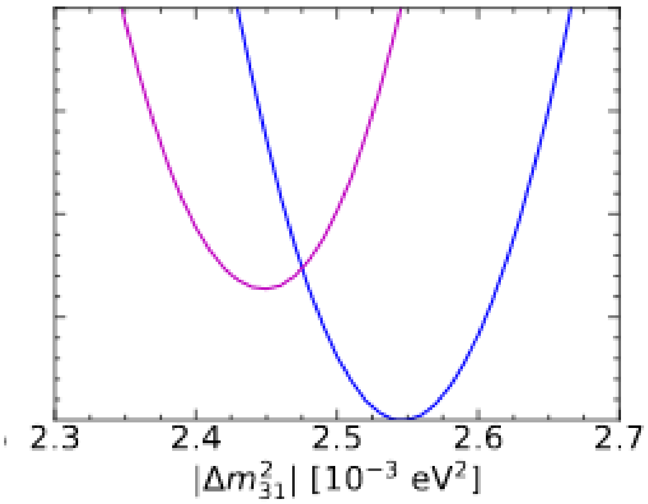
Current experimental situation

- standard 3-ν paradigm (well) established

atmospheric sector



problem of the θ_{23} octant



problem of the mass ordering

NO slighlty preferred

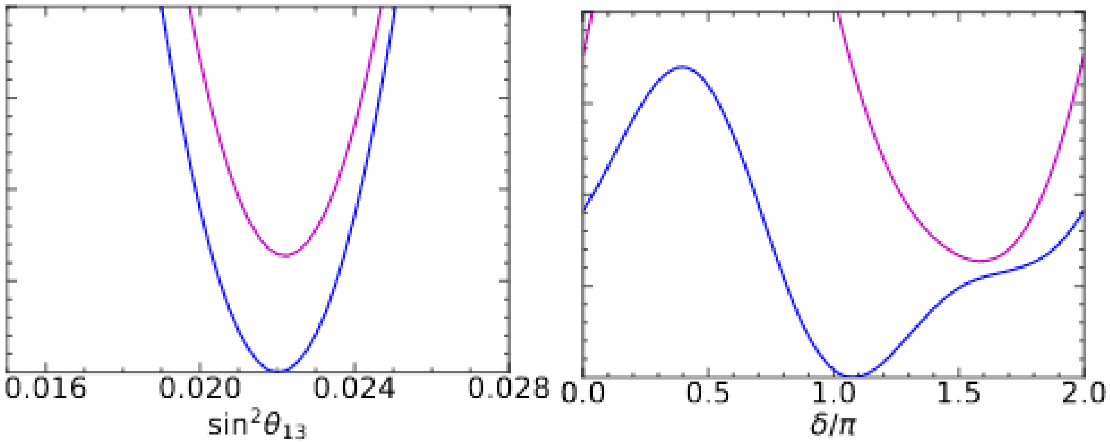
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$

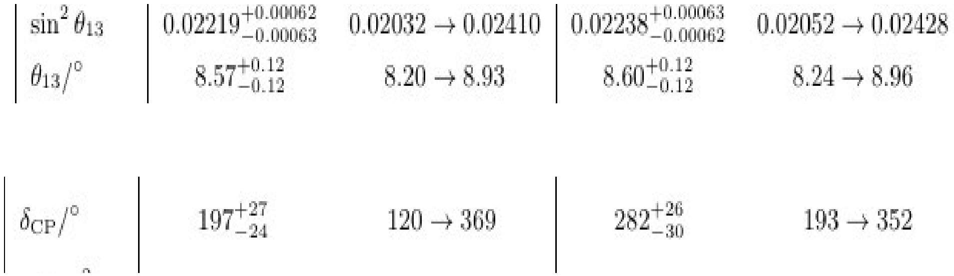
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

Current experimental situation

- standard 3-ν paradigm (well) established

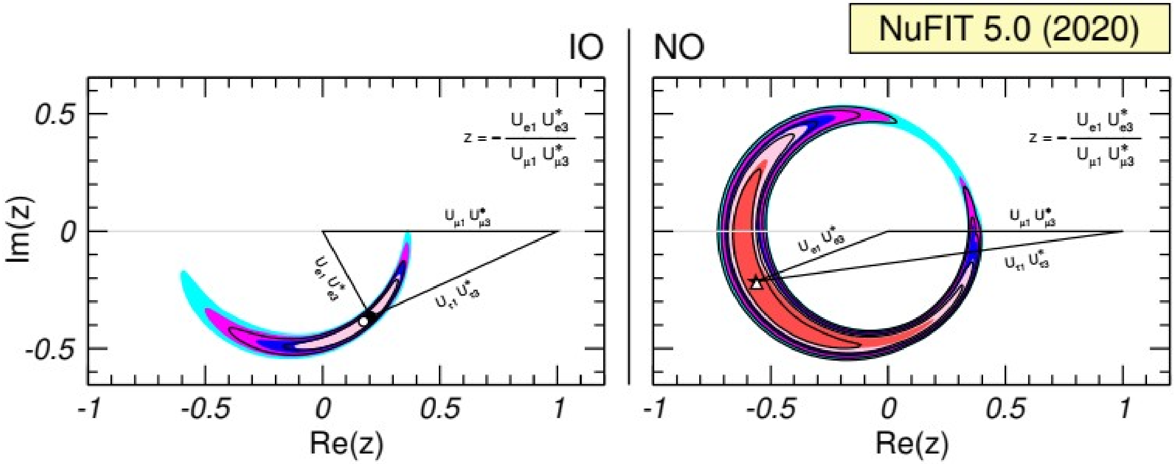
reactor sector





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

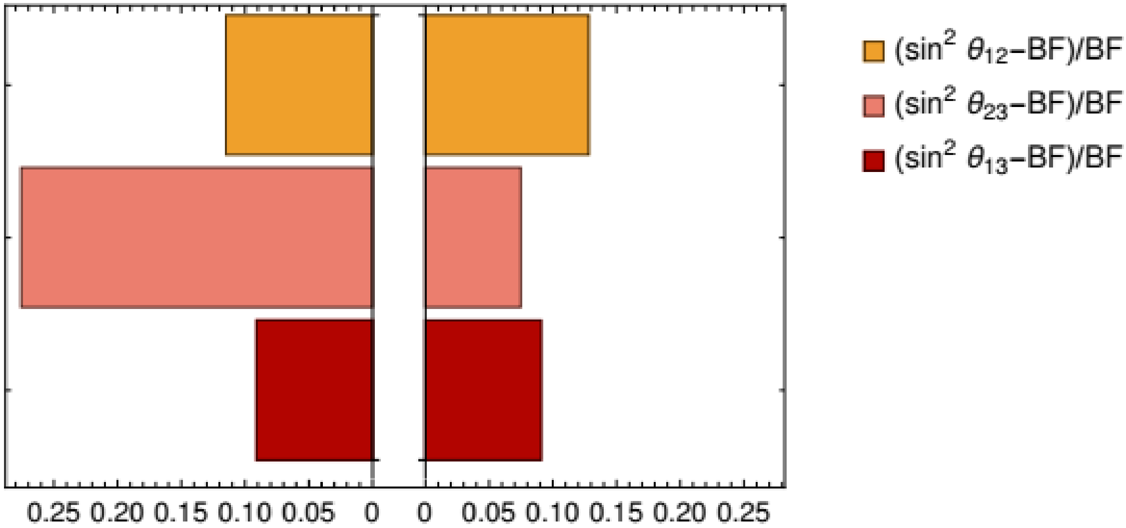
Existence of CP violation in the lepton sector (?)



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



e absence of correlation between NP
andard 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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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

- 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**$_i$ **→ m**$_i$ **– i Γ/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 – The Future

- $\nu_3 \rightarrow \nu_4$ + 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

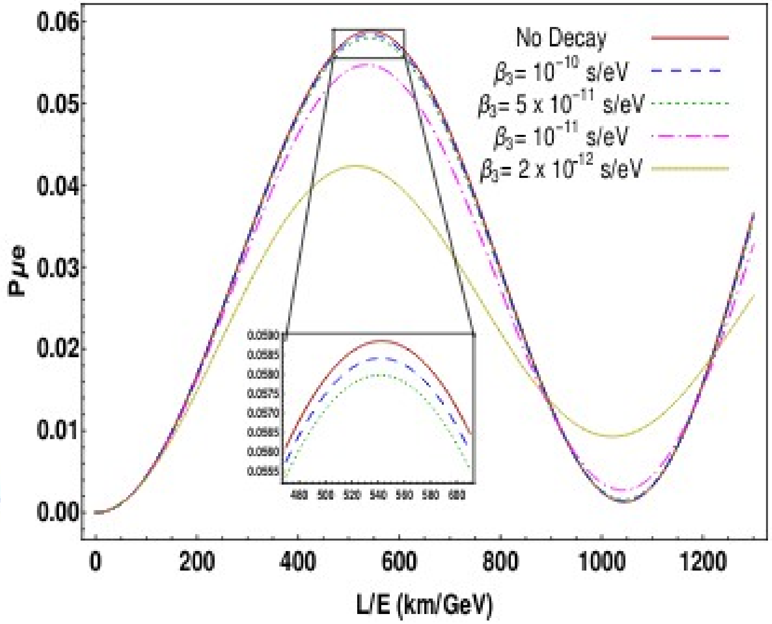
"constant term"

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

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

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

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



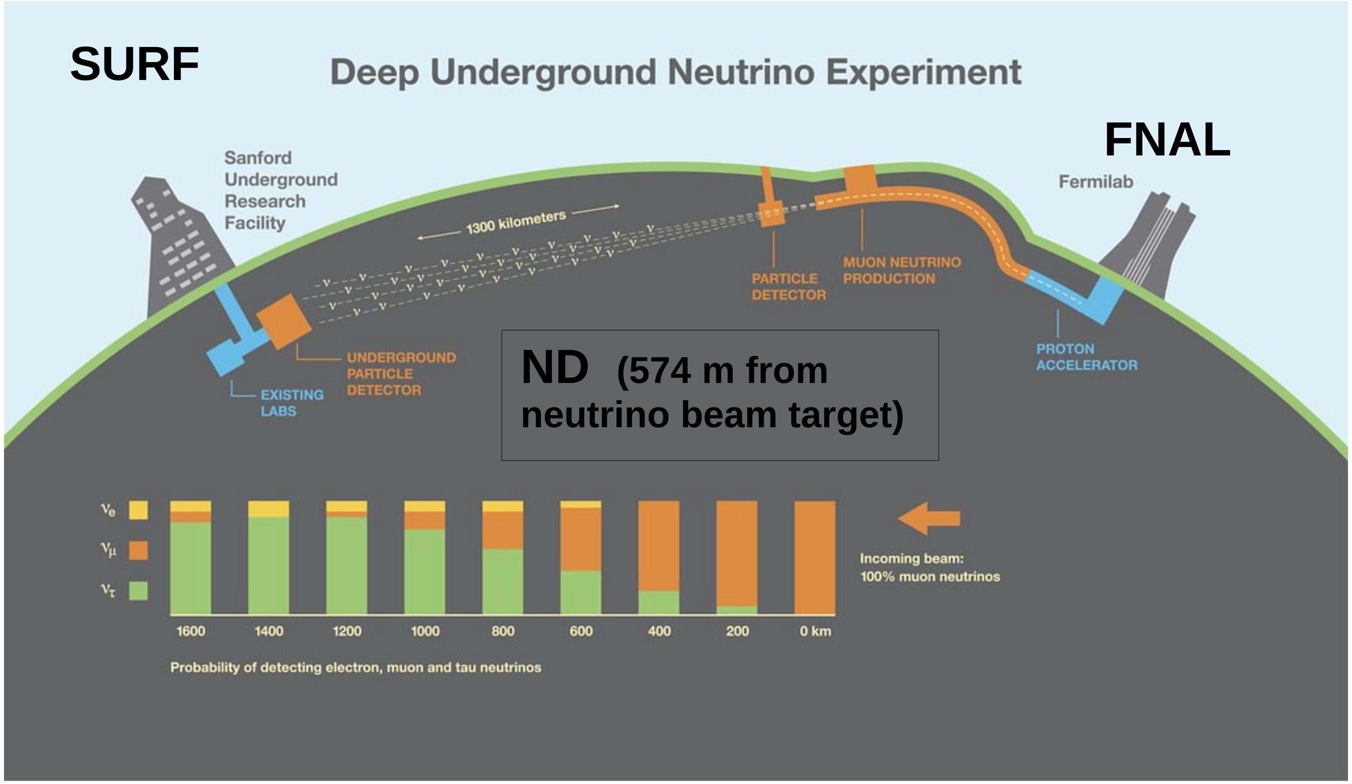
Introducing DUNE

“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



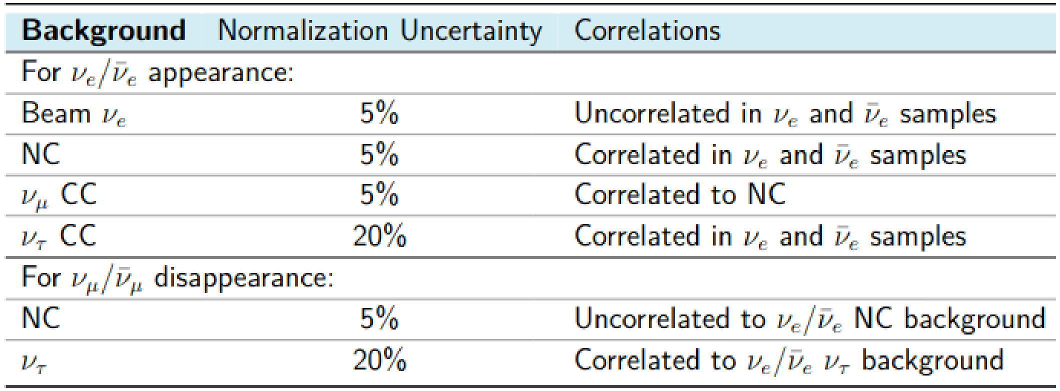
ND (574 m from neutrino beam target)

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

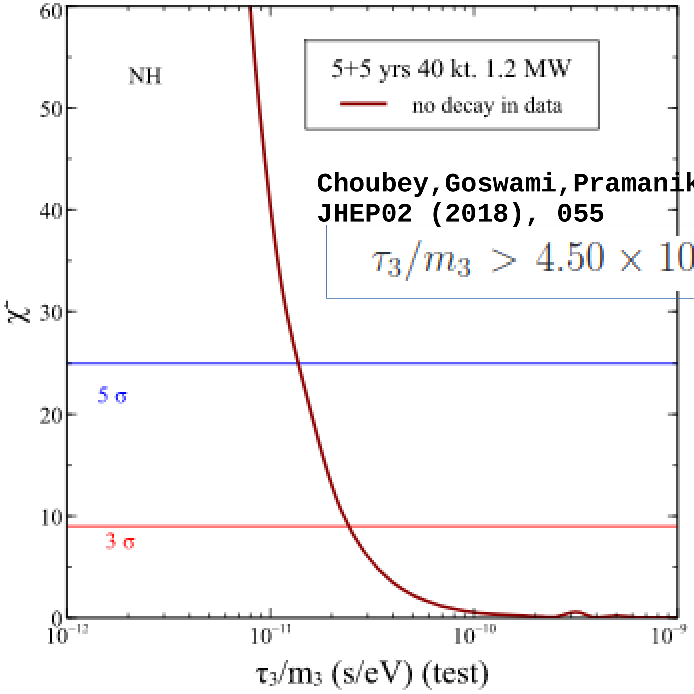
- we take into account that only 30% of the τ-s are detected
- 0.5% of the NC events as a background

- 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

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

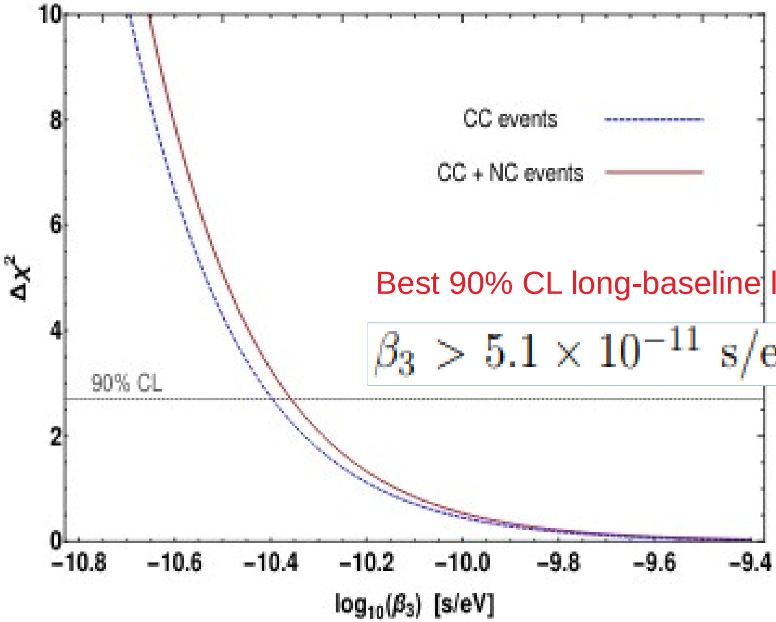
DUNE

results from other future experiments

a muon-decay medium-baseline neutrino beam facility

MOMENT	$2.8\ (1.6) \times 10^{-11}$	
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

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

Non-standard Neutrino Interactions (NSI)

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

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

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

lα = lepton doublet

f= components of an arbitrary weak doublet

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

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

ε represents the strength of the new interaction compared to G_F

source and detector interactions

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

non-standard matter effects

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

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

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:

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

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

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

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

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

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

Modified Oscillation Probabilities

- Existing bounds

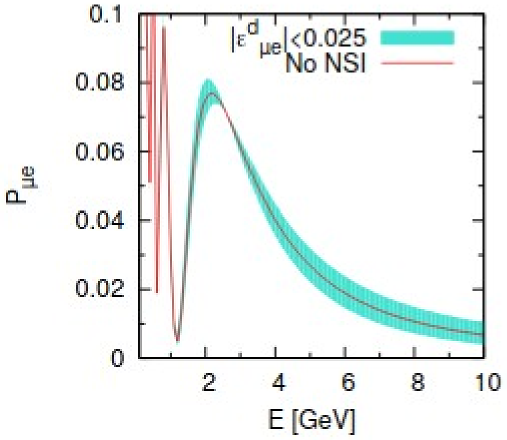
Blennow, Choubey, Ohlsson, Pramanik and Raut, JHEP08 (2016), 090
Biggio, Blennow, and Fernandez-Martinez, JHEP08, 090 (2009), 0907.0097

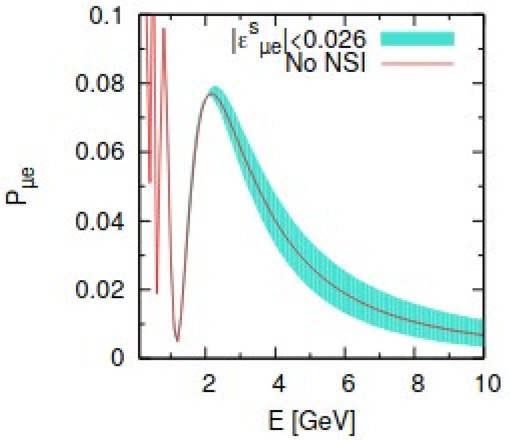
from G_F , pion decay, unitarity of CKM, oscillation experiments

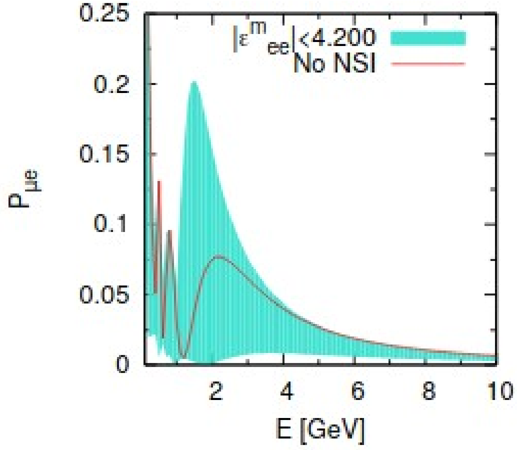
$$|\varepsilon^{s/d}_{\alpha\beta}| < \begin{bmatrix} 0.041 & 0.025 & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.12 & 0.018 & 0.13 \end{bmatrix}$$

mainly from neutrino-electron scattering and neutrino oscillations

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



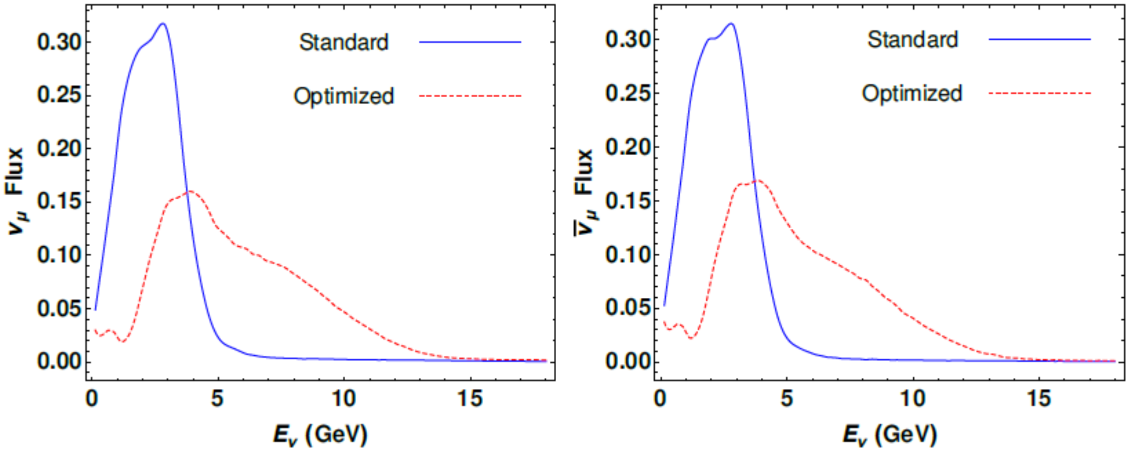




since the existing bounds on matter NSIs are weaker, they affect the probability more

Flux options in DUNE

M. Bishai and M. Dolce, *Optimization of the LBNF/DUNE beamline for tau neutrinos*, in Document Database (DocDB) for DUNE and LBNF [http://docs.dunescience.org/cgi-bin/RetrieveFile?docid=2013&filename=DOLCE_M_report.pdf&version=1].



standard

ν mode	
ν_τ Signal	277
$\bar{\nu}_\tau$ Signal	26
Total Signal	303
$\nu_e + \bar{\nu}_e$ CC Bkg (beam)	333 + 38
$\nu_e + \bar{\nu}_e$ CC Bkg (oscillation)	1753 + 12

$\bar{\nu}$ mode	
ν_τ Signal	68
$\bar{\nu}_\tau$ Signal	85
Total Signal	153
$\nu_e + \bar{\nu}_e$ CC Bkg (beam)	117 + 104
$\nu_e + \bar{\nu}_e$ CC Bkg (oscillation)	90 + 188

optimized

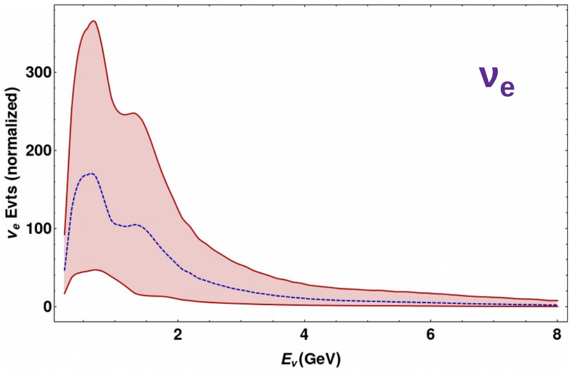
ν mode	
ν_τ Signal	2673
$\bar{\nu}_\tau$ Signal	34
Total Signal	2707
$\nu_e + \bar{\nu}_e$ CC Bkg (beam)	688 + 63
$\nu_e + \bar{\nu}_e$ CC Bkg (oscillation)	1958 + 11

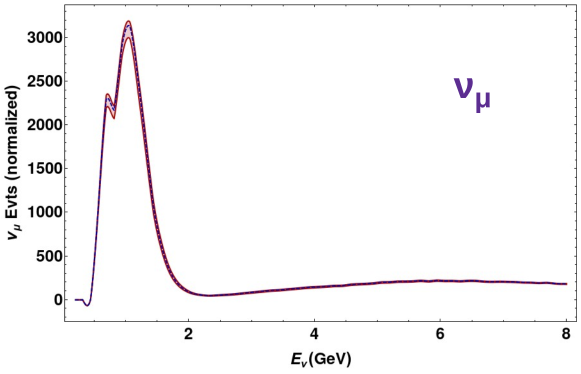
$\bar{\nu}$ mode	
ν_τ Signal	98
$\bar{\nu}_\tau$ Signal	983
Total Signal	1081
$\nu_e + \bar{\nu}_e$ CC Bkg (beam)	176 + 177
ν_e CC Bkg (oscillation)	76 + 324

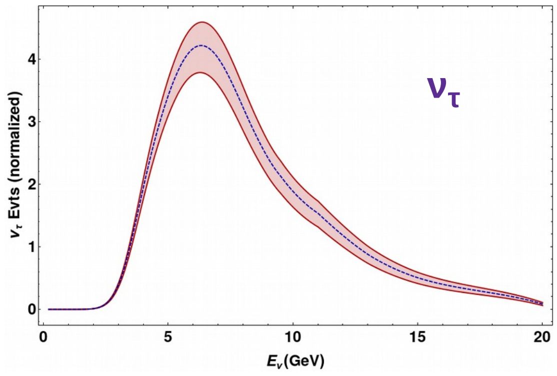
A factor of ~10 more tau events

Flux options in DUNE

- standard flux







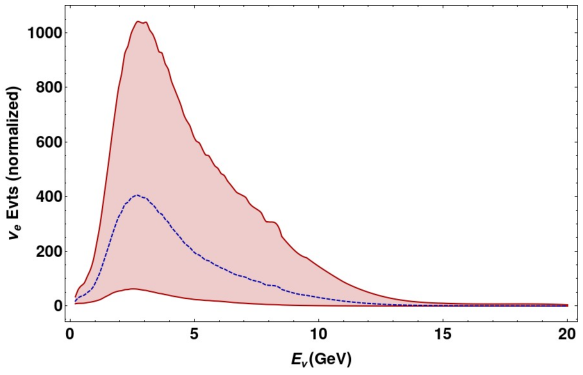
Dotted blue lines: SM events

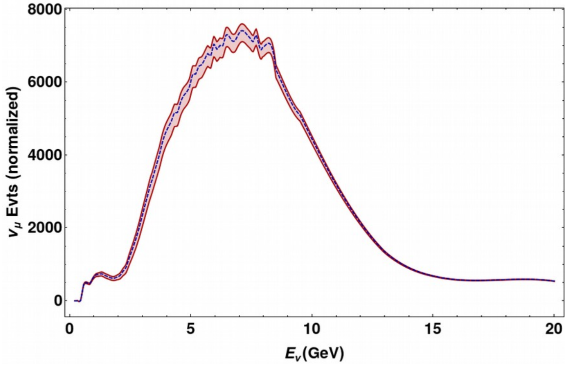
Red bands: range of events while varying matter NSI parameters in their allowed ranges

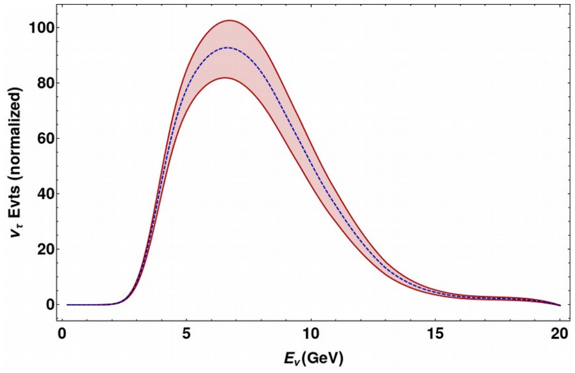
$\nu_\mu \rightarrow \nu_e$ is the most sensitive channel

how sensitive ?

- optimized flux







Thanks to Alessio Giarnetti

CP Asymmetries

$$A_{\alpha\beta}=\frac{P_{\alpha\beta}-P_{\bar{\alpha}\bar{\beta}}}{P_{\alpha\beta}+P_{\bar{\alpha}\bar{\beta}}}$$

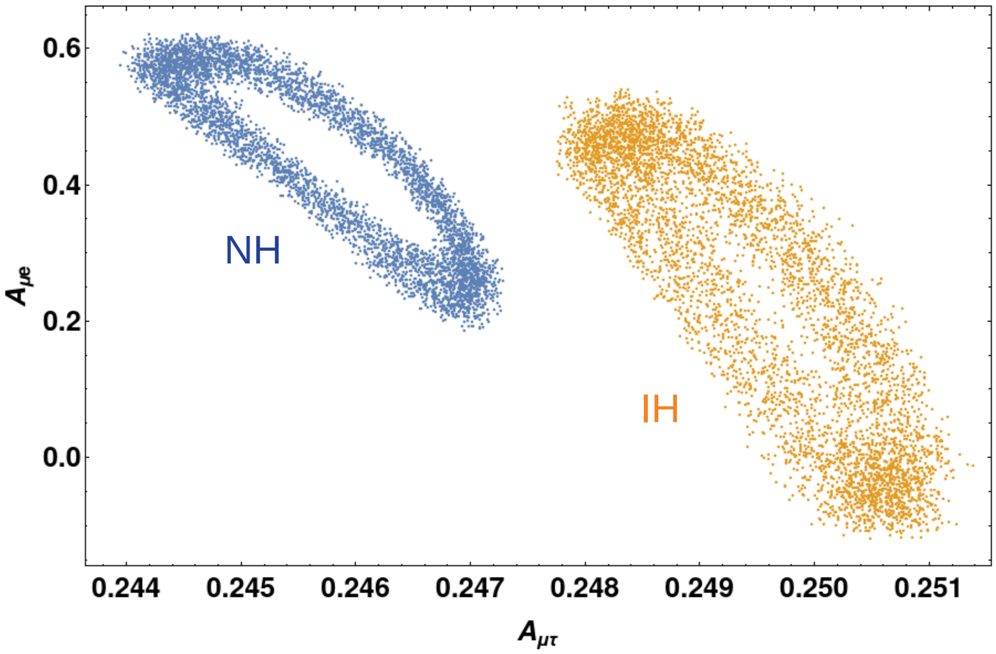
Use perturbation theory to evaluate them (given here the vacuum case):

$$\Delta_{21}=\Delta m^2_{21}L/4E_\nu \ll 1 \qquad s_{13}=\frac{r}{\sqrt{2}},\quad s_{12}=\frac{1}{\sqrt{3}}(1+s),\quad s_{23}=\frac{1}{\sqrt{2}}(1+a)$$

r, s, a ~ O(10%)

$$A_{\mu e}=\frac{-12\,r\,\Delta_{21}\sin\delta\ \sin^2\Delta_{31}}{4\Delta^2_{21}+9r^2\sin^2\Delta_{31}+6\,r\,\Delta_{21}\cos\delta\ \sin 2\Delta_{31}}$$

$$A_{\mu\tau}=\frac{4}{3}r\,\Delta_{21}\sin\delta$$



- all asymmetries in vacuum are suppressed by the small quantities Δ_{21} and θ_{13}
- since the denominators $A_{\mu e}$ is also suppressed, a partial cancellation is at work and, in particular, one generically expects $A_{\mu e} > A_{\mu\tau}$

CP asymmetries – Adding the NSI contributions

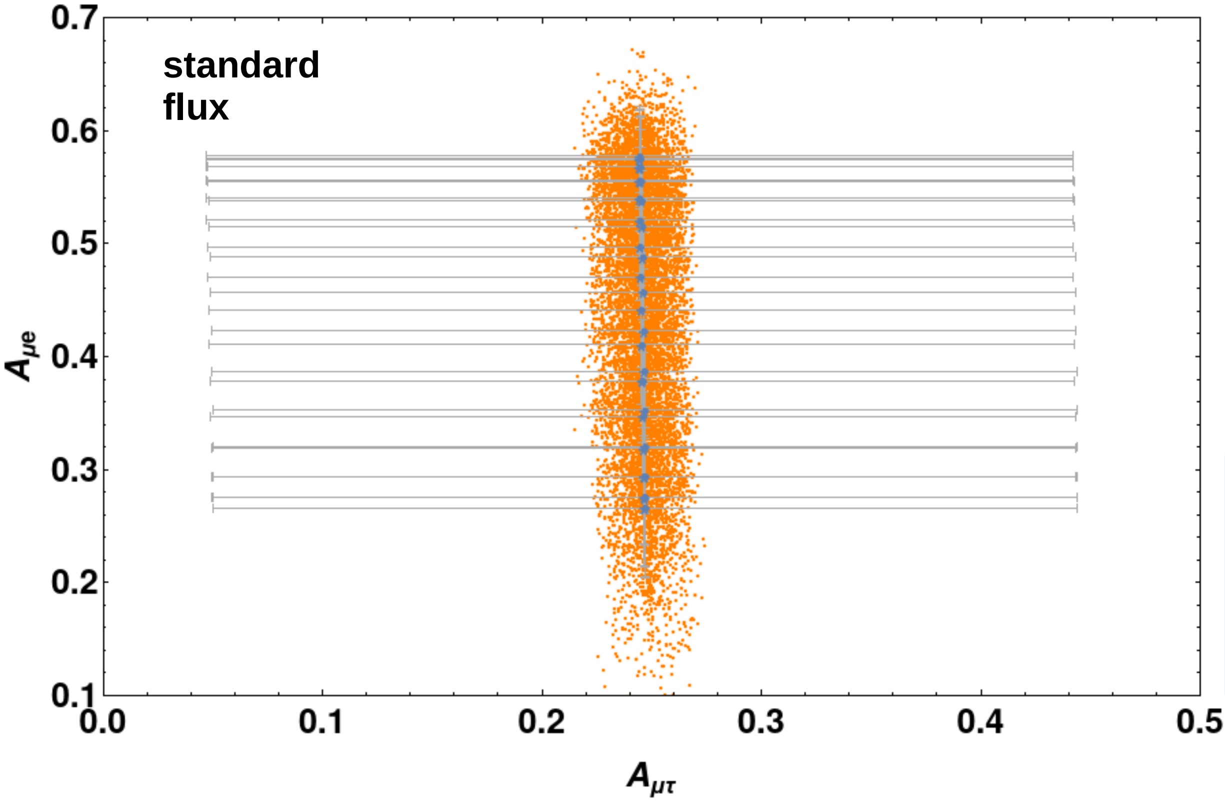
very long expressions (vacuum no longer a good approximation)

$$A^{NSI}_{\mu e} = A^{SM}_{\mu e} + F[\epsilon_{e\mu}, \epsilon_{e\tau}]$$

$$A^{NSI}_{\mu\tau} = A^{SM}_{\mu\tau} + G[\epsilon_{e\mu}, \epsilon_{e\tau}, \epsilon_{\mu\tau}, \epsilon_{\tau\tau}]$$

working with number of events

$$A_{\alpha\beta} = \frac{N_\beta - \bar{N}_\beta}{N_\beta + \bar{N}_\beta}$$



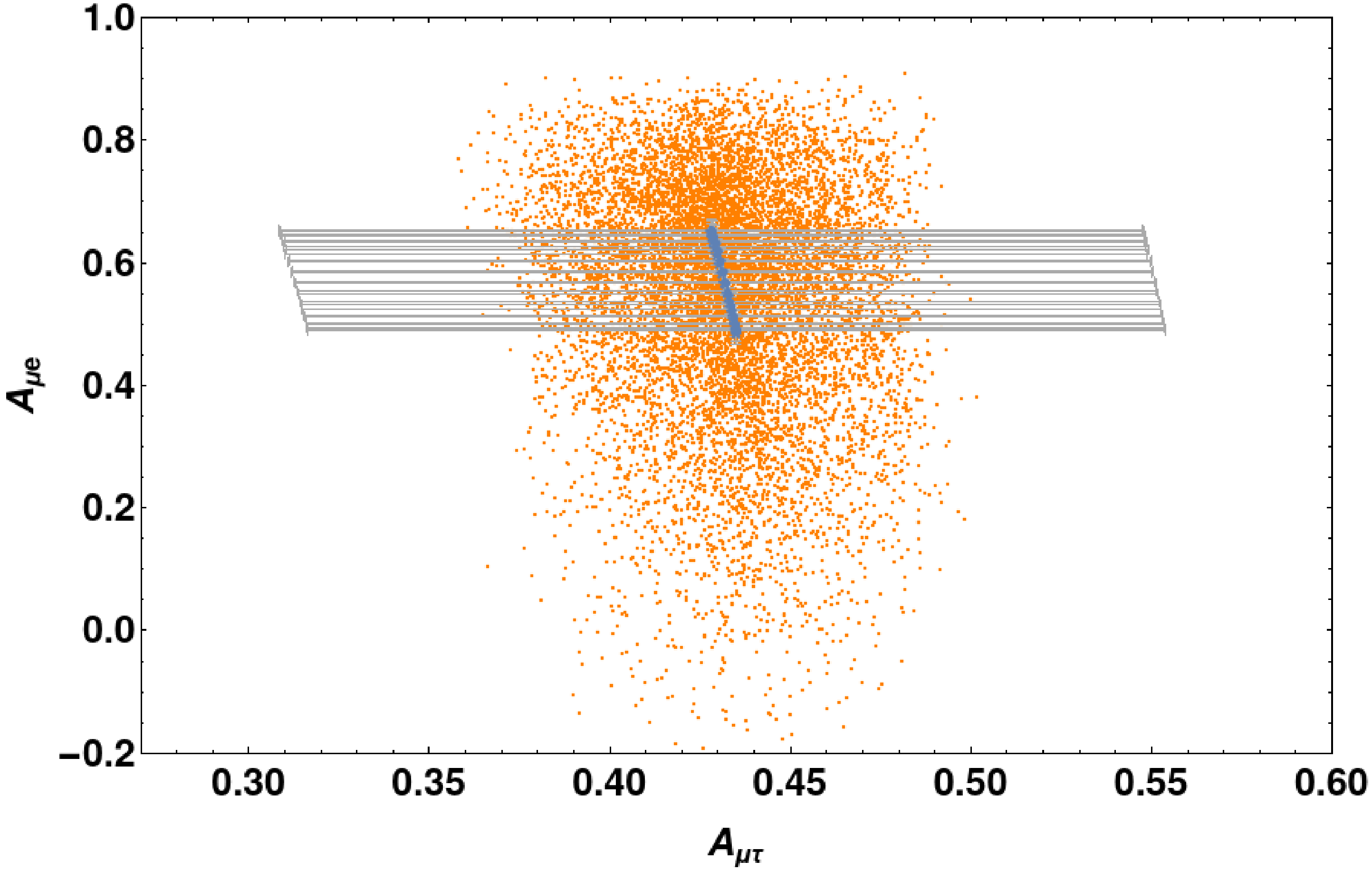
- scatter plot: asymmetries obtained varying NSI parameters
- error bars from statistics + systematic errors

Due to the small statistics, $A_{\mu\tau}$ does not seem to perform well

$A_{\mu e}$ show the best sensitivity to NSI

CP asymmetries – Adding the NSI contributions

optimized flux



Same conclusions as before: $A_{\mu e}$ show the best sensitivity to NSI

Conclusions

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

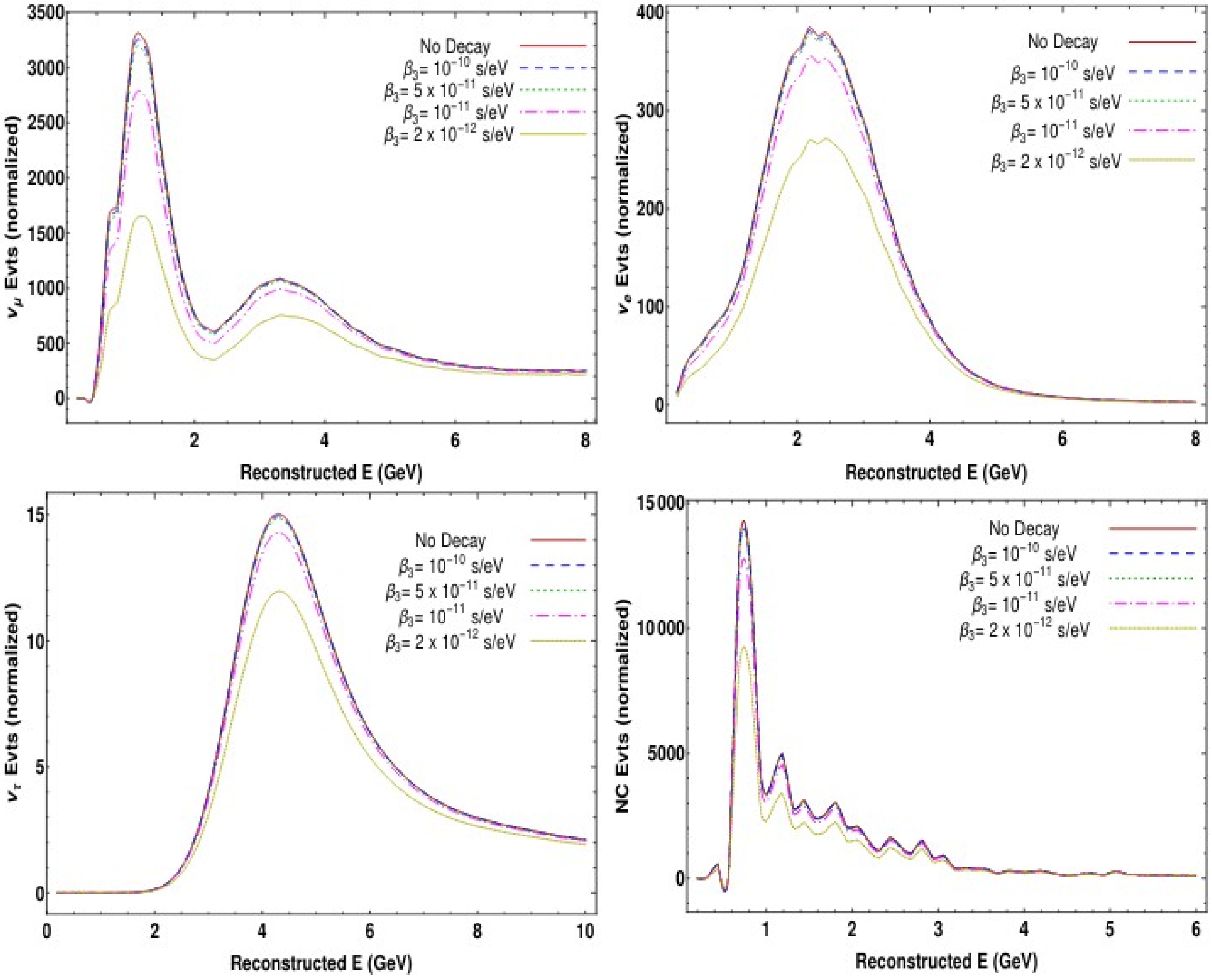
  several “Beyond the Standard Model” scenarios, including Neutrino Decay and Non-Standard Interactions
- For the latter, interestingly enough the mu-e CP asymmetry shows the best sensitivity

Backup slides

DUNE events

Energy spectra:

Ghoshal, Giarnetti, Meloni, 2003.09012



Effect of the decay parameter:

- on the CC spectra is a decrease in the number of events for every value of the reconstructed neutrino energy, with a shape reproducing the behavior implied by the oscillation probabilities

- same dependence on β3, but also a remarkable decrease in the number of expected events at high energies (mainly due to the wrong reconstruction of the neutrino energy)

Neutrino Decay

- Simplified 2-flavor approach

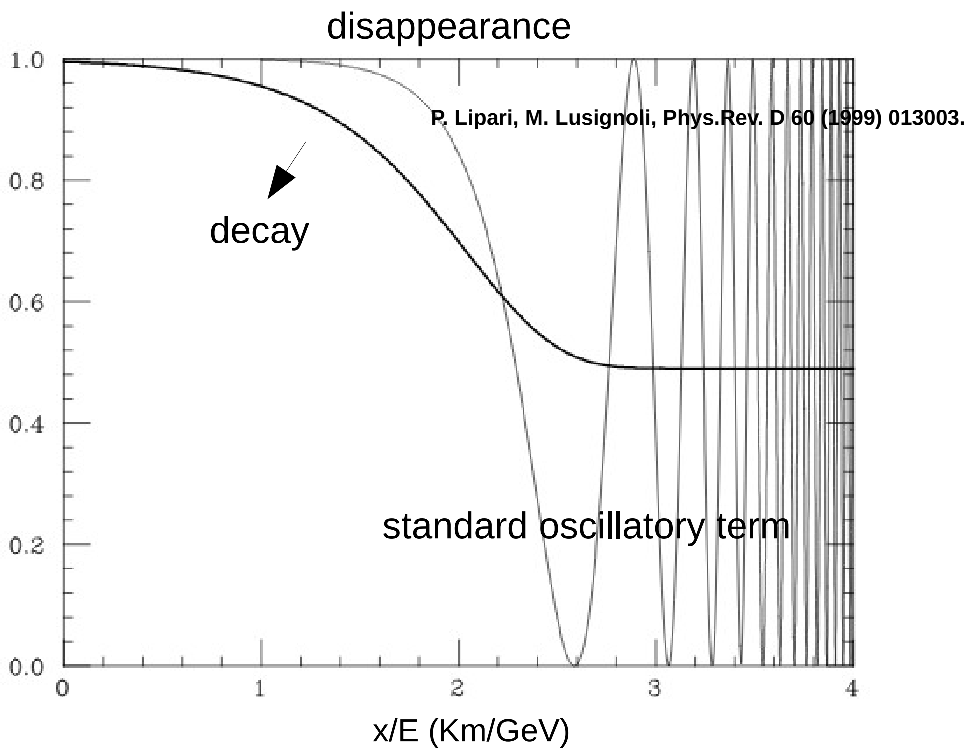
One unstable neutrino:

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

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

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

$$P(\nu_\alpha\rightarrow\nu_\alpha)+P(\nu_\alpha\rightarrow\nu_\beta)=\cos^2\theta+e^{-\frac{\alpha x}{E_\nu}}\sin^2\theta\neq1$$



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

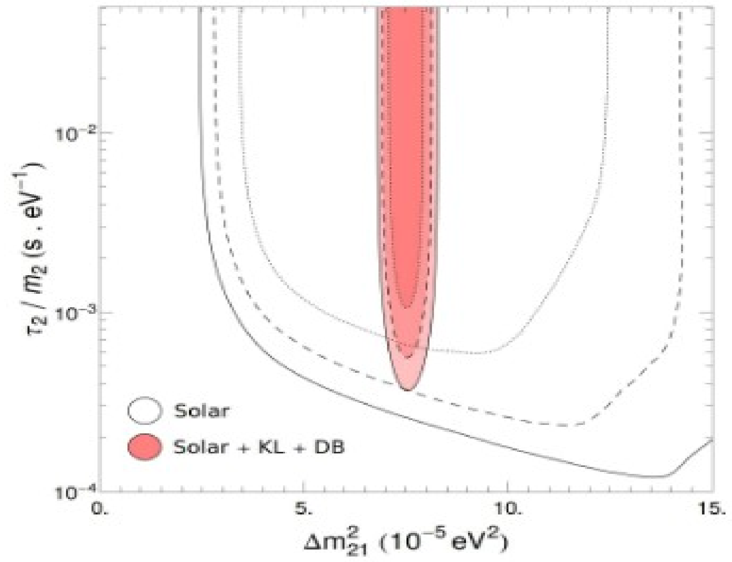
Neutrino Decay

- more recent analyses (invisible case - only ν_2 mass unstable)

$$\tau_2 \,/\, m_2 \geq 7.7 \times 10^{-4}\ \mathrm{s\,.\,eV^{-1}},\ \text{at } 99\%\ \text{C.L.}$$

R. Picoreti, M. M. Guzzo, P. C. de Holanda, O. L. G. Peres,

Phys. Lett. B 761 (2016) 70–73

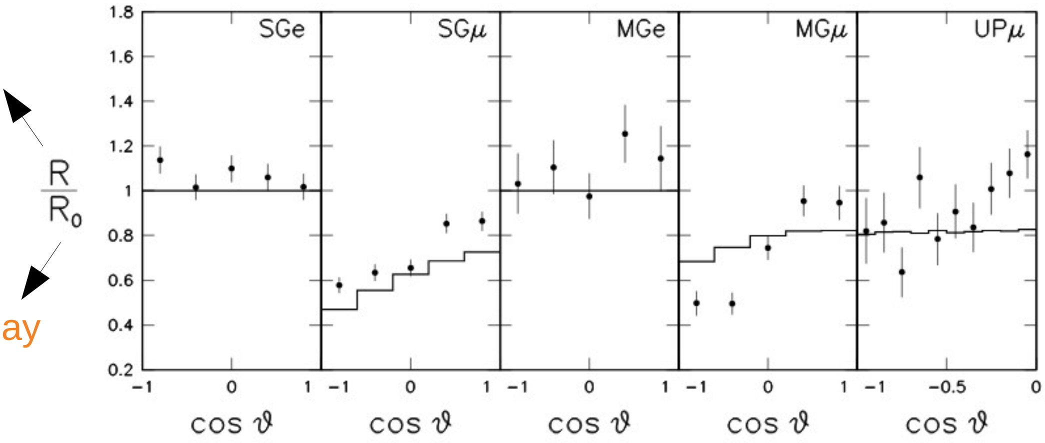


- possible explanation of the atmospheric deficit (the measurements of the fluxes of atmospheric neutrinos give evidence for the disappearance of muon neutrino)

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

`G.Fogli, E.Lisi, A.Marrone and G.Scioscia,Phys.Rev.D59(1999)117303`

predicted rates



no decay

$$\chi^2_{dec\,,\,min} / ND = 86/28$$

$$\chi^2_{osc\,,\,min} / ND \sim 1$$

Neutrino Decay

- Simplified 2-flavor approach

One unstable neutrino:

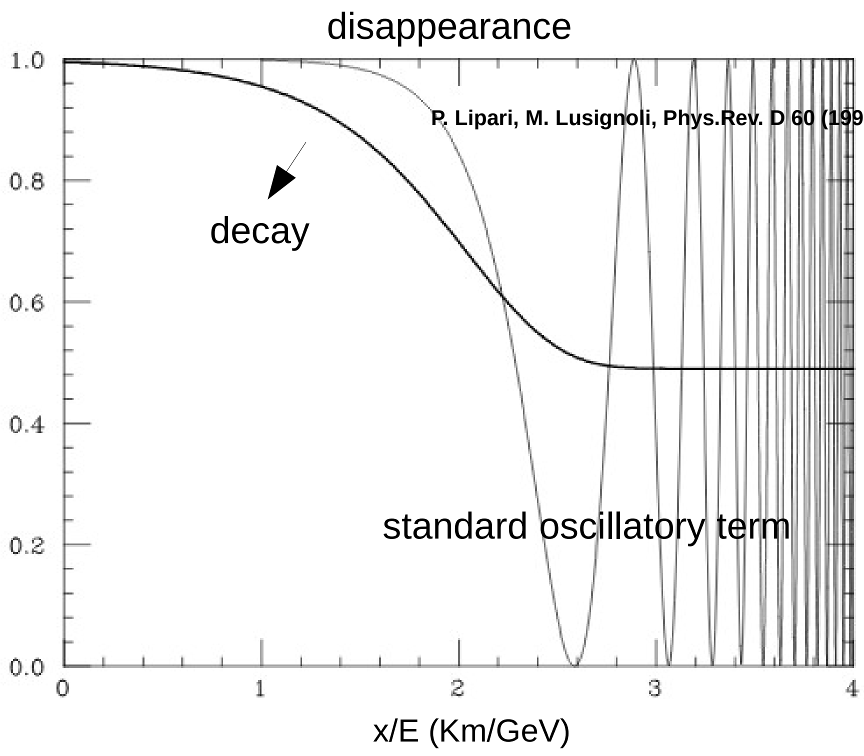
$$i\frac{d}{dx}\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix}=U\left[\frac{\Delta m^2}{2E}\begin{pmatrix}0&0\\0&1\end{pmatrix}-i\frac{\alpha}{2E}\begin{pmatrix}0&0\\0&1\end{pmatrix}\right]U^+\begin{pmatrix}\nu_\alpha\\ \nu_\beta\end{pmatrix}\qquad \alpha=\frac{m}{\tau}\qquad U=\begin{pmatrix}\cos\theta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

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

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

$$\Downarrow$$

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

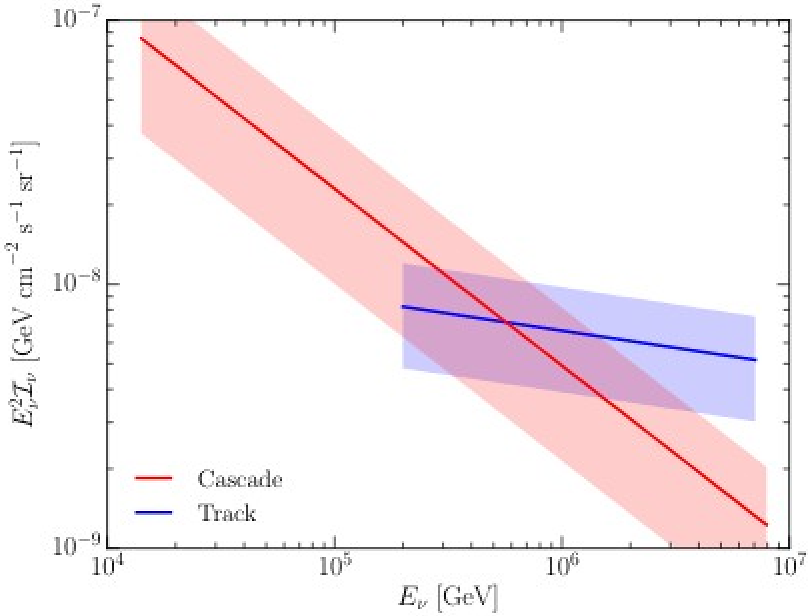


P. Lipari, M. Lusignoli, Phys.Rev. D 60 (1999) 013003.

Invisible Neutrino Decay in IceCube

- Track-to-cascade tension in the IceCube data

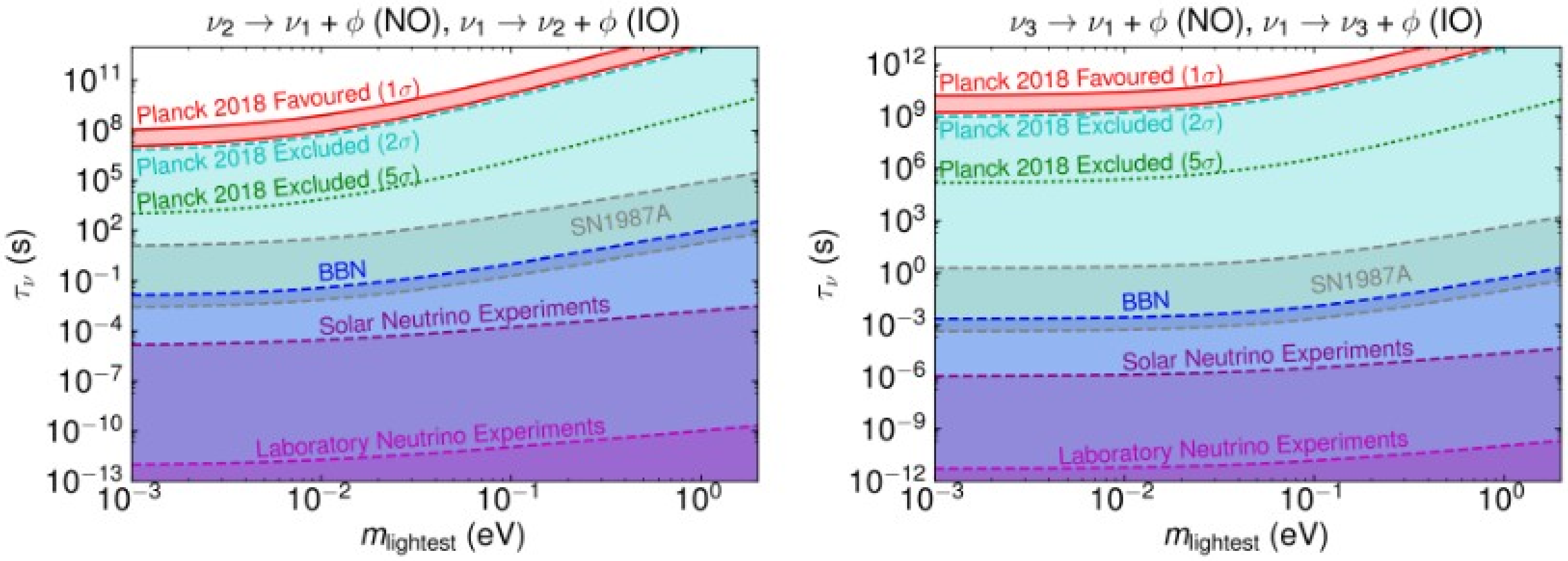
Denton and Tamborra,Phys. Rev. Lett.121 (2018) no.12, 121802



Cosmological Constraints on Invisible Neutrino Decays

Cosmology can serve as a powerful probe of invisible neutrino decays

M.Escudero and M.Fairbairn,
Phys. Rev. D100 (2019) no.10, 103531



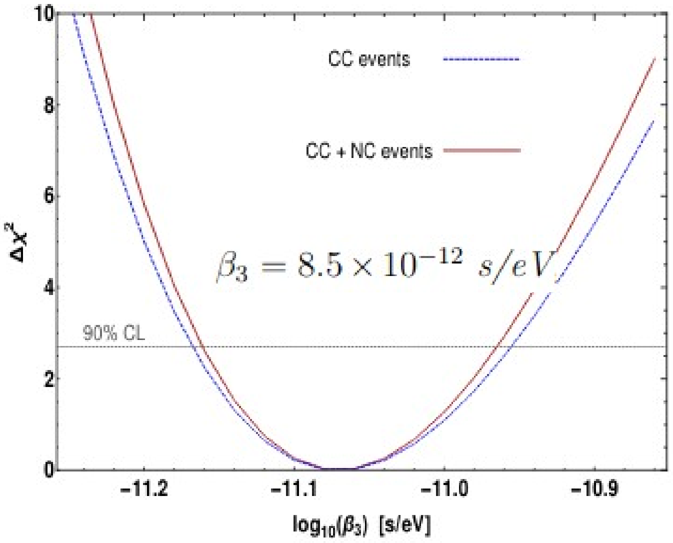
for Big Bang Nucleosynthesis to be successful, the invisible neutrino decay lifetime is bounded to be $\tau > 10^{-3}$s at 95% CL

For SN, the role of Majorons in the cooling of the core is relevant

Latest sensitivities to nu lifetime

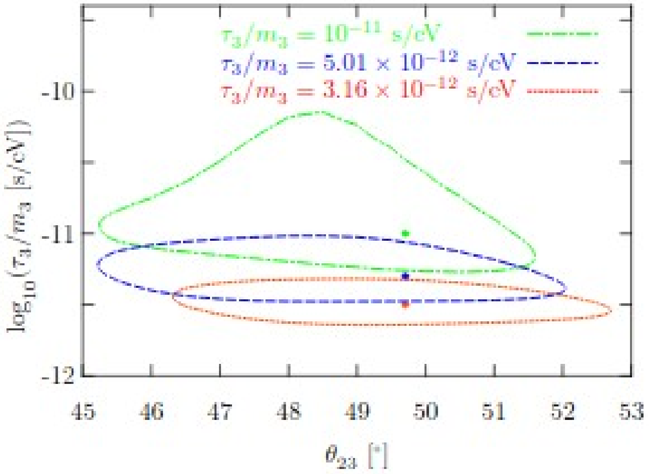
- precision measurement in DUNE

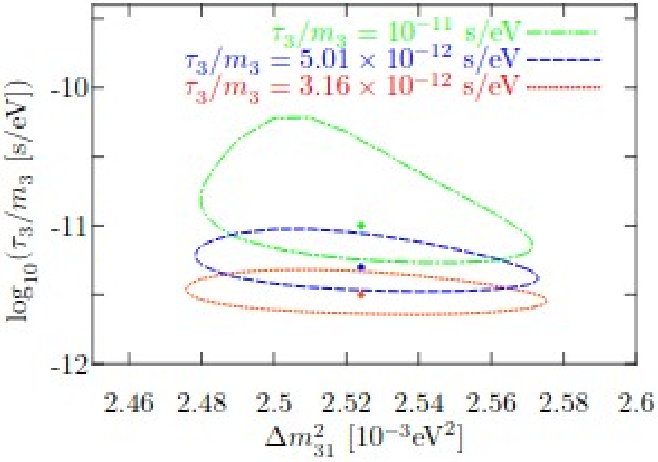
assuming $\beta_3 \neq 0$, uncertainty of about [10−30]% can be set at 90% CL, depending on the central value used.



- 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)

- A matter NSI operator is induced in fermionic seesaw models once the heavy fermions (singletsor triplets) are integrated out leading to a d= 6 operator that modifies the neutrino kinetic energy.
- After a transformation to obtain canonical kinetic terms, modified couplings of the leptons to the gauge bosons, characterized by deviations from unitarity of the leptonic mixing matrix, are induced.
- Upon integrating out the gauge bosons with their modified couplings, NSI operators are therefore obtained.

SU(2) formulation

- Large NSI could be generated by some other new physics at an energy above the electroweak scale. As a consequence, an SU(2) gauge invariant formulation of NSI is mandatory
- However, in that case, strong bounds stemming from four-charged fermion processes would apply
- In order to avoid these constraints, cancellations among different higher-dimensional operators are required

Non-standard Neutrino Interactions (NSI)

- Many new-physics parameters, huge parameter space:

$\tilde{\varepsilon}^{s,f,f}_{\alpha\beta}$ arbitrary complex matrices

$\tilde{\varepsilon}^{m,f}_{\alpha\beta}$ hermitean complex matrices

there exists arguments to reduce the parameter space

- for the non-standard matter effects, only coupling to electrons, up quarks, and down quarks is important
- non-standard couplings involving τ leptons are irrelevant in reactor and beam sources since τ-production is impossible
- for l_α = e, all corresponding ε's are vanishing in superbeams because of no-e production
- in Superbeam source and detector: f=u, f′=d .
- ...

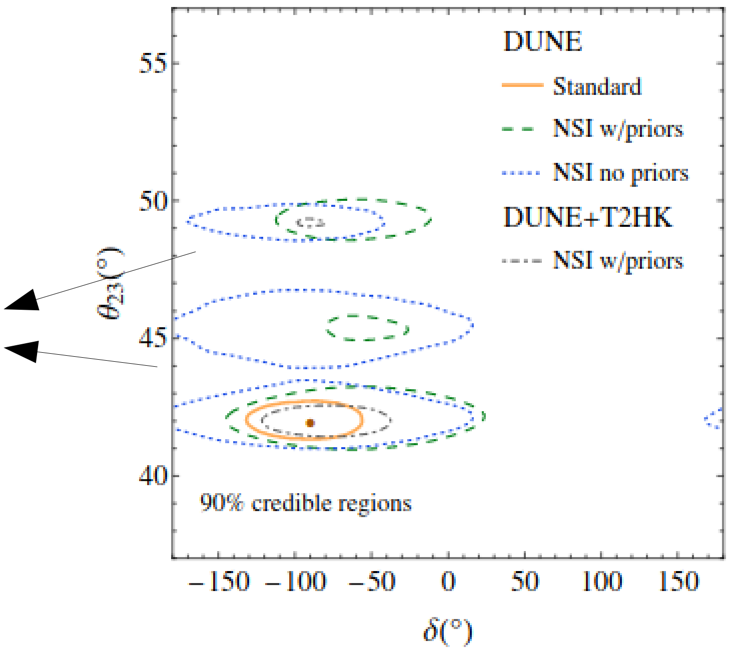
Possible effects of NSI

- Correlation with mixing parameters

Blennow, Choubey, Ohlsson, Pramanik and Raut, JHEP08 (2016), 090
Girardi, Meloni and Petcov, Nucl. Phys. B886 (2014), 31-42
P.Coloma, JHEP03 (2016), 016

precision in the standard oscillation parameters in the presence of NSIs at DUNE

degenerate solution



Blennow, Choubey, Ohlsson, Pramanik and Raut,
JHEP08 (2016), 090

- the source/detector NSIs do not play much of a role

- some worsening of the sensitivity to δ

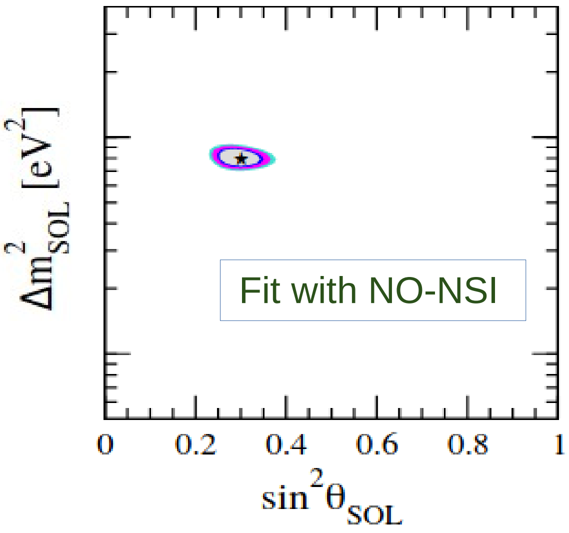
Possible effects of NSI

- Solar neutrinos

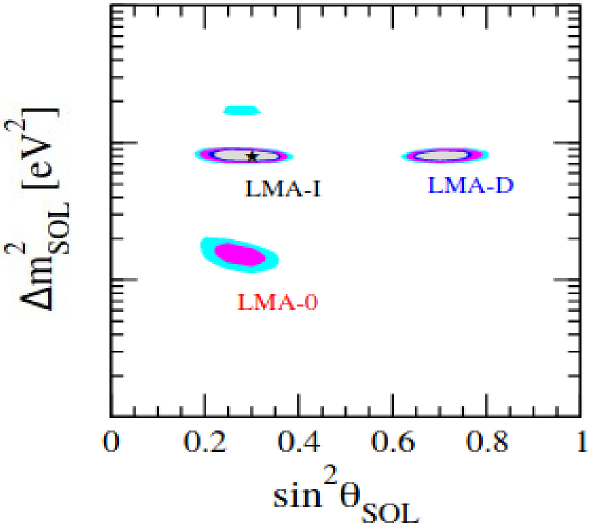
In the 2-flavor regime: $H_{\rm NSI} = \sqrt{2} G_F N_d \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}$ ⇒

$$P(\nu_e \to \nu_e) = \frac{1}{2}\left[1 + \cos 2\theta \cos 2\theta_m\right]$$

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



⇒



Miranda, Tortola and Valle, JHEP10 (2006), 008

	$\sin^2\theta_{\rm SOL}$	$\Delta m^2_{\rm SOL}$ [eV^2]	ε	ε'	χ^2
OSC analysis					
LMA-I	0.29	8.1×10^{-5}	–	–	79.9
OSC+NSI analysis					
LMA-I	0.30	7.9×10^{-5}	0	-0.05	79.7
LMA-D	0.70	7.9×10^{-5}	-0.15	0.90	80.2
LMA-0	0.25	1.6×10^{-5}	0.10	0.30	86.8

no NSI

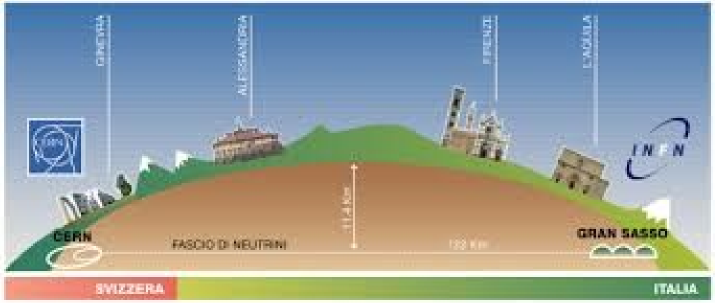
dark-side

light-side

The Present: signal at OPERA

- Introducing tau neutrinos into the game

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



D. Meloni, Phys.Lett.B792 (2019), 199-204

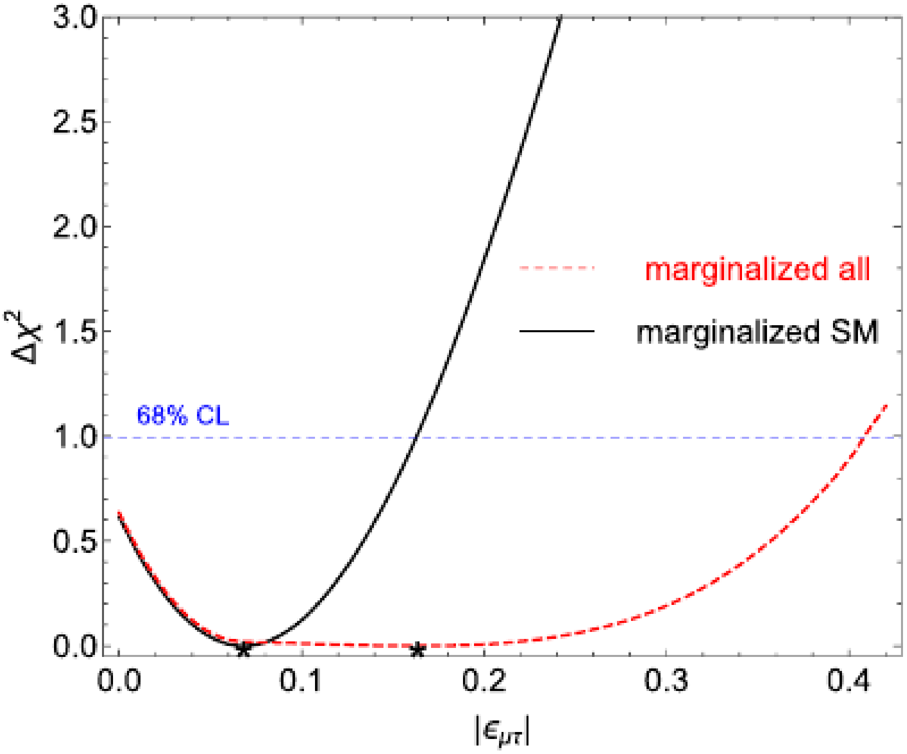


Table 1

Number of ν_τ appearance (app), charm and neutral current background (back) events expected in OPERA, corresponding to $17.97 \cdot 10^{19}$ pot and 1.25 Kton mass. Events are divided in 6 energy bins of variable size in the energy range $E_\nu \in [0, 60]$ GeV.

Events	[0 – 5] GeV	[5 – 10] GeV	[10 – 15] GeV
ν_τ app	0.49	2.35	2.1
Charm back	0.03	0.17	0.19
NC back	0.06	0.36	0.41
	[15 – 25] GeV	[25 – 40] GeV	[40 – 60] GeV
ν_τ app	1.6	0.25	0.05
Charm back	0.18	0.04	0.02
NC back	0.4	0.1	0.04

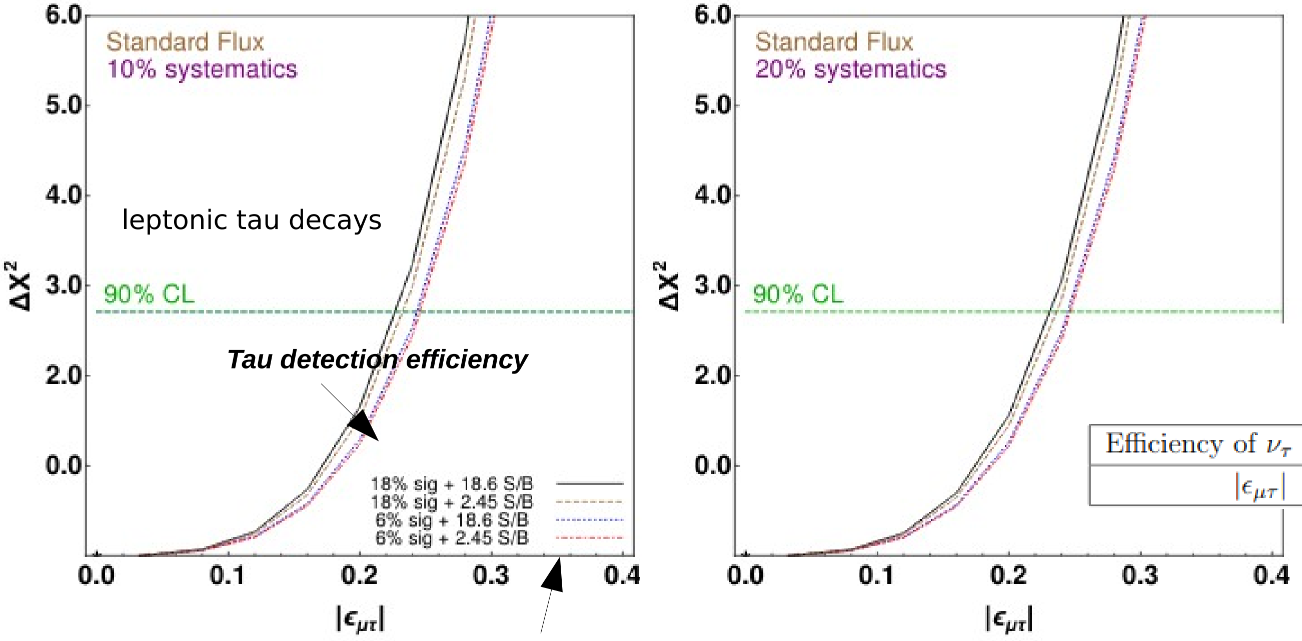
$|\varepsilon_{\mu\tau}|^{SM} < 0.16$ $|\varepsilon_{\mu\tau}|^{all} < 0.41$

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, $|\varepsilon_{\mu\tau}|<0.32$

The future: signals at the DUNE Near Detector

- Source and detecton NSI

Giarnetti, Meloni 2005.10272

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

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

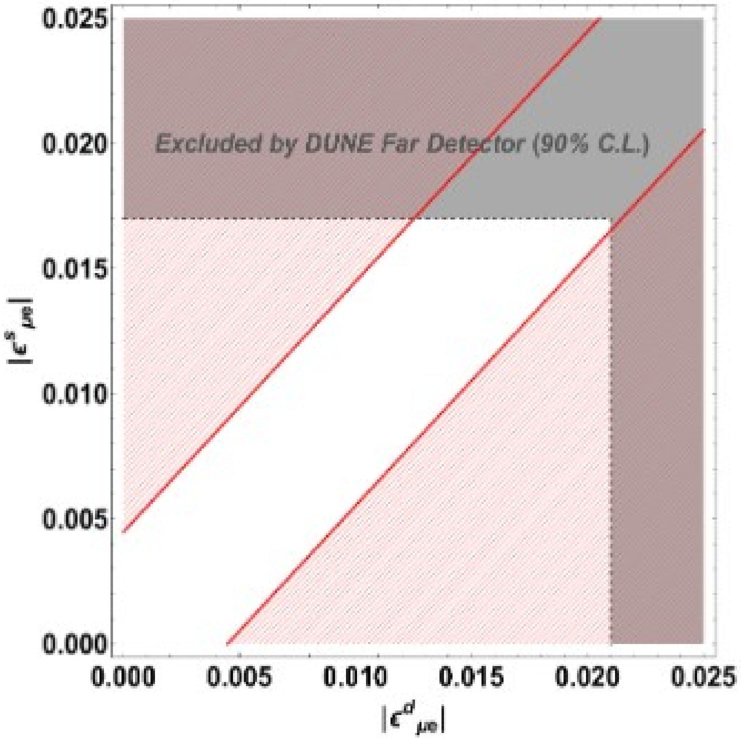
- Source and detecton NSI

Giarnetti, Meloni 2005.10272

- 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!