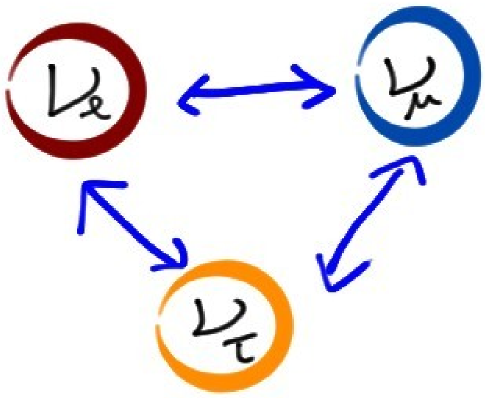
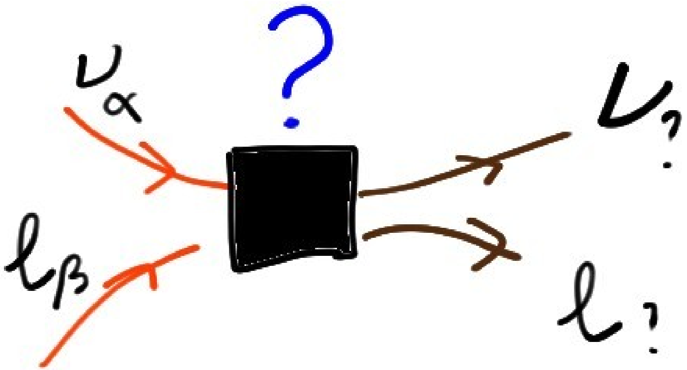
New Physics in the Lepton sector from future Neutrino Experiments



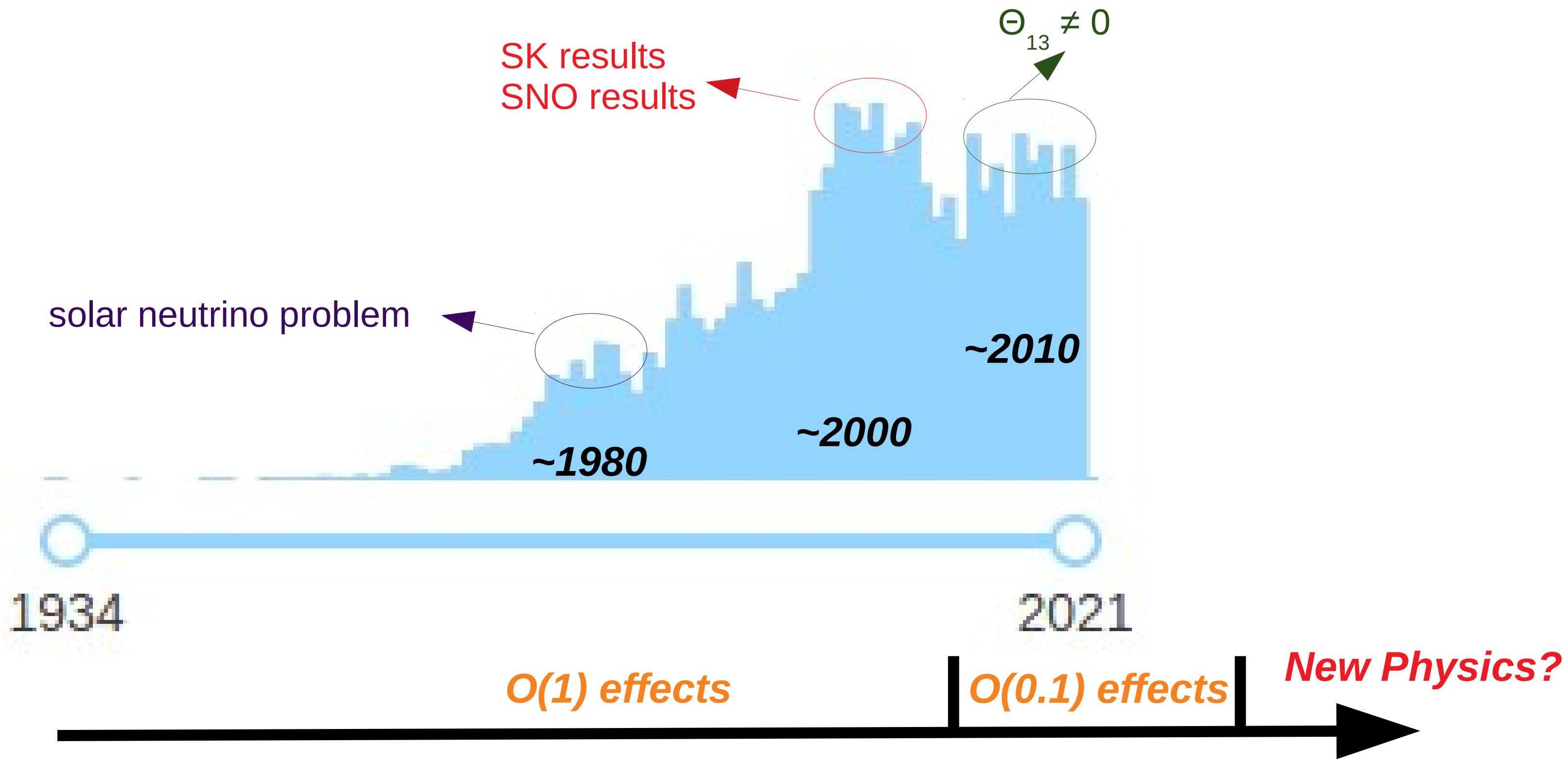


Davide Meloni
Dipartimento di Matematica e Fisica
Roma Tre

9-2-2021
Dipartimento di Fisica "Enrico Fermi"
Università di Pisa

Neutrino Physics and the Precision Era

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



$\Theta_{13} \neq 0$

SK results
SNO results

solar neutrino problem

~1980

~2000

~2010

O(1) effects

O(0.1) effects

New Physics?

Neutrino Physics and the Precision Era

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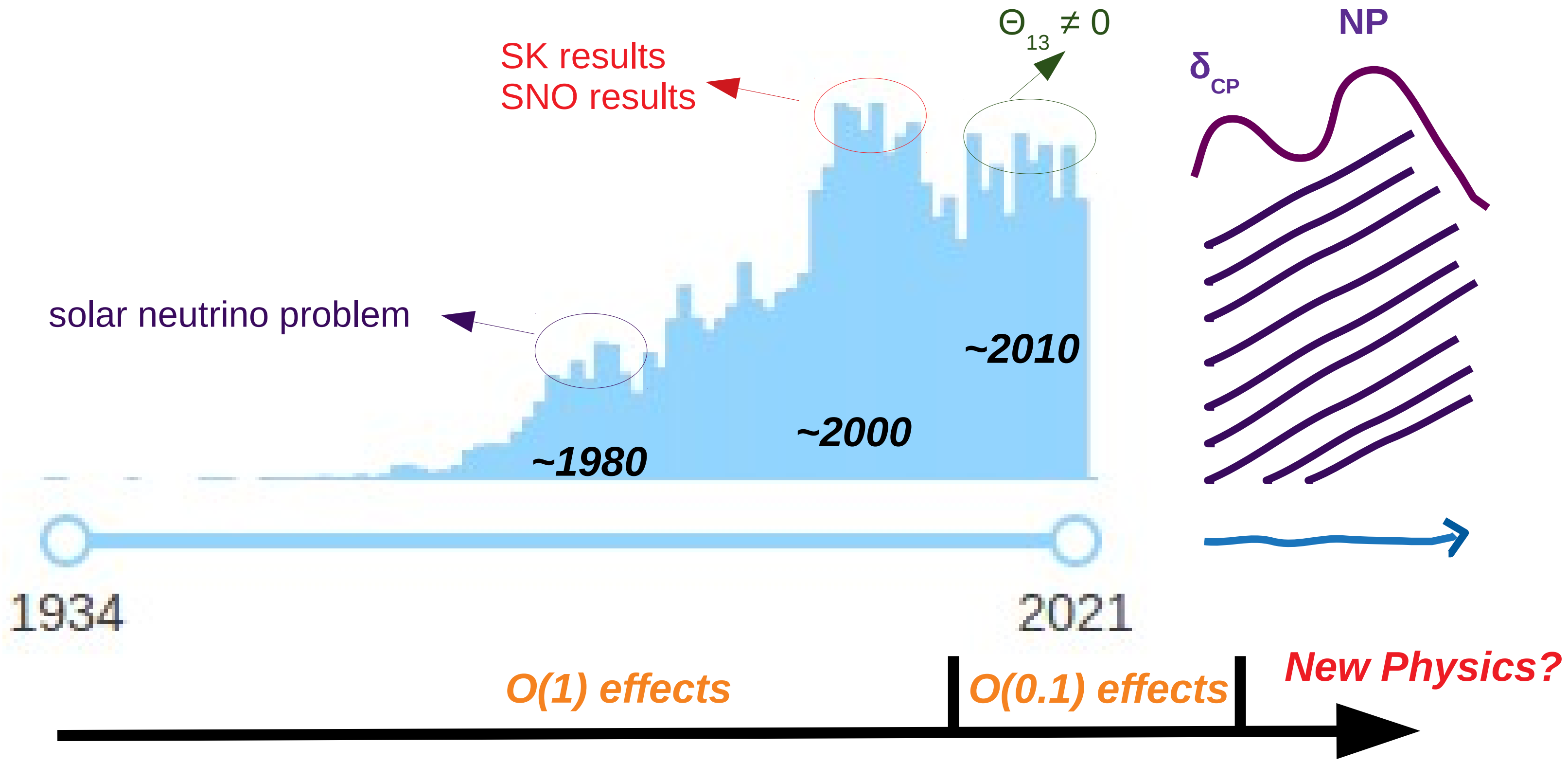
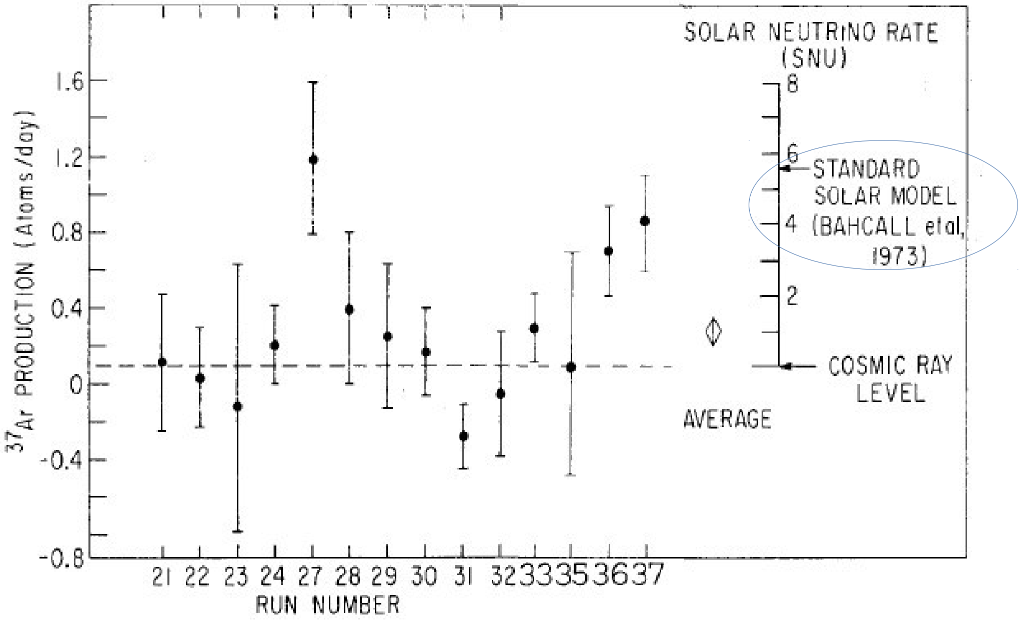


The Physics of Neutrino Oscillation: *O(1) effects*

O(1) effects

- More than 40 years ago:

transformation of ^{37}Cl atoms induced by neutrinos ν_e
into radioactive ^{37}Ar atoms



1968-1976

Homestake solar neutrino experiment and the

solar neutrino problem

https://neutrino-history.in2p3.fr/historical-plots/

The Physics of Neutrino Oscillation: *O(1) effects*

- Almost 20 years ago:

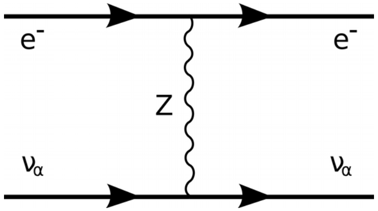
Sudbury Neutrino Observatory (SNO)
solves the solar neutrino problem

solar neutrinos: SNO (2001)

from ^{8}B neutrino flux

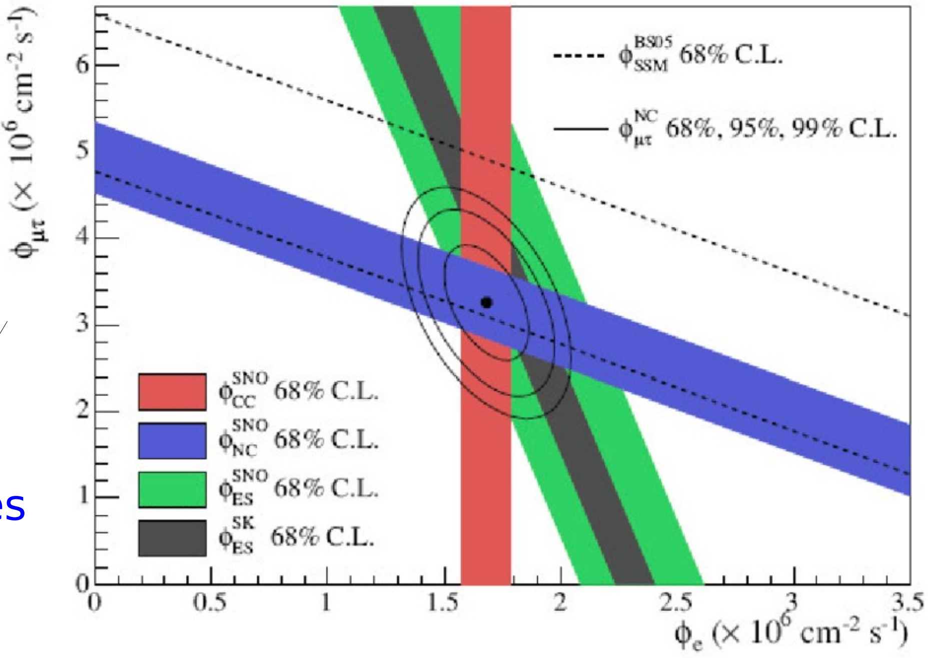
CC $\nu_e + d \rightarrow p + p + e^-$

NC $\nu_\alpha + d \rightarrow p + n + \nu_\alpha \quad \alpha = e, \mu, \tau$



ES $\nu_\alpha + e \rightarrow \nu_\alpha + e \quad \alpha = e, \mu, \tau$

A significant deficit in the ^{8}B ν-flux measured by the CC reaction over that measured by the NC reaction would directly demonstrate that the Sun's electron neutrinos were changing to one of the other two types, without reference to solar models



$(\nu_\mu + \nu_\tau)$ fluxes

pure electron flux

The Physics of Neutrino Oscillation: *O(1) effects*

- More than 20 years ago:

SK (1998)

a 50 kton Water Cherenkov detector

Neutrino observed via charged-current interactions with nuclei in water

1- an anomalous number of muon neutrino events compared to electron neutrino events

(N_mu / N_e)_data

----------------------------- = 0.63 +- .03 (statistical) +- .05 (systematic)

(N_mu / N_e)_predicted

The Physics of Neutrino Oscillation: *O(1) effects*

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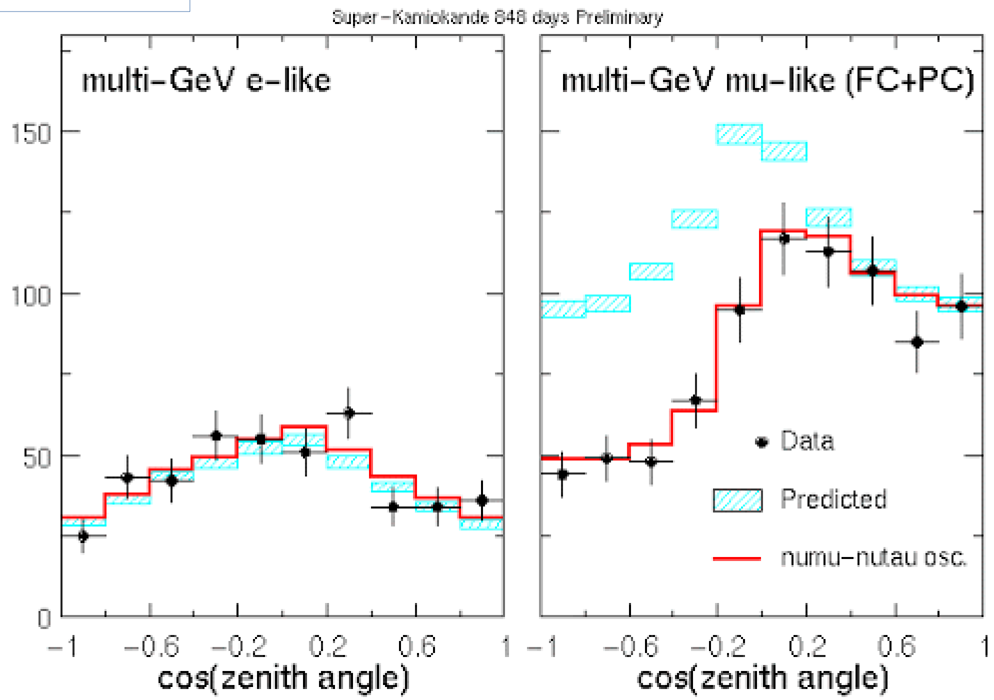
----------------------------- = 0.63 +- .03 (statistical) +- .05 (systematic)

(N_mu / N_e)_predicted

2- significant up-down asymmetry of high energy muon neutrino events

A = (UP-DOWN)/(UP+DOWN) =

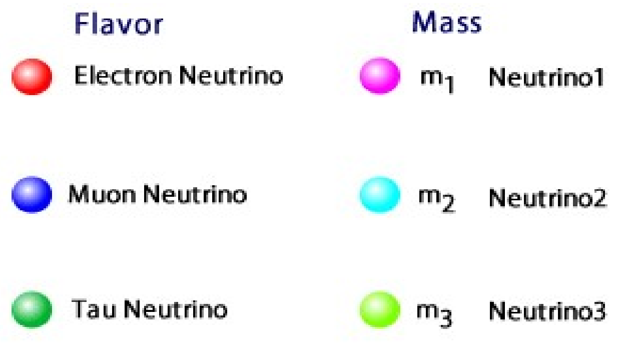
0.296 +- 0.048(statistical) +- 0.01(systematic)

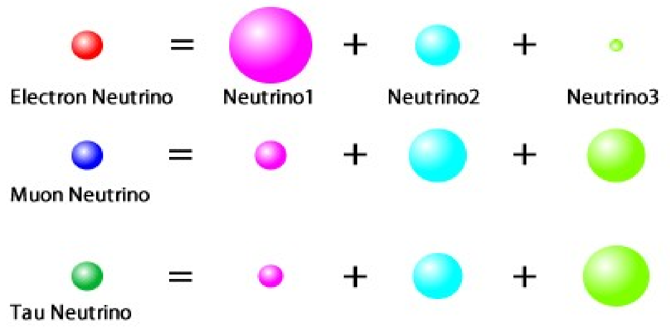


Two-flavor Neutrino Oscillation

- flavor and mass eigenstates are different objects

SK web pages





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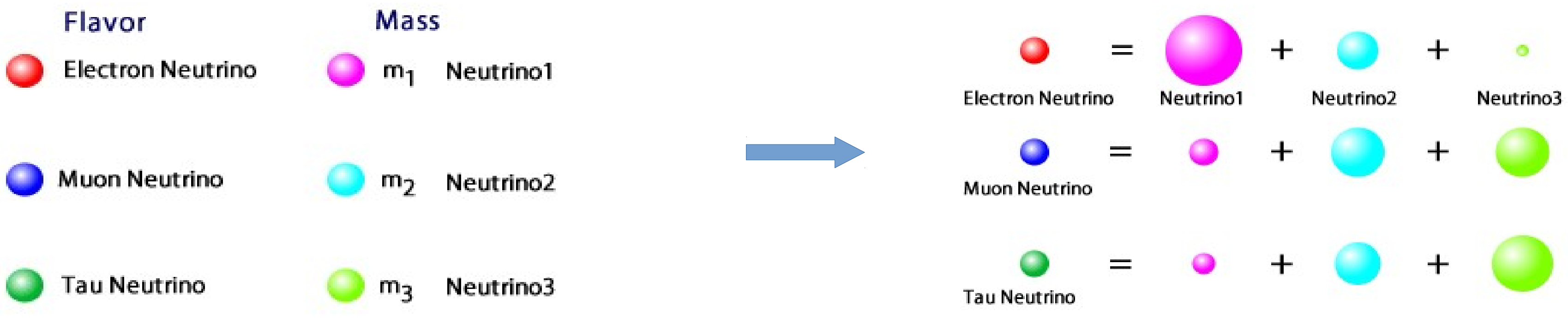


$$\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

The time evolution of the flavor states is:

$$|\nu_e\rangle = \cos\theta e^{-iE_1 t}|\nu_1\rangle + \sin\theta e^{-iE_2 t}|\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin\theta e^{-iE_1 t}|\nu_1\rangle + \cos\theta e^{-iE_2 t}|\nu_2\rangle$$

For a beam that is pure ν_μ at t=0,

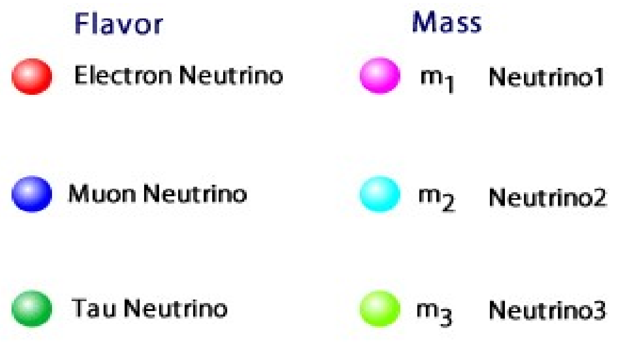
$$P(\nu_\mu \to \nu_e) = \left|\langle\nu_e|\nu_\mu\rangle\right|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E}L\right),$$

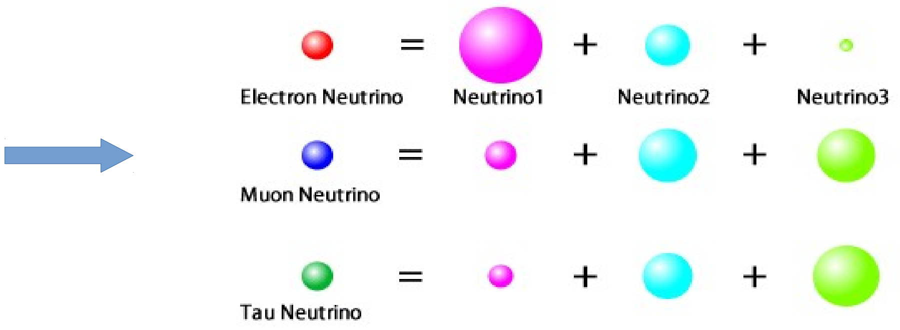
where $\Delta \mathrm{m}^2 = m_2^2 - m_1^2$

Two-flavor Neutrino Oscillation

- flavor and mass eigenstates are different objects

SK web pages





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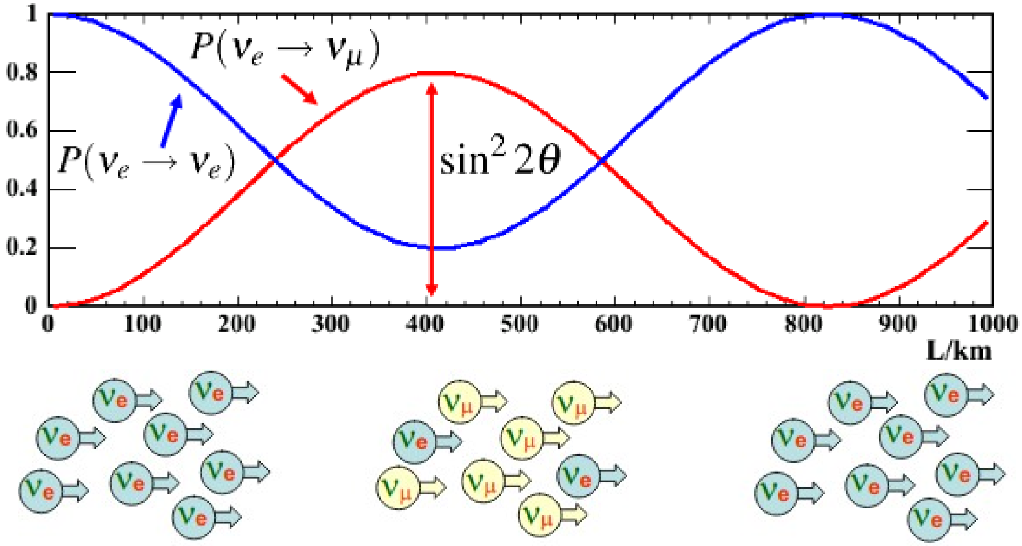
where $\Delta m^2 = m_2^2 - m_1^2$

$$\Delta m^2 = 0.003\,\mathrm{eV}^2, \qquad \sin^2 2\theta = 0.8, \qquad E_\nu = 1\,\mathrm{GeV}$$

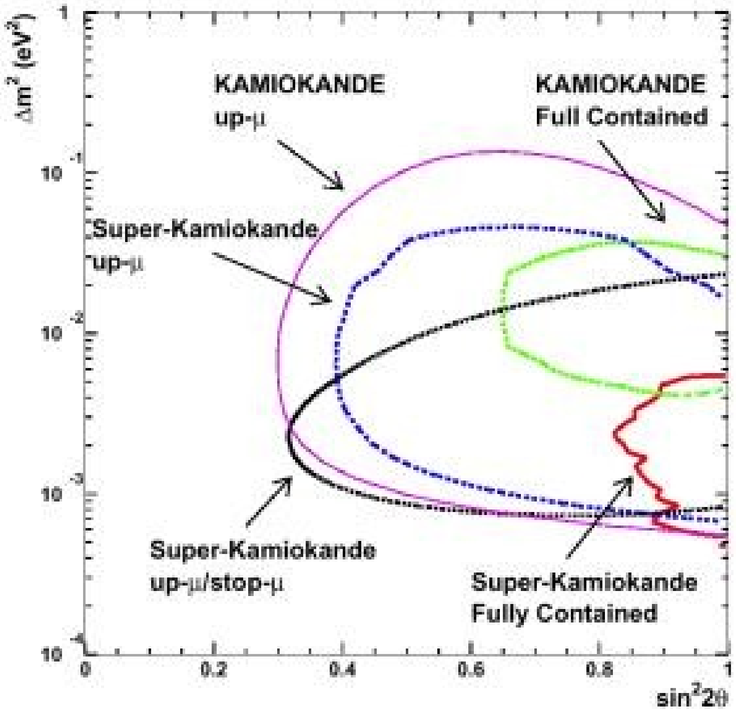


The Physics of Neutrino Oscillation: *O(1) effects*

In the world of ***O(1) effects***:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{2E_\nu}\right)$$ and $$1 - P(\nu_\alpha \rightarrow \nu_\beta)$$ (a simple 2-parameter formula)

atmospheric



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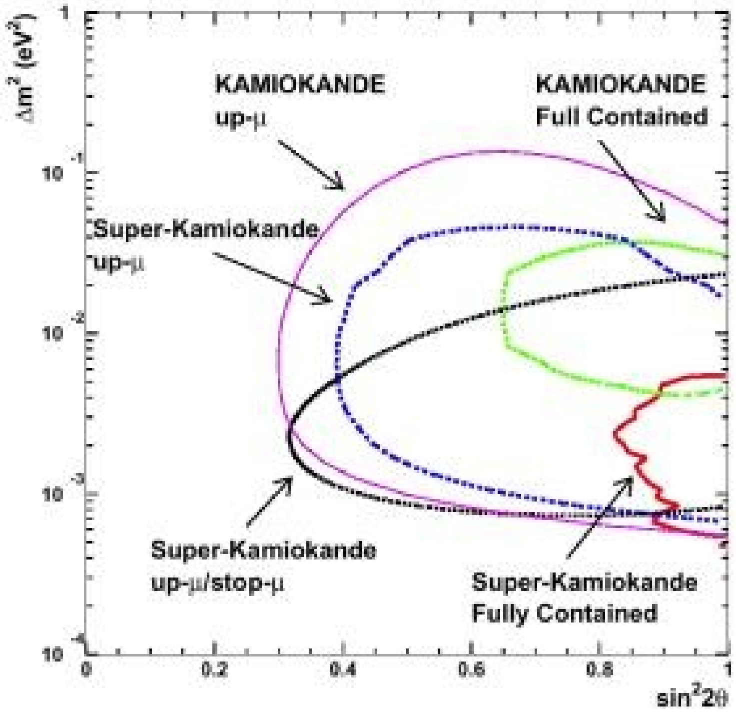
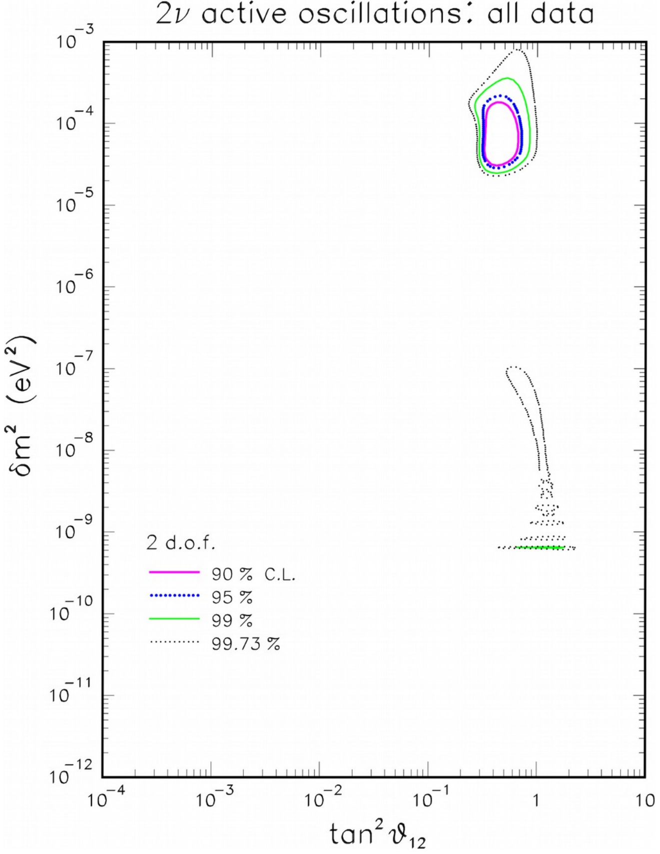


solar

Lisi2002



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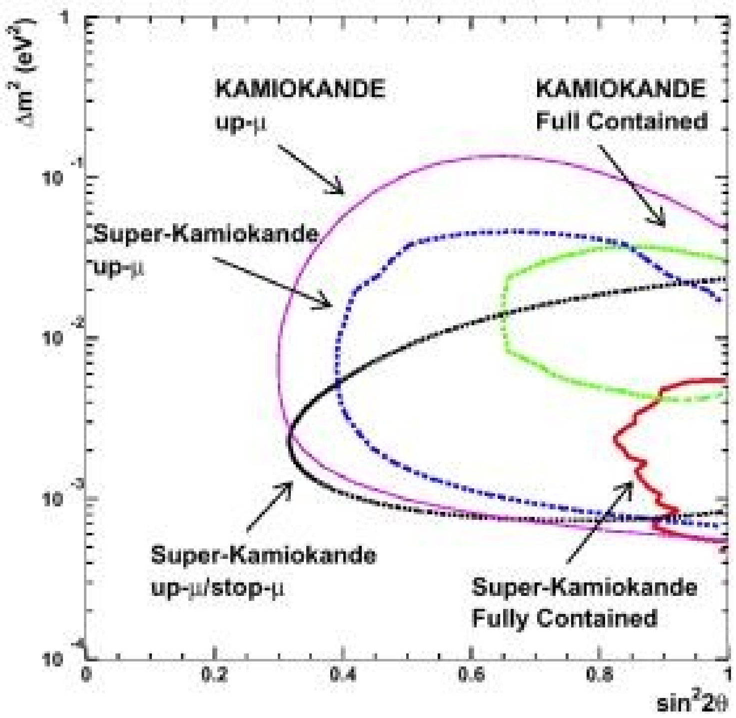
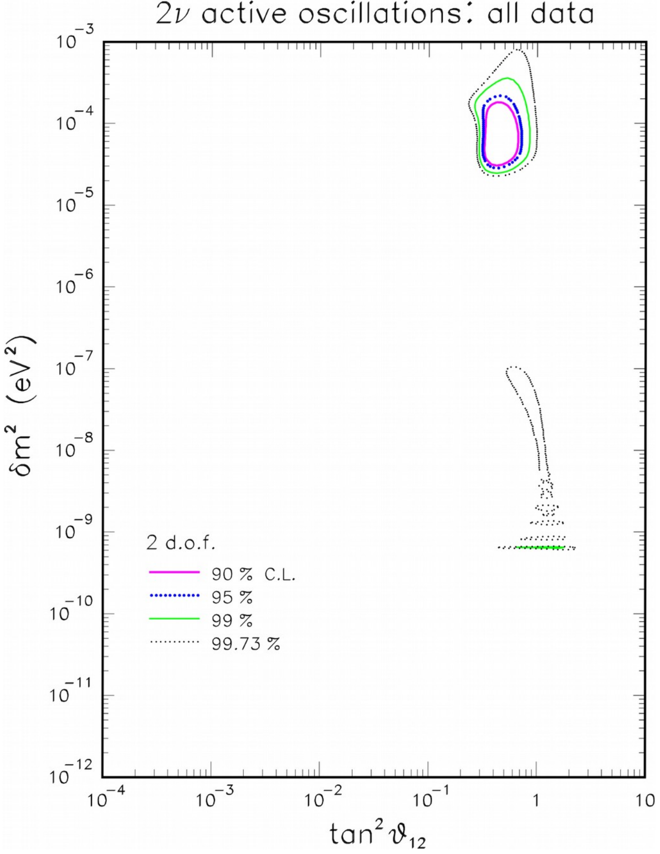


solar

Lisi2002



different values of mixing and mass differences !

The Physics of Neutrino Oscillation: *O(1) effects*

- Values of mass differences are *too different* to be accommodated with two neutrinos only --→ **three** neutrinos (at least) are needed

from this…

$$U=\begin{bmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \end{bmatrix}$$

...to this

$$U=\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12}c_{23} & c_{12}c_{23} & s_{23} \\ s_{12}s_{23} & -c_{12}s_{23} & c_{23} \end{bmatrix}$$

- OK, but now we need to describe mixing using the most generic 3x3 unitary matrix

The Physics of Neutrino Oscillation: *O(1) → O(0.1) effects*

- Values of mass differences are *too different* to be accommodated with two neutrinos only --→ **three** neutrinos (at least) are needed

from this…

$$U = \begin{bmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \end{bmatrix}$$

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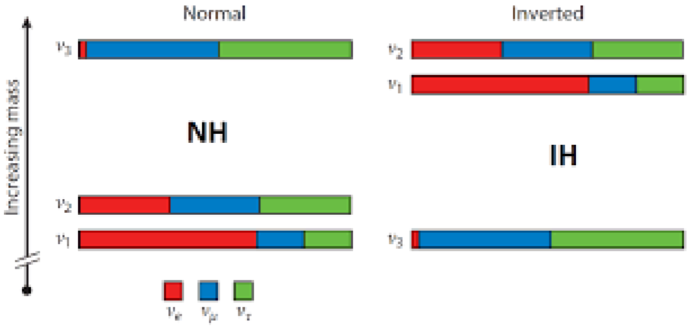
going to ***O(0.1) effects***

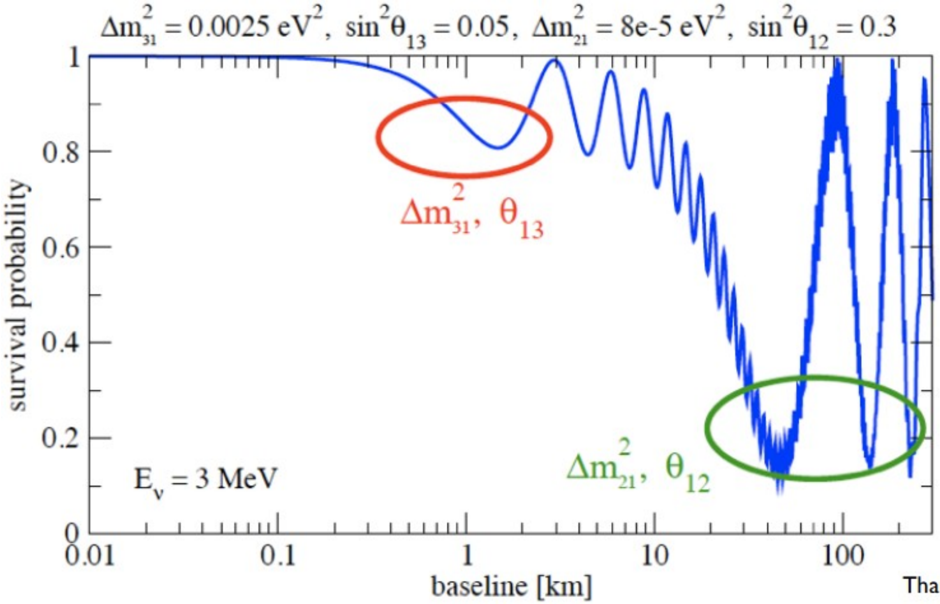
…to this

$$\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$



Next-to-Leading Order: *O(0.1) effects*

- disappearance probability

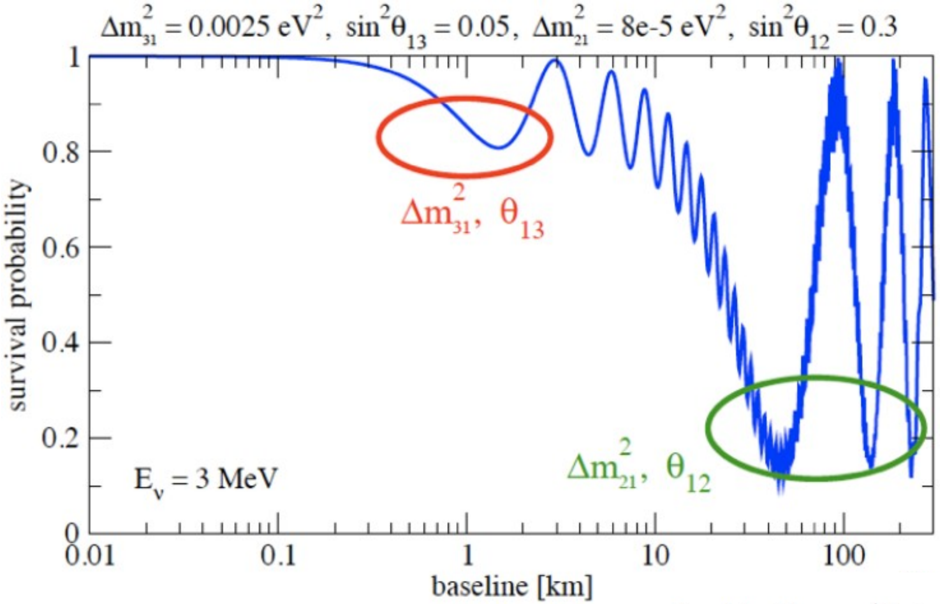


Thanks to T. Schwetz

$$P_{ee} \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{13} L}{4 E_\nu}\right) - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{12} L}{4 E_\nu}\right)$$

Next-to-Leading Order: *O(0.1) effects*

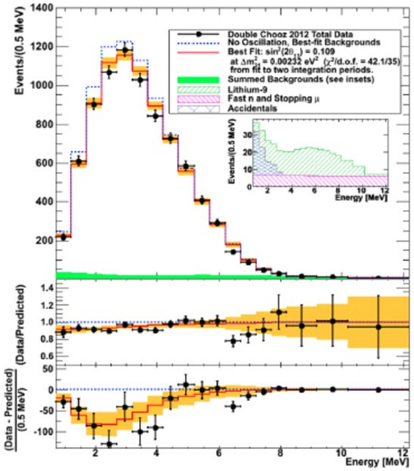
- disappearance probability



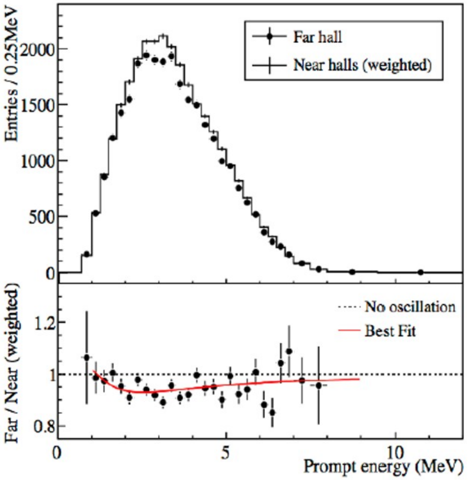
$$P_{ee} \approx 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{13} L}{4E_\nu}\right) - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{12} L}{4E_\nu}\right)$$

- reactor angle

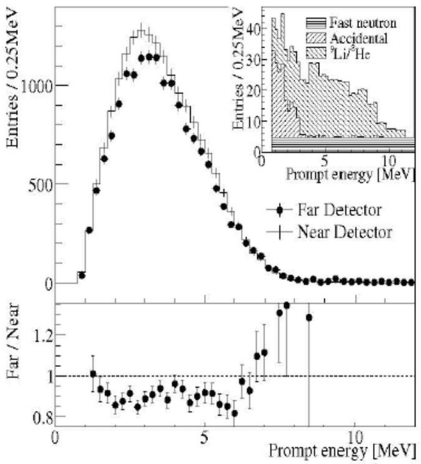
Double Chooz (Oct. 2011)



Daya Bay (March 2012)



RENO (April 2012)



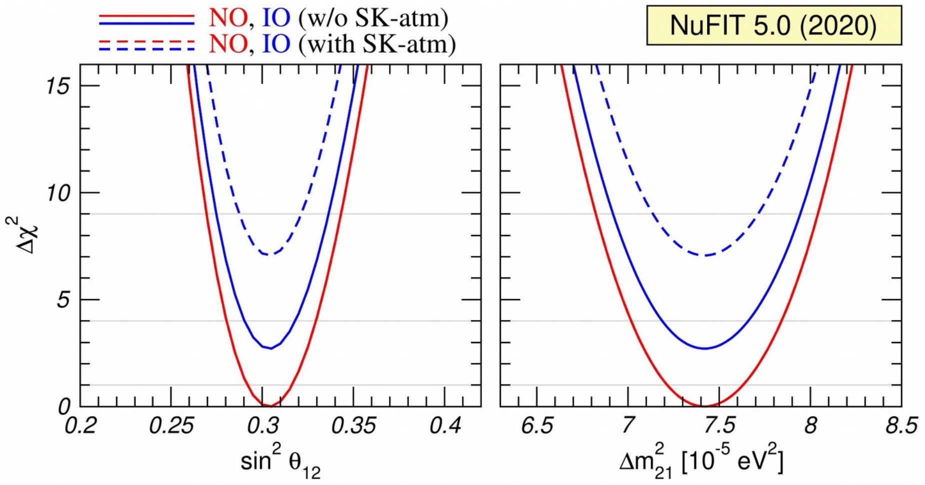
Current experimental situation

- standard 3-ν paradigm (well) established

http://www.nu-fit.org

solar sector

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

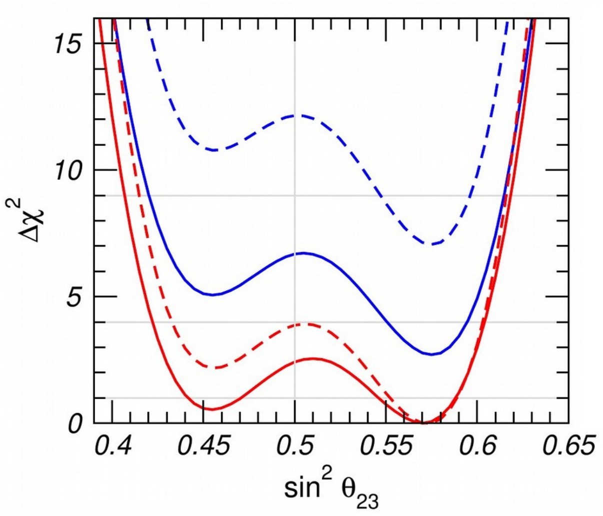


Erros at the level of 3-4 %

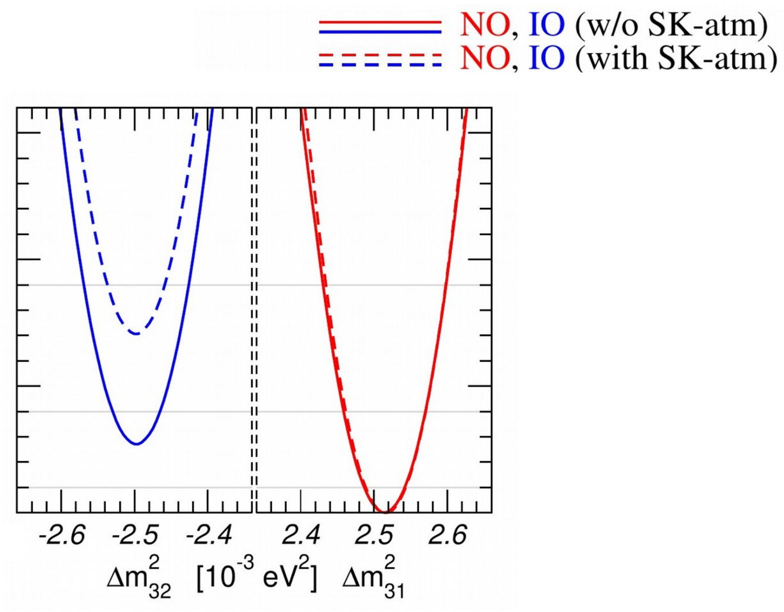
Current experimental situation

- standard 3-ν paradigm (well) established

atmospheric sector

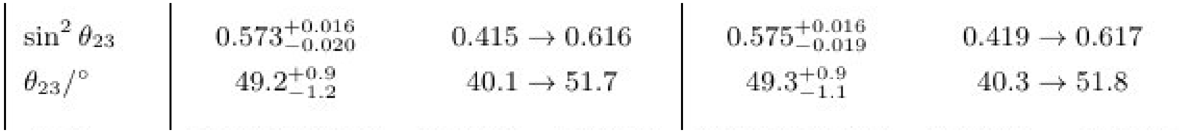


problem of the θ_{23} octant

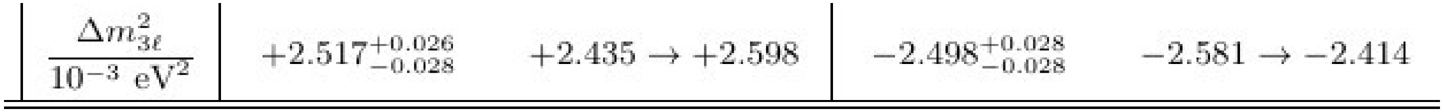


problem of the mass ordering

NO preferred at 2.6 σ



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

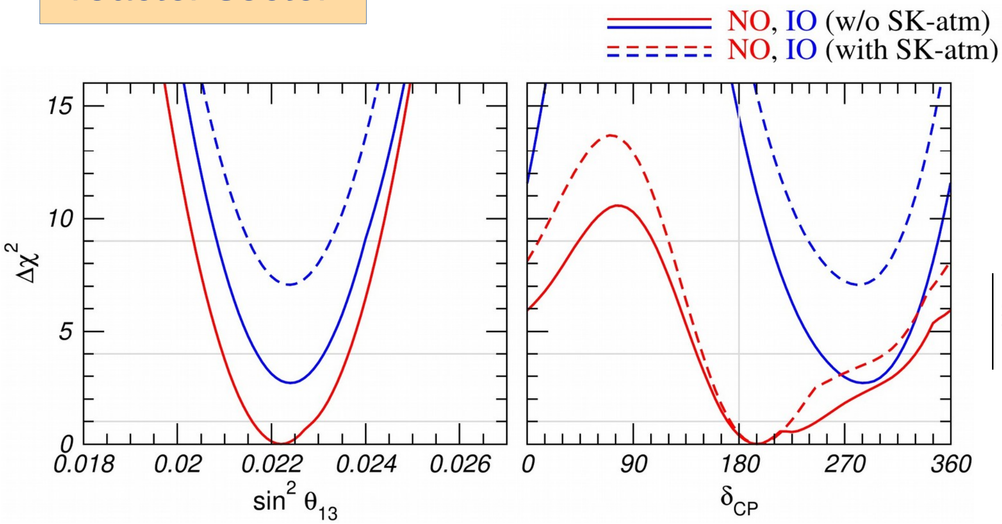


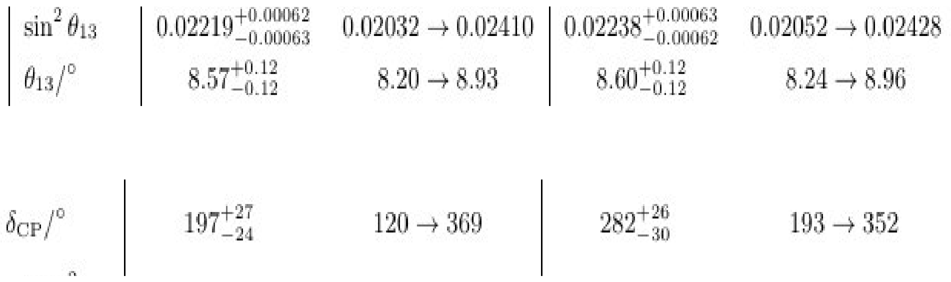
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

Current experimental situation

- standard 3-ν paradigm (well) established

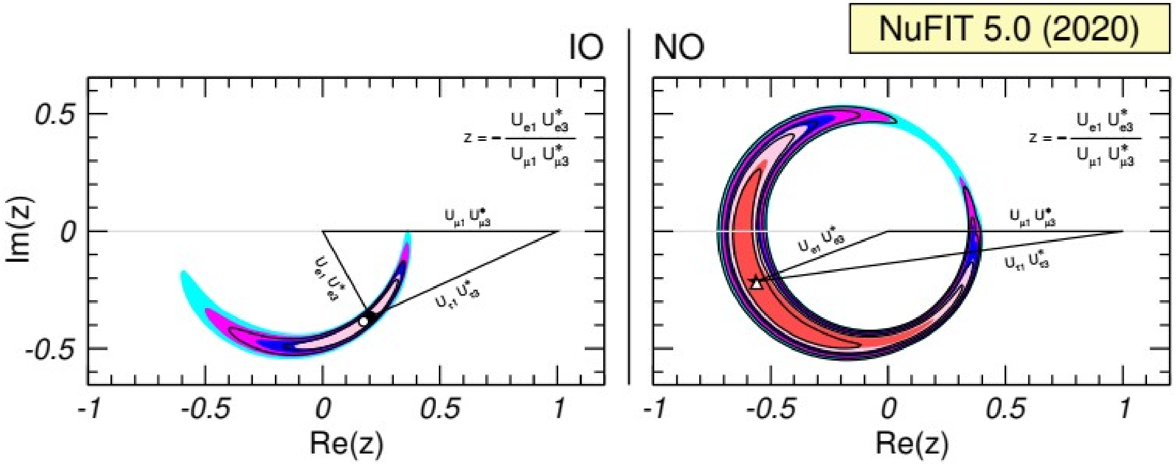
reactor sector





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

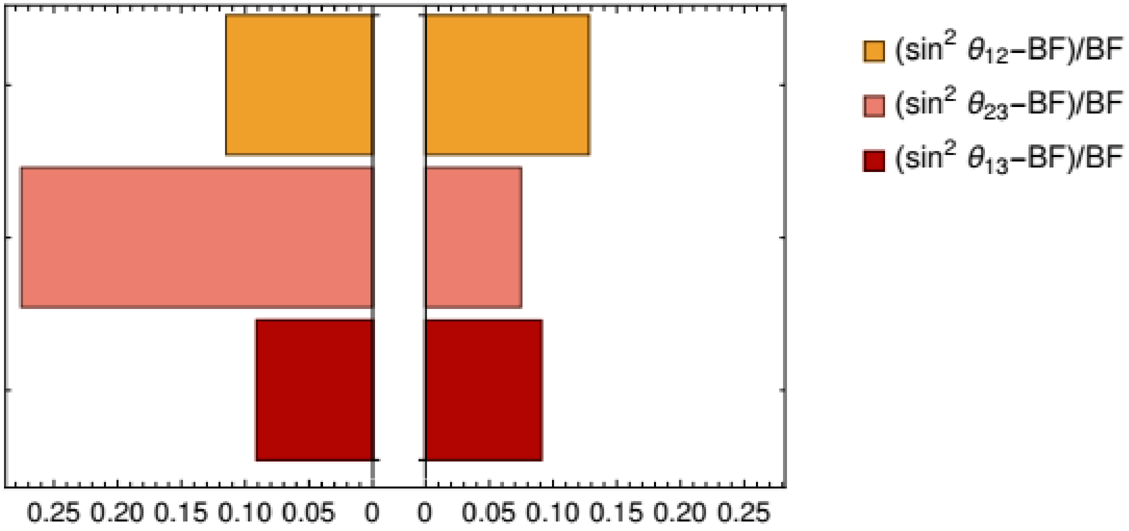
Existence of CP violation in the lepton sector (?)



Where is New Physics ?

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

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 Oscillations

Neutrino mass models

- scenarios where neutrinos are unstable

neutrino decay

"interdisciplinar" NP

imprint on laboratory experiments

imprint on "*astrophysical*" neutrinos

- scenarios where neutrinos test new interactions

modified interactions with detector atoms

modified interactions with matter

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

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*** ***($m_i \to m_i - i\,\Gamma/2$)***

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

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

Neutrino Decay

- Simplified 2-flavor approach

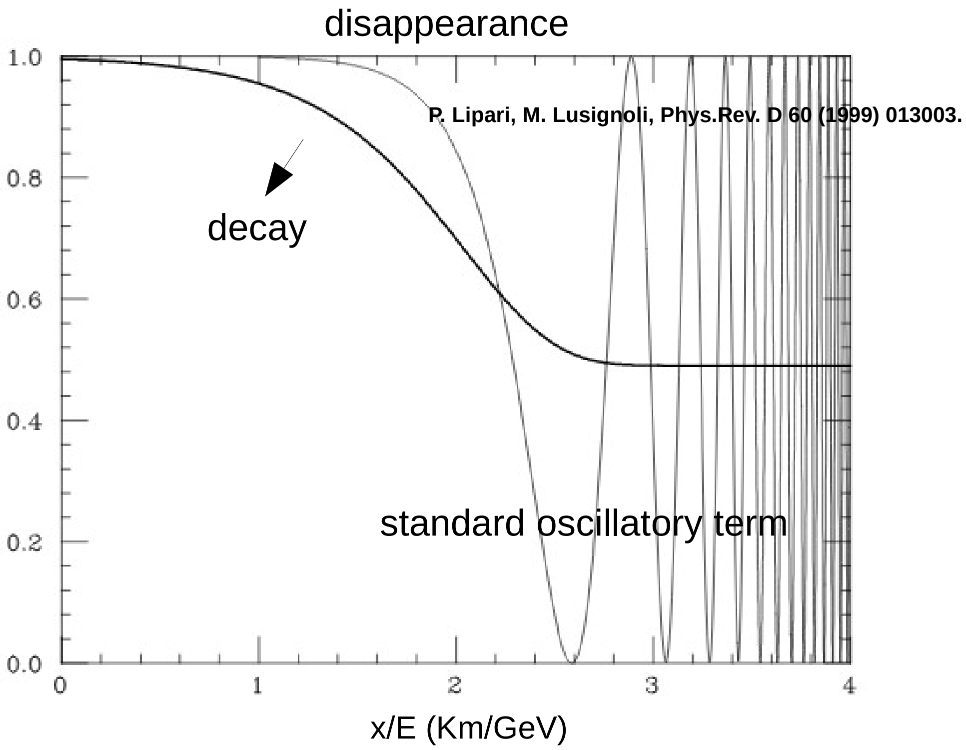
One unstable neutrino:

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

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

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

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



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

Neutrino Decay

- possible explanation of the solar neutrino problem

J. N. Bahcall, N. Cabibbo, A. Yahil, Phys. Rev. Lett.28 (1972) 316–318

A. Acker, S. Pakvasa, Phys. Lett. B 320 (1994)

Assuming ν_2 is unstable with rest mean-life τ_0

$\boldsymbol{\tau(E) = (E/m_2)\tau_0}$

Fluxes from the Sun

$$\phi(\nu_e, E) = \phi_\odot(E) \times \{(1 - |U_{e2}|^2)^2 + |U_{e2}|^4 exp[-t/\tau(E)]\}$$

$$\phi(\nu_\mu, E) = \phi_\odot(E)|U_{e2}|^2\{(1 - |U_{e2}|^2)[1 + exp(-t/\tau(E))]\}$$

Results from SAGE, GALLEX I and GALLEX II, Homestake^{37}Cl experiment and the Kamioka experiments exclude the in flight decay of solar neutrino at the 99% CL

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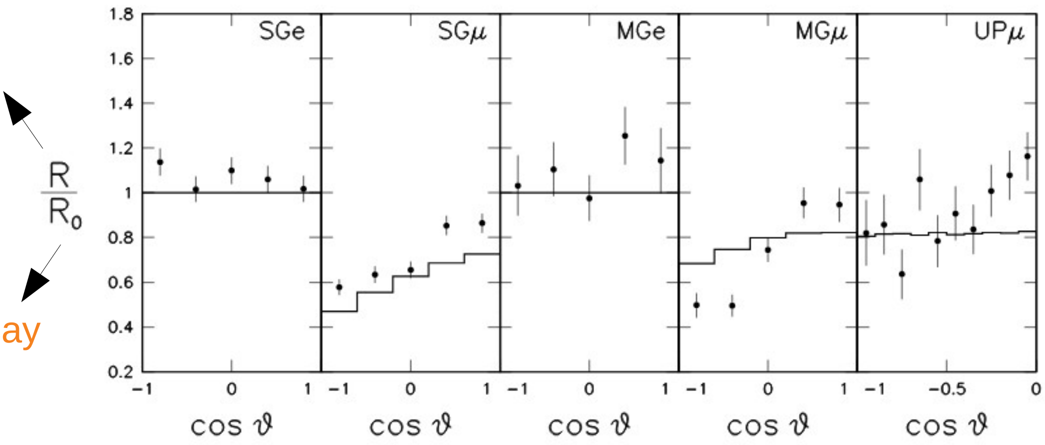
- possible explanation of the atmospheric deficit

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

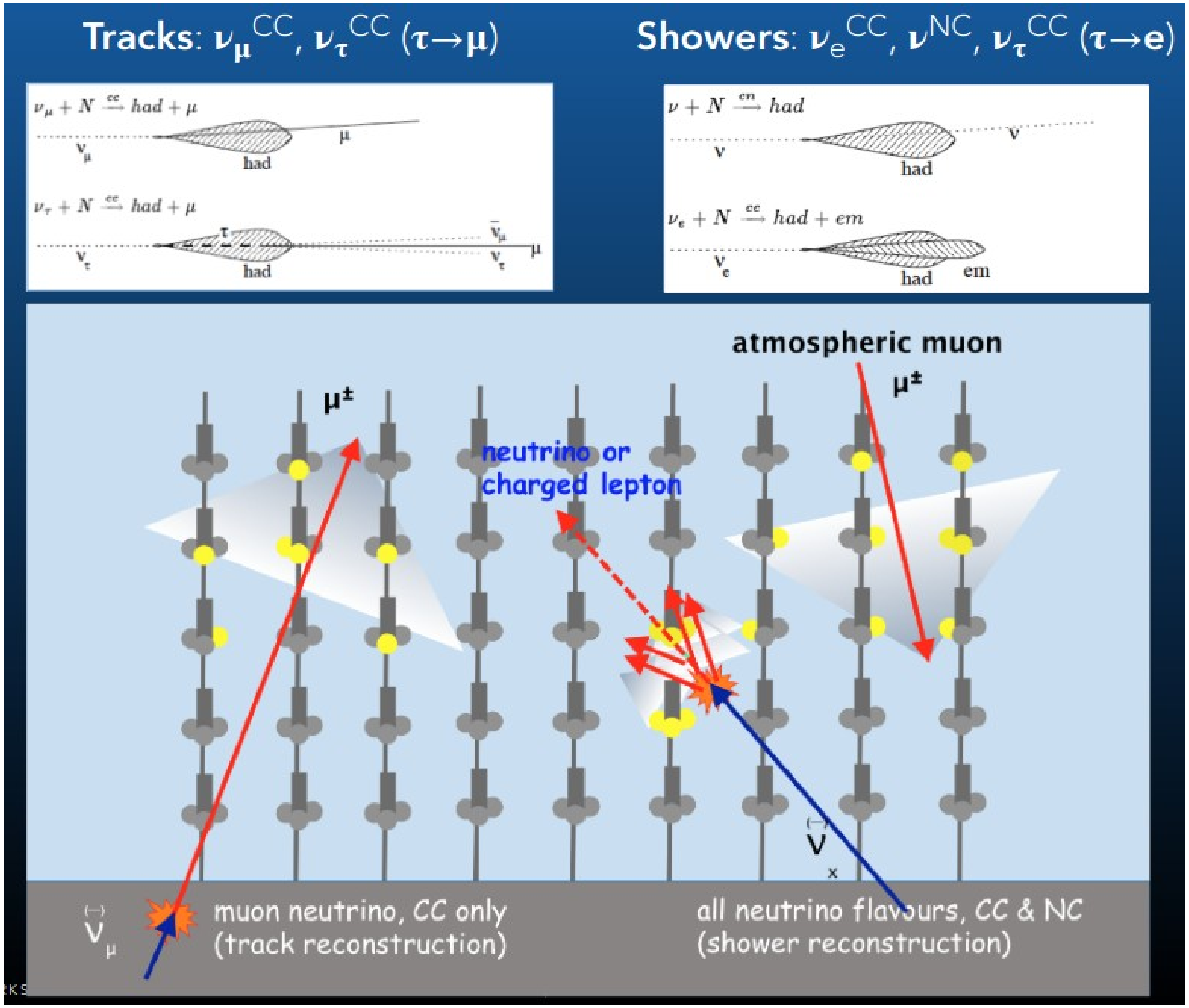
$$\chi^2_{dec,min}/ND = 86/28$$

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

Neutrino Decay at Neutrino Telescopes

The case where L/E >> $(\Delta m^2_{ij})^{-1}$

A. DOMI, talk at NuTel2019



event topology

experimental signature

Neutrino Decay at Neutrino Telescopes

Meloni and Ohlsson,Phys.Rev.D75 (2007), 125017
Serpico and Kachelrieß, Phys.Rev.Lett.94,211102

- averaged neutrino oscillations probabilities

$$\langle P_{\alpha\beta}\rangle = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

If we include decay:

$$\langle P_{\alpha\beta}\rangle = \sum_{i=1}^{3} d_i J_{\alpha\beta}^{ii}$$

under the simplifying assumptions that
the neutrinos completely decay: d=0

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under the simplifying assumptions that
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- starting from the flux ratios at a source: $\varphi^0_{\nu e} : \varphi^0_{\nu\mu} : \varphi^0_{\nu\tau} = 1 : 2 : 0$

Fluxes on Earth:

$$\begin{aligned}\phi_{\nu_e} &= \langle P_{ee}\rangle + 2\,\langle P_{\mu e}\rangle, \\ \phi_{\nu_\mu} &= \langle P_{e\mu}\rangle + 2\,\langle P_{\mu\mu}\rangle \\ \phi_{\nu_\tau} &= \langle P_{e\tau}\rangle + 2\,\langle P_{\mu\tau}\rangle\end{aligned}$$

robust predictions in absence of decay

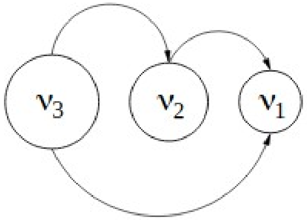
$\varphi_{\nu e} : \varphi_{\nu\mu} : \varphi_{\nu\tau} = 1 : 1 : 1$

Neutrino Decay at Neutrino Telescopes

Meloni and Ohlsson,Phys.Rev.D75 (2007), 125017

Serpico and Kachelrieß, Phys.Rev.Lett.94,211102

exotic scenario:
only v1 is stable



predictions in presence of decay

$$\phi_{\nu e} : \phi_{\nu\mu} : \phi_{\nu\tau} \approx 5 : 1 : 1 \text{ (NH)}$$

$$\phi_{\nu e} : \phi_{\nu\mu} : \phi_{\nu\tau} \approx 0 : 1 : 1 \text{ (NH)}$$

very peculiar results but
experimentally challenging

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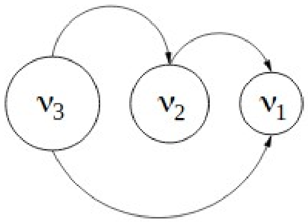

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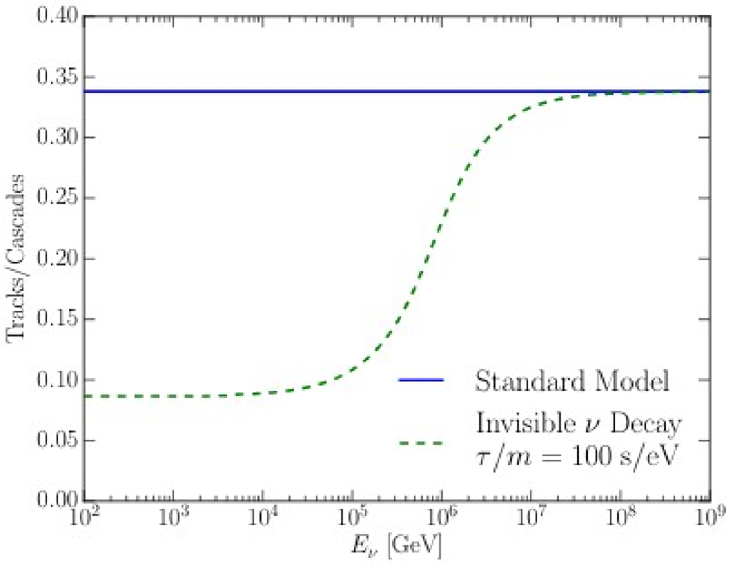
$\Phi_{\nu e} : \Phi_{\nu\mu} : \Phi_{\nu\tau} \approx 0 : 1 : 1$ (NH)

very peculiar results but
experimentally challenging

More appropriate experimental quantity: muon tracks-to-shower ratios

$$\mathcal{R} = \frac{N_{\rm tr}}{N_{\rm sh}} = \frac{\phi_{\nu_\mu}\, N_{\rm tr}}{\sum_{i=e,\tau} \phi_{\nu_i}\,(N^{\rm CC}_{{\rm sh},\nu_i} + N^{\rm NC}_{{\rm sh},\nu_i}) + \phi_{\nu_\mu}\, N^{\rm NC}_{{\rm sh},\nu_\mu}}$$



tension in the track and
cascade data samples
in IceCube

invisible neutrino decay of ν_2 and ν_3 with τ/m= 10^2s/eV is preferred by the IceCube data by 3.4σ

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

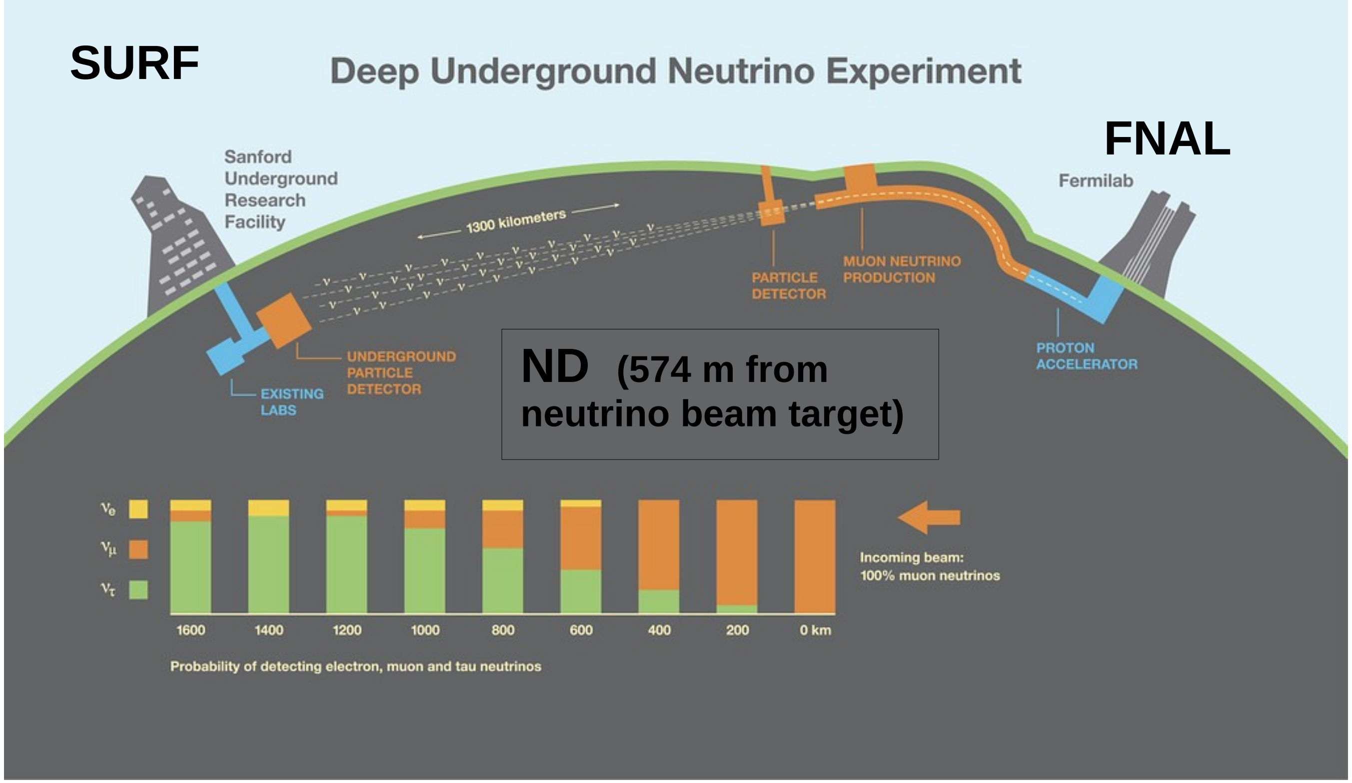
Introducing DUNE

“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

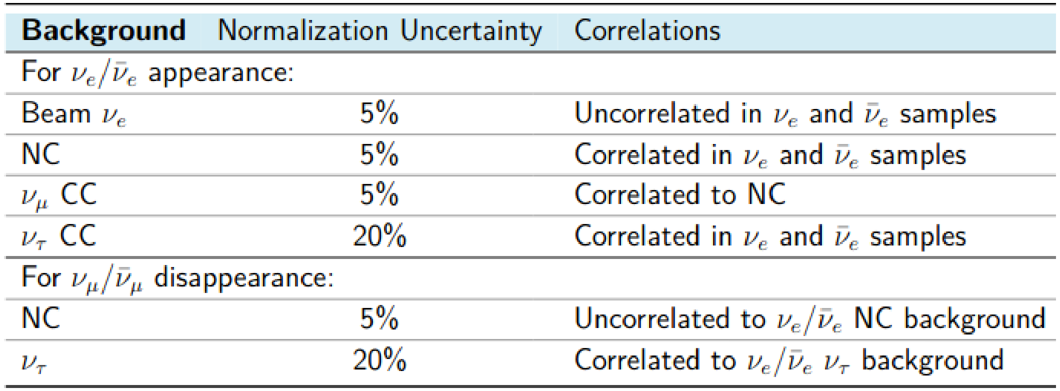
ND (574 m from neutrino beam target)

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)

Neutrino Decay – The Future

- $\nu_3 \to \nu_4$ + 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

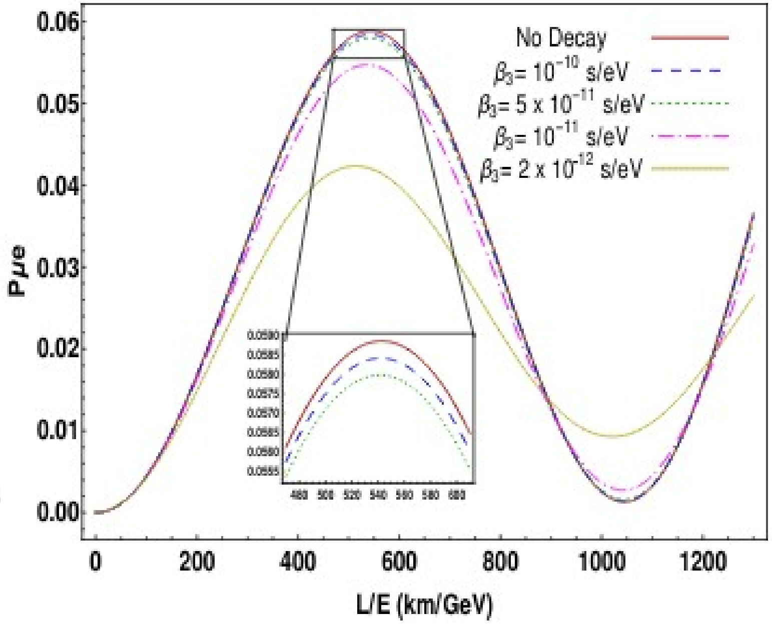
“constant term”

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

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

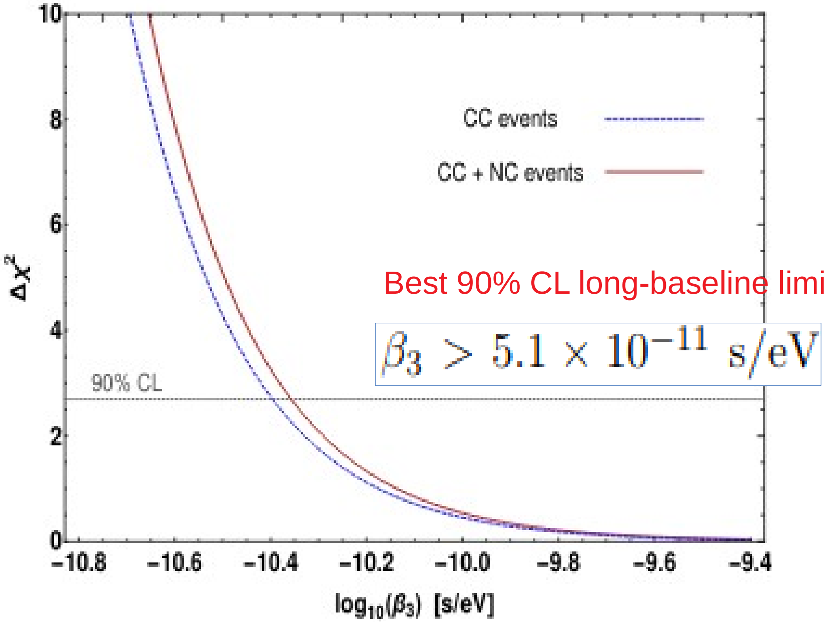
$$\begin{aligned}P^{(0)}_{\mu\mu} = & 1 + 2\left(e^{-\frac{1}{\beta_3}\frac{L}{2E}} - 1\right)\cos^2\theta_{13}\sin^2\theta_{23} + \left(e^{-\frac{1}{\beta_3}\frac{L}{2E}} - 1\right)^2\cos^4\theta_{13}\sin^4\theta_{23}\\ & - e^{-\frac{1}{\beta_3}\frac{L}{2E}}\left(\cos^4\theta_{13}\sin^2 2\theta_{23}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

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



Latest sensitivities to nu lifetime

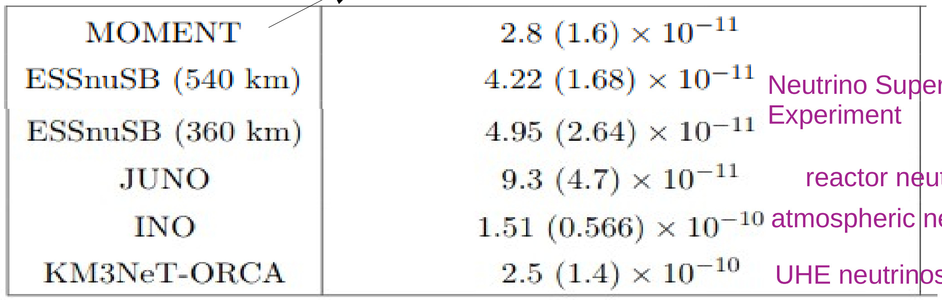
- sensitivity



Best 90% CL long-baseline limit

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

results from other future experiments



MOMENT	$2.8\ (1.6) \times 10^{-11}$
ESSnuSB (540 km)	$4.22\ (1.68) \times 10^{-11}$
ESSnuSB (360 km)	$4.95\ (2.64) \times 10^{-11}$
JUNO	$9.3\ (4.7) \times 10^{-11}$
INO	$1.51\ (0.566) \times 10^{-10}$
KM3NeT-ORCA	$2.5\ (1.4) \times 10^{-10}$

a muon-decay medium-baseline neutrino beam facility

Neutrino Super Beam Experiment

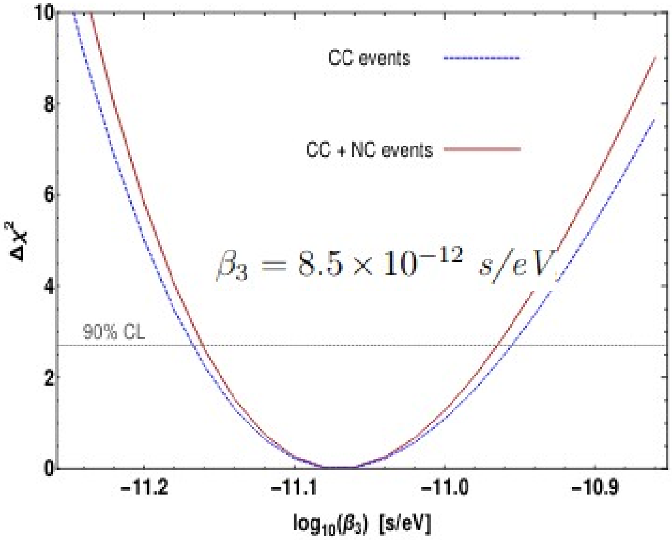
reactor neutrinos

atmospheric neutrinos

UHE neutrinos

- precision measurement

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



Non-standard Neutrino Interactions (NSI)

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

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

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

lα = lepton doublet

f= components of an arbitrary weak doublet

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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

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

non-standard matter effects

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

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

Non-standard Neutrino Interactions (NSI)

- Many new-physics parameters, huge parameter space:

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

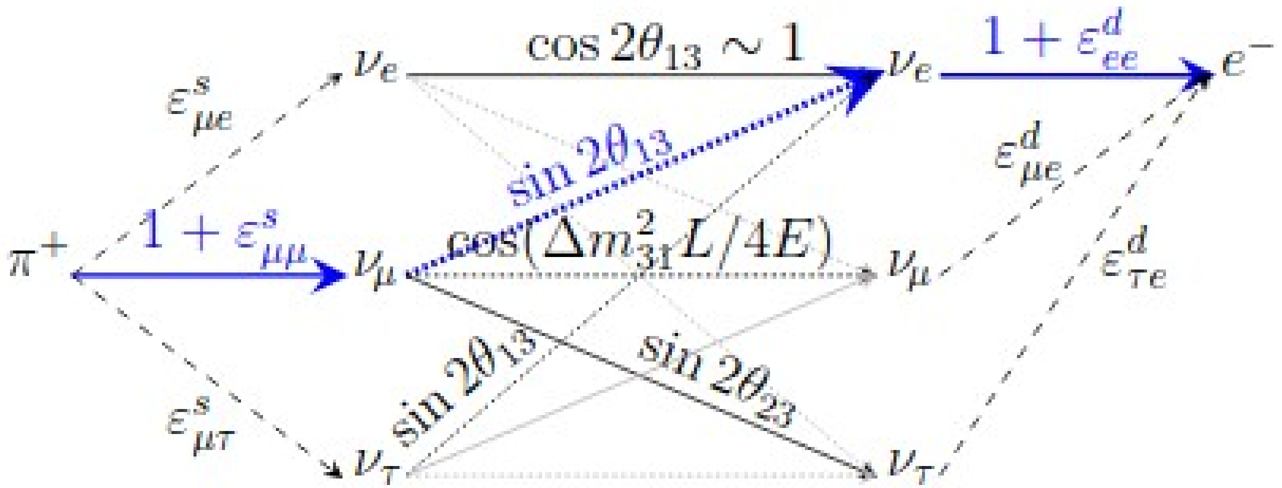
$\tilde{\varepsilon}^{m,f}_{\alpha\beta}$ hermitean complex matrices

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 .
- ...

Non-standard Neutrino Interactions (NSI)

- An example:



Kopp,Lindner,Ota and Sato, Phys. Rev. D77 (2008), 013007

Modified Oscillation Probabilities

- Standard oscillations:

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

- Oscillations with Neutral Current NSI:

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

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

$$P(\nu_\alpha^s \rightarrow \nu_\beta^d) = |\langle \nu_\beta^d | e^{-i(H+V_{NSI})L} | \nu_\alpha^s \rangle|^2$$

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

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

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

Modified Oscillation Probabilities

- Existing bounds

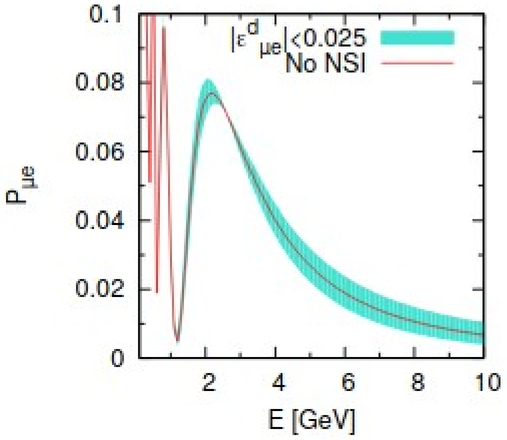
Blennow, Choubey, Ohlsson, Pramanik and Raut, JHEP08 (2016), 090
Biggio, Blennow, and Fernandez-Martinez, JHEP08, 090 (2009), 0907.0097

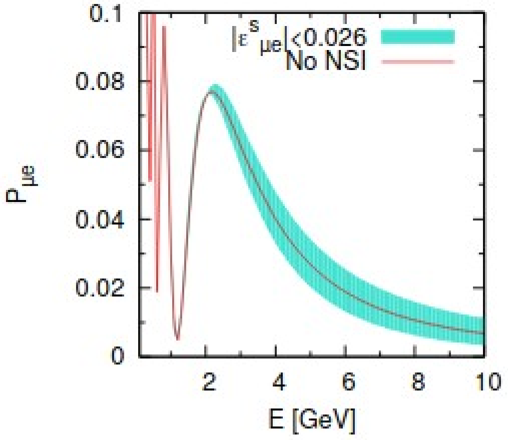
from G_F , pion decay, unitarity of CKM, oscillation experiments

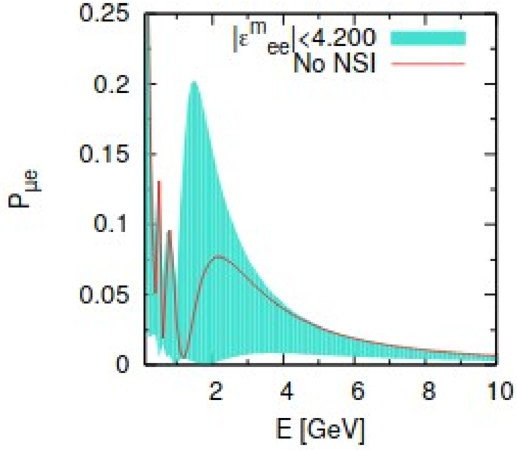
$$|\varepsilon^{s/d}_{\alpha\beta}| < \begin{bmatrix} 0.041 & 0.025 & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.12 & 0.018 & 0.13 \end{bmatrix}$$

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

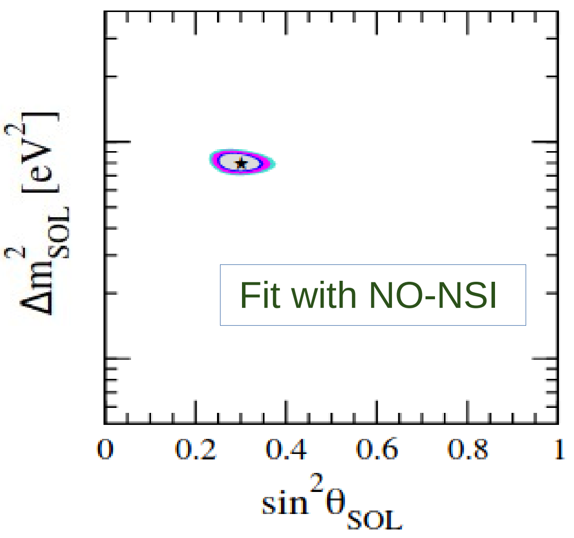
Possible effects of NSI

- Solar neutrinos

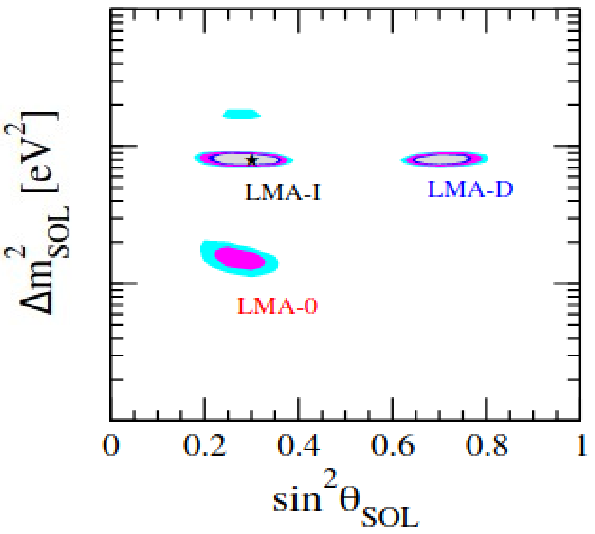
In the 2-flavor regime: $H_{\rm NSI} = \sqrt{2} G_F N_d \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}$ →

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

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



→



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

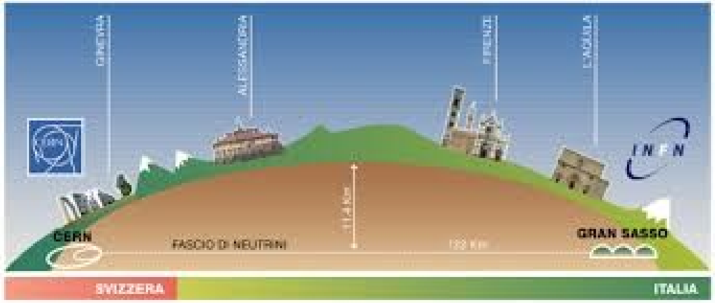
no NSI

dark-side

light-side

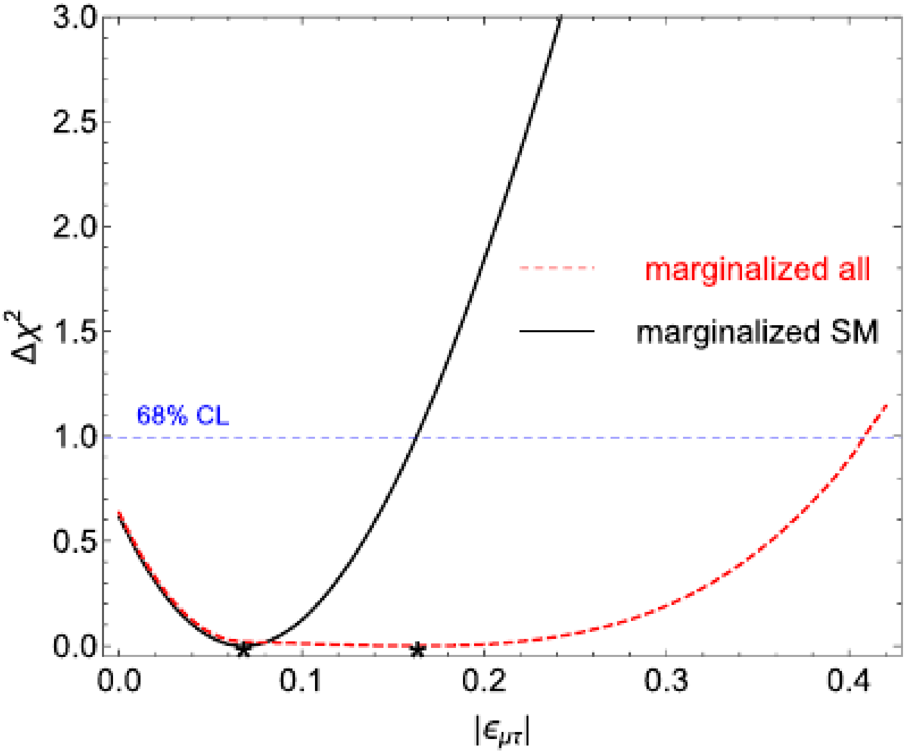
The Present: signal at OPERA

- Introducing tau neutrinos into the game



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

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



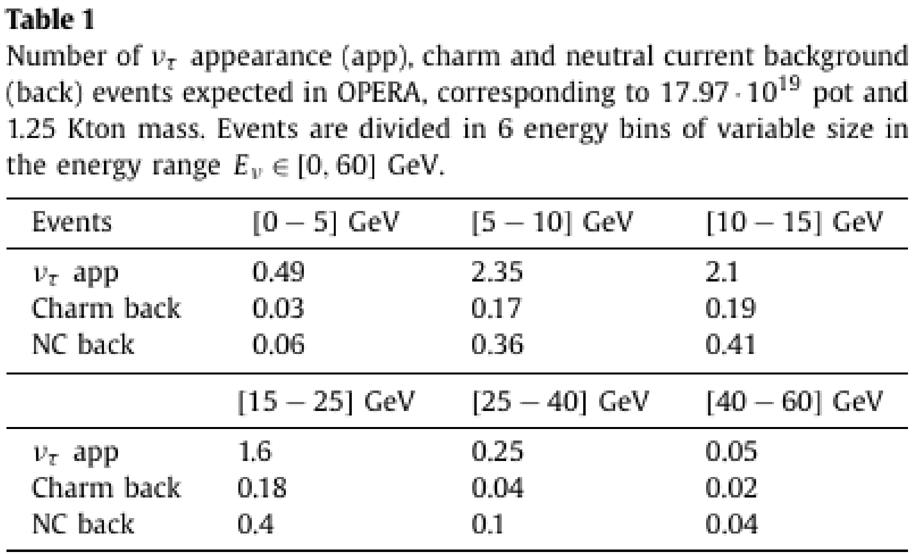


Table 1

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.

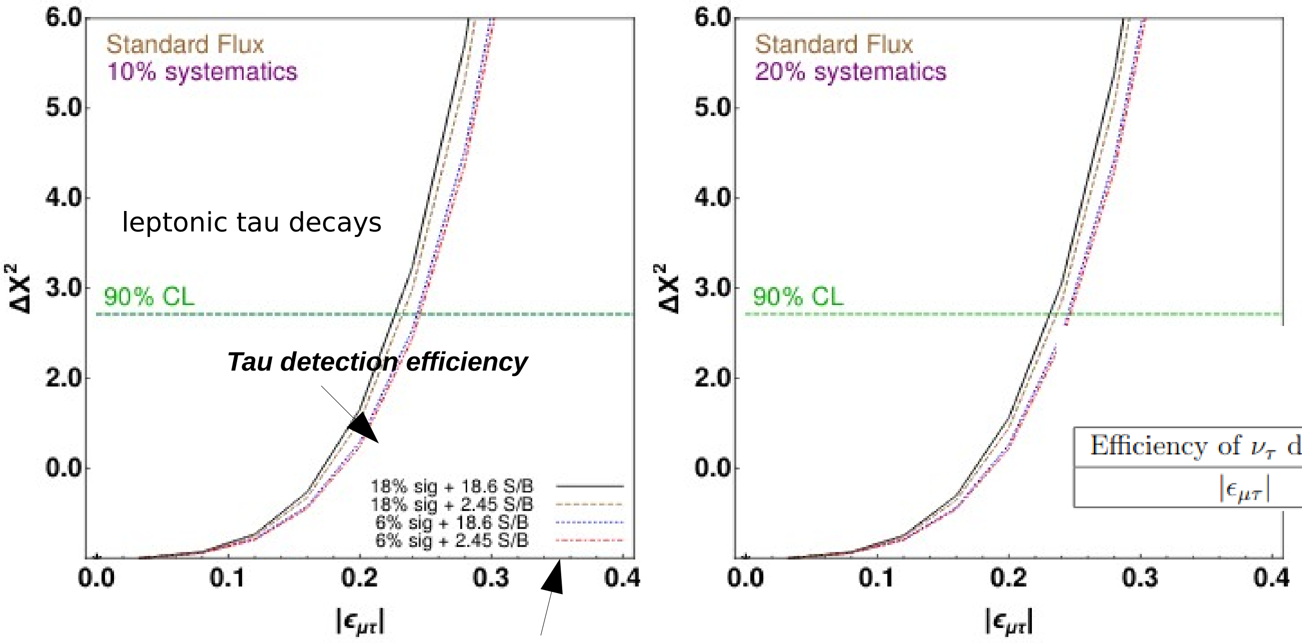
Events	[0 – 5] GeV	[5 – 10] GeV	[10 – 15] GeV
ν_τ app	0.49	2.35	2.1
Charm back	0.03	0.17	0.19
NC back	0.06	0.36	0.41
	[15 – 25] GeV	[25 – 40] GeV	[40 – 60] GeV
ν_τ app	1.6	0.25	0.05
Charm back	0.18	0.04	0.02
NC back	0.4	0.1	0.04

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

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



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

Giarnetti, Meloni 2005.10272

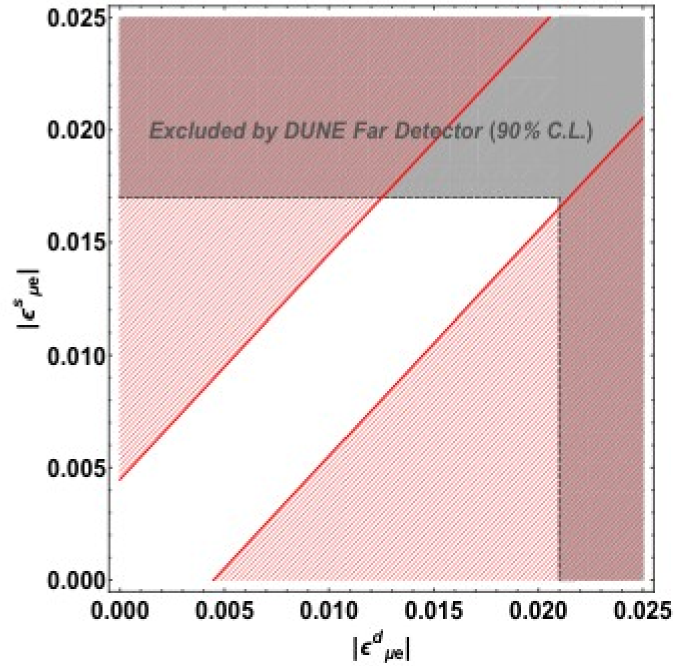
$$P(\nu^s_\alpha \to \nu^d_\beta) = \left|\left[(1+\epsilon^d)^T e^{-i(H+V_{NSI})L}(1+\epsilon^s)^T\right]_{\beta\alpha}\right|^2 \xrightarrow{L=0} \boxed{P_{\alpha\beta} = |[(1+\varepsilon^d)^T(1+\varepsilon^s)^T]_{\beta\alpha}|^2}$$

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

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

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

- main dependence on ε with the same flavor indeces



Investigation of parameter space complementary to Far Detector studies

Very competitive bounds!

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

Fascinating research lines

- more <u>phenomenological</u> point of view:
  - Complete the study of sensitivity of future facilities to tiny effects (combining them ?)
  - Clarify the role of ***tau neutrinos*** in such searches
  - Clarify the role of ***Neutrino Telescopes*** in such searches (fit to real data ?)

- more <u>theoretical</u> point of view:
  - Study of the leptonic CP triangles
  - Check the compatibility of neutrino mass models against the recent hints for delta CP and the mass ordering
  - Extension of the Standard Model allowing neutrino masses beyond Dirac

Backup slides

Conclusions

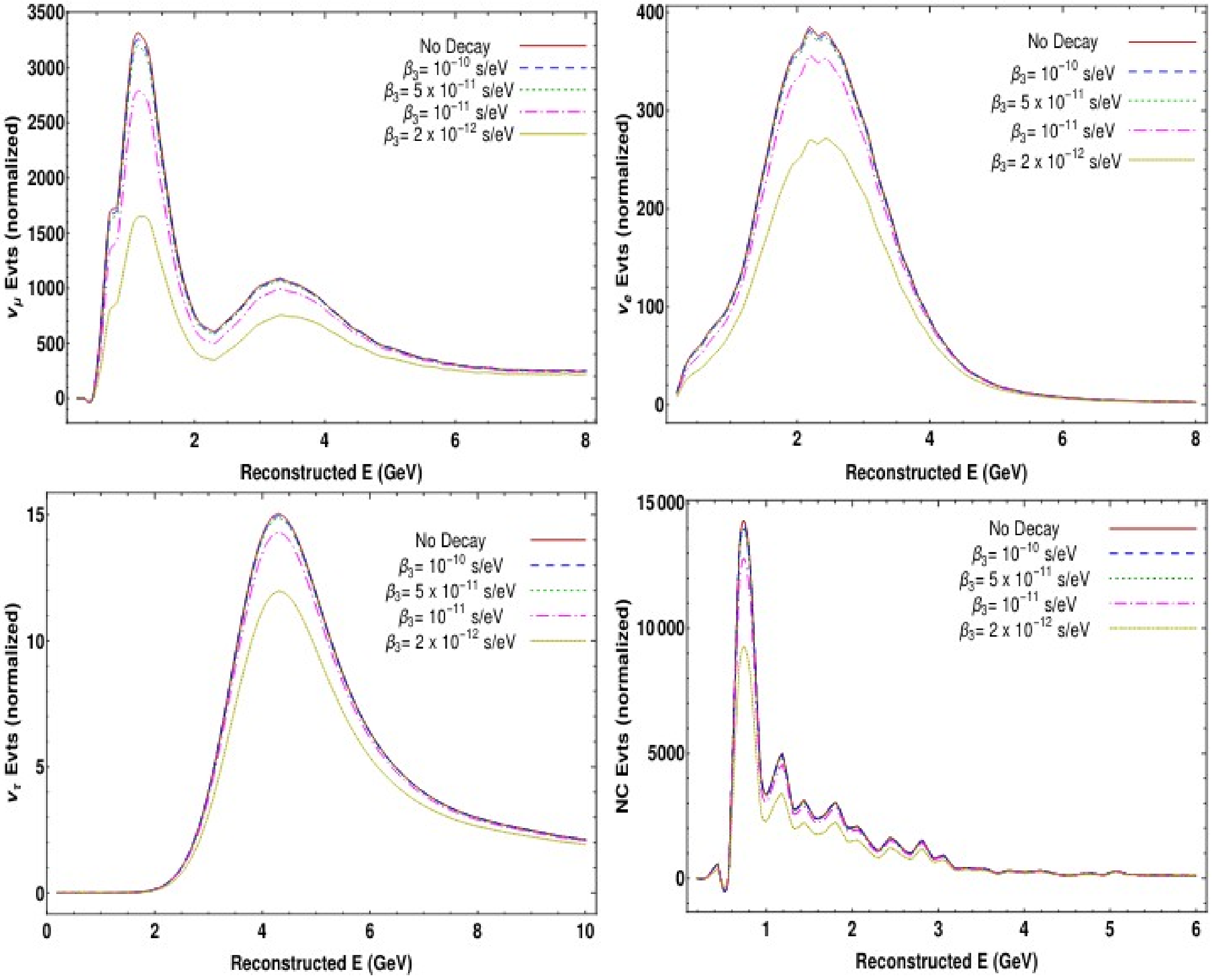
- On-going and planned neutrino experiments will probe the PMNS with huge precision
- Good chance to investigate New Physics effects in Neutrino oscillations:

  several “Beyond the Standard Model” scenarios, including Neutrino Decay and Non-Standard Interactions

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)

New Physics in the Neutrino Sector

- going beyond standard physics looking at $\boxed{\nu_\mu \to \nu_\tau}$ 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}

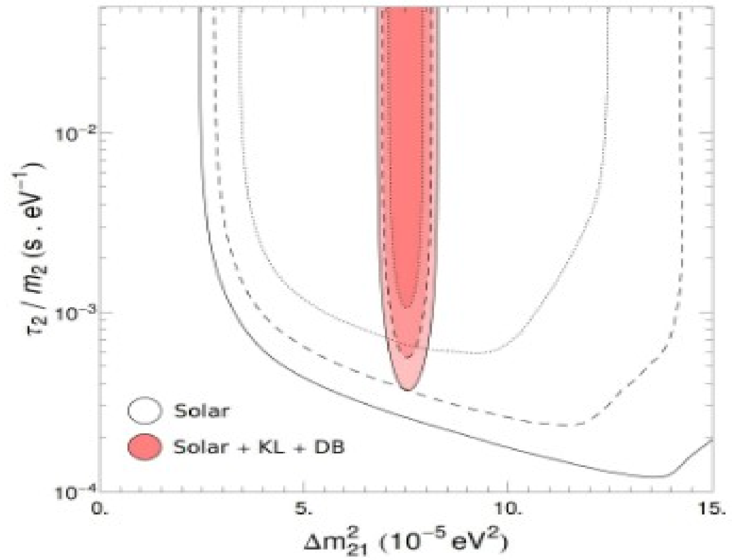
Neutrino Decay

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

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

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

Phys. Lett. B 761 (2016) 70–73



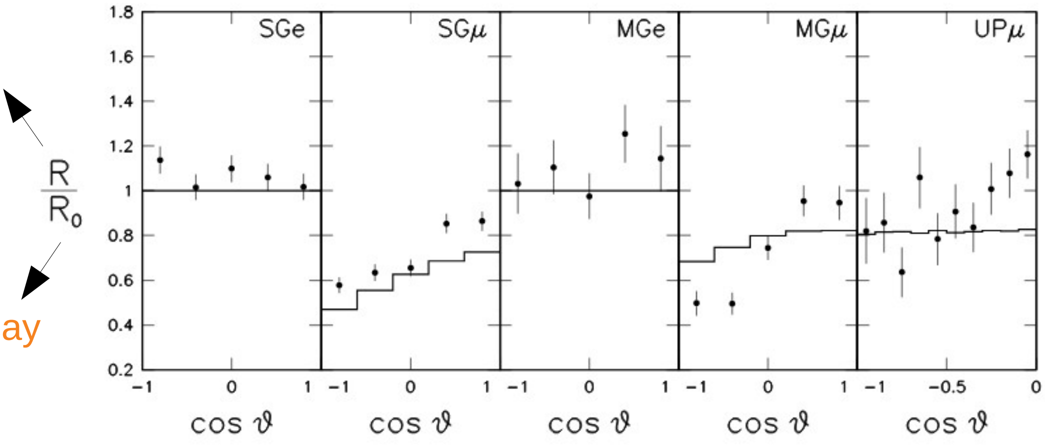
- possible explanation of the atmospheric deficit (the measurements of the fluxes of atmospheric neutrinos give evidence for the disappearance of muon neutrino)

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



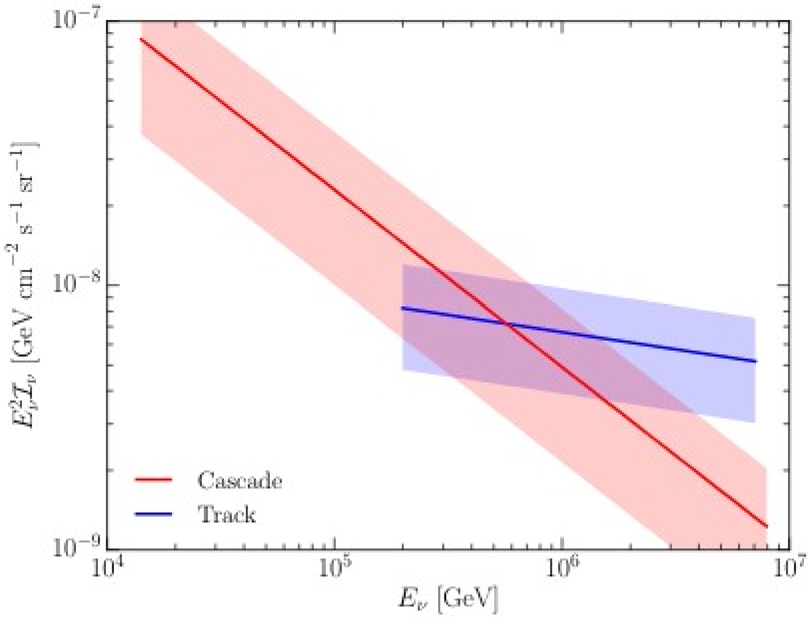
$$\chi^2_{dec,min}/ND = 86/28$$

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

Invisible Neutrino Decay in IceCube

- Track-to-cascade tension in the IceCube data

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

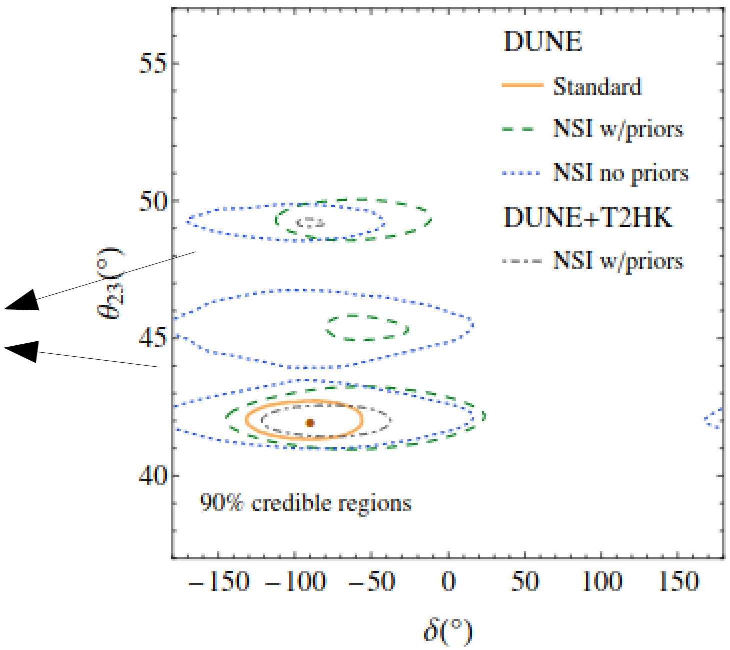


Possible effects of NSI

- 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

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.

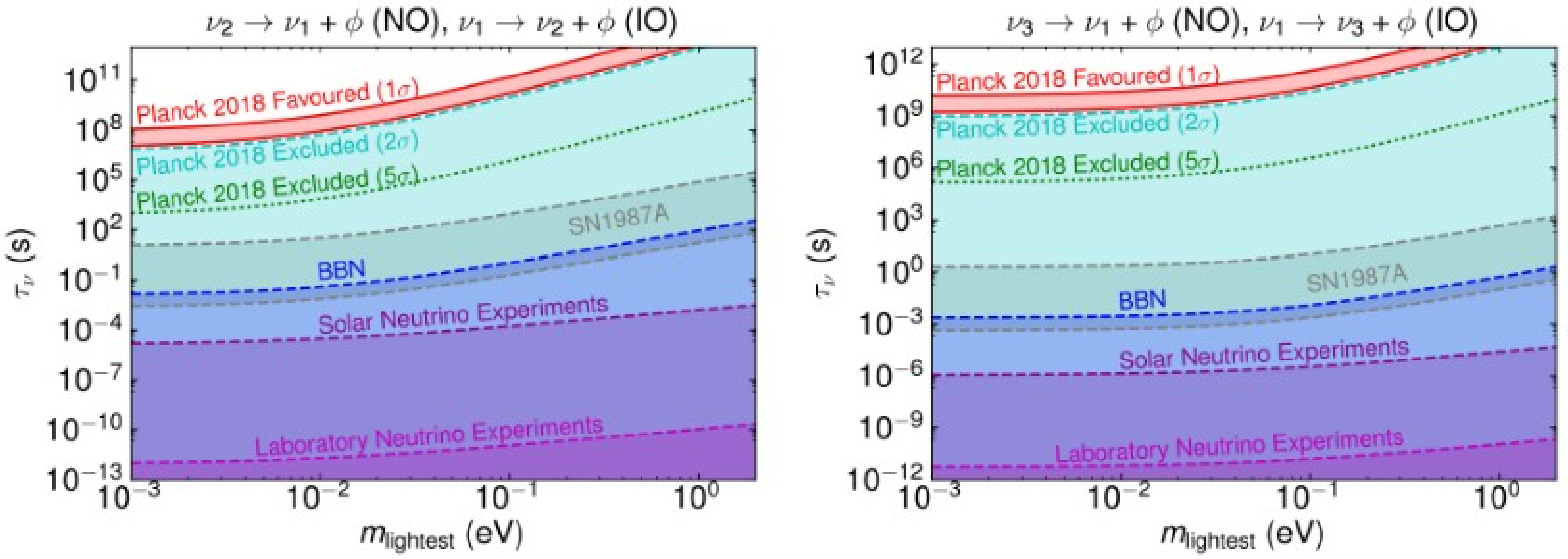
SU(2) formulation

- 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

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