Invisible and Visible Neutrino Decay and Constraints on them from Oscillation Experiments

O. L. G. Peres[1]

[1]Instituto de Física Gleb Wataghin
UNICAMP, Brazil

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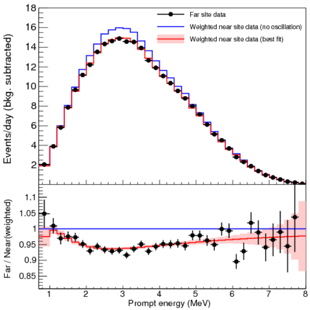
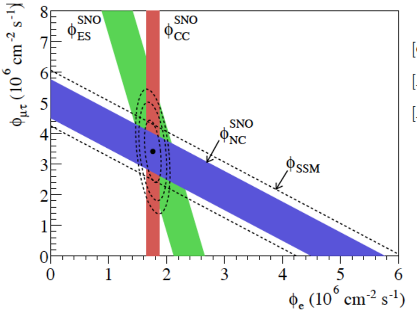
Neutrino Oscillations

- In the latest years there are stronger evidences for neutrino oscillation



Daya Bay Experiment



SNO experiment

All evidences point to non-zero neutrino masses.

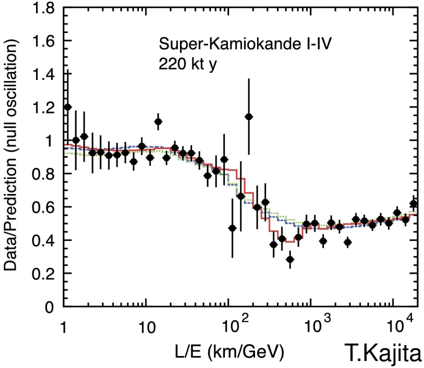
Why include neutrino decay in this picture?

If the neutrino have mass then it can decay.

Can we test the neutrino stability using present neutrino detectors? YES.

The suppression factor of the decay is

$$\frac{\phi^{\mathrm{decay}}}{\phi} = P_{\mathrm{decay}} = e^{-\left(\frac{t}{\tau_{\mathrm{LAB}}}\right)} = e^{-\left(\frac{m}{\tau}\right)\frac{L}{E_\nu}}$$

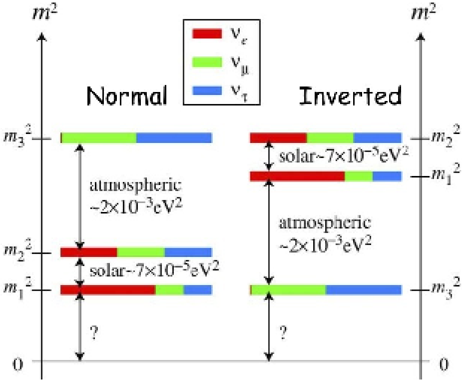


Exclude **PURE** decay at 4σ

What happened when we have oscillation and decay **AT** same time?

T.Kajita *et al.*, Nuclear Physics 908, 14 (2016)

Framework of Neutrino Decay



We will assume that the

Heavier neutrinos decay to lighter neutrinos (normal hierarchy)

Framework of Neutrino Decay

Possible scenarios:

Initial neutrino states $\longrightarrow$ final neutrino states

final neutrino states $\begin{cases} \text{INVISIBLE} \\ \text{VISIBLE} \end{cases}$

INVISIBLE:
- Sterile states
- Below the threshold of experiment
- Depletion of event rates: even for NC rates

VISIBLE:
- Flavor states
- Increase/Depletion of event rates

Constrains on Invisible neutrino decay

Invisible neutrino decay scenario for solar neutrinos:

Berezhiani *et al.* 1992, Choubey it et al. 2000, Beacom/Bell 2002,Choubey/Goswami 2003 Berryman, Gouvea/Hernandez 2015, Picoreti *et al.* 2016

$$P(\nu_e \to \nu_e) = c_{13}^4 \left[P_{e1}^{\odot} P_{1e}^{\oplus} + P_{e2}^{\odot} \exp\left[- \left(\frac{m_2}{\tau_2} \right) \frac{L}{E_\nu} \right] P_{2e}^{\oplus} \right] + s_{13}^4 \,,$$

- Picoreti *et al.* 2016 : energy distortion and seasonal dependence

Analysis	Neutrino	Decay mode	Limit
Solar data Picoreti *et al.*	ν_2	Invisible	$\tau_2/m_2 > 7.2 \times 10^{-4}$ s/eV
Solar data Berryman *et al.*	ν_2	Invisible	$\tau_2/m_2 > 7.1 \times 10^{-4}$ s/eV

Constrains on Invisible neutrino decay

Invisible neutrino decay scenario for long-baseline experiments and atmospheric ν

Barger *et al.* 1999, Fogli *et al.* 2004, Gonzalez-Garcia *et al.* 2008, Gomes *et al.* 2015, Choubey, Goswami and Pramani 2017

Analysis	Neutrino	Decay mode	Limit
Atmospheric and LBL data	ν_3	Invisible	$\tau_3/m_3 > 2.9 \times 10^{-10}$ s/eV
MINOS and T2K data Gomes *et al.*	ν_3	Invisible	$\tau_3/m_3 > 2.8 \times 10^{-12}$ s/eV
DUNE sensitivity (CHOUBEY *et al.*)	ν_3	Invisible	$\tau_3/m_3 > 4.3 \times 10^{-11}$ s/eV

and medium baseline reactor experiments
Abrahão *et al.* 2015

Analysis	Neutrino	Decay mode	Limit
JUNO expected sensitivity	ν_3	Invisible	$\tau_3/m_3 > 7.5 \times 10^{-11}$ s/eV

Visible neutrino decay

The visible neutrino scenario take into account the final states of neutrino decay:

Lindner/Ohlsson/Winter 2001, Palomarez-Ruiz/ Pascoli/Schwetz 2005

Gago/Gomes^2/Jones-Pérez/ Peres 2017, Coloma and Peres 2017

It is dependent of specific decay model of neutrino.

We will assume a two-body neutrino decay $\nu' \to \nu + \phi$, ϕ is a scalar/pseudo-scalar.

$$\mathcal{L}_{\rm int} = \sum_{i=1,2} \frac{g_{3i}}{2} \bar{\nu}_i \nu_3 \phi + \frac{g'_{3i}}{2} \bar{\nu}_i i\gamma_5 \nu_3 \phi + \text{h.c.}\,,$$

SCALAR PSEUDO-SCALAR

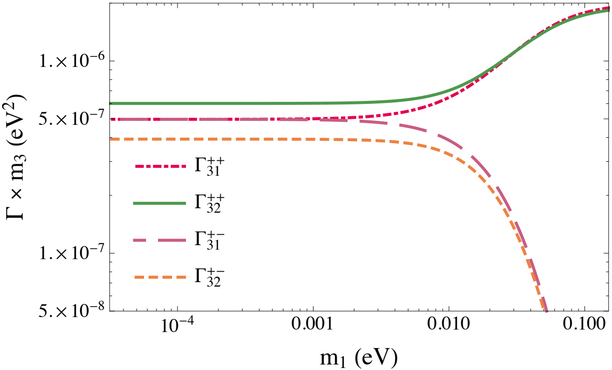
Visible neutrino decay

- Helicity conserving decays : $\nu_3 \to \nu_1 + \phi$
- Helicity non-conserving decays : $\nu_3 \to \bar{\nu}_2 + \phi$

Given a original ν_μ flux, we have ($\nu_\mu = U_{\mu 1}\nu_1 + U_{\mu 2}\nu_2 + U_{\mu 3}\nu_3$). If ν_3 decay to ν_2

then the ν_2 mass eigenstate ($\nu_2 = U^*_{e2}\nu_e + U^*_{\mu 2}\nu_\mu + U^*_{\tau 2}\nu_\tau$)

An original pure ν_μ can from the chain above to have $\nu_\mu \to \nu_e$ and also $\nu_\mu \to \bar{\nu}_e$.



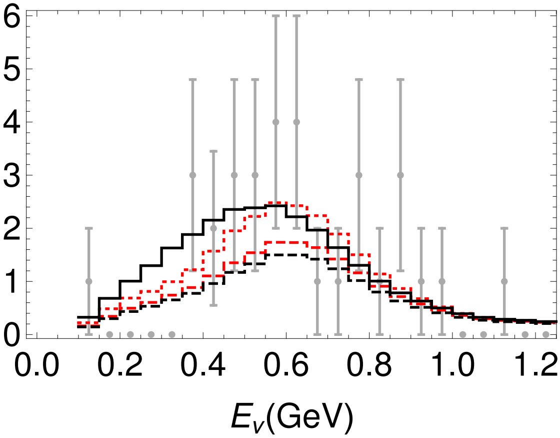
: m_{heavy}, m_{light} and from neutrino-scalar couplings.

Coloma and Peres 2017

Analysis of Visible decay for MINOS and T2K

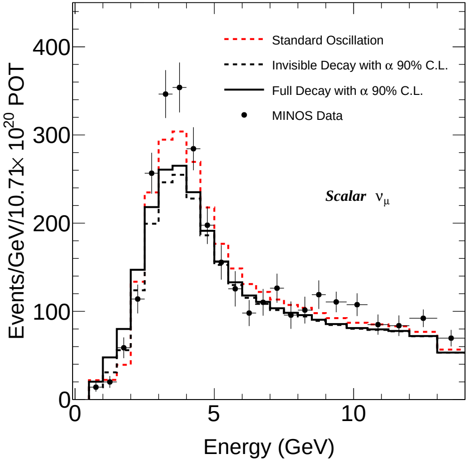
Work in collaboration with Gago/Gomes^2/Jones-Pérez/ Peres 2017,

ν_e: invisible decay black dashed , **visible decay: solid black** (both with $\delta_{\mathrm{CP}} = \pi/2$) and standard oscillation is in $\delta_{\mathrm{CP}} = \pi/2(\delta_{\mathrm{CP}} = -\pi/2)$ for red dotted(dashed) curve



$\nu_3 \to \nu_1 + \phi$ /one non-zero coupling

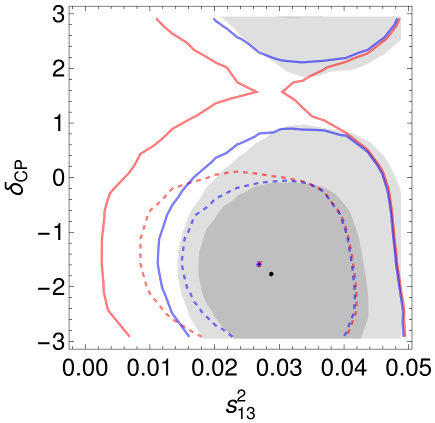
Analysis of Visible decay for MINOS and T2K



ν_μ neutrino events from MINOS

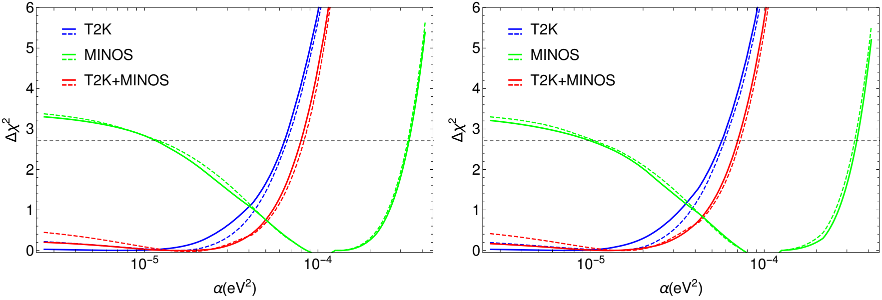
Analysis of Visible decay for MINOS and T2K

Allowed regions for MINOS and T2K: solid regions are standard oscillations and hollow regions are with decay



$\Delta\chi^2$ for T2K and MINOS showing the constrains on the decay parameter:

left : scalar, right :pseudo-scalar



Visible neutrino decay for DUNE

Made in collaboration with Pilar Coloma

Assume $\nu_3 \to \nu_1/\nu_2 + \phi$ with democratic couplings

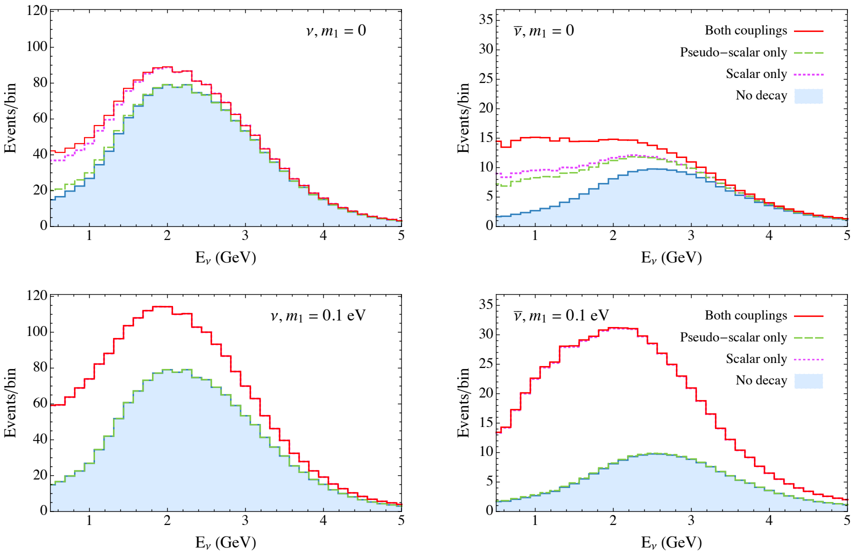
$$H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} - i\frac{\Gamma_3}{2} \end{pmatrix} U^\dagger + A \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

Matter effects are important for DUNE

$$m_3 = \sqrt{m_1^2 + \Delta m^2_{31}} \longrightarrow \tilde{m}_3 = \sqrt{m_1^2 + \Delta \tilde{m}^2_{31}}\,,$$

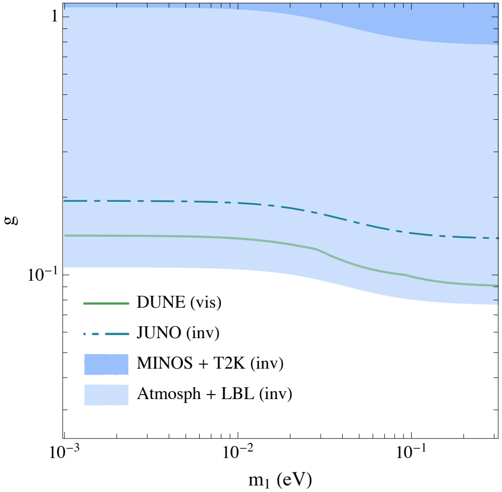
Affecting the total width as $\Gamma_3 \longrightarrow \tilde{\Gamma}_3 \equiv \tilde{m}_3/(\tau_3 E)$.

Visible neutrino decay for DUNE



Visible neutrino decay for DUNE

Sensitivity for DUNE experiment



Conclusions

- Neutrino decay can change the solar neutrino phenomenology? .
- Solar ν data $+$ KamLand/ Daya Bay: strongest bounds on ν_2 decay

LBL experiments can give a bound on the ν_3 lifetime

Invisible and visible ν decay have different behaviours: depletion and excess of events.

We got from T2K+MINOS present data $\alpha^{(s)}_{\rm T2K} < 6.3 \times 10^{-5}\ {\rm eV}^2$, $\alpha^{(p)}_{\rm T2K} < 5.6 \times 10^{-5}\ {\rm eV}^2$

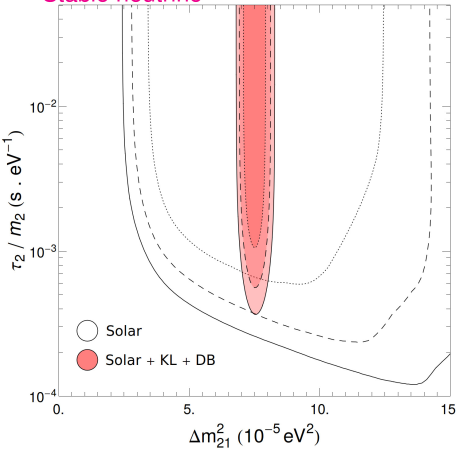
$\alpha^{(s)}_{\rm TK2+MINOS} < 7.8 \times 10^{-5}\ {\rm eV}^2\ , \qquad \alpha^{(p)}_{\rm TK2+MINOS} < 6.9 \times 10^{-5}\ {\rm eV}^2\ .$

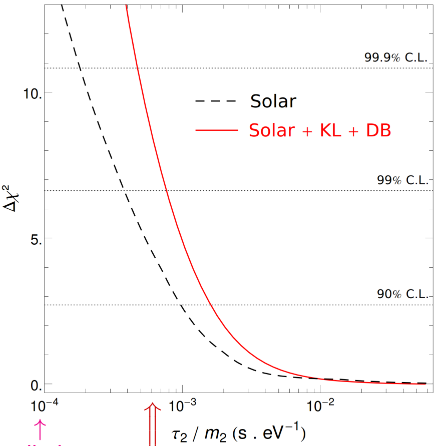
Conclusions

Analysis	Neutrino	Decay mode	Limit
Solar data	ν_2	Invisible	$\tau_2/m_2 > 7.2 \times 10^{-4}$ s/eV
Solar data	ν_2	Invisible	$\tau_2/m_2 > 7.1 \times 10^{-4}$ s/eV
Atmospheric and LBL data	ν_3	Invisible	$\tau_3/m_3 > 2.9 \times 10^{-10}$ s/eV
MINOS and T2K data	ν_3	Invisible	$\tau_3/m_3 > 2.8 \times 10^{-12}$ s/eV
MINOS and T2K data	ν_3	Visible	$\tau_3/m_3 > 1.5 \times 10^{-11}$ s/eV
JUNO expected sensitivity	ν_3	Invisible	$\tau_3/m_3 > 7.5 \times 10^{-11}$ s/eV
DUNE expected sensitivity	ν_3	Visible	$\tau_3/m_3 > 1.95 - 2.6 \times 10^{-10}$s/eV

Results for neutrino decay

Stable neutrino





↑ Previous limit

Our limit: $\frac{\tau_2}{m_2} > 7.7 \times 10^{-4}$ s/eV [1]

[1] Similar bound from J.M.Berryman, A. Gouvea and D. Hernandez,Phys. Rev. D **92**, 073003 (2015)

Seasonal variation

Solar neutrino fluxes have geometrical dependence on distance

$$\phi_\nu^\oplus = \frac{\phi_\nu^\odot}{4\pi(L(t))^2},$$

$$\frac{\phi_\nu^\oplus(L_{\min})}{\phi_\nu^\oplus(L_{\max})} = \frac{(1+\epsilon_0)^2}{(1-\epsilon_0)^2}$$ → seasonal variation of solar neutrino flux

ϵ_0 is the Earth eccentricity

With decay we have geometrial factor+decay factor

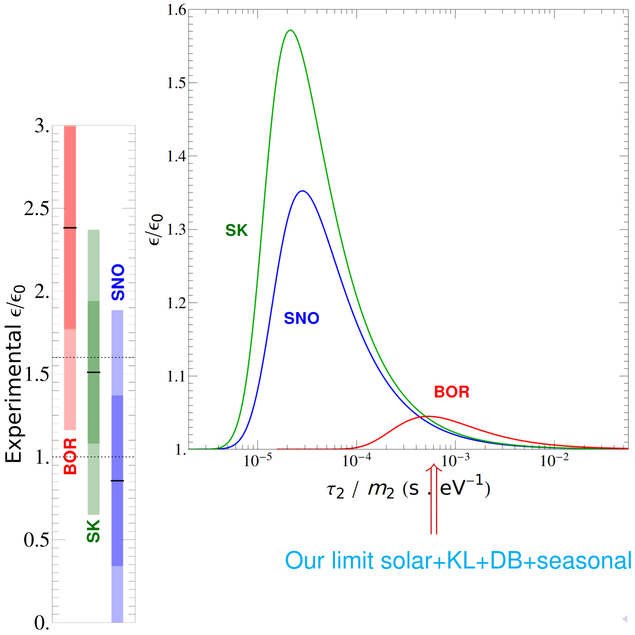
$$P(\nu_e \to \nu_e) = c_{13}^4 \left[P_{e1}^\odot P_{1e}^\oplus + P_{e2}^\odot \exp\left[-\left(\frac{m_2}{\tau_2}\right) \frac{L}{E_\nu} \right] P_{2e}^\oplus \right] + s_{13}^4 ,$$

$$(P(\nu_e \to \nu_e))(L_{\min}) > (P(\nu_e \to \nu_e))(L_{\max})$$

$$\left(\frac{\phi_\nu^\oplus(L_{\min})}{\phi_\nu^\oplus(L_{\max})}\right)_{\text{decay}} = \left(\frac{\phi_\nu^\oplus(L_{\min})}{\phi_\nu^\oplus(L_{\max})}\right)_{\text{no decay}} \left(\frac{P(\nu_e \to \nu_e)(L_{\min})}{P(\nu_e \to \nu_e)(L_{\max})}\right) > \left(\frac{\phi_\nu^\oplus(L_{\min})}{\phi_\nu^\oplus(L_{\max})}\right)_{\text{no decay}}$$

Bigger seasonal effect with ν decay

Seasonal variation



SK I (2003)

SNO (2005)

Borexino (2013)

ϵ: eccentricity with decay

ϵ_0: eccentricity with no decay

Our limit solar+KL+DB+seasonal: $\frac{\tau_2}{m_2} > 7.2 \times 10^{-4}$ s/eV

Backup

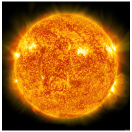
MSW effect Decay

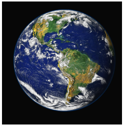
ν_e → ν_1, ν_2, ν_3

ν_1, ν_2, ν_3

ν_e, ν_μ, ν_τ

We assume ν_2 is unstable.

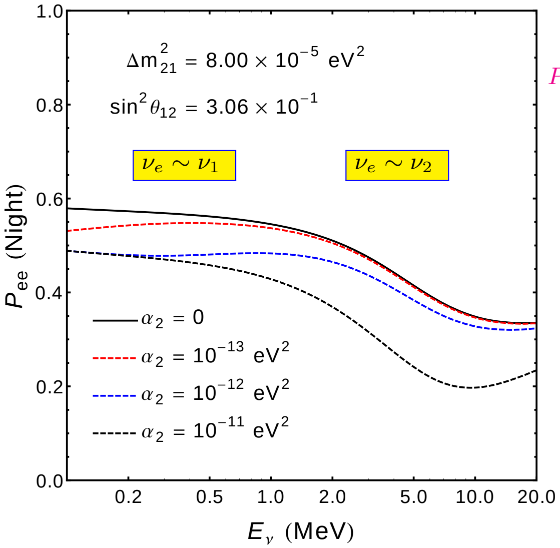




$$P(\nu_e \to \nu_e) = c_{13}^4 \left[P_{e1}^{\odot} P_{1e}^{\oplus} + P_{e2}^{\odot} \exp\left[-\left(\frac{m_2}{\tau_2}\right) \frac{L}{E_\nu} \right] P_{2e}^{\oplus} \right] + s_{13}^4 \,,$$

Backup

$$P(\nu_e \to \nu_e) = c_{13}^4 \left[P_{e1}^{\odot} P_{1e}^{\oplus} + P_{e2}^{\odot} \left(P_2^{\mathrm{decay}} \right) P_{2e}^{\oplus} \right] + s_{13}^4 \,,$$

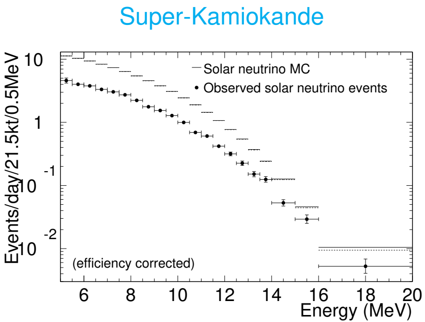


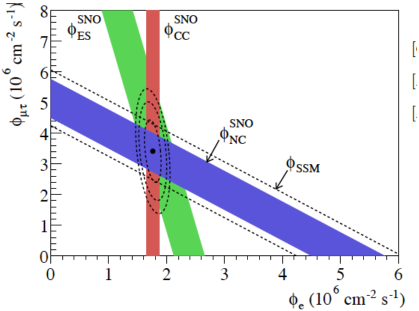
$$P_2^{\mathrm{decay}} = \exp\left[-\left(\frac{\alpha_2}{E_\nu} \right) L \right]$$

$$\alpha_2 = \frac{m_2}{\tau_2}$$

Backup

Solar neutrino data





+Homestake total rate, GALLEX and GNO combined total rate , SAGE total rate and Borexino 192-day low-energy data

Backup

$$P(\nu_e \to \nu_e) = c_{13}^4 \left[P_{e1}^{\odot} P_{1e}^{\oplus} + P_{e2}^{\odot} \exp\left[-\left(\frac{m_2}{\tau_2} \right) \frac{L}{E_\nu} \right] P_{2e}^{\oplus} \right] + s_{13}^4 \, ,$$

Parameters of problem: $\theta_{12}, \Delta m_{21}^2, \theta_{13}$ $\quad \alpha_2 = \dfrac{m_2}{\tau_2}$

External constrains: KamLand and Daya Bay

KamLand : $\theta_{12}, \Delta m_{21}^2, \theta_{13} \to (\chi^2)_{\mathrm{KL}}^{3\nu} = (\chi^2)_{\mathrm{KL}}^{\text{no decay}}$

Daya Bay : $\theta_{13}, \Delta m_{ee}^2 \to (\chi^2)_{\mathrm{DB}}^{3\nu} = (\chi^2)_{\mathrm{DB}}^{\text{no decay}}$

KamLand: http://www.awa.tohoku.ac.jp/KamLAND/4th_result_data_release/

From previous decay limits [2]: $\dfrac{\tau_2}{m_2} > 8.7 \times 10^{-5}$ s/eV

ν_2 is stable for these experiments.

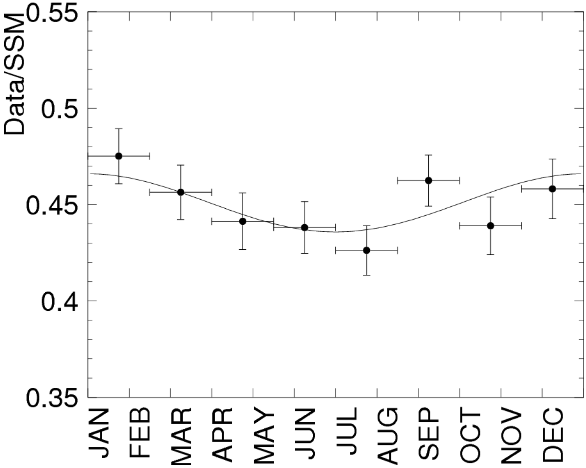
$$(\chi^2)_{\mathrm{KL}}^{\text{decay}} = (\chi^2)_{\mathrm{KL}}^{\text{no decay}}$$
$$(\chi^2)_{\mathrm{DB}}^{\text{decay}} = (\chi^2)_{\mathrm{DB}}^{\text{no decay}}$$

Experimental Analysis from KamLand and Daya Bay can help to constrain the decay scenario

[2] A. Bandyopadhyay, S. Choubey, S. Goswami, P. Letters B555, 33 (2003).

Backup

Super-Kamiokande I seasonal dependence



Backup

Experiment	$\epsilon_{\rm exp} \pm \sigma_{exp}$	$\left(\epsilon_{\rm exp} \pm \sigma_{exp}\right) / \epsilon_0$
Borexino (2013)	0.0398 ± 0.0102	2.38 ± 0.61
SK-I (2003)	0.0252 ± 0.0072	1.51 ± 0.43
SNO Phase I (2005)	0.0143 ± 0.0086	0.86 ± 0.51