Neutrino oscillation measurements with KamLAND and JUNO in the presence of scalar NSI

Based on arXiv: 2306.07343v3
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VIT - Chennai
August, 2024

Frontiers In Particle Physics, CHEP, IISc Bengaluru

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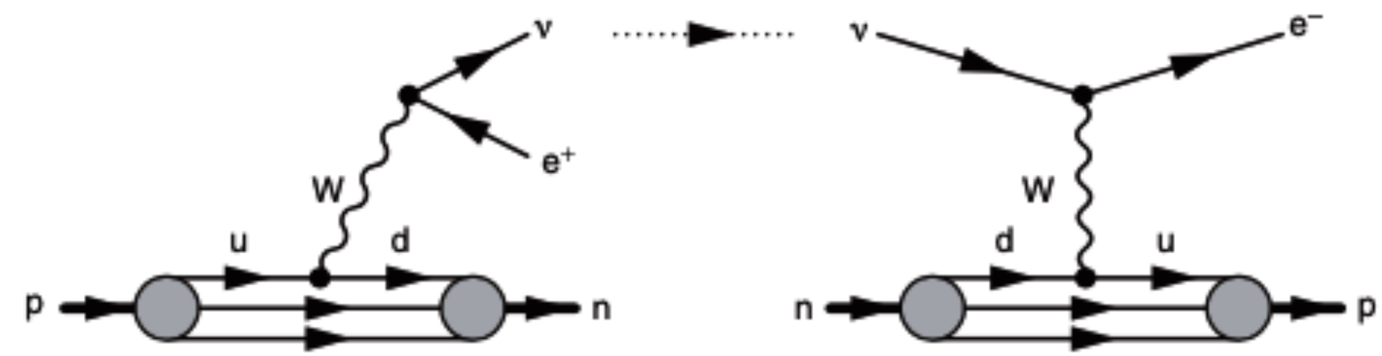
Neutrinos

- Neutrinos are one of the elementary particles in the standard model of particle physics (SM).
- They are the second most abundant particles in the universe. 100 billion solar neutrinos are passing through our thumbnail per second.
- They are spin 1/2, electrically neutral leptons.
- They interact only through weak interactions. Thus, detecting them is a big challenge. Typical neutrino absorption length in Earth-like matter is 10^{14} km.
- Their weak interactions are successfully described by the standard model of particle physics.
- In SM, neutrinos are considered to be massless. Thus, neutrino oscillations which require neutrinos to be massive is the first physics beyond the standard model.
- Neutrinos come in three flavors - ν_e , ν_μ and ν_τ.
- Neutrino from several sources can be studied - Solar, atmospheric, geo-neutrinos, nuclear reactors, long-baseline accelerator super-beams, astrophysical and they span a vast range of energies from few MeV to hundreds of GeV.

Mass and weak eigenstates

Weak eigenstates : ν_e , ν_μ , ν_τ

- ✳ Eigenstates of the weak interaction
- ✳ Tagged by the co-produced charged lepton in charged-current weak interaction



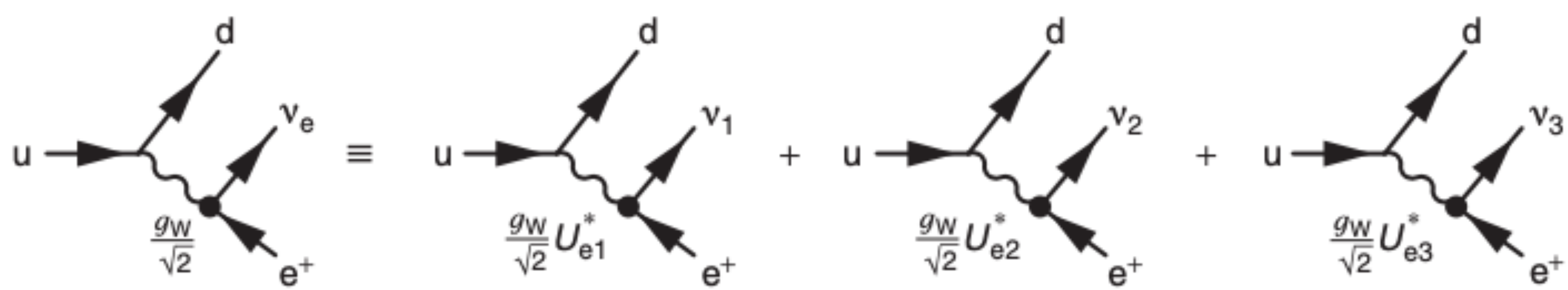
Neutrino production and quick subsequent detection

Mass eigenstates : ν_1 , ν_2 , ν_3

- ✳ Correspond to the physical particle states
- ✳ Stationary states of the free-particle hamiltonian
- ✳ Time-evolution given by the Schrödinger equation for plane waves : $|\nu_k(t)\rangle = |\nu_k\rangle e^{-ip_k\cdot x}$

1) Produced and detected indirectly via weak interactions.

2) Propagate as mass eigenstates



β^+ decay: contribution from different mass eigenstates

Any of the above three processes can happen and it is not possible to know which one!

$\Longrightarrow$ ν_e **coherent linear superposition of** ν_1 , ν_2 , ν_3

(Figs. from Mod. Part. Phys, M. Thomson)

Neutrino mixings leading to flavor oscillations

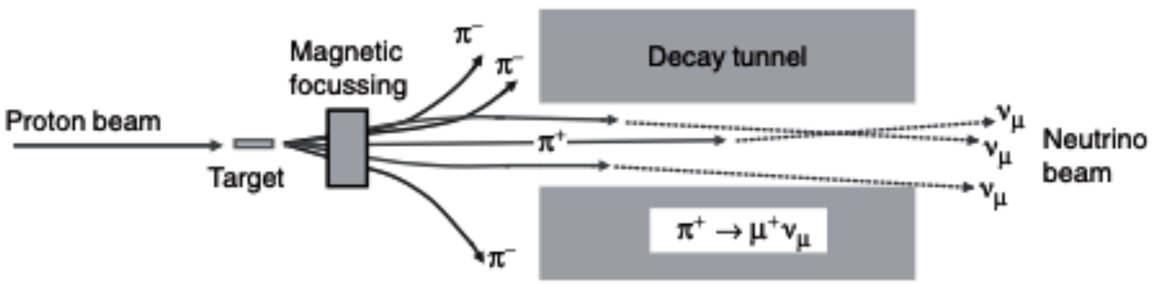
(1975-76 by Eliezer and Swift, Fritzsch and Minkowsky, Bilenky and Pontecorvo)

$$\nu_\alpha = \sum_k U^*_{\alpha k} |\nu_k\rangle$$

$$\bar{\nu}_\alpha = \sum_k U_{\alpha k} |\bar{\nu}_k\rangle$$

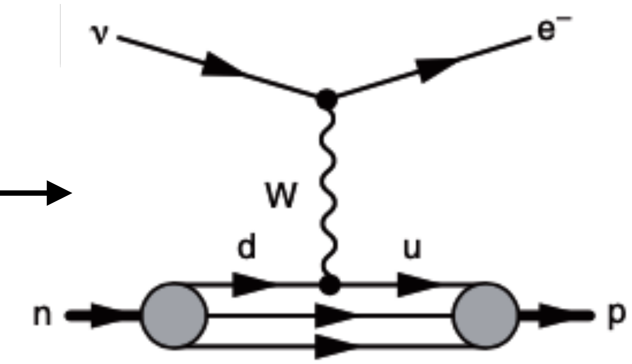
$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

3x3 Unitary "PMNS" matrix



ν production in accelerators

Propagation over distance L



Subsequent detection

initial state

$$|\psi(t=0)\rangle = |\nu_\mu\rangle = \sum_k U^*_{\mu k} |\nu_k\rangle$$

final state

$$|\psi(t=T)\rangle = \sum_k U^*_{\mu k} |\nu_k\rangle e^{-i\phi_k}$$

(Here $\phi_k = E_k t - \vec{p} \cdot \vec{x}$)

$$\mathrm{P}_{\mu e} = \mathrm{P}(\nu_\mu \to \nu_\mathrm{e}) = |\langle \nu_\mathrm{e} | \psi(\mathrm{l} = \mathrm{T})\rangle|^2 = |\ U_{e1} U^*_{\mu 1} e^{-i\phi_1} + U_{e2} U^*_{\mu 2} e^{-i\phi_2} + U_{e3} U^*_{\mu 3} e^{-i\phi_3}\ |^2$$

$$= |\ U_{e2} U^*_{\mu 2}\ (e^{-i\frac{\Delta m^2_{21} L}{2E}} - 1) + U_{e3} U^*_{\mu 3}\ (e^{-i\frac{\Delta m^2_{31} L}{2E}} - 1)\ |^2$$

(Here $\Delta m^2_{ij} = m^2_i - m^2_j$; L = distance travelled and E = neutrino energy)

(Figs. from Mod. Part. Phys, M. Thomson)

What we already know

Oscillation probabilities: $\mathscr{F}(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}, \Delta m^2_{21}, \Delta m^2_{31})$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

LBL superbeam + Atmospheric exp. $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$

SBL reactor exp. $\bar{\nu}_e \to \bar{\nu}_e$

Solar + LBL reactor exp. $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$

Well-measured parameters:
(best-fit $\pm 1\sigma$)

$\theta_{12}(^\circ) = 34.3 \pm 1.0$

$\Delta m^2_{21} = 7.50^{+0.22}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$

$\theta_{13}(^\circ) = 8.53^{+0.13}_{-0.12}$

$|\Delta m^2_{31}| = 2.55^{+0.02}_{-0.03} \times 10^{-3}\ \mathrm{eV}^2$

Not so well measured:

$\theta_{23}(^\circ) \approx 49.0$

3σ range $(^\circ)$: 41.20 – 51.33

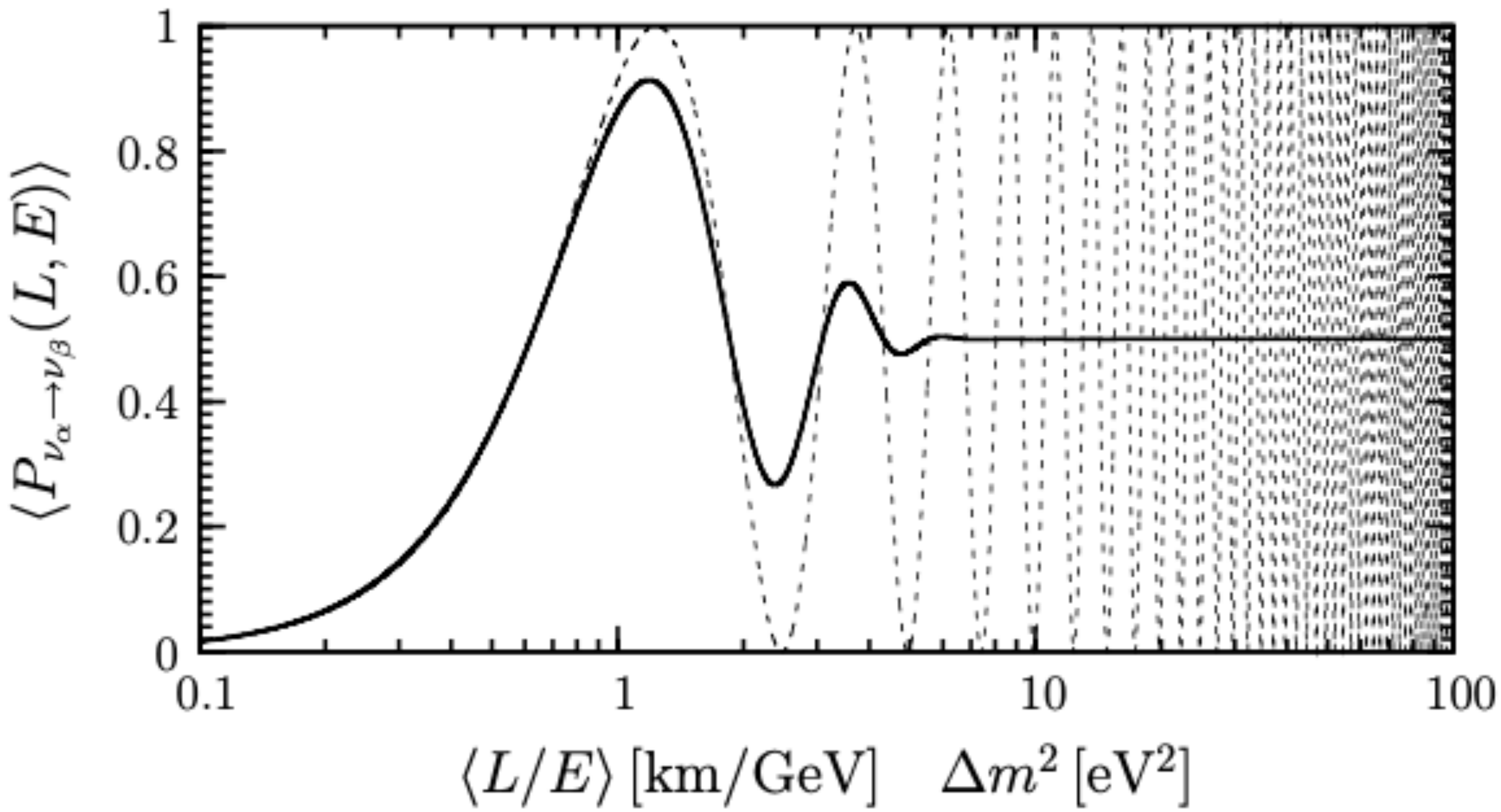
What is the neutrino mass ordering
- normal i.e. $m_3 \gg m_2 > m_1$ or
- inverted i.e. $m_2 > m_1 \gg m_3$?

Do neutrinos violate CP?
- Is $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$?
- $\delta_{CP}(^\circ) = ??$

de Salas et. al. JHEP02(2021),071

Probabilities in two-flavors

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(\vec{x}, t)\rangle|^2$$



Assumption 1: All energy eigenstates are produced with the same 3-momentum i.e. $p_1 = p_2 = p$

Assumption 2: Neutrinos are relativistic i.e.
(1) $t = T = L$
(2) $E_i = p + m_i^2/2p$

Type of experiment	L	E	Δm^2 sensitivity
Reactor SBL	~ 10 m	~ 1 MeV	~ 0.1 eV^2
Accelerator SBL (Pion DIF)	~ 1 km	$\gtrsim 1$ GeV	$\gtrsim 1$ eV^2
Accelerator SBL (Muon DAR)	~ 10 m	~ 10 MeV	~ 1 eV^2
Accelerator SBL (Beam Dump)	~ 1 km	$\sim 10^2$ GeV	$\sim 10^2$ eV^2
Reactor LBL	~ 1 km	~ 1 MeV	$\sim 10^{-3}$ eV^2
Accelerator LBL	$\sim 10^3$ km	$\gtrsim 1$ GeV	$\gtrsim 10^{-3}$ eV^2
ATM	20–10^4 km	0.5–10^2 GeV	$\sim 10^{-4}$ eV^2
Reactor VLB	$\sim 10^2$ km	~ 1 MeV	$\sim 10^{-5}$ eV^2
Accelerator VLB	$\sim 10^4$ km	$\gtrsim 1$ GeV	$\gtrsim 10^{-4}$ eV^2
SOL	$\sim 10^{11}$ km	0.2–15 MeV	$\sim 10^{-12}$ eV^2

$$P\left(\nu_e \to \nu_e\right) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

Disappearance Channel

$$P\left(\nu_e \to \nu_x\right) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

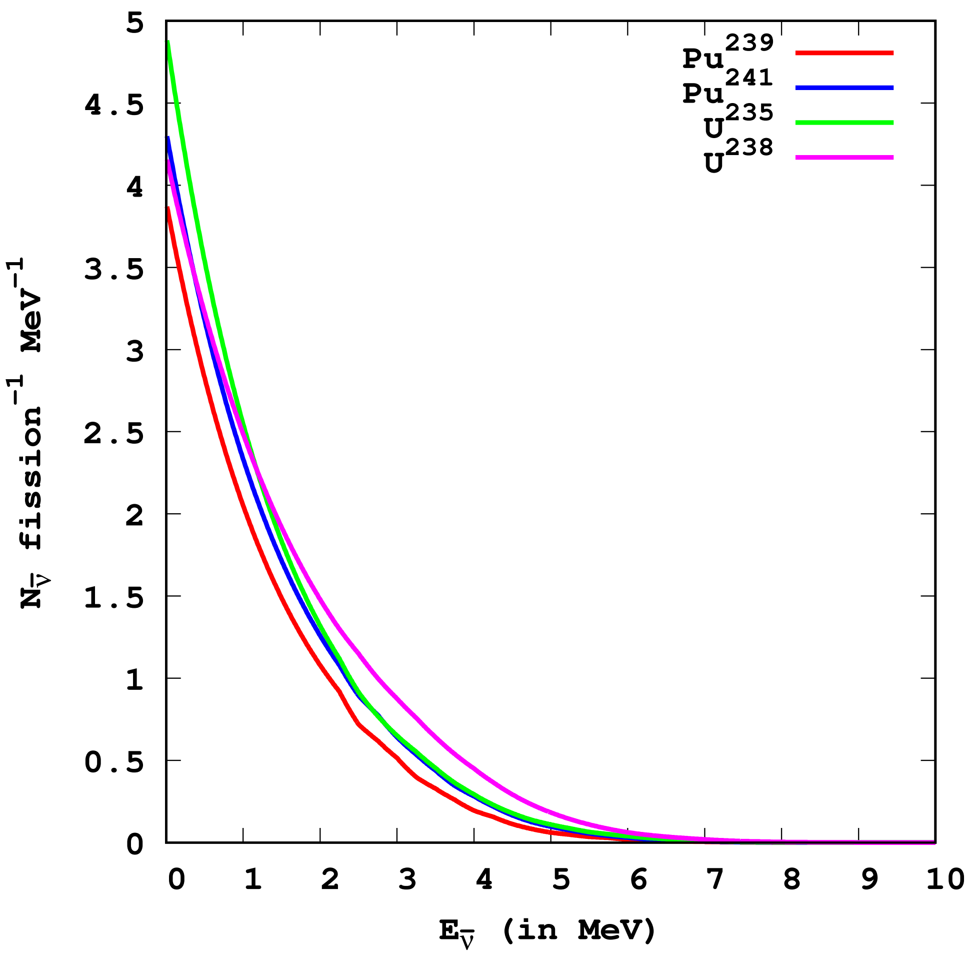
Appearance Channel

(from Neutrino Phys. and Astrophys., Giunti and Kim)

Reactor antineutrino fluxes and cross sections

Huber-Mueller Fluxes

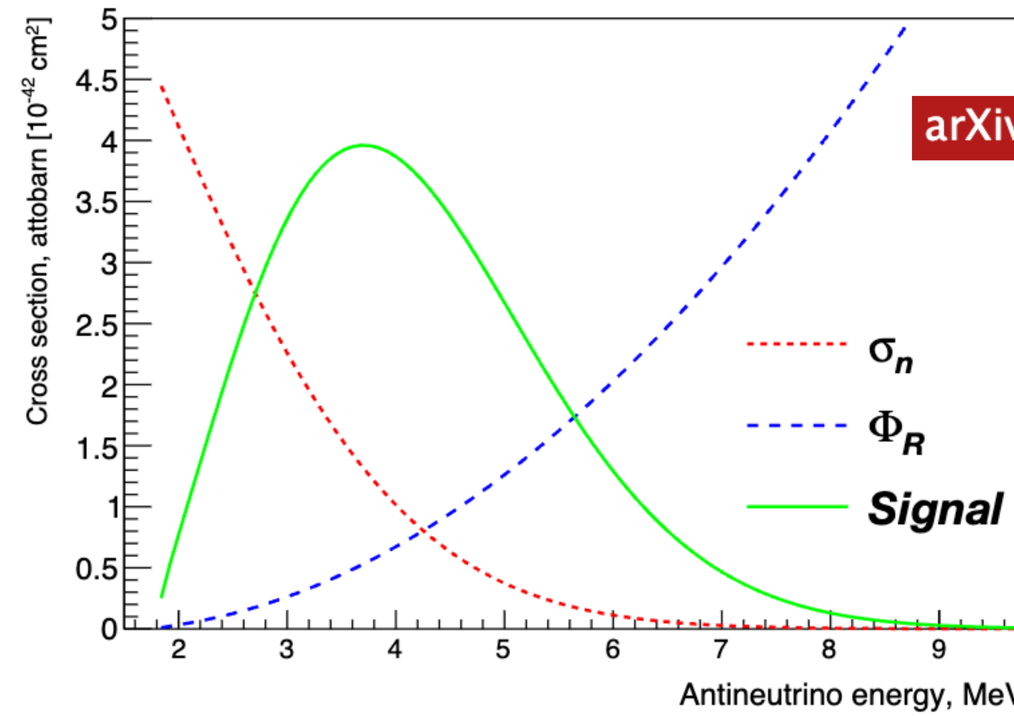
Phys. Rev. C 83 (2011) 054615
Phys. Rev. C 84 (2011) 024617



$$\phi(E_\nu) = f_{^{235}U} \exp\left(0.870 - 0.160E_\nu - 0.091E_\nu^2\right) + f_{^{239}Pu} \exp\left(0.896 - 0.239E_\nu - 0.0981E_\nu^2\right) + f_{^{238}U} \exp\left(0.976 - 0.162E_\nu - 0.0790E_\nu^2\right) + f_{^{241}Pu} \exp\left(0.793 - 0.080E_\nu - 0.1085E_\nu^2\right)$$

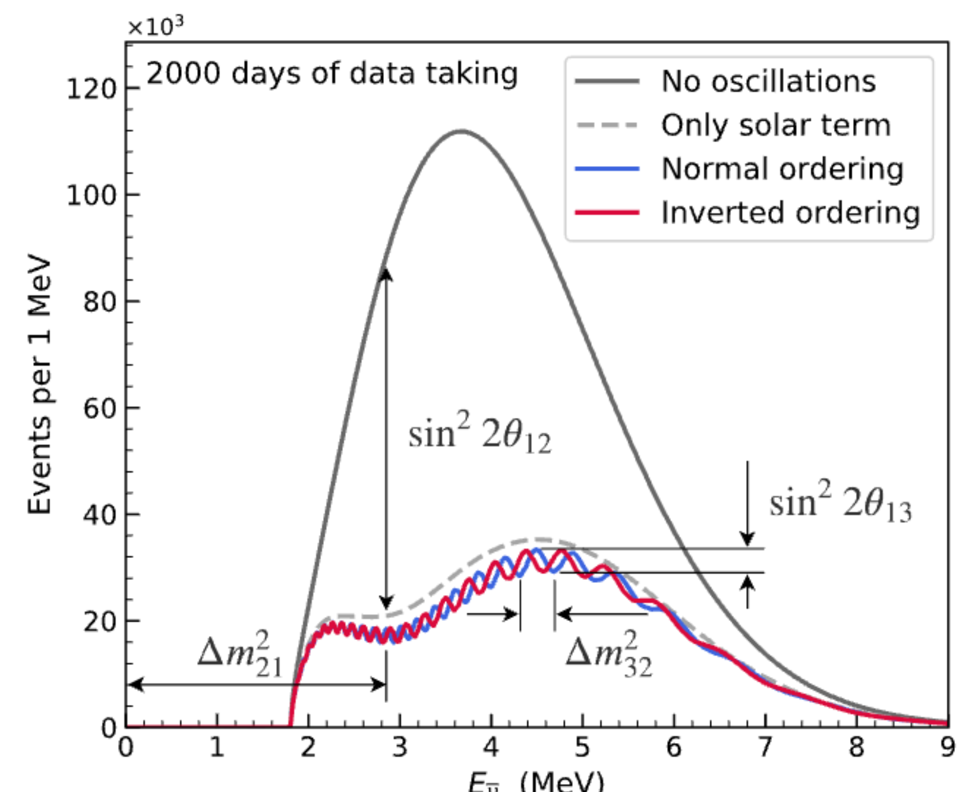
Phys. Rev. D 39 (1989) 3378

Inverse β decay cross sections



arXiv:1910.09321

expected events @JUNO

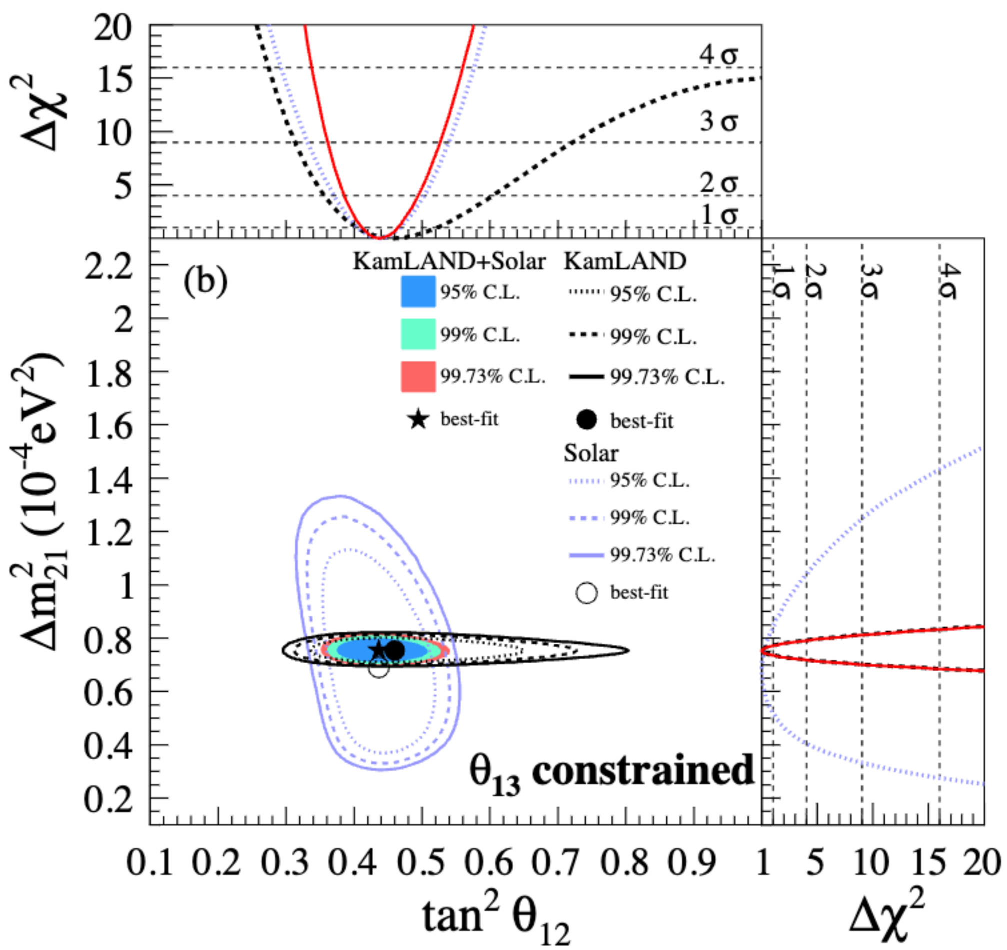


PoS ICRC2021 (2021) 1194

The Experiments

KamLAND (2002-2012)

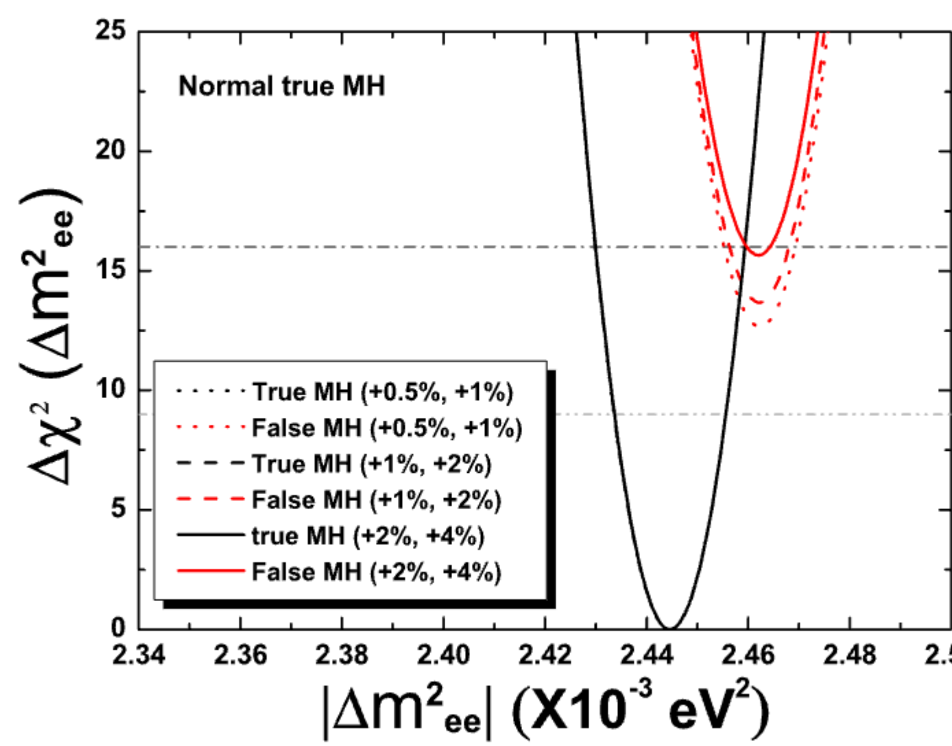
- ✳ Reactor antineutrino experiment in Japan
- ✳ Liquid Scintillator
- ✳ Baselines of the order of 200 km
- ✳ Looked for $\bar{\nu}_e$ disappearance



Phys. Rev. D **88**, 033001 (2013)

JUNO (upcoming)

- ✳ Reactor antineutrino experiment in China
- ✳ Liquid Scintillator
- ✳ Baselines of the order of 50 km
- ✳ Will look for $\bar{\nu}_e$ disappearance



sub-percent precision on θ_{12} and Δm^2_{21}

J. Phys. **G43**, 030401 (2016), arXiv:1507.05613

Scalar NSI

A scalar field ϕ with mass m_ϕ couples with neutrinos via NSI:

$$\mathcal{L}_{\rm NSI}^{\rm eff\ scalar} = \frac{y_f Y_{\alpha\beta}}{m_\phi^2}[\bar{\nu_\alpha}(p_3)\nu_\beta(p_2)][\bar{f}(p_1)f(p_4)],$$

Am. J. Phys. **72**, 1100 (2004), arXiv:hep-ph/0306087.

The effective hamiltonian:

$$\mathcal{H}_S^{\rm eff} \approx \frac{1}{2E_\nu}\left[(\mathcal{M}+\delta M)(\mathcal{M}+\delta M)^\dagger + 2E_\nu V_{CC}\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right],$$

$$\delta M \equiv \sum_f \frac{N_f y_f Y_{\alpha\beta}}{m_\phi^2}$$

Mass matrix in flavour basis:

$$\mathcal{M} = U_\nu \begin{pmatrix}m_1 & 0 & 0\\ 0 & m_2 & 0\\ 0 & 0 & m_3\end{pmatrix} U_\nu^\dagger$$

δM is parameterised as:

$$\delta M \equiv \sqrt{|\Delta m_{31}^2|}\begin{pmatrix}\eta_{ee} & \eta_{e\mu} & \eta_{e\tau}\\ \eta_{e\mu}^\star & \eta_{\mu\mu} & \eta_{\mu\tau}\\ \eta_{e\tau}^\star & \eta_{\mu\tau}^\star & \eta_{\tau\tau}\end{pmatrix}$$

In our work, we consider only $\eta_{\rm ee}$ term.

Analytical expressions

$$\epsilon_1 = \beta\eta_{ee}(m_1 c_{12}^2 + m_2 s_{12}^2 + m_3)$$
$$\epsilon_2 = 2\beta\eta_{ee}c_{13}^2(m_1 c_{12}^2 + m_2 s_{12}^2)$$
$$\epsilon_3 = \beta\eta_{ee}(-m_1 + m_2)$$
$$\beta = \sqrt{|\Delta m_{31}^2|}$$

$$\tan 2\theta_{12}{}' = \frac{\sin 2\theta_{12}\left(\Delta m_{21}^2 + \epsilon_3\cos^2\theta_{13}\right)}{\Delta m_{21}^2\cos 2\theta_{12} - \epsilon_2}$$

$$\Delta m_{21}^2{}' = \Delta m_{21}^2\cos 2\left(\theta_{12} - \theta_{12}'\right) + \cos^2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{12}'\epsilon_3 - \cos 2\theta_{12}'\epsilon_2$$

We find that θ_{13} and Δm_{31}^2 corrections due to η_{ee} are suppressed. Daya Bay measurements are robust.

KamLAND $$P_{\bar{\nu}_e\to\bar{\nu}_e} = \cos^4\theta_{13}(1 - \sin^2 2\tilde{\theta}_{12}\sin^2(\Delta\tilde{m}_{21}^2 L/4E)) + \sin^4\theta_{13}$$

JUNO $$\begin{aligned} P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 &- \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ &- \sin^2 2\theta_{13}\sin^2\left(|\Delta_{31}|\right) \\ &- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{21}\cos\left(2|\Delta_{31}|\right) \\ &\pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin\left(2\Delta_{31}\right)\sin\left(2|\Delta_{31}|\right) \end{aligned}$$

Measurements in vacuum

- In order to calculate mass matrix free from NSI terms, we need to perform neutrino oscillation measurements in vacuum.

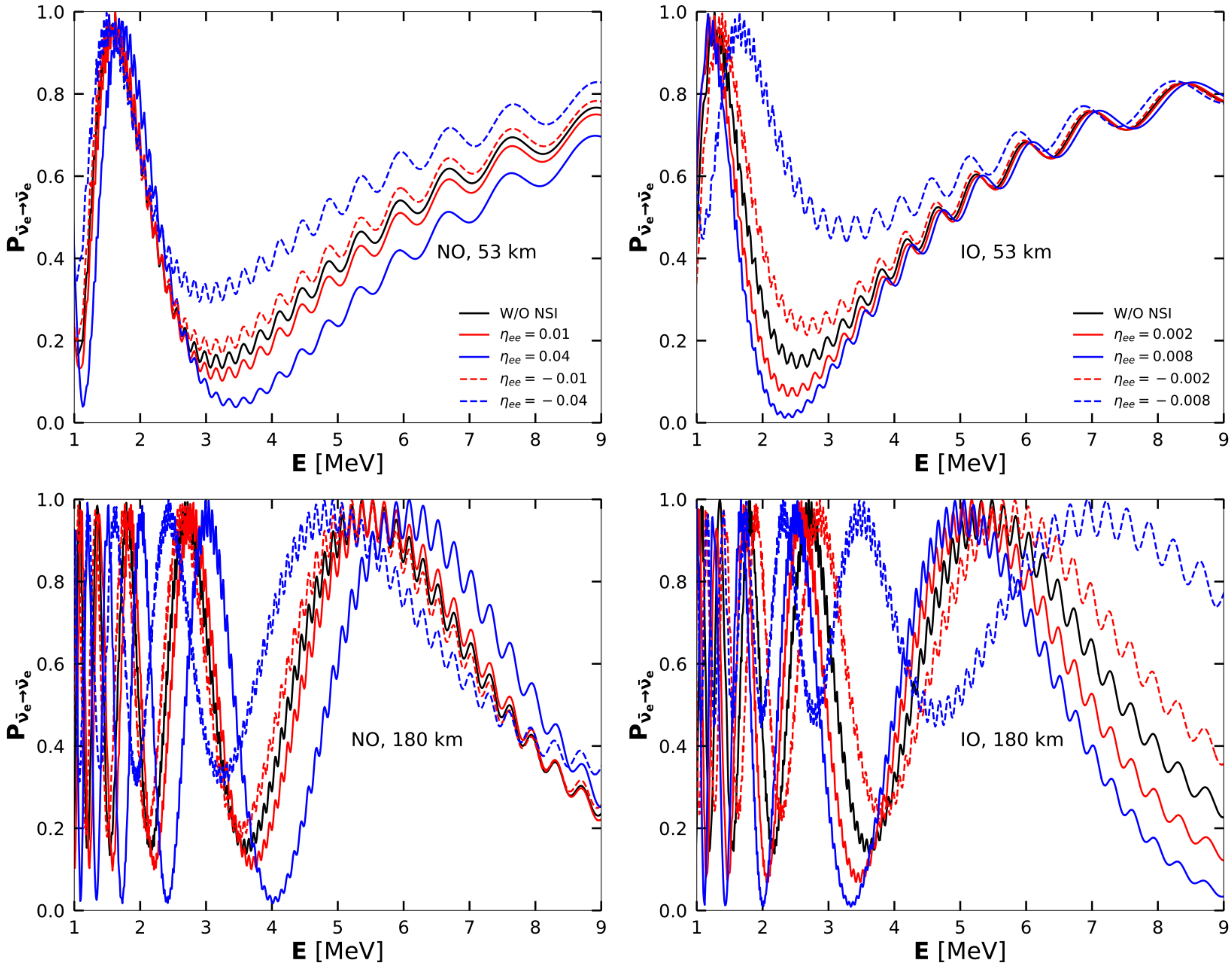
- Therefore, measurements done in terrestrial settings always calculate the effective neutrino parameters.

- In other works, authors consider the reactor neutrino measurements to be the benchmark for least NSI affected values. Thus, reactor neutrinos cannot measure/establish NSI.

- The NSI parameters are then estimated by measuring how the mass matrix scales as longer baselines with increasing densities are considered.

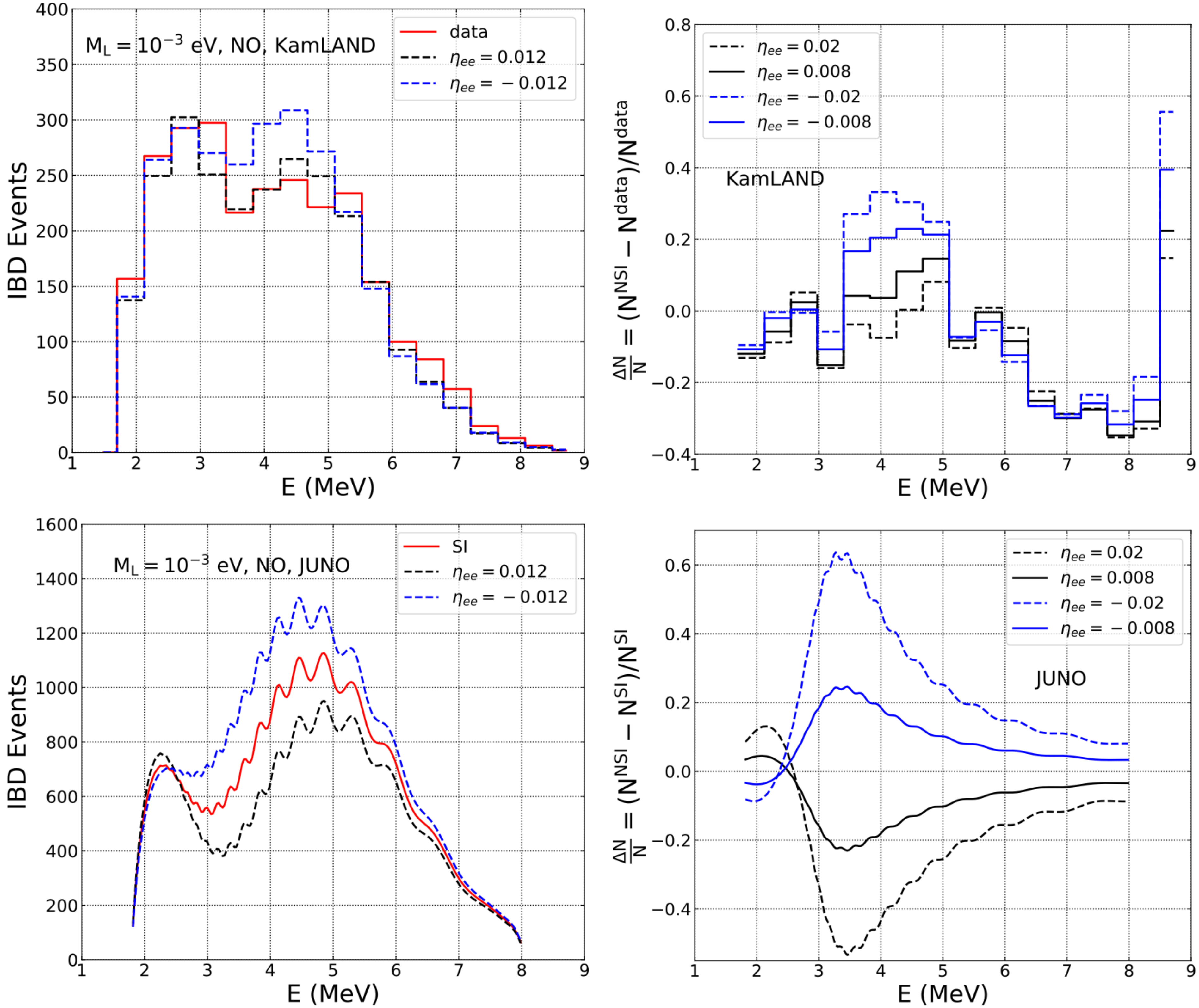
- In our work, we have simply assumed that NSI exist which makes it model-dependent.

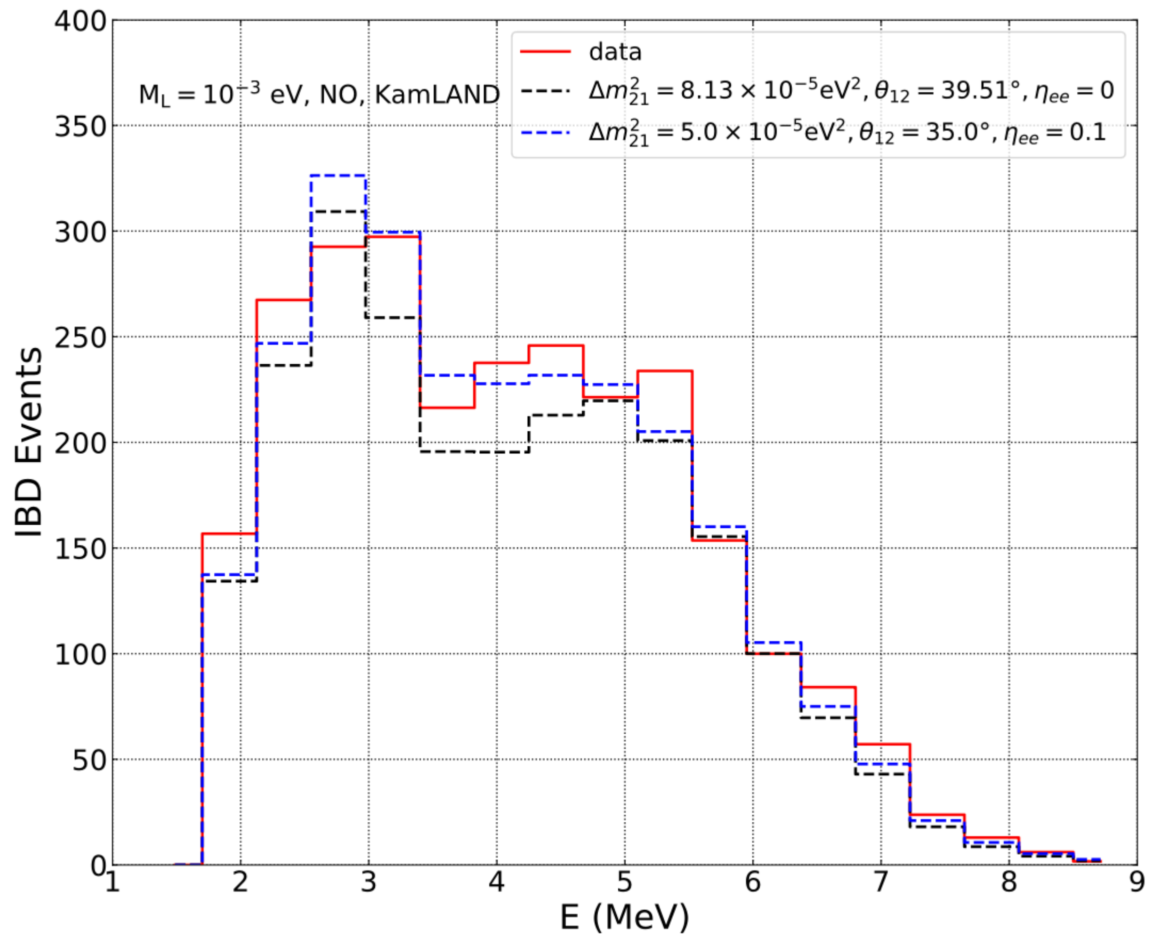
Probabilities with NSI

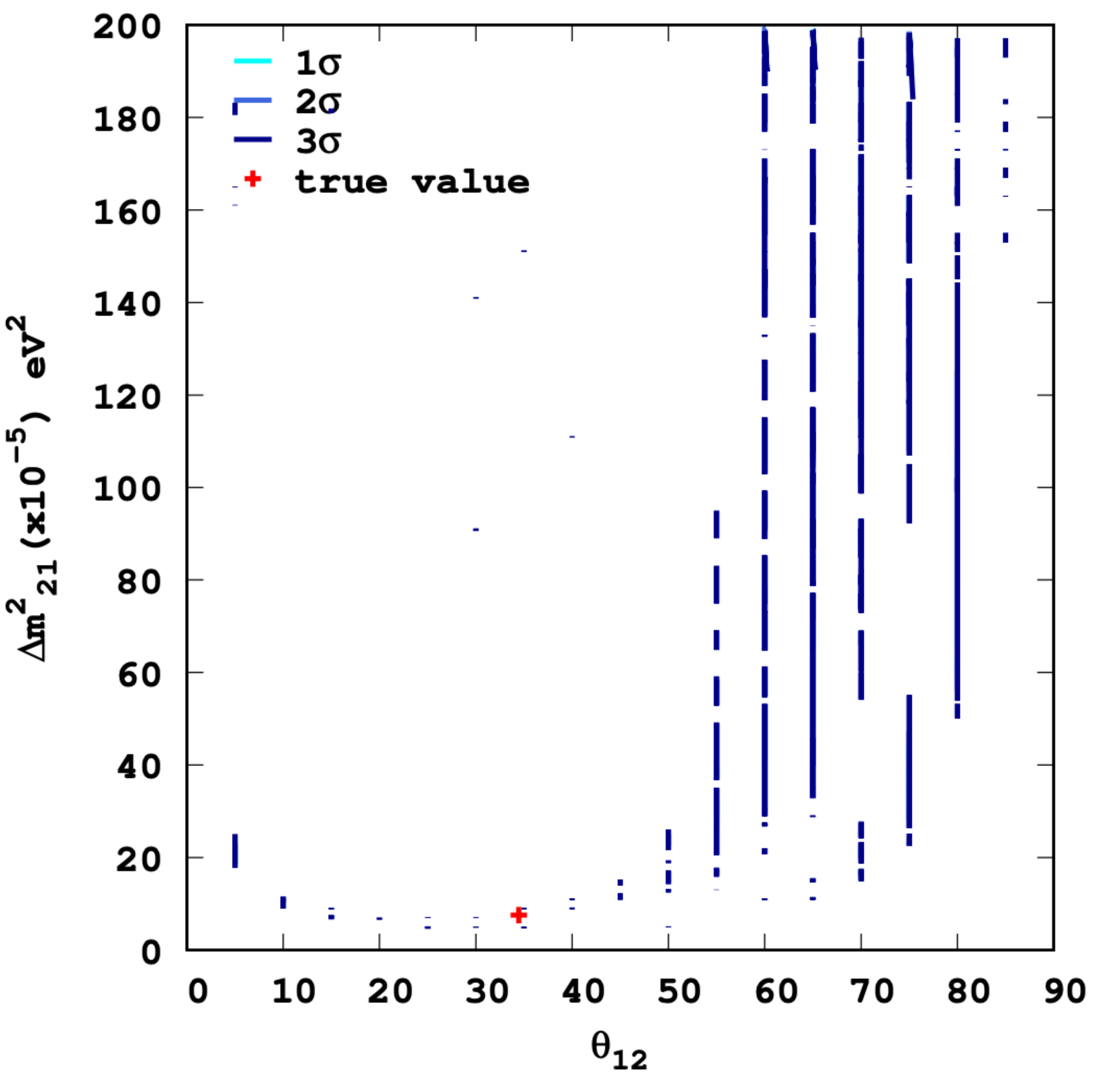


both θ_{12} - suppression and Δm^2_{21} - dip are affected by NSI

Events plots with NSI







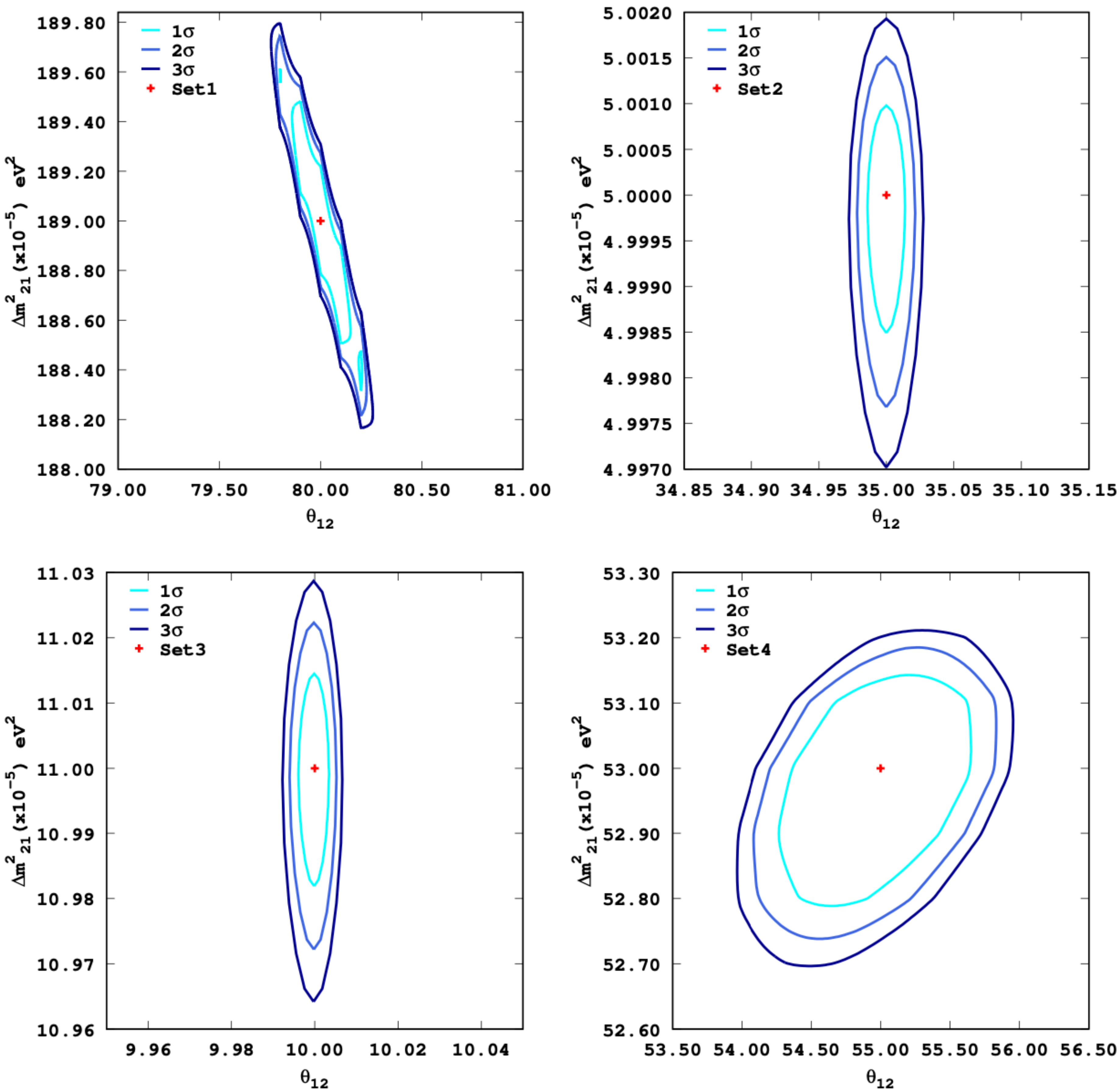
θ_{12} and Δm^2_{21} vastly different from current best-fit values are allowed

Input values	Δm^2_{21} ($\times 10^{-5}$ eV^2)	θ_{12} [deg]	η_{ee}
Set1	189.0	80.0	-1.0
Set2	5.0	35.0	0.1
Set3	11.0	10.0	0.25
Set4	53.0	55.0	-0.45

Estimates from JUNO

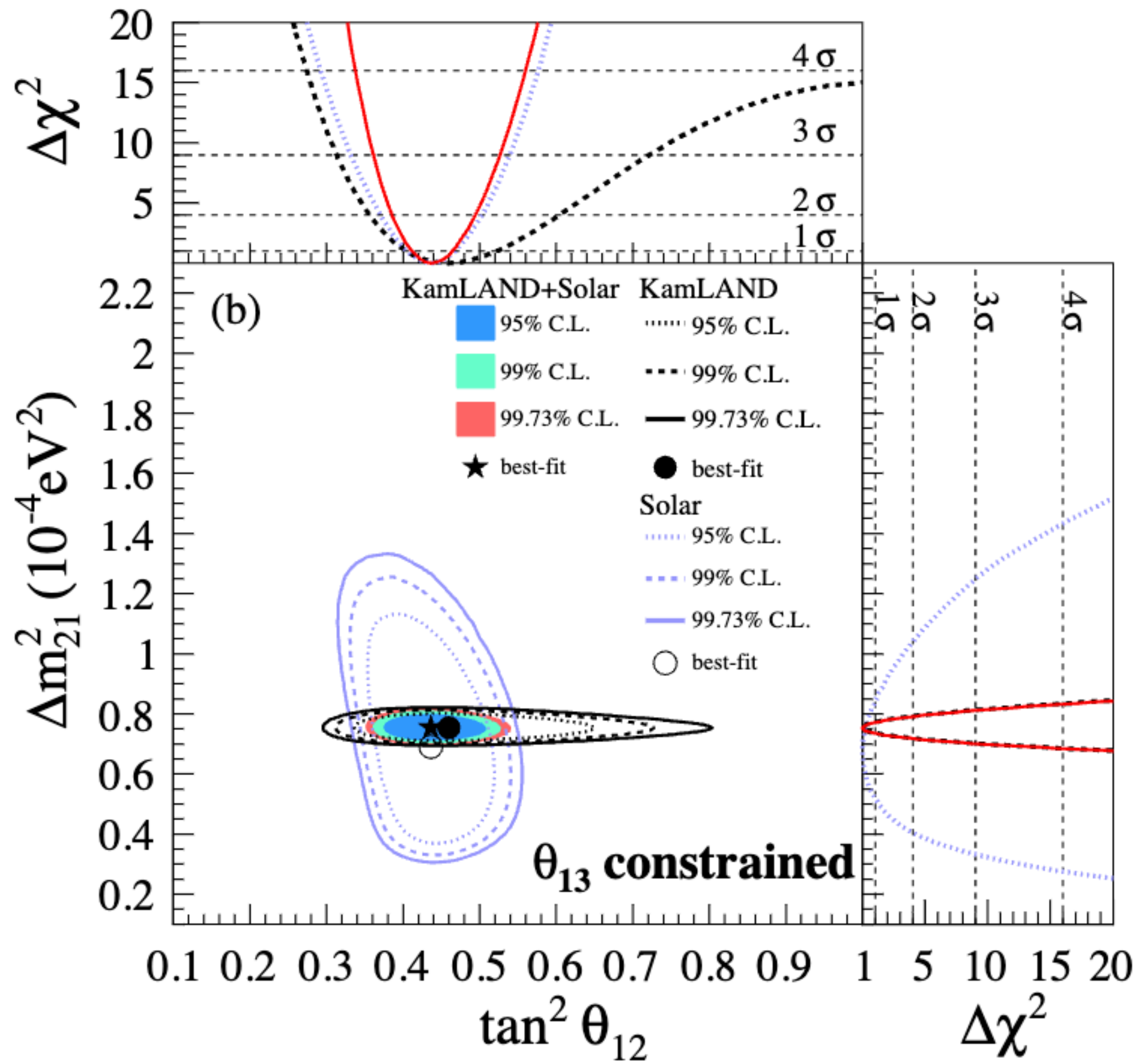
Input values	Δm^2_{21} ($\times 10^{-5}$ eV^2)	θ_{12} [deg]	η_{ee}
Set1	189.0	80.0	-1.0
Set2	5.0	35.0	0.1
Set3	11.0	10.0	0.25
Set4	53.0	55.0	-0.45

JUNO is able to constrain std osc parameters unambiguously



Solar neutrino experiments

- ✳ θ_{12} is constrained effectively by solar neutrino experiments.
- ✳ Δm^2_{21} is measured effectively by KamLAND
- ✳ We need to test the scalar NSI hypothesis against the solar neutrino data (Work in progress).



Conclusions

- ✳ In the era of precision measurements with neutrino experiments, it is natural to explore signatures of new physics.
- ✳ We study scalar non standard interactions within the context of reactor neutrino experiments KamLAND and JUNO.
- ✳ Scalar NSI appear as a correction to the neutrino mass terms in the Hamiltonian.
- ✳ KamLAND data can constrain $\eta_{ee} \in [-1.0, +1.0]$ assuming lightest ν mass to be 10^{-3} eV
- ✳ However, θ_{12} and Δm^2_{21} vastly different from current best-fit values are allowed.
- ✳ We show that JUNO will be able to measure these parameters unambiguously whatever they turn out to be.
- ✳ This stresses on the need to first check the robustness of standard oscillation parameters against new physics scenarios by performing fits to existing neutrino data.