SEARCH FOR STERILE NEUTRINO WITH JUNO

Presented by

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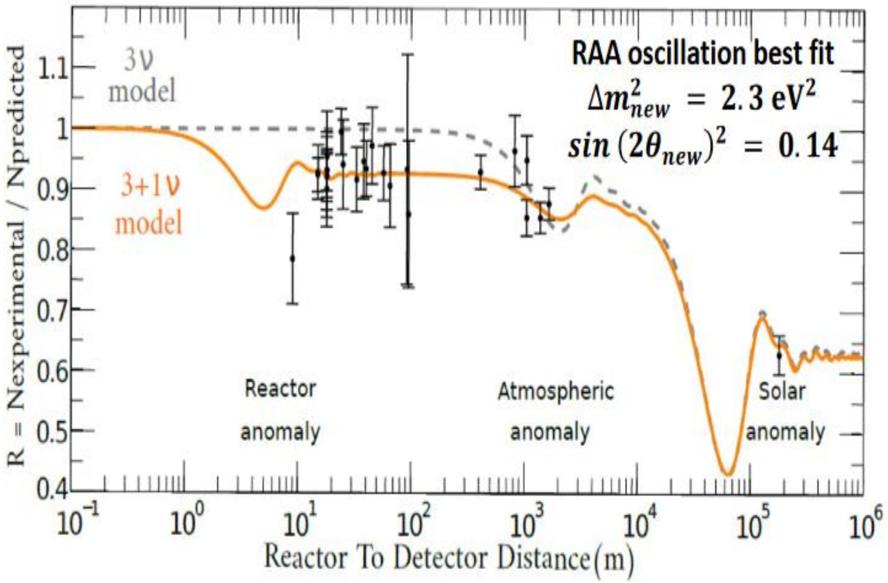
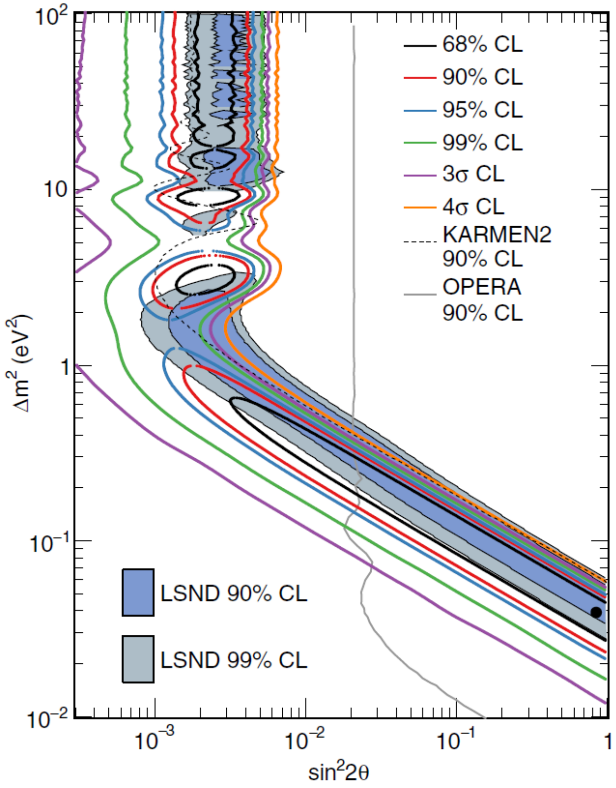
Signature of sterile neutrinos

- Combined analysis of LSND and MiniBoone experiment shows presence of excess ν_e ($\bar{\nu}_e$) in ν_μ ($\bar{\nu}_\mu$) beam (P.R.L. 121, 221801, (2018)).
- Analysis of reactor neutrino spectrum shows deficit of $\bar{\nu}_e$ (Jetp Lett. 109, 213-221 (2019), Phys. Rev. D 104, 032003 (2021), Phys. Rev. C 83 054615).
- These results can be explained assuming mixing with a fourth neutrino, with the mass squared difference Δm^2_{41} more than 1 eV^2, which is much larger than the measured mass squared differences.

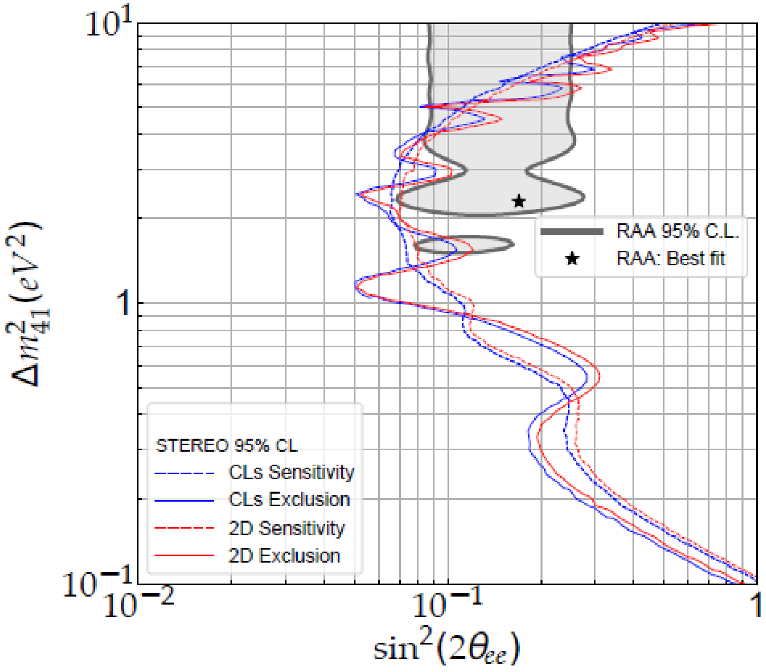


Ref: Reactor anti-neutrino anomaly (RAA), PRD 83:073006 (2011)

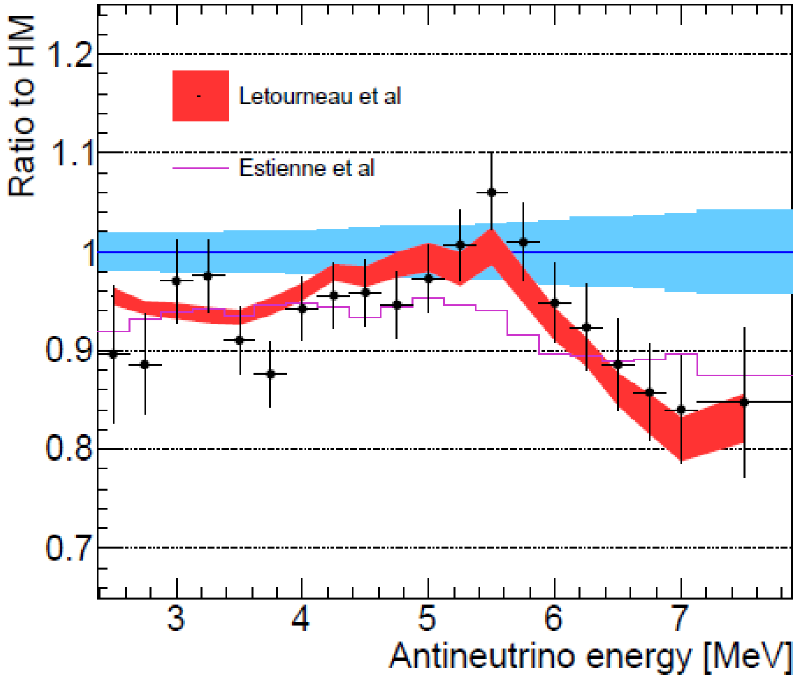


Allowed regions of Mini-Boone and LSND. Ref: P.R.L. 121, 221801, (2018)

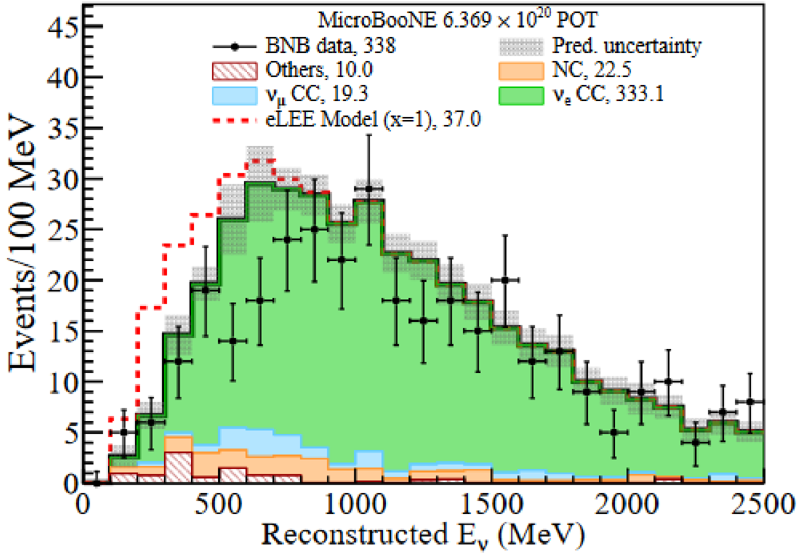
Recent results



Reactor anti-neutrino experiment result from STEREO experiment. Ref: *Nature* **613**, 257–261 (2023)



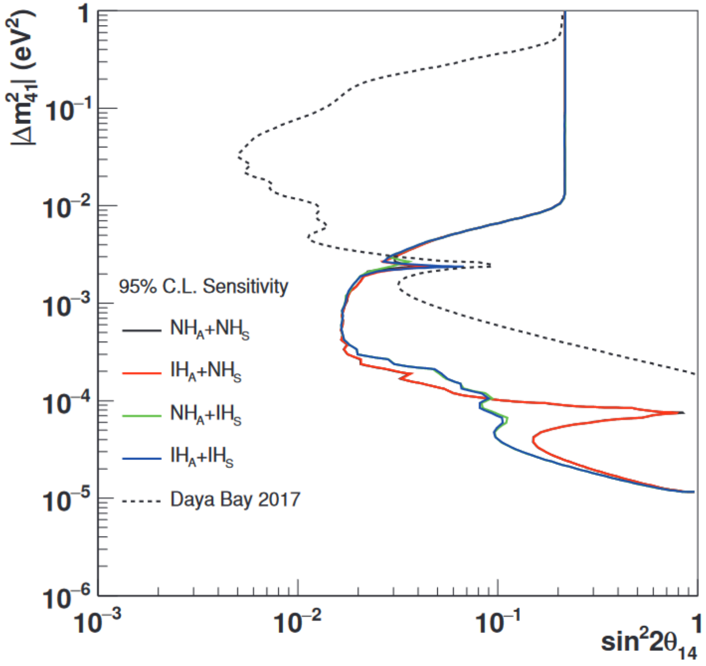
Comparison between STEREO anti-neutrino spectra and new theoretical models. Ref: arXiv: *Nature* **613**, 257–261 (2023)



MicroBoone result (*Phys.Rev.Lett.* 128 (2022) 24, 241801) does not support the MiniBoone excess.

Motivation

- Though the large value of Δm^2_{41} is now disfavored, it is still interesting to see where JUNO will be competitive
- JUNO can probe the presence of sterile neutrinos with (i) radioactive source near the detector, (ii) with reactor anti-neutrino flux in TAO (short distance), (iii) with reactor anti-neutrino flux in JUNO (medium distance) - probing different Δm^2_{41} regions
- Initially this study was carried out assuming generator level data smeared with detector response functions.
- We are studying feasibility of JUNO, with the reconstructed information. The generator level data is passed through the offline software version J21-v2-Pre0 to get the reconstructed information and used for the study.



The initial feasibility study for sterile neutrinos with JUNO. Ref. arXiv:1503.05613

Methodology

Un-oscillated IBD event generation for JUNO.

→ Detector and electronics simulation, calibration and reconstruction.

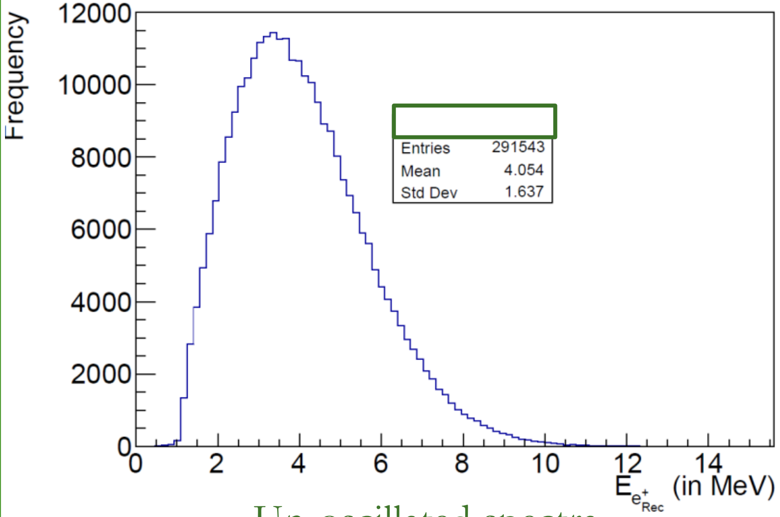
→ Identification of the properly reconstructed positron events.

→ Calculation of survival probabilities for 3-flavor and (3+1) flavor, using generator neutrino energy

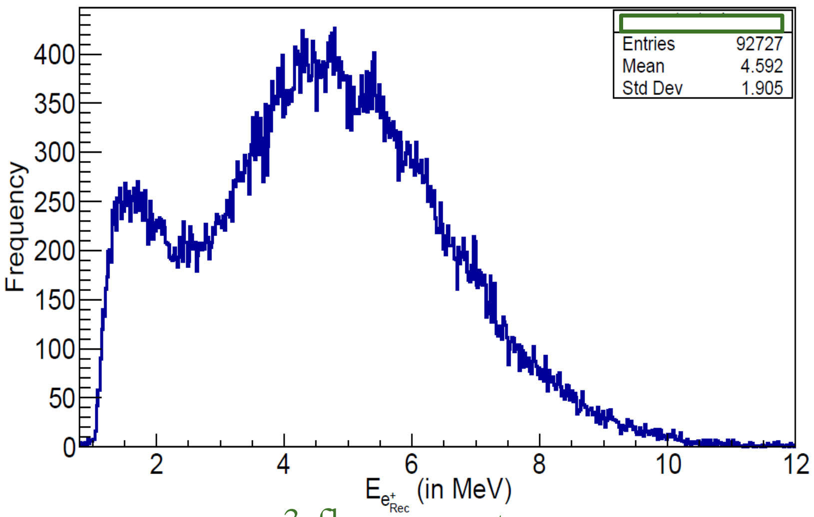
→ The oscillation probability has been imposed by accept/reject method event-by-event

→ Calculation of χ^2 values for different combinations of Δm_{41}^2 and $sin^2 2\theta_{14}$ to find the allowed range.

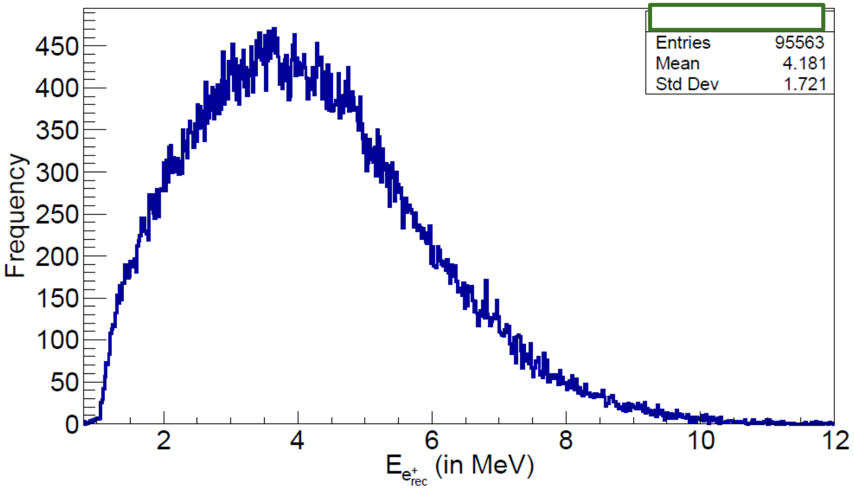
Event spectra



Un-oscillated spectra



3-flavor spectra



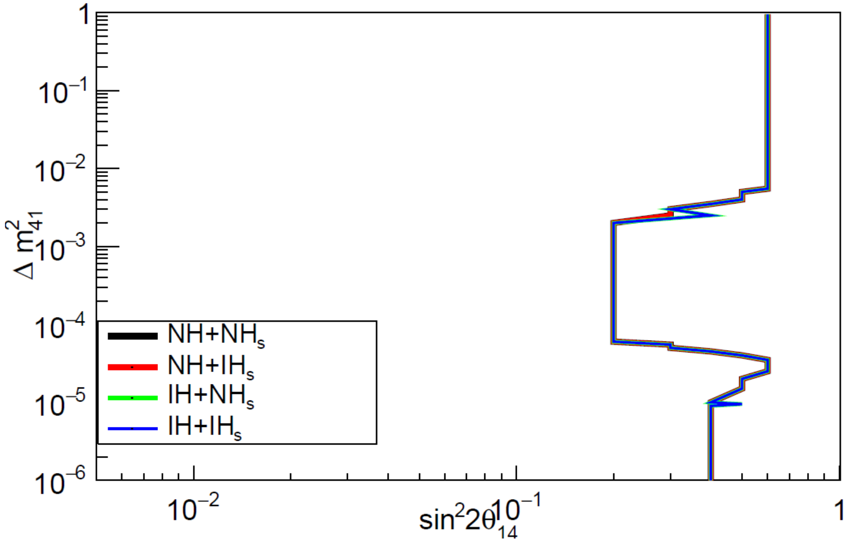
Δm^2_{41} = 1 eV^2, $sin^2 2\theta_{14}$ = 1.0

- The oscillation parameters are the global best fit values from nuFit collaboration (arXiv:2007:14792).
- The sterile parameters Δm^2_{41} and $sin^2 2\theta_{14}$ have been varied between (10^{-6} , 1.0)eV^2 and (0.001, 1.0) respectively. (Total 3052 test combinations).
- The mass squared value and the mixing angle have been varied logarithmically.
- For each of the 300 un-oscillated set, 20 oscillated sets were generated using different random number seed.
- All the oscillated sets are clubbed together to generate 360 years of oscillated data set.

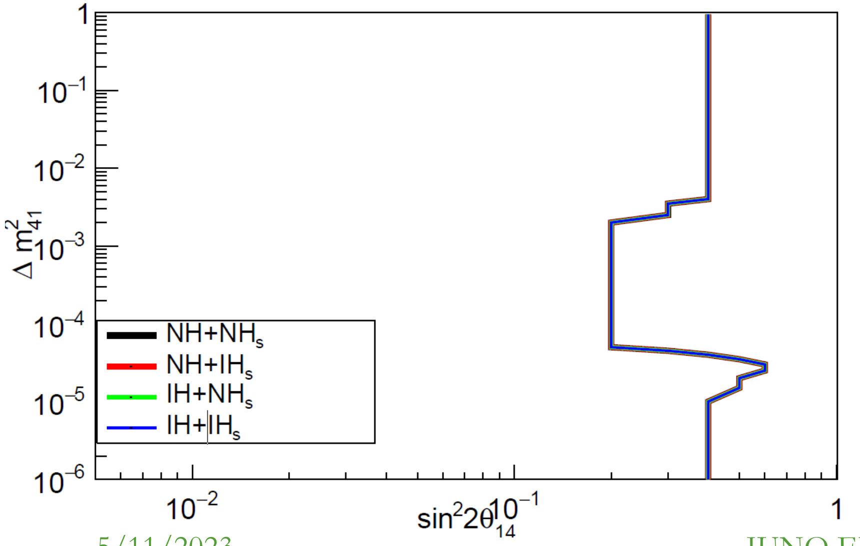
χ^2 calculation procedure

- Backgrounds not taken into account.
- Two systematic errors have been chosen with bin independent values and incorporated using pull variable method.
- For each combination of Δm^2_{41} and $\sin^2 2\theta_{14}$ a theory sample has been created N_i^{pdf}.
- We calculate the test event samples N_i^{test} as follows $N_i^{test} = N_i^{pdf}[1 + \pi_i^l \xi_l]$, l=1, 2. π_i^l is the systematic error and ξ_l is the pull parameter.
- Poisson definition of $\chi^2 = 2\sum_i \left[N_i^{test} - N_i^{obs} + N_i^{obs} \ \ln \frac{N_i^{obs}}{N_i^{obs}}\right] + \sum_{l=1}^{2} \xi_l^2$ has been used for calculation of chi-square.

Result



Flux uncertainty 6%

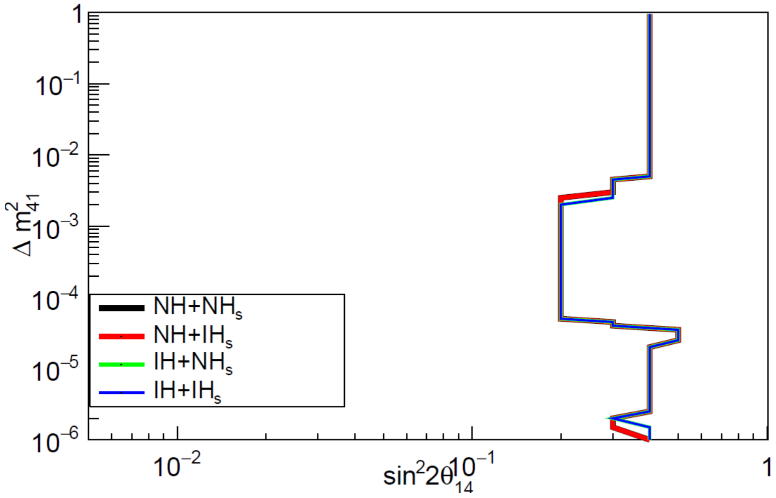


Flux uncertainty 2.2%

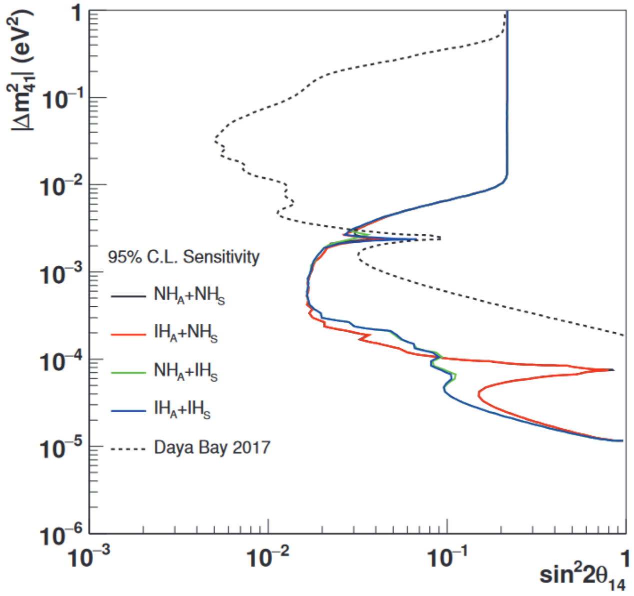
- The figure shows the 95% C.L. curve for four mass hierarchy combinations for the sterile neutrino parameter space.
- Right hand side of the contour is excluded region.
- Number of degrees of freedom is (560-1)+2
- Corresponding χ^2 value is 616.58
- The result has been generated assuming two systematic errors, namely the uncertainty of the absolute energy scale of positron signal (1%) and the uncertainty in reactor anti-neutrino flux for with and without TAO detector.
- In absence of TAO the flux uncertainty is 6% and with TAO, it reduces to 2.2%.

Result

- If we consider 60 events/day, the exclusion plots change a little
- The excluded region does not match with the reported region in JUNO yellow book.



Flux uncertainty 6%



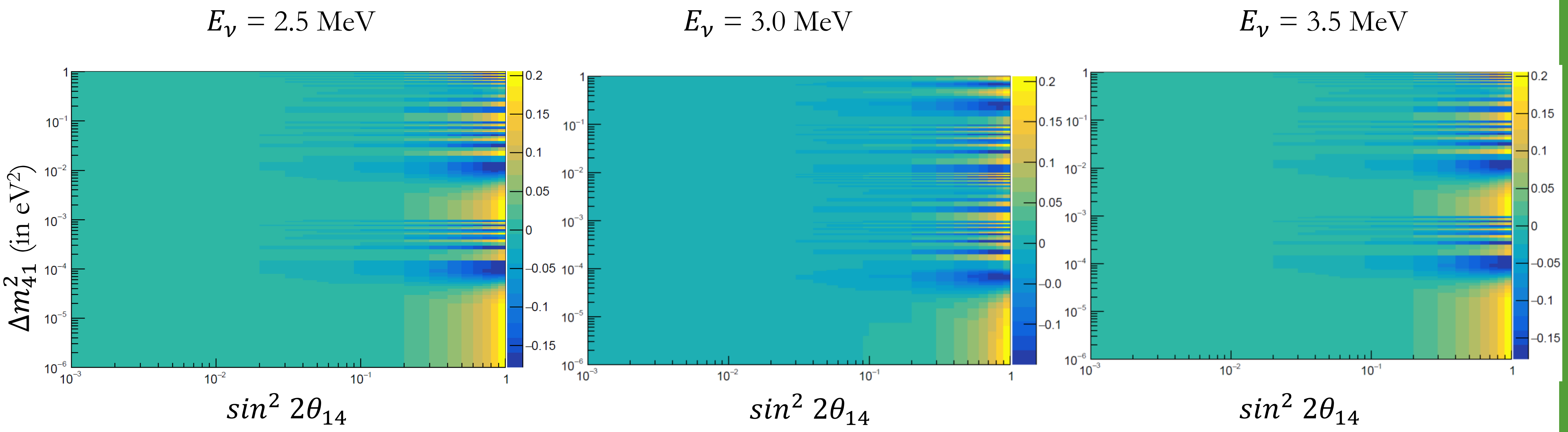
JUNO Yellow book result. Ref. DOI: 10.1088/0954-3899/43/3/030401

Survival Probability

$$P\left(\overset{(-)}{\nu_e} \to \overset{(-)}{\nu_e}\right) = 1 - \cos^4\theta_{14}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$- \cos^4\theta_{14}\sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$
$$- \cos^4\theta_{13}\sin^2 2\theta_{14}\left(\cos^2\theta_{12}\sin^2\Delta_{41} + \sin^2\theta_{12}\sin^2\Delta_{42}\right)$$
$$- \sin^2\theta_{13}\sin^2 2\theta_{14}\sin^2\Delta_{43},$$

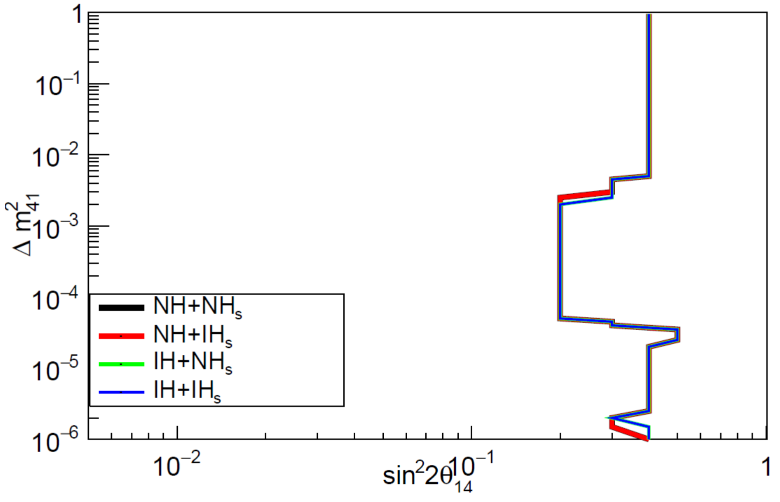
- The (3+1) flavor survival probability is given by this formula.
- Small value of Δm^2_{41} makes the other mass squared differences, namely Δm^2_{42} and Δm^2_{43} as large as the solar mass difference and atmospheric mass difference.
- Δm^2_{42} term = $cos^4\theta_{13}\ sin^2\ 2\theta_{14}\ sin^2\theta_{12}\ sin^2\left(1.267 * \frac{\Delta m^2_{42} * L}{E}\right)$
- Δm^2_{43} term = $sin^2\theta_{13}\ sin^2\ 2\theta_{14}\ sin^2\left(1.267 * \frac{\Delta m^2_{43} * L}{E}\right)$

Effect on total survival probability

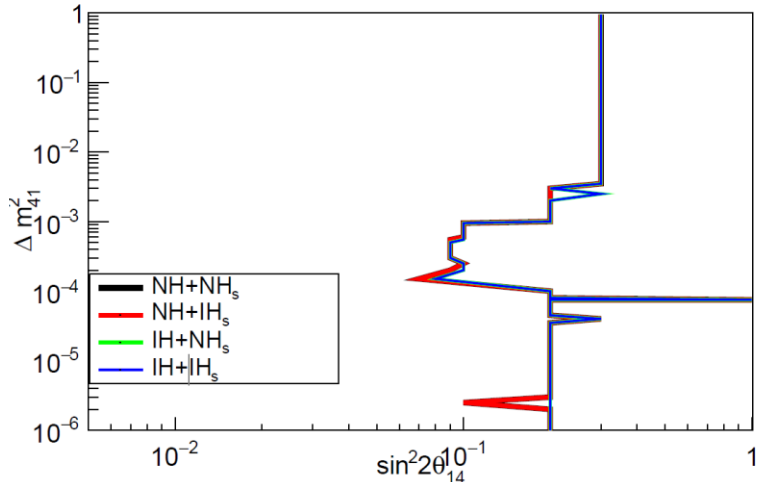


- Difference between (3+1)-flavor and 3-flavor survival probabilities are shown here
- At large values of $sin^2 2\theta_{14}$ the difference is as large as 0.2 for Δm^2_{41} as small as 10^{-6} eV^2.

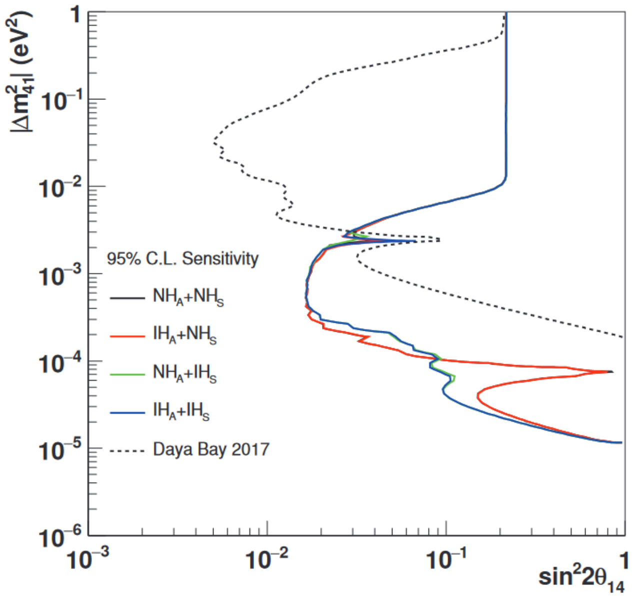
Results neglecting Δm_{42}^2 and Δm_{43}^2 terms



Without neglecting Δm_{42}^2 and Δm_{43}^2 terms



Neglecting Δm_{42}^2 and Δm_{43}^2 terms



JUNO Yellow book result. Ref. DOI: 10.1088/0954-3899/43/3/030401

- Presence of the Δm_{42}^2 and Δm_{43}^2 terms clearly play their roles.
- Even after neglecting these terms at lower mass-squared values JUNO has sensitivity.

Effect of large $sin^2 2\theta_{14}$

- Reason is $cos^4\theta_{14}$ term multiplied to the 3-flavor oscillation probability term.

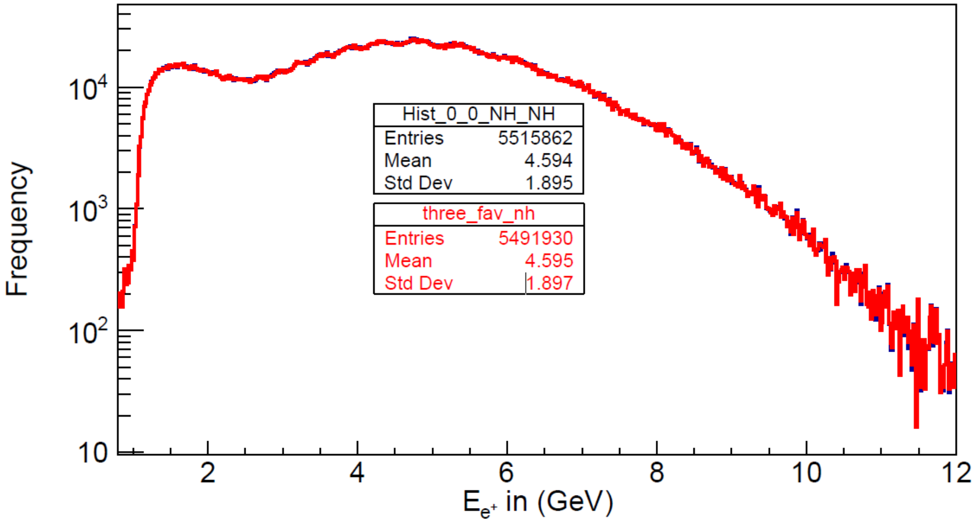
- 3-flavor survival probability =1 - $cos^4\theta_{13}\, sin^2\, 2\theta_{12}\, sin^2\left(1.267 * \frac{\Delta m^2_{21} * L}{E}\right) +$ $sin^2 2\theta_{13}\, (cos^2\theta_{12}\, sin^2\left(1.267 * \frac{\Delta m^2_{31} * L}{E}\right) + sin^2\theta_{12}\, sin^2\left(1.267 * \frac{\Delta m^2_{32} * L}{E}\right))$

$$
\begin{aligned}
P\left(\overset{(-)}{\nu_e} \rightarrow \overset{(-)}{\nu_e}\right) = 1 & - \cos^4\theta_{14}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\
& - \cos^4\theta_{14}\sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right) \\
& - \cos^4\theta_{13}\sin^2 2\theta_{14}\left(\cos^2\theta_{12}\sin^2\Delta_{41} + \sin^2\theta_{12}\sin^2\Delta_{42}\right) \\
& - \sin^2\theta_{13}\sin^2 2\theta_{14}\sin^2\Delta_{43},
\end{aligned}
$$

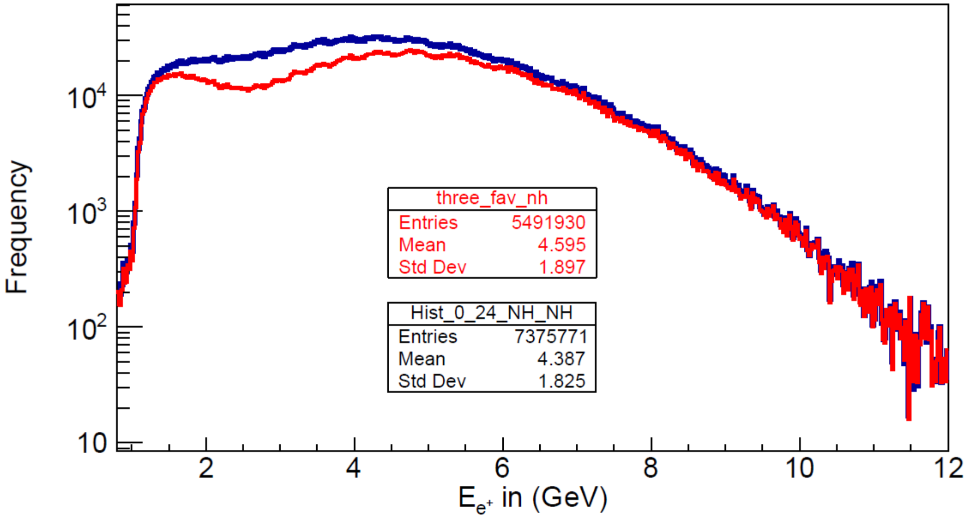
- For $sin^2 2\theta_{14}$ as large as 1, θ_{14} is $\pi/4$, making $cos^4\theta_{14} = 0.25$.

- So, even after neglecting Δm^2_{42} and Δm^2_{43} terms, at small value of Δm^2_{41}, the (3+1)-flavour oscillation probability is just 25% of the 3-flavor oscillation probability, making the survival probability larger.

Effect of large $sin^2 2\theta_{14}$



Δm^2_{41} = 10^{-6} eV^2, $sin^2 2\theta_{14}$ = 0.001



Δm^2_{41} = 10^{-6} eV^2, $sin^2 2\theta_{14}$ = 0.7

- Large value of $sin^2 2\theta_{14}$ means large θ_{14} which implies that the mixing between m_1 *and* m_4 is large.
- This should have affected solar neutrino flux as the oscillation of electron flavor neutrino to sterile neutrino will be more probable.
- But that is not observed.

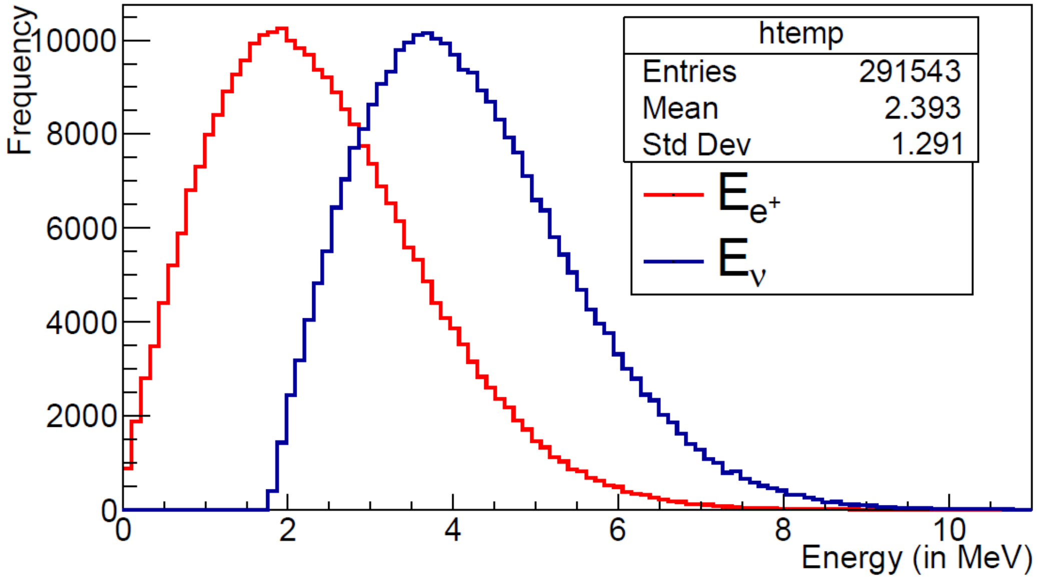
Conclusion

- Sensitivity of JUNO to sterile neutrinos has been carried out using event-by-event reactor neutrino reconstructed data simulated by GEANT4 based software (J21-v2-Pre0).
- The parameter space covers Δm^2_{41} and $sin^2 2\theta_{14}$ between $(10^{-6}$, $1.0)eV^2$ and (0.001, 1.0) respectively.
- Systematic errors have been included but not the backgrounds.
- The excluded region differs from that reported in JUNO yellow book.
- The study shows effect of Δm^2_{42} and Δm^2_{43} terms are not negligible at small Δm^2_{41} values and JUNO is sensitive to large $sin^2 2\theta_{14}$ irrespective of Δm^2_{41} values.
- Marginalization over 3-flavor oscillation parameters will be carried out.
- Joint analysis of JUNO and TAO has been planned to carry out.

THANK YOU

Detector and electronics simulation

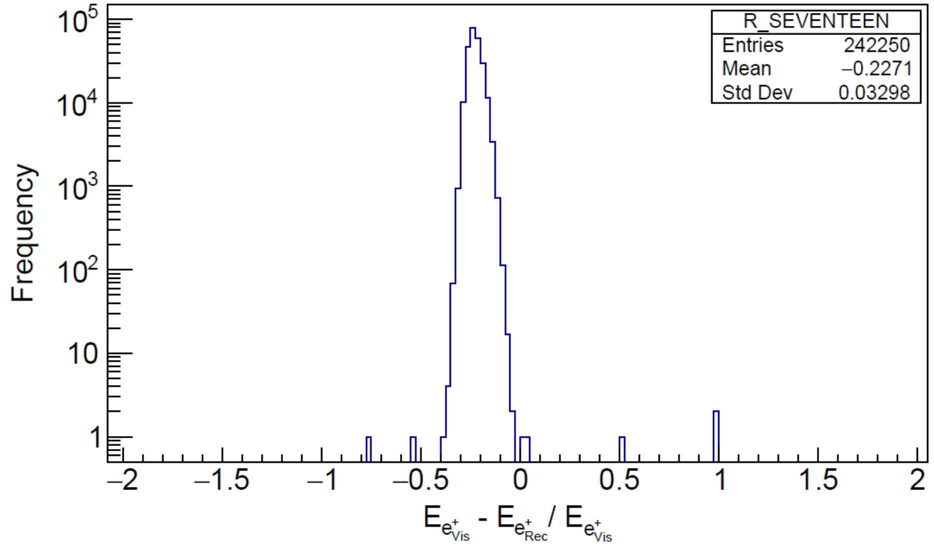
- 300 sets each with 3000 events have been generated with different seeds assuming no oscillation.
- No radioactive background simulated.
- Trigger occurs if >=300 PMT has fired with trigger window of 300 ns.
- IBD rate has been assumed to 1 Hz and calibration was done with only the default options.



Generator level energy spectra of reconstructed neutrino events

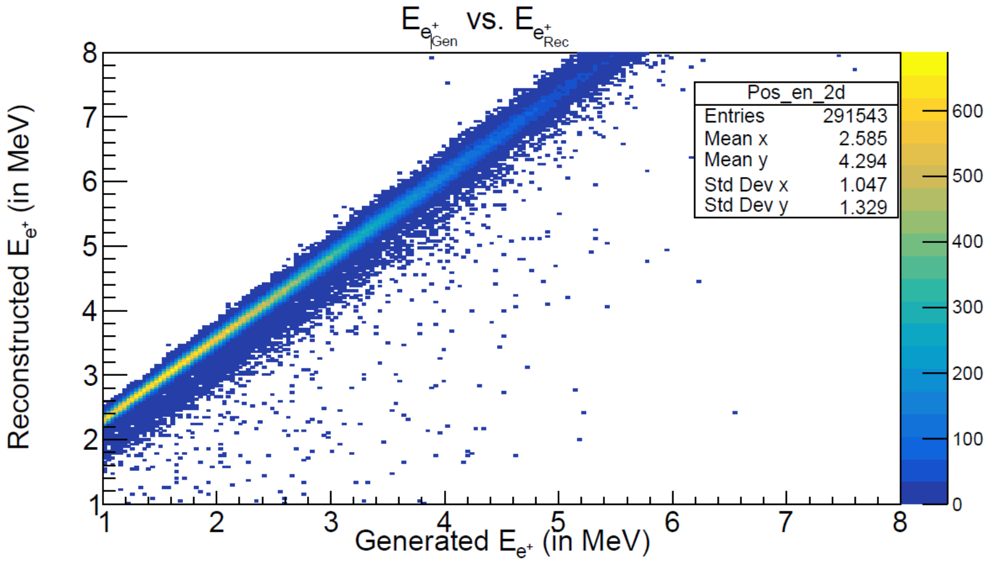
Reconstruction and positron identification

- Time information, charge related time pdfs and time offset correction for QTMLE enabled.
- Fiducial volume cut of 17.7 m used.
- Readout events with < 800 PE were rejected
- The positron and neutron of the same event identified using
- vertex distance <= 2 m.
- time difference <= 1 ms.
- A bias is observed in relative energy difference and an energy resolution of 3% is observed

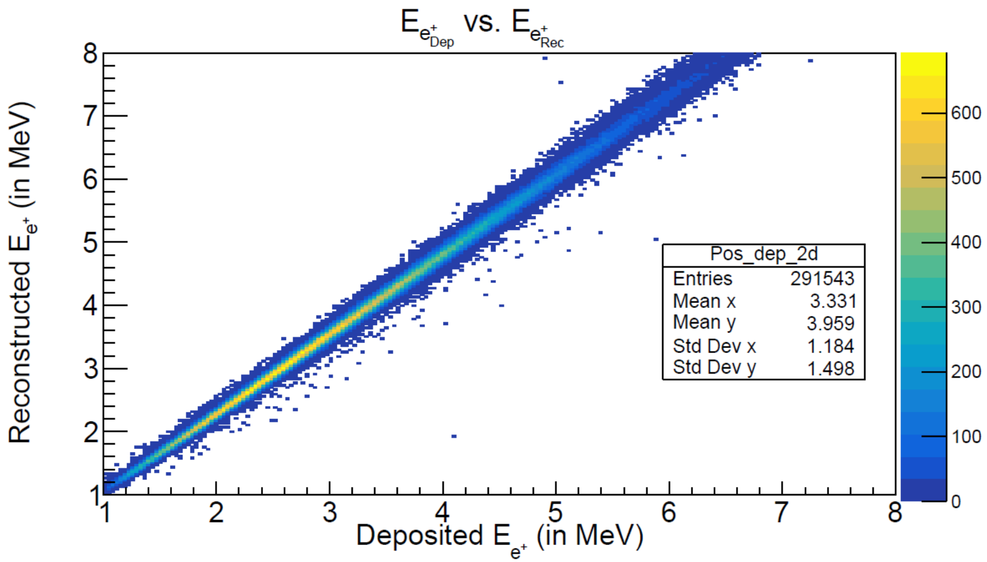


Relative difference in reconstructed energy

Correlation between E_{Rec,e^+} and $E_{\bar{\nu}}$



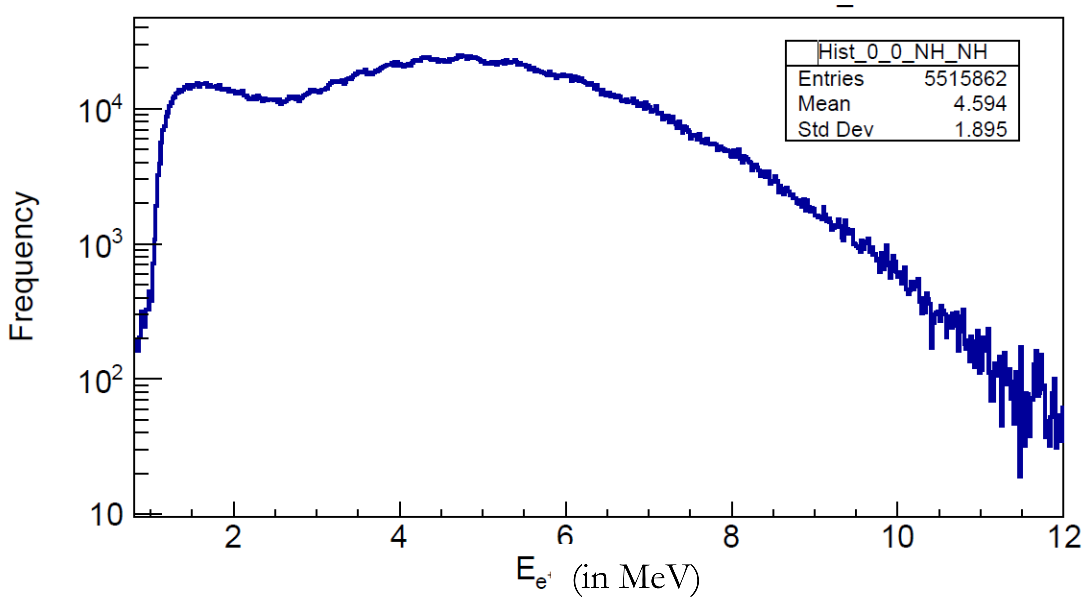
Correlation between reconstructed and generated positron energy



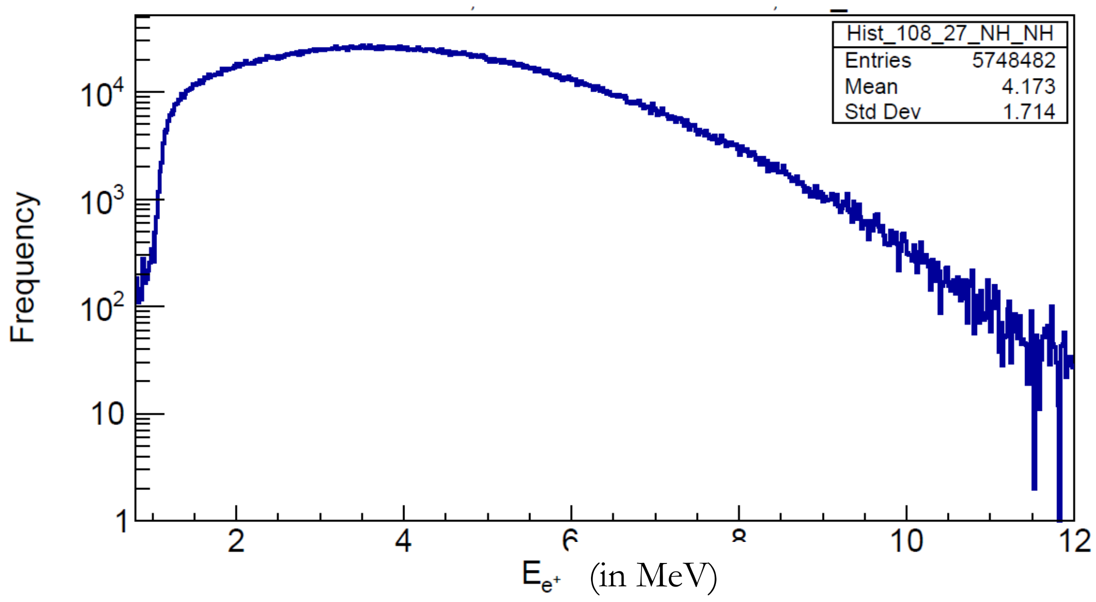
Correlation between reconstructed and deposited positron energy

- Generated positron energy is the kinetic energy of the positrons
- Deposited positron energy includes the energy deposition from the annihilation photons
- The reconstructed positron energy is reconstructed visible deposited energy
- The correlation between the reconstructed and generated positron energy justifies the use of positron energy as final observable

Event Spectra



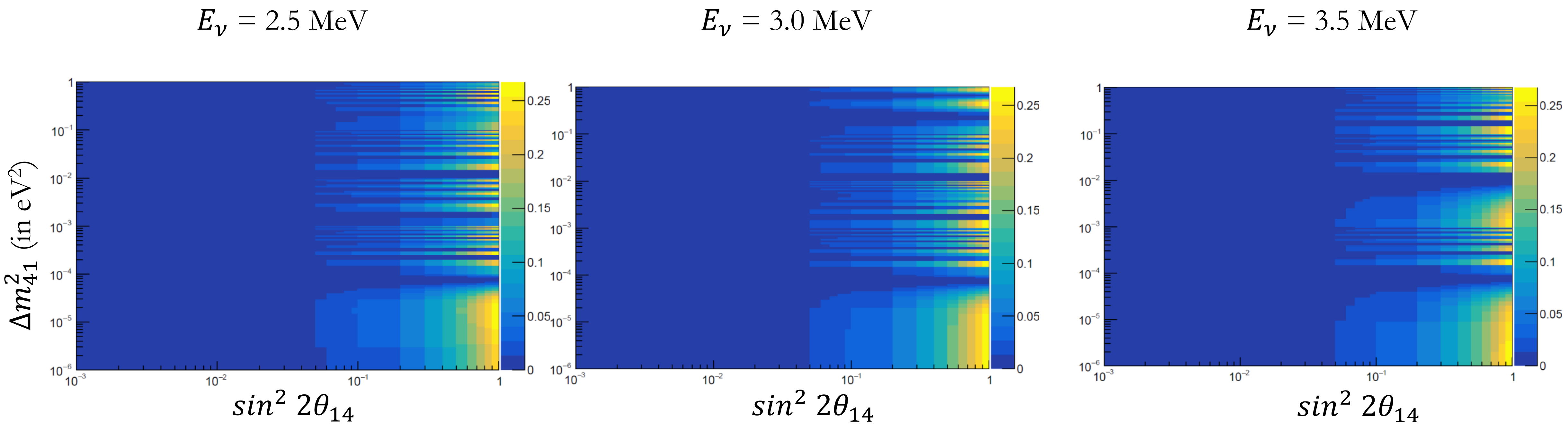
Δm^2_{41} = 10^{-6} eV^2, $sin^2 2\theta_{14}$ = 0.001



Δm^2_{41} = 1 eV^2, $sin^2 2\theta_{14}$ = 1.0

- The sterile parameters Δm^2_{41} and $sin^2 2\theta_{14}$ have been varied between (10^{-6} , 1.0)eV^2 and (0.001, 1.0) respectively.
- The mass squared value and the mixing angle have been varied logarithmically.
- For each of the 300 un-oscillated set, 20 oscillated sets were generated using different random number seed.
- All the oscillated sets are clubbed together to generate 360 years of oscillated data set.

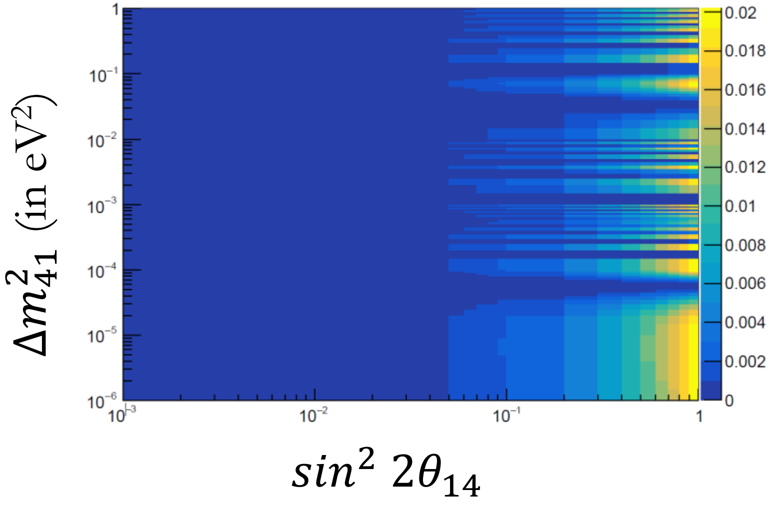
Effect of Δm^2_{42}



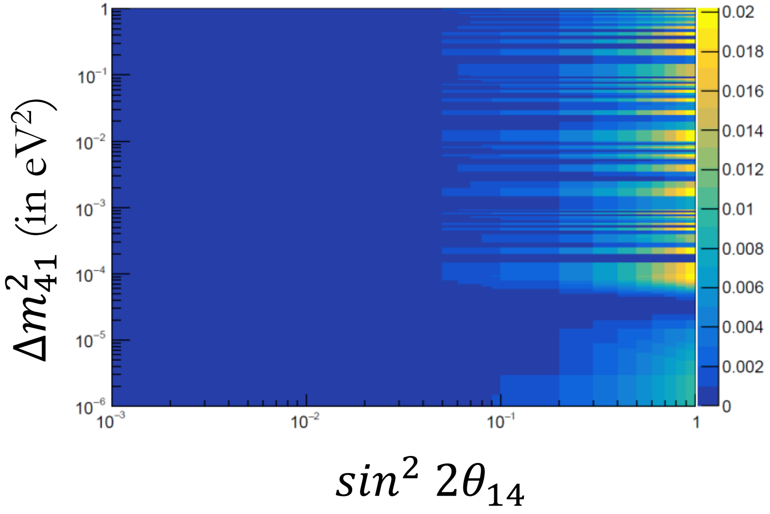
- The 3-flavour oscillation spectra has dip between 2.0 MeV and 4.0 MeV.
- So, if JUNO is insensitive to sterile, then in this region the value of the terms related to sterile should be negligible.
- These plots shows the value of the term related to Δm^2_{42}, for the whole Δm^2_{41} and $sin^2\, 2\theta_{14}$ range.

Effect of Δm_{43}^2

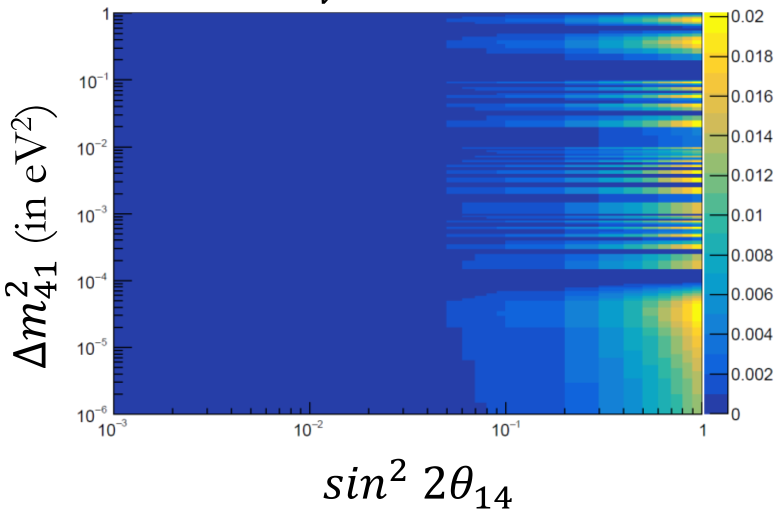
E_ν = 2.0 MeV



E_ν = 2.5 MeV

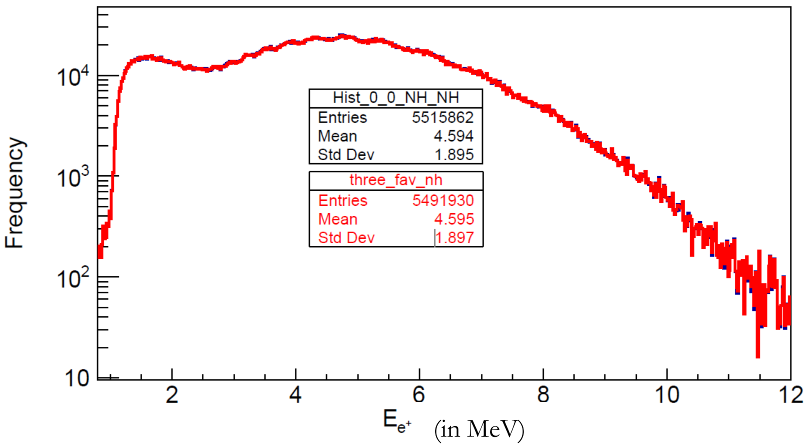


E_ν = 3.0 MeV

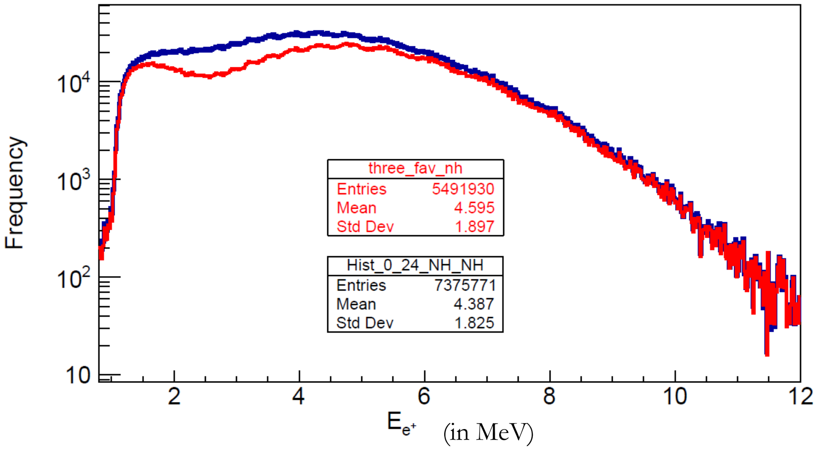


- These plots shows the value of the term related to Δm_{43}^2, for the whole Δm_{41}^2 and $sin^2\, 2\theta_{14}$ range.
- The value of this term goes as large as 0.02 for high values of $sin^2\, 2\theta_{14}$.

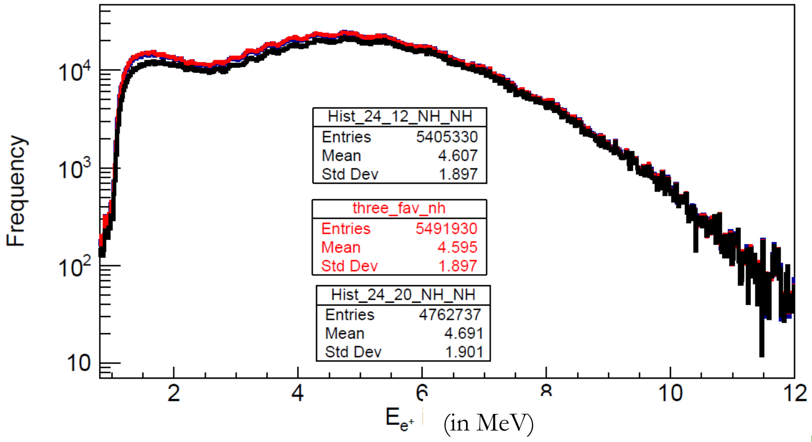
Comparison spectra



Δm_{41}^2 = 10^{-6} eV^2, $sin^2 2\theta_{14}$ = 0.001



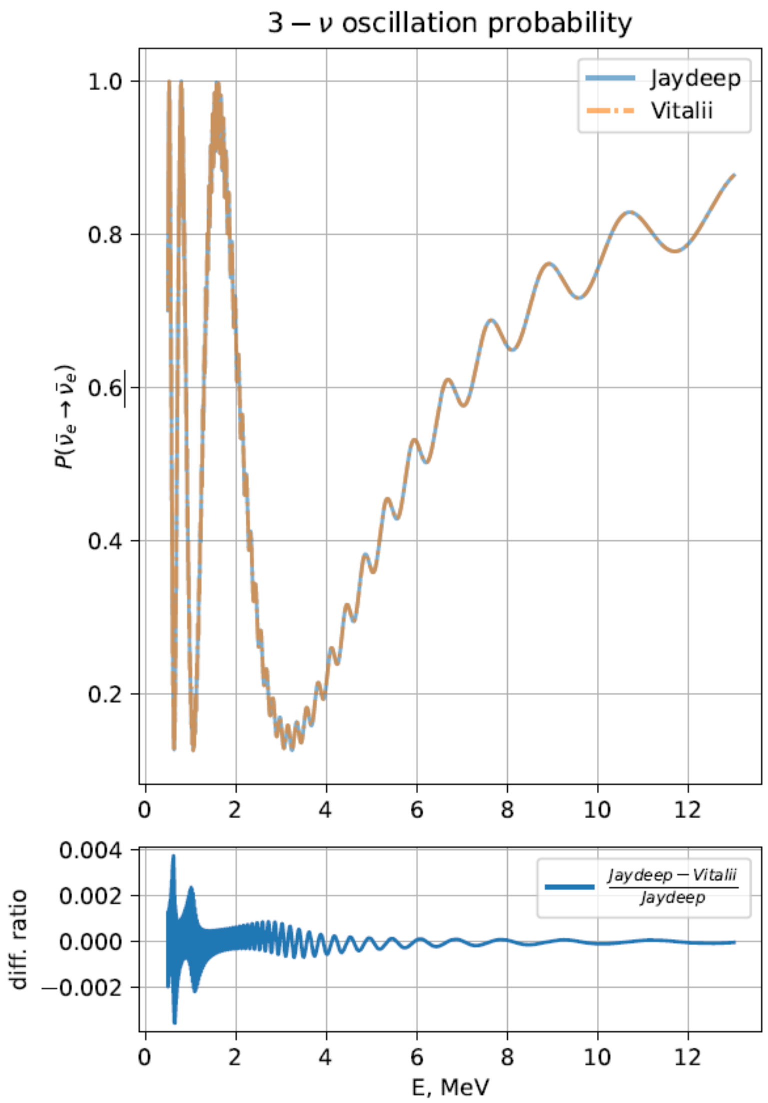
Δm_{41}^2 = 10^{-6} eV^2, $sin^2 2\theta_{14}$ = 0.7

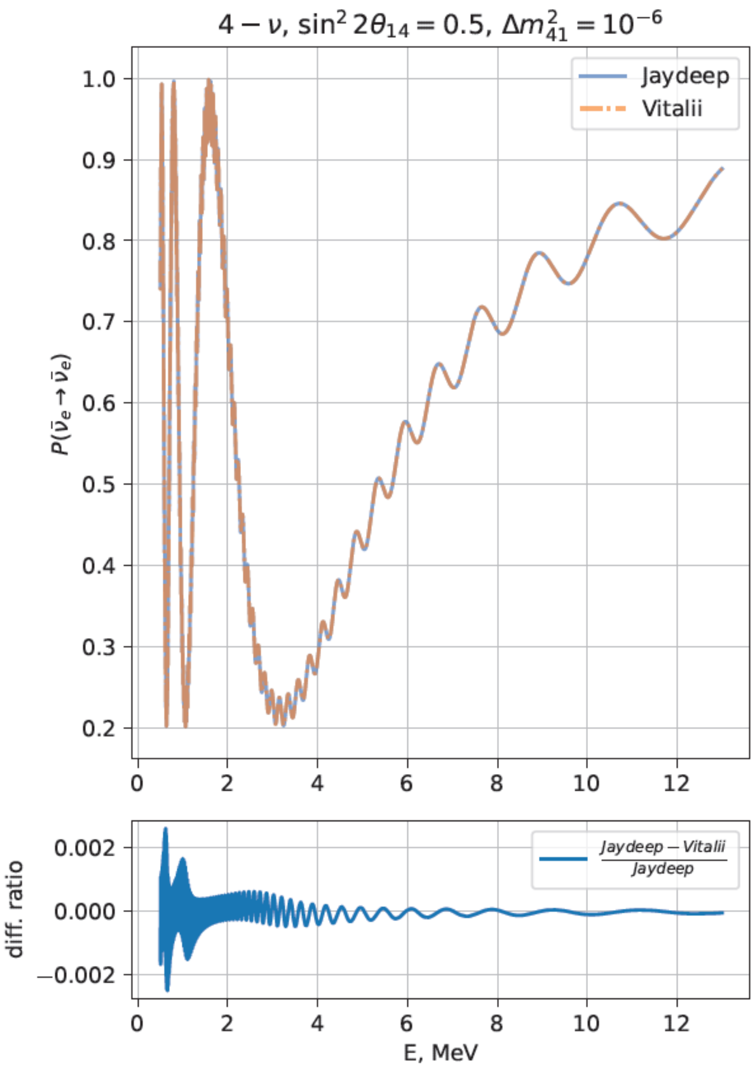


Δm_{41}^2 = 4*10^{-5} eV^2, $sin^2 2\theta_{14}$ = 0.02
Δm_{41}^2 = 4*10^{-5} eV^2, $sin^2 2\theta_{14}$ = 0.9

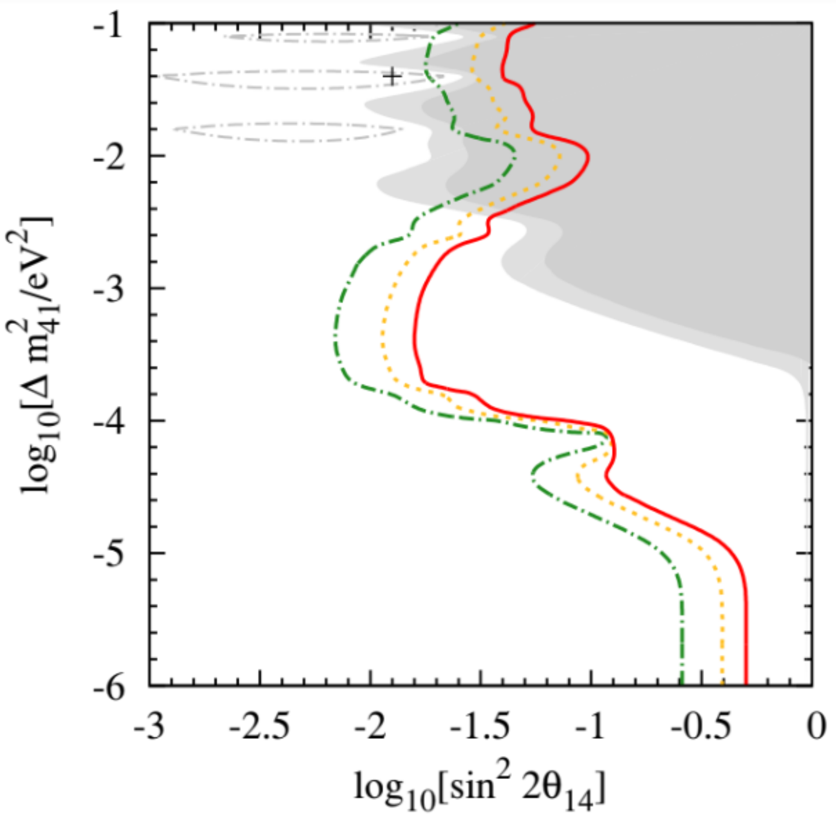
- Event spectra for 3-flavor oscillation and (3+1) oscillation with sterile oscillation parameters Δm_{41}^2 = 10^{-6} eV^2, $sin^2 2\theta_{14}$ = 0.001 overlaps completely
- But for higher value of the oscillation angle, the two spectra differ significantly.
- For Δm_{41}^2 = 4*10^{-5} eV^2 , the spectra for $sin^2 2\theta_{14}$ = 0.02 overlaps, but at higher value of the angle, they differ.

Probability cross-check





Results by Giradi et. al.



- Experimental sensitivity of JUNO to sterile neutrino parameter space studied by Giradi et. al. (*JHEP* 08 (2014) 057)
- Marginalized over all the oscillation parameters