Light Sterile Neutrino in T2HK

Sabya Sachi Chatterjee

Institute for Particle Physics Phenomenology, Durham University

PASCOS 2019 XXV 2019 International Symposium
The University of Manchester

04.07.2019

Outline

- Basic understanding and hints to eV scale sterile neutrino

- Theoretical framework of light sterile neutrino oscillation

- Impact of sterile neutrino on the resolution of octant of θ_{23} , on the determination of mass hierarchy, and on the possibility of discovering CPV and reconstructing the standard and new CP-phases.

- Conclusion

A Few Known Unknowns in Neutrino Physics

3ν Framework

1. Whether neutrino is Dirac or Majorana particle.

2. Absolute masses (m_1, m_2, and m_3) of neutrinos are unknown. We know the magnitude of mass squared differences ($|\Delta m^2_{21}|$, $|\Delta m^2_{31}|$, or $|\Delta m^2_{32}|$).

3. The sign of the solar mass splitting ($|\Delta m^2_{21}|$) is known that is +ve that is $m_2 > m_1$. But the sign of the atmospheric mass splitting ($|\Delta m^2_{31}|$) is unknown. This is known as mass hierarchy problem. $m_1 < m_2 < m_3$, called normal hierarchy, and $m_3 < m_1 < m_2$ called inverted hierarchy.

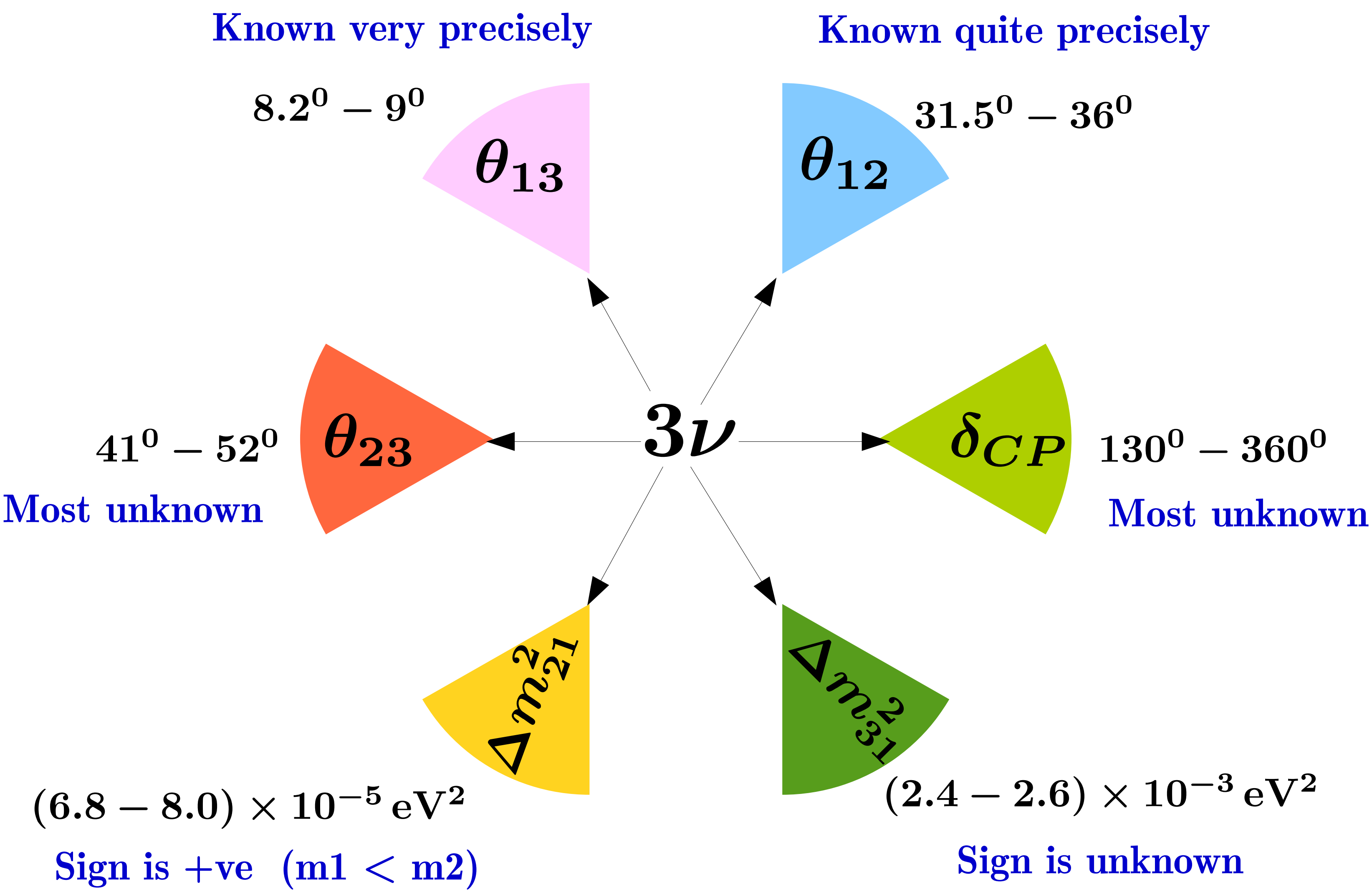
4. The magnitude of 2-3 mixing angle (θ_{23}) is unknown. This is known as octant ambiguity.

5. No confirmation yet about the CP-violation in leptonic sector.

New Physics ?

Presence of sterile neutrino, long-range forces, non-unitary nature of PMNS matrix, CPT violation, non-standard neutrino interaction, and many others.

Current status of 3ν parameters (3σ uncertainties)



For details please see arXiv: 1811.05487 by Esteban et al.

Appearance of eV scale sterile neutrino

Probability of oscillation from one flavor to another flavor with neutrino energy E and baseline L, given as

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$
$$+ 2\sum_{i>j} Im\left(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}\right)\sin 2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

Where, $\Delta m^2_{ij} = m^2_i - m^2_j$

Now, for simplicity, if we work in effective 2-flavor framework, then

$$\boxed{\mathrm{P}(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)}$$

Where, Δm^2 is expressed in eV^2, L in m (km), and E in MeV (GeV) respectively.

$$P \propto \sin^2 \left[1.27\, \Delta m^2\, (\mathrm{eV}^2)\, \frac{\mathrm{L\,(m)}}{\mathrm{E\,(MeV)}} \right]$$

If L(m) / E(MeV) ~ 1, then for maximum probability of changing one to another flavor, one needs

$$\Delta m^2 \sim 1\, \mathrm{eV}^2$$

We may observe neutrino oscillation even in the short-baseline !

This mass-squared splitting is much bigger than the two existing solar ($\mathbf{7.5 \times 10^{-5}\ eV^2}$) and atmospheric ($\mathbf{2.4 \times 10^{-3}\ eV^2}$) mass-squared splittings.

Now, there are certain anomalous phenomena exist which actually demand the existence of such big mass-squared splitting. For example, Gallium anomaly, LSND anomaly, Reactor anomaly and MiniBooNE anomaly.

Theoretical Framework for Sterile Neutrino Oscillation

In presence of a sterile neutrino, the time evolution equation in matter is written as

$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\\|\nu_s\rangle\end{pmatrix} = \left[\frac{1}{2E}U\begin{pmatrix}m_1^2 & 0 & 0 & 0\\0 & m_2^2 & 0 & 0\\0 & 0 & m_3^2 & 0\\0 & 0 & 0 & m_4^2\end{pmatrix}U^\dagger + \begin{pmatrix}V_{CC}+V_{NC} & 0 & 0 & 0\\0 & +V_{NC} & 0 & 0\\0 & 0 & +V_{NC} & 0\\0 & 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\\|\nu_s\rangle\end{pmatrix}$$

Δm_{21}^2 , Δm_{31}^2 , Δm_{41}^2 are the independent mass squared difference in 3+1 sector

$\mathrm{V}_{CC} = \sqrt{2}\,G_F\,N_e$ Charge current potential for neutrino

$\mathrm{V}_{NC} = -\frac{G_F\,N_n}{\sqrt{2}}$ Neutral current potential for neutrino

We can not phase out V_{NC} contribution in 3+1 sector.

V_{NC} may play an important role in detecting sterile neutrino !

In our work, the 4x4 mixing matrix between flavor & mass eigenstates is parametrized as :

$$U = \tilde{R}_{34} R_{24} \tilde{R}_{14} R_{23} \tilde{R}_{13} R_{12} \longrightarrow 3\nu$$

where, R_{ij} & $\tilde{R}_{ij}$ *are* real (complex) 4×4 rotations in the (i, j) plane containing the 2×2 submatrix

$$R_{ij}^{2\times2} = \begin{pmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{pmatrix} \quad \textbf{and} \quad \tilde{R}_{ij}^{2\times2} = \begin{pmatrix} c_{ij} & \tilde{s}_{ij} \\ -\tilde{s}^{*}_{ij} & c_{ij} \end{pmatrix}$$

3ν → **Mixing angles (3)**; → **Phases (Dirac + Majorana) (1+2)**

4ν → **Mixing angles (6)**; → **Phases (Dirac + Majorana) (3+3)**

$\mathbf{3(N-2)}$ no. of mixing angles

$\mathbf{(2N-5)}$ no. of Dirac CP-phases

$\mathbf{(N-1)}$ no. of Majorana CP-phases

Appearance probability ($P_{\mu e}^{4\nu}$) in vacuum in LBL experiment

We consider $\Delta m_{41}^2 \sim 1\,\mathrm{eV}^2$ light sterile neutrino

$\Delta m_{41}^2 \gg \Delta m_{31}^2$ $\longrightarrow$ Fast oscillations get averaged out

No phase information related to Δm_{41}^2 in contrast to SBL

But LBL setups are sensitive to CP phases in contrast to SBL

$$P_{\mu e}^{4\nu} \simeq P_0^{\mathrm{ATM}} + P_{\mathrm{I}}^{\mathrm{INT}} + P_{\mathrm{II}}^{\mathrm{INT}}$$

$$P_0^{\mathrm{ATM}} \simeq 4 s_{13}^2 s_{23}^2 \sin^2\Delta \quad \sim O(\varepsilon^2)$$

$$P_I^{\mathrm{INT}} \simeq 8 s_{12} c_{12} s_{13} s_{23} c_{23} (\alpha\Delta) \sin\Delta \cos(\Delta \pm \delta_{13}) \quad \sim O(\varepsilon^3)$$

$$P_{II}^{\mathrm{INT}} \simeq 4 s_{13} s_{23} s_{14} s_{24} \sin\Delta \sin(\Delta \pm \delta_{13} \mp \delta_{14}) \quad \sim O(\varepsilon^3)$$

$$s_{13} \sim s_{14} \sim s_{24} \sim \varepsilon$$

$$\alpha \equiv \Delta m_{21}^2 / \Delta m_{31}^2 \sim \varepsilon^2$$

$$\Delta \equiv \Delta m_{31}^2 L / 4E$$

See Klop & Palazzo; PRD 91 (2015) 073017

Independent of θ_{34} & δ_{34} in vacuum

Matter Effect

In presence of matter, the leading term in transition probability $P\left(\nu_\mu \rightarrow \nu_e\right)$ modified as (upto third order)

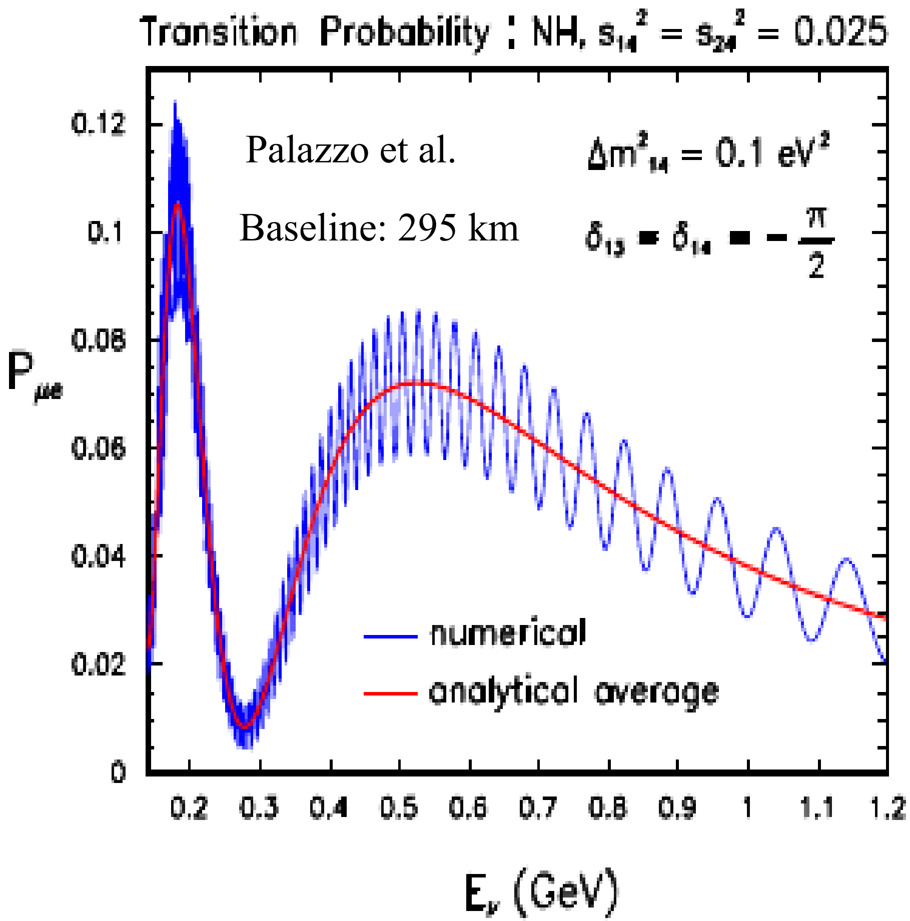
$$P_{\mathrm{m}}^{\mathrm{ATM}} \simeq (1+2\mathrm{k})\, P_0^{\mathrm{ATM}}$$

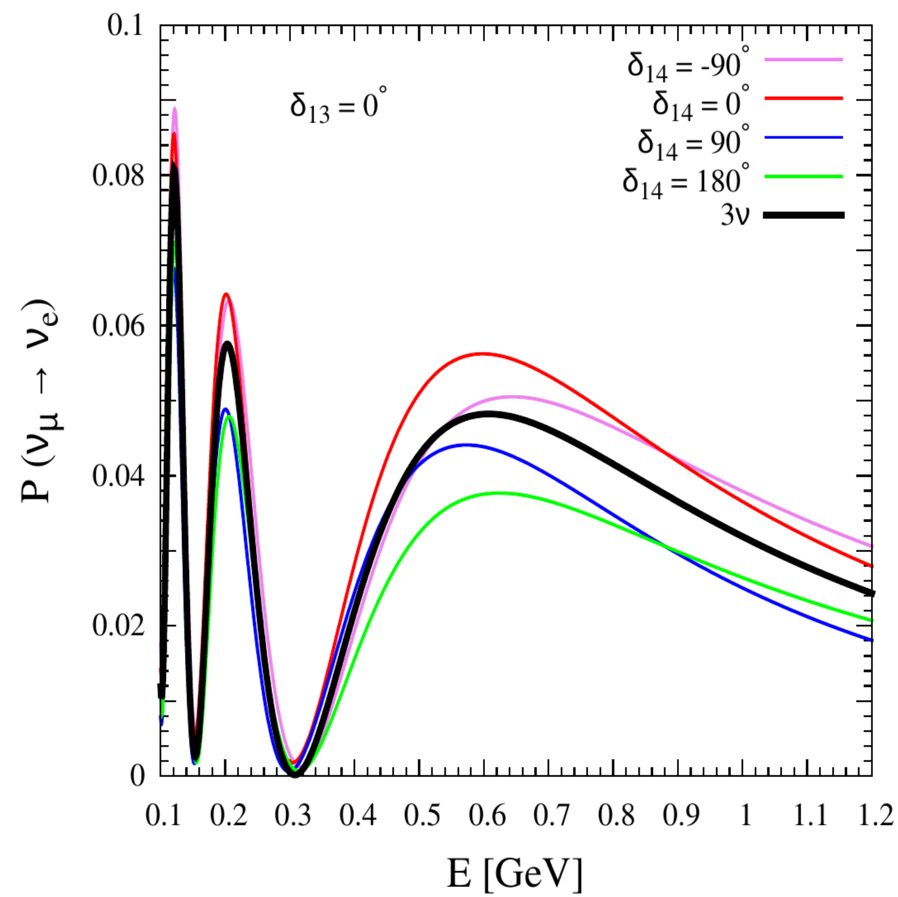
$$k = \frac{2 V_{CC} E}{\Delta m_{31}^2} \quad \& \quad V_{CC} = \sqrt{2} G_F N_e$$

In matter, the two interference terms acquire corrections which are of the fourth order. For our better analytical understanding, we limit ourselves upto third order i.e., ε^3. So the interference terms will have the vacuum expressions even in the presence of matter.

However, in our numerical analysis, we consider all the corrections.

T2HK is a 295 km baseline LBL experiment. In our work we have assumed equal number of neutrino and antineutrino statistics with 10 yrs of total run time. We have also assumed 560 kt Water Cherenkov detector. We have followed **arXiv:1412.4673**.





Though the oscillation driven by Δm^2_{41} gets averaged out, it has huge effect at far detector.

Impact of sterile neutrino on the octant resolution

The vacuum survival Probability $\nu_\mu \to \nu_\mu$ in 3-flavor is given by

$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2\Delta + \alpha\,\Delta\, c_{12}^2 \sin^2 2\theta_{23} \sin 2\Delta - 4\, s_{13}^2\, s_{23}^2 \sin^2\Delta$$

Insensitive to the resolution of octant as it gives rise to octant degeneracy

Where, $\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2}$, $\Delta = \frac{\Delta m_{31}^2 L}{4E}$

In a simplified case, we can write

$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2\Delta$$

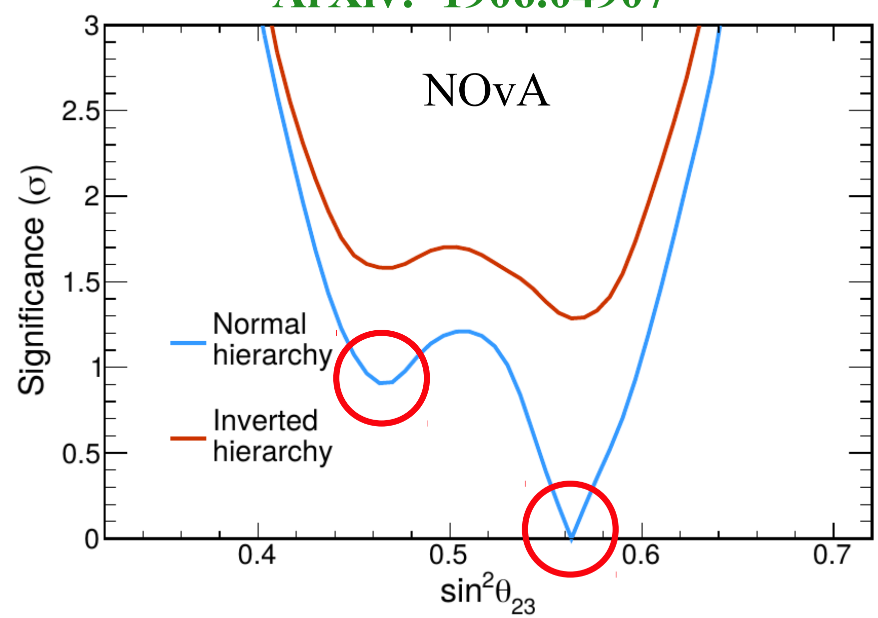
$$P_{\mu\mu}(\theta_{23}) = P_{\mu\mu}(\pi/2 - \theta_{23})$$

$\theta_{23} < 45^0$ **Known as lower octant**

$\theta_{23} > 45^0$ **Known as higher octant**

$\theta_{23} = 45^0$ **Called maximal mixing**

ArXiv: 1906.04907



There are two solutions, called Octant degeneracy

Our goal here is to see the capability of an experiment (say, DUNE) to distinguish the two octants of θ_{23} .

The appearance probability $\nu_\mu \to \nu_e$ is given by

$$P_{\mu e} \simeq 4\sin^2\theta_{13} \sin^2\theta_{23} \sin^2\Delta$$
$$+ 2\sin\theta_{13}\, \sin 2\theta_{12}\, \sin 2\theta_{23}\,(\alpha\Delta)\sin\Delta\, \cos(\Delta \pm \delta_{13})$$

Sensitive to the resolution of octant degeneracy

$$\boxed{P_{\mu e}(\theta_{23}) \neq P_{\mu e}(\pi/2 - \theta_{23})}$$

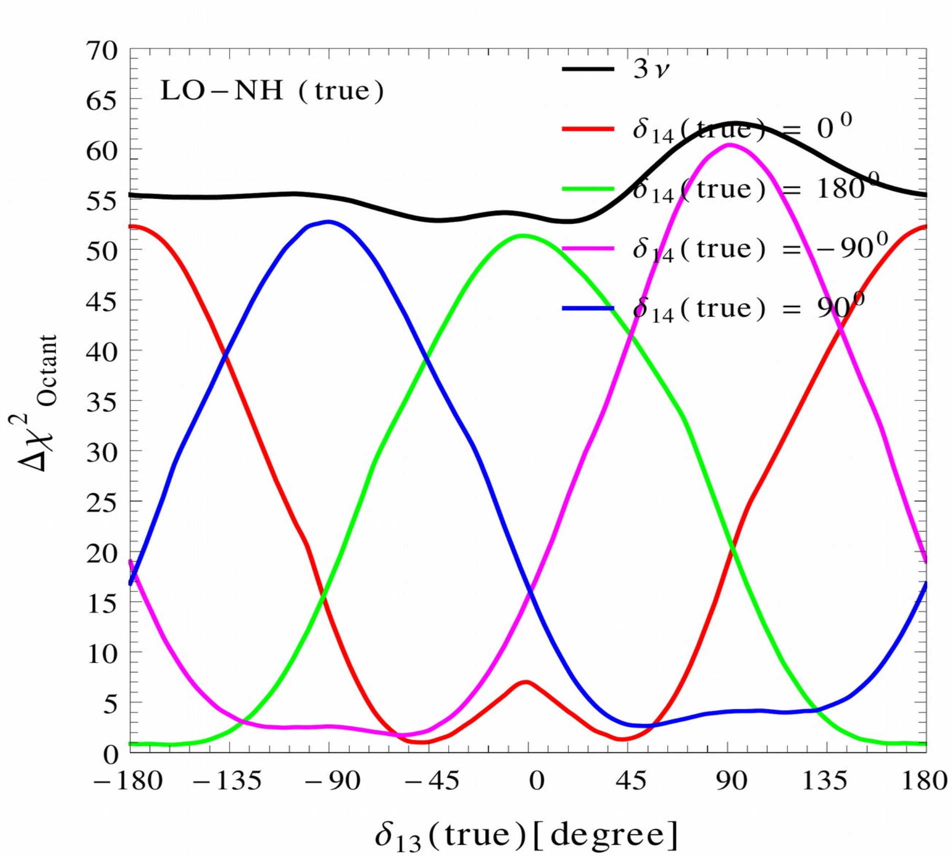
Both appearance and survival channels play complementary role in resolving octant degeneracy.

We can rewrite θ_{23} as, $$\theta_{23} = \pi/4 \pm \eta$$

+ (-) corresponds to HO (LO). η is a deviation from maximality

An experiment can be sensitive to the octant if, despite the freedom introduced by the unknown CP phases and other parameters, there is still a difference between the probabilities in the two octants, i.e.,

$$\Delta P \equiv P_{\mu e}\left(\delta_{13}, \delta_{14}, \theta_{23}^{HO}\right) - P_{\mu e}\left(\delta_{13}, \delta_{14}, \theta_{23}^{LO}\right) \neq 0$$



Benchmark choice:

$\sin^2\theta_{23}(\text{true}) = 0.42(0.58)$ as LO(HO)

Free parameters: $\boldsymbol{\delta_{13}}$**(test),** $\boldsymbol{\delta_{14}}$**(test), and** $\boldsymbol{\theta_{23}}$**(test in opposite octant)**

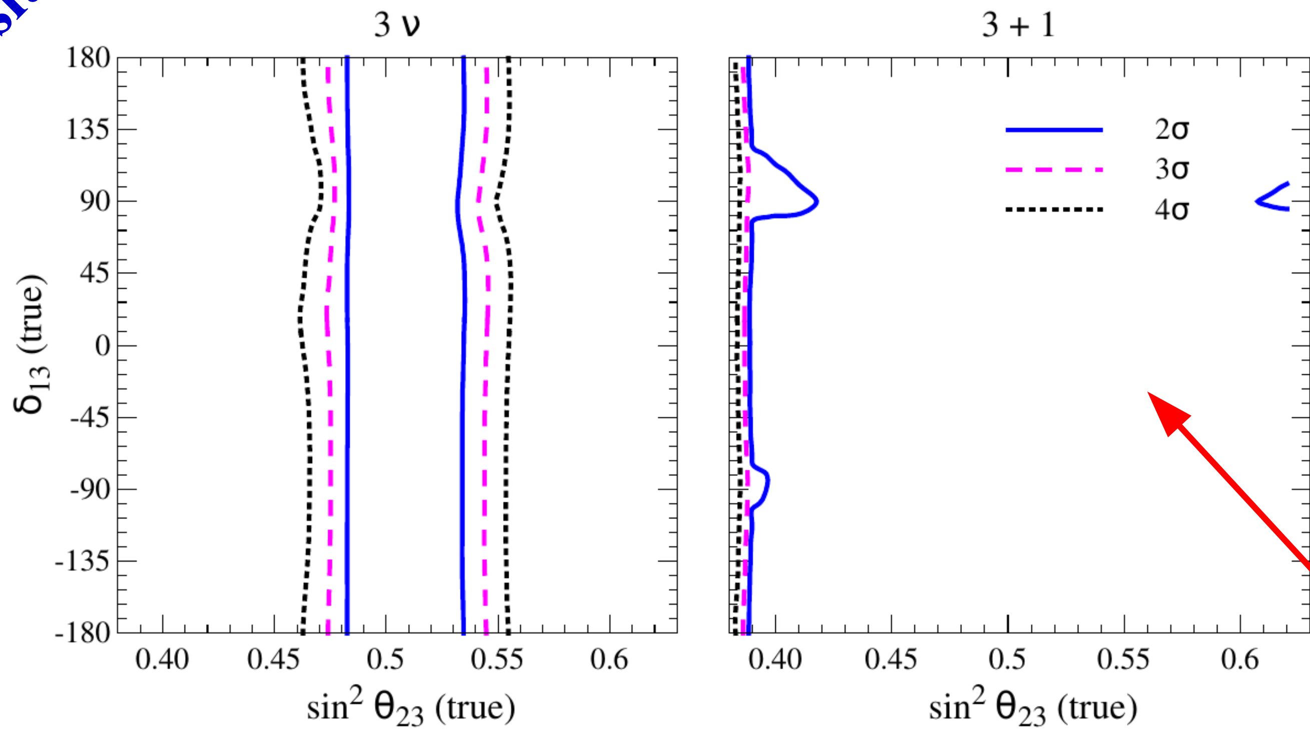
$\boldsymbol{\theta_{34} = 0}$ **considered in both true and test**

In 3+1, the sensitivity goes down in compare to 3+0 sector

A good sensitivity to an octant means if an experiment excludes the wrong octant at certain confidence level, provided the true data is generated with the right octant.

T2HK sensitivity

JHEP 1804 (2018) 091 by Agarwalla, SSC, and Palazzo



No sensitivity!

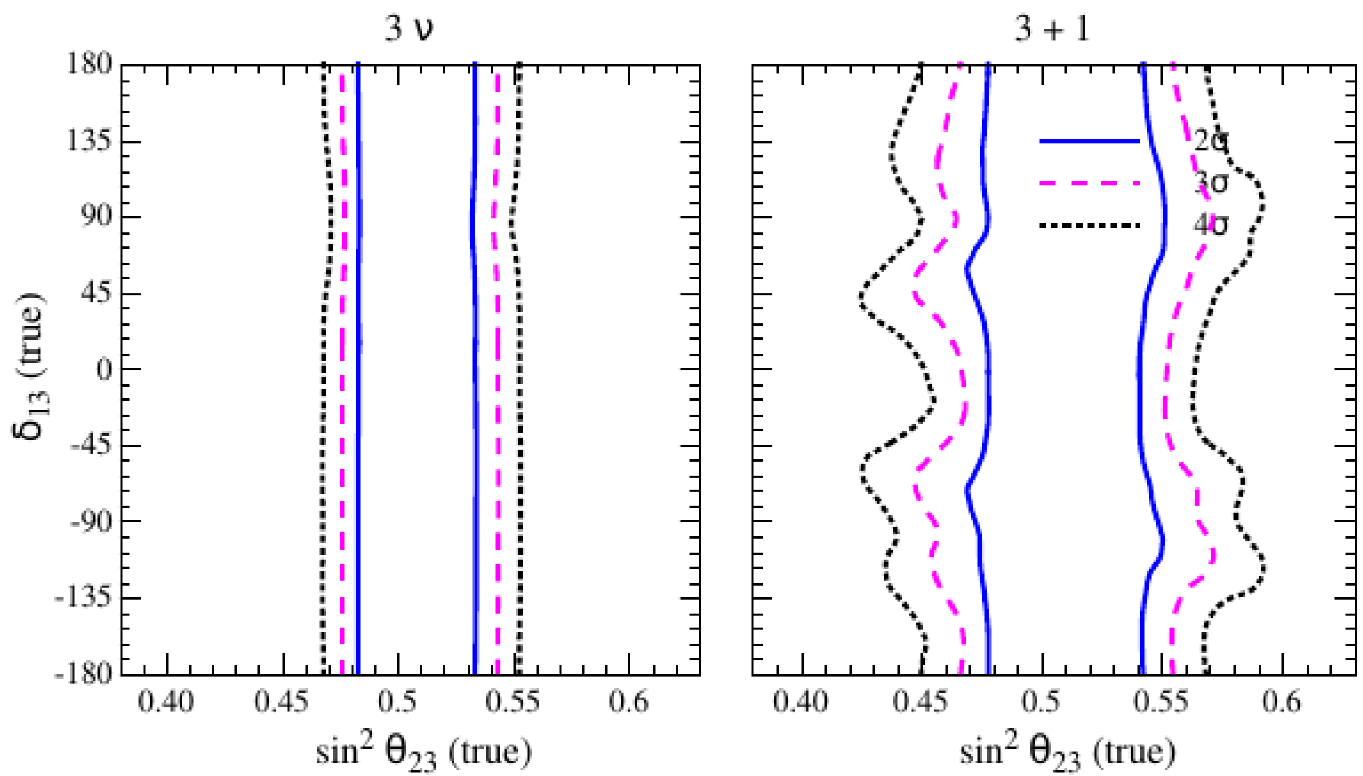
$$\Delta\chi^2_{\rm octant} = \chi^2_{\rm test\ octant} - \chi^2_{\rm true\ octant}$$

$$P^{INT}_{II} \simeq 4\, s_{13}\, s_{23}\, s_{14}\, s_{24} \sin\Delta \, \sin(\Delta + \delta_{13} - \delta_{14})$$

extra degree of freedom

In 3+1, the sensitivity to the octant of θ_{23} gets completely lost.

T2HK sensitivity



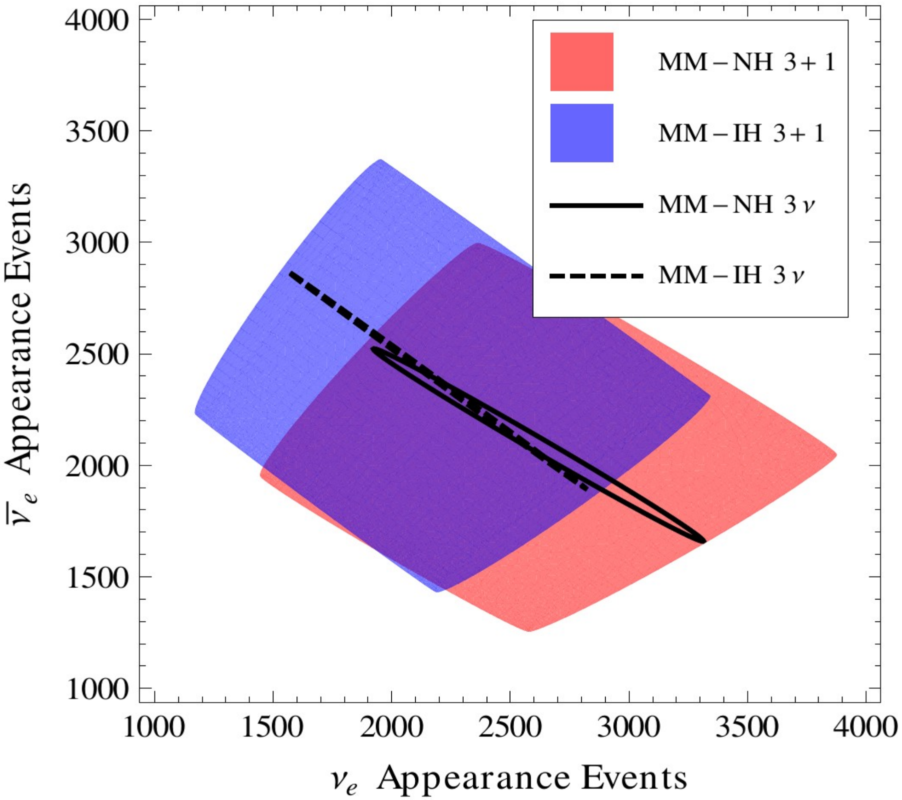
δ_{14} has been fixed both in data and theory.

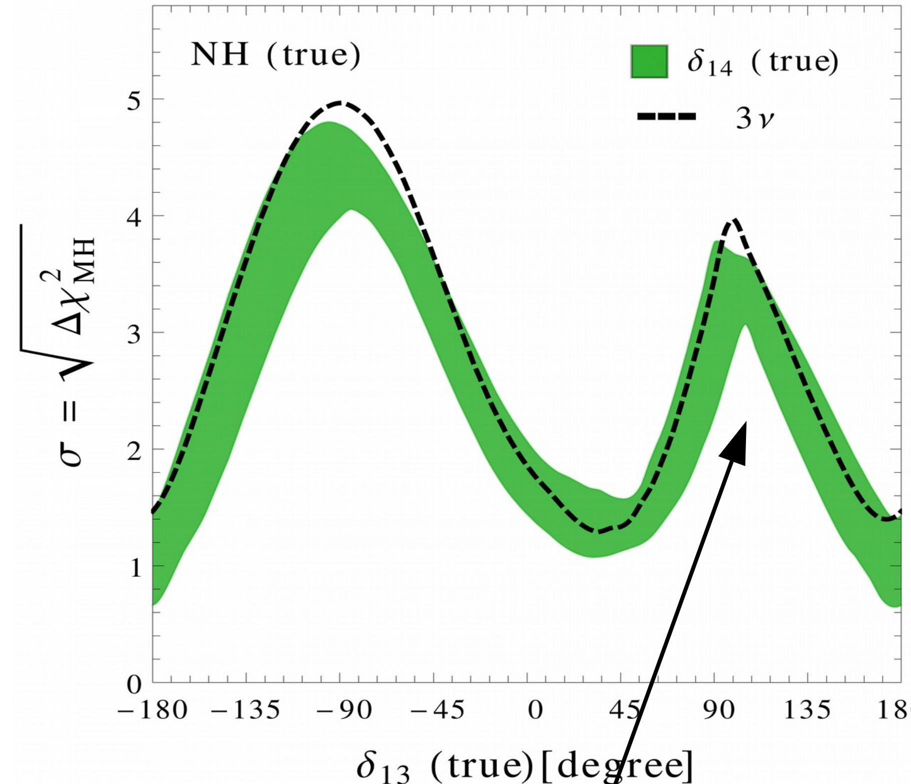
We assume δ_{14} is known very precisely in nature

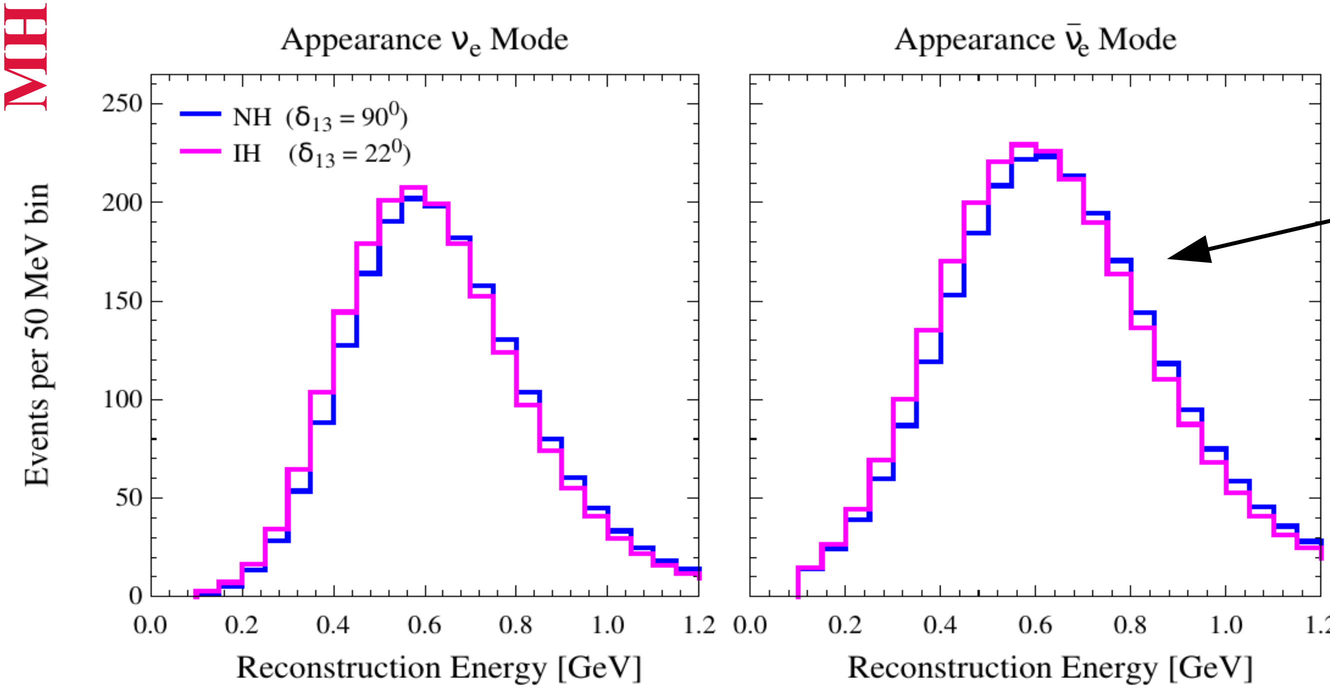
Not so realistic. Difficult task to pinpoint δ_{14} precisely.

A long way to go !

MH sensitivity





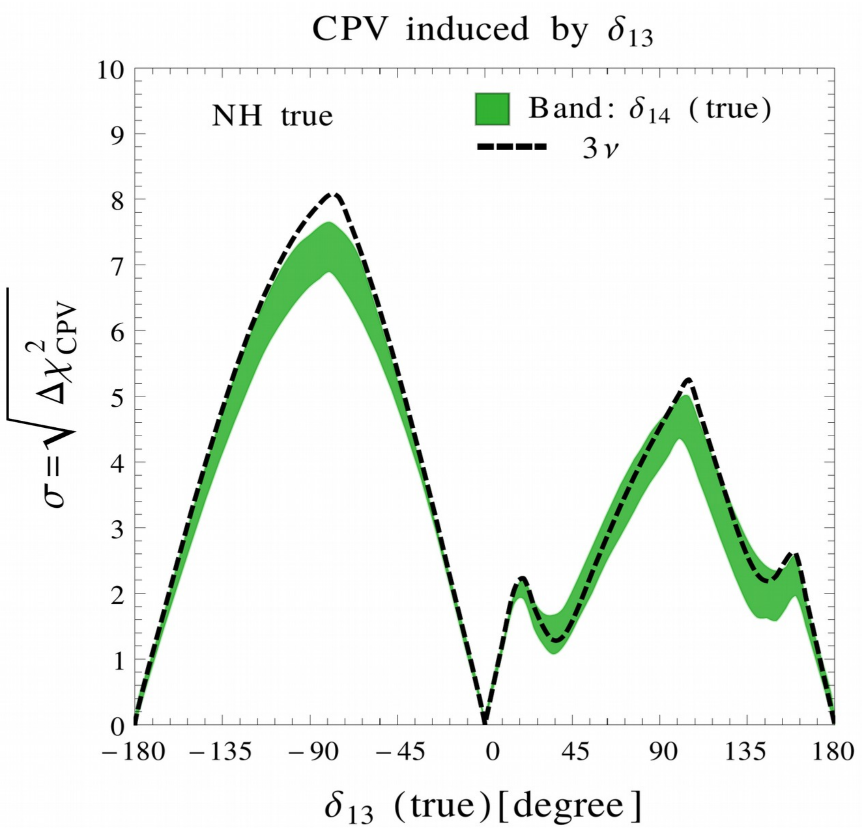


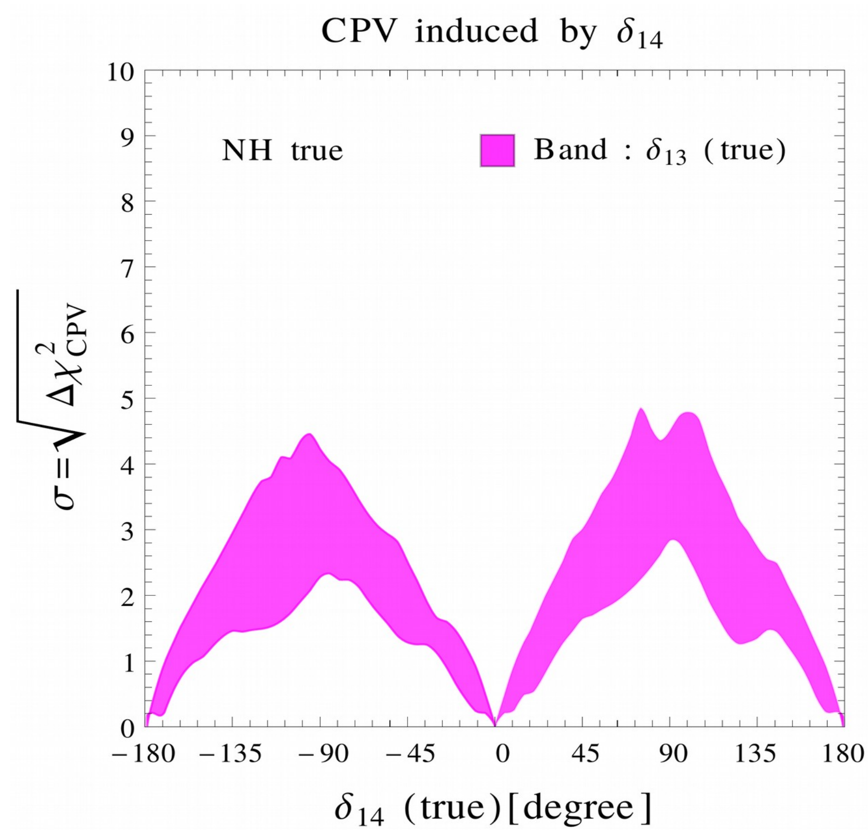
Spectral information secures a good MH sensitivity

MH discovery potential is defined as the confidence level at which one can exclude the false hierarchy given a data is generated with true hierarchy.

JHEP 1804 (2018) 091 by Agarwalla, SSC, and Palazzo

CP-Violation search in presence of a sterile neutrino





CPV discovery is defined as the confidence level at which an experiment can reject the test hypothesis of no CPV i.e., $\delta_{13}(\text{test}) = 0, \pm\pi$

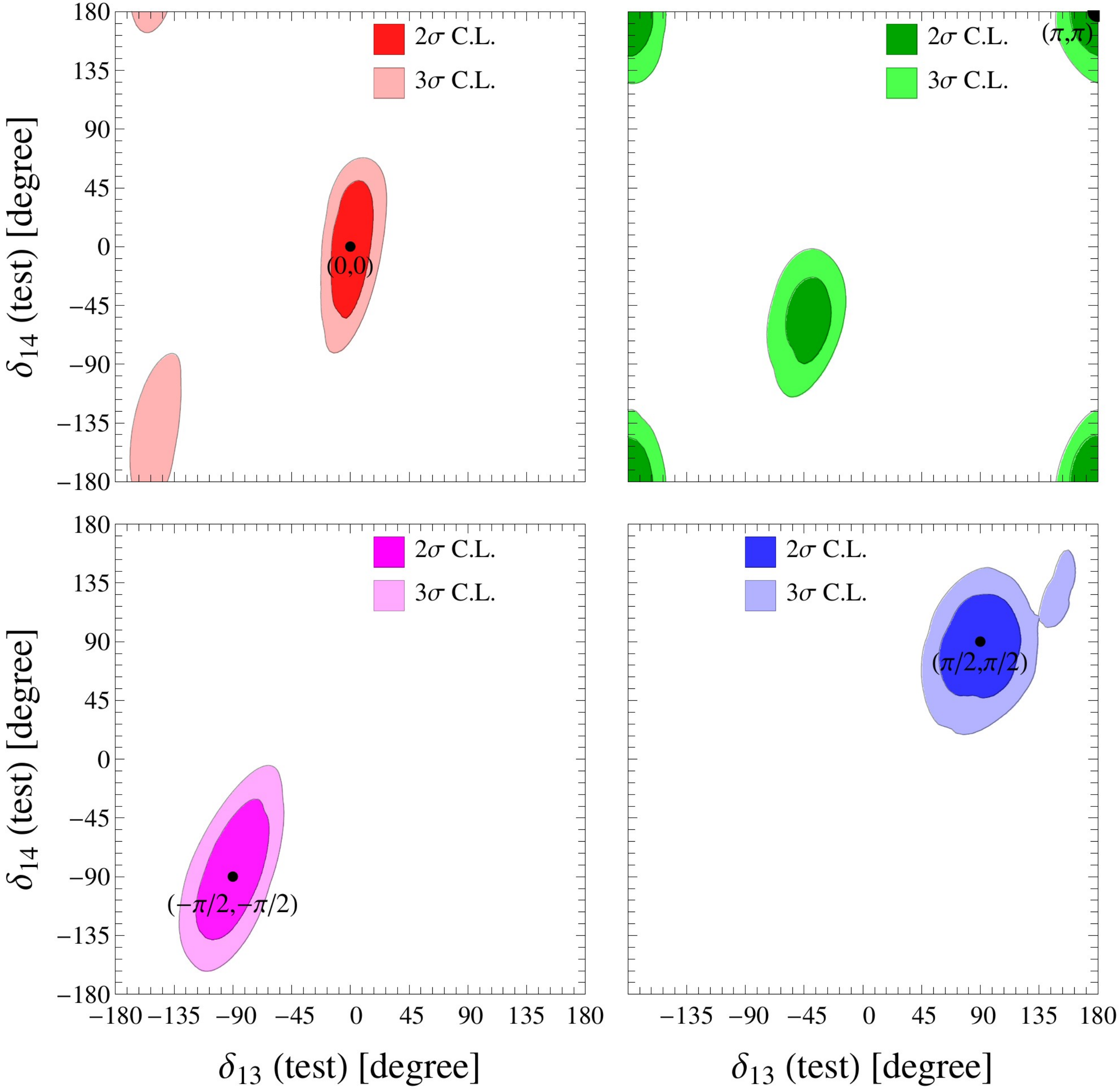
JHEP 1804 (2018) 091 by Agarwalla, SSC, and Palazzo

T2HK offers excellent sensitivity to the CPV discovery!

Small matter effect, high statistics, and spectral information assures minimum of 3σ sensitivity in the unfavorable situation of CP-phase and hierarchy degeneracy.

Reconstruction of CP-phases in T2HK

Irrespective of any CP-violation



Precise knowledge of MH is needed to remove the spurious islands

JHEP 1804 (2018) 091 by Agarwalla, SSC, and Palazzo

Typical 1σ uncertainty on the reconstructed CP-phases is $15^\circ(30^\circ)$ for $\delta_{13}(\delta_{14})$

Conclusion

- SBL experiments are not sensitive to the CP phases. We need LBL to explore the new phases. So, in the eventuality of a light sterile neutrino, the LBL setups would play a complementary role to the SBL experiments.

- We have shown that in 3+1, a new interference term that enters into the $(\nu_\mu \rightarrow \nu_e)$ transition probability can perfectly mimic a swap of the octant of θ_{23} and as a result the sensitivity towards the resolution of octant of θ_{23} may goes to zero.

- Large statistics and spectral information assure a good MH sensitivity in 3-flavor as well as in 3+1 framework.

- T2HK offers excellent sensitivity to the CPV discovery! There is a mild deterioration of CPV discovery in 3+1 scheme. In addition the possibility of discovering CPV induced by δ_{14} is appreciable.

- The typical 1σ level uncertainty on the reconstructed phases in T2HK is approximately $15^\circ\,(30^\circ)$ for $\delta_{13}\,(\delta_{14})$

- Prior knowledge of MH is very important to measure the CP phases precisely for T2HK.

- We hope that the analysis performed in these papers may give deep insight in exploring the new mass eigenstate.

Thank you

The choice of this parametrization is very useful for our understanding. Such as

(i) With the left most positioning of the matrix $\tilde{R}_{34}$ the vacuum transition probability $\nu_\mu \to \nu_e$ becomes independent of θ_{34} & δ_{34} [See Klop & Palazzo; PRD 91 (2015) 073017]

(ii) For small values of θ_{13} & mixing angles involving 4th state, we have,

$$|U_{e3}^2| \simeq s_{13}^2,\ |U_{e4}^2| \simeq s_{14}^2,\ |U_{\mu 4}^2| \simeq s_{24}^2, \text{ and } |U_{\tau 4}^2| \simeq s_{34}^2$$

with an immediate physical interpretation of mixing angles.

Oscillation Probability in 3+1 in vacuum

$$P^{4\nu}_{\mu e} \simeq \left(1 - s^2_{14} - s^2_{24}\right) P^{3\nu}_{\mu e}$$

$$+ 4\, s_{14}\, s_{24}\, s_{13}\, s_{23}\, \sin\Delta\, \sin\left(\Delta + \delta_{13} - \delta_{14}\right)$$

$$- 4\, s_{14}\, s_{24}\, c_{23}\, s_{12}\, c_{12} \left(\alpha\Delta\right) \sin\delta_{14}$$

$$+ 2\, s^2_{14}\, s^2_{24}$$

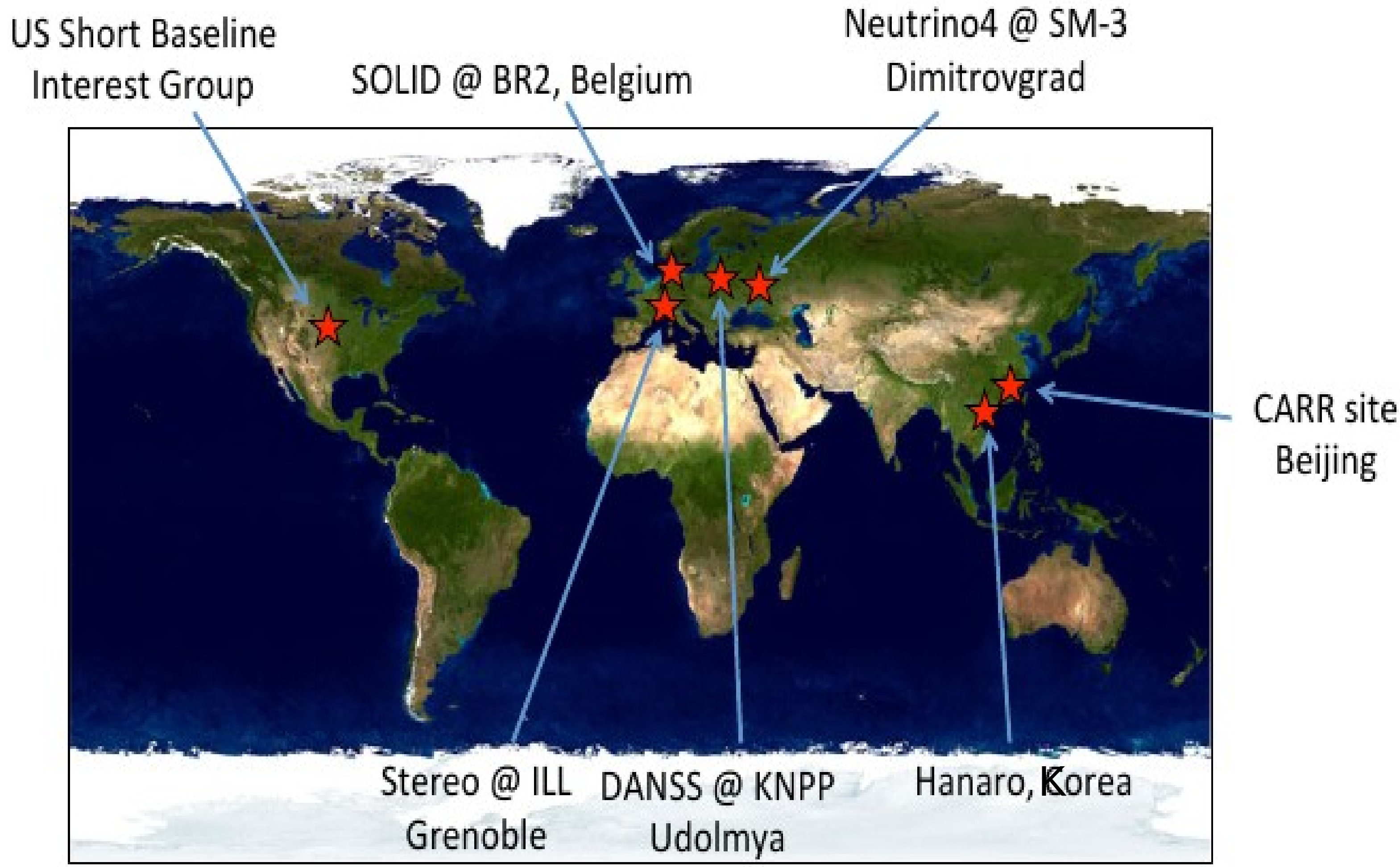
In presence of matter

$$P^{4\nu}_{\mu e} \simeq \left(1 - s^2_{14} - s^2_{24}\right) \bar{P}^{3\nu}_{\mu e}$$

$$+ 2\, s_{14}\, s_{24}\, \Re\left(e^{-i\,\delta_{14}}\, \bar{S}_{ee}\bar{S}^{*}_{e\mu}\right)$$

$$+ s^2_{14}\, s^2_{24}\left(1 + \bar{P}^{3\nu}_{ee}\right)$$

Where, $\bar{P}^{3\nu}_{ee} = |\bar{S}_{ee}|^2$ and $\bar{P}^{3\nu}_{\mu e} = |\bar{S}_{e\mu}|^2$



Taken from the talk by D.Lhuillier - CEA Saclay

Experiments to Search for Sterile Neutrinos

There are four types of experiments broadly categorized as:

Radioactive Neutrino Sources: SOX, LENS, Baksan, Ce−LAND, RICOCHET …….

Reactor Neutrinos: Stereo, DANSS, US SBR, Neutrino−4, SoLid, Nucifier, NEOS …..

Stopped π beams : OscSNS, LSND−Reloaded, IsoDAR …..

Decay in Flight Beams : nuSTORM, LAr1, ICARUS / NESSiE ….

For details please see the talk by Jonathan Link, Virginia Tech.

Some Theoretical Motivations

1. Split Seesaw mechanism

$$\mathrm{M}_s = k_i \, v_{B-L} \, \frac{2\tilde{m}}{M(e^{2\tilde{m}l-1})} \qquad \mathrm{y} = \sqrt{\frac{2\tilde{m}}{M(e^{2\tilde{m}l}-1)}} \; \tilde{\lambda}$$

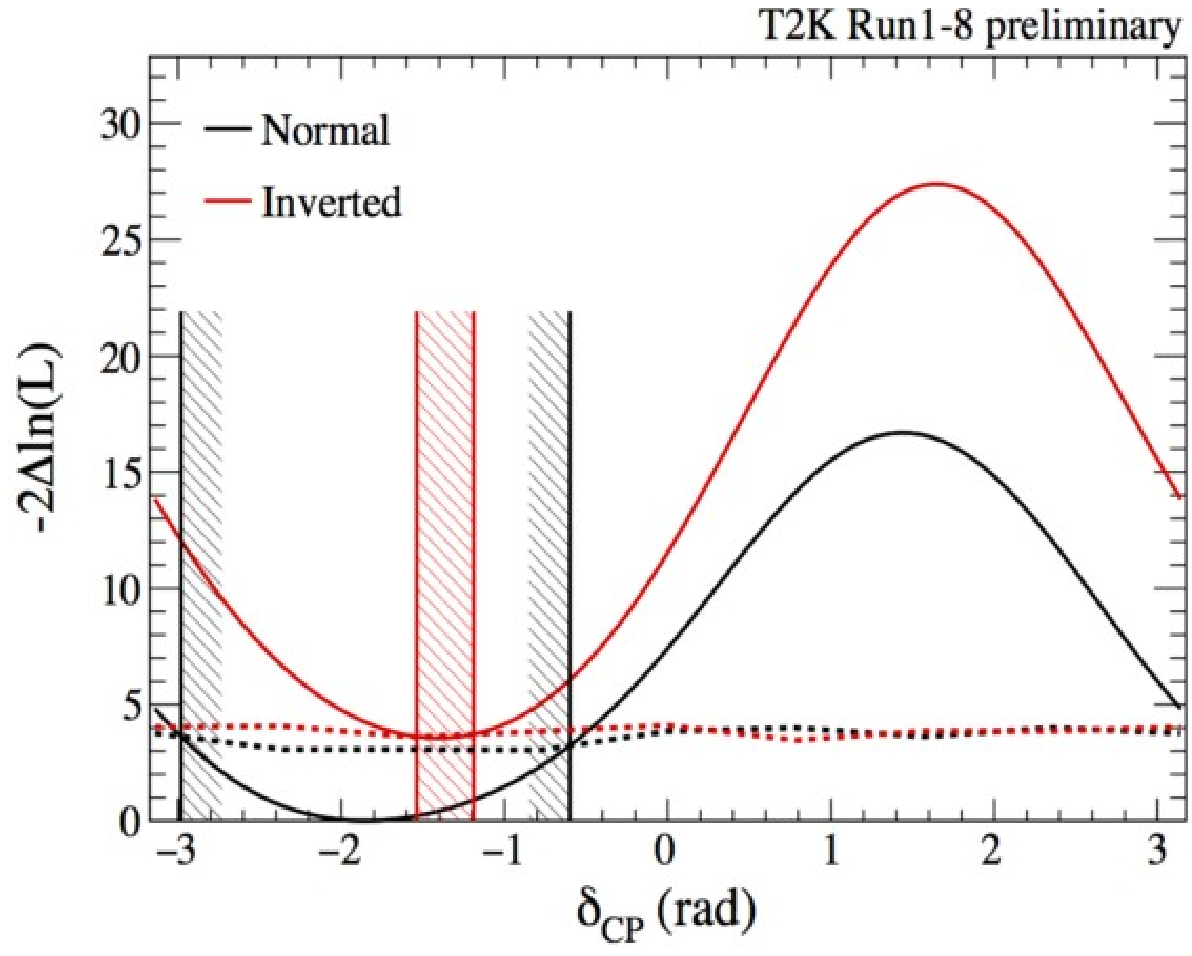
v_{B-L} is B-L symmetry breaking scale

M_s is effective mass of sterile neutrino, k_i, $\tilde{\lambda}$ are the couplings of 5-dimensional theory

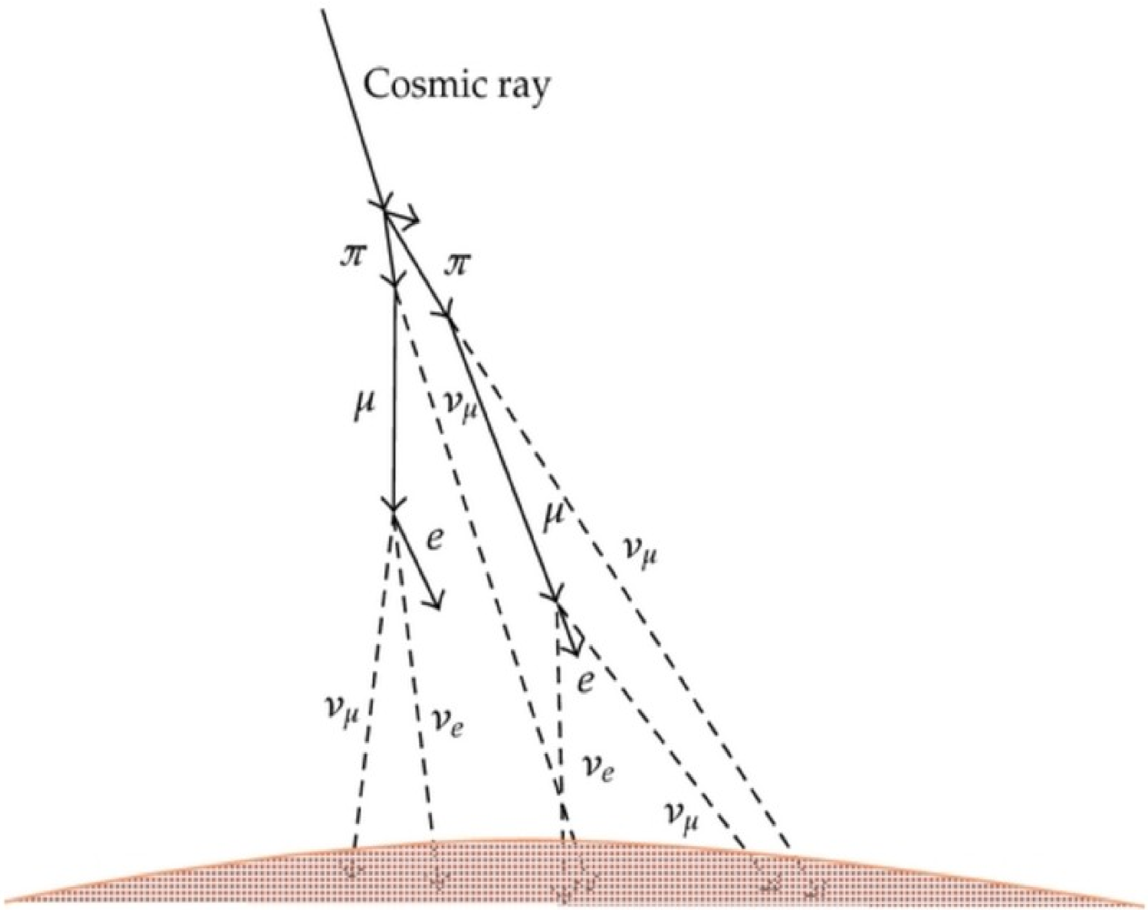
M is Planck mass, $\tilde{m}$ bulk mass of sterile, l is the distance between the two branes

y is Yukawa coupling

2. Froggatt-Nielsen Mechanism



T2K result of MH and CPV indication at 95% C.L.

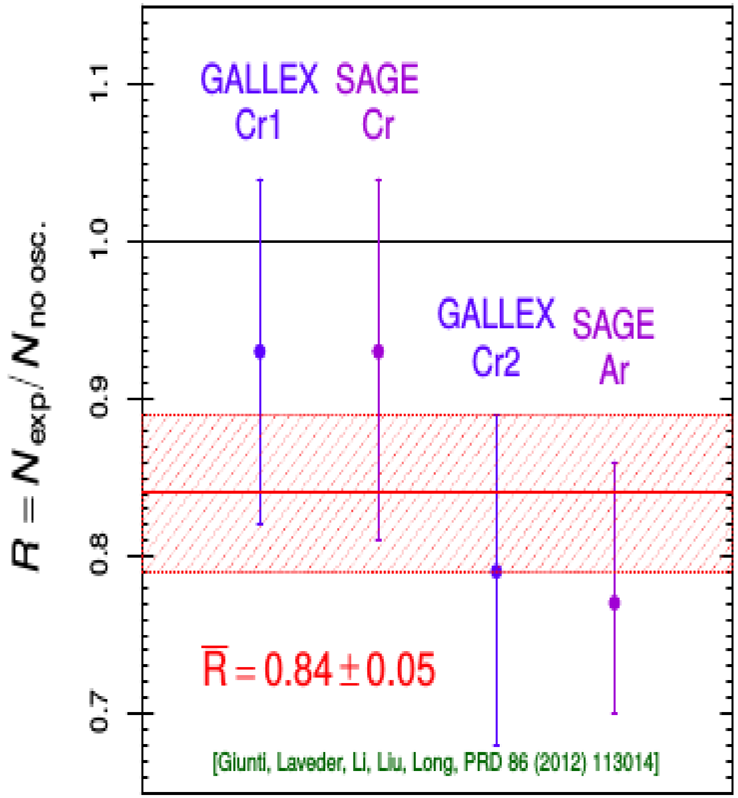

Cosmic ray
π
π
μ
ν_μ
μ
e
ν_μ
e
ν_μ
ν_e
ν_e
ν_μ

Gallium Anomaly

Two Gallium Experiments : GALLEX & SAGE

ν_e sources : $e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$

$e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$



Detection process : $\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$

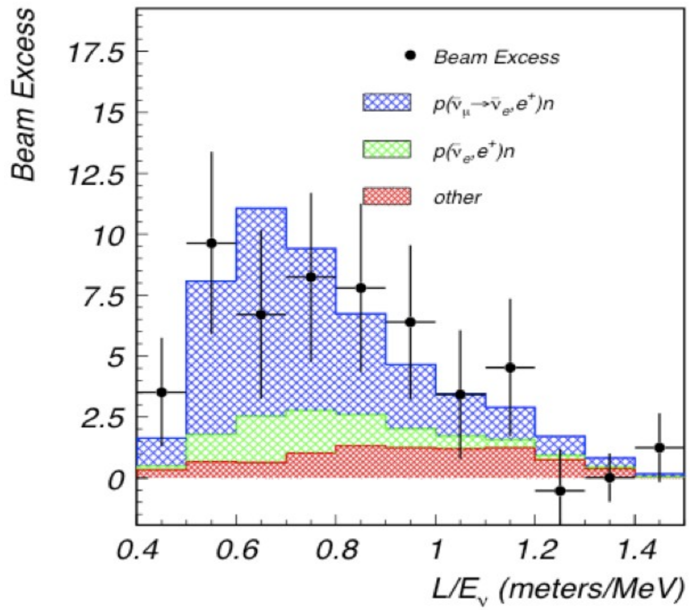
$\nu_e \to \nu_e$ Oscillation

$L \simeq 1\,m$, $E \simeq 1$ MeV, 2.9σ deficit

To explain it, one possibility may be $\Delta m^2 \approx 1\ eV^2$

SAGE PRC 73(2006) 045805; PRC 80 (2009) 015807
Laveder et al. Nucl. Phys. Proc. Suppl. 168 (2007) 344; MPLA 22 (2007) 2499;
PRD 78 (2008) 073009; PRC 83 (2011) 065504; PRD 86 (2012) 113014

LSND Anomaly



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation

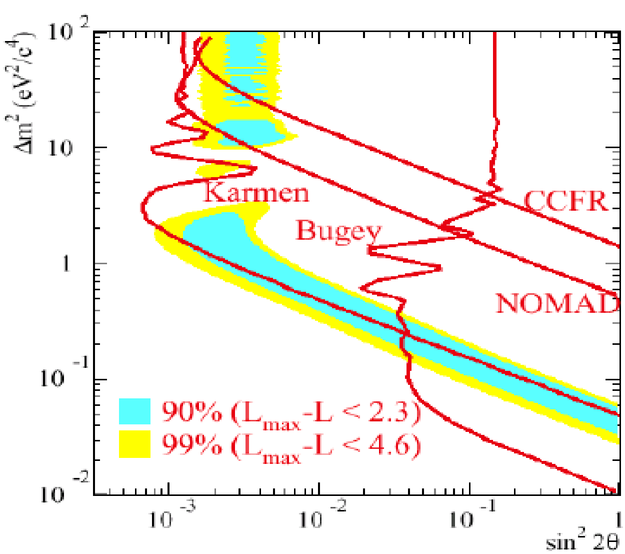
$L \simeq 30\ m,\ \ 20\ MeV \leqslant E \leqslant 60\ MeV$

Source : $\mu^+ (\text{rest}) \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Detection process : $\bar{\nu}_e + P \rightarrow n + e^+$

LSND observed an excess 3.9σ $\bar{\nu}_e$ events in $\bar{\nu}_\mu$ beam

The signal can be explained if $\Delta m^2 \gtrsim 0.1\ eV^2$

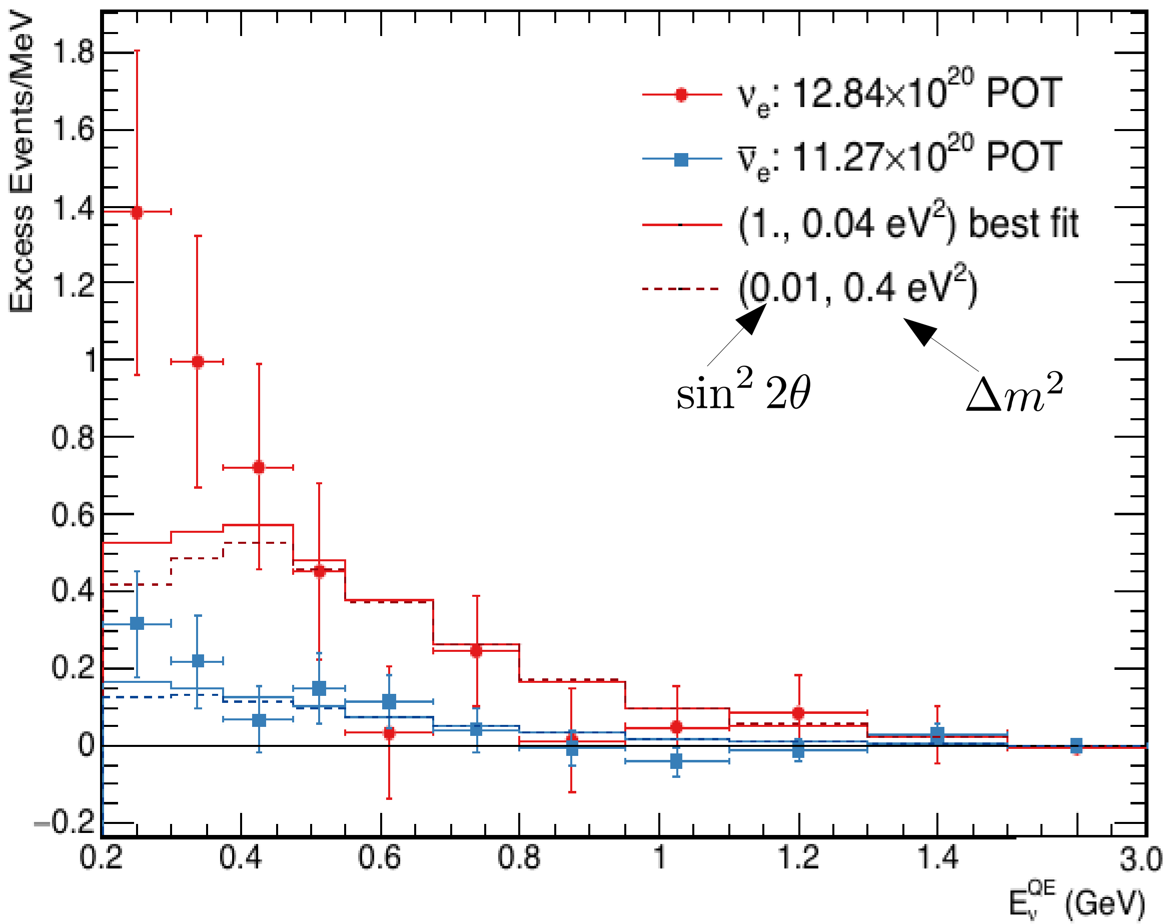


The Karmen (L ∼ 18 m) Collaboration did not see the same but could not exclude the entire allowed region.

A.Aguilar-Arevalo et al. [LSND Collb.], PRD 64 (2001) 112007

B.Armbruster et al. [KARMEN Collb.], PRD 65 (2002) 112001

MiniBooNE Anomaly



This expt. was dedicatedly Designed in Fermilab to test the LSND results.

Baseline ~ 540 m

$\nu_\mu \to \nu_e$ oscillation

$\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation

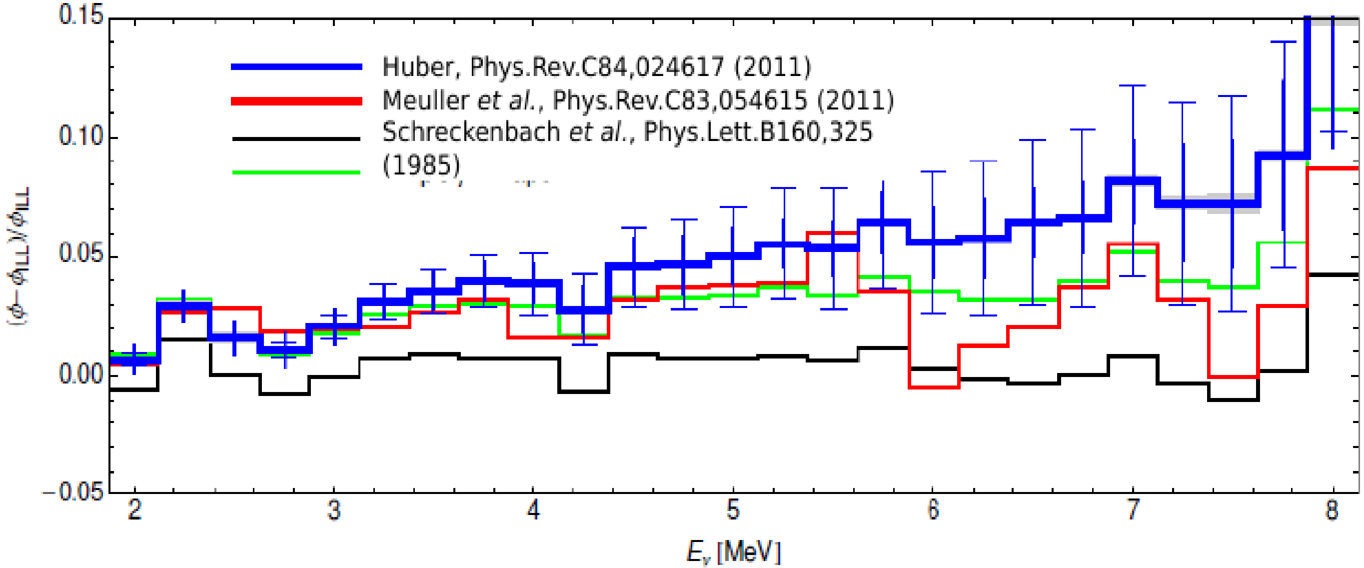
Please see 1805.12028

Observed 4.8σ excess events at low energy both for neutrino and antineutrino mode.

For other kind of explanation please see for example, 1808.02915 by P. Ballet, S. Pascoli, and M. Ross-Lonergan.
1807.09877 by E. Bertuzzo, S. Jana, P. Machado, and R. Funchal

Reactor Antineutrino Anomaly

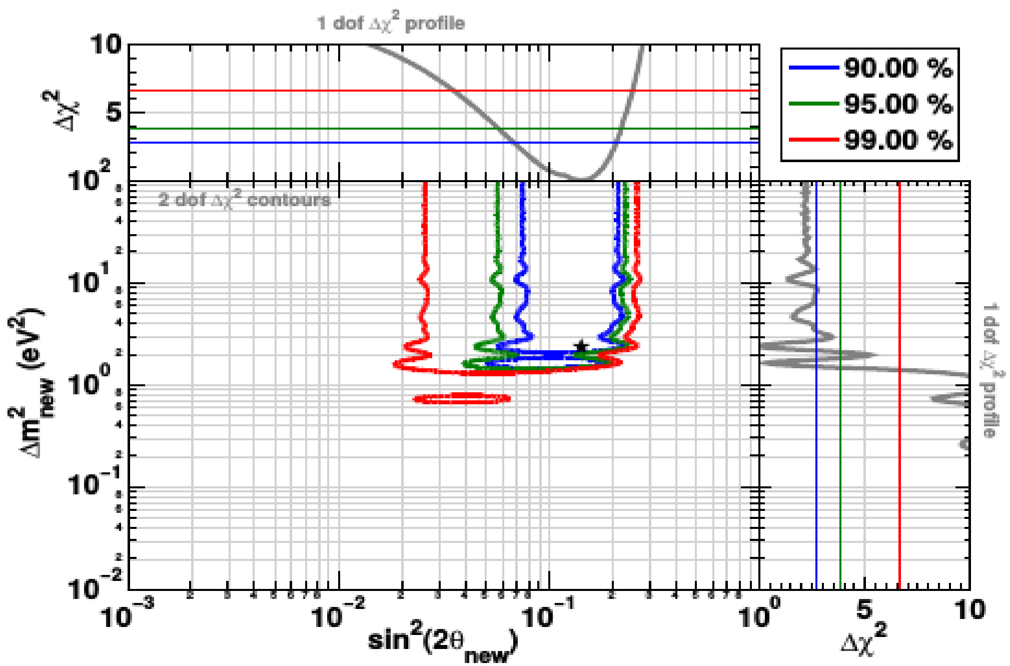
New analyses (blue and red) of the reactor $\overline{\nu}$e spectrum predict a 3% higher flux than the existing calculation (black).



There is almost 7% discrepancy between observed to expected event rates

Obs. events < expected

$\overline{\nu}_e \rightarrow \overline{\nu}_e$ oscillation



Require eV scale sterile neutrino to explain the anomaly

See "The reactor antineutrino anomaly" by G Mention

[J. Phys. :Conf. Ser. 408 (2013) 012025]

Theoretical framework for 3-flavor oscillation

The time evolution equation for the neutrino flavor eigenstates in vacuum is given by

$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix} = \frac{1}{2E}\left[U\begin{pmatrix}m_1^2 & 0 & 0\\0 & m_2^2 & 0\\0 & 0 & m_3^2\end{pmatrix}U^\dagger\right]\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix}$$

Similarly, the time evolution equation in matter is given by

$$i\frac{d}{dt}\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix} = \left[\frac{1}{2E}U\begin{pmatrix}m_1^2 & 0 & 0\\0 & m_2^2 & 0\\0 & 0 & m_3^2\end{pmatrix}U^\dagger + \begin{pmatrix}V_{CC}+V_{NC} & 0 & 0\\0 & +V_{NC} & 0\\0 & 0 & +V_{NC}\end{pmatrix}\right]\begin{pmatrix}|\nu_e\rangle\\|\nu_\mu\rangle\\|\nu_\tau\rangle\end{pmatrix}$$

$\mathrm{V}_{CC} = \sqrt{2}\,G_F\,N_e$ **Charge current potential for neutrino**

$\mathrm{V}_{NC} = -\frac{G_F\,N_n}{\sqrt{2}}$ **Neutral current potential for neutrino**

For antineutrino, $\mathrm{V}_{CC} \rightarrow -V_{CC}$ **and** $\mathrm{V}_{NC} \rightarrow -V_{NC}$