Exploring Light Sterile Neutrinos in Long-Baseline Experiments: Looking at the Future

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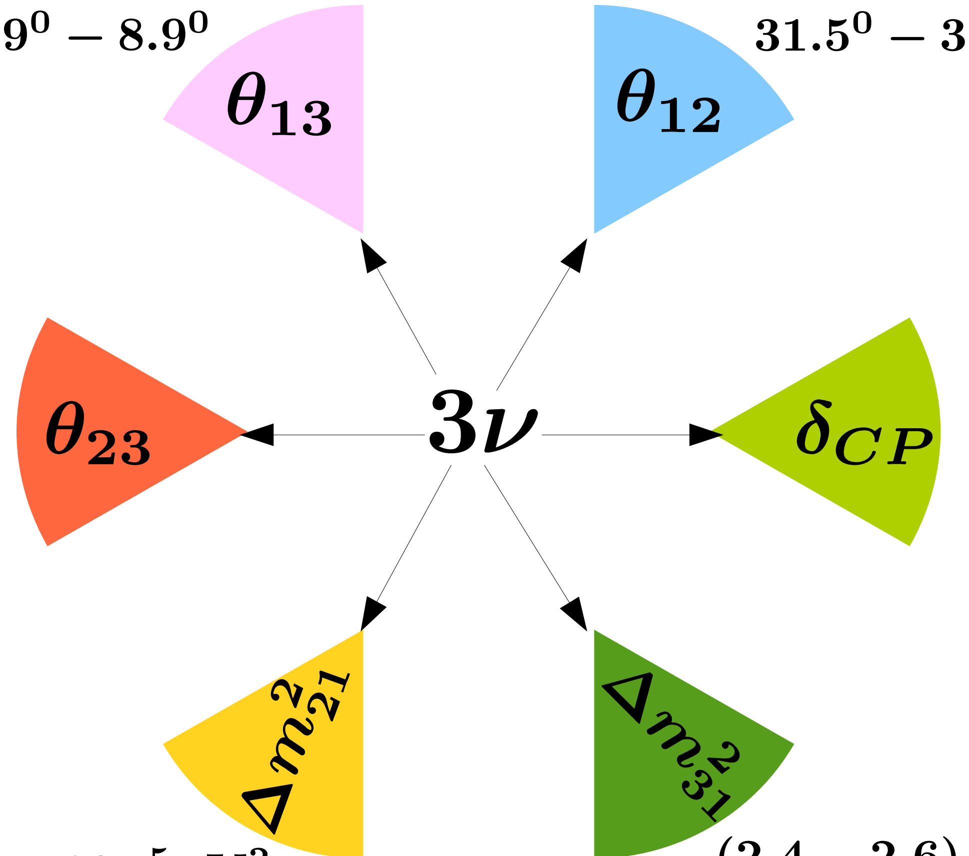
Current status of 3ν parameters (3σ uncertainties)

Known very precisely

$\mathbf{7.9^0 - 8.9^0}$

Known quite precisely

$\mathbf{31.5^0 - 38^0}$



Octant ambiguity

$\mathbf{38^0 - 53^0}$

Most unknown

May contribute to CP-violation

$\mathbf{0^0 - 360^0}$

Most unknown

$\mathbf{(7.05 - 8.14) \times 10^{-5}\,eV^2}$

Sign is +ve (m1 < m2)

$\mathbf{(2.4 - 2.6) \times 10^{-3}\,eV^2}$

Sign is unknown

+ve: Normal hierarchy
-ve: Inverted hierarchy

arXiv:1708.01186 by P. Salas, D. V. Forero, C. Ternes, M. Tortola & J. W. F. Valle

We know that the probability of oscillation from one flavor to another flavor with neutrino energy E and baseline L, can be written as

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2 \frac{\Delta_{ij}}{2}$$

$$+2\sum_{i>j} \Im\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin \Delta_{ij}$$

Where, $\Delta_{ij} = \frac{\Delta m^2_{ij} L}{2E}$ Oscillation driving term

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

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

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

Hints for eV scale sterile neutrino

We have seen that the oscillation probability

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

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

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

This mass squared splitting is much bigger than the two existing Solar (7.5×10^{-5} eV^2) and atmospheric (2.4×10^{-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.

See talk by Samiran Roy

Theoretical Framework for Sterile Neutrino

In presence of a sterile neutrino, the effective Hamiltonian becomes

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

$V_{CC} = \pm\sqrt{2}G_F N_e$ **+(-) : charge current potential for neutrino (antineutrino)**

$V_{NC} = \pm G_F N_n / \sqrt{2}$ **+(-) : neutral current potential for neutrino (antineutrino)**

$\Delta m_{21}^2, \Delta m_{31}^2, \Delta m_{41}^2$ are the independent mass squared difference in 3+1 sector

For details of neutral current effect, see talk by Suprabh

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

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

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

3ν → Mixing angles (3)

3ν → Phases (Dirac + Majorana) (1 + 2)

4ν → Mixing angles (6)

4ν → Phases (Dirac + Majorana) (3 + 3)

Appearance Probability ($P_{\mu e}^{4\nu}$) in Vacuum

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

[For SBL review, please see arXiv: 1609.04688 by Carlo Giunti]

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

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

$$\mathrm{P}_0^{ATM} \simeq 4 s_{13}^2 s_{23}^2 \sin^2\Delta \quad \sim O(\varepsilon^2)$$

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

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

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

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

See Klop & Palazzo; PRD 91 (2015) 073017

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

Matter Effect

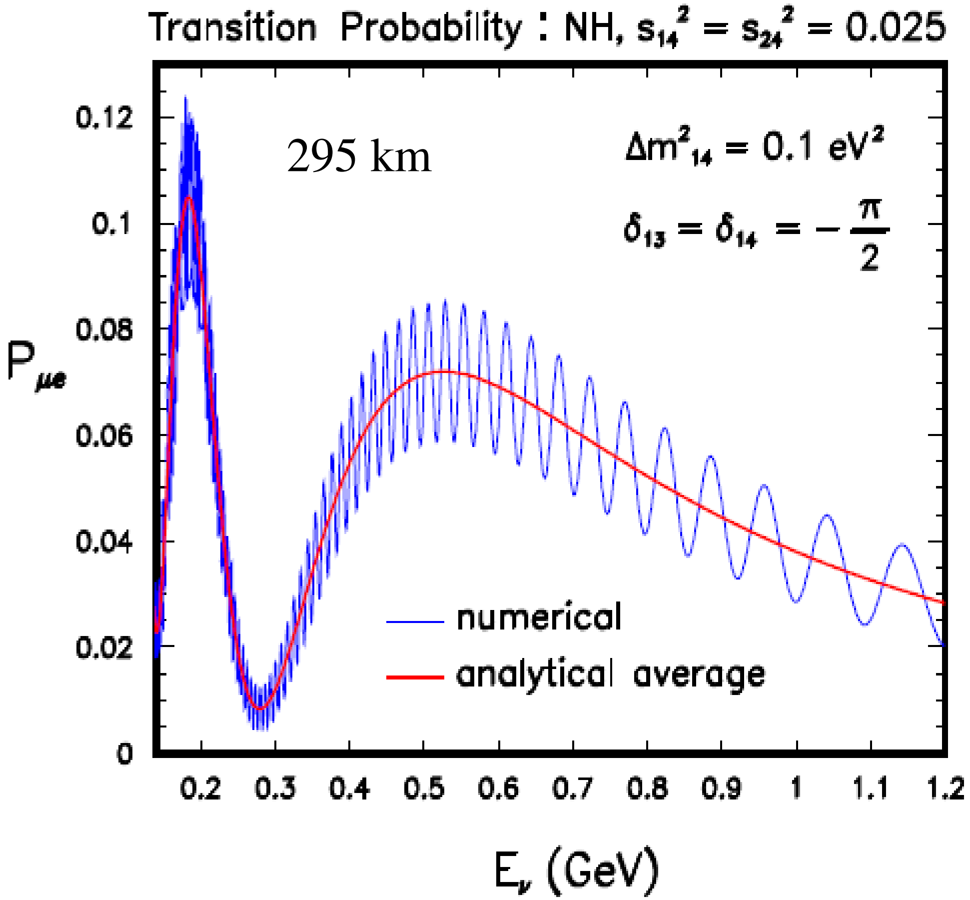
In presence of matter, the leading term in transition probability $P\left(\nu_\mu \rightarrow \nu_e\right)$ modified as (upto third order)

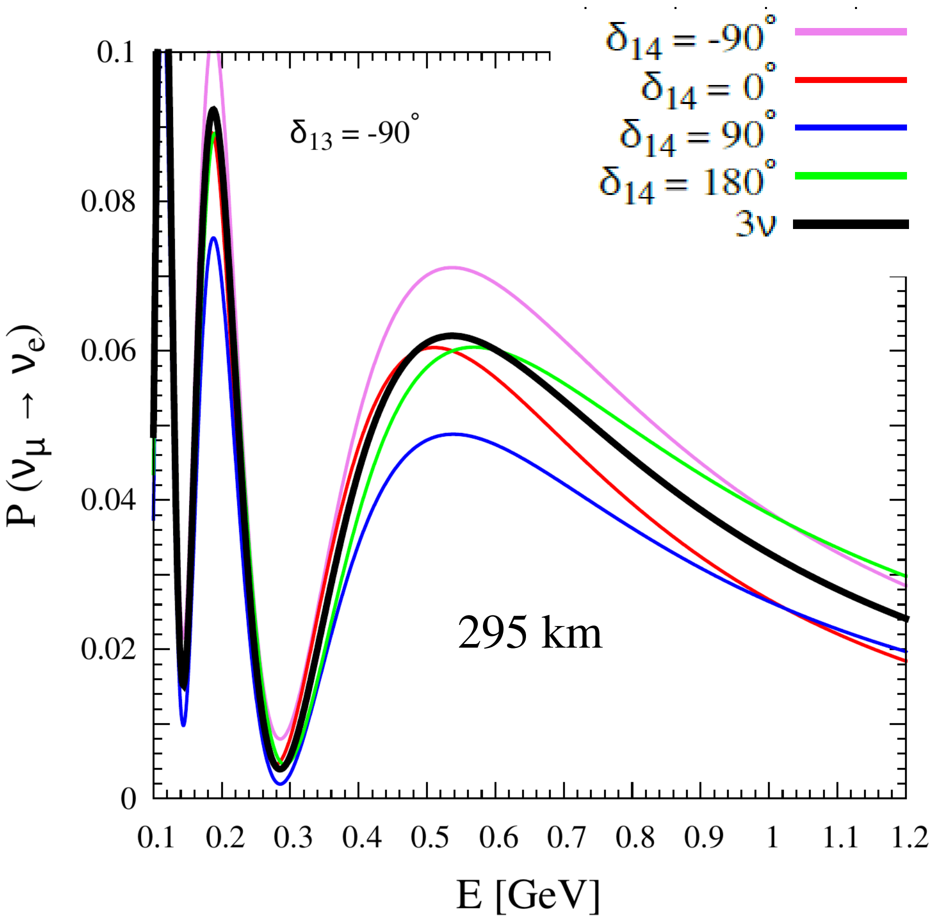
$$P_{\mathrm{m}}^{\mathrm{ATM}} \simeq (1+2\mathrm{k})\, P_{0}^{\mathrm{ATM}}$$

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

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

$$P_m^{ATM} \simeq (1+2k)\, P^{ATM}$$

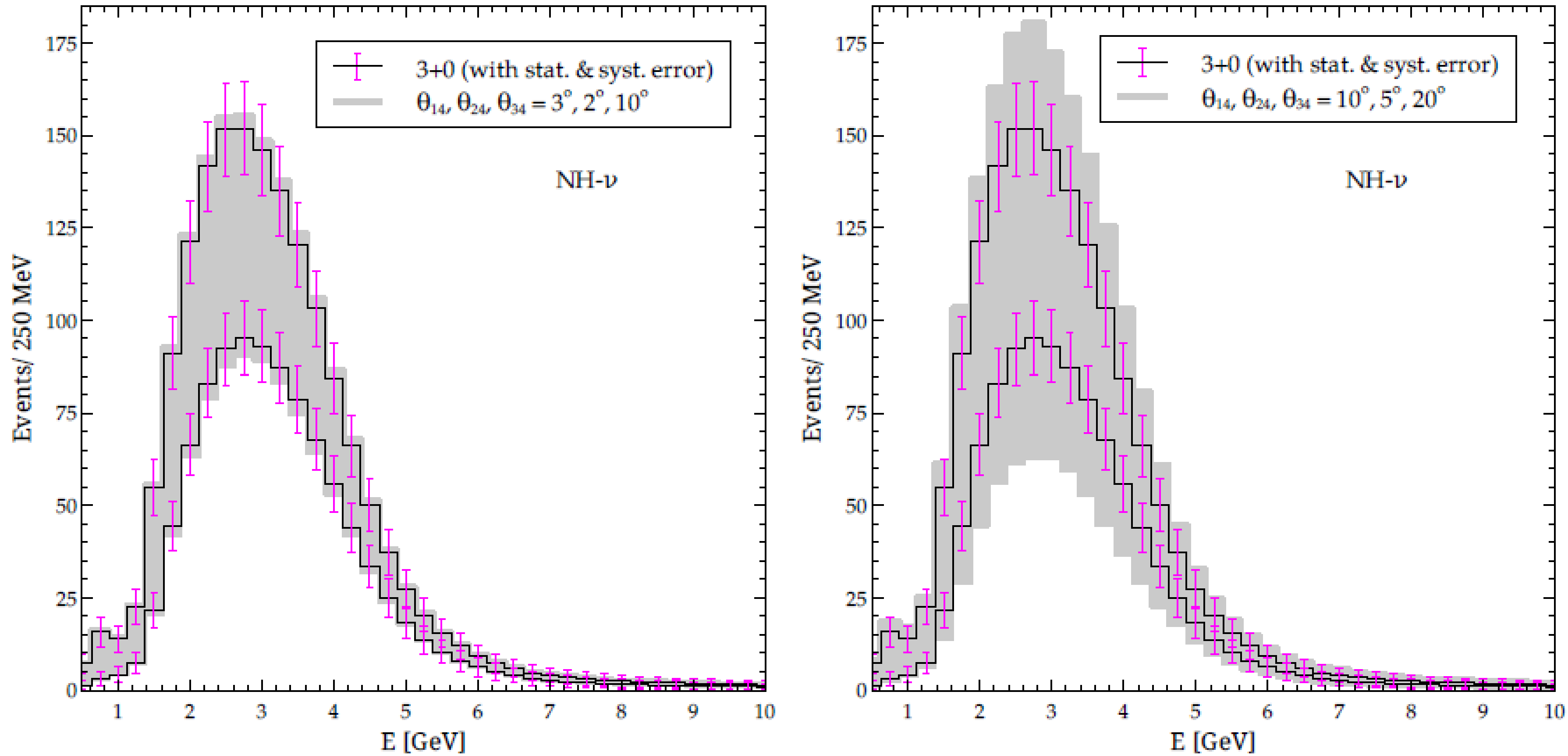




Though the oscillation driven by Δm^2_{41} gets averaged out, it may have high impact at far detector.

Phys.Rev. D91 (2015) no.7, 073017 by Klop & Palazzo,
JHEP 1602 (2016) 111 by Agarwalla, SSC, and Palazzo

DUNE spectra



JHEP 1611 (2016) 122 by D. Dutta, R. Gandhi, B. Kayser, M. Masud, and S. Prakash

Brief description of Long-Baseline Set-ups

Light sterile neutrinos in the context of T2K, T2HK, NOvA, and DUNE.

A rough idea

T2K (Tokai to Kamioka)	
Baseline	295 KM
Detector mass	22.5 Kt
Run time $\nu : \bar{\nu}$	2.5 yrs + 2.5 yrs
Proton Energy	30 GeV
Beam Power	750 KW
Total POT / yr	1.56×10^{21}
Signal app. error	5%
Signal disapp. error	5%
Background app. error	10%
Background disapp. error	10%

NOvA (Fermilab to Minnesota)	
Baseline	810 KM
Detector mass	14 Kt
Run time $\nu : \bar{\nu}$	3 yrs + 3 yrs
Proton Energy	120 GeV
Beam Power	700 KW
Total POT / yr	3×10^{20}
Signal app. error	5%
Signal disapp. error	5%
Background app. error	10%
Background disapp. error	10%

DUNE (Fermilab to South Dakota)	
Baseline	1300 KM
Detector mass	35 Kt
Run time $\nu : \bar{\nu}$	5 yrs + 5 yrs
Proton Energy	120 GeV
Beam Power	708 KW
Total POT / yr	6×10^{20}
Signal app. error	5%
Signal disapp. error	5%
Background app. error	5%
Background disapp. error	5%

T2HK, T2HK-JD, T2HK-KD	
Baseline	295, 295, 1100 KM
Detector mass	560, 187, 187 Kt
Run time $\nu : \bar{\nu}$	2.5 yrs + 7.5 yrs
Proton Energy	30 GeV
Beam Power	750 KW
Total POT / yr	1.56×10^{22}
Signal app. error	5%
Signal disapp. error	5%
Background app. error	5%
Background disapp. error	5%

Benchmark values of the oscillation parameters used for our analysis

$$\sin^2\theta_{12} = 0.304$$
$$\sin^2 2\theta_{13} = 0.025$$
$$\sin^2\theta_{23} = 0.42(0.58)\, as\, LO(HO)$$
$$\sin^2\theta_{14} = 0.025$$
$$\sin^2\theta_{24} = 0.025$$
$$\sin^2\theta_{34} = 0,\ 0.025, 0.25$$
$$\delta_{13} = -\pi\, to\, \pi$$
$$\delta_{14} = -\pi\, to\, \pi$$
$$\delta_{34} = -\pi\, to\, \pi$$
$$\Delta m^2_{21} = 7.5 \times 10^{-5}\, eV^2$$
$$\Delta m^2_{31} = 2.4 \times 10^{-3}\, eV^2$$
$$\Delta m^2_{41} = 1.0\, eV^2$$

JHEP 1305 (2013) 050 by J. Kopp, P. Machado, M. Maltoni, & T. Schwetz

arXiv:1708.01186 by P. Salas, D. V. Forero, C. Ternes, M. Tortola & J. W. F. Valle

JHEP 1701 (2017) 087 by I. Esteban, Gonzalez-Garcia, M. Maltoni, I. Soler, & T.Schwetz

Nucl.Phys. B908 (2016) 218-234 by F. Capozzi, E. Lisi, A. Marrone, D. Montanino & A. Palazzo

JHEP 1711 (2017) 099 by M. Dentler, A. Cabezudo, J. Kopp, M. Maltoni, T. Schwetz

Impact of sterile neutrino on the octant resolution

The vacuum survival Probability $\nu_\mu \rightarrow \nu_\mu$ 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

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

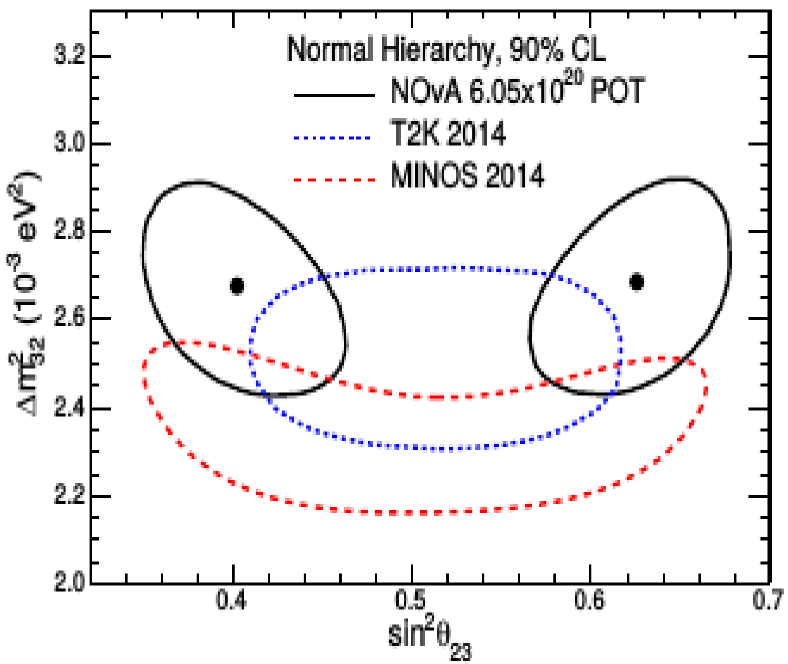
$$P_{\mu\mu}(\theta_{23}) = P_{\mu\mu}(\pi/2 - \theta_{23})$$

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

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

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

PRL 118 (2017) no.15, 151802



There are two solutions, called Octant degeneracy

Our goal here is to see the capability of an experiment to distinguish between the two octants in presence of a sterile neutrino.

The appearance Probability $\nu_\mu \rightarrow \nu_e$ 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

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

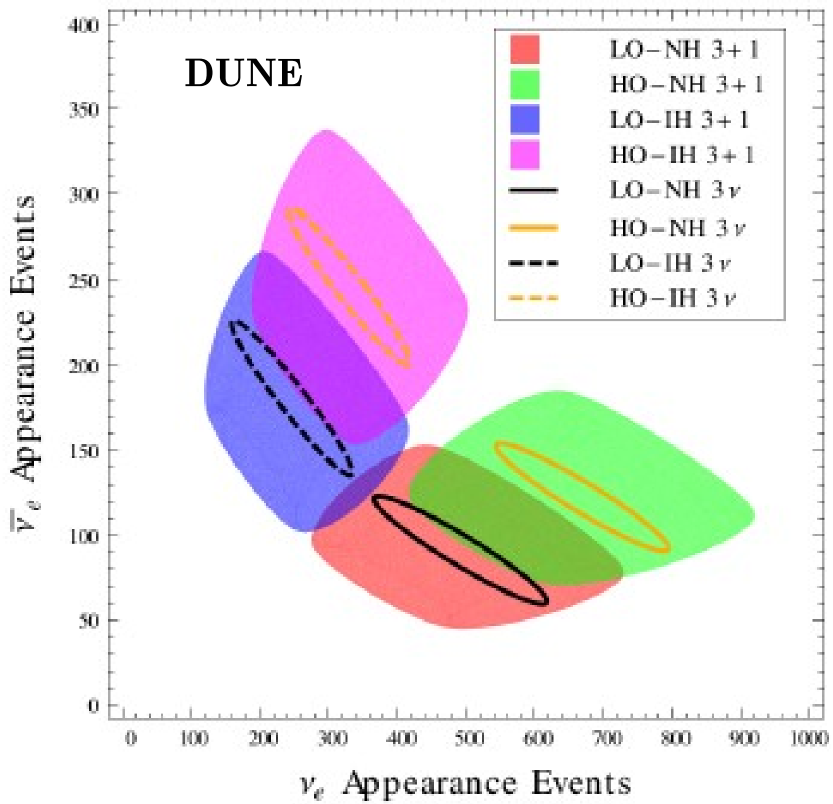
We can rewrite θ_{23} as, $\theta_{23} = \pi/4 \pm \eta$

+ (-) 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, there is still a difference between the probabilities in the two octants, i.e.,

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

Bi-events convoluted plot



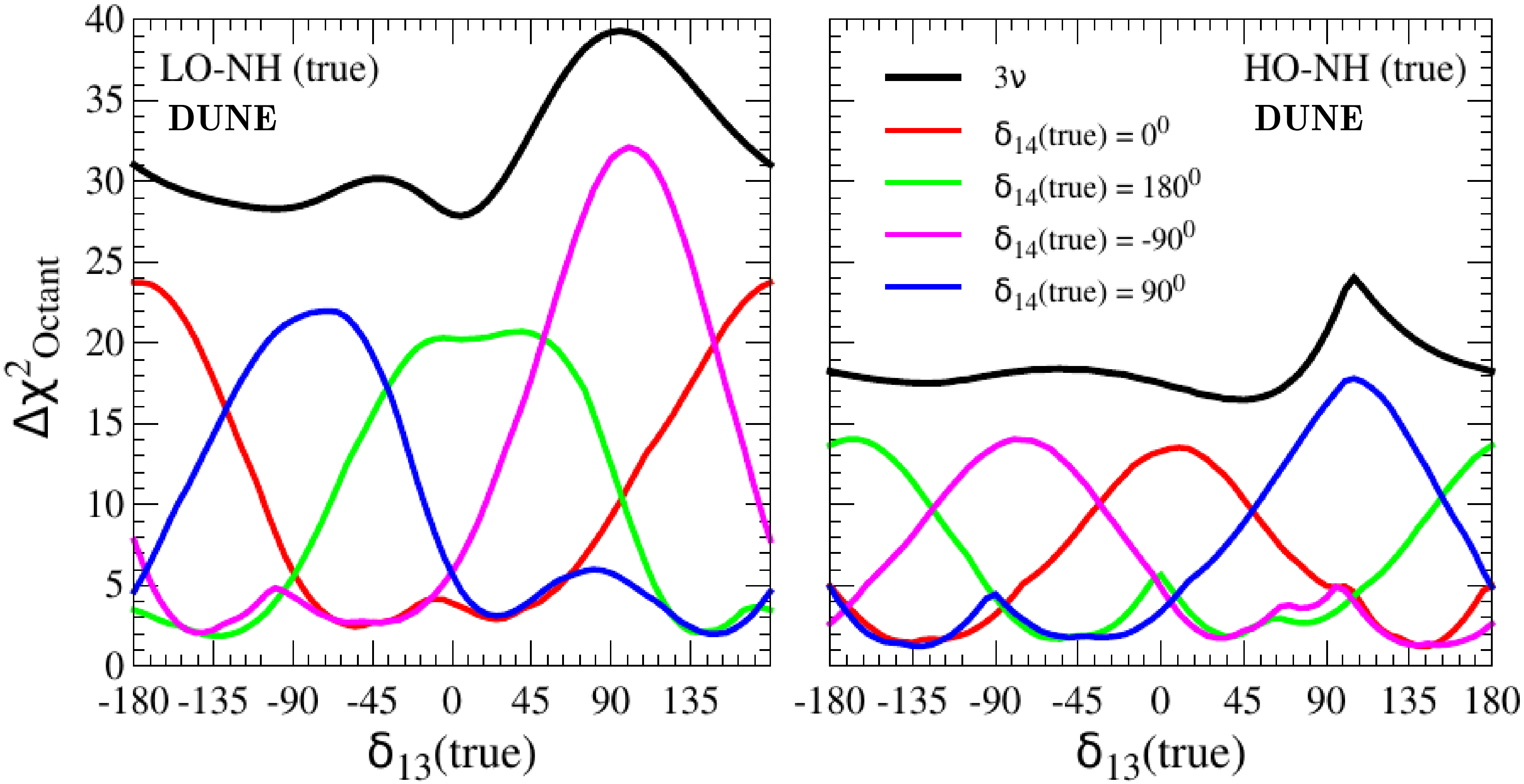
$\sin^2\theta_{23}(\text{true}) = 0.42(0.58)$ as LO(HO)

In 3+1, ellipses becomes blobs. color blobs are the convolution of different combinations of δ_{13} & δ_{14}

Phys.Rev.Lett. 118 (2017) no.3, 031804
by Agarwalla, SSC, and Palazzo

An experiment is sensitive to an octant if it can exclude the wrong octant provided the true data is generated with the right octant.

$\sin^2\theta_{23}(\text{true}) = 0.42(0.58)$ as LO(HO) $\quad \boldsymbol{\theta_{14} = \theta_{24} = 9^0}$

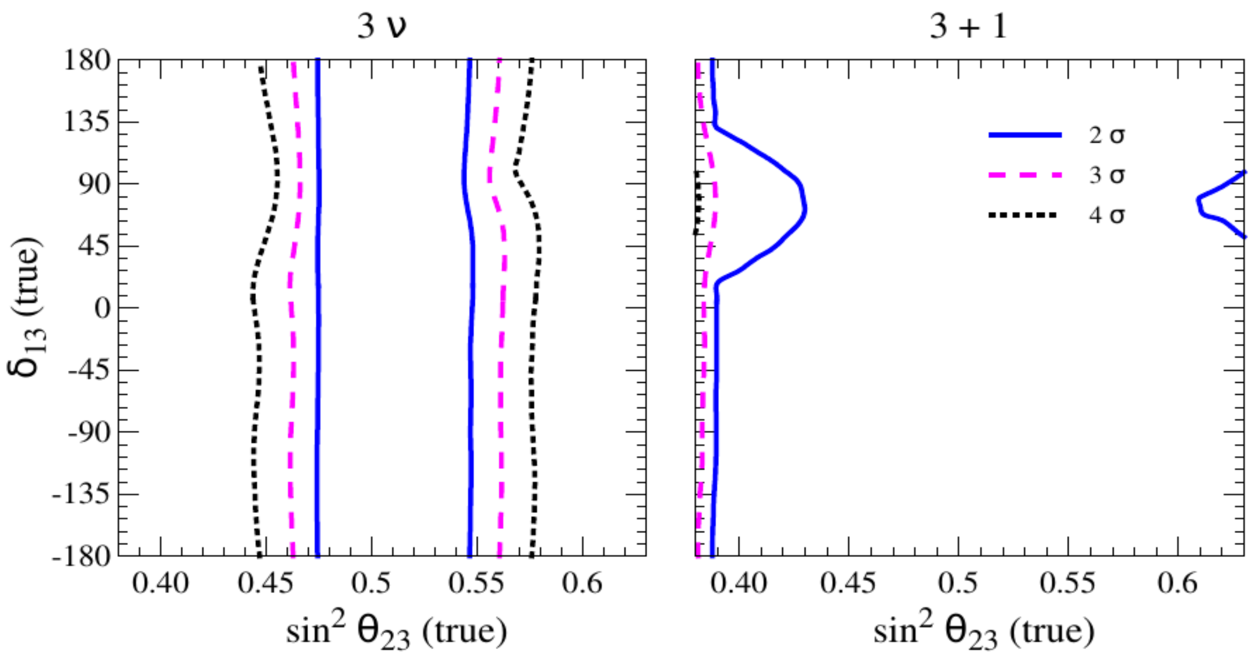


$$\Delta\chi^2_{\mathbf{octant}} = \chi^2_{\mathbf{test\ octant}} - \chi^2_{\mathbf{true\ octant}}$$

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

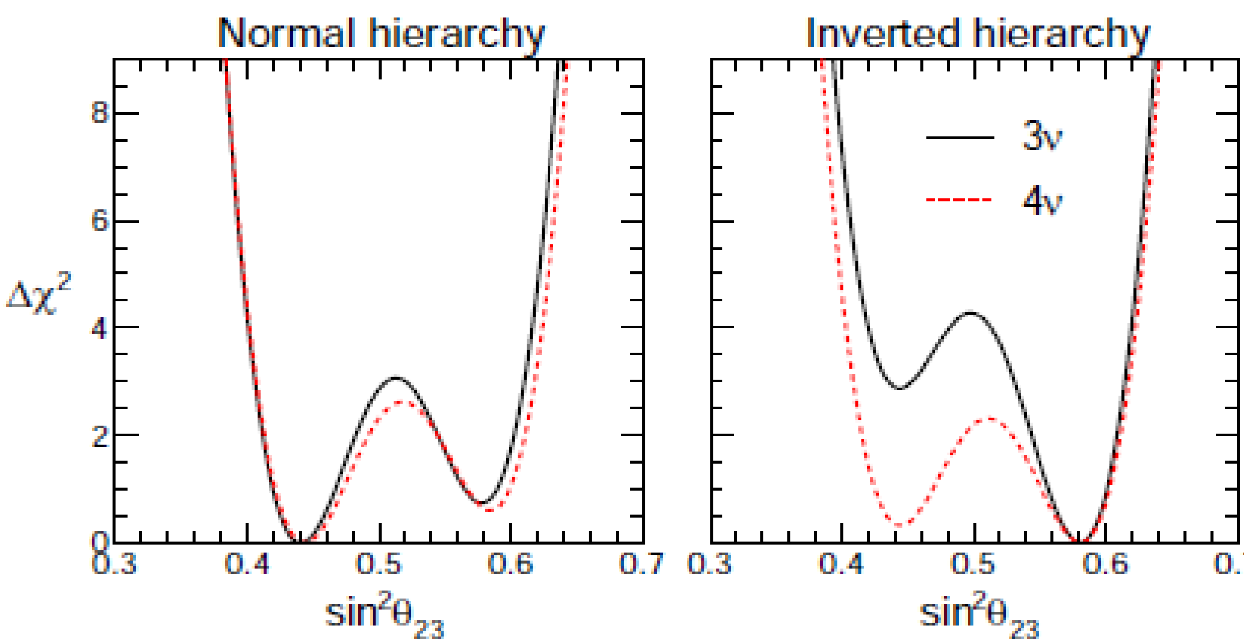
$\boldsymbol{\theta_{34} = 0}$ **considered in both true and test**

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



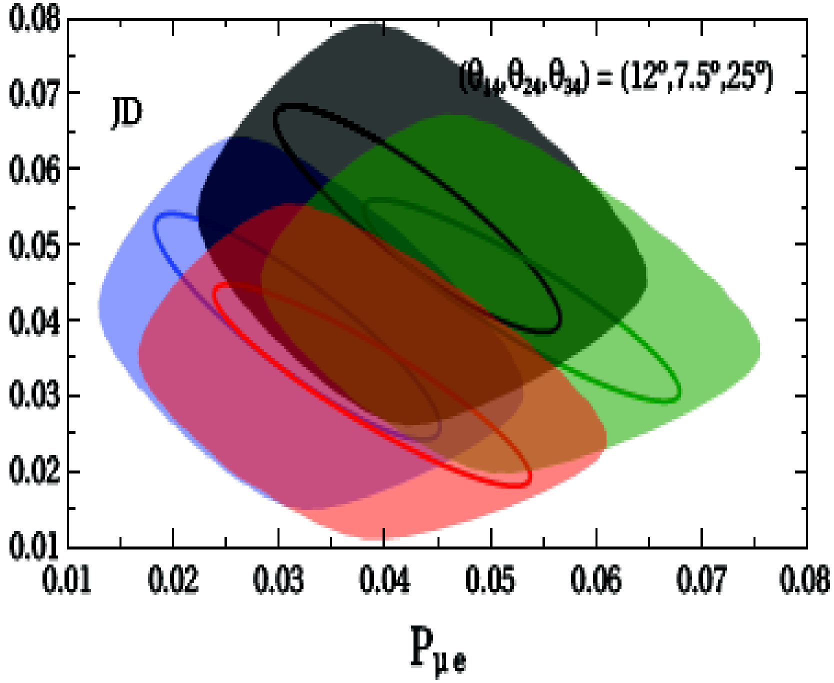
In 3+1, the sensitivity to the octant of θ_{23} gets lost.

Phys.Rev.Lett. 118 (2017) no.3, 031804 by Agarwalla, SSC, and Palazzo



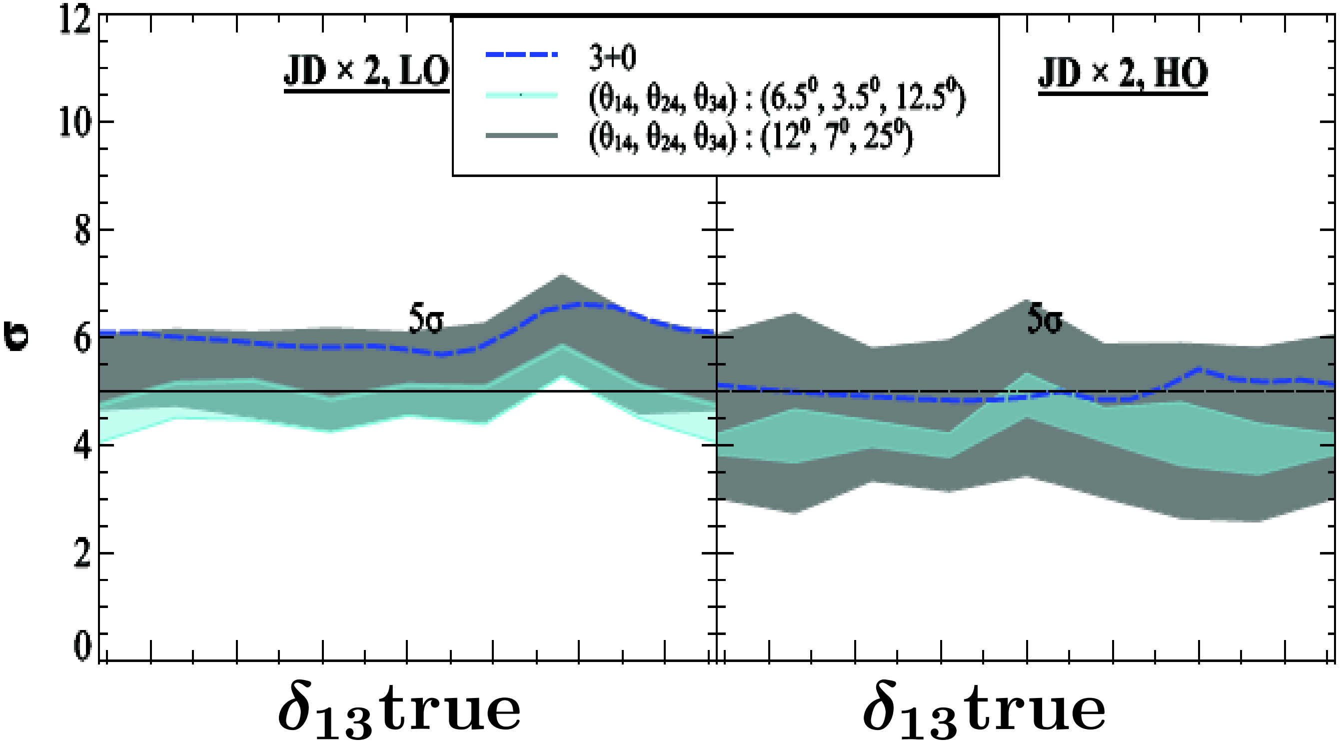
Phys.Rev. D95 (2017) no.3, 033006 by Capozzi, Giunti, Lavedar, and Palazzo

Phys.Rev.Lett. 118 (2017) no.3, 031804 by Agarwalla, SSC, and Palazzo

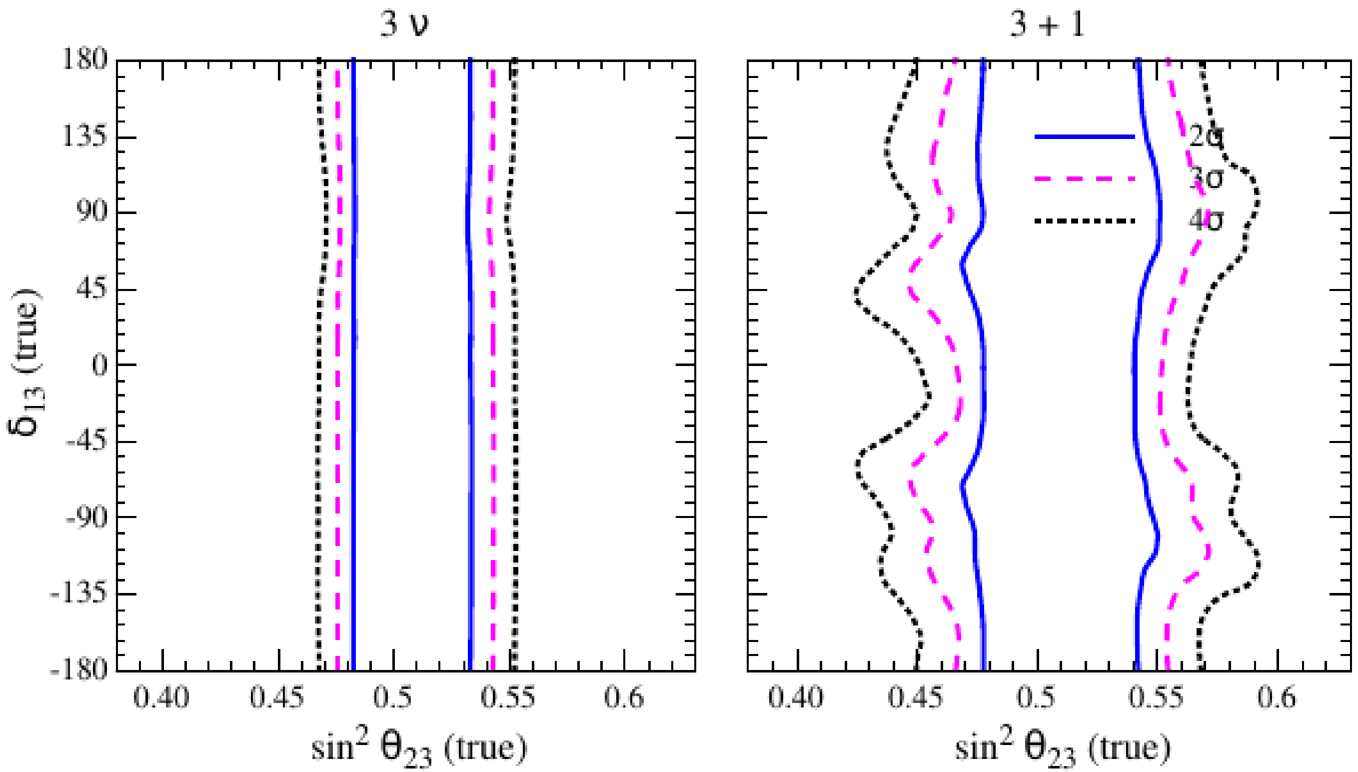


Octant discrimination sensitivity decreases substantially in 3+1 sector compare to 3+0 case

Phys.Rev. D96 (2017) no.5, 056026 by Choubey, Dutta, and Pramanik



T2HK



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

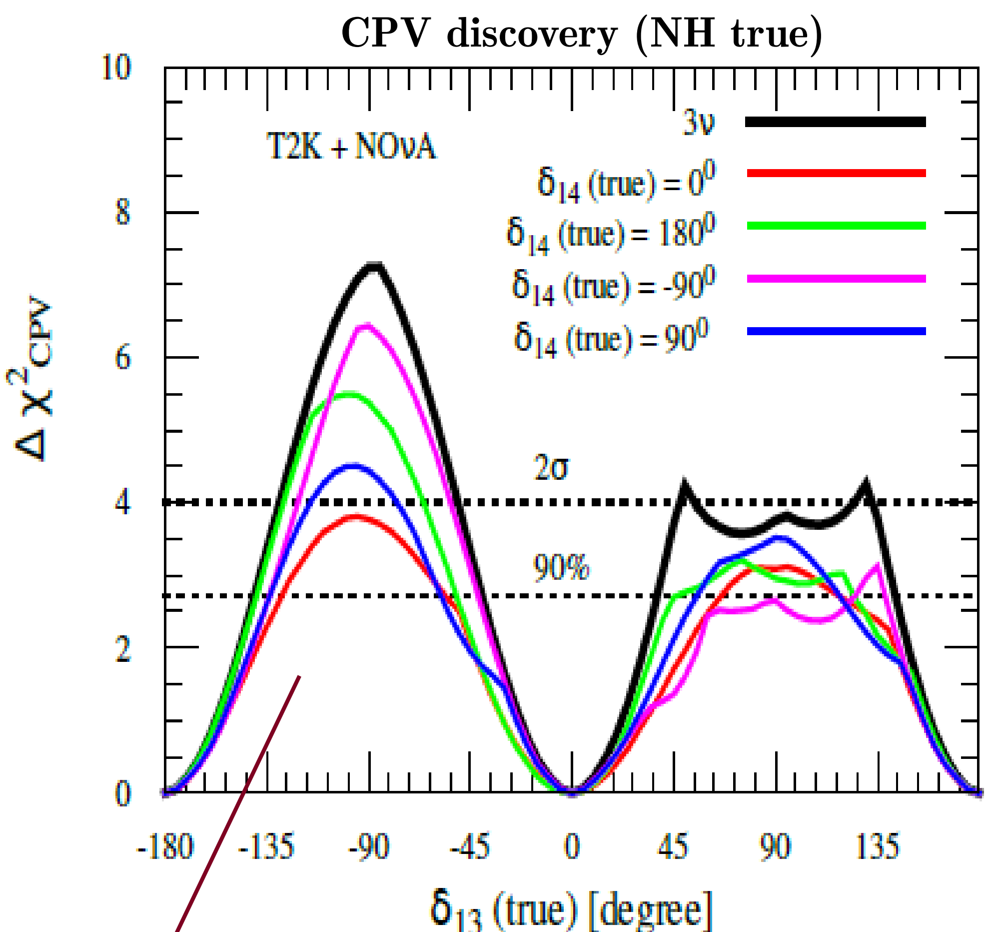
We assume δ_{14} is known very precisely in nature

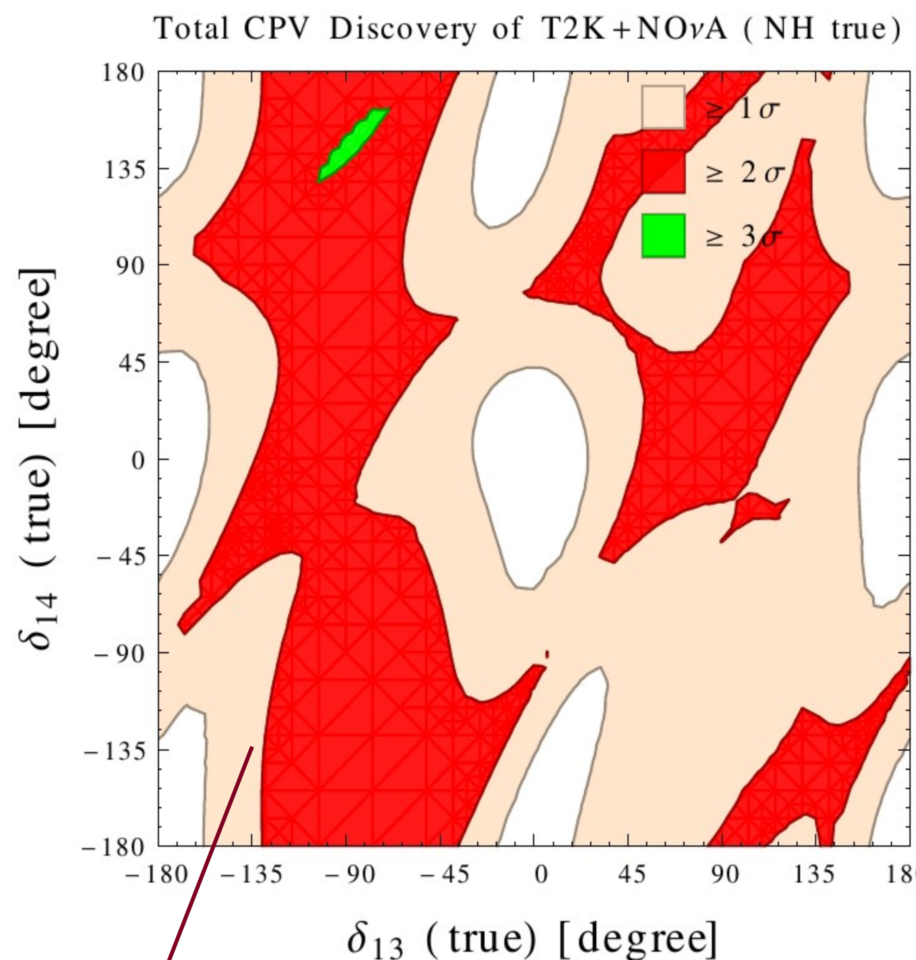
Not so realistic. Difficult task to pin point δ_{14} precisely.

A long way to go !

CP-violation Searches 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., $\delta_{13}\,(\text{test}) = 0, \pm\pi$





Source of CPV known

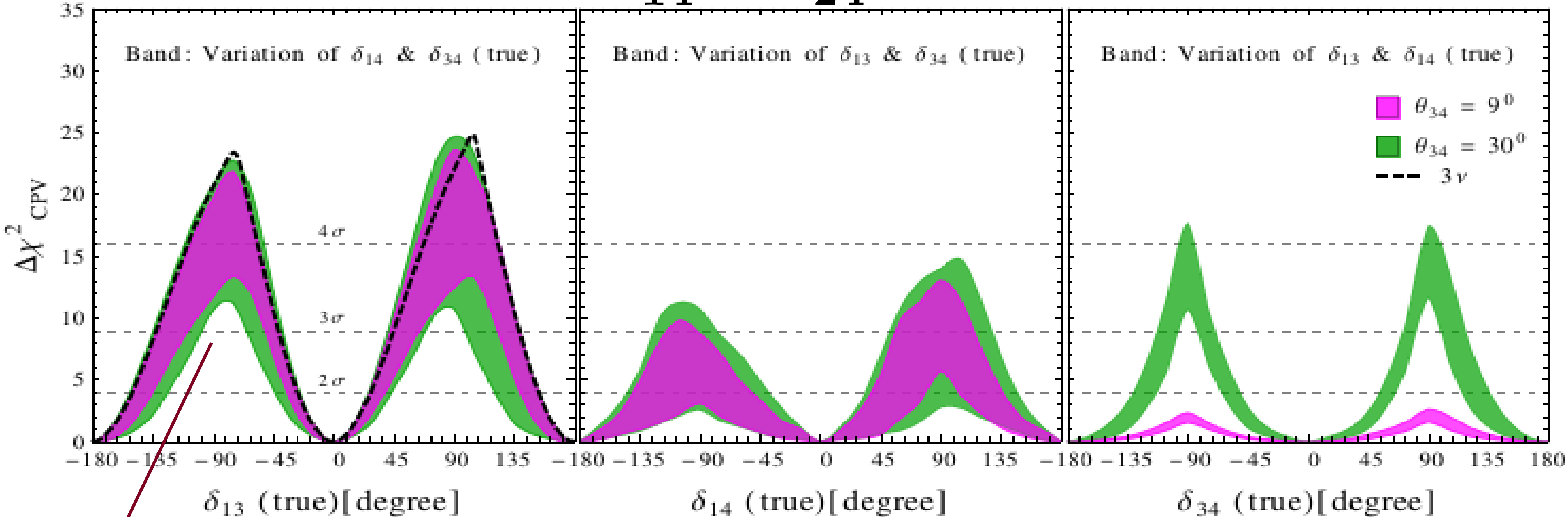
Source of CPV unknown

$$\Delta\chi^2_{\rm CPV} = \chi^2\left[\delta_{13}(\text{true})\right] - \chi^2\left[\delta_{13}(\text{test}) = 0, \pm\pi\right]$$

JHEP 1602 (2016) 111 by Agarwalla, SSC, Palazzo

CPV Discovery potential at DUNE

$$\theta_{14} = \theta_{24} = 9^0$$

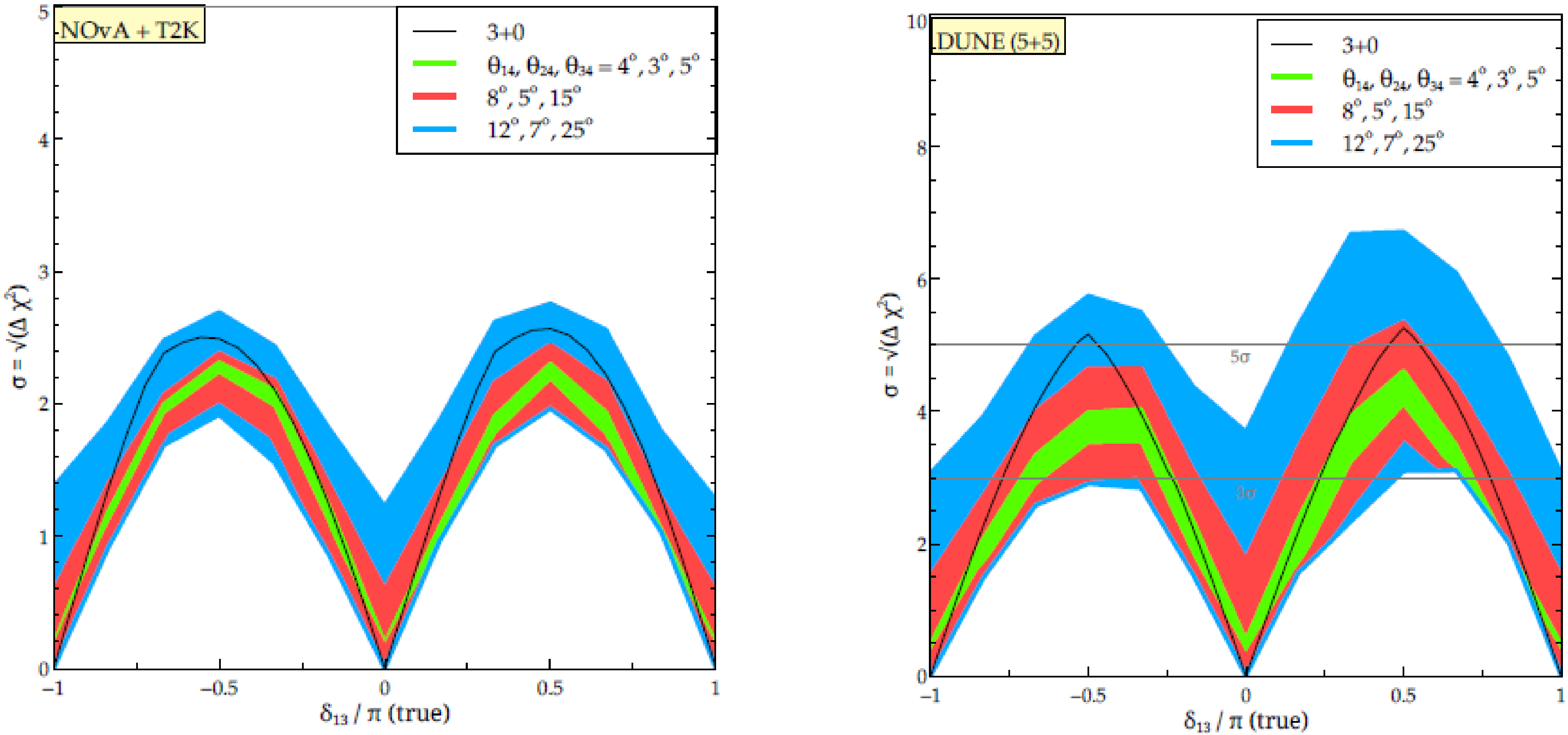


Source of CPV known

	θ_{34}	$N\sigma_{min}$ [δ_{13}(true) = -90^0]	CPV coverage (3σ)
3ν		4.5	50.0%
3+1	0^0	3.9	43.2%
	9^0	3.4	32.0%
	30^0	3.3	16.0%

induced by δ_{13}

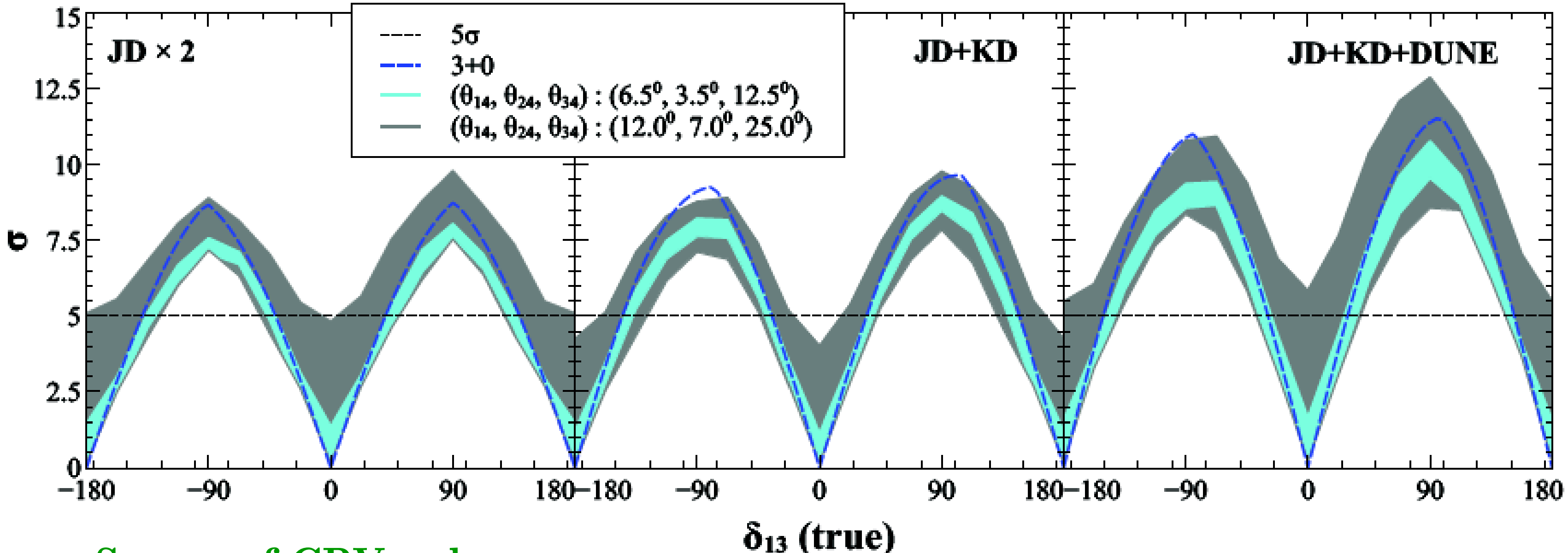
JHEP 1609 (2016) 016 by Agarwalla, SSC, and Palazzo



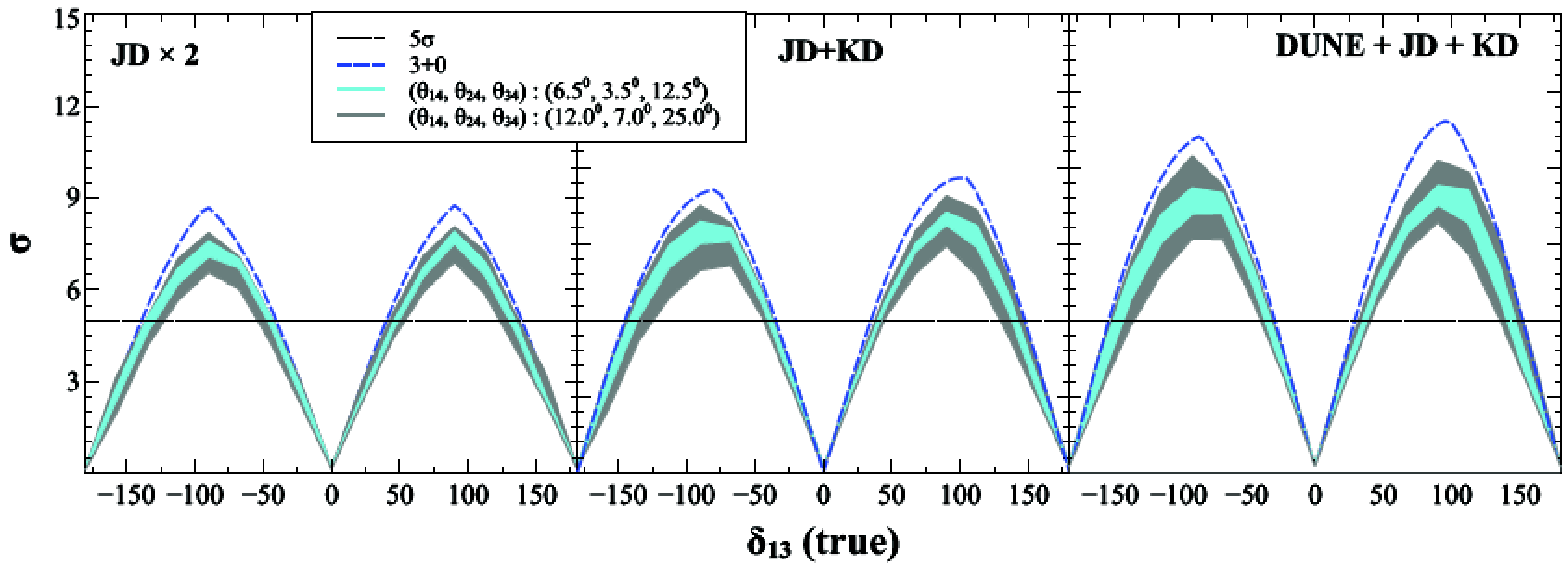
Source of CPV is unknown

JHEP 1511 (2015) 039 by Gandhi, Kayser, Masud, and Prakash

T2HK + DUNE analysis



Source of CPV unknown



Source of CPV known

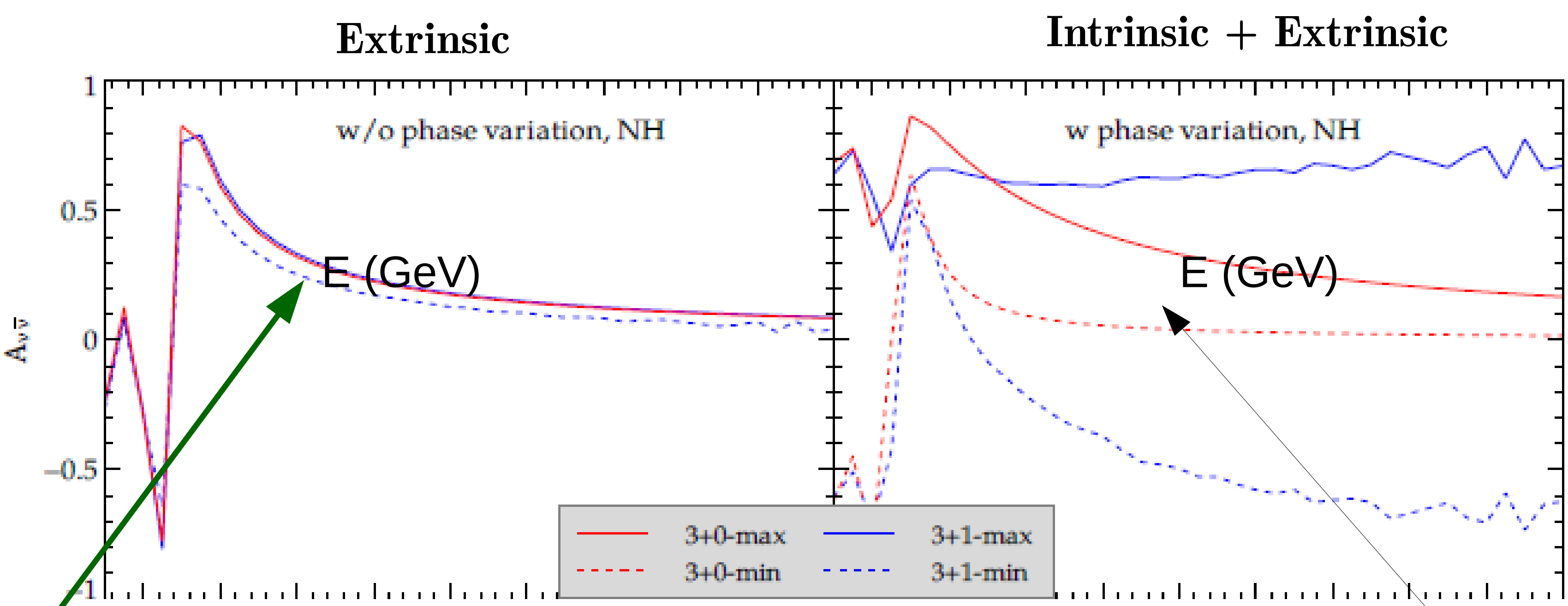
Phys.Rev. D96 (2017) no.5, 056026 by Choubey, Dutta, and Pramanik

CP-Asymmetry

$$\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e}.$$ 3 + 0 sector

$\Delta P_{\alpha\beta}$: $\Delta P_{e\mu}$, $\Delta P_{\mu\tau}$, $\Delta P_{\tau e}$, ΔP_{es}, $\Delta P_{\mu s}$ and $\Delta P_{\tau s}$ 3 + 1 sector

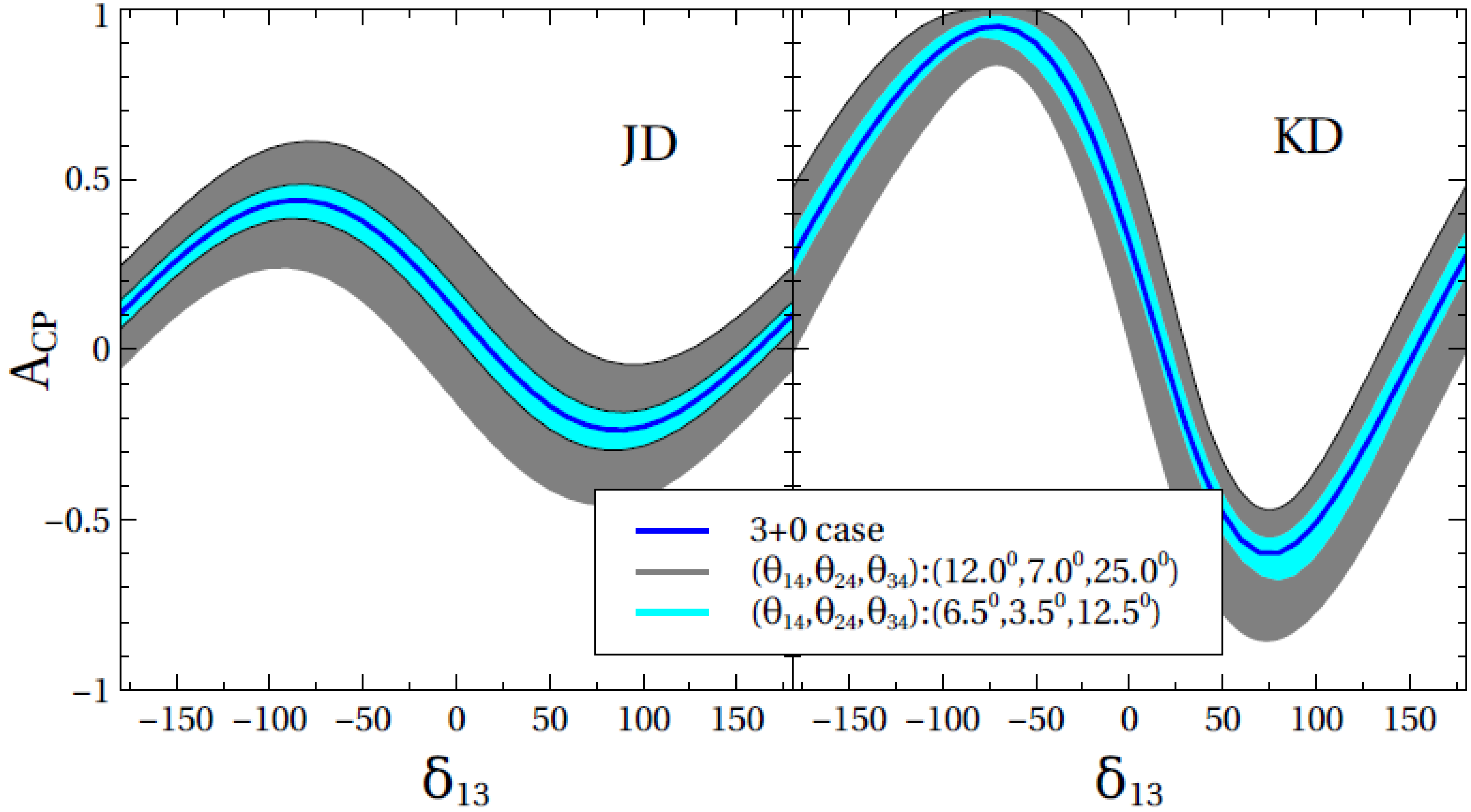
$$\Delta P_{e\mu} = \Delta P_{\mu\tau} + \Delta P_{\mu s}.$$ 3 + 1 sector



Cant conclude no leptonic CPV for 3+1 even within the band

degeneracy

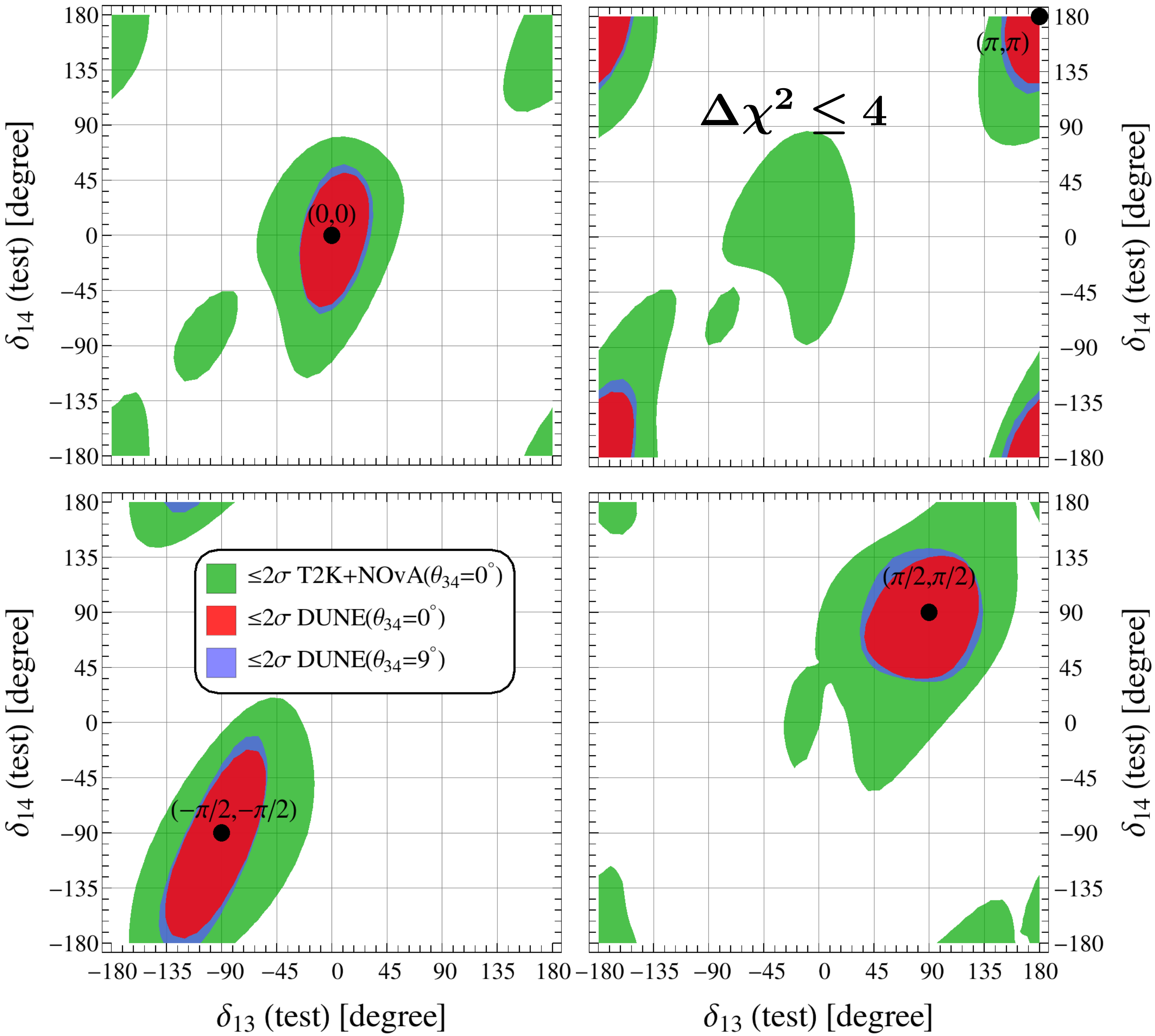
JHEP 1511 (2015) 039 by Gandhi, Kayser, Masud, and Prakash



Reference: Phys.Rev. D96 (2017) no.5, 056026 by Choubey, Dutta, and Pramanik

CP-reconstruction

How well we can measure the CP-phases in presence of sterile neutrino irrespective of any CP-violation



Black dot denotes the true choice

$\theta_{34} = 0$
has been considered here

Free Parameters :
$\theta_{23}, \delta_{13}, \delta_{14}$

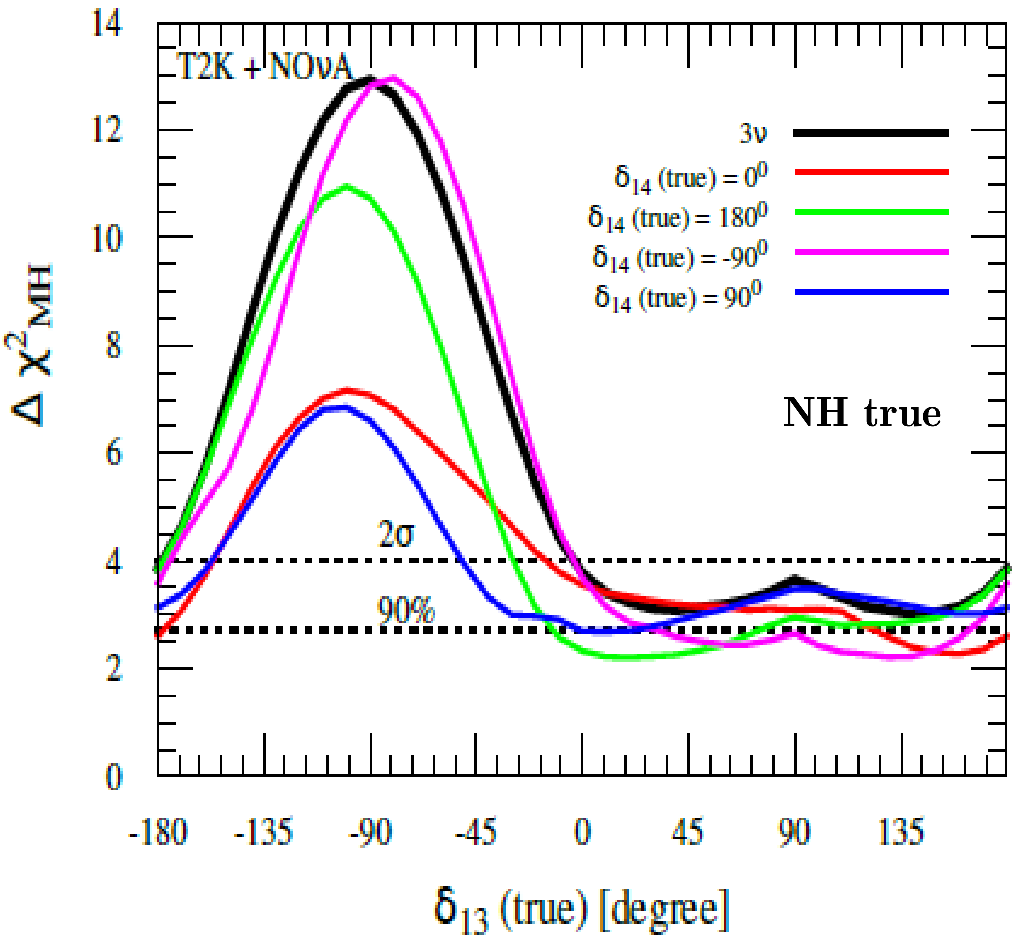
1σ uncertainty for T2K+NOvA
40^0 for δ_{13} and 50^0 for δ_{14}

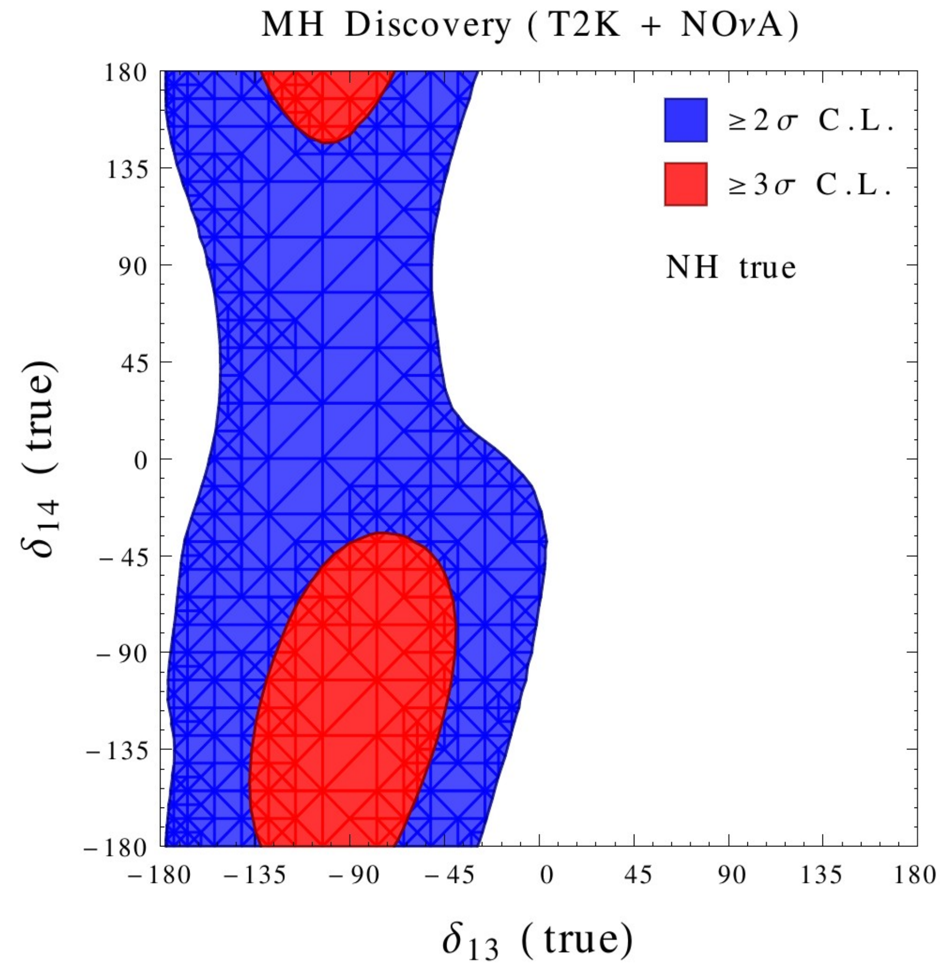
1σ uncertainty for DUNE
$20^0(30^0)$ for $\delta_{13}(\delta_{14})$
if $\theta_{34} = 0$

JHEP 1602 (2016) 111, JHEP 1609 (2016) 016 by Agarwalla, SSC, Palazzo

Impact of one sterile neutrino on Mass Hierarchy determination

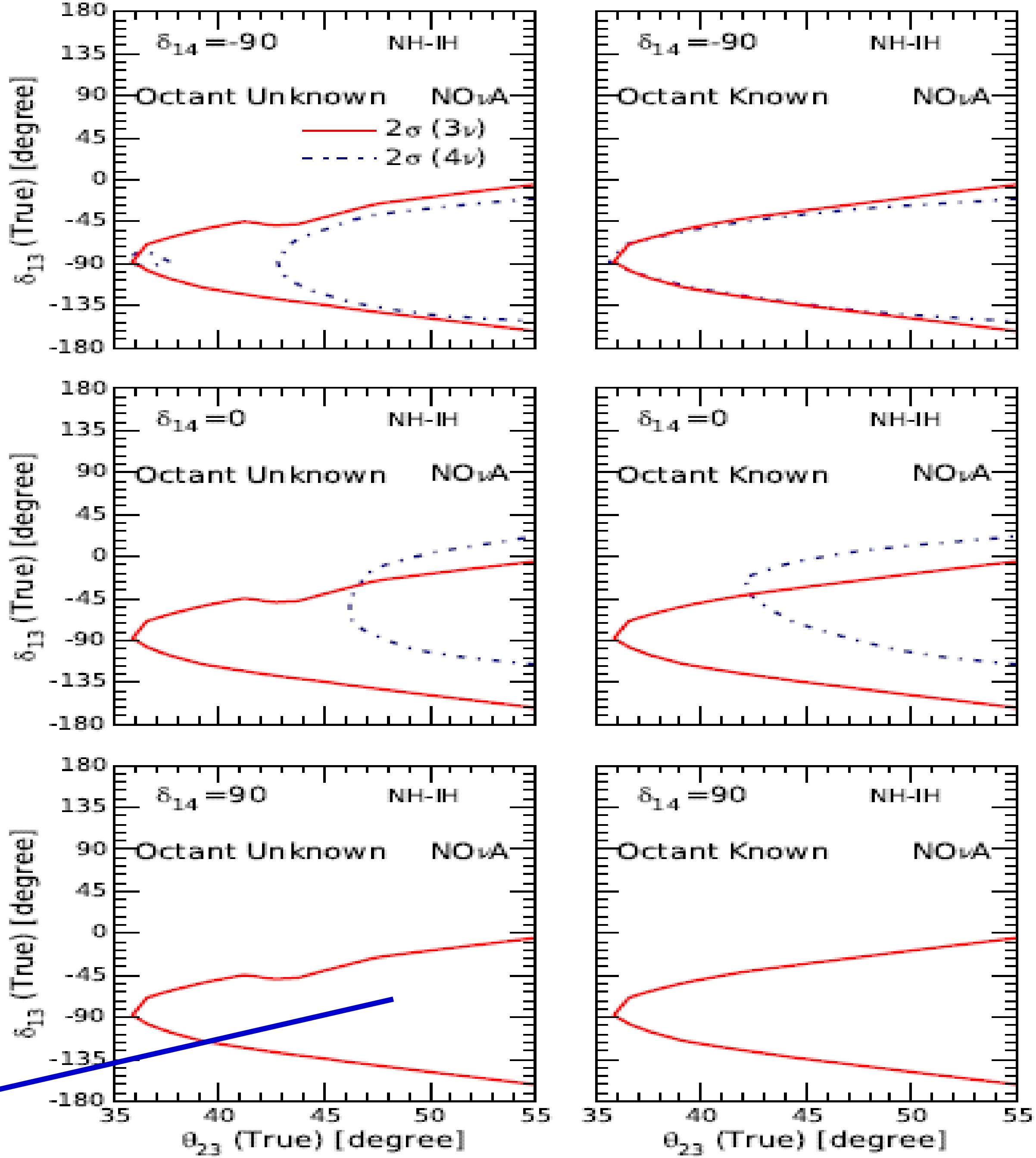
MH discovery potential is defined as the confidence level at which one can exclude the false test hierarchy given a data is generated with true hierarchy.





$$\Delta\chi^2_{\text{MH}} = \chi^2\,[(\text{true hierarchy})] - \chi^2\,[(\text{test hierarchy})]$$

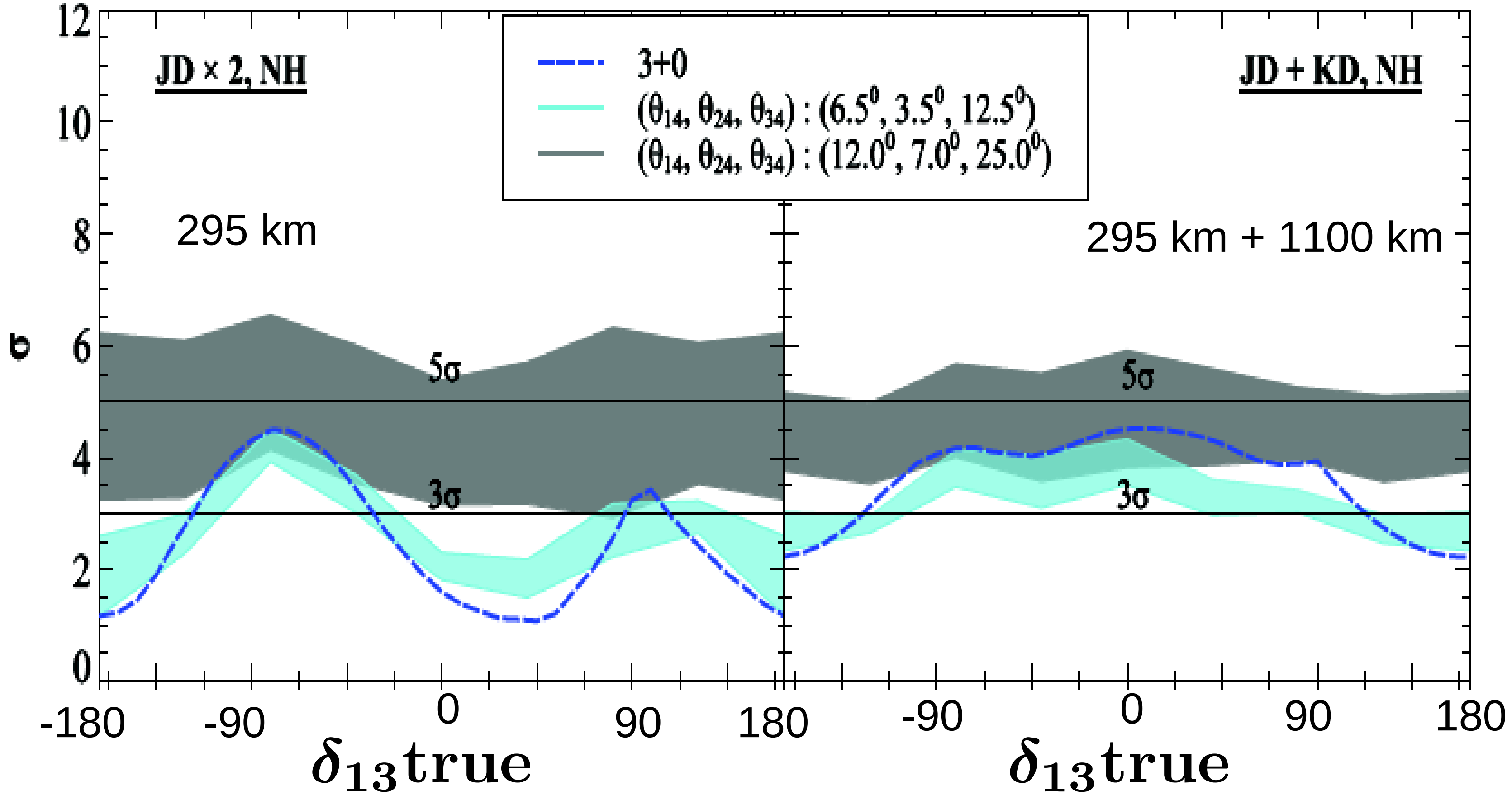
JHEP 1602 (2016) 111 by Agarwalla, SSC, Palazzo



2σ Sensitivity vanishes

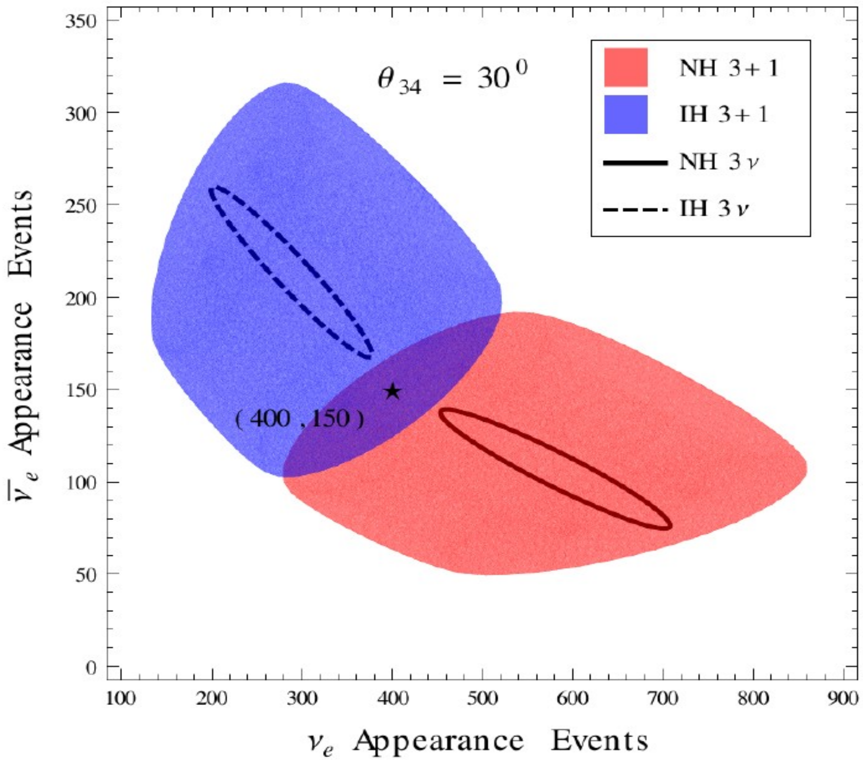
Phys.Rev. D96 (2017) no.7, 075018 by M. Ghosh, S. Gupta, Z. Matthews, P. Sharma, A. Williams

MH sensitivity at T2HK

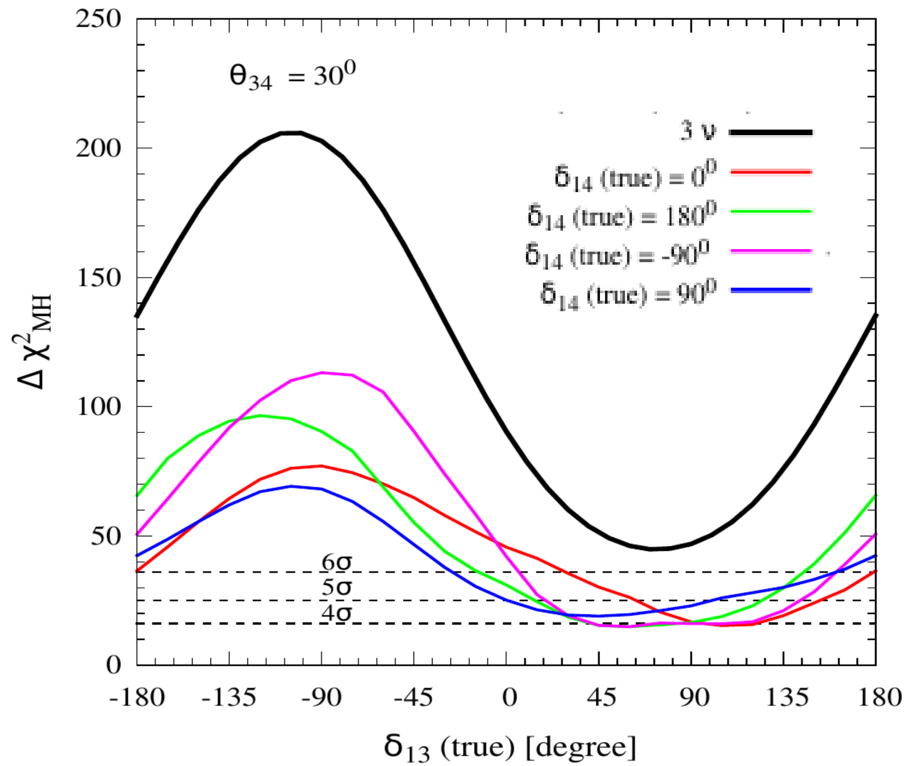


Phys.Rev. D96 (2017) no.5, 056026 by Choubey, Dutta, and Pramanik

Bi-events convoluted plot



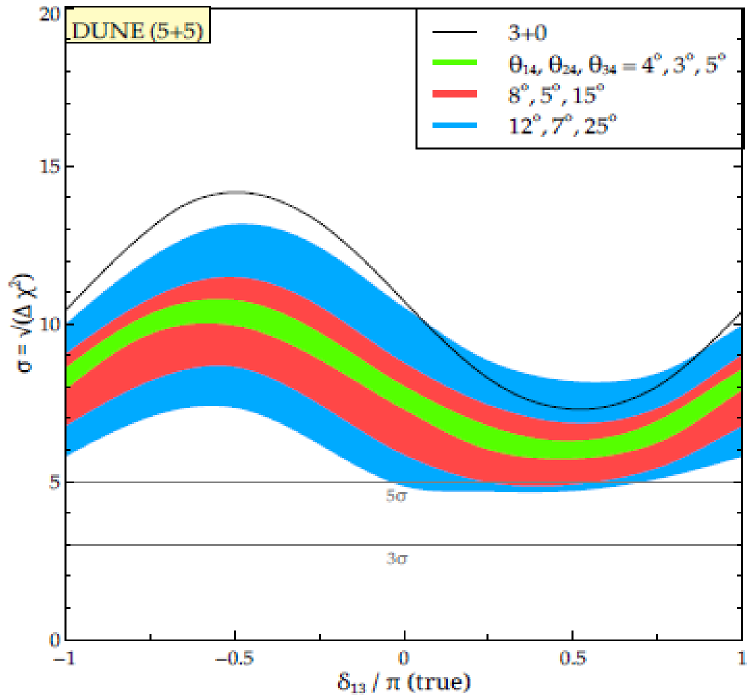
MH Discovery potential (NH true)



$$\theta_{14} = \theta_{24} = 9^0$$

MH can drop down to 4σ for large value of θ_{34} due to the degeneracy between three CP phases δ_{13}, δ_{14} & δ_{34}

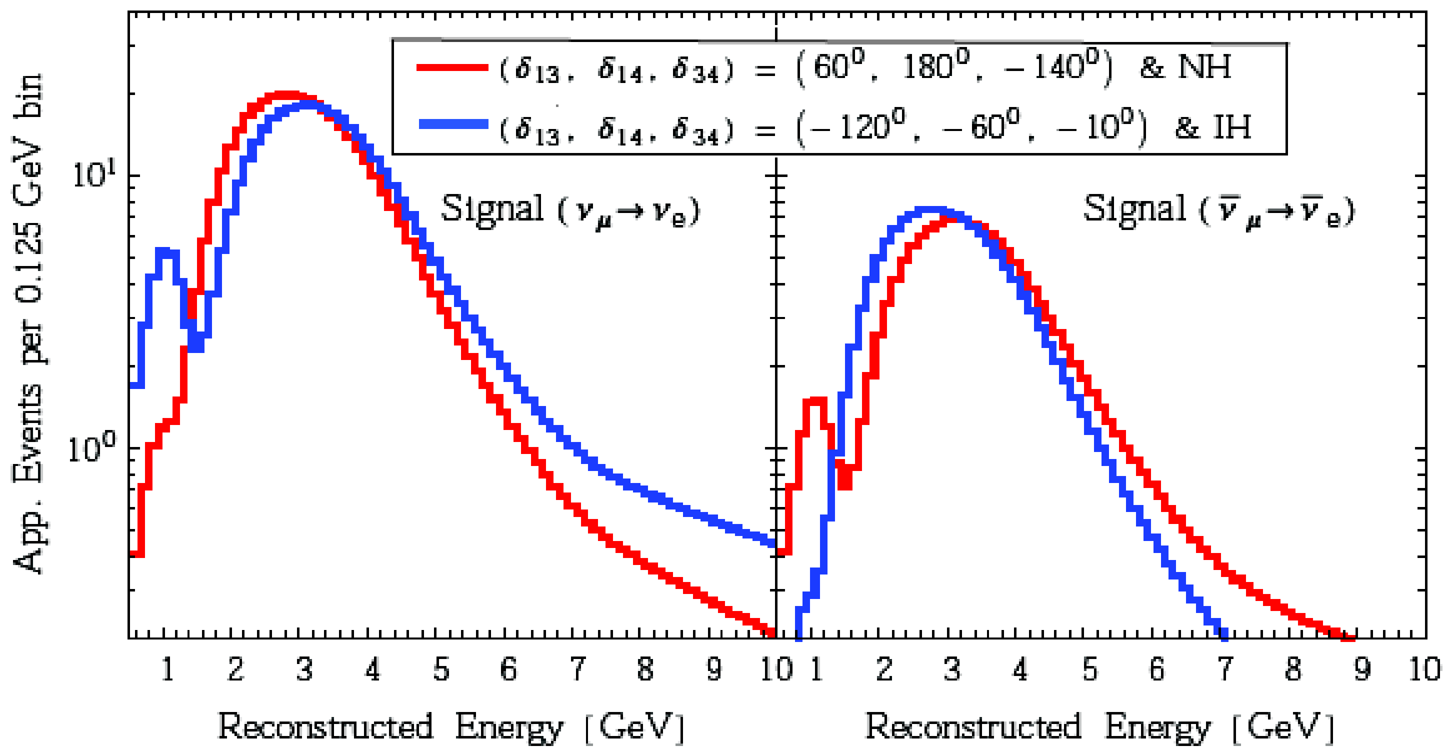
JHEP 1609 (2016) 016 by Agarwalla, SSC, Palazzo



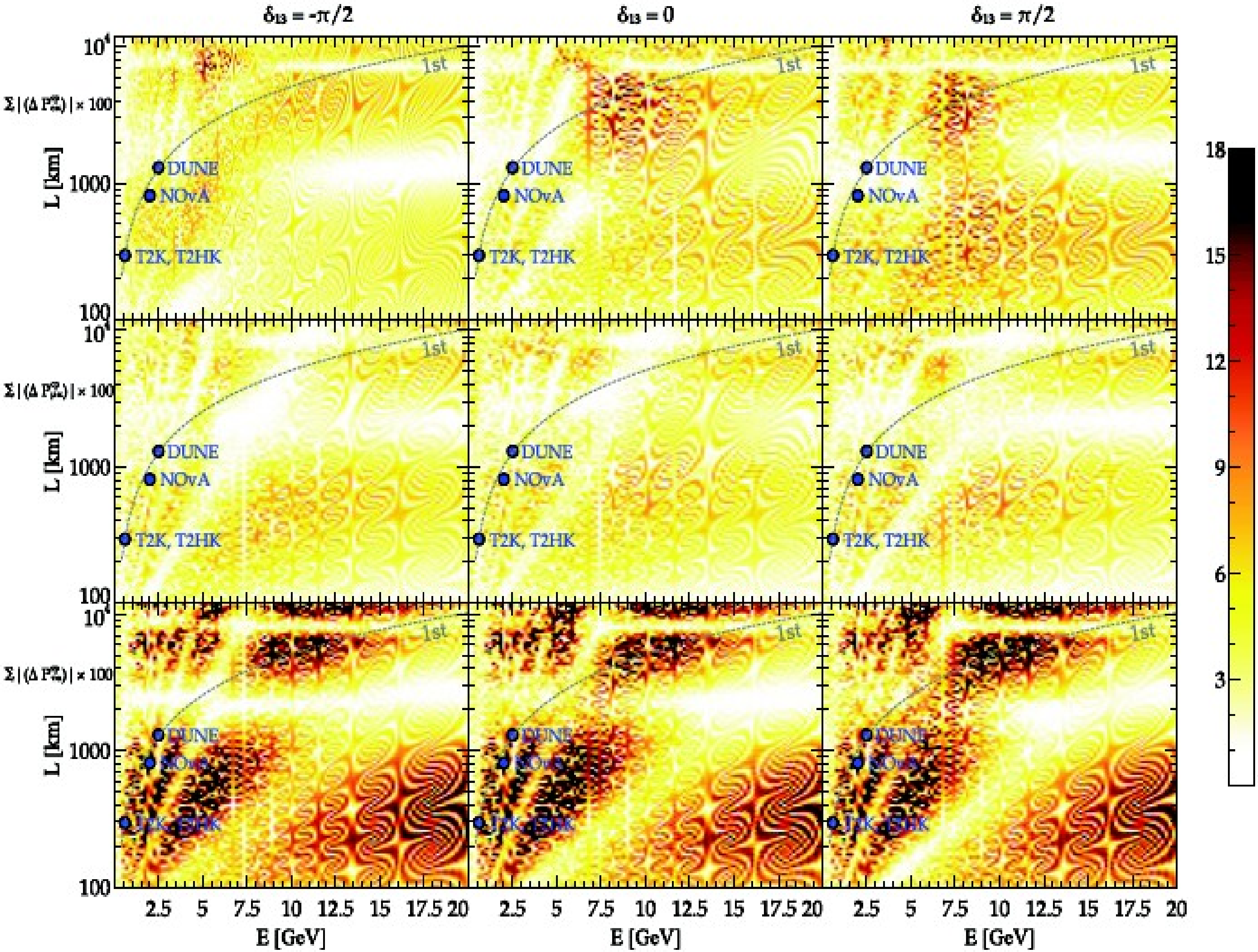
Spectral information of DUNE helps to retain a minimum 4σ sensitivity even under degenerate condition.

JHEP 1611 (2016) 122 by Dutta, Gandhi, Kayser, Masud, and Prakash

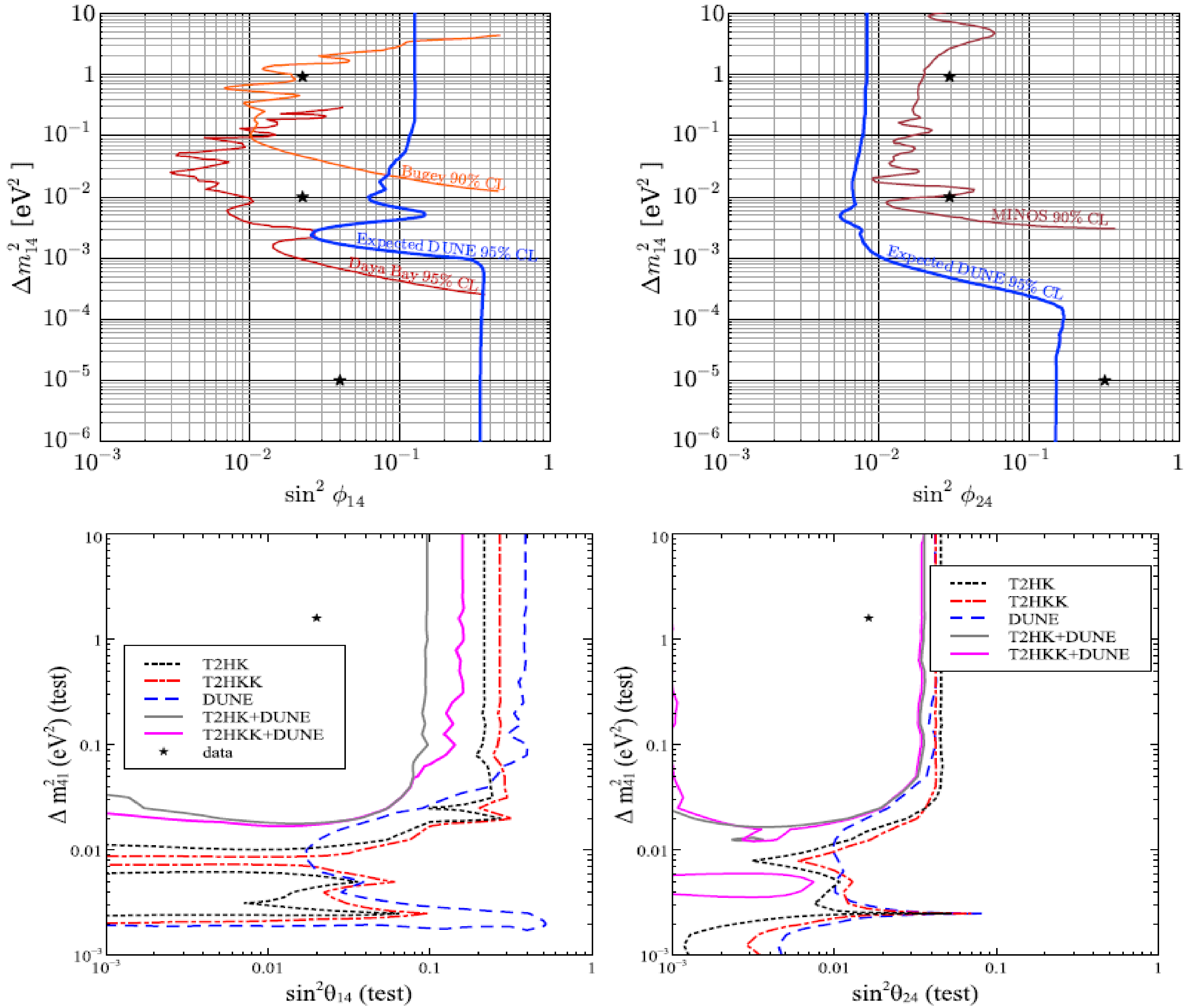
JHEP 1609 (2016) 016 by Agarwalla, SSC, and Palazzo



Testing sterile hypothesis measuring the Non-Unitarity



Phys.Rev. D95 (2017) no.7, 075035 by Rout, Masud, and Mehta



PRD92 (2015) no.7, 073012 by Berryman, Gouvea et al, PRD95 (2017) no.11, 115009 by KJ. Kelly, 1711.07464 by Choubey at al.

1. Joint analysis of SBL + LBL data would be interesting to pursue

2. A detailed analysis of NC component to explore sterile neutrino.

3. Need to think the techniques to improve the sterile induced CP phase sensitivity.

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

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

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

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

$$+ 2\, s_{14}^2\, s_{24}^2$$

In presence of matter

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

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

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

Now, we can write, $$\Delta P = \Delta P_0 + \Delta P_I + \Delta P_{II}$$

Where,

$$\Delta P_0 \simeq 8\,\eta\,\sin^2\theta_{13}\,\sin^2\Delta$$

Positive definite quantity

$$\Delta P_1 = A\left[\cos\left(\Delta \pm \varphi^{HO}\right) - \cos\left(\Delta \pm \varphi^{LO}\right)\right]$$

$$\Delta P_{II} = B\left[\sin\left(\Delta \pm \psi^{HO}\right) - \sin\left(\Delta \pm \psi^{LO}\right)\right]$$

Can be +ve or -ve

$$A = 4\,\sin\theta_{13}\,\sin\theta_{12}\,\cos\theta_{12}\,(\alpha\,\Delta)\,\sin\Delta$$

$$B = 2\sqrt{2}\,\sin\theta_{14}\,\sin\theta_{24}\,\sin\theta_{13}\,\sin\Delta$$

$$\varphi = \delta_{13} \qquad \psi = \delta_{13} - \delta_{14}$$

$$P_{\mathrm{II}}^{\mathrm{INT}} \simeq 4\,s_{13}\,s_{23}\,s_{14}\,s_{24}\,\sin\Delta\,\sin\left(\Delta + \delta_{13} - \delta_{14}\right)$$

Cosmological constraints on sterile neutrinos:

Sum of neutrino masses: $\sum m_\nu < 0.2$ eV

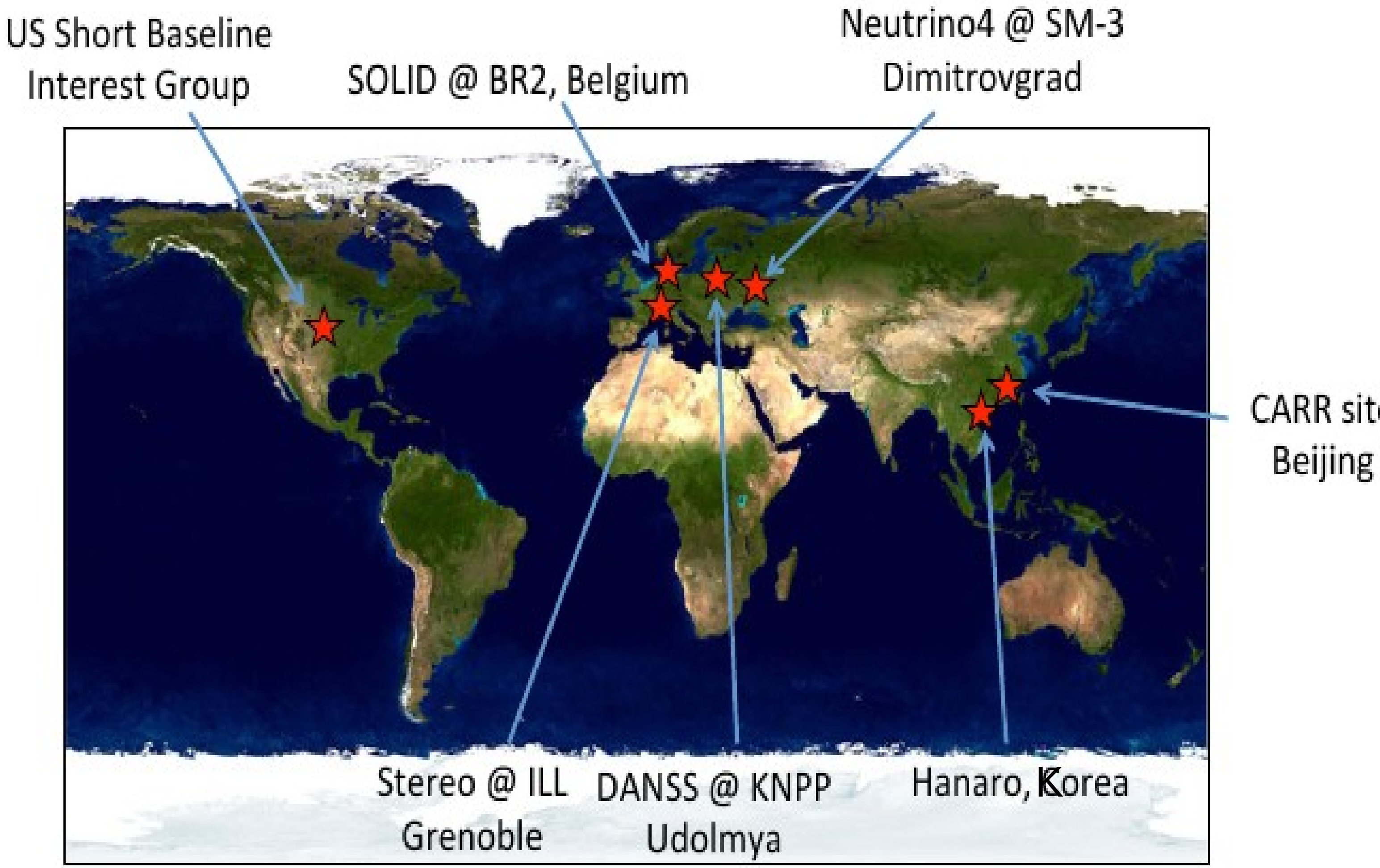
No. of effective relativistic neutrino species : $N_\nu < 3.2$

So, cosmologically one extra sterile neutrino is not allowed.

For possible way out, please see:

"Cosmologically Safe eV-Scale Sterile Neutrinos and Improved Dark Matter Structure",
By Basudeb Dasgupta, Joachim Kopp, PRL 112 (2014) no.3, 031803

ArXiv: 1310.5926 "Steen Hannestad, Rasmus Sloth Hansen, Thomas Tram"
ArXiv: 1505.02795 "Xiaoyong Chu, Basudeb Dasgupta, Joachim Kopp"
ArXiv: 1606.07673 "Maria Archidiacono, Stefano Gariazzo, Carlo Giunti, Steen Hannestad, Rasmus Hansen, Marco Laveder, Thomas Tram"



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, DANNS, 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

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

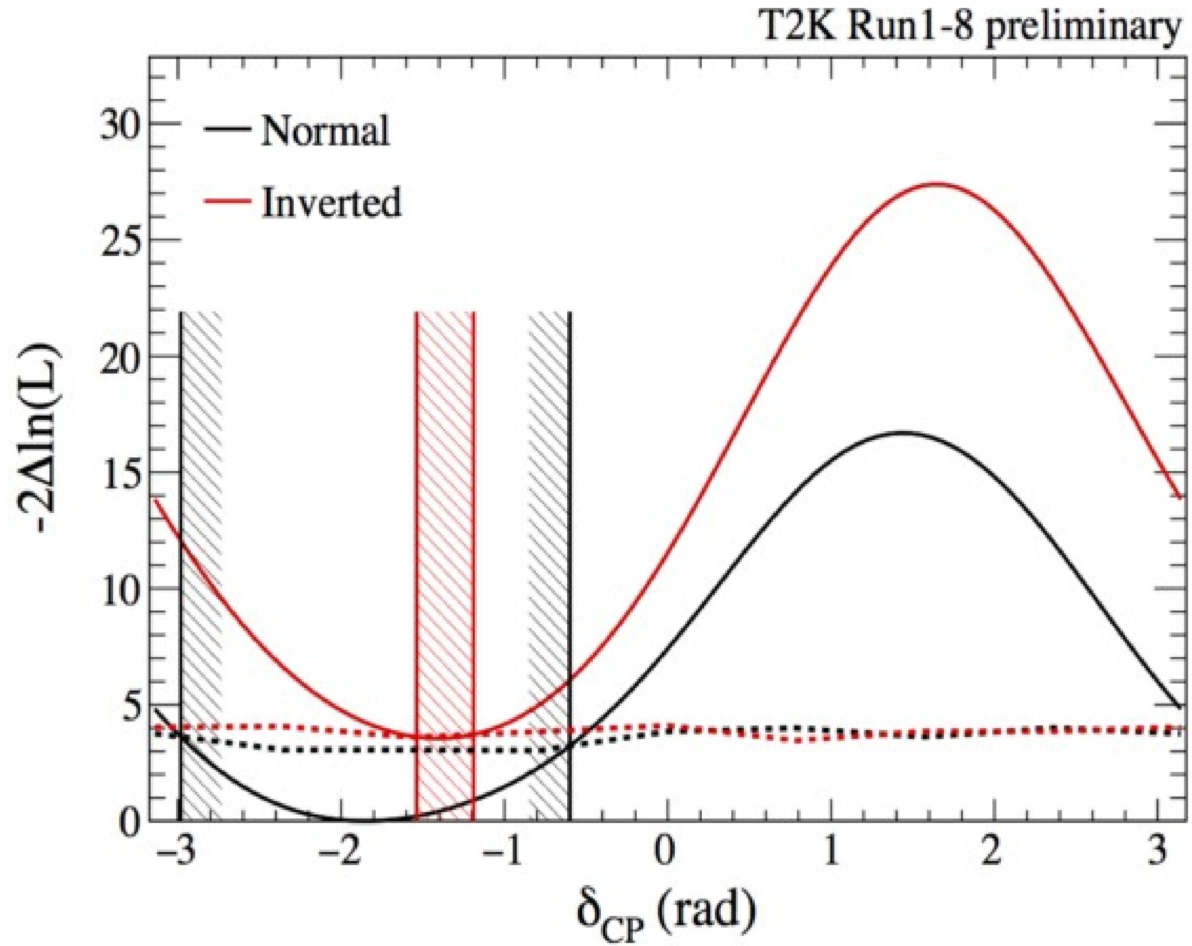
v_{B-L} is B-L symmetry breaking scale

M_s is effective mass of sterile neutrino, $\mathrm{k}_i, \ \tilde{\lambda}$ 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.

Gallium Anomaly

Two Gallium Experiments : GALLEX & SAGE

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

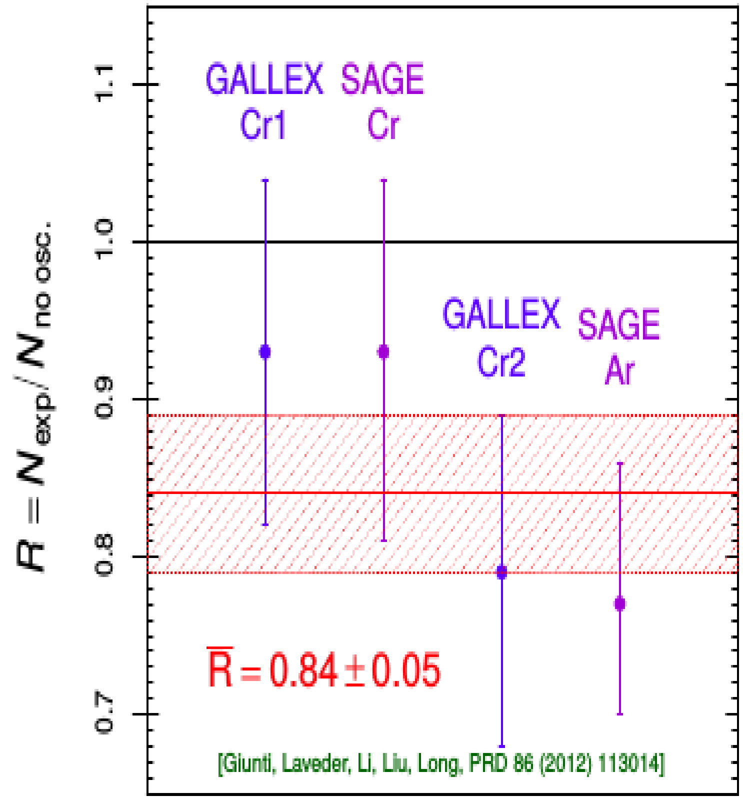
$e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$

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

$\nu_e \to \nu_e$ Oscillation

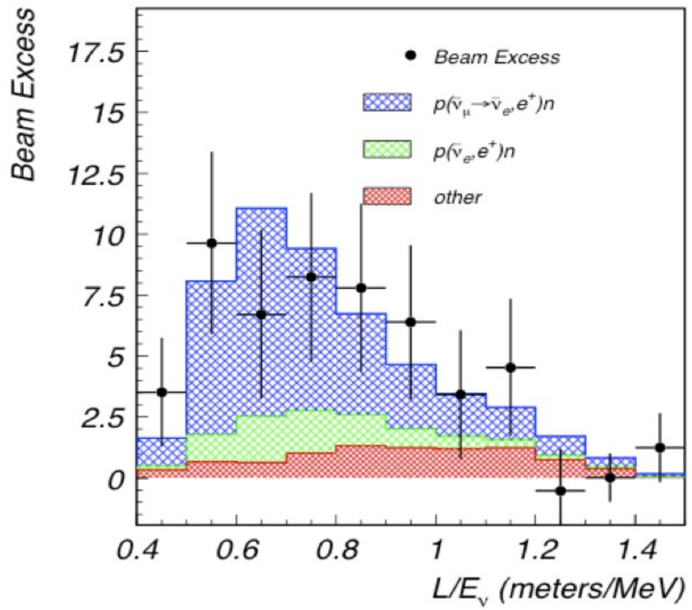
$L \simeq 1\,m$, $E \simeq 1$ MeV, 2.9σ deficit

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



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

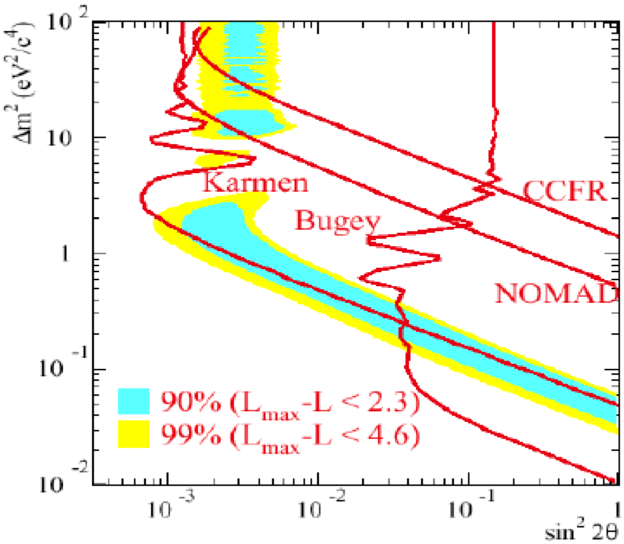
$L \simeq 30\ m, \ \ 20\ MeV \leqslant E \leqslant 60\ MeV$

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

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

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

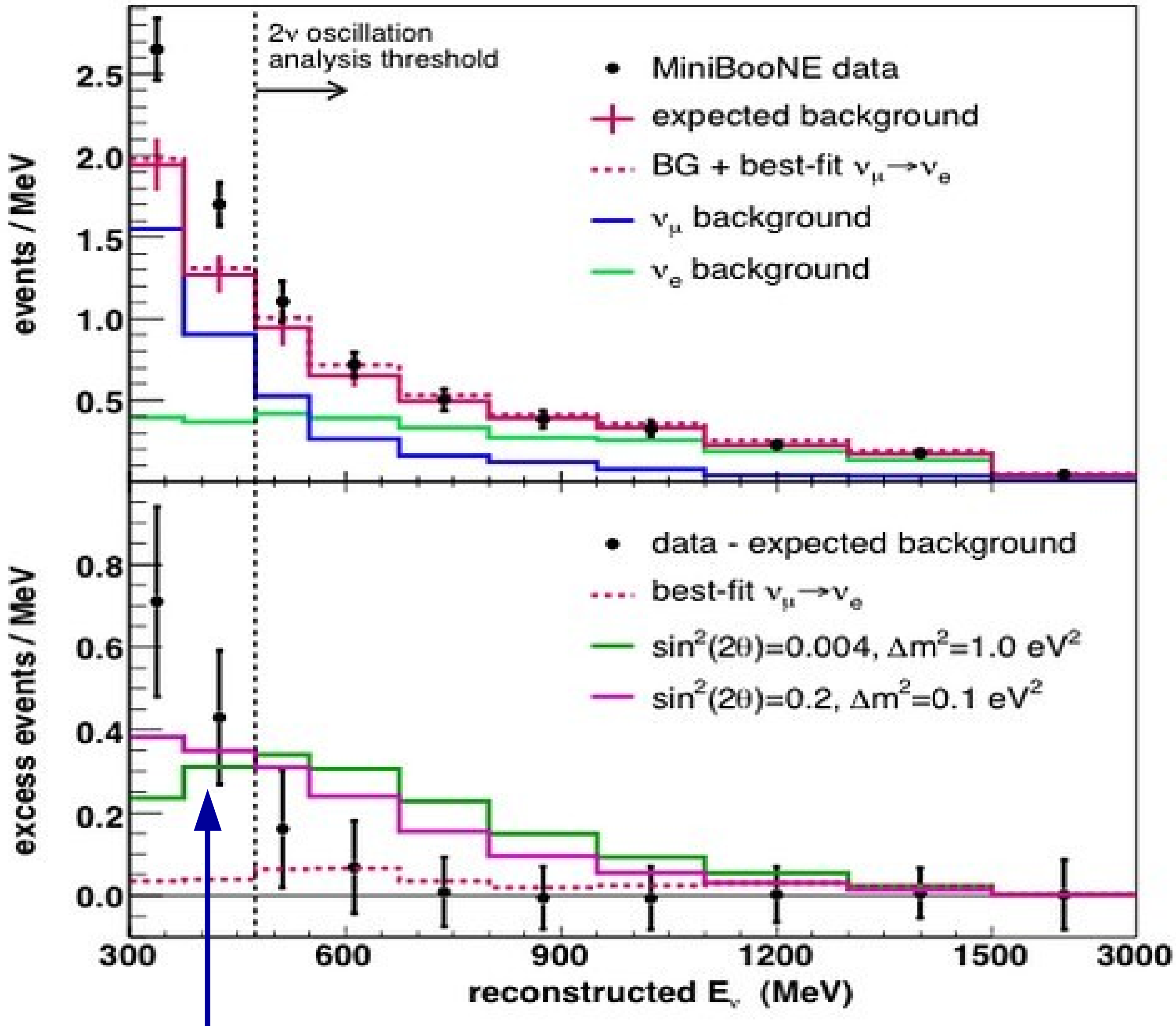
The signal can be explained if $\Delta m^2 \gtrsim 0.1\ eV^2$



The Karmen (L ~ 18 m) Collaboration did not see the same but could not exclude it fully.

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

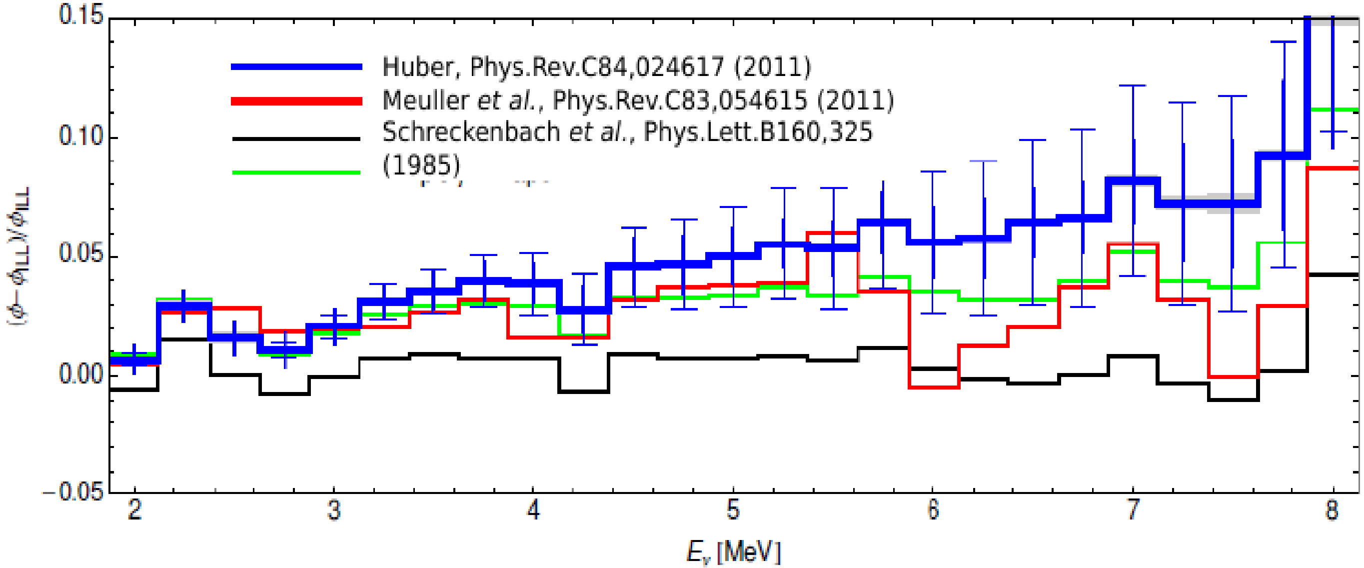
$\nu_\mu \to \nu_e$ oscillation

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

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

Reactor Anomaly

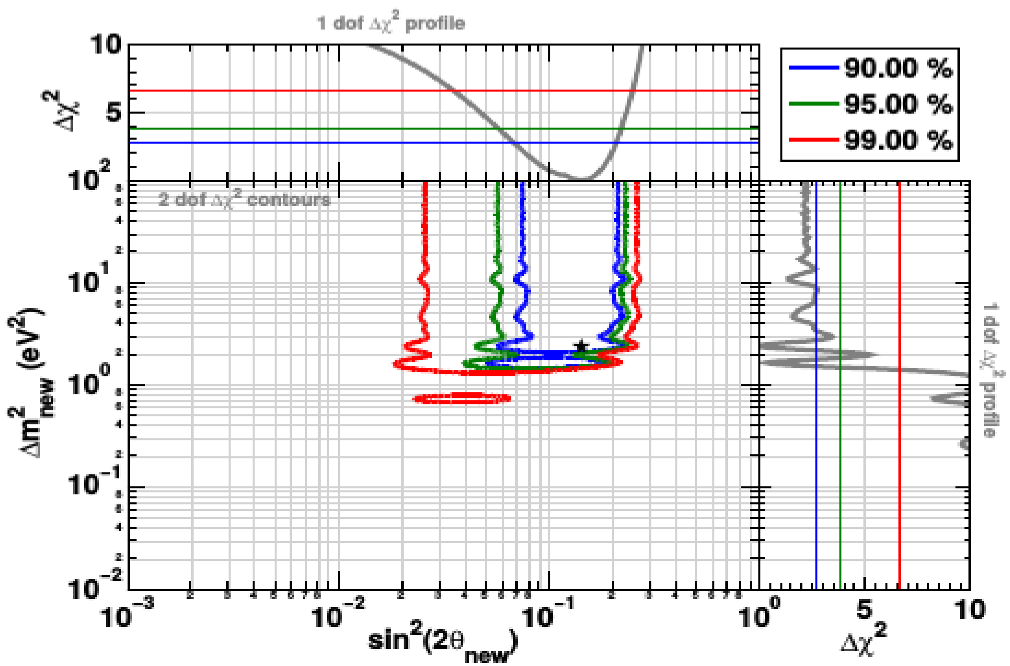
New analyses (blue and red) of the reactor $\bar{\nu}e$ spectrum predict a 3% higher flux than the existing calculation (black).



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

Obs. events < expected

$\overline{\nu}_e \to \overline{\nu}_e$ **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]

Basic understanding

The neutrino flavor eigenstates $|\nu_\alpha\rangle$ are related to its mass eigenstates $|\nu_i\rangle$ by the relation

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

where, $\alpha = e^-, \mu^-, \tau^-$ and $i = 1,2,3$

U is the PMNS unitary matrix parametrized as

$$U = R_{23} \widetilde{R}_{13} R_{12}$$

$$R_{ij}^{2\times 2} = \begin{pmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{pmatrix} \text{ and } \widetilde{R}_{ij}^{2\times 2} = \begin{pmatrix} c_{ij} & \widetilde{s}_{ij} \\ -\widetilde{s}_{ij}^{\,*} & c_{ij} \end{pmatrix}$$

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

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

Similarly, the time evolution Schrodinger equation in matter is given by

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

(Effective Hamiltonian)

$V_{CC} = \pm\sqrt{2}G_F N_e$ **Charge current potential for neutrino(antineutrino)**

$V_{NC} = \pm G_F N_n / \sqrt{2}$ **Neutral current potential neutrino(antineutrino)**