Exploring the leptonic CP-violation in the presence of a light sterile neutrino

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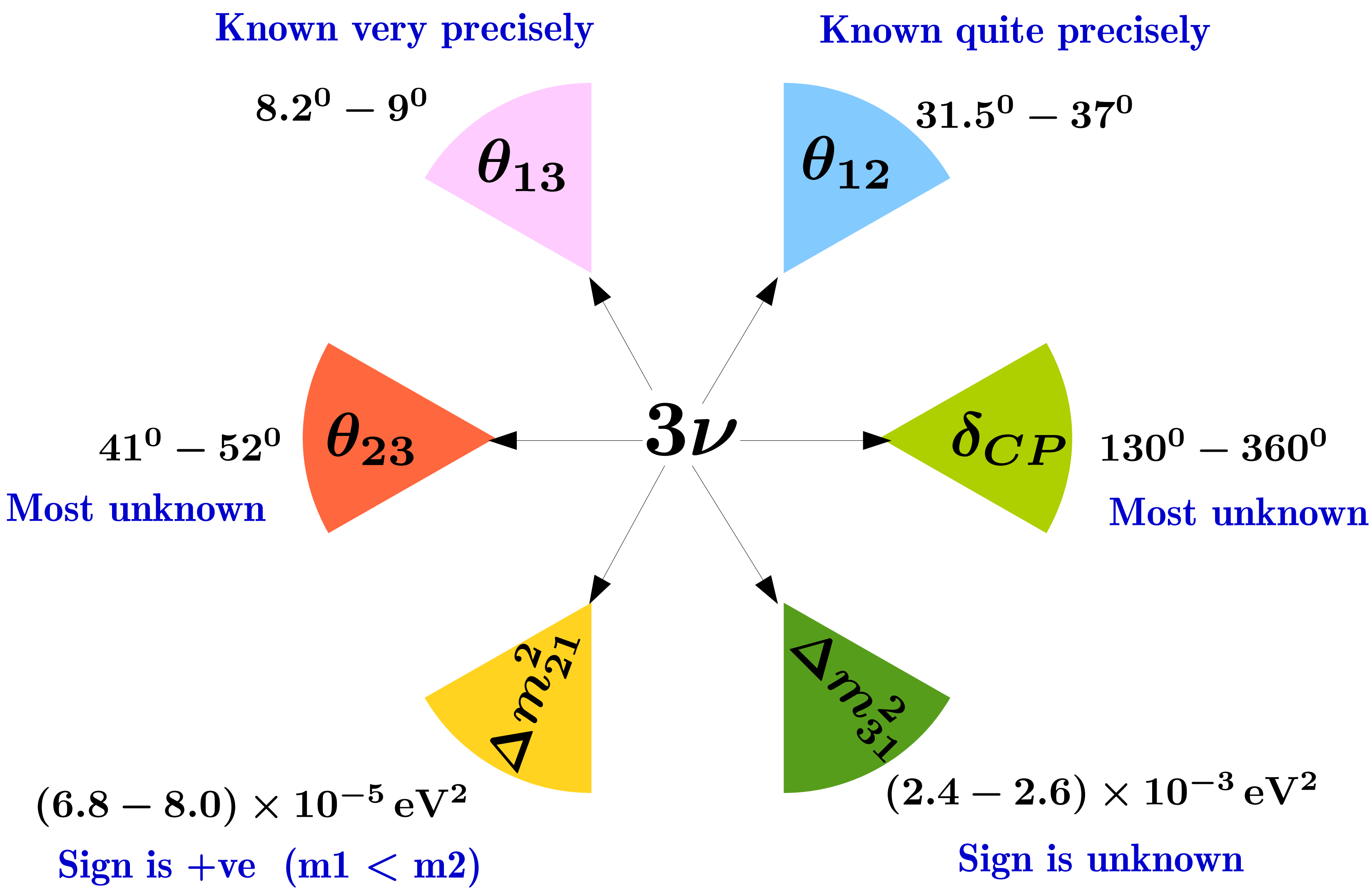
Outline

- **Current status of the 3-neutrino framework**
- **Theoretical framework of light sterile neutrino oscillation**
- **Exploring the CP-Violation in the current and future LBL experiments in presence of a sterile neutrino.**
- **Conclusions**

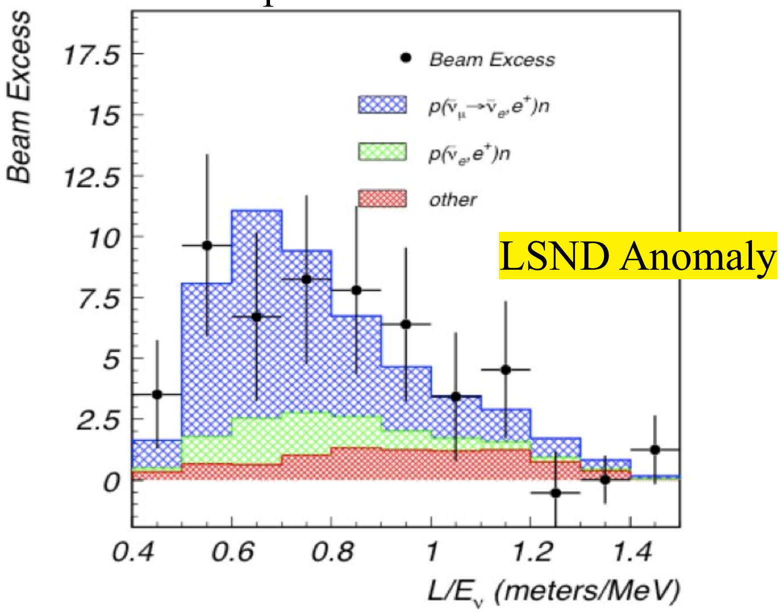
Current status of 3ν parameters (3σ uncertainties)



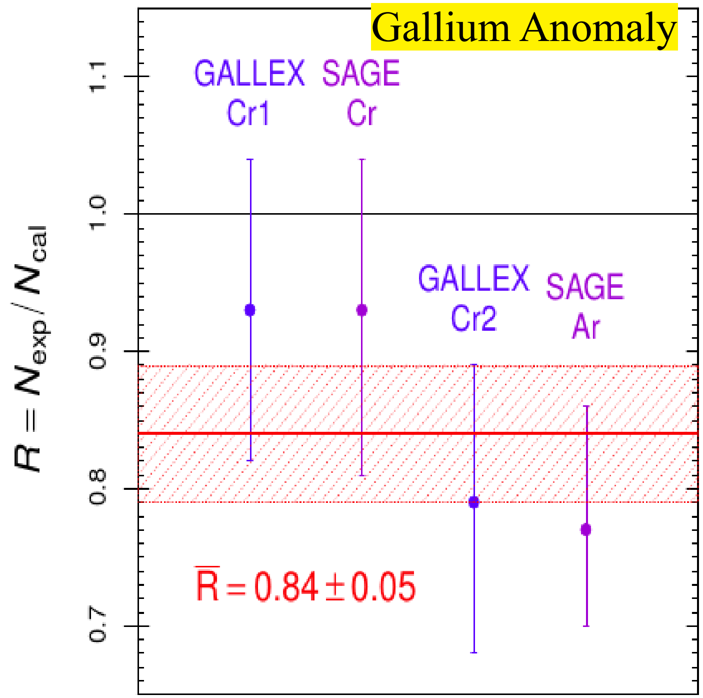
ArXiv: 2006.11237 by P. Salas et al., arXiv: 2007.14792 by Esteban et al., and arXiv: 1804.09678 by F. Capozzi et al.

Hints towards the sterile neutrino

hep-ex/0104049



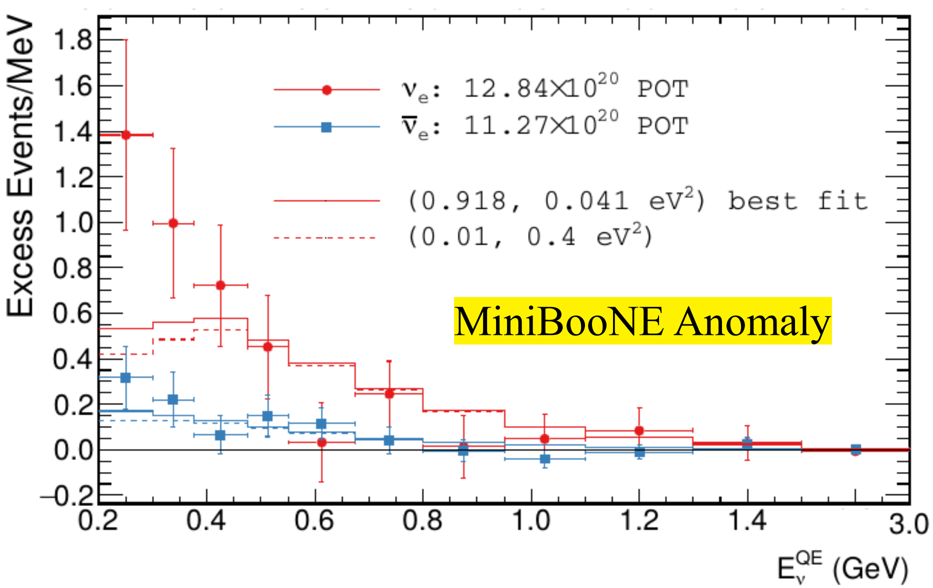
ArXiv: 1507.08204



Requires

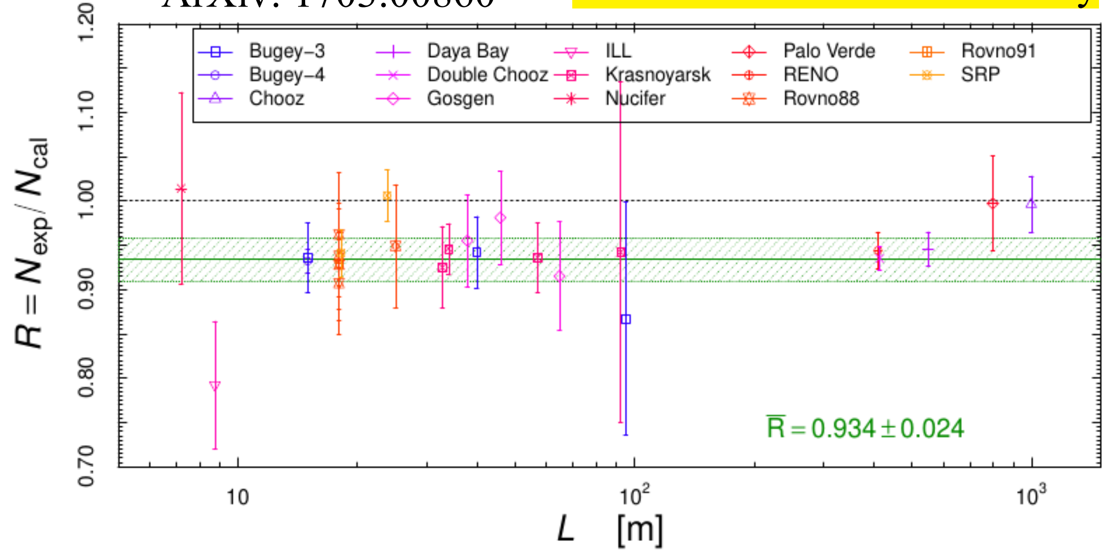
$$\Delta m^2_{41} \sim 1\,\mathrm{eV}^2$$

ArXiv: 1805.12028



ArXiv: 1703.00860

Reactor Antineutrino Anomaly



Theoretical Framework for Sterile Neutrino Oscillation in LBL Expt.

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

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

Δm^2_{21} , Δm^2_{31} , Δm^2_{41} 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

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

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

V_{NC} can also 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

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

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 ($P^{4\nu}_{\mu e}$) in vacuum in LBL experiment

A few points to note

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

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

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

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

The probability for one flavor ν_α transforming to another flavor ν_β is calculated as

$$\mathrm{P}(\nu_\alpha \to \nu_\beta) = |S_{\beta\alpha}(L)|^2 = |(e^{-iHL})_{\beta\alpha}|^2$$

For neutrinos and antineutrinos

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

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

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

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

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

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

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

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)

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

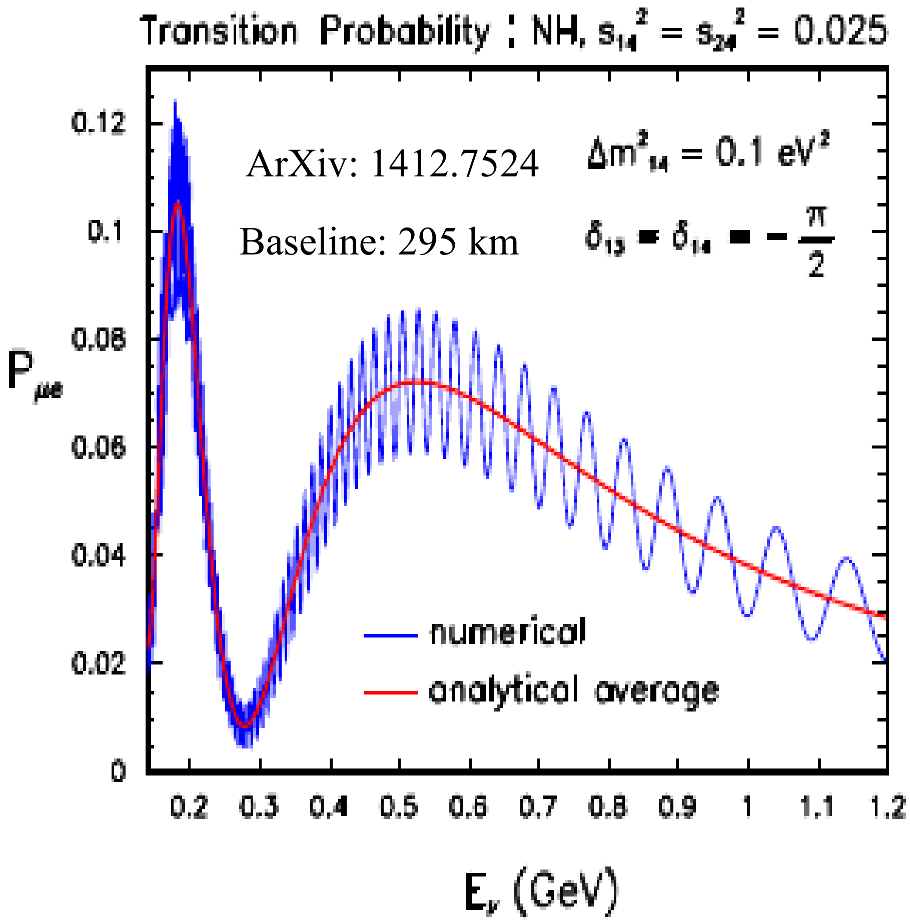
$$k = \frac{2\, V_{CC}\, E}{\Delta m^2_{31}} \quad \& \quad V_{CC} = \sqrt{2}\, G_F N_e$$

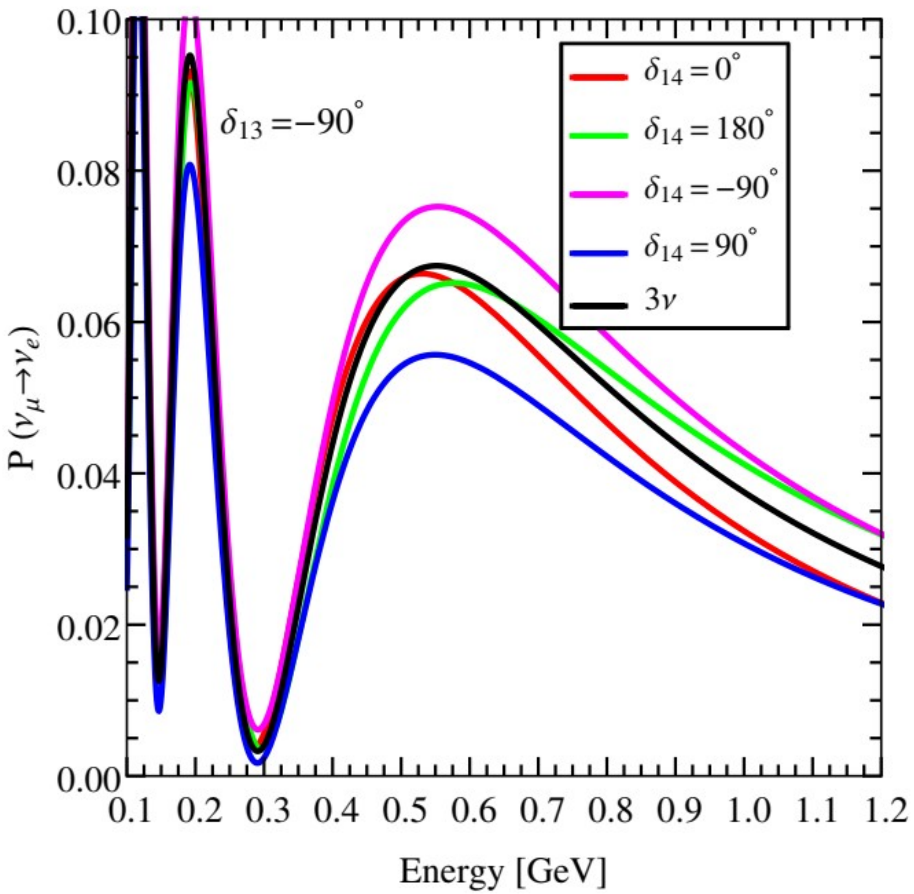
In matter, the two interference terms acquire corrections which are of the fourth order. For our better analytical understanding, we limit ourselves upto third order i.e., ε^3. So the interference terms will have the vacuum expressions even in the presence of matter.

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

Example of numerical probabilities

Question: Can sterile neutrino generate observable CP-Violating effects at LBL ?

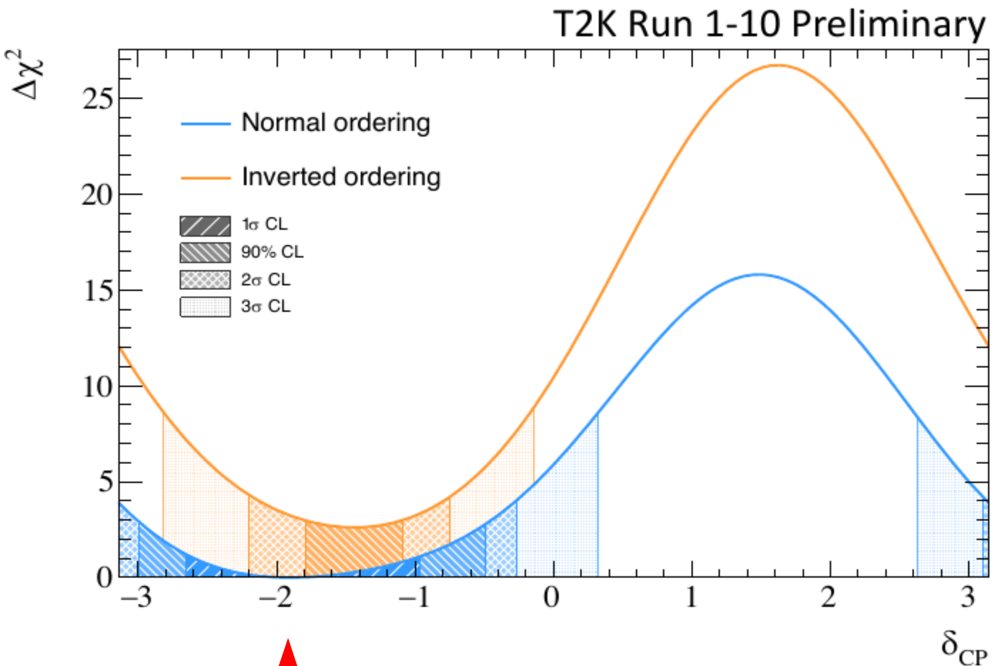


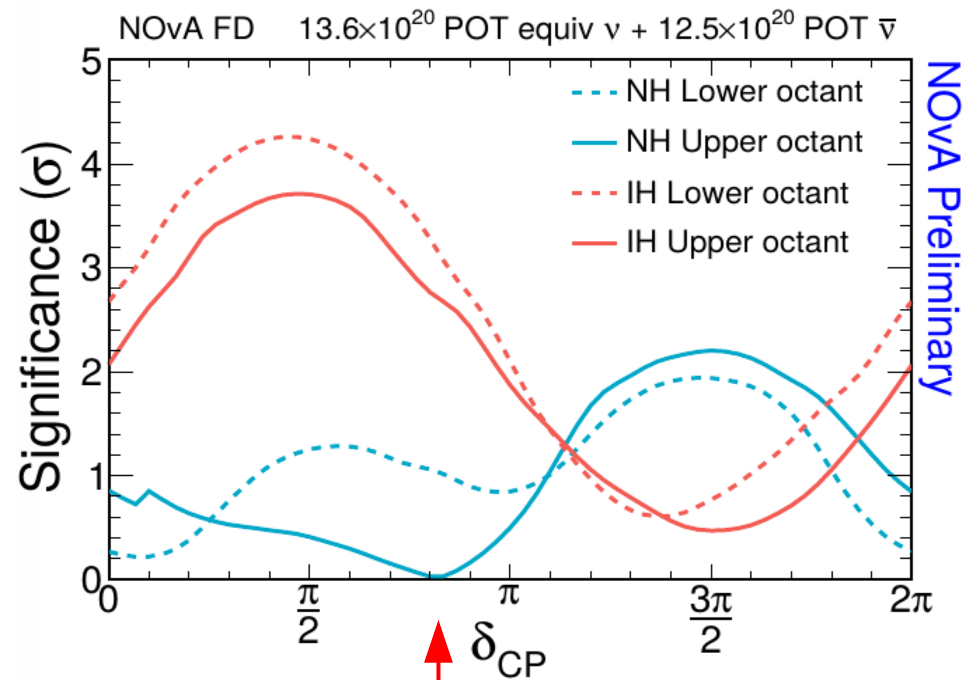


Though the oscillation driven by Δm^2_{41} gets averaged out, it has appreciable effect at far detector.

Current constraint on the standard and new CP-phases using T2K and NovA data

$\boldsymbol{\nu}$ **:** $\mathbf{1.97 \times 10^{21}}$ POT $\bar{\boldsymbol{\nu}}$ **:** $\mathbf{1.63 \times 10^{21}}$ POT





Prefers maximal CP-violation

Prefers no CP-violation

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

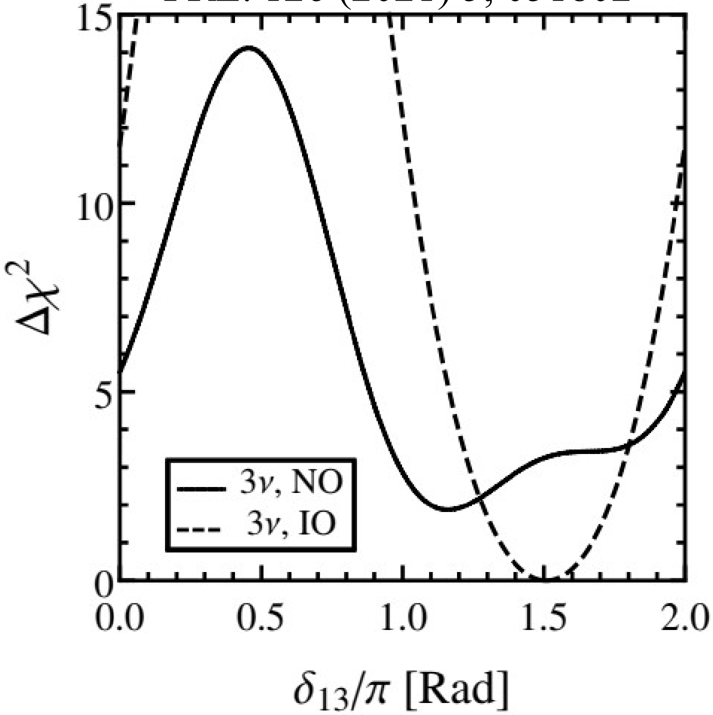
$$\Delta\chi^2_{\text{CPV}} = \chi^2\left[\delta_{13}(\text{true})\right] - \chi^2\left[\delta_{13}(\text{test}) = 0, \pm\pi\right]$$

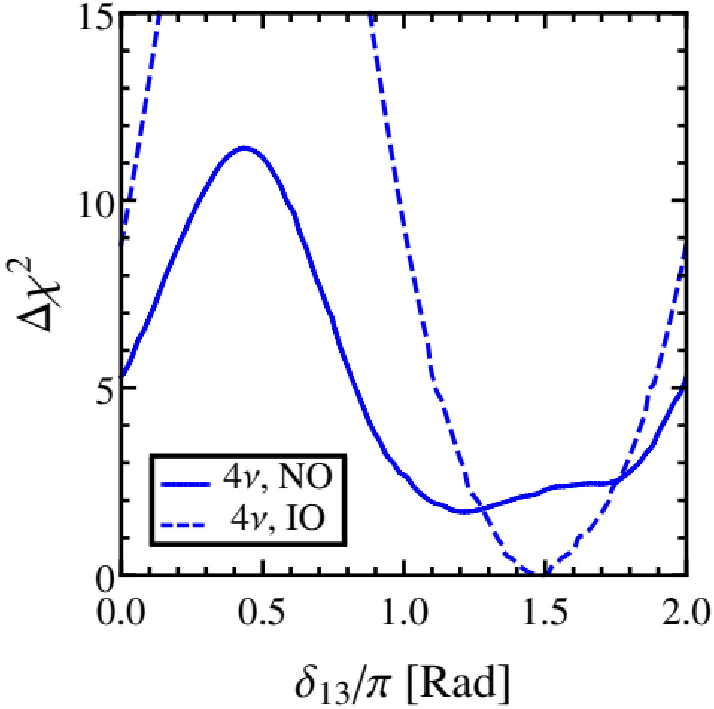
Similar is true for any CP-phases

Please see the talk by P. Dunne and A. Himmel at Neutrino 2020

T2K + NOvA combined analysis

PRL. 126 (2021) 5, 051802

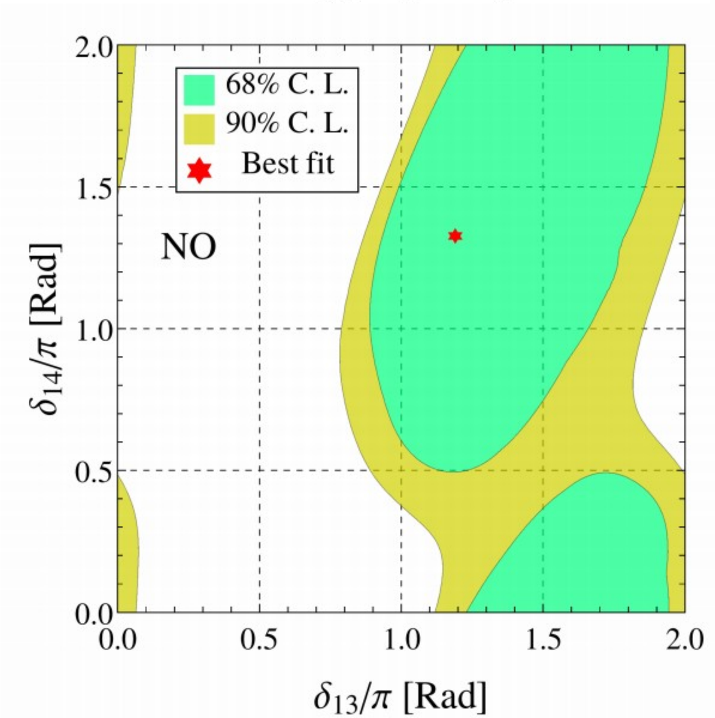


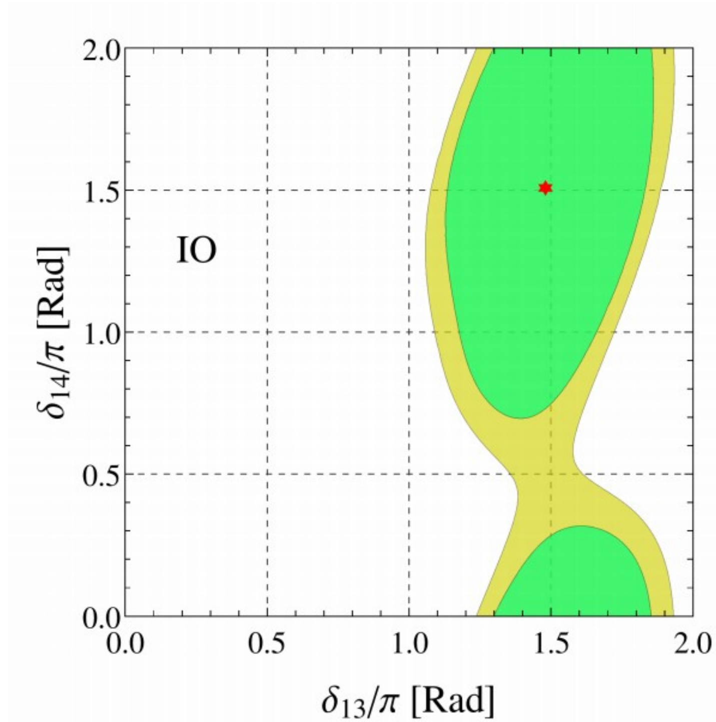


$$\theta_{14} \sim \theta_{24} \sim 8^\circ$$

CPV discovery potential decreases in the presence of a sterile neutrino !!

CPV induced by δ_{14} is very very low





Both the phases indicate Towards maximal CPV !!

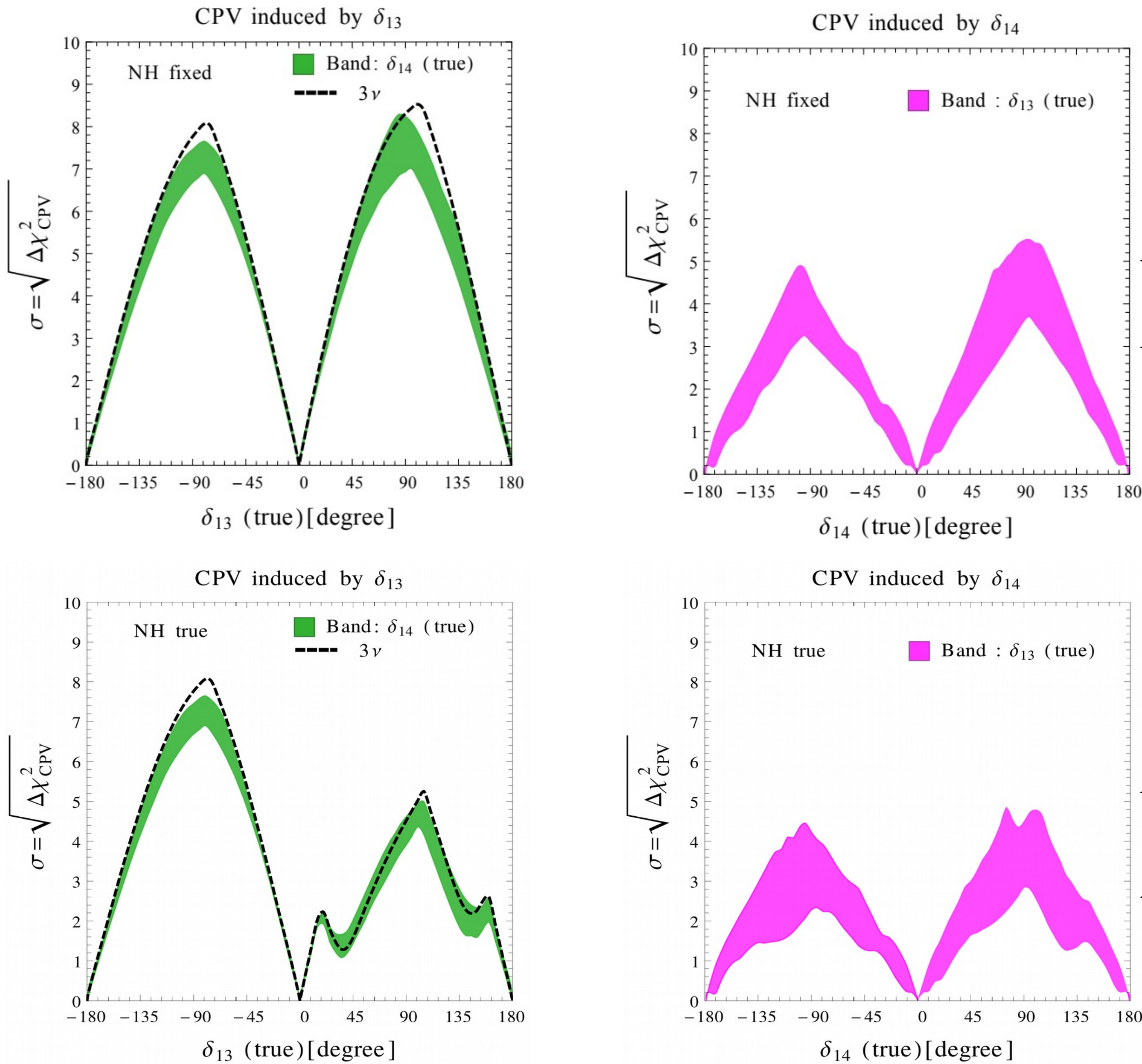
Only 1-sigma preference Over SM

To be updated ArXiv: 2005.10338 by S.S. Chatterjee & Antonio Palazzo

Looking at the Future

CP-Violation search in T2HK

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



295 Km baseline, 560 Kt detector

MH fixed

Minimum 3.5σ sensitivity

Excellant sensitivity towards CPV

MH marginalized

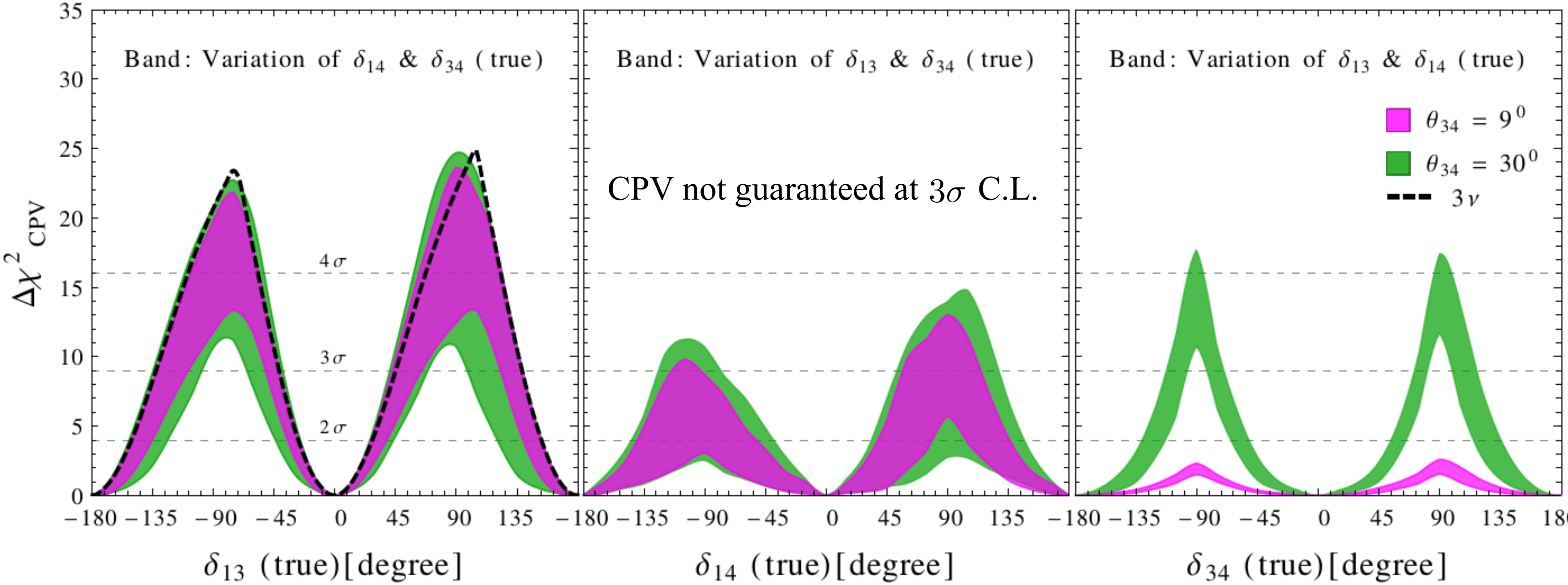
Minimum 2.5σ sensitivity

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

1300 Km baseline

CPV discovery potential in DUNE

JHEP 09 (2016) 016 by Agarwalla, SSC, and Palazzo



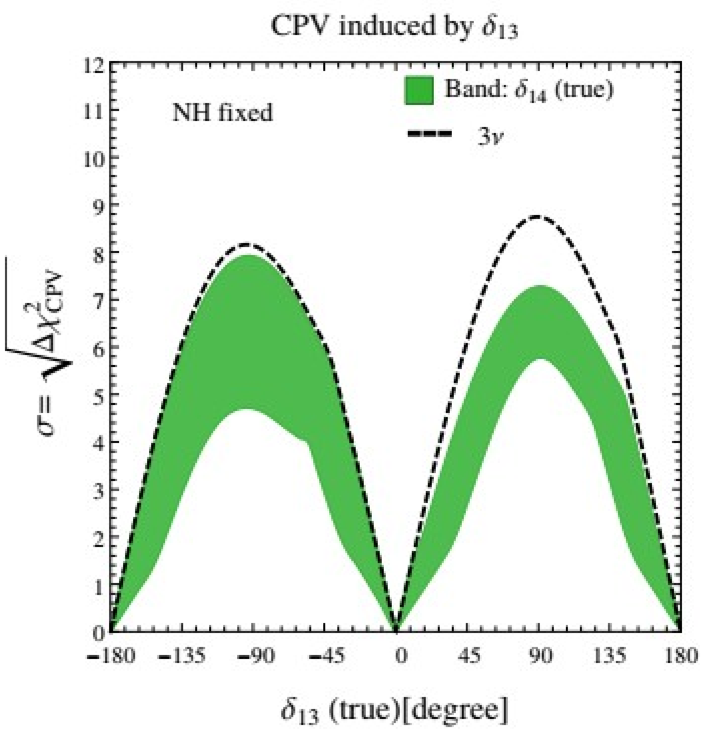
	θ_{34}	$N\sigma_{min}$ [δ_{13}(true) = -90^0]	CPV coverage (3σ)
3ν		4.5	50.0%
3+1	0^0	3.9	43.2%
	9^0	3.4	32.0%
	30^0	3.3	16.0%

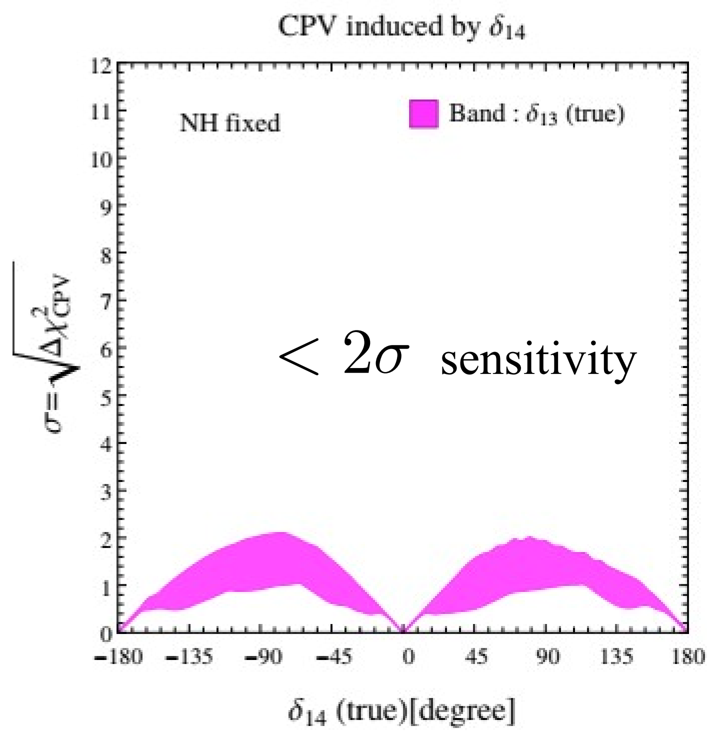
CPV coverage induced by δ_{13}

With the very new setup the sensitivities improve slightly

ESS2+8 setup

JHEP 12 (2019) 174 by Agarwalla, SSC, and Palazzo





Baseline 540 km
Detector mass 500 Kt

Works at 2nd oscillation maximum

$$\Delta = 3\pi/2$$

Narrow energy spectrum and low statistics

Provides excellant CPV sensitivity in the SM case

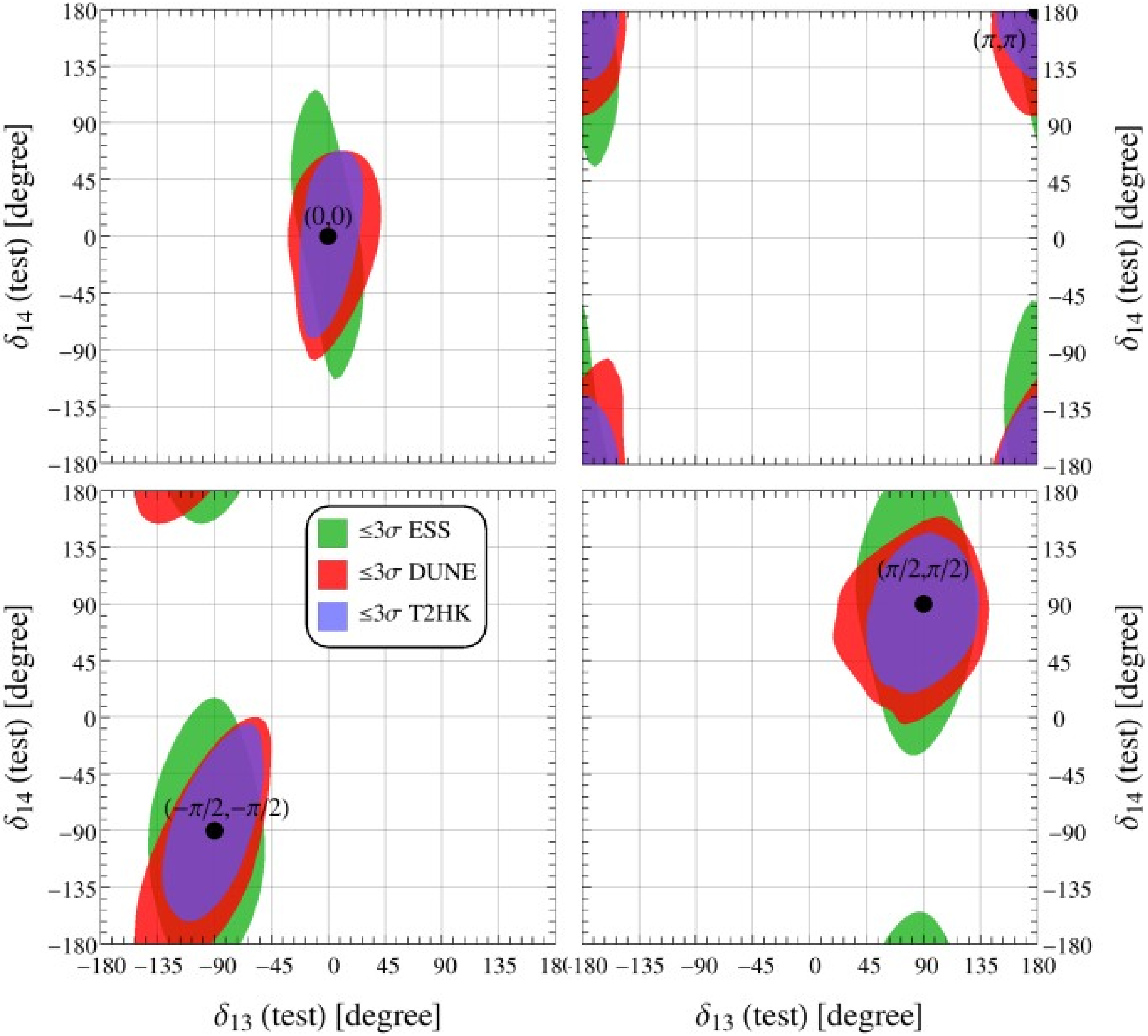
$$P_I^{\rm INT} \simeq 8 s_{12} c_{12} s_{13} s_{23} c_{23} (\alpha \Delta) \sin\Delta \cos(\Delta \pm \delta_{13}) \longrightarrow \Delta \text{ amplification term}$$

$$P_{II}^{\rm INT} \simeq 4 s_{13} s_{23} s_{14} s_{24} \sin\Delta \sin(\Delta \pm \delta_{13} \mp \delta_{14}) \longrightarrow \text{No amplification term}$$

Poor sensitivity towards δ_{14} and CPV induced by δ_{14}

Reconstruction of CP-phases in DUNE, T2HK, and ESS

JHEP 12 (2019) 174 by Agarwalla, SSC, and Palazzo



Experiments	1σ uncertainty δ_{13} (δ_{14})
T2HK	12° (25°)
DUNE	15° (32°)
ESS	15° (35°)

Performance of DUNE and T2HK is slightly better in constraining the delta14 phase

Conclusions

- LBL experiments are sensitive to the CP phases, play a complementary role to the SBL experiments.

- Currently running two LBL experiments T2K and NovA are playing a leading role in exploring the standard as well as new CP-phases.

- T2HK offers excellent sensitivity to the CPV discovery! There is always 3-sigma sensitivity ensured both by δ_{13} & δ_{14}

- There is guaranteed 3-sigma level CPV discovery induced by delta13. CPV induced by delta14 is not guaranteed at 3-sigma level. If th34 is large enough DUNE can observe CPV induced by delta34.

- ESS offers excellant CPV sensitivity induced by delta13 in the SM case. It also assures a minimum 4.5-sigma sensitivity in presence of sterile neutrino. There is a very poor sensitivity to delta14.

- Most importantly T2K, NovA, T2HK, and ESS will play a complementary role to DUNE in exploring the full 3+1 sector.

- We hope that the analyses performed in these papers may give deep insight in exploring the CP-violation and the standard and new CP-phases.

Thank you

Gallium Anomaly

Two Gallium Experiments : GALLEX & SAGE

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

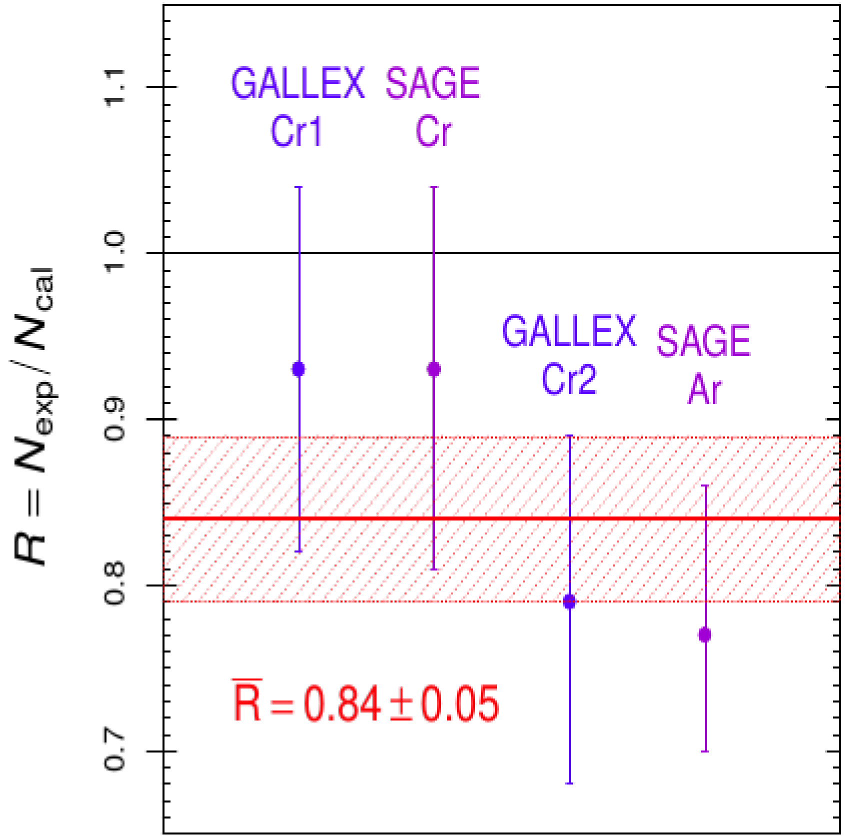
$e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$

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

$\nu_e \to \nu_e$ Oscillation

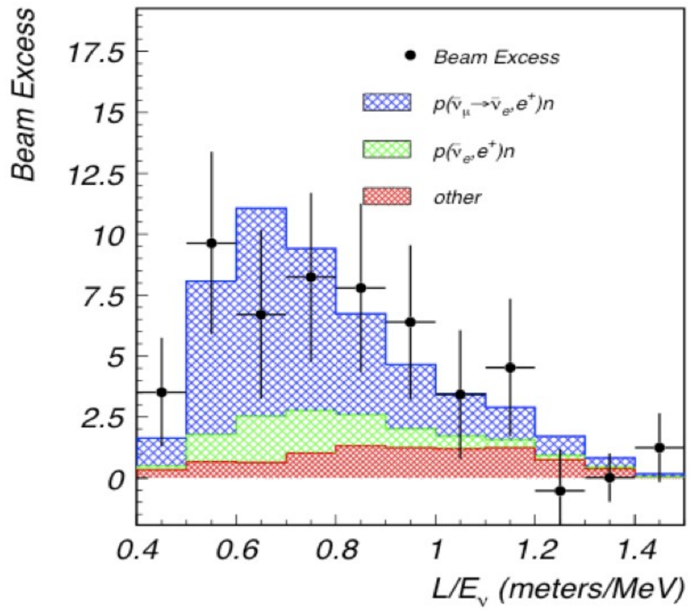
$L \simeq 1\,m$, $E \simeq 1$ MeV, 2.9σ deficit

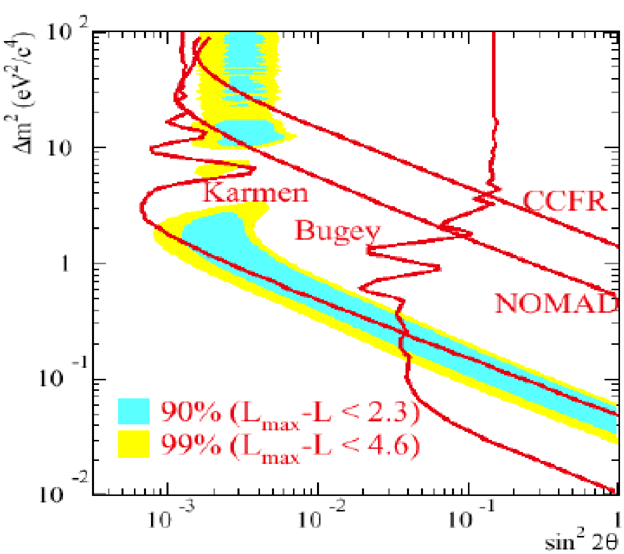
To explain it, one possibility may be $\Delta m^2 \approx 1\ eV^2$



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

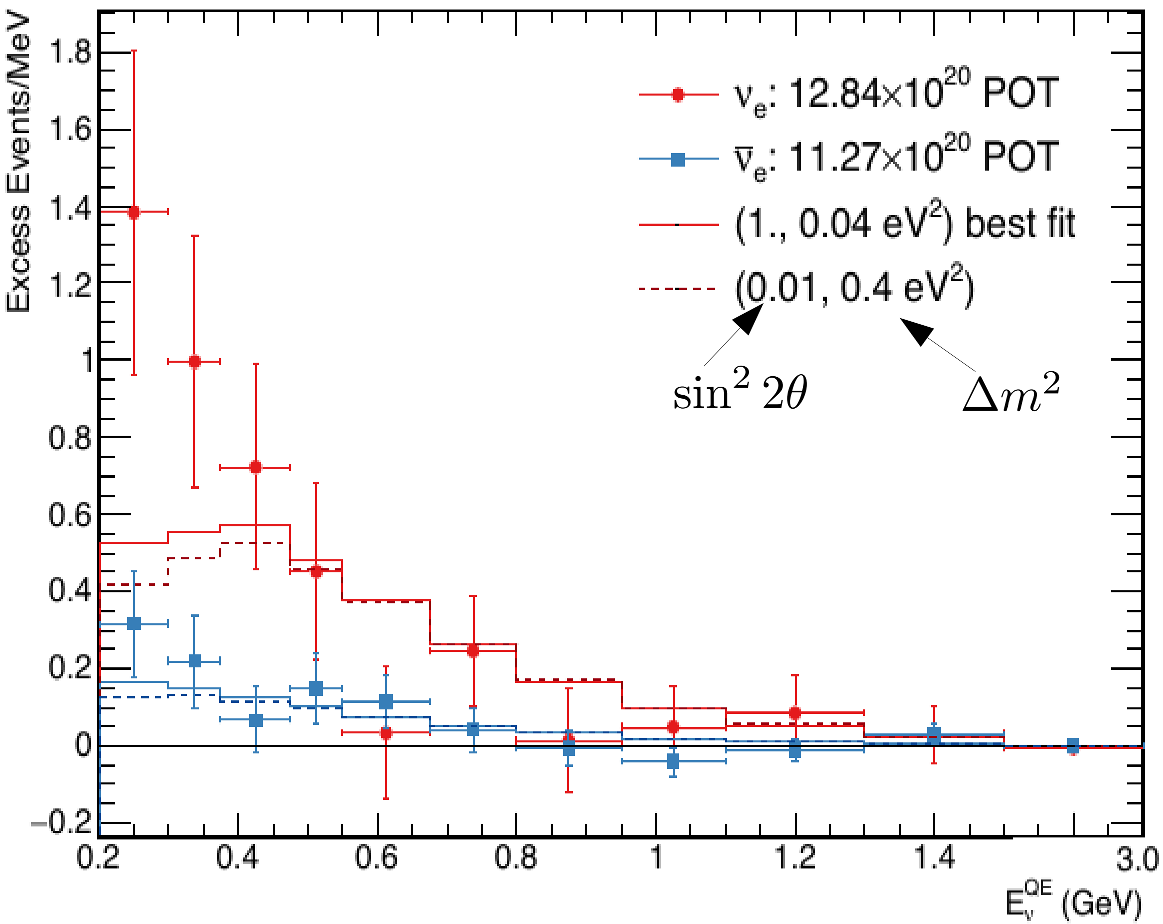
The signal can be explained if $\Delta m^2 \gtrsim 0.1\ eV^2$

The Karmen (L $\sim$ 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

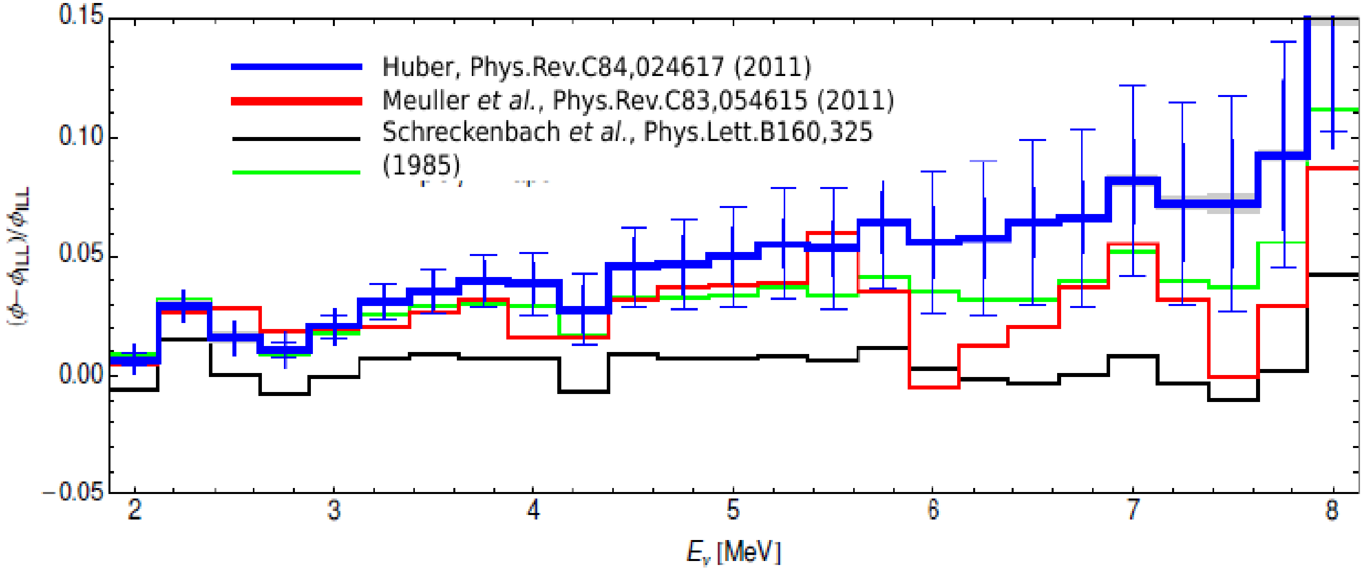
Observed 4.8σ excess events at low energy both for neutrino and antineutrino mode.

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

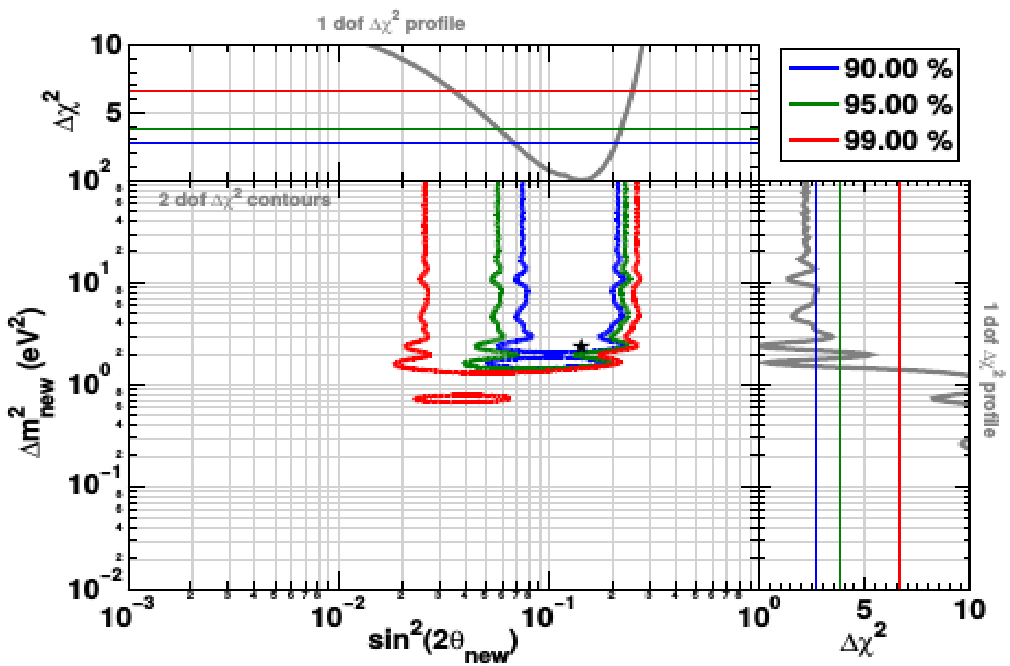
New analyses (blue and red) of the reactor $\overline{\nu}e$ spectrum predict a 3% higher flux than the existing calculation (black).



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

Obs. events < expected

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

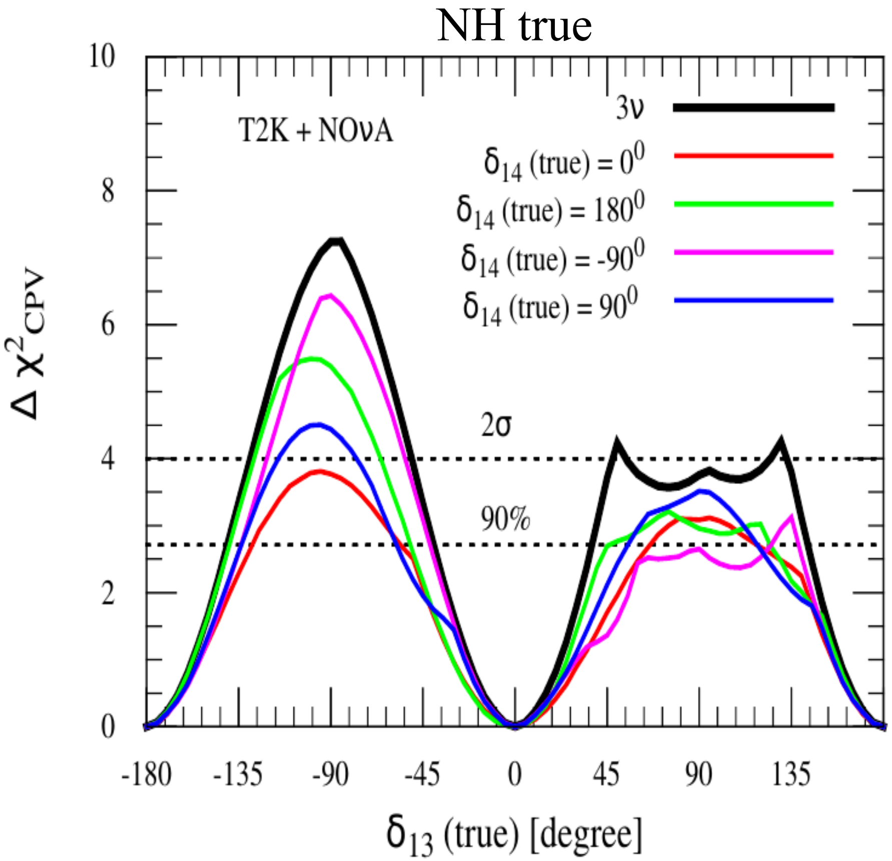


Might require eV scale sterile neutrino to explain the anomaly

See "The reactor antineutrino anomaly" by G Mention

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

Future prediction from T2K + NOvA

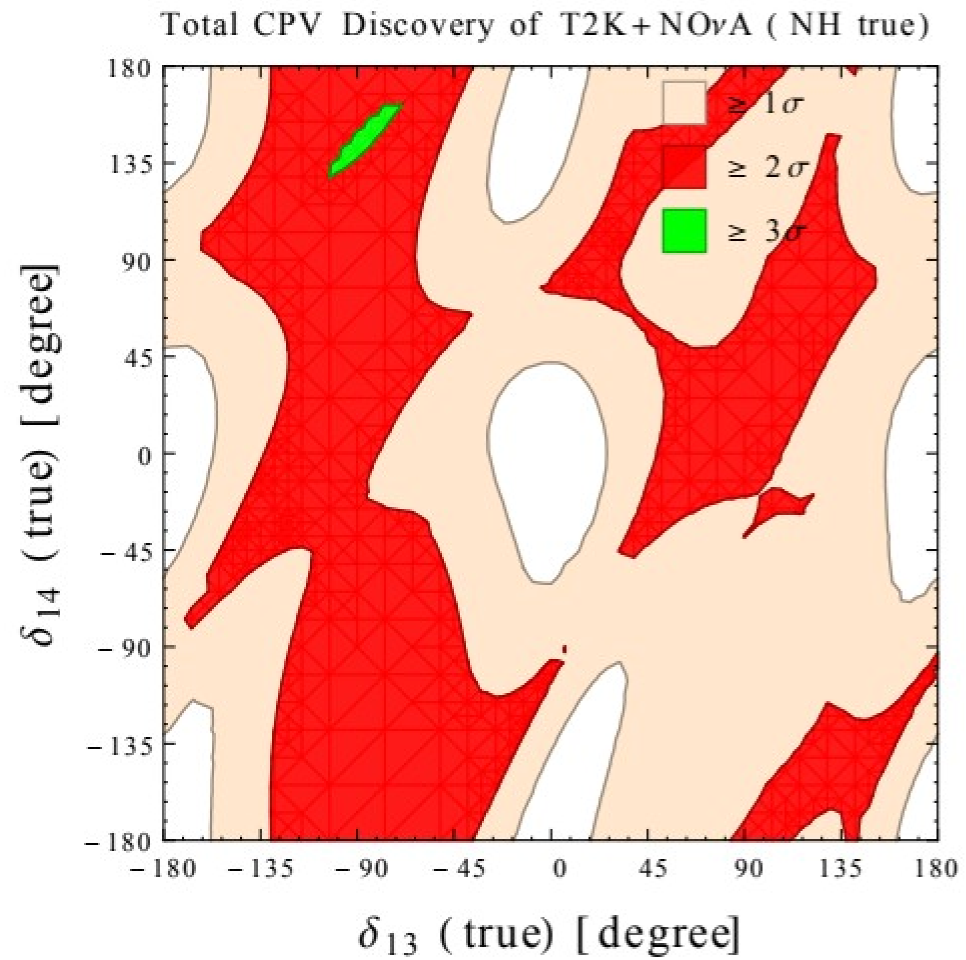


CPV discovery induced by δ_{13} gets deteriorated in the presence of sterile neutrino

CPV induced by δ_{14} never reaches 2σ C.L.

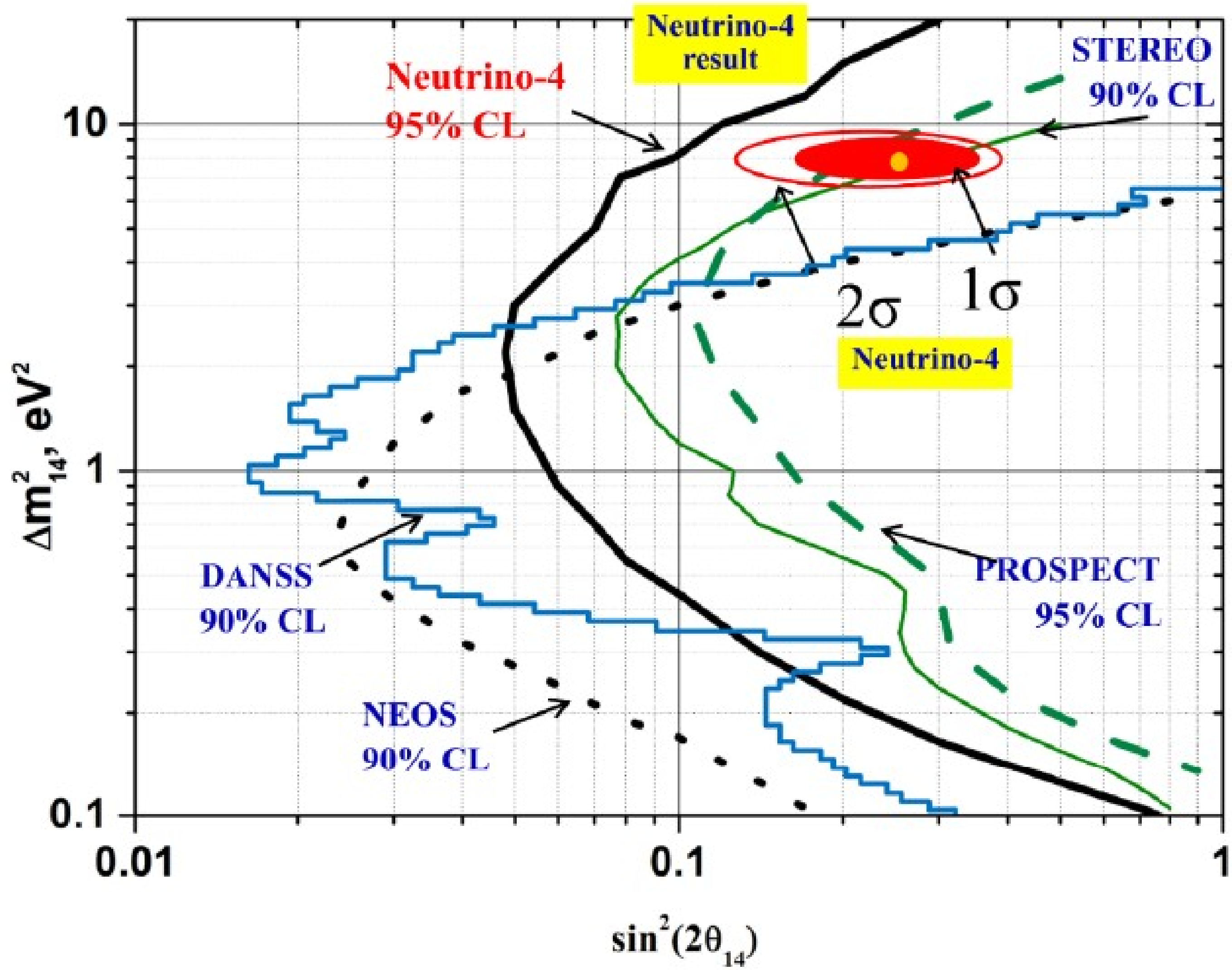
MH marginalized

Total CPV discovery



Source of CPV is not known

JHEP 02 (2016) 111 by Agarwalla, SSC, Dasgupta, and Palazzo



Experiments	Preference over SM
DANSS	1.5σ
NEOS	No significance
Neutrino-4	3.2σ