Neutral Current Events

and the Long-baseline neutrino experiments

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The impact of sterile neutrinos on CP measurements at long baselines

Raj Gandhi, Boris Kayser, Mehedi Masud, Suprabh Prakash

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Journal-ref: JHEP 1511 (2015) 039

arXiv:1607.02152 [pdf, other]

Capabilities of long-baseline experiments in the presence of a sterile neutrino

Debajyoti Dutta, Raj Gandhi, Boris Kayser, Mehedi Masud, Suprabh Prakash

Comments: Published in JHEP, 24 pages, 12 figures, IH results added

Journal-ref: JHEP 11(2016)122

arXiv:1708.01816 [pdf, other]

What measurements of neutrino neutral current events can reveal

Raj Gandhi, Boris Kayser, Suprabh Prakash, Samiran Roy

Comments: 22 pages, 10 figures

Journal-ref: JHEP 1711 (2017) 202

Implications from previous works

From a probability and event rate analysis, we show that the effects of the sterile oscillation parameters can be large at the chosen baseline of 1300 km.

Depending on the values of sterile mixing angles and phases, the sensitivities can be both significantly enhanced or suppressed compared to the 3+0 case.

We have noted above that in the presence of even a single sterile neutrino, conclusions such as a) CP is conserved or violated, or, b) if the latter, whether the violation is ascribable to the active neutrinos or the additional sterile neutrino, or a combination of the two, are all rendered significantly ambiguous.

A precise knowledge of the source fluxes, relevant cross-sections and the reduction of systematic errors by a near detector assumes an even more crucial role than it did before.

Synergistic linkage between global LBL and SBL efforts.

Sterile neutrinos and NC measurements

Most studies of new physics at long and short-baselines have focused on the charged current measurements. We investigate the potential of the neutral current (NC) events at these experiments.

NC events can comprise:

neutrino-nucleon $\nu + A \rightarrow \nu + A$

neutrino-electron elastic scattering $\nu + e \rightarrow \nu + e$,

neutrino deep-inelastic scattering $\nu + n \rightarrow \nu + X$,

neutrino-nucleon resonant scattering $\nu + p \rightarrow \nu + p + \pi^0$ (or $n + \pi^+$),

$\nu + n \rightarrow \nu + n + \pi^0$ (or $p + \pi^-$)

neutrino coherent pion scattering $\nu + A \rightarrow \nu + A + \pi^0$.

Sterile neutrinos and NC measurements

The measurement and study of NC events can in some cases provide a qualitatively different, complementary and statistically superior handle on neutrino properties in new physics scenarios compared to CC measurements.

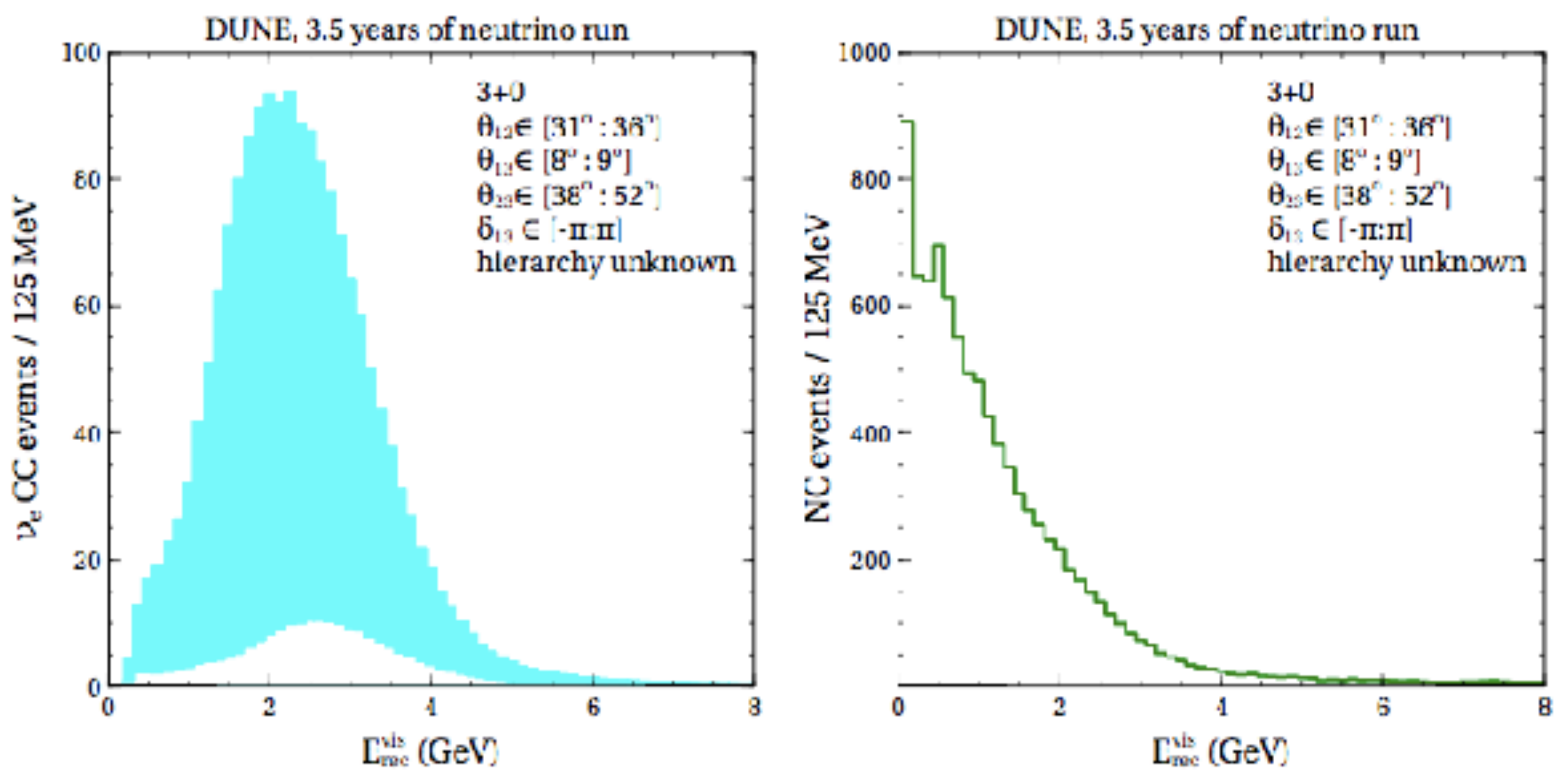


Figure 1: The left and right panel correspond to ν_e CC and NC events respectively. Here, all parameters are varied in their currently allowed range. E_{rec}^{vis} represents the reconstructed visible energy of the events in the detector. In the case of CC events, it closely matches the true energy of the incoming neutrino. For the NC events, E_{rec}^{vis} can be very different from the true incoming neutrino energy, as we discuss later.

NC event measurements are typically statistically rich. For instance, in the Deep Underground Neutrino Experiment (DUNE), a 7-ton fine-grained tracking near detector at 500 m is planned, and it is expected to detect in excess of 400000 NC current events in a year. Even at long baselines, NC events are typically higher in number compared to any one measured CC channel.

Short baselines and CPV - 3+2

The oscillation probability between the flavours α and β can be given by:

$$P(\alpha \to \beta) = \delta_{\alpha\beta} - 4Re\sum_{k>j}(U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j})\sin^2\Delta_{kj}$$
$$+ 2Im\sum_{k>j}(U^*_{\alpha k}U_{\beta k}U_{\alpha j}U^*_{\beta j})\sin 2\Delta_{kj}.$$

- Express $P_{\mu e}$, and $P_{NC} = 1 - P_{\mu s1} - P_{\mu s2}$ in the above form.
- Calculate $D_{NC} = P_{NC} - \mathrm{bar}(P_{NC})$ and $D_{CC} = P_{\mu e} - \mathrm{bar}(P_{\mu e})$

Short baselines and CPV - 3+2

In a scenario geared towards explaining the short baseline anomalies [49–53], further simplifications are possible, *e.g.* $\delta m^2_{lm} >> \delta m^2_{mn}$, $l = 4$ or $l = 5$, $m, n = 1, 2, 3$ [5]. After a little algebra, one then finds that the CP violating difference between NC events measured using an initially muon-flavoured neutrino beam, and those measured using its anti-neutrino counterpart, will be proportional to the quantity D_{NC}, given by

$$D_{NC} \propto Im\left[U^*_{\mu 5} U_{\mu 4} (U_{s_1 5} U^*_{s_1 4} + U_{s_2 5} U^*_{s_2 4})\right] \sin\Delta_{54} \sin\Delta_{43} \sin\Delta_{53}. \tag{2.5}$$

On the other hand, the analogous difference for CC events from $\nu_\mu \to \nu_e$ transitions is proportional to

$$D_{CC} \propto Im\left[U^*_{\mu 5} U_{\mu 4} U_{e5} U^*_{e4}\right] \sin\Delta_{54} \sin\Delta_{43} \sin\Delta_{53}. \tag{2.6}$$

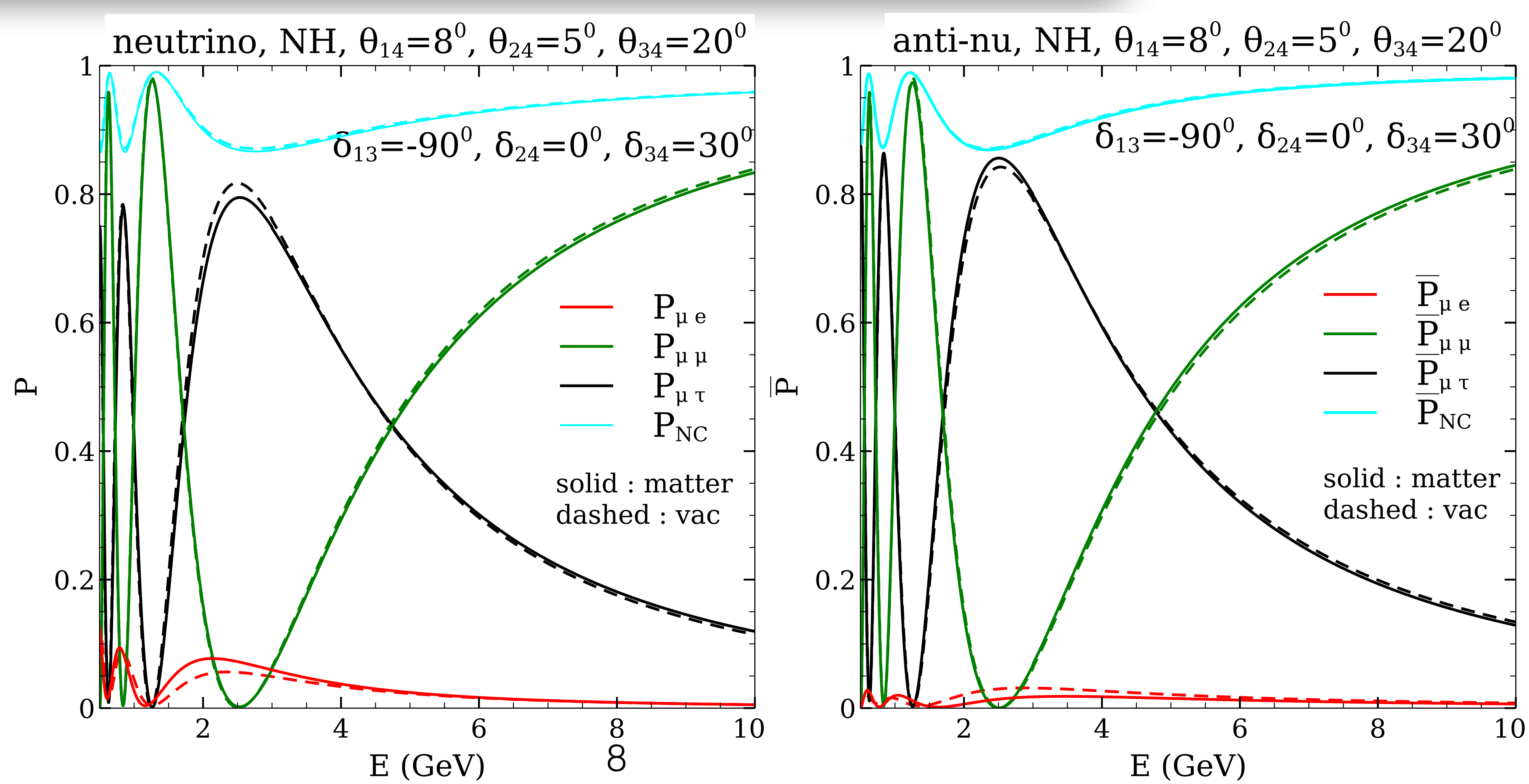
Thus, it can be said that CC and NC channels in general would tap into different CPV phases. Consequently, the NC measurements will provide a qualitatively and quantitatively different window into the CP violating and mixing sectors of a new physics scenario compared to the CC measurements.

$P_{\mu s}$: sterile neutrino appearance probability

$$U^{3+1}_{\rm PMNS} = O(\theta_{34},\delta_{34})O(\theta_{24},\delta_{24})O(\theta_{14})O(\theta_{23})O(\theta_{13},\delta_{13})O(\theta_{12})$$

$$\begin{aligned}
\mathrm{P}^{\rm vac}_{\mu s} \simeq\ & \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\frac{\Delta m^2_{41}L}{4E} \\
&+ \Big[\cos^4\theta_{13}\cos^2\theta_{24}\sin^2\theta_{34} - \cos^2\theta_{13}\cos^2\theta_{24}\cos^2\theta_{34}\sin^2\theta_{24} \\
&+ \frac{1}{\sqrt{2}}\sin 2\theta_{13}\sin 2\theta_{34}\sin\theta_{14}\cos^3\theta_{24}\cos(\delta_{13}+\delta_{34})\Big]\sin^2\frac{\Delta m^2_{31}L}{4E} \\
&+ \frac{1}{2}\cos^2\theta_{13}\cos^2\theta_{24}\sin 2\theta_{34}\sin\theta_{24}\sin(\delta_{34}-\delta_{24})\sin\frac{\Delta m^2_{31}L}{2E}.
\end{aligned}$$

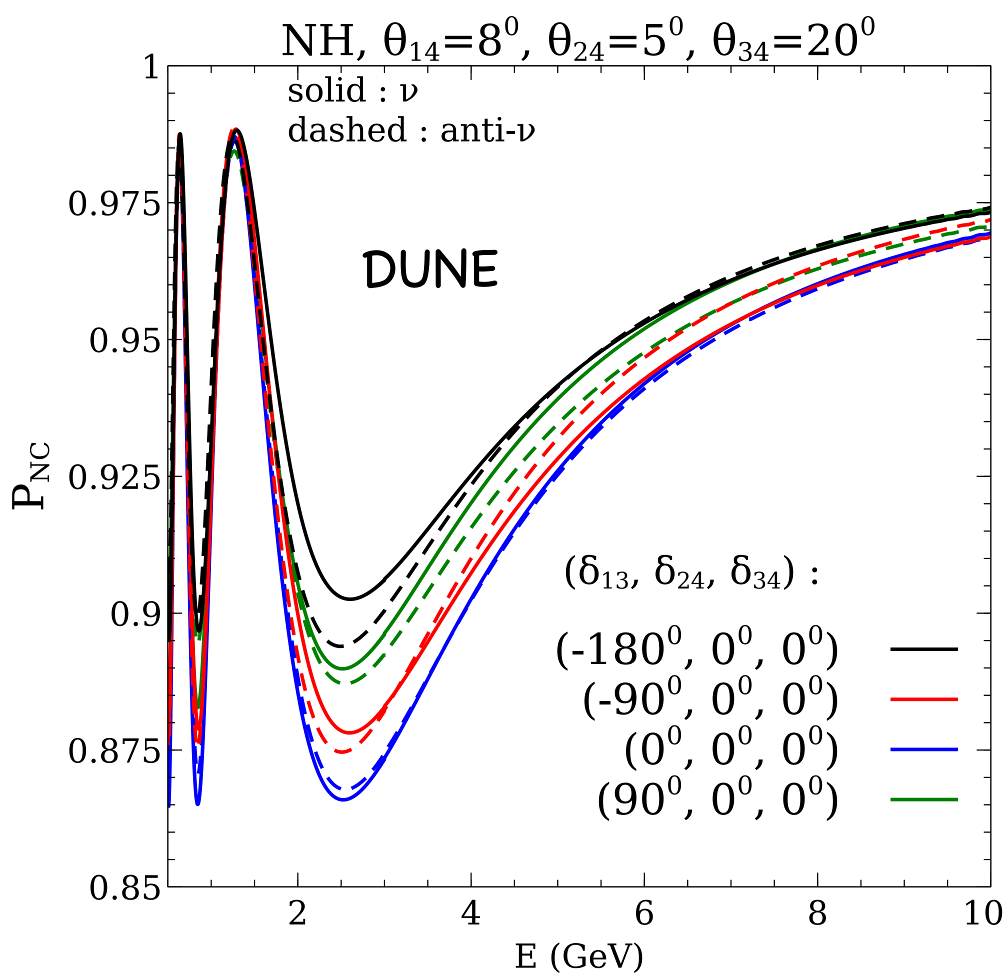
for DUNE
$P_{NC} = 1 - P_{\mu s}$

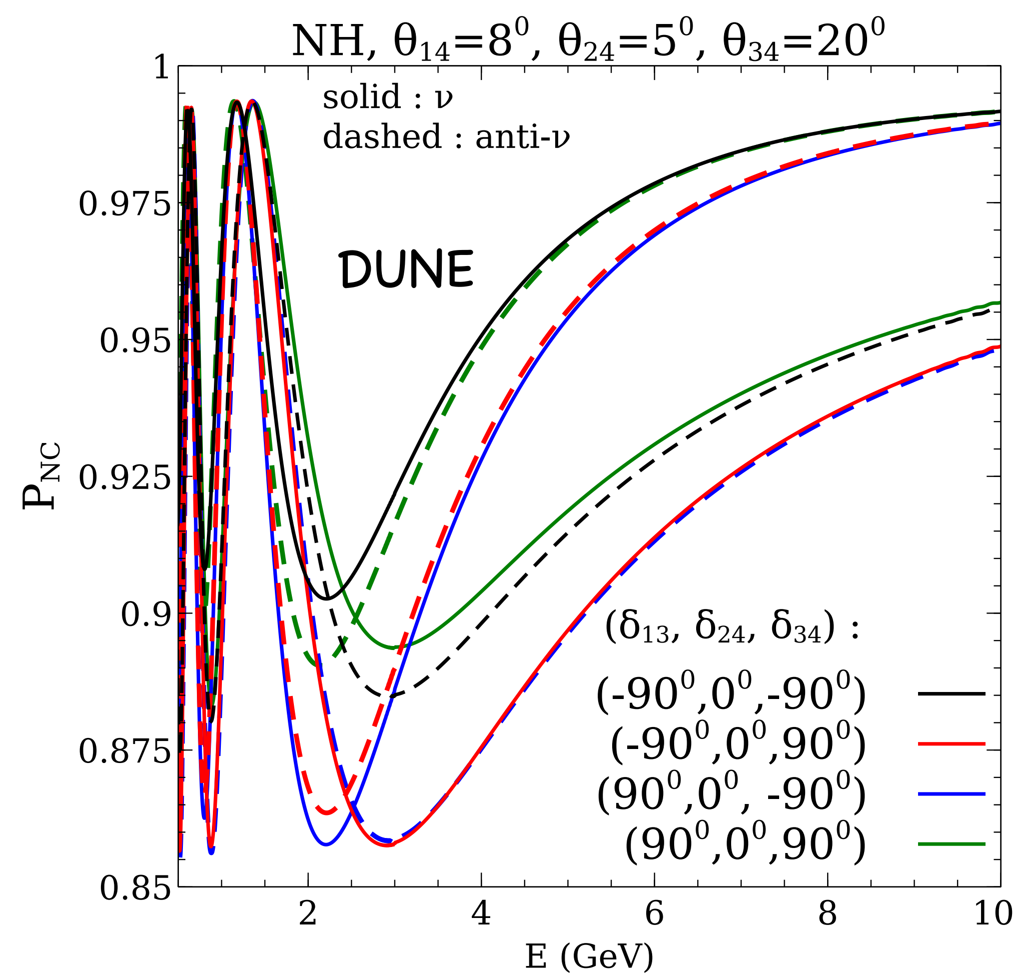


$P_{\mu s}$: sterile neutrino appearance probability

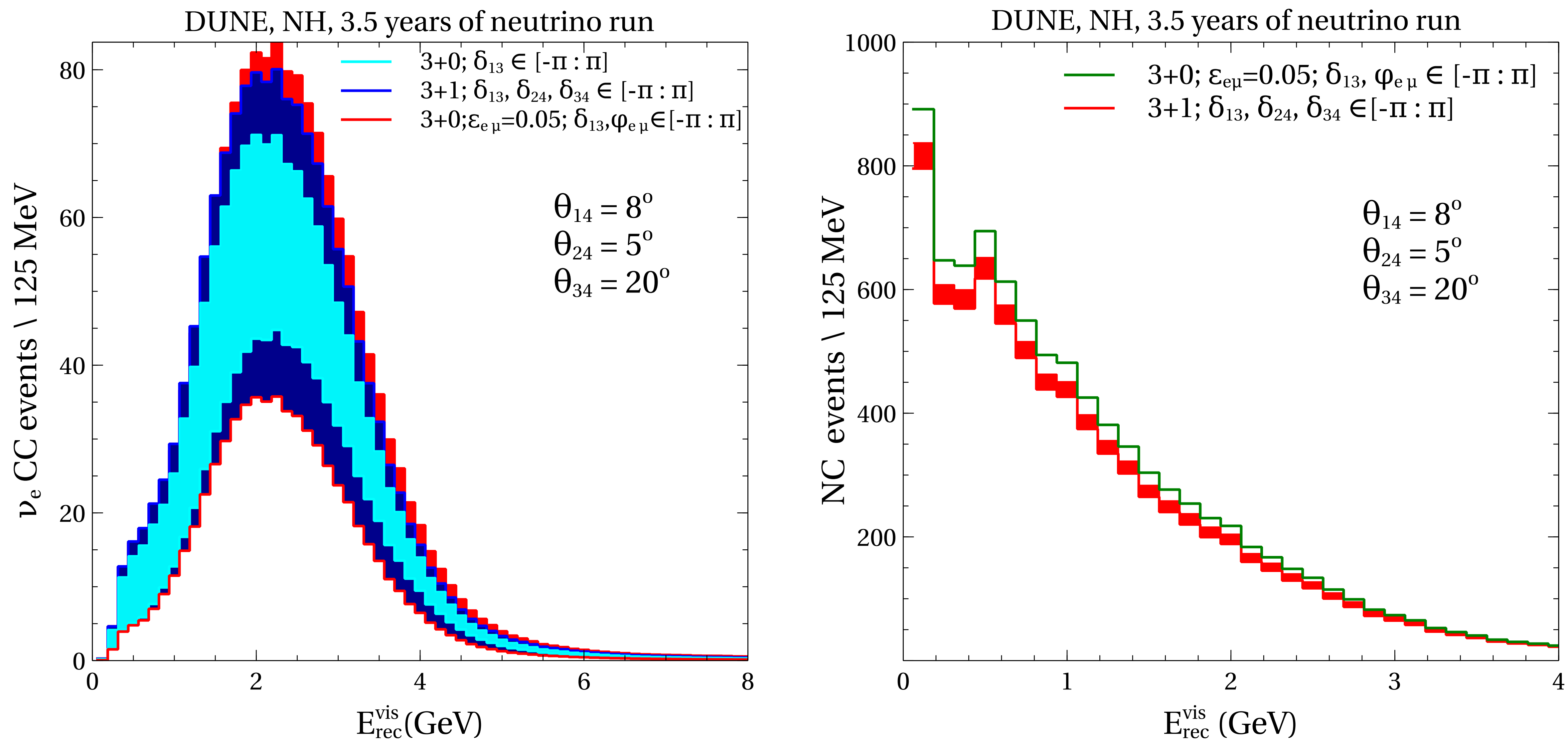
$$
\begin{aligned}
P^{\rm vac}_{\mu s} \simeq\ & \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\frac{\Delta m^2_{41}L}{4E} \\
& + \Big[\cos^4\theta_{13}\cos^2\theta_{24}\sin^2\theta_{34} - \cos^2\theta_{13}\cos^2\theta_{24}\cos^2\theta_{34}\sin^2\theta_{24} \\
& + \frac{1}{\sqrt{2}}\sin 2\theta_{13}\sin 2\theta_{34}\sin\theta_{14}\cos^3\theta_{24}\cos(\delta_{13}+\delta_{34})\Big]\sin^2\frac{\Delta m^2_{31}L}{4E} \\
& + \frac{1}{2}\cos^2\theta_{13}\cos^2\theta_{24}\sin 2\theta_{34}\sin\theta_{24}\sin(\delta_{34}-\delta_{24})\sin\frac{\Delta m^2_{31}L}{2E}.
\end{aligned}
$$

Note the y axis scale!!





NC events as a tool to distinguish new physics scenarios



While we choose propagation based non-standard interactions (NSI) and a 3+1 sterile scenario to demonstrate our point, our conclusion will hold for any two new physics settings, one of which does not break 3+0 unitarity (in this example, the propagation NSI) and another one which does (3+1 sterile). A similar conclusion would hold, for example, for NSI in propagation and neutrino decay, or NSI in propagation and NSI in production or detection (which inherently violate unitarity by adding to or depleting the source neutrino beam).

Constraints on the mixings

[8] It should be noted that there are global analyses of the existing oscillation data that provide constraints on the 3+1 paradigm [65–67]. However, there exist differences in their results corresponding to the fits in the parameter space $\Delta m^2_{41} - \sin^2\theta_{34}$. There is also the difficulty in reconciling the appearance data with the disappearance data. Keeping these points in mind, we adhere to the constraints on 3+1 from the disappearance data from the above-mentioned standalone experiments.

[65] J. Kopp, P. A. N. Machado, M. Maltoni, and T. Schwetz, JHEP **05**, 050 (2013), 1303.3011.

[66] G. H. Collin, C. A. Argelles, J. M. Conrad, and M. H. Shaevitz, Phys. Rev. Lett. **117**, 221801 (2016), 1607.00011.

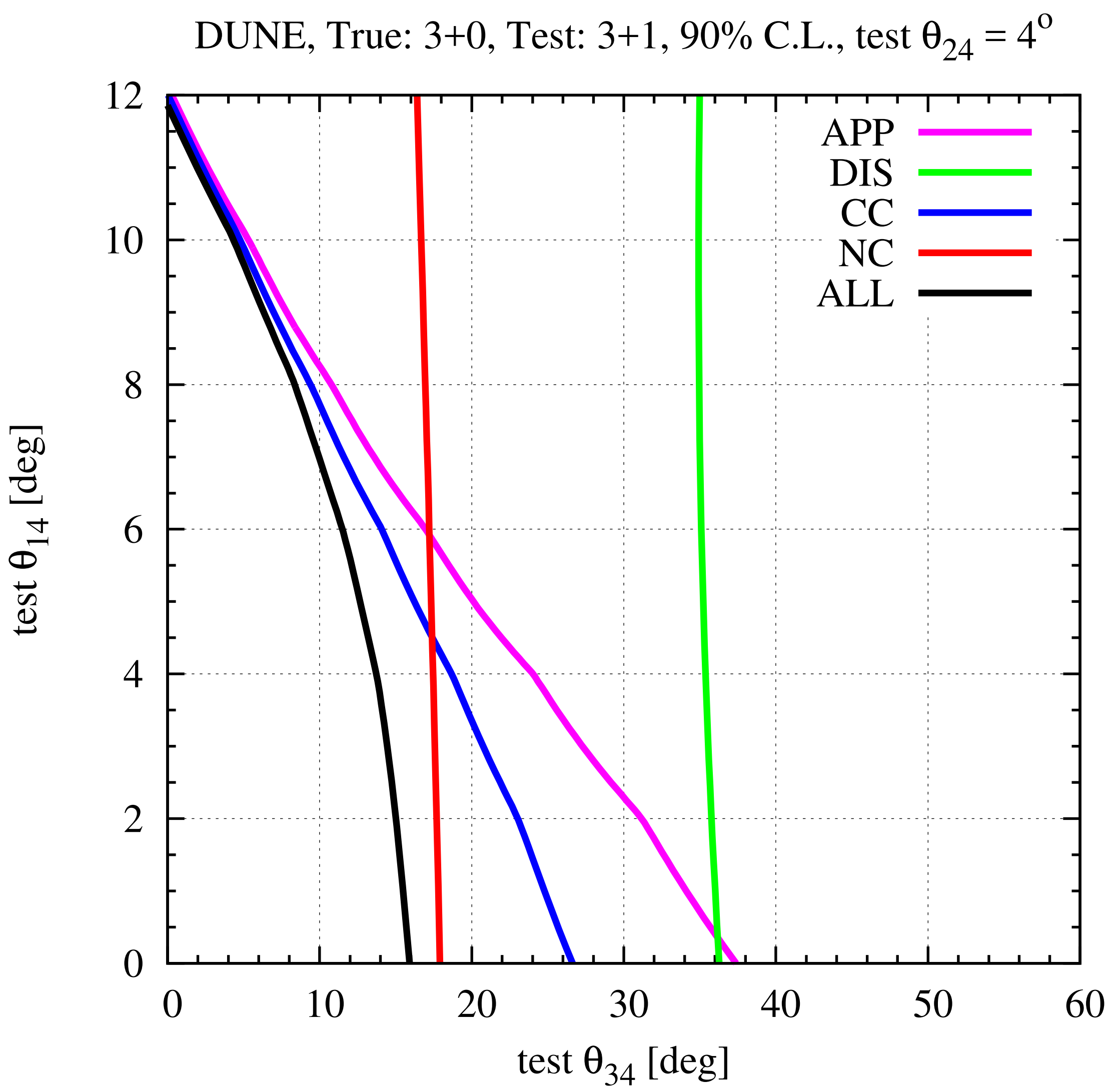
[67] S. Gariazzo, C. Giunti, M. Laveder, and Y. F. Li, JHEP **06**, 135 (2017), 1703.00860.

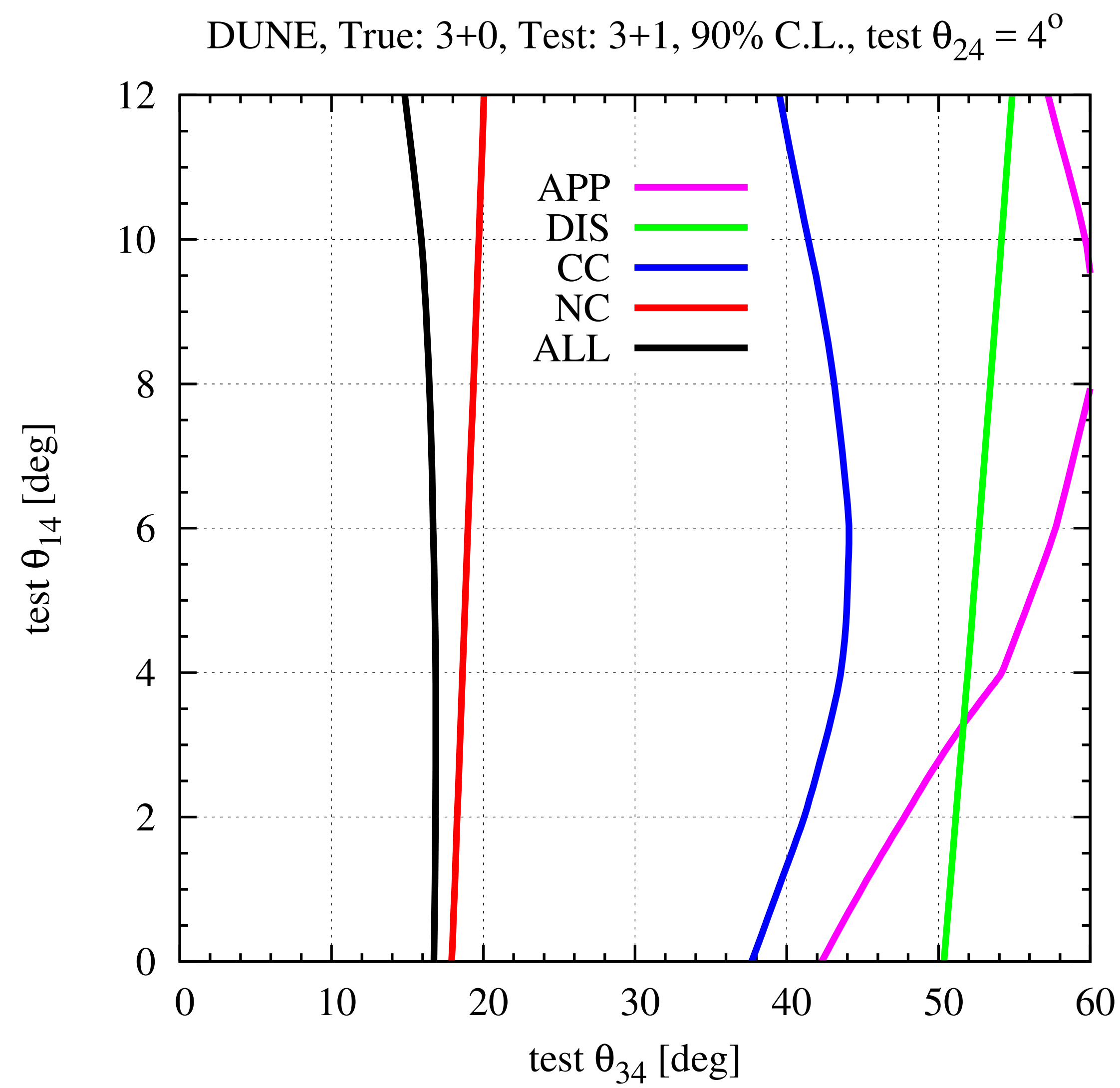
P. Adamson et al. (NOvA) (2017), 1706.04592

TABLE III: The 90% C.L. upper limits on sterile mixing angles and matrix elements for NOvA compared to MINOS [24], Super-Kamiokande [26], IceCube [27], and IceCube-DeepCore [68]. The limits are shown for $\Delta m^2_{41} = 0.5$ eV^2 for all experiments, except for IceCube-DeepCore, where the results are reported for $\Delta m^2_{41} = 1.0$ eV^2.

	θ_{24}	θ_{34}	$\lvert U_{\mu 4}\rvert^2$	$\lvert U_{\tau 4}\rvert^2$
NOvA	20.8°	31.2°	0.126	0.268
MINOS	7.3°	26.6°	0.016	0.20
SuperK	11.7°	25.1°	0.041	0.18
IceCube	4.1°	-	0.005	-
IceCube-DeepCore	19.4°	22.8°	0.11	0.15

Constraining 3+1 with NC events



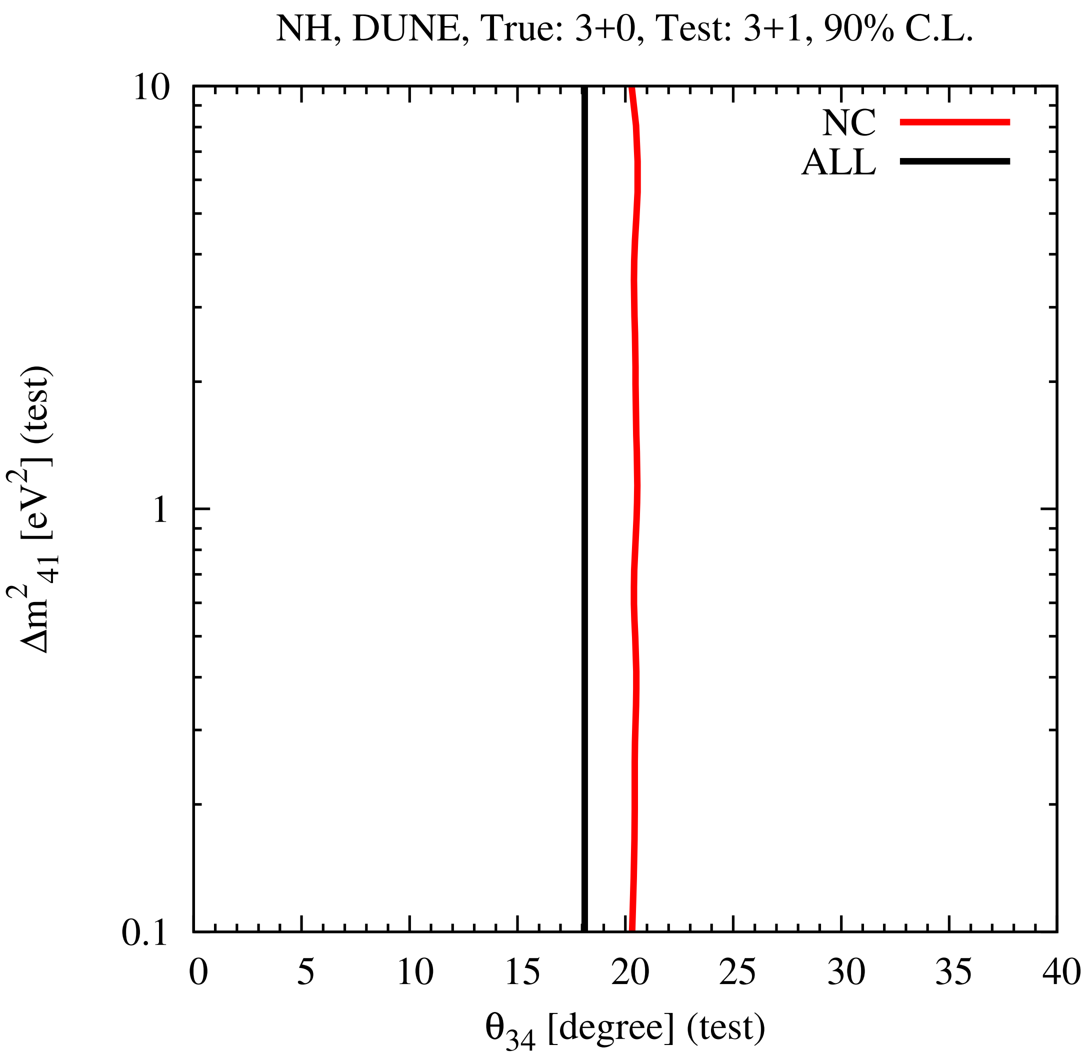


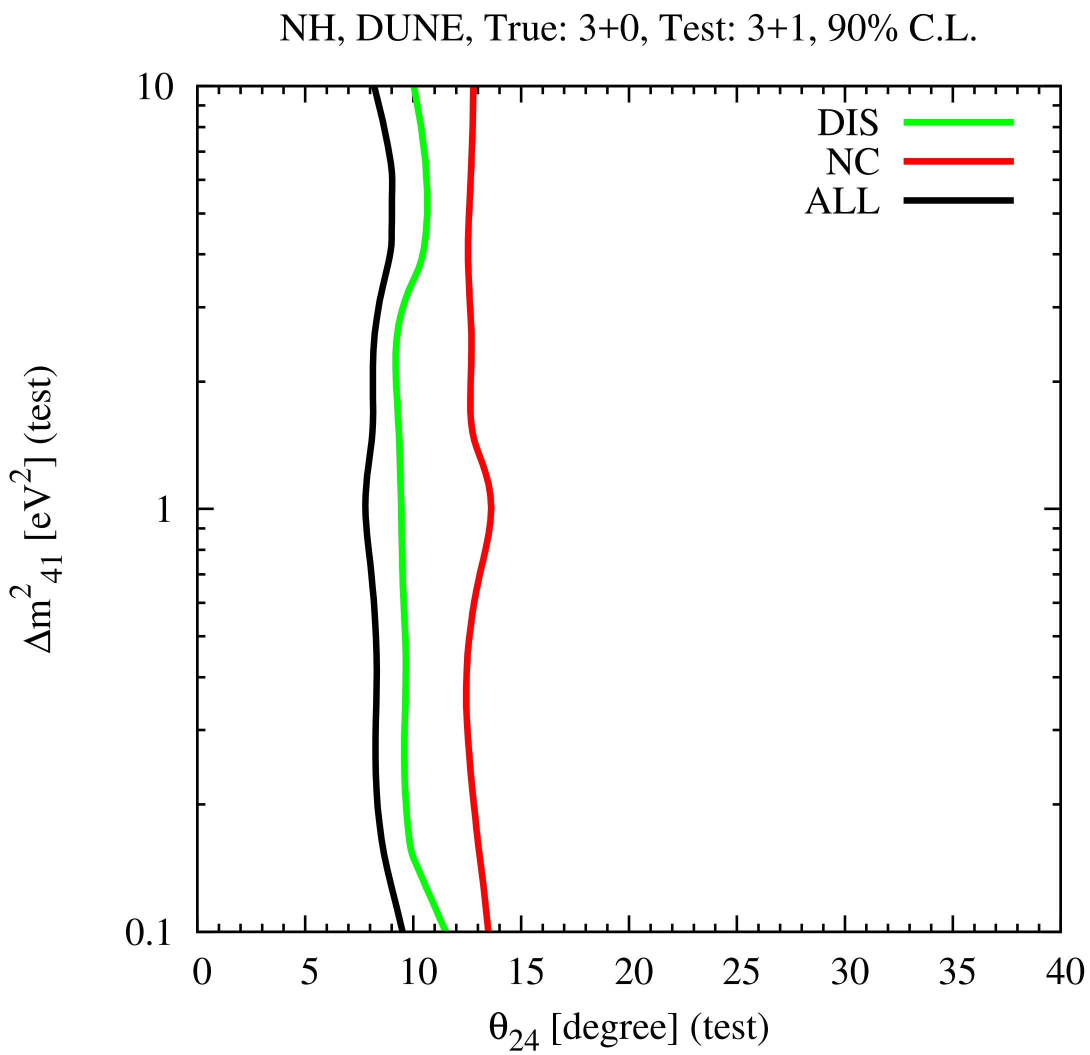
Left: CP phases fixed at true values
Right: CP phases varied in the fit

test Δm^2_{41} = 1 eV^2
true δ_{13} = -90^o

Even with CP violating phases present, it would be easier to rule out a moderately large value of Θ_{34} with the NC data compared to ruling out moderately large values of Θ_{14} and Θ_{24} with the CC data

Constraining 3+1





sensitivity to the exclusion of Θ_{34} comes from the NC data

sensitivity to the exclusion of Θ_{24} comes from the disappearance data

DUNE can provide a strong constraint on Θ_{24} and Θ_{34} that is relatively independent of test Δm^2_{41}

arXiv:hep-ph/1707.05348

DUNE sensitivities to the mixing between sterile and tau neutrinos

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(Dated: July 17, 2017)

Implications & Conclusions

We examine how NC events can synergistically aid the search for new physics and CP violation when combined with other measurements.

We show that typically the NC events offer a window to CP phases and mixing angles that is complementary to that accessed by CC event measurements.

They can break degeneracies existing in CC measurements, allowing one to distinguish between new physics that violates 3+0 unitarity and new physics that does not.

NC events seem not to be affected greatly by matter effects which arise at energies and baselines relevant to DUNE, rendering analytical understanding of new physics somewhat easier.

Thank you :)

Sterile Neutrinos

The standard three flavour framework provides a satisfactory fit to most of the existing data.

However, there are several observed anomalies (excesses or deficits) in the data which cannot be fit with a three flavour framework.

These anomalies can be accommodated (in varying capacities) in an extended framework where we have one or more additional neutrino flavours.

From LEP measurements, the number of active neutrinos which participate in the weak interactions can only be three. Therefore, these additional flavours must be $SU(2) \times U(1)$ singlets.

These "Sterile" neutrinos will not undergo any of the known standard interactions except gravitational.

They can however mix with the active flavours and can possibly be detected via neutrino oscillations.

Latest Oscillation Measurements

Status of neutrino oscillations 2017

P. F. de Salas, D. V. Forero, C. A. Ternes, M. Tortola, J. W. F. Valle

parameter	best fit $\pm$ 1σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.56$\pm$0.19
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.55$\pm$0.04
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	2.49$\pm$0.04
$\sin^2\theta_{12}/10^{-1}$	$3.21^{+0.18}_{-0.16}$
$\theta_{12}/^\circ$	$34.5^{+1.1}_{-1.0}$
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$ [a]
$\theta_{23}/^\circ$	41.0$\pm$1.1
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.96^{+0.17}_{-0.18}$ [b]
$\theta_{23}/^\circ$	50.5$\pm$1.0
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.155^{+0.090}_{-0.075}$
$\theta_{13}/^\circ$	$8.44^{+0.18}_{-0.15}$
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.140^{+0.082}_{-0.085}$
$\theta_{13}/^\circ$	$8.41^{+0.16}_{-0.17}$
δ/π (NO)	$1.40^{+0.31}_{-0.20}$
$\delta/^\circ$	252^{+56}_{-36}
δ/π (IO)	$1.44^{+0.26}_{-0.23}$
$\delta/^\circ$	259^{+47}_{-41}

hep-ex/0104049 PRD
1306.6494

The LSND experiment

Liquid Scintillator Neutrino Detector (1993-1998)
Los Alamos National Laboratory

Source: Decay-at-rest Pions

$\pi^+ \rightarrow \nu_\mu + \mu^+$

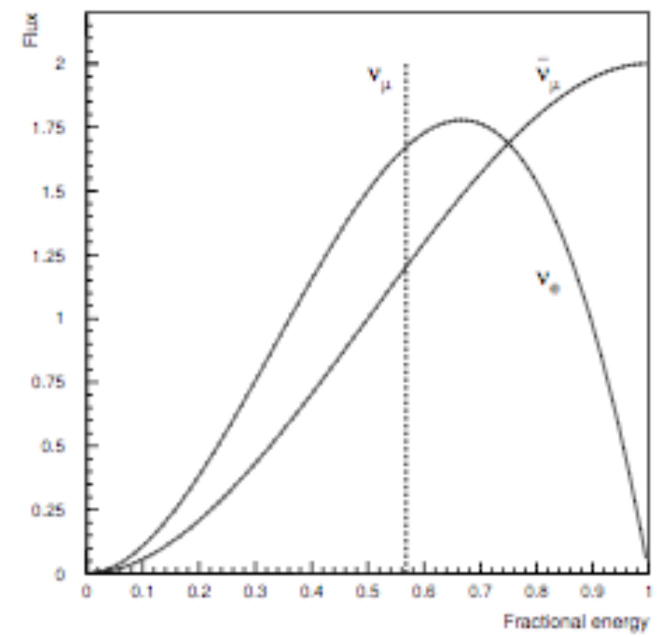
$\mu^+ \rightarrow$ anti-$\nu_\mu + \nu_e + e^+$

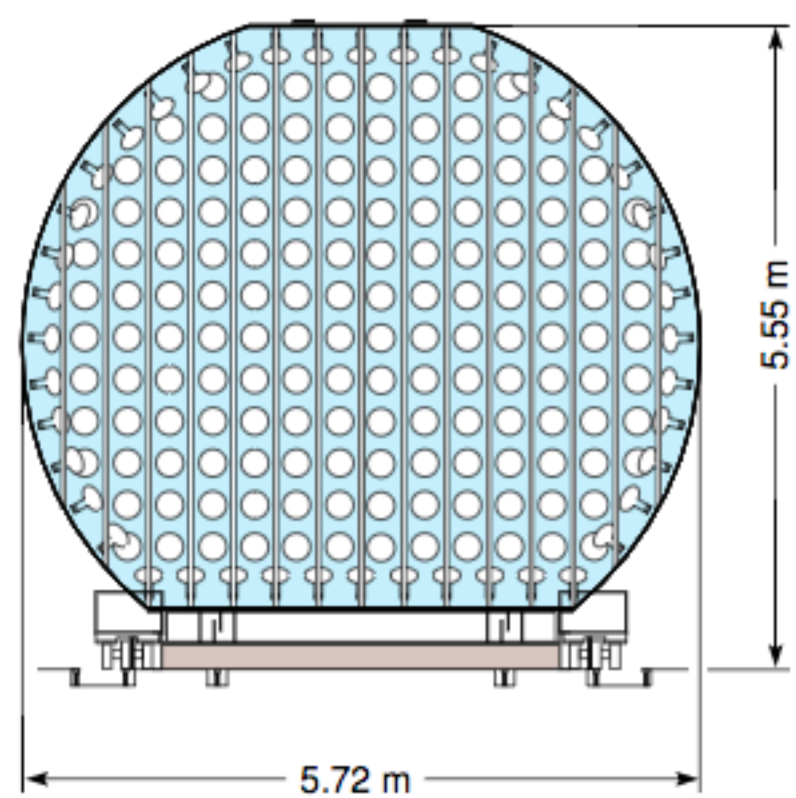
Signal events:
App: anti-ν_e + p $\rightarrow$ e^+ + n - IBD events
Correlated neutron capture - 2.2 MeV γ

Signal events:
Disapp: $\nu_e + {}^{12}C \rightarrow {}^{12}N_{gs} + e^-$
No correlated neutron capture

L = 30 m, $E_\nu \in$ **[20 MeV, 52 MeV]** **L/E ~ 1m/MeV**

Neutrino Fluxes





8.3 m long by 5.7 m in diameter

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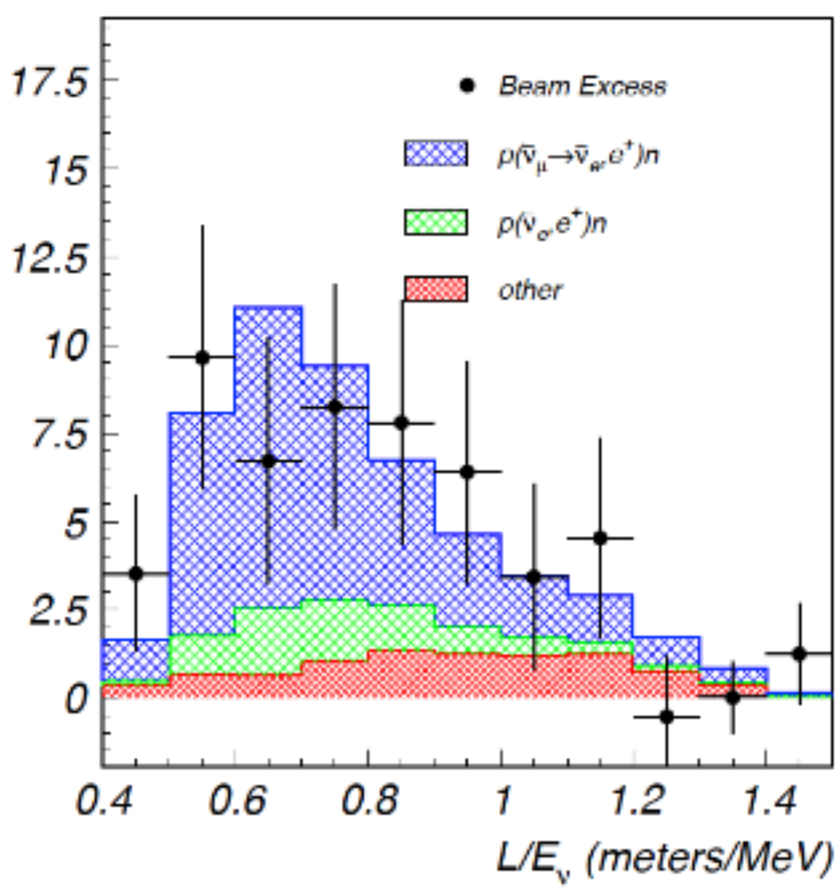
The LSND excess

LSND observed an excess of 87.9±22.4±6.0 events over the expected backgrounds

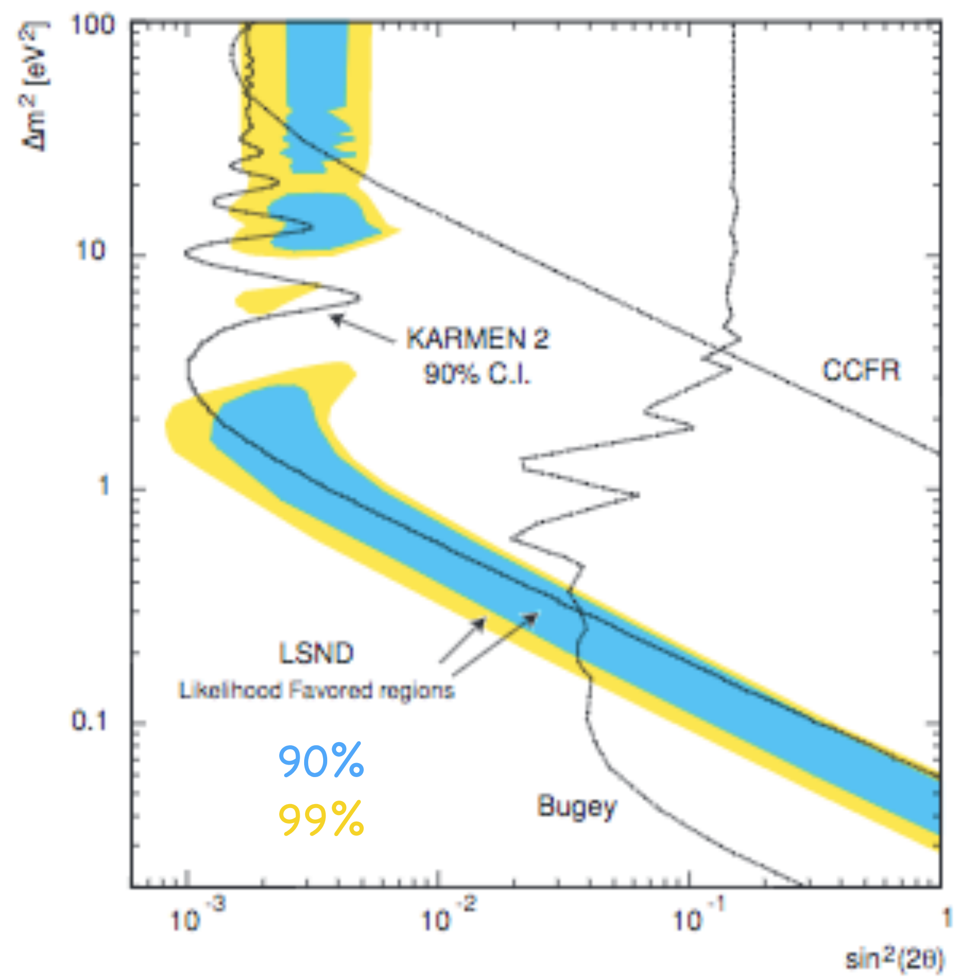
For 100% conversion of $\overline{\nu}_\mu$ to $\overline{\nu}_e$, 33,300±3,300 events expected.
Prob = (0.00264±0.00067±0.00045)



The Karlsruhe-Rutherford Medium Energy Neutrino

D-A-R beam, L = 17.7 m

N^{obs} = 15 anti-ν_e events, consistent with N^{exp}_{BG} = 15.8±0.5



MiniBooNE

Mini Booster Neutrino Experiment
made use of the conventional
decay-in-flight neutrino beam at Fermilab.

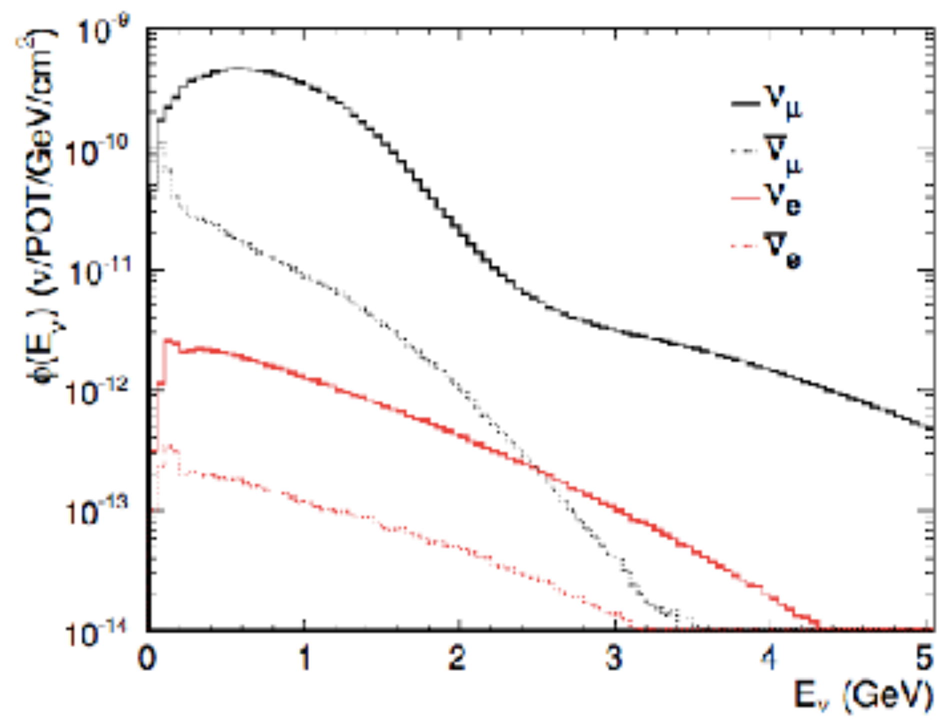
L = 541 m, peak E_ν ~ 800 MeV

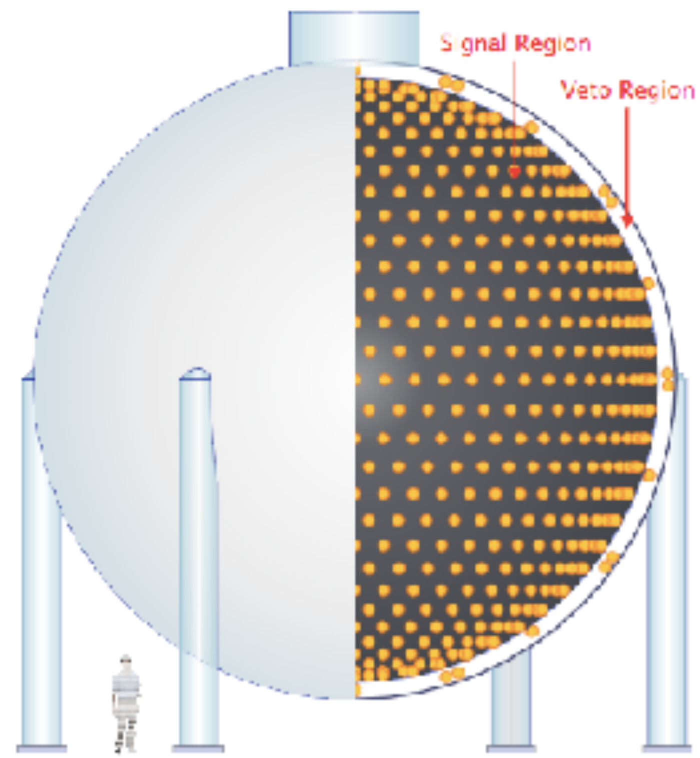
Although LSND and MiniBooNE
probe similar L/E region, they have
very different event signatures,
backgrounds and systematics.

2002 - 2012
ν : 6.46e20 POT
anti-ν: 11.27e20 POT

$\nu_\mu \rightarrow \nu_e$: $\nu_e + n \rightarrow e^- + p$
anti-$\nu_\mu \rightarrow$ anti-ν_e : anti-$\nu_e + p \rightarrow e^+ + n$
CCQE events

Booster Neutrino Beam





12.2 m diameter spherical
tank filled with Mineral Oil

1207.4809 PRL
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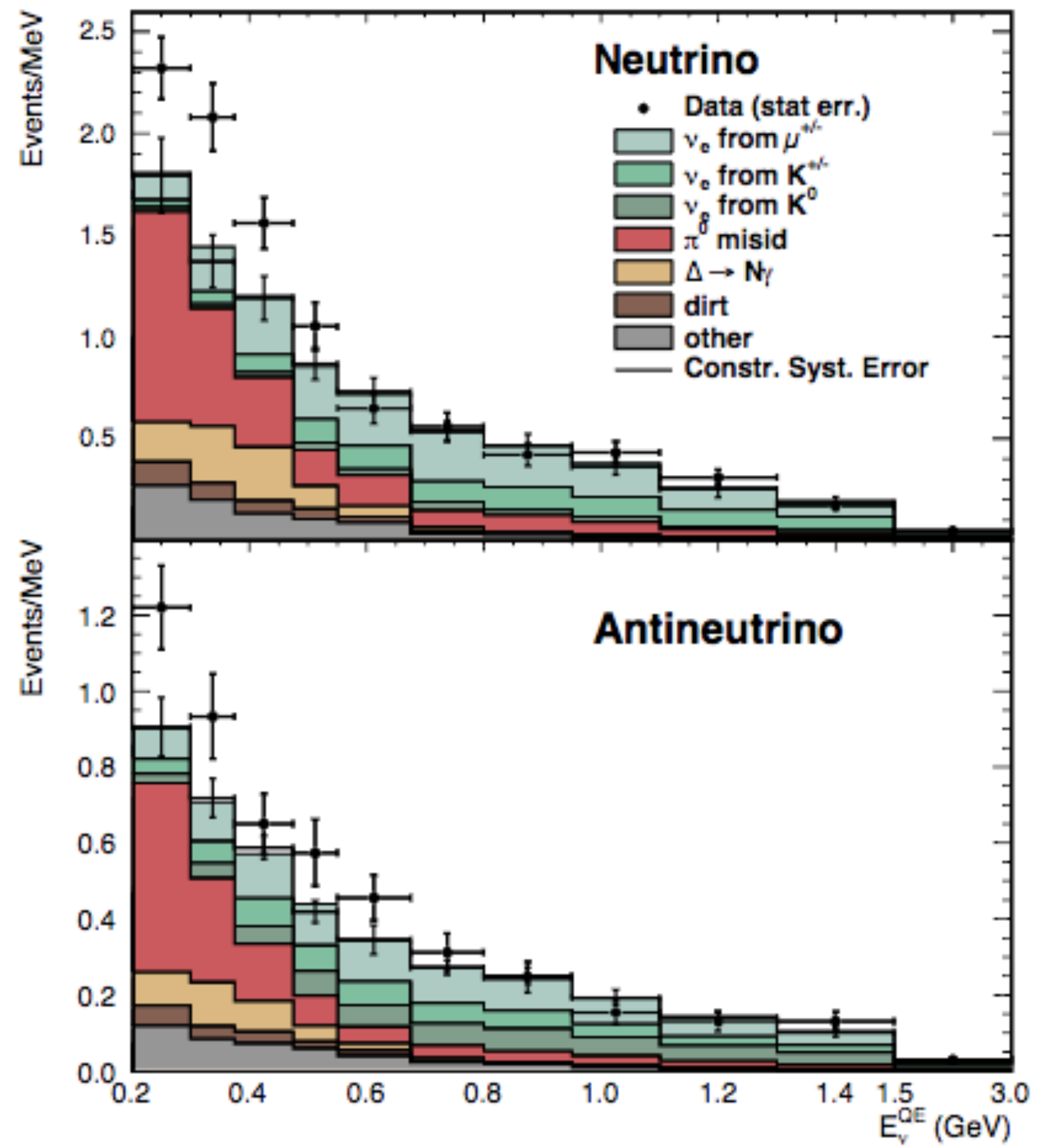
MiniBooNE results

$E_\nu^{QE} \in$ [200 MeV, 1250 MeV]

Low energy excess



ν mode:
expected BG: 790.0±28.1±38.7
observed: 952
excess: 162±47.8

anti-ν mode:
expected BG: 399.6±20.0±20.3
observed: 478
excess: 78.4±28.5

The backgrounds in MiniBooNE are very well understood and are constrained directly from in-situ measurements.

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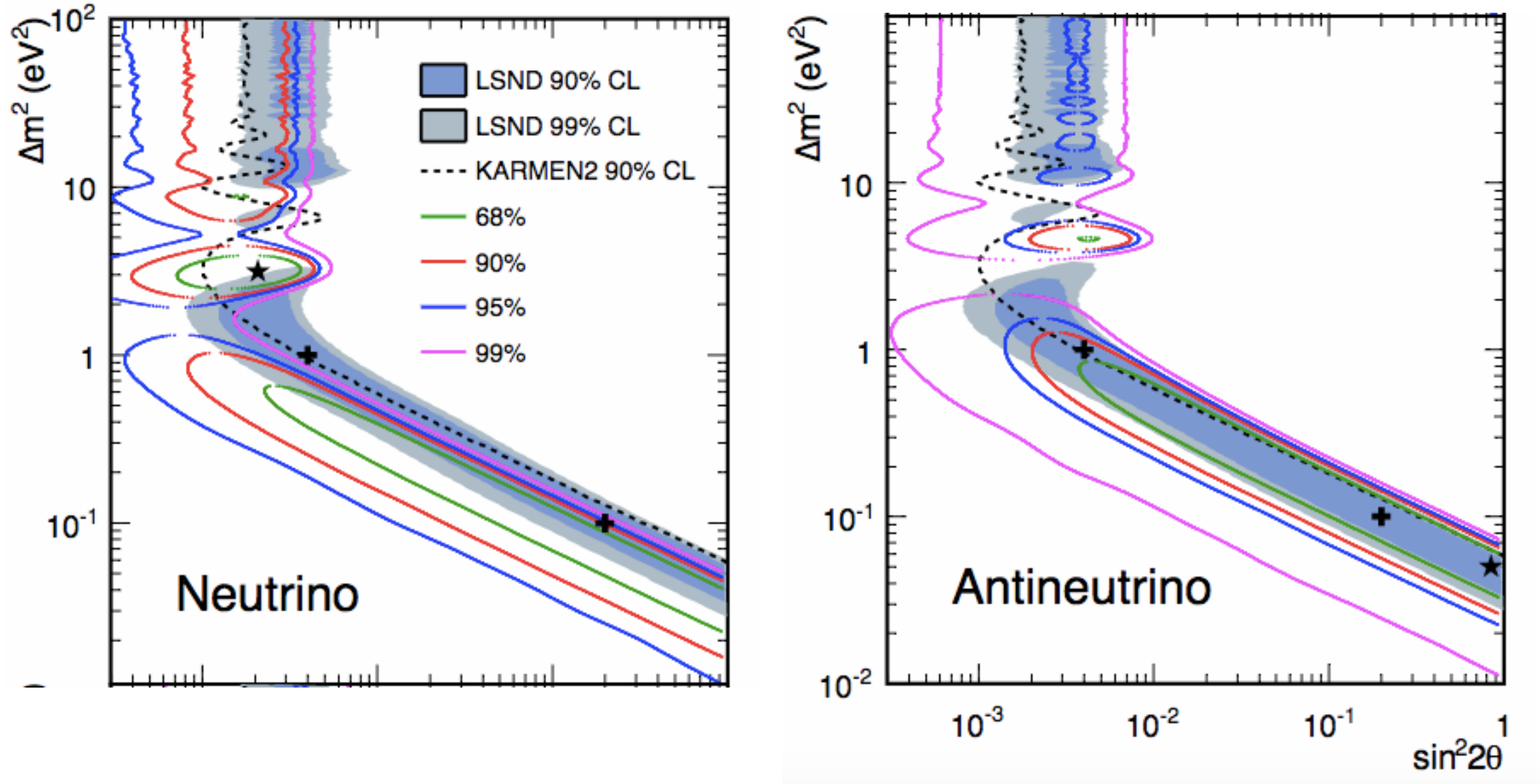
1306.6494

MiniBooNE results in 3+1

MiniBooNE anti-neutrino results are consistent with LSND

The neutrino results are less so!



LSND & MiniBooNE: Stressed-out 3+1

$$\sin^2 2\theta_{\mu\mu} = 4U_{\mu4}^2(1-U_{\mu4}^2) \quad (\mu\ flavor),$$

$$\sin^2 2\theta_{ee} = 4U_{e4}^2(1-U_{e4}^2) \quad (e\ flavor).$$

$$\sin^2 2\theta_{e\mu} = 4U_{e4}^2 U_{\mu4}^2.$$

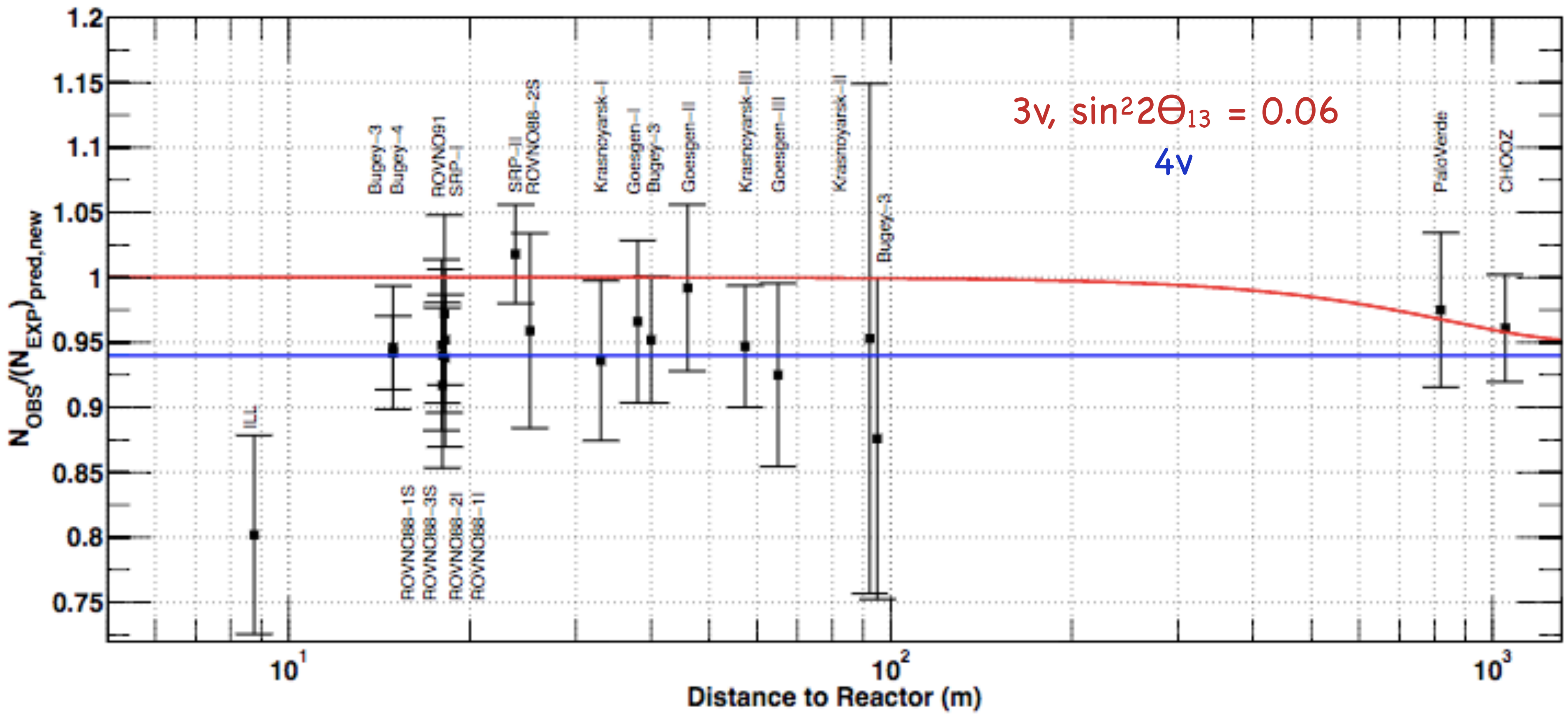
LSND - KARMEN cross section analyses : $|U_{e4}|^2 \lesssim 0.05$

MiniBooNE - SciBooNE joint analysis : $|U_{\mu4}|^2 \lesssim 0.025$

The disappearance results favour a very small appearance mixing angle $\sin^2 2\Theta_{\mu e} \sim 0.005$ - inconsistent with LSND and MiniBooNE

3+2 fits improve the disagreement between ν and anti-ν but worsen the discrepancy between appearance and disappearance

The Reactor Antineutrino anomaly



A recalculation of the reactor antineutrino spectrum leads to an increment of the mean flux by about 3%

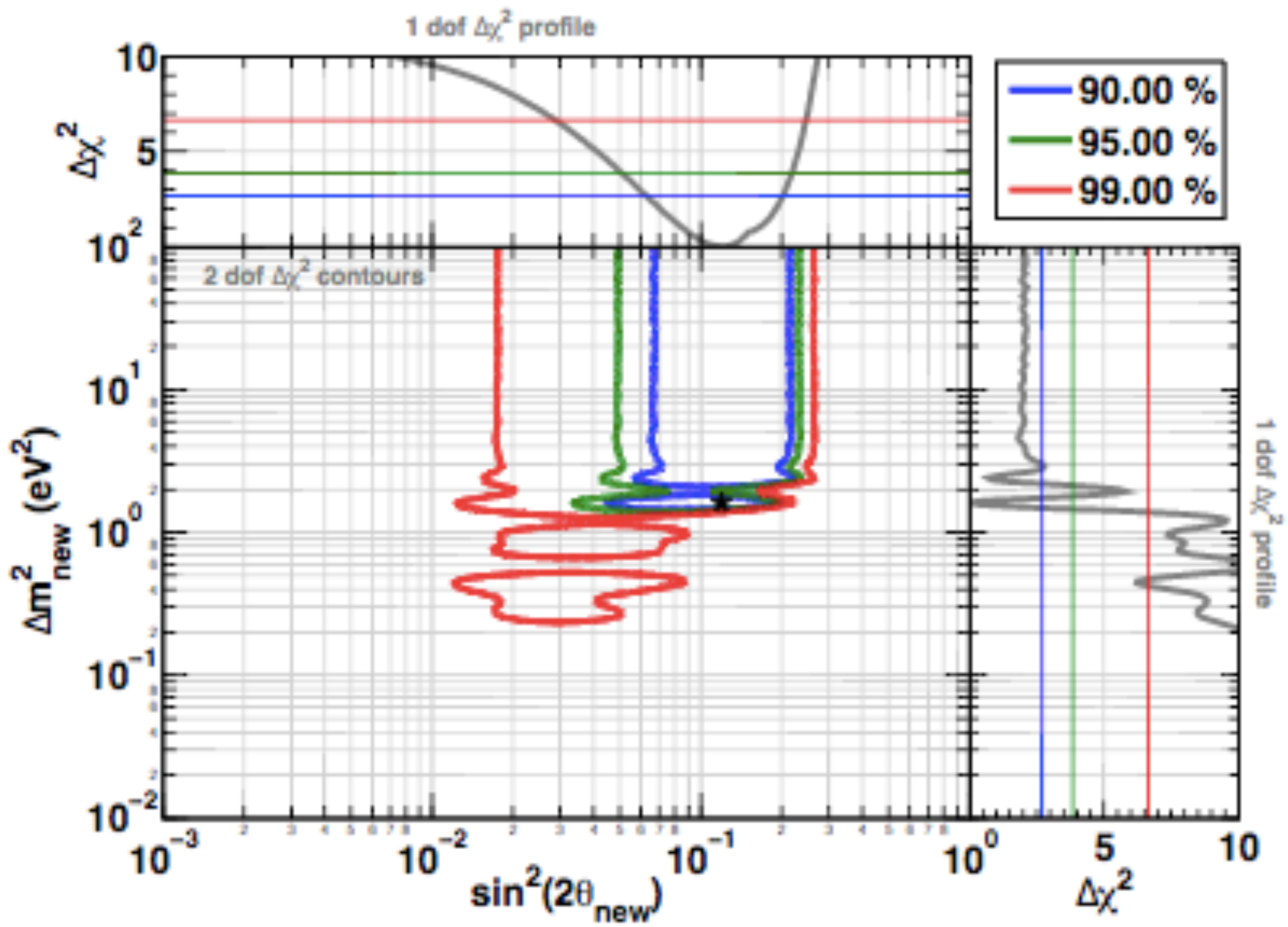
N^{obs}/N^{exp} for experiments with L > 15 m changes from 0.976±0.02 to 0.943±0.023, leading to 98.6% C.L. deviation from Unity.

1107.2755 PRD

The Reactor Antineutrino anomaly

For baselines below 2 km, assuming 3+1,

$$P_{ee} = 1 - \cos^4\theta_{\rm new}\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E_{\bar{\nu}_e}}\right) - \sin^2(2\theta_{\rm new})\sin^2\left(\frac{\Delta m^2_{\rm new}L}{4E_{\bar{\nu}_e}}\right).$$



The no-oscillation hypothesis is disfavoured at 99.8% C. L.

$|\Delta m^2_{\rm new}| > 1.5$ eV^2 95% C.L.

$\sin^2 2\Theta_{\rm new} = 0.14 \pm 0.08$ 95% C.L.

1107.2755 PRD

3+1 Searches : Daya Bay/Bugey-3 & MINOS

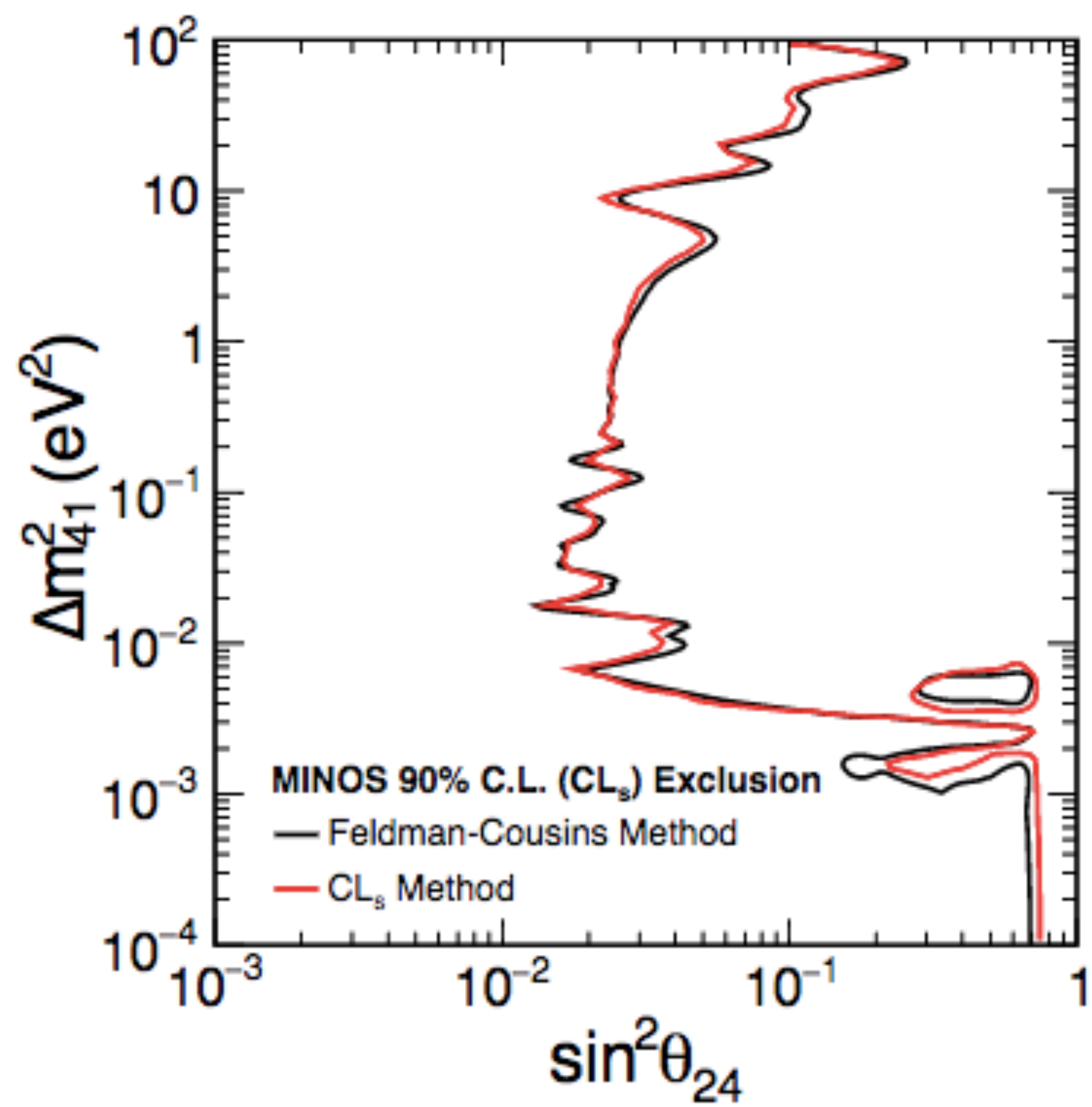
MINOS: Long-baseline super beam experiment
L = 734 km, peak Eν = 3 GeV
1 kton Near and 5.4 ton Far magnetised steel and scintillation calorimeters

1607.01177 PRL

Constrains $|U_{\mu 4}|^2$ via (anti-)ν_μ → (anti-)ν_μ

Additional sensitivity is obtained by analysing the reconstructed energy spectrum of NC events

Depending on the Δm^2, there can be an oscillatory signature or a depletion and therefore a sensitivity to 3+1



3+1 Searches : Daya Bay/Bugey-3 & MINOS

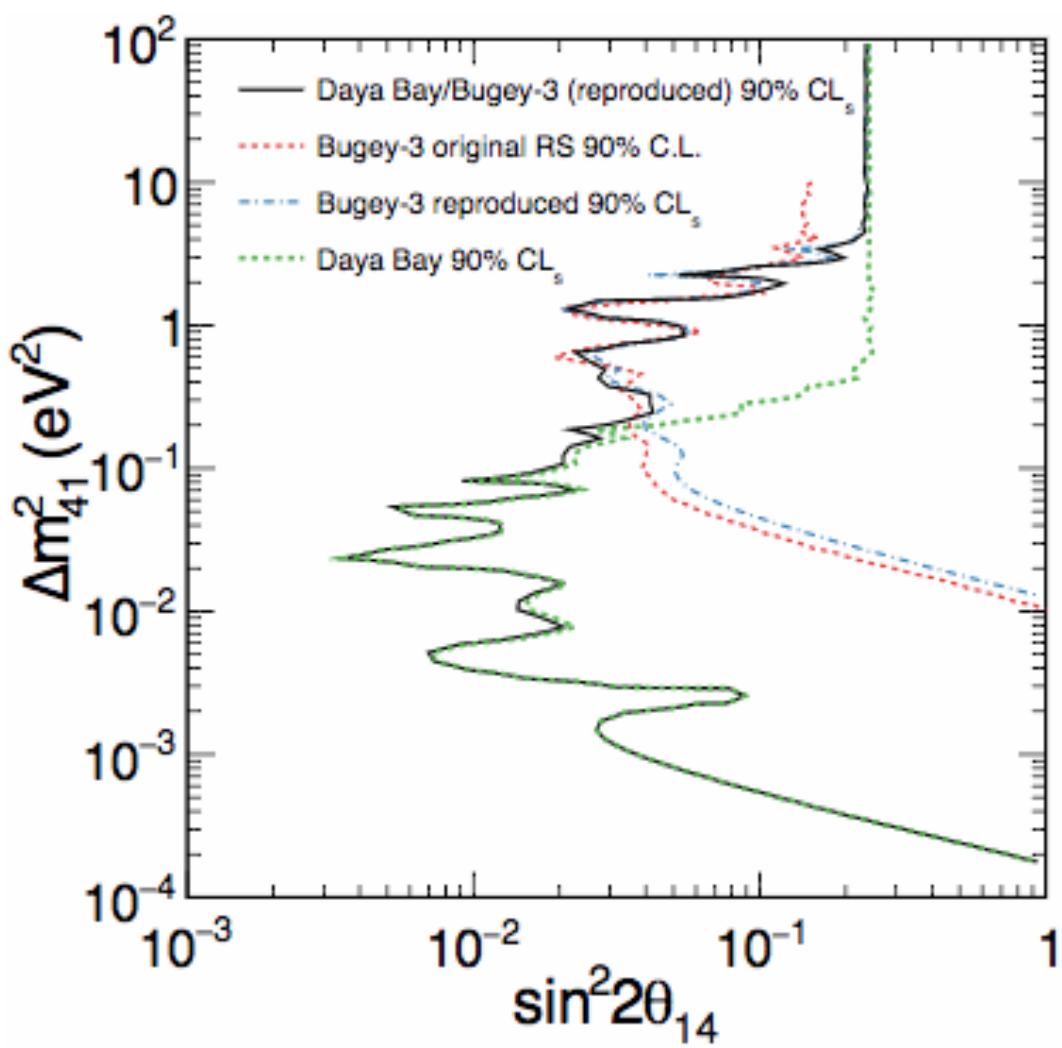
Daya Bay: Reactor anti-ν
L = 520, 570, and 1590 m

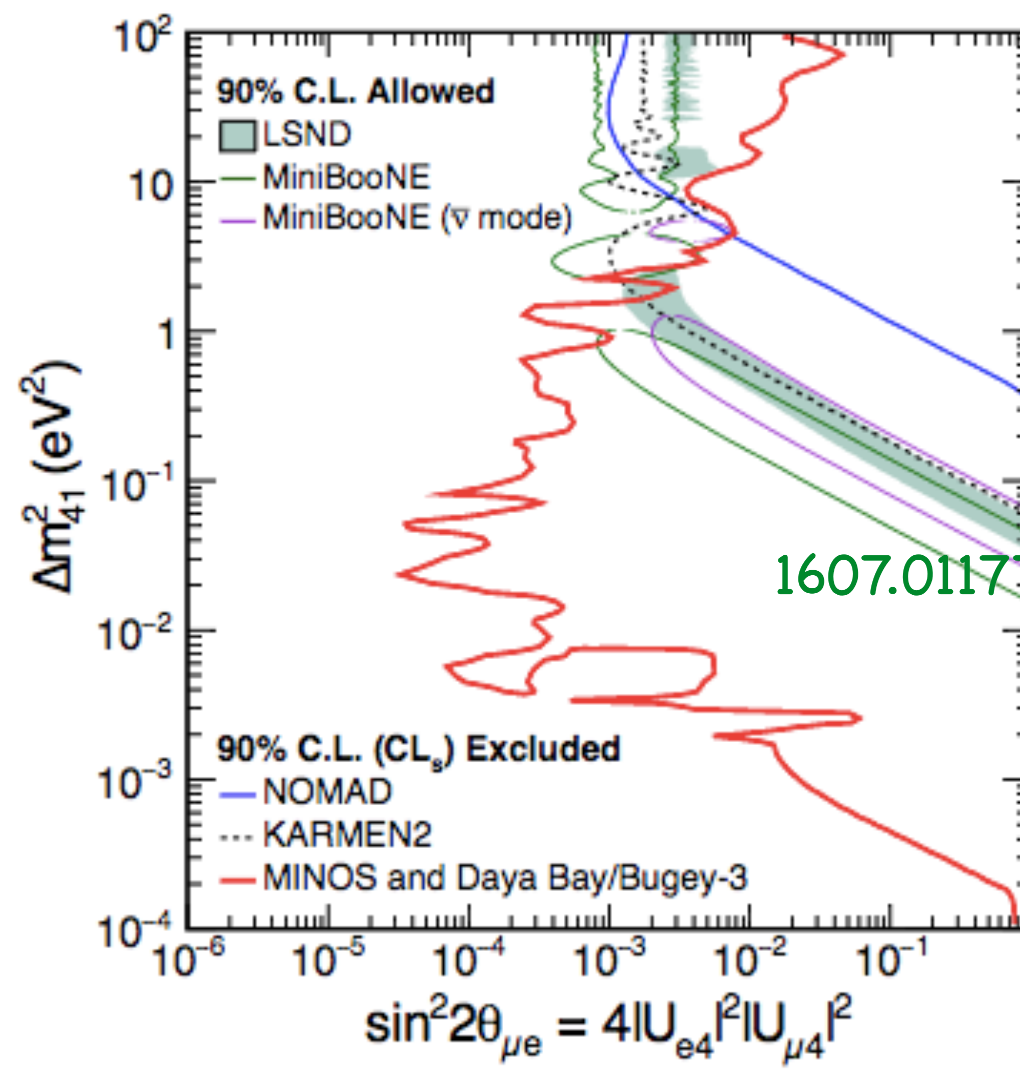
Bugey-3: Reactor anti-ν
L = 15, 40 and 95 m

Constrains $|U_{e4}|^2$ via anti-ν_e → anti-ν_e

The combined data from MINOS, Daya Bay and Bugey-3
can constrain the LSND and MiniBooNE allowed regions

Δm^2_{41} > 0.8 eV2 regions are excluded at 95% C.L.





1607.01177 PRL

3+1 searches : IceCube

Detects atmospheric neutrinos produced in Cosmic showers throughout the Earth's atmosphere

Only up-going neutrinos are selected

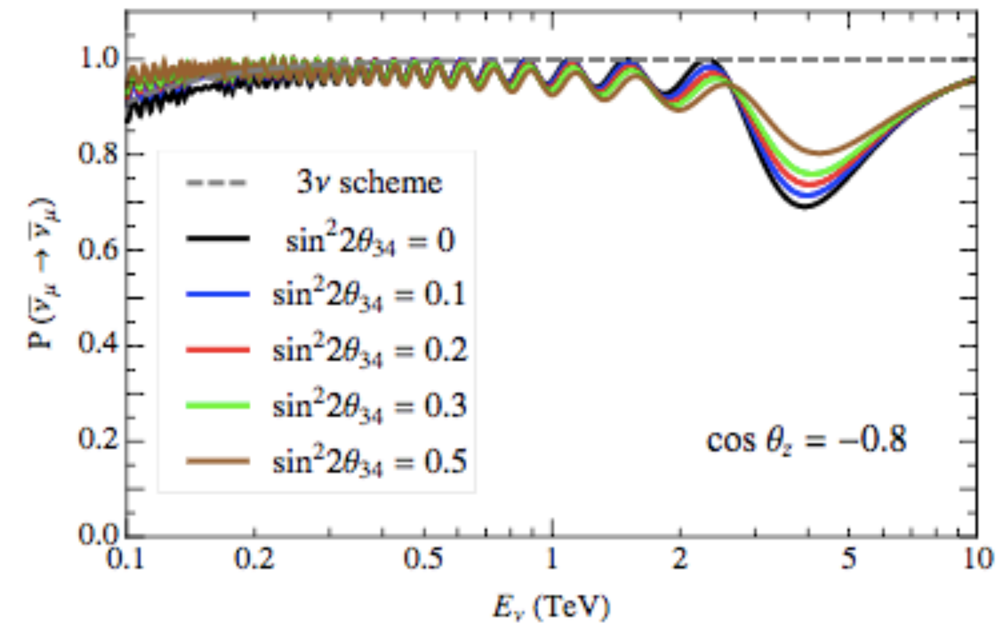
For E_ν > 100 GeV, oscillations due to Δm^2_{31} and Δm^2_{21} can be ignored

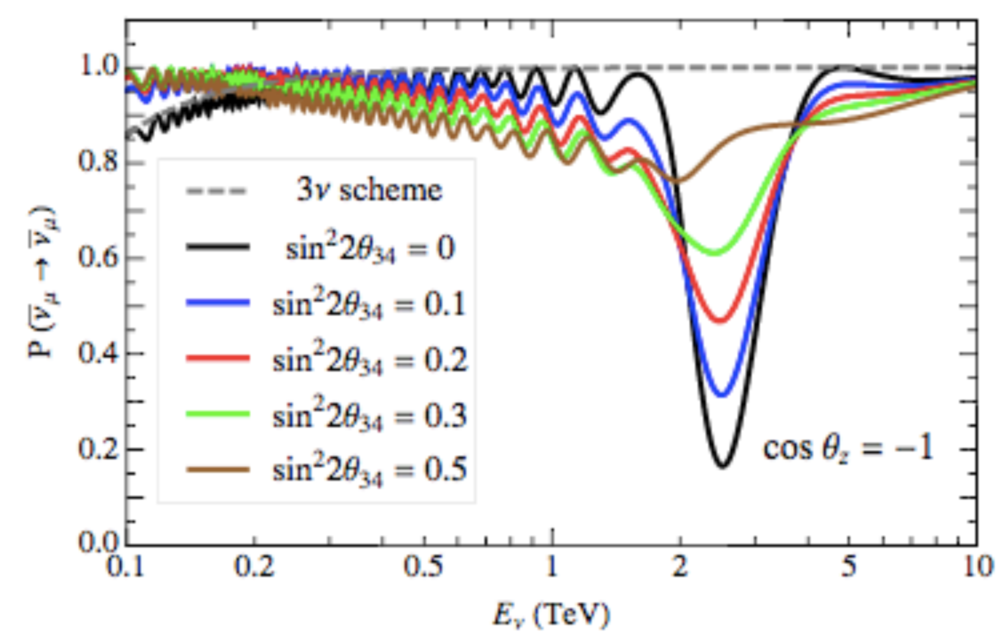
Search for (ν_μ + anti-ν_μ) disappearance in 320 GeV to 20 TeV range

The MSW effect depletes anti-ν in the 3+1 model or ν in 1+3 for $\Delta m^2_{41} \in$ [0.01eV^2, 10eV^2]

The choice Θ_{34} = 0 leads to the most conservative exclusion in Θ_{24}

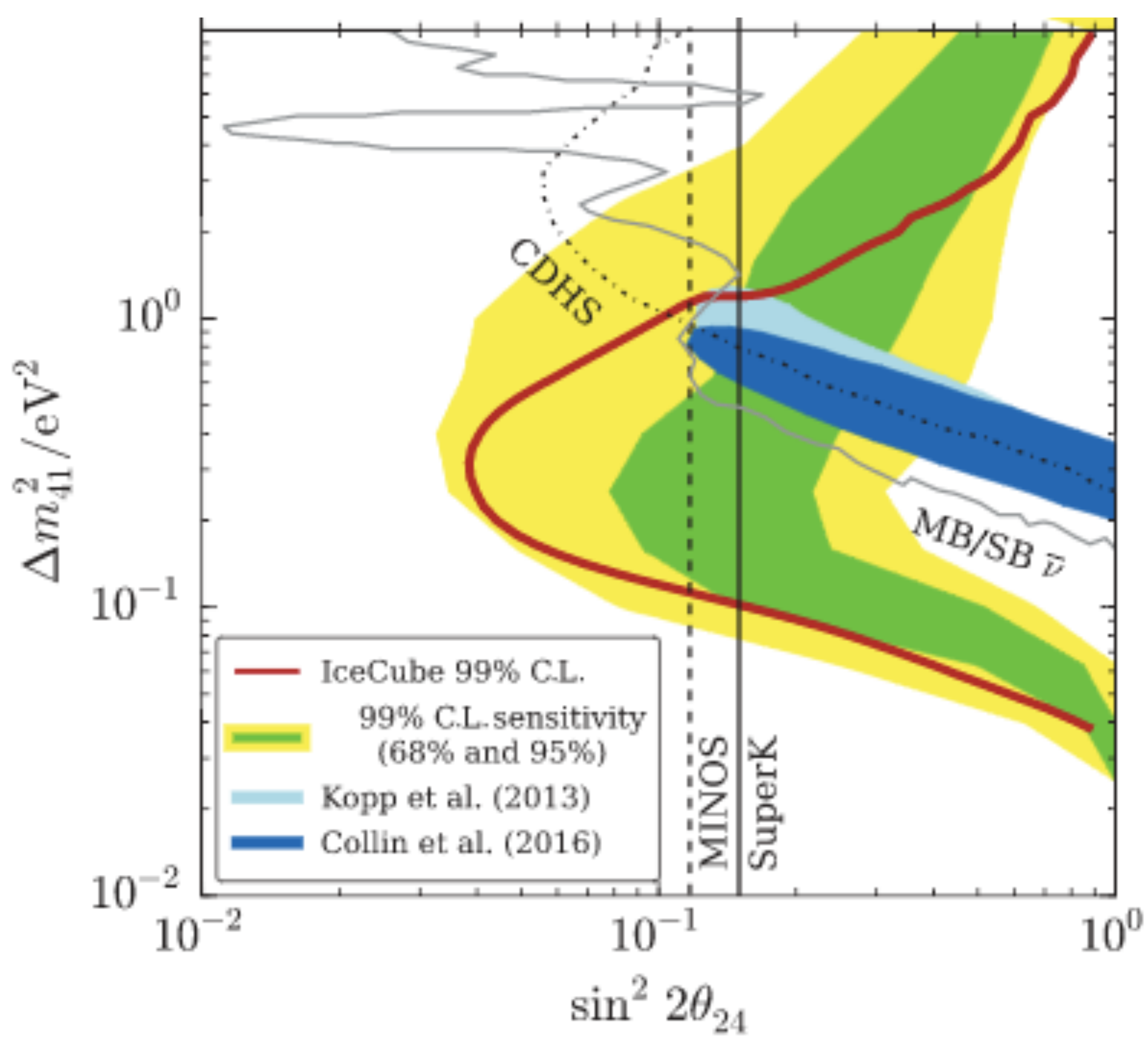
1307.6824 JHEP





3+1 searches : IceCube

IceCube results along with 99% C. L. allowed regions from Global fits appearance experiments including MiniBooNE and LSND assuming
$|U_{e4}|^2 = 0.023$ and $|U_{e4}|^2 = 0.027$



1605.01990 PRL

Collin-Arguelles-Conrad-Shaevitz 1602.00671

Global 3+1 fits

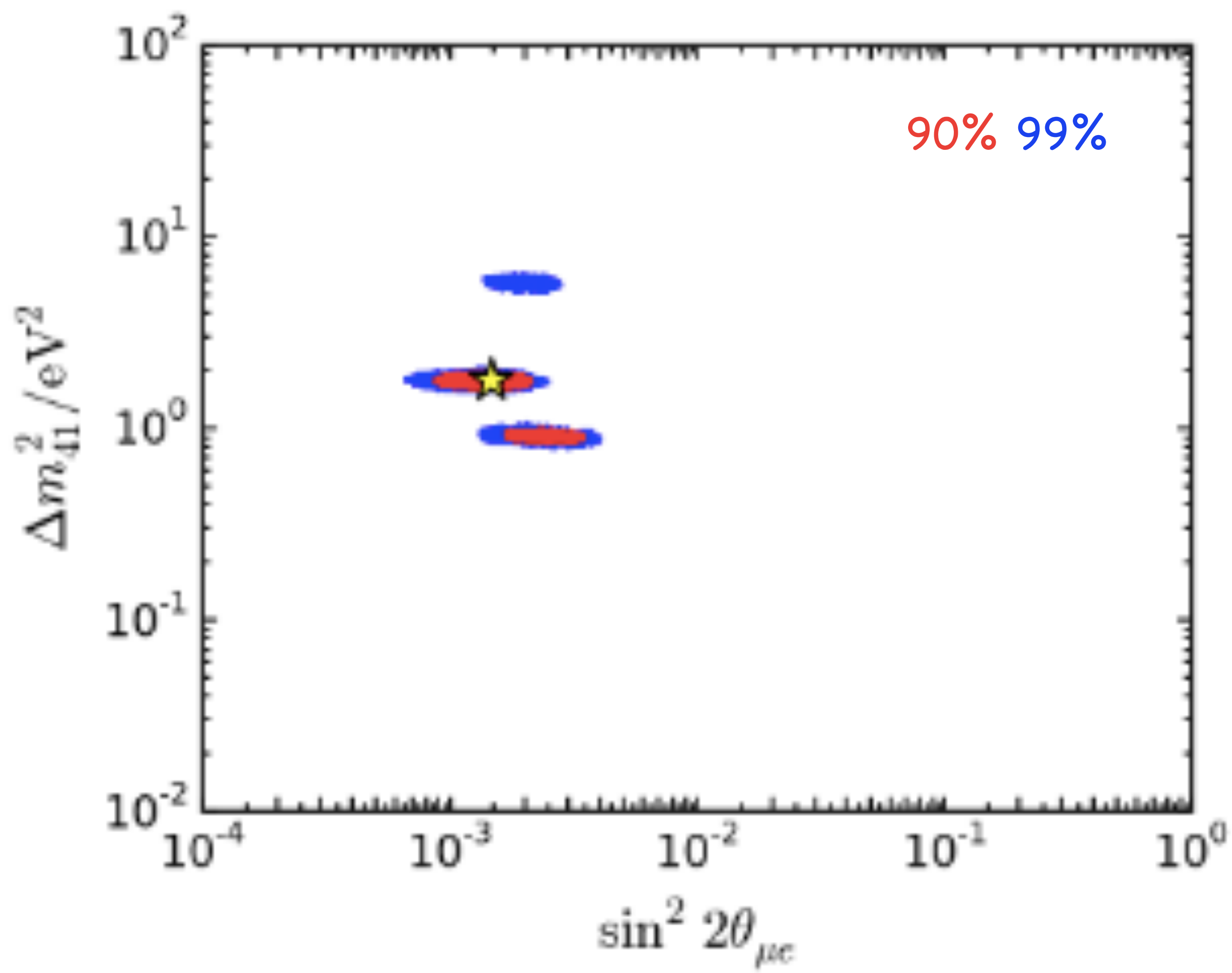
Data considered

Tag	Process	ν vs. $\bar{\nu}$	Type	N_{bins}
LSND [2]	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App	5
KARMEN [9]	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App	9
KARMEN/LSND(xsec) [11]	$\nu_e \to \nu_e$	ν	Dis	11
BNB-MiniBooNE-ν [3, 28]	$\nu_\mu \to \nu_e$	ν	App	19
BNB-MiniBooNE-$\bar{\nu}$ [4, 29]	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App	19
NuMI-MB(νapp) [10]	$\nu_\mu \to \nu_e$	ν	App	10
Bugey [5, 6]	$\bar{\nu}_e \to \bar{\nu}_e$	$\bar{\nu}$	Dis	60
Gallium [7, 8]	$\nu_e \to \nu_e$	ν	Dis	4
BNB-MiniBooNE/SciBooNE-ν [15]	$\nu_\mu \to \nu_\mu$	ν	Dis	48
BNB-MiniBooNE/SciBooNE-$\bar{\nu}$ [16]	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\bar{\nu}$	Dis	42
NOMAD [12]	$\nu_\mu \to \nu_e$	ν	App	30
CCFR84 [13]	$\nu_\mu \to \nu_\mu$	ν	Dis	18
CDHS [14]	$\nu_\mu \to \nu_\mu$	ν	Dis	15
MINOS-CC [17, 18]	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\bar{\nu}$	Dis	25

Best fit

3+1	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$
All	1.75	0.163	0.117

$\Delta\chi^2$ (dof) = 52.34 (3) w.r.t. null hypothesis



Collin-Arguelles-Conrad-Shaevitz 1607.00011

Global 3+1 fits

Data considered + IceCube IC86

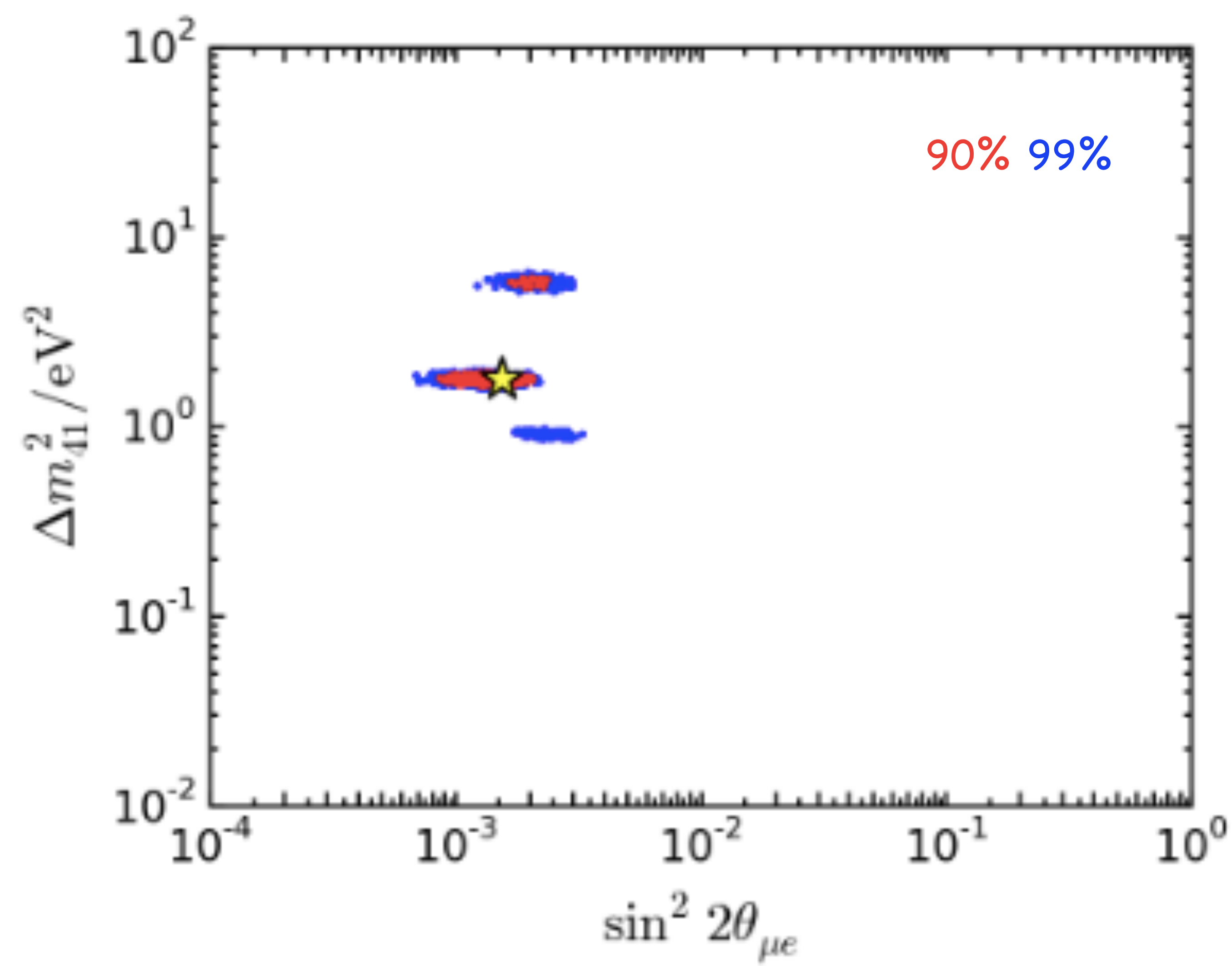
Tag	Process	ν vs. $\bar{\nu}$	Type	N_{bins}
LSND [2]	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App	5
KARMEN [9]	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App	9
KARMEN/LSND(xsec) [11]	$\nu_e \to \nu_e$	ν	Dis	11
BNB-MiniBooNE-ν [3, 28]	$\nu_\mu \to \nu_e$	ν	App	19
BNB-MiniBooNE-$\bar{\nu}$ [4, 29]	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App	19
NuMI-MB(νapp) [10]	$\nu_\mu \to \nu_e$	ν	App	10
Bugey [5, 6]	$\bar{\nu}_e \to \bar{\nu}_e$	$\bar{\nu}$	Dis	60
Gallium [7, 8]	$\nu_e \to \nu_e$	ν	Dis	4
BNB-MiniBooNE/SciBooNE-ν [15]	$\nu_\mu \to \nu_\mu$	ν	Dis	48
BNB-MiniBooNE/SciBooNE-$\bar{\nu}$ [16]	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\bar{\nu}$	Dis	42
NOMAD [12]	$\nu_\mu \to \nu_e$	ν	App	30
CCFR84 [13]	$\nu_\mu \to \nu_\mu$	ν	Dis	18
CDHS [14]	$\nu_\mu \to \nu_\mu$	ν	Dis	15
MINOS-CC [17, 18]	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\bar{\nu}$	Dis	25

The significance of the IceCube data is that it excludes the LSND solution at ~ 1eV^2 at 90% although it does exist at 99%

Best fit

3+1	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\tau 4}\rvert$
SBL	1.75	0.163	0.117	-
SBL+IC	1.75	0.164	0.119	0.00

$\Delta\chi^2$ (dof) = 50.61 (4) w.r.t. null hypothesis

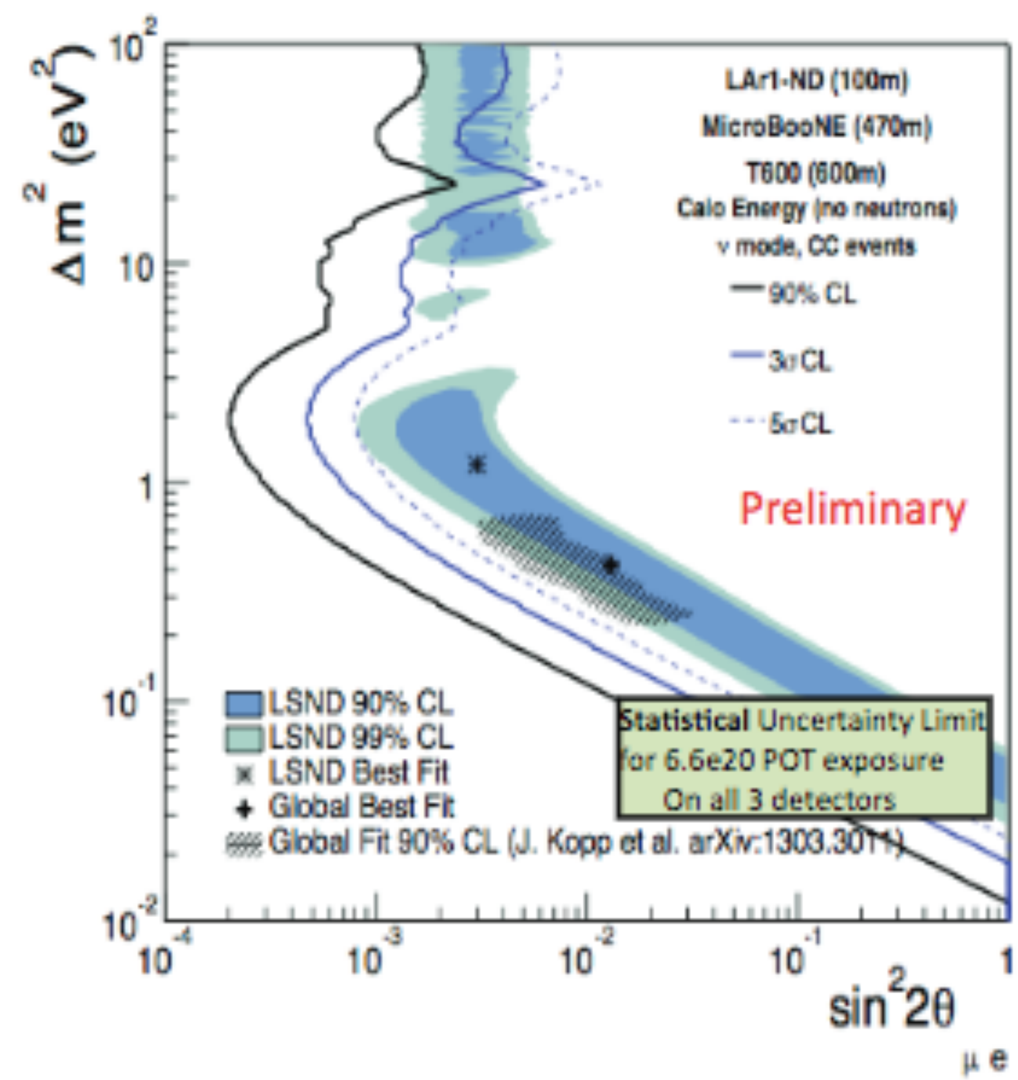


The Fermilab SBL neutrino program

The primary aim of the Fermilab SBL neutrino program is to search for the evidence of Sterile neutrinos as hinted by MiniBooNE and LSND

The program consists of three experiments:
MicroBooNE at 470 m
LAr1-ND at 110 m
ICARUS at 600 m

1) Precise measurements of fluxes
2) Determine the nature of MiniBooNE excess
3) Observe (anti-)$\nu_\mu \rightarrow$ (anti-)ν_e



L. Camilleri AIP Conference Proceedings 1680, 020004 (2015)

Future Sterile neutrino searches: Accelerators

Pion Decay-in-flight experiment: Fermilab SBL

Muon Decay-in-flight experiment: NuSTORM

Pion Muon and Kaon Decay-at-rest experiment: OscSNS, JPARK MLF

Isotope Decay-at-rest experiment: ISODAR

J. Spitz AIP Conference Proceedings 1666, 180004 (2015)

Future Sterile neutrino searches: Reactors

To investigate the Reactor Antineutrino anomaly

Experiment	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e)
Nucifer (France)	70	0.8	7	13
Poseidon (Russia)	100	3	5-8	15
Stereo (France)	57	1.75	8.8-12	18
Neutrino4 (Russia)	100	1.5	6-11	10
Hanaro (Korea)	30-2800	1	6	few
DANSS (Russia)	3000	0.9	9.7-12.2	50
Prospect (USA)	85	1& 10	7-18	few
Solid (UK)	45-80	2.9	6-8	10

D. Lhuillier AIP Conference Proceedings 1666, 180003 (2015)

A short summary...

There are several inconclusive hints which point towards the existence of a fourth neutrino.

A simple 3+1 model seems unlikely especially in the wake of contradictory evidences. 3+1 may just be a marginal description.

Recent measurements by MINOS, Daya Bay and IceCube tightly constrain the MiniBooNE-LSND allowed regions.

A host of SBL neutrino experiments to follow to conclusively prove or disprove the four-neutrino hypothesis.

Sterile neutrinos at LBL

1708.01816, 1607.02152, 1508.06275

A major goal of the present and future long-baseline neutrino oscillation experiments is to establish that leptons violate CP, or else to place a stringent upper limit on any such violation.

The studies related to these experiments have been done assuming the standard three-neutrino-only paradigm.

Several short-baseline anomalies hint at the possible existence of short-wavelength oscillations driven by one or more $O(1\ \mathrm{eV}^2)$ mass-squared splittings.

These oscillations are significant when $L/E \sim 1$ km/GeV but they are also present at the far detector where $L/E \sim 500$ km/GeV.

At $L/E \sim 500$ km/GeV, the rapid oscillations driven by $O(1\ \mathrm{eV}^2)$ neutrinos get averaged to a L/E-independent value due to the finite energy resolution of any realistic detector.

Sterile neutrinos at LBL

However, these oscillations can have a major impact on the probability amplitudes over and above that of the standard oscillations.

We restrict ourselves to the scenario where there is only one additional mass eigenstate (3+1).

For 3+N scenarios where N>1, the consequences on measurements made at the far-detector site can be expected to be manifold.

We perform some calculations relevant to the CP searches in the 3+1 scenario as manifested in the proposed Deep Underground Neutrino Experiment (DUNE).

See arXiv:1303.3011, Kopp et. al. for a global fit of data for 3+N.

See arXiv:1605.03829, Hannestad et. al. for a compatibility study with Cosmology.

The 3+1 model

We consider a O(1 eV^2) mass sterile neutrino, heavier than the other 3 mass eigenstates => $\Delta m^2_{41} = +1$ eV^2. Δm^2_{31} can be + or -

The oscillations are now characterised by 6 mixing angles, 3 CP-violating phases and 3 mass-squared differences.

$$U^{3+1}_{PMNS} = \boxed{O(\Theta_{34},\delta_{34})O(\Theta_{24},\delta_{24})O(\Theta_{14})}\, O(\Theta_{23})O(\Theta_{13},\delta_{13})O(\Theta_{12})$$

$\sin^2\Delta_{4i}$ averages to 0.5

$\sin 2\Delta_{4i}$ averages to 0

$$\begin{aligned}
P^{3+1}_{\mu e} \;=\; & \boxed{4|U_{\mu 4}U_{e4}|^2 \times 0.5} \\
- \; & 4Re(U_{\mu 1}U^*_{e1}U^*_{\mu 2}U_{e2})\sin^2\Delta_{21} + 2Im(U_{\mu 1}U^*_{e1}U^*_{\mu 2}U_{e2})\sin 2\Delta_{21} \\
- \; & 4Re(U_{\mu 1}U^*_{e1}U^*_{\mu 3}U_{e3})\sin^2\Delta_{31} + 2Im(U_{\mu 1}U^*_{e1}U^*_{\mu 3}U_{e3})\sin 2\Delta_{31} \\
- \; & 4Re(U_{\mu 2}U^*_{e2}U^*_{\mu 3}U_{e3})\sin^2\Delta_{32} + 2Im(U_{\mu 2}U^*_{e2}U^*_{\mu 3}U_{e3})\sin 2\Delta_{32}
\end{aligned}$$

Why are the 3+1 effects large?

$$
\begin{aligned}
P_{\mu e}^{3+1} &= \frac{1}{2}\sin^2 2\theta_{\mu e}^{4\nu} \\
&+ (a^2\sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta_{\mu e}^{4\nu})\Big[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\Big] \\
&+ \cos(\delta_{13})ba^2\sin 2\theta_{\mu e}^{3\nu}\Big[\cos 2\theta_{12}\sin^2\Delta_{21} + \sin^2\Delta_{31} - \sin^2\Delta_{32}\Big] \\
&+ \cos(\delta_{24})ba\sin 2\theta_{\mu e}^{4\nu}\Big[\cos 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} - \sin^2\theta_{13}(\sin^2\Delta_{31} - \sin^2\Delta_{32})\Big] \\
&+ \cos(\delta_{13}+\delta_{24})a\sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\Big[-\frac{1}{2}\sin^2 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} \\
&+ \cos 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})\Big] \\
&- \frac{1}{2}\sin(\delta_{13})ba^2\sin 2\theta_{\mu e}^{3\nu}\Big[\sin 2\Delta_{21} - \sin 2\Delta_{31} + \sin 2\Delta_{32}\Big] \\
&+ \frac{1}{2}\sin(\delta_{24})ba\sin 2\theta_{\mu e}^{4\nu}\Big[\cos^2\theta_{13}\sin 2\Delta_{21} + \sin^2\theta_{13}(\sin 2\Delta_{31} - \sin 2\Delta_{32})\Big] \\
&+ \frac{1}{2}\sin(\delta_{13}+\delta_{24})a\sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\Big[\cos^2\theta_{12}\sin 2\Delta_{31} + \sin^2\theta_{12}\sin 2\Delta_{32}\Big] \\
&+ (b^2a^2 - \frac{1}{4}a^2\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{4\nu})\sin^2\Delta_{21}
\end{aligned}
$$

where $\sin 2\theta_{\mu e}^{3\nu} = \sin 2\theta_{13}\sin\theta_{23}$, $b = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}$,

$\sin 2\theta_{\mu e}^{4\nu} = \sin 2\theta_{14}\sin\theta_{24}$ and $a = \cos\theta_{14}\cos\theta_{24}$

Appearance probability in 3+1 in vacuum

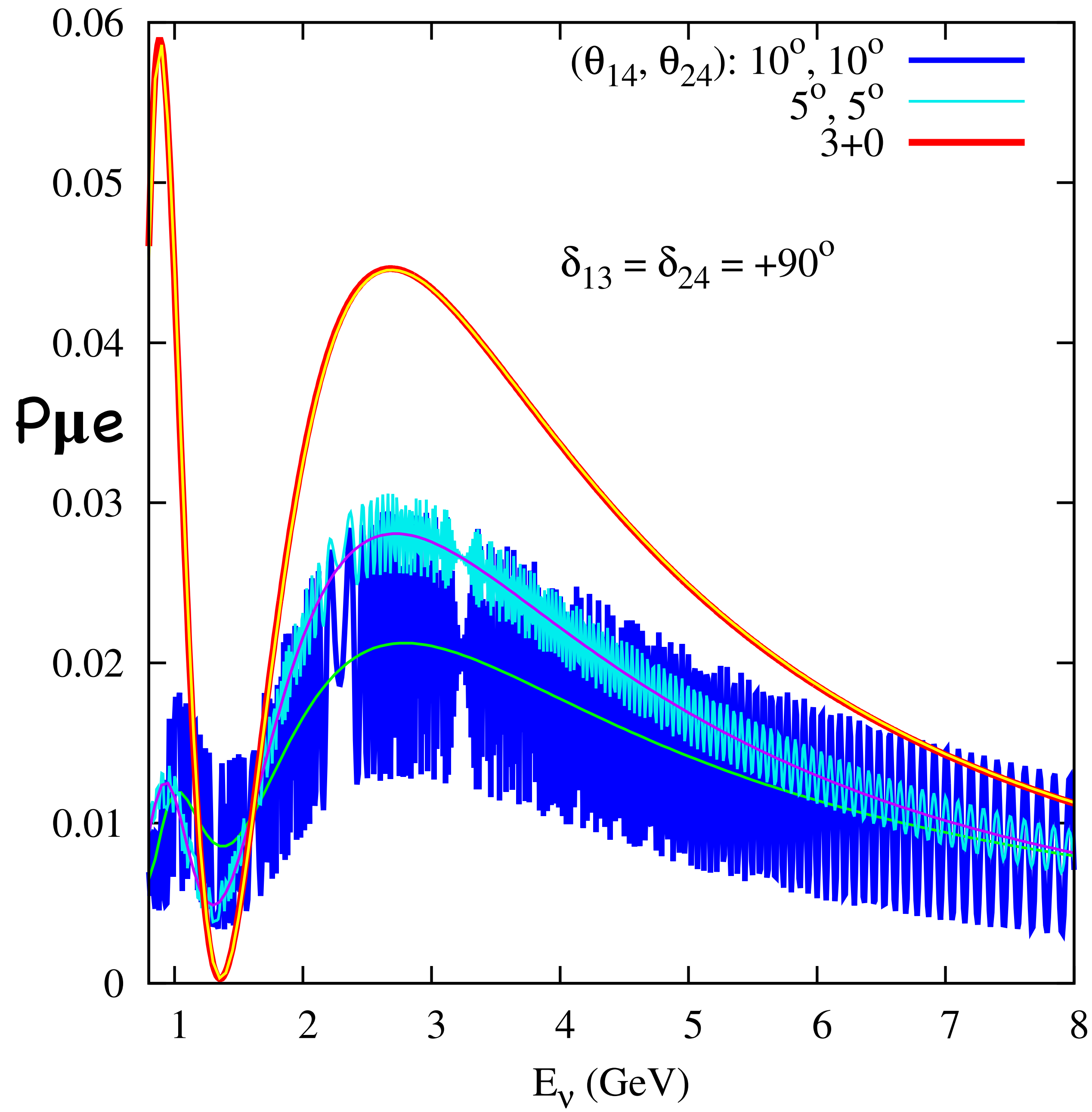
Comparison of analytical expression with GLoBES =>

In the limit that $\Theta_{i4} = 0$, the 3+0 probabilities are reproduced.

When 3+1 effects are switched on, the probabilities match quite well.

The rapid oscillations due to Δm^2_{4i} for a 1 eV^2 sterile neutrino will not be visible in the DUNE far detector.

DUNE, L = 1300 km, vacuum



$\Theta_{12} = 33.48^o$, $\Theta_{13} = 8.5^o$, $\Theta_{23} = 45^o$

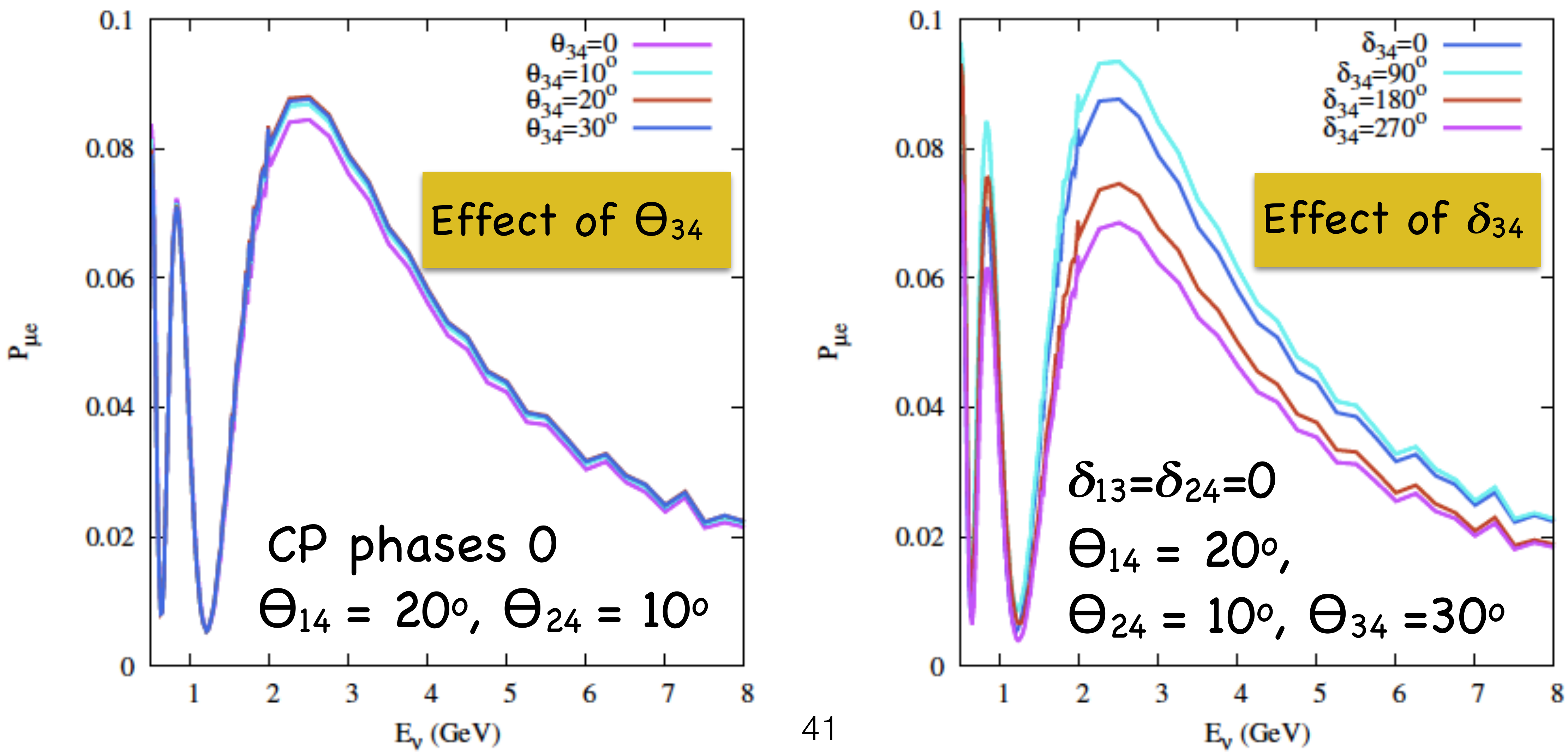
$\Delta m^2_{31} = +2.4e\text{-}3\ eV^2$, $\Delta m^2_{21} = 7.5e\text{-}5\ eV^2$

Appearance probability in 3+1 in matter

θ_{34} and δ_{34} which were irrelevant for 3+1 electron appearance in vacuum, play significant roles in the presence of matter.

In producing these plots, we have averaged over the Δm^2_{4i} induced oscillations.

DUNE, L = 1300 km, matter

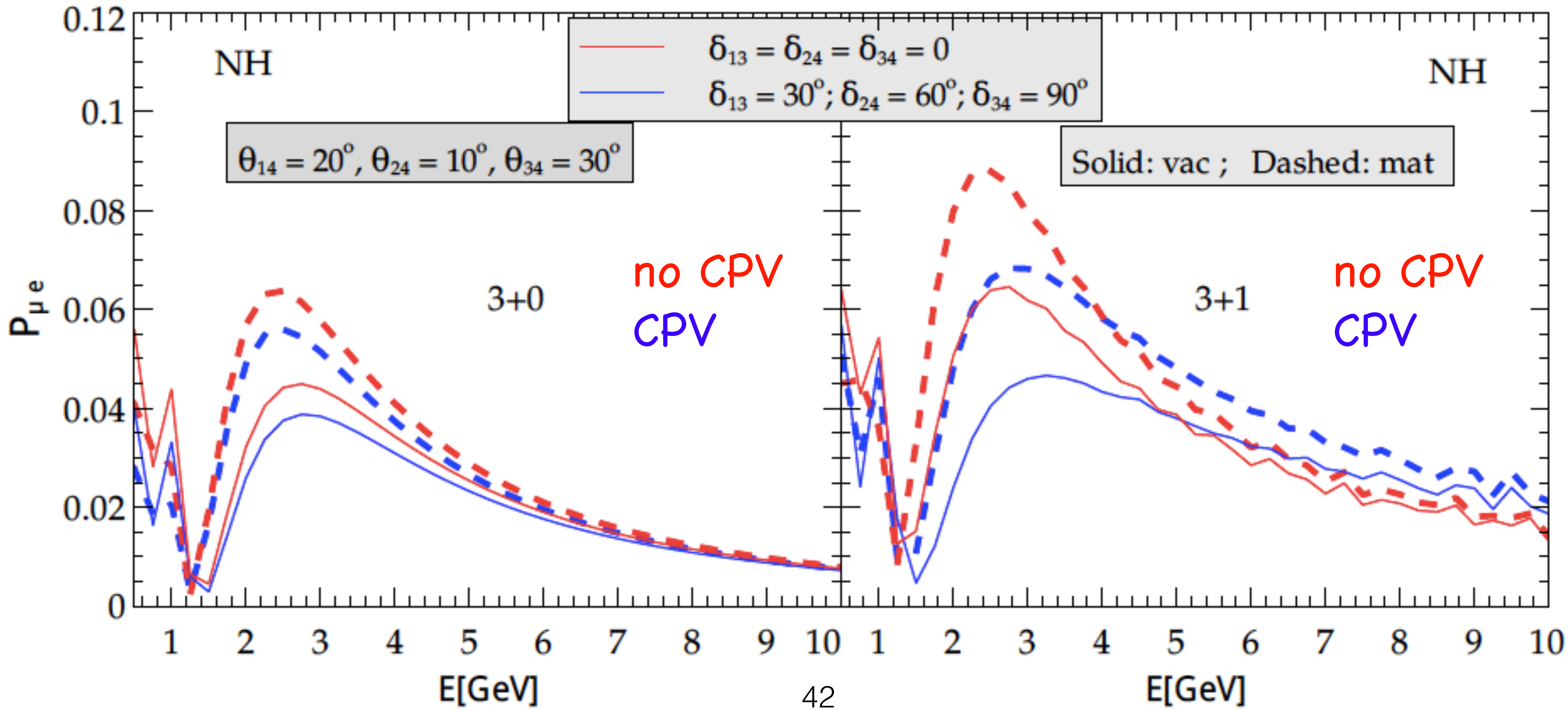


Appearance probability in 3+1 in matter

Left vs. Right - Even at far detector, sterile neutrinos have large effects.

Red vs. Blue - Phases play an important role, more so in 3+1.

Solid vs. Dashed - Matter effects are important, more in 3+1.



Constraints on the active-sterile mixings

Constraints derived are calculated in the region of Δm^2_{41} of 1 eV^2 .

Consistent parameterisation.

We assume the lower limits on the active-sterile mixings to be 0.

ν_e and anti-ν_e disappearance searches probe $|U_{e4}| = \sin\Theta_{14}$.
ν_μ, anti-ν_μ and NC disappearance searches probe $|U_{\mu4}| = \cos\Theta_{14}\sin\Theta_{24}$ and $|U_{\tau4}| = \cos\Theta_{14}\cos\Theta_{24}\sin\Theta_{34}$.

Daya Bay: $\Theta_{14} \in [0, 13^o]$ 95% C.L. PRL 113, 141802 (2014), 1407.7259.
IceCube: $\Theta_{24} \in [0, 7^o]$ 99% C.L. PRL 117, 071801 (2016)
MINOS(+): $\Theta_{34} \in [0, 26^o]$ 90% C.L. PRL 107, 011802 (2011), 1104.3922.

The CP phases remain unconstrained.

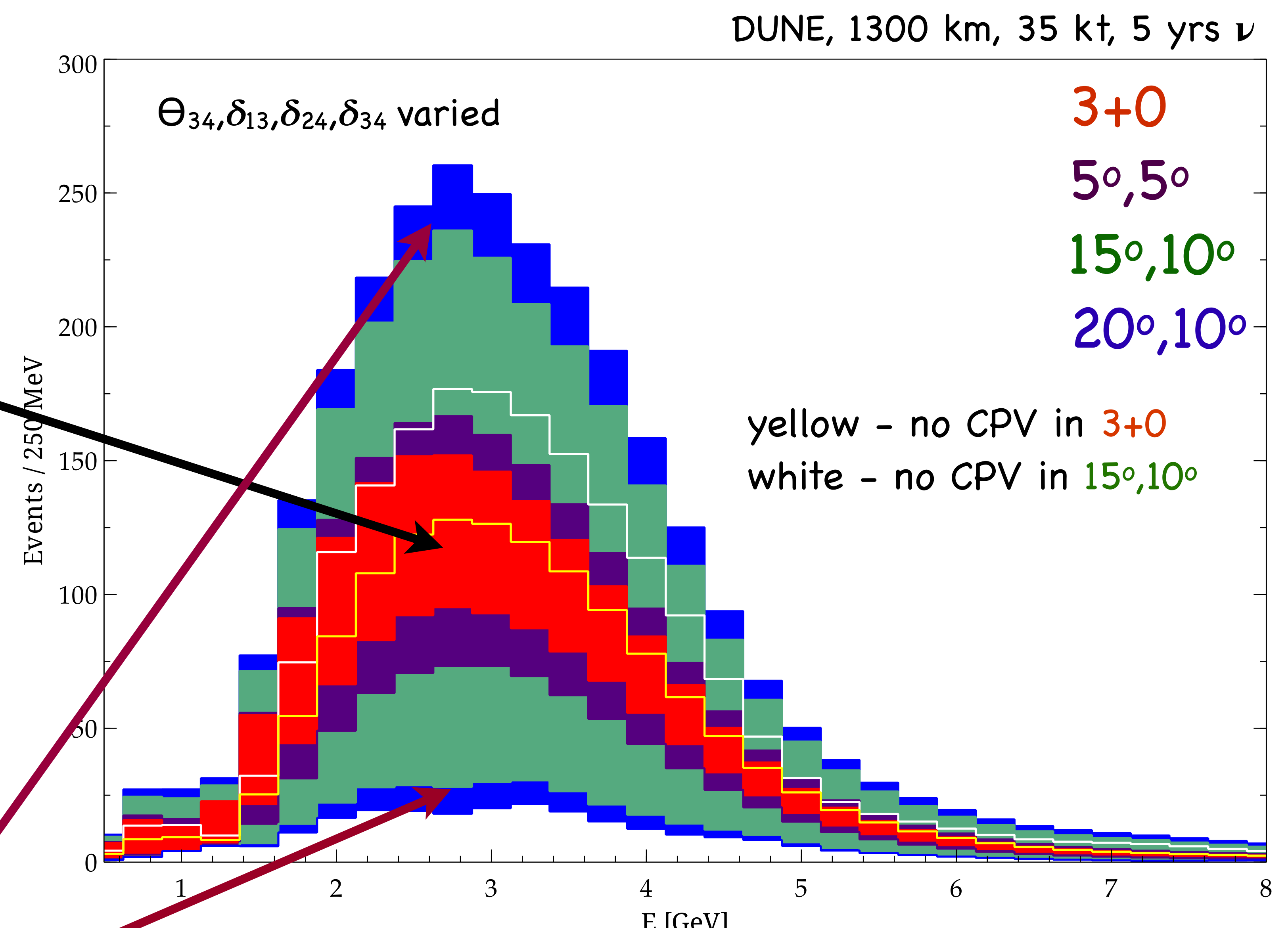
LSND: $\sin^2 2\Theta_{\mu e} < 0.008$ for Δm^2_{41} of around 1 eV^2

Events rates plots for DUNE

We assume the standard DUNE setup (arXiv:1311.0212, Bass et. al.) and use GLoBES for carrying out simulations. 1.2 MW - 120 GeV beam. 10^{21} POT/yr

The 3+1 band can potentially encompass the 3+0 band, leading to substantial degeneracy.

For large active-sterile mixings, an excess or shortage of events, esp. at osc. max. will be pointers to the existence of new physics.



$\theta_{12} = 33.48^\circ$, $\theta_{13} = 8.5^\circ$, $\theta_{23} = 45^\circ$

$\Delta m^2_{31} = +2.457\text{e-}3$ eV^2, $\Delta m^2_{21} = 7.5\text{e-}5$ eV^2

Robustness of 3+0 parameters

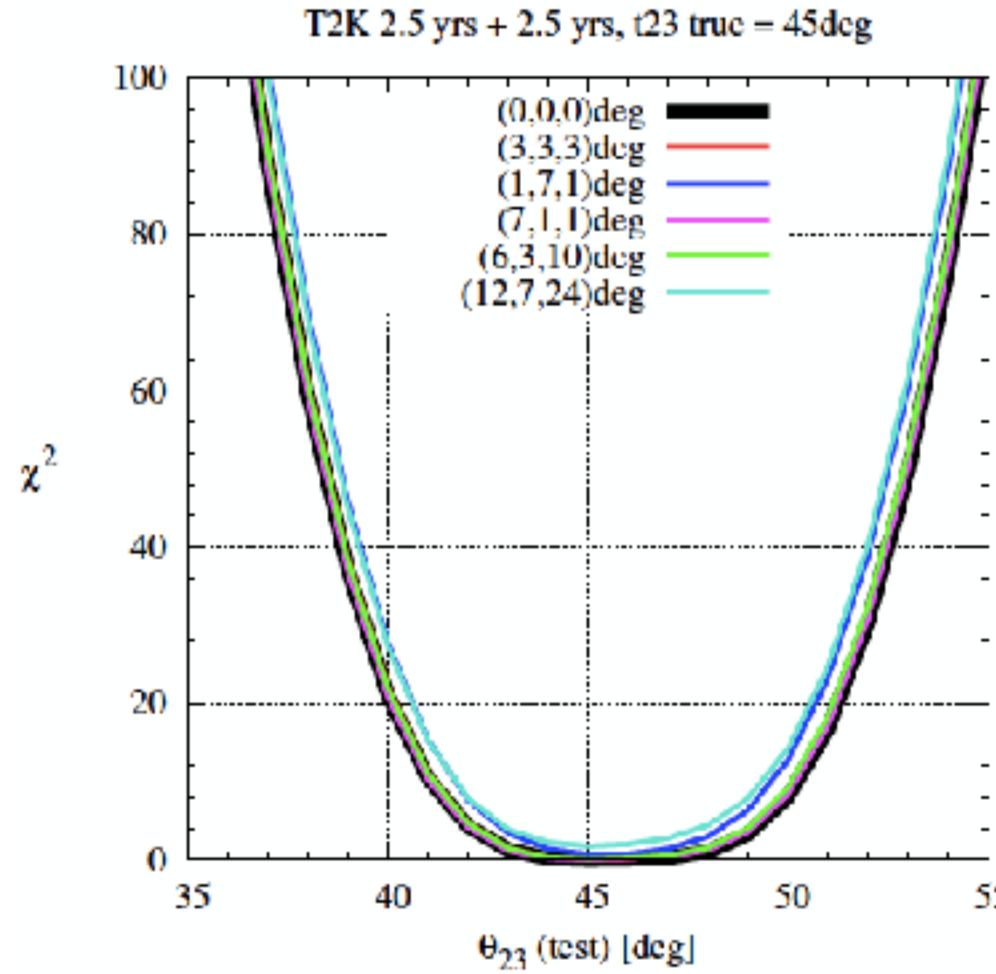
Some of our early calculations showed that the disappearance data at the far detector are less affected by the active-sterile mixing angles compared to the appearance data.

See arXiv:1308.6218, Esmaili et. al. for robustness of Θ_{13} in 3+1.

Berryman et. al. arXiv:1507.03986

3-nu-fit to 4-nu-data:

1) similar best-fits and precisions
2) bad goodness-of-fit



For the first time, this new result on $|U_{\tau 4}|$ allows us to have a complete picture of the extended lepton mixing matrix:

Collin et. al. (arXiv:1607.00011)

$$|U| = \begin{bmatrix} 0.79 \to 0.83 & 0.53 \to 0.57 & 0.14 \to 0.15 & 0.13\,(0.17) \to 0.20\,(0.21) \\ 0.25 \to 0.50 & 0.46 \to 0.66 & 0.64 \to 0.77 & 0.09\,(0.10) \to 0.15\,(0.13) \\ 0.26 \to 0.54 & 0.48 \to 0.69 & 0.56 \to 0.75 & 0.0\,(0.0) \to 0.7\,(0.05) \\ \cdots & \cdots & \cdots & \cdots \end{bmatrix}. \quad (6)$$

Above, "…" represents parameters constrained by the overall unitarity of the 4×4 matrix. The ranges in the matrix correspond to 90% confidence intervals. The entries in the last column correspond to this work and are given for $\Delta m^2 \sim 2$ eV^2 ($\Delta m^2 \sim 6$ eV^2). The intervals

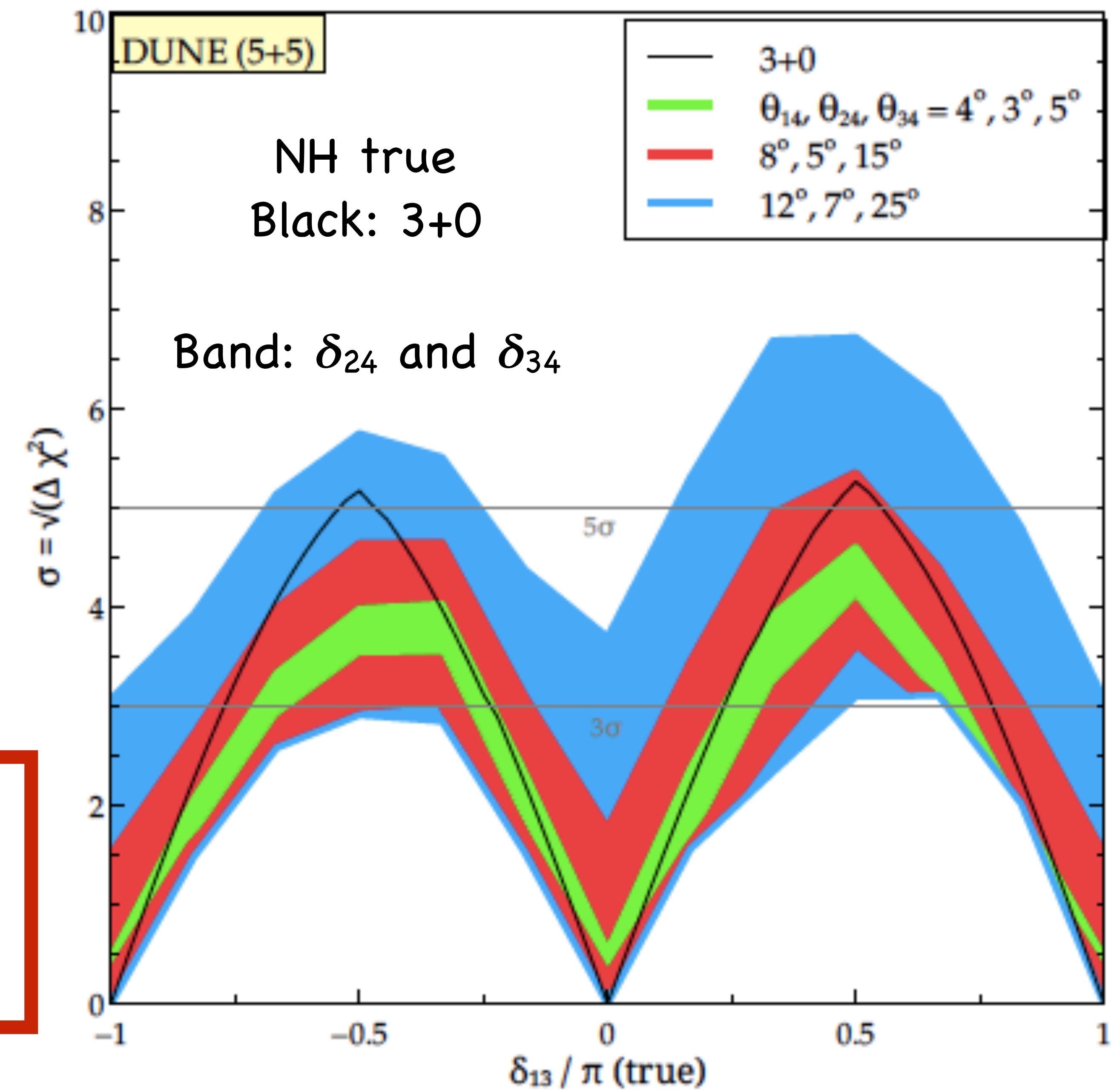
CP violation

Excluding CP conserving values as a function of true 3+1 oscillation parameters

Fit: CP conserving
δ_{13}, δ_{24} and δ_{34}

No marginalisation
over 3+0 osc. params

Marginalisation over CP
conserving phases and
active-sterile mix. angles



Small mixings: Sensitivity decreases
Large mixings: Sensitivity spans
on both sides of the 3+0 sensitivity

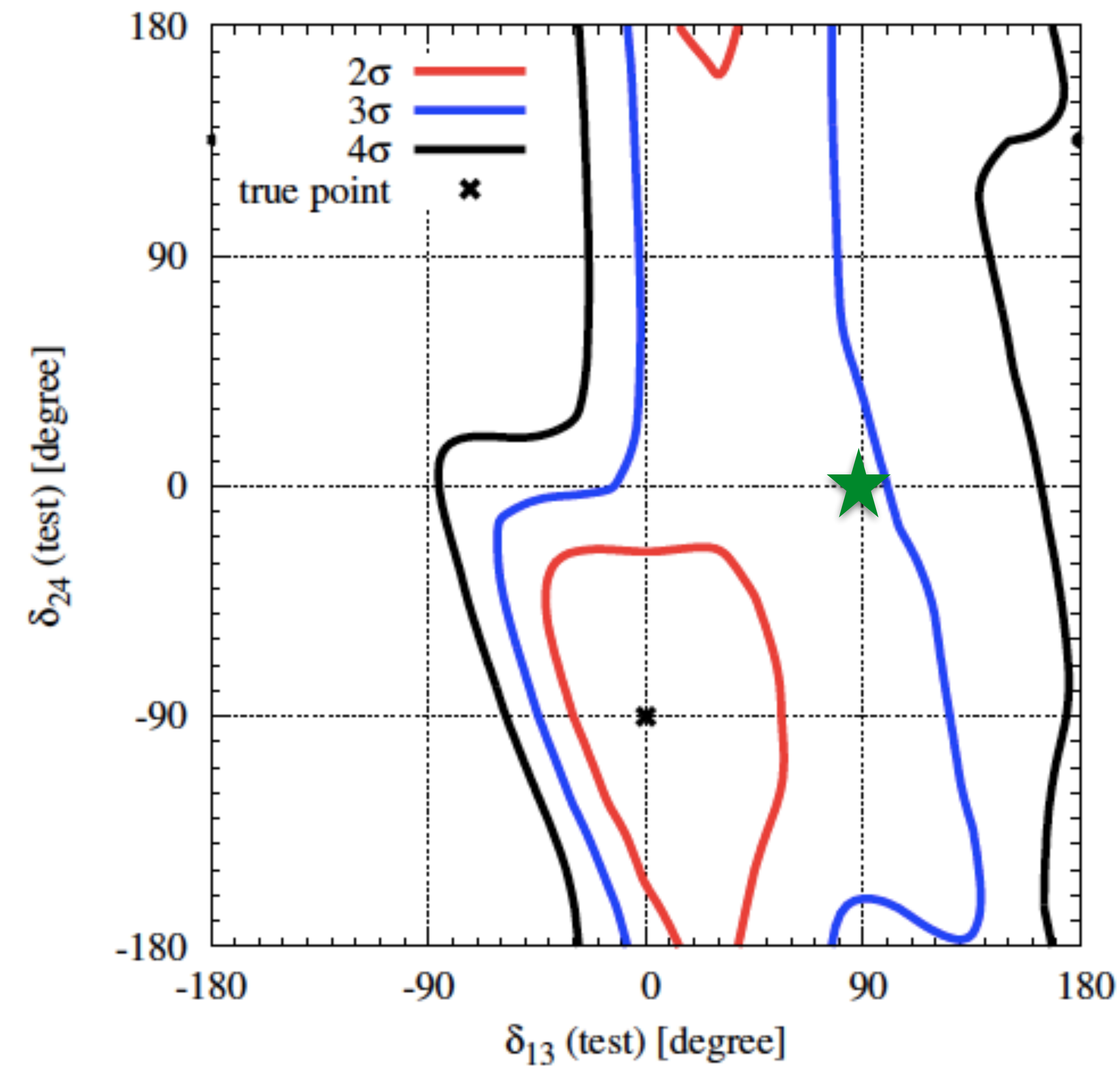
Determining the phase responsible for CPV

Suppose that the results of short-baseline experiments indicate the presence of a 1 eV^2 neutrino, and, in addition, DUNE finds evidence of CP violation. Can then DUNE identify the source of this violation?

Test values of (δ_{13} ,δ_{24}) close to (90°, 0) and (90°, 180°) are allowed within 3σ

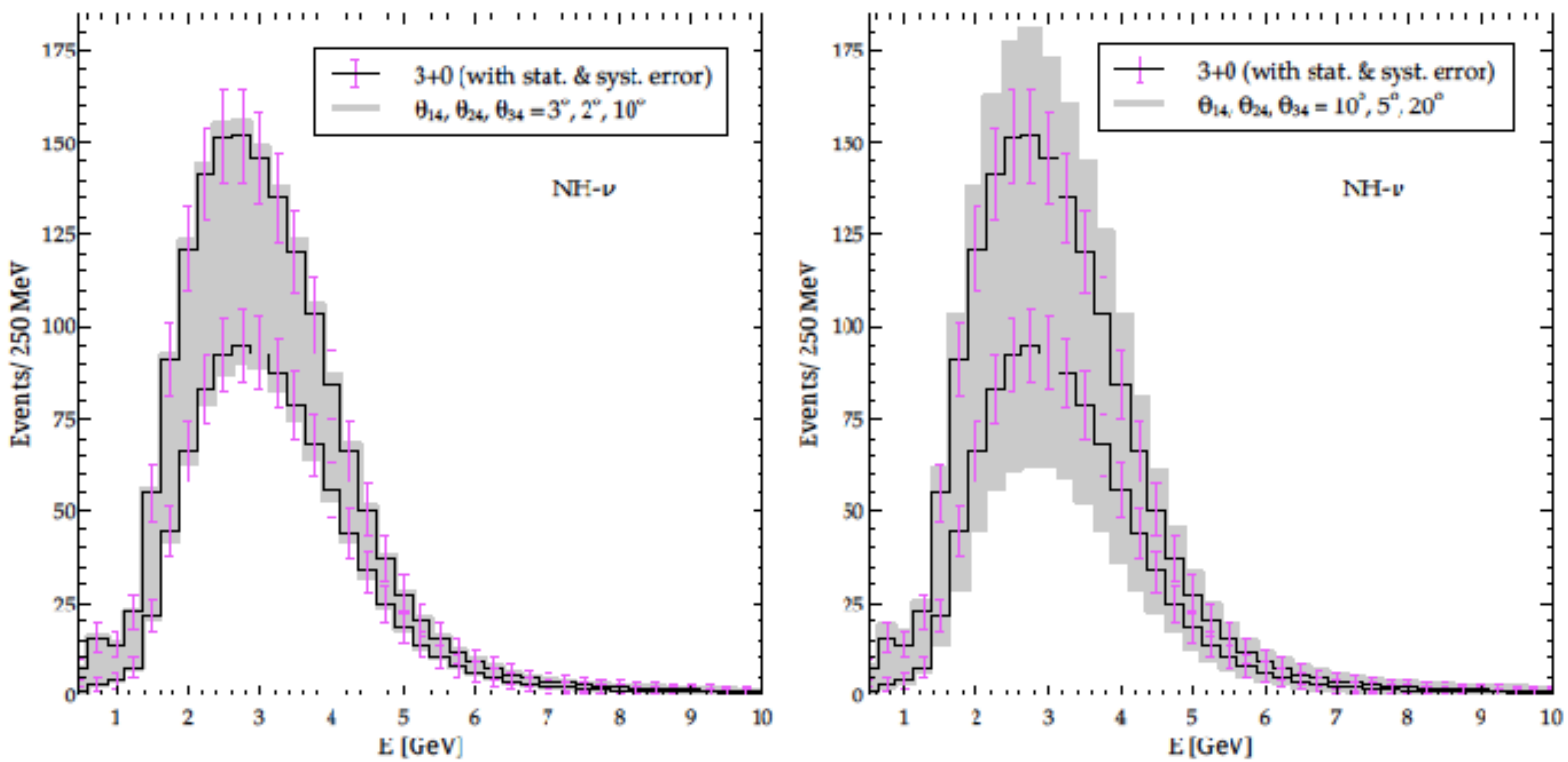
Attributing CP violation unambiguously to any one phase may not be possible at 3σ

True: Θ_{14} = 12°, Θ_{24} = 7°, Θ_{34} = 25°,δ_{34} = 0



Far-detector's sensitivity to 3+1

How large do active-sterile mixings need to be before DUNE becomes sensitive to their presence?



Bands: CP variation

Left: the 3+1 band is degenerate with the 3+0, incl. errors
Right: grey band now extends significantly beyond the expected event rates for 3+0, even after accounting for errors.

Mass hierarchy

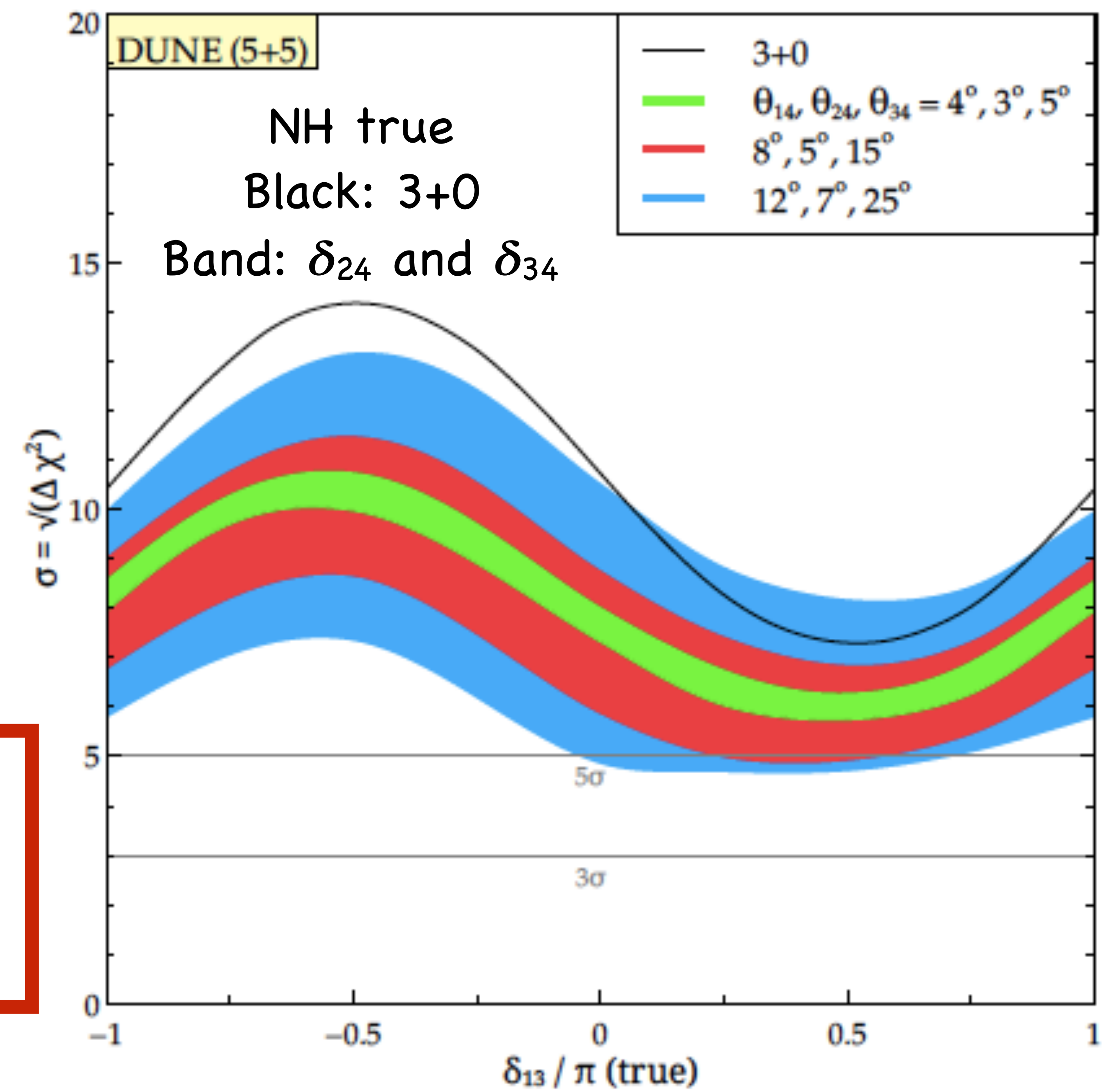
Establishing MH as a function of true
3+1 oscillation parameters

Fit: IH

No marginalisation
over 3+0 osc. params

Marginalisation over all
CP values and
active-sterile mix. angles

Sensitivity usually below 3+0
but 5σ discovery with DUNE

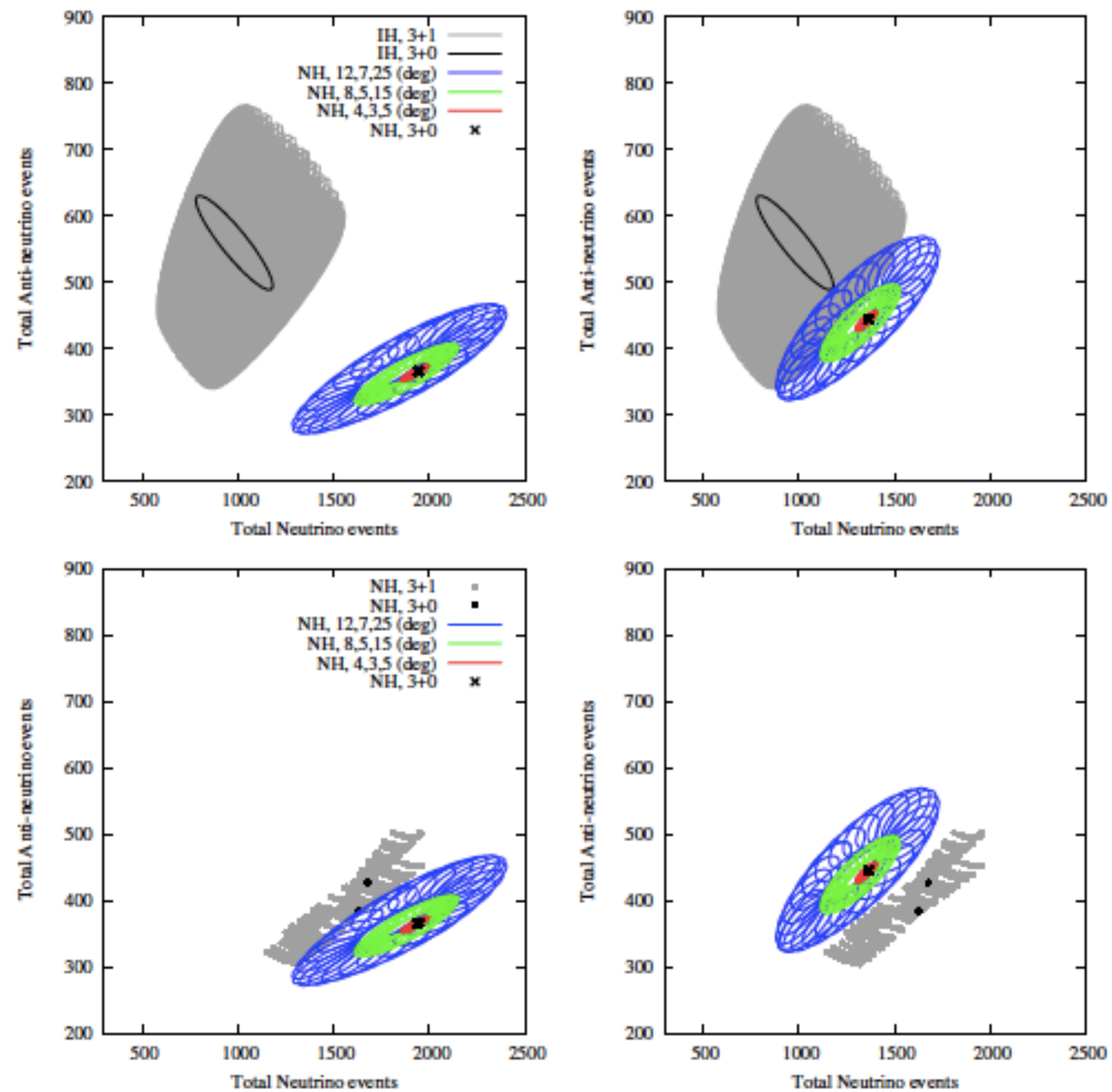


MH and CPV behaviour in 3+1

The fit event rates region increases drastically as we go from 3+0 to 3+1 (black ellipses and dots compared to grey regions).

For small mixing angles the event rate regions are small compared to their size for large mixing angles (red compared to green and blue).

DUNE, 1300 km, 35 kt, 5 yrs ν + 5 yrs anti-ν



Left: δ_{13} = -90°

Right: δ_{13} = 90°

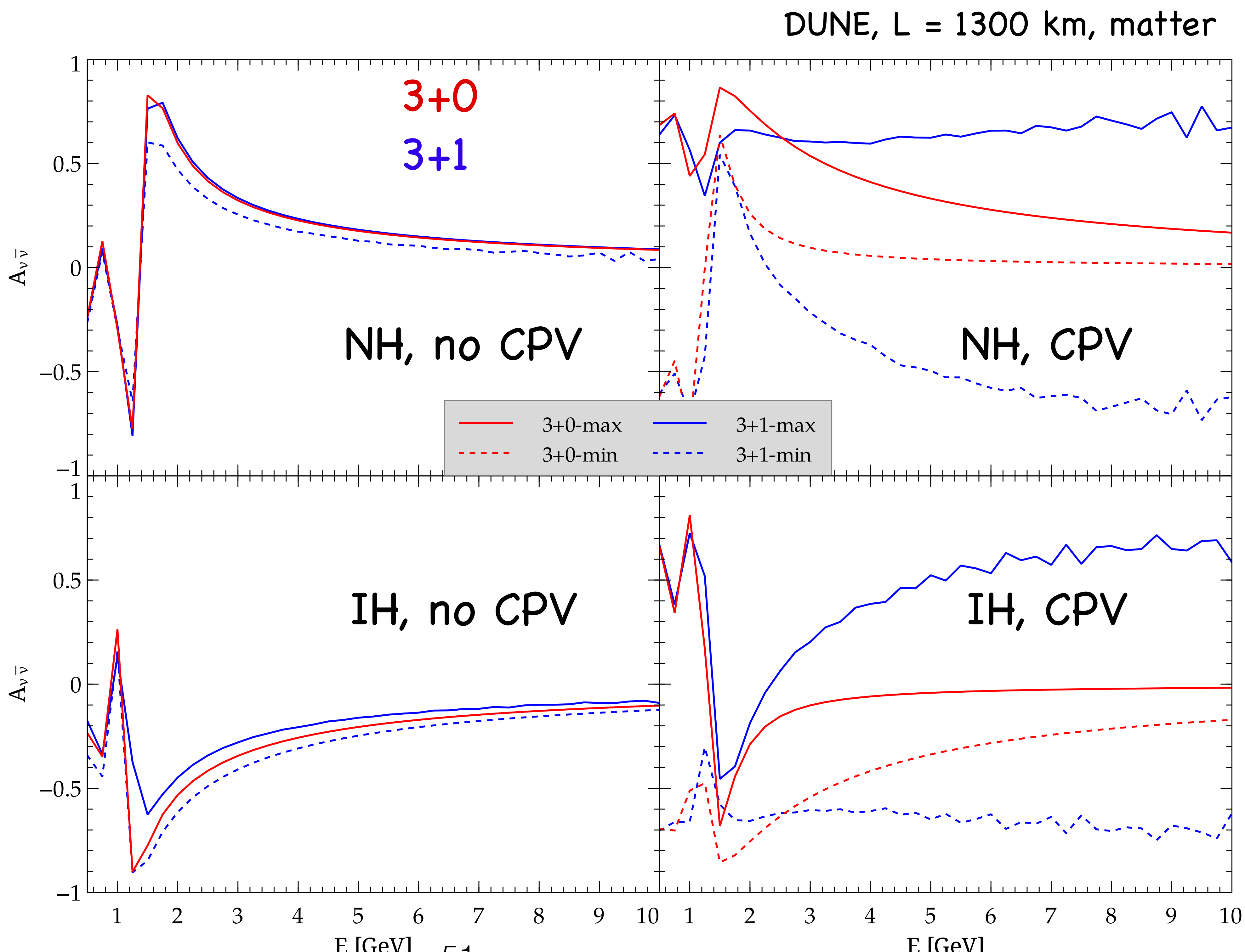
Top: MH

Bottom: CPV

CP asymmetries in 3+0 and 3+1

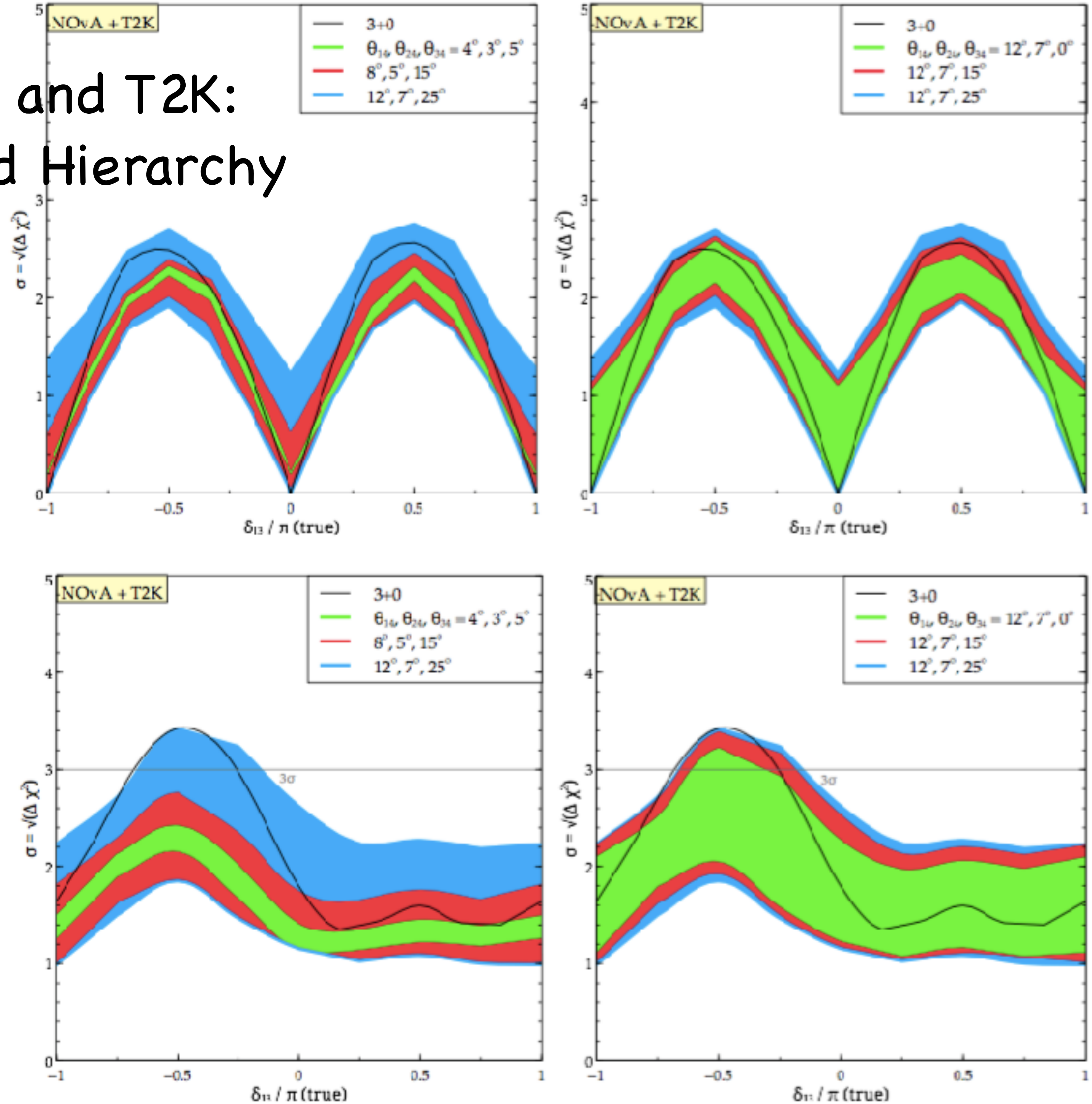
$$A^{\alpha\beta}_{\nu\bar{\nu}} = \frac{P(\alpha \to \beta) - P(\bar{\alpha} \to \bar{\beta})}{P(\alpha \to \beta) + P(\bar{\alpha} \to \bar{\beta})} = \frac{\Delta P_{\alpha\beta}}{P(\alpha \to \beta) + P(\bar{\alpha} \to \bar{\beta})}$$

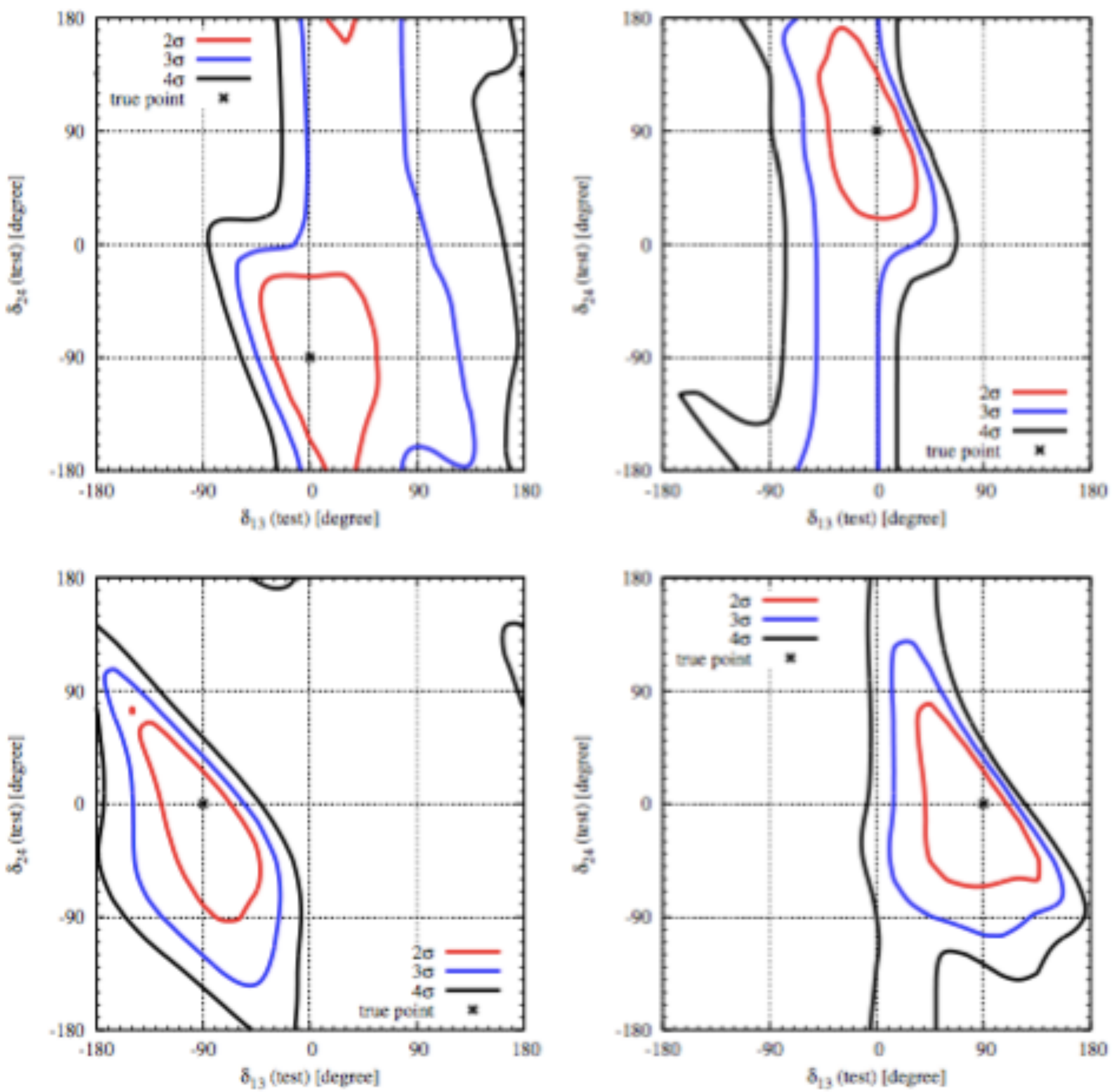
If an experiment were to measure asymmetries which consistently lie outside these two bands it would provide evidence of CP violation in either the 3+0 or the 3+1 case.

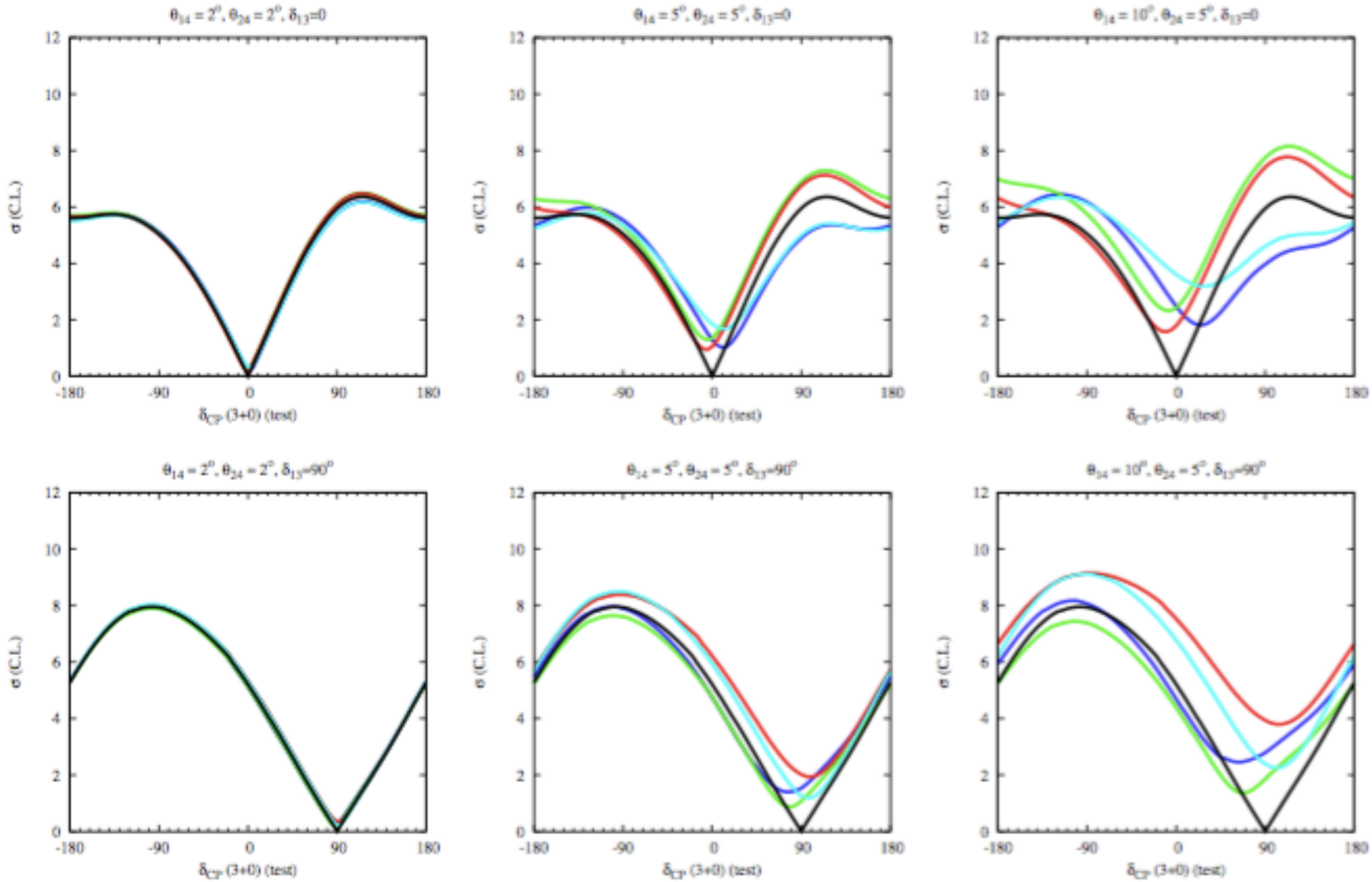


Asymmetry values measured within these two bands in the left panels do not unambiguously signal a CP conserving situation.

NOvA and T2K: CPV and Hierarchy




2σ
3σ
4σ
true point
δ24 (test) [degree]
δ13 (test) [degree]
-180
-90
0
90
180


θ14 = 2°, θ24 = 2°, δ13=0
θ14 = 5°, θ24 = 5°, δ13=0
θ14 = 10°, θ24 = 5°, δ13=0
θ14 = 2°, θ24 = 2°, δ13=90°
θ14 = 5°, θ24 = 5°, δ13=90°
θ14 = 10°, θ24 = 5°, δ13=90°
σ (C.L.)
δCP (3+0) (test)

Appearance probability in 3+1 in vacuum

$$
\begin{aligned}
P^{3+1}_{\mu e} \;=\; & \frac{1}{2}\sin^2 2\theta^{4\nu}_{\mu e} \\
+\; & \left(a^2 \sin^2 2\theta^{3\nu}_{\mu e} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta^{4\nu}_{\mu e}\right)\left[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right] \\
+\; & \cos(\delta_{13})ba^2 \sin 2\theta^{3\nu}_{\mu e}\left[\cos 2\theta_{12}\sin^2\Delta_{21} + \sin^2\Delta_{31} - \sin^2\Delta_{32}\right] \\
+\; & \cos(\delta_{24})ba \sin 2\theta^{4\nu}_{\mu e}\left[\cos 2\theta_{12}\cos^2 \ldots)\right] \\
+\; & \cos(\delta_{13}+\delta_{24})a \sin 2\theta^{3\nu}_{\mu e}\sin 2\theta^{4\nu}_{\mu e}\left[\ldots \right. \\
+\; & \cos 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})] \\
-\; & \frac{1}{2}\sin(\delta_{13})ba^2 \sin 2\theta^{3\nu}_{\mu e}\left[\sin 2\Delta_{21} - \ldots \right] \\
+\; & \frac{1}{2}\sin(\delta_{24})ba \sin 2\theta^{4\nu}_{\mu e}\left[\cos^2\theta_{13}\sin \ldots \right. \\
+\; & \frac{1}{2}\sin(\delta_{13}+\delta_{24})a \sin 2\theta^{3\nu}_{\mu e}\sin 2\theta^{4\nu}_{\mu e}\left[\cos^2\theta_{12}\sin 2\Delta_{31} + \sin^2\theta_{12}\sin 2\Delta_{32}\right] \\
+\; & \left(b^2a^2 - \frac{1}{4}a^2\sin^2 2\theta_{12}\sin^2 2\theta^{3\nu}_{\mu e} - \frac{1}{4}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 2\theta^{4\nu}_{\mu e}\right)\sin^2\Delta_{21}
\end{aligned}
$$

Θ_{14} and Θ_{24} come in certain combinations only..

In vacuum, the expression does not depend on Θ_{34} and δ_{34}

where $\sin 2\theta^{3\nu}_{\mu e} = \sin 2\theta_{13}\sin\theta_{23}$, $\quad b = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}$,

$\sin 2\theta^{4\nu}_{\mu e} = \sin 2\theta_{14}\sin\theta_{24}$ and $a = \cos\theta_{14}\cos\theta_{24}$

Appearance probability in 3+1 in vacuum

$$
\begin{aligned}
P_{\mu e}^{3+1} &= \frac{1}{2}\sin^2 2\theta_{\mu e}^{4\nu} \\
&+ (a^2 \sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta_{\mu e}^{4\nu})\Big[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\Big] \\
&+ \cos(\delta_{13}) b a^2 \sin 2\theta_{\mu e}^{3\nu}\Big[\cos 2\theta_{12}\sin^2\Delta_{21} + \sin^2\Delta_{31} - \sin^2\Delta_{32}\Big] \\
&+ \cos(\delta_{24}) b a \sin 2\theta_{\mu e}^{4\nu}\Big[\cos 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} - \sin^2\theta_{13}(\sin^2\Delta_{31} - \sin^2\Delta_{32})\Big] \\
&+ \cos(\delta_{13}+\delta_{24}) a \sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\Big[-\frac{1}{2}\sin^2 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} \\
&+ \cos 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})\Big] \\
&- \frac{1}{2}\sin(\delta_{13}) b a^2 \sin 2\theta_{\mu e}^{3\nu}\Big[\sin 2\Delta_{21} - \sin 2\Delta_{31} + \sin 2\Delta_{32}\Big] \\
&+ \frac{1}{2}\sin(\delta_{24}) b a \sin 2\theta_{\mu e}^{4\nu}\Big[\cos^2\theta_{13}\sin 2\Delta_{21} + \sin^2\theta_{13}(\sin 2\Delta_{31} - \sin 2\Delta_{32})\Big] \\
&+ \frac{1}{2}\sin(\delta_{13}+\delta_{24}) a \sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\Big[\cos^2\theta_{12}\sin 2\Delta_{31} + \sin^2\theta_{12}\sin 2\Delta_{32}\Big] \\
&+ (b^2 a^2 - \frac{1}{4}a^2\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{4\nu})\sin^2\Delta_{21}
\end{aligned}
$$

where $\sin 2\theta_{\mu e}^{3\nu} = \sin 2\theta_{13}\sin\theta_{23}$, $b = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}$,

$\sin 2\theta_{\mu e}^{4\nu} = \sin 2\theta_{14}\sin\theta_{24}$ and $a = \cos\theta_{14}\cos\theta_{24}$

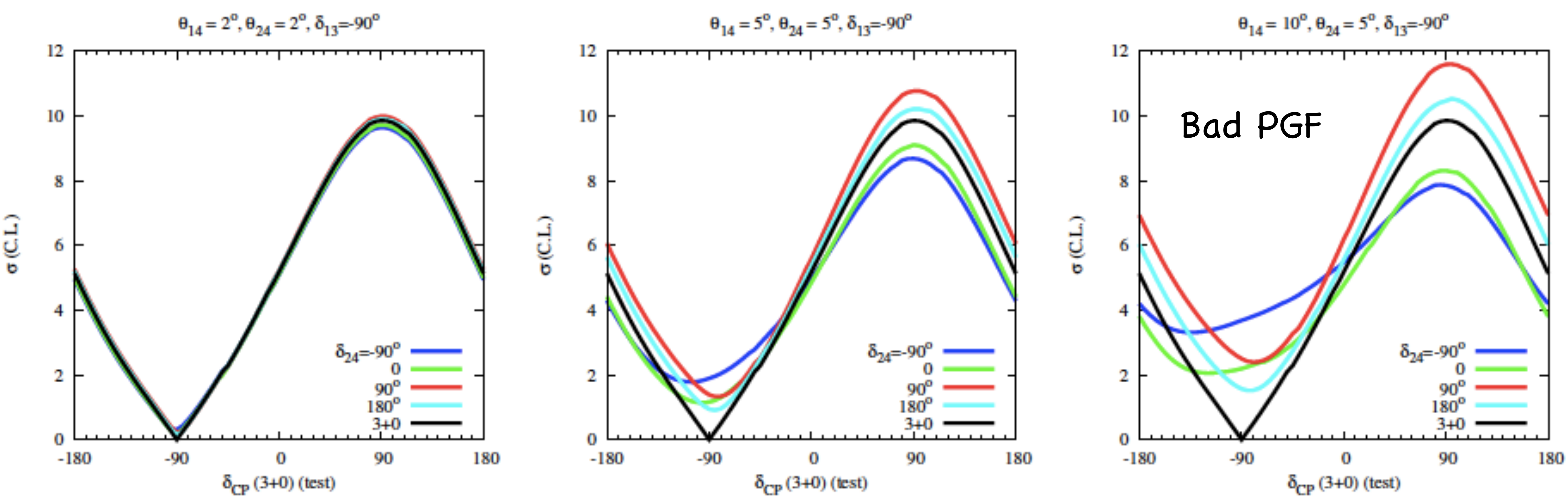
How small a 3+1 can LBL ignore?

Can CP measurements at DUNE get affected by assuming the absence of sterile neutrinos when they exist in reality, but are obscure because of very small mixings?

Left: the results obtained are essentially the same
Middle: small deviations from the 3+0 results
Right: the precision can vary by around 10^{o}

Sim. Data: 3+1
Fit: 3+0, δ_{CP}

$\sin^2 2\Theta_{\mu e} < 0.001$
(SBL Limit)



Sterile Neutrinos or Flux Uncertainties? - Status of the Reactor Anti-Neutrino Anomaly

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(Submitted on 13 Sep 2017)

The $\sim 3\sigma$ discrepancy between the predicted and observed reactor anti-neutrino flux, known as the reactor anti-neutrino anomaly, continues to intrigue. The recent discovery of an unexpected bump in the reactor anti-neutrino spectrum, as well as indications that the flux deficit is different for different fission isotopes seems to disfavour the explanation of the anomaly in terms of sterile neutrino oscillations. We critically review this conclusion in view of all available data on electron (anti)neutrino disappearance. We find that the sterile neutrino hypothesis cannot be rejected based on global data and is only mildly disfavored compared to an individual rescaling of neutrino fluxes from different fission isotopes. The main reason for this is the presence of spectral features in recent data from the NEOS and DANSS experiments. If state-of-the-art predictions for reactor fluxes are taken at face value, sterile neutrino oscillations allow a consistent description of global data with a significance close to 3σ relative to the no-oscillation case. Even if reactor fluxes and spectra are left free in the fit, a 2σ hint in favour of sterile neutrinos remains, with allowed parameter regions consistent with an explanation of the anomaly in terms of oscillations.

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