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Exploring Light sterile νs with LBL experiments

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Outline

Introduction

Interference effects mediated by sterile neutrinos

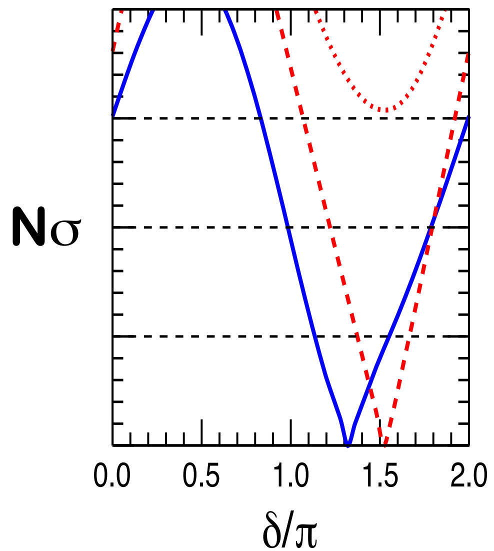
LBL constraints on new CP phases: present

LBL constraints on new CP phases: future

Conclusions

Introduction

It is timely to pose a new question



Capozzi, Lisi, Marrone, A.P,
PPNP 102, 48 (2018)

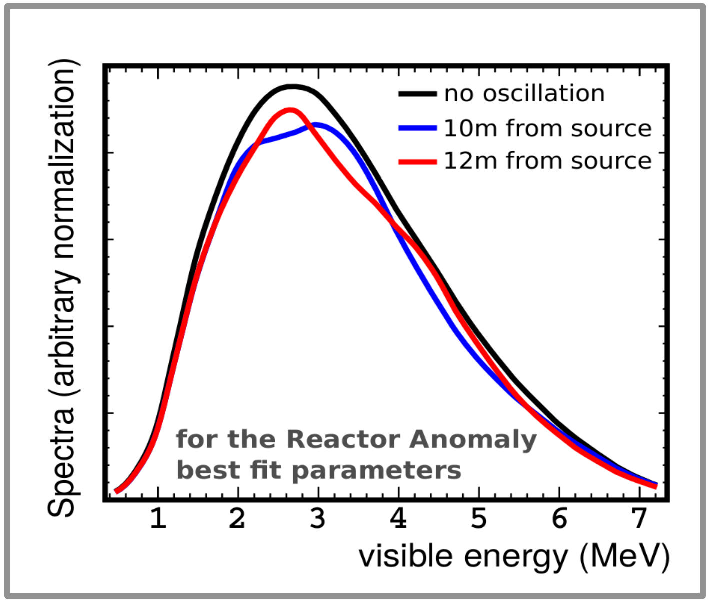
LBL experiments start to be sensitive to the CP violating phase δ

Can sterile neutrinos generate observable CP violating effects at LBL experiments?

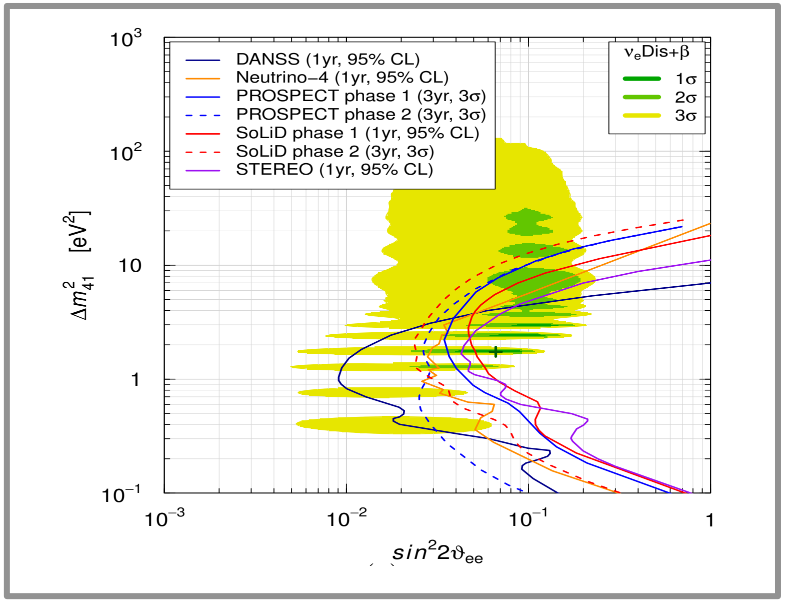
Question basically ignored in the past !

Most probably, the discovery of sterile νs can come only from SBL experiments

STEREO



Gariazzo et al., 1703.00860



by observing the characteristic oscillation pattern

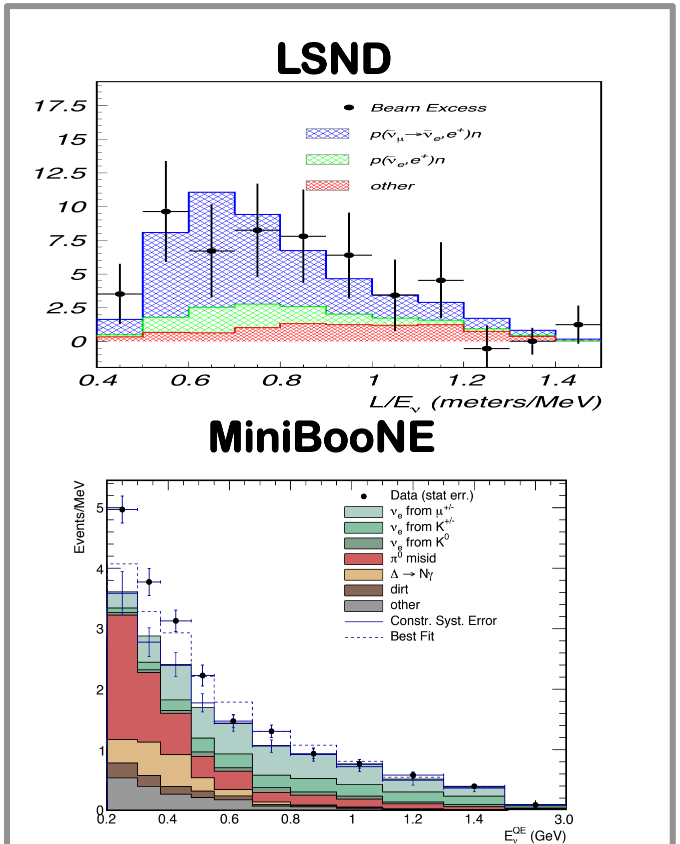
and we have already some hints…

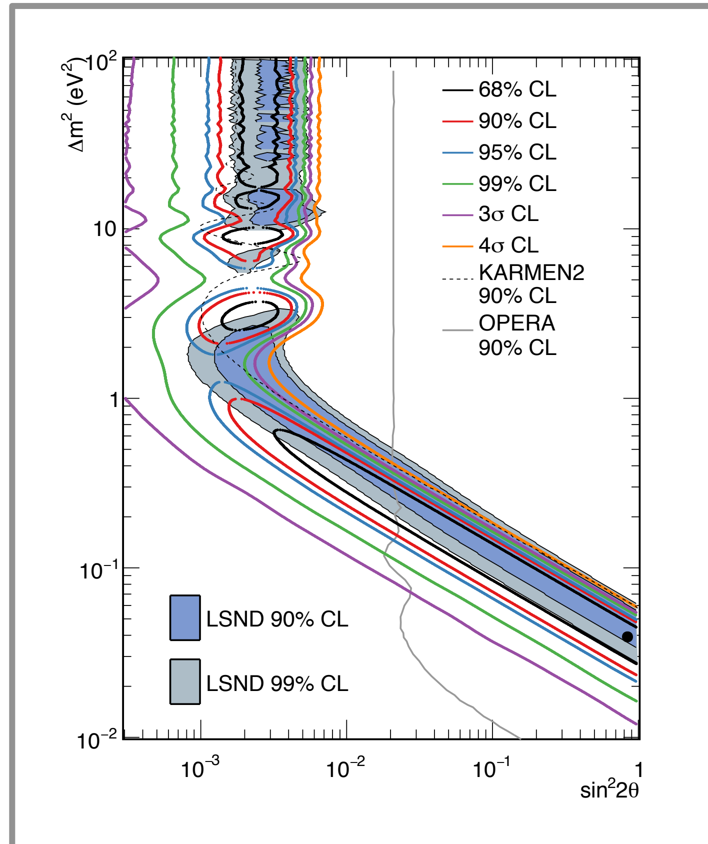
from accelerators

(unexplained ν_e appearance in a ν_μ beam)

3.8σ

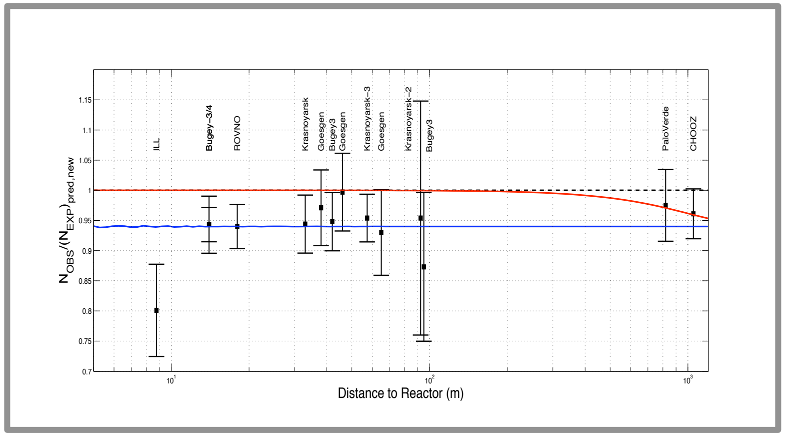
4.8σ



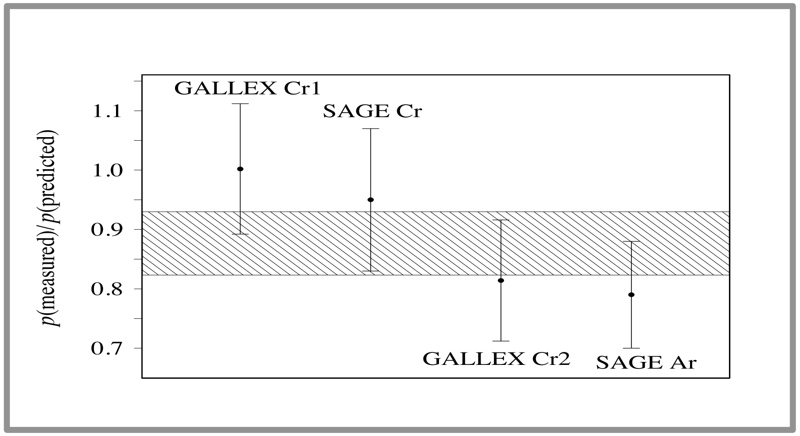


from reactor rates and solar calibration

(unexplained ν_e disappearance)



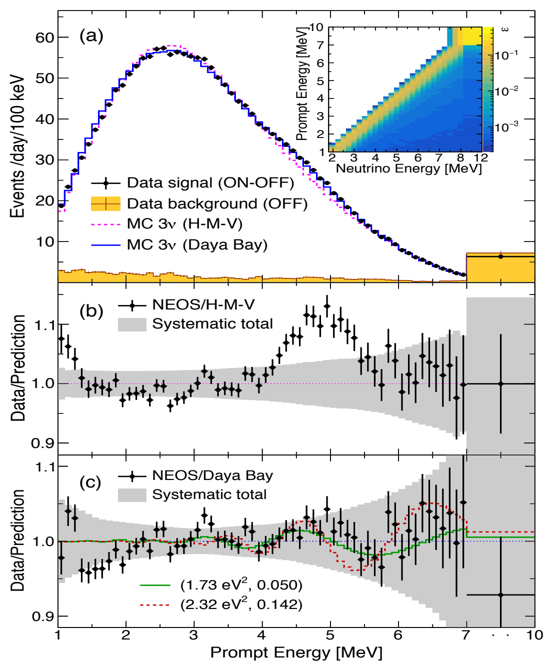
Mention et al. arXiv:1101:2755 [hep-ex]



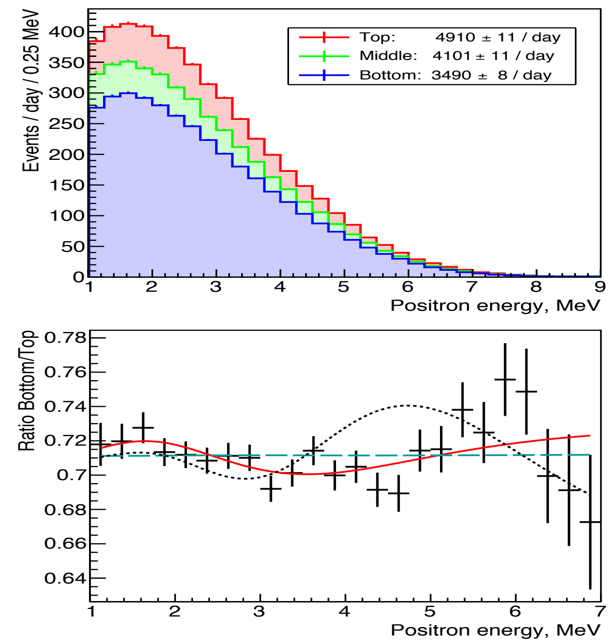
SAGE coll., PRC 73 (2006) 045805

…and recently also from reactor spectra

NEOS arXiv:1610:05134



DANSS arXiv:1804:04046



$$\chi^2_{4\nu} - \chi^2_{3\nu} = -6.5$$

$$\chi^2_{4\nu} - \chi^2_{3\nu} = -13.1$$

Best fit points very similar: $(\sin^2 2\theta,\ \Delta m^2) \simeq (0.05,\ 1.4\mathrm{eV}^2)$

However, SBL have an intrinsic limitation

At SBL atm/sol oscillations are negligible

$$\frac{L}{E} \sim \frac{m}{\mathrm{MeV}}$$

$$\Delta_{12} \simeq 0$$
$$\Delta_{13} \simeq 0$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

Impossible to observe phenomena of interference between the new frequency ($\Delta_{14} \sim 1$) and atm/sol ones

This limitation can be overcome at LBL's…

Interference effects mediated by sterile νs

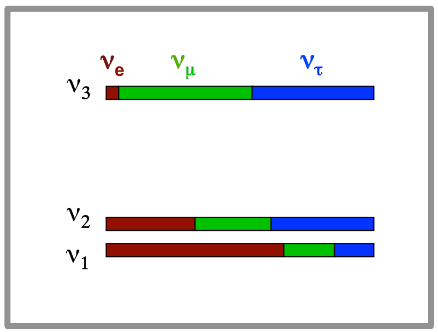
N. Klop & **A.P.**, PRD 91 073017 (2015) arXiv: 1412.7524

How to enlarge the 3-flavor scheme

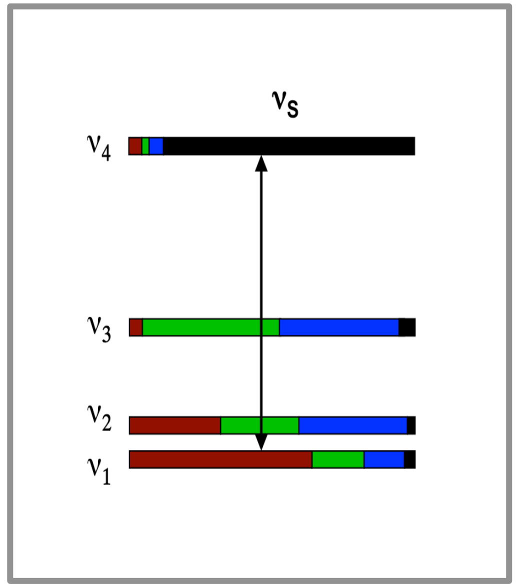
3ν scheme

Δm^2_{atm}

Δm^2_{sol}



3+1 scheme



$|U_{s4}| \sim 1$

$\Delta m^2_{14} \sim 1\ eV^2$

At LBL the effective 2-flavor SBL description is no more valid and calculations should be done in the 3+1 (or 3+N_s) scheme

Mixing Matrix in the 3+1 scheme

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

$$R_{ij} = \begin{bmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{bmatrix} \qquad \tilde{R}_{ij} = \begin{bmatrix} c_{ij} & \tilde{s}_{ij} \\ -\tilde{s}^*_{ij} & c_{ij} \end{bmatrix}$$

$$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij} \qquad \tilde{s}_{ij} = s_{ij} e^{-i\delta_{ij}}$$

3ν {
- **3 mixing angles**
- **1 Dirac phase**
- **2 Majorana phases**

3+1 {
- **6**
- **3**
- **3**

3+N {
- **3+3N**
- **1+2N**
- **2+N**

In general, we have additional sources of CPV

LBL transition probability in 3-flavor

$$P^{3\nu}_{\nu_\mu\to\nu_e} = P^{\rm ATM} + P^{\rm SOL} + P^{\rm INT}$$

In vacuum:

$$P^{\rm ATM} = 4s^2_{23}s^2_{13}\sin^2\Delta$$
$$P^{\rm SOL} = 4c^2_{12}c^2_{23}s^2_{12}(\alpha\Delta)^2$$
$$P^{\rm INT} = 8s_{23}s_{13}c_{12}c_{23}s_{12}(\alpha\Delta)\sin\Delta\cos(\Delta + \delta_{CP})$$

$$\Delta = \frac{\Delta m^2_{31}L}{4E}, \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$\Delta \sim \pi/2$

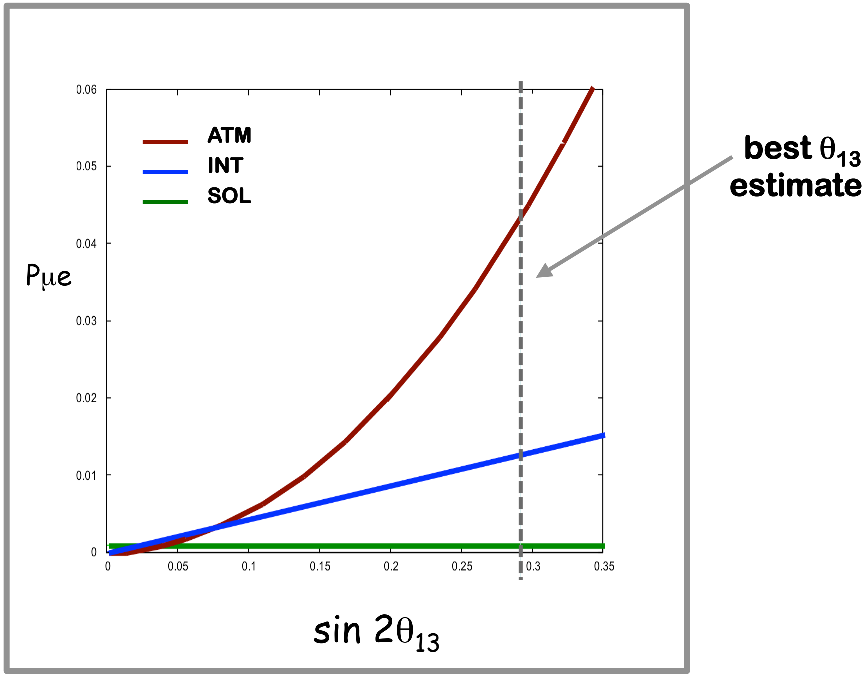
$\alpha \sim 0.03$

$P^{\rm ATM}$ leading → $\theta_{13} > 0$

$P^{\rm INT}$ subleading → dependency on δ

$P^{\rm SOL}$ negligible

T2K osc. maximum E = 0.6 GeV



A new interference term in the 3+1 scheme

N. Klop & A.P., PRD (2015)

- $\Delta_{14} >> 1$: fast oscillations are averaged out

- But interference of Δ_{14} & Δ_{13} survives and is observable

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

$s_{13} \sim s_{14} \sim s_{24} \sim 0.15 \sim \varepsilon$

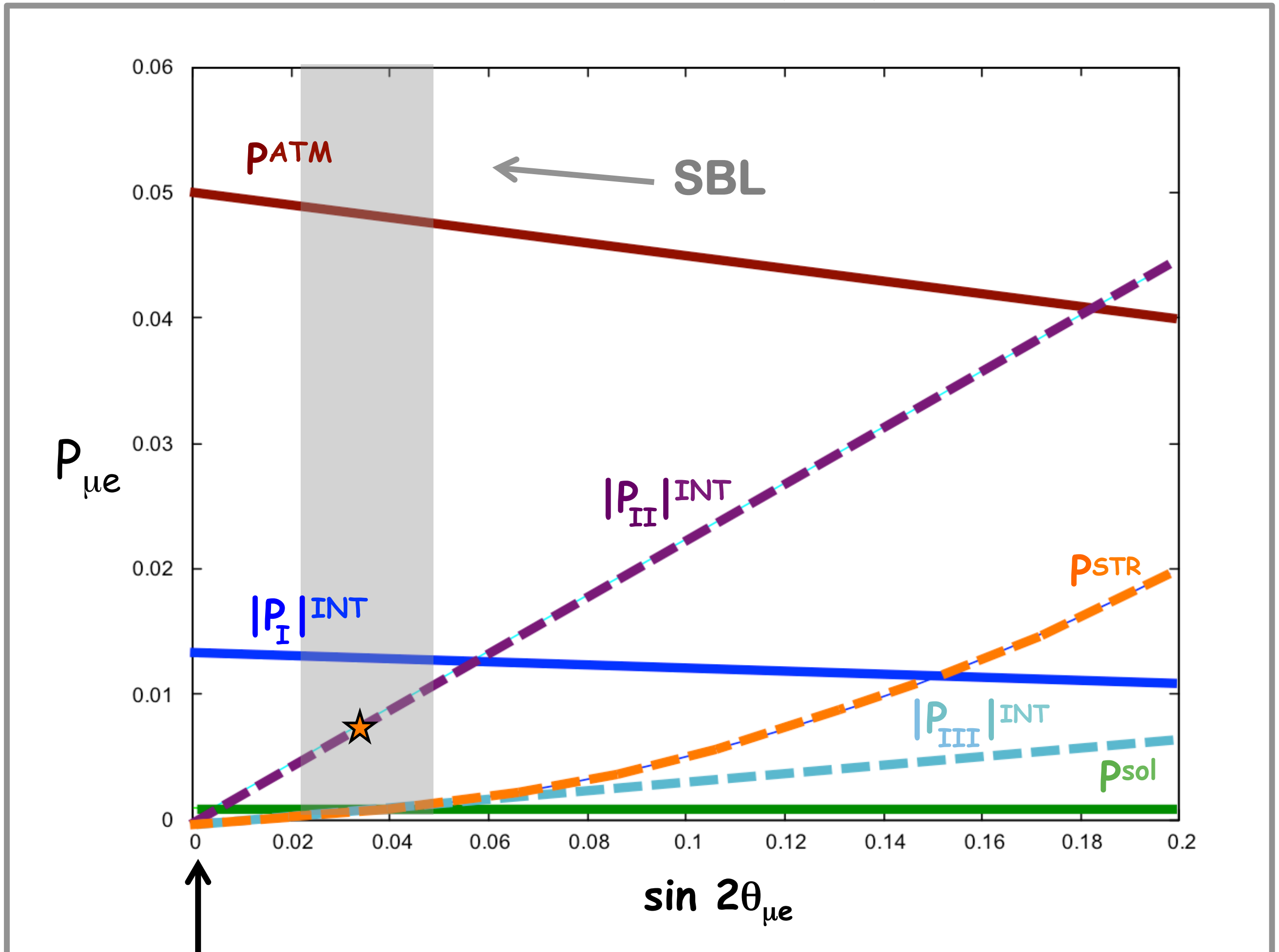
$\alpha = \delta m^2/\Delta m^2 \sim 0.03 \sim \varepsilon^2$

$$\begin{cases} P^{\rm ATM} \simeq 4 s^2_{23} s^2_{13} \sin^2 \Delta & \sim \varepsilon^2 \\ P^{\rm INT}_{\rm I} \simeq 8 s_{13} s_{23} c_{23} s_{12} c_{12} (\alpha\Delta) \sin\Delta \cos(\Delta + \delta_{13}) & \sim \varepsilon^3 \\ P^{\rm INT}_{\rm II} \simeq 4 s_{14} s_{24} s_{13} s_{23} \sin\Delta \sin(\Delta + \delta_{13} - \delta_{14}) & \sim \varepsilon^3 \end{cases}$$

Sensitivity to the new CP-phase δ_{14}

Amplitude of the new interference term

N. Klop & A.P., PRD (2015)

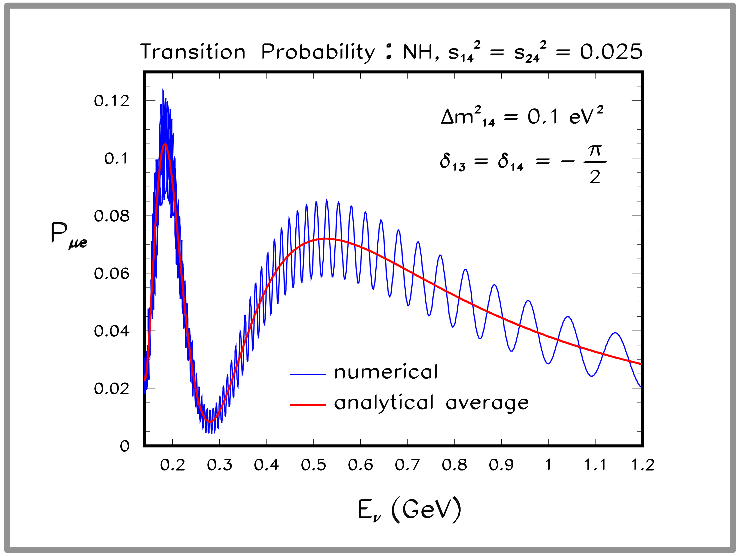


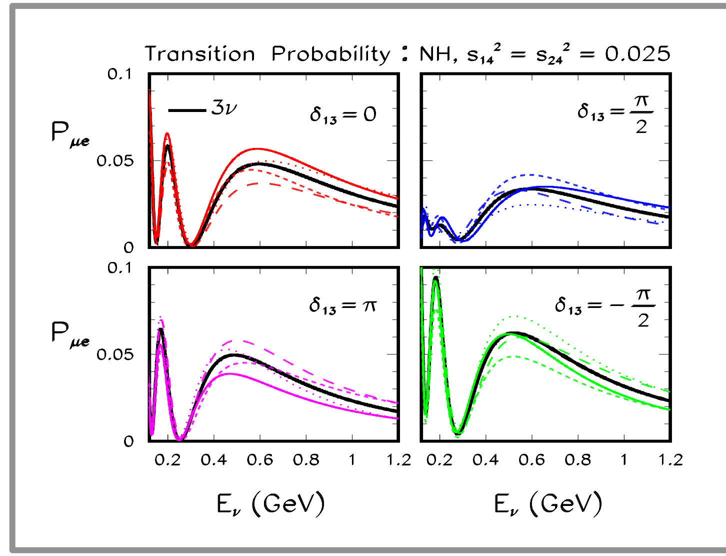
3ν limit

T2K
θ_{13} = 9°
E = 0.6 GeV

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

Numerical examples of 4ν probability





The fast oscillations get averaged out due to the finite energy resolution

Different line styles ⇔ Different values of δ_{14}

The modifications induced by δ_{14} are almost as large as those induced by the standard CP-phase δ_{13}

Consequences…

LBL constraints on sterile νs: present

A.P., PRD (RC) 91, 091301 (2015)
arXiv:1503.03966

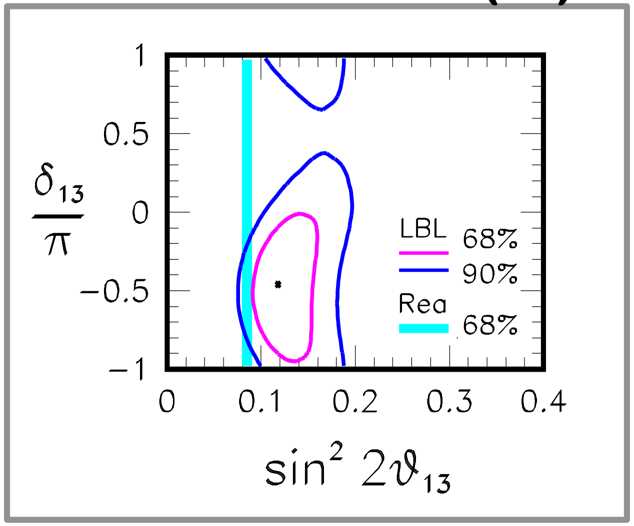
A.P., PLB 757, 142 (2016)
arXiv:1509.03148

Capozzi, Giunti, Laveder & **A.P.**,
PRD 95 (2017)
arXiv:1612.07764

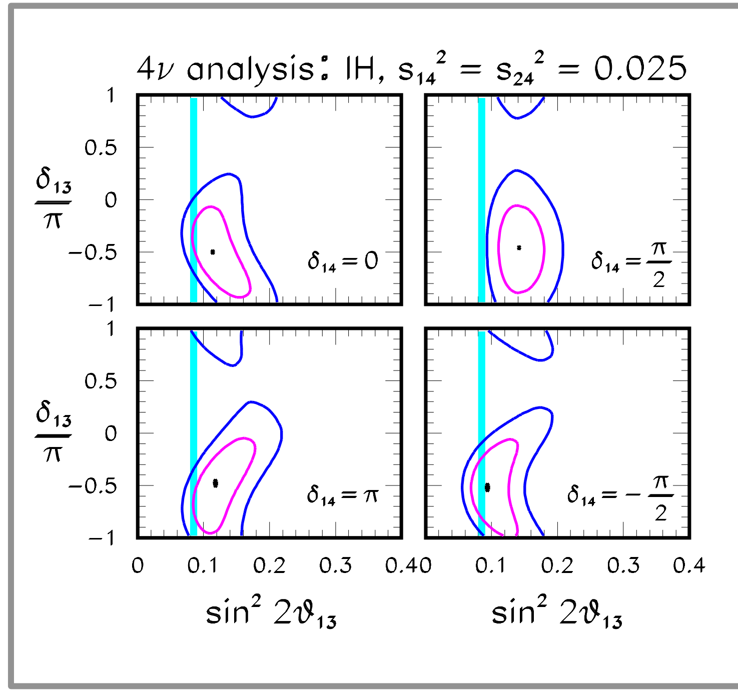
LBL constraints change in the 3+1 scheme

PLB (2016)

3ν: T2K + NOνA (IH)



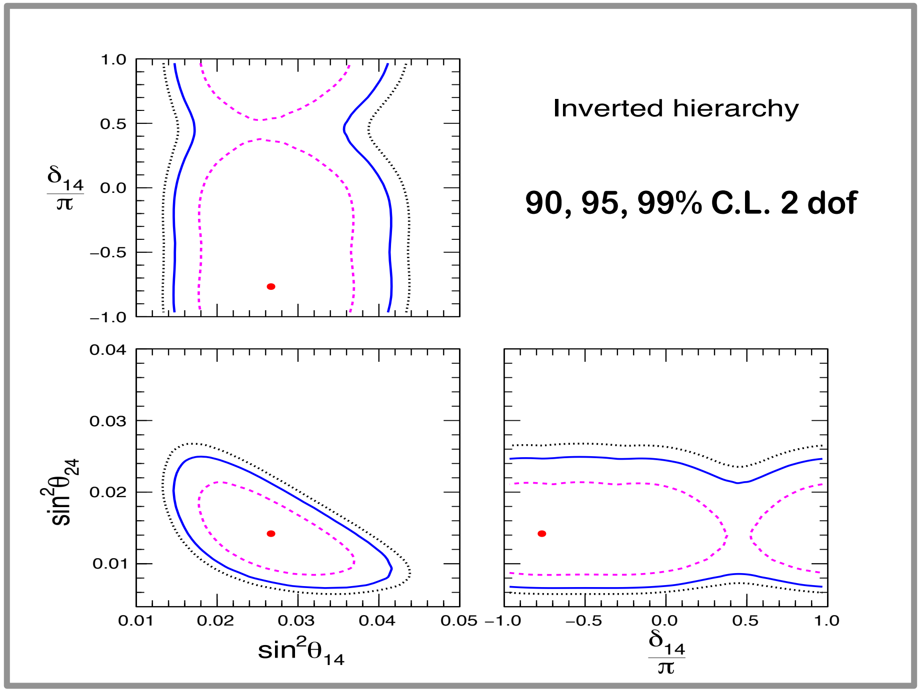
4ν



- **The level of (dis-)agreement of LBL & Rea. depends on δ_{14}**
- **In this analysis θ_{14} and θ_{24} are fixed at the SBL best fit values**
- **These results call for a more refined analysis …**

Joint SBL and LBL constraints on $[\theta_{14},\theta_{24},\delta_{14}]$

PRD (2017) **SBL + LBL**



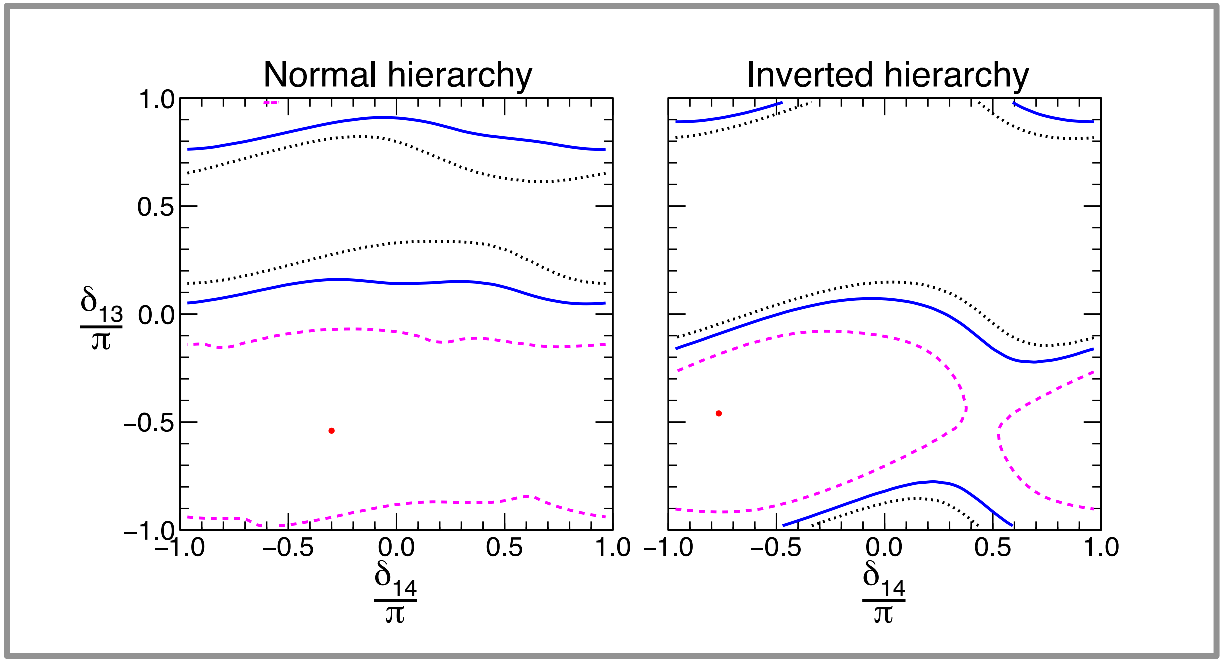
- $[\theta_{14,}\ \theta_{24}]$ **determined by SBL experiments**

- δ_{14} **constrained by LBL experiments**

Constraints on the two CP-phases

PRD (2017)

SBL + LBL



- **δ_{13} is more constrained than δ_{14}**

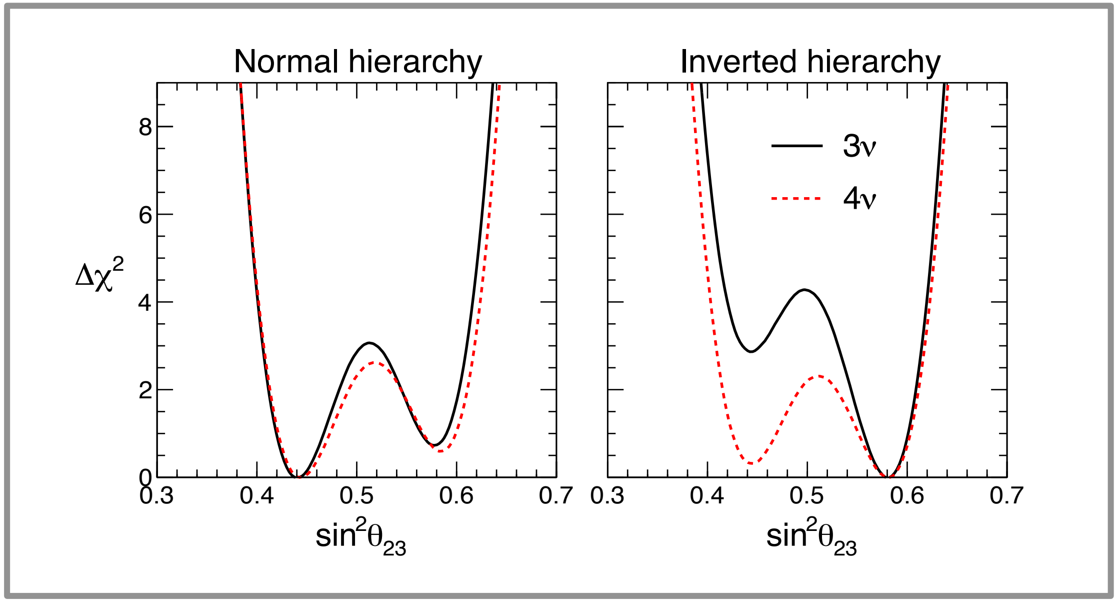
- **Best fit values: $\delta_{13} \sim \delta_{14} \sim -\pi/2$**

- **This information cannot be extracted from SBL alone !**

Impact of sterile neutrinos on θ_{23}

PRD (2017)

SBL + LBL



Indication for non-maximal θ_{23} persists in 3+1 scheme

Preference for θ_{23} octant disappears in 3+1 scheme

Octant fragility seems to be a general feature (see later)

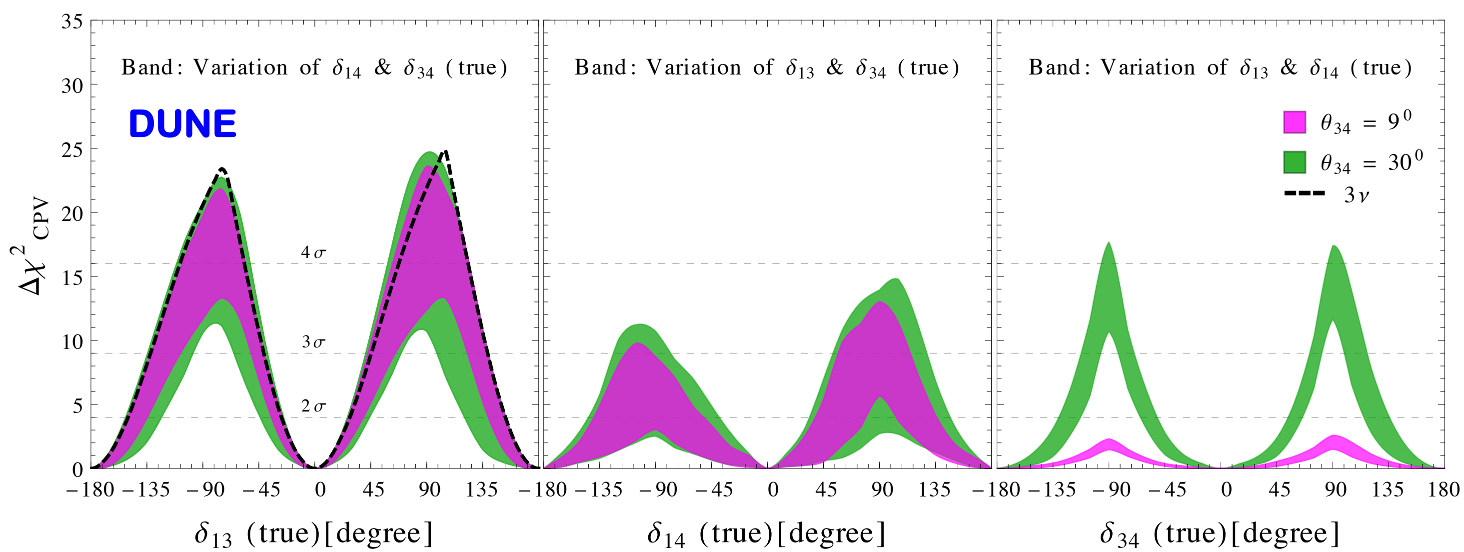
Looking to the future

Agarwalla, Chatterjee, Dasgupta, **A.P.**,
arXiv: 1601.05995 (JHEP 2016)

Agarwalla, Chatterjee, **A.P.**,
arXiv: 1603.03759 (JHEP 2016)
arXiv: 1607.01745 (PLB 2016)
arXiv: 1605.04299 (PRL 2017)
arXiv: 1801.04855 (JHEP 2018)
arXiv: 1906.XXXX (in preparation)

CPV discovery potential

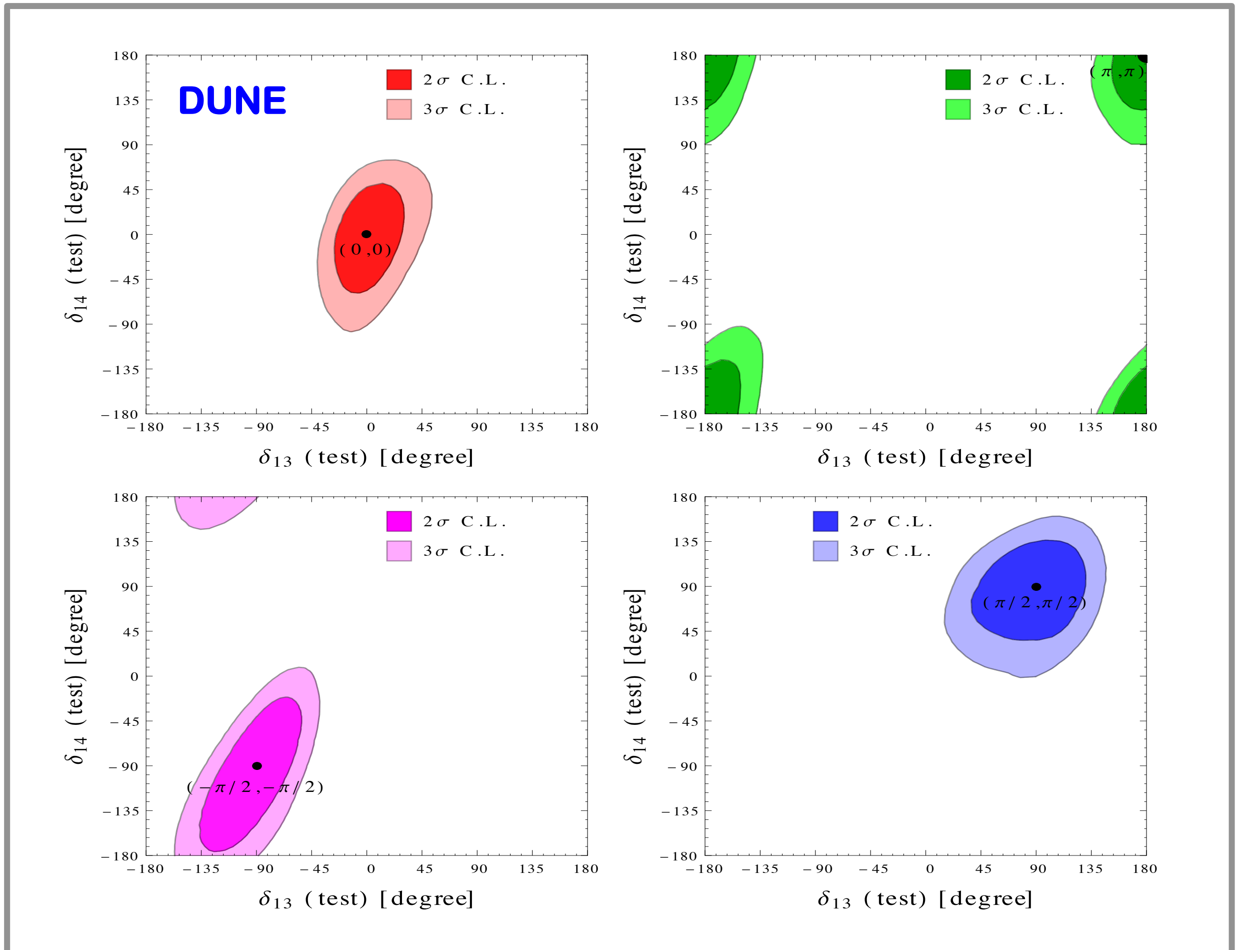
JHEP 2016



- **Sensitivity to CPV induced by δ_{13} reduced in 3+1 scheme**
- **Potential sensitivity also to the new CP-phases δ_{14} e δ_{34}**
- **Clear hierarchy in the sensitivity: $\delta_{13}>\delta_{14}>\delta_{34}$ for $\theta_{14}=\theta_{24}=\theta_{34}=9^0$**

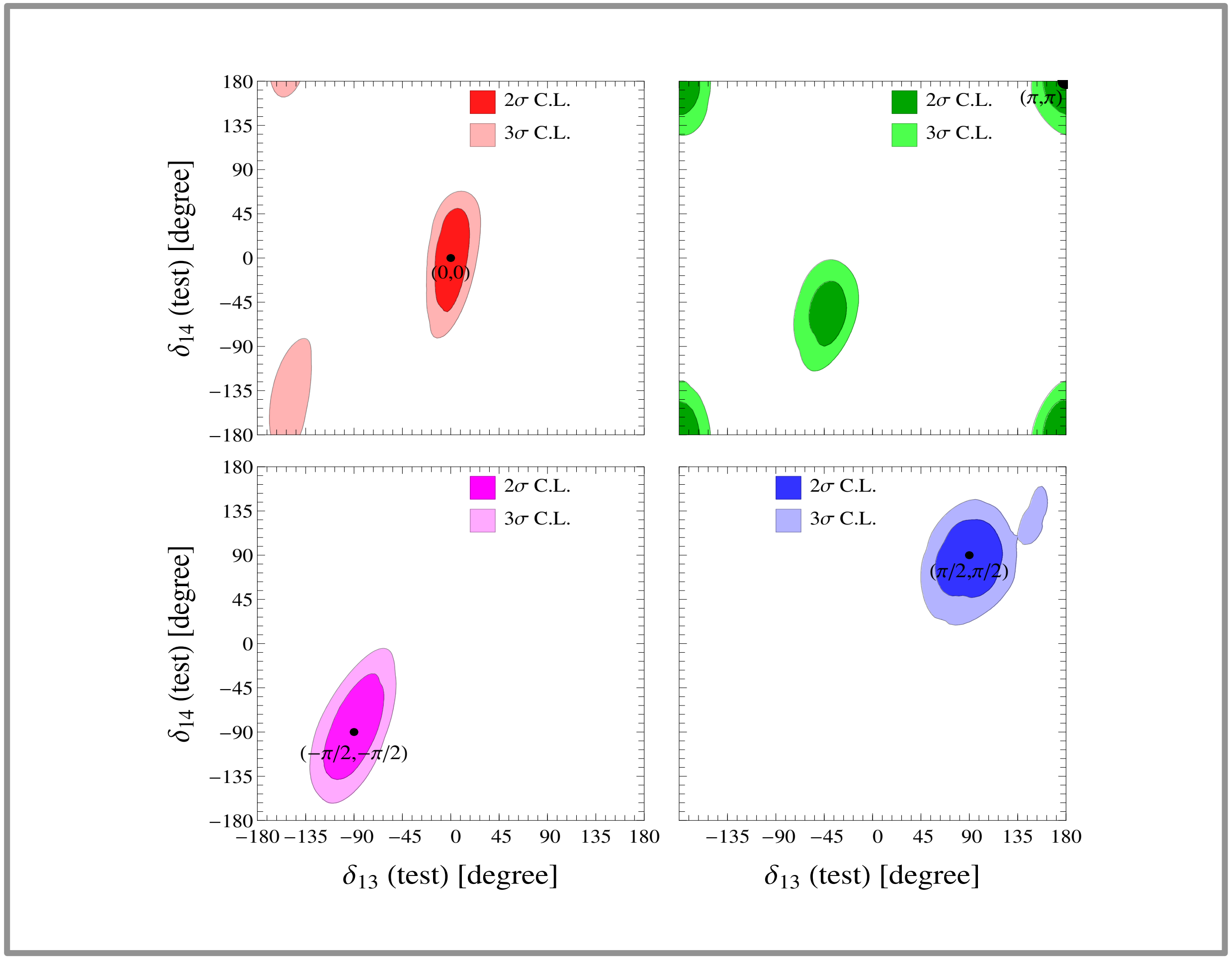
Reconstruction of the CP phases in DUNE

JHEP 2016



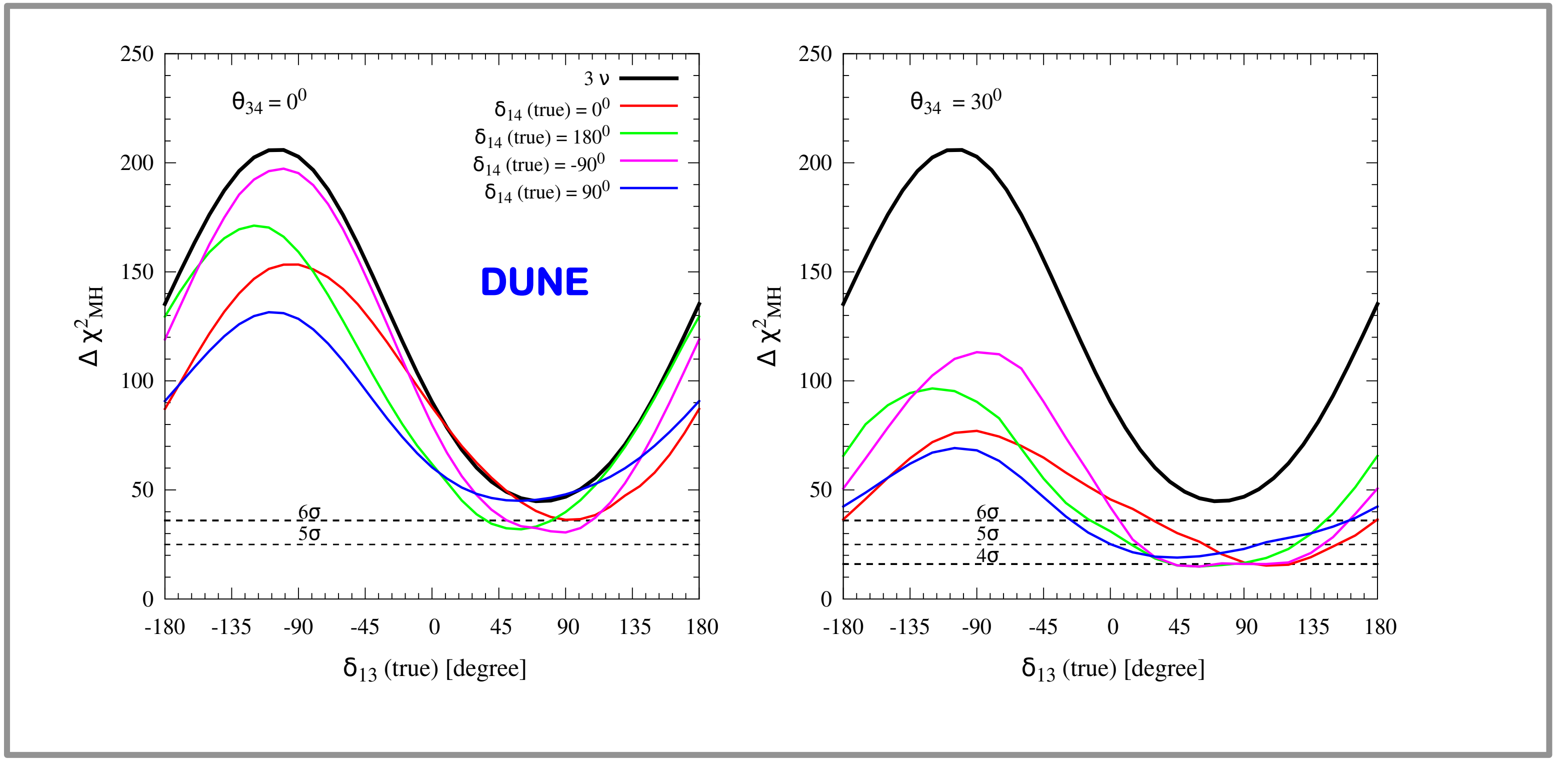
Reconstruction of the CP phases in T2HK

JHEP 2018



Discovery potential of mass hierarchy

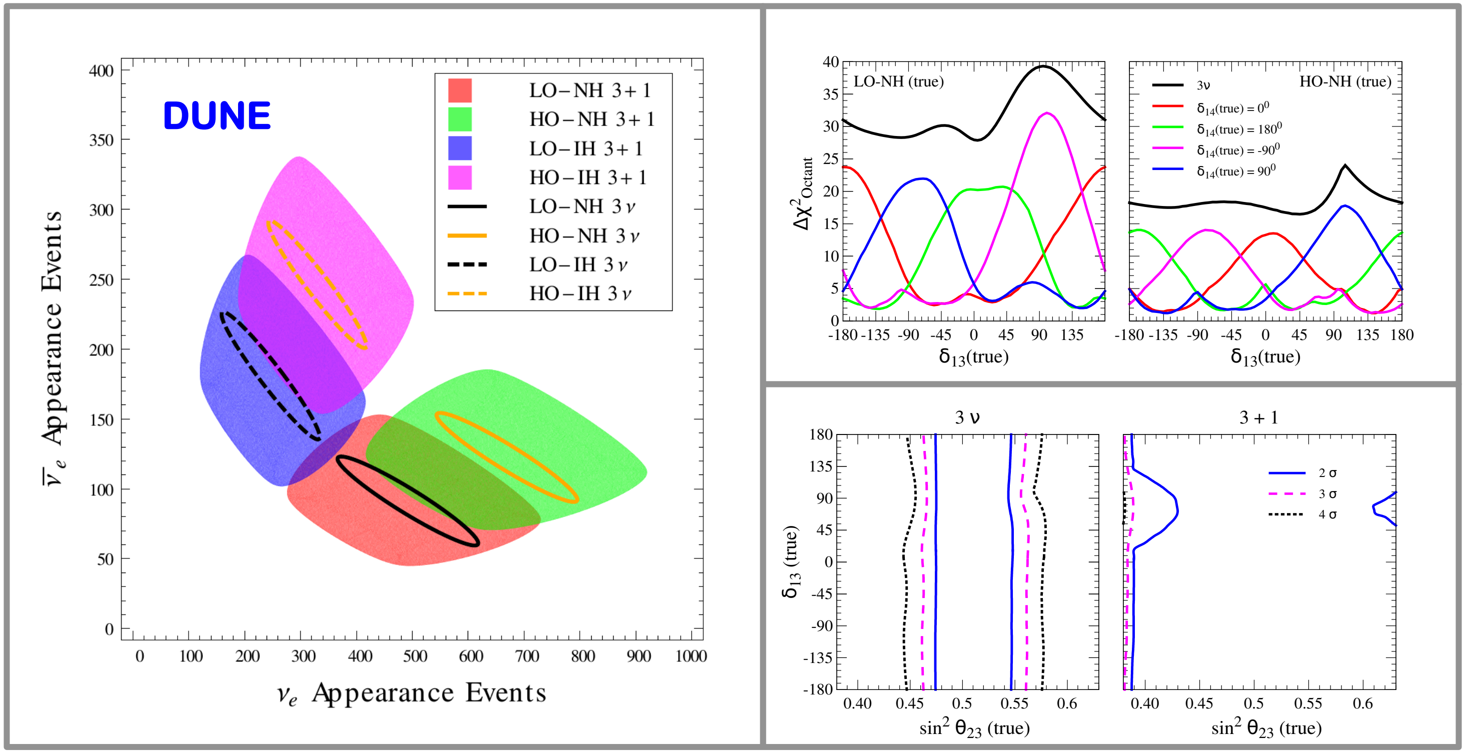
JHEP 2016



Degradation of sensitivity but 4σ level preserved

Octant of θ_{23} in danger with a sterile neutrino

PRL 2017



Distinct ellipses (3ν) become overlapping blobs (3+1)

For unfavorable combinations of δ_{13} & δ_{14} sensitivity is lost

Conclusions

- Sterile neutrinos are sources of additional CPV

- Consequences for the LBL estimates of the standard parameters (MH, CP-phase δ, octant of θ_{23})

- Full exploration of new CP-phase (δ_{14},δ_{34}) possible only with LBL's

- LBL experiments complementary to the SBL ones

Thank you
for your attention!

Back up slides

CPV and averaged oscillations

$$A^{CP}_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

$$A^{CP}_{\alpha\beta} = -16 J^{12}_{\alpha\beta} \sin\Delta_{21} \underbrace{\sin\Delta_{13} \sin\Delta_{32}}$$

if $\Delta \equiv \Delta_{13} \simeq \Delta_{23} \gg 1$ $\rightarrow$ $\langle \sin^2 \Delta \rangle = 1/2$

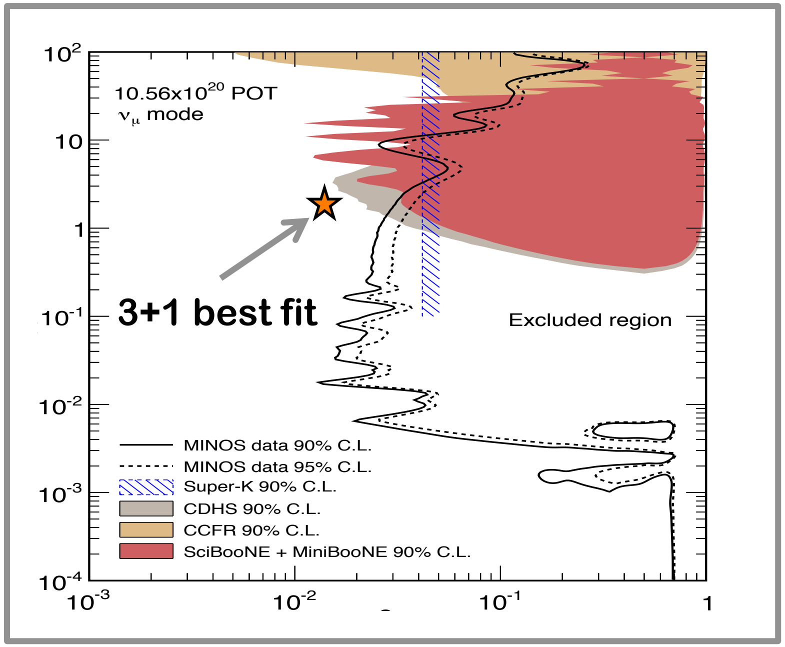
osc. averaged out by finite E resol.

It can be: $A^{CP}_{\alpha\beta} \neq 0$ **(if sin δ = ∅̸)**

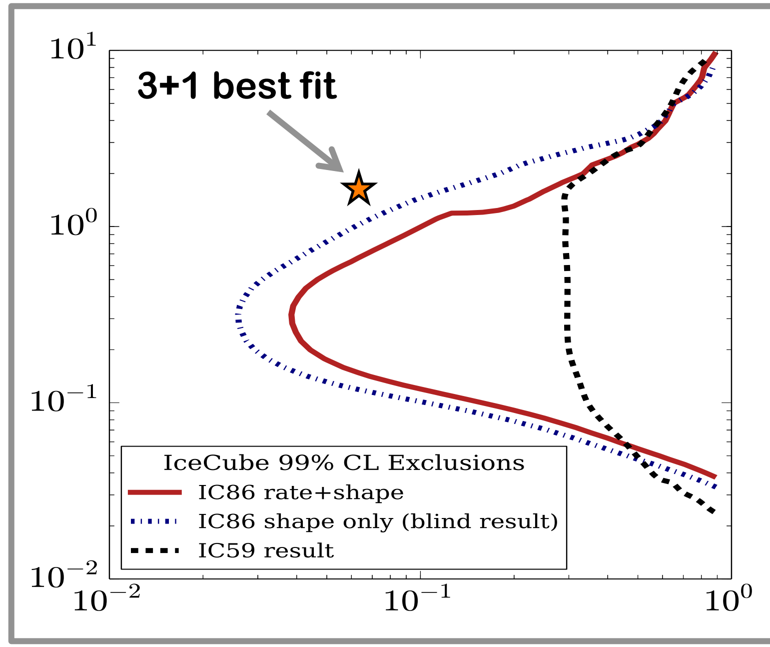
The bottom line is that if one of the three ν_i is ∞ far from the other two ones this does not erase CPV
(relevant for the 4ν case)

No anomaly in ν_μ disappearance

SBL & MINOS (NC)



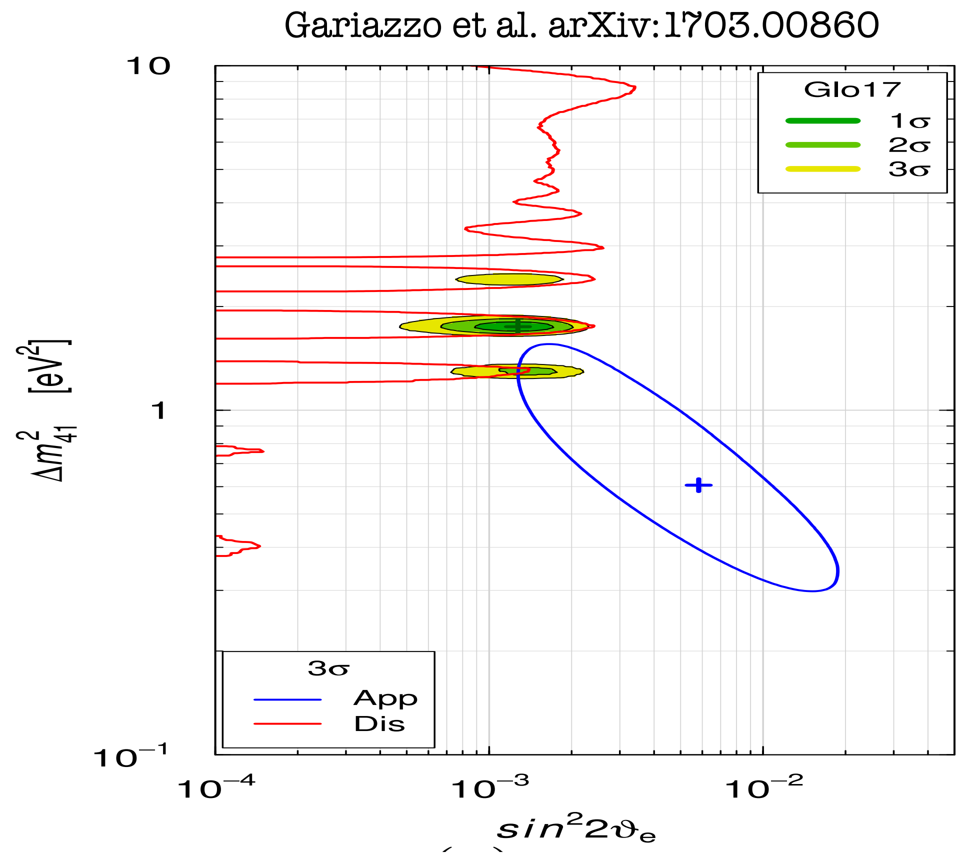
IceCube



Δm^2

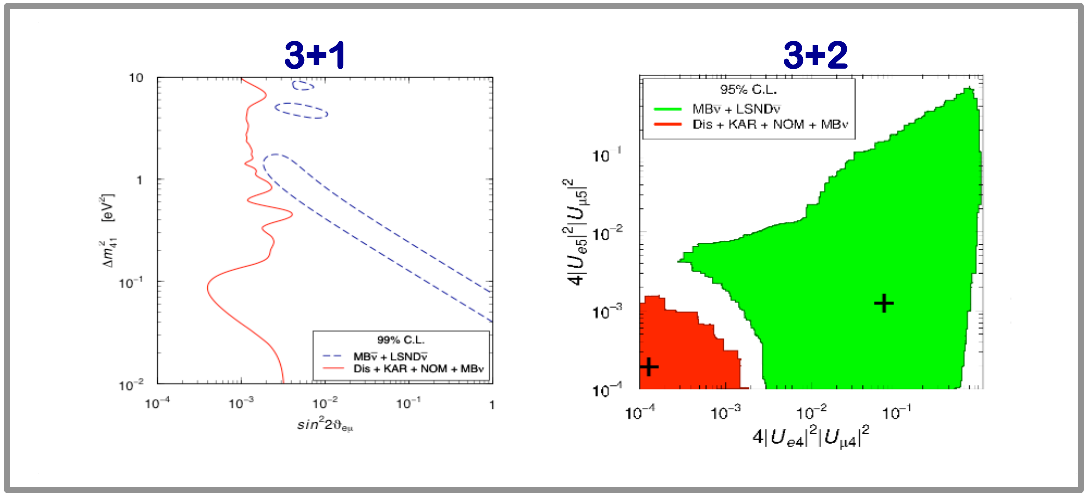
$\sin^2\theta_{\mu\mu}$ $\sin^2 2\theta_{\mu\mu}$

Global SBL data fit in the 3+1 scheme



There is strong internal tension

Tension in all ν_s models



Giunti
&
Laveder

arXiv:1107.1452

$\nu_\mu \to \nu_e$ **positive** $|U_{e4}||U_{\mu 4}| > 0$

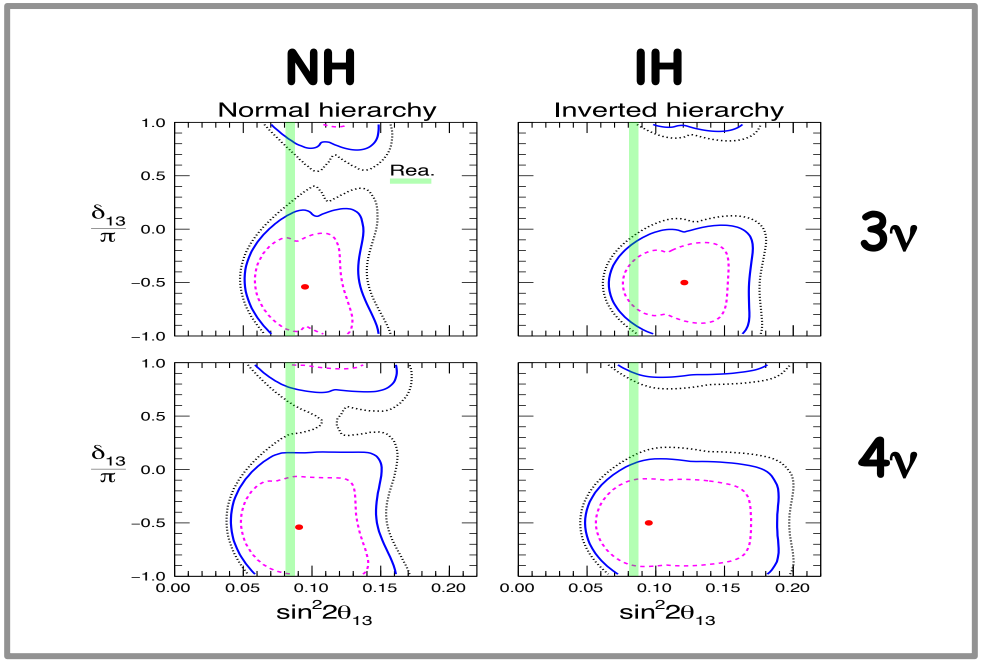
$\nu_e \to \nu_e$ **positive** $|U_{e4}| > 0$

$\nu_\mu \to \nu_\mu$ **negative** $|U_{\mu 4}| \sim 0$

$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu} \simeq 4|U_{e4}|^2|U_{\mu 4}|^2$$

Impact on the standard parameters [θ_{13},δ_{13}]

PRD (2017) **SBL + LBL**



- **Allowed range for θ_{13} from LBL alone gets enlarged**
- **Values preferred for $\delta_{13} \equiv \delta$ basically unaltered**
- **Mismatch (in IH) of LBL and Reactors decreases in 3+1**