Solvay Workshop

Beyond the Standard Model with Neutrinos and Nuclear Physics

Brussels, 1 December 2017

Neutrino fits with steriles

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SMARTPUGLIA FutureInResearch

Outline

Introduction

SBL anomalies and the hypothesis of sterile νs

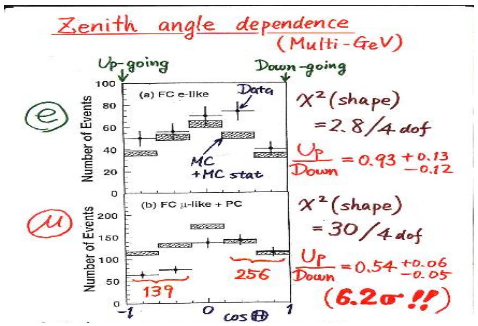
Role of LBL experiments in sterile ν searches

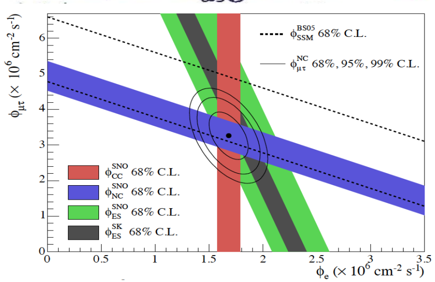
Conclusions

Introduction

Outstanding progress in ν physics in ~ 20 years

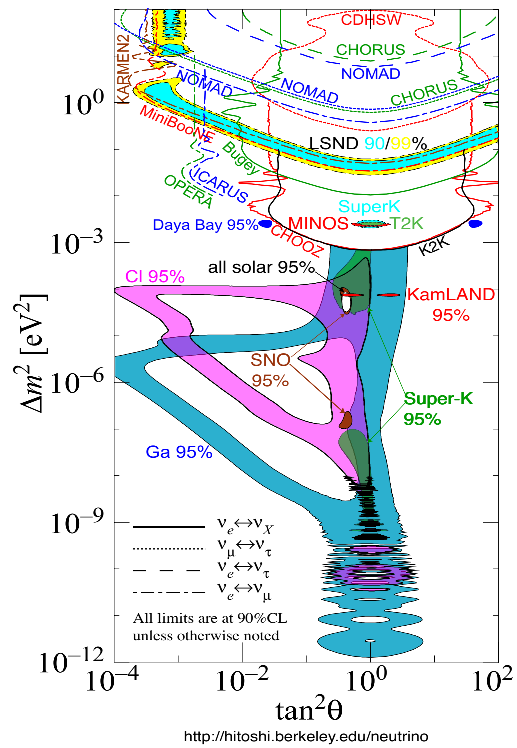
Discoveries





+ many other ones: solar, KamLAND, θ_{13} at reactors & T2K …

Interpretation



known knowns

$\delta m^2/eV^2$	~ 7.37×10^{-5}	±2.3%
$\Delta m^2/eV^2$	~ 2.52×10^{-3}	±1.6%
$\sin^2\theta_{12}$	~ 0.297	±3.4%
$\sin^2\theta_{13}$	~ 0.0215	±4.0%
$\sin^2\theta_{23}$	~ 0.5	±9.6%

known unknowns

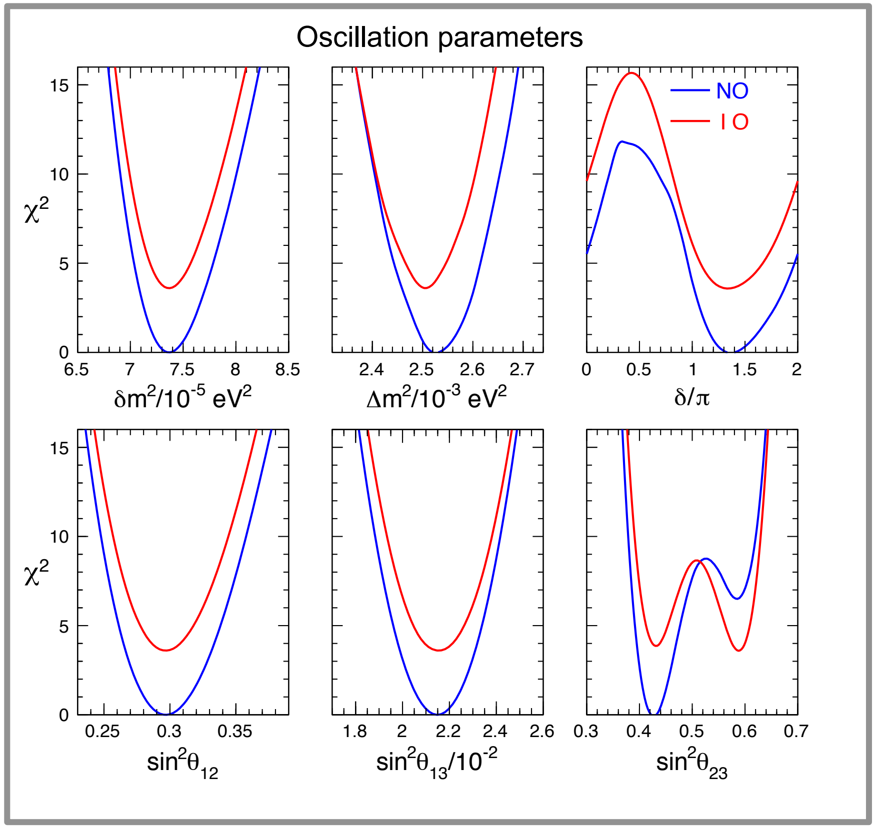
CPV (δ)
sign(Δm^2)
θ_{23} (non-maximal, octant)
absolute ν mass
Dirac/Majorana

unknown unknowns

NSI, sterile states,
PMNS non-unitarity, …?

3-flavor scheme now established as the standard framework…

Current status of 3-flavor parameters



Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, A.P.
arXiv: 1703.04471, PRD 95 096014 (2017)

~ 2σ preference for normal mass ordering

~ 2σ indication of CPV
$\delta \in [\pi, 2\pi]$ ($\sin\delta < 0$)

Hint of non-maximal θ_{23}

Beyond the standard picture

Many extensions of the Standard Model predict new effects in neutrino oscillations

An incomplete list:

- **Sterile neutrinos**
- **Non standard neutrino interactions**
- **Non unitarity of the PMNS matrix**
- **Long-range forces**
- **Lorentz and CPT violations**
- **Quantum decoherence …**

Sterile neutrinos

Sterile neutrinos, i.e. singlets of SU(2)xU(1) gauge group, provide a very economical extension of SM

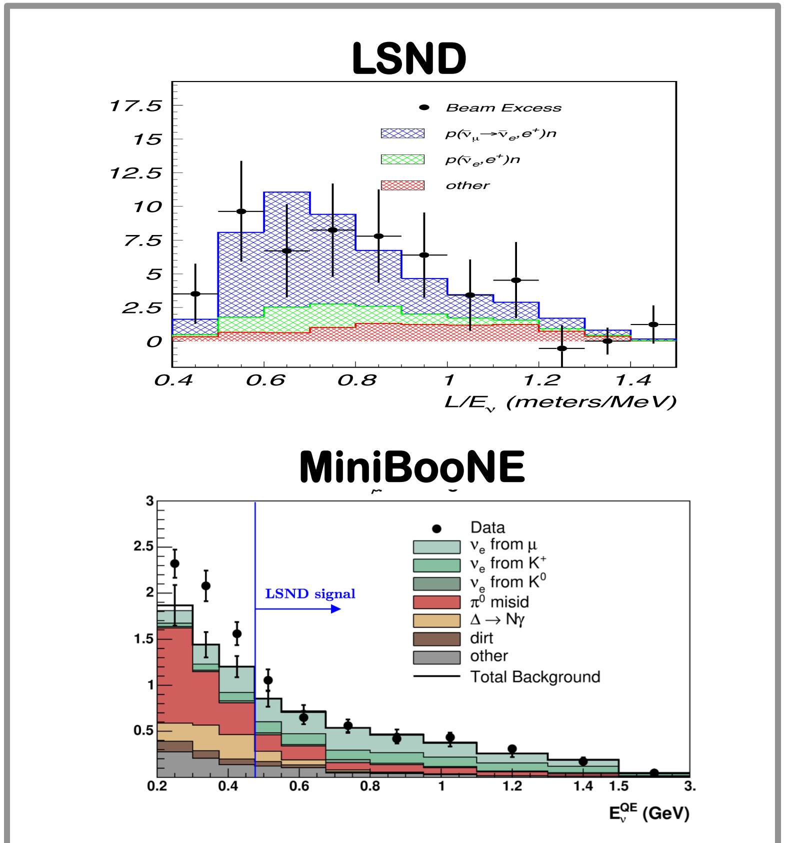
ν_s investigated at several scales:

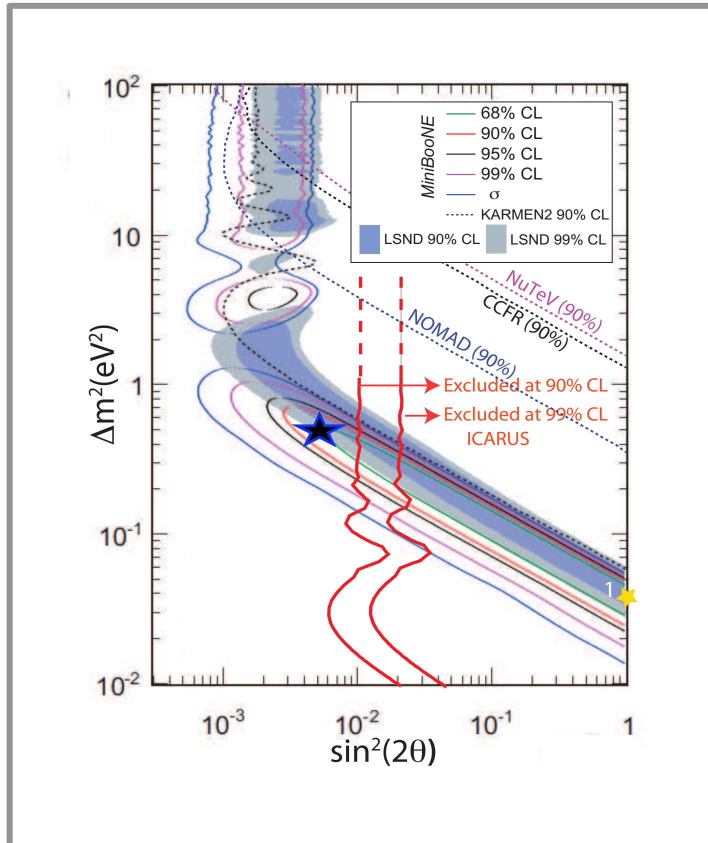
- **GUT, see-saw models of ν mass, leptogenesis**
- **TeV, production at LHC and impact on EWPOs**
- **keV, (warm) dark matter candidates**
- ✓ **eV, SBL (and LBL) oscillation experiments**
- **sub-eV, θ_{13}-reactors and solar neutrinos**

The SBL anomalies and the hypothesis of sterile νs

1) The SBL accelerator anomalies

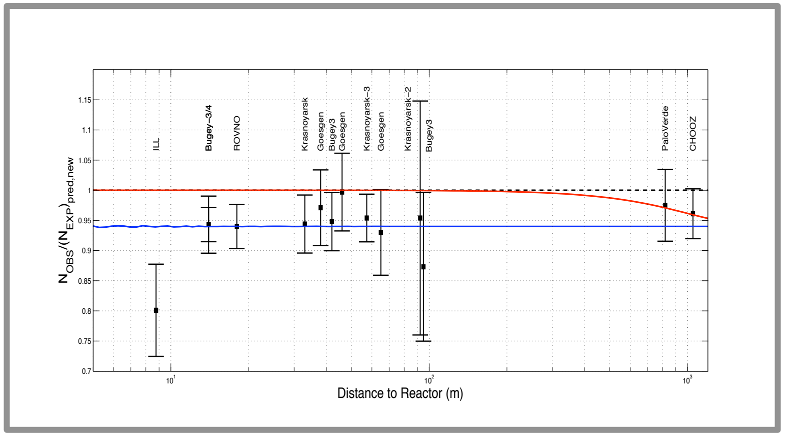
(unexplained ν_e appearance in a ν_μ beam)



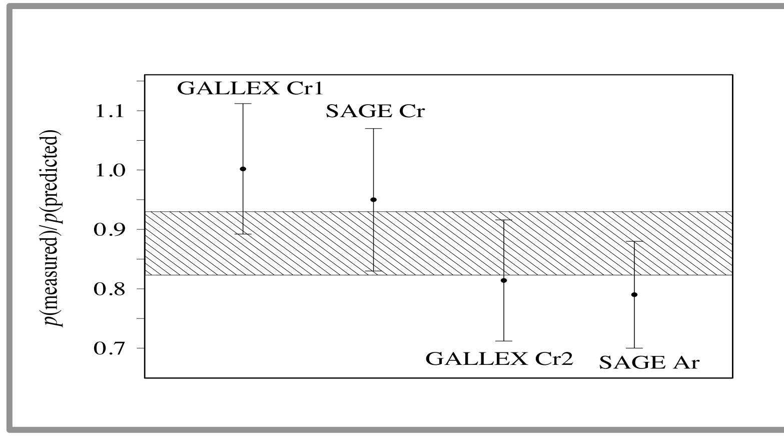


2) The reactor and gallium anomalies

(unexplained ν_e disappearance)



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



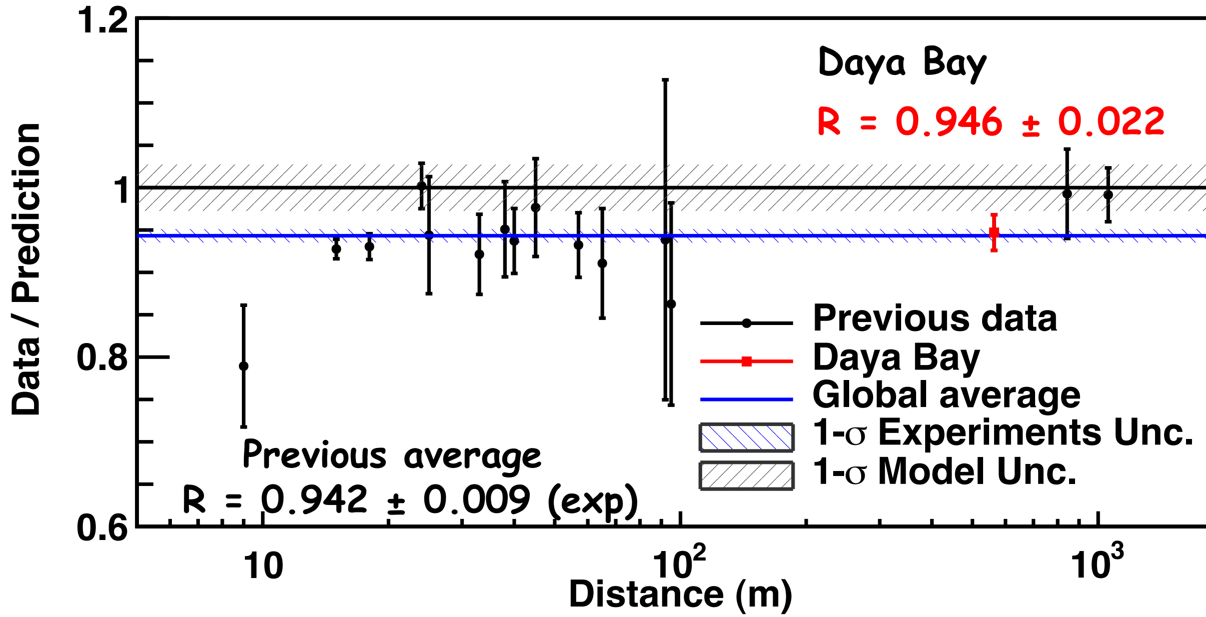
SAGE coll., PRC 73 (2006) 045805

Warning: both are mere normalization issues

The culprit may be hidden in unknown systematics

New-generation detectors confirm deficit

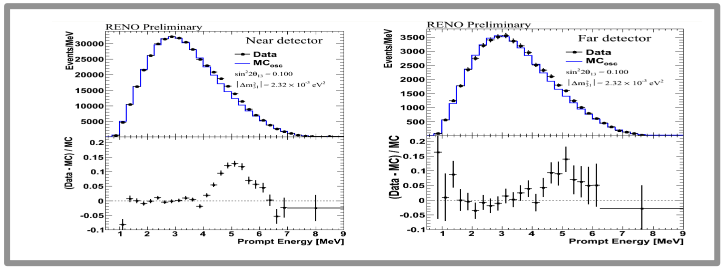
Daya Bay, PRL 061801 (2016) [1508.04233]



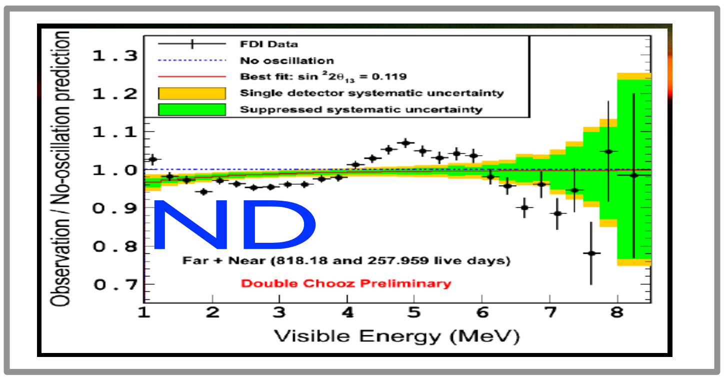
However, the same detectors give us a warning …

Understanding of reactor spectrum is incomplete

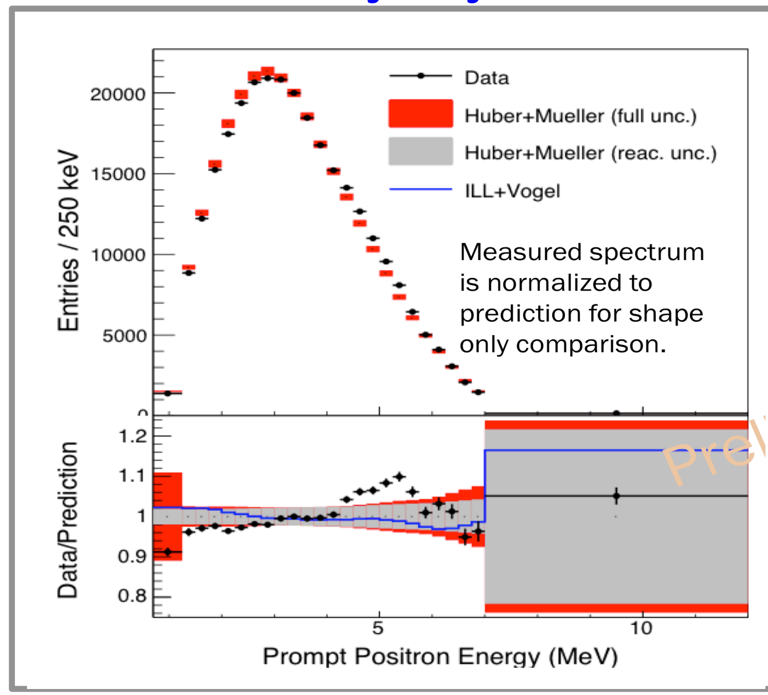
RENO



Double-CHOOZ



Daya Bay

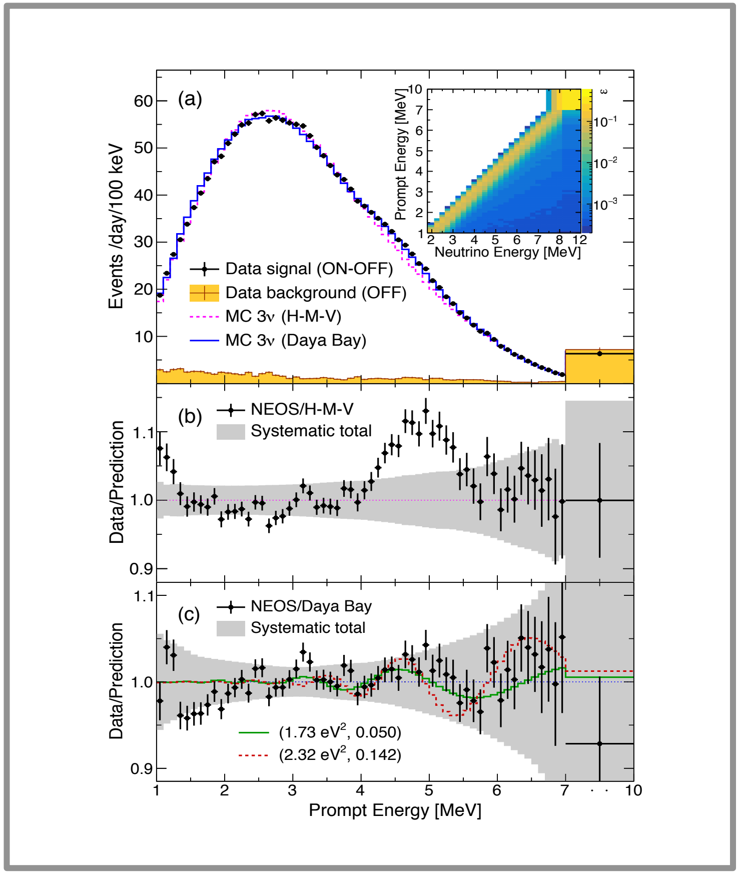


Bump/shoulder at 5 MeV observed in all the three experiments

Found both a near & far sites: not imputable to new osc. physics

θ_{13} extraction is unaffected (based on near/far comparison)

3) NEOS: scent of sterile neutrinos?



NEOS arXiv:1610:05134

Hanbit Nuclear Power Complex, Korea

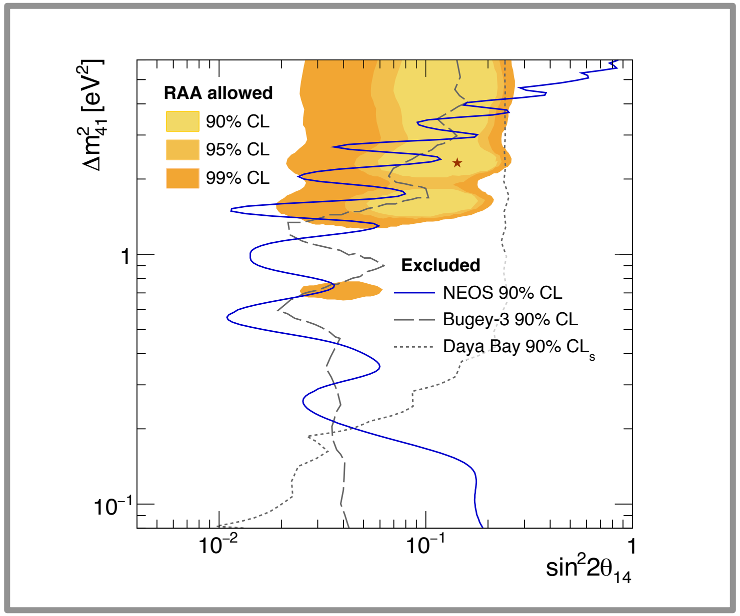
Detector: 1 ton Gd-loaded liquid scintillator 24 m from the reactor core

Daya-Bay absolute spectrum used as a normalization

Oscillating pattern visible after normalization

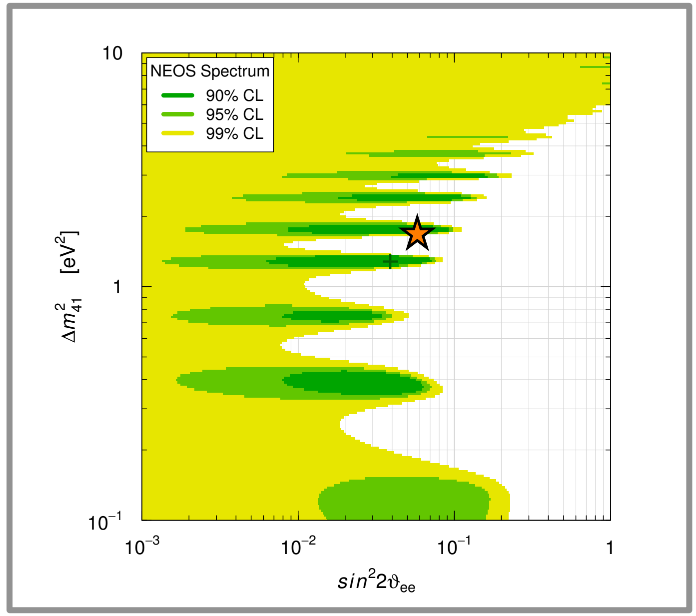
Two different perspectives

negative view



NEOS, arXiv:1610:05134

positive view



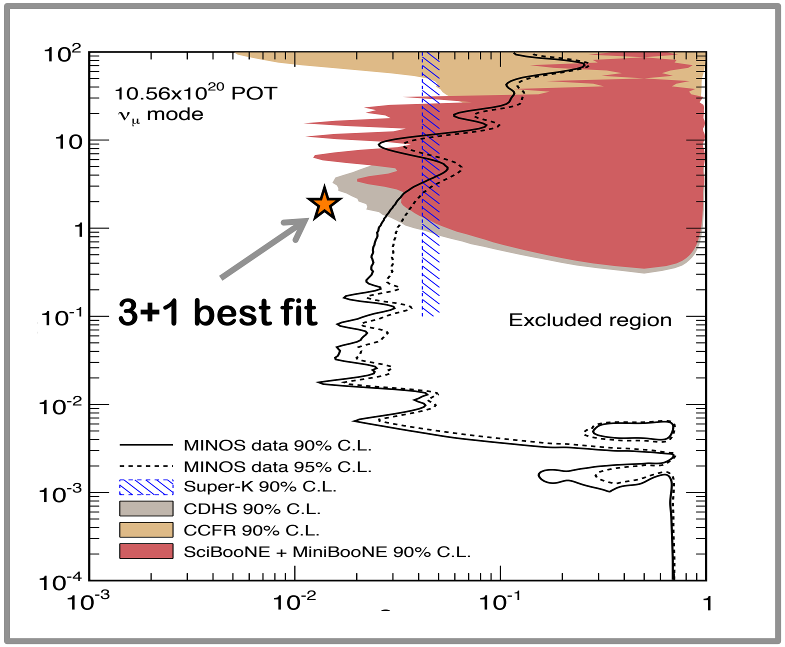
Gariazzo et al., arXiv: 1703.00860

Best fit: Δm^2 = 1.73 eV $\sin^2 2\theta$ = 0.05

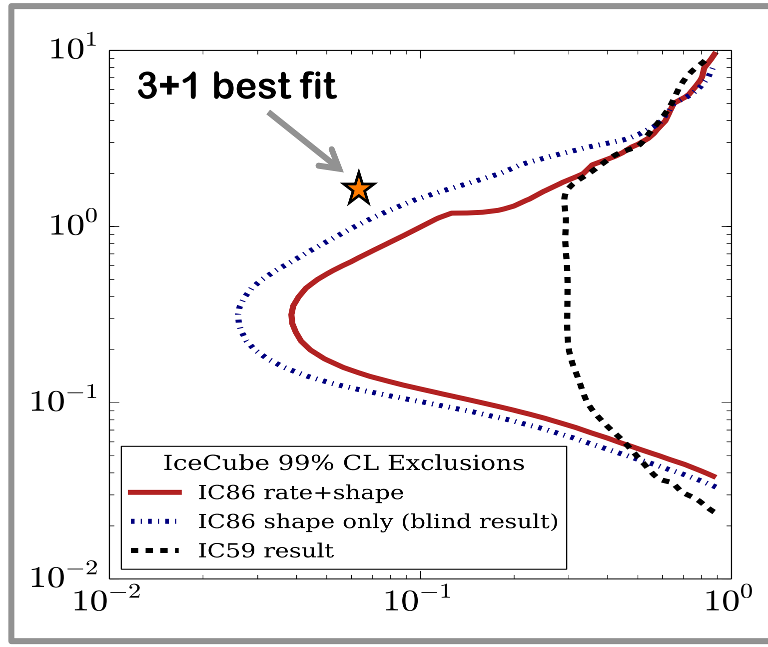
$$\chi^2_{\text{no osc}} - \chi^2_{\text{min}} = 6.5$$ **> 95% CL indication!**

No anomaly in ν_μ disappearance

SBL & MINOS (NC)



IceCube

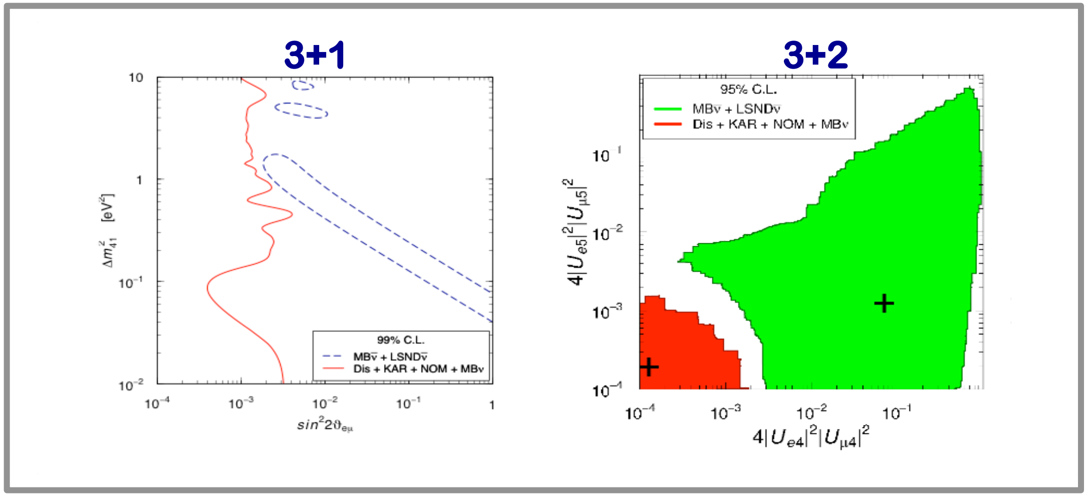


Δm^2

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

A thorn in the side of sterile neutrinos …

Tension in all ν_s models



Giunti
&
Laveder

arXiv:1107.1452

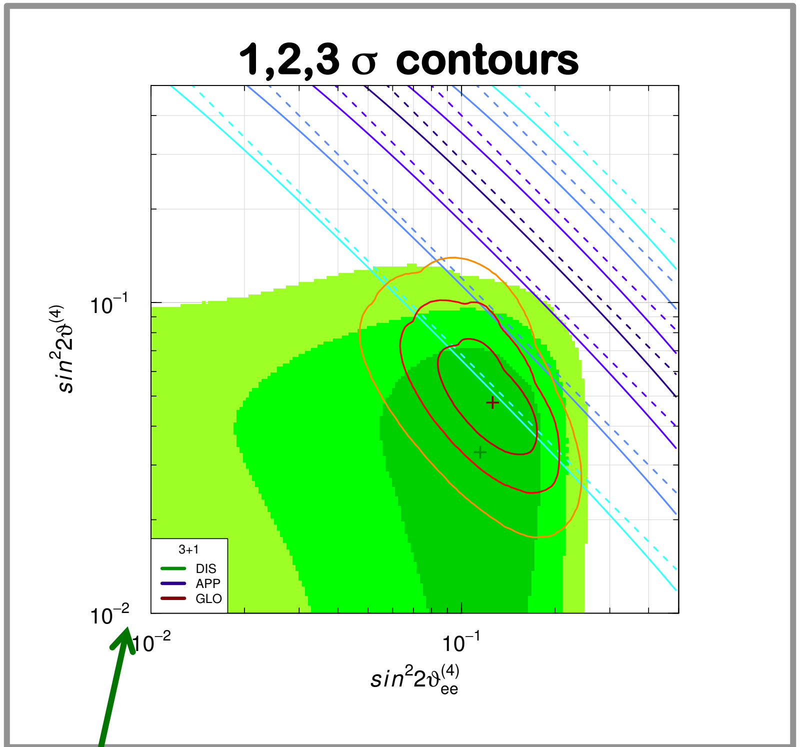
$\nu_\mu \rightarrow \nu_e$ **positive** $|U_{e4}||U_{\mu4}| > 0$

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

$\nu_\mu \rightarrow \nu_\mu$ **negative** $|U_{\mu4}| \sim 0$

$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4}\sin^2 2\theta_{ee}\sin^2 2\theta_{\mu\mu} \simeq 4|U_{e4}|^2|U_{\mu4}|^2$$

An "undecidable" problem



3ν limit

App. & Dis. barely overlap at 2σ level

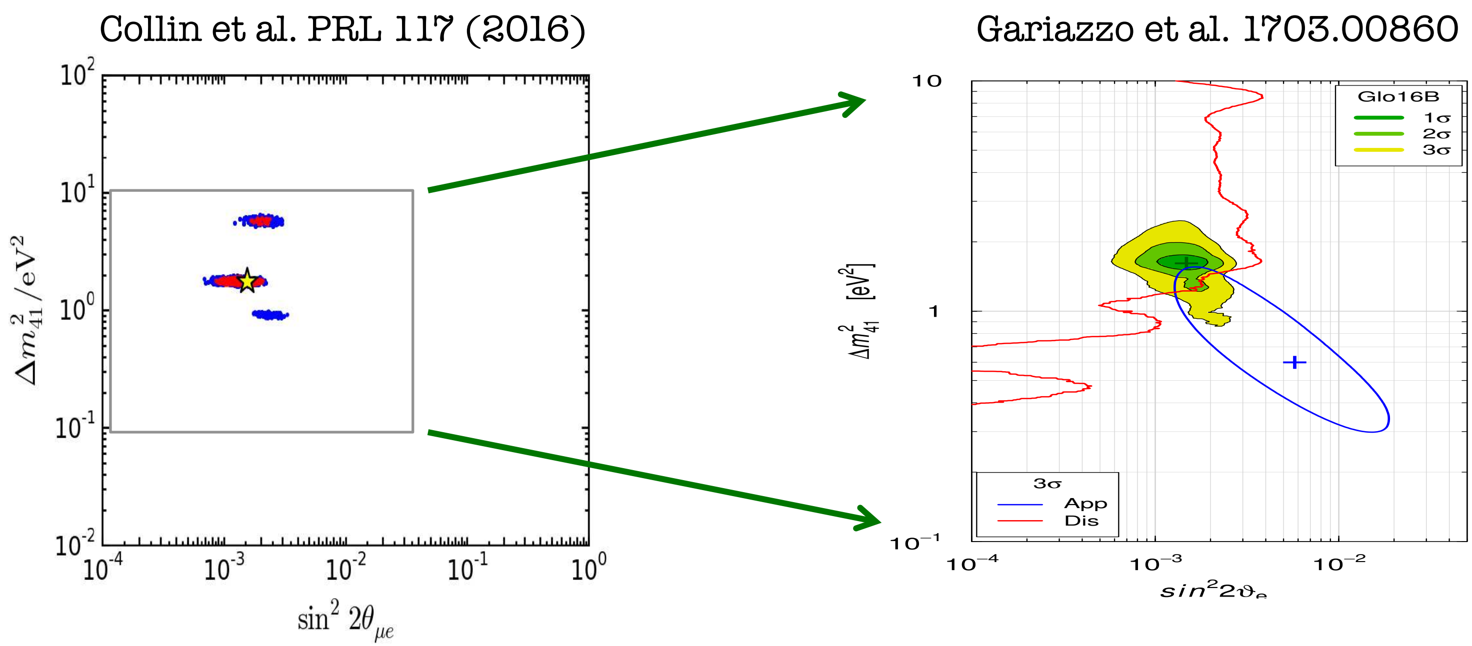
But their combination gives a 6σ improvement with respect to the 3ν case

Difficult to take a decision on sterile νs !

Only new more sensitive experiments can decide

Figure from Giunti & Zavanin, arXiv:1508:03172
(tension slightly increased after NEOS, MINOS, IceCube)

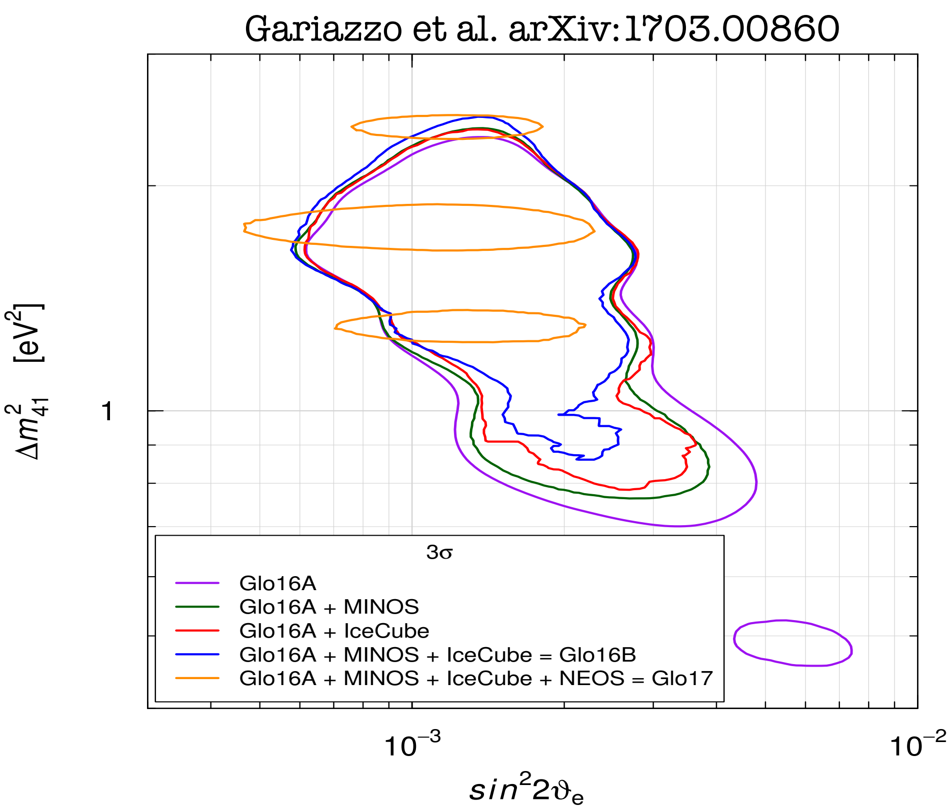
If one accepts to live with the tension



Both analyses include IceCube data

Similar best fit points around $\Delta m^2 \sim 1.7$ eV^2

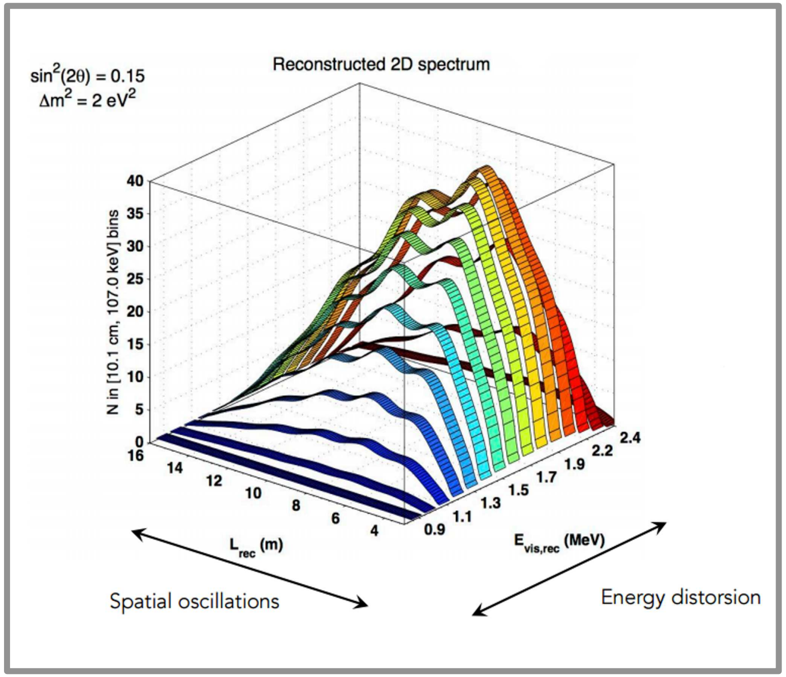
Impact of the latest measurements

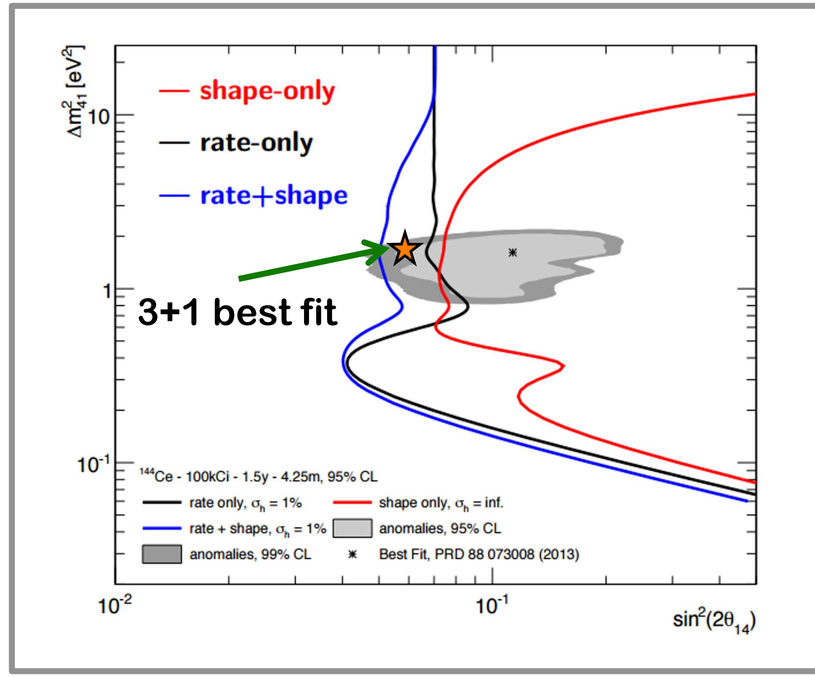


NEOS selects a subregion of the region allowed by all the other data : very intriguing!

The smoking gun

The oscillation pattern (in energy and/or space)



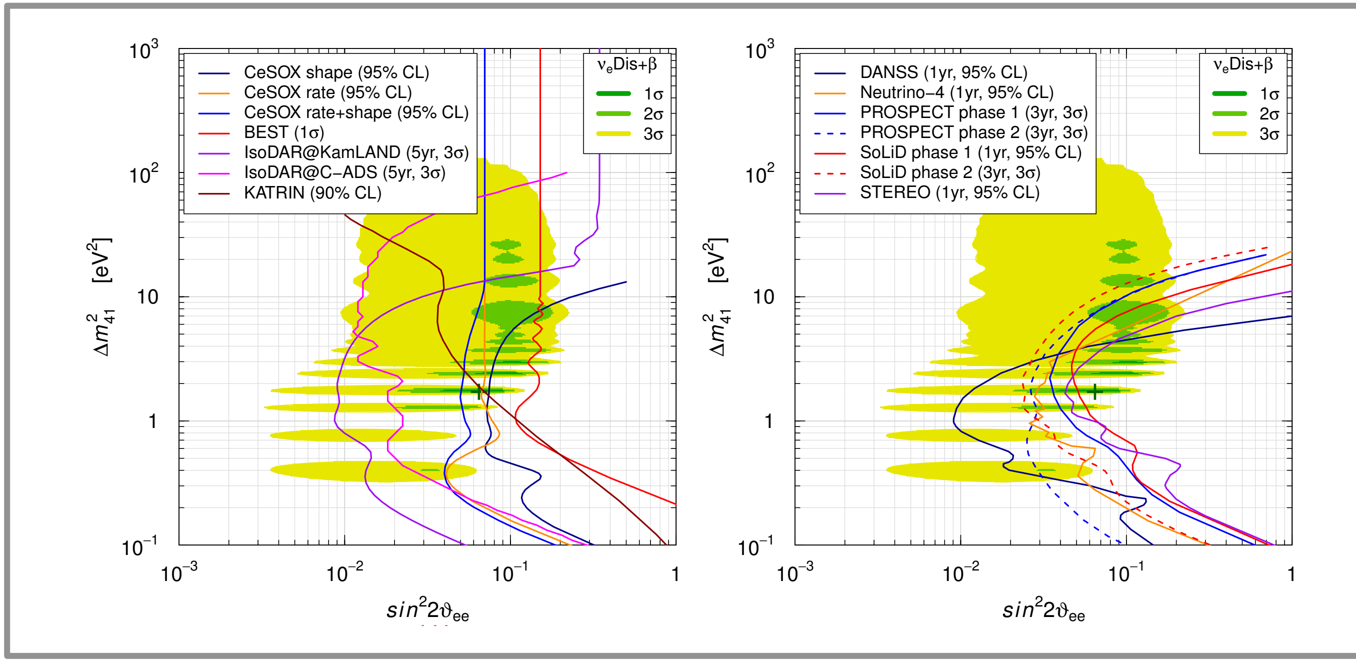


SOX experiment @ LNGS

A lower best fit implies that detection/exclusion may be more difficult than expected

The SBL race for the light sterile neutrino

Gariazzo et al., arXiv: 1703.00860



But sterile neutrinos are not just a SBL affair

Opportunity and challenge for LBL experiments…

Role of LBL experiments in sterile neutrino searches

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

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

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

An intrinsic limitation of SBL

At SBL atm/sol oscillations are negligible

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

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

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

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

This is relevant because we need to observe such phenomena in order to measure the new CP-phases induced by sterile neutrinos

But we have LBL, which are sensitive interferometers

PHYSICAL REVIEW D **91,** 073017 (2015)

Imprints of *CP* violation induced by sterile neutrinos in T2K data

N. Klop and A. Palazzo

Max-Planck-Institut für Physik (Werner Heisenberg Institut), Föhringer Ring 6, 80805 München, Germany

(Received 9 February 2015; published 29 April 2015)

We investigate the impact of light ($\sim$eV) sterile neutrinos in the long-baseline experiment T2K. We show that, within the $3+1$ scheme, for mass-mixing parameters suggested by the short-baseline anomalies, the interference among the sterile and the atmospheric oscillation frequencies induces a new term in the $\nu_\mu \to \nu_e$ transition probability, which has the same order of magnitude of the standard 3-flavor solar-atmospheric interference term. We show, for the first time, that current T2K data, taken together with the results of the θ_{13}-dedicated reactor experiments, are sensitive to two of the three *CP*-violating phases involved in the $3+1$ scheme. Both the standard *CP* phase and the new one ($\delta_{13} \equiv \delta$ and δ_{14} in our parameterization choice) tend to have a common best-fit value $\delta_{13} \simeq \delta_{14} \simeq -\pi/2$. Quite intriguingly, the inclusion of sterile neutrino effects leads to better agreement between the two estimates of θ_{13} obtained, respectively, from reactors and T2K, which in the 3-flavor framework are slightly different.

DOI: 10.1103/PhysRevD.91.073017 PACS numbers: 14.60.Pq, 14.60.St

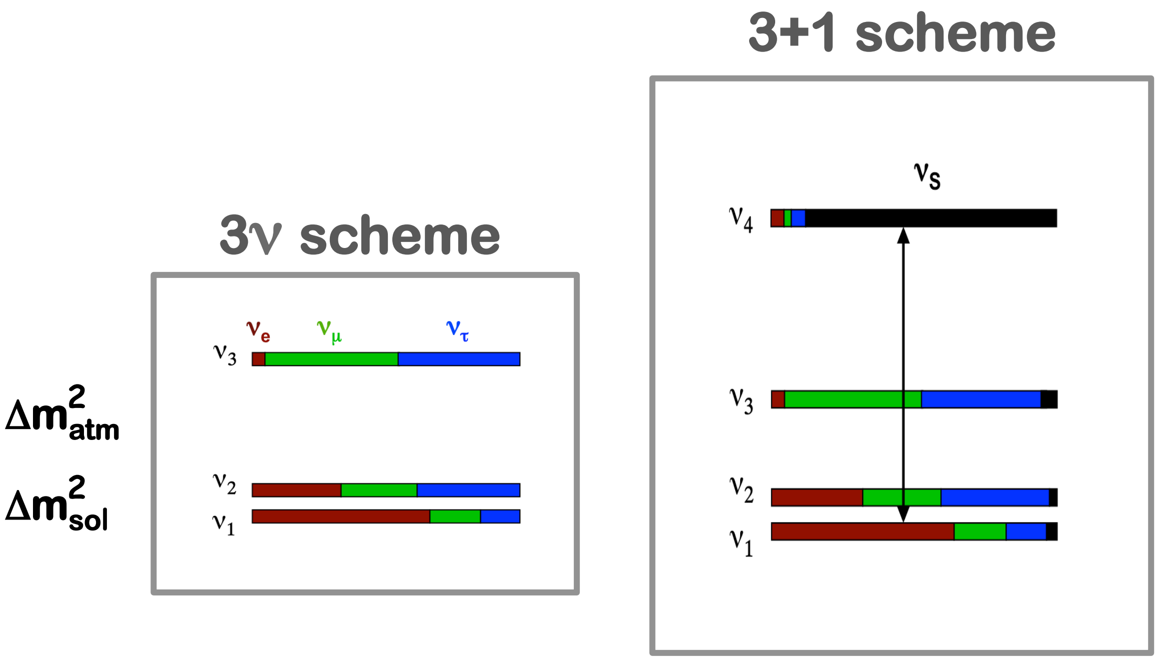
I. INTRODUCTION

Neutrino physics is entering a new era. The discovery of a relatively large value of the long-sought third mixing angle θ_{13} has raised hopes of completing the picture of the standard 3-flavor framework. The determination of the two missing unknown properties, i.e., the amount (if any) of leptonic *CP*-violation (CPV) and the neutrino mass hierarchy are now realistic targets.

frameworks, new *CP* phases automatically appear and, thus, the question naturally arises as to whether the current and planned LBL experiments, designed to underpin the standard *CP* phase δ, also have some chance to detect the new potential sources of CPV.[1]

In this work we show, for the first time, that the existing measurements of $\nu_\mu \to \nu_e$ appearance performed by the LBL experiment T2K, taken in combination with those of $\bar{\nu}_e \to \bar{\nu}_e$ disappearance deriving from the θ_{13}-dedicated

How to enlarge the 3-flavor scheme



$|U_{s4}| \sim 1$

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

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

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

$$R_{ij} = \begin{bmatrix} c_{ij} & s_{ij} \\ -s_{ij} & c_{ij} \end{bmatrix}$$

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

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

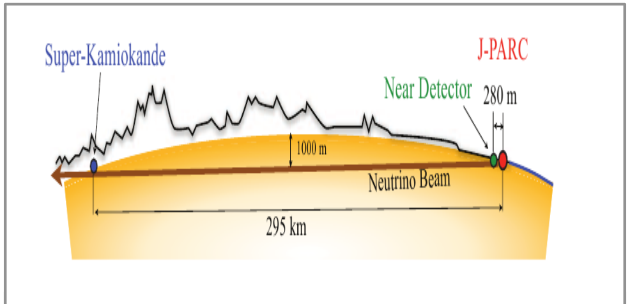
3ν { **3 mixing angles**, **1 Dirac phase**, **2 Majorana phases**

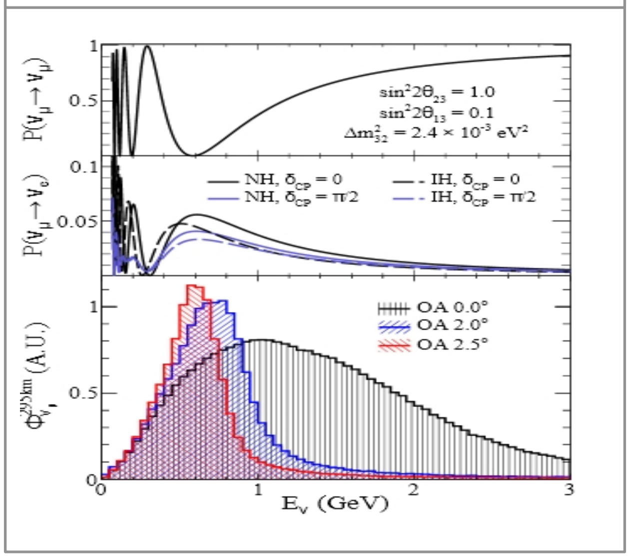
3+1 { **6**, **3**, **3**

3+N { **3+3N**, **1+2N**, **2+N**

In general, we have additional sources of CPV

LBL Experiments: T2K & NOνA

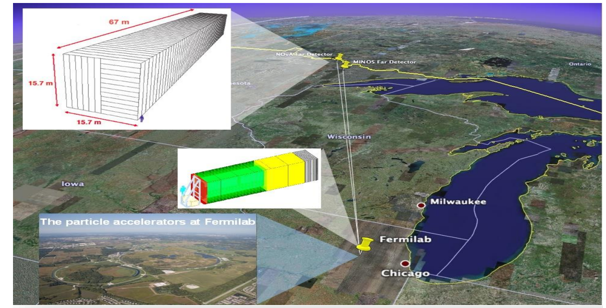


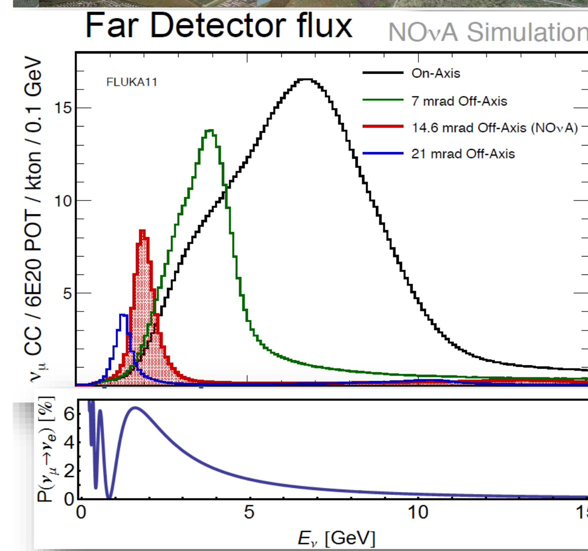


off-axis beam

$$\Delta = \frac{\Delta m^2_{13} L}{4E} \simeq \frac{\pi}{2}$$

First oscillation maximum





E = 0.6 GeV
L = 295 km

E = 2 GeV
L = 810 km

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:

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

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

$\Delta \sim \pi/2$

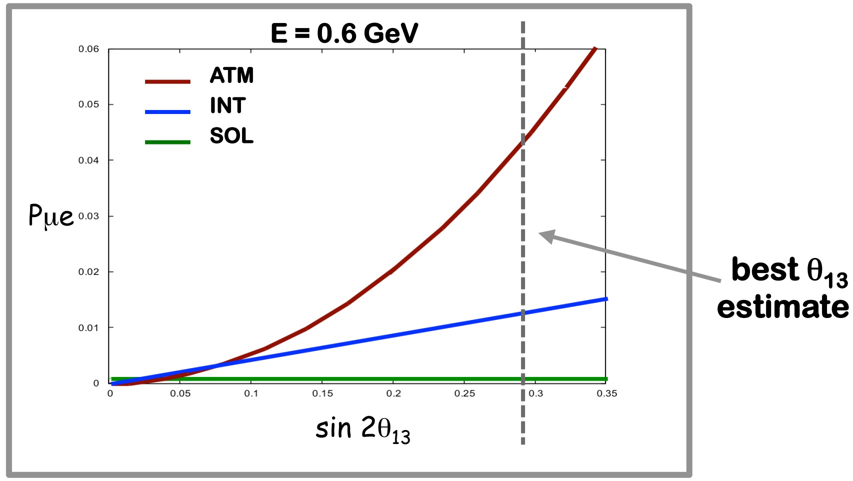
$\alpha \sim 0.03$

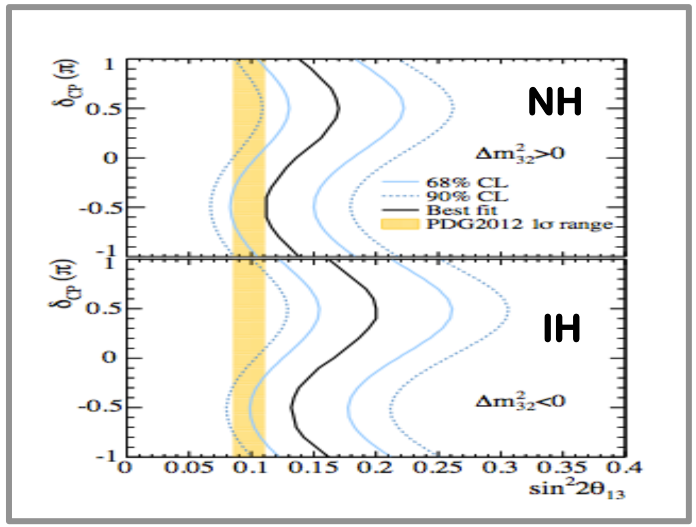
$P^{\rm ATM}$ leading → $\theta_{13} > 0$

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

$P^{\rm SOL}$ negligible

Matter effects break NH-IH degeneracy





CPV and averaged oscillations

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

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

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

osc. averaged out by finite E resol.

It can be: $A^{\rm CP}_{\alpha\beta} \neq 0$ (if $\sin\delta = \emptyset$)

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)

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

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

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

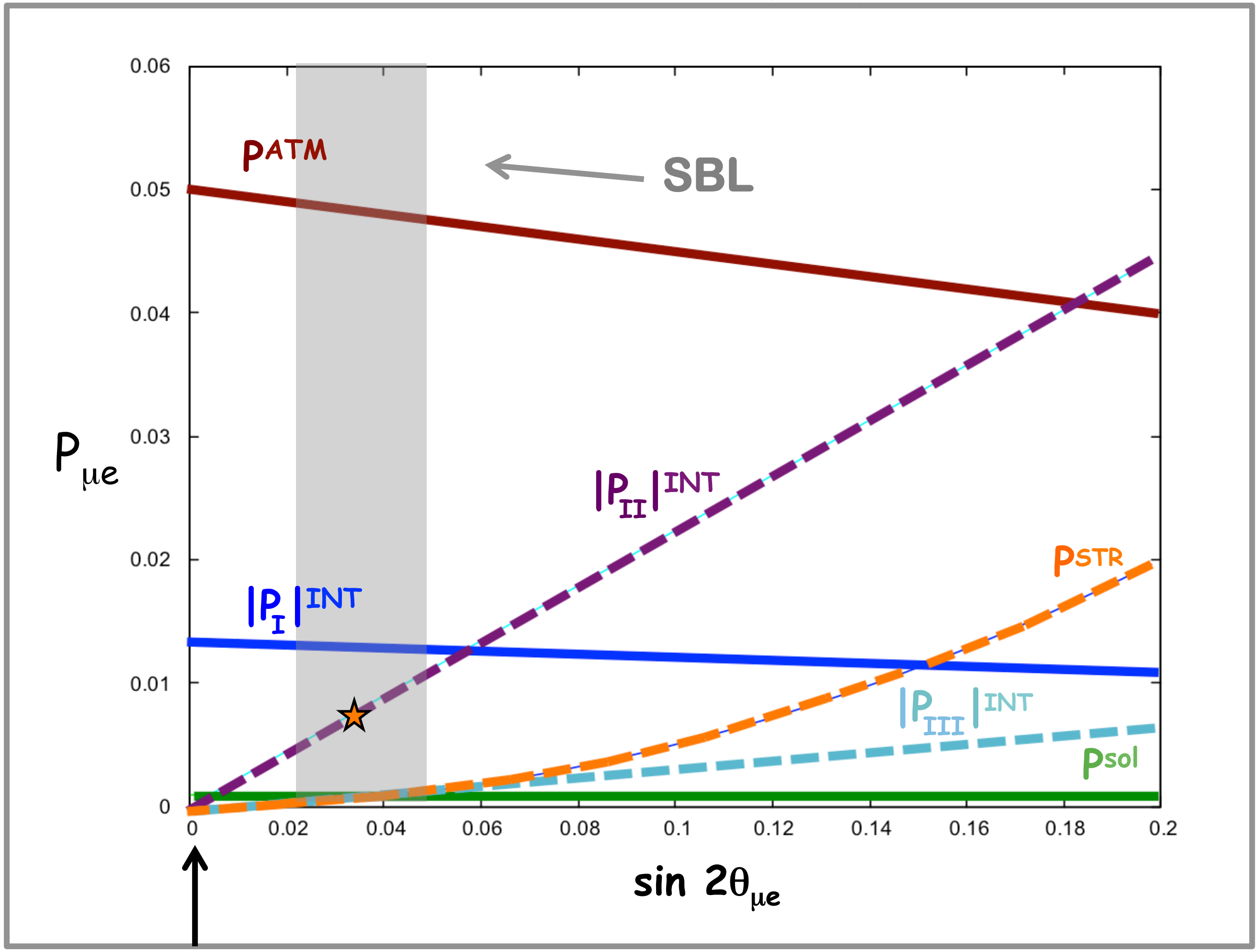
$\alpha = \delta m^2/\Delta m^2 \sim 0.03 \sim \varepsilon^2$

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

Sensitivity to the new CP-phase δ_{14}

Amplitude of the new interference term

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

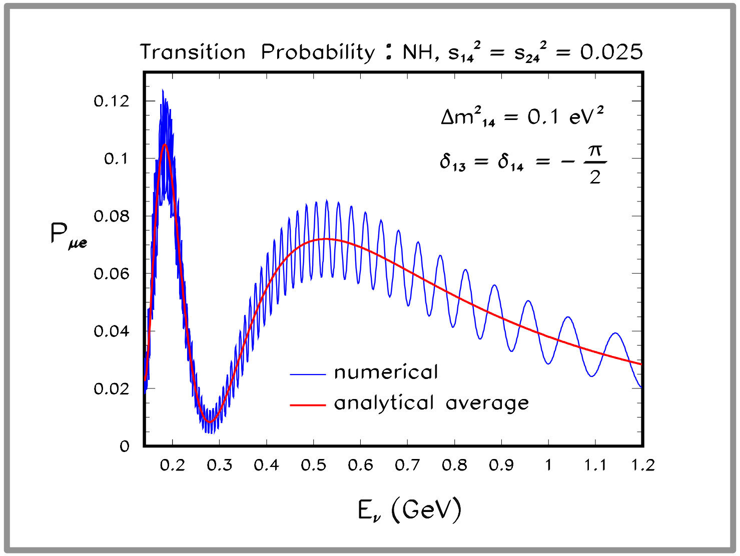


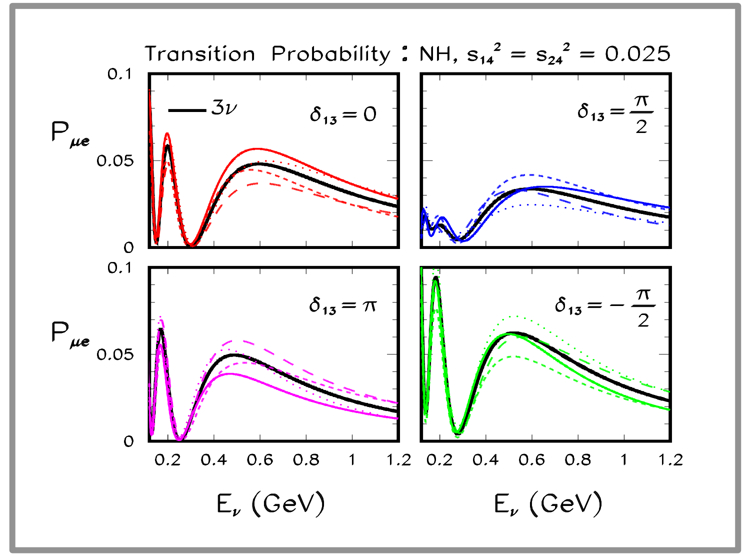
3ν limit

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}

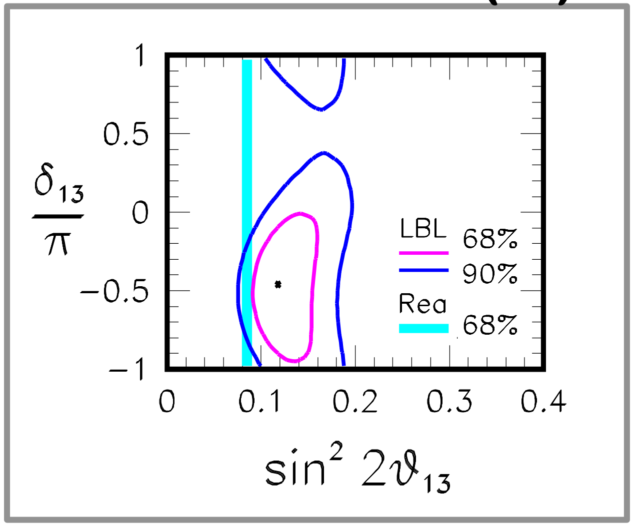
The modifications induced by δ_{14} are almost as large as those induced by the standard CP-phase δ_{13}

Consequences…

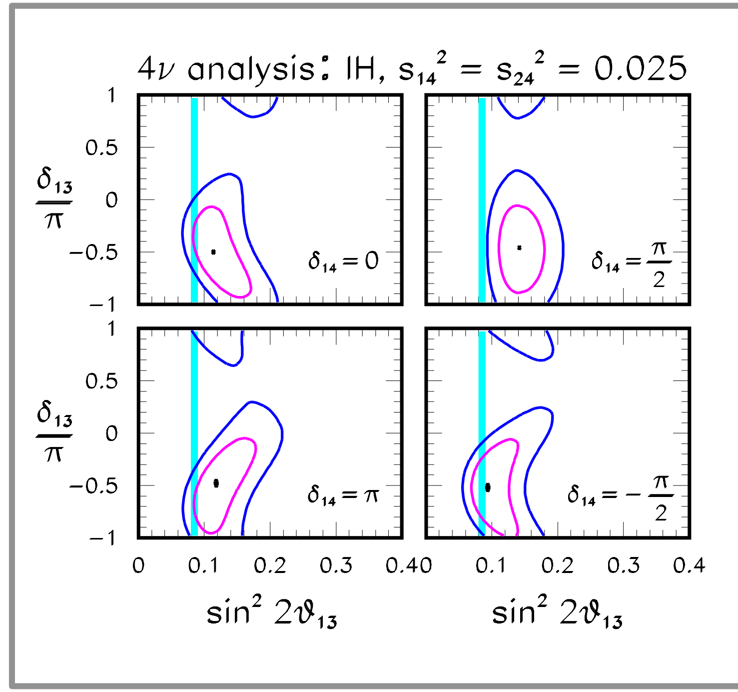
LBL constraints change in the 3+1 scheme

PLB (2016)

3ν: T2K + NOνA (IH)



4ν



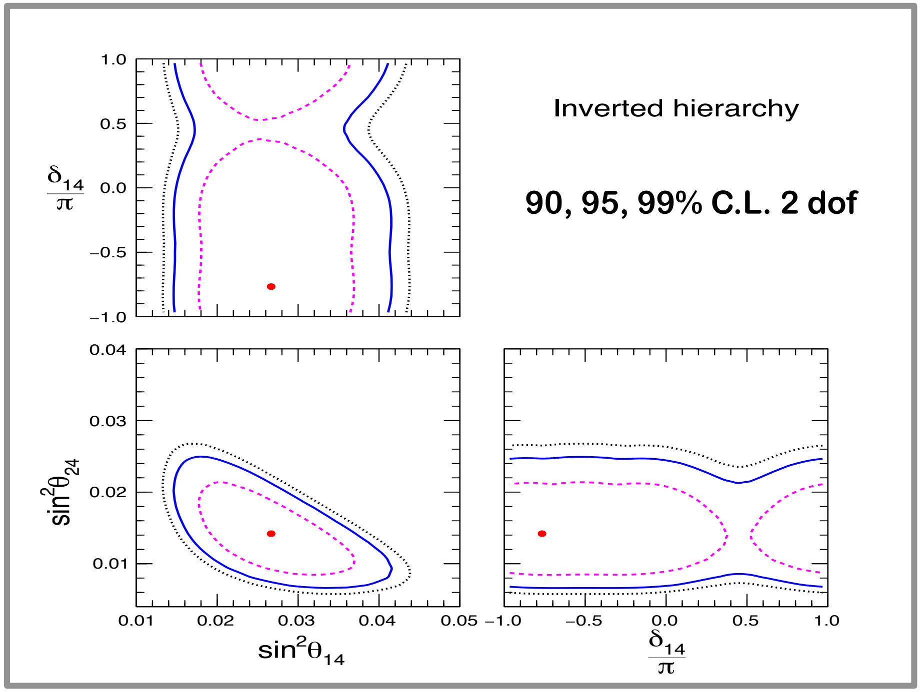
- **The level of (dis-)agreement of LBL & Rea. depends on δ_{14}**
- **In this analysis θ_{14} and θ_{24} are fixed at the SBL best fit values**
- **These results call for a more refined analysis …**

A joint analysis of SBL & LBL data

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

Constraints on the new parameters [θ_{14},θ_{24},δ_{14}]

SBL + LBL



SBL (all available data)

(Icecube and NEOS not included in this analysis)

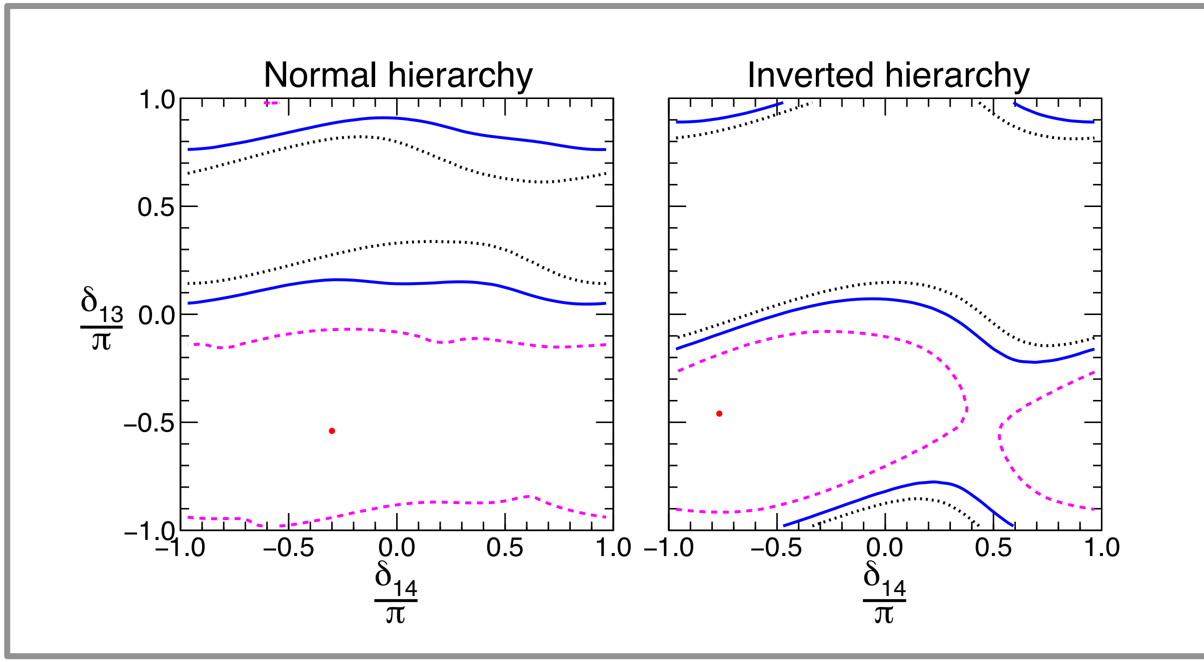
LBL ≡ T2K + NOνA

(Neutrino 2016 data)

- **[θ_{14}, θ_{24}] determined by SBL experiments**
- **δ_{14} constrained by LBL experiments**

Constraints on the two CP-phases

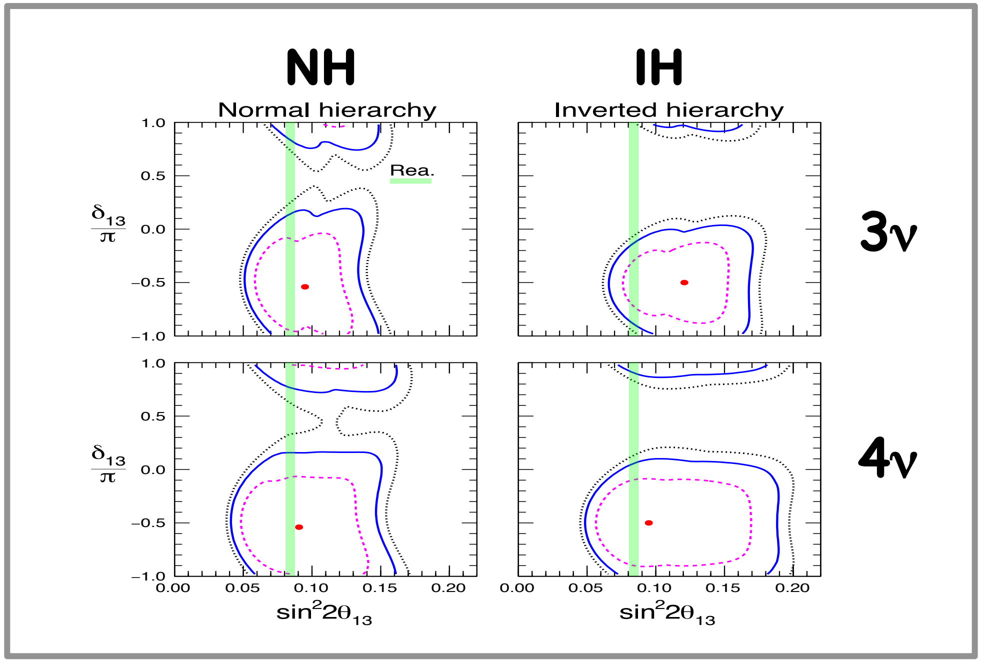
SBL + LBL



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

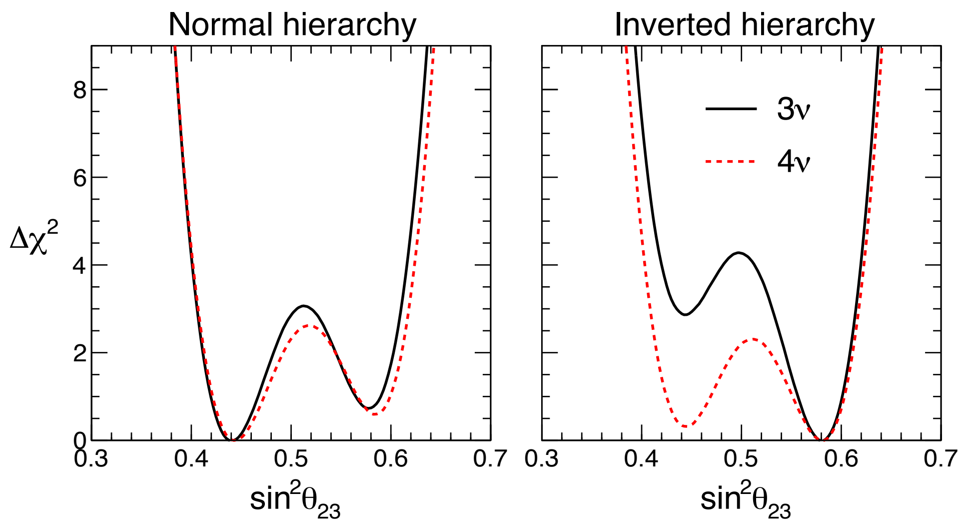
SBL + LBL



- **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**

Impact of sterile neutrinos on θ_{23}

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)

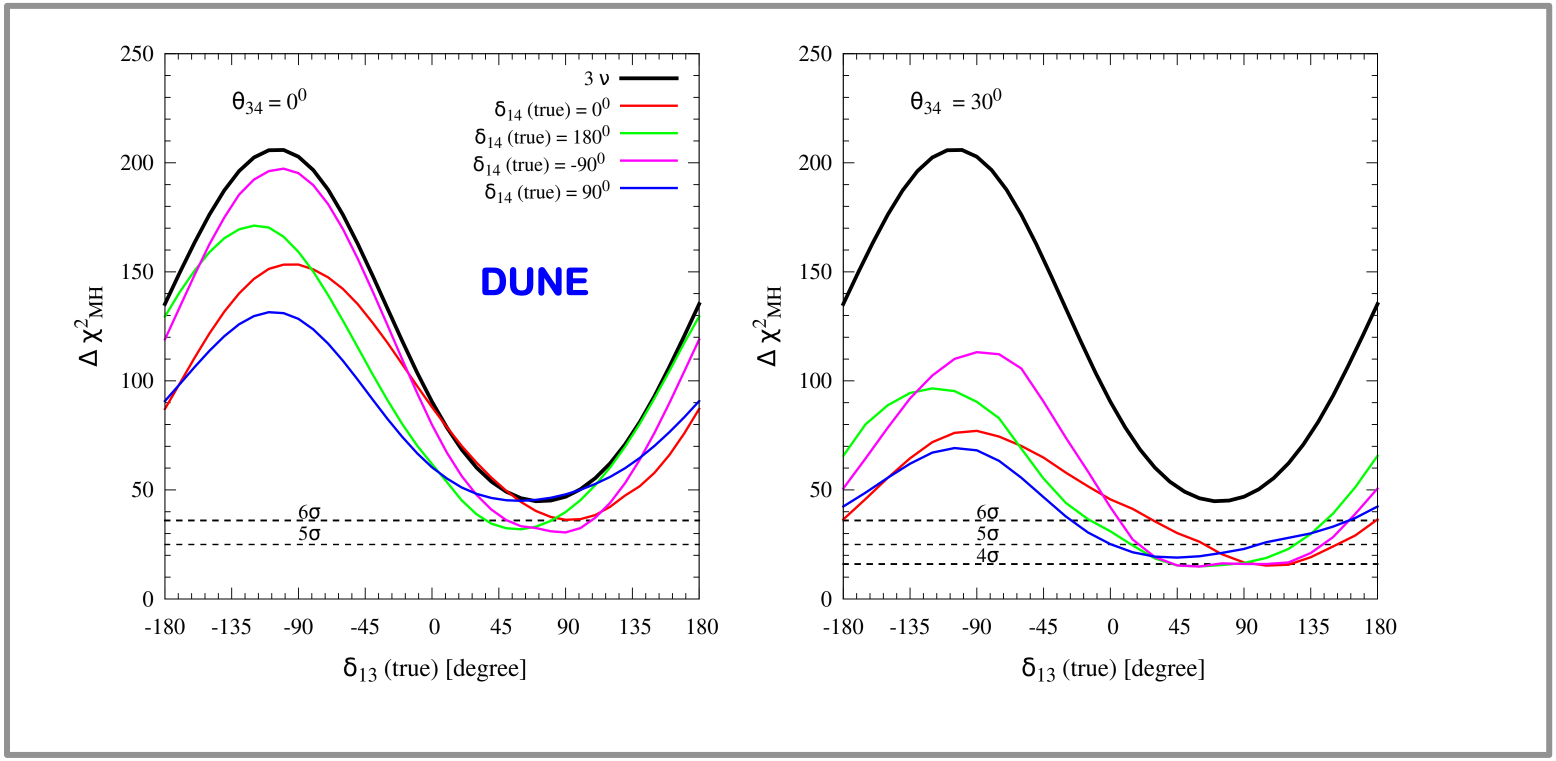
Agarwalla, Chatterjee, A.P.,
arXiv: 1607.01745 (PLB 2016)

Agarwalla, Chatterjee, A.P.,
arXiv: 1605.04299 (PRL 2017)

Agarwalla, Chatterjee, A.P.,
In preparation

Discovery potential of mass hierarchy

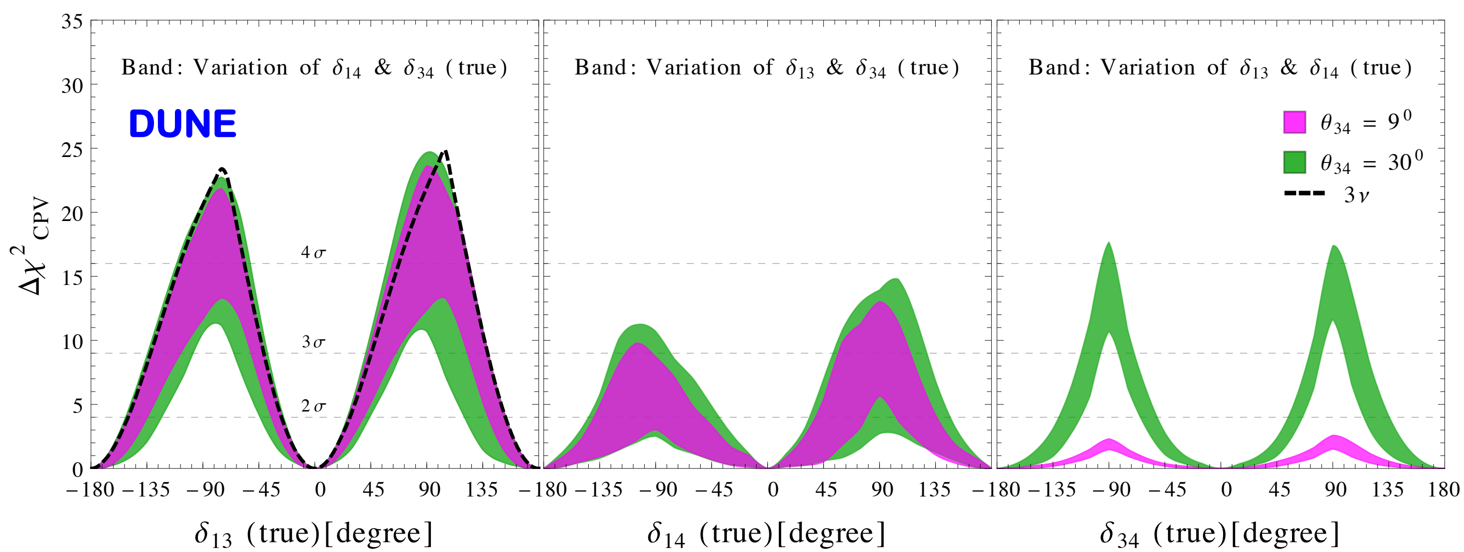
JHEP 2016



Degradation of sensitivity but 4σ level preserved

CPV discovery potential

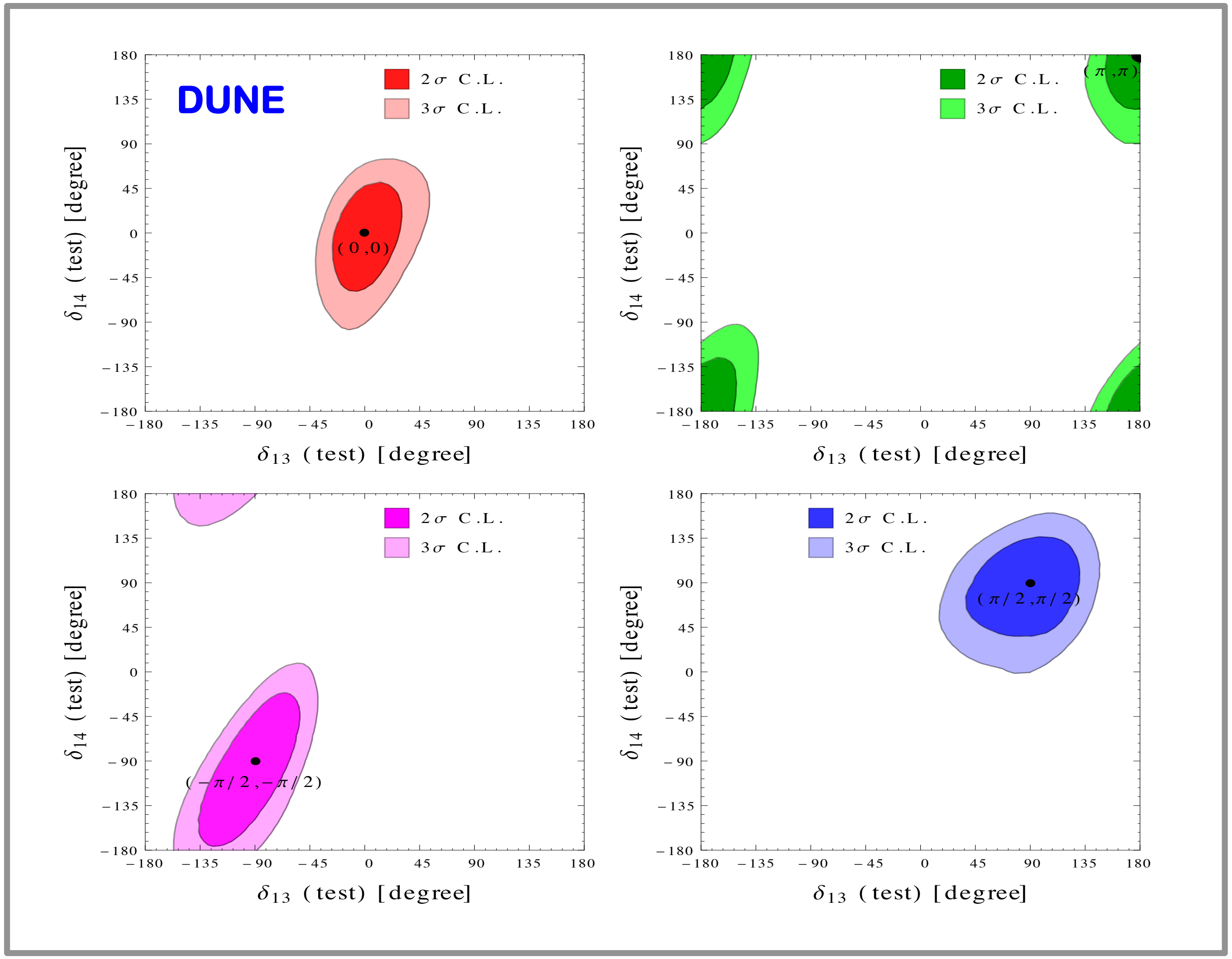
JHEP 2016



- 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 $\theta_{14}=\theta_{24}=\theta_{34}=9^0$

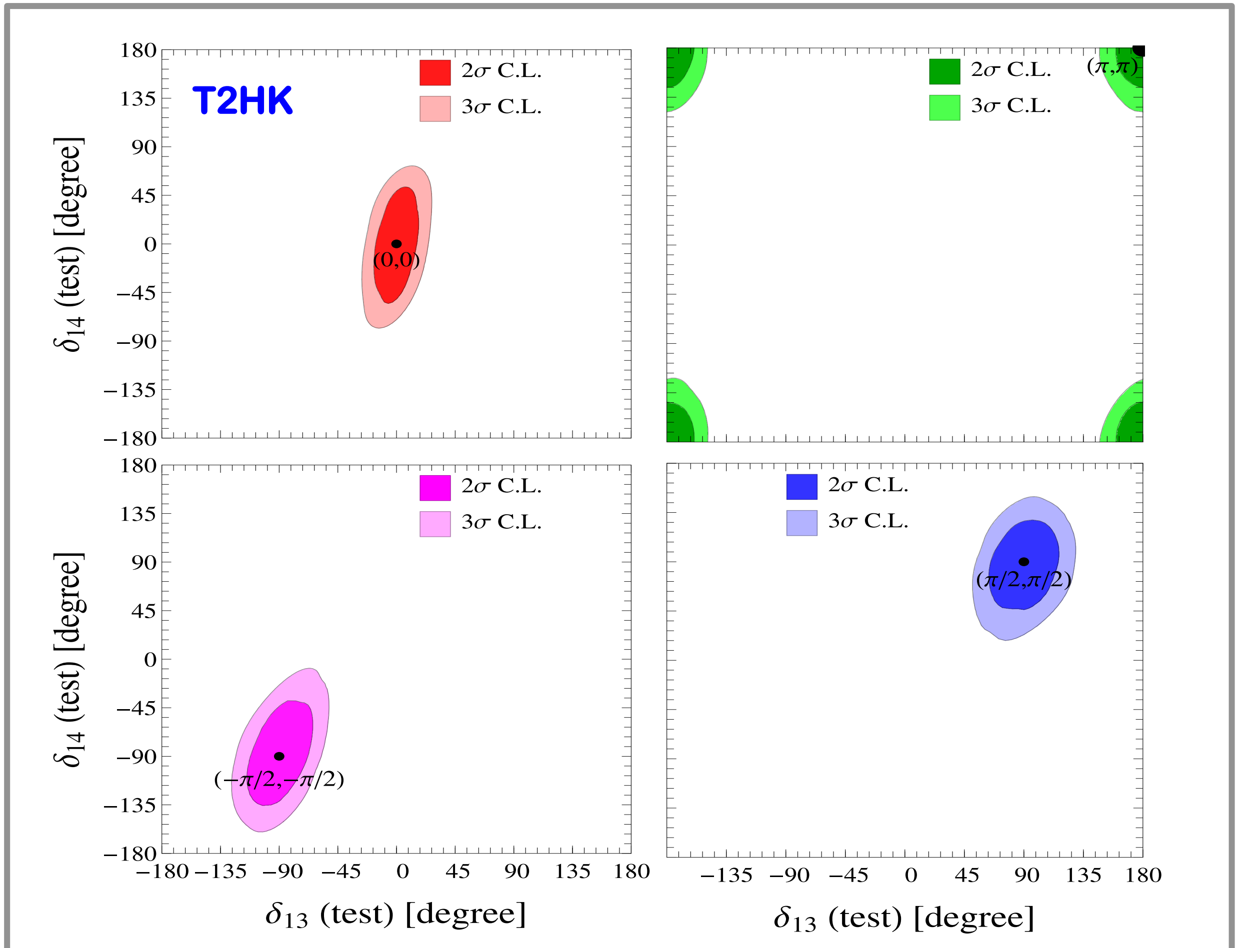
Reconstruction of the CP phases in DUNE

JHEP 2016



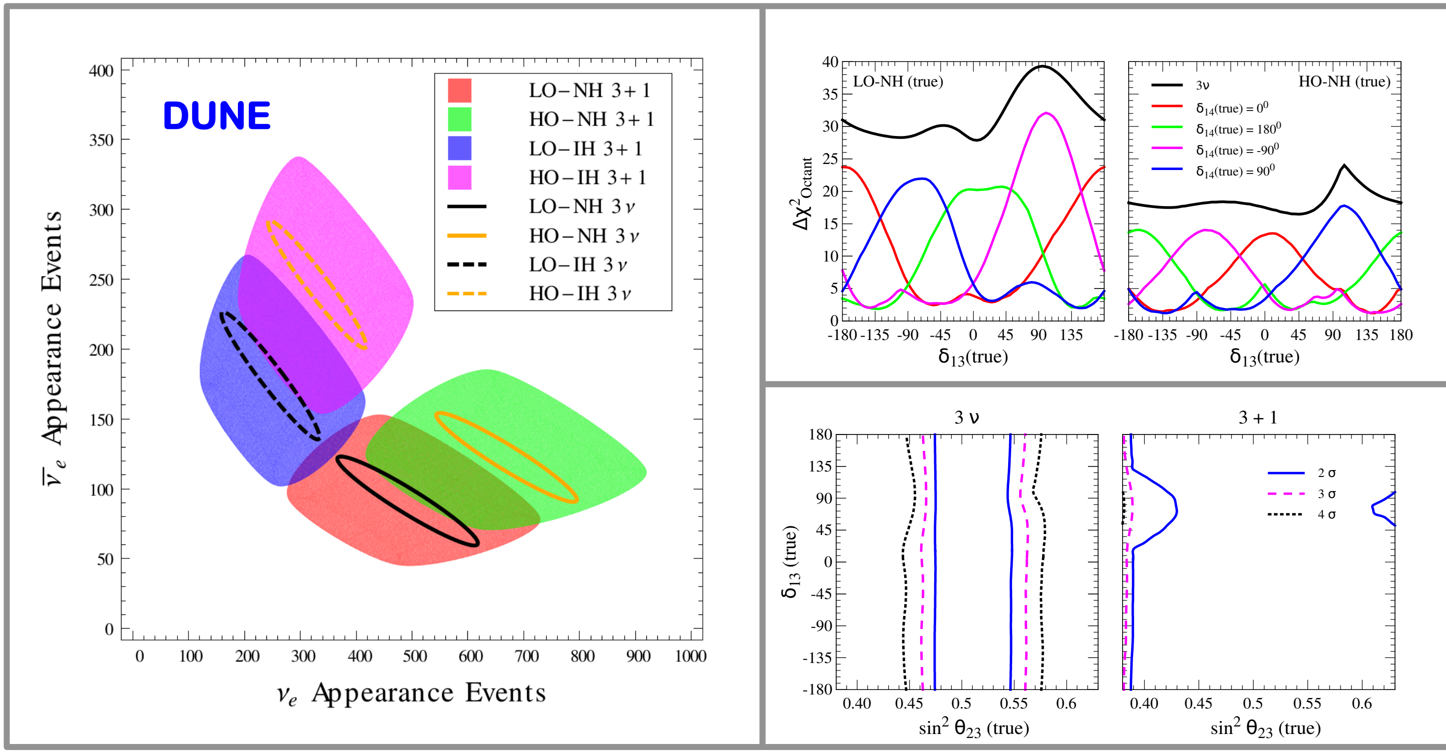
Reconstruction of the CP phases in T2HK

work in preparation



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

PRL 2017

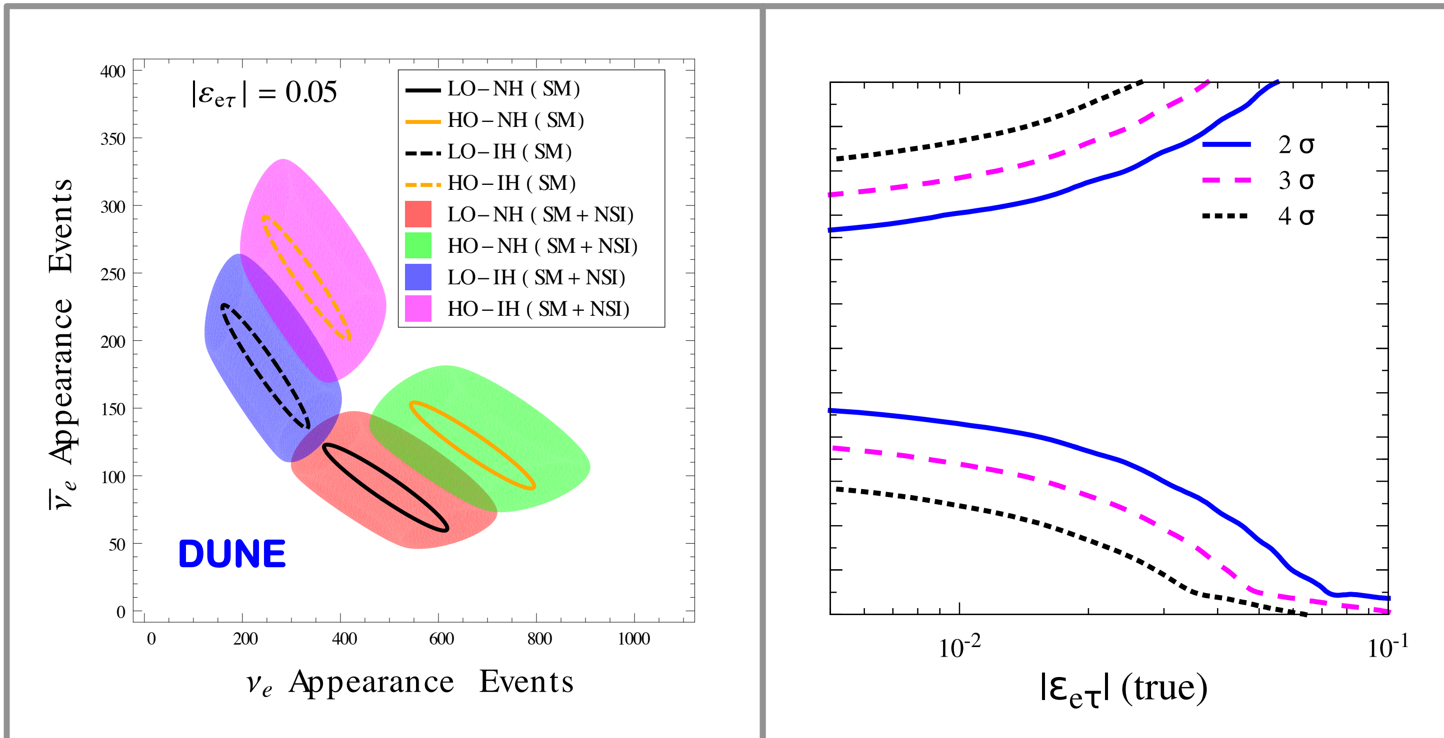


Distinct ellipses (3ν) become overlapping blobs (3+1)

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

Striking analogy between steriles and NSIs

PLB 2016

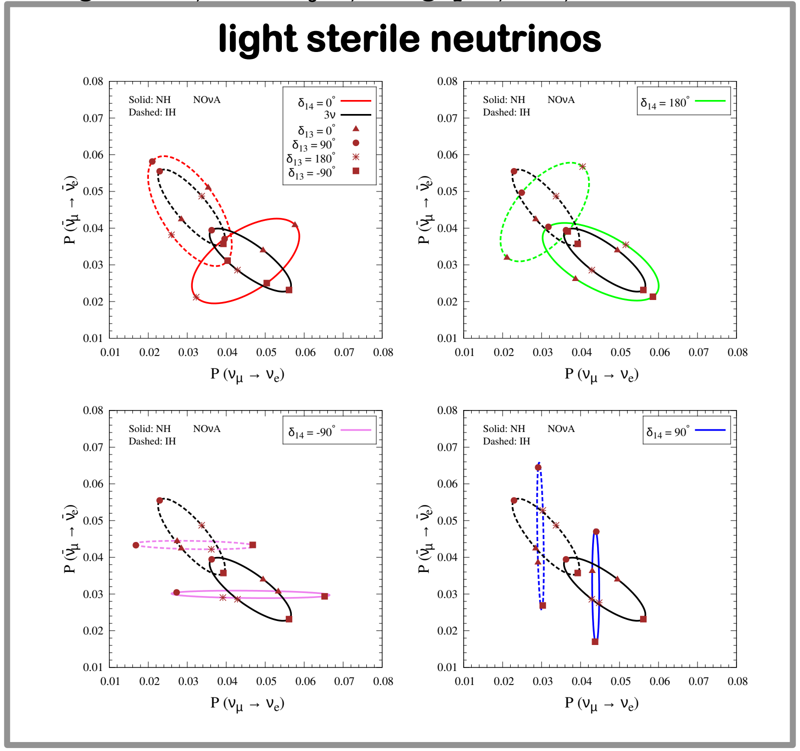


Also in this case a new CP-phase introduces a degeneracy

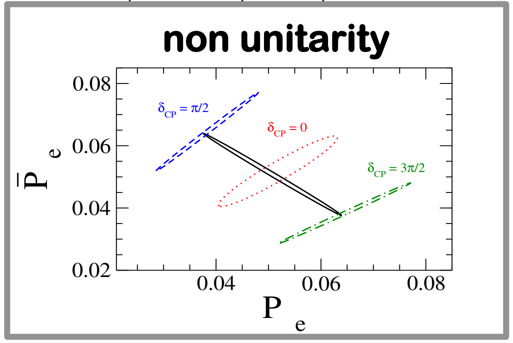
Very small values of the coupling may be harmful

The dance of the ellipses

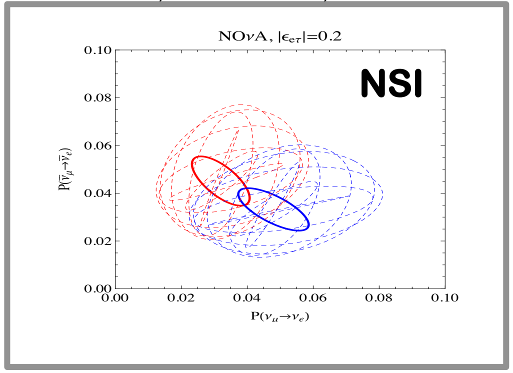
Agarwalla, Chatterjee, Dasgupta, A.P., 1601.05995



Miranda, Tortola, Valle, 1604:05690



Friedland, Shoemaker, 1207.6642



Extensions of SM are often sources of extra CP-phases

In all cases a new interference term appears in $P_{\mu e}$ at LBL

Bi-probability plots clearly represent this physical fact

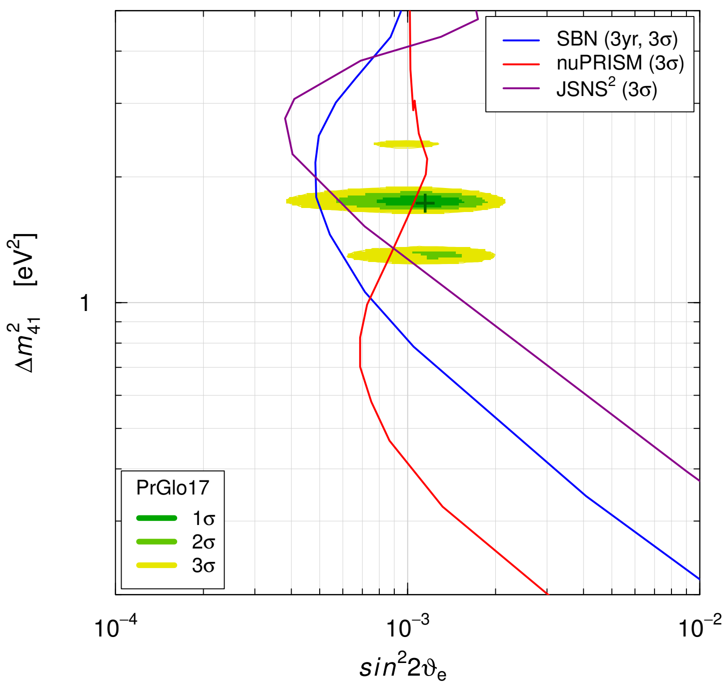
Conclusions

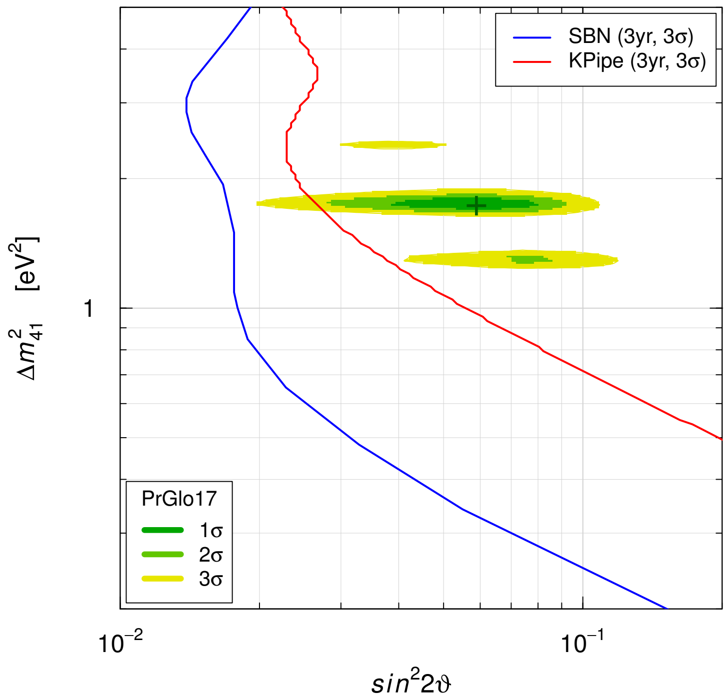
- **Several SBL anomalies point to sterile neutrinos but the global picture is not clear (internal tension)**
- **A novel intriguing hint emerges from NEOS**
- **New SBL experiments are needed to shed light. Clarification may require more time than expected**
- **Sterile neutrinos are sources of additional CPV**
- **Full exploration of 3+1 CPV possible only with LBL**
- **LBL experiments complementary to the SBL ones**

Thank you for your attention!

Back up slides

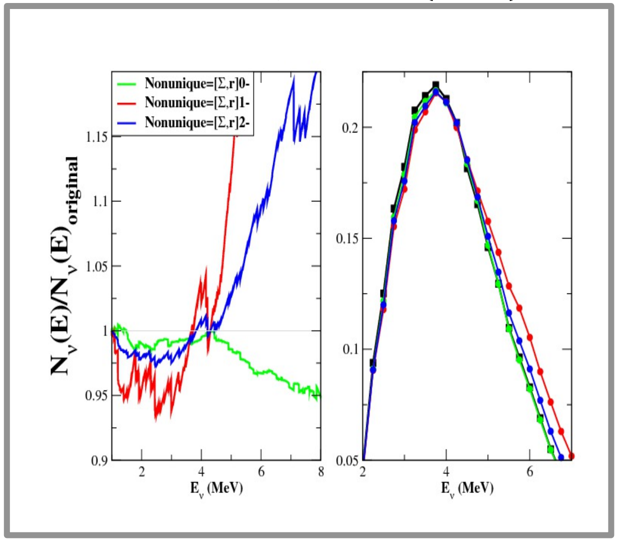
Sensitivity of future SBL experiments in the $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ channels



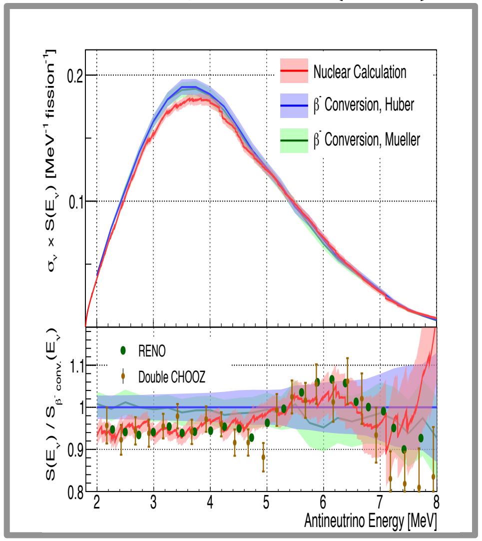


5 MeV bump is under active investigation

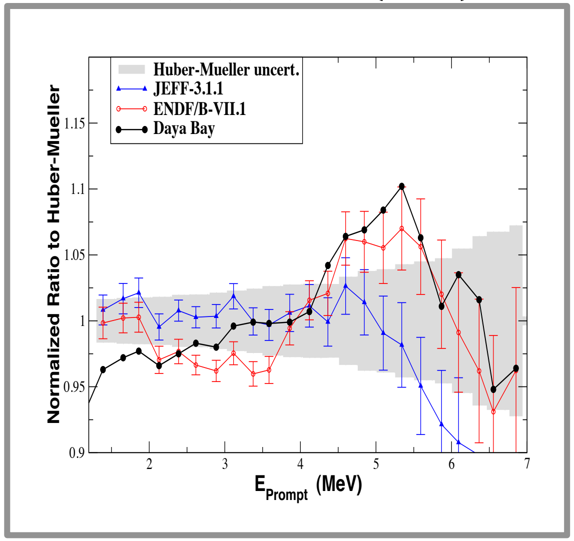
Hayes et al.
PRL 112, 202501 (2014)



Dwyer and Langford
PRL 114, 012502 (2015)

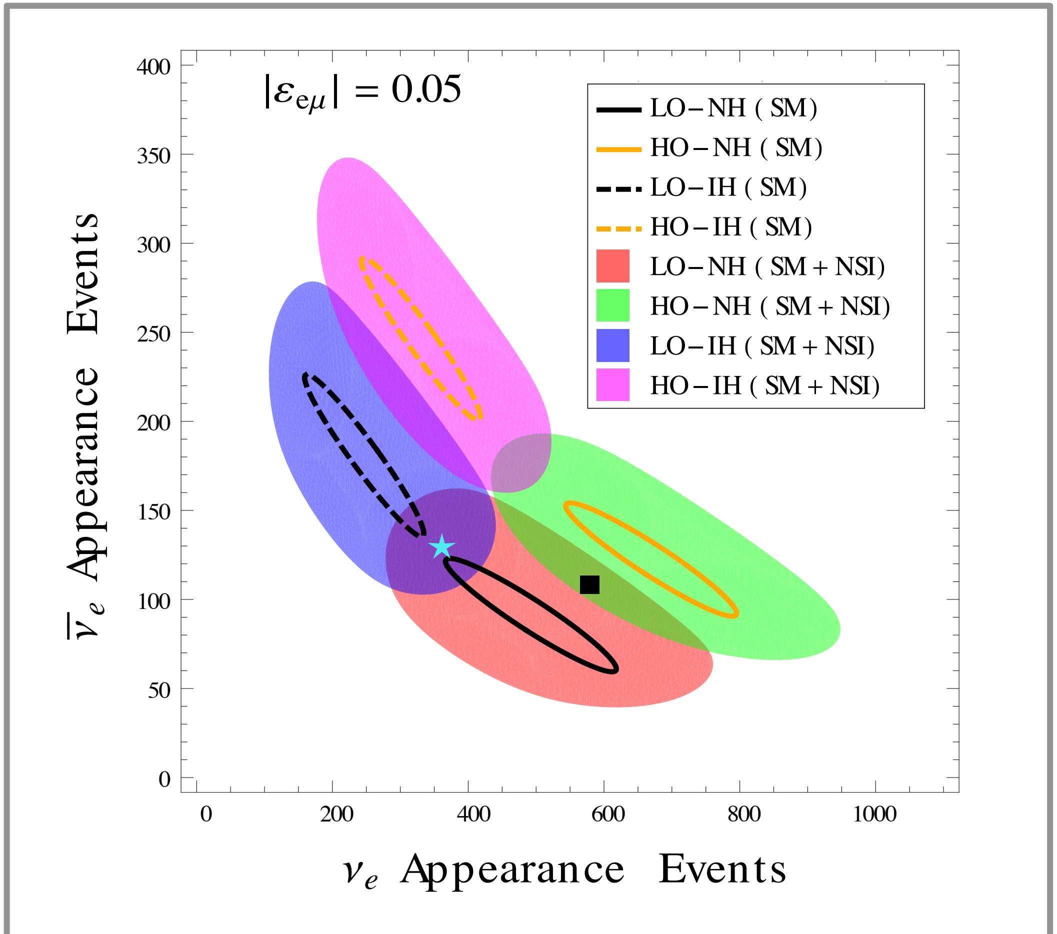


Hayes et al.
PRD 92, 033015 (2015)

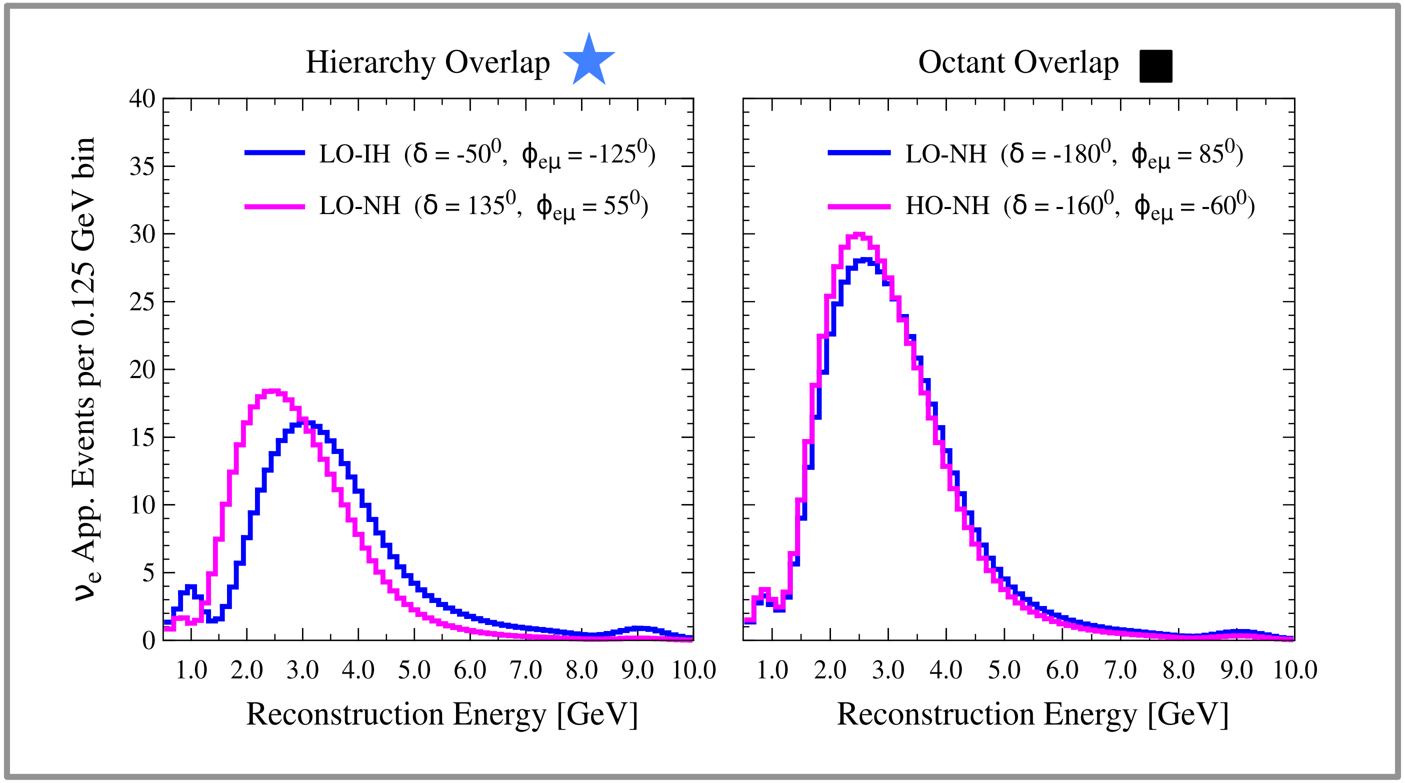


- **Systematics in reactor spectra not entirely under control**
- **Dissimilar results with two different nuclear databases**
- **Normalization & spectral shape issues not necessarily related**
- **New SBL experiments needed to shed light on both issues**

Impact of the NSI coupling $\varepsilon_{e\mu}$



Role of the spectral information



Mass hierarchy: spectrum helps

Octant of θ_{23}: spectrum does not help