NNN'16

Beijing, 3 November 2016

(Light) sterile neutrinos

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Outline

Introduction

SBL anomalies and the hypothesis of sterile νs

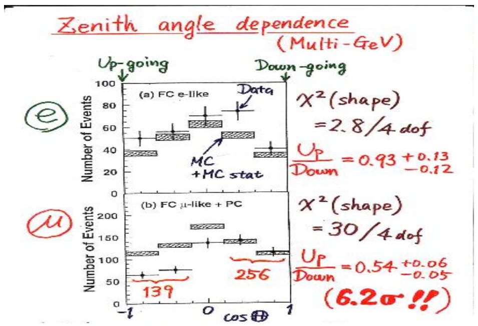
Role of LBL experiments in sterile ν searches

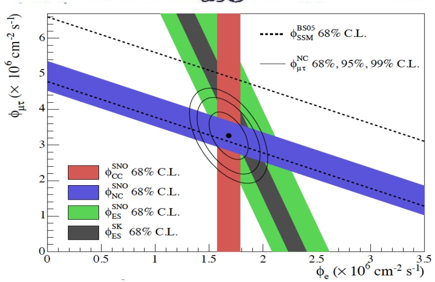
Conclusions

Introduction

Outstanding progress in ν physics in ~ 20 years

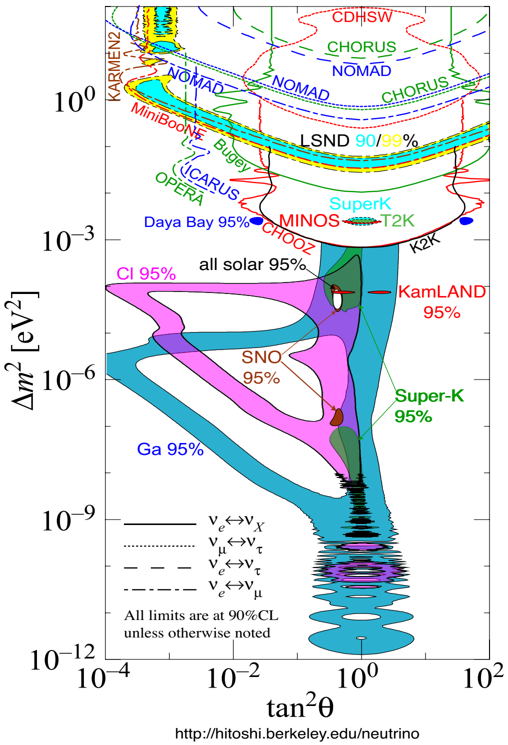
Discoveries





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

Interpretation



known knowns

$\delta m^2/eV^2$	~ 7.4×10^{-5}	±2.4%
$\Delta m^2/eV^2$	~ 2.5×10^{-3}	±1.8%
$\sin^2\theta_{12}$	~ 0.30	±5.8%
$\sin^2\theta_{13}$	~ 0.022	±4.7%
$\sin^2\theta_{23}$	~ 0.5	±9.0%

known unknowns

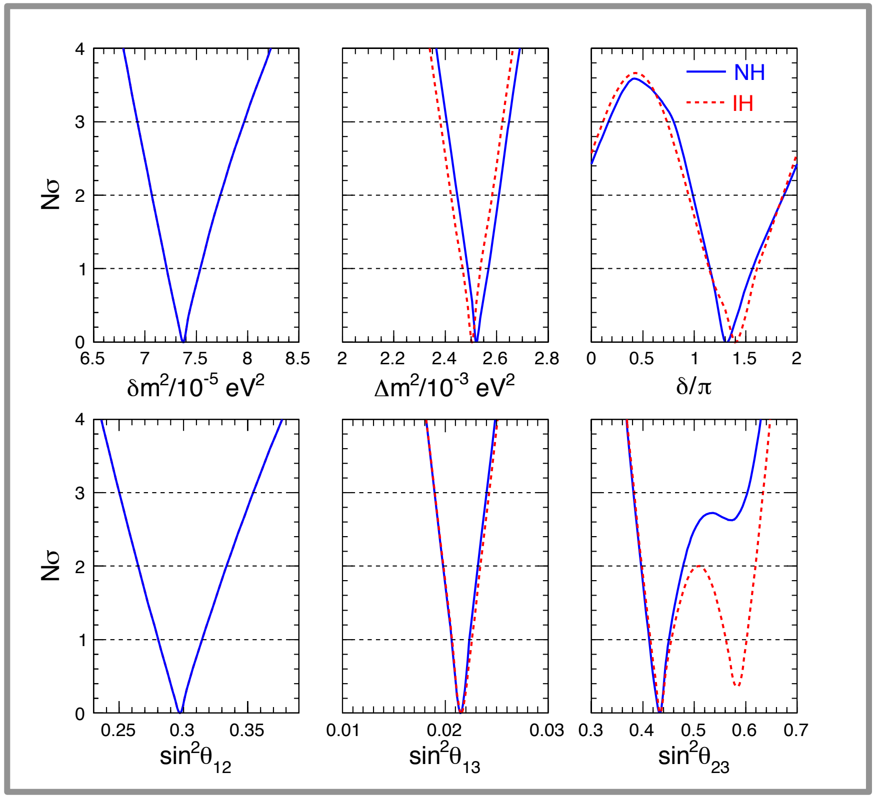
CPV (δ)
sign(Δm^2)
octant(θ_{23})
absolute ν mass
Dirac/Majorana

unknown unknowns

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

3-flavor scheme now established as the standard framework…

Current status of 3-flavor parameters



Bari Group (in preparation)
Capozzi @ NOW 2016
Marrone @ Neutrino 2016

~ 2σ preference for $\delta \in [\pi, 2\pi]$ ($\sin\delta < 0$)

Octant of θ_{23}
NH: LO preferred
IH: LO/HO degeneracy

~ 2σ preference for normal MH

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

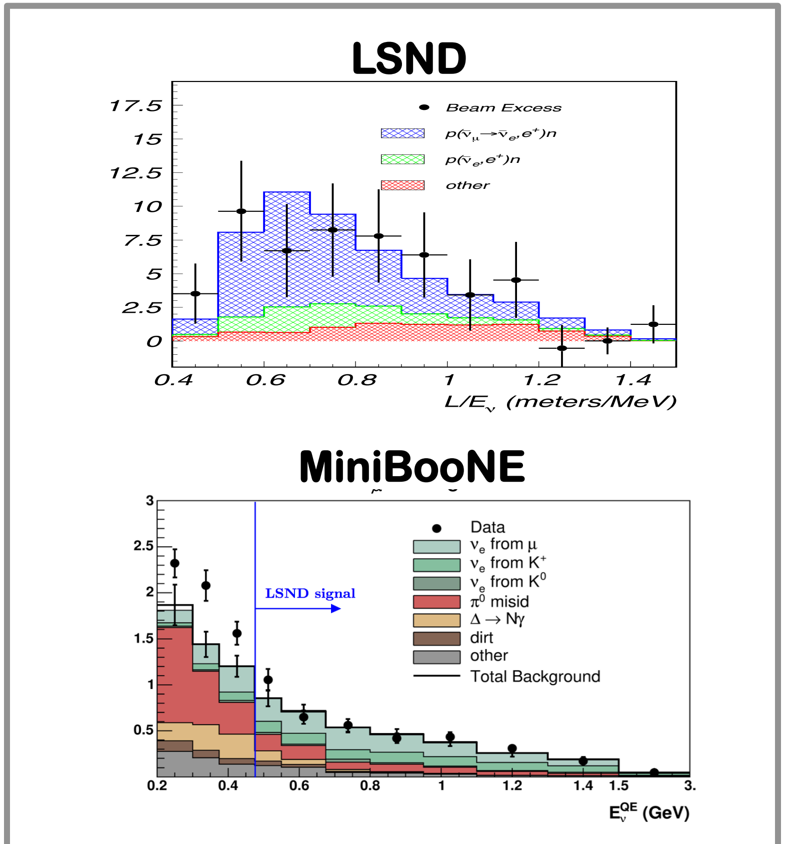
ν_s investigated at several scales:

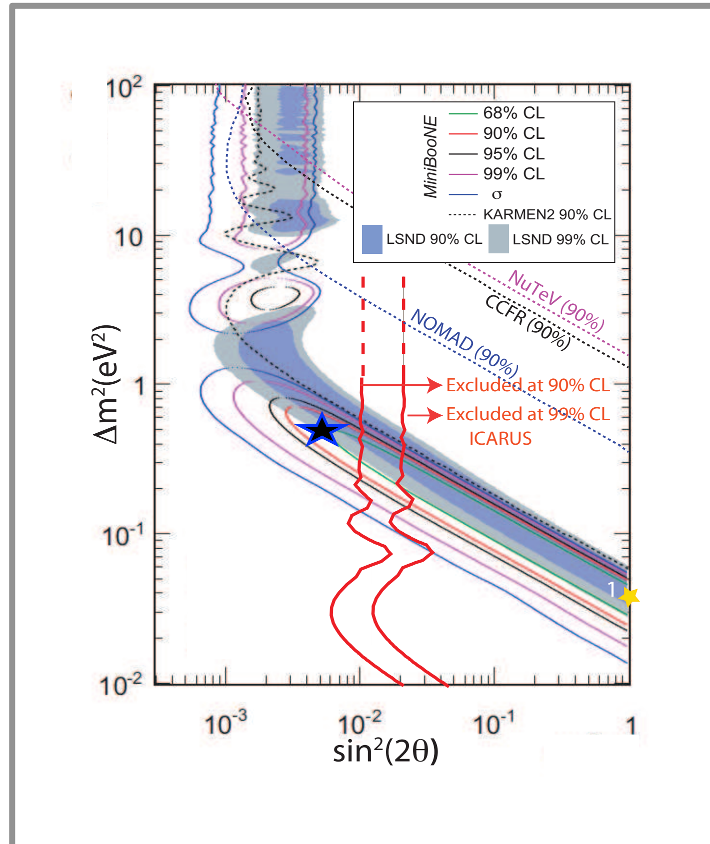
- **GUT, see-saw models of ν mass, leptogenesis**
- **TeV, production at LHC and impact on EWPOs**
- **keV, (warm) dark matter candidates**
- ✓ **eV, SBL (and LBL) oscillation experiments**
- **sub-eV, θ_{13}-reactors and solar neutrinos**

The SBL anomalies and the hypothesis of sterile νs

The SBL accelerator anomalies

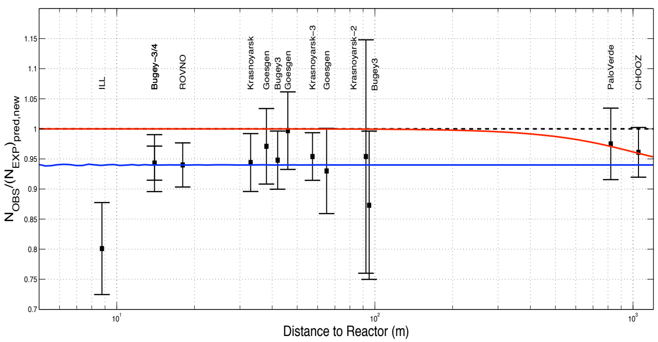
(unexplained ν_e appearance in a ν_μ beam)



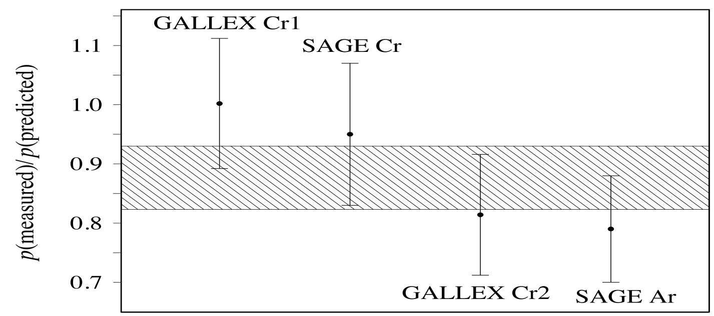


The reactor and gallium anomalies

(unexplained ν_e disappearance)



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



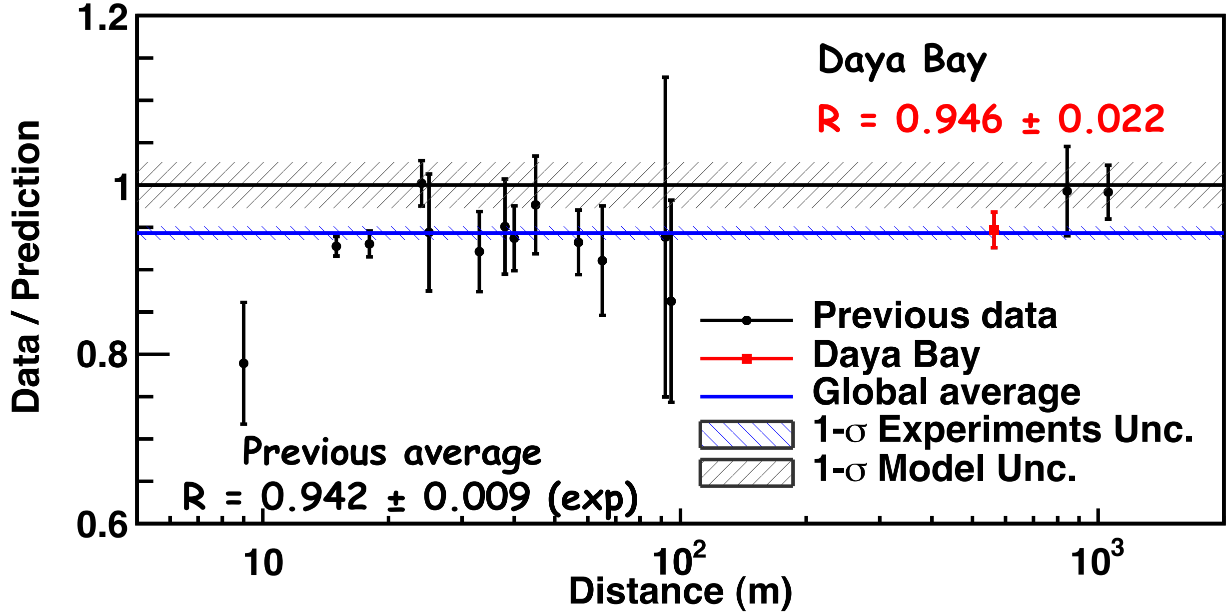
SAGE coll., PRC 73 (2006) 045805

Warning: both are mere normalization issues

The culprit may be hidden in unknown systematics

New-generation detectors confirm deficit

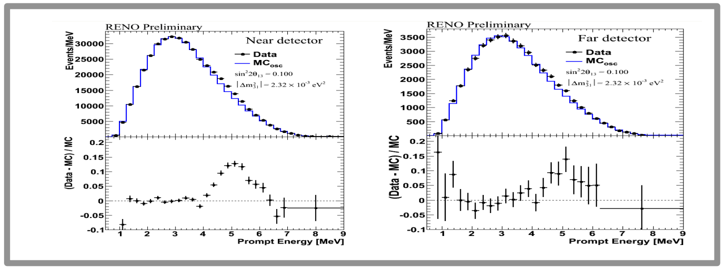
Daya Bay, PRL 061801 (2016) [1508.04233]



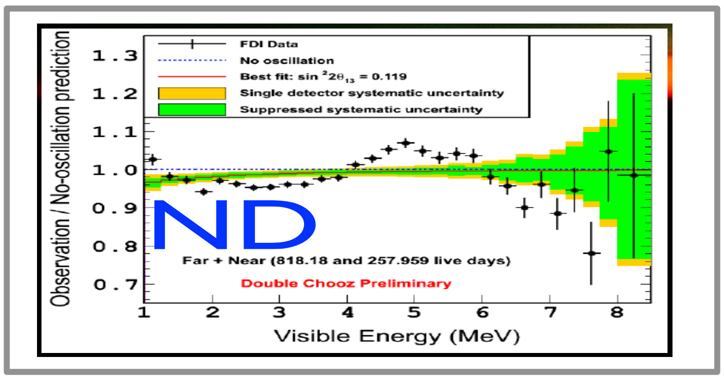
However, the same detectors give us a warning …

Understanding of reactor spectrum is incomplete

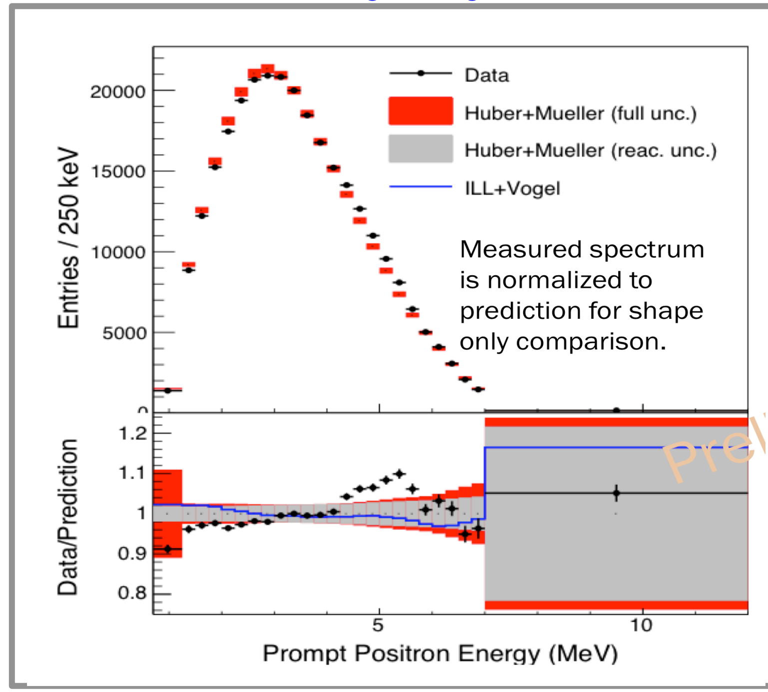
RENO



Double-CHOOZ



Daya Bay



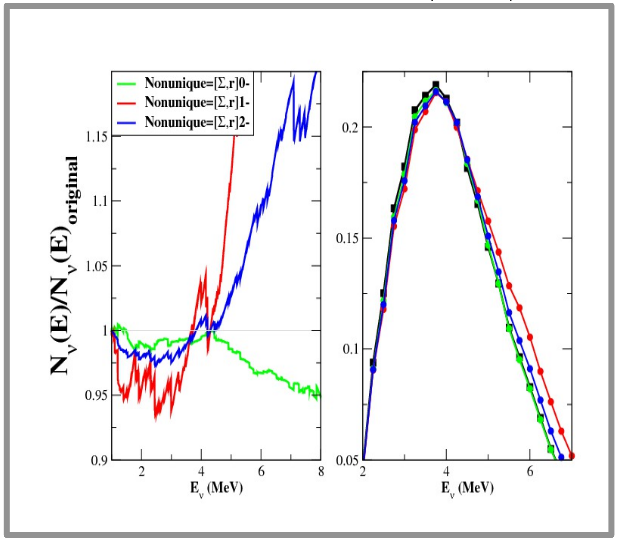
Bump/shoulder at 5 MeV observed in all the three experiments

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

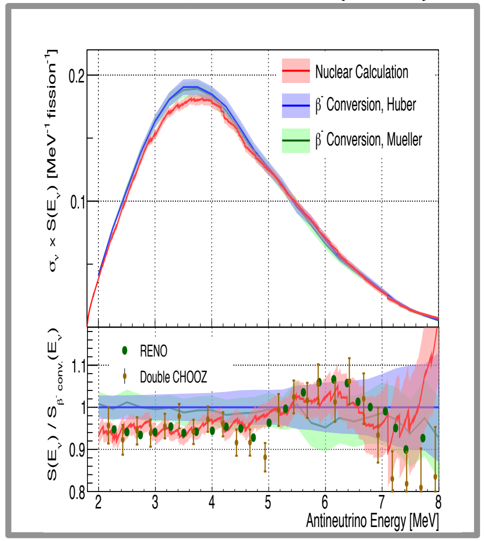
θ_{13} extraction is unaffected (based on near/far comparison)

5 MeV bump is under active investigation

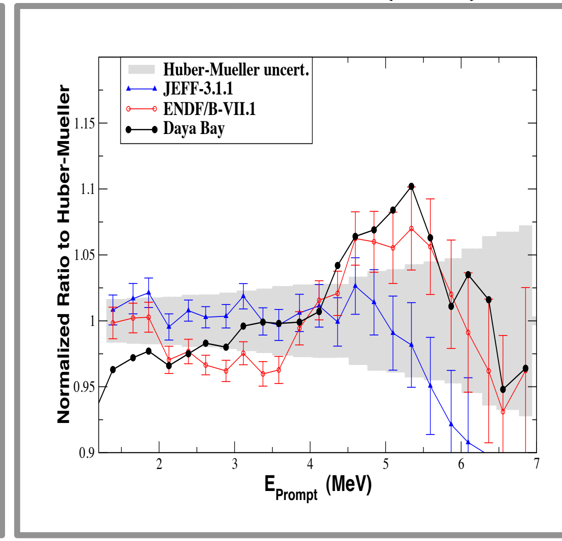
Hayes et al.
PRL 112, 202501 (2014)



Dwyer and Langford
PRL 114, 012502 (2015)



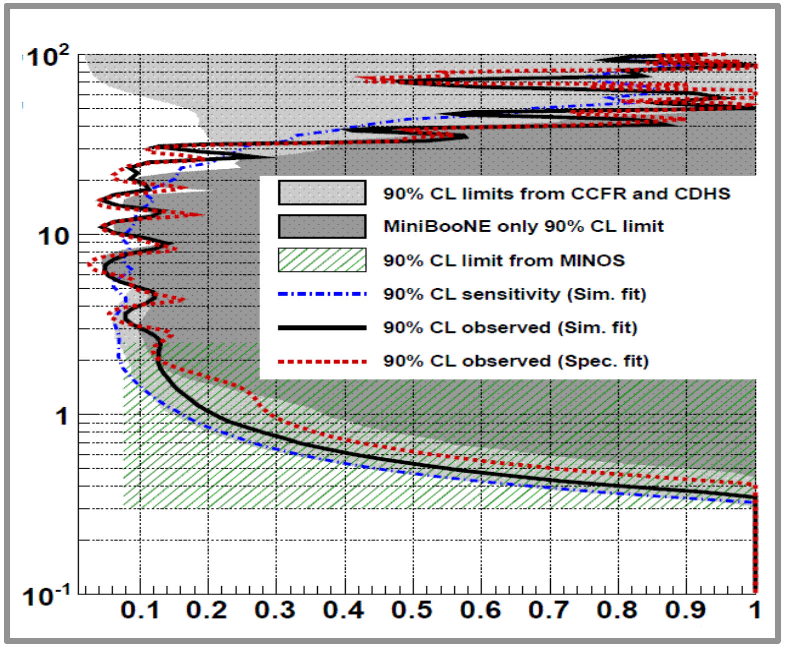
Hayes et al.
PRD 92, 033015 (2015)



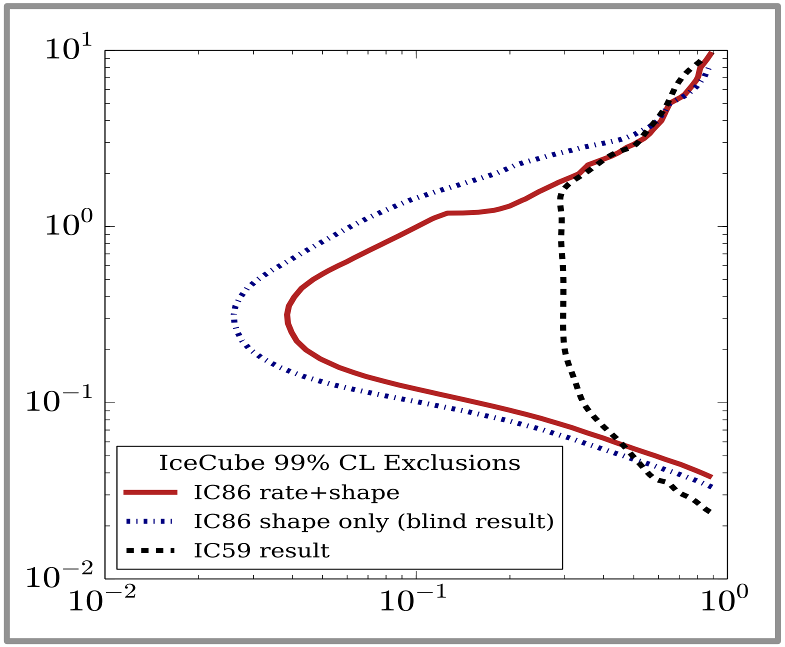
- Systematics in reactor spectra not entirely under control
- Dissimilar results with two different nuclear databases
- Normalization & spectral issues not necessarily related
- New SBL experiments needed to shed light on both issues

No anomaly in ν_μ disappearance

SBL & MINOS (NC)



IceCube

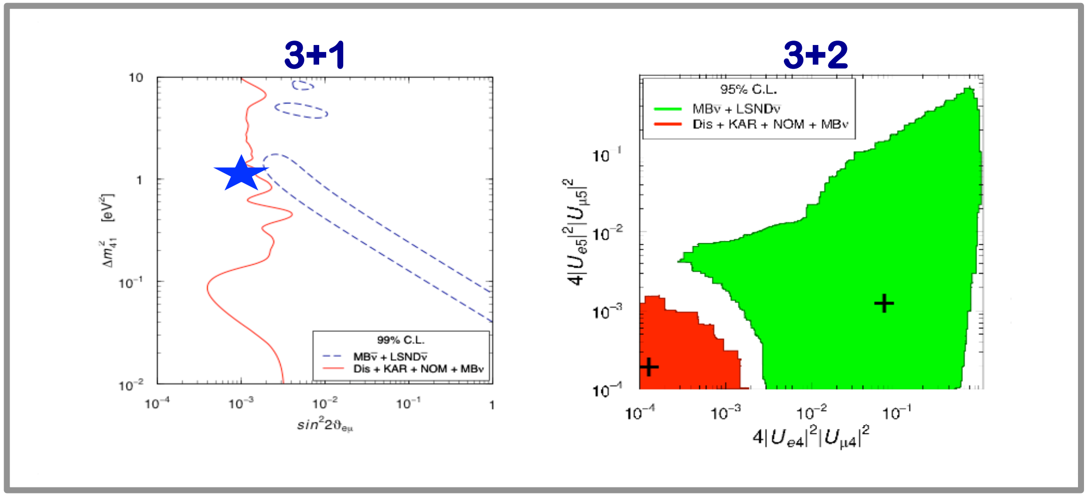


Δm^2

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

A thorn in the side of the sterile neutrino …

Tension in all ν_s models



Giunti
&
Laveder

arXiv:1107.1452

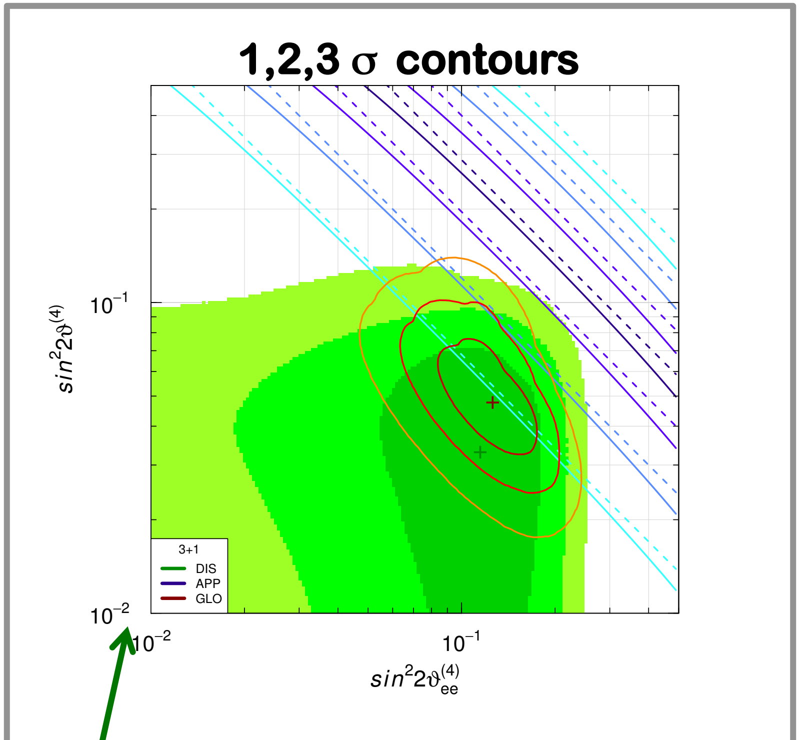
$\nu_\mu \to \nu_e$ **positive** $|U_{e4}||U_{\mu4}| > 0$

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

$\nu_\mu \to \nu_\mu$ **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

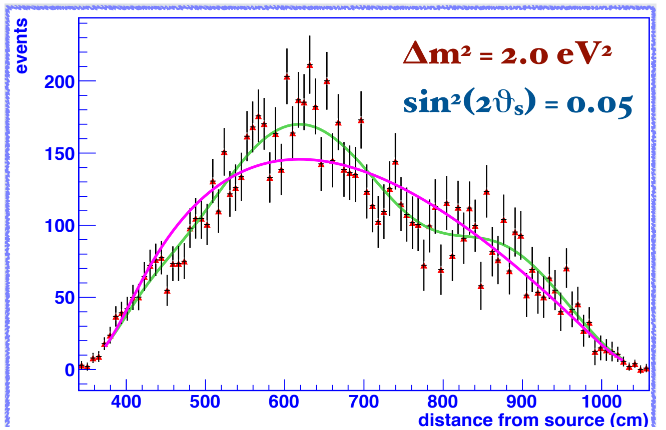
Difficult to take a decision on sterile νs !

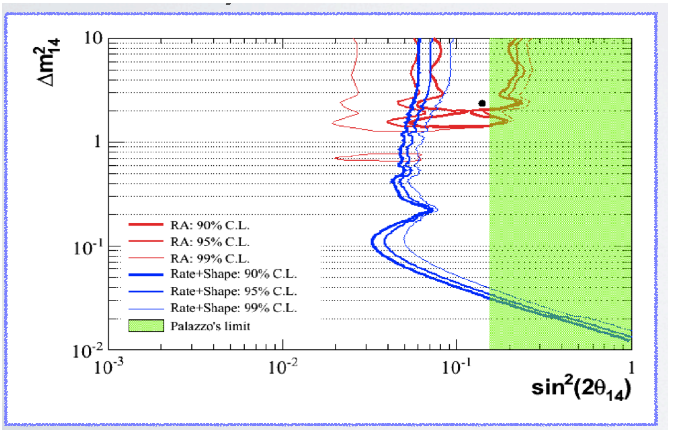
Only new more sensitive experiments can decide …

Figure from Giunti & Zavanin, arXiv:1508:03172

The smoking gun

The oscillation pattern (in energy and/or space)





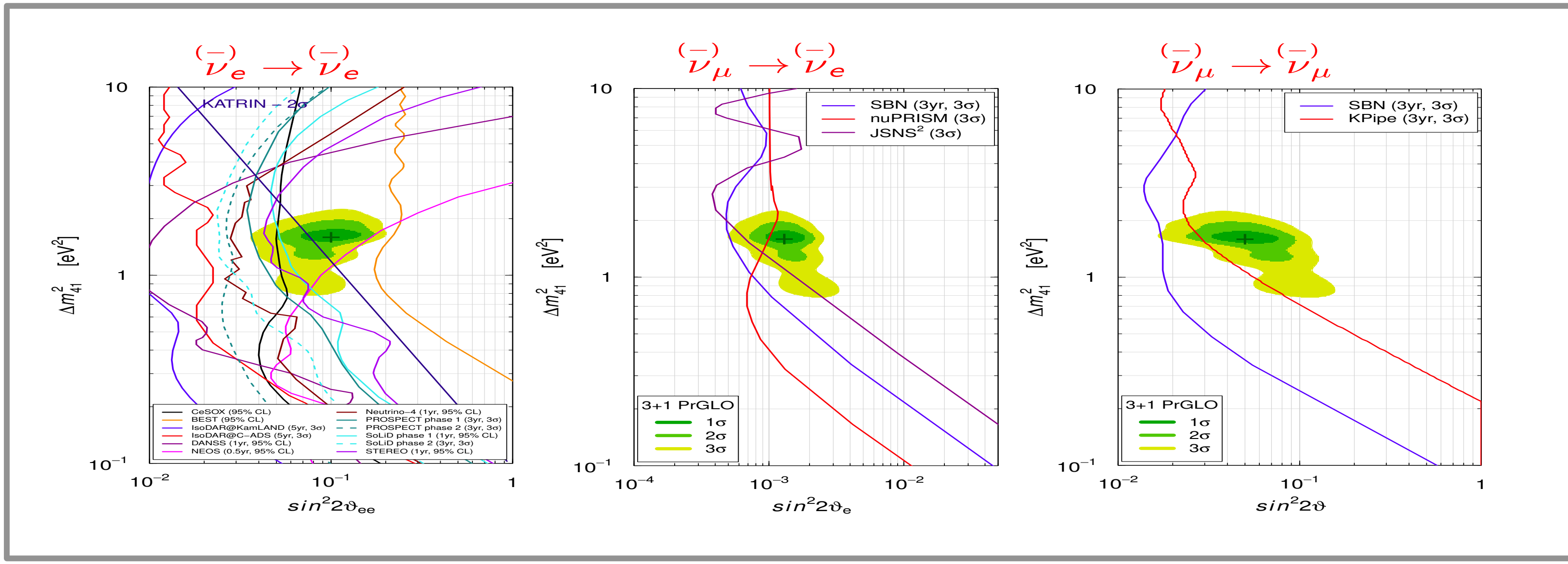
M. Pallavicini @ Neutrino 2012

This can be observed only at SBL

Many projects under consideration…

The SBL race for the light sterile neutrino

Figure from C. Giunti @ NOW 2016



But sterile neutrinos are not just a SBL affair

Opportunity and challenge for LBL experiments…

Role of LBL experiments in sterile neutrino searches

An intrinsic limitation of SBL

At SBL atm/sol oscillations are negligible

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

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

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

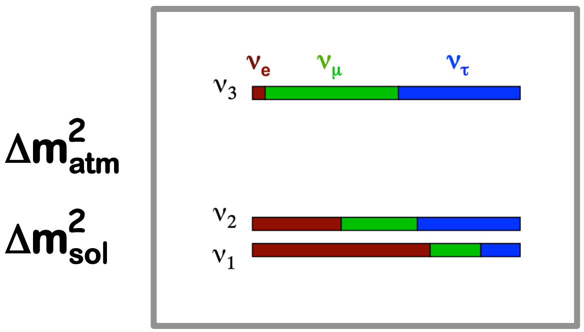
Impossible to observe phenomena of interference between the new frequency ($\Delta_{14} \sim 1$) and atm/sol ones

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

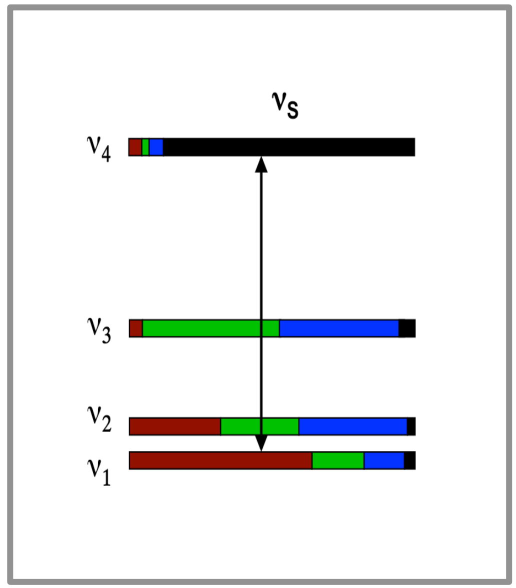
But we have LBL, which are sensitive interferometers

How to enlarge the 3-flavor scheme

3ν scheme



3+1 scheme



$|U_{s4}| \sim 1$

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

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 more sources of CPV

LBL transition probability in 3-flavor

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

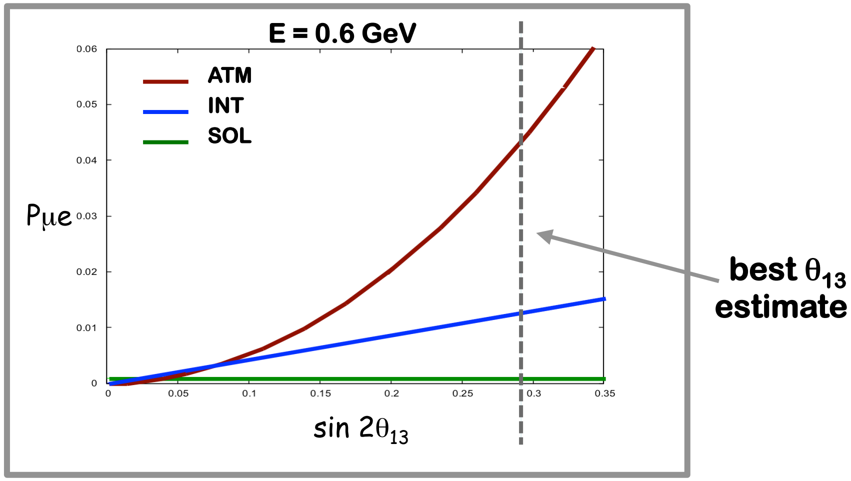
in vacuum:

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

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

$\Delta \sim \pi/2$

$\alpha \sim 0.03$

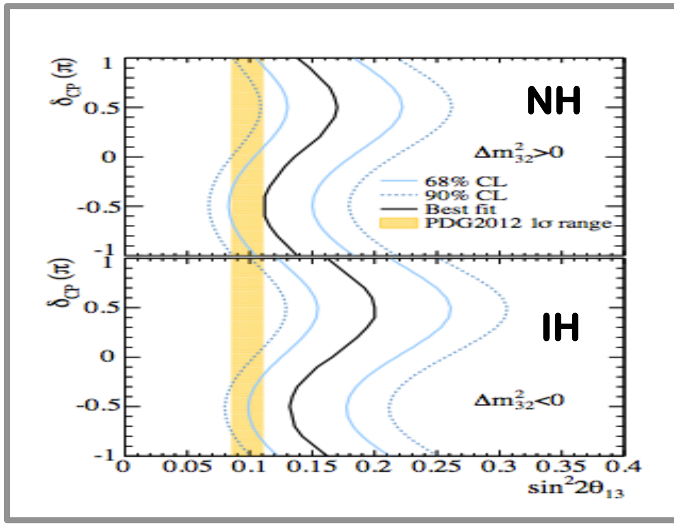


P^{ATM} leading → $\theta_{13} > 0$

P^{INT} subleading → dependency on δ

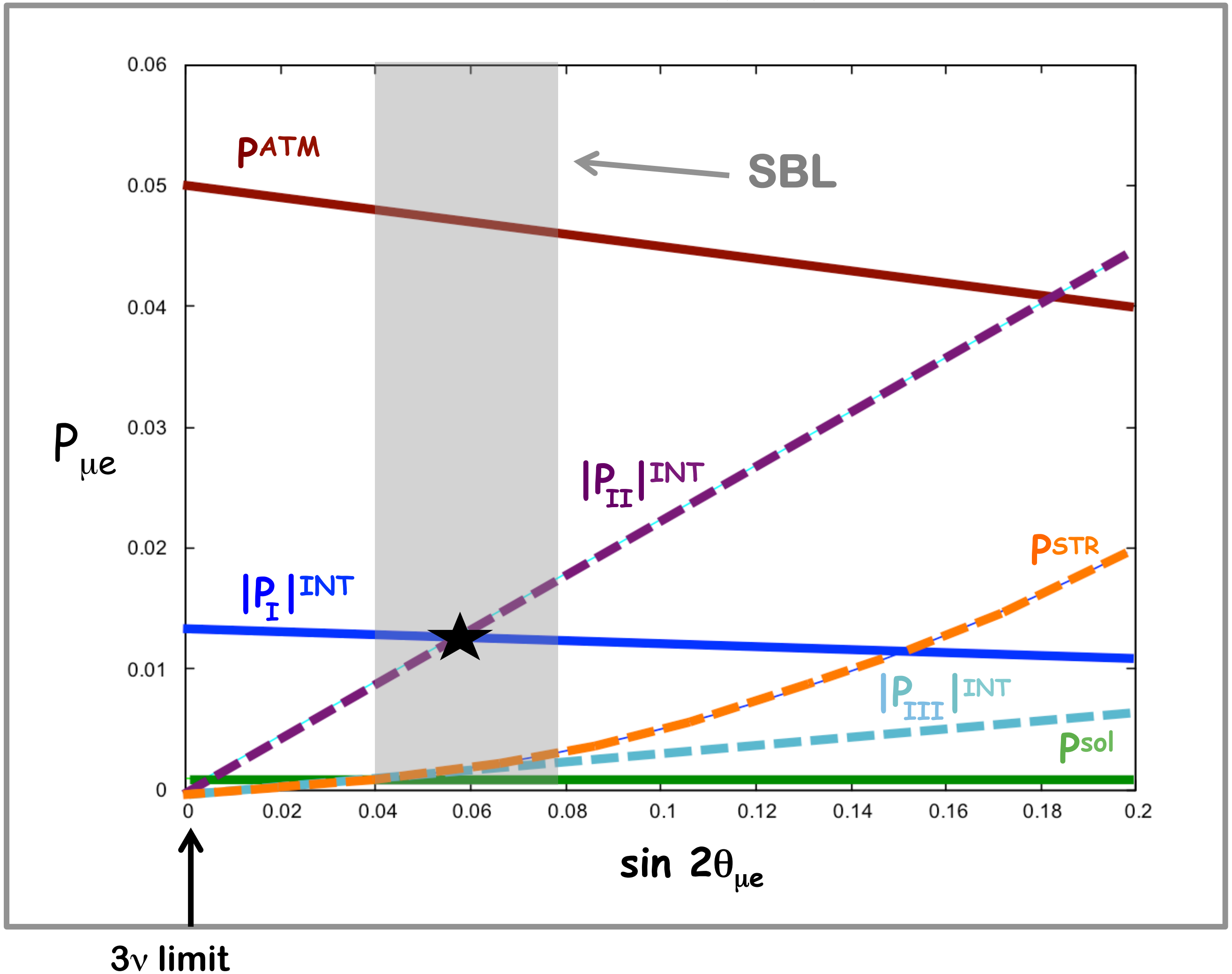
P^{SOL} negligible

Matter effects break NH-IH degeneracy



A new interference term in the 3+1 scheme

N. Klop & A.P., PRD 91 073017 (2015) [1412.7524]



T2K
θ_{13} = 9°
E = 0.6 GeV

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

LBL transition probability in 3+1 scheme

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

- Information on Δm^2_{14} lost (in contrast with SBL)

- Differently from SBL, interference of Δ_{14} & Δ_{13} is observable

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

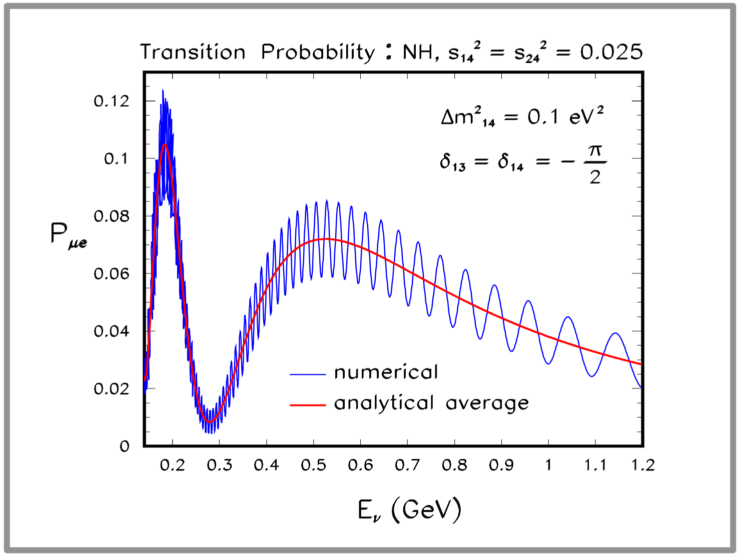
$s_{13} \sim s_{14} \sim s_{24} \sim 0.15 \sim \varepsilon$

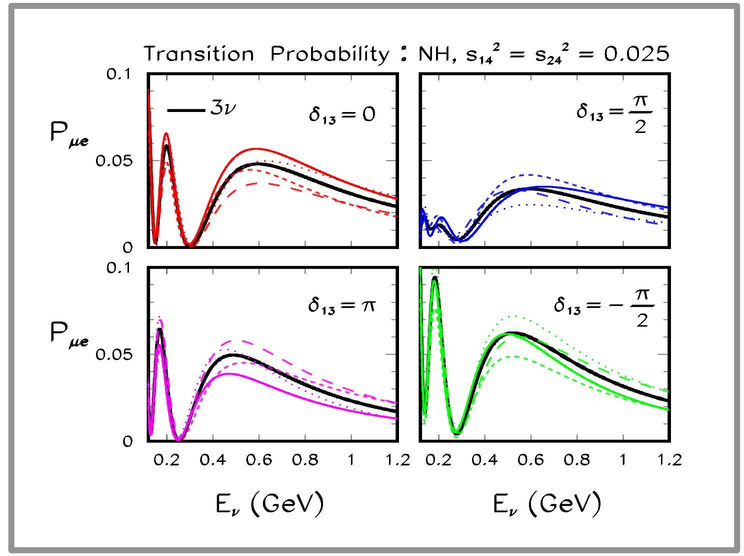
$\alpha = \delta m^2/\Delta m^2 \sim 0.03 \sim \varepsilon^2$

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

Sensitivity to the new CP-phase δ_{14}

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}

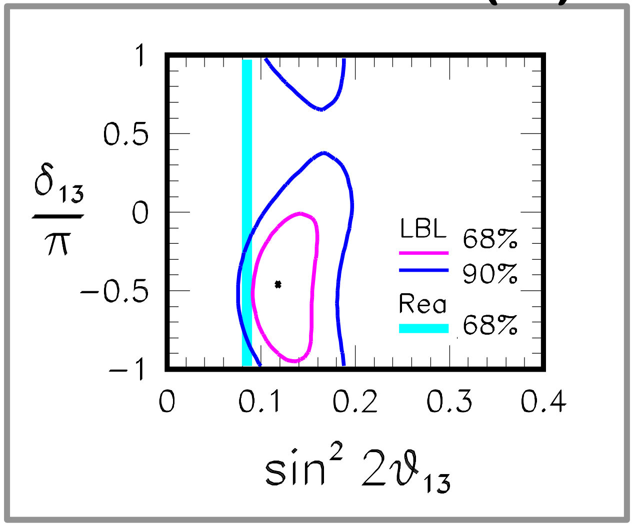
The modifications induced by δ_{14} are as large as those induced by the standard CP-phase δ_{13}

Consequences…

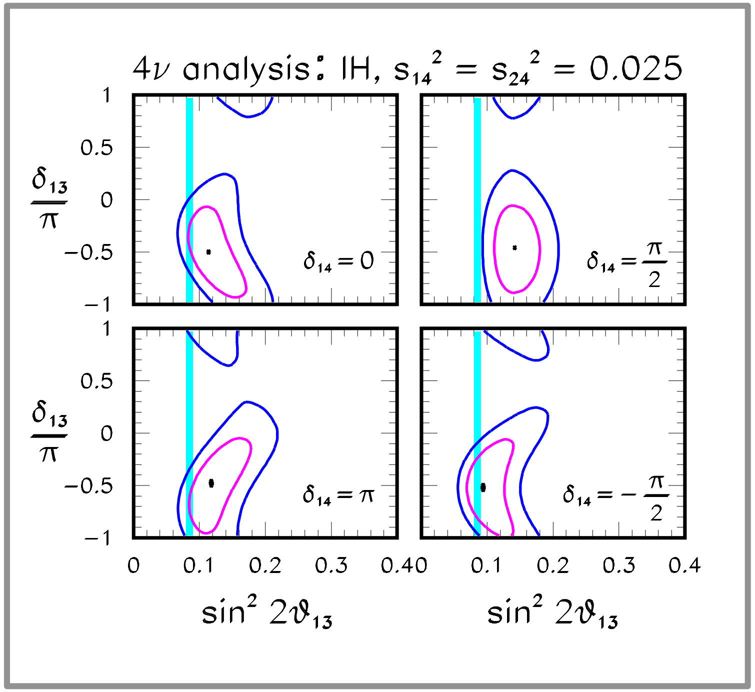
LBL constraints change in the 3+1 scheme

A.P., PLB 757, 142 (2016) [1509.03148]

3ν: T2K + NOνA (IH)



4ν



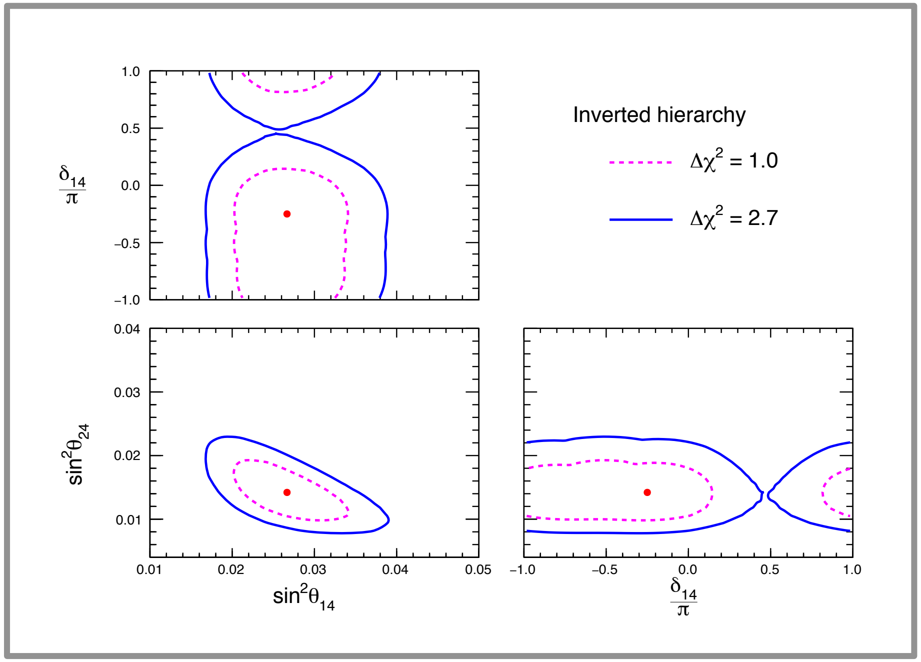
- **The level of (dis-)agreement of LBL & Rea. depends on δ_{14}**
- **In this analysis θ_{14} and θ_{24} are fixed at the SBL best fit values**
- **These results call for a more refined analysis …**

A joint analysis of SBL & LBL data

Capozzi, Giunti, Laveder & A.P. (in preparation)

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

SBL + LBL



SBL (all available data)

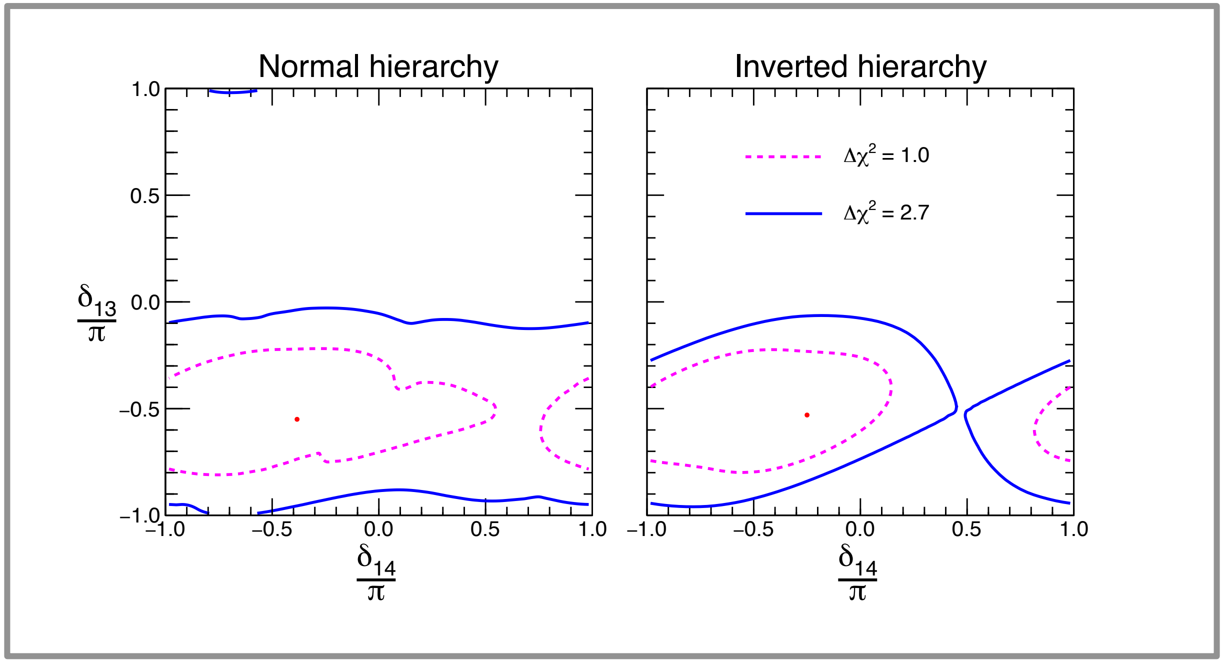
LBL ≡ T2K + NOνA

(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



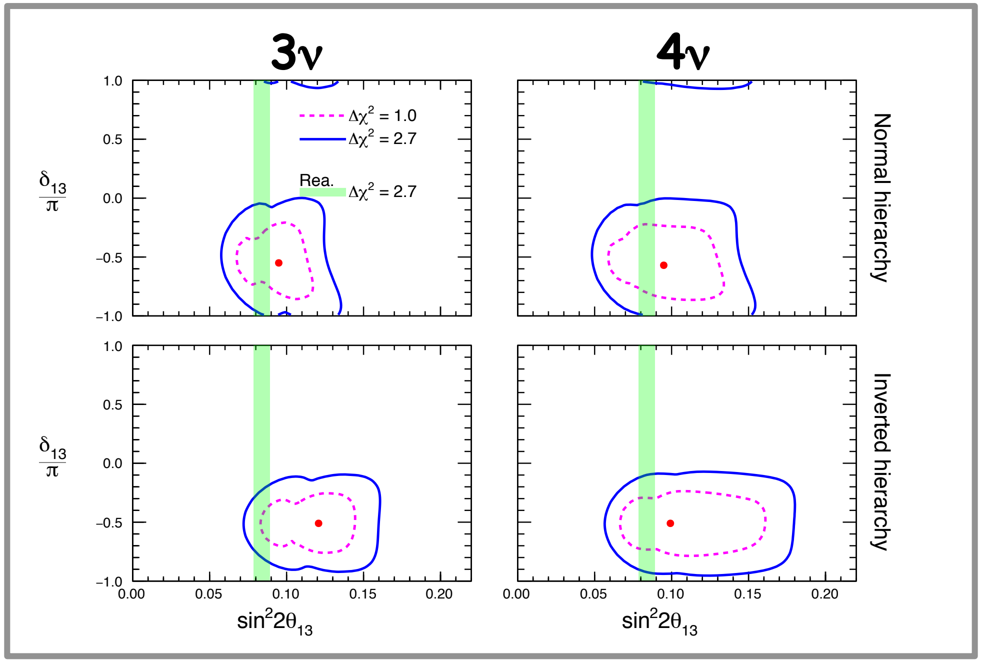
- δ_{13} **is more constrained than** δ_{14}

- **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}]

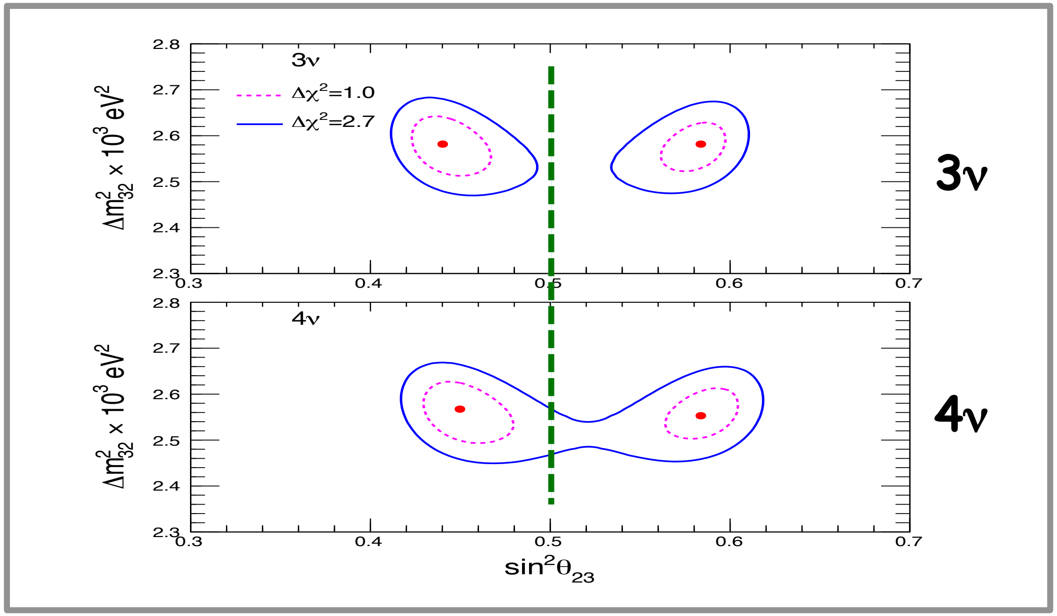
SBL + LBL



- **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 on the standard parameter θ_{23}

SBL + LBL



- **Preference for non-maximal θ_{23} persists in the 3+1 scheme**
- **Note that $\theta_{23} \cong 45^o$ corresponds to μ-τ symmetry also in the 3+1 scheme** (see for example, Merle, Morisi, Winter, 1402.6332)
- **Even in the presence of a ν_s, the preference for non-maximal θ_{23}, if confirmed, would imply that μ-τ symmetry is violated**

Looking to the future

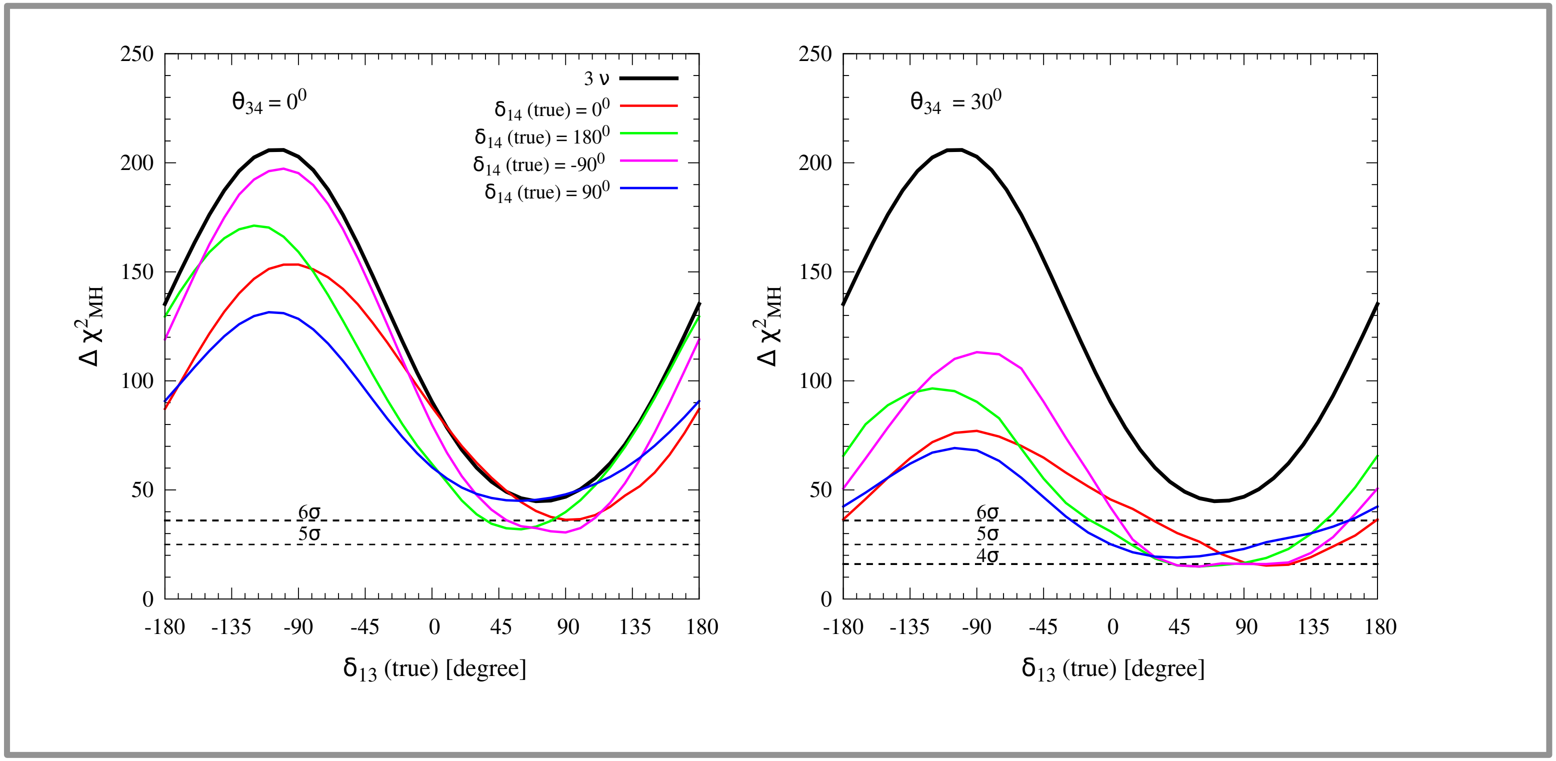
Agarwalla, Chatterjee, A.P., arXiv: 1601.05995 (JHEP 2016)

Agarwalla, Chatterjee, A.P., arXiv: 1603.03759 (JHEP 2016)

Agarwalla, Chatterjee, A.P., arXiv: 1605.04299

Discovery potential of mass hierarchy

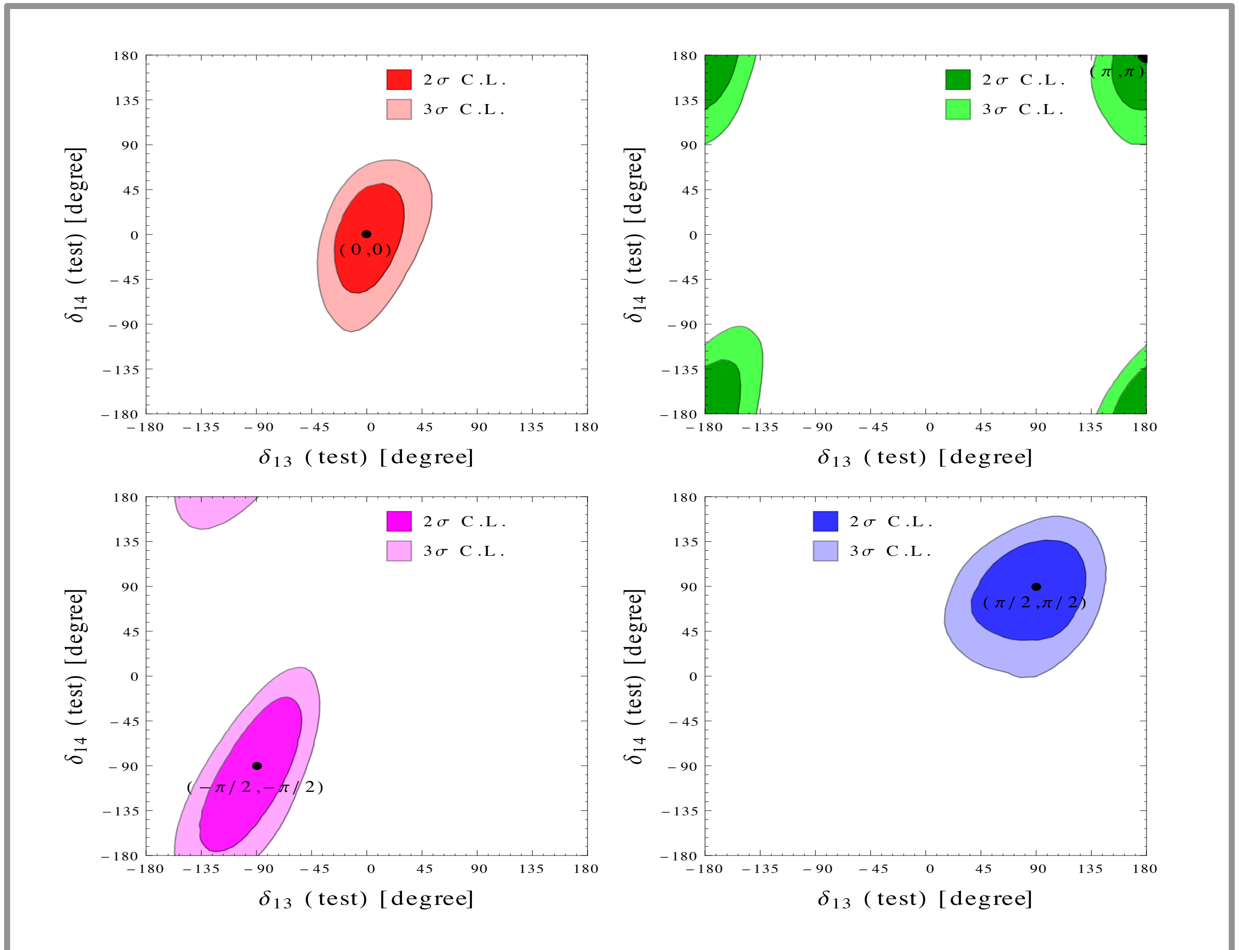
DUNE



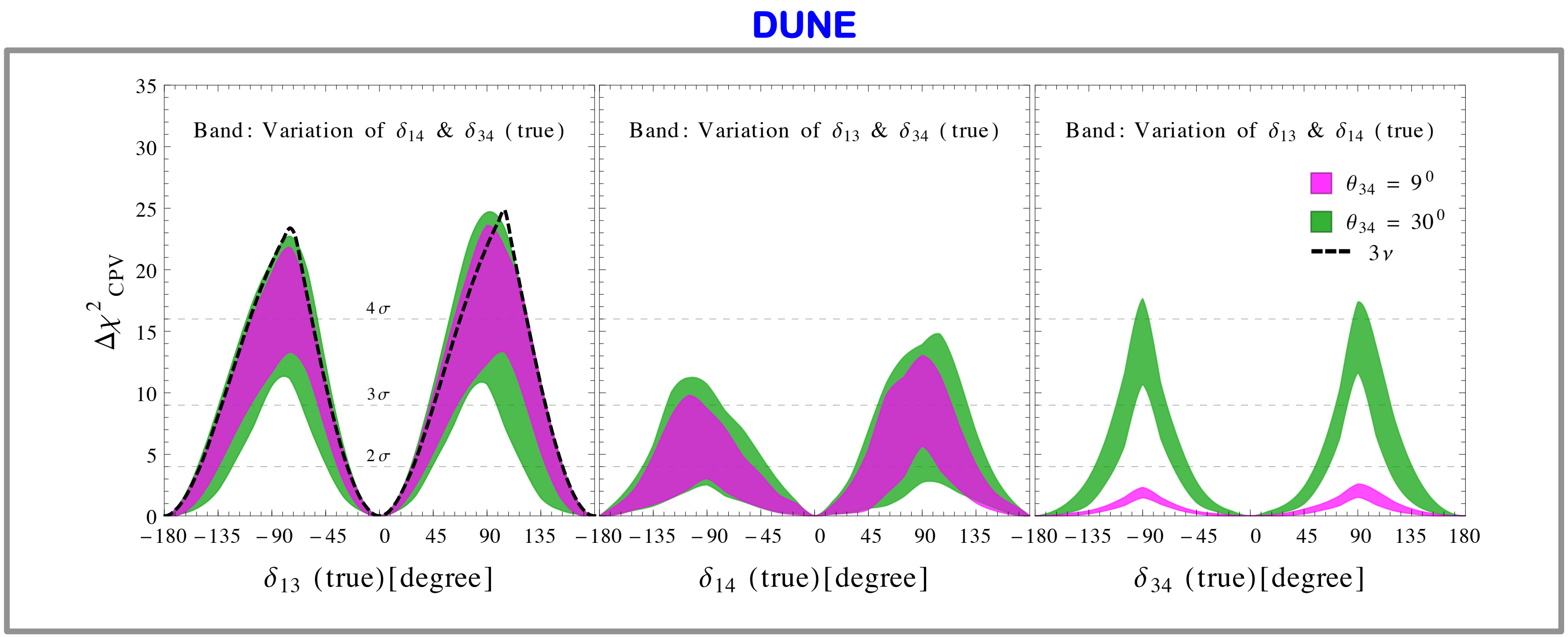
Degradation of sensitivity but 4σ level preserved

Reconstruction of the CP phases

DUNE



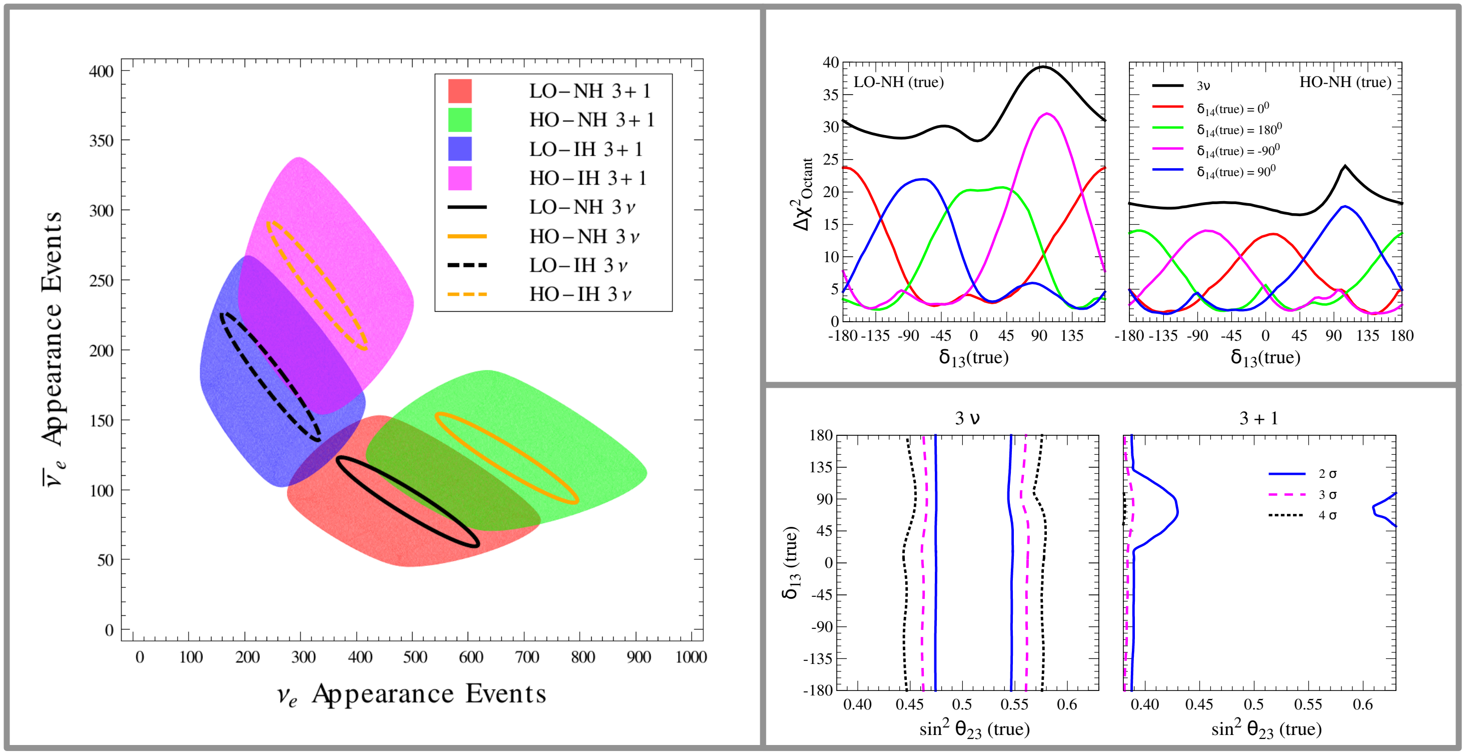
CPV discovery potential



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

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

DUNE

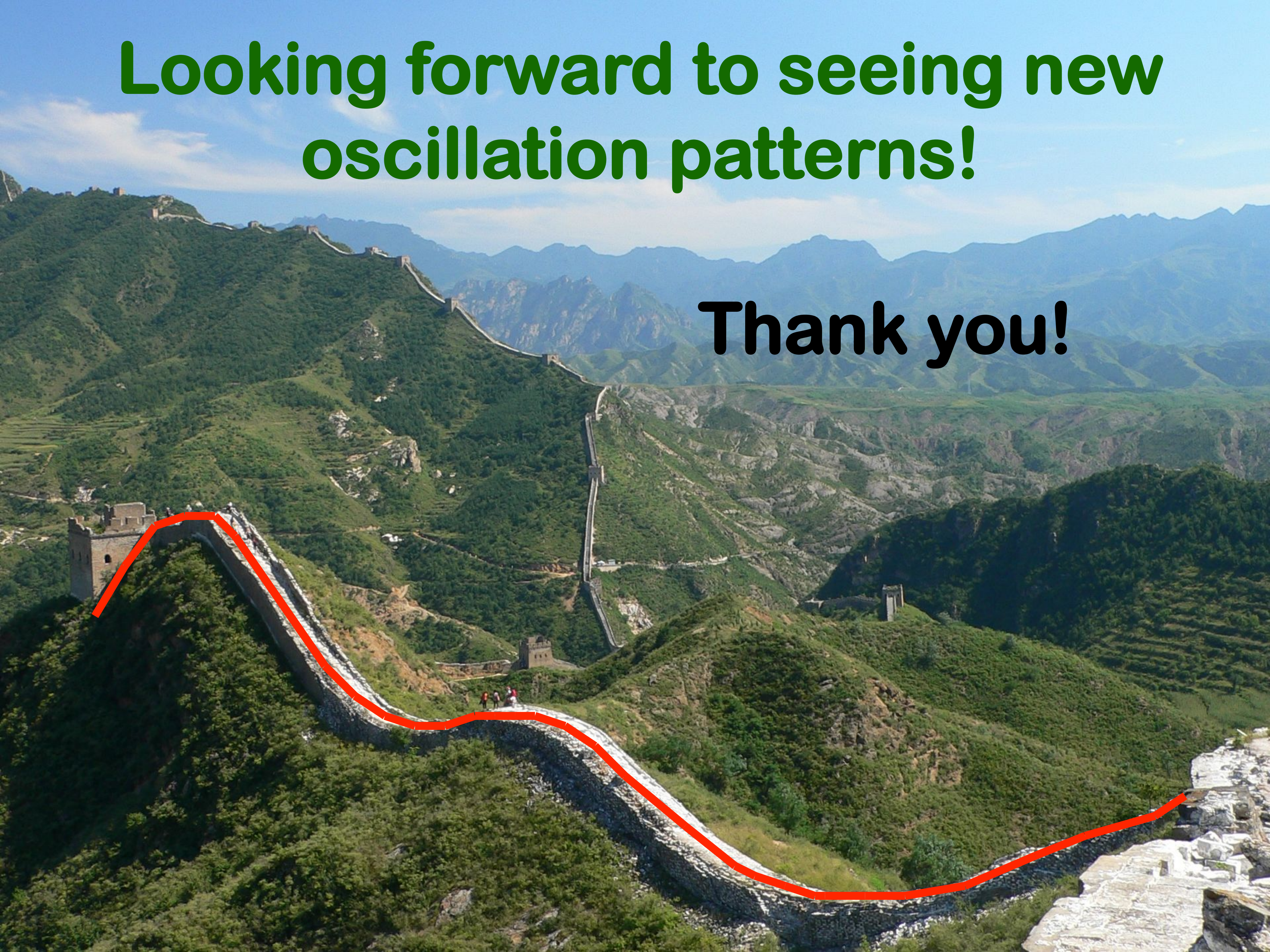


Distinct ellipses (3ν) become overlapping blobs (3+1)

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

Conclusions

- Several SBL anomalies point to sterile neutrinos but the global picture is not clear (internal tension)
- New SBL experiments needed to shed light
- Sterile neutrinos are sources of additional CPV
- LBL experiments sensitive to the new CP-phases
- T2K and NOνA give already interesting information
- Full exploration of 3+1 scheme possible only with LBL
- LBL program complementary to SBN program


Looking forward to seeing new oscillation patterns!
Thank you!

Back up slides

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 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)