Uppsala, 26.09.2017

NuFact 2017

Global neutrino oscillation fits

University of Bari & INFN

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Outline

Introduction

3-flavor fit

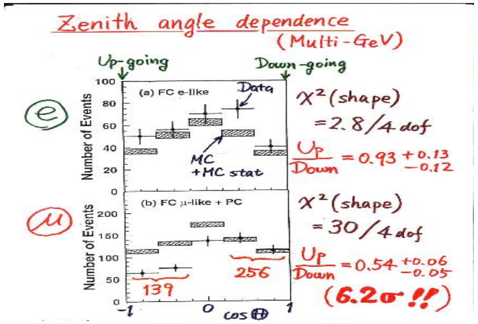
4-flavor fit

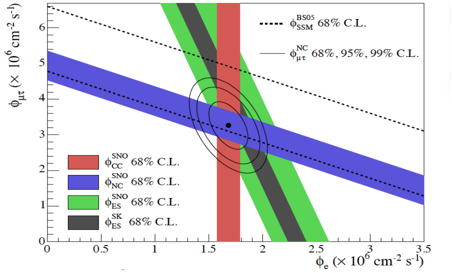
Conclusions

Introduction

Outstanding progress in ν physics in ~ 20 years

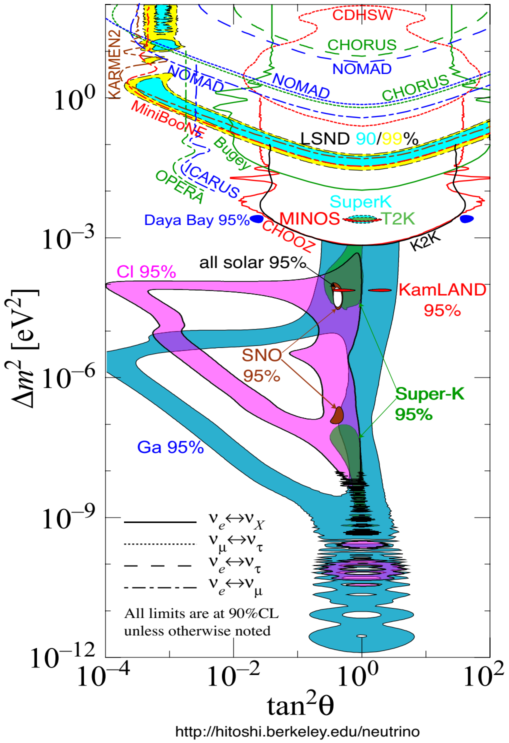
Discoveries





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

Interpretation



http://hitoshi.berkeley.edu/neutrino

known knowns

$\delta m^2/\mathrm{eV}^2$	~ 7.4 x 10^{-5}	±2.3%
$\Delta m^2/\mathrm{eV}^2$	~ 2.5 x 10^{-3}	±1.6%
$\sin^2\theta_{12}$	~ 0.30	±5.8%
$\sin^2\theta_{13}$	~ 0.022	±4.0%
$\sin^2\theta_{23}$	~ 0.5	±9.0%

known unknowns

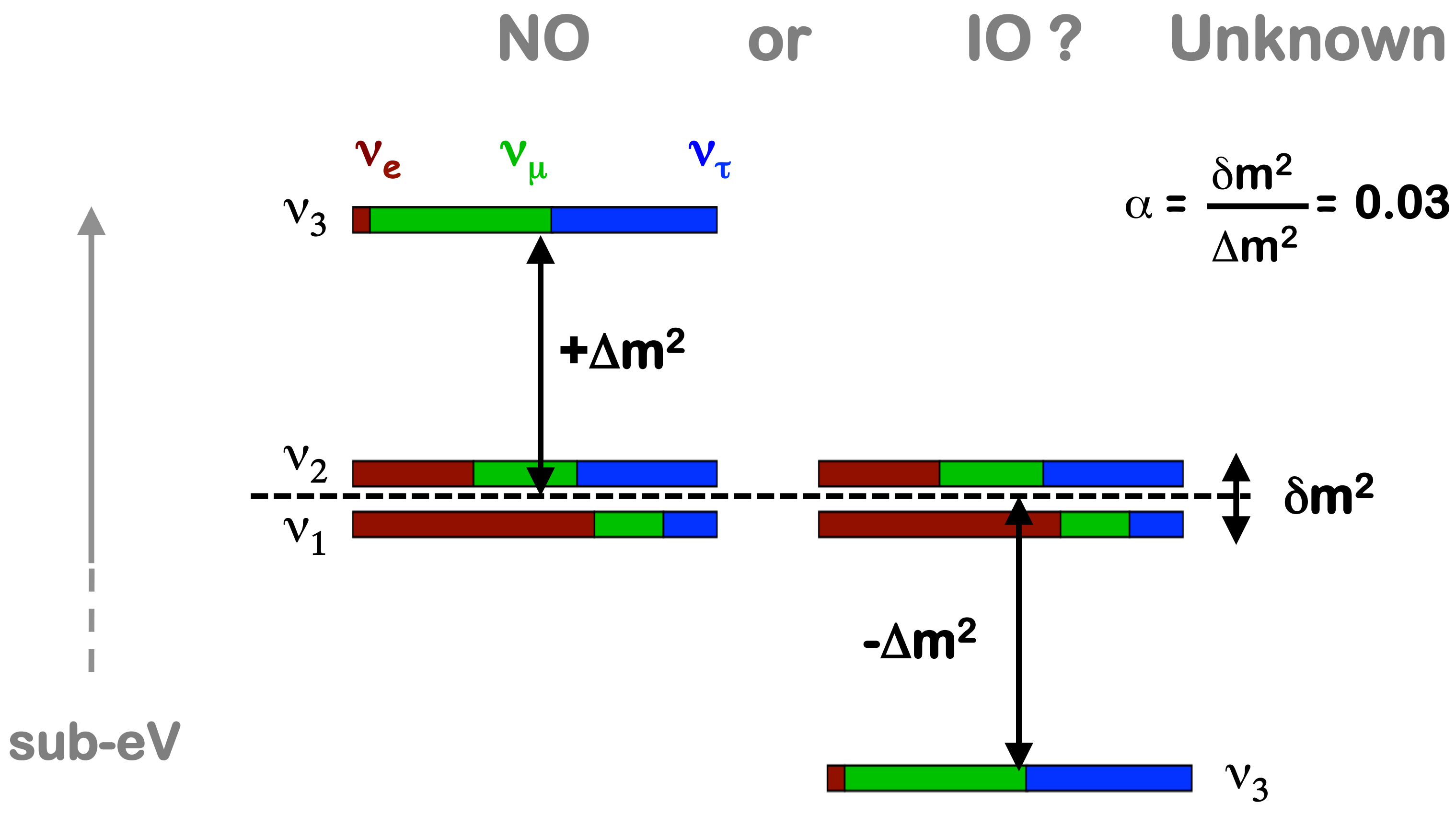
δ(CP)
sign(Δm^2)
octant(θ_{23})
absolute ν mass
Dirac/Majorana

unknown unknowns

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

3-flavor scheme now established as the standard framework…

The 3ν mass spectrum



$$\alpha = \frac{\delta m^2}{\Delta m^2} = 0.03$$

The 3ν mixing matrix

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle \qquad U = O_{23}\Gamma_\delta O_{13}\Gamma^\dagger_\delta O_{12}$$

$$\Gamma_\delta = \mathrm{diag}(1, 1, e^{+i\delta})$$

$$\delta \in [0, 2\pi]$$

Dirac CP-violating phase δ

U is non-real if $\delta \neq (0, \pi)$

Explicit form

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 45^\circ$ $\theta_{13} \sim 9^\circ$ $\theta_{12} \sim 34^\circ$

Three non-zero θ_{ij}: Way open to CPV searches…

CPV is a genuine 3-flavor effect

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

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

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

$$\boxed{J^{ij}_{\alpha\beta} \equiv \mathrm{Im}\,[U_{\alpha i} U_{\beta j} U^*_{\alpha j} U^*_{\beta i}] \equiv J \sum_{\gamma=e,\mu,\tau} \epsilon_{\alpha\beta\gamma} \sum_{k=1,2,3} \epsilon_{ijk}}$$

J is parameterization independent (Jarlskog invariant)

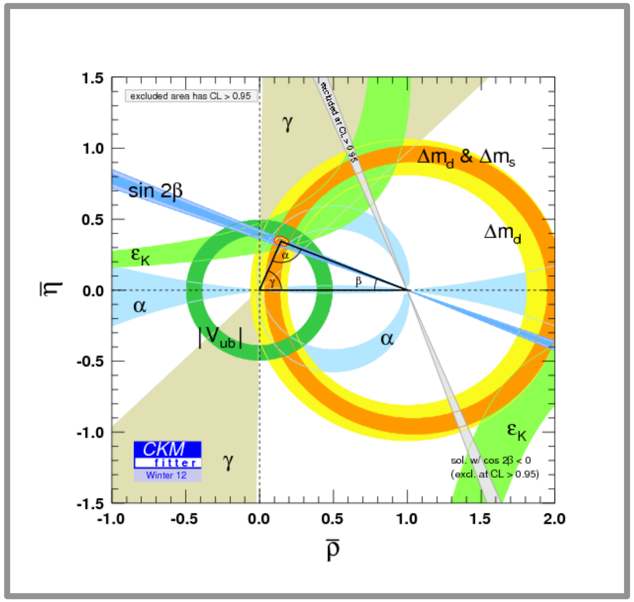
In the standard parameterization:

$$\boxed{J = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta}$$

Conditions for CPV:

- **No degenerate (ν_i,ν_j)** ✔
- **No θ_{ij} = (0, π/2)** ✔
- **δ ≠ (0, π)** **(hints)**

Quarks & Leptons vis-à-vis



In the neutrino sector the precision is much lower than that reached for quarks (albeit is quickly increasing!)

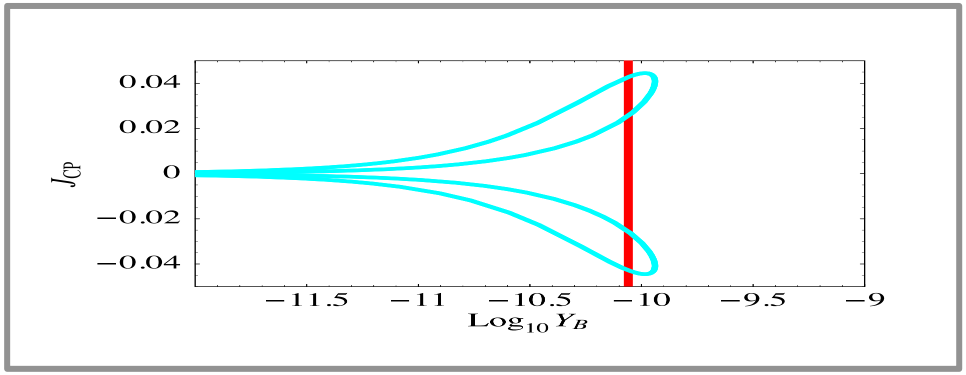
However, chances to discover a large CPV are much bigger…

$$J = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta$$

- **$J_{CKM} \sim 3 \times 10^{-5}$**
- **J_{PMNS} may be as large as 3×10^{-2}**

Implications of a large J_{PMNS}

While it would not prove the leptogenesis mechanism it may have an impact on it



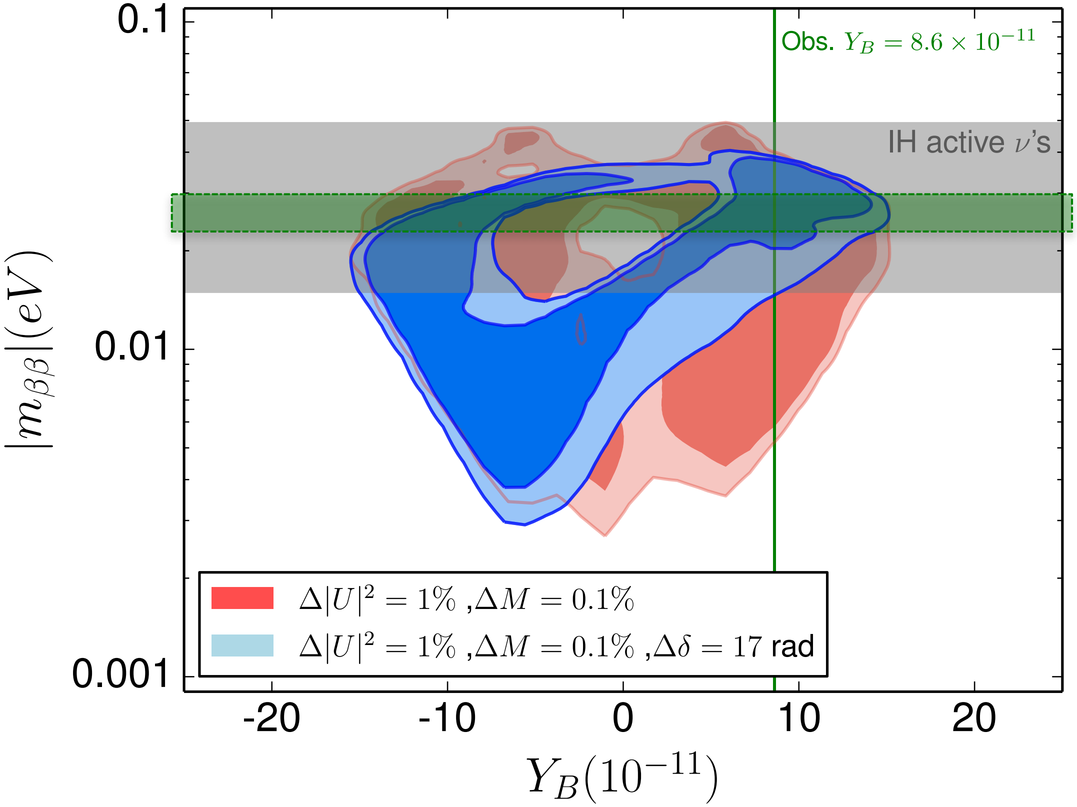
Pascoli, Petcov, Riotto PRD 75 083511 (2007)

The sole δ may suffice to produce the observed amount of baryon asymmetry provided

$|\sin\theta_{13} \sin\delta| > 0.11$

~ 0.15 ↗ ↖ **~ -1.0 (see later)**

Y_B in a minimal seesaw model (M~GeV)



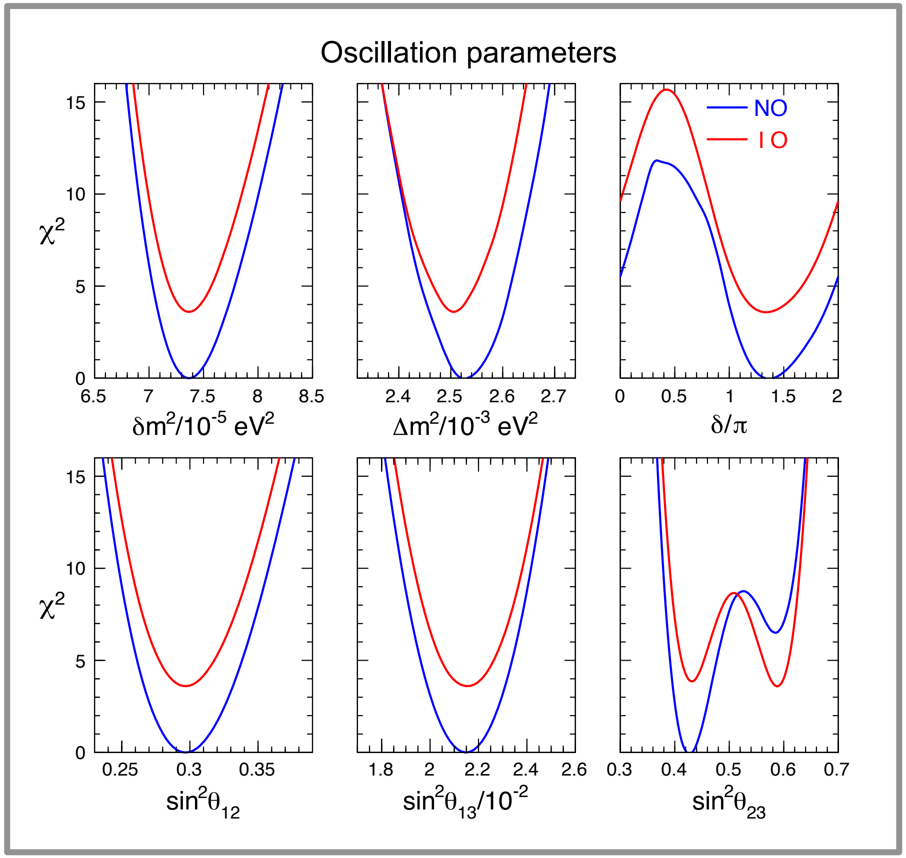
Talk by
P. Hernandez

P. Hernandez et al.
arXiv:1606.06719

Prediction depends also on the value of δ

3-flavor fit

Global 3ν oscillation analysis (2017)



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

NO: Normal Ordering

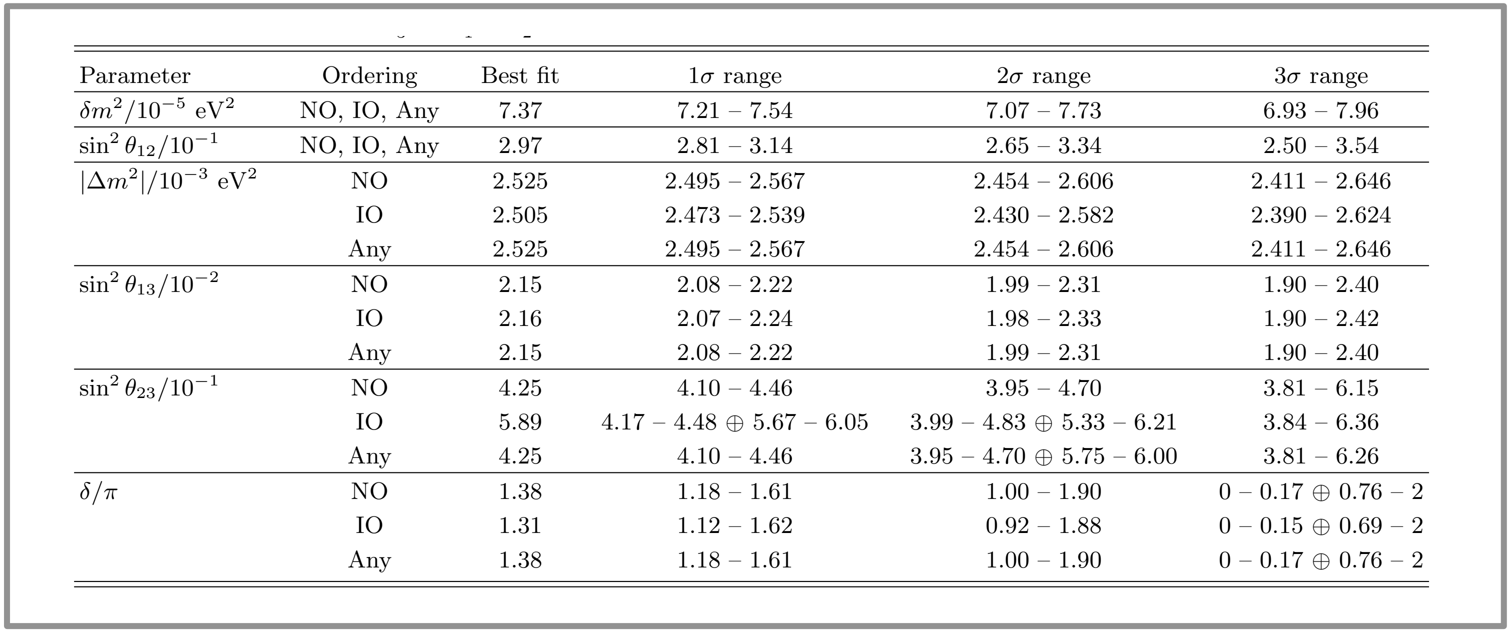
IO: Inverted Ordering

~ 2σ preference for NO

Preference for $\delta \in [\pi, 2\pi]$ ($\sin\delta < 0$)

Octant of θ_{23}
- lower in NO
- no preference in IO

Estimates of the 3-flavor parameters



Parameter	Ordering	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2	NO, IO, Any	7.37	7.21 – 7.54	7.07 – 7.73	6.93 – 7.96
$\sin^2\theta_{12}/10^{-1}$	NO, IO, Any	2.97	2.81 – 3.14	2.65 – 3.34	2.50 – 3.54
$\|\Delta m^2\|/10^{-3}$ eV^2	NO	2.525	2.495 – 2.567	2.454 – 2.606	2.411 – 2.646
	IO	2.505	2.473 – 2.539	2.430 – 2.582	2.390 – 2.624
	Any	2.525	2.495 – 2.567	2.454 – 2.606	2.411 – 2.646
$\sin^2\theta_{13}/10^{-2}$	NO	2.15	2.08 – 2.22	1.99 – 2.31	1.90 – 2.40
	IO	2.16	2.07 – 2.24	1.98 – 2.33	1.90 – 2.42
	Any	2.15	2.08 – 2.22	1.99 – 2.31	1.90 – 2.40
$\sin^2\theta_{23}/10^{-1}$	NO	4.25	4.10 – 4.46	3.95 – 4.70	3.81 – 6.15
	IO	5.89	4.17 – 4.48 ⊕ 5.67 – 6.05	3.99 – 4.83 ⊕ 5.33 – 6.21	3.84 – 6.36
	Any	4.25	4.10 – 4.46	3.95 – 4.70 ⊕ 5.75 – 6.00	3.81 – 6.26
δ/π	NO	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 ⊕ 0.76 – 2
	IO	1.31	1.12 – 1.62	0.92 – 1.88	0 – 0.15 ⊕ 0.69 – 2
	Any	1.38	1.18 – 1.61	1.00 – 1.90	0 – 0.17 ⊕ 0.76 – 2

Best estimates and fractional errors (defined as 1/6 of ±3σ ranges):

$\delta m^2/\mathrm{eV}^2$	~ 7.4×10^{-5}	±2.3%
$\Delta m^2/\mathrm{eV}^2$	~ 2.5×10^{-3}	±1.6%
$\sin^2\theta_{12}$	~ 0.30	±5.8%
$\sin^2\theta_{13}$	~ 0.022	±4.0%
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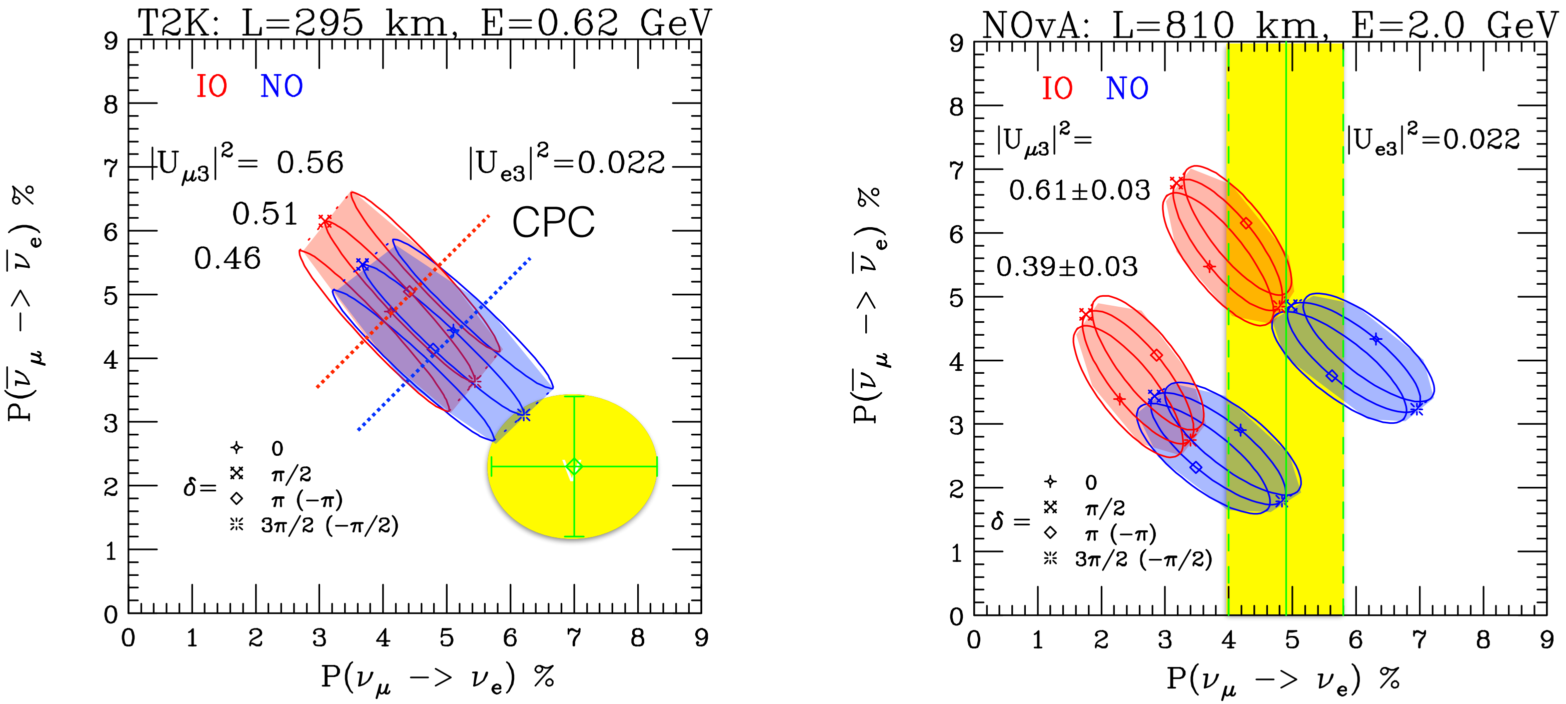
How the hints of CPV & MH arise (1)

T2K and NOνA biprobability plots

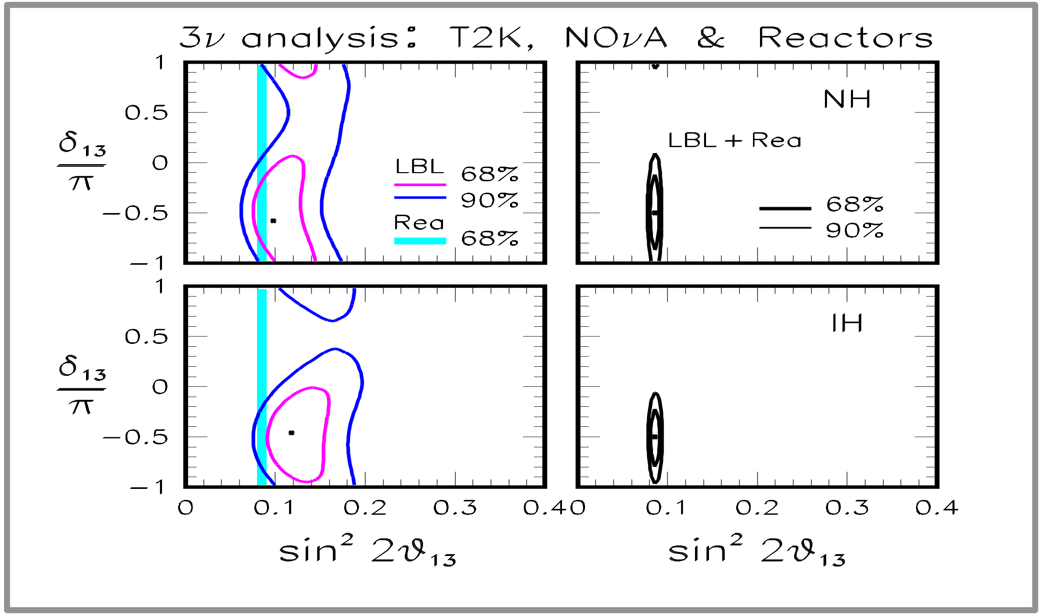


S. Parke @ Invisibles 2016

Experimental data closer to δ = -π/2 and NO

Numerical analysis of T2K and NOνA

T2K (ν_e+$\bar{\nu}_e$) & **NOνA** (ν_e)

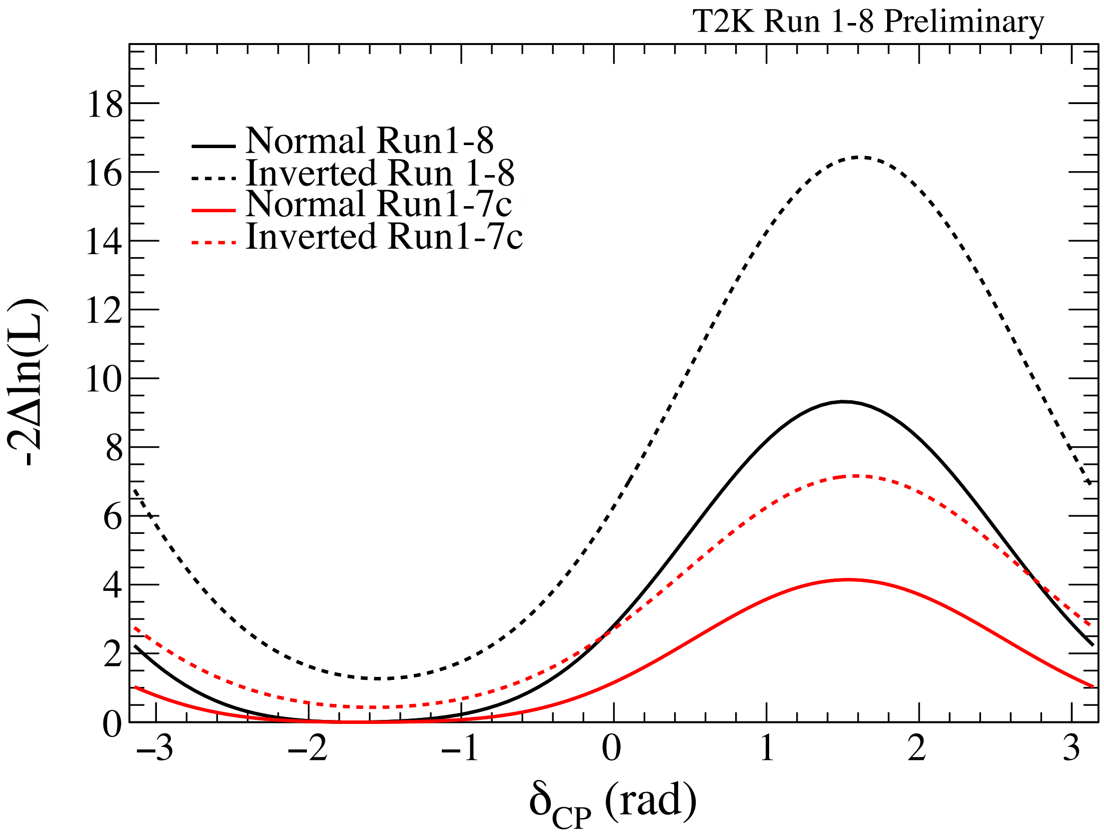


A.P., PLB 757 142-147 (2016) arXiv: 1509.03148

- Preference for CPV in T2K+NOνA
- Reinforced when T2K+NOνA are combined with Reactors
- IH slightly disfavored because of LBL-REA tension

Latest T2K data confirm the trend

M. Hartz,
KEK Colloquium,
August 4, 2017

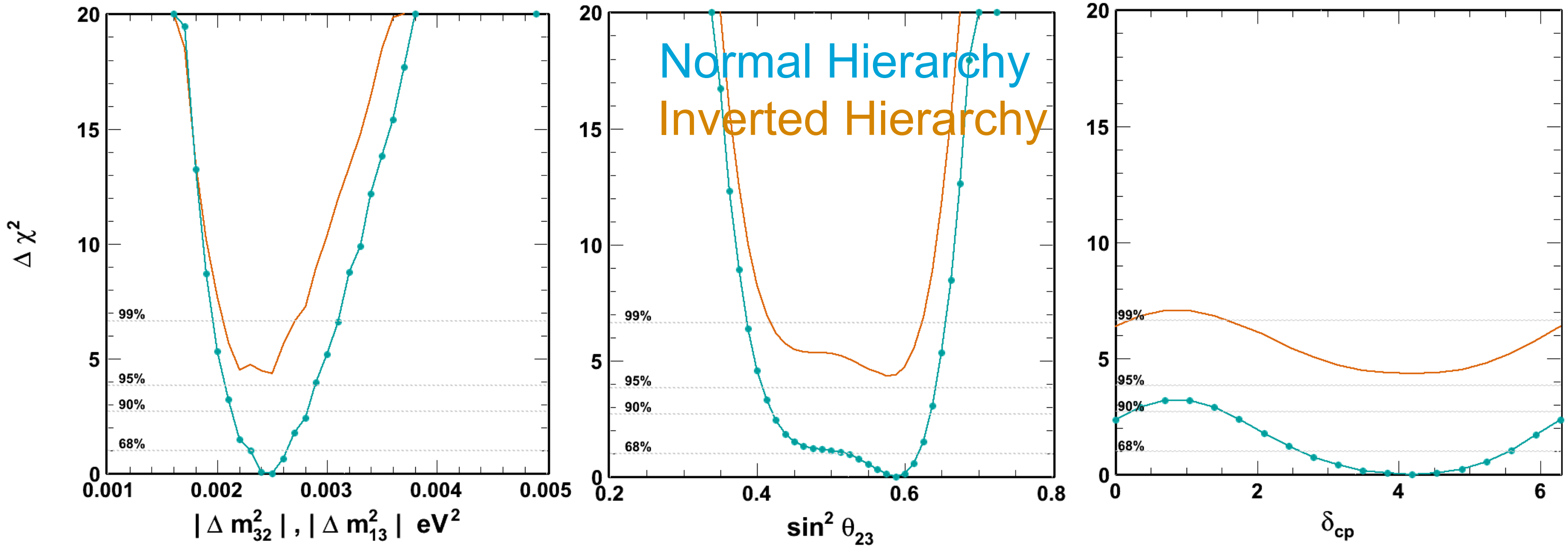


Summer 2017

Summer 2016
(no CC1π sample)

How the hints of CPV & MH arise (2)

SK atmospheric neutrinos

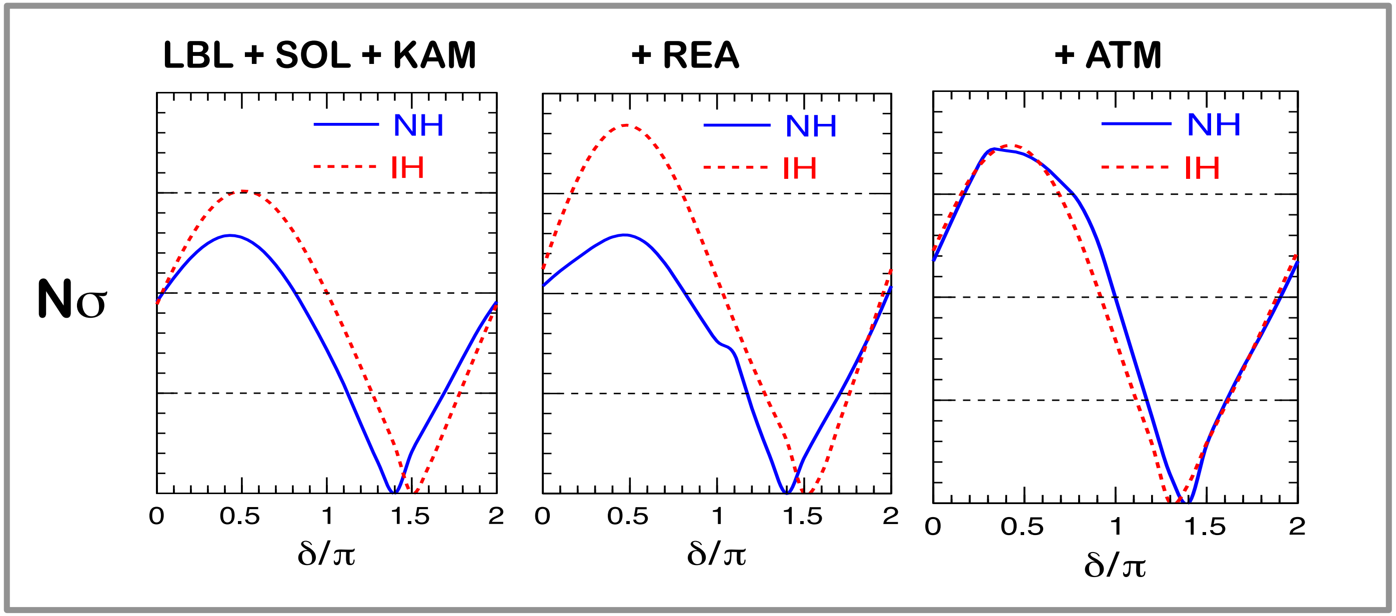


Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ eV^2
SK (IH)	576.08	0.0219 (fix)	4.189	0.575	2.5×10^{-3}
SK (NH)	571.74	0.0219 (fix)	4.189	0.587	2.5×10^{-3}

- Mass hierarchy: $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -4.3$ (-3.1 expected)

M. Shiozawa @ NeuTel 2017

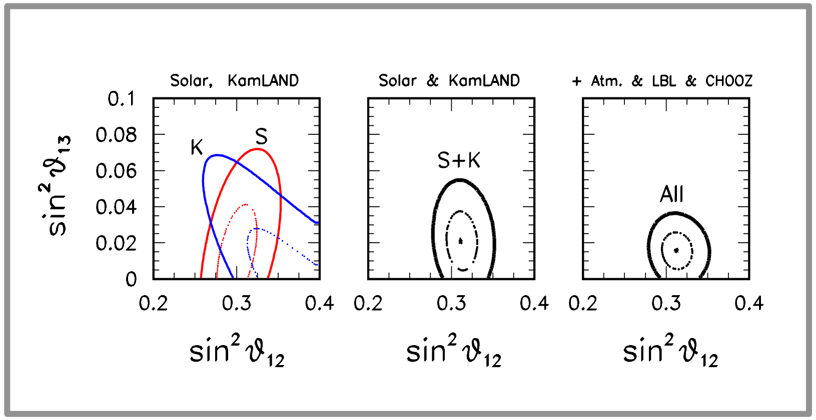
CPV indication reinforced for increasingly rich data set



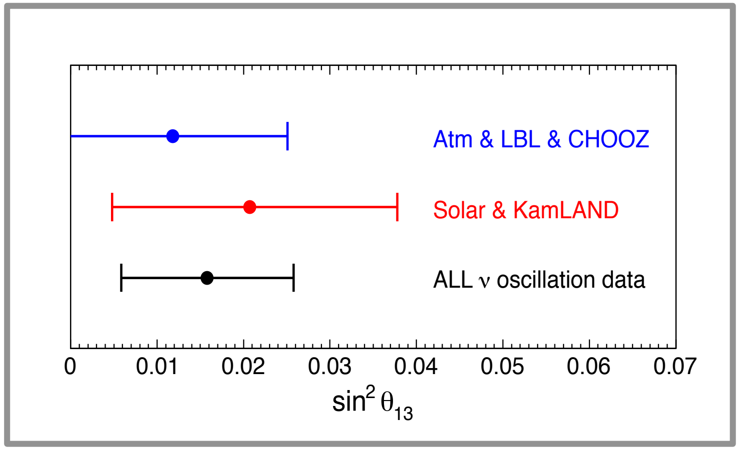
Supplementary to PRD 95, 096014 (2017) arXiv:1703.04471

This is a good sign!...

A déjà vu: First hints of θ_{13}>0



Fogli, Lisi, Marrone, A.P., Rotunno,
Phys. Rev. Lett. (2008)



Also in that case we had two weak but converging hints

The same story may be repeated with δ !

4-flavor fit

Beyond the standard picture

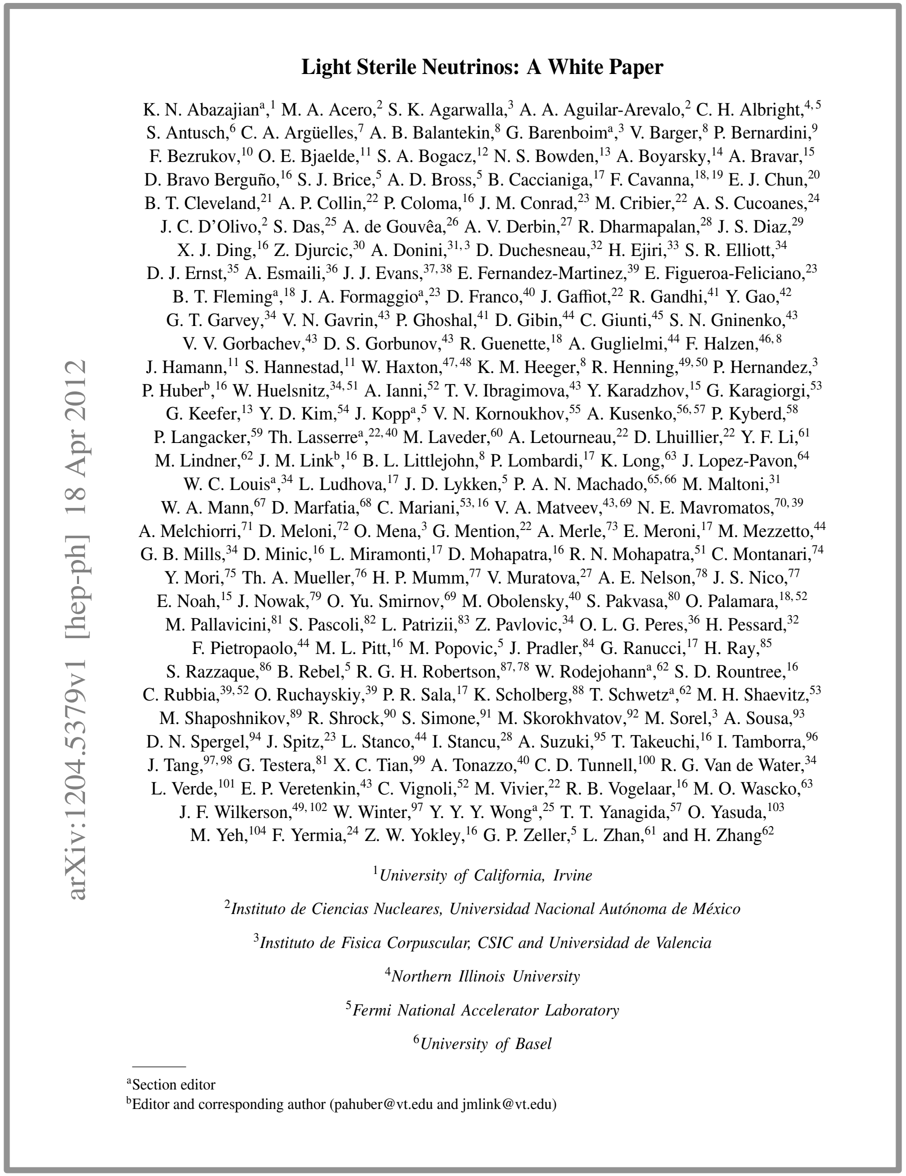
Many extensions of the Standard Model predict new effects in neutrino oscillations

An incomplete list:

✓
- **Light sterile neutrinos**
- **Non standard neutrino interactions (NSI)**
- **Non unitarity of the PMNS matrix**
- **Long-range forces**
- **Lorentz and CPT violations**
- **Quantum decoherence …**

Light sterile neutrinos

Wide interest in the scientific community



arXiv:1204.5379v1 [hep-ph] 18 Apr 2012

Light Sterile Neutrinos: A White Paper

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V. V. Gorbachev,[43] D. S. Gorbunov,[43] R. Guenette,[18] A. Guglielmi,[44] F. Halzen,[46,8]
J. Hamann,[11] S. Hannestad,[11] W. Haxton,[47,48] K. M. Heeger,[8] R. Henning,[49,50] P. Hernandez,[3]
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G. Keefer,[13] Y. D. Kim,[54] J. Kopp[a],[5] V. N. Kornoukhov,[55] A. Kusenko,[56,57] P. Kyberd,[58]
P. Langacker,[59] Th. Lasserre[a],[22,40] M. Laveder,[60] A. Letourneau,[22] D. Lhuillier,[22] Y. F. Li,[61]
M. Lindner,[62] J. M. Link[b],[16] B. L. Littlejohn,[8] P. Lombardi,[17] K. Long,[63] J. Lopez-Pavon,[64]
W. C. Louis[a],[34] L. Ludhova,[17] J. D. Lykken,[5] P. A. N. Machado,[65,66] M. Maltoni,[31]
W. A. Mann,[67] D. Marfatia,[68] C. Mariani,[53,16] V. A. Matveev,[43,69] N. E. Mavromatos,[70,39]
A. Melchiorri,[71] D. Meloni,[72] O. Mena,[3] G. Mention,[22] A. Merle,[73] E. Meroni,[17] M. Mezzetto,[44]
G. B. Mills,[34] D. Minic,[16] L. Miramonti,[17] D. Mohapatra,[16] R. N. Mohapatra,[51] C. Montanari,[74]
Y. Mori,[75] Th. A. Mueller,[76] H. P. Mumm,[77] V. Muratova,[27] A. E. Nelson,[78] J. S. Nico,[77]
E. Noah,[15] J. Nowak,[79] O. Yu. Smirnov,[69] M. Obolensky,[40] S. Pakvasa,[80] O. Palamara,[18,52]
M. Pallavicini,[81] S. Pascoli,[82] L. Patrizii,[83] Z. Pavlovic,[34] O. L. G. Peres,[36] H. Pessard,[32]
F. Pietropaolo,[44] M. L. Pitt,[16] M. Popovic,[5] J. Pradler,[84] G. Ranucci,[17] H. Ray,[85]
S. Razzaque,[86] B. Rebel,[5] R. G. H. Robertson,[87,78] W. Rodejohann[a],[62] S. D. Rountree,[16]
C. Rubbia,[39,52] O. Ruchayskiy,[39] P. R. Sala,[17] K. Scholberg,[88] T. Schwetz[a],[62] M. H. Shaevitz,[53]
M. Shaposhnikov,[89] R. Shrock,[90] S. Simone,[91] M. Skorokhvatov,[92] M. Sorel,[3] A. Sousa,[93]
D. N. Spergel,[94] J. Spitz,[23] L. Stanco,[44] I. Stancu,[28] A. Suzuki,[95] T. Takeuchi,[16] I. Tamborra,[96]
J. Tang,[97,98] G. Testera,[81] X. C. Tian,[99] A. Tonazzo,[40] C. D. Tunnell,[100] R. G. Van de Water,[34]
L. Verde,[101] E. P. Veretenkin,[43] C. Vignoli,[52] M. Vivier,[22] R. B. Vogelaar,[16] M. O. Wascko,[63]
J. F. Wilkerson,[49,102] W. Winter,[97] Y. Y. Y. Wong[a],[25] T. T. Yanagida,[57] O. Yasuda,[103]
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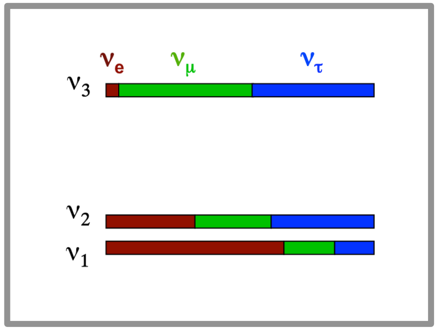
How to enlarge the 3-flavor scheme

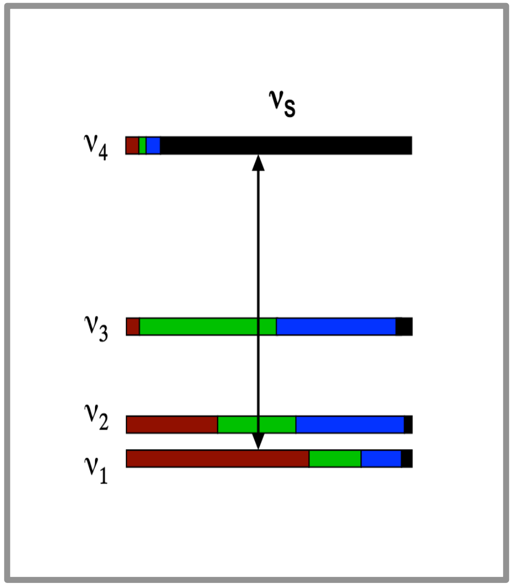
3+1 scheme

3ν scheme

Δm^2_{atm}

Δm^2_{sol}





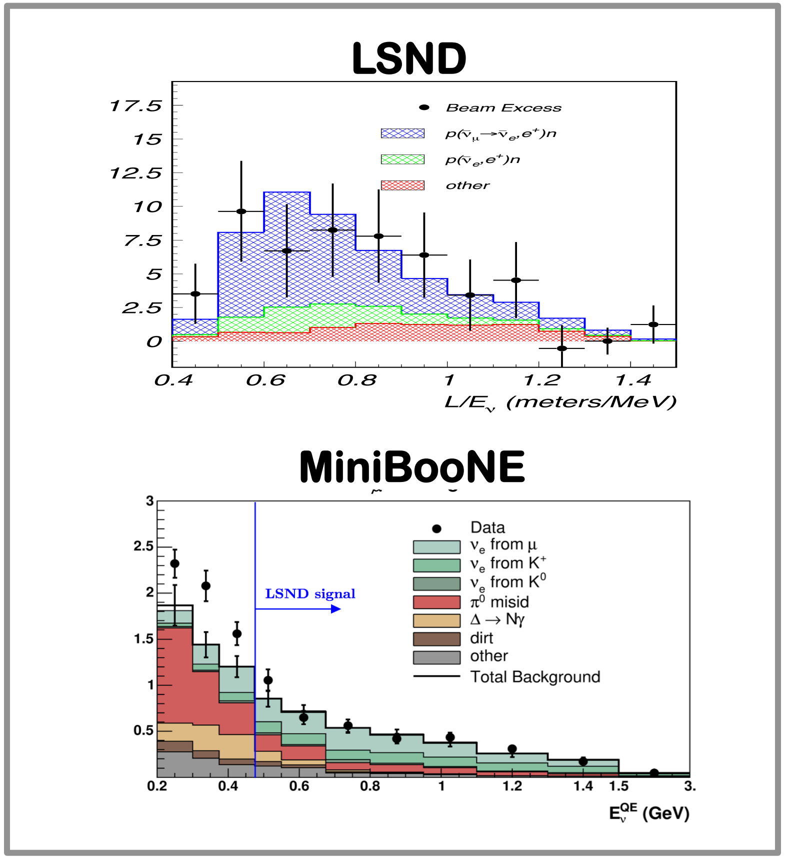
$|U_{s4}| \sim 1$

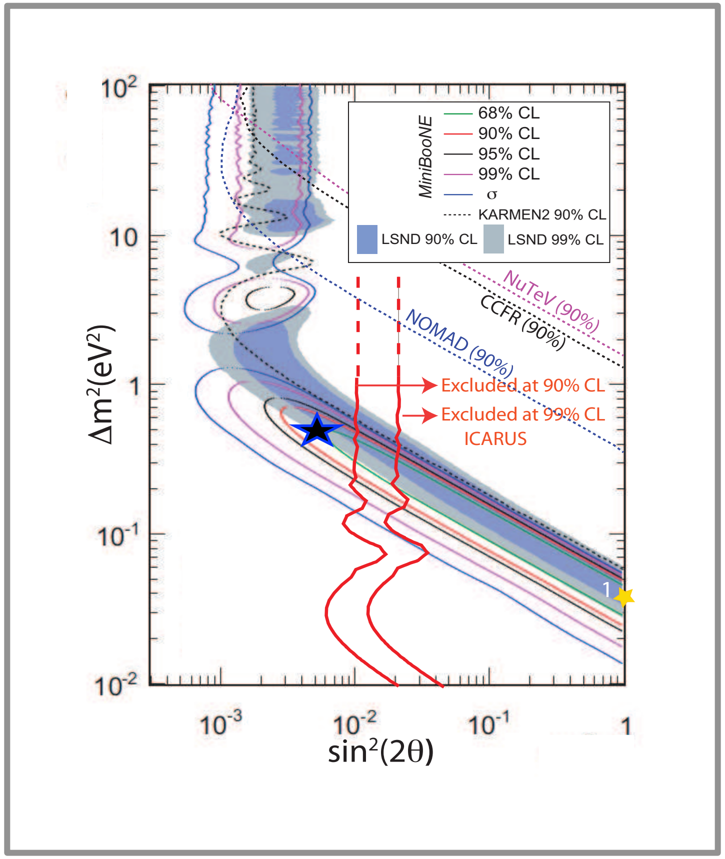
$\Delta m^2_{14} \sim 1\ \mathrm{eV}^2$

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

1) The SBL accelerator anomalies

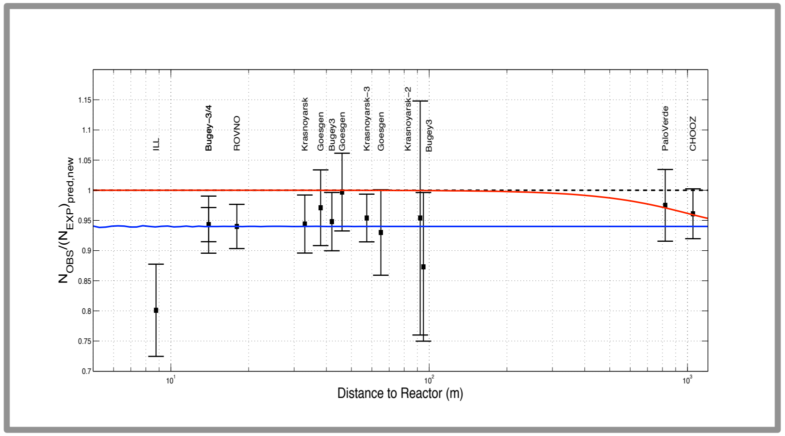
(unexplained ν_e appearance in a ν_μ beam)



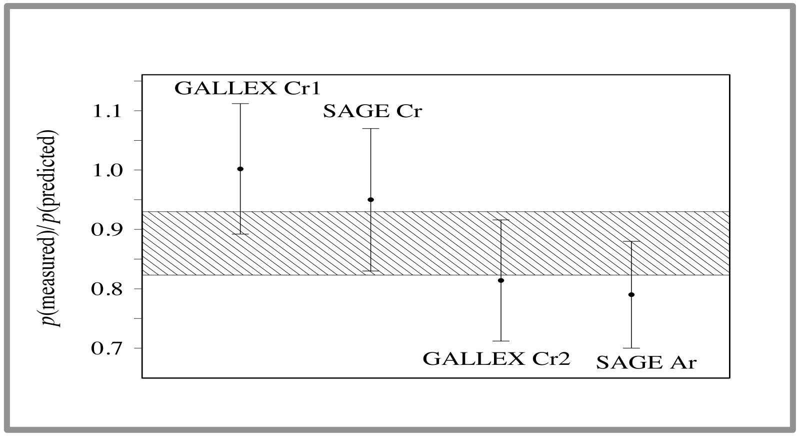


2) The reactor and gallium anomalies

(unexplained ν_e disappearance)



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

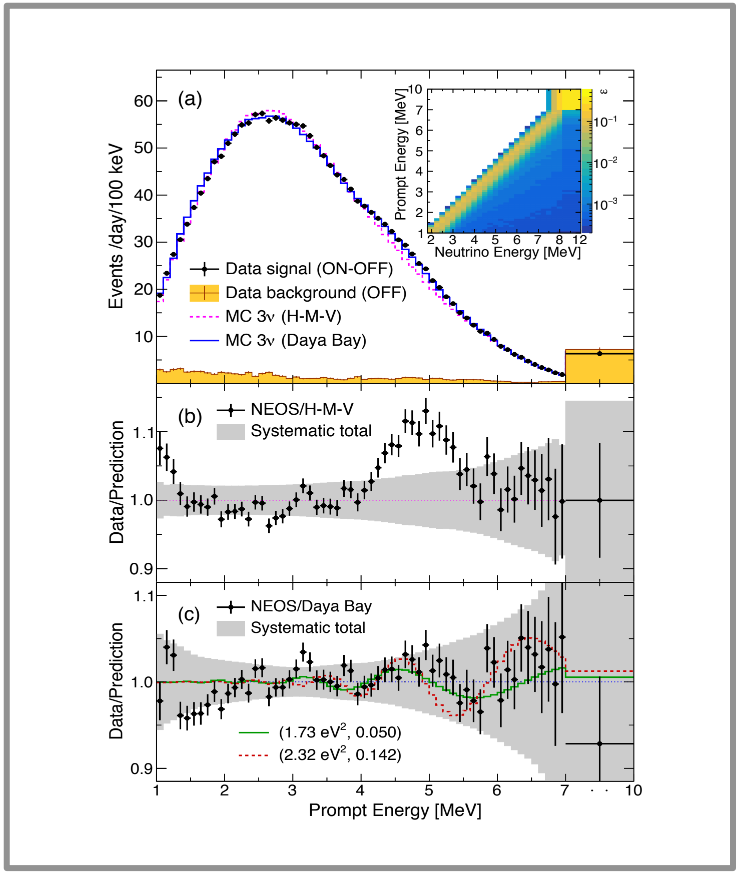


SAGE coll., PRC 73 (2006) 045805

Warning: both are mere normalization issues

The culprit may be hidden in unknown systematics

3) NEOS: a new hint of sterile neutrinos?



NEOS arXiv:1610:05134

Hanbit Nuclear Power Complex, Korea

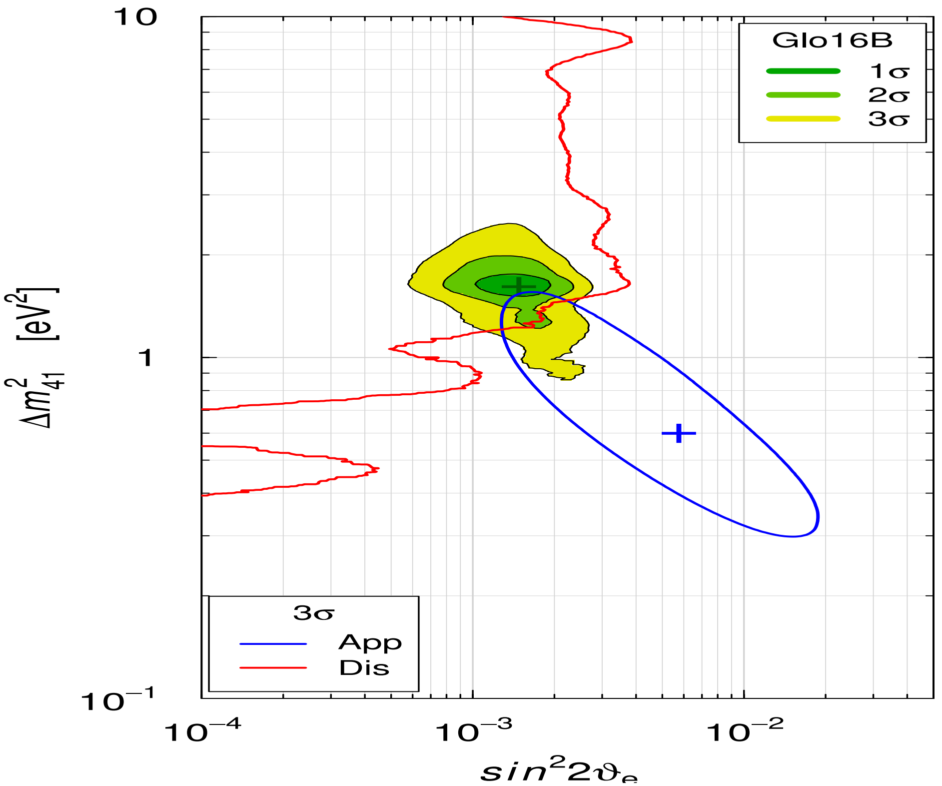
Detector: 1 ton Gd-loaded liquid scintillator 24 m from the reactor core

Daya-Bay absolute spectrum used as a normalization

Oscillating pattern visible after normalization

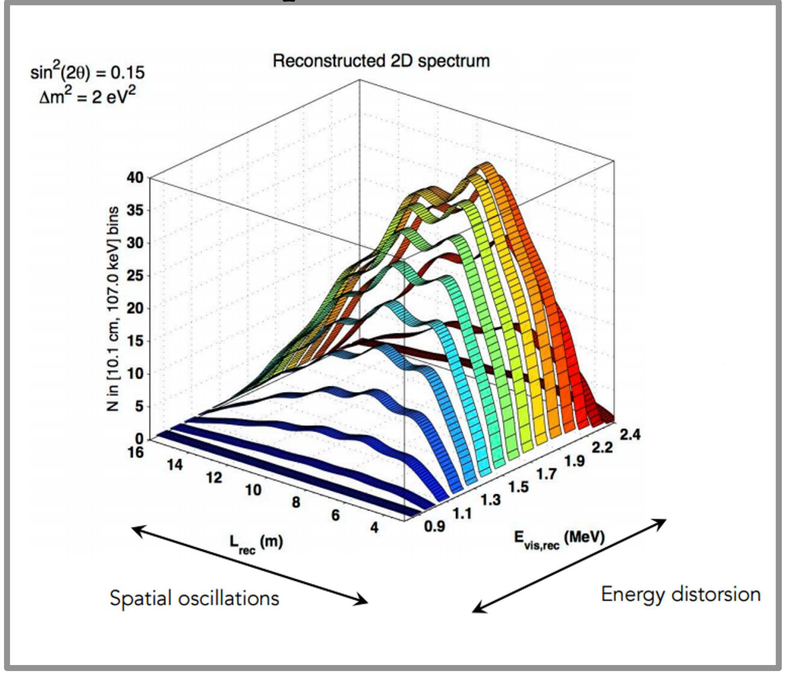
Global SBL data fit in the 3+1 scheme

Gariazzo et al. arXiv:1703.00860

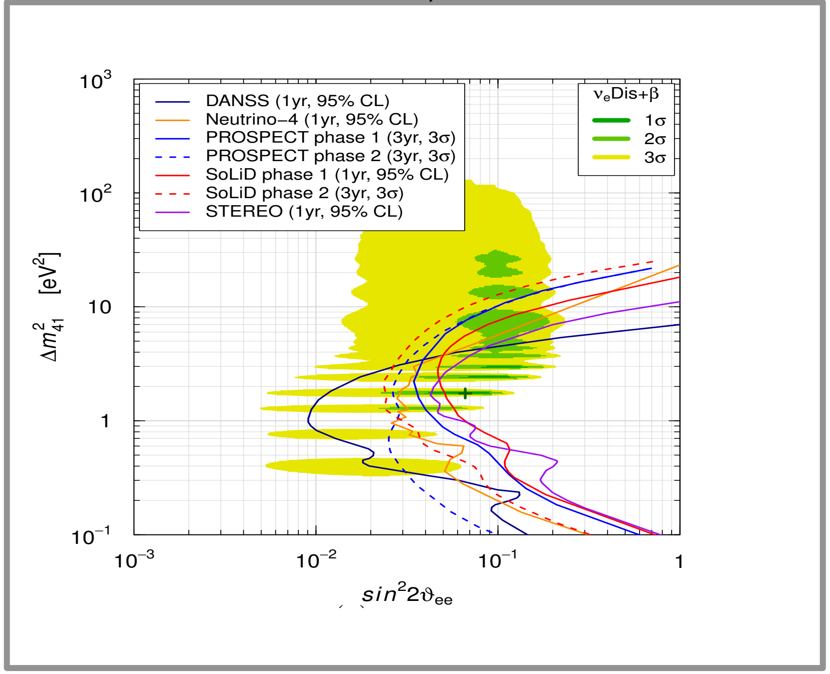


The smoking gun

SOX experiment @ LNGS



Gariazzo et al., 1703.00860



Observation of the oscillation pattern at SBL experiments

Many projects are under consideration

But sterile neutrinos are not just a SBL "affair"…

An intrinsic limitation of SBL

At SBL atm/sol oscillations are negligible

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

$$\boxed{\begin{array}{l}\Delta_{12} \simeq 0 \\ \Delta_{13} \simeq 0\end{array}}$$

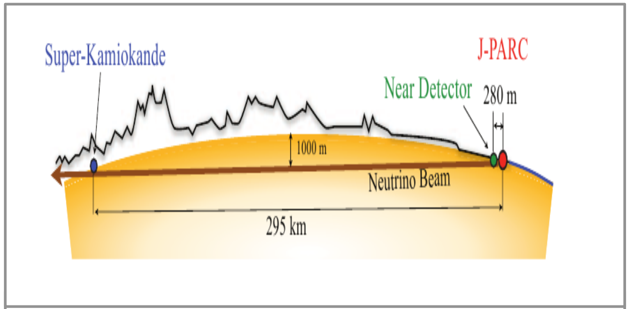
$$\boxed{\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}}$$

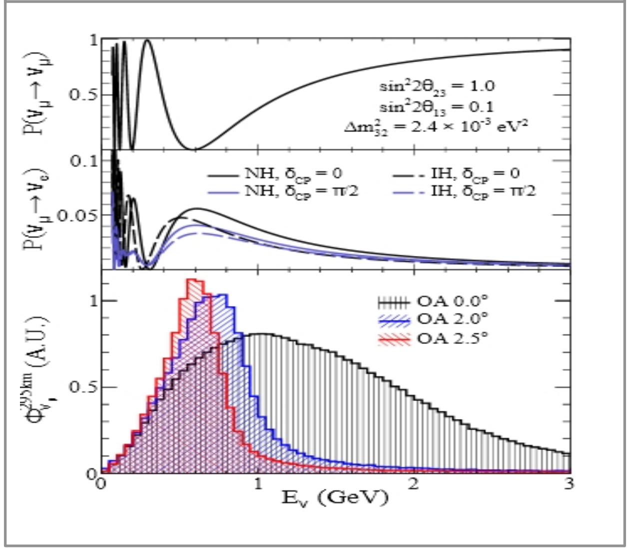
Impossible to observe phenomena of interference between the new frequency ($\Delta_{14} \sim 1$) and atm/sol ones

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

LBL Experiments: T2K & NOνA

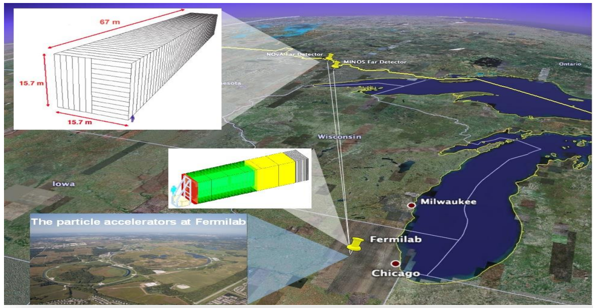


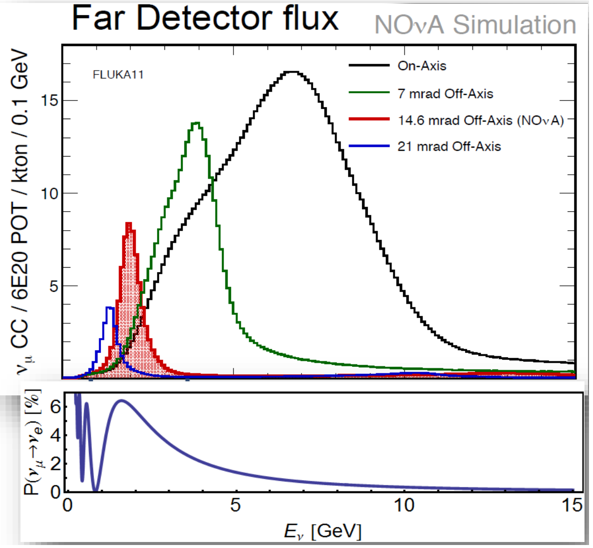


off-axis beam

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

First oscillation maximum





E = 0.6 GeV

L = 295 km

E = 2 GeV

L = 810 km

LBL transition probability in 3-flavor

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

in vacuum:

$$\begin{aligned} P^{\mathrm{ATM}} &= 4 s_{23}^2 s_{13}^2 \sin^2 \Delta \\ P^{\mathrm{SOL}} &= 4 c_{12}^2 c_{23}^2 s_{12}^2 (\alpha \Delta)^2 \\ P^{\mathrm{INT}} &= 8 s_{23} s_{13} c_{12} c_{23} s_{12} (\alpha \Delta) \sin \Delta \cos(\Delta \boxed{+ \delta_{CP})} \end{aligned}$$

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

$\Delta \sim \pi/2$

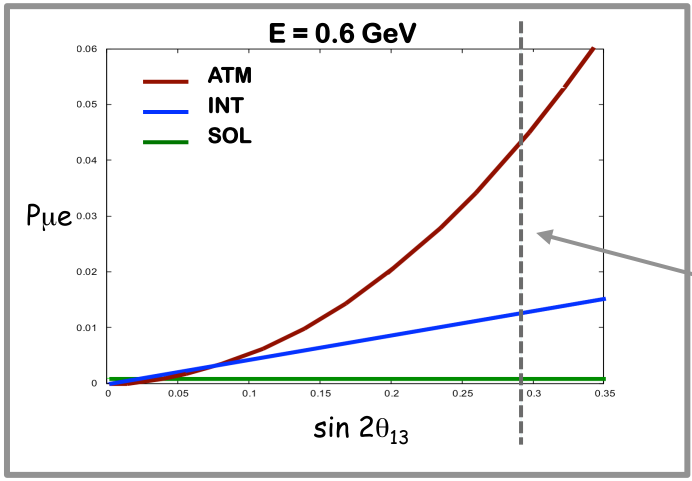
$\alpha \sim 0.03$

P^{ATM} leading → $\theta_{13} > 0$

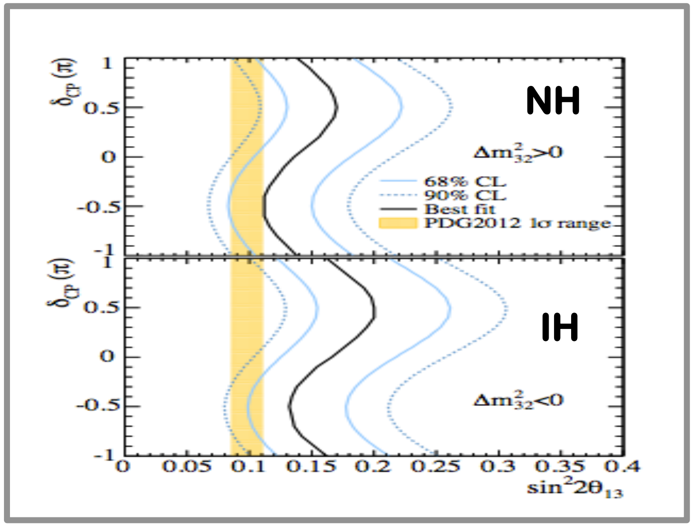
P^{INT} subleading → dependency on δ

P^{SOL} negligible

Matter effects break NH-IH degeneracy



best θ_{13} estimate



Sterile νs bring new CPV sources

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

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

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

$$\begin{aligned} s_{ij} &= \sin\theta_{ij} \\ c_{ij} &= \cos\theta_{ij} \\ \tilde{s}_{ij} &= s_{ij} e^{\boxed{-i\delta_{ij}}} \end{aligned}$$

$$3\nu \left\{ \begin{array}{l} \text{3 mixing angles} \\ \text{1 Dirac phases} \\ \text{2 Majorana phases} \end{array} \right. \qquad 3+1 \left\{ \begin{array}{l} 6 \\ 3 \\ 3 \end{array} \right. \qquad 3+N \left\{ \begin{array}{l} 3+3N \\ 1+2N \\ 2+N \end{array} \right.$$

Invisible at SBL but visible at LBL experiments…

A new interference term in the 3+1 scheme

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

- Δ_{14} >> 1 : fast oscillations are averaged out

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

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

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

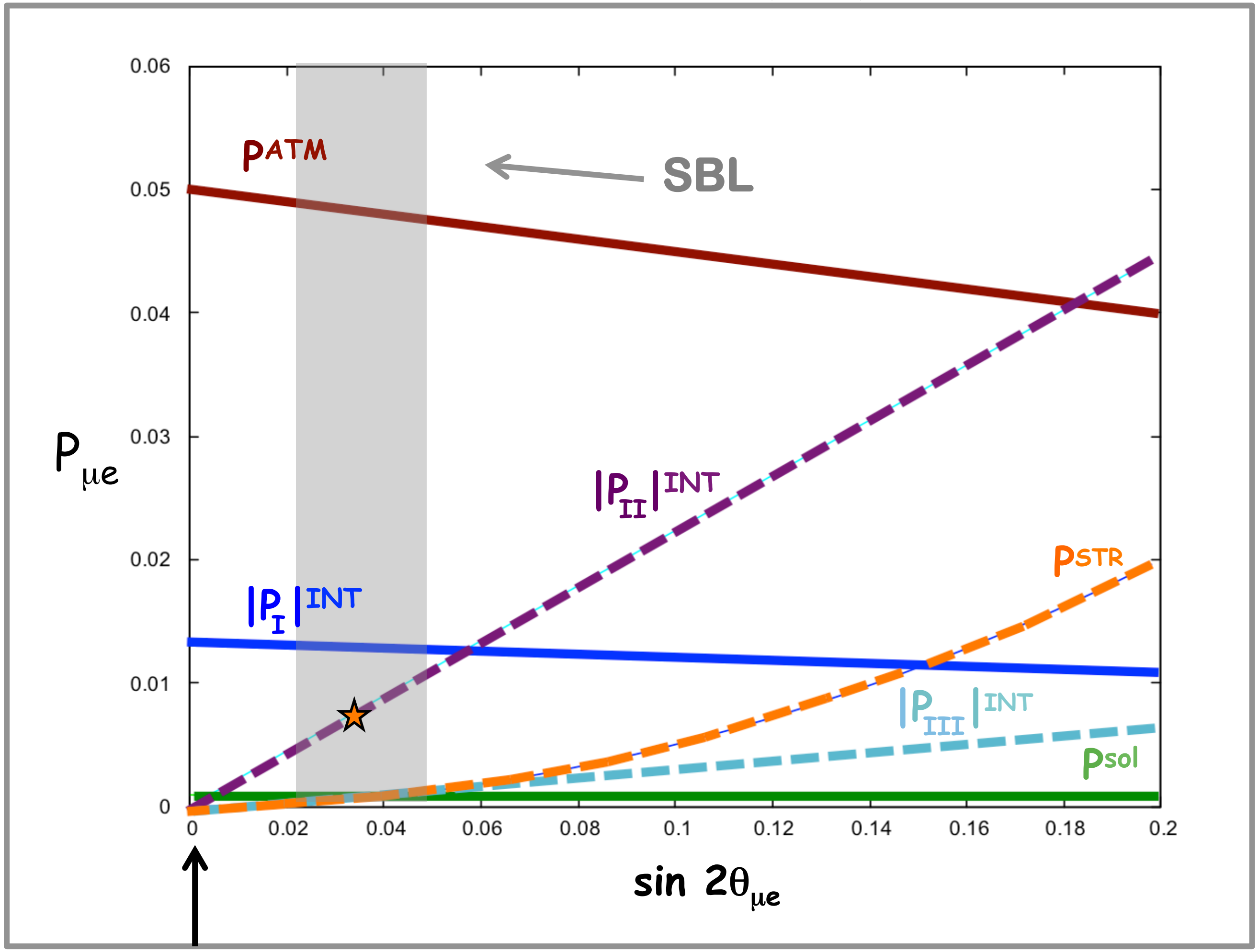
$\alpha = \delta m^2/\Delta m^2 \sim 0.03 \sim \varepsilon^2$

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

Sensitivity to the new CP-phase δ_{14}

Amplitude of the new interference term

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

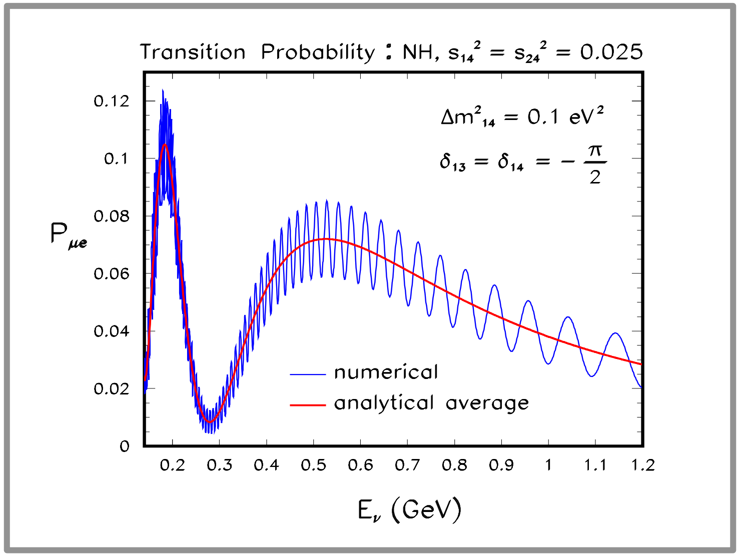


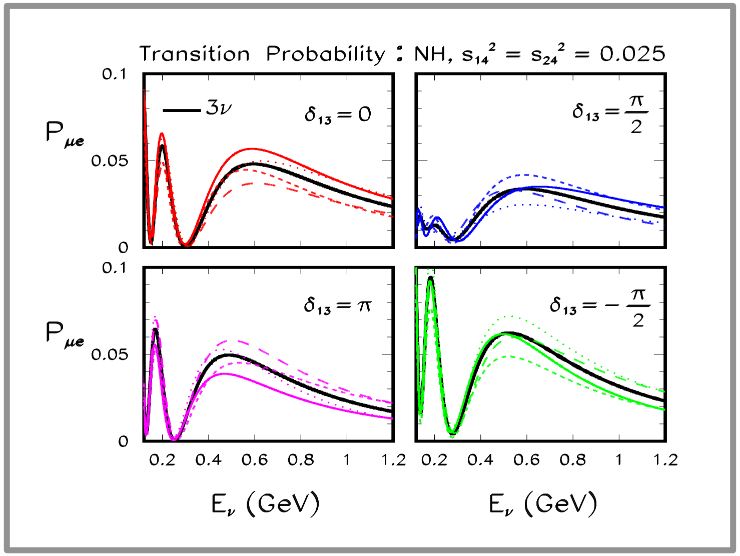
3ν limit

T2K
$\theta_{13} = 9^{o}$
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

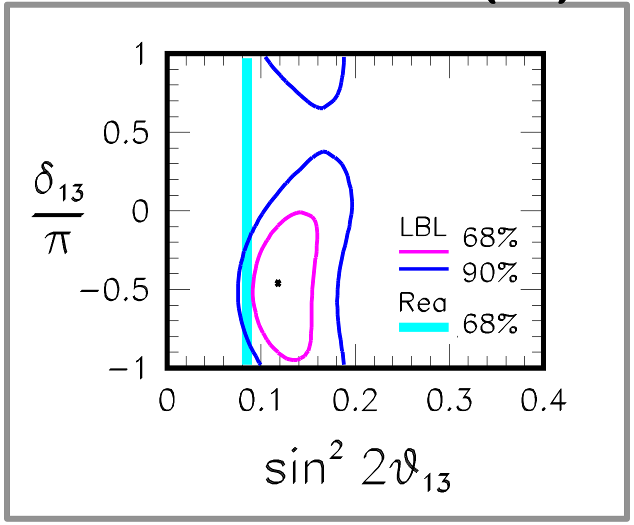
Different line styles
⇔
Different values of δ_{14}

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

Consequences…

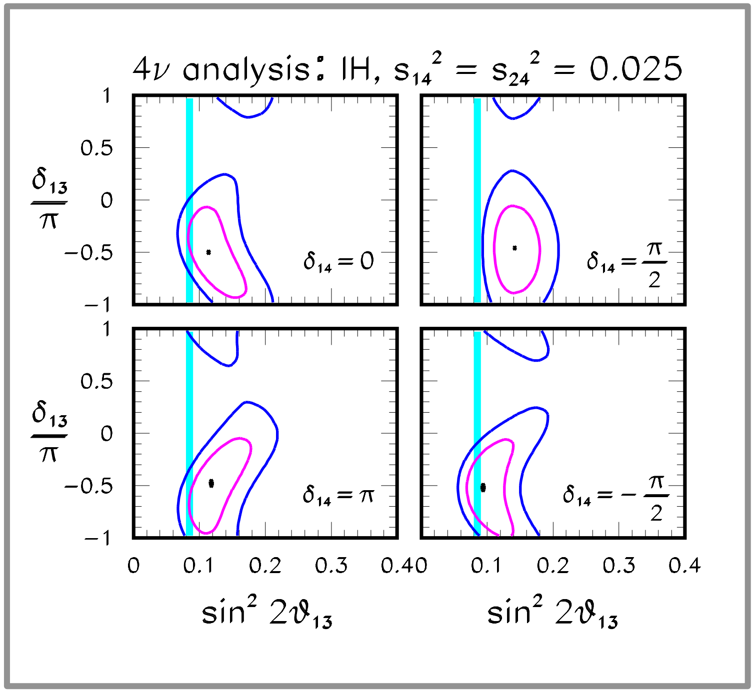
LBL constraints change in the 3+1 scheme

3ν: T2K + NOνA (IO)



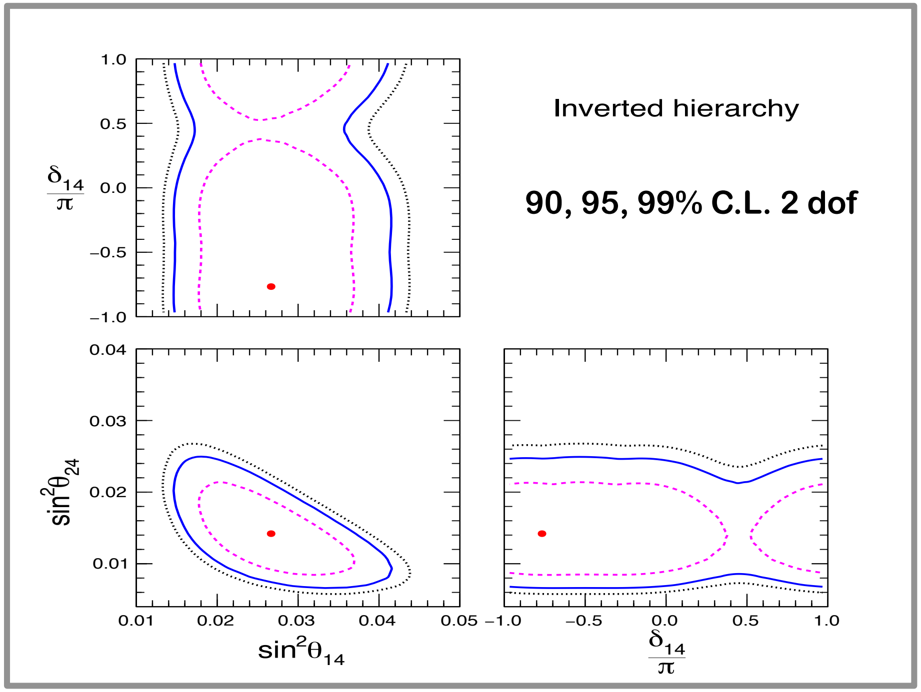
A.P., PLB 757, 142 (2016) arXiv:1509.03148

4ν



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

SBL + LBL



SBL (all available data)

(Icecube and NEOS not included in this analysis)

LBL ≡ T2K + NOνA

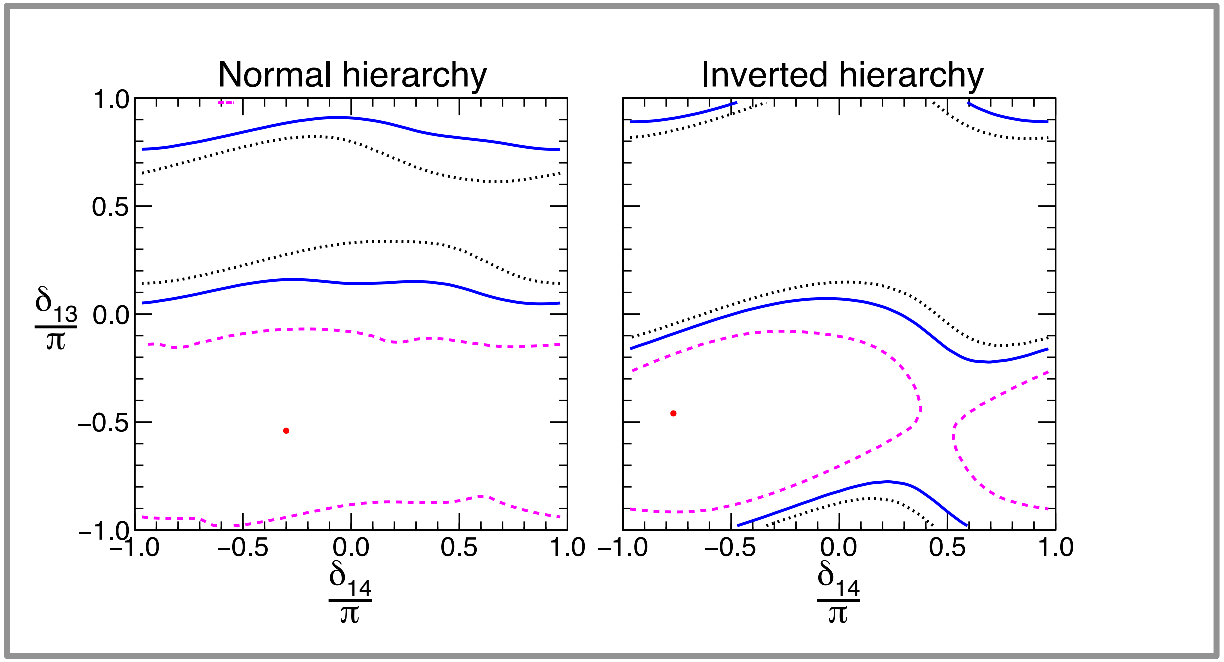
(Neutrino 2016 data)

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

- $[\theta_{14}, \theta_{24}]$ determined by SBL experiments
- δ_{14} constrained by LBL experiments

Constraints on the two CP-phases

SBL + LBL



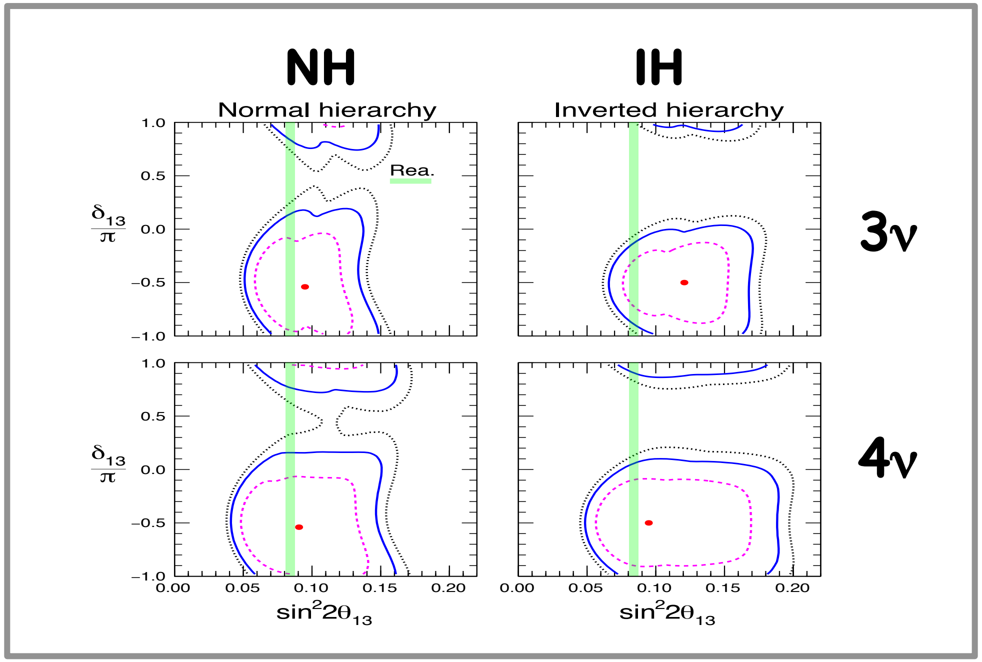
- δ_{13} **is more constrained than** δ_{14}

- **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



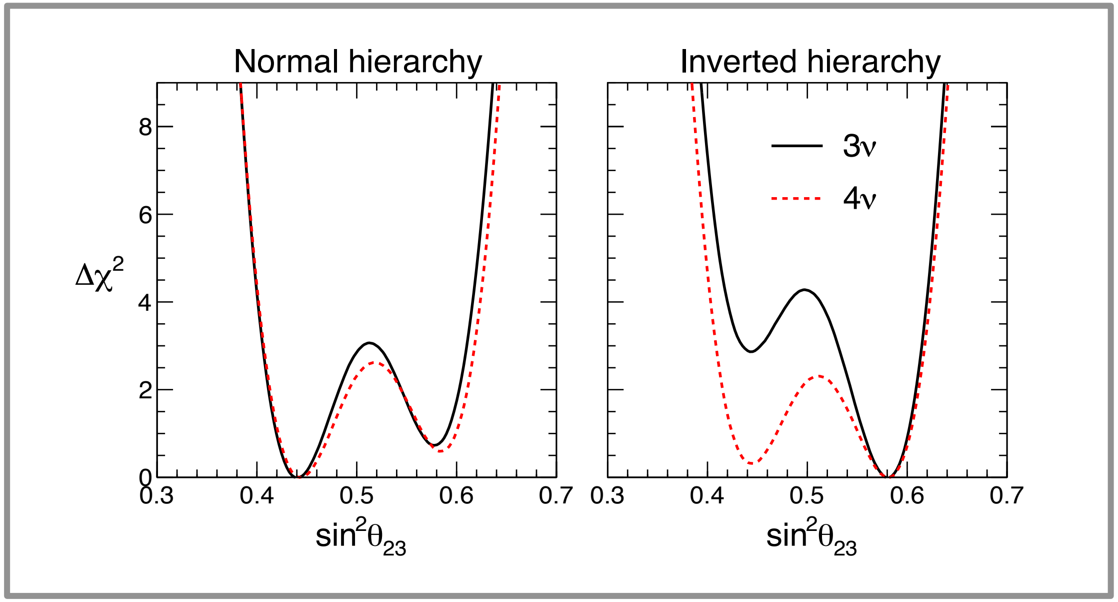
- **Allowed range for θ_{13} from LBL alone gets enlarged**

- **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



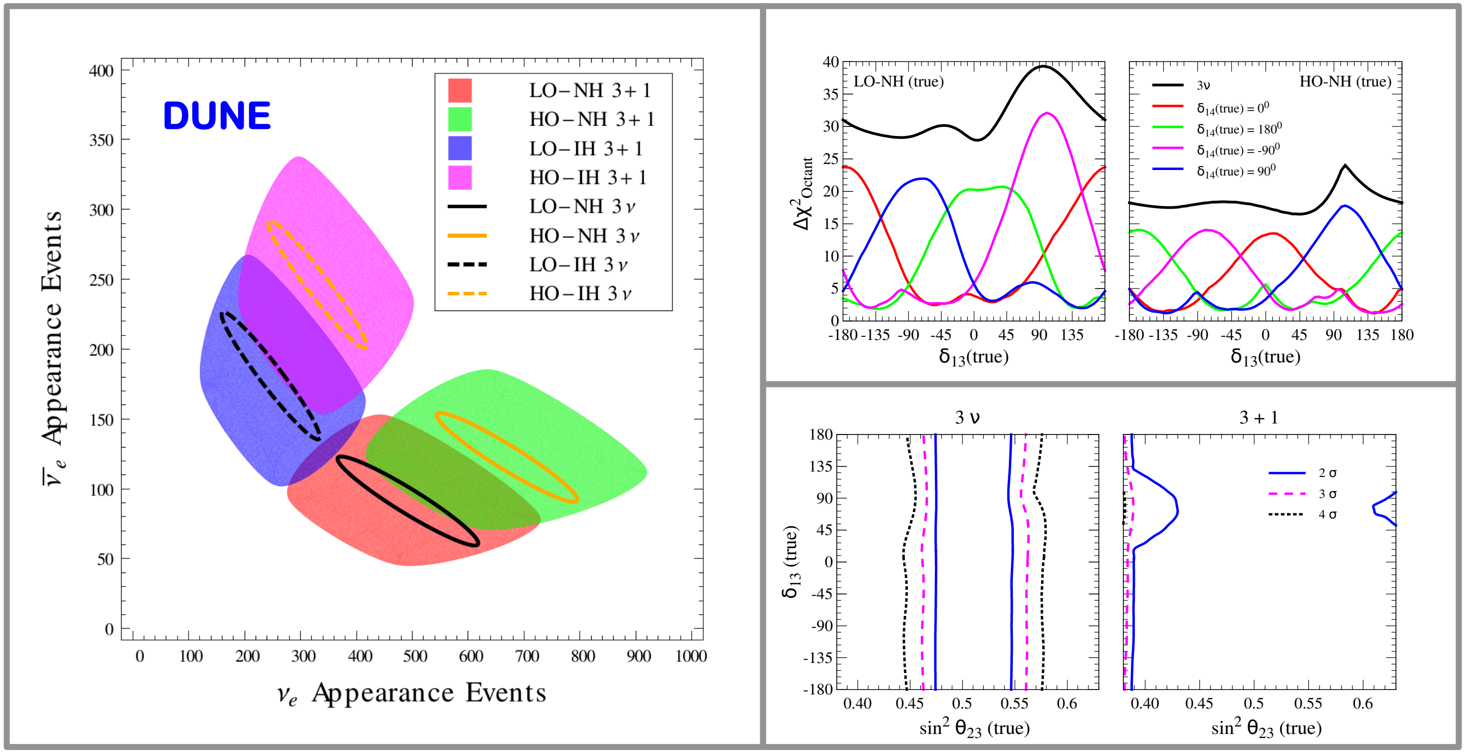
Indication for non-maximal θ_{23} persists in 3+1 scheme

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

Octant fragility seems to be a general feature…

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

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

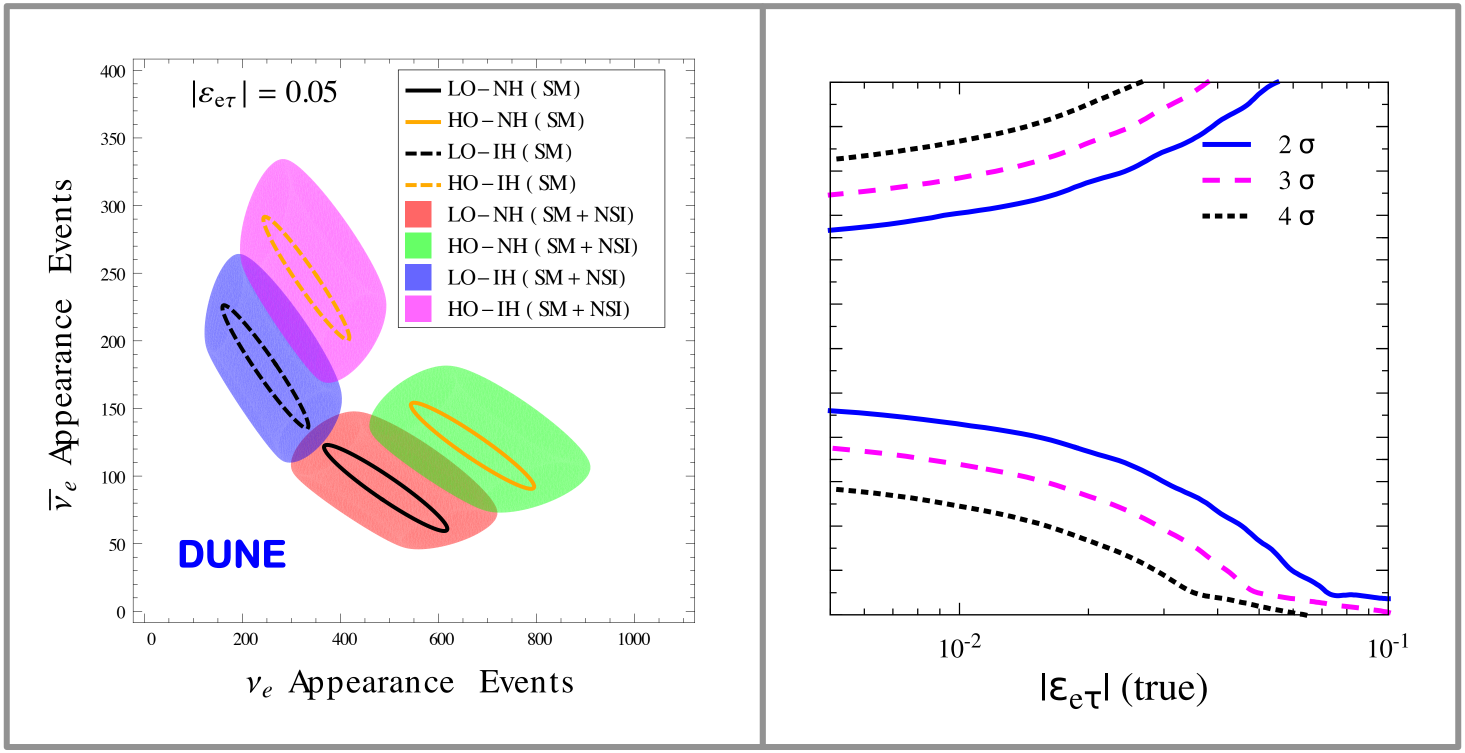


Distinct ellipses (3ν) become overlapping blobs (3+1)

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

Striking analogy between steriles and NSIs

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

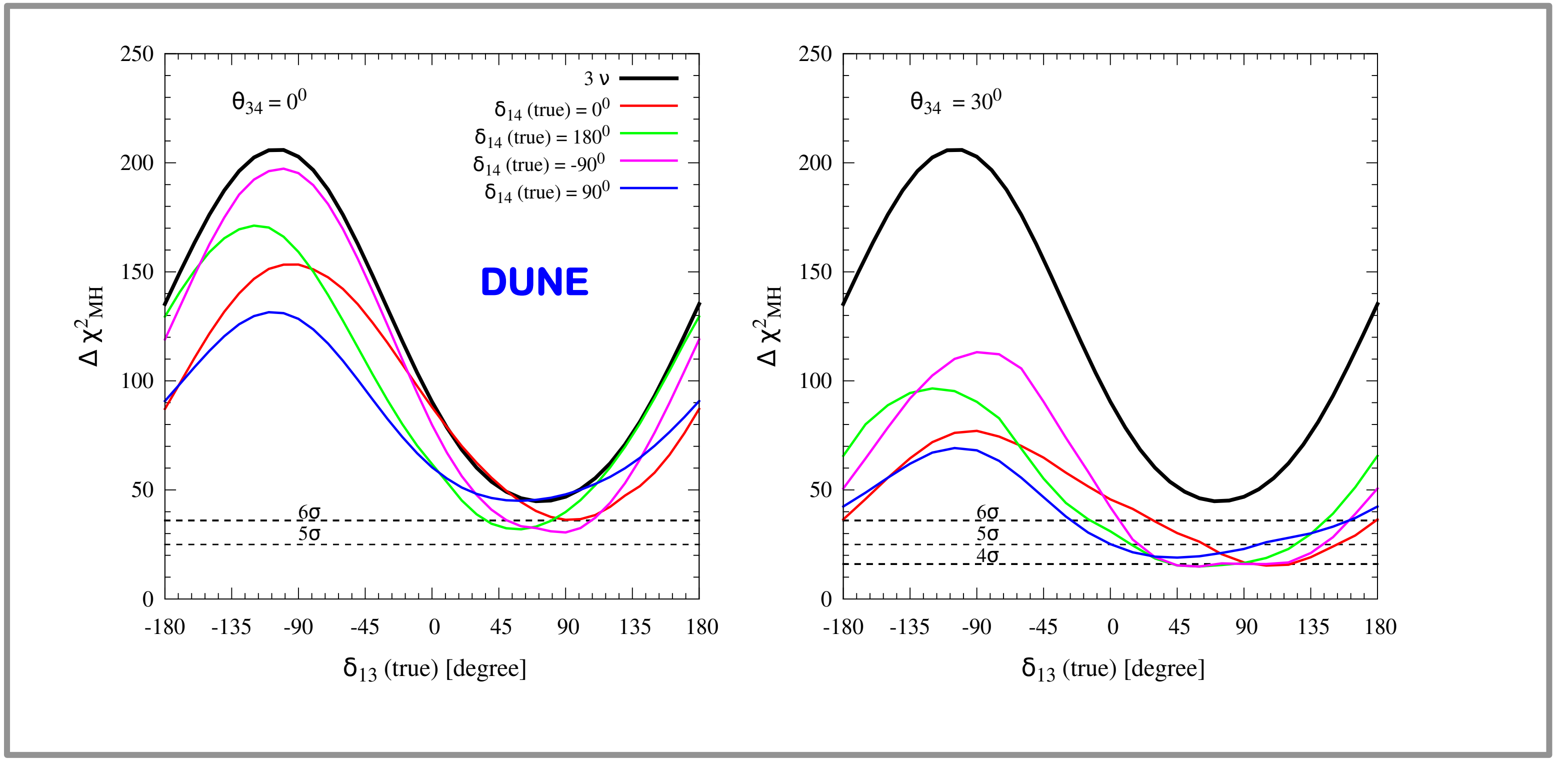


Also in this case a new CP-phase introduces a degeneracy

Very small values of the coupling may be harmful

Discovery potential of mass hierarchy

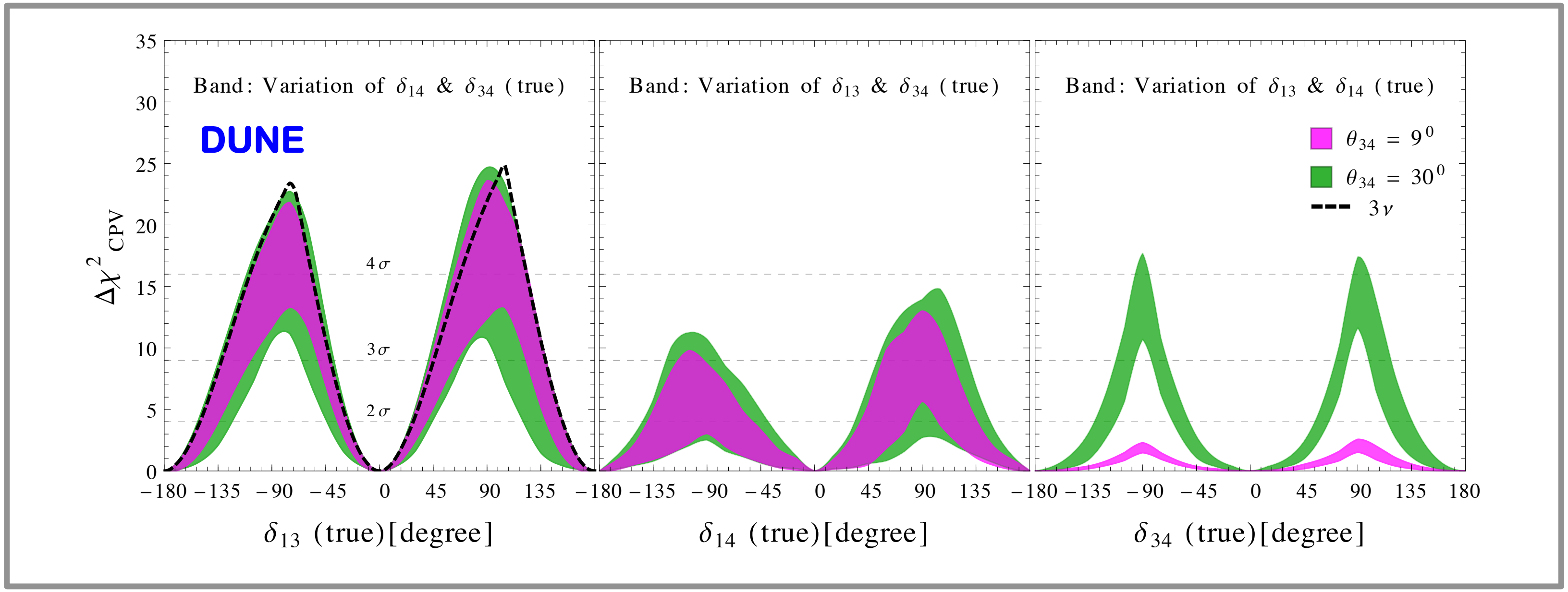
Agarwalla, Chatterjee, A.P., arXiv: 1603.03759 (JHEP 2016)



Degradation of sensitivity but 4σ level preserved

CPV discovery potential

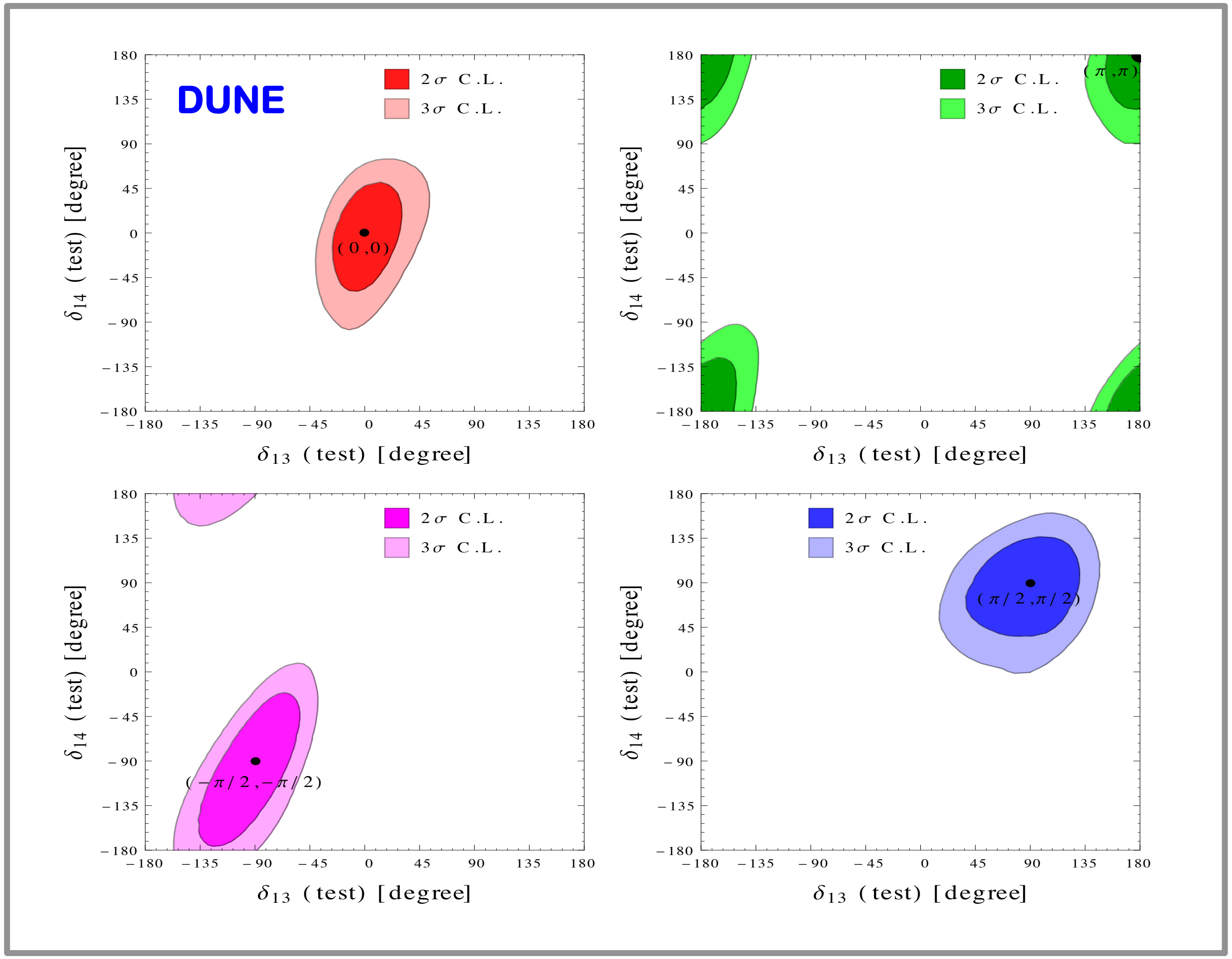
Agarwalla, Chatterjee, A.P., arXiv: 1603.03759 (JHEP 2016)



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

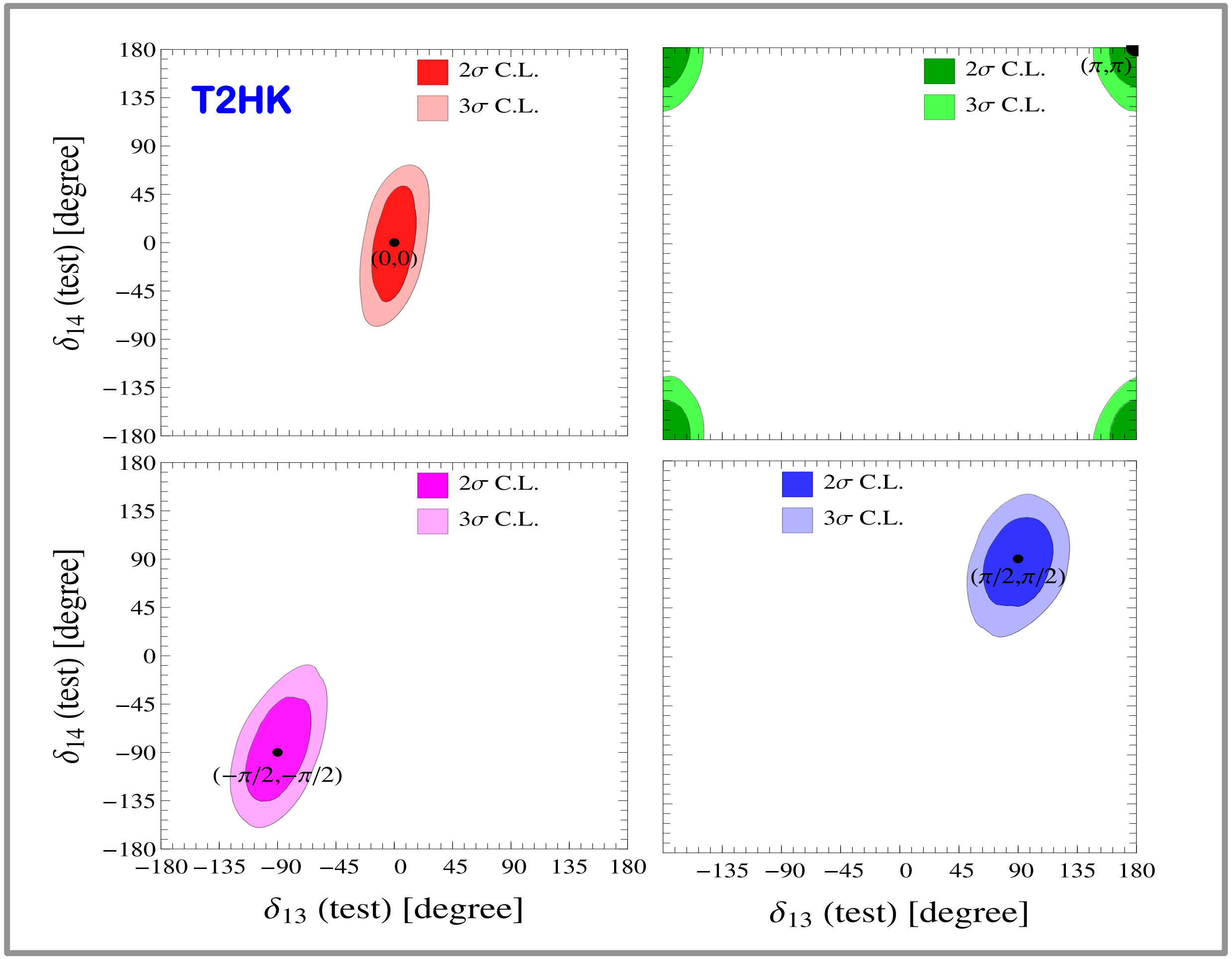
We may be able to measure two CP phases

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



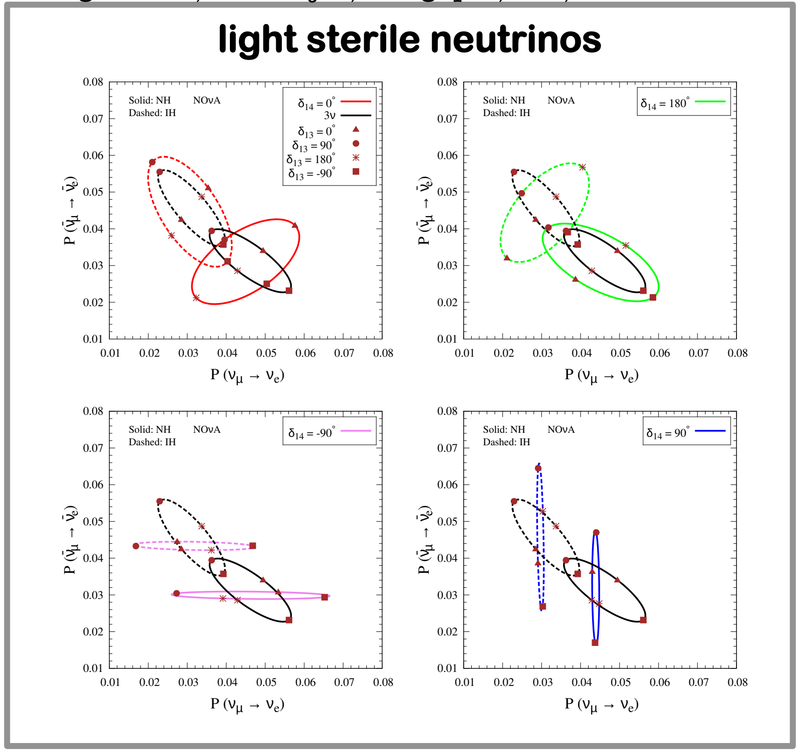
Reconstruction of the CP phases in T2HK

Preliminary plot realized by S.S. Chatterjee

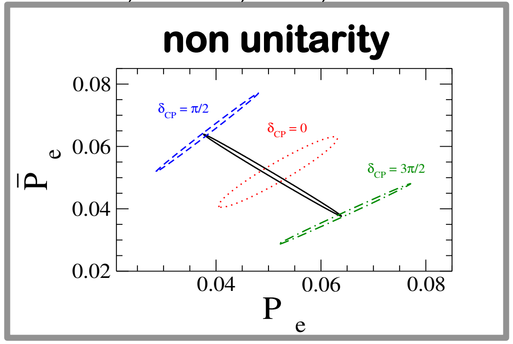


The dance of the ellipses

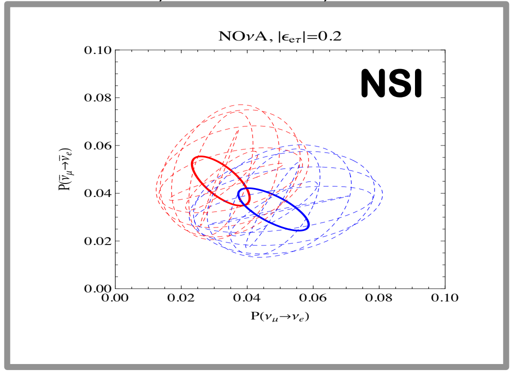
Agarwalla, Chatterjee, Dasgupta, A.P., 1601.05995



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

- 3-flavor searches in evolution
- First indications about CPV and MO
- Intriguing hints of light sterile neutrinos
- New SBL experiments will shed light
- Full exploration of sterile νs possible with LBL only
- LBL program complementary to SBL one

Back up slides

CPV and averaged oscillations

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

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

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

osc. averaged out by finite E resol.

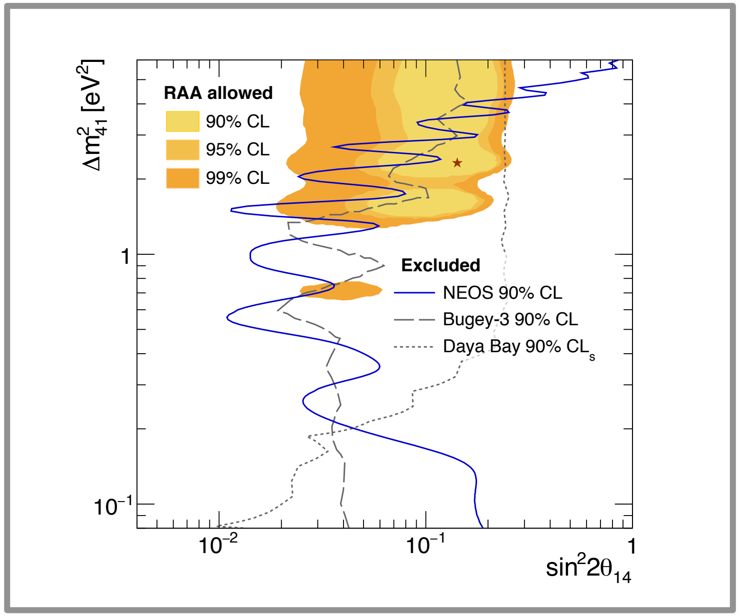
It can be: $\boxed{A^{\rm CP}_{\alpha\beta} \neq 0}$ **(if sin δ = 0)**

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)

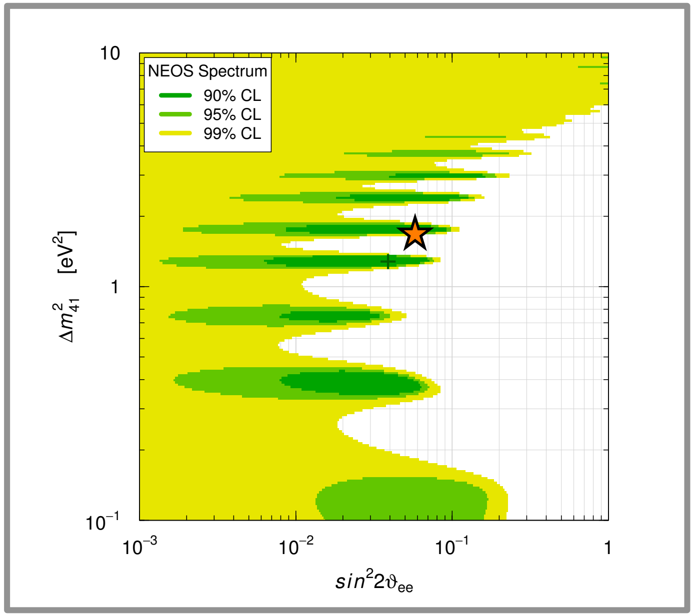
Two different perspectives

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

$$\chi^2_{\text{no osc}} - \chi^2_{\text{min}} = 6.5$$

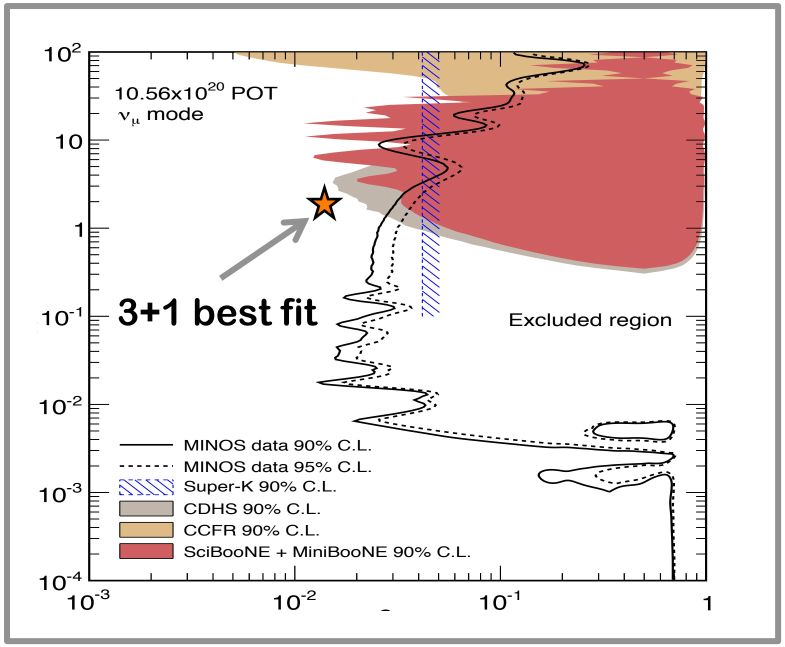
> 95% CL indication!

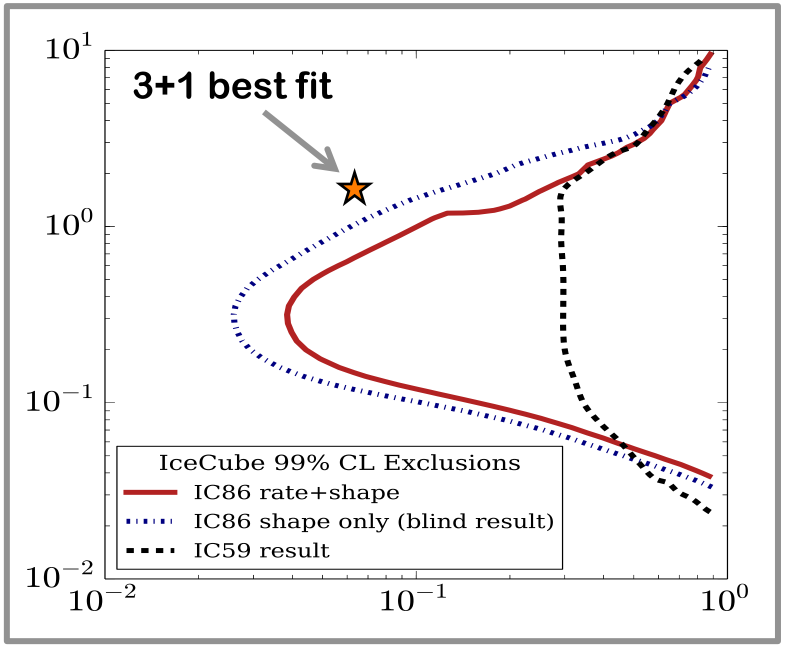
No anomaly in ν_μ disappearance

SBL & MINOS (NC)

IceCube

Δm^2

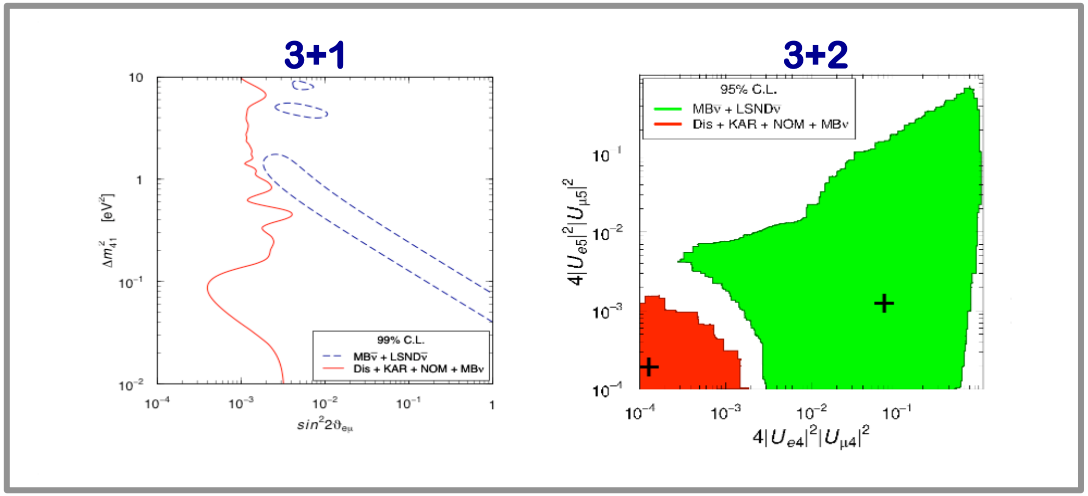




$\sin^2\theta_{\mu\mu}$

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

Tension in all ν_s models



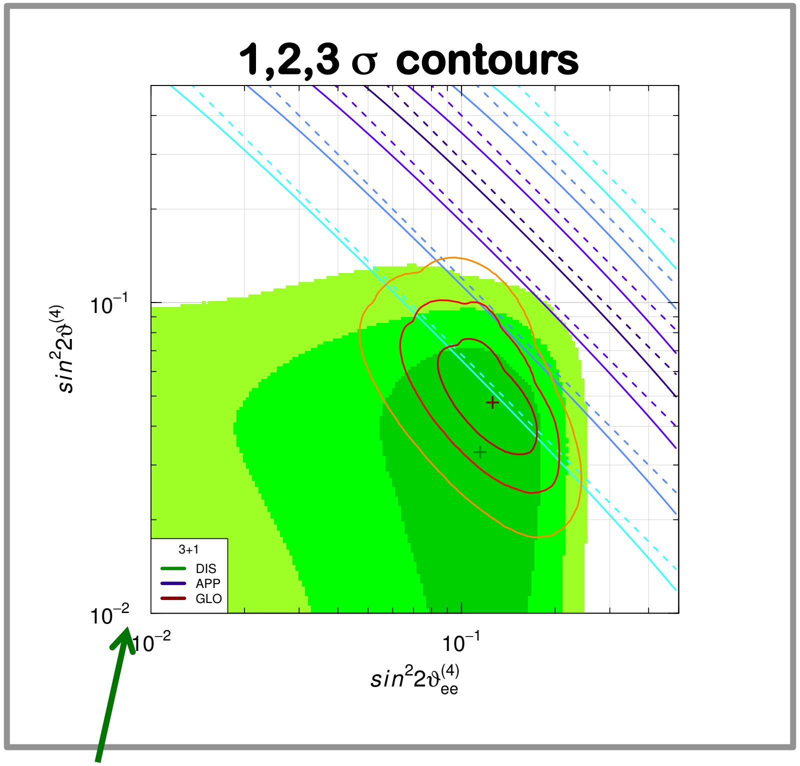
Giunti
&
Laveder

arXiv:1107.1452

ν_μ -> ν_e **positive**	$\|U_{e4}\|\|U_{\mu4}\| > 0$
ν_e -> ν_e **positive**	$\|U_{e4}\| > 0$
ν_μ -> ν_μ **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

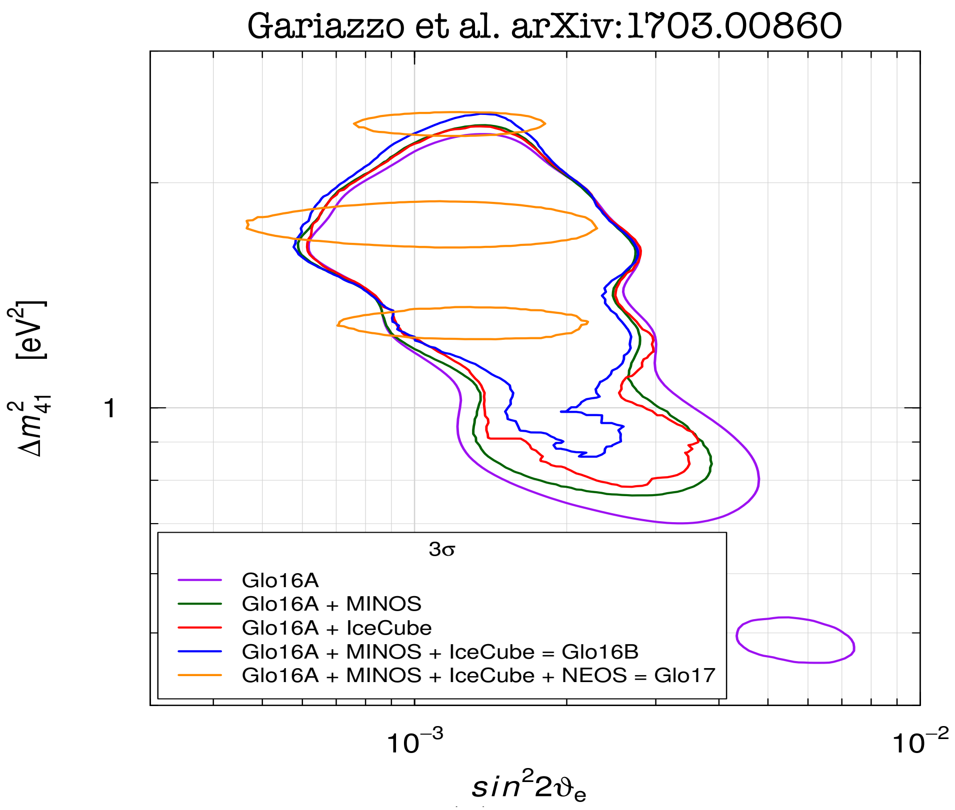
But their combination gives a 6σ improvement with respect to the 3ν case

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)

Impact of the latest measurements



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