TAUP 2015 — Torino, 9/9

Sterile neutrinos

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Outline

Introduction

- Short baseline anomalies, a critical overview
- Sterile νs and CPV: a new challenge for LBLs
- Other potential windows onto sterile νs

Conclusions

Sterile neutrinos

Many extensions of the SM involve sterile neutrinos, i.e. singlets of the SM gauge group

ν_s investigated at several scales:

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

Light ν_s

Wide interest in the scientific community

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

Light Sterile Neutrinos: A White Paper

K. N. Abazajian[a,1] M. A. Acero,[2] S. K. Agarwalla,[3] A. A. Aguilar-Arevalo,[2] C. H. Albright,[4,5] S. Antusch,[6] C. A. Argüelles,[7] A. B. Balantekin,[8] G. Barenboim[a,3] V. Barger,[8] P. Bernardini,[9] F. Bezrukov,[10] O. E. Bjaelde,[11] S. A. Bogacz,[12] N. S. Bowden,[13] A. Boyarsky,[14] A. Bravar,[15] D. Bravo Berguño,[16] S. J. Brice,[5] A. D. Bross,[5] B. Caccianiga,[17] F. Cavanna,[18,19] E. J. Chun,[20] B. T. Cleveland,[21] A. P. Collin,[22] P. Coloma,[16] J. M. Conrad,[23] M. Cribier,[22] A. S. Cucoanes,[24] J. C. D'Olivo,[2] S. Das,[25] A. de Gouvêa,[26] A. V. Derbin,[27] R. Dharmapalan,[28] J. S. Diaz,[29] X. J. Ding,[16] Z. Djurcic,[30] A. Donini,[31,3] D. Duchesneau,[32] H. Ejiri,[33] S. R. Elliott,[34] D. J. Ernst,[35] A. Esmaili,[36] J. J. Evans,[37,38] E. Fernandez-Martinez,[39] E. Figueroa-Feliciano,[23] B. T. Fleming[a,18] J. A. Formaggio[a,23] D. Franco,[40] J. Gaffiot,[22] R. Gandhi,[41] Y. Gao,[42] G. T. Garvey,[34] V. N. Gavrin,[43] P. Ghoshal,[41] D. Gibin,[44] C. Giunti,[45] S. N. Gninenko,[43] 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] P. Huber[b,16] W. Huelsnitz,[34,51] A. Ianni,[52] T. V. Ibragimova,[43] Y. Karadzhov,[15] G. Karagiorgi,[53] 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] M. Yeh,[104] F. Yermia,[24] Z. W. Yokley,[16] G. P. Zeller,[5] L. Zhan,[61] and H. Zhang[62]

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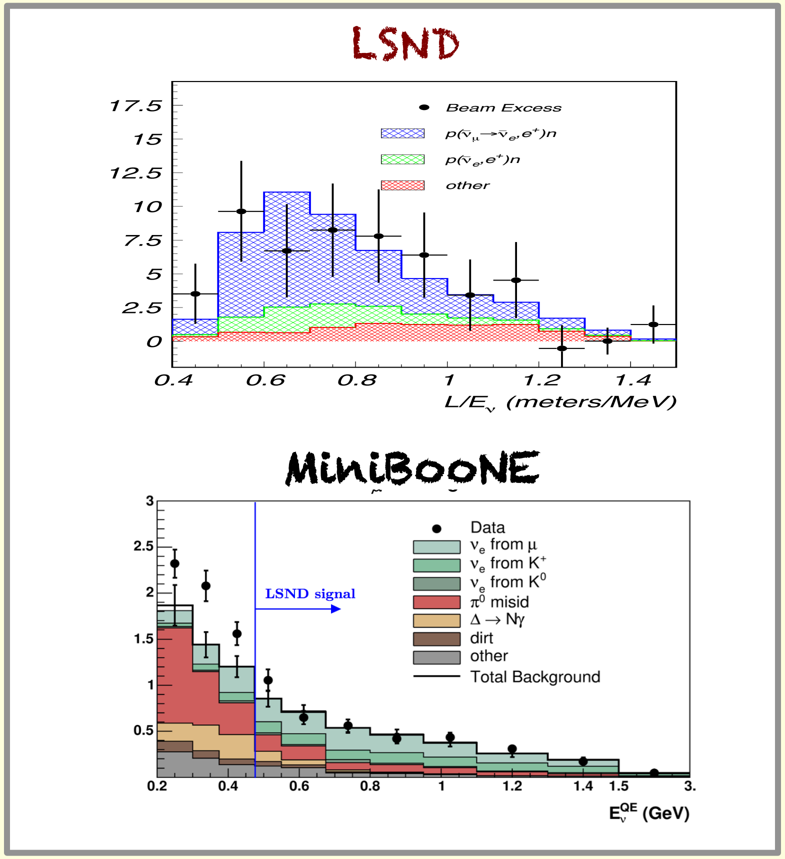
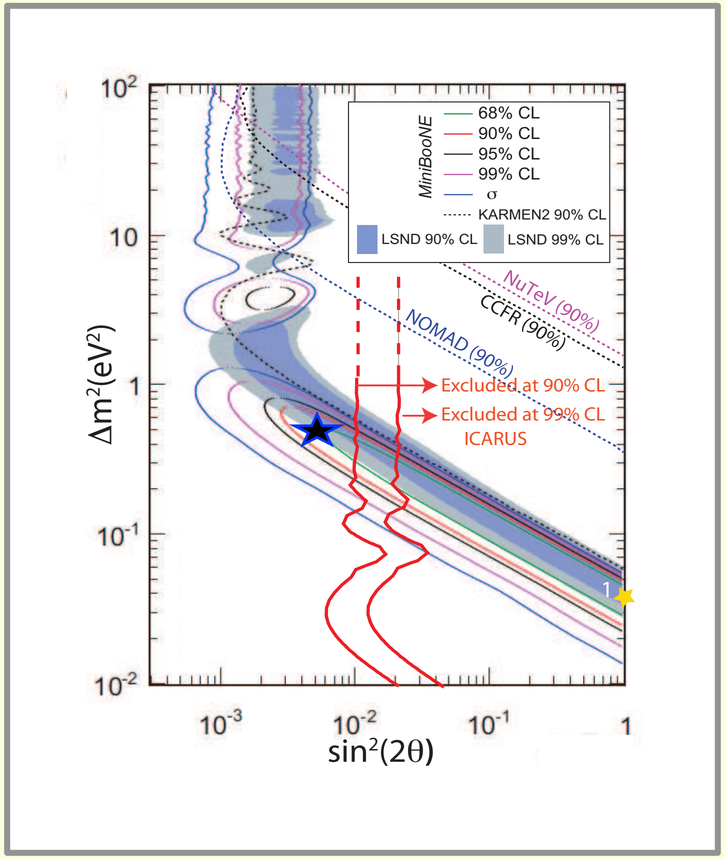
The short baseline anomalies, a critical overview

The SBL accelerator anomalies

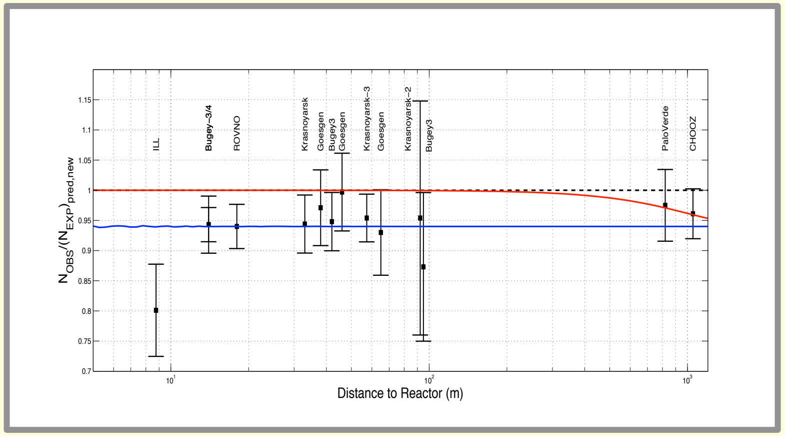
(unexplained ν_e appearance in a ν_μ beam)



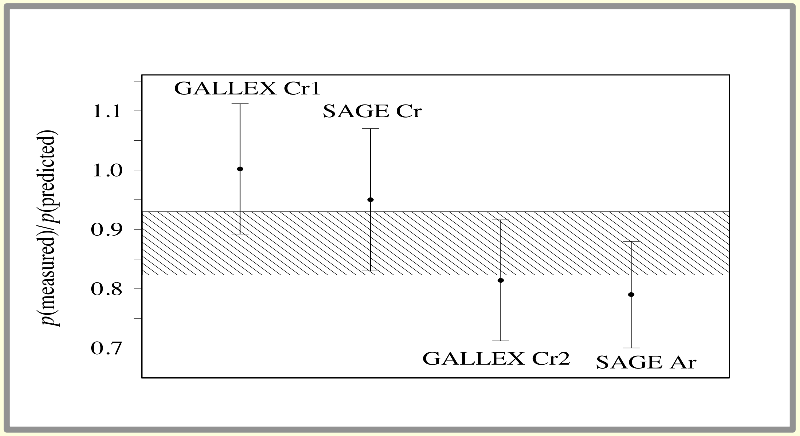


The reactor and gallium anomalies

(unexplained ν_e disappearance)



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



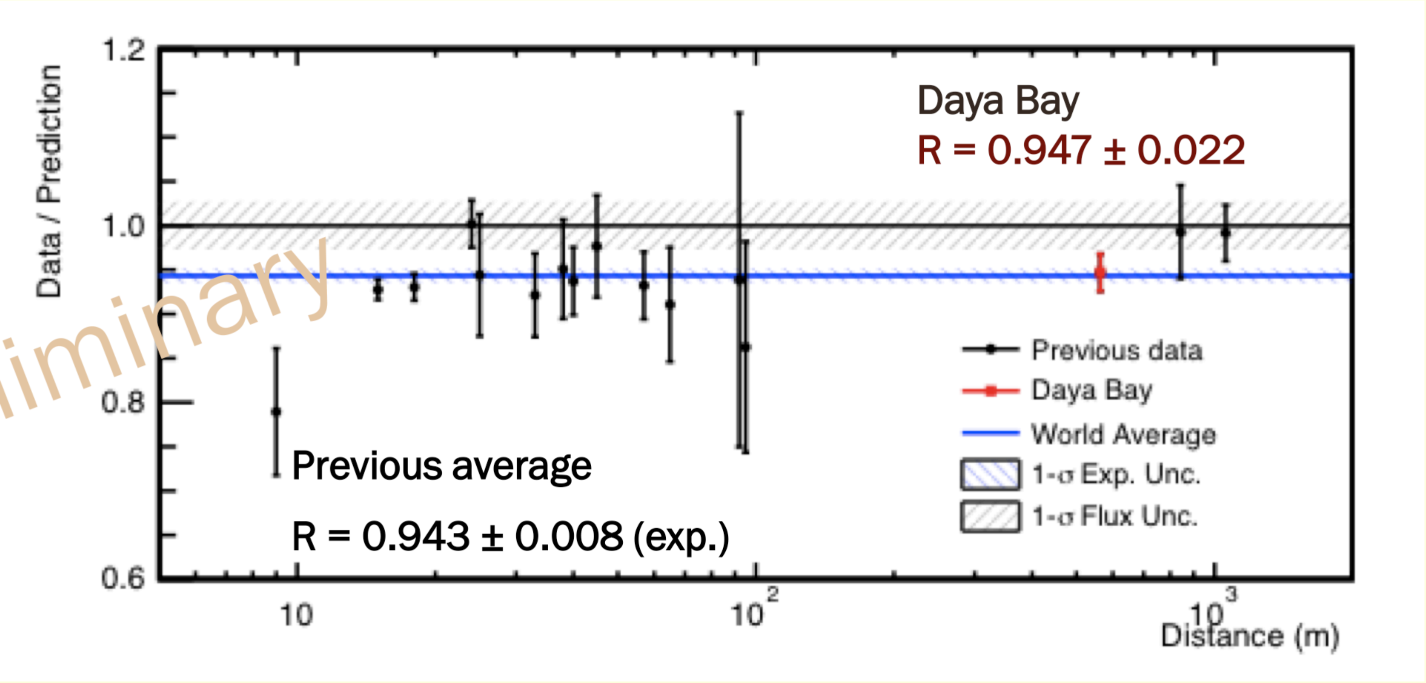
SAGE coll., PRC 73 (2006) 045805

Warning: both are mere normalization issues

The culprit may be in hidden systematics

New-generation detectors confirm deficit

Daya Bay @ Neutrino 2014 & ICHEP 2014

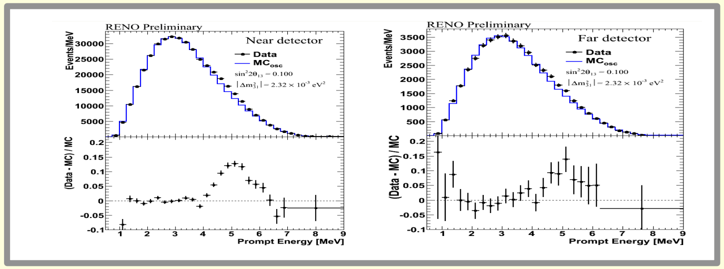


Definitive results appeared 3 weeks ago on arXiv:1508.04233

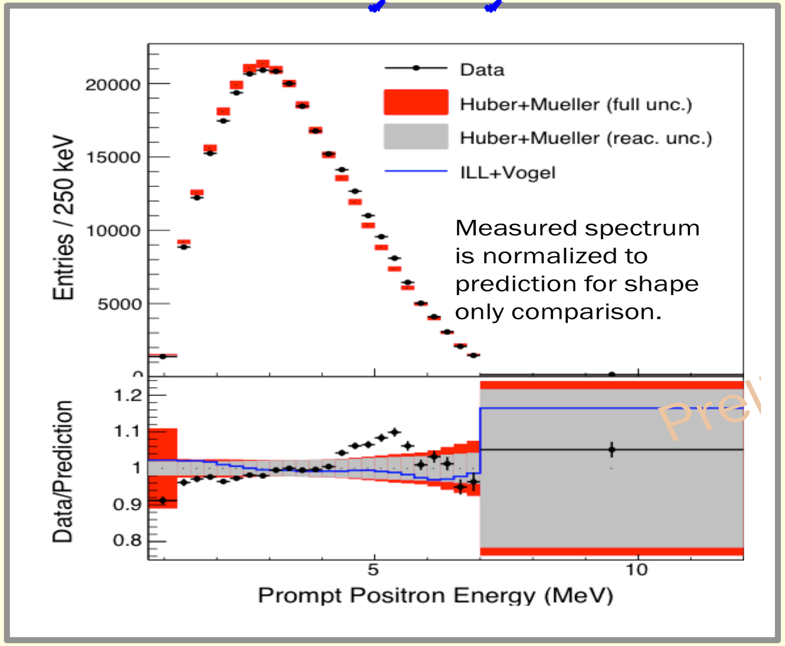
However, the same detectors give us a warning…

Understanding of rea. spectrum is incomplete

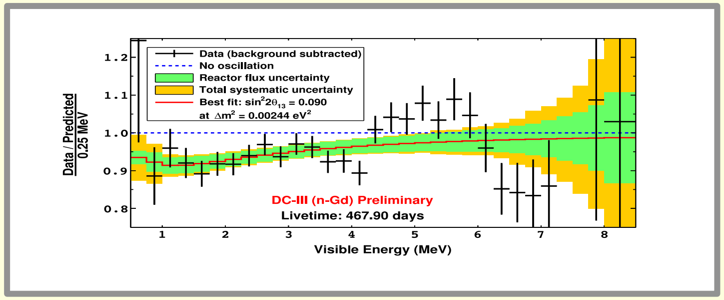
RENO



Daya Bay



Double-CHOOZ



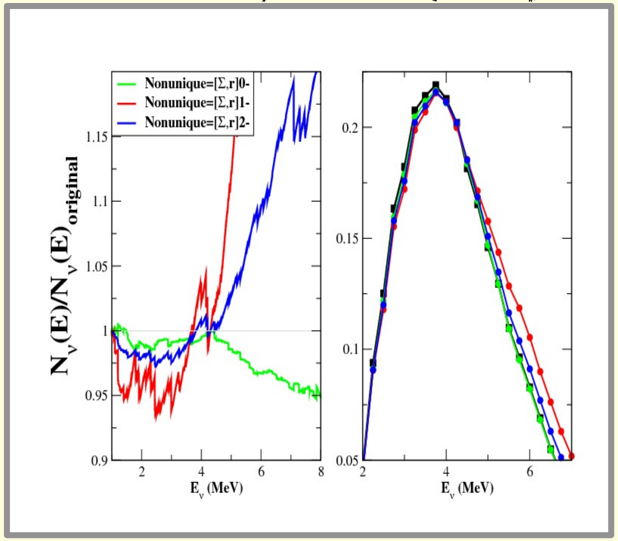
Shoulder at 4-6 MeV observed in all the three experiments

Identical at Near & Far sites: not imputable to new osc. physics

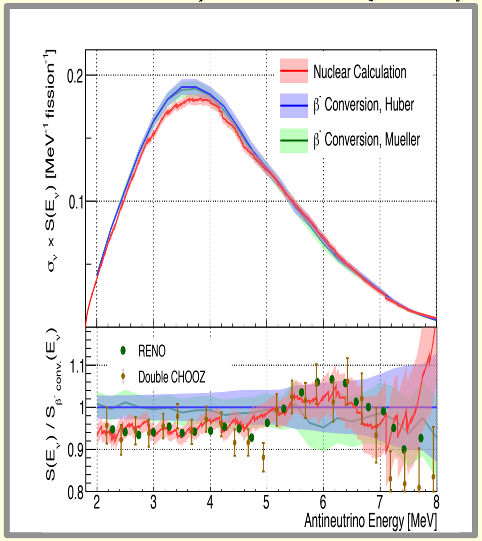
θ_{13} extraction is unaffected (based on near/far comparison)

Discrepancy under active investigation

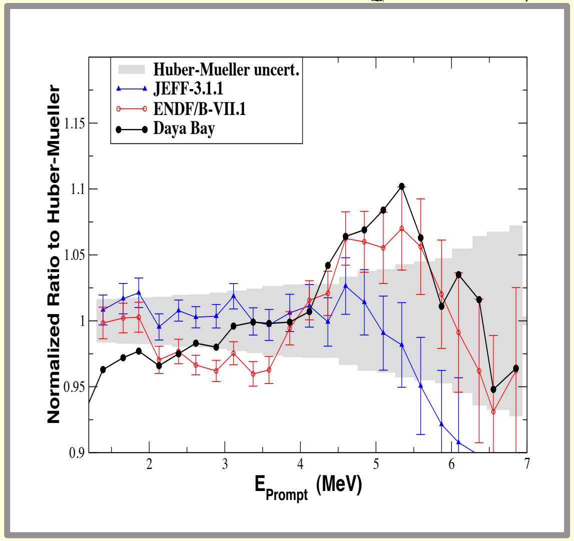
Hayes et al.
PRL 112, 202501 (2014)



Dwyer and Langford
PRL 114, 012502 (2015)

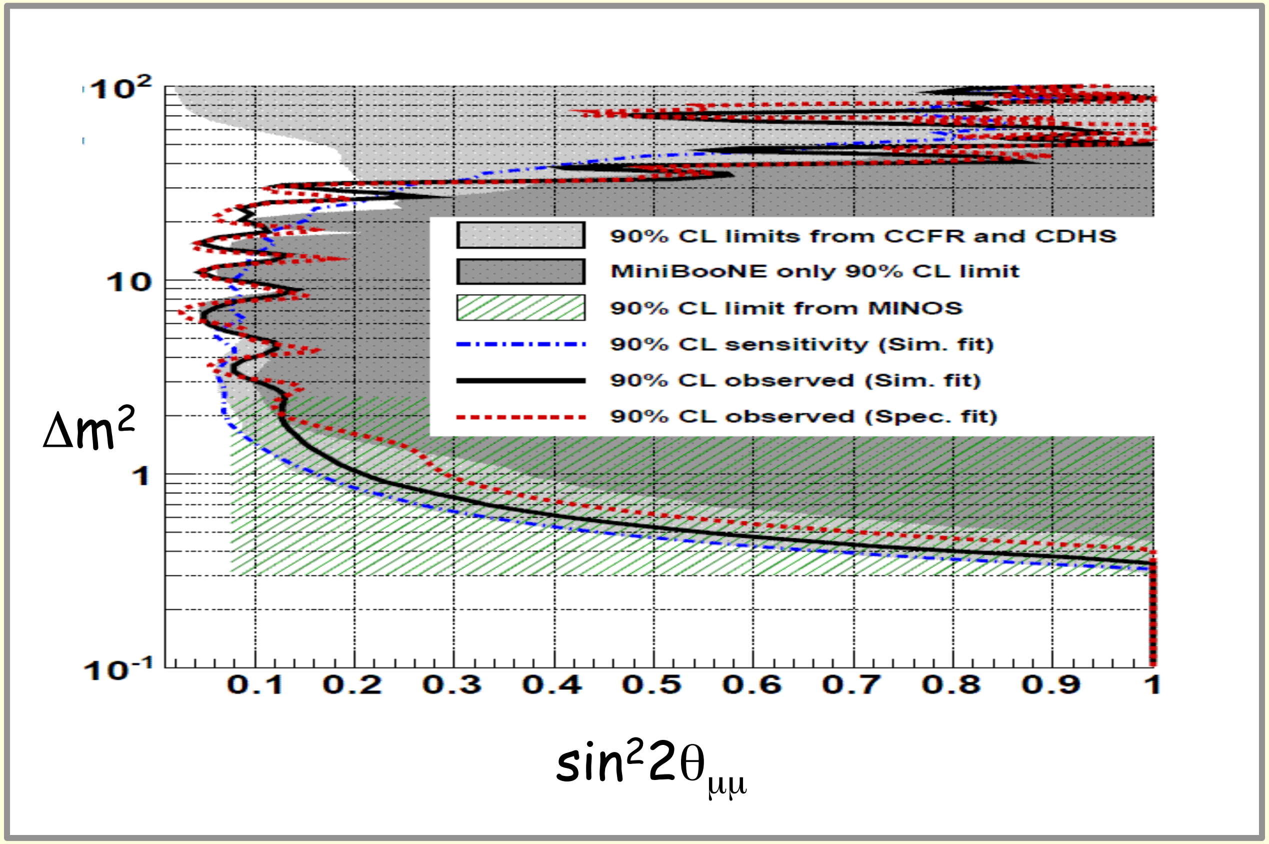


Hayes et al.
arXiv:1306.00583 [nucl-th]



- 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

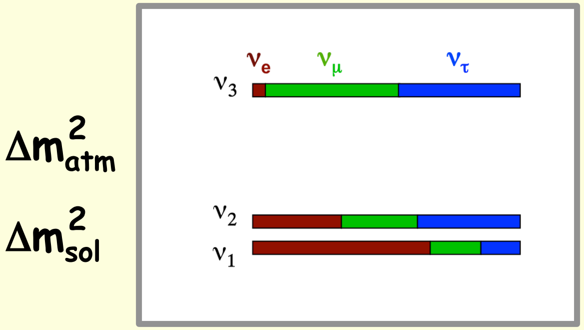


only upper bounds (till now)

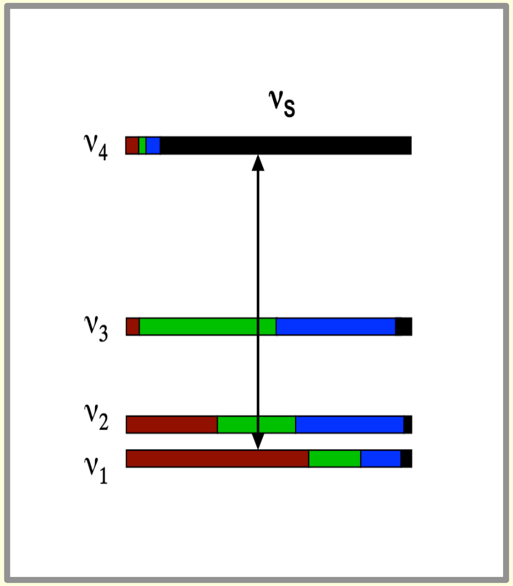
Can the sterile neutrino hypothesis
explain consistently
all the three different channels?

Introducing a sterile neutrino

3ν scheme



3+1 scheme



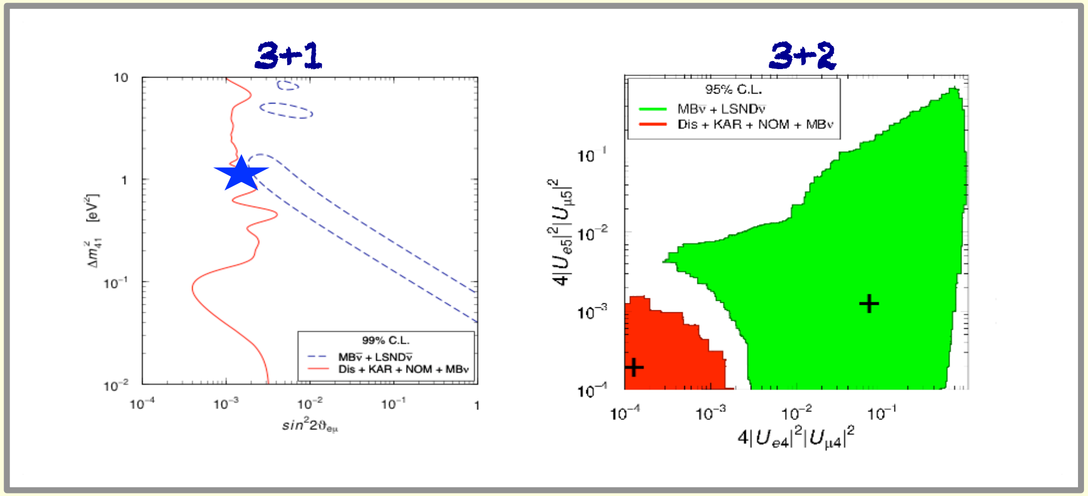
$|U_{s4}| \sim 1$

$\Delta m^2_{14} \sim 1$ eV²

Only a small perturbation of the 3ν framework

But potential big revolution for particle physics!

Tension in all ν_s models



Giunti & Laveder

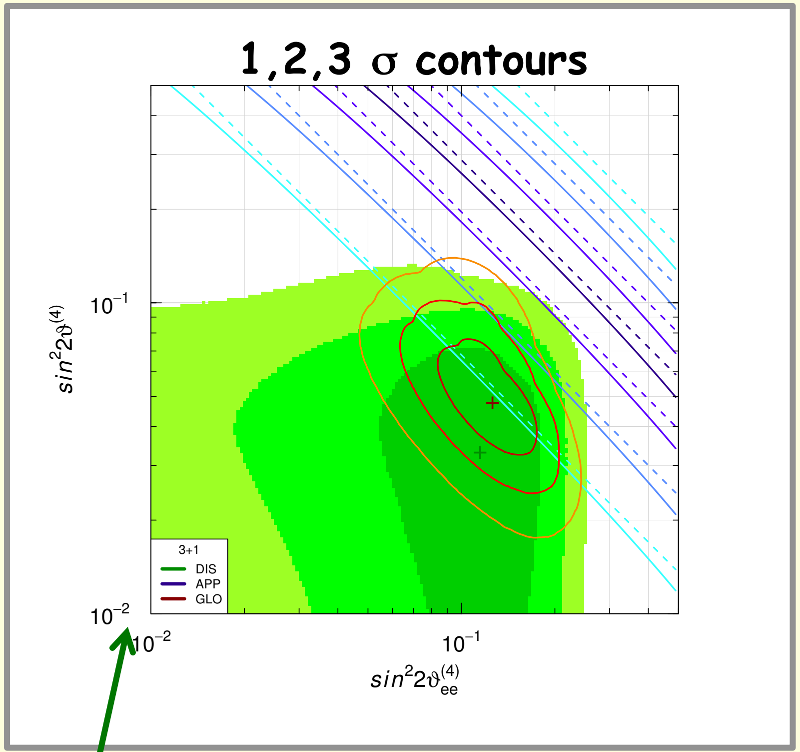
arXiv:1107.1452

$\nu_\mu \to \nu_e$ positive
$\nu_e \to \nu_e$ positive
$\nu_\mu \to \nu_\mu$ negative

$|U_{e4}||U_{\mu4}| > 0$
$|U_{e4}| > 0$
$|U_{\mu4}| \sim 0$

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

An undecidable problem



3ν limit

APP. & DIS. barely overlap at 2σ level

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

Difficult to take a decision on sterile vs !

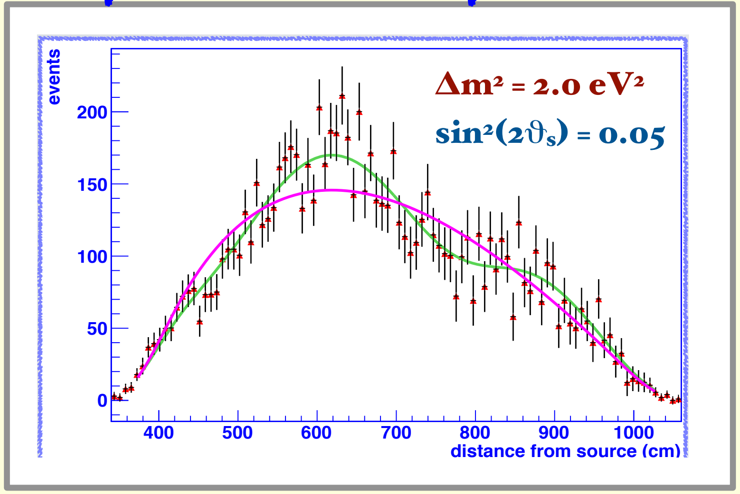
Only new more sensitive experiments can decide …

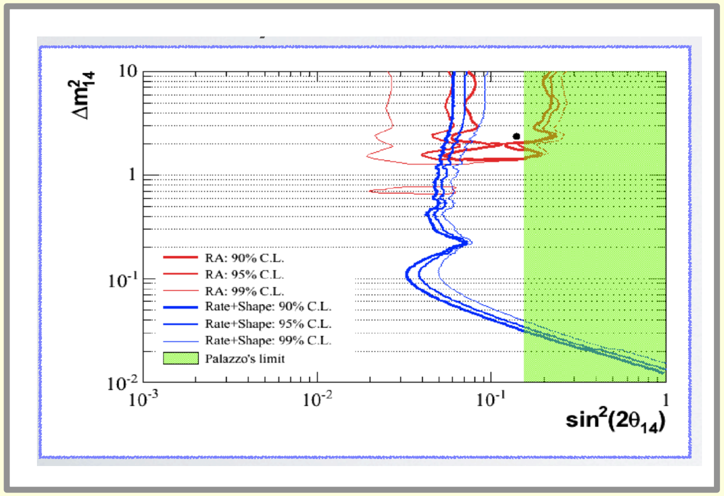
Figure from Giunti & Zavanin, arXiv:1508:03172

The smoking gun

Oscillatory pattern (in energy and/or space)

A promising option: ν source close to Borexino





M. Pallavicini @ Neutrino 2012

Several other projects under scrutiny

But such an observation would be only the start of the adventure in the sterile neutrino world..

Sterile neutrinos and CPV: a new challenge for the LBL experiments

Based on:

- N. Klop and A.P., PRD 91 073017 (2015)
- A.P., PRD 91 091301 (2015) Rapid Communication
- A.P., in preparation

An intrinsic limitation of SBLs

At SBL setups atm/sol oscillations negligible

$$\boxed{\frac{L}{E} \sim \frac{m}{\mathrm{MeV}}} \qquad \boxed{\begin{array}{l}\Delta_{12} \simeq 0 \\ \Delta_{13} \simeq 0\end{array}} \qquad \boxed{\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}}$$

- Not possible to observe interference phenomena between the sterile and atm/sol frequencies

- This is relevant because we need to observe such phenomena in order to measure the new CP phases that accompany the new sterile states

Mixing matrix in 3+1 scheme

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

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

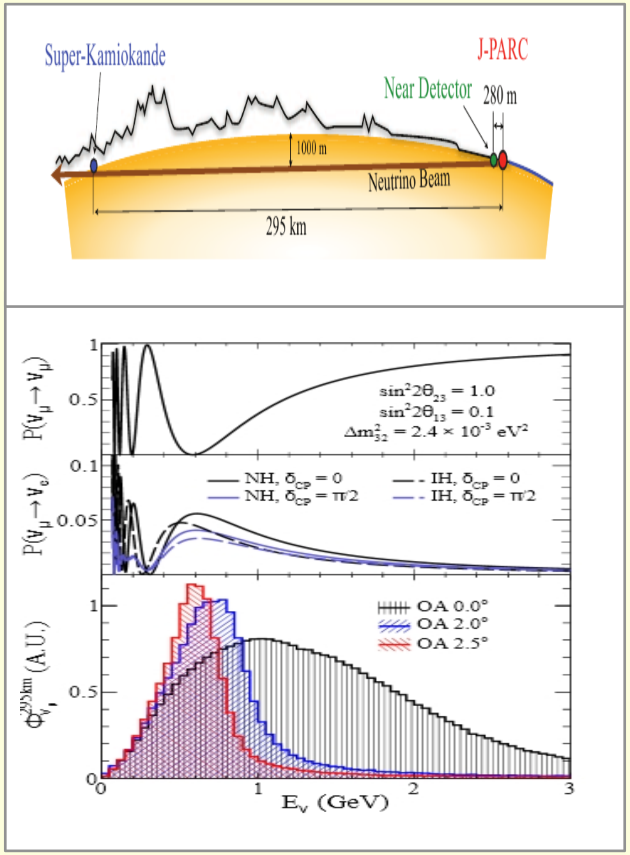
$$\tilde{R}_{ij} = \begin{bmatrix} c_{ij} & \tilde{s}_{ij} \\ -\tilde{s}^*_{ij} & c_{ij} \end{bmatrix}$$

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

3ν $\begin{cases} \text{3 mixing angles} \\ \text{1 Dirac CP-phases} \\ \text{2 Majorana phases} \end{cases}$ 3+1 $\begin{cases} 6 \\ 3 \\ 3 \end{cases}$ 3+N $\begin{cases} 3+3N \\ 1+2N \\ 2+N \end{cases}$

$\theta_{14} = \theta_{24} = \theta_{34} = 0$ → 3-flavor case

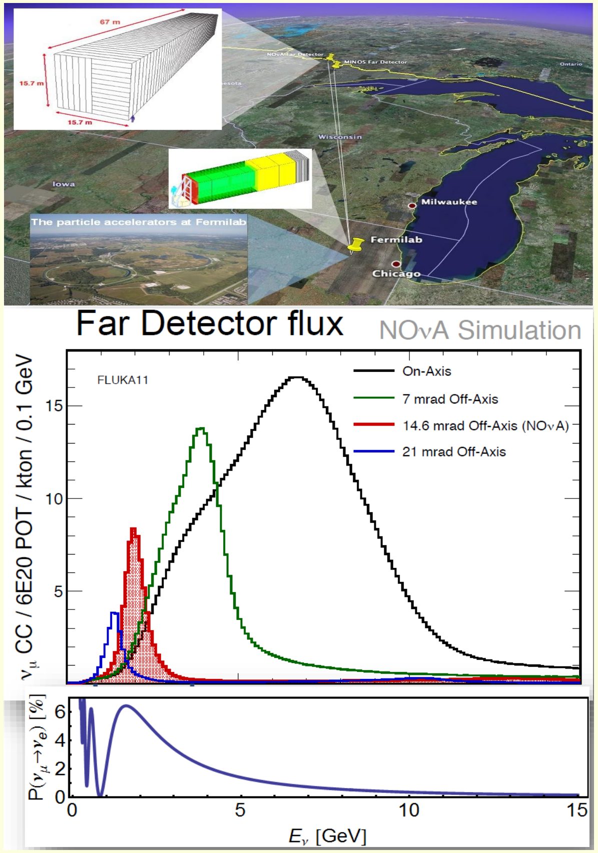
Outline of T2K & NOvA



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

3-flavor transition probability

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

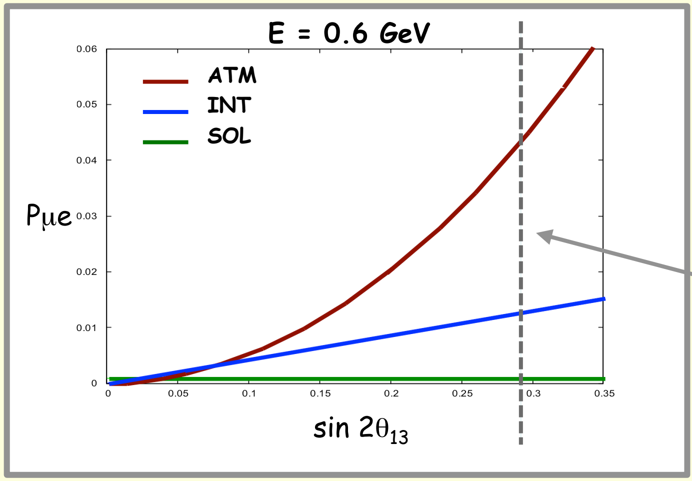
In vacuum:

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

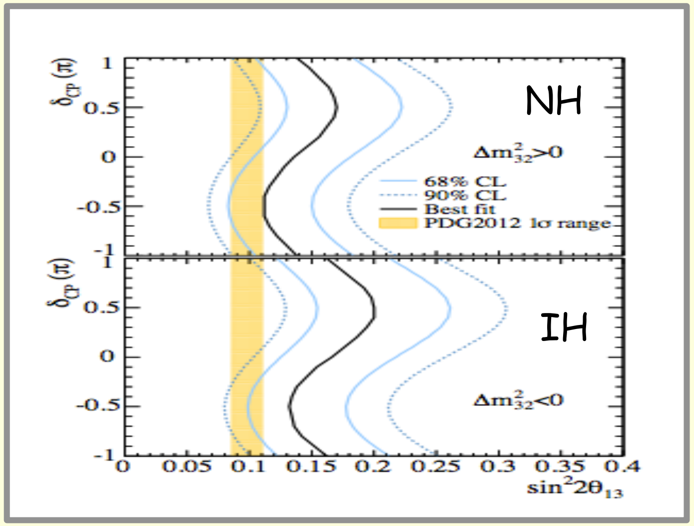
$$\Delta = \frac{\Delta m^2_{31} L}{4E}, \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$\Delta \sim \pi/2$

$\alpha \sim 0.03$



best θ_{13} estimate



P^{ATM} leading → $\theta_{13} > 0$

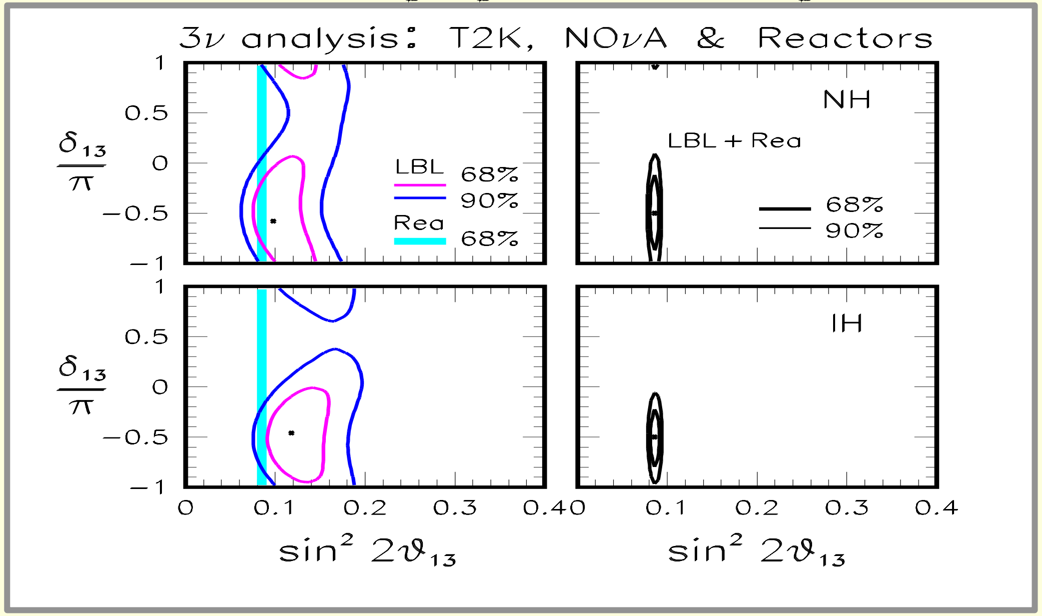
P^{INT} subleading → δ dependence

P^{SOL} negligible

Matter effects break the degeneracy between NH & IH

First hints of CPV and NMH

T2K (ν_e+$\bar{\nu}_e$) & NOvA (ν_e)



First hint of manifest CPV

CP-conservation (δ = 0, π) disfavored at ~ 90% C.L.

Best fit $\delta \sim -\pi/2$

Hint of NH $\Delta\chi^2 \sim -1.3$

Two existing trends tend to consolidate:

- Slight preference for NH
- Slight preference for sin δ < 0

Next data releases should be more informative

4-flavor transition probability

- $\Delta m^2_{14} >> \Delta m^2_{13}$: fast Δm^2_{14} osc. are averaged out
- Phase info. (Δm^2_{14}) gets lost (in contrast to SBL)
- Unlike SBL, interf. of Δm^2_{14} & Δm^2_{13} is observable

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

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

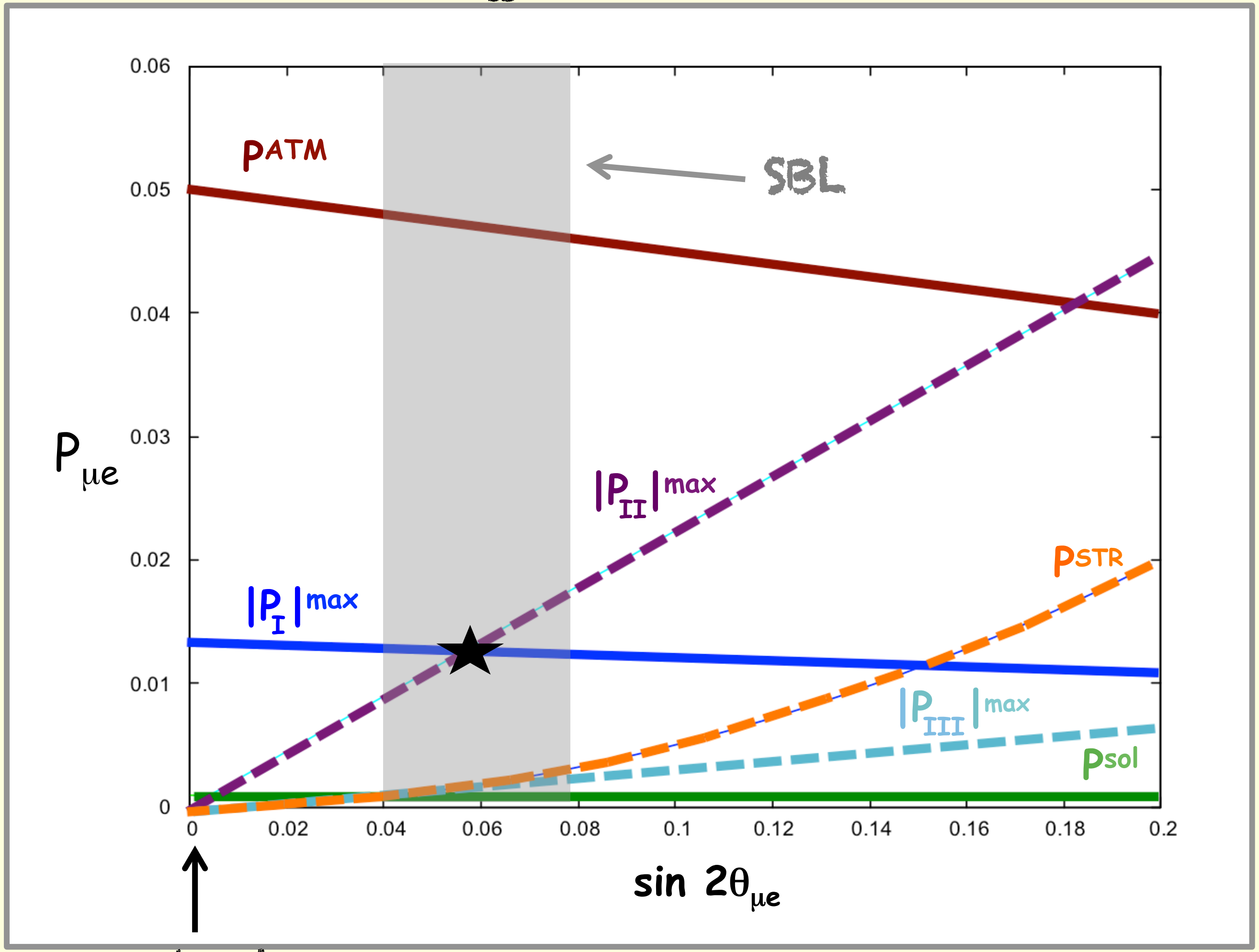
$\alpha = \delta m^2/\Delta m^2 \sim \varepsilon^2$

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

Sensitivity to the new CP-phase δ_{14}

New int. term is as large as the standard one

T2K: $\theta_{13} = 9°$ E = 0.6 GeV

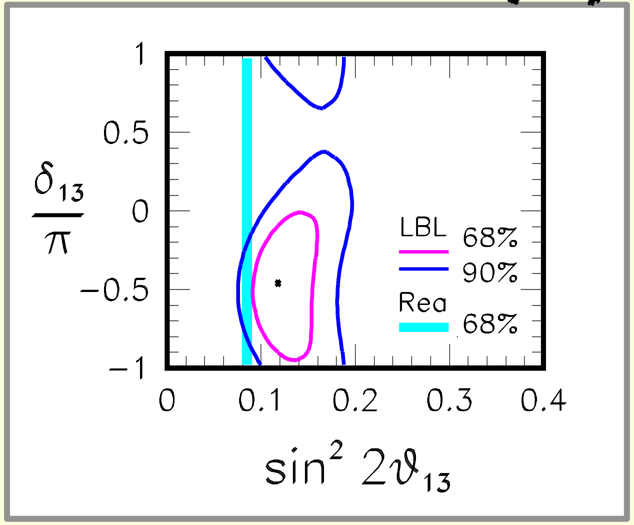


3ν limit

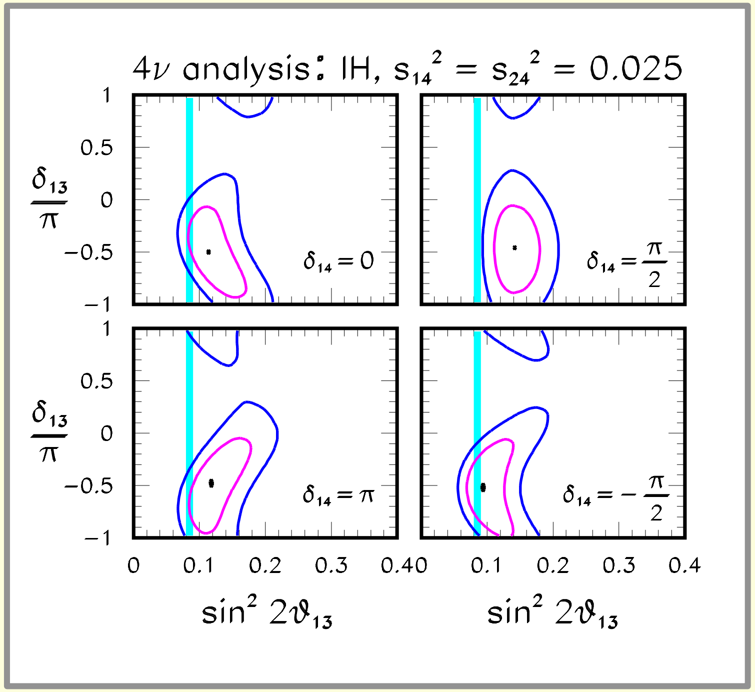
$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

Results of the 4ν analysis (LBL,IH)

3ν: T2K + NOνA (IH)

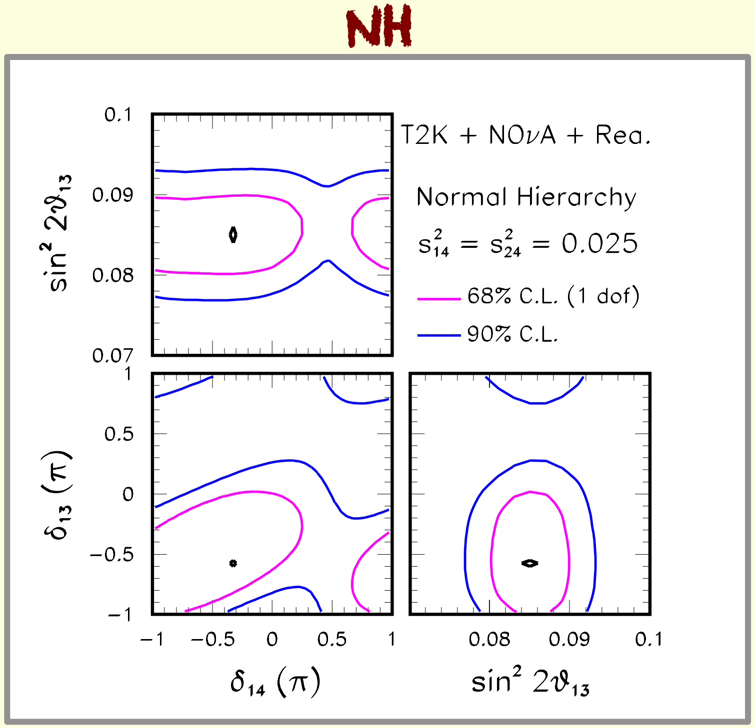


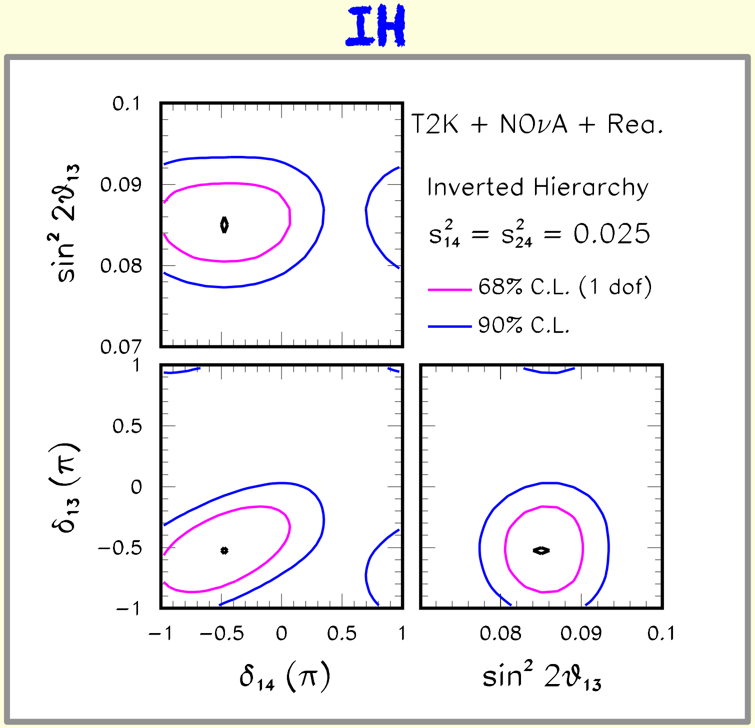
4ν



- For $\delta_{14} = -\pi/2$ perfect agreement of LBL & Rea
- As a consequence no hint of NH in a 3+1 scheme
- Fragility of the LBL discovery potential of the NMH ?

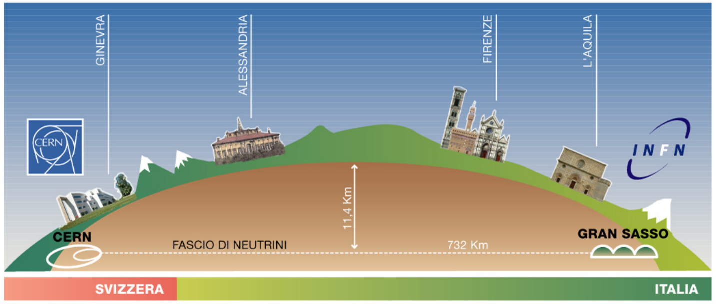
Constraints on the two CP-phases

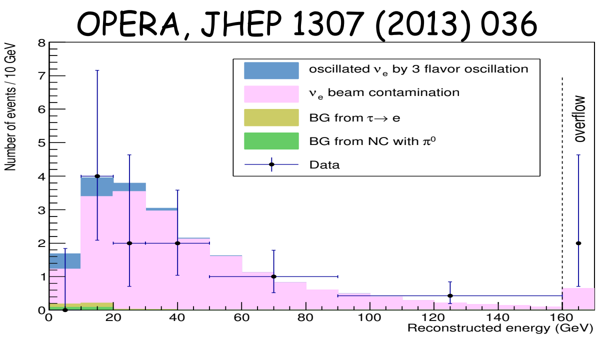


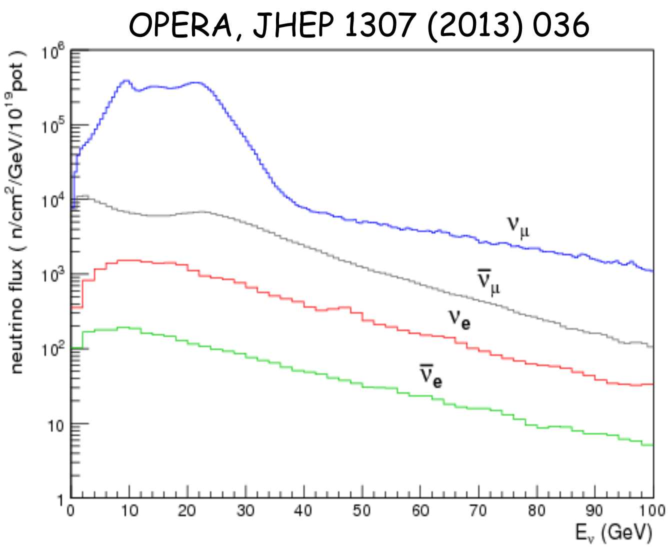


- Comparable sensitivity to δ_{13} & δ_{14}
- Best fit values: $\delta_{13} \sim \delta_{14} \sim -\pi/2$
- This information cannot be achieved with SBLs !

CP-phases matter also in CNGS expts.







$\langle E \rangle = 17$ GeV

$L = 732$ km

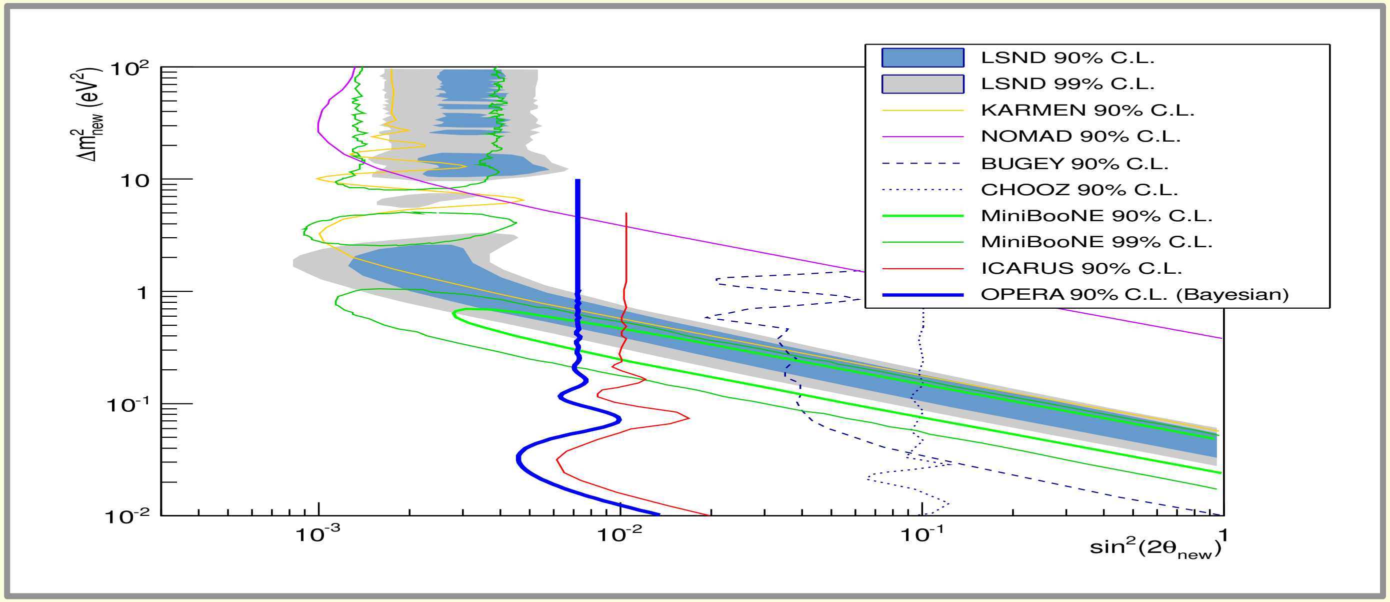
$\Delta m^2_{13} = 2.4 \times 10^{-3}$

$$\Delta = \frac{\Delta m^2_{13} L}{4E} \simeq 0.13$$

3ν oscillations play a minor role

Good place where to look for sterile νs

Official bounds from OPERA & ICARUS



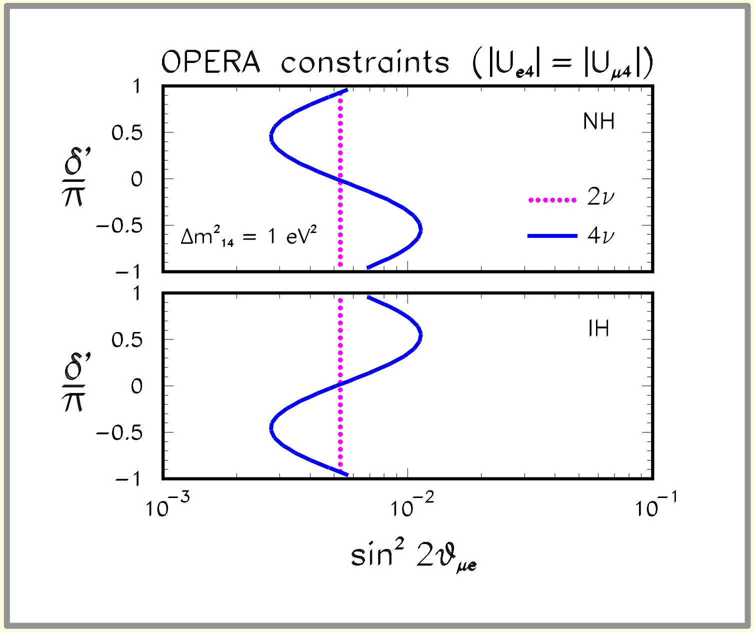
2-flavor treatment adopted by both collaborations

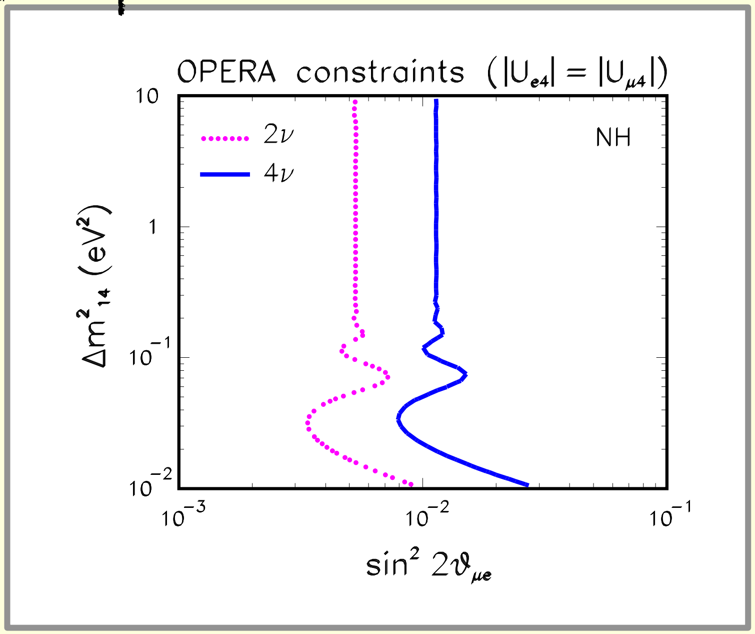
$P(\nu_\mu \to \nu_e) = 4 \sin^2 2\theta_{\mu e} \sin^2 \Delta_{14}$ + small Atm. term

$P(\nu_e \to \nu_e) = 1$ (ν_e bck fixed)

Impact of the 4ν interference term

A.P., PRD 91 091301 (2015) Rapid Communication





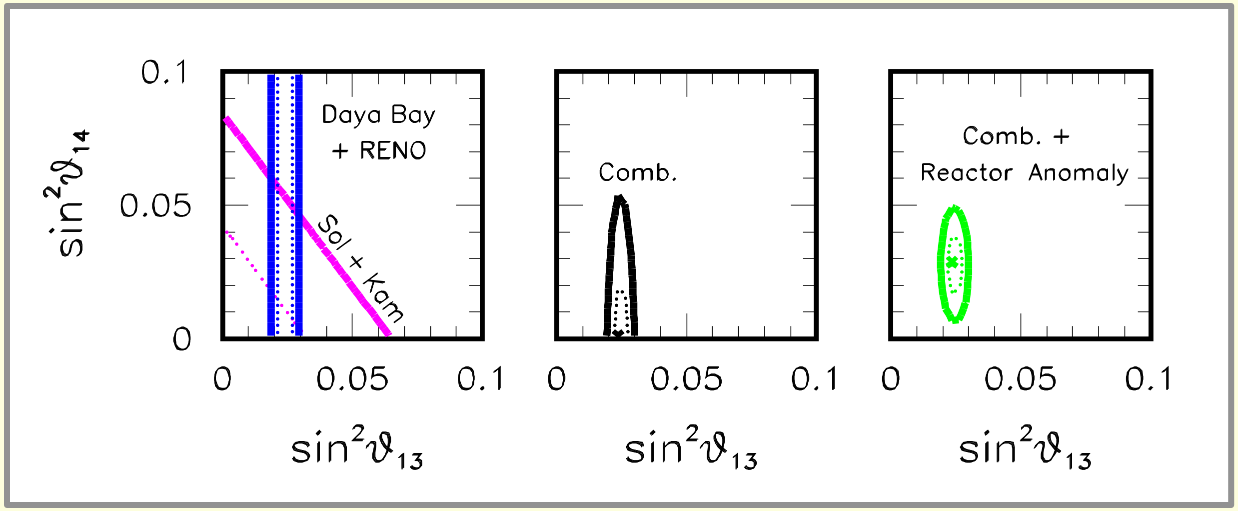
After marginalization of the unknown CP-phases

the upper bounds get relaxed by a factor of two

Other potential windows onto sterile νs

What solar exp. have to say on ν_ss ?

A.P., Review for Mod. Phys. Lett. A 28, 1330004 (2013)

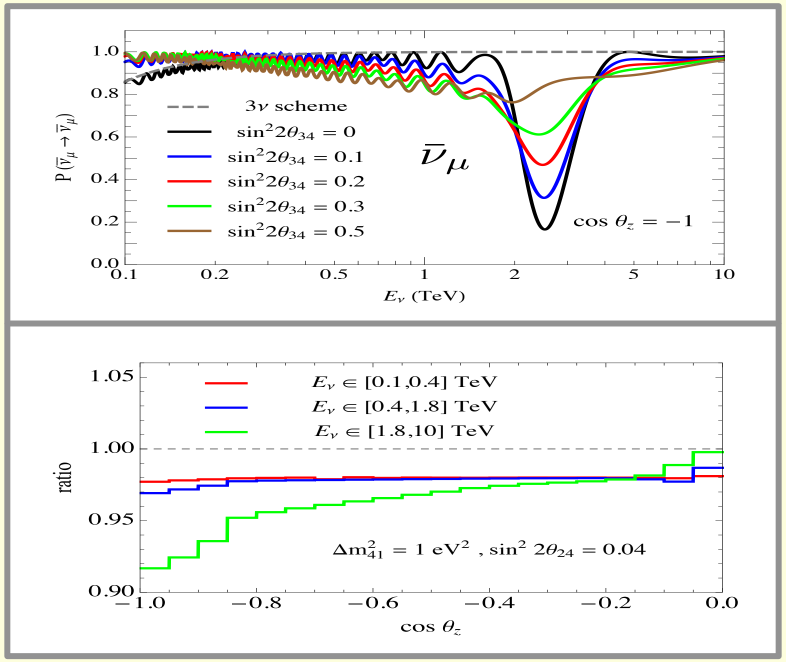


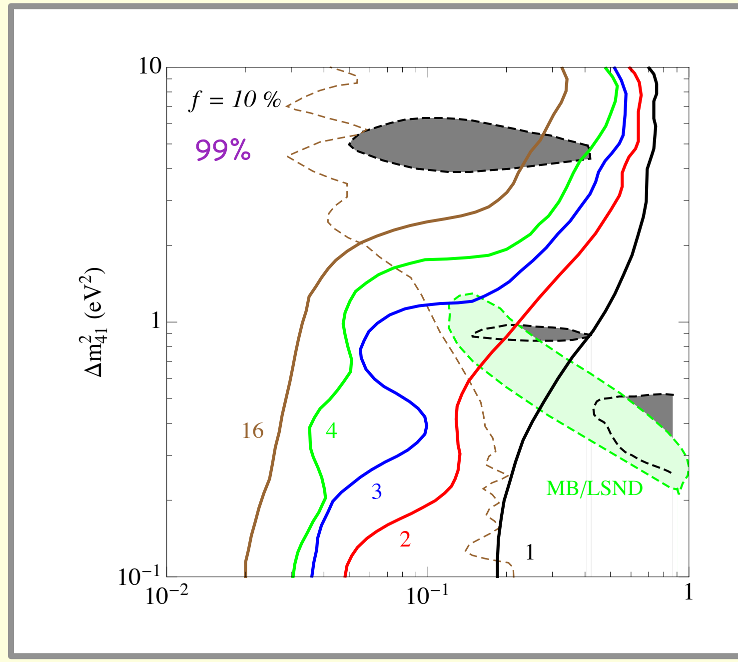
- **Solar + θ_{13} reactors:** $\sin^2\theta_{14} < 0.04 \quad (90\% \text{ C.L.})$
- Bound indep. of reactor fluxes (KamLAND only shape)
- It constitutes the only robust information on $|U_{e4}|^2$

Information from atmospheric ν in IceCube

Smoking gun: Dip at E ~ TeV due to MSW resonance

Nunokawa, Peres, Zuchanovich-Funchal PLB 562, 279 (2003)





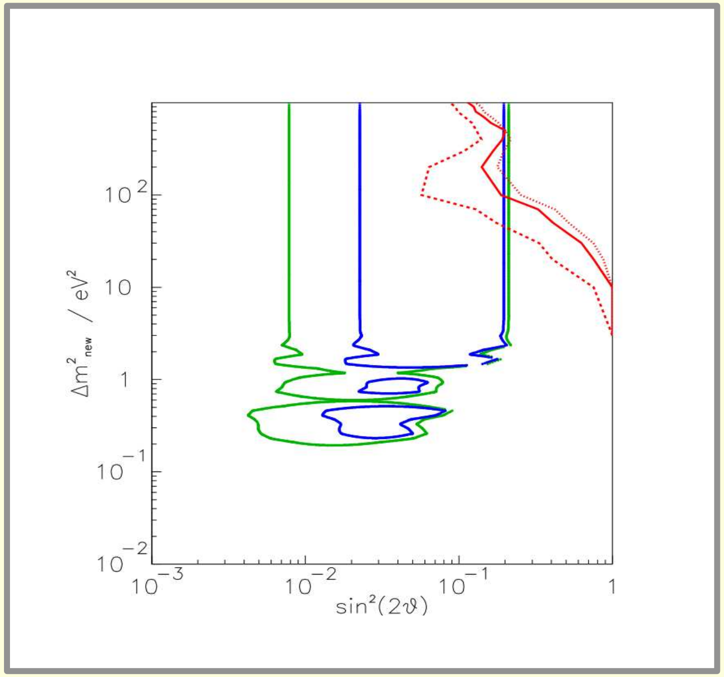
Figures from Esmaili & Smirnov JHEP 1312, 014 (2013)

Data are already there & wait to be analyzed!

Impact of a light sterile neutrino in β-decay

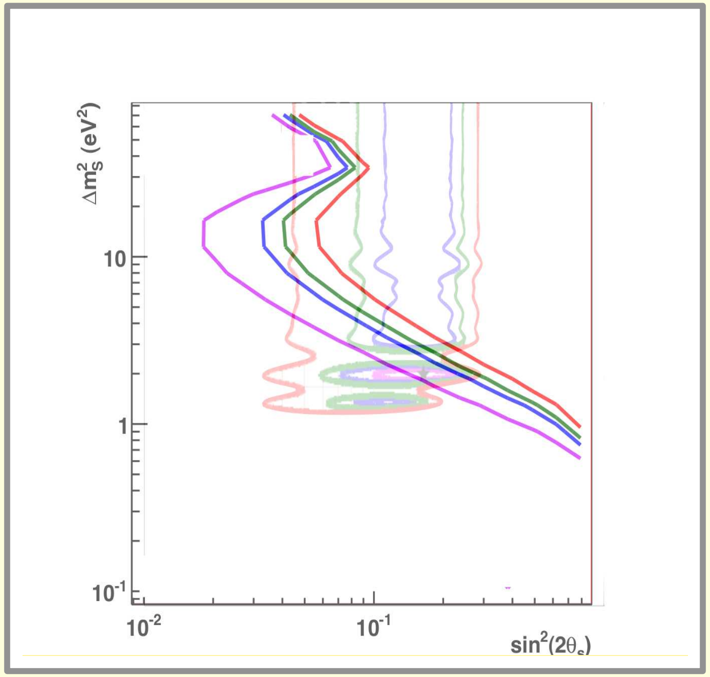
$$m_\beta = \sqrt{\sum |U_{ei}|^2 m_i^2} = \left| c_{12}^2 c_{13}^2 c_{14}^2 m_1^2 + s_{12}^2 c_{13}^2 c_{14}^2 m_2^2 + s_{13}^2 c_{14}^2 m_3^2 + s_{14}^2 m_4^2 \right|^{1/2}$$

Present: Mainz



Kraus et al., arXiv:1105.1326

Future: KATRIN



Formaggio & Barrett, arXiv:1105.1326

Impact of a light sterile in 0ν2β-decay

$$m_{\beta\beta} = \left|\sum U_{ei}^2 m_i\right| = \left|c_{12}^2 c_{13}^2 c_{14}^2 m_1 + s_{12}^2 c_{13}^2 c_{14}^2 m_2 e^{i\alpha} + s_{13}^2 c_{14}^2 m_3 e^{i\beta} + s_{14}^2 m_4 e^{i\gamma}\right|$$

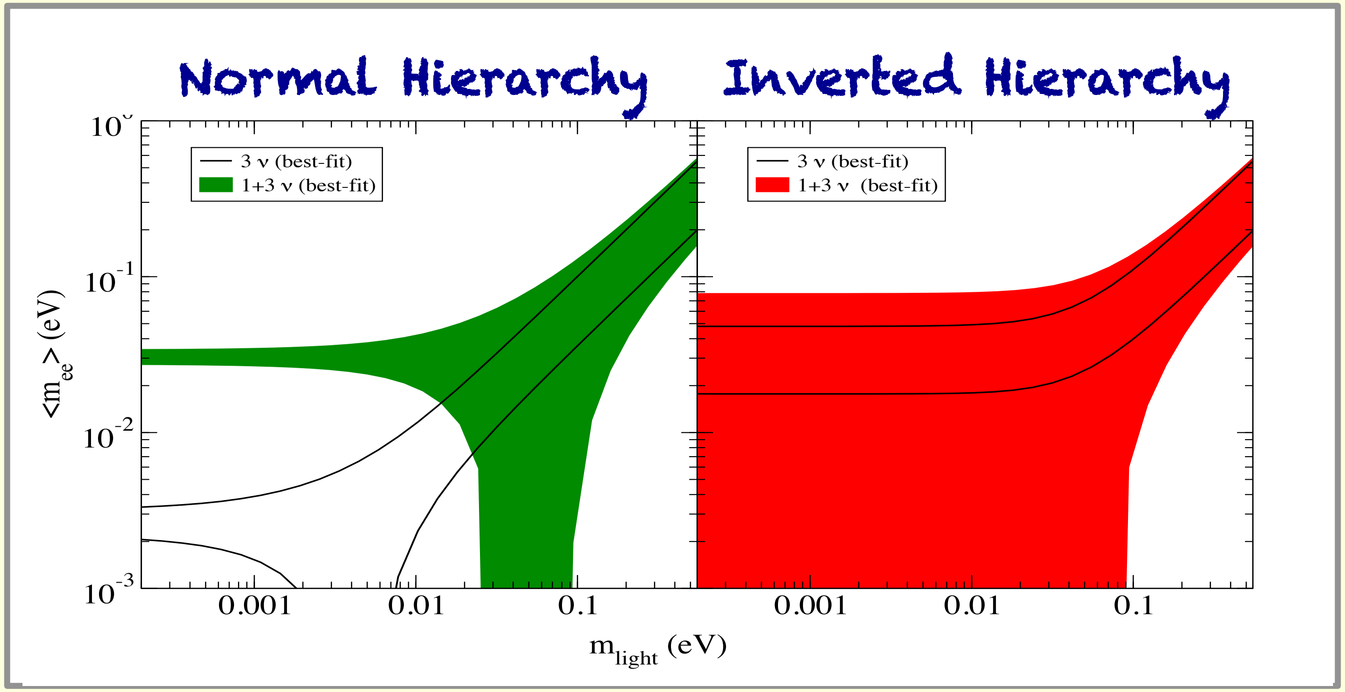


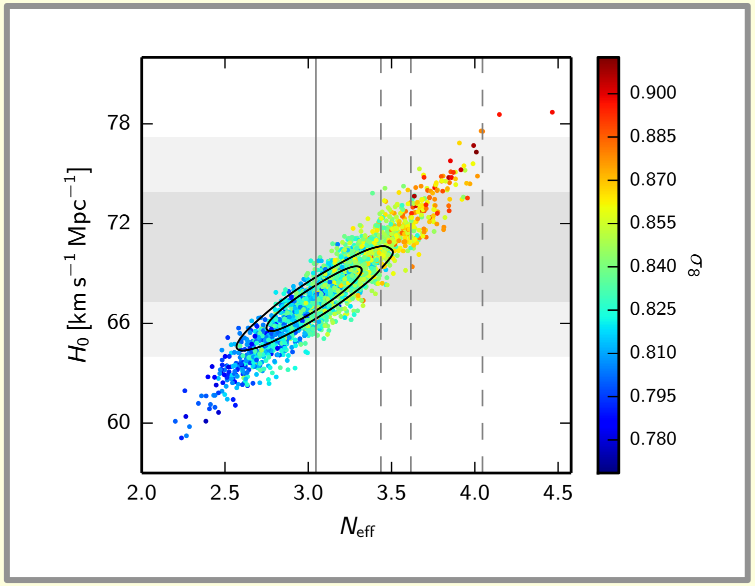
Figure from Barry, Rodejohann, Zhang, JHEP 1107, 091 (2011)

See also Girardi, Meroni, Petcov, JHEP 1311, 146 (2013)

Giunti and Zavanin, JHEP 1507, 171 (2015)

What cosmology tells us?

Planck (2015)



Small room for extra relativistic content

- A "standard" eV sterile neutrino fully thermalizes ($\Delta N_{\mathrm{eff}} = 1$)
- $\Delta N_{\mathrm{eff}} = 0$ requires a mechanism that prevents thermalization
- Several possibilities (lepton asymmetry, self-interactions, ...)

Summary

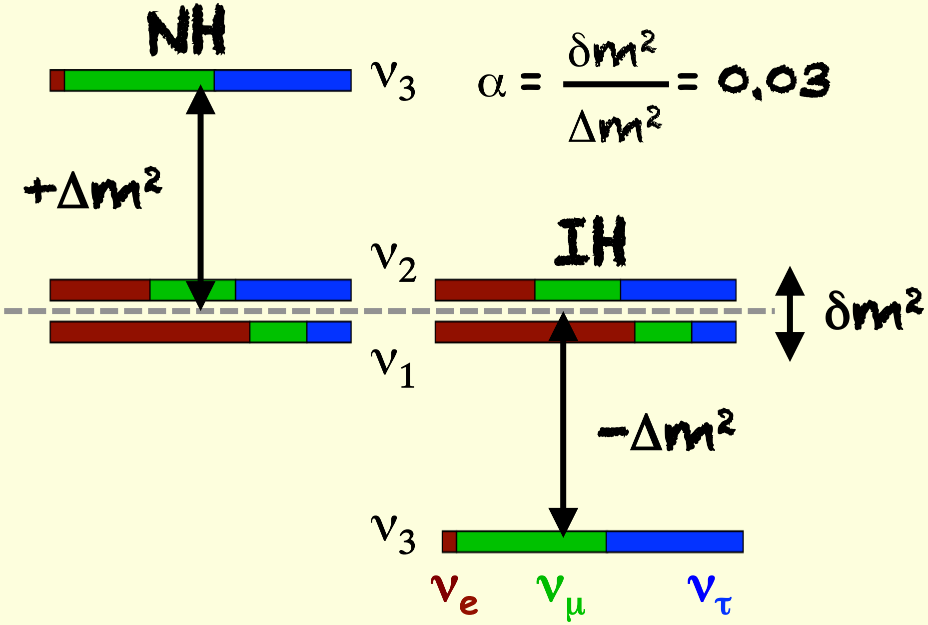
- Several SBL anomalies point to sterile neutrinos but the global picture is not clear (internal tension)
- New SBL experiments needed to shed light
- Sterile neutrinos are sources of additional CPV
- LBLs unique interferometers sensitive to CP-phases
- T2K and NOνA give already interesting information
- Sterile neutrinos may manifest in many other places

Be ready for a discovery!

Thank you
for your attention!

Back up slides

The 3-flavor scheme



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

unknowns:

CP-phase δ

(Hints of $\delta \neq 0, \pi$)

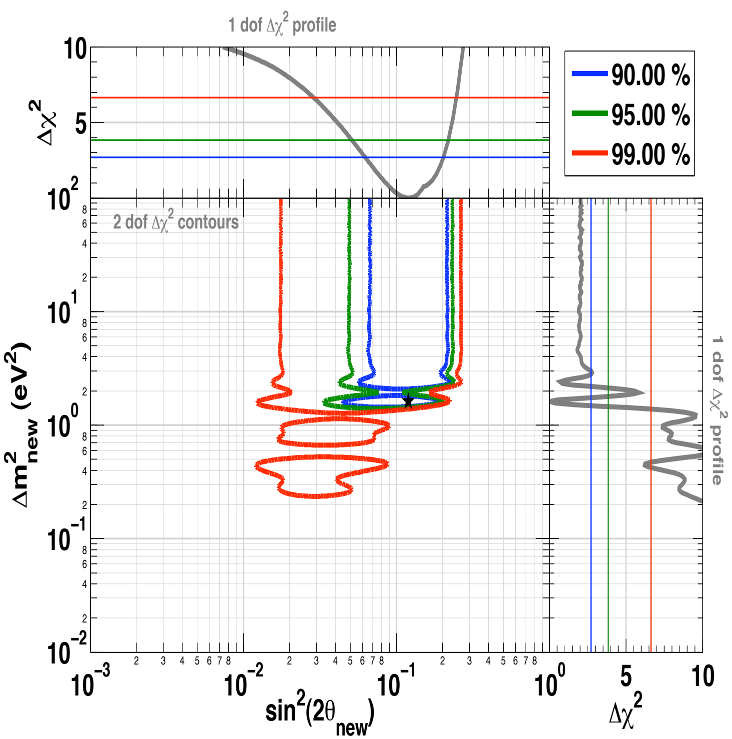
NMH

(Hints of NH)

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

$\theta_{23} \sim 41^\circ$ $\theta_{13} \sim 9^\circ$ $\theta_{12} \sim 34^\circ$

Fitting the reactor anomaly with sterile νs



In a 2ν framework:

$$P_{ee} \simeq 1 - \sin^2 2\theta_{new} \sin^2 \frac{\Delta m^2_{new} L}{4E}$$

In a 3+1 scheme:

$$P_{ee} = 1 - 4 \sum_{j>k} U^2_{ej} U^2_{ek} \sin^2 \frac{\Delta m^2_{jk} L}{4E}$$

$$\Delta m^2_{sol} \ll \Delta m^2_{atm} \ll \Delta m^2_{new}$$

$$\sin^2 \theta_{new} \simeq U^2_{e4} = \sin^2 \theta_{14}$$

Mention et al., PRD 83 073006 (2011)

CPV is a genuine 3-flavor effect

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

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

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

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

J is parameterization independent (Jarlskog invariant)

In the standard parameterization:

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

Conditions for CPV:

- No degenerate (ν_i, ν_j) ✔
- No $\theta_{ij} = (0, \pi/2)$ ✔
- $\delta \neq (0, \pi)$?

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

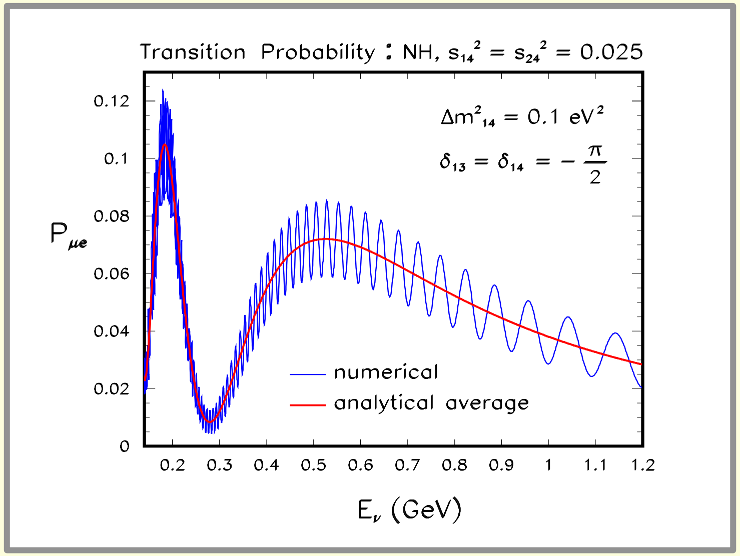
Osc. averaged out by finite E resol.

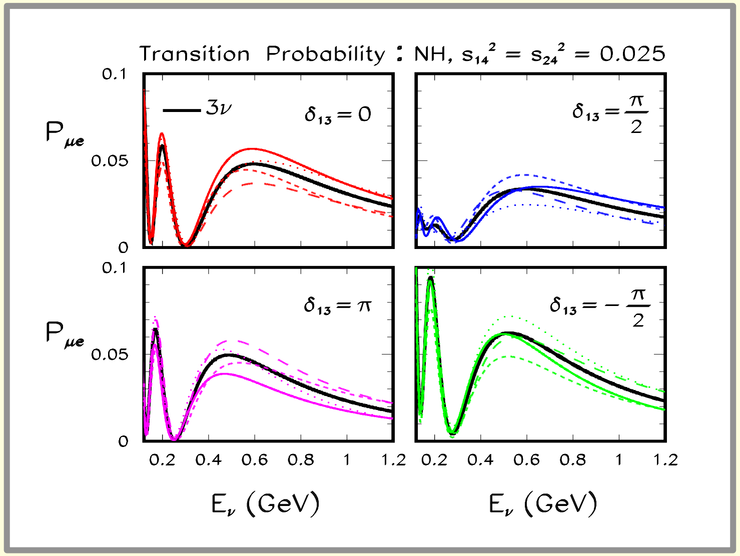
It can be: $\boxed{A^{\rm CP}_{\alpha\beta} \neq 0}$ (if $\sin\delta \neq 0$)

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)

Numerical examples of 4ν probability





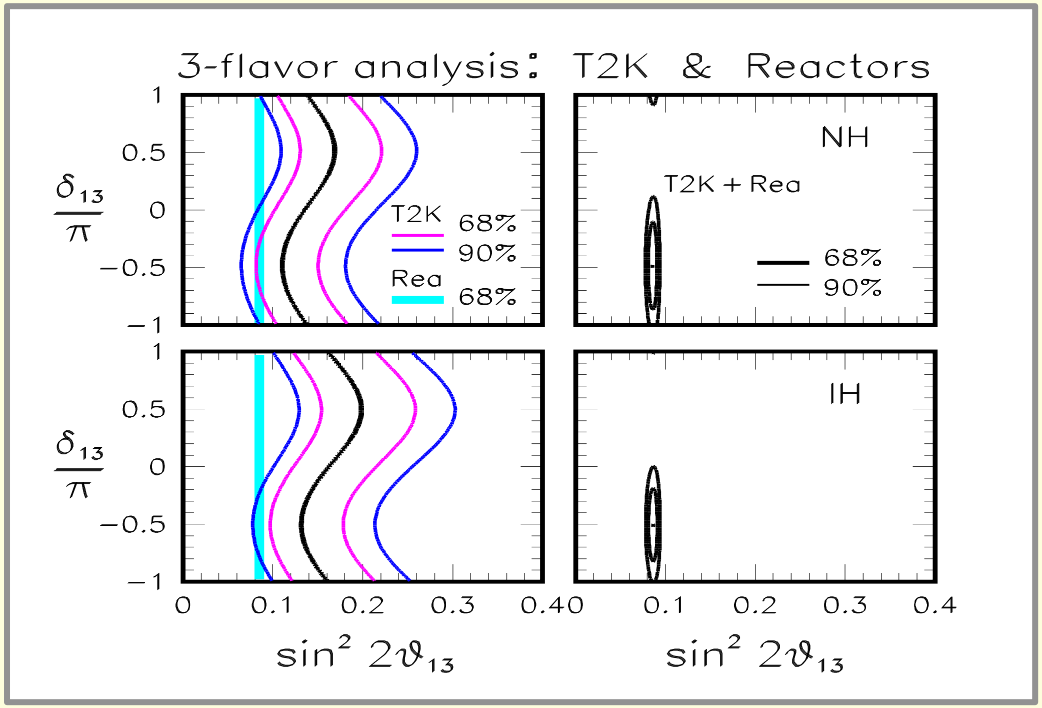
The fast oscillations get averaged out due to the finite energy resolution

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}

Completely analogous conclusions for NOνA

Some sensitivity to δ already from T2K + Rea



Slight θ_{13} mismatch T2K vs Reactors

No CPV ($\delta = 0, \pi$) disfavored at ~ 90% C.L.

Best fit $\delta \sim -\pi/2$

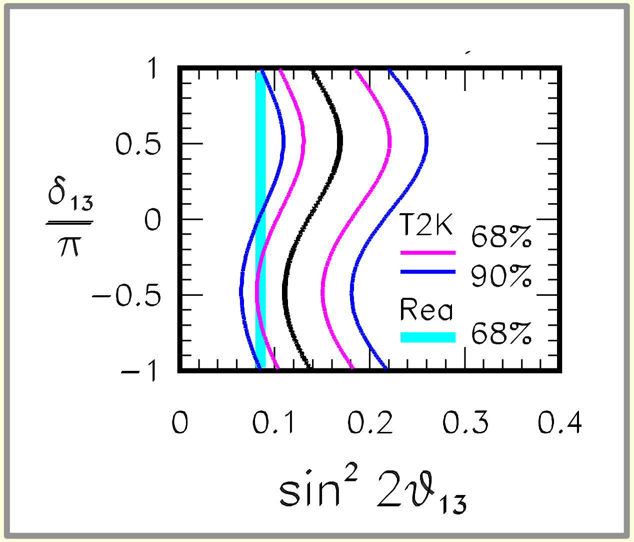
NH slightly favored $\Delta\chi^2 \sim -0.8$ (similar finding in SK atmospheric νs)

Note that δ is not extracted from observation of manifest CPV

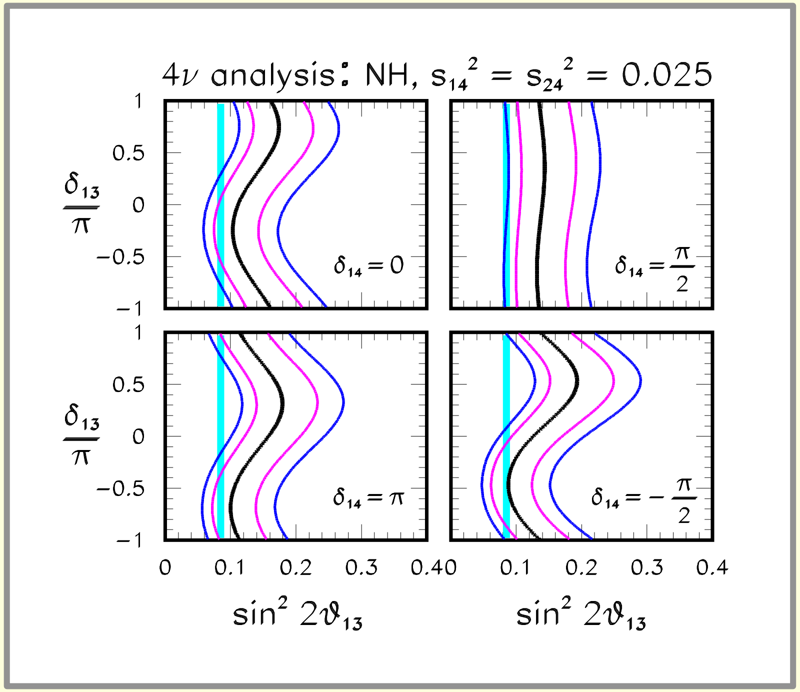
Combination of $\begin{cases} \text{Pee (}\delta\text{-independent), LBL Reactors} \\ \text{P}\mu\text{e (}\delta\text{-dependent), LBL Accelerators (T2K)} \end{cases}$

Results of the 4ν analysis (T2K, NH)

3ν: T2K



4ν

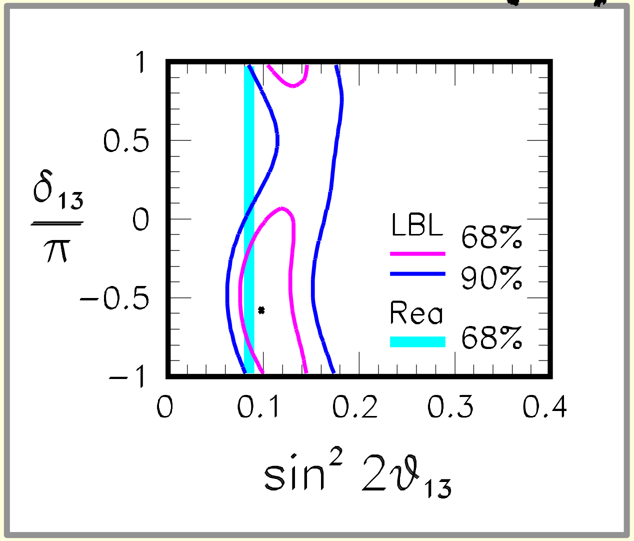


Similar findings in IH

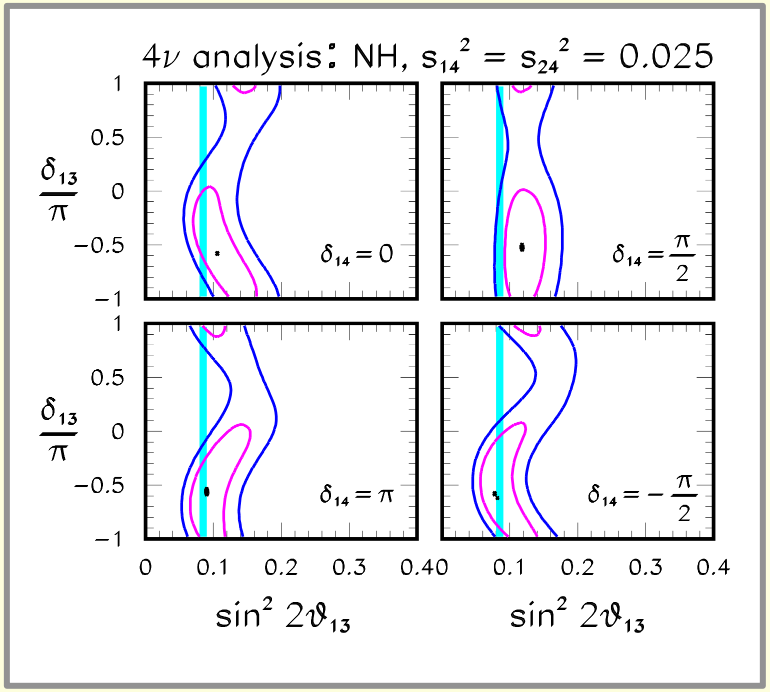
- Big impact on T2K "wiggles"
- 4ν gives better agreement of T2K & Reactors

Results of the 4ν analysis (LBL,NH)

3ν: T2K + NOνA (NH)

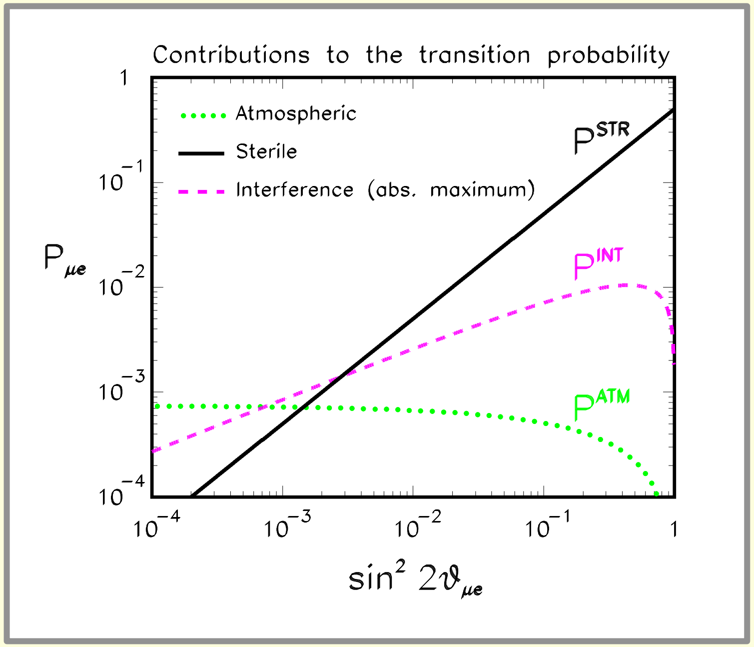


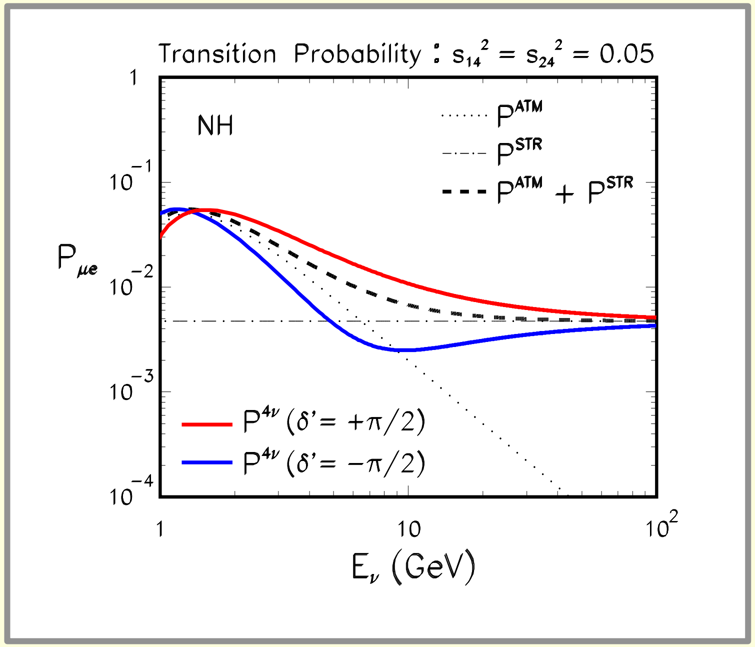
4ν



- LBL combination more stable than T2K alone

4ν effects at the CNGS beam





- Interference has substantial impact on P (ν_μ -> ν_e)
- The official analyses neglect the interference term
- Proper inclusion of such effects is necessary

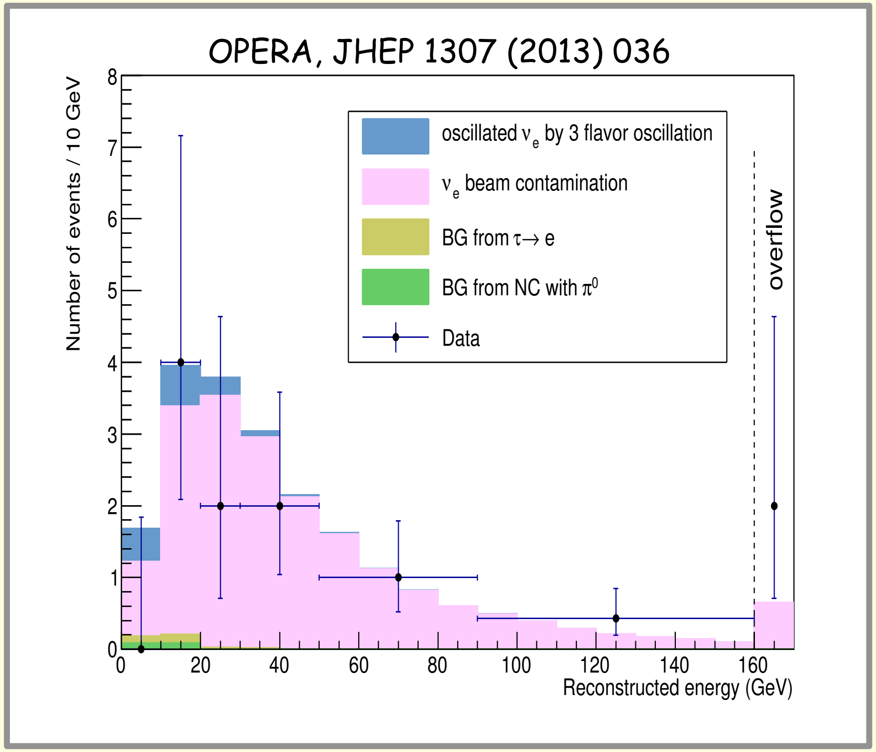
A further remark on 4ν effects

In a 4ν scheme:
$P_{ee} \sim 1 - 2\, U_{e4}^2 < 1$

ν_e bkg is not fixed!

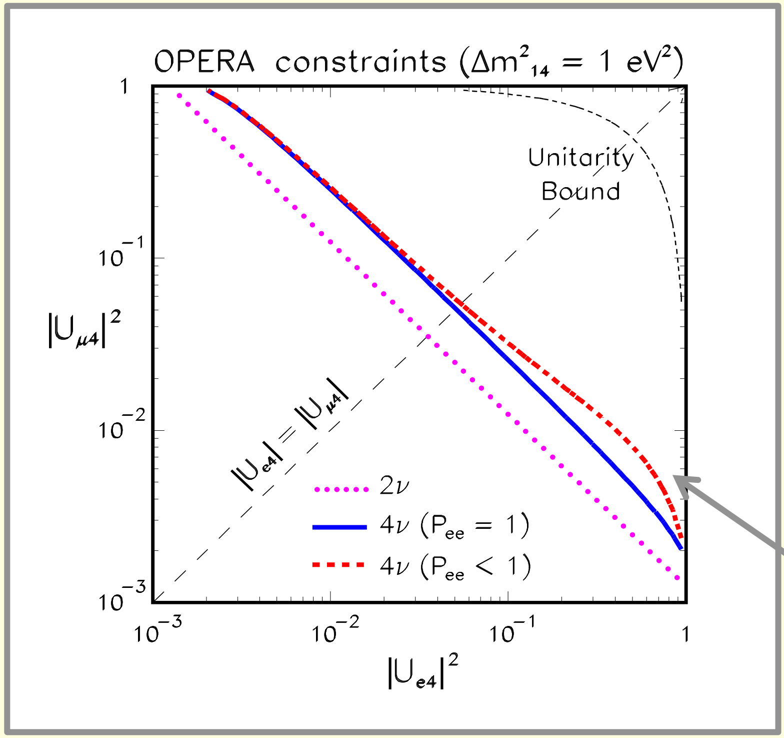
Relevant because ICARUS & OPERA are bkg-dominated

Measured # of events smaller than bkg



Expected bkg tends to be lower for $U_{e4} \neq 0$ allowing for a larger signal

General analysis with (U_{e4}, $U_{\mu 4}$) free



Fit prefers big values of $|U_{e4}|^2$

Larger values of $\sin^2 2\theta_{\mu e}$ tolerated

$\sin^2 2\theta_{\mu e} < 1.7 \times 10^{-2}$ at the 90% C.L.

Overall, bounds relaxed by a factor of 3 with respect to the 2-flavor case ($\sin^2 2\theta_{\mu e} < 5 \times 10^{-3}$)