Nu@Fermilab

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Sterile neutrinos and CP violation searches at LBL's

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Outline

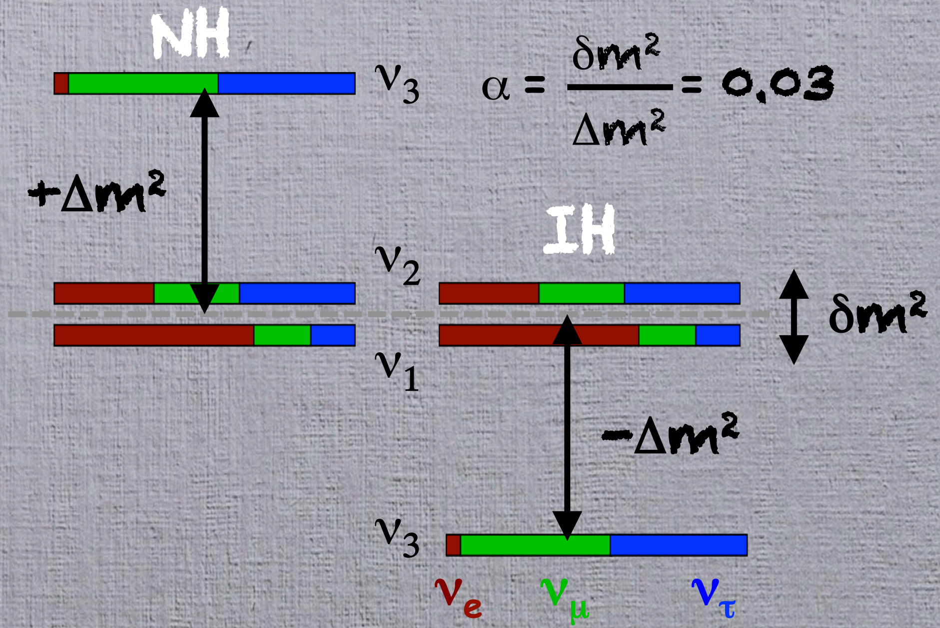
Introduction

- Imprints of the CP violation effects induced by sterile neutrinos in T2K

- Impact of the 4ν interference effects on the interpretation of ICARUS and OPERA

Conclusions

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

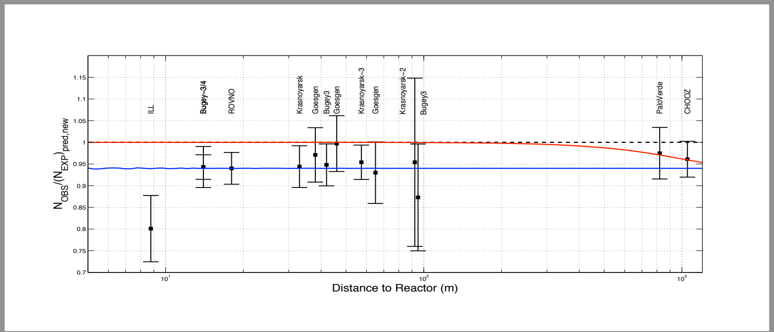
(Hints of NH)

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

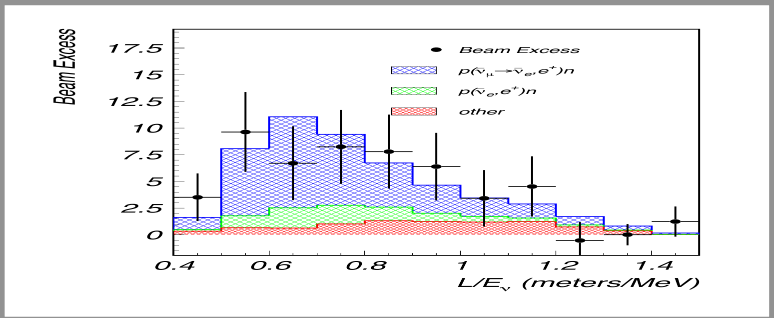
$\theta_{23} \sim 41^\circ$ $\theta_{13} \sim 9^\circ$ $\theta_{12} \sim 34^\circ$

SBL anomalies point to a 4th neutrino

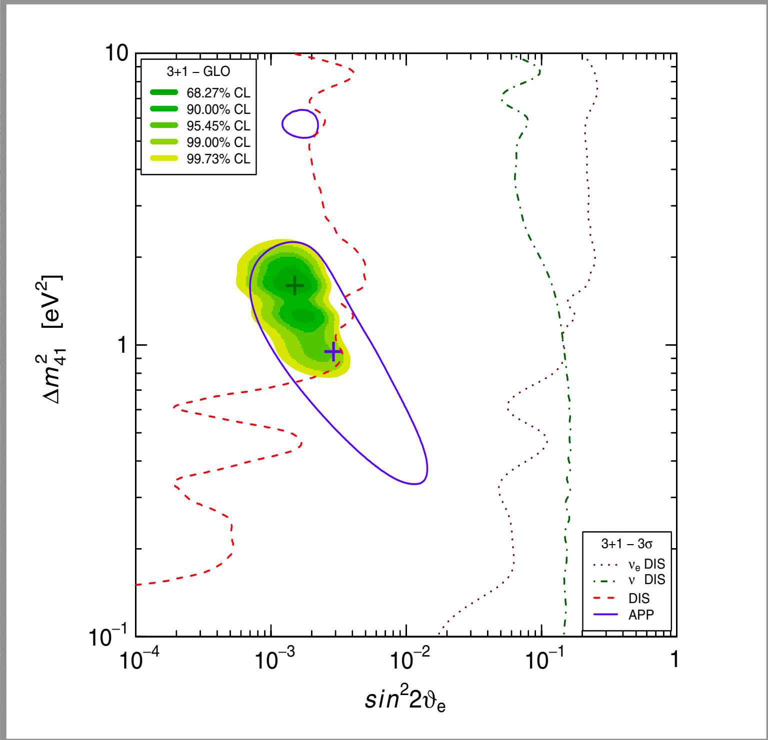
Reactor & Gallium: Pee < 1



Accelerators: Pμe > 0



Giunti et al., PRD 2013

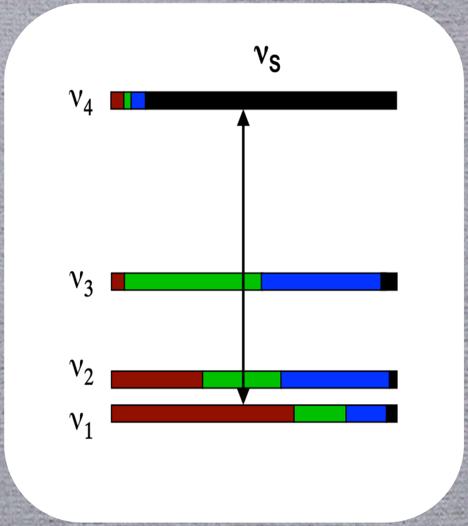


$$\frac{L}{E} \sim \frac{m}{\mathrm{MeV}} \quad \rightarrow \quad \begin{array}{l} \Delta_{12} \simeq 0 \\ \Delta_{13} \simeq 0 \end{array}$$

Need of a new larger Δm²
~ 1 eV²

Introducing a sterile neutrino

3+1 scheme



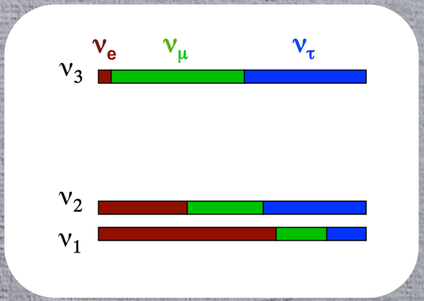
$|U_{s4}| \sim 1$

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

3ν scheme

Δm^2_{atm}

Δm^2_{sol}



Only small perturbations to the 3ν framework

However, 3ν CP-violation effects are very small!

Can new 4ν CPV effects compete with the 3ν ones?

Mixing matrix in 3+1 scheme

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

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

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

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

	3ν	3+1	3+N
mixing angles	3	6	3+3N
Dirac CP-phases	1	3	1+2N
Majorana phases	2	3	2+N

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

An important remark

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

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

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

Osc. averaged out by finite E resol.

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

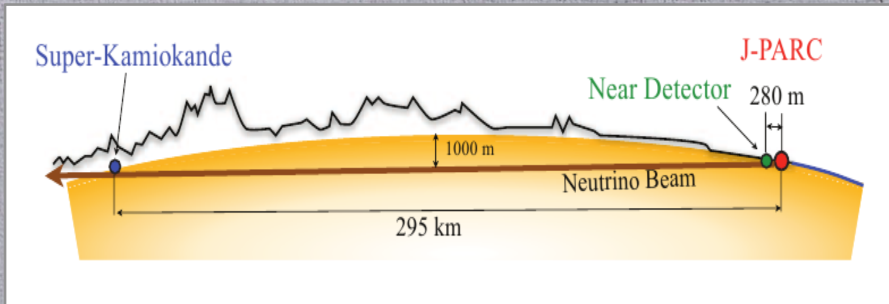
The bottom line is that if one of the three ν_i is ∞ far from the other two ones this does not erase CPV

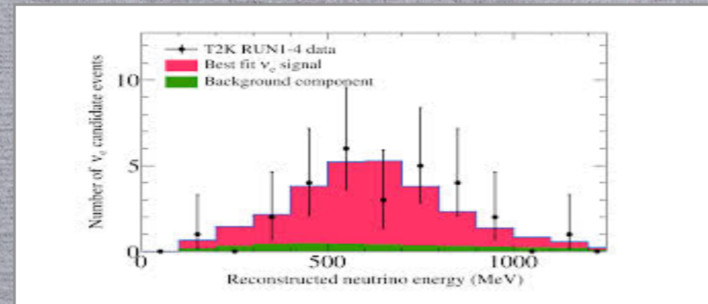
(relevant for the 4ν case)

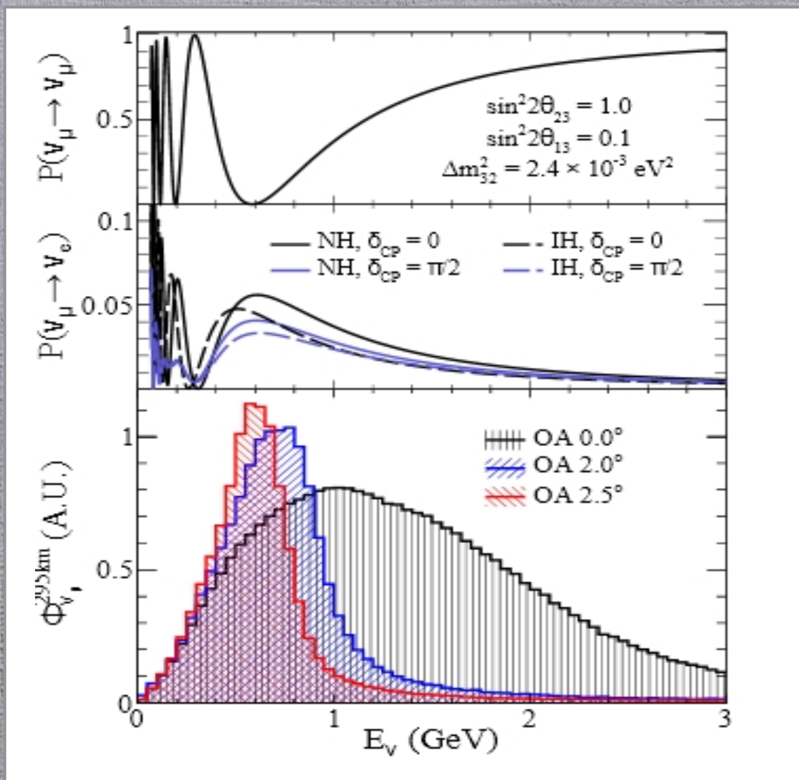
Hints on the new CP-phases from T2K (and θ_{13}-reactor experiments)

N. Klop and A.P., PRD 91 073017 (2015)

Outline of the T2K experiment







E = 0.6 GeV

L = 295 km

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

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

First oscillation maximum

T2K: 3-flavor transition probability

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

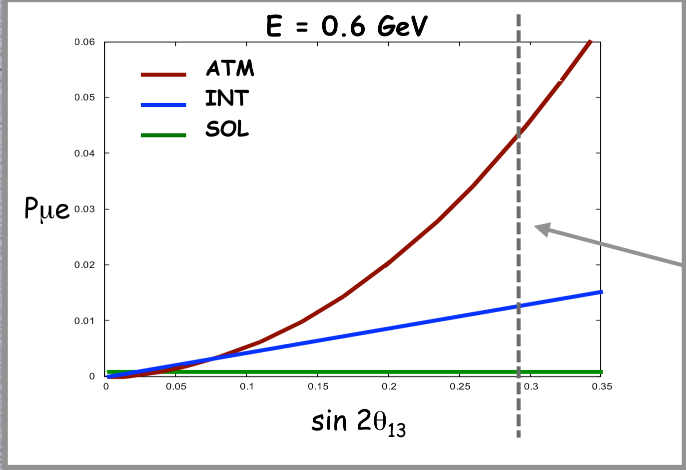
In vacuum:

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

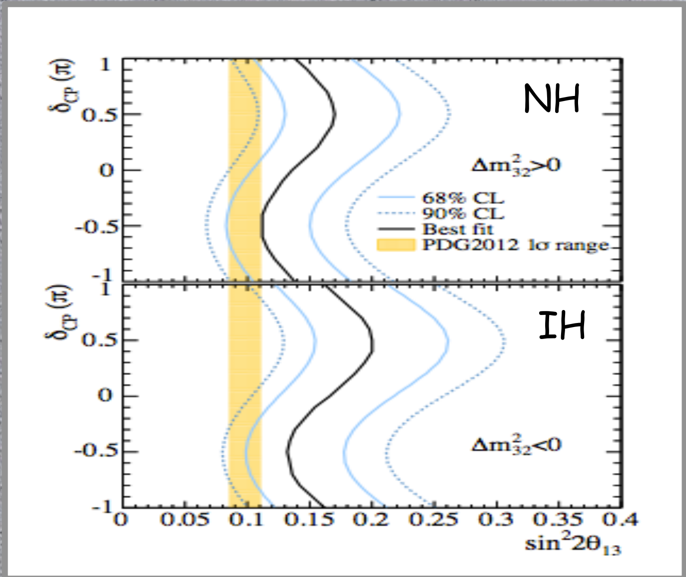
$$\Delta = \frac{\Delta m^2_{31} L}{4E}, \qquad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$\Delta \sim \pi/2$

$\alpha \sim 0.03$



best θ_{13} estimate



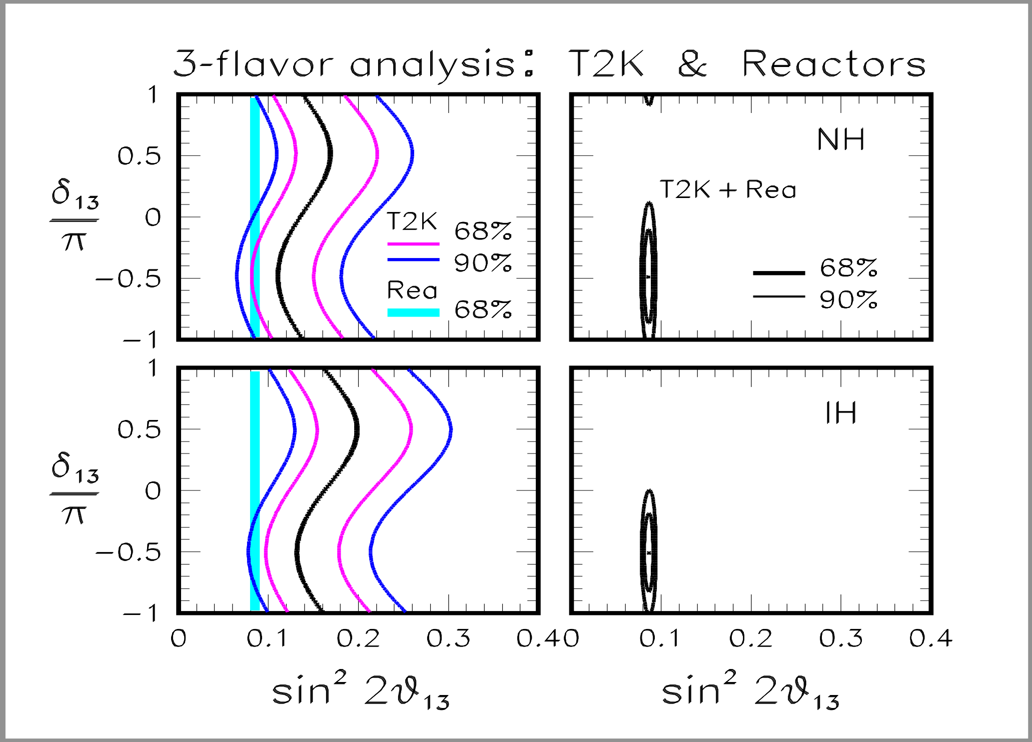
P^{ATM} leading → $\theta_{13} > 0$

P^{INT} subleading → δ dependence

P^{SOL} negligible

Matter effects induce some difference among NH and IH

Present data have some sensitivity to δ



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 $\Delta\chi^2 \sim -1$ (similar finding in SK atmospheric νs)

Note that δ is not extracted from observation of manifest CPV

Combination of
- Pee (δ-independent), LBL Reactors
- Pμe (δ-dependent), LBL Accelerators (T2K)

T2K: 4-flavor transition probability

- $\Delta m^2_{14} \gg \Delta m^2_{13}$: fast oscillations induced by Δm^2_{14} are averaged out
- Phase information (value of Δm^2_{14}) gets lost (in contrast to SBL)
- Unlike SBL, interf. of Δm^2_{14} & $\Delta m^2_{13,12}$ observable: sensitivity to CP-phases

In vacuum, for $\Delta m^2_{14} \to \infty$

$$
\begin{aligned}
P^{4\nu}_{\nu_\mu \to \nu_e} = & \; 4|U_{\mu3}|^2|U_{e3}|^2 \sin^2\Delta + 4|U_{\mu2}|^2|U_{e2}|^2(\alpha\Delta)^2 \\
& + 8|U^*_{\mu3}||U_{e3}||U_{\mu2}||U^*_{e2}|(\alpha\Delta)\sin\Delta\cos(\Delta+\delta_{13}) \\
& + 4|U^*_{\mu3}||U_{e3}||U_{\mu4}||U^*_{e4}|\sin\Delta\sin(\Delta+\delta_{13}-\delta_{14}) \\
& - 4|U^*_{\mu2}||U_{e2}||U_{\mu4}||U^*_{e4}|(\alpha\Delta)\sin\delta_{14} \\
& + 2|U_{\mu4}|^2|U_{e4}|^2
\end{aligned}
$$

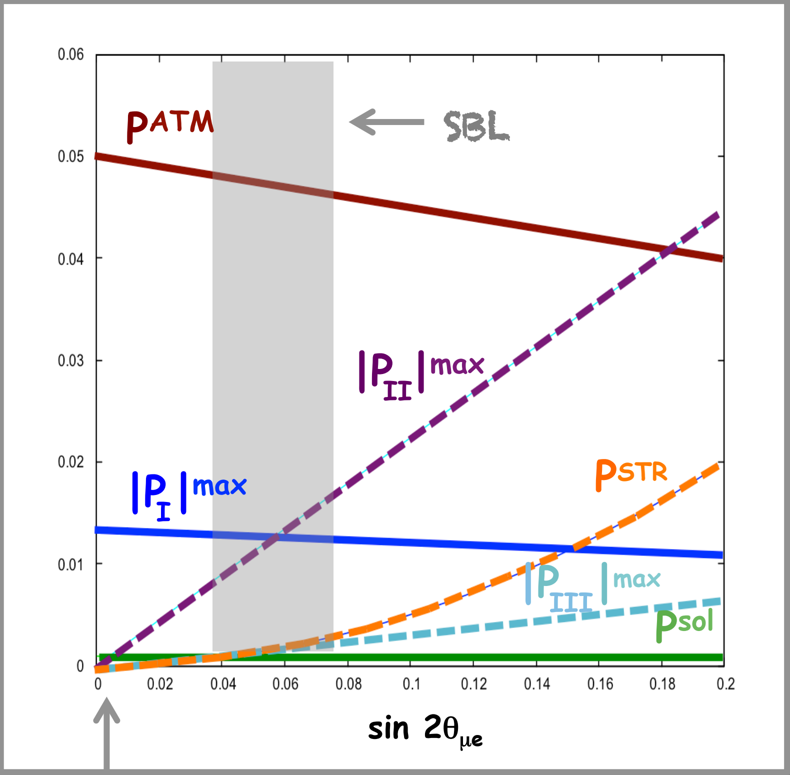
$$P^{4\nu}_{\nu_\mu\to\nu_e} \sim (1-|U_{e4}|^2-|U_{\mu4}|^2)P^{3\nu}_{\mu e} + P^{\rm INT}_{\rm II} + P^{\rm INT}_{\rm III} + P^{\rm STR}$$

$$
\begin{aligned}
P^{\rm INT}_{\rm II} &= 2\sin 2\theta_{\mu e} s_{13}s_{23}\sin\Delta\sin(\Delta+\delta_{13}-\delta_{14}) \\
P^{\rm INT}_{\rm III} &= -2\sin 2\theta_{\mu e} c_{23}s_{12}c_{12}(\alpha\Delta)\sin\delta_{14} \\
P^{\rm STR} &= \frac{1}{2}\sin^2 2\theta_{\mu e}.
\end{aligned}
$$

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu4}|^2$$

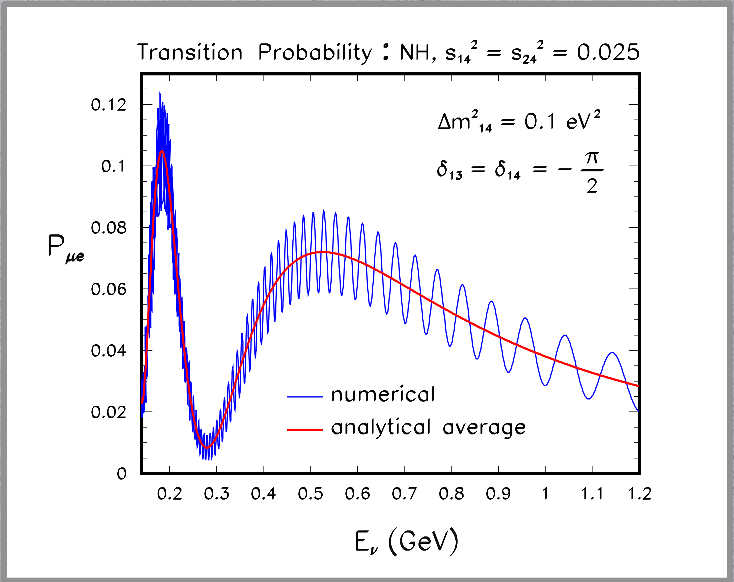
$P^{\rm INT}_{\rm II}$ can be as large as $P^{\rm INT}_{\rm I}$

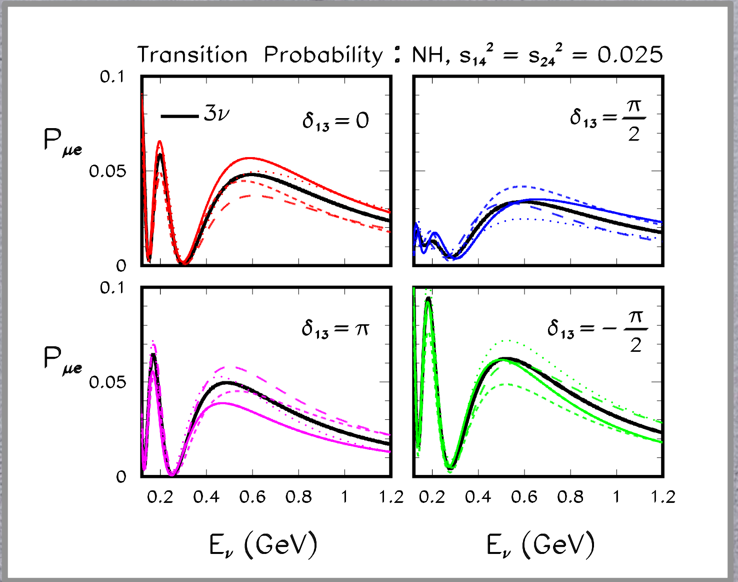
$\theta_{13} = 9°$ E = 0.6 GeV



3ν limit

Numerical examples of 4ν probability



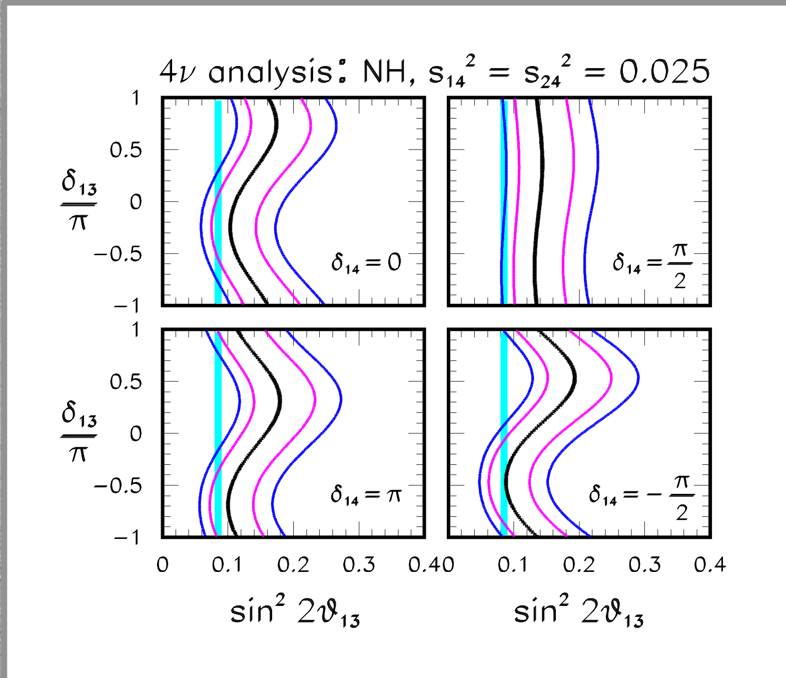


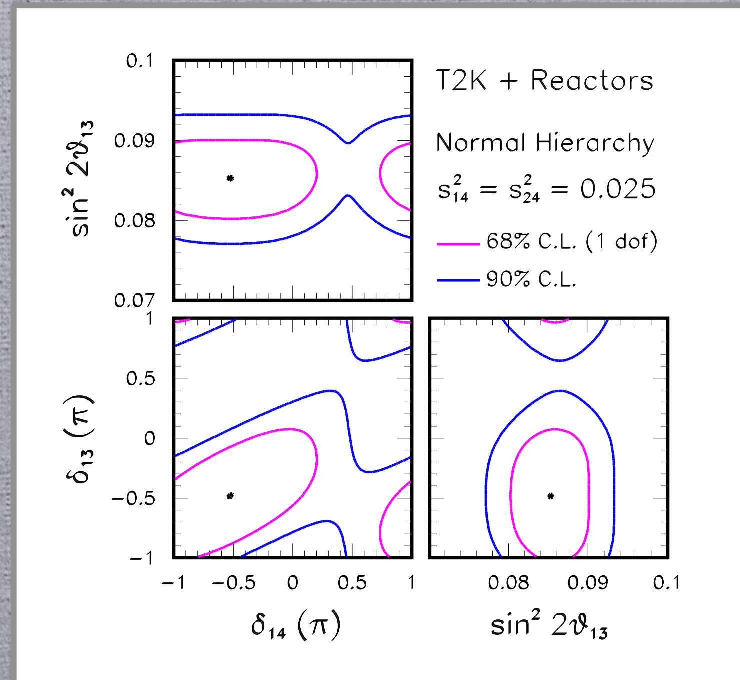
The fast oscillations get averaged out due to the finite energy resolution

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}

Results of the 4ν analysis (NH)





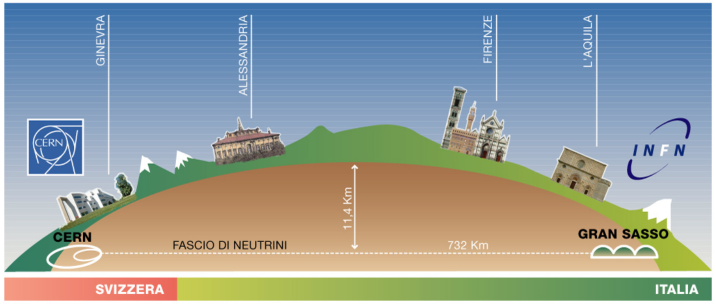
Similar findings in IH

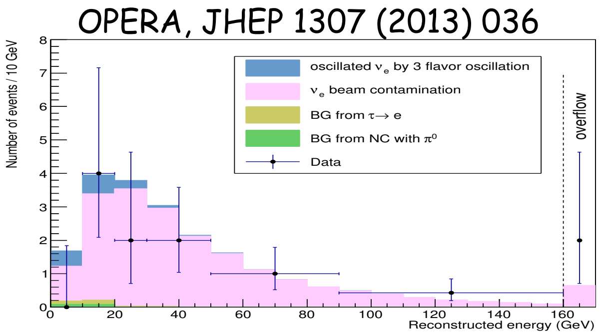
- Big impact on T2K "wiggles"
- Comparable sensitivity to δ_{13} & δ_{14}
- Best fit values: $\delta_{13} \sim \delta_{14} \sim -\pi/2$
- 4ν gives better agreement of T2K & Reactors

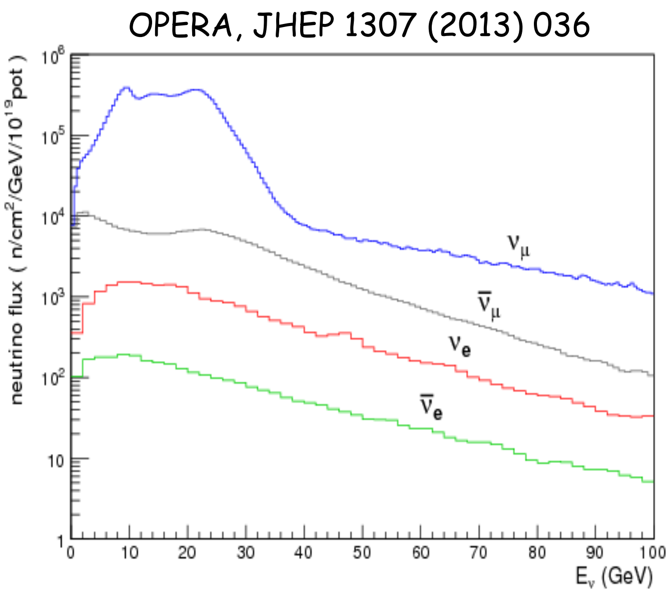
Impact of the new CP-phases on the interpretation of the $\nu_\mu \rightarrow \nu_e$ sterile ν searches of ICARUS & OPERA

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

Outline of the CNGS experiments







$\langle E \rangle$ = 17 GeV

L = 732 km

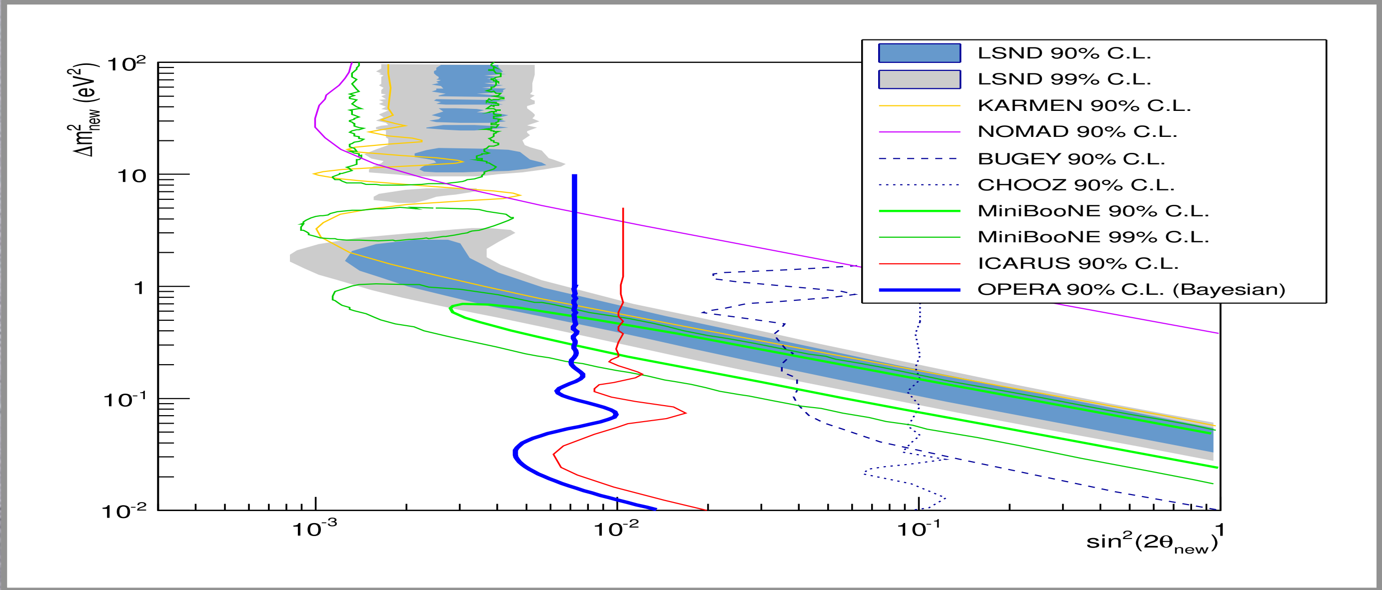
Δm^2_{13} = 2.4 x 10^{-3}

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

3ν oscillations play a minor role

Good place where to look for sterile νs

Official bounds from OPERA & ICARUS

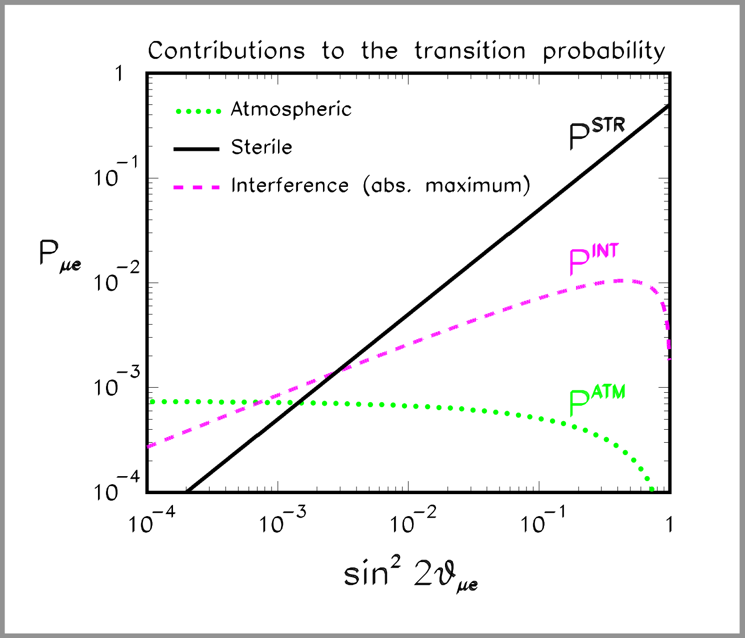


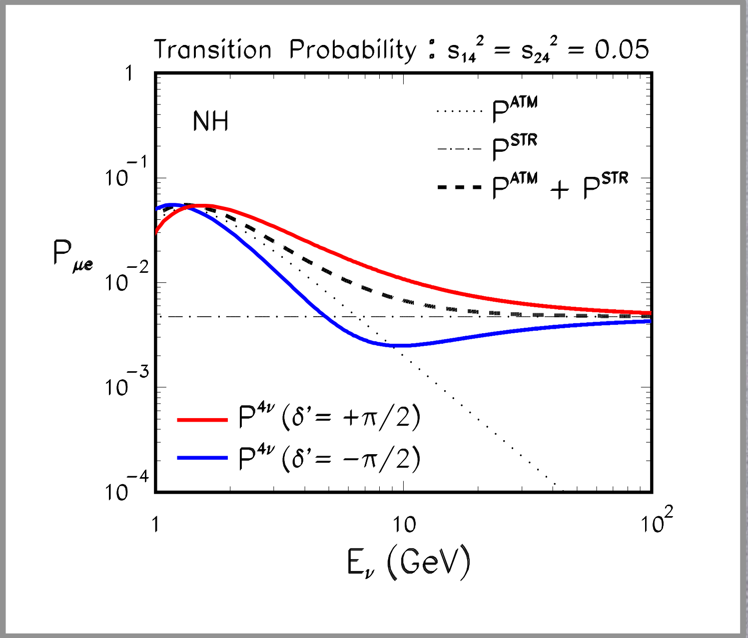
2-flavor treatment adopted by both collaborations

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

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

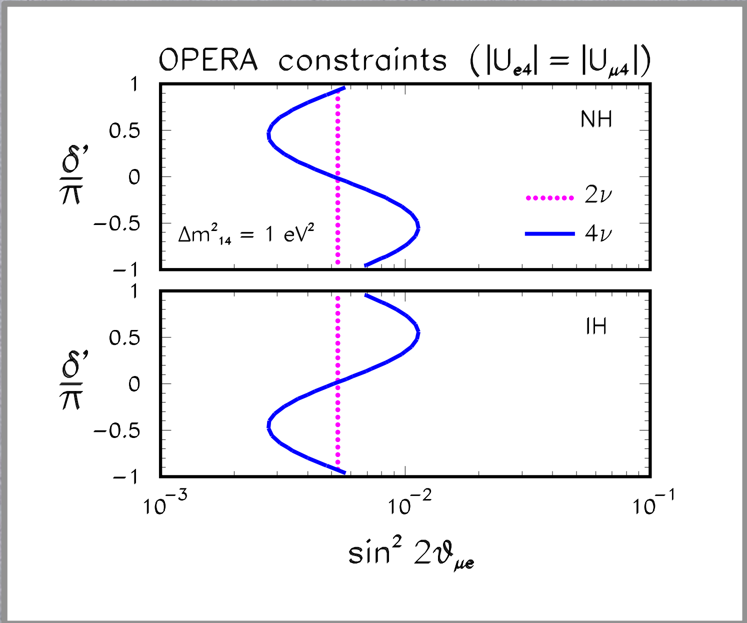
4ν effects at the CNGS beam

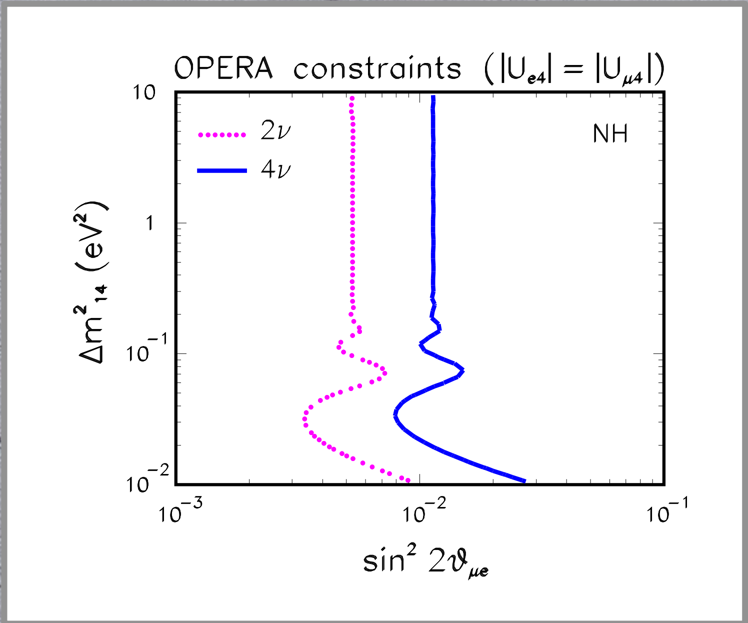




- Interference has substantial impact on P ($\nu_\mu \to \nu_e$)
- The official analyses neglect the interference term
- Proper inclusion of such effects is necessary

Impact of the 4ν interference term





Upper bound depends on the (unknown) CP-phase δ'

After marginalization of the CP-phase...

The upper bounds get relaxed by a factor of two

(2ν) $\sin^2 2\theta_{\mu e} < 5 \times 10^{-3}$ –> (4ν) $\sin^2 2\theta_{\mu e} < 1.2 \times 10^{-2}$

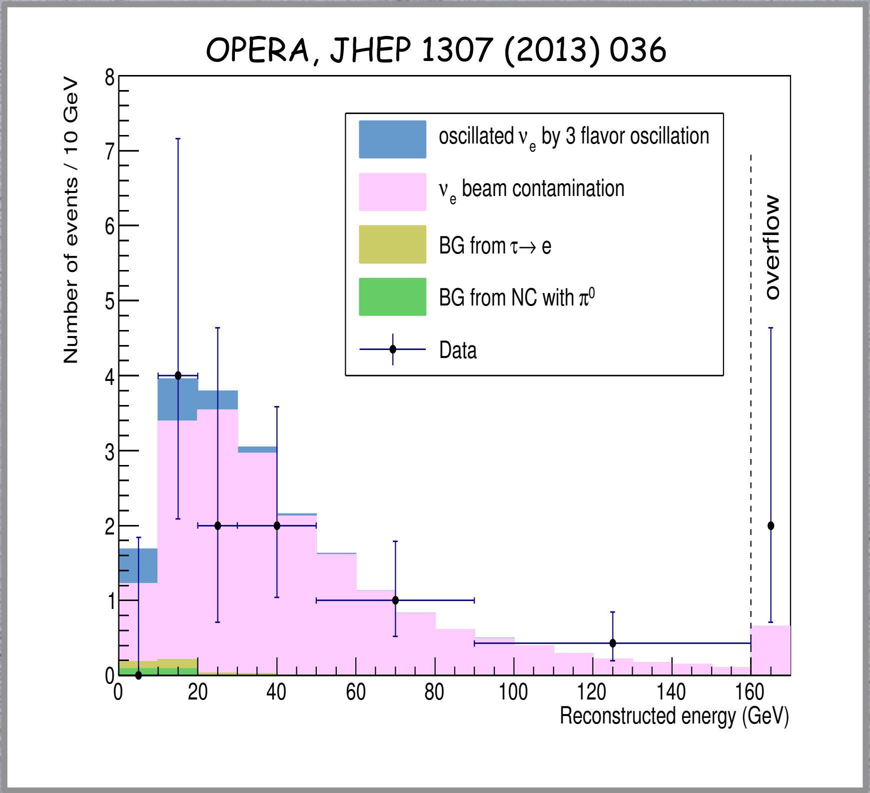
A further remark on 4ν effects

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

ν_e bkg is not fixed!

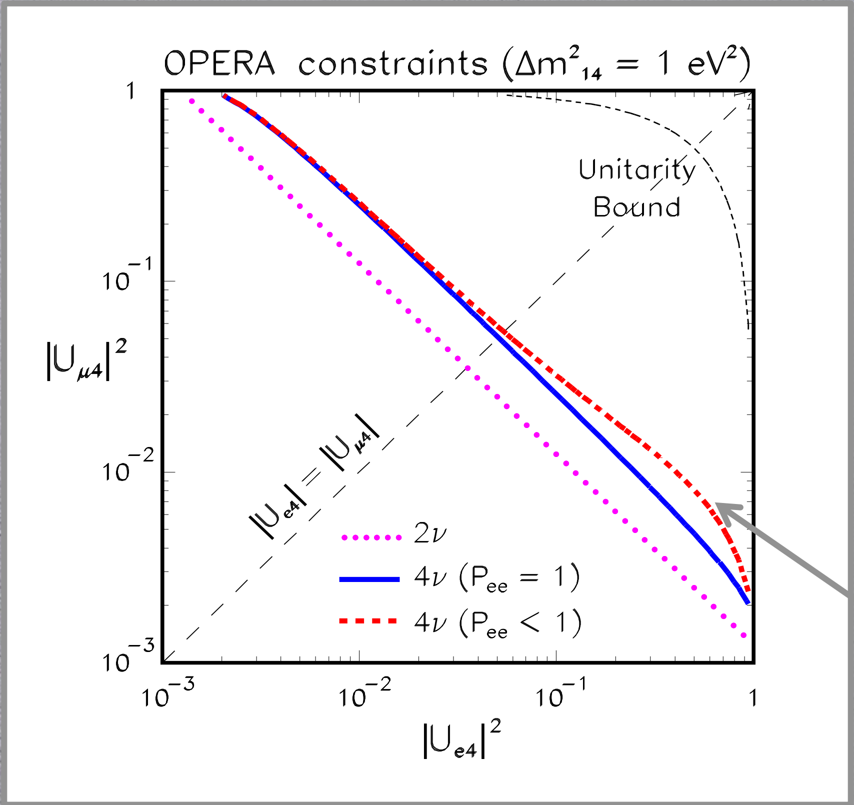
Relevant because ICARUS & OPERA are bkg-dominated

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}, $U_{\mu4}$) 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 ($\sin^2 2\theta_{\mu e} < 5 \times 10^{-3}$)

Summary

- Several indications of light sterile ν species
- Sterile neutrinos are sources of additional CPV
- LBL expts. can give info on the new CP-phases
- The experiment T2K has already some sensitivity
- Accurate treatment of 4ν effects is important for a correct interpretation of the LBL results

Investigation of sterile νs and related CPV at LBL experiments is a unique opportunity

Back up slides

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 $\theta_{ij} = (0, \pi/2)$ ✔
- $\delta \neq (0, \pi)$?

Results of the T2K 4ν analysis (IH)