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Search for sterile neutrinos at Long-BL

- The present scenario and the "sterile" issue at 1 eV mass scale
- OPERA results for $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ searches
- Other results from MINOS and SuperK
- Perspectives and Conclusions

The "sterile" issue

From masses to flavours:

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$
$$|\nu_\mu\rangle = U_{\mu 1}|\nu_1\rangle + U_{\mu 2}|\nu_2\rangle + U_{e\mu 3}|\nu_3\rangle$$
$$|\nu_\tau\rangle = U_{\tau 1}|\nu_1\rangle + U_{\tau 2}|\nu_2\rangle + U_{\tau 3}|\nu_3\rangle$$

U is the 3 × 3 Neutrino Mixing Matrix
mixing given by 3 angles, θ_{23}, θ_{12}, θ_{13}

transition amplitudes driven by
$\Delta m^2_{solar} = \Delta m^2_{21}$
$\Delta m^2_{atm} = |\Delta m^2_{31}| \approx |\Delta m^2_{32}|$

The wonderful frame pinpointed for the 3 standard neutrinos, beautifully adjusted by the θ_{13} measurement, left out some relevant questions:

- Leptonic CP violation
- Mass values
- Dark Matter
- Anomalies and discrepancies in several results

The “sterile” issue (cnt.)

The previous picture is working wonderfully.
So it should stay whenever extensions are allowed !

Exploit 3+1 or even 3+2 oscillating models, by adding one or more “**sterile**” neutrinos

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

APPEARANCE

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

DISAPPEARANCE

when $\Delta m_{21}^2 << \Delta m_{31}^2 << \Delta m_{41}^2$ and $\left|U_{s4}^2\right| \leq 1$

with

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

for **APPEARANCE**

and

$$\sin^2 2\theta_{ee} = 4\left|U_{e4}\right|^2 \left(1 - \left|U_{e4}\right|^2\right)$$

$$\sin^2 2\theta_{\mu\mu} = 4\left|U_{\mu 4}\right|^2 \left(1 - \left|U_{\mu 4}\right|^2\right)$$

for **DISAPPEARANCE**

sterile: *not weakly interacting neutrinos* (B. Pontecorvo, JETP, 53, 1717, 1967)

The "sterile" issue (cnt.)

➔ Experimental hints for more than 3 standard neutrinos, at eV scale
➔ Strong tension with any formal extension of 3x3 mixing matrix

ν_e disappearance

Reactor anomaly ~2.5σ
Re-analisys of data on anti-neutrino flux from reactor short-baseline (L~10-100 m) shows a small deficit of
R=0.943 ±0.023
G.Mention et al, Phys.Rev.D83, 073006 (2011) , A.Mueller et al. Phys.Rev.C **83,** 054615 (2011).

Gallex/SAGE anomaly ~3σ
Deficit observed by Gallex in neutrinos coming from a ^{51}Cr and ^{37}Ar sources
***R* = 0.76+0.09 −0.08**
C. Giunti and M. Laveder, Phys.Rev. C83, 065504 (2011), arXiv:1006.3244

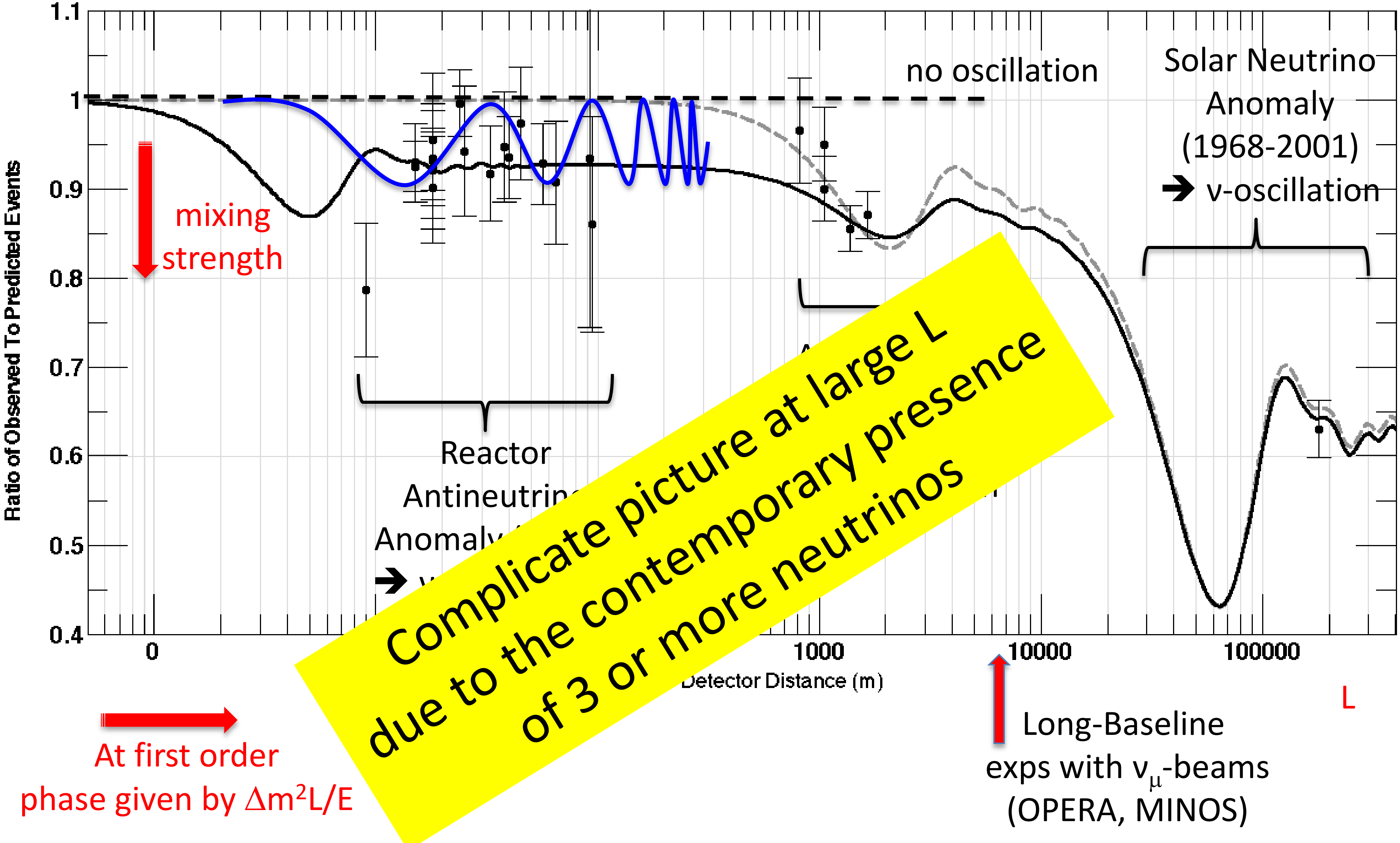
ν_e appearance

Accelerator anomaly ~3.8σ
Appearance of anti-ν_e in a anti-ν_μ beam (LSND). *A.Aguilar et al. LSND Collaboration Phys.Rev.D 64 112007 (2001).*

Confirmed (?) by miniBooNE (which also sees appearance of ν_e in a ν_μ beam) *A.Aguilar et al. (MiniBooNE Collaboration) Phys.Rev.Lett. 110 161801 (2013)*

No hint so far for
- **ν_μ disappearance**
- **ν_τ appearance/disappearance**

The oscillation scenario in terms of distance **L** from the source



➔for L/E >>1 the disappearance averages to ½ of mixing strength: $\sin^2(\Delta m^2 L/4E)=0.5$

Tau appearance in the presence of a sterile neutrino (3+1)

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

neglect solar driven oscillation $\Delta_{21} \sim 0$

~ standard oscillation

pure exotic oscillation

interference terms

$$P_{\nu_\mu \to \nu_\tau} = 4|U_{\mu 3}|^2 |U_{\tau 3}|^2 \sin^2 \frac{\Delta_{31}}{2} + 4|U_{\mu 4}|^2 |U_{\tau 4}|^2 \sin^2 \frac{\Delta_{41}}{2}$$
$$+ 2\Re[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin \Delta_{31} \sin \Delta_{41}$$
$$- 4\Im[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin^2 \frac{\Delta_{31}}{2} \sin \Delta_{41}$$
$$+ 8\Re[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2}$$
$$+ 4\Im[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2}$$

$$C = 2|U_{\mu 3}||U_{\tau 3}|$$
$$\phi = Arg(U^\star_{\mu 3} U^\star_{\tau 3} U^\star_{\mu 4} U^\star_{\tau 4})$$
$$\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$$

(effective mixing)

$$P(Energy) = C^2 \sin^2 \frac{\Delta_{31}}{2} + \sin^2 2\theta_{\mu\tau} \sin^2 \frac{\Delta_{41}}{2}$$
$$+ \frac{1}{2} C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin \Delta_{31} \sin \Delta_{41}$$
$$- C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin \Delta_{41}$$
$$+ 2\, C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2}$$
$$+ C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2}$$

CP-violating

Mass Hierarchy dependence

At Long-Baselines and eV mass scale:

$$\sin \Delta_{41} \approx 0$$

$$\sin^2 \frac{\Delta_{41}}{2} \approx \frac{1}{2}$$

$$P(Energy) = C^2 \sin^2 \frac{\Delta_{31}}{2} + \frac{1}{2} \sin^2 2\theta_{\mu\tau} + C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} + \frac{1}{2} C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin \Delta_{31}$$

Sensitive to mixing "sterile" angles, MH and phase CP-violation

Separate analyses for NH and IH and maximize Likelihood as $L(\phi_{\mu\tau}, \sin^2 \theta_{\mu\tau}, C^2)$

Use $|\Delta m^2_{31}|$=0.00243 eV^2 for NH and 0.00238 eV^2 for IH

effective mixing of sterile with ν_μ and ν_τ

effective mixing of standard $\nu_\mu - \nu_\tau$ oscillation

OPERA search for ν_τ sterile "anomalies"

just published in JHEP, 6, 69 (2015) and arXiv:1503.01876, based on 4 taus' candidates

Separate analyses for "high" and low $|\Delta m^2_{41}|$

For $|\Delta m^2_{41}| > 1\ eV^2$ → $\sin^2 2\theta_{\mu\tau} < 0.116$ at 90% C.L.

when integrating over ϕ

(quasi-equal results for NH and IH)

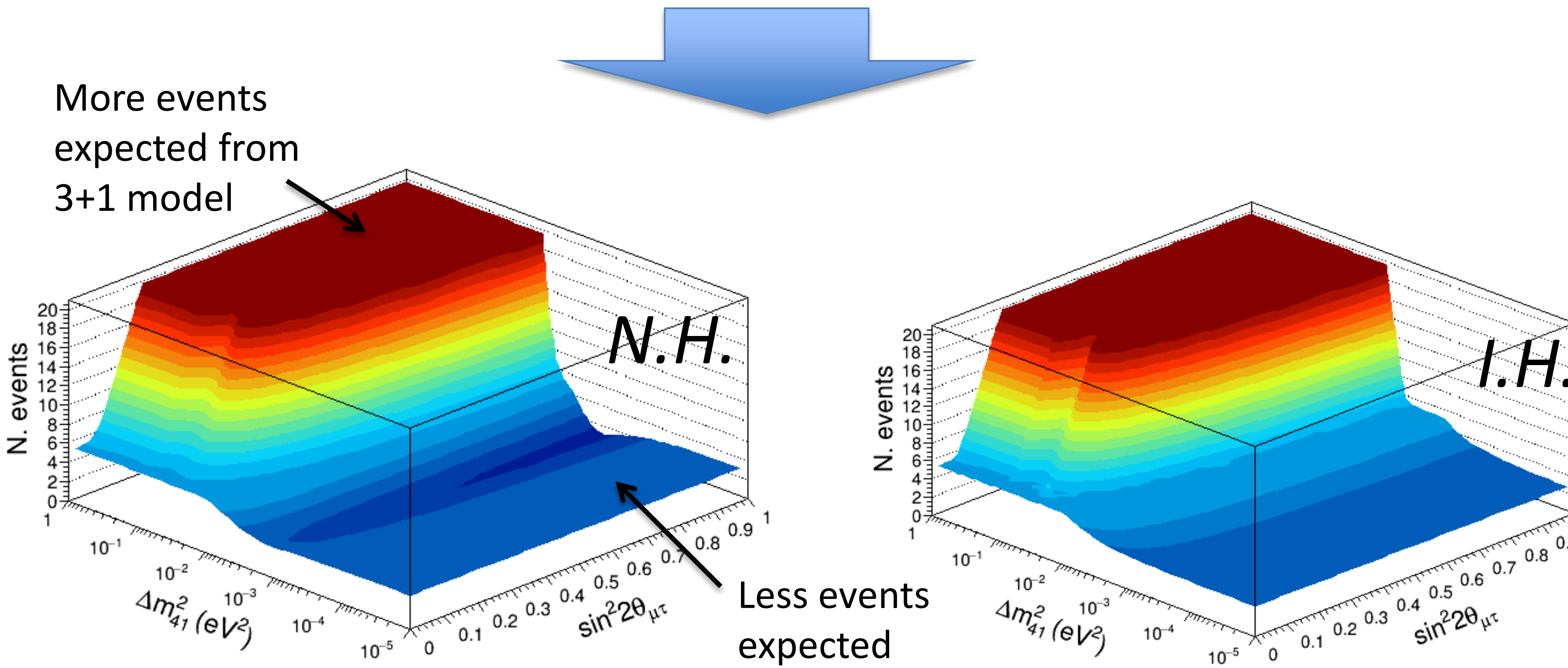
Note: 0.069 obtained if neglect interference terms

OPERA just observed a 5th candidate ! *(arXiv:1507.01417, submitted to PRL)*

Channel	Expected background				Expected signal	Observed
	Charm	Had. re-interac.	Large μ-scat.	Total		
$\tau \to 1h$	0.017 ± 0.003	0.022 ± 0.006	–	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.003 ± 0.001	–	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001	–	0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \to e$	0.03 ± 0.01	–	–	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.22 ± 0.04	0.02 ± 0.01	0.0002 ± 0.0001	0.25 ± 0.05	2.64 ± 0.53	5

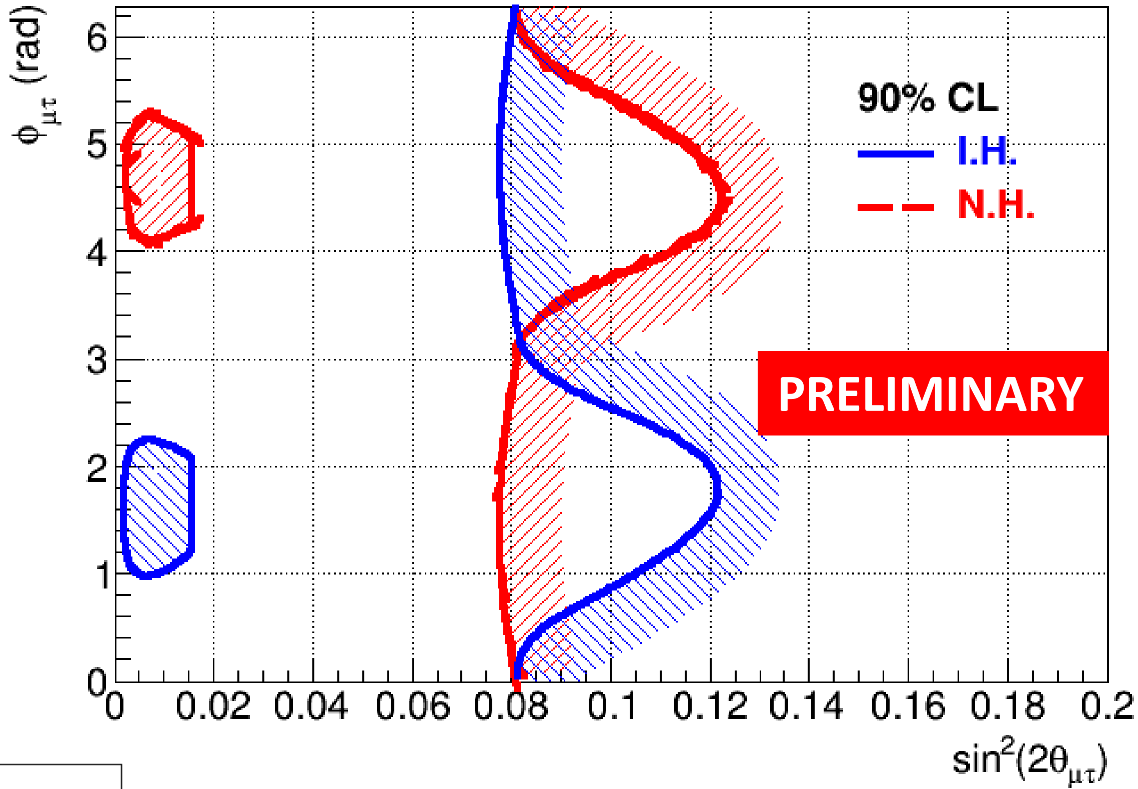
NEW: preliminary update of the analysis with 5 ν_τ candidates

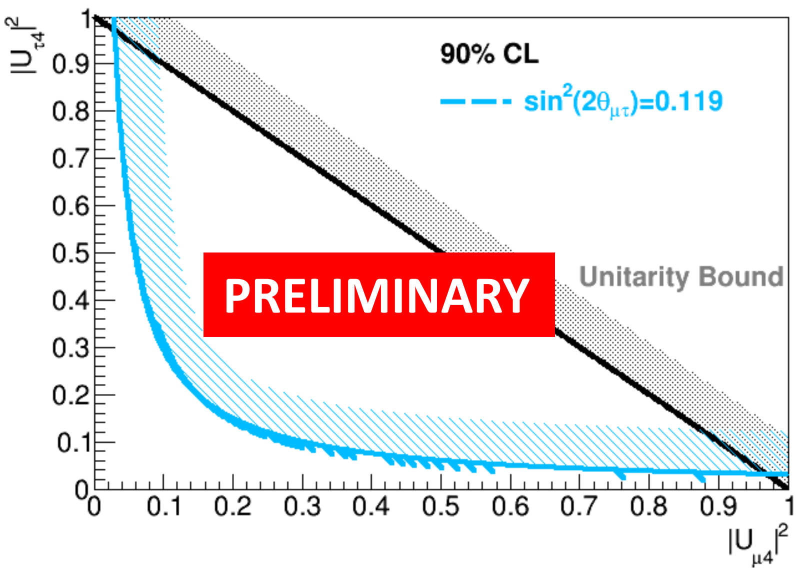
Interplay of interference



For $|\Delta m^2_{41}| > 1$ eV^2

(Raster-scan à la Feldman&Cousins)





$\sin^2 2\theta_{\mu\tau} < 0.119$ at 90% C.L.

when integrating over ϕ

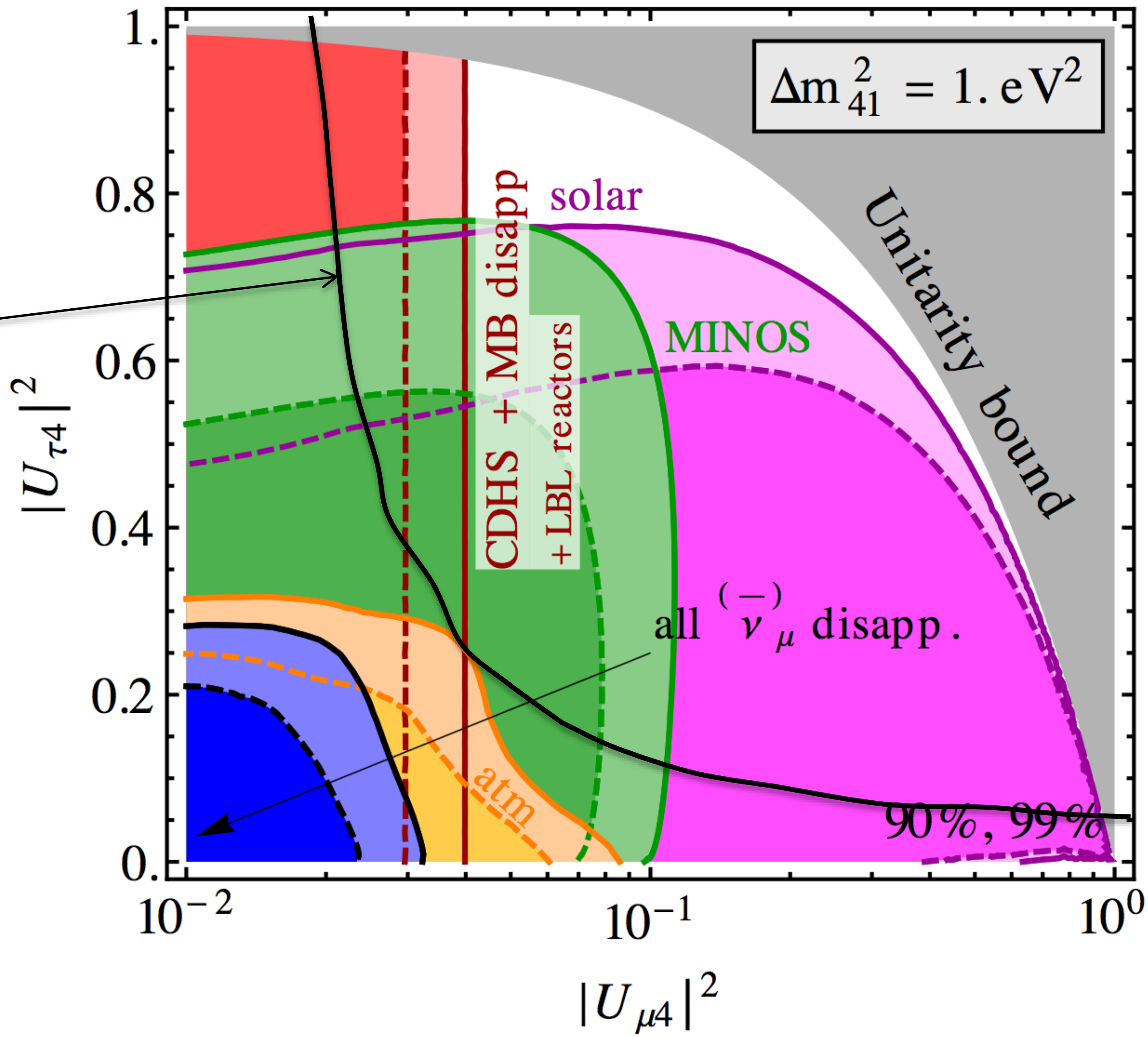
(quasi-equal results for NH and IH)

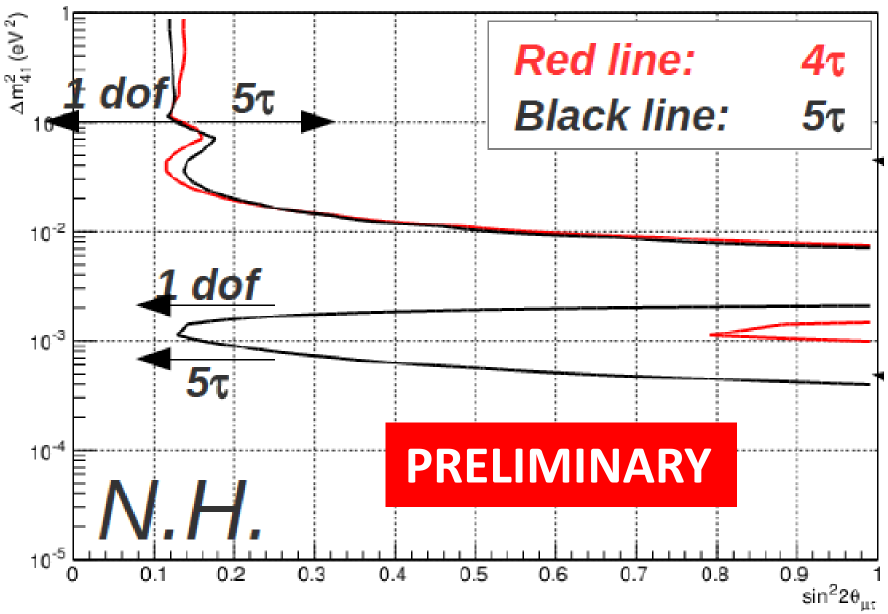
PRELIMINARY

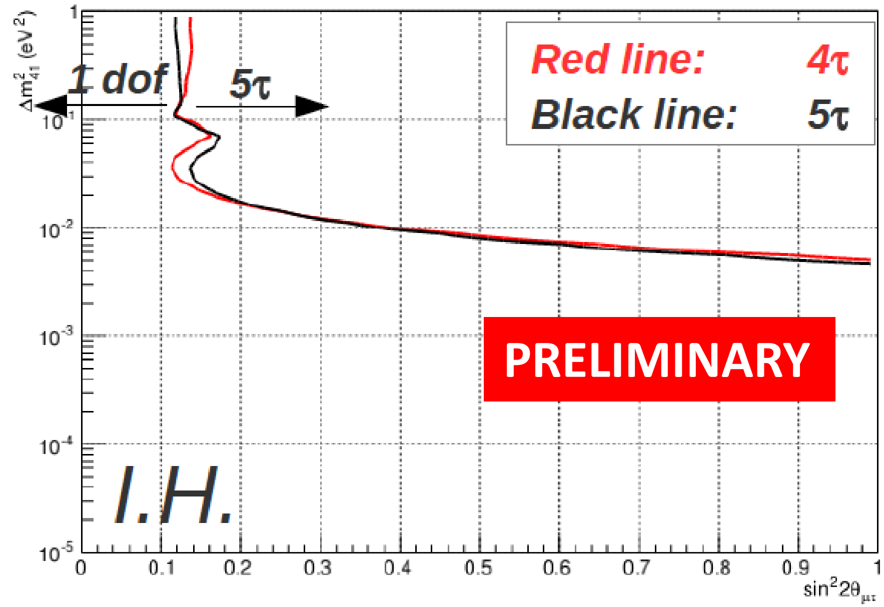
Complementary measurement wrt disappearance experiments

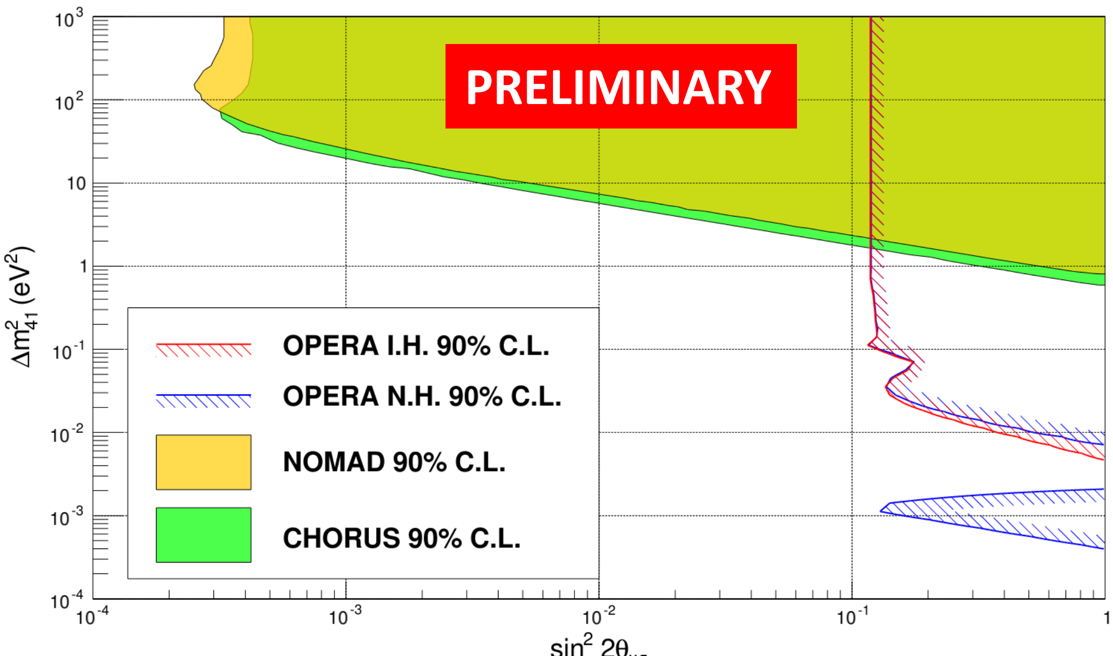
OPERA PRELIMINARY

(just sketched)





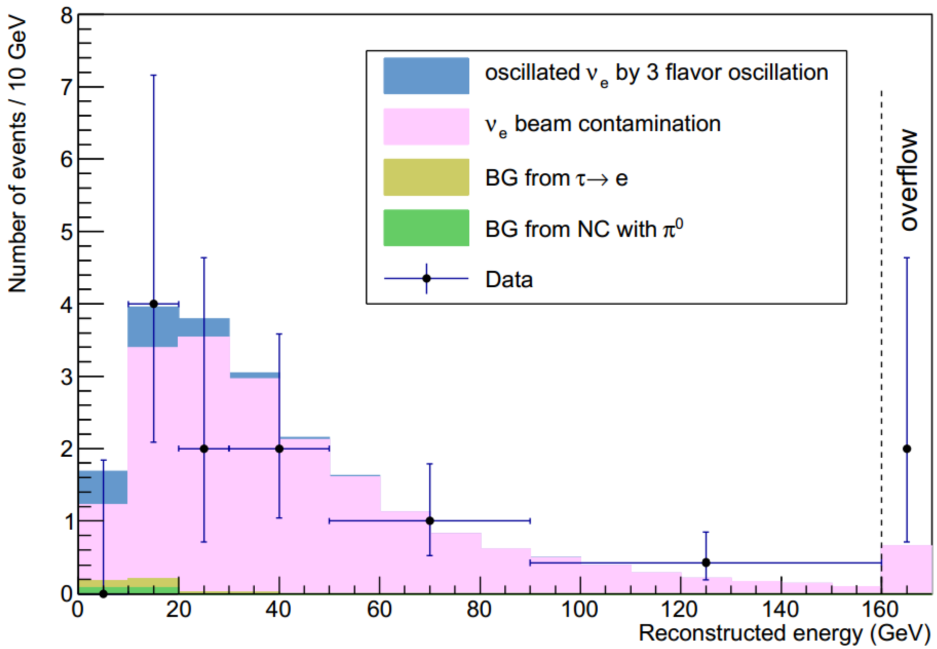




Full analysis with GLOBES (matter effects, Δm^2_{21} included, profiled out on Δm^2_{31})

OPERA can perform similar analysis based on ν_e observation

Old result from 2008+2009 data sample (30% of total): JHEP 4, 1307 (2013) and arXiv:1303.3953



		E<20 GeV
ν_e candidates	19	4
background	19.8±2.8	4.6

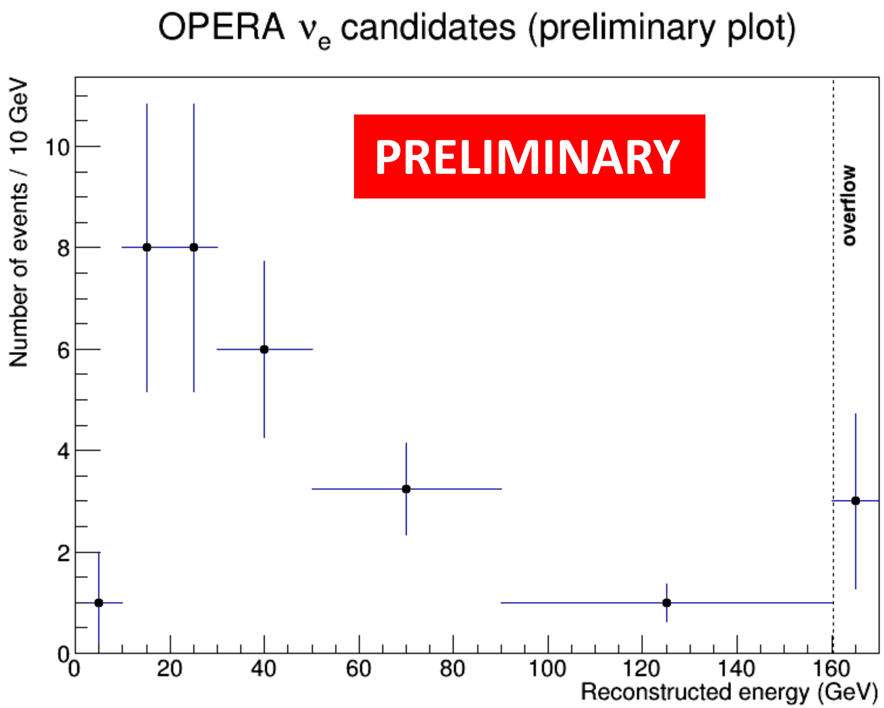
Compatible with expectation from intrinsic ν_e component in the CNGS ν_μ beam: 0.9%

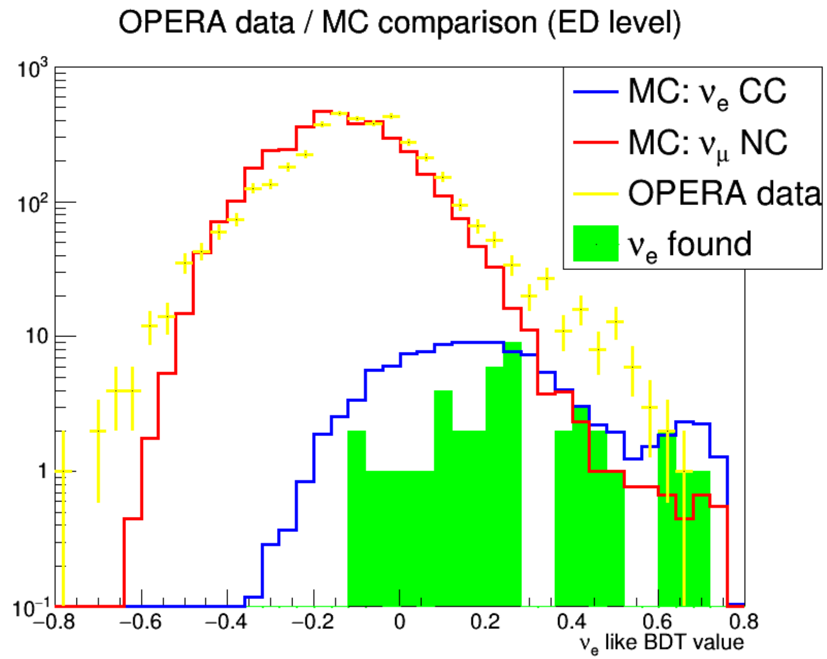
We may put rough limits to exclude mixing on θ_{14} with a 2 flavour model

Approximate analysis, see our previous result and e.g. A.Palazzo, PRD 91, 91301(R) (2015)

OPERA is extending the ν_e analysis on the full data sample !

ν_e candidates selected by Emulsion Analysis



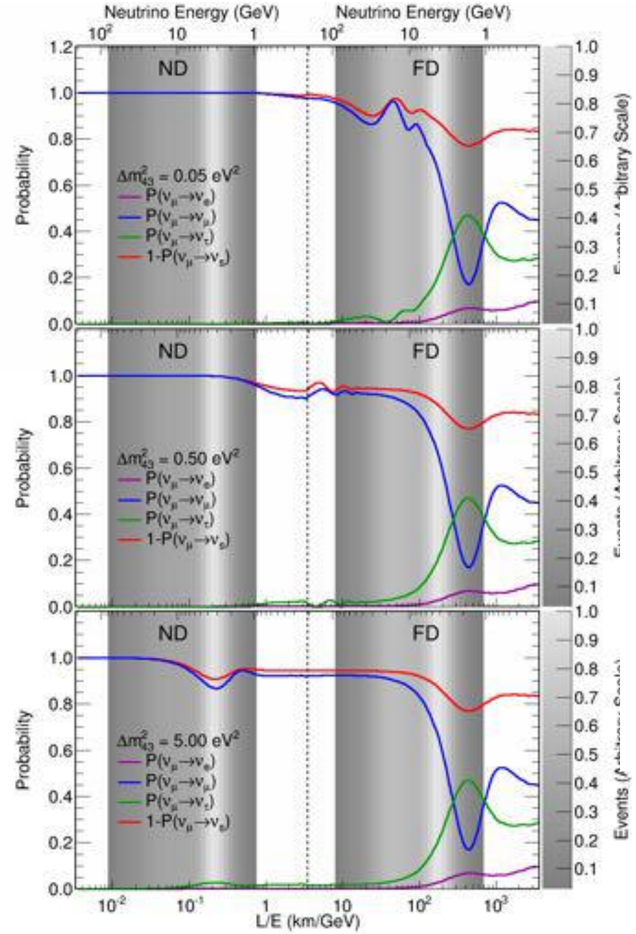


		E<20 GeV
ν_e candidates (30% data)	19	4
ν_e candidates (all data)	52	9

PRELIMINARY

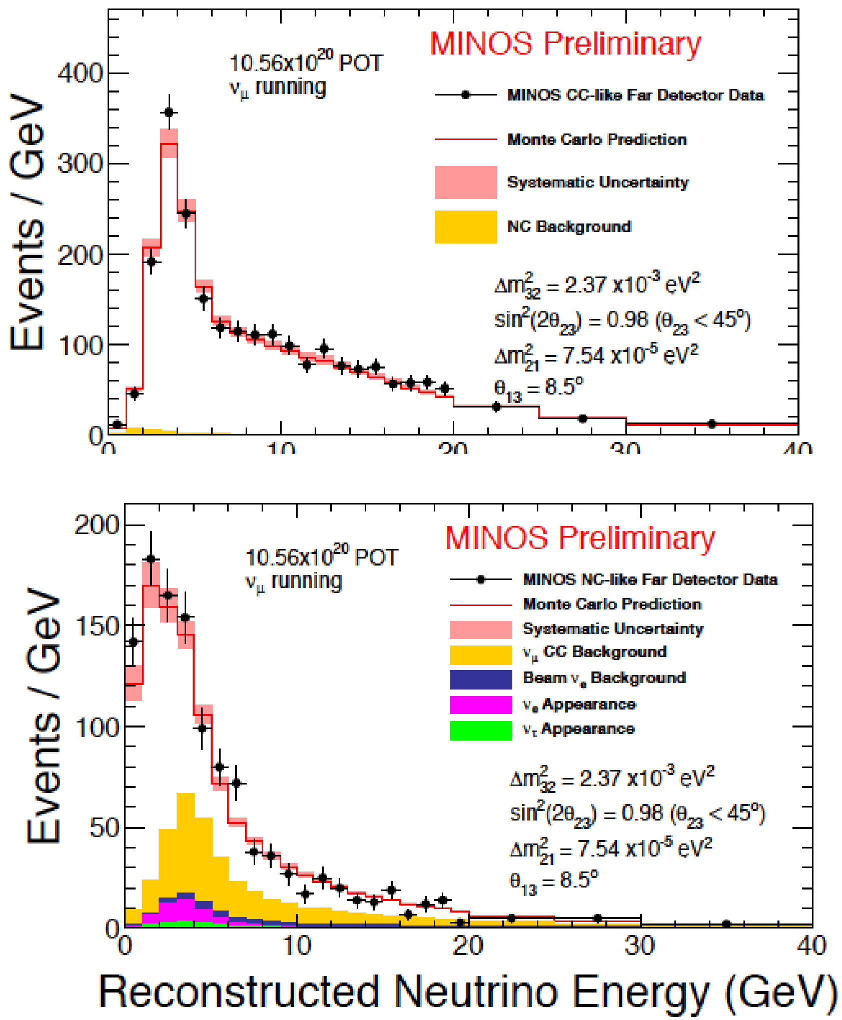
Good confirmation of ν_e events from Electronic Detectors (via Boosted-Decision-Tree)

MINOS+ on ν_μ sterile "anomalies"

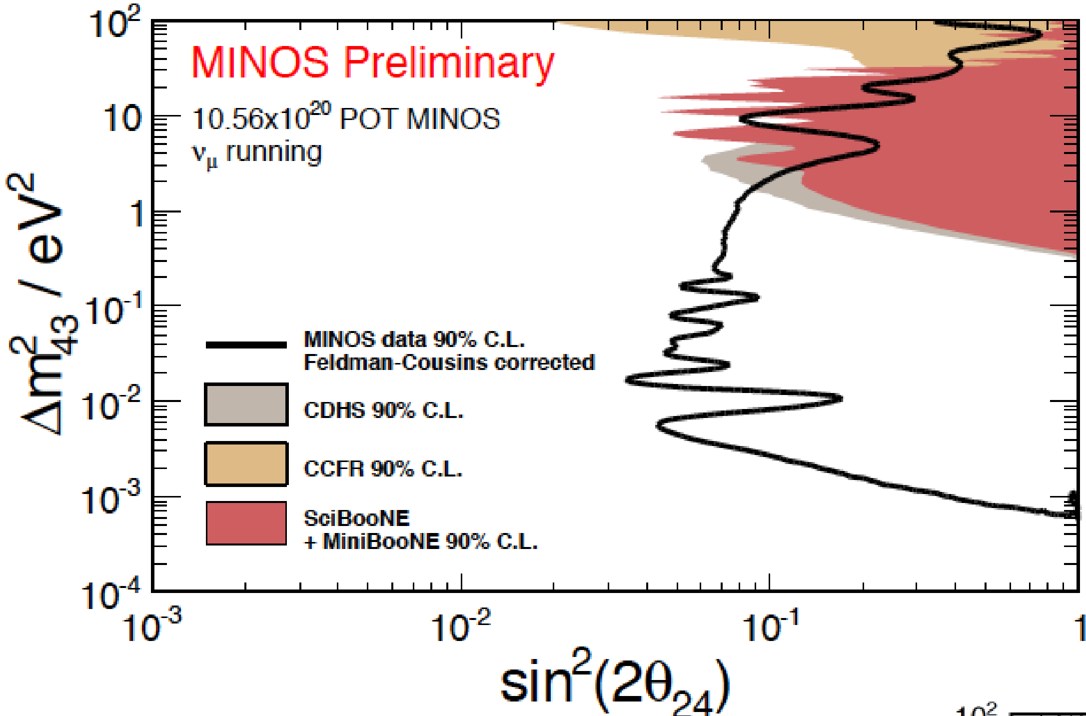


CC and NC searches:

- Excellent agreement with best-fit with 3 flavors
- Extended range in Δm^2 due to large energy span

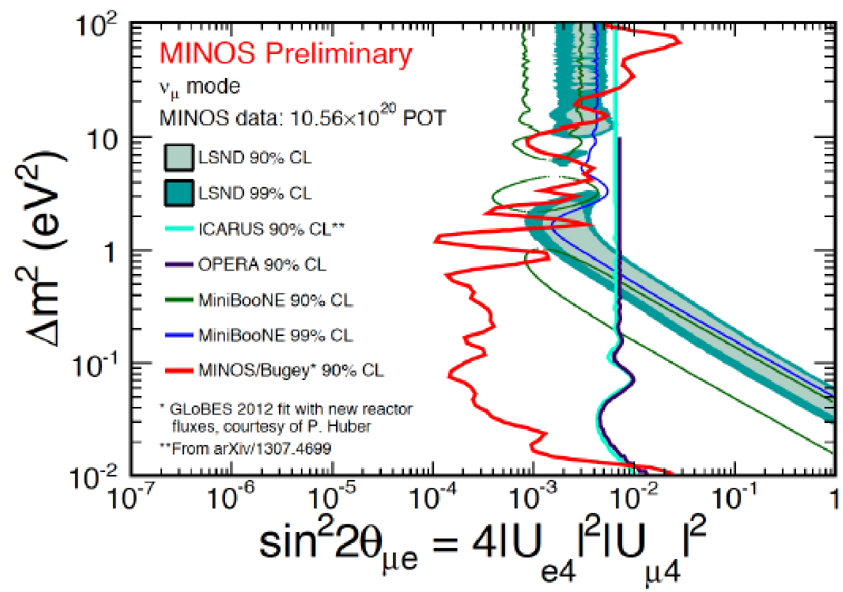


arXiv:1502.07715
arXiv:1504.04046



increase tension with ν_e sterile "anomalies"

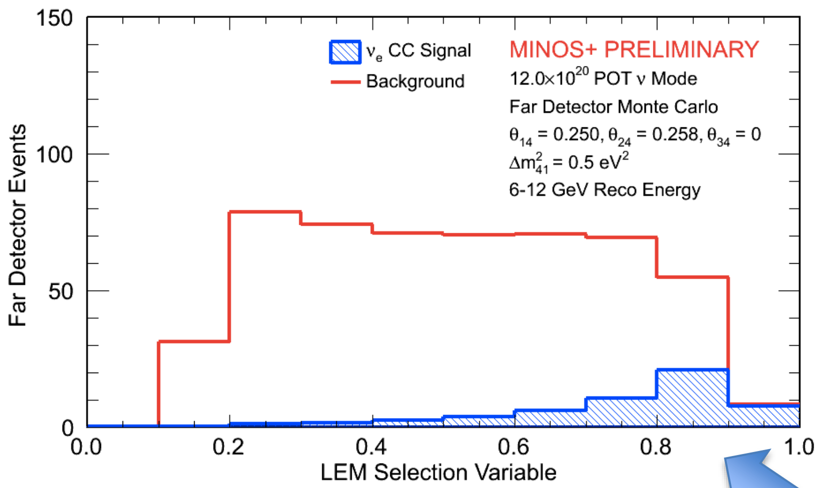
By combining MINOS 90% limit on θ_{24} to Bugey reactor experiment limit on θ_{14}

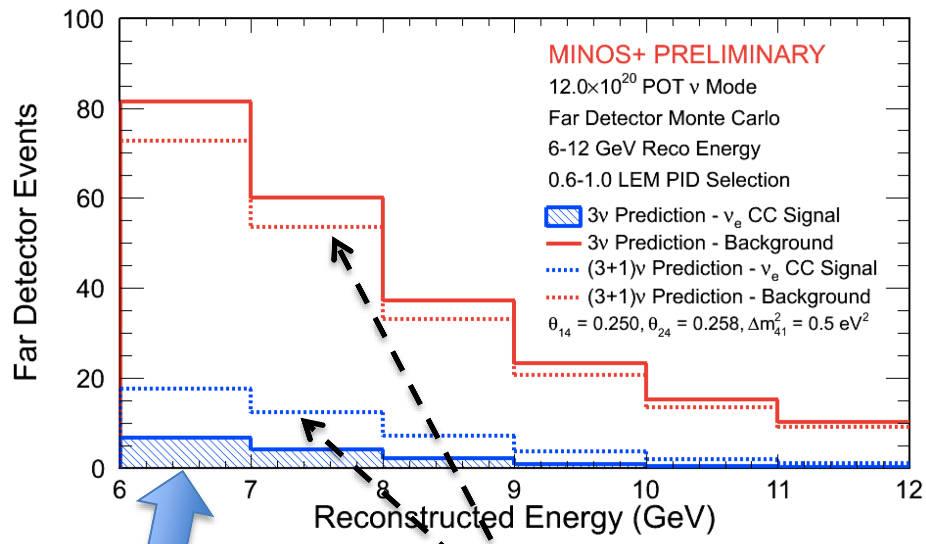


Ongoing work on anti-ν_μ mode running

Ongoing Analysis on $\nu_\mu \rightarrow \nu_e$

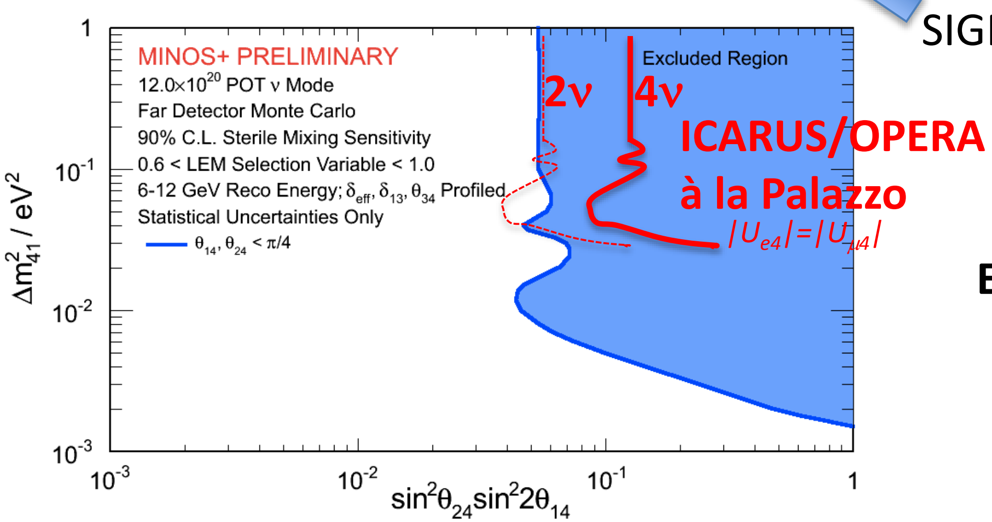
(Very recent blessed MINOS plots: public release at INFO2015 few days ago)





SIGNAL

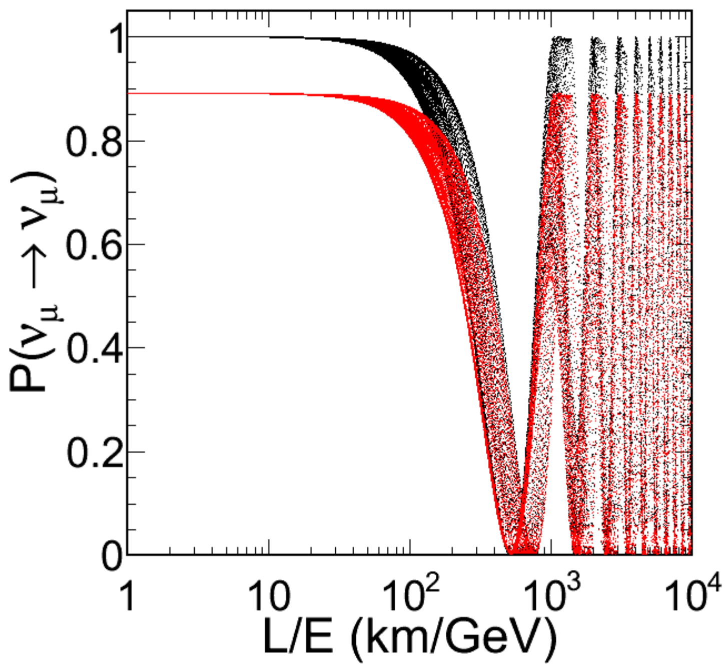
Expected "sterile" effect



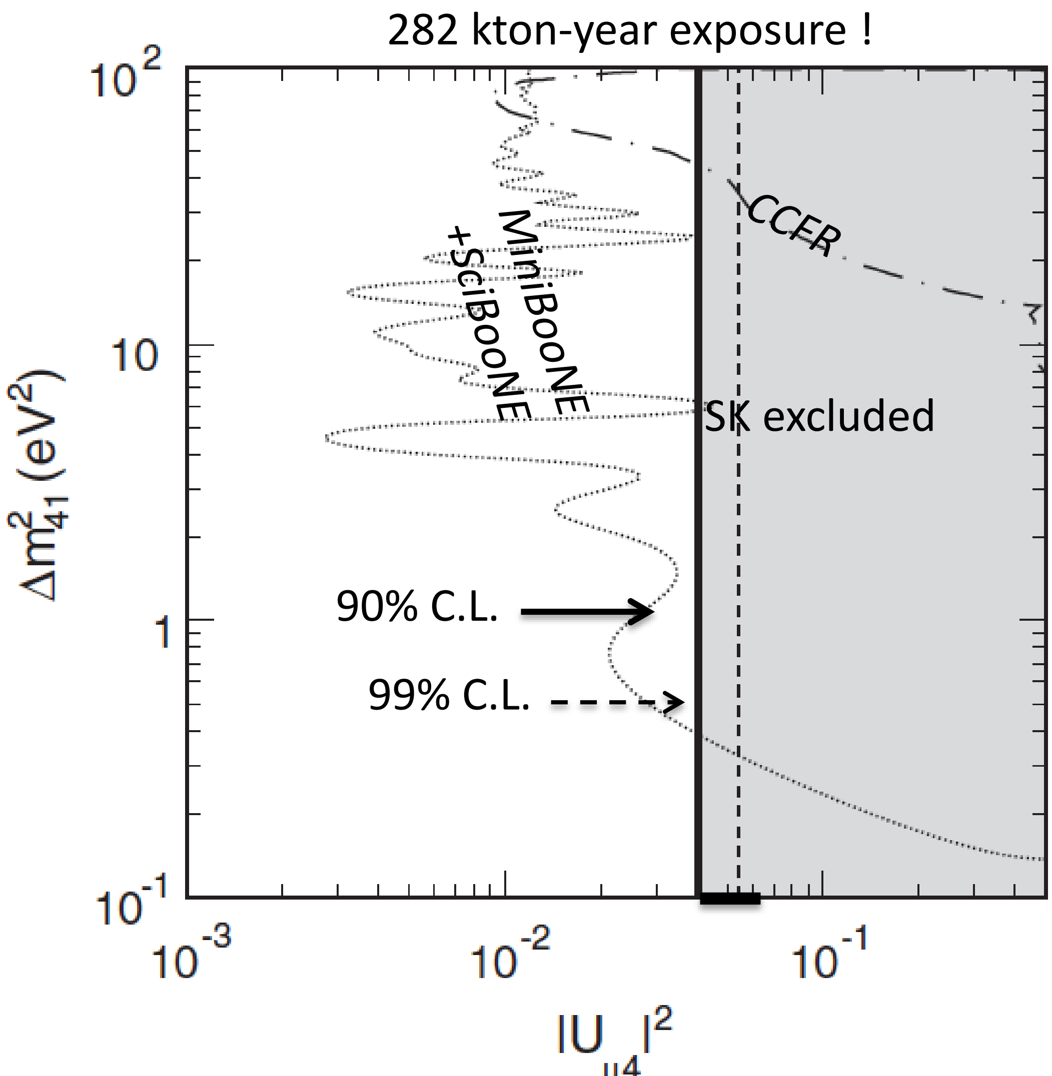
Expected SENSITIVITY for $12x10^{20}$ pot

SuperK on ν_μ sterile "anomalies"

(Sterile neutrino oscillation in Atmospheric Neutrinos)



PRD 91, 052019 (2015)



even stronger tension with ν_e anomalies

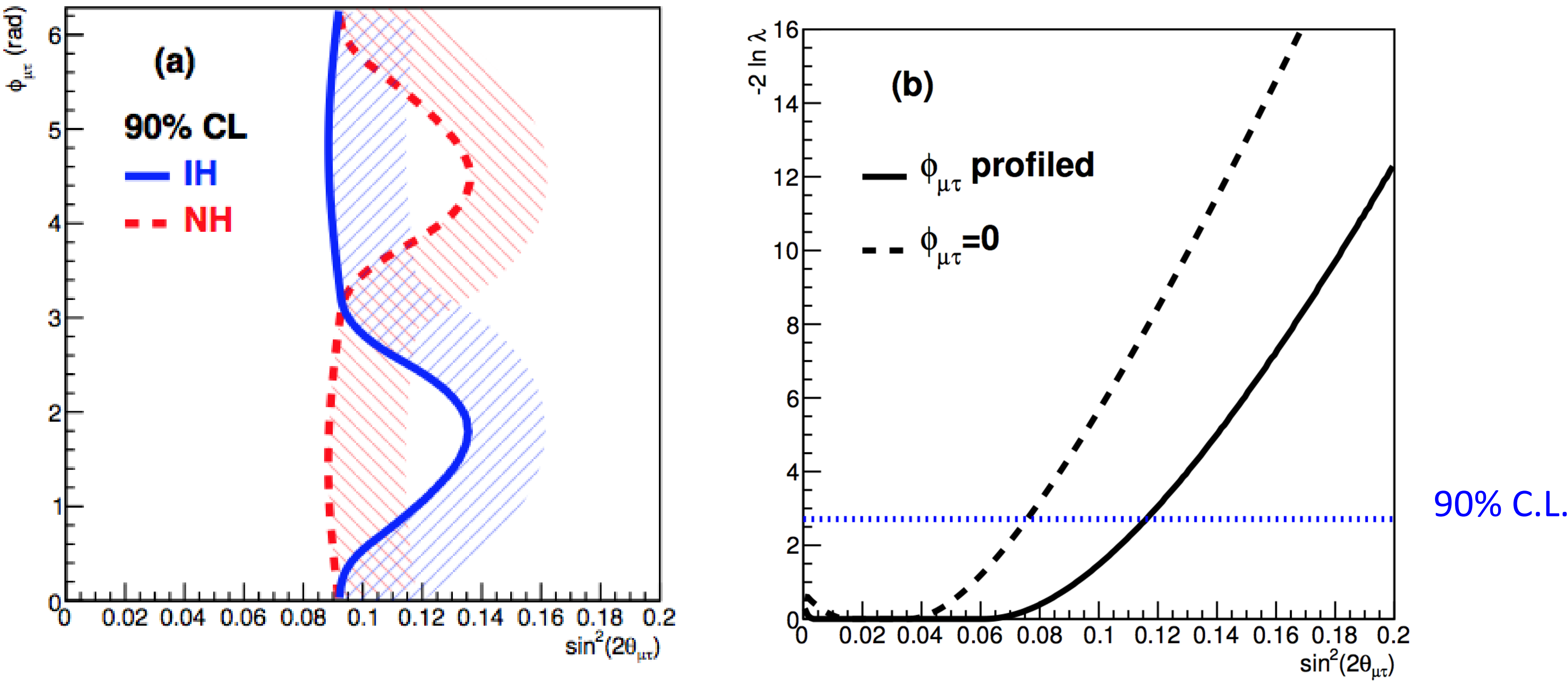
Conclusions and perspectives

- The sterile issue at eV mass scale can be studied also at Long-Baseline ν_μ beams
- Many results from OPERA, MINOS, Super-K are already available
- New preliminary result from OPERA on possible ν_τ sterile “anomalies” (presented at this conference)
- Soon new results (without too restrictive assumptions) from OPERA on ν_e oscillation
- Expected soon new results from MINOS+ on ν_e oscillation
- Sterile mixing, if it exists, corresponds to low values (order of 1%)
- New specific experiments should be settled and approved

BACKUP

OPERA search for ν_τ sterile "anomalies"

JHEP, 6, 69 (2015) and arXiv:1503.01876, based on 4 taus' candidates



Number of expected ν_τ sterile events