Search for sterile neutrino mixing in the $\nu_\mu \rightarrow \nu_\tau$ appearance channel with the OPERA detector

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on behalf of the OPERA Collaboration

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Outline

- Physics motivations
  - **sterile neutrinos**
- The OPERA experiment
  - **detector and physics case**
- Sterile neutrino mixing search
  - **3+1 model**
  - **$\nu_\mu \rightarrow \nu_\tau$ appearance channel**
- Conclusions

Introduction

- In the last decades several experiments provided evidence for neutrino oscillations: conversion in-flight of lepton flavor
  - **3 neutrino paradigm** well established
  - **mixing matrix parameters** precisely measured

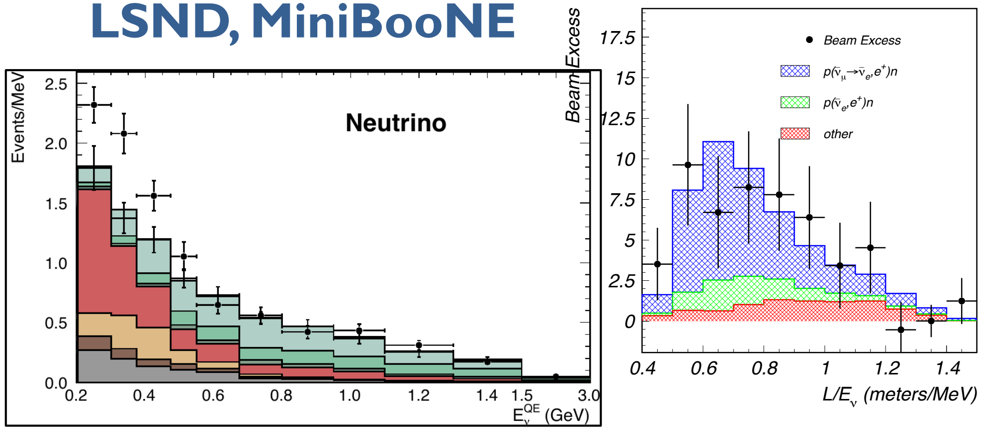
BUT

- A certain number of *anomalies* shows tensions with the 3 flavor framework, both in appearance and in disappearance modes

Appearance

anti-ν_μ → anti-ν_e

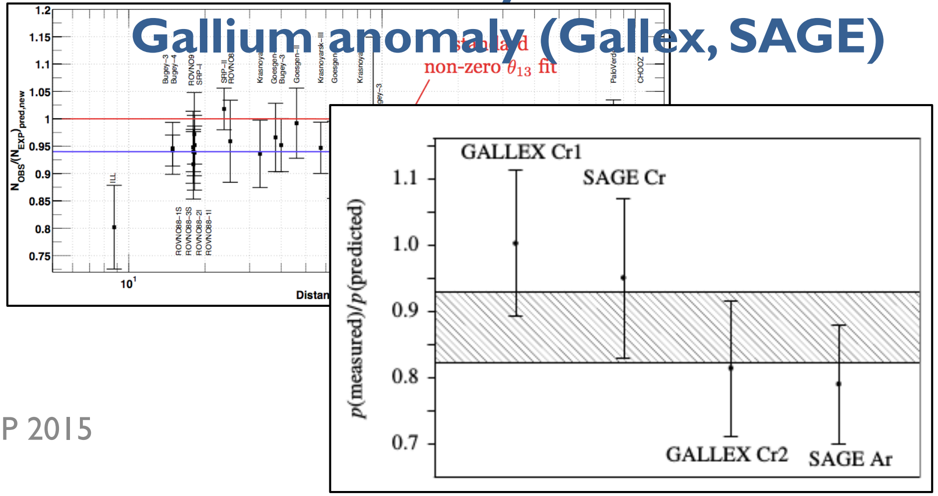
LSND, MiniBooNE



Disappearance

ν_e, anti-ν_e

Reactor anomaly, Gallium anomaly (Gallex, SAGE)

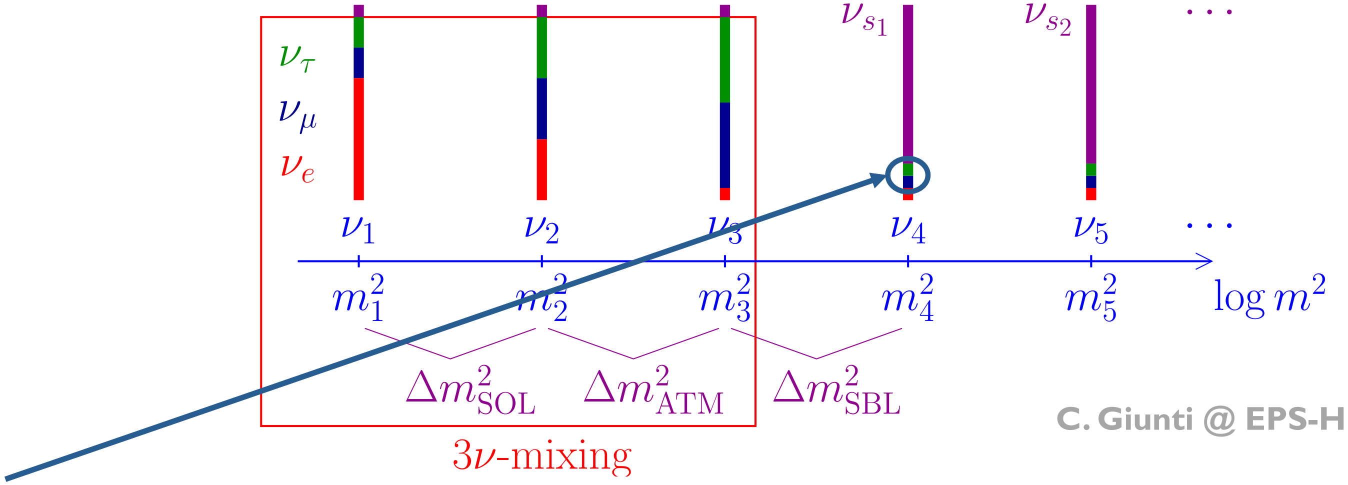


Sterile neutrinos

- Anomalies point toward a new parameter region **$\Delta m^2 \sim eV^2$**
  - "only" 3 active neutrinos ($N_{active} = 3$, bound by the the *Z* invisible decay width measured at LEP)

    → **Sterile neutrino hypothesis** [Pontecorvo, JETP 26 (1968) 984]
- The new model should include the standard 3ν framework

  → Perturbation of 3ν mixing



C. Giunti @ EPS-HEP 2015

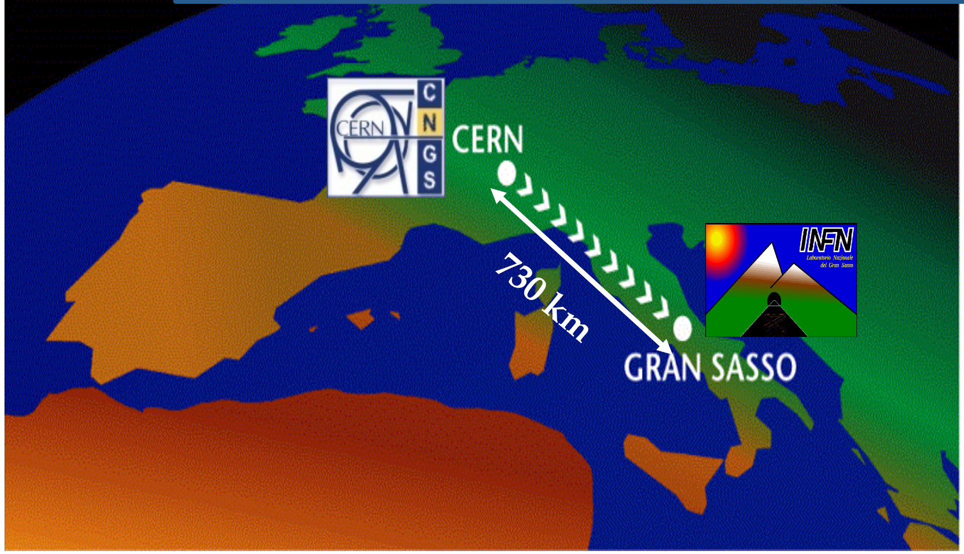
- OPERA can test the sterile neutrino hypothesis in the **ν_τ appearance channel** looking for deviations from the standard 3ν model

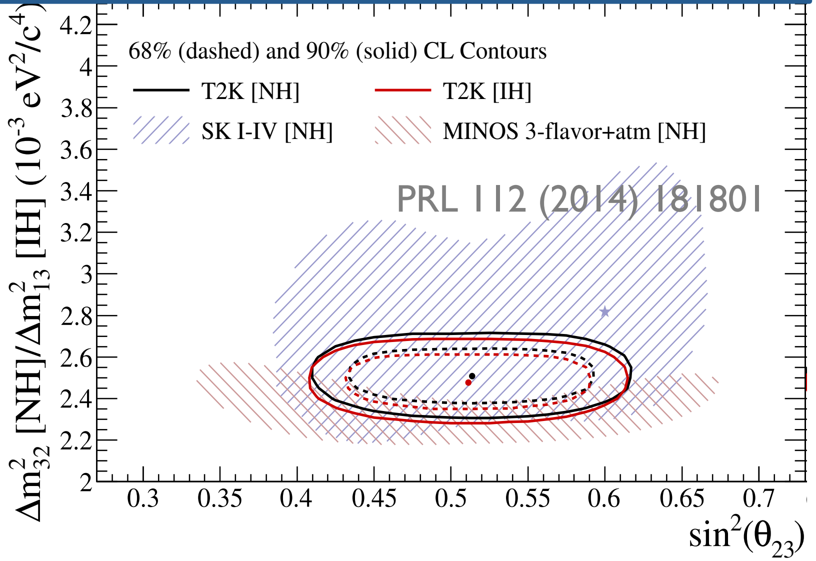
  (in addition to the ν_e appearance channel) [JHEP 4 (2013) 1307]

The OPERA experiment

Main physics goal: **prove (standard) $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode**

See tomorrow talk: Results from the OPERA experiment at the CNGS beam



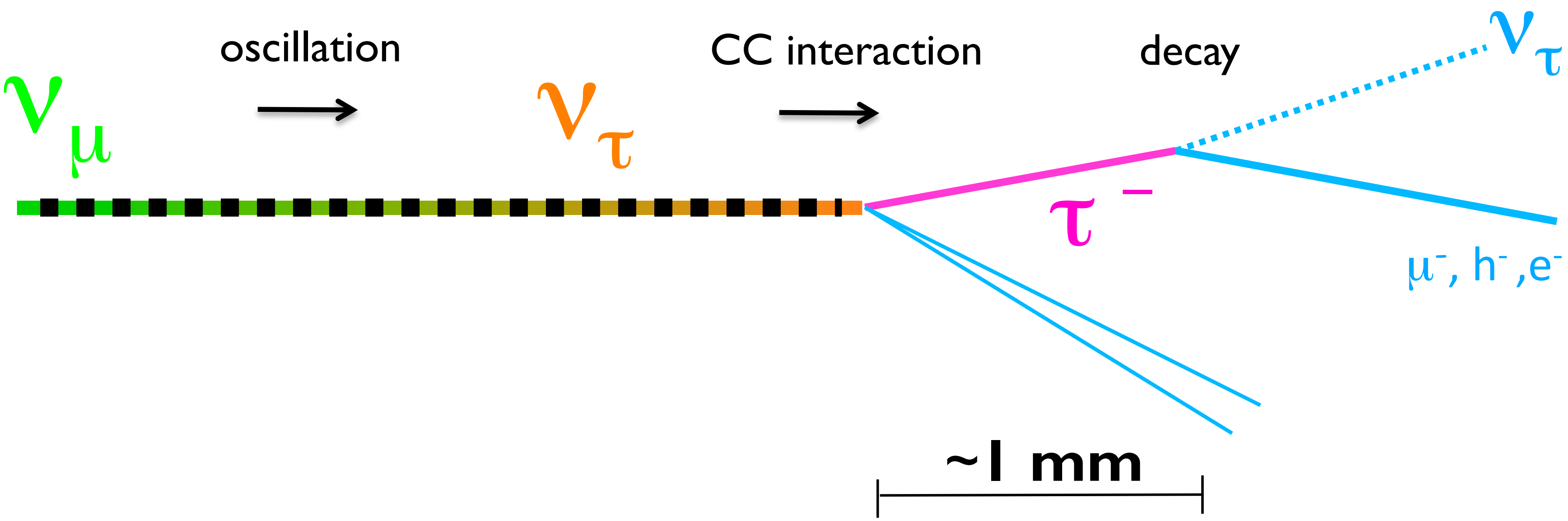


Full coverage of the parameter space for the atmospheric neutrino sector

- Long baseline neutrino oscillation experiment located in the CNGS (CERN Neutrinos to Gran Sasso) ν_μ beam
- Direct search for $\nu_\mu \rightarrow \nu_\tau$ oscillations detecting the τ lepton produced in ν_τ CC interactions (appearance mode)

Appearance detection

Direct observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation



- $N_\tau = N_A M_D \int \phi_{\nu_\mu}(E) P_{\nu_\mu \rightarrow \nu_\tau}(E, \Delta m^2) \sigma_{\nu_\tau}^{CC}(E) \varepsilon(E) dE$ → Large mass ~O(kton)
- signal selection and background rejection → High granularity ~1 μm resolution

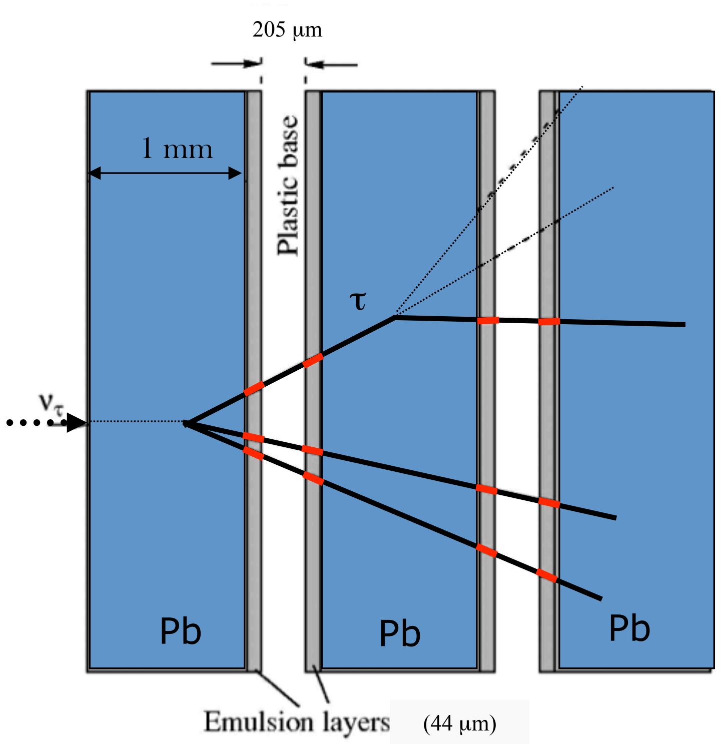
→ **Emulsion Cloud Chamber**

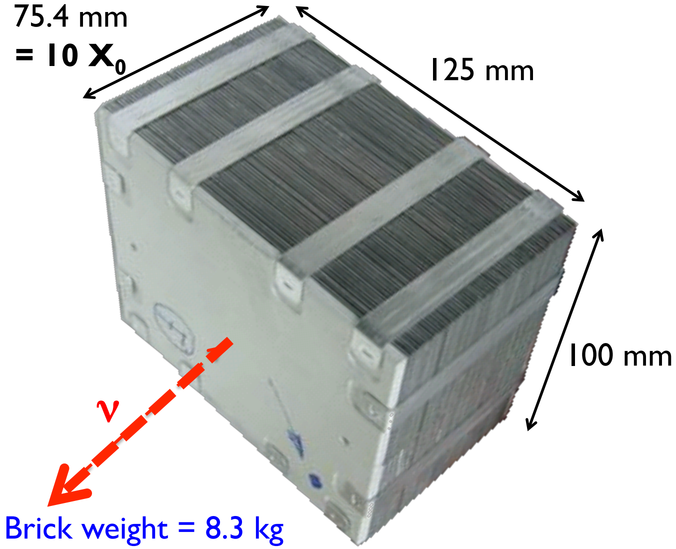
Neutrino interaction detector (ECC)

- Target basic unit: brick of 57 nuclear emulsions interleaved by lead plates + 2 interface emulsions (CS)

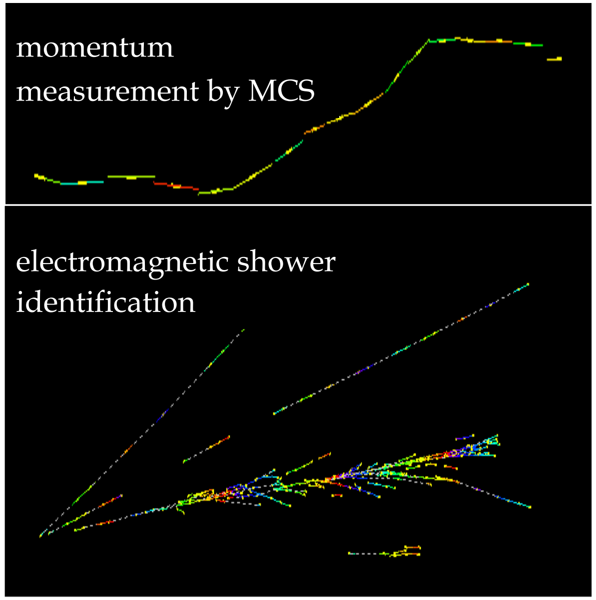
→ high resolution and large mass in a modular way

- unambiguous measurement of the kink



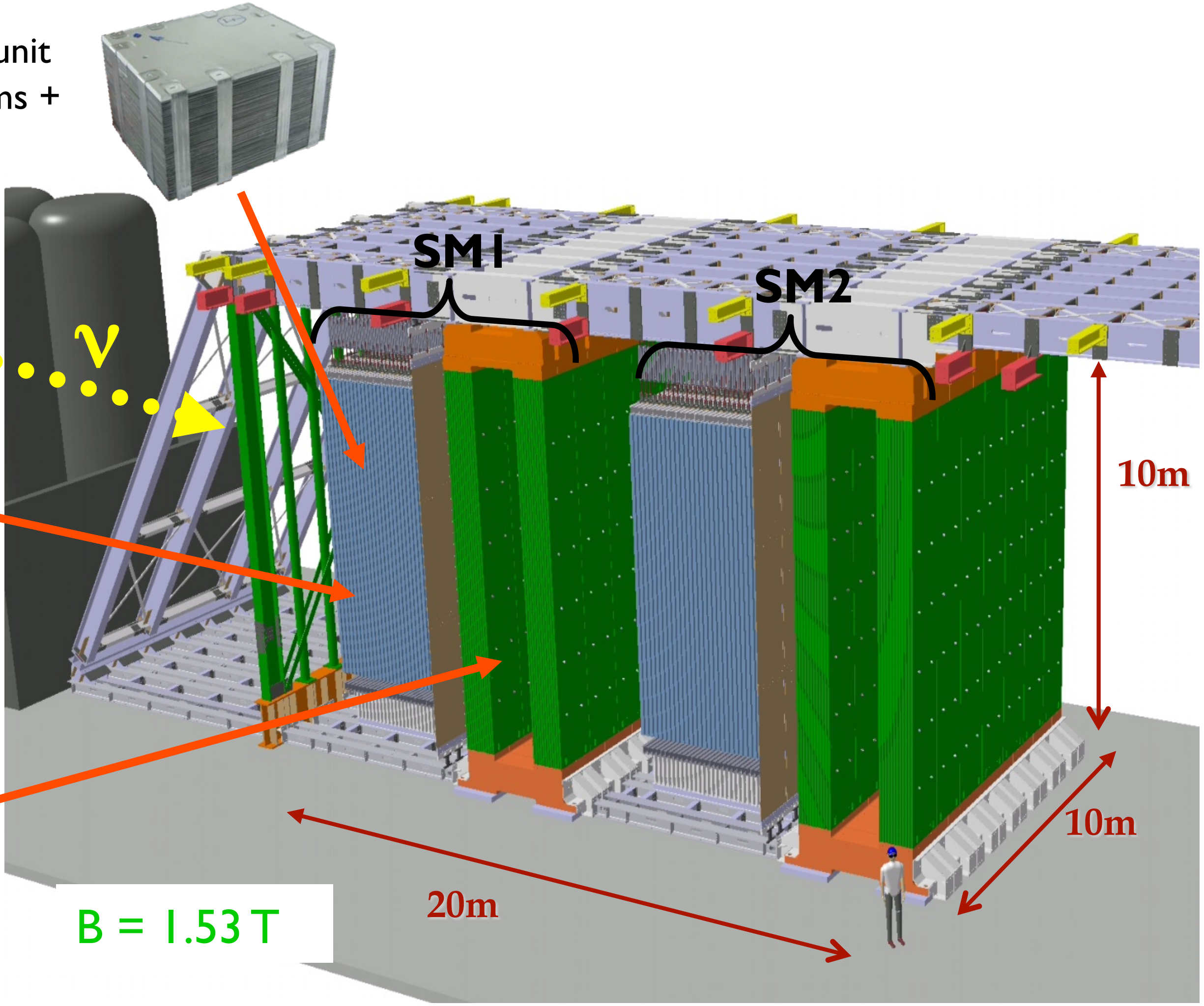


- “stand-alone” detector



OPERA general structure

Brick: ECC target basic unit
(57 nuclear emulsion films +
56 lead plates)



Target section:
27 brick walls (75000 bricks)
31 Target Tracker walls (TT)

Neutrino interaction trigger
Brick selection
Calorimetry

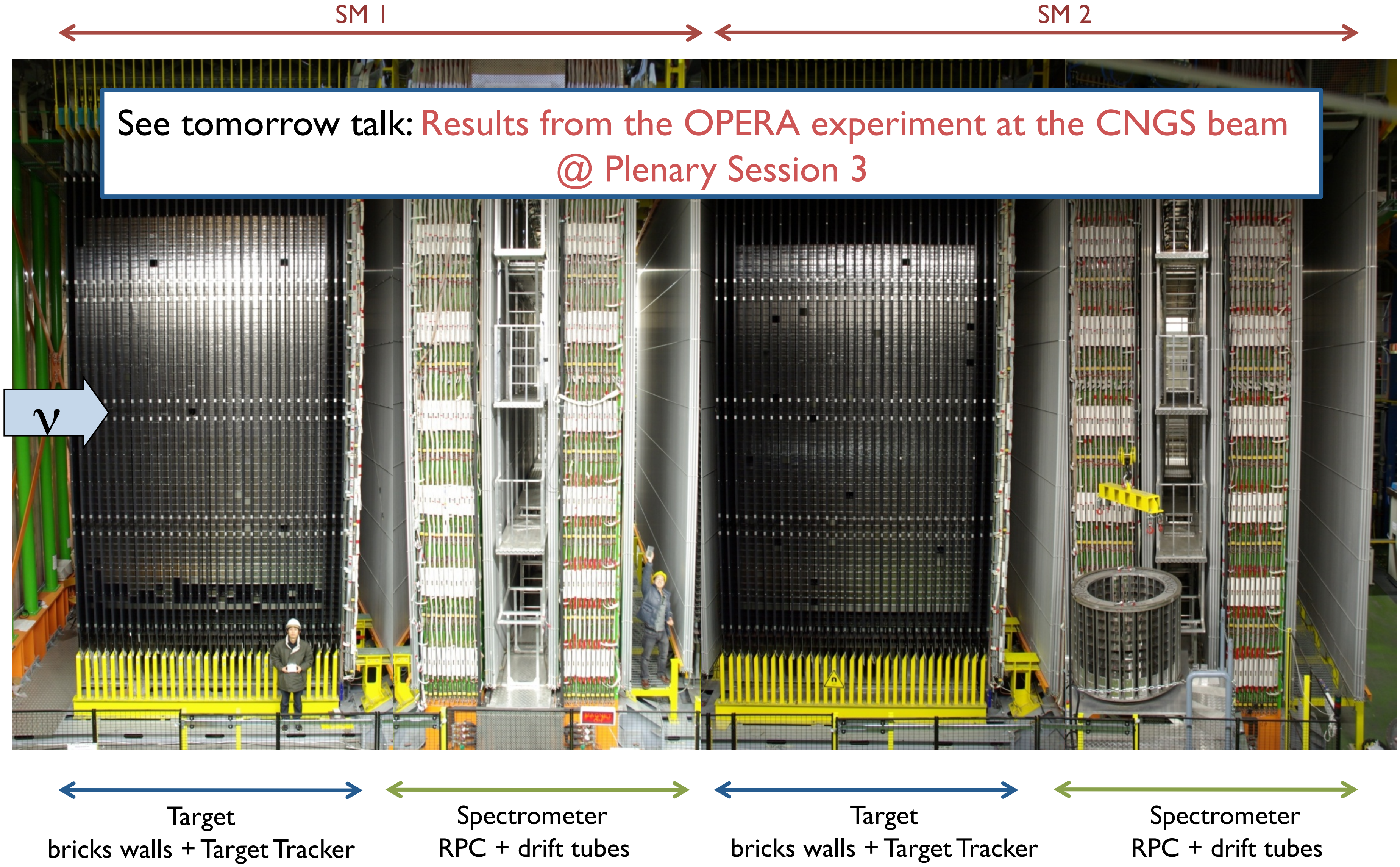
Magnetic spectrometer:
22 RPC planes
6 drift tube layers (PT stations)

B = 1.53 T

μ ID, charge, momentum

Total target mass = 1.25 ktons

OPERA: an hybrid detector



See tomorrow talk: Results from the OPERA experiment at the CNGS beam @ Plenary Session 3

$\nu_\mu \rightarrow \nu_\tau$: Results

Exposure	17.97×10^{19} p.o.t.
Interactions in target volume	19505
Located interactions	6932

5 ν_τ candidates

[$\Delta m^2 = 2.44 \times 10^{-3}$ eV^2]

Compatible with expectations from standard 3ν model

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

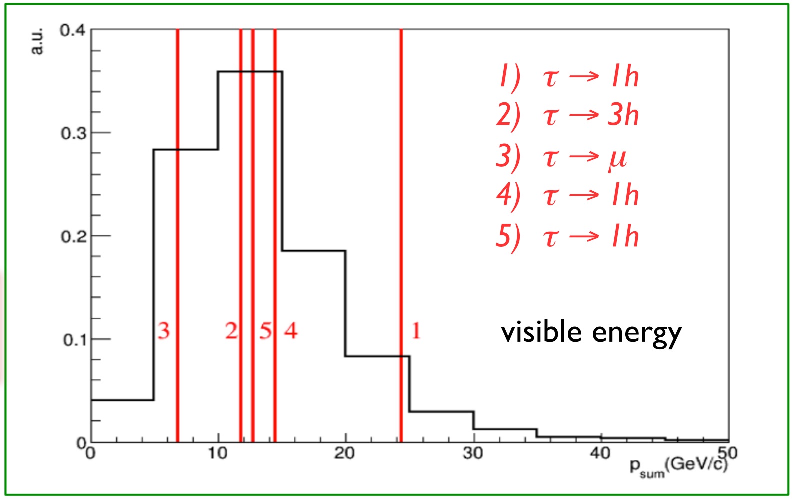
Background

p-value (likelihood ratio): **1.1×10^{-7}**

Significance: 5.1σ

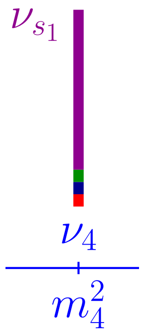
Discovery of tau neutrino appearance

Accepted by PRL, arXiv:1507.01417



Tau appearance in the 3+1 model

Sterile hypothesis test: standard 3ν + 1 sterile



- Consider a new mass eigenstate m_4 with Δm^2_{41} up to a few eV^2, almost exclusively composed by a flavour sterile eigenstate, ν_s

- 4 x 4 mixing matrix parameterized by a product of complex rotational matrices

Parameters of interest in ν_τ appearance

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

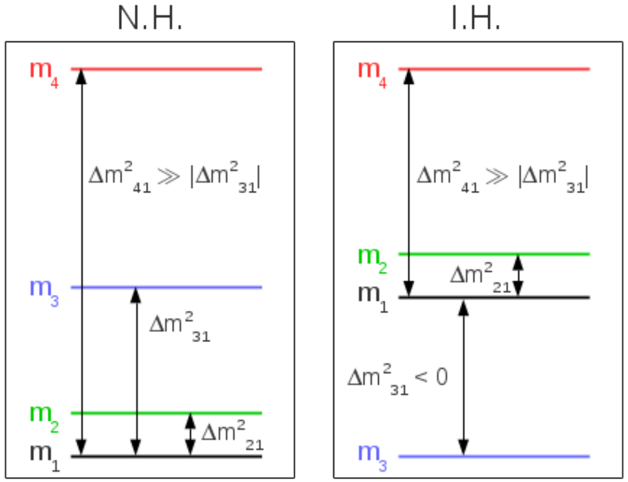
- Number of expected events evaluated as:

$$\mu = N_{bkg} + K \int \phi(E)\, P_{\mu\tau}(E)\, \sigma(E)\, \varepsilon(E)\, dE$$

- Both Normal and Inverted mass Hierarchies considered

$[\Delta m^2_{31} > 0 \text{ (NH)}, \Delta m^2_{31} < 0 \text{ (IH)}]$

$\Delta m^2_{41} > 0$ $[\Delta m^2_{41} < 0$ disfavoured by cosmological limits on $\Sigma m_\nu]$



3+1 Model

Oscillation probability in presence of a sterile neutrino becomes:

~ standard oscillation

pure exotic oscillation

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

interference terms

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

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

Effective mixing

$C = 2|U_{\mu3}||U_{\tau3}|$

$\phi_{\mu\tau} = Arg(U^\star_{\mu3} U^\star_{\tau3} U^\star_{\mu4} U^\star_{\tau4})$

$\sin 2\theta_{\mu\tau} = 2|U_{\mu4}||U_{\tau4}|$

Sterile effective mixing

Oscillation probability in presence of a sterile neutrino becomes:

~ standard oscillation

pure exotic oscillation

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

$$+ \frac{1}{2} C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin \Delta_{31} \sin \Delta_{41}$$

$$- C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin \Delta_{41}$$

$$+ 2\, C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2}$$

$$+ C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2}$$

interference terms

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

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

Effective mixing parameter (leading mixing term at SBL)

Effective mixing

$C = 2|U_{\mu 3}||U_{\tau 3}|$

$\phi_{\mu\tau} = Arg(U^\star_{\mu 3} U^\star_{\tau 3} U^\star_{\mu 4} U^\star_{\tau 4})$

$\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$

Mass hierarchy

Oscillation probability in presence of a sterile neutrino becomes:

~ standard oscillation

pure exotic oscillation

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

$$+ \frac{1}{2} C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin \Delta_{31} \sin \Delta_{41}$$

$$- C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin \Delta_{41}$$

$$+ 2\, C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2}$$

$$+ C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2}$$

interference terms

Mass Hierarchy dependence

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

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

Effective mixing

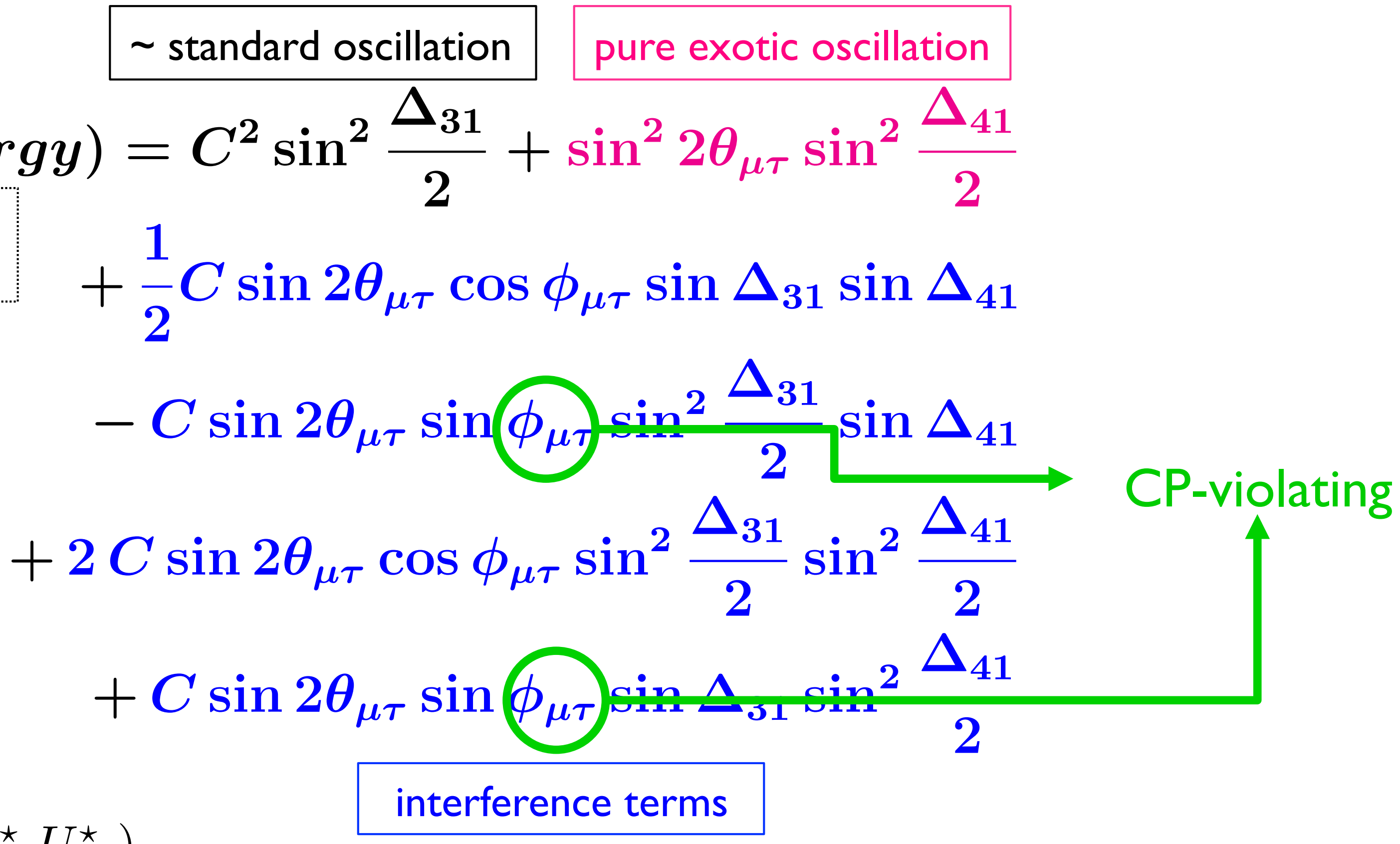
$$C = 2|U_{\mu3}||U_{\tau3}|$$

$$\phi_{\mu\tau} = Arg(U^{\star}_{\mu3} U^{\star}_{\tau3} U^{\star}_{\mu4} U^{\star}_{\tau4})$$

$$\sin 2\theta_{\mu\tau} = 2|U_{\mu4}||U_{\tau4}|$$

CP-violation

Oscillation probability in presence of a sterile neutrino becomes:



~ standard oscillation

pure exotic oscillation

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

CP-violating

interference terms

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

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

Effective mixing

$C = 2|U_{\mu 3}||U_{\tau 3}|$

$\phi_{\mu\tau} = Arg(U^\star_{\mu 3} U^\star_{\tau 3} U^\star_{\mu 4} U^\star_{\tau 4})$

$\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$

New results

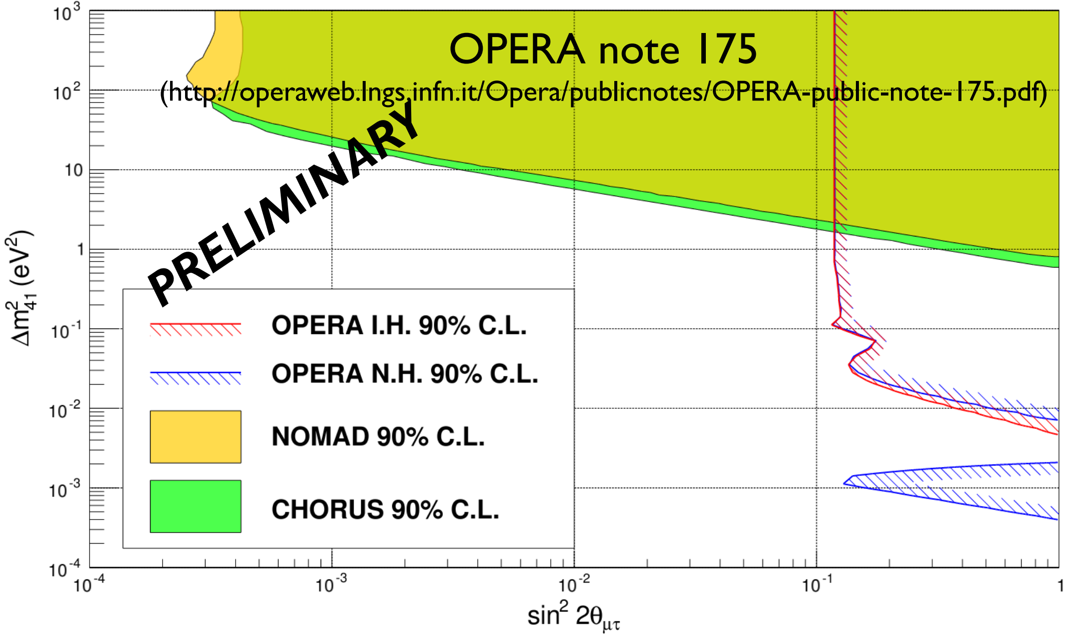
5 ν_τ candidates

- ✓ Use **GLoBES** to evaluate number of expected events
- ✓ **Δm^2_{21} set costant** to 7.54×10^{-5} eV^2
- ✓ **Δm^2_{31} assumed Gaussian**
  - NH: $(2.47 \pm 0.06) \times 10^{-3}$ eV^2
  - IH: $(-2.34 \pm 0.06) \times 10^{-3}$ eV^2
- ✓ Likelihood

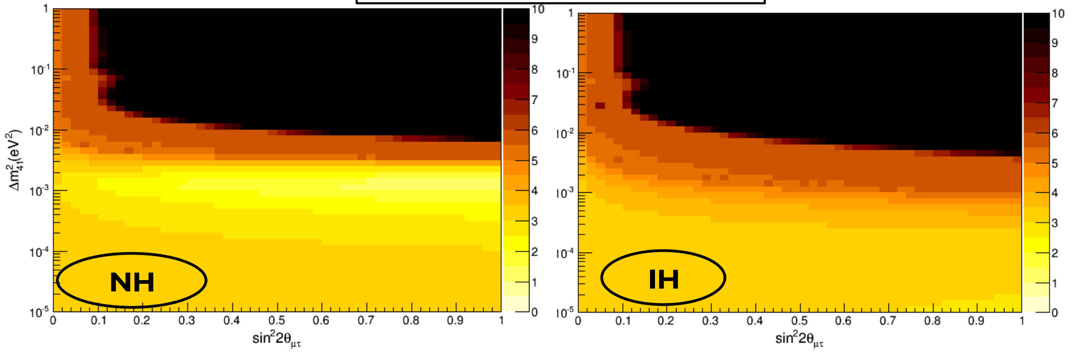
  L = Poisson($n|\mu$) x Gaus(Δm^2_{31})
- ✓ Test statistic:

  profile likelihood ratio
- ✓ Not interesting parameters profiled out

$\Delta m^2_{41} < 0$ (disfavoured by cosmological limits on Σm_ν) gives similar results with hierarchies inverted



N. of expected events



New results

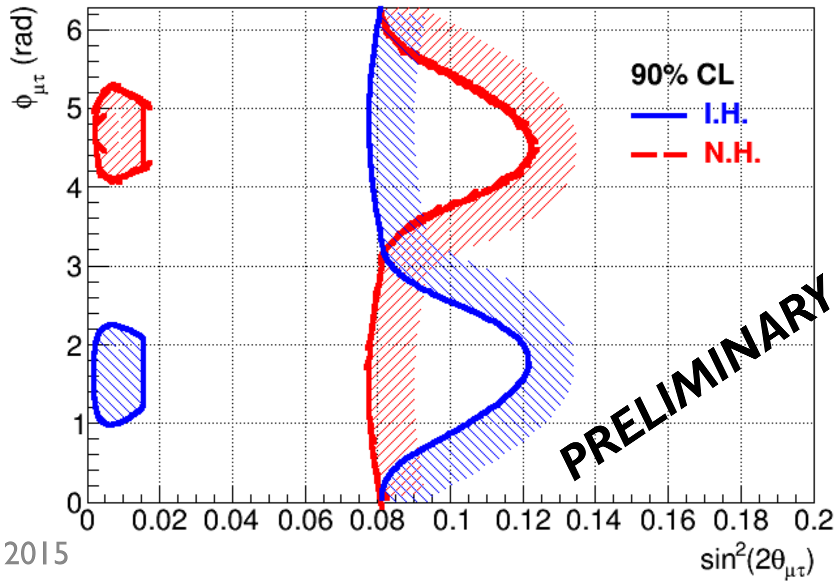
5 ν_τ candidates

At Long-Baseline and high Δm^2_{41} (eV scale mass):

$$\sin\Delta_{41} \approx 0$$
$$\sin^2\frac{\Delta_{41}}{2} \approx \frac{1}{2}$$

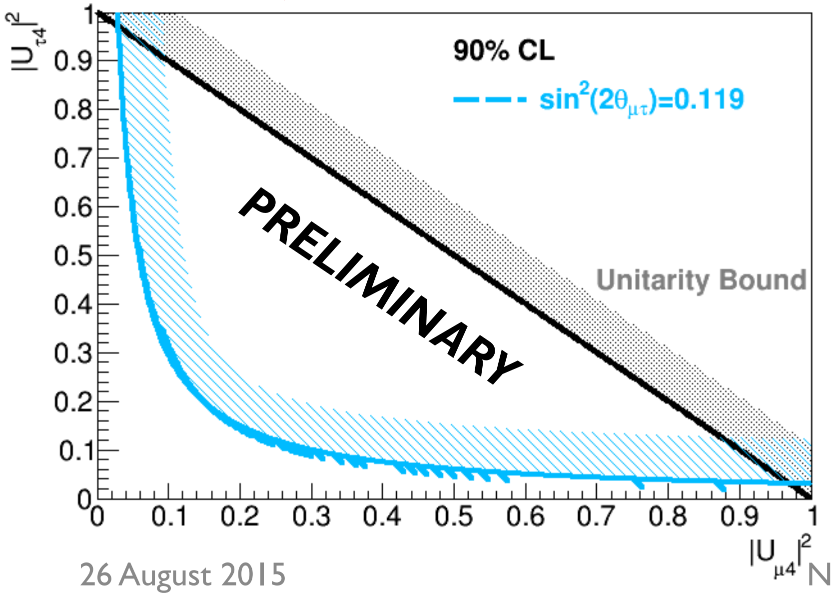
$$P(Energy) = C^2\sin^2\frac{\Delta_{31}}{2} + \frac{1}{2}\sin^2 2\theta_{\mu\tau} + C\sin 2\theta_{\mu\tau}\cos\phi_{\mu\tau}\sin^2\frac{\Delta_{31}}{2} + \frac{1}{2}C\sin 2\theta_{\mu\tau}\sin\phi_{\mu\tau}\sin\Delta_{31}$$

Profiling out C and fixing Δm^2_{31} to the PDG 2014 best fit value



Profiling out $\phi_{\mu\tau}$

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

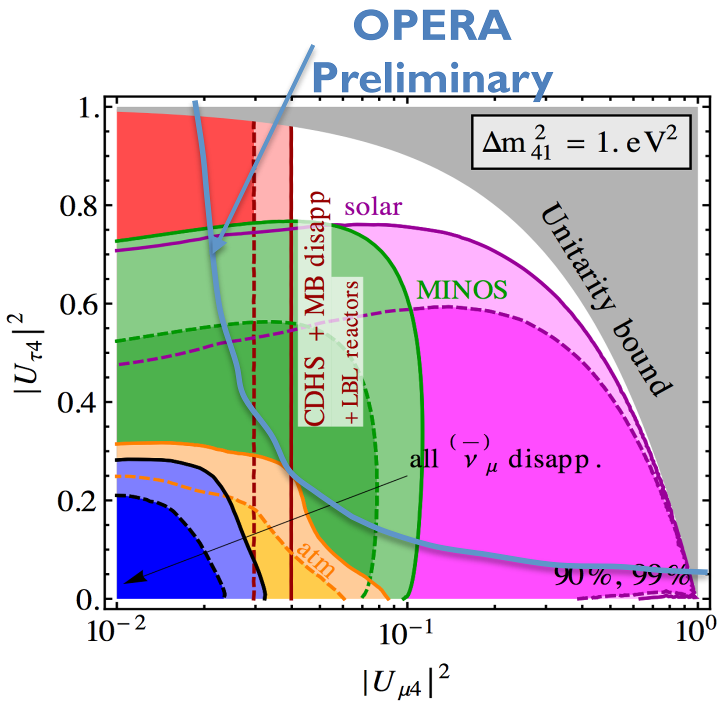


Conclusions

- OPERA was designed to observe $\nu_\mu \rightarrow \nu_\tau$ **oscillations** in appearance mode in the atmospheric sector
  - Currently **5 ν_τ event candidates** were identified with a background expectation of 0.25 events → 5σ discovery of tau neutrino appearance!

- The sterile mixing at eV mass scale can be studied also at Long-Baseline ν_μ beams
  - OPERA sterile search in appearance mode provides a complementary measurement w.r.t. disappearance experiments

- 3+1 sterile neutrino working hypothesis
  → derived exclusion regions for oscillation parameters
  - 90% C.L. exclusion region on Δm^2_{41} lowered down to 10^{-2} eV² for $\sin^2 2\theta_{\mu\tau} > 0.5$
  - At large Δm^2_{41}: $\sin^2 2\theta_{\mu\tau} < 0.119$ at 90% C.L.



Thank you for your attention!

Image taken using **OPERA nuclear emulsion film**
with a pinhole hand made camera
courtesy by Donato Di Ferdinando

Back Up

Published Results

4 ν_τ candidates

Results based on 4 taus' candidates published in JHEP 06 (2015) 069

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)

Results given in terms of an effective mixing parameter

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

which is the leading mixing term at short baseline experiments