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

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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

Disappearance
ν_e, anti-ν_e

LSND, MiniBooNE

Reactor anomaly, Gallium anomaly (Gallex, SAGE)

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**Sterile neutrinos**

- Anomalies point toward a new parameter region $\Delta m^2 \sim \text{eV}^2$
  - “only” 3 active neutrinos ($N_{\text{active}} = 3$, 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 $3\nu$ framework
  → Perturbation of $3\nu$ mixing

- OPERA can test the sterile neutrino hypothesis in the $\nu_\tau$ appearance channel looking for deviations from the standard $3\nu$ model
  (in addition to the $\nu_e$ 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) $\nu_\mu$ beam
- Direct search for $\nu_\mu \rightarrow \nu_\tau$ oscillations detecting the $\tau$ lepton produced in $\nu_\tau$ CC interactions (appearance mode)
Appearance detection

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

$N_\tau = N_\mu M_D \int \phi_{\nu_\mu}(E)P_{\nu_\mu \rightarrow \nu_\tau}(E, \Delta m^2)\sigma_{CC}(E)\epsilon(E)dE$ \rightarrow \text{Large mass } \sim O(\text{kton})

$\triangleright$ signal selection and background rejection \rightarrow \text{High granularity } \sim 1 \mu m \text{ 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

Brick weight = 8.3 kg

momentum measurement by MCS

electromagnetic shower identification
**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)

$\mu$ ID, charge, momentum

**Total target mass = 1.25 ktons**

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See tomorrow talk: Results from the OPERA experiment at the CNGS beam @ Plenary Session 3
ν$_{\mu}$ → ν$_{\tau}$: Results

<table>
<thead>
<tr>
<th>Exposure</th>
<th>17.97 × 10$^{19}$ p.o.t.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interactions in target volume</td>
<td>19505</td>
</tr>
<tr>
<td>Located interactions</td>
<td>6932</td>
</tr>
</tbody>
</table>

5 ν$_{\tau}$ candidates

[Δm$^2$ = 2.44 × 10$^{-3}$ eV$^2$]

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

p-value (likelihood ratio): 1.1 × 10$^{-7}$
Significance: 5.1σ

Discovery of tau neutrino appearance

Accepted by PRL, arXiv:1507.01417

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Consider a new mass eigenstate $m_4$ with $\Delta m^2_{41}$ up to a few eV$^2$, almost exclusively composed by a flavour sterile eigenstate, $\nu_s$

$4 \times 4$ mixing matrix parameterized by a product of complex rotational matrices

Number of expected events evaluated as:

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

Both Normal and Inverted mass Hierarchies considered

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

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

Parameters of interest in $\nu_\tau$ appearance

$\nu_\tau$ appearance in the 3+1 model
3+1 Model

Oscillation probability in presence of a sterile neutrino becomes:

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

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

Effective mixing

\[
C = 2|U_{\mu 3}||U_{\tau 3}|
\]

\[
\phi_{\mu\tau} = \text{Arg}(U_{\mu 3}^* U_{\tau 3}^* U_{\mu 4}^* U_{\tau 4}^*)
\]

\[
\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|
\]
Sterile effective mixing

Oscillation probability in presence of a sterile neutrino becomes:

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

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

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

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

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

Effective mixing

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

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

Effective mixing parameter (leading mixing term at SBL)

\[\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{2E}\]
Oscillation probability in presence of a sterile neutrino becomes:

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

Mass Hierarchy dependence

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

Effective mixing
\[
C = 2|U_{\mu 3}| |U_{\tau 3}| \\
\phi_{\mu\tau} = \text{Arg}(U_{\mu 3}^* U_{\tau 3}^* U_{\mu 4}^* U_{\tau 4}^*) \\
\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}| |U_{\tau 4}|
\]
\[ P(Energy) = C^2 \sin^2 \frac{\Delta_{31}}{2} + \sin^2 2\theta_{\mu\tau} \sin^2 \frac{\Delta_{41}}{2} \]
\[ + \frac{1}{2} C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin \Delta_{31} \sin \Delta_{41} \]
\[ - C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin \Delta_{41} \]
\[ + 2 C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2} \]
\[ + C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2} \]

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

\[ \Delta = \text{CP-violating terms} \]

\[ C = 2 |U_{\mu 3}| |U_{\tau 3}| \]
\[ \phi_{\mu\tau} = \text{Arg} \left(U_{\mu 3}^* U_{\tau 3}^* U_{\mu 4}^* U_{\tau 4}^* \right) \]
\[ \sin 2\theta_{\mu\tau} = 2 |U_{\mu 4}| |U_{\tau 4}| \]

Oscillation probability in presence of a sterile neutrino becomes:

- standard oscillation
- pure exotic oscillation

Oscillation probability in presence of a sterile neutrino becomes:

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Oscillation probability in presence of a sterile neutrino becomes:
New results

5 $\nu_\tau$ candidates

✓ Use **GLoBES** to evaluate number of expected events

✓ $\Delta m^2_{21}$ set constant to $7.54 \times 10^{-5}$ eV$^2$

✓ $\Delta m^2_{31}$ 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
  \[ L = \text{Poisson}(n|\mu) \times \text{Gaus}(\Delta m^2_{31}) \]

✓ Test statistic: profile likelihood ratio

✓ Not interesting parameters profiled out

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

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New results

5 $\nu_\tau$ candidates

At Long-Baseline and high $\Delta m^2_{41}$ (eV scale mass):

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

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

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

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

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Conclusions

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

- The sterile mixing at eV mass scale can be studied also at Long-Baseline $\nu_\mu$ 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 $\Delta m^2_{41}$ lowered down to $10^{-2}$ eV$^2$ for $\sin^2 2\theta_{\mu\tau} > 0.5$
    - At large $\Delta m^2_{41}$: $\sin^2 2\theta_{\mu\tau} < 0.119$ 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 $\nu_\tau$ candidates

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

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

$$\sin^22\theta_{\mu\tau} < 0.116 \text{ at } 90\% \text{ C.L.}$$

when integrating over $\phi$

(quasi-equal results for NH and IH)

Results given in terms of an effective mixing parameter

$$\sin^22\theta_{\mu\tau} = 4|U_{\mu4}|^2|U_{\tau4}|^2$$

which is the leading mixing term at short baseline experiments