Final results from OPERA

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on behalf of the OPERA Collaboration

NOW 2018 – Neutrino Oscillation Workshop, Rosa Marina (Ostuni, Italy), Sept. 9-16, 2018
26 institutions
~150 physicists

✓ $\nu_\tau$ appearance
  (std & looser selection)
✓ $\nu_e$ search update
✓ $\nu_\mu$ disappearance
✓ sterile neutrinos
✓ non-oscillation physics
Oscillations Project with Emulsion TRacking Apparatus

- **Long baseline** experiment: 735 km
- **Aim:** verify the $\nu_\mu \rightarrow \nu_\tau$ oscillations at atmospheric $\Delta m^2$ scale
- **How:** $\nu_\tau$ appearance on event-by-event basis in a $\nu_\mu$ beam

**Conventional muon neutrino beam**

- neutrino mean energy: 17 GeV
- Optimized for $\nu_\tau$ appearance at LNGS
- Maximize the number of $\nu_\tau$ CC interactions

- $(\nu_e + \bar{\nu}_e)/\nu_\mu$: 0.9%
- $\bar{\nu}_\mu/\nu_\mu$: 2.1%
- $\nu_\tau$ prompt: negligible

**Low background environment**

- Laboratori Nazionali del Gran Sasso (Italy)
  - 1400 m rock overburden
  - atm. $\mu$ reduction $\sim 10^6 [1\mu/(m^2\cdot h)]$
  - low radioactivity rock

**Detector:**

- Hybrid apparatus
  - Massive (1.25 kt) and fine-grained (100$\mu$m)
The $\nu_\tau$ detection challenge

Detect a few $\nu^{CC}_\tau$ from the bulk of $\nu^{CC}_\mu$

$$\tau^- \rightarrow \mu^- \nu_\tau \nu_\mu \quad 17\%$$
$$\tau^- \rightarrow e^- \nu_\tau \nu_e \quad 18\%$$
$$\tau^- \rightarrow h^- \nu_\tau n(\pi^0) \quad 50\%$$
$$\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau n(\pi^0) \quad 14\%$$

"long" decays: kink

"short" decays: I.P.

Modular detector of “Emulsion Cloud Chambers” (or bricks)

Match the needs for:

- **Large mass**
  $$N_\tau \propto (\Delta m^2)^2 M_{\text{target}}$$

- **Extreme granularity**
  $\sim \mu$m space resolution

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The OPERA detector

Target section (6.7 x 6.7 m²):
- Target
  ~ 625 ton
  ~ 75000 bricks in 27 walls
- Target Tracker
  31 XY doublets of 256 scintillator strips planes

Tracking of the target region
Brick selection
Calorimetry

Muon spectrometer (8 x 10 m²)
- 1.53 T magnet
- 22 XY RPC planes +
  2 RPC planes rotated by 42.6°
- 6 stations of 4-fold drift tubes layers

μ Identification +
charge and momentum measurements

Super Module 1
Super Module 2

+ several ancillary facilities “off-site”:
- Assembly of bricks (LNGS)
- Brick Manipulator System (LNGS)
- Labelling and X ray marking (LNGS)
- Automatized development (LNGS)
- Scanning of CS doublets (LNGS+JP)
- Scanning bricks (European Labs + JP)

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0) tracks tagged in the CS films followed upstream to **stopping point**
1) 1 cm³ **volume centered in the stopping point** scanned and tracks reconstructed
2) cosmic ray tracks (from a dedicated exposure) used for the fine **alignment** of films
3) passing through tracks discarded, the **vertexing algorithm** reconstructs the vertex
4) Short-lived particle decays identified (**decay search**)
Monte Carlo simulation benchmarked on control samples

**CC with charm production** (all channels)
If primary lepton is not identified and the daughter charge is not (or incorrectly) measured

\[ \nu_\mu, e^- \]

MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

Reduced by "track follow down", procedure and large angle scanning

**Hadronic interactions**
Background for \( \tau \to h \)

\[ \nu_\mu \]

FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

**Large angle muon scattering**
Background for \( \tau \to \mu \)

\[ \nu_\mu, \mu^- \]

Measurements in the literature (Lead form factor)

Improved MC simulations
The 5 years long CNGS run

- **1.8 \times 10^{20} p.o.t.** collected (80% of the design)
- **19505** \( \nu \) interactions in the emulsion targets.
- **5 \( \nu_\tau \) candidate events** fulfill kinematical selection \([S/B \text{ ratio } \sim 10]\)

### Signal Background Modelization

- Multichannel (uncorrelated) **counting model** based on Poisson Statistics
- Gaussian for Background Uncertainties

\[
\mathcal{L} = \prod \text{Pois}(n_i, \mu s_i + b_i) \text{ Gaus}(b_0i, b_i, \sigma_{bi})
\]

- \( \mu \to \text{strength of the signal} \) (parameter of interest)
- with \( \mu = 0 : \text{background-only hypothesis} \)
- and \( \mu = 1 : \text{nominal signal+background} \)

**test statistics:**
- i) Profile Likelihood Ratio;
- ii) Fisher’s rule \((\mu = 0)\).

### Observed Data: 4 hadronic + 1 muonic candidates

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected background</th>
<th>Expected signal</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau \to 1h )</td>
<td>0.04 \pm 0.01</td>
<td>0.52 \pm 0.10</td>
<td>3</td>
</tr>
<tr>
<td>( \tau \to 3h )</td>
<td>0.17 \pm 0.03</td>
<td>0.73 \pm 0.14</td>
<td>1</td>
</tr>
<tr>
<td>( \tau \to \mu )</td>
<td>0.004 \pm 0.001</td>
<td>0.61 \pm 0.12</td>
<td>1</td>
</tr>
<tr>
<td>( \tau \to e )</td>
<td>0.03 \pm 0.01</td>
<td>0.78 \pm 0.16</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.25 \pm 0.05</strong></td>
<td><strong>2.64 \pm 0.53</strong></td>
<td><strong>5</strong></td>
</tr>
</tbody>
</table>

### Background-only hypothesis:

- **p-value** = \( 1.1 \times 10^{-7} \)
- **excluded at 5.1\( \sigma \)** significance

Compatibility with 3\( \nu \) oscillation: \( \bar{\mu} = 1.8^{+1.8}_{-1.1} \) at 90% C.L

Probability of less likely data:
- 17\% based on total number
- 6.4\% if channels considered
The five $\nu_\tau$ candidates (2015)

- $\tau \rightarrow h$
- $\tau \rightarrow 3h$
- $\tau \rightarrow \mu$

**References:***
- JHEP 11 (2013) 036
- Phys. Rev. D 89 (2014) 051102
- PTEP 2014 (2014) 10, 101C01
ντ appearance: loose event selection (2018)

- Loose kinematical cuts:
  - Minimal requirements to identify the topologies showing 2 vertices
  - Negligible additional background from K/π decays

<table>
<thead>
<tr>
<th>Variable</th>
<th>τ → 1h</th>
<th>τ → 3h</th>
<th>τ → μ</th>
<th>τ → e</th>
</tr>
</thead>
<tbody>
<tr>
<td>z_{dec} (mm)</td>
<td>&lt;2.6</td>
<td>&lt;2.6</td>
<td>&lt;2.6</td>
<td>&lt;2.6</td>
</tr>
<tr>
<td>θ_kink (rad)</td>
<td>&gt;0.02</td>
<td>&gt;0.02</td>
<td>&gt;0.02</td>
<td>&gt;0.02</td>
</tr>
<tr>
<td>p_{2ty} (GeV/c)</td>
<td>&gt;1</td>
<td>&gt;1</td>
<td>[1, 15]</td>
<td>&gt;1</td>
</tr>
<tr>
<td>p_{2sy} (GeV/c)</td>
<td>&gt;0.15</td>
<td>&gt;0.1</td>
<td>&gt;0.1</td>
<td></td>
</tr>
<tr>
<td>Charge_{2ty}</td>
<td></td>
<td></td>
<td>Negative</td>
<td>or unknown</td>
</tr>
</tbody>
</table>

- Increment of ντ sample: x2
- Reduction of S/B from ~10 to ~3

- Multivariate approach (based on BDT)
  - exploit kinematical, topological information and their correlations
    → higher discrimination power

⇒ Improvement in |Δm_{23}^2| or alternatively ⟨σ⟩ estimation

[Phys.Rev.Lett. 120 (2018) no.21, 211801]
Statistical Analysis and Results (2018)

\[ \mathcal{L}(\mu, \beta_c) = \prod_{c=1}^{4} \left( \mathcal{P}(n_c | \mu s_c + \beta_c) \prod_{i=1}^{n_c} f_c(x_{ci}) \right) \times \prod_{c=1}^{4} G(b_c | \beta_c, \sigma_{b_c}) \]

where

- Test statistic: profile likelihood ratio
- Best-fit signal strength:
  \[ \mu = 1.1^{+0.5}_{-0.4} \]
  \[ \mu \propto |\Delta m_{32}^2| \cdot \langle \sigma \rangle \]
  \[ |\Delta m_{32}^2| = (2.7^{+0.7}_{-0.6}) \times 10^{-3} \text{ eV}^2 \]
  assuming maximal mixing
  first measure in appearance mode
- Effective tau neutrino cross section
  \[ \langle \sigma \rangle = (5.1^{+2.4}_{-2.0}) \times 10^{-36} \text{ cm}^2 \]
  assuming maximal mixing and \( |\Delta m_{32}^2| = 2.5 \times 10^{-3} \text{ eV}^2 \)
  \[ \langle \sigma_{\text{Genie}} \rangle = 4.29 \pm 0.04 \times 10^{-36} \text{ cm}^2 \]

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• Muon-less neutrino event

• Most probable topology: 
  $\nu$ interaction vertex + 2 decay vertices

• Rare topology not considered in the experiment proposal 
  (0.1 events expected in full data sample)

• Dedicated simulations + ANN (2 Layers MLP) 
  to disentangle possible interpretations:

  • $\nu_\tau CC + c$
  • $\nu_\mu CC + c + had.\ int.$
  • $\nu_\mu NC + c \bar{c}$
  • $\nu_\tau CC + had.\ int.$
  • $\nu_\mu CC + 2 had.\ int.$
  • $\nu_\mu NC + 2 had.\ int.$

The hypothesis the event not being $\nu_\tau CC + charm$ is excluded:

$p$-value $\sim 10^{-4} \rightarrow$ Significance $= 3.4 \sigma$
- OPERA detector granularity allows e.m. shower id → $v_e$ search.
- A dedicated procedure, balancing time need vs efficiency.

![Diagram](image)

<table>
<thead>
<tr>
<th>Component</th>
<th>Expectations w/o $\nu$ mixing</th>
<th>Expectations w/ std $\nu$ mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)</td>
<td>30.7</td>
<td>31.1</td>
</tr>
<tr>
<td>$\tau$ (unidentified) $\to e$</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>$\pi^0$ $\to \gamma$ (misidentified)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)</td>
<td>0.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Total</td>
<td>31.9</td>
<td>34.3</td>
</tr>
</tbody>
</table>

**Table**

- observed: 35

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$\nu_\mu$ disappearance

$\nu_\mu$ disappearance sensitivity **limited** by flux uncertainties

$\rightarrow$ no NEAR detector

**Ratio** ($R$) of NC-like over CC-like **mitigates** limitation due to flux uncertainties

**Electronic detector data:**
smaller uncertainties w.r.t. emulsion data

Test compatibility with expectation for given values of $|\Delta m_{23}^2|$
(assuming maximal mixing)

$|\Delta m_{23}^2| < 4.1 \times 10^{-3} \text{ eV}^2 \ @ \ 90\% \ C.L.$
Sterile neutrino search

Some experimental results may hint to an additional massive (~1 eV^2) sterile neutrino

Mixing described by 4 x 4 matrix

\[
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\
U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{bmatrix}
\begin{align*}
\nu_e \text{ appearance} \\
\nu_\mu \text{ disappearance} \\
\nu_\tau \text{ appearance} \\
\text{NC disappearance}
\end{align*}
\]

**OPERA** can test the sterile neutrino hypothesis looking for deviations from predictions in the electron neutrino appearance or tau neutrino appearance channels.

Predictions of the 3+1 model evaluated with **GLOBES**

- $\Delta m^2_{21}$ fixed to PDG value
- Gaussian constraint on $\Delta m^2_{31}$ (PDG mean and sigma)
- **Matter effects**: constant Earth crust density (PREM onion shell model) [Phys. Earth Planet. Interiors 25 (1981) 297]

- $\Delta m^2_{41} > 0$ favored by $\sum m_\nu$ result from cosmological surveys [A&A 594, A13 (2016)]

- **Profiled likelihood ratio** $\lambda$
  (nuisance parameter profiled out)

- Representation: $U = R_{34} R_{24} \hat{R}_{23} R_{14} \hat{R}_{13} \hat{R}_{12}$
$\nu_\mu \rightarrow \nu_\tau$ oscillation probability in presence of a sterile neutrino:

\begin{align*}
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} \\
&+ 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} \\
&+ \Delta m_{21}^2 \text{ terms ...}
\end{align*}

**Effective parameters**

\begin{align*}
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 2\theta_{\mu\tau} &= 2 |U_{\mu 4}| |U_{\tau 4}|
\end{align*}
• **Counting** analysis

\[ L = Pois(n; \mu) \times Gaus(\Delta m_{23}^2; \Delta m_{23}^2, \sigma_{\Delta m}) \]

- \( \mu \): expectation (GLoBES)
- \( n \): observation (data)

\( \Delta m_{23}^2, \sigma_{\Delta m} \) PDG values

- Both normal and inverted neutrino mass hierarchies considered

- Exclusion region on \( \Delta m_{41}^2 \) vs \( \sin^22\theta_{\mu\tau} \) plane

- **Energy selection** \( (E_\nu < 30 \text{ GeV}) \) maximizes sensitivity

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**At high \( \Delta m_{41}^2 \)**

**Profiling out \( \phi_{\mu\tau} \); \( \sin^22\theta_{\mu\tau} < 0.119 \) 90% C.L.**

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• $\nu_e$ energy distribution
to evaluate exclusion region on:

$$\Delta m_{41}^2 \text{ vs } \sin^2 2\theta_{\mu e}$$

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

Systematics errors $\sigma_i$ due to:

- Beam and efficiencies uncertainties
- 20% $E_\nu < 10$ GeV & 10% $E_\nu > 10$ GeV
- Bin-to-bin uncorrelated (conservative approach)

Likelihood

Constraints on $\Delta m_{23}^2$

$\bar{\Delta m}_{23}^2$, $\sigma_{\Delta m}$ from PDG

$\sin^2 2\theta_{\mu e} < 0.022$ @ 95%CL at high $\Delta m_{41}^2$
Combining $\nu_\tau$ and $\nu_e$

Exploiting simultaneously results of

- $\nu_\tau$ search: 10 candidates
- $\nu_e$ search: 35 candidates

... to extract limits on the parameters of the $3 + 1$ neutrino model

(Small) exclusion power enhancement w.r.t previous analyses

\[ \sin^2 2\theta_{\mu e} < 0.019 \quad [90\% \text{ C.L.}] \]
\[ @ \Delta m^2_{41} \sim 1 \text{ eV}^2 \]

\[ \sin^2 2\theta_{\mu \tau} < 0.099 \quad [90\% \text{ C.L.}] \]
\[ @ \Delta m^2_{41} \sim 1 \text{ eV}^2 \]
\[ \Delta T \text{ in the upper atmosphere} \Rightarrow \text{variation in atm. density} \Rightarrow \text{variation in } \pi \text{ interaction length} \Rightarrow \text{variation in the fraction of mesons decaying before interacting} \]

**Annual modulation of } \mu \text{ rate } (R_{\mu})\]
(More muons in summer than in winter)

Fit with: \[ R_{\mu} = R_0 + \delta R \cos \frac{2\pi}{T} (t - \phi) \]

\[ T = 359 \pm 2 \text{ days} \]
\[ \delta \frac{R}{R_0} = (1.55 \pm 0.08)\% \]
\[ \phi = 197 \pm 5 \text{ days} \]

\[ \alpha_T = \frac{\Delta R_{\mu}}{\Delta T_{eff}} = 0.95 \pm 0.04 \]

\[ \text{If } T \text{ is set to 365 days } \Rightarrow \phi = 5^{th} \text{ July} \]

\[ \alpha_T \text{ VS depth} \]
Atmospheric muon charge ratio

- Highest-E region reached

- Opposite magnet polarities runs → lower systematics

- Strong reduction of the charge ratio for multiple muon events
  - single-μ 1.377 ± 0.006
  - multi-μ 1.098 ± 0.023

- Results compatible with a simple π-K model

- No significant contribution of the prompt component up to $E_\mu \cos \theta^* \sim 10$ TeV

- Validity of Feynman scaling in the fragmentation region up to $E_\mu \sim 20$ TeV ($E_N \sim 200$ TeV)

\[ \phi_{\mu^\pm} \propto \frac{a_\pi f_{\pi^\pm}}{1 + b_\pi \epsilon_\mu \cos \theta / \epsilon_\pi} + R_{K\pi} \frac{a_K f_{K^\pm}}{1 + b_K \epsilon_\mu \cos \theta / \epsilon_K} \]

\[ f_{\pi^+} = 0.5512 \pm 0.0014 \]
\[ f_{K^+} = 0.705 \pm 0.014 \]
Neutrino interactions multiplicity

unbiased sample of $\nu_\mu CC$ interactions

charged hadron multiplicity distribution


average multiplicity $\langle n_{ch} \rangle$ as function of $\ln W^2$

$W = \text{invariant mass of the hadronic system}$

Koba-Nielsen-Olesen (KNO) scaling distribution verification

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Summary

• **Discovery of** $\nu_\mu \rightarrow \nu_\tau$ **appearance** in the CNGS neutrino beam: $5.1\sigma$

• Loose selection analysis *increase discovery significance* $6.1\sigma$
  • Measurement of $\Delta m_{23}^2$ (first measurement in appearance mode)
  • Measurement of effective $\nu_\tau$ cross-section

• Muon-less **double decay event** has been reported.
  Favored interpretation $\nu_\tau$ CC interaction with charm production

• **Final results from** $\nu_\mu \rightarrow \nu_e$ **oscillation search**

• Search for $\nu_\mu$ **disappearance**
  • Upper limit on $\Delta m_{23}^2$

• Constraints on **sterile neutrinos**
  from $\nu_\mu \rightarrow \nu_e, \nu_\mu \rightarrow \nu_\tau$ and their combination in the 3+1 flavor model

• **Non-oscillation Physics:**
  • atmospheric muons charge ratio
  • annual modulation of atmospheric muons rate
  • Neutrino interactions charged multiplicity study
OPERA taking a "selfie"... Thank you!

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