RESULTS FROM THE OPERA EXPERIMENT

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Napoli, Italy
on behalf of OPERA Collaboration

5th International Conference on New Frontiers in Physics
6th-14th July, 2016
The OPERA Collaboration

140 physicists, 26 institutions in 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
LNGS Assergi
Bari
Bologna
LNF Frascati
L’Aquila,
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Nihon

Korea
Jinju

Russia
INR RAS Moscow
LPI RAS Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern

Turkey
METU Ankara

http://operaweb.web.cern.ch/operaweb/index.shtml

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• The OPERA experiment
  - Physics goal
  - Detection principle
  - The OPERA detector
• Detector performances
• Physics results
• Conclusions
The OPERA Experiment

Oscillation Project with Emulsion-tRacking Apparatus

- Long baseline neutrino oscillation experiment in the CNGS (CERN Neutrino to Gran Sasso) $\nu_\mu$ beam
- Direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in APPEARANCE mode
- Full coverage of the parameter space for atmospheric neutrino sector
- Search for subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

BEAM PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;E_{\nu_\mu}&gt;$ (GeV)</td>
<td>17</td>
</tr>
<tr>
<td>$\frac{(\bar{\nu}<em>e + \nu_e)}{\nu</em>\mu}$</td>
<td>0.8% *</td>
</tr>
<tr>
<td>$\frac{\bar{\nu}<em>\mu}{\nu</em>\mu}$</td>
<td>2.0% *</td>
</tr>
<tr>
<td>$\nu_\tau$ prompt</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

* Interaction rate at LNGS

PRL 112 (2014) 181801

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**THE PRINCIPLE**

- Massive active target with micrometric space resolution
- Detect \( \tau \)-lepton production and decay
- Underground location (10^6 reduction of cosmic ray flux)
- Usage of electronic detectors to provide “time resolution” to the emulsions and preselect the interaction region

<table>
<thead>
<tr>
<th>( \tau ) DECAY CHANNEL</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau \rightarrow \mu )</td>
<td>17.7</td>
</tr>
<tr>
<td>( \tau \rightarrow e )</td>
<td>17.8</td>
</tr>
<tr>
<td>( \tau \rightarrow h )</td>
<td>49.5</td>
</tr>
<tr>
<td>( \tau \rightarrow 3h )</td>
<td>15.0</td>
</tr>
</tbody>
</table>
The Detector

SM-1

Target
brick walls + Target Tracker

Spectrometer
RPC + Drift Tubes

SM-2

Target
brick walls + Target Tracker

Spectrometer
RPC + Drift Tubes

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Emulsion Cloud Chamber (ECC)
- passive material → lead (massive target)
- tracking device → nuclear emulsion (high resolution)

Brick
- 57 emulsion films
- 56 lead plates
- 1 Changeable Sheet doublet
- 10 $X_0$
- 8.3 kg

momentum measurement by MCS

emulsion films

electromagnetic shower identification

THE TARGET
MADE OF ~150000 BRICKS
**Neutrino Interactions In The Target**

**“1μ” Event**

\[ \nu_\mu N \rightarrow \mu^- X \]

**“0μ” Event**

\[ \nu_\mu N \rightarrow \nu_\mu X \]
1. Scan 15 emulsion films around stopping plate

2. Reject passing through tracks

3. Search tracks making vertex

**Event Analysis**

**Electronic Detector Reconstruction**

**Vertex Location in the Brick**
**Charm Data Sample**

**Proof of $\tau$ Detection Efficiency**

- Charm decay has the same topology as the $\tau$
- Charmed hadrons from $\nu_\mu$ CC interactions
- Muon at the primary vertex
- Used as "control sample"

**Observed:** 50  
**Expected:** $54 \pm 4$
## COLLECTED DATA

<table>
<thead>
<tr>
<th>YEAR</th>
<th>P.O.T. (10^{19})</th>
<th>Number of $\nu$ interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>1.74</td>
<td>1931</td>
</tr>
<tr>
<td>2009</td>
<td>3.53</td>
<td>4005</td>
</tr>
<tr>
<td>2010</td>
<td>4.09</td>
<td>4515</td>
</tr>
<tr>
<td>2011</td>
<td>4.75</td>
<td>5131</td>
</tr>
<tr>
<td>2012</td>
<td>3.86</td>
<td>3923</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>17.97</strong></td>
<td><strong>19505</strong></td>
</tr>
</tbody>
</table>

80% of the nominal value

**DATA SAMPLE**

- **2008-2009**: 1\textsuperscript{st} and 2\textsuperscript{nd} probable brick
- **2010-2012**: 1\textsuperscript{st} probable brick

- Extension of the analysis up to 4\textsuperscript{th} probable brick in progress
$\nu_\mu \rightarrow \nu_\tau$ Oscillation Search

5 $\nu_\tau$ candidate events observed in the analysed sample

1st candidate:
$\tau \rightarrow h$

2nd candidate:
$\tau \rightarrow 3h$

3rd candidate:
$\tau \rightarrow \mu$

4th candidate:
$\tau \rightarrow h$

5th candidate:
$\tau \rightarrow h$

References:
- JHEP 11 (2013) 036
- Phys. Rev. D 89 (2014) 051102
- PTEP 10 (2014) 101C01
- PRL 115 (2015) 121802

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THE 5TH $\nu_\tau$ CANDIDATE EVENT

RECONSTRUCTION IN THE BRICK

$\tau^- \rightarrow \pi^- \nu_\tau$
**SELECTION CRITERIA**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>kink &gt; 20 mrad</td>
<td>90 ± 2 mrad</td>
</tr>
<tr>
<td>decay length &lt; 2600 μm</td>
<td>634 ± 30 μm</td>
</tr>
<tr>
<td>P daughter &gt; 2 GeV/c</td>
<td>11 +14 -4 GeV/c</td>
</tr>
<tr>
<td>$P_t &gt; 600$ MeV/c</td>
<td>1000 +1200 -400 MeV/c</td>
</tr>
<tr>
<td>missing $P_t &lt; 1$ GeV/c</td>
<td>300 ± 100 GeV/c</td>
</tr>
<tr>
<td>$\varphi &gt; 90^\circ$</td>
<td>151 ± 1 °</td>
</tr>
</tbody>
</table>

The event passes all the required kinematical cuts.
Charmed hadron decay with missed muon at primary vertex

MC tuned on CHORUS data
Reduced by Track Follow-down procedure

Hadronic interaction

PTEP9 (2014) 093C01
FLUKA + test beam data
Reduced by large angle scanning and nuclear fragment search

Large angle muon scattering

MC tuned on old measurements on lead form factor
**RESULTS**

$\nu_\mu \rightarrow \nu_\tau$

- Exposure: $17.97 \times 10^{19}$ p.o.t.
- Interactions in the target volume: 19505
- Located interactions: 6932

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

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Signal Expectation</th>
<th>Total Background</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow h$</td>
<td>$0.52 \pm 0.10$</td>
<td>$0.04 \pm 0.01$</td>
<td>3</td>
</tr>
<tr>
<td>$\tau \rightarrow 3h$</td>
<td>$0.73 \pm 0.14$</td>
<td>$0.17 \pm 0.03$</td>
<td>1</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu$</td>
<td>$0.61 \pm 0.12$</td>
<td>$0.004 \pm 0.001$</td>
<td>1</td>
</tr>
<tr>
<td>$\tau \rightarrow e$</td>
<td>$0.78 \pm 0.16$</td>
<td>$0.03 \pm 0.01$</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>$2.64 \pm 0.53$</td>
<td>$0.25 \pm 0.05$</td>
<td>5</td>
</tr>
</tbody>
</table>

- 5 observed events with 0.25 background events
- 5.1 $\sigma$ exclusion of the background-only hypothesis

Two statistical methods:
- Fisher combination of single channel p-values
- Profile likelihood ratio

Compatible with expectations in standard 3-flavours neutrino model

$\nu_{\mu\mu} \rightarrow \nu_{\tau} R$

Compatible with expectations in standard 3-flavours neutrino model
**ν Interaction with 3 Vertices**

- Muonless event
- A primary and two secondary vertices found in emulsion
- Electromagnetic activity (γ's) at the kink point

<table>
<thead>
<tr>
<th>Vertex ID</th>
<th>Attached tracks</th>
<th>x (μm)</th>
<th>y (μm)</th>
<th>z (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I (primary)</td>
<td>2, 4, 5</td>
<td>15077.0</td>
<td>59157.9</td>
<td>-33081.8</td>
</tr>
<tr>
<td>II (secondary)</td>
<td>1, 3</td>
<td>15085.9</td>
<td>59149.9</td>
<td>-32979.2</td>
</tr>
<tr>
<td>III (kink)</td>
<td>4, 6</td>
<td>15073.9</td>
<td>59262.4</td>
<td>-31926.4</td>
</tr>
</tbody>
</table>

Flight lengths:
II: 103 μm  
III: 1160 μm

- Invariant masses at both secondary vertices are larger than 1 GeV
- Event not classified as ντ interaction candidate by standard analysis
- Ad hoc simulations and multivariate analysis performed to distinguish between possible interpretations

*More detail in C. Sirignano's presentation on 9th Jul*
νμ DISAPPEARANCE

- Full data sample (2008-2012)
- Use of electronic detector data only and separation between CC and NC like events
- To reduce systematic effects coming from the beam uncertainty (no near detector), NC like over CC like ratio is used

- A fit using NC-like/CC-like ratio in which all mixing parameters are fixed to the PDG values BUT Δm²_{23}
- Reweighting MC according to oscillation probability and minimizing χ² between MC and data
- Systematics under study

Preliminary measurement of Δm²_{23}
Consistent with the world average and the internal OPERA appearance results
**ν_e Appearance Search**

2008-2012 data sample (17.97 x 10^{19} p.o.t.)

**Observed ν_e events:** 34

Expected ν_e events
- from ν_e beam contamination: 37 ± 5
- from bkg τ → e + mis-id π^0: 1.2 ± 0.1
- from 3-flavour oscillation: 2.9 ± 0.4 \( \sin^2(2\theta_{13}) = 0.098 \)

Work in progress to extract exclusion limits on sterile search.
\( \nu_\mu \rightarrow \nu_\tau \) oscillation probability in presence of a **sterile neutrino**

neglecting solar driven oscillation \( \Delta m^2_{21} \approx 0 \)

**Effective mixing**

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

\[ \Delta_{ij} = \frac{1.27 \Delta m^2_{ij} L}{E} \]

\[ \nu_\tau \text{ Appearance In 3+1 Model} \]

\[ P_{\nu_\mu \rightarrow \nu_\tau} = C^2 \sin^2 \Delta_{31} + \sin^2 2\theta_{\mu \tau} \sin^2 \Delta_{41} \]

- **Standard oscillation**
  - \( +0.5C \sin 2\theta_{\mu \tau} \cos \phi_{\mu \tau} \sin 2\Delta_{31} \sin 2\Delta_{41} \)
  - \( -C \sin 2\theta_{\mu \tau} \sin \phi_{\mu \tau} \sin^2 \Delta_{31} \sin 2\Delta_{41} \)
  - \( +2C \sin 2\theta_{\mu \tau} \cos \phi_{\mu \tau} \sin^2 \Delta_{31} \sin^2 \Delta_{41} \)
  - \( +C \sin 2\theta_{\mu \tau} \sin \phi_{\mu \tau} \sin 2\Delta_{31} \sin^2 \Delta_{41} \)

- **Exotic oscillation**
- **CP-violating terms**
- **Mass hierarchy dependence**
\( \sin^2 2\theta_{\mu\tau} < 0.119 \) at 90% C.L
when integrating over \( \phi \)
(almost identical results for NH and IH)
CONCLUSIONS

- First observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode
- 5 $\nu_\tau$ candidate events found with 0.23 background
- No oscillation hypothesis excluded at 5.1 $\sigma$

- $\nu_\mu$ disappearance analysis => preliminary $\Delta m^2_{32}$ consistent with world average
- $\nu_\mu \rightarrow \nu_e$ oscillation search => number of events observed in agreement with expected background + standard oscillation
- Sterile neutrino oscillation constraints from $\nu_e$ and $\nu_\tau$ studies

PERSPECTIVES

- re-analysis of the data with looser selection and multivariate analysis: more signal and background but significant statistical gain
- Exploiting the unique feature of being able to identify all three neutrino flavours: $\nu_\tau$ appearance + $\nu_e$ appearance + $\nu_\mu$ disappearance data
  => Constraints on the oscillation parameters with one single experiment
90% C.L. intervals on $\Delta m^2_{23}$ by Feldman & Cousins method

$[2.0 - 4.7] \times 10^{-3}$ eV$^2$

(assuming full mixing)
Summary of Four Events

Visible energy of all $\nu_\tau$ events
Scalar sum of momentum and $\gamma$ energies

<table>
<thead>
<tr>
<th>MODE</th>
<th>$P_{\text{sum}}$(GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^{\text{st}}$</td>
<td>$\tau \rightarrow h$ 24.3 $^{+6.1}_{-3.2}$</td>
</tr>
<tr>
<td>$2^{\text{nd}}$</td>
<td>$\tau \rightarrow 3h$ 12.7 $^{+2.3}_{-1.7}$</td>
</tr>
<tr>
<td>$3^{\text{rd}}$</td>
<td>$\tau \rightarrow \mu$ 6.8 $^{+0.9}_{-0.6}$</td>
</tr>
<tr>
<td>$4^{\text{th}}$</td>
<td>$\tau \rightarrow h$ 14.4 $^{+3.9}_{-2.7}$</td>
</tr>
<tr>
<td>$5^{\text{th}}$</td>
<td>$\tau \rightarrow h$ 11 $^{+14}_{-4}$</td>
</tr>
</tbody>
</table>
The First $\nu_\tau$ Candidate

As seen by electronic detectors...
The First $\nu_\tau$ Candidate

... and in the Brick

\[ \tau^- \rightarrow \rho^- \nu_\tau \]
\[ \rho^- \rightarrow \pi^0 \pi^- \]
\[ \pi^0 \rightarrow \gamma \gamma \]
The First $\nu_\tau$ Candidate

<table>
<thead>
<tr>
<th>SELECTION CRITERIA</th>
<th>MEASURED</th>
</tr>
</thead>
<tbody>
<tr>
<td>kink &gt; 20 mrad</td>
<td>41 ± 2 mrad</td>
</tr>
<tr>
<td>decay length &lt; 2600 μm</td>
<td>1335 ± 35 μm</td>
</tr>
<tr>
<td>$P_{\text{daughter}} &gt; 2$ GeV/c</td>
<td>12 $^{+6}_{-3}$ GeV/c</td>
</tr>
<tr>
<td>$P_t &gt; 300$ MeV/c</td>
<td>470 $^{+230}_{-120}$ MeV/c</td>
</tr>
<tr>
<td>missing $P_t &lt; 1$ GeV/c</td>
<td>0.57 $^{+0.32}_{-0.17}$ GeV/c</td>
</tr>
<tr>
<td>$\varphi &gt; 90^\circ$</td>
<td>173 ± 2 °</td>
</tr>
</tbody>
</table>

The event passes all the kinematical cuts required
Kinematical selection for $\tau \rightarrow h$ decay channel
THE SECOND $\nu_\tau$ CANDIDATE

AS SEEN BY ELECTRONIC DETECTORS ...
The Second $\nu_\tau$ Candidate

... And In The Brick

$\nu^{-} \rightarrow \nu_\tau \pi^{-} \pi^{+}\pi^{+}$
The event passes all the kinematical cuts required
THE THIRD $\nu_{\tau}$ CANDIDATE

AS SEEN BY ELECTRONIC DETECTORS ...

Event: 12123032048, 2 May 2012, 10:12 (UTC), YZ projection

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The Third $\nu_\tau$ Candidate

... And In The Brick

$\tau^- \rightarrow \mu^- \nu_\tau \nu_\mu$
### The Third $\nu_\tau$ Candidate

<table>
<thead>
<tr>
<th>SELECTION CRITERIA</th>
<th>MEASURED</th>
</tr>
</thead>
<tbody>
<tr>
<td>kink $&gt; 20$ mrad</td>
<td>$245 \pm 5$ mrad</td>
</tr>
<tr>
<td>decay length $&lt; 2600$ $\mu$m</td>
<td>$376 \pm 10$ $\mu$m</td>
</tr>
<tr>
<td>$P_{\text{muon}} &gt; 1$ GeV/c</td>
<td>$2.8 \pm 0.2$ GeV/c</td>
</tr>
<tr>
<td>$P_t &gt; 250$ MeV/c</td>
<td>$690 \pm 50$ MeV/c</td>
</tr>
</tbody>
</table>

The event passes all the kinematical cuts required.
The Third $\nu_\tau$ Candidate

Kinematical selection for $\tau \rightarrow \mu$ decay channel
The 4th $\nu_\tau$ Candidate Event

... And In The Brick

$\nu \xrightarrow{} \pi^- \nu_\tau$
The 4th $\nu_\tau$ Candidate Event

Reconstruction in the Brick

$\tau^- \rightarrow \pi^- \nu_\tau$
Particle Identification

Track Follow-Down

**Track 2** from neutrino interaction vertex
- \( p = 1.9 \text{ GeV/c} \)
- stopping in the first iron slab of the magnet
- muon hypothesis rejected

\[ D = 0.40^{+0.04}_{-0.05} \]

**Daughter** track from \( \tau \) decay
- \( p = 6.0 \text{ GeV/c} \)
- stopping in the first arm of the spectrometer
- classified as **hadron**

\[ D = 0.18 \pm 0.04 \]

Charm background hypothesis rejected

Hadronic decay channel

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The event passes all the required kinematical cuts

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<td>137 ± 4 mrad</td>
</tr>
<tr>
<td>decay length &lt; 2600 μm</td>
<td>1090 ± 30 μm</td>
</tr>
<tr>
<td>P daughter &gt; 2 GeV/c</td>
<td>6.0 +2.2 -1.2 GeV/c</td>
</tr>
<tr>
<td>P_t &gt; 600 MeV/c</td>
<td>820 +300 -160 MeV/c</td>
</tr>
<tr>
<td>missing P_t &lt; 1 GeV/c</td>
<td>0.55 +0.30 -0.20 GeV/c</td>
</tr>
<tr>
<td>(\varphi &gt; 90^\circ)</td>
<td>166 +2 -31 °</td>
</tr>
</tbody>
</table>
Kinematical selection for $\tau \rightarrow h$ decay channel
CHARM DATA SAMPLE

DATA/MC COMPARISON

Observed: 50
Expected: 54 ± 4

Good agreement between data and Monte Carlo