Search for $\nu_\mu \to \nu_\tau$ oscillations in appearance mode in the OPERA experiment

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on behalf of the OPERA Collaboration

Dipartimento di Fisica Galileo Galilei
INFN-PADOVA

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# The OPERA Collaboration

**180 physicists, 32 institutions in 12 countries**

<table>
<thead>
<tr>
<th>Belgium</th>
<th>Croatia</th>
<th>France</th>
<th>Germany</th>
<th>Israel</th>
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<td>LAPP Annecy</td>
<td>Hamburg</td>
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[http://operaweb.lngs.infn.it/scientists/?lang=en](http://operaweb.lngs.infn.it/scientists/?lang=en)
Aiming at the first direct detection of neutrino oscillations in appearance mode where is identified by the charged lepton created in its CC interaction.

Oscillation parameters in the atmospheric neutrino sector

Full mixing and $\Delta m^2_{23} \sim 2.4 \times 10^{-3} \text{eV}^2$

The light blue band indicates the OPERA allowed region (90% CL) for the above parameter values for $22.5 \times 10^{19} \text{pot}$
Direct detection of \( \nu_\mu \rightarrow \nu_\tau \) appearance signal

The challenge is to identify \( \nu_\tau \) interactions from \( \nu_\mu \) interactions.

Requirements: high neutrino energy & intensity & long base line & large target mass & sub-micron resolution & detect short lived \( \tau \)’s
CNGS neutrino beam

CNGS beam optimized to study $\nu_\tau$ appearance by $\tau$ detection

$$N_\tau = N_A M_D \int \phi_{\nu_\mu}(E) P_{\nu_\mu \rightarrow \nu_\tau}(E) \sigma_{\nu_\tau}^{CC}(E) \epsilon(E) dE$$

Expected interactions for $22.5 \times 10^{19}$ pot ($4.5 \times 10^{19}$ pot nominal pot in 5 years):

- $\sim 24300 \nu_\mu^{CC} + NC$
- $\sim 115 \nu_\tau^{CC} (\Delta m^2 = 2.5 \times 10^{-3} eV^2)$
- $\sim 10$ tau decays are expected to be observed (BG<1)

<table>
<thead>
<tr>
<th>$&lt; E\nu &gt;$</th>
<th>17 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>730 km</td>
</tr>
<tr>
<td>$(\nu_e + \bar{\nu}<em>e)/\nu</em>\mu$</td>
<td>0.87% *</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu/\nu</em>\mu$</td>
<td>2.1% *</td>
</tr>
<tr>
<td>$\nu_\tau$ prompt</td>
<td>Negligible *</td>
</tr>
</tbody>
</table>

* Interaction rate at LNGS
Typical $\nu^\mu_{CC}$-like and NC-like events
**The overall efficiency** **for CC events > 97.5%**

Charge id efficiency above 96% for $45\text{GeV}/c > |P| > 2.5\text{GeV}/c$

**Momentum resolution** as computed from MC is about 10% at $2.5\text{GeV}/c$ and 20% at $25\text{GeV}/c$ and **transverse spatial resolution** is better than 1mm.
Performance: Energy deposit in the Target Tracker

**CC**

- Total reconstructed energy

**NC**

For energy above 200MeV in a good agreement. Investigating the energy deposition in the low energy region.

$dE/E$ is between $(20-40)\%$ for the energy range $(5-40)\text{GeV/c}^2$
**Performance:**

**Bjorken-y variable:**

\[ y = 1 - \frac{E_\mu}{E_{\nu_\mu}} = \frac{E_{\text{had}}}{E_\mu + E_{\text{had}}} \]

connects muon momentum measurement with calorimetric measurement of all the hadrons

---

**Left:** events selected just with muon ID  
NC background **5.2%**

**Right:** muon ID + bending in spectrometer  
NC background **0.8%**

The resolution is good enough to clearly see QE peak.  
NC background could be eliminated by requiring momentum measurement in the spectrometer.
The OPERA target: Emulsion Cloud Chamber

OPERA emulsion film

Recorded as silver grains along the line where a charged particle passed through

50 micron

Resolution of 0.3 micron

Lead plate: 1mm

75.4mm

125mm

8.3kg

10X0

Neutrino Beam

Emulsion Cloud Chamber (ECC)

100mm

1mm

0.3mm

57 films interleaved by 1 mm thick lead plates

2 emulsion layers (44 μm thick) poured on a 205 μm plastic base
OPERA as hybrid detector

Extract ECC brick and CS, scan CS. Confirm the event in the ECC brick.

150,000 ECC bricks.
105,000 m² of lead
111,000 m² of film
~ 8.9 million films
Total mass: 1.25 kton
Emulsion scanning

Parallel ECC brick analysis in ~ 10 labs.
CS Scan & analysis
→ NAGOYA : LNGS = 50:50
ECC brick Scan & analysis
→ NAGOYA : EU = 50:50

CS Scanning Stations
The Changeable Sheets (CS)
the interface between Electronic Detector and ECC brick

Position accuracy of the electronic predictions

CS doublet alignment by Compton electrons

Angular accuracy of the electronic predictions

σ_{dy} \sim 10.0 \text{mm}

σ \sim 2.5 \mu m

σ_{dy} \sim 23 \text{mrad}
Emulsion gives 3D vector data, with a few micron precision of the vertex accuracy.

The frames correspond to scanning area. Yellow short lines are measured tracks. Other colored lines are interpolation or extrapolation.
Impact Parameter (IP) measurement:
The IP evaluation is a crucial point to detect decay topology.
Momentum measurement by MCS

\[
\theta_0 = \frac{13.6 \text{MeV}}{\beta \gamma p} \sqrt{x/X_0} [1 + 0.038 \ln(x/X_0)]
\]

Evaluating scattering of particles

Linearity of momentum center

\[
\pi \text{ test beam}
\]

Resolution

soft muons in the bricks

\[
\sigma = (22 \pm 4)\%
\]
Gamma reconstruction analysis in ECC brick

\[ \pi^0 \text{ mass reconstruction (data)} \]

- \( \chi^2 / \text{ndf} = 1.954 / 6 \)
- Constant: 7.388 ± 1.757
- Mean: 142.2 ± 13.2
- Sigma: 65.76 ± 11.56

35 gamma pairs

\( \sigma \sim 45\% \)
## CNGS physics runs

<table>
<thead>
<tr>
<th>year</th>
<th>beam days</th>
<th>protons on target</th>
<th>SPS eff.</th>
<th>events in the bricks</th>
<th>run</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>123</td>
<td>$1.78 \times 10^{19}$</td>
<td>61%</td>
<td>1698</td>
<td>Physics runs</td>
</tr>
<tr>
<td>2009</td>
<td>155</td>
<td>$3.52 \times 10^{19}$</td>
<td>70%</td>
<td>3693</td>
<td>Physics runs</td>
</tr>
<tr>
<td>2010</td>
<td>187</td>
<td>$4.04 \times 10^{19}$</td>
<td>81%</td>
<td>4248</td>
<td>Physics runs</td>
</tr>
</tbody>
</table>

In total 9639 events collected (within 1σ w.r.t. expectation from pot) ➔ 2.1 nominal years in 3 years
3006 neutrino interactions located, 98% of the 2008-09 neutrino run expected yield.

The first results was opened and published at June 2010*

Charm candidate events

- proof of the $\tau$ efficiency -

On the published data sample

- **20 charm events** selected
  (3 events with 1-prong kink topology)

- **Expected: 16.0 ± 2.9**
  (0.80 ± 0.22 with kink)

- **~ 2 BG events** expected
The first $\nu_\tau$ candidate event was found

Observation of a first $\nu_\tau$ candidate event in the OPERA experiment in the CNGS beam

Event number 9234119599, taken on 22 August 2009, 19:27 (UTC)

This result was opened at June/2010.
The $\nu_e$ candidate event as seen by the electronic detectors...
...and as seen in emulsion
Event topological features (Side view)

- Primary vertex
- Kink point
- 1 radiation length
- 0.033 interaction length

<table>
<thead>
<tr>
<th>track #</th>
<th>$\tan \theta_x$</th>
<th>$\tan \theta_y$</th>
<th>$p\beta$ [GeV/c]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.176</td>
<td>0.363</td>
<td>0.78 $^{+0.13}_{-0.10}$</td>
</tr>
<tr>
<td>2</td>
<td>-0.650</td>
<td>0.000</td>
<td>0.32 $^{+0.31}_{-0.11}$</td>
</tr>
<tr>
<td>3</td>
<td>0.108</td>
<td>0.113</td>
<td>1.97 $^{+0.33}_{-0.25}$</td>
</tr>
<tr>
<td>4 (parent)</td>
<td>-0.027</td>
<td>0.022</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.157</td>
<td>0.267</td>
<td>1.30 $^{+0.22}_{-0.16}$</td>
</tr>
<tr>
<td>6</td>
<td>0.334</td>
<td>-0.584</td>
<td>0.36 $^{+0.18}_{-0.09}$</td>
</tr>
<tr>
<td>7 (from neutral track)</td>
<td>0.438</td>
<td>0.419</td>
<td>0.49 $^{+0.29}_{-0.13}$</td>
</tr>
<tr>
<td>8 (daughter)</td>
<td>-0.007</td>
<td>-0.014</td>
<td>12 $^{+6}_{-3}$</td>
</tr>
</tbody>
</table>

The viewer of scintillation Target Tracker
### γ attachment to the vertices

Pointing resolution ($\sigma$) for a given gamma: function of scattering and distance

![Diagram showing γ attachment to the vertices](image)

<table>
<thead>
<tr>
<th>Distance from 2ry vertex (mm)</th>
<th>IP to 1ry vertex (μm) &lt;resolution&gt;</th>
<th>IP to 2ry vertex (μm) &lt;resolution&gt;</th>
<th>Prob. of attach. to 1ry vtx*</th>
<th>Prob. of attach. to 2ry vtx*</th>
<th>Attachment hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_1$</td>
<td>2.2</td>
<td>45.0 &lt;11&gt;</td>
<td>7.5 &lt;7&gt;</td>
<td>&lt;10⁻³</td>
<td>0.32</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>12.6</td>
<td>85.6 &lt;56&gt;</td>
<td>22 &lt;50&gt;</td>
<td>0.10</td>
<td>0.82</td>
</tr>
</tbody>
</table>

* probability to find an IP larger than the observed one

<table>
<thead>
<tr>
<th>Energy [GeV]</th>
<th>$\gamma_1$</th>
<th>$\gamma_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_1$</td>
<td>5.6 ± 1.0 ± 1.7</td>
<td></td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>1.2 ± 0.4 ± 0.4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\pi^-(K) + \gamma_1 + \gamma_2$</th>
<th>640 $^{+125}<em>{-80}$ $^{+100}</em>{-90}$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_1 + \gamma_2$</td>
<td>120 ± 20 ± 35 MeV</td>
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</tbody>
</table>
## Kinematical variables

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>Measured</th>
<th>Selection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kink (mrad)</td>
<td>$41 \pm 2$</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Decay length (μm)</td>
<td>$1335 \pm 35$</td>
<td>Within 2 plates</td>
</tr>
<tr>
<td>$P_t$ daughter (GeV/c)</td>
<td>$12^{+6}_{-3}$</td>
<td>&gt;2</td>
</tr>
<tr>
<td>$P_t$ daughter (MeV/c)</td>
<td>$470^{+230}_{-120}$</td>
<td>&gt;300 ($\gamma$ attached)</td>
</tr>
<tr>
<td>Missing $P_t$ (MeV/c)</td>
<td>$570^{+320}_{-170}$</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>$\phi$ (deg)</td>
<td>$173 \pm 2$</td>
<td>&gt;90</td>
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</table>

The uncertainty on $P_t$ due to the alternative $\gamma^2$ attachment is <50 MeV.

The event passes all the kinematical cuts required.

Animation
Background sources

- Prompt $\nu_\tau$ ~ $10^{-7}$/CC
- Decay of charmed particles produced in $\nu_e$ interactions ~ $10^{-6}$/CC
- Double charm production ~ $10^{-6}$/CC

Main backgrounds:
- Decay of charmed particles produced in $\nu_\mu$ interactions (CC & NC) ~ $10^{-5}$/CC
- Hadronic interactions (CC & NC) ~ $10^{-5}$/CC
Charm background

Primary lepton not identified

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

\[ D^+ \]

\[ \mu^+, e^+, h^+ \]

- This background can be suppressed by identifying the primary lepton \( \rightarrow \sim 96\% \) muon ID

- For the 1-prong hadronic channel \( 0.007 \pm 0.004 \text{ (syst.)} \) background events are expected for the analyzed statistics
Simulation of the hadronic interaction BG

- 160 million events (0.5-15 GeV/c) of $\pi^+, \pi^-, K^+, K^-, p$ impinging 1 mm of lead, equivalent to 160 km of hadronic track length produced with FLUKA

Typical Monte Carlo scattering distributions for 5 GeV $\pi^+$

Pion angular deflection

20 mrad

Pt of secondary pion

300 MeV/c

Kink probability integrated over the $\nu_\mu\ NC$ hadronic spectrum after 2 mm Pb and taking in to account the cuts on the event global kinematics:

$(3.8 \pm 0.2) \times 10^{-5}$ kinks/NC
Hadronic interaction background study in OPERA data

- Search for “decay-like” interactions track far away from the primary vertex
- no background-like interaction has been found in the signal region
  90% CL upper limit of $1.54 \times 10^{-3}$ kinks/NC event
**Statistical significance**

We observe 1 event in the 1-prong hadron $\tau$ decay channel, with a background expectation of:

- 0.007 events (charm)
- 0.011 events (hadronic interactions)

**Events 1-prong hadron:**

0.018 ± 0.007 (syst)

**All decay modes:** 1-prong hadron, 3-prongs + 1-prong $\mu$ + 1-prong $e$:

0.045 ± 0.020 (syst) events total BG

<table>
<thead>
<tr>
<th>Channel</th>
<th>Probability to observe 1 event due to BG</th>
<th>Statistical significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-prong hadron</td>
<td>1.8 %</td>
<td>2.36</td>
</tr>
<tr>
<td>all decay mode</td>
<td>4.5 %</td>
<td>2.01</td>
</tr>
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</table>
$\nu_e$ events

13 $\nu_e$ candidate events have been observed.

2.6 ± 0.8 GeV
Summary

• The OPERA experiment is aimed at the discovery of neutrino oscillations in direct appearance mode through the study of the $\nu_\mu - \nu_\tau$ channel.

• A subsample of 2008-2009 data taking corresponding to $1.85 \times 10^{19}$ pot (20% of the available statistics) have been opened and published on June 2010.
  • Decay topologies due to charmed particles have been observed in good agreement with expectations, as well as several events induced by $\nu_e$ present as a contamination in the $\nu_\mu$ beam.
  • One muon-less event candidate for the $\tau \rightarrow$ 1-prong hadron decay topology has been detected ($0.54 \pm 0.13$ (syst.) expected).

• By considering 1-prong hadron channel, the statistical significance on the measurement of a first $\nu_\tau$ candidate event is $2.36 \sigma$. 
Outlook

• In 2008 – 2010, data has been taken corresponding to 2.1 nominal years. In 2010, beam intensity has reached 90% nominal and SPS efficiency 81%.

• Analysis on 2008+2009 full sample will be released soon.

• Analysis of 2010 events is being performed in parallel.
Next CNGS run will in 2011 and 2012.

From 18th of March 2011, CNGS run will start with 6 extra weeks of beam in dedicated mode. It will correspond to 1.2 nominal years if CNGS and OPERA efficiencies are at the 2010 level.

If 2012 run is like 2011: data on \( \sim 19.9 \times 10^{19} \) POT or \( \sim 88\% \) of Proposal beam intensity will be collected.
Thank you for your attention!
BACKUP
INDUSTRIAL EMULSION FILMS BY FUJI FILM

Emulsion Layer (44 microns)

Plastic Base (205 microns)

basic detector: AgBr crystal, size = 0.2 micron
detection eff. = 0.16/crystal

$10^{13}$ “detectors” per film

sensitivity 15 grains/44 microns

mip

electron $\sim 100$ keV

20 $\mu$m

high dE/dx tracks from nuclear evaporation

intrinsic resolution: 50 nm

deviation from linear-fit line. (2D)
### OPERA expected performance (Proposal)

<table>
<thead>
<tr>
<th>τ decay channel</th>
<th>B.R. (%)</th>
<th>Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu$</td>
<td>17.7</td>
<td>2.9</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \rightarrow e$</td>
<td>17.8</td>
<td>3.5</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \rightarrow h$</td>
<td>49.5</td>
<td>3.1</td>
<td>0.24</td>
</tr>
<tr>
<td>$\tau \rightarrow 3h$</td>
<td>15.0</td>
<td>0.9</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10.4</strong></td>
<td></td>
<td><strong>0.75</strong></td>
</tr>
</tbody>
</table>

Main background sources:
- Production and decay of charmed particles
- Hadron reinteractions
- Large angle muon scattering

Assume $22.5 \times 10^{19}$ pot

#### Example: charm BG to tau decays

**Signal**

$\nu_\tau$ CC

$\tau$

$\mu$, e, hadron

**Background**

$\nu_\mu$ CC + charm production

charm

muon misidentified
Nominal selection criteria for hadron kink topology

- Kink occurring within 2 lead plates downstream of the primary vertex
- Kink angle larger than 20 mrad
- Daughter momentum higher than 2 GeV/c
- Decay $P_t$ higher than 600 MeV/c,
  300 MeV/c if $\geq 1 \gamma$ pointing to the decay vertex
- Missing $P_t$ at primary vertex lower than 1 GeV/c
- Azimuth angle between the primary hadron shower momentum direction and the parent track direction larger than $\pi/2$ rad

Signal: $\phi = 180^\circ$
BG: small $\phi$
Features of the decay topology

red bands: values for the “interesting” event with uncertainties
**Kinematical cuts**

Reject hadron interactions with small $P_t$ at secondary vertex.

Reject NC events with larger missing $P_t$ at primary vertex.
Signal: $\phi = 180^\circ$

BG: small

$\tau$-decay

$\pi^-$

$\phi = 180^\circ$

$\nu_\tau$ $N$ $\tau^-$ $X$

$\phi$

$kink$

Transverse momentum

Hadrons

Parent

$172.6^\circ$

$P_T$ (GeV/c)

$P_x$ (GeV/c)
DATA/MC comparison: good agreement in normalization and shape

Beam test 4 GeV pion 18 times track length (20m) of tau search.
**Sensitivity to $\Theta_{13}$**

Simultaneous fit on: $E_e$, missing $p_T$ and visible energy

**Operational Limits**

<table>
<thead>
<tr>
<th>$\Theta_{13}$ (deg)</th>
<th>$\nu_\mu \rightarrow \nu_e$</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau \rightarrow e$</td>
<td>$\nu_\mu$ CC</td>
</tr>
<tr>
<td>9</td>
<td>9.3</td>
<td>1.5</td>
</tr>
<tr>
<td>7</td>
<td>5.8</td>
<td>4.5</td>
</tr>
<tr>
<td>5</td>
<td>3.0</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Limits at 90% CL for $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$ full mixing

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2 2\Theta_{13}$</th>
<th>$\Theta_{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHOOZ</td>
<td>&lt;0.14</td>
<td>11°</td>
</tr>
<tr>
<td>OPERA</td>
<td>&lt;0.03</td>
<td>7.1°</td>
</tr>
</tbody>
</table>