Evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the OPERA experiment

Giovanni De Lellis

University “Federico II” of Napoli and INFN Napoli

On behalf of the OPERA Collaboration
The OPERA Collaboration

150 physicists, 28 institutions in 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

Switzerland
Bern

Turkey
METU, Ankara

http://operaweb.lngs.infn.it
Physics motivation in the neutrino physics landscape

Super-K (1998): atmospheric neutrino anomaly interpretable as $\nu_\mu \rightarrow \nu_\tau$ oscillation

CHOOZ (reactor): $\nu_\mu \rightarrow \nu_e$ oscillation could not explain the anomaly

K2K and MINOS (accelerator) confirmed the $\nu_\mu$ disappearance signal of Super-K

Missing tile: direct observation of $\nu_\tau$ appearance in a pure $\nu_\mu$ beam

Oscillation in appearance mode in the atmospheric sector

Giovanni De Lellis, Princeton: US-Italy Physics Program at LNGS
The CNGS Neutrino Beam

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>$(\bar{\nu}<em>e + \nu_e)/\nu</em>\mu$</td>
<td>0.8% *</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu/\nu</em>\mu$</td>
<td>2.0% *</td>
</tr>
<tr>
<td>$\nu_\tau$ prompt</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

* Interaction rate at LNGS
The Principle: hybrid detector with modular structure

- Massive active target (1.25 kton) with micrometric space resolution
- Detect $\tau$-lepton production and decay
- Underground location ($10^6$ reduction of cosmic ray flux)
- Electronic detectors to provide the “time stamp”, preselect the interaction brick and reconstruct muon charge/momentum

<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>
Cosmic ray studies on an airplane at about 9 km and at Pic du Midi

600 μm thick emulsions with new gel to detect the passage of ionising particles (sensitive to m.i.p.) in collaboration with industry (Ilford)

By exposing these emulsions to cosmic rays, Powell solved in 1947 the mystery of the Yukawa meson

Lattes, Muirhead, Occhialini and Powell,

Powell got the Nobel Prize for Physics in 1950.
The Committee underlined the simplicity of the used detector
“Charm” was born as “X-particle” (1971) in a 500 h exposure of a ~ 50 kg Emulsion Cloud Chamber (ECC) on a Jet Cargo Airplane.

(a) First evidence for the production and decay of short-lived particles (~ $10^{13}$ s) in cosmic rays\(^{[1]}\),
(b) the event was observed in an emulsion chamber.


A Possible Decay in Flight of a New Type Particle

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA

our X particle could not be included either in strange particle or in resonance particle.
Direct observation production and decay of beauty particles

WA75 at CERN
Phys. Lett. 158B (1985) 186
Nuclear Emulsion Experiments

Revival of the emulsion technique in 1990 due to the development of fully automated scanning systems

DONUT: 120kg emulsion at FNAL

CHORUS at CERN: 780kg (140x140x3 cm³) emulsion

Evolution of the scanning speed

Evolution of the scanning speed

15/10/13

Giovanni De Lellis, Princeton: US-Italy Physics Program at LNGS

15 years
A sub-sample of 147 $\nu_\mu$ CC interactions was analysed

\[ a_{\text{dis}} = 0.68^{+0.09}_{-0.11} \text{(stat)} \pm 0.02 \text{(syst)} \]

\[ a_{\text{qc}} = 0.20^{+0.06}_{-0.07} \text{(stat)} \pm 0.02 \text{(syst)} \]

\[ a_{\text{res}} = 0.12 \pm 0.04 \text{(stat)} \pm 0.02 \text{(syst)} \]
The Detector

SM-1

Target brick walls + Target Tracker

Spectrometer

RPC + Drift Tubes

SM-2

Target brick walls + Target Tracker

Spectrometer

RPC + Drift Tubes
Final performances of the CNGS beam after five years of data taking

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam days</th>
<th>P.O.T. ($10^{19}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>123</td>
<td>1.74</td>
</tr>
<tr>
<td>2009</td>
<td>155</td>
<td>3.53</td>
</tr>
<tr>
<td>2010</td>
<td>187</td>
<td>4.09</td>
</tr>
<tr>
<td>2011</td>
<td>243</td>
<td>4.75</td>
</tr>
<tr>
<td>2012</td>
<td>257</td>
<td>3.86</td>
</tr>
<tr>
<td>Total</td>
<td>965</td>
<td>17.97</td>
</tr>
</tbody>
</table>

20% less than the proposal value (22.5)
Charmed hadron production:
an application of the decay search
a control sample for $\tau$
Charm sample: same topology but muon at interaction vertex

Figure 5. Shape comparison of the distributions of the flight length (left) and the tracks’ impact parameters with respect to the primary vertex (right) for the charm data sample of 50 events, described in Sect. 3.4.1, (bullets) and the MC simulation of 40 ± 3 expected charm events (green hatched histogram) and 14 ± 3 expected hadronic interactions and strange meson decays (yellow hatched histograms).

The decay search efficiency is estimated to be (58 ± 8)% for long charm decays and (18 ± 2)% for short charm decays. The main sources of background in the charm selection are hadronic re-interactions (about 87% of the total background) and decays of \( K_0^s \) or \( \pi^- \). In the analysed sample of events from the 2008, 2009 and 2010 years having at least a muon tagged 3D-track, a total of (40 ± 3) charm events and (14 ± 3) background events are expected while 50 charm candidate events are observed in the data. The distributions of the flight length of the charm candidates and of the impact parameters of the secondary particles with respect to the primary vertex are presented in Fig. 5 for data and MC. Not only the absolute yields but also the shapes of the distributions are in very good agreement, which indicates that the systematic error on the estimated efficiency of the full analysis chain cannot exceed 20%. A more extensive discussion of the charm sample will be presented in [62].

3.5 Kinematic selection

Several kinematic quantities of the neutrino interaction are accessible at brick-level via momentum reconstruction using MCS. The energy of electrons and photons is also measured by employing calorimetric techniques [63, 64]. Kinematic criteria can be defined to improve the signal-to-background ratio. To improve the acceptance for electromagnetic showers and reduce the error on the track momentum measurement the standard volume considered for the location (Sect. 3.3) is enlarged and tracks are followed downstream, eventually in other bricks (Sect. 3.6).
## Charm yield from the analysis of 2008÷2010 data

<table>
<thead>
<tr>
<th></th>
<th>charm</th>
<th>Background</th>
<th>expected</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 prong</td>
<td>21 ± 2</td>
<td>9 ± 3</td>
<td>30 ± 4</td>
<td>19</td>
</tr>
<tr>
<td>2 prong</td>
<td>14 ± 1</td>
<td>4 ± 1</td>
<td>18 ± 2</td>
<td>22</td>
</tr>
<tr>
<td>3 prong</td>
<td>4 ± 1</td>
<td>1.0 ± 0.3</td>
<td>5 ± 1</td>
<td>5</td>
</tr>
<tr>
<td>4 prong</td>
<td>0.9 ± 0.2</td>
<td>-</td>
<td>0.9 ± 0.2</td>
<td>4</td>
</tr>
<tr>
<td>All</td>
<td>40 ± 3</td>
<td>14 ± 3</td>
<td>54 ± 4</td>
<td>50</td>
</tr>
</tbody>
</table>

Background, mostly from hadronic interactions  
(contribution from strange particle decay)
Oscillation results
$\nu_\mu \rightarrow \nu_e$ analysis

32 events found in the analyzed sample

4.1 GeV electron
ν_μ → ν_e analysis with 2008 and 2009 run data

one of the ν_e events with a π^0 as seen in the brick

19 candidates found in a sample of 505 neutrino interactions without muon
Background from $\nu_\mu$NC ($\pi^0 \rightarrow \gamma\gamma$)

A close-up of an electron pair

Gamma-ray

BG: 0.17 events (less than 1%)
Energy distribution of the 19 $\nu_e$ candidates

### Observation compatible with background-only hypothesis: $19.8\pm2.8$ (syst) events

#### 3 flavour analysis

**Energy cut to increase the S/N**

*4 observed events*

4.6 expected

$\Rightarrow \sin^2(2\theta_{13})<0.44$ at 90% C.L.
Search for non-standard oscillations at large $\Delta m^2$ values: exclusion plot in the $\sin^2(2\theta_{\text{new}}) - \Delta m^2_{\text{new}}$ plane


Caveat: experiments with different L/E values
$\nu_\mu \rightarrow \nu_\tau$ analysis

• 2008-2009 run analysis
• Get confidence on the detector performances before applying any kinematical cut
• No kinematical cut
• Slower analysis speed (signal/noise not optimal)
• Good data/MC agreement achieved
The first $\nu_\tau$ “appearance” candidate (2010)

Candidate $\nu_\tau$ interaction and $\tau$ decay from $\nu_\mu \rightarrow \nu_\tau$ oscillation

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

Giovanni De Lellis, Princeton: US-Italy Physics Program at LNGS
Event reconstruction in the brick

$\tau^- \rightarrow \rho^- \nu_{\tau}$

$\rho^- \rightarrow \pi^0 \pi^-$

$\pi^0 \rightarrow \gamma \gamma$
Kinematical variables

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>AVERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>kink (mrad)</td>
<td>41 ± 2</td>
</tr>
<tr>
<td>decay length (µm)</td>
<td>1335 ± 35</td>
</tr>
<tr>
<td>P daughter (GeV/c)</td>
<td>12 $^{+6}_{-3}$</td>
</tr>
<tr>
<td>Pt (MeV/c)</td>
<td>$470^{+240}_{-120}$</td>
</tr>
<tr>
<td>missing Pt (MeV/c)</td>
<td>$570^{+320}_{-170}$</td>
</tr>
<tr>
<td>$\phi$ (deg)</td>
<td>173 ± 2</td>
</tr>
</tbody>
</table>
Strategy for the 2010÷2012 runs

• Apply kinematical selection
• 15 GeV $\mu$ momentum cut (upper bound)
• Anticipate the analysis of the most probable brick for all the events: optimal ratio between efficiency and analysis time
• Anticipate the analysis of 0$\mu$ events (events without any $\mu$ in the final state)
Second $\nu_\tau$ Candidate Event

arXiv:1308.2553, to appear on JHEP
## Kinematics of the second Candidate Event

<table>
<thead>
<tr>
<th></th>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$ (Tau - Hadron) [degree]</td>
<td>&gt;90</td>
<td>167.8±1.1</td>
</tr>
<tr>
<td>average kink angle [mrad]</td>
<td>&lt; 500</td>
<td>87.4±1.5</td>
</tr>
<tr>
<td>Total momentum at 2ry vtx [GeV/c]</td>
<td>&gt; 3.0</td>
<td>8.4±1.7</td>
</tr>
<tr>
<td>Min Invariant mass [GeV/c^2]</td>
<td>0.5 &lt; &lt; 2.0</td>
<td>0.96±0.13</td>
</tr>
<tr>
<td>Invariant mass [GeV/c^2]</td>
<td>0.5 &lt; &lt; 2.0</td>
<td>0.80±0.12</td>
</tr>
<tr>
<td>Transverse Momentum at 1ry vtx [GeV/c]</td>
<td>&lt; 1.0</td>
<td>0.31±0.11</td>
</tr>
</tbody>
</table>
Satisfying the criteria for $\nu_\tau \to \tau \to 3$hadron decay.
After 2012 Summer conferences

• Extension of the analysed sample to events with one $\mu$ in the final state
Third tau neutrino event taken on May 2\textsuperscript{nd} 2012
τ→μ candidate
brick analysis and decay search

Decay in the plastic base
$\tau \rightarrow \mu$ candidate
Third tau neutrino event

\[ \tau \rightarrow \mu \]
# Event tracks’ features

<table>
<thead>
<tr>
<th>TRACK NUMBER</th>
<th>PID</th>
<th>MEASUREMENT 1</th>
<th>MEASUREMENT 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\Theta_x$</td>
<td>$\Theta_y$</td>
</tr>
<tr>
<td>1</td>
<td>DAUGHTER</td>
<td>MUON</td>
<td>-0.217</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range</td>
<td>0.203</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>HADRON</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>PHOTON</td>
<td>-0.040</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>PARENT</td>
<td></td>
</tr>
</tbody>
</table>

## $\gamma$ attachment

<table>
<thead>
<tr>
<th>$\delta\theta_{\text{RMS}}$ (mrad)</th>
<th>DZ (mm)</th>
<th>Measured IP (µm)</th>
<th>IP resolution (µm)</th>
<th>ATTACHMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1ry vertex</td>
<td>6</td>
<td>3.1</td>
<td>18.2</td>
<td>13.6</td>
</tr>
<tr>
<td>2ry vertex</td>
<td>6</td>
<td>2.8</td>
<td>68.7</td>
<td>12.2</td>
</tr>
</tbody>
</table>

15/10/13

Giovanni De Lellis, Princeton: US-Italy Physics Program at LNGS
Muon momentum by range in the electronic detector: $2.8 \pm 0.2 \text{ GeV/c}$
MCS in the brick consistent: $3.1 \ [2.6, 4.0] \text{ GeV/c}$

Bending by the magnetic field
Charge determination of the muon

Charge measurement based on TT and RPC hits
Parabolic Fit with p2 as quadratic term coefficient in the magnetized region
Linear fit in the non-magnetized region

\[ \chi^2 / \text{ndf} = 2.614 / 4 \]
\[ p0 = 189.5 \pm 0.5518 \]
\[ p1 = -0.3453 \pm 0.005458 \]
\[ p2 = -0.003892 \pm 0.0006894 \]

Target Tracker hits
RPC hits
p2 < 0 → negative charge
5.6 \( \sigma \) significance
R \( \sim \) 85 cm

The negative muon charge rules out charm background!

Giovanni De Lellis, Princeton: US-Italy Physics Program at LNGS
Track follow down to assess the nature of track 2

Track 2 interacting in the downstream brick without visible charged particles

Momentum/range inconsistent with $\mu$ hypothesis

$0.9$ GeV/4 cm Lead

$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{lead}}{\rho_{average}}$$

$L = \text{track length}$
$R_{lead} = \mu$ range
$\rho_{average} = \text{average density}$
$\rho_{lead} = \text{lead density}$
$p = \text{momentum in emulsion}$
## Kinematical variables

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>AVERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kink angle (mrad)</td>
<td>245 ± 5</td>
</tr>
<tr>
<td>decay length (µm)</td>
<td>376 ± 10</td>
</tr>
<tr>
<td>$P_\mu$ (GeV/c)</td>
<td>2.8 ± 0.2</td>
</tr>
<tr>
<td>$P_T$ (MeV/c)</td>
<td>690 ± 50</td>
</tr>
<tr>
<td>$\phi$ (degrees)</td>
<td>154.5 ± 1.5</td>
</tr>
</tbody>
</table>

![PHI ANGLE](image)

**$\tau \rightarrow \mu$ MC**

**$\tau \rightarrow \mu$ candidate**
Kinematical variables. All cuts passed: $\tau \rightarrow \mu$ candidate

### Kink angle

- $\tau$ MC
- data

### Decay position

- LEAD
- $z_{\text{dec}}$ (mm)

### Muon momentum

- $p_\mu$ (GeV/c)

### 2ry transverse momentum

- $p_{T}^{2\text{ry}}$ (GeV/c)
Statistical considerations

<table>
<thead>
<tr>
<th></th>
<th>Background</th>
<th>Charm</th>
<th>$\mu$ scattering</th>
<th>had int</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \to h$</td>
<td>0.027±0.005</td>
<td>0.011</td>
<td></td>
<td>0.016</td>
</tr>
<tr>
<td>$\tau \to 3h$</td>
<td>0.12±02</td>
<td>0.11</td>
<td></td>
<td>0.0021</td>
</tr>
<tr>
<td>$\tau \to \mu$</td>
<td>0.02±0.01</td>
<td>0.0023</td>
<td>0.009</td>
<td></td>
</tr>
<tr>
<td>$\tau \to e$</td>
<td>0.020±0.004</td>
<td>0.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>0.184±0.025</td>
<td>0.15</td>
<td>0.018</td>
<td>0.019</td>
</tr>
</tbody>
</table>

3 events observed in the $\tau \to h$ and $\tau \to 3h$ and $\tau \to \mu$ channels with a total background of 0.184±0.025

p-values of each channel combined with an estimator $p^* = p_\mu p_e p_h p_{3h}$

Probability to be explained as a background, $p^* < p_{obs} = 2.9 \times 10^{-4}$

$\Rightarrow 3.4 \sigma$ significance of non-null observation

Evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode
Thank you for your attention

Image taken using OPERA emulsion film with pinhole handmade camera by D. Di Ferdinando

Giovanni De Lellis, Princeton: US-Italy
Physics Program at LNGS

15/10/13