Search for $\nu_\mu \rightarrow \nu_\tau$ in appearance mode: the OPERA experiment

Giovanni De Lellis
University and INFN of Naples
on behalf of the OPERA Collaboration

Oscillation Project with Emulsion tRacking Apparatus

34 INSTITUTIONS, ~200 PHYSICISTS
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

Direct observation of $\nu_\tau$ appearance in a pure $\nu_\mu$ beam still missing

[Maltoni and Schwetz, arXiv: 0812.3161]
**CNGS beam**

Beam optimized to maximize $\nu_\tau$ CC interaction rate at LNGS

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;E_{\nu_\mu}&gt;$</td>
<td>17 GeV</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%</td>
</tr>
<tr>
<td>$\nu_\tau$ prompt</td>
<td>negligible</td>
</tr>
<tr>
<td>$\nu_\mu$ (CC + NC) /year</td>
<td>$\sim$ 4700</td>
</tr>
<tr>
<td>$\nu_\tau$ CC /year</td>
<td>$\sim$ 20</td>
</tr>
<tr>
<td></td>
<td>($\Delta m^2 = 2.4 \times 10^{-3}$ eV$^2$, maximal mixing)</td>
</tr>
</tbody>
</table>

Target mass: 1.25 Kton

Design goal: $4.5 \times 10^{19}$ p.o.t./year
CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

- **Excavated**
- **Concreted**
- **Decay tube** (2nd contract)

- SPS tunnel
- LHC/T18 tunnel
- LEP/LHC tunnel
- Access shaft PGCN
- Access galleries
- TJ8
- SPS/eca4
- Hadron stop and first muon detector
- Second muon detector
- Muons neutrinos
- Connection gallery to T18/LHC
- Protons
- Pions kaons
- Neutrinos to Gran Sasso
CNGS beam performances

GPS synchronization with 100 ns accuracy

SPS super-cycle with 4 CNGS cycles with LHC 49.2 s, without 39.6 s

Cosmic-ray background

1663 candidate interactions in the target
0.7 $\tau$ expected
Second physics run: 2009

2.47 E19

pot collected up to Monday October 5th

2580 candidate interactions in the target (2.47 E19 pot)
present extrapolation 3.2 E19 pot (~ 70% of a nominal year)
The OPERA hybrid detector

- Rock thickness 1400m (3800 m.w.e.)
- Cosmic muon flux: \(\sim 1/m^2/h\)

Target mass: 1250 tons, 150000 ECC bricks
(9 M of Pb + 9 M of emulsion plates)
The hybrid detector

Detector construction:
Sept. 2003 - Spring 2007

TARGET TRACKERS
- Trigger task
- Brick identification
- 2 x 31 scintillating strip walls read with PMT
- 0.8 cm resolution

INNER TRACKERS
- 990-ton dipole magnets (B= 1.55 T)
- RPC resolution ~1.3 cm

HIGH PRECISION TRACKERS
- spatial resolution < 0.5 mm

RPC and drift tubes for μ identification, charge and momentum measurement

JINST 4 (2009) P04018
150036 bricks produced in a dark room and inserted in the detector

Brick Assembly Machine

5 piling robots, ~700 bricks/day

Brick wall and the manipulator system
**OPERA bricks**

- ECC: target unit (compact and modular structure)
- Emulsions provide high space resolution and lead acts as passive target mass

1 ECC = 56 Pb + 57 emulsions

Measure momentum through multiple scattering

ν interaction with 2 showers:
invariant mass 160±30 MeV

E ~ 8.1 GeV

E ~ 0.5 GeV
Event analysis

Event trigger and reconstruction

Brick identification

- Select the brick containing the neutrino interaction
  - Reduce the analysis time
  - Minimize the target mass loss
Interface emulsion films: high signal/noise ratio for event trigger and scanning time reduction

Position accuracy of the electronic predictions

Angular accuracy of the electronic predictions
Scanning of Changeable Sheets

LNGS: 10 microscopes, 200 cm$^2$/h

Nagoya: 5 S-UTS, 220 cm$^2$/h

σ ∼ 2 µm

accuracy ∼ 10 µm
Changeable sheet analysis

All CS scanned for 2008 run

Vertex pre-definition

10 cm

12.5 cm
Brick identification rate

- Analysis of third and forth brick per event ongoing (time consuming)
Track follow-up and vertex finding

Track follow-up film by film:
- alignment using cosmic ray tracks
- definition of the stopping point

Volume scanning (~2 cm³) around the stopping point
# Status of event location for 2008 run

<table>
<thead>
<tr>
<th></th>
<th>0mu</th>
<th>1mu</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events predicted by the electronic detector</td>
<td>356</td>
<td>1242</td>
<td>1598</td>
</tr>
<tr>
<td>Found in CS</td>
<td>239</td>
<td>975</td>
<td>1214</td>
</tr>
<tr>
<td>Located in ECC</td>
<td>138</td>
<td>752</td>
<td>890</td>
</tr>
<tr>
<td>Located in dead material</td>
<td>5</td>
<td>21</td>
<td>26</td>
</tr>
<tr>
<td>Interactions in the upstream brick</td>
<td>10</td>
<td>43</td>
<td>53</td>
</tr>
</tbody>
</table>
### Location rate on a subsample

<table>
<thead>
<tr>
<th></th>
<th>0mu</th>
<th>1mu</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick scanning started</td>
<td>104</td>
<td>500</td>
<td>604</td>
</tr>
<tr>
<td>Vertices located in the brick</td>
<td>64</td>
<td>395</td>
<td>459</td>
</tr>
<tr>
<td>Interactions in the upstream brick</td>
<td>9</td>
<td>26</td>
<td>35</td>
</tr>
<tr>
<td>Vertices in the dead material</td>
<td>3</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>Location rate (%)</td>
<td>73±4</td>
<td>86.8±1.5</td>
<td>84.4±1.5</td>
</tr>
</tbody>
</table>

**Event categories for interactions not yet located**

- Events involving more than one brick (edge event)
- Low momentum secondary particles found in CS analysis
  - analysis in progress (~20%)
  - bad film quality (~10%)
Data analysis and decay search

Good agreement in the angular distribution of muon tracks

Impact parameter of tracks at the primary vertex 2.4 µm on average relevant for the decay search
Charm candidates

- Charm topology analogous to $\tau$ (similar lifetime): reference sample for the decay finding efficiency
- Systematic decay search started

<table>
<thead>
<tr>
<th>Topology</th>
<th>Kink</th>
<th>Vee</th>
<th>Trident</th>
<th>4Vee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>5+2N1</td>
<td>5</td>
<td>1+N3</td>
<td>1</td>
</tr>
</tbody>
</table>

Event in Europe (D0 $\rightarrow$ 4 prong)  
Event in Japan (kink)
Topological identification and kinematical confirmation

Event 234654975

Brick 85405

<table>
<thead>
<tr>
<th>VERTEX 1</th>
<th>Impact Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track 1</td>
<td>1.36</td>
</tr>
<tr>
<td>Track 2</td>
<td>0.88</td>
</tr>
<tr>
<td>Track 7</td>
<td>0.51</td>
</tr>
<tr>
<td>X</td>
<td>66716.60</td>
</tr>
<tr>
<td>Y</td>
<td>49892.8</td>
</tr>
<tr>
<td>Z</td>
<td>90.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VERTEX 2</th>
<th>Impact Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track 3</td>
<td>1.13</td>
</tr>
<tr>
<td>Track 4</td>
<td>1.81</td>
</tr>
<tr>
<td>Track 5</td>
<td>1.99</td>
</tr>
<tr>
<td>Track 6</td>
<td>1.39</td>
</tr>
<tr>
<td>X</td>
<td>66710.10</td>
</tr>
<tr>
<td>Y</td>
<td>49899</td>
</tr>
<tr>
<td>Z</td>
<td>403.9</td>
</tr>
</tbody>
</table>

D0

<table>
<thead>
<tr>
<th>Tx</th>
<th>Ty</th>
<th>Flight Length (µm)</th>
<th>phi</th>
<th>minimum mass (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0,0207</td>
<td>0,0198</td>
<td>313,1</td>
<td>173,2°</td>
<td>1,7</td>
</tr>
</tbody>
</table>
Status of 2009 run: CS scanning

Analyzing 2009 run events while completing the 2008 run queue

- 650 events scanned
- 350 events tagged for vertex location
## Location of 2009 run interactions

<table>
<thead>
<tr>
<th></th>
<th>NC</th>
<th>CC</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick scanning started</td>
<td>9</td>
<td>73</td>
<td>82</td>
</tr>
<tr>
<td>Vertices located in ECC</td>
<td>6</td>
<td>50</td>
<td>56</td>
</tr>
<tr>
<td>Interactions in the upstream brick</td>
<td>0</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Vertices in the dead material</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Conclusions

- OPERA is successfully operating on the CNGS neutrino beam and currently taking data for the second physics year.
- CNGS performances improved: 2008+2009 expected to be \(\sim 1\) nominal year, 2010 expected as a nominal year.
- First physics run in 2008: \(\sim 900\) interactions located.
- 15 charm candidates found: systematic decay search started with an uniform selection on all the data sample.
- Analysis of 2009 progressing while completing the queue of 2008 run.
- First \(\tau(s)\) expected soon in the analysis of 2008/09 runs.