SEARCH FOR $\nu_\mu \rightarrow \nu_\tau$ OSCILLATIONS:
STATUS OF THE OPERA EXPERIMENT

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Università degli Studi di Bari & INFN
On behalf of the OPERA Collaboration
SEARCH FOR $\nu_\mu \rightarrow \nu_\tau$ OSCILLATIONS:
STATUS OF THE OPERA EXPERIMENT

- The OPERA experiment:
  - Physics goal
  - $\nu_\tau$ detection principle
  - Detector
  - Status of data-taking and analysis

- $\nu_\mu \rightarrow \nu_\tau$ oscillation results

- Preliminary results on $\nu_\mu \rightarrow \nu_e$ oscillation search
OPERA: Oscillation Project with Emulsion tRacking Apparatus

- Long baseline neutrino oscillation experiment
- Aim: Direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode covering the whole interesting region of the parameter space indicated by atmospheric neutrino data
- CNGS (CERN Neutrinos to Gran Sasso) $\nu_\mu$ beam optimised for $\nu_\tau$ appearance
CNGS beam

Conventional $\nu_\mu$ beam

Beam parameters

<table>
<thead>
<tr>
<th>Parameter</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>0.89, 0.06 %</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>
<tr>
<td>pot/year</td>
<td>$4.5 \times 10^{19}$</td>
</tr>
</tbody>
</table>

Contaminations given in terms of interaction rates in OPERA

Nominal intensity: $22.5 \times 10^{19}$ p.o.t.

Expected events: 7.6 signal, 0.8 background


Gran Sasso National Laboratory

Largest underground laboratory for astro-particle physics

1400 m rock shield (cosmic $\mu$ flux reduction $\sim 10^{-6}$)

INFN - LNGS
L’Aquila (Italy), 120 km from Rome
ν\textsubscript{τ} detection principle

Event-by-event separation of ν\textsubscript{τ} CC interactions from dominant ν\textsubscript{μ} interactions by direct observation of τ lepton decay

Requirements:

- Large target mass to compensate for small neutrino interaction cross-section
- Micrometric resolution to observe τ decay kink

⇒ Nuclear emulsions

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<tr>
<td>τ → h</td>
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</tr>
<tr>
<td>τ → 3h</td>
<td>15.0</td>
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</tbody>
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Target segmented into basic units called bricks. Brick: sandwich of 57 emulsion films interleaved with 1mm-thick lead plates

Total target mass ~ 1.25 kt (about 150000 bricks)
**ν_τ** detection principle

- Event-by-event separation of ν_τ CC interactions from dominant ν_μ interactions by direct observation of τ lepton decay

**Requirements:**
- Large target mass to compensate for small neutrino interaction cross-section
- Micrometric resolution to observe τ decay *kink* ➞ Nuclear emulsions
- High muon identification efficiency to reduce charm background; event region pre-selection ➞ Electronic detectors

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Target segmented into basic units called *bricks*. Brick: *sandwich* of 57 emulsion films interleaved with 1mm-thick lead plates

Total target mass ~ 1.25 kt (about 150000 bricks)
OPERA detector

First $\nu_e$ candidate

$\sigma \approx 10 \text{ mm}$

$\sigma \approx 25 \text{ mrad}$

Changeable Sheets (CS): pair of emulsion films acting as TT – brick interface

TT – brick connection
OPERA detector

Each brick is a stand-alone detector with sub-micrometric resolution.

• Momentum measurement by multiple Coulomb scattering
  • E.m. shower detection and energy measurement
  • Detection of highly-ionizing nuclear fragments produced in hadronic interactions (discrimination between interactions and decays)
Run 2012 in progress.
Foreseen integrated intensity at the end of the run: 18.9 x 10^{19} p.o.t.
(\sim 84\% of nominal intensity)

<table>
<thead>
<tr>
<th>Run</th>
<th>Protons on target</th>
<th>SPS efficiency</th>
<th>In-target events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>1.78x10^{19}</td>
<td>61%</td>
<td>1698</td>
</tr>
<tr>
<td>2009</td>
<td>3.52x10^{19}</td>
<td>70%</td>
<td>3557</td>
</tr>
<tr>
<td>2010</td>
<td>4.04x10^{19}</td>
<td>81%</td>
<td>3912</td>
</tr>
<tr>
<td>2011</td>
<td>4.84x10^{19}</td>
<td>78%</td>
<td>4210</td>
</tr>
</tbody>
</table>

Located neutrino interactions 4611

Fully analysed events 4126

\nu_\tau candidate events 2

compatible with the expectations for the analysed sample
First $\nu_\tau$ candidate

Decay vertex: $\tau^-$ $\rightarrow$ $h\pi^0 \nu_\tau$

First direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>AVERAGE</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 ($\mu$m)</td>
<td>$1335 \pm 35$</td>
<td>within 2 lead plates</td>
</tr>
<tr>
<td>$P$ daughter (GeV/c)</td>
<td>$12^{+6}_{-3}$</td>
<td>$&gt;2$</td>
</tr>
<tr>
<td>$PT$ (MeV/c)</td>
<td>$470^{+230}_{-120}$</td>
<td>$&gt;300$ (\gamma attached)</td>
</tr>
<tr>
<td>missing $PT$ (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>
</tr>
</tbody>
</table>
$\nu_\mu \rightarrow \nu_\tau$ oscillation search

New $\nu_\tau$ candidate

2-prong $\nu$ interaction with one track showing a secondary vertex compatible with the hypothesis of $\tau^- \rightarrow h^+ h^- h^- \nu_\tau$
$\nu_\mu \to \nu_\tau$ oscillation search

New $\nu_\tau$ candidate

Event kinematics

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phi (Tau - Hadron) [degree]</td>
<td>$&gt;$90</td>
<td>167.8 $\pm$ 1.1</td>
</tr>
<tr>
<td>average kink angle [mrad]</td>
<td>&lt; 500</td>
<td>87.4 $\pm$ 1.5</td>
</tr>
<tr>
<td>Total momentum at 2ry vtx [GeV/c]</td>
<td>&gt; 3.0</td>
<td>8.4 $\pm$ 1.7</td>
</tr>
<tr>
<td>Min Invariant mass [GeV/c$^2$]</td>
<td>$0.5 &lt; &lt; 2.0$</td>
<td>0.96 $\pm$ 0.13</td>
</tr>
<tr>
<td>Invariant mass [GeV/c$^2$]</td>
<td>$0.5 &lt; &lt; 2.0$</td>
<td>0.80 $\pm$ 0.12</td>
</tr>
<tr>
<td>Transverse Momentum at 1ry vtx [GeV/c]</td>
<td>&lt; 1.0</td>
<td>0.31 $\pm$ 0.11</td>
</tr>
</tbody>
</table>

No muon detected at the primary vertex:

track other than $\tau$ lepton candidate
not compatible with muon hypothesis based on momentum - range correlation
\( \nu_\mu \rightarrow \nu_\tau \) oscillation search

New \( \nu_\tau \) candidate

Satisfying the specified criteria for \( \tau \rightarrow 3 \)hadron decay
### $\nu_\mu \rightarrow \nu_\tau$ oscillation search: summary

<table>
<thead>
<tr>
<th>Run</th>
<th>Status</th>
<th>Number of analysed events</th>
<th>Expected $\nu_\tau$ events (Preliminary)</th>
<th>Observed $\nu_\tau$ candidate events</th>
<th>Expected BG (Preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 - 2009</td>
<td>Finished</td>
<td>2783</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2010 - 2011</td>
<td>Analysis in progress</td>
<td>1343</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>Started</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>4126</strong></td>
<td><strong>2.1</strong></td>
<td><strong>2</strong></td>
<td><strong>0.2</strong></td>
</tr>
</tbody>
</table>
\( \nu_\mu \rightarrow \nu_\tau \) oscillation search: control sample

Control sample for \( \nu_\tau \) detection efficiency:

charm production and decay (flight length and decay topologies similar to those of the \( \tau \) lepton)

Charmed hadron – muon angle in the plane transverse to \( \nu \) direction

Expected events: 51 ± 7.5
Observed events: 49
$\nu_\mu \rightarrow \nu_e$ oscillation search

Systematic search for electron neutrinos applied to 505 events without muon in the final state (runs 2008 – 2009)

Expected events: 19.2 (beam) + 1.5 (oscillated)
Observed events: 19

$E_\nu = 15.6$ GeV
\[ \nu_\mu \rightarrow \nu_e \text{ oscillation search} \]

Systematic search for electron neutrinos applied to 505 events without muon in the final state (runs 2008 – 2009)

Expected events: 19.2 (beam) + 1.5 (oscillated)
Observed events: 19

\[ E_\nu < 20 \text{ GeV} \text{ (improve S/N ratio)} \]

Expected events: 3.7 (beam) + 1.1 (oscillated)
Observed events: 4

\[ \Delta m_{23}^2 = 2.45 \times 10^{-3} \]
\[ \sin^2 \theta_{23} = 0.51 \]
Conclusions and Outlooks

- OPERA is successfully collecting data since 2008.

  We expect to reach $18.9 \times 10^{19}$ integrated p.o.t. by the end of 2012 run, corresponding to $\sim 84\%$ of the nominal intensity.

- $\nu_\mu \rightarrow \nu_\tau$ oscillation search:
  - 2 $\nu_\tau$ candidate events observed so far
  - (expected: 2 signal, 0.2 BG – preliminary - )
  - A few more events are under study.

- $\nu_\mu \rightarrow \nu_e$ oscillation search:
  - 19 $\nu_e$ events observed in 2008 – 2009 statistics,
  - 4 with $E_\nu < 20$ GeV (expected: 1.1 oscillated, 3.7 BG).
  - Statistics will be improved by a factor of $\sim 3$
  - $\Rightarrow$ set constraints in the high $\Delta m^2$ region
Thank you!
Control sample: charm events

(ﬂight length and decay topologies similar to those of the $\tau$)

<table>
<thead>
<tr>
<th>Topology</th>
<th>Observed events</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Charm</td>
</tr>
<tr>
<td>Charged 1-prong</td>
<td>13</td>
<td>15.9</td>
</tr>
<tr>
<td>Neutral 2-prong</td>
<td>18</td>
<td>15.7</td>
</tr>
<tr>
<td>Charged 3-prong</td>
<td>5</td>
<td>5.5</td>
</tr>
<tr>
<td>Neutral 4-prong</td>
<td>3</td>
<td>2.0</td>
</tr>
<tr>
<td>Total</td>
<td>39</td>
<td>39.1±7.5</td>
</tr>
</tbody>
</table>

2738 located and fully analysed events

($\leftrightarrow 4.8 \times 10^{19}$ p.o.t.)

1 $\nu_\tau$ candidate observed in the $\tau \rightarrow h$ channel

Expected: $0.49\pm0.12$ signal events,
$0.05\pm0.01$ background events

Expected (all decay channels):
1.65±0.41 signal events,
0.16±0.03 background events
$\nu_{\mu} \rightarrow \nu_{\tau}$ oscillation analysis 2008-2009

Hadronic interaction background

Hadronic tracks produced in $\nu$ interactions showing kink topology:

- 14 m of tracks scanned
- No events in the signal region
- 10 events in reference region
  
  ($P_t \ 200 \div 600 \ \text{MeV/c}$), 10.8 expected

90% C.L. upper limit of $1.0 \times 10^{-3}$ kinks/NC event

4 GeV/c pion interactions in test beam bricks:

- 190 m of tracks scanned
- 534 interactions found
- 214 kinks detected
- No events in the signal region
Background reduction: black track search

Highly ionizing nuclear fragments produced in hadronic interactions

Background reduction: track follow-down

Tracks produced in potentially interesting \( \nu \) interactions are followed in downstream bricks to detect secondary interactions and/or apply momentum-range consistency checks:

- Misidentified muons from charm events: 5% \( \rightarrow \) 3.3%

- Factor 100 BG reduction in \( \tau \rightarrow \mu \) channel due to muon mismatch in CC and NC interactions
$\nu_\mu \rightarrow \nu_\tau$ oscillation search: study of hadronic interactions

Comparison between data and MC (Fluka)

Multiplicity

10GeV/c

4GeV/c

2GeV/c

Kink angle (1-prong)

Error bars: Experimental data
Histogram: Simulated data
• Event sample:
  – 505 NC-like events (runs 2008 and 2009)

• For each event:
  – Extrapulate 1ry tracks to CS
  – For each track, search for shower signal in CS
  – If shower-like tracks are found, measure additional volume around 1ry track.

• Results:
  – 96 events selected
  – 19 $\nu_e$ interactions confirmed

$\nu_\mu \rightarrow \nu_e$ oscillation search
$\nu_\mu \rightarrow \nu_e$ oscillation search

A close-up of an electron pair as seen in emulsion

Gamma-ray

1micron

Low-energy electrons produced in gamma conversion are difficult to recognise in emulsion $\Rightarrow$ Background source

Estimated background in 2008-2009 sample: 0.16 events
Performance of the Electronic detectors

Muon identification efficiency ~ 95% (track length \times \text{density} > 660 \text{ g cm}^{-2})

Muon momentum reconstruction

Deposited energy in the TT – CC events

m.i.p. 5 photo-electrons (2.15 MeV)

New Journal of Physics 13 (2011) 053051
THE PRINCIPLE OF THE EXPERIMENT: ECC + ELECTRONIC DETECTORS

- Intense, high-energy muon-neutrino beam
- Massive active target with micrometric space resolution
- Detect tau-lepton production and decay
- Use electronic detectors to provide “time resolution” to the emulsions and preselect the interaction region