RECENT RESULTS OF THE OPERA EXPERIMENT

- Appearance: $\nu_\mu \rightarrow \nu_\tau$
- Exotic $\nu_\mu \rightarrow \nu_\tau$, $\nu_\mu \rightarrow \nu_e$
- Cosmic ray physics

Fabio Pupilli (INFN – Laboratori Nazionali di Frascati) on behalf of the OPERA Collaboration

30/06/2015 – PPC2015 – Deadwood, SD
**Oscillation Project with Emulsion Tracking Apparatus**

**Goal:** first direct observation of $\nu_\tau$ appearance from $\nu_\mu$ oscillation at atmospheric scale

- Long Baseline (730 km) experiment in the CNGS (CERN Neutrino to Gran Sasso) $\nu_\mu$ beam
- Located at LNGS $\rightarrow$ 1400 m rock overburden, low cosmic $\mu$ flux (1/m$^2$/h)

Conventional **high energy** beam optimised for $\nu_\tau$ CC interactions observation

<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>$\nu_\mu / \bar{\nu}_\mu$</td>
<td>2.1 %</td>
</tr>
<tr>
<td>$\nu_\tau$ prompt</td>
<td>Negligible</td>
</tr>
</tbody>
</table>

Interaction rates (1.8 x 10$^{20}$ p.o.t.):

~ 20k $\nu_\mu$ CC+NC

66 $\nu_\tau$ CC (not efficiency corrected)

$\Delta m^2_{23} = 2.32 \times 10^{-3}$ eV$^2$

Threshold for $\tau$ production $\sim$ 3.5 GeV.
**The $\nu_\tau$ Detection Principle**

The challenge is to distinguish $\nu_\tau$ interactions from $\nu_\mu$ interactions, through the detection of $\tau$ leptons produced in $\nu_\tau$-CC interactions.

- Decay "kink"
  - $\mu^-, h^-, 3h^-, e^-$
  - $c\tau \sim 87 \mu m$

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**Event by event topological and kinematical reconstruction**

- Target mass $O(\text{kton})$
  - (low $\nu$ interaction cross-section)
- High granularity detector
  - ($\tau$ decay detection, background rejection)

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1.2 kton lead – nuclear emulsion target
segmented into basic units called *bricks*
THE OPERA DETECTOR*

*JINST 4 (2009) P04018

SM1

SM2

Target area
~ 150000 ECC bricks → 1.2 (avg 1.18) kton

Muon Spectrometer
Dipole Magnet + RPC + Drift Tubes

Each brick followed by 2 removable emulsion films (CS) and planes of plastic scintillator strips in X/Y direction (TT)

ECC (Emulsion Cloud Chamber) brick:
56 lead plates (1mm) + 57 emulsion films (300 µm)
Event Reconstruction: Electronic Detectors

- Selection of contained and “on-time” events

<table>
<thead>
<tr>
<th>Year</th>
<th>Days</th>
<th>p.o.t. ((10^{18}))</th>
<th>(\nu) interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>123</td>
<td>1.74</td>
<td>1698</td>
</tr>
<tr>
<td>2009</td>
<td>155</td>
<td>3.53</td>
<td>3693</td>
</tr>
<tr>
<td>2010</td>
<td>187</td>
<td>4.09</td>
<td>4248</td>
</tr>
<tr>
<td>2011</td>
<td>243</td>
<td>4.75</td>
<td>5131</td>
</tr>
<tr>
<td>2012</td>
<td>257</td>
<td>3.86</td>
<td>3923</td>
</tr>
<tr>
<td>tot</td>
<td>965</td>
<td>17.97</td>
<td>19505</td>
</tr>
</tbody>
</table>

80% of the design value

- Muon reconstruction and classification as CC-like \((1\mu)\) or NC-like \((0\mu)\)

- Muon momentum and charge measurement through the spectrometer

- Identification of interaction brick, using TT data in interplay with CS analysis

With \(\mu\):  
- \(\nu_\mu\) CC  
- \(\nu_\tau\) CC, \(\tau\rightarrow\mu\) (17.7%)

Without \(\mu\):  
- \(\nu_\mu\) NC  
- \(\nu_\tau\) CC, \(\tau\rightarrow e\) (17.8%)  
- \(\nu_\tau\) CC, \(\tau\rightarrow h, 3h\) (64.5%)  
- \(\nu_e\) CC

Event Reconstruction: ECC Brick

- **CS analysis**: interface between electronic detectors ($\sigma_{\text{pos}} \sim 8$ mm, $\sigma_{\theta} \sim 15$ mrad) and emulsion

- **CS to brick connection** ($\sigma_{\text{pos}} \sim 70$ µm, $\sigma_{\theta} \sim 8$ mrad) and scan back: stopping point definition

- **Volume scan**: topological vertex reconstruction and decay search

2 cm$^3$ volume

Data/MC comparison of the location efficiency as a function of the visible energy in TT
Reasonable agreement
Event Reconstruction: **Decay Search and Kinematics**

**Decay topologies** detected through:

- Impact Parameter (IP) evaluation
- kink angle along tracks attached to the vertex

**Event kinematics** reconstructed using:

- momentum measurement by Multiple Coulomb Scattering in lead (20-30% resolution)  
- e.m. shower energy measurement using calorimetric techniques (brick thickness 10 $X_0$)

<table>
<thead>
<tr>
<th>variable</th>
<th>$\tau \rightarrow 1h$</th>
<th>$\tau \rightarrow 3h$</th>
<th>$\tau \rightarrow \mu$</th>
<th>$\tau \rightarrow e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton-tag</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$z_{dec} (\mu m)$</td>
<td>[44, 2600]</td>
<td>&lt; 2600</td>
<td>[44, 2600]</td>
<td>&lt; 2600</td>
</tr>
<tr>
<td>$p_T^{\text{miss}} (\text{GeV}/c)$</td>
<td>$&lt; 1^*$</td>
<td>$&lt; 1^*$</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>$\phi_{lH} (\text{rad})$</td>
<td>$&gt; \pi/2^*$</td>
<td>$&gt; \pi/2^*$</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>$p_T^{2\gamma} (\text{GeV}/c)$</td>
<td>$&gt; 0.6(0.3)^*$</td>
<td>/</td>
<td>$&gt; 0.25$</td>
<td>$&gt; 0.1$</td>
</tr>
<tr>
<td>$p^{2\gamma} (\text{GeV}/c)$</td>
<td>$&gt; 2$</td>
<td>$&gt; 3$</td>
<td>$&gt; 1$ and $&lt; 15$</td>
<td>$&gt; 1$ and $&lt; 15$</td>
</tr>
<tr>
<td>$\theta_{kink} (\text{mrad})$</td>
<td>$&gt; 20$</td>
<td>$&lt; 500$</td>
<td>$&gt; 20$</td>
<td>$&gt; 20$</td>
</tr>
<tr>
<td>$m, m_{\min} (\text{GeV}/c^2)$</td>
<td>/</td>
<td>$&gt; 0.5$ and $&lt; 2$</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

**Kinematical cuts for $\nu_\tau$ selection to increase S/B ratio**

IP distribution for:

- $\nu_\tau$ events (MC)
- NC+CC $\nu_\mu$ events (MC)
- NC+CC $\nu_\mu$ events (Data)
Monte Carlo simulation benchmarked on control samples.

**CC with charm production** (all channels)
IF the primary lepton is not identified and the daughter charge is not (or incorrectly) measured

**Hadronic interactions**
Background for \( \tau \rightarrow h \)

**Large angle muon scattering**
Background for \( \tau \rightarrow \mu \)

MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

Reduced by "track follow down" procedure and large angle scanning

FLUKA + pion test beam data
Reduced by large angle scanning and nuclear fragment search

Simulation study (lead form factor) benchmarked with available data

Reduction of a factor \(~ 100\) wrt to previous estimation
**Status of Data Analysis**

Analysis status:
- 2008-09 1\textsuperscript{st} and 2\textsuperscript{nd} bricks completed
- 2010-12 1\textsuperscript{st} bricks completed, 2\textsuperscript{nd} brick nearly completed

![Graph showing data analysis status]
$\nu^\tau$ GALLERY

1° candidate (2010): $\tau \rightarrow h$

$\tau^- \rightarrow \rho^- \nu^\tau$
$\rho^- \rightarrow \pi^0 \pi^-$
$\pi^0 \rightarrow \gamma \gamma$


2° candidate (2012): $\tau \rightarrow 3h$

JHEP 11 (2013) 036

3° candidate (2013): $\tau \rightarrow \mu$


4° candidate (2014): $\tau \rightarrow h$

PTEP (2014) 101C01
THE FIFTH $\nu_\tau$ CANDIDATE

Primary track identified as proton by $dE/dX$ and interaction in downstream brick

Cuts for $\tau \rightarrow h$ channel passed

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured value</th>
<th>Selection Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \phi_{TH}$ ($^\circ$)</td>
<td>151±1</td>
<td>&gt;90</td>
</tr>
<tr>
<td>$p_T^{\text{miss}}$ (GeV/c)</td>
<td>0.3 ± 0.1</td>
<td>&lt;1</td>
</tr>
<tr>
<td>$\theta_{kink}$ (mrad)</td>
<td>90 ± 2</td>
<td>&gt;20</td>
</tr>
<tr>
<td>$z_{\text{dec}}$ ($\mu$m)</td>
<td>634 ± 30</td>
<td>[44, 2600]</td>
</tr>
<tr>
<td>$p_{\tau}^{2\text{ry}}$ (GeV/c)</td>
<td>11$^{+14}_{-4}$</td>
<td>&gt;2</td>
</tr>
<tr>
<td>$p_{\tau}^{3\text{ry}}$ (GeV/c)</td>
<td>1.0$^{+1.2}_{-0.4}$</td>
<td>&gt;0.6 (no $\gamma$ attached)</td>
</tr>
</tbody>
</table>
### ANALYSIS RESULTS

\[ \nu_\mu \rightarrow \nu_\tau \]

<table>
<thead>
<tr>
<th>Channel</th>
<th>Expected background</th>
<th>Expected signal</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Charm</td>
<td>Had. re-interac.</td>
<td>Large (\mu)-scat.</td>
</tr>
<tr>
<td>(\tau \rightarrow 1h)</td>
<td>0.017 ± 0.003</td>
<td>0.022 ± 0.006</td>
<td>–</td>
</tr>
<tr>
<td>(\tau \rightarrow 3h)</td>
<td>0.17 ± 0.03</td>
<td>0.003 ± 0.001</td>
<td>–</td>
</tr>
<tr>
<td>(\tau \rightarrow \mu)</td>
<td>0.004 ± 0.001</td>
<td>–</td>
<td>0.0002 ± 0.0001</td>
</tr>
<tr>
<td>(\tau \rightarrow e)</td>
<td>0.03 ± 0.01</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>0.22 ± 0.04</td>
<td>0.02 ± 0.01</td>
<td>0.0002 ± 0.0001</td>
</tr>
</tbody>
</table>

5 observed events with 0.25 background events expected

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

**Exclusion of null hypothesis: 5.1 \(\sigma\)**

**Marginality of the observation**

\[
P(n \geq 5 | \mu = 2.9) = 16.6 \%
\]

\[
P^\dagger = 6.4\%
\]

\(P^\dagger\) = probability to obtain a configuration less likely than (3, 1, 1, 0)
$\nu_\mu \rightarrow \nu_\tau$: EFFECT OF A STERILE?

3+1 model: bounds from $\nu_\tau$ appearance with profile Likelihood method

$\Delta m^2_{41} > 1 \text{ eV}^2$

Analysis based on 4 $\nu_\tau$ events

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

$\sim$ standard oscillation \hspace{1cm} exotic oscillation

$+ 0.5C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin 2\Delta_{31} \sin 2\Delta_{41}$

$- C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin^2 \Delta_{31} \sin 2\Delta_{41}$

$+ 2C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \Delta_{31} \sin^2 \Delta_{41}$

$+ C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin 2\Delta_{31} \sin^2 \Delta_{41}$

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

$C = 2 \left| U_{\mu 3} U^*_{\tau 3} \right|$

$\phi_{\mu\tau} = \text{Arg}(U_{\mu 3} U^*_{\tau 3} U_{\mu 4} U^*_{\tau 4})$

Effective mixing:

$\sin^2 2\theta_{\mu\tau} = 4 \left| U_{\mu 4} \right|^2 \left| U_{\tau 4} \right|^2$
$\nu_\mu \rightarrow \nu_e$ OSCILLATION SEARCH STATUS

2008 $\rightarrow$ 2009 data sample

19 $\nu_e$ candidates observed
19.8 ± 2.8 (syst.) events expected from bkg

Three flavour mixing analysis ($E_{\text{cut}} = 20$ GeV):

4 observed events $\Rightarrow \sin^2(2\theta_{13}) < 0.44$ (90% C.L.)
4.6 expected

Non standard oscillations at large $\Delta m^2$ ($E_{\text{cut}} = 30$ GeV):

6 observed events $\Rightarrow \sin^2(2\theta_{\text{new}}) < 7.2 \times 10^{-3}$ (90% C.L.)
9.4 expected

New analysis with more than twice candidates (50, 9 with $E<20$ GeV) on going
Cosmic ray physics: Muon charge ratio

\[ R_\mu \equiv \frac{N_{\mu^+}}{N_{\mu^-}} \]

Highest E region reached

Results compatible with a simple \( \pi \)-k model

CONCLUSIONS

• 17.97 x 10^{19} p.o.t. by CNGS in the period 2008-12

• 5 ν_τ candidates observed with 0.25 background events expected

• No oscillation hypothesis excluded at 5.1 σ level

Discovery of ν_τ appearance!

\[ \Delta m^2_{23} = [2.0 – 4.7] \times 10^{-3} \text{ eV}^2 \ (90\% \ C.L.) \]

• Search for anomalies in ν_μ \rightarrow ν_e and ν_μ \rightarrow ν_τ at a peculiar L/E. First limits on |U_{μ4}|^2 |U_{τ4}|^2 from direct measurement of ν_τ

• Interesting cosmic ray physics results (muon charge ratio)
Image taken using OPERA emulsion film with pinhole hand made camera courtesy by D. Di Ferdinando (INFN-Bologna)
BACKUP SLIDES
Validation with the CNGS Charm Events Sample

Test for: reconstruction efficiencies, description of kinematical variables, charm background.

54 ± 4 expected ↔ 50 observed

Charm and $\tau$ decays are topologically similar

Data/MC comparison in good agreement both in normalization and shape

Charm background constrained within 20%
**Hadronic Background**

**π Test Beams**

**Nuclear fragments**: a smoking gun for the occurrence of a π interaction instead of a decay.

Hadronic background constrained within 30%
LARGE ANGLE Μ SCATTERING

2 GeV/c muons on Lead

Phys. Rev. 122 (1961) 937

7.3 GeV/c muons on Copper

NIM A243 (1986) 518

New estimate based on GEANT4
- Simulation modified by introducing form factors (FF) for Lead
  (Saxon-Woods parameterization)
MC predictions compared to available data
The first $\nu_\tau$ candidate

Decay vertex:
$\tau^- \to \rho^- \nu_\tau$
$\rho^- \to \pi^0 \pi^-$
$\pi^0 \to \gamma \gamma$

All primary tracks incompatible with muon hypothesis

Found in 2008-2009 decay searched data, released in 2010
THE SECOND $\nu_\tau$ CANDIDATE

- Primary track incompatible with muon hypothesis
- All tracks identified as hadrons

Event satisfies criteria for:

$\tau \rightarrow h^+h^-\nu_\tau$

[ arXiv:1308.2553 ]
(submitted to JHEP)

<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  ± 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/c²]</td>
<td>0.5 &lt; 2.0</td>
<td>0.96 ± 0.13</td>
</tr>
<tr>
<td>Invariant mass [GeV/c²]</td>
<td>0.5 &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>
Negative charge of the secondary muon assessed with 5.6 σ significance (by spectrometer measurement)

Cuts for $\tau \to \mu$ channel passed

Primary track incompatible with muon hypothesis
The fourth $\nu_T$ candidate

$$D = \frac{L}{R_{\text{lead}}(p)} \frac{\rho_{\text{average}}}{\rho_{\text{lead}}} = 0.40^{+0.04}_{-0.05}$$

$D < 0.8$ : hadron

Hadronic decay channel

$$D = 0.18 \pm 0.04$$
The atmospheric muon charge ratio

- The atmospheric muon charge ratio $R_{\mu} \equiv N_{\mu^+}/N_{\mu^-}$ is being studied and measured since many decades
  - Depends on the **chemical composition** and energy spectrum of the primary cosmic rays
  - Depends on the **hadronic interaction features**
  - At high energy, depends on the **prompt component**
- Possibility to check HE hadronic interaction models ($E>1$ TeV) in the **fragmentation region** (phase space complementary to collider’s one)
- Atmospheric muons are kinematically related to atmospheric neutrinos (same sources) $\rightarrow R_{\mu}$ provides a benchmark for atmospheric $\nu$ flux computations (e.g. background for neutrino telescopes)
Highest-E region reached!

Opposite magnet polarities runs → lower systematics

Strong reduction of the charge ratio for multiple muon events

\[ \text{\textbf{1.377 ± 0.006}} \text{ } \]

\[ \text{\textbf{1.098 ± 0.023}} \text{ } \]

Results compatible with a simple π-K model

No significant contribution of the prompt component up to \( E_\mu \cos \theta^* \sim 10 \text{ TeV} \)

Validity of Feynman scaling in the fragmentation region up to \( E_\mu \sim 20 \text{ TeV} \) (\( E_N \sim 200 \text{ TeV} \))