The OPERA experiment : new results

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Vulcano Workshop 2014 – May 18-24 , Vulcano
Introduction

The OPERA Detector

Data Analysis

OPERA latest news ...
Physics motivation

- Super-K (1998), MACRO and Soudan-2: atmospheric neutrino anomaly interpretable as $\nu_\mu \rightarrow \nu_\tau$ oscillation
- K2K and MINOS (accelerator): confirmation of the Super –K $\nu_\mu$ disappearance signal

![Plot showing MINOS Atmospheric Neutrinos, 37.9 kt-yrs](image)

\[ P(\nu_\mu \rightarrow \nu_\tau) \approx \sin^2(2\theta_{23})\cos^4(\theta_{13})\sin^2\left(\frac{1.27\Delta m^2_{32}L(Km)}{E(\text{GeV})}\right) \]

Opera was designed to confirm that the disappearance was because of an oscillation phenomena.
Detection of $\nu_{\tau}$ CC interaction by a full reconstruction of the primary interaction and observation of the $t$ lepton decay topologies.

$\tau^- \rightarrow \mu^- \nu_{\tau} \nu_{\mu}$ 17.4%
$\tau^- \rightarrow e^- \nu_{\tau} \nu_e$ 17.8%
$\tau^- \rightarrow h^- \nu_{\tau} n(\pi^0)$ 49.5%
$\tau^- \rightarrow \pi^+ \pi^- \pi^- \nu_{\tau} n(\pi^0)$ 14.5%

Nuclear emulsions + Lead (ECC) “active target”

- 3D particle reconstruction
- Sub-micron spatial resolution

High background rejection
• Long baseline neutrino physics experiment
• **CNGS** quasi – pure wide band $\nu_\mu$ beam, $<L> = 732$ km, $<E> = 17$ GeV optimized to maximize the number of $\nu_\tau$ CC interactions

<table>
<thead>
<tr>
<th>$\nu_\mu$(CC + NC)/year</th>
<th>~4700</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\tau$ CC/year</td>
<td>~20</td>
</tr>
<tr>
<td>$(\nu_e + \bar{\nu}<em>e)/\nu</em>\mu$ CC</td>
<td>0.87%</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu/\nu</em>\mu$ CC</td>
<td>2.1%</td>
</tr>
<tr>
<td>$\nu_\tau$ prompt</td>
<td>negligible</td>
</tr>
</tbody>
</table>
LNGS – Gran Sasso National Lab

The largest underground laboratory in the world (180 000 m³)
about 3100 m.w.e. shielding

1 cosmic muon /m²/h
The OPERA Collaboration
140 physicists - 28 institutions - 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
LNF Frascati
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Nihon

Korea
Jinju

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

Switzerland
Bern

Turkey
METU Ankara

http://operaweb.lngs.infn.it
OPERA detector

TARGET TRACKERS
- Trigger task
- Brick identification
- 2 x 31 scintillating strip walls read by 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

53 BRICK WALLS
- ~150000 bricks
- ~1.25 kton

(Ref. JINST 4 (2009) P04018)
1. Extract Brick and CS, scan CS.
2. Confirm the event in the ECC brick.
3. Develop the brick and send to scanning labs.

Target area
(ECC + CS + TT)

Muon spectrometer
(Magnet+RPC+PT)

Brick Manipulator System
**ECC target brick**

- 57 emulsion films + 2 CS interface sheet
  
  **Ref:** *NIM A556 (2006) 80-86*

- 56 * 1 mm Pb (lead + 0.04 % Ca) plates
  
  **Ref:** *JINST 3 P07002 (2008)*

- 2 emulsion layers (42 µm thick) poured on a 200 µm plastic base
Interface emulsion films: high signal/noise ratio for event trigger and scanning time reduction

Ref: JINST 3 P07005 (2008)

Angular accuracy of the electronic predictions

Position accuracy of the electronic predictions
**Emulsion films scanning**

**EU: ESS (European Scanning System)**
- Scanning speed/system: 20cm$^2$/h
- Customized commercial optics and mechanics
- Asynchronous DAQ software

**Japan: SUTS (Super Ultra Track Selector)**
- Scanning speed/system: 75cm$^2$/h
- High speed CCD camera (3 kHz), Piezo-controlled objective lens
- FPGA Hard-coded algorithms

Both systems demonstrate:
- ~ 0.3 μm spatial resolution
- ~ 2 mrad angular resolution
- ~ 95% base track detection efficiency
Track follow-up film by film:

- alignment using cosmic ray tracks
- definition of the stopping point

Volume scanning (~2 cm³) around the stopping point

Ref. JINST 4 (2009) P06020
Decay search

The IP evaluation is a crucial point in order to detect decay topologies:

Each track is attached to the primary vertex only if:

\[
\text{IP} < 10 \ \text{µm} \quad \text{and} \quad \Delta Z < 500 \ \text{µm}
\]

\[
\text{IP} < 5 + 0.01 * \Delta Z \ \text{µm} \quad \text{and} \quad \Delta Z > 500 \ \text{µm}
\]

IP of the tracks attached to the neutrino vertices found

[Graph showing normalized number of tracks vs. IP (µm) and impact parameter (µm) vs. ΔZ (µm)]
The charmed hadrons decay has a similar topology to the tau lepton but the muon identified at the primary vertex, the charm sample was used as a "control sample".

<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)

[arXiv:1404.4357][hep-ex]
Data analysis

Final performances of the CNGS beam after five years (2008 ÷ 2012) 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>

Record performances in 2011
Overall 20% less than the proposal value
**OPERA brick handling**

About 25000 bricks manipulated for event analysis, 12000 bricks developed

Average mass = 1.18 kton
Data analysis

Run 2008 → 2012

6520 located interactions
5917 decay search
νμ → νe analysis

≈ 40 events found in the analyzed sample

4.1 GeV electron

Figure 5: Display of the reconstructed emulsion tracks of one of the νe candidate events. The reconstructed neutrino energy is 32.5 GeV. Two tracks are observed at the neutrino interaction vertex. One of the two generates an electromagnetic shower and is identified as an electron. In addition, two electromagnetic showers due to the conversion of two γ are observed (seen as one shower in this projection), starting from 2 and 3 films downstream of the vertex.

The νe detection efficiency as a function of the neutrino energy was computed with a GEANT3 based MC simulation. The simulated events were reconstructed with the same algorithms as used for the data. Slight differences in the scanning strategy used along the years have been taken into account and enter in the evaluation of the systematic uncertainty. The results of the simulation are shown in figure 6. The systematic uncertainty relative to its efficiency is calculated to be 10% for energies above 10 GeV.
Observation compatible with background-only hypothesis: 19.8±2.8 (syst) events

3 flavour analysis
Energy cut to increase the S/N

4 observed events
4.6 expected
⇒ \( \sin^2(2\theta_{13}) < 0.44 \) at 90\% C.L.
First $\nu_\tau$ candidate

$\tau \rightarrow \rho \left( \pi^- \pi^0 \right) \nu_\tau$

Kinematical cuts for a candidate event
Second $\nu_\tau$ candidate
\( \nu_\mu \rightarrow \nu_\tau \) oscillation search

No muon detected at the primary vertex:
track other than \( \tau \) lepton candidate not compatible with muon hypothesis based on momentum – range correlation

**Event kinematics**

<table>
<thead>
<tr>
<th></th>
<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</td>
<td>± 1.1</td>
</tr>
<tr>
<td>average kink angle [mrad]</td>
<td>&lt; 500</td>
<td>87.4</td>
<td>± 1.5</td>
</tr>
<tr>
<td>Total momentum at 2ry vtx [GeV/c]</td>
<td>&gt; 3.0</td>
<td>8.4</td>
<td>± 1.7</td>
</tr>
<tr>
<td>Min Invariant mass [GeV/c^2]</td>
<td>0.5 &lt; &lt; 2.0</td>
<td>0.96</td>
<td>± 0.13</td>
</tr>
<tr>
<td>Invariant mass [GeV/c^2]</td>
<td>0.5 &lt; &lt; 2.0</td>
<td>0.80</td>
<td>± 0.12</td>
</tr>
<tr>
<td>Transverse Momentum at 1ry vtx [GeV/c]</td>
<td>&lt; 1.0</td>
<td>0.31</td>
<td>± 0.11</td>
</tr>
</tbody>
</table>
Third $\nu_\tau$ candidate

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>AVERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>kink (mrad)</td>
<td>$245 \pm 5$</td>
</tr>
<tr>
<td>decay length ($\mu$m)</td>
<td>$376 \pm 10$</td>
</tr>
<tr>
<td>$P$ daughter (GeV/c)</td>
<td>$2.8 \pm 0.2$</td>
</tr>
<tr>
<td>$Pt$ daughter (MeV/c)</td>
<td>$690 \pm 50$</td>
</tr>
<tr>
<td>$\varphi$ (deg)</td>
<td>$154.5 \pm 1.5$</td>
</tr>
</tbody>
</table>
NEW $\nu_\tau$ candidate
NEW $\nu_\tau$ candidate

CS scanning results

ECC scanning results
NEW $\nu_\tau$ candidate

Search for nuclear fragments in an extended angular range $|\tan \theta| \leq 3.5$
No track found
**NEW $\nu_\tau$ candidate**

<table>
<thead>
<tr>
<th>Values</th>
<th>Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>P daughter (GeV/c)</td>
<td>6.0 $^{+2.2}_{-1.2}$, $&gt; 2$</td>
</tr>
<tr>
<td>Kink $P_t$ (GeV/c)</td>
<td>0.82 $^{+0.30}_{-0.16}$, $&gt; 0.6$</td>
</tr>
<tr>
<td>$P_t$ at 1ry (GeV/c)</td>
<td>0.55 $^{+0.30}_{-0.20}$, $&lt; 1.0$</td>
</tr>
<tr>
<td>Phi (degrees)</td>
<td>166 $^{+2}_{-31}$, $&gt; 90$</td>
</tr>
<tr>
<td>Kink angle (mrad)</td>
<td>137 ± 4, $&gt; 20$</td>
</tr>
<tr>
<td>Decay position ($\mu$m)</td>
<td>1090 ± 30, $&lt; 2600$</td>
</tr>
</tbody>
</table>

![Diagram showing decay angles and $\gamma$ particles](image)
Found in the CS of the most downstream brick

\[ P = 6.0^{+2.9}_{-1.2} \text{ GeV/c} \]

Range/momentum → hadron

\[ D = \frac{L \rho_{\text{average}}}{R_{\text{lead}}(p) \rho_{\text{lead}}} = 0.15 \]
NEW $\nu_\tau$ candidate

![Graphs showing distributions of various physical quantities such as kink angle, daughter momentum, decay Pt, missing Pt at 1ry, and $\Delta\phi$.]
**NEW $\nu_\tau$ candidate**

<table>
<thead>
<tr>
<th>$\Delta m^2 = 2.32 \times 10^{-3} \text{ eV}^2$</th>
<th>Expected</th>
<th>Observed</th>
<th>Background</th>
<th>Charm</th>
<th>$\mu$ scatt</th>
<th>had int</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow h$</td>
<td>0.38</td>
<td>2</td>
<td>0.03</td>
<td>0.014</td>
<td></td>
<td>0.019</td>
</tr>
<tr>
<td>$\tau \rightarrow 3h$</td>
<td>0.53</td>
<td>1</td>
<td>0.15</td>
<td>0.142</td>
<td></td>
<td>0.003</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu$</td>
<td>0.58</td>
<td>1</td>
<td>0.02</td>
<td>0.004</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow e$</td>
<td>0.58</td>
<td>0</td>
<td>0.02</td>
<td>0.025</td>
<td></td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>2.1</td>
<td>4</td>
<td>0.22</td>
<td>0.185</td>
<td>0.016</td>
<td>0.022</td>
</tr>
</tbody>
</table>

The $p$ values of the single channels are combined into an estimator $p^* = p_\mu p_e p_h p_{3h}$. $p^* \leq p^*$ (observed) gives the probability of the background-only hypothesis.

✓ 4 observed events with 0.22 background events expected
✓ Probability to be explained by background = $1.1 \times 10^{-5}$
✓ 4.2 $\sigma$ significance of non-null observation
Measurement of TeV atmospheric muon charge ratio

\[ R_\mu = \frac{\text{Number of charged muons}}{\text{Number of neutral muons}} \]

\[ R_\mu (E) = a \times \frac{E}{10^4} + b \]

\[ R_\mu (E) = c \times \log \frac{E}{10^4} + d \]

\[ R_\mu (E) = e \times \frac{E}{10^4} + f \]

\[ R_\mu (E) = g \times \log \frac{E}{10^4} + h \]

\[ R_\mu (E) = i \times \frac{E}{10^4} + j \]

\[ R_\mu (E) = k \times \log \frac{E}{10^4} + l \]

\[ R_\mu (E) = m \times \frac{E}{10^4} + n \]

\[ R_\mu (E) = o \times \log \frac{E}{10^4} + p \]

\[ R_\mu (E) = q \times \frac{E}{10^4} + r \]

\[ R_\mu (E) = s \times \log \frac{E}{10^4} + t \]

\[ R_\mu (E) = u \times \frac{E}{10^4} + v \]

\[ R_\mu (E) = w \times \log \frac{E}{10^4} + x \]

\[ R_\mu (E) = y \times \frac{E}{10^4} + z \]

\[ R_\mu (E) = A \times \frac{E}{10^4} + B \]

\[ R_\mu (E) = C \times \log \frac{E}{10^4} + D \]

\[ R_\mu (E) = E \times \frac{E}{10^4} + F \]

\[ R_\mu (E) = G \times \log \frac{E}{10^4} + H \]

\[ R_\mu (E) = I \times \frac{E}{10^4} + J \]

\[ R_\mu (E) = K \times \log \frac{E}{10^4} + L \]

\[ R_\mu (E) = M \times \frac{E}{10^4} + N \]

\[ R_\mu (E) = O \times \log \frac{E}{10^4} + P \]

\[ R_\mu (E) = Q \times \frac{E}{10^4} + R \]

\[ R_\mu (E) = S \times \log \frac{E}{10^4} + T \]

\[ R_\mu (E) = U \times \frac{E}{10^4} + V \]

\[ R_\mu (E) = W \times \log \frac{E}{10^4} + X \]

\[ R_\mu (E) = Y \times \frac{E}{10^4} + Z \]

\[ R_\mu (E) = aK \text{ model} \]

\[ R_\mu (E) = aK + \text{RQPM model} \]

\[ R_\mu (E) = aK + \text{QGSM model} \]

\[ R_\mu (E) = aK + \text{VFGS model} \]

arXiv:1403.0244
Submitted to EPJC
Conclusions

- “OPERA RUN” is going on
- More than 6000 neutrino interactions fully reconstructed and studied in ECC.
- 4 candidate events found
- 4.2 σ significance of non-null observation
Spares
Visible energy of all the candidates

Sum of the momenta of charged particles and $\gamma$'s measured in emulsion
Muon charge and momentum reconstruction

Muon momentum by range in the electronic detector: $2.8 \pm 0.2$ GeV/c
MCS in the brick consistent 3.1 [2.6,4.0] GeV/c
Muon charge and momentum reconstruction

Parabolic fit with $p_2$ as quadratic term coefficient in the magnetized region
Linear fit in the non-magnetized region

$\chi^2 / \text{ndf} = 2.614 / 4$

$p_0 = 189.5 \pm 0.5518$

$p_1 = -0.3453 \pm 0.005458$

$p_2 = -0.003892 \pm 0.0006894$

$p_2 < 0 \rightarrow$ negative charge
5.6 $\sigma$ significance
$R \sim 85$ cm

The negative muon charge rules out charm background!
## Track features

<table>
<thead>
<tr>
<th></th>
<th>First measurement</th>
<th>Second measurement</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Track ID</td>
<td>Particle ID</td>
<td>Slopes</td>
</tr>
<tr>
<td>1ry</td>
<td>1 parent</td>
<td>τ</td>
<td>-0.143, 0.026</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Hadron (Range)</td>
<td>-0.044, 0.082</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Hadron (interact)</td>
<td>0.122, 0.149</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>proton</td>
<td>-0.083, 0.348</td>
</tr>
<tr>
<td></td>
<td>γ1</td>
<td>e-pair</td>
<td>-0.229, 0.068</td>
</tr>
<tr>
<td></td>
<td>γ2</td>
<td>e-pair</td>
<td>0.111, -0.014</td>
</tr>
<tr>
<td>2ry</td>
<td>daughter</td>
<td>Hadron (Range)</td>
<td>-0.084, 0.148</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>ΔZ (µm)</th>
<th>δθ&lt;sub&gt;RM&lt;/sub&gt; (mrad)</th>
<th>IP (µm)</th>
<th>IP Resolution (µm)</th>
<th>Attachment</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ1</td>
<td>To 1ry</td>
<td>676</td>
<td>2</td>
<td>8</td>
<td>OK</td>
</tr>
<tr>
<td>γ2</td>
<td>To 1ry</td>
<td>7176</td>
<td>9.2</td>
<td>43</td>
<td>OK</td>
</tr>
<tr>
<td></td>
<td>To 2ry</td>
<td>6124</td>
<td>9.2</td>
<td>267</td>
<td>Excluded</td>
</tr>
</tbody>
</table>

\[
M = 0.59^{+0.20}_{-0.15} \text{ GeV/c}^2
\]

Not a single π^0
Track follow-down: a powerful tool to assess the muon-less nature of the event
Follow-down all tracks in downstream bricks

- 3 primary tracks to discard the charm hypothesis
- kink daughter to identify the $\tau$ decay channel

![Transverse plane with CS tracks and analysis](image)

- CS analysis
- Y (cm)
- Transverse plane
- One rectangle: brick front size

- Daughter track
- Track2 (1ry)
- Track3 (1ry)
- Track4 (1ry)
Track follow-down: primary track n. 2

Track 2 followed-down along 10 bricks

Average loss of $62\pm49$ MeV/brick

Most downstream brick
Track n. 2 follow-down

Neutrino vertex

Extrapolation from the last measured emulsion track

Last measured track in emulsion

No hits in the RPC’s
Measured length x density, $L \rho$

$L \rho$ for the track = 604 g/cm² (<660 g/cm²)

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

- Prob. for a $\mu$ to cross $\leq$ 12 planes $\sim 0.35%$
- Prob. for a $\pi$ to cross $\geq$ 12 planes $\sim 10.2%$
Track follow-down: primary track n. 3

Track 3 found down to the CS of the 2\textsuperscript{nd} brick
P = 1.1 GeV/c at 2\textsuperscript{nd} brick

A vertex found near its predicted position in the 3\textsuperscript{rd} downstream brick

\[(\Delta x, \Delta y) = (101, -735) \mu m\]

Interaction detected
Track follow-down: primary track n. 4

From the ionization, the proton hypothesis is made
$P\gamma \sim 0.4$, ($P = 0.7$ assuming proton mass)

Track path of 77.8 mm lead, Range/Mass $\sim 94$ g cm$^{-2}$ GeV$^{-1}$
Expected Range/Mass from measured momentum $\sim 70$ [45-100] g cm$^{-2}$ GeV$^{-1}$

Consistent with the proton hypothesis

Track confirmed in the CS of the 2nd brick