OPERA, Emulsion Scanning, Analysis and Recent Results on Muon-Neutrino to Electron-Neutrino Oscillations

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On behalf of the OPERA Collaboration
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High Energy Physics and Quantum Field Theory
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Outline of The Talk

- The OPERA Experiment
  - Data Taking
- ECC Event Reconstruction
  - Scanning
  - Decay Search
- $\nu_\mu \rightarrow \nu_e$ Oscillation
  - Electromagnetic shower reconstruction
- Conclusion
140 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
- **Russia** INR RAS Moscow LPI RAS Moscow ITEP Moscow SINP MSU Moscow JINR Dubna
- **Switzerland** Bern
- **Turkey** METU, Ankara

http://operaweb.lngs.infn.it
The OPERA experiment was mainly designed to unambiguously prove the oscillation phenomenon through direct $\nu_\tau$ appearance.

**OPERA: FIRST DIRECT DETECTION OF NEUTRINO OSCILLATIONS IN APPEARANCE MODE**

3x3 Unitary Mixing Matrix

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta_{cp}} \\
0 & 1 & 0 \\
-s_{13} e^{i\delta_{cp}} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
$$

- Atmospheric terms
- Unknown terms
- Solar terms

Where $c_{ij} = \cos \theta_{ij}$, $s_{ij} = \sin \theta_{ij}$

$$
P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 (1.27 \Delta m_{23}^2 L / E)
$$

$$
P(\nu_\mu \rightarrow \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \sin^2 (1.27 \Delta m_{23}^2 L / E)
$$

Dominant channel
Oscillation Project with Emulsion tRacking Apparatus

CNGS
CERN Neutrino to Gran Sasso beam
High energy $\nu_\mu$ beam from CERN to Gran Sasso

OPERA requires:
1) long baseline,
2) high neutrino energy,
3) high beam intensity
4) detection of short lived $\tau$'s
The OPERA Detector

Super Module 1

Super Module 2

2 supermodules, 31 walls, 150,000 bricks

Target mass: 1.2 ktons

BMS Brick Manipulator System

57 emulsion films 56 Pb plate

The OPERA Experiment
ECC Event Reconstruction
$\nu_\mu \rightarrow \nu_e$ Oscillation
Conclusion

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The OPERA Brick

The target principle: the ‘brick’

- ECC brick = sequence of emulsion-lead layers
  - High resolution and large mass in a modular way
- The brick is the basic component
  - 57 nuclear emulsion films interleaved with 1 mm thick lead plates
  - a box with a removable pair of films called Changeable Sheets

Track reconstruction accuracy in emulsions: \( \Delta x \approx 1 \mu m \) \( \Delta \theta \approx 2 \text{ mrad} \)

The “BRICK” can provide:
- neutrino vertex reconstruction
- search for decay topologies
- electron ID and energy measurement

8.3 Kg
The Data Taking

**Trigger** + event selection “on time” with CNGS

**Brick finding** reconstruction algorithm applied to electronic data to select the best candidate brick to contain the neutrino interaction vertex

Brick removed by the **Brick Manipulation System (BMS)** and exposed to **frontal X-rays** to make an alignment reference between CS and brick

CS detached from brick, films developed and analysed in one of the **CS Scanning Stations**, in Europe (LNGS) or Japan (Nagoya)

If a TT-predicted track is found in the CS, the **brick** is exposed to **lateral X-rays** beam and to **cosmic rays** for sheets alignment. Brick is disassembled and emulsion films **developed** and sent to one of the scanning labs

Tracks found in the CS are searched for in the most downstream film of the brick and followed

A **volume scan** around the neutrino interaction point is performed and the neutrino vertex is located and studied
The Data Taking

1. TT-CS Connection

2. CS film to film Connection

3. CS-to-ECC Brick connection

4. ECC brick film-to-film connection

The OPERA Experiment
ECC Event Reconstruction

$\nu_\mu \rightarrow \nu_e$ Oscillation

Conclusion

QFTHEP 2013
Automated Emulsion Scanning

CS and bricks are shared among emulsion scanning labs:

Europe

ESS microscope
- Commercial hardware
- Software algorithms
- Scanning speed 20 cm²/h

Japan

S-UTS microscope
- High speed CCD camera (3 kHz)
- Hard-coded algorithms and custom mechanics
- Scanning speed up to 75 cm²/h

Piezo-controlled objective lens
Emulsion

INDUSTRIAL EMULSION FILMS BY FUJI FILM

- **top layer**
  - Emulsion Layer (44 microns)
  - Plastic Base (205 microns)

- **bottom layer**
  - Emulsion Layer

**Charged particle**

**AgBr crystal**

**Development treatment**

**basic detector:** AgBr crystal,
size = 0.2 micron
detection eff. = 0.16/crystal

$10^{13}$ “detectors” per film
Emulsion Scanning

3D Microtracks reconstruction

Microtracks alignment via the plastic base
BASETRACK

Basetracks alignment of several emulsions

Reconstruction
Vertex/Decay

1 plastic base (200 μm)

2 emulsion sheets (45 μm)

1 lead sheet (1 mm)

3D reconstruction of particle tracks

Field of view

16 tomographic images

2D Image processing

νµ → νe Oscillation

Conclusion
The OPERA Experiment

**ECC Event Reconstruction**

$\nu_\mu \rightarrow \nu_e$ Oscillation

**Conclusion**

### ECC Event Reconstruction

#### 1. CS Scanning
- Manual Check

#### 2. Event Location
- Manual Check

#### 3. Volume Scan
- Manual Check

#### 4. Decay Search
- Manual Check

#### 5. Publish

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**Vertex Finding**

**Field of view**

390 $\mu$m × 310 $\mu$m

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

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ECC Event Reconstruction

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The OPERA Experiment

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QFTHEP’2013
1. Changeable Sheet Scanning

1. CS Scanning

2. Event Location

3. Volume Scan

4. Decay Search

5. Publish

In the CS scanning, an area of 4x6 cm² per emulsion is scanned around the muon prediction in case of CC interactions, for NC events a larger area is scanned.

The scanning is performed at the CS Scanning station, located at the Gran Sasso laboratory, and in the Nagoya scanning laboratory.

vertex signature already evident in the CS
During the Scanback procedure the extrapolations of the CS tracks back into the brick are followed upstream, until the tracks can not be found anymore. To find the CS track prediction in the first emulsion plate, an area of $3 \times 3 \text{mm}^2$ is scanned.
After the CS tracks were followed and the stopping point was confirmed, the volume scan must be performed. The scanning volume consists of 15 consecutive plates, 10 downstream of the stopping point, 5 upstream, each scanned with an area of 1 cm².
Scan about 10 plates around stop plate by follow up from downstream.
Applying cuts to eliminate the background tracks.
Search tracks making vertex by neutrino interaction.
4. Decay Search

Decay search is in progress and special events have already been found.

The Decay Search Procedure is performed to find possible events, as $\tau$ or charm-decays and/or $\nu_e$ interactions, a topological search of decay daughters or parent tracks is done, including a electron/gamma separation search for showers.

- a multi-prong vertex has been reconstructed
- a different procedure is applied
- an isolated muon or hadron has been found
4.1. Events With A Reconstructed Vertex

**Decay Search**

1. **Vertex Definition And Analysis**
   - re-compute the vertex position.
   - $e^+e^-$ pairs can be identified
   - recovery of missing segments
   - low momentum particles are excluded

2. **Extra-track Decay Search**
   Searching for possible daughter tracks,
   - $\Delta z < 3.6 \text{ mm}$
   - the impact parameter $< 300 \mu\text{m}$
   - the track has at least three segments the reconstruction.

3. **In-track Decay Search**
   A search for possible small kinks along the tracks attached to the neutrino interaction,
4.2. Events With An Isolated Muon Or Hadron

- the most upstream segment is in any of the three emulsion films upstream of the scan-back track stopping point or in any of the three films downstream of it;
- the impact parameter, computed with respect to the extrapolation of the scan-back track to the centre of the upstream lead plate, is smaller than 500 \( \mu m \);
- the track has at least three segments in the reconstruction.
6067 located interactions
4969 decay search

2008 and 2009 completed
2010-2012 on going

Status of data analysis

- Events reconstructed in the target
- Events with at least 1 brick extracted
- Events with at least 1 CS scanned
- Events with a positive CS result
- Events with a brick scanned
- Interactions located in the bricks
- Decay Search Completed

Record Performances above quasi-online

QFTHEP'2013
Electromagnetic shower reconstruction with emulsion films in the OPERA experiment

An algorithm for electron shower reconstruction have been developed

**Electromagnetic shower reconstruction**

- e/π separation
- shower energy measurement

The total number of base-tracks and the longitudinal and transverse profiles of the showers can be used for particle identification.

Collect base-tracks inside a given cone:

- δθ < 150 mrad
- δr < 150μm
A first reconstructed $\nu_\mu$ CC event recorded during the October 2007 run in the OPERA detector. The 3 long straight tracks are directly attached to the primary vertex. The colored shower in the middle is a gamma conversion coming from a $\pi^0$ decay and is also well attached to the primary vertex.

<table>
<thead>
<tr>
<th>Pion Contamination</th>
<th>Energy</th>
<th>Electron efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1%</td>
<td>&gt;2 GeV</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td>~1%</td>
<td>&lt;1 GeV</td>
<td>~ 80%</td>
</tr>
</tbody>
</table>
The identification of an electron is essentially based on the detection of the associated electromagnetic shower.

- The tracks with angles similar (Δθ < 150 mrad) to that of the corresponding primary track are searched in the CS region within 2 mm around the projected point.
- a scan-back procedure along the electromagnetic shower is applied.
- the presence of an electron track is confirmed at the neutrino interaction vertex, the event is classified as a νₑ interaction.
Display of the reconstructed emulsion tracks of one of the $\nu_e$ 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 showers from $\Upsilon$ conversions are observed.

Detection efficiency of $\nu_e$ events as a function of the neutrino energy, obtained from MC simulations.
Among the 5255 candidate neutrino interactions collected during the 2008 and 2009 runs, 19 $\nu_e$ candidate events were found.
The OPERA Experiment  ECC Event Reconstruction  $\nu_\mu \rightarrow \nu_e$ Oscillation  Conclusion

Distribution of the reconstructed energy of the $\nu_e$ events

<table>
<thead>
<tr>
<th>Energy cut</th>
<th>20 GeV</th>
<th>30 GeV</th>
<th>No cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>BG common to both analyses</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BG (a) from $\pi^0$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>BG (b) from $\tau \rightarrow e$</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$\nu_e$ beam contamination</td>
<td>4.2</td>
<td>7.7</td>
<td>19.4</td>
</tr>
<tr>
<td>Total expected BG in 3-flavour oscillation analysis</td>
<td>4.6</td>
<td>8.2</td>
<td>19.8</td>
</tr>
<tr>
<td>BG to non-standard oscillation analysis only</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\nu_e$ via 3-flavour oscillation</td>
<td>1.0</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td>Total expected BG in non-standard oscillation analysis</td>
<td>5.6</td>
<td>9.4</td>
<td>21.3</td>
</tr>
<tr>
<td>Data</td>
<td>4</td>
<td>6</td>
<td>19</td>
</tr>
</tbody>
</table>
The experiment searched for the appearance of $\nu_e$ in the CNGS neutrino beam using the data collected in 2008 and 2009, corresponding to an integrated intensity of $5.25 \times 10^{19}$ pot. The observation of 19 $\nu_e$ candidate events is compatible with the non-oscillation expectation of $19.8\pm2.8$ events.

<table>
<thead>
<tr>
<th>C.L.</th>
<th>Upper limit (F&amp;C)</th>
<th>Upper limit (Bayes)</th>
<th>Sensitivity (F&amp;C)</th>
<th>Sensitivity (Bayes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of oscillated $\nu_e$ events</td>
<td>90%</td>
<td>3.1</td>
<td>4.5</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>4.3</td>
<td>5.7</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>99%</td>
<td>6.7</td>
<td>8.2</td>
<td>10.7</td>
</tr>
<tr>
<td>$\sin^2(2\theta_{new})$ at large $\Delta m^2$</td>
<td>90%</td>
<td>$5.0 \times 10^{-3}$</td>
<td>$7.2 \times 10^{-3}$</td>
<td>$9.7 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>95%</td>
<td>$6.9 \times 10^{-3}$</td>
<td>$9.1 \times 10^{-3}$</td>
<td>$12.4 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>99%</td>
<td>$10.6 \times 10^{-3}$</td>
<td>$13.1 \times 10^{-3}$</td>
<td>$17.1 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
OPERA is the first experiment searching for direct $\nu_\tau$ appearance in the framework of $\nu_\mu$ oscillation

- CNGS beam concluded: 2008 – 2012
- 18941 ontime target interactions
- Confirmed $\nu_\tau$ candidate events : 3 (See Michele's presentation)
- Confirmed $\nu_e$ candidate events : 19 (2008 + 2009 data)
- 60% of the all data was analyzed

Outlook
- Extraction of candidate bricks: Until ~ 2014
- Scanning & analysis of candidate interactions: Until ~ 2015
Thank You For Your Attention
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 (22.5)