Neutrino Oscillations Studies with the Opera Experiment at CNGS Beam

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Outline:

- The OPERA collaboration
- Physics motivation
- CNGS beam
- Topological tau detection
- The OPERA detector
- Analysis Flow chart
- Physics results
- Conclusions
The OPERA collaboration

- 33 Institutions
- ~200 physicist
Physics motivation

- CHOOZ (1997): $\nu_\mu \rightarrow \nu_e$ oscillations excluded as dominant process responsible for atmospheric neutrino disappearance
- SK (1998): atmospheric neutrino anomaly interpretable as $\nu_\mu \rightarrow \nu_\tau$ oscillations

In $\nu$ oscillations there is not yet a direct evidence of new flavour APPEARANCE tagged by identification of the charged lepton produced in charged current interactions

OPERA

(Oscillation Project with Emulsion tRacking Apparatus) long baseline neutrino oscillation experiment aiming the direct observation of the $\nu_\tau$ appearance in an initially pure $\nu_\mu$ beam through the $\nu_\tau$ CC interactions.

The sub-leading oscillation $\nu_\mu \rightarrow \nu_e$ is also studied
CNGS (CERN Neutrino To Gran Sasso) beam

- Protons from SPS: 400 GeV/c
- Cycle length: 6 s
- 2 extractions separated by 50 ms
- Pulse length: 10.5 $\mu$s
- Beam intensity: $2.4 \times 10^{13}$ proton/extr.
- Expected performance: $4.5 \times 10^{19}$ pot/year

Flux optimized to produce the max. number of $\nu_\tau$ CC

<table>
<thead>
<tr>
<th>&lt;E ($\nu_\mu$)&gt;</th>
<th>17 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>730 km</td>
</tr>
<tr>
<td>L/E</td>
<td>43 Km/GeV</td>
</tr>
<tr>
<td>($\nu_e + \bar{\nu}<em>e$)/$\nu</em>\mu$ CC</td>
<td>0.87%</td>
</tr>
<tr>
<td>$\nu_\mu$ / $\nu_\mu$ CC</td>
<td>2.1%</td>
</tr>
<tr>
<td>$\nu_\tau$ prompt</td>
<td>negligible</td>
</tr>
</tbody>
</table>

- Nominal beam performance ($4.5 \times 10^{19}$ pot/y)
- Target mass of 1.25 kton

$\rightarrow$ Expected number of interactions in 5 years running:
- $\sim 23600 \nu_\mu$ CC+NC
- $\sim 170 \nu_e + \bar{\nu}_e$ CC
- $\sim 115 \nu_\tau$ CC ($\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$)

After efficiencies, 10 tau decays are expected to be observed, with <1 background events.
**Principle of topological $\tau$ detection**

$\nu_\tau$ CC interaction:

$\nu_\mu \rightarrow \nu_\tau + N \rightarrow \tau^- + X$

oscillation

$\tau^- \rightarrow \mu^- \nu_\tau \nu_\mu$

$B. R. \sim 17%$

$h^- \nu_\tau n(\pi^0)$

$B. R. \sim 49%$

$e^- \nu_\tau \nu_e$

$B. R. \sim 18%$

$\pi^+ \pi^- \pi^- \nu_\tau n(\pi^0)$

$B. R. \sim 15%$

Decay “kink”

(35% of Non-Scaling QE and 65% DIS)

$\nu_\mu \rightarrow \nu_\tau$

$\tau^- \rightarrow \mu^-$

(35% of Non-Scaling QE and 65% DIS)

no-oscillation

$\nu_\mu \rightarrow \nu_\mu$

(11% of Non-Scaling QE and 89% DIS)

2 conflicting requirements:

- Target mass $O(\text{kton})$
  
  (low $\nu$ interaction cross-section)

- High granularity: signal identification background rejection

ECC (Emulsion Cloud Chamber) concept:

thin metal plates interleaved with nuclear photographic emulsions on films

3D tracking:

32 grains/100$\mu$m

Emulsion layers

$\nu$

Pb

1 mm

(\text{Path length})

$\nu_{\tau} \sim 87 \mu m \approx 600 \mu m$
OPERA sensitivity

5 years of nominal beam $4.5 \times 10^{19}$ pot/year:

<table>
<thead>
<tr>
<th>$\tau$ decay channel</th>
<th>B.R. (%)</th>
<th>Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \to \mu$</td>
<td>17.7</td>
<td>2.9</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \to e$</td>
<td>17.8</td>
<td>3.5</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \to h$</td>
<td>49.5</td>
<td>3.1</td>
<td>0.24</td>
</tr>
<tr>
<td>$\tau \to 3h$</td>
<td>15.0</td>
<td>0.9</td>
<td>0.17</td>
</tr>
<tr>
<td>All</td>
<td>BR*eff  =10.6%</td>
<td>10.4</td>
<td>0.75</td>
</tr>
</tbody>
</table>

The number of signal events goes as $(\Delta m^2)^2$

Background components:

Production of charmed particles in CC interactions (all decay channels)

Coulombian large angle scattering of muons in lead Bck. to $\tau \to \mu$

Primary lepton unidentified

Hadronic interactions in lead:
Bck. to $\tau \to h$

or to $\tau \to \mu$
(if hadron misid. as muon)

MINOS 2008
The OPERA basic unit: the « Brick »

Based on the concept of the Emulsion Cloud Chamber:
- 57 emulsion films + 56 Pb plates
- a box with a removable pair of films (Changeable Sheets) interface to the electronic detectors

→ High space resolution in a large mass detectors with a completely modular scheme

Track reconstruction accuracy in emulsions:
\[ \Delta x \approx 0.3 \, \mu m \quad \Delta \theta \approx 2 \, \text{mrad} \]

Bricks are completely stand-alone detectors:
- Neutrino interaction vertex and kink topology reconstruction
- Measurement of hadrons momenta by multiple scattering
- \(dE/dx\) pion/muon separation at low energy (at end of range)
- Electron identification and measurement of the energy of electrons and gammas
The OPERA hybrid detector

The bricks are stand-alone passive detectors

Electronic Detectors are needed for:
- Triggering, Timing
- Neutrino interactions Location
- Calorimetry
- Muon I.D. and Spectrometry

TARGET TRACKERS
- 2x31 scintillator strips walls
- 256+256 X-Y strips/wall
- WLS fiber readout
- 64-channel PMTs
- 63488 channels
- 0.8 cm resolution, 99% ε
- rate 20 Hz/pixel @1 p.e.

BRICK WALLS
- 2850 bricks/wall
- 53 walls
- 150000 bricks ~ 1.25 kton

HIGH PRECISION TRACKERS
- 6 drift-tube layers/spectrometer spatial resolution < 0.5 mm

INNER TRACKERS
- 990-ton dipole magnets (B= 1.55 T) instrumented with 22 RPC planes
- 3050 m², ~1.3 cm res.
OPERA as real time experiment

- CNGS events are selected on a delayed time coincidence between proton extractions from SPS and the events in OPERA.
- The synchronization is based on GPS with precision of ~100 ns (can be improved to 10ns)
- DAQ livetime during CNGS is 98.8%
- Real time detection of neutrino interaction in target and in the rock surrounding OPERA

![Diagram of OPERA setup with GPS synchronization and event timing distributions](image)

- Time distribution of events in the neutrino run.
- Event time difference wrt the closest extraction.
- Angular distribution of muons produced by $\nu$ interactions in the rock.
1. Trigger on events “on time” with CNGS and selection of the brick with $\nu$ interaction using electronic detectors information (brick finding algorithm)

2. Brick removed by BMS (brick manipulator system)
   - Semi-online ECC target analysis
   - Minimize the target mass loss
3. The emulsion interface films (CS), are separated from the brick and scanned looking for a connection with respect to the electronic detectors predictions.

- High signal/noise ratio for event trigger and scanning time reduction.

Position accuracy of the electronic predictions:

\[ \sigma_{dy} \approx 10.0 \text{mm} \]

Angular accuracy of the electronic predictions:

\[ \sigma_{\theta y} \approx 23 \text{mrad} \]
4. If tracks are found in the CS, the brick is exposed to X-rays beam and to cosmic rays for sheets alignment.

5. The brick is disassembled and the emulsion films are developed and sent to one of scanning labs.

**EUROPE:**
Brick emulsion scanning: 9 labs
LNGS is CS scanning center

**JAPAN:**
Brick emulsion scanning: 2 labs
Nagoya is CS scanning center

European Scanning System
CMOS camera
Scanning speed 20 cm²/h

Super-UltraTrackSelector
High speed CCD camera (3 kHz)
Scanning speed up to 75 cm²/h
6. Brick Scanning and neutrino interaction vertex location

Tracks found in CS are followed in the most downstream films of the brick up to their stopping point: **Scan-back procedure**

**Volume scan**: a zone of ~ 1 cm² in several films is measured around track disappearance point(s) to confirm the presence of the interaction.

7. **Vertex tracks may be followed in the forth direction for kinematical measurements**

Data are published on the central **Data Base**
Offline treatment of emulsion data

- Emulsion data (scanback, volume scan, scanforth) stored in the DB are extracted to produce root ntuple for offline analysis $O(Gb/event\ data\ volume)$

- Operational for alignment-tracking-vertexing

- MC output integrated in the framework, mixing with real data background from scanned empty volumes

- Integrated interactive display

Memory utilisation (MB)
This value is stable during job execution
$\nu_\mu$ CC events: quantities measured in the ED

Muon reconstruction and hadronic showers behaviour in reasonable agreement data/MC for $\nu_\mu$ CC events

- Muon momentum
- Track length x density (range for muon id)

Muon identification:
- Range identification
- Range vs momentum measured in bricks with MCS
- Best brick-ED angular matching

Raw hadronic energy deposited in TT scintillator (MeV)

Shower transverse profile

NC/CC ratio measurement after removal of external bck accumulation at target borders:
- Data 2008: NC/CC = 0.230 ± 0.014 (stat.)
- Data 2009: NC/CC = 0.230 ± 0.009 (stat.)
- MC: NC/CC = 0.236 ± 0.005 (stat.)
Reconstructed tracks and momenta in bricks

Reconstructed tracks at the primary vertex for $\nu_\mu$ CC events

Muon slopes measured at primary vertex compared to MC (at generator level!)

Event track multiplicity distribution

MCS measurement of soft muons ($p<6$ GeV) in order to validate the technique for kinematical measurements and compare to momentum from ED

Soft muon measured in OPERA

$\sigma = (22\pm4)\%$
A systematic DECAY SEARCH was started on 2008 and 2009 data in order to find all possible decay topologies:
1) improvement of the vertex definition and IP distribution
2) detection of possible kink topologies (on tracks attached to primary vertex)
3) search for extra tracks from decays not attached to primary vertex

20 charm candidates were found so far (in good part with the scan-back and vertex location procedures). Charm events are the control sample for decay search → completion of systematic decay search for final evaluation.

Impact parameter distribution

Muon I.P. $\rightarrow \mu$ (MC)
## CNGS beam performance

<table>
<thead>
<tr>
<th></th>
<th>2008 run</th>
<th>2009 run</th>
</tr>
</thead>
<tbody>
<tr>
<td>total pot</td>
<td>$1.782 \times 10^{19}$</td>
<td>$3.522 \times 10^{19}$</td>
</tr>
<tr>
<td>On-time events</td>
<td>10122</td>
<td>21428</td>
</tr>
<tr>
<td>candidate in the target</td>
<td>1698</td>
<td>3693</td>
</tr>
</tbody>
</table>

### Foreseen stops

- $2 \times 10^{13}$ pot/extraction

### Unforeseen stops

- Average efficiency 72.1%
<table>
<thead>
<tr>
<th>Events location summary for 2008 run</th>
<th>0mu</th>
<th>1mu</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events predicted by the electronic detector</td>
<td>406</td>
<td>1292</td>
<td>1698</td>
</tr>
<tr>
<td>Found in CS</td>
<td>271</td>
<td>1045</td>
<td>1316</td>
</tr>
<tr>
<td>Vertices located in bricks</td>
<td>151</td>
<td>792</td>
<td>943</td>
</tr>
<tr>
<td>Vertices located in dead materials</td>
<td>6</td>
<td>38</td>
<td>44</td>
</tr>
<tr>
<td>Interactions in the upstream brick</td>
<td>6</td>
<td>33</td>
<td>39</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Events location summary for 2009 run</th>
<th>0mu</th>
<th>1mu</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events predicted by the electronic detector</td>
<td>865</td>
<td>2297</td>
<td>3162</td>
</tr>
<tr>
<td>Extracted CS</td>
<td>829</td>
<td>2211</td>
<td>3040</td>
</tr>
<tr>
<td>CS Scanned</td>
<td>666</td>
<td>1802</td>
<td>2468</td>
</tr>
<tr>
<td>Found in CS</td>
<td>376</td>
<td>1139</td>
<td>1515</td>
</tr>
<tr>
<td>Vertices located in bricks</td>
<td>67</td>
<td>371</td>
<td>438</td>
</tr>
<tr>
<td>Vertices located in dead materials</td>
<td>2</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Interactions in the upstream brick</td>
<td>3</td>
<td>36</td>
<td>39</td>
</tr>
</tbody>
</table>
A $\nu_e$ candidate:

- Primary vertex
- Electromagnetic shower
- Hadron
- $e^+e^-$ pairs
Topological identification and kinematical confirmation of a charm event

Event 234654975

Brick 85405

All units are in microns

<table>
<thead>
<tr>
<th>Track</th>
<th>Impact Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.36</td>
</tr>
<tr>
<td>2</td>
<td>0.88</td>
</tr>
<tr>
<td>7</td>
<td>0.51</td>
</tr>
</tbody>
</table>

| X      | 66716,60         |
| Y      | 49092,9          |
| Z      | 90,9             |

<table>
<thead>
<tr>
<th>Track</th>
<th>Impact Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1.13</td>
</tr>
<tr>
<td>4</td>
<td>1.81</td>
</tr>
<tr>
<td>5</td>
<td>1.99</td>
</tr>
<tr>
<td>6</td>
<td>1.39</td>
</tr>
</tbody>
</table>

| X      | 66710,10         |
| Y      | 49899            |
| Z      | 403,9            |

$D^0$

<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>
70% of 1-prong hadronic $\tau$ decays include one or more $\pi^0$. Important to detect gamma from tau decay to improve S/N.

Gamma detection
- detection of shower
detection e-pair at start point

$\pi^0$ reconstruction is in progress.

2 e-showers give a reconstructed mass $\sim 160$ MeV/c$^2$

$E \sim 8.1$ GeV
$E \sim 0.5$ GeV
Conclusions:

- OPERA has taken data in 2008 and 2009 for 5.3E19 pot, proving the full chain of events handling/analysis
- Electronic detectors performance reliable and well understood
- A systematic decay search was started on all 2008 (and then 2009) events in order to find all possible decay topologies
- Several charm events found as expected
- Global analysis well in progress, ongoing studies on kinematics and hadronic interactions
- The 2010 run will start soon. Hoping to achieve nominal CNGS performance
- No tau signal yet, stay tuned “estote parati” !!!
SPARES
Scanning efficiency (single emulsion film base-track reconstruction efficiency) with different methods (oil immersion objectives, dry objectives)

Parametrizations taken into account at the simulation level
Example of decay search procedure with recovery of the vertex topology

Charged charm candidate with one prong not reconstructed or hadronic interaction (large angle)?

For this particular event an unforeseen extra handle allows to clarify its nature: the decay vertex is just at the surface of the downstream lead plate, nuclear fragments backscattered are visible in the emulsion upstream

→ It is an hadronic interaction and not a charm
Finalization of events selection and validation of the background from external neutrino interactions in the soft NC candidates sample

Event categories

Soft NC BCK

Space distribution of soft NC sample:
Data, Total MC, External Bck MC

Contamination due to interactions of neutrals produced in neutrino interactions external to the target (about 200 events for 2009) affects NC/CC ratio
Visible NC/CC takes into account:

- NC/CC true ratio (0.3)
- Target interactions sele. Eff. (OpCarac)
- Muon ID efficiencies
- Events migrations due to misidentification CC↔NC

Visible NC/CC full target:
MC: NC/CC = 21.7%
Data: NC/CC = 28.3%

- NC excess in data described by MC when including BCK due to external interactions:
  → MC including external BCK full simulation 27.1%

- Full MC well reproduces BCK reduction and NC/CC ratio by cutting harder on the fiducial volume:

Visible NC/CC fid. Volume:
Data 2008: NC/CC = 0.230 ± 0.014 (stat.)
Data 2009: NC/CC = 0.230 ± 0.009 (stat.)
MC: NC/CC = 0.236 ± 0.005 (stat.)
Automatic search for microtracks in order to compensate BT inefficiency

1st Step

VERTEX DEFINITION

2nd Step

ALL TRACKS ANALYSIS

ATTACHED TO VERTEX?

yes

no

DECAY SEARCH

IN-TRACK DECAY SEARCH

Improvement in the vertex definition and IP distribution

Background to automatic microtracks search ~0.2 %
Detection of possible kink topologies

1st Step

VERTEX DEFINITION

2nd Step

ALL TRACKS ANALYSIS

ATTACHED TO VERTEX?

yes

no

DECAY SEARCH

\[ \Delta \theta_{\text{RMS}}^{\text{kink}} = \sqrt{\sum_{i! = \text{kink}} \frac{\Delta \theta_i^2}{(\Delta npl)_i} / (N - 1)} \]

Compare the kink angle to average angular deviations due to MCS, cut at 3 (example on 30 events)
Tracks not attached to primary vertex:

Evaluation of IP vs DZ

Sample cleaning

**Decay Search Procedure**

- Stopping tracks downstream the vertex
- Cut on IP as a function of $\Delta Zeta$
- Extend selected tracks searching for microtracks in upstream plates (tool already developed in Naples)
- Reject tracks with $N_{seg} \leq 2$
- Cut on $\Delta Zeta < 6000 \mu$m
- Identification of $e^+e^-$ pairs by manual check

**Selection:** 95% of signal
Test beam data samples of pions and several MC samples were produced and used for the development of the method. Very detailed results are given and should be considered as reference ones for further MCS investigations.

Ref: OPERA internal note #92
**Gamma/electrons**

- Gamma attachment to primary/secondary vertices (tau → rho)

By extrapolating the first base-track of the shower

![Gamma shower](image)

**Vertex position**

![Efficiency of gamma attachment](image)

Purely attachment efficiency (does not include the probability that the gamma converts in the volume scan)
Data vs MC for $\gamma$ reconstruction

Comparison data/MC for the Gamma multiplicity in $\mu$ CC+NC events

Volume scan of 20 plates downstream vertex and area of 1 cm$^2$