The OPERA Experiment

Latest Results

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Neutrino Oscillations

Neutrino oscillation in **disappearance** mode:

- **First observation:** SK, MACRO...
- **Further studies:** SNO, MINOS, KamLAND, Borexino...

Neutrino oscillation in **appearance** mode:

- Observation needed to establish the picture of neutrino oscillations

**Solar scale:**

- $\nu_e \rightarrow \nu_\mu$: Below threshold for $\mu$ production

**Atmospheric scale:**

- $\nu_\mu \rightarrow \nu_e$: Sub-leading (T2K, OPERA)
- $\nu_\mu \rightarrow \nu_\tau$: $\nu_\mu$ from cosmic rays (SK: statistical analysis, large BG)
- $\nu_\mu \rightarrow \nu_\tau$: $\nu_\mu$ from long-baseline beams

**OPERAS:** $\tau$ lepton identification on an event-by-event basis
The OPERA Experiment

The OPERA experiment in the CERN to Gran Sasso neutrino beam, JINST 4 (2009) P04018
The OPERA Experiment

OPERA: Oscillation Project with Emulsion Tracking Apparatus

- Appearance search: Direct observation of $\nu_\mu \rightarrow \nu_\tau$ oscillations
detection of $\tau$ production & decay

▷ Characteristic 'kink' topology:

- $\nu$ beam: High-intensity & high-energy long-baseline $\nu_\mu$ beam
- Detector: Large target mass, high precision $\mathcal{O}(\mu m)$
- Location: Laboratori Nazionali del Gran Sasso (LNGS)
  1400 m rock coverage, 3800 m w.e.
The CNGS $\nu_\mu$ Beam

CNGS: CERN Neutrinos to Gran Sasso (2008 – 2012)

$\langle E_\nu \rangle$ \hspace{1cm} 17 GeV

\begin{align*}
\bar{\nu}_\mu / \nu_\mu & \quad \text{CC} & 2.1 \% \\
n_\nu / \nu_\mu & \quad \text{CC} & 0.89 \% \\
\bar{n}_\nu / \nu_\mu & \quad \text{CC} & 0.06 \% \\
n_\tau / \nu_\mu & \quad \text{CC} & < 10^{-4} \% \\
\text{p.o.t. (total)} & & 17.97 \times 10^{19}
\end{align*}
The OPERA Detector

Hybrid detector (ED & ECC):

- 2 identical Super Modules (SM) + VETO system
- Spectrometer: RPC & XPC, PT
- Target Area: TT, ECC bricks
The OPERA Detector

Emulsion Cloud Chamber (ECC) bricks:

- 57 × 2 AgBr nuclear emulsions on plastic bases, interleaved with 56 lead plates (∼10 X₀)
- Total: ∼150,000 × 8.3 kg  ∼1.25 kt total target mass
- Spatial / angular resolution: ∼1 μm / ∼2 mrad
Changeable Sheets (CS):

- 2 extra **nuclear emulsion sheets** per brick

Target Tracker (TT) detectors:

- **Plastic scintillator** strips (horizontal & vertical), 31 walls per SM
The OPERA Detector

Magnetic Spectrometer:

- Downstream of each target area
- **Magnets**: Iron core dipole, 1.55 T
- **RPC, XPC**: Resistive plate chambers
- **Precision Tracker (PT)**: \(\sim 10\,000\) drift tubes
Event Reconstruction

ED event reconstruction:

- **Time resolution:** $\mathcal{O}(\text{ns})$
- $\mu$ identification, charge & momentum measurement
- Hadronic shower energy reconstruction
- $\nu$ interaction brick localisation
- **Trigger:** ECC event reconstruction
ECC event reconstruction:

- **Spatial resolution**: $\mathcal{O}(\mu m)$
- 3D track segment & track reconstruction
- $\nu$ interaction **vertex localisation**
- $\tau$ decay search procedure:
  - kink angle / IP measurement, parent / daughter search...
- Momentum measurement via MCS
Oscillation Search:

\( \nu_\mu \rightarrow \nu_\tau \)

*Observation of \( \nu_\tau \) appearance in the CNGS beam with the OPERA experiment*,

*Limits on muon-neutrino to tau-neutrino oscillations induced by a sterile neutrino state obtained by OPERA at the CNGS beam*,
4 confirmed $\nu_\tau$ candidate events:
**Fully analysed data sample:** 4685 events

- **2008/09:** 1st & 2nd most probable bricks
- **2010/11/12:** 1st most probable brick
- **0μ events & 1μ events with p_μ < 15 GeV/c**

<table>
<thead>
<tr>
<th>τ decay channel</th>
<th>Signal (exp.)</th>
<th>Total BG (exp.)</th>
<th>Data (obs.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>τ → h</td>
<td>0.41 ± 0.08</td>
<td>0.033 ± 0.006</td>
<td>2</td>
</tr>
<tr>
<td>τ → 3h</td>
<td>0.57 ± 0.11</td>
<td>0.155 ± 0.030</td>
<td>1</td>
</tr>
<tr>
<td>τ → μ</td>
<td>0.52 ± 0.10</td>
<td>0.018 ± 0.007</td>
<td>1</td>
</tr>
<tr>
<td>τ → e</td>
<td>0.62 ± 0.12</td>
<td>0.027 ± 0.005</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.11 ± 0.42</strong></td>
<td><strong>0.233 ± 0.041</strong></td>
<td><strong>4</strong></td>
</tr>
</tbody>
</table>

**Observation of ν_τ appearance:**

- **p-value:** \(1.24 \times 10^{-5}\) (Fisher) / \(1.03 \times 10^{-5}\) (Likelihood)
- **No-oscillation hypothesis excluded @ 4.2σ**
First measurement of $\Delta m_{23}^2$ in appearance mode:

- $\Delta m_{23}^2 = [1.8 - 5.0] \times 10^{-3}$ eV$^2$ (Feldman & Cousins)
- $\Delta m_{23}^2 = [1.9 - 5.0] \times 10^{-3}$ eV$^2$ (Bayes)

(for $\sin^2(2\theta_{23}) = 1$ at 90% C.L.)
3 + 1 analysis (approx.):

\[ P(E) = C^2 \sin^2 \Delta_{31} + \frac{1}{2} \sin^2 2\theta_{\mu\tau} \\ + C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \Delta_{31} \\ + \frac{1}{2} C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin 2\Delta_{31} \]

Likelihood analysis:

- **\( \nu_\tau \) candidates:** 4 events
- **Expected (2-fl. + BG):**
  - 2.30 + 0.23 events (NH)
  - 2.21 + 0.23 events (IH)

▷ **New limits (FC, 90% C.L.):**
  - \( \sin^2 (2\theta_{\mu\tau}) < 0.116 \) for large \( \Delta m_{41}^2 \)
  - \( \Delta m_{41}^2 < 7.4 \times 10^{-3} \text{eV}^2 \) (NH)
  - \( \Delta m_{41}^2 < 5.2 \times 10^{-3} \text{eV}^2 \) (IH)
  - for maximal mixing
Control Sample: Charmed Particle Decays

*Procedure for short-lived particle detection in the OPERA experiment and its application to charm decays,*
Main BG to $\tau$ search:

- $\nu_\mu$ CC interactions with charm production

- Topology similar to $\tau$ decay
- $\mu$ at 1rny vertex

Other BG:

- Hadronic re-interactions in lead
- Large-angle $\mu$ scattering
## 2008 – 2010 OPERA data:

<table>
<thead>
<tr>
<th></th>
<th>Charm (exp.)</th>
<th>BG (exp.)</th>
<th>Total (exp.)</th>
<th>Data (obs.)</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 ± 1</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><strong>Total</strong></td>
<td><strong>40 ± 3</strong></td>
<td><strong>14 ± 3</strong></td>
<td><strong>54 ± 4</strong></td>
<td><strong>50</strong></td>
</tr>
</tbody>
</table>
Oscillation Search:

$\nu_\mu \rightarrow \nu_e$

Search for $\nu_\mu \rightarrow \nu_e$ oscillations with the OPERA experiment in the CNGS beam, JHEP 1307 (2013) 004
A $\nu_e$ Event

**ECC reconstruction:**

![ECC reconstruction image]

**ED reconstruction:**

![ED reconstruction image]
Systematic $\nu_e$ Event Selection

**CS em shower hints:**
- Interpolation of 1ry vertex tracks to CS
- Expanded scan volume
- Analysis of downstream bricks

**Backgrounds:**
- $\nu_e$ from intrinsic beam contamination
- $e^+e^-$ from $\pi^0$ decays misidentified as single-$e$
- $\nu_\tau$ CC interactions with $\tau \to e$
2008 + 2009 data sample:

- 5255 $\nu$ CC interactions
  - $(5.25 \times 10^{19}$ p.o.t.)
- $\nu_e$ candidates: 19 events

Separation of signal & BG: Cuts on $E_{\nu,\text{rec}}$

- 3-flavour oscillations: $E_{\nu,\text{rec}} < 20$ GeV
- Nonstandard oscillations: $E_{\nu,\text{rec}} < 30$ GeV
Oscillation Analysis

3-flavour: \[ P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2 (\Delta m_{23}^2 \frac{L}{4E}) \]

- $\nu_e$ candidates: 4 events
- Expected BG + signal: 4.6 + 1.0 events

▷ Compatible with no-oscillation hypothesis:
\[ \sin^2(2\theta_{13}) < 0.44 \quad (90\% \text{ C.L.}) \]

Nonstandard: \[ P_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta_{\text{new}}) \cdot \sin^2(1.27 \cdot \Delta m_{\text{new}}^2 \frac{L[\text{km}]}{E[\text{GeV}]}) \]

- $\nu_e$ candidates: 6 events
- Expected BG: 9.4 events

▷ New limits (Bayes, 90\% C.L.):
\[ \sin^2(2\theta_{\text{new}}) < 7.2 \times 10^{-3} \]
for $\Delta m_{\text{new}}^2 > 0.1 \text{ eV}^2$
Conclusion & Outlook
Conclusion & Outlook

Oscillation Search: $\nu_\mu \rightarrow \nu_\tau$

- 4 $\nu_\tau$ candidate events observed (0.23 BG events expected)
- **Observation of $\nu_\tau$ appearance @ 4.2$\sigma$**
- First measurement of $\Delta m_{23}^2$ in appearance mode
- **Non-standard analysis:** New limits on $\Delta m_{41}^2$ vs. $\sin^2(2\theta_{\mu\tau})$

Outlook:
- **Improvements:** Data sample, statistical methods, knowledge of BG...

Oscillation Search: $\nu_\mu \rightarrow \nu_e$

- **3-flavour analysis:** Compatible with no-oscillation hypothesis
- **Non-standard analysis:** New limits on $\Delta m_{new}^2$ vs. $\sin^2(2\theta_{new})$

Outlook:
- **Improvements:** Data sample, energy reconstruction...
Thank you for your attention!

11 countries, 28 institutes, 140 physicists...

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