Recent results from the OPERA experiment

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University of Hamburg
## The Collaboration

~140 physicists, 28 institutions, 11 countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td>IIHE-ULB Brussels</td>
</tr>
<tr>
<td>Croatia</td>
<td>IRB Zagreb</td>
</tr>
<tr>
<td>France</td>
<td>LAPP Annecy IPHC Strasbourg</td>
</tr>
<tr>
<td>Germany</td>
<td>Hamburg</td>
</tr>
<tr>
<td>Israel</td>
<td>Technion Haifa</td>
</tr>
<tr>
<td>Italy</td>
<td>LNGS Assergi Bari</td>
</tr>
<tr>
<td></td>
<td>LNF Frascati</td>
</tr>
<tr>
<td></td>
<td>L’Aquila Naples</td>
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<td></td>
<td>Padova Rome Salerno</td>
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<tr>
<td>Japan</td>
<td>Aichi Toho Kobe Nagoya Nihon</td>
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<td>Korea</td>
<td>Jinju</td>
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<tr>
<td>Russia</td>
<td>INR RAS Moscow LPI RAS Moscow</td>
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<td>ITEP Moscow SINP MSU Moscow</td>
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<td></td>
<td>JINR Dubna</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Bern</td>
</tr>
<tr>
<td>Turkey</td>
<td>METU Ankara</td>
</tr>
</tbody>
</table>
Overview

The OPERA Experiment

$\nu_\tau$ Candidates

$\nu_e$ Analysis

Outlook
The OPERA Experiment

$\nu_\tau$ Candidates
$\nu_e$ Analysis
Outlook
Long baseline neutrino oscillation experiment

Very pure $\nu_\mu$ beam from CERN to LNGS

Goal:

Observation of $\nu_\tau$ appearance
CERN Neutrinos to Gran Sasso Beam

**Beam Characteristics:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>p.o.t./year</td>
<td>$4.5 \times 10^{19}$</td>
</tr>
<tr>
<td>$&lt;E_\nu&gt;$</td>
<td>17 GeV</td>
</tr>
<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>$\bar{\nu}<em>\mu/\nu</em>\mu$</td>
<td>2.0% *</td>
</tr>
<tr>
<td>$\nu_\tau/\nu_\mu$</td>
<td>negligible ($\sim 10^{-7}$)</td>
</tr>
</tbody>
</table>

*Interaction rates at LNGS

1.7% oscillation to $\tau$
• Goal: Direct observation of $\nu_\tau$ in $\nu_\mu$ beam

\[ \nu_\mu \rightarrow \nu_\tau \rightarrow \tau^- + X \]

Oscillation

CC- interaction

$\tau$ decay

\[ \begin{align*}
\mu^- & \quad \nu_\tau \quad \bar{\nu}_\mu & \quad 17.4 \% \\
h^- & \quad \nu_\tau \quad \text{neutrals} & \quad 52.5 \% \\
e^- & \quad \nu_\tau \quad \bar{\nu}_e & \quad 17.8 \% \\
\text{h}^+\text{h}^-\text{h}^- & \quad \nu_\tau \quad \text{neutrals} & \quad 12.3 \%
\end{align*} \]

• OPERA has to look for this special topology
Most important background processes:

- Charm production and decay
- Hadron re-interactions in lead
- Large-angle muon scattering in lead (LAS)

Use Emulsion Cloud Chambers (ECC) to achieve a high enough spatial resolution and density.
The OPERA Brick

- Sandwich of 56 Pb sheets (1mm) + emulsions
- High spatial resolution (track: $\sigma_x \approx 0.05\mu m$, $\sigma_\theta \approx 2\text{mrad}$, vertex: $\sigma_x \approx 1\mu m$)
- Changeable Sheets (CS) emulsion doublet for first checks

ECC = Stand-alone Detector:
- Momentum measurements for hadrons (multiple scattering)
- Pion/Muon separation at low energy (dE/dx)
- Electron identification and energy measurements for e, $\gamma$
Hybrid Detector

Emulsion Cloud Chambers
The OPERA Detector
The OPERA Detector

Super Module 1 (SM1)

Super Module 2 (SM2)
The OPERA Detector

Target Region:
- Target Tracker (Scintillator)
- Lead/Emulsion bricks (75,000 per SM)

Target mass: ~1.25 kton
The OPERA Detector

Magnetic spectrometer:
- Magnet region: Iron & RPCs
- Precision Tracker: 6 planes of drift tubes
Reconstruction (I): Magnetic Spectrometer

Electronic data (Target Tracker & Muon spectrometer)

Event: 218184565, 6 Jul 2008, 03:27 (UTC), XZ projection

Event: 218184565, 6 Jul 2008, 03:27 (UTC), YZ projection

Track identified as a muon (P=3.394 GeV/c)
Reconstruction (II): Brick Finding

Electronic data (Target Tracker)

Event: 218184565, 6 Jul 2008, 03:27 (UTC), XZ projection

Iterative process: on average 1.6 bricks involved

~1.5 m

Track identified as a muon (P=3.394 GeV/c)
Brick Manipulation System

- Bricks are automatically extracted
- Position of brick at given time is recorded in database
Emulsion Scanning

Field of view: 300µm

3D image: 16 tomographic images

44 µm emulsion sheet
Scan volume around track stopping point reconstructed in several plates

Scanned volume around interaction point $\sim 2\text{cm}^3$
Emulsion Scanning

Reject passing-through and low-energy tracks

Scanned volume around interaction point $\sim 2\text{cm}^3$
Emulsion Scanning

Identify tracks pointing to common interaction point

Scanned volume around interaction point $\sim 2\text{cm}^3$
Oscillation Analysis
Status of the Data Analysis

Run 2008 → 2012

- 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
Status of the Data Analysis

In total $18 \cdot 10^{19}$ pot $\rightarrow$ 20% less than in proposal

$\rightarrow$ 19505 neutrino interaction within target

At the point of this analysis:

- 6067 located interaction points
- 4969 completed decay searches

<table>
<thead>
<tr>
<th>Years</th>
<th>p.o.t. (x10^{19})</th>
<th>Status</th>
<th>Selected Data sample</th>
<th># of Decay Searched events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008-2009</td>
<td>5.27</td>
<td>Completed</td>
<td>mutli-bricks + all P_\mu</td>
<td>2783</td>
</tr>
<tr>
<td>2010-2011-2012</td>
<td>12.7</td>
<td>In progress</td>
<td>1 brick + P_\mu &lt; 15 GeV</td>
<td>2186</td>
</tr>
<tr>
<td>Total</td>
<td>18.0</td>
<td></td>
<td>~64%</td>
<td>4969</td>
</tr>
</tbody>
</table>
Charm Hadron Production

Topology similar to $\tau$-decay (decay modes and lifetime) but with $\mu$ at primary vertex $\rightarrow$ good control sample
Charm Hadron Production

2008-2010 data analysis:

<table>
<thead>
<tr>
<th>prong</th>
<th>charm</th>
<th>background</th>
<th>expected</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 prong</td>
<td>20 ± 3</td>
<td>9 ± 3</td>
<td>29 ± 4</td>
<td>19</td>
</tr>
<tr>
<td>2 prong</td>
<td>15 ± 2</td>
<td>3.8 ± 1.1</td>
<td>19 ± 2</td>
<td>22</td>
</tr>
<tr>
<td>3 prong</td>
<td>5 ± 1</td>
<td>1.0 ± 0.3</td>
<td>6 ± 1</td>
<td>5</td>
</tr>
<tr>
<td>4 prong</td>
<td>0.8 ± 0.2</td>
<td>-</td>
<td>0.8 ± 0.2</td>
<td>4</td>
</tr>
<tr>
<td>All</td>
<td>41±4</td>
<td>14±3</td>
<td>55±5</td>
<td>50</td>
</tr>
</tbody>
</table>

Background mainly from hadronic interaction
Charm Hadron Production

2008-2010 data analysis:

Kolmogorov test > 0.99 for all plots
Overview

The OPERA Experiment

$\nu_\tau$ Candidates

$\nu_e$ Analysis

Summary/Outlook
1st $\tau$ Candidate

Electronic Detector View:

Event: 9234119599, 22 Aug 2009, 19:27 (UTC), $XZ$ projection

Event: 9234119599, 22 Aug 2009, 19:27 (UTC), $YZ$ projection

(Date: 22 August 2009, 19:27 (UTC))
1st $\nu$τ Candidate

Electronic Detector View:

Event: 9234119599, 22 Aug 2009, 19:27 (UTC), XZ projection

Event: 9234119599, 22 Aug 2009, 19:27 (UTC), YZ projection

(Date: 22 August 2009, 19:27 (UTC))
From CS to Vertex Localisation

- CS prediction

Brick 72693

\[ x^{10^3} \]

\[ 120 \]

\[ 100 \]

\[ 80 \]

\[ 60 \]

\[ 40 \]

\[ 20 \]

\[ 0 \]

\[ -20 \]

\[ -20 \]

\[ 0 \]

\[ 20 \]

\[ 40 \]

\[ 60 \]

\[ 80 \]

\[ 100 \]

\[ 120 \]

\[ 140 \]

\[ 10^3 \]

\[ X (\mu m) \]

\[ Y (\mu m) \]
From CS to Vertex Localisation
From CS to Vertex Localisation

Scan-back in ECC
From CS to Vertex Localisation

Scan-back in ECC

Kink detection

200 um
From CS to Vertex Localisation

Large-area scan, full reconstruction of vertices and \( \gamma \)
Reconstructed 1st $\nu_\tau$ Candidate

$\tau^- \rightarrow \rho^- \nu_\tau$

$\rho^- \rightarrow \pi^0\pi^-$

$\pi^0 \rightarrow \gamma \gamma$

Characteristics of Decay Topology

Red regions: Measured values for $\nu_\tau$ candidate

- Decay length
- Daughter momentum
- Kink angle

Cut values:
- Decay length: reject < 20 mrad
- Kink angle: reject < 20 mrad
Kinematical Cuts to be Passed

Reject NC events with larger missing $P_t$ (neutrino)

Reject hadron re-interactions
Pt Characteristics

**Signal:** $\phi = 180^\circ$

- $\tau$-decay

$\nu_\tau N \rightarrow \tau X$

**BG:** small $\phi$

- kink

$\nu_\mu N \rightarrow \nu_\mu \pi X$

**Transverse momentum**

- Hadrons
- Parent

$172.6^\circ$

**NC (MC)**

- $\tau$ (MC)

**Cut**

<table>
<thead>
<tr>
<th>Entries</th>
<th>23074</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.445</td>
</tr>
<tr>
<td>RMS</td>
<td>0.7382</td>
</tr>
</tbody>
</table>
2nd $\nu_\tau$ Candidate

Event: 11113019758, 23 Apr 2011, 07:15 (UTC), XZ projection

Event: 11113019758, 23 Apr 2011, 07:15 (UTC), YZ projection
$\tau \rightarrow 3h \, \nu_\tau$
• Nuclear fragments visible as short highly ionizing tracks

• Give additional information for background reduction
2nd $\nu_\tau$ Candidate

**Phi angle**
- Mean: $136.7 \pm 1.664$
- RMS: $43.65 \pm 1.177$

**Average kink angle**
- Mean: $0.1709 \pm 0.00351$
- RMS: $0.0955 \pm 0.002482$

**Daughter Momentum**
- Mean: $8.224 \pm 0.1617$
- RMS: $4.4 \pm 0.1143$

**Minimum Invariant Mass**
- Mean: $1.636 \pm 0.01661$
- RMS: $0.4523 \pm 0.01175$

**Invariant Mass**
- Mean: $1.096 \pm 0.009202$
- RMS: $0.2504 \pm 0.006506$

**Transverse Momentum at 1ry vtx**
- Mean: $0.7198 \pm 0.01867$
- RMS: $0.5122 \pm 0.0132$
Muon momentum: $2.8 \pm 0.2$ GeV/c from range
Consistent with MCS in bricks 3.1 [2.6, 4.0] GeV/c
Charge Determination of $\mu$

Parabolic fit of RPC hits: $X(z)=p_0+p_1 \cdot x \cdot (z-z_0)+p_2 \cdot x \cdot (z-z_0)^2$

Together with linear fit of TT hits: $X(z)=p_0+p_1 \cdot x \cdot (z-z_0)$

$p_2<0 \rightarrow$ negative charge

5.6 $\sigma$ significance

$R \sim 85$ cm
3rd $\nu_\tau$ Candidate

$\tau \rightarrow \mu$ decay

$\gamma$ attached to primary vertex
3rd $\nu_\tau$ Candidate

Decay in the plastic base
Nature of Track 2

- Stops in downstream brick without visible charged particles
- Range vs. momentum inconsistent with muon hypothesis

\[ D = \frac{L}{R_{lead}(p) \rho_{lead} / \rho_{average}} \]

- \( L \) = track length
- \( R_{lead} = \mu \) range
- \( \rho_{average} = \) average density
- \( \rho_{lead} = \) lead density
- \( p = \) momentum in emulsion
3rd $\nu_\tau$ Candidate

**PHI ANGLE**

- $\tau \rightarrow \mu$ MC
- $\tau \rightarrow \mu$ candidate

**KINK ANGLE**

**MUON MOMENTUM**

**DECAY LENGTH**

**TRANSVERSE MOMENTUM AT 2RY VTX**
$\nu_\mu \rightarrow \nu_\tau$ Analysis Overview

Subsample corresponding to 64% of total expectation:
(2008-2009 & selected 2010-2012 sample)

→ 3 events observed vs. 0.23 events bkg.
→ $p$-value for bgk-fluctuation: $7.3 \cdot 10^{-4}$

→ No-oscillation hypothesis excluded at 3.2 $\sigma$

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>expected signal events $\Delta m^2 = 2.32 \times 10^{-3} \text{ eV}^2$</th>
<th>PRELIMINARY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full sample 18$ \times 10^{19}$ p.o.t.</td>
<td>Analysed sample</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu$</td>
<td>0.90</td>
<td>0.56</td>
</tr>
<tr>
<td>$\tau \rightarrow e$</td>
<td>1.06</td>
<td>0.49</td>
</tr>
<tr>
<td>$\tau \rightarrow h$</td>
<td>0.70</td>
<td>0.66</td>
</tr>
<tr>
<td>$\tau \rightarrow 3h$</td>
<td>0.99</td>
<td>0.51</td>
</tr>
<tr>
<td>Total</td>
<td>3.65</td>
<td>2.22</td>
</tr>
</tbody>
</table>
Overview

The OPERA Experiment

ντ Candidates
νe Analysis

Summary/Outlook
\( \nu_e \) Appearance Analysis
\( \nu_e \) Appearance Analysis

2008+2009 sample (5.25 x 10^{19} \text{ p.o.t.})
\[ \rightarrow \] Observed 19 \( \nu_e \) events
2008+2009 sample \((5.25 \times 10^{19} \text{ p.o.t.})\)
→ Observed 19 \(\nu_e\) events

**Expected \(\nu_e\) events:**
- \(\nu_e\) beam contamination \(19.4 \pm 2.8\)
- Background: \(\tau \rightarrow e\)
  + misidentified \(\pi_0\) \(0.5 \pm 0.2\)

From 3-flavour oscillation:
\(\nu_\mu \rightarrow \nu_e\) 1.4 events \((\sin^2(2\theta_{13}) = 0.098)\)
ν_e Appearance Analysis

2008+2009 sample (5.25 x 10^{19} p.o.t.) → Observed 19 ν_e events

→ compatible with non-oscillation hypothesis

Expected ν_e events:
- ν_e beam contamination 19.4 ± 2.8
- Background: τ → e  
  + misidentified π_0 0.5 ± 0.2

From 3-flavour oscillation:
ν_µ → ν_e 1.4 events (sin^2(2θ_{13}) = 0.098)
$\nu_e$ Appearance Analysis

![Graph showing number of events vs reconstructed energy with different categories of backgrounds and signal.

- Oscillated $\nu_e$ by 3 flavor oscillation
- $\nu_e$ beam contamination
- BG from $\tau \rightarrow e$
- BG from NC with $\pi^0$

Data points plotted with error bars for each category.
\( \nu_e \) Appearance Analysis

For optimal signal-to-background ratio: \( E < 20 \text{ GeV} \)

\[ \rightarrow 4 \text{ events observed vs. 4.6 bkg expected} \]

\[ \rightarrow \sin^2(2\theta_{13}) < 0.44 \text{ @ 90\% CL} \]

(3-flavour analysis)
Search for non-standard oscillations with larger $\Delta m^2$

$\sin^2(2\theta_{\text{new}}) < 7.2 \cdot 10^{-3}$

30 GeV energy cut $\Rightarrow S/N = 6/9.4$

1-flavour analysis

JHEP07 (2013) 004
arXiv:1303.3953
Overview

The OPERA Experiment

$\nu_\tau$ Candidates
$\nu_e$ Analysis

Summary/Outlook
\( \nu_\tau \) appearance:
- 3 events observed
- Conservative background estimation
  \( \rightarrow \) no-oscillation hypothesis excluded at 3.2 \( \sigma \)
- Likelihood analysis slightly increases the significance
- Improved background studies under way
  \( \rightarrow \) 4 \( \sigma \) in reach

\( \nu_e \) appearance:
- No oscillation observed
  \( \rightarrow \) restrict parameter space for large \( \Delta m^2 \) significantly

Analysis ongoing, some interesting events under investigation
Thank you for your attention!
Backup slides
Impact Parameter

- Impact Parameter
- $\nu_\tau$ events (MC)
- NC+CC $\nu_\mu$ events (MC)
- NC+CC $\nu_\mu$ events (Data)
Expected Performance (Proposal)

Assumptions: Maximal mixing, $22.5 \times 10^{19} \text{p.o.t.}$ (5 years @ $4.5 \times 10^{19} \text{p.o.t./year}$)

<table>
<thead>
<tr>
<th>$\tau$ Decay Channel</th>
<th>B.R. (%)</th>
<th>Signal</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><strong>Total</strong></td>
<td></td>
<td><strong>10.4</strong></td>
<td><strong>0.75</strong></td>
</tr>
</tbody>
</table>

Expected Events:
- $\sim 23600 \ \nu_\mu$ CC+NC interactions
- $\sim 520 \ \nu_\mu$ interactions
- $\sim 205 \ \nu_e + \bar{\nu}_e$ interactions
- $\sim 115 \ \nu_\tau$ CC interactions

For full mixing and $\Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2$ (scales with $(\Delta m^2)^2$).
Emulsion Scanning

The frames correspond to the scanning area:
- Yellow short lines: Measured tracks
- Other colored lines: Interpolation or extrapolation

Vertex reconstruction & kinematical analysis
Brick Location Efficiency

\[ E_{\text{loc}}, \text{with MB analysis} \]

2008-2009 control sample

- 0 \( \mu \) data
- 1 \( \mu \) data

0 \( \mu \) MC sys. = (10-20)%

1 \( \mu \) MC sys. = 10%
**Status of data analysis**

6423 located interactions (5229 in Annecy, +1200 in 12 months)

5675 decay search (4294, +1381 in 12 months)

- Recovery of “lost” events
- At plateau
- First brick analysis completed
- Boost in the decay search

03/12/2013

Giovanni De Lellis, Gran Sasso Collaboration Meeting