Latest results on $\nu_\mu \rightarrow \nu_\tau$ oscillations from the OPERA experiment

On behalf of the OPERA collaboration
M. Komatsu – Nagoya University
Neutrino oscillation in appearance

- Atmospheric neutrino oscillation has been mostly studied through its disappearance.
- Both in atmospheric and accelerator experiments.
  - Super-KAMIOKANDE, MACRO and Soudan-2
    - SK reported tau appearance in statistical basis.
    - MINOS, K2K and T2K ....

- OPERA is designed to observe $\nu_\mu \to \nu_\tau$ oscillations in appearance mode.
  - Tau lepton identification on an event by event basis.

- The neutrino appearance is a key observation to establish neutrino oscillation.
OPERA Collaboration

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

Japan
Aichi
Toho
Kobe
Nagoya
Nihon

Korea
Jinju

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

Switzerland
Bern

Turkey
METU, Ankara

http://operaweb.lngs.infn.it/
High energy neutrino
- $<E_\nu> \sim 17$ GeV (tau neutrino CC cross section above 3.5 GeV)

Long baseline
- $L=732$ km

High energy beam optimized to maximize tau neutrino interactions
- $P(\nu_\mu \to \nu_\tau) \sim 1\%$
Key technology for tau neutrino detection

- Micrometric accuracy in kilotons of detector.
- Highly modular structure ECC (Emulsion Cloud Chamber)
  - The only one detector which directly observed tau neutrino interaction in DONUT experiment.
**OPERA ECC brick**

- **ECC properties**
  - 56 of 1mm thick lead plates interleaved with 57 emulsion films.
  - 8.3kg / brick
  - 10 radiation length

- **150,000 ECC bricks**
  - 1.25 ktons
  - 9 million films

- **Capability**
  - Micrometric accuracy vertex analysis
  - Kinematical analysis
    - Momentum measurement by MCS.
    - EM energy measurement
OPERA detector

• 150,000 ECC bricks = 1.25 ktons of active target
Collected data

<table>
<thead>
<tr>
<th>Year</th>
<th>P.O.T. (10^{19})</th>
<th>SPS Eff.</th>
<th>Beam days</th>
<th>ν interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>1.74</td>
<td>61%</td>
<td>123</td>
<td>1931</td>
</tr>
<tr>
<td>2009</td>
<td>3.53</td>
<td>73%</td>
<td>155</td>
<td>4005</td>
</tr>
<tr>
<td>2010</td>
<td>4.09</td>
<td>80%</td>
<td>187</td>
<td>4515</td>
</tr>
<tr>
<td>2011</td>
<td>4.75</td>
<td>79%</td>
<td>243</td>
<td>5131</td>
</tr>
<tr>
<td>2012</td>
<td>3.86</td>
<td>82%</td>
<td>257</td>
<td>3923</td>
</tr>
<tr>
<td>Total</td>
<td>17.97</td>
<td>77%</td>
<td>965</td>
<td>19505</td>
</tr>
</tbody>
</table>

80% of the design

- **Analysis strategy**
  - 2008-2009: 1st and 2nd probable brick
  - 2010-2012: 1st brick only
    - Analysis will be extended.
Status of ongoing data analysis

Run 2008 → 2012

- 6636 located interactions
- 6190 decay search
Vertex location and decay search

- **Vertex location in a brick**

- **Decay search**
  - Impact parameter
  - Kink search
  - Parent search

arXiv:1404.4357v1
Decay search control sample

- Charm decay has similar topology as tau decay
- Muon at the interaction point

<table>
<thead>
<tr>
<th>Track Type</th>
<th>Charm Events</th>
<th>Background Events</th>
<th>Expected Events</th>
<th>Observed Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 prong</td>
<td>$21 \pm 2$</td>
<td>$9 \pm 3$</td>
<td>$30 \pm 4$</td>
<td>19</td>
</tr>
<tr>
<td>2 prong</td>
<td>$14 \pm 1$</td>
<td>$4 \pm 1$</td>
<td>$18 \pm 2$</td>
<td>22</td>
</tr>
<tr>
<td>3 prong</td>
<td>$4 \pm 1$</td>
<td>$1.0 \pm 0.3$</td>
<td>$5 \pm 1$</td>
<td>5</td>
</tr>
<tr>
<td>4 prong</td>
<td>$0.9 \pm 0.2$</td>
<td>-</td>
<td>$0.9 \pm 0.2$</td>
<td>4</td>
</tr>
<tr>
<td>All</td>
<td>$40 \pm 3$</td>
<td>$14 \pm 3$</td>
<td>$54 \pm 4$</td>
<td>50</td>
</tr>
</tbody>
</table>

54±4 charm events expected
50 observed in control sample

Good agreement between data and MC.

arXiv:1404.4357v1
Oscillation analysis

<table>
<thead>
<tr>
<th>RUN</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>PoT (10^{19})</td>
<td>1.74</td>
<td>3.53</td>
<td>4.09</td>
<td>4.75</td>
<td>3.86</td>
<td>17.97</td>
</tr>
<tr>
<td>0_\mu events</td>
<td>148</td>
<td>250</td>
<td>209</td>
<td>223</td>
<td>149</td>
<td>979</td>
</tr>
<tr>
<td>1_\mu events (p_\mu&lt;15\text{GeV/c})</td>
<td>534</td>
<td>1019</td>
<td>814</td>
<td>749</td>
<td>590</td>
<td>3706</td>
</tr>
<tr>
<td>Total</td>
<td>682</td>
<td>1269</td>
<td>1023</td>
<td>972</td>
<td>739</td>
<td>4685</td>
</tr>
</tbody>
</table>

- Data sample
  - 2008-2009: 1\text{st} and 2\text{nd} probable brick
  - 2010-2012: 1\text{st} probable brick
  - In total 4685 events for oscillation analysis
    - 5520 events including charm control sample
- Expected 2.1\pm0.4
  - \(\delta m_{23}^2 = 2.32 \times 10^{-3} \text{eV}^2\), \(\theta_{23} = \pi/4\)
- Observed 4 events

ICHEP 2-9 July 2014

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New event (4\textsuperscript{th} $\nu_\tau$ event)

Track “2” from neutrino interaction vertex, $p = 1.9$ GeV/c stopping in first iron slab of the magnet

$D < 0.8$ : hadron
**Properties**

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\tau \rightarrow 1\ell$</th>
<th>$\tau \rightarrow 3\ell$</th>
<th>$\tau \rightarrow \mu$</th>
<th>$\tau \rightarrow e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton-tag</td>
<td>No $\mu$ or $e$ at the primary vertex</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$z_{\text{dec}}$ ($\mu$m)</td>
<td>$[44, 2600]$</td>
<td>$&lt; 2600$</td>
<td>$[44, 2600]$</td>
<td>$&lt; 2600$</td>
</tr>
<tr>
<td>$p_{T}^{\text{miss}}$ (GeV/c)</td>
<td>$&lt; 1^*$</td>
<td>$&lt; 1^*$</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>$\phi_{HH}$ (rad)</td>
<td>$&gt; \pi/2^*$</td>
<td>$&gt; \pi/2^*$</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>$p_{T}^{2\text{rv}}$ (GeV/c)</td>
<td>$&gt; 0.6(0.3)^*$</td>
<td>$&gt; 1$ and $&lt; 15$</td>
<td>$&gt; 1$ and $&lt; 15$</td>
<td>$&lt; 2600$</td>
</tr>
<tr>
<td>$p_{T}^{2\text{rv}}$ (GeV/c)</td>
<td>$&gt; 2$</td>
<td>$&gt; 3$</td>
<td>$&gt; 20$</td>
<td>$&gt; 20$</td>
</tr>
<tr>
<td>$\theta_{\text{kink}}$ (mrad)</td>
<td>$&gt; 20$</td>
<td>$&lt; 500$</td>
<td>$&gt; 20$</td>
<td>$&gt; 20$</td>
</tr>
<tr>
<td>$m, m_{\text{min}}$ (GeV/c²)</td>
<td>/</td>
<td>$&gt; 0.5$ and $&lt; 2$</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

**Kinematical selection cuts kept fixed from beginning.**

**Values**

- **Kink angle (mrad)**: $137 \pm 4$ (cut > 20)
- **Decay position ($\mu$m)**: $406 \pm 30$ (cut $< 2600$)
- **$P_{\text{daughter}}$ (GeV/c)**: $6.0^{+2.2}_{-1.2}$ (cut $> 2$)
- **$P_{T}$ (GeV/c)**: $0.82^{+0.30}_{-0.16}$ (cut $> 0.6$)
- **$P_{T}^{\text{miss}}$ (GeV/c)**: $0.55^{+0.30}_{-0.20}$ (cut $< 1.0$)
- **Phi (degrees)**: $166^{+2}_{-31}$ (cut $> 90$)
Summary of four events

Visible energy of all $\nu_\tau$ events. Scalar sum of momentum and $\gamma$ energies.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$p_{\text{sum}}$ (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^{\text{st}}$ $\tau \rightarrow h$</td>
<td>$24.3^{+6.1}_{-3.2}$</td>
</tr>
<tr>
<td>$2^{\text{nd}}$ $\tau \rightarrow 3h$</td>
<td>$12.7^{+2.3}_{-1.7}$</td>
</tr>
<tr>
<td>$3^{\text{rd}}$ $\tau^- \rightarrow \mu^-$</td>
<td>$6.8^{+0.9}_{-0.6}$</td>
</tr>
<tr>
<td>$4^{\text{th}}$ $\tau \rightarrow h$</td>
<td>$14.4^{+3.9}_{-2.7}$</td>
</tr>
</tbody>
</table>
Background to ICHEP 2

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

MC tuned on CHORUS data (cross section and fragmentation functions), validate with measured charm events (CNGS)

Reduced by Track Follow-down procedure

Hadronic interactions in lead:

Bck. to $\tau \rightarrow h$

FLUKA + test beam data (OPERA bricks exposed to pion beams)

Reduced by large angle scanning and nuclear fragment search

or to $\tau \rightarrow \mu$

Suppressed by track follow-down procedure

(if hadron misid or mismatched with muon)

Coulomb large angle scattering of muons in lead

Bck. to $\tau \rightarrow \mu$

MC tuned on old measurements on lead form factor + dedicated test beam (in progress)
Significance

2008/09 : 398 (0μ events) + 1553 (1μ events with \( P_\mu < 15 \text{ GeV/c} \))
2010/11/12 : 581 (0μ events) + 2153 (1μ events with \( P_\mu < 15 \text{ GeV/c} \))

The expected signal and background is normalized to the number of analyzed events

\[
n^0\mu(\nu^C \nu)^C = \frac{\langle \sigma(\nu^C \nu) \rangle}{\langle \sigma(\nu^C \nu) \rangle} \frac{\langle \epsilon^0\mu(\nu^C \nu) \rangle}{\langle \epsilon^0\mu(\nu^C \nu) \rangle + \alpha \langle \epsilon^0\mu(\nu^C \nu) \rangle} n^0\mu \quad \alpha = \frac{NC}{CC}
\]

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Expected signal ( \Delta m_{23}^2 = 2.32 \text{ meV}^2 )</th>
<th>Total background</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau \rightarrow h )</td>
<td>0.41 ± 0.08</td>
<td>0.033 ± 0.006</td>
<td>2</td>
</tr>
<tr>
<td>( \tau \rightarrow 3h )</td>
<td>0.57 ± 0.11</td>
<td>0.155 ± 0.030</td>
<td>1</td>
</tr>
<tr>
<td>( \tau \rightarrow \mu )</td>
<td>0.52 ± 0.10</td>
<td>0.018 ± 0.007</td>
<td>1</td>
</tr>
<tr>
<td>( \tau \rightarrow e )</td>
<td>0.62 ± 0.12</td>
<td>0.027 ± 0.005</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>2.11 ± 0.42</td>
<td>0.233 ± 0.041</td>
<td>4</td>
</tr>
</tbody>
</table>

**Two statistical methods**
- p-value = 1.24 x 10^{-5} : Fisher combination
- p-value = 1.03 x 10^{-5} : Likelihood ratio

no oscillations excluded at 4.2 \( \sigma \) CL
First measurement of $\Delta m_{32}^2$ with tau appearance

\[
N_{\nu_t} \propto \int \phi(E) \sin^2 \left( \frac{\Delta m_{32}^2 L}{4E} \right) \epsilon(E) \sigma(E) dE
\]

\[
\propto (\Delta m_{32}^2)^2 L^2 \int \phi(E) \epsilon(E) \frac{\sigma(E)}{E^2} dE
\]

90% CL intervals assuming $\sin^2(2\theta)=1$.

- **Feldman&Cousin**
  - $[1.8 - 5] \times 10^{-3}$ eV$^2$

- **Bayesian**
  - $[1.9 - 5] \times 10^{-3}$ eV$^2$

**OPERA Off-peak**

$L/\langle E \rangle \sim 43$ Km/GeV

$(L/\langle E \rangle)_{\text{peak}} \sim 500$ Km/GeV

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Conclusion

- OPERA has recorded neutrino interactions equivalent to $\sim 1.8 \times 10^{20}$ pot delivered by CNGS beam from 2008 to 2012 (80% of design).
- 4 $\nu_\tau$ events observed with 0.23 background.
- No oscillation hypothesis excluded at 4.2 $\sigma$.

**Observation of $\nu_\tau$ appearance**

- First measurement of $\Delta m^2_{32} = [1.8 - 5.0] \times 10^{-3}$ eV$^2$ (90% CL) for $\sin^2(2\theta_{23}) = 1$ in appearance mode.
Stay tuned

- Measurement of the TeV atmospheric muon charge ratio with the full OPERA data set (5\textsuperscript{th} July)
- Search for $\nu_\mu \rightarrow \nu_e$ oscillations with the OPERA experiment in the CNGS beam (Poster)
- Search procedure for short-lived particles and charm physics with the OPERA experiment (Poster)
Backup
OPERA-CNGS roadmap

- 1998: Approval
- 2000: End of civil engineering
- 2002: End of construction
- 2004: Commissioning
- 2006: Ele-det only
- 2008: 60000 bricks
- 2009: 150000 bricks
- 2010
- 2011
- 2012
- 2013
- 2014

L = 732 km

Gran Sasso

CNGS RUN

Today!

τ → h

τ → 3h

μ → h

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Other three events
1st $\nu_\tau$ candidate ($\tau \to h$) (2010)

$\tau \to \rho \nu_\tau$ candidate
$\rho \to \pi^-\pi^0$ ($\pi^0 \to \gamma\gamma$)

$m(\gamma\gamma) = 120 \pm 20 \pm 35$ MeV
$m(\pi^-\gamma\gamma) = 640^{+125}_{-80}^{+100}_{-90}$ MeV
Br($\tau \to \rho \nu_\tau$) $\sim 25\%$
2\textsuperscript{nd} $\nu_\tau$ candidate (2012)

($\tau \rightarrow 3h$)

Tau decay in plastic base (low density)
3rd $\nu_\tau$ candidate ($\tau \to \mu$) (2013)

First measurement of the lepton charge in appearance mode
Detail of 4\textsuperscript{th} events
### Track features

<table>
<thead>
<tr>
<th>Track ID</th>
<th>Particle ID</th>
<th>First measurement</th>
<th>Second measurement</th>
<th>Average</th>
<th>P (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1ry</td>
<td>1 parent</td>
<td>τ</td>
<td>τ</td>
<td>τ</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Hadron (Range)</td>
<td>-0.143, 0.026</td>
<td>-0.145, 0.014</td>
<td>-0.144, 0.020</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Hadron (Range)</td>
<td>-0.145, 0.014</td>
<td>-0.146, 0.020</td>
<td>-0.146, 0.020</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Hadron (interact)</td>
<td>Hadron (interact)</td>
<td>Hadron (interact)</td>
<td>Hadron (interact)</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Hadron (interact)</td>
<td>Hadron (interact)</td>
<td>Hadron (interact)</td>
<td>Hadron (interact)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>proton</td>
<td>proton</td>
<td>proton</td>
<td>0.7 [0.6, 0.8]</td>
</tr>
<tr>
<td></td>
<td>γ1</td>
<td>e-pair</td>
<td>e-pair</td>
<td>e-pair</td>
<td>0.7 [0.6, 0.9]</td>
</tr>
<tr>
<td></td>
<td>γ2</td>
<td>e-pair</td>
<td>e-pair</td>
<td>e-pair</td>
<td>4.0 [2.6, 8.7]</td>
</tr>
<tr>
<td>2ry</td>
<td>daughter</td>
<td>Hadron (Range)</td>
<td>Hadron (Range)</td>
<td>Hadron (Range)</td>
<td>Hadron (Range)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ΔZ (μm)</th>
<th>δθ_{RM} (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>21.9</td>
<td>2</td>
</tr>
<tr>
<td>γ2</td>
<td>To 1ry</td>
<td>7176</td>
<td>9.2</td>
<td>33</td>
</tr>
<tr>
<td>γ2</td>
<td>To 2ry</td>
<td>6124</td>
<td>9.2</td>
<td>267</td>
</tr>
</tbody>
</table>

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

Not a single π⁰
Measured length x density, $L\rho$

$L\rho$ for the track = 604 g/cm$^2$ (<660 g/cm$^2$)

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

- Prob. for a $\mu$ to cross $\leq 12$ planes ~ 0.35%
- Prob. for a $\pi$ to cross $\geq 12$ planes ~ 10.2%
Follow-down all tracks in downstream bricks

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

CS tracks

Transverse plane

Y (cm)

X (cm)

One rectangle: brick front size

CS analysis

- Daughter track
- Track2 (1ry)
- Track3 (1ry)
- Track4 (1ry)
## Background

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Expected signal</th>
<th>Observed</th>
<th>Expected background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
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</table>
Track follow down

For the first $\nu_\tau$ candidate we followed down all the tracks to search for possible muon not identified by the Electronic Detector

We can suppress backgrounds due to

- Charm
- Hadron interactions in $\nu_\mu$ CC with misidentified $\mu$ ($\tau \rightarrow h$ channel)
- Hadron interactions in $\nu_\mu$ CC and NC ($\tau \rightarrow \mu$ channel)

**Charm background**

**Hadron interactions background**
Classification of the tracks:
- Interaction visible in the brick
- $dE/dx$ at end point of the track for $\pi/\mu$ separation
- Momentum/Range correlation

$D = \frac{L}{R_{\text{lead}}(p)} \frac{\text{lead}}{\text{average}}$

$D = \frac{\text{track length}}{\text{moun range in lead}}$

$\rho_{\text{average}} = \text{average density along the path}$

$\rho_{\text{lead}} = \text{lead density}$

$p = \text{momentum measured in the emulsion}$

Results:
- Mis-ID muons in Charm events: $3.28\%$ (34% reduc.)
- 2 orders of magnitude reduction of hadronic background to $\tau \rightarrow \mu$ due to $\mu$ mismatch in CC and NC events
Hadron interaction background

Estimated with Fluka MC and validated with test beam data (OPERA bricks exposed to pion beams)

Background to
\[ \tau \rightarrow h = 3.09 \times 10^{-5} / \text{located events} \]
\[ \tau \rightarrow 3h = 1.5 \times 10^{-5} / \text{located events} \]

Hadron interaction rate suppressed by search of large angle tracks produced by nuclear fragments
Nuclear fragments in 1 and 3 prong interactions

Multiplicities for 2 GeV/c, 4 GeV/c, and 10 GeV/c are shown.

Error bars: experiment; Histogram: simulation.

Agreement within the statistical error: systematic error is 10%.

MC: $\beta < 0.7$
No measurements except an upper limit from scattering on Cu: S.A. Akimenko et al., NIM A243 (1986) 518 (< $10^{-5}$ in lead). $10^{-5}$ rate used

Plan to revise this number by an experimental measurement with emulsion
Oscillation Project with Emulsion tRacking Apparatus

**Detector supermodules construction:** Sept. 2003 - spring 2007

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

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

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

**BRICK WALLS**
- 2850 bricks/wall
- 53 walls

**Veto**

**ECCs**
- scint. strips

**Muon Spectrometer**

**Target Trackers**
- neutrino trigger
- brick localization

**BMS Brick Manipulator system**

**RPC + drift tubes in spectrometers:**
- muon ID,
- momentum,
- charge
## Analyzed events

<table>
<thead>
<tr>
<th>RUN</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>PoT $(10^{19})$</td>
<td>1.74</td>
<td>3.53</td>
<td>4.09</td>
<td>4.75</td>
<td>3.86</td>
<td>17.97</td>
</tr>
<tr>
<td>$0_\mu$ events</td>
<td>148</td>
<td>250</td>
<td>209</td>
<td>223</td>
<td>149</td>
<td>979</td>
</tr>
<tr>
<td>$1_\mu$ events $(p_\mu&lt;15\text{GeV/c})$</td>
<td>534</td>
<td>1019</td>
<td>814</td>
<td>749</td>
<td>590</td>
<td>3706</td>
</tr>
<tr>
<td>$1_\mu$ events $(p_\mu\geq15\text{GeV/c})$</td>
<td>286</td>
<td>549</td>
<td></td>
<td></td>
<td></td>
<td>835</td>
</tr>
<tr>
<td>Total</td>
<td>968</td>
<td>1818</td>
<td>1023</td>
<td>972</td>
<td>739</td>
<td>5520</td>
</tr>
</tbody>
</table>
Sterile neutrinos

**Tau appearance in the presence of sterile neutrino (3+1)**

Solar driven oscillation neglected $\Delta_{21} \sim 0$

$$P_{\nu_\mu \rightarrow \nu_\tau} = 4|U_{\nu_\mu}|^2|U_{\nu_\tau}|^2 \sin^2 \frac{\Delta_{31}}{2} + 4|U_{\nu_\mu}|^2|U_{\nu_\tau}|^2 \sin^2 \frac{\Delta_{41}}{2} + 2\Re[U_{\nu_\mu}^* U_{\nu_\tau} U_{\nu_\mu}^* U_{\nu_\tau}] \sin \Delta_{31} \sin \Delta_{41} - 4\Im[U_{\nu_\mu}^* U_{\nu_\tau} U_{\nu_\mu}^* U_{\nu_\tau}] \sin^2 \frac{\Delta_{31}}{2} \sin \Delta_{41} + 8\Re[U_{\nu_\mu}^* U_{\nu_\tau} U_{\nu_\mu}^* U_{\nu_\tau}] \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2} + 4\Im[U_{\nu_\mu}^* U_{\nu_\tau} U_{\nu_\mu}^* U_{\nu_\tau}] \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2}$$

Profile likelihood using ** Tau rate only**

$\Delta m^2_{32} = 2.32 \times 10^{-3} \text{eV}^2$

90% CL bounds on $U_{\tau_4}$ and $U_{\nu_4}$

**Operational Preliminary**

Two extreme values ($\pi / 2, 3\pi / 2$) of

$$\text{Arg}[U_{\nu_\mu}^* U_{\nu_\tau} U_{\nu_\mu}^* U_{\nu_\tau}]$$

**Complementarim measurement wrt disappearance experiments**
Sterile neutrinos

Choosing a particular representation

\[ U = R_{34}(\theta_{34}) R_{24}(\theta_{24}, \delta_2) R_{14}(\theta_{14}) R_{23}(\theta_{23}) R_{13}(\theta_{13}, \delta_1) R_{12}(\theta_{12}, \delta_3) \]

\[
U = \begin{bmatrix}
U_{e1} & U_{e2} & c_{14} s_{13} e^{-i \delta_1} \\
U_{\mu 1} & U_{\mu 2} & -s_{14} s_{13} e^{-i \delta_1} s_{24} e^{-i \delta_2} + c_{13} s_{23} c_{24} \\
U_{\tau 1} & U_{\tau 2} & -s_{14} c_{24} s_{34} s_{13} e^{-i \delta_1} - c_{13} s_{23} s_{34} s_{24} e^{i \delta_2} + c_{13} c_{23} c_{34} \\
U_{s 1} & U_{s 2} & -s_{14} c_{24} c_{34} s_{13} e^{-i \delta_1} - c_{13} s_{23} c_{34} s_{24} e^{i \delta_2} - c_{13} c_{23} c_{34} \end{bmatrix}
\]

\[
90\% \text{ CL} - 95\% \text{ CL}
\]

\[
\Delta_{21} \sim 0 \text{ (solar oscillation)}
\]

\[
s_{14} \sim 0 \text{ (reactor anomaly)} \rightarrow \delta_1 = 0
\]

\[ \sin^2 2\theta_{\mu\tau} = 4 |U_{\mu 4}|^2 |U_{\tau 4}|^2 \]

Profiling over \(\delta_2\)

- OPERA preliminary
  - 68% CL
  - 90% CL
  - 95% CL
  - CHORUS \(\nu_\mu \rightarrow \nu_\tau\) (2ν)
  - NOMAD \(\nu_\mu \rightarrow \nu_\tau\) (2ν)

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