The OPERA experiment
Oscillation Project with Emulsion tRacking Apparatus

Direct search for the $\nu_\mu \rightarrow \nu_\tau$ oscillation by looking at the appearance of $\nu_\tau$ in a pure $\nu_\mu$ beam

- CNGS program
- OPERA detector and experimental strategy
- Physics potential
- First operations of CNGS and OPERA

Collaboration:
Belgium (IIHE(ULB-VUB) Brussels), Bulgaria (Sofia University), China (IHEP Beijing Shandong University), Croatia (Zagreb University), France (LAPP Annecy, IPNL Lyon, LAL Orsay, IPHC Strasbourg), Germany (Berlin Humboldt University, Hagen, Hamburg University, Münster University, Rostock University), Israel (Technion Haifa), Italy (Bari, Bologna, LNF Frascati, L’Aquila, LNGS, Naples, Padova, Rome, Salerno), Japan (Aichi, Toho, Kobe, Nagoya, Utsunomiya), Russia (INR Moscow, ITEP Moscow, JINR Dubna, Obninsk), Switzerland (Bern, Neuchâtel, Zürich), Tunisia (Tunis University), Turkey (METU Ankara)

Cécile Jollet, IN2P3-ULP Strasbourg on behalf of the OPERA collaboration
TAUP07 Conference - Sendai - September 11-15, 2007
The Cern Neutrino to Gran Sasso (CNGS) program

Motivated by the atmospheric neutrino disappearance

CERN $\nu_\mu$ beam optimized to study the $\nu_\tau$ appearance by $\tau$ detection in the parameters region:

$\Delta m^2=2.4 \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta \approx 1.0$

$\tau$ production threshold=3.5 GeV

$$N_\tau = N_A M_D \int \phi_{\nu_\mu} (E) P_{\nu_\mu \rightarrow \nu_\tau} (E) \sigma^{CC}_{\nu_\tau} (E) \varepsilon (E) dE$$

Beam mean features:

$\mathbf{L}=730 \text{ km} ; \langle E_{\nu_\mu} \rangle =17 \text{ GeV}$

$(\nu_e + \bar{\nu}_e)/\nu_\mu =0.87\% ; \nu_\tau$ prompt negligible

In shared mode $\rightarrow 4.5 \times 10^{19}$ pot/year

$\Rightarrow 2900 \nu_\mu \text{ CC/kton/year}$ \quad expected at

$\Rightarrow 13 \nu_\tau \text{ CC/kton/year}$ \quad Gran Sasso
The CNGS beam

CNGS beam fully completed and operational since August 2006
The OPERA experimental design

Detection of $\tau$ decay ($\sim 10^{-13}$ s; $\Delta r \sim 87 \mu$m) topologies created by $\nu_\tau$ CC interactions

- $\mu$m resolution
- $\Rightarrow$ Photographic emulsions (DONUT)

$\Rightarrow$ Detector based on bricks:
- Sandwich of 56 (1mm) Pb sheets
  + 57 FUJI emulsion layers
  + 1 changeable sheet

Brick weight: 8.3 kg

Emulsion “grains” $\rightarrow$ track segment

~16 grains/50 $\mu$m

Decay “kink” $>25$ mrad

$\sigma_{\theta x} \sim 2.1$ mrad
$\sigma_x \sim 0.21 \mu$m
2 supermodules.
Target: 31 walls/supermodule with ~2500 bricks each

Target mass: 1.35 ktons

Gran Sasso, Hall C

• Robot to remove the candidate brick
• Scan by automatic microscope

Muonspectrometer

Electronicedetector to find candidate brick

Brick wall

The OPERA detector
**The OPERA Target Tracker**

Find the right brick to extract

Plastic scintillator + wave length shifting fiber + 64 channel multi-anode Hamamatsu PM

- $N_{pe} > 5$ p.e. for a mip (2.15 MeV)
- $\sim 99\%$ detection efficiency $\Rightarrow$ trigger
- brick finding: $\epsilon_{\text{brick}} \sim 80\%$
- initiate muon tagging
The OPERA Muon Spectrometer

- Performant $\mu$ tagging (improvement of $\tau \rightarrow \mu$ efficiency and tag of $\nu_\mu$ CC events)
- $\mu$ charge measurement to reduce background induced by charm decay:

$\Rightarrow$ Inner tracker (RPC in magnet) and precision tracker (drift tube, 8 m length)

- $\epsilon_{\text{miss charge}} \sim (0.1 - 0.3)\%$
- $\Delta p/p < 20\%$ for $p < 50$ GeV
- $\mu_{\text{id}} > 95\%$ (with target tracker)
The OPERA detector

Veto

BMS: Brick Manipulating System

Spectrometer: RPC, Drift Tubes, magnet

Target Tracker
The OPERA detector

Filling bricks into detector

Bricks walls

Target Tracker

Filling bricks into detector
Bricks elements and production

- Lead (PbCa colaminated) mass production in JL Goslar firm (Germany)
- Emulsion Refreshing Facility in Tono Mine (Japan)
- Brick mechanical packaging demanded for custom metal and plastic components

154 750 bricks to produce \(\Rightarrow\) automatically using a Brick Assembling Machine (BAM)

5 piling-up and compression stations

1 packaging station

Goal: construct 936 bricks/day
Detector fully filled by April 2008
At now: \(\sim\) 45000 bricks inside the detector
Events detection sequence

1- Brick tagging by Target Tracker:

2- Brick removed with the BMS (Brick Manipulating System)

3- Brick exposed to cosmic rays for sheets alignment
4- Brick disassembled and emulsions developed

Automatic emulsions scanning:

- ~30 bricks will be daily extracted from the target
- Distributed to several labs in Europe and Japan
- 2 high-speed automatic scanning systems:
  - The European Scanning System (commercial products, software algorithms)
  - The S-UTS (Japan) (Dedicated hardware, hard coded algorithms)
- Scanning speed: 20 cm²/h
Off-line emulsions scanning

3D Microtracks reconstruction

Microtracks alignment via the plastic base

BASETRACK

Basetracks alignment of several emulsions

Vertex reconstruction

Reconstruction

Vertex/Decay

- Momentum measurement by Multiple Scattering
- Electron identification and energy measurement
- \( dE/dx \) for \( \pi/\mu \) separation at low energy
### $\nu_\mu \rightarrow \nu_\tau$ oscillation sensitivity

**full mixing, 5 years run @ $4.5 \times 10^{19}$ pot / year**

**Efficiency:** $\varepsilon_{\text{trigger}} \times \varepsilon_{\text{brick}} \times \varepsilon_{\text{geom}} \times \varepsilon_{\text{primary vertex}}$

99% $\times$ 80% $\times$ 94% $\times$ 90%

fringe effect for scanning

<table>
<thead>
<tr>
<th>$\tau$ decay channels</th>
<th>$\varepsilon$(%)</th>
<th>BR(%)</th>
<th>$\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$</th>
<th>$\Delta m^2 = 3.0 \times 10^{-3}$ eV$^2$</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu$</td>
<td>17.5</td>
<td>17.7</td>
<td>2.9</td>
<td>4.2</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \rightarrow e$</td>
<td>20.8</td>
<td>17.8</td>
<td>3.5</td>
<td>5.0</td>
<td>0.17</td>
</tr>
<tr>
<td>$\tau \rightarrow h$</td>
<td>5.8</td>
<td>50</td>
<td>3.1</td>
<td>4.4</td>
<td>0.24</td>
</tr>
<tr>
<td>$\tau \rightarrow 3h$</td>
<td>6.3</td>
<td>15</td>
<td>0.9</td>
<td>1.3</td>
<td>0.17</td>
</tr>
<tr>
<td><strong>ALL</strong></td>
<td>$\varepsilon \times $BR=10.6%</td>
<td></td>
<td>10.4</td>
<td>15.0</td>
<td>0.76</td>
</tr>
</tbody>
</table>

**Main background sources:**
- charm production and decays
- hadron re-interactions in lead
- large-angle muon scattering in lead
1st CNGS run: August 2006

- 121 hours of real beam operation
- Used for electronic detectors, DAQ, GPS commissioning and tests of CNGS-OPERA information exchange
- No bricks in the detector
- 70% of nominal intensity → $1.7 \times 10^{13}$ pot/extraction

CNGS beam:
**Events time structure**

**Time selection of beam events:**

\[ T_{\text{OPER}} - (T_{\text{CERN}} + T_{\text{flight}}) < \Delta T_{\text{gate}} \]

\[ T_{\text{flight}} = 2.44 \, \text{ms} \]

GPS Time Stamp resolution \( \sim 100 \, \text{ns} \)

\( \Delta T_{\text{gate}} \sim 10.5 \, \mu \text{s} \)

Cosmic ray events

⇒ The events time distribution is peaked around the 2 extractions peak times within negligible cosmic-ray background
OPERA beam events

- 319 beam events collected:
  - 3/4 external events (interaction in the rock)
  - 1/4 internal events (interaction in the detector)

νμCC in rock (rock muons)  νμCC in the magnet
Events direction

Zenith angle of muon track:

Cosmic ray MC simulation from MACRO parametrization

Beam events:

\[ \langle \Theta_y \rangle = 3.4 \pm 0.3^\circ \text{ (as expected)} \]

(statistically dominated)
**Physics commissioning runs**

- **CNGS run in October 2006:**
  - 3 double fast extraction distant by 6 seconds per 36 seconds SPS cycle
  - $0.6\times10^{17}$ pot delivered and 30 events stored
  - Run stopped due to a water leak in the reflector (2\(^{nd}\) horn) → CNGS “reparation”

- **Cosmic runs** for commissioning of electronic detectors, target-tracker to brick connection

- **Beam runs** (CERN, Desy…) for emulsion development commissioning, scanning strategy, and tune the vertex finding methods

- **CNGS run in 2007** (beginning 18 September):
  - 3 weeks of CNGS commissioning
  - 3 additional weeks of physics run
  - 70% of nominal intensity: $1.7\times10^{13}$ pot/extraction
  - 505 tons (~59000 bricks) at the start of the run
  - 616 tons (~72000 bricks) at the end of the run
Conclusions

• The OPERA experiment has completed almost entirely the construction of all electronic detectors and faces the last effort of brick production and insertion.

• The electronic detectors took data almost continuously and with the expected tracking performances.

• The electronic detectors-brick connection has been tested with success.

• First, low intensity, CNGS run operated smoothly for both beam and detector with good quality and stability.

• The detector is ready for the next phase: observing neutrino inside bricks.

Backup Slides
Automatic emulsions scanning

Off-line Data Taking
~ 30 bricks will be daily extracted from target and analyzed using high-speed automatic systems
Several labs distributed in Europe and Japan

European Scanning System

scanning speed ~ 20 cm² / h

Customized commercial optics and mechanics + asynchronous DAQ software

S-UTS (Japan)

High speed CCD Camera (3 kHz)

Piezo-controlled objective lens

Synchronization of objective lens and stage

Constant speed stage

Hard-coded algorithms
**OPERA goal: \( \nu_\tau \) appearance signal detection**

The challenge is to identify \( \nu_\tau \) interactions from \( \nu_\mu \) interactions.

Principle of OPERA experiment:

**Detection of \( \tau \) decay (\( \sim 10^{-13} \) s; \( c\tau \sim 87 \) \( \mu \)m) topologies created by \( \nu_\tau \) CC interactions**

- \( \mu \)m resolution
  - \( \Rightarrow \) Photographic emulsions (DONUT)

- Large target mass
  - \( \Rightarrow \) Lead materials
Sensitivity to $\Theta_{13}$

Simultaneous fit on:
$E_e$, missing $p_T$ and visible energy

<table>
<thead>
<tr>
<th>$\Theta_{13}$ (deg)</th>
<th>Signal $\nu_\mu \rightarrow \nu_e$</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau \rightarrow e$ $\nu_\mu$ CC</td>
<td>$\nu_\mu$ NC</td>
</tr>
<tr>
<td>9</td>
<td>9.3</td>
<td>4.5</td>
</tr>
<tr>
<td>7</td>
<td>5.8</td>
<td>4.5</td>
</tr>
<tr>
<td>5</td>
<td>3.0</td>
<td>4.5</td>
</tr>
</tbody>
</table>

full mixing, 5 years run @ 4.5x10$^{19}$ pot / year

Limits at 90% CL for
$\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$ full mixing

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2 2\Theta_{13}$</th>
<th>$\Theta_{13}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHOOZ</td>
<td>&lt;0.14</td>
<td>11°</td>
</tr>
<tr>
<td>OPERA</td>
<td>&lt;0.06</td>
<td>7.1°</td>
</tr>
</tbody>
</table>
**OPERA discovery probability vs $\Delta m^2$**

![Graph showing OPERA discovery probability vs $\Delta m^2$ with two lines representing 4-s evidence and 3-s evidence.](image-url)