On behalf of the OPERA Collaboration
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**OPERA**: first direct detection of neutrino oscillations in appearance mode through the $\nu_\mu \rightarrow \nu_\tau$ channel following the Super-Kamiokande discovery of oscillations with atmospheric neutrinos and the confirmation obtained with solar neutrinos and accelerator beams. Important, missing tile in the oscillation picture.

**Requirements:**

1) long baseline, 2) high neutrino energy, 3) high beam intensity, 4) large mass, 5) detect short lived $\tau$'s

![Expected neutrino interactions for 22.5x10$^{19}$ pot:](image)

$\sim 23600 \, \nu_\mu \, \text{CC + NC}$

$\sim 160 \, \nu_e + \nu_e \, \text{CC}$

$\sim 115 \, \nu_\tau \, \text{CC (}\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2\text{)}$
Detecting short lived particles

The heart of the experiment: THE ECC TARGET BRICKS

Stack of 57 OPERA films, 56 lead plates (10 X₀)

ECC is the detector first observation of νₓ events

DONUT experiment at FERMILAB: (K. Niwa and collaborators):
9 τ events, 1.5BG.
THE IMPLEMENTATION OF THE PRINCIPLE

Target area  Muon spectrometer
LNGS of INFN, the world largest underground physics laboratory:

~180'000 m³ caverns’ volume, ~3'100 m.w.e. overburden, ~1 cosmic μ/ m²xhour, experimental infrastructure, variety of experiments. Perfectly fit to host detector and related facilities, caverns oriented towards CERN.
11 173 events collected until 19 July 2010 (within 1σ in agreement with expectations)

Improving features, high CNGS efficiency (97% in 2008-2009)

2010: close to nominal year;

Aim at high-intensity runs in 2011 and 2012.
GLOBAL ANALYSIS PERFORMANCE
Typical $\nu_\mu$ CC- and NC-like events

The measured ratio of NC-like/CC-like events after muon ID and event location is ~20%, as expected from simulations.
Impact parameter measurement

IP distribution for $\nu_\tau$ events (MC)

Mean $104.3 \, \mu m$

IP distribution for $\nu_\tau$ events (MC),
NC+CC $\nu_\mu$ events (MC),
NC+CC $\nu_\mu$ events (Data)

expanded scale
DATA/MC comparison: good agreement in normalization and shape

(pion test-beam exposure)
Momentum measurement by Multiple Coulomb Scattering...

...in the lead/emulsion film sandwich and comparison with electronic detector measurements.

\[ \frac{\Delta p}{p} = (22 \pm 4)\% \]
\( \gamma \) detection and \( \pi^0 \) mass reconstruction

2 EM showers give a reconstructed mass \( \sim 160 \text{ MeV} \)

EM shower energy measured by shower shape analysis and Multiple Coulomb Scattering method
$\pi^0$ mass resolution (real data)

$\chi^2 / \text{ndf} = 1.954 / 6$
- Constant: $7.388 \pm 1.757$
- Mean: $142.2 \pm 13.2$
- Sigma: $65.76 \pm 11.56$

35 gamma pairs

1$\sigma$ mass resolution: $\sim 45\%$
Charm candidate event (dimuon)

- Flight length: 1330 microns
- Kink angle: 209 mrad
- IP of daughter: 262 microns
- Daughter muon: 2.2 GeV/c
- Decay Pt: 0.46 GeV/c
Charm candidate event (4-prong)

$D^0$ hypothesis: F.L.: 313.1 mm, $\phi$: 173.2°, invariant mass: 1.7 GeV
From a subsample of ~ 800 located events we detected 6 $\nu_e$ candidates.

Additional physics subject: study $\nu_\mu-\nu_e$ oscillations.
(Old) Event statistics

Total found neutrino vertices: 1617

Events for which “decay search” was completed: 1088 (187 NC)

This is ~35% of the total 2008-2009 run statistics, corresponding to 1.85 x 10^{19} pot

With the above statistics, and for $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2 and full mixing, OPERA expects:  ~0.5 $\nu_\tau$ events
A VERY INTERESTING EVENT...
Muonless event 9234119599, taken on 22 August 2009, 19:27 (UTC) (as seen by the electronic detectors)
From CS to vertex location

Large area scanning
Full reconstruction of vertices and gammas

careful visual inspection of the films behind/in front the secondary vertex:
no “black” or “evaporation” tracks. Support topological hypothesis of a particle decay
Event reconstruction (1)
Event reconstruction (II)
## Event tracks’ features

<table>
<thead>
<tr>
<th>TRACK NUMBER</th>
<th>PID</th>
<th>Probability</th>
<th>MEASUREMENT 1</th>
<th>MEASUREMENT 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>tan $\Theta_X$</td>
<td>tan $\Theta_Y$</td>
</tr>
<tr>
<td>1</td>
<td>HADRON</td>
<td>$\text{range in Pb/emul}=4.1/1.2$ cm</td>
<td>Prob($\mu$)$\approx10^{-3}$</td>
<td>0.177</td>
</tr>
<tr>
<td>2</td>
<td>PROTON</td>
<td>range, scattering and $dE/dx$</td>
<td></td>
<td>-0.646</td>
</tr>
<tr>
<td>3</td>
<td>HADRON</td>
<td>interaction seen</td>
<td></td>
<td>0.105</td>
</tr>
<tr>
<td>4 (PARENT)</td>
<td></td>
<td></td>
<td>-0.023</td>
<td>0.026</td>
</tr>
<tr>
<td>5</td>
<td>HADRON: range in Pb/emul=9.5/2.8 cm</td>
<td>Prob($\mu$)$\approx10^{-3}$</td>
<td>0.165</td>
<td>0.275</td>
</tr>
<tr>
<td>6</td>
<td>HADRON: range in Pb/emul=1.6/0.5 cm</td>
<td>Prob($\mu$)$\approx10^{-3}$</td>
<td></td>
<td>0.334</td>
</tr>
<tr>
<td>7</td>
<td>From a prompt neutral particle</td>
<td></td>
<td>0.430</td>
<td>0.419</td>
</tr>
<tr>
<td>8 (DAUGHTER)</td>
<td>HADRON</td>
<td>interaction seen</td>
<td>-0.004</td>
<td>-0.008</td>
</tr>
</tbody>
</table>

*Residual probability of $\nu CC$ event (due to a possibly undetected large angle muon) $\approx 1\%$. Nominal value of $5\%$ assumed.*
Kinematical analysis

OPERA nominal analysis flow applied to the hadronic kink candidates:

(more refined selection criteria being developed were not considered here not to bias our analysis)

- kink occurring within 2 lead plates downstream of the primary vertex
- kink angle larger than 20 mrad
- daughter momentum higher than 2 GeV/c
- decay Pt higher than 600 MeV/c, 300 MeV/c if ≥ 1 gamma pointing to the decay vertex
- missing Pt at primary vertex lower than 1 GeV/c
- azimuth angle between the resulting hadron momentum direction and the parent track direction larger than $\pi/2$ rad
\( \gamma \) detection

- total radiation length downstream the vertices: \( 6.5 X_0 \)
- gamma search performed in the whole scanned volume
- careful visual scanning checks

<table>
<thead>
<tr>
<th>Distance from 2ry vertex (mm)</th>
<th>Energy (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1\textsuperscript{st} ( \gamma )</td>
<td>2.2</td>
</tr>
<tr>
<td>2\textsuperscript{nd} ( \gamma )</td>
<td>12.6</td>
</tr>
</tbody>
</table>
### γ attachment to the vertices

<table>
<thead>
<tr>
<th></th>
<th>Distance from 2ry vertex (mm)</th>
<th>IP to 1ry vertex (μm) &lt;resolution&gt;</th>
<th>IP to 2ry vertex (μm) &lt;resolution&gt;</th>
<th>Prob. of attach. to 1ry vtx*</th>
<th>Prob. of attach. to 2ry vtx*</th>
<th>Attachment hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; γ</td>
<td>2.2</td>
<td>45.0 &lt;11&gt;</td>
<td>7.5 &lt;7&gt;</td>
<td>&lt;10&lt;sup&gt;-3&lt;/sup&gt;</td>
<td>0.32</td>
<td>2ry vertex</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; γ</td>
<td>12.6</td>
<td>85.6 &lt;56&gt;</td>
<td>22 &lt;50&gt;</td>
<td>0.10</td>
<td>0.82</td>
<td>2ry vertex (favored)</td>
</tr>
</tbody>
</table>

* probability to find an IP larger than the observed one

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Pointing resolution (1σ) for a given gamma: function of scattering and distance
Kinematical variables

- The kinematical variables are computed by averaging the two sets of track parameter measurements.
- We assume that:
  \( \gamma_1 \) and \( \gamma_2 \) are both attached to the 2\( \gamma \) vertex.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>AVERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>kink (mrad)</td>
<td>41 ± 2</td>
</tr>
<tr>
<td>decay length (( \mu )m)</td>
<td>1335 ± 35</td>
</tr>
<tr>
<td>P daughter (GeV/c)</td>
<td>12 +6 -3</td>
</tr>
<tr>
<td>Pt daughter (MeV/c)</td>
<td>470 +230 -120</td>
</tr>
<tr>
<td>missing Pt (MeV/c)</td>
<td>570 +320 -170</td>
</tr>
<tr>
<td>( \phi ) (deg)</td>
<td>173 ± 2</td>
</tr>
</tbody>
</table>

The average values are used in the following kinematical analysis.

The uncertainty on Pt due to the alternative \( \gamma_2 \) attachment is < 50 MeV.
Kinematical cuts to be passed

Reject NC events with larger missing Pt (neutrino)

Reject hadron interactions
Azimuthal angle between the resulting hadron momentum direction and the parent track direction

Signal: $\phi = 180^\circ$

BG: small $\phi$

$\tau$-decay

$\nu_\tau N \rightarrow \tau^{-} X$

$kink$

$\nu_\mu N \rightarrow \nu_\mu \pi^{-} X$

$X$ (hadron shower)
Event nature and invariant mass reconstruction

- The event passes all cuts, with the presence of at least 1 gamma pointing to the secondary vertex, and is therefore a candidate to the $\tau \rightarrow 1$-prong hadron decay mode.

- The invariant mass of the two detected gammas is consistent with the $\pi^0$ mass value (see table below).

- The invariant mass of the $\pi^- \gamma \gamma$ system has a value (see below) compatible with that of the $\rho$ (770). The $\rho$ appears in about 25% of the $\tau$ decays: $\tau \rightarrow \rho (\pi^- \pi^0) \nu_\tau$.

<table>
<thead>
<tr>
<th>$\pi^0$ mass</th>
<th>$\rho$ mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$120 \pm 20 \pm 35$ MeV</td>
<td>$640 \pm^{125}<em>{-80} \pm^{100}</em>{-90}$ MeV</td>
</tr>
</tbody>
</table>
• Prompt $\nu_\tau$ 
  $\sim 10^{-7}/CC$

• Decay of charmed particles produced in $\nu_e$ interactions  
  $\sim 10^{-6}/CC$

• Double charm production  
  $\sim 10^{-6}/CC$

• Decay of charmed particles produced in $\nu_\mu$ interactions  
  $\sim 10^{-5}/CC$

• Hadronic reinteractions (UPDATE wrt Proposal)  
  $\sim 10^{-5}/CC$
• Search for “kinks” and interactions along a total of 9 m of hadron track measured for scanned events. This is about a factor 8 larger than the so far scanned track length for NC events (number of NC x hadron multiplicity x 2 mm decay length).

• Goal: ~100 m as needed to fully validate (eventually replace) the MC information
• no events in the signal region

• 90% $\text{CL}$ upper limit of $1.54 \times 10^{-3}$ kinks/NC event

• the number of events outside the signal region is confirmed by MC (within the ~30% statistical accuracy of the measurement)
Charmed particles have similar decay topologies to the $\tau$

- charm production in $CC$ events represents a background source to all $\tau$ decay channels
- this background can be suppressed by identifying the primary lepton $\rightarrow \sim 95\%$ muon ID
- for the 1-prong hadronic channel $0.007 \pm 0.004$ (syst) background events are expected for the analyzed statistics
- further charm BG reduction is under evaluation by implementing the systematic follow-down of low energy tracks in the bricks and the inspection of their end-range, as done for the “interesting” event. For the latter we have 98-99% muon ID efficiency.

Charm search: 20 candidate events selected by the kinematical cuts,
Expected: $(16.0 \pm 2.9) + \sim 2$ BG events (loose cuts: work in progress to reduce BG)
We observe 1 event in the 1-prong hadron $\tau$ decay channel, with a background expectation ($\sim 50\%$ error for each component) of:

- 0.011 events (re-interactions)
- 0.007 events (charm)

\[0.018 \pm 0.007 \text{ (syst)} \text{ events 1-prong hadron}\]

all decay modes: 1-prong hadron, 3-prongs + 1-prong $\mu$ + 1-prong $e$:

- 0.045 $\pm$ 0.020 (syst) events total BG

By considering the 1-prong hadron channel only, the probability to observe 1 event due to a background fluctuation is 1.8%, for a statistical significance of 2.36 $\sigma$ on the measurement of a first $\nu_{\tau}$ candidate event in OPERA.

If one considers all $\tau$ decay modes which were included in the search, the probability to observe 1 event for a background fluctuation is 4.5%.

This corresponds to a significance of 2.01 $\sigma$. 
Summary of the interesting event

One muonless event showing a $\tau \rightarrow 1$-prong hadron decay topology has been detected and studied in detail. It passes all kinematical cuts required to reduce the physics background.

It is the first $\nu_\tau$ candidate event in OPERA.
Outlook

Note the change of speed in the event location from June 2010

With the present scanning speed we expect to complete the analysis of 2008+2009 runs by the end of 2010 (NB we expect about 2 taus in this sample)

In parallel the scanning of 2010 run events is in progress
Thank you for your attention