A neutrino interaction with two secondary vertices detected by OPERA

Chiara Sirignano on behalf of the OPERA collaboration
Padova University & INFN

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Outline

• The OPERA experiment **

• Muon-less event 114301850

• Event analysis and results

** neutrino oscillation analysis on July 13th, “Results from the OPERA experiment in the CNGS beam”, A.Di Crescenzo
**Oscillation Project with Emulsion tRacking Apparatus**

- Long baseline neutrino oscillation experiment
- **CNGS** quasi – pure wide band $\nu_\mu$ beam
- $<E> = 17 \text{ GeV}$ optimized to maximize $\nu_\tau$ CC interactions
- More than 19 000 neutrino interactions collected in 5 years
- Detection of $\nu_\tau$ CC interaction by a full reconstruction of the primary vertex and observation of the $\tau$ lepton decay topologies
- Nuclear emulsions + Lead (150 000 ECC bricks) “active target”, allowing 3D particle reconstruction, sub-micron spatial resolution and high background rejection rate.

**Reconstruction**

57 $\times$ 2 emulsion layers (42 $\mu$m thick) poured on a 200 $\mu$m plastic base
1. Extract Brick and CS, scan CS.
2. Confirm the event in the ECC brick.
3. Develop the brick and send films to scanning labs.

Target area: (ECC + CS + planes of scintillator strips) ~ 150,000 bricks 1.25 kt mass

Muon spectrometer (Magnet+RPC+PT)
New generation automatic emulsion scanning systems
- Scanning speed/system: 20cm²/h
- Customized commercial optics and mechanics
- Customized DAQ & event reconstruction software
- ~0.3 μm spatial resolution
- ~2 mrad angular resolution
- ~95% detection efficiency on a single emulsion film

Neutrino interaction reconstruction chain

- More than 7000 neutrino interaction reconstructed and studied
- 5 ντ interactions detected

*discovery of ντ appearance, 5.1σ significance*
(PRL 115 (2015) 121802)
Muon-less event 114301850

Full detector event display

Zoom of the interaction region: pink brick selected

Event Summary

Event: 11143018505 Brick Number 1077152
BrickID: SM Wall: Row: Column: Side: Probability:
1077152 1 12 23 10 1 0.515
1024745 1 12 23 11 1 0.424
1024746 1 12 22 10 1 0.028

MuonID: 0

3DTrks: 1
3D track: θx = -0.0338 θy = 0.3836 P = -0.786 GeV/c flag: 0
E_TT: 529.2 MeV E_RPC: 20.0 GeV

EventLength (TT+RPC planes) 9 + 0: 9
- All tracks followed upstream in the brick
- Electromagnetic activity hints already after CS films analysis
Primary vertex

Five tracks emerge from a common point. Evaluated $I_p$ of such tracks are over the standard threshold (10 $\mu$m), the configuration that maximizes the vertex probability is computed.

Images acquired with a microscope having an improved optical resolution (100x magnification)
Two secondary vertices reconstructed:

- short two prong (F.L. = 103 μm)
- charged one prong (kink) (F.L. = 1174 μm, θ_k = 97mrad)
Electromagnetic showers

Two $\gamma$ detected in the volume and related to the event

$\gamma_1$ can be attached to the kink point according to the IP and the resolution. The energy of the two showers was evaluated with a calorimetric approach inside the brick, such algorithm was validated on MC data.
Event analysis

Particles momenta evaluated by MCS

<table>
<thead>
<tr>
<th>Track ID</th>
<th>$p$ best fit (GeV/c)</th>
<th>68% $p$ range (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.1</td>
<td>[1.6; 3.1]</td>
</tr>
<tr>
<td>3</td>
<td>4.3</td>
<td>[3.1; 7.1]</td>
</tr>
<tr>
<td>5</td>
<td>0.54</td>
<td>[0.45; 0.68]</td>
</tr>
<tr>
<td>6 (daughter)</td>
<td>2.7</td>
<td>[2.1; 3.7]</td>
</tr>
</tbody>
</table>

Invariant masses at secondary vertices

<table>
<thead>
<tr>
<th>Vertex ID</th>
<th>Invariant Mass $M$ (GeV/c$^2$)</th>
<th>Minimum Invariant Mass $M_{\text{min}}$ (GeV/c$^2$)</th>
<th>Difference $\Delta$ (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>1.8 ± 0.5</td>
<td>2.5 ± 0.8</td>
<td>0.7 ± 0.4</td>
</tr>
<tr>
<td>III (kink)</td>
<td>0.9 ± 0.1</td>
<td>1.2 ± 0.2</td>
<td>0.3 ± 0.1</td>
</tr>
</tbody>
</table>

Vertex II can be the decay of a charmed particle, vertex III does not satisfy standard OPERA cut ($p_T > 300$ MeV/c for a tau decay candidate). ...but the topology is interesting and additional analysis was performed
### Event interpretation

**Two possible rare processes:**

a) $\nu \text{ NC} + c\bar{c}$ (only 3 events in CHORUS)

b) $\nu_\tau \text{ CC} + \text{charm}$ (never observed)

and possible backgrounds:

- $\nu_\tau \text{ CC} + \text{hadron interaction}$
- $\nu_\mu \text{ CC} + \text{charm} + \text{hadron interaction}$
- $\nu_\mu \text{ NC} + 2 \text{ hadron interactions}$
- $\nu_\mu \text{ CC} + 2 \text{ hadron interactions}$

A complete simulation was performed, considering the observed topology and OPERA event location efficiencies, we expect 0.1 events.
The signal discrimination was performed by multivariate analysis, twelve kinematic variables were defined. Some of them are derived from the standard OPERA analysis while others were newly introduced as peculiar of such topology.

- Daughter particle momentum
- Daughter transverse momentum with respect to the parent direction
- Kink angle between parent and daughter;
- Flight length

- Total EM visible energy
- Transverse angle with respect to the beam direction between the tracks which end up in 1pr-like and 2pr-like vertices
- Modified hadronic momentum which is the module of the momenta coming from the primary vertex discarding tracks that end up in a secondary 1pr-like or 2pr-like vertex.
- Missing transverse momentum

Four classifiers were explored: **Artificial Neural Networks (ANN)**, two flavors of Boost Decision Trees and the Fisher Discriminant
Event analysis

(a) Total EM energy

(b) $\varphi$

(c) Missing transverse momentum

(d) Other hadronic momenta

Signature sources:
- Red: Signal Tau CC + charm
- Green: Background Muon CC + 2 had reinte
- Blue: Background Muon CC + charm + had reinte
- Yellow: Background NC + 2 had reinte
- Pink: Background Tau CC + had reinte
- Purple: Background NC + charm pair
The event is classified as a tau neutrino interaction with charm production.

The confidence level evaluated with respect to the background only hypothesis is $3.5 \sigma$. 

Results & conclusions
Thanks for the attention

28 institutions - 140 physicists

Image taken using OPERA nuclear emulsion film with pinhole hand made camera courtesy by Donato Di Ferdinando

http://operaweb.lngs.infn.it
Spare slides
Fine alignment done by penetrating CR tracks

17 penetrating tracks (1x1 cm^2 x 25 plates)

Angular resolution $\approx 3.4/\sqrt{2}$ mrad

Position resolution $\approx 0.8/\sqrt{2}$ μm

Improved resolution for MCS measurements in emulsion
Shower reconstruction

- Data acquisition: image files (~ 9 mm², at least 20 plates)
- Image acquisition with 1 μm pitch
- Optical defects correction and 3D grains reconstruction
- Tuned on an a microscope with enhanced resolution
- 3D precision tracking

- Grains, micro-tracks and base-tracks reconstruction on each plate
- Full volume reconstruction and automatic shower hint
- All image files are linked to the reconstruction and can be visually inspected
Showers’ energy resolution
Both photons were identified

They are reconstructed as separate showers.

\[ \gamma_1 : (7.2 \pm 1.7) \text{ GeV} \]

\[ \gamma_2 : (5.3 \pm 2.2) \text{ GeV} \]