Particles and Cosmology
16th Baksan School on Astroparticle Physics

Final results of the search for $\nu_\mu \to \nu_e$ oscillations with the OPERA detector in CNGS beam

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The OPERA experiment

Goals

- The observation of the $\nu_\mu \to \nu_\tau$ oscillations in the appearance mode through the detection of the τ-lepton PRL 120, 211801 (2018)
- The tracking capabilities of the emulsion allow to identify electrons produced in CC interactions of ν_e and, hence, to study $\nu_\mu \to \nu_e$ oscillations in appearance mode JHEP06(2018)151

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Experimental requirements:

- long baseline
- high energy neutrinos
- high intensity beam
- low background
- large active target mass
- μm space resolution

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LNGS

$\sim$3 800 m w.e.

$\sim$1 cosmic muon per ($m^2 \times h$)

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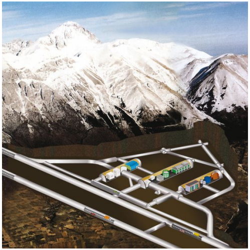


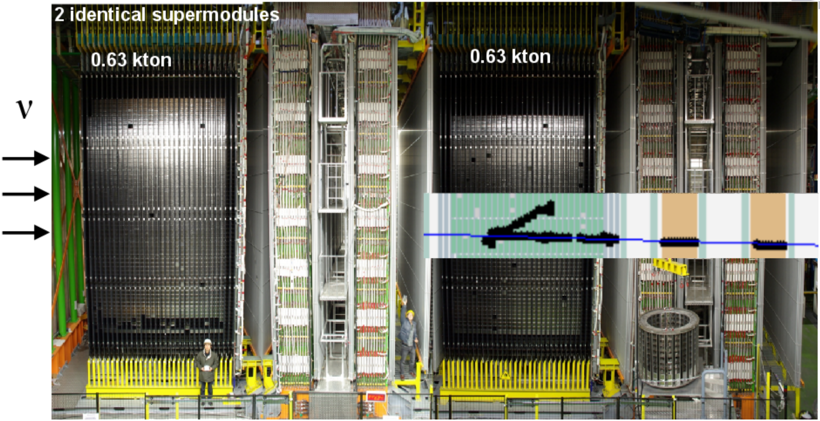
baseline $\sim$ 732 km

CNGS beam

$< E_{\nu_\mu} >$ (GeV)	17
$(\nu_e + \overline{\nu}_e)/\nu_\mu$	0.87%
$\overline{\nu}_\mu/\nu_\mu$	2.1%
ν_τ prompt	Negligible

interactions rates at LNGS site

The OPERA experiment



Target and Target Tracker
($6.7m \times 6.7m$)
$\sim$75000 bricks

Muon
Spectrometer
($8m \times 10m$)

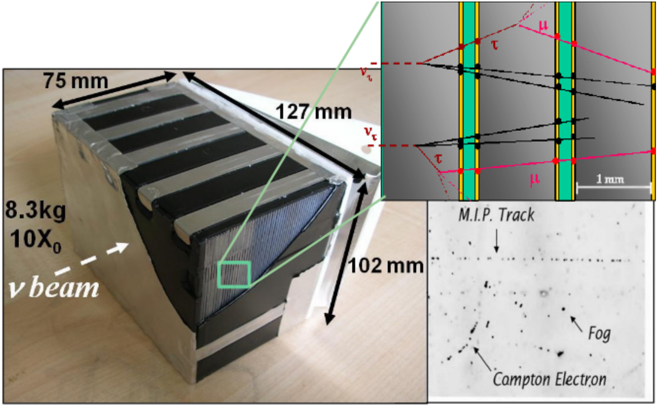
Target and Target Tracker
($6.7m \times 6.7m$)
$\sim$75000 bricks

Brick
Manipulator
System

The OPERA experiment

Emulsion Cloud Chamber technique provides large target mass and high spatial resolution:

- $\sim$150 000 ECC, 56 lead plates and 57 emulsions each
- $\sim$ 9 million films in total (sensitivity 30 grains per 100 μm)
- $\sim$ 1.25 kton total target mass



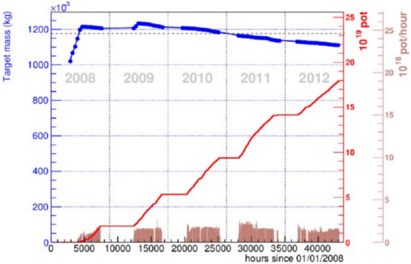
Collected data sample

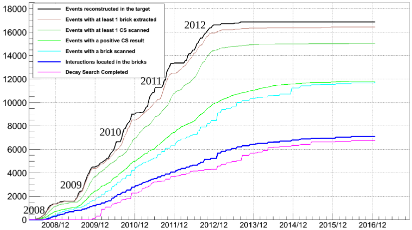
2008-2012 CNGS run

- 17.97×10^{19} p.o.t.
- 1.18 kt average detector mass
- 19505 on-time interactions in detector
- 6785 decay searched events*

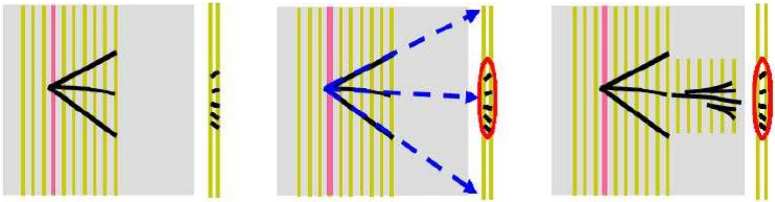
* Decay searched events:

- vertex is located in the lead/emulsion target
- event topology is reconstructed





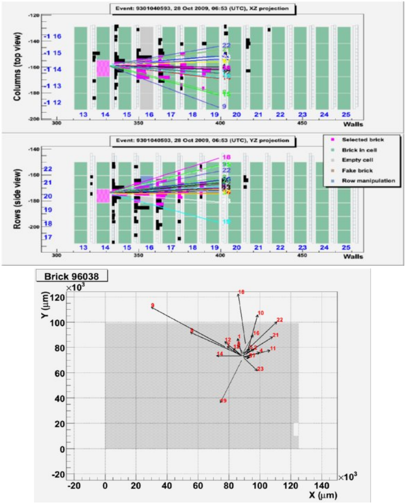
Search for ν_e CC interactions

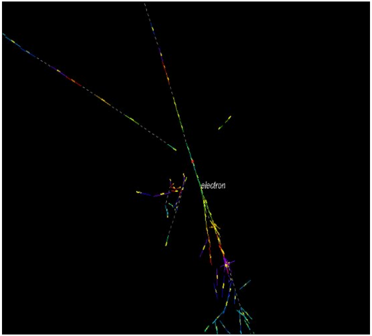


Search for ν_e candidates JHEP 1307 (2013) 004

- The electron identification is based on the search of associated electromagnetic shower. Primary tracks extrapolated to the changeable emulsion doublets. The tracks with angles and positions similar to projection ones are searched ($\Delta\theta < 150 mrad$, 2 mm).
- If 3 or more tracks found, an additional volume along the candidate track is scanned.

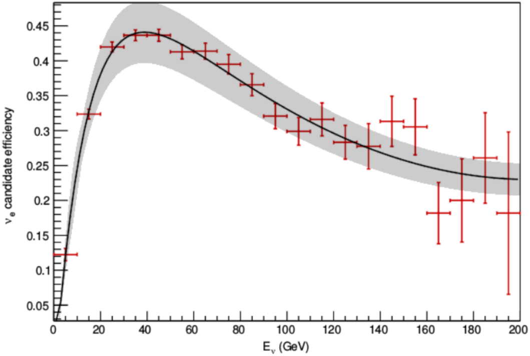
Search for ν_e CC interactions





one ν_e candidate event

Search for ν_e CC interactions



The ν_e CC candidates selection efficiency as a function of neutrino energy (red error bars — MC statistical errors; grey area represents the systematical error.)

Analysed data sample

- 17.97×10^{19} p.o.t.
- 19505 on-time events
- 5868 vertexes in 1st or 2nd most probable brick
- 1281 events tagged as 0μ
- 35 ν_e candidates were found

Background and ν_e beam contamination

- Intrinsic $\nu_e(\bar{\nu}_e)$ beam components
- ν_τ CC with the decay of $\tau \rightarrow e$
- $\pi^0 \rightarrow \gamma \rightarrow e^+ + e^-$ in ν interaction without a reconstructed μ

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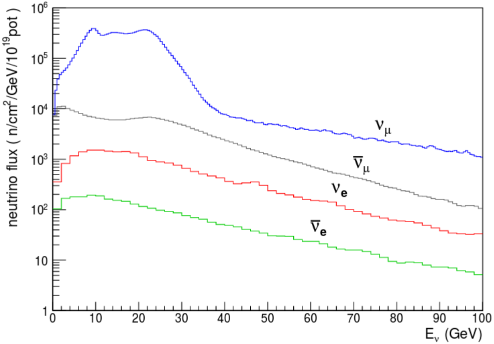
Neutrino fluxes at Gran Sasso JHEP 1307 (2013) 004



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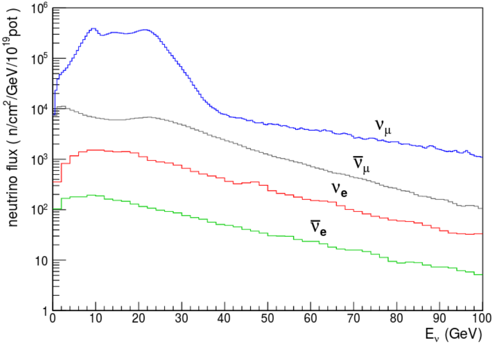
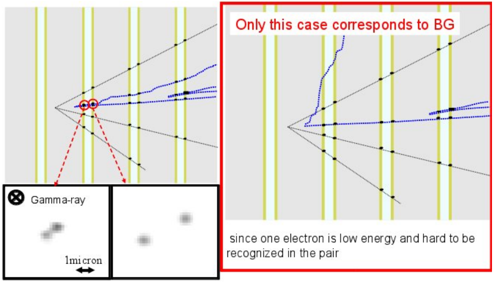


- $\tau \to e$ in the same lead plate as the primary vertex with IP<10 μm (an impact parameter of the e to the 1ry vertex).
- An undetected kink (θ_{kink}<20 mrad) from a $\tau \to e$ in further downstream material.

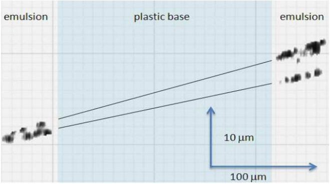
$\mathbf{0.7 \pm 0.2(syst.)}$ bg events

Background and ν_e beam contamination

$$\pi^0 \to \gamma \to e^+ + e^-$$



- e^+e^- can not be distinguished from a single particle in the first 2 emulsion films after the vertex
- one pair component undetected



Side view of e^+e^- pair detected in the emulsion film
JHEP 1307 (2013) 004
BG evaluated from the data:
$\mathbf{0.5} \pm \mathbf{0.5}(\mathbf{stat.})$ events

$\nu_\mu \to \nu_e$ analysis

No oscillation scenario

- ν_e beam contamination
  $30.7 \pm 0.9(stat.) \pm 3.1(syst.)$
- other background
  $1.2 \pm 0.5(stat.) \pm 0.2(syst.)$

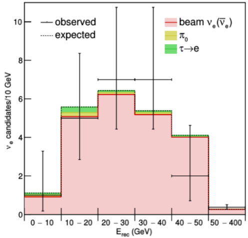
3-flavour oscillation scenario

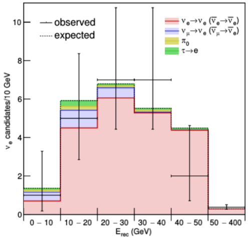
- $34.3 \pm 1.0(stat.) \pm 3.4(syst.)$ (including BG)

2008-2012 data (17.97×10^{19} p.o.t.)

- 35 ν_e candidates found

Result: $sin^2(2\theta_{13}) < 0.43$ (90% C.L.)





JHEP06(2018)151

$\nu_\mu \to \nu_e$ analysis

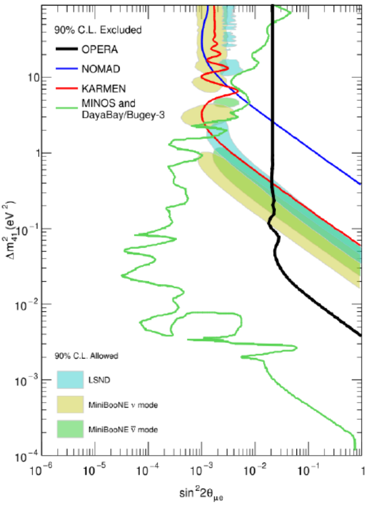
Sterile neutrino search

The excess of ν_e and $\bar{\nu}_e$ reported by LSND and MiniBooNE can be interpreted as due to the presence of light sterile neutrino.

3+1 model bounds from ν_e appearance with profile Likelihood method.

An upper limit on $\sin^2(2\theta_{\mu e}) = 0.021$ is set for $\Delta m^2_{41} > 0.1\ \mathrm{eV}^2$.

Moreover, OPERA contributes to limit the effective mixing for low Δm^2_{41} and excludes $\Delta m^2_{41} \gtrsim 4 \times 10^{-3}\ \mathrm{eV}^2$ for maximal mixing.



JHEP06(2018)151 (arXiv 1803.11400)

Summary

- Search for ν_e in full data set analysis is completed (17.97×10^{19} p.o.t.)
- Number of observed ν_e candidates is in agreement with the expected background and the standard oscillation signal
- Constraint on sterile neutrinos in the 3+1 flavour model
- Combined $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ appearance analysis in progress...

Thank you for attention!

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JINR Dubna

Switzerland
Bern

Turkey
METU, Ankara

http://operaweb.lngs.infn.it

Backup slides

Beam contamination

N_{beam} was obtained using a data-driven approach from the number of observed events with no charged leptons:

$$N_{beam} = n_{0l} \frac{R^{CC}_{\nu_e} \left\langle \varepsilon^{\nu_e}_{CC}(\nu_e) \right\rangle}{\sum\limits_{i=\mu,e} \sum\limits_{j=CC,NC} R^{j}_{\nu_i} \left\langle \varepsilon^{0l}_{j}(\nu_i) \right\rangle}, \quad (1)$$

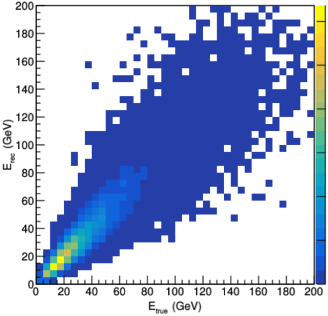
where

$$\left\langle \varepsilon^{\nu_e(0l)}_{j}(\nu_i) \right\rangle = \int \phi_{\nu_i} \epsilon^{\nu_e(0l)}_{j} \sigma^{j}_{\nu_i} \, dE \Big/ \int \phi_{\nu_i} \sigma^{j}_{\nu_i} \, dE, \quad (2)$$

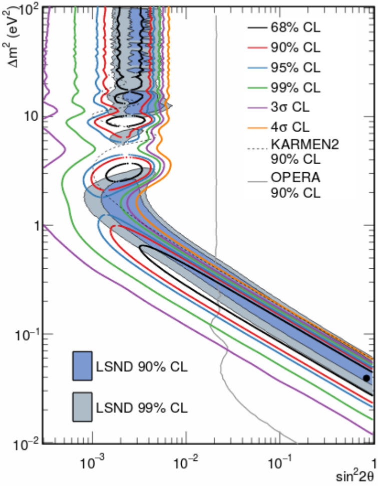
while $R^{j}_{\nu_i}$ are the interaction rates of neutrino and antineutrino:

$$R^{j}_{\nu_i} = \int \phi_{\nu_i} \sigma^{j}_{\nu_i} \, dE. \quad (3)$$

3+1 analysis



$$\frac{\Delta E}{E} = 0.18 + \frac{0.55}{\sqrt{(E(GeV))}}$$



MiniBooNE allowed region
arXiv:1805.12028 [hep-ex]

3+1 analysis

~standard oscillation   Exotic oscillation

$$P_{\nu_\mu \to \nu_e} = C^2 \sin^2 \Delta_{31} + \sin^2 2\theta_{\mu e} \sin^2 \Delta_{41}$$

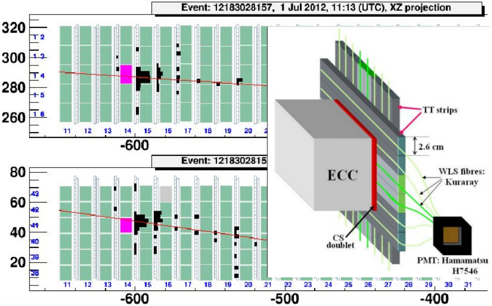
Interference term

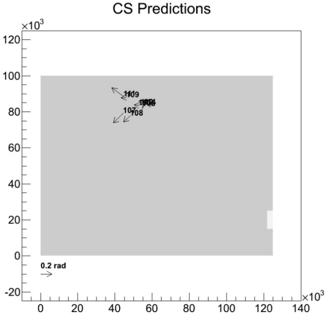
$$+ 0.5\, C \sin 2\theta_{\mu e} \cos \phi_{\mu e} \sin 2\Delta_{31} \sin 2\Delta_{41}$$
$$- C \sin 2\theta_{\mu e} \sin \phi_{\mu e} \sin^2 \Delta_{31} \sin 2\Delta_{41}$$
$$+ 2\, C \sin 2\theta_{\mu e} \cos \phi_{\mu e} \sin^2 \Delta_{31} \sin^2 \Delta_{41}$$
$$+ C \sin 2\theta_{\mu e} \sin \phi_{\mu e} \sin 2\Delta_{31} \sin^2 \Delta_{41}$$

$$C = 2|U_{\mu 3} U^*_{e3}|$$
$$\Delta_{ij} = \frac{1.27 \Delta m^2_{ij} L}{E}$$
$$\phi_{\mu e} = Arg(U_{\mu 3} U^*_{e3} U_{\mu 4} U^*_{e4})$$
$$sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2 |U_{e4}|^2$$

$$-2 \ln L = -2 \sum_i^N (n_i \ln \mu_i - N\mu_i) + \sum_{j=1}^{2} \frac{k_j^2}{\sigma_j^2} + \frac{\left(\Delta m^2_{31} - \widehat{\Delta m^2_{31}}\right)^2}{\sigma^2_{\Delta m^2_{31}}}. \quad (4)$$

Event location procedure

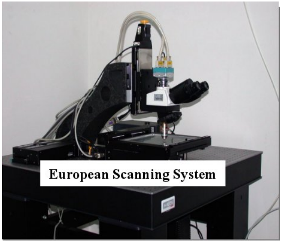




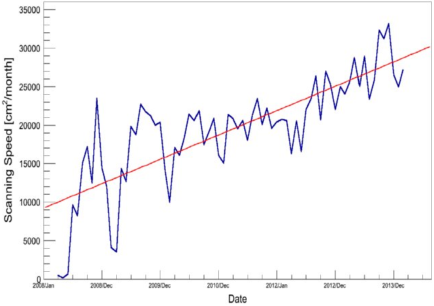
- TT data is used for a prediction of the bricks which contain the neutrino interactions
- A large area of the corresponding changeable film is scanned (so far 2'500'000 cm^2 of CS surface analysed)

Event location procedure

Scanning of Changeable Sheets: two large facilities

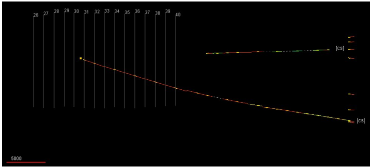


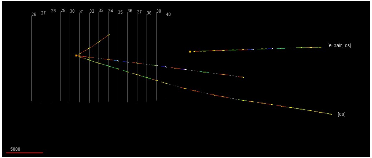
Scanning speed per facility: improvement during the run

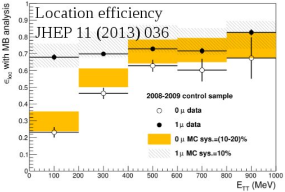


- LNGS: 10 microscopes, 200 cm^2/h
- Nagoya: 5 S-UTS, 220 cm^2/h

Event location procedure







- brick exposure at the surface laboratory to collect cosmic-rays for alignment
- scan-back: CS-tracks are followed upstream from film to film to find the ν-interaction vertex
- total-scan: scanning of the 1 cm^2 around the vertex in 15 plates is performed
- scan-forth: improvement of the momentum measurement of the reaction products New J. of Phys. 4 (2012) 013026
- decay search Eur.Phys.J. C74(2014) 2986

Decay search procedure

- Primary vertex definition
  - visual inspection of segments on the vertex plate
  - impact parameter $< 10(5 + 0.01\Delta z)\mu m, if \Delta z < 500\mu m$
- Extra-track search
  - selection of tracks reconstructed in the volume but not attached to primary vertex
  - identification of e^+e^- pairs by visual inspection
- In-track search
  - search for small kinks along the tracks attached to the primary vertex
- Parent search
  - search for a track connecting the selected extra-track and the primary vertex

(more details: arXiv:1404.4357 [hep-ex])