Search for $\nu_\mu \to \nu_e$ oscillations with the OPERA experiment

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Outline

The goals of the OPERA experiment

- The main goal of the OPERA experiment is the observation of the $\nu_\mu \rightarrow \nu_\tau$ oscillations in the appearance mode through the detection of τ-lepton

  Phys. Lett. B691 (2010) 138
  JHEP 11 (2013) 036
  Phys. Rev. D 89 (2014) 051102(R)
  Gran Sasso seminar (march 2014)

- Furthermore, the tracking capabilities of the emulsion allow to identify electrons produced in CC interactions of ν_e and, hence, to study $\nu_\mu \rightarrow \nu_e$ oscillations in appearance mode as well

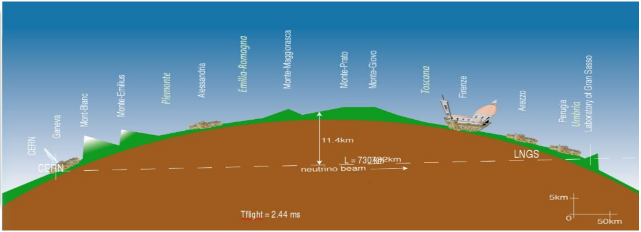
  JHEP 1307 (2013) 004

CNGS beam

Beam tuned for τ-appearance at LNGS 730 km away from CERN

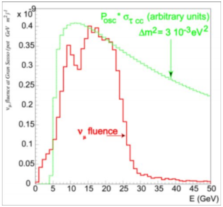
Beam properties:

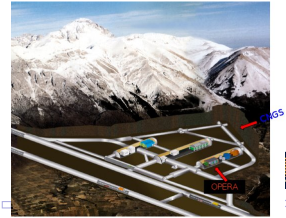
- high ν energy
- long baseline
- high beam intensity



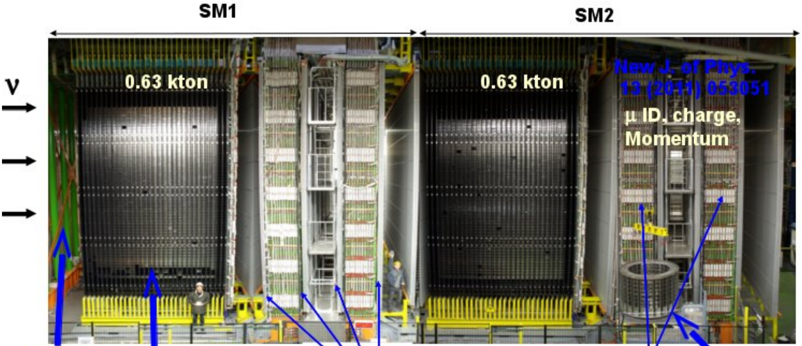
Beam parameters

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





OPERA detector



Veto plane (RPC)

Target and Target Tracker (6.7*m* × 6.7m)

- Target : ~75000 bricks, 29 walls
- Target tracker : 31 XY doublets of 256 scintillator strips + WLS fibres + multi-anodes PMT for
  - Brick selection
  - Calorimetry

Muon spectrometer (8m×10*m*)

Instrumented dipole magnet

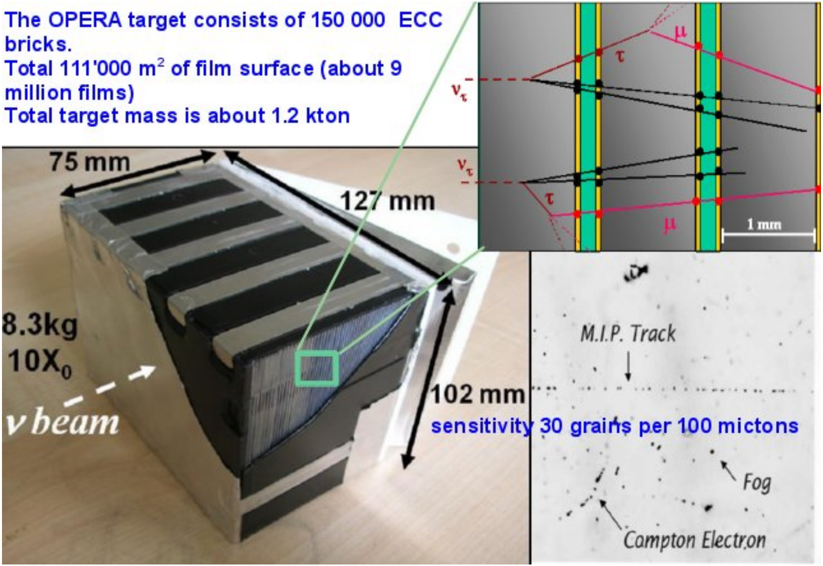
- 1.53 *T*
- 22 XY planes of RPC in both arms
- 2 XPC planes rotated by 42.6°

High precision tracker

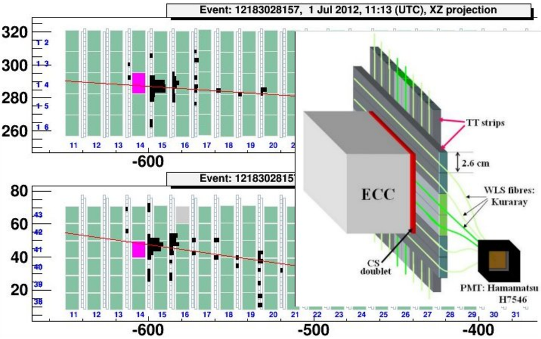
- 6 4-fold layers of drift tubes

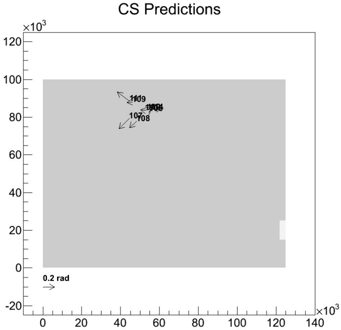
Brick Manipulator System

OPERA detector



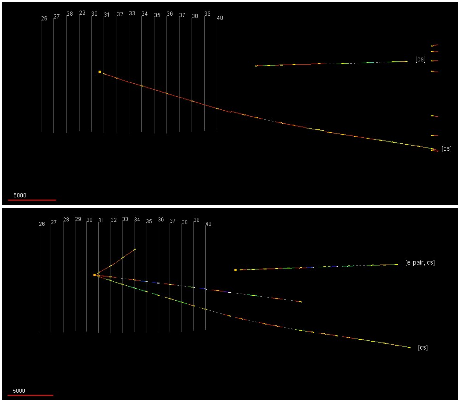
Event location





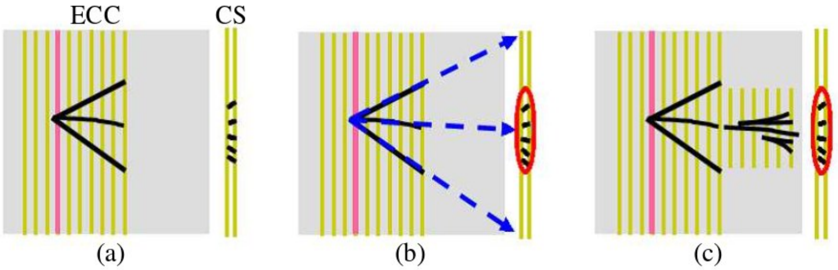
- TT data is used for a prediction of the bricks which contain the neutrino interactions
- large area of the corresponding changeable film is scanned (so far 2'500'000 cm^2 of CS surface analysed)

Event location



- brick exposure at the surface laboratory to collect cosmic-rays for alignment
- scan-back: CS-tracs 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 a momentum measurement of the tracks New J. of Phys. 4 (2012) 013026
- decay search arXiv:1404.4357 [hep-ex]

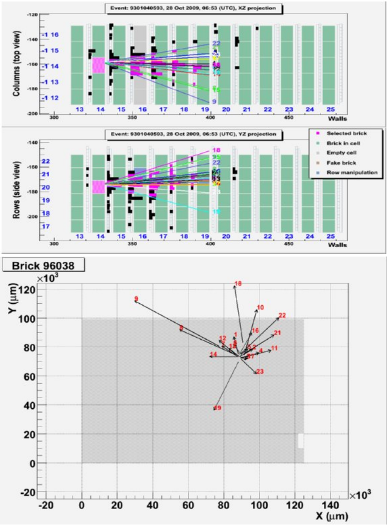
Search for ν_e topoligy

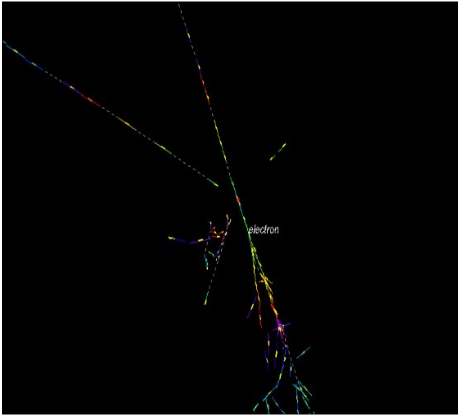


Systematic ν_e candidates search JHEP 1307 (2013) 004

- electron identifiction is based on the search of associated electromagnetic shower: search for CS tracks with the coordinate and angular acceptance (2 mm and 150 mrad respectively) to each extrapolation of the primary tracks
- if 3 or more tracks were found, additional volume along the candidate track is scanned

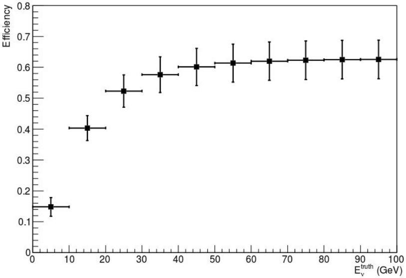
Search for ν_e topoligy





one of the ν_e candidates

Analysed data sample



2008-2009 data sample:

- 5.25×10^{19} pot
- 5255 events predicted in the bricks
- 2853 vertices were located
- 505 have no muon identified
- 19 ν_e candidate events were found

detection efficiency of ν_e events as a function of the neutrino energy (obtained from MC simulation), the error bars show the estimated systematic uncertainties

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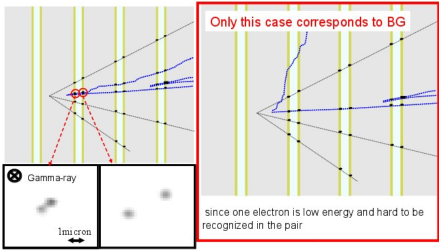
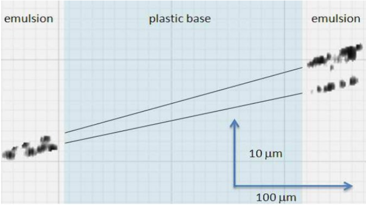
Background to $\nu_\mu \to \nu_e$ appearance

- π^0 misidentified as electron in neutrino interactions without a reconstructed μ
- ν_τ CC interactions with the decay of the τ into electron
- ν_e background associated to the beam contamination

π^0 misidentified as electron in neutrino interactions without a reconstructed μ

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





Side view of e^+e^- pair detected in the emulsion film
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BG was evaluated directly from the data: 0.2 ± 0.2 events

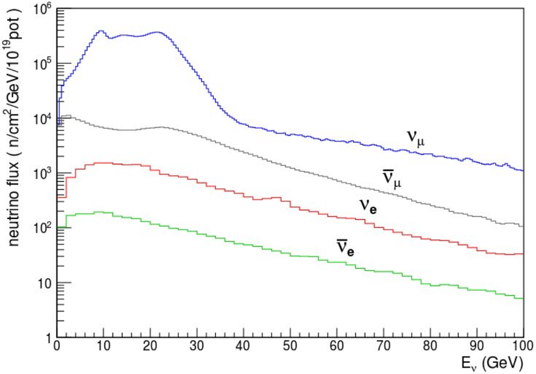
- e^+e^- appears to be connected to the vertex and can not be distinguished from a single particle in the first 2 emulsion films after the vertex
- one branch of the pair is very low and undetected

ν_τ CC interactions with the decay of the τ into electron

BG comes mainly from τ decaying in the same lead plate as the primary vertex with the impact parameter of the daughter electron to the primary vertex smaller than 10 μm and from the undetected kink (θ_{kink}<20 mrad) from τ decaying in further downstream material

BG was computed by Monte Carlo simulation assuming the three-flavour $\nu_\mu \rightarrow \nu_\tau$ oscillation at maximal mixing and $\Delta m^2 = 2.32 \times 10^{-3} eV^2$ - 0.3 ± 0.1 events

ν_e background associated to the beam contamination



Neutrino fluxes of the different components at Gran Sasso in log scale (simulation base on FLUCA MC code) taking into account the target mass and the p.o.t. corresponding to our data, 19.4 ± 2.8 (syst) events are expected JHEP 1307 (2013) 004

Background to $\nu_\mu \to \nu_e$ appearance

Expected and observed number of events for the different energy cuts

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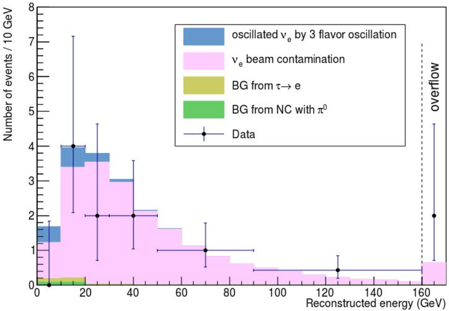
Energy cut		20 GeV	30 GeV	No cut
BG common to both analysis	BG from π^0	0.2	0.2	0.2
	BG from $\tau \to e$	0.2	0.3	0.3
	ν_e beam contamination	4.2	7.7	19.4
Total expected BG in 3-flavour oscillation analysis		4.6	8.2	19.8
BG to non-standard oscillation analysis only	ν_e via 3-flavour oscillation	1.0	1.3	1.4
Total expected BG in non-standard oscillation analysis		5.6	9.4	21.3
Data		4	6	19

The number of expected oscillated ν_e CC events was calculated with the following oscillation parameters:

- $sin^2(2\theta_{13}) = 0.098$
- $sin^2(2\theta_{23}) = 1$
- $\Delta m^2_{32} = \Delta m^2_{31} = 2.32 \times 10^{-3} eV^2$

Three-flavour mixing scenario



Distribution of the reconstructed energy of the ν_e events, and the expected spectrum from the different sources JHEP 1307 (2013) 004
$\Delta E/E = 0.37 + 0.74/\sqrt{E}$ (E in GeV) New J. Phys. 13 (2011) 053051
E<20 GeV cut was applied on the reconstructed energy of the events to increase signal to BG ratio

The number of observed events is compatible with the non-oscillation hypothesis and an upper limit $sin^2(2\theta_{13}) < 0.44$ is derived at the 90% C.L.

Non-standard oscillations

Expected and observed number of events for the different energy cuts

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Data		4	6	19

E<30 GeV cut was applied on the reconstructed energy of the events (the optimal cut in term of sensitivity)

OPERA data was used to set an upper limit on non-standard $\nu_\mu \to \nu_e$ oscillation parameters indicated by the LSND and MiniBooNE experiments

$$P_{\nu_\mu \to \nu_e} = sin^2(2\theta_{new}) sin^2(1.27 \Delta m^2{}_{new} L(km)/E(GeV))$$

Non-standard oscillations

Energy cut	Upper limit		Sensitivity	
	F&C	Bayes	F&C	Bayes
20 GeV	8.5×10^{-3}	10.4×10^{-3}	14.2×10^{-3}	14.2×10^{-3}
30 GeV	5.0×10^{-3}	7.2×10^{-3}	9.7×10^{-3}	10.4×10^{-3}
No cut	8.6×10^{-3}	9.5×10^{-3}	10.8×10^{-3}	11.0×10^{-3}

90% C.L. upper limits and sensitivities on $sin^2(2\theta_{new})$, for different energy cuts, according to the Feldman and Cousins and Bayesian methods.

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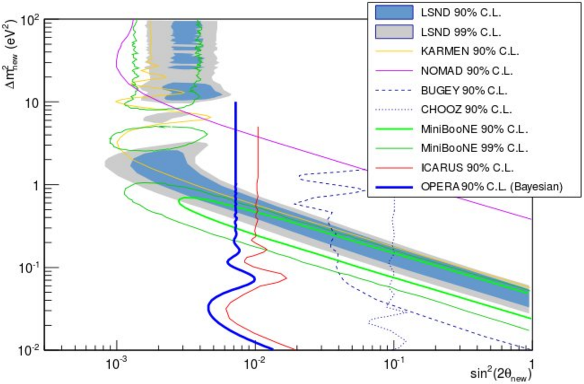
Non-standard oscillations

	C.L.	Upper limit		Sensitivity	
		F&C	Bayes	F&C	Bayes
Number of oscillated ν_e events	90%	3.1	4.5	6.1	6.5
	95%	4.3	5.7	7.8	6.5
	99%	6.7	8.2	10.7	10.9
$sin^2(2\theta_{new})$at large Δm^2	90%	5.0×10^{-3}	7.2×10^{-3}	9.7×10^{-3}	10.4×10^{-3}
	95%	6.9×10^{-3}	9.1×10^{-3}	12.4×10^{-3}	12.7×10^{-3}
	99%	10.6×10^{-3}	13.1×10^{-3}	17.1×10^{-3}	17.4×10^{-3}

Upper limits on the number of oscillated ν_e CC events and $sin^2(2\theta_{new})$ obtained by the Feldman and Cousins and Bayesian methods, for C.L. 90%, 95%, 99%. The sensitivity computed assuming that the number of observed events is 9, which is the closest integer to the 9.4 expected background events.
JHEP 1307 (2013) 004

The exclusion plot for the parameters of the non-standard $\nu_\mu \to \nu_e$ oscillation. JHEP 1307 (2013) 004



OPERA limit at large $\Delta m^2{}_{new}$, $sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ (Bayesian)
new ICARUS limit at large $\Delta m^2{}_{new}$, $sin^2(2\theta_{new}) < 6.8 \times 10^{-3}$ (F&C) (EPJ C73 (2013) 2599)
preliminary results on MINOS+ were presented on neutrino 2014

Conclusions

- The results of a search for $\nu_\mu \to \nu_e$ oscillations using 2008-2009 data (5.25×10^{19} pot) have been presented
- The observation of 19 ν_e candidate events is compatible with the non-oscillation expectation of 19.8 ± 2.8 events
- The current result on a search for the three-flavour neutrino oscillation yields an upper limit $sin^2(2\theta_{13}) < 0.44$ (90% C.L.)
- OPERA limits the parameter space available for a non-standard ν_e appearance (suggested by LSND, MiniBooNE). It constrains region around $\Delta m^2_{new} = 5 \times 10^{-2} eV^2$. For larger Δm^2_{new} values, the 90% C.L. upper limit on $sin^2(2\theta_{new})$ reaches 7.2×10^{-3} .

Perspectives

- The increasing of statistics by factor of 3.4 by completing of analysis of the collected data is expected
- The reconstructed energy resolution will be improved by complementation of the calorimetric measurement in the TT with the emulsion data
- The increasing of the sample size and the improvements in the analysis, the effect of a possible statistical underfluctuation of the background will be reduced and OPERA should be able to access the parameter region comparable to its sensitivity below $sin^2(2\theta_{new}) = 5.0 \times 10^{-3}$

Thank you for attention!

Backup slides

CNGS beam

Final performances of the CNGS beam after five years (2008-2012) of data taking

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

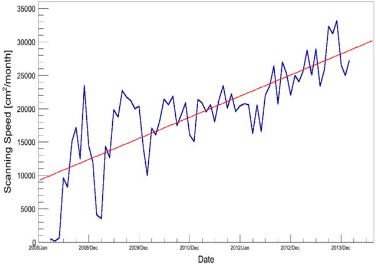
overall $\sim$ 20% less than the proposal value (22.5×10^{19} pot)

* $\sim$ 87% of events were predicted in the bricks

Event location

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

Decay search

- 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])