IV International Conference on Particle Physics and Astrophysics

New results from the OPERA experiment in the CNGS neutrino beam

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The OPERA experiment

The OPERA experiment performed first detection of ν_τ in pure ν_μ beam playing a unique role to prove the neutrino oscillation mechanism in **appearance** mode.

Experimental requirements:

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

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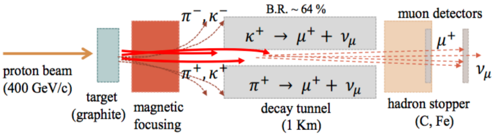
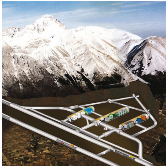
CNGS beam

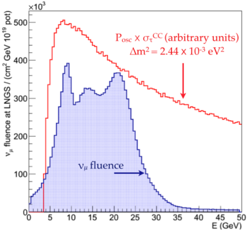




LNGS

~3 800 m w.e.

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



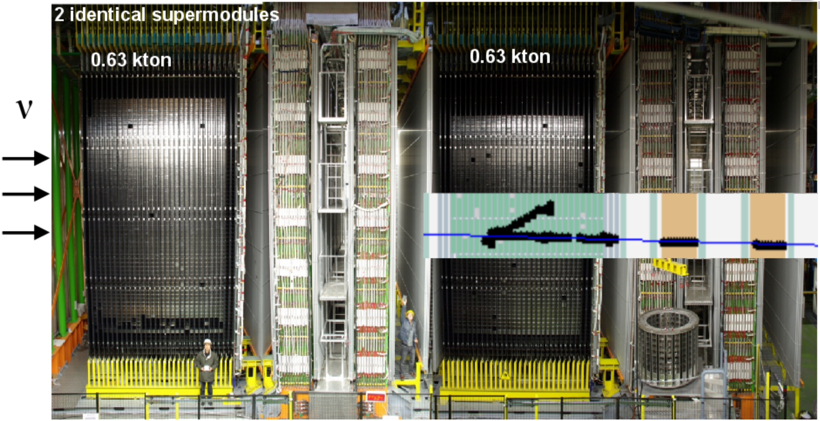
Beam parameters

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

interactions rates at LNGS site

(baseline ~ 732 km)

The OPERA experiment



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

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

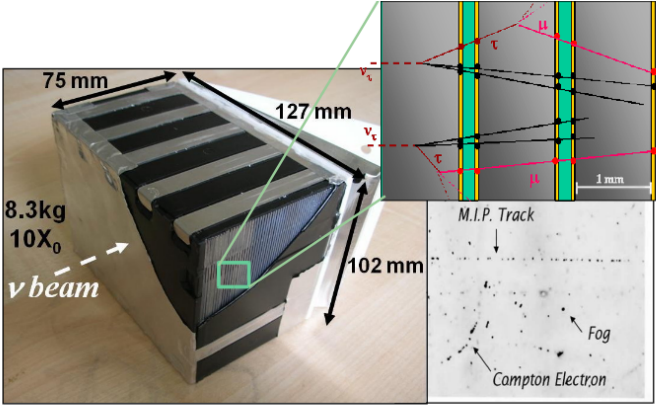
Target and Target Tracker
($6.7m \times 6.7m$)
$\sim$75000 bricks

Brick
Manipulator
System

The OPERA experiment

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

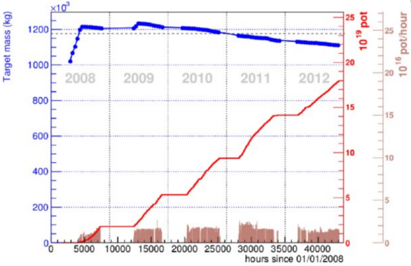
- ∼150 000 ECC, 56 lead plates and 57 emulsions each
- ∼ 9 million films in total (sensitivity 30 grains per 100 μm)
- ∼ 1.25 kton total target mass

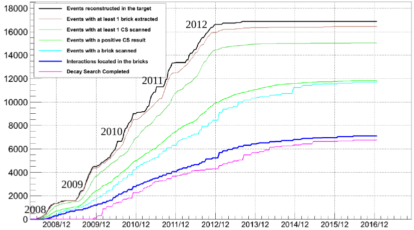


Collected data sample

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



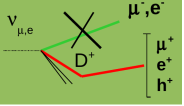


Year	Beam days	P.O.T. (10^{19})	ν interactions
2008	123	1.74	1931
2009	155	3.53	4005
2010	187	4.09	4515
2011	243	4.75	5131
2012	257	3.86	3923
Total	965	17.97	19505

$\nu_\mu \to \nu_\tau$ analysis

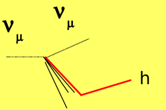
$\nu_\mu \to \nu_\tau$ background

CC with charm production (all channels) IF the primary lepton is not identified and the daughter charge is not (or incorrectly) measured



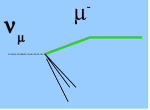
MC tuned on CHORUS data, validated with measured OPERA charm events
Reduced by “track following down” procedure and large angle scanning
Eur. Phys. J C74 (2014) 2986

Hadronic interactions
Background for $\tau \to h$



FLUKA simulation and test beam data
Reduced by nuclear fragment search and large angle scattering
PTEP 9 (2014) 093C01

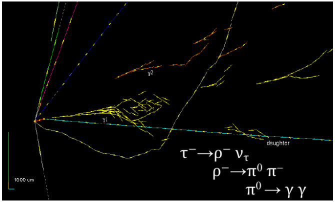
Large angle muon scattering
Background for $\tau \to \mu$

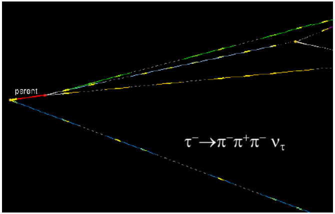


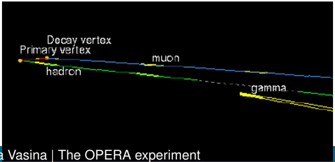
Estimate by implementing a proper form factor for Lead Simulation bench-marked on experimental data
IEEE Transactions on Nucl. Sci. Vol. 62, 5, 2015

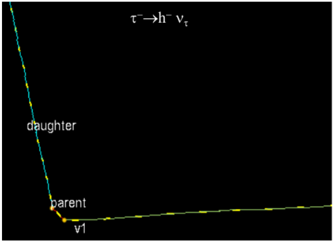
$\nu_\mu \rightarrow \nu_\tau$ analysis

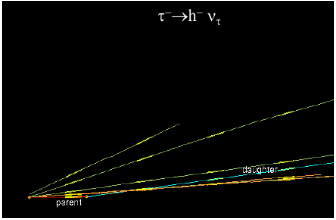
5 ν_τ candidates











Phys. Lett. B 691 (2010) 183
JHEP 11 (2013) 036
Phys. Rev. D 89 (2014) 051102
PTEP (2014) 10, 101C01

PRL 115 (2015) 12, 121802

$\nu_\mu \rightarrow \nu_\tau$ analysis

PRL **115,** 121802 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

Discovery of τ Neutrino Appearance in the CNGS Neutrino Beam with the OPERA Experiment

	Expected background					
Channel	Charm	Had. reinterac.	Large μ scat.	Total	Expected signal	Observed
$\tau \rightarrow 1h$	0.017 ± 0.003	0.022 ± 0.006		0.04 ± 0.01	0.52 ± 0.10	3
$\tau \rightarrow 3h$	0.17 ± 0.03	0.003 ± 0.001		0.17 ± 0.03	0.73 ± 0.14	1
$\tau \rightarrow \mu$	0.004 ± 0.001		0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \rightarrow e$	0.03 ± 0.01			0.03 ± 0.01	0.78 ± 0.16	0
Total	0.22 ± 0.04	0.02 ± 0.01	0.0002 ± 0.0001	0.25 ± 0.05	2.64 ± 0.53	5

- probability of the background fluctuation 1.1×10^{-7}
- absence of the signal excluded with a significance of **5.1** σ

Scientific Background on the Nobel Prize in Physics 2015

NEUTRINO OSCILLATIONS

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

Super-Kamiokande's oscillation results were later confirmed by the detectors MACRO [55] and Soudan [56], the long-baseline accelerator experiments K2K [57], MINOS [58] and T2K [59] and more recently also by the large neutrino telescopes ANTARES [60] and IceCube [61]. Appearance of tau-neutrinos in a muon-neutrino beam has been demonstrated on an event-by-event basis by the OPERA experiment in Gran Sasso, with a neutrino beam from CERN [62].

PRL 115 (2015) 121802

$\nu_\mu \rightarrow \nu_\tau$ analysis

Data sample re-analysis:

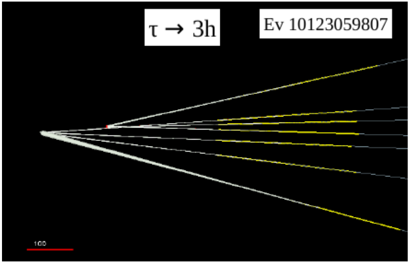
- Minimum bias kinematical cuts
- Multivariate analysis: Boosted Decision Tree

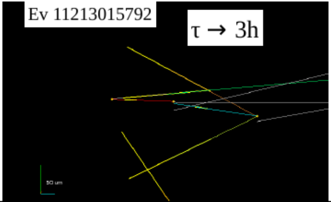
Variable	$\tau \rightarrow 1h$ OLD	$\tau \rightarrow 1h$ NEW	$\tau \rightarrow 3h$ OLD	$\tau \rightarrow 3h$ NEW	$\tau \rightarrow \mu$ OLD	$\tau \rightarrow \mu$ NEW	$\tau \rightarrow e$ OLD	$\tau \rightarrow e$ NEW
z_{dec} (μm)	$[44, 2600]$	<2600	<2600		$[44, 2600]$	<2600	<2600	
θ_{kink} (rad)	>0.02		<0.5	>0.02	>0.02		>0.02	
p_{2ry} (GeV/c)	>2	>1	>3	>1	$[1, 15]$		$[1, 15]$	>1
p^T_{2ry} (GeV/c)	$>0.6\,(0.3)$	>0.15	/		>0.25	>0.1	>0.1	
p^T_{miss} (GeV/c)	<1	/	<1	/	/		/	
ϕ_{lH} (rad)	$>\pi/2$	/	$>\pi/2$	/	/		/	
m, m_{min} (GeV/c^2)	/		$[0.5, 2]$	/	/		/	

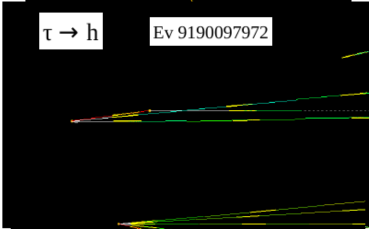
Channel	Expected Background: Charm	Expected Background: Had. re-interaction	Expected Background: Large μ-scat.	Expected Background: Total	ν_τ Exp.	Observed
$\tau \rightarrow 1h$	0.15 ± 0.03	1.28 ± 0.38	–	1.43 ± 0.39	2.96 ± 0.59	6
$\tau \rightarrow 3h$	0.44 ± 0.09	0.09 ± 0.03	–	0.52 ± 0.09	1.83 ± 0.37	3
$\tau \rightarrow \mu$	0.008 ± 0.002	–	0.016 ± 0.008	0.024 ± 0.008	1.15 ± 0.23	1
$\tau \rightarrow e$	0.035 ± 0.007	–	–	0.035 ± 0.007	0.84 ± 0.17	0
Total	0.63 ± 0.10	1.37 ± 0.38	0.016 ± 0.008	2.0 ± 0.4	6.8 ± 0.75	10

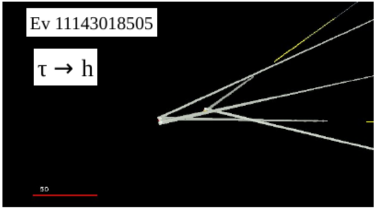
$\nu_\mu \to \nu_\tau$ analysis

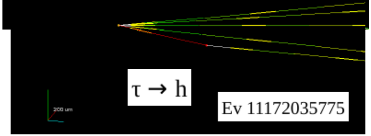
5 more ν_τ candidates





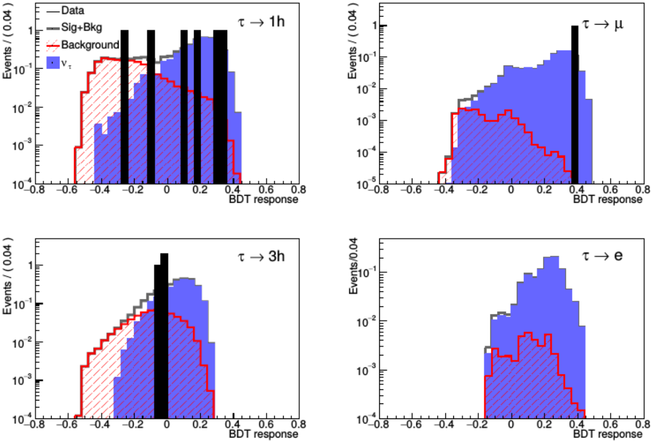






$\nu_\mu \rightarrow \nu_\tau$ analysis

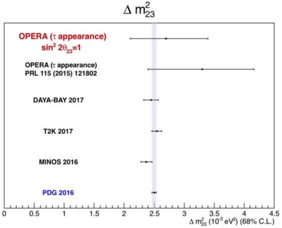
BDT responce for all possible τ-decay channels



Likelihood based analysis: No oscillation hypothesis excluded at **6.1** σ (P-value = 4×10^{-10})

Δm^2_{23} and cross section measurement

First measurement in appearance mode

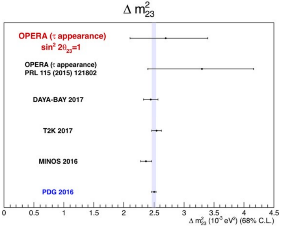


$$|\Delta m^2_{23}| = 2.7^{+0.7}_{-0.6} \times 10^{-3}\ eV^2$$

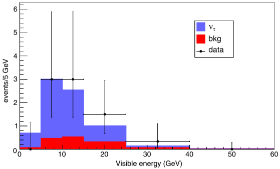
$\nu_\mu \rightarrow \nu_\tau$ analysis

Δm^2_{23} and cross section measurement

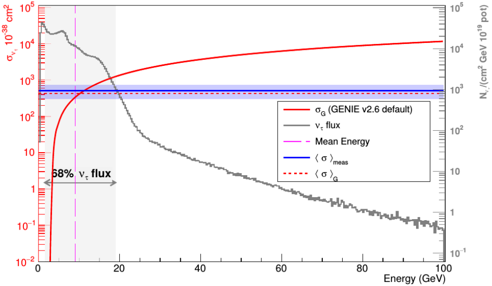
First measurement in appearance mode



$$|\Delta m^2_{23}| = 2.7^{+0.7}_{-0.6} \times 10^{-3}\ eV^2$$



First measurement with negligible contamination from anti-ν_τ



Measured average cross-section weighted over ν_τ flux:

$$< \sigma >_{meas} = (5.1^{+2.4}_{-2.0}) \times 10^{-36}\ cm^2$$

$$< \sigma >_{meas} = (1.2^{+0.6}_{-0.5}) < \sigma_G >$$

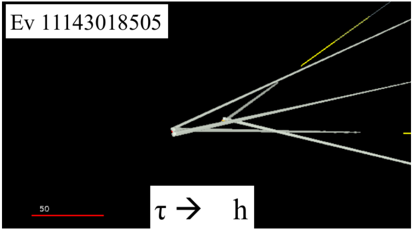
PRL 120, 211801 (2018)

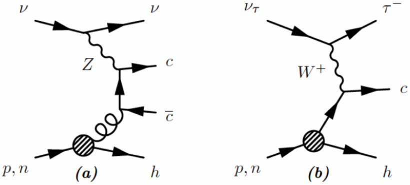
$\nu_\mu \to \nu_\tau$ analysis

Among the 5 new ν_τ candidates: an event with 3 verteces

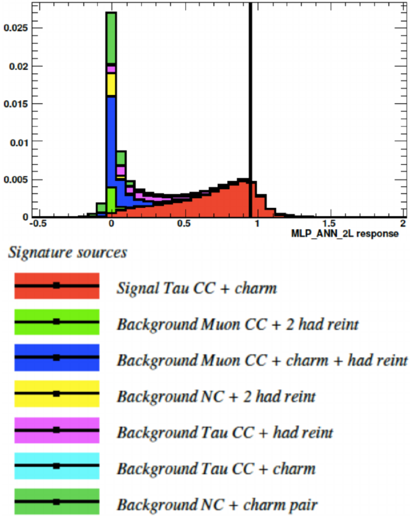
Classified as ν_τ interaction with charm production (first event even observed)

BG hypothesis rejected at 3.4 σ C.L.



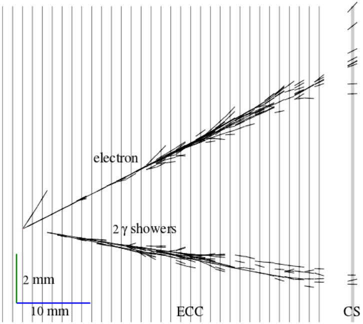


PRELIMINARY



$\nu_\mu \to \nu_e$ analysis

ν_e candidates identification is based on the detection of the electromagnetic shower associated with the primary interaction vertex



$\nu_\mu \to \nu_e$ analysis

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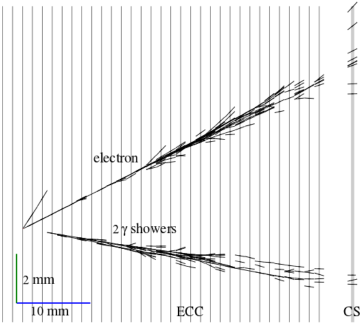
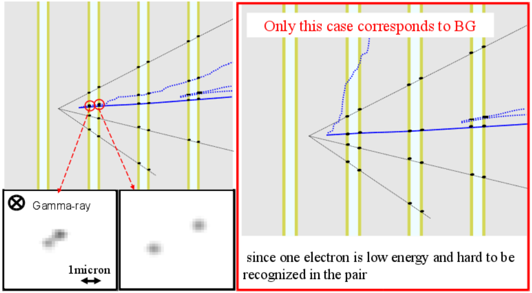


Background sources:

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



$\nu_\mu \to \nu_e$ analysis

No oscillation scenario

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

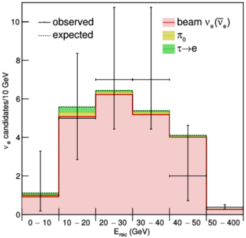
3-flavour oscillation scenario

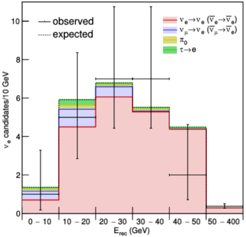
- $34.3 \pm 1.0(stat.) \pm 3.4(syst.)$ (including BG)

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

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

~standard oscillation   Exotic oscillation

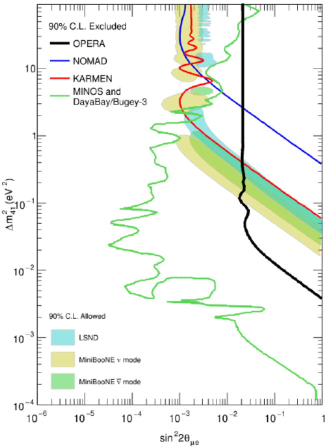
$$P_{\nu_\mu \to \nu_e} = C^2 \sin^2 \Delta_{31} + \sin^2 2\theta_{\mu e} \sin^2 \Delta_{41}$$

Interference term:

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

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

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



JHEP06(2018)151 (arXiv 1803.11400)

Summary

- Full data set analysis is completed (17.97×10^{19} p.o.t.)
- $\nu_\mu \to \nu_\tau$ analysis
  - 10 ν_τ candidates with 2.0 ± 0.4 expected background events
  - No oscillation hypothesis excluded at 6.1 σ using a multi-variate analysis technique
  - First ν_τ cross section measurement with negligible anti-ν_τ contamination
  - ν_τ neutrino interaction with charm production observed
- $\nu_\mu \to \nu_e$ analysis
  - Number of observed candidates is in agreement with the expected background and the standard oscillation signal
  - Constraint on sterile neutrinos in the 3+1 flavour model
- The data is at CERN OPEN Data Portal (first non-LHC experiment to make it's data open)
- Non-oscillation physics: hadron multiplicities, cosmic rays modulation
- Combined oscillation analysis in progress...

Thank you for attention!

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
Frascati,
L'Aquila
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Nihon

Korea
Jinju

Russia
INR RAS Moscow
LPI RAS Moscow
SINP MSU Moscow
JINR Dubna

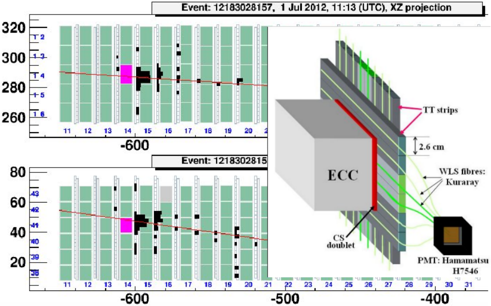
Switzerland
Bern

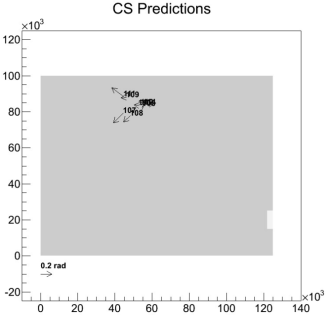
Turkey
METU, Ankara

http://operaweb.lngs.infn.it

Backup slides

Event location procedure

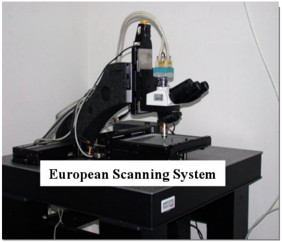




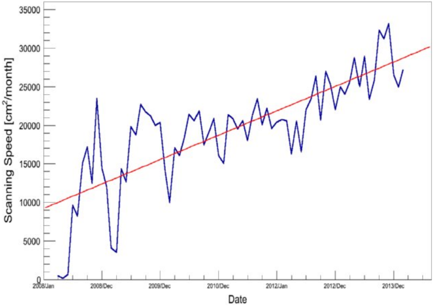
- TT data is used for a prediction of the bricks which contain the neutrino interactions
- A large area of the corresponding changeable film is scanned (so far 2'500'000 cm^2 of CS surface analysed)

Event location procedure

Scanning of Changeable Sheets: two large facilities

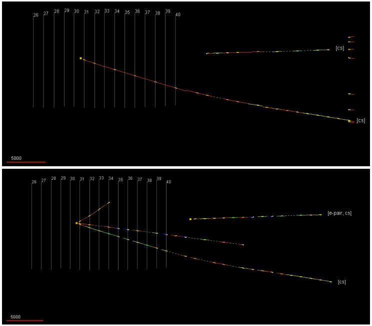


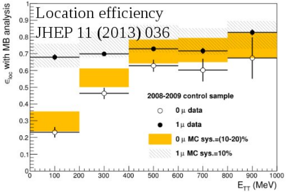
Scanning speed per facility: improvement during the run



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

Event location procedure





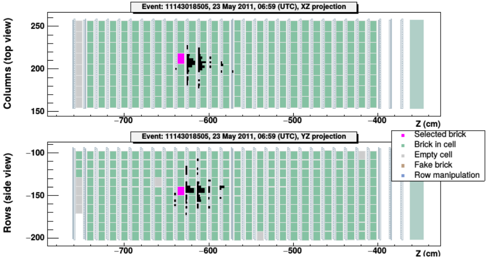
- brick exposure at the surface laboratory to collect cosmic-rays for alignment
- scan-back: CS-tracks are followed upstream from film to film to find the ν-interaction vertex
- total-scan: scanning of the 1 cm^2 around the vertex in 15 plates is performed
- scan-forth: improvement of the momentum measurement 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

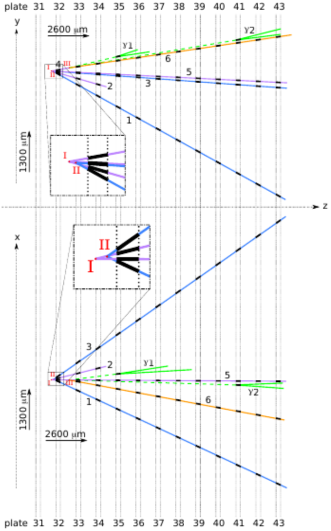
(more details: arXiv:1404.4357 [hep-ex])

3 vertex event



Sample	Muon misidentified	Expected events (10^{-3})
ν_τ CC + charm		45
ν_μ CC + charm + h_{int}	yes	21
ν_μ NC + $c\bar{c}$		13
ν_τ CC + h_{int}		9
ν_μ CC + $2h_{\text{int}}$	yes	4
ν_μ NC + $2h_{\text{int}}$		4
Total		100

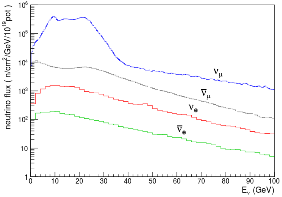
Vertex ID	Attached tracks	x (μm)	y (μm)	z (μm)
I (primary)	2, 4, 5	15077.0	59157.9	-33081.8
II (secondary)	1, 3	15085.9	59149.9	-32979.2
III (kink)	4, 6	15073.9	59262.4	-31926.4



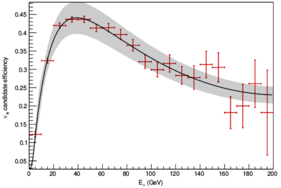
$\nu_\mu \to \nu_e$ analysis

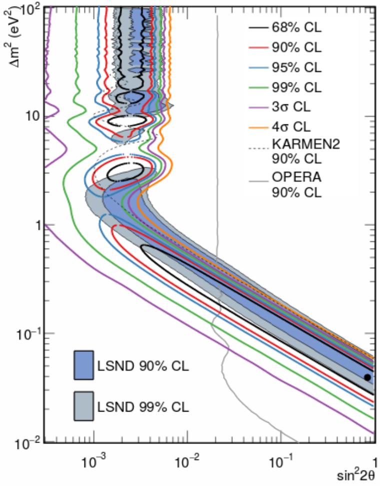
Neutrino fluxes at Gran Sasso

JHEP 1307 (2013) 004



ν_e CC candidates selection efficiency

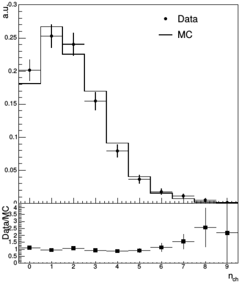




MiniBooNE allowed region

arXiv:1805.12028 [hep-ex]

Study of charged particles multiplicity distribution in Pb

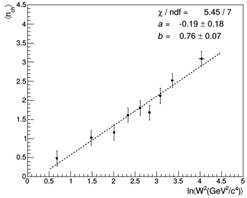


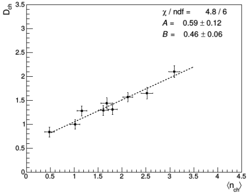
The study is aimed in tuning the models used in MC generators. Eur.Phys.J. C78 (2018) 1, 62

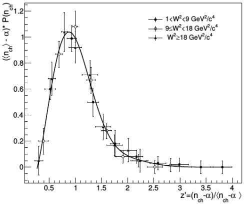
- Linear dependence $< n_{ch} >= a + b \cdot lnW^2$
- Linear dependence $< D_{ch} >= A + B \cdot < n_{ch} >$
- Aproximate KNO (Koba, Nielsen, Olesen) scaling is valid for the charged hadrons multiplicity

$< n_{ch} >$ — the average multiplicity
$< D_{ch} >$ — dispersion of $< n_{ch} >$

W^2 — invariant mass of the hadronic system





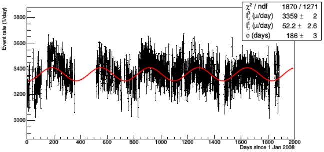


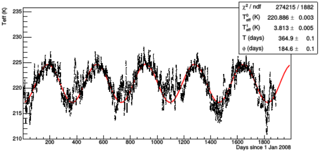
Annual modulations of atmospheric muons

Gran Sasso underground ~3 800 m w.e. → Minimum muon energy ~1.8 TeV

Atmospheric temperature increase → density decrease → the pions and kaons decay rate increase → muon rate increase

$I_\mu(t) = I^0_\mu + \Delta I_\mu = I^0_\mu + \delta I_\mu cos[\frac{2\pi}{T}(t - t_0)]$ **PRELIMINARY**





Temperature data by the ECMWF

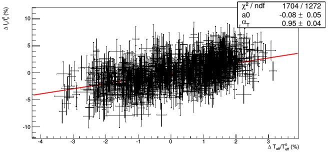
$T = 364.9 \pm 0.1$

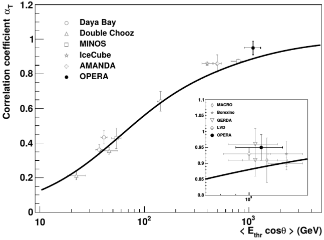
$t_0 = 186 \pm 3_{stat} \pm 5_{sys}$

$\frac{\Delta I_\mu}{I^0_\mu} = \alpha_T \frac{\Delta T_{eff}}{T_{eff}}$

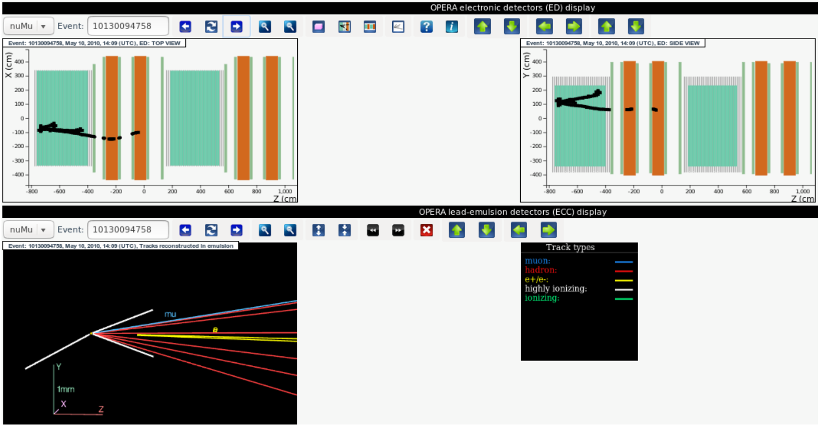
$\frac{\Delta I_\mu}{I^0_\mu} = (1.55 \pm 0.08)\%$

$\alpha_T = 0.95 \pm 0.04$





CERN Open Data Portal



http://opendata.cern.ch/visualise/events/opera
http://opendata.cern.ch/docs/opera-news-first-release-2018