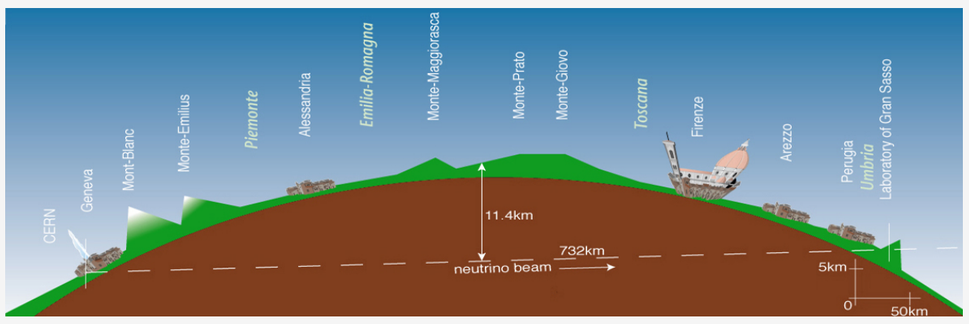
OPERA - Oscillation Project with Emulsion Tracking Apparatus

Benjamin Büttner, Joachim Ebert, Christoph Göllnitz, Caren Hagner, Annika Hollnagel, Jan Lenkeit, Walter Schmidt-Parzefall, Björn Wonsak

The OPERA Experiment

Appearance search:

- First direct observation of $\nu_\mu \to \nu_\tau$ oscillations
- Detection of τ lepton production & decay

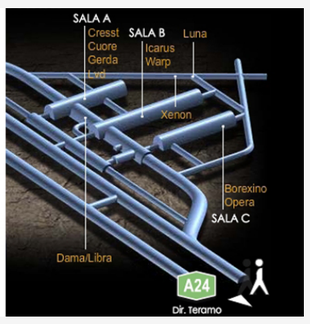


Realisation:

- High-intensity long-baseline ν_μ beam from CERN to LNGS
- **Large target mass ($\lesssim 1.28\,\mathrm{kt}$):**
  - ▷ Instrumentation with electronic detector elements (ED)
- **μm-precision:**
  - ▷ Emulsion Cloud Chamber photo emulsions (ECC)

The LNGS Underground Laboratory

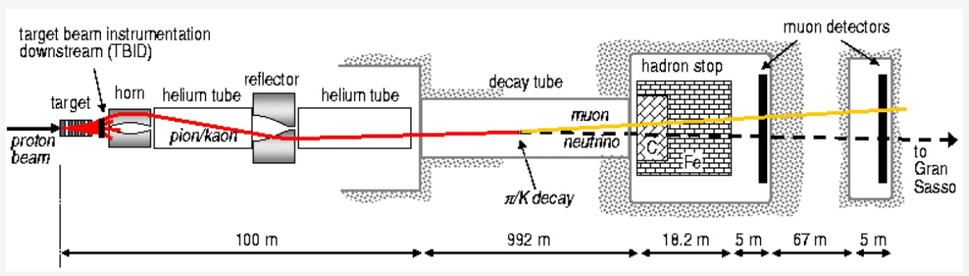
LNGS: Laboratori Nazionali del Gran Sasso



- **Location:** Gran Sasso, Italy
- **Baseline:** $\sim 732\,\mathrm{km}$ away from the ν_μ source at CERN
- **Vertical rock coverage:** $1\,300\,\mathrm{m}$ ($3\,400\,\mathrm{m}\ w.e.$)
- ▷ **Number of cosmic μ:** $\sim 1\,\mathrm{m^{-2}h^{-1}}$

The CNGS Neutrino Beam

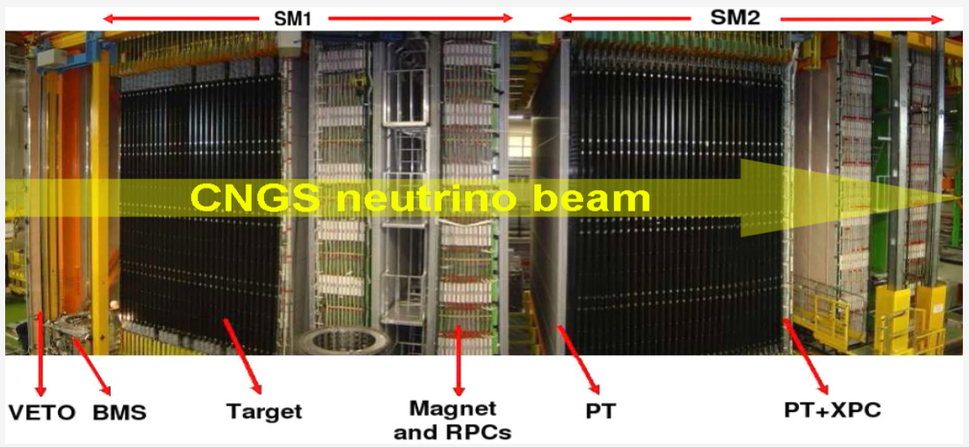
CNGS: CERN Neutrinos to Gran Sasso



year	$p.o.t.$	# ν interactions
2008	1.78×10^{19}	1698
2009	3.52×10^{19}	3557
2010	4.04×10^{19}	3912
2011	4.84×10^{19}	4210
2012	3.89×10^{19}	3680
Total	18.1×10^{19}	17057

$\langle E_p \rangle$	400 GeV
$\langle E_\nu \rangle$	17 GeV
ν_e/ν_μ (CC)	0.89 %
$\overline{\nu}_\mu/\nu_\mu$ (CC)	2.1 %
$\overline{\nu}_e/\nu_\mu$ (CC)	0.06 %
ν_τ/ν_μ (CC)	$< 10^{-4}$ %

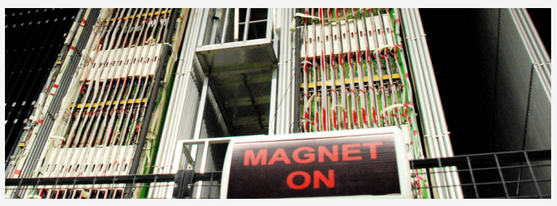
The OPERA Detector



2 **identical Super Modules (SM), each consisting of:**

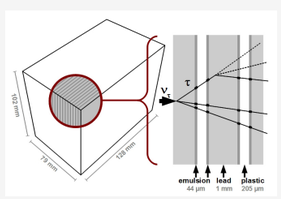
- **Target area**
- **Magnetic spectrometer**, downstream of the target area

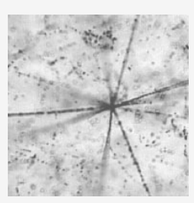
Magnetic Spectrometer



- **Dipole Magnets:** $1.55\,\mathrm{T}$
- **Resistive Plate Chambers (RPC & XPC)**
- **Precision Trackers (PT):** $\sim 10\,000$ drift tubes ($80\%\,\mathrm{Ar}, 20\%\,\mathrm{CO_2}$), built by the Hamburg group

Target Area





- **Target Trackers (TT):** 31 walls of horizontal and vertical scintillator strips
- **Each ECC brick:** 57×2 photo emulsions on plastic bases, 56 lead plates
- **In total:** $\sim 150\,000$ bricks of $8.3\,\mathrm{kg}$ lead each ($\sim 1.28\,\mathrm{kt}$ target mass)

3-Flavour Neutrino Oscillations

Mixing of mass and flavour eigenstates:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}}_{U} \times \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

$$U = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \times \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix} \times \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \times \begin{pmatrix}e^{i\epsilon_1/2} & 0 & 0\\ 0 & e^{i\epsilon_2/2} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Atmospheric terms — Unknown terms — Solar terms — Majorana terms

SuperKamiokande, MINOS, OPERA — **DoubleChooz,T2K** — **KamLAND**

Oscillation Parameters:

$\lvert\Delta m^2_{32}\rvert$	$(2.32^{+0.12}_{-0.08}) \times 10^{-3}\,\mathrm{eV}^2$
Δm^2_{21}	$(7.50 \pm 0.20) \times 10^{-5}\,\mathrm{eV}^2$
$\sin^2(2\theta_{23})$	> 0.95
$\sin^2(2\theta_{12})$	0.857 ± 0.024
$\sin^2(2\theta_{13})$	0.098 ± 0.013
δ	?

OPERA Expected Performance

($22.5 \times 10^{19} p.o.t.$, $\Delta m^2_{23} = 2.5 \times 10^{-3}\,\mathrm{eV}^2$)

- **ν_μ CC + NC interactions:** ~ 23600
- **$\nu_e + \overline{\nu}_e$ CC interactions:** ~ 160
- **ν_τ CC interactions:** ~ 115

τ decay channel	BR [%]	Number of signal events	Number of BG events
$\tau^- \to \mu^-$	17.7	1.79	0.09
$\tau^- \to e^-$	17.8	2.89	0.22
$\tau^- \to h^-$	49.5	2.25	0.24
$\tau^- \to 3h$	15.0	0.71	0.18
Total		7.63	0.73

ν_τ Detection

τ creation:

- **ν_τ CC reactions:** $\nu_\tau + N \to \tau^- + X$

τ decay modes (1-prong):

- **Muonic:** $\tau^- \to \mu^- + \nu_\tau + \overline{\nu}_\mu$
- **Electronic:** $\tau^- \to e^- + \nu_\tau + \overline{\nu}_e$
- **Hadronic:** $\tau^- \to h^- + \nu_\tau + X^0$

τ decay modes (3-prong):

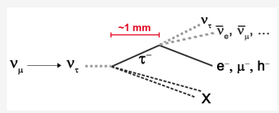
- **Hadronic:** $\tau \to 2h^- + h^+ + \nu_\tau + X^0$

τ decay length:

- $\sim 600\,\mu\mathrm{m}$

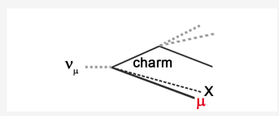
ν_τ signal:

- ν_τ CC interactions and τ^- lepton decay with 'kink' topology:



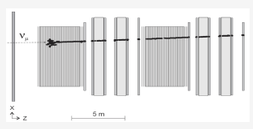
Background processes:

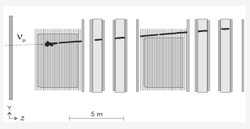
- ν_μ CC reactions with charm production & undetected 1ry μ:



- Hadronic re-interactions in lead
- Large-angle μ scattering

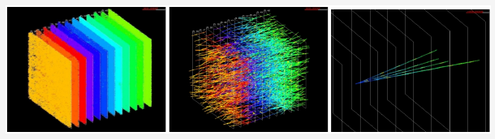
ED Event Reconstruction





- Provision of time resolution
- ν interaction vertex localisation
- CC/NC separation
- μ identfication & momentum measurement
- Hadronic shower energy reconstruction

ECC Event Reconstruction



- Reconstruction of $3D$ track segments
- Rejection of passing-through and low-energy tracks
- Vertex reconstruction
- Decay search procedure

The First ν_τ Candidate Events

A ν_e Event

OPERA Publications of Note

- N. Agafonova *et al.* [OPERA Collaboration], "Search for $\nu_\mu \to \nu_\tau$ oscillation with the OPERA experiment in the CNGS beam", New J. Phys. **14** (2012) 033017
- N. Agafonova *et al.* [OPERA Collaboration], "Study of neutrino interactions with the electronic detectors of the OPERA experiment", New J. Phys. **13** (2011) 053051
- N. Agafonova *et al.* [OPERA Collaboration], "Observation of a first ν_τ candidate event in the OPERA experiment in the CNGS beam", Phys. Lett. B **691** (2010) 138-145
- N. Agafonova *et al.* [OPERA Collaboration], "Measurement of the atmospheric muon charge ratio with the OPERA detector", Eur. Phys. J. C **67** (2010) 25-37
- N. Agafonova *et al.* [OPERA Collaboration], "The detection of neutrino interactions in the emulsion/lead target of the OPERA experiment", JINST **4** (2009) P06020
- R. Acquafredda *et al.* [OPERA Collaboration], "The OPERA experiment in the CERN to Gran Sasso neutrino beam", JINST **4** (2009) P04018
- R. Zimmermann *et al.*, "The precision tracker of the OPERA detector", NIMA **555** (2005) 435

The OPERA Collaboration

Belgium:
- IIHE-ULB Bruxelles

Croatia:
- IRB Zagreb

France:
- LAPP Annecy
- IPHC Strasbourg

Germany:
- Hamburg University

Italy:
- Bari
- Bologna
- Frascati
- l'Aquila
- Naples
- Padova
- Roma
- Salerno

Israel:
- Technion Haifa

Japan:
- Aichi University
- Toho University
- Kobe University
- Nagoya University
- Utsunomiya University

Korea:
- Jinju University

Russia:
- INR RAS Moscow
- LPI RAS Moscow
- ITEP Moscow
- SINP MSU Moscow
- JINR Dubna

Switzerland:
- Bern University

Turkey:
- METU Ankara