The OPERA Experiment

Latest Results

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Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

bmb+f - Förderschwerpunkt
OPERA
Großgeräte der physikalischen Grundlagenforschung

Neutrino Oscillations

Neutrino oscillation in disappearance mode:

- **First observation:** SK, MACRO...
- **Further studies:** SNO, MINOS, KamLAND, Borexino...

Neutrino oscillation in appearance mode:

- Observation needed to establish the picture of neutrino oscillations

Solar scale:

- $\nu_e \to \nu_\mu$: Below threshold for μ production

Atmospheric scale:

- $\nu_\mu \to \nu_e$: Sub-leading (T2K, OPERA)
- $\nu_\mu \to \nu_\tau$: ν_μ from cosmic rays (SK: statistical analysis, large BG)
- $\nu_\mu \to \nu_\tau$: ν_μ from long-baseline beams
  OPERA: τ lepton identification on an event-by-event basis

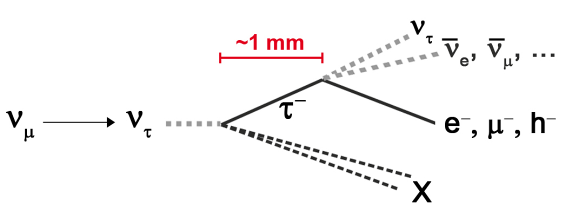
The OPERA Experiment

The OPERA experiment
in the CERN to Gran Sasso neutrino beam,
JINST **4** (2009) P04018

The OPERA Experiment

OPERA: Oscillation Project with Emulsion Tracking Apparatus

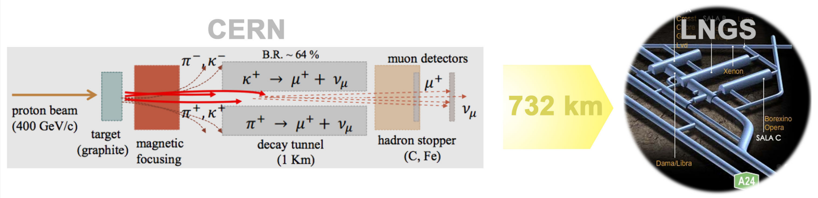
- **Appearance search:** Direct observation of $\nu_\mu \to \nu_\tau$ oscillations
  detection of τ production & decay
  - **Characteristic 'kink' topology:**



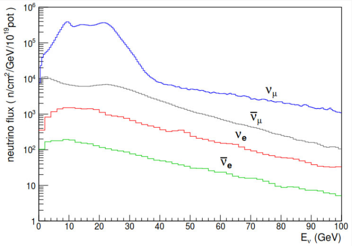
- **ν beam:** High-intensity & high-energy long-baseline ν_μ beam
- **Detector:** Large target mass, high precision $\mathcal{O}(\mu\text{m})$
- **Location:** Laboratori Nazionali del Gran Sasso (LNGS)
  $1\,400\,\text{m}$ rock coverage, $3\,800\,\text{m}$ *w.e.*

The CNGS ν_μ Beam

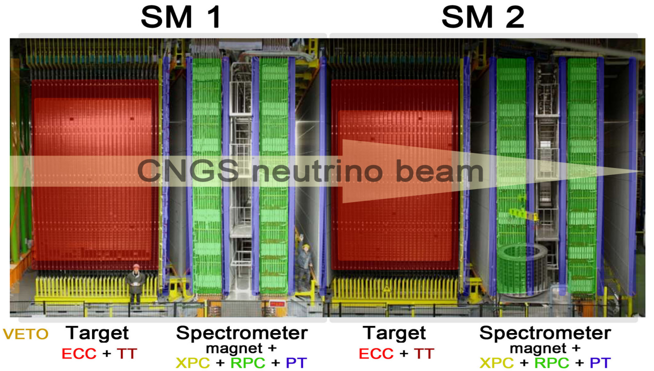
CNGS: CERN Neutrinos to Gran Sasso (2008 – 2012)



$\langle E_\nu \rangle$		17 GeV
$\overline{\nu}_\mu/\nu_\mu$	CC	2.1 %
ν_e/ν_μ	CC	0.89 %
$\overline{\nu}_e/\nu_\mu$	CC	0.06 %
ν_τ/ν_μ	CC	$< 10^{-4}$ %
p.o.t. (total)		17.97×10^{19}



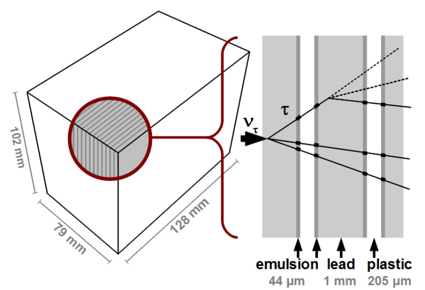
The OPERA Detector

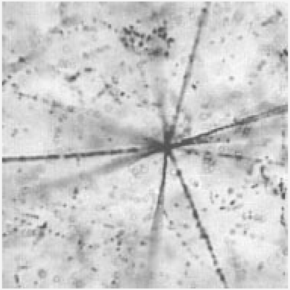


Hybrid detector (ED & ECC):

- 2 identical Super Modules (SM) + VETO system
- **Spectrometer:** RPC & XPC, PT
- **Target Area:** TT, ECC bricks

The OPERA Detector

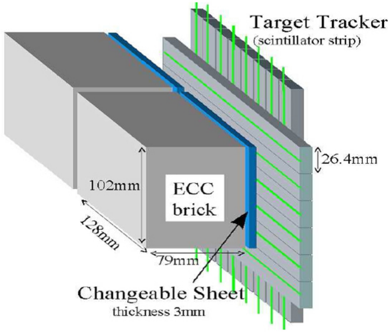




Emulsion Cloud Chamber (ECC) bricks:

- 57 × 2 AgBr nuclear emulsions on plastic bases, interleaved with 56 lead plates ($\sim 10\,X_0$)
- **Total:** $\sim 150\,000 \times 8.3\,\mathrm{kg}$ $\sim 1.25\,\mathrm{kt}$ total target mass
- **Spatial / angular resolution:** $\sim 1\,\mu\mathrm{m}$ / $\sim 2\,\mathrm{mrad}$

The OPERA Detector



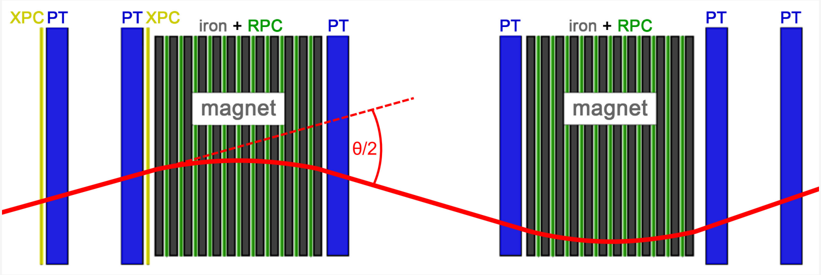
Changeable Sheets (CS):

- 2 extra nuclear emulsion sheets per brick

Target Tracker (TT) detectors:

- Plastic scintillator strips (horizontal & vertical), 31 walls per SM

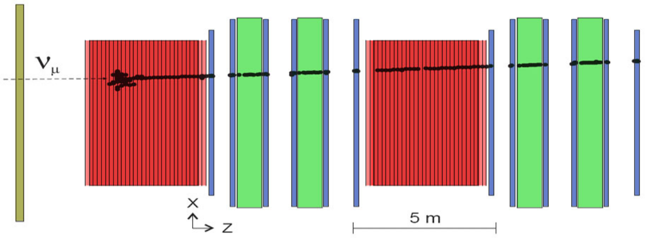
The OPERA Detector



Magnetic Spectrometer:

- Downstream of each target area
- **Magnets**: Iron core dipole, $1.55\,\mathrm{T}$
- **RPC, XPC:** Resistive plate chambers
- **Precision Tracker (PT):** $\sim 10\,000$ drift tubes

Event Reconstruction

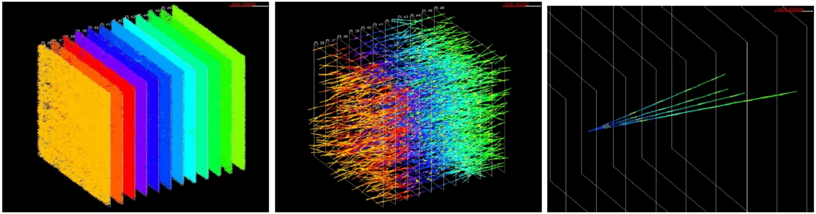


ED event reconstruction:

- **Time resolution:** $\mathcal{O}(\mathrm{ns})$
- μ identification, charge & momentum measurement
- Hadronic shower energy reconstruction
- ν interaction brick localisation

▷ **Trigger:** ECC event reconstruction

Event Reconstruction



ECC event reconstruction:

- **Spatial resolution:** $\mathcal{O}(\mu\mathrm{m})$
- $3D$ track segment & track reconstruction
- ν interaction vertex localisation
- τ decay search procedure:
  - ▷ kink angle / IP measurement, parent / daughter search...
- Momentum measurement via MCS

Oscillation Search:

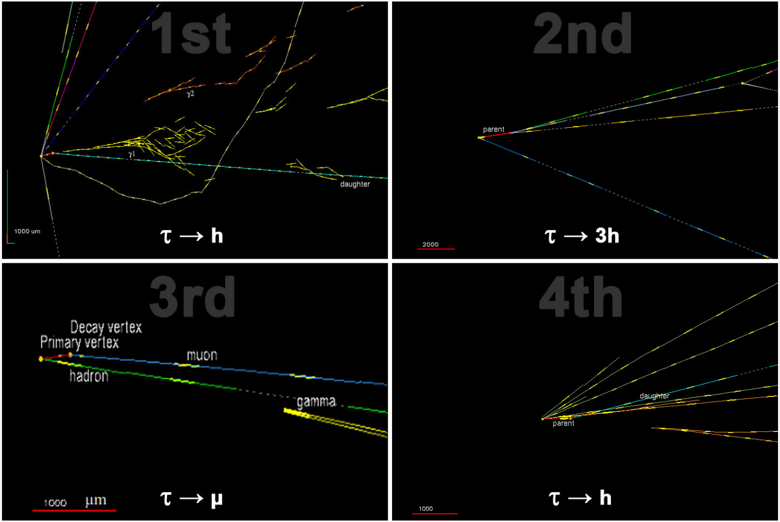
$$\nu_\mu \to \nu_\tau$$

Observation of ν_τ appearance in the CNGS beam with the OPERA experiment,
Prog. Theor. Exp. Phys. (2014) 101C01

Limits on muon-neutrino to tau-neutrino oscillations induced by a sterile neutrino state obtained by OPERA at the CNGS beam,
arXiv:1503.01876v1 (2015), submitted to JHEP

$\nu_\mu \to \nu_\tau$ Oscillation Search

4 confirmed ν_τ candidate events:



$\nu_\mu \to \nu_\tau$ Oscillation Search

Fully analysed data sample: 4685 events

- **2008/09:** 1st & 2nd most probable bricks
- **2010/11/12:** 1st most probable brick
- 0μ events & 1μ events with $p_\mu < 15\,\mathrm{GeV/c}$

τ decay channel	Signal (exp.) $\Delta m^2_{23} = 2.32\,\mathrm{meV}^2$	Total BG (exp.)	Data (obs.)
$\tau \to h$	0.41 ± 0.08	0.033 ± 0.006	2
$\tau \to 3h$	0.57 ± 0.11	0.155 ± 0.030	1
$\tau \to \mu$	0.52 ± 0.10	0.018 ± 0.007	1
$\tau \to e$	0.62 ± 0.12	0.027 ± 0.005	0
Total	2.11 ± 0.42	0.233 ± 0.041	4

Observation of ν_τ appearance:

- **p-value:** 1.24×10^{-5} (Fisher) / 1.03×10^{-5} (Likelihood)

▷ **No-oscillation hypothesis excluded @ 4.2σ**

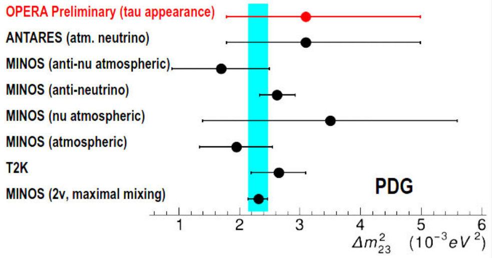
$\nu_\mu \to \nu_\tau$ Oscillation Search

$$N_{\nu_\tau} \propto \int \Phi(E)\sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right)\epsilon(E)\sigma(E)dE \propto (\Delta m^2_{23})^2 L^2 \int \Phi(E)\epsilon(E)\frac{\sigma(E)}{E^2}dE$$

First measurement of Δm^2_{23} in appearance mode:

- $\Delta m^2_{23} = [1.8 - 5.0] \times 10^{-3}\,\mathrm{eV}^2$ **(Feldman&Cousins)**
- $\Delta m^2_{23} = [1.9 - 5.0] \times 10^{-3}\,\mathrm{eV}^2$ **(Bayes)**

(for $\sin^2(2\theta_{23}) = 1$ at 90% C.L.)



$\nu_\mu \to \nu_\tau$ Non-Standard Oscillations

$3+1$ analysis (approx.):

$$P(E) = C^2 \sin^2\Delta_{31} + \frac{1}{2}\sin^2 2\theta_{\mu\tau} + C\sin 2\theta_{\mu\tau}\cos\phi_{\mu\tau}\sin^2\Delta_{31} + \frac{1}{2}C\sin 2\theta_{\mu\tau}\sin\phi_{\mu\tau}\sin 2\Delta_{31}$$

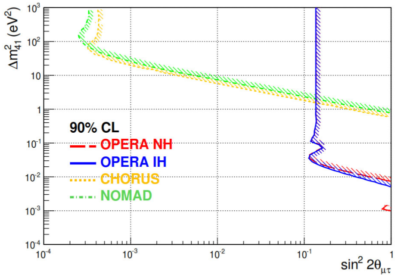
Likelihood analysis:

- ν_τ **candidates:** 4 events
- **Expected (2-fl. + BG):**
  $2.30 + 0.23$ events (NH)
  $2.21 + 0.23$ events (IH)

▷ **New limits (FC, 90% C.L.):**

$\sin^2(2\theta_{\mu\tau}) < 0.116$
for large Δm^2_{41}

$\Delta m^2_{41} < 7.4 \times 10^{-3}\,\mathrm{eV}^2$ (NH)
$\Delta m^2_{41} < 5.2 \times 10^{-3}\,\mathrm{eV}^2$ (IH)
for maximal mixing



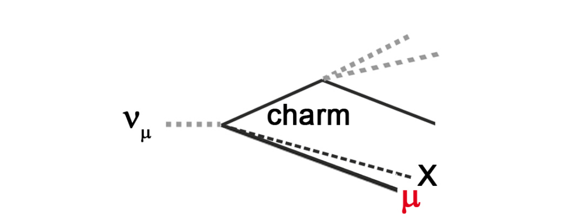
Control Sample: Charmed Particle Decays

Procedure for short-lived particle detection in the OPERA experiment and its application to charm decays,
Eur. Phys. J. C **74** (2014) 2986

Control Sample: Charmed Particle Decays

Main BG to τ search:

- ν_μ CC interactions with charm production



- Topology similar to τ decay
- μ at 1ry vertex

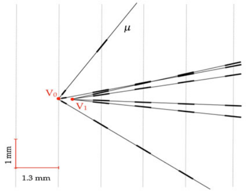
Other BG:

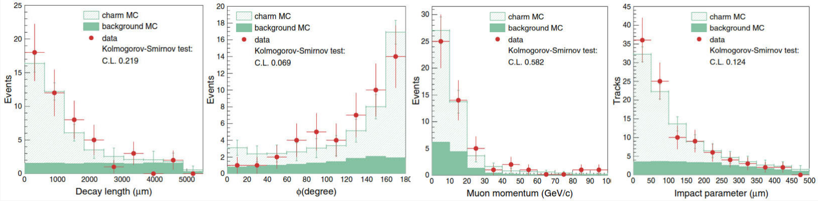
- Hadronic re-interactions in lead
- Large-angle μ scattering

Control Sample: Charmed Particle Decays

2008 – 2010 OPERA data:

	Charm (exp.)	BG (exp.)	Total (exp.)	Data (obs.)
1-prong	21 ± 2	9 ± 3	30 ± 4	19
2-prong	14 ± 1	4 ± 1	18 ± 1	22
3-prong	4 ± 1	1.0 ± 0.3	5 ± 1	5
4-prong	0.9 ± 0.2	–	0.9 ± 0.2	4
Total	40 ± 3	14 ± 3	54 ± 4	50





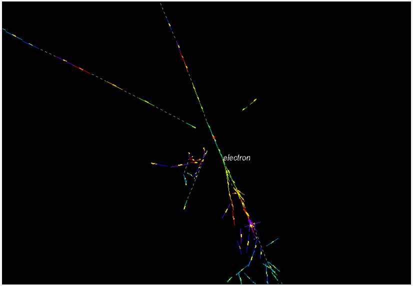
Oscillation Search:

$$\nu_\mu \to \nu_e$$

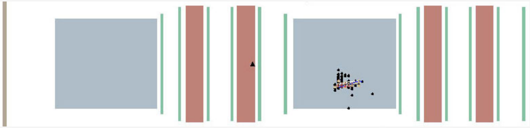
Search for $\nu_\mu \to \nu_e$ oscillations with the OPERA experiment in the CNGS beam, JHEP **1307** (2013) 004

A ν_e Event

ECC reconstruction:

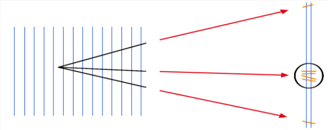


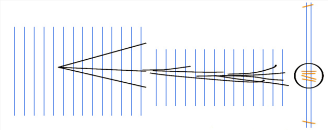
ED reconstruction:



Systematic ν_e Event Selection

CS *em* shower hints:





- Interpolation of 1ry vertex tracks to CS
- ▷ Expanded scan volume
- Analysis of downstream bricks

Backgrounds:

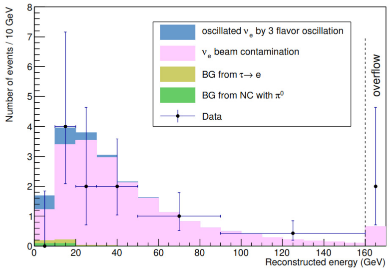
- ν_e from intrinsic beam contamination
- e^+e^- from π^0 decays misidentified as single-e
- ν_τ CC interactions with $\tau \to e$

ν_e Energy Reconstruction

2008 + 2009 data sample:

- 5255 ν CC interactions $(5.25 \times 10^{19}\ \mathrm{p.o.t.})$
  - ▷ **ν_e candidates:** 19 events

Separation of signal & BG: Cuts on $E_{\nu,rec}$



- **3-flavour oscillations:** $E_{\nu,rec} < 20\ \mathrm{GeV}$
- **Nonstandard oscillations:** $E_{\nu,rec} < 30\ \mathrm{GeV}$

Oscillation Analysis

3-flavour: $P(\nu_\mu \to \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2 \left(\Delta m^2_{23} \frac{L}{4E}\right)$

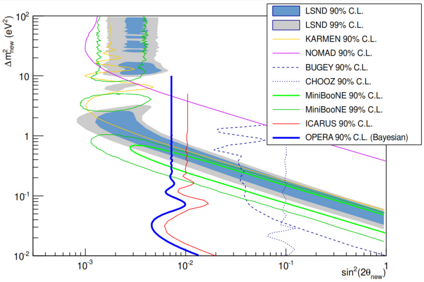
- **ν_e candidates:** 4 events
- **Expected BG + signal:** $4.6 + 1.0$ events

▷ **Compatible with no-oscillation hypothesis:**
$\sin^2(2\theta_{13}) < 0.44$ (90% C.L.)

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

- **ν_e candidates:** 6 events
- **Expected BG:** 9.4 events

▷ **New limits (Bayes, 90% C.L.):**
$\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$
for $\Delta m^2_{new} > 0.1\,\mathrm{eV}^2$



Conclusion & Outlook

Conclusion & Outlook

Oscillation Search: $\nu_\mu \to \nu_\tau$

- 4 ν_τ candidate events observed (0.23 BG events expected)
  - ▷ **Observation of ν_τ appearance @ 4.2σ**
  - ▷ First measurement of Δm^2_{23} in appearance mode
- **Non-standard analysis:** New limits on Δm^2_{41} vs. $\sin^2(2\theta_{\mu\tau})$

Outlook:

- **Improvements:** Data sample, statistical methods, knowledge of BG...

Oscillation Search: $\nu_\mu \to \nu_e$

- **3-flavour analysis:** Compatible with no-oscillation hypothesis
- **Non-standard analysis:** New limits on Δm^2_{new} vs. $\sin^2(2\theta_{new})$

Outlook:

- **Improvements:** Data sample, energy reconstruction...

Thank you for your attention!

11 countries, 28 institutes, 140 physicists...

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- IIHE-ULB Brussels

Croatia:
- IRB Zagreb

France:
- LAPP Annecy
- IPHC Strasbourg

Germany:
- Hamburg University

Israel:
- Technion Haifa

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

Japan:
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- Toho
- Kobe
- Nagoya
- Nihon

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- ITEP Moscow
- INR-RAS Moscow
- LPI-RAS Moscow
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