The OPERA Experiment

Concluding the Neutrino Oscillation Analysis

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DPG-Frühjahrstagung 2017, Münster

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:** **SuperKamiokande**, MACRO...
- **Further studies:** **SNO**, K2K, MINOS...

Neutrino oscillation in appearance mode:

- Observation needed to establish the picture of neutrino oscillations

Solar scale:

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

Atmospheric scale:

- $\nu_\mu \rightarrow \nu_\tau$: ν_μ from cosmic rays (SK, IceCube, ORCA)
- $\nu_\mu \rightarrow \nu_\tau$: ν_μ from long-baseline beams
  OPERA: Event-by-event τ lepton identification
- $\nu_\mu \rightarrow \nu_e$: Sub-leading (T2K, OPERA)

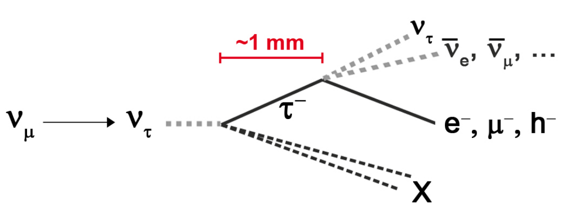
The OPERA Experiment

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

OPERA: Oscillation **P**roject with **E**mulsion **T**racking **A**pparatus

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

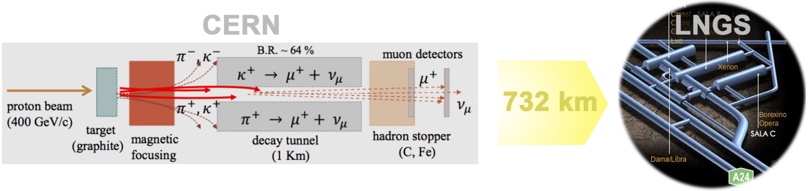
▷ **Characteristic 'kink' topology:**



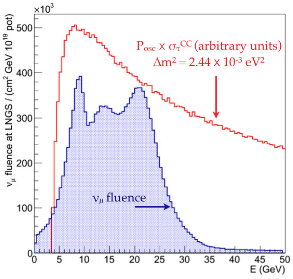
- **ν beam:** High-intensity & high-energy long-baseline ν_μ beam
- **Detector:** Large target mass, high precision $\mathcal{O}(\mu\mathrm{m})$
- **Location:** **L**aboratori **N**azionali del **G**ran **S**asso (LNGS)
  $1\,400\,\mathrm{m}$ rock coverage, $3\,800\,\mathrm{m}$ *w.e.*

The CNGS ν_μ Beam

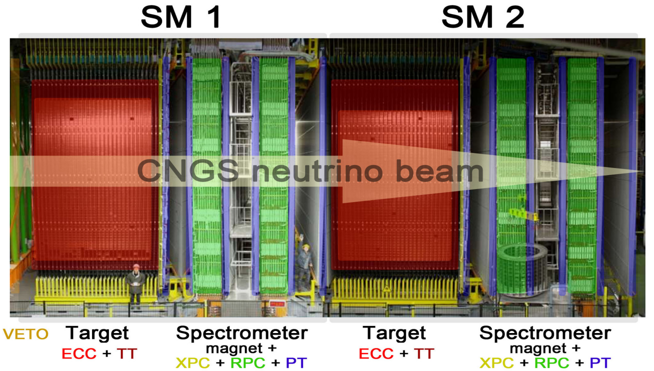
CNGS: CERN Neutrinos to Gran Sasso (2008 – 2012)



$\langle E_\nu \rangle$		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}
ν interactions		19505

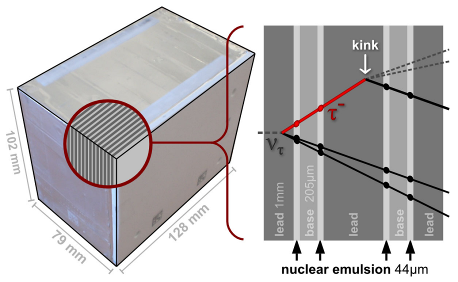


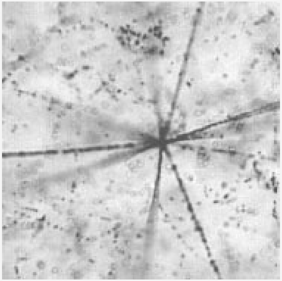
The OPERA Detector



Hybrid detector (ED & ECC):

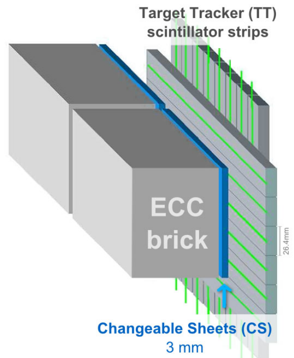
- 2 identical Super Modules (SM) + VETO system
- **Spectrometer:** RPC & XPC, PT
- **Target Area:** TT, ECC bricks





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:** $\sim 1\,\mu\mathrm{m}$ / $\sim 2\,\mathrm{mrad}$

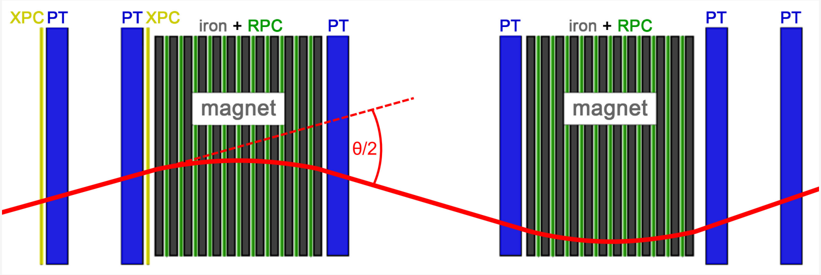


Changeable Sheets (CS):

- 2 extra nuclear emulsion sheets per brick

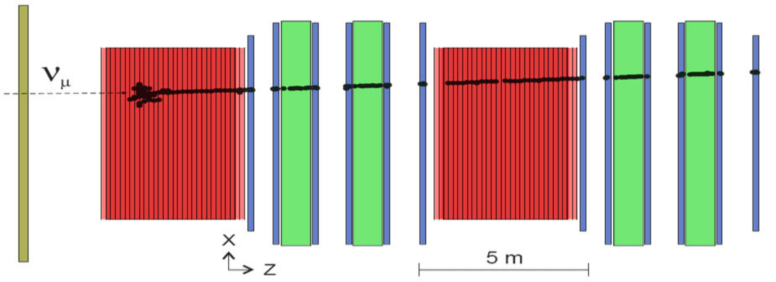
Target Tracker (TT) detectors:

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



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

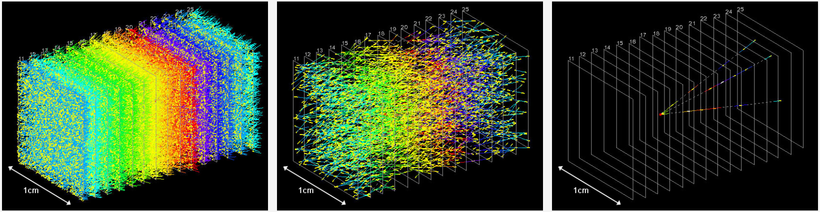


ED event reconstruction:

- **Time resolution:** $\mathcal{O}(\text{ns})$
- 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 Analysis:

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

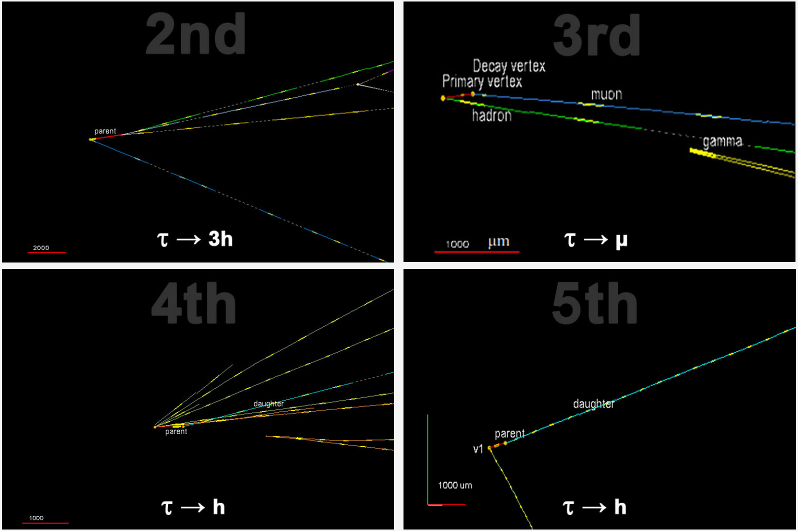
Discovery of τ Neutrino Appearance in the CNGS Neutrino Beam with the OPERA experiment, Physical Review Letters **115**, 121802 (2015)

The 1st ν_τ Candidate Event:

- **1ry vertex:** 7 tracks
- τ **candidate:** 1-prong decay after $(1335 \pm 35)\,\mu\text{m}$

▷ **Decay channel:** $\tau \to h$

The Following 4 ν_τ Candidates



Previous data sample (2008 – 2012): 5408 DS events

- 1st & 2nd most probable bricks
- All 0μ events & 1μ events with $p_\mu < 15\,\mathrm{GeV/c}$

τ decay channel	Signal (exp.) $\Delta m^2_{23} = 2.44\,\mathrm{meV}^2$ $\sin^2 2\theta_{23} = 1$	Total BG (exp.)	Data (obs.)
$\tau \to 1h$	0.52 ± 0.10	0.04 ± 0.01	3
$\tau \to 3h$	0.73 ± 0.14	0.17 ± 0.03	1
$\tau \to \mu$	0.61 ± 0.12	0.004 ± 0.001	1
$\tau \to e$	0.78 ± 0.16	0.03 ± 0.01	0
Total	2.64 ± 0.53	0.25 ± 0.05	5

Discovery of ν_τ appearance:

- **p-value:** 1.10×10^{-7} (Fisher) / 1.07×10^{-7} (profile likelihood)

▷ **No-oscillation hypothesis excluded @ 5.1σ**

Final data sample (2008 – 2012): 5603 DS events

- 1st & 2nd most probable bricks
- All 0μ events & 1μ events with $p_\mu < 15\,\mathrm{GeV/c}$

▷ **Increased statistics: +195 DS events**

Minimum bias analysis:

- Loosened kinematical cuts
- Boosted Decision Trees (kin. & topol. variables)

▷ Improved signal-to-noise ratio

▷ **Increased statistics:**

	Signal (exp.)	Total BG (exp.)	Data (obs.)
Total	5.88 ± 1.18	1.86 ± 0.5	10

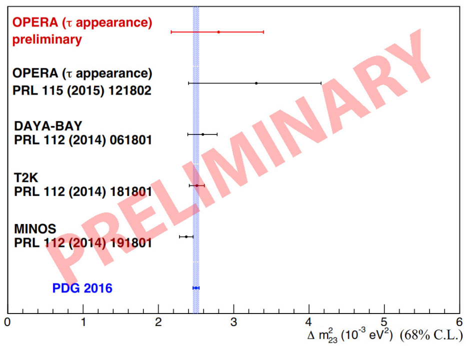
PRELIMINARY

▷ **5 new ν_τ candidates**

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

- $N_{\nu_\tau} \propto (\Delta m^2_{23})^2 L^2 \int \Phi(E)\epsilon(E)\frac{\sigma(E)}{E^2} dE$
- $\Delta m^2_{23} = 2.95 \times 10^{-3}\,\mathrm{eV}^2 \quad ([1.98 - 3.95] \times 10^{-3}\,\mathrm{eV}^2)$ PRELIM.

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



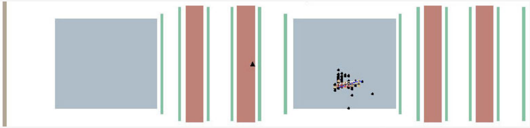
Oscillation Analysis:

$$\nu_\mu \rightarrow \nu_e$$

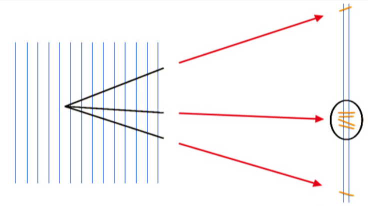
Search for $\nu_\mu \rightarrow \nu_e$ oscillations with the OPERA experiment in the CNGS beam, JHEP **1307** (2013) 004

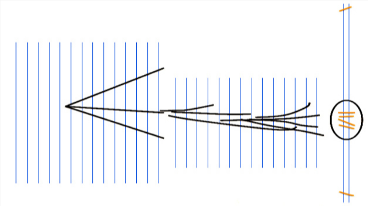
ECC reconstruction:

ED reconstruction:



CS *em* shower hints:





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

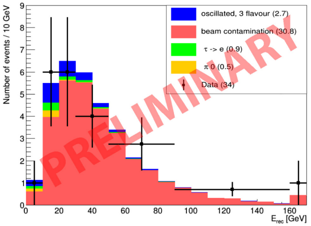
Backgrounds:

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

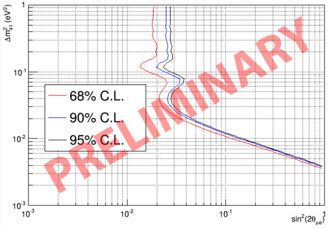
Final data sample (2008 – 2012): 1185 events

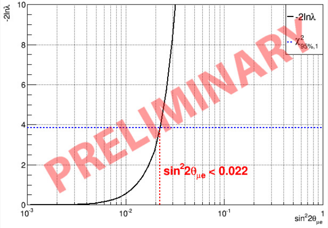
Contribution	Expected events 17.97×10^{19} p.o.t.
Beam contamination	30.8
$\tau \rightarrow e$	0.9
π^0	0.5
$\nu_\mu \rightarrow \nu_e$	2.7
Total	34.9
Observed	34

PRELIMINARY



3+1 energy shape analysis: $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$





Conclusion & Outlook

Conclusion & Outlook

$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis: Standard analysis

- 5 ν_τ candidate events observed (0.25 BG events expected)
  - ▷ **Discovery of ν_τ appearance** @ 5.1σ

Outlook: $\nu_\mu \rightarrow \nu_\tau$ Minimum bias analysis

- Improved statistics and signal-to-noise ratio
  - ▷ **Measurement of Δm^2_{23}** in appearance mode
  - ▷ **Measurement of ν_τ cross section**
  - ▷ **Sterile neutrino analysis**

Outlook: $\nu_\mu \rightarrow \nu_e$ analysis (full data sample)

- Improved statistics and analysis method
  - ▷ **Sterile neutrino analysis:** 3+1 energy shape analysis
  - ▷ **3-flavour neutrino analysis**

Conclusion & Outlook

Further studies:

- **Combined analysis:** $\nu_\mu \to \nu_\tau$, $\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\mu$
- 0μ double decay event
- Charged particle multiplicity distributions
- Annual μ rate modulation

Future experiments:

- **Improved nuclear emulsions & scanning techniques:**
  - ▷ Muon radiography, directional DM search, γ telescopes...
- **SHiP:**
  - ▷ OPERA-like ECC bricks
  - ▷ Drift tubes
- **JUNO:**
  - ▷ OPERA RPC

Thank you for your attention!

11 countries, 28 institutes, 140 physicists...

Belgium:
- IIHE-ULB Brussels

Croatia:
- IRB Zagreb

France:
- LAPP Annecy
- IPHC Strasbourg

Germany:
- Hamburg University

Israel:
- Technion Haifa

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

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- Toho
- Kobe
- Nagoya
- Nihon

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- ITEP Moscow
- INR-RAS Moscow
- LPI-RAS Moscow
- SINP-MSU Moscow

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