The OPERA Experiment

Neutrino Oscillation Search
– Group Report –

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Universität Hamburg
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bmb+f - Förderschwerpunkt
OPERA
Großgeräte der physikalischen Grundlagenforschung

Overview

The OPERA Experiment

The OPERA Experiment

OPERA: Oscillation **P**roject with **E**mulsion **T**r**a**cking **A**pparatus

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

Appearance measurement:

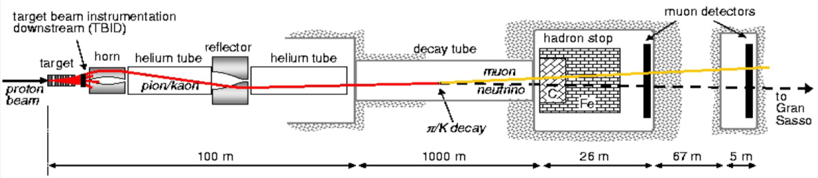
- First direct observation of $\nu_\mu \to \nu_\tau$ oscillation
- ▷ Observation of creation & decay of τ leptons

Realisation:

- High-energy long-baseline ν_μ beam
- **Large target mass:**
- ▷ Instrumentation with electronic detector components (ED)
- μm-**precision:**
- ▷ Emulsion Cloud Chamber (ECC) nuclear emulsions

The CNGS ν_μ Beam

CNGS: CERN Neutrinos to Gran Sasso

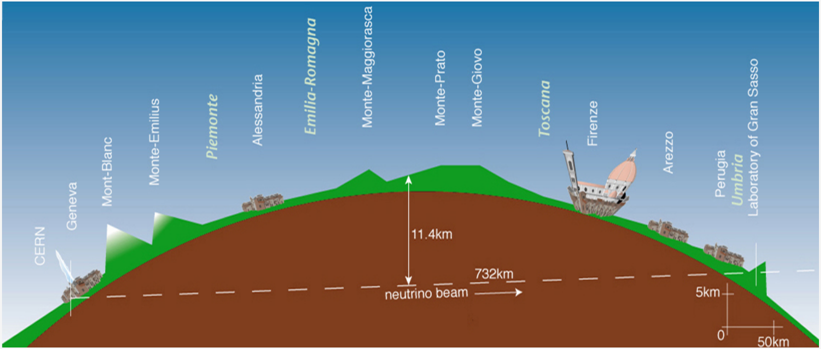


Year	p.o.t.	ν target interactions
2008	1.74×10^{19}	1854
2009	3.53×10^{19}	3914
2010	4.09×10^{19}	4403
2011	4.75×10^{19}	4956
2012	3.86×10^{19}	3814
Total	17.97×10^{19}	18941

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

The CNGS ν_μ Beam

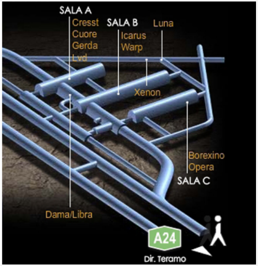
CNGS: CERN Neutrinos to Gran Sasso



- **Baseline:** $\sim 730\,\mathrm{km}$ distance from CERN to LNGS

LNGS

LNGS: Laboratori Nazionali del Gran Sasso

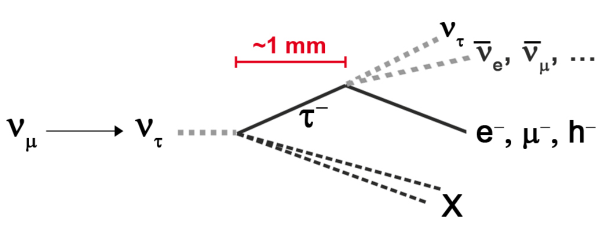


- **Location:** Below Mt. Corno Grande of Gran Sasso, Italy
- **Vertical rock coverage:** $1\,400\,\mathrm{m}$ $(3\,800\,\mathrm{m\,w.e.})$

▷ **Cosmic μ rate:** $\sim 1\,\mathrm{m}^{-2}\mathrm{h}^{-1}$

ν_τ Detection

ν_τ signal:

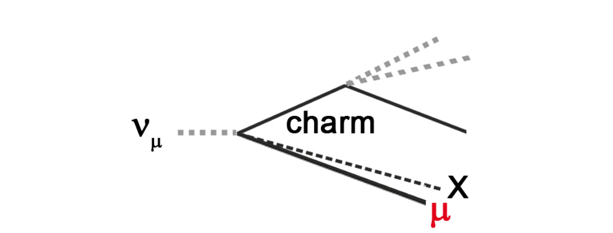


- τ^- creation in ν_τ CC interactions
- Decay of the τ^- lepton after $\sim 600\,\mu\mathrm{m}$

▷ **Topology:** Characteristic 'kink'

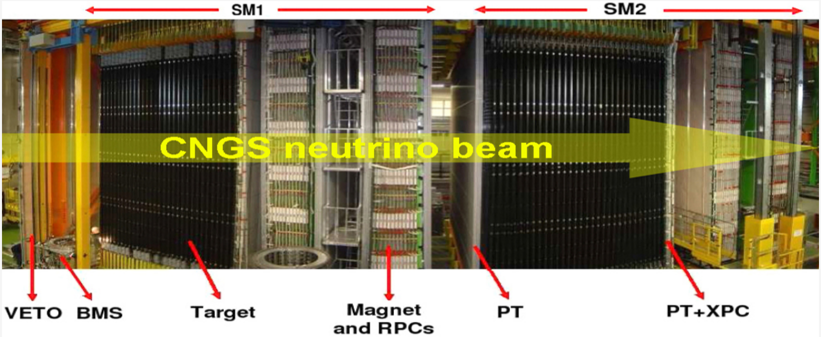
ν_τ Detection

Background processes:



- ν_μ CC interactions with charm production & undetected 1ry μ
- Hadronic re-interactions in lead
- Large-angle μ scattering

The OPERA Hybrid Detector

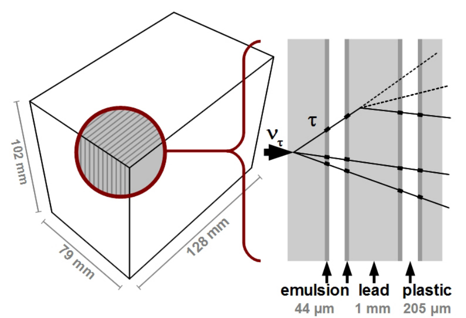


2 identical Super Modules (SM), each consisting of:

- Target area (ECC + ED)
- Magnetic spectrometer (ED)

μ **VETO system upstream of the detector**

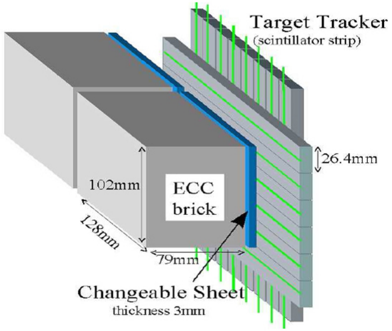
Target Area

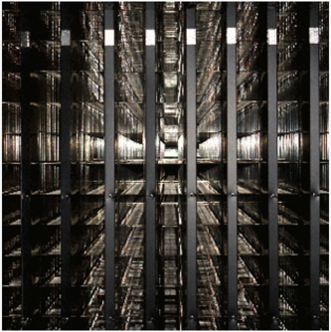


Emulsion Cloud Chamber (ECC) bricks:

- **Per brick:** 57×2 nuclear emulsions on plastic bases, 56 lead plates (altogether corresponding to $\sim 10\,X_0$)
- **Total:** $\sim 150\,000$ bricks of $8.3\,\mathrm{kg}$ each ($\sim 1.25\,\mathrm{kt}$ total target mass)
- **Spatial/angular resolution:** $\sim 1\,\mu\mathrm{m}$ / $\sim 2\,\mathrm{mrad}$

Target Area





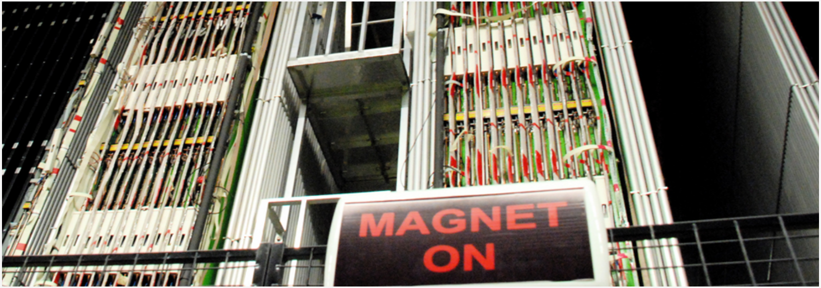
Changeable Sheets (CS):

- **Per brick:** 2 extra emulsion sheets

Target Tracker (TT) detectors:

- **Per SM:** 31 walls of plastic scintillator strips (horizontal & vertical)

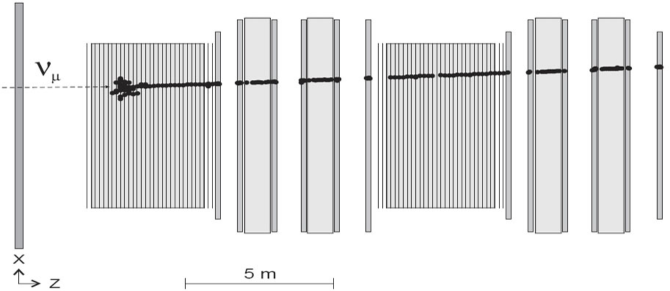
Magnetic Spectrometer



Magnetic Spectrometer:

- **Per SM:** Downstream of each target area
- **Dipole magnets**: $\sim 1.53\,\mathrm{T}$
- **Resistive Plate Chamber (RPC & XPC) detectors**
- **Precision Tracker (PT) drift tubes**

Event Reconstruction

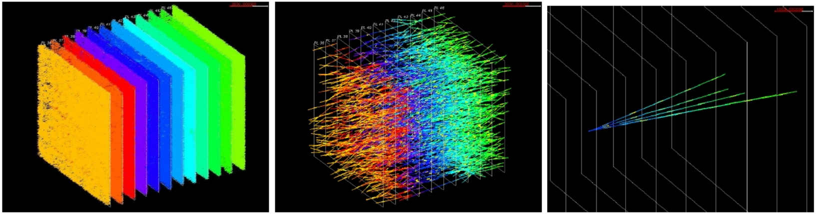


ED event reconstruction:

- High-accuracy time resolution
- ν interaction vertex localisation
- μ identification (CC/NC separation) & momentum measurement
- Hadronic shower energy estimation

▷ **Trigger:** ECC event reconstruction

Event Reconstruction



ECC event reconstruction:

- Emulsion scanning by automatic microscopes
- Track & ν interaction vertex reconstruction
- Kinematical analysis

τ decay search procedure:

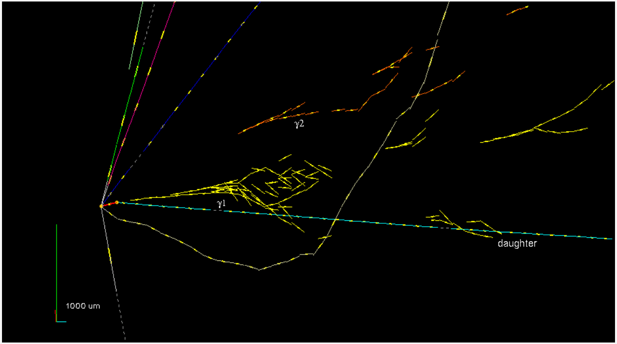
- In-track kink search
- Search for extra tracks

Oscillation Search:

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

The 1st ν_τ Candidate Event

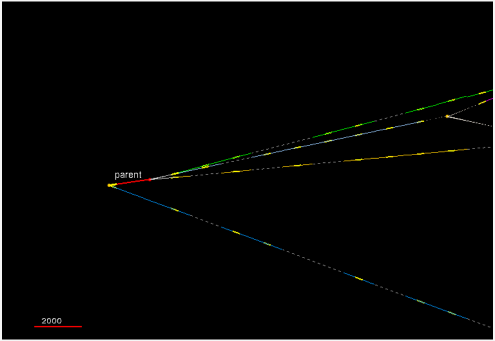
ECC reconstruction:



- **1ry vertex:** 7 tracks
- **Red/cyan track(s):** Kink after 1.35 mm
- ▷ **Decay channel:** $\tau \to h \quad (\tau^- \to \rho^-(\pi^-\pi^0)\nu_\tau)$

The 2nd ν_τ Candidate Event

ECC reconstruction:



- **1ry vertex:** 2 tracks
- **Red track:** 3-prong decay after 1.54 mm

▷ **Decay channel:** $\tau \rightarrow 3h$

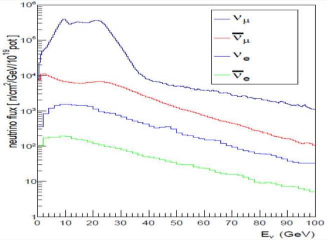
Oscillation Search:

$$\nu_\mu \longrightarrow \nu_e$$

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

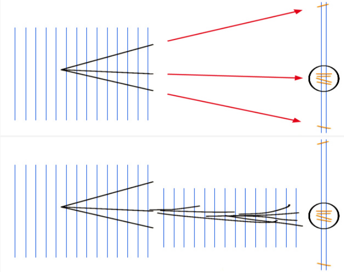
Challenges:

- **ν_e beam contamination:** $(\nu_e + \overline{\nu}_e)/\nu_\mu \lesssim 1\,\%$
- No OPERA near detector
- ▷ **Reliable MC required** (rates & efficiencies)



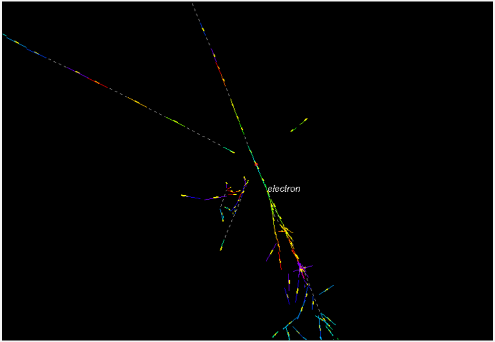
Event selection:

- **ED:** NC-like events
- **ECC:** Track follow-down
- **CS:** em shower hints
- ▷ Expanded scan volume
- ▷ Extraction & analysis of downstream bricks



A ν_e Event

ECC reconstruction:



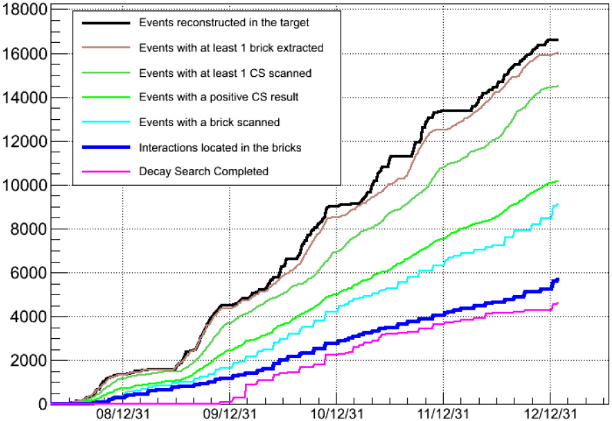
- **2008 + 2009 data sample:** 19 ν_e candidate events
- **Separation of beam cont. ν_e and oscillated ν_e :** Cuts on $E_{\nu,rec}$

▷ $E_{\nu,rec} < 20\,\mathrm{GeV}$: 4 ν_e candidate events remaining

Performance & Statistics

Event Statistics

Analysis status January 2013 (run years 2008 – 2012)



- **Vertex located:** 5 675 events
- **Decay search performed:** 4 584 events

OPERA Expected Performance

Target interactions expected*:

- ν_μ **CC + NC interactions:** ~ 23600 (80%: ~ 18800)
- $\nu_e + \overline{\nu}_e$ **CC interactions:** ~ 160 (80%: ~ 130)
- ν_τ **CC interactions:** ~ 115 (80%: ~ 90)

Detected signal and BG events expected*:

τ decay channel	BR [%]	Number of signal events	Number of BG events
$\tau^- \to \mu^-$	17.7	1.79	0.09 ± 0.04
$\tau^- \to e^-$	17.8	2.89	0.22 ± 0.05
$\tau^- \to h^-$	49.5	2.25	0.24 ± 0.06
$\tau^- \to 3h$	15.0	0.71	0.18 ± 0.04
Total		7.63	0.73 ± 0.15

*) Assuming $\Delta m^2_{23} = 2.5 \times 10^{-3}\,\mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1$, and 22.5×10^{19} p.o.t.

Conclusion & Outlook

Conclusion & Outlook

Conclusion:

- **CNGS beam concluded:** 2008 – 2012
  - ▷ 17.97×10^{19} p.o.t.
  - ▷ 18941 ontime ν target interactions
- **Confirmed ν_τ candidate events:** 2
- **Confirmed ν_e candidate events:** 19 (2008 + 2009 data)

Outlook

- **Extraction of ν candidate bricks:** Until $\sim$ 2014
- **Scanning & analysis of ν candidate interactions:** Until $\gtrsim$ 2015
- Improvement of BG rejection
- Improvement of efficiencies (location, decay search...)
- Improvement of statistical treatment

Conclusion & Outlook

Outlook: $\nu_\mu \to \nu_\tau$ oscillation search

- **New paper:** Analysis of 2008 + 2009 data (unbiased), 2010 + 2011 data (predefined selection)
- **Further ν_τ candidate events:** To be confirmed

Outlook: $\nu_\mu \to \nu_e$ oscillation search

- **New paper:** Analysis of 2008 + 2009 data (unbiased)
- **Search for $\nu_\mu \to \nu_e$ oscillations:** 3-flavour formalism
- **Limits on $\nu_\mu \to \nu_e$ oscillations:** W.r.t. sterile ν

Other research topics:

- ν velocity measurement
- Atmospheric ν oscillation search
- Atmospheric μ charge ratio measurement

Thank you for your attention!

The OPERA Collaboration

11 countries, 29 institutes, $\sim$ 150 physicists:

Belgium:
- IIHE-ULB Brussels

Croatia:
- IRB Zagreb

France:
- LAPP Annecy
- IPHC Strasbourg

Germany:
- Hamburg University

Israel:
- Technion Haifa

Italy:
- INFN-LNGS Assergi
- University & INFN Bari
- University & INFN Bologna
- University & INFN-LNF Frascati
- University & INFN l'Aquila
- University & INFN Naples
- Univeristy & INFN Padova
- University & INFN Rome
- University & INFN Salerno

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

Korea:
- University Jinju

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

Switzerland:
- LHEP Bern
- ETH Zurich

Turkey:
- METU Ankara

Backup Slides

3-Flavour Oscillation Formalism

Neutrino 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:

$$U =$$

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

$$=$$

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

Atmospheric terms	Unknown terms	Solar terms	Majorana terms
SuperKamiokande MINOS, OPERA	**DoubleChooz, T2K**	**KamLAND**	

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

3-Flavour Oscillation Formalism

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

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

$\nu_\alpha \to \nu_\beta$ oscillation probability in vacuum:

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) &= |\langle \nu_\alpha | \nu_\beta(t) \rangle|^2 \\ &= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\Delta m^2_{ij} \frac{L}{2E}\right) \\ &\quad + 2 \sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\Delta m^2_{ij} \frac{L}{4E}\right) \end{aligned}$$

with $\Delta m^2_{ij} = m^2_i - m^2_j$

Oscillation Parameters

State of knowledge:

Oscillation parameter	Current best fit	
$\lvert\Delta m^2_{32}\rvert$	$(2.32^{+0.12}_{-0.08})$	$\times 10^{-3}\,\mathrm{eV}^2$
Δm^2_{21}	(7.50 ± 0.020)	$\times 10^{-5}\,\mathrm{eV}^2$
$\sin^2(2\theta_{23})$	> 0.95	
$\sin^2(2\theta_{12})$	0.857 ± 0.024	
$\sin^2(2\theta_{13})$	0.098 ± 0.013	
δ	?	

Future:

- **T2K, MINOS, DoubleCHOOZ, DayaBay:** Large value of θ_{13}
- ▷ $\nu_\mu \to \nu_e$ appearance measurement with OPERA
- ▷ Measurement of the mass hierarchy
- ▷ Measurement of δ_{cp}

ν_τ Detection

τ creation in ν_τ CC interactions:

$$\nu_\tau + N \to \tau^- + X$$

τ decay modes (1-prong):

- **Muonic:** $\tau^- \to \mu^- + \nu_\tau + \overline{\nu}_\mu$ (BR 17.7 %)
- **Electronic:** $\tau^- \to e^- + \nu_\tau + \overline{\nu}_e$ (BR 17.8 %)
- **Hadronic:** $\tau^- \to h^- + \nu_\tau + X^0$ (BR 49.5 %)

τ decay modes (3-prong):

- **Hadronic:** $\tau \to 2h^- + h^+ + \nu_\tau + X^0$ (BR 15.0 %)

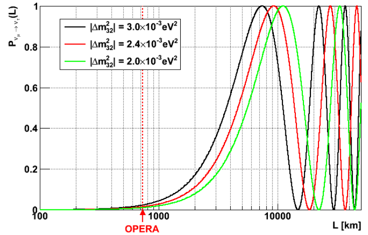
τ decay length:

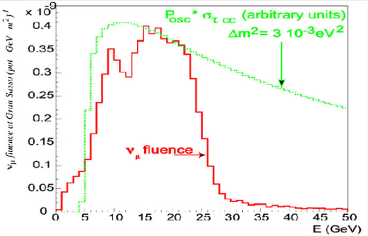
- $\sim 600\,\mu\text{m}$

Beam Characteristics at LNGS

$\nu_\mu \to \nu_\tau$ oscillation probability (2-flavour approximation):

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

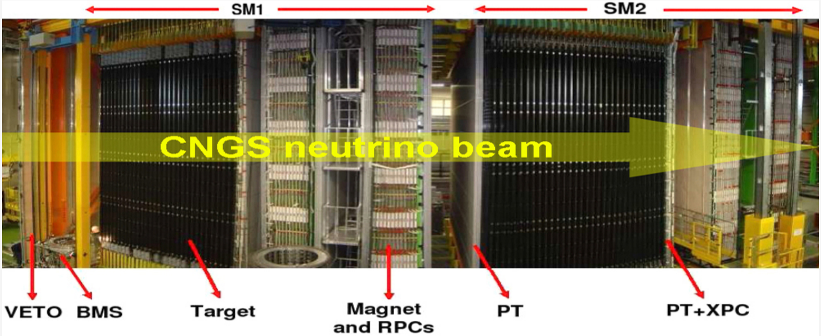




- ν_μ **beam energy:** Optimised for τ detection
- **Location:** OPERA detector @off-peak* position

*) **Longer baseline:** Increase in ν_τ flux cancelled by ν_μ beam divergence

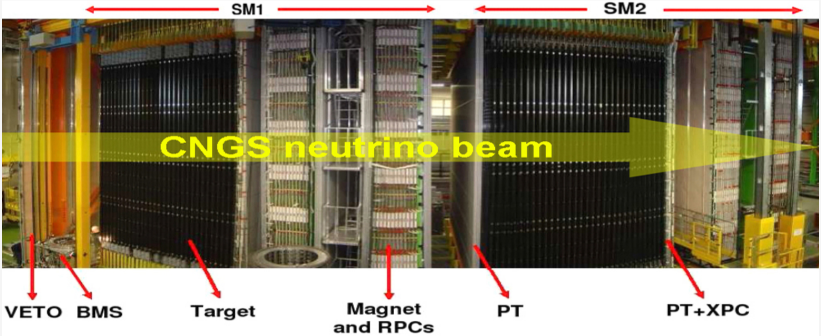
The OPERA Hybrid Detector



μ VETO system:

- 2 planes of glass Resistive Plate Chambers (RPC) in front of the detector
  - ▷ Rejection of upstream ν interactions

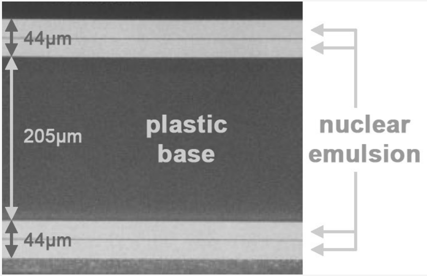
The OPERA Hybrid Detector

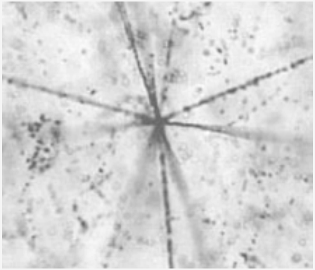


Brick Manipulator System (BMS):

- 1 automatic robot per semi-wall, working in parallel to CNGS data taking
- **Brick extraction speed:** ~ 25 ν interaction bricks per $8\,\mathrm{h}$

Target Area

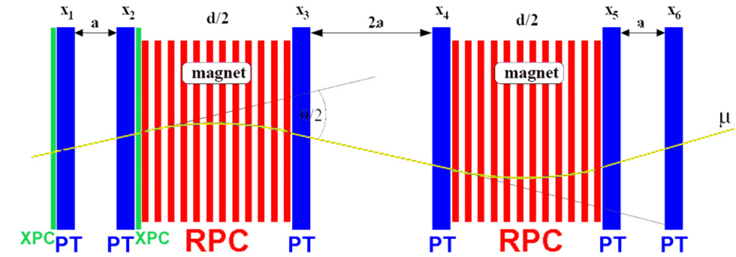




Emulsion Cloud Chamber (ECC) nuclear emulsions:

- **Basic detector elements:** AgBr crystals ($0.2\,\mu$m)
- ▷ **Intrinsic resolution:** $50\,$nm
- **Hadronic momentum measurement:** Via MCS
- π/μ **separation:** Via dE/dx (at low energies)
- e identification, em shower energy estimation

Magnetic Spectrometer



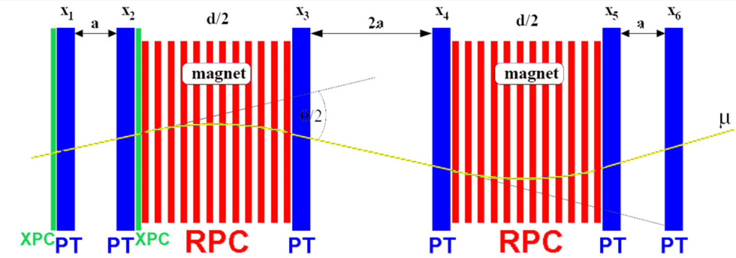
Dipole magnets:

- **Per SM:** 2 copper coils with 12 iron slabs each

Resistive Plate Chamber (RPC & XPC) detectors:

- **Per SM:** 24 planes of bakelite RPC within each magnet (horizontal & vertical: RPC)
- **Per SM:** 2 extra planes upstream of each magnet (rotated by 42.6°: XPC)

Magnetic Spectrometer

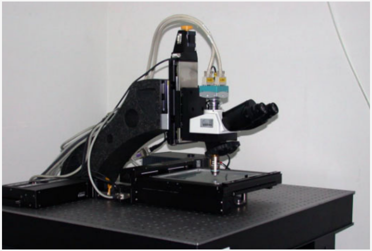


Precision Tracker (PT) detectors:

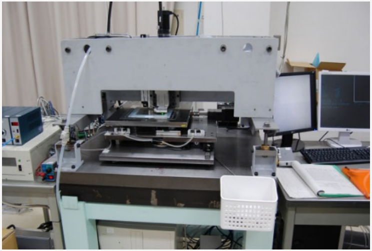
- **Per SM:** 6 walls of vertical drift tubes
- **Spatial resolution:** $\sim 250\,\mu\mathrm{m}$
- **Momentum resolution:** $\sim 20\,\%$ (for $p < 30\,\mathrm{GeV/c}$)
- Precise measurement of the angular deflection of charged particles

Event Reconstruction

Europe:



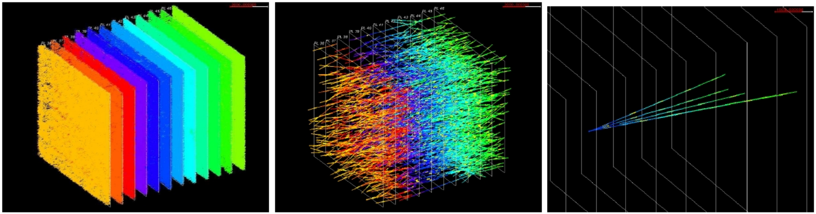
Japan:



ECC scanning and alignment:

- **CS & ECC brick scanning:** Conducted by automatic microscopes (scanning labs in Europe & Japan)
- **CS & ECC brick alignment:** Via X-rays and cosmic ray tracks

Event Reconstruction

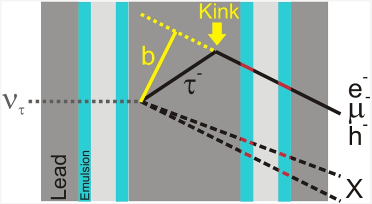


ECC event reconstruction:

- Reconstruction of $3D$ track segments
- Rejection of passing-through and low-energy tracks
- Scanback of tracks found in CS
- **Vertex reconstruction:** Track scanback, $1\,\mathrm{cm}^3$ volume scan around stopping point
- **Kinematical analysis:** Momentum measurement via MCS, em shower energy reconstruction

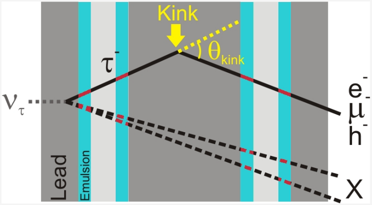
Decay Search Procedure

Short decay:



- Impact parameter b

Long decay:



- Kink angle θ_{kink}

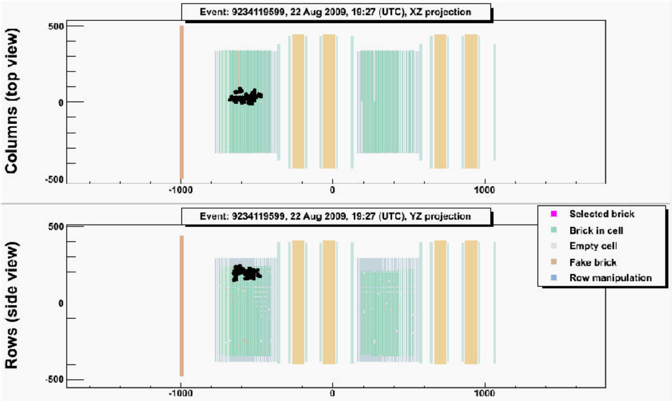
Decay search procedure:

- In-track decay search
- Search for extra tracks

▷ Measurement of kink angle θ_{kink} or impact parameter b

The 1st ν_τ Candidate Event

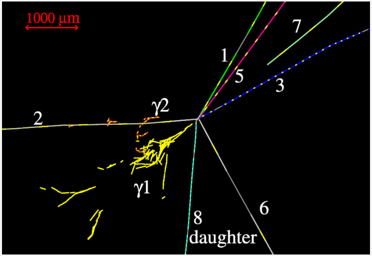
ED view:

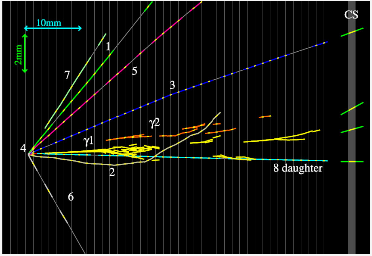


- 2009-08-22, 19:27h (UTC)
- 0-μ event 9234119599

The 1st ν_τ Candidate Event

ECC reconstruction:





Kinematical cuts (1-prong hadronic τ decay channel):

Variable		Value	Selection cut	
Missing p_T @1ry vertex	[GeV/c]	$0.57^{+0.32}_{-0.17}$	$<$	1.0
Transverse angle between parent track & 1ry hadronic shower	[rad]	3.01 ± 0.03	$>$	$\pi/2$
Kink angle	[mrad]	41 ± 2	$>$	20
Daughter particle momentum	[GeV/c]	12^{+6}_{-3}	$>$	2
Daughter p_T for γ @decay vertex	[GeV/c]	$0.47^{+0.24}_{-0.12}$	$>$	0.3
Decay length	[μm]	1335 ± 35	$<$	2 Pb plates

The 1st ν_τ Candidate Event

Daughter particle:

- **2**-prong decay 7 walls downstream of the production vertex
- **Momentum:** $p = 12^{+6}_{-3}\,\mathrm{GeV}$

▷ **Hypothesis:** π^-

Invariant mass of the $\gamma\gamma$ system:

- $(120 \pm 20(stat.) \pm 35(syst.))\,\mathrm{MeV/c^2}$

▷ **Consistent with π^0 mass:** $m_{\pi^0} = 135\,\mathrm{MeV/c^2}$

Invariant mass of the $\pi^-\gamma\gamma$ system:

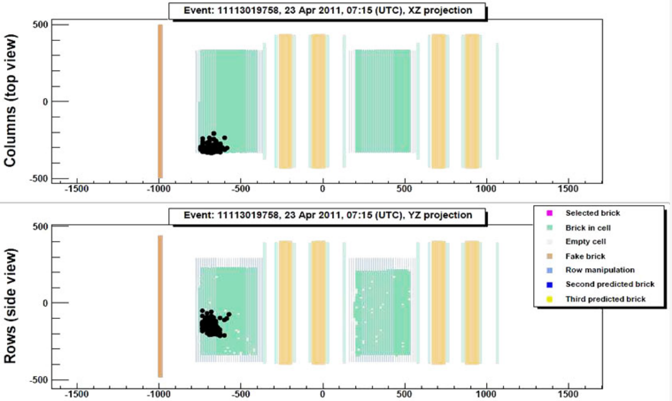
- $(640^{+125}_{-80}(stat.)^{+100}_{-90}(syst.))\,\mathrm{MeV/c^2}$

▷ **Consistent with $\rho^-(770)$ mass*:** $m_{\rho^-} = 775\,\mathrm{MeV/c^2}$

*) $\rho^-(770)$ are created in 25% of τ^- decays: $\tau^- \to \rho^-(\pi^-\pi^0)\nu_\tau$

The 2nd ν_τ Candidate Event

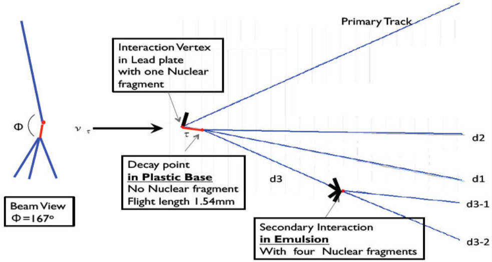
ED view:



- 2011-04-23, 07:15h (UTC)
- 0-μ event 11113019758

The 2nd ν_τ Candidate Event

Schematic view:



Kinematical cuts (3-prong hadronic τ decay channel):

Variable		Value	Selection cut	
Transverse angle between parent track & 1ry hadronic shower	[°]	167.8 ± 1.1	$>$	90
Average kink angle	[mrad]	87.4 ± 1.5	$<$	500
Total momentum @decay vertex	[GeV/c]	8.4 ± 1.7	$>$	3.0
Min. invariant mass	[GeV/c^2]	0.96 ± 0.13	$>$	0.5, $<$ 2.0
Invariant mass	[GeV/c^2]	0.80 ± 0.12	$>$	0.5, $<$ 2.0
Transverse momentum @1ry vertex	[GeV/c]	0.31 ± 0.11	$<$	1.0

Significance of ν_τ Observation [paper2]

Analysed sample of 2008 + 2009 data:

- 2978 ± 75 events expected (incl. efficiencies)
- **2738 decay-searched events, corresponding to** 4.88×10^{19} p.o.t. (92 % of the total 2008 + 2009 data)
- **1 signal event (1-prong hadronic τ decay channel)**

Signal expectation* (1-prong hadronic τ decay channel):

- ν_τ **CC:** $0.49 \pm 0.12(syst.)$ **events**

Signal expectation* (all τ decay channels):

- ν_τ **CC:** $1.65 \pm 0.41(syst.)$ **events**

*) Assuming $\Delta m^2_{23} = 2.5 \times 10^{-3}\,\mathrm{eV}^2$ and $\sin^2 2\theta_{23} = 1$

Significance of ν_τ Observation [paper2]

BG expectation (1-prong hadronic τ decay channel):

- **Total:** $0.05 \pm 0.01(syst.)$ events
- ▷ **p-value (BG-only):** 5 %
- ▷ **Significance of $\nu_\mu \to \nu_\tau$ observation:** 95 %

BG expectation (all τ decay modes):

- **Total:** $0.16 \pm 0.03(syst.)$ events
- ▷ **p-value (BG-only):** 15 %
- ▷ **Significance of $\nu_\mu \to \nu_\tau$ observation:** 85 %

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

Detected τ signal events expected*:

τ decay channel	Vertex localisation efficiency	Global τ detection efficiency	Number of signal events for 22.5×10^{19} p.o.t.	4.88×10^{19} p.o.t.
$\tau^- \to \mu^-$	0.54	0.09	1.79	0.39
$\tau^- \to e^-$	0.59	0.14	2.89	0.63
$\tau^- \to h^-$	0.59	0.04	2.25	0.49
$\tau^- \to 3h$	0.64	0.04	0.71	0.15
Total	0.59	0.07	7.63	1.65

Detected ν_τ BG events expected:

τ decay channel	Number of BG events for 22.5×10^{19} p.o.t.				4.88×10^{19} p.o.t.			
	charm	h	μ	Total	*charm*	h	μ	Total
$\tau^- \to \mu^-$	0.025	0.00	0.07	0.09 ± 0.04	0.00	0.00	0.02	0.02 ± 0.01
$\tau^- \to e^-$	0.22	0.00	0.00	0.22 ± 0.05	0.05	0.00	0.00	0.05 ± 0.01
$\tau^- \to h^-$	0.14	0.11	0.00	0.24 ± 0.06	0.03	0.02	0.00	0.05 ± 0.01
$\tau^- \to 3h$	0.18	0.00	0.00	0.18 ± 0.04	0.04	0.00	0.00	0.04 ± 0.01
Total	0.55	0.11	0.07	0.73 ± 0.15	0.12	0.02	0.02	0.16 ± 0.03

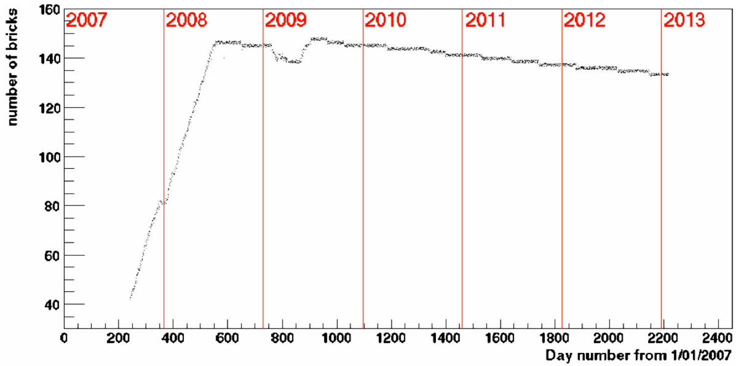
Detected charm and charm BG events:

Topology	Expected events *charm*	BG	Total	Observed *charm* candidate events
1-prong charged	15.9	1.9	17.8	13
2-prong neutral	15.7	0.8	16.5	18
3-prong charged	5.5	0.3	5.8	5
4-prong neutral	2.0	< 0.1	2.1	3
Total	39.1 ± 7.5	3.0 ± 0.9	42.2 ± 8.3	39

*) Assuming $\Delta m^2_{23} = 2.5 \times 10^{-3}\,\mathrm{eV}^2$ and $\sin^2 2\theta_{23} = 1$

Target Mass Decrease

OPERA target mass decrease:



- **2008-07-16:** 146398 bricks
- **2013-01-28:** 133751 bricks

▷ **Loss of target mass:** 105 t (12647 bricks)

Publications

OPERA publications of note:

- T. Adam *et al.* [OPERA Collaboration], *Measurement of the neutrino velocity with the OPERA detector in the CNGS beam using the 2012 dedicated data*, JHEP **01** (2013) 153
- T. Adam *et al.* [OPERA Collaboration], *Measurement of the neutrino velocity with the OPERA detector in the CNGS beam*, JHEP **10** (2012) 093
- 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

Soon to come:

- *Search for $\nu_\mu \to \nu_e$ oscillation with the OPERA experiment in the CNGS beam* (2008 – 2009 data)
- *New results on $\nu_\mu \to \nu_\tau$ appearance with the OPERA experiment at the CNGS neutrino beam* (2008 – 2011 data)