New results from the OPERA experiment

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on behalf of the OPERA Collaboration

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Outline

- About OPERA
  - Goals of the experiment
  - CNGS neutrino beam
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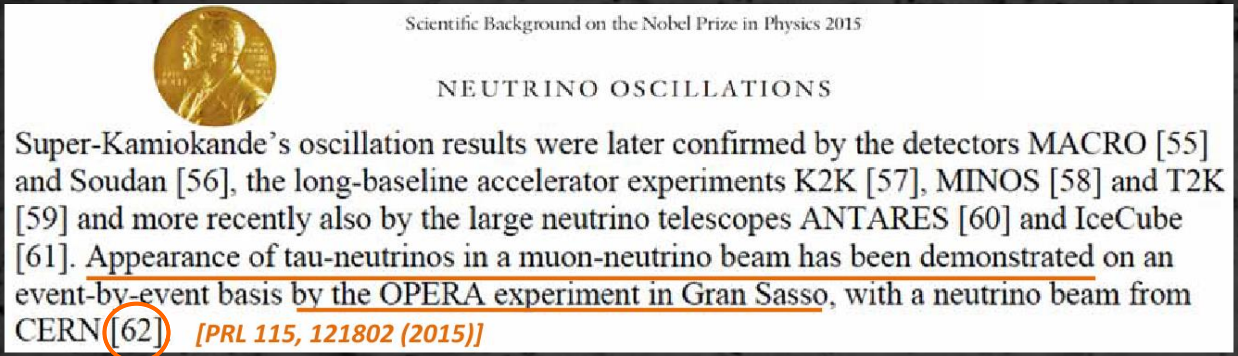
  - Description of the detector
- Results on $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillation searches
- Analysis of the annual modulation of the cosmic muon rate
- Conclusions and outlook

Goals of the experiment


Scientific Background on the Nobel Prize in Physics 2015

NEUTRINO OSCILLATIONS

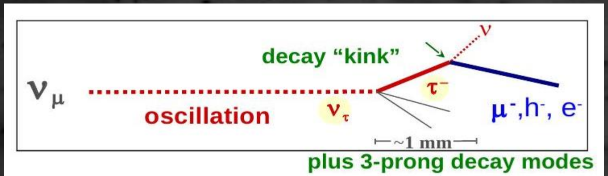
Super-Kamiokande's oscillation results were later confirmed by the detectors MACRO [55] and Soudan [56], the long-baseline accelerator experiments K2K [57], MINOS [58] and T2K [59] and more recently also by the large neutrino telescopes ANTARES [60] and IceCube [61]. Appearance of tau-neutrinos in a 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, 121802 (2015)]*

Since its discovery, the phenomenon of neutrino oscillations is being studied mostly in *disappearance* mode.

Observation of the *appearance* of oscillated neutrinos consistent with the disappearance results was a very important issue.

The main goal

the first *direct observation* of ν_τ appearance in a pure ν_μ beam through the detection of the short-lived τ leptons produced in ν_τ charged-current (CC) interactions.



Channel	BR
$\tau^- \to e^- \nu_\tau \overline{\nu_e}$	17.8%
$\tau^- \to \mu^- \nu_\tau \overline{\nu_\mu}$	17.7%
$\tau^- \to h^- \nu_\tau (n\pi^0)$	49.5%
$\tau^- \to 3h \nu_\tau (n\pi^0)$	15.0%

Expanded physics program

– oscillation physics:

- $\nu_\mu \to \nu_e$ study
- sterile neutrino analysis

– non-oscillation physics:

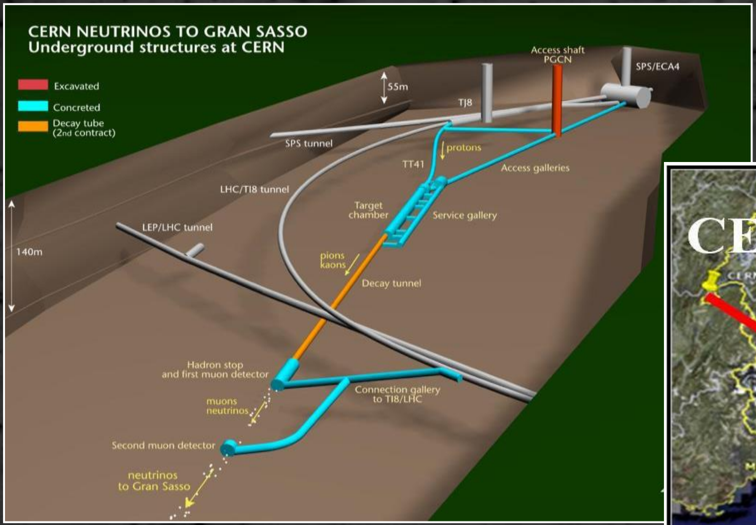
- charged particle multiplicity analysis
- cosmic ray physics

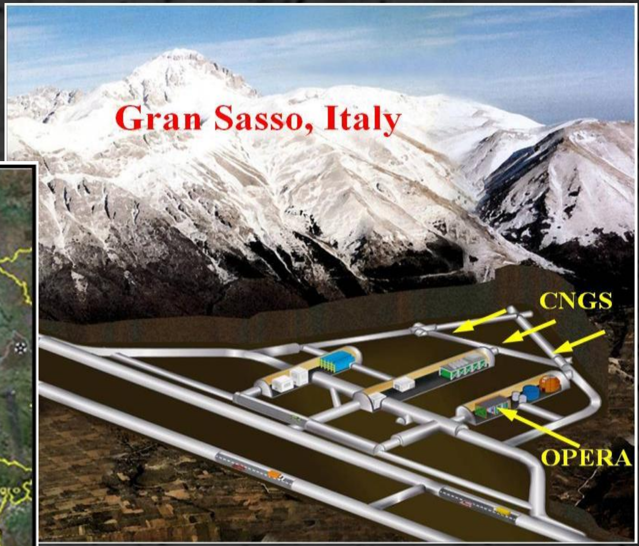
Requirements

for ν beam: high energy for τ production, high intensity, long baseline for oscillation at the atmospheric scale

for detector: high density and large target mass, micrometric resolution, low background (underground location)

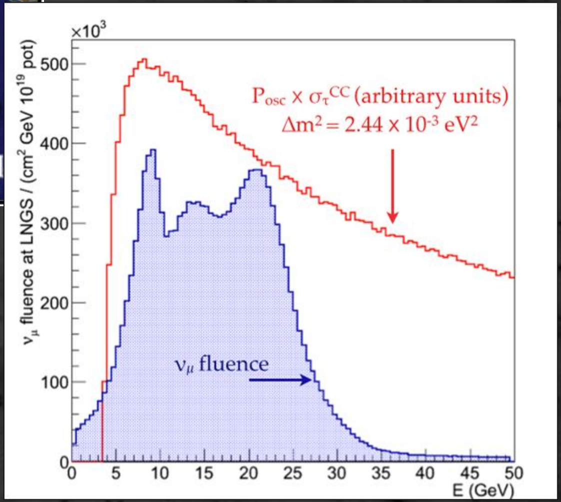
CNGS neutrino beam





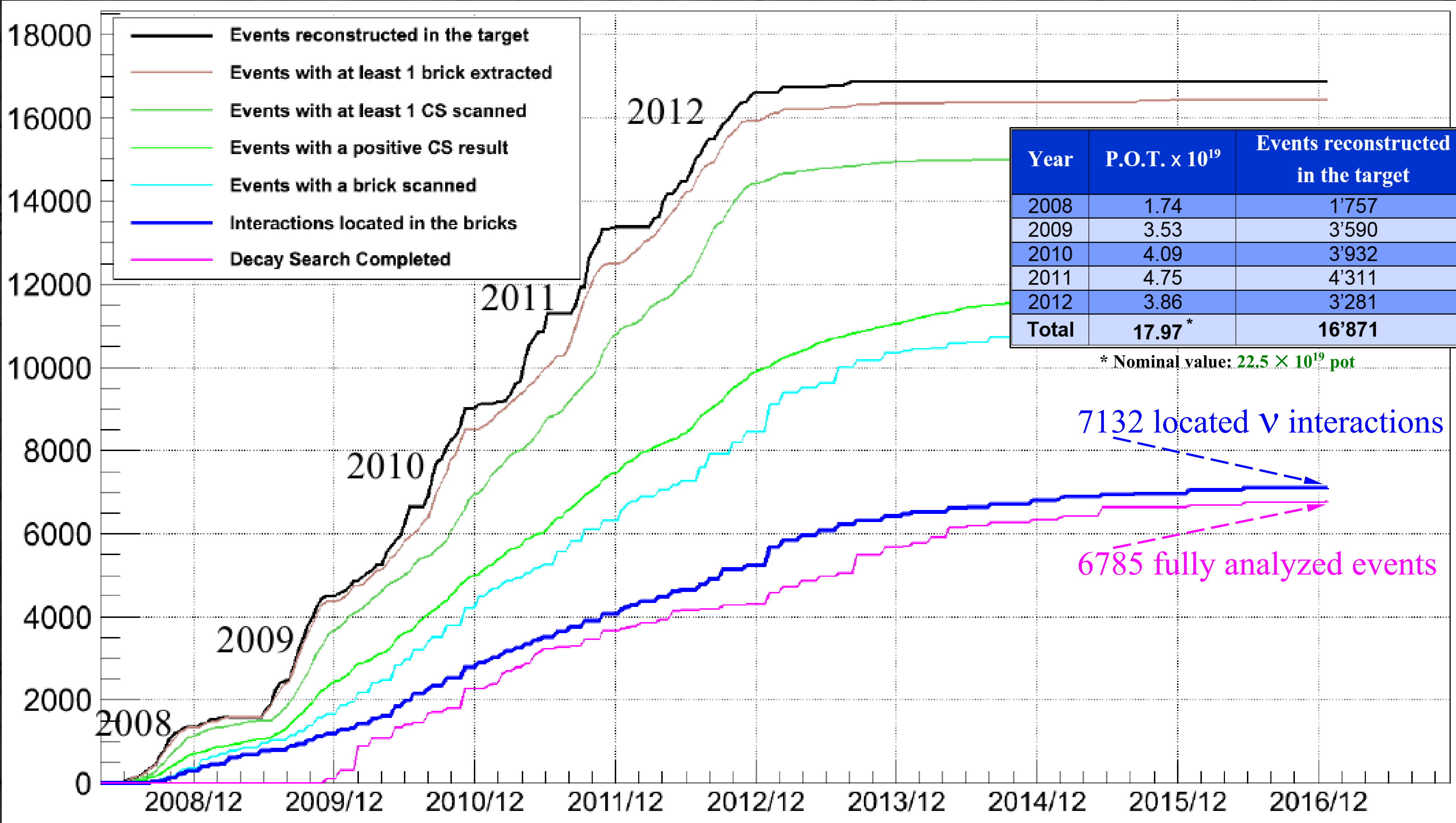
$\langle E_{\nu_\mu} \rangle$	17 GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.9%*
$\bar{\nu}_\mu/\nu_\mu$	2.0%*
ν_τ prompt	negligible

* interaction rate @ LNGS



The beam was optimized to maximize the number of ν_τ CC interactions in the detector

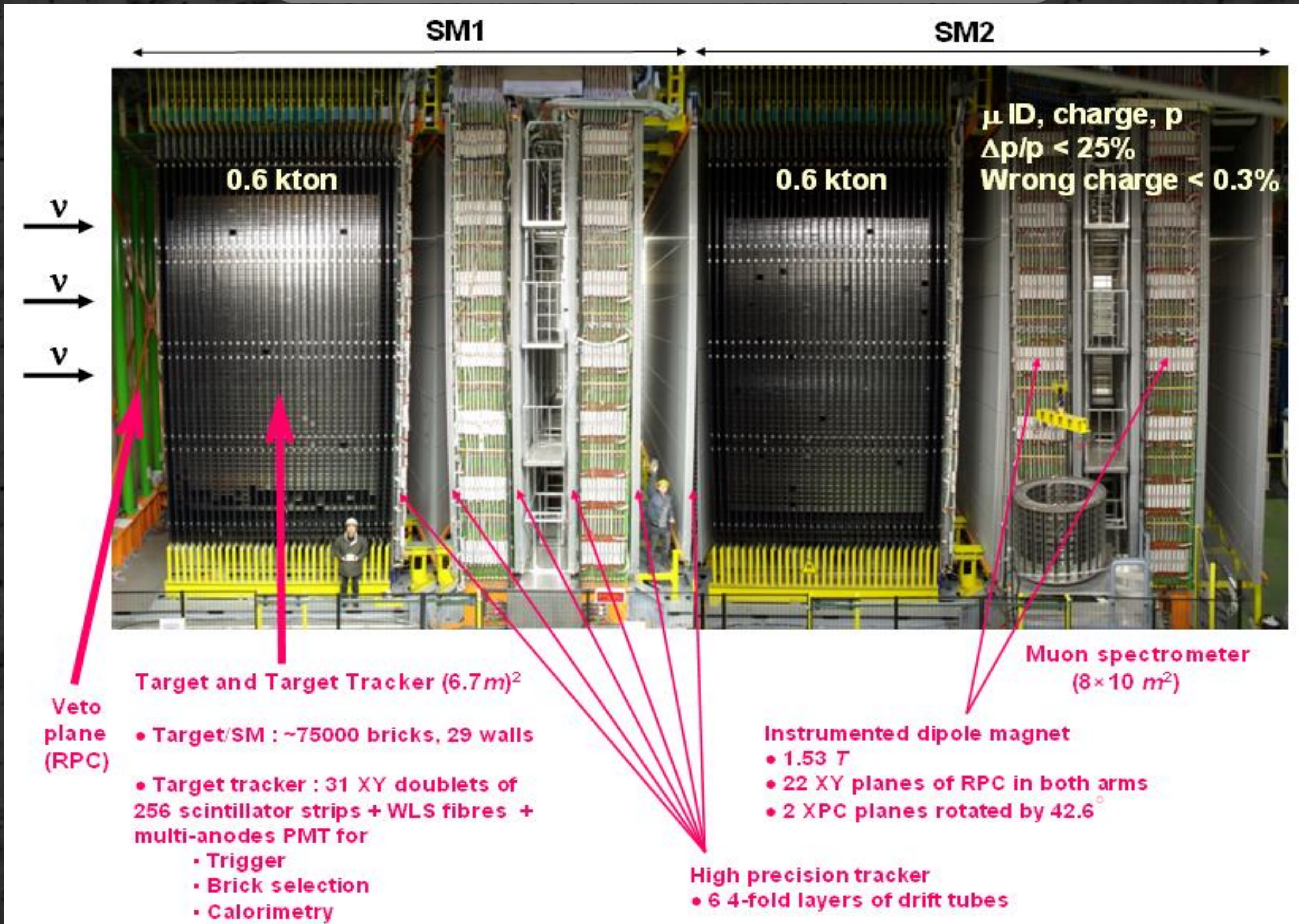
Status of data analysis



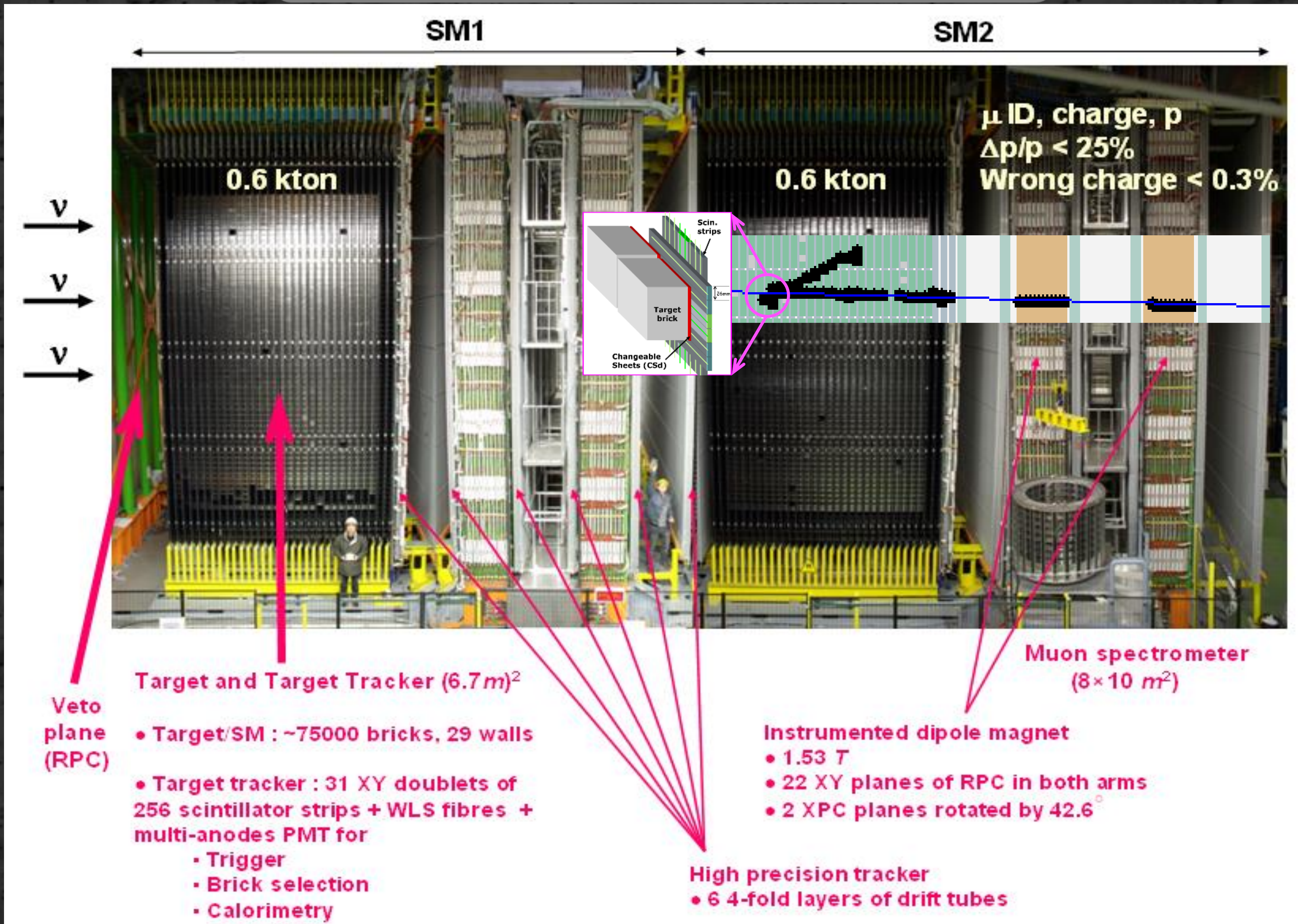
Year	P.O.T. x 10^{19}	Events reconstructed in the target
2008	1.74	1'757
2009	3.53	3'590
2010	4.09	3'932
2011	4.75	4'311
2012	3.86	3'281
Total	**17.97** *	**16'871**

* Nominal value: 22.5×10^{19} pot

OPERA hybrid detector

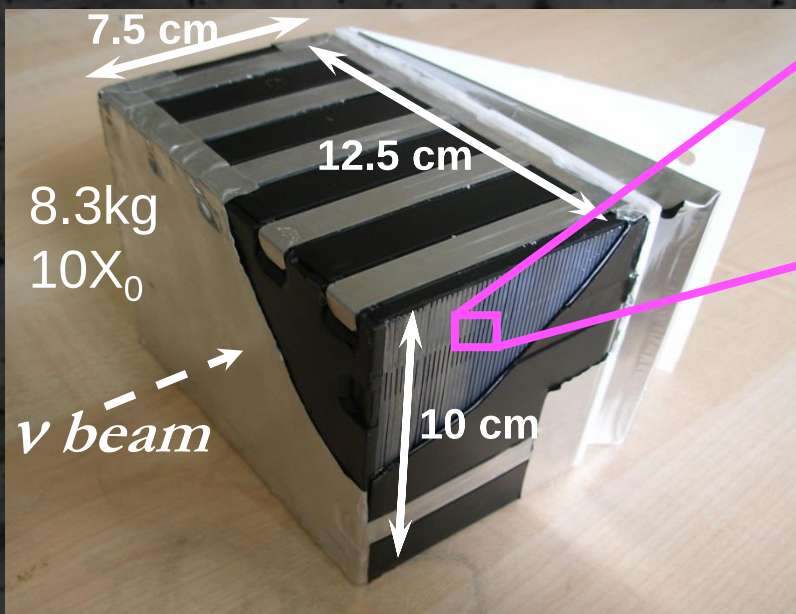


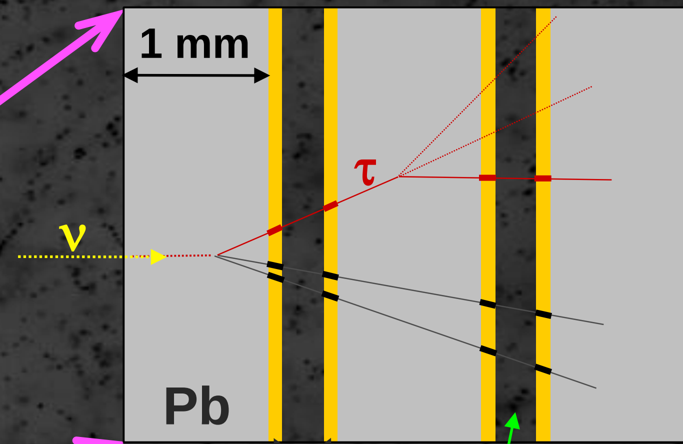
OPERA hybrid detector



OPERA ECC brick

Basic unit of the OPERA detector was an *Emulsion Cloud Chamber* module *(ECC brick)*: sandwich of **57** emulsion films interleaved with lead plates + a separate box with a removable pair of films (CSd)





2 emulsion layers (44 μm thick) poured on a 200 μm plastic base

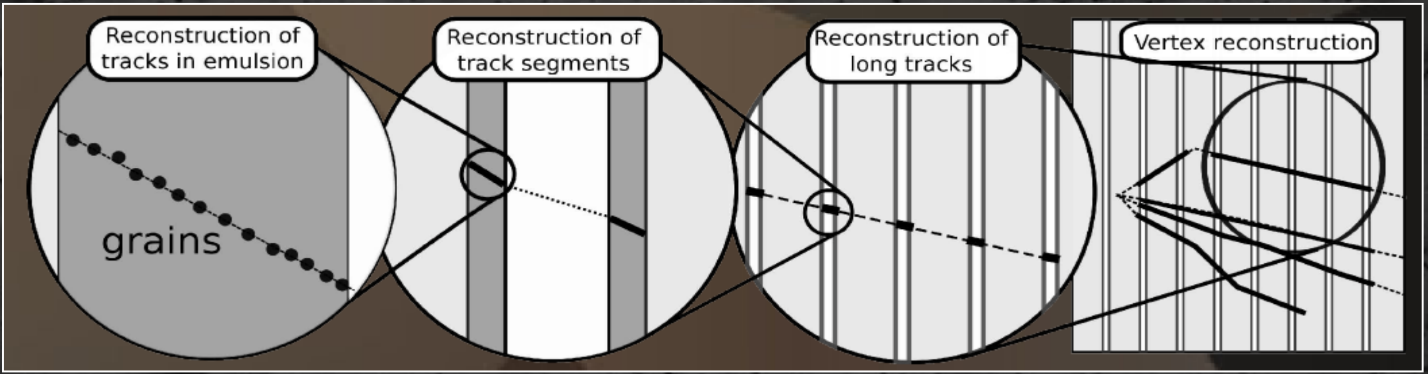
The OPERA target

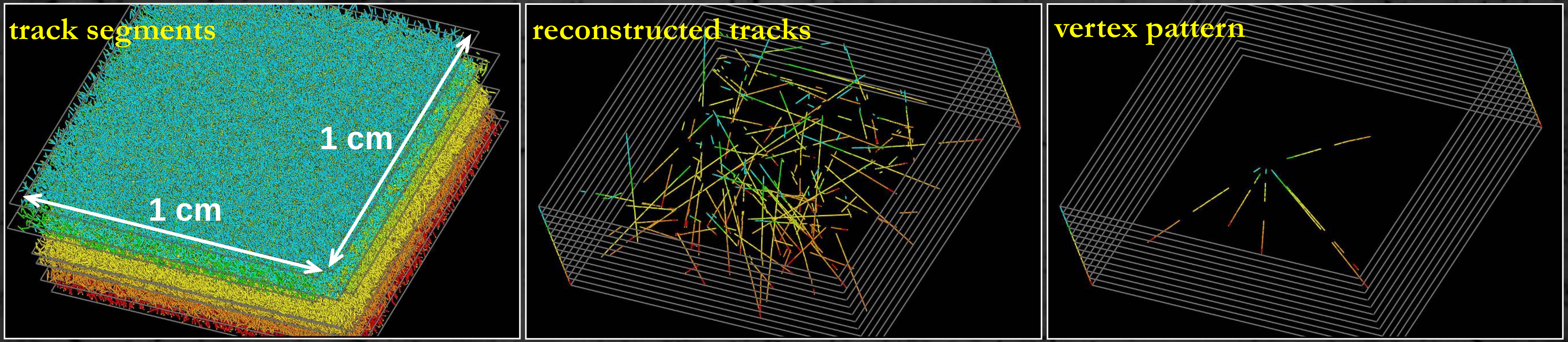
Number of bricks:	**~150’000**
Total mass:	**~1.2 kton**
Total film surface:	**~111’000 m^2**

The ECC technique proved its efficiency and is going to be used in future experiments for ν_τ registration (DsTau, SHiP, …) and even for directional dark matter search (NEWSdm).

Location of a neutrino interaction vertex

- Search for converging tracks (or tracks matching the electronic detectors hits) in emulsion films
- Follow back of the found tracks in the upstream films of the brick until their stopping point
- Scanning of a large volume (~2 cm^3 around the stopping point)





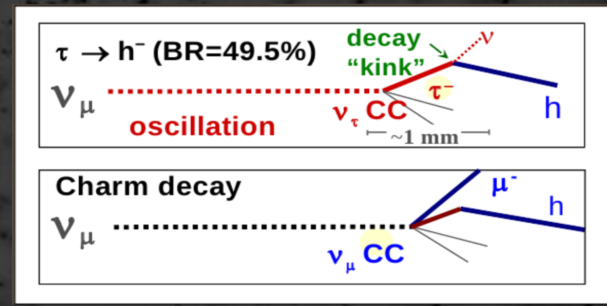
$\nu_\mu \rightarrow \nu_\tau$: main sources of background

Charmed hadron decay with missed muon at the primary vertex:

MC simulation tuned on CHORUS data

Reduced by multi-brick tracking

[Eur. Phys. J C74 (2014), 2986]

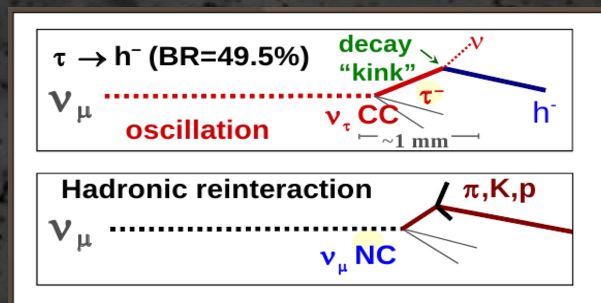


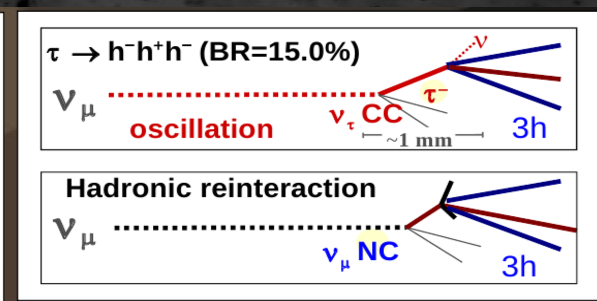
Hadronic re-interaction:

FLUKA simulation + test beam data

Reduced by large angle scanning and nuclear fragment search

[PTEP9 (2014) 093C01]

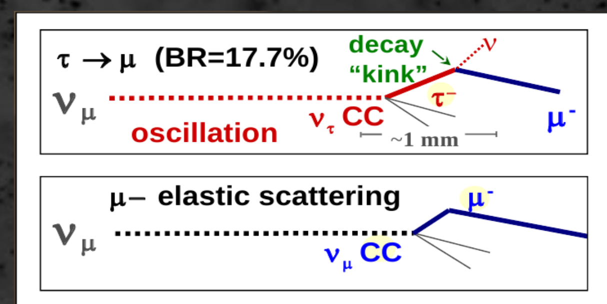




Large-angle muon scattering:

Simulation modified by introducing form factors for Lead + dedicated test beam data

[IEEE Trans. Nucl. Sci. Vol.62 (2015) No.5, 2216]



In order of decreasing importance

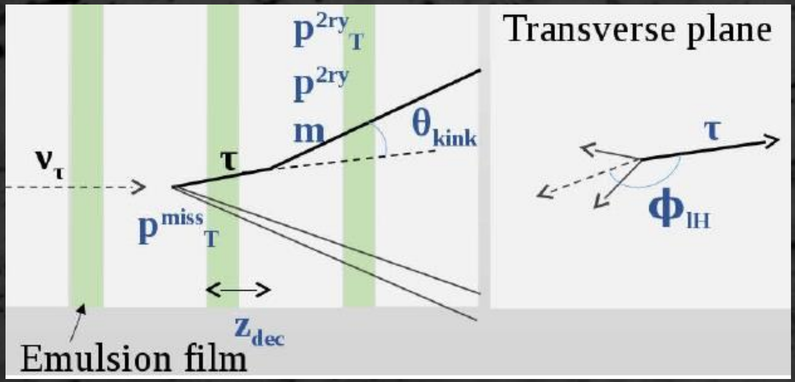
$\nu_\mu \to \nu_\tau$: minimal bias kinematical selection

Cuts fixed since the beginning of the experiment

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

Cuts marked with $\star$ are not applied for Quasi-Elastic event

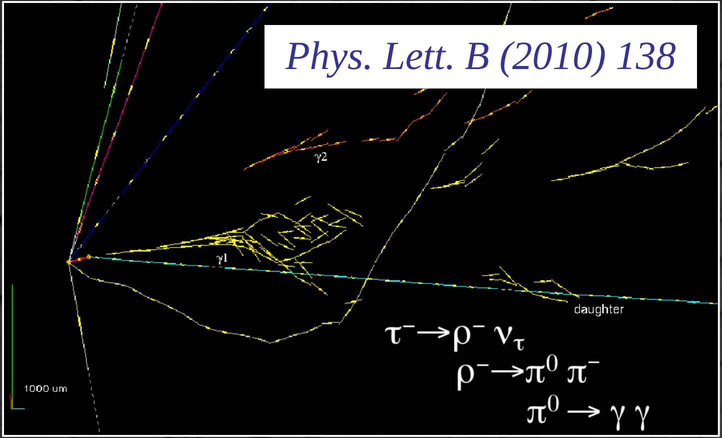
* p^T_{2ry} cut is 0.3 in the presence of γ particles associated to the decay vertex

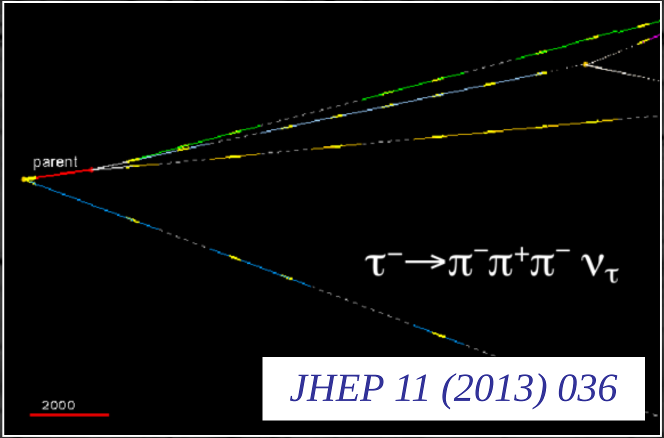


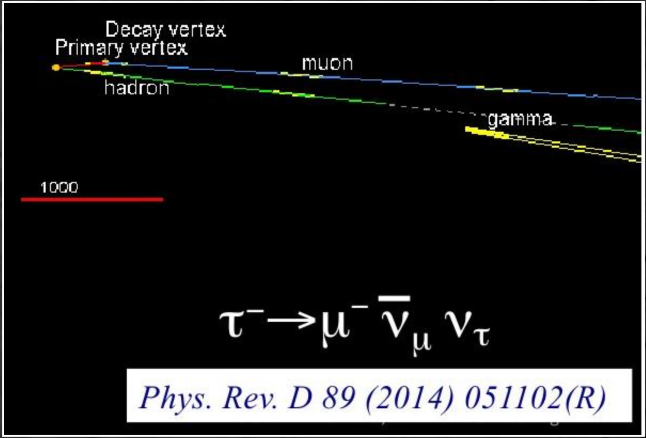
p^{miss}_T: vectorial sum of the transverse momenta of primaries (except the parent) and daughters with respect to the beam direction.

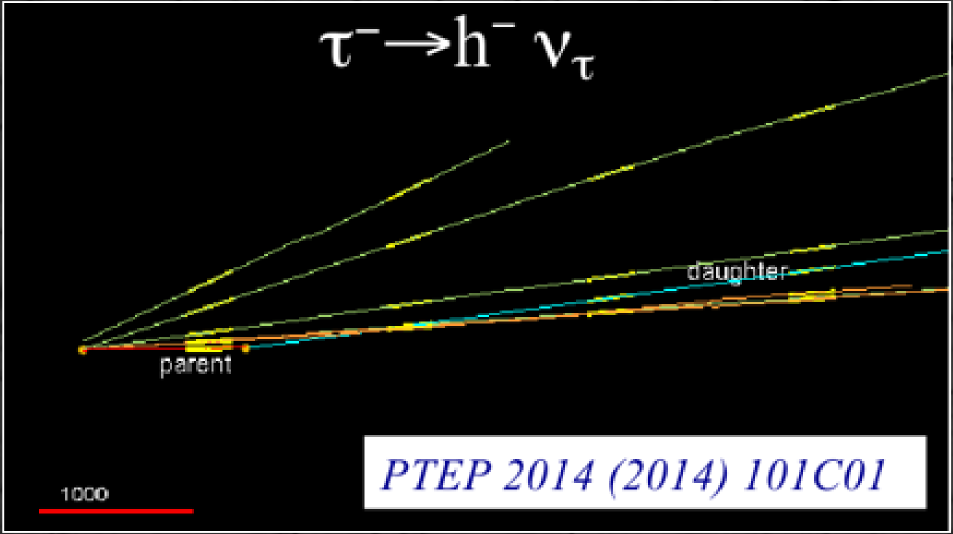
p^{2ry}_T: transverse momentum of the daughter with respect to the parent direction.

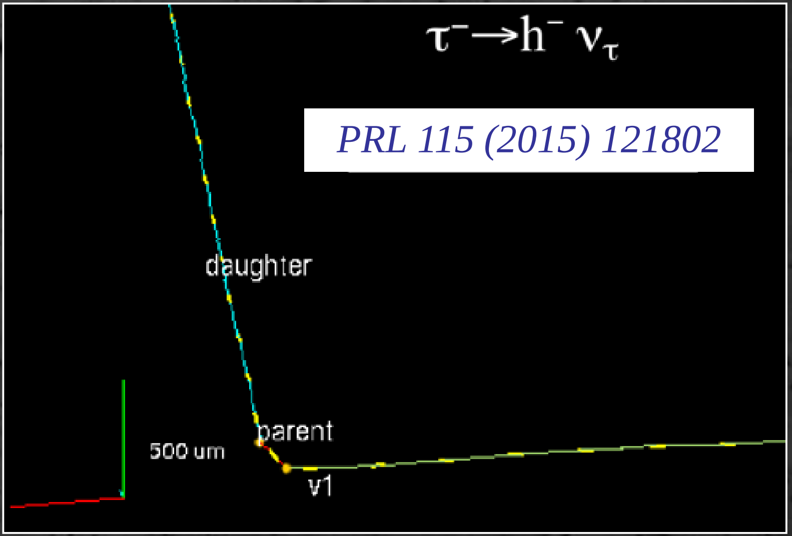
5 “golden” ν_τ candidates











Discovery of ν_τ appearance in the CNGS beam

Channel	Expected background				Expected* signal	Observed
	Charm	Had. reinterac.	Large μ scat.	Total		
$\tau \to 1h$	0.017 ± 0.003	0.022 ± 0.006		0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.003 ± 0.001		0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001		0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \to e$	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

* expectations for *full mixing* and $\Delta m^2_{32} = 2.44 \times 10^{-3}\ eV^2$

Observed in data: **5** events in the $\tau \to h$, $\tau \to 3h$, and $\tau \to \mu$ channels

Probability to be explained by background: 1.1×10^{-7}

This corresponds to 5.1σ significance of non-null observation

[PRL 115 (2015) 121802]

$\nu_\mu \rightarrow \nu_\tau$: new event analysis

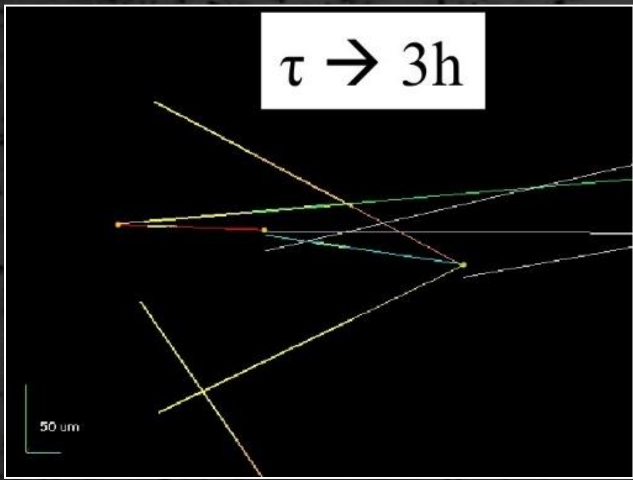
New selection strategy was defined in order to increase the number of ν_τ candidates to estimate Δm^2_{23} (the first measurement in *appearance* mode) and ν_τ cross-section with less statistical error:

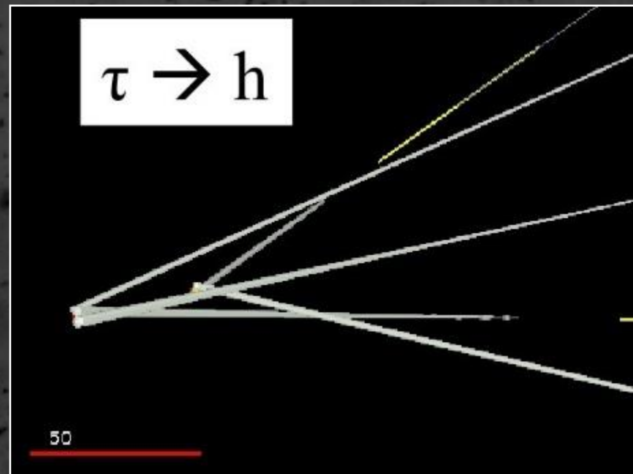
- looser kinematical cuts
- multivariate analysis (Boosted Decision Tree)

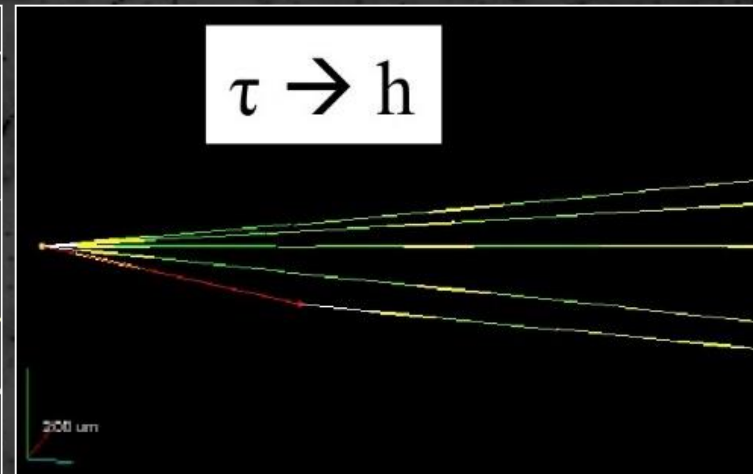
Variable	$\tau \rightarrow 1h$ PREV.	$\tau \rightarrow 1h$ NEW	$\tau \rightarrow 3h$ PREV.	$\tau \rightarrow 3h$ NEW	$\tau \rightarrow \mu$ PREV.	$\tau \rightarrow \mu$ NEW	$\tau \rightarrow e$ PREV.	$\tau \rightarrow e$ NEW
z_{dec} (μm)	$[44, 2600]$	< 2600	< 2600		$[44, 2600]$	< 2600	< 2600	
θ_{kink} (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)	$< 1\star$	/	$< 1\star$	/	/		/	
ϕ_{lH} (rad)	$> \pi/2\star$	/	$> \pi/2\star$	/	/		/	
m, m_{min} (GeV/c^2)	/		$[0.5, 2]$	/	/		/	

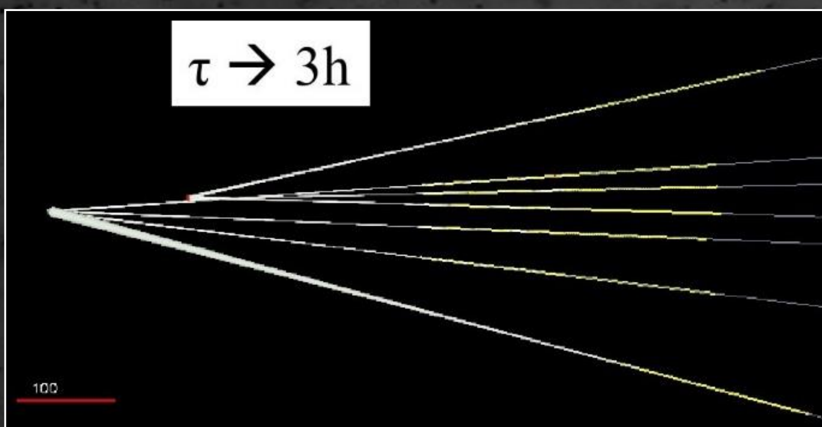
Channel	Expected Background: Charm	Had. re-interaction	Large μ-scat.	Total	Exp. Signal	Observed
$\tau \rightarrow 1h$	0.15 ± 0.03	1.28 ± 0.38	–	1.43 ± 0.41	2.96 ± 0.59	6
$\tau \rightarrow 3h$	0.44 ± 0.09	0.09 ± 0.03	–	0.53 ± 0.12	1.83 ± 0.37	3
$\tau \rightarrow \mu$	0.008 ± 0.002	–	0.02 ± 0.008	0.03 ± 0.01	1.15 ± 0.23	1
$\tau \rightarrow e$	0.035 ± 0.007	–	–	0.03 ± 0.007	0.84 ± 0.17	0
Total	0.63 ± 0.13	1.37 ± 0.41	0.02 ± 0.008	2.0 ± 0.5	6.8 ± 1.4	10

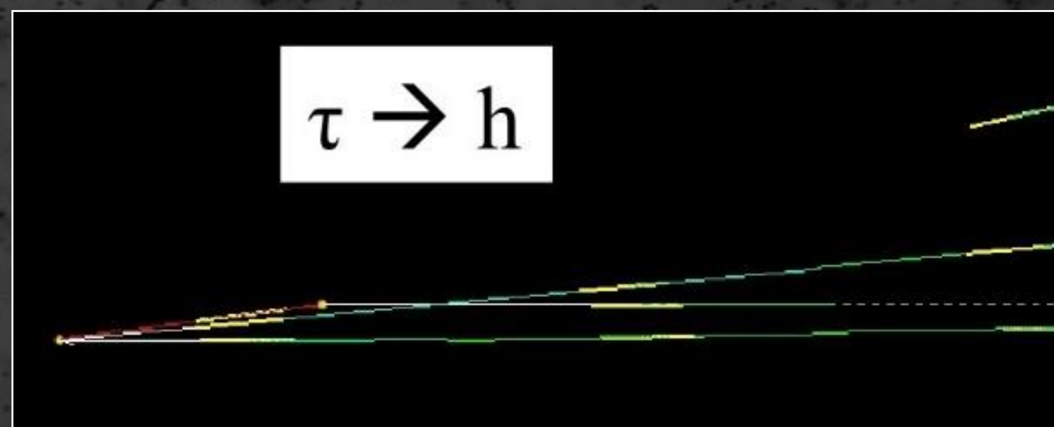
5 “silver” ν_τ candidates







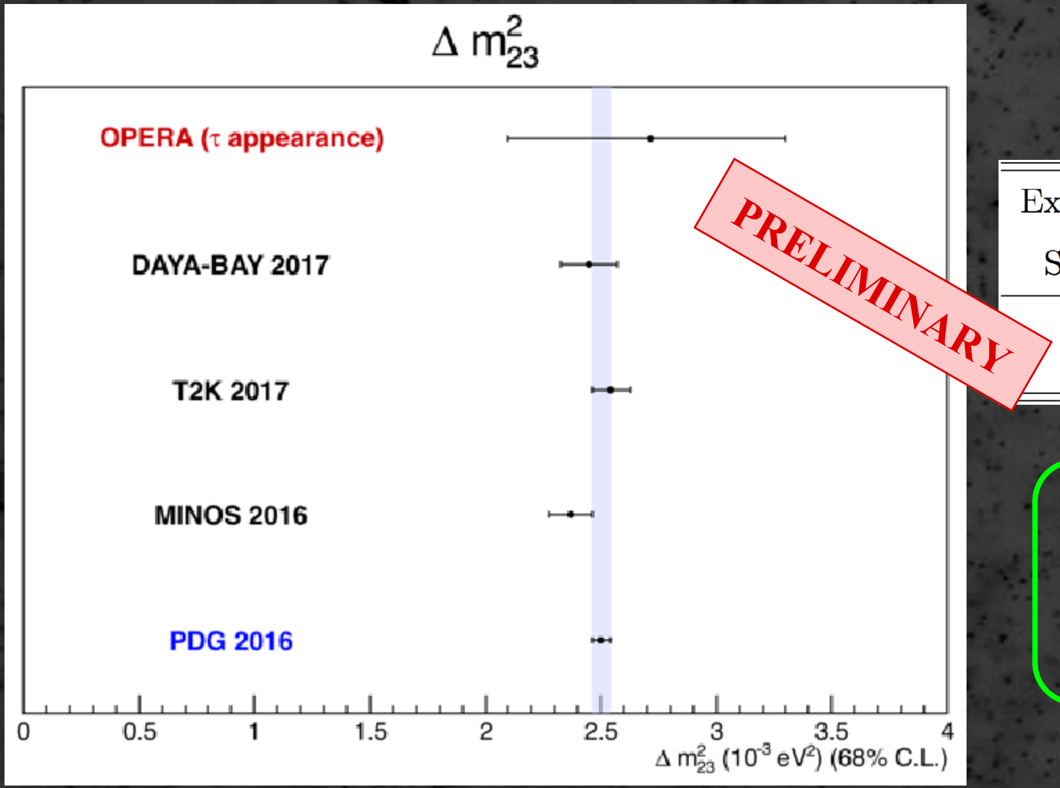




Δm^2_{23} measurement

$$N_{\nu_\tau} \propto P(\nu_\mu \to \nu_\tau)\sigma_{\nu_\tau} \cong (\Delta m^2_{23})^2 L^2 \int \Phi(E)\frac{\sigma_{\nu_\tau}(E)}{E^2}\epsilon(E)dE$$

(assuming full mixing)



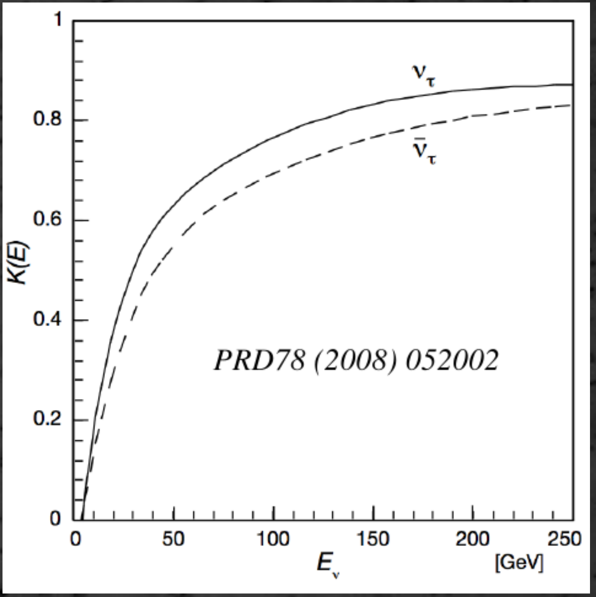
68% C.L. interval by Feldman & Cousins method

Expected Signal	Expected Background	Observed ν_τ	Δm^2_{23} (10^{-3} eV^2)
6.8	2.0	10	2.7 ± 0.6 68% C.L

Agreement with PDG 2016 value and with the results found in *disappearance mode* by other experiments within 1σ

ν_τ cross-section measurement

$$\sigma_{\nu_\tau} = \sigma^0_{\nu_\tau} E K(E)$$



Until now, ν_τ cross-section was measured only by the DONuT experiment which *could not distinguish* ν_τ *from* $\bar{\nu}_\tau$:

$$\sigma^0_{\nu_\tau+\bar{\nu}_\tau} = 0.72 \pm 0.24 \pm 0.36 \times 10^{-38}\ cm^2 GeV^{-1}$$

OPERA: the first measurement with ν_τ only

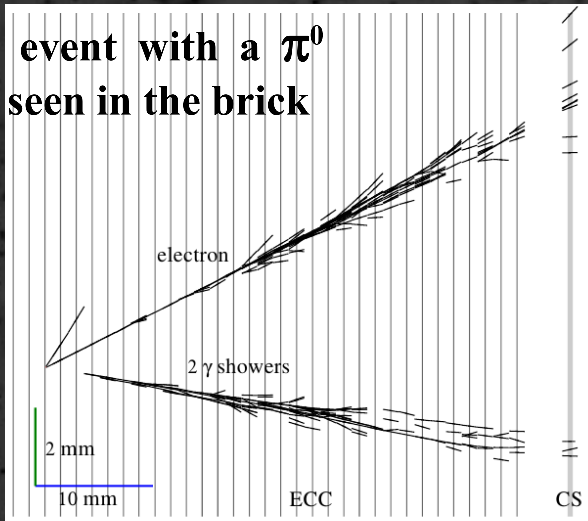
PRELIMINARY

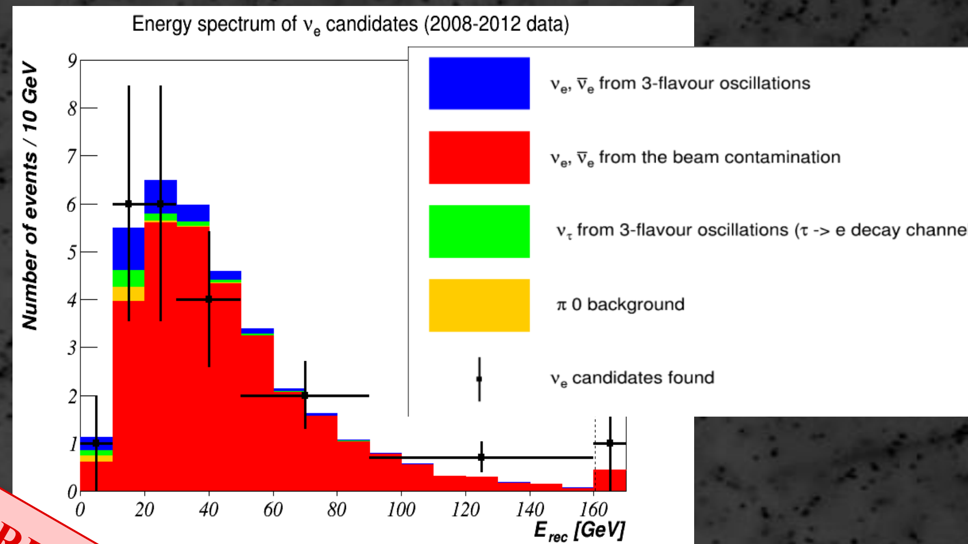
Δm^2_{23} (10^{-3} eV^2)	Expected Signal	Expected Background	Observed ν_τ	$\sigma^0_{\nu_\tau}$ (10^{-39}cm^{2}GeV^{-1})
2.5	6.8	2.0	10	8^{+4}_{-3}

Agreement with the SM value $6.7 \times 10^{-39}\ cm^2 GeV^{-1}$ within 1σ

$\nu_\mu \rightarrow \nu_e$: full data sample analysis

ν_e event with a π^0 as seen in the brick





PRELIMINARY

Energy cut, GeV	10	20	30	40	50	No cut
ν_e, $\bar{\nu}_e$ from the beam contamination	0.6	4.6	10.2	15.7	20.0	30.8
π^0	0.1	0.4	0.5	0.5	0.5	0.5
ν_τ from 3-flavour oscillations ($\tau \rightarrow e$ channel)	0.1	0.5	0.6	0.7	0.8	0.9
Total expected BG	0.8	5.5	11.3	16.9	21.3	32.2
ν_e, $\bar{\nu}_e$ from 3-flavour oscillations	0.3	1.1	1.8	2.3	2.4	2.7
Expected spectrum in case of 3 flavour oscillations	1.1	6.6	13.1	19.2	23.7	34.9
Data	1	7	13	19	21	35

Number of observed events is in agreement with the expected background and 3 flavour oscillation signal

Sterile neutrinos mixing searches

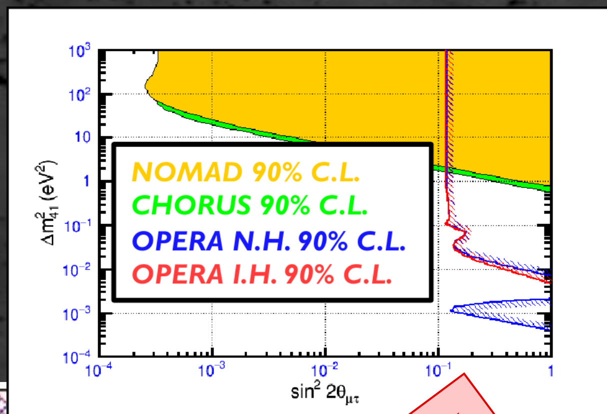
Results of ν_τ and ν_e searches are used to derive limits on the mixing parameters of a massive sterile neutrino in the 3+1 flavour model.

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

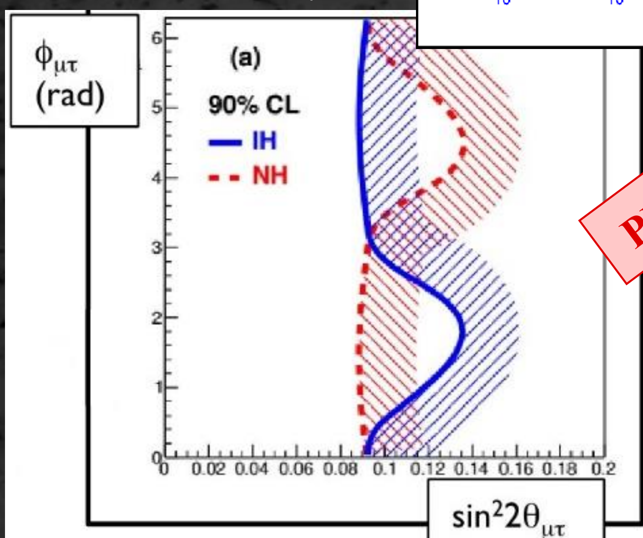
parameters of interest: U_{e4} (ν_e appearance), $U_{\mu 4}$, $U_{\tau 4}$ (ν_τ appearance)

ν_τ appearance

(5 ν_τ candidate events)



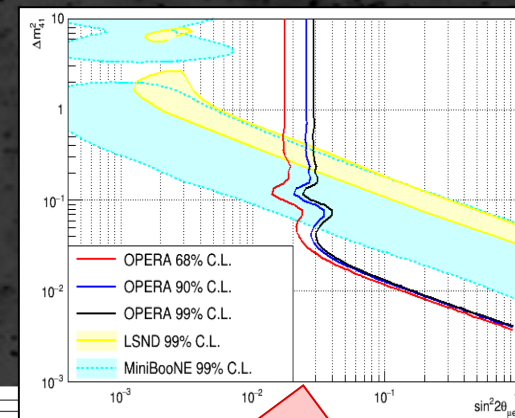
$$\phi_{\mu\tau} = Arg(U_{\mu 3} U^*_{\tau 3} U^*_{\mu 4} U_{\tau 4})$$



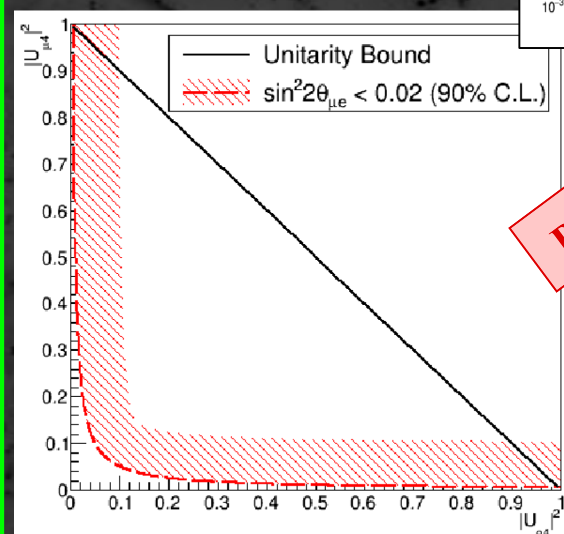
PRELIMINARY

ν_e appearance

(35 ν_e candidate events)



$$sin^2 2\theta_{\mu e} = 4|U^2_{\mu 4}||U^2_{e4}|$$



PRELIMINARY

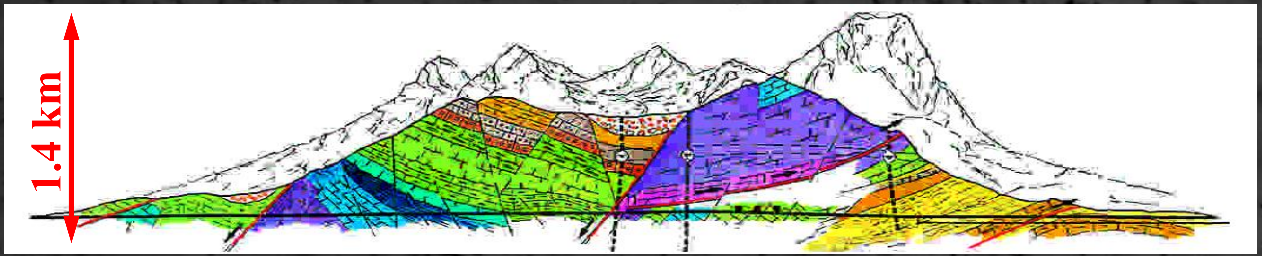
OPERA as a cosmic ray detector

Gran Sasso underground lab: 1400 m of rock (~3800 m w.e.) shielding, cosmic ray flux reduced by a factor of 10^6 w.r.t. surface.

$\langle E_\mu \rangle$ underground: $\sim 270\ GeV$

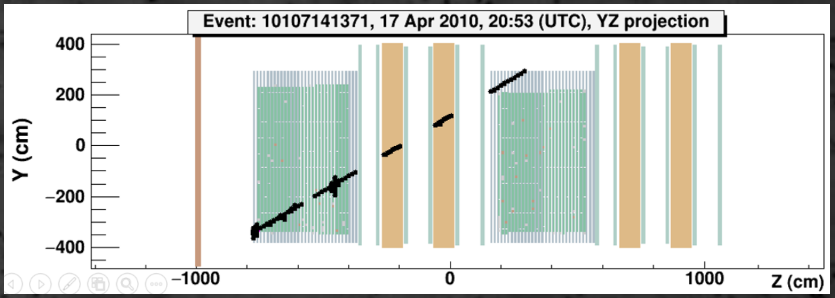
$\langle E_\mu \rangle$ surface cut-off: $\sim 1.5\ TeV$

OPERA: $\langle E_\mu cos\theta \rangle \approx 2\ TeV$



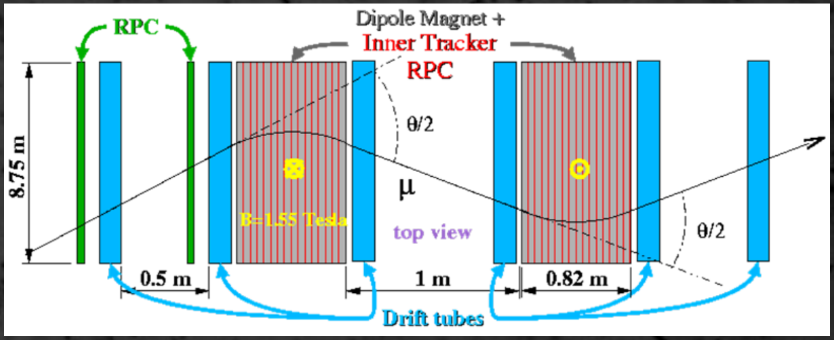
CNGS beam events were identified through a timing coincidence with the beam spill,

➡ cosmic events were collected during the physics runs.



OPERA electronic detectors provided muon charge and momentum reconstruction and had excellent timing capabilities (~10 ns).

- Atmospheric muon charge ratio **[Eur. Phys. J. C (2014) 74]**
- Annual modulation of atmospheric muons

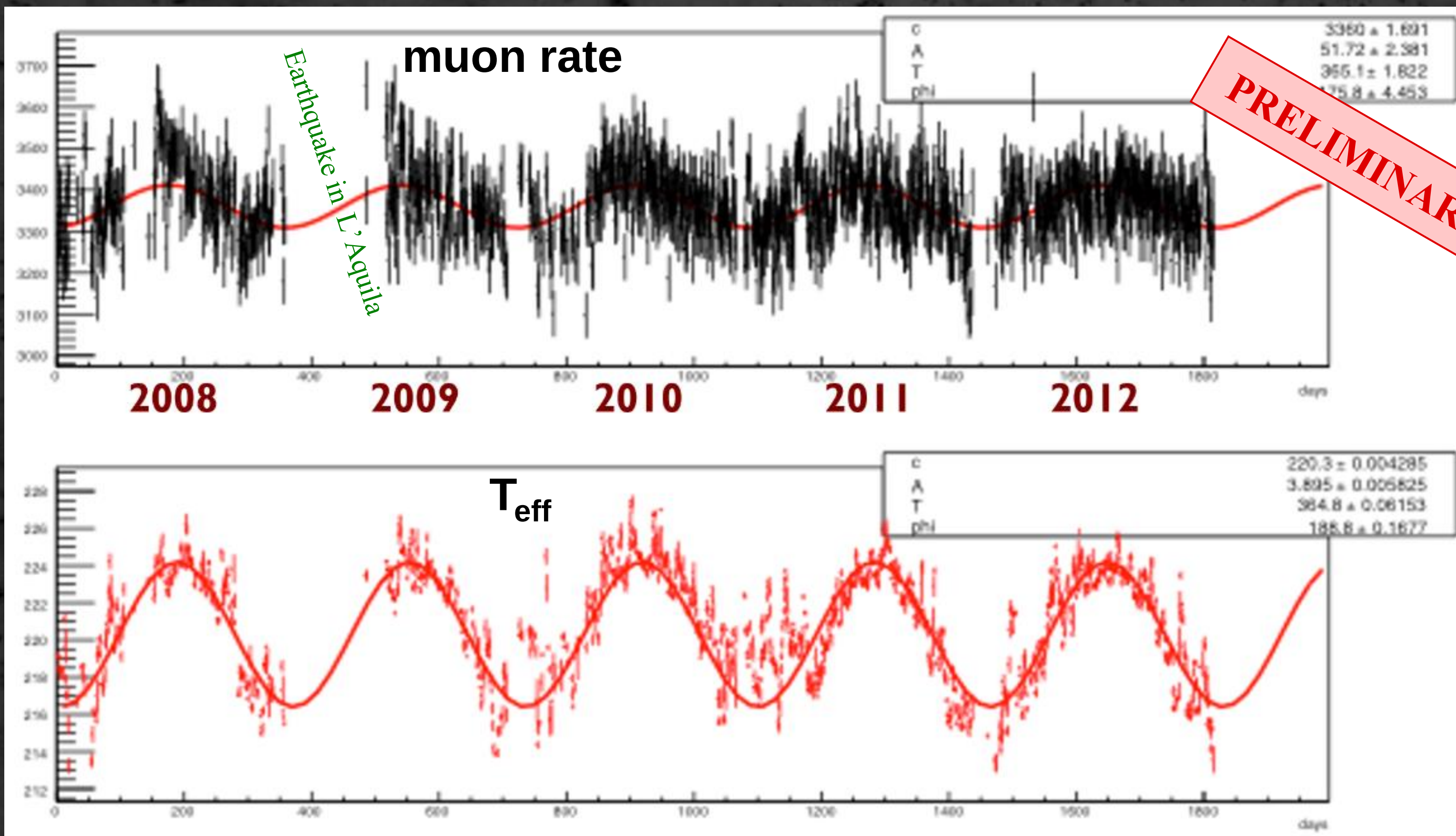


Annual modulation of the cosmic muon rate

Atmospheric temperature ↗ ⟹ gas density ↘ ⟹ π and K decay rate ↗ ⟹ muon rate ↗

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

Complete OPERA data set: 2008-2012 (only single muons are taken into account)



$$T = (365 \pm 2)\ days$$
$$t_0 = (176 \pm 4)\ days$$

$$\frac{\Delta I_\mu}{I_\mu^0} = (1.54 \pm 0.07)\%$$

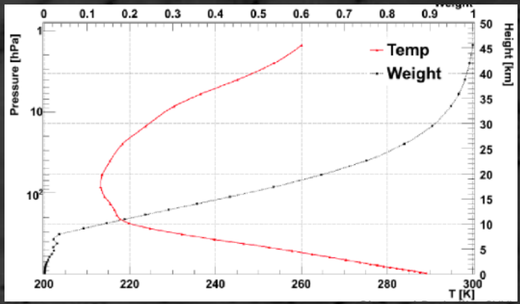
Temperature data provided by the European Center for Medium-range Weather Forecasts (ECMWF)

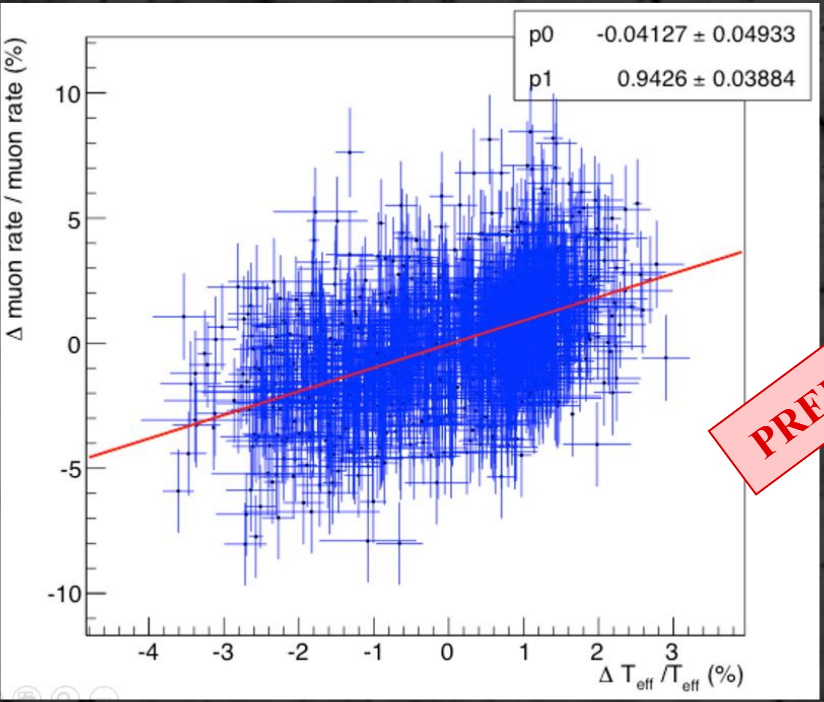
Muon rate vs temperature variations

Correlation between relative variations in the muon rate and the effective temperature:

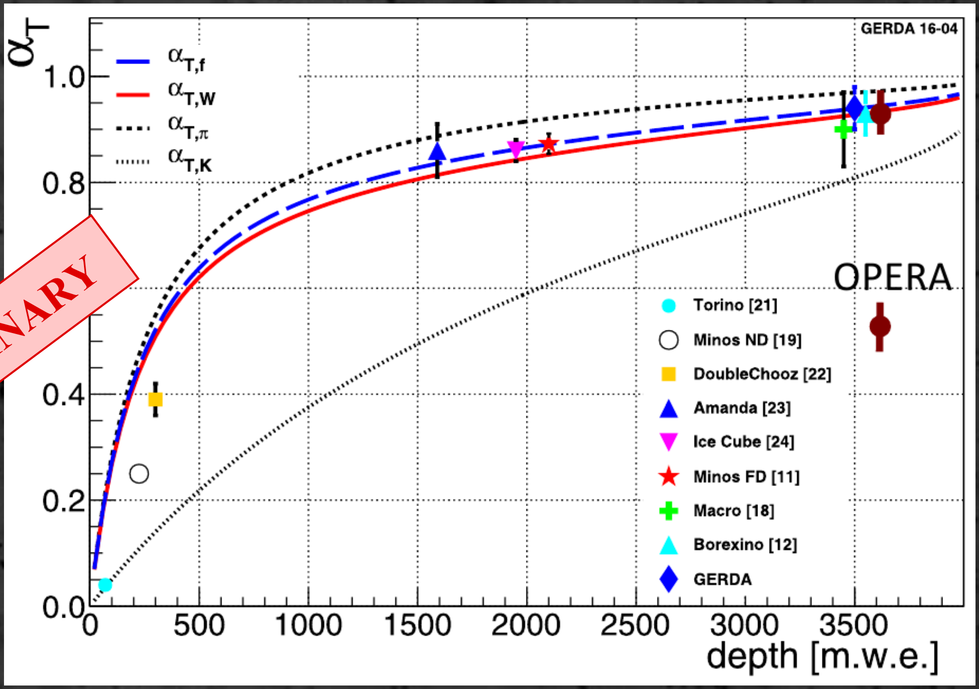
$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{eff}}{T_{eff}}$$

$$T_{eff} = \frac{\int_0^\infty T(x)W(x)dx}{\int_0^\infty W(x)dx}$$





PRELIMINARY



$\alpha_T = 0.94 \pm 0.04$

In agreement with predictions for LNGS site and with other experiments

Conclusions and outlook

- *Discovery of $\nu_\mu \to \nu_\tau$ appearance* in the CNGS neutrino beam: 5.1σ.

- *Loose selection analysis* to increase the number of ν_τ candidates for estimation of:

  Δm^2_{23} (*the first measurement in appearance mode*);

  ν_τ cross-section (*the first measurement with ν_τ only*).

- $\nu_\mu \to \nu_e$ *oscillation search*: number of events observed in the full data sample is in agreement with the expected background and the standard oscillation signal.

- *Constraints on sterile neutrino oscillations* from $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ with the 3+1 flavour model.

- Non-oscillation physics: *analysis of the annual modulation of the cosmic muon rate*.

PERSPECTIVES:

- Exploit OPERA unique feature of identifying all three flavours: use of ν_μ *disappearance* and both ν_τ and ν_e *appearance* to constrain neutrino oscillation parameters with one single experiment.

- Successful OPERA experience of nuclear emulsion use for ν_τ detection is going to be applied in future experiments (DsTau, SHiP @CERN, …), and for directional dark matter search (NEWSdm @LNGS).

Backup slides

Data analysis chain in OPERA

Reconstruction of interaction events

Association of events with the CNGS beam (selection of *on-time* events)

Track reconstruction and muon identification

Recognition of events originated in the target (selection of *contained* events)

Brick Finding: localization of the brick containing the neutrino interaction vertex

} *in electronic detectors*

Confirmation of the selected brick by analysis of the interface emulsion films (CS)

Location of a neutrino interaction vertex

Decay search: analysis of event topology

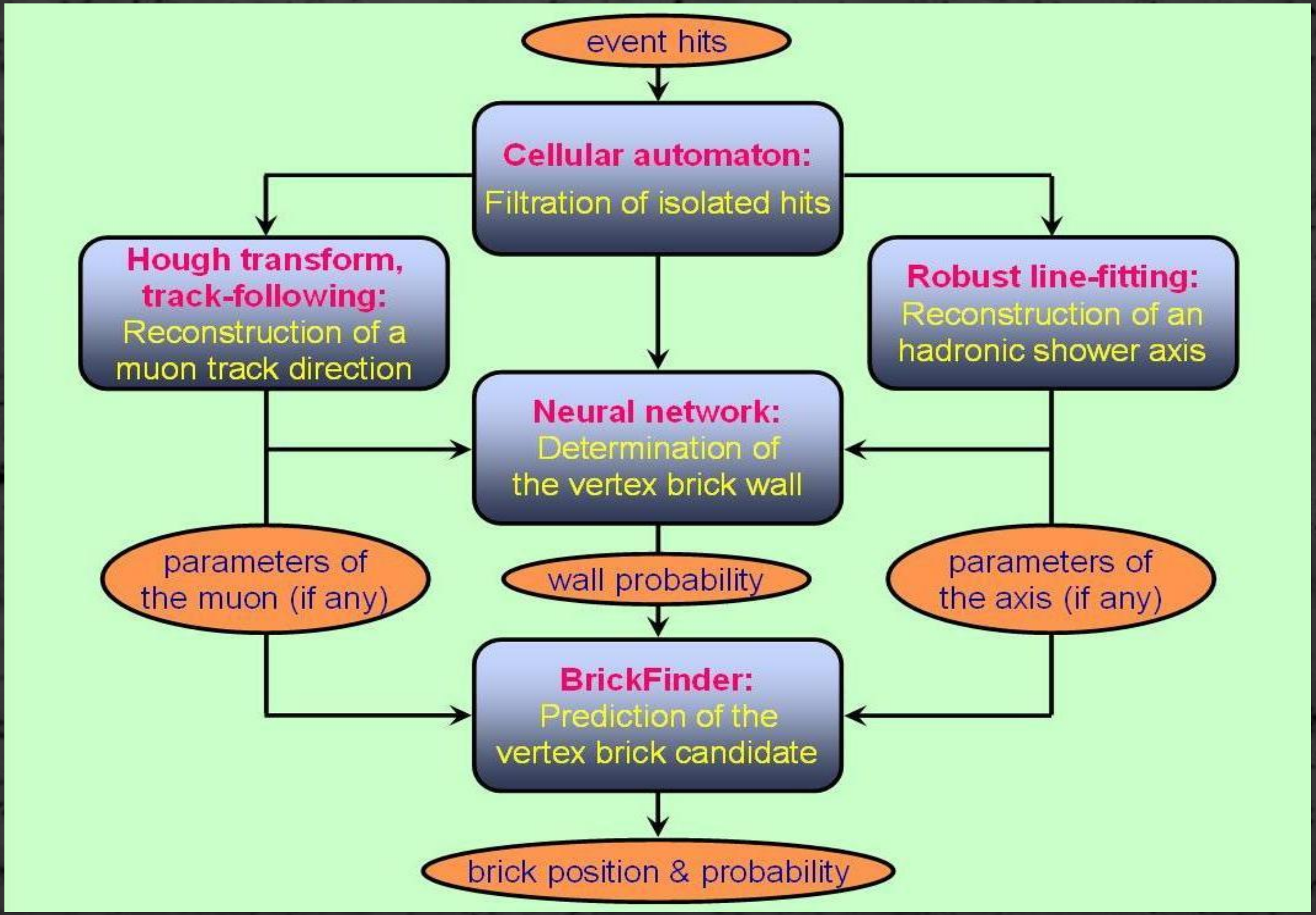
Kinematic selection

} *in emulsion*

Vertex brick finding

The most important task of the Target Tracker (TT) electronic detector is to localize the ECC brick where the neutrino interaction occurred. A high BF efficiency is needed in order to reduce the emulsion processing load and to minimize the target mass loss.

procedure of the vertex brick prediction

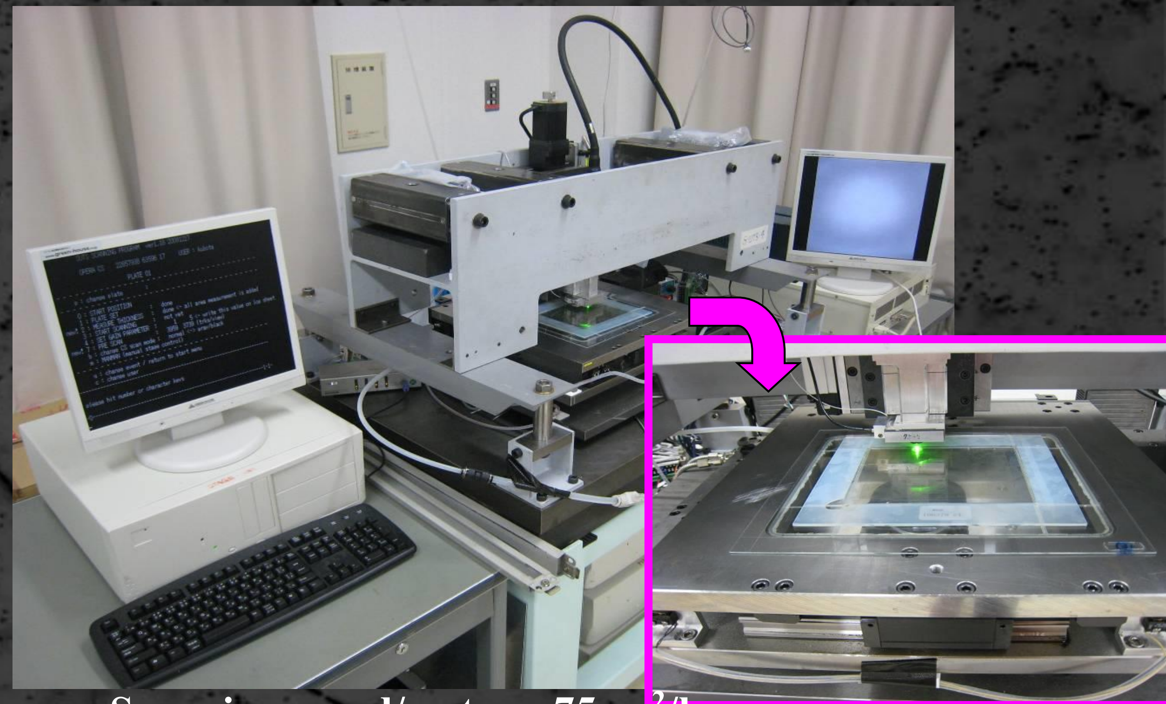


Emulsion scanning stations

EU: ESS (European Scanning System)

- Scanning speed/system: 20cm^2/h
- Customized commercial optics and mechanics
- Asynchronous DAQ software

Japan: S-UTS (Super Ultra Track Selector)



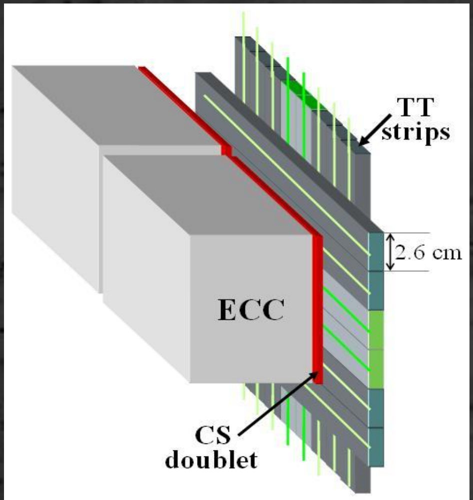
- Scanning speed/system: 75cm^2/h
- High speed CCD camera, Piezo-controlled objective lens
- FPGA Hard-coded algorithms

Both systems demonstrate:

- ~0.3 μm spatial resolution
- ~2 mrad angular resolution
- ~95% base track detection efficiency

Analysis in the Changeable Sheets (CS)

Changeable Sheets (or *CS doublet*) is a pair of emulsion films attached on the downstream face of each brick used as interface between the ED and ECC detectors.



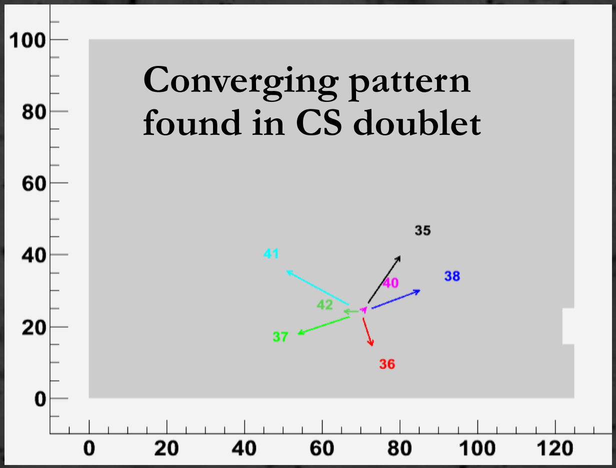
The predicted brick is approved for dismantling, development, and analysis if at least:

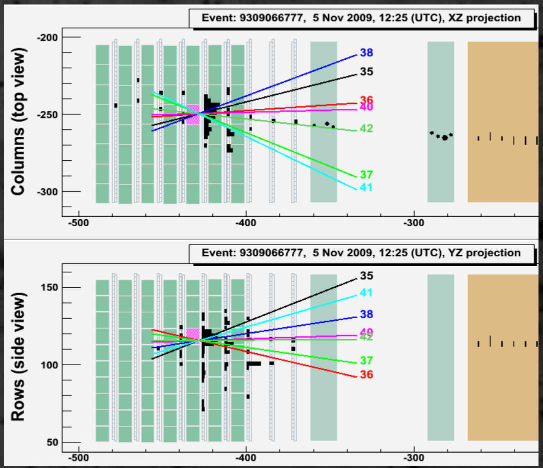
- a CS track compatible with the ED muon track within 60 mrad
- a CS track matching an isolated ED track
- two or more CS tracks possibly converging towards a common origin in the brick

CSd alignment by Compton electrons:
~2.5 μm

Position accuracy of ED predictions:
~8 mm

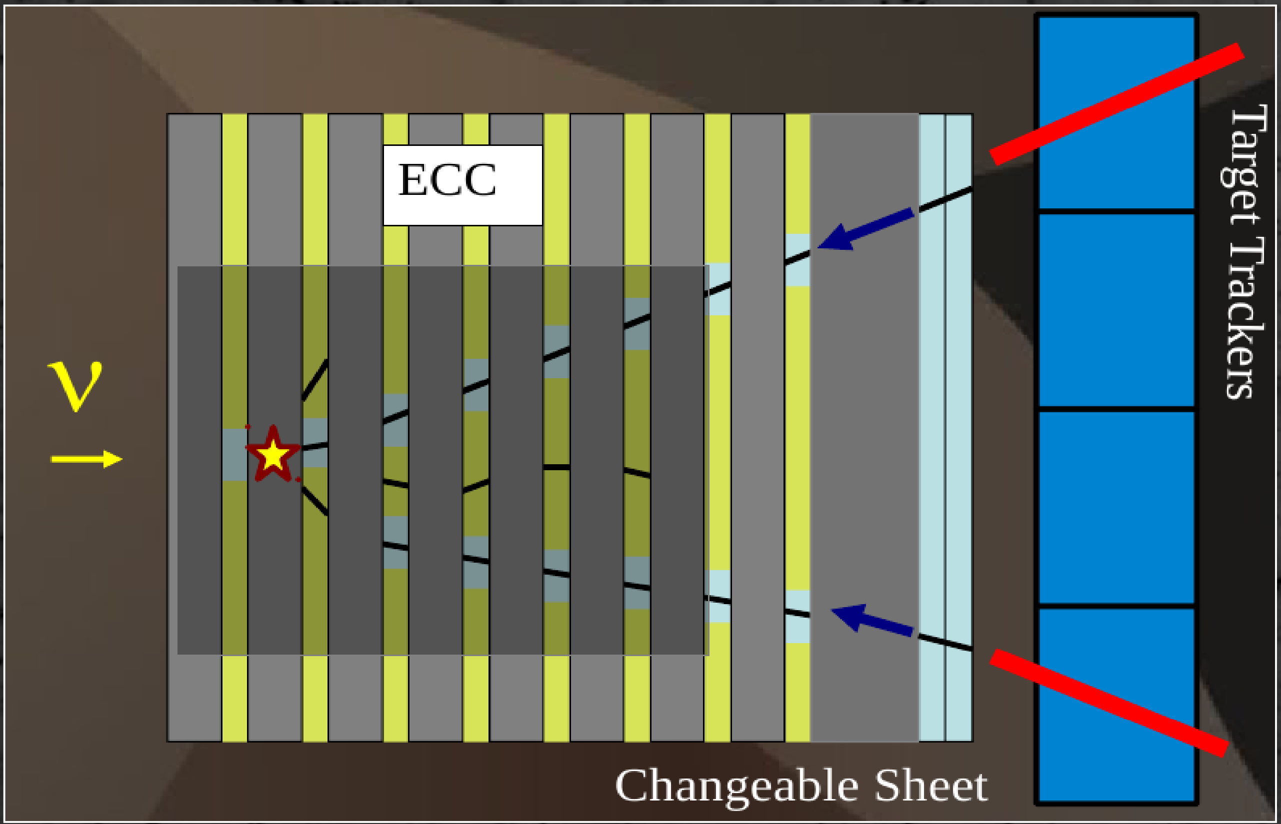
Angular accuracy of ED predictions:
~15 mrad





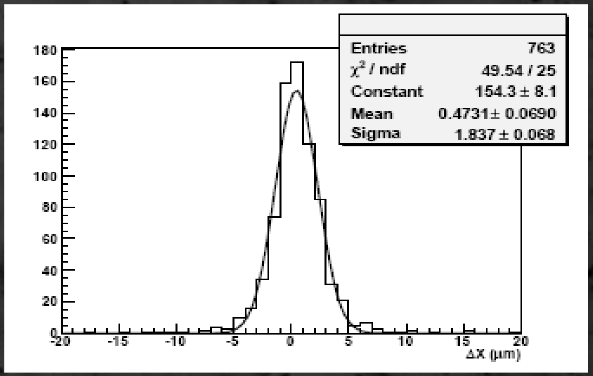
Analysis in the ECC: Scan-back

- Search for track segments connected to the CS tracks in the most downstream films of the brick.
- Follow back of the found tracks in the upstream films of the brick until stopping point (signature of a vertex) is found.



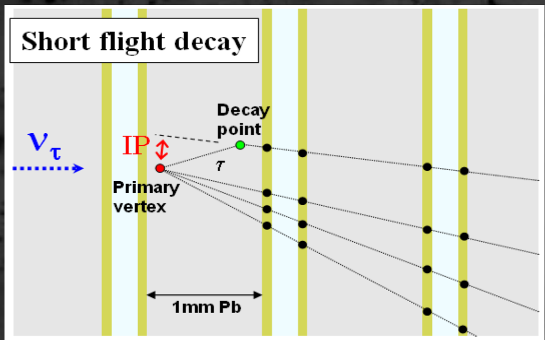
CSd-ECC alignment by X-ray marks: ~10 μm

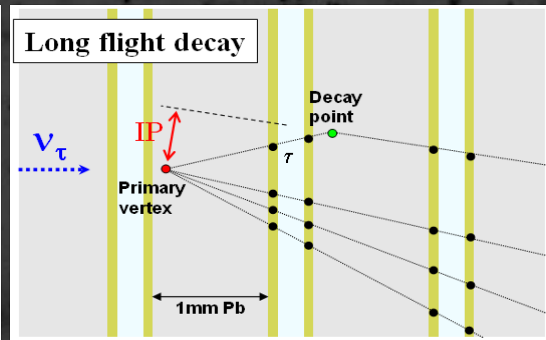
ECC films alignment by cosmic rays: ~2 μm

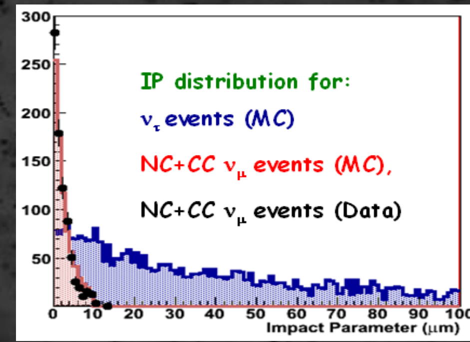


Decay search

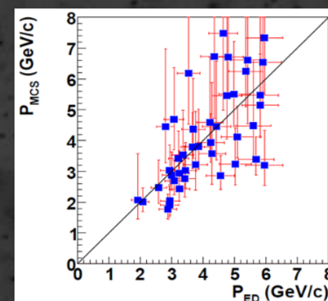
Detection of decay or interesting topologies on tracks attached to the primary vertex

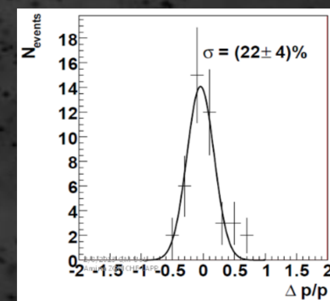


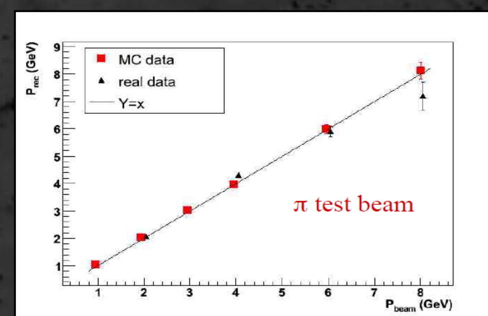




- Impact parameter (IP) evaluation
- Momentum measurement by multiple Coulomb scattering (MCS)
- Search for significant kink/trident topology
- Additional track search
- E.m. shower detection and energy measurement
- Detection of nuclear fragments







Charmed particle decays

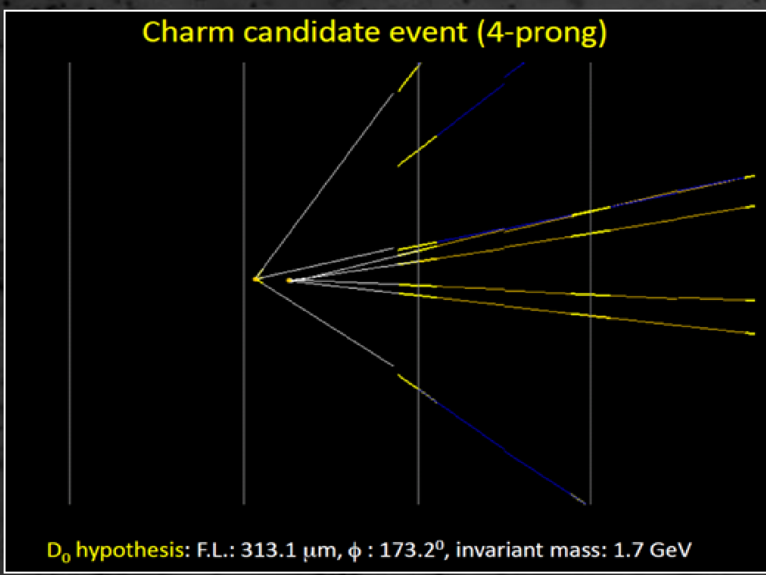
Charmed hadrons, produced in ν_μ DIS on nucleus, have similar mass, lifetime and decay modes as τ:

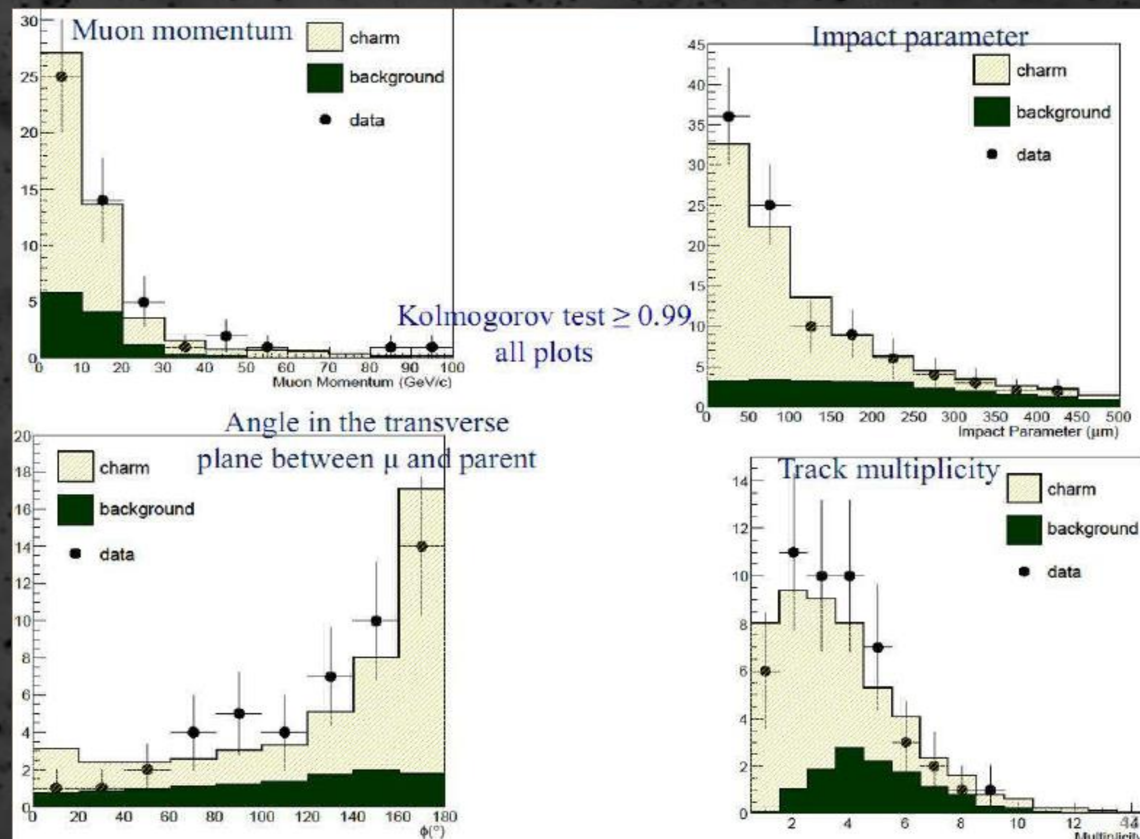
- → Main source of background
- → Reference sample to verify the understanding of τ detection efficiency

Good agreement between data & MC:

Expected events: 54 ± 5

Observed events: 50





$\nu_\mu \rightarrow \nu_\tau$: analysis strategy

2008-2009 runs:

- No kinematical selection: get confidence on the detector performances before applying any kinematical cut
- Slower analysis speed (signal/noise not optimal!)
- Kinematical selection applied for the candidate selection, coherently for all runs
- Good data/MC agreement shown

2010-2012 runs:

- Kinematical selection of CC-like events: $P_\mu < 15$ GeV/c, to suppress charm background
- Prioritize the analysis of the most probable brick in the probability map: optimal ratio between efficiency and analysis time
- Analyze the other bricks in the probability map

OPERA Open Data at CERN

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> About

CERN Open Data Portal

The CERN Open Data portal is the access point to a growing range of data produced through the research performed at CERN. It disseminates the preserved output from various research activities, including accompanying software and documentation which is needed to understand and analyse the data being shared.

The portal adheres to established global standards in data preservation and Open Science: the products are shared under open licenses; they are issued with a digital object identifier (DOI) to make them citable objects in the scientific discourse (see details below on how to do this).

The CMS (Compact Muon Solenoid) experiment is one of two large general-purpose detectors built on the Large Hadron Collider (LHC). Its goal is to investigate a wide range of physics such as the characteristics of the Higgs boson, extra dimensions or dark matter.

Explore CMS >

ALICE (A Large Ion Collider Experiment) is a heavy-ion detector designed to study the physics of strongly interacting matter at extreme energy densities, where a phase of matter called quark-gluon plasma forms. More than 1000 scientists are part of the collaboration

Explore ALICE >

The ATLAS (A Toroidal LHC ApparatuS) experiment is a general-purpose detector exploring topics like the properties of the Higgs-like particle, extra dimensions of space, unification of fundamental forces and evidence for dark matter candidates in the Universe.

Explore ATLAS >

The LHCb (Large Hadron Collider beauty) experiment aims to record the decay of particles containing b and anti-b quarks, known as B mesons. The detector is designed to gather information about the identity, trajectory, momentum and energy of each particle.

Explore LHCb >

The Oscillation Project with Emulsion-tRacking Apparatus (OPERA) is a scientific experiment for detecting tau neutrinos from muon neutrino oscillations. The experiment is a collaboration between CERN in Geneva, Switzerland, and the Laboratori Nazionali del Gran Sasso (LNGS) in Gran Sasso, Italy

Explore OPERA >

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OPERA

The OPERA experiment (Oscillation Project with Emulsion-tRacking Apparatus) has been taking data from 2008 to 2012 at the Gran Sasso INFN Laboratory on the CNGS muon neutrino beam produced at CERN. The experiment was aiming at demonstrating the tau neutrino appearance in a muon neutrino beam due to neutrino oscillations. This goal was achieved in 2015 when the observation of five tau neutrino candidates was reported and the discovery of tau neutrino appearance was published with a significance larger than 5 sigma. The experiment is unique in its capability of detecting all three neutrino flavours. Tau neutrinos are identified through their charged-current interactions where the short-lived tau lepton is produced and its decay vertex is detected. This challenging goal is achieved thanks to the Emulsion Cloud Chamber technology based on nuclear emulsion films with the unsurpassed sub-micrometric accuracy, readout by fully-automated and high-speed optical microscopes. The OPERA Collaboration includes about 150 physicists from 26 Institutes in 11 Countries.

A sample of neutrino interactions reconstructed in the bricks is available in the portal: data & event display (effective for education).

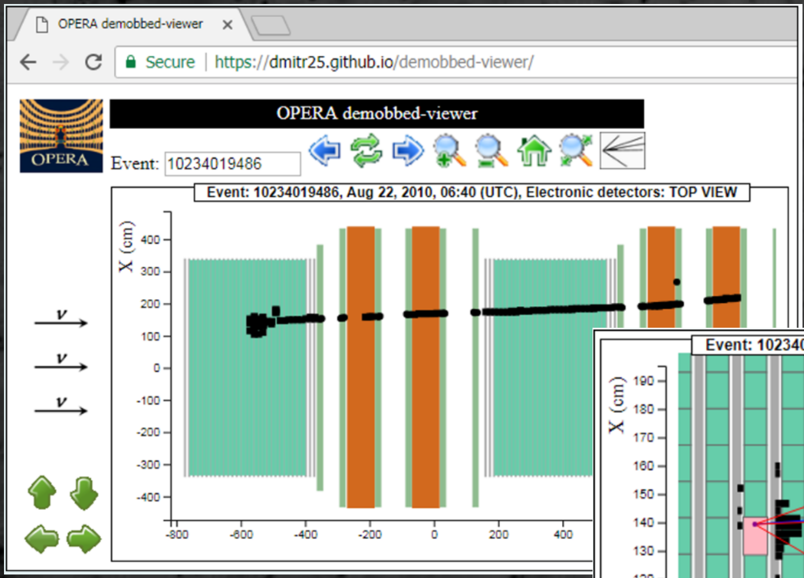
OPERA Electronic Detector Datasets	OPERA Emulsion Detector Datasets	OPERA Detector Events
This collection contains OPERA Electronic Detectors (ED) datasets.	This collection contains OPERA Emulsion Cloud Chamber (ECC) datasets.	This collection contains OPERA detector events.
Total records: 1	**Total records:** 1	**Total records:** 818

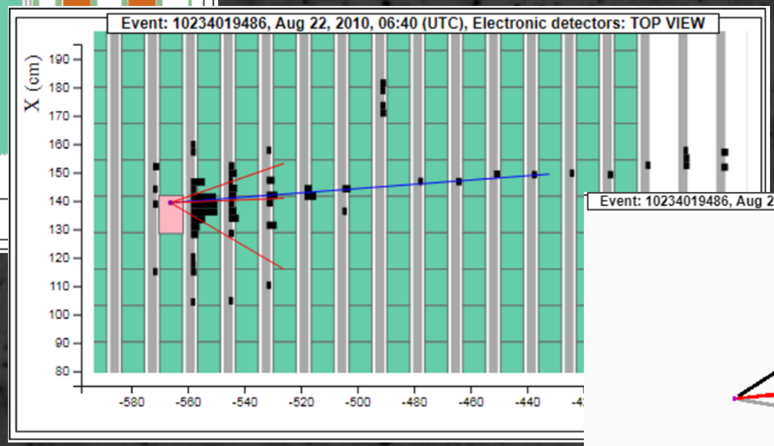
OPERA is the first non-LHC experiment joining the educational and research program of the Open Data Access group.

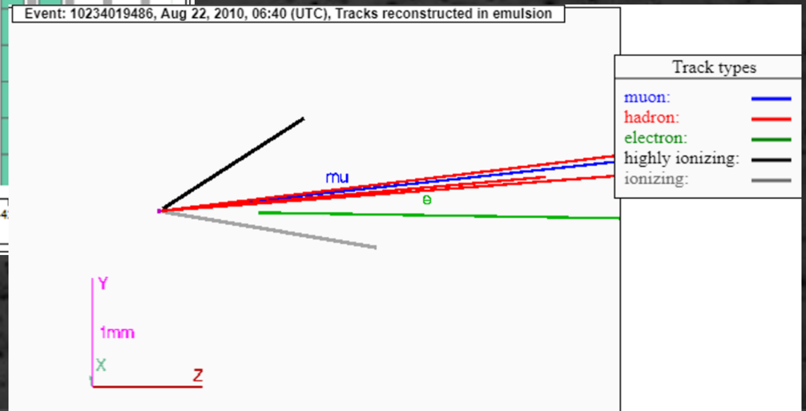
OPERA browser-based event display

OPERA browser-based event display was implemented by analogy with an existing web-interface for visualization of open data of the CMS experiment developed by **Thomas McCauley**
https://opendata.cern.ch/visualize/events/CMS

The display includes two 2D-views (XZ & YZ) of an event in *Electronic Detectors* + one simplified 3D-view of tracks found in OPERA lead-emulsion brick near the primary neutrino interaction vertex.







Basic functionality of the **2D-display**
- browsing through the event list
- moving of a camera views
- general (un)zooming
- zooming to the area of the beginning of an event
- zooming to the area of a whole event

Basic functionality of the **3D-display**
- browsing through the event list
- animated rotation of the ECC tracks around the vertex