Analysis and interactive visualization of neutrino event topologies registered in the OPERA experiment

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Introductory lecture, 2023/11/01

INTEREST @JINR, Wave 9, Project #253

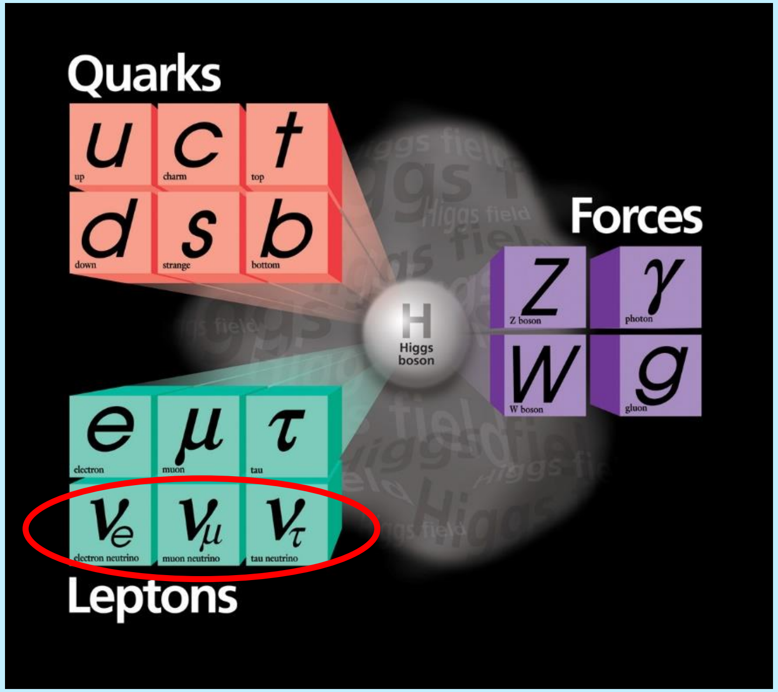
Outline

- About neutrinos
- About the OPERA experiment
- About CERN Open Data Portal

About neutrinos

Understanding the neutrino sector is a worldwide priority promising development of a fundamental theory beyond the Standard Model of particle physics.

Fundamental particles of the Standard Model



- Neutrinos are the second (after photons) most abundant known elementary particles in the universe. There are ~340 neutrinos per cubic centimeter, averaged over the whole space.

- They are electrically neutral leptons, fermions (spin – 1/2).

- The only known forces they experience are the *weak force* and *gravity*.

- This means that they do not interact with other matter very much at all.

  Thus, neutrinos are difficult to detect and study.

Prediction and discoveries of neutrinos

1930: Hypothesis of existence of such a specific particle (a light-weight "neutron") was proposed by **W.Pauli** in order to solve a perplexing problem in nuclear physics (apparent disappearance of energy in the decay of certain atomic nuclei).

In 1932 **J.Chadwick** discovered the real “neutron”, with a mass similar to that of the proton and being the missing building block of the nuclei. So, it was suggested to rename Pauli’s “neutron” to “neutrino”. (*Neutrone* in Italian means big and neutral, and *neutrino* means small and neutral.)

1956: **F.Reines** and **C.Cowan** discovered neutrino ($\bar{\nu}_e$) using a nuclear reactor in Savannah River (USA).

Nobel Prize 1995

1962: Muon neutrinos ($\nu_\mu \neq \nu_e$) were discovered by **L.Lederman**, **M.Schwartz**, **J.Steinberger** and their colleagues at Brookhaven National Laboratory (USA).

Nobel Prize 1988

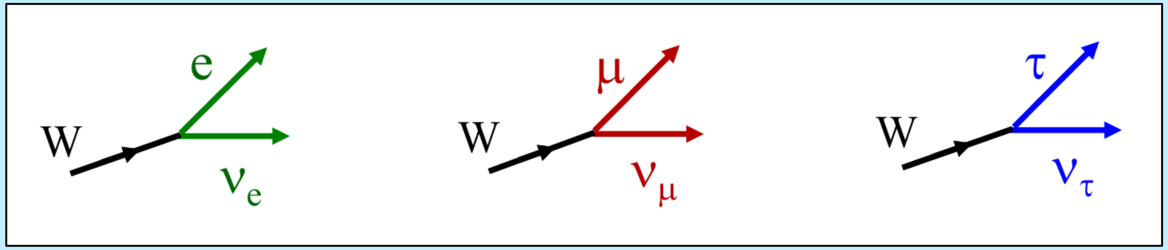
1989: The LEP accelerator experiments at CERN (Switzerland, France) and the SLC at SLAC (USA) determined that there were only 3 light neutrino species (ν_e, ν_μ, and ν_τ?).

2000: The DONuT Collaboration made the first direct observation of tau neutrino (ν_τ) at Fermilab (USA) using *nuclear emulsion detectors*.

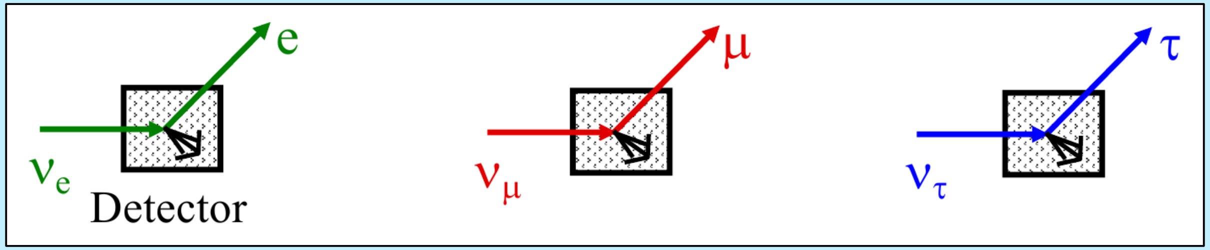
Three flavours of leptons

There are three flavours of charged leptons: e (electron), μ (muon), and τ (tau lepton).

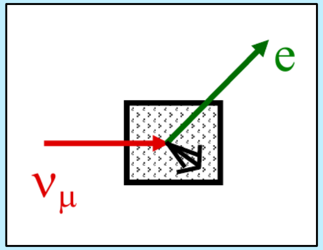
The three known flavours of neutrinos (ν_e, ν_μ, and ν_τ) are defined by **W** boson decays:



As far as we know, when a neutrino of given flavour interacts and turns into a charged lepton, that charged lepton will always be of the same flavour as the neutrino:



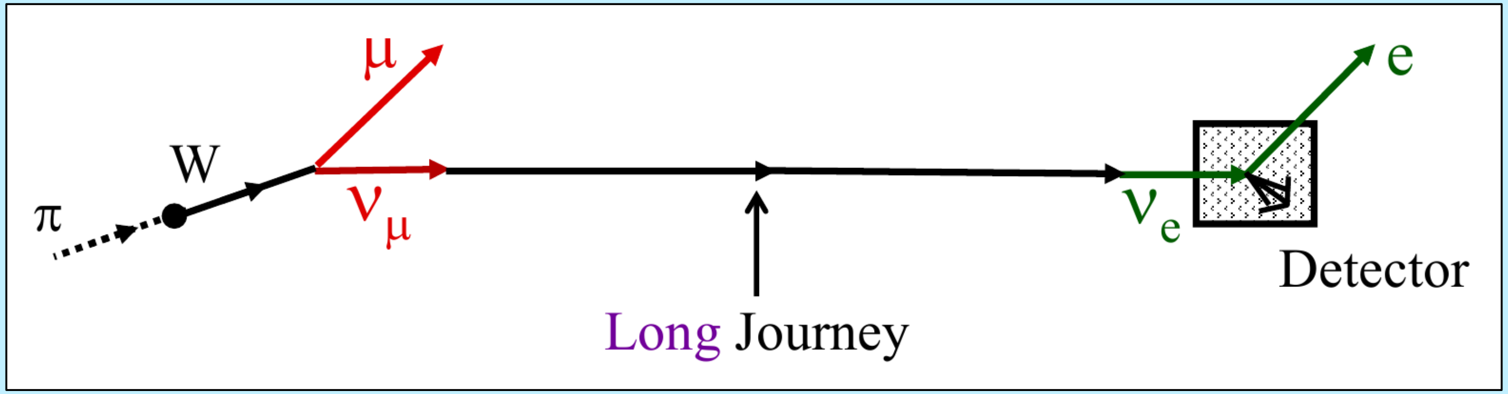
But not



The week interaction couples the neutrino of a given flavour only to the charged lepton of the same flavour.

Neutrino flavour change (Neutrino oscillations)

Nevertheless, if neutrinos have masses, and leptons mix, neutrino's flavor can change:



The first idea (of neutrino-antineutrino oscillations) was considered by **B.Pontecorvo** in 1957.

Neutrino flavour mixing and flavor oscillations were introduced at the beginning of the '60 by **Z.Maki**, **M.Nakagawa**, and **S.Sakata**.

Experimental indications and discovery of neutrino oscillations

First indications of ν oscillations came in 1968 from **R.Davis**'s solar neutrino experiment at Homestake Mine (USA). A significant deficit of solar neutrino fluxes was found and called "solar neutrino problem“.

Similar anomaly was also found in atmospheric neutrino experiments. The first relevant indication of the anomaly was presented in 1988 by Kamiokande Collaboration (Japan).

Nobel Prize 2002

1998: Super-Kamiokande Collaboration (Japan) presented strong evidence that ν oscillations were the cause of the atmospheric neutrino anomaly.

2001: SNO Collaboration (Canada) provided convincing evidence that ν oscillations were the cause of the solar neutrino problem.

Nobel Prize 2015

As for today, neutrino oscillations have been confirmed in many various experiments.

The properties of neutrinos continue to be actively investigated using next-generation detectors.

About the OPERA experiment

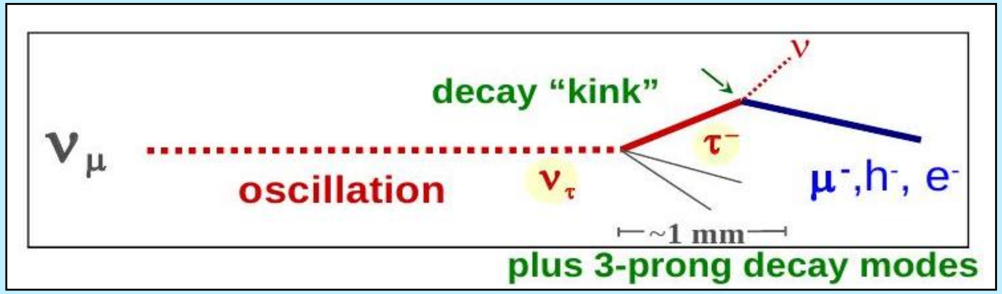
Since its discovery, the phenomenon of neutrino oscillations is being studied mostly in ***disappearance*** mode (i.e., when one looks for a deficit in the expected flux of neutrino at a detector located downstream from the ν source).

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

Oscillation Project with Emulsion tRacking Apparatus

The main goal of OPERA:

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



Expanded physics program:

– oscillation physics:

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

– non-oscillation physics:

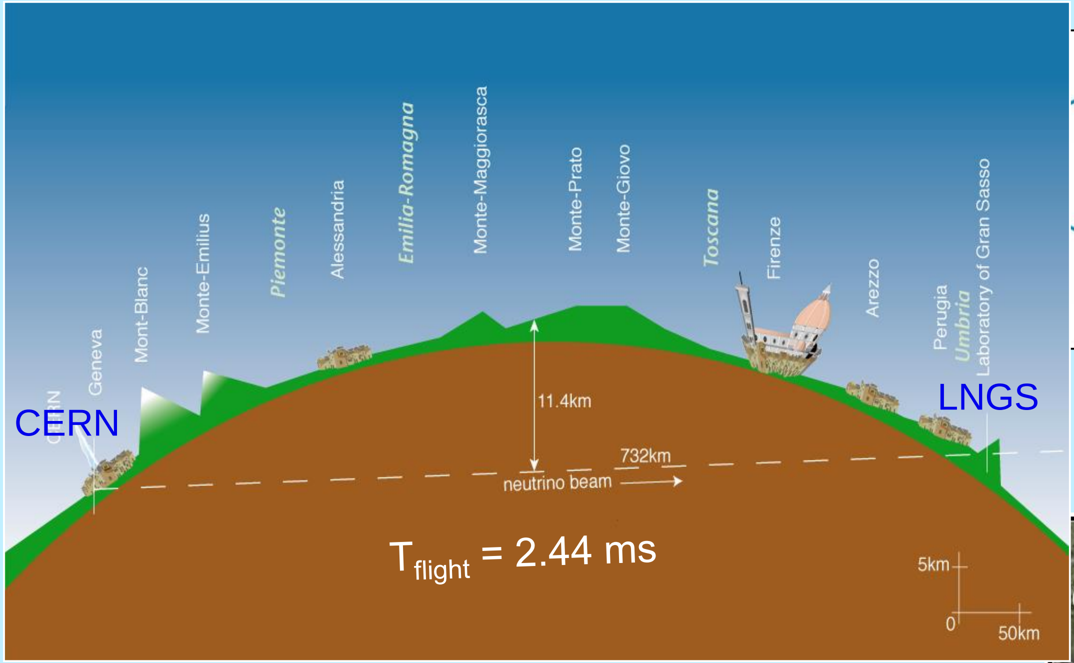
- charged particle multiplicity analysis
- cosmic ray physics

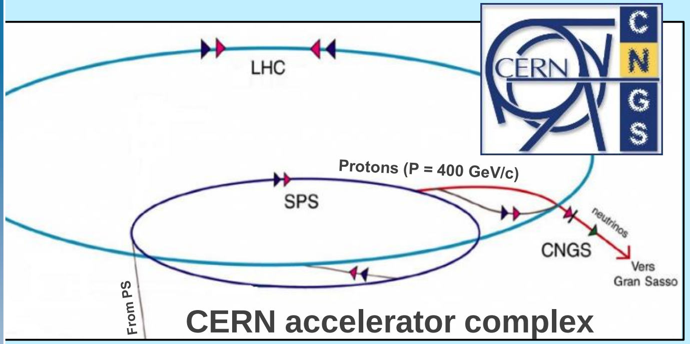
Requirements:

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 project: CERN neutrinos to Gran Sasso (2006 - 2012)





1.8×10^{20} protons on target were delivered

The neutrino beam characteristics

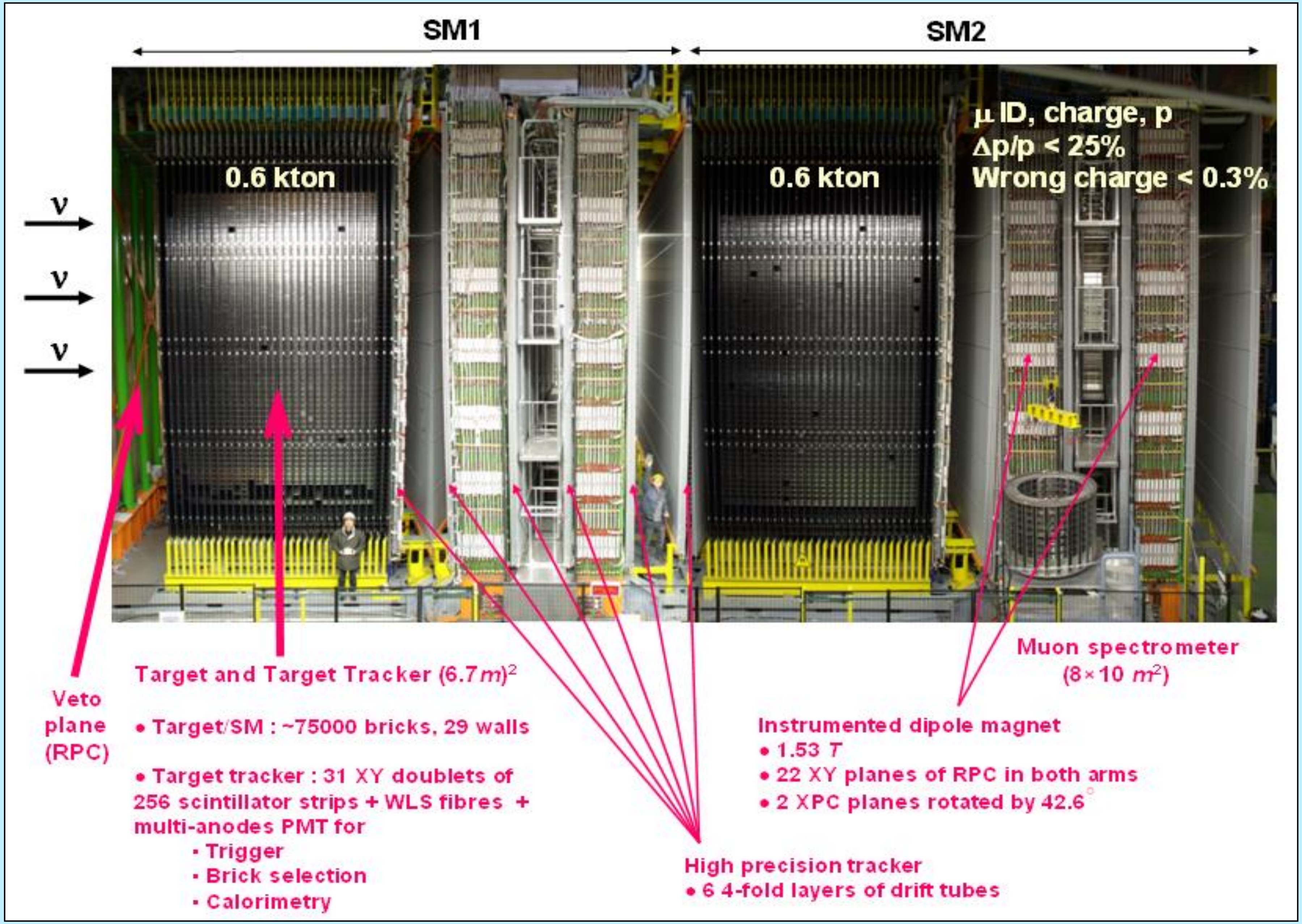
$\langle E_{\nu_\mu} \rangle$	17 GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.9%*
$\bar{\nu}_\mu/\nu_\mu$	2.0%*
ν_τ prompt	negligible

* interaction rate @ LNGS

LNGS (Laboratori Nazionali del Gran Sasso) of INFN, the world largest underground physics laboratory

- ~180000 m^3 caverns' volume
- ~1400 m rock overburden
- ~1 cosmic $\mu/(m^2 \times \text{hour})$
- experimental infrastructure suitable to host detector and related facilities
- caverns oriented towards CERN

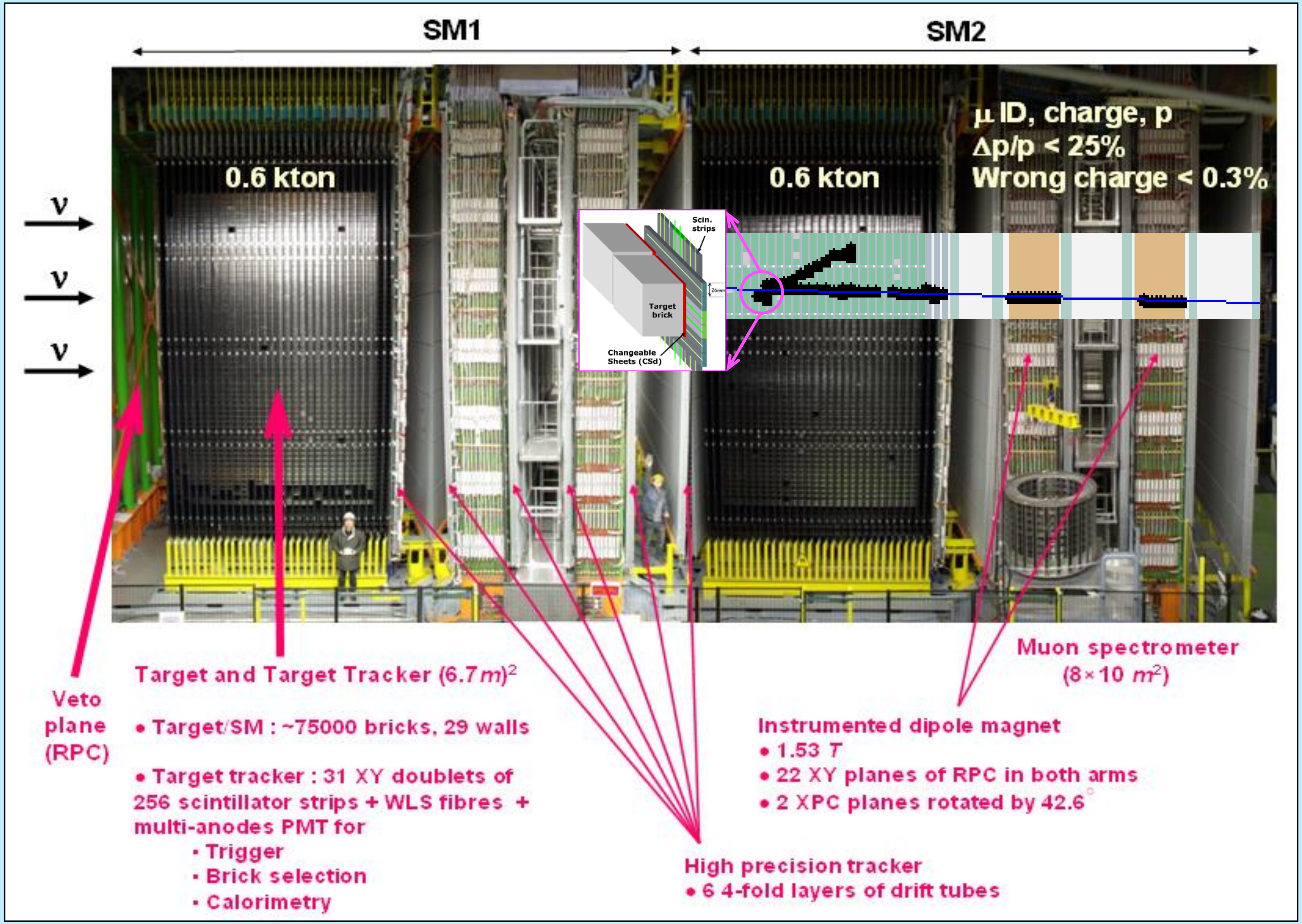
OPERA hybrid detector



- Two identical target super-modules (**SM1** and **SM2**), each with an iron spectrometer for muon detection
- Nuclear emulsions + electronic detectors
- High spatial resolution (~1 μm) over a "dense" macroscopic volume (~100 m^3)

[JINST 4, P04018 (2009)]

OPERA hybrid detector



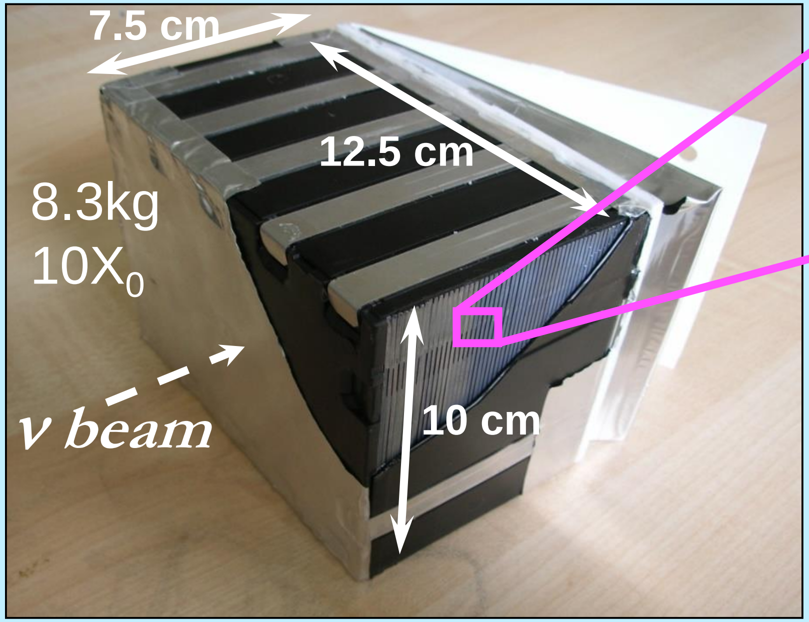
Once a neutrino interaction event was reconstructed in the electronic detectors, the target bricks most probably containing the primary ν interaction vertex were identified by dedicated offline algorithms.

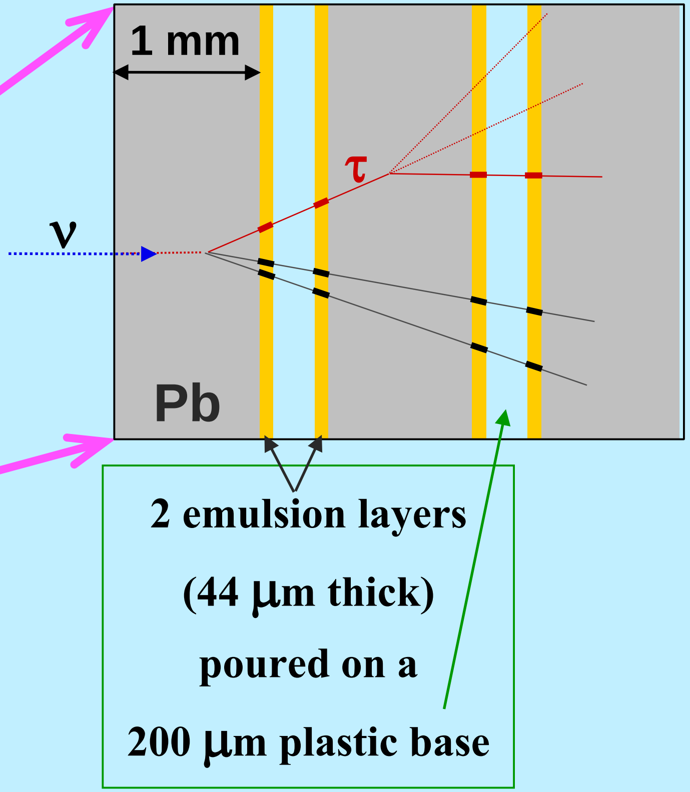
[PPNL 12, 89–99 (2015)]

The most probable bricks were then extracted from the detector and their emulsion films were analyzed by automatic optical scanning microscopes.

OPERA lead-emulsion brick

Basic target 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).





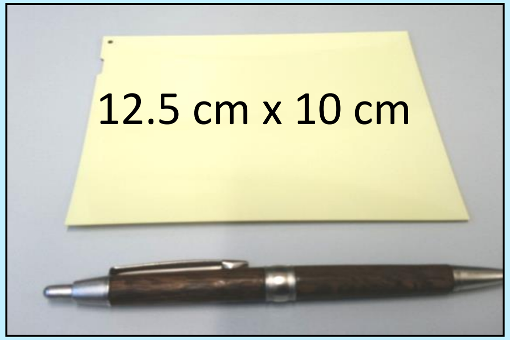
The ECC technique proved its efficiency and is going to be used in future experiments for ν_τ registration (DsTau, FASERν, SHiP, … @CERN) and even for directional dark matter search (NEWSdm @LNGS).

The OPERA target

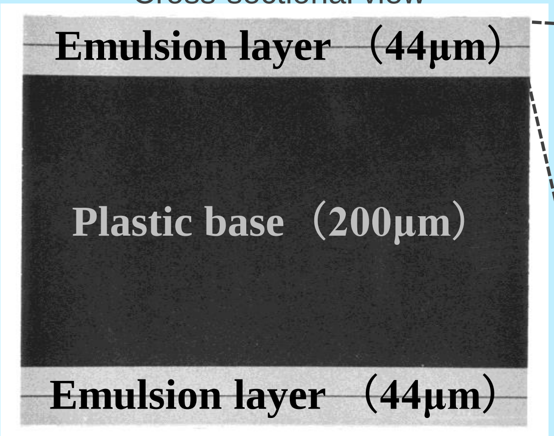
Number of bricks:	**~150'000**
Total mass:	**~1.2 kton**
Total film surface:	**~111'000 m^2**

Nuclear emulsion detectors

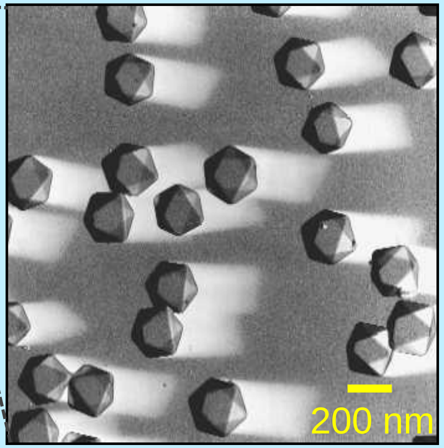
Emulsion film

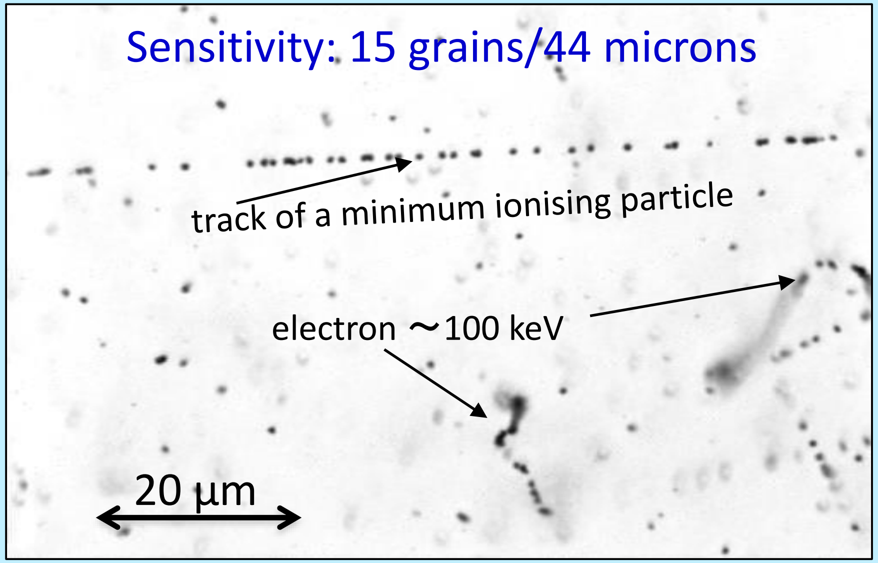


Cross-sectional view



Silver halide crystals as seen with an electron microscope





A minimal detector:

Silverbromide (AgBr) Crystal

- diameter = 200 nm
- core-shell structure
- detection eff. = 0.16/crystal
- noise rate = 0.5×10^{-4}/crystal
- volume occupancy = 30%

10^{14} crystals in a film

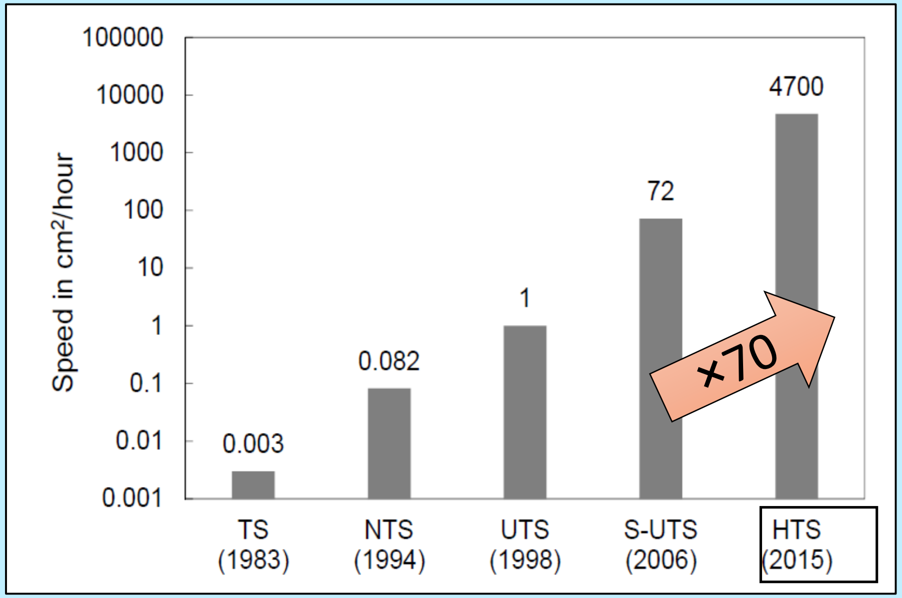
Core-shell structure

Nuclear emulsion is an ultra high resolution 3D tracking device and data storage media at the same time

	Square	Capacity	Readout speed
DVD disk	111 cm^2	8.5 GB	≤266 Mbps
Blue-ray disk	111 cm^2	50 GB	≤576 Mbps
Emulsion film	125 cm^2	1-10 TB	>1 Gbps

Emulsion readout systems: high-speed automatic microscopes

The modern use of nuclear emulsion would be impossible without fantastic development of emulsion readout technique.

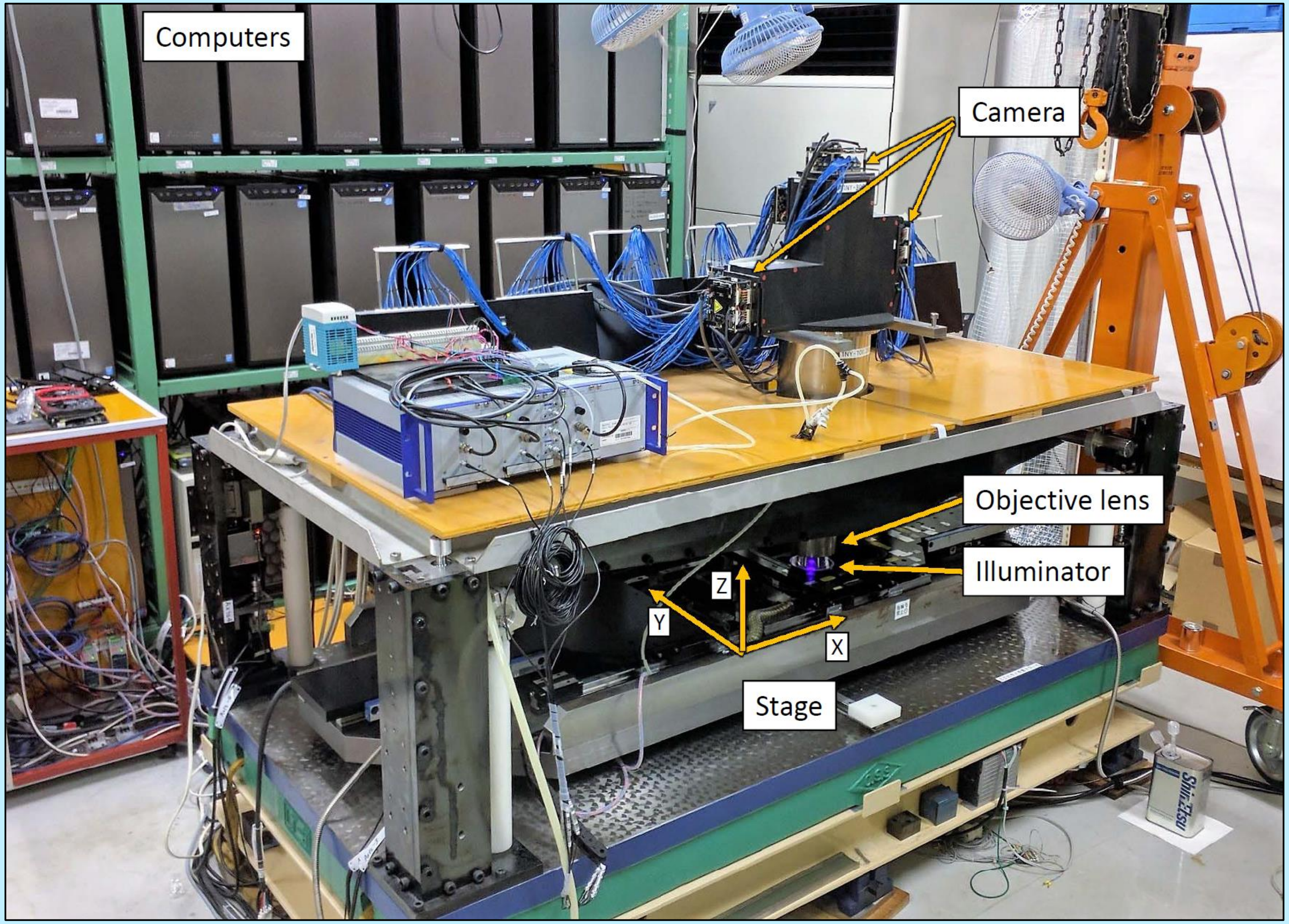


arXiv:1704.06814

Emulsion detectors are no longer analog detectors, but rather digital ones.

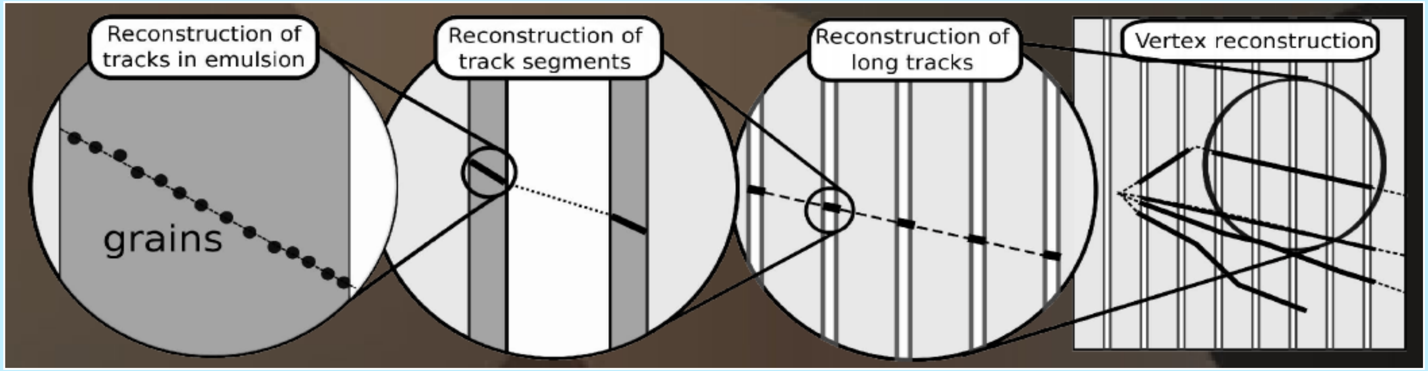
Example of a modern scanning system (in Nagoya University) which has a capability to read-out 1000 m^2

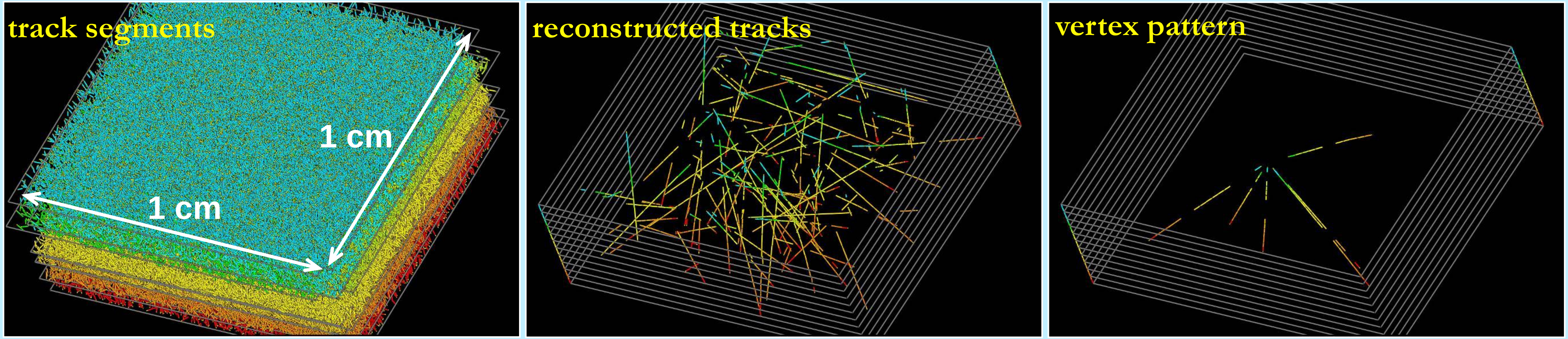
- with wide field lens, multi-sensors, and GPUs.
- 20 Giga-Bytes/sec or 2 Peta-Bytes/day



Location of a neutrino interaction vertex

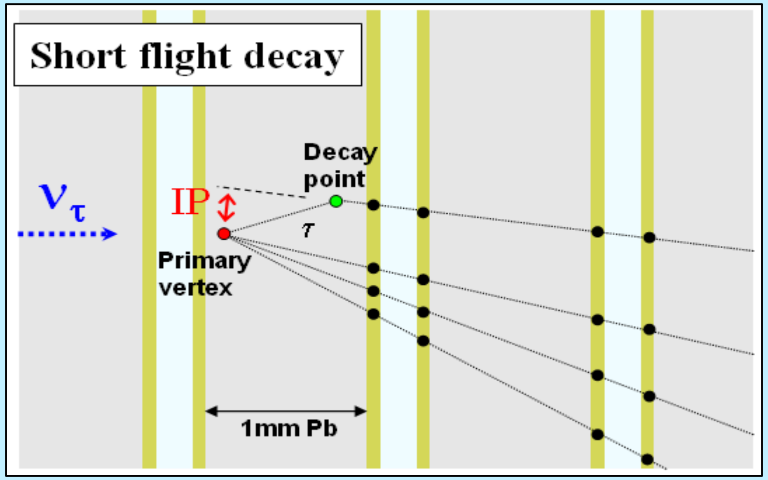
- Search for converging tracks (or tracks matching the electronic detectors hits) in emulsion films
- Follow back of the found tracks in the upstream films of the brick until their stopping point
- Scanning of a large volume (~2 cm^3 around the stopping point)

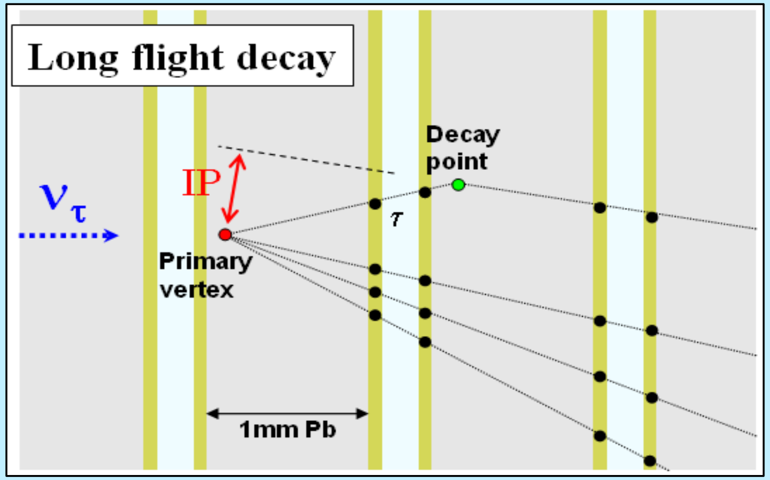


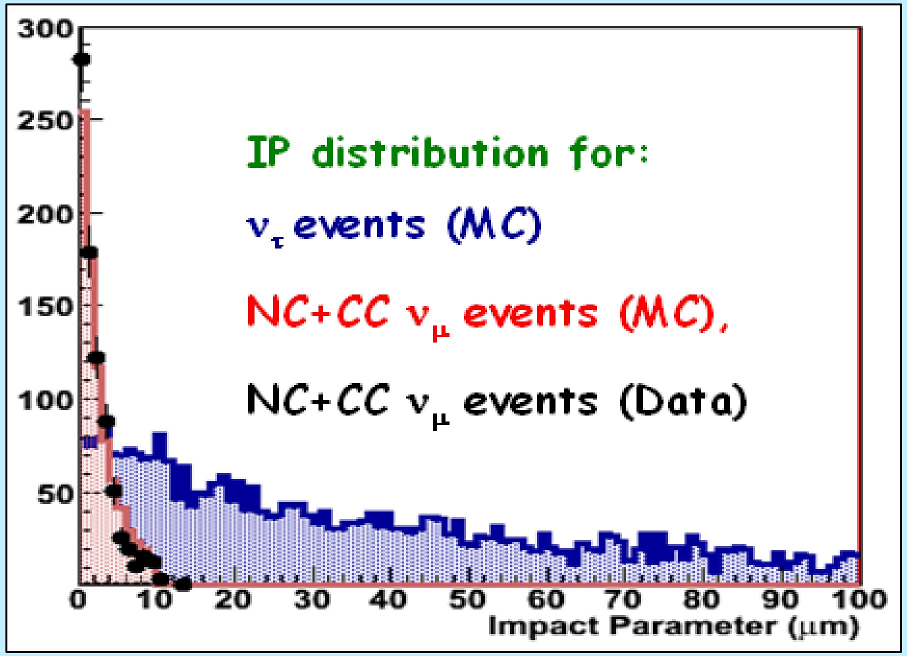


Decay search: analysis of event topology

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

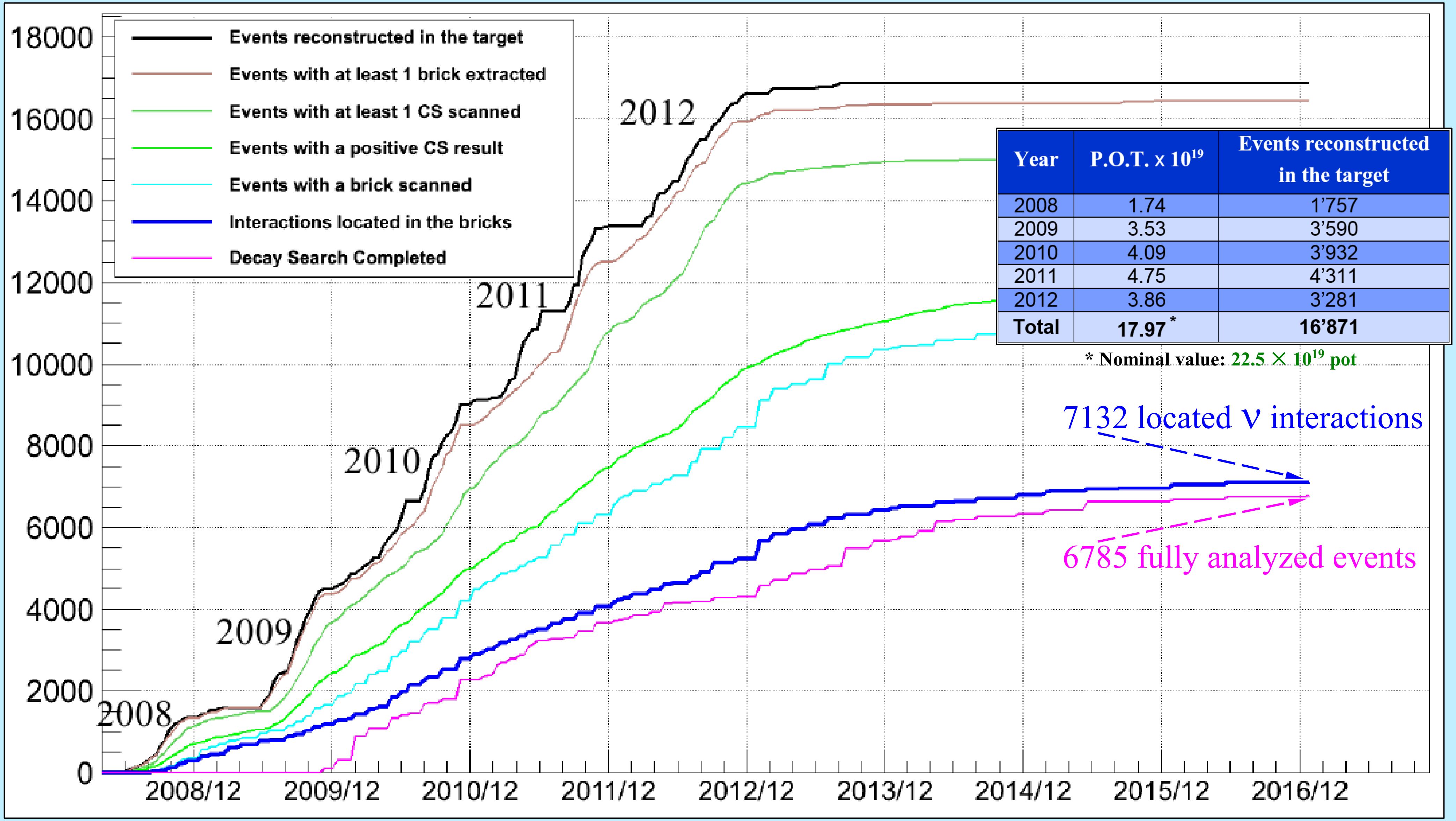






- Impact parameter (IP) evaluation
- Momentum measurement by multiple Coulomb scattering (MCS)
- Search for significant kink/trident topology
- Additional track search
- Electromagnetic shower detection and energy measurement
- Detection of nuclear fragments

Statistics of OPERA neutrino events

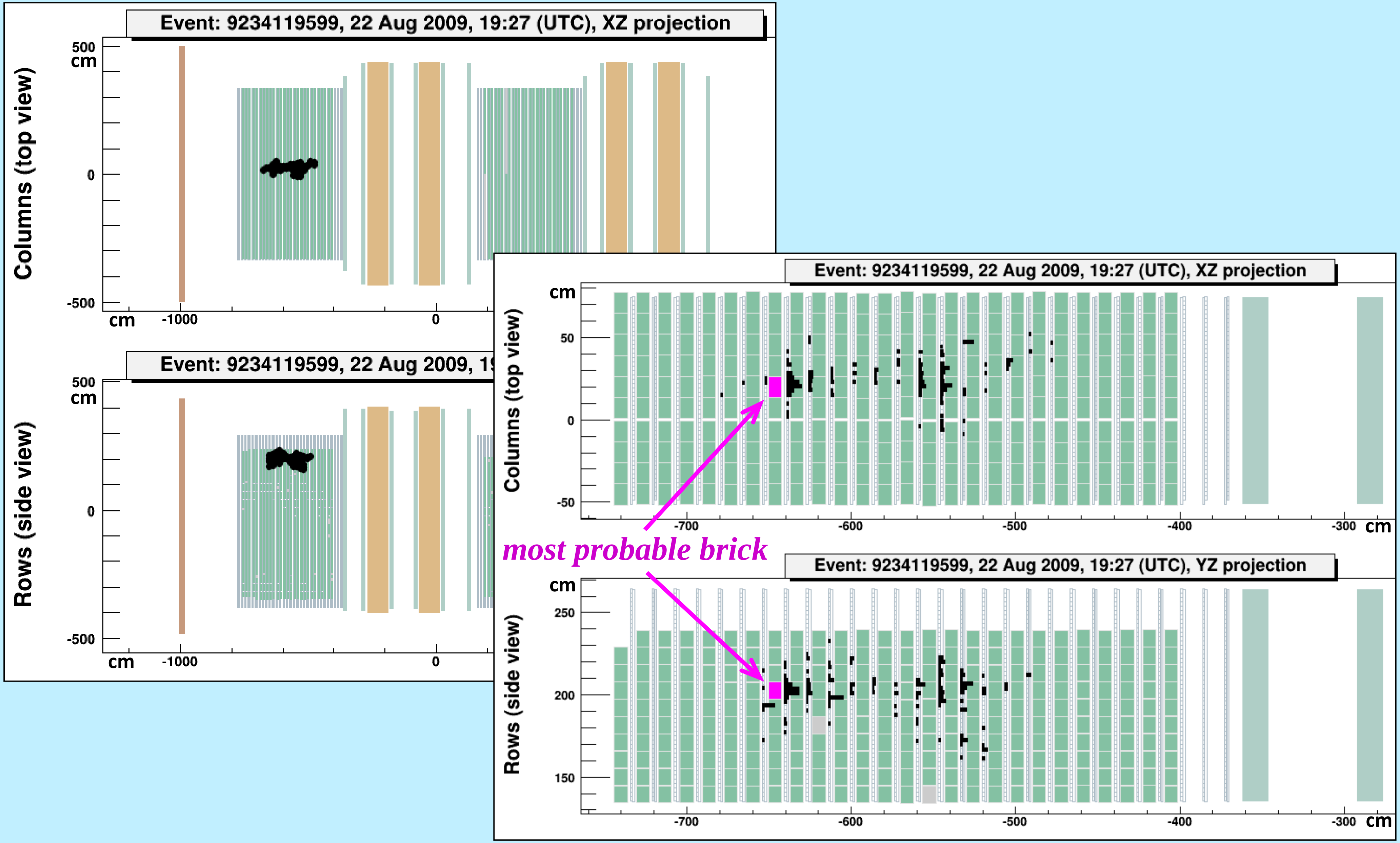


Year	P.O.T. x 10^{19}	Events reconstructed in the target
2008	1.74	1'757
2009	3.53	3'590
2010	4.09	3'932
2011	4.75	4'311
2012	3.86	3'281
Total	**17.97** *	**16'871**

* Nominal value: 22.5×10^{19} pot

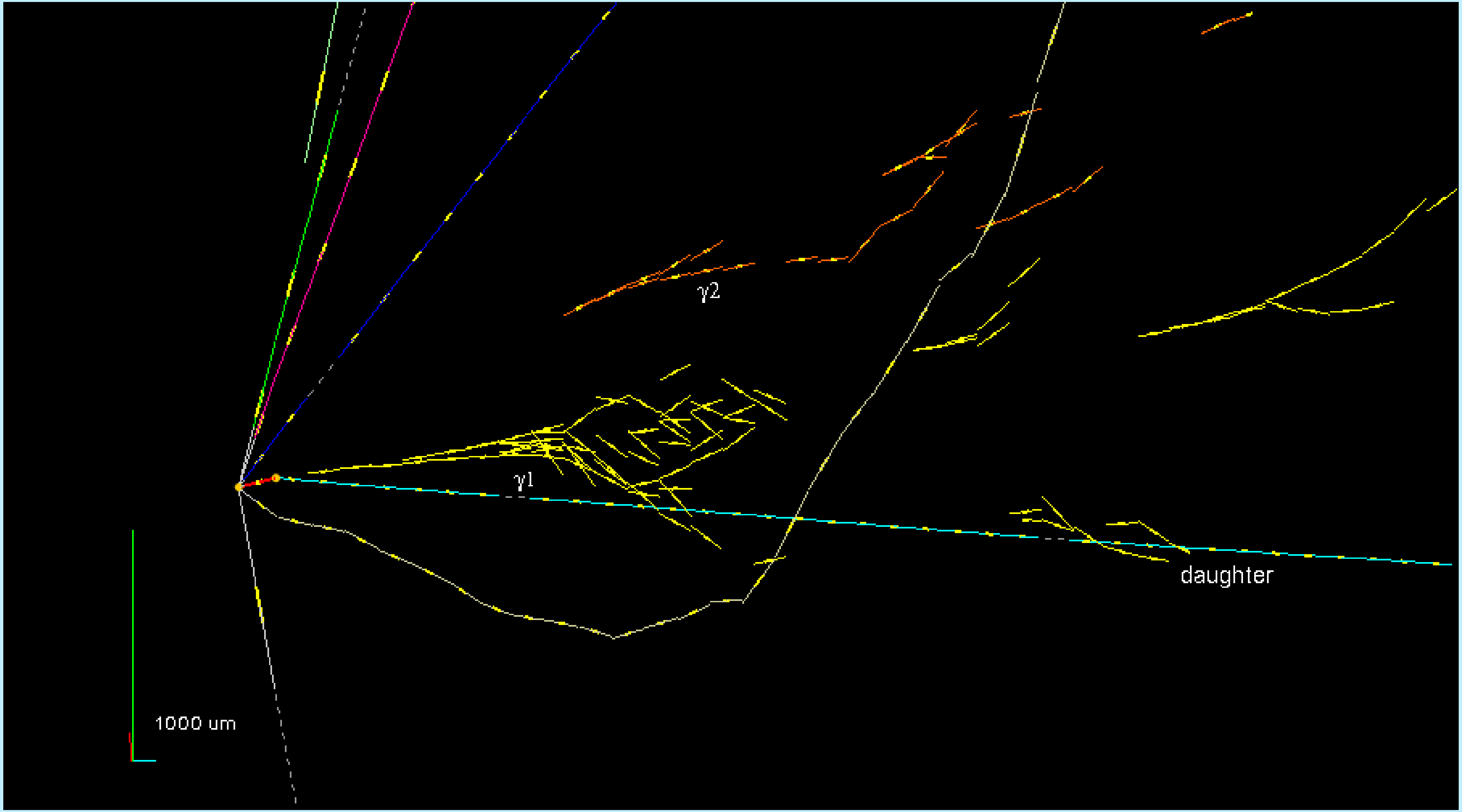
The first OPERA ν_τ-candidate event

(as seen by the electronic detectors)



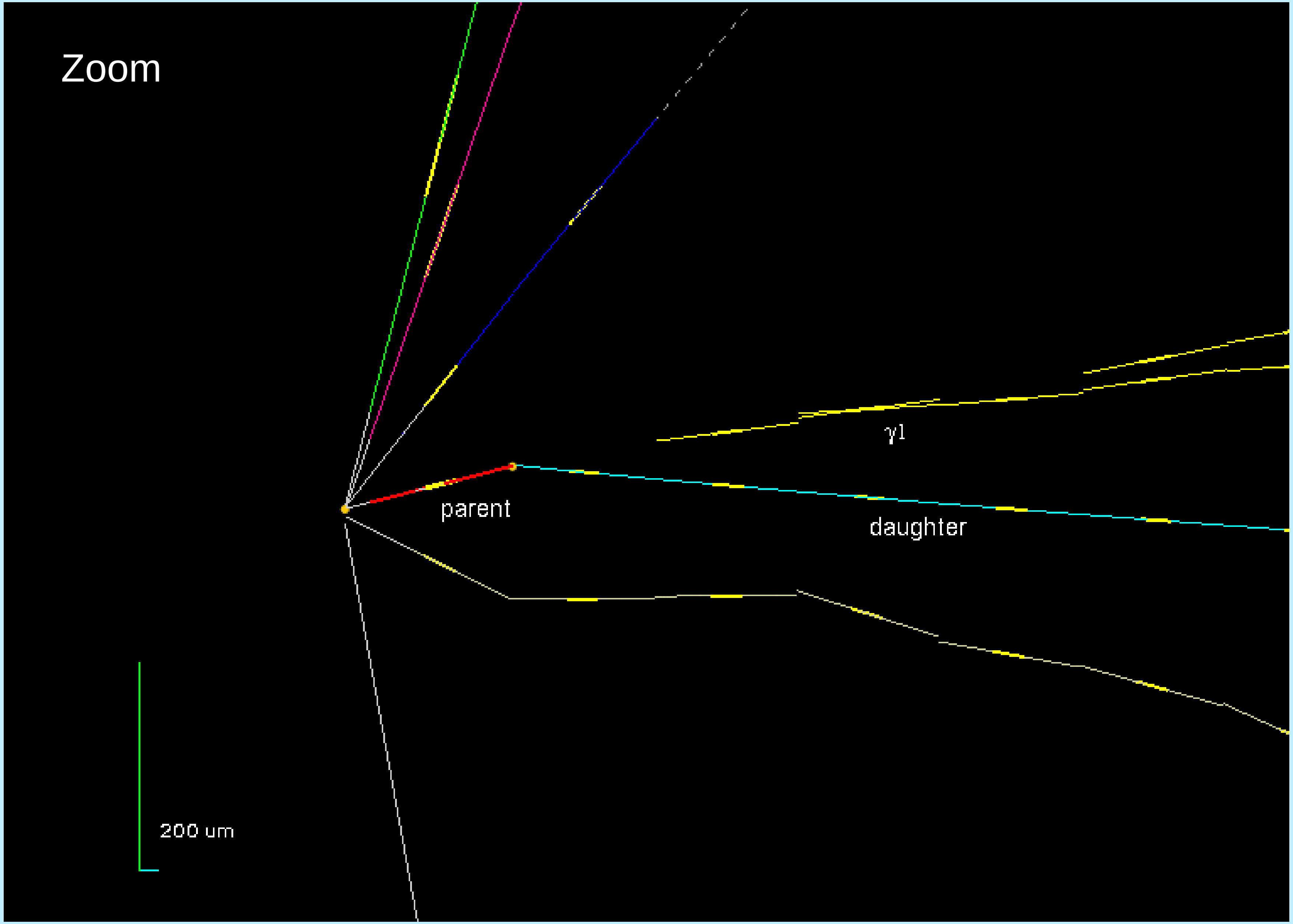
The first OPERA ν_τ-candidate event

(reconstructed in the emulsion films)



The first OPERA ν_τ-candidate event

(reconstructed in the emulsion films)



Discovery of ν_τ appearance in the CNGS beam

Statistics of OPERA events in the analyzed sample

Channel	Expected Background	Expected Signal*	Observed
$\tau \to 1h$	1.43 ± 0.39	2.96 ± 0.59	6
$\tau \to 3h$	0.52 ± 0.09	1.83 ± 0.37	3
$\tau \to \mu$	0.024 ± 0.008	1.15 ± 0.23	1
$\tau \to e$	0.035 ± 0.007	0.84 ± 0.17	0
Total	**2.0 ± 0.4**	**6.8 ± 1.4**	**10**

* expectations for *full mixing* and $\Delta m^2_{32} = 2.5 \times 10^{-3}\ eV^2$

Observed in data: 10 events in the $\tau \to h$, $\tau \to 3h$, and $\tau \to \mu$ channels

Probability to be explained by background: 4×10^{-10}

This corresponds to 6.1σ significance of non-null observation

[PRL 120 (2018) 21, 211801],
[PRL 121 (2018) 13, 139901 (erratum)]

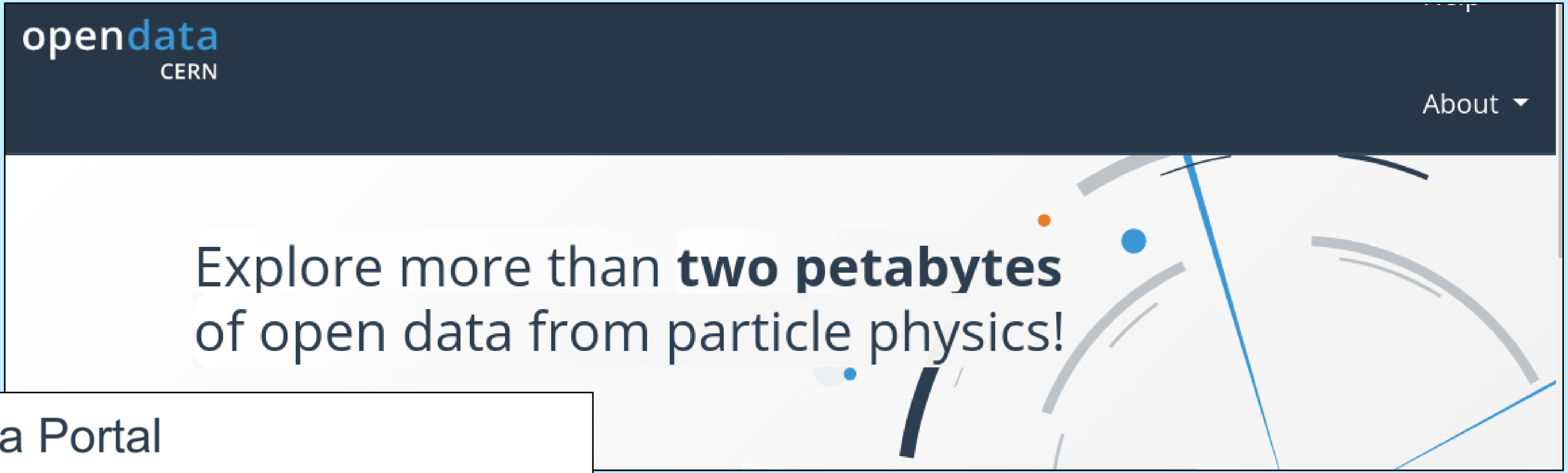
Scientific Background on the Nobel Prize in Physics 2015

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)]*

About CERN Open Data Portal

opendata.cern.ch



CERN Open Data Portal

Documentation About

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).

ALICE ATLAS EXPERIMENT CMS LHCb OPERA PHENIX

OPERA was the first non-LHC experiment presented on the portal.

May 2018: the first release of OPERA data (ν_μ and ν_τ samples).

May 2020: new release of **OPERA** data (ν_e and the **charm** samples).

Downloading the OPERA datasets

Dataset × OPERA × zip ×

include on-demand datasets

Filter by type

- [x] Dataset 8

Filter by experiment

- [x] OPERA 8

Filter by year

- [ ] 2009 6
- [ ] 2010 8
- [ ] 2011 8
- [ ] 2012 8

Filter by file type

- [ ] csv 904
- [x] zip 8

Filter by event number

- [ ] 0--999 8
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- [ ] 10000--99999 0
- [ ] 100000--999999 0
- [ ] 1000000--9999999 0
- [ ] 10000000-- 0

Emulsion data for neutrino-induced charmed hadron production studies

The dataset was extracted from the official OPERA data repository. It contains 50 muon neutrino interactions with the lead target where a charmed hadron is reconstructed in the final state. Neutrin...

Dataset Derived OPERA

for the Task 1)

Emulsion data for track multiplicity

The dataset was extracted from the official OPERA data repository. It contains 817 muon neutrino interactions with the lead target where a muon was reconstructed in the final state. This happens in th...

Dataset Derived OPERA

for the Task 2)

Emulsion data for neutrino tau appearance studies

This dataset was extracted from the official OPERA data repository and it contains all the emulsion data information for the ten tau neutrino candidates, identified after an extensive analysis that...

Dataset Derived OPERA

for the Task 3)

Electronic detector data for tau neutrino appearance studies

This dataset was extracted from the official OPERA data repository and it contains all the data of the electronic detectors for the ten tau neutrino candidates, identified after an extensive analys...

Dataset Derived OPERA

for the Task 4)

How were these data validated?

During the data taking, all the runs recorded by OPERA are certified as good for physics analysis if the trigger and all sub-detectors show the expected performance. Moreover, the time stamp of the event should lie within the gate open by the CNGS beam signal. The data certification is based first on the offline shifters evaluation and later on the feedback provided by all sub-detector experts. Based on the above information, stored in a specific database, the Data Quality Monitoring group verifies the consistency of the certification and prepares an ascii file of certified runs to be used for physics analysis. For this specific data record, dedicated calibration procedures are performed to align the emulsion films each other and with the electronic detectors. These procedures with the corresponding results are saved in a dedicated database where data quality experts certify the results and prepare files to be used for the track and vertex reconstruction, thus being available for physics analysis.

Files

Filename	Size	
emulsion-data-for-charm-studies.zip	48.5 kB	Download

Disclaimer

The open data are released under the Creative Commons CC0 waiver. Neither OPERA nor CERN endorse any works, scientific or otherwise, produced using these data. All releases will have a unique DOI that you are requested to cite in any applications or publications.

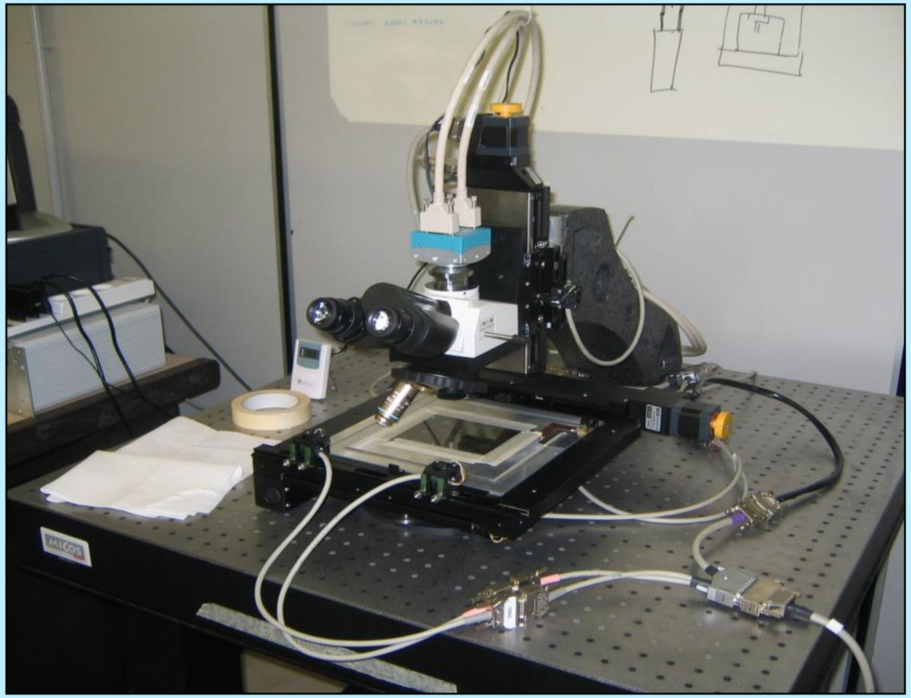
PUBLIC DOMAIN

Backup slides

General view of the OPERA detector in the Hall C of LNGS

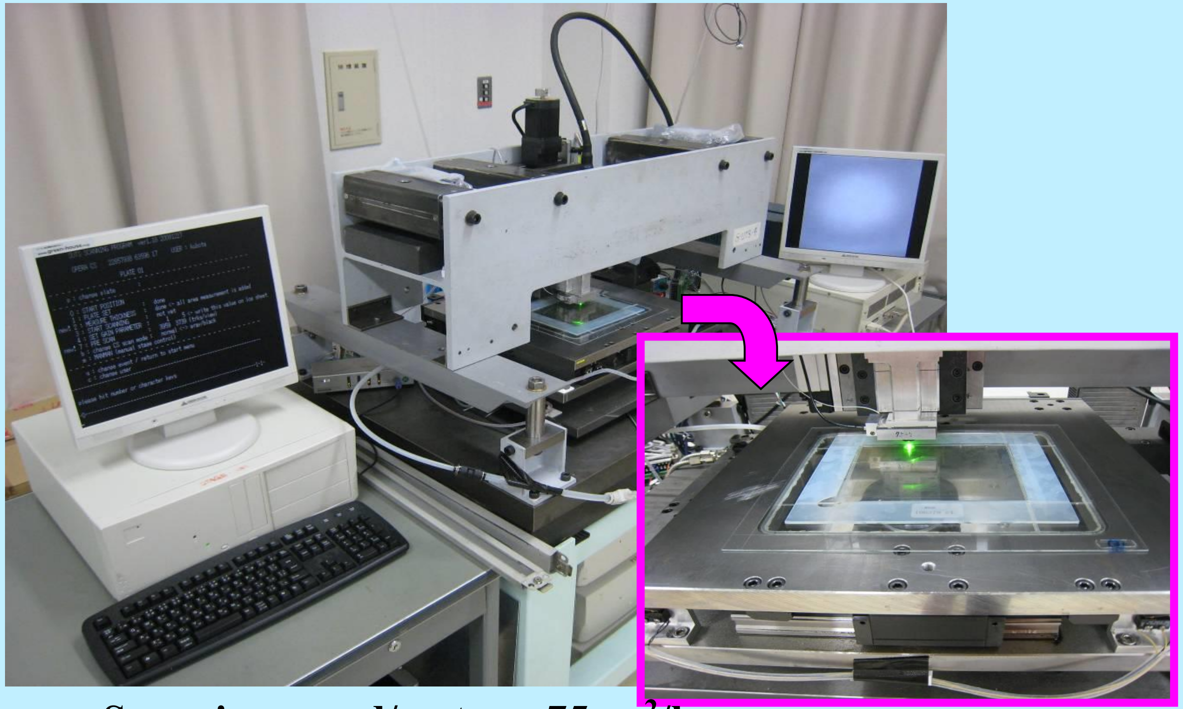
Emulsion scanning stations used in OPERA

EU: ESS (European Scanning System)



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

Japan: S-UTS (Super Ultra Track Selector)



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

Both systems demonstrated:

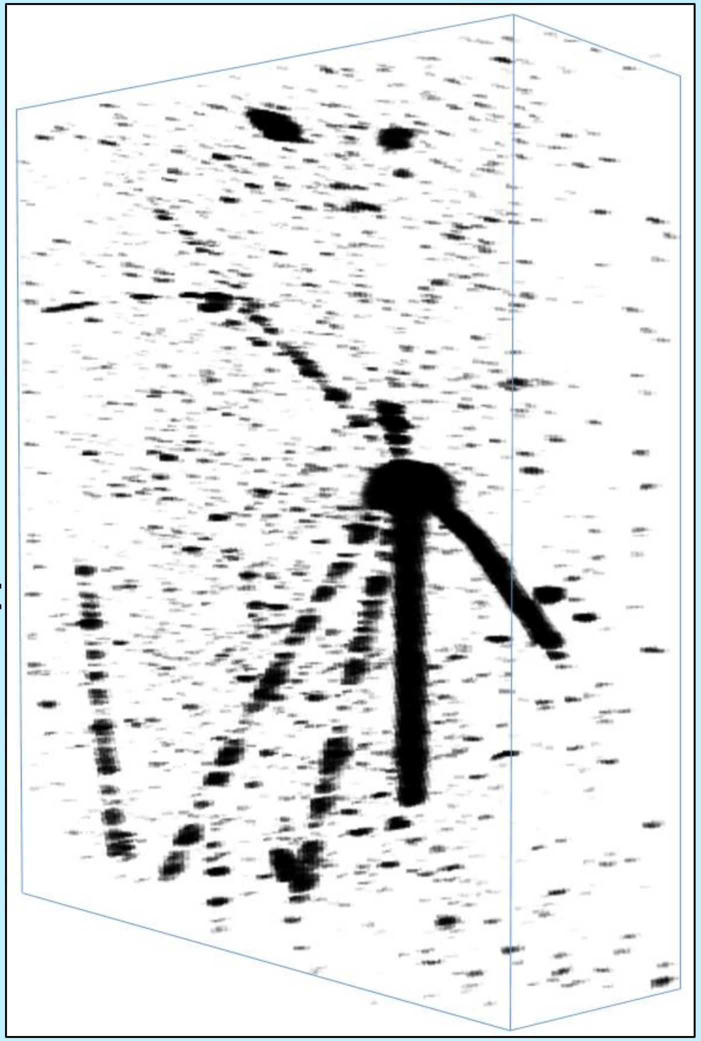
- ~0.3 μm spatial resolution
- ~2 mrad angular resolution
- ~95% base track detection efficiency

Emulsion = detector with high detection channel density

- 3D high resolution hits
- Works as tracker
- dE/dx proportional to darkness (number of grains)

150 μm x 120 μm x 50 μm:

1.2×10^8 channels (crystals) in this volume.



Just to be compared:

ATLAS-IBL pixel sensor FE-14

Size of 1 pixel = 250 μm x 50 μm x 200 μm

Sum of all channels in ATLAS = ~**10^8**

High density of detection channels, O(10^{14}) channels/film, makes emulsion attractive for many purposes.

Future experiments with nuclear emulsion

OPERA technology

New technology

Physics experiments
- Neutrino oscillation
- Neutrino Cross-section
- Lepton Universality (ν_e-ν_μ-ν_τ)
- Hadron physics
- Charm physics
- Antimatter
- Double hyper nuclei

Accelerator
- beam monitoring
- Muon beam study in neutrino beamline

Medical application
- neutron source imaging
- proton radiography

Geosciences
- muon radiography
- Volcanoes
- Glaciers

Astronomy
- Gamma-ray telescope

Dark matter
- Directional sensitivity