The OPERA Emulsions

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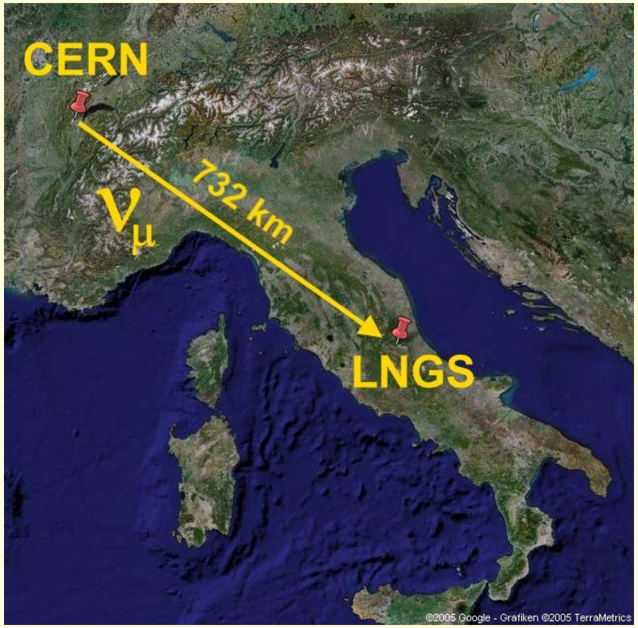
bmb+f - Förderschwerpunkt
OPERA
Großgeräte der physikalischen Grundlagenforschung

Outline

- The OPERA experiment
- Nuclear emulsions
- The OPERA emulsions
- The OPERA target bricks
- Data taking with the OPERA emulsions
- Summary

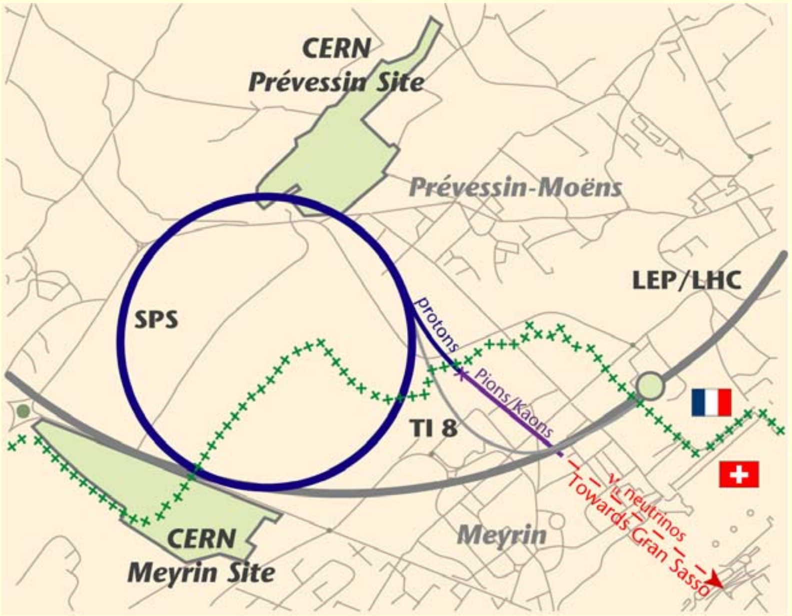
Oscillation **P**roject with **E**mulsion t**R**acking **A**pparatus

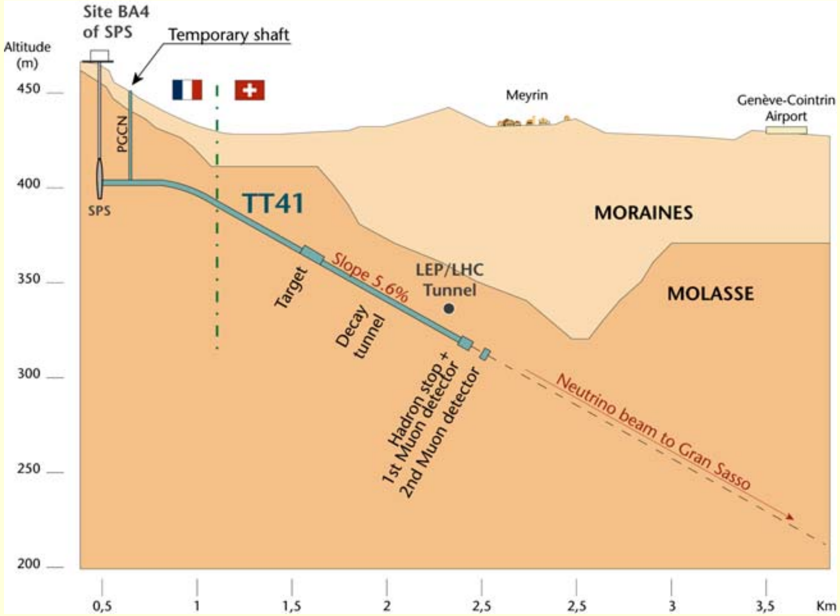
- Goal: First direct validation of flavour–mixing neutrino oscillations $\nu_\mu \rightarrow \nu_\tau$ (appearance mode)
- Concept: Long–baseline search for ν_τ in ν_μ–beam above τ–threshold
  ➔ τ observable
- Problem: Large target mass <u>and</u> high resolution needed
- Solution: Emulsion Cloud Chambers (ECC) + electronic detector



CNGS Beam

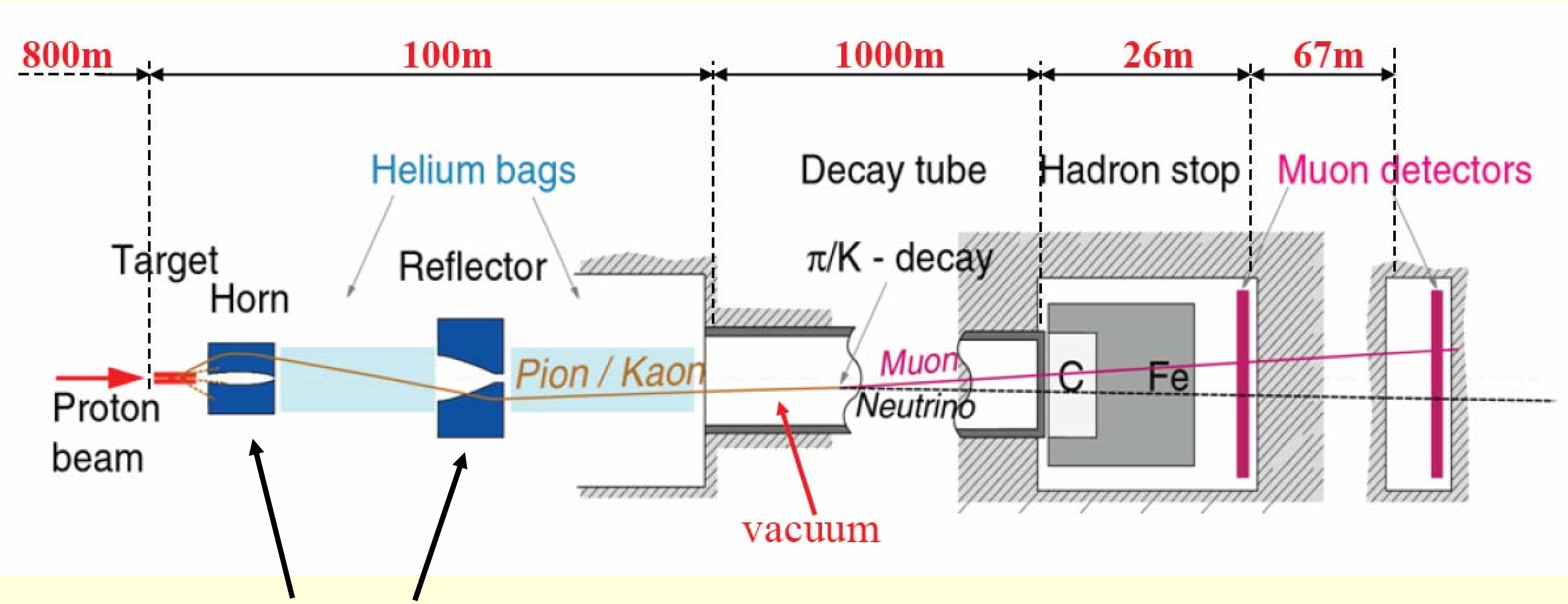
CERN Neutrinos to Gran Sasso





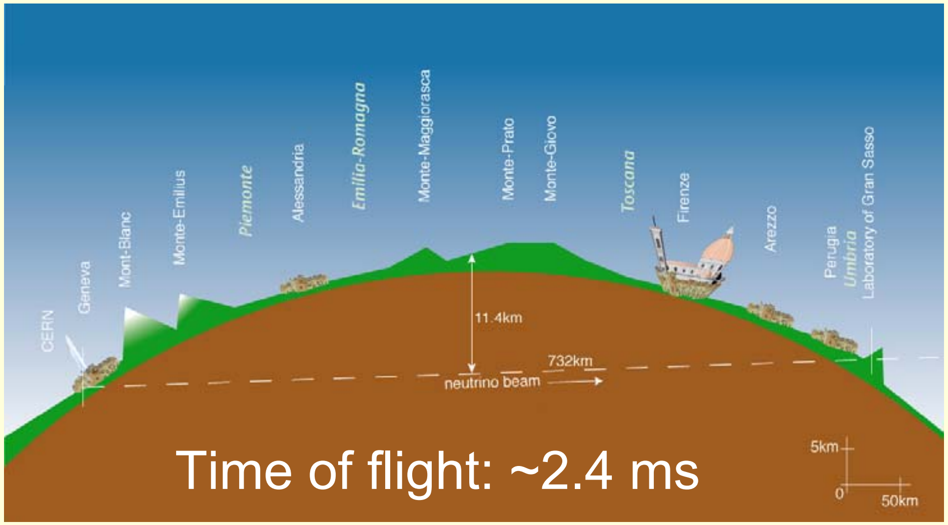
- 400 GeV protons from SPS accelerator at CERN
- 3.2° downward slope towards Gran Sasso
- Helium cooled graphite target ➔ π^+ and K^+

CNGS Beam



- Two magnetic lenses focus secondary particles
- K^+ and π^+ decay in flight ➔ mainly into μ^+ and ν_μ
- Remaining hadrons stopped by ~2 kt of graphite and iron
- Two muon detectors for tuning beam profile and alignment

CNGS Beam



Beam characteristics	
pot / year	$4.5 \cdot 10^{19}$
$\langle E_\nu \rangle$	17.9 GeV
$\bar{\nu}_\mu / \nu_\mu$	3.9 %
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.73 %
ν_τ / ν_μ	negligible

- Number of events expected in the OPERA detector with target mass 1.35 kt (not regarding reconstruction and detection efficiencies):

  ν_μ NC + CC = 5170 / year
  ν_e CC = 34 / year
  ν_τ CC = 23 / year

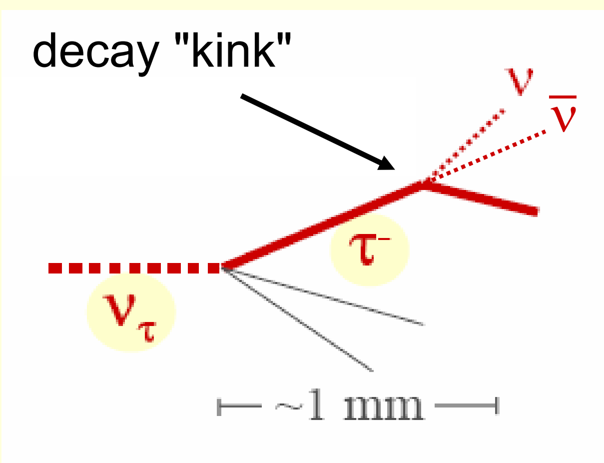
Tau Detection

- Direct observation of ν_τ in the ν_μ beam:

ν_μ ·········· (oscillation) $\nu_\tau + N \rightarrow \tau^- + X$

tau decay → single–prong decay channels:

$h^- + \nu_\tau + (n\pi^0)$	BR 49.4 %
$e^- + \nu_\tau + \bar{\nu}_e$	BR 17.8 %
$\mu^- + \nu_\tau + \bar{\nu}_\mu$	BR 17.4 %



- Tau-lepton is identified by its characteristic decay topology
- Detector with high spatial resolution ~ 10 µm needed

➔ Emulsions are the only affordable large scale solution (120,000 m²)

Nuclear Emulsions

- Used in particle physics to record 3D–tracks of charged particles

  + Spatial resolution ~1 µm and high hit density along tracks (~300 hits / mm)
    ➔ Suitable for the detection of short–lived particles

  + Low € / m^3 sensitive detector volume (compared to semiconductor detectors)

  – The emulsion detector is always sensitive

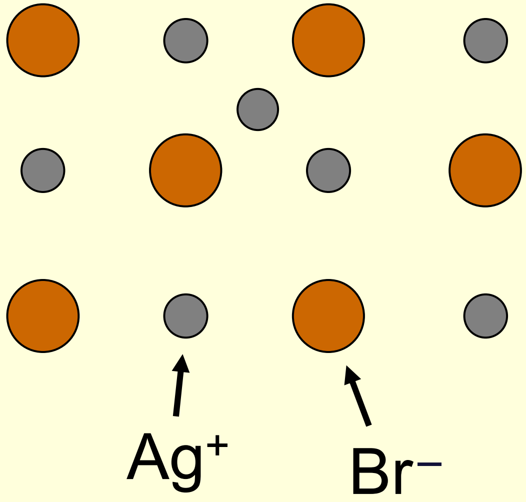
  – External trigger is needed

Nuclear Emulsions

- Suspension of silver halide crystals in gelatin
- usually AgBr micro–crystals (crystal diameter < 1 μm)
- Fundamentally the same as photographic emulsions, but:
  - Silver halide crystals in nuclear emulsions are uniform in size
  - Volume occupancy of silver halide crystals is much higher
  - Thicker emulsion layers are used for particle detection

Photographic Process

Latent image:



- Prerequisite: Crystal lattice contains point defects (Frenkel defects + it is doped, usually with sulfur)

- Charged particle crosses the emulsion
  ➔ Ionisation in AgBr crystal = electrons raised into the crystal's conduction band

- Impurities act as electron traps ("sensitivity specks"), if their lowest conduction band is below that of AgBr

Photographic Process

(Latent image)

- Negative electric charge at the electron trap site attracts interstitial Ag^+ ions
  ➔ Ag^+ ions are neutralised and remain as Ag atoms
- Electric charge at the speck is reduced
  ➔ more conduction electrons can be captured
- Process repeats until charge is neutralised
- Cluster of Ag atoms ≥ 4 ➔ latent image

Photographic Process

Development:

- Reduction of silver ions to metallic silver
- Developer: Weak reducing agent; provides electrons
  ➔ silver clusters grow and become visible
- Prerequisite: Vacant electronic levels of the latent image site (= Ag–cluster) have to be low enough
- Development process depends on pH–value
  ➔ Acid stop bath

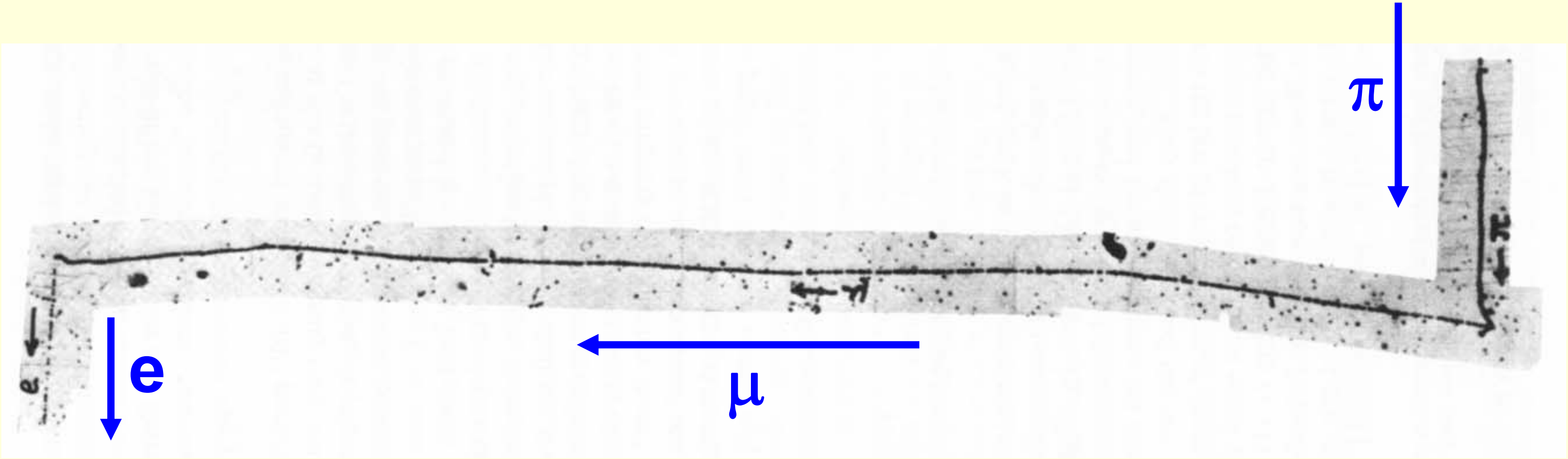
Photographic Process

Fixation, washing, drying:

- Removal of all remaining silver halide, leaving the metallic silver to form the image
- Fixing agent chemically binds AgBr
- Dissolved silver halide can be removed from the emulsion by washing
- During fixation and washing emulsions are very sensitive to distortions
- Emulsions are dried in an alcohol–glycerin bath

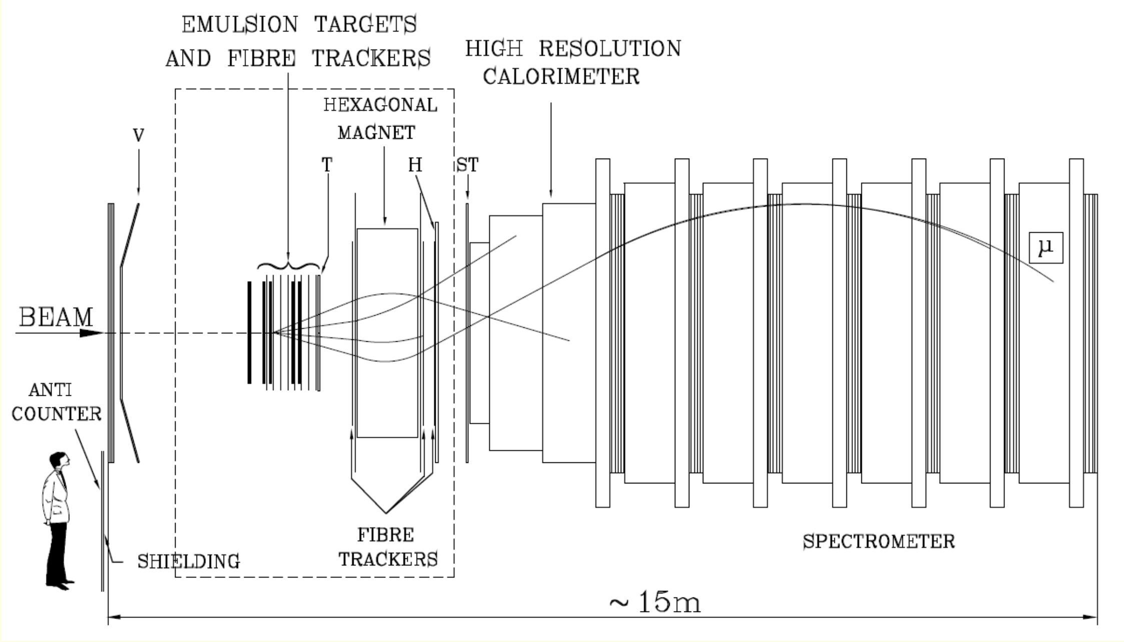
History of Nuclear Emulsions

- Emulsions used as detector for charged particle tracks since early 20th century
- 1947: Discovery of the charged pion
- 1959: Research on radiation in the lower Van Allen belt
- CHORUS + DONUT



CERN **H**ybrid **O**scillation **R**esearch Apparat**US**

- Search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in a ν_μ–beam
- Sensitive to oscillations at high Δm^2 ➔ short baseline
- Emulsion target + electronic detector



CHORUS

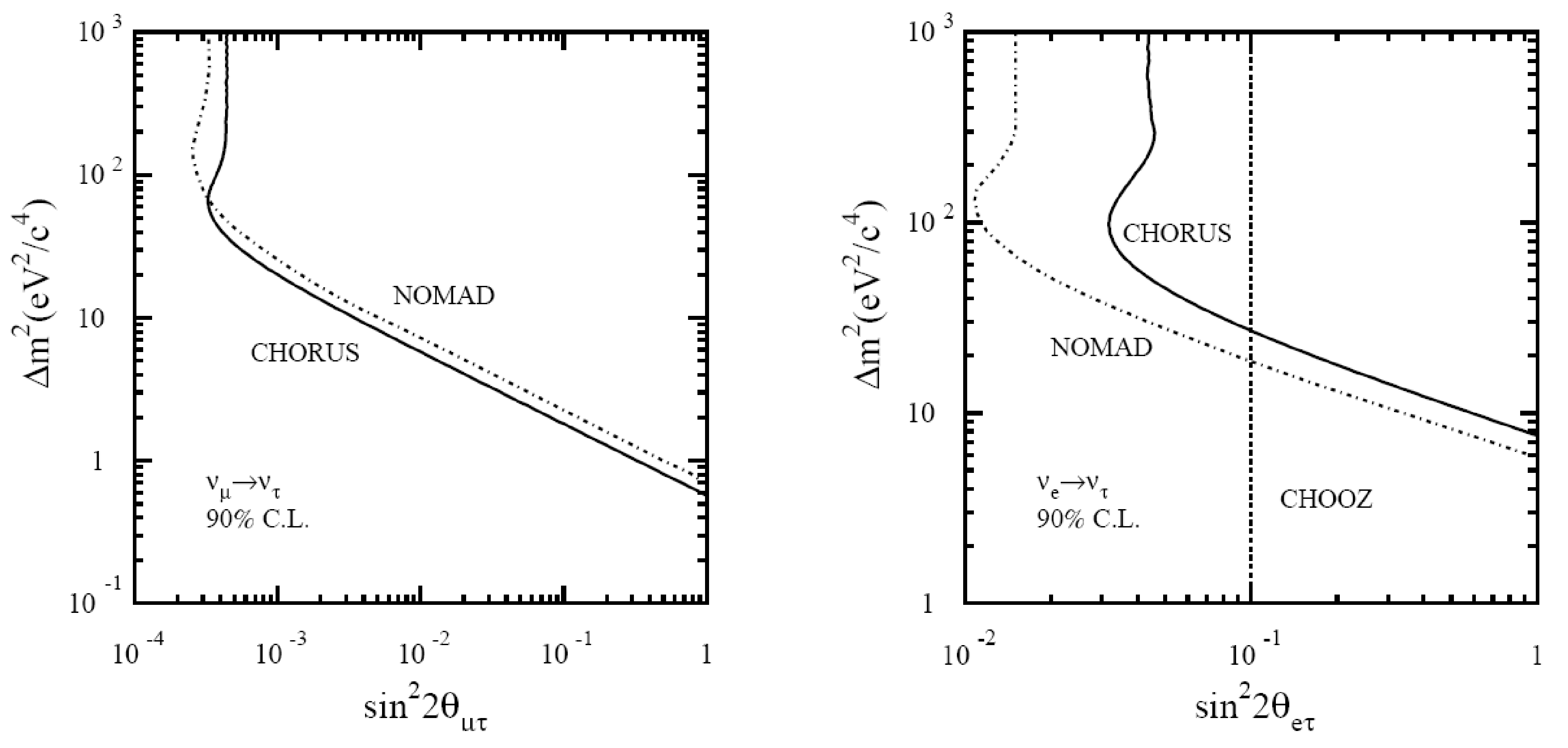
Data taking:

- From 1994 to 1997, divided into 2 phases
  ➔ 2 sets of exposed emulsions
- Emulsions used for 2 years ≈ 10 months beam exposure
- Development of all emulsions after each phase
- Scanning according to vertex predictions of the electronic detector

➔ No oscillation signal detected

CHORUS

- Result: Upper limit for appearance probability at high Δm^2



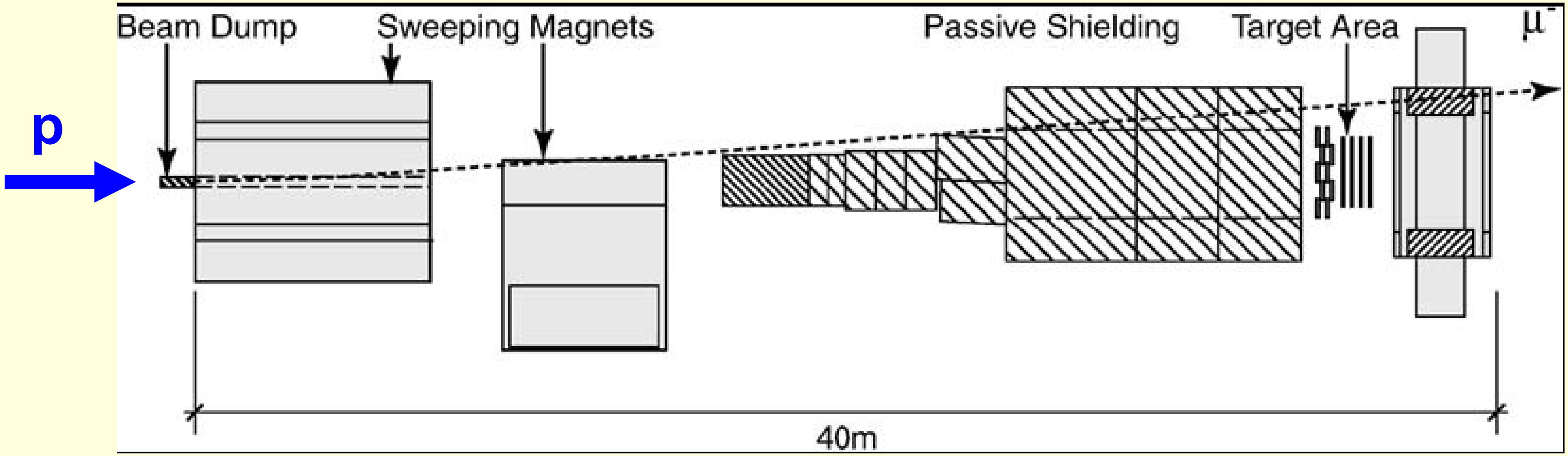
DONUT

Direct **O**bservation of **NU T**au

- Goal: First direct observation of ν_τ CC interactions

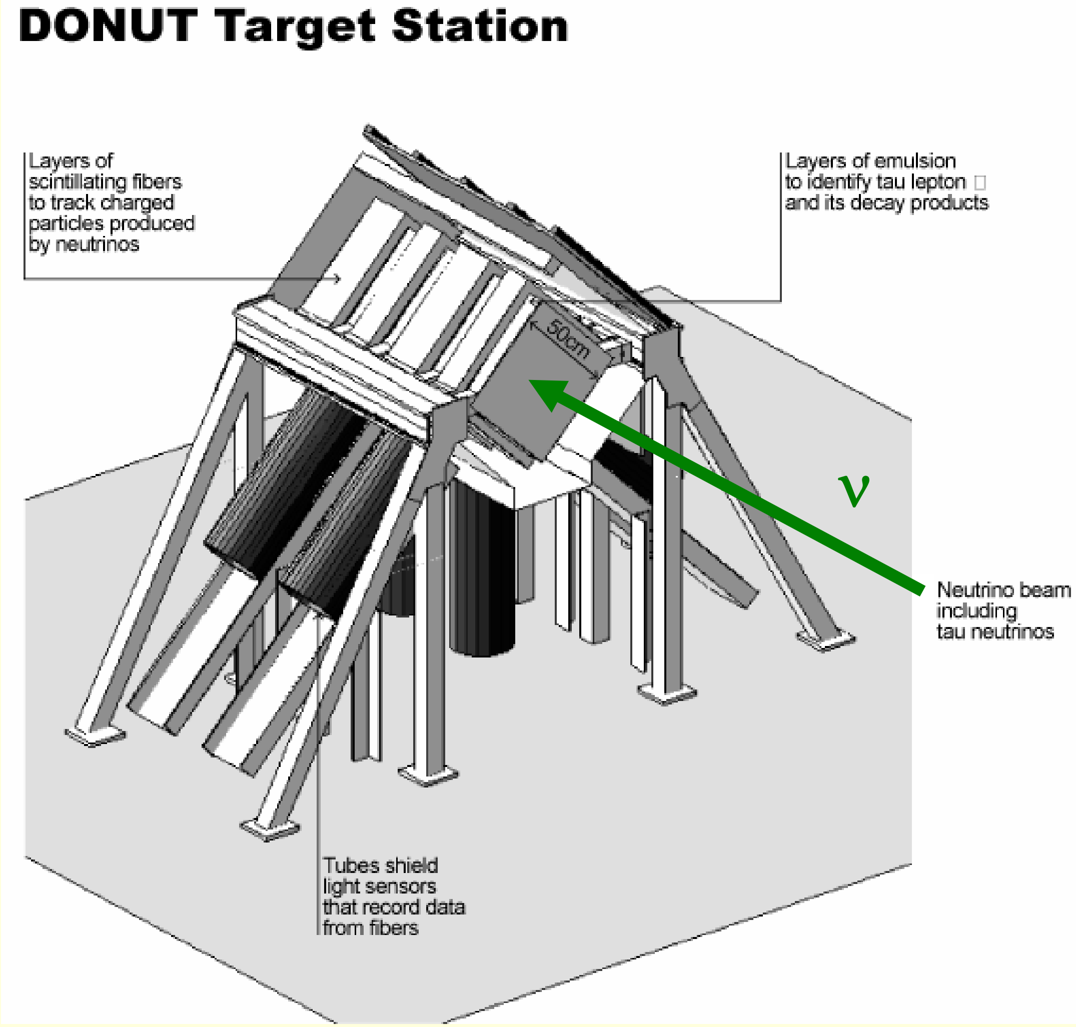
Neutrino beam:

- 800 GeV protons from the Fermilab Tevatron

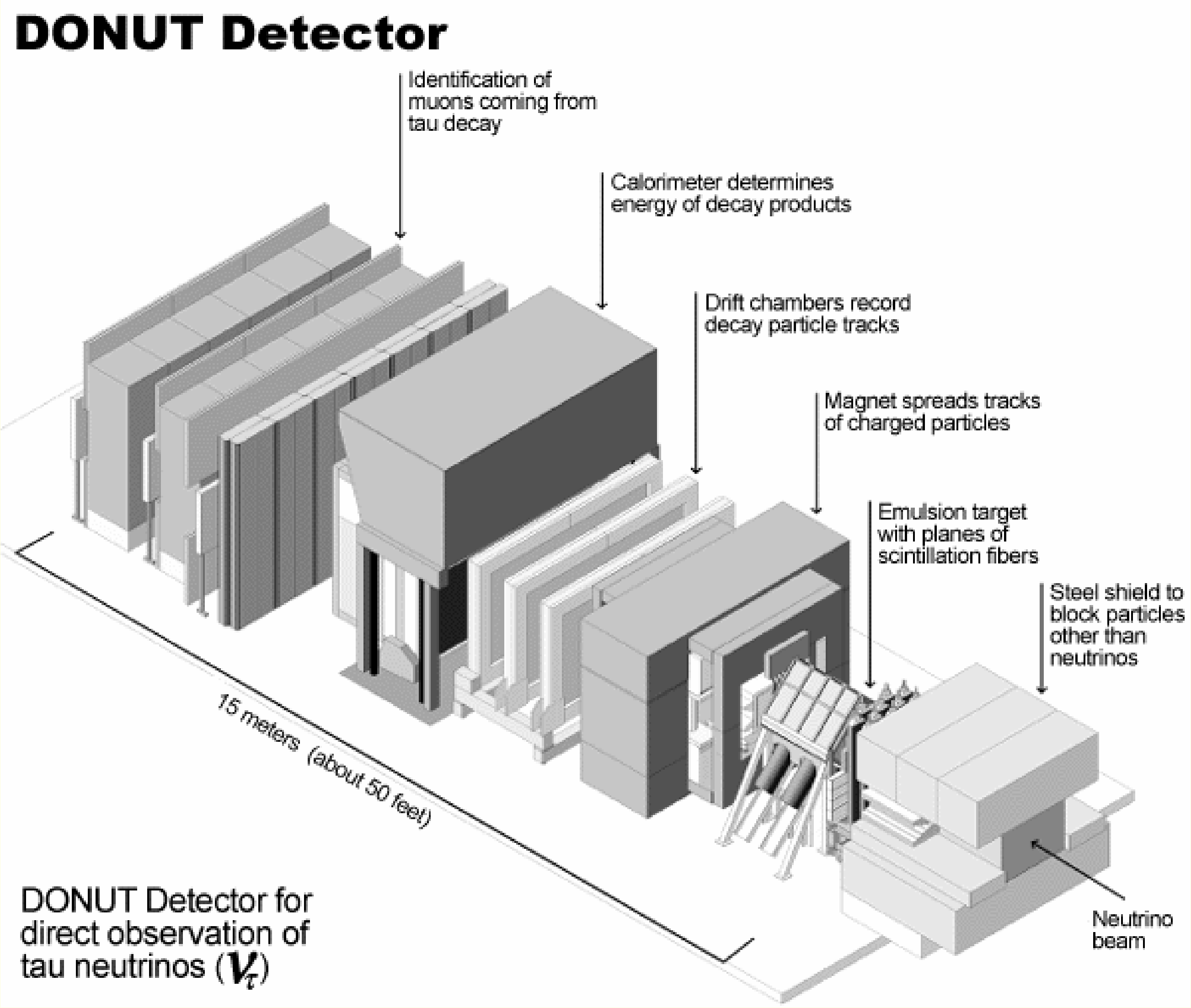


DONUT

- Beam composition: approx. 60 % ν_μ, 35 % ν_e, 5 % ν_τ
- $\langle E_\nu \rangle$ = 53 GeV
- Total of 7 target modules exposed
- Partially with ECCs



DONUT

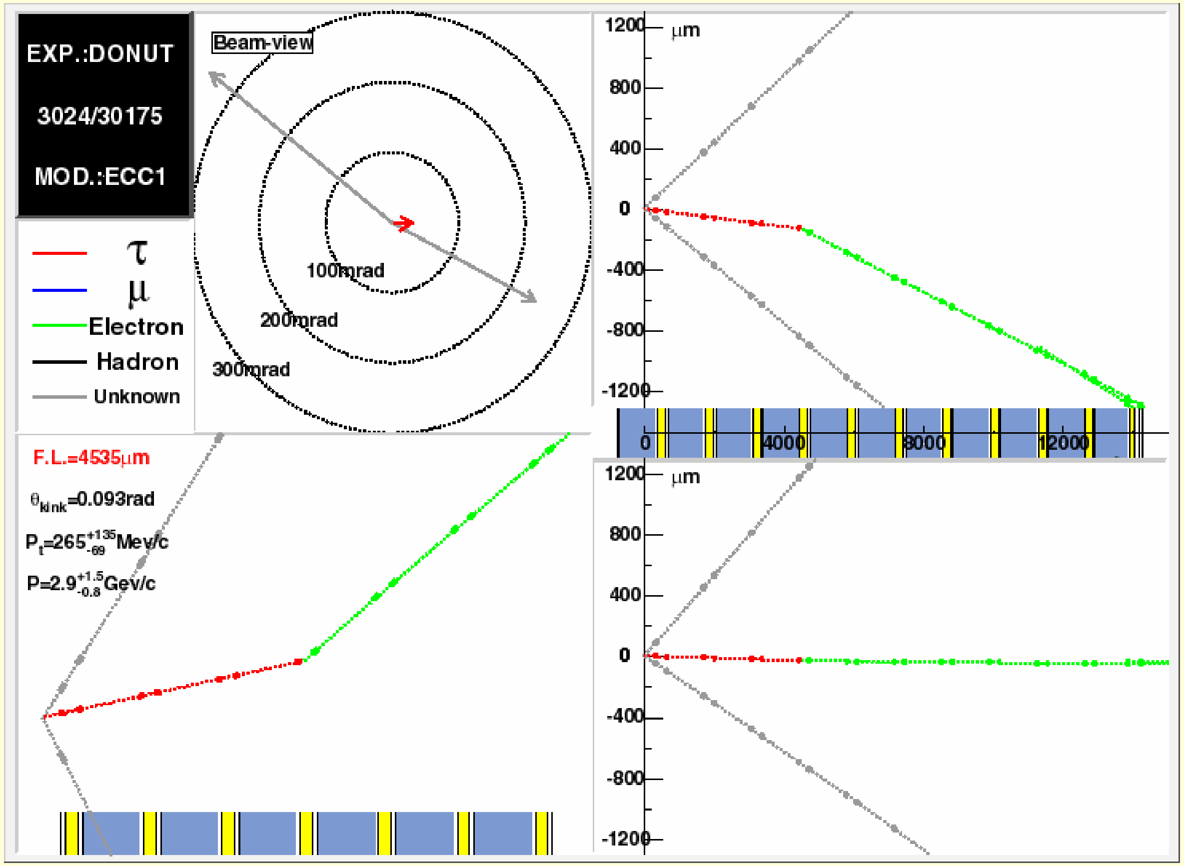


DONUT Detector
Identification of muons coming from tau decay
Calorimeter determines energy of decay products
Drift chambers record decay particle tracks
Magnet spreads tracks of charged particles
Emulsion target with planes of scintillation fibers
Steel shield to block particles other than neutrinos
15 meters (about 50 feet)
Neutrino beam
DONUT Detector for direct observation of tau neutrinos (ν_τ)

DONUT

- Data taking from April to September 1997
- Result:

5 ν_τ CC interactions with a background of 0.34 ± 0.05



OPERA Emulsions

- OPERA emulsion surface: 120,000 m^2
  ➔ mass production

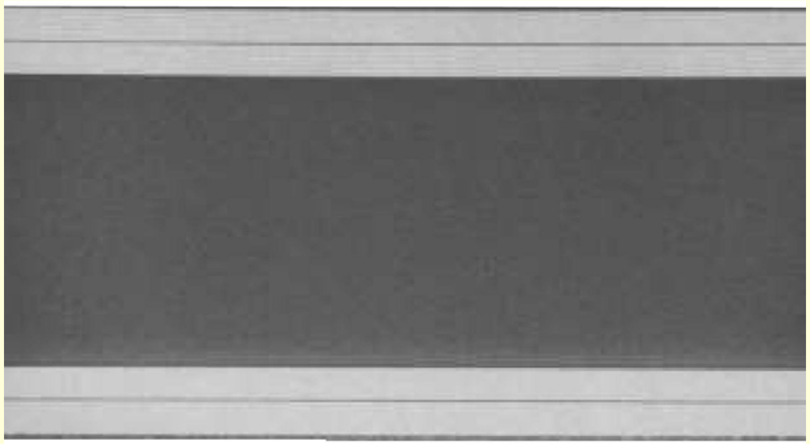
  - \+ Production speed
  - \+ Low deviations in emulsion thickness
  - – Limit on emulsion thickness
  - – Limit on emulsion viscosity (= crystal content)

- R&D project by Nagoya University + Fuji Photo Film Co.
  ➔ machine coating of nuclear emulsions

The "OPERA film":

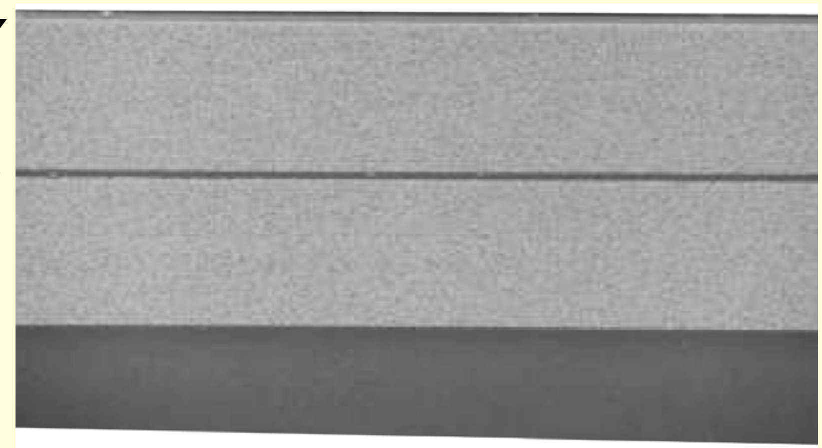
43 μm emulsion layer

205 μm plastic base



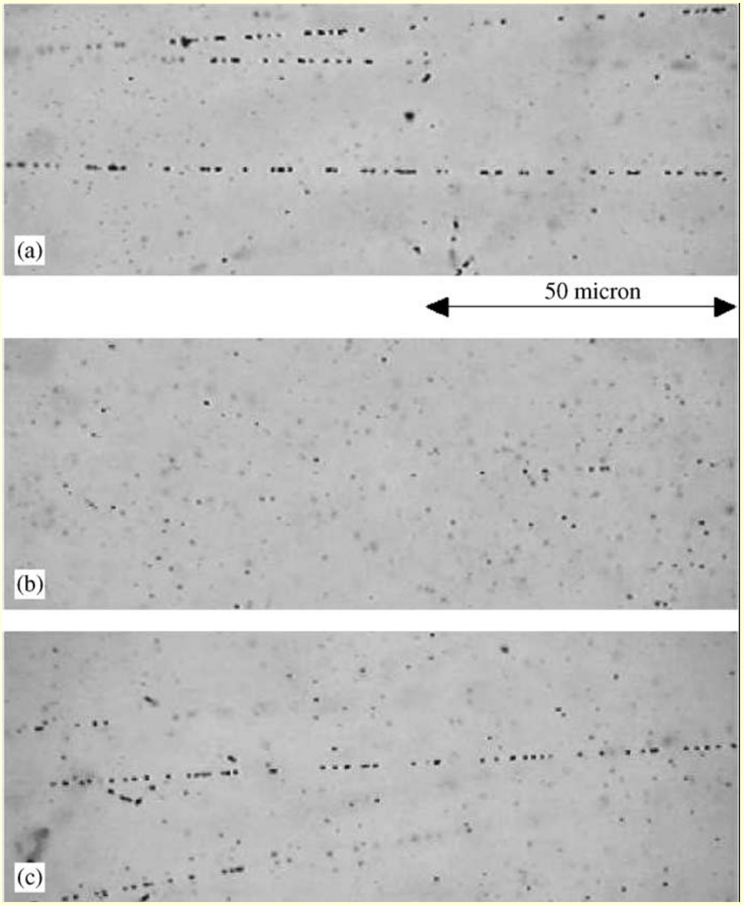
protective gelatin layers:
~1 μm each

one coating layer: ~20 μm



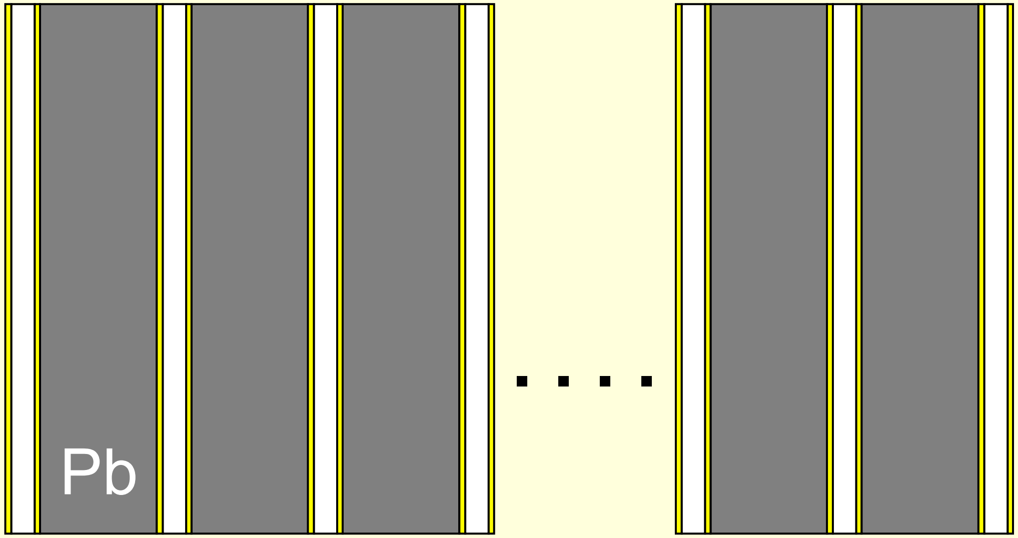
OPERA Emulsions

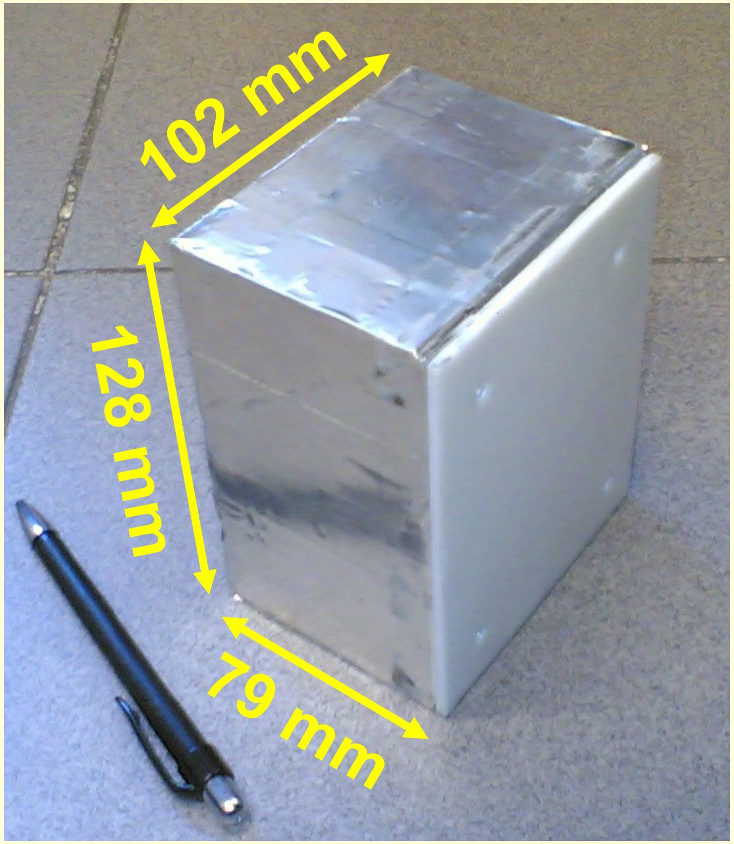
- "Gel tuning": Implementation of refreshing capability
  → Fading of latent image
- Production took place from 2003 to 2005 in Japan
- Refreshing underground in the TONO mine, Japan
- Transportation to Italy by ship
- Storage underground at LNGS



Target Bricks

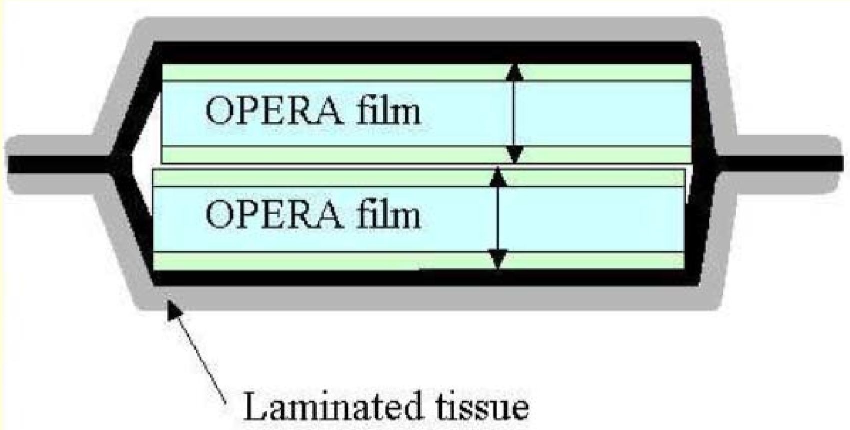
- 57 emulsion sheets (~0.3 mm)
- 56 lead plates (1 mm)
- 1 Changeable Sheet

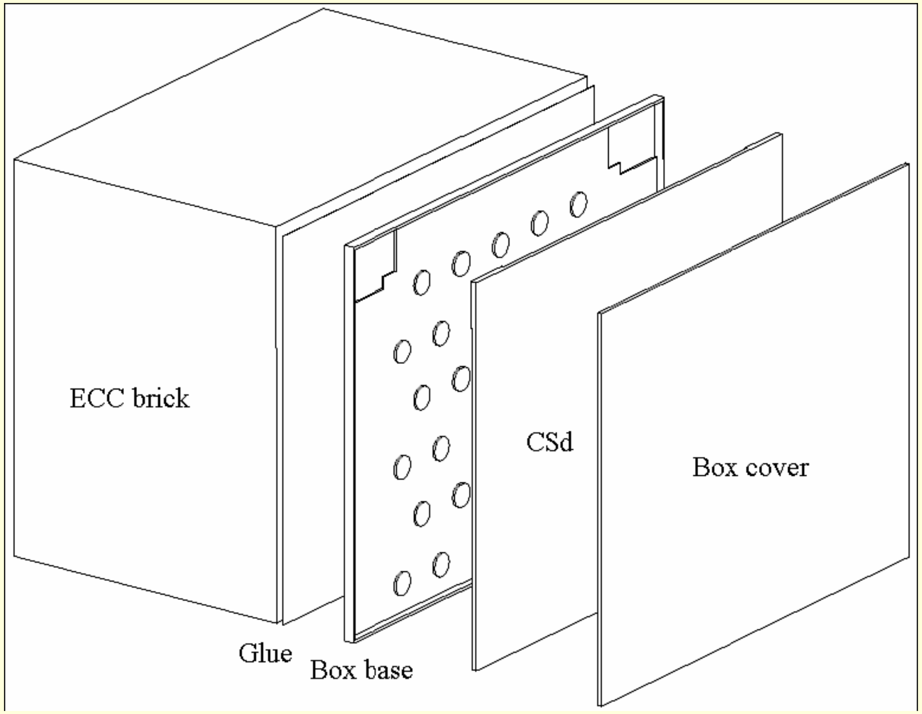


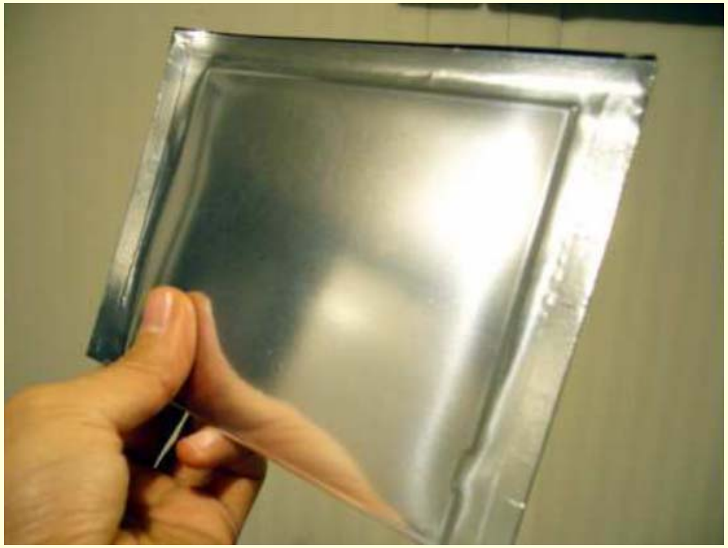


Changeable Sheet:

- 2 extra emulsion sheets outside the brick





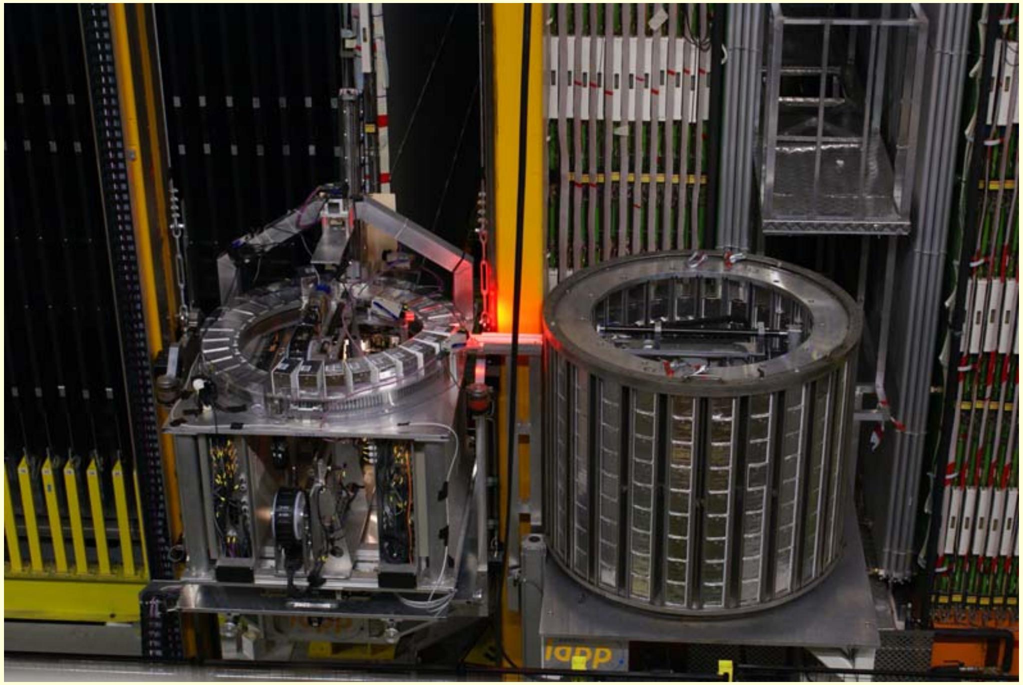


Brick Assembly Machine

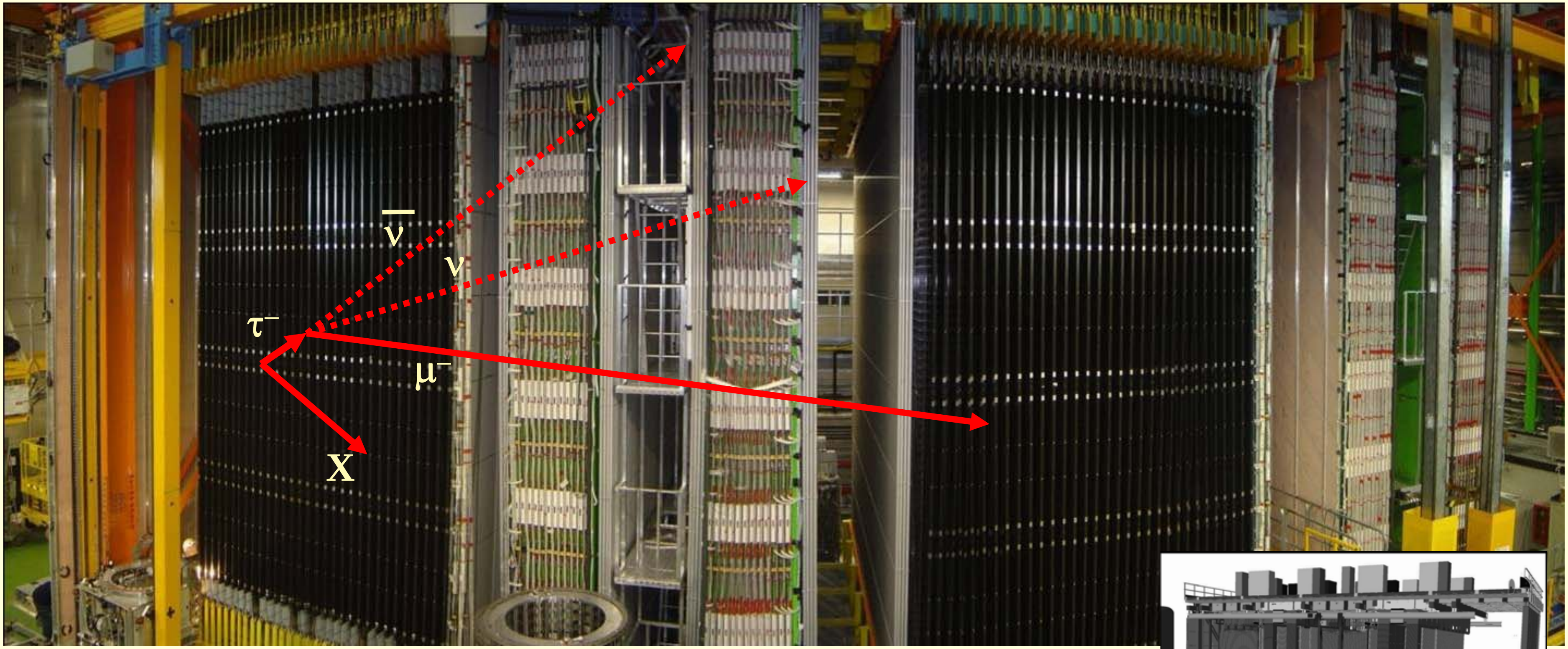
- Robotic production line inside darkroom
- Total number of bricks: 154,750
- Production (almost) finished

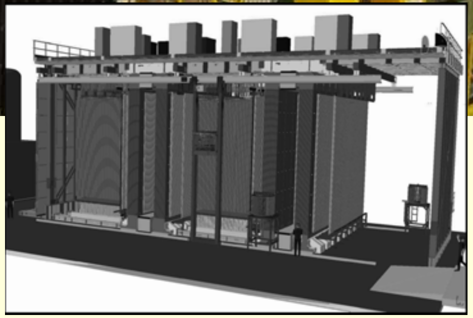
Brick Manipulator System

- 1 system on each side of the detector
- 52 bricks in one row



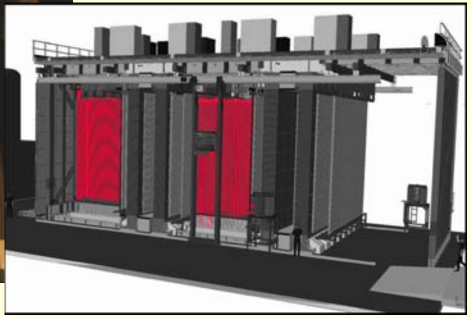
Electronic Detector





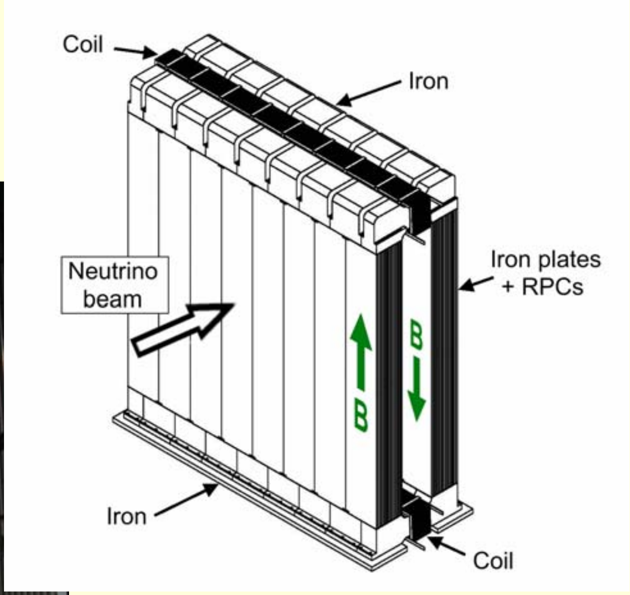
Electronic Detector

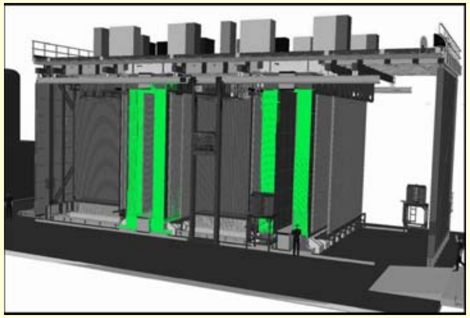
Target Tracker:



Electronic Detector

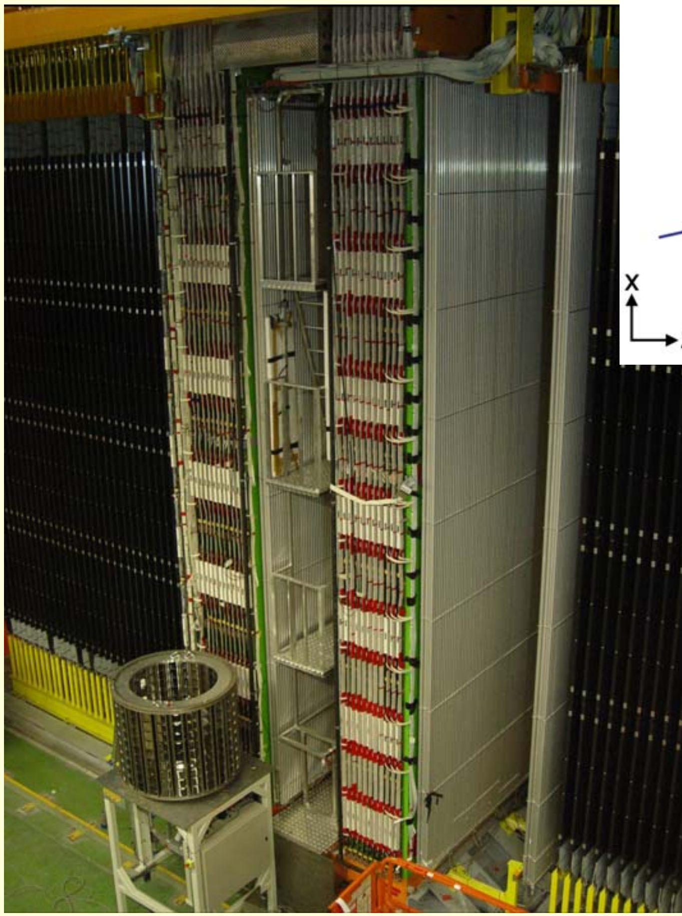
Magnet + RPCs:

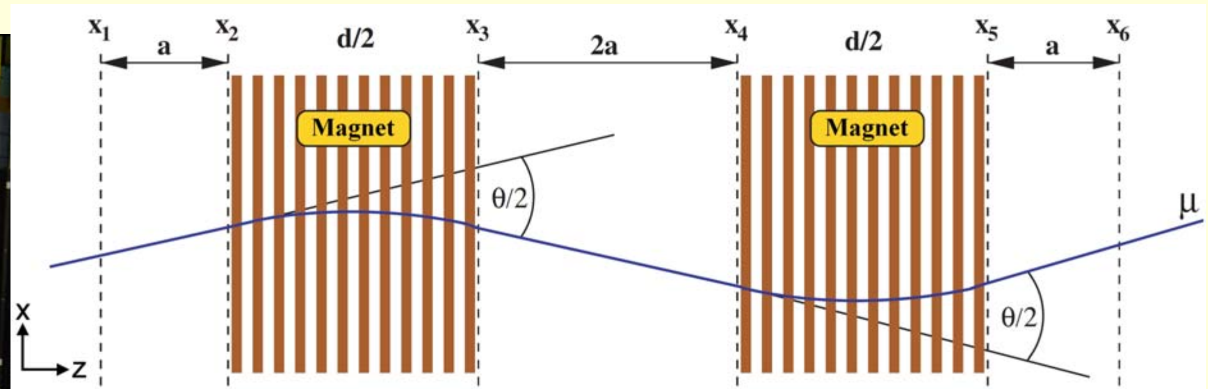


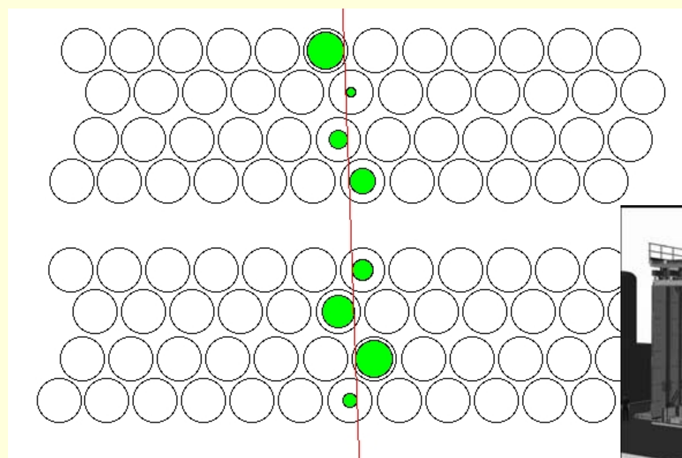


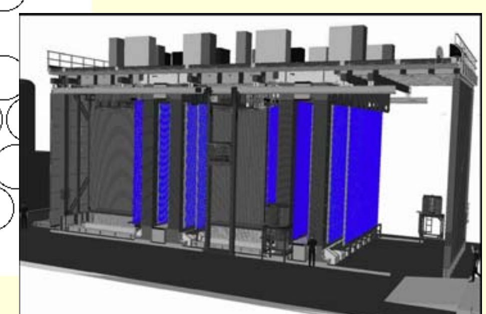
Electronic Detector

Precision Tracker:





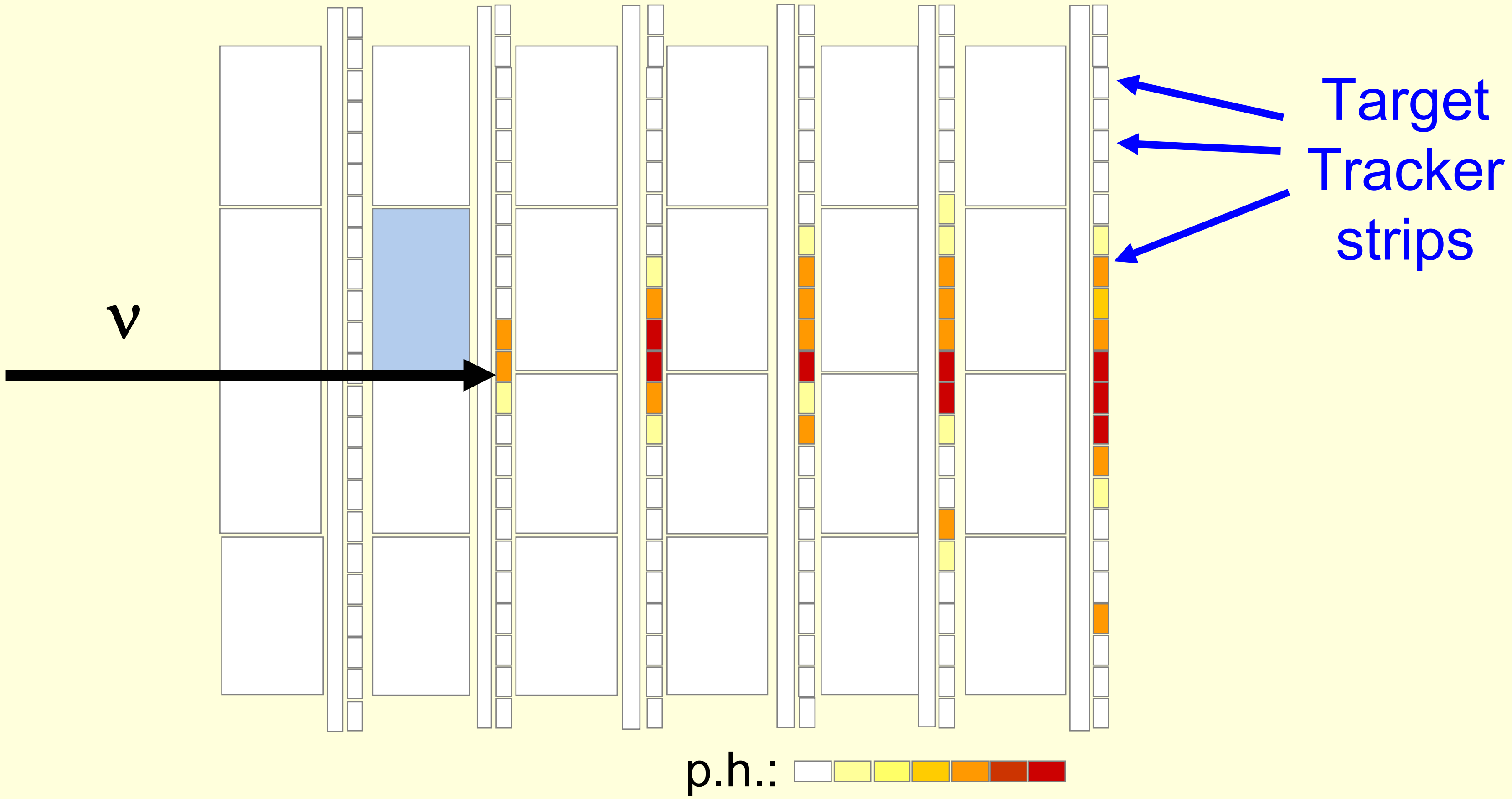




Data Taking

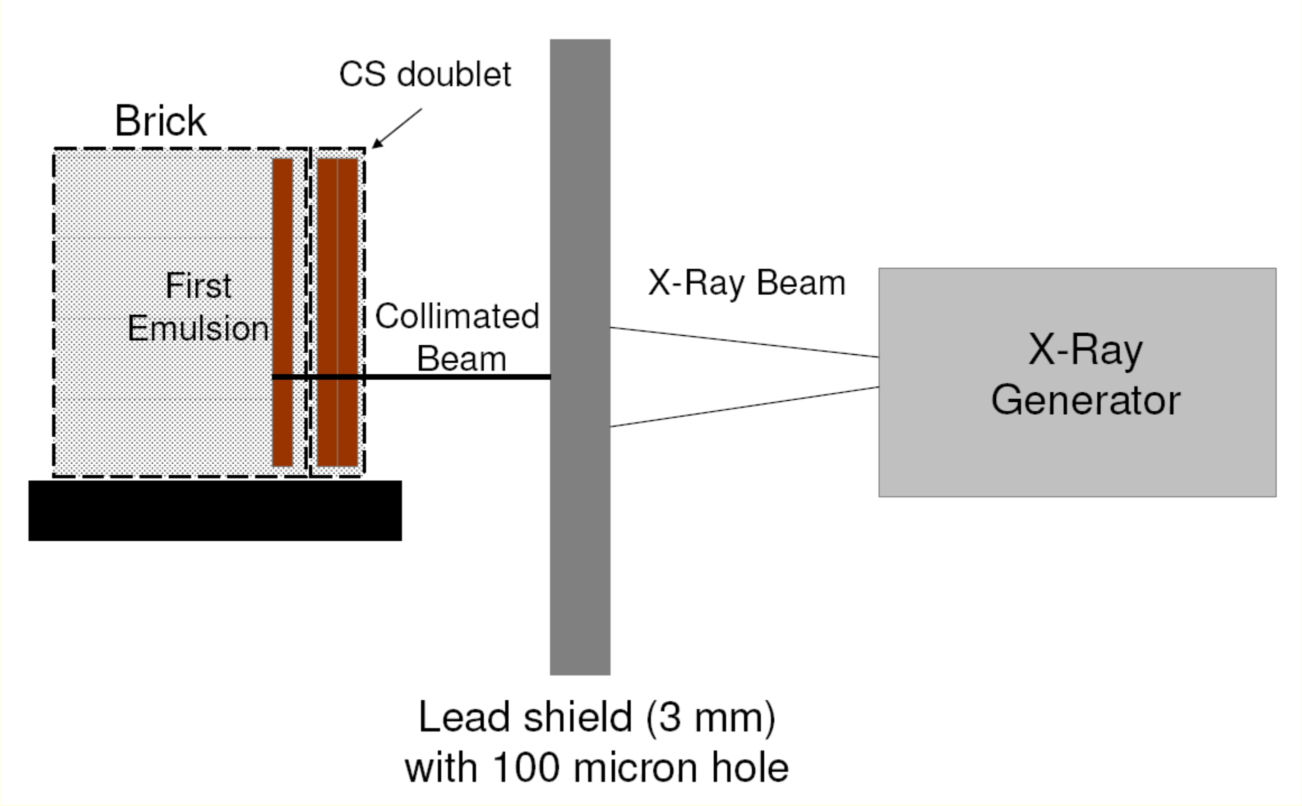
Process of data taking:

- Electronic detector predicts a vertex inside the target



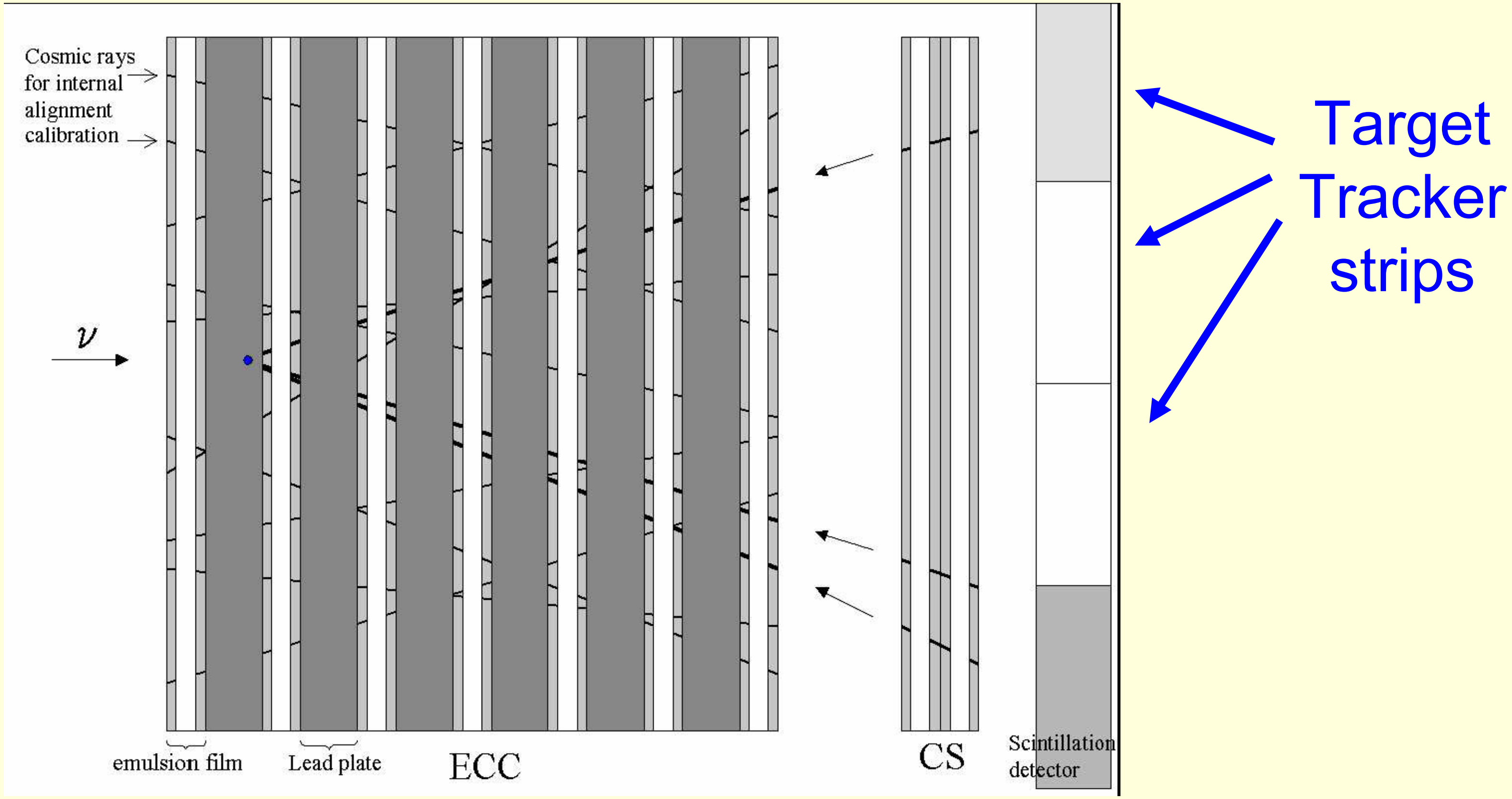
CS analysis:

- X–ray marking, detachment of the CS, film development



CS analysis:

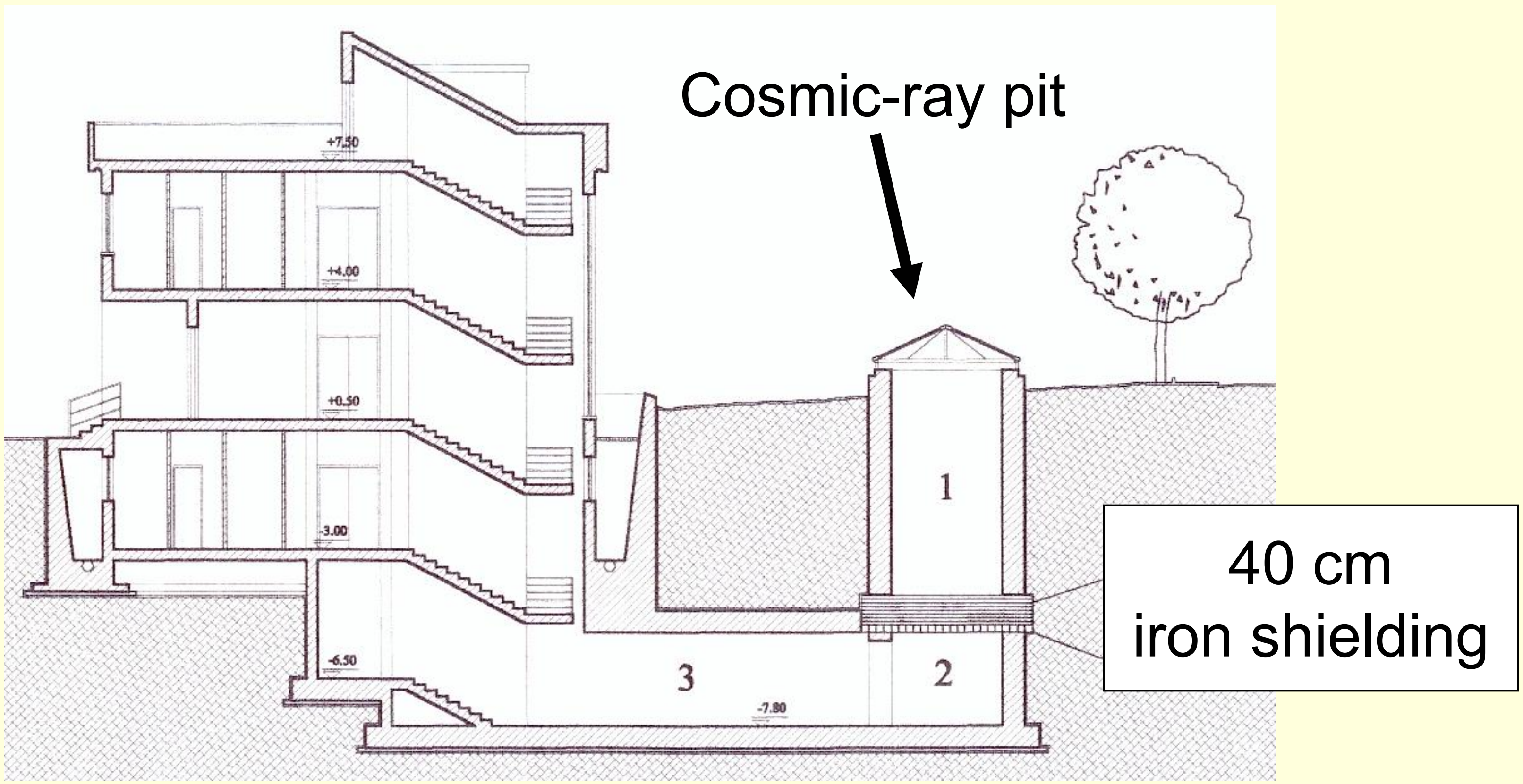
- CS offers a far more accurate vertex prediction



Data Taking

Brick emulsions:

- ~24 h cosmic–ray exposure for alignment



Data Taking

Development process:

- Unpacking + labelling (semi–automated)
- Emulsions set into film holders (manually)
- Fully automated:
  - Presoaking
  - Development
  - Stop bath
  - Cleaning
  - Fixation
  - Washing
  - Drying

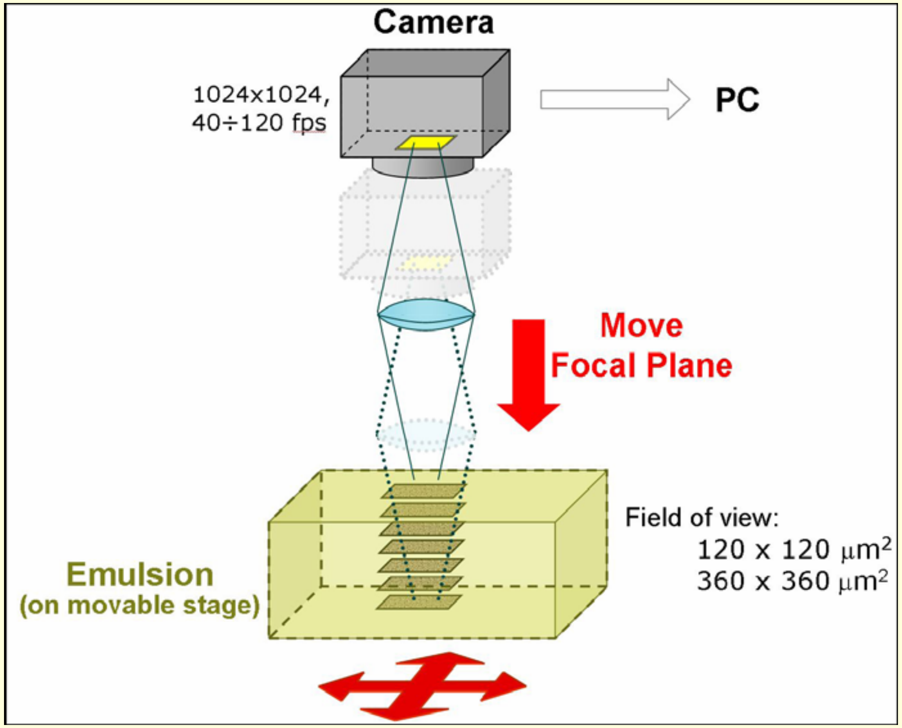
Data Taking

Development process:

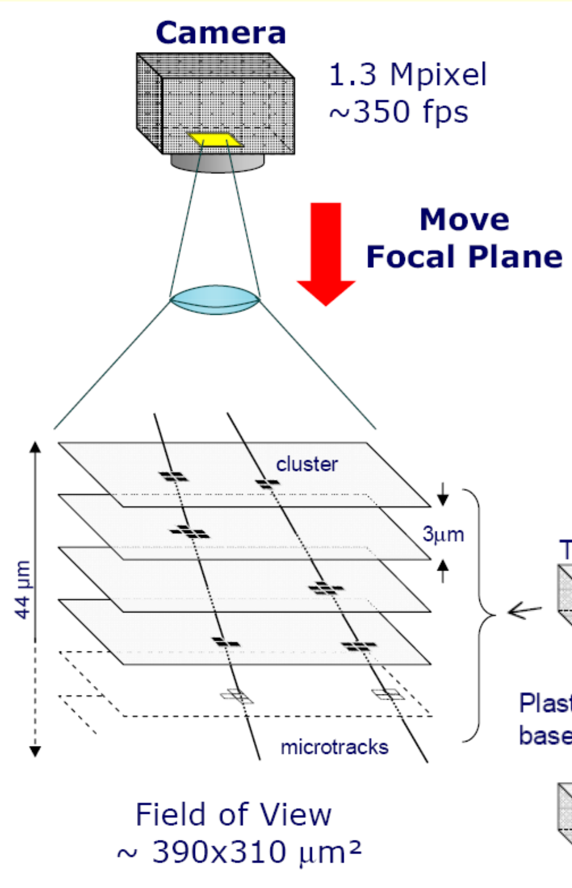
Data Taking

Scanning:

- 10 scanning laboratories in Europe and Japan

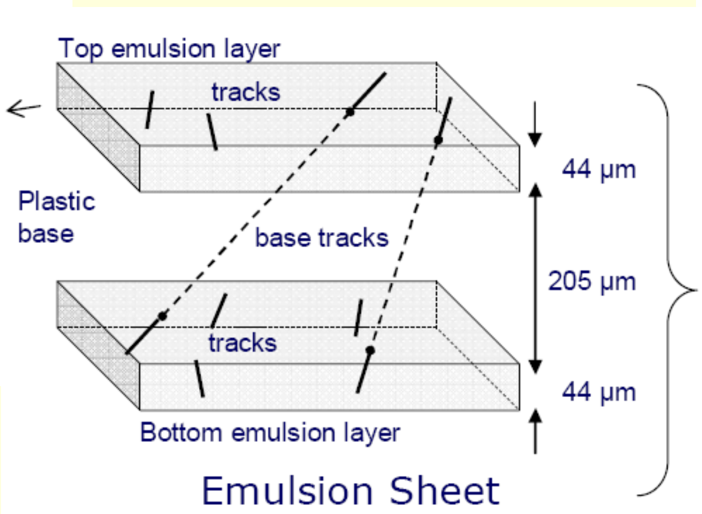


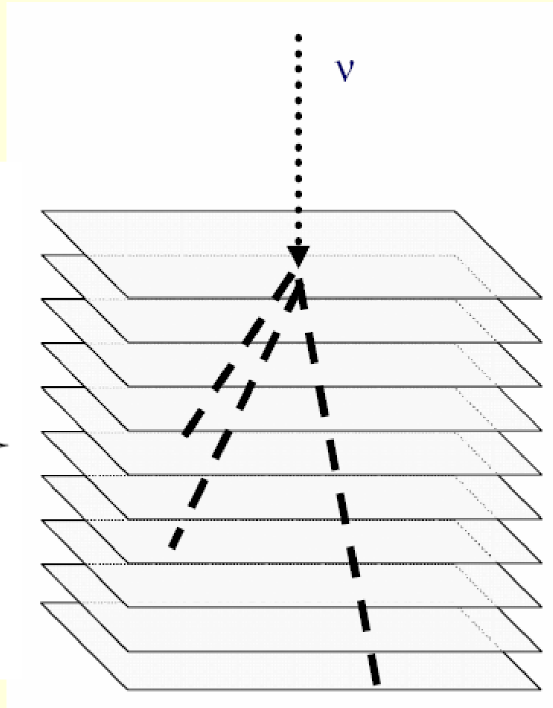
Data Taking



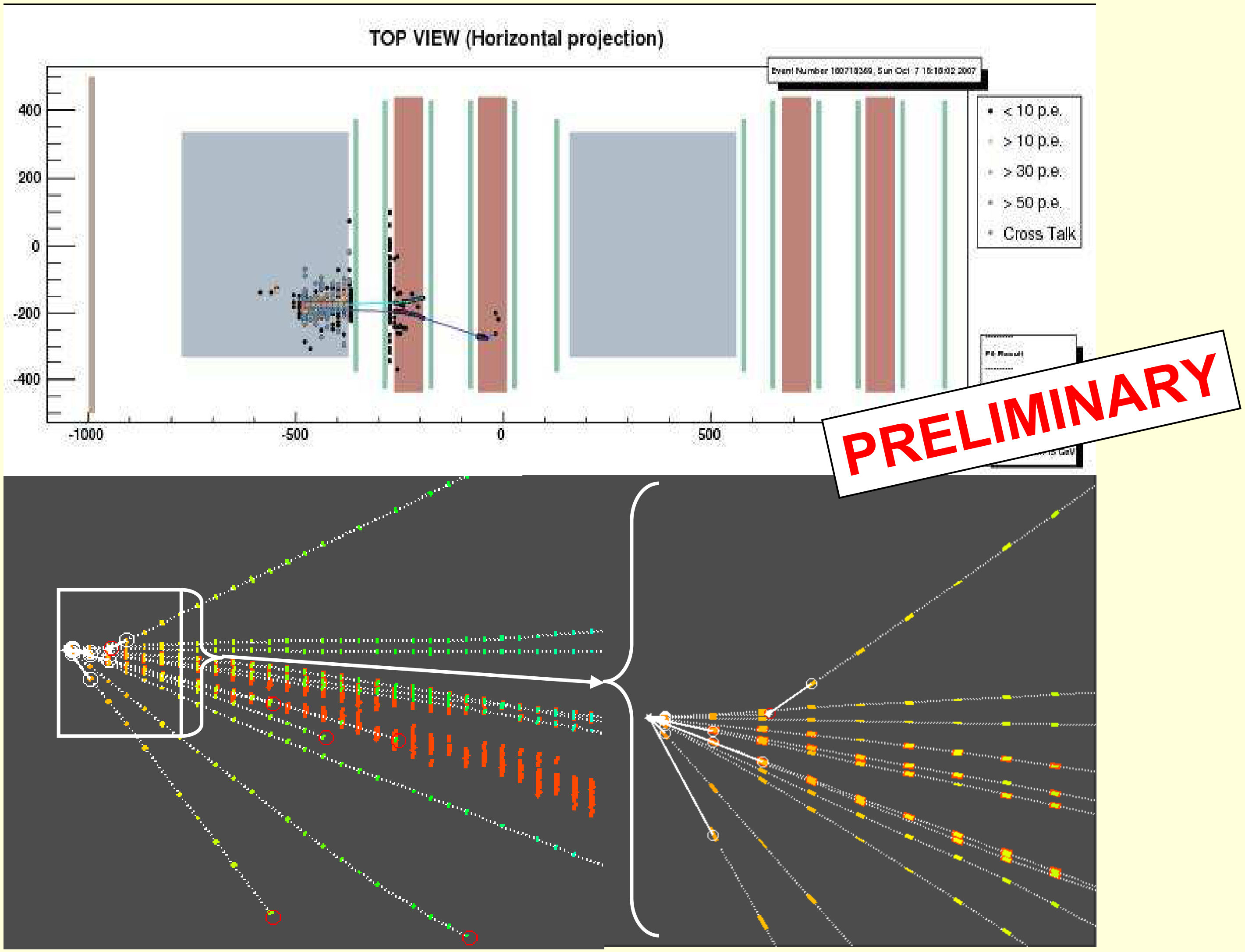
Track reconstruction:

- Micro–tracks ➔ base–tracks
  ➔ particle–tracks





First Results



Summary

- Nuclear emulsions offer a still unrivalled spatial resolution
- The OPERA emulsions are the first mass production nuclear emulsions
- Large–scale use is possible today with the help of high–speed scanning systems
- Full analysis chain of OPERA has been validated

→ OPERA is ready for catching tau–neutrinos

The End