First events from the OPERA experiment at Gran Sasso

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on behalf of the OPERA COLLABORATION

OPERA Collaboration

L'Aquila
Bari
Bologna
LNF Frascati
LNGS
Napoli
Padova
Roma
Salerno

LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Bern
Neuchâtel
ETH Zurich

IHE Brussels

Hamburg
Münster
Rostock

IRB Zagreb

Sofia

INR Moscow
NPI Moscow
ITEP Moscow
SINP NSU Moscow
JINR Dubna
Obninsk

OPERA is an international collaboration of ~ 200 physicists from 36 institutions and 13 countries

Tunis

METU Ankara

Technion Haifa

Aichi
Toho
Kobe
Nagoya
Utsunomiya

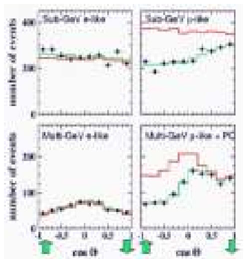
Jinjiu

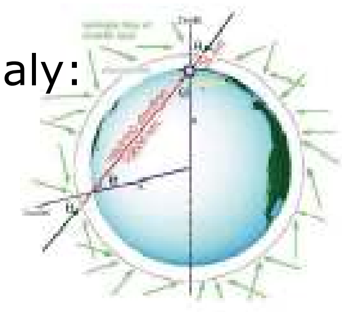
Outline

- Physics motivations
- CNGS Beam
- OPERA Detector
- Physics potential
- First events in the CNGS 2007 run
- CNGS 2008 run
- Conclusions

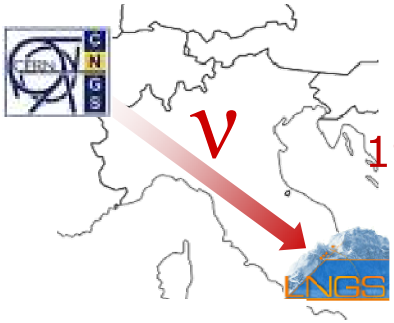
OPERA Physics Motivation

Road to OPERA
1998 Atmospheric neutrino anomaly: deficit of ν_μ with zenith angle dependence. → OSCILLATION

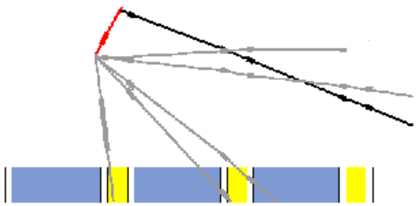




CHOOZ: final flavour not ν_e …



1999 CNGS beam design



2000 direct observation of ν_τ in nuclear emulsions (DONUT)

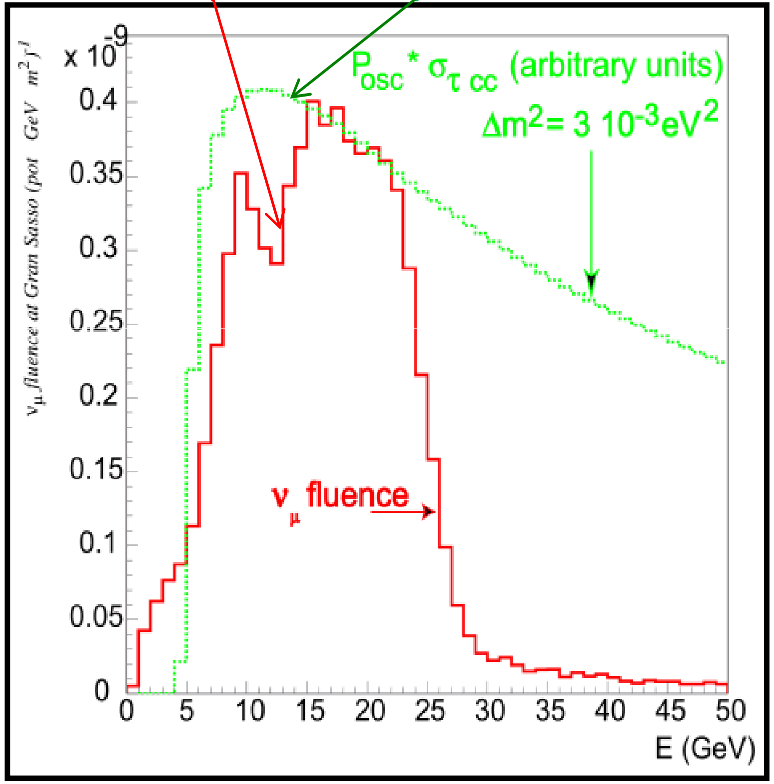
2000 OPERA proposal

OPERA
provide an unambiguous evidence for
$\nu_\mu \rightarrow \nu_\tau$ oscillation in the region of atmospheric neutrinos by looking for
ν_τ appearance
in a pure ν_μ beam

CNGS CERN Neutrino to Gran Sasso beam

optimized to maximize ν_τCC interaction rate at LNGS

$$N_\tau = N_A M_D \int \phi_{\nu_\mu}(E) P_{\nu_\mu \to \nu_\tau}(E) \sigma_{\nu_\tau}^{CC}(E) \varepsilon(E) dE$$



BEAM MAIN FEATURES

$<E\nu_\mu>$	**17 GeV**
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	**0.87%**
$\bar{\nu}_\mu / \nu_\mu$	**2.4%**
ν_τ prompt	**negligible**

- 4.5×10^{19} p.o.t./year
- 200 days/year

CNGS event rate (nominal beam)

Nominal CNGS beam (running 200 days/year): 4.5 × 10^{19} pot/year

OPERA (1.35 kton), 5 years running

ν_μ CC	19572
ν_μ NC	5880
$\bar{\nu}_\mu$ CC	411
ν_e CC	156
$\bar{\nu}_e$ CC	13

		Δm^2 (eV^2)
ν_τ CC	80	(2.0×10^{-3})
	125	(2.5×10^{-3})
	180	(3.0×10^{-3})

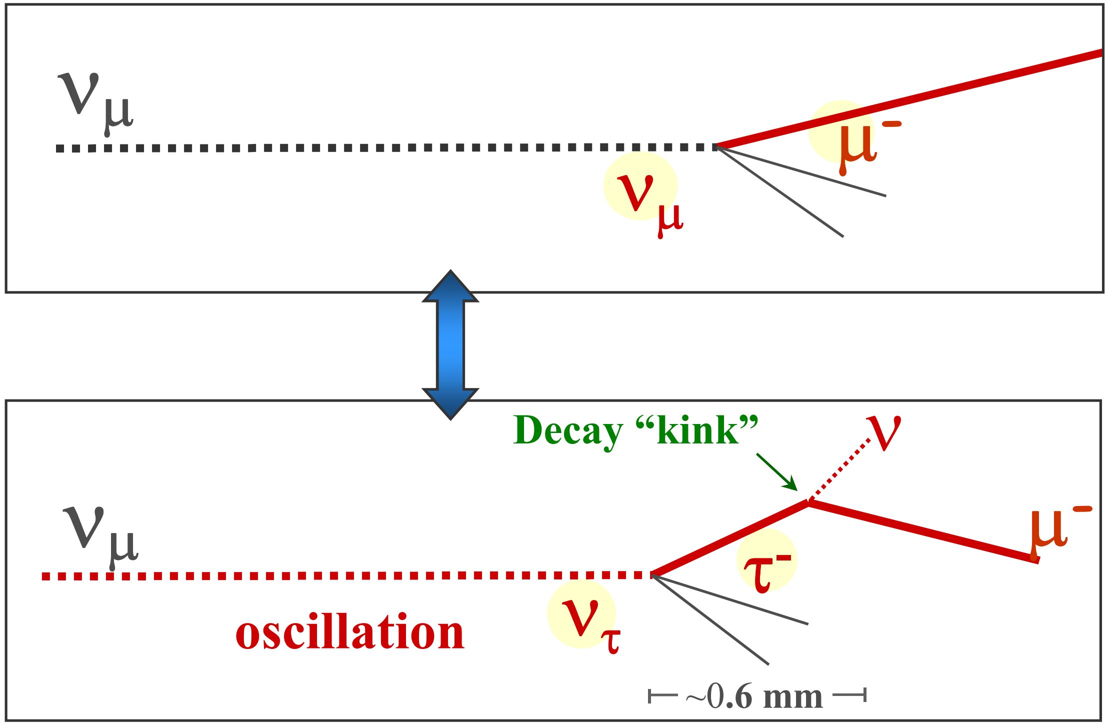
these numbers do not include the detection efficiencies

Total: ~ 26000 interactions

Additional 10000 events in the OPERA magnets

(Ongoing studies @ CERN to increase the intensity × 1.5)

OPERA: Detection of the ν_τ appearance



The challenge is to identify ν_τ interactions from ν_μ interactions

τ decay modes

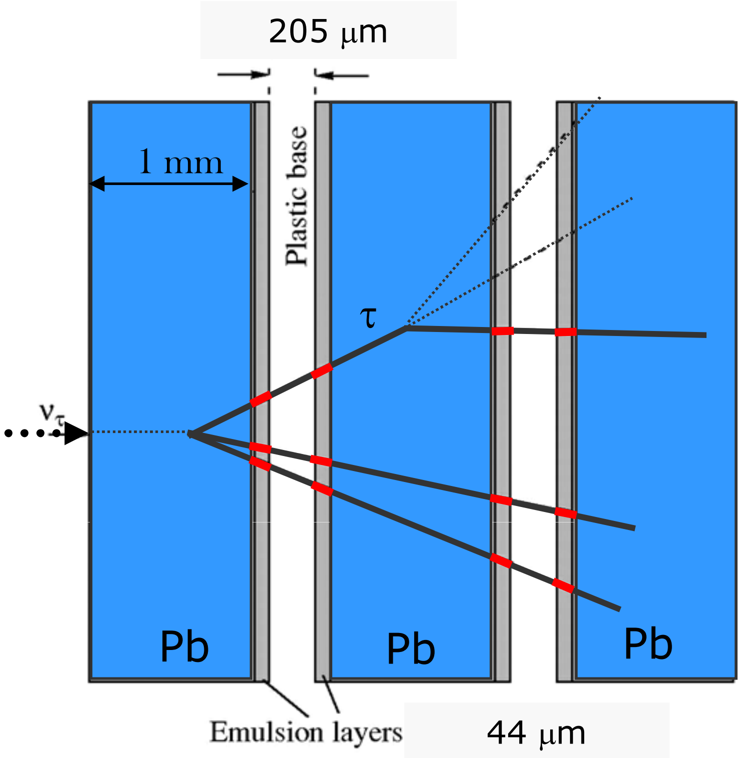
$\mu^- \, \nu_\tau \, \bar{\nu}_\mu$	**B. R. ~ 17%**
$h^- \, \nu_\tau \, n(\pi^o)$	**B. R. ~ 50%**
$e^- \, \nu_\tau \, \bar{\nu}_e$	**B. R. ~ 18%**
$\pi^+ \, \pi^- \, \pi^- \, \nu_\tau \, n(\pi^o)$	**B. R. ~ 14%**

conflicting requirements:

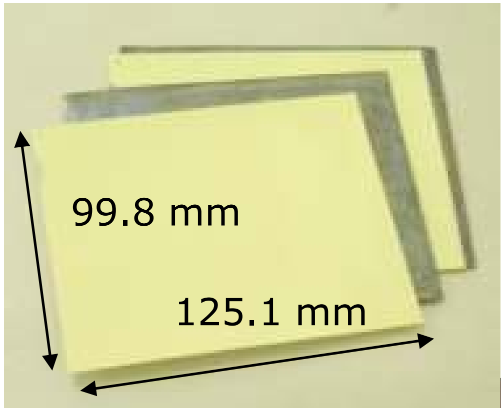
- Large mass
  - ➔ low Xsection
- High granularity
  - ➔ signal selection
  - ➔ background rejection

OPERA solution:
Emulsion Cloud Chamber (ECC) tecnique

The Emulsion Cloud Chamber technique



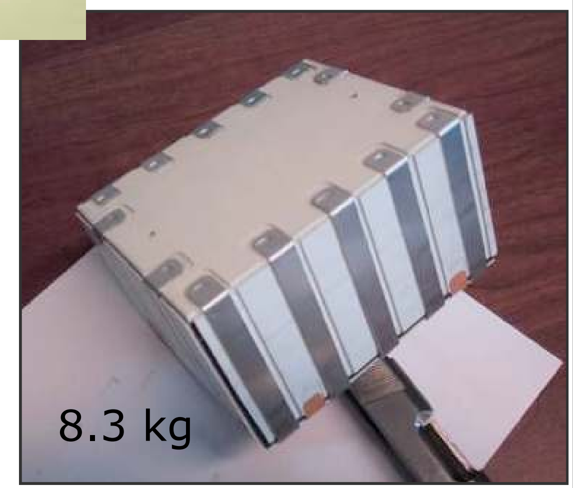
ECC ≡ sequence of emulsion-lead layers:
Lead: target mass
Emulsion: tracking device



Emulsion Resolution:
$\delta x = 1\ \mu m$
$\delta\theta = 2$ mrad

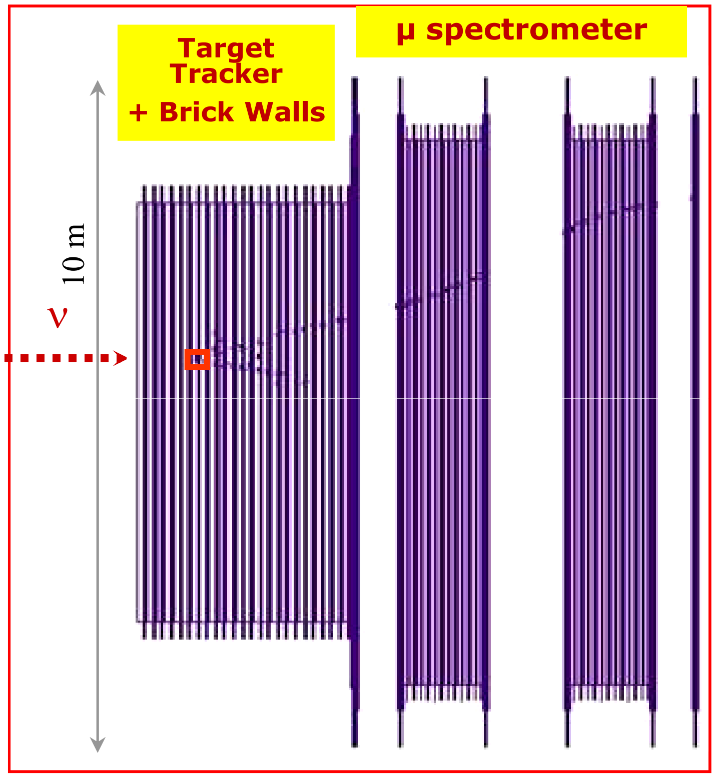
High spatial resolution capability and large masses in a modular way.
In OPERA, the basic ECC unit is the "BRICK":
56 Pb sheets + 57 emulsion layers ($10X_0$)

Total # of bricks ~ 155000



Strategy for the ν_τ location

OPERA: an hybrid detector



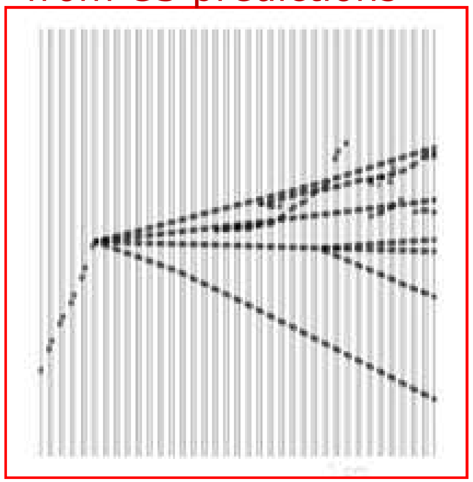
Target Tracker:
trigger ($\varepsilon > 99\%$)
localize brick with ν interaction ($\varepsilon \approx 70\div90\%$)

Spectrometer: μ ID, charge and momentum
Up to p ~ 25 GeV : $\Delta p/p < 25\%$; Wrong charge < 0.3%

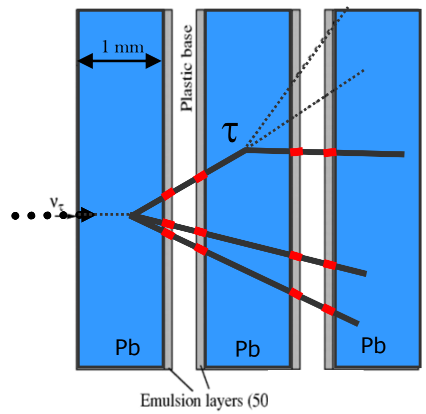
On-line analysis of electronic data (Brick selection)

Brick Extraction and scanning of 2 external films (CS) (higher level trigger)

Brick exposure to CR (fine alignment) and scanning backwards from CS predictions

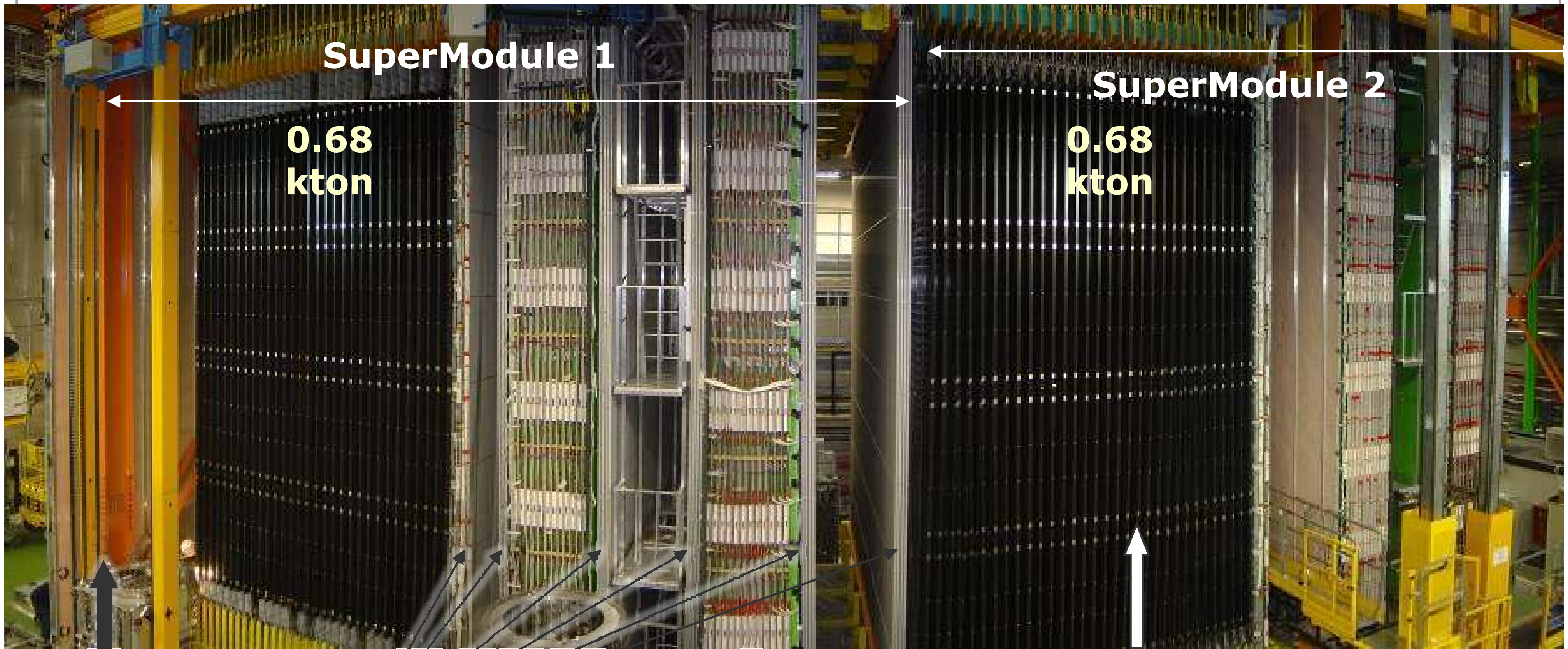


Vertex location and τ ID



ECC: measure kink, pID, momentum (via MCS), dE/dX, e/γ separation, general event kinematics

The OPERA detector



Veto plane
(RPC)

High precision tracker
magnet
- 6 4-fold layers of drift tubes

Instrumented dipole
- 1.53 *T*
- 22 XY planes of RPC in both arms

Muon spectrometer (8×10 m^2)

Target and Target Tracker 6.7×6.7 m^2

- Target : 77500 bricks, 29 walls
- Target tracker : 31 XY doublets of 256 scintillator strips + WLS fibres + multi-anodes PMT for
  - Brick selection
  - Calorimetry

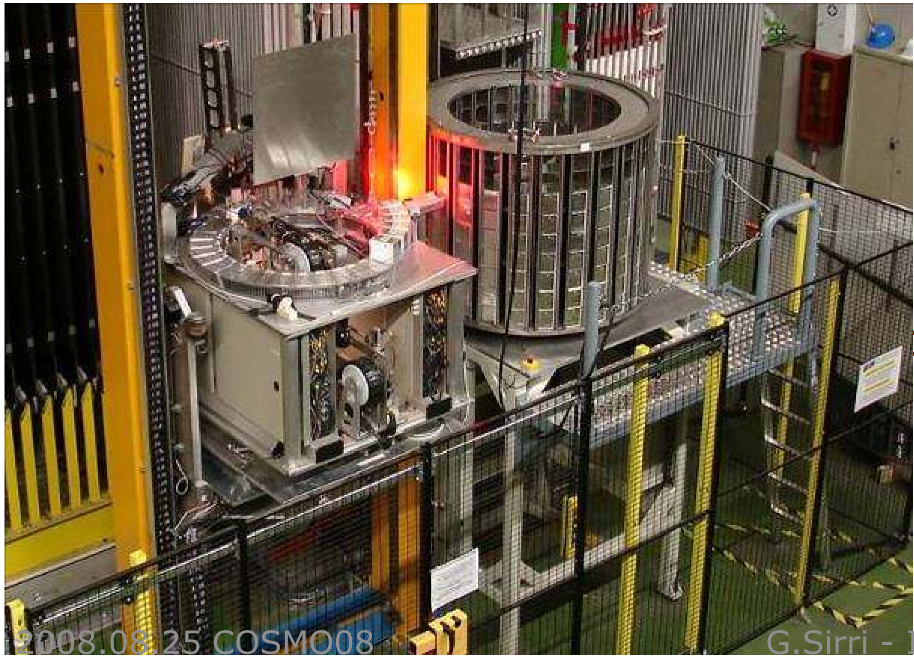
Target Filling

BAM (Brick Assembling Machine)

Automatic
lead/emulsion piling
in a dark room

(~700 bricks/day)

The BMS (Brick Manipulator System)



one robot on each
side of the
detector

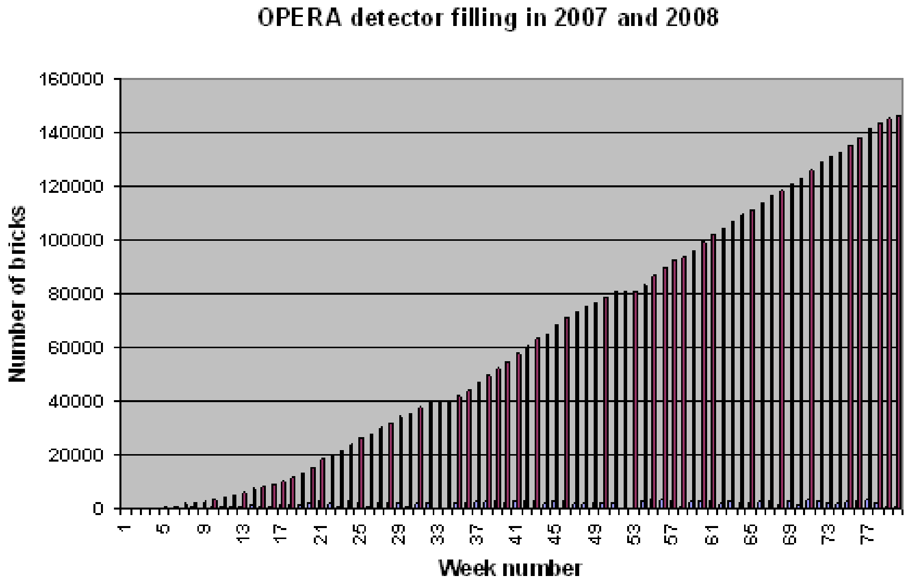
Insertion and extraction
of bricks following
complex procedures.

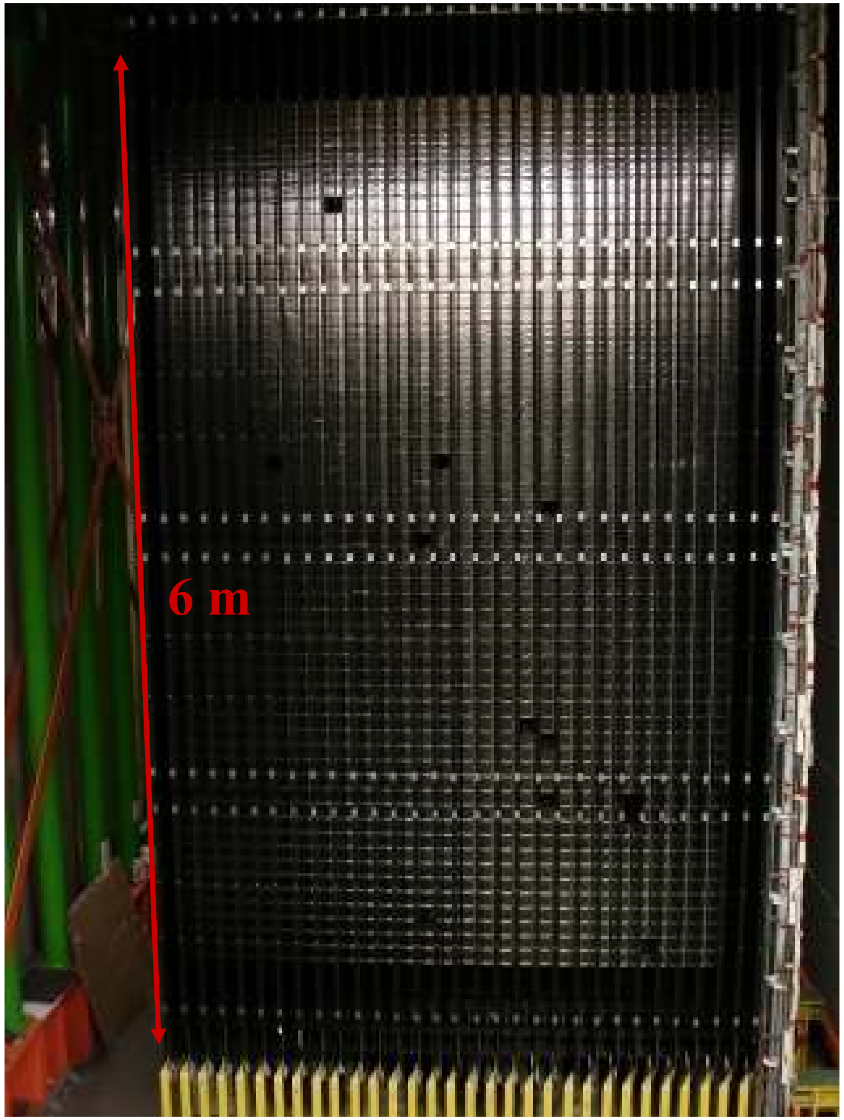
Target Filling

January 2007: start filling target

July 2008 : end of filling target

146200 bricks today
⇔ 1.26 kton

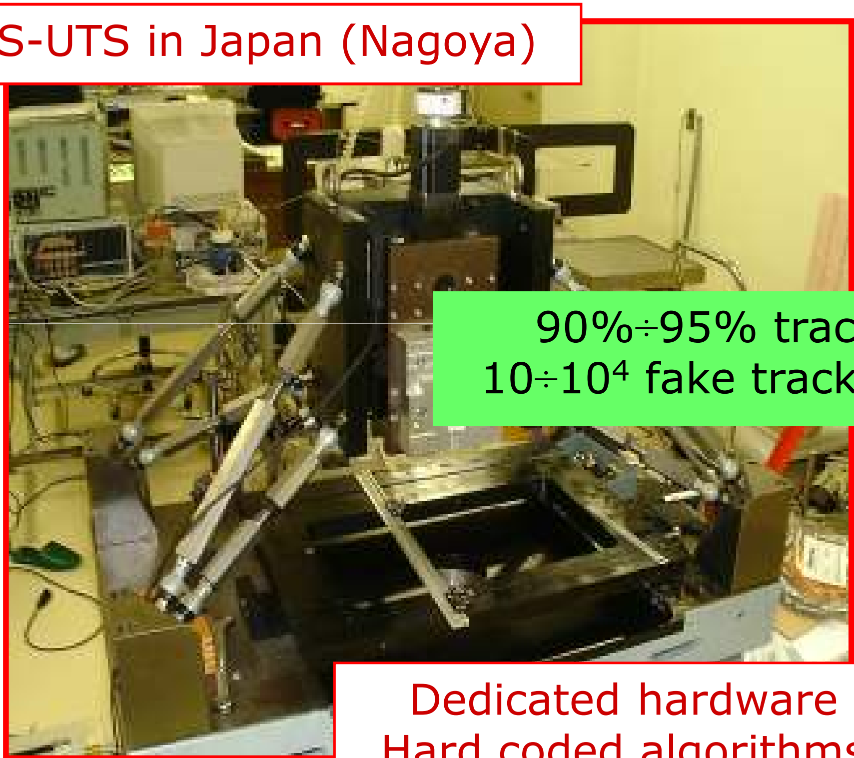




Automatic emulsion scanning

Based on the tomographic acquisition of emulsion layers.
The experiment size requires a scanning speed of ~20 cm^2/h.
~ 30 bricks will be daily extracted → thousands of cm^2/day)

S-UTS in Japan (Nagoya)

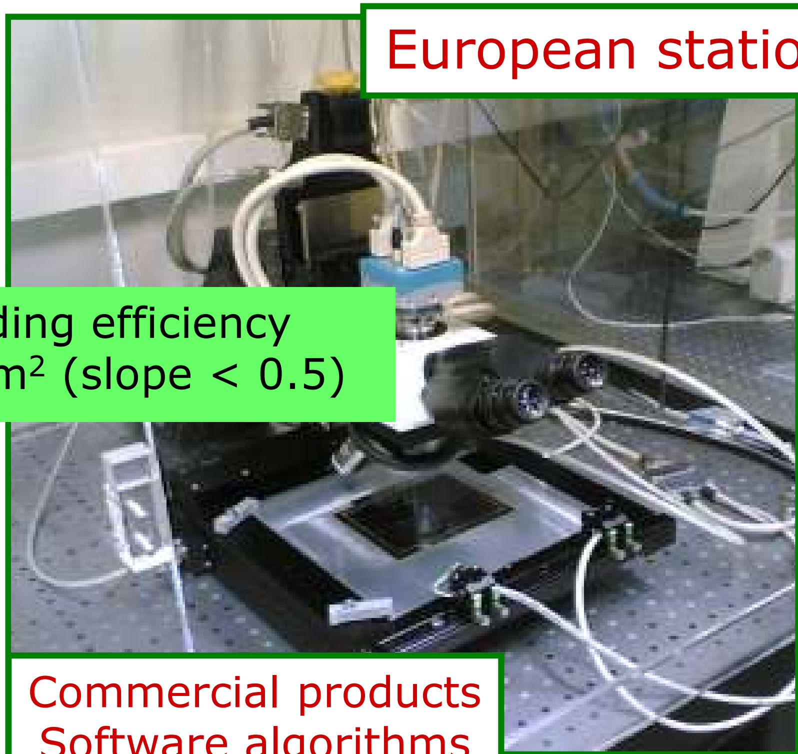


Dedicated hardware
Hard coded algorithms

High speed CCD Camera (3 kHz)
Synchronization of objective lens and stage
1.5h/brick for 100 predictions

90%÷95% track finding efficiency
$10 \div 10^4$ fake tracks / cm^2 (slope < 0.5)

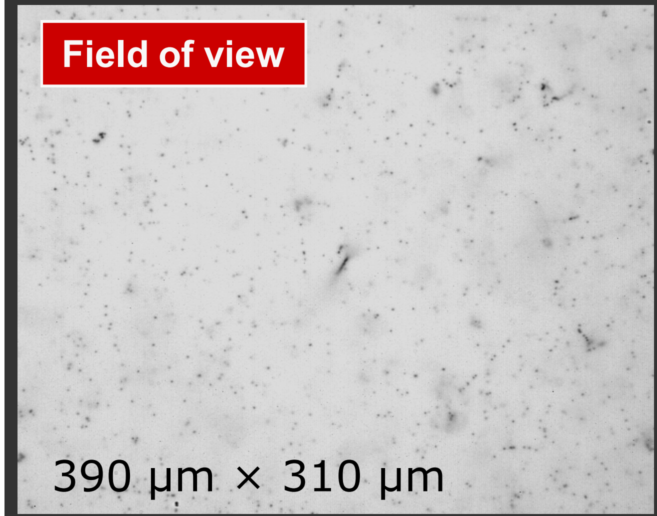
European station

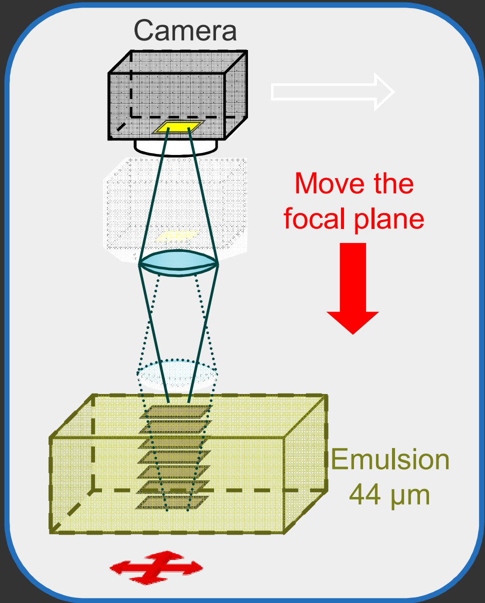


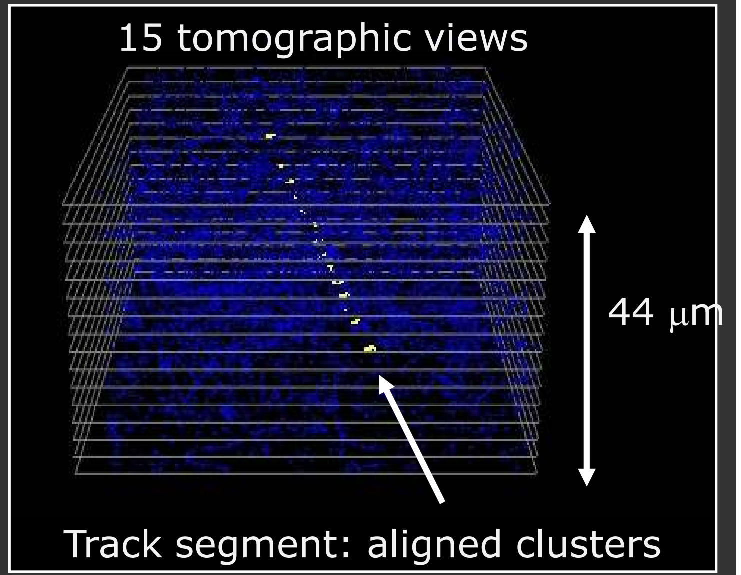
Commercial products
Software algorithms

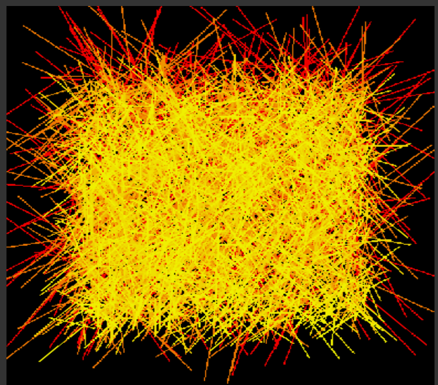
Customized commercial optics and
mechanics + asynchronous DAQ software
Running at ~20 cm^2/h

Tracks in Emulsion

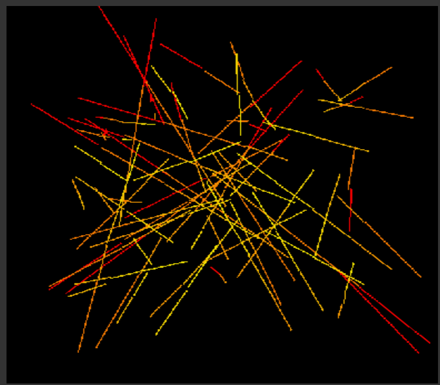




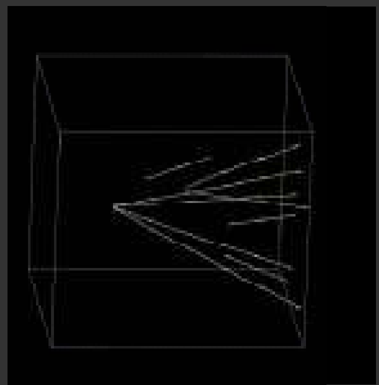




Passing-through tracks rejection



Track segments found in 8 consecutive plates



Vertex reconstruction in the brick

Expected number of events

τ identification
NOT included

full mixing, 5 years run, 4.5x10^{19} pot/year, 1.35 kton
Efficiency $\varepsilon = \varepsilon_{trigger} \times \varepsilon_{brick} \times \varepsilon_{geom} \times \varepsilon_{primary\_vertex}$
99% x 80% x 94% x 90 %

τ decay channel	ε(%) with τ identification	BR(%)	signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Background
$\tau \to \mu$	17.5	17.7	2.9	0.17
$\tau \to e$	20.8	17.8	3.5	0.17
$\tau \to h$	5.8	49.5	3.1	0.24
$\tau \to 3h$	6.3	15	0.9	0.17
Total	ε x BR = 10.6 %		10.4	0.76

Main background sources:
- large-angle muon scattering in lead

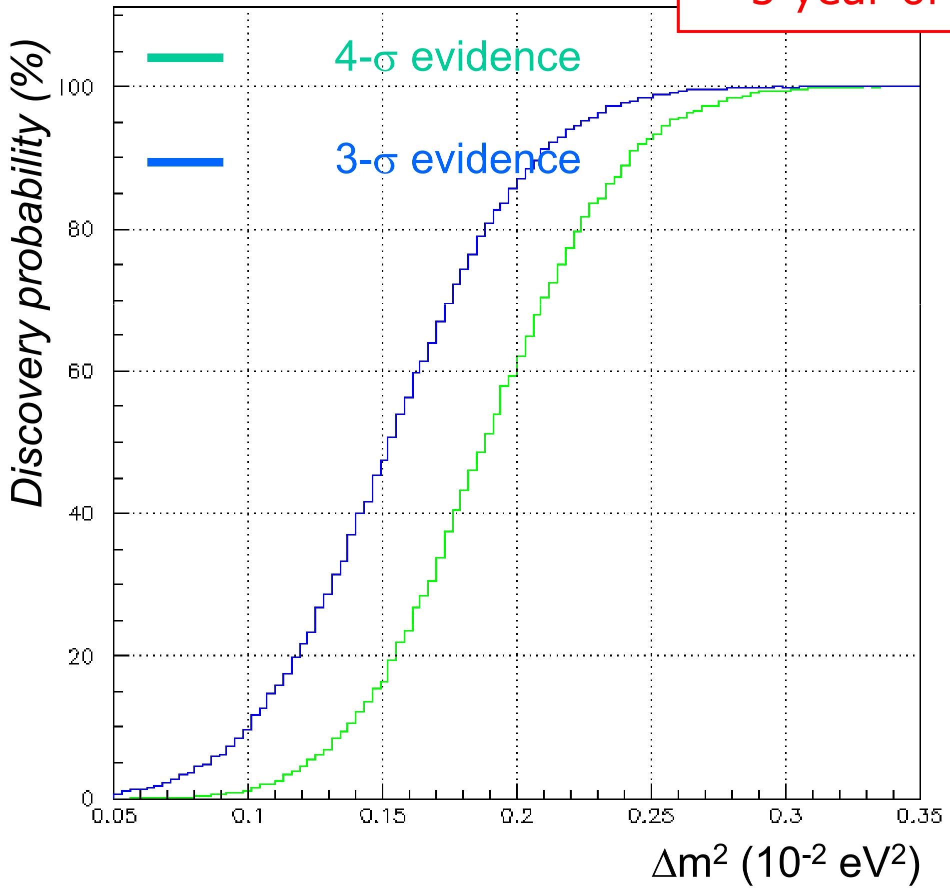
If no primary muon identified:
- charm production and decays
- hadron re-interactions in lead

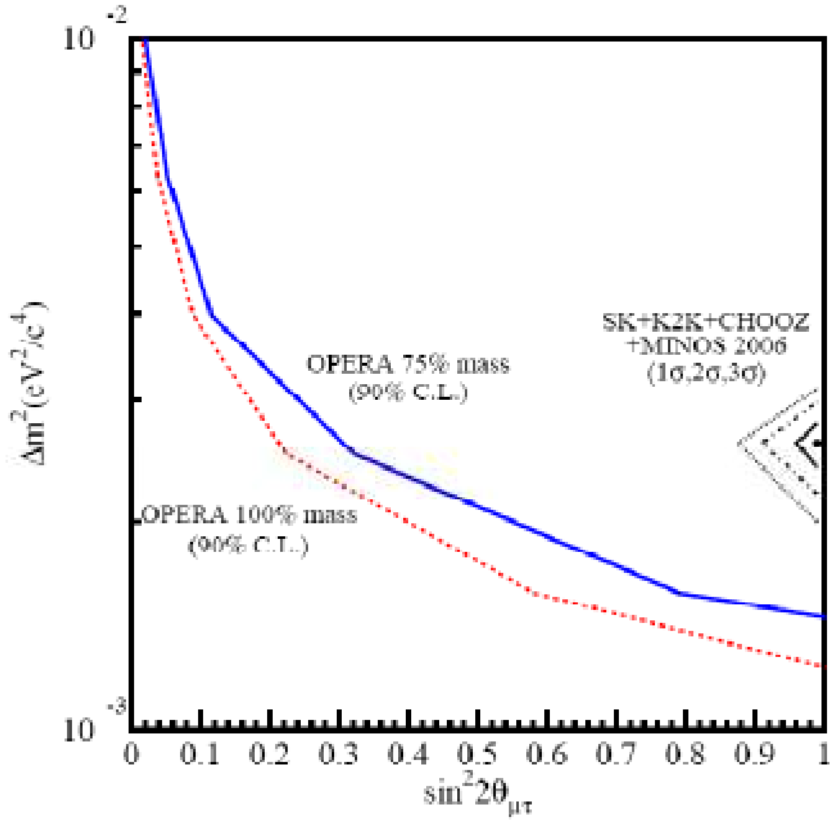
$\nu_\mu \leftrightarrow \nu_\tau$ discovery potential

Discovery probability vs Δm^2

90% CL exclusion plot

5 year of data taking



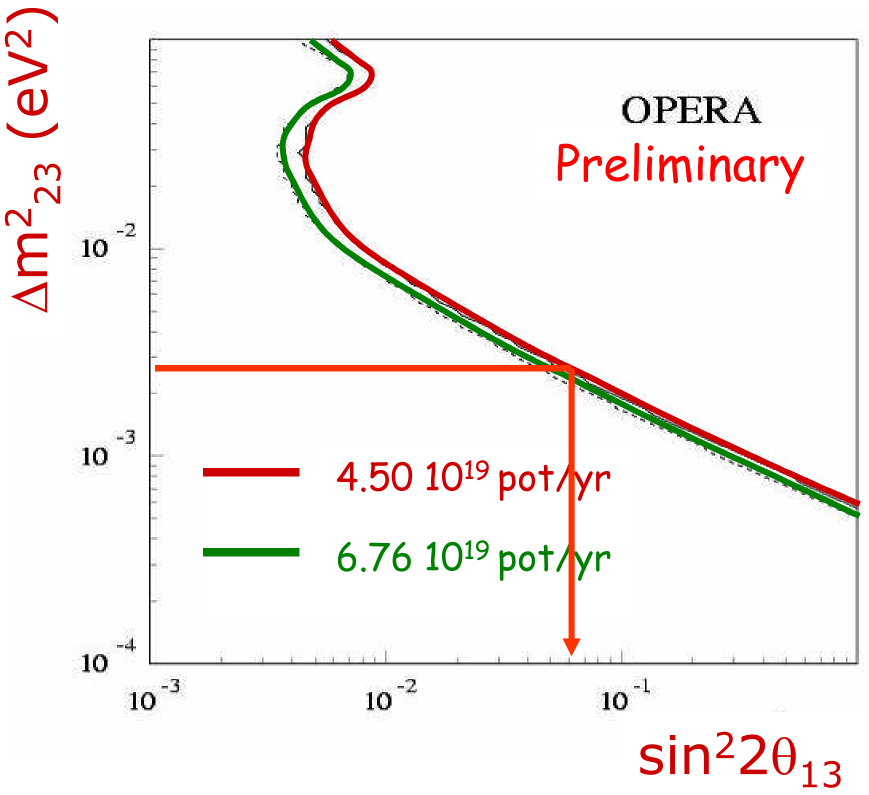


$\nu_\mu \to \nu_e$ expected signal and background 5 years: 2.25x10^{20} pot

θ_{13} (deg)	$\sin^2 2\theta_{13}$	$\nu_\mu \to \nu_e$ signal	$\nu_\mu \to \nu_\tau$, $\tau \to e\nu_\tau\nu_e$	ν_μ CC	ν_μ NC	ν_e CC beam
9	0.095	9.3	4.5	1.0	5.2	18
7	0.058	5.8	4.6	1.0	5.2	18
5	0.030	3.0	4.6	1.0	5.2	18

OPERA sensitivity to θ_{13}

syst. on the ν_e contamination up to 5%



Limits at 90% CL for
$\Delta m^2 = 2.5\times10^{-3}$ eV^2, full mixing

	$\sin^2 2\theta_{13}$	θ_{13}
CHOOZ	**<0.14**	**11^0**
OPERA	**<0.06**	**7.1^0**

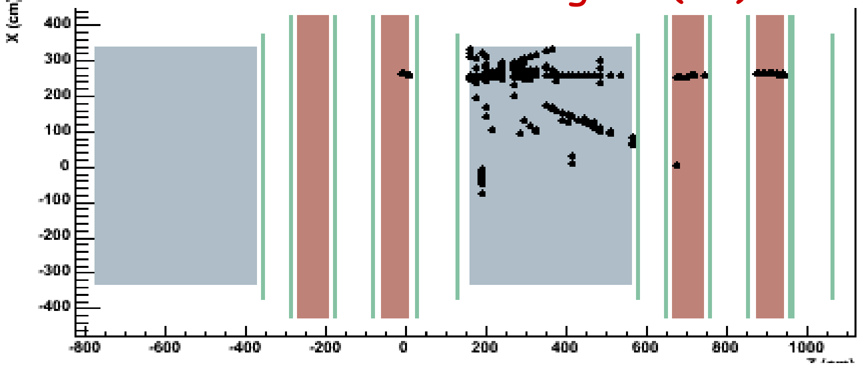
[Komatsu et al. J. Phys. G29 (2003) 443]

First run with CNGS neutrinos (without bricks)

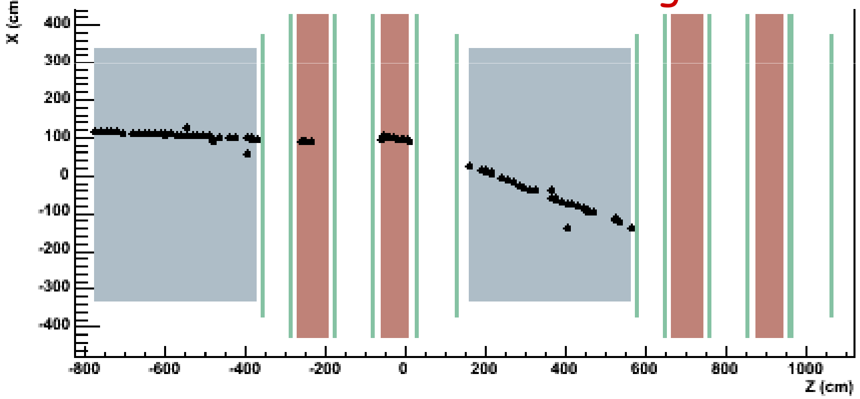
[New J. Phys. 8 (2006) 303]

→ August 2006: **7.6×10^{17} integrated pot**

ν interaction in magnet (Fe)

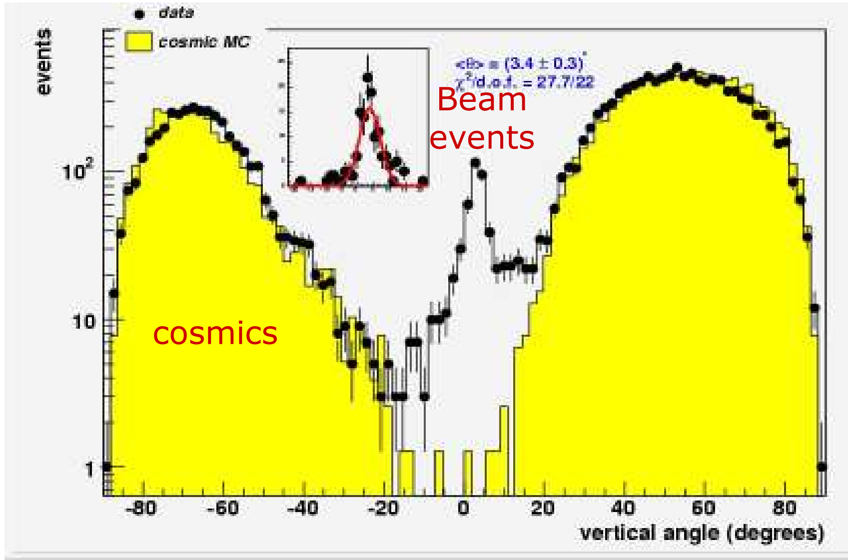


ν interaction in surrounding rock

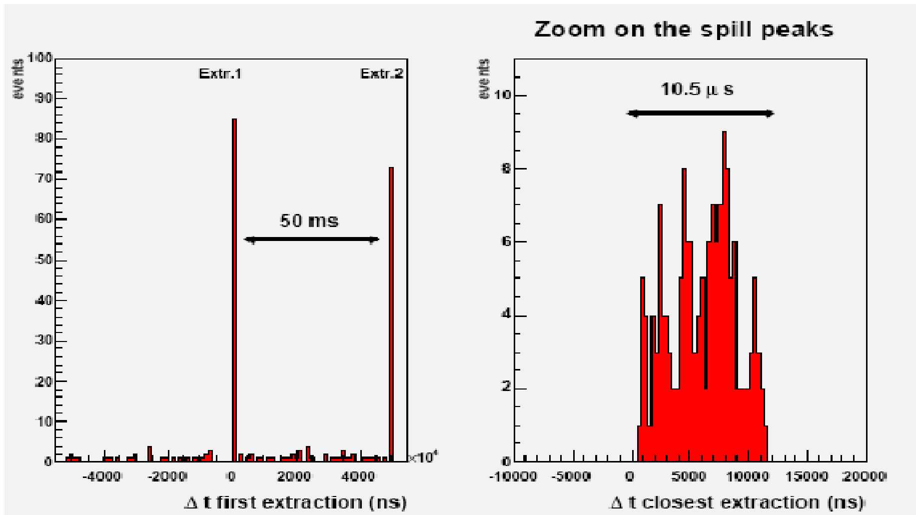


- event selection by using GPS timing information
- practically no background $O(10^{-4})$

⇒ ***319 registered events*** correlated in time with beam : interactions inside the rock and inside the detector (TT and spectrometers)

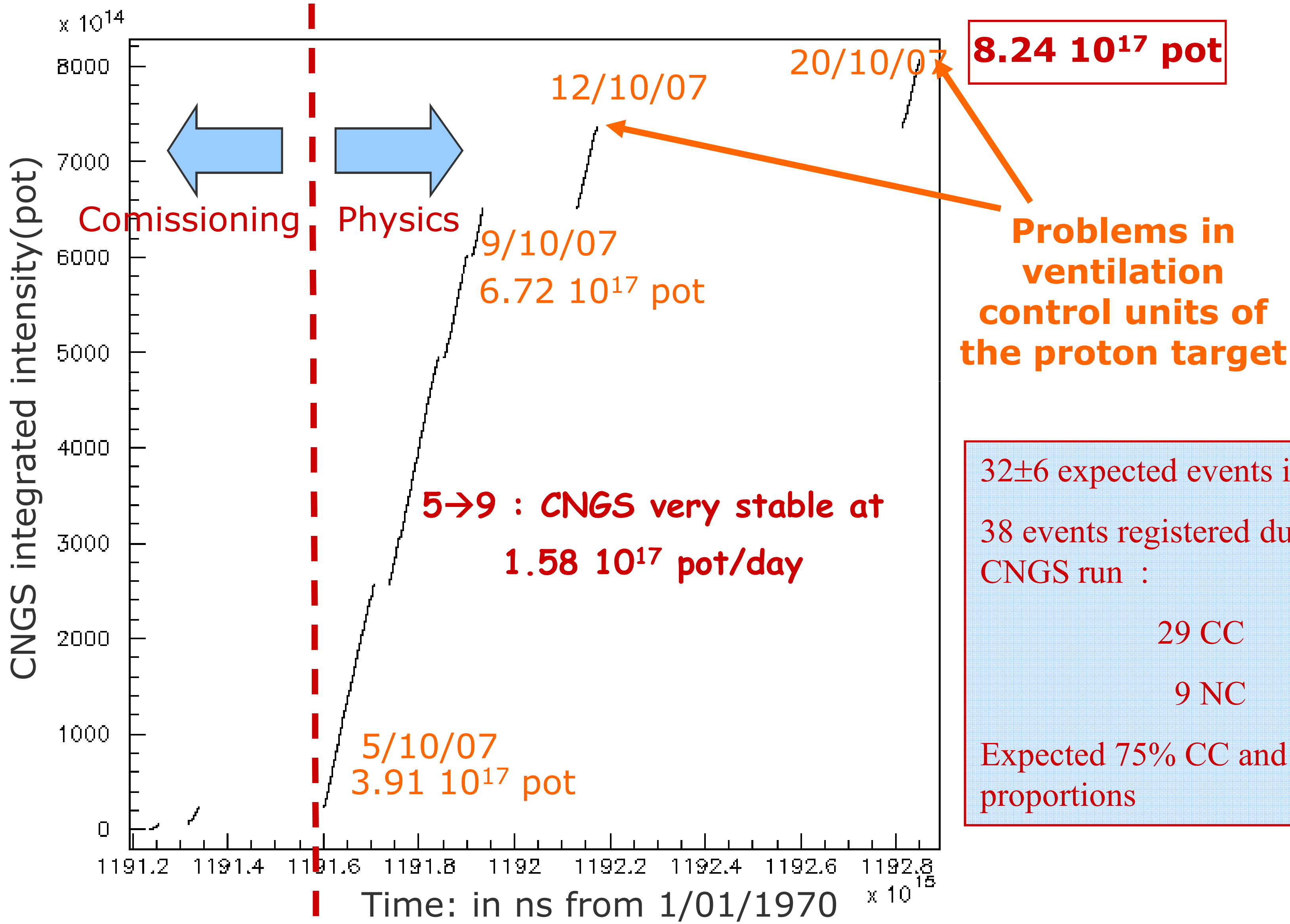


Proton extractions from SPS with 3 cycles of 6s each
2 extractions of 10.5 ms, separated by 50 ms



First CNGS run with lead-emulsion target (80% SM1 filled = 0.5 kton)

→ Sept-Oct 2007: **8.24x10^{17} integrated pot**



32±6 expected events in bricks

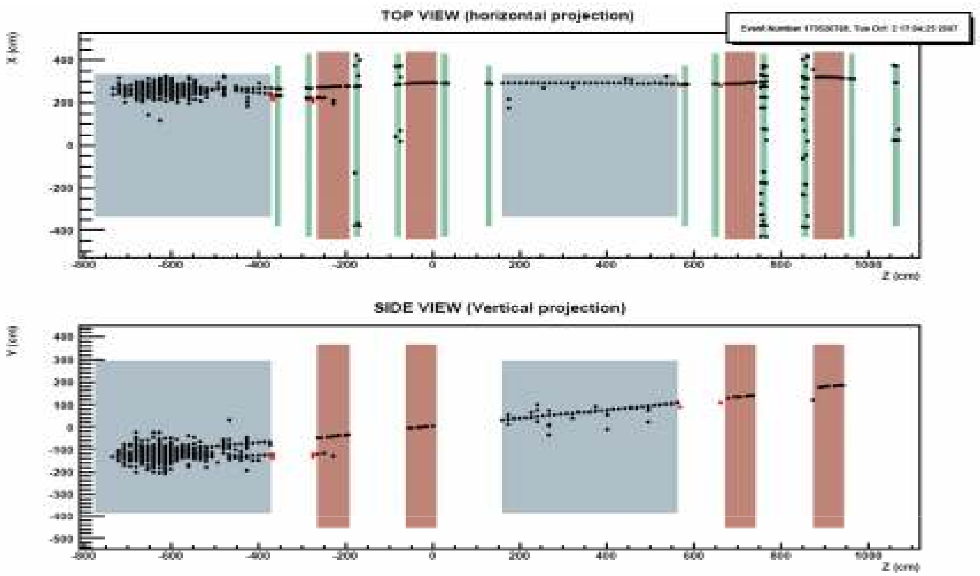
38 events registered during the 2007 CNGS run :

29 CC

9 NC

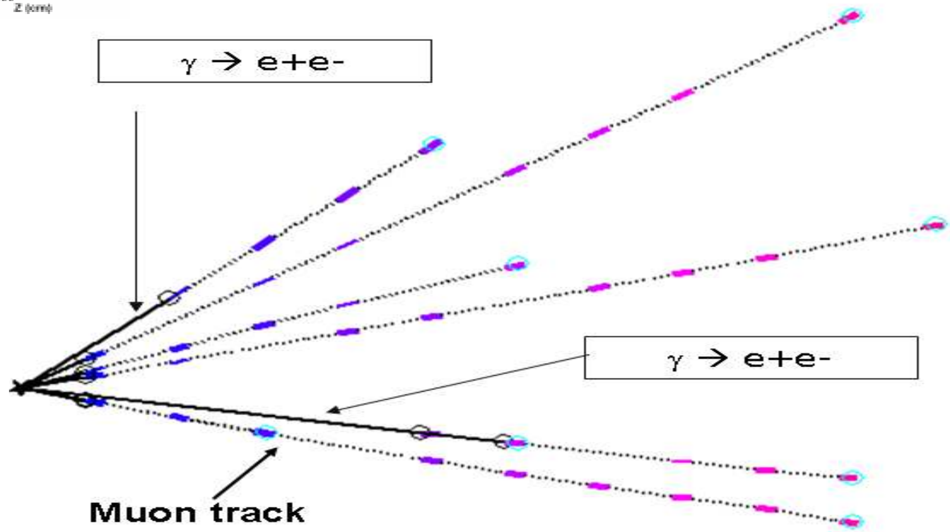
Expected 75% CC and 25%NC proportions

Neutrino events in OPERA – Event gallery …

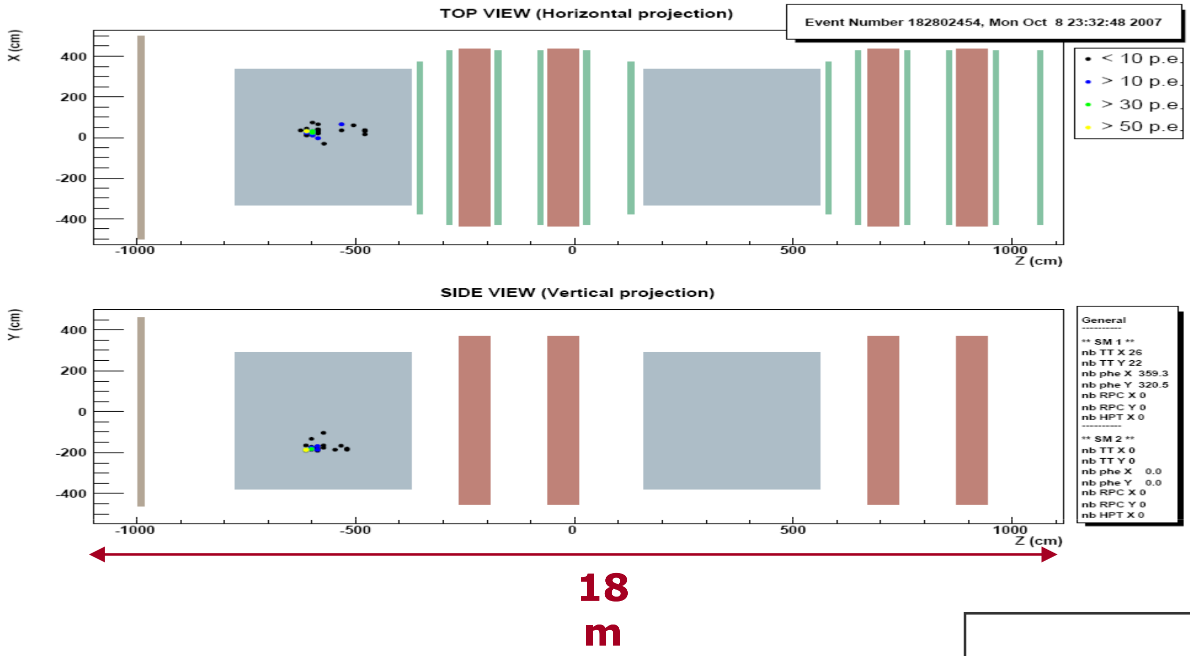


The first event recorded in the OPERA target (2007 - tue Oct 2, 17:04)

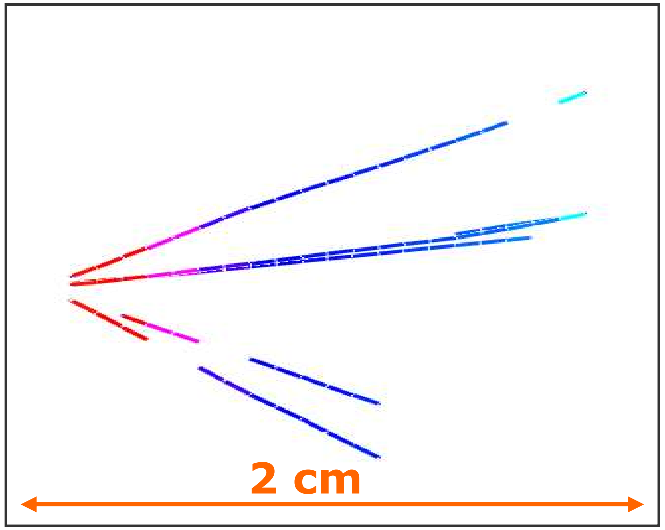
compatible $\pi 0 \rightarrow 2\gamma$:
$\pi 0$ mass: 110 ± 30 MeV



Neutrino events in OPERA – Event gallery …

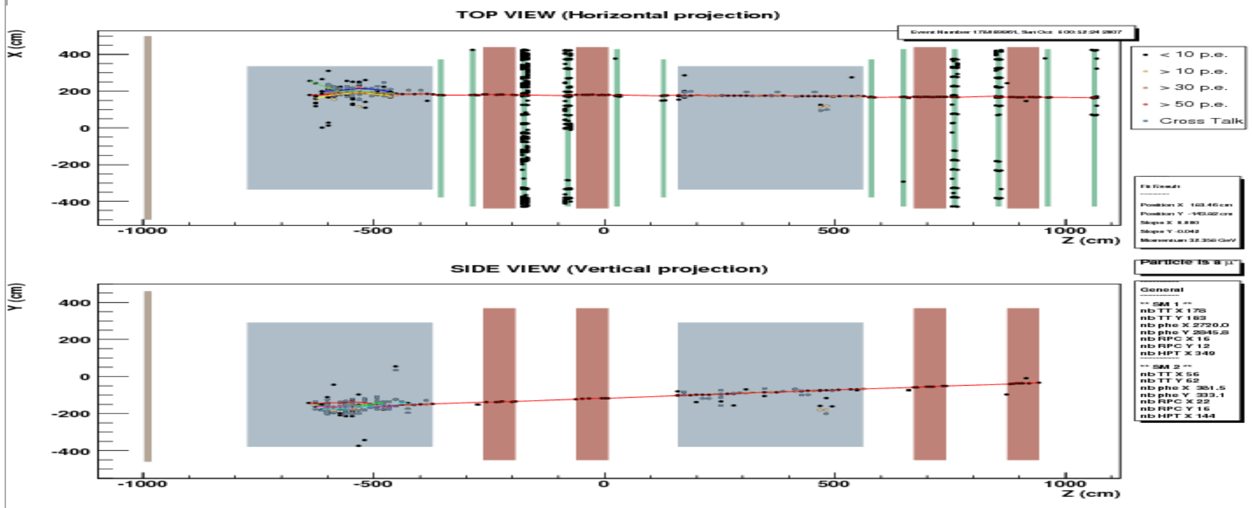


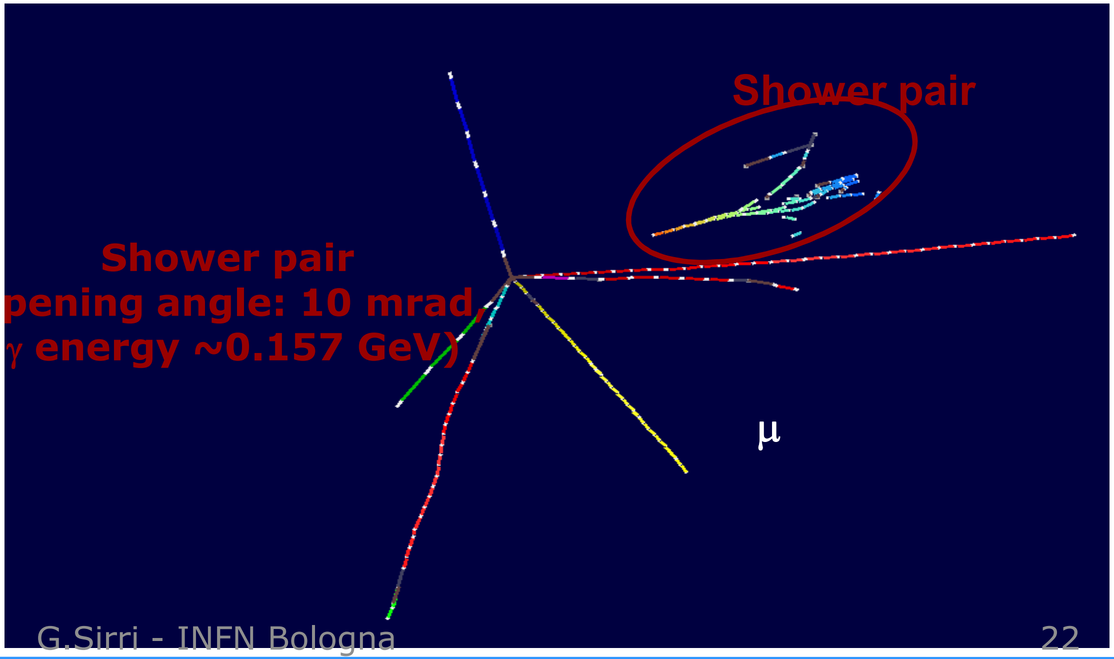
NC event



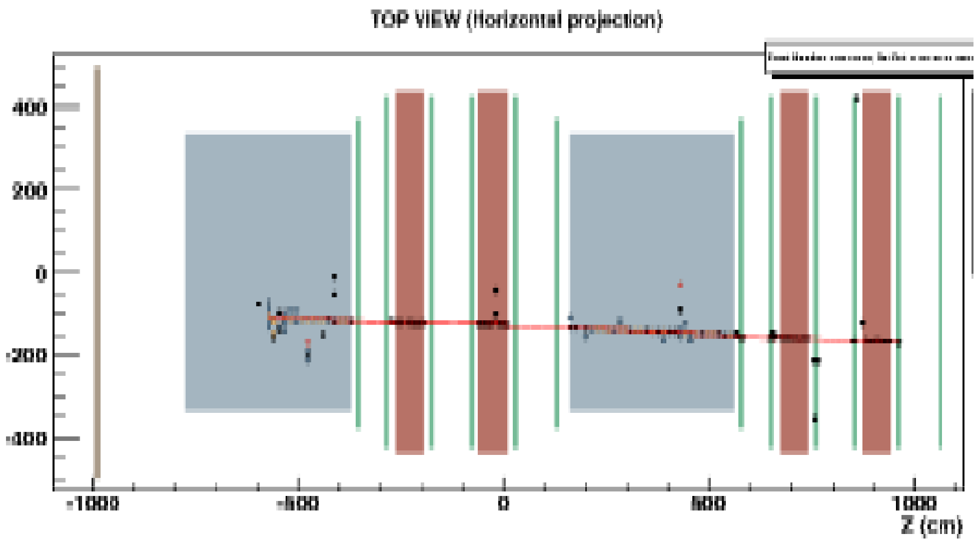
These are the "tough" events due to the lack of a clear vertex pointing high energy track ! ~> larger area to be scanned in Changeable Sheets

Neutrino events in OPERA – Event gallery …

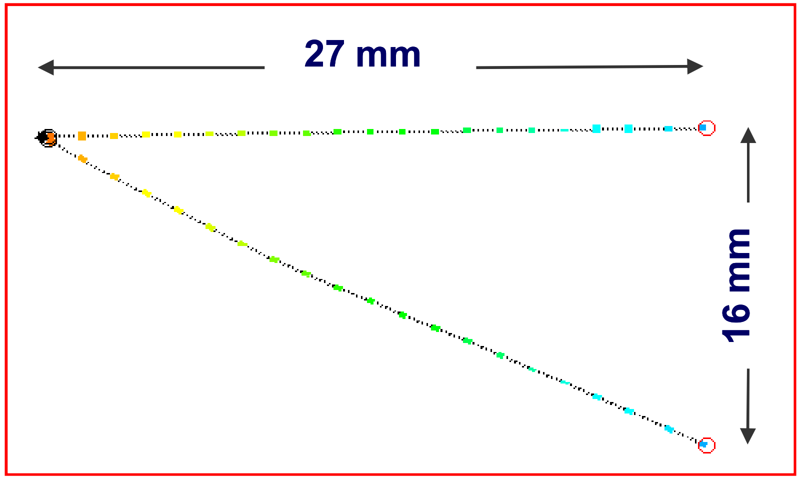


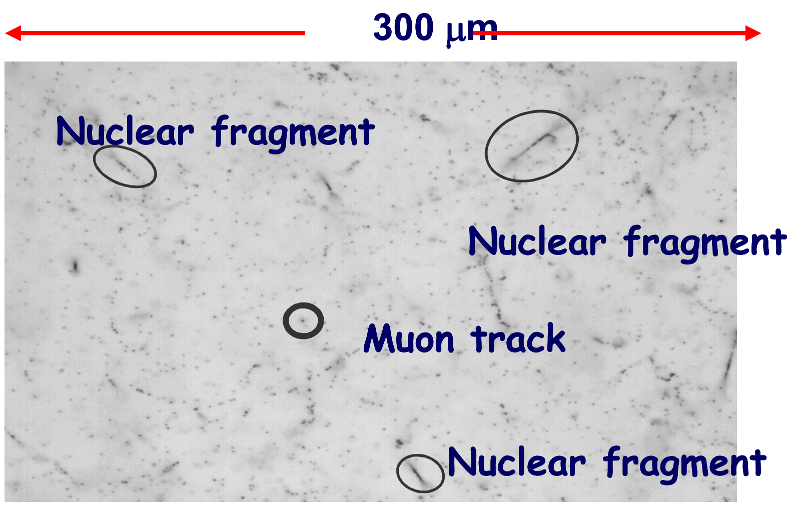


Neutrino events in OPERA – Event gallery …



Event 179673325 QE-like topology

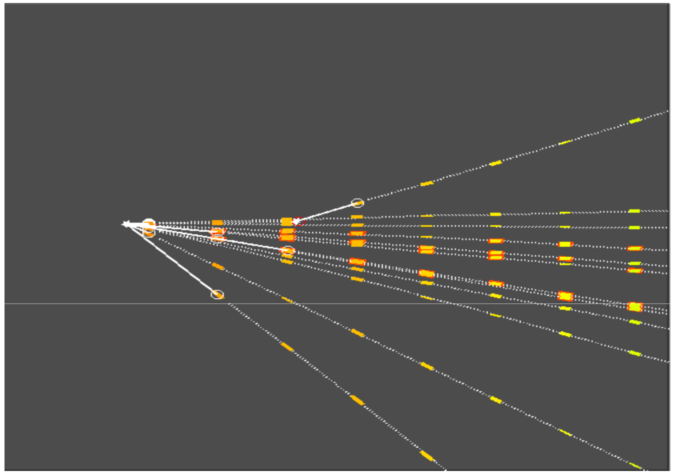


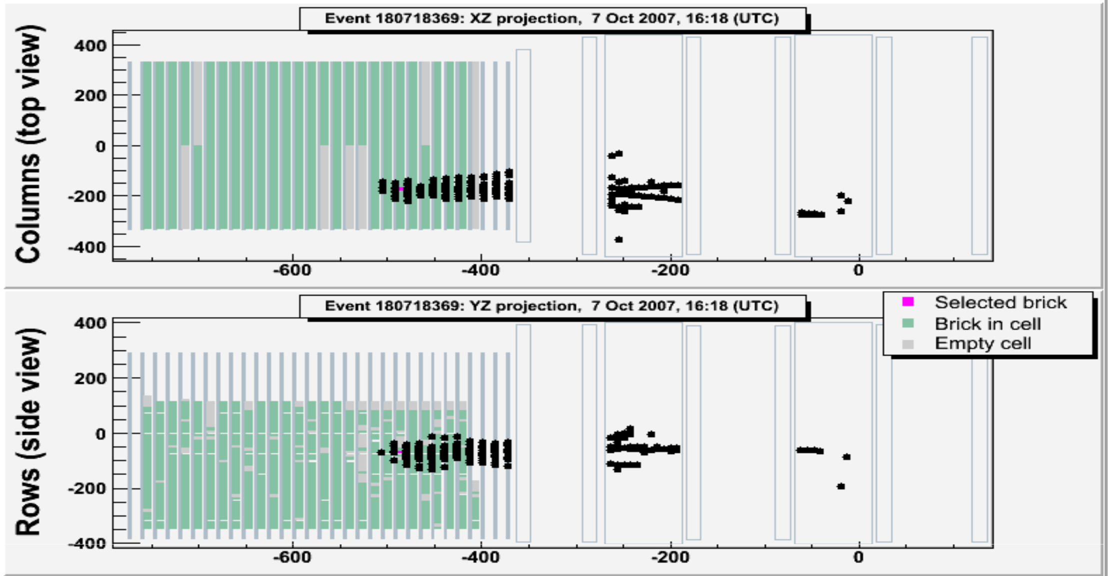


The visual inspection allows the observation of nuclear fragments and the classification of the event as DIS

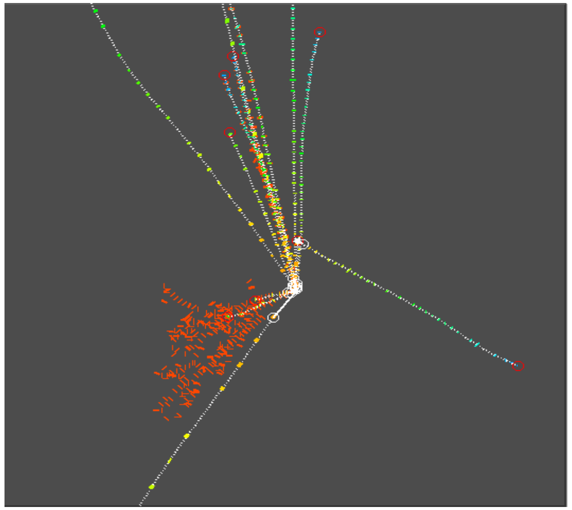
Neutrino events in OPERA – Event gallery …

…a charm candidate!





Flight lenght: 3247.2 μm
θ_{kink}: 0.204 rad
$P_{daughter}$: 3.9 (+1.7 -0.9) GeV
P_T: 796 MeV (> 606 MeV)



Two e. m. showers pointing to vertex

2008 CNGS Run

2008 CNGS run from June to November (mass 1.26 kton, 95%)

- Start: June 18th
- High intensity beam since June 20th (2×10^{13} pot/extraction)
- Statistics until Sunday, August 24th
  - total number of pot accumulated : **4.5×10^{18} pot**
  - ~ 400 candidate interactions in the OPERA bricks
- brick extraction, emulsion development, event location are following on

Statistics expected this year :

- ~ **2×10^{19} pot** in 123 days of SPS running
- ~ 2200 interactions over the 2008 run

→ expected the observation of the 1st ν_t event

Conclusions

The OPERA experiment is running

- Electronic detectors fully commissioned
- Target filling at 97% (will be completed in September)
- **Scanning labs are ready (~40 microscopes available)**

The OPERA 2007 run allowed to test the full operation chain:

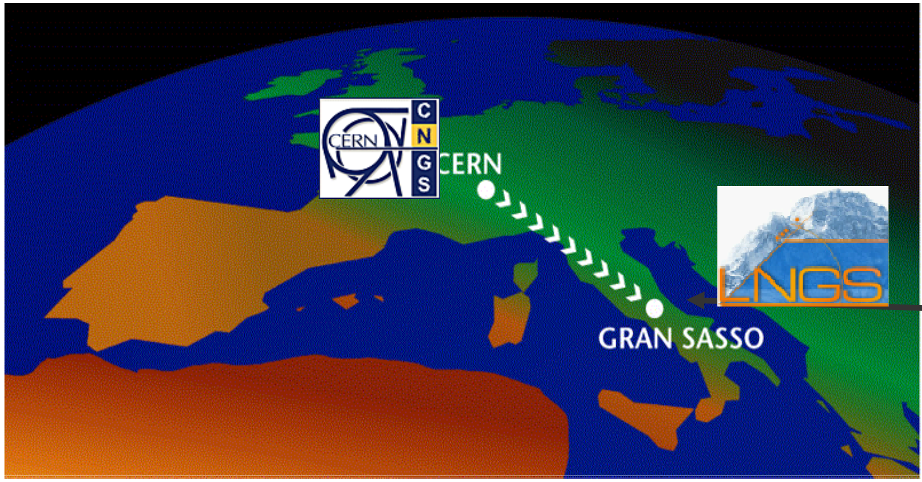
- Test electronic detectors and data acquisition
- Test the brick finding algorithm
- Test of brick handling
- Test CS doublet scanning
- Test the target tracker to brick matching and scanning strategy

The concept of the OPERA detector has been experimentally validated by measuring neutrino events in the detector

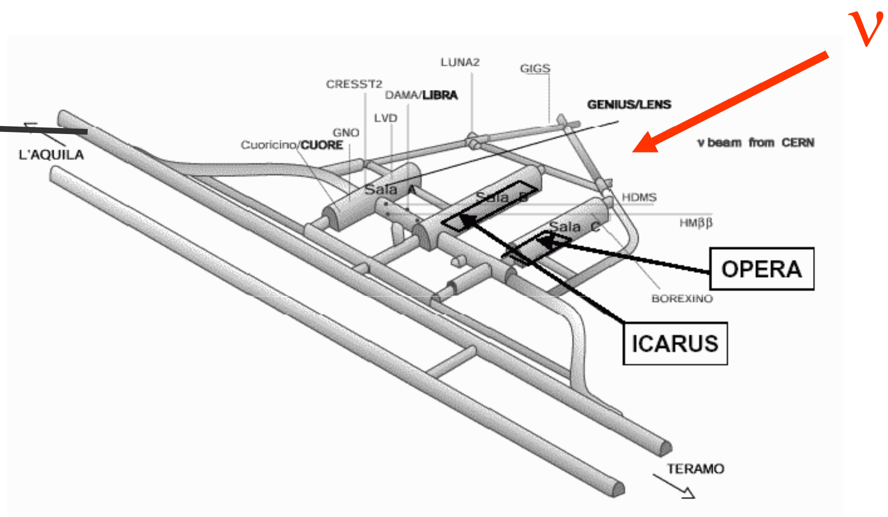
The first high luminosity OPERA run is running these days. With some luck we will measure the first ν_τ candidate event by the end of this year!

END

The experimental site



The Gran Sasso Laboratory (Central Italy, 900 m a.s.l.)



Underground Lab:

1400 m of rock shielding: Cosmic Ray flux reduced by a factor 10^6 wrt surface; very reduced environmental radioactivity.

Next step: 2008 CNGS neutrino run from June to November

✓Expect about **2.28×10^{19} pot** in 123 days of SPS running assuming a nominal intensity of 2×10^{13} pot/extraction

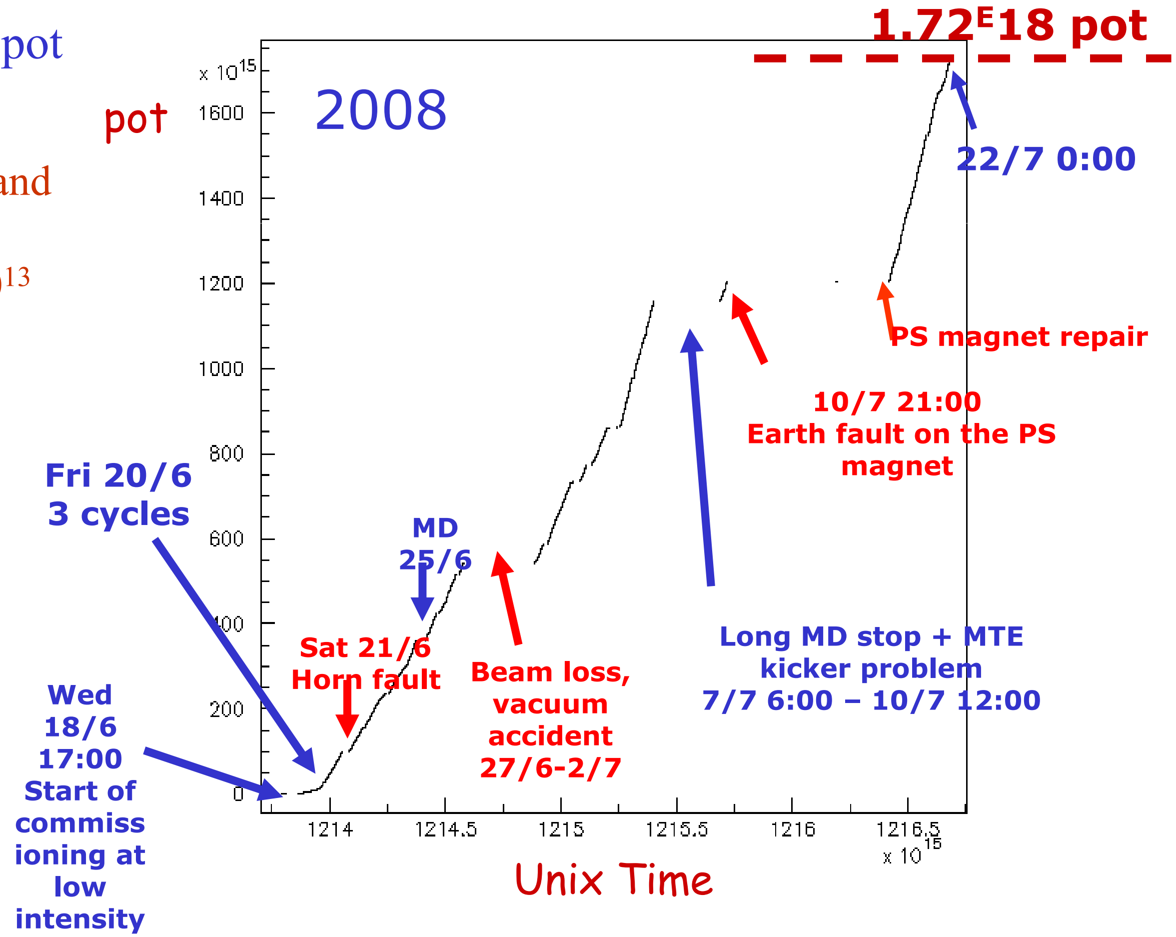
✓ ~20 neutrino interactions / day → observation of the 1st τ event …

CNGS actual performances:

✓Started since June 20th : 160 events already in OPERA target and 834 events in surrounding material

✓ Integrated intensity of 1.72×10^{18} pot

- ε=50% including accidents and small beam interruptions
- Achieved intensity = 1.6×10^{13} pot/extraction

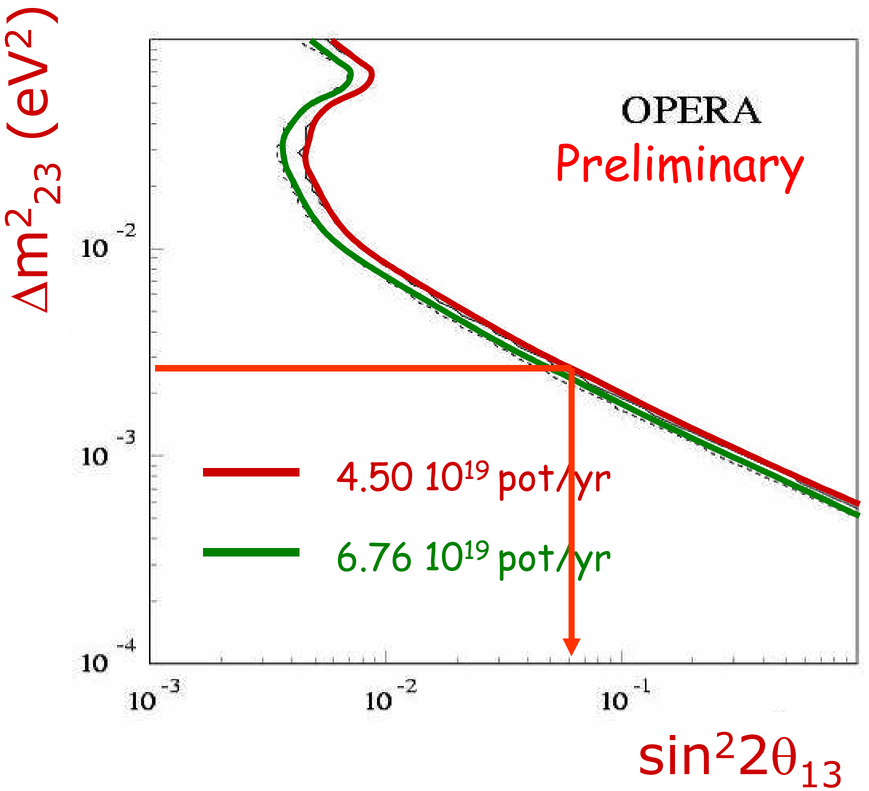


$\nu_\mu \to \nu_e$ expected signal and background 5 years: 2.25×10^{20} pot

θ_{13} (deg)	$\sin^2 2\theta_{13}$	$\nu_\mu \to \nu_e$ Signal	$\nu_\mu \to \nu_\tau$, $\tau \to e\nu_\tau\nu_e$	ν_μ CC	ν_μ NC	ν_e CC
9	0.095	9.3	4.5	1.0	5.2	18
7	0.058	5.8	4.6	1.0	5.2	18
5	0.030	3.0	4.6	1.0	5.2	18

OPERA sensitivity to θ_{13}

syst. on the ν_e contamination up to 5%

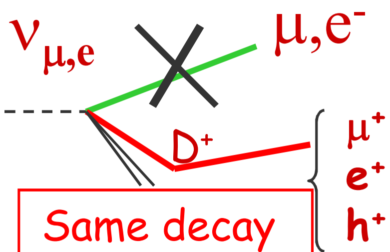


Limits at 90% CL for
$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2, full mixing

	$\sin^2 2\theta_{13}$	θ_{13}
CHOOZ	**<0.14**	**11^0**
OPERA	**<0.06**	**7.1^0**

[Komatsu et al. J. Phys. G29 (2003) 443]

τ search : Backgrounds

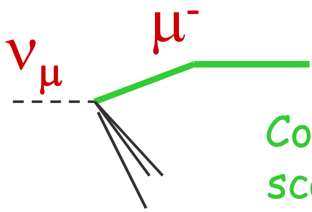


Primary lepton
not identified

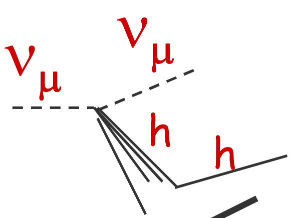
Same decay
topology as τ

Charm production in CC,
common to the 3 channels

Good muon identification
is fundamental



Coulombian large angle
scattering of muons in
Lead : Bck. to $\tau \to \mu$



**Hadronic interactions
in Pb: Bck. to $\tau \to$ h
or to $\tau \to \mu$
(if hadron mis-
identified as muon)**

Expected number of
background events
after 5 years running
with nominal beam:

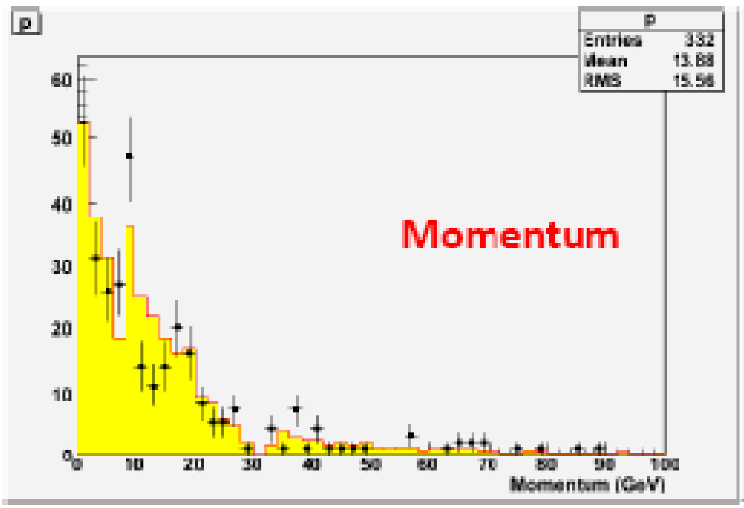
	$\tau \to e$	$\tau \to \mu$	$\tau \to h$	$\tau \to 3h$	Total
Charm background	.173	.008	.134	.181	.496
Large angle μ scattering		.096			.096
Hadronic background		.077	.095	.	.172
Total per channel	.173	.181	.229	.181	.764

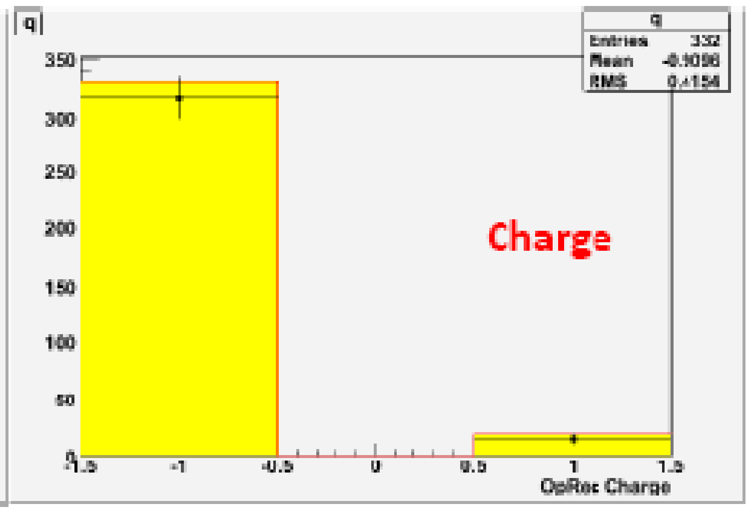
CNGS DATA/MC comparison

- 2007 Data = 8.24 x 10^{17} pot
- MC not corrected for detector and DAQ lifetime estimated to be 95%

	Data	MC	
		Oscil. spect + rock muon reweight	Non oscil. + no rock muon reweight
1 Hit	464	660,7	634,5
Trigger	435	503,1	497,3
OpRec	332	349.9	354,2

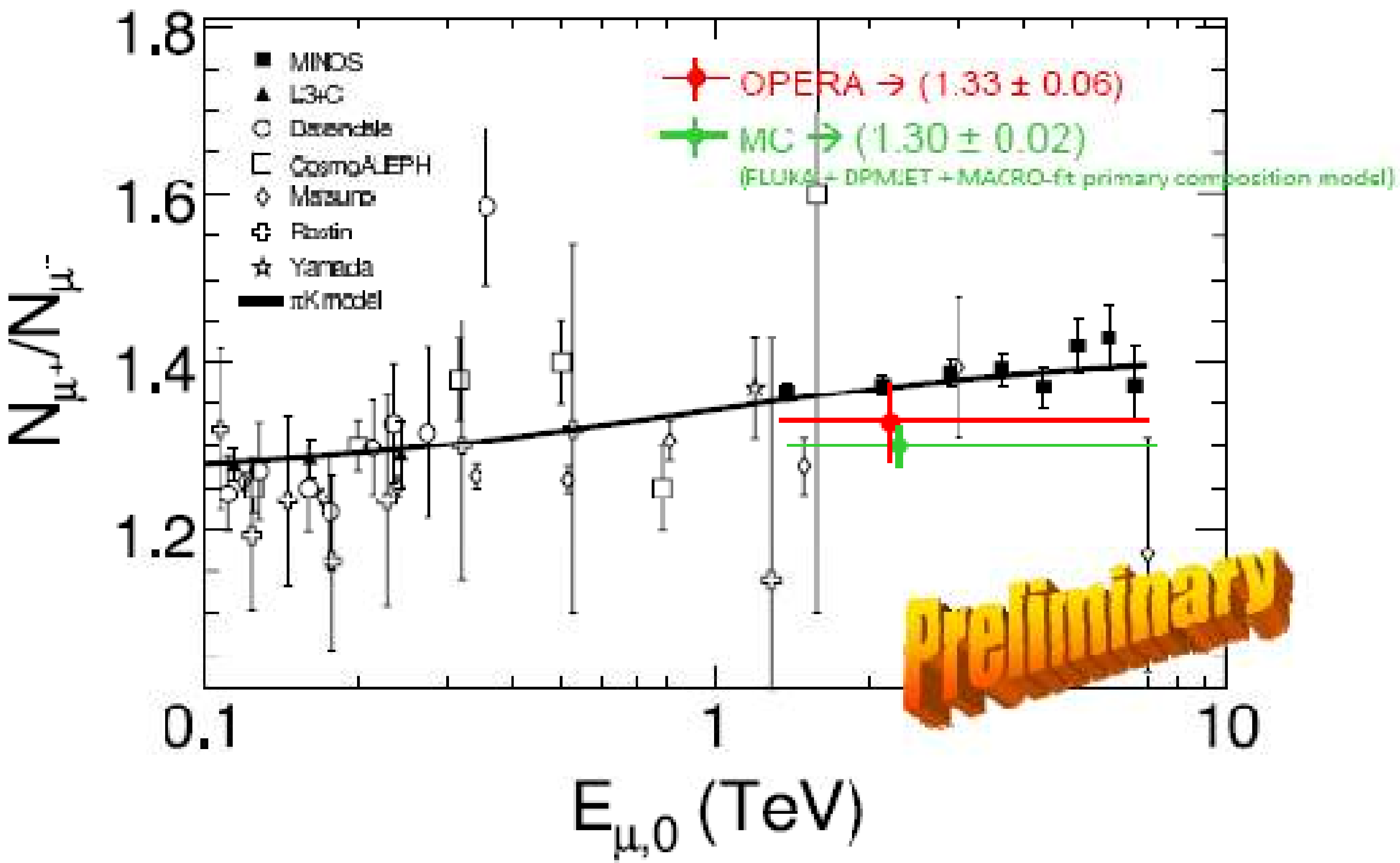
- Base line MC: Oscillated spectrum + "rock events" re-weighted





Atmospheric muon charge ratio

- Points are median values, intervals contain 90% of the distributions
- 17.2 days of effective live-time
- Data contain events with all multiplicities
- Possibility to select high multiplicity events → higher primary energies (work in progress)

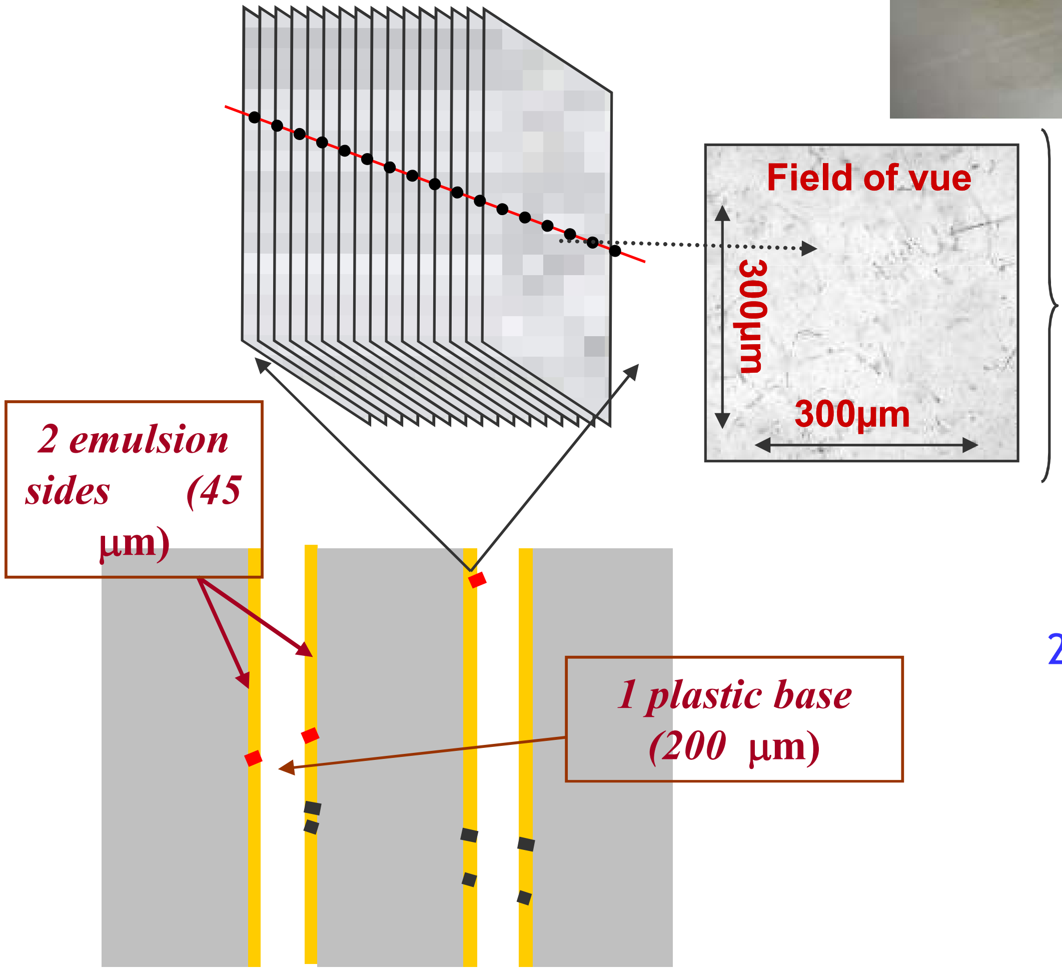


Scanning :

emulsion digitisation

Reconstruction of micro-tracks (45μm)

10 scanning laboratories in Europe and Japan: different technology



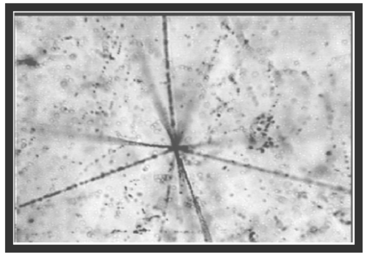
16 tomographic images = 45μm

2D images processing

3D reconstruction of particle tracks

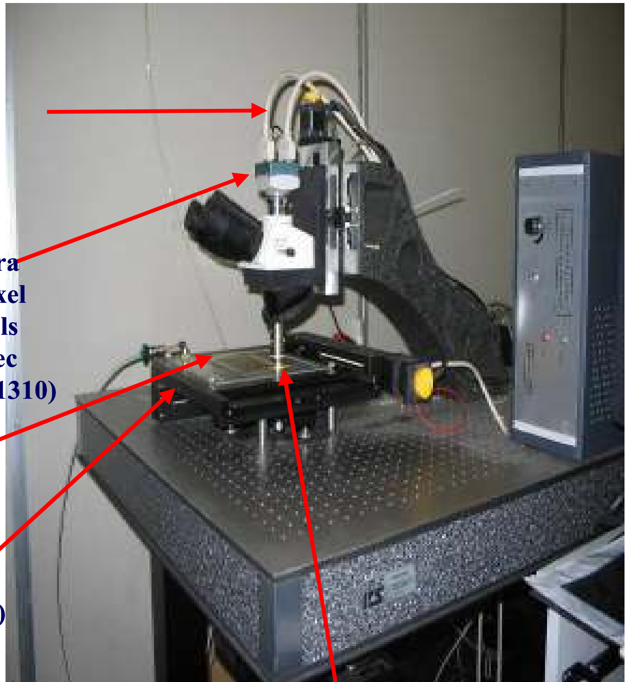
20÷50 cm^2/h/side on 43μm emulsion layers
0.3÷0.7 μm precision
90%÷95% track finding efficiency
10÷10^4 fake tracks / cm^2 (slope < 0.5)

Emulsion scanning in OPERA



State-of-art automated microscopes
fast bi-dimensional image analysis
real-time high precision 3D tracking

The European Scanning System



Z stage (Micos)
0.05 µm nominal
precision

CMOS camera
1280×1024 pixel
256 gray levels
376 frames/sec
(Mikrotron MC1310)

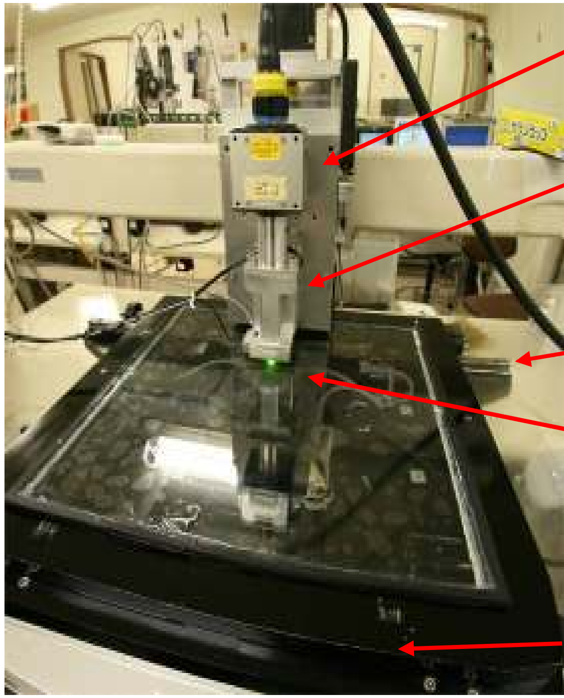
Emulsion Plate

XY stage (Micos)
0.1 µm nominal
precision

Illumination system, objective
(Oil 50× NA 0.85)
and optical tube (Nikon)

- Scanning speed: 20 cm^2/h/side
  (40 GB/day/microscope of raw data)
- Purity: 10 fake tracks / cm^2 (slope < 0.5)
- Efficiency: up to 95% using tracks,
  ~100% using microtracks
- 0.3÷0.7 µm precision for recons. tracks

- Scanning speed: 50 cm^2/h/side average
  (72 cm^2/h/side peak)
  custom parallel processing (FPGAs)
- Purity: 10 fake tracks / cm^2 (slope < 0.4)
- Efficiency: 95% using tracks



Custom CMOS camera
512×512 pixel
3000 frames/sec

Piezoelectric fine drive
for Z motion of lens

X axis is driven
with continuous motion

Oil objective 35× NA 0.85

Mechanics based on Nikon
microscope stages
X/Y/Z nominal
precision = 0.1mm

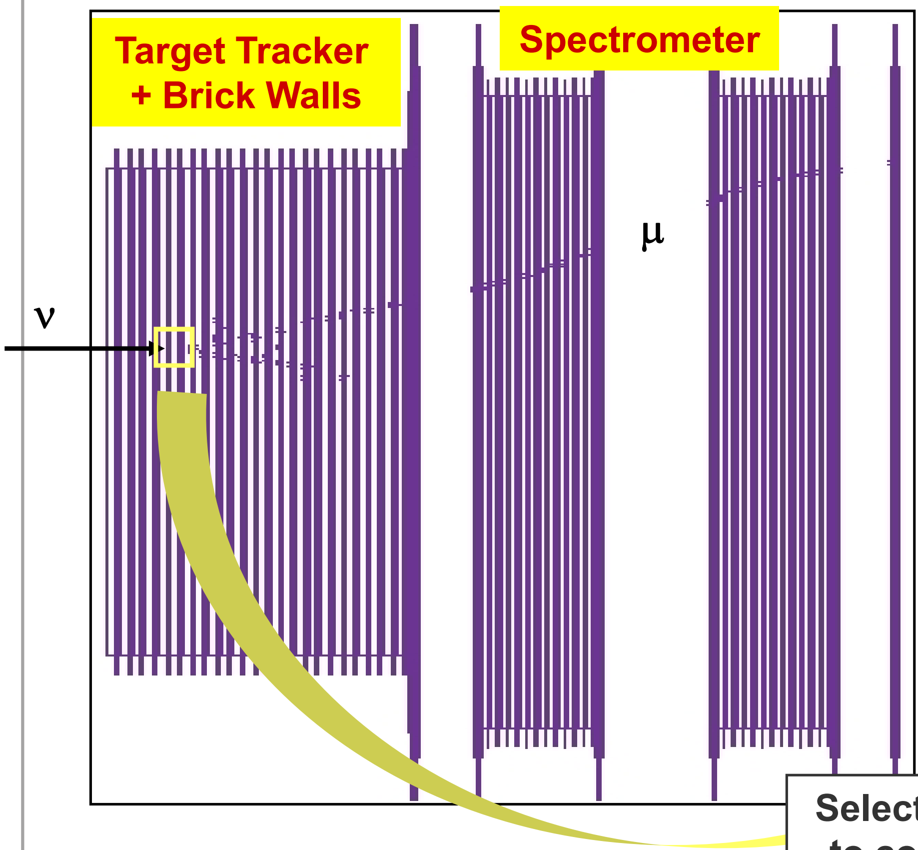
The S-UTS (Japan)

OPERA an hybrid detector

What the nuclear emulsion cannot do:

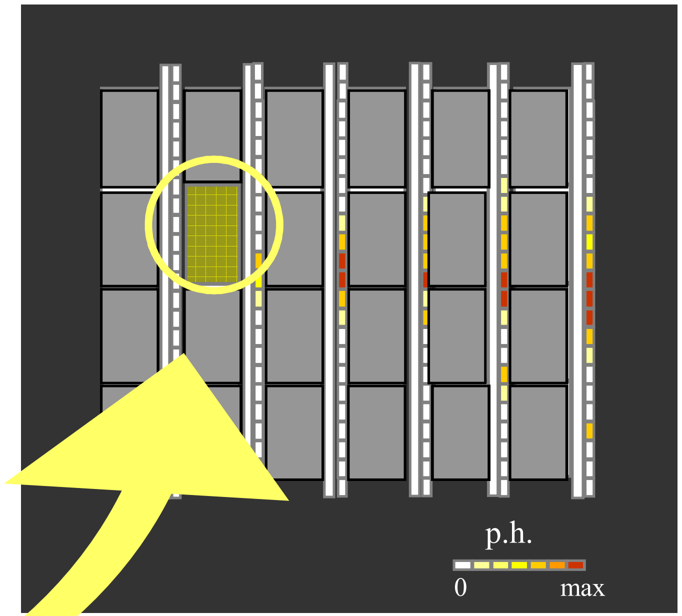
- trigger for a neutrino interaction
- approximate location of the interaction vertex
- muon identification and momentum/charge measurement

➔ **need a hybrid detector**



On-line analysis of electronic data

Brick finding algorithm

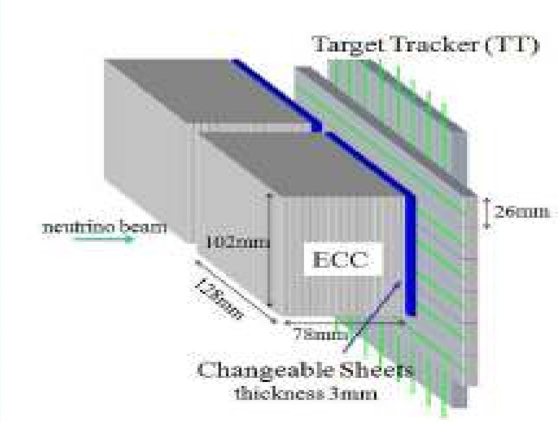


Selected brick is removed from the target and exposed to cosmic rays (alignment). Emulsions are developed and sent to scanning stations / labs

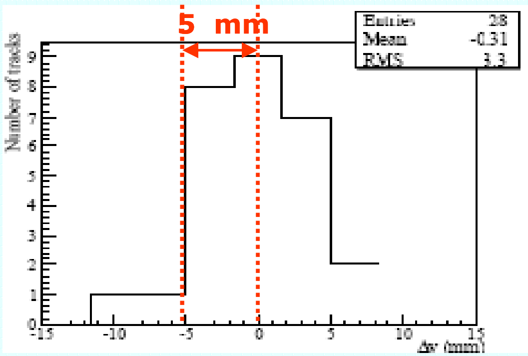
At work with passing-through μ (2007) - *Intercalibration* issues

JINST3 (2008) P07005, arXiv:0804.1985

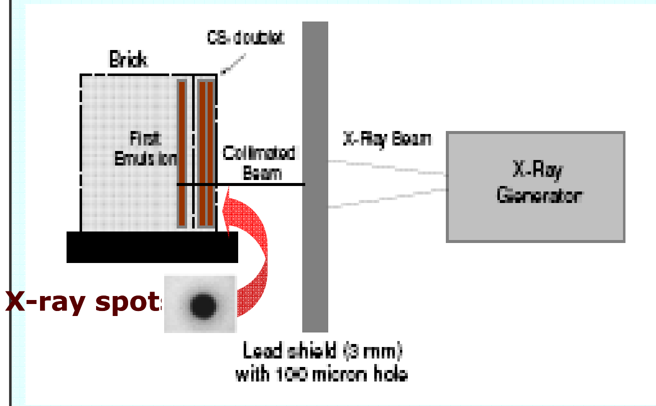
(I) - From TT to CS



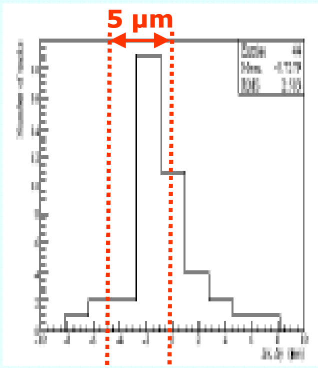
Triggered "horizontal" CR μ's:
ε ≅ 93 %, slope difference ≅ 15 mrad



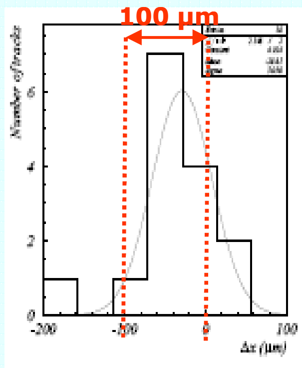
(II) - From CS to brick



Two methods for in-doublet film-to-film:
X-ray spots, Compton's maps

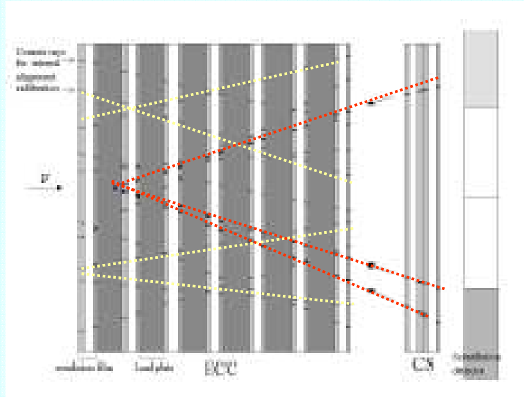


Inside CS film-to-film



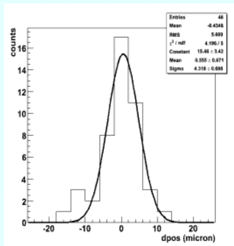
CS to last film in ECC brick

(III) - In brick, film-to-film

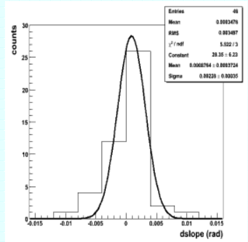


CS decoupled underground, ECC brick exposed to CR at surface, before unpiling:

scan-back tracks
penetrating CR



Position: σ= 4 μm



Slope: σ= 2 mrad