First Events from the CNGS Neutrino Beam Detected in the OPERA Experiment

Maria Teresa Muciaccia
Università degli Studi & INFN
Bari

Summary

- Aim and strategy of the experiment
- OPERA detector
- Nuclear emulsion analysis
- CNGS run results
- Conclusion

The Oscillation Project with Emulsion tRacking Apparatus

OPERA

Long baseline experiment searching for the ν_τ *appearance* in a pure ν_μ beam

CNGS beam, <E> = 17 GeV, L = 732 km

Hybrid set-up (nuclear emulsions + electronic detectors)

Detection of ν_τ CC interactions and *direct* observation of τ decays

⇓

Provide an unambiguous evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the parameter region indicated by the atmospheric neutrino data

Neutrino oscillations in the atmospheric sector state-of-the-art

SK I + II

$1.9 \times 10^{-3}\ eV^2 < \Delta m^2 < 3.1 \times 10^{-3}\ eV^2$
$\sin^2 2\vartheta > 0.93$ (90% C.L.)
best fit:
$\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$, $\sin^2 2\vartheta = 1$

SK oscillation signal confirmed by:

MINOS

$2.48 \times 10^{-3}\ eV^2 < \Delta m^2 < 3.18 \times 10^{-3}\ eV^2$
$\sin^2 2\vartheta > 0.87$ (90% C.L.)
best fit:
$\Delta m^2 = 2.74 \times 10^{-3}\ eV^2$, $\sin^2 2\vartheta > 0.87$

K2K

$1.9 \times 10^{-3}\ eV^2 < \Delta m^2 < 3.5 \times 10^{-3}\ eV^2$
$\sin^2 2\vartheta = 1$ (90% C.L.)
best fit:
$\Delta m^2 = 2.8 \times 10^{-3}\ eV^2$, $\sin^2 2\vartheta = 1$

All the experiments indicate $\nu_\mu \rightarrow \nu_\tau$ dominant
oscillation mode….

but still missing:

<u>direct</u> observation of

oscillated ν_τ

Experimental signature of the ν_τ appearance

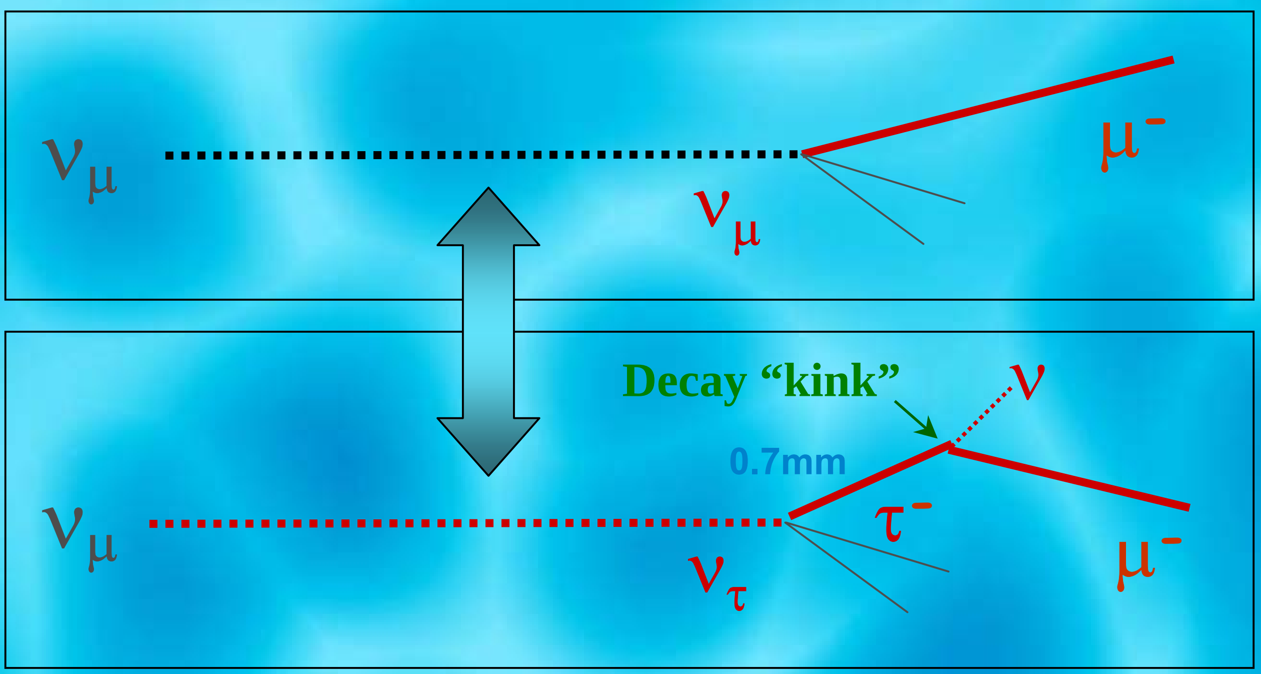
CC interaction

$\nu_\mu \sim \nu_\tau \rightarrow \tau^- + X$

oscillation

$\mu^- \nu_\tau \bar{\nu}_\mu$	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%

The challenge is to distinguish ν_τ interactions from ν_μ interactions



Topology selection:

⇓

kink signature

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

τ decay channel	Signal		Background
	$\Delta m^2 = 2.4 \times 10^{-3}$ eV^2	$\Delta m^2 = 3.0 \times 10^{-3}$ eV^2	
$\tau \to \mu$	3.6	5.6	0.23
$\tau \to e$	4.3	6.7	0.23
$\tau \to h$	3.8	5.9	0.32
$\tau \to 3h$	1.1	1.7	0.22
ALL	12.8	19.9	1.0

full mixing, 5 year run @ 4.5×10^{19} pot/year

Main background sources:
- charm production and decays
- hadron re-interactions in lead
- large-angle muon scattering in lead

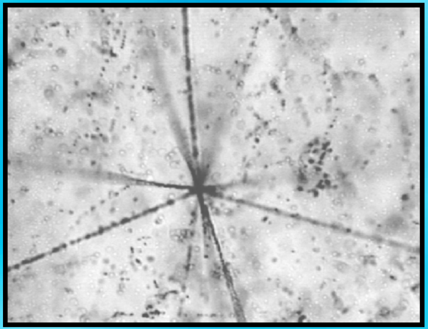
Detection of the ν_τ

Two conflicting requirements:

large mass → low cross-section

high granularity { signal selection, background rejection }

lead–nuclear emulsion target segmented into basic units called *bricks*



Nuclear emulsions

- **3D particle reconstruction**
- **Sub-micron spatial resolution**
- **High granularity (~300*hits*/mm)**

Target: 1800 tons, 5 year running

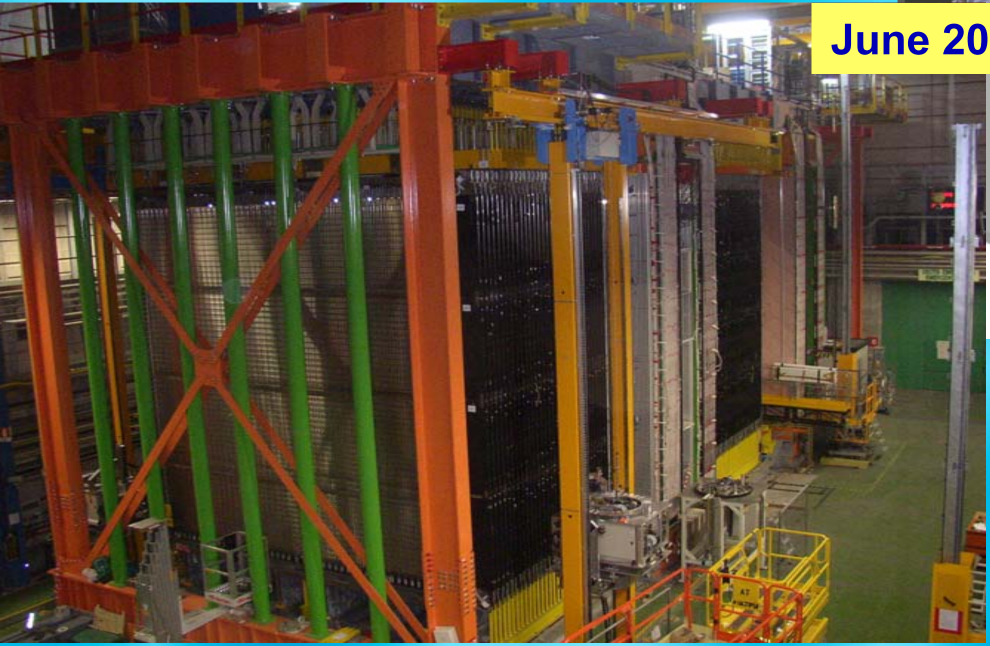
- **30,000 neutrino interactions**
- **~150 ν_τ interactions**
- **~15 ν_τ identified**
- **<1 event of background**

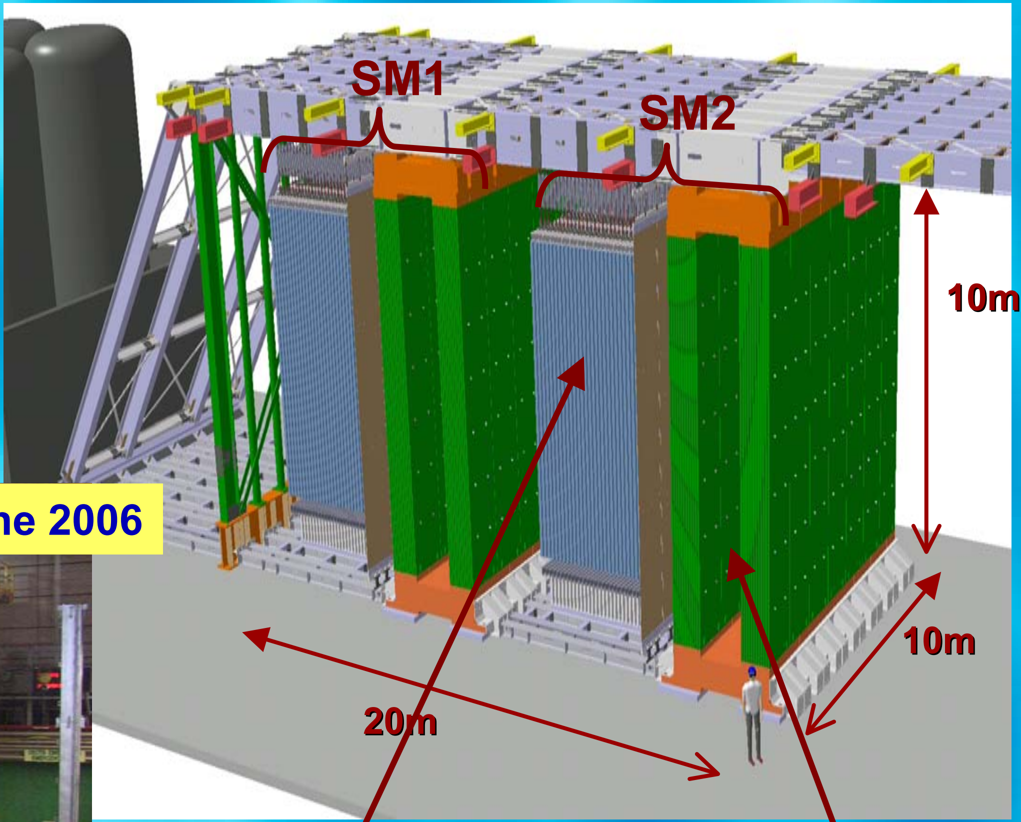
What the brick cannot do:

- **signal a neutrino interaction**
- **identify muons**

Structure of the OPERA Detector

Installation started in
May 2003
First observation of CNGS
beam neutrinos:
August 18th, 2006





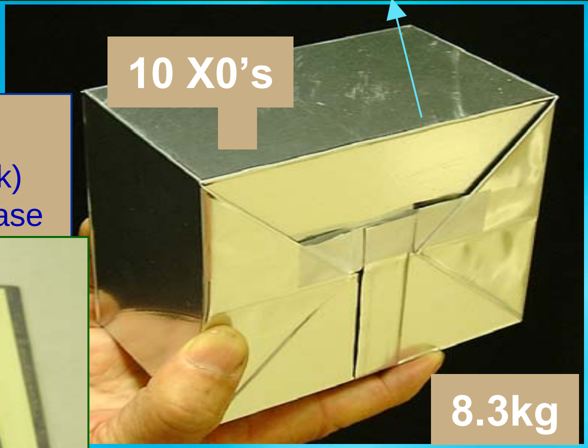
Target
31 lead/emulsion brick walls, alternated to scintillator planes, T T , to select the brick containing neutrino interaction

Muon Spectrometer
Magnet equipped with RPC,HPT planes: ID muons , charge and momentum measurement

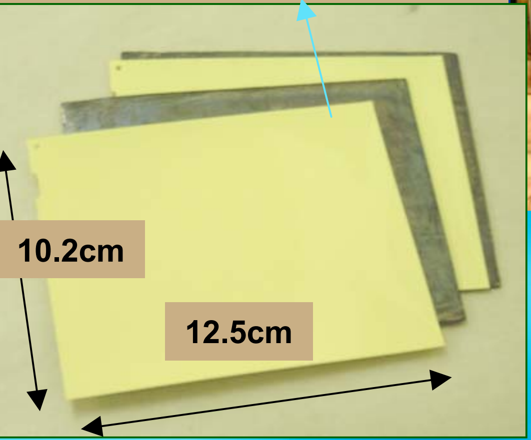
Brick Target

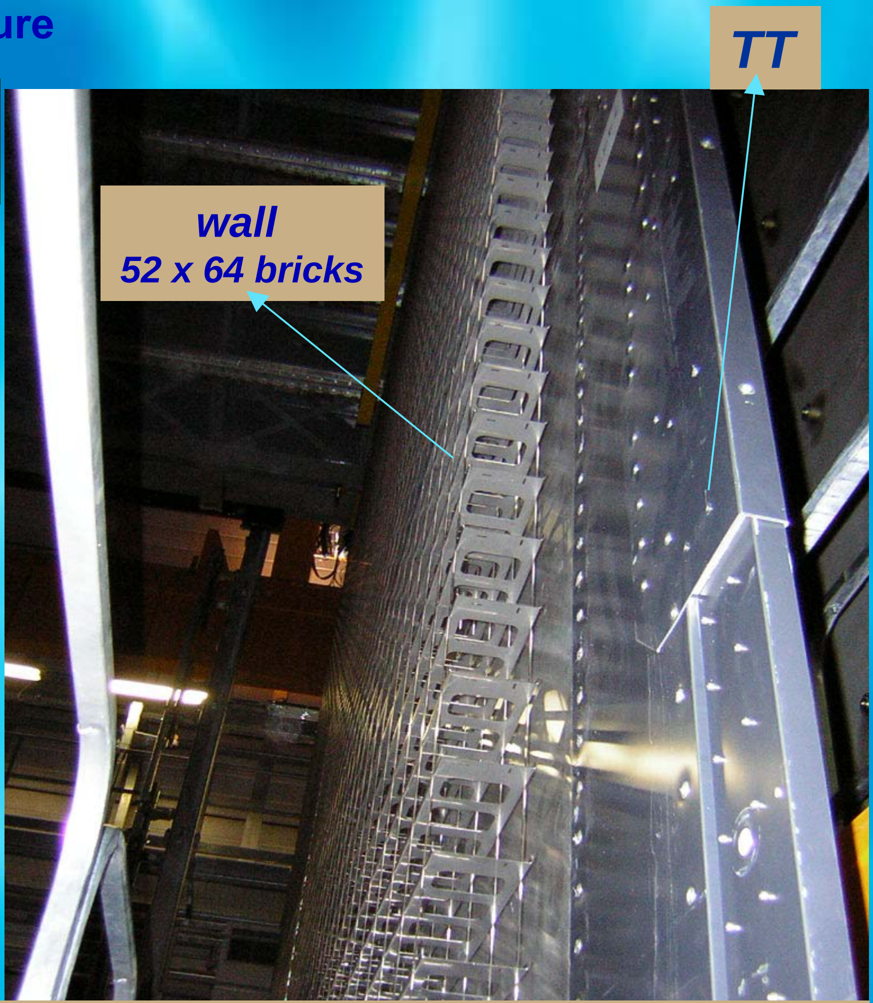
- Micro-metric space resolution (emulsion) + target mass (lead)
- Compact and modular structure

***Brick* (basic unit)**
56 Pb plates + 57 emulsion films



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





CS doublet (connection T T- brick)
two double refreshed emulsion films,vacuum packed and glued onto the bottom of each brick

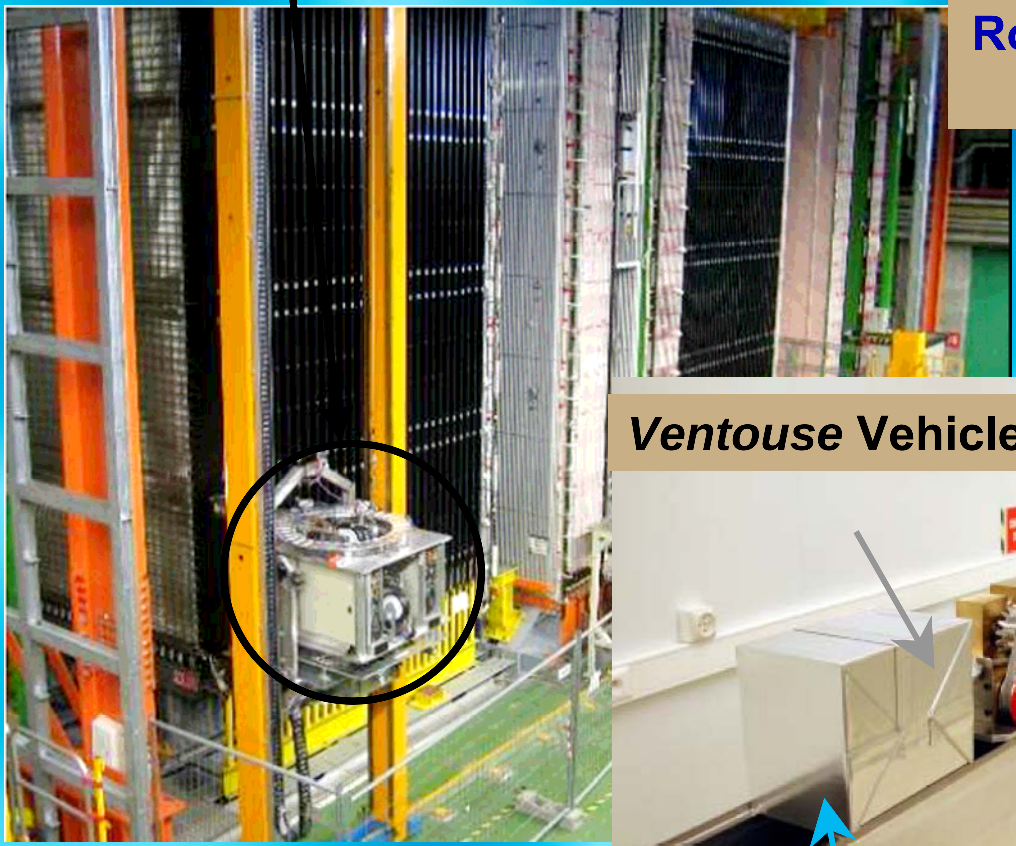
Total target mass : ~ 1800 t
(~200000 bricks, 12M emulsions and Pb plates)

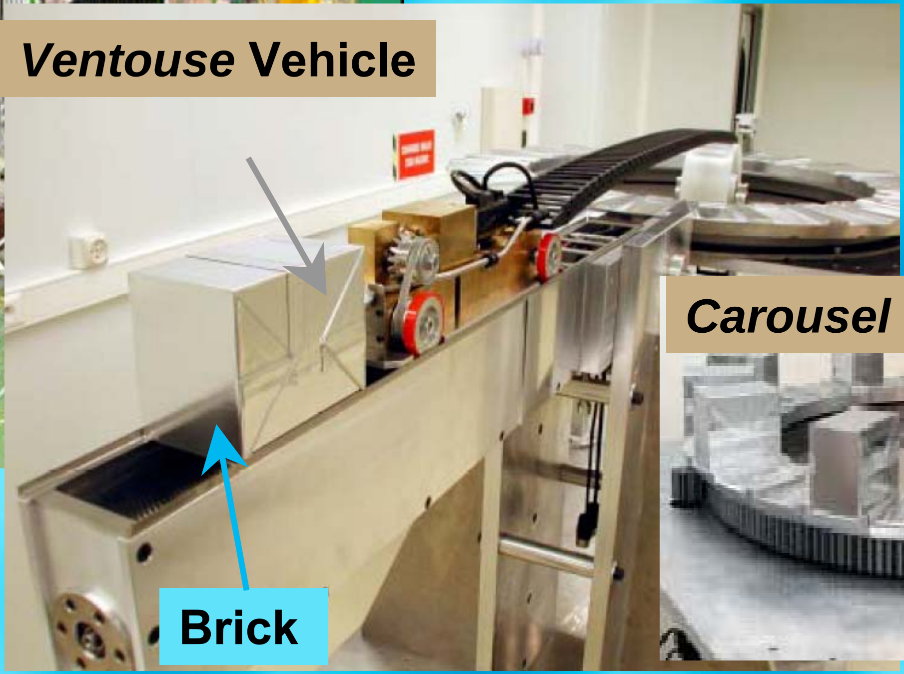
Brick Assembly Machine

Robots will pile up bricks
at a rate of ~ 800 bricks/day

Brick Manipulator System

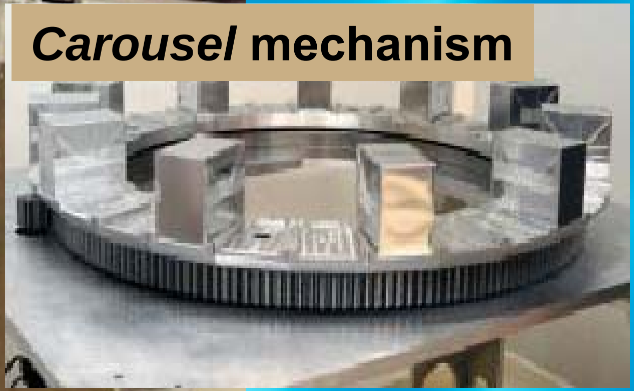
Robot for brick insertion (target filling) and removal (during run)





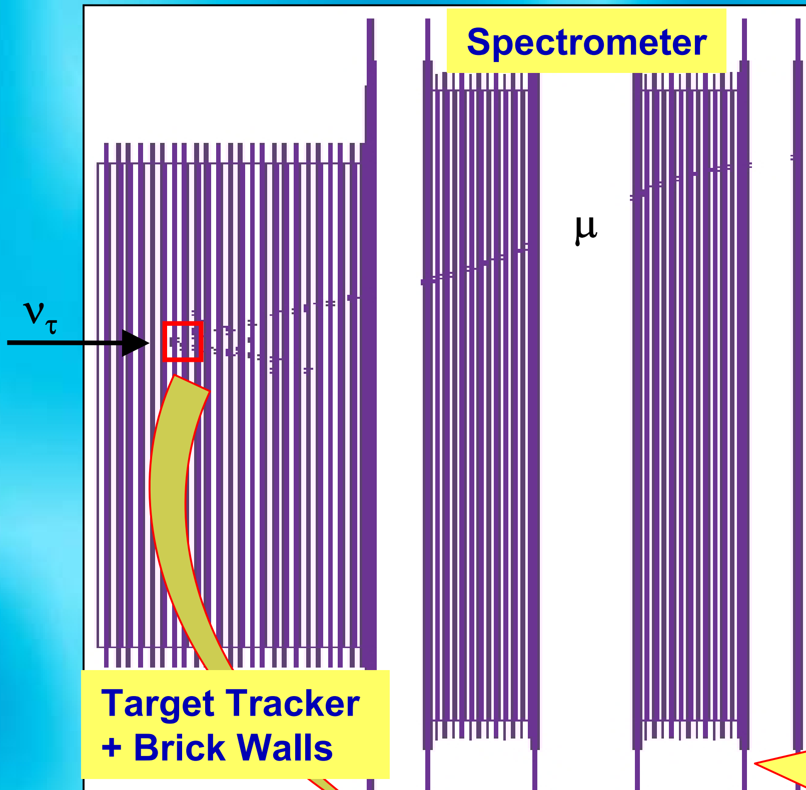
***Ventouse* Vehicle**

Brick



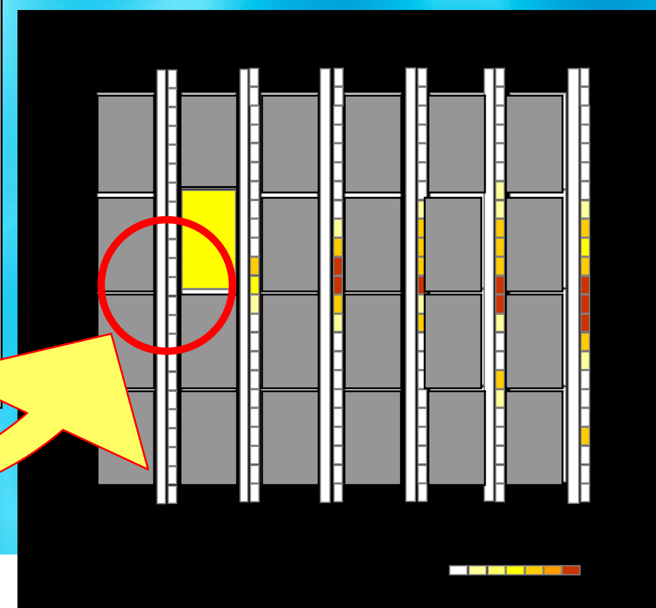
***Carousel* mechanism**

OPERA running



On-line analysis of electronic data

Brick finding algorithm



The selected brick is removed from the target and, after CS measurement, exposed to cosmic rays (alignment). Emulsions are developed and sent to scanning stations/labs

Event location
Decay search
Particle ID and kinematics
Event classification

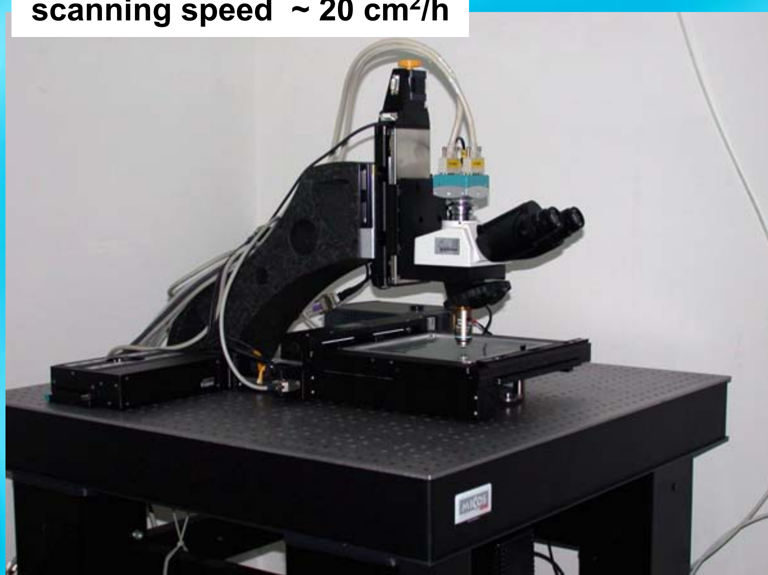
Automated microscopes for nuclear emulsions

~ 30 bricks will be daily extracted from target and analyzed using high-speed automatic systems

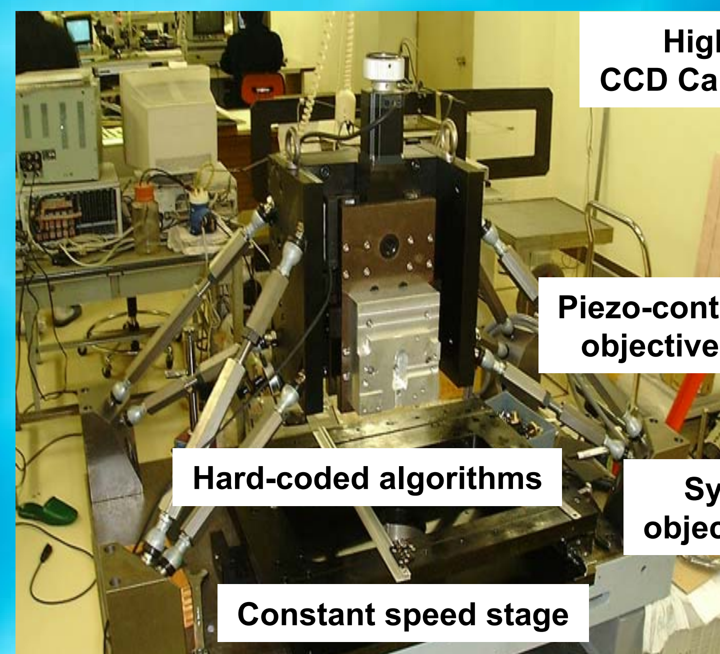
European Scanning System

S-UTS (Japan)

scanning speed ~ 20 cm^2/h



Customized commercial optics and mechanics + asynchronous DAQ software



High speed CCD Camera (3 kHz)

Piezo-controlled objective lens

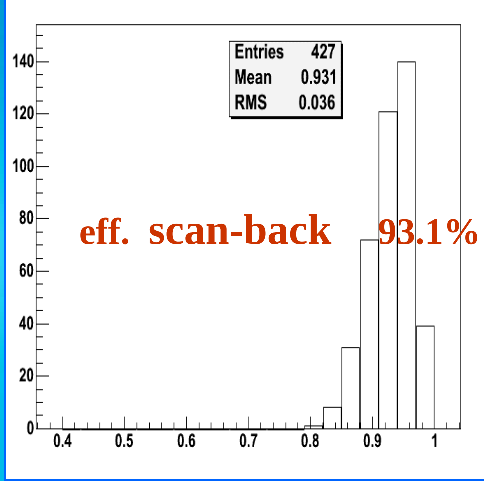
Hard-coded algorithms

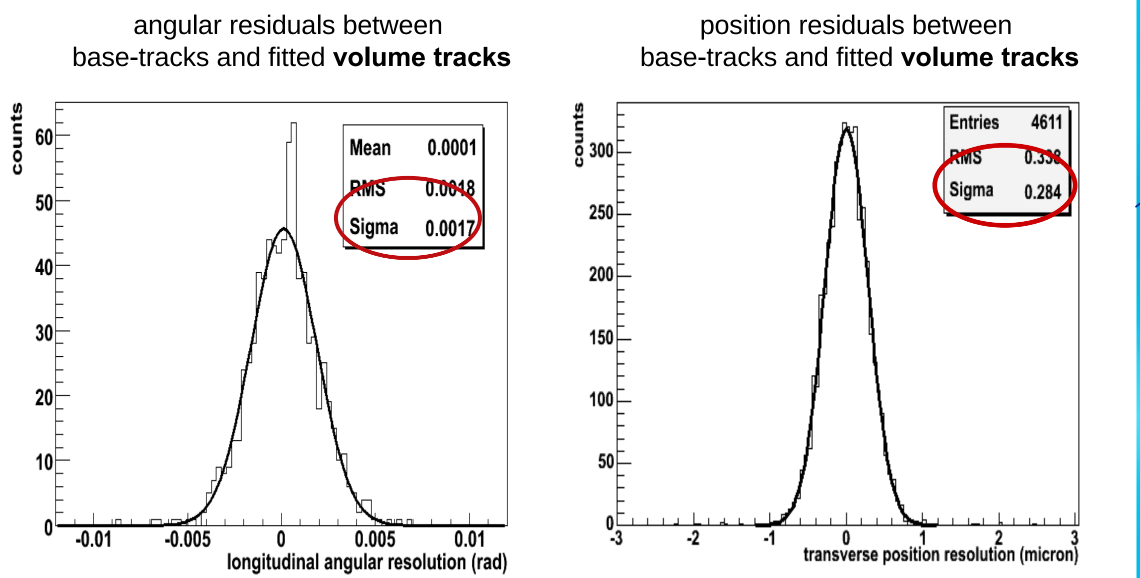
Synchronization of objective lens and stage

Constant speed stage

Track Reconstruction and Interaction search

The search for interactions in the brick is fully automated





tracks in the CS doublet

↓

alignement (< 1 mrad)

↓

scan-back
tracks followed backward film by film

↓

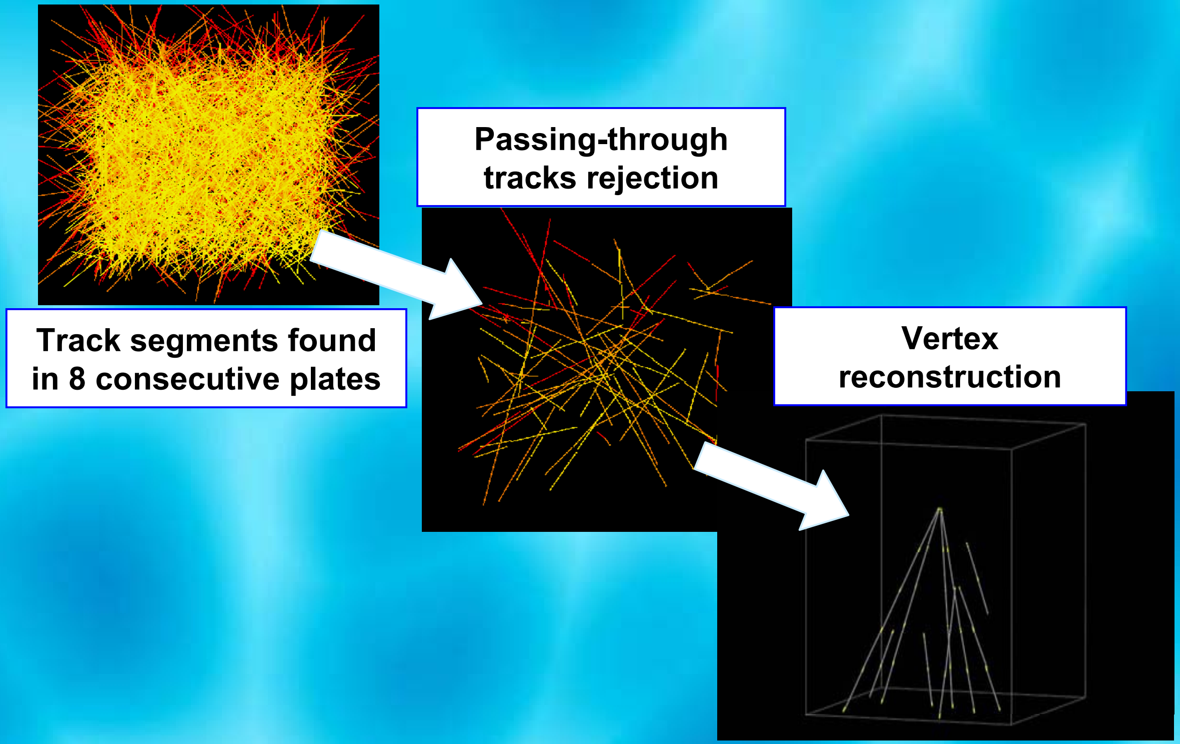
volume tracks
(tracking efficiency= 0.93)

↓

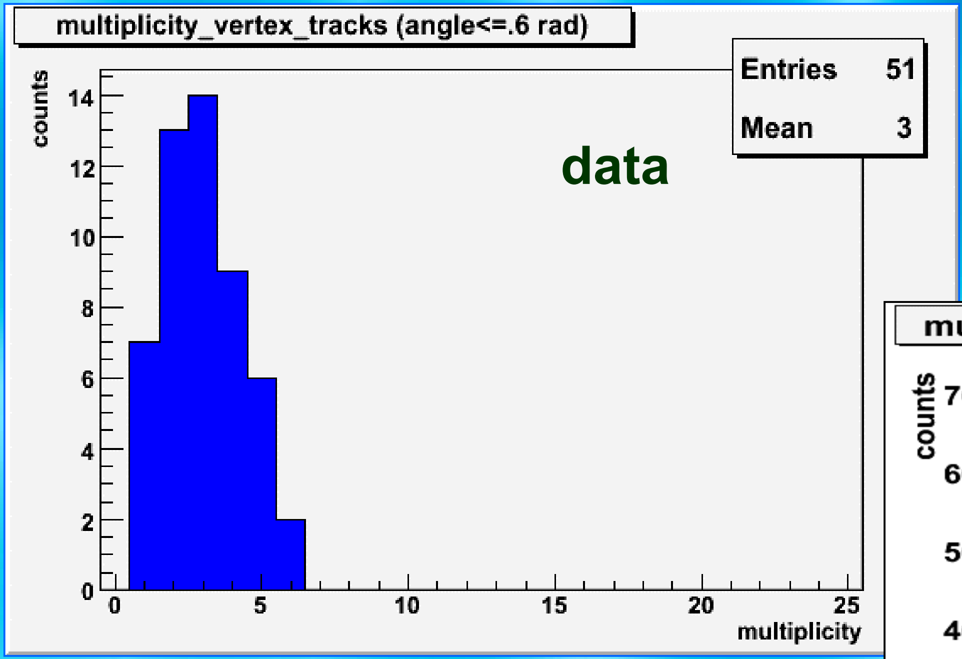
vertex reconstruction

Automated Vertex Search

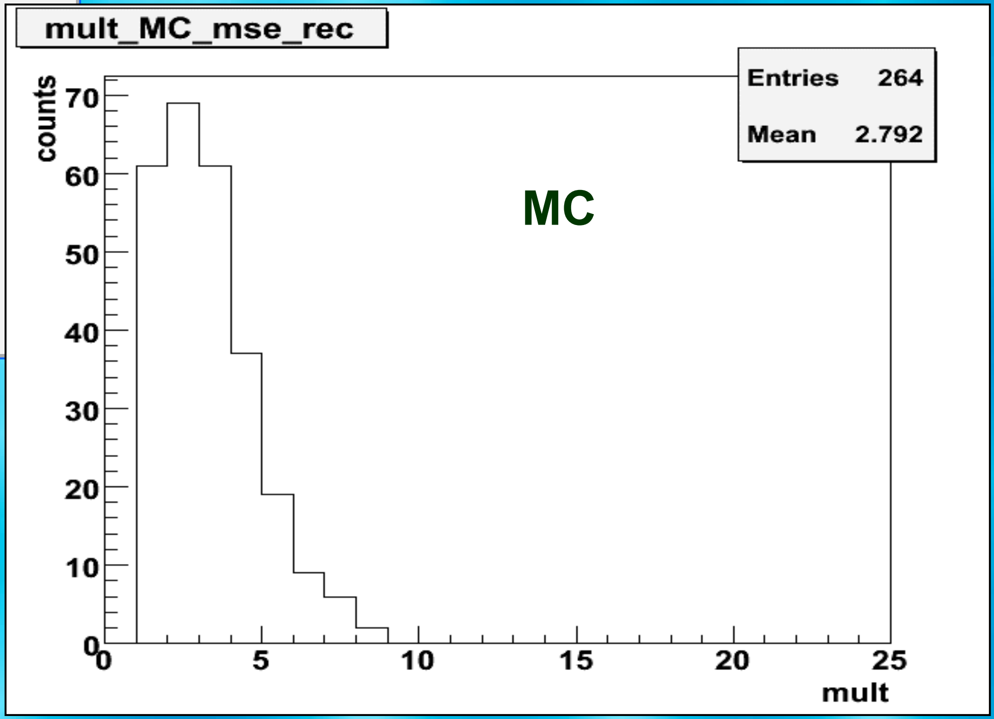
1) Cosmic alignment
2) Scan Back
3) Vertex analysis



Data-MC comparison

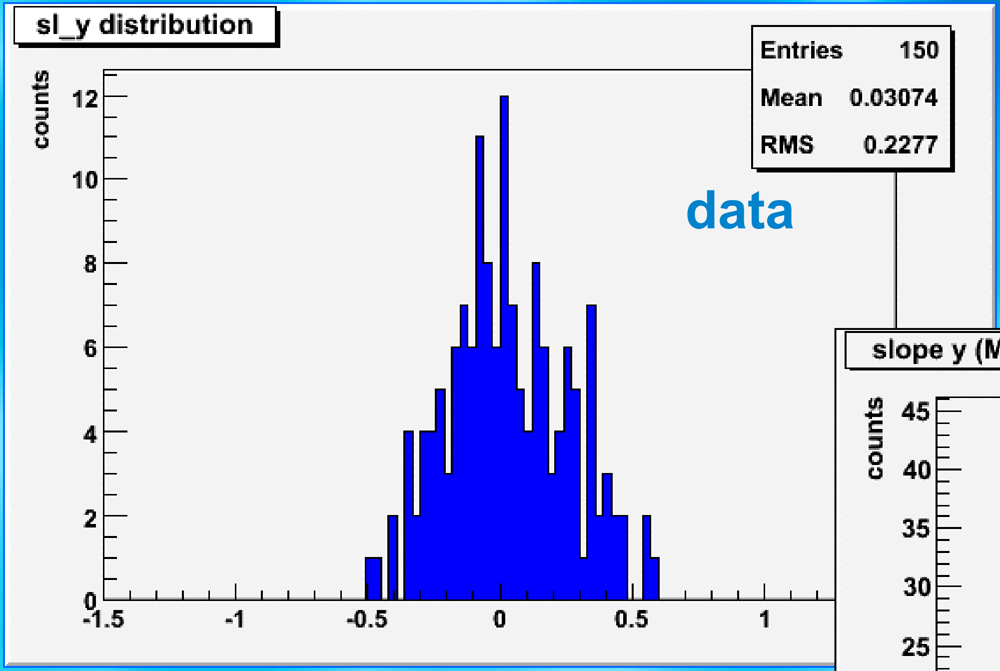


test beam at CERN PS
π beam @ 8 Gev/c



preliminary

Data-MC comparison



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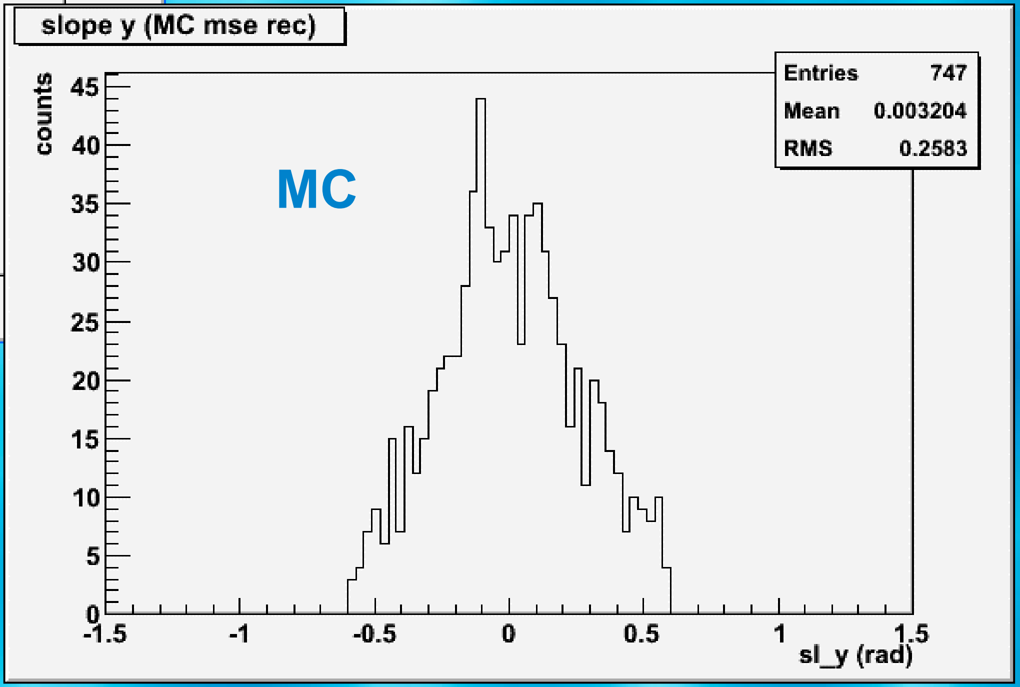
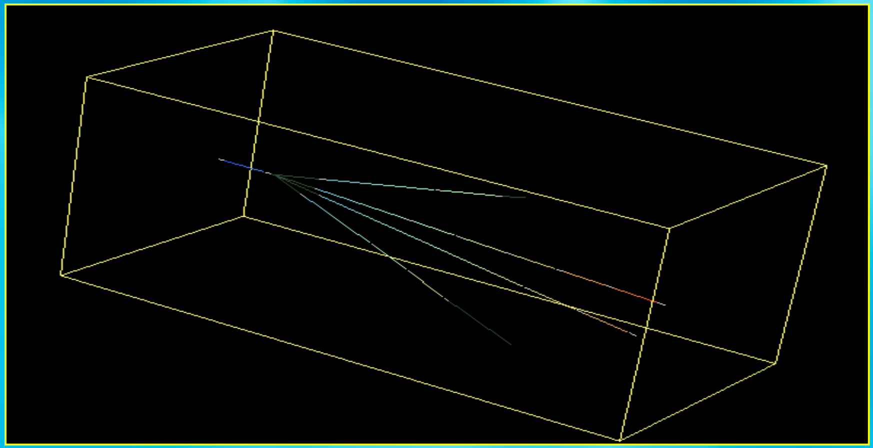
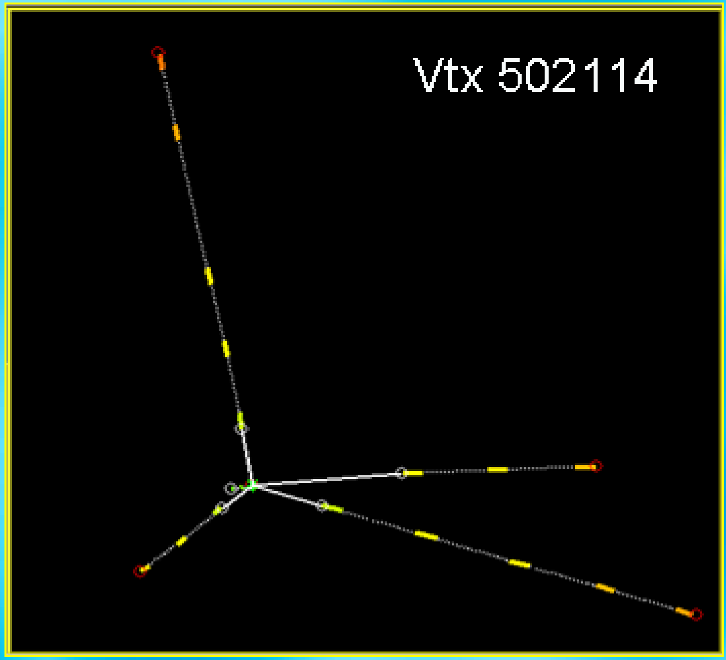
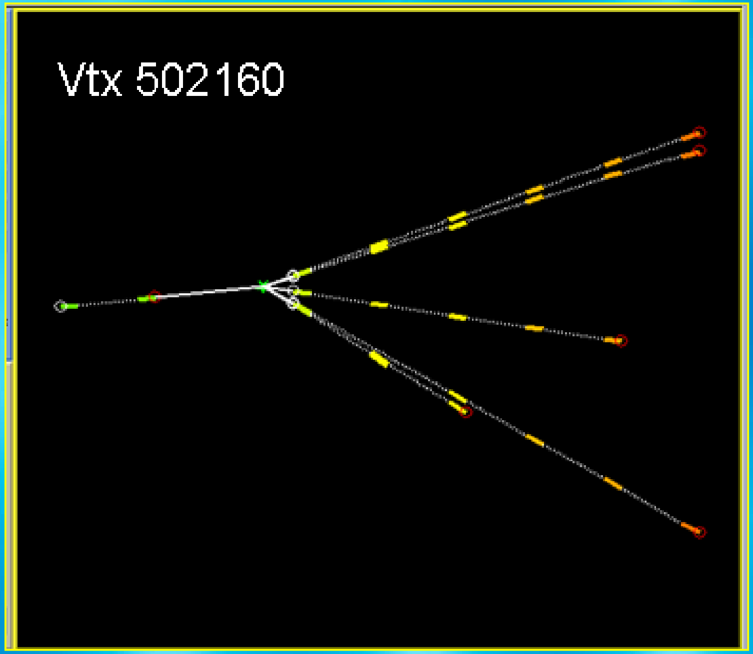


preliminary

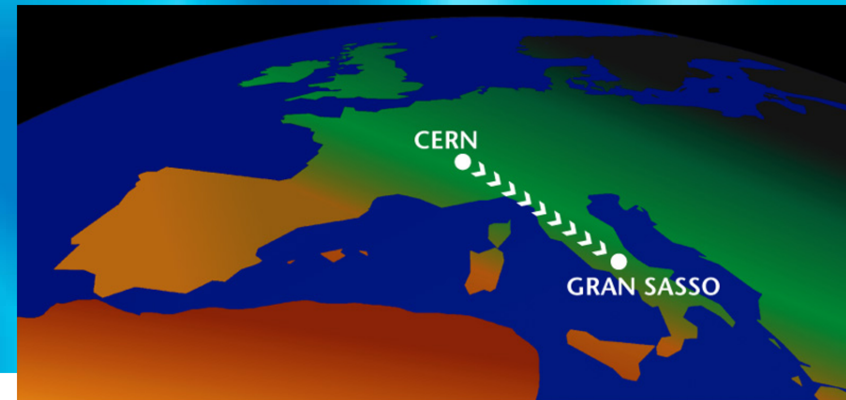
Reconstructed vertices



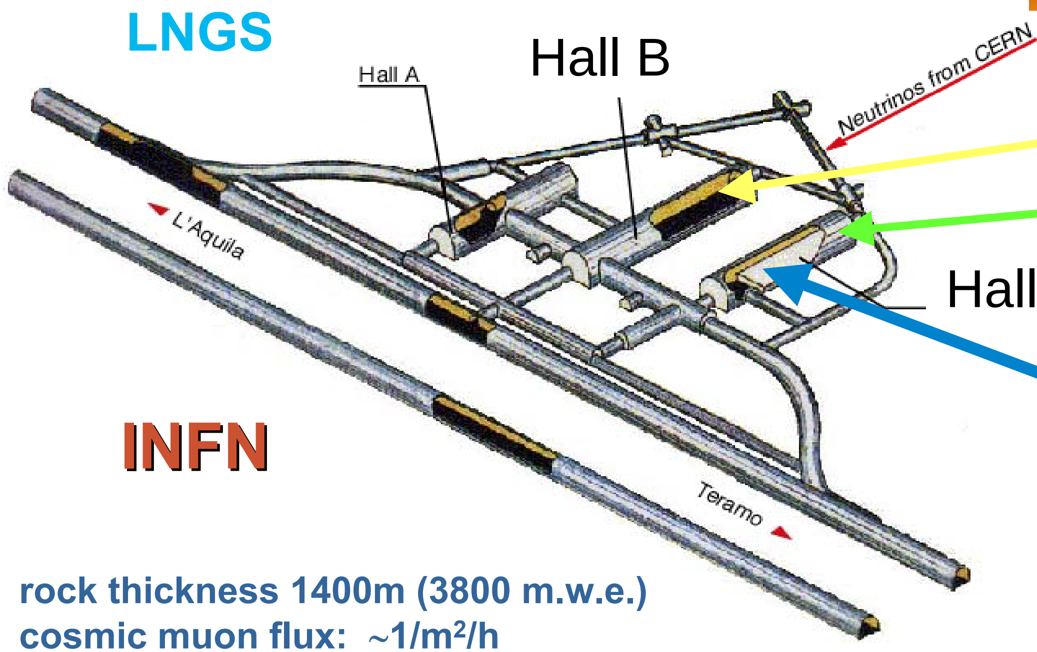




OPERA at LNGS



Largest underground laboratory for astro-particle physics



ICARUS

BOREXINO

Hall C

OPERA (CNGS1)

rock thickness 1400m (3800 m.w.e.)
cosmic muon flux: ~1/m²/h

underground area: 18 000 m²
external facilities
easy access

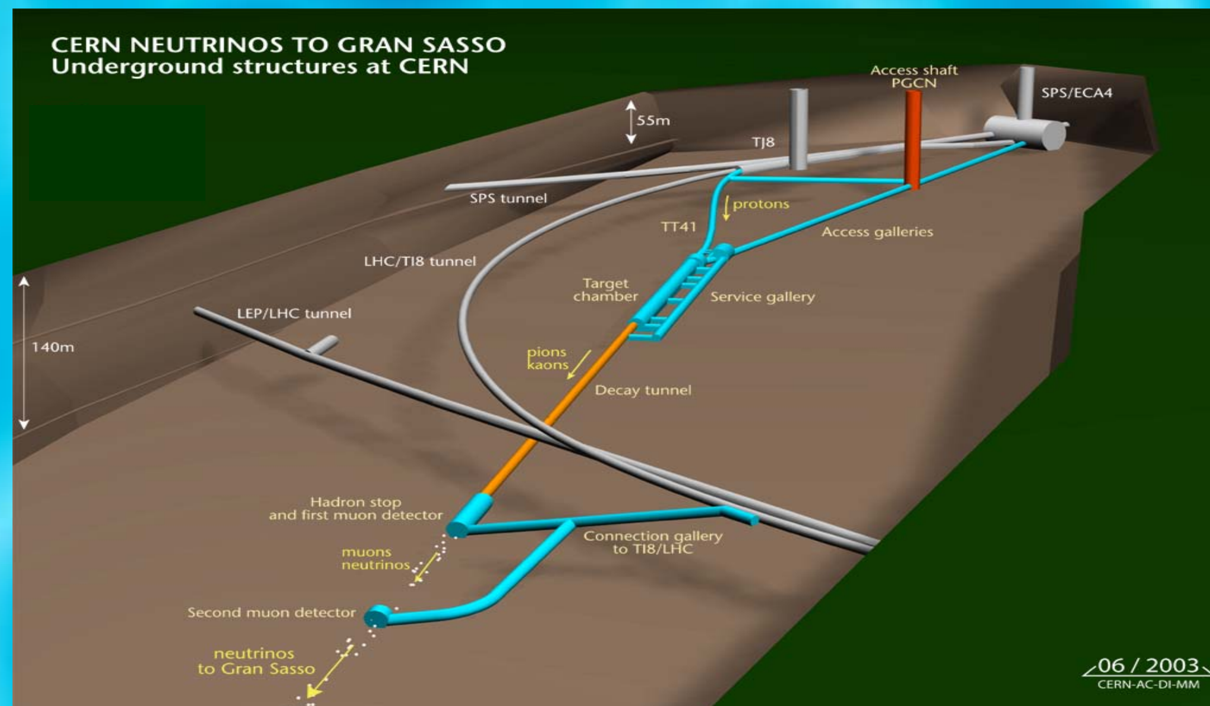
The CERN Neutrino to Gran Sasso beam

CNGS

400 GeV/c protons (CERN SPS) on graphite target
ν beam produced in the decay in flight of secondary π, K's in 1km-long decay tunnel towards LNGS

optimized for appearance

$\langle E\nu_\mu \rangle$	17 GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.87%
$\bar{\nu}_\mu / \nu_\mu$	2.1%
ν_τ prompt	negligible



4.5×10^{19} p.o.t./year,
200days/year
ε = 55% shared mode

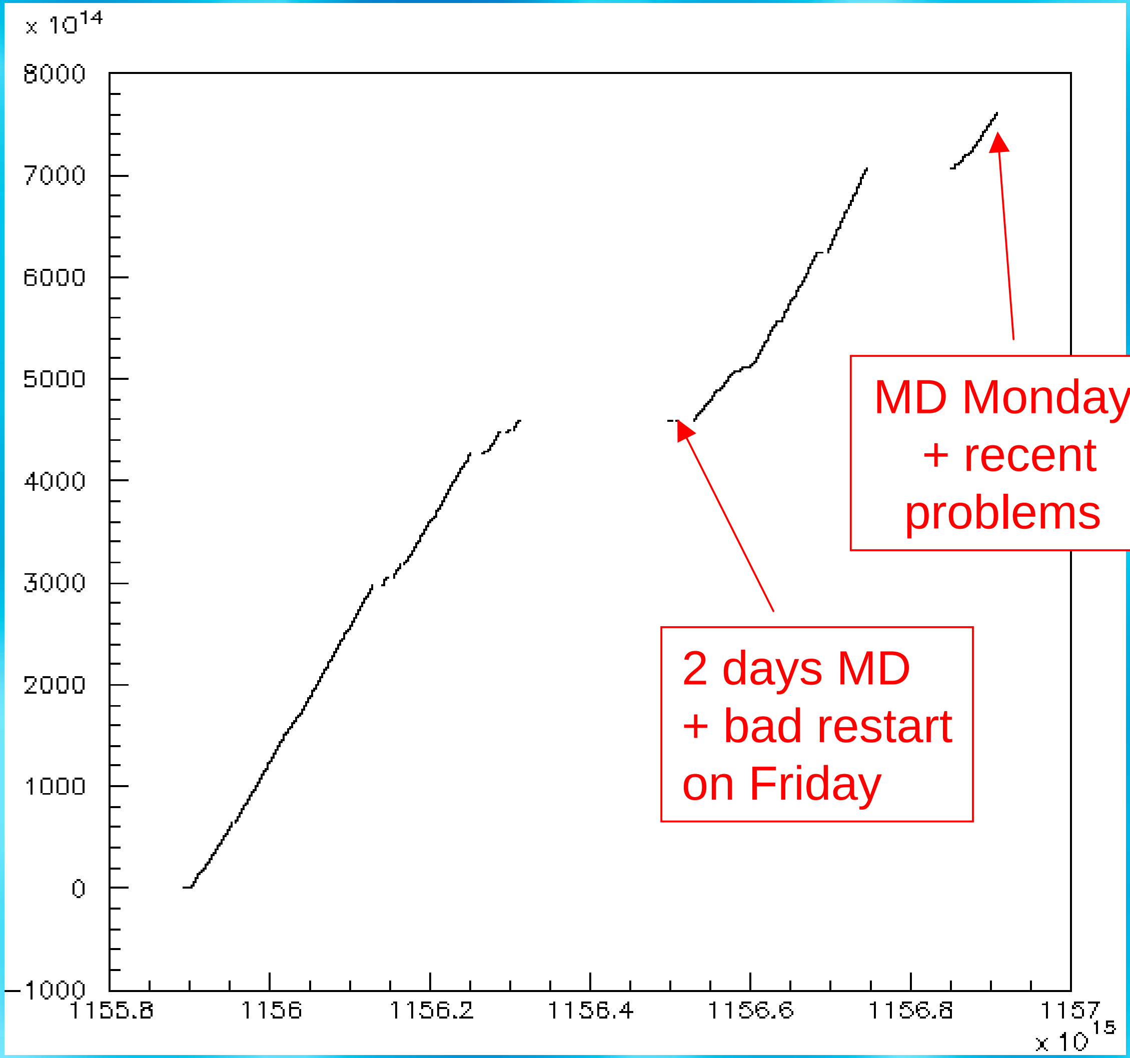
August 2006 run: integrated intensity (pot) as a function of time

First CNGS neutrinos sent towards LNGS on August 18th

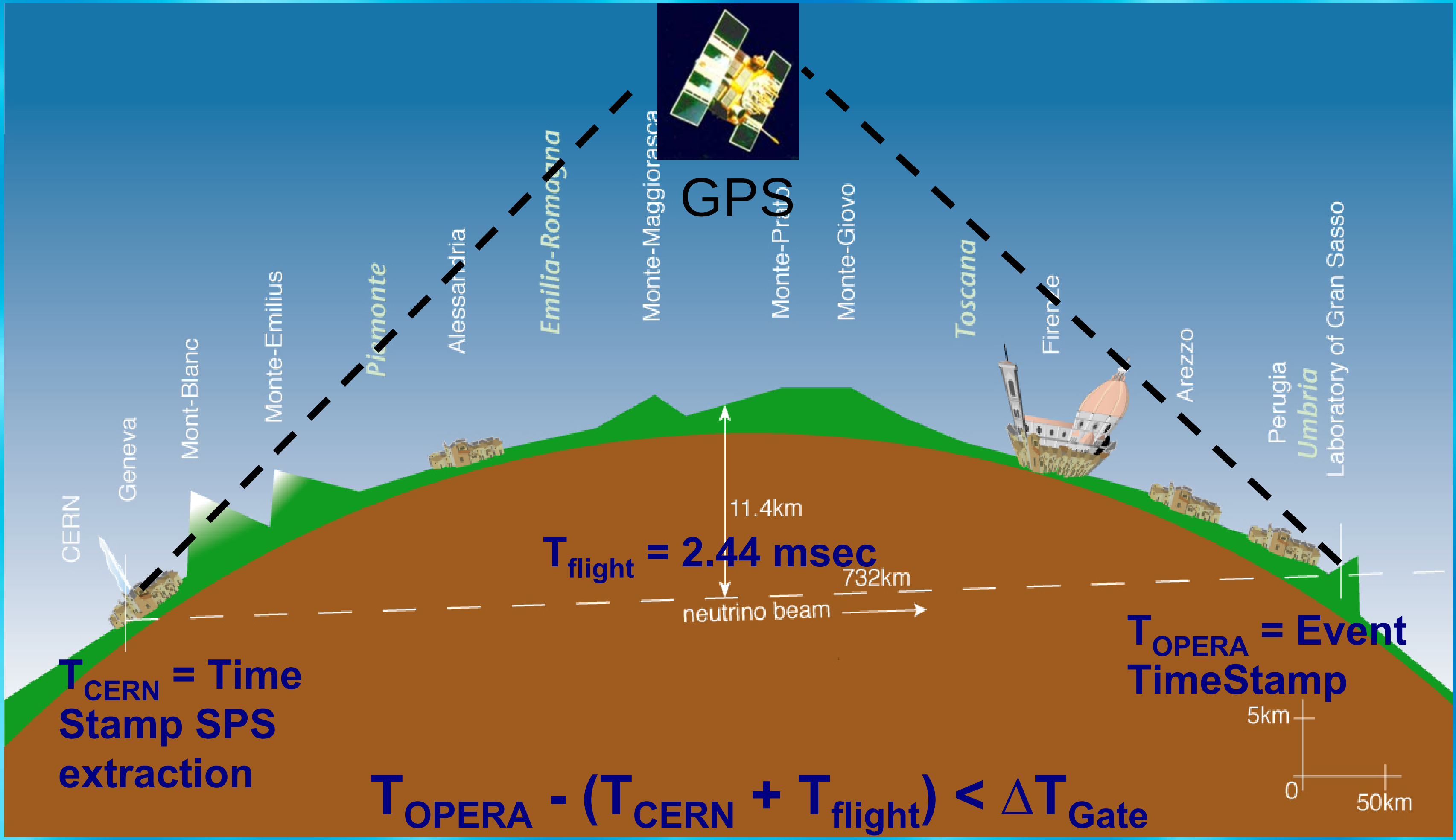
Low intensity run from August 18th to 30th

EXT1: 3.81 E17 pot
EXT2: 3.79 E17 pot

TOTAL : 7.6 E17 pot



Time Selection of Beam Events



T_{flight} = 2.44 msec

T_{CERN} = Time Stamp SPS extraction

T_{OPERA} = Event TimeStamp

$$T_{OPERA} - (T_{CERN} + T_{flight}) < \Delta T_{Gate}$$

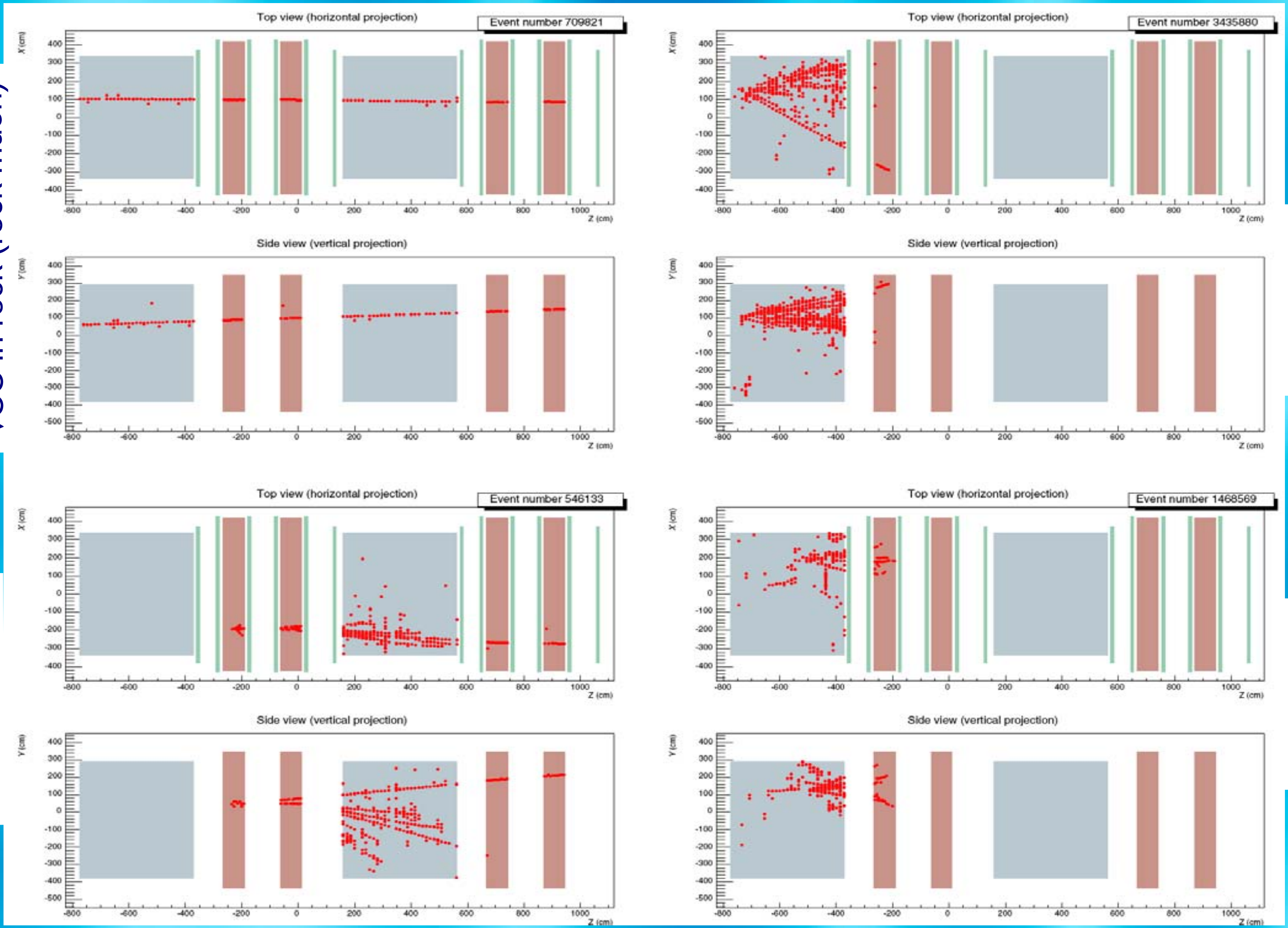
GPS Time Stamp resolution ~ 100 ns

Beam Events

320 events registered, 300 expected

νCC in rock (rock muon)

νCC in T T



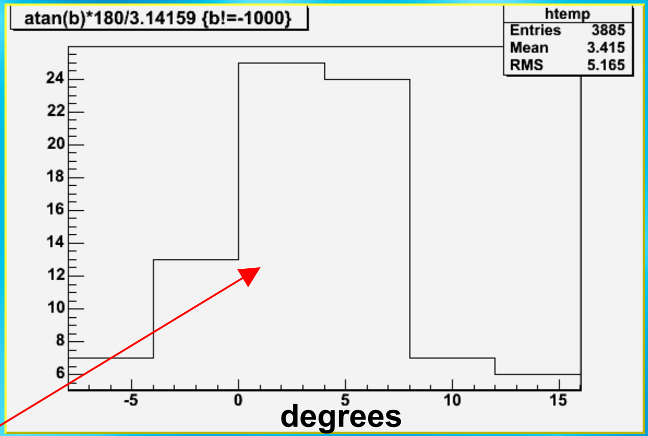
νCC in Magnet

νNC in T T

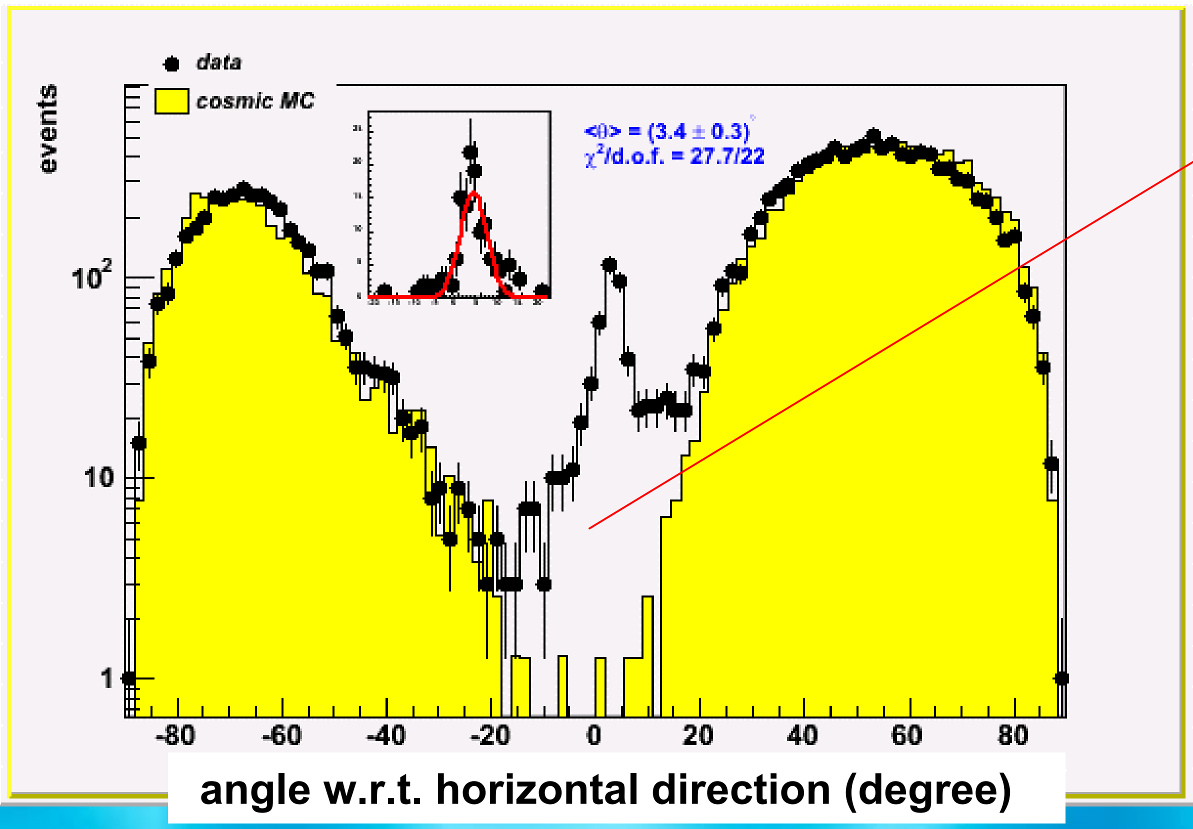
Beam Direction Measurement

$\langle\theta\rangle = 3.4 \pm 0.3$ *(statistically dominated)*

as expected

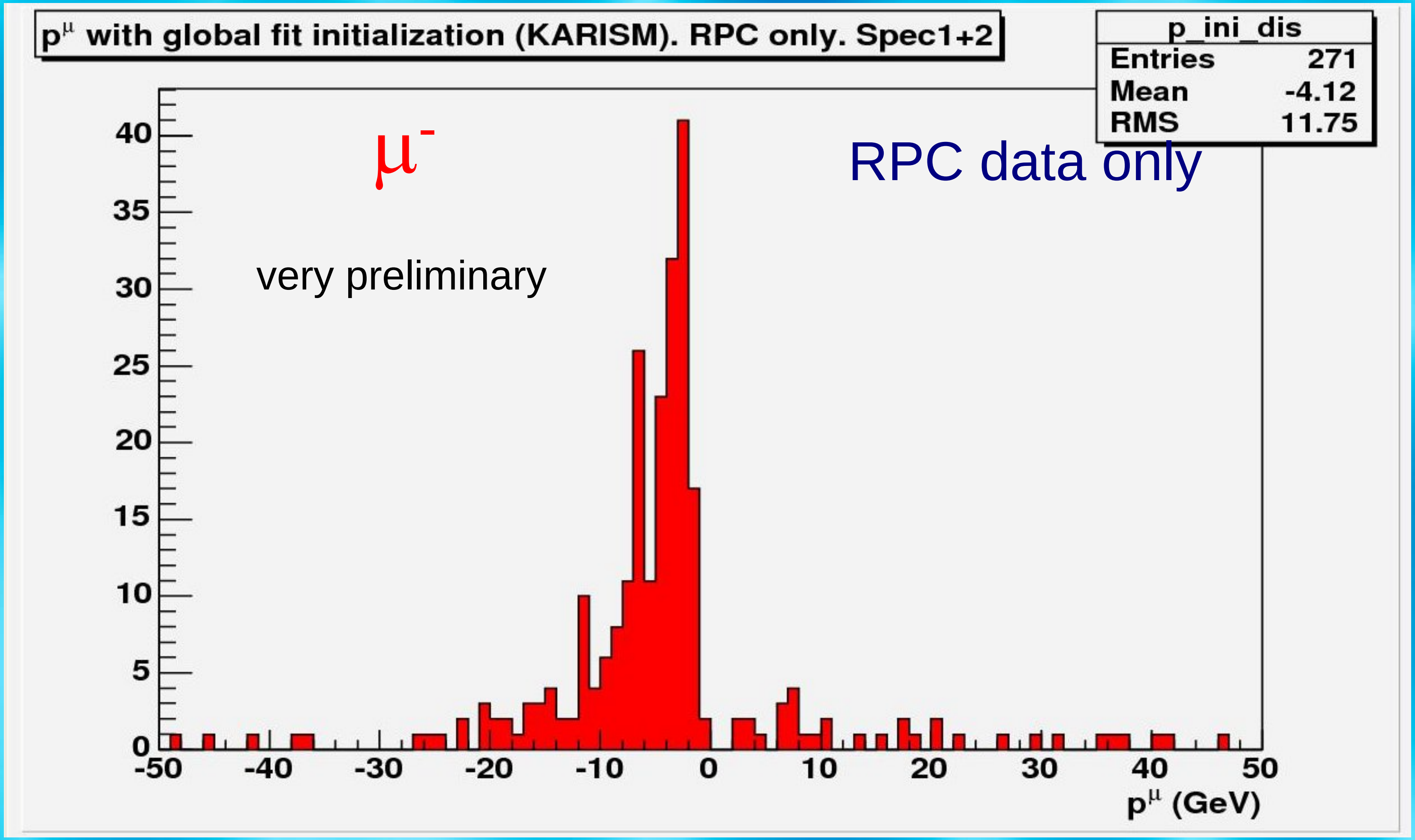


Number of on-time beam events registered in the August run ~320

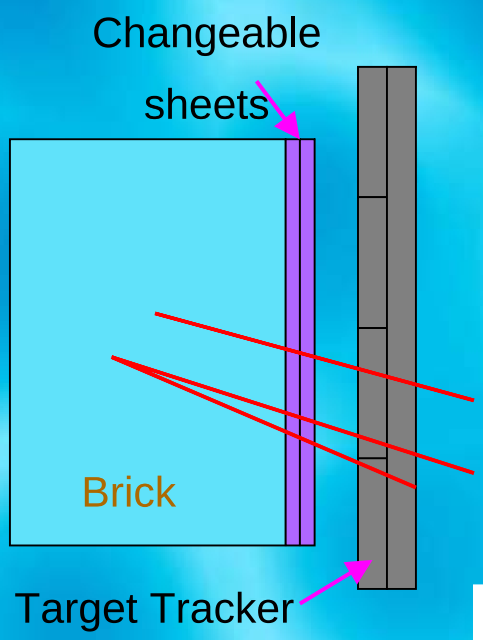


MC: simulation from MACRO parametrization, ABSOLUTE normalization

Muon momentum measurement



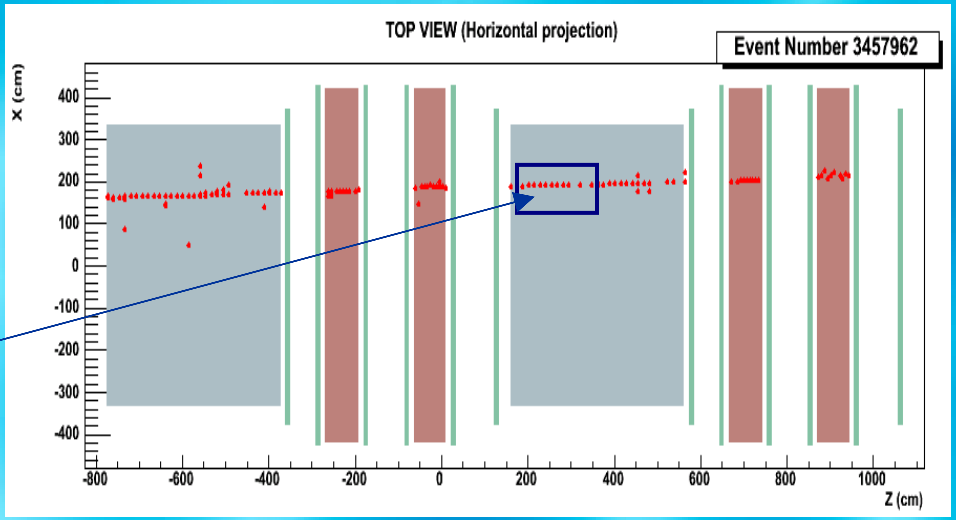
Changeable Sheets in the August run



In the August run:
one target wall was partially equipped with dummy bricks with Changeable Sheet (CS) doublet, to test the Target Tracker to Brick connection

9 rock-muons crossed the CS surface

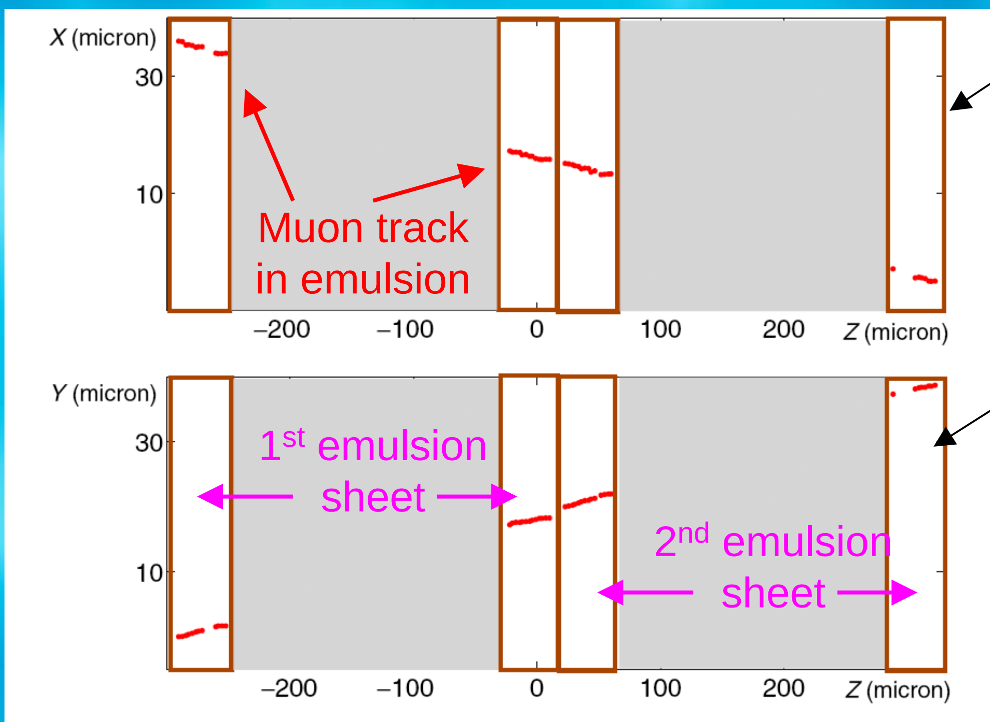
muon crossing a CS doublet



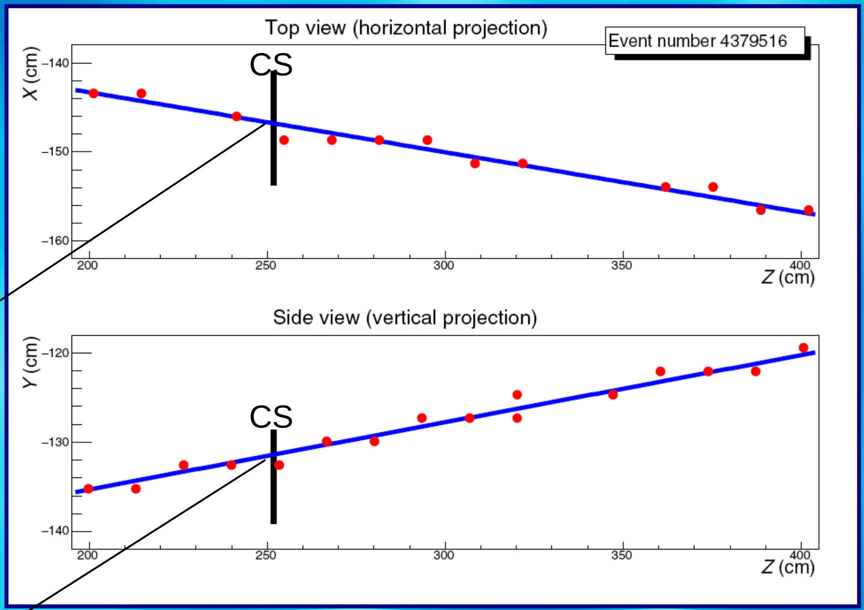
Target Tracker to Brick connection

T T → CS → brick

Muon track predicted by target tracker found in the CS doublets.



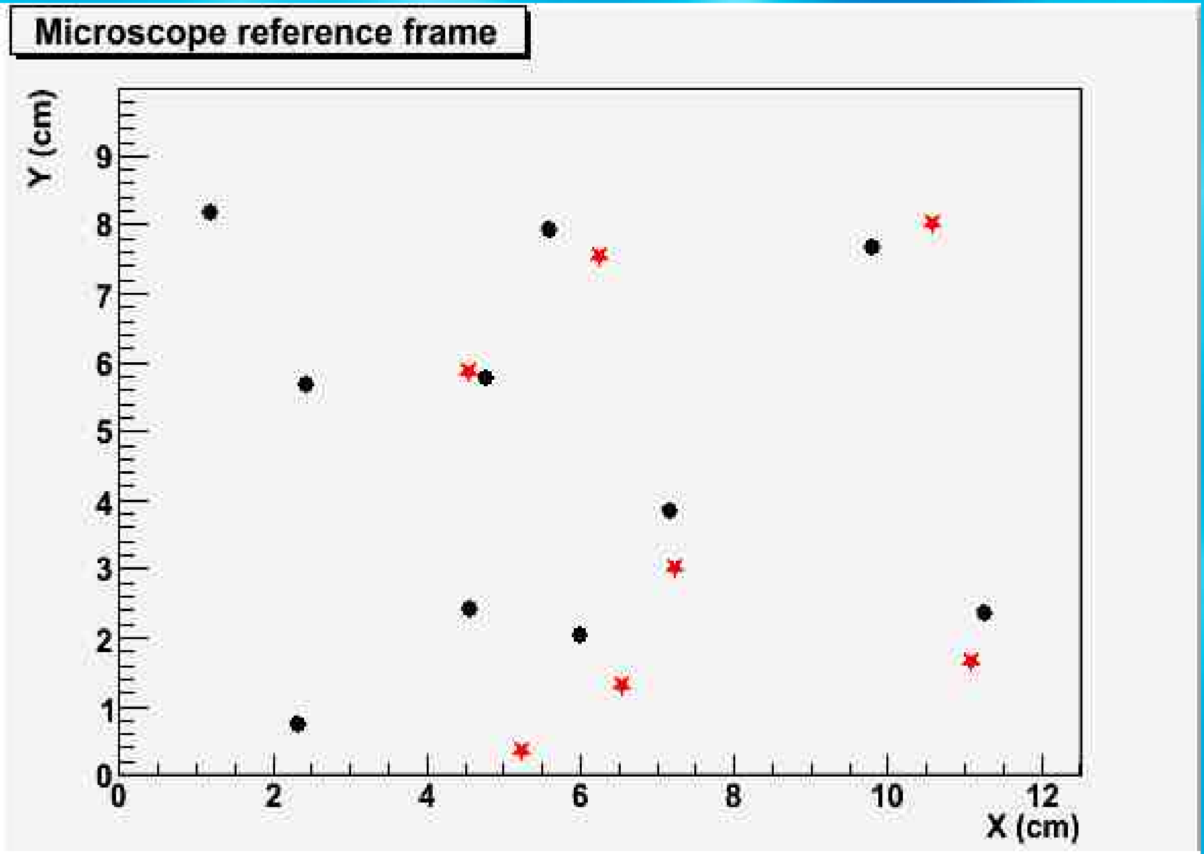
Muon crossing the CS doublet



Difference between prediction and found track dominated by electronic detector resolution

T T - CS

T T Predicted position CS Located position



Differences between TT- CS :

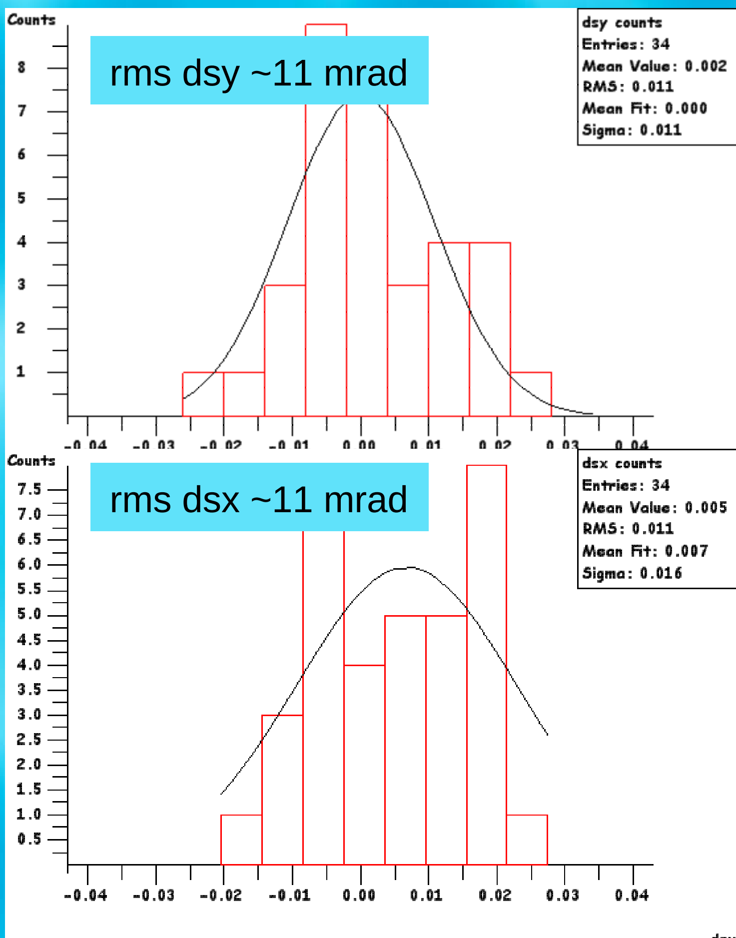
1 cm in position---15 mrad in slope

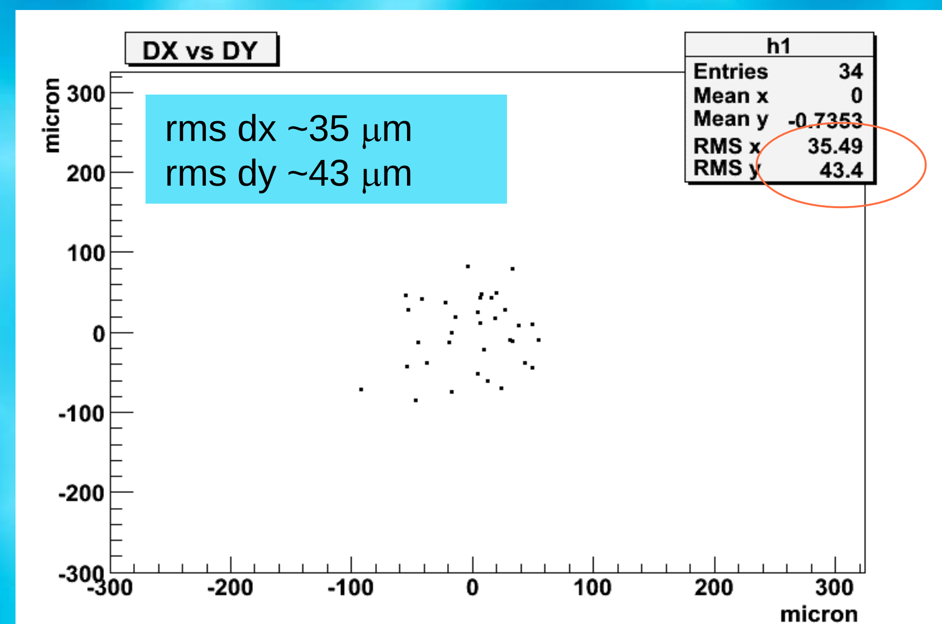
AUGUST RUN

CS to brick connection accuracy

T T → CS → brick

low density cosmic ray exposure at LNGS
few minutes (~100 tracks per brick)





to study CS – brick connection in *realistic* conditions

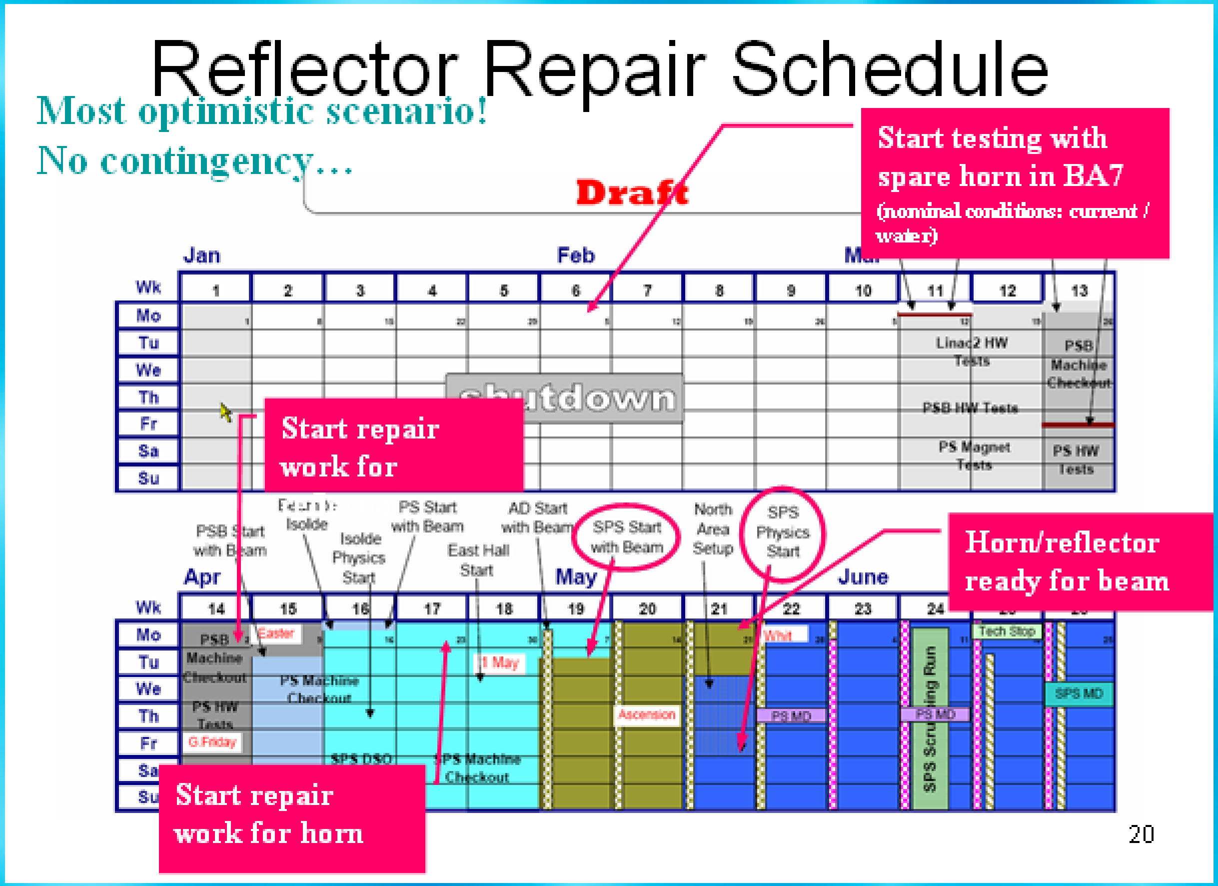
October run

Starting October 25th in the morning
Stop October 27th in the morning

0.6 E17 pot, collected 29 on time events

Found a leak in the closed water cooling circuit of the reflector:
broken the insulating ceramic part of the most downstream
tube connecting the outer conductor with the water drain pipe

Horn-Reflector Repair Schedule



End of works before CNGS start (26/5/07)

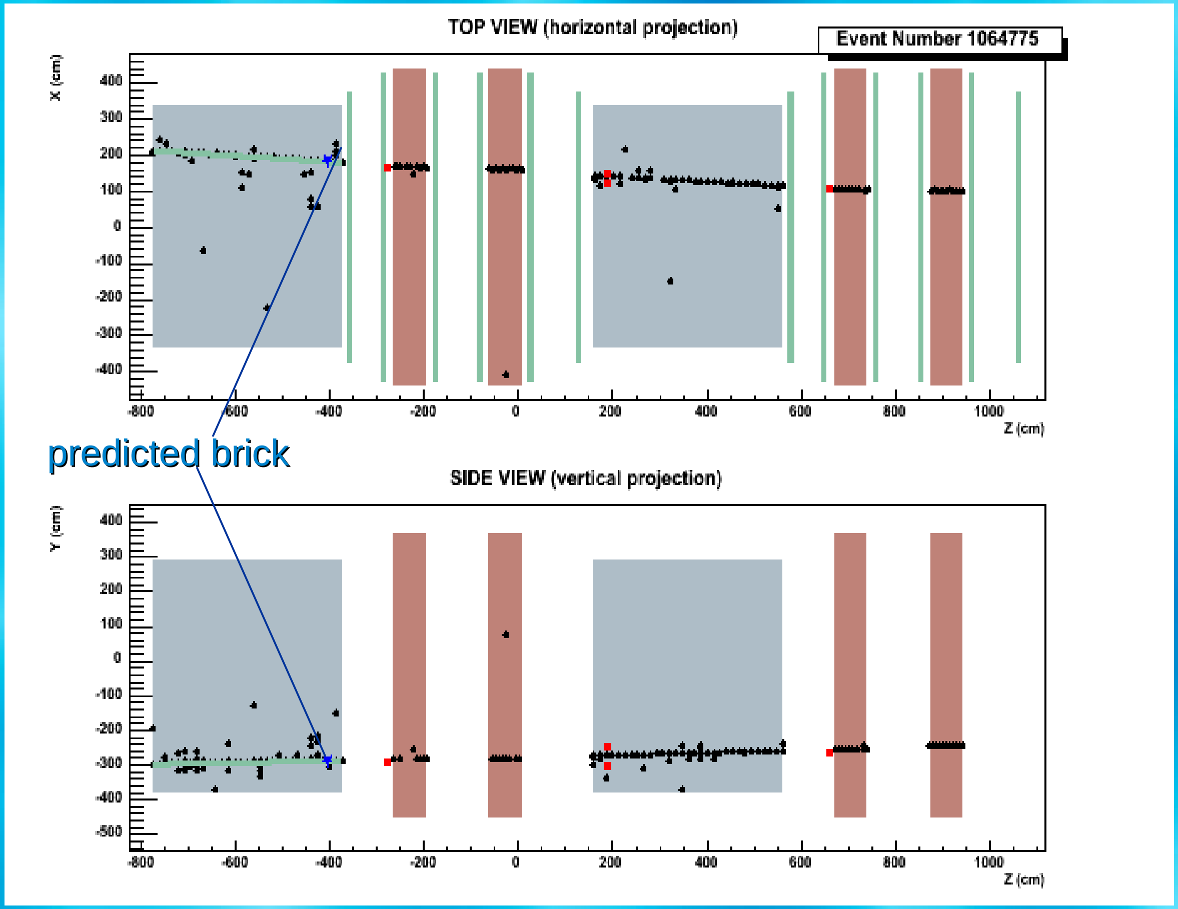
Immediately followed by two weeks of CNGS commissioning

No contingency in the planning

Event 1064775/Brick 1000370

TT prediction

X(cm)	Y(cm)	Z (cm)	SX(rad)	SY(rad)
181.5	-288.0	-401.8	-0.0839	0.0259



First OPERA event recorded in emulsion

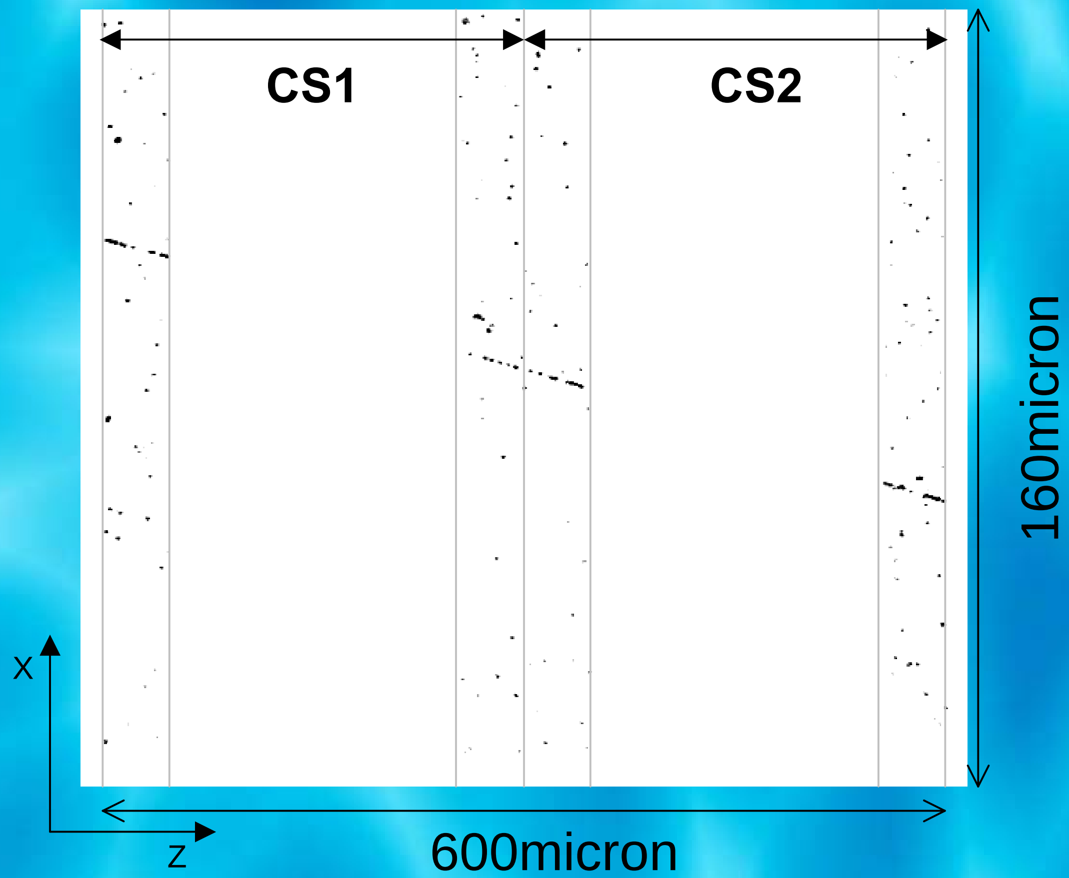
OCTOBER RUN

1 candidate found by automatic scanning in the CS doublet
(confirmed by visual inspection)

TT-CS differences:

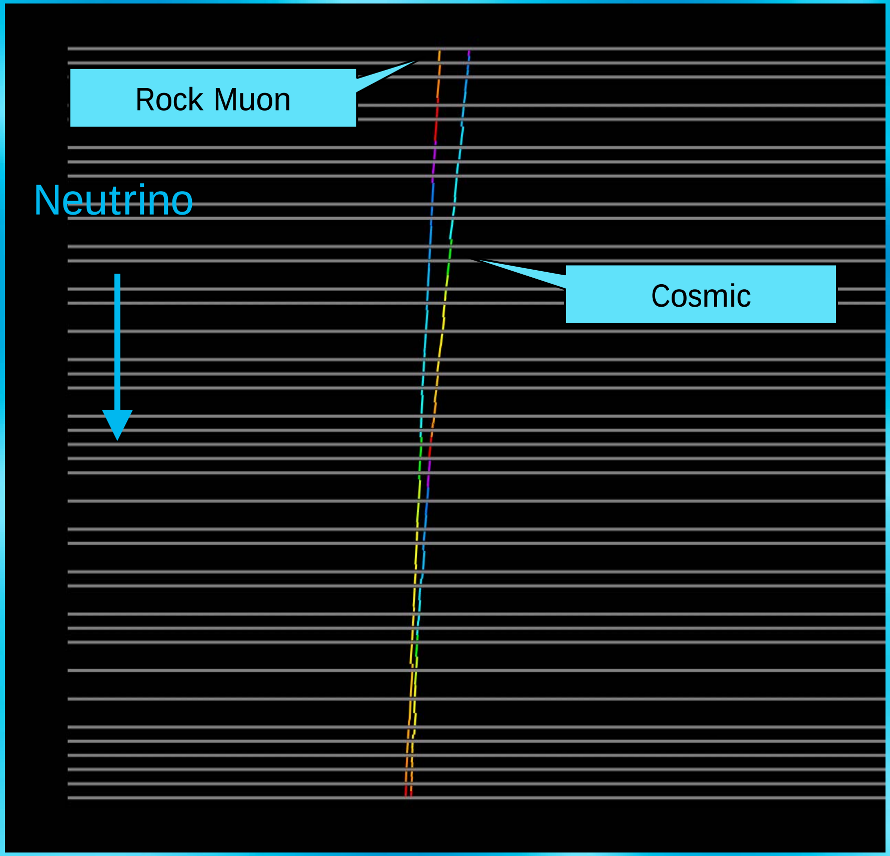
DX(cm)	DY(cm)
-0.550	**0.0415**

DSX(rad)	DSY(rad)
-0.0166	**-0.0248**

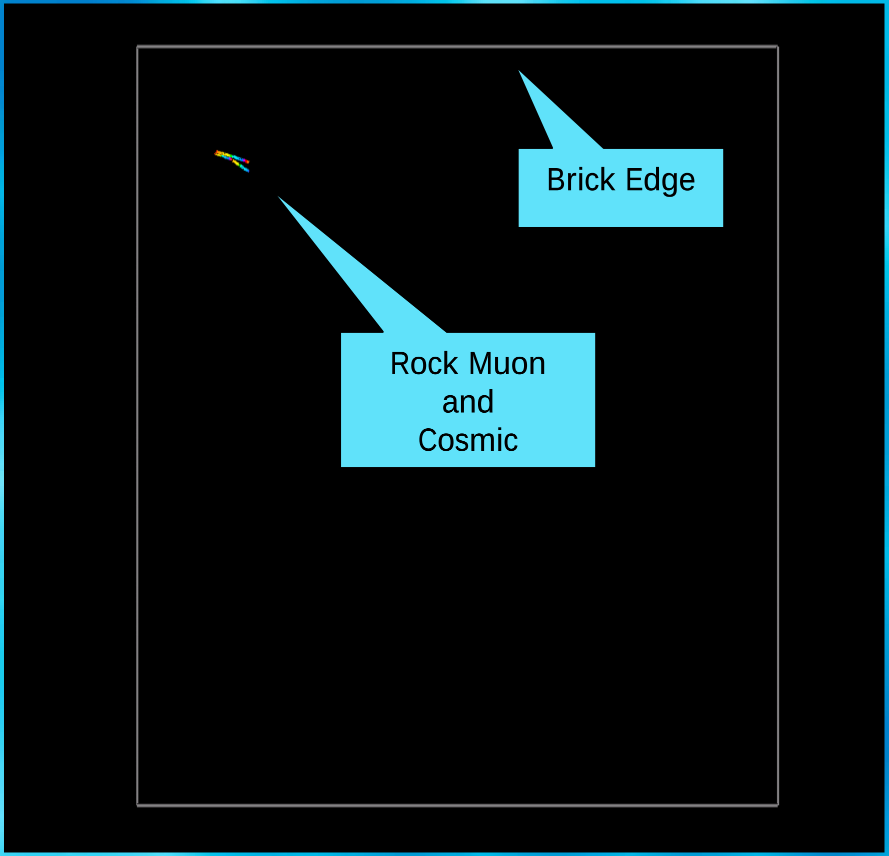


Event 1064775 (Rock muon) Brick 1000370

Track reconstruction in emulsion



Tracks in the brick



Tracks in one emulsion sheet

Study in emulsion of the event 10643775/Brick1000370

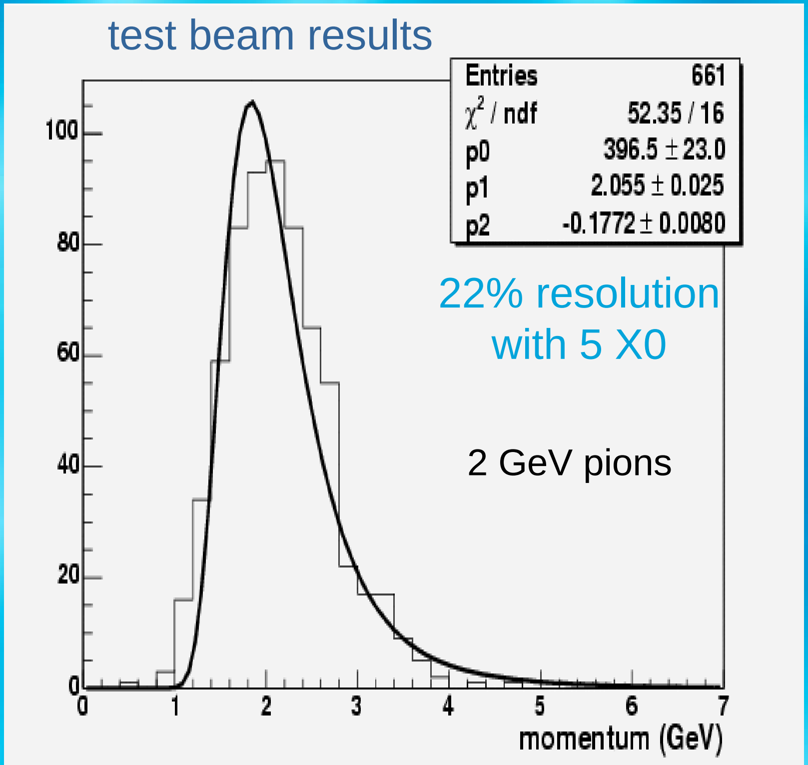
Rock-muon aligned using Cosmic Rays

RMS of position displacement ~ 1micron.

RMS of angle center displacement ~ 2-3mrad

Momentum measurement by Multiple Scattering (Coordinate Method)
6.4 +1.2 -0.9 GeV/c

Momentum measurement by Spectrometer
7.05 +/- 0.4 GeV/c



2007 Run
Problems in the PS extraction

The extraction intensity is limited to 70% of the nominal intensity due to beam losses, mainly at the level of the extraction from the PS

The problem is more acute for the CNGS running, because it requires a high intensity beam

For 2007, in order to « survive », some fixes, which will allow the lost beam to be dispersed over a larger area, are foreseen. These should allow us to run in stable conditions with limited intensity for a long period

⇩

important radioprotection problems
severe radiation damage to the equipment

The problem can be solved only by changing the PS extraction scheme to the multi-turn extraction

Multi-turn extraction scheme

Virtually lossless

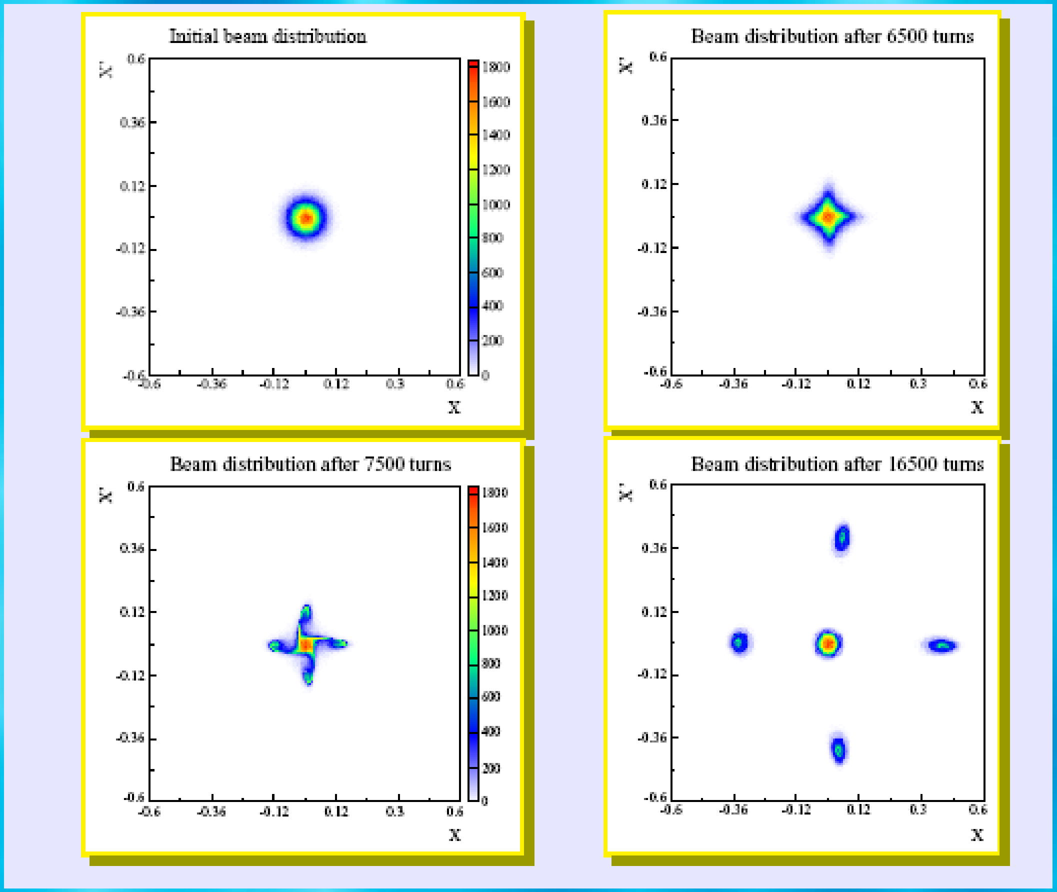
2001 First proposal (linked to 1.5 intensity increase for CNGS)

R&D and tests 2002-2004

Implementation study group 2005

March 2006 TDR
October 2006 Project approved

2008 completion



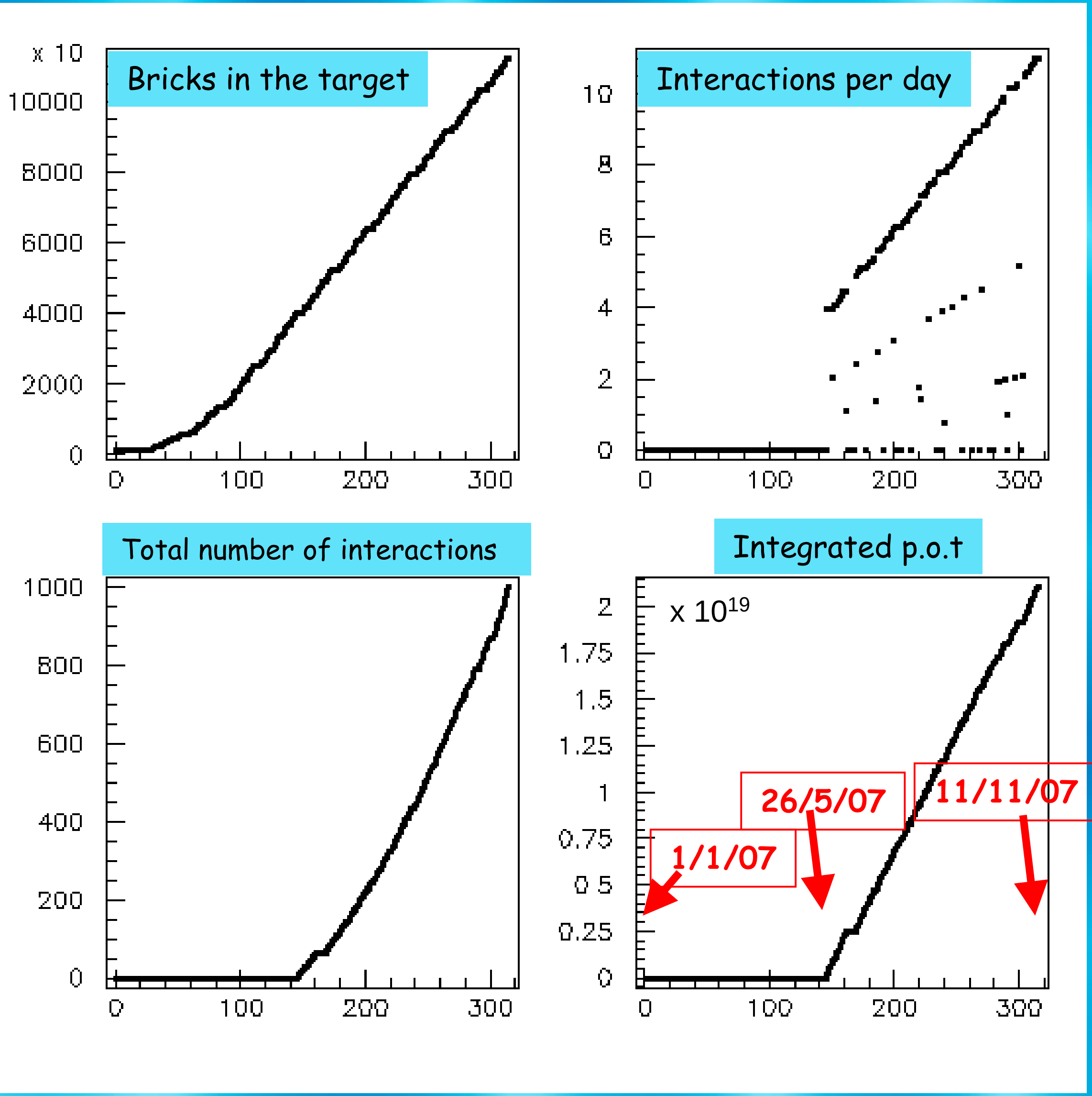
2007 OPERA Run

Assumptions :

3 CNGS cycles
(39.6 s, 1.56^{E}17 p.o.t/day)

700 bricks/day
by the End of March

Bricks
PS physics program
S art: End:
41000 112000



Interaction rate

Official SPS schedule: 135.15 useful days

1.7 E13 p.o.t/extraction, 70% efficiency for the machines complex

Option	Bricks at the start of the run 26/5/07	Bricks at the end of the run 11/11/07	Integrated p.o.t	Bricks with interactions	Rock muons
3 CNGS	40738	111982	2.1E19	1001	3360
1 CNGS	40738	111982	1.65E19	787	2640

Completion of the detector filling: End of March 2008

due to the lack of funding in Japan, 20% of the emulsions are missing for the time being, maximum number of bricks to be produced 170000

OPERA in the 2007 Run

not only neutrino events but also rock muon events

TT accuracy
location test TT-CS

Delta rays, scattering,
Shower development
Brick to Brick connection

Brick finding
Vertex finding

CNGS beam cross check

Check of decay search
Kinematical analysis tuning

Conclusions

The OPERA experiment has been designed to unambiguously confirm/disproove the

$\nu_\mu \leftrightarrow \nu_\tau$ oscillations

at atmospheric Δm^2 scale using a complex detector combining visual and electronic detection techniques

In the August run, the low intensity CNGS beam operated smoothly for both beam and detector with good quality and stability

The electronic detectors of OPERA took data almost continuously (95% live time) and with the expected tracking performances

319 neutrino-induced events were collected for an integrated intensity of 7.6 E17 pot in agreement with the expectation of 300 events

The zenith angle distribution for rock-muon tracks was measured and found to be in agreement with the expectation

The October run was unfortunately very short due to a leak in the water cooling circuit of the CNGS reflector: in about 24 hours we recorded 30 events

The first event detected in emulsion was analyzed: the momentum was measured in the emulsion and found to be in agreement with the spectrometer measurement

The detector is ready for the next phase

…waiting for the first neutrino interaction in emulsion…..