



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

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# 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  $\nu_\tau$  *appearance* in a pure  $\nu_\mu$  beam

CNGS beam,  $\langle E \rangle = 17$  GeV,  $L = 732$  km

Hybrid set-up (nuclear emulsions + electronic detectors)

Detection of  $\nu_\tau$  CC interactions and *direct* observation of  $\tau$  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

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

SK oscillation signal confirmed by:

MINOS

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

K2K

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

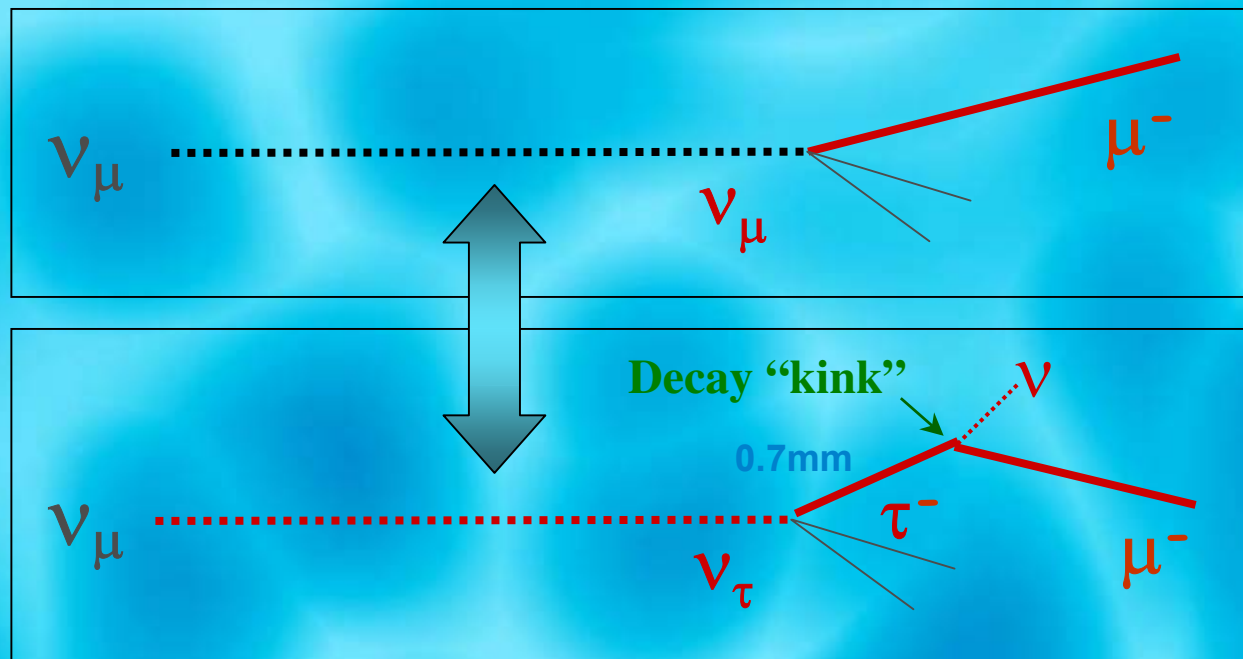
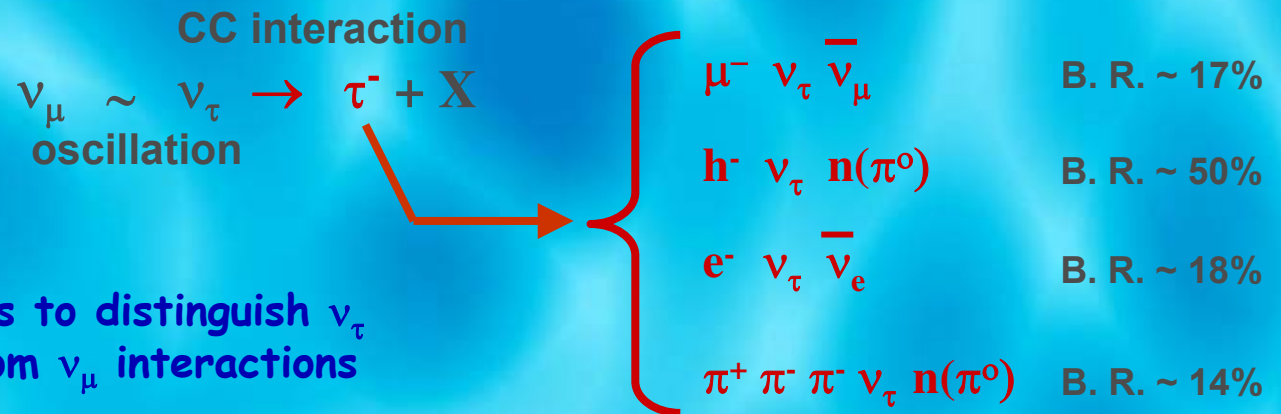
All the experiments indicate  $\nu_\mu \rightarrow \nu_\tau$   
dominant  
oscillation mode....

but still missing:  
direct observation of  
oscillated  $\nu_\tau$





# Experimental signature of the $\nu_\tau$ appearance



Topology selection:  
 $\Downarrow$   
 kink signature



# $\nu_{\mu} \rightarrow \nu_{\tau}$ Oscillation Search

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

Main background sources:

- charm production and decays
- hadron re-interactions in lead
- large-angle muon scattering in lead

full mixing, 5 year run @  $4.5 \times 10^{19}$  pot/year



# Detection of the $\nu_\tau$

Two conflicting requirements:

large mass

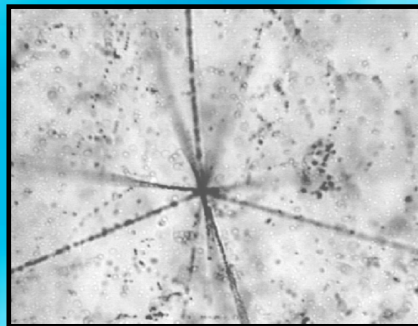
high granularity

→ low cross-section

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 ( $\sim 300$  hits/mm)

Target: 1800 tons, 5 year running

- 30,000 neutrino interactions
- $\sim 150$   $\nu_\tau$  interactions
- $\sim 15$   $\nu_\tau$  identified
- $< 1$  event of background

What the brick cannot do:

- signal a neutrino interaction
- identify muons





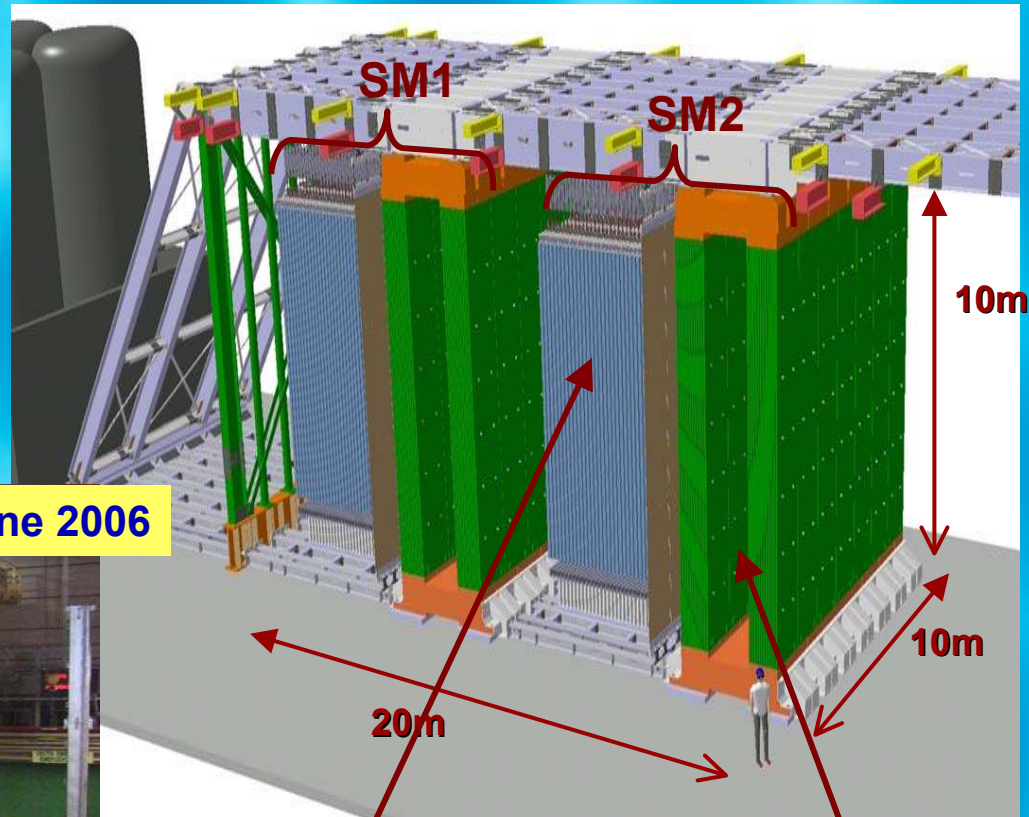
# Structure of the OPERA Detector

Installation started in

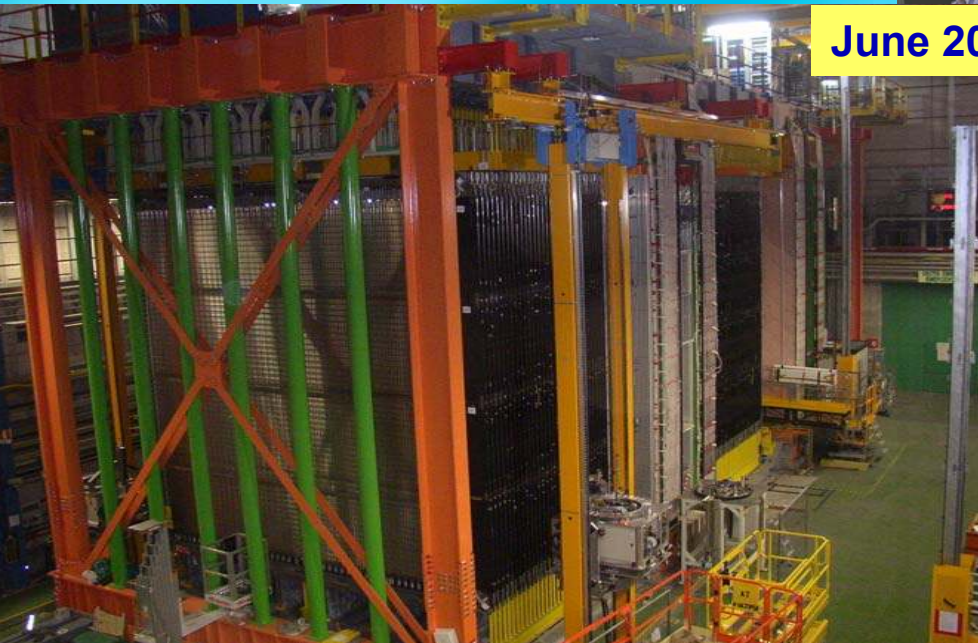
May 2003

First observation of CNGS  
beam neutrinos:

August 18<sup>th</sup>, 2006



June 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



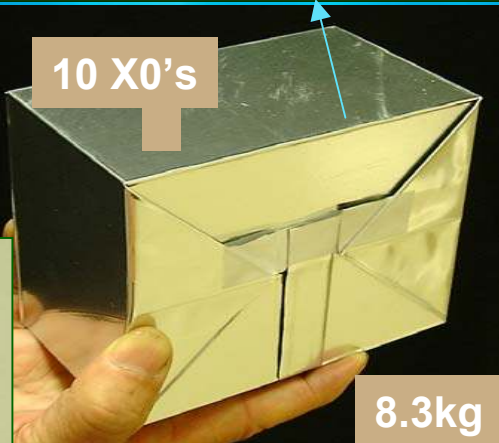
# Brick Target

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

## Brick (basic unit)

56 Pb plates + 57 emulsion films

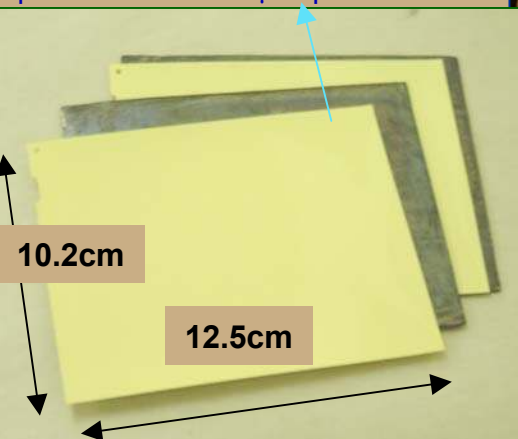
10 X0's



8.3kg

## Emulsion film

2 emulsion layers (44  $\mu\text{m}$  thick)  
poured on a 200  $\mu\text{m}$  plastic base



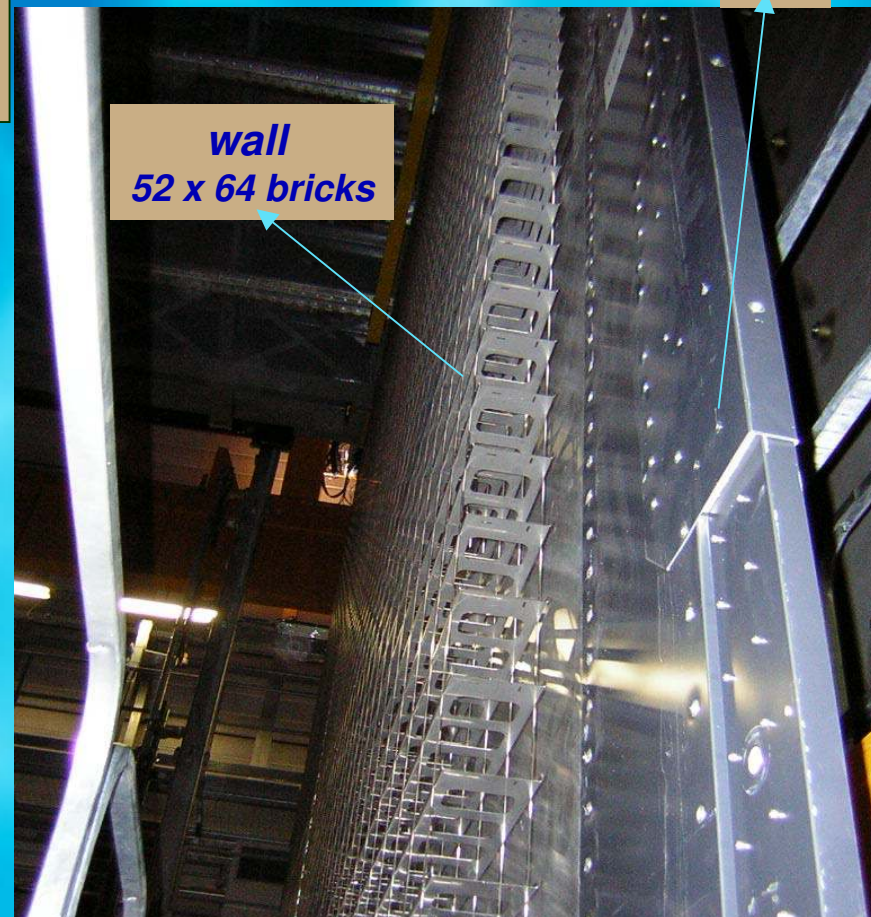
10.2cm

12.5cm

## CS doublet (connection T T- brick)

two double refreshed emulsion films, vacuum packed and glued onto the bottom of each brick

TT



wall  
52 x 64 bricks

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



# Brick Assembly Machine

Robots will pile up bricks  
at a rate of  $\sim 800$  bricks/day





# Brick Manipulator System

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

*Ventouse Vehicle*

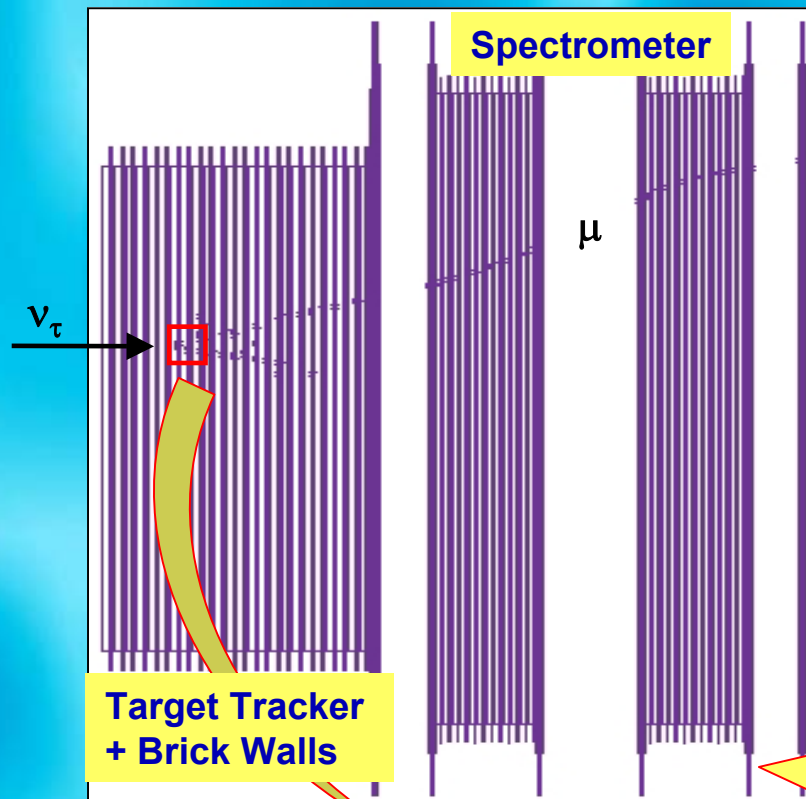
*Carousel mechanism*

Brick

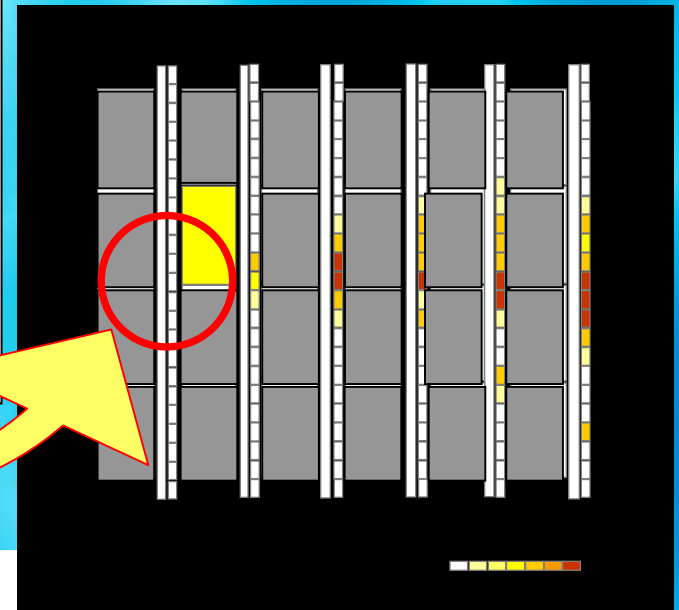




# OPERA running



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

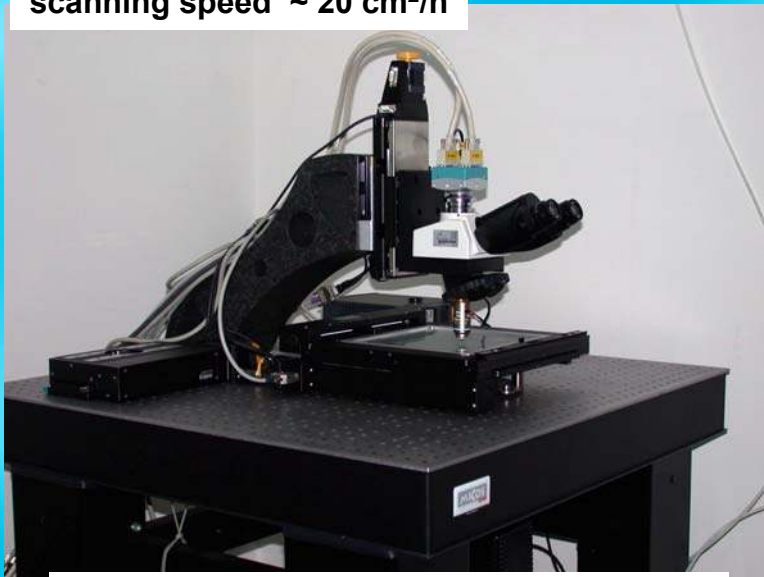
# Automated microscopes for nuclear emulsions

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

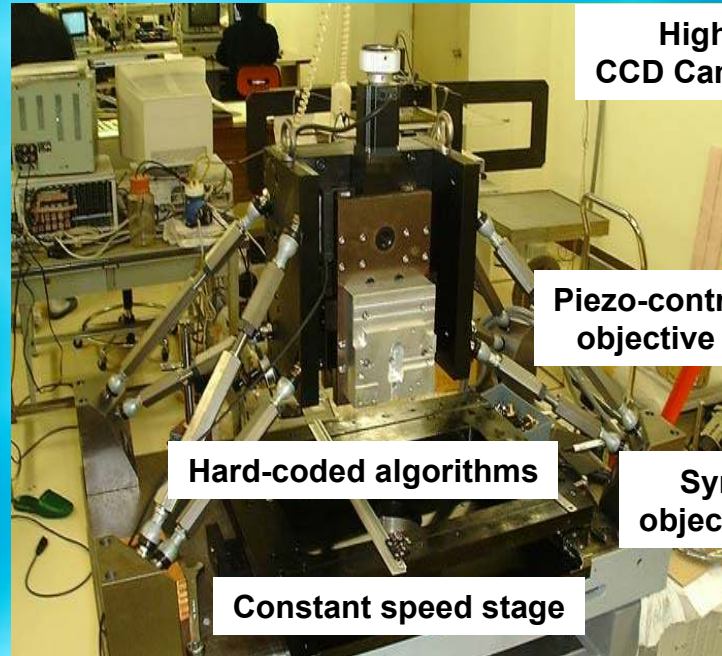
European Scanning System

S-UTS (Japan)

scanning speed ~ 20 cm<sup>2</sup>/h



Customized commercial optics and mechanics + asynchronous DAQ software



High speed  
CCD Camera (3 kHz)

Piezo-controlled  
objective lens

Hard-coded algorithms

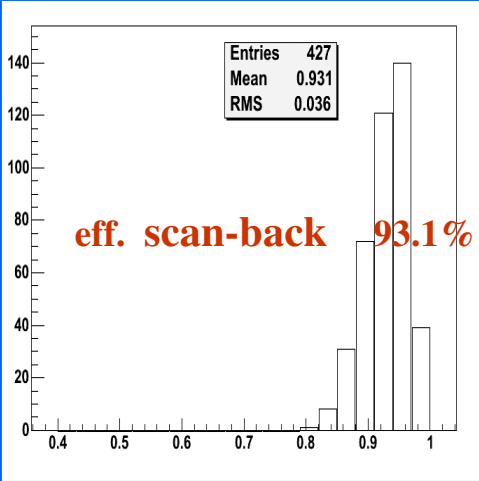
Synchronization of  
objective lens and stage

Constant speed stage



# Track Reconstruction and Interaction search

The search for interactions in the brick is fully automated



tracks in the CS doublet

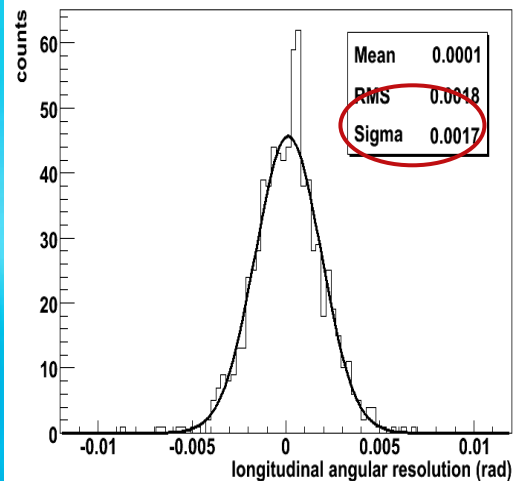
alignement ( $< 1$  mrad)

scan-back  
tracks followed backward  
film by film

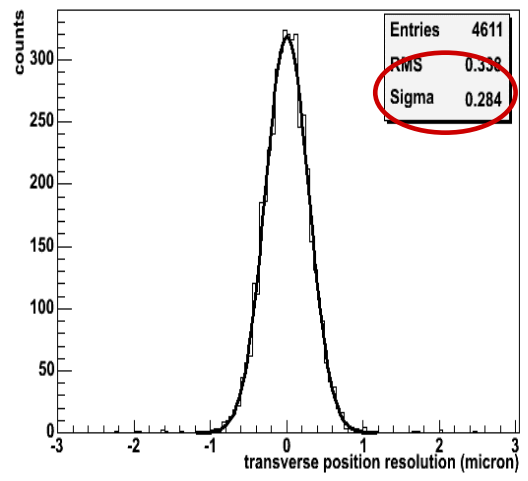
volume tracks  
(tracking efficiency= 0.93)

vertex  
reconstruction

angular residuals between  
base-tracks and fitted **volume tracks**



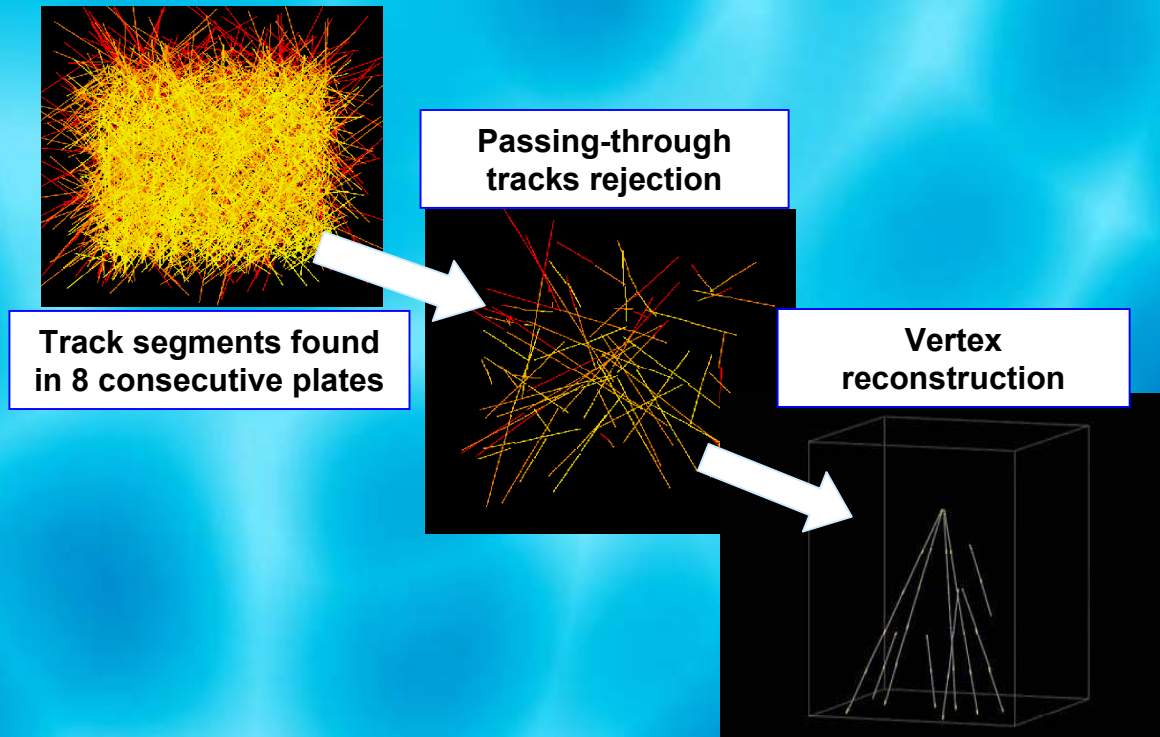
position residuals between  
base-tracks and fitted **volume tracks**





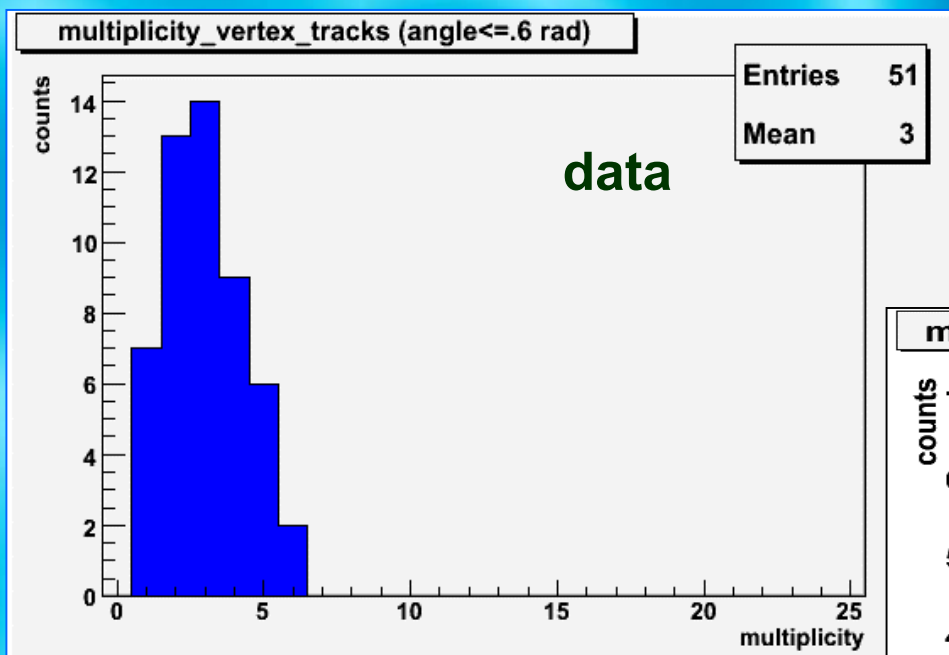
# Automated Vertex Search

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

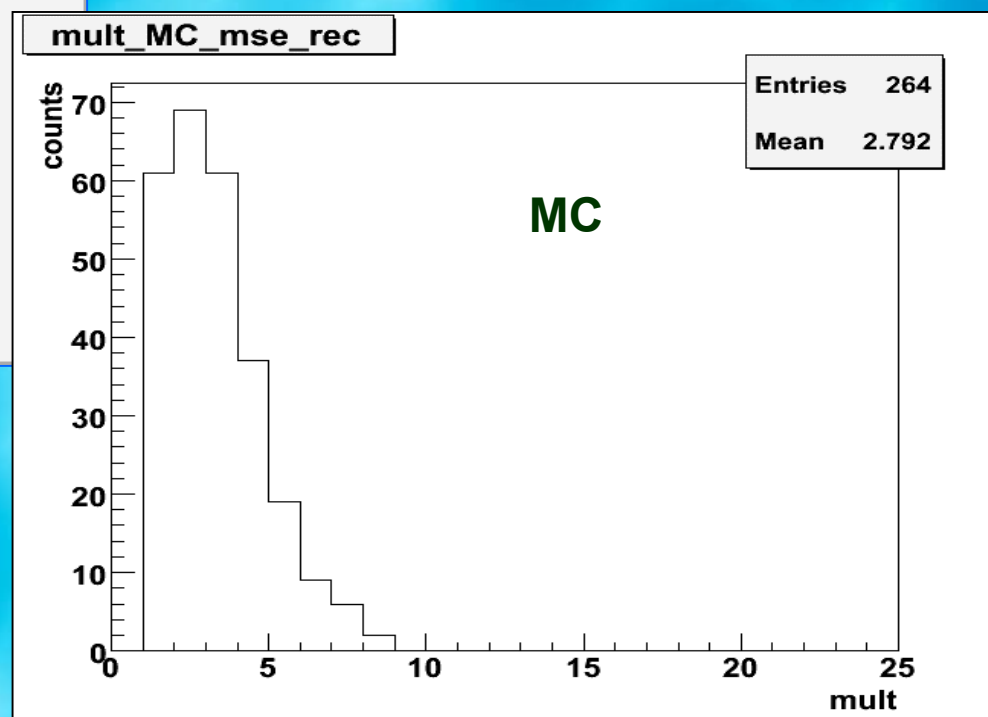




# Data-MC comparison



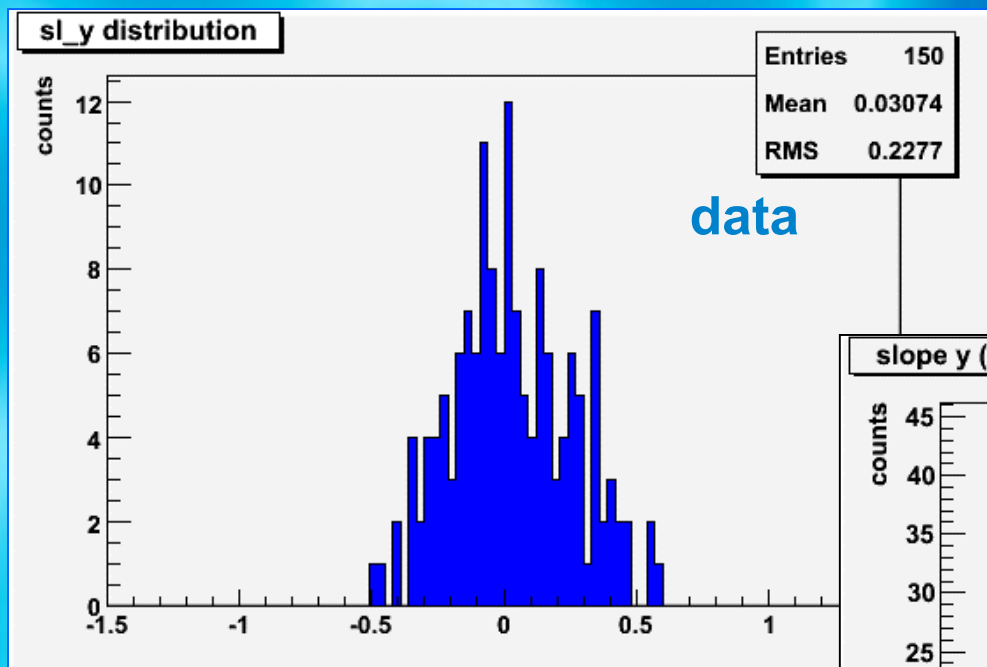
test beam at CERN PS  
 $\pi$  beam @ 8 GeV/c



preliminary

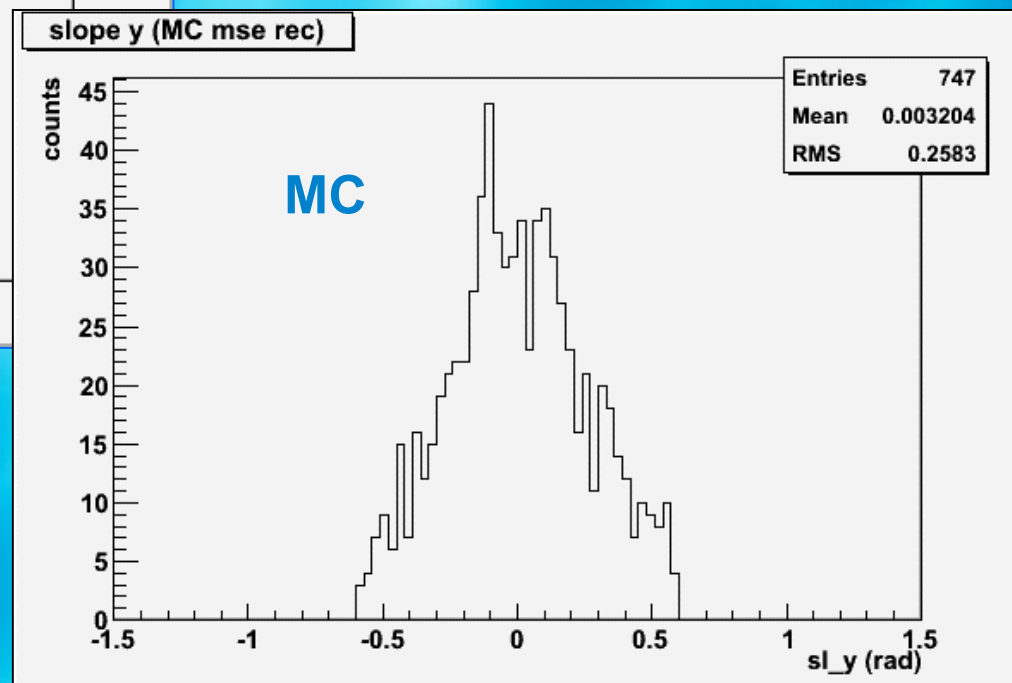


# Data-MC comparison



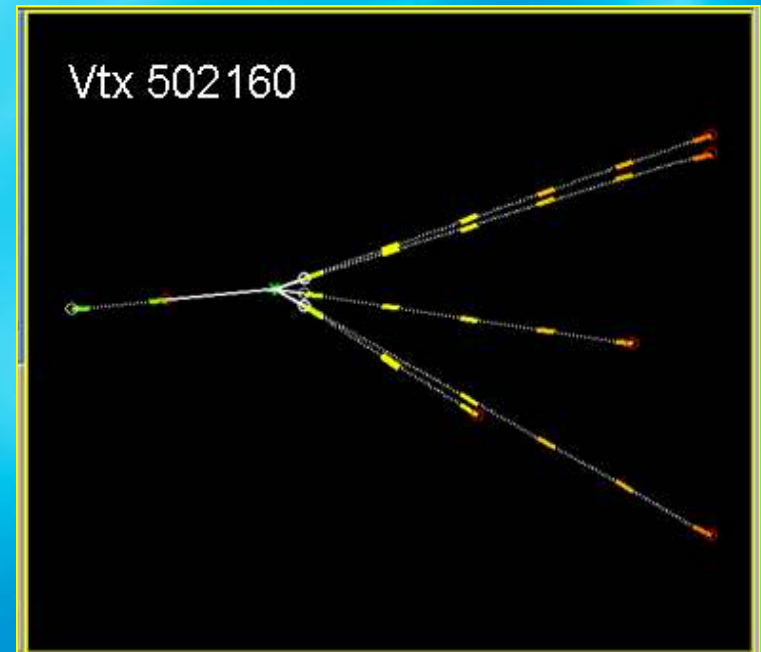
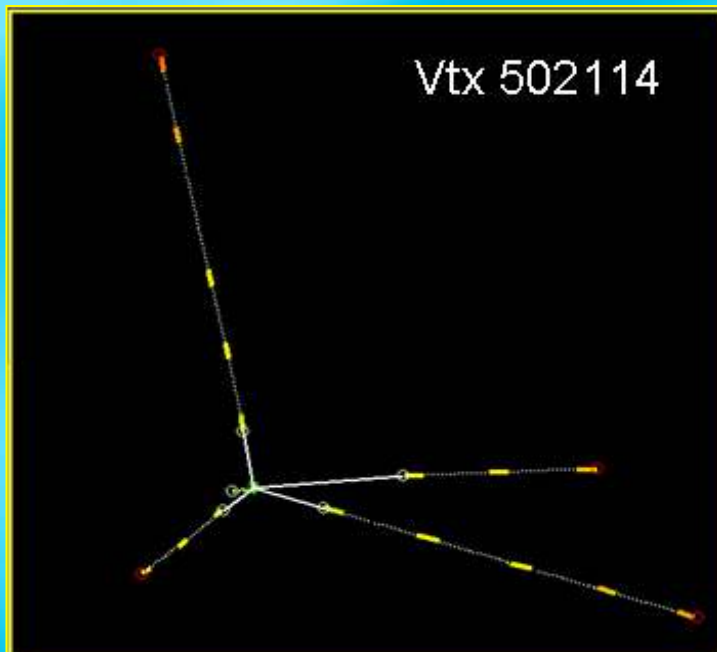
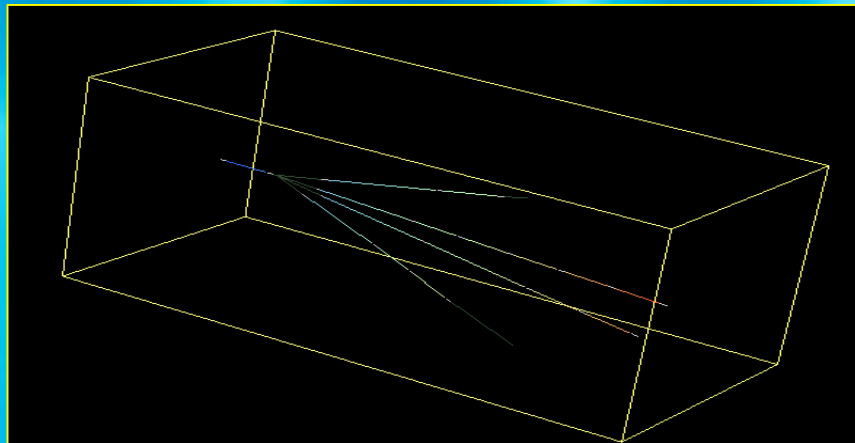
test beam at CERN PS  
 $\pi$  beam @ 8 GeV/c

preliminary





# Reconstructed vertices



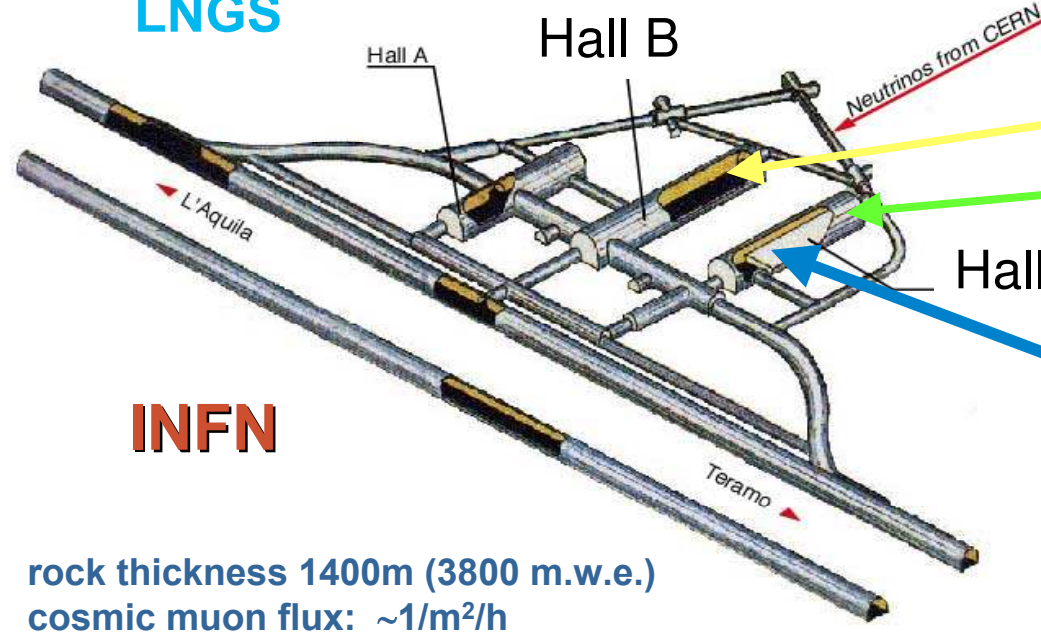


# OPERA at LNGS

Large underground laboratory  
for astro-particle physics



LNGS



INFN

ICARUS

BOREXINO

Hall C

OPERA (CNGS1)

underground area: 18 000 m<sup>2</sup>  
external facilities  
easy access



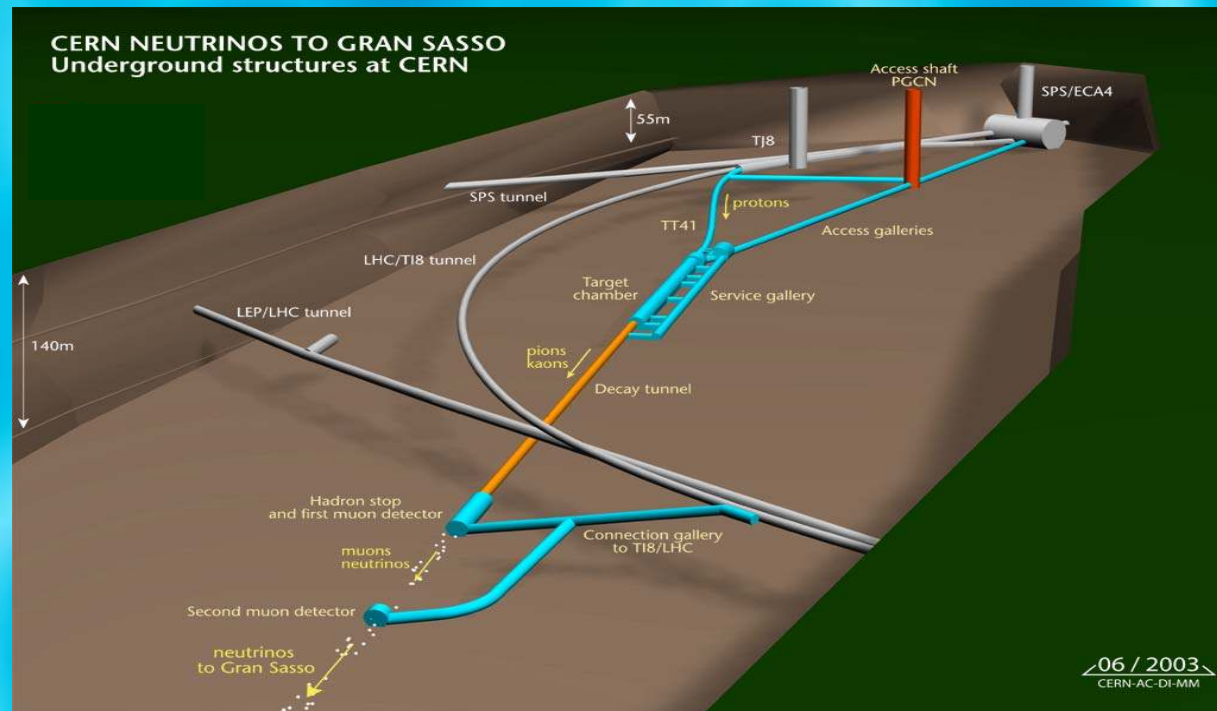
# The CERN Neutrino to Gran Sasso beam

## CNGS

400 GeV/c protons (CERN SPS) on graphite target  
 $\nu$  beam produced in the decay in flight of secondary  $\pi$ , 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%
$\nu_{\tau}$ prompt	negligible



$4.5 \times 10^{19}$  p.o.t./year,  
 200days/year  
 $\varepsilon = 55\%$  shared mode





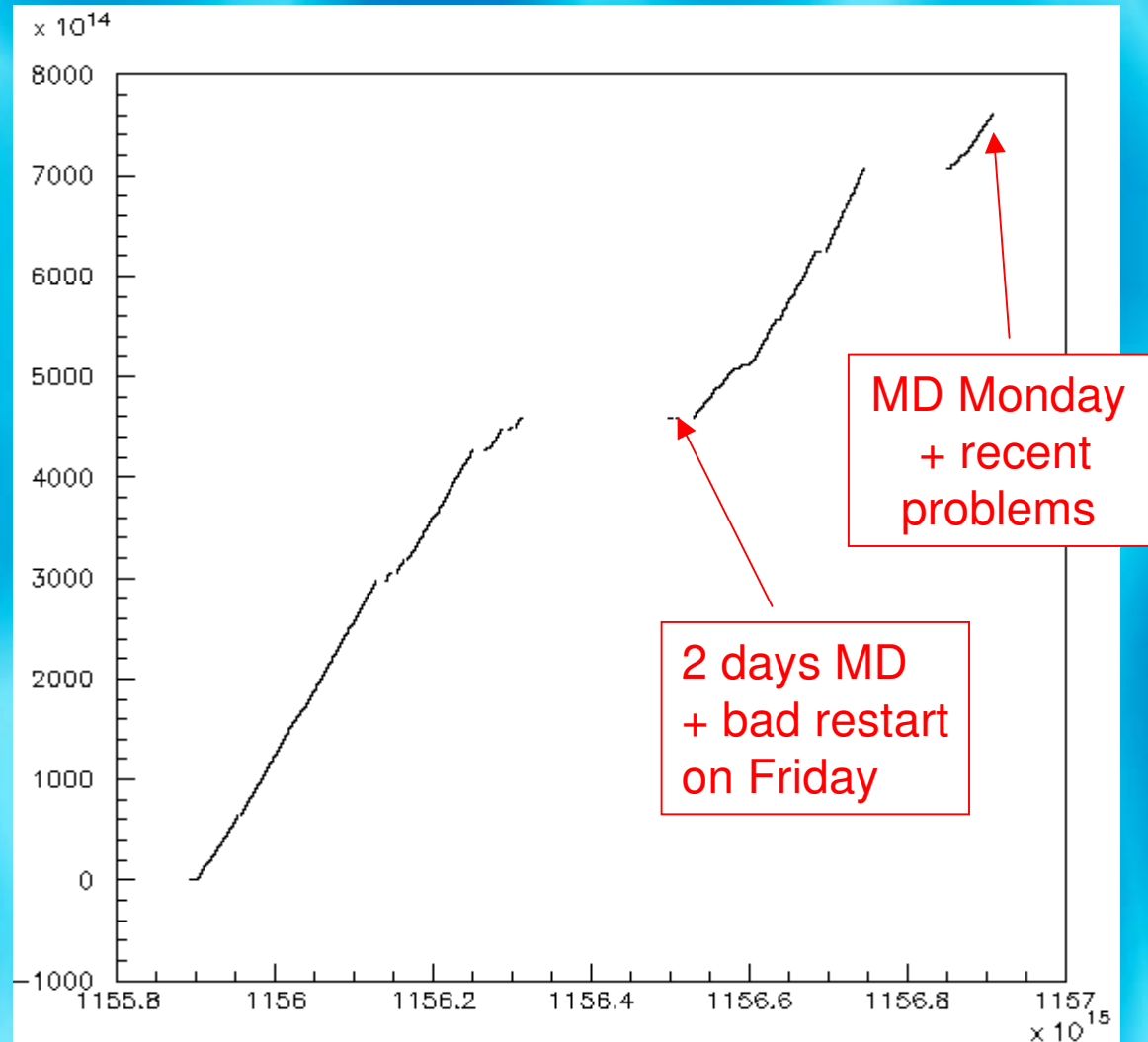
# August 2006 run: integrated intensity (pot) as a function of time

First CNGS neutrinos sent towards LNGS on August 18th

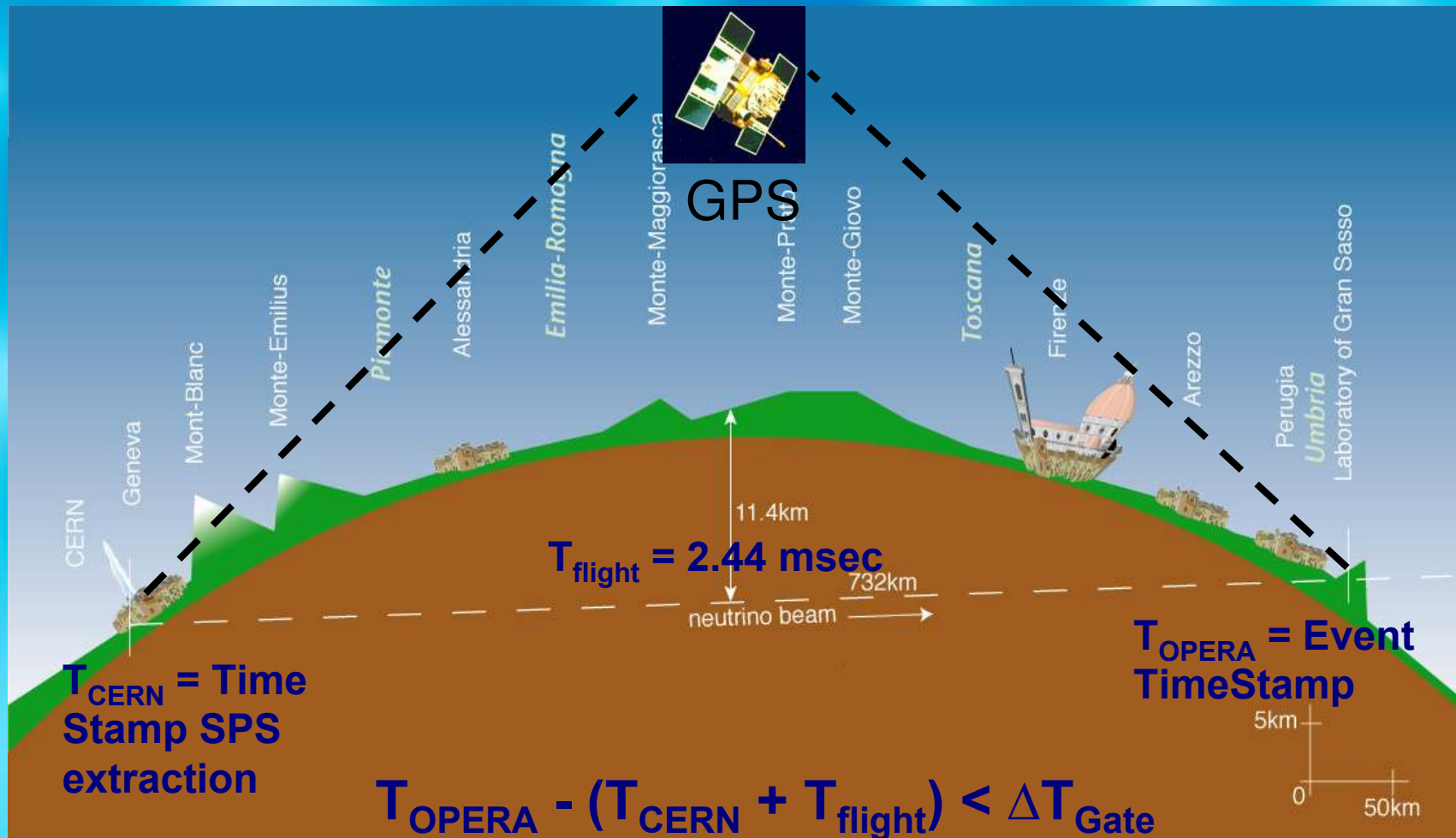
Low intensity run from August 18th to 30th

EXT1:  $3.81 \text{ E}17 \text{ pot}$   
EXT2:  $3.79 \text{ E}17 \text{ pot}$

**TOTAL :  $7.6 \text{ E}17 \text{ pot}$**



# Time Selection of Beam Events



GPS Time Stamp resolution  $\sim 100 \text{ ns}$

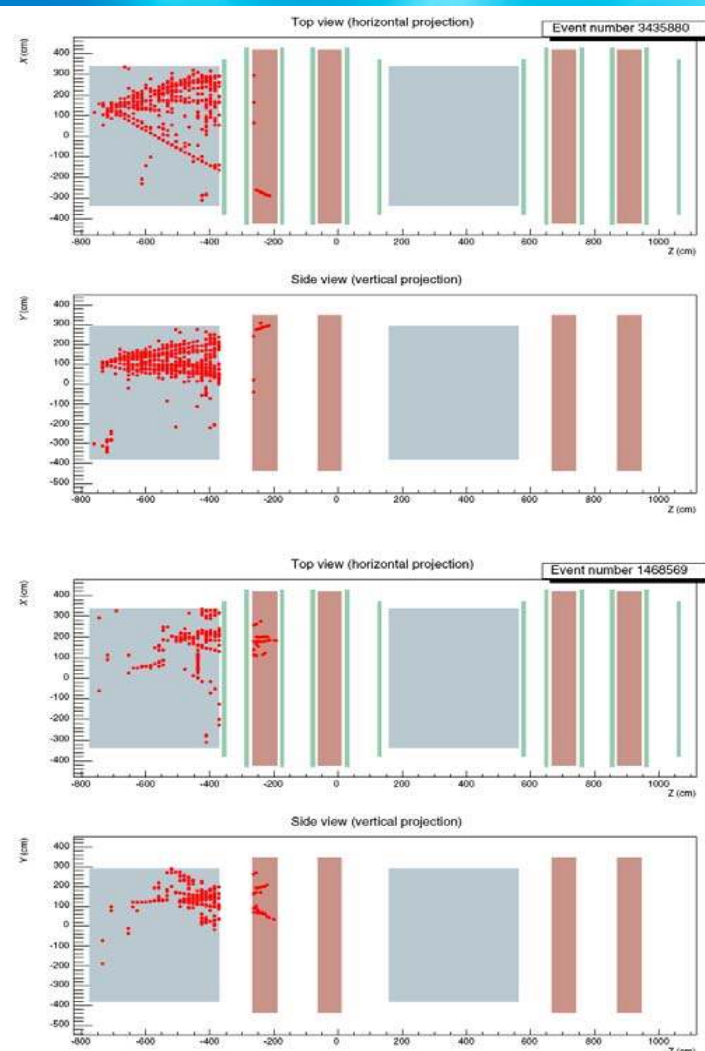
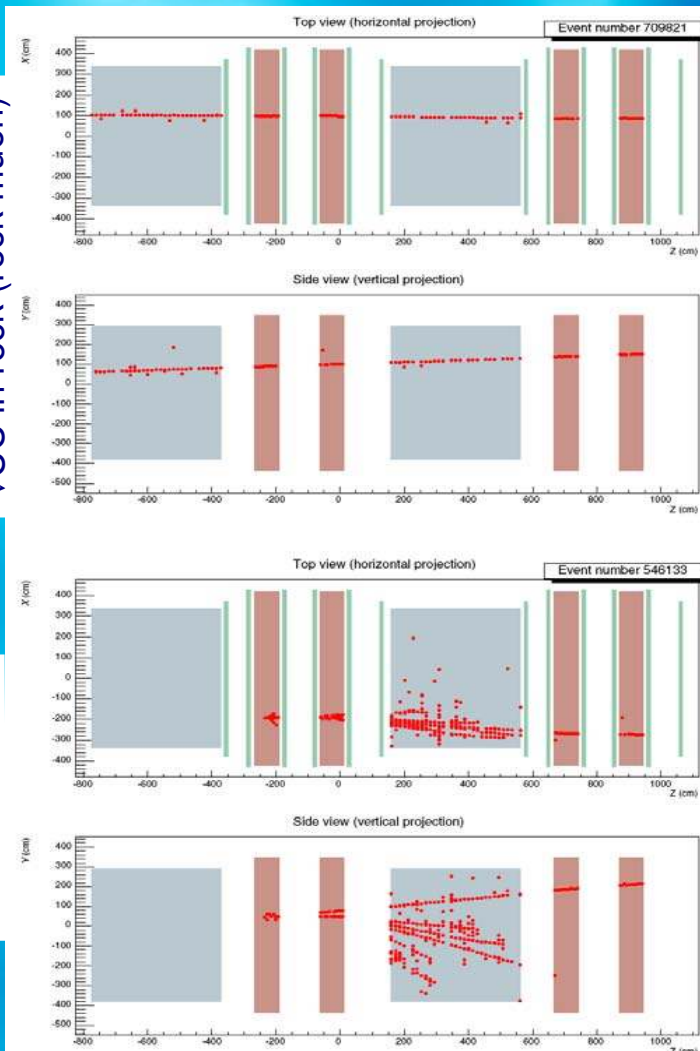


# Beam Events

320 events registered, 300 expected

$\nu_{CC}$  in rock (rock muon)

$\nu_{CC}$  in Magnet



$\nu_{CC}$  in T T

$\nu_{NC}$  in T T

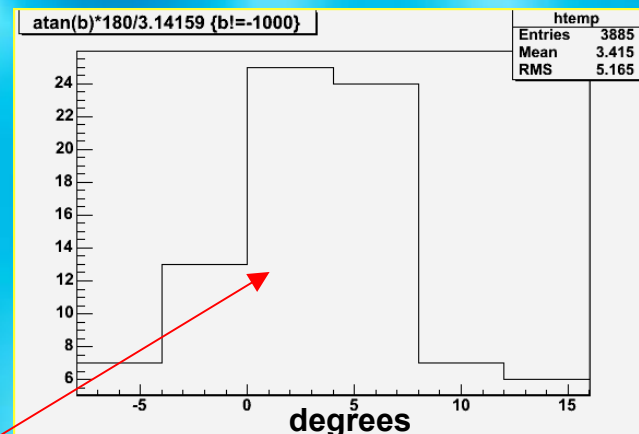
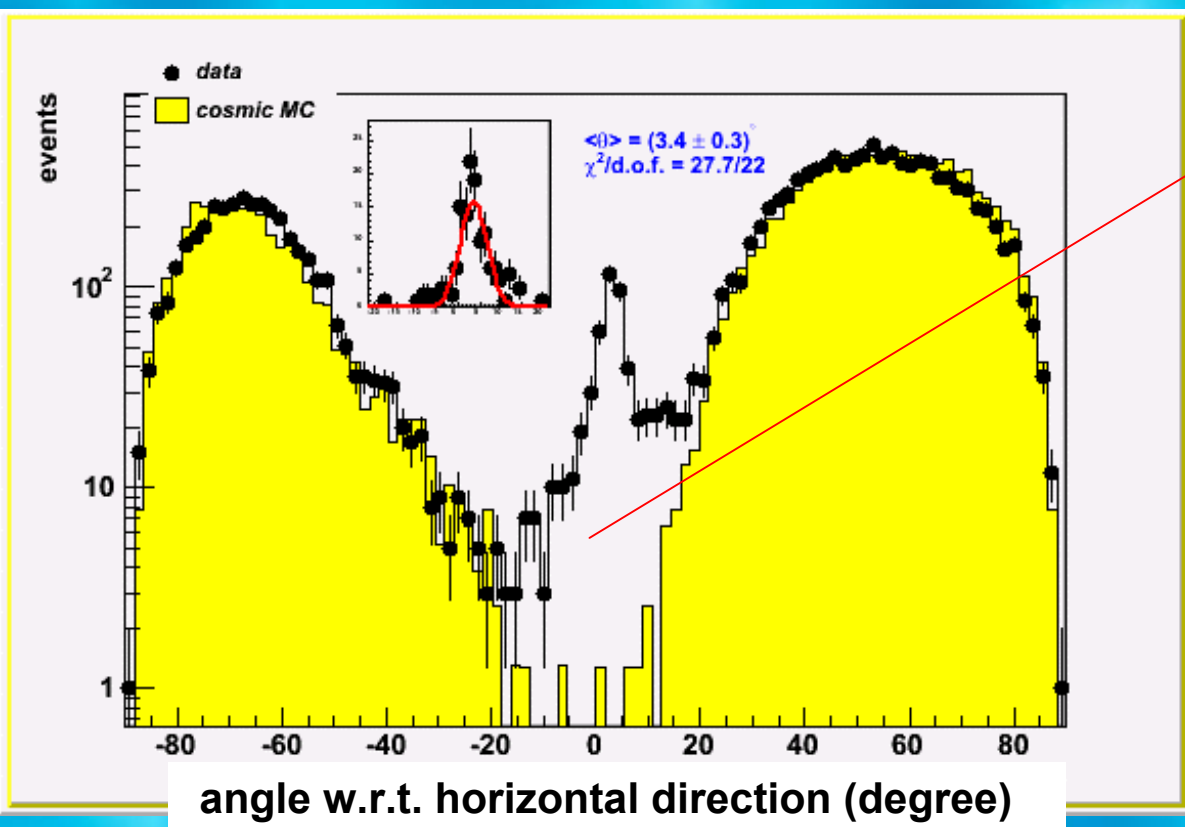




# Beam Direction Measurement

$$\langle \theta \rangle = 3.4 \pm 0.3 \text{ (statistically dominated)}$$

as expected

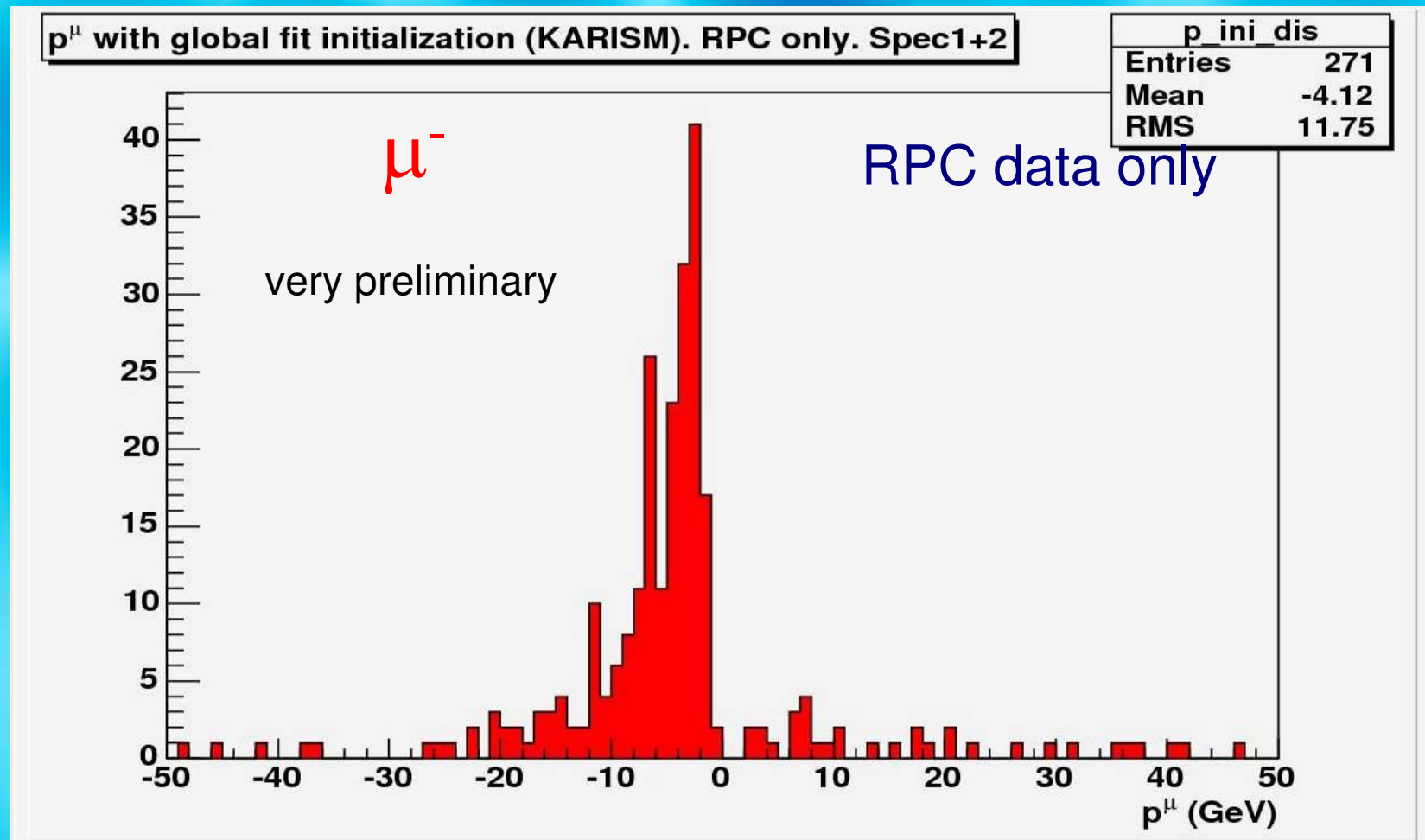


Number of on-time beam events  
registered in the August run  
~320

MC: simulation from MACRO  
parametrization,  
ABSOLUTE normalization



# Muon momentum measurement

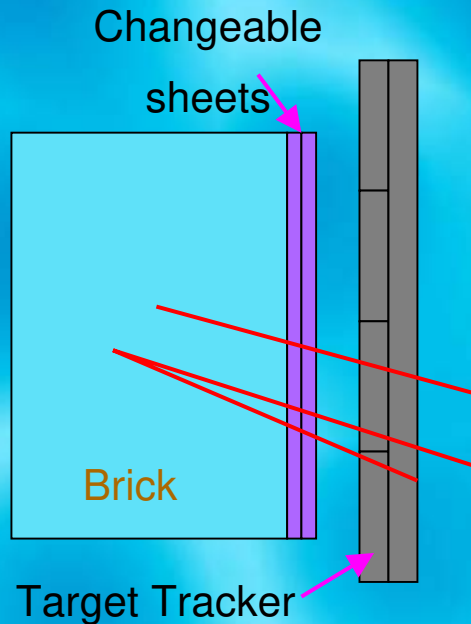




# Changeable Sheets in the August run

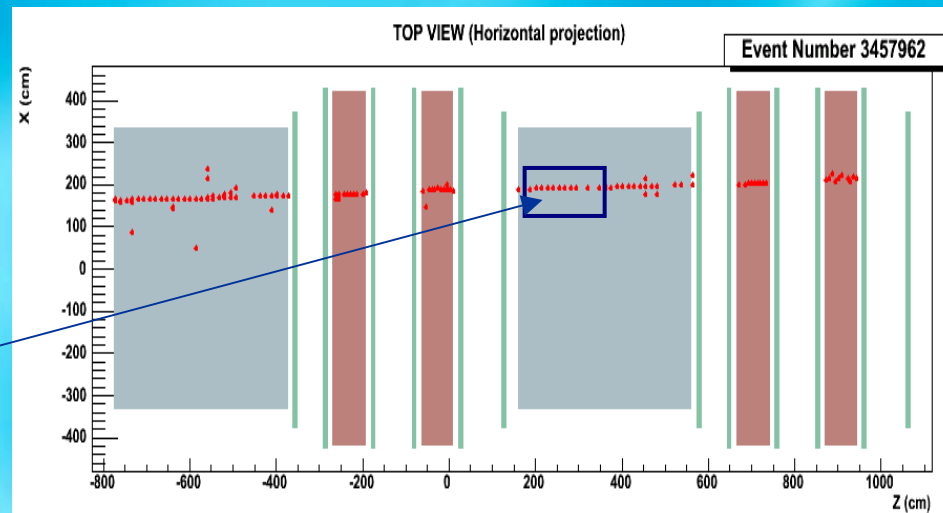
In the August run:

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



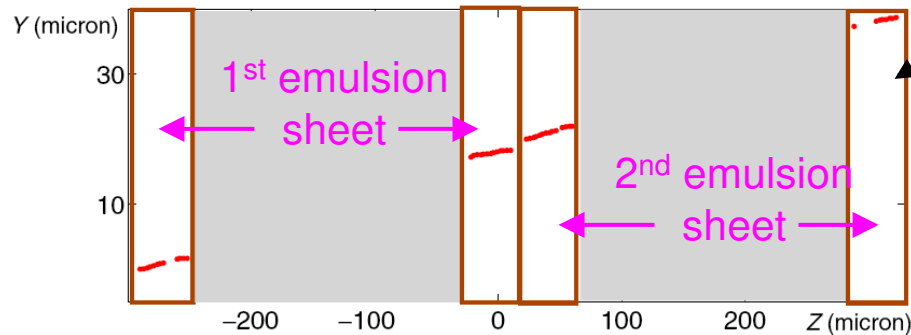
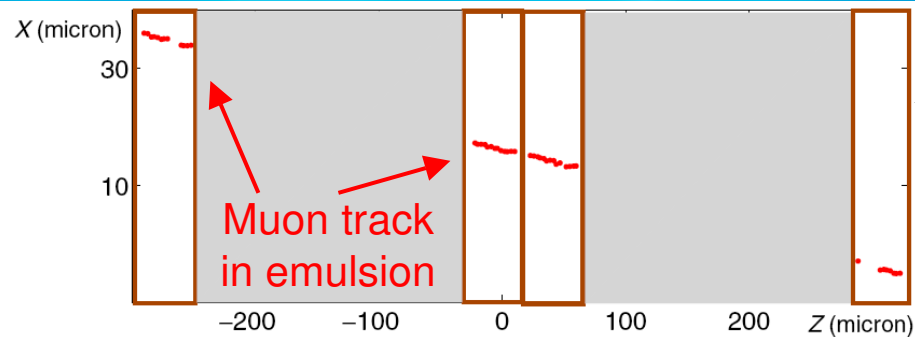




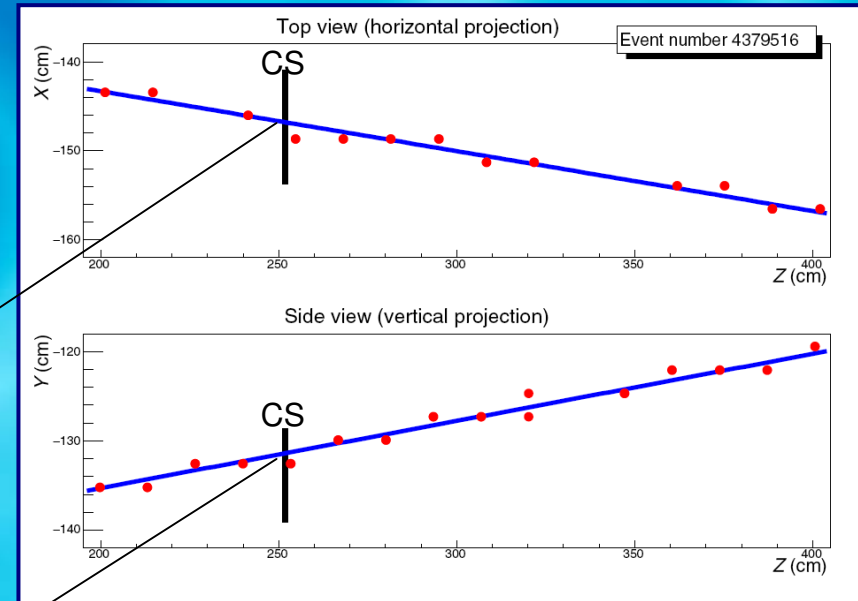
# Target Tracker to Brick connection

TT → CS → brick

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



Muon crossing the CS doublet

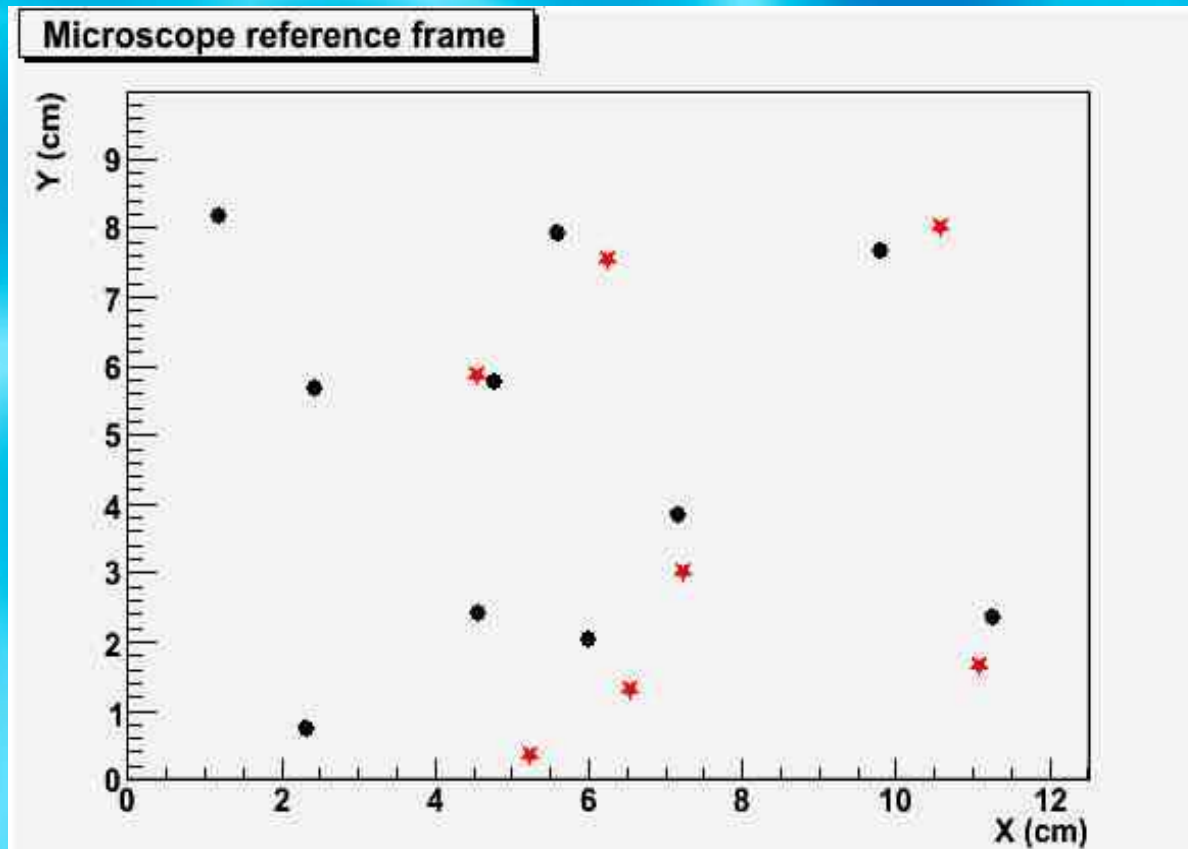


Difference between prediction and found track dominated by electronic detector resolution



# TT - CS

TT Predicted position CS Located position



AUGUST RUN

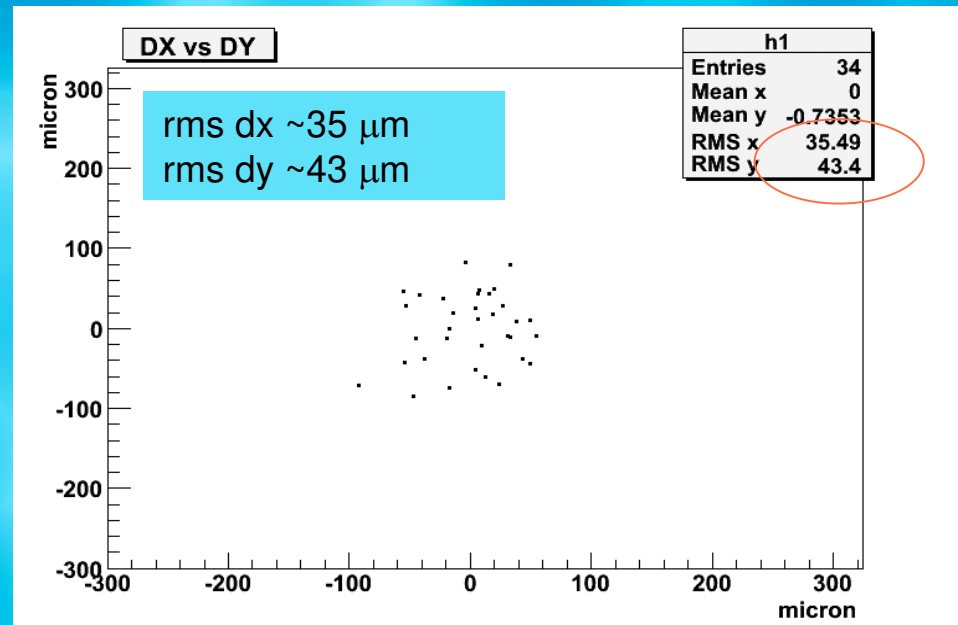
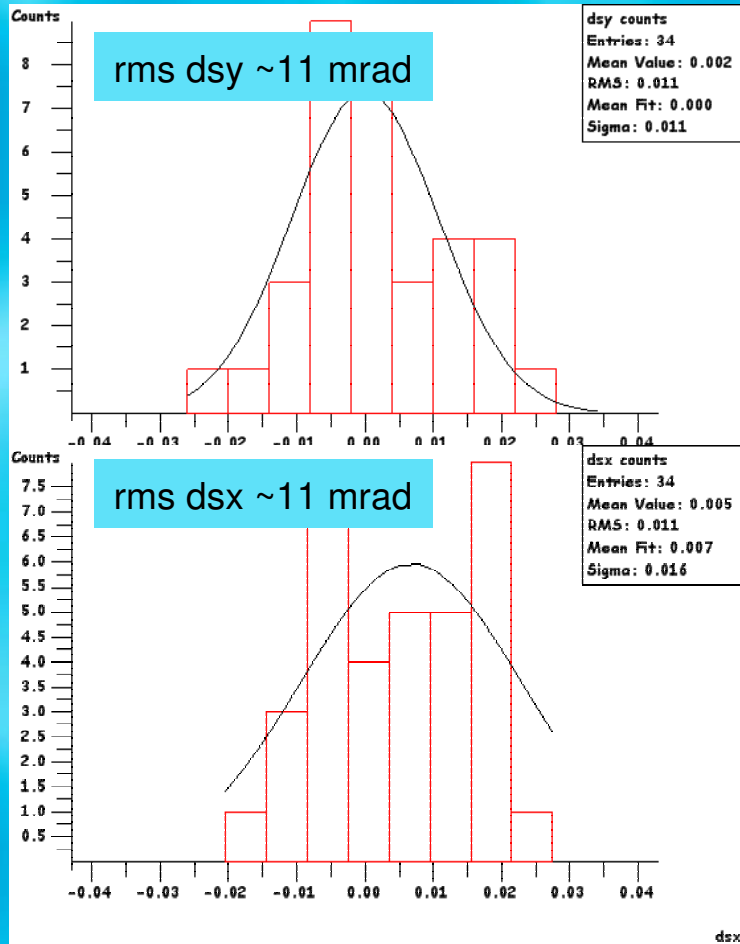
Differences between TT- CS :  
1 cm in position---15 mrad in slope



# CS to brick connection accuracy

TT → 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

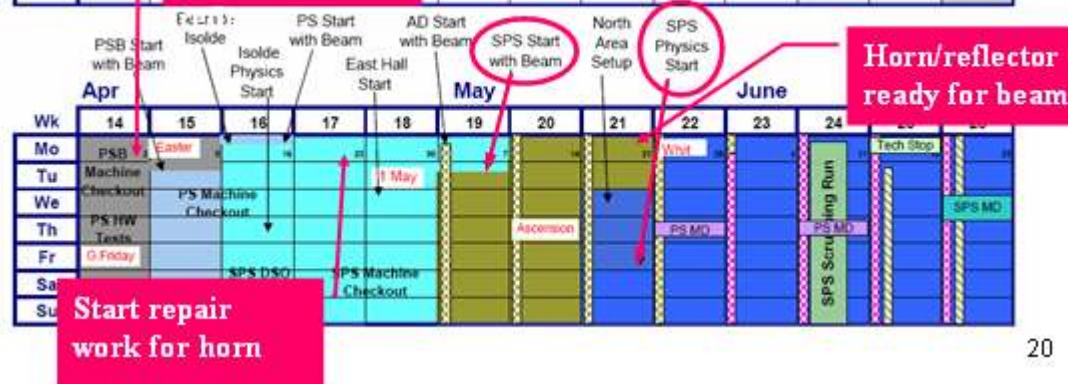
## Reflector Repair Schedule

Most optimistic scenario!

No contingency...

**Draft**

Start testing with  
spare horn in BA7  
(nominal conditions: current /  
water)



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

Immediately followed  
by two weeks of  
CNGS commissioning

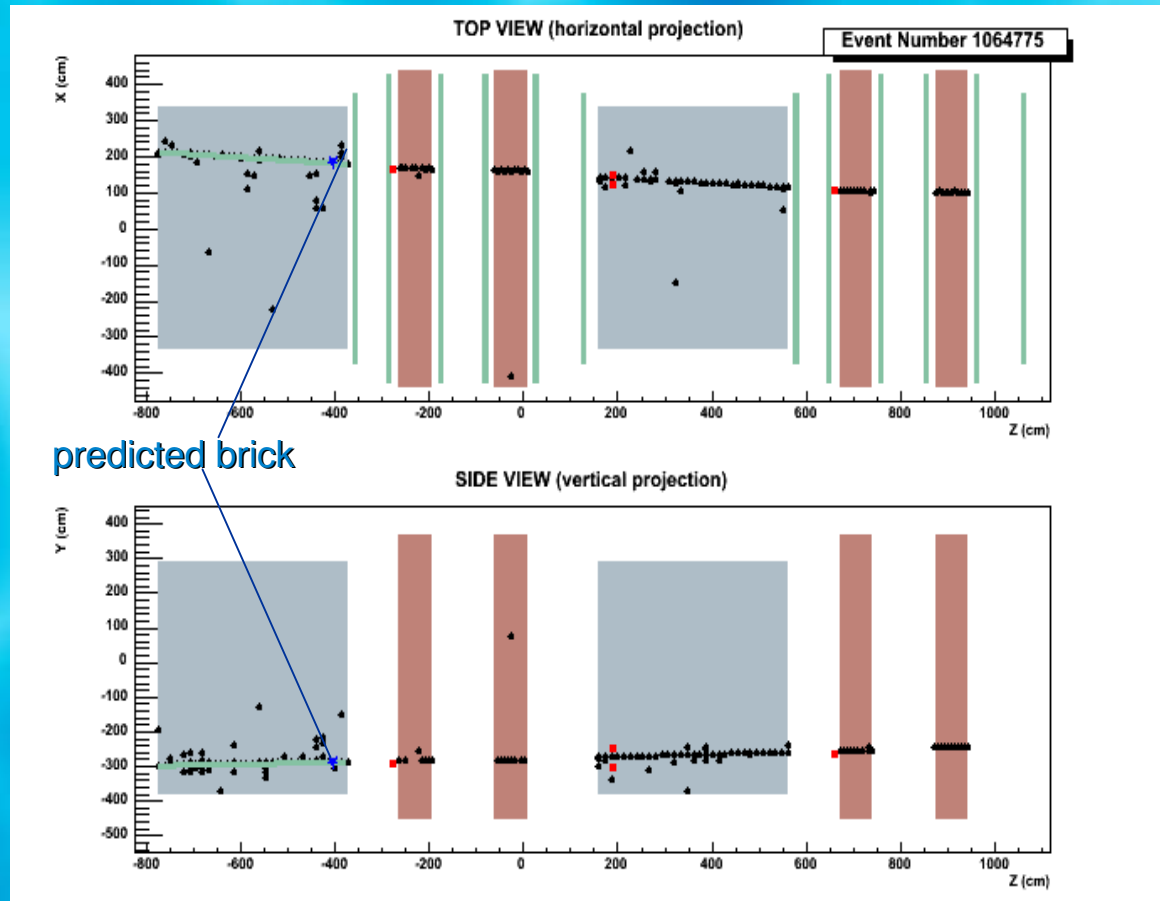
No contingency in the planning



# 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







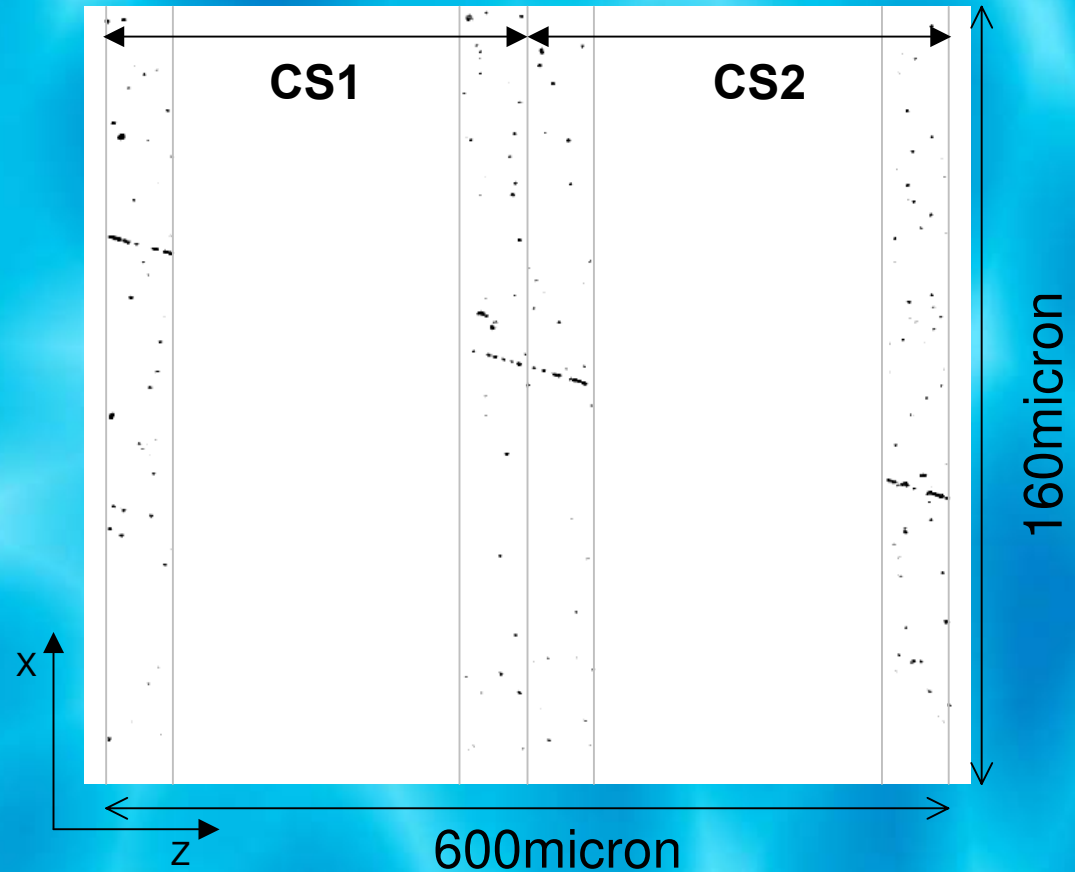
# First OPERA event recorded in emulsion

OCTOBER RUN

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

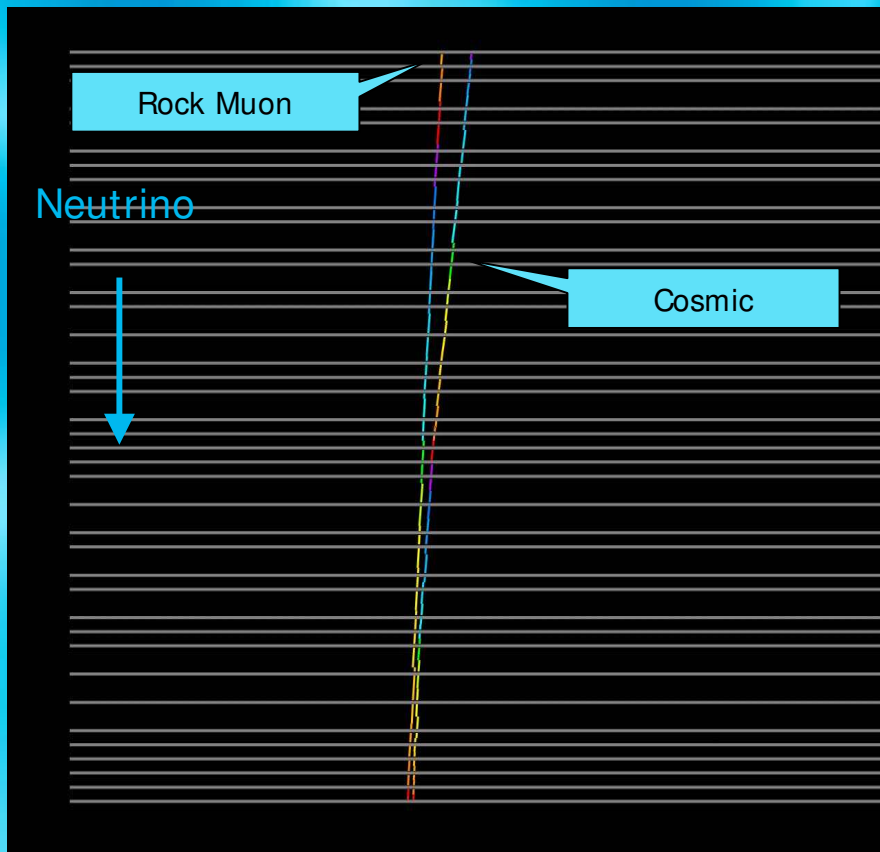
**TT-CS differences:**

<b>DX(cm)</b>	<b>DY(cm)</b>
-0.550	0.0415
<b>DSX(rad)</b>	<b>DSY(rad)</b>
-0.0166	-0.0248

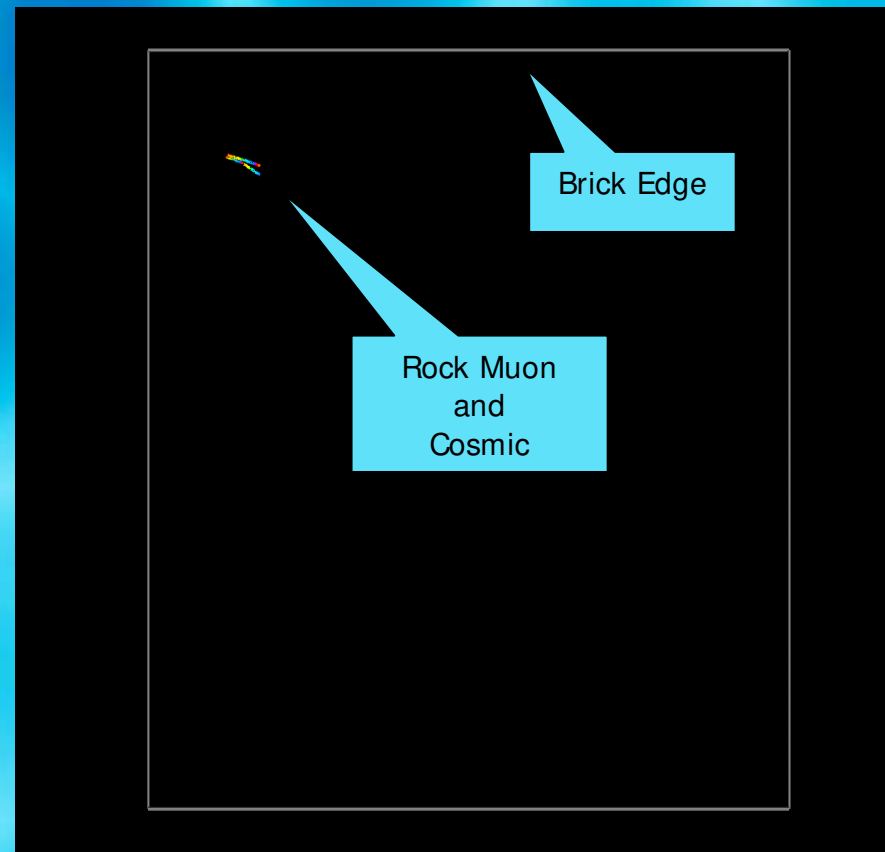


**Event 1064775 (Rock muon) Brick 1000370**

# 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  $\sim 1$  micron.

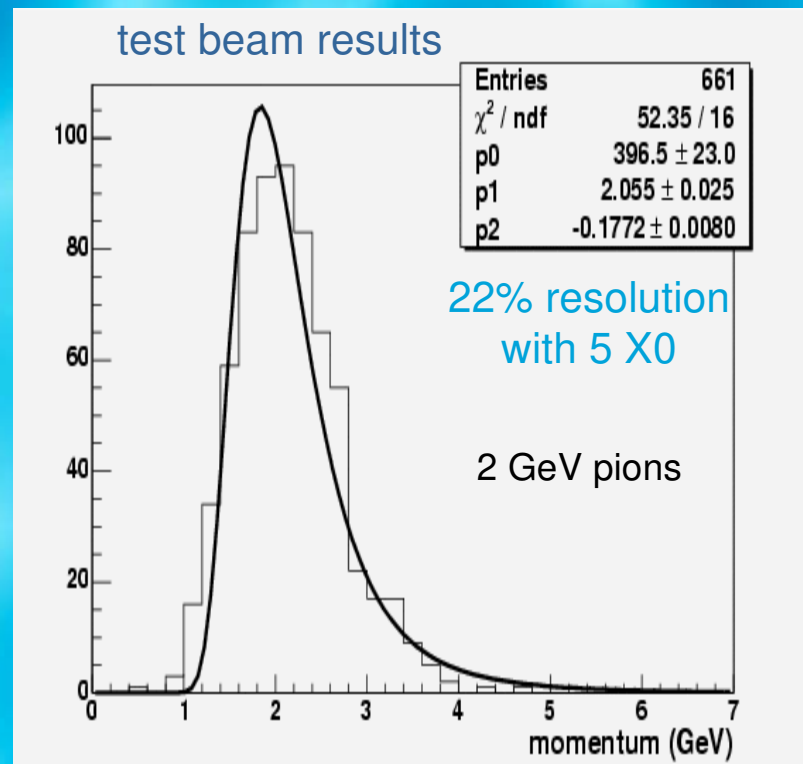
RMS of angle center displacement  $\sim 2$ -3 mrad

Momentum measurement  
by Multiple Scattering  
(Coordinate Method)

$6.4 +1.2 -0.9$  GeV/c

Momentum measurement  
by Spectrometer

$7.05 \pm 0.4$  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)

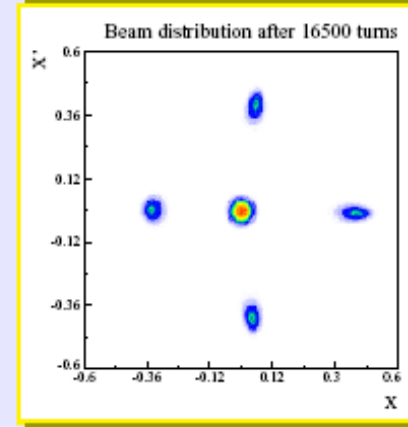
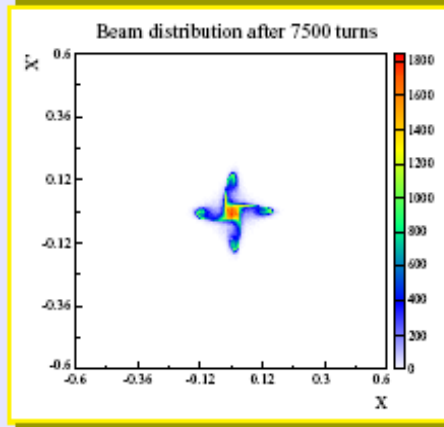
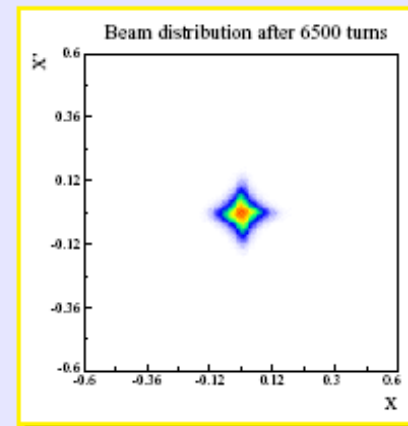
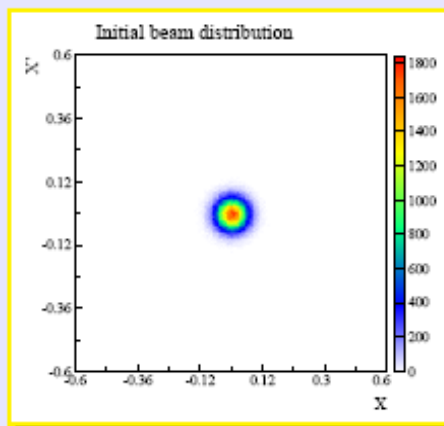
R&D and tests 2002-2004

Implementation study group 2005

March 2006 TDR

October 2006 Project approved

2008 completion





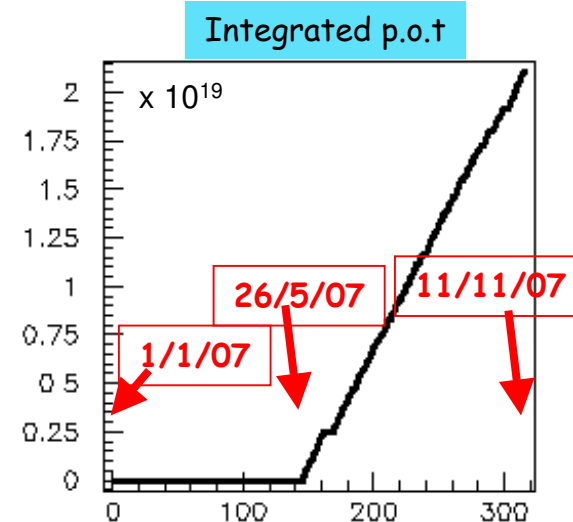
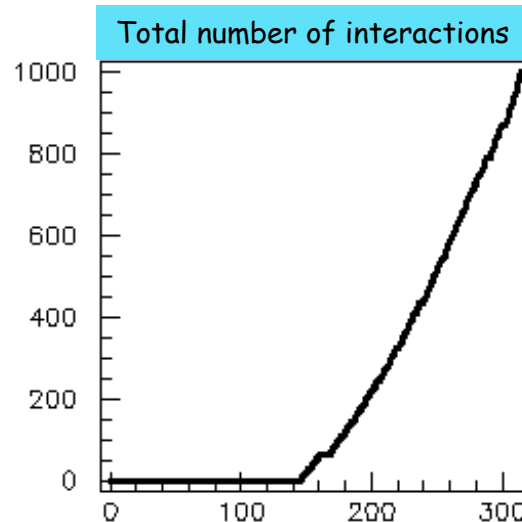
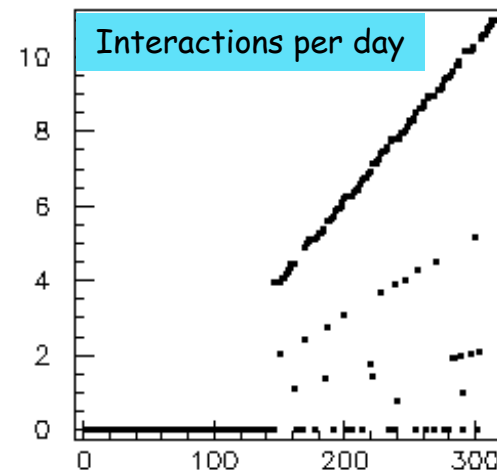
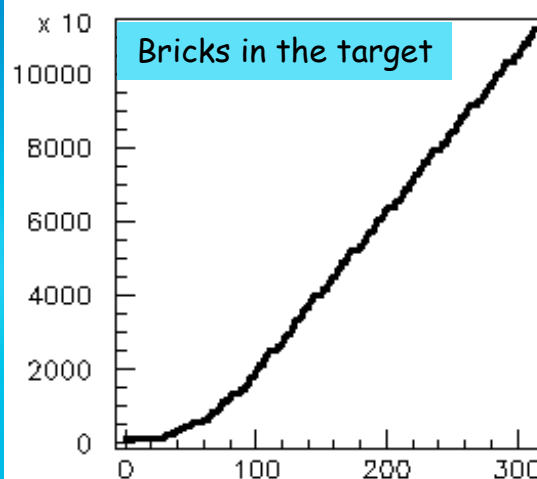
# 2007 OPERA Run

## Assumptions :

3 CNGS cycles  
(39.6 s,  $1.56^{E17}$  p.o.t/day)

700 bricks/day  
by the End of March

Bricks  
PS physics program  
Start: End:  
41000 112000







# Interaction rate

Official SPS schedule: 135.15 useful days

$1.7 \text{ } ^E13$  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	$2.1 \text{ } ^E19$	1001	3360
1 CNGS	40738	111982	$1.65 \text{ } ^E19$	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/disprove the  $\nu_\mu \leftrightarrow \nu_\tau$  oscillations at atmospheric  $\Delta m^2$  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.....