OPERA

Padova 15 aprile 2003
Lezioni per corso di Dottorato in Fisica

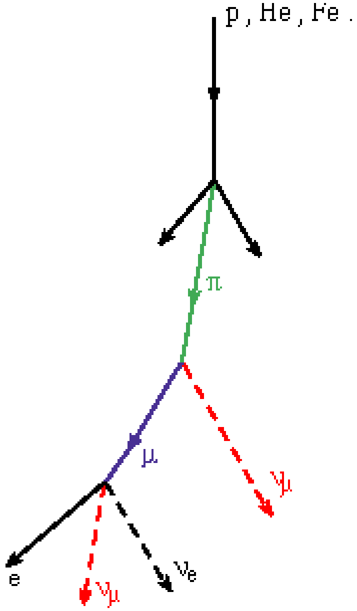
# Review of accelerator Long Baseline Neutrino Experiments

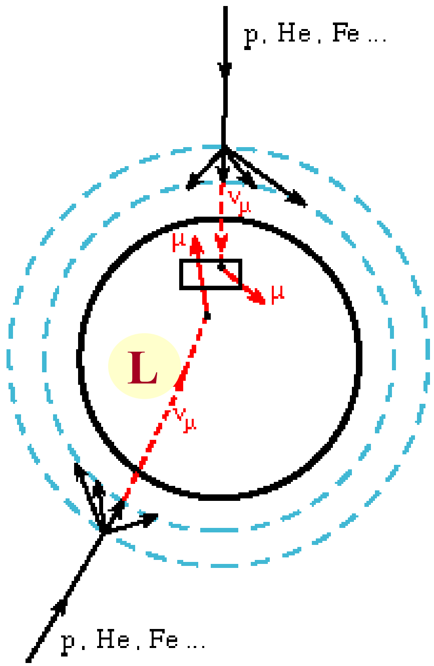
MINOS

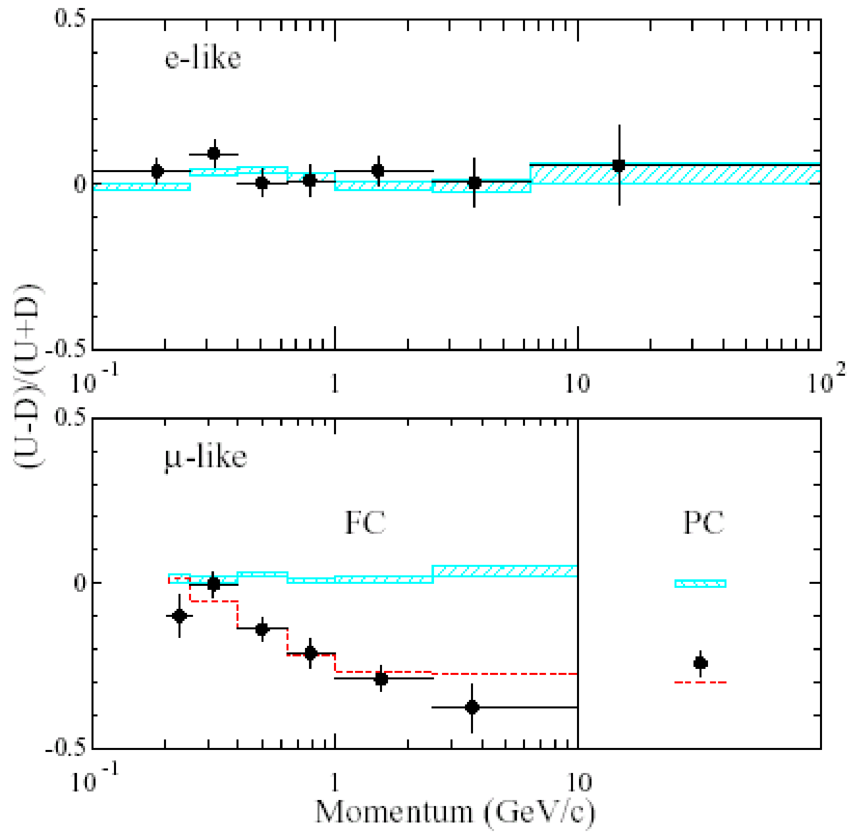
Imaging Cosmic And Rare Underground Signals

# Evidences from atmospheric neutrinos

(Kamiokande - SuperKamiokande , supported by MACRO and Soudan 2)



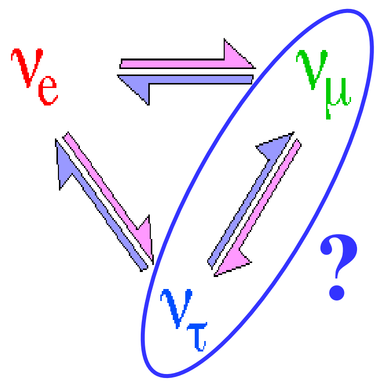




**Overall ratio**

**$\nu_\mu : \nu_e$**

**~ ½**

of **2:1** as expected

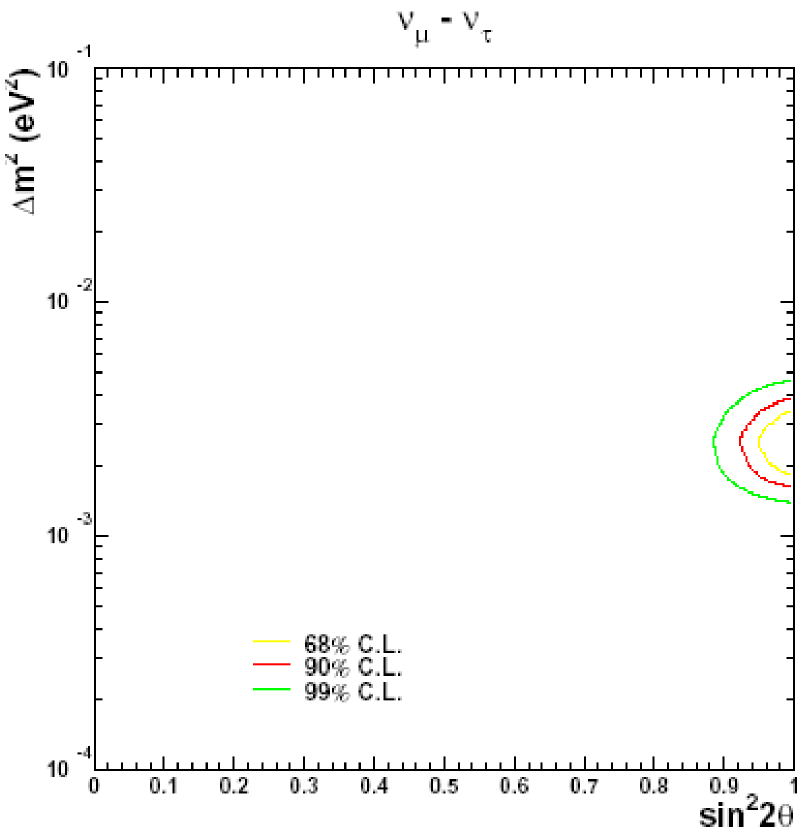



**$\nu_\mu$ deficit increasing with L**

**no anomaly for $\nu_e$ : no $\nu_\mu \rightarrow \nu_e$**

**$\nu_\mu \rightarrow \nu_\tau$ oscillation?**

# SK atmospheric neutrinos




## No oscillation

$\chi^2_{min} = 456.5/170$ d.o.f.)

## $\nu_\mu \leftrightarrow \nu_\tau$

Best fit:

$\Delta m^2 = 2.5 \times 10^{-3} eV^2, \sin^2 2\theta = 1.0$

$\chi^2_{min} = 163.2/170$ d.o.f.)

$\Delta m^2 \in 1.6 \sim 3.9 \times 10^{-3} eV^2$

$\sin^2 2\theta > 0.92$ 90% C.L.

$\nu_\mu \rightarrow \nu_{sterile}$ disfavored at 99%

# The atmospheric $\nu_\mu$ deficit

- There is an apparent deficit of atmospheric $\nu_\mu$'s seen in both Cerenkov detectors and calorimeters
- While the atmospheric flux has large uncertainties, the L/E dependence implies oscillations
- If it is oscillations, $\Delta m^2 \sim 3 \times 10^{-3}$ eV$^2$ @$\sin^2 2\theta = 1$
- It is likely to be $\nu_\mu$-$\nu_\tau$ ($\nu_\mu$-$\nu_s$ oscillations are excluded at 99% CL)

# Why long baseline experiments?

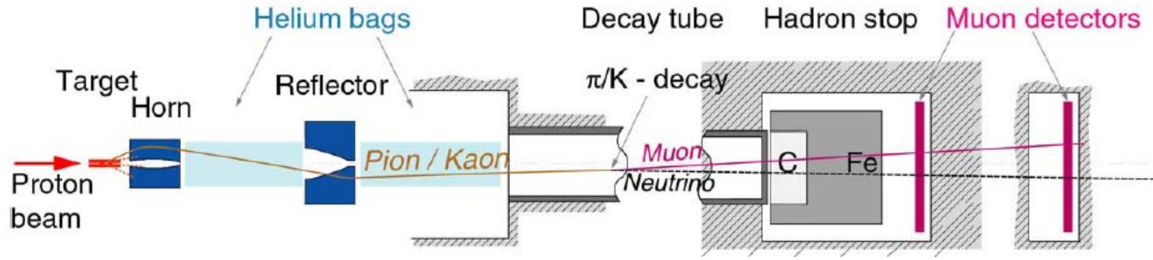
- ✓ Check atmospheric neutrino results with a controllable $\nu_\mu$ beam
- ✓ See $\nu_\tau$ appearance
- ✓ Measure the product $|\Delta m^2_{23}| \times \theta_{23}$ with ~10% precision
- ✓ Measure $\nu_\mu \to \nu_e$ and $\theta_{13}$
- ✓ Constrain or measure $\nu_\mu \to \nu_s$

# Introduction to Long Baseline experiments



- Intense pure $\nu_\mu$ beam from $\pi$/K decay with low $\nu_e$ contamination
- $\Delta m^2 = 2.5 \cdot 10^{-3}$ eV$^2$

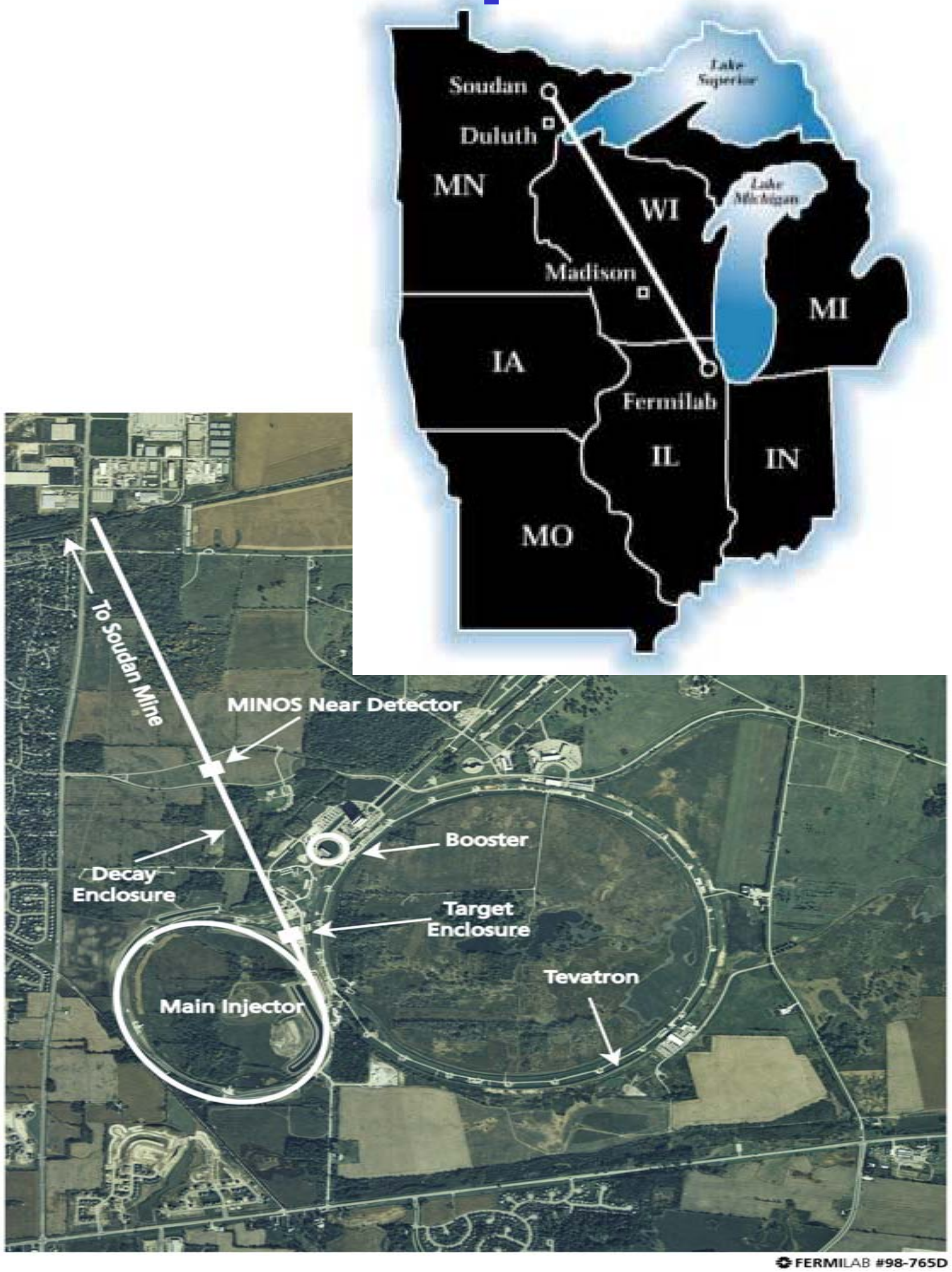
  $\Rightarrow$ L/E ~ 500 Km



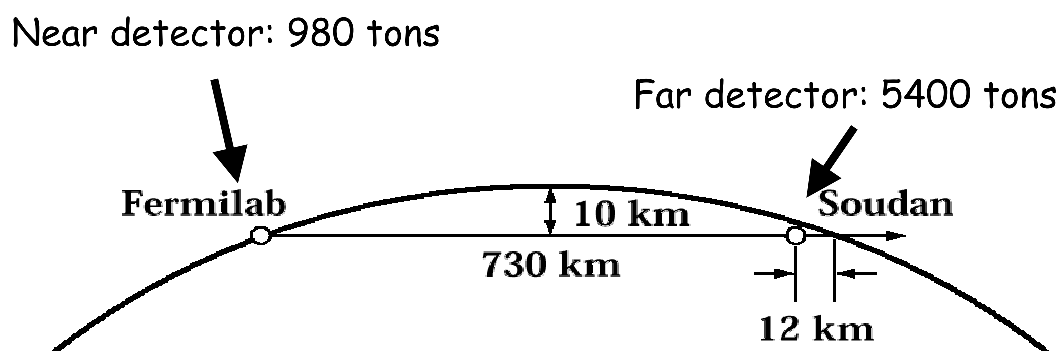

- Experiments
  - Disappearance or Statistical appearance experiment: K2K – MINOS
    - oscillation evidence and parameters measurement from
      - ➢ Charged Current (CC) interaction rate and energy distribution
      - ➢ NC/(CC+NC) ratio
    - Two detectors to reduce systematic errors
    - Beam energy tuned according $\Delta m^2$
    - Observe L/E dependence of $P_{\alpha\rightarrow\beta}$
  - Appearance experiments: OPERA – ICARUS
    - Direct observation of $\nu_\tau$
      - ➢ OPERA: visual scanning $\rightarrow$ high spatial resolution $\sigma < 1\mu$m
      - ➢ ICARUS: kinematical analysis $\rightarrow$ precision calorimetry

        $\sigma(E)/E = 3\%(12\%)/\sqrt{E}$ e.m. (had)
    - Beam tuned for $\tau$ production

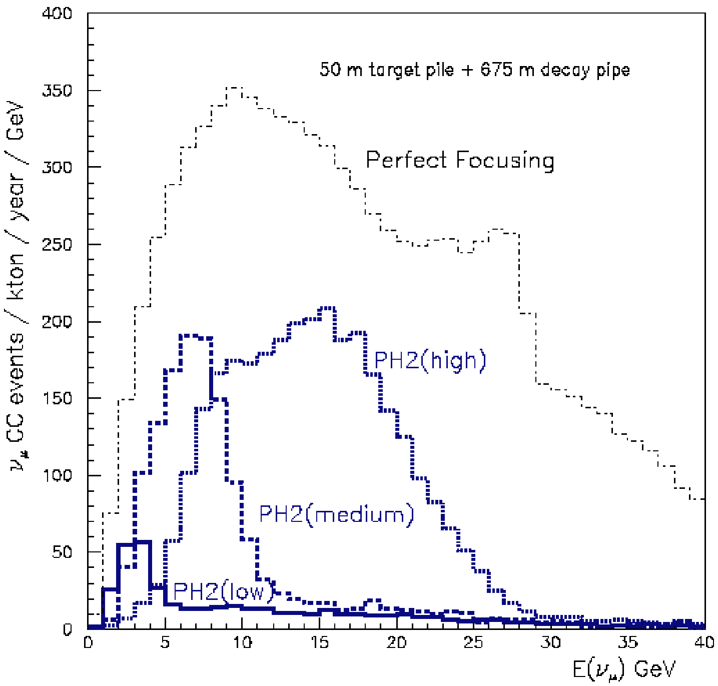
# MINOS Experiment

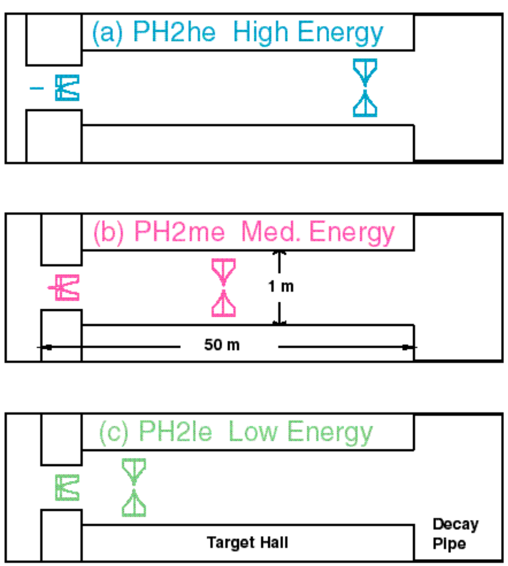



- Located in Soudan mine,
  730 Km from Fermilab
- $\nu_\mu$ (NuMi) beam: 120 GeV protons from Main Injector ($3.7 \cdot 10^{20}$ pot/year)
- Near and Far detector
  Iron/Scintillator tracking calorimeter
- Start taking data 2005

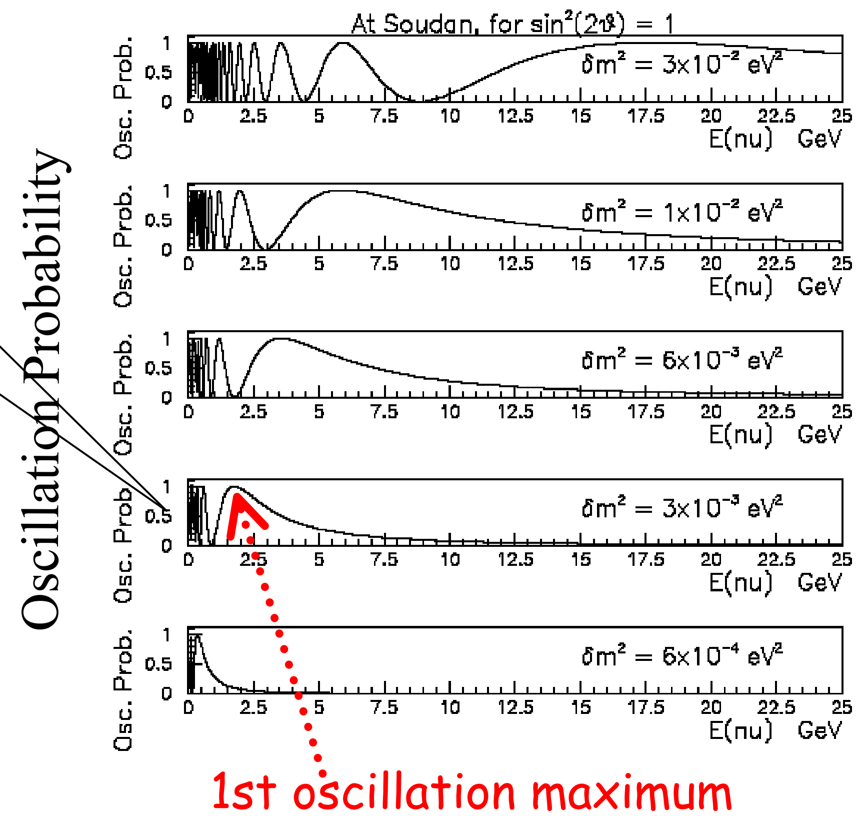


# The NuMi neutrino Beam



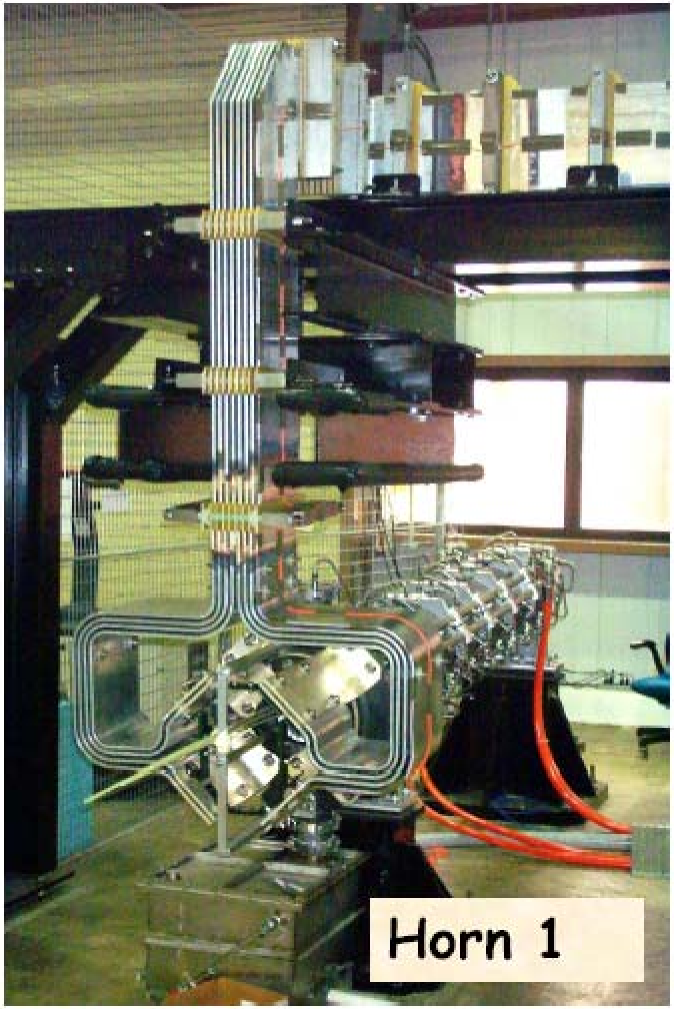

SK best fit

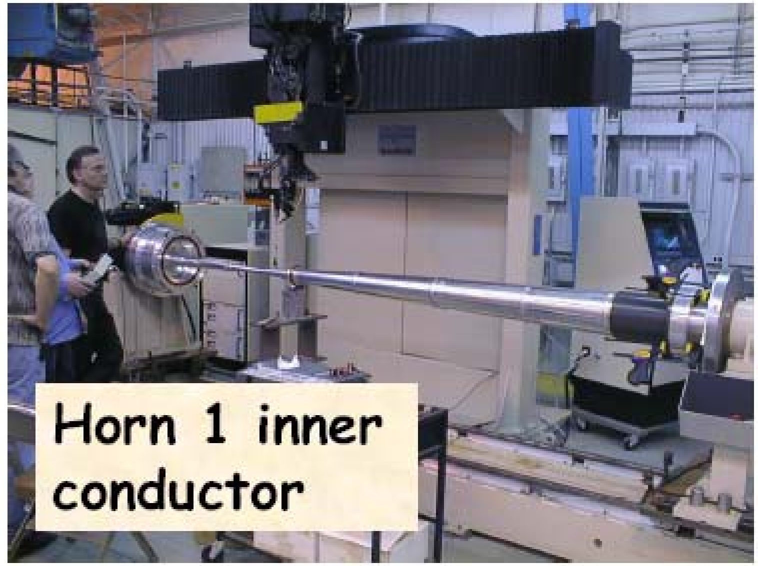


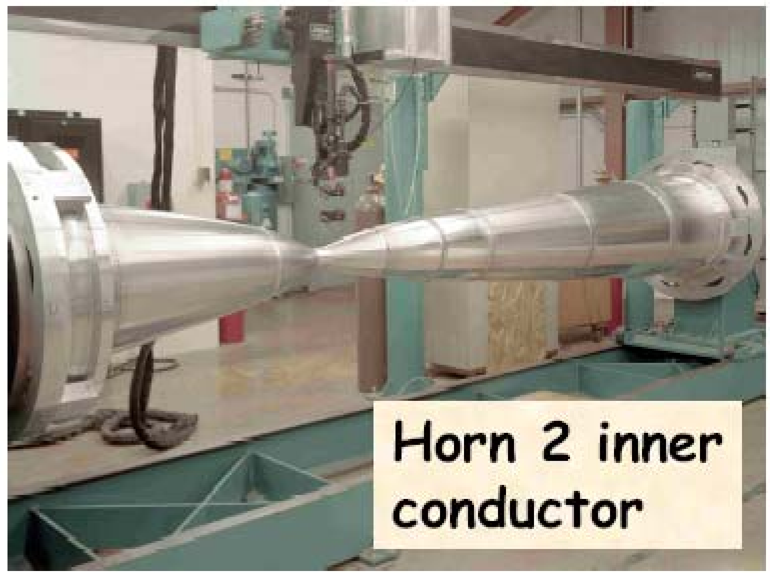

- With a parabolic shaped horn inner conductor, the horn behaves like a lens ($p_t$ kick proportional to the distance from the axis) with a focal length proportional to the momentum.
- Horn 2 and target are movable to change beam energy

Need the low energy beam with $\langle E_\nu \rangle$ = 7.6 GeV to see 1st oscillation maximum which occurs at ~ 2 GeV

# NuMI horns

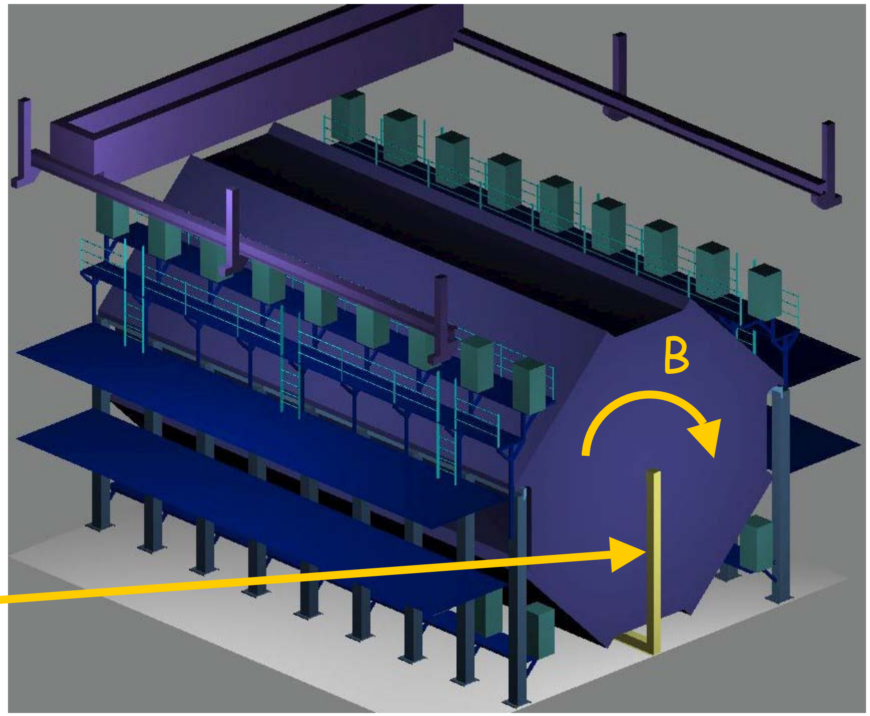


# MINOS Far Detector

- 8m Octagonal Tracking Calorimeter
- 486 layers of 2.54cm Fe
- 2 sections, each 15m long
- 4cm wide solid scintillator strips with WLS fiber readout
- 25,800 $m^2$ active detector planes
- Magnet coil provides <B> ≈ 1.3T
- 5.4kt total mass (3.3 kt fiducial)

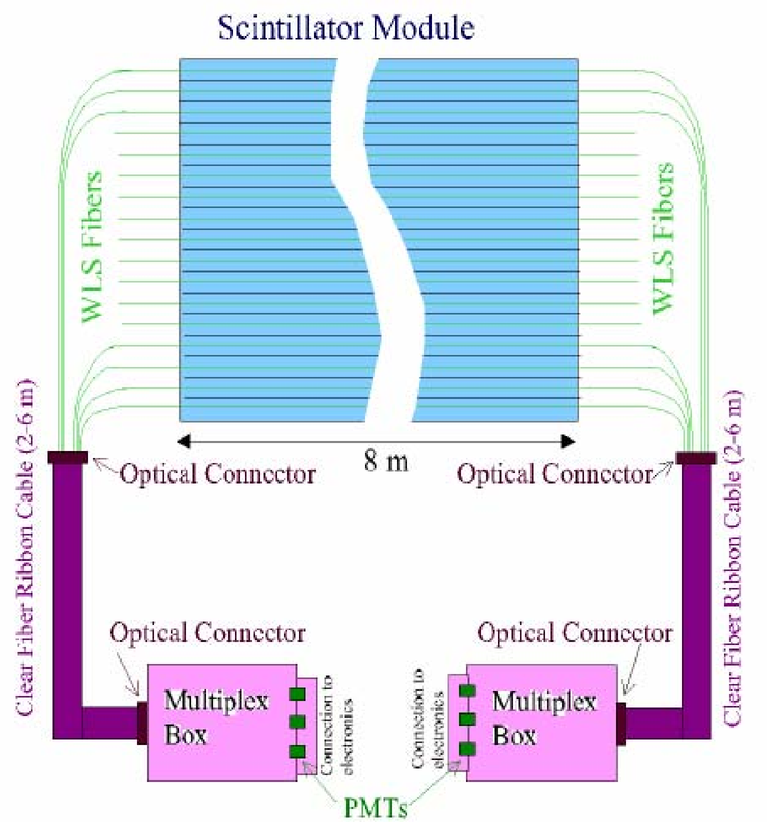



Half of the MINOS Detector

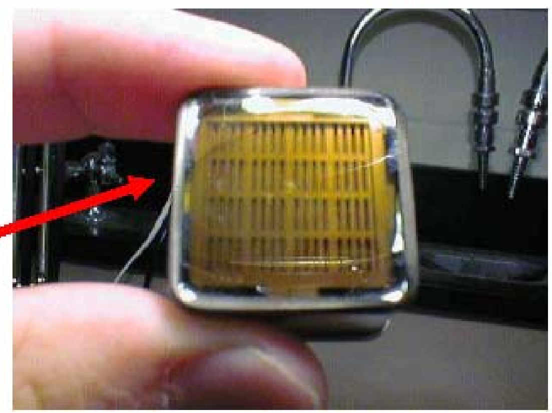
8m x 8m x15m

# Detector Technology

Detector module with 20 scintillator strips




MUX boxes route 8 (1 in Near Detector) fibers to one MAPMT pixel



# MINOS Near Detector

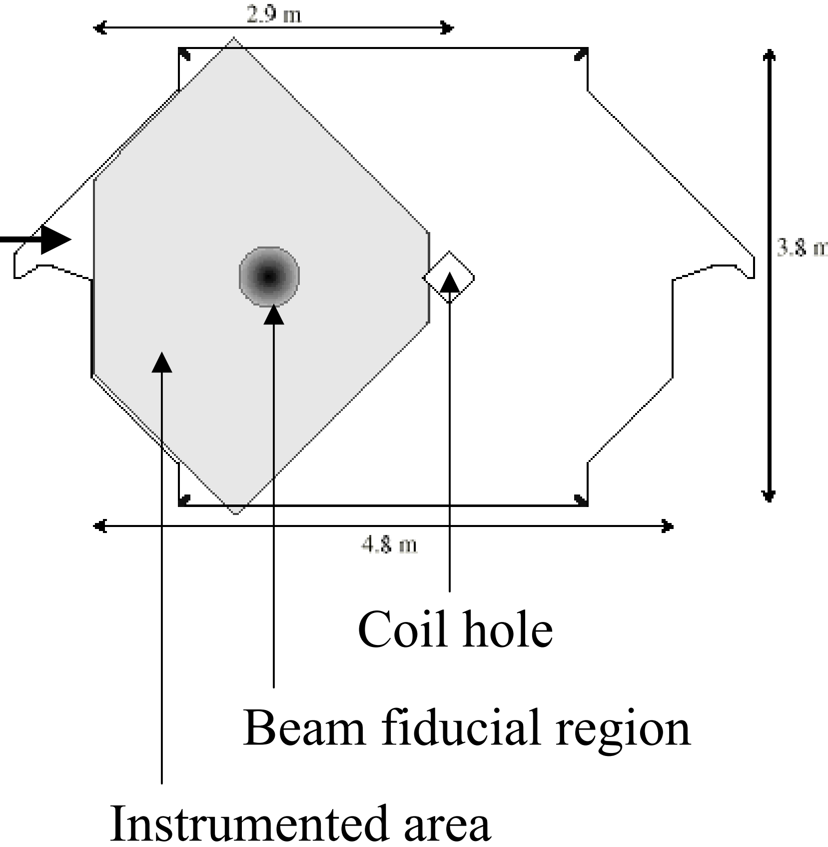
- 16.6 m long, 980 tons (100 fiducial)
- 282 "squashed octagon" planes
- Forward section: 120 planes

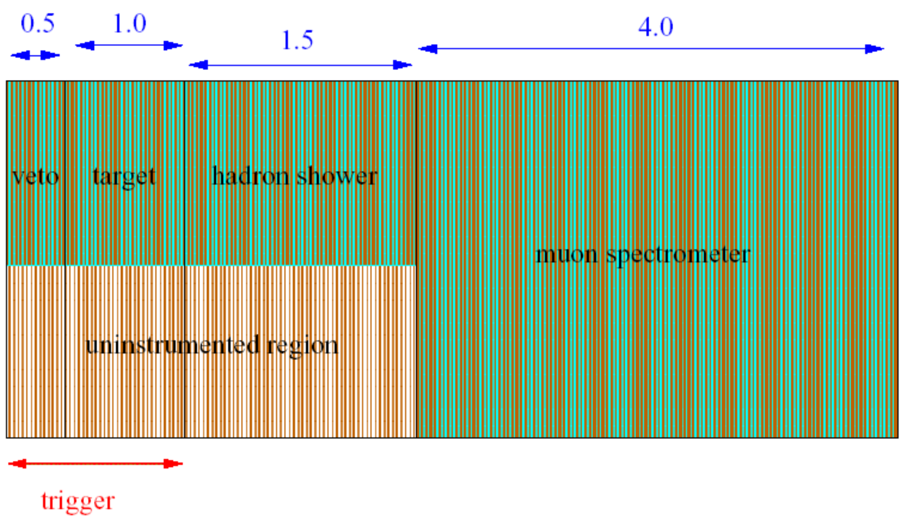
    4/5 partially instrumented

    1/5 planes: full area coverage
- Spectrometer section:162 planes

    4/5 planes not instrumented

    1/5 planes: full area coverage




Detector located 250 m downstream from end decay pipe

# Physics Measurements

- **Obtain firm evidence for oscillations**
  - ✓ Charge current (CC) interaction rate and energy distribution
  - ✓ NC/(CC+NC) ratio (T-test)
- **Measurement of oscillation parameters, $\Delta m^2$, $\sin^2 2\theta$**
  - ✓ CC energy distribution
- **Determination of the oscillation mode(s)**
  - ✓ $\nu_\tau$ or $\nu_s$ from NC and CC energy distributions
  - ✓ $\nu_\mu \rightarrow \nu_e$ limits or observation by identification of electrons

# Limits from the T-Test

$$T = \frac{N_{CC-like}}{N_{CC-like} + N_{NC-like}}$$

$N_{CC\text{-}like}$ ≡ events with identified muon

$N_{NC\text{-}like}$ ≡ events with no muon

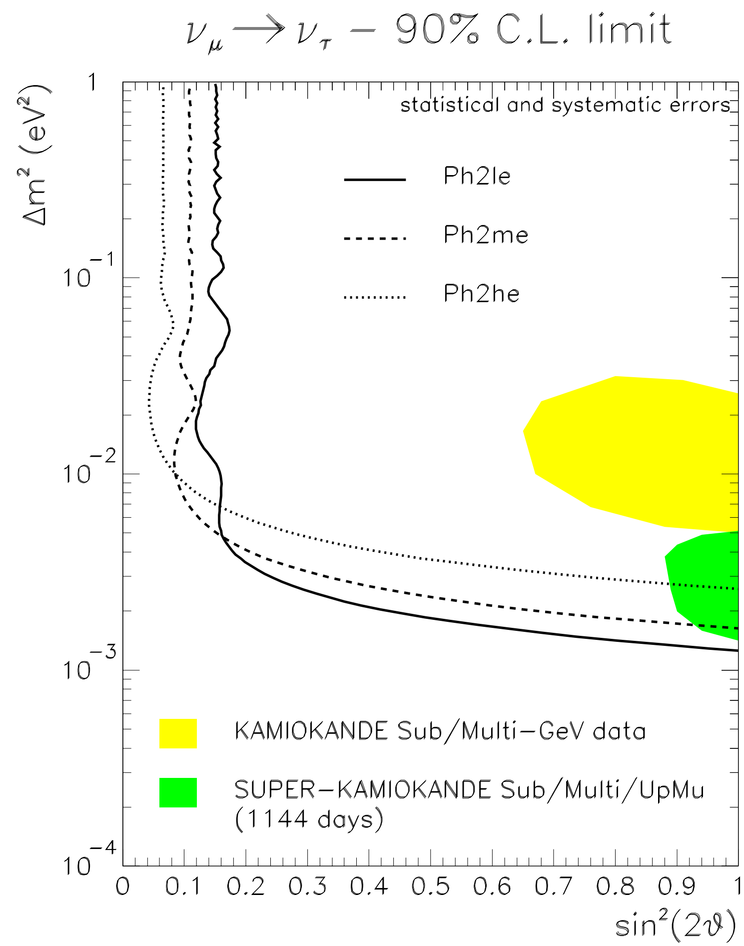
- $\nu_\mu \leftrightarrow \nu_\tau$ or $\nu_\mu \leftrightarrow \nu_e$ increase $N_{NC\text{-}like}$
  $\Rightarrow T_{far} > T_{near}$
- $\nu_\mu \leftrightarrow \nu_s$ or no oscillation $T_{far} = T_{near}$

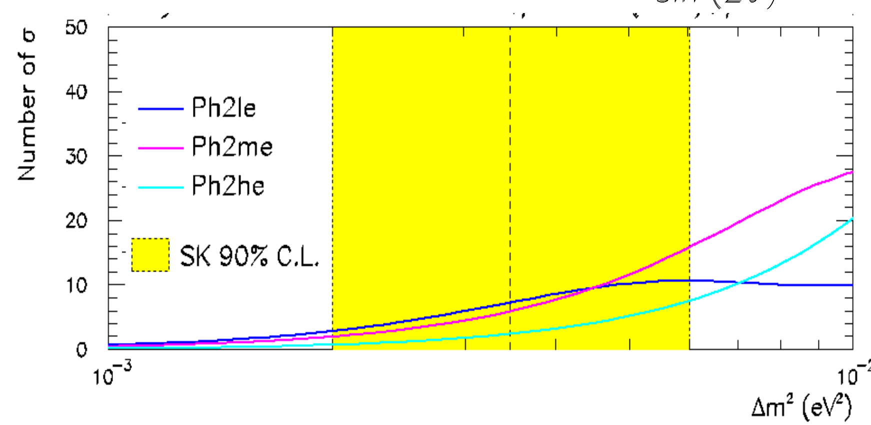
10 kton-yr exposure – 3.7 $10^{20}$ pot/yr

2% overall flux uncertainty

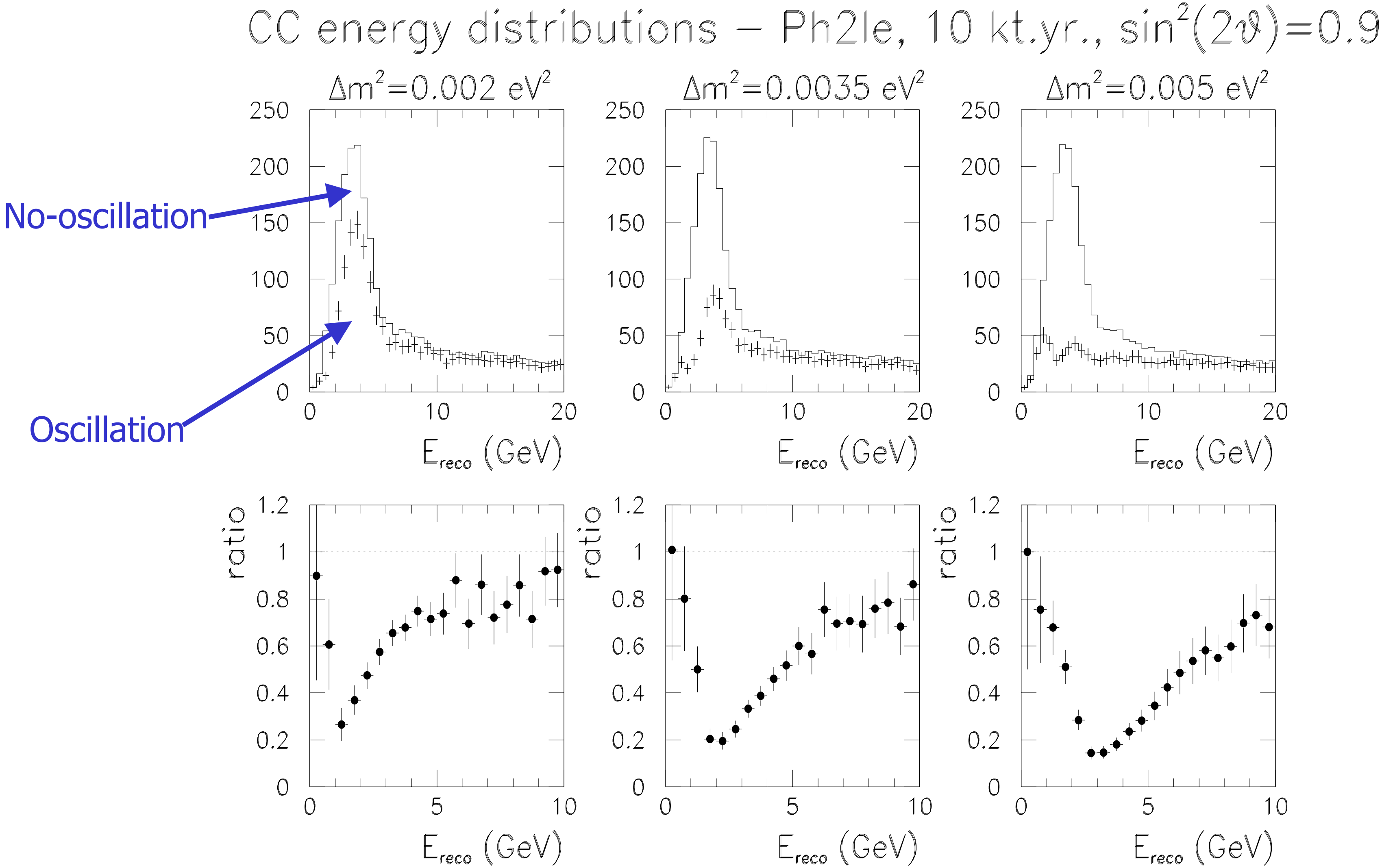
2% CC efficiency uncertainty

2% NC trigger efficiency uncertainty



# CC Energy Spectrum @ far detector



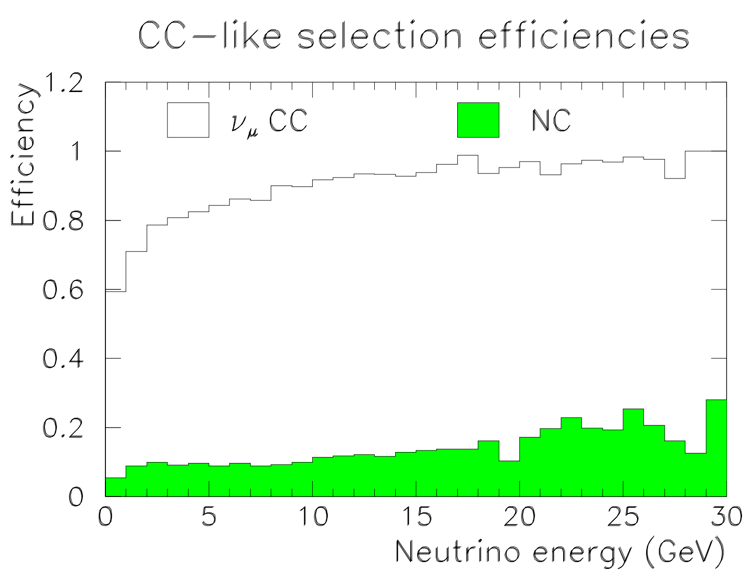
# Limit from the CC Energy Spectrum

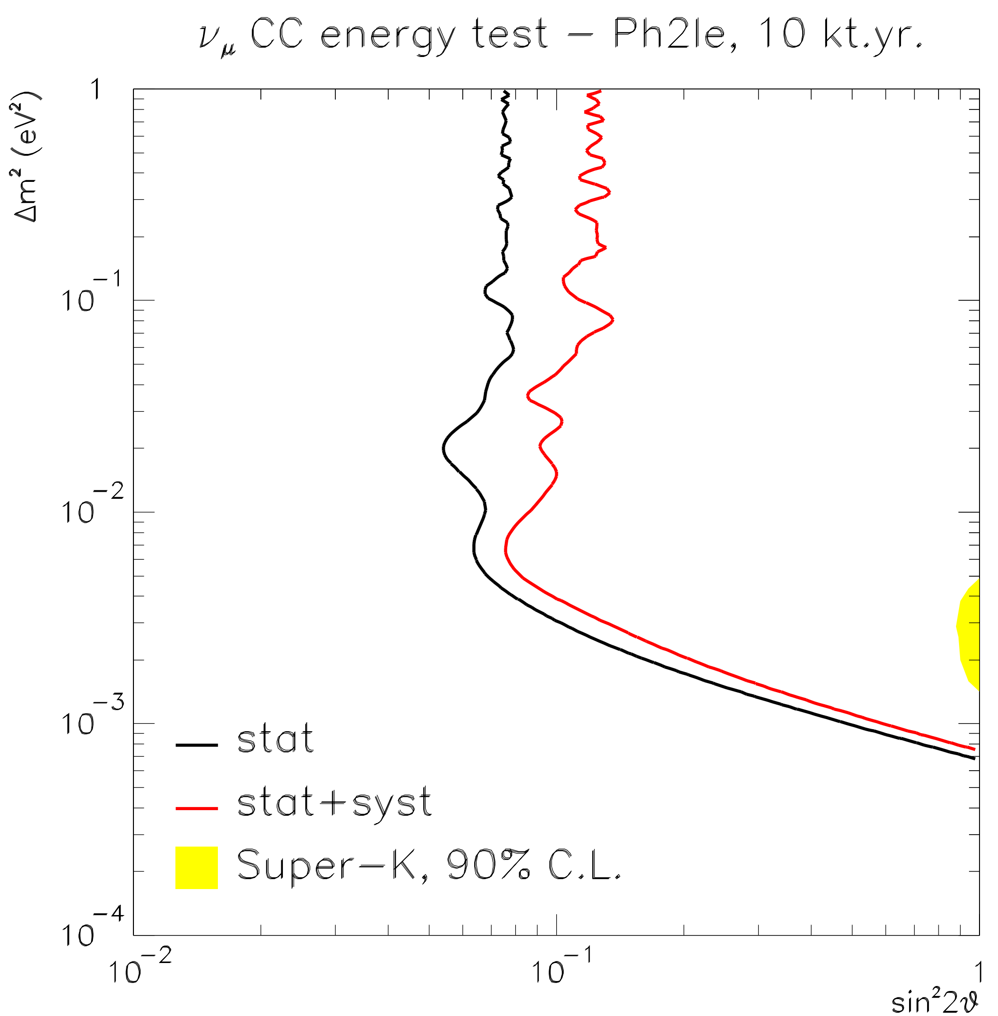
10 kton-yr exposure 3.7 $10^{20}$ pot/yr

2% overall flux uncertainty

2% bin-to-bin flux uncertainty

2% CC efficiency uncertainty



# $\Delta m^2$, $\sin^2(2\theta)$ sensitivity

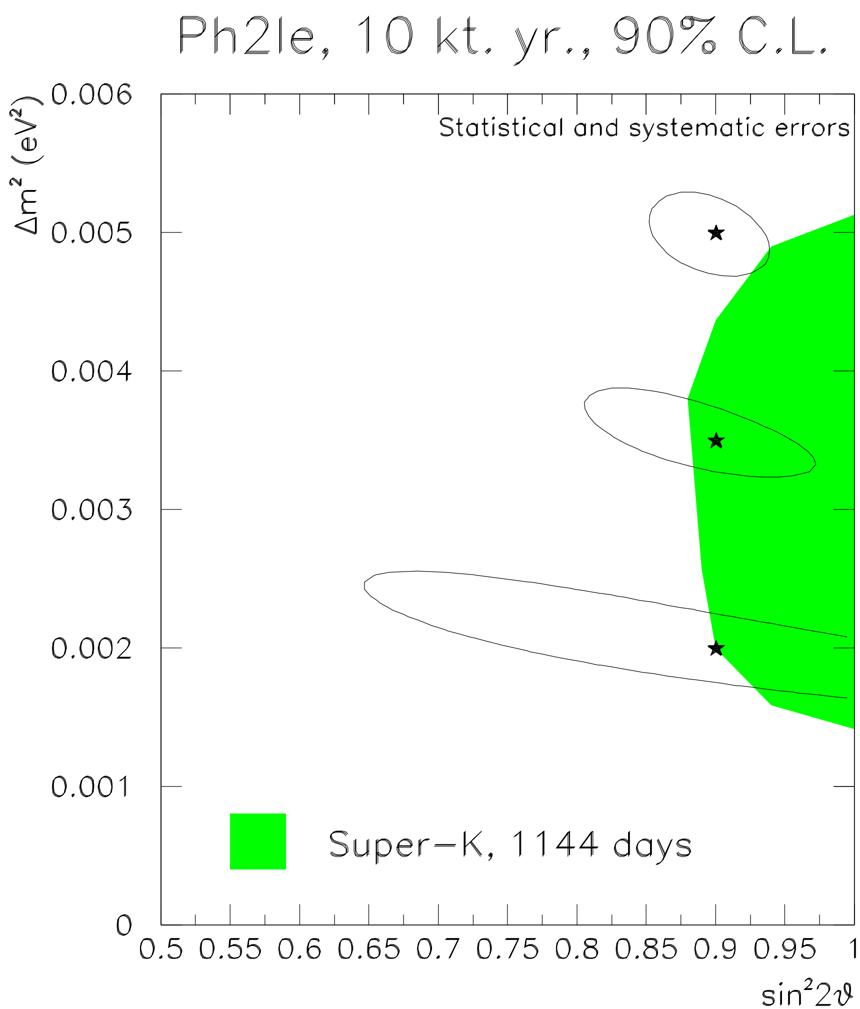
10 kton-yr exposure - 3.7 $10^{20}$ pot/yr

2% overall flux uncertainty

2% bin-to-bin flux uncertainty

2% CC efficiency uncertainty

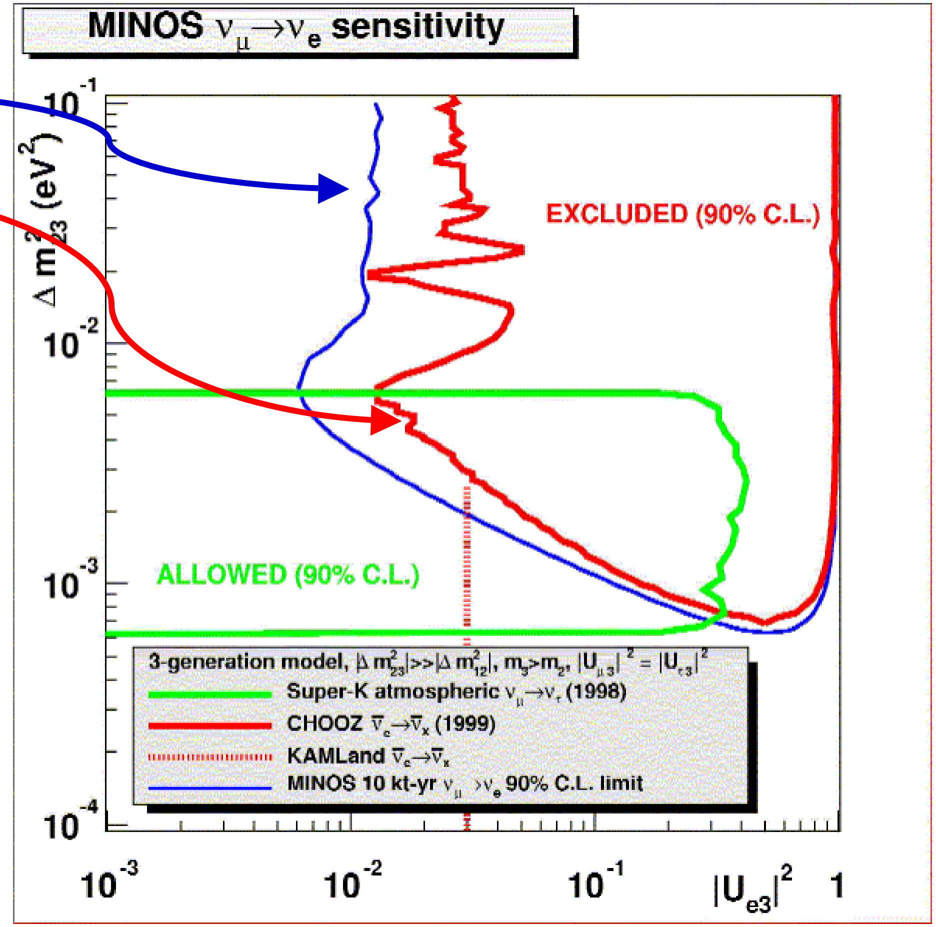
For $\Delta m^2 = 0.0035$ eV$^2$ should be able to achieve better than 10% error at 68% C.L on both $\Delta m^2$ and $\sin^2 2\theta$



# Limit on $\nu_\mu \rightarrow \nu_e$

MINOS 10 kt-yr
90% C.L. limit

Chooz 1999

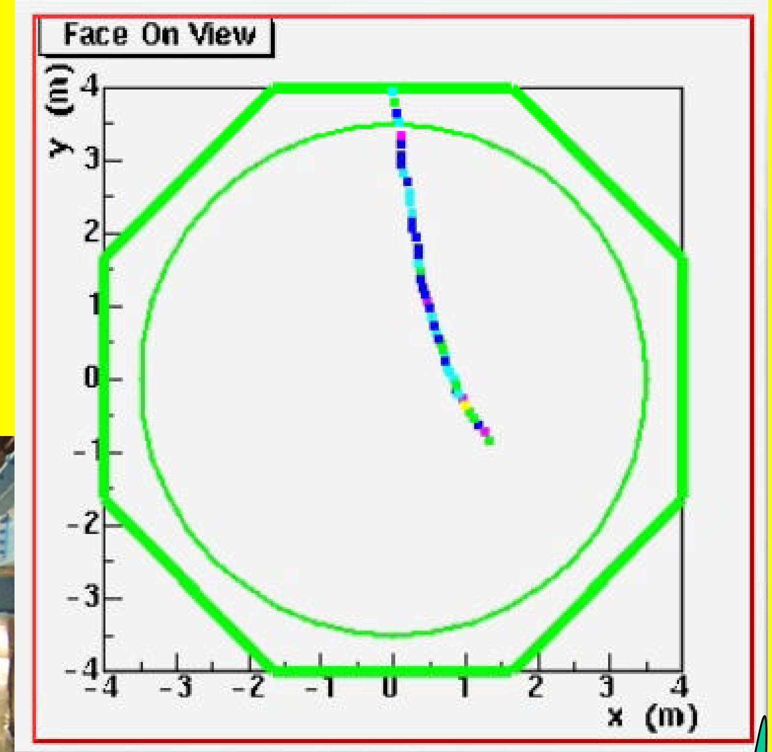



$m_3 > m_2$
Matter effects included
$\Delta m^2_{solar} = 3 \times 10^{-5}$ eV$^2$
$\theta_{12} = \theta_{23} = 45$ degrees
$\delta = 0$
10% systematic error on background

$U_{e3}^2 < 0.013$ @ $\Delta m^2 > 3 \times 10^{-3}$ eV$^2$
$\sin^2 2\theta_{13} < 0.05$ @ $\Delta m^2 > 3 \times 10^{-3}$ eV$^2$

**Already close to systematic limited with 10% error on background**

- 1st Supermodule (1/2 detector) done, other almost finished
- Meanwhile first magnetized data on atmospheric ν

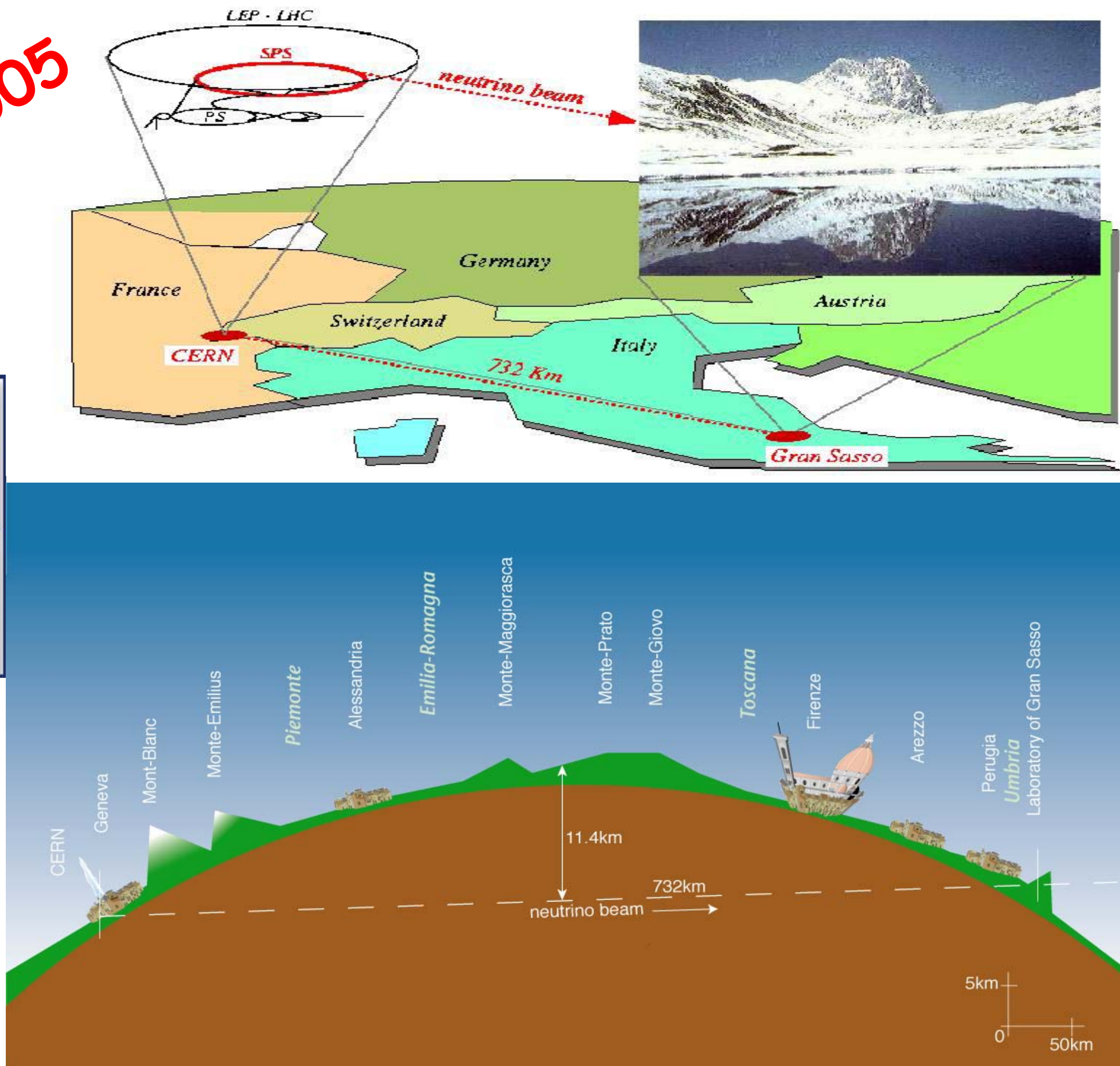



↑ Core Energized !!!

# The CNGS neutrino beam

The beam will start in may 2005

CERN to Gran Sasso Neutrino Beam

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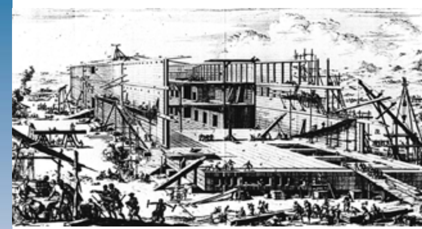
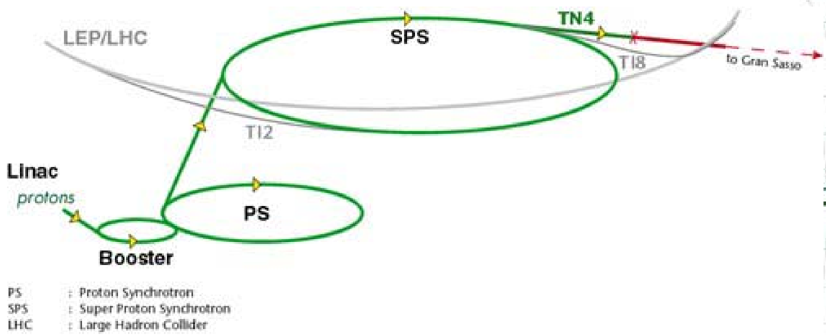
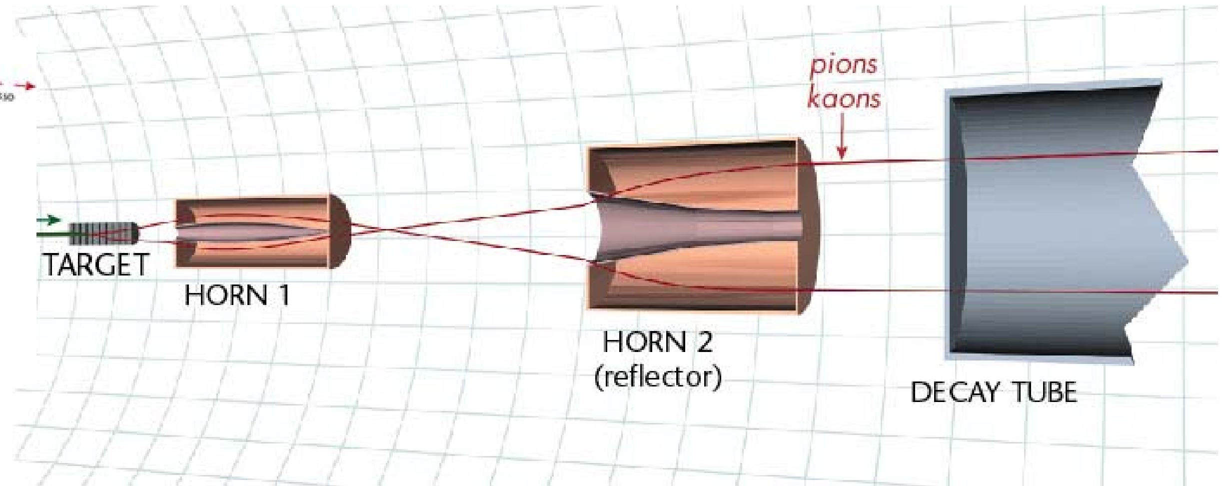
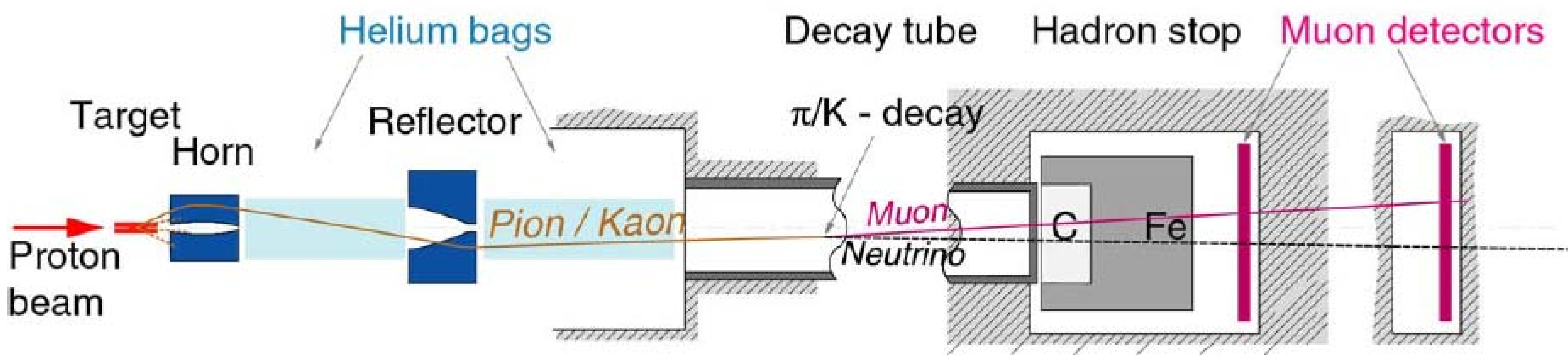


ICARUS

# The CNGS neutrino beam

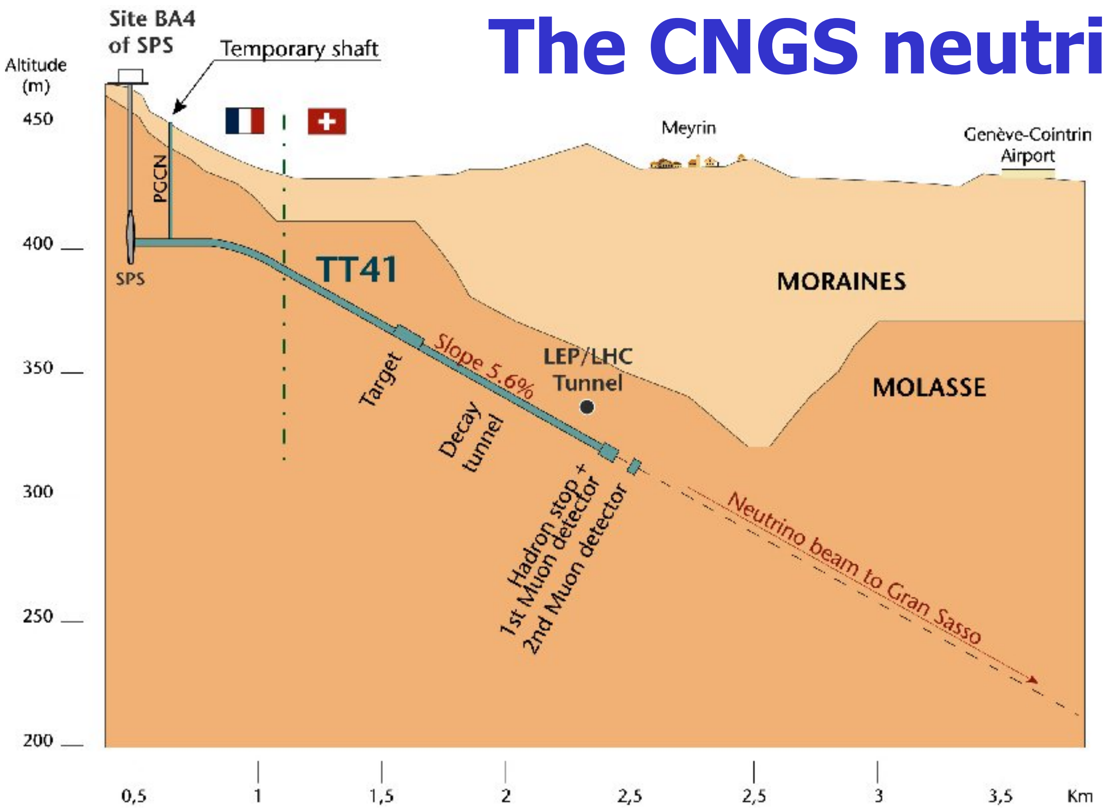



- 400 GeV proton beam on graphite: 200 days/year $4.5 \times 10^{19}$ pot / year
- First Horn @ 1.7 m from the target
- Second Horn (reflector) @ 43.4 m
- Decay tube: 1000 m long & 2.45 m wide (π decay length 2.2Km @ 40 GeV)

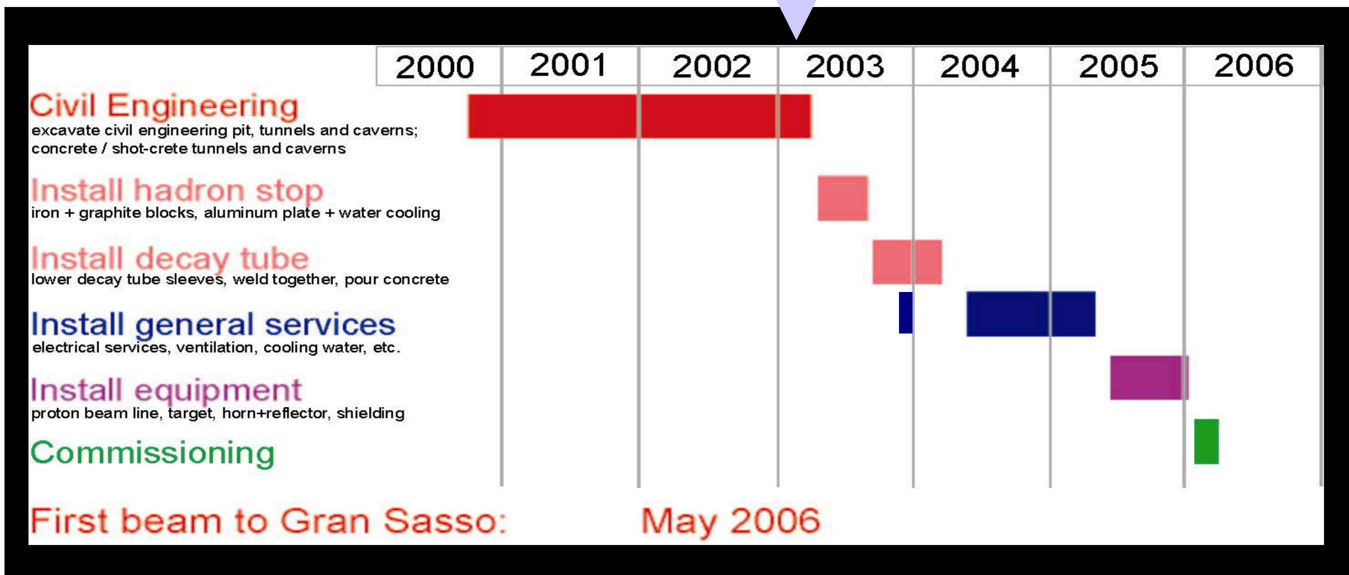
# The CNGS neutrino beam




## CNGS schedule

(schematic, simplified version)

"today"




Prepared by K. Elsener

# Neutrino beam for τ appearance

CNGS program is primary dedicated to τau appearance

$E_\nu$ > 3.5 GeV to produce τ

Number of τ

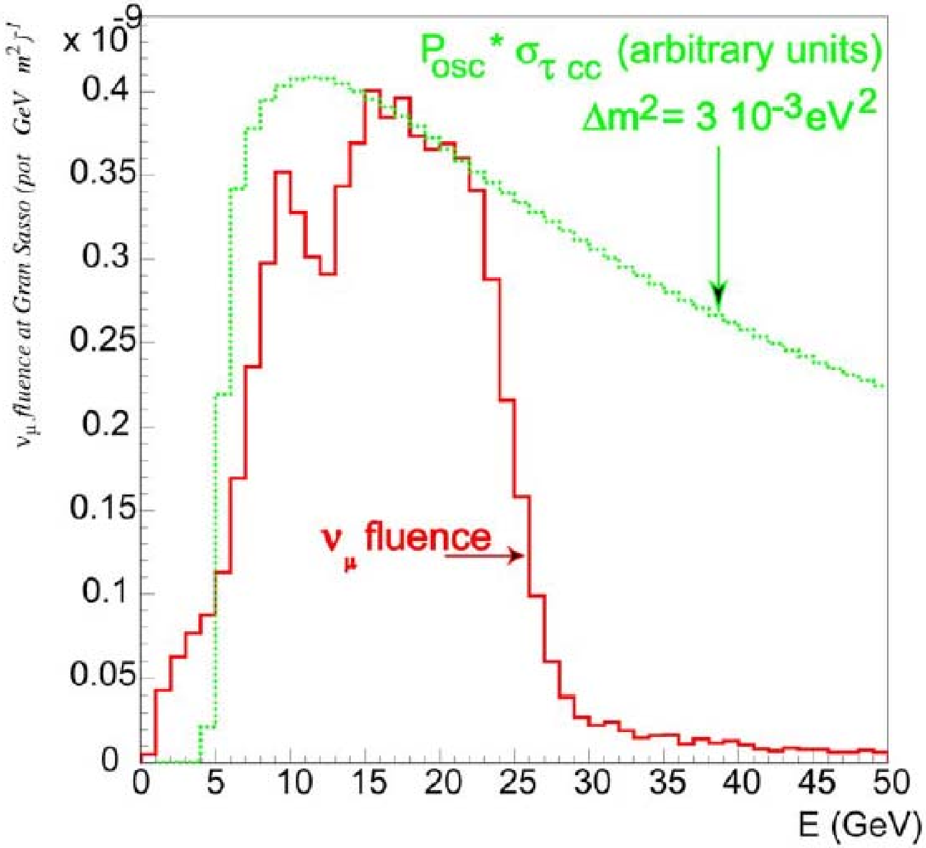
$$N_\tau = A \int \phi_{\nu_\mu}(E) P_{\mu\tau}(E) \sigma_\tau(E) dE$$

$$P_{\nu_\tau \to \nu_\tau} = \sin^2(2\theta) \sin^2\left(\frac{1.267 \Delta m^2 L}{E}\right)$$

*$\Delta m^2 = 2.5\ 10^{-3}\ eV^2$, L=730 Km, E > 3.5 GeV*

$$N_\tau = 1.61 A \sin^2(2\theta)(\Delta m^2)^2 L^2 \int \phi_{\nu_\mu} \sigma_\tau(E) \frac{dE}{E}$$

- $N_\tau \propto (\Delta m^2)^2$
- $\phi_{\nu\mu} \propto L^{-2} \Rightarrow N_\tau$ dose not dependent on L
- signal/background ~ $L^2$
- beam optimised independently from $\Delta m^2$



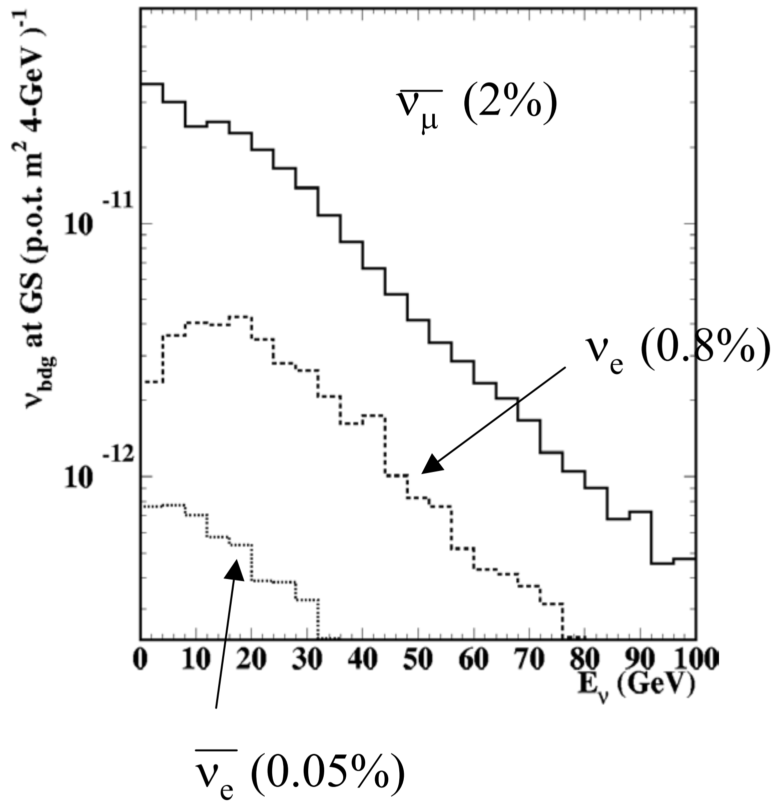

Beam optimised for τau appearance:

For $\Delta m^2 = 2.5 \bullet 10^{-3}\ eV^2$ and maximal mixing expect 15 $\nu_\tau$ CC/kton/year at Gran Sasso

# CNGS neutrino beam performance

Shared SPS operation:

- 200 days/year
- 4.5x10[19] pot / year




## Nominal ν beam @ LNGS

| | |
|---|---|
| $\nu_\mu$ ( $m^{-2}$ / pot) | $7.78 \times 10^{-9}$ |
| $\nu_\mu$ CC / pot / kton | $5.85 \times 10^{-17}$ |
| $< E >_\nu$ ( GeV ) | 17 |
| $(\nu_{e} + \nu_e) / \nu_\mu$ | 0.87 % |
| $\nu_\mu$ / $\nu_\mu$ | 2.1 % |
| $\nu_\tau$ prompt | negligible |

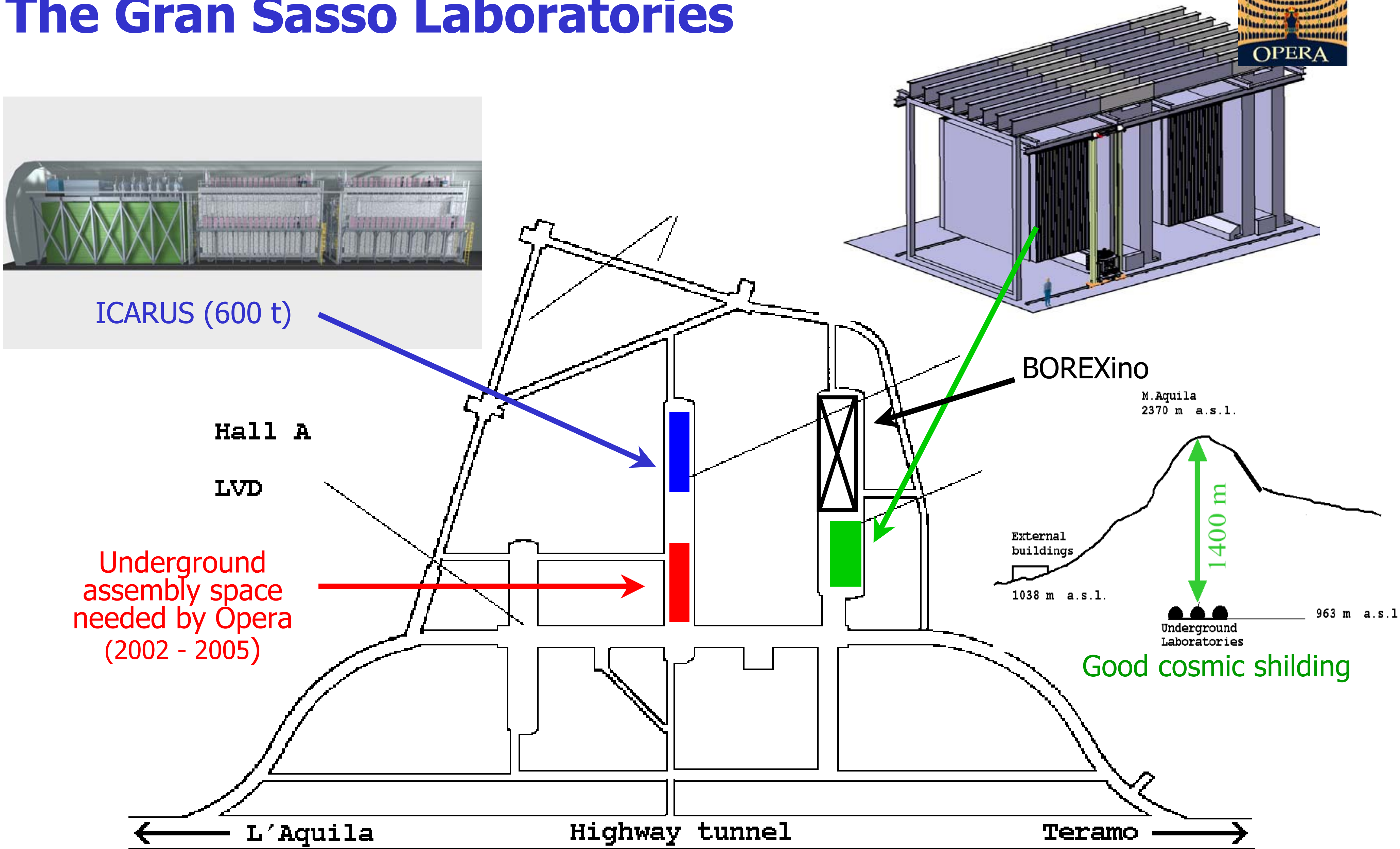
Beam optimised for τau appearance:

For $\Delta m^2 = 2.5 \bullet 10^{-3}$ eV$^2$ and maximal mixing expect 15 $\nu_\tau$ CC/kton/year at Gran Sasso

- Beam intensity increase granted : 1.5 expected

First beam will be ~ middle 2006 ?

# The Gran Sasso Laboratories



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IHEP Beijing, Shandong

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Zagreb

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## Russia
INR Moscow, ITEP Moscow, JINR Dubna, Obninsk

## Switzerland
Bern, Neuchâtel

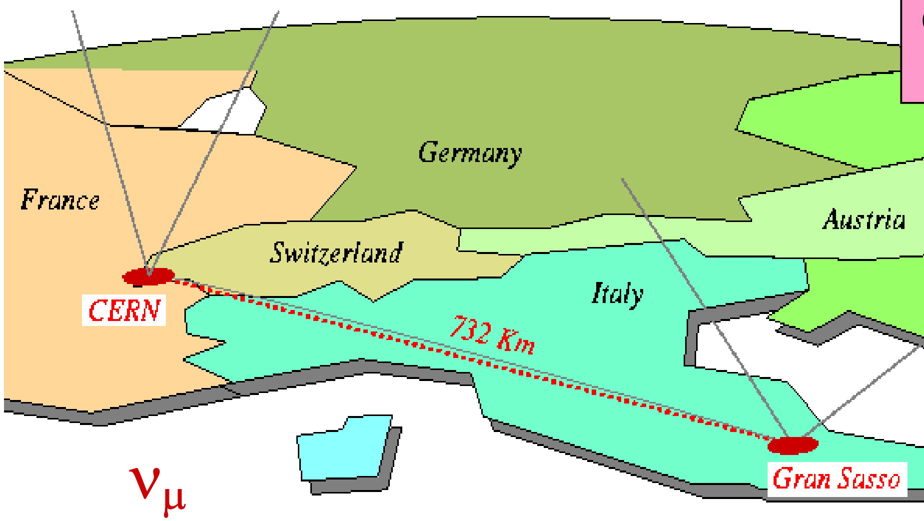
## Turkey
METU Ankara

35 groups
~ 170 physicists

# OPERA references

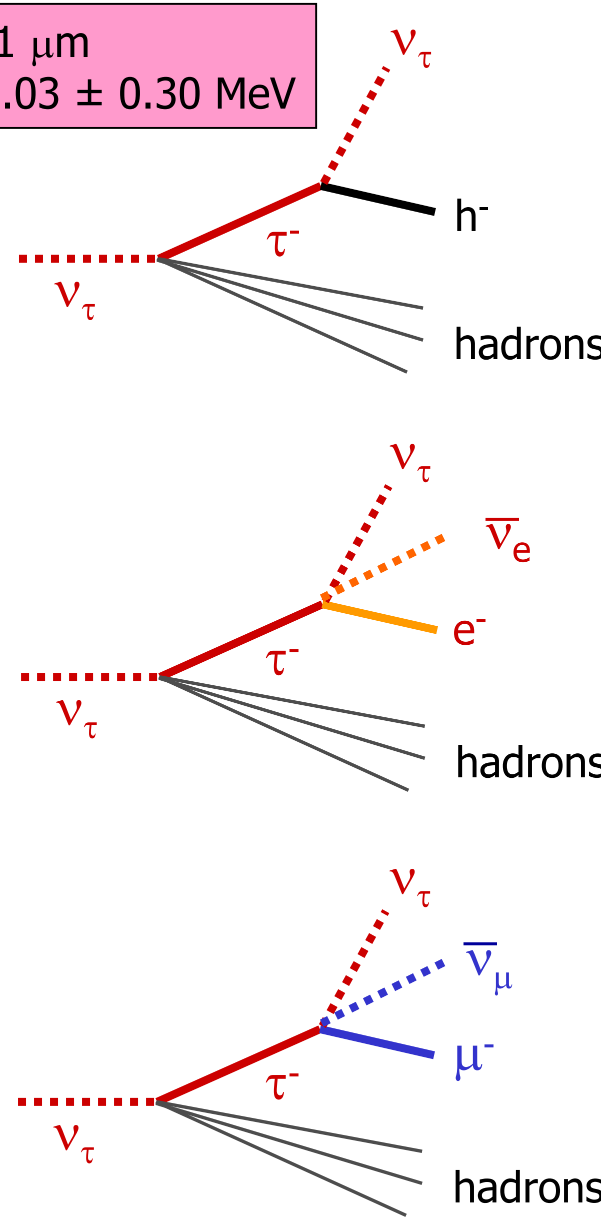

- H.Shibuya et al, "Letter of Intent. The OPERA emulsion detector for a long-baseline neutrino-oscillation experiment ", LNGS-LOI 8/97, September 8 1997.
- K.Kodama et al., CERN/SPSC 98-25, SPSC/M612, LNGS-LOI 8/97, Add. 1.
- K.Kodama et al., OPERA Coll., "Progress Report. OPERA: a long baseline $\nu_\tau$ appearance experiment in the CNGS beam from Cern to Gran Sasso", CERN/SPSC 99-20, SPSC/M635, LNGS-LOI 19/99, August 27, 1999.
- M.A.Guler et al., OPERA Coll., "An appearance experiment to search for $\nu_\tau \rightarrow \nu_\tau$ oscillations in the CNGS beam", CERN/SPSC 2000-028, SPSC/P318, LNGS P25/2000, July 10, 2000. (Proposal).
- M.A.Guler et al., OPERA Coll., "Status Report on the OPERA experiment", CERN/SPSC 2001-025, SPSC/M668, LNGS=EXP 30/2001 add. 1/01, August 21, 2001.
- Official web page: http://operaweb.web.cern.ch/operaweb/index.shtml

# The OPERA Long Baseline experiment




$\nu_\tau$ ?

$c\tau$ = 87.11 μm
m = 1777.03 ± 0.30 MeV




BR ~ 65 %

BR = 17 %

BR = 17 %

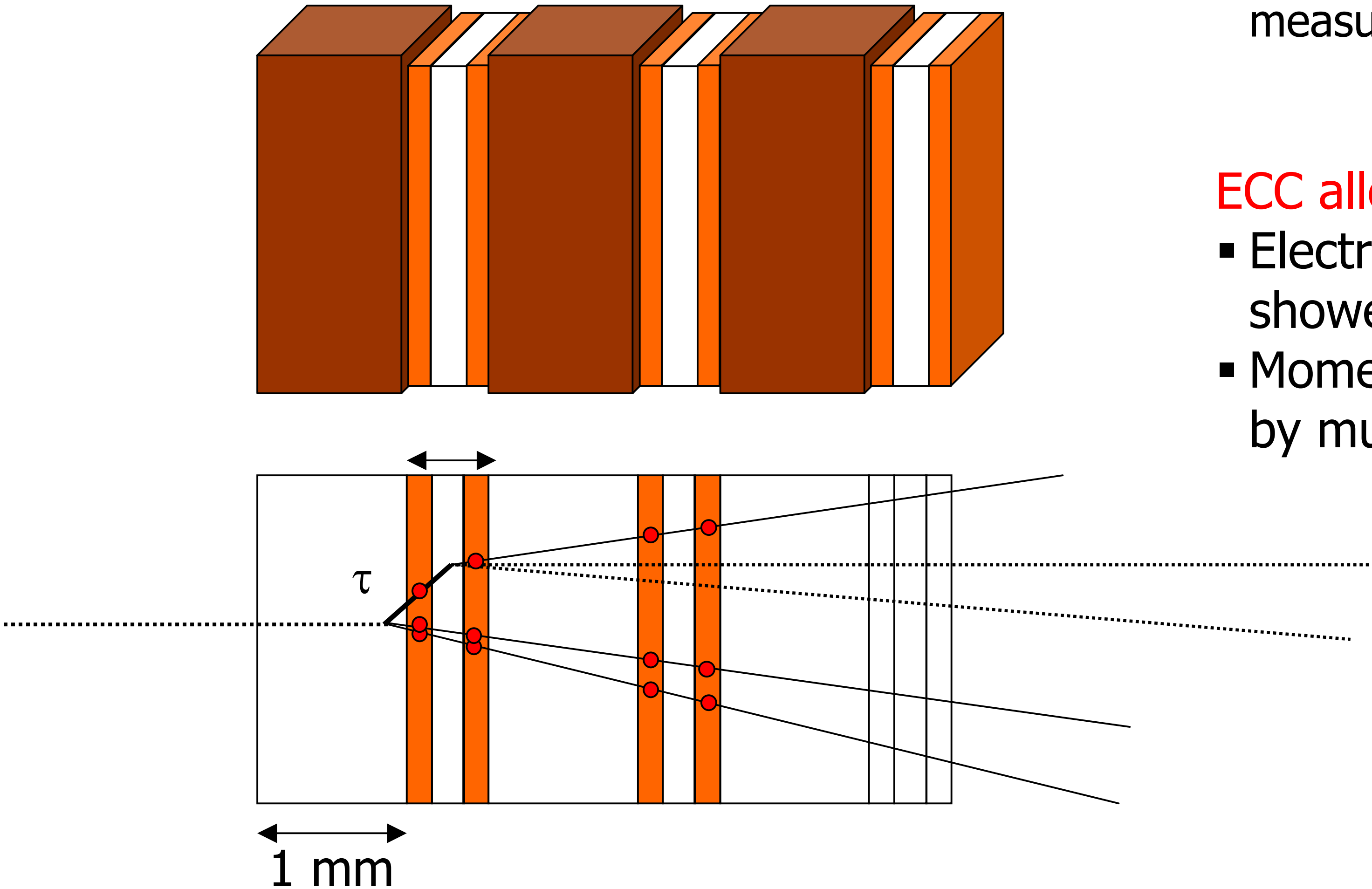
Detect $\nu_\tau$ through $\nu_\tau$-CC interactions ($\tau$ decay topology).

Need massive detector and micron resolution.

⇒ Emulsion-Cloud-Chamber (ECC), i.e. Pb-Nuclear Emulsion sandwich.

# ECC principles

ECC: Emulsion Cloud Chamber, sandwich of:
- heavy material (target);
- nuclear emulsion (tracker w/ O(μm) resolution)

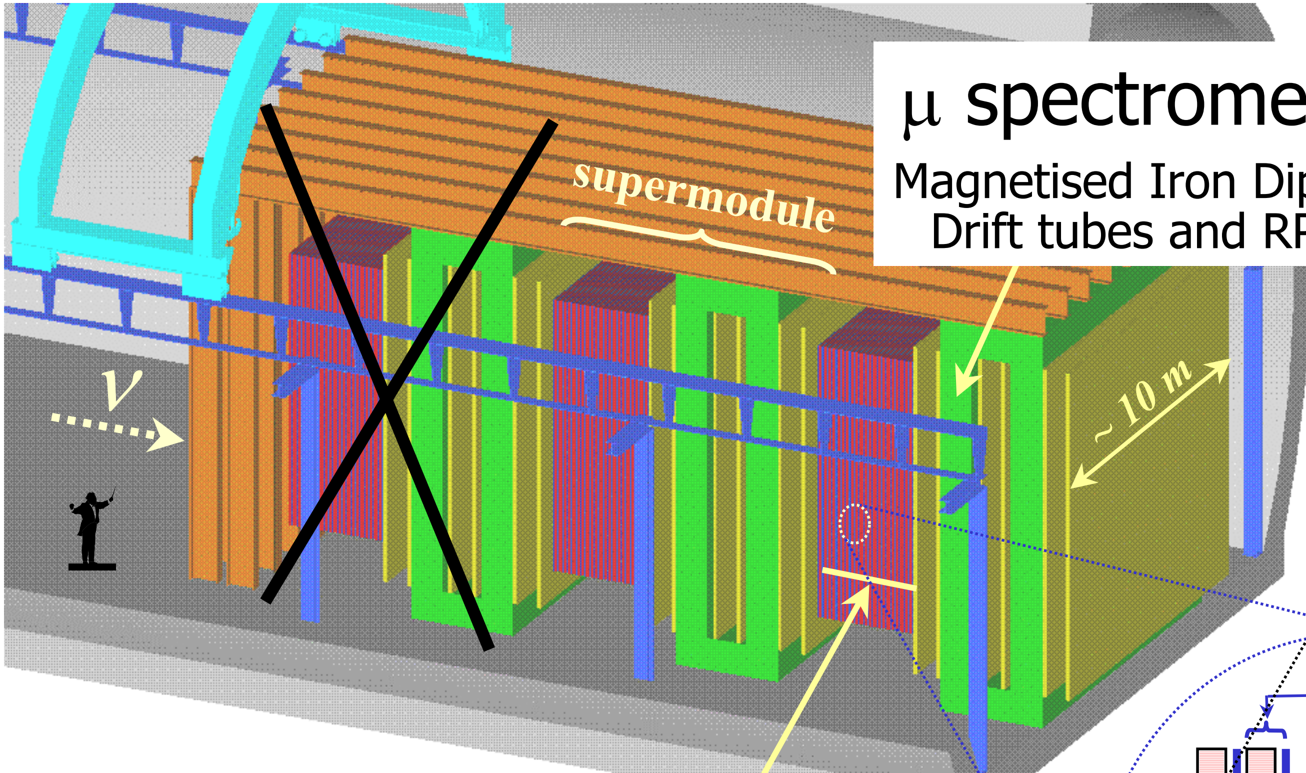


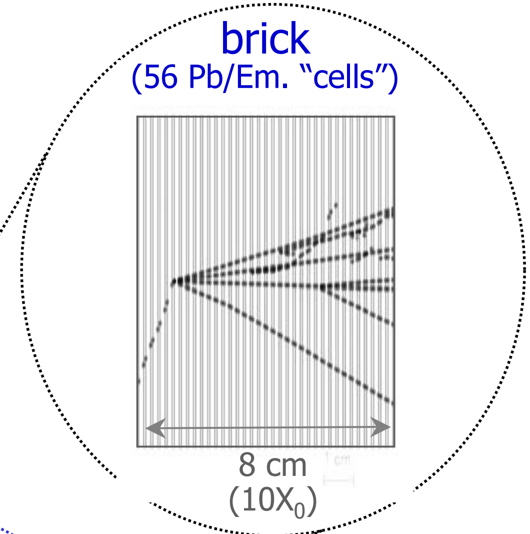

Heavy material:
- XX CHORUS
- Fe DONUT
- Pb OPERA (better for P measurement and electron ID)

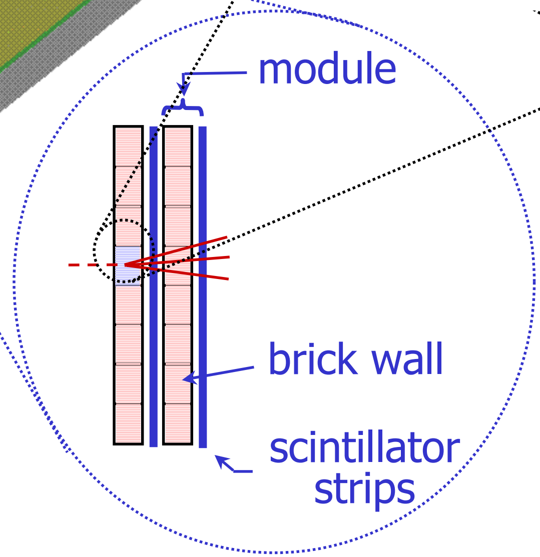
ECC allows:
- Electron identification by showering;
- Momentum measurement by multiple scattering.

# Detector structure

Traget: 1.8 kton



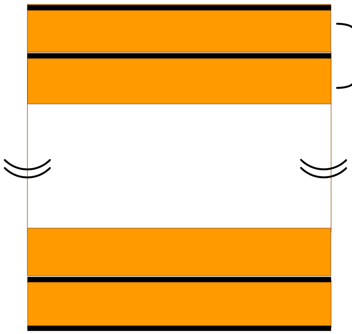




206,336
bricks

## ν target and τ decay detector

- 2 "supermodule":
- 31 walls/SuperModule
- 52x64 bricks/wall (206336 in total)
- two planes of orthogonal scintillator strips/wall

# Fuji emulsion films



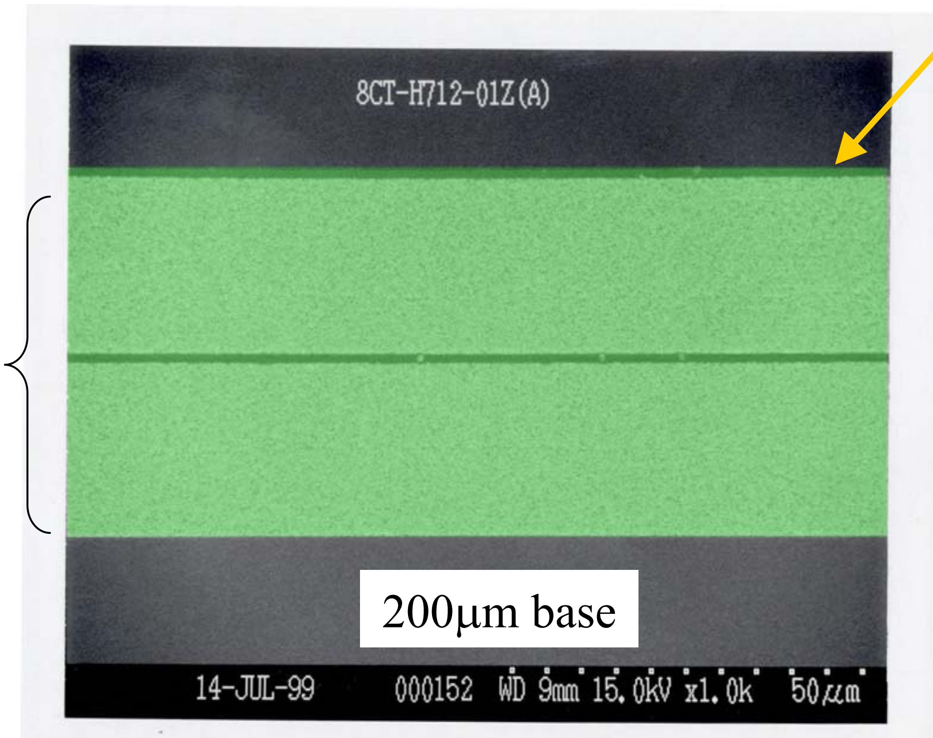
emulsion ( 2 layers of 21 μm)

plastic base ( 200 μm)

Protection coat (1 μm)

Surface protection by gelatin layer for Pb plate contact

21 + 21 μm emulsion layer




Products by Fuji Film Co.

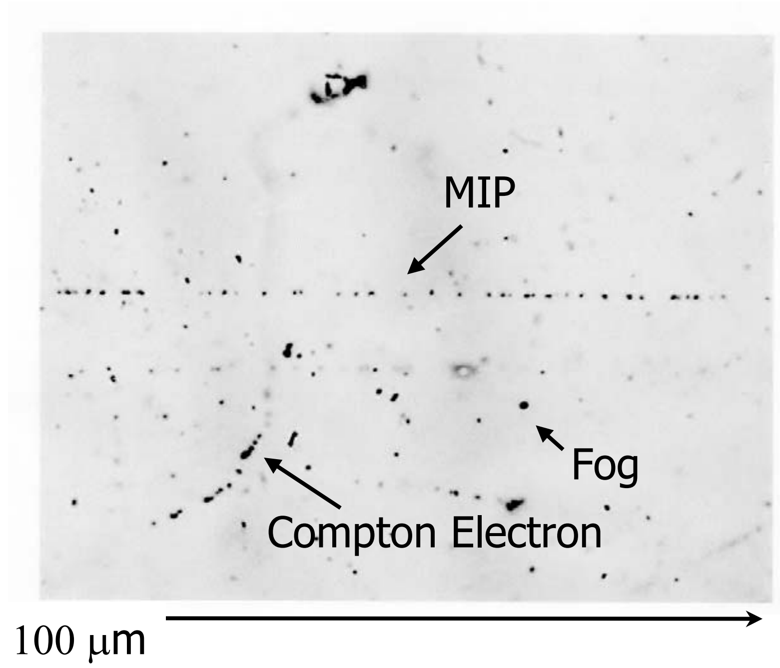
Suitable for mass production: < 2 years for production for OPERA (13.6M films)

Precise mechanical size : emulsion layer thickness (~ 1 μm accuracy)

# Emulsion properties

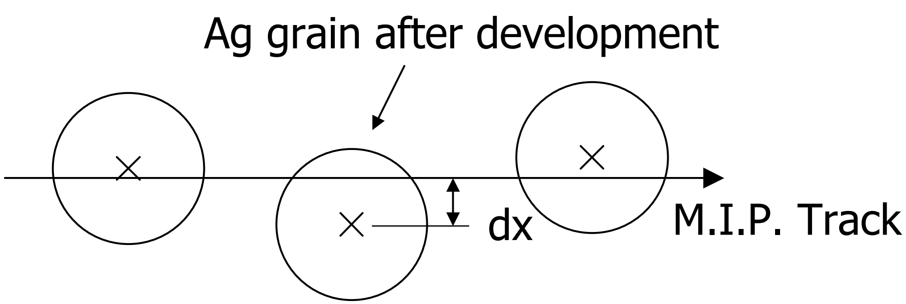
Fog Density (FD) = 1-2/1000 $\mu m^3$

Grain Density (GD) for 1 M.I.P.
~ 30-40 grains / 100 $\mu$m.




intrinsic tracking accuracy

$\sigma = 0.06\ \mu m$




Emulsions: gelatin with AgBr crystals;
Grain size: 0.2 $\mu$m (0.8 $\mu$m after development);
Energy loss / crystal: ~ 300 eV;
dE/dx = 37 keV/$\mu$m

# Emulsion plate performances

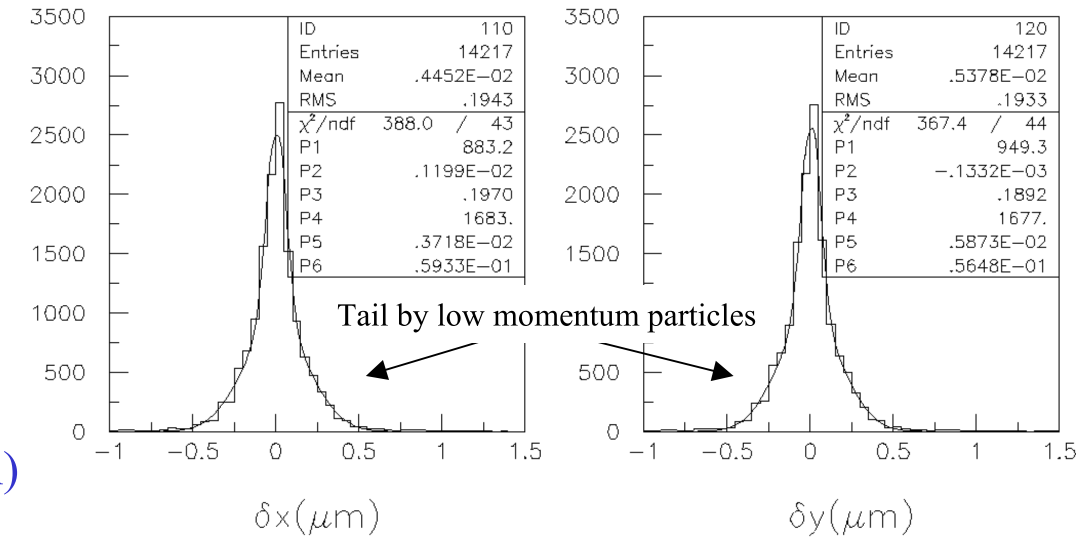
## Position Resolution

$\sigma \sim 0.2\mu m \sim$ readout accuracy

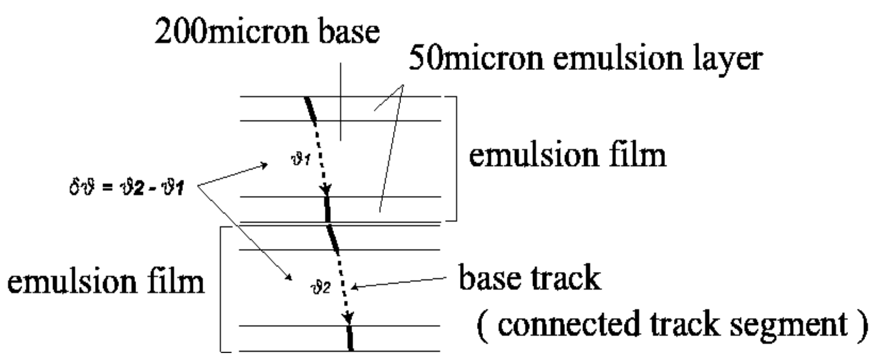
$> $ intrinsic limit ( $0.06\mu m$ )

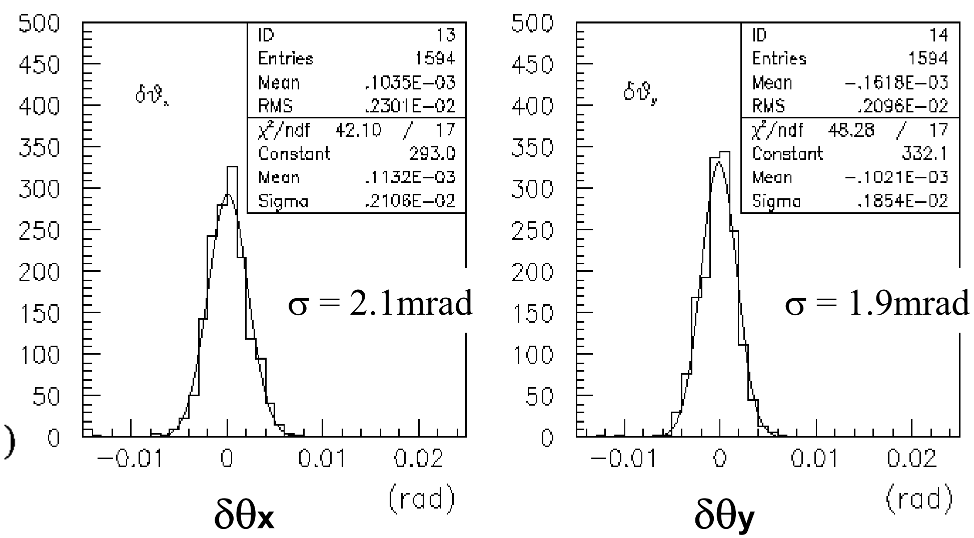
Limited by
CCD pixel size ($0.3\mu m$)
Stage coordinate readout pitch ($0.5\mu m$)

( Residual from Straight Fit in DONUT )

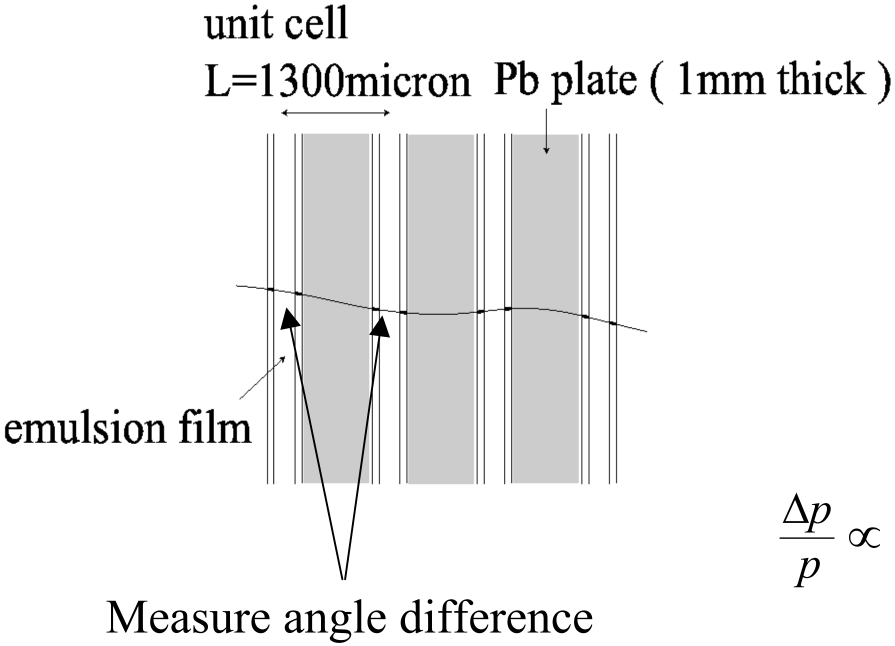



## Angular Resolution



# Momentum measurement by Angular Method




$$\mathrm{MDM} = \frac{13.6\mathrm{MeV}/c}{2\delta\theta}\sqrt{\frac{1\mathrm{mm}}{5.6\mathrm{mm}}}$$

Maximum Detectable Momentum
scattering in a unit cell ( 1mm Pb ) > $2\delta\theta$

$$\frac{\Delta p}{p} \propto \sqrt{\#\text{ of independent measurements}}$$

**~10% by following 1ECC ( 55×2=110 measurements )**

MDM = 1.4GeV/c with $\sigma_\theta$= 2.1mrad ( current readout )

MDM = 7.1GeV/c with $\sigma_\theta$= 0.4mrad ( intrinsic limit )

NO Fine Alignment required
Pb plate thickness must be flat ( better than 2.1mrad for current readout )

# Momentum measurement by multiple scattering

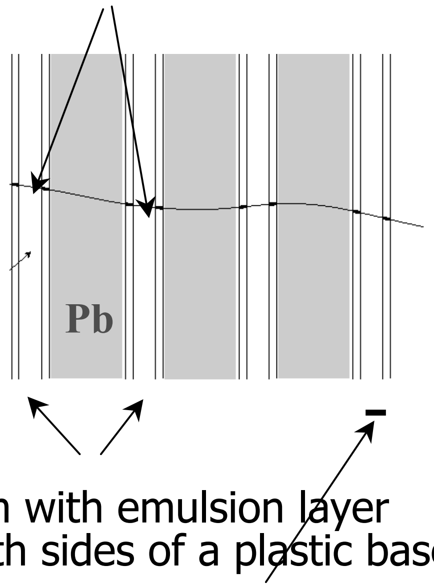
## Angular method

- Not relying on alignment of emulsion films
- Relying on parallelism of Pb plates and emulsion films

$$\mathrm{MDM} = \frac{13.6\,\mathrm{MeV/c}}{2\delta\theta}\sqrt{\frac{1\,\mathrm{mm}}{5.6\,\mathrm{mm}}}$$

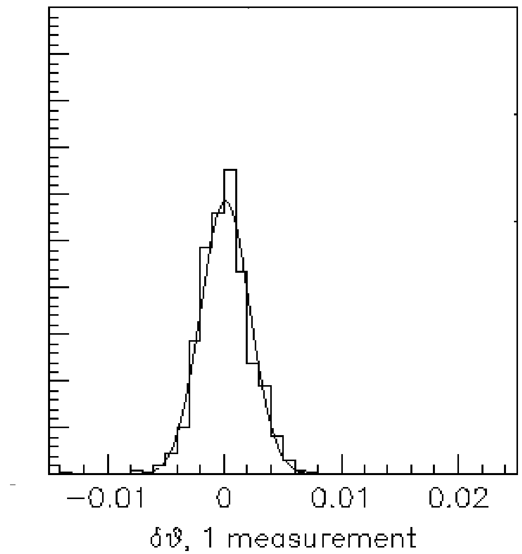
Maximum Detectable Momentum
scattering in a unit cell ( 1mm Pb ) > $2\delta\theta$

Angle difference

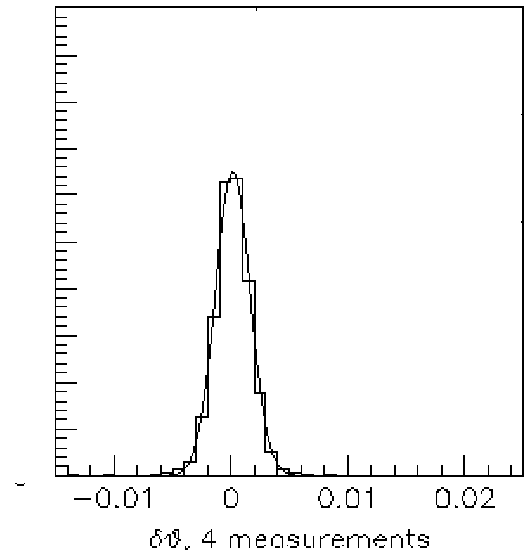



Film with emulsion layer on both sides of a plastic base

Plastic base thickness: lever arm for angle measurement




**Single measurement**
**2.0 GeV/c**




**Multiple measurements**
**2.8 GeV/c**

**With intrinsic resolution 10.0 GeV/c**

**$\delta p/p < 10\%$ after $10\ X_0$**

# Momentum measurement (coordinate method)

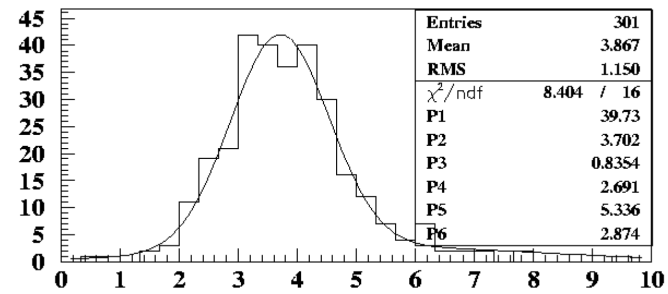
MDM is higher than angular method
measure scattering with longer lever arm

$\delta p/p=14\%$
following a track
for one entire brick

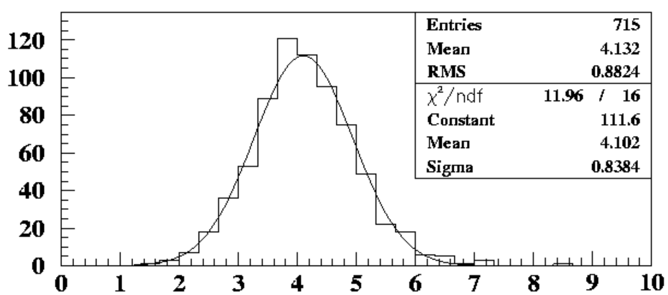
requires precise alignment
- using cosmic rays exposure after extraction
- cosmic ray density of several/mm$^2$

alignment accuracy → OK

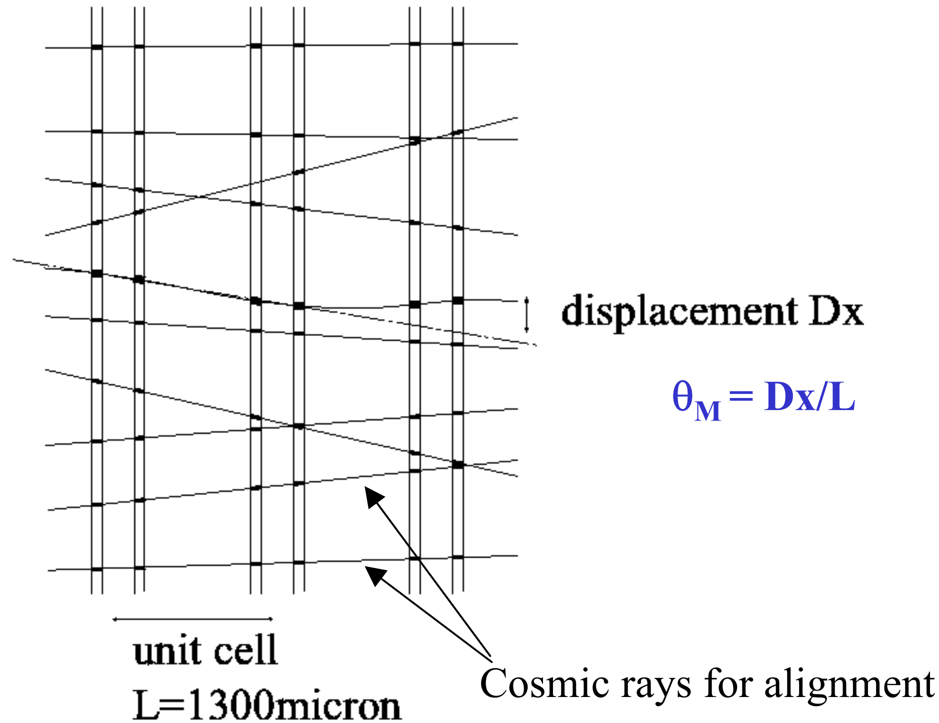
MDM = 5.9 GeV/c with $\sigma$=0.21µm




Data 4 GeV/c




M.C. 4 GeV/c




TEST experiment at KEK PS

MDM becomes 39.1GeV/c with $\sigma$=0.06µm ( intrinsic limit )

# Electron identification in ECC brick

**(1) Different energy loss by multiple scattering**

$E(x)=E_0 e^{(-x/X0)}$ for electrons $\chi^2_e$

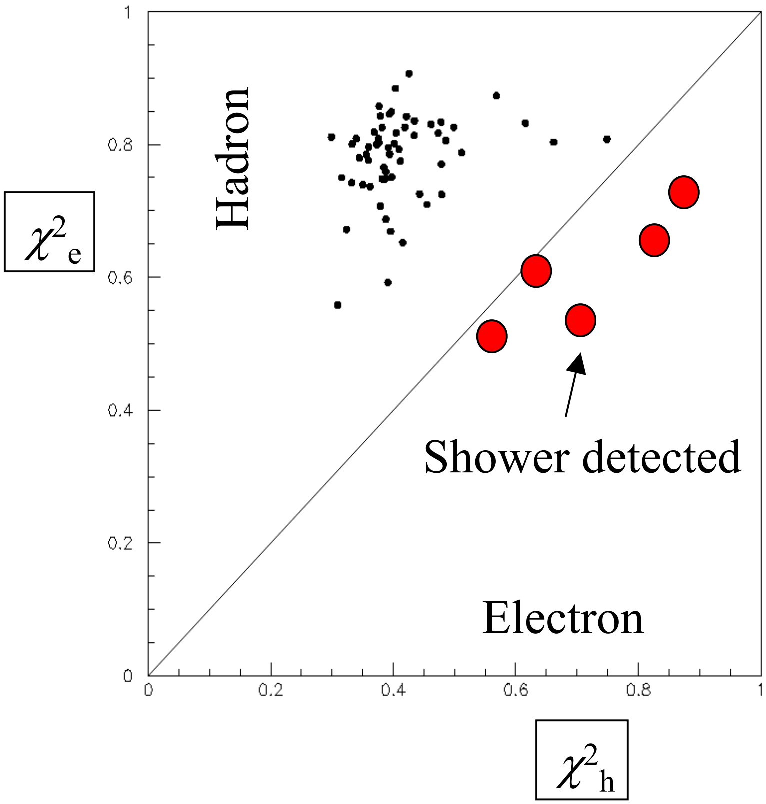
$E(x)=E_0(1-(dE/dx)x)$ for hadrons $\chi^2_h$

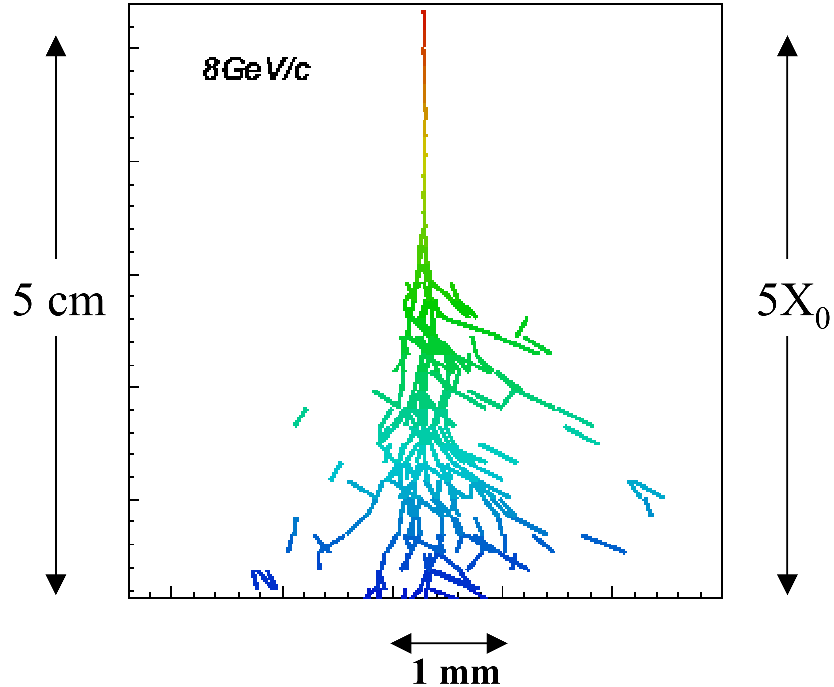
**(2) Detection of electromagnetic shower**

Requires low background track density → controlled fading

Sensitive to electrons close to the Pb critical energy

$\varepsilon_e$ = 88 (91)%
$\pi$ mis-ID 6% (4%) @ 2 (4) GeV



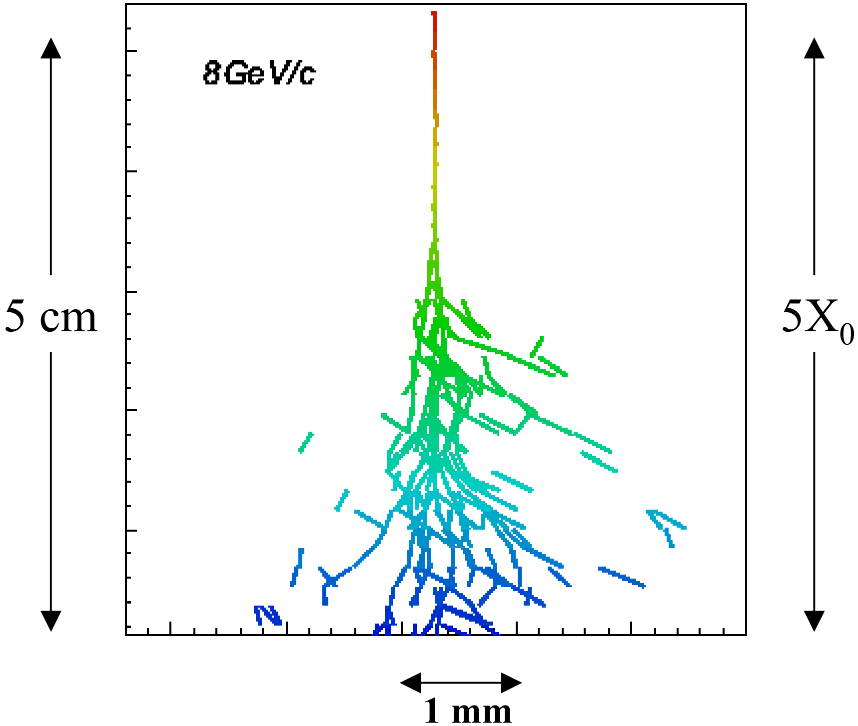




TEST experiment at CERN PS

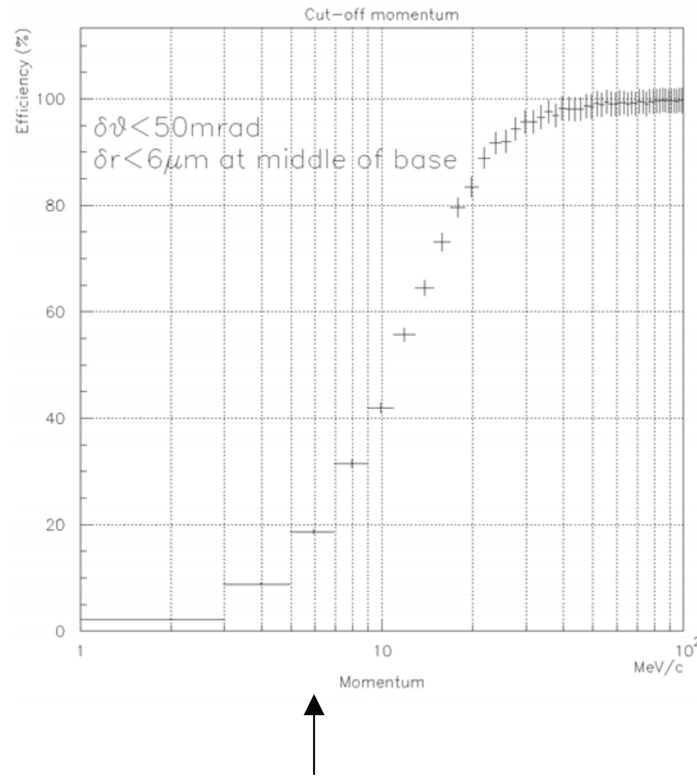
# Electron Energy Measurement

# of track segments ( shower electrons ) $\propto E_{electron}$

**S/E = 40%/√E**

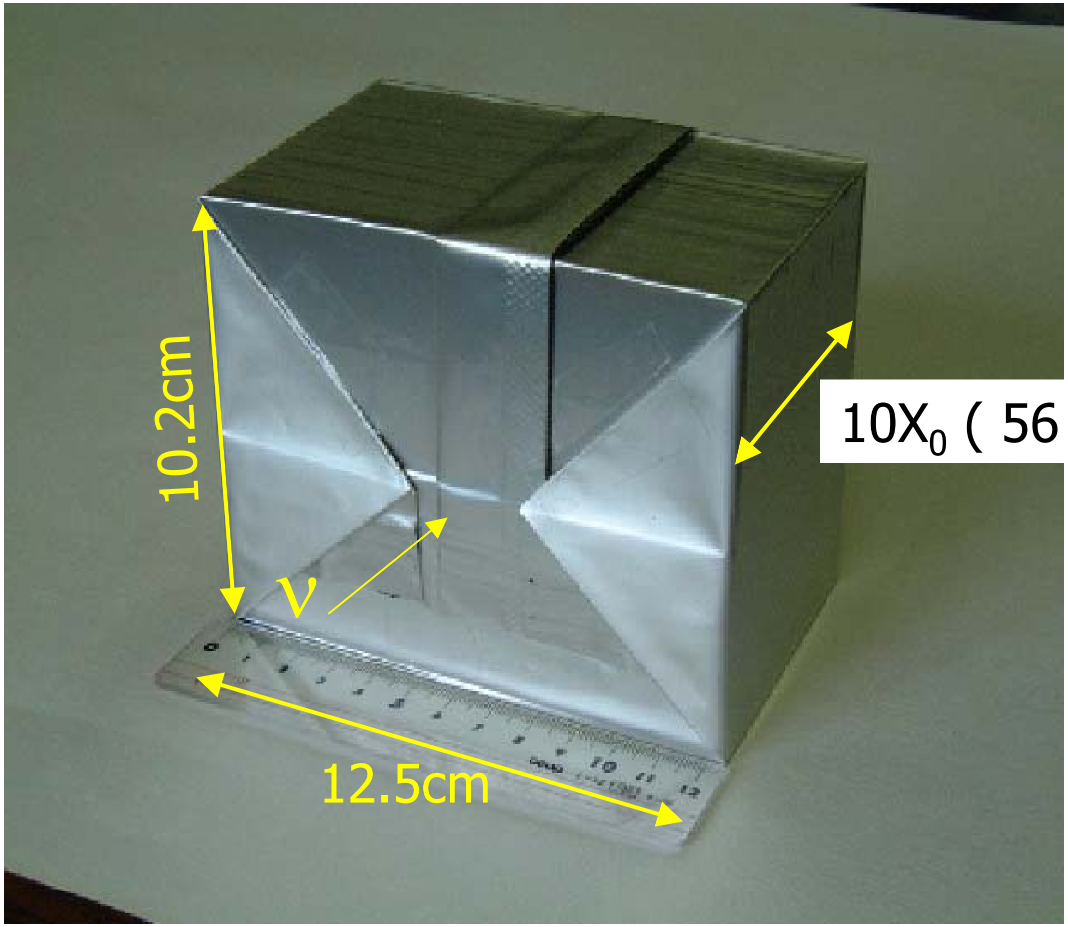



TEST experiment at CERN PS




Emulsion sheet can be sensitive
to electrons
near the critical energy ( 10MeV ) of Pb

# The OPERA Brick




$X_0(Pb) = 5.6$ mm

$10X_0$ ( 56 emulsion films + 56 lead plates )

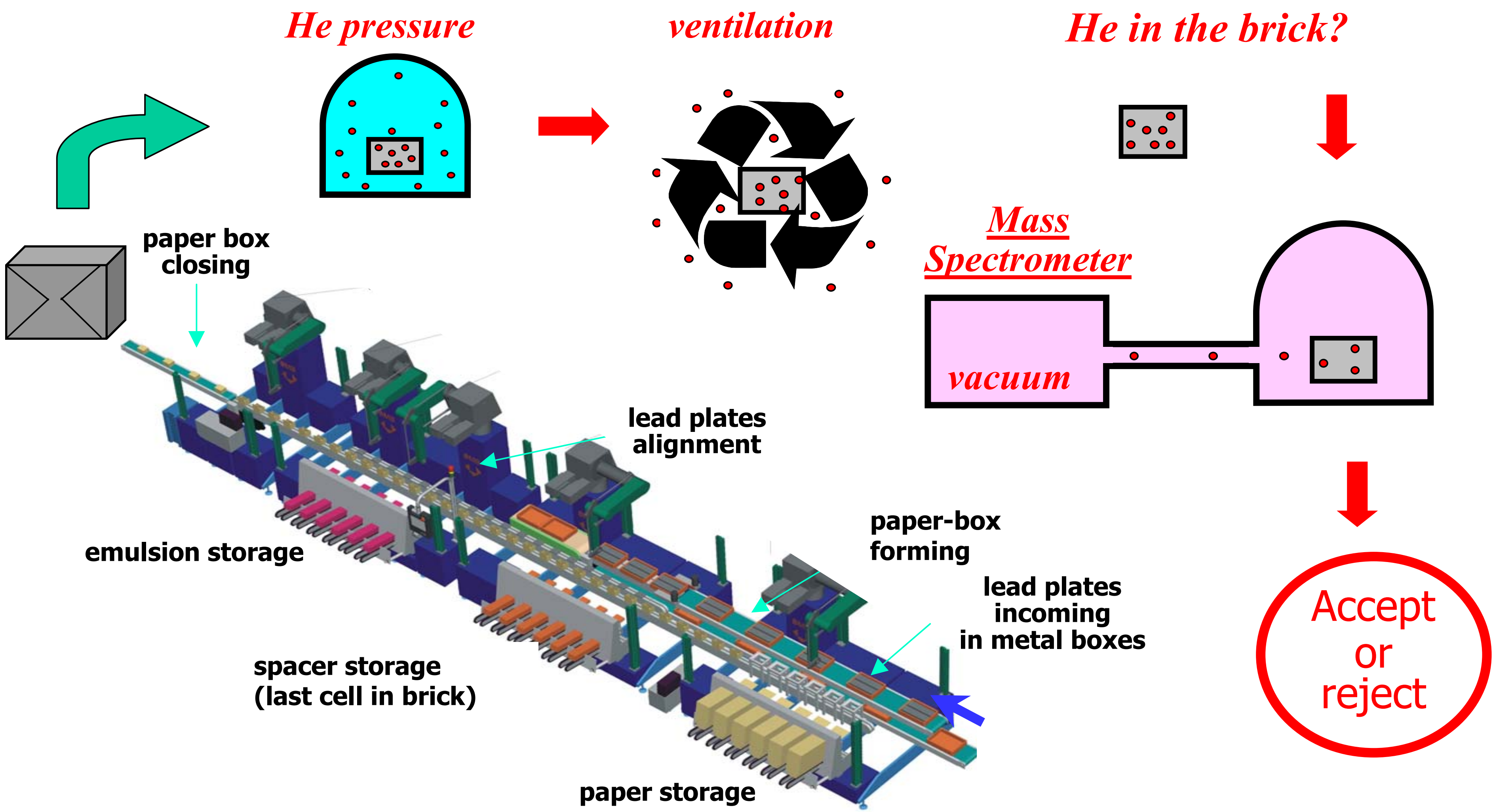
8.3 kg / brick

206k bricks
for 1.8 kton
in 2 supermodules

Origami packing = vacuum packing
(1) Protection against light and humidity variations.
(2) Keep the position between films and Pb plates.
(3) Vacuum preserved over 10 years

# The Brick Assembly Machine (BAM)

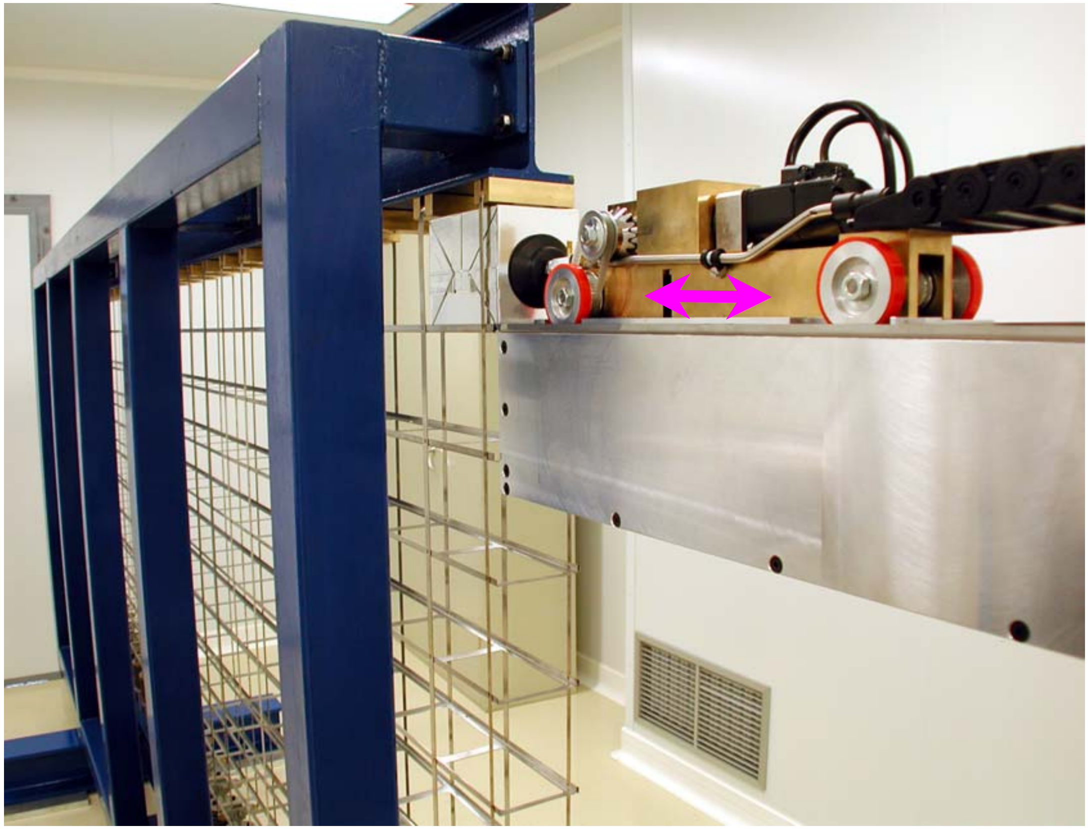
27M Pb plates (and emulsion sheets) ⇒ 235k bricks (2 bricks/minute)
Need assembly w/ industrial standards and quality controls (severe vacuum tests)



# Brick manipulator system (BMS)

Fill the brick walls
*235,000 bricks / year*

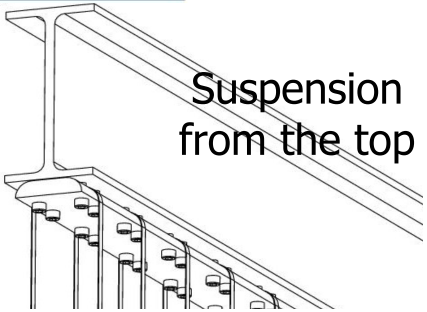
Extract bricks with $\nu$ interactions
*~ 40 bricks / day*



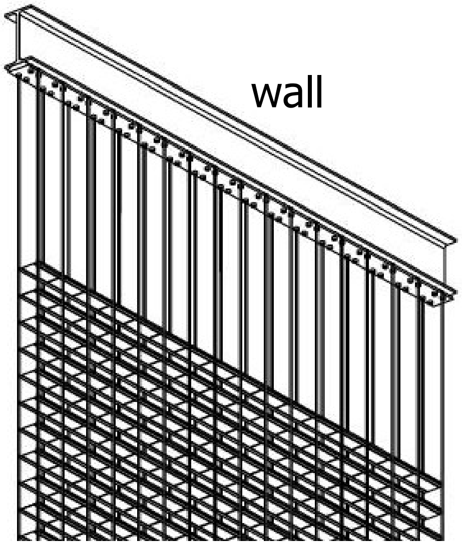
Tests with the prototype wall from Frascati-Napoli

"Carousel" brick dispensing and storage system

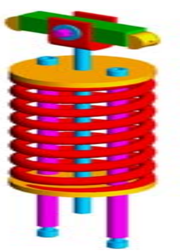
# Brick wall structure



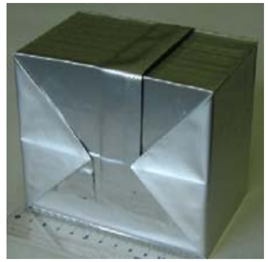
Suspension from the top



wall

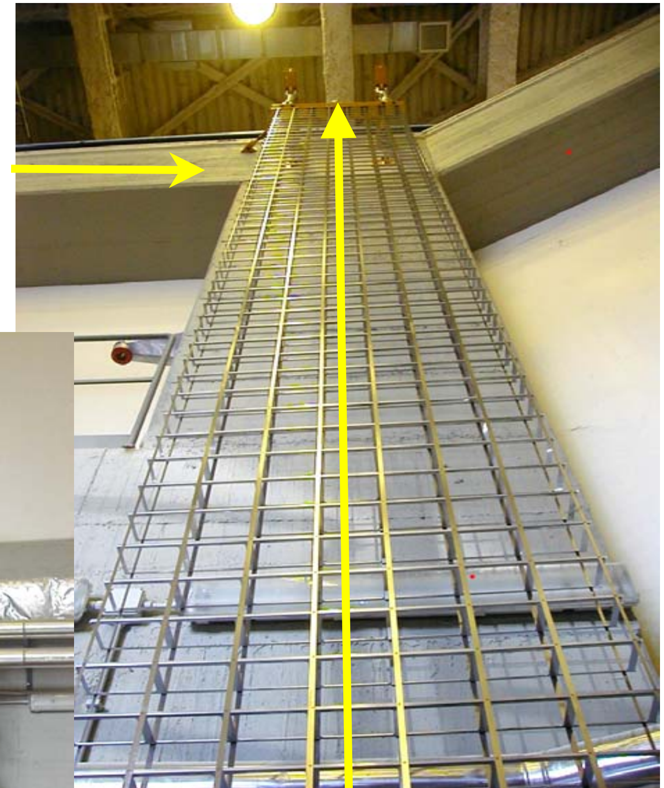


Tensioning from the bottom



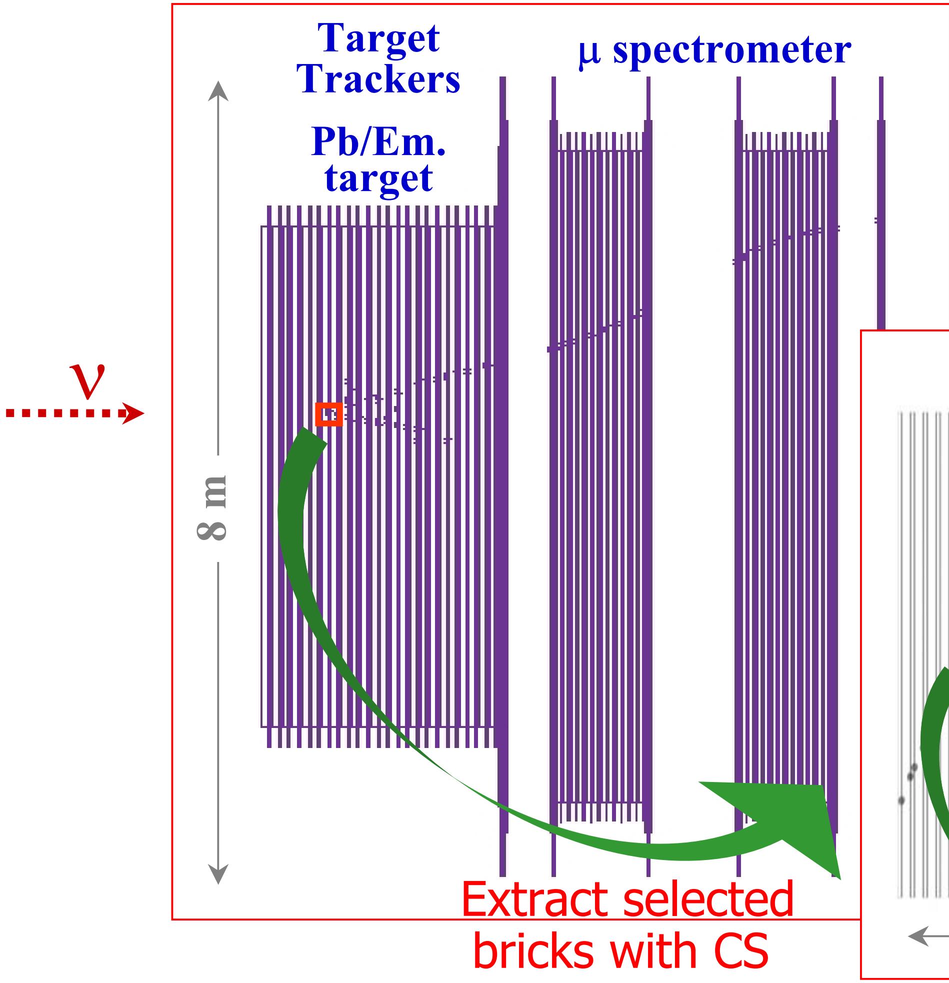
Bricks inserted from the side

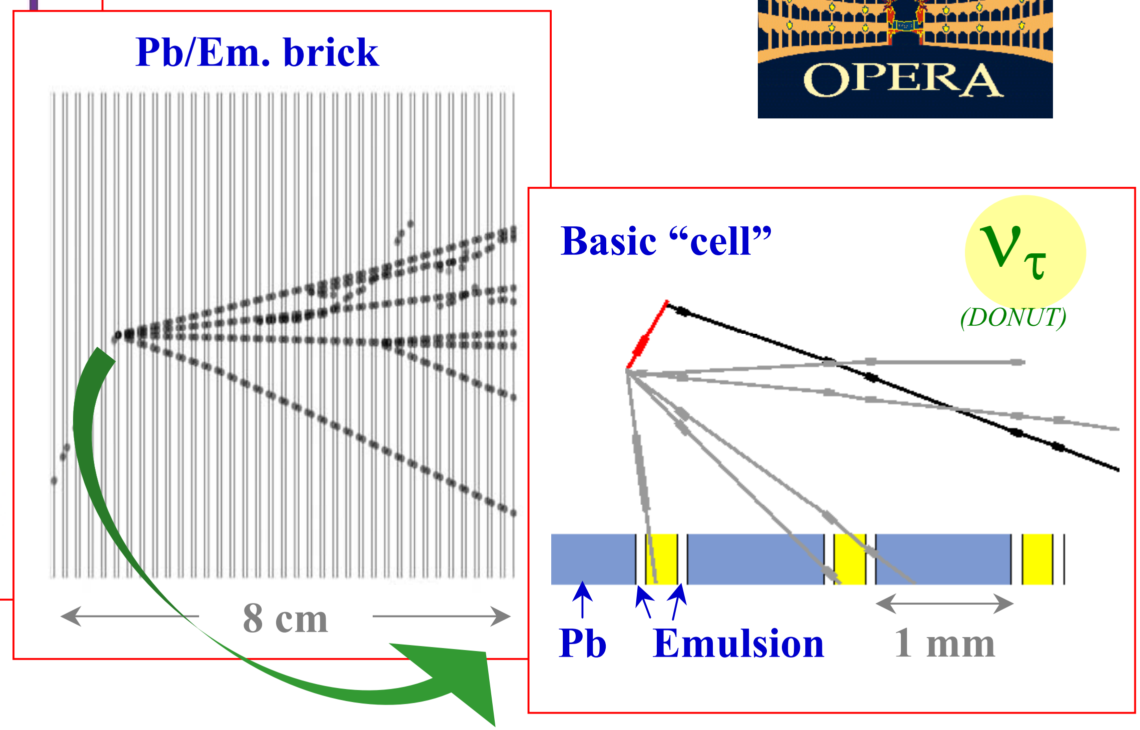
Brick loading test



Height ~ 6.7 m

# One event in OPERA




Electronic detectors

→ select ν interaction brick and CS

→ μ ID, charge and p

Emulsion analysis

→ vertex search

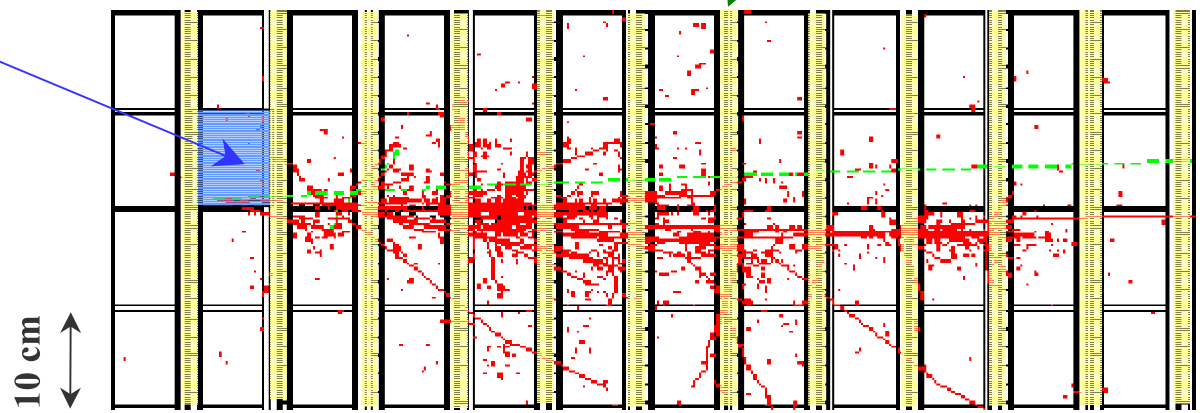
→ decay search

→ e/γ ID, kinematics

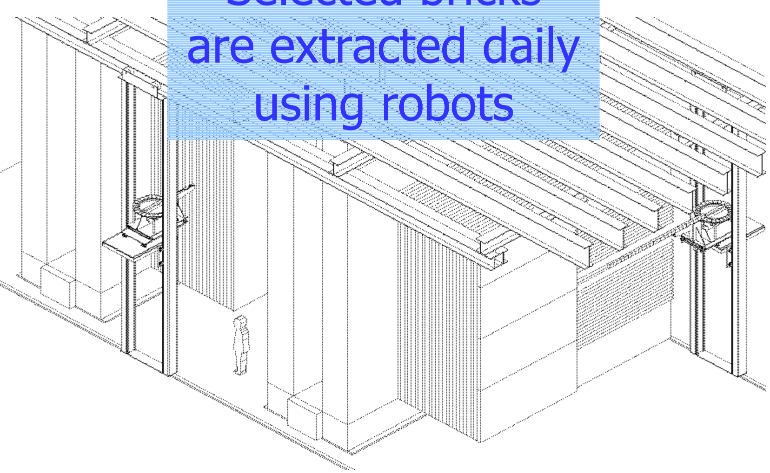
# Electronics detectors in the Target

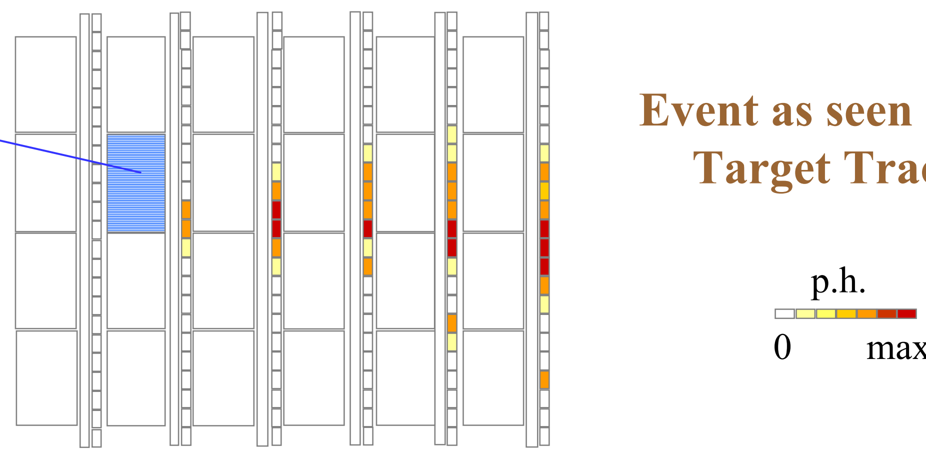
- Target Tracker tasks :
  - select bricks efficiently
  - initiate muon tagging
- High scanning power + low background : allow coarse tracking

Sampling by Target Tracker planes ( X,Y )



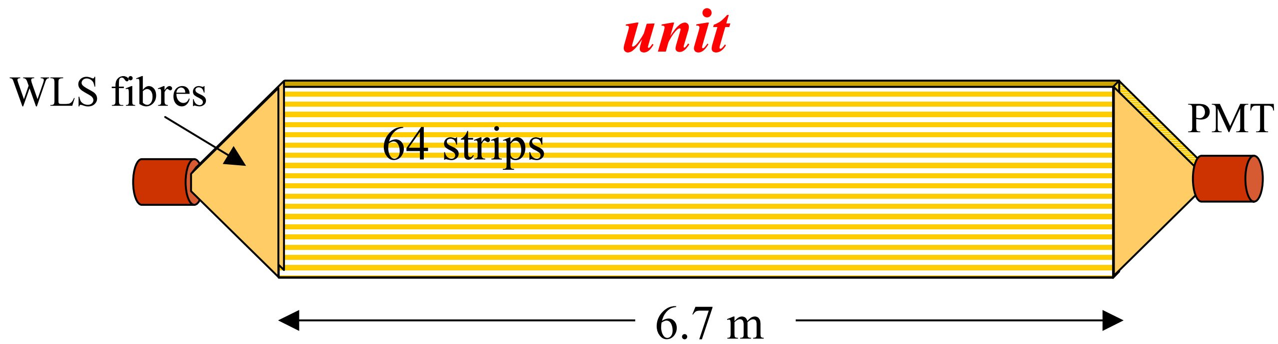

Selected bricks are extracted daily using robots

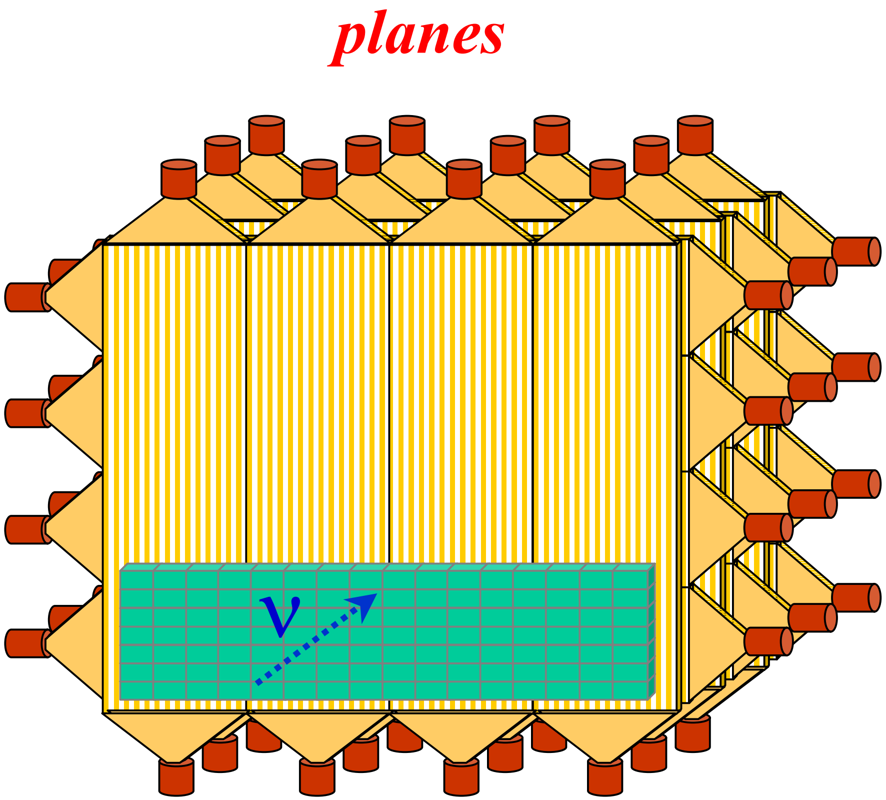


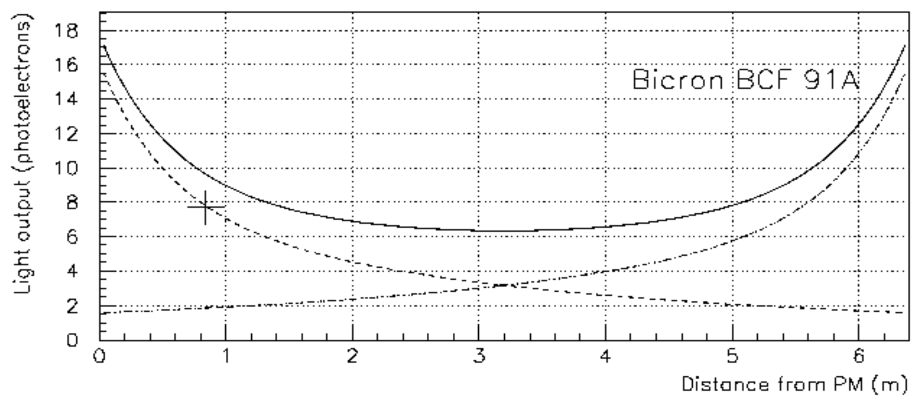



Event as seen by the Target Tracker

# Target tracker



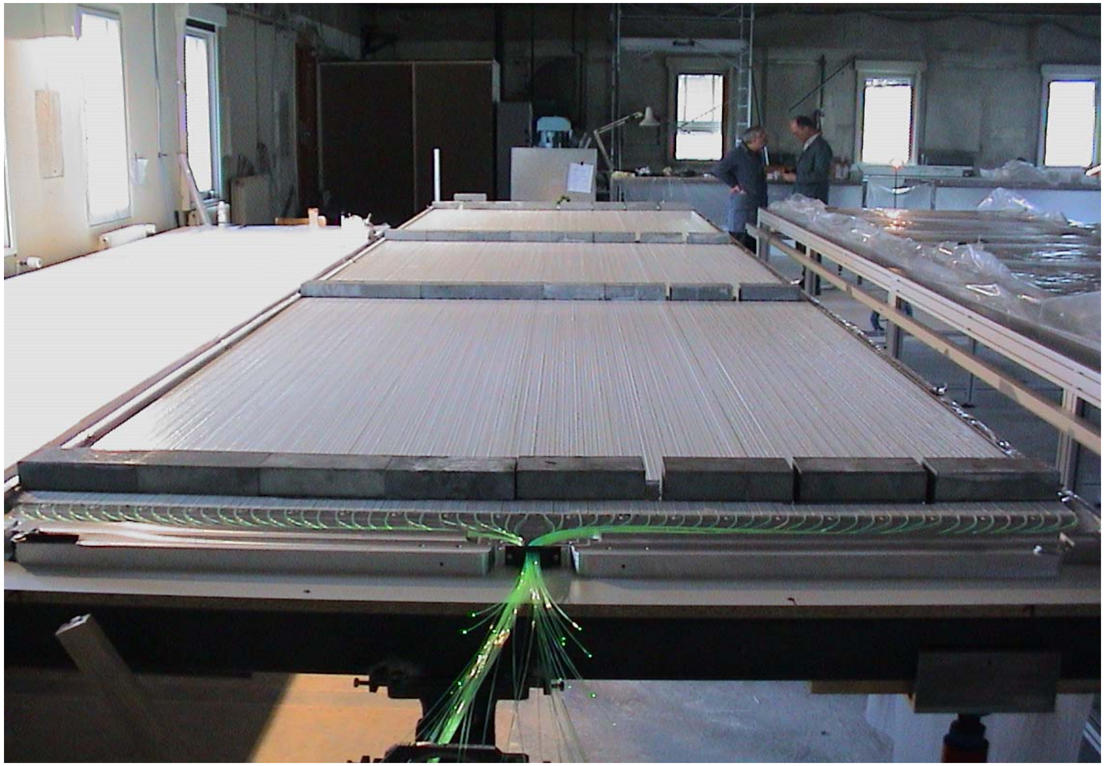



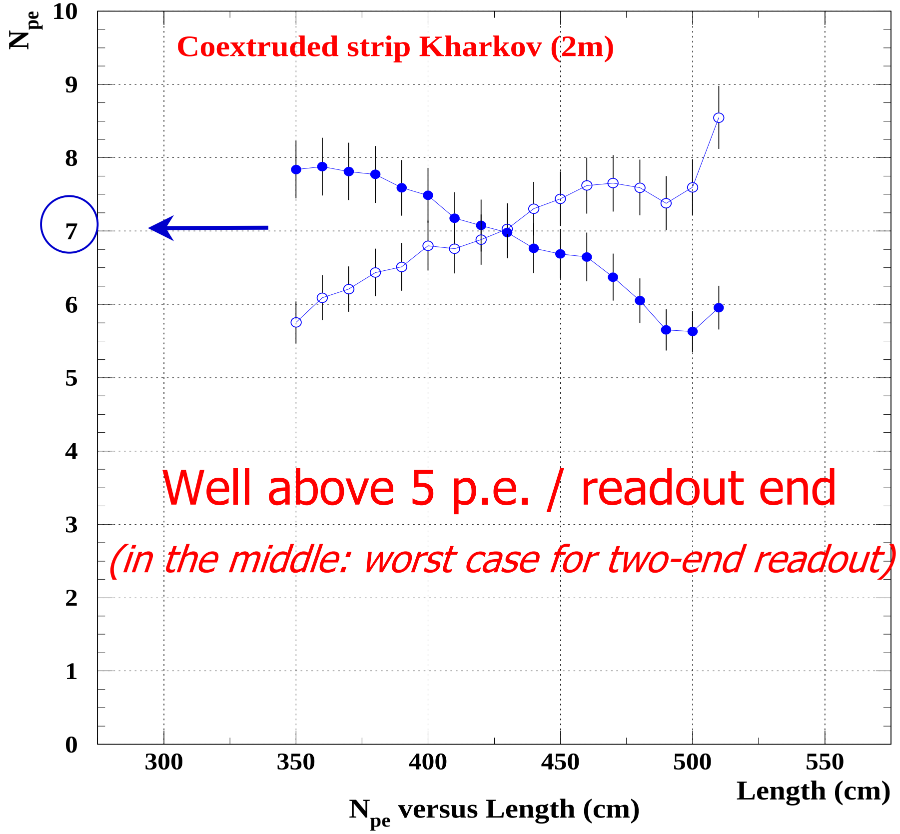

- Scintillator strips (**2.6 cm wide**, 1 cm thick)
- Light read out at both WLS fibre ends
- Multianode 64 ch. PMT (baseline)
- Minimum: 6 p.e.
- Probability for 0 p.e. = 0.2%

# Target Tracker prototype

- 64 strips of 6.7 m length, 2.6 cm width, 1 cm thickness
- Readout by wavelength shifting optical fibres in co-extruded grooves
- Tests of co-extruded strips from Amcrys-H (Kharkov), Pol.Hi.Tech and Chemo Technique
- Co-extruded $TiO_2$ coating
- Contacts for assembly of modules by industry



Full scale prototype module *(Strasbourg)*

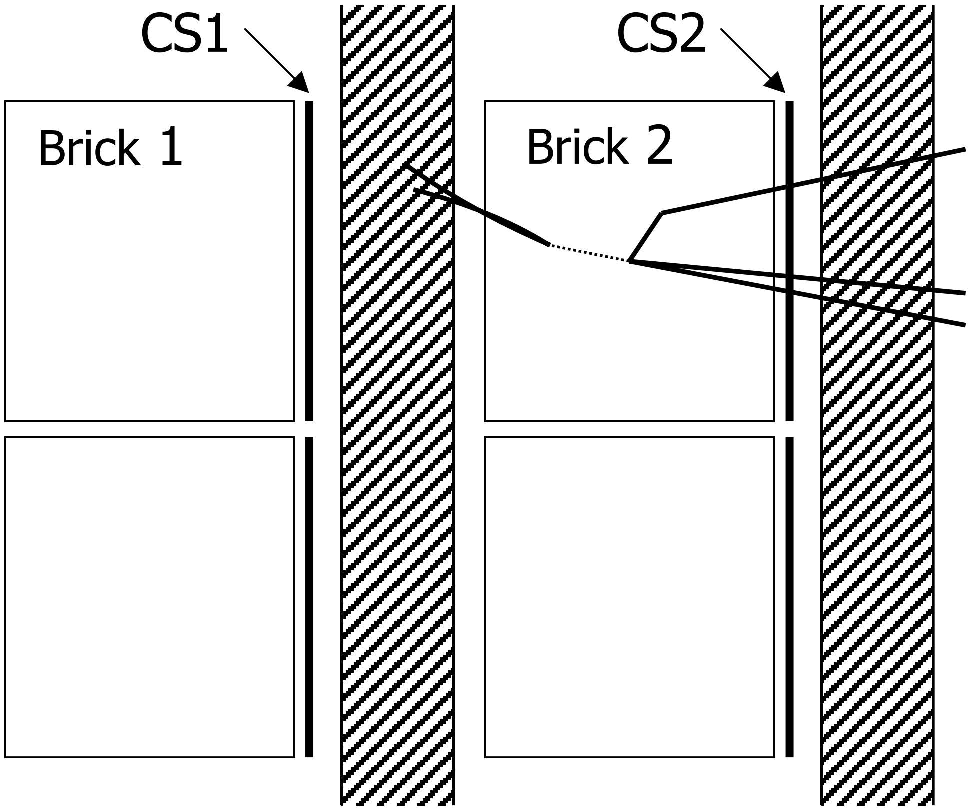



Well above 5 p.e. / readout end

*(in the middle: worst case for two-end readout)*

# The Changeable Sheet






TT uncertainties:

1. along the beam (wall ambiguities), mostly backscattering;
2. perp. To beam (brick ambiguities), limited TT transverse resolution;

Procedure (for CC-events, with $\mu$ track):

1. scan CS1 for predicted $\mu$ track;
2. if $|\theta_{CS} - \theta_{\mu}| < 20$mrad stop CS analysis, extract brick 1
3. if not scan CS2 for predicted $\mu$ track
4. if candidate, stop CS analysis, extract brick 2.

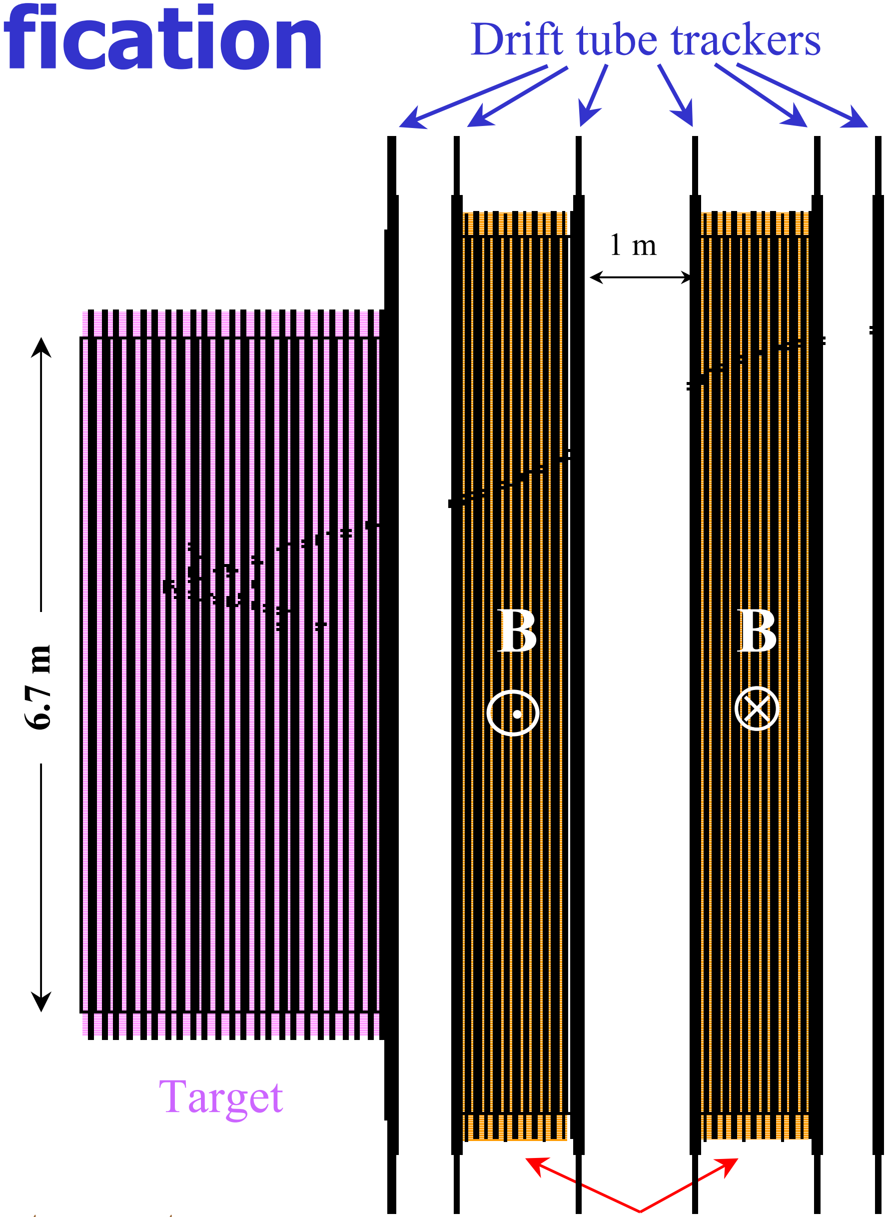
- ✓ Development and scanning before unpacking the brick;
- ✓ Reduce the scanning load ($5 \times 5$ cm$^2$ for CC candidates, $12 \times 12$ cm$^2$ for NC)
- ✓ Suppress efficiently backscattering (could lead to the wrong brick)
- ✓ Reduce the number of 'empty' bricks removed (preserve effective target mass)
- ✓ Improve event location efficiently
- ✓ Use different self-refreshing rate, ~ 1 month (only way to erase tracks from beam and Pb radioactivity)
- ✓ Need scanning facility close to experimental Halls (low cosmic background)

# Muon identification

- ✸ Measure momentum and identify charge:
- ✸ Reject charm background
- ② Tag and analyse $\tau^- \rightarrow \mu^-$ candidates

Dipole Fe wall (7.1 $\lambda_{int}$) instrumented with RPCs:

- identify muons shower energy measurement (with $p_m$ gives $E_n$ spectrum )




Muon spectrometer
(top view )

- **Drift Tube trackers**

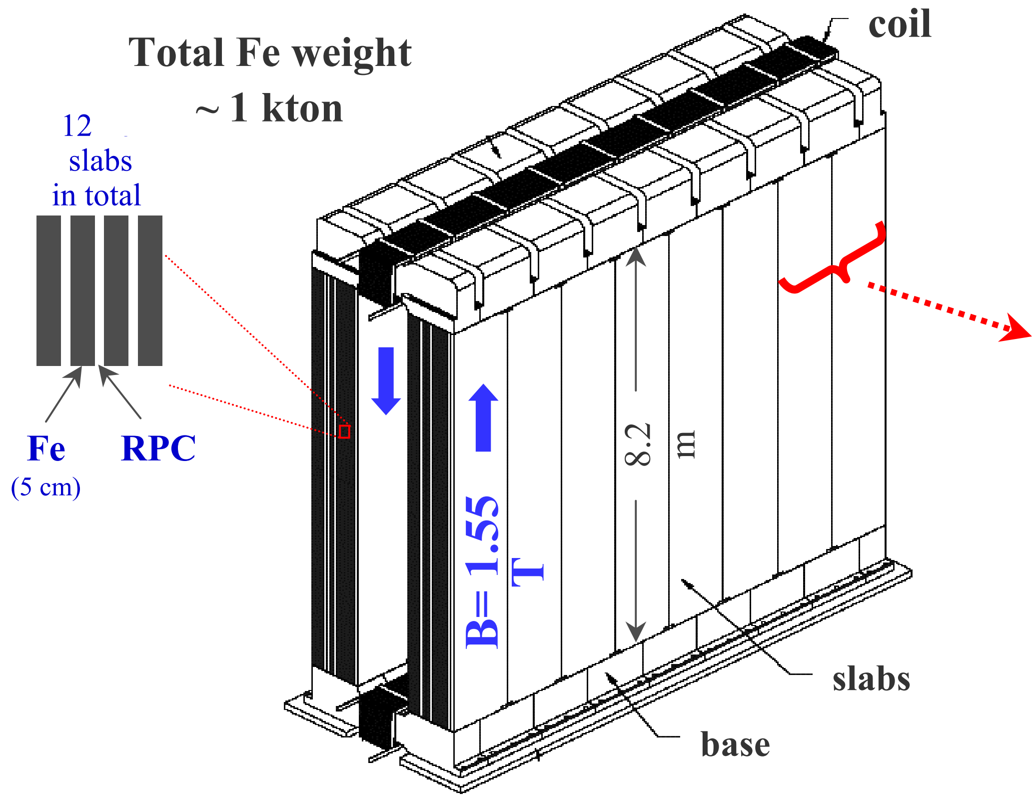
$$\frac{\sigma_p}{p} < 25\% \quad \text{for } p < 25 GeV/c$$

**Wrong charge < 0.5 %**

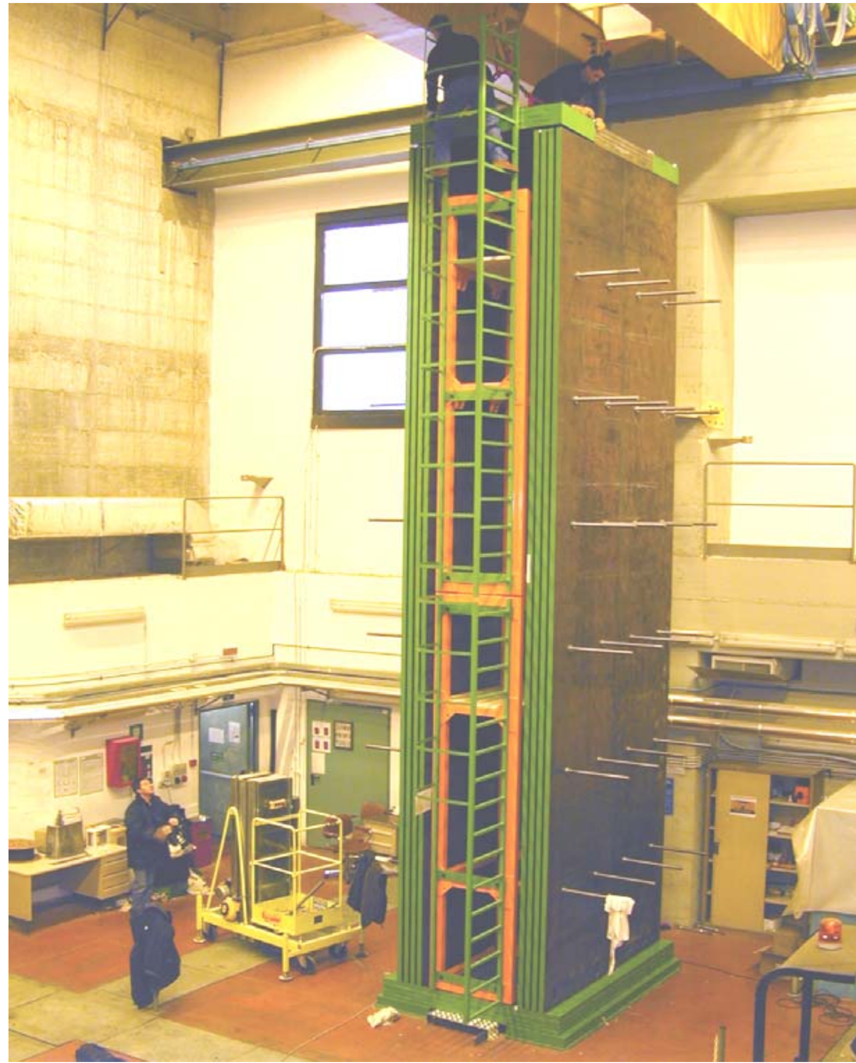
# Dipole Magnet

RPCs inside gaps: muon identification , shower energy

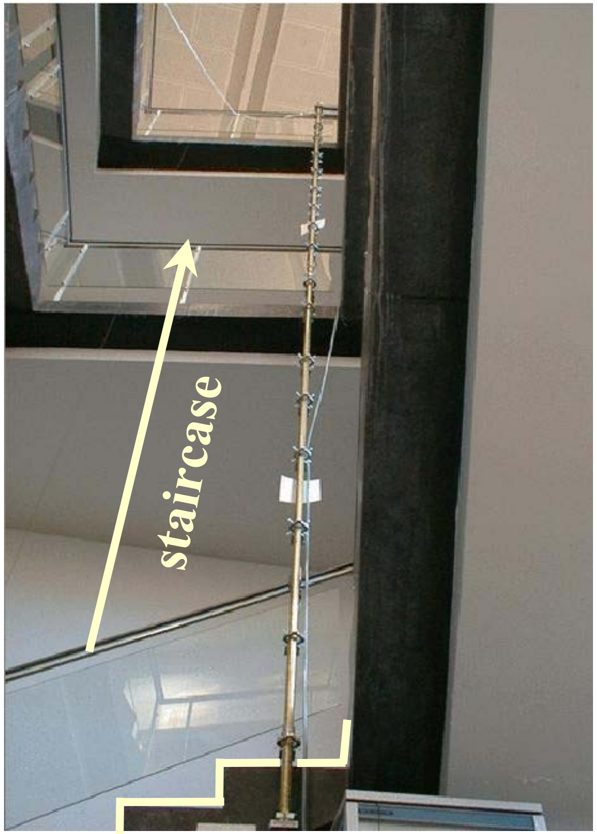
Drift Tubes: muon momentum

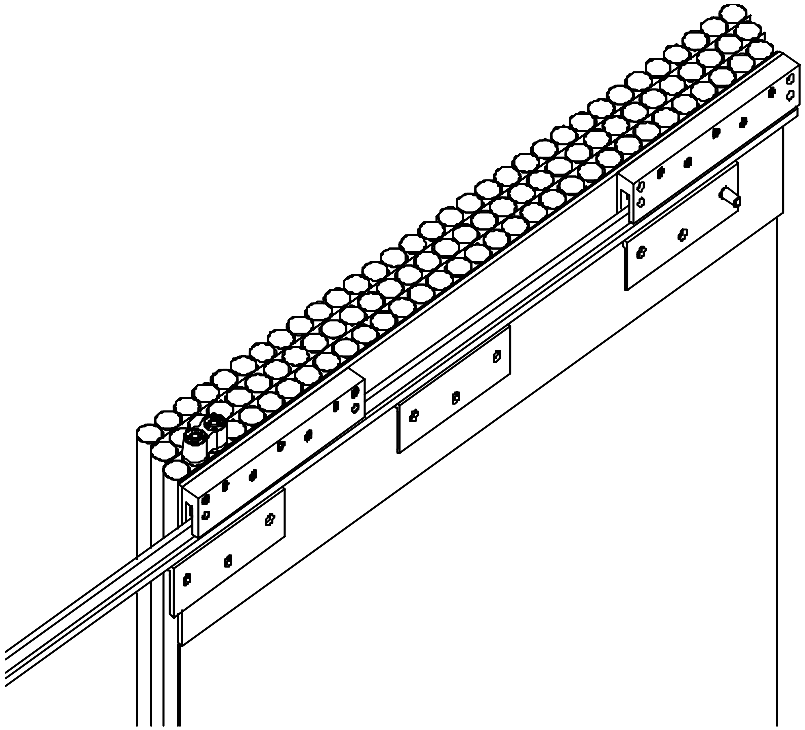


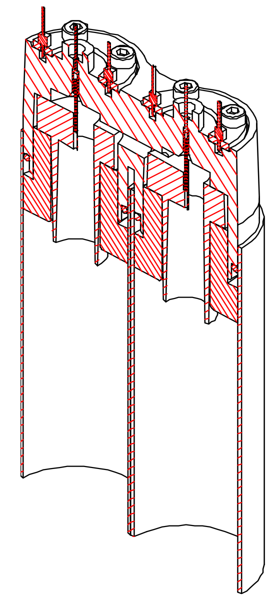

Full scale prototype of magnet section constructed and tested in Frascati



# Precision Tracker (Drift Tubes)





### *Tests of 8.1 m tubes*
- *Wire stability*
- *Attenuation length*

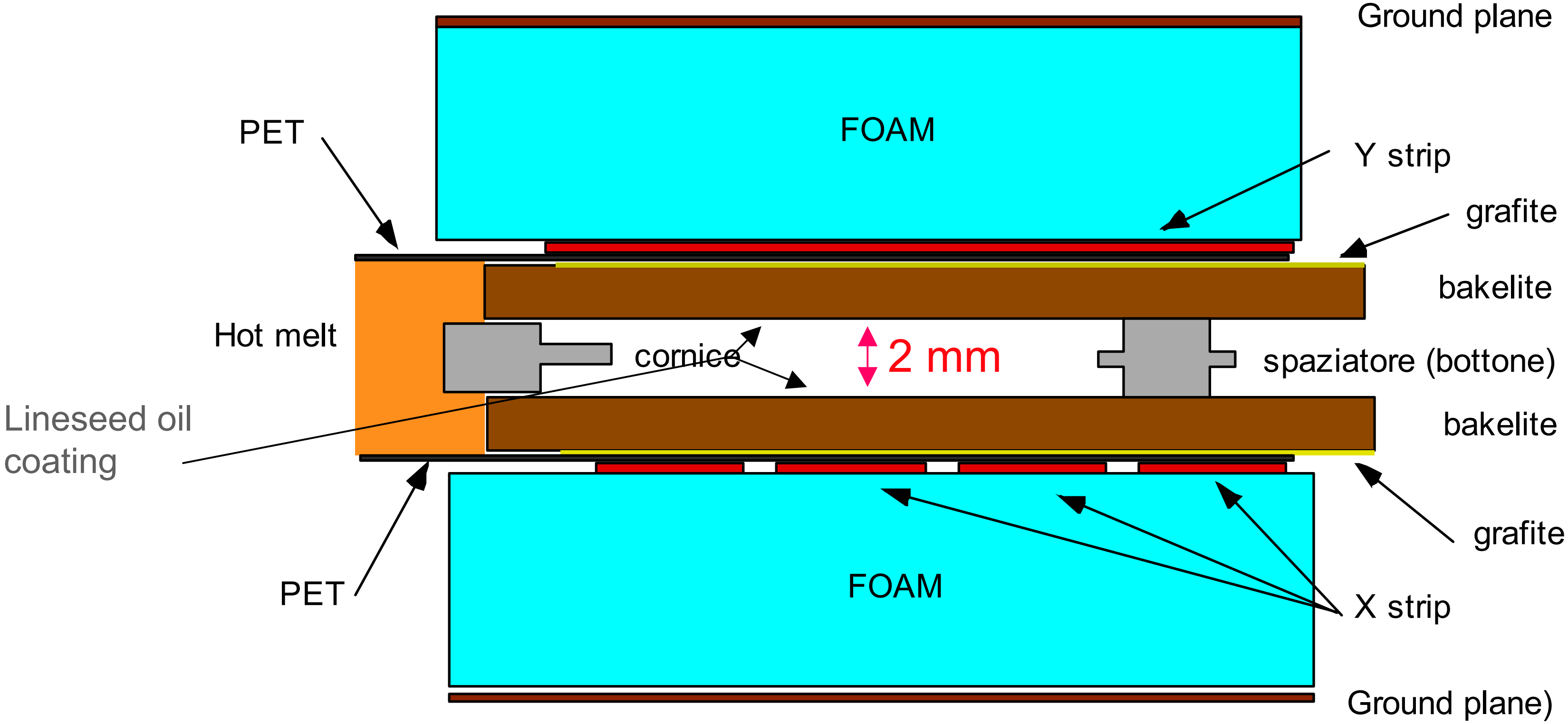
### *Overall Assembly*
- *Study of optimal staggering*
- *Mechanical design*
- *Negotiations for mass production*
- *Production of prototype (1 m) module started*

### *End Caps*
- *Design and tests*
- *Negotiations for mass production*

### *Electronics*
- *Design and tests*

# Inner tracker

- Requirements: ~ **4600 m²**, high geometrical efficiency, low cost, robustness, industrial production, ease of segmentation
- Technology: Resistive Plate Chambers (standard bakelite RPC)
- Features: signal: 100 pF, rise time 2 ns, 10 ns long; HV= 8 kV, 5 μA/m² , no flammable gas
- Construction: 28 elements/magnet gap (1848 elements in total), 3 cm copper strips

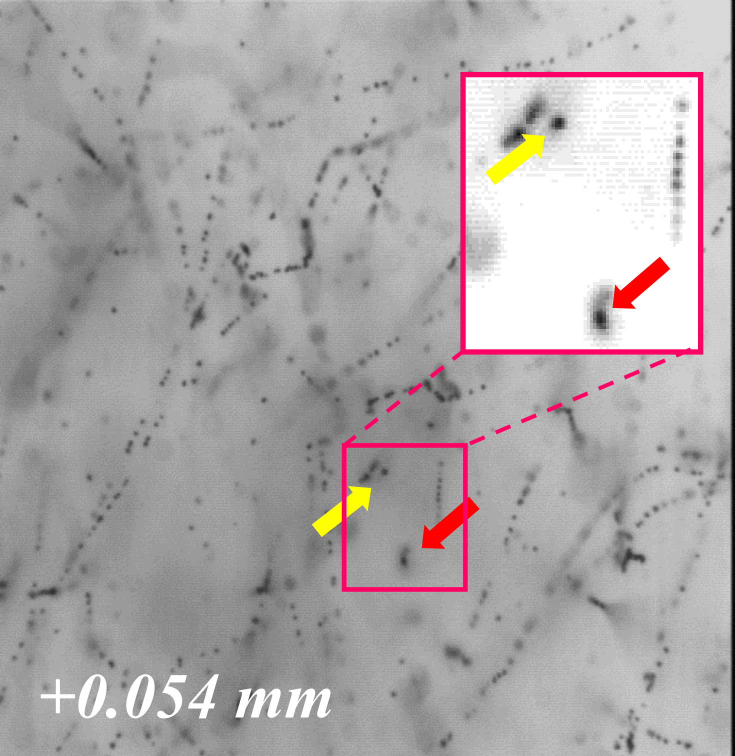


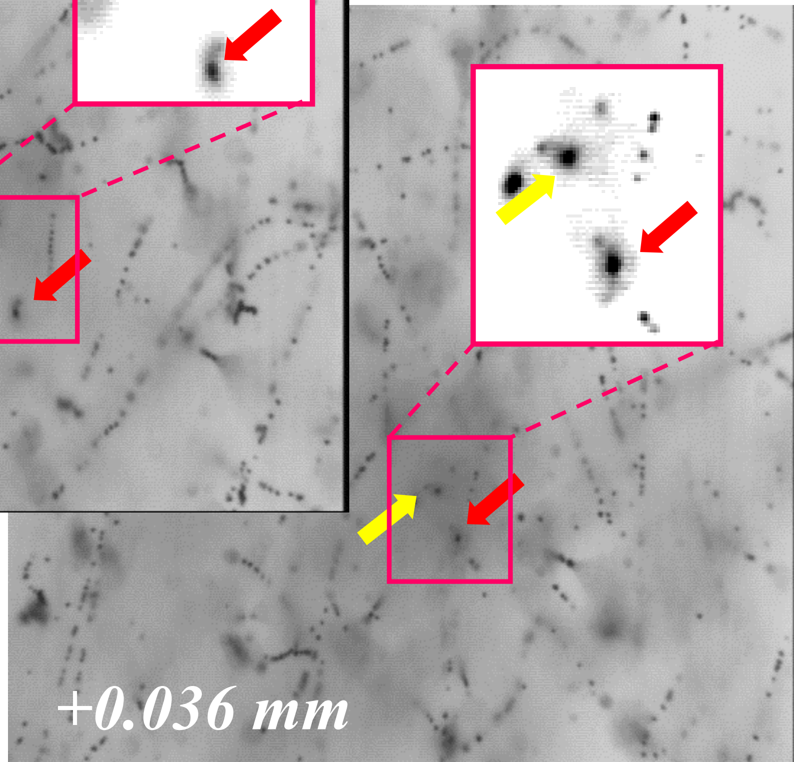
# Emulsion analyses

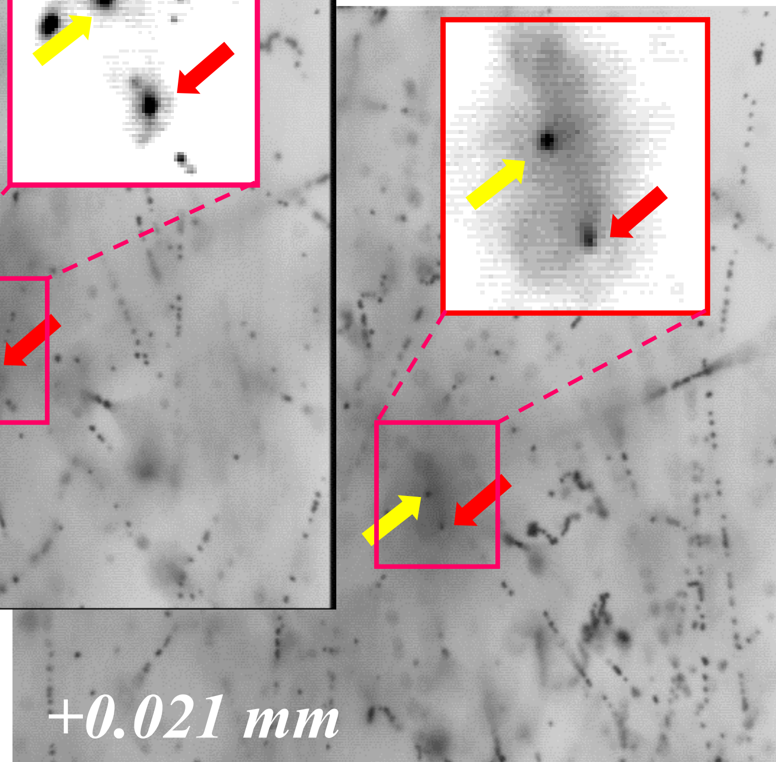
# Moving the focal plane down to the ν vertex

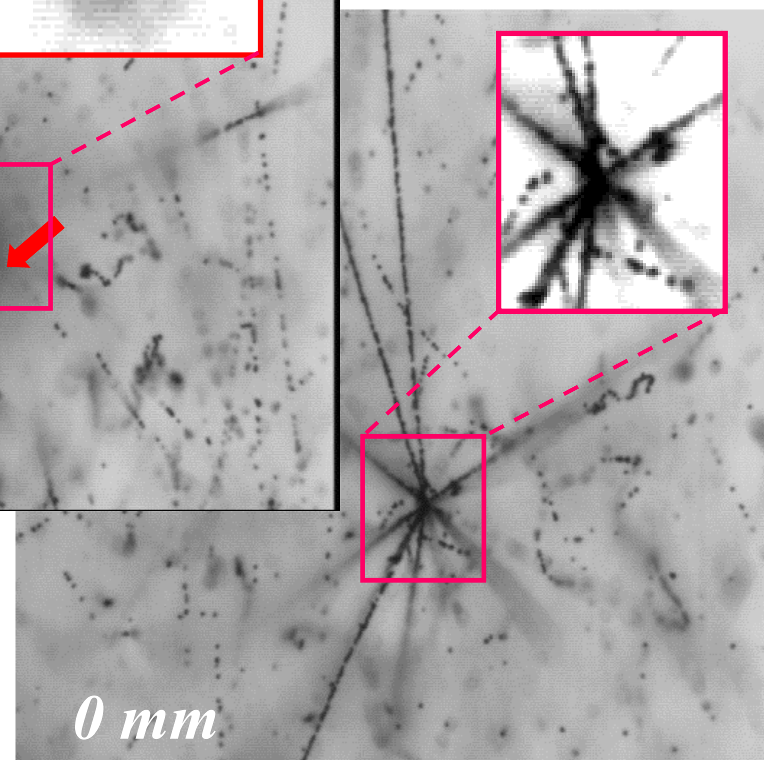
*Optical "tomographic slices" with focal depth ~ 0.005 mm*

*Moving down the focal plane through the emulsion thickness gives the third dimension*

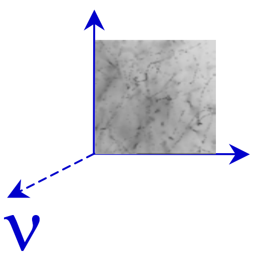


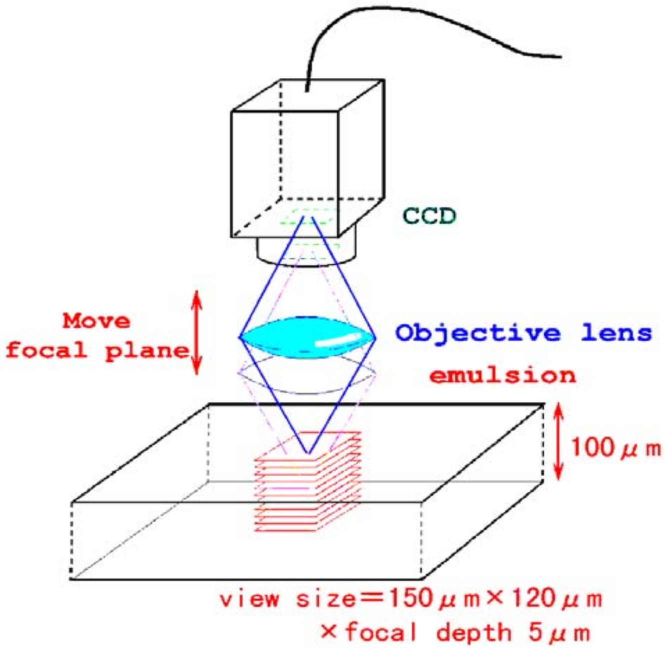




← 0.1 mm →



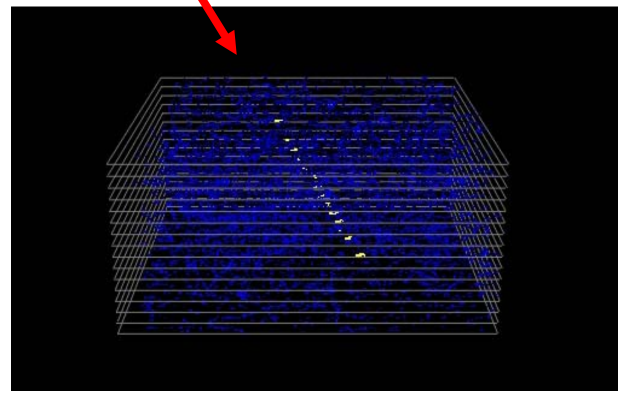

Particles produced in ν interactions
exit from the image
Interesting tracks appear as dots

# Track Selector (principle)

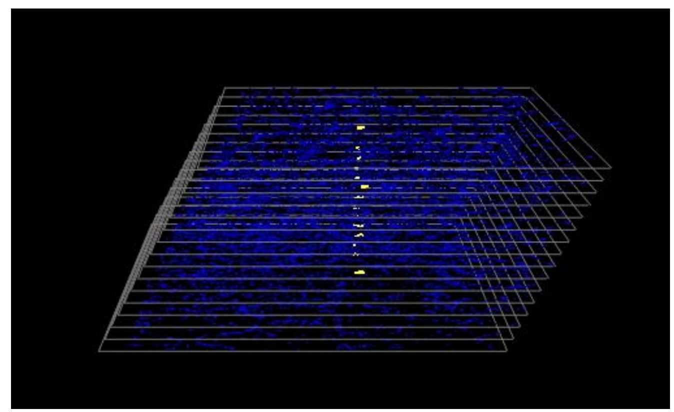



Tomographic
16 Images

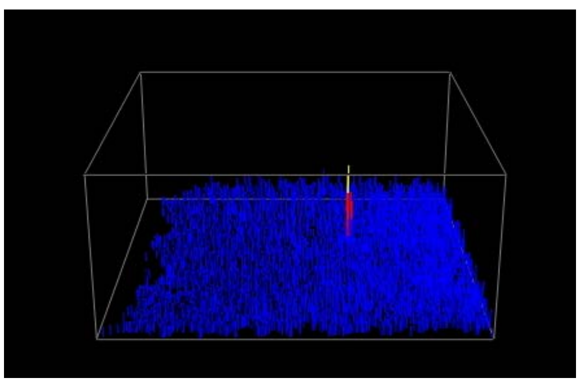
Penetrating Track



Give counter shift



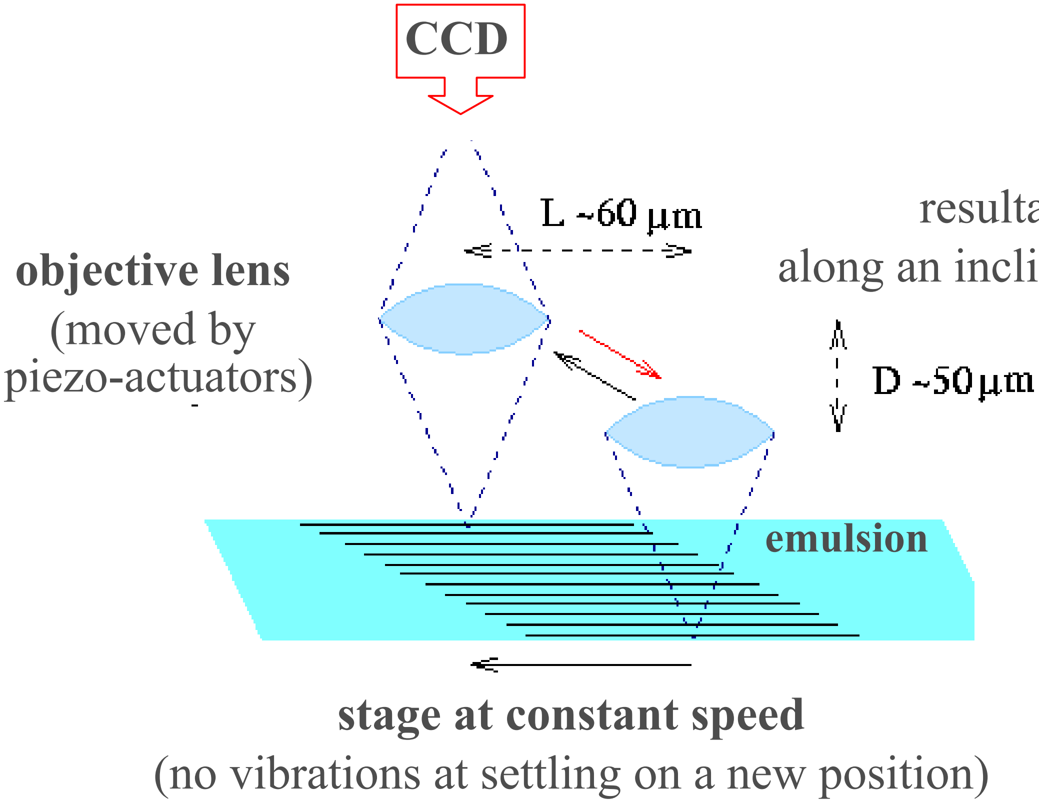
Sum and
Discriminate



# The emulsion scanning facility at Nagoya Univ.

# Automatic scanning in Nagoya: S-UTS

*(take images without stopping the stage, to increase the speed)*




S-UTS will achieve **40cm²/hr.** 60views/sec, the effective view size is (140μm)².

***Objective and stage movements <u>have to be synchronised</u>***

***Emulsions are scanned vertically, in <u>their</u> reference frame***

# Automatic scanning in Europe

R&D in Bari, Bern, Bologna, Lyon, Münster, Napoli, Roma, Salerno

## Design philosophy

*Optics with large view*
***hence***
***no critical mechanics***

***Commercial components***
*(in continuous development)*

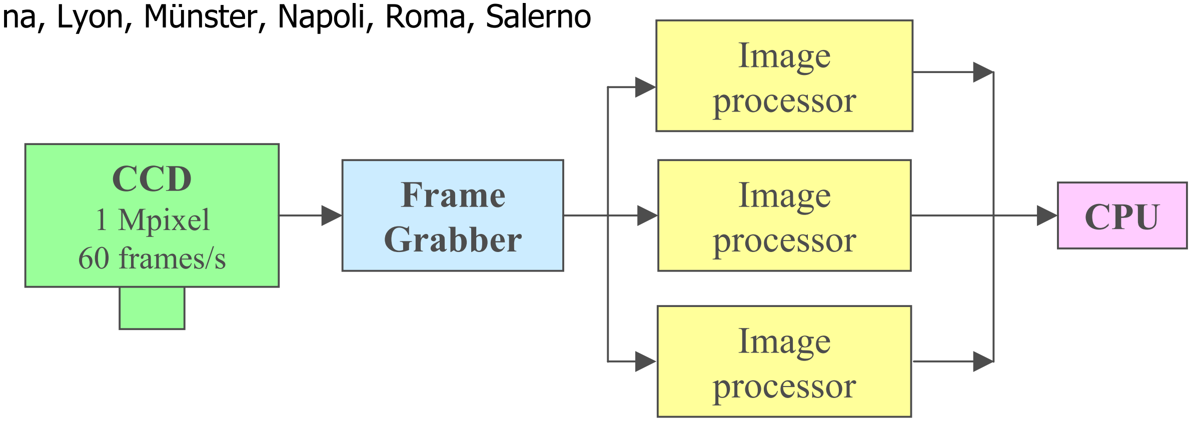
***Software approach***

⬇

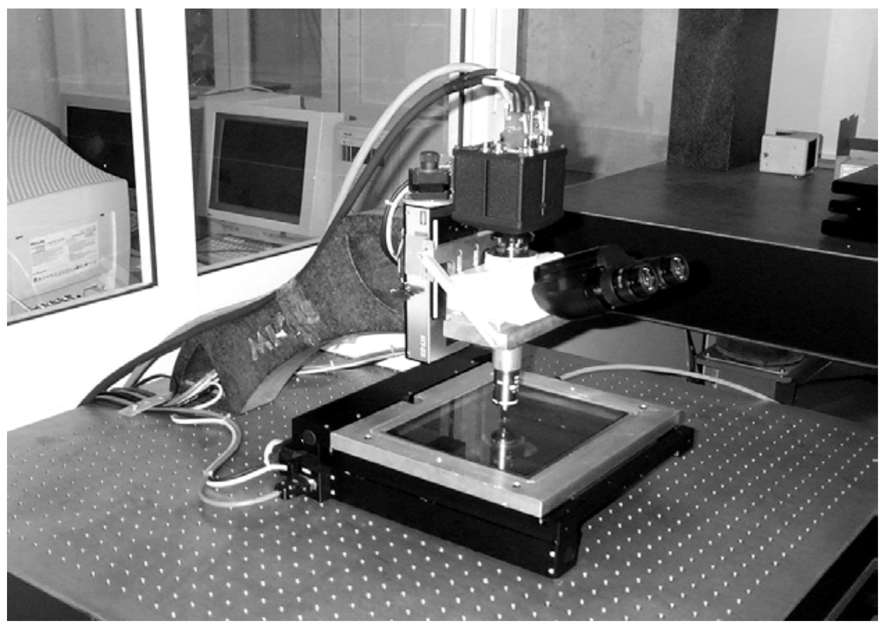
Excellent performance
with present technology
**10 $cm^2$/hour**

⬇

**Aim**
**20 $cm^2$/hour**




**Parallel processing**



New small and fast automated microscope (Naples)

*50 x magnification*

*330 x 330 $\mu m^2$ view*

*Change of view*
*with <80 ms settling time*

***R&D:***

***CMOS sensor: x2 frames/s***

***Oil immersion → dry objectives***

*4 Mpixel sensors ?*

# The OPERA $\nu_\tau$ search

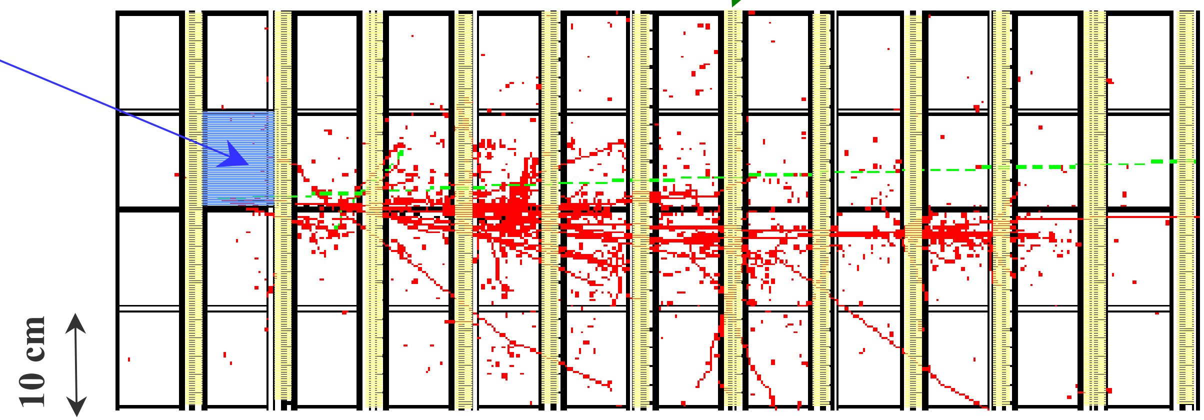
- The Electronic detectors are used to find the BRICK where the neutrinio interaction occurred
  - ✓ Bricks extracted and CS developed and scanned.
  - ✓ If CS say YES Brick developed and scanned otherwise Brick replaced.
- Tracks are followed back in the brick to locate the primary VERTEX with NETSCAN procedure (procedure already used by DONUT & CHORUS Phase II)
- The DECAY search is performed in two topologies
  - ✓ long decay topology $\Rightarrow$ kink
  - ✓ short decay topology $\Rightarrow$ impact parameter
- The full event is reconstructed in order to perform a Kinematical Analysis of the selected events:
  - ✓ track momentum by Multiple Coulomb Scattering (MS)
  - ✓ EM shower energy from total track lenght
  - ✓ specific $\pi^0$ reconstruction for $\tau \rightarrow \rho$ search

# Wall and Brick finding

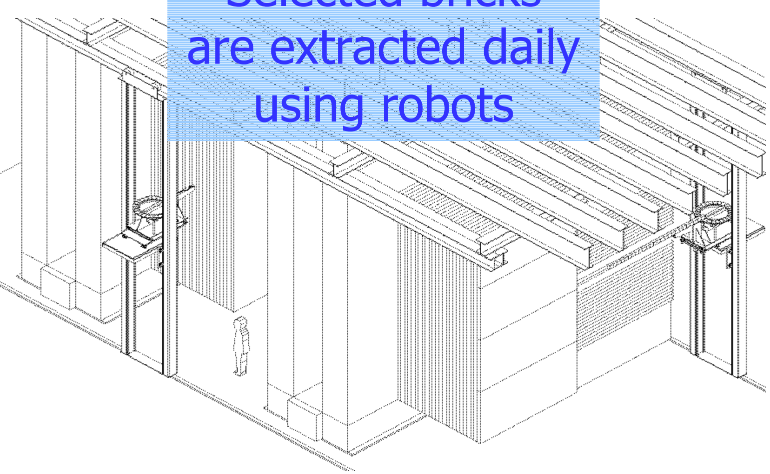
- Target Tracker tasks :
  - select bricks efficiently
  - initiate muon tagging

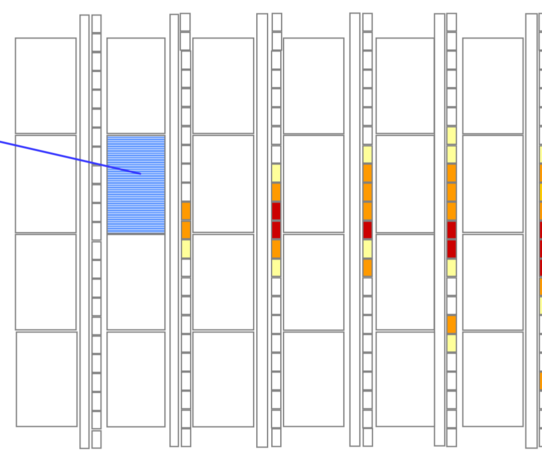
- High scanning power
  + low background :
  allow coarse tracking

Sampling by Target Tracker planes ( X,Y )

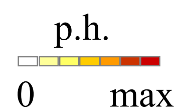



Selected bricks are extracted daily using robots

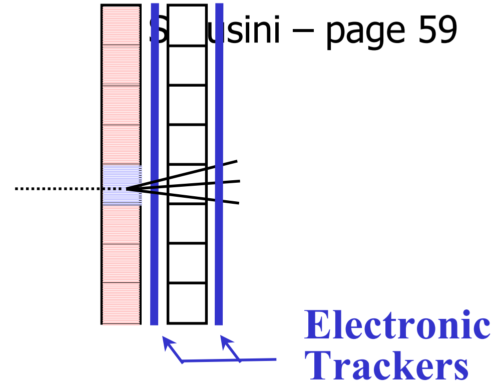




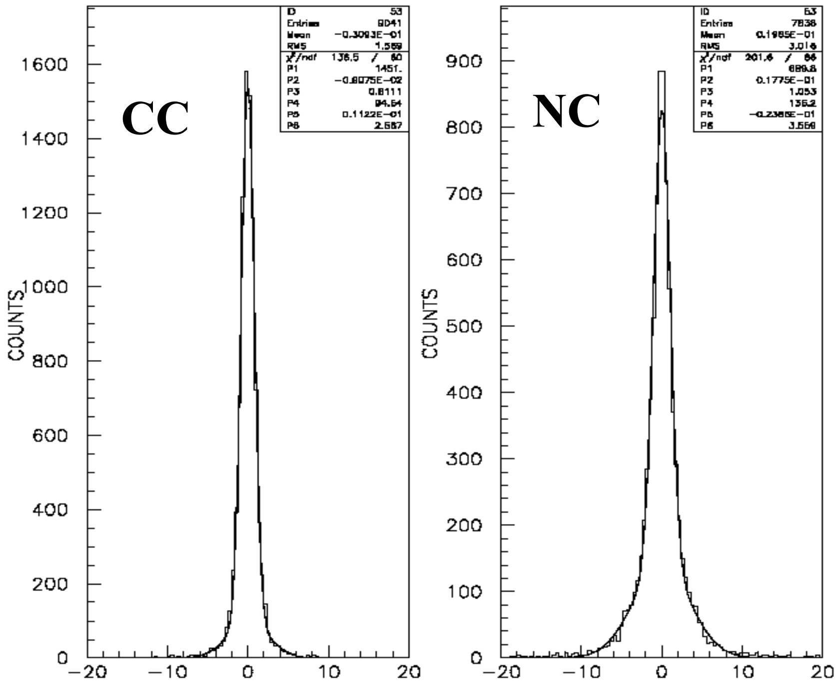
Event as seen by the Target Tracker



# Wall and Brick finding(II)




Centre of gravity of Scint. Strips
+ μ track for CC events




$x_{true}$ - $x_{rec}$ (cm)

$\sigma$ = 1.5 cm CC
3.0 cm NC

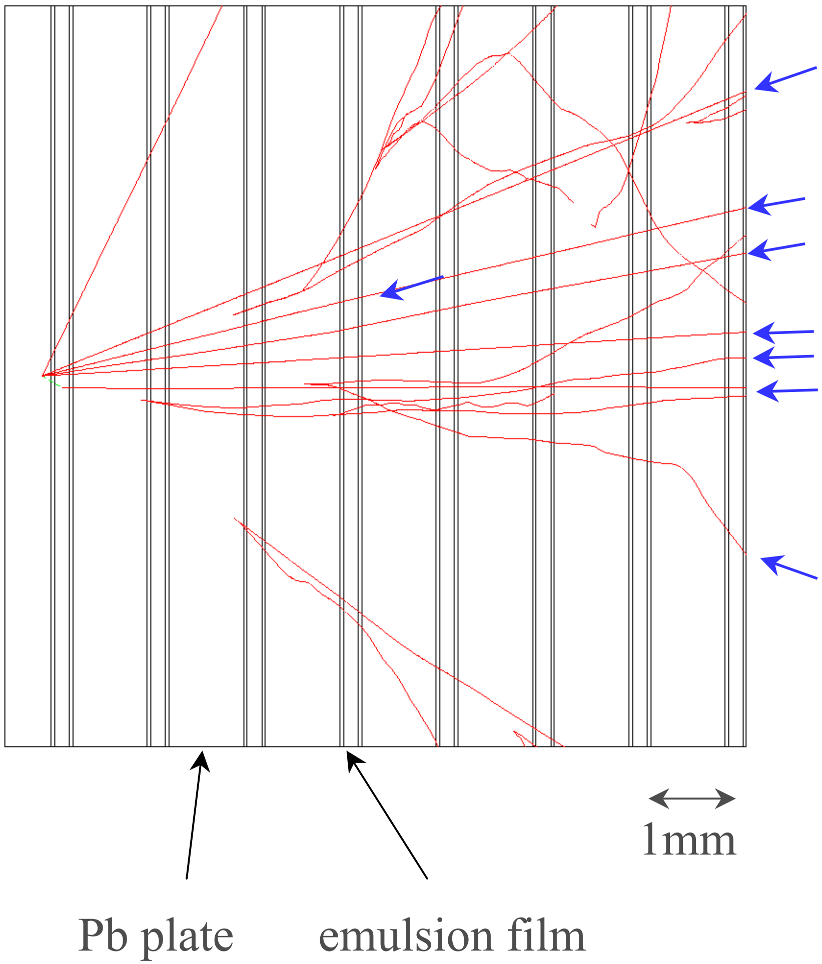
$\varepsilon_{brick}$ ( including $\varepsilon_{wall}$ ) in %

| | DIS | QE |
|---|---|---|
| $\tau \rightarrow e$ | 79.4 | 81.4 |
| $\rightarrow \mu$ | 73.5 | 72.1 |
| $\rightarrow h$ | 76.0 | 58.7 ($h = \pi$) |
| | | 78.8 ($h = \rho$) |

**Assuming the removal of 1 brick / event**

(more elaborate brick removal strategies are under study)

# How to locate ν interactions in bricks




(1) Pick up all tracks from ν interaction
on the most downstream film
$5x5cm^2$ for CC
full brick surface for NC

→ **$250cm^2$/brick**

**Requires scanning power**

(2) Scan back picked up tracks :
ν interaction vertex when track disappears
in 2 consecutive films

(3) check the existence of a vertex by "NET scan"

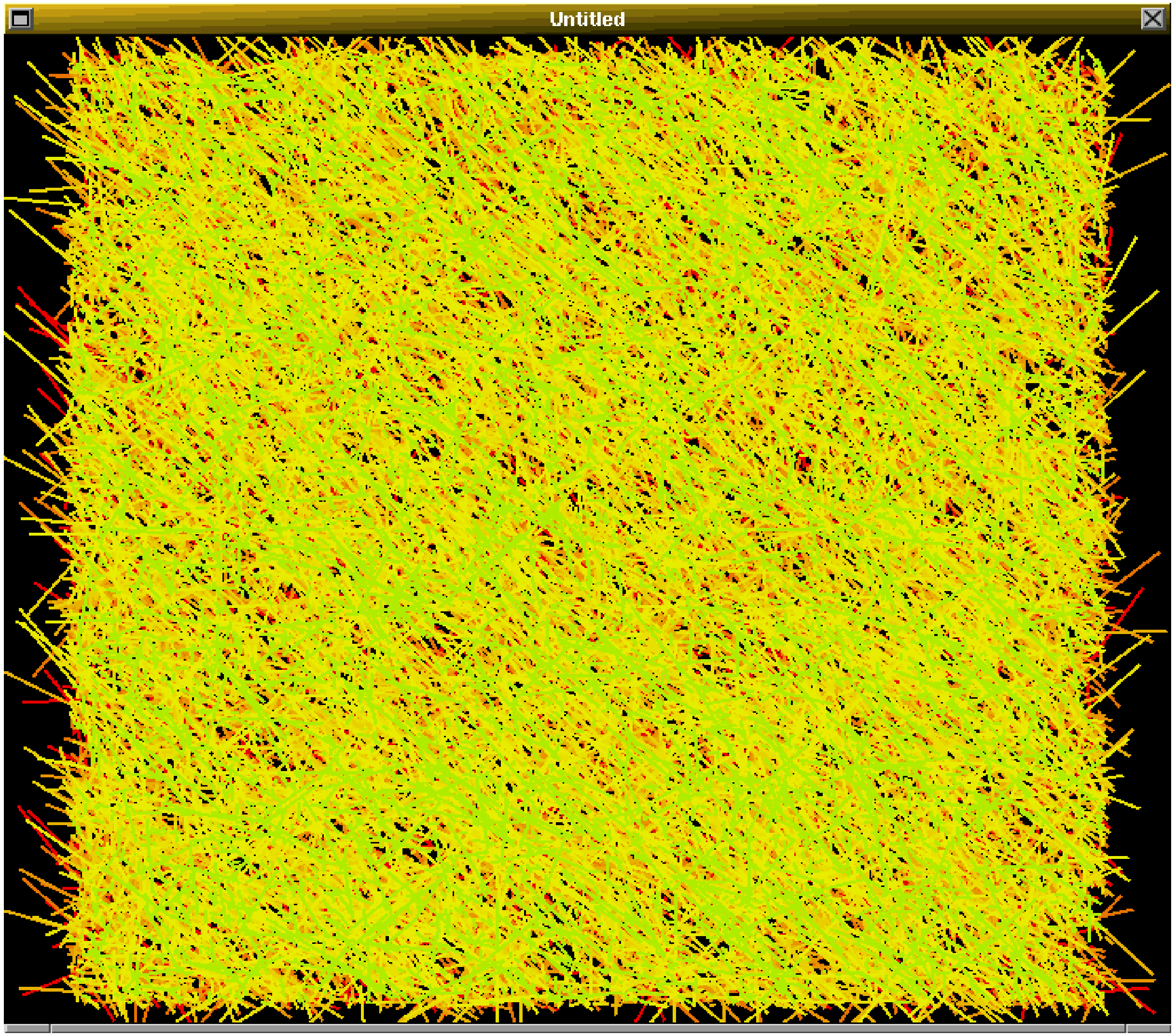
**Established techniques**
**in CHORUS and DONUT**

DONUT

Courtesy of S.Aochi

# Netscan (1)

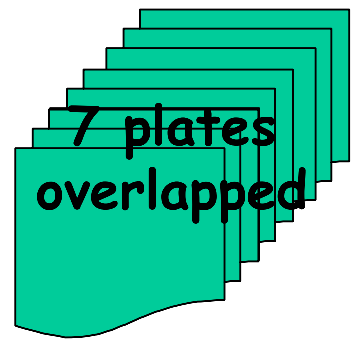
Yellow : Upstream
Red : Downstream




5 mm

5 mm

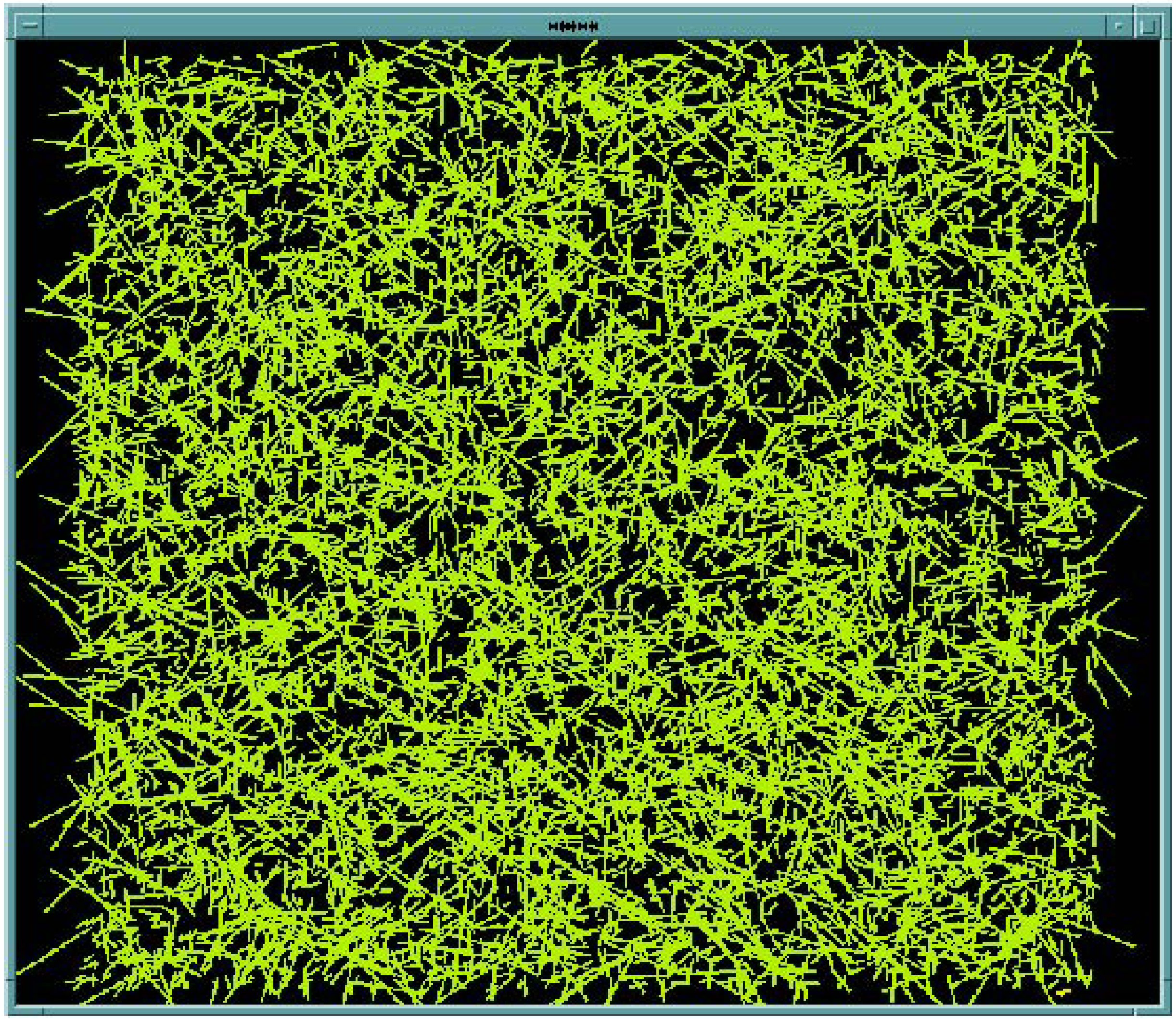
All track segments (~70k seg)



DONUT

Courtesy of S.Aochi

# Netscan (2)



5 mm

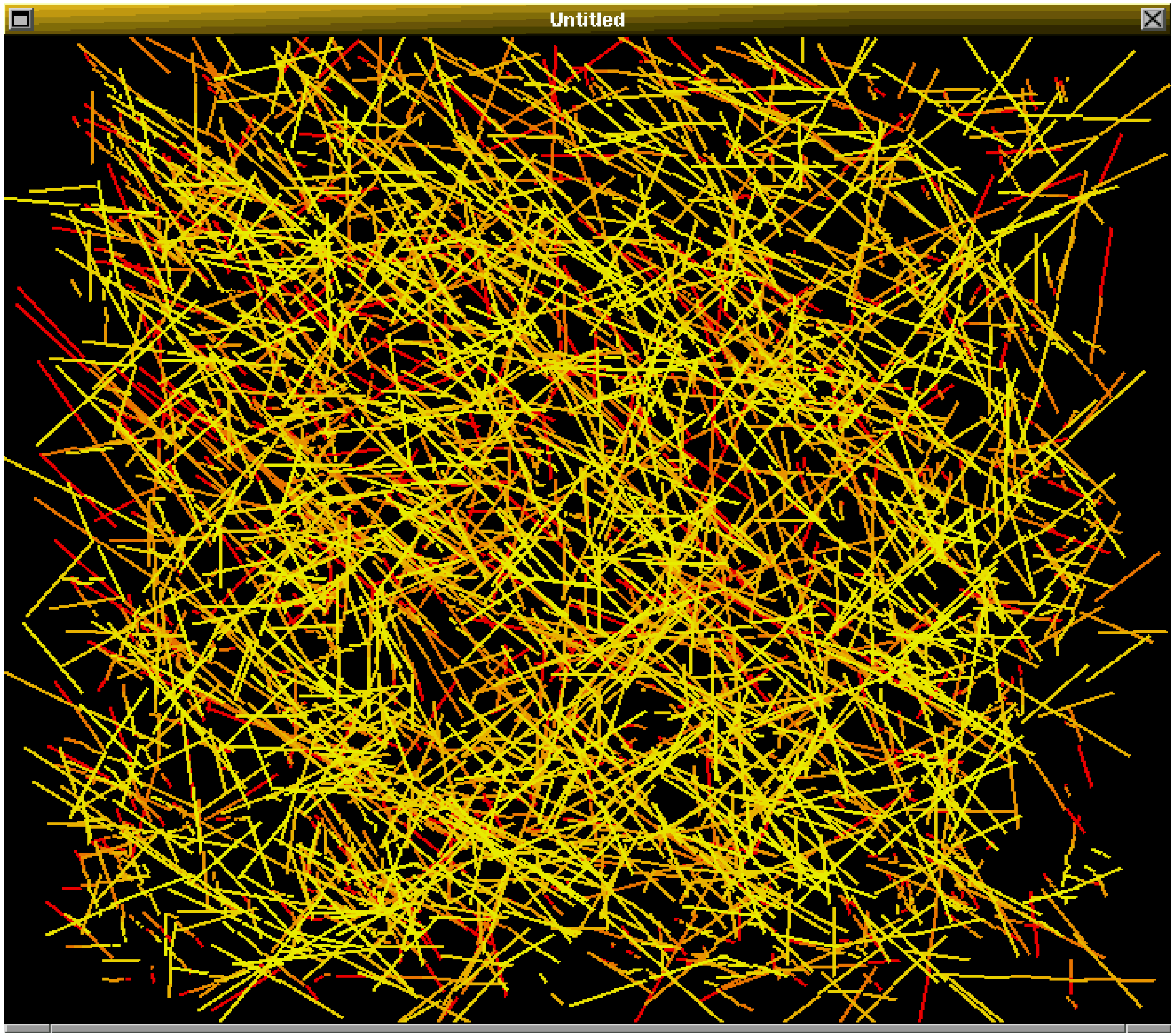
5 mm

All track segments from single plate (~10k seg)

DONUT

Courtesy of S.Aochi

# Netscan (3)



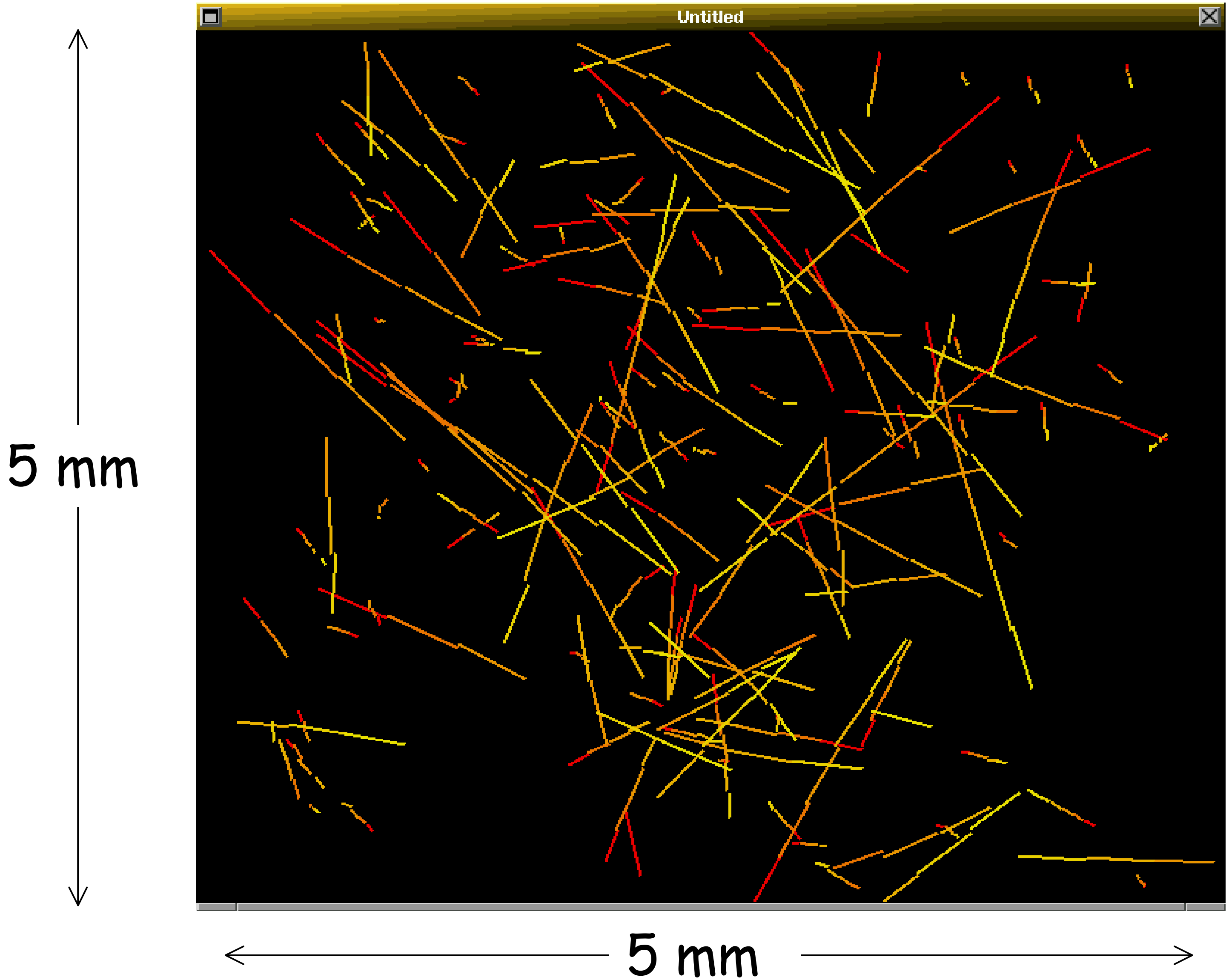

5 mm

5 mm

Not passing through (~1k track)

Courtesy of S.Aochi

# Netscan (4)

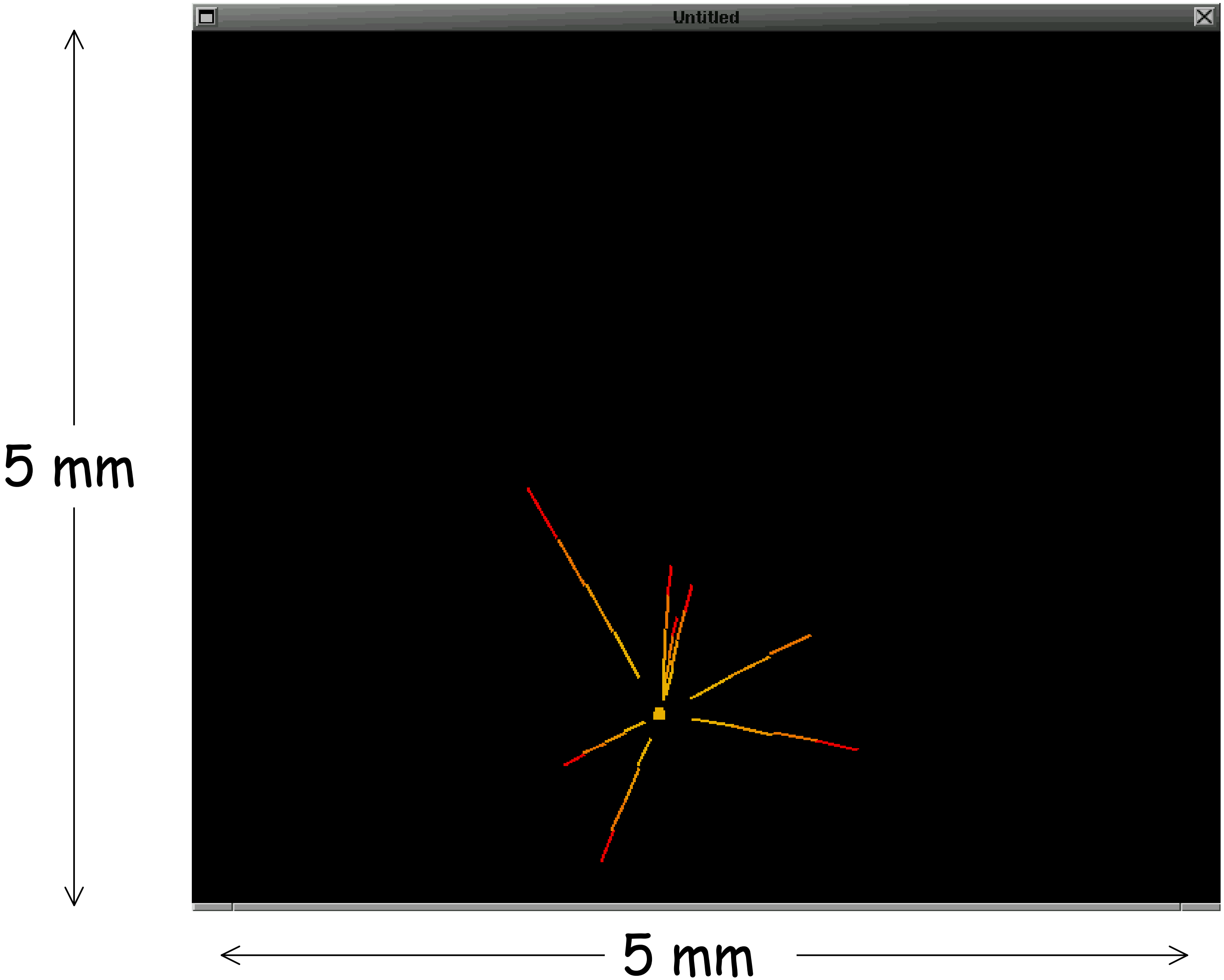



≥2 plates connected (~200 track)

DONUT

Courtesy of S.Aochi

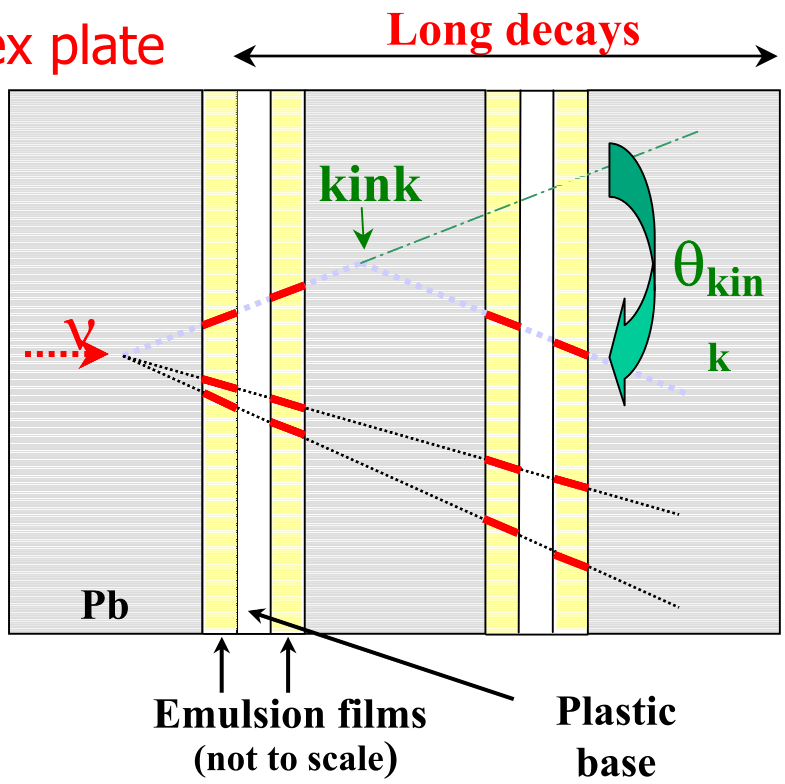
# Netscan (5)



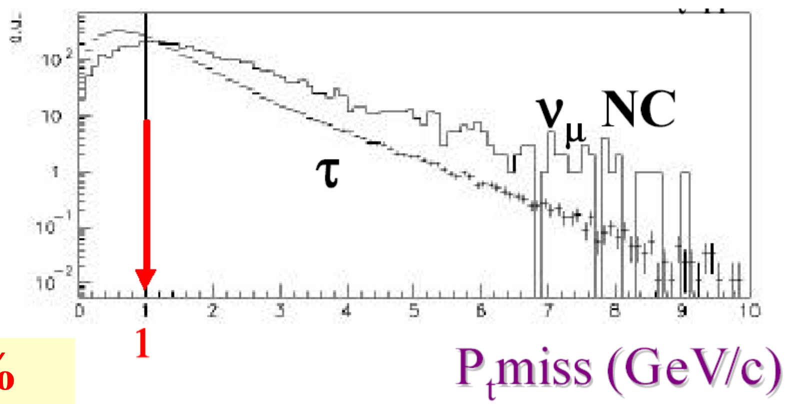

Small impact parameter

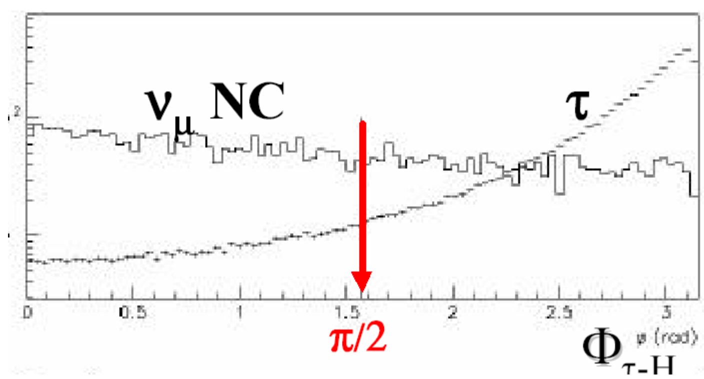
# 1. " Long " decays ( ~ 39 % of $\tau$ decays )

i.e. in 1st or 2nd Pb plate after vertex plate




- Search for a kink with an angle $\theta_{kink}$ > 20 mrad
  - ✓ leptonic channels $\tau \to$ **e, $\mu$**
  - ✓ hadronic channels $\tau \to$ **h, $\rho$**
- Require large $P_T = P^* \theta_{kink}$ at 2ry vtx.
  - ✓ leptonic channels > **100, 250 Mev/c**
  - ✓ hadronic channels > **600, 300 Mev/c**
- Additional kinematic cuts at 1ry vtx. for the hadronic channels
  - ✓ $\Phi_{\tau-H} > \pi/2$
  - ✓ **$P_t$miss < 1 GeV/c**



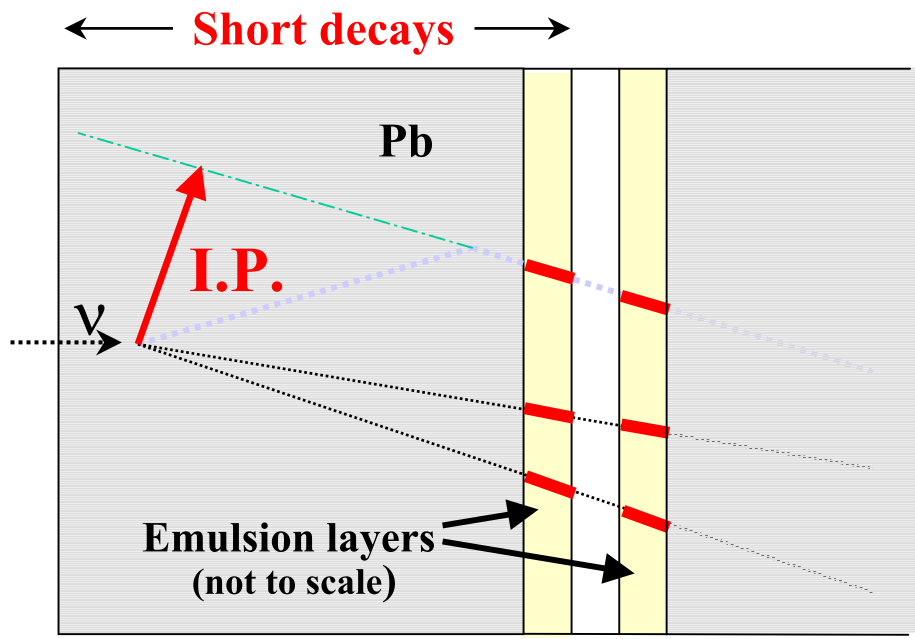

**eff. · BR = 2.8-3.5 %**

OPERA

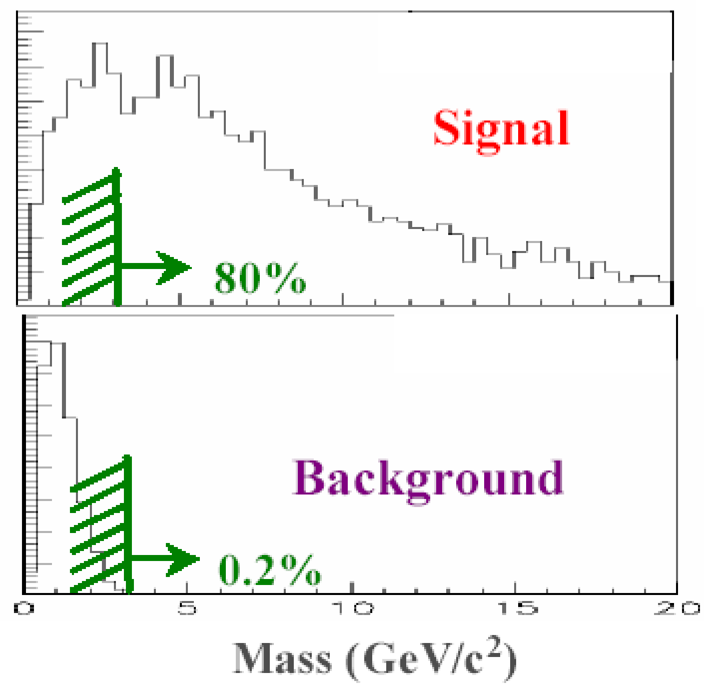
# 2. " Short " decays

## ( ~ 60 % of $\tau$ decays )

## i.e. in vertex Pb plate




- At least two additional 1ry tracks for vertex reconstruction
  - ✓ **P > 1.0 GeV/c**
- Require a large impact parameter I.P. > 5 to 20 mm
  - ✓ leptonic channels $\tau \to e, \mu$
- Additional kinematic cuts on minimal mass/$P_T$ for $n_e$CC/charm rejection
  - ✓ $(P_T)_{min} >$ 50 Mev/c $\tau \to e$
  - ✓ $(M_{inv})_{min} >$ 3 GeV/c $\tau \to \mu$




**efficiency · BR = 0.7-1 %**

# Main backgrounds

- Charm production
  - Cross-section and charmed fractions based on neutrino data
- Large angle $\mu$ scattering
  - Rate of $\mu$ scattering off lead estimated by using
    - MC simulation including nuclear form factors (cross-checked with NOMAD data)
    - data from 7.3 GeV/c $\mu$ scattering off copper
    - $\mu$ scanned in the CHORUS emulsions
  - Scattering off lead of $\mu$ (p= 6-10 GeV/c) experimentally studied by the Collaboration
- Hadron reinteractions with kink topology
  - the present estimate is based on a GEANT simulation
  - consistent with preliminary results from dedicated experiments

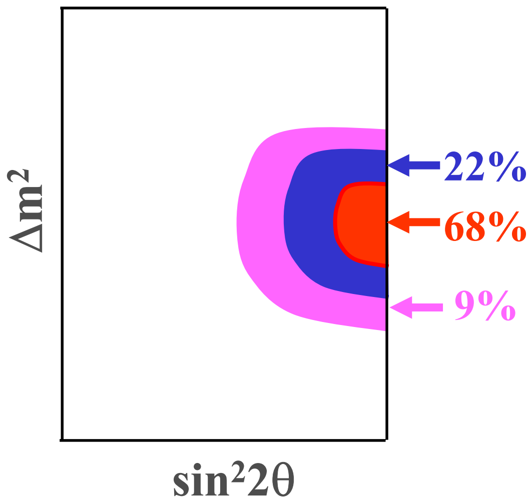
# Sensitivity to $\nu_\mu \rightarrow \nu_\tau$ oscillations

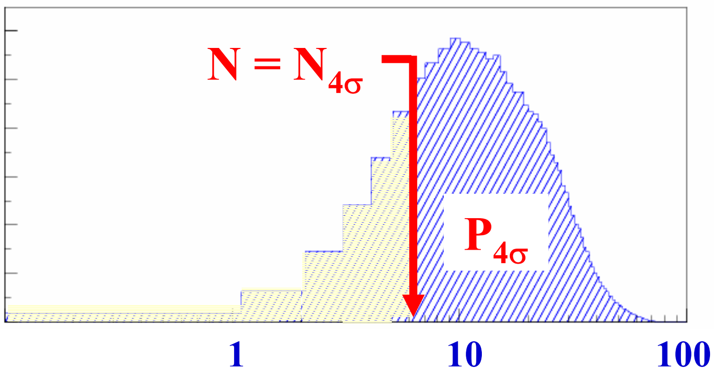
- full mixing
- 5 years run @ $6.76 \times 10^{19}$ pot / year

| | signal ($\Delta m^2 = 1.8 \times 10^{-3}$ eV$^2$) | signal ($\Delta m^2 = 2.5 \times 10^{-3}$ eV$^2$) | signal ($\Delta m^2 = 4.0 \times 10^{-3}$ eV$^2$) | Back |
|---|---|---|---|---|
| **Final Design** | 9.0 | 17.2 | 43.8 | 1.06 |
| **With possible improvements** | 10.3 | 19.8 | 50.4 | 0.67 |

# Probability of $\geq n\sigma$ significance

*Schematic view of the Super-K allowed region*




*Distribution of events observed*

- **Simulate a large number of experiments** with oscillation parameters generated according to the Super-K probability distribution
- **$N_{4\sigma}$ events are required for a discovery at $4\sigma$**
- **Evaluate the fraction $P_{4\sigma}$ of experiments observing $N \geq N_{4\sigma}$ events**

| $\Delta m^2 (eV^2)$ | 3 years (20.3x $10^{19}$ pot) | | 5 years (33.8x $10^{19}$ pot) | |
|---|---|---|---|---|
| | $P_{3\sigma}$(%) | $P_{4\sigma}$ | $P_{3\sigma}$(%) | $P_{4\sigma}$ |
| 1.8x $10^{-3}$ | 77.2(91.1) | 46.8(68.2) | 97.2(99.5) | 87.4(96.2) |
| 2.2x $10^{-3}$ | 94.9(98.9) | 80.5(93.0) | 99.9(100) | 99.0(99.9) |
| 2.5x $10^{-3}$ | 98.9(99.9) | 93.9(98.6) | 100(100) | 99.9(100) |
| 3.0x $10^{-3}$ | 100(100) | 99.6(100) | 100(100) | 100(100) |
| 4.0x $10^{-3}$ | 100(100) | 100(100) | 100(100) | 100(100) |

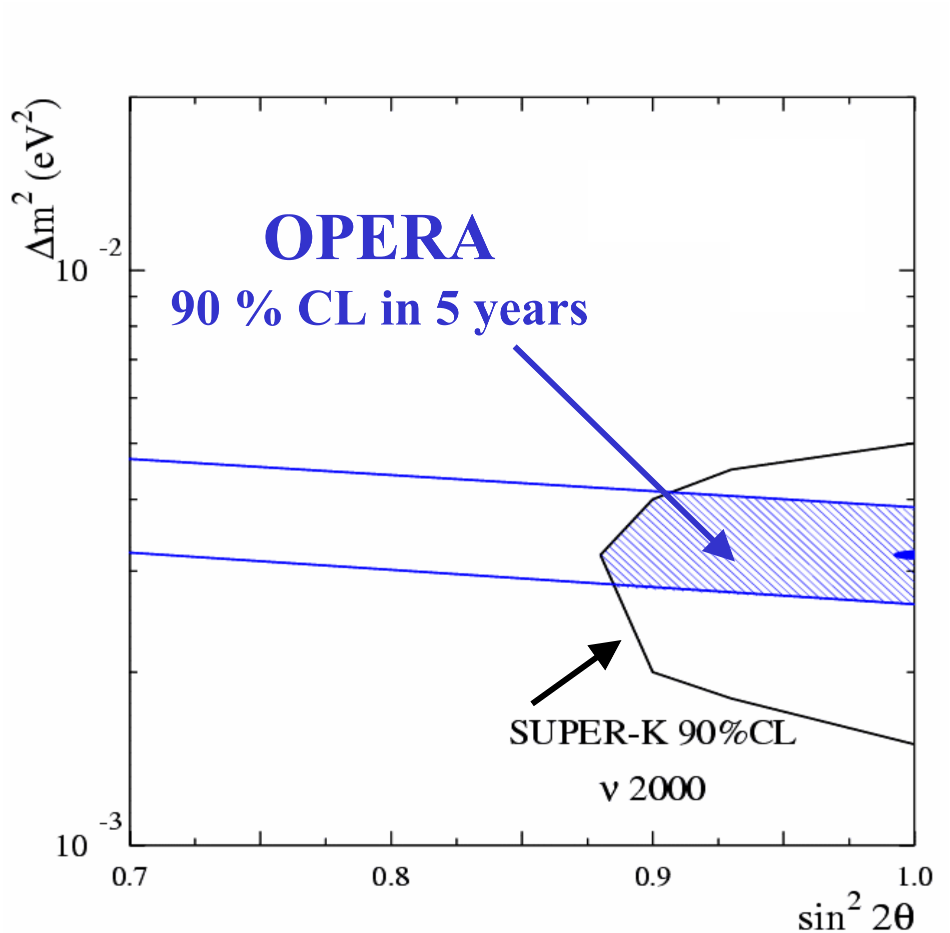
Best fit of SK + K2K is $Dm^2 = (2.6 \pm 0.4)$ $eV^2$ Fogli et al. hep-ph/0303064

The number in parenthesis are obtained assuming possible improvements

# Determination of $\Delta m^2$

(mixing constrained by SuperK)

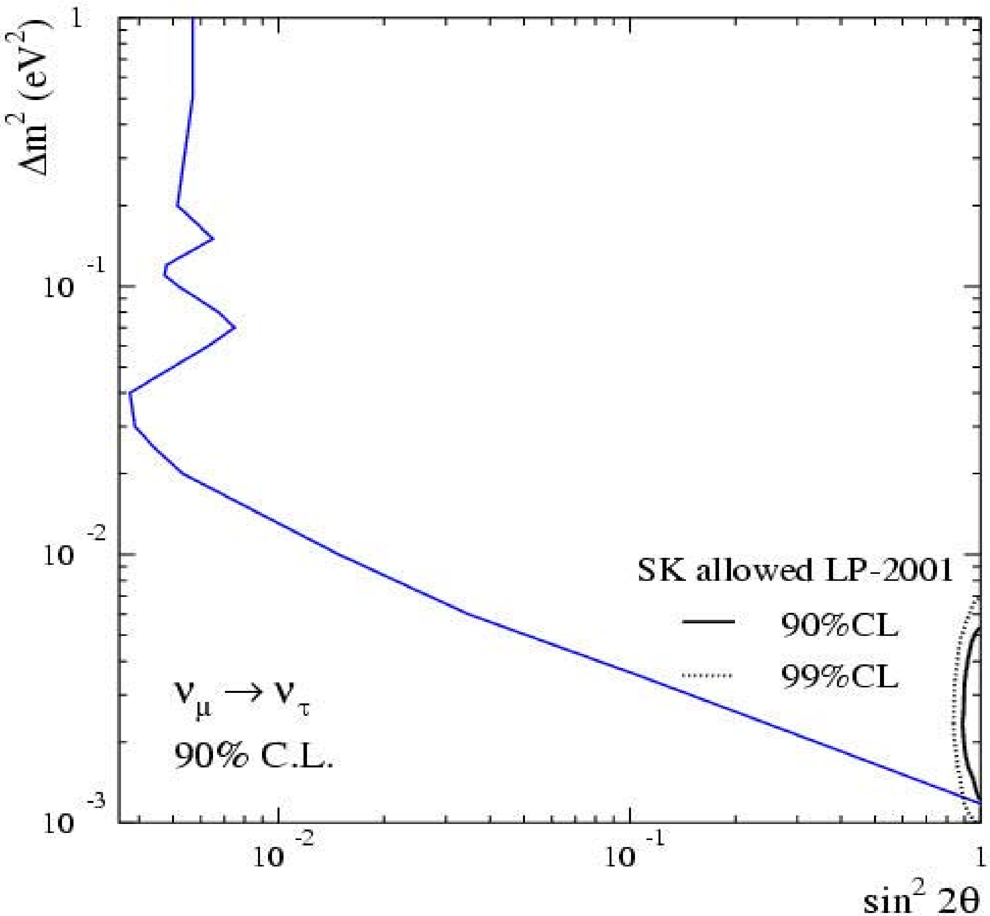
| 90 % CL limits * | $\Delta m^2$ ( $10^{-3}$ eV$^2$ ) | | |
|---|---|---|---|
| | 1.6 | 2.5 | 4.0 |
| Upper limit | 2.2 | 3.1 | 4.6 |
| Lower limit | 0.9 | 1.8 | 3.4 |
| (U - L) / (2xTrue) | 41 % | 26 % | 15 % |




* assuming the observation of a number of events corresponding to those expected for the given $\Delta m^2$

# Exclusion plot in the absence of a signal

***(5 year run with 1.8 kton average target mass)***




***90 % CL upper limit obtained on average by a large ensemble of experiments***

| | |
|---|---|
| **$\Delta m^2$** | **$< 1.2 \times 10^{-3}$ eV$^2$ at full mixing** |
| **$\sin^2(2\theta)$** | **$< 5.7 \times 10^{-3}$ at large $\Delta m^2$** |

*Gives an indication of the sensitivity ... but of course we expect to see a signal*

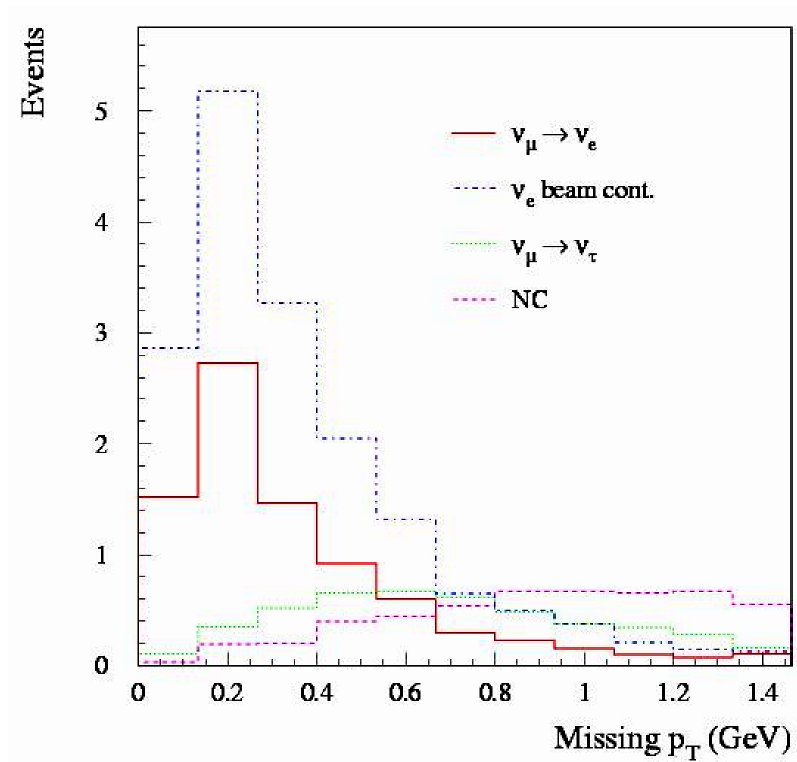
***Uncertainties on background (±33%) and on efficiencies (±15%) accounted for here and in the following***

# $\nu_\mu \to \nu_e$: selection criteria

- Background
  - $\nu_e$ beam contamination
  - $\pi^0$ identified as electrons produced in $\nu_\mu$NC and $\nu_\mu$CC with the $\mu$ not identified
  - $\tau \to e$ from $\nu_\mu \to \nu_\tau$ oscillations
- Cuts
  - $E_e > 1$ GeV
  - Visible energy smaller than 20 GeV
  - Missing $p_T$ of the event smaller than 1.5 GeV

Expected signal and background

| $\Theta_{13}$ | signal | $\tau \to e$ | $\nu_\mu$CC | $\nu_\mu$NC | $\nu_e$CC beam |
|---|---|---|---|---|---|
| 9° | 9.3 | 4.5 | 1.0 | 5.2 | 18 |
| 8° | 7.4 | 4.5 | 1.0 | 5.2 | 18 |
| 7° | 5.8 | 4.6 | 1.0 | 5.2 | 18 |
| 5° | 3.0 | 4.6 | 1.0 | 5.2 | 18 |
| 3° | 1.2 | 4.7 | 1.0 | 5.2 | 18 |

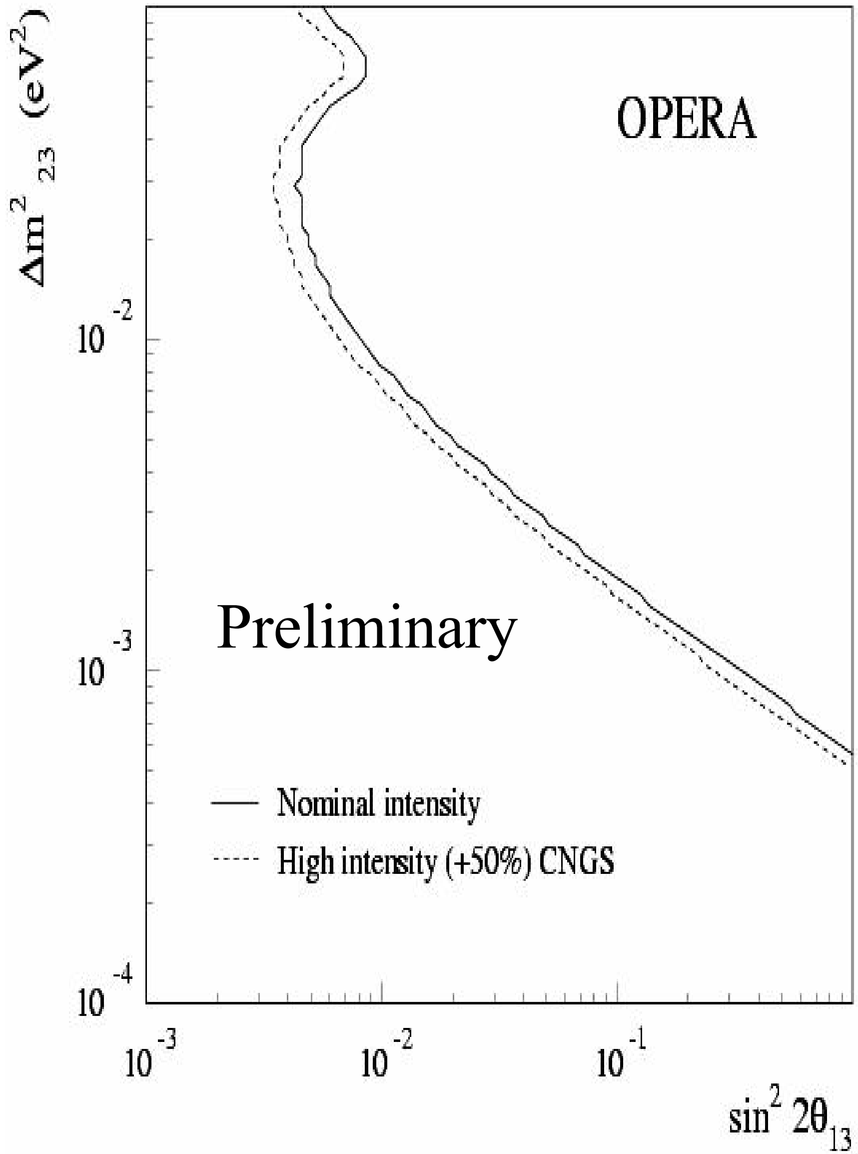


# OPERA sensitivity to $\theta_{13}$

**In parallel with appearance search**

Limits at 90% C.L. on $\sin^2 2\theta_{13}$ and $\theta_{13}$
($\Delta m^2_{23}=2.5\times10^{-3}$ eV$^2$; $\sin^2\theta_{23}=1$)

| Experiment | $\sin^2 2\theta_{13}$ | $\theta_{13}$ |
|---|---|---|
| CHOOZ | <0.14 | <11° |
| MINOS | <0.06 | <7.1° |
| ICARUS | <0.04 | <5.8° |
| OPERA | <0.06 | <7.1° |
| JHF | <0.006 | <2.5° |



# The ICARUS Collaboration

S. Amoruso, P. Aprili, F. Arneodo, B. Babussinov, B. Badelek, A. Badertscher, M. Baldo-Ceolin, G. Battistoni, B. Bekman, P. Benetti, A. Borio di Tigliole, M. Bischofberger, R. Brunetti, R. Bruzzese, A. Bueno, E. Calligarich, D. Cavalli, F. Cavanna, F. Carbonara, P. Cennini, S. Centro, A. Cesana, C. Chen, Y. Chen, D. Cline, P. Crivelli, A. Dabrowska, Z. Dai, M. Daszkiewicz, R. Dolfini, A. Ereditato, M. Felcini, A. Ferrari, F. Ferri, G. Fiorillo, S. Galli, Y. Ge, D. Gibin, A. Gigli Berzolari, I. Gil-Botella, A. Guglielmi, K. Graczyk, L. Grandi, K. He, J. Holeczek, X. Huang, C. Juszczak, D. Kielczewska, J. Kisiel, L. Knecht, T. Kozlowski, H. Kuna-Ciskal, M. Laffranchi, J. Lagoda, Z. Li, B. Lisowski, F. Lu, J. Ma, G. Mangano, G. Mannocchi, M. Markiewicz, F. Mauri, C. Matthey, G. Meng, C. Montanari, S. Muraro, G. Natterer, S. Navas-Concha, M. Nicoletto, S. Otwinowski, O. Palamara D. Pascoli, L. Periale, G. Piano Mortari, A. Piazzoli, P. Picchi, F. Pietropaolo, W. Polchlopek, T. Rancati, A. Rappoldi, G.L. Raselli, J. Rico, E. Rondio, M. Rossella, A. Rubbia, C. Rubbia, P. Sala, D. Scannicchio, E. Segreto, Y. Seo, F. Sergiampietri, J. Sobczyk, N. Spinelli, J. Stepaniak, M. Stodulski, M. Szarska, M. Szeptycka, M. Terrani, R. Velotta, S. Ventura, C. Vignoli, H. Wang, X. Wang, M. Wojcik, G. Xu, X. Yang, A. Zalewska, J. Zalipska, C. Zhang, Q. Zhang, S. Zhen, W. Zipper.

University and INFN of: L'Aquila, LNF, LNGS, Milano, Naples, Padova, Pavia, Pisa - Italy
ETH Hönggerberg, Zürich - Switzerland
IHEP, Academia Sinica, Beijing - China
CNR Istitute of cosmogeophysics, Torino - Italy
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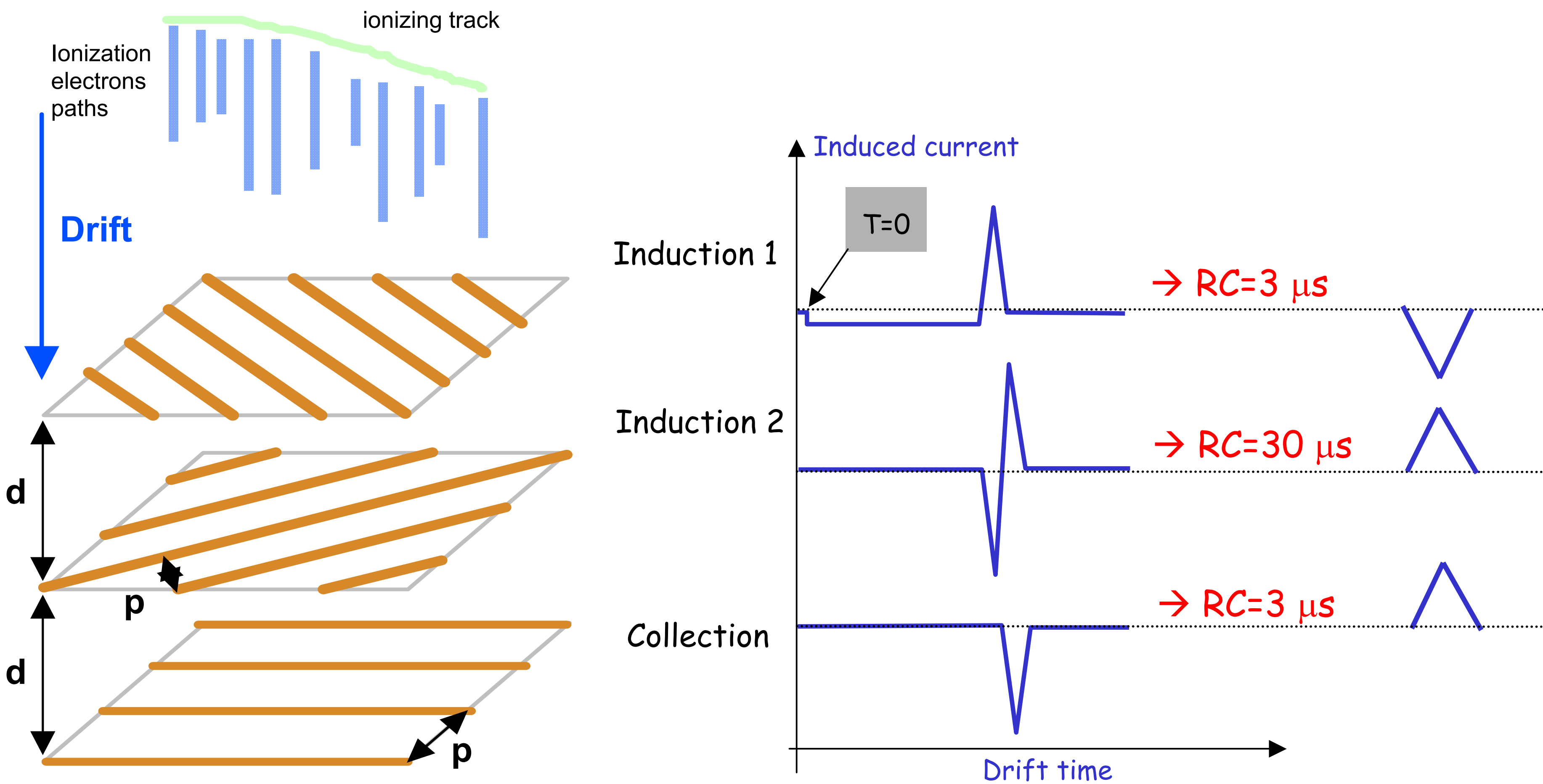
A.Soltan Inst. for Nucl. Studies, Warszawa - Poland
Warsaw University, Warszawa - Poland
Wroclaw University, Wroclaw - Poland
UCLA, Los Angeles - USA
University of Granada - Spain

# Principle and signals

Ionization electrons drift (msec) over large distances (meters) in a volume of highly purified liquid Argon (0.1 ppb of $O_2$) under the action of an E field. With a set of wire grids (traversed by the electrons in ~ 2-3 μs) one can realize a massive, continuously sensitive electronic "bubble chamber".

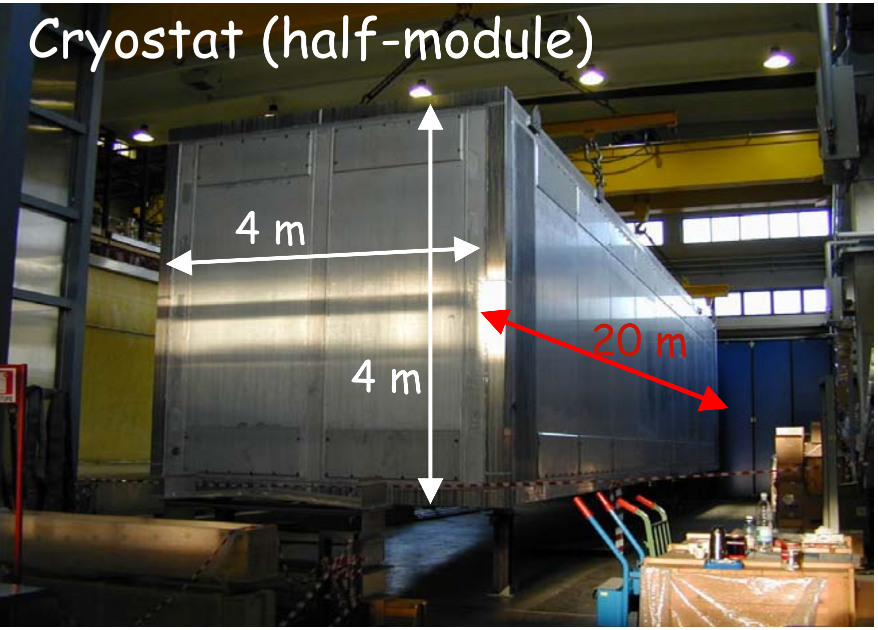


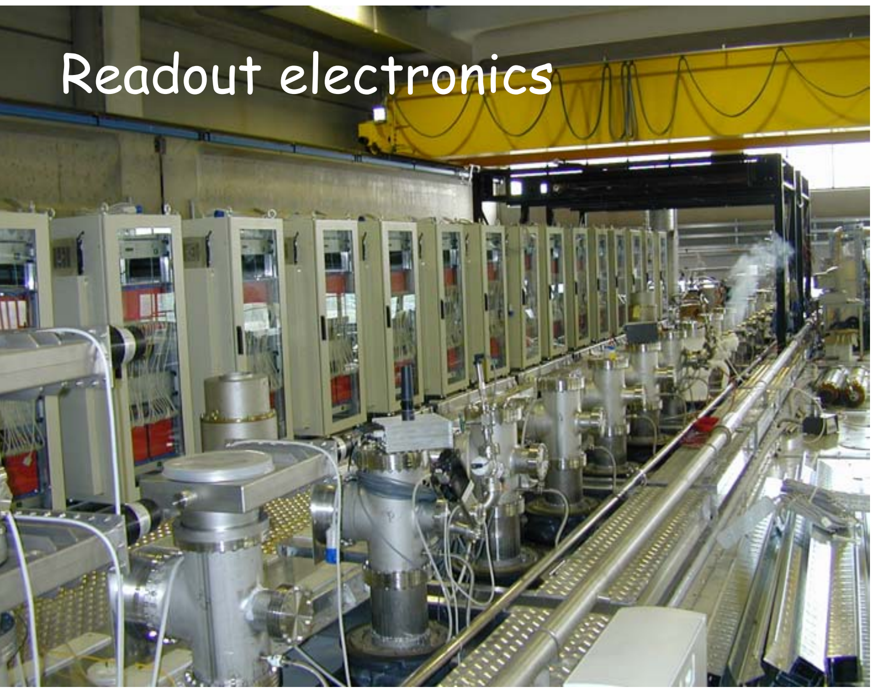
# Liquid Argon TPC properties

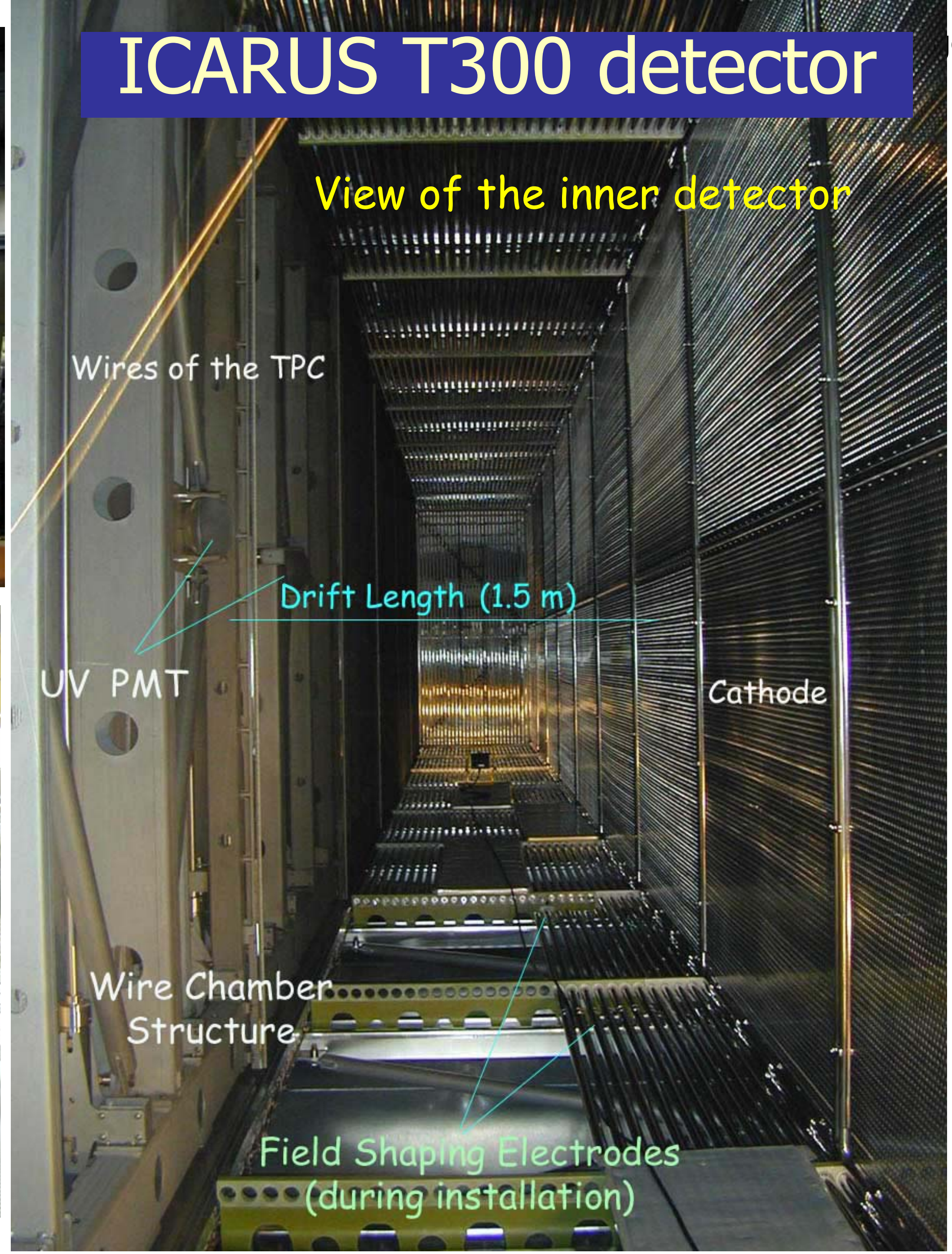
- High density, heavy ionization medium
  - $\rho$ = 1.4 g/cm$^3$, $X_0$=14 cm, $\lambda_{int}$ = 80 cm
- Very high resolution detector
  - 3D image 3 x 3 x 0.6 mm$^3$ (400 ns sampling)
- Continuously sensitive
- Self-triggering or through prompt scintillation light
- Stable and safe
  - Inert gas/liquid
  - High thermal inertia (230 MJ/m$^3$)
- Relatively cheap detector
  - Liquid argon is cheap, it is only "stored" in the experiment
  - TPC: # of channels proportional to surface

- Cryogenic temperature ← **Cryogenic plant**
  - T = 88 K at 1 bar
- High purity required for long-drift time ← **Argon purification**
  - 0.1 ppb of $O_2$ equivalent for 3 ms drift
- No signal amplification in liquid ← **Low noise electronics**
  - 1 m.i.p. over 3 mm yields 20000 electrons
  - equivalent noise charge 1200 electrons

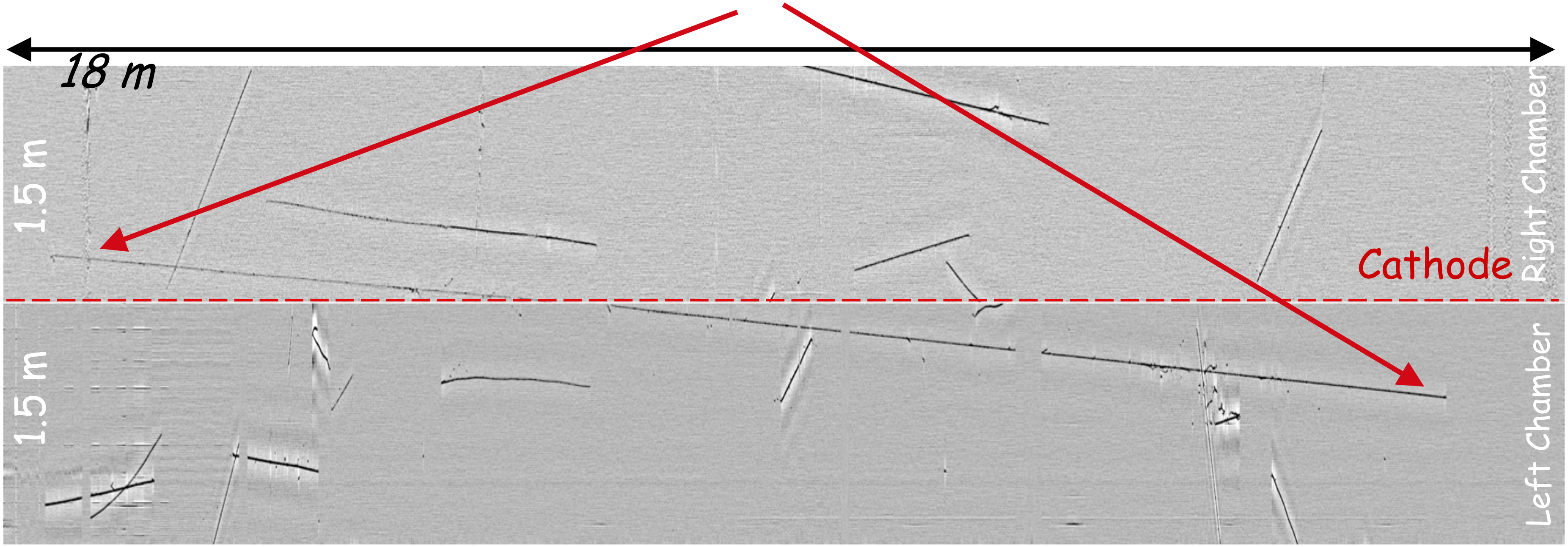
# ICARUS T300 detector

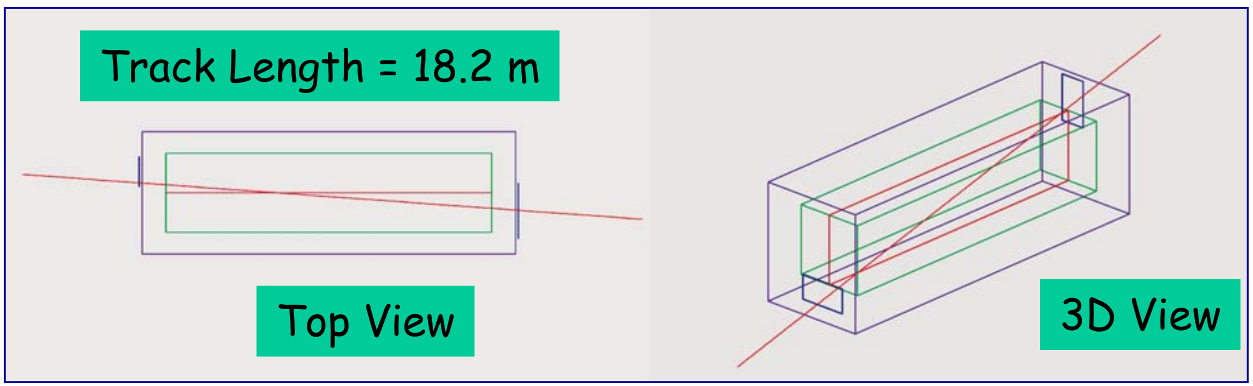


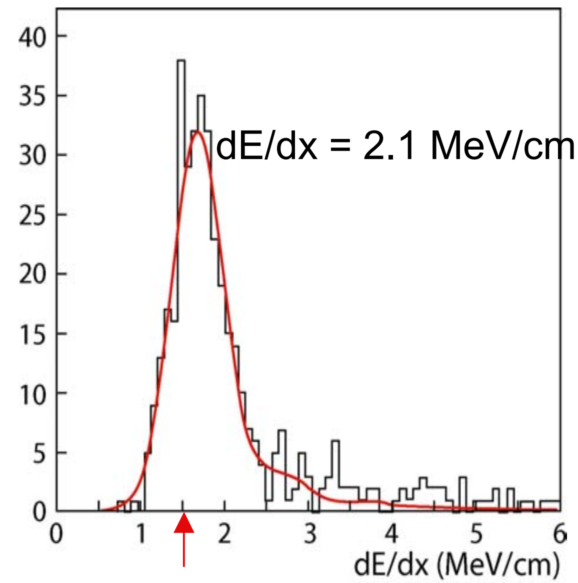



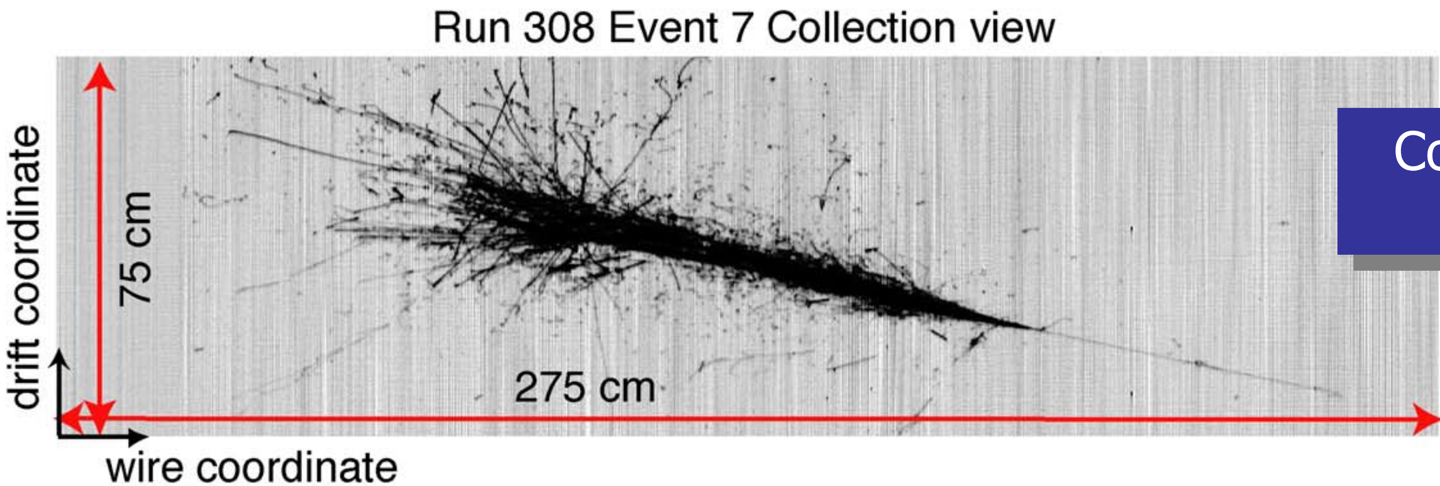
# Long longitudinal muon track crossing the cathode plane



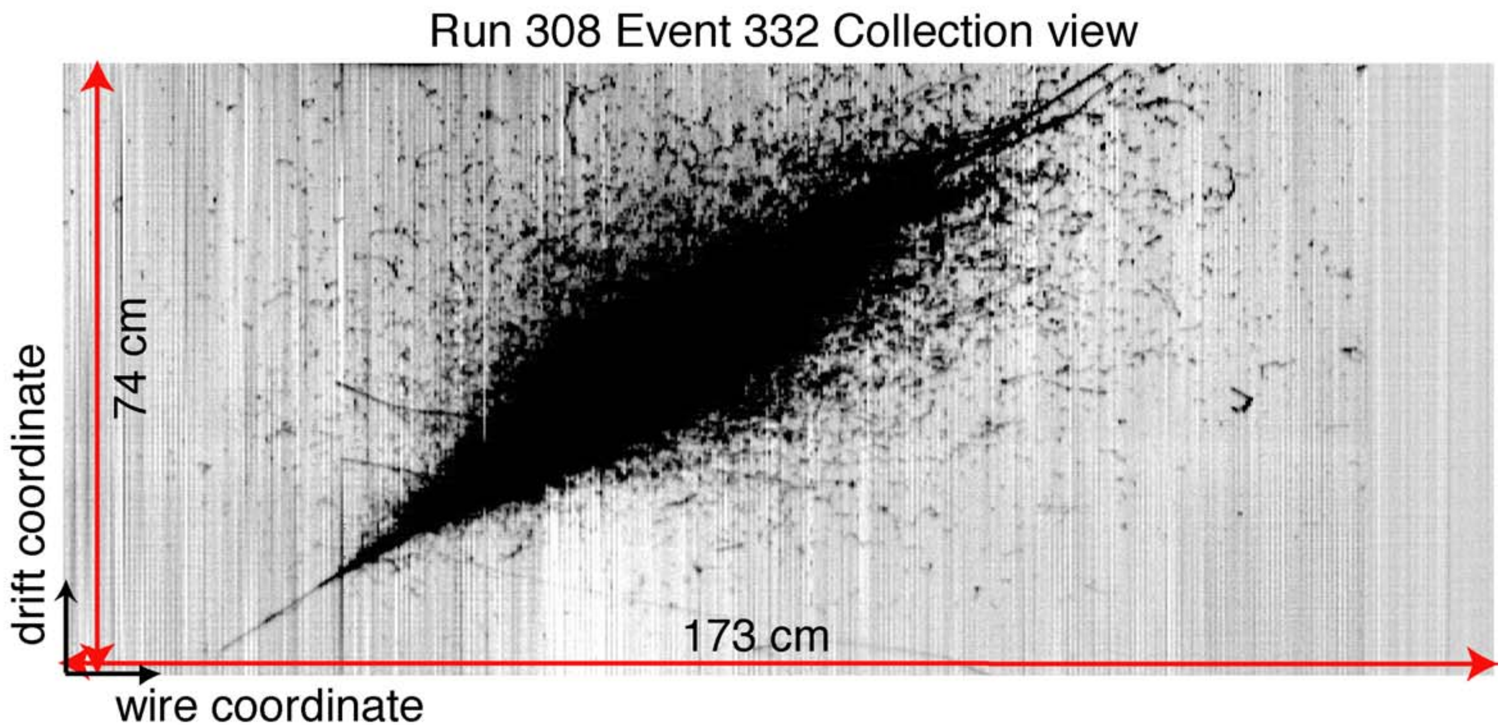



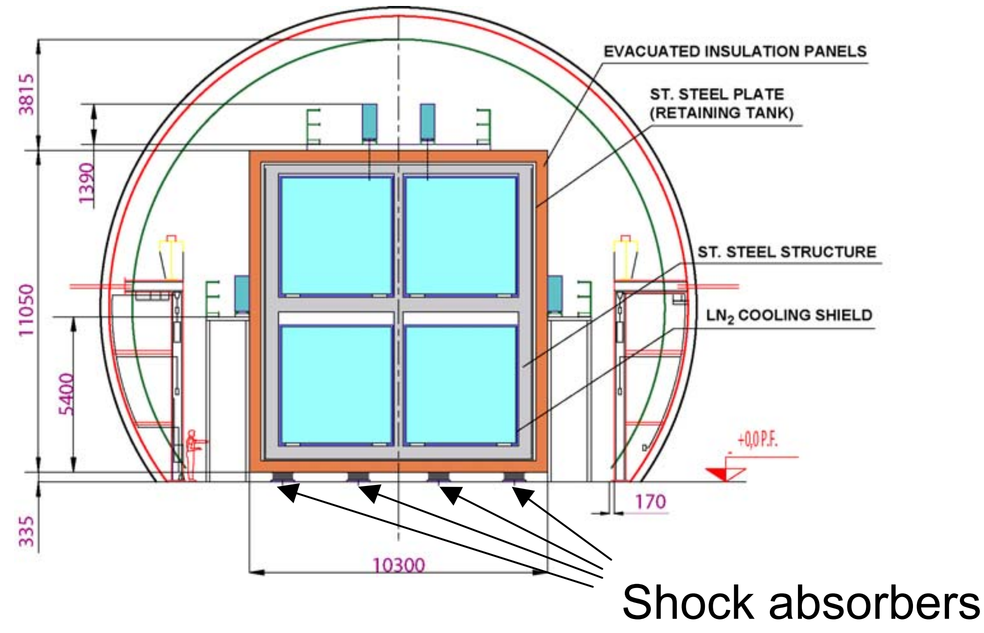
# "Electronic" bubble chamber

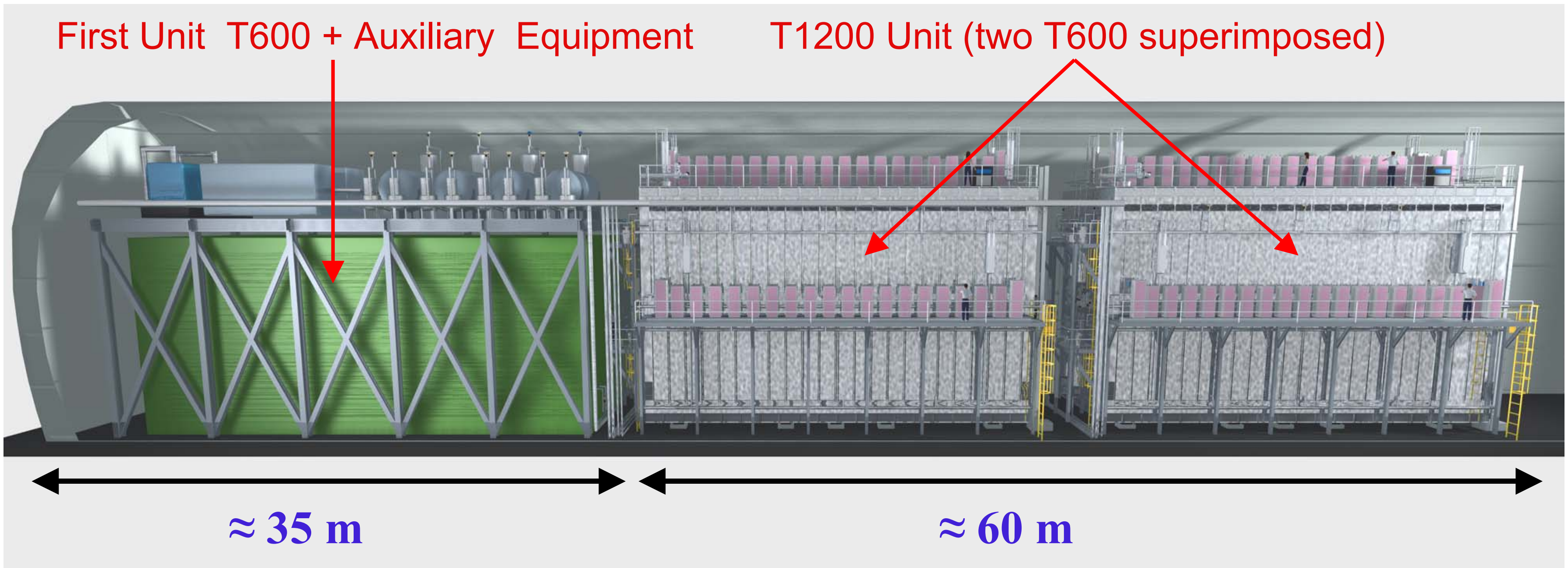



Cosmic ray showers (T600)



# ICARUS detector configuration at LNGS Hall B (T3000)



# ICARUS Physics issues

## What we get for 5 ktons:

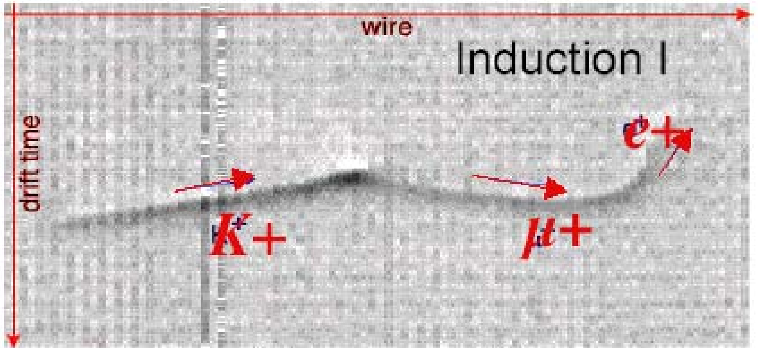
- **Atmospheric ν's:**
  - → ≈ **1000** atm CC events / year
  - → ≈ **5** $\nu_\tau$ CC /year from oscillations
- **Solar ν's:** ≈ **8100** oscillated solar neutrinos / year @ E > 5 MeV
- **Supernova ν's:** ≈ **350** events at 10 kpc
- **CERN-CNGS:** **13600** $\nu_\mu$ CC per year @ L = 730 km
- **ν factory:** **1130** $\nu_\mu$ CC per $10^{20}$ $\mu$ @ L = 7400 km
- **Number of targets for nucleon stability:**
  - → $3 \times 10^{33}$ nucleons ⇒ $\tau_p$**$(10^{32}$ years) > 6 × T(yr) ×** $\varepsilon$ @ 90 C.L.

The performance of a neutrino detector is *proportional* to its *total mass* but also to its *geometrical granularity* with which the events can be reconstructed.

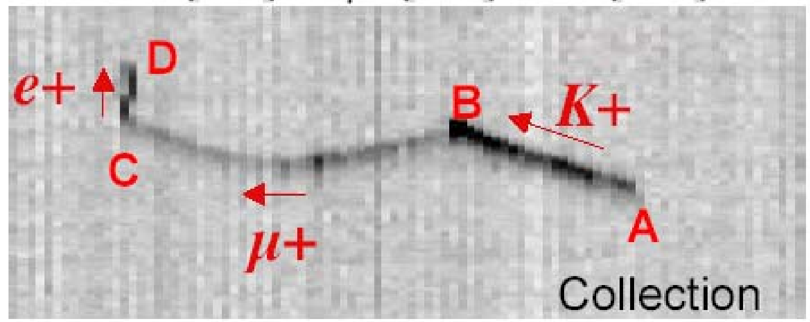
# ICARUS physics program

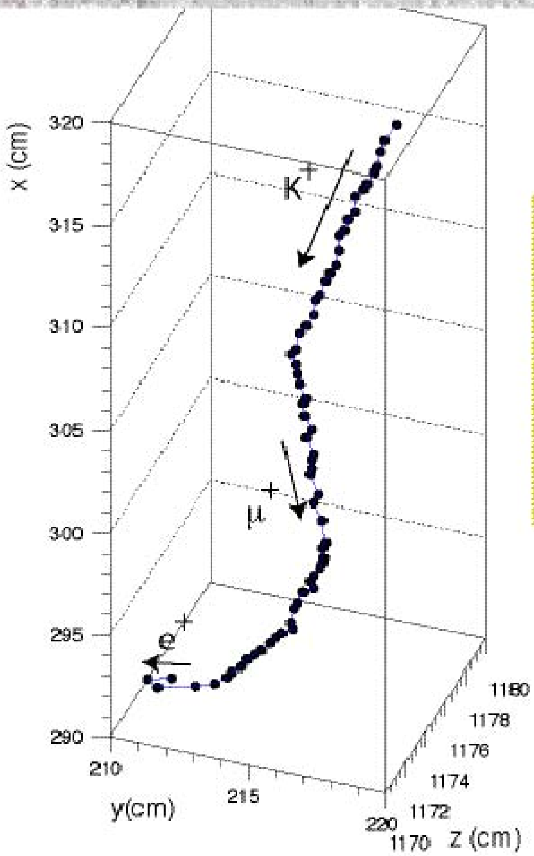
- **Phase I: (starts in 2003)**
  - 600 ton ICARUS detector
  - Observation of solar and atmospheric neutrinos
- **Phase II: (starts ca. 2005)**
  - 3000 ton ICARUS detector
  - Continue observation of solar und atmospheric neutrinos with larger statistics
  - Investigation of stability of matter (proton-decay)
  - Detection of artificial neutrino beam from CERN
- **Phase III (??? >2010)**
  - >3000 ton ICARUS
  - Investigation of new neutrino beams with very high intensity (i.e.. "Superbeams" or "neutrino-factory")
  - Improved sensitivity for proton-decay

# Particle identification

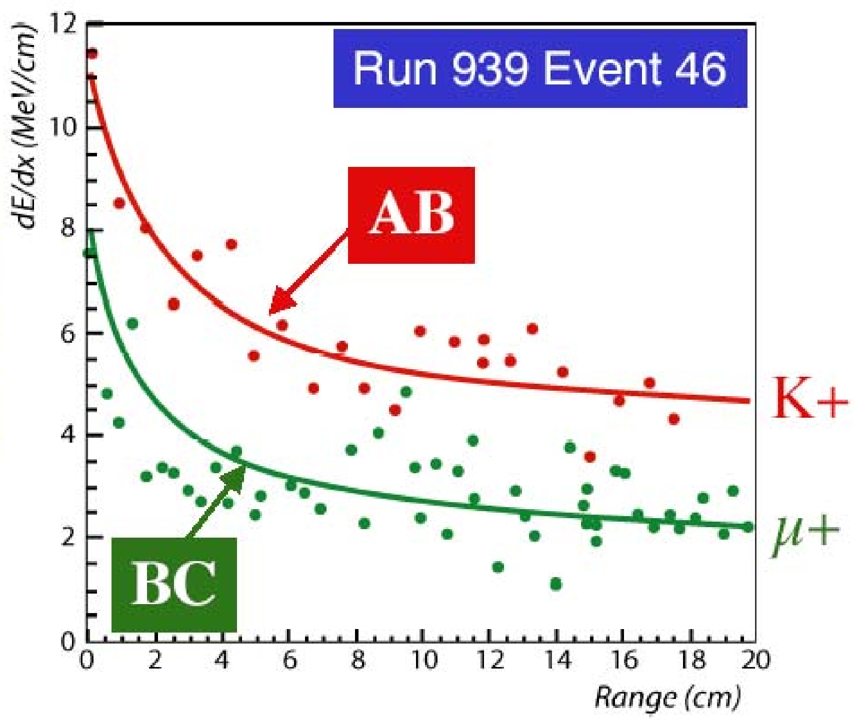



$K^+[AB] \rightarrow \mu^+[BC] \rightarrow e^+[CD]$




The **3D reconstruction** allows to compute the **dE/dx** and **range**



# Direct detection of flavor oscillation

*The expected $\nu_e$ and $\nu_\tau$ contamination of the CNGS neutrino beam in absence of oscillations is in the order of $10^{-2}$ and $10^{-7}$ relative to the main $\nu_\mu$ component*

$\nu_\mu \rightarrow \nu_\tau$

$$\nu_\tau + Ar \rightarrow \tau + jet; \quad \tau \rightarrow \begin{cases} e\nu\nu & 18\% \\ \mu\nu\nu & 18\% \\ h^- n h^0 \nu & 50\% \\ h^- h^+ h^- n h^0 \nu & 14\% \end{cases}$$

Charged current (CC)

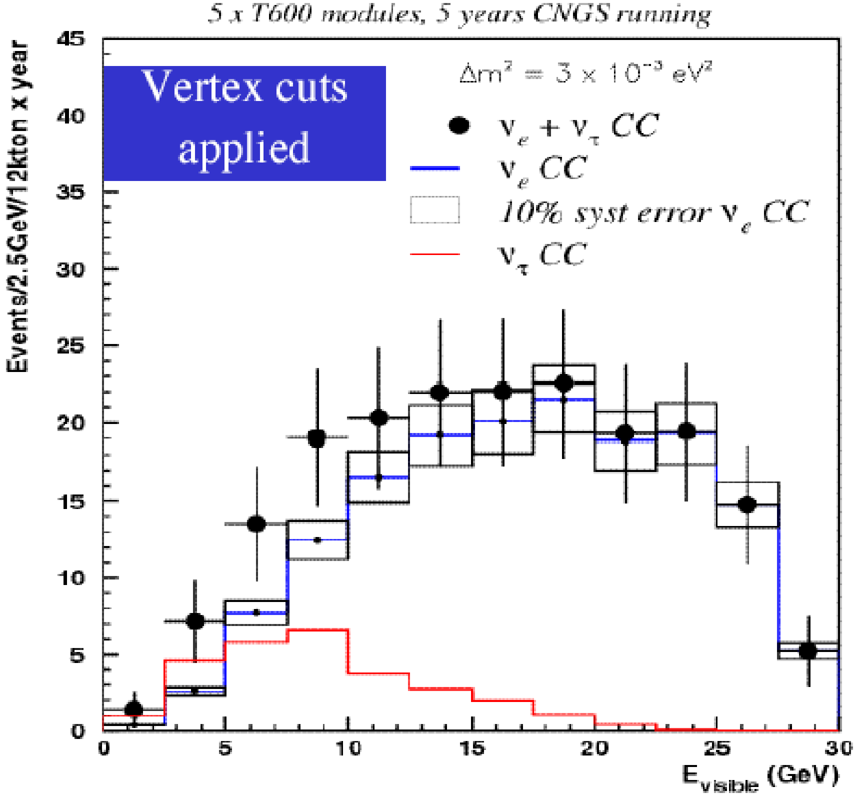
$\nu_\mu \rightarrow \nu_e$

$$\nu_e + Ar \rightarrow e + jet$$

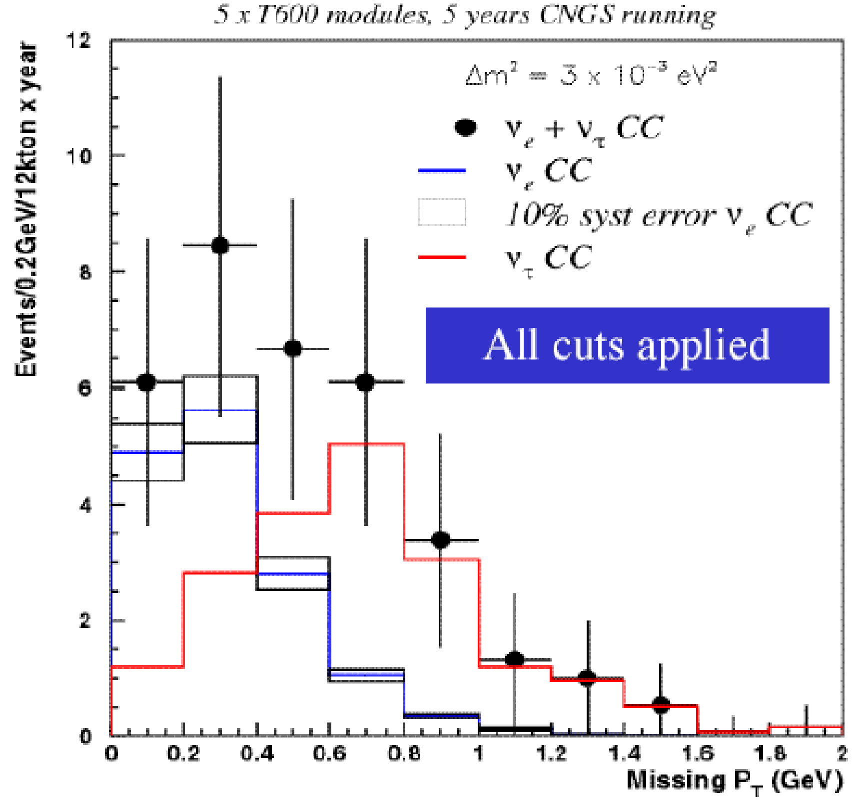
Charged current (CC)

# τ→e analysis: sequential cuts

**Total visible energy**




**Missing $P_T$**




- Exploit small natural contamination of $\nu_e$
- Expected excess at low energy

Before cuts:

262 $\nu_e$ CC

49 $\nu_\tau$ CC, $\tau \rightarrow e$

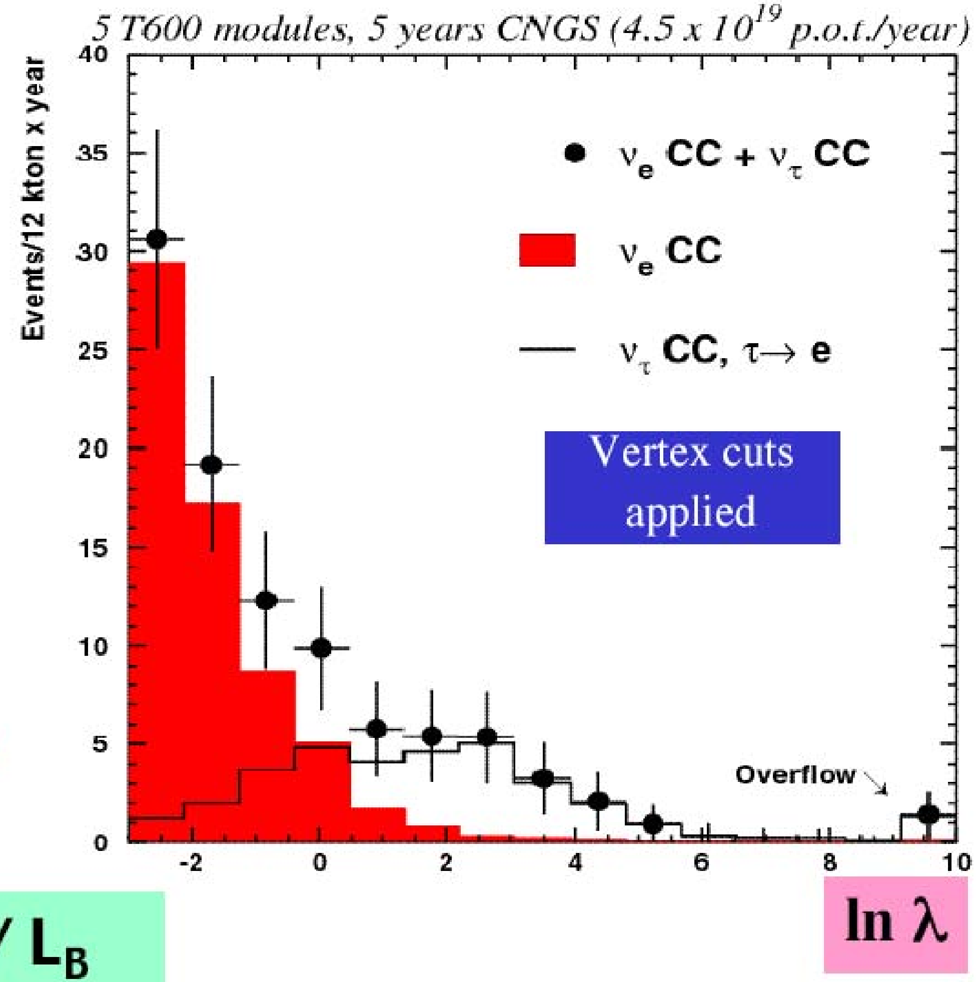
$\Delta m^2 = 3 \times 10^{-3} eV^2$

# $\nu_\mu \rightarrow \nu_\tau$ oscillations ($\tau \rightarrow e$ search)

Analysis based on 3 dimensional likelihood

- $E_{visible}$, $P_T^{miss}$, $\rho_l \equiv P_T^{lep}/(P_T^{lep} + P_T^{had} + P_T^{miss})$
- Exploit correlation between variables
- Two functions built:
  - $L_S$ ([$E_{visible}$, $P_T^{miss}$, $\rho_l$]) (signal)
  - $L_B$ ([$E_{visible}$, $P_T^{miss}$, $\rho_l$]) ($\nu_e$ CC backg
- Discrimination given by

$$\ln \lambda \equiv L([E_{visible}, P_T^{miss}, \rho_l]) = L_S / L_B$$



# $\nu_\mu \rightarrow \nu_\tau$ appearance search summary

**5 T600 modules**

**(2.35 kton active LAr)**

**5 year CNGS running**

**(2.25 x $10^{20}$ p.o.t.)**

| $\tau$ decay mode | Signal $\Delta m^2 =$ $1.6 \times 10^{-3}$ eV$^2$ | Signal $\Delta m^2 =$ $2.5 \times 10^{-3}$ eV$^2$ | Signal $\Delta m^2 =$ $3.0 \times 10^{-3}$ eV$^2$ | Signal $\Delta m^2 =$ $4.0 \times 10^{-3}$ eV$^2$ | BG |
|---|---|---|---|---|---|
| $\tau \rightarrow e$ | 3.7 | 9 | 13 | 23 | 0.7 |
| $\tau \rightarrow \rho$ DIS | 0.6 | 1.5 | 2.2 | 3.9 | $< 0.1$ |
| $\tau \rightarrow \rho$ QE | 0.6 | 1.4 | 2.0 | 3.6 | $< 0.1$ |
| **Total** | **4.9** | **11.9** | **17.2** | **30.5** | **0.7** |

**Super-Kamiokande: 1.6 < $\Delta m^2$ < 4.0 at 90% C.L.**

# $\nu_\mu \rightarrow \nu_e$ oscillations: search for $\theta_{13} > 0$

$\Delta m^2_{32} = 3.5 \times 10^{-3}$ eV$^2$; $\sin^2 2\theta_{23} = 1$

***5 years dedicated SPS***
2.35 kton fid. mass

Cuts: Fiducial, $E_e > 1$ GeV, $E_{vis} < 20$ GeV

$\Delta m^2_{23} = 3.5 \times 10^{-3}$ eV$^2$, $\theta_{23} = 45^o$

| $\theta_{13}$ (degrees) | $\sin^2 2\theta_{13}$ | $\nu_e$ CC | $\nu_\mu \rightarrow \nu_\tau$ $\tau \rightarrow e$ | $\nu_\mu \rightarrow \nu_e$ | Total | Statistical significance |
|---|---|---|---|---|---|---|
| 9 | 0.095 | 79 | 74 | 84 | 237 | $6.8\sigma$ |
| 8 | 0.076 | 79 | 75 | 67 | 221 | $5.4\sigma$ |
| 7 | 0.058 | 79 | 76 | 51 | 206 | $4.1\sigma$ |
| 5 | 0.030 | 79 | 77 | 26 | 182 | $2.1\sigma$ |
| 3 | 0.011 | 79 | 77 | 10 | 166 | $0.8\sigma$ |

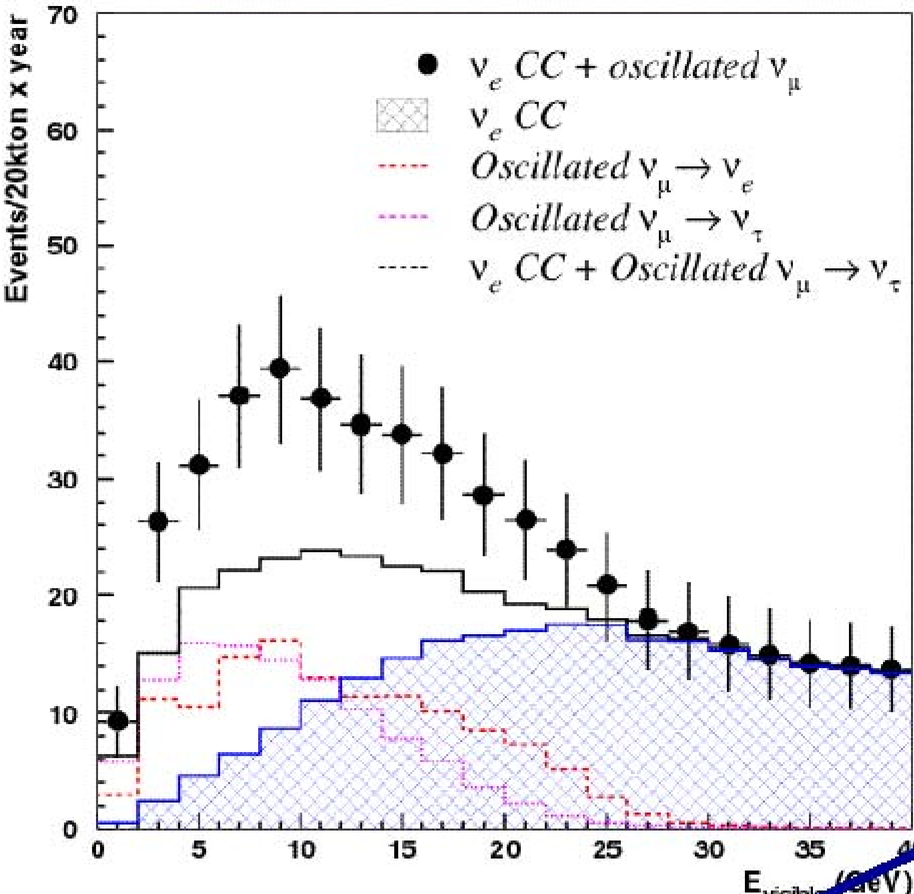
$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\Delta^2_{32}$$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\Delta^2_{32}$$

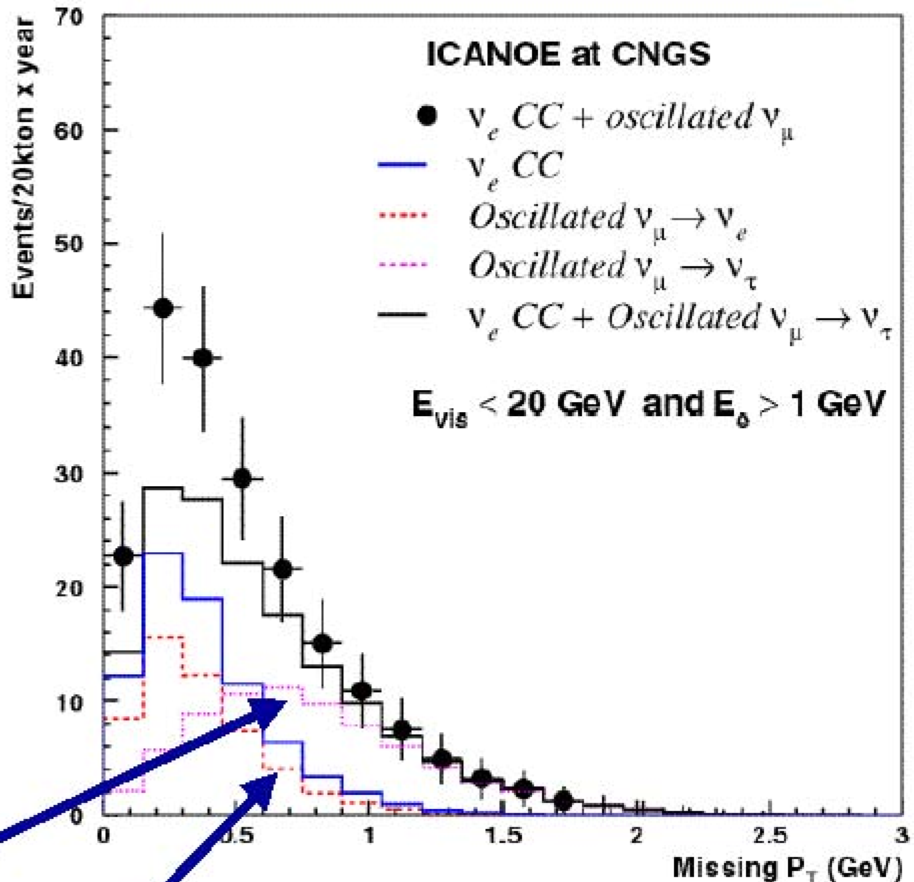
$\Rightarrow$ $\Delta m^2_{32}, \theta_{23}, \theta_{13}$

## $\Delta m^2_{32}=3.5\times10^{-3}\ eV^2$; $\sin^2 2\theta_{23} = 1$ ; $\sin^2 2\theta_{13} = 0.05$

### *Total visible energy*



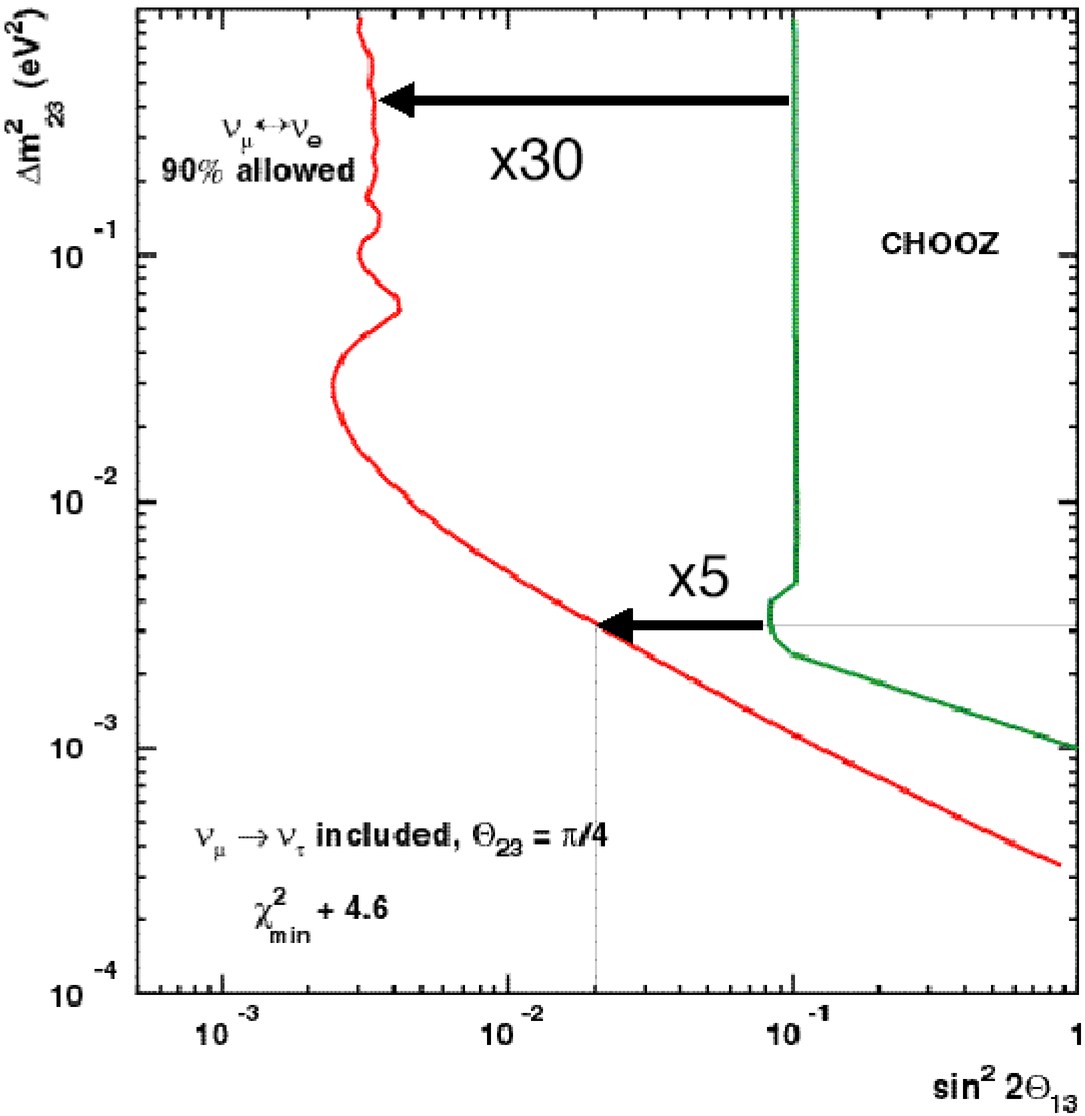

### *Transverse missing $P_T$*




$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\Delta^2_{32}$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\Delta^2_{32}$$

# Sensitivity to $\theta_{13}$ in three family-mixing




***ICARUS***
***5 years dedicated SPS***
2.35 kton fid. mass

Sensitivity assuming both $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ at the same $\Delta m^2$ (three family mixing)

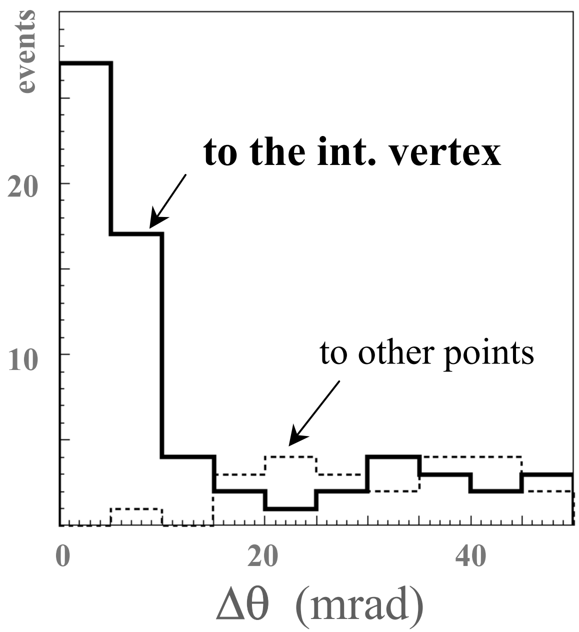
$$\sin^2 2\theta_{13} > 2 \times 10^{-2}$$
$$for \ \ \Delta m^2_{32} = 3 \times 10^{-3} eV^2$$

# End of Letture

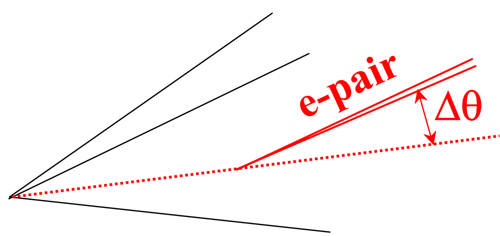
# Pointing accuracy to the vertex of e-pairs from $\gamma$ conversions

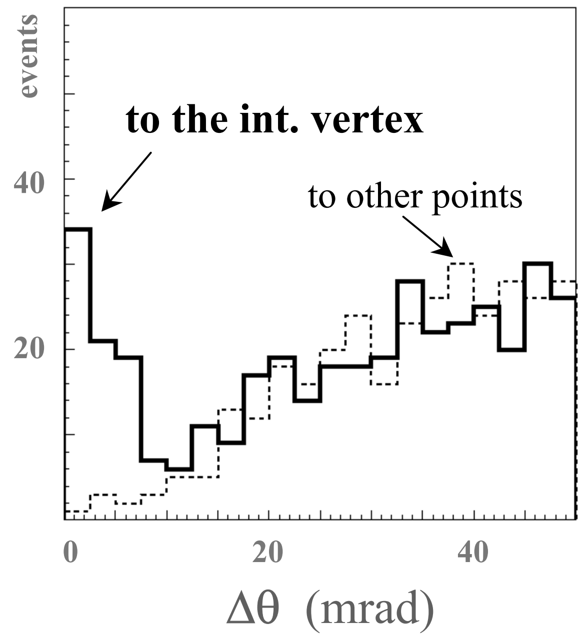
***Studied in CHORUS and DONUT by NetScan***

*(½ $X_0$ depth in ECC)*




**CHORUS**



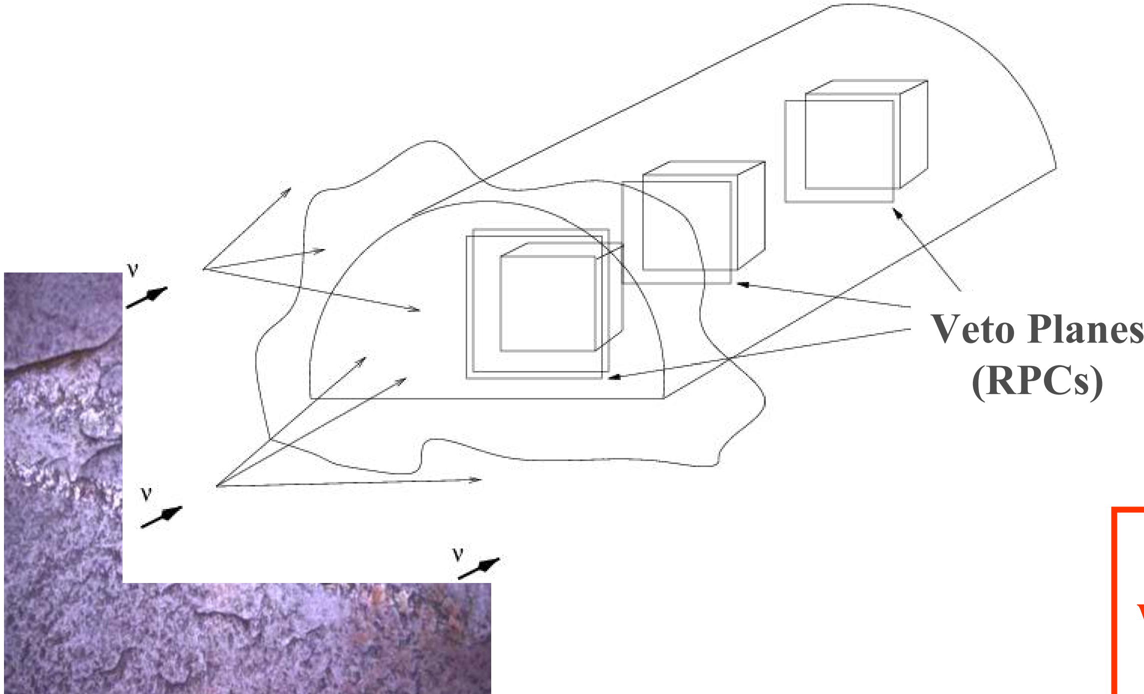

**DONUT**

*(ECC Fe-emulsion)*

***Important for increasing the sensitivity to $\tau \rightarrow h\, n\pi^0$***

# Veto and beam monitoring system

1. **Reject ν interactions outside the target (mainly in the rock)**
2. **Together with the spectrometers, monitor the beam related μ flux**




**Possibility of TOF for back-scattering from target**

**Design staged,**
**will be done by LNGS group**
**Not on the critical path**

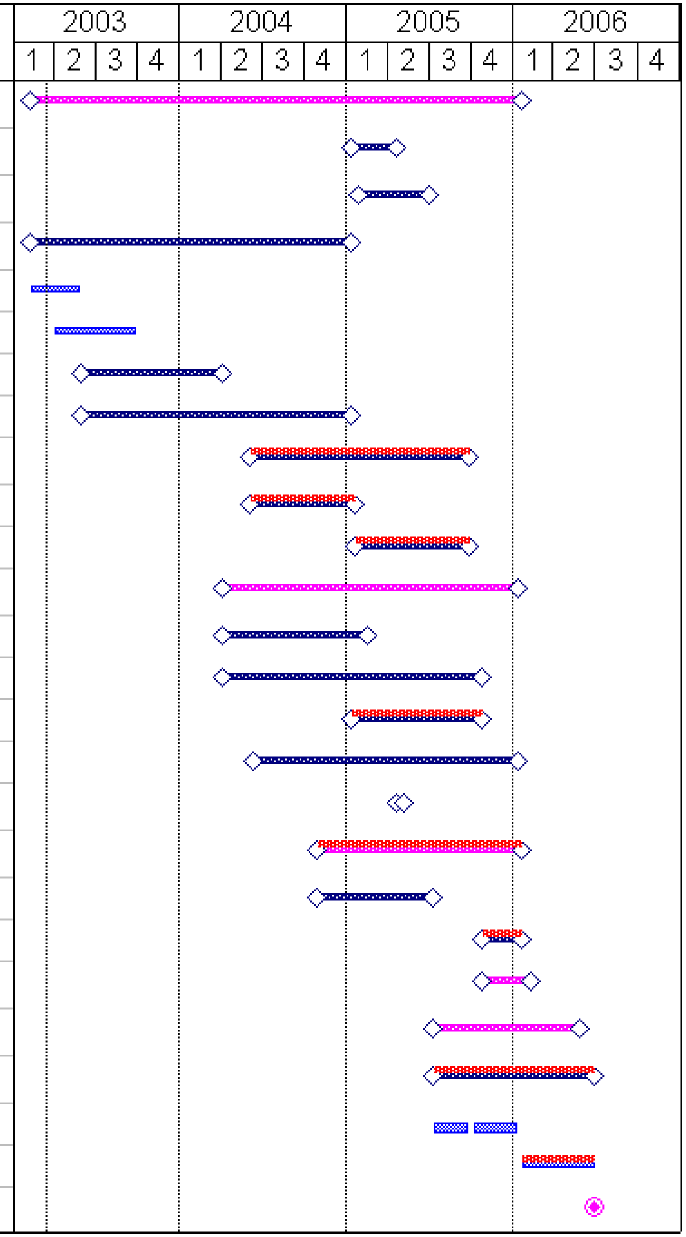
***Preliminary calculations of trigger rate from the rock***

- *Without veto:* ~ *equal to that from ν interactions in the target*
- *With veto:* *reduced to* ***6 – 8 %*** *depending on veto configuration*
- *Adding topology and pattern recognition:* *further* ***reduced by a factor ~ 3***

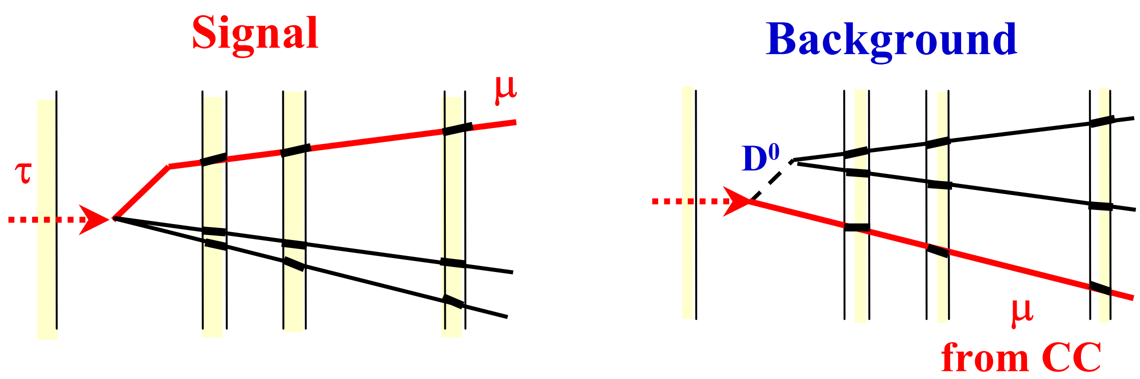
OPERA

# Updated Schedule for Installation

| ID | Task Name | Duration | Start |
|---|---|---|---|
| 343 | INSTALLATION IN LNGS HALL C | 144.71 w | Mon 2/10/03 |
| 344 | **C R & ELECTRONIC ROOM** | 13.46 w | Fri 1/14/05 |
| 350 | **BAM** | 21.5 w | Fri 1/28/05 |
| 354 | **SPECTROMETERS (2 MAGNETS & RPC's)** | 94.65 w | Mon 2/10/03 |
| 355 | Preliminary working | 15 w | Mon 2/10/03 |
| 356 | **Veto plane** | 24 w | Thu 4/3/03 |
| 357 | **Magnet 1** | 41.95 w | Fri 5/30/03 |
| 384 | **Magnet 2** | 79.65 w | Fri 5/30/03 |
| 411 | **TARGET WALLS + TARGET TRACKERS** | 65.9 w | Fri 6/4/04 |
| 412 | **SM1** | 30.4 w | Fri 6/4/04 |
| 489 | **SM2** | 35.5 w | Wed 1/19/05 |
| 566 | **XPC's & PRECISION TRACKERS** | 86.76 w | Mon 4/5/04 |
| 567 | **XPC 1** | 42.26 w | Mon 4/5/04 |
| 570 | **Precision tracker 1** | 77.16 w | Mon 4/5/04 |
| 603 | **XPC 2** | 40.06 w | Fri 1/14/05 |
| 606 | **Precision tracker 2** | 77.76 w | Fri 6/11/04 |
| 639 | **CABLING (detector to control room)** | 2 w | Thu 4/21/05 |
| 642 | **MANIPULATORS** | 59.06 w | Fri 10/29/04 |
| 643 | **SM1** | 33.56 w | Fri 10/29/04 |
| 649 | **SM2** | 10 w | Thu 10/27/05 |
| 653 | COMMISSIONNING | 13.6 w | Mon 10/24/05 |
| 656 | ECC BRICK MANUFACTURING WITH BAM | 43 w | Mon 7/11/05 |
| 658 | WALL FILLING | 47.5 w | Mon 7/11/05 |
| 659 | filling SM1 (2b/min 8h/day)=960 bricks | 22 w | Mon 7/11/05 |
| 660 | *filling SM2 (2b/min 8h/day)* | *22 w* | *Fri 1/20/06* |
| 661 | FULL DETECTOR COMPLETED | 0 d | Fri 6/30/06 |

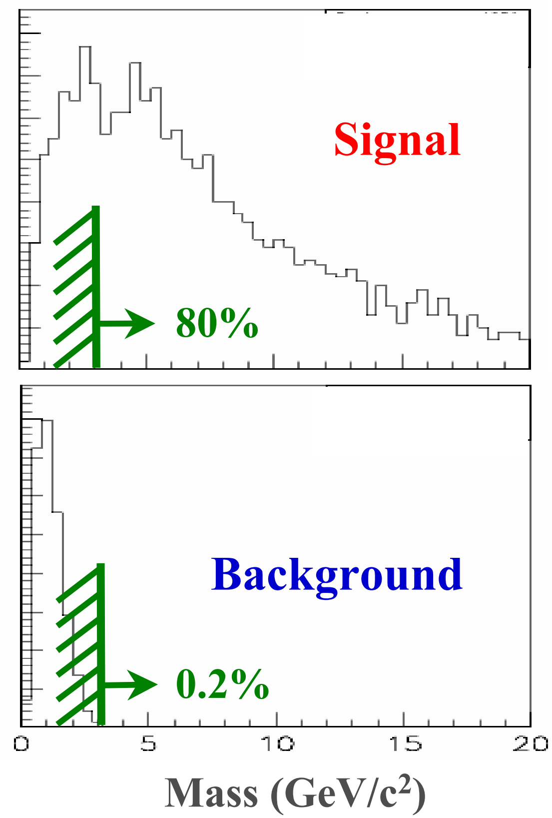


# Muonic short decays by Impact Parameter



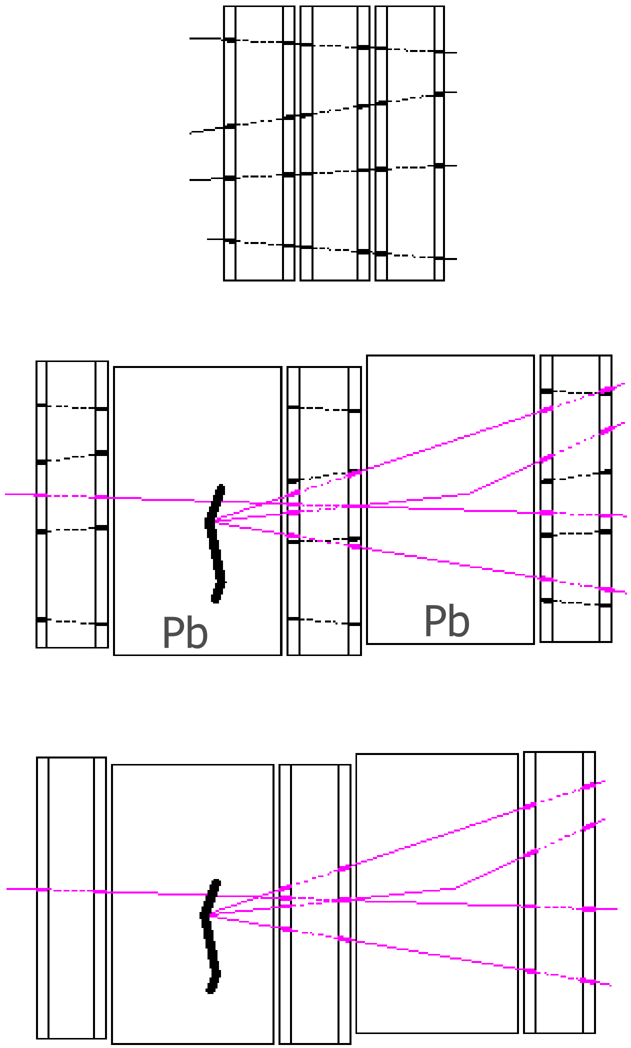

- **Main background**
  - charmed particle decay vertex mistaken as primary vertex
  - μ from $\nu_\mu$ CC faking $\tau \to \mu$ because of its large IP

- **Event selection**
  - Reconstruct the invariant mass M of the particles assigned to the vertex defined as primary (≥ 2 tracks)
  - With 50% mass resolution and M > 3 GeV/$c^2$ cut only 0.2% of the charm background survives




**Contribution to τ detection efficiency x BR : 0.7 %**

# Virtual erasing of tracks




**For transportation**
Emulsions packed (without lead)

**Exposure**
Micro-tracks recorded during transportation appear as staggered

**Analysis**
"virtual erasing"
of micro-tracks connected
in the configuration without lead

Established technique in CHORUS

*(for periods with different emulsion alignment)*

# Emulsion self-refreshing

Principle: Erasing of unwanted tracks (accumulated during production & transportation).

Full utilization of low BG environment of LNGS (1 cosmic/$m^2$/hour).

Mechanism: destroy the latent image $Ag_4 + O_2 + 2H_2O \rightarrow 4Ag^+ + 4OH^-$

Method: high humidity (90-98%) and relatively high temperature (20-40 °C).

Test performed with CERN 10 GeV $\pi$ beam: (30 °C, 98% RH)

| Time | Tracking Efficiency (%) | Erasing rate (%) |
|---|---|---|
| 1 day | 99 | 90 |
| 2 days | 99 | 94 |
| 3 days | 99 | 90 |

production

beam exposure

refreshing (3 days)

development

GD < 8/100 $\mu$m
FD = 2.1/1000 $\mu m^3$

production

refreshing (3 days)

beam exposure

development

GD < 35/100 $\mu$m
FD = 1.5/1000 $\mu m^3$

$\Rightarrow$ no signal degradation

# Physics Performance : Events Rate Update

- Beam intensity increase granted : 1.5 expected

- Non-isoscalarity corrections for Lead target :
  1. Signal events increase by 11%
  2. $\nu\mu/\nu e$ CC (and related backgrounds) increase by 8%
  3. Number of extracted bricks (dominated by $\nu\mu$ CC+NC) increase by 6%
  4. NC (and NC related background) are practically unchanged

| Evts/day | Shared mode $4.5\ 10^{19}$ pot/year | Dedicated mode $7.6\ 10^{19}$ pot/year |
|---|---|---|
| NC | 10.96 | 18.52 |
| CC DIS | 31.42 | 53.10 |
| CC QE+RES | 4.07 | 6.38 |
| Total | 46.45 | 78.5 |

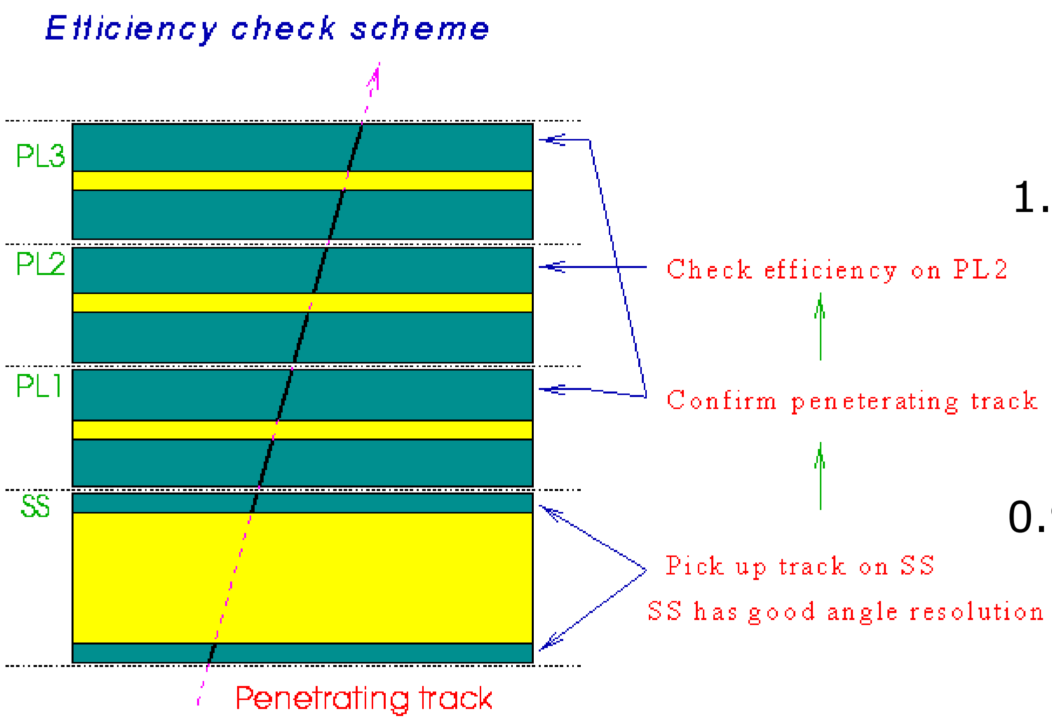
- target mass 1766 tons
- 1 year : 200 days
- shared :
  46452 x .895 evts in 5 years
- dedicated :
  78504 x .831 evts in 5 years

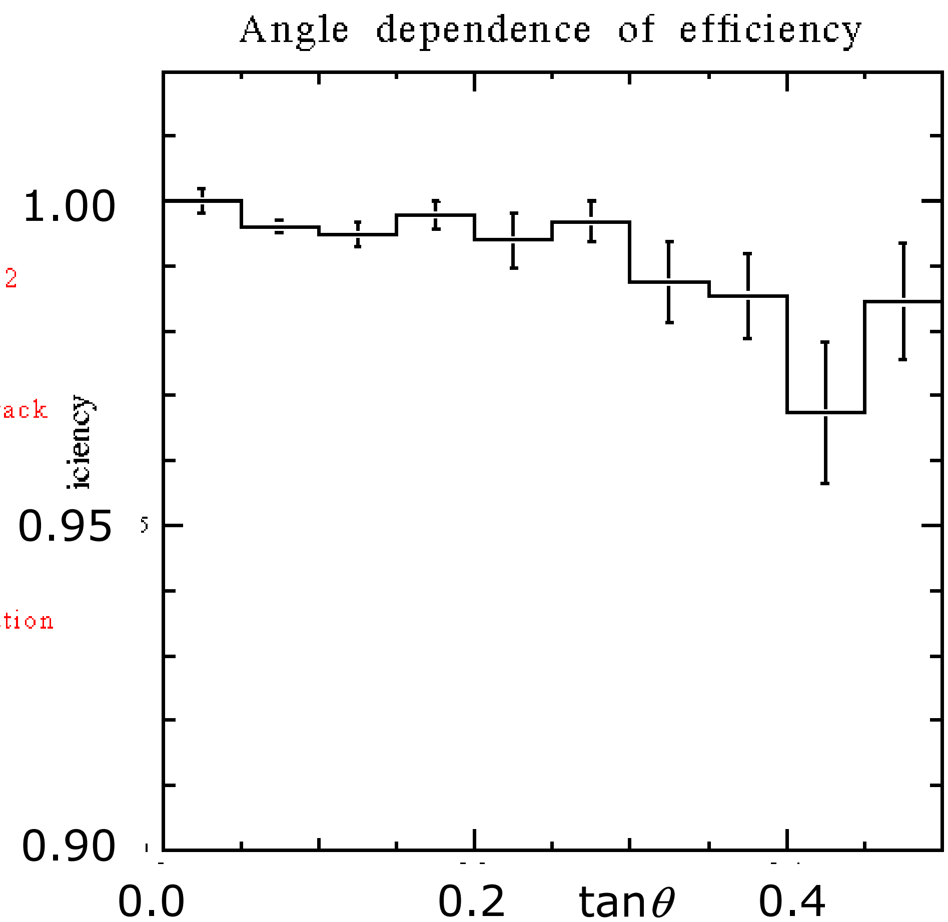
This has to be taken into account
for the scanning power

Courtesy of S.Aochi

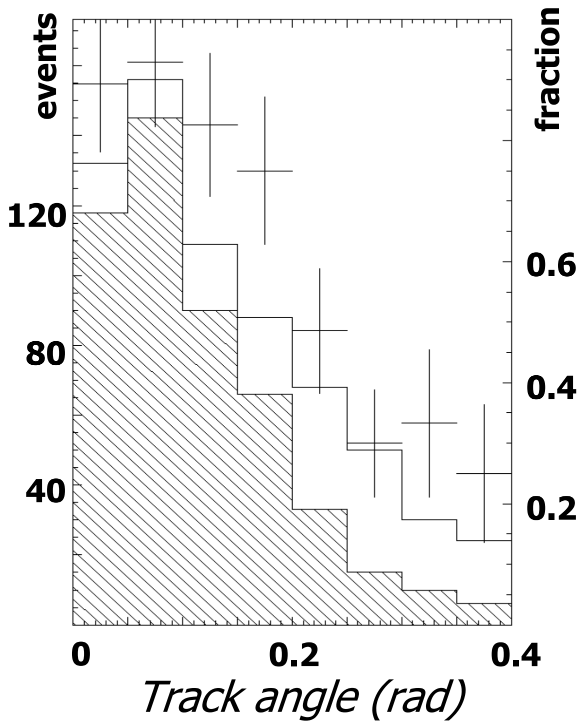
# Single plate efficiency

S.Aoki, NIMA 473 (2001) 192.



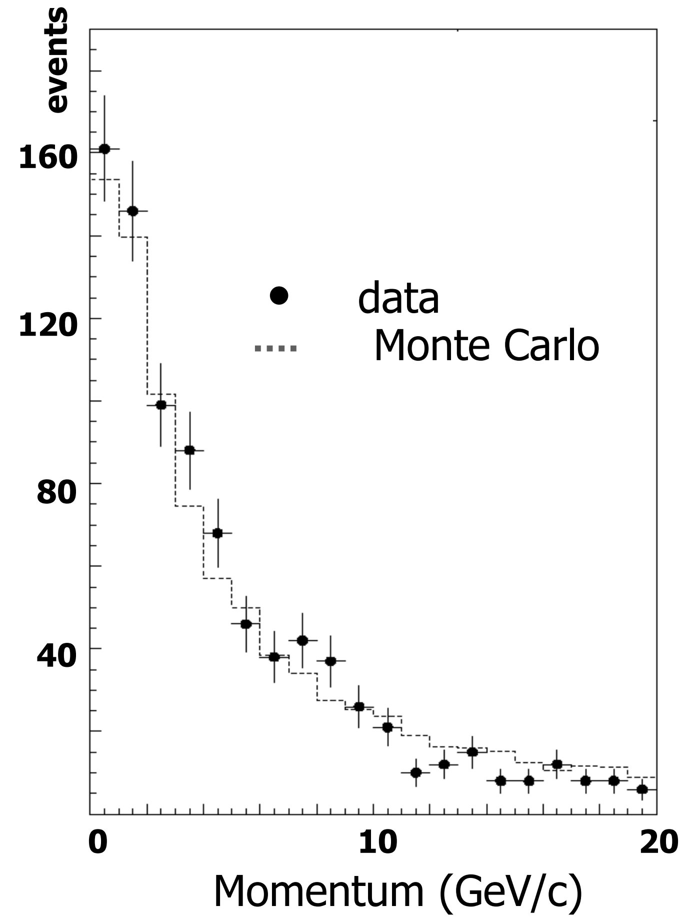
# Momentum measurement (coordinate method – DONUT)




- solid line: all tracks

\ hatched: momentum measured tracks

+ crosses: as above as a fraction (right axis) of all reconstructed tracks

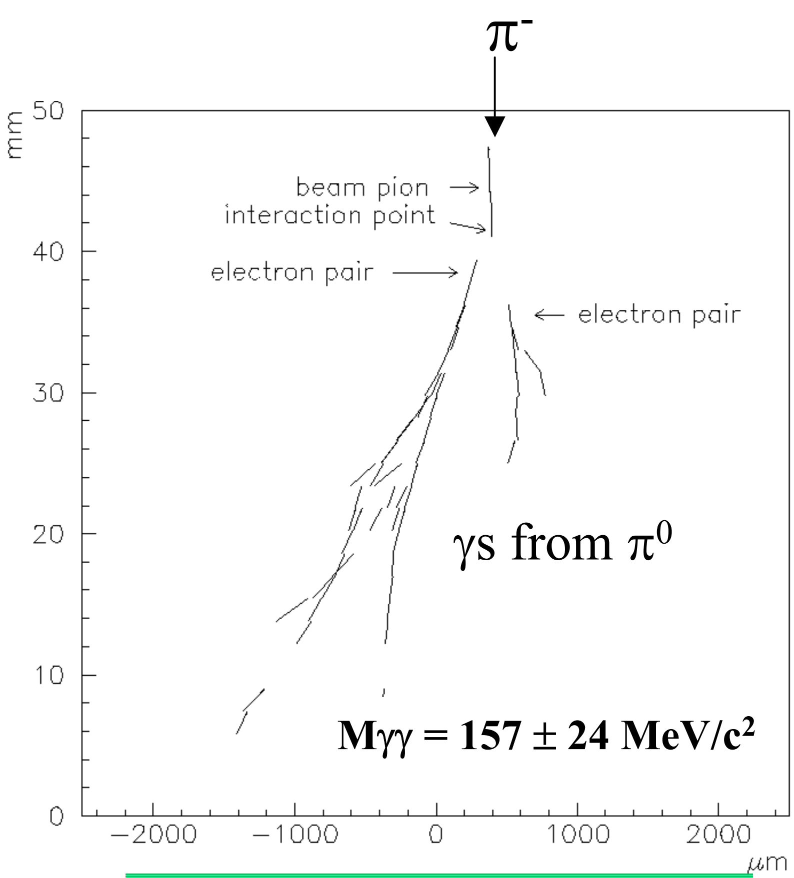



269 located events on the histograms

Angular dependence specific of DONUT analysis

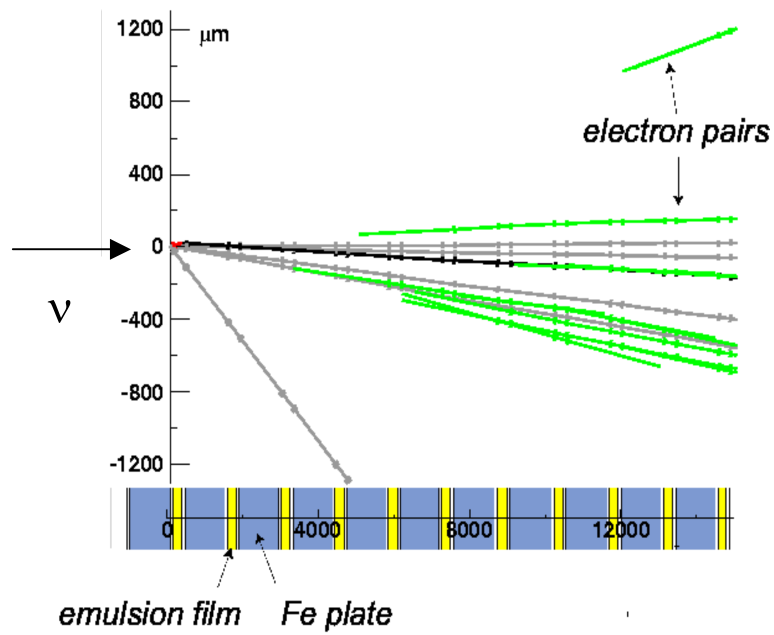
Important for event kinematics in OPERA

# $\gamma$ detection and energy measurement in ECC brick



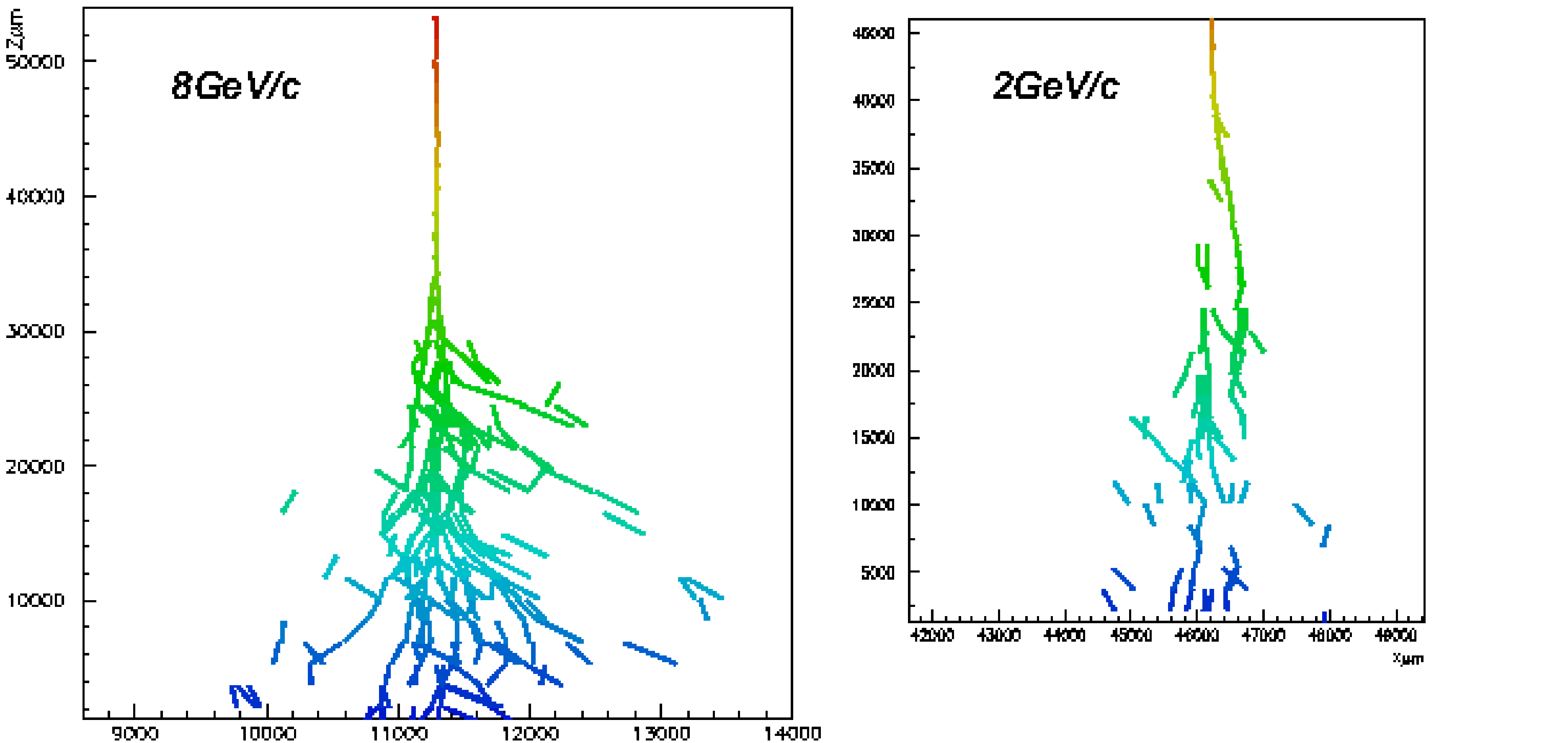

Test experiment at CERN PS
8 GeV/c $\pi^-$ interaction
in OPERA type ECC

Improvement for missing PT analysis
$\tau \rightarrow$ h decay mode
charged particle + $\pi^0$ ($\rightarrow \gamma\gamma$ )

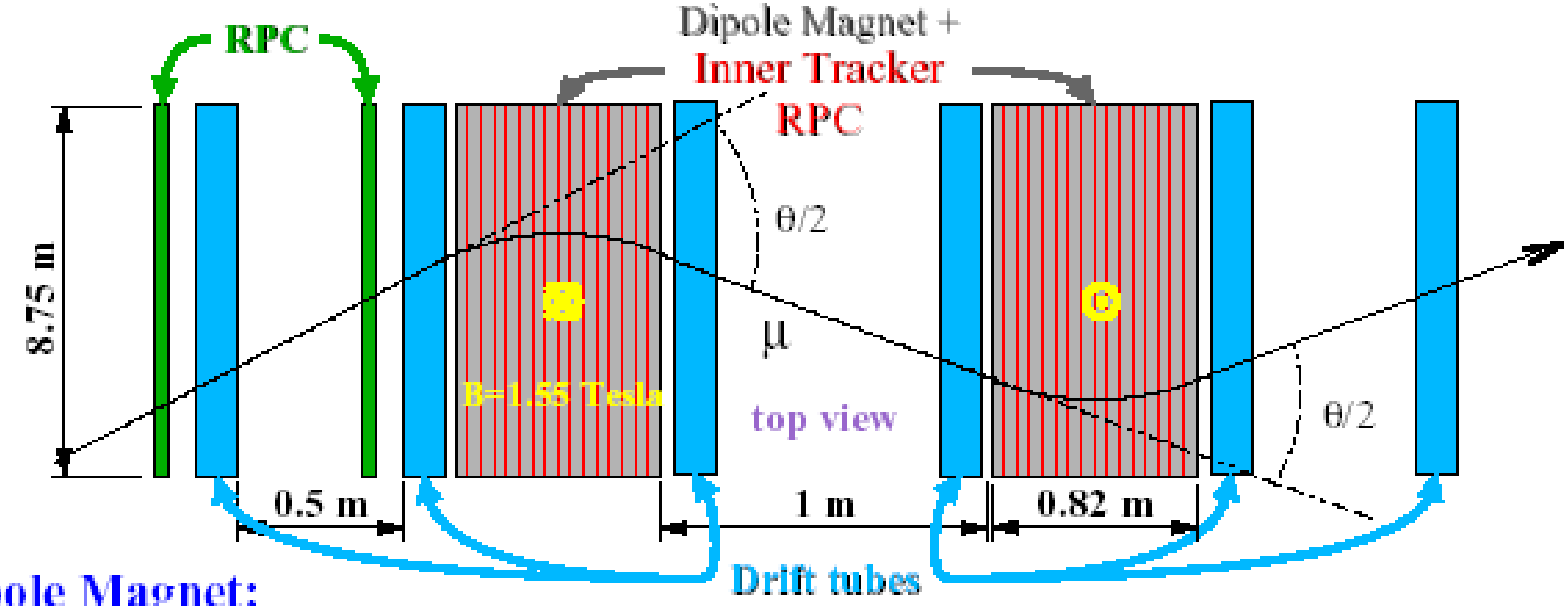



Example of $\gamma$ detection in DONUT
( Fe not suited for energy measurement)

# Electron ID in Emulsion Module



# Muon Spectrometer




## Dipole Magnet:

- 2 x 12 8.75 x 8.2 $m^2$ and 50mm thick Fe Walls
- B = 1.55 Tesla
- 2 x 11 gap, 20mm thick, instrumented with RPC – muon tracking, energy by range

## Precision Tracker:

- 6 station of vertical drift tube with 0.5 mm space resolution

$$\frac{\delta p}{p} \leqslant 0.25 \quad \text{for } p < 25\ GeV$$

- RPC for drift tube timing space ambiguities