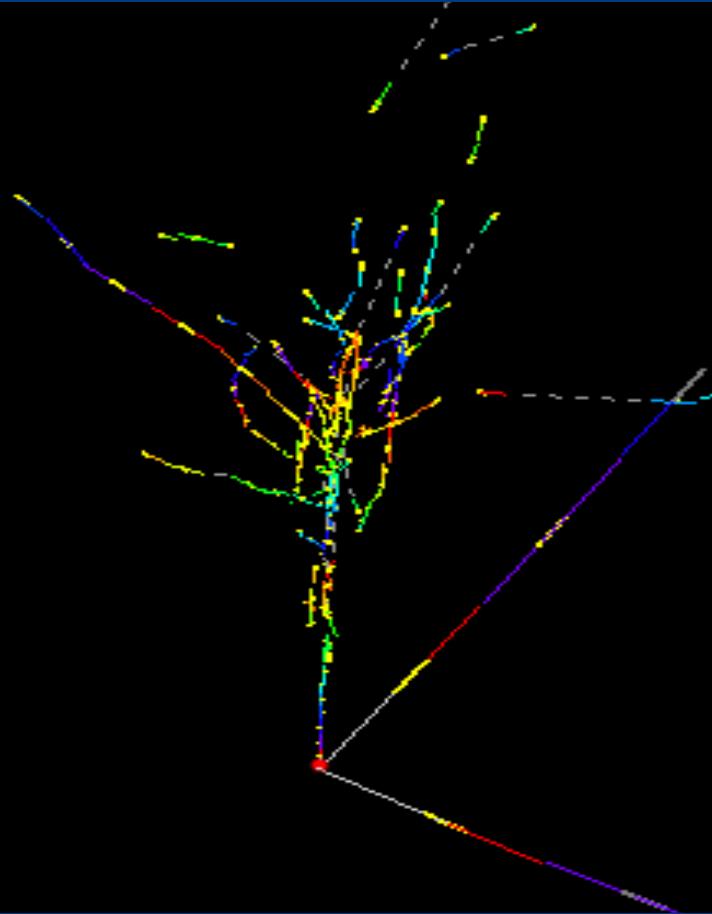
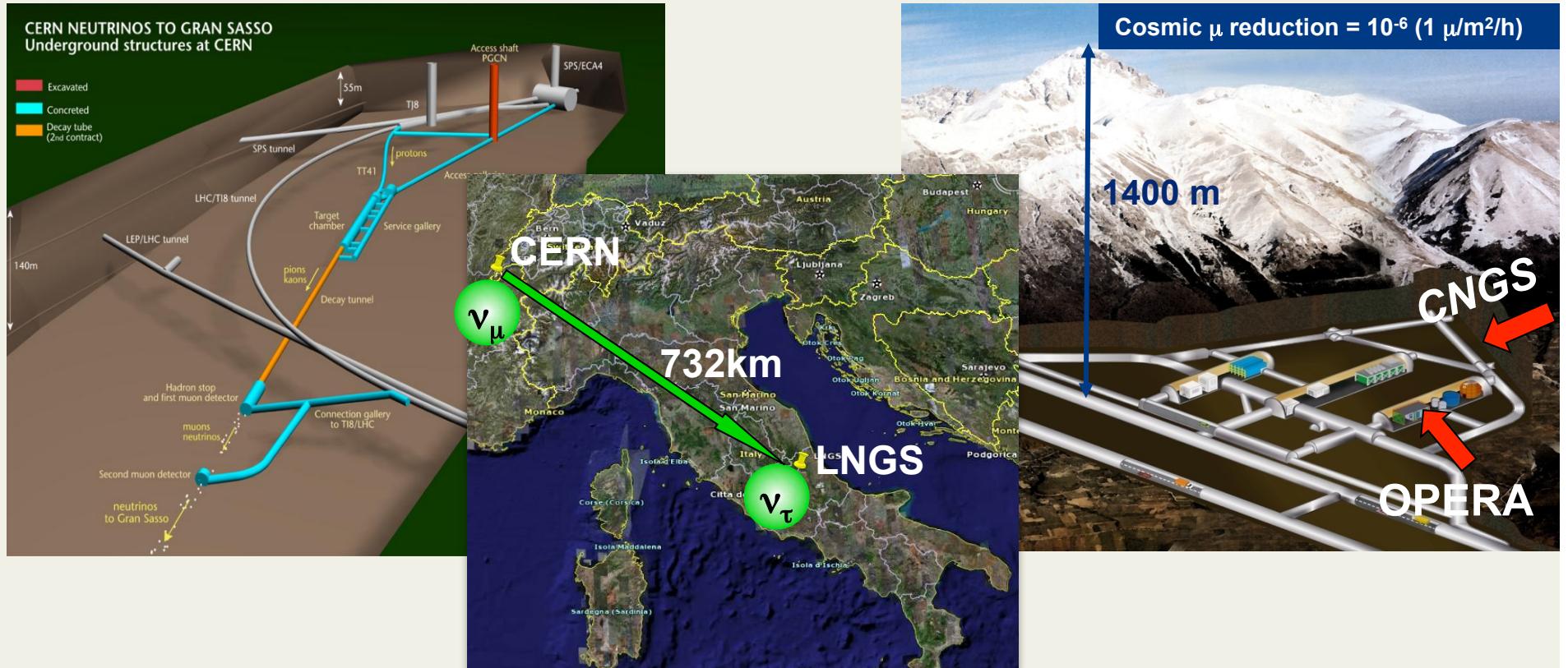


# OPERA Neutrino Oscillation Results



A. Murat Güler  
METU Physics Department  
(on behalf of the OPERA Collaboration)

# OPERA Experiment



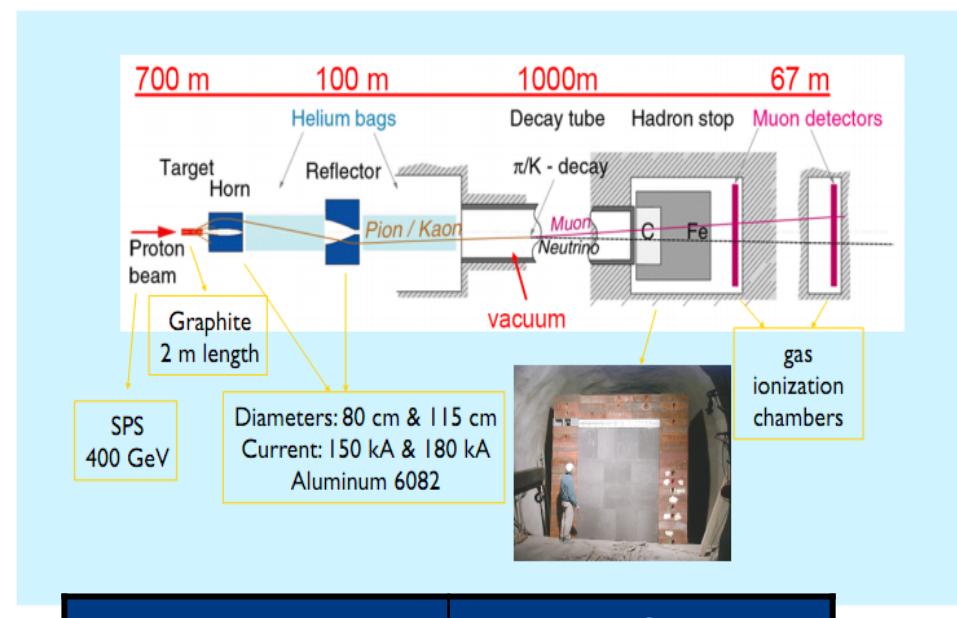
- Direct search for  $\nu_\mu \rightarrow \nu_\tau$  oscillations by looking at the appearance of  $\nu_\tau$  in a pure  $\nu_\mu$  beam
- Requirements:
  - 1) long baseline, 2) high neutrino energy, 3) high beam intensity,
  - 4) large mass, 5) detect short lived  $\tau$ 's

# OPERA Collaboration

160 physicists, 30 Institutions, 11 Countries

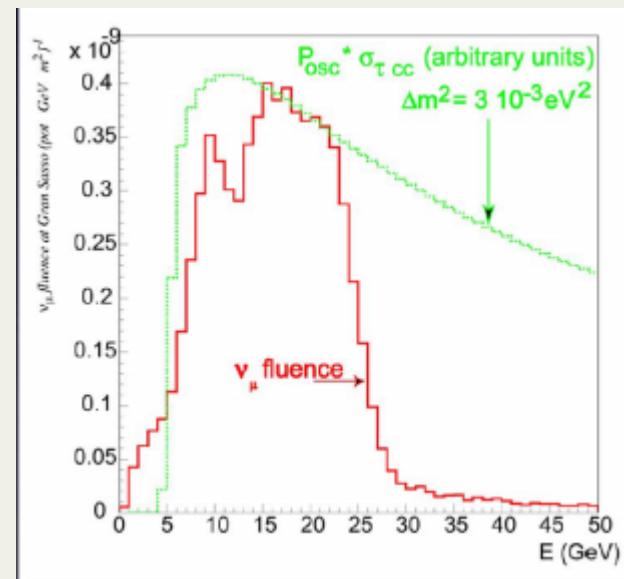


# CNGS Beam



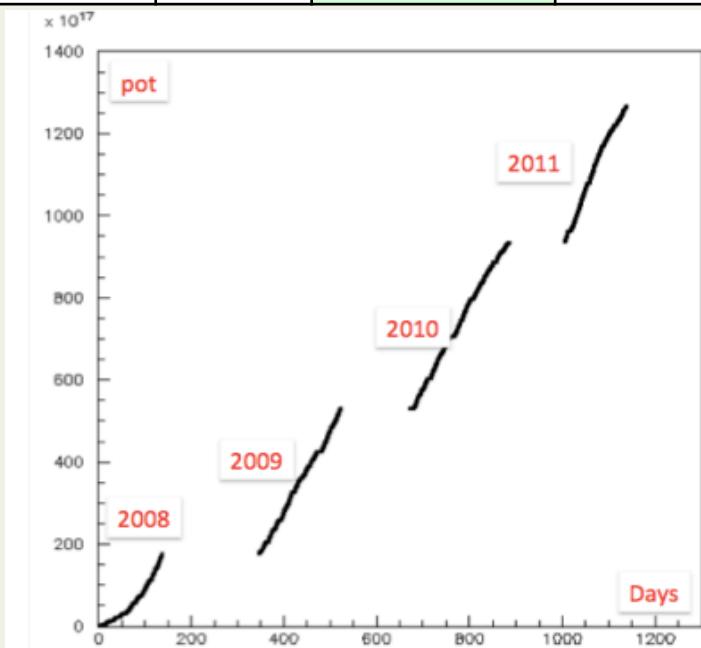
$\langle E_{\nu_\mu} \rangle$	17 GeV
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.87%
$\bar{\nu}_\mu / \nu_\mu$	2.1 %
$\nu_\tau$ prompt	negligible
Total p.o.t	$22.5 \times 10^{19}$
$\nu_\mu$ CC + NC	$\sim 23600$
$\nu_e + \bar{\nu}_e$ CC	$\sim 160$
$\nu_\tau$	$\sim 115$

- The neutrino beam is optimized for  $\nu$  appearance in atmospheric region:  $\Delta m^2 \approx 2.5 \times 10^{-3} \text{ eV}^2$  and  $\sin^2 \theta_{23} \approx 1.0$ .
- Although the maximum of oscillation probability at 730 km is at about 1.5 GeV, the  $\nu_\tau$  CC cross section and the production threshold of 3.5 GeV should be taken into account.



# CNGS Performance

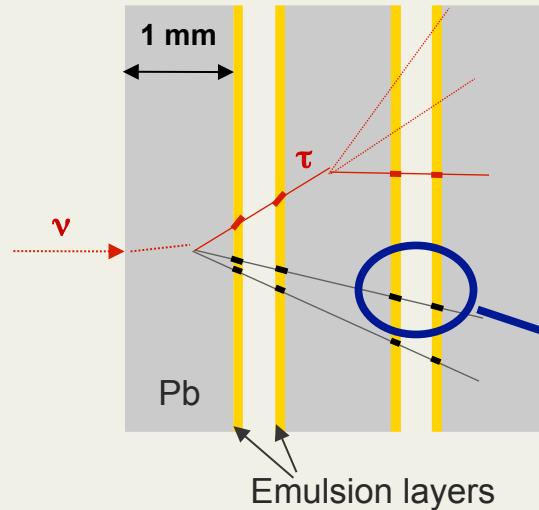
Year	Days beam	POT	SPS efficiency	Contain. Events	Run
2006		$0.076 \times 10^{19}$		no bricks	Commissioning
2007		$0.082 \times 10^{19}$		38	Commissioning
<b>2008</b>	<b>123</b>	<b><math>1.78 \times 10^{19}</math></b>	<b>61%</b>	<b>1724</b>	<b>First physics run</b>
<b>2009</b>	<b>155</b>	<b><math>3.52 \times 10^{19}</math></b>	<b>70%</b>	<b>3576</b>	<b>Physics run</b>
<b>2010</b>	<b>187</b>	<b><math>4.04 \times 10^{19}</math></b>	<b>81%</b>	<b>4049</b>	<b>Physics run</b>
<b>2011</b>	<b>214</b>	<b><math>4.84 \times 10^{19}</math></b>	<b>78%</b>	<b>4762</b>	<b>Physics run</b>



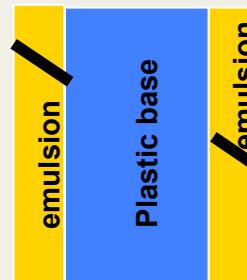
- Goal of the experiment:  $22.5 \times 10^{19}$  pot
- Until now (2008-2011):  $14.2 \times 10^{19}$  pot
- 2011:  $4.84 \times 10^{19}$  pot (more than expected)

# Detection Principle

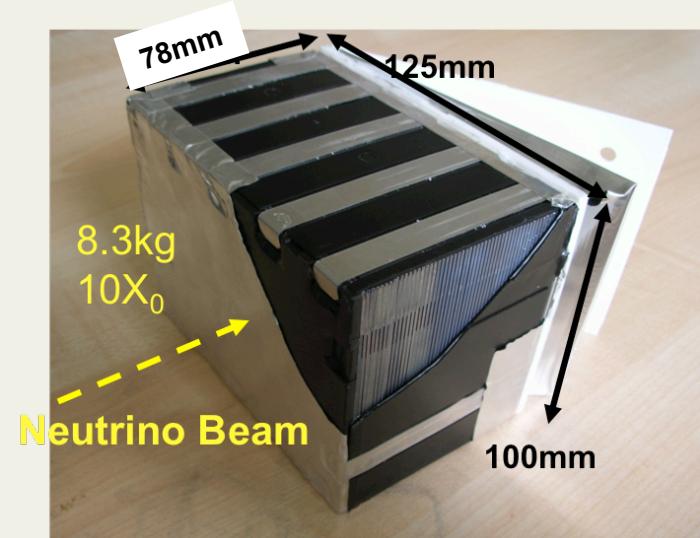
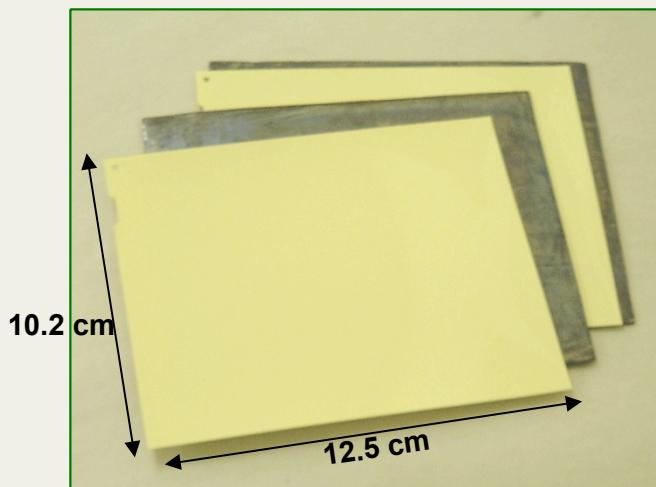
- 1 mm thick Pb plate interleaved with emulsion film; 2 emulsion layers 44 µm thick poured on a 205 µm plastic base.



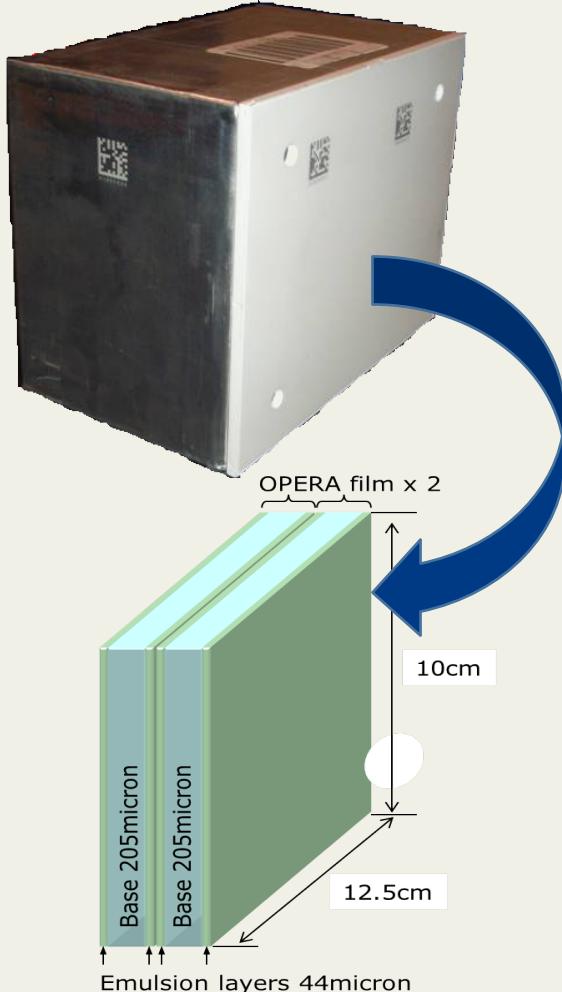
➤ Provides sub-micron spatial resolution



arranged in a “BRICK”:  
- 57 emulsion films  
- 56 Pb layers

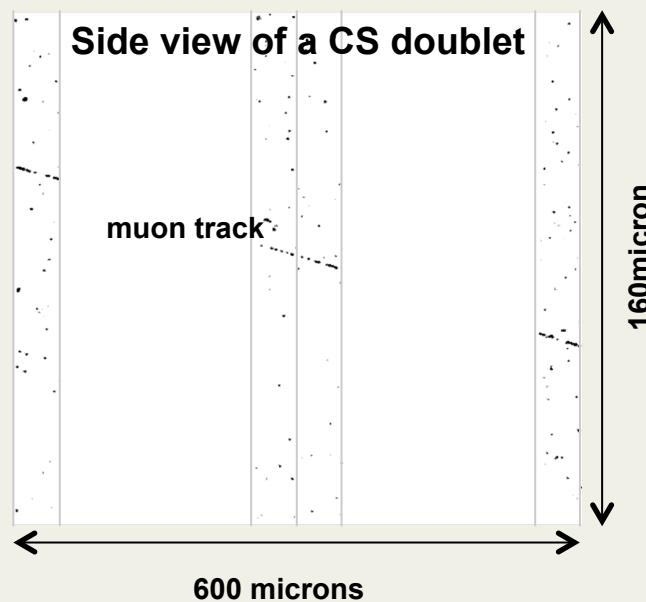


# Changeable sheet (CS)

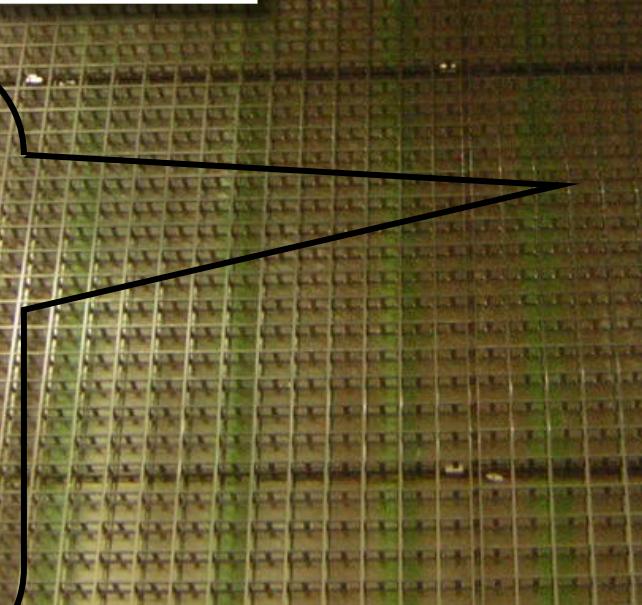


## From meters to microns:

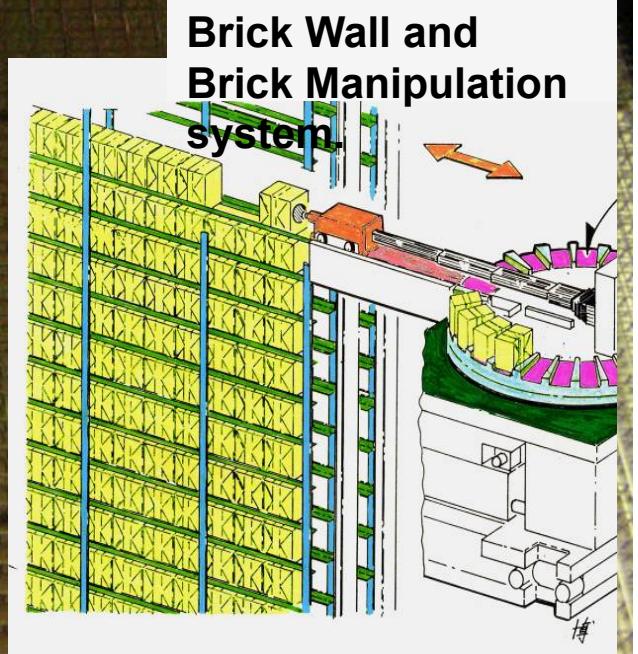
- OPERA:  $10 \times 10 \text{ m}^2$
- TT – indicate brick  $\sim 1 \text{ cm}$  accuracy
- CS –  $\sim 100 \text{ microns}$
- Inside brick near the vertex  $\sim 1 \text{ micron}$
  
- CS background requirements:  
    1 track/ $10 \times 10 \text{ cm}^2$
- Doublet film for coincidence



# OPERA Target

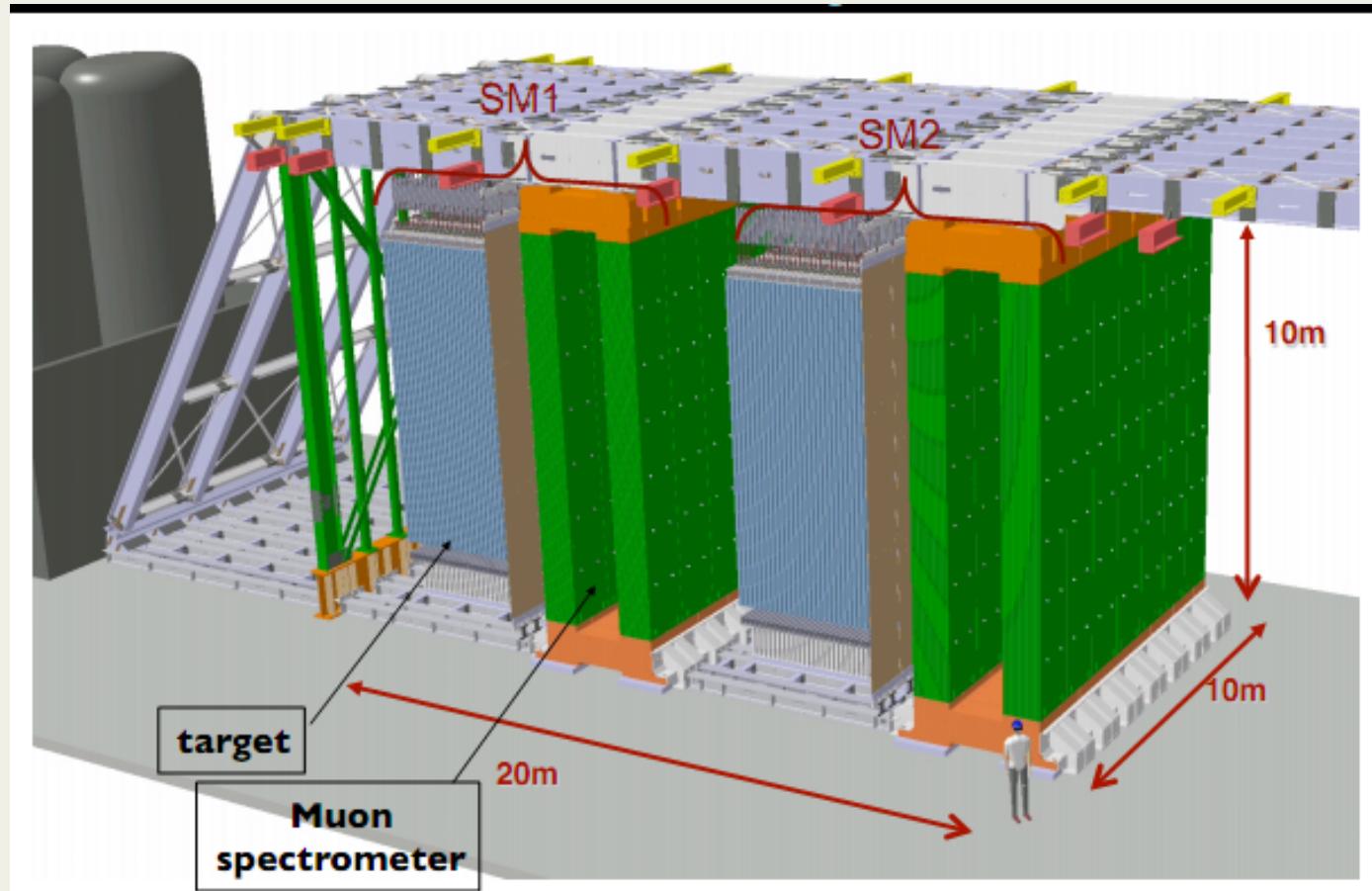


- Brick filling is finished in July 2008
- 146621 bricks with ~8 millions of nuclear emulsions films.
- Bricks assembling was technologically challenging. The small mechanical industry installed underground and worked in the red-light dark room

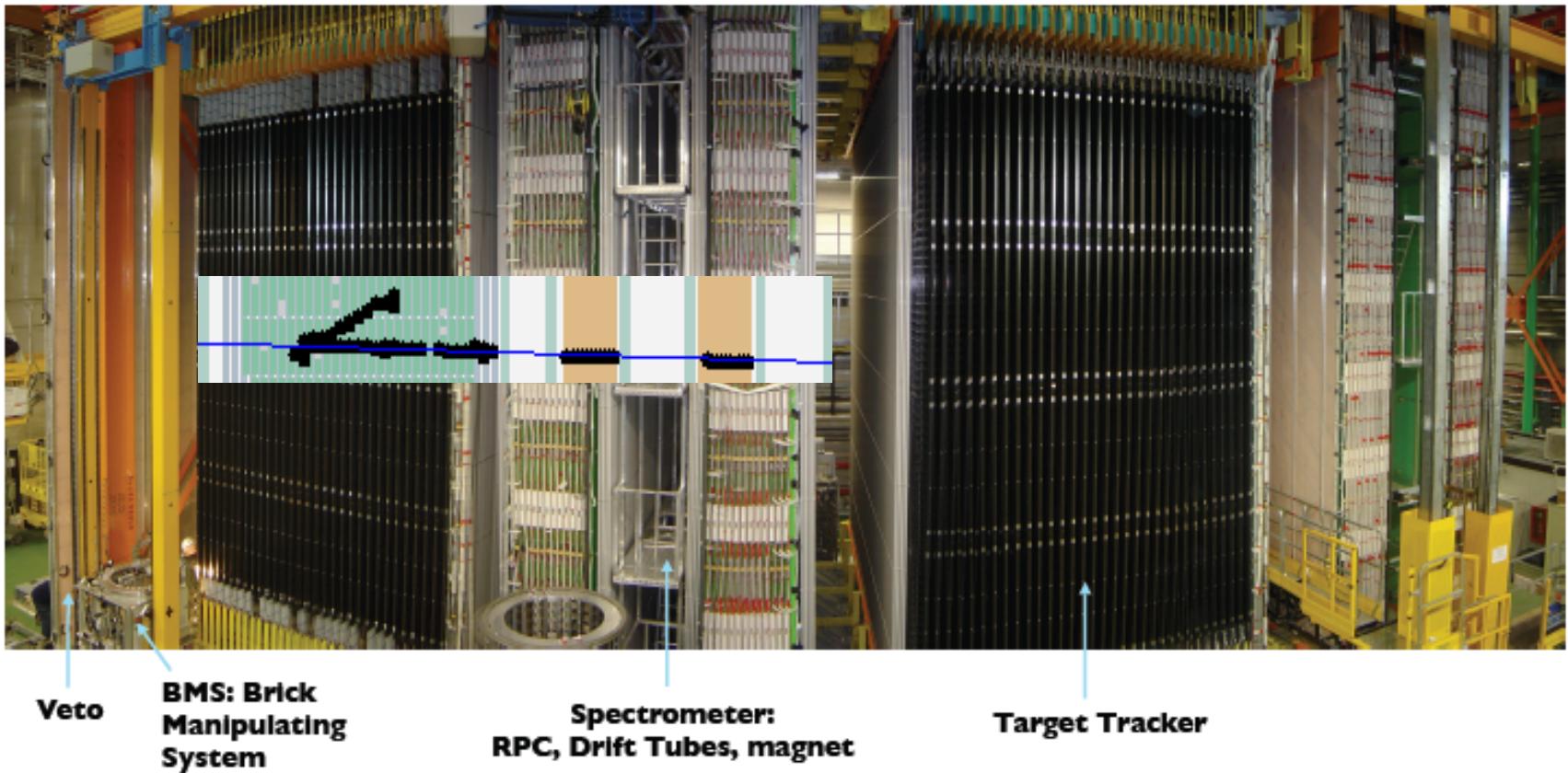


# OPERA Detector

Hybrid detector (electronic + emulsions) with a modular structure:  
2 supermodules =  $2 \times (31 \text{ walls} + 1 \text{ spectrometer})$   
The total target mass = 1.35 kton



# The OPERA electronic detectors



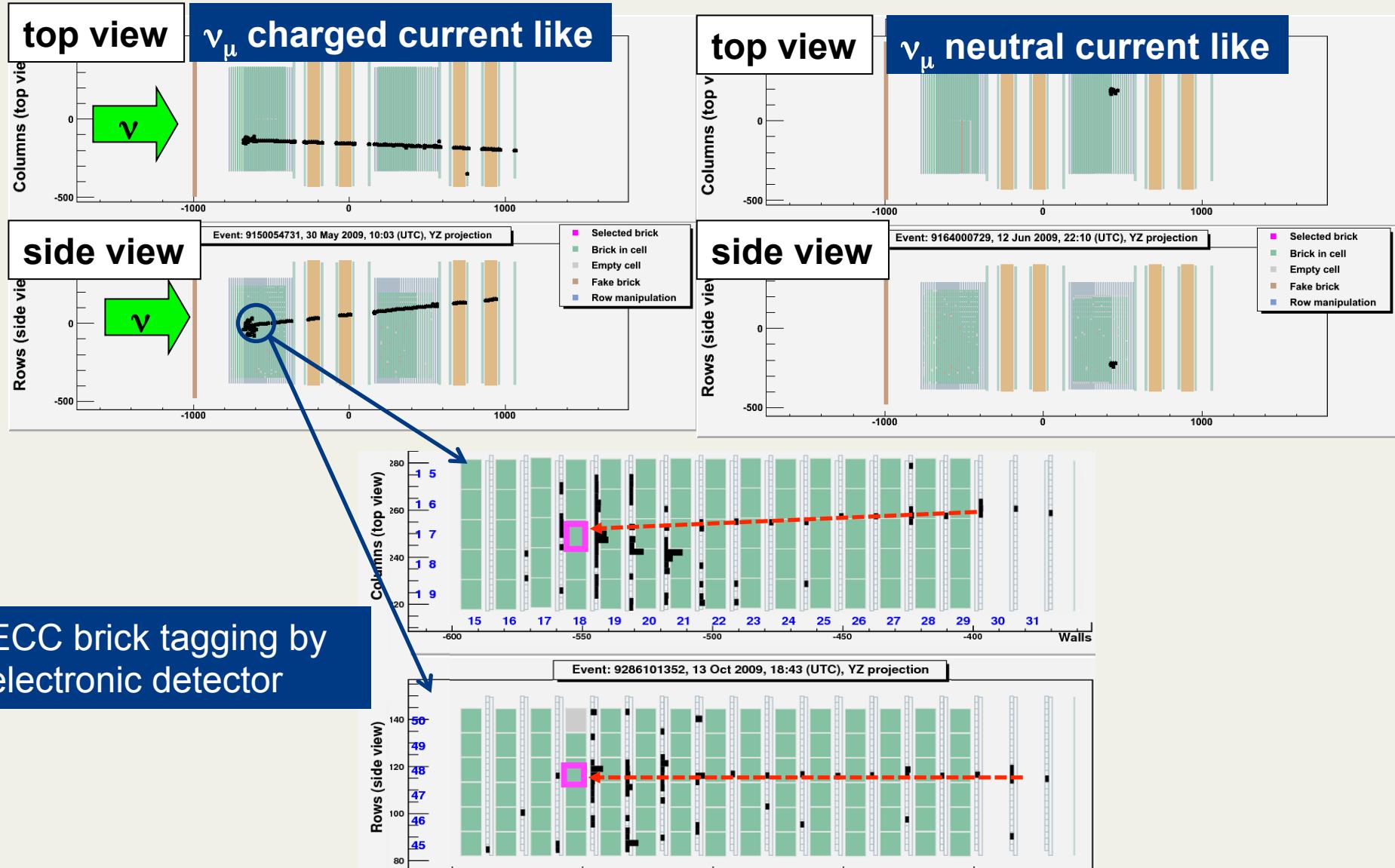
## Target Tracker

- Made of plastic scintillation strips with wavelength shifting fibers.
- p.e/mip > 5
- Brick finding efficiency: ~80 %

## Muon spectrometer

- RPC and drift tubes in 1.5 T magnet
- charge miss id (<25 GeV/c): <1%
- $\Delta P/P$  (<50GeV/c) ~ 20%
- $\mu$  id (with TT) ~ 95%

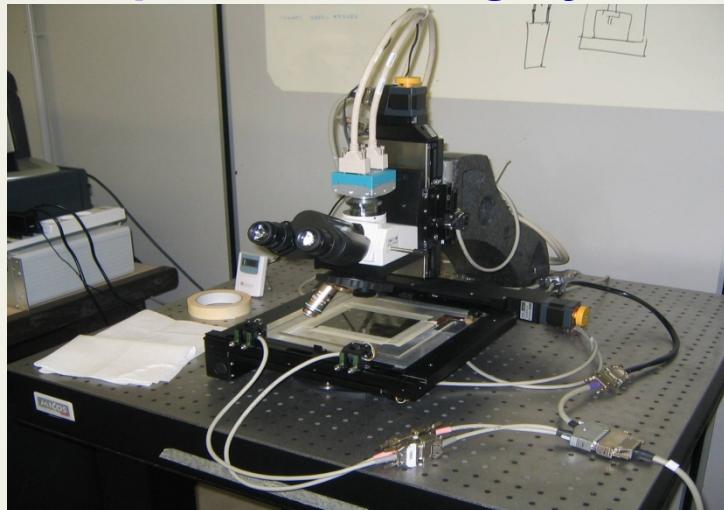
# Neutrino Interactions



# Automatic Scanning System

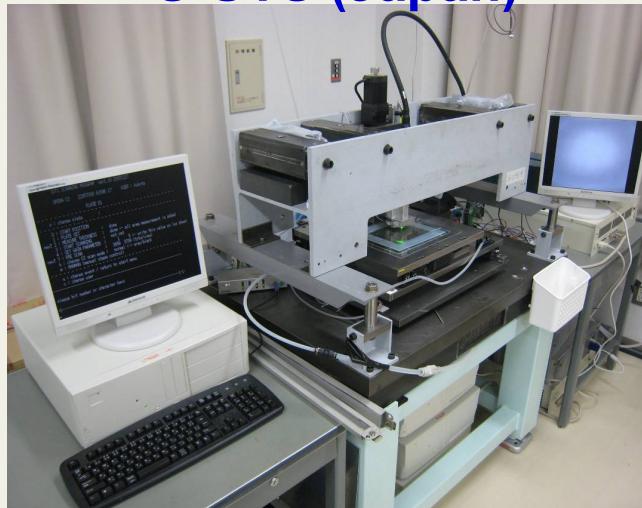
- The mean area to be scanned is  $\sim 200 \text{ cm}^2$  per each OPERA event.
- Considering 20000 events to process the full area to be scanned is  $400 \text{ m}^2$  of the emulsion surface.

## European Scanning System



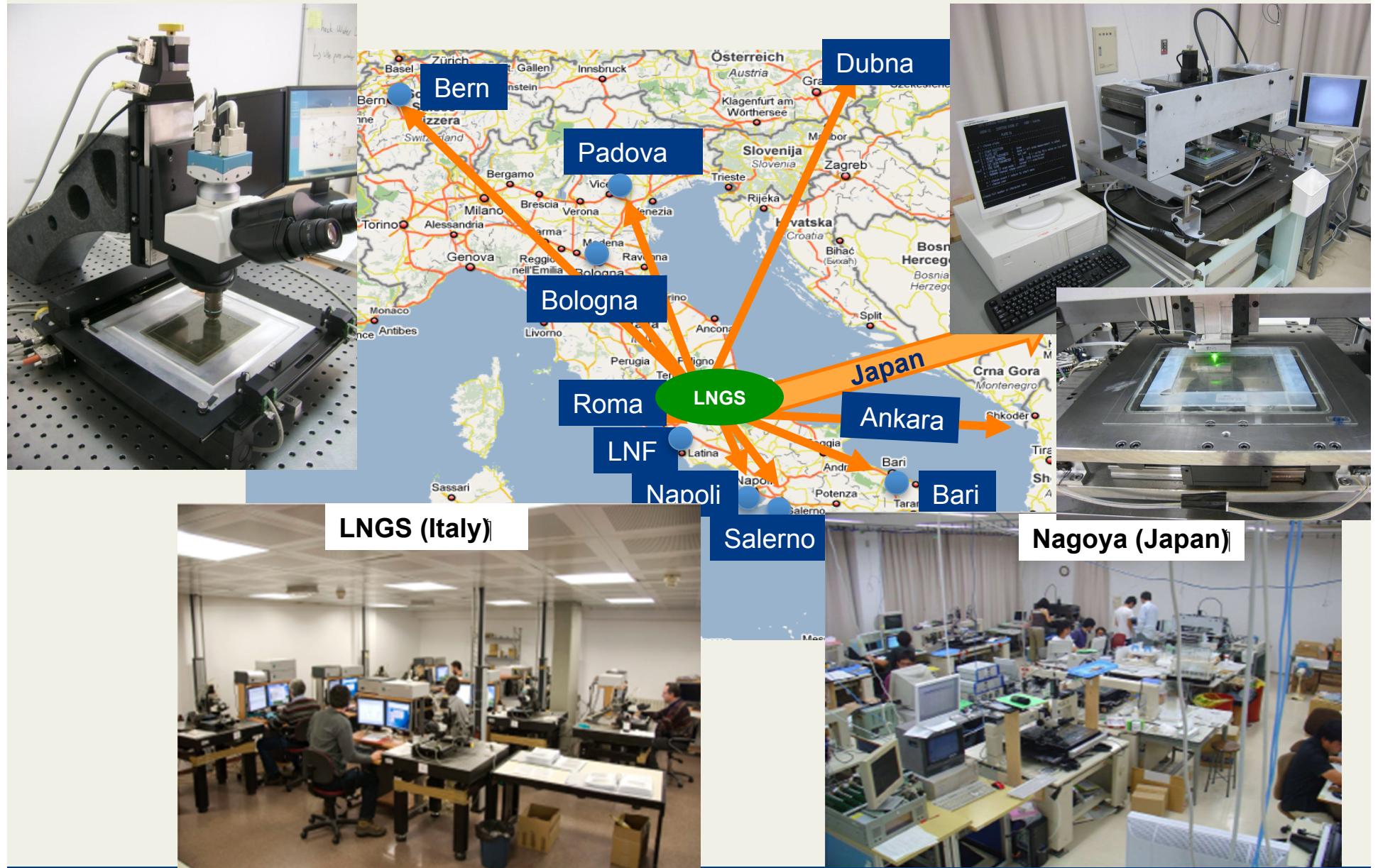
- Customized commercial optics and mechanics.
- Scanning speed:  $20 \text{ cm}^2/\text{h}$ .

## S-UTS (Japan)



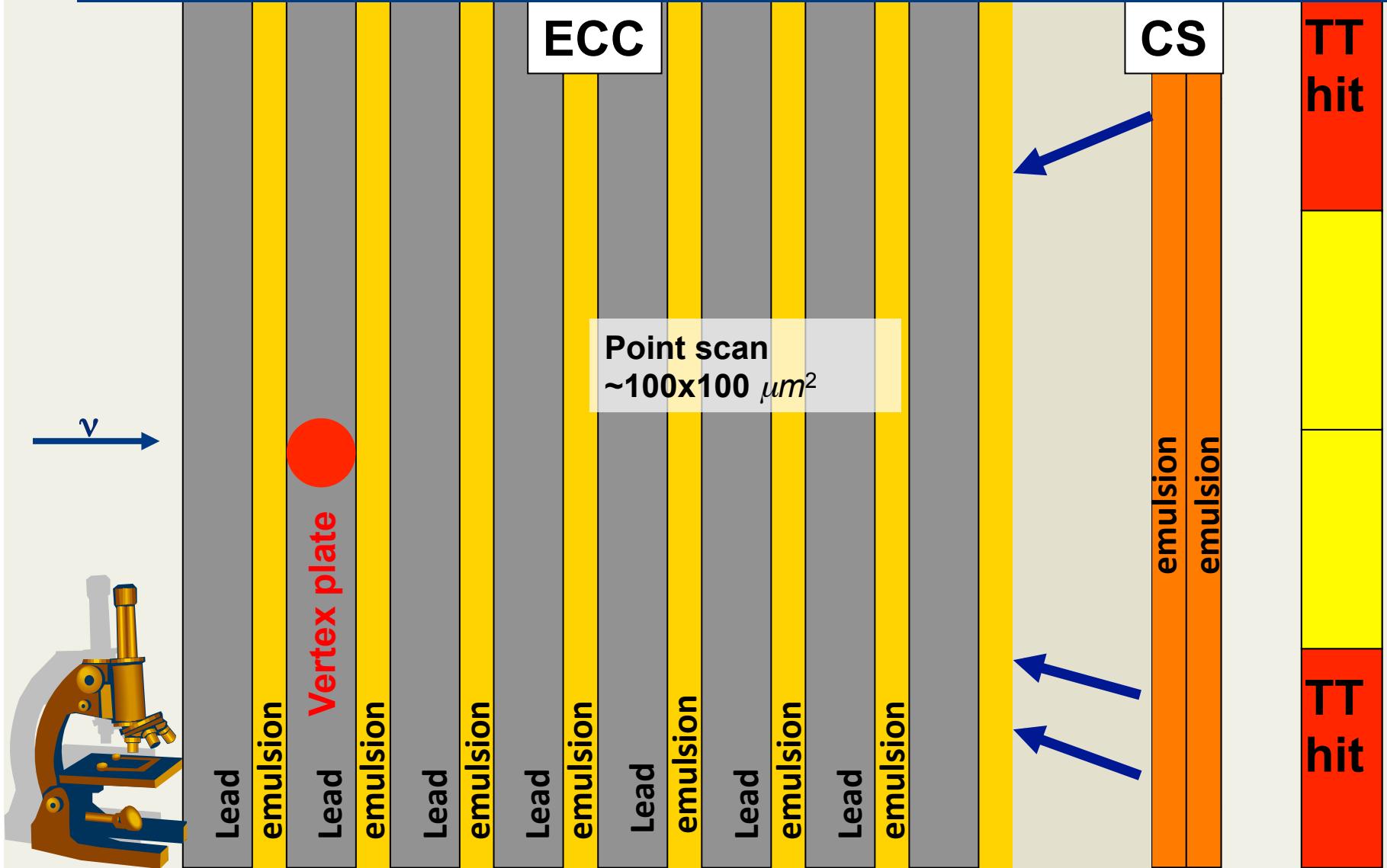
- High speed CCD Camera (3 KHz)
- Objective lens moved by piezo-element.
- Hard-coded algorithms.
- Scanning speed:  $75 \text{ cm}^2/\text{h}$ .

# Emulsion Scanning



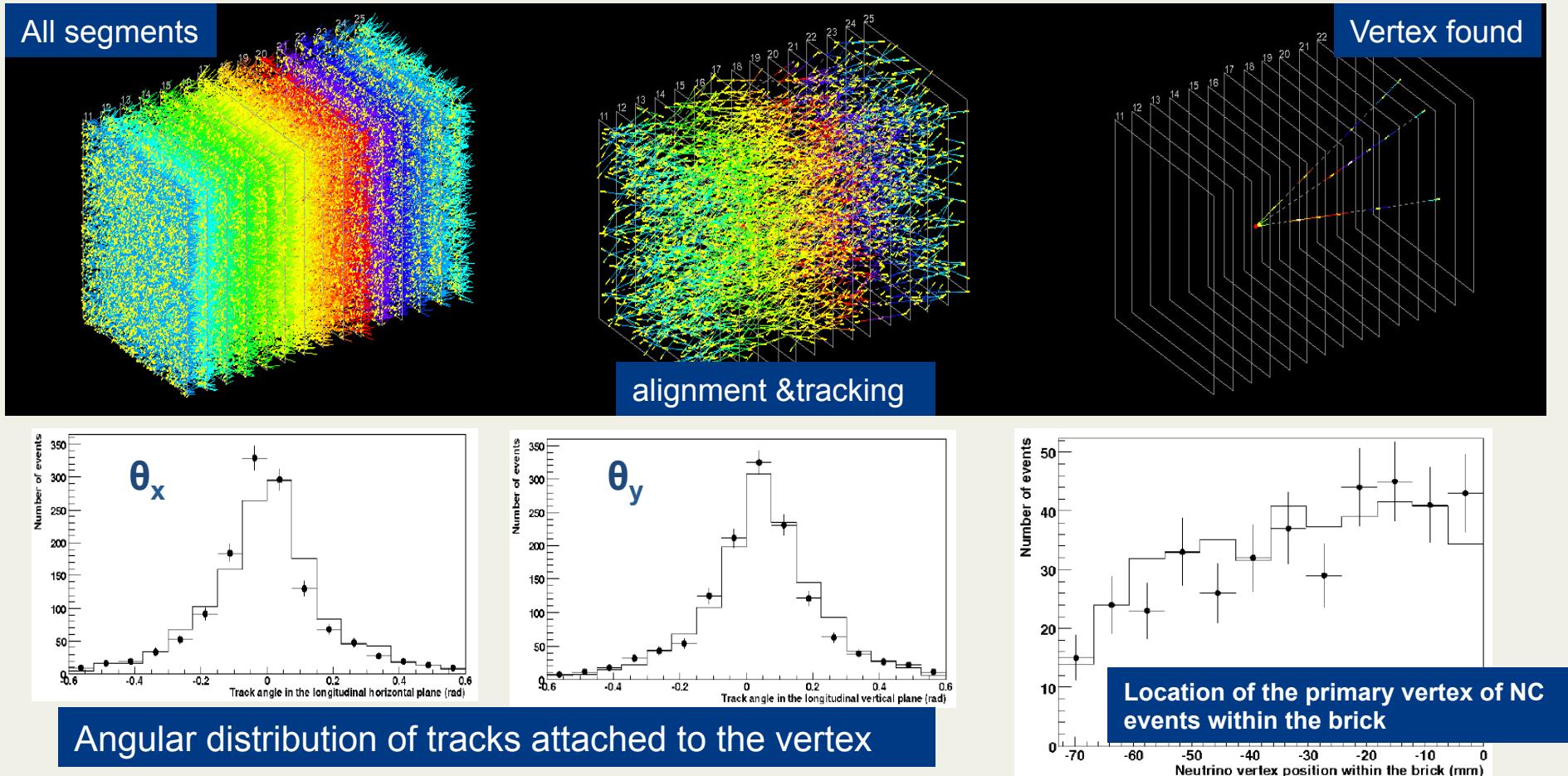
# Emulsion data reconstruction

➤ Track following: TT->CS-Brick upstream till the vertex



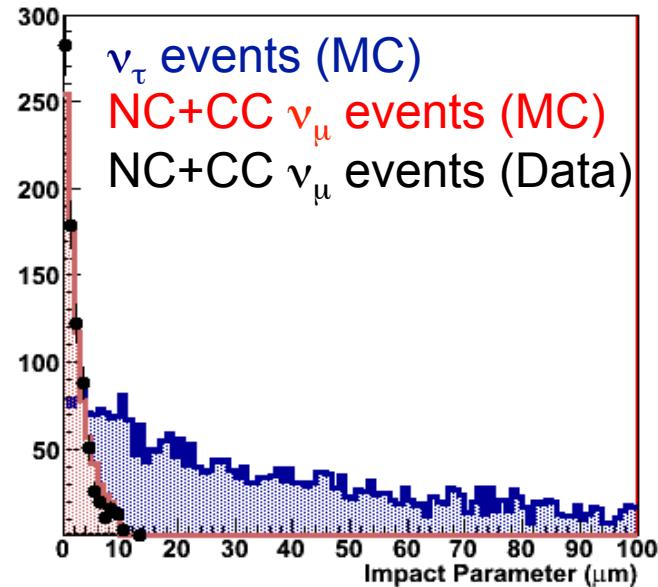
# Emulsion data reconstruction

- Volume scan and reconstruction of all tracks around the expected vertex position

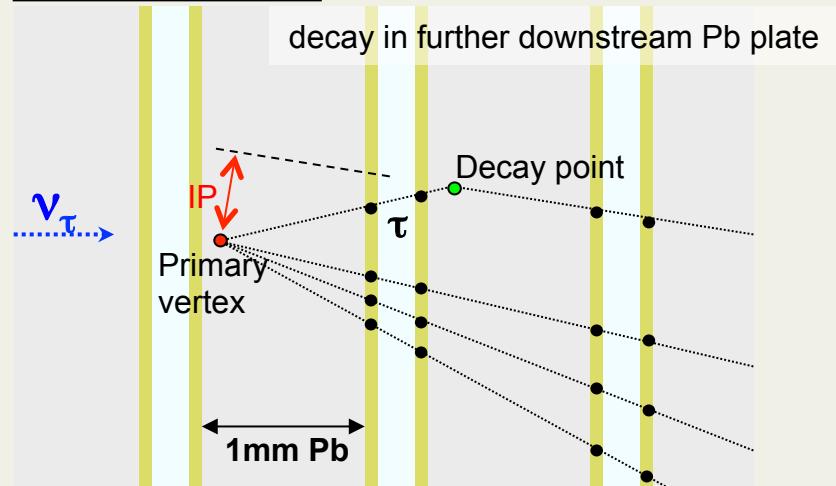


# Decay Search

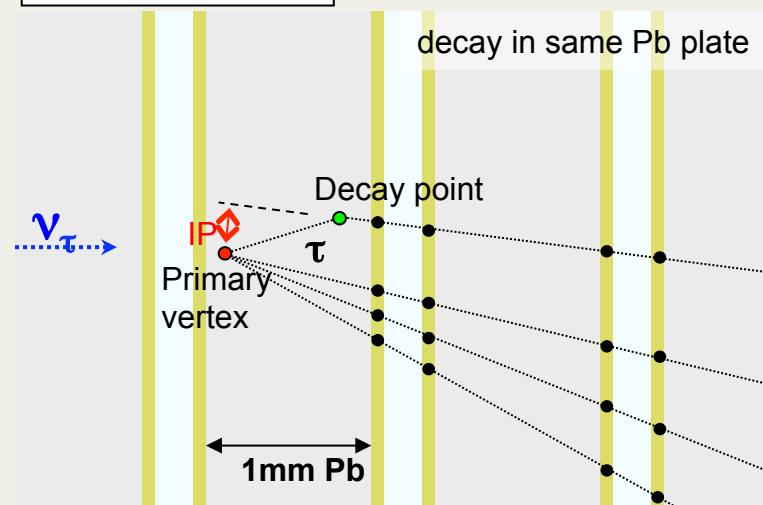
## Impact Parameter distribution



## Long flight decay



## Short flight decay

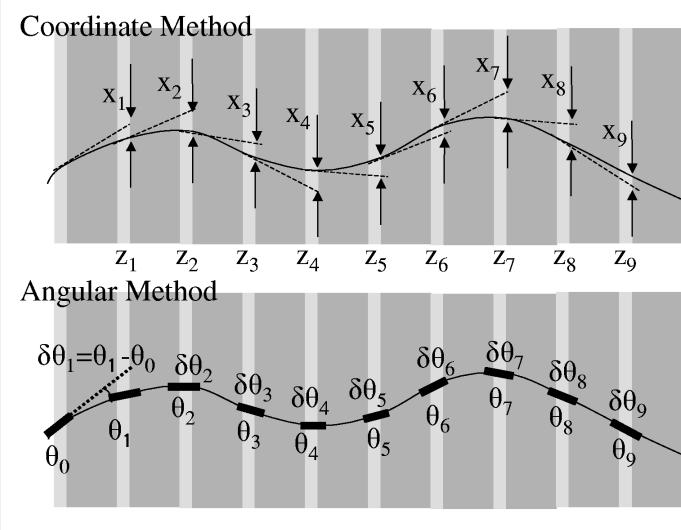


## $\tau$ decay topology

<b>Kink</b>	$\tau^- \rightarrow e^-$	17.8 %
	$\tau^- \rightarrow \mu^-$	17.4 %
	$\tau^- \rightarrow h^-$	49.5 %
<b>Trident</b>	$\tau^- \rightarrow h^- h^- h^+$	15.2 %

# Event Kinematics

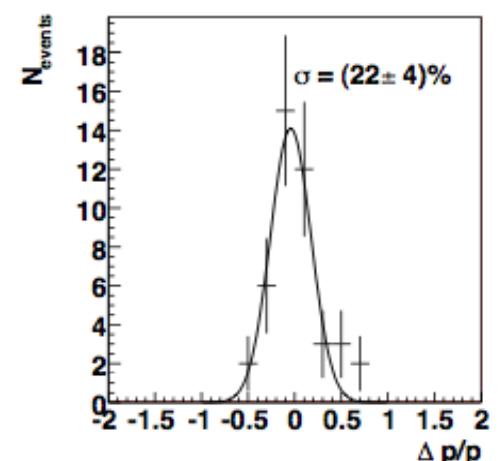
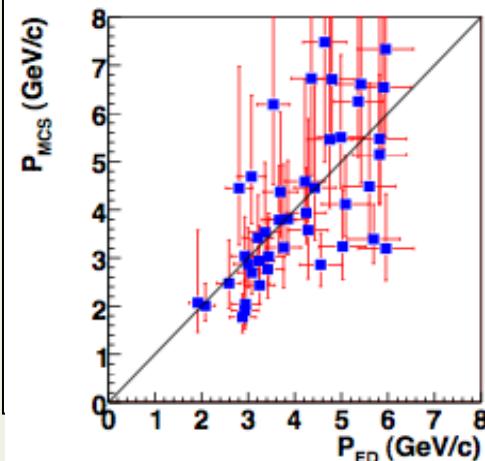
- Particle ID is possible in ECC by dE/dx. (hadron or muon or electron)
- Measurement of the position or angular displacement caused by the multiple Coulomb scattering



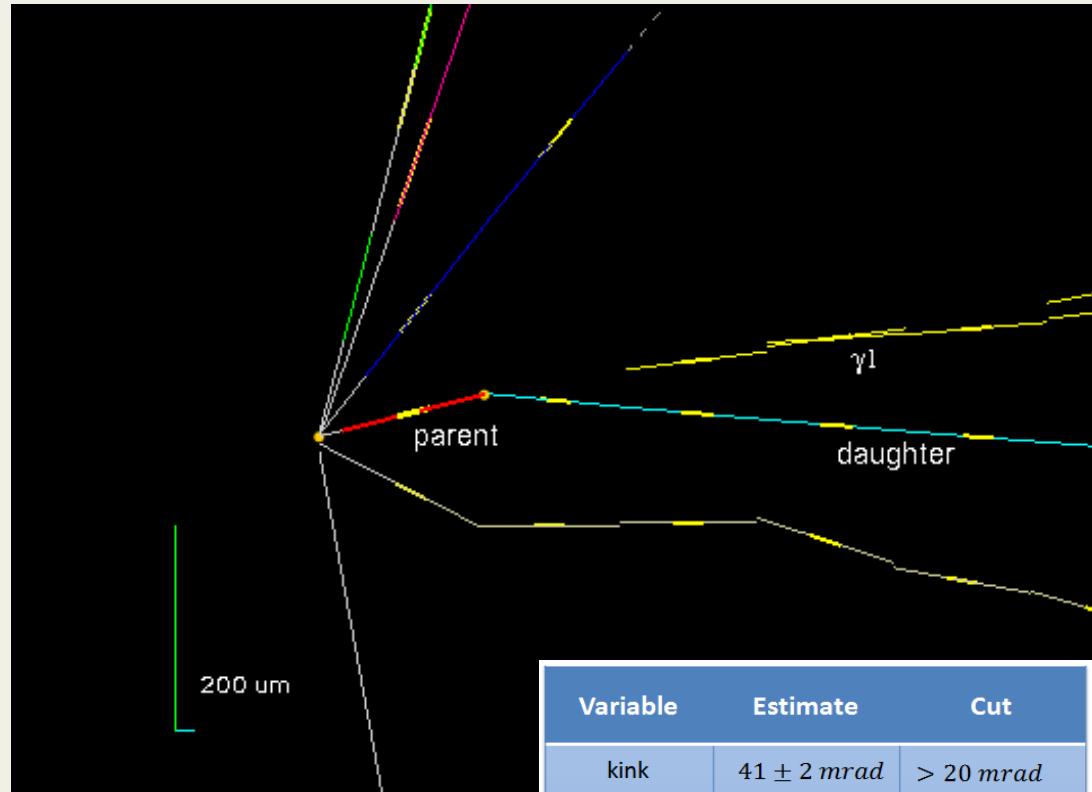
$$d\theta^{RMS} = \frac{13.6}{pc\beta} z \sqrt{\frac{x}{X_0}} \left( 1 + 0.038 \ln\left(\frac{x}{X_0}\right) \right)$$

## Soft data sample

Muon momenta measured by MCS as a function of the momenta obtained from the electronic detectors.  
Published in NJP (2012).

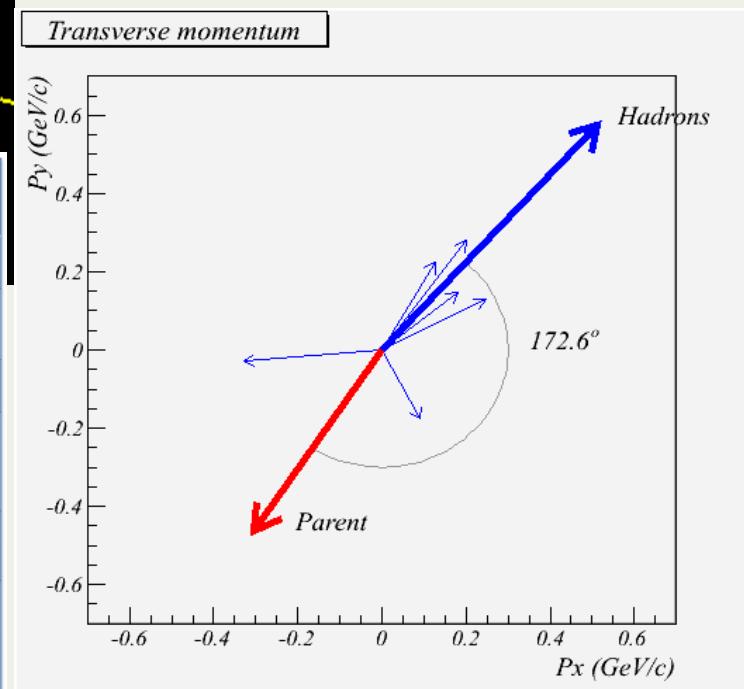


# The first $\tau$ candidate



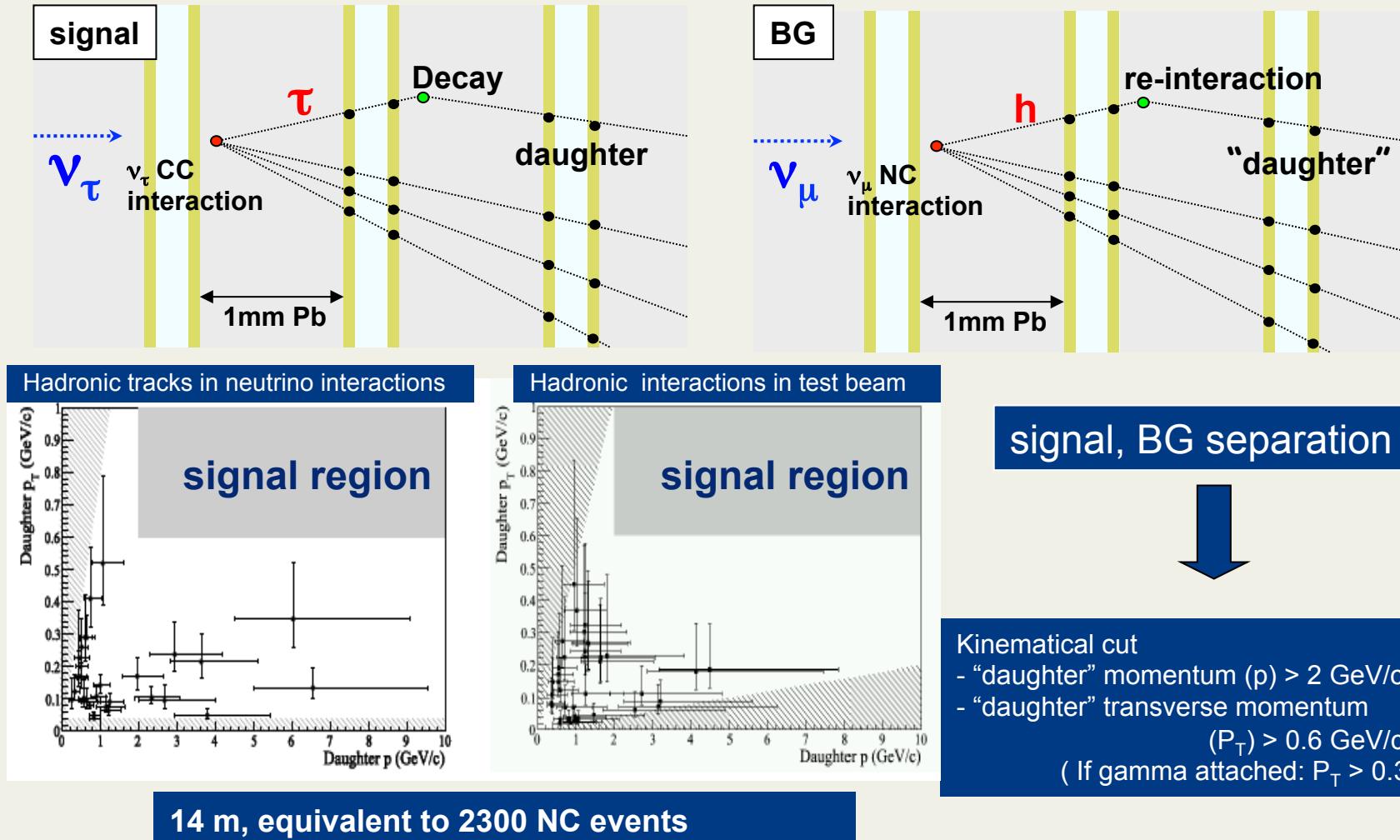
Variable	Estimate	Cut
kink	$41 \pm 2$ mrad	$> 20$ mrad
decay length	$1335 \pm 35$ $\mu\text{m}$	$< 2$ lead plates ( $\sim 2600$ $\mu\text{m}$ )
daughter P	$12^{+6}_{-3} \text{GeV}/c$	$> 2 \text{GeV}/c$
decay Pt	$620^{+310}_{-155} \text{MeV}$	$> 300 \text{MeV}/c$ ( $600$ if no $\gamma$ at decay vtx)
missing Pt	$530^{+300}_{-160} \text{MeV}$	$< 1 \text{GeV}/c$
$\phi$ (angle btw. had. system and tauon)	$173^\circ \pm 2^\circ$	$> 90^\circ$

- In spring 2010 OPERA present the first  $\nu_\tau$  candidate base on the analysis of 35% of '08+09' statistics.
- Data selection was done using the cuts defined at the time experimental proposal (2001).



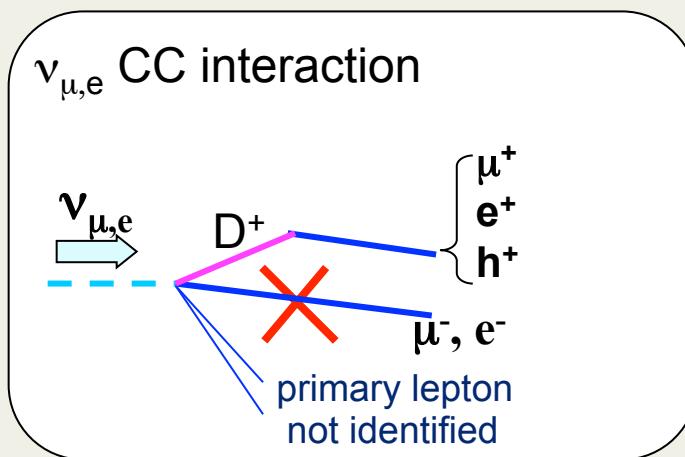
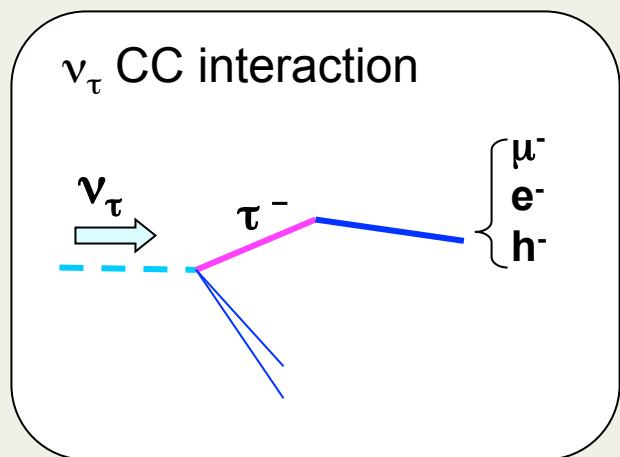
# Background sources for $\nu_\tau$

➤ Interactions of hadrons produced in  $\nu_\mu$  interactions



# Background sources for $\nu_\tau$

- Charmed particles have similar decay topologies to the  $\tau$

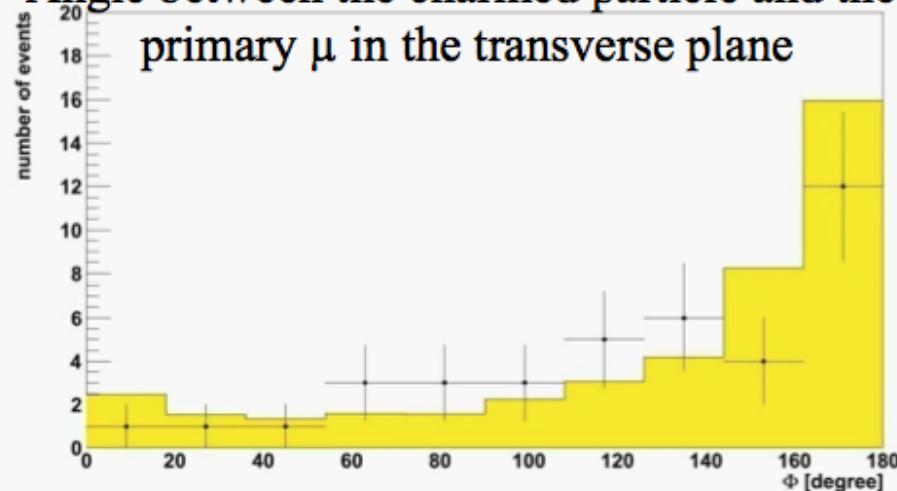


- Charm production in CC events represents a background source to all tau decay channels
- This background can be suppressed by identifying the primary lepton

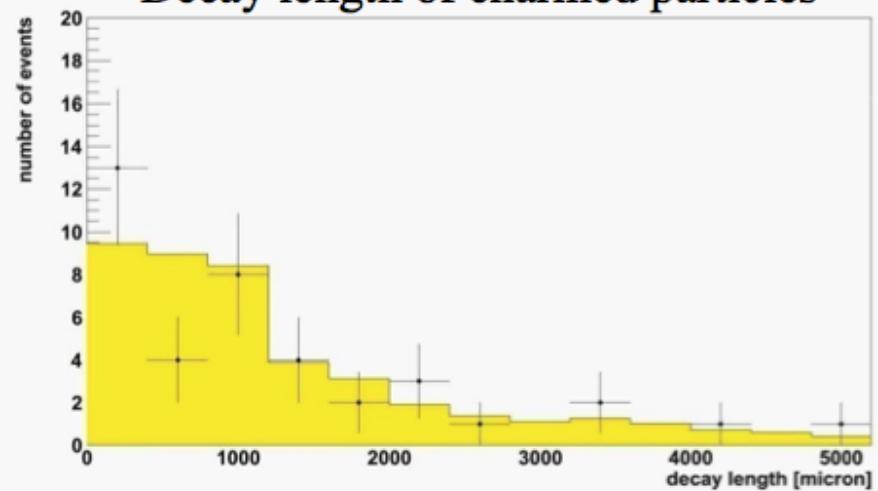
# Charm Candidates (2008-2009)

Topology	Observed events	Expected events		
		Charm	Background	Total
Charged 1-prong	13	15.9	1.9	17.8
Neutral 2-prong	18	15.7	0.8	16.5
Charged 3-prong	5	5.5	0.3	5.8
Neutral 4-prong	3	2.0	<0.1	2.1
Total	39	$39.1 \pm 7.5$	$3.0 \pm 0.9$	$42.2 \pm 8.3$

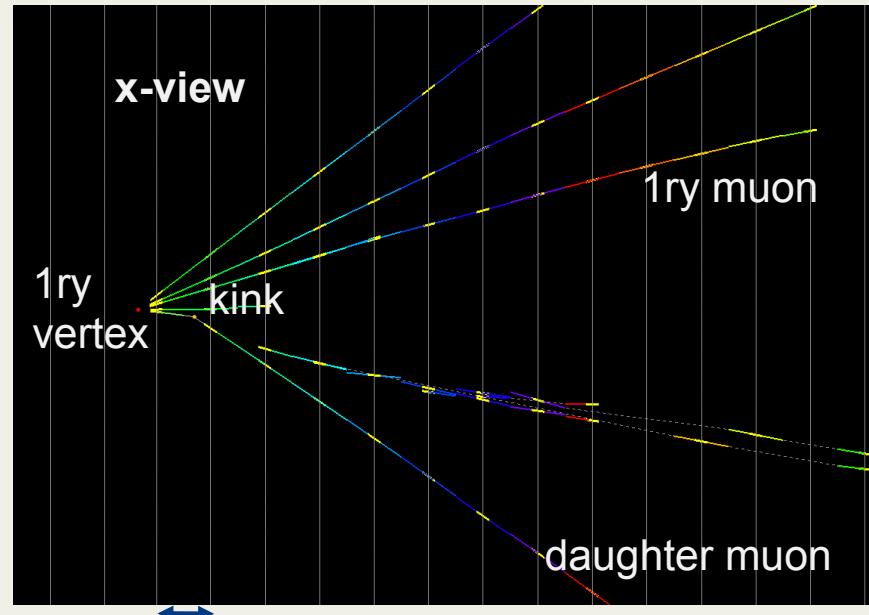
Angle between the charmed particle and the primary  $\mu$  in the transverse plane



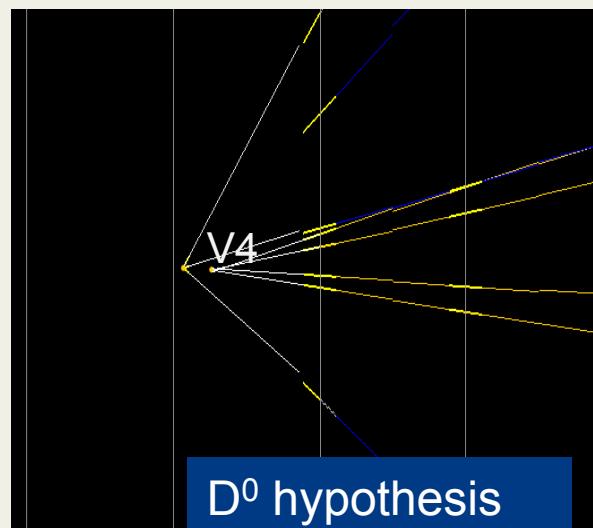
Decay length of charmed particles



# Charm Candidate



FL: 1330 microns  
kink angle: 209 mrad  
IP : 262 microns  
daughter muon: 2.2 GeV/c  
Pt: 0.46 GeV/c



FL: 313.1 mm,  
 $\phi : 173.2^\circ$ ,  
invariant mass: 1.7 GeV

# Background summary

- Production and decay of charmed particles
- Hadrons re-interactions
- Large angle Muons Scattering

Decay channel	Number of background events for:							
	$22.5 \times 10^{19}$ p.o.t.				Analysed sample			
	Charm	Hadron	Muon	Total	Charm	Hadron	Muon	Total
$\tau \rightarrow \mu$	0.025	0.00	0.07	0.09±0.04	0.00	0.00	0.02	0.02±0.01
$\tau \rightarrow e$	0.22	0	0	0.22±0.05	0.05	0	0	0.05±0.01
$\tau \rightarrow h$	0.14	0.11	0	0.24±0.06	0.03	0.02	0	0.05±0.01
$\tau \rightarrow 3h$	0.18	0	0	0.18±0.04	0.04	0	0	0.04±0.01
<b>Total</b>	<b>0.55</b>	<b>0.11</b>	<b>0.07</b>	<b>0.73±0.15</b>	<b>0.12</b>	<b>0.02</b>	<b>0.02</b>	<b>0.16±0.03</b>

# Expected OPERA signal

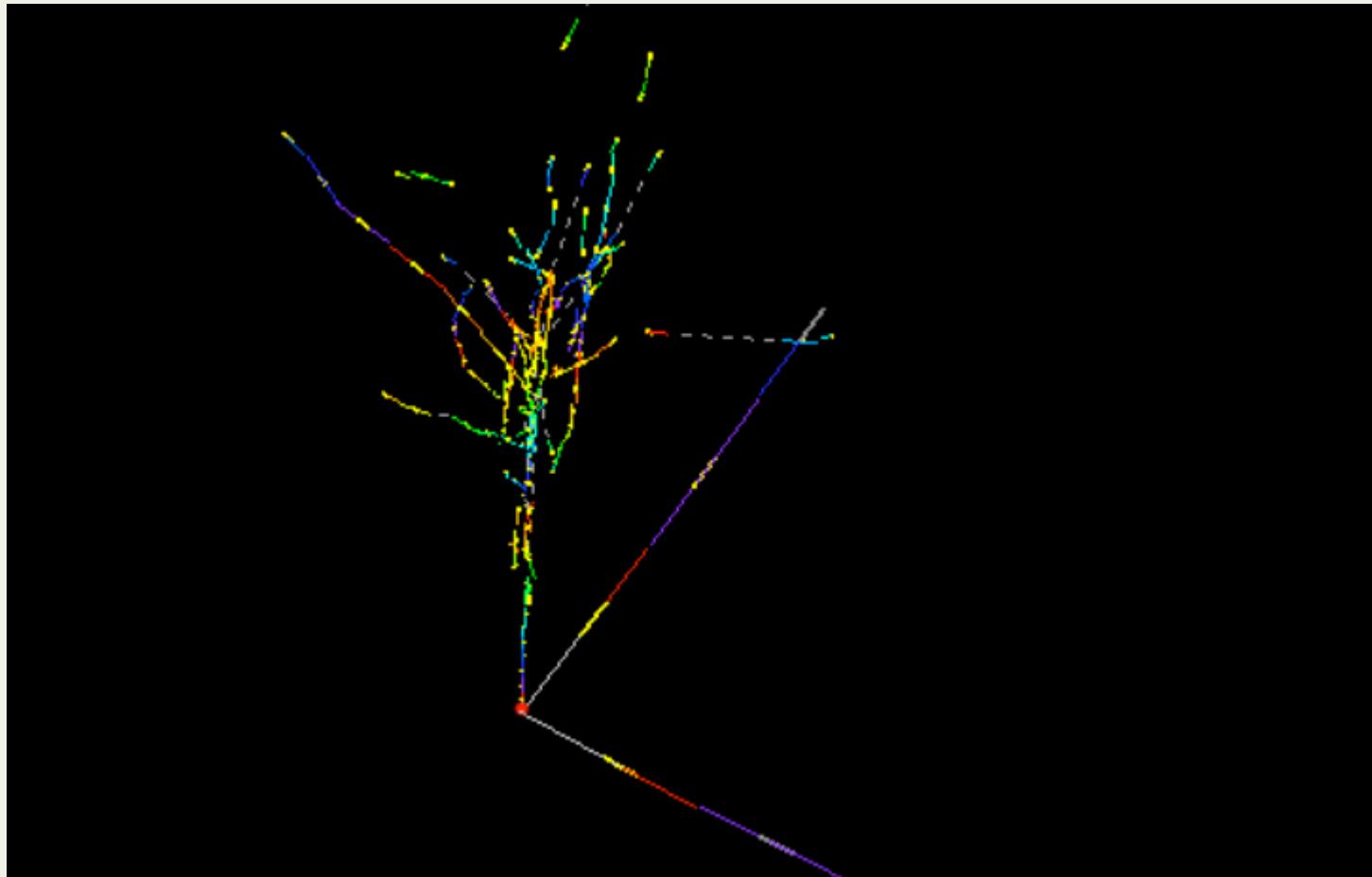
- In the analyzed sample (92% of '08+09' data) one  $\nu_\tau$  observed in the  $\tau \rightarrow h$  channel compatible with the expectation of 1.65 signal events\*.

Decay channel	Number of signal events expected for $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$	
	$22.5 \times 10^{19} \text{ p.o.t.}$	Analysed sample
$\tau \rightarrow \mu$	1.79	0.39
$\tau \rightarrow e$	2.89	0.63
$\tau \rightarrow h$	2.25	0.49
$\tau \rightarrow 3h$	0.71	0.15
<b>Total</b>	<b>7.63</b>	<b>1.65</b>

(\*) N.Agafonova et al., "Search for  $\nu_\mu \rightarrow \nu_\tau$  oscillation with the OPERA experiment in the CNGS beam "; to be published in NJP

# $\nu_e$ events

- Developed the dedicated strategy for  $\nu_e$  search to increase the detection efficiency



# Conclusion

- Analysis of 2010-2011 data is going on and expect to release new results in 3-4 months.
- 2738 events ( $4.88 \times 10^{19}$  p.o.t) searched for decays from 2008-2009 runs and one  $\nu_\tau$  is observed.
- The observation so far of a single  $\nu_\tau$  candidate event is compatible with the expectation of 1.65 signal events. The significance of the observation of one decay in the  $\tau \rightarrow h$  channel is 95%.
- $\nu_\mu - \nu_e$  oscillation analysis in progress, first results are in few months.

# OPERA Events

	Events Located	Decay search	Charm Candidates	$\nu_e$	$\nu_\tau$ candidates
Total	3765	3289	52	20	1

