

# Status of the OPERA experiment



$\nu_{\mu}CC$  event with  
charm production  
Candidate (Data)

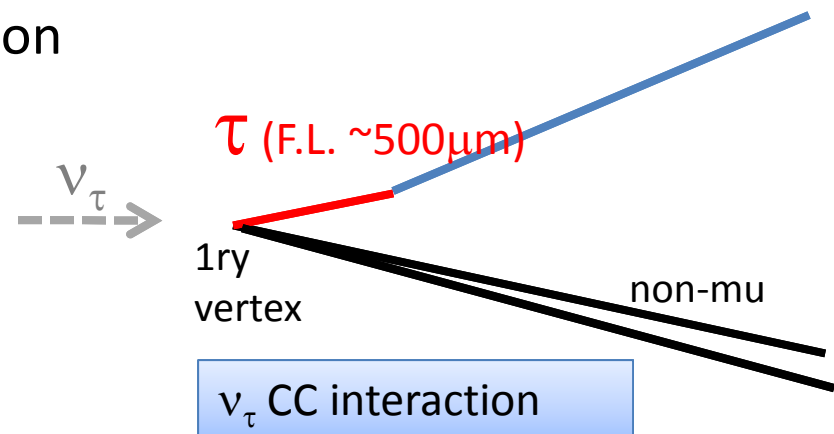
Akitaka Ariga

LHEP, University of Bern

on behalf of the OPERA collaboration

# OPERA experiment

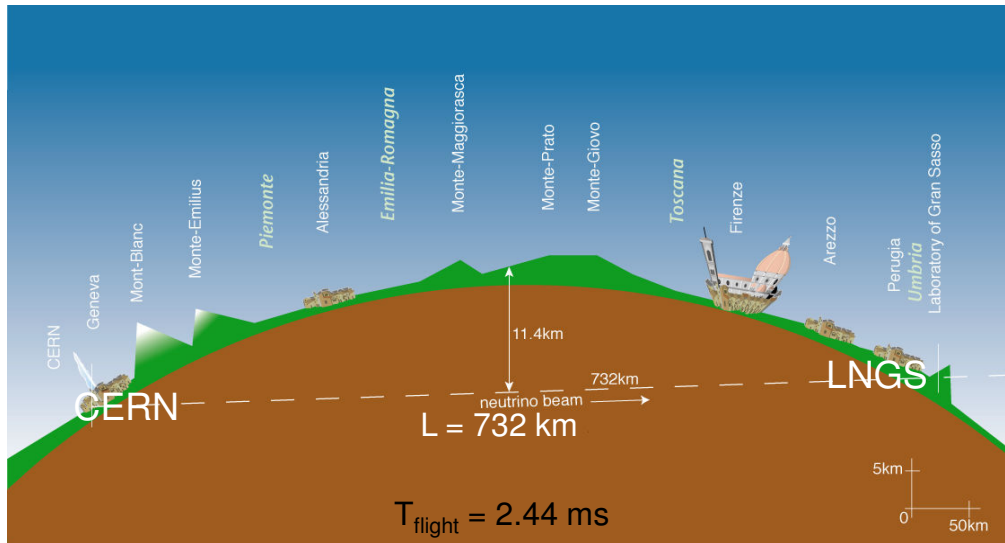
- Aiming to prove the Flavor-Mixing neutrino oscillation hypothesis by appearance method.
  - Appearance of new flavor:  $\nu_\mu \rightarrow \nu_\tau$
  - Search in the region predicted by disappearance experiments (SK, K2K, MINOS).
- Direct observation of  $\nu_\tau$  events in Nuclear Emulsion detectors.
  - Only detector which can detect  $\nu_\tau$  (DONUT exp.).
  - Sub-micron position resolution
  - mrad angular resolution.
  - 1.25 kt of target mass



# CNGS beam



$\langle E_{\nu_\mu} \rangle$	17 GeV
L	730 km
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87%
$\bar{\nu}_\mu / \nu_\mu$	4%
$\nu_\tau$ prompt	negligible



Expected produced interactions ( $22.5 \times 10^{19}$ ):

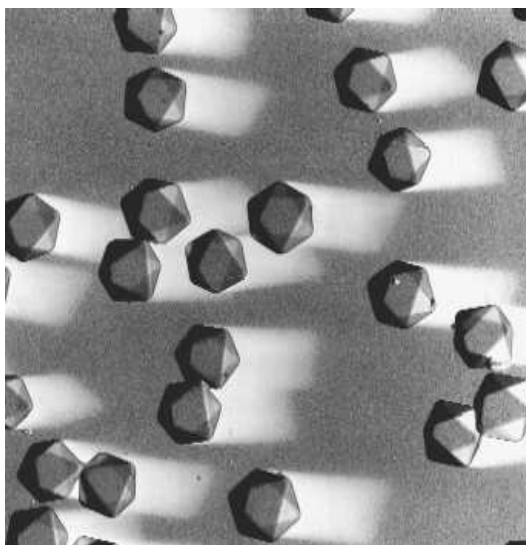
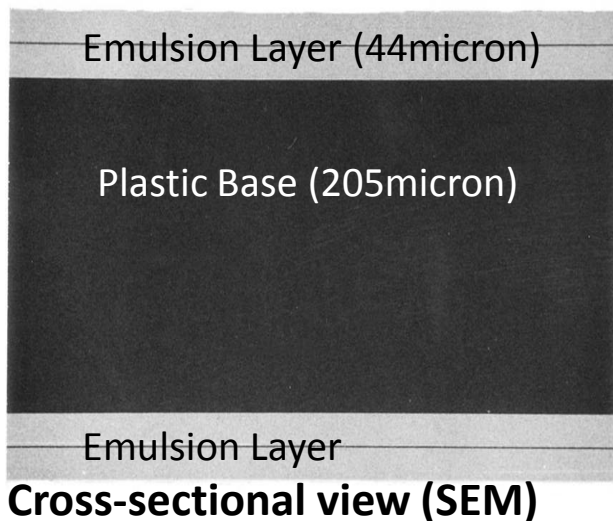
$$\sim 25400 \nu_\mu \text{ CC} + \text{NC}$$

$$\sim 170 \nu_e + \bar{\nu}_e \text{ CC}$$

$$\sim 125 \nu_\tau \text{ CC} (\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2)$$

$\sim 10$  tau decays are expected  
to be observed  
Less than 1 background  
after 5 years running

# Emulsion film by FUJI Film

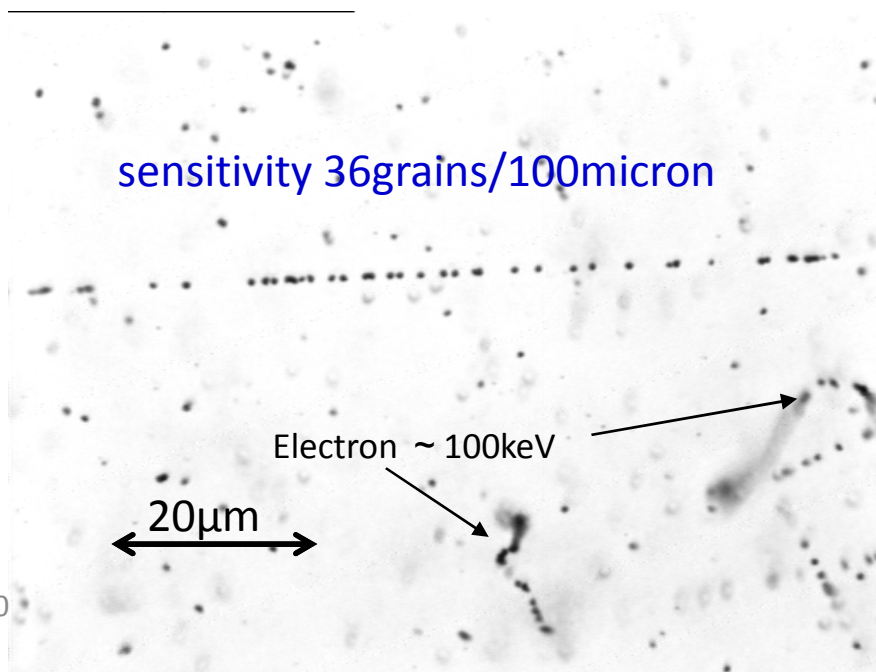


A minimal detector  
**AgBr Cristal,**

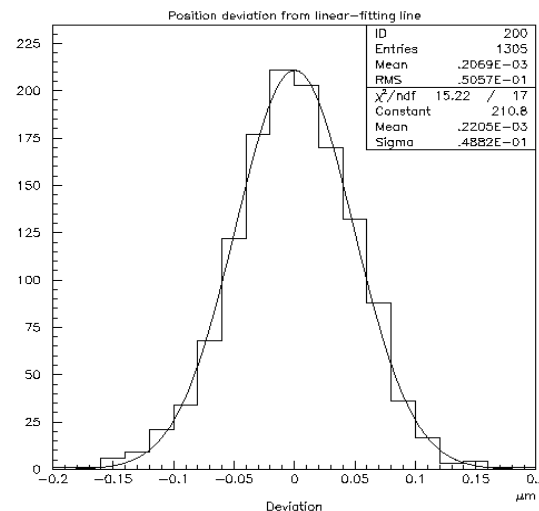
Size = 0.2micron

Detection efficiency  
 = 0.16/crystal

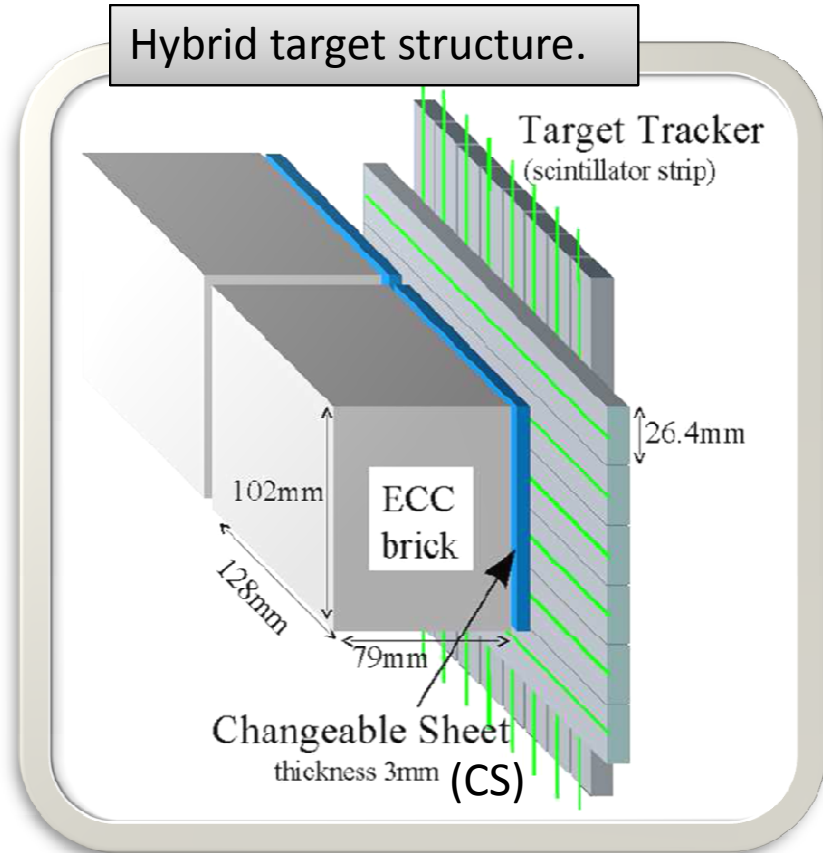
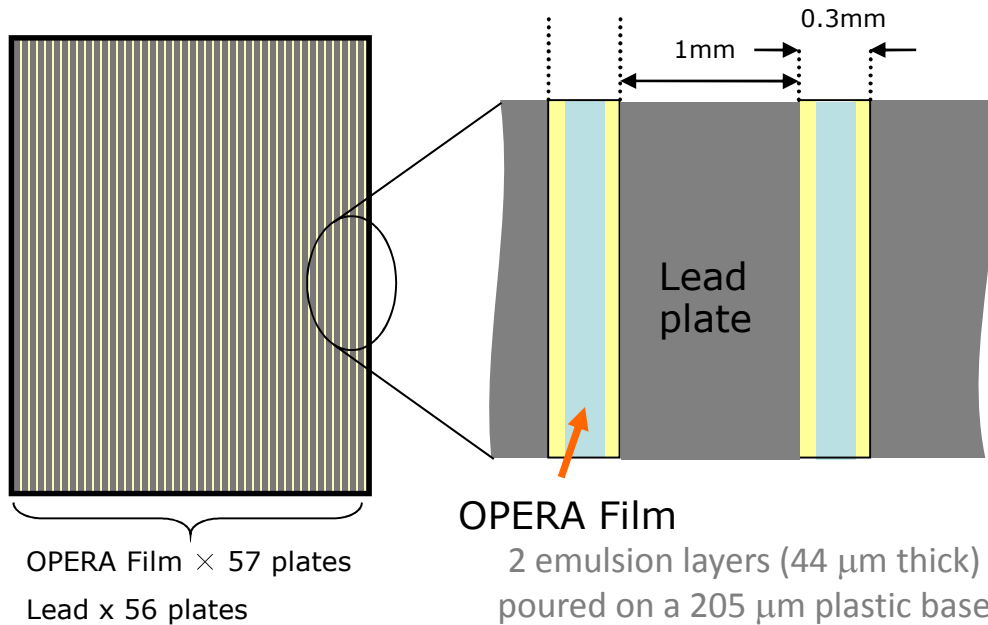
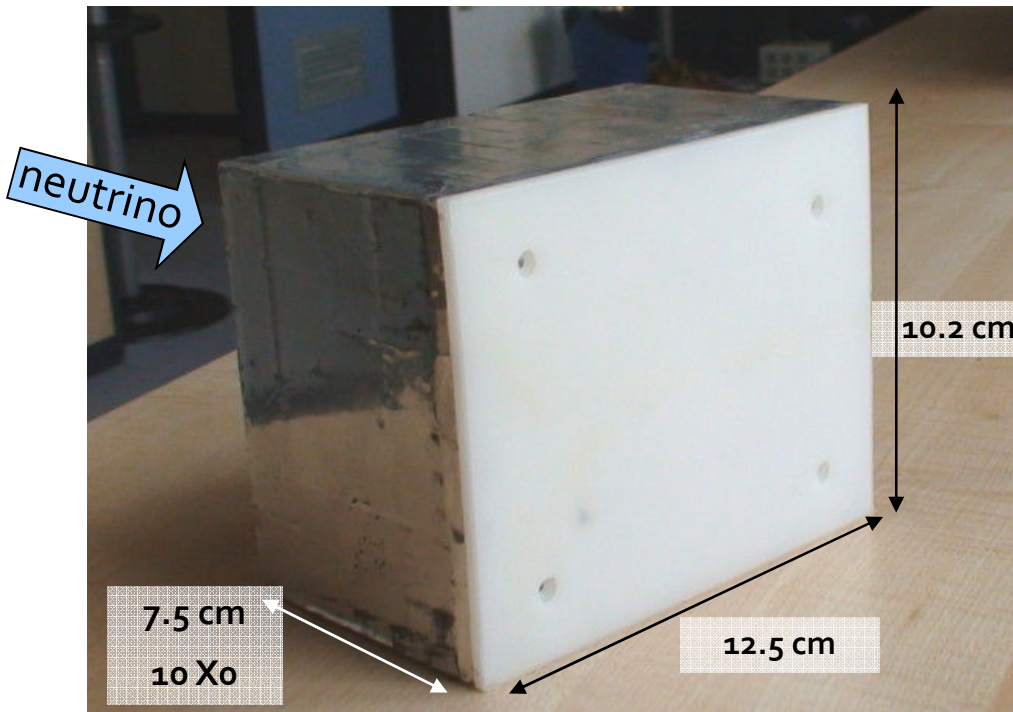
**10<sup>13</sup> channels in a film**



Intrinsic resolution 50nm  
 Deviation from linear-fit line. (2D)



# ECC brick

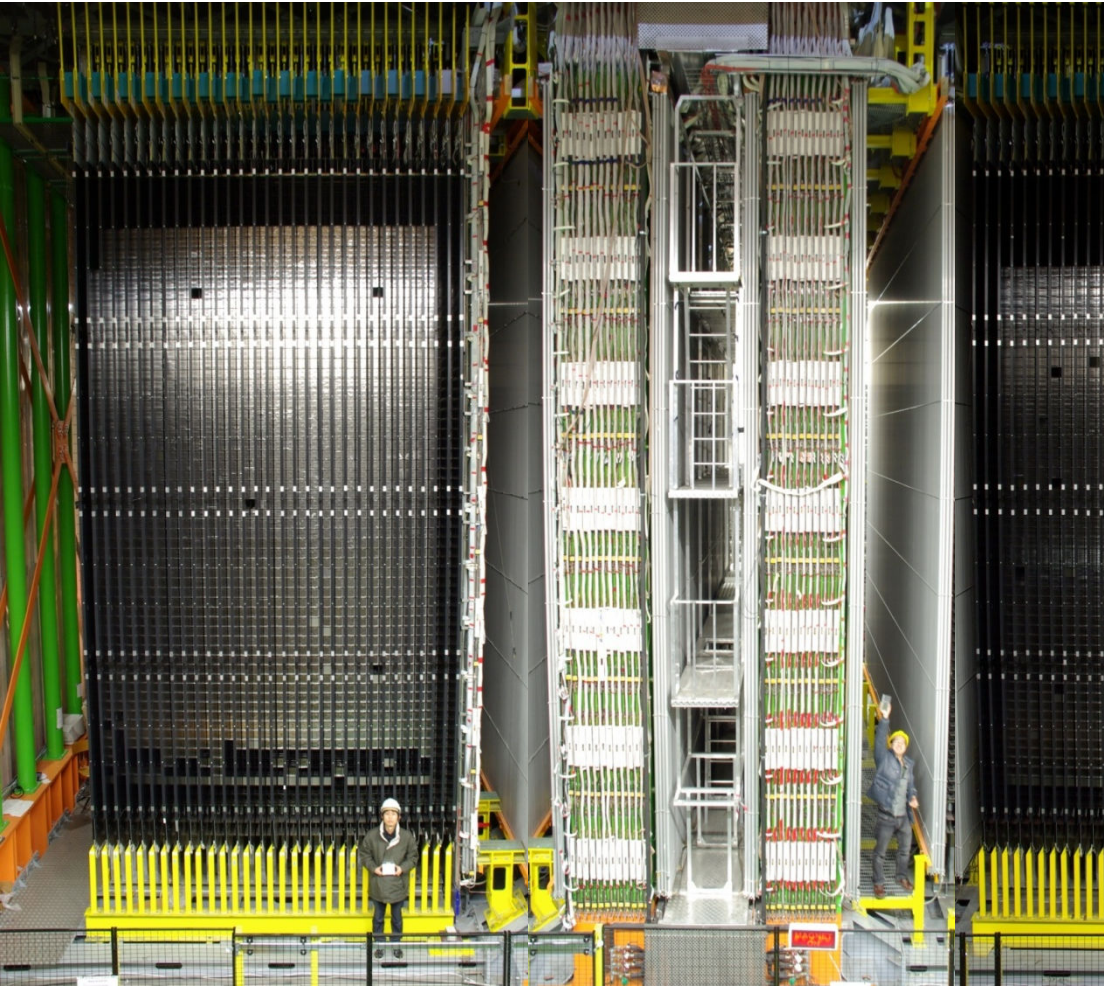


The OPERA target consists of about 150,000 bricks.  
Total target mass: 1.25 kton

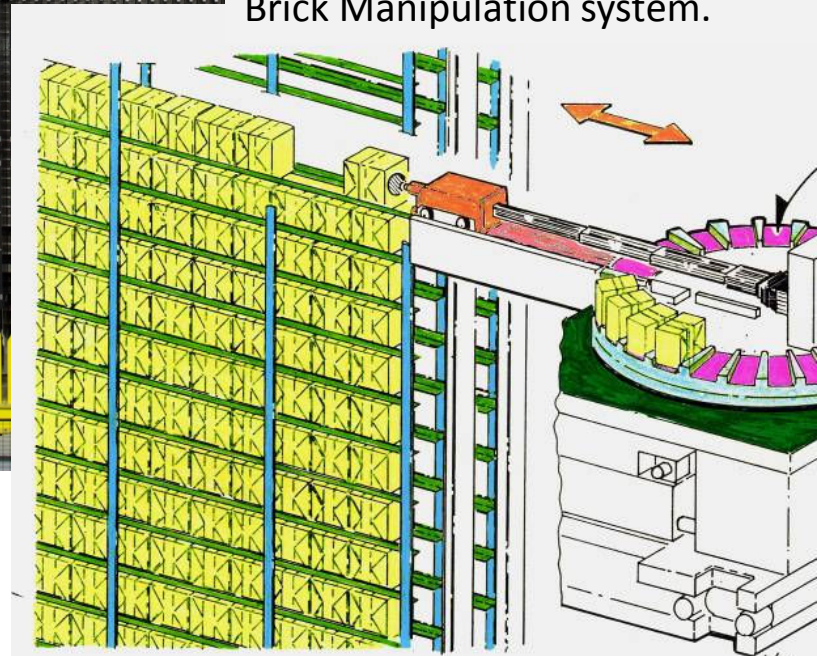
# OPERA detector

SM1

SM2



Brick Wall and Brick Manipulation system.



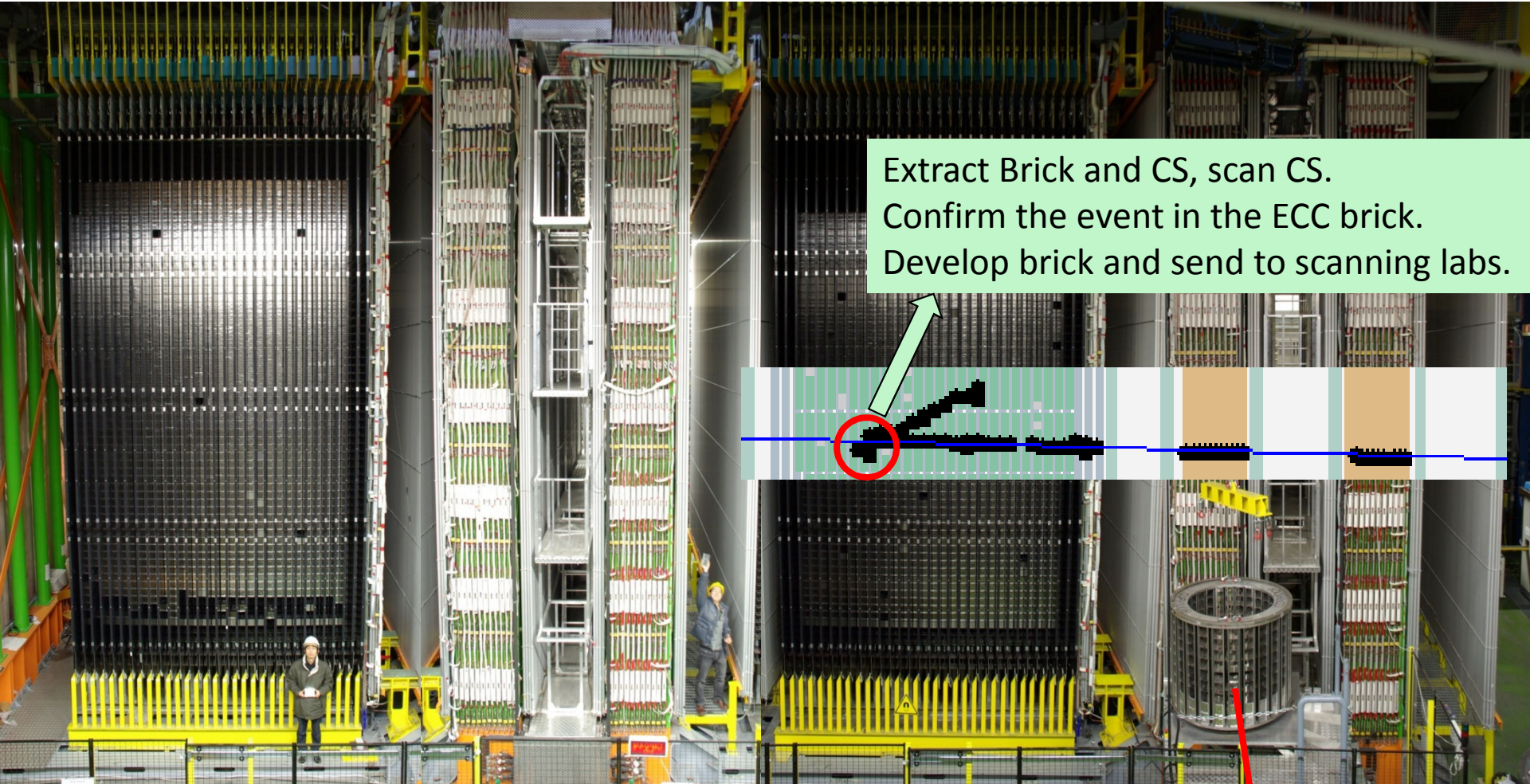
Target area  
(ECC + CS + TT)

Muon spectrometer  
(Magnet+RPC+PT)

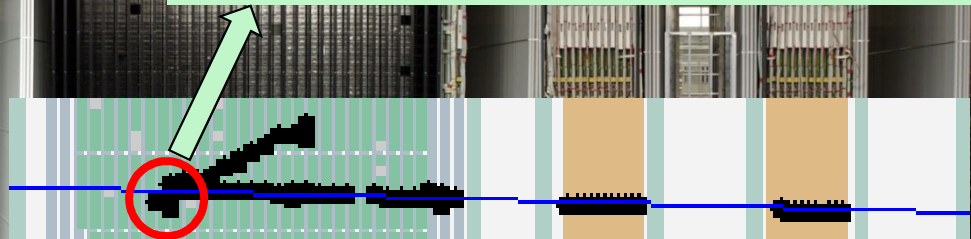
# OPERA detector

SM1

SM2



Extract Brick and CS, scan CS.  
Confirm the event in the ECC brick.  
Develop brick and send to scanning labs.

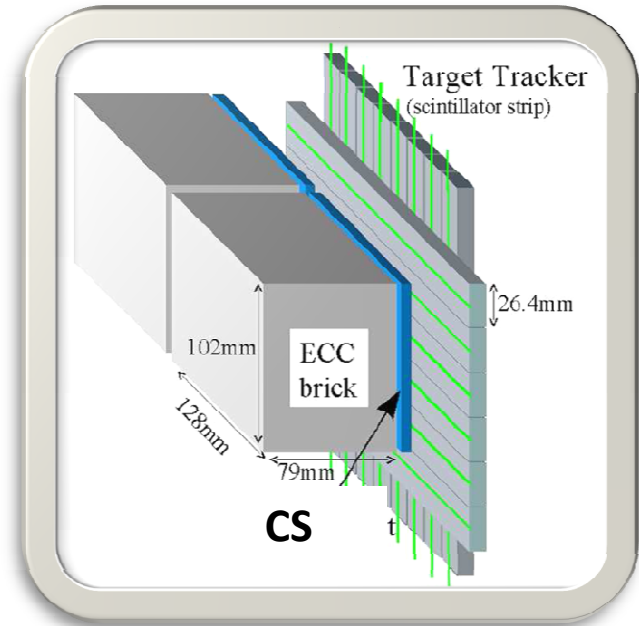
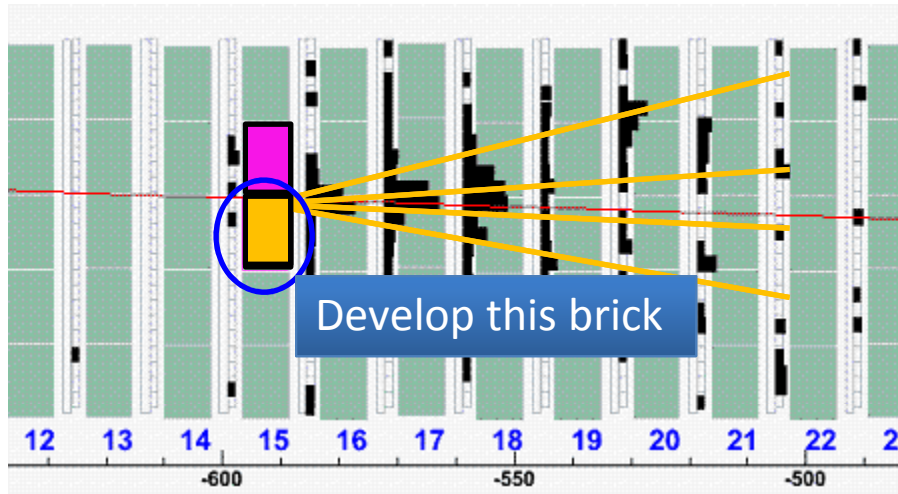


Target area  
(ECC + CS + TT)

Muon spectrometer  
(Magnet+RPC+PT)

Brick Manipulator System

# ECC validation by CS



- Select proper ECC brick which contains neutrino interactions.
  - Save analysis time
  - Minimize the loss of target mass

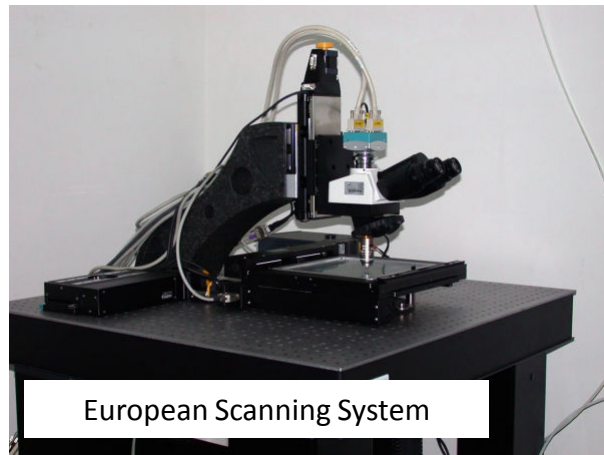


# CS Scanning Stations

LNGS (Italy)



Nagoya (Japan)



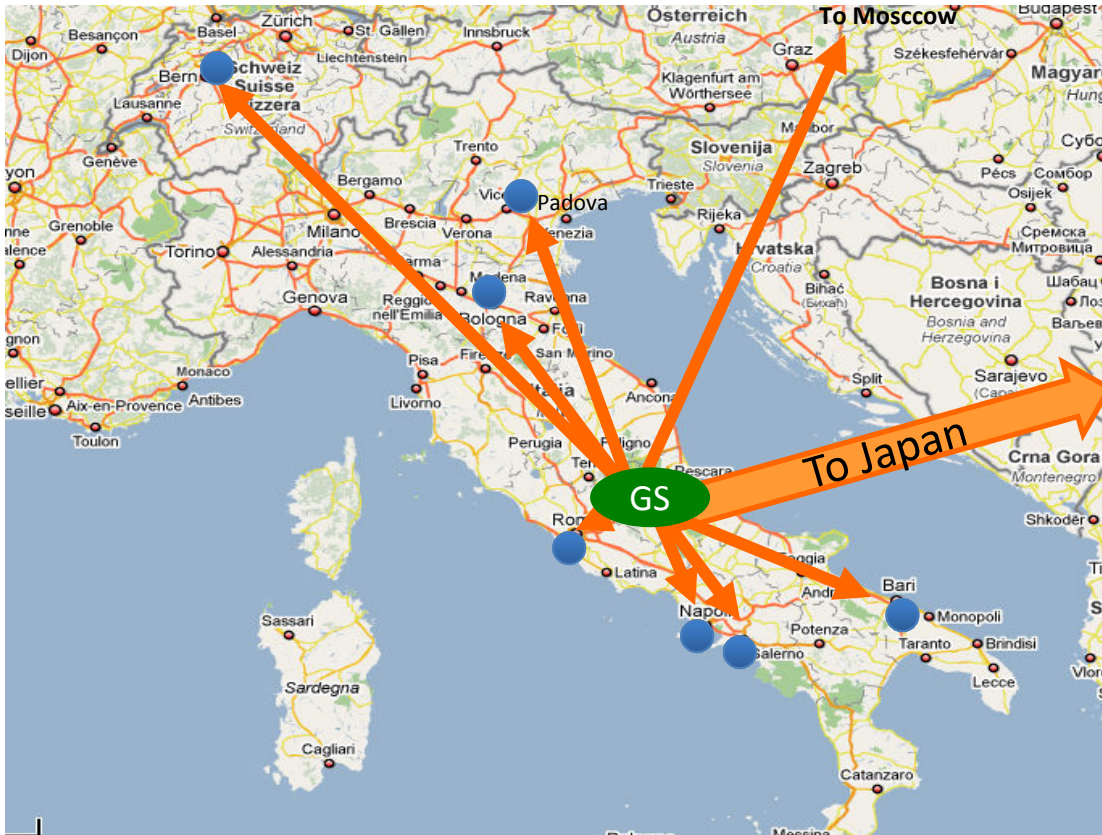
European Scanning System



Super-UltraTrackSelector

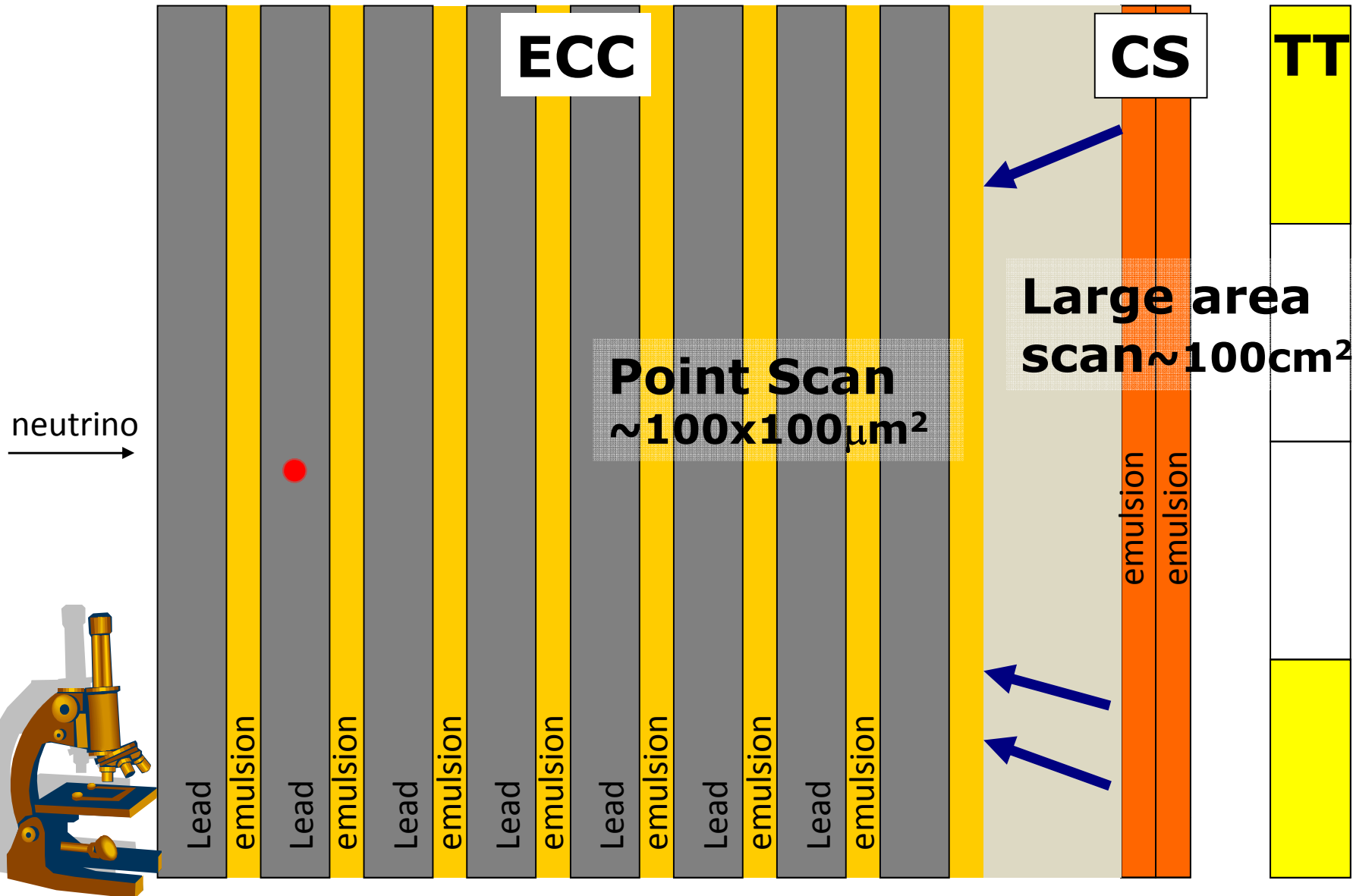
# Parallel analysis of ECC bricks

- Validated bricks are sent to the scanning labs.
  - 10 scanning labs share the scanning. (Increasing!)

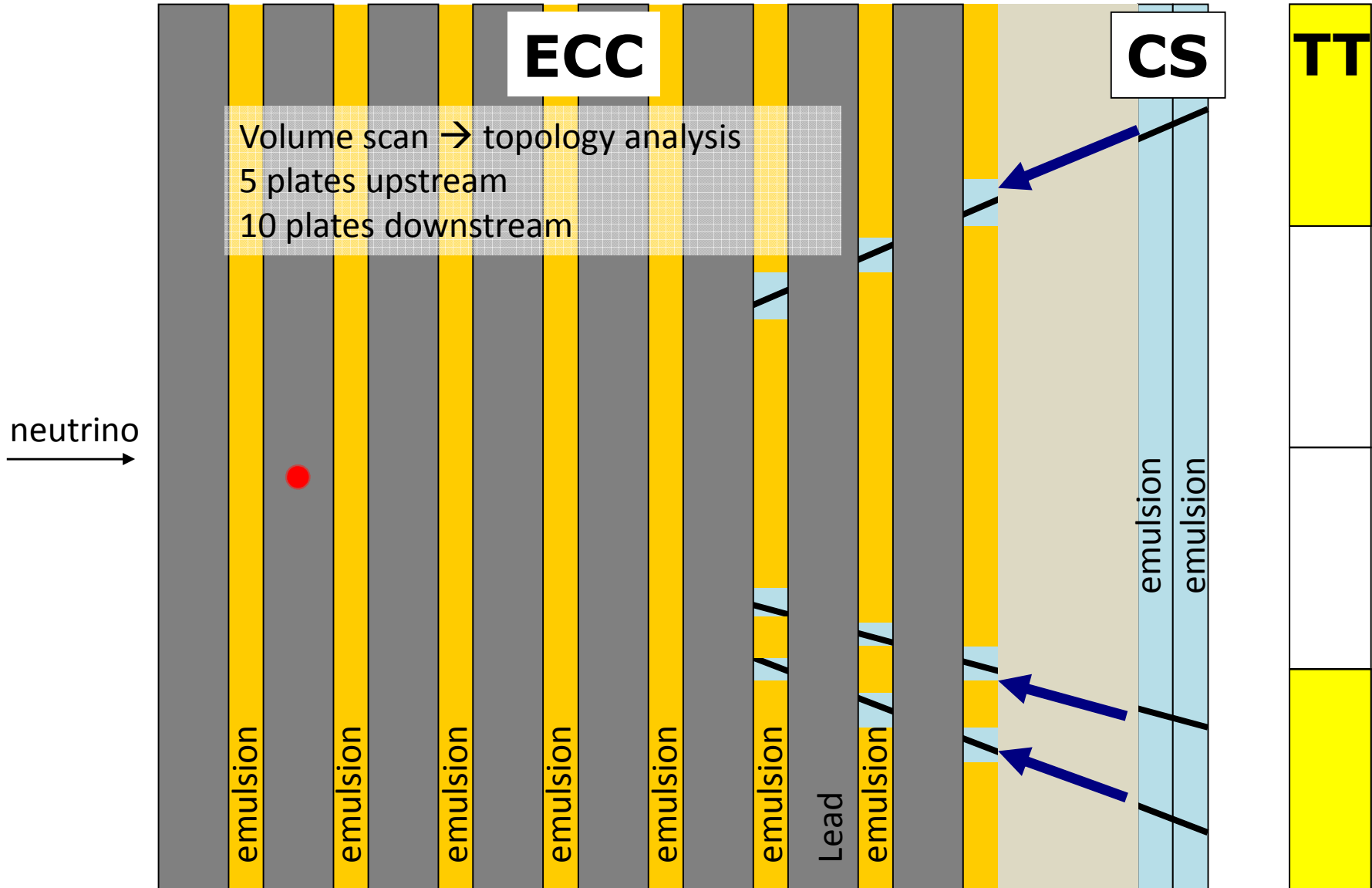


Scanning station  
in LHEP Bern

# Flow of Location – ECC Scanback –

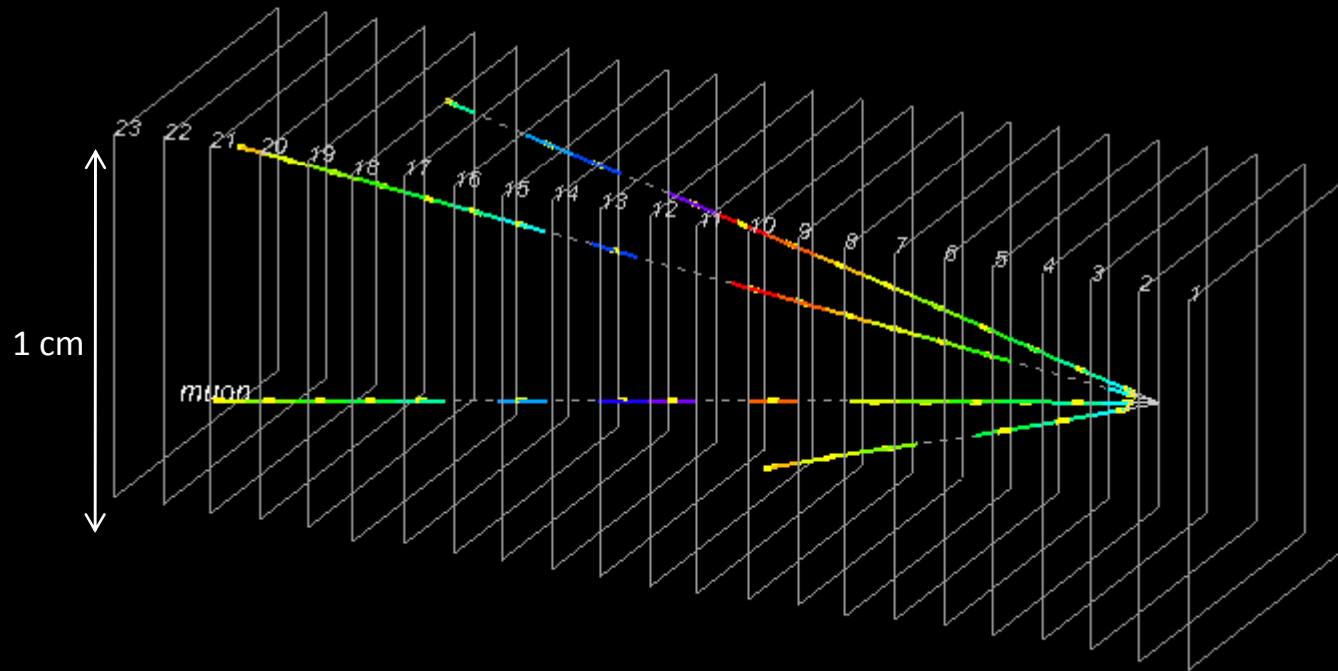


# Flow of Location – Volume Scan –



# Located neutrino interaction

Emulsion gives 3D vector data, giving a micrometric precision of the vertexing accuracy. (The frames correspond to scanning area. Yellow short lines → measured tracks. The other colored lines → interpolation or extrapolation. The colors indicate the Z-depth in the module.)

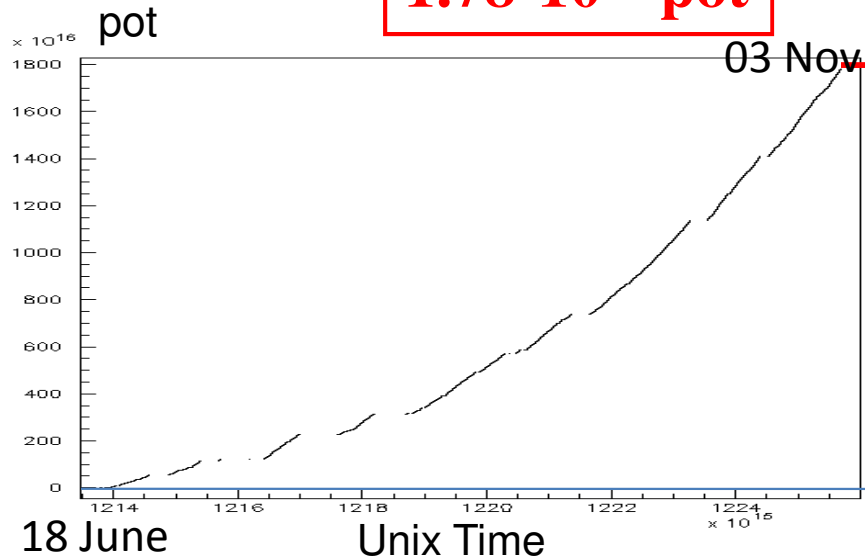


# Status and prospect of Data taking.

2006	$0.076 \times 10^{19}$ pot	0 int.	Commissioning
2007	$0.082 \times 10^{19}$ pot	38 int.	Commissioning
2008	<b><math>1.78 \times 10^{19}</math> pot</b>	<b>1598 int.</b>	<b>First physics run</b>
2009	<b><math>1.93 \times 10^{19}</math> pot up to now (Sep 6<sup>th</sup>)</b>	<b>2036 int.</b>	<b>Extrapolation is <math>3.5 \times 10^{19}</math> pot at end of the run. (~2 tau expected in total)</b>
Nominal	$4.5 \times 10^{19}$ pot x 5 year. total $22.5 \times 10^{19}$ pot		

2008

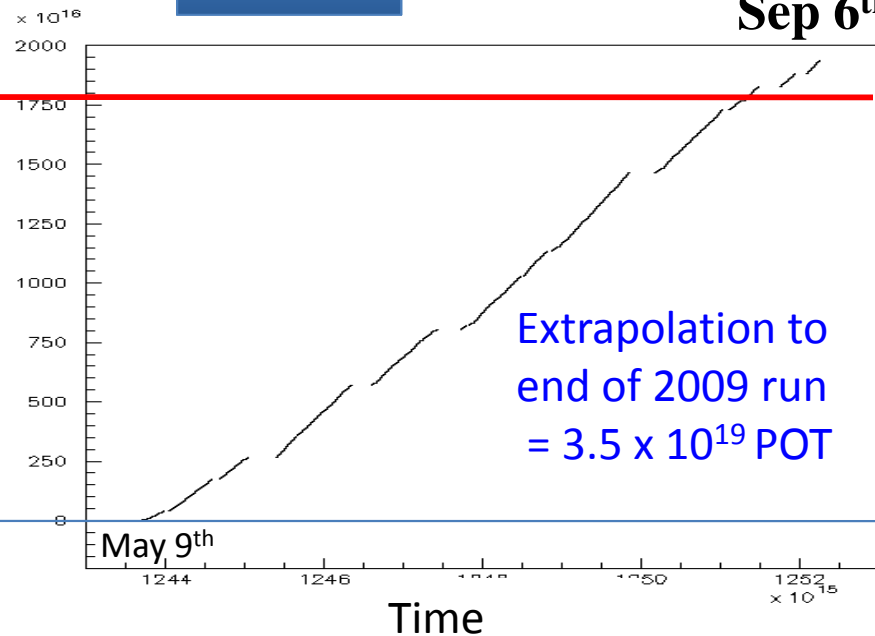
**$1.78 \cdot 10^{19}$  pot**



2009

**$1.93 \cdot 10^{19}$  pot**

**Sep 6<sup>th</sup>**



18 June

Unix Time

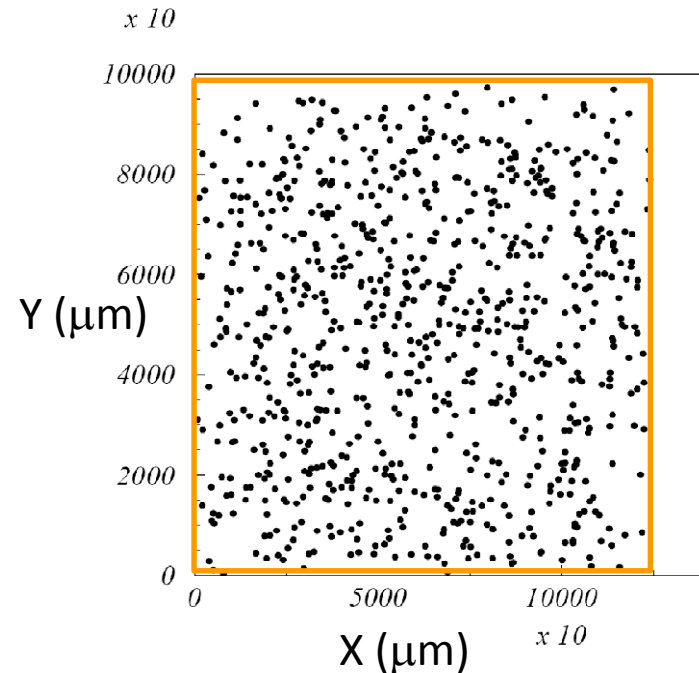
May 9<sup>th</sup>

Time

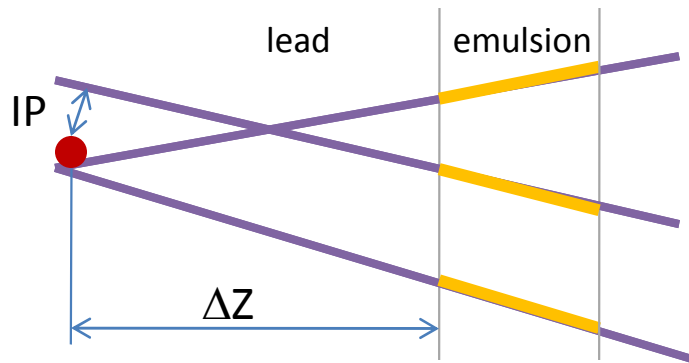
# Status of event location in ECC for 2008 run

	with muon	without muon	Total
Events in target	1242	356	<b>1598</b>
Bricks developed	993	249	1242
Vertices located in ECC	738	135	<b>873</b>
Vertices located in the dead material	16	6	22

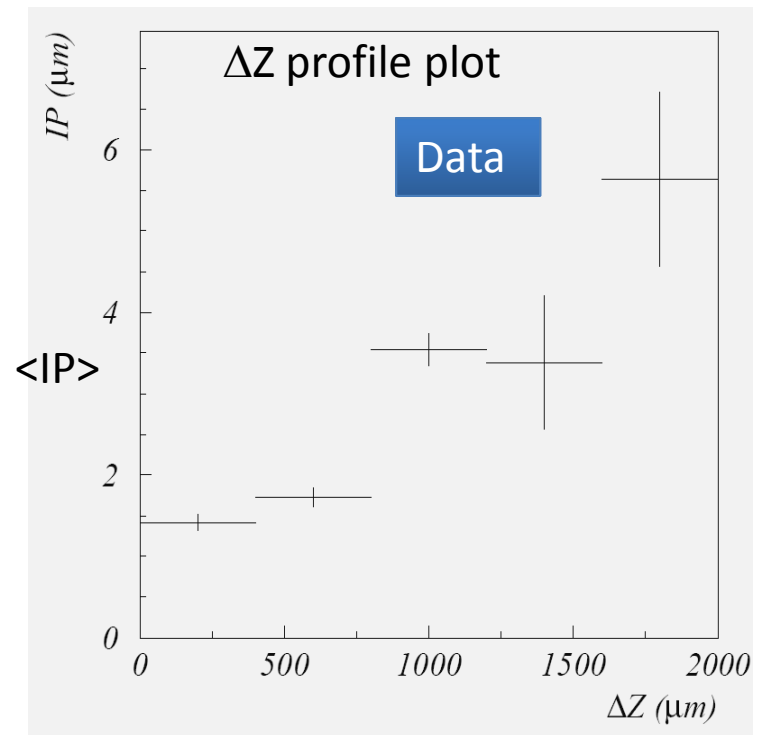
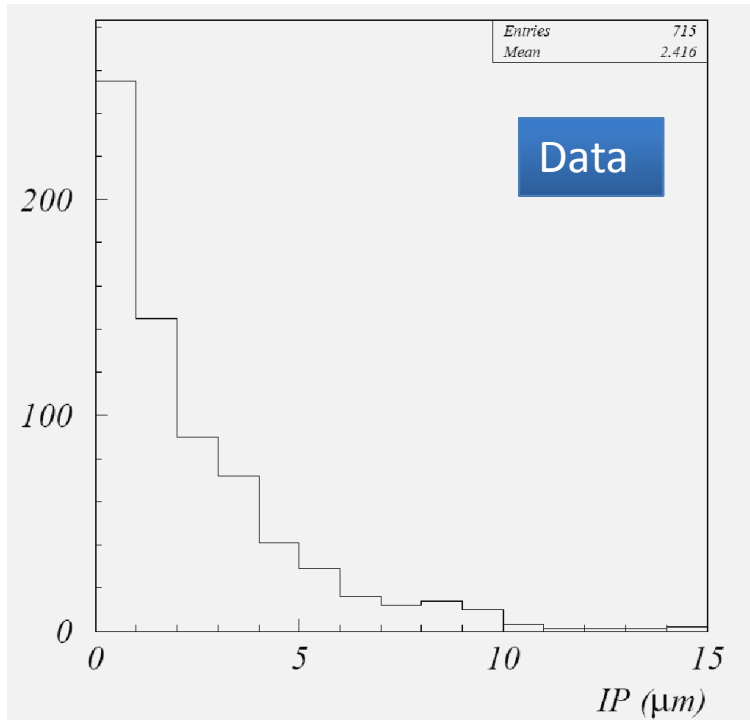
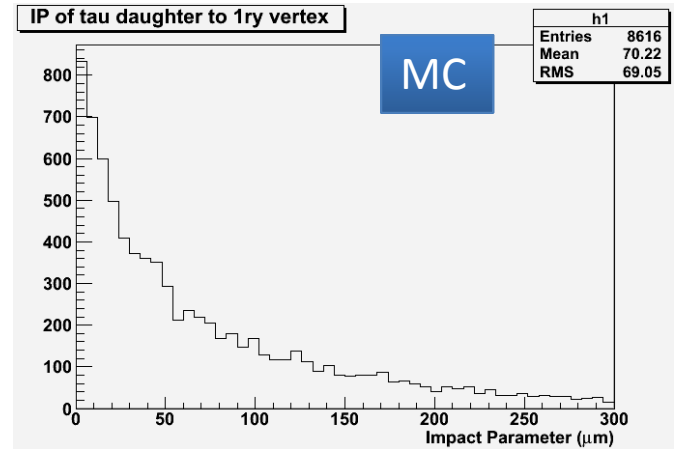
Scanning for 2008 run will be completed by September 2009.



# Impact parameters

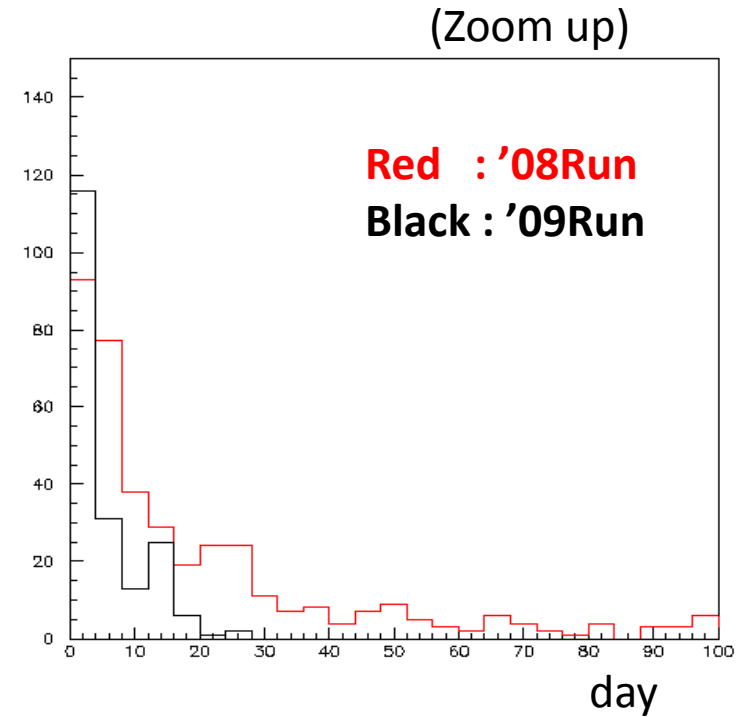
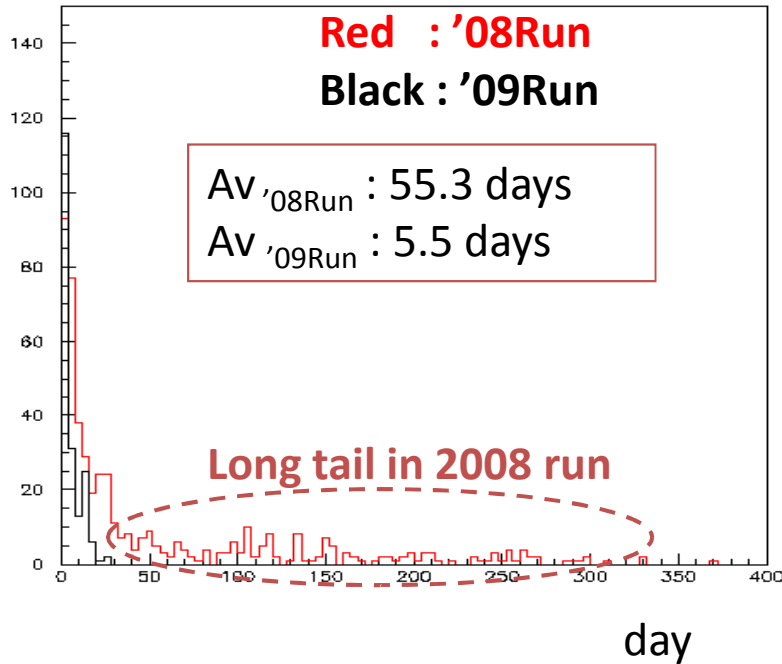
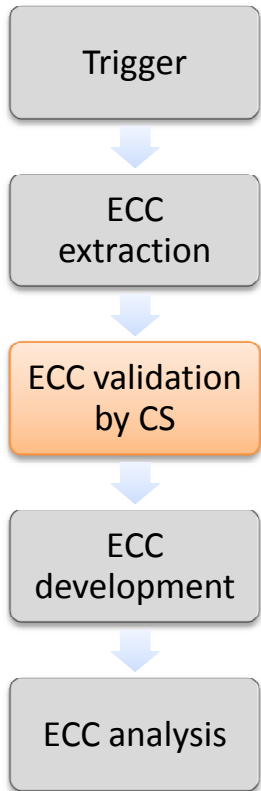


IP = Distance from the reconstructed vertex



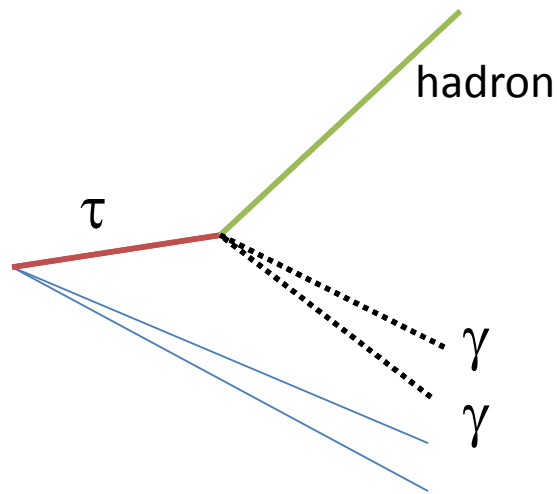


# Improvement of analysis speed in ECC validation by CS



Most of events in 2009 are processed with in a few days.

# Gamma detection and $\pi^0$ reconstruction



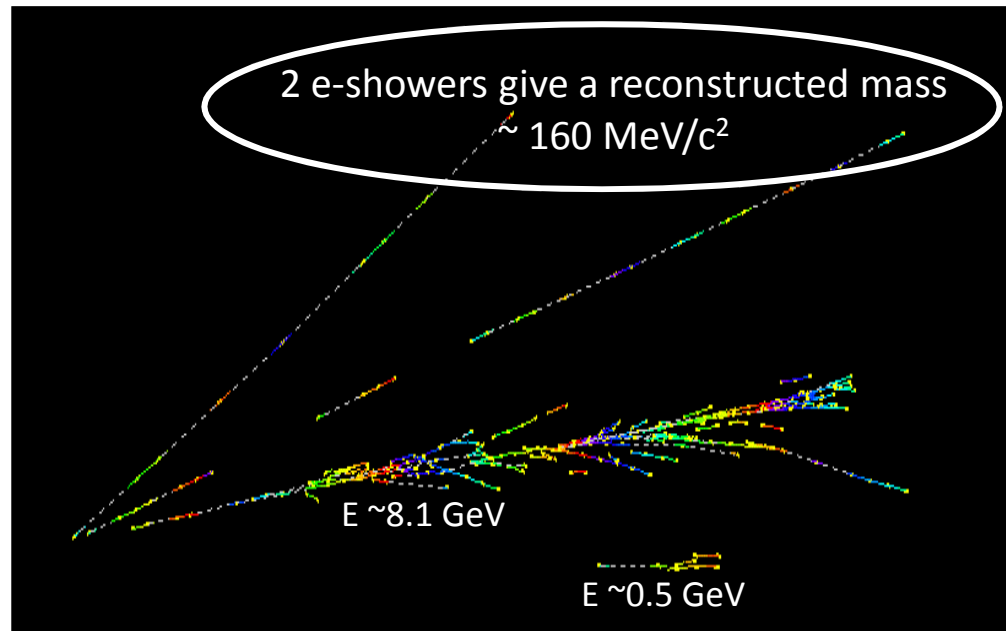
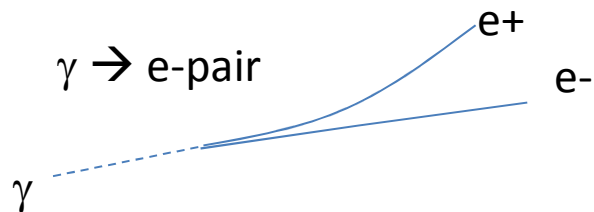
70% of 1-prong hadronic tau decays include one or more  $\pi^0$ . Important to detect gamma from tau decay to improve S/N.

Gamma detection

detection of shower

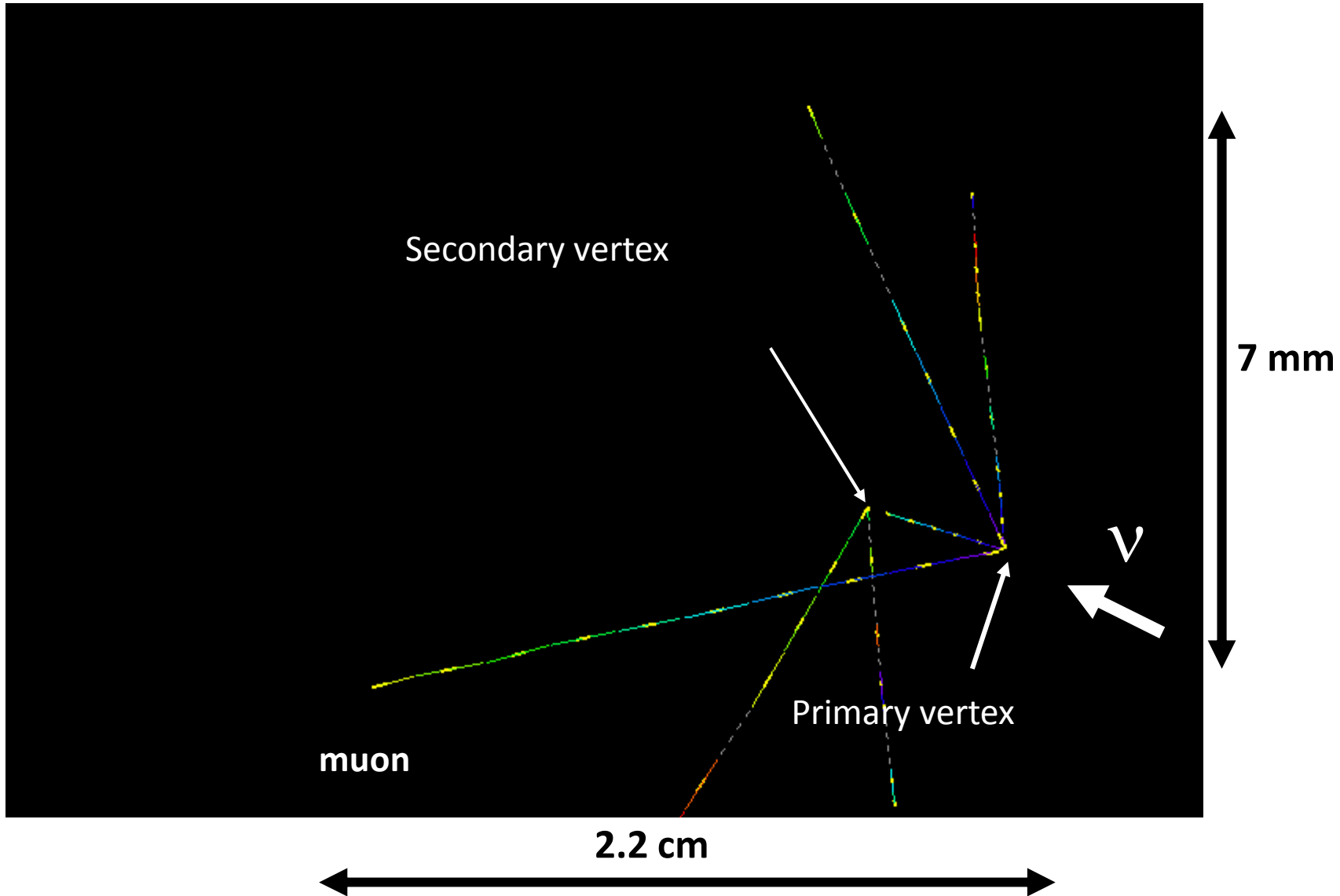
detection e-pair at start point

$\pi^0$  reconstruction is in progress.

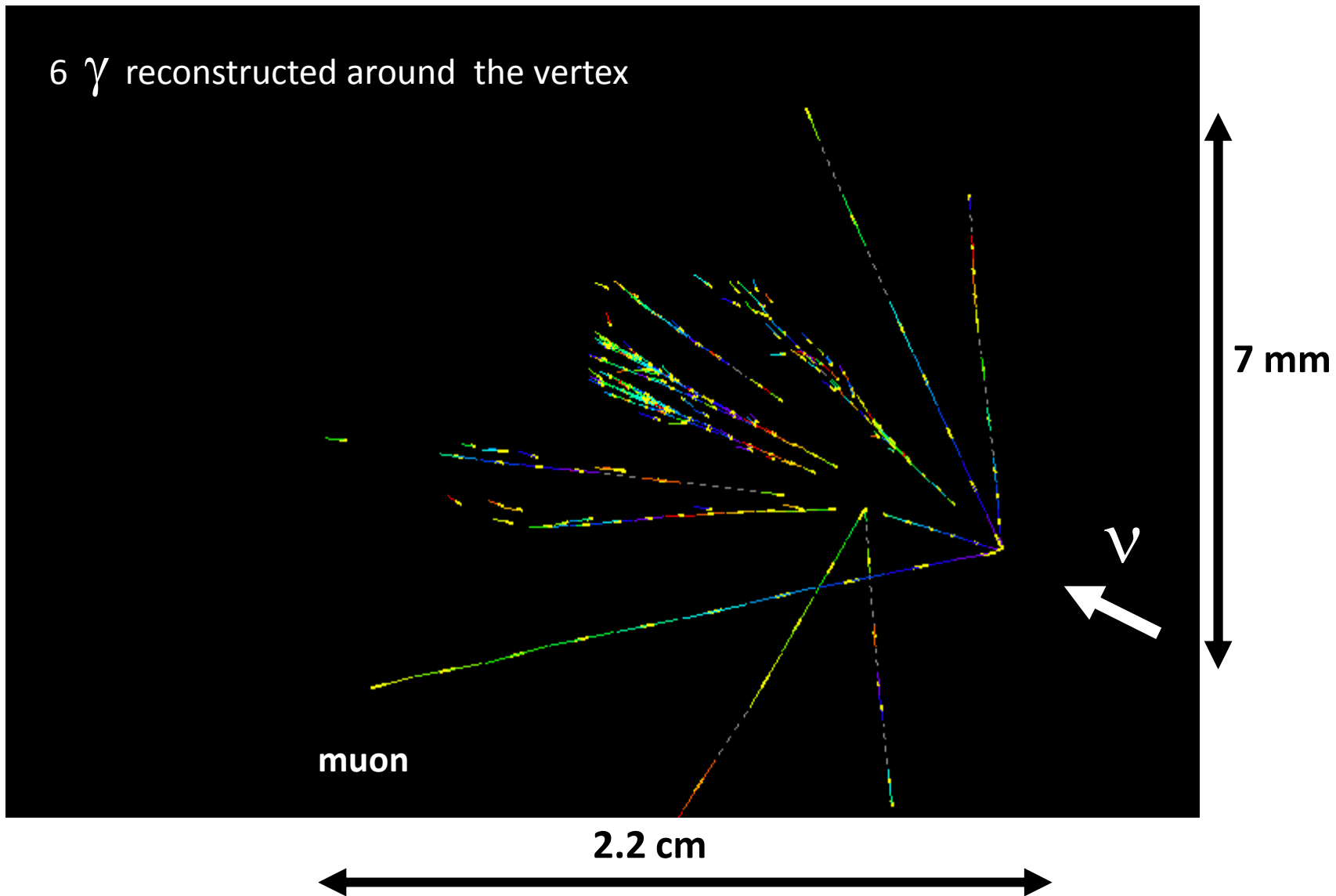


# *Example of Gamma to vertex attachment*

- $\nu_{\mu}$  CC interaction with hadronic re-interaction



# *Example of Gamma to vertex attachment*



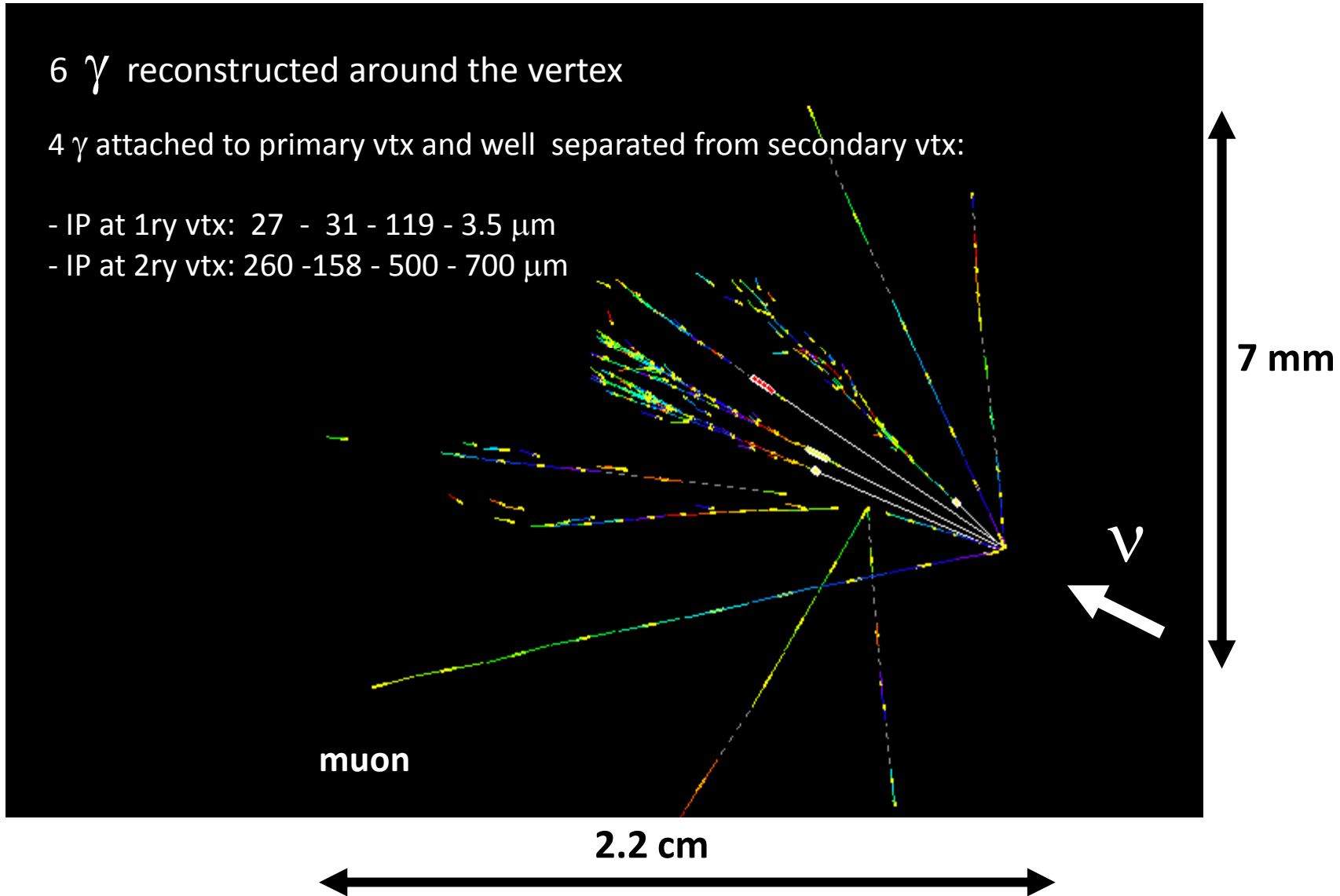
# *Example of Gamma to vertex attachment*

6  $\gamma$  reconstructed around the vertex

4  $\gamma$  attached to primary vtx and well separated from secondary vtx:

- IP at 1ry vtx: 27 - 31 - 119 - 3.5  $\mu\text{m}$

- IP at 2ry vtx: 260 - 158 - 500 - 700  $\mu\text{m}$



# Example of Gamma to vertex attachment

6  $\gamma$  reconstructed around the vertex

2  $\gamma$  attached to secondary vtx and well separated from primary vtx:

- IP at 2ry vtx: 8 - 10  $\mu\text{m}$

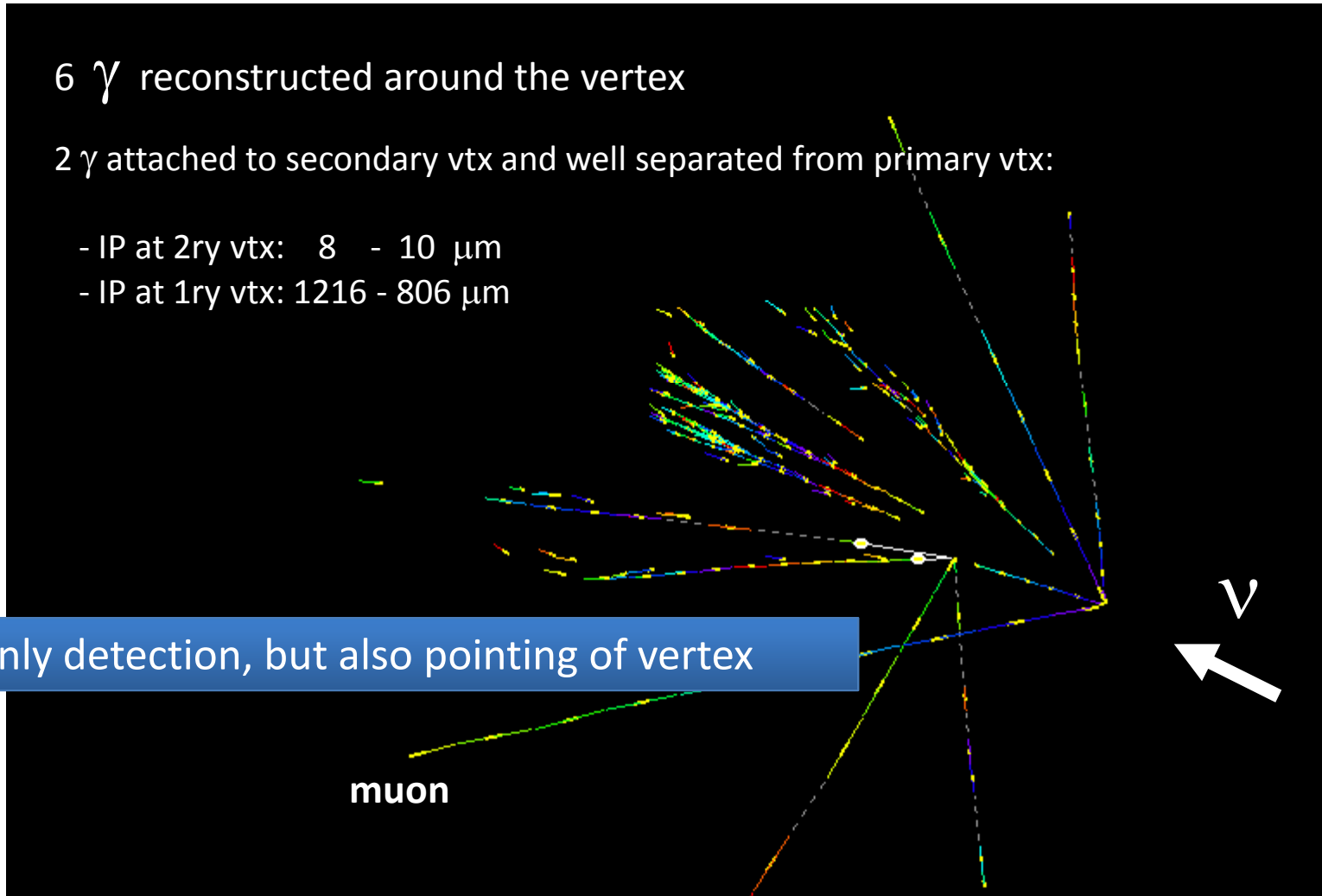
- IP at 1ry vtx: 1216 - 806  $\mu\text{m}$

Not only detection, but also pointing of vertex

muon

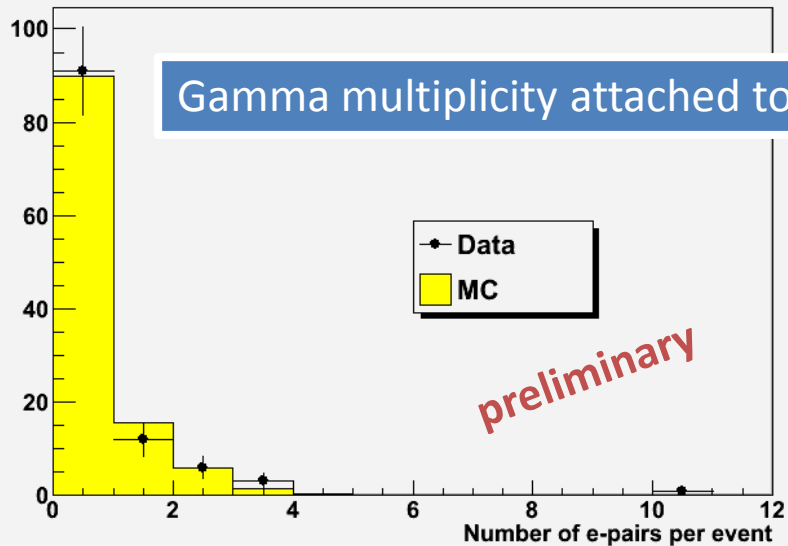
7 mm

2.2 cm

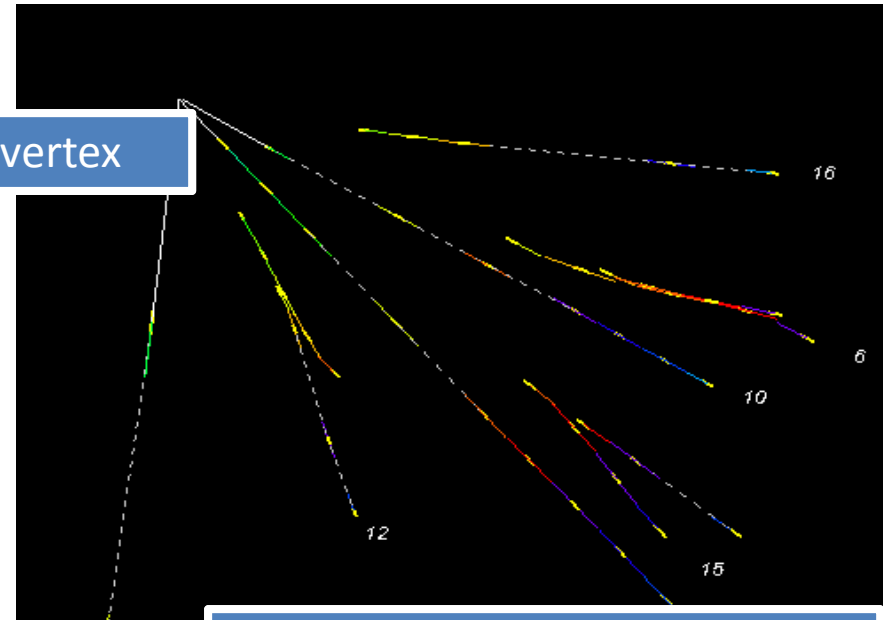
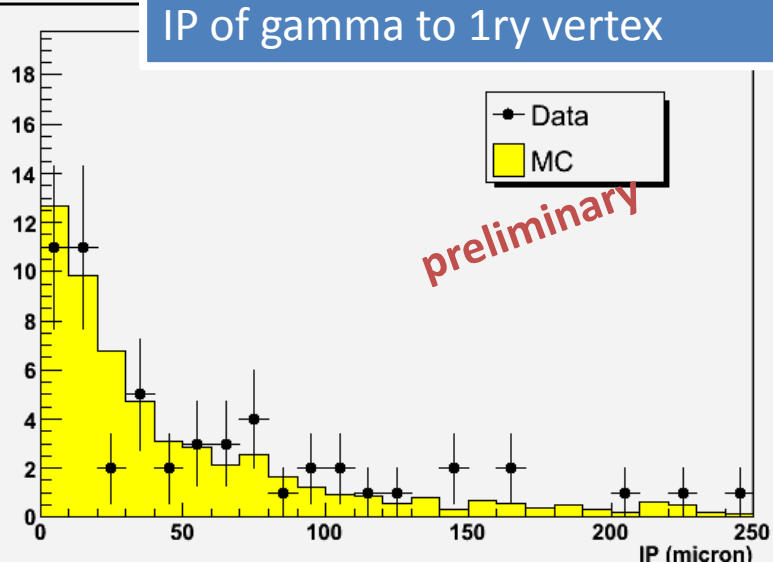


# Gamma study and MC/data comparison

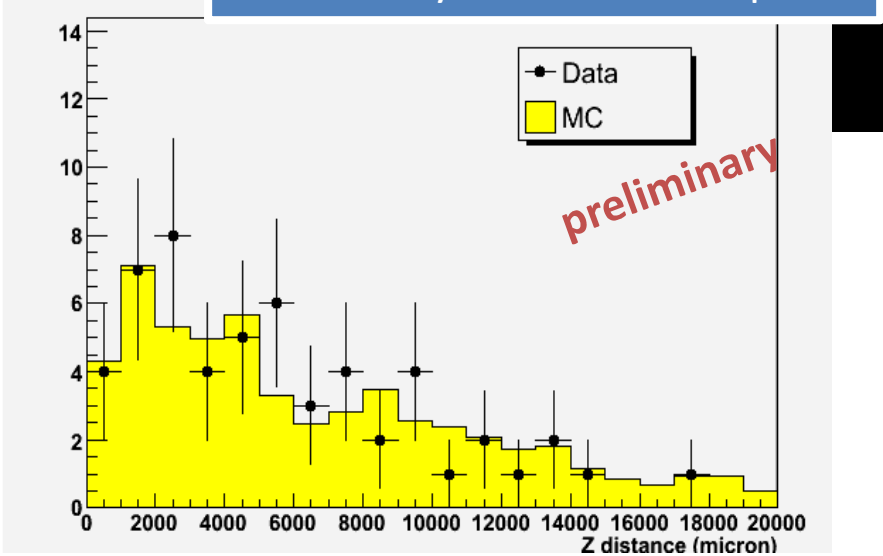
Gamma multiplicity (CC-like events, MC: pdg11)



IP distribution

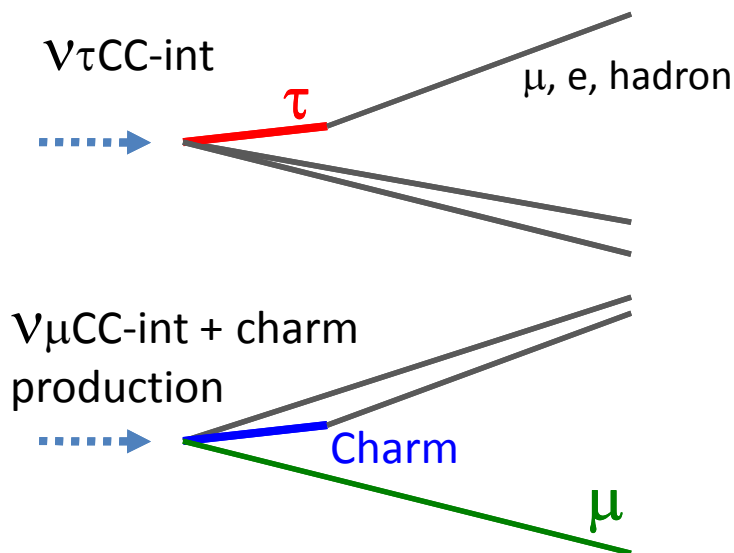


dZ from 1ry vertex to start point



# Analysis for located events

- 2008 run
  - Nu-tau detection
    - 0.7 event observation is expected
    - Background 0.05 event.
  - Check nu-tau detection efficiency by detecting charmed particles (similar life time and mass with tau)
    - Charm particles are produced in nu-mu CC interactions (~4.5%)

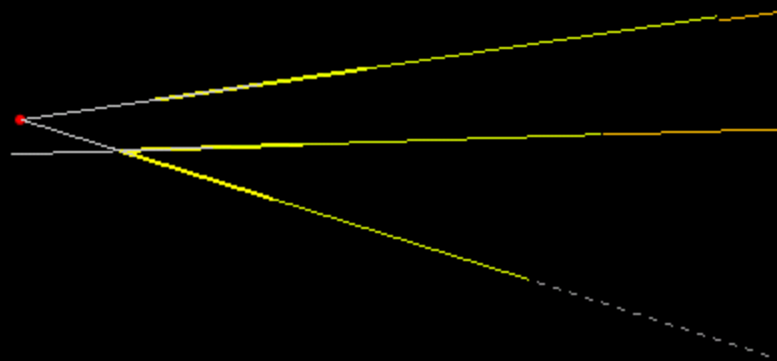
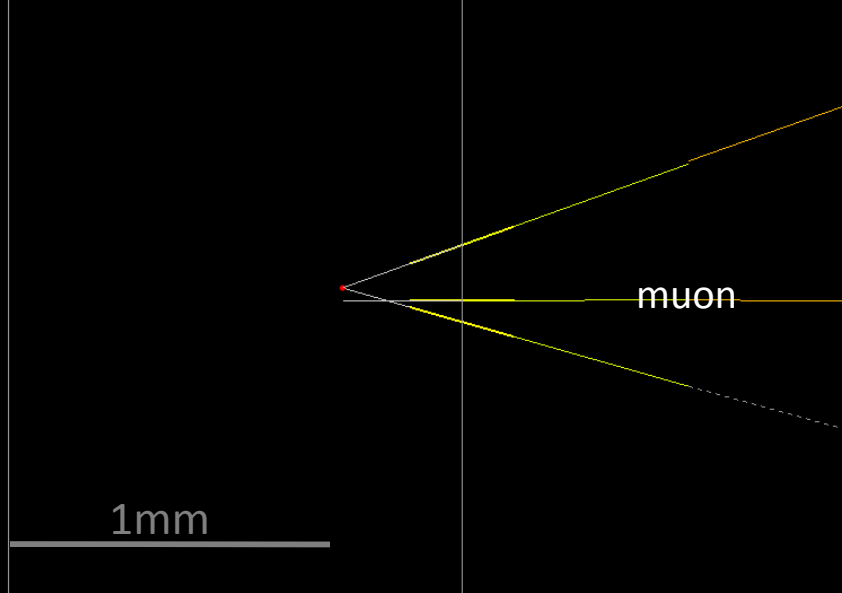
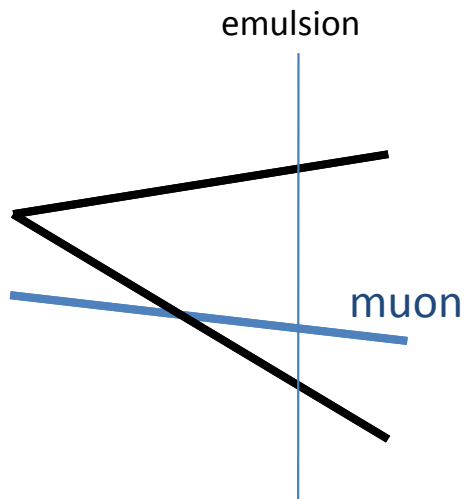


Particle	Mass (MeV/c <sup>2</sup> )	Life time (10 <sup>-15</sup> s)	cτ (micron)
$\tau$	1776.9	291	87.1
$D^+$	1869.3	1040	311.8
$D_s^+$	1968.2	500	149.9
$\Lambda_c^+$	2286.5	200	59.9



# Example of Detected Topologies 1.

A Muon is isolated from the vertex.

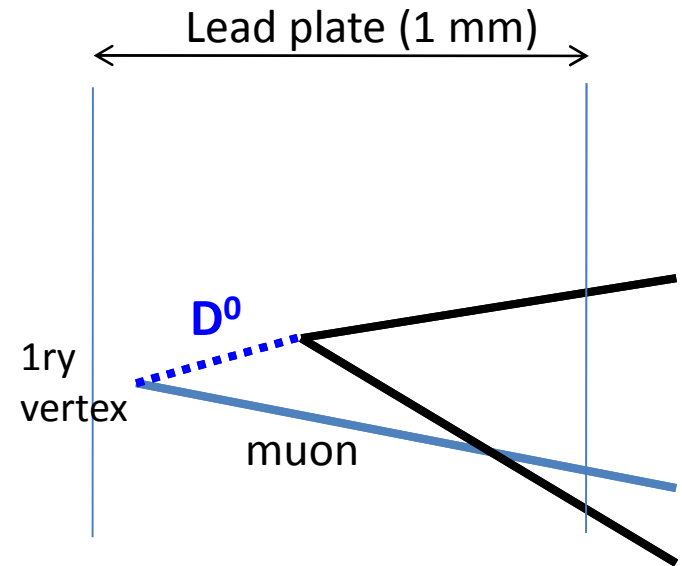


	IP w.r.t. muon (micron)	IP w.r.t. decay point (micron)	Momentum (GeV/c)
Daughter1	37.0	0.5	1.3
Daughter2	13.5	0.4	2.3

(animation)

Yellow short line is data. Lines with other color are extension.

## Hypothesis (1) $D^0$ candidate



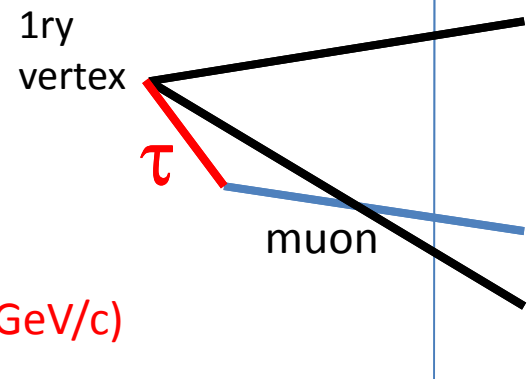
## Hypothesis (2) $\tau$ candidate?

minimum kink angle: 312 mrad

muon momentum: 17 GeV/c

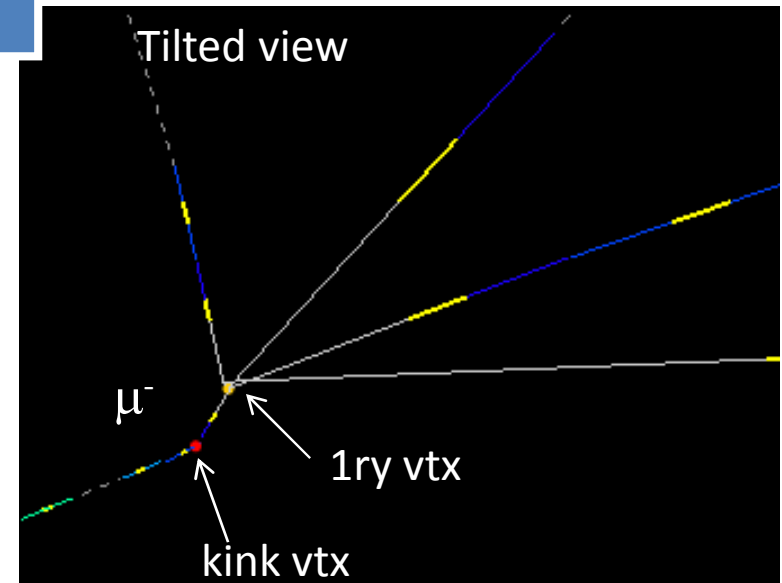
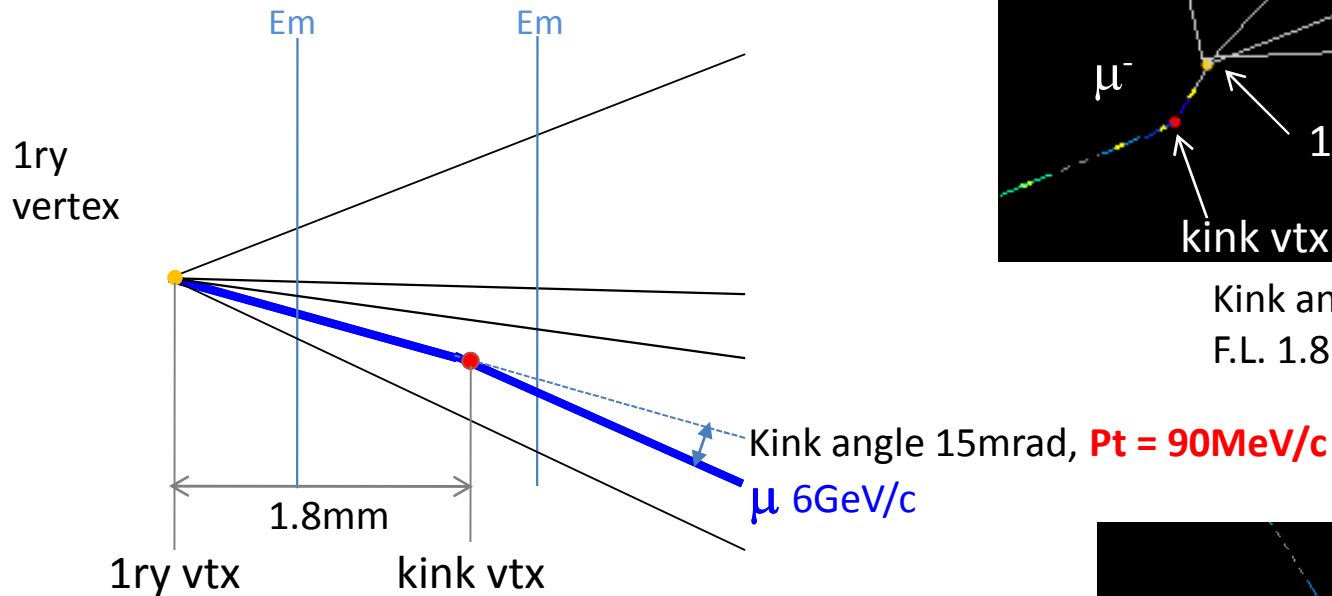
Decay Pt > 5.3 GeV/c

**Excluded by Pt:** Pt > maximum decay Pt of  $\tau$  (about 0.9 GeV/c)



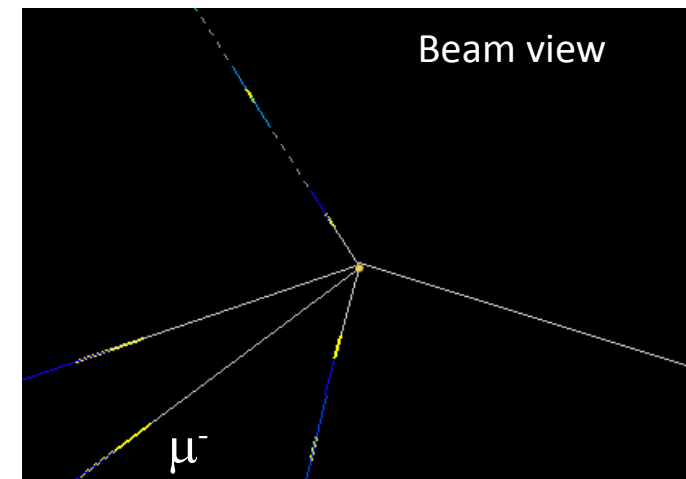
## Example of Detected Topologies 2.

- A muon kink detected in rather short flight length.



Kink angle 15 mrad  
F.L. 1.8 mm

- Topology looks similar to tau decay.
  - Kink angle = 7 sigma away from the resolution.
- **Rejected** by Kinematical analysis (Pt cut).
  - Pt cut for tau decay :  $Pt > 250 \text{ MeV}/c$
  - Possibly, muon single large-angle scattering or hadronic particle decay ( $\pi$ , K) into muon.



# Current status for 2008 run.

## Tau candidates

Analysis ongoing.

No candidate yet. (0.7 expected, 0.05 BG)

## Charm candidates.

Analysis ongoing for located ~700 nu-mu CC events.

Up to now, we have collected 15 candidates.

Agreement with our expectation

	Branching ratio	Number of candidates
1-prong	37 %	7
2-prong	30 %	5
3-prong	19 %	2
4-prong	7 %	1

## The L'Aquila earthquake

A strong earthquake ( $M_f=6.2$ ) hit L'Aquila on April 6<sup>th</sup> 2009. The epicenter was 15 km away from the Gran Sasso laboratory. 306 killed, 1600 injured, many houses collapsed, 15000 buildings were damaged.

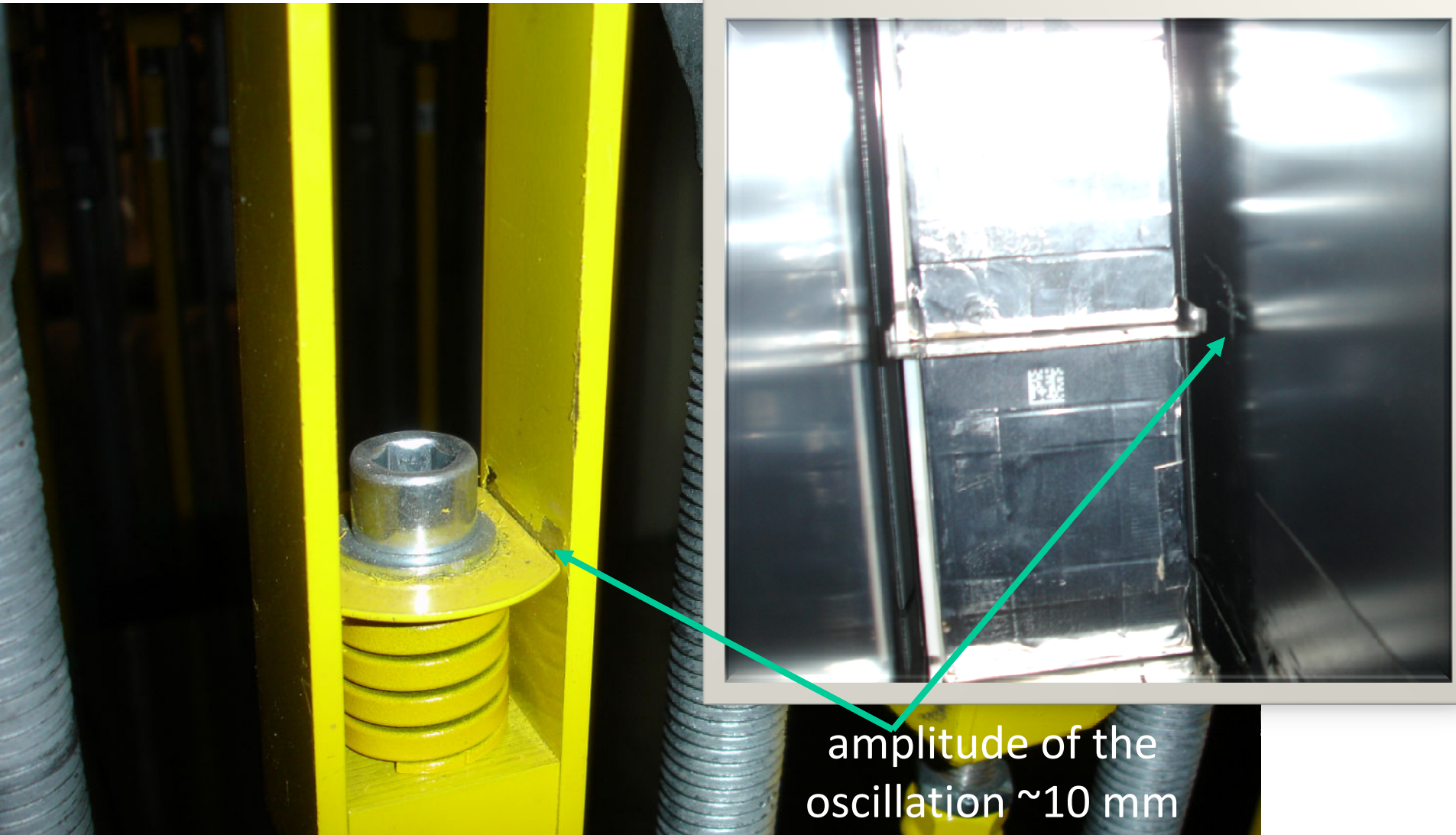
OPERA found basically intact, geometric measurements showed no significant alignment changes.

Gran Sasso activities, stopped for  $\sim 1.5$  months.

Big OPERA effort to let CNGS start with only 2 weeks delay !



# TT and the earthquake

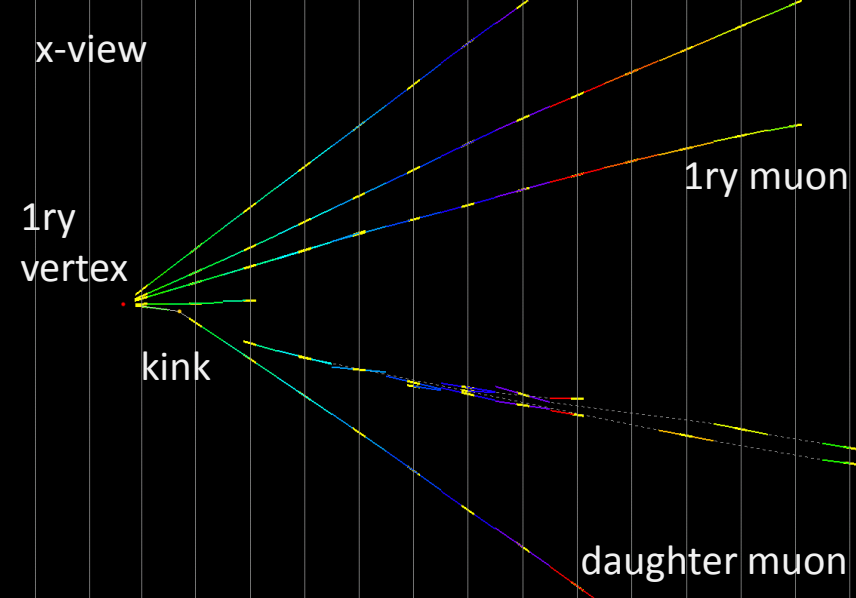


No other consequences of the earthquake were observed, thanks to the anti-seismic studies made for OPERA

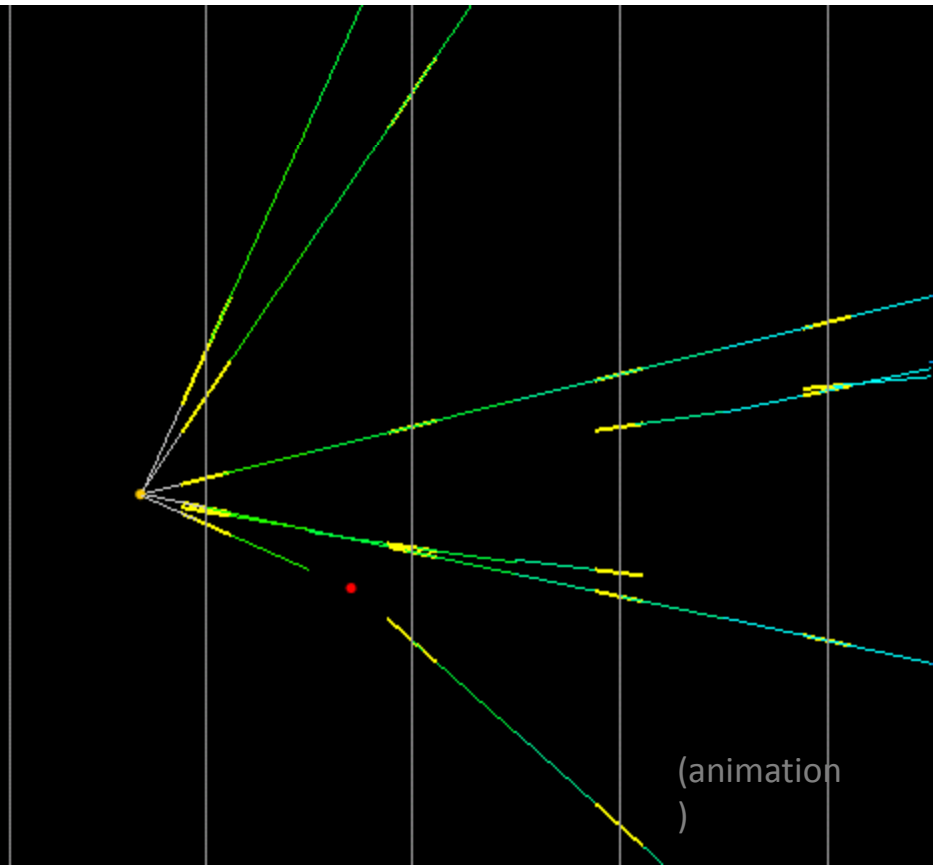
# Summary

- The OPERA experiment is taking data in the CNGS beam.
- $1.78 \times 10^{19}$  pot were collected during the first physics run in 2008.
  - 800 out of 1600 located in ECC
  - Scanning to be finished this month
- The analysis of 2008 data is in progress.
  - Expected detector performances.
  - No nu tau signal yet.
  - Several charmed candidates are detected as expected.
- The evaluation of total efficiencies and background is ongoing.
- In 2009 run,  $1.93 \times 10^{19}$  pot were already collected.
  - $4.5 \times 10^{19}$  pot are requested.
  - $3.5 \times 10^{19}$  pot are expected at the end of the run.
  - Detection of  $\sim 2$  nu-tau events is expected...SOON.

Charm candidate: 51284 (di-muon event)



flight length: 1330 micron  
kink angle: 209 mrad  
IP of daughter: 262 micron  
daughter muon: 2.2 GeV/c  
decay Pt: 0.46 GeV/c



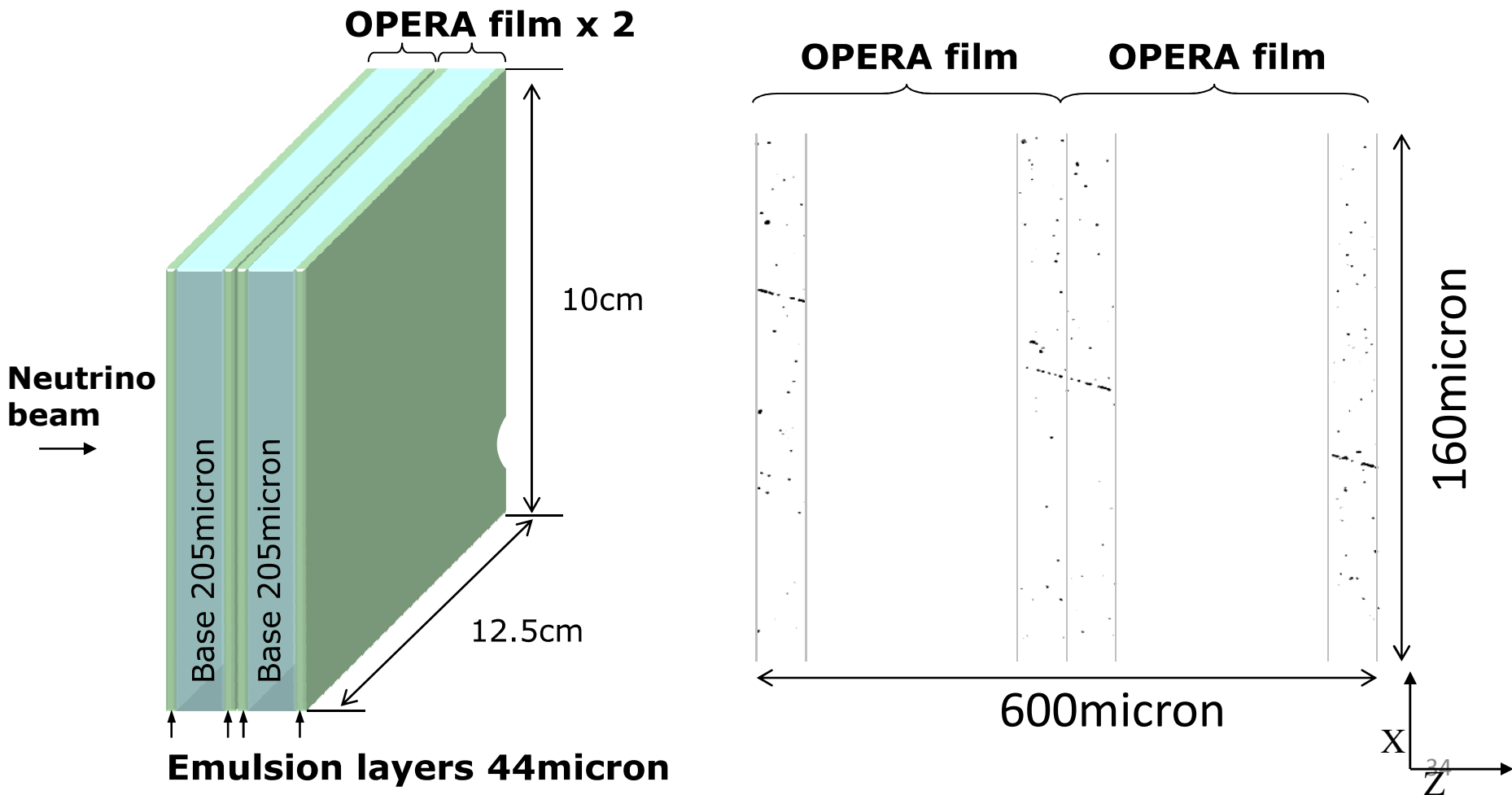


**BACKUP**

# Changeable Sheet (CS)

## Roles of CS

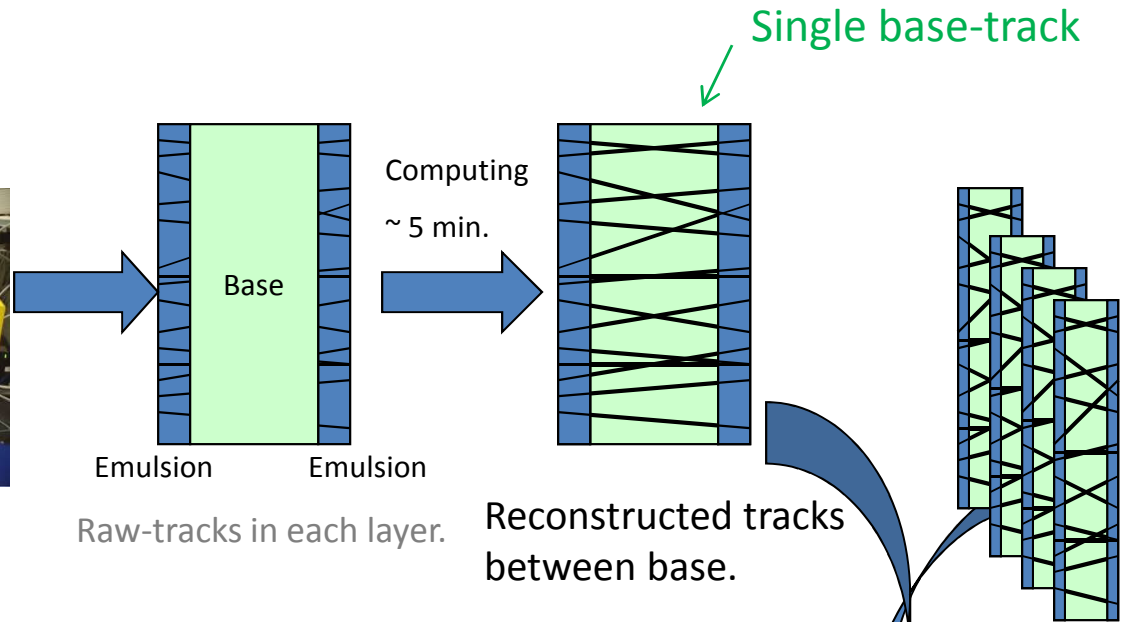
- Pick up tracks from neutrino interaction
- Helps tagging ECC → Saving Scanning load and Target Mass



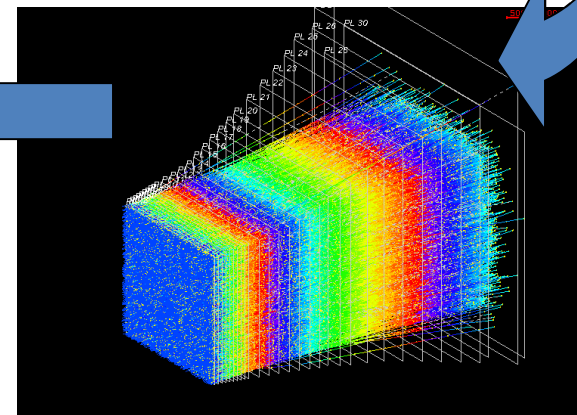
# Scanning and reconstruction



Scanning  $\sim 10$  min /  $\text{cm}^2$   
Most time consuming.



Analysis



Reconstructed tracks between films

Computing  
 $\sim 5$  min

# OPERA signal and background

$\tau$ decay channel	B.R. (%)	Signal $\Delta m^2 = 2.5 \times 10^{-3} \text{ eV}^2$	Background
$\tau \rightarrow \mu$	17.7	2.9	0.17
$\tau \rightarrow e$	17.8	3.5	0.17
$\tau \rightarrow h$	49.5	3.1	0.24
$\tau \rightarrow 3h$	15.0	0.9	0.17
<b>Total</b>		<b>10.4</b>	<b>0.75</b>

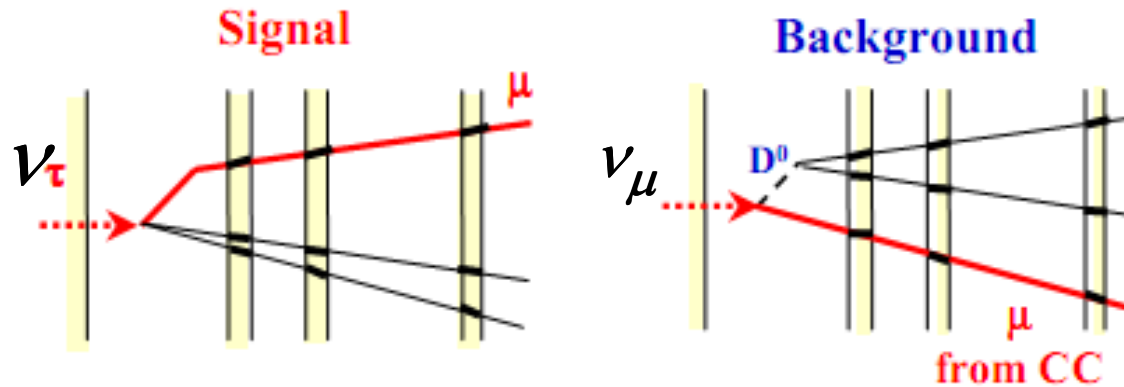
Full mixing, 5 years run,  $4.5 \times 10^{19}$  pot /year

Main background sources:

- Production and decay of charmed particles
- Hadron re-interactions
- Large angle muon scattering

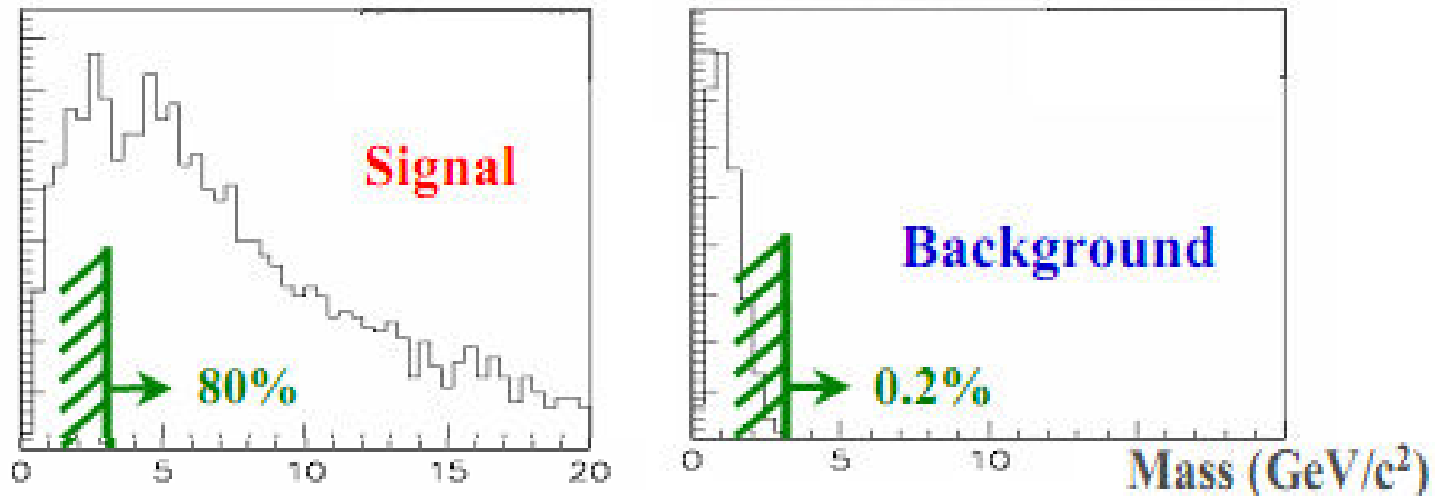
# Tau background by $D^0$

$\tau \rightarrow \mu$  channel



- Neutral charmed particle decay vertex mistaken as primary vertex in events where only a muon and  $D^0$  are produced at primary vertex

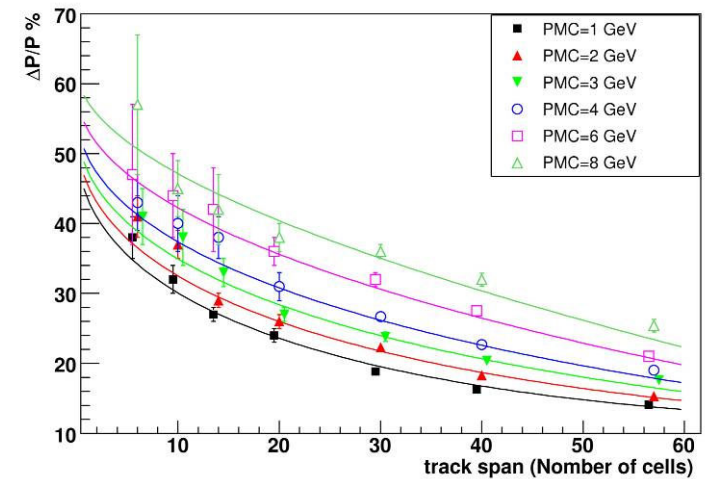
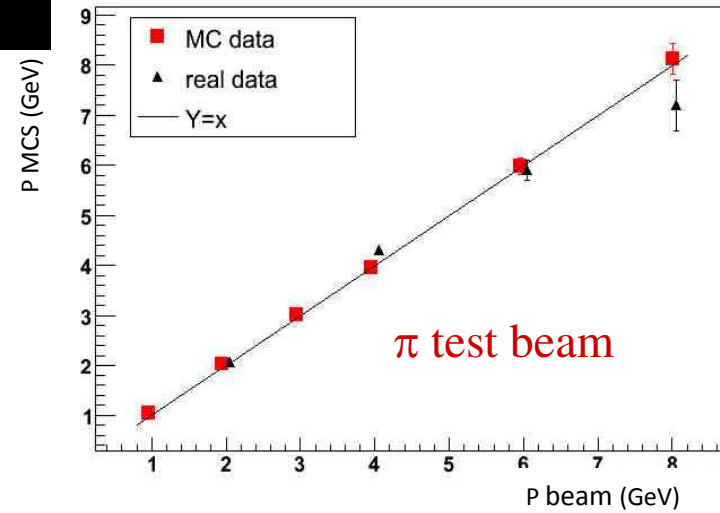
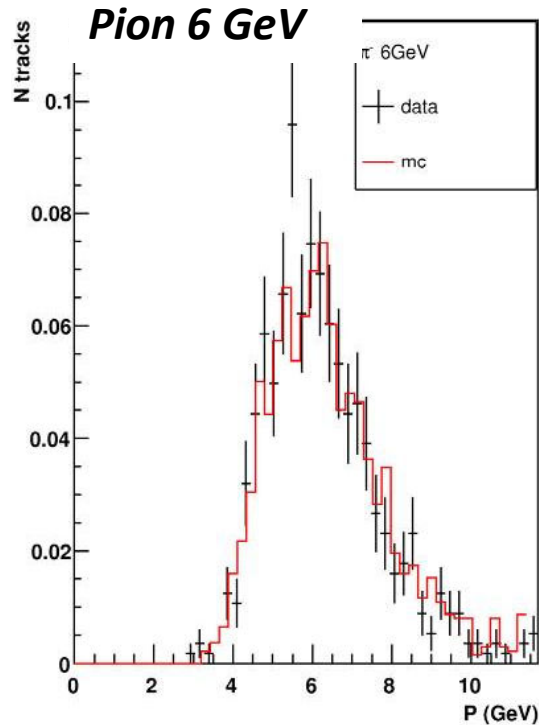
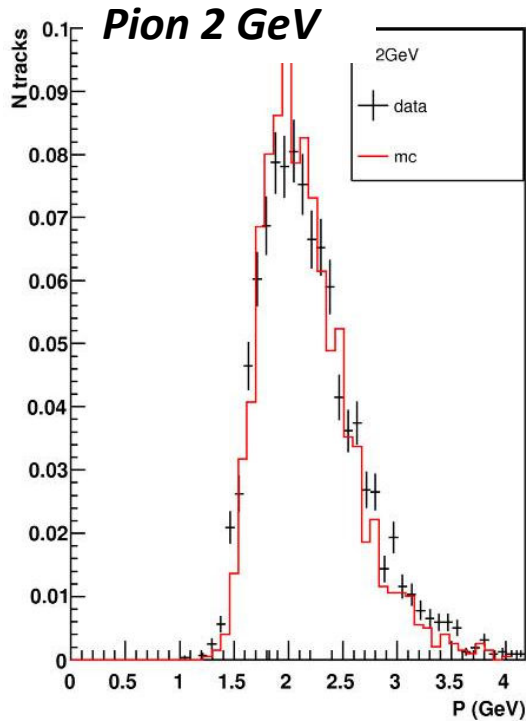
Cut on the invariant mass to be used to reduce this background source



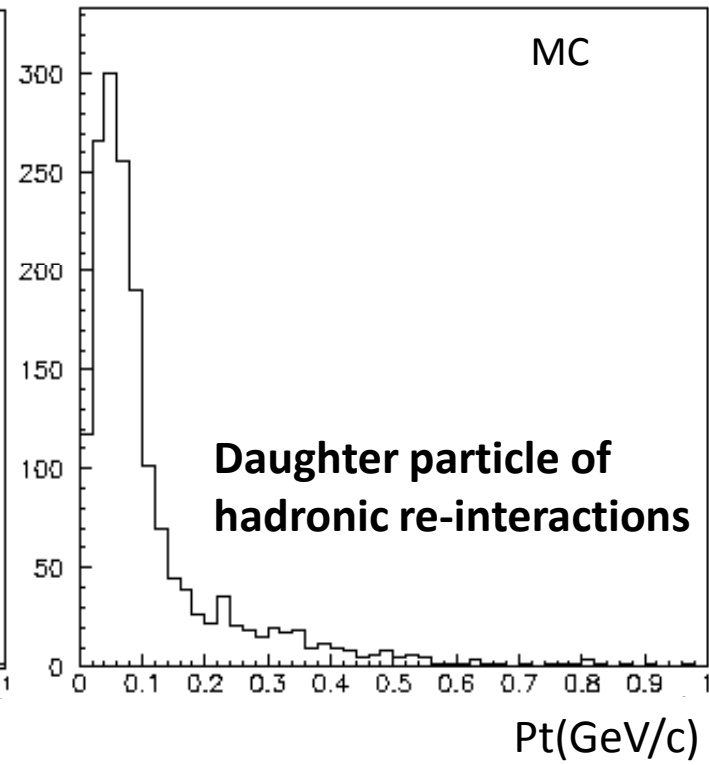
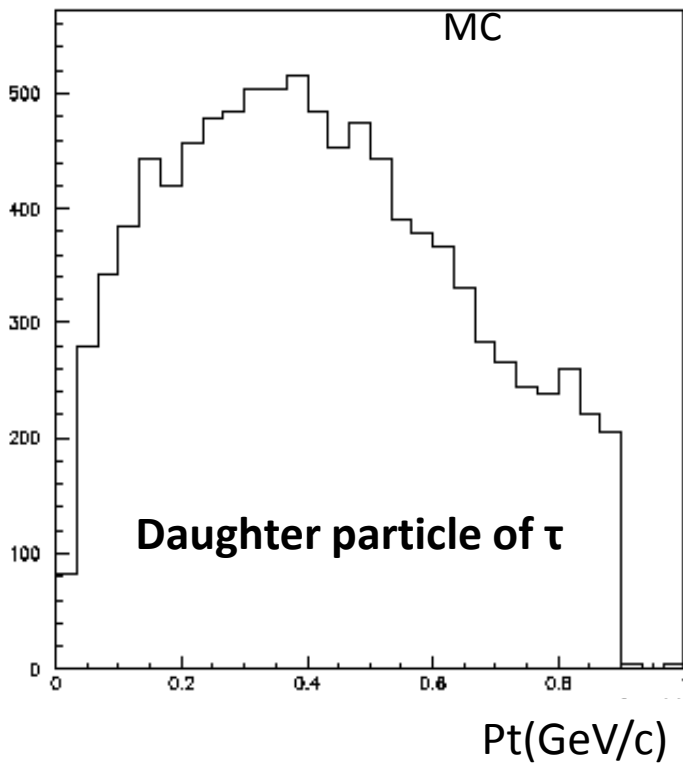
# Momentum measurement in ECC by Multiple Coulomb Scattering.

Evaluate scattering of particles

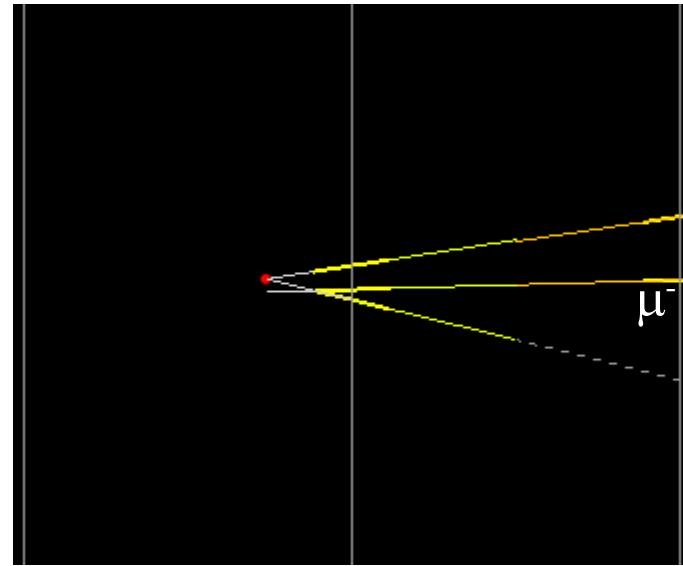
Data from Test exposure to pion beam



# Pt cut



# 72853



muon single stop at pl 22.

a vertex found 342  $\mu\text{m}$  upstream from pl 22.

minimum distance w.r.t muon

trk 145 37.0  $\mu\text{m}$  (confirmed in CS)

trk 206 13.5  $\mu\text{m}$

## Transverse momentum estimation

