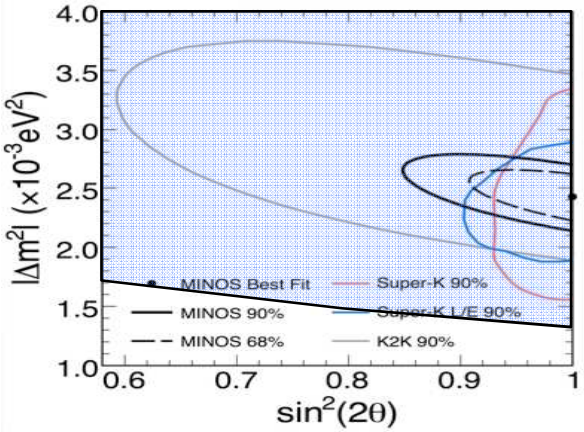
The OPERA Experiment

Jiro Kawada
Albert Einstein Center for Fundamental Physics
LHEP, University of Bern
on behalf of the OPERA Collaboration

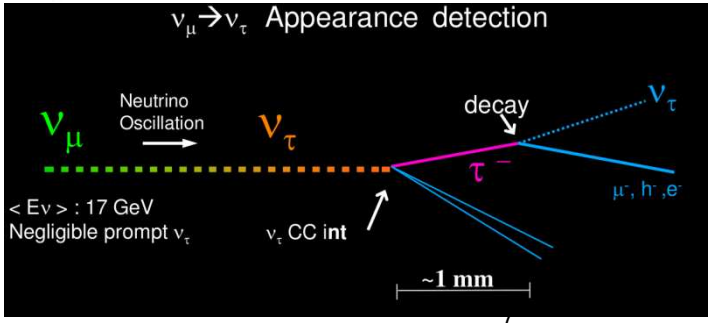
Workshop on Nuclear Track Emulsion and its Future
14-18 October 2013
Predeal, Romania

OPERA experiment

- Purpose:
  - Long baseline(730km) neutrino oscillation in CNGS(CERN Neutrinos to Gran Sasso) ν_μ beam
    - search for $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode
    - search for $\nu_\mu \rightarrow \nu_e$ oscillation



Covers the region indicated by Super-K, K2K & MINOS



$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2(2\theta_{23}) \cdot \sin^2\left(1.27 \cdot \Delta m^2{}_{23} \cdot \frac{L}{E}\right) \sim 1.7\%$$

Long History of emulsion in neutrino physics

	Target Mass
• 1978–1983 Fermilab E531 charm physics, $\nu_\mu \rightarrow \nu_\tau$ oscillation	~ 100kg
• 1990–2000 CERN WA95 CHORUS $\nu_\mu \rightarrow \nu_\tau$ oscillation, charm physics	~ 1 ton
• 1994–2001 Fermilab E872 DONUT First ν_τ observation	~ 1 ton
• 2008– CERN CNGS01 OPERA $\nu_\mu \rightarrow \nu_\tau$ oscillation, $\nu_\mu \rightarrow \nu_e$ oscillation	1250 ton

The OPERA Collaboration

Belgium
ULB Brussels

Croatia
IRB Zagreb

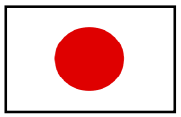
France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
LNF Frascati
L'Aquila
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi edu.
Kobe
Nagoya
Toho
Nihon



Korea
Jinju

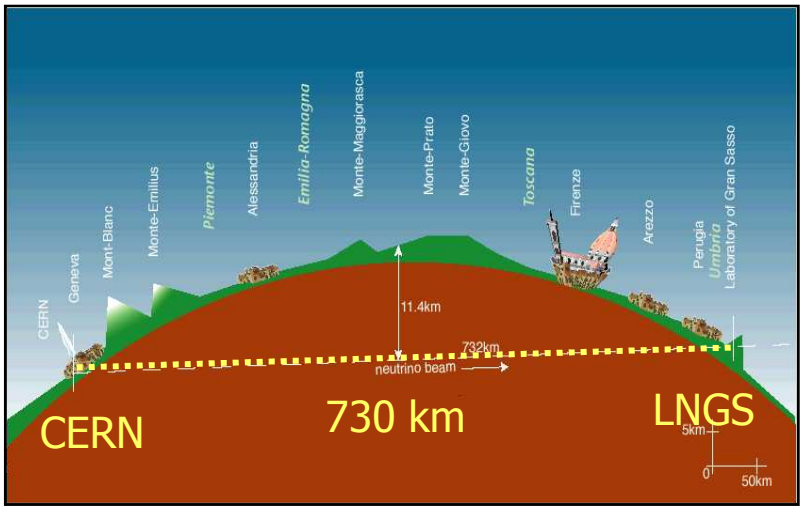
Russia
INR RAS Moscow
LPI RAS Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern

Turkey
METU Ankara

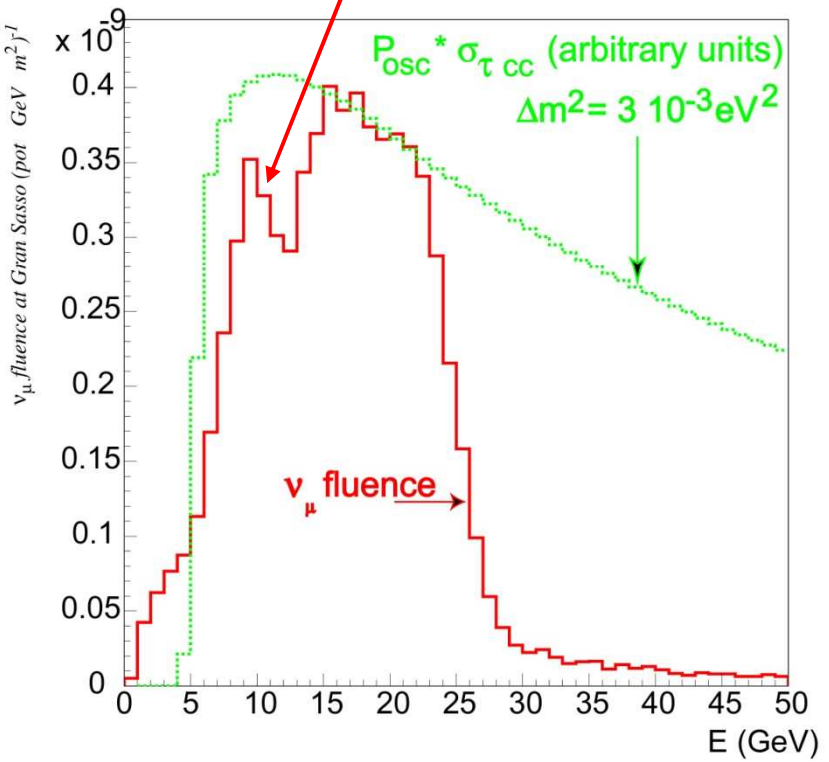
（11 countries、28Institutes、~140 researchers）

The CNGS beam

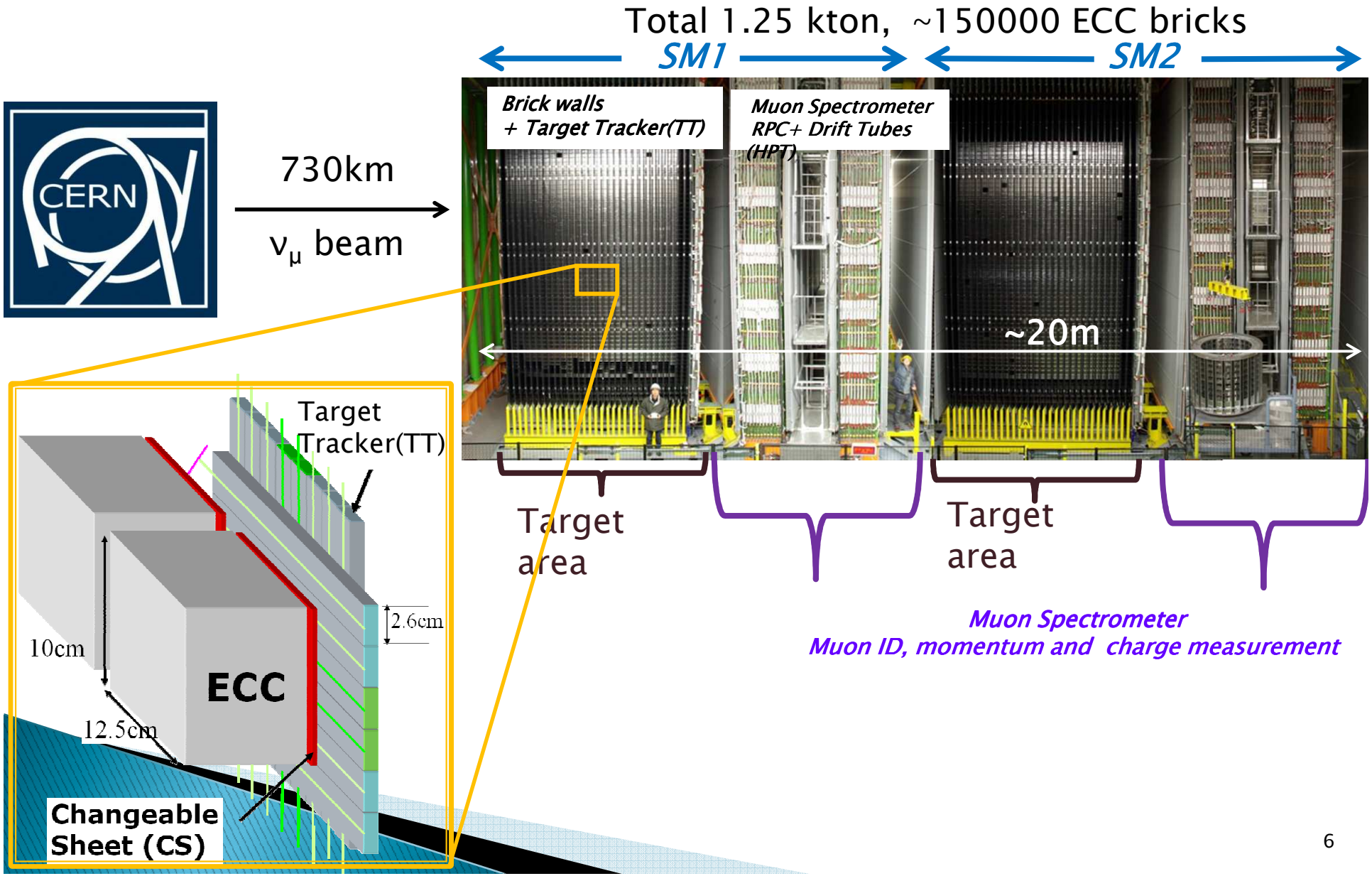


Beam main features	
L	**730 km**
<E$_\nu$>	**17 GeV**
$(\nu_e+\overline{\nu}_e)/\nu_\mu$ interactions	0.87%
$\overline{\nu}_\mu$ / ν_μ interactions	2.1%
ν_τ prompt	**negligible**

$$N_\tau = N_A M_D \int \phi_{\nu_\mu}(E) P_{\nu_\mu \to \nu_\tau}(E) \sigma_{\nu_\tau}{}^{CC}(E) \varepsilon(E) dE$$

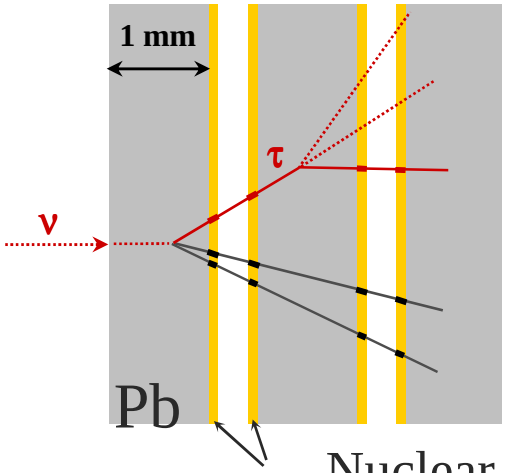


OPERA detector

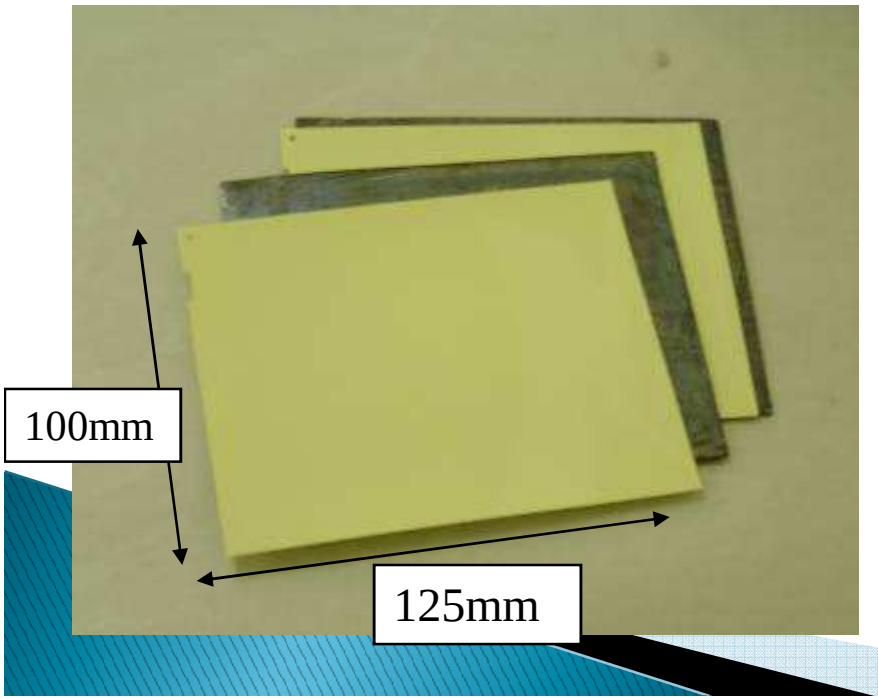


OPERA ECC

Pb(1mm) / Nuclear Emulsion (OPERA film) Sandwich



Nuclear emulsion



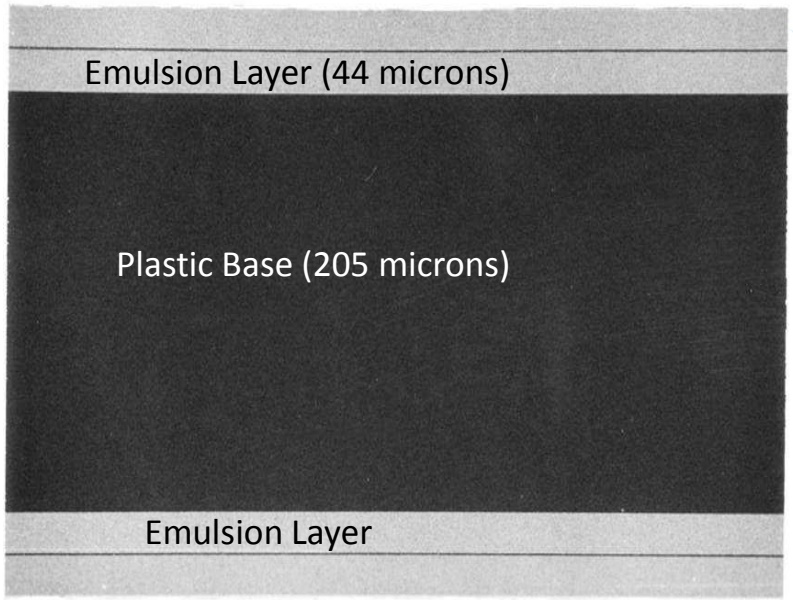
56Lead plates + 57films = 8.3 Kg (10 X_0)

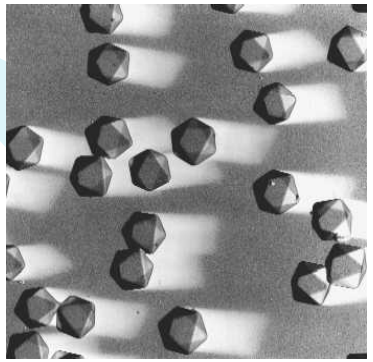
In total 150,000 Bricks!!

Brick Assembly Machine (BAM) at LNGS

Robots produce bricks
at a rate of ~ 700 bricks / day

OPERA film (made by *FUJI Film)*





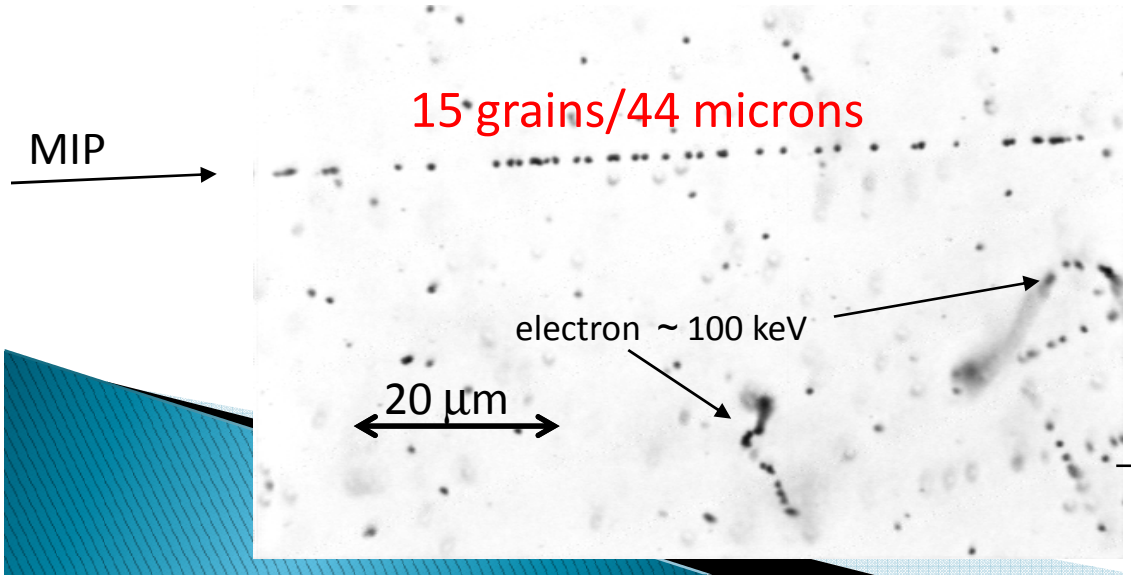
AgBr crystal size

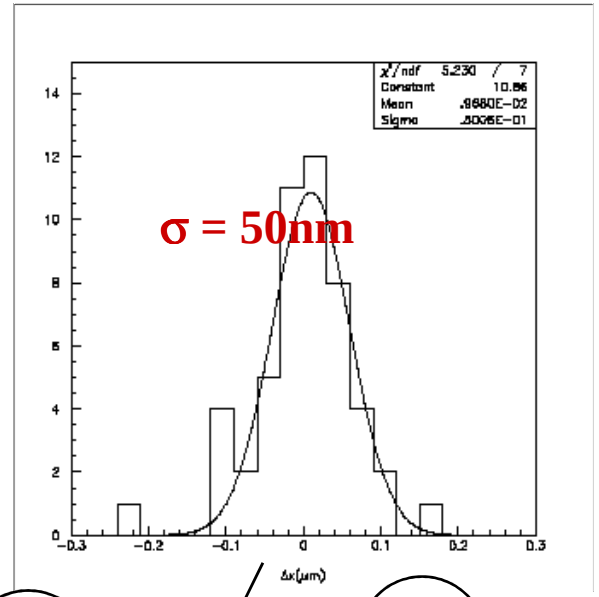
= 0.2 micron

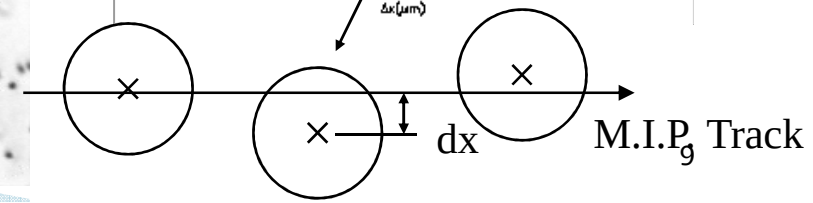
Intrinsic resolution

= 50 nm

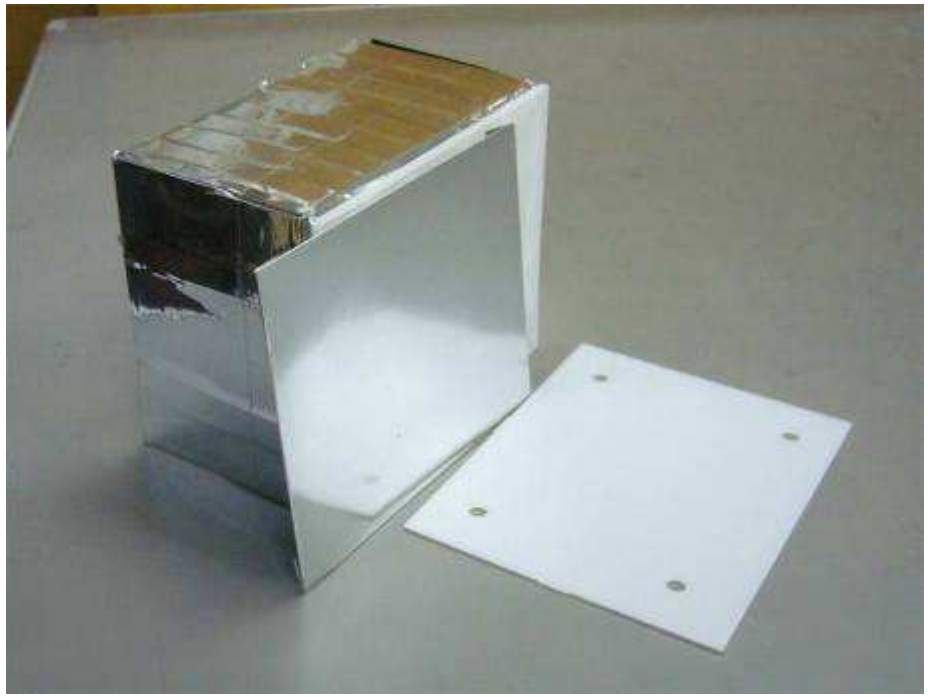
Automatic machine pouring by Fuji

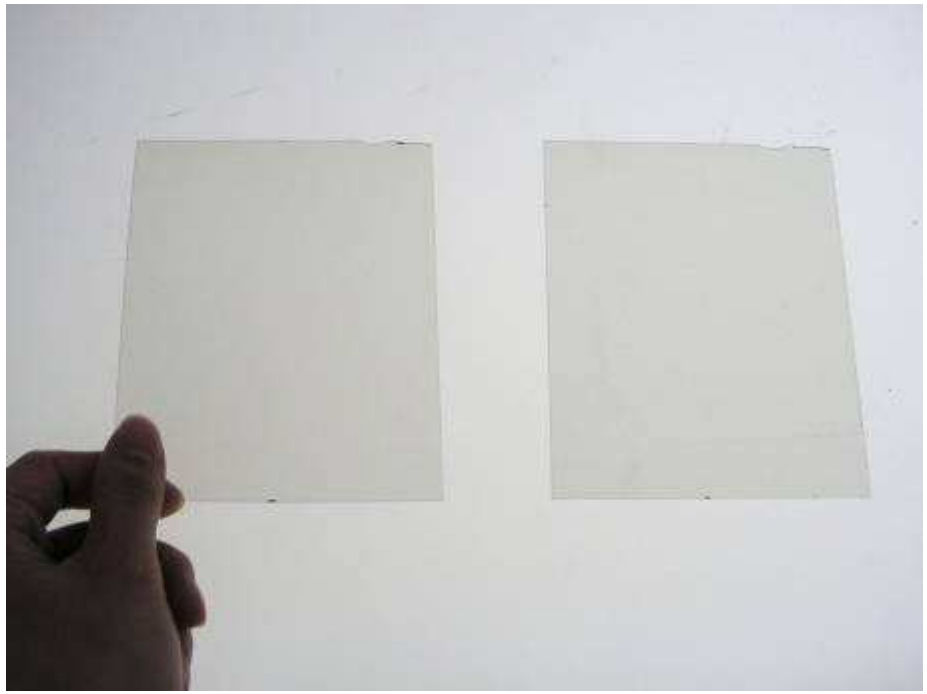






Changeable Sheets (CS)





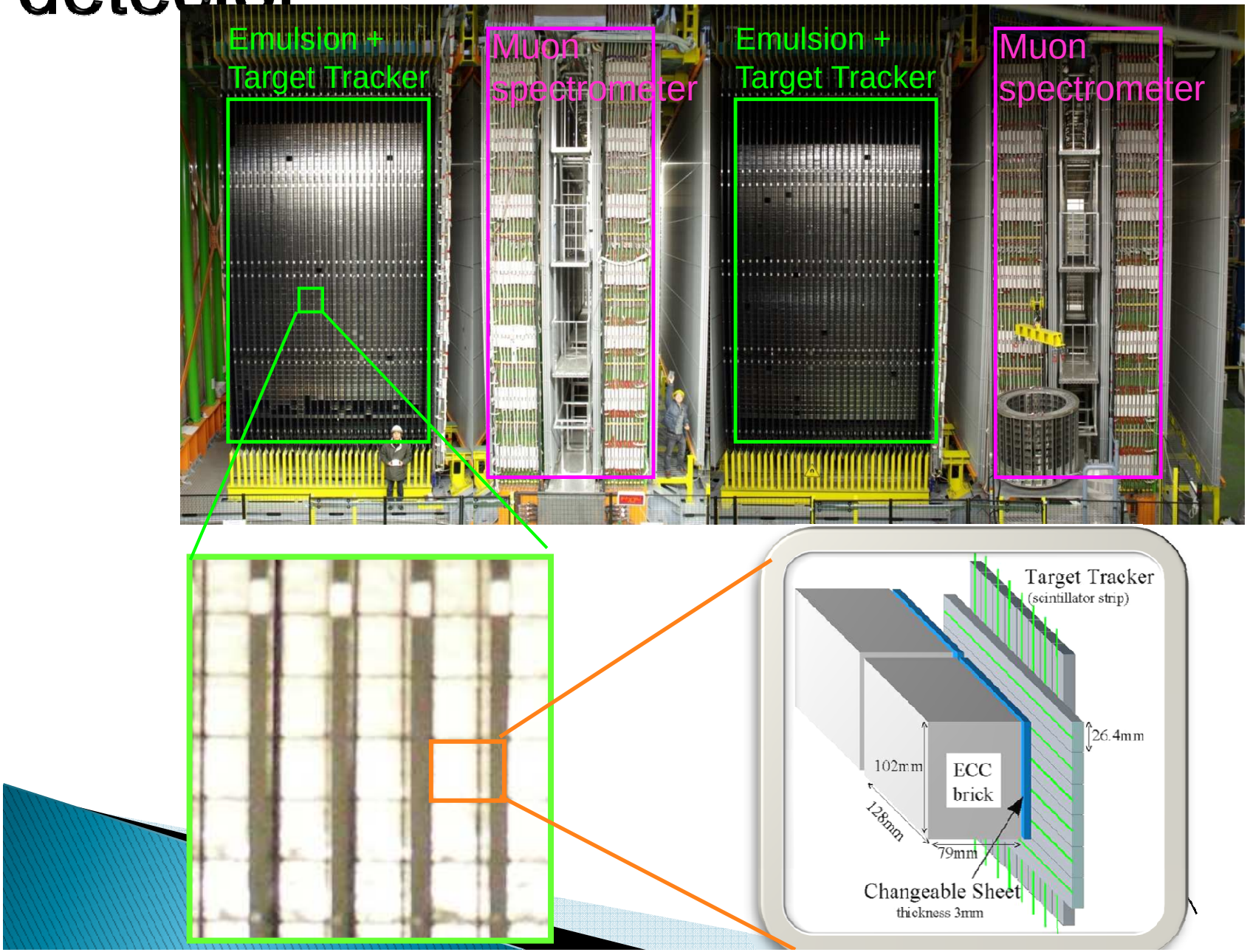
After taking out bricks, **Only 2 films are developed and scanned**

*Changeable sheets, easy to detach

*Extremely low background with special treatment

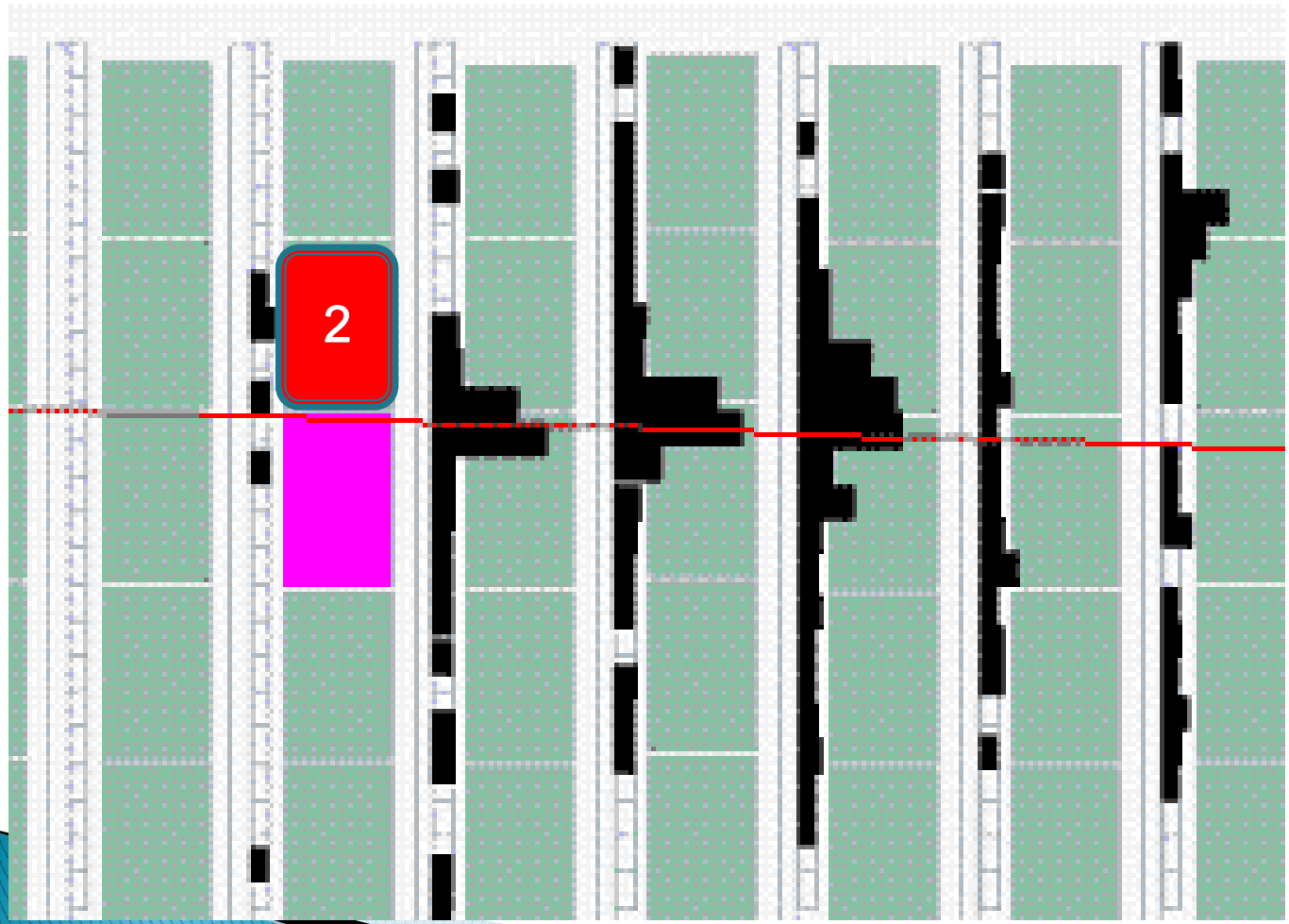
→ Minimize the loss of target mass , Save analysis time

The OPERA detector

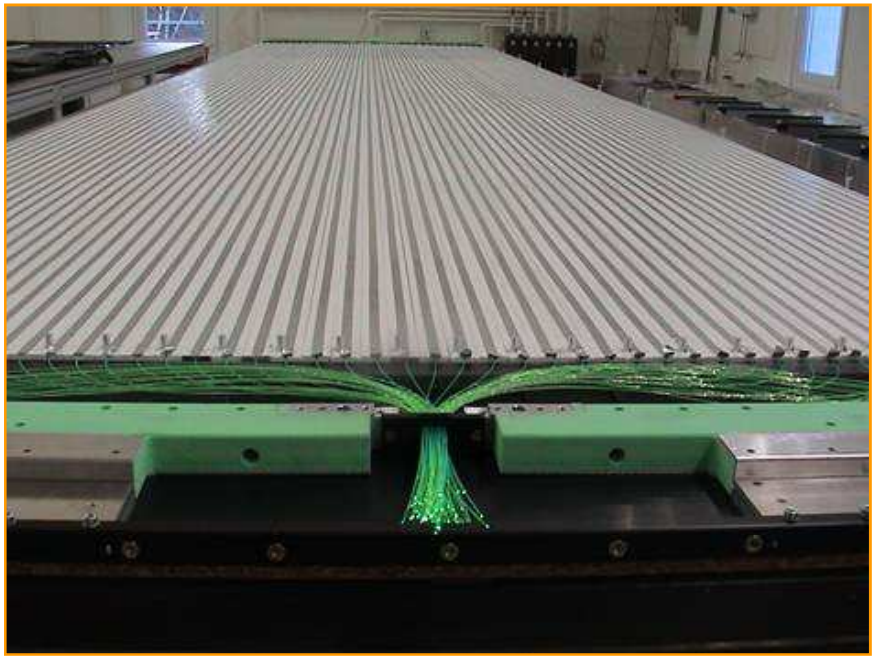


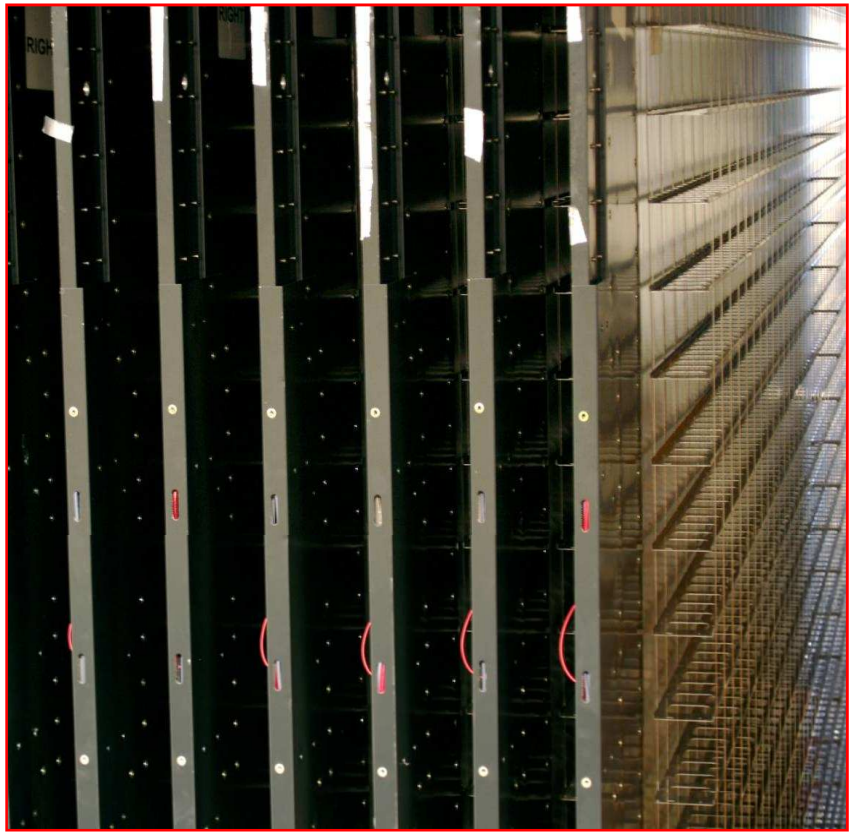
Brick selection by CS

If no track was confirmed by CS,
Next probable ECC is extracted and CS scanned .



Scintillator Strips Target Tracker

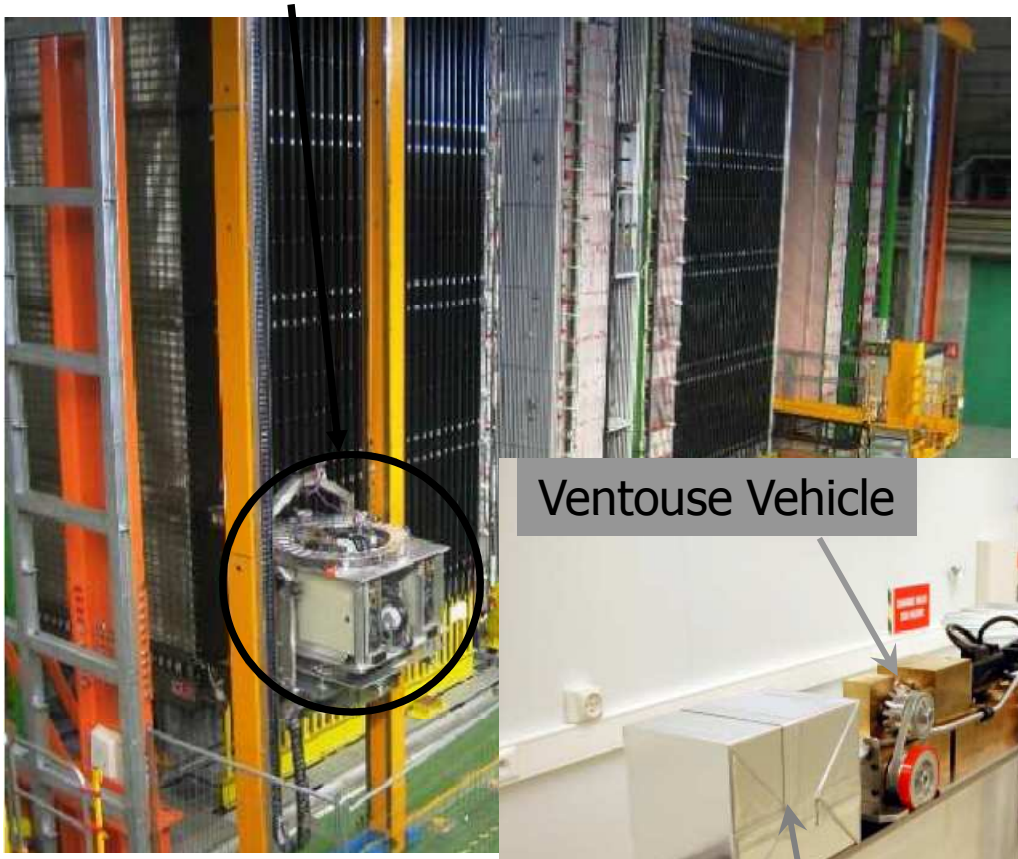




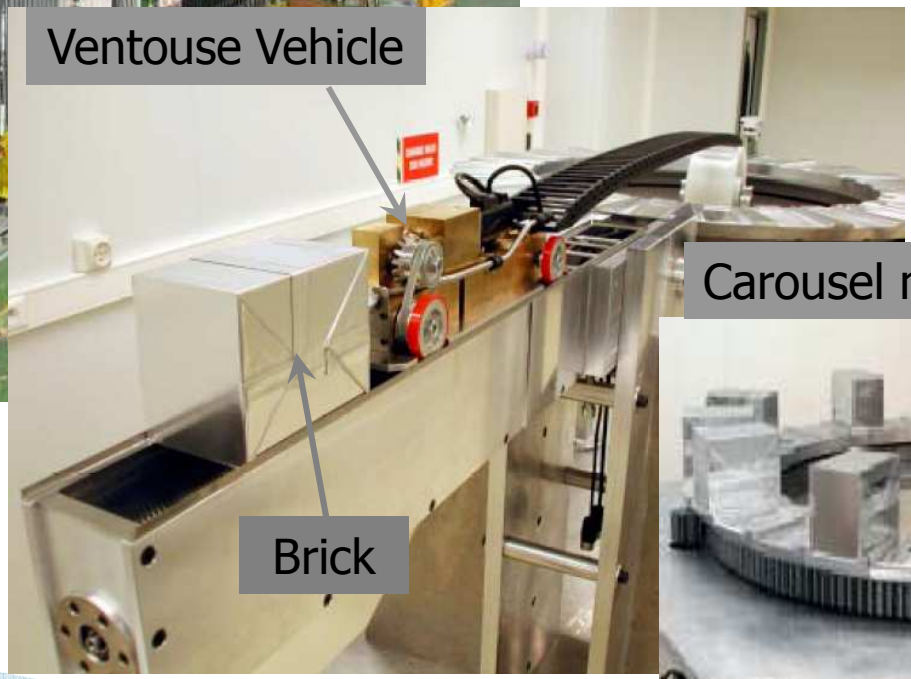
Module: 64 scintillator strips
Signal transmitted by WLS fibers
Read at both ends by 64-PMT

- ~ 99% detection efficiency $\Rightarrow$ trigger
- Position accuracy: ~ 8 mm $\Rightarrow$ brick location
- Probability map of event location in bricks

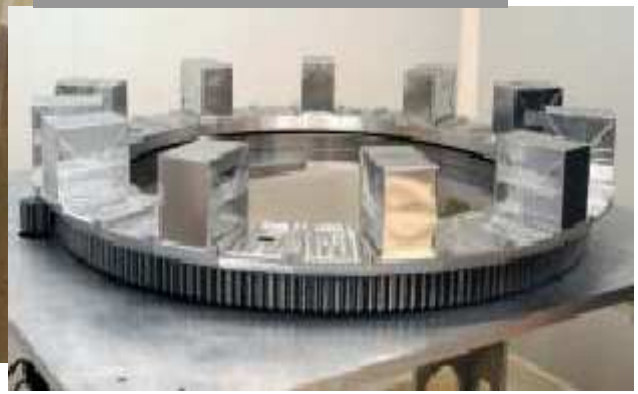
Brick Manipulator System (BMS)



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



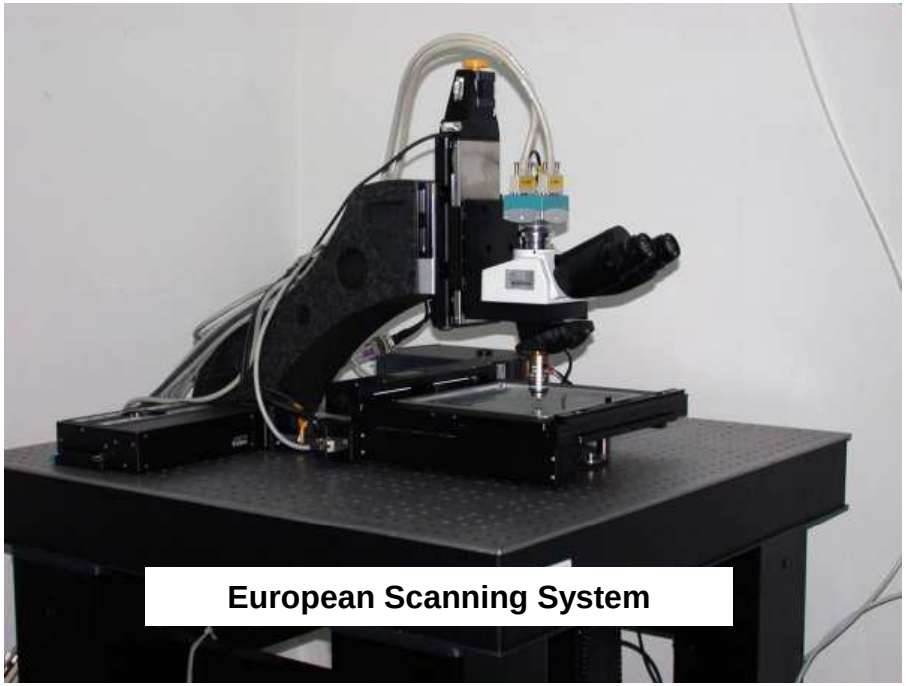
Carousel mechanism



Automatic developing system

Capability ~20 ECC/day

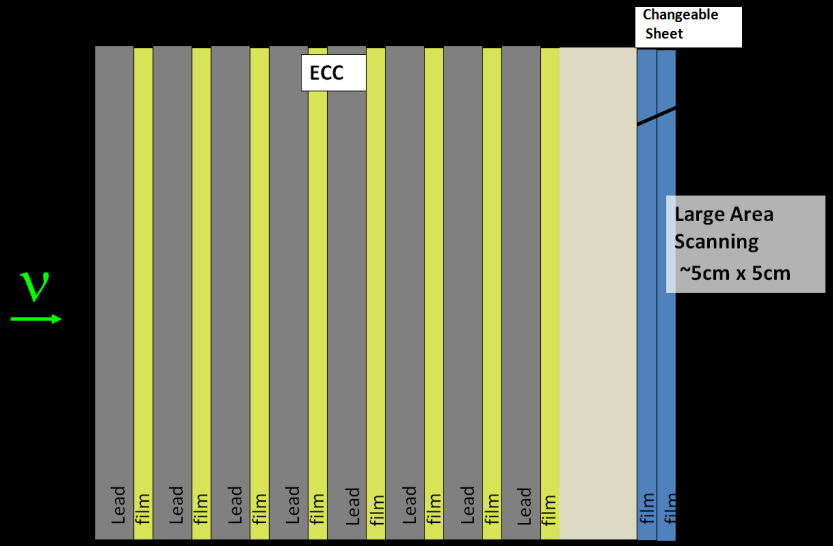
OPERA Emulsion scanning system


European Scanning System

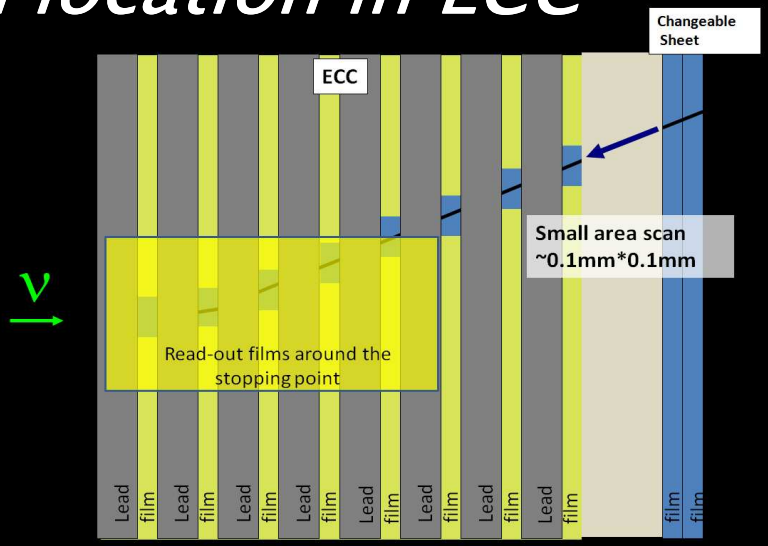

Super-UltraTrackSelector

High speed automatic microscopes:
~ 200 cm^2 emulsion film surface/hour/facility
Based on state of the art technologies:
precision mechanics, high-speed CMOS, pattern recognition, image analysis
Data flow: ~ 1 GB/s/facility

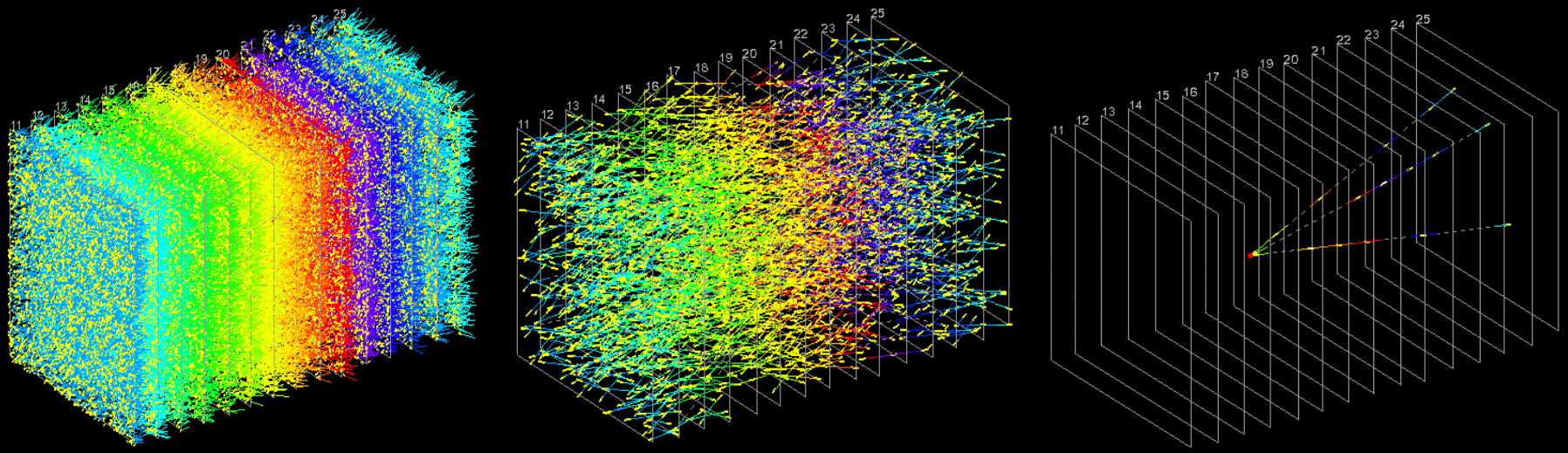
Neutrino interaction location in ECC



Step 1: CS scanning

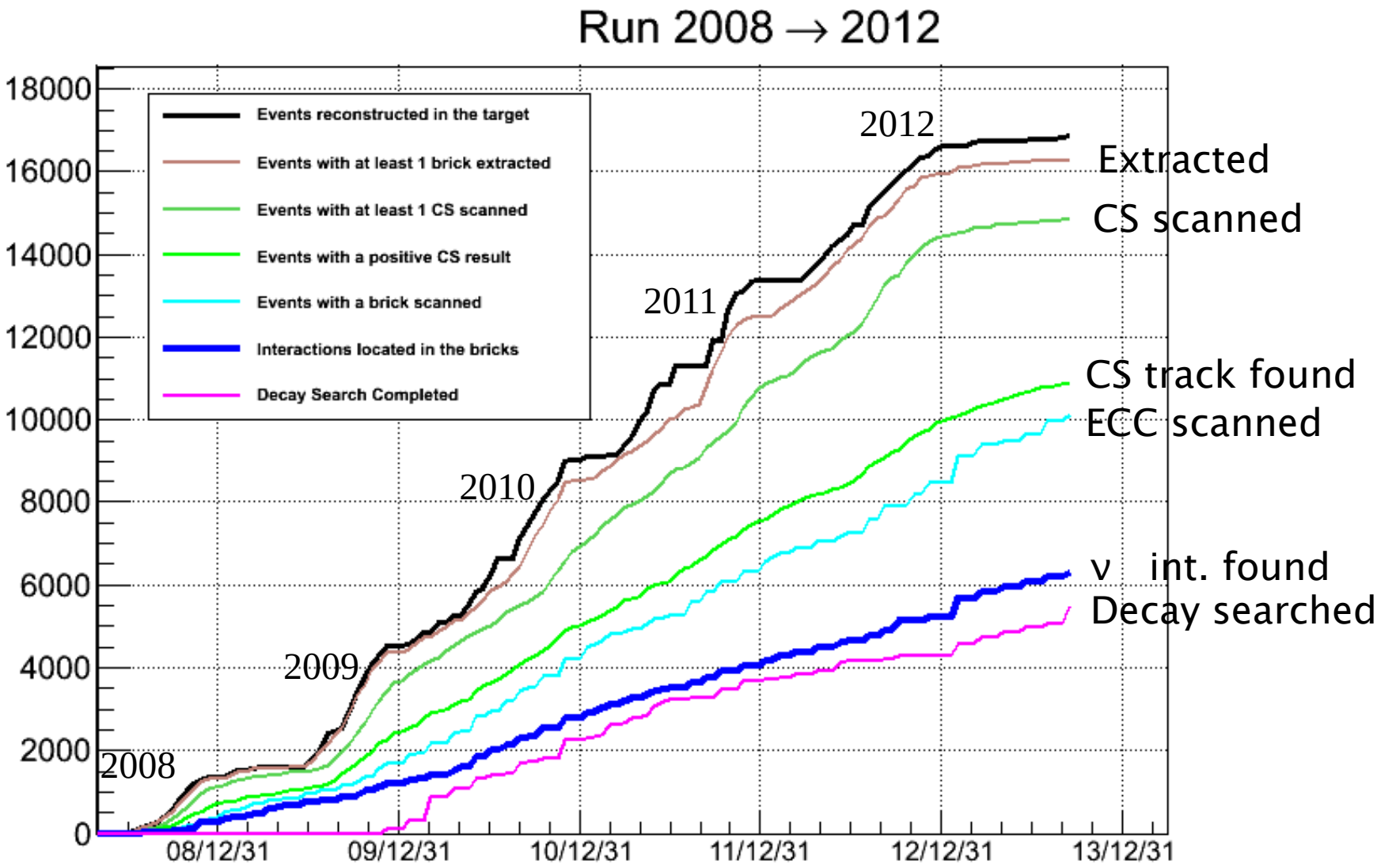


Step 2-4: CS-ECC connection, ScanBack, Volume data taking



Step 5-6: validation of neutrino interaction vertex and decay search for short lived particles

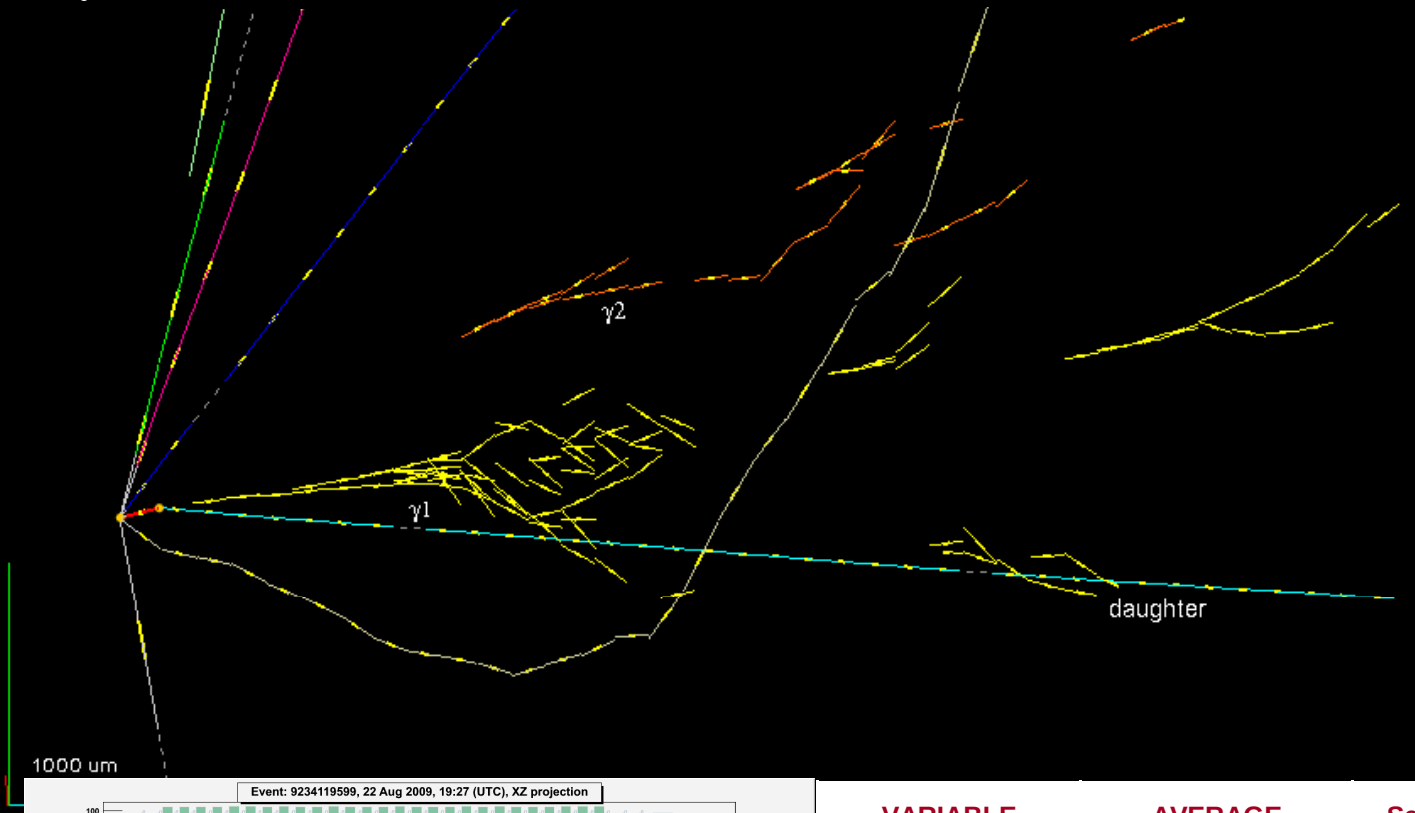
Status of data analysis

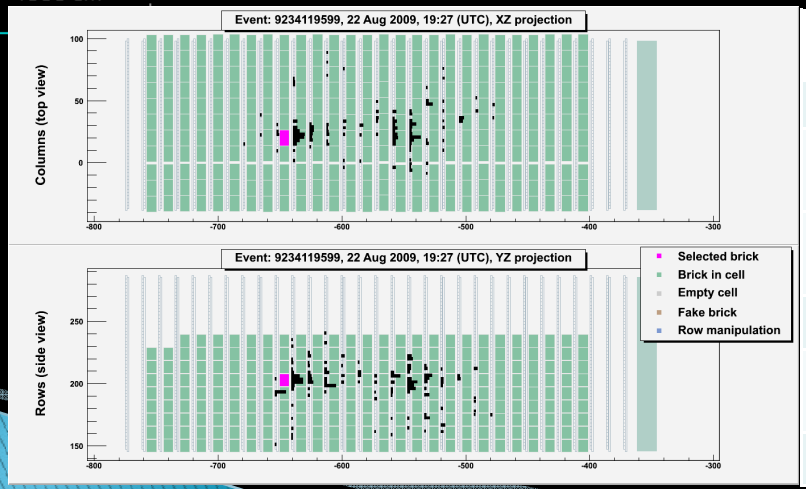


6299 located interactions

5497 decay search

First ν_τ candidate Event

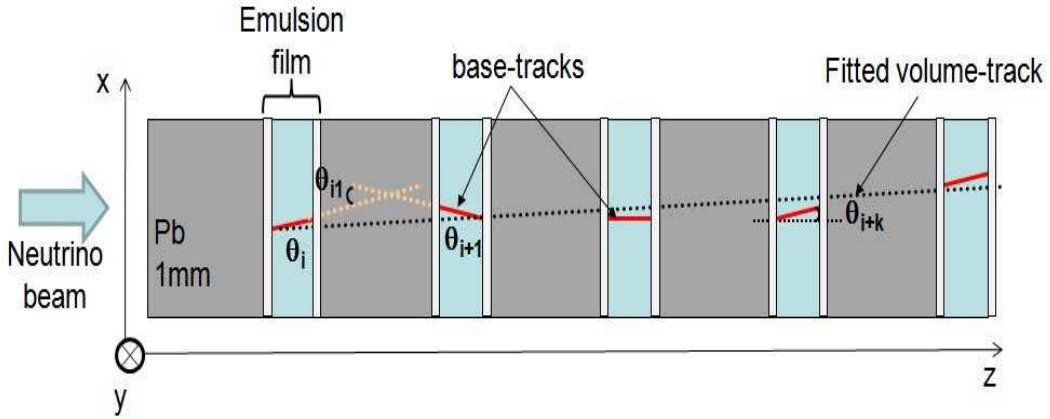


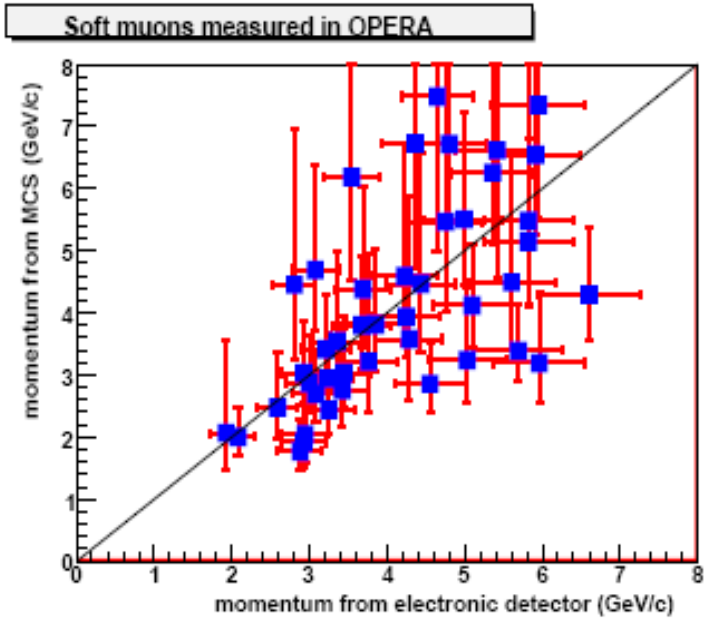


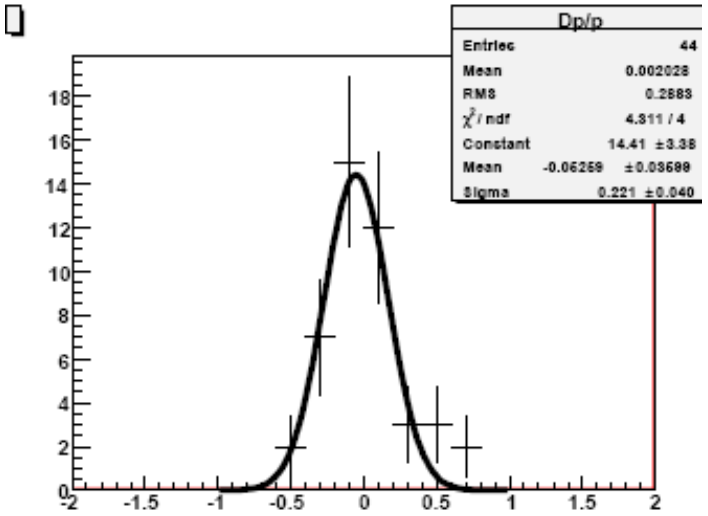
VARIABLE	AVERAGE	Selection criteria
kink (mrad)	41 ± 2	>20
decay length (μm)	1335 ± 35	within 2 lead plates
P daughter (GeV/c)	$12\ ^{+6}_{-3}$	>2
Pt (MeV/c)	$470\ ^{+230}_{-120}$	>300 (γ attached)
missing Pt (MeV/c)	$570\ ^{+320}_{-170}$	<1000
ϕ (deg)	173 ± 2	>90

Published: Physics Letters B, Vol. 691(138–145)

Momentum measurement in ECC



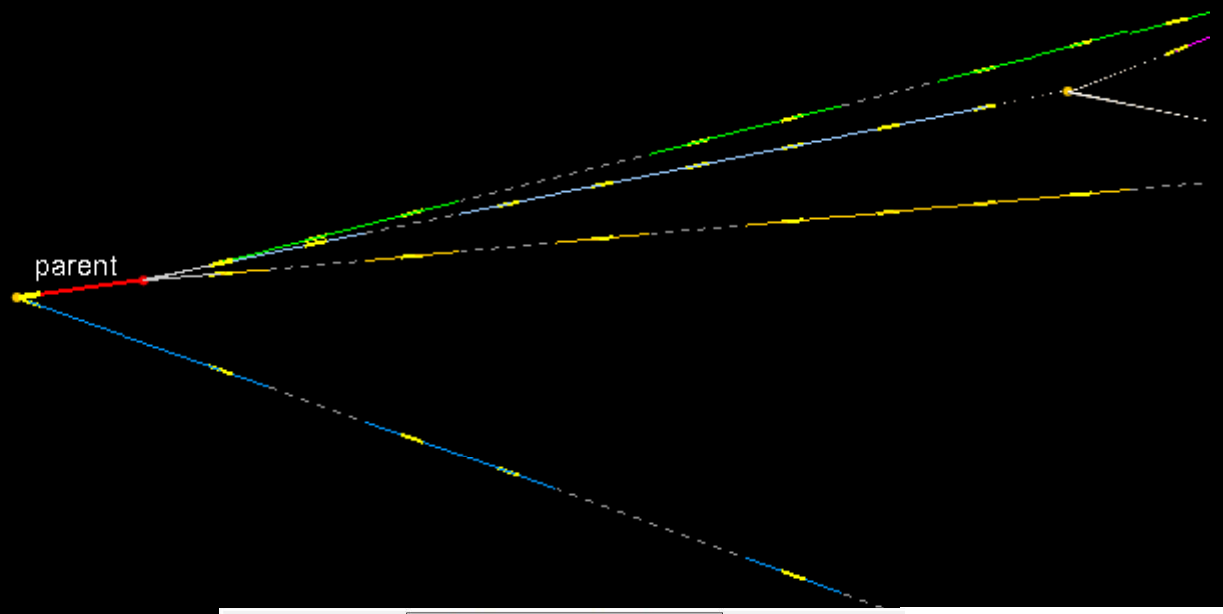




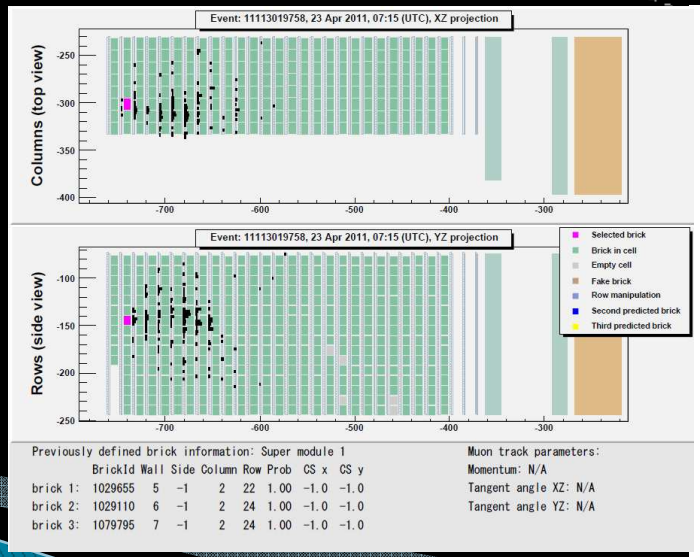
$\Delta p/p$

σ = (22±4)%

Second ν_τ Candidate Event

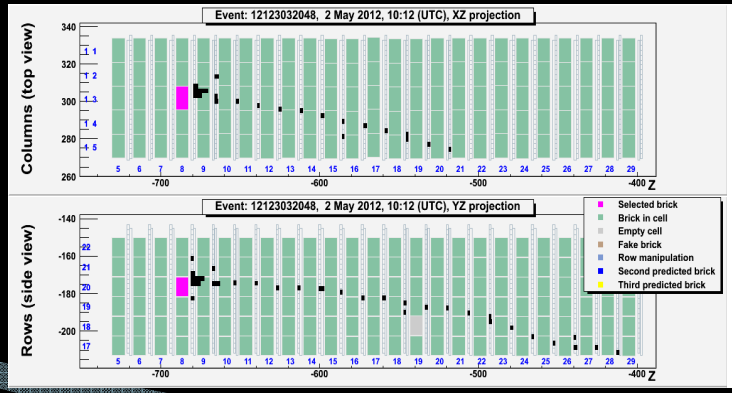


2000 μm



Track	Momentum (1σ interval) [GeV/c]	Particle ID
Primary track	2.8 (2.1-3.5)	Hadron
Daughter-1	6.6 (5.2 - 8.6)	Hadron
Daughter-2	1.3 (1.1 -1.5)	Hadron
Daughter-3	2.0 (1.4 - 2.9)	Hadron

Third ν_τ Candidate Event



Track	Momentum (1σ interval) [GeV/c]	Particle ID
Primary track	0.9±0.2	Hadron
Daughter-1	2.8±0.2	Muon
Gamma ray	2.9±0.3	γ

$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis

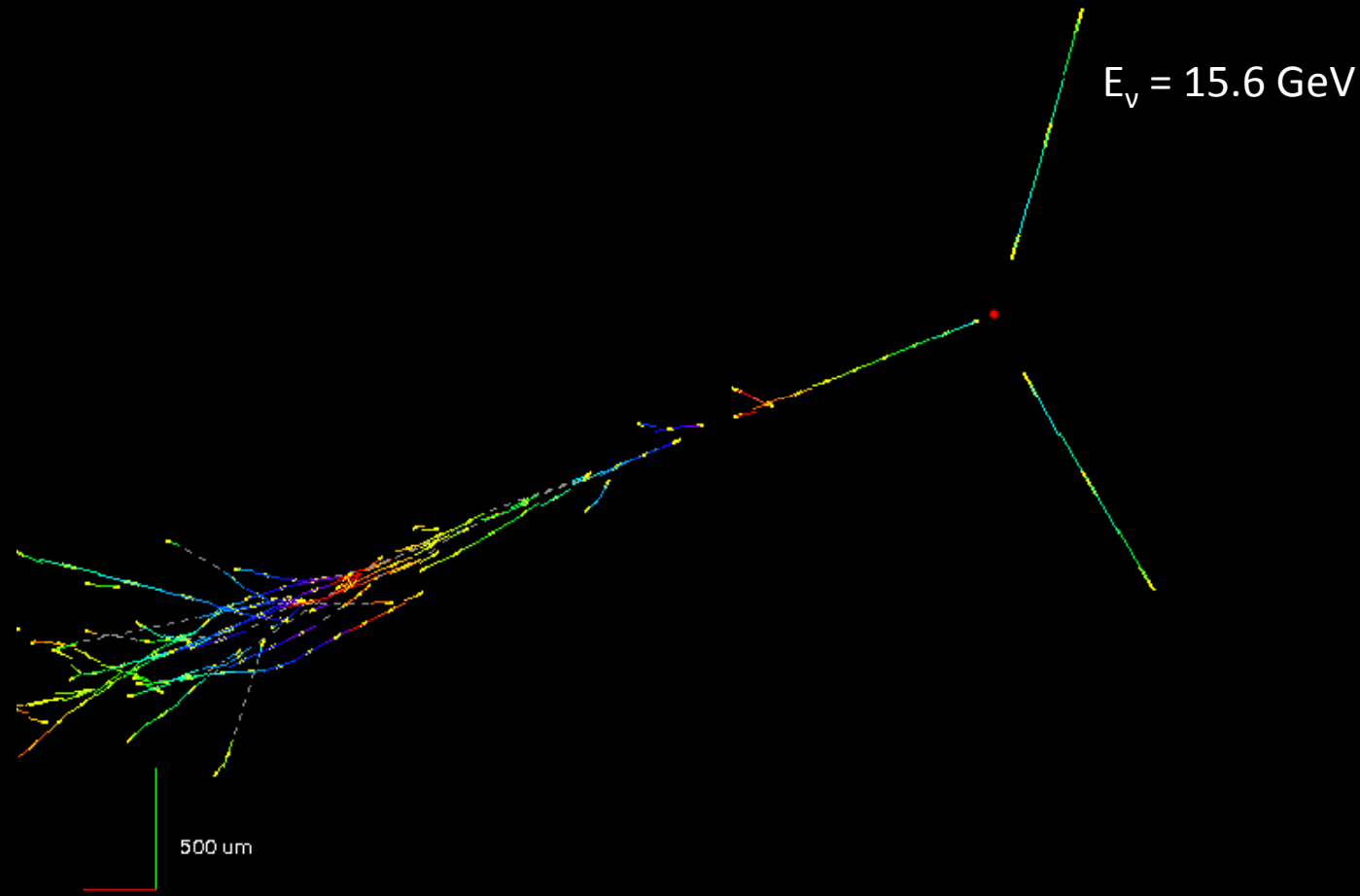
- 3 observed events in τ → h, τ → 3h, τ → μ channels.
- 3.4σ significance of non-null observation

Expected Signal and Background for 2-tau(τ → h, τ → 3h)

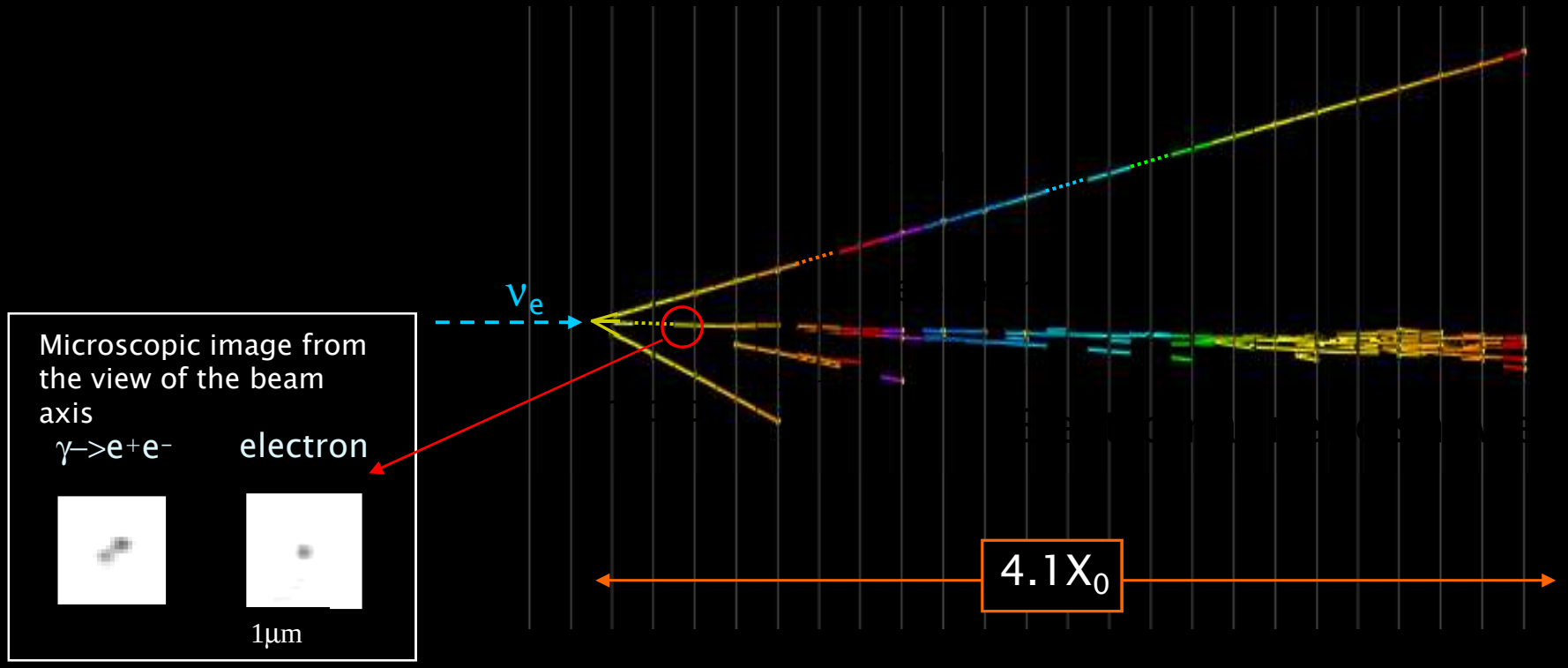
	Signal events $\Delta m^2_{23} = 2.32\text{m}(\text{eV}^2)$	All backgrounds	Charm background	muon scattering background	Hadronic background
$\tau \rightarrow h$	0.31 ± 0.06	0.027 ± 0.005	0.011 ± 0.002	/	0.016 ± 0.005
$\tau \rightarrow 3h$	0.43 ± 0.09	0.12 ± 0.02	0.11 ± 0.02	/	0.0021 ± 0.0006
$\tau \rightarrow \mu$	0.33 ± 0.07	0.012 ± 0.005	0.0023 ± 0.0004	0.009 ± 0.005	/
$\tau \rightarrow e$	0.46 ± 0.09	0.020 ± 0.004	0.020 ± 0.004	/	/
all	1.53 ± 0.16	0.175 ± 0.024	0.15 ± 0.02	0.009 ± 0.005	0.018 ± 0.005

ν_e appearance search

- $\nu_\mu \rightarrow \nu_e$ appearance search in 2008+2009 sample (5.25×10^{19} PoT)



Electron Identification in ECC



- Primary electron track observed as an isolated track, not as a pair tracks

fine position resolution of nuclear emulsion and fine segmentation (track reconstruction

each 1mm lead plate ($0.18X_0$)) in ECC

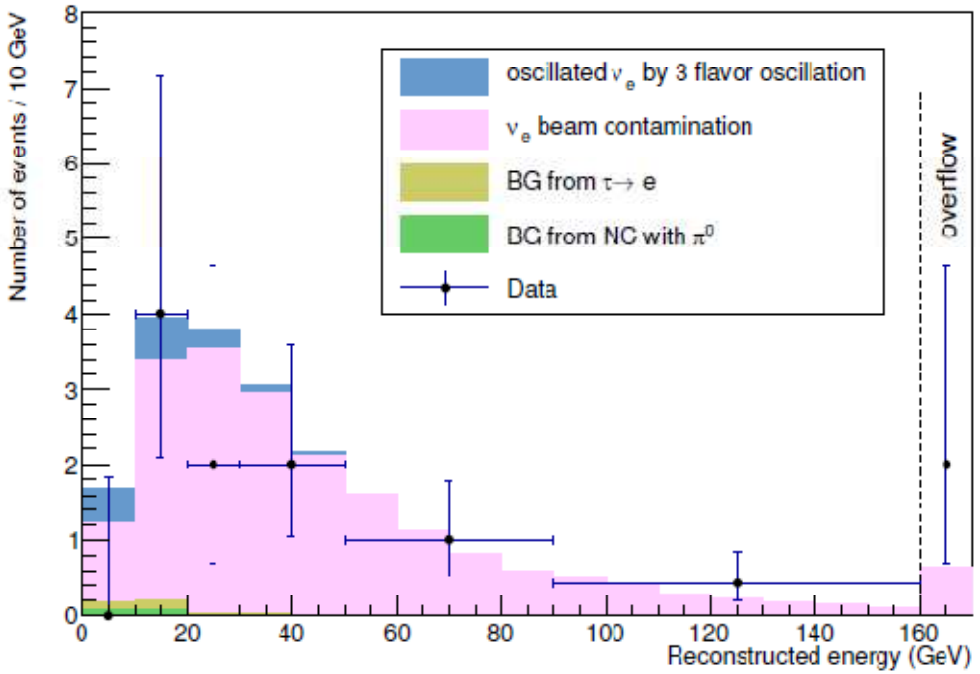
–> separate electron from γ–>e+e-

- Electromagnetic shower developed in ECC

–> separate electron from pion

Analysis of 2008-2009 data sample

19 ν_e events observed out of 505 0μ events



Systematic Uncertainty

1 : Beam flux 10%
2 : Detection efficiency
10%(Eν>=10GeV)
20%(Eν<10GeV)

Expected number of background ν_e events :19.8±2.8(sys)

(prompt ν_e, NC with π^0, τ->e)

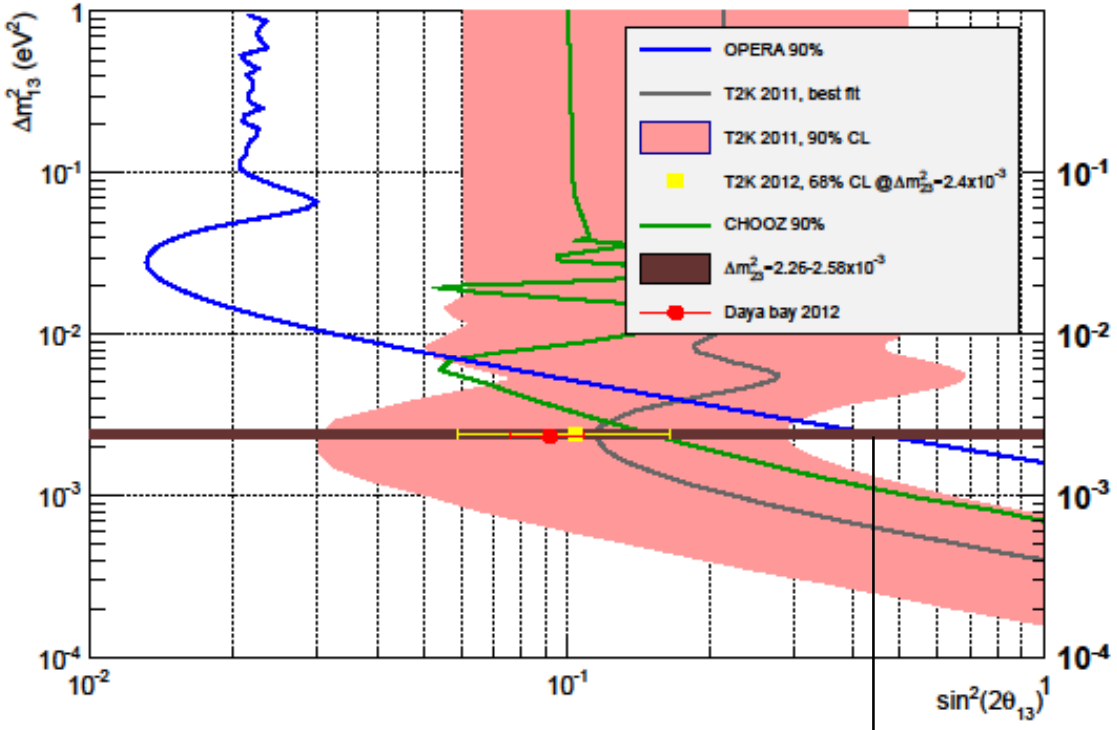
-> Observation agrees with background expectation

Published: JHEP07(2013)004

OPERA $\nu_\mu \rightarrow \nu_e$ oscillation results

(in 2008+2009 data set)

3 flavor mixing model for standard oscillation



Upper limit (90%C.L.) @Δm^2_{13}=2.32 x 10^{-3} (eV^2)

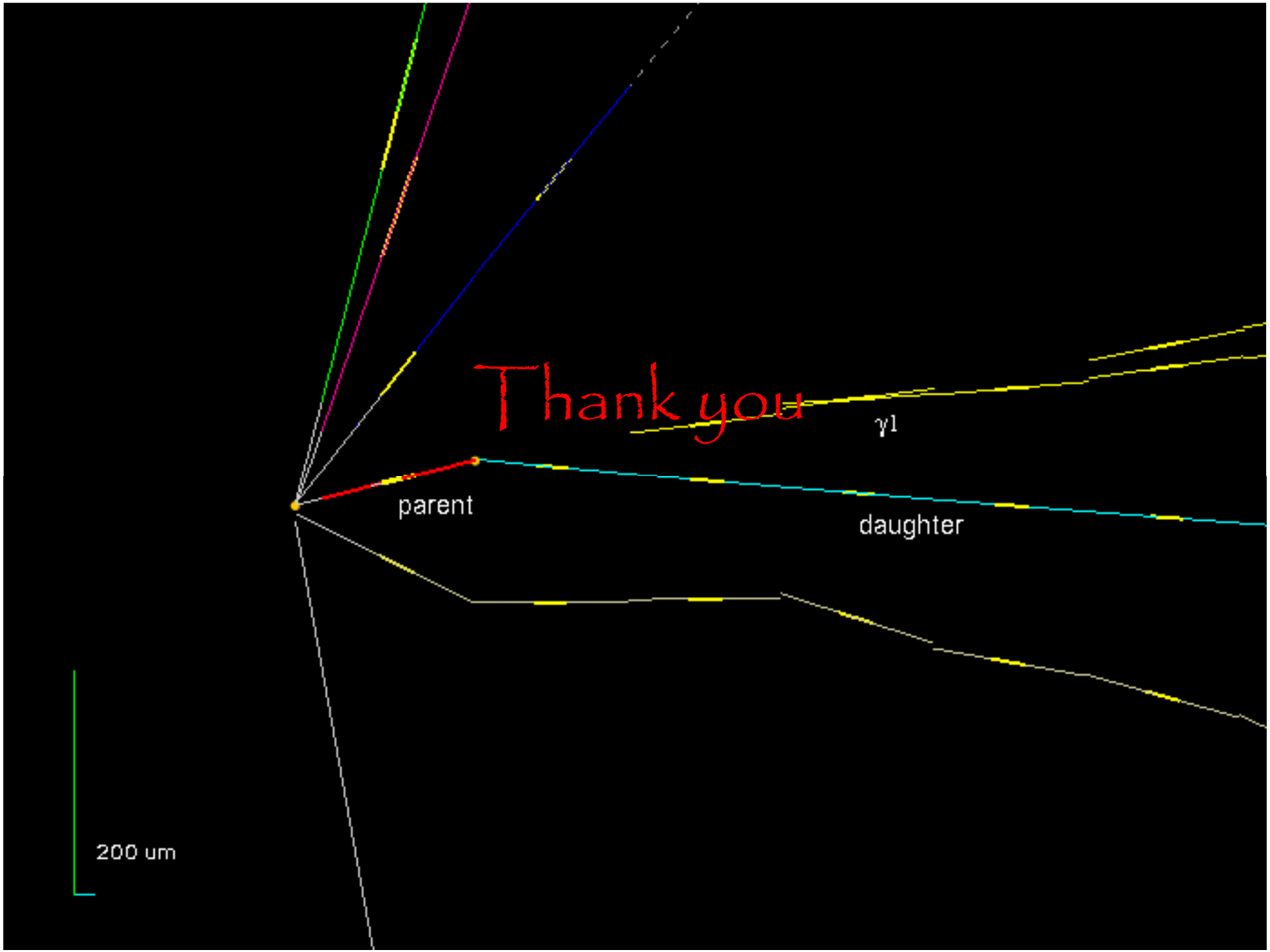
$\sin^2(2\theta_{13}) = 0.44$

$N_{expBG} = 4.6 \pm 0.7(sys)$, $N_{obs} = 4$ ($E_{\nu\text{-}rec}$<20GeV)

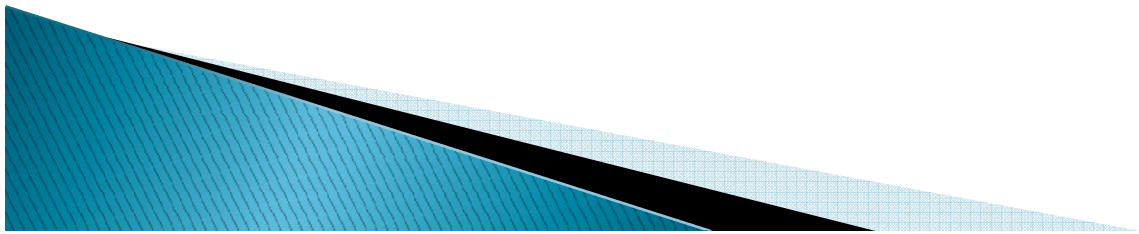
Observation is compatible with non-oscillation hypothesis

Summary

- OPERA successfully collected data from 2008 to 2012. CS/ECC analysis is going on.
- A total number of 18.0 x 10^{19} p.o.t integrated.
- $\nu_\mu \rightarrow \nu_\tau$ oscillation results:
  - 3 events found in the analyzed sample
  - 3.4σ significance
  - Likelihood method is under study
- $\nu_\mu \rightarrow \nu_e$ oscillation results:
  - Upper limit $\sin^2(2\theta_{13}) < 0.44$ at 90% CL

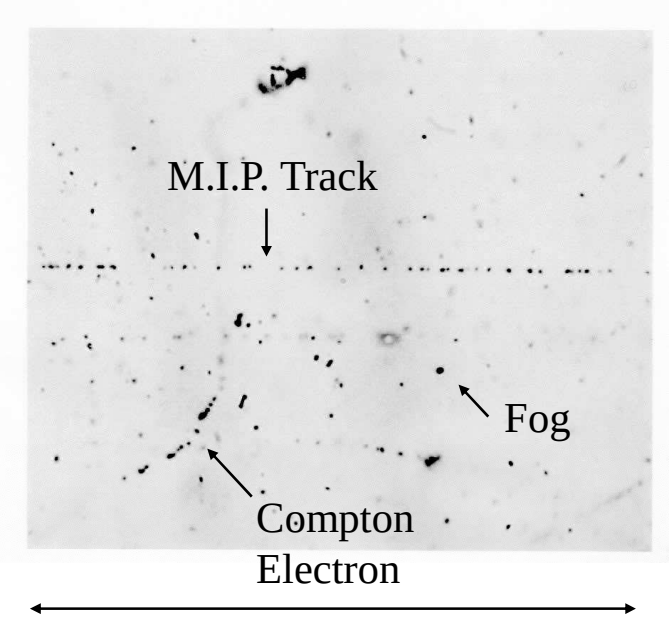

Thank you
γ1
parent
daughter
200 um

Backup

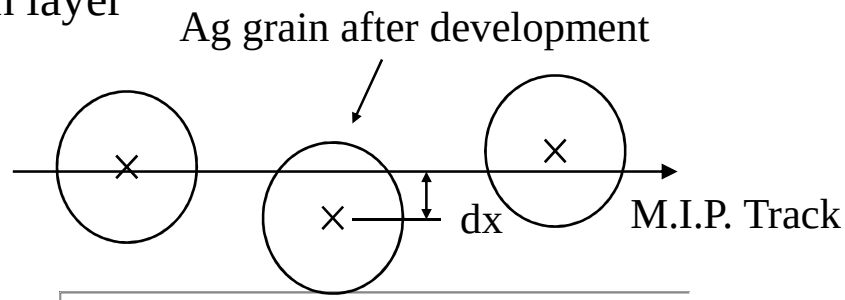


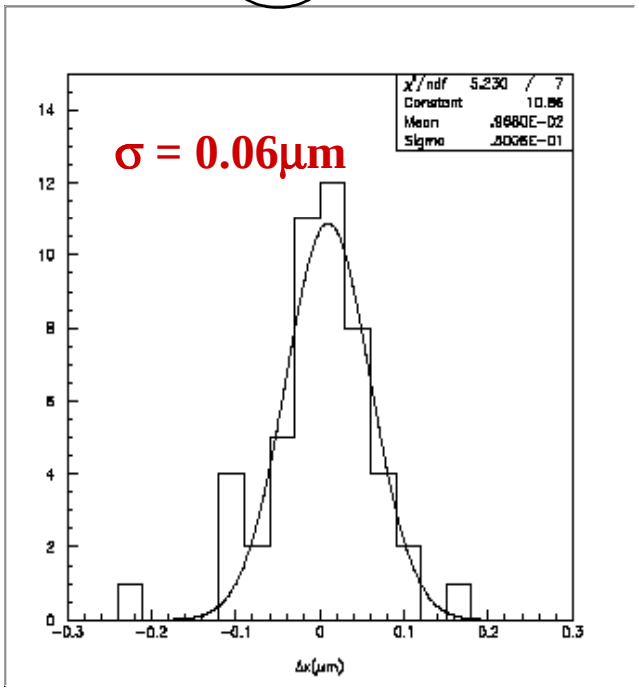
Intrinsic position resolution

Cross sectional view of an emulsion layer



30grains/100μm
grain diameter ~ 0.6μm



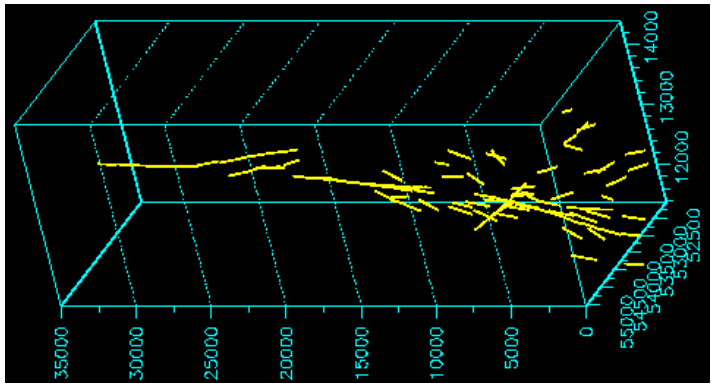


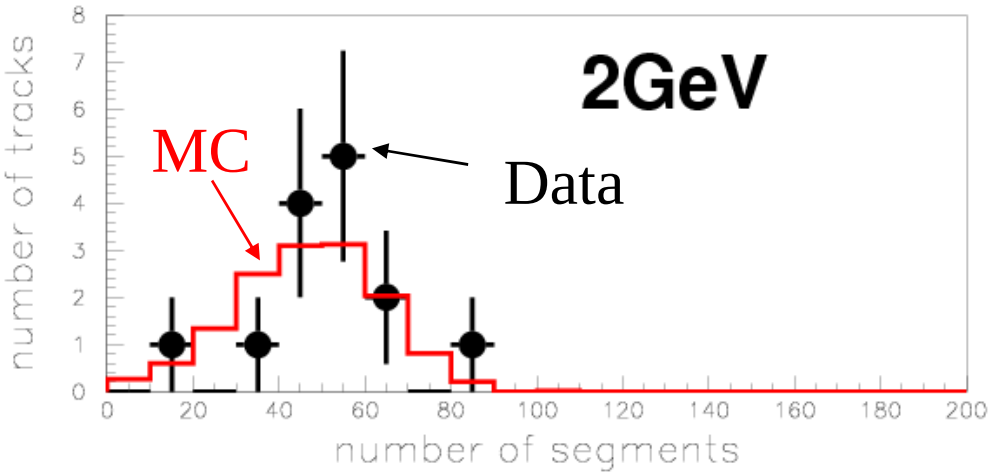
One Emulsion Layer = vector chamber with 60nm position resolution

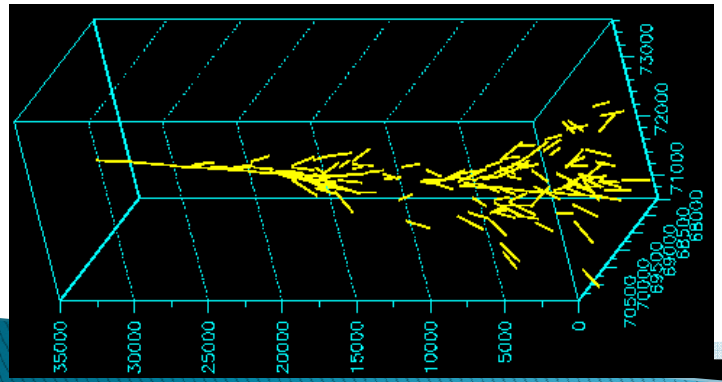
& ~1mrad Angular resolution (100micron layer)

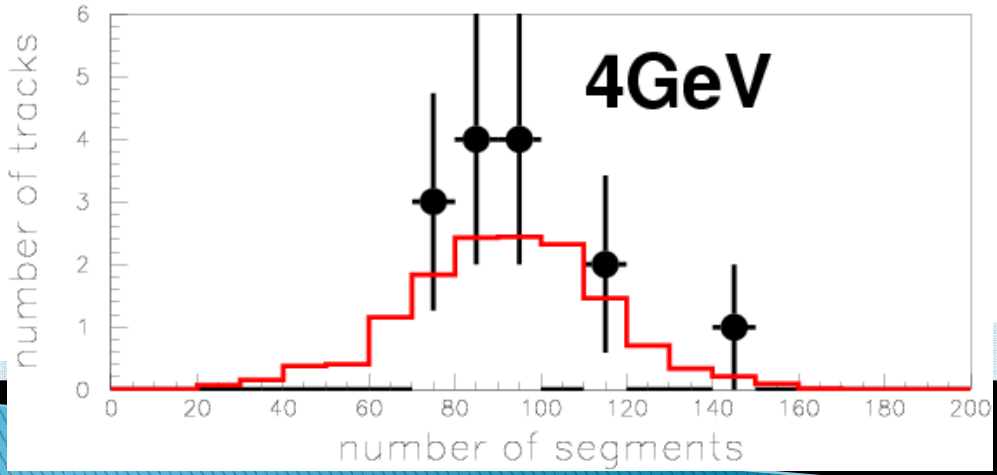
Electron energy measurement

Test exp. @ CERN









Energy determination by calorimetric method (in study)

$$\frac{\Delta E}{E} \sim \frac{0.4}{\sqrt{E(GeV)}}$$ @ a few GeV

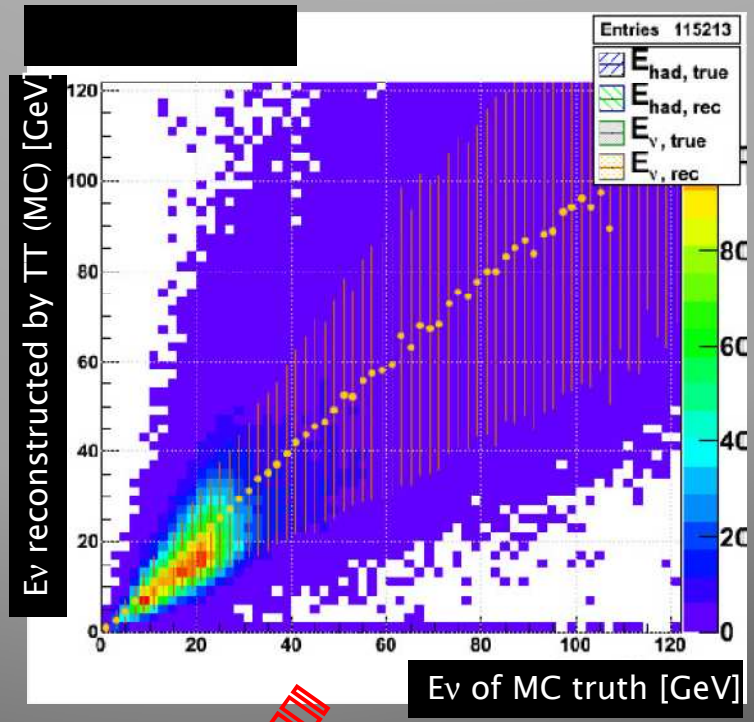
ν_e energy estimation

- Reconstruct the energy deposition (E_{vis}) in Target Tracker.

- Obtain the fitting parameter from E_{vis} to reconstructed ν_e energy (E_{ve_rec}) through the MC simulation.

⇩

Estimate the E_{ve_rec}



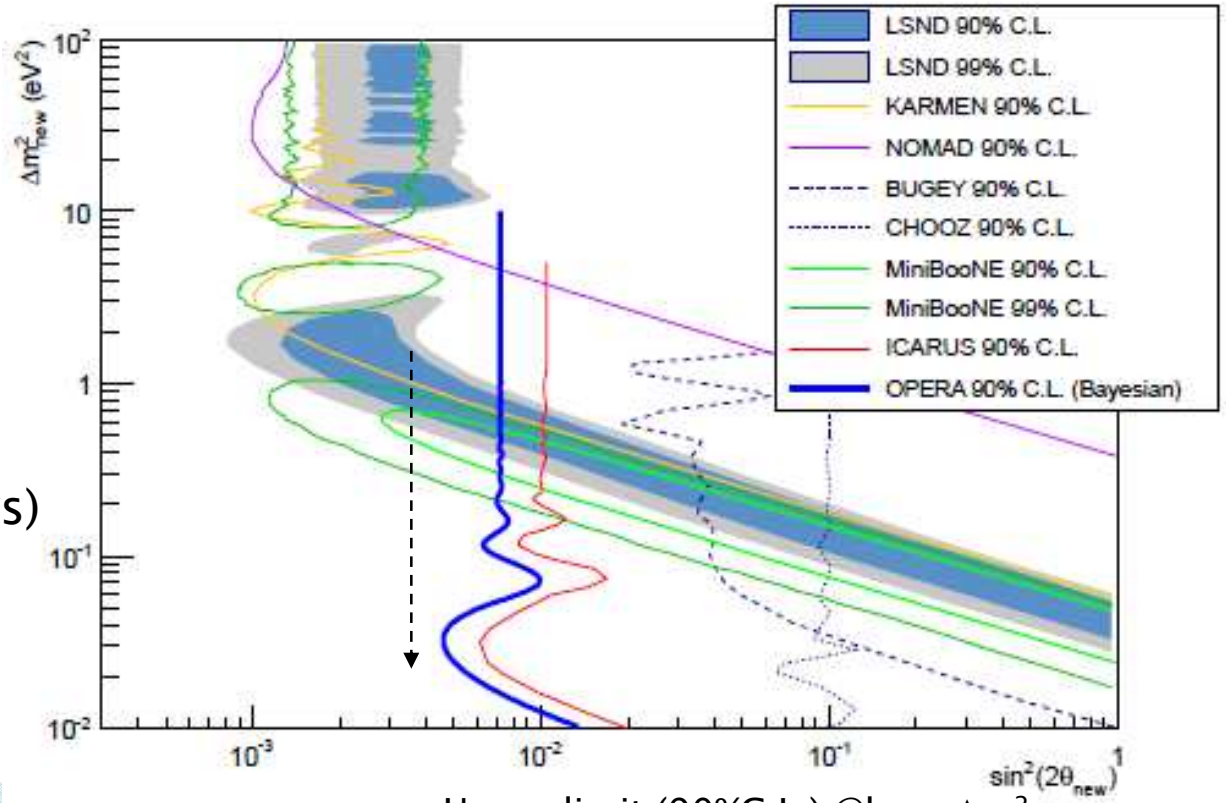
Energy resolution

$\Delta E / E = 0.37 + 0.74 / \mathrm{sqrt}(E)$

OPERA $\nu_\mu \rightarrow \nu_e$ oscillation results

(in 2008+2009 data set)

2 flavor mixing model for non-standard oscillation
with a dominant mass scale
(analysis for LSND-MiniBooNE observation results)



$N_{expBG} = 9.4 \pm 1.3(sys)$
$N_{obs} = 6$
($E_{\nu-rec} < 30GeV$)

Upper limit (90%C.L.) @largeΔm^2
$\sin^2(2\theta_{new}) = 7.2 \times 10^{-3}$