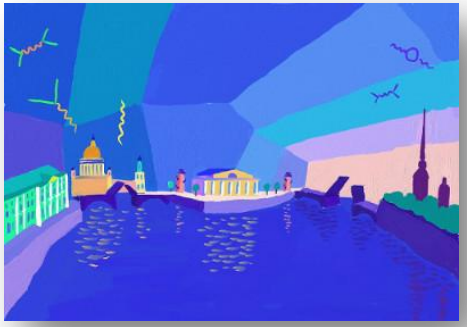
OPERA, Emulsion Scanning, Analysis and Recent Results on Muon-Neutrino to Electron-Neutrino Oscillations

Çağın KAMIŞCIOĞLU
(METU- Turkey)



On behalf of the OPERA Collaboration

The XXI International Workshop
High Energy Physics and Quantum Field Theory
June 23 – June 30, 2013
Saint Petersburg Area, Russia

Outline of The Talk

- *The OPERA Experiment*
  - *Data Taking*
- *ECC Event Reconstruction*
  - *Scanning*
  - *Decay Search*
- *ν_μ --> ν_e Oscillation*
  - *Electromagnetic shower reconstruction*
- *Conclusion*

The OPERA Collaboration

140 physicists, 28 institutions in 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

Switzerland
Bern

Turkey
METU, Ankara

http://operaweb.lngs.infn.it

The Physics Case

The OPERA experiment was mainly designed to unambiguously prove the oscillation phenomenon through <u>direct</u> ν_τ appearance

OPERA: FIRST DIRECT DETECTION OF NEUTRINO OSCILLATIONS IN APPEARANCE MODE

3x3 Unitary Mixing Matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric terms **Unknown terms** **Solar terms**

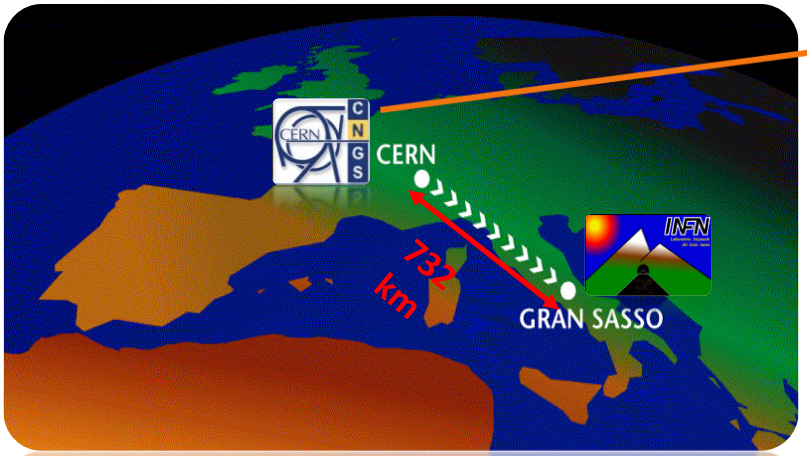
$c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$

$$P(\nu_\mu\rightarrow\nu_e)=\sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2(1.27\Delta m^2_{23}L/E)$$

$$P(\nu_\mu\rightarrow\nu_\tau)=\cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2(1.27\Delta m^2_{23}L/E)$$

dominant channel

Oscillation Project with Emulsion tRacking Apparatus



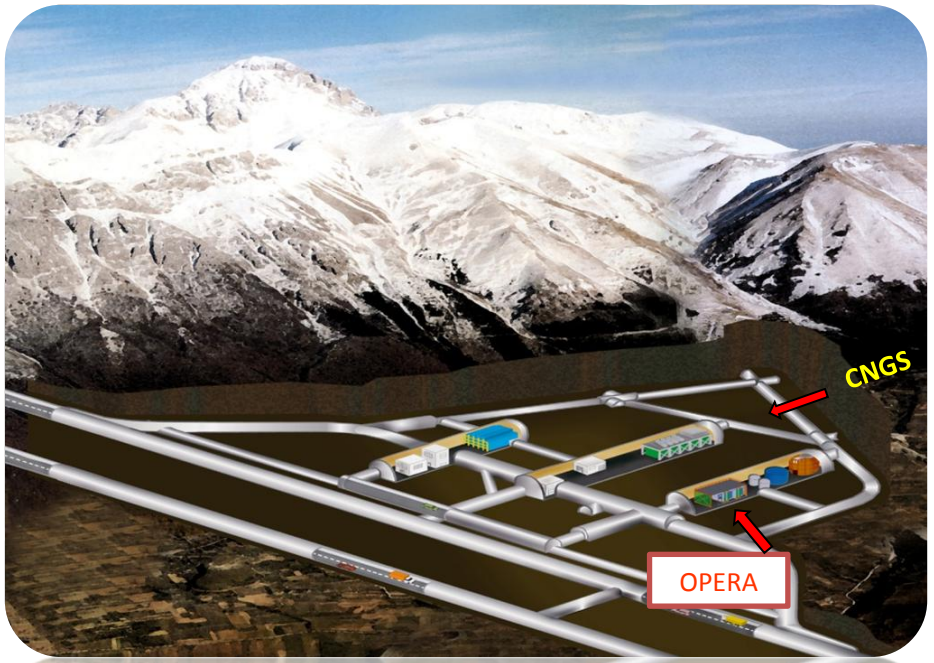
CNGS

CERN Neutrino to Gran Sasso beam

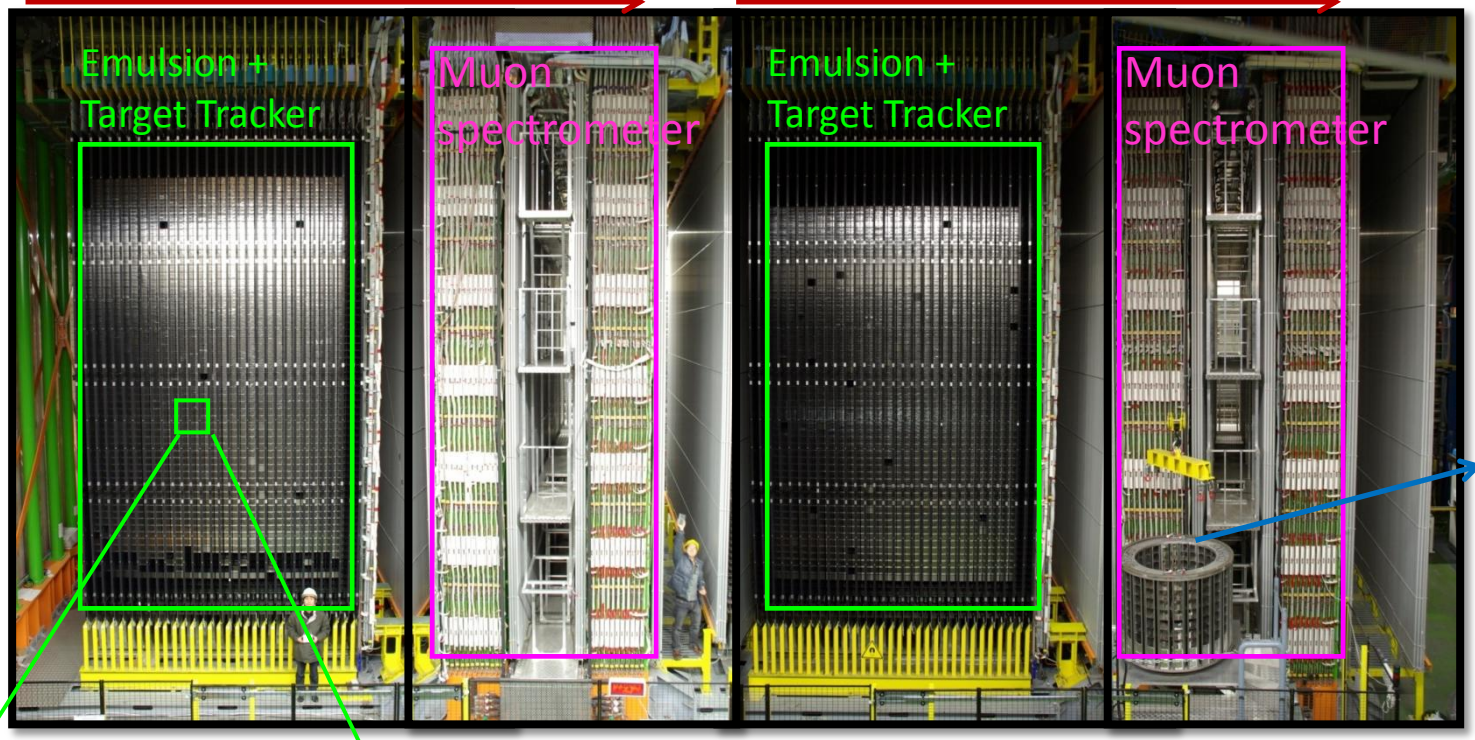
High energy ν_μ beam from CERN to Gran Sasso

OPERA requires :

1) long baseline,
2) high neutrino energy,
3) high beam intensity
4) detection of short lived τ's



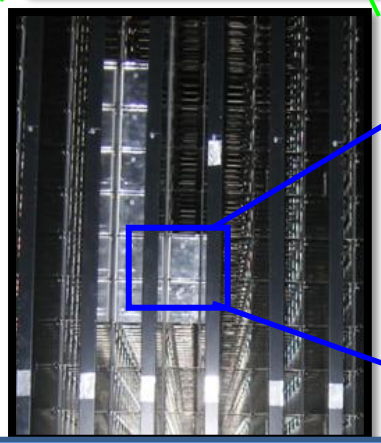
The OPERA Detector

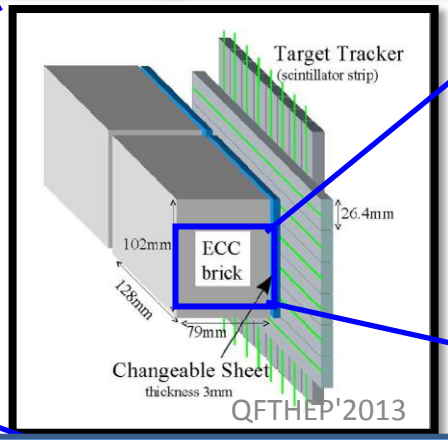


2 supermodules,
31 walls,
150,000 bricks

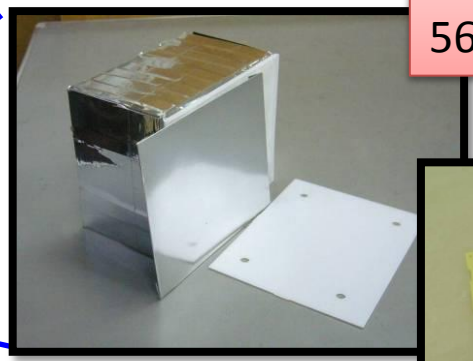
Target mass:
1.2 ktons

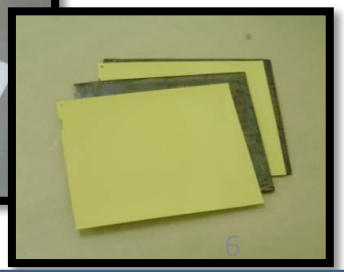
BMS
Brick Manipulator System





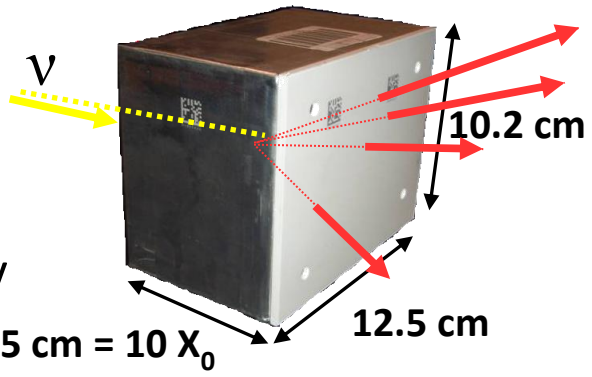
57 emulsion films
56 Pb plate



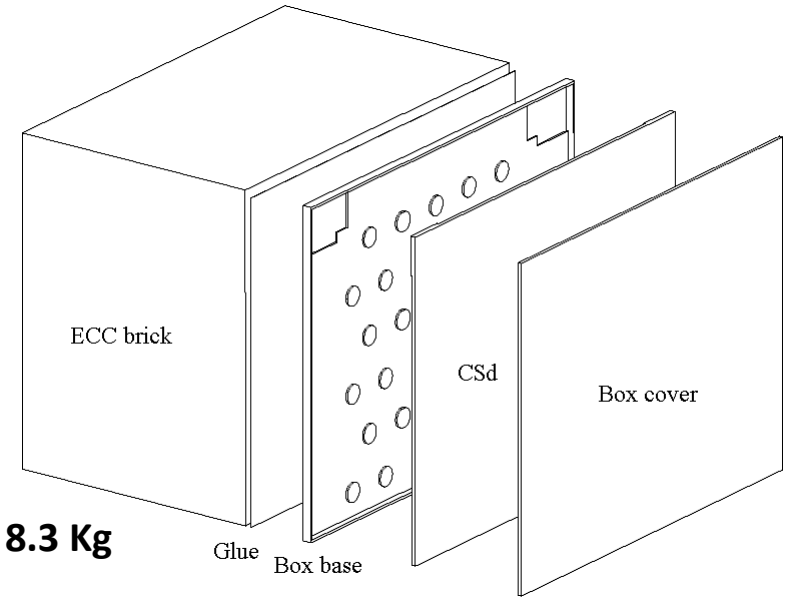


The OPERA Brick

The target principle: the 'brick'



- ECC brick= sequence of emulsion-lead layers
  - High resolution and large mass in a modular way
- The brick is the basic component
  - 57 nuclear emulsion films interleaved with 1 mm thick lead plates
  - a box with a removable pair of films called **Changeable Sheets**

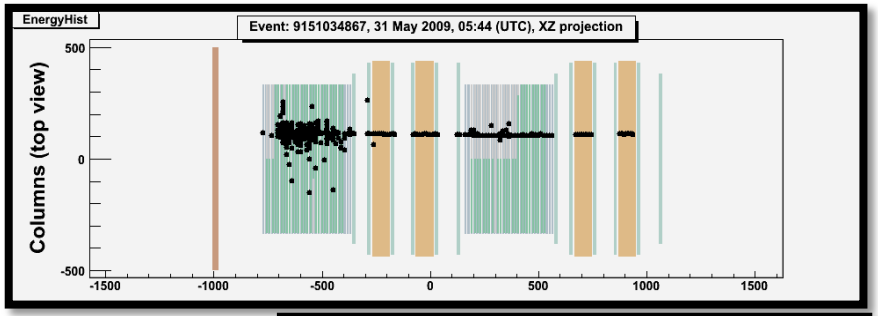


Track reconstruction accuracy in emulsions: $\Delta x \approx 1\ \mu m$ $\Delta\theta \approx 2$ mrad

The "BRICK" can provide:
- neutrino vertex reconstruction
- search for decay topologies
- electron ID and energy measurement

The Data Taking

OPERA as a real-time detector, CERN-LNGS synchronization based on GPS. Precision 100 ns



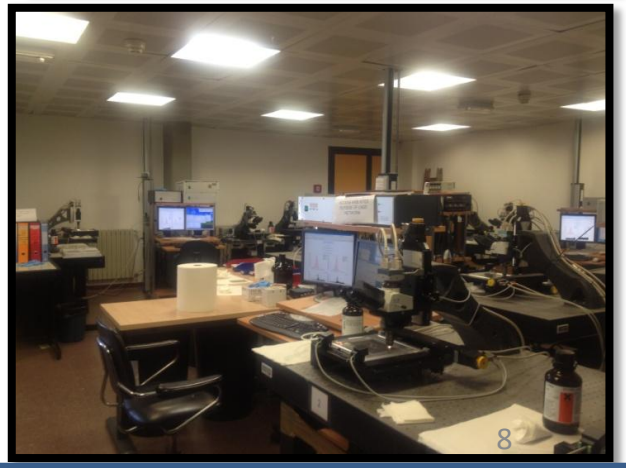
Trigger + event selection "on time" with CNGS

Brick finding reconstruction algorithm applied to electronic data to select the best candidate brick to contain the neutrino interaction vertex

Brick removed by the *Brick Manipulation System (BMS)* and exposed to *frontal X-rays* to make an alignment reference between CS and brick

CS detached from brick, films developed and analysed in one of the *CS Scanning Stations*, in Europe (LNGS) or Japan (Nagoya)

If a TT-predicted track is found in the CS, the *brick* is exposed to *lateral X-rays* beam and to *cosmic rays* for sheets alignment. Brick is disassembled and emulsion films *developed* and sent to one of the scanning labs

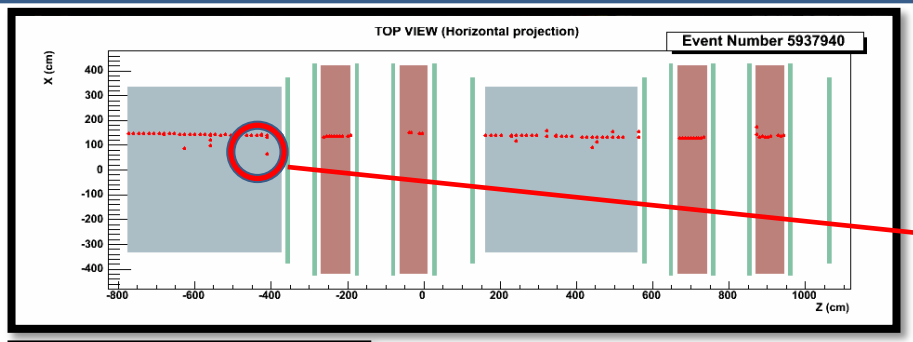


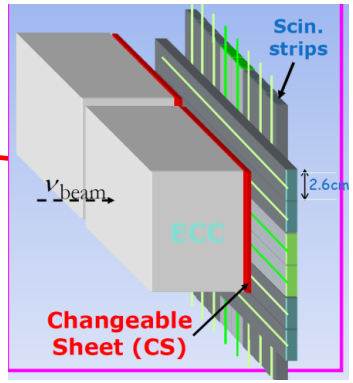
Tracks found in the CS are searched for in the most downstream film of the brick and followed

A *volume scan* around the neutrino interaction point is performed and the neutrino vertex is located and studied

The Data Taking

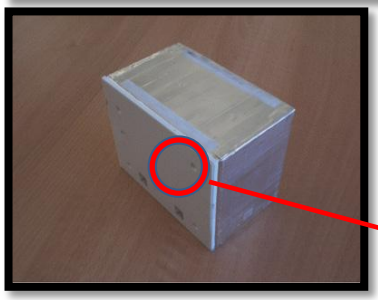
1

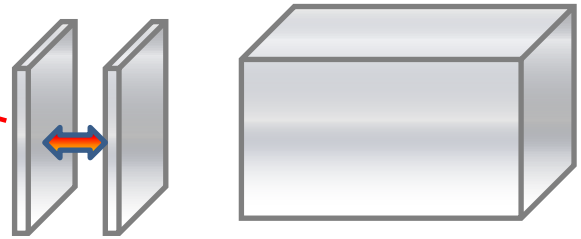




TT-CS Connection

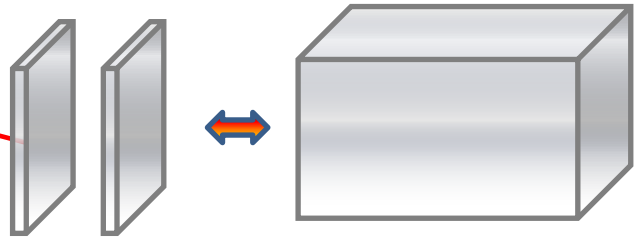
2





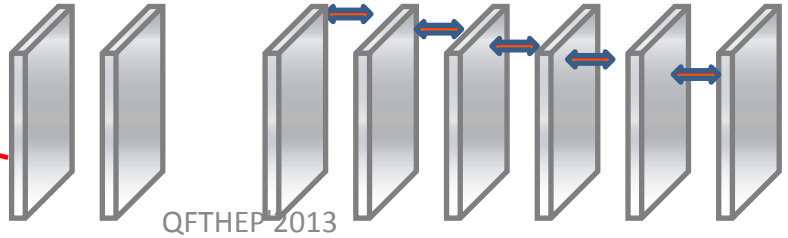
CS film to film Connection

3



CS-to-ECC Brick connection

4



ECC brick film-to-film connection

Automated Emulsion Scanning

CS and bricks are shared among emulsion scanning labs:

Europe

ESS microscope

CMOS camera

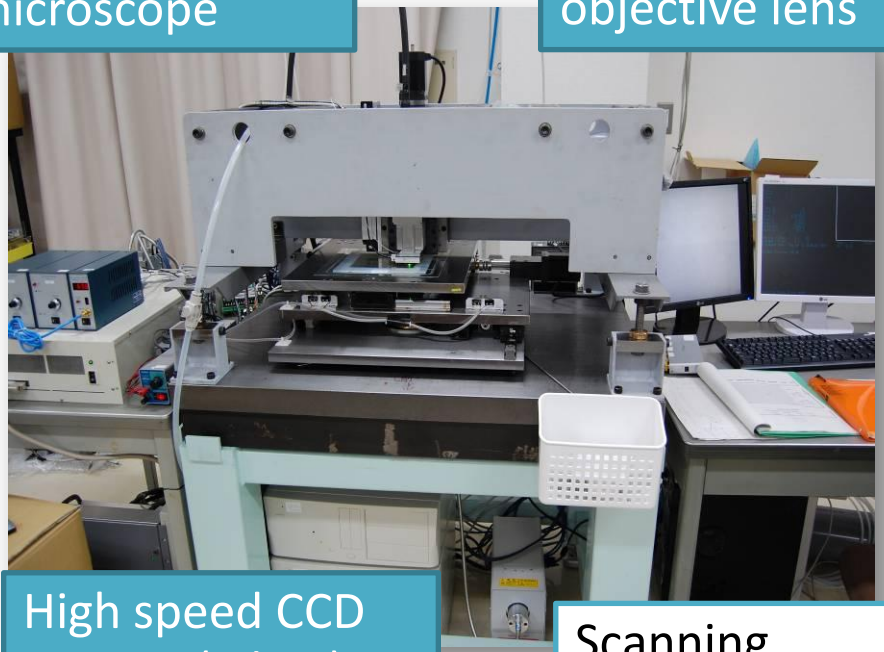
Commercial hardware
Software algorithms

Scanning speed 20 cm^2/h

Japan

S-UTS microscope

Piezo-controlled objective lens



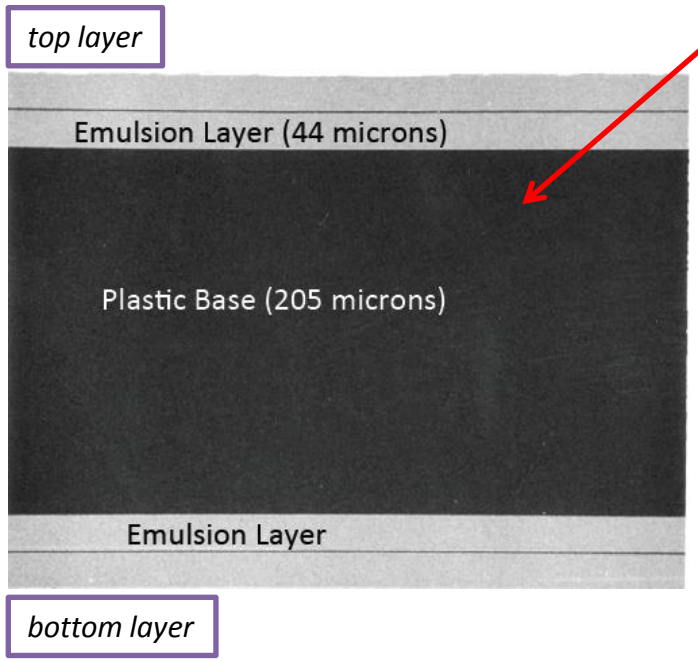
High speed CCD camera (3 kHz)

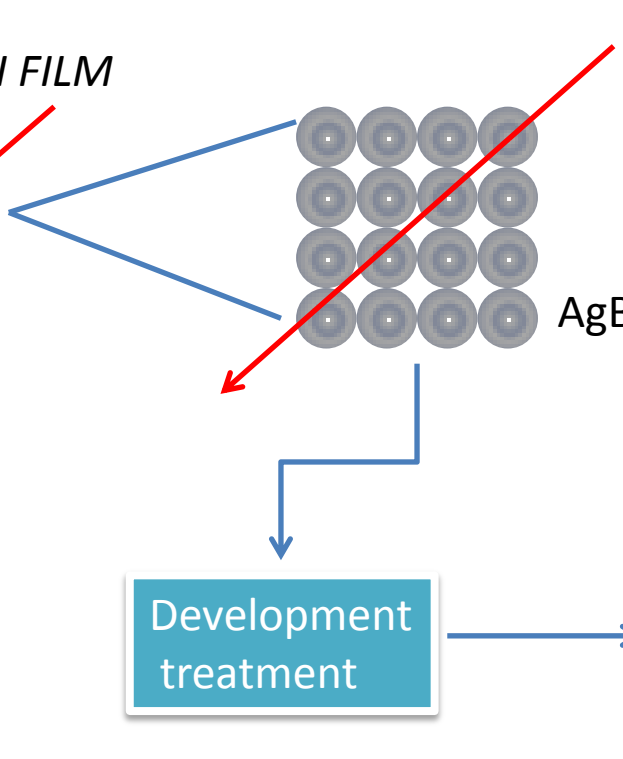
Hard-coded algorithms and custom mechanics

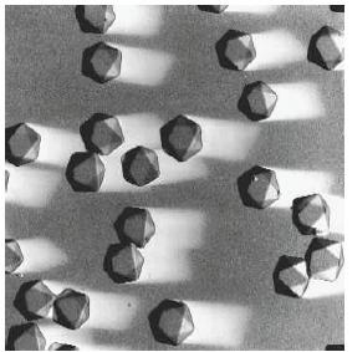
Scanning speed up to 75 cm^2/h

Emulsion

INDUSTRIAL EMULSION FILMS BY *FUJI FILM*







basic detector: AgBr crystal,

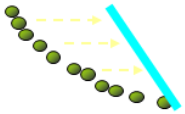
size = 0.2 micron

detection eff.= 0.16/crystal

10^{13} "detectors" per film

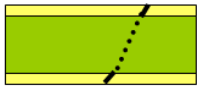
Emulsion Scanning

3D Microtracks reconstruction

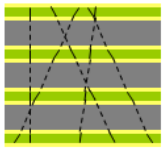


Microtracks alignment via the plastic base

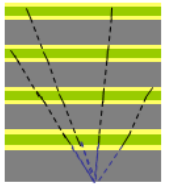
BASETRACK

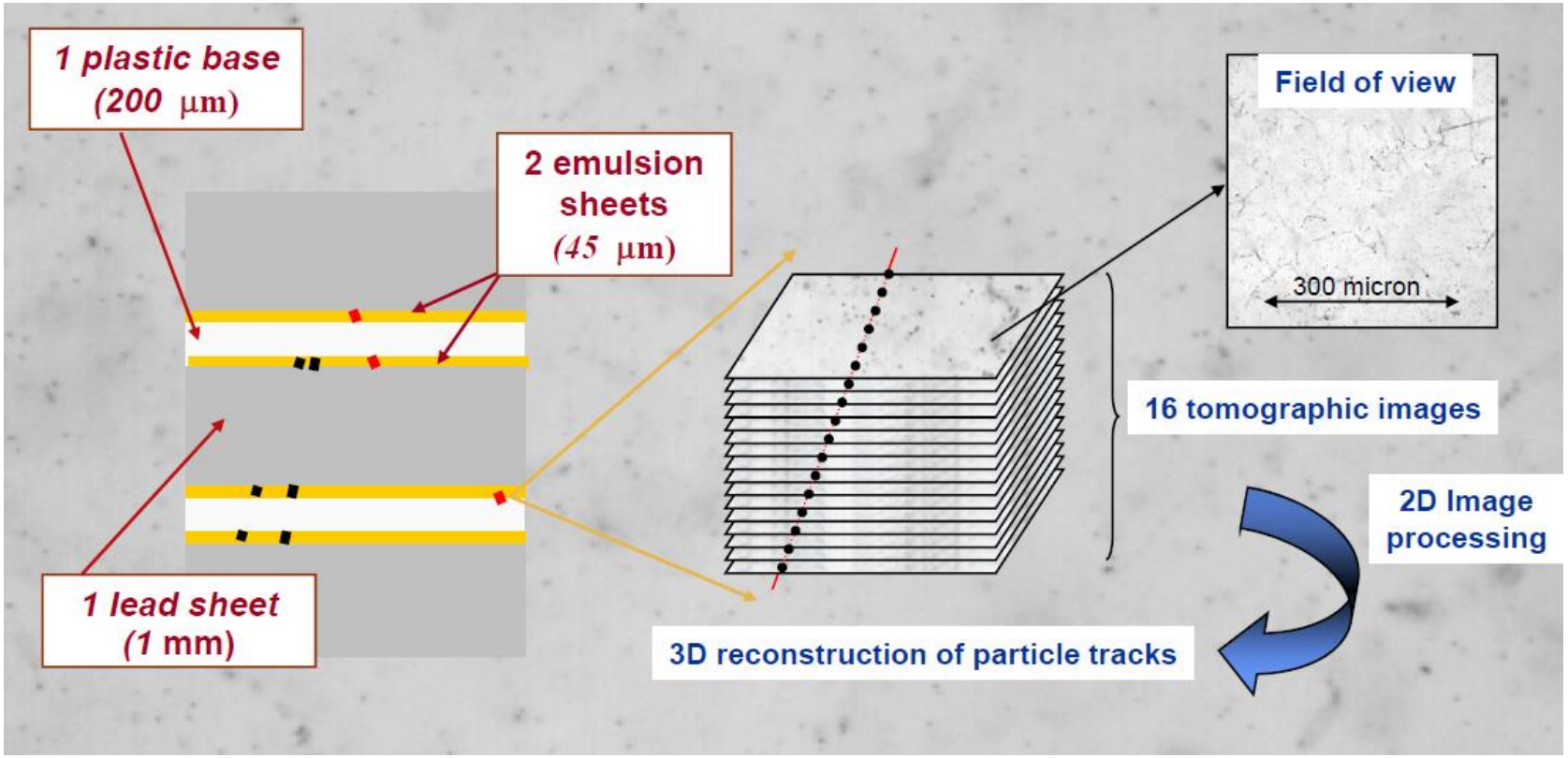


Basetracks alignment of several emulsions



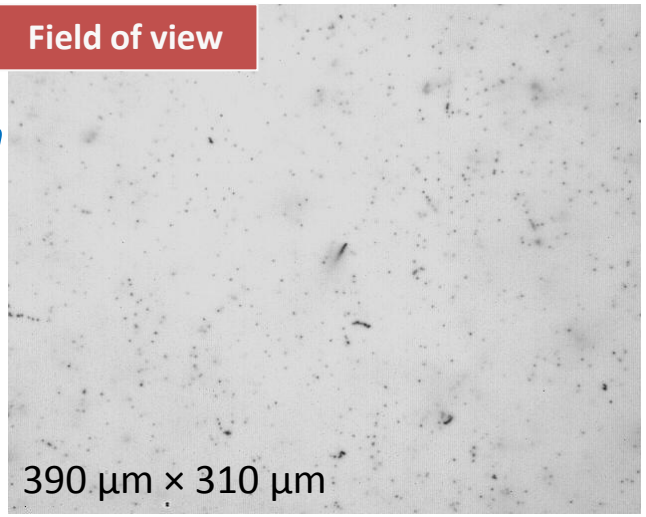
Reconstruction Vertex/Decay



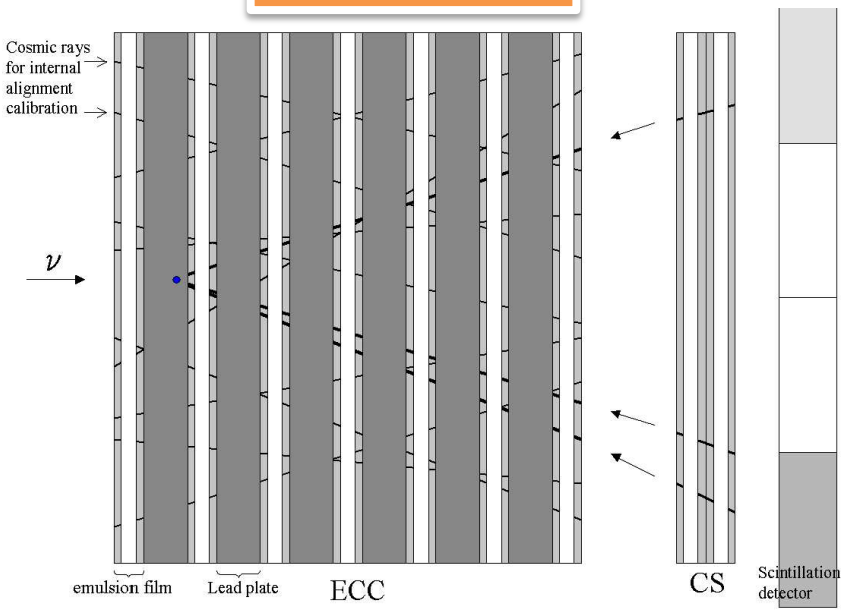


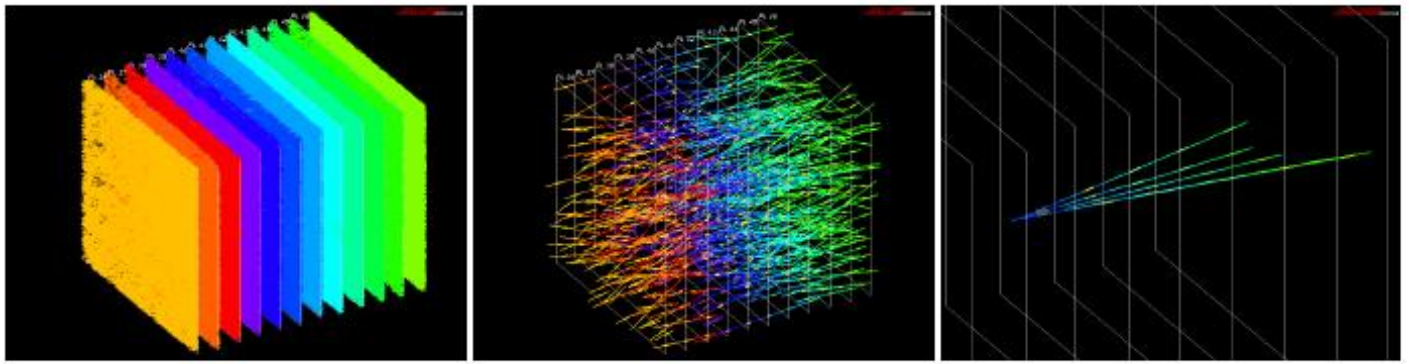
ECC Event Reconstruction

1. CS Scanning
   - Manual Check
2. Event Location
   - Manual Check
3. Volume Scan
   - Manual Check
4. Decay Search
   - Manual Check
5. Publish



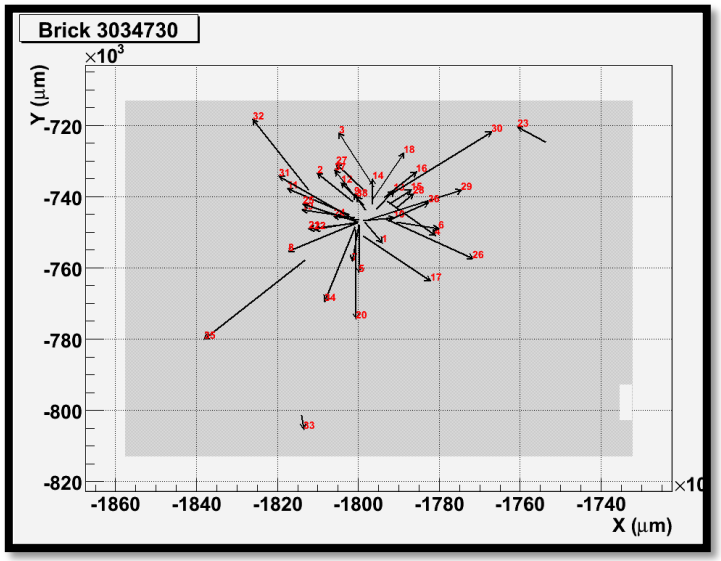
Vertex Finding





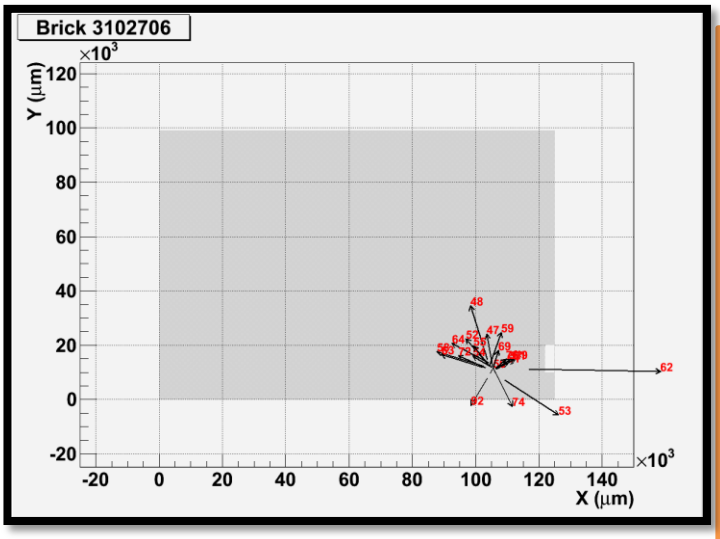
Track follow-up film by film:
- alignment using cosmic ray tracks
- definition of the stopping point

1. Changeable Sheet Scanning

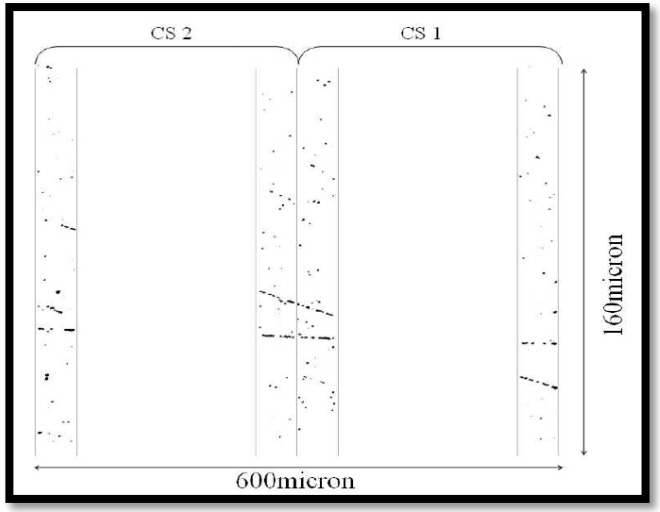


vertex signature already evident in the CS

The scanning is performed at the CS Scanning station, located at the Gran Sasso laboratory, and in the Nagoya scanning laboratory

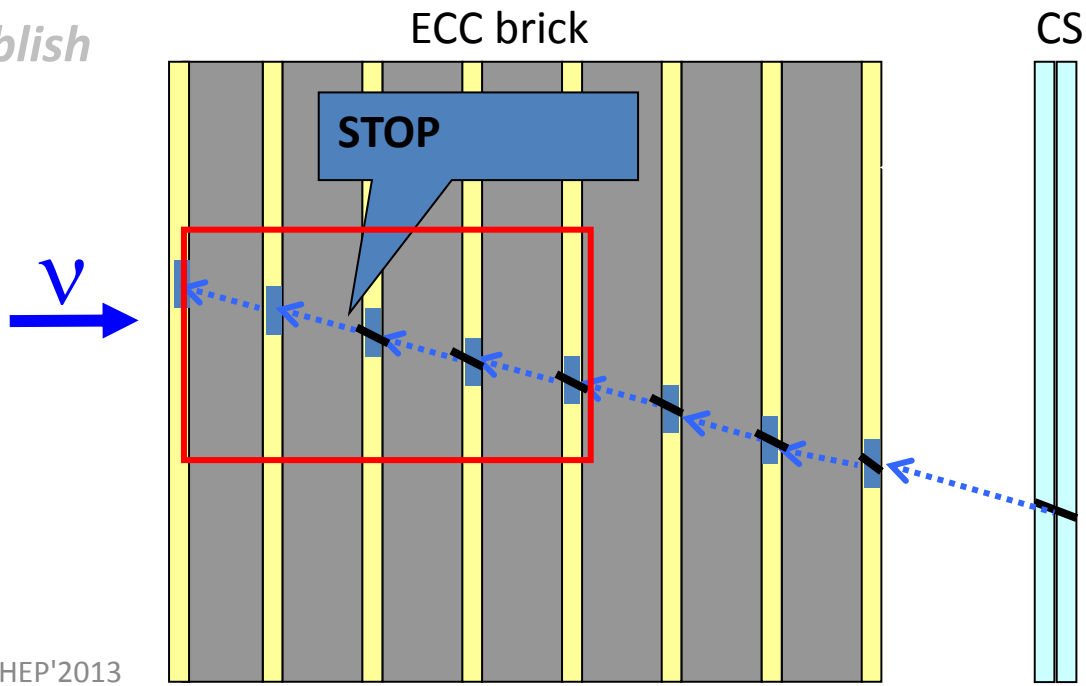


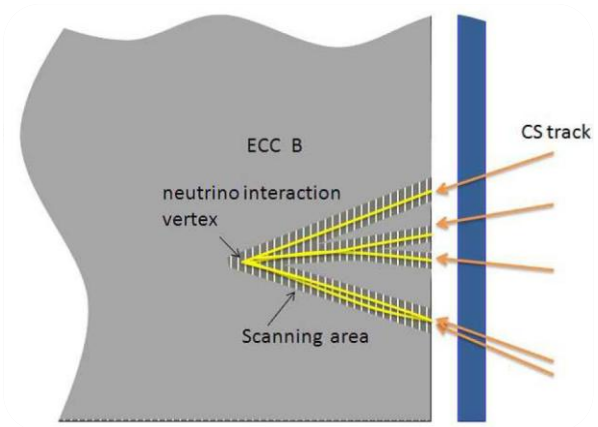
In the CS scanning, an area of ***4x6 cm²*** *per emulsion is scanned around* the muon prediction in case of CC interactions, for NC events a larger area is scanned.



2. Event Location

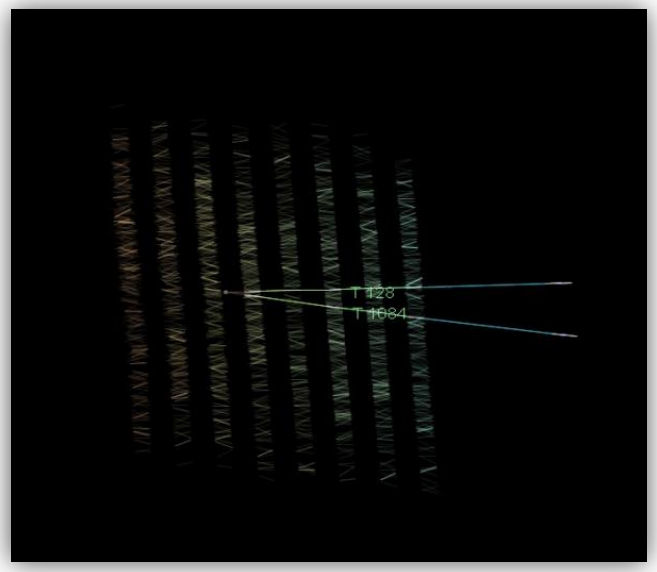
During the Scanback procedure the extrapolations of the CS tracks back into the brick are followed upstream, until the tracks can not be found anymore. To find the CS track prediction in the first emulsion plate, an area of ***3 x 3mm²*** *is scanned.*

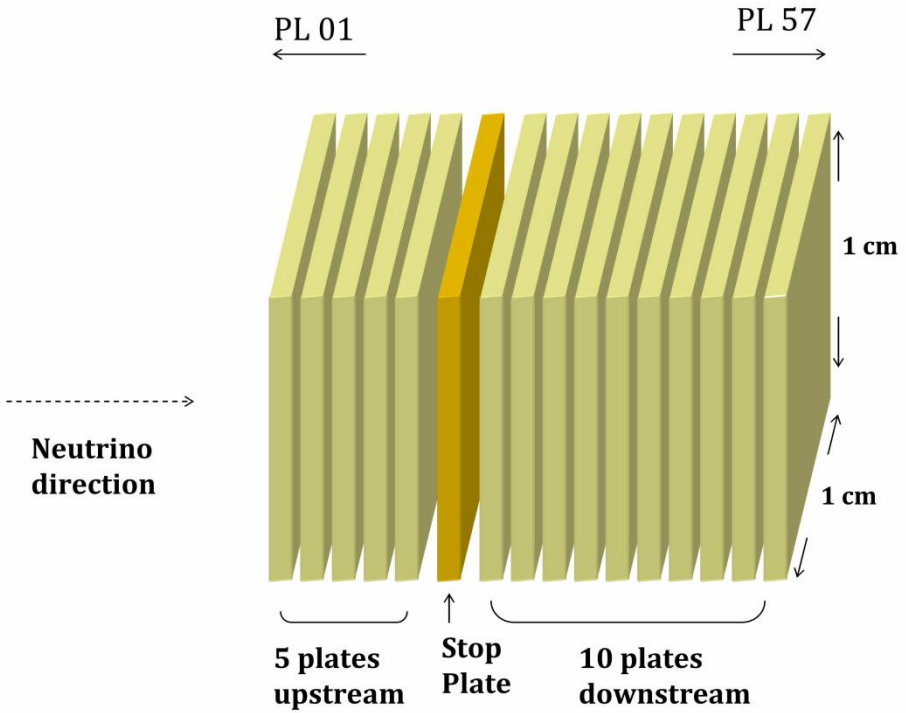




3. Volume Scan

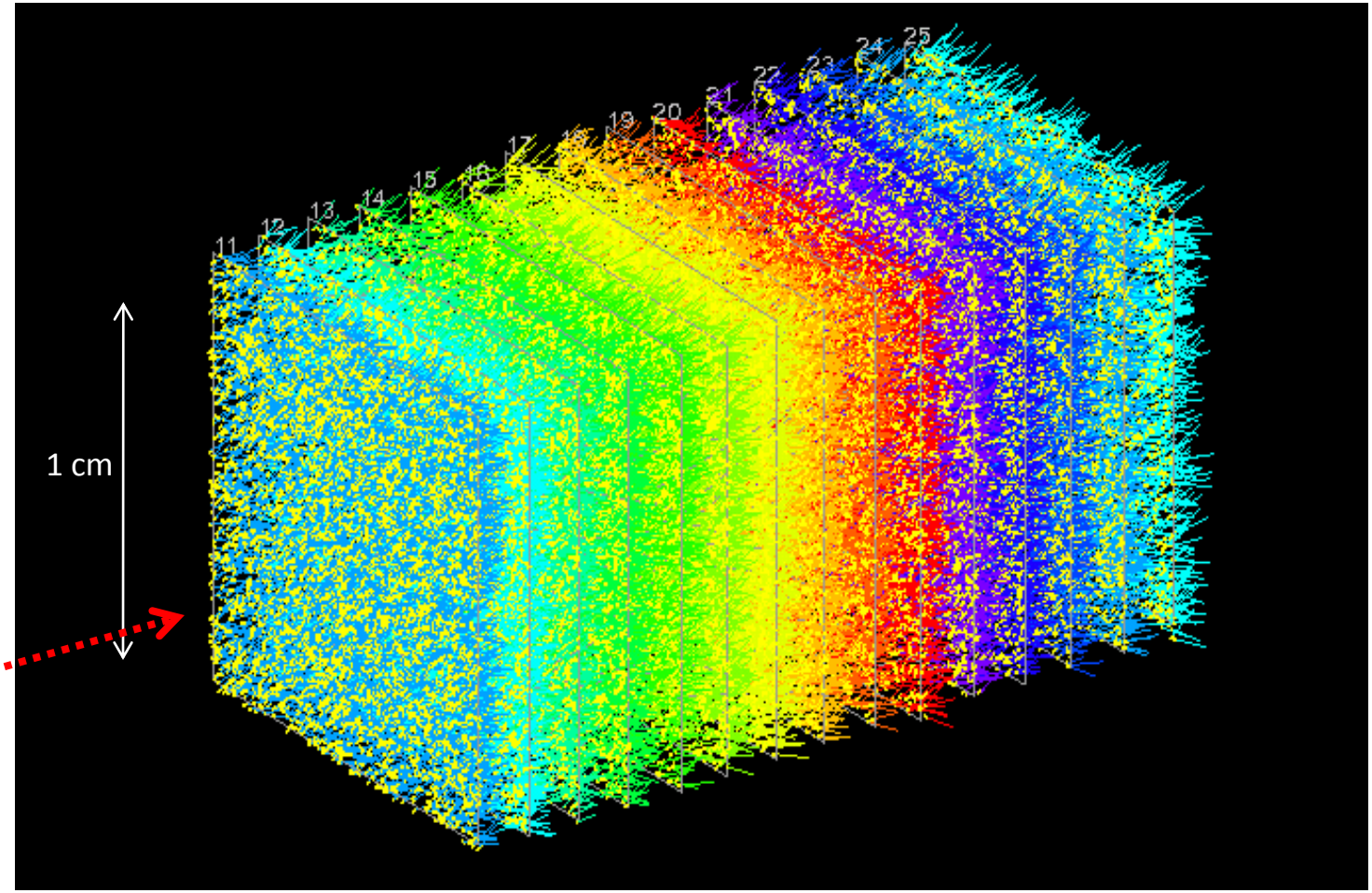
After the CS tracks were followed and the stopping point was confirmed , the volume scan must be performed. The scanning volume consists of 15 consecutive plates, **10 downstream of the stopping point, 5 upstream,** each scanned with an area of **1 cm².**





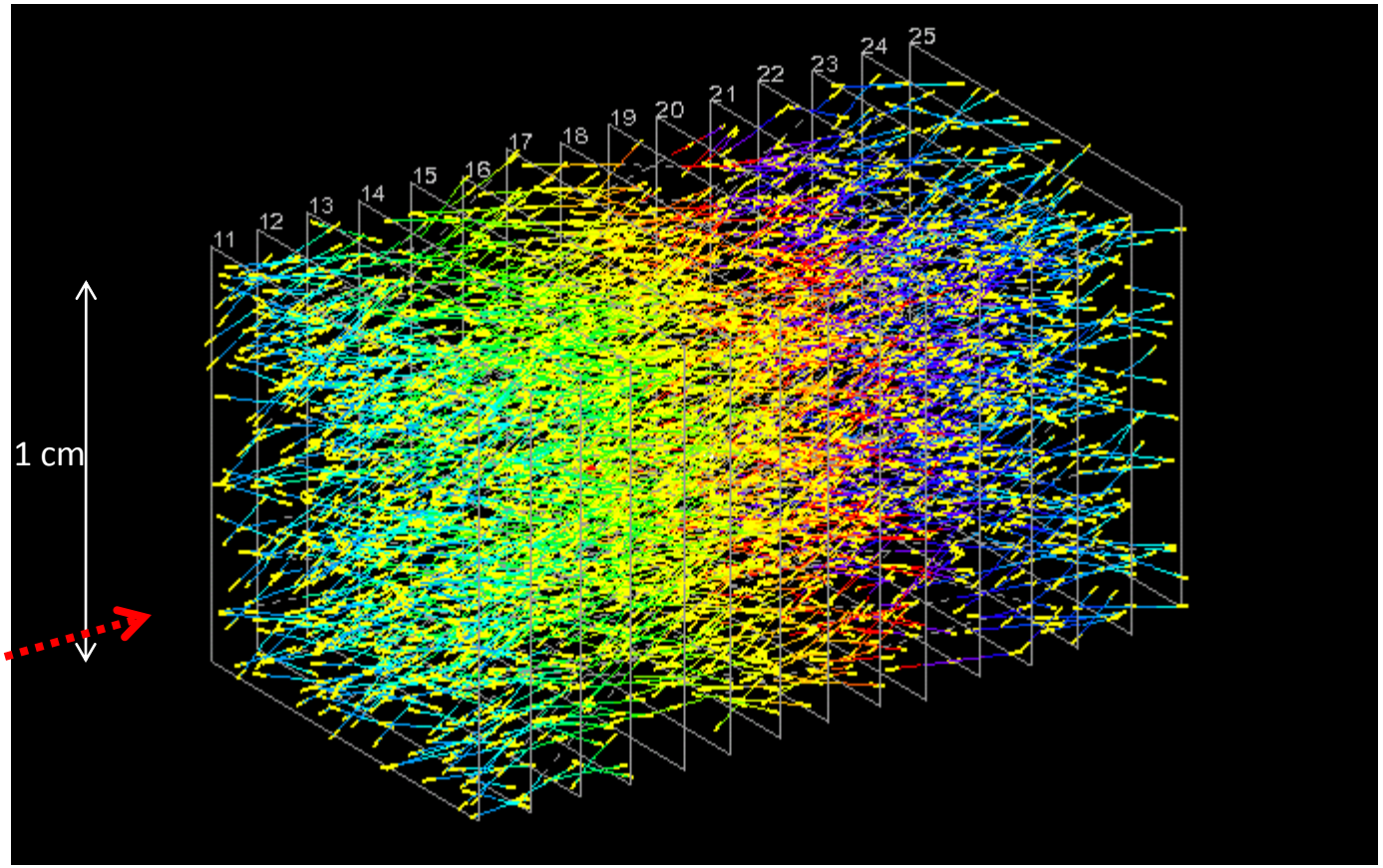
Located Neutrino Interaction in ECC Brick

Scan about 10 plates around stop plate by follow up from downstream.



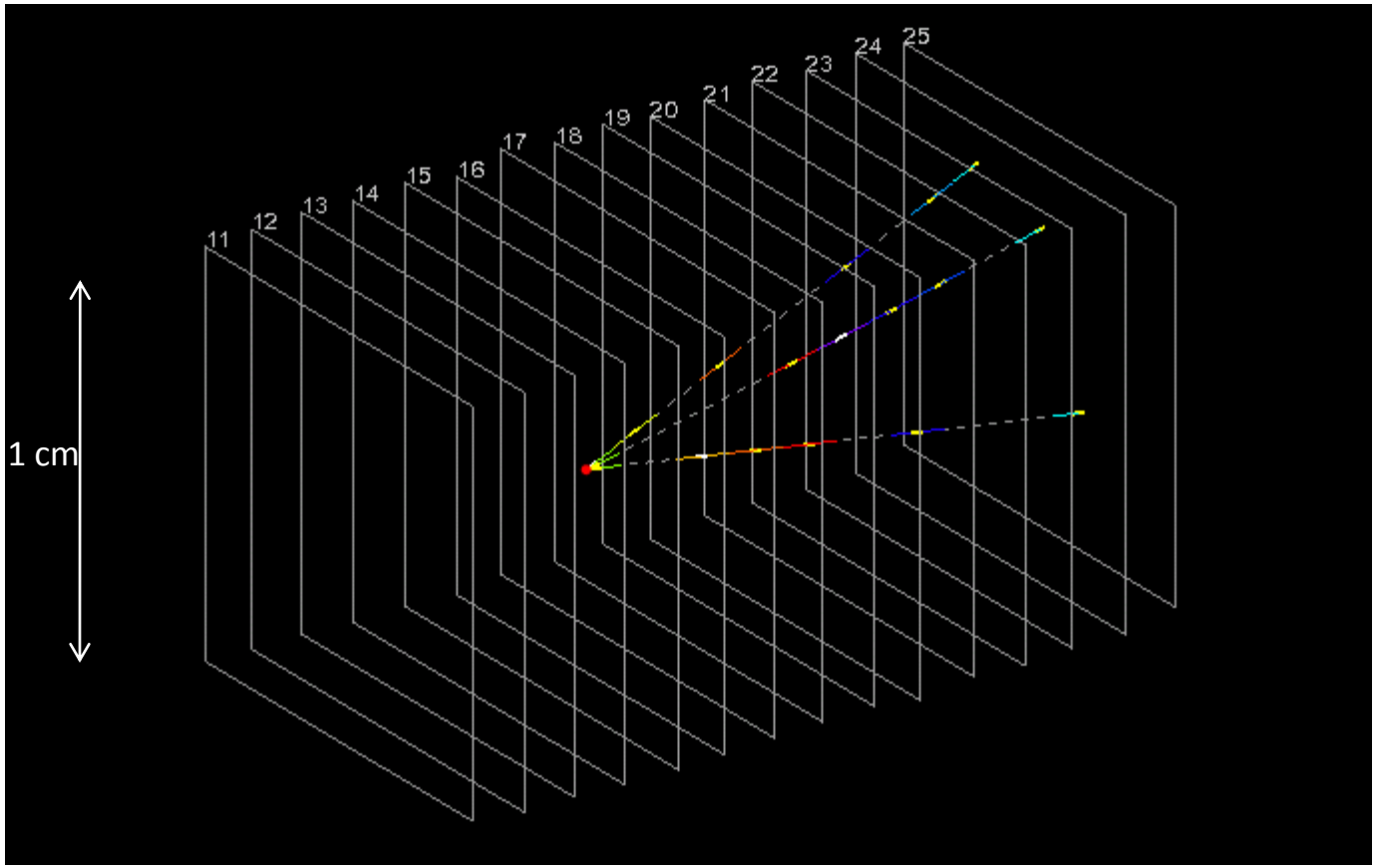
Located Neutrino Interaction in ECC Brick

Applying cuts to eliminate the background tracks.



Located Neutrino Interaction in ECC Brick

Search tracks making vertex by neutrino interaction .



4. Decay Search

Decay search is in progress and special events have already been found.

The Decay Search Procedure is performed to find ; possible events, as *τ or charm-decays and/or ν_e interactions, a topological search of decay daughters or* parent tracks is done, including a electron/gamma separation search for showers.

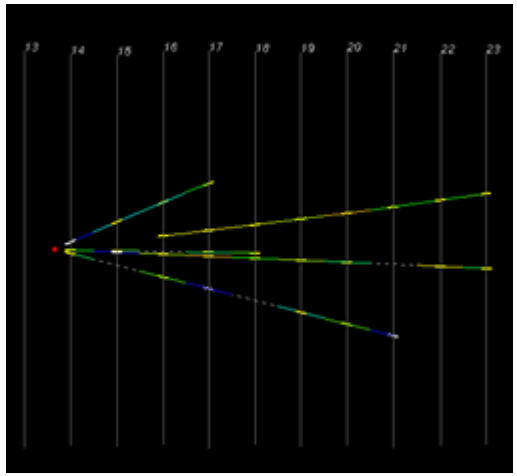
a multi-prong vertex has been reconstructed

a different procedure is applied

an isolated muon or hadron has been found

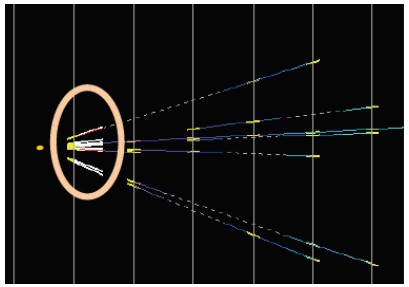
4.1. Events With A Reconstucted Vertex

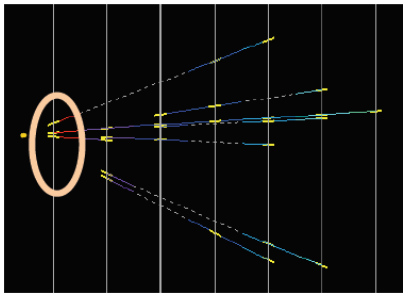
Decay Search



1. Vertex Definition And Analysis

- re-compute the vertex position.
- *e+e− pairs can be identified*
- recovery of missing segments
- *low momentum particles are excluded*





2. Extra-track Decay Search

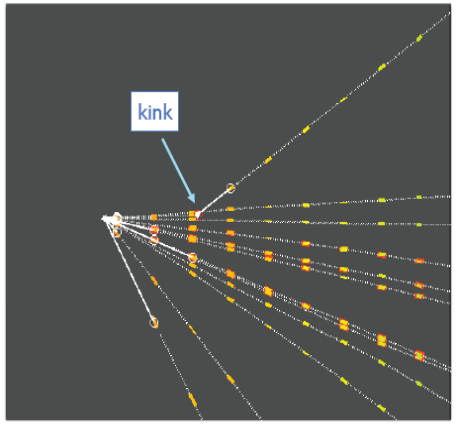
Searching for possible daughter tracks,

- $\Delta z < 3.6$ *mm*
- *the impact parameter < 300 μm*
- *the track has at least three segments*

the reconstruction.

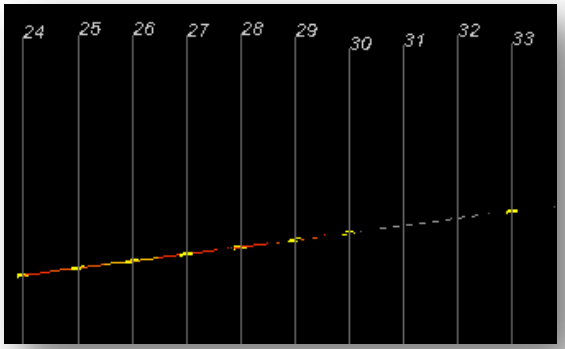
3. In-track Decay Search

A search for possible *small kinks along the tracks attached to the neutrino* interaction,

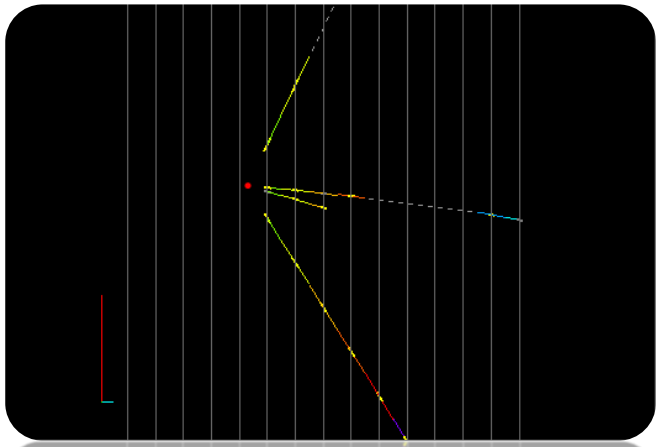


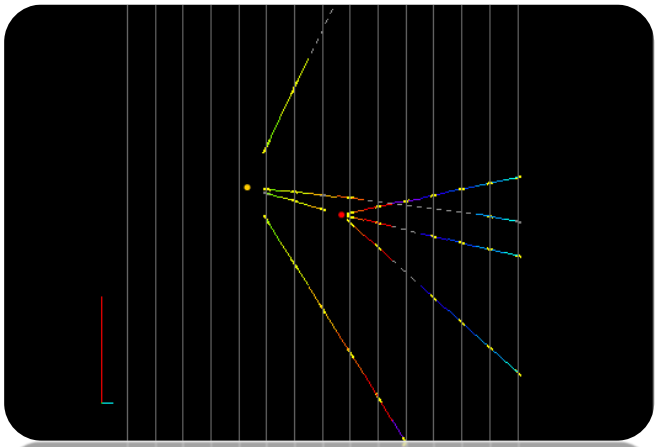
4.2. Events With An Isolated Muon Or Hadron

Decay Search



- *the most upstream segment is in any of the three emulsion films* upstream of the scan-back track stopping point or in any of the three films downstream of it;
- *the impact parameter, computed with respect to the extrapolation of* the scan-back track to the centre of the upstream lead plate, is smaller than 500 *μm;*
- *the track has at least three segments in the reconstruction.*



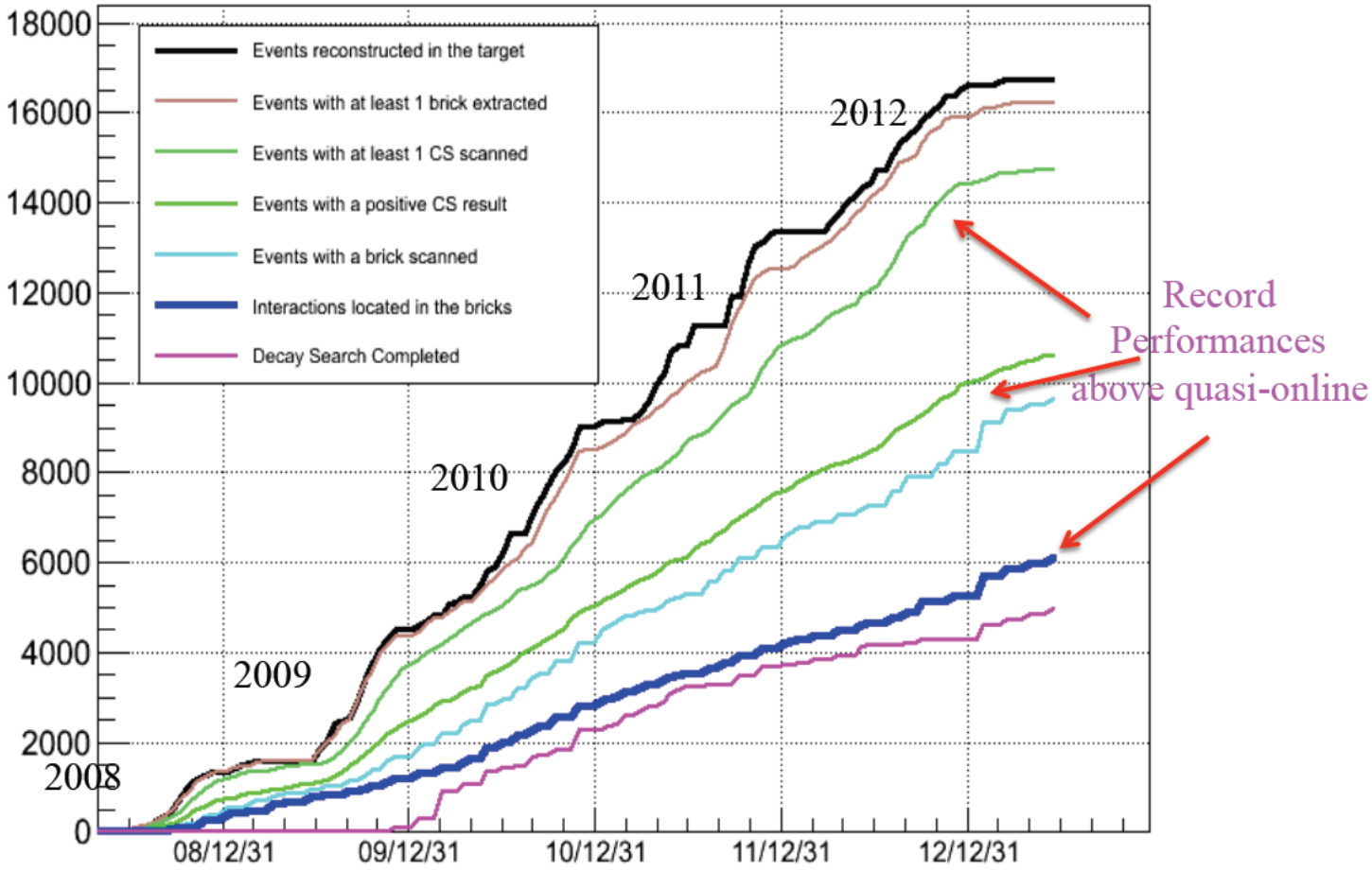


Performance

6067 located interactions
4969 decay search

2008 and 2009 completed
2010-2012 on going

Status of data analysis



Electromagnetic Shower Reconstruction

Electromagnetic shower reconstruction with emulsion films in the OPERA experiment

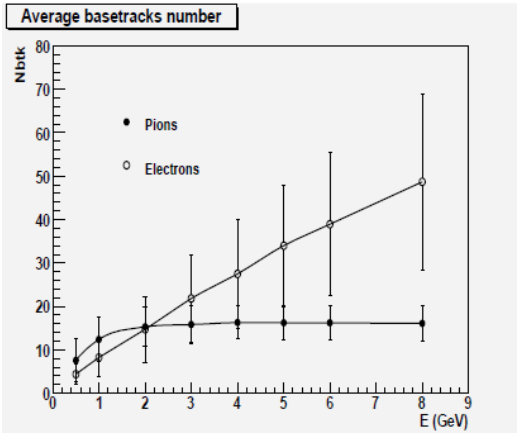
OPERA ECC

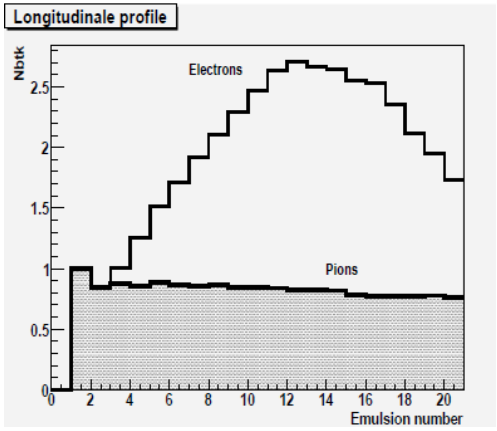
An algorithm for electron shower reconstruction have been developed

Electromagnetic shower reconstruction
e/π seperation
shower energy measurement

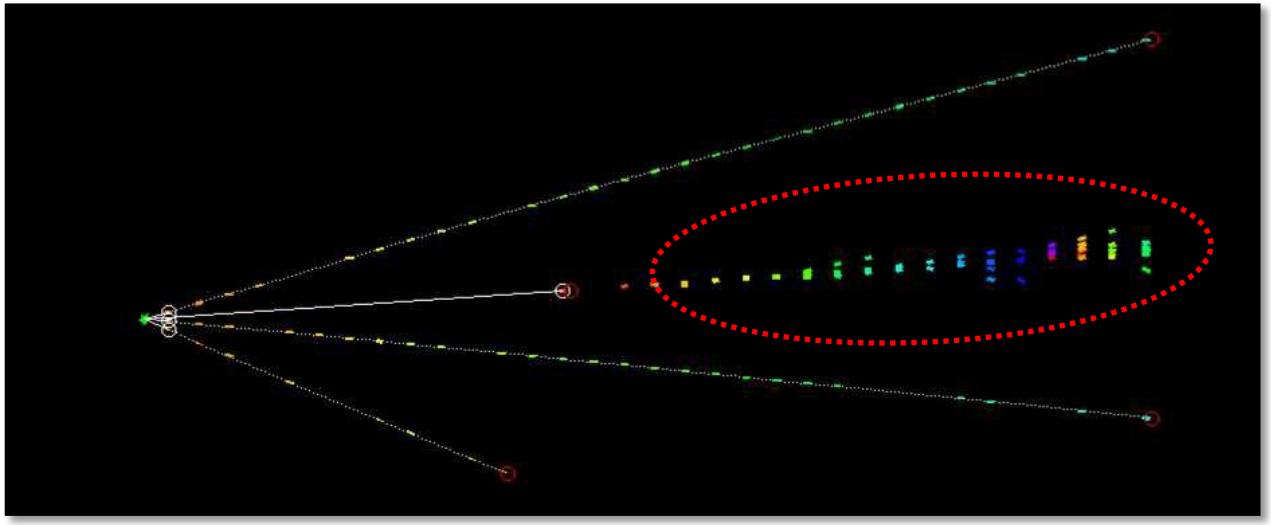
collect base-tracks
inside a given cone
δθ < 150 mrad
δr < 150μm

The total number of base-tracks and the longitudinal and transverse profiles of the showers can be used for particle identification.





Electromagnetic Shower Reconstruction

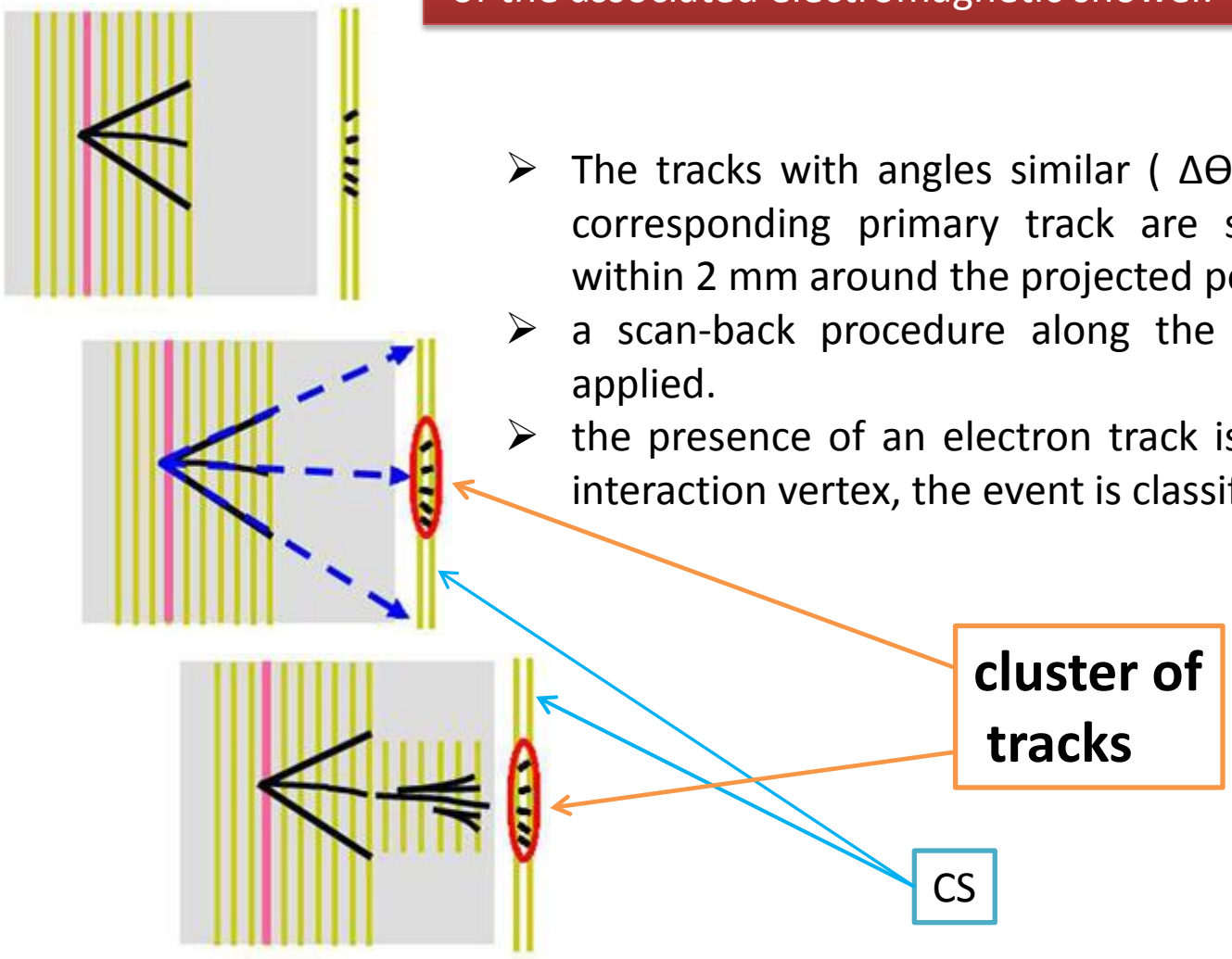


A first reconstructed ν_μ CC event recorded during the October 2007 run in the OPERA detector. The 3 long straight tracks are directly attached to the primary vertex. The colored shower in the middle is a gamma conversion coming from a π^0 decay and is also well attached to the primary vertex.

Pion Contamination	Energy	Electron efficiency
<1%	>2 GeV	> 90%
~ 1%	<1GeV	~ 80%

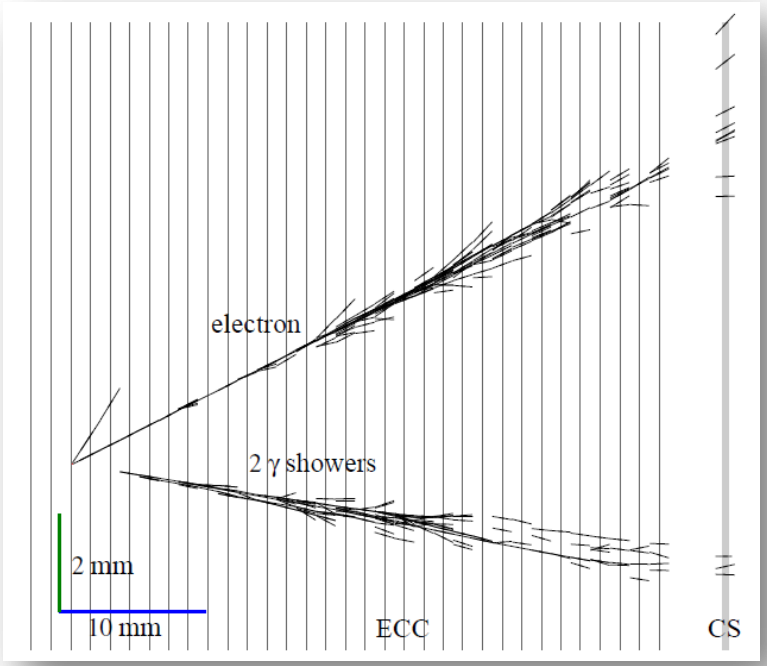
ν_μ --> ν_e

The identification of an electron is essentially based on the detection of the associated electromagnetic shower.



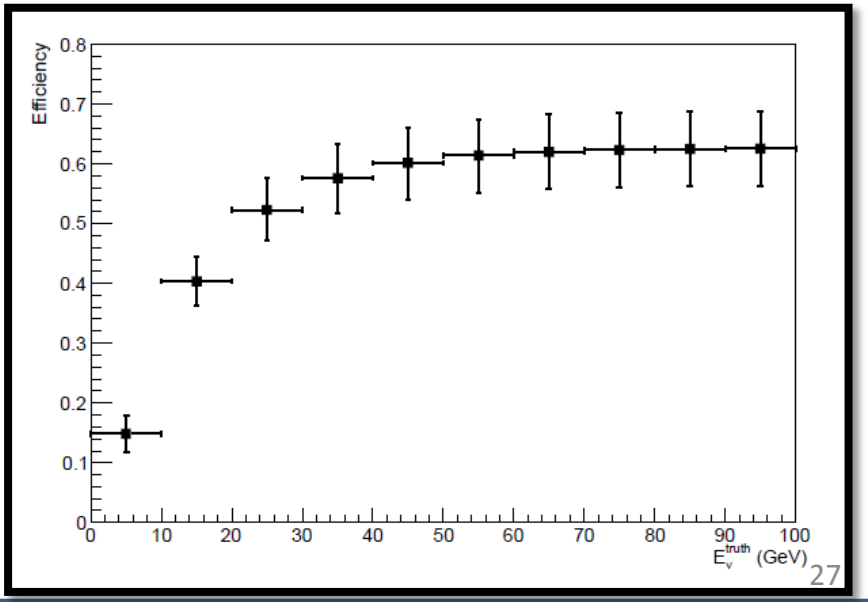
- The tracks with angles similar ($\Delta\Theta$< 150 mrad) to that of the corresponding primary track are searched in the CS region within 2 mm around the projected point.
- a scan-back procedure along the electromagnetic shower is applied.
- the presence of an electron track is confirmed at the neutrino interaction vertex, the event is classified as a ν_e interaction.

ν_μ --> ν_e

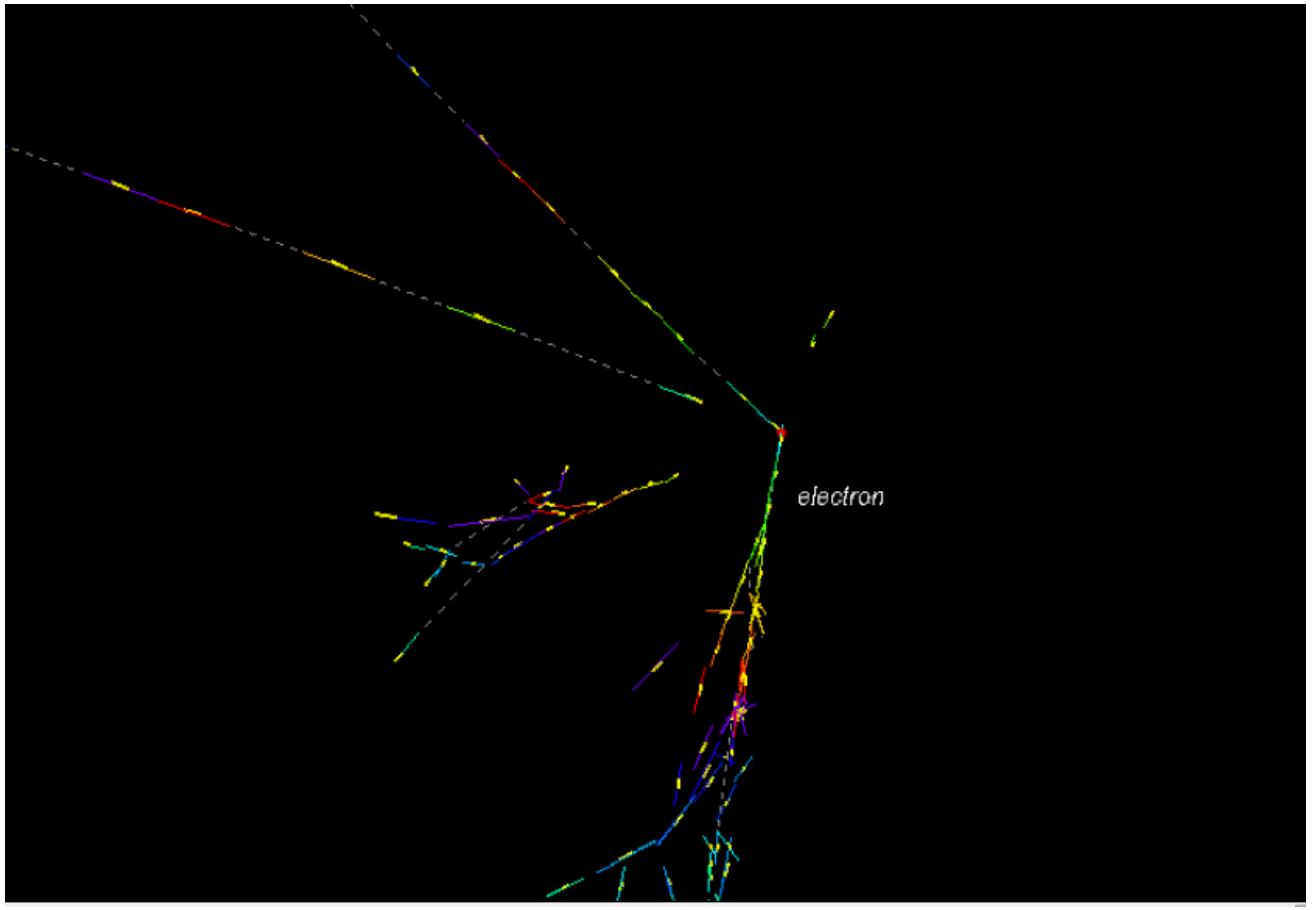


Display of the reconstructed emulsion tracks of one of the ν_e candidate events. The reconstructed neutrino energy is 32.5 GeV. Two tracks are observed at the neutrino interaction vertex. One of the two generates an electromagnetic shower and is identified as an electron. In addition, two showers from ϒ conversions are observed

Detection efficiency of ν_e events as a function of the neutrino energy, obtained from MC simulations.



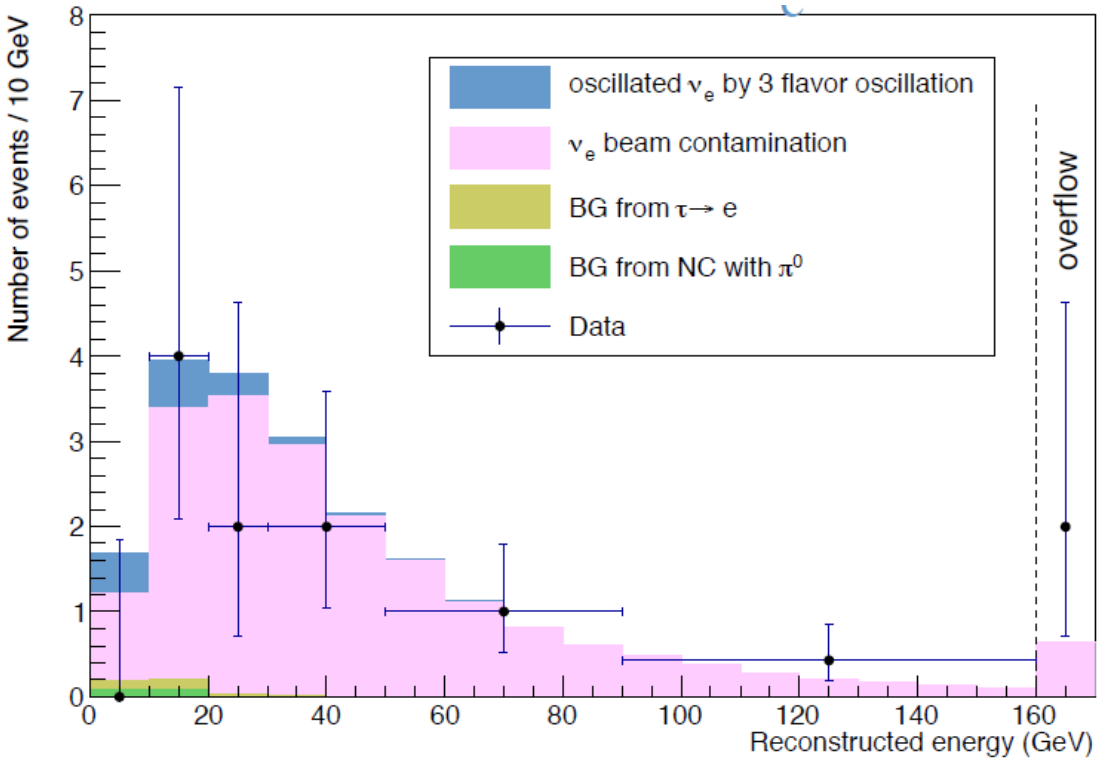
A ν_e Event



Among the 5255 candidate neutrino interactions collected during the 2008 and 2009 runs, 19 ν_e candidate events were found.

ν_μ --> ν_e

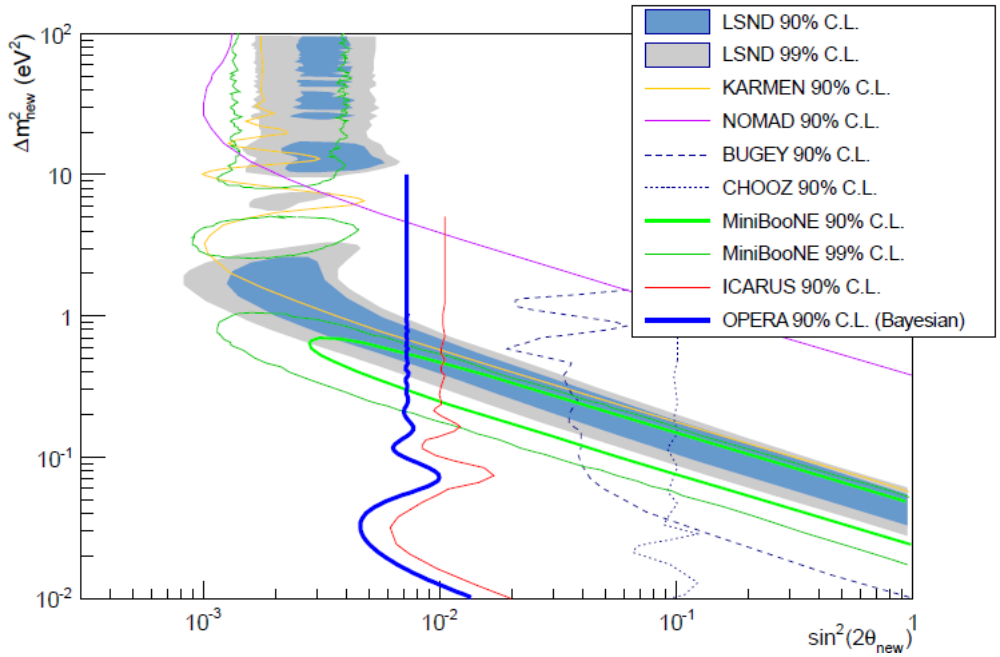
Distribution of the reconstructed energy of the ν_e events



Energy cut		20 GeV	30 GeV	No cut
BG common to both analyses	BG (a) from π^0	0.2	0.2	0.2
	BG (b) from $\tau \rightarrow e$	0.2	0.3	0.3
	ν_e beam contamination	4.2	7.7	19.4
Total expected BG in 3-flavour oscillation analysis		4.6	8.2	19.8
BG to non-standard oscillation analysis only	ν_e via 3-flavour oscillation	1.0	1.3	1.4
Total expected BG in non-standard oscillation analysis		5.6	9.4	21.3
Data		4	6	19

ν_μ --> ν_e

Bayesian statistical method



The experiment searched for the appearance of ν_e in the CNGS neutrino beam using the data collected in 2008 and 2009, corresponding to an integrated intensity of 5.25×10^{19} pot. The observation of 19 ν_e candidate events is compatible with the non-oscillation expectation of 19.8±2.8 events.

		Upper limit		Sensitivity	
	C.L.	F&C	Bayes	F&C	Bayes
Number of oscillated ν_e events	90%	3.1	4.5	6.1	6.5
	95%	4.3	5.7	7.8	7.9
	99%	6.7	8.2	10.7	10.9
$\sin^2(2\theta_{new})$ at large Δm^2	90%	5.0×10^{-3}	7.2×10^{-3}	9.7×10^{-3}	10.4×10^{-3}
	95%	6.9×10^{-3}	9.1×10^{-3}	12.4×10^{-3}	12.7×10^{-3}
	99%	10.6×10^{-3}	13.1×10^{-3}	17.1×10^{-3}	17.4×10^{-3}

Conclusion

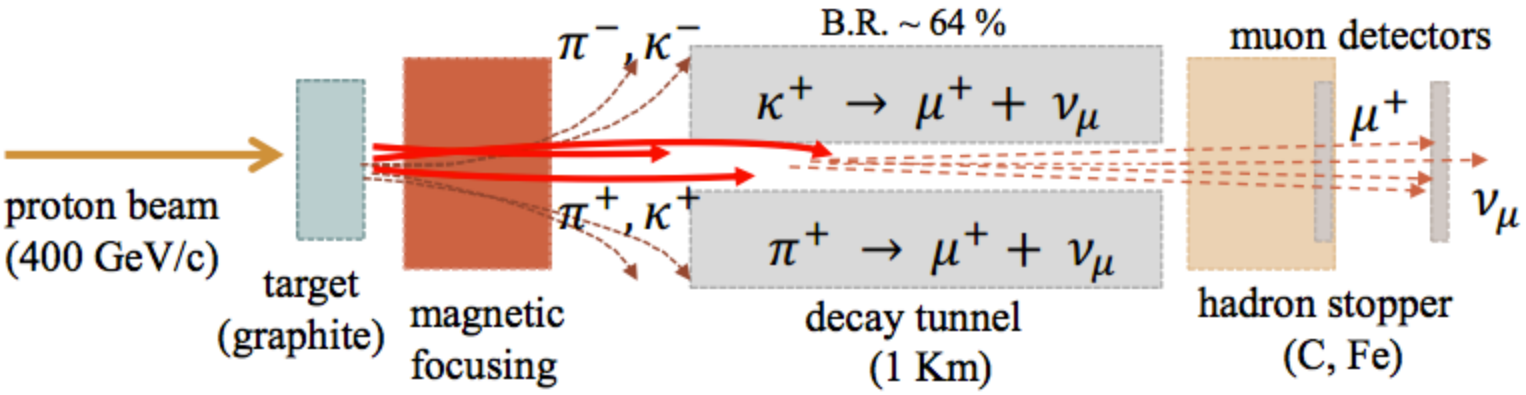
OPERA is the first experiment searching for direct ν_τ appearance in the framework of ν_μ oscillation

- CNGS beam concluded: 2008 – 2012
- *18941 ontime target interactions*
- Confirmed ν_τ *candidate events : 3* **(See Michele's presentation)**
- Confirmed ν_e *candidate events : 19 (2008 + 2009 data)*
- *60% of the all data was analyzed*

- **Outlook**
- *Extraction of candidate bricks: Until ~ 2014*
- *Scanning & analysis of candidate interactions: Until ~ 2015*

Thank You For Your Attention

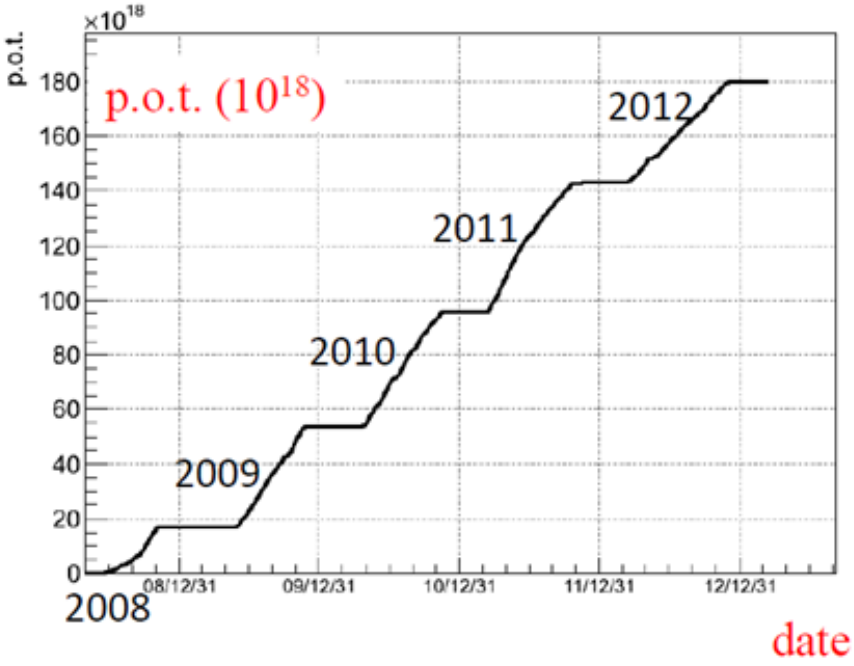
Backup Slides



Backup Slides

Final performances of the CNGS beam after five years (2008 ÷ 2012) of data taking

Year	Beam days	P.O.T. (10^{19})
2008	123	1.74
2009	155	3.53
2010	187	4.09
2011	243	4.75
2012	257	3.86
Total	**965**	**17.97**



Record performances in 2011
Overall 20% less than the proposal value (22.5)