Recent results of the OPERA experiment

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on behalf of the OPERA Collaboration

XLVI Recontres de Moriond – EW 2011

The OPERA Collaboration
170 physicists, 30 institutions in 11 countries

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IIHE-ULB
Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
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LNGS
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Outline

- Introduction
- The OPERA experiment
  - Requirements
  - CNGS neutrino beam
  - OPERA detector
- Detector Performances
- Physics Results
- Conclusions.

Introduction

- In the last decades several experiments provided evidence for neutrino oscillations (disappearance mode).

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

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

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

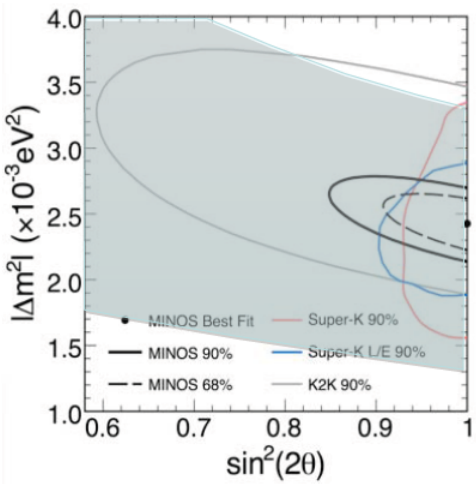
-CHOOZ (1997): The main oscillation channel responsible for atmospheric neutrino disappearance is not $\nu_\mu \rightarrow \nu_e$;
-SK (1998): The main oscillation channel responsible for atmospheric neutrino anomaly is not $\nu_\mu \rightarrow \nu_s$ and can be interpreted as $\nu_\mu \rightarrow \nu_\tau$ oscillations.
-(2004-2009) K2K, MINOS precision measurments of ν_μ disappearance

The OPERA experiment

Oscillation Project with Emulsion-tRacking Apparatus

ν_τ appearance from an initially pure ν_μ high energy artificial beam through the ν_τ CC interaction with the target mass.

Oscillation parameters in the atmospheric neutrino sector

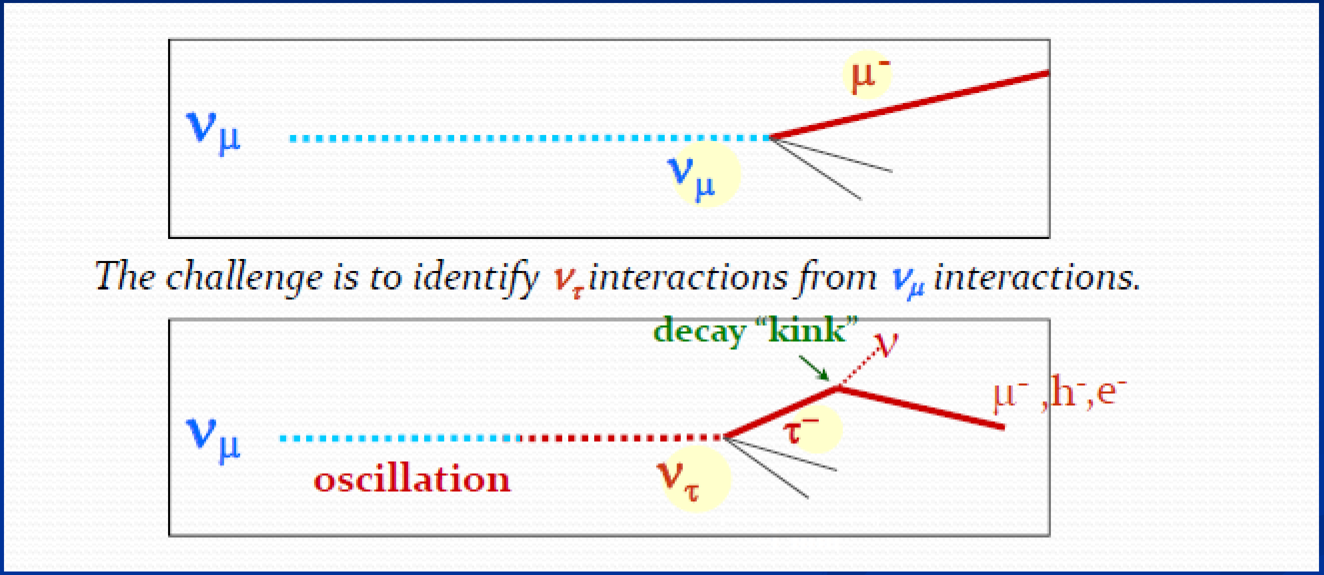


Full mixing and $\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV^2

The light blue band indicates the OPERA allowed region (90% CL) for the above parameter values for 22.5×10^{19} pot

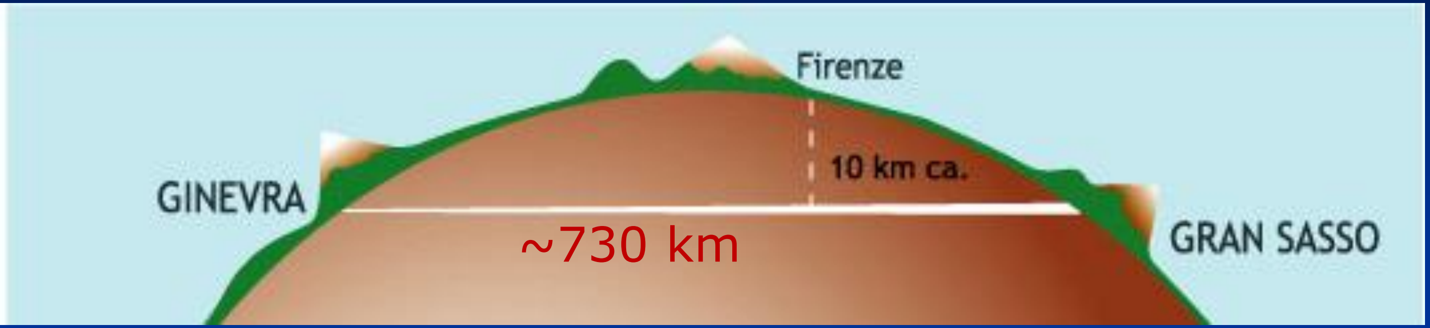
Decay Channels	BR
$\tau^- \longrightarrow e^- \bar{\nu}_e \nu_\tau$	17.8%
$\tau^- \longrightarrow \mu^- \bar{\nu}_\mu \nu_\tau$	17.4%
$\tau^- \longrightarrow h^- \bar{\nu}_\tau (n\pi^0)$	49.5%

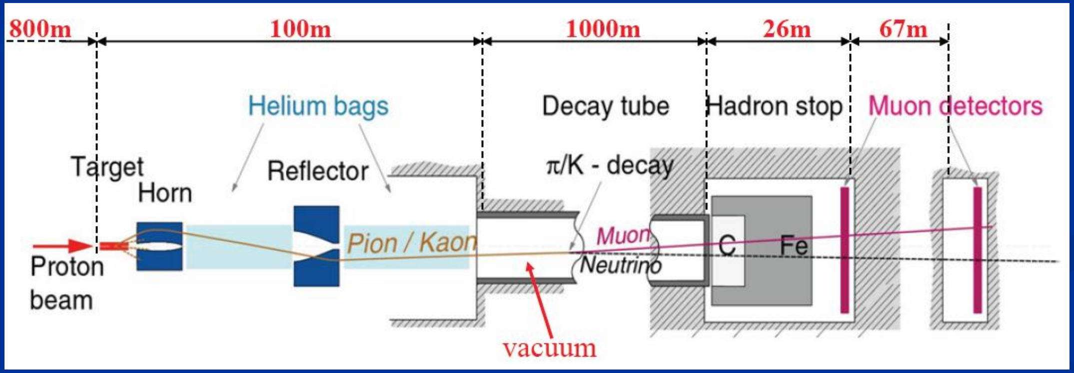
Requirements



- Intense high-energy long baseline muon-neutrino beam;
- Massive active target with a spatial resolution of the order of µm;
- Detection capability of the tau-lepton production and decay
- Underground location (low backgroud)

The CNGS neutrino beam





- Protons from SPS: 400 GeV/c
- Cycle length: 6 s
- 2 extractions separated by 50 ms
- Pulse length: 10.5 ms
- Beam intensity: $2.4\ 10^{13}$ proton/extr.

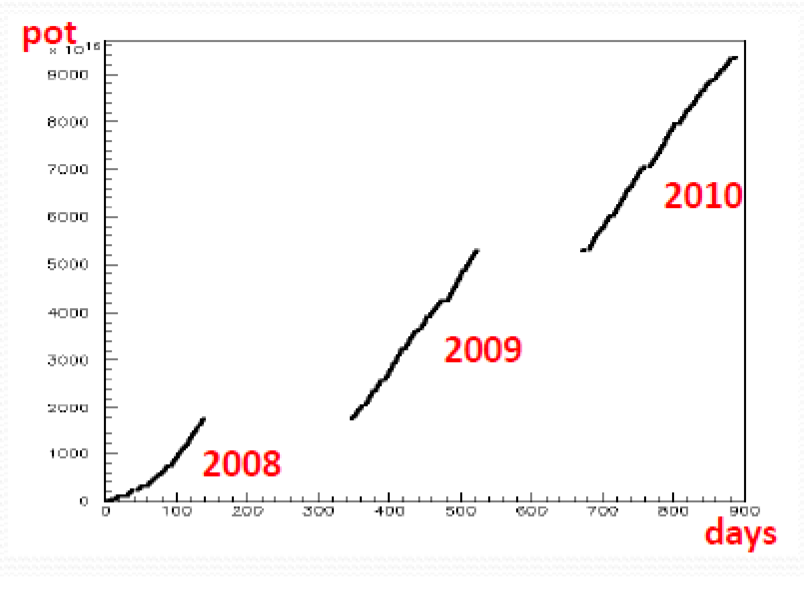
$<E\nu_\mu>$	17 GeV
$(\nu_e+\bar{\nu}_e)/\nu_\mu$	0.8% (*)
$\bar{\nu}_\mu / \nu_\mu$	2.1% (*)
ν_τ prompt	Negligible (*)

(*) interaction rate at LNGS

Nominal Intesity:
$4.5\ 10^{19}$ pot/year
5 years (nominal pot):
~ 23600 ν_μ CC + NC
~ 160 $\nu_e + \bar{\nu}_e$ CC
~ 110 ν_τ CC ($\Delta m^2 = 2.5\ 10^{-3}\ eV^2$)
~ 10 τ decays are expected to be observed (BG < 1)

CNGS performaces

Year	Proton On Target	Events in the brick	Run
2006	0.076×10^{19}	no bricks	Commissioning
2007	0.082×10^{19}	38 ev.	Commissioning
2008	**1.78×10^{19}**	**1698 ev.**	**First physics run**
2009	**3.52×10^{19}**	**3693 ev.**	**Physics run**
2010	**4.04×10^{19} pot**	**4248 ev.**	**Physics run**

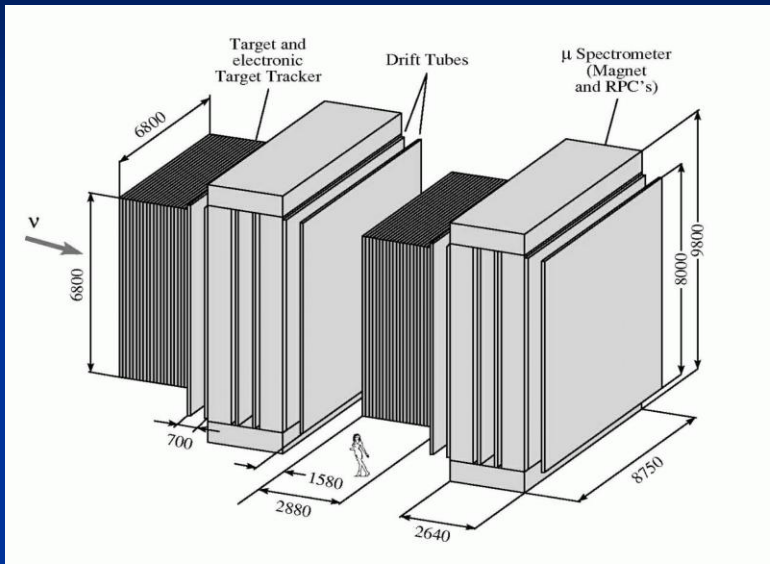


9639 events collected
(within 1σ in agreement with what expected on the basis of pots)
2010 close to nominal year

2.1 nominal year in 3 years

Aim at high-intensity runs in 2011 and 2012

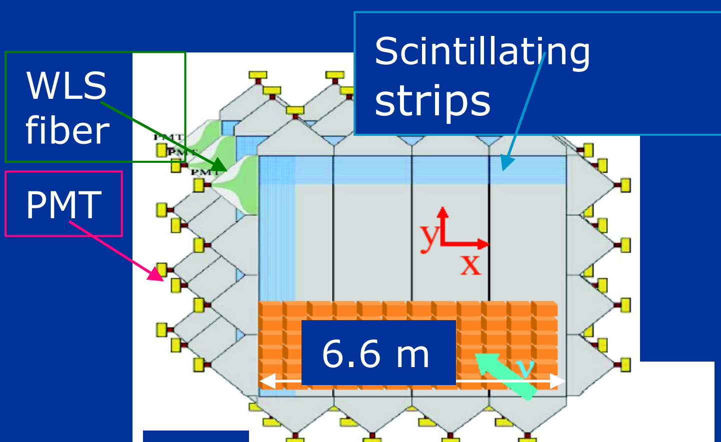
The OPERA detector



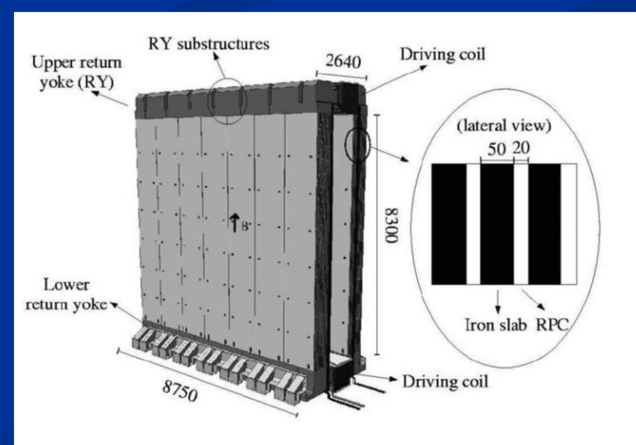
Detector elements:
-Electronic detectors
-Muon spectrometers
-Emulsion Cloud Chamber

1 SuperModule:

-31 walls;
- ~77000 bricks;
- ~620 ton.



Strip granularity: 2.6 x 2.6 cm^2

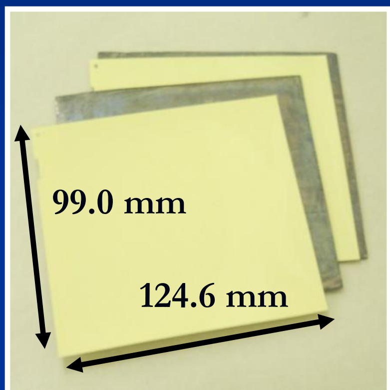


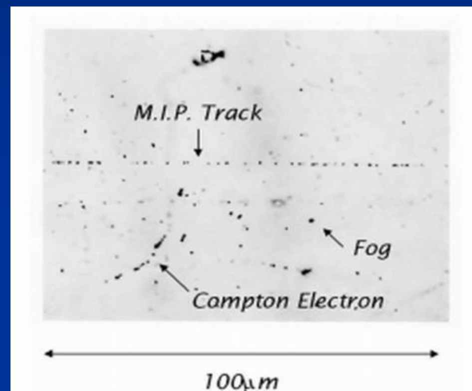
Measured magnetic field: 1.52 T

Emulsion Cloud Chamber (ECC)

ECC: series of emulsions sheets interspaced with lead plates.

- Provide high resolution and large mass in a modular way

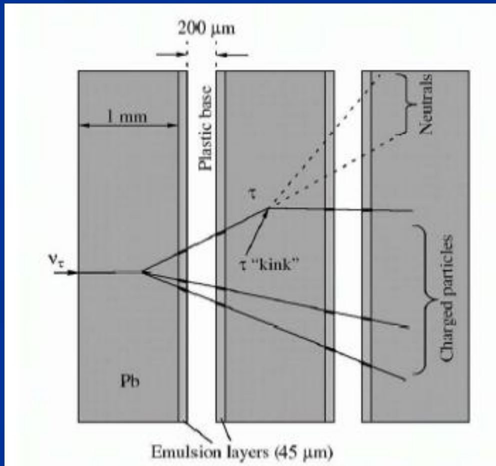




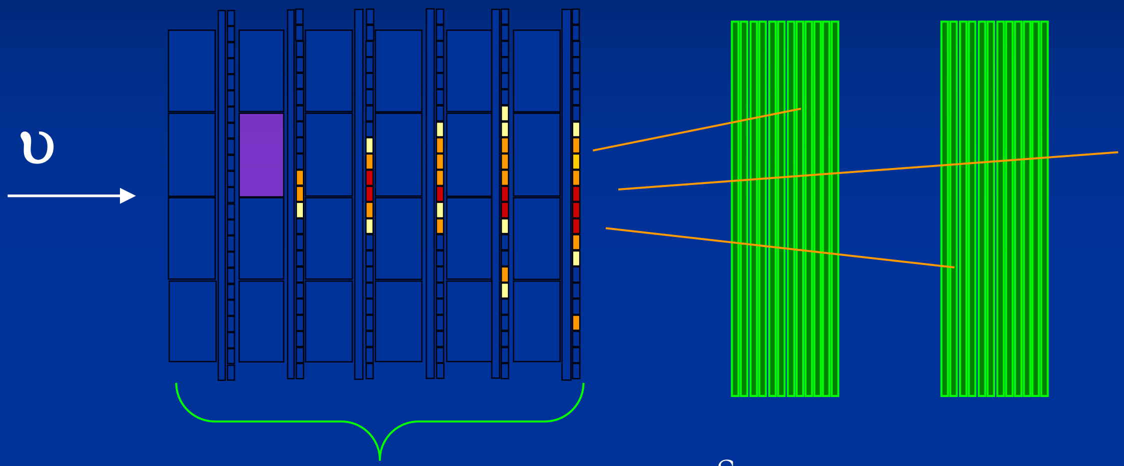
Emulsion resolution:
$dx = 1\ \mu m$
$d\theta = 2$ mrad

Brick: is the target basic component

- 57 nuclear emulsion films interleaved with 1 mm thick lead plates
- a box with a removable pair of films (**C**hangeable **S**heets) interface to the electronic detectors



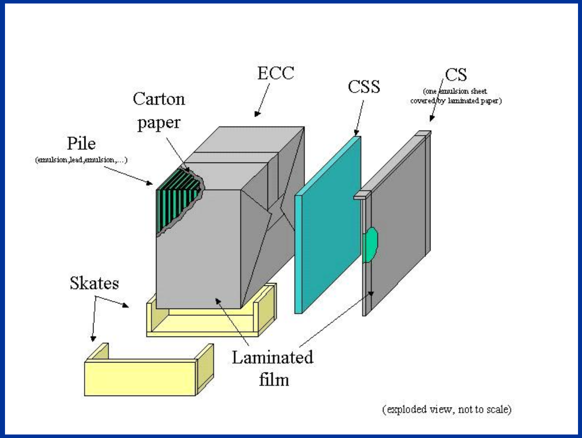
Detector working principle



TT : identifies the brick with the candidate interaction

Spectrometer:
μ identification , measurement of charge and momentum

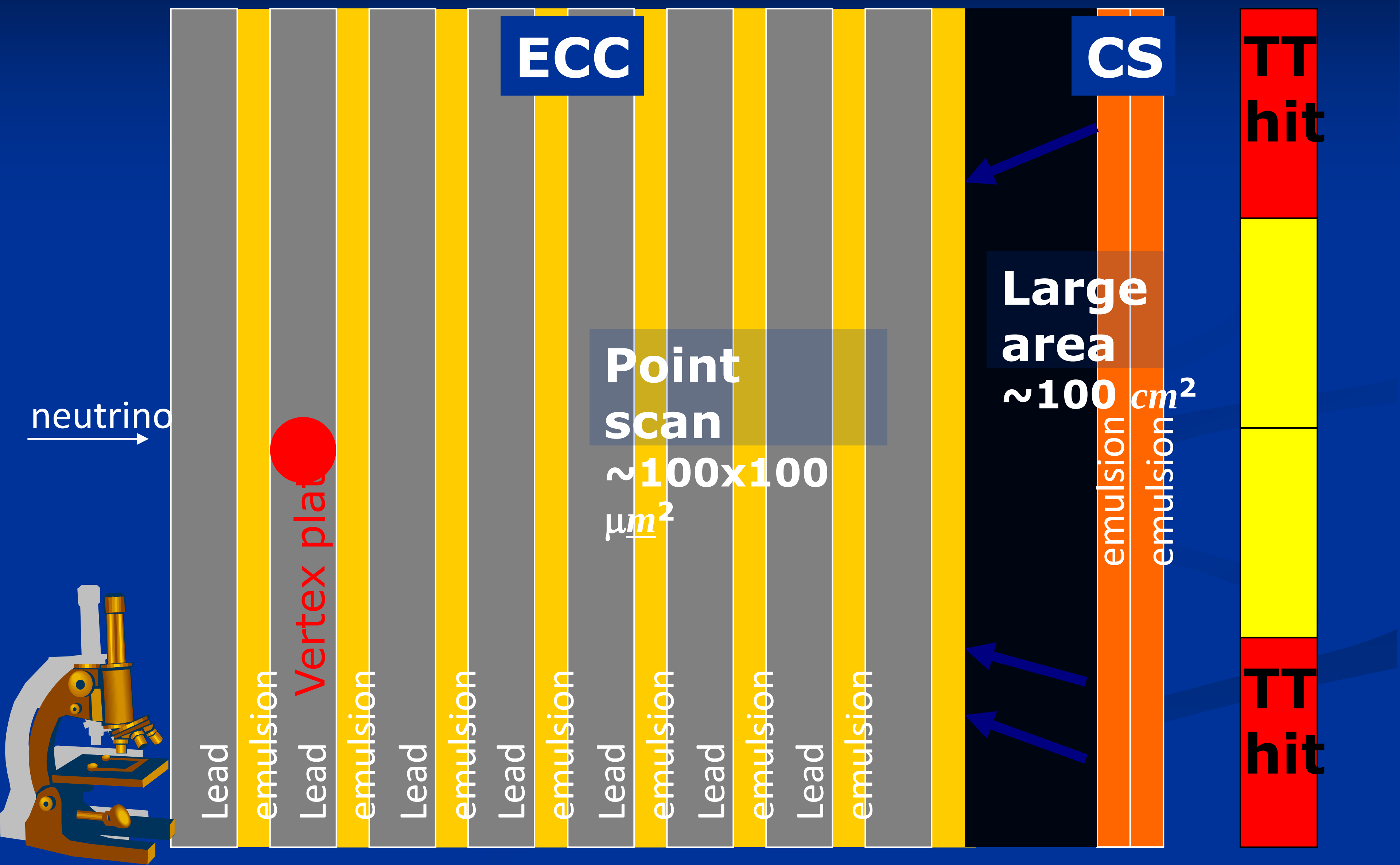
The Brick Manipulator System extracts the candidate brick from the wall



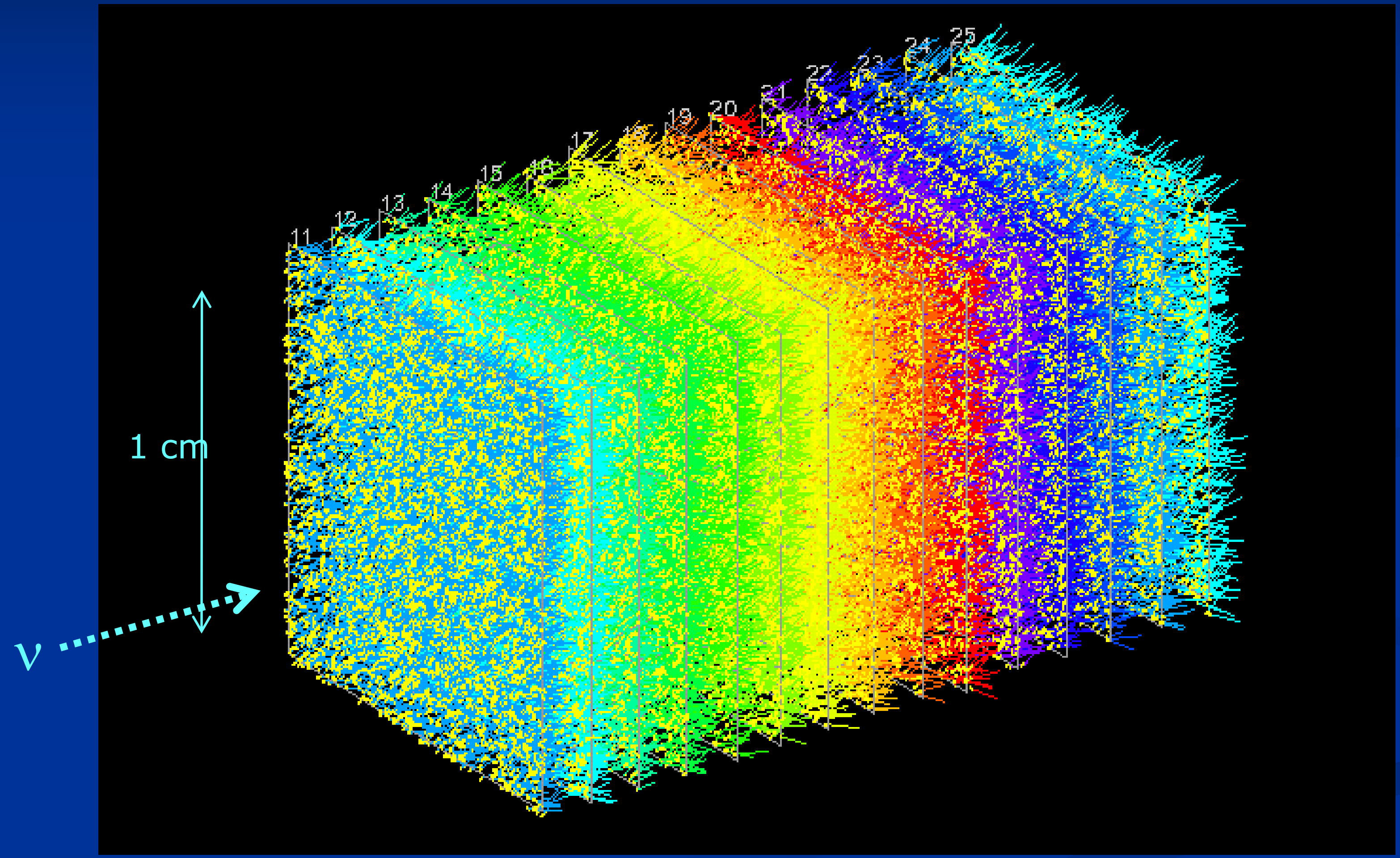
- CS developed in the cavern;
- CS measured half at LNGS half in JP (area depending on event type);
- If CS-TT tracks found → Brick expose to Cosmic rays (12 h);
- Brick assigned to a lab for locating the neutrino interaction → see next slides

Interaction location in ECC brick

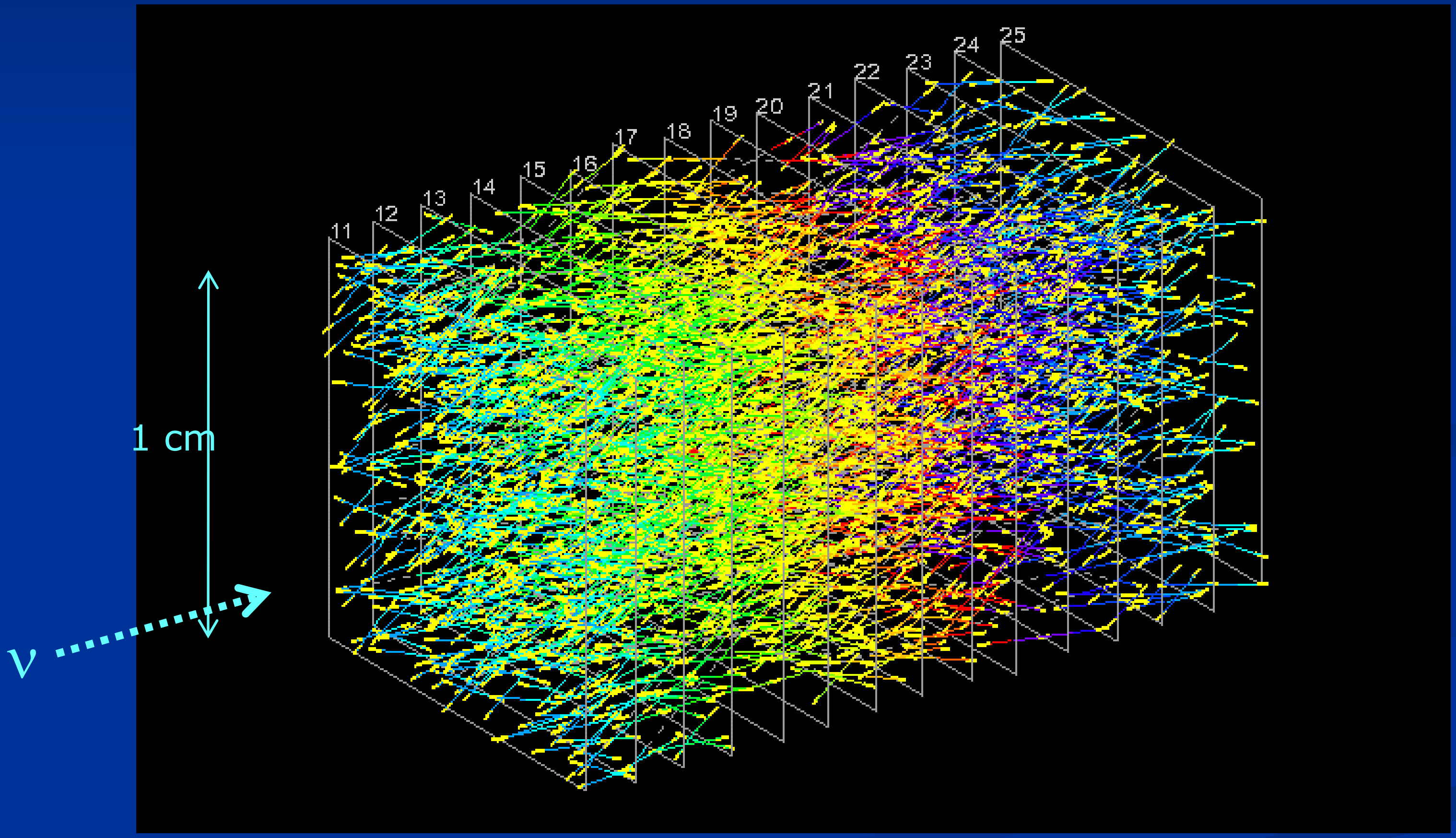
1. Follow back in brick tracks found in CS until they disappear: vertex plate



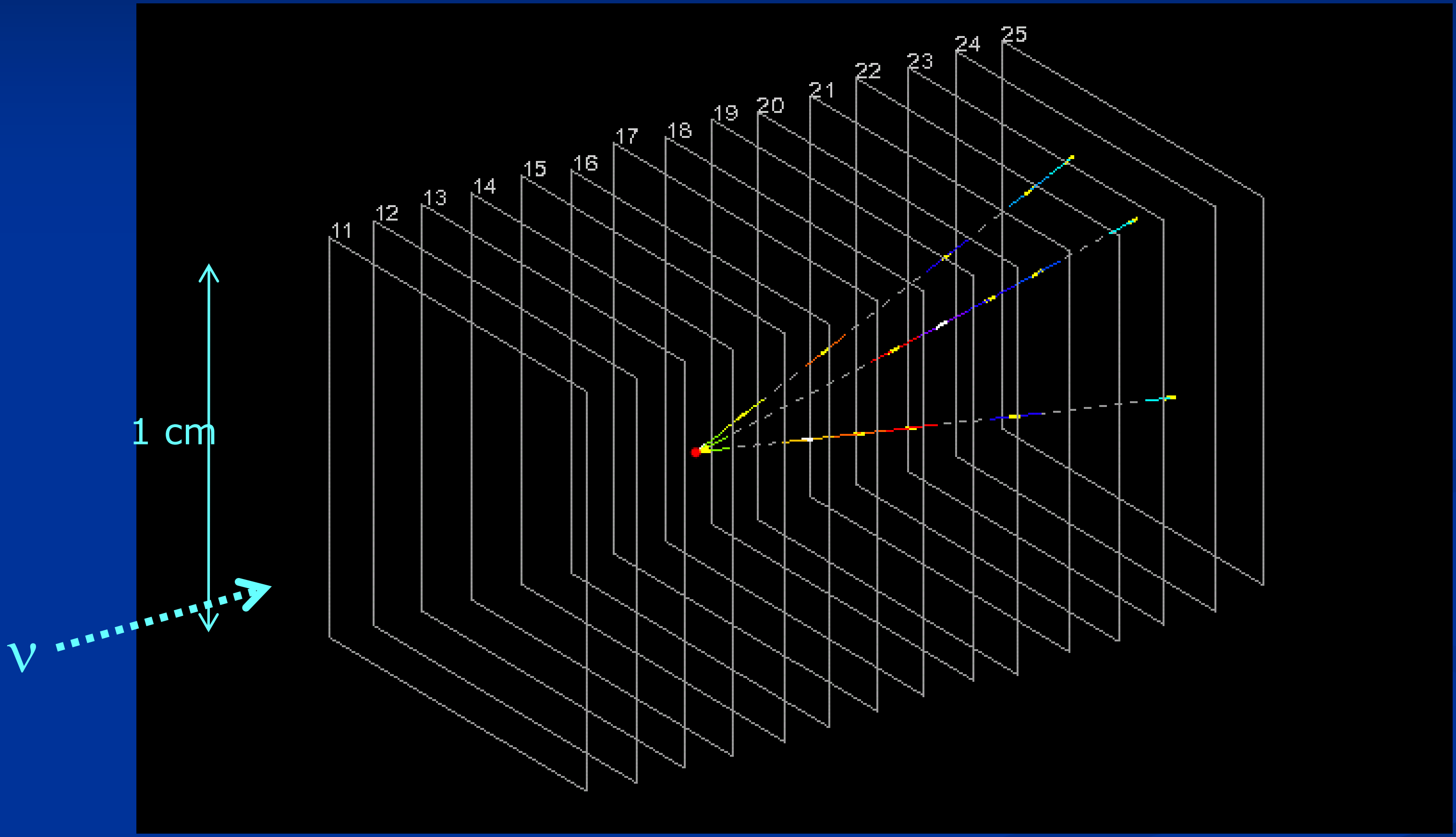
2. Search for all track segments in volume of $1 \times 1\ cm^2 \times 15$ films around plate where scanned back tracks disappear.



3. Reject all track segments that do not form tracks or that form tracks traversing the whole volume.



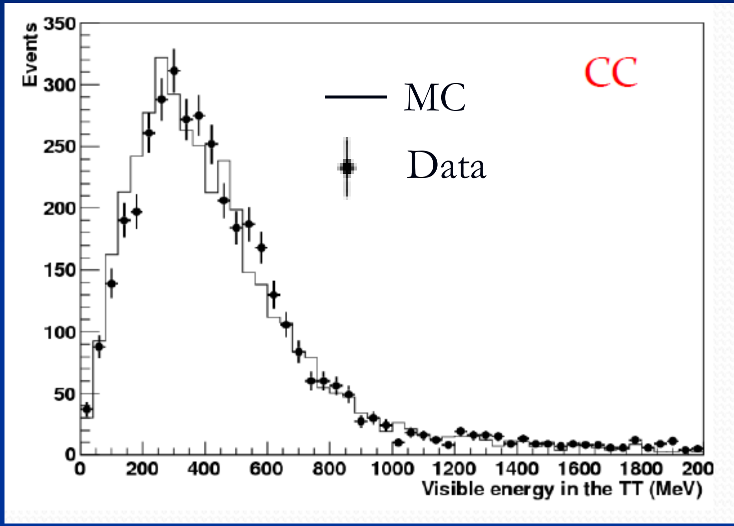
4. Keep only tracks converging to a vertex → micrometric precision around the vertex.

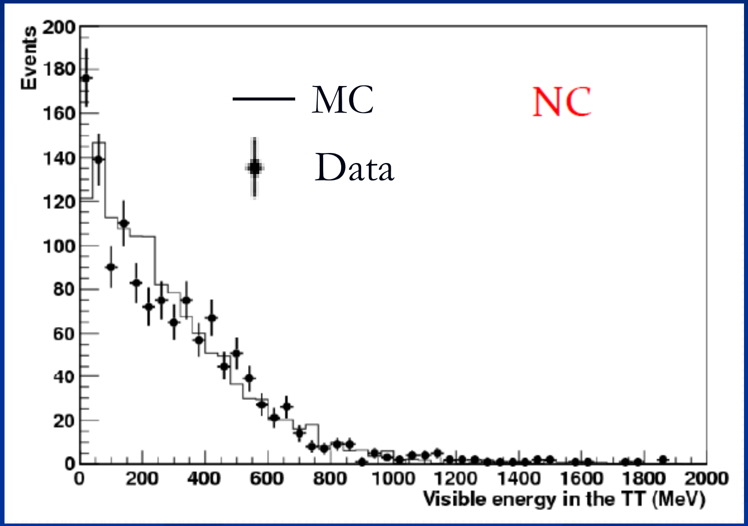


Frames correspond to the scanning area in successive films.
Yellow short lines → measured tracks.
Other colored lines → interpolation or extrapolation

Electronic Detector Performances

- Energy deposit in the Target Tracker

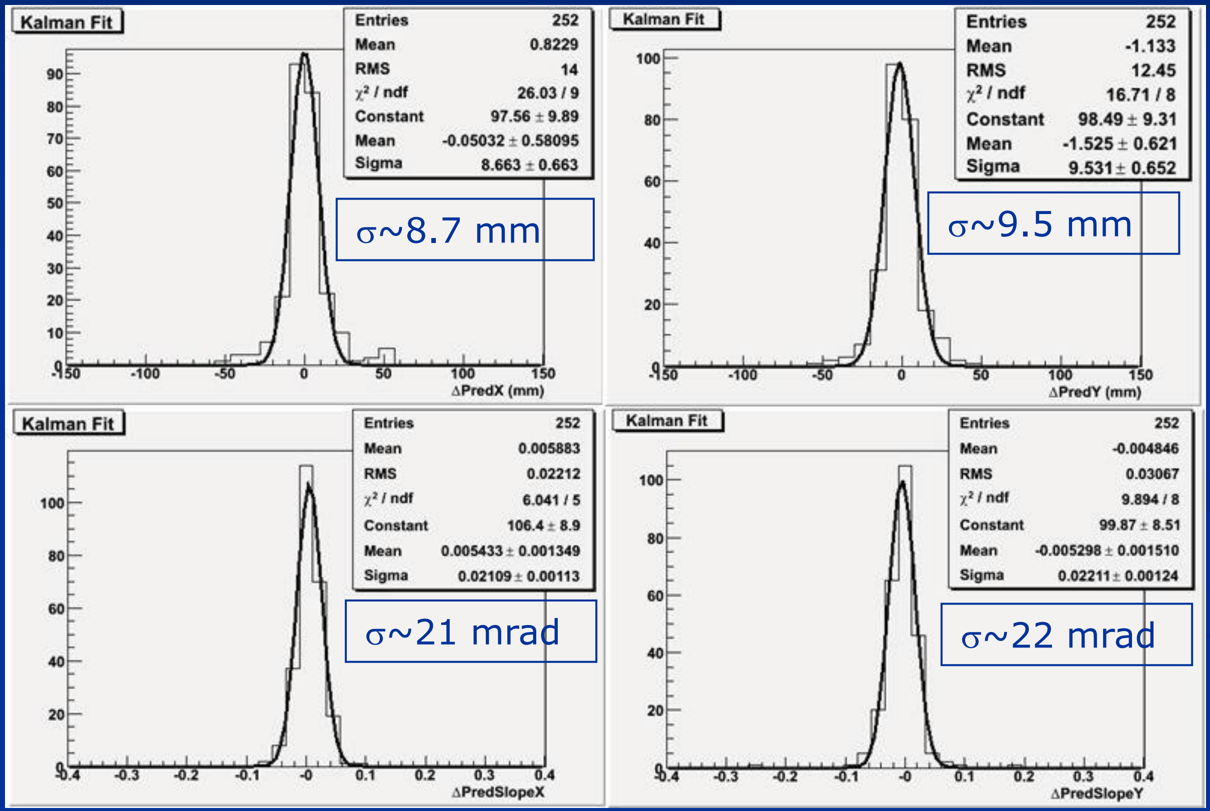


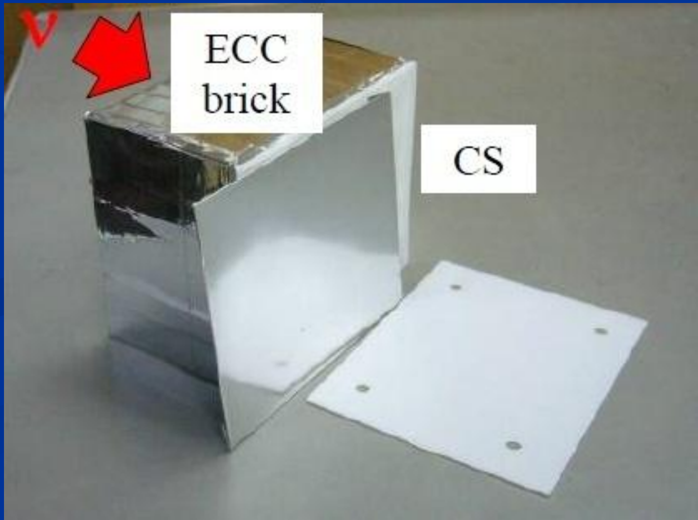


Good agreement for E>200 MeV
→ Under investigation the energy deposition in the low energy region.

- Overall efficiency (Trigger + reconstruction) for CC events > 97.5%
- Charge id efficiency > 96% (2.5 GeV/c < |P| < 45 GeV/c)
- Momentum resolution (MC computation): 10% at 2.5GeV/c
  20% at 25 Gev/c
- Transverse spatial resolution < 1 mm

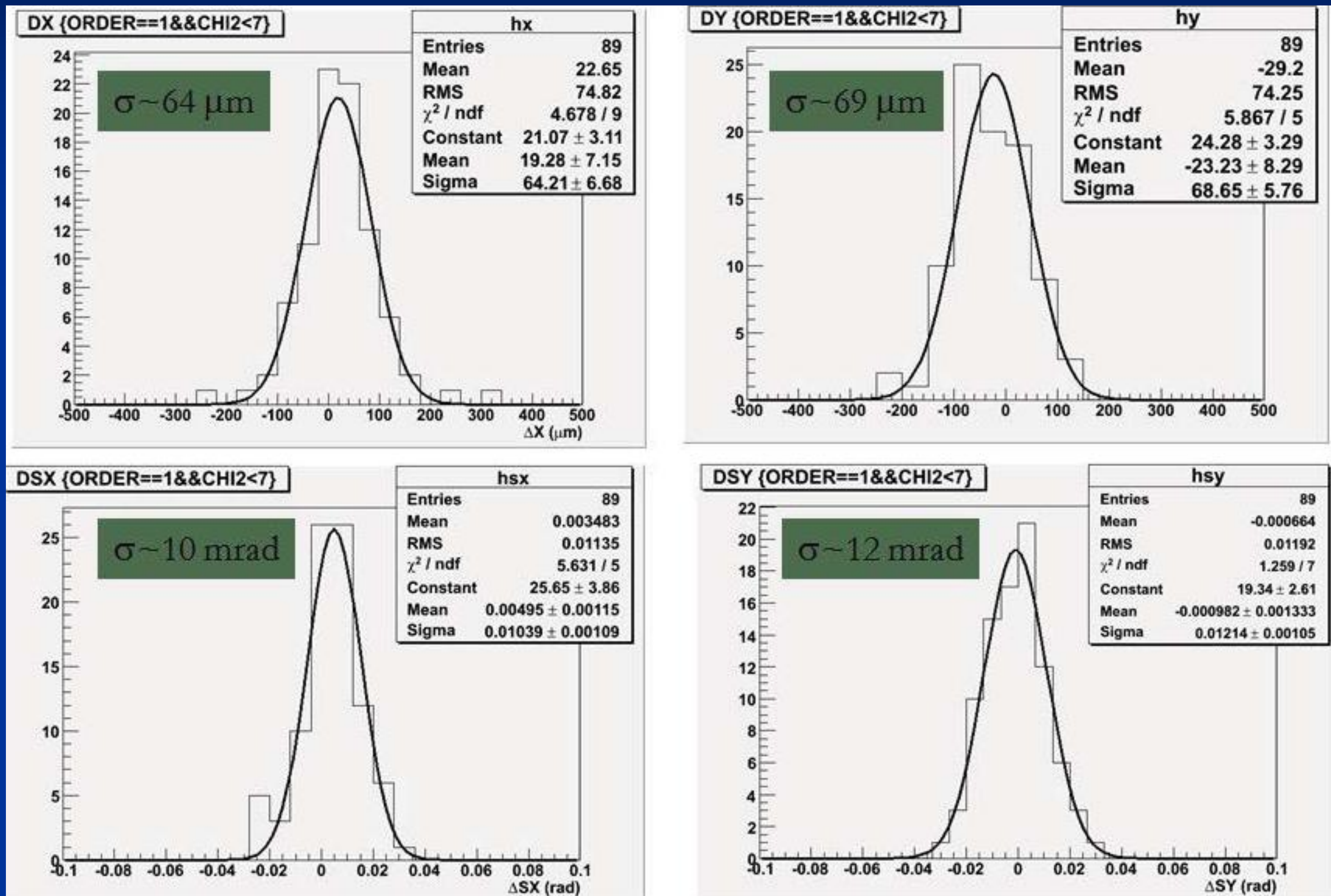
Changeable Sheets interface between ED and ECC





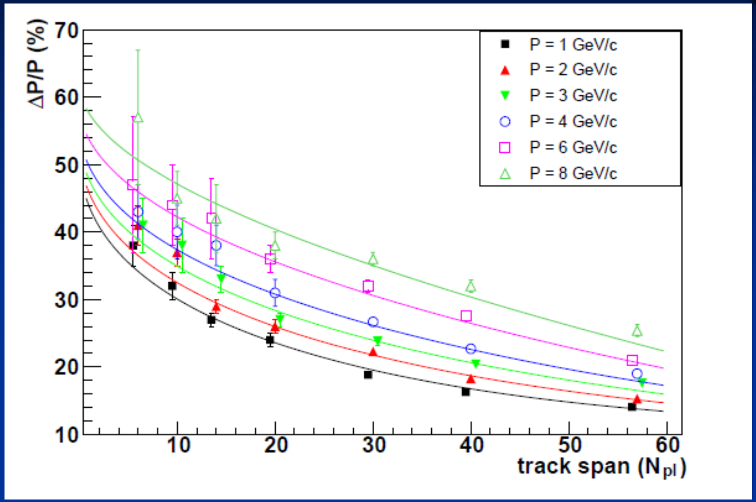
-CS used to validate the brick selected by electronic detector;
-Allows to go from a "scale" of the order of cm to one of the order of μm
→ see next slide

CS – Brick connection

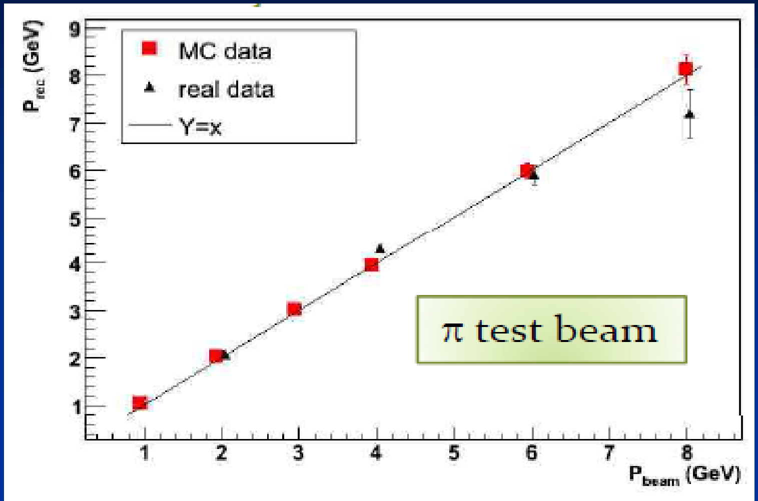


Tracks connected are not only muons.

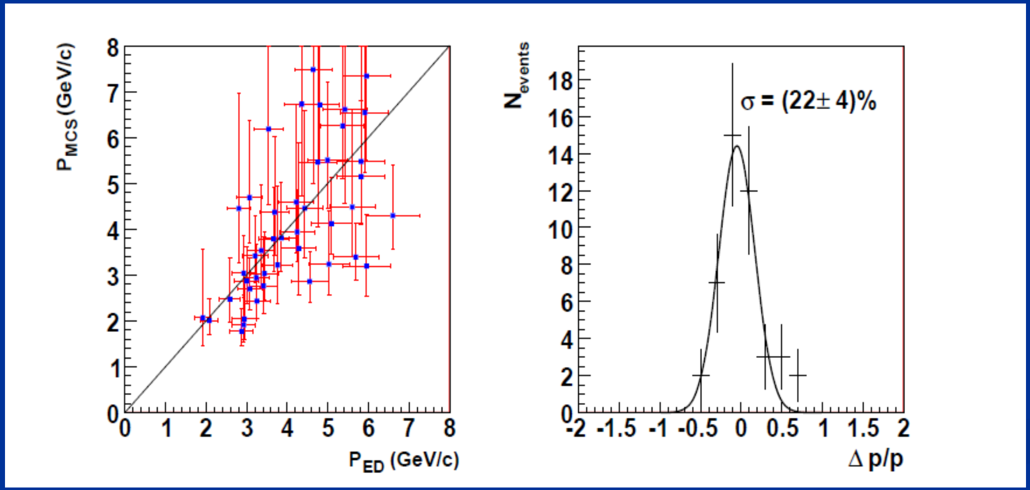
ECC performances



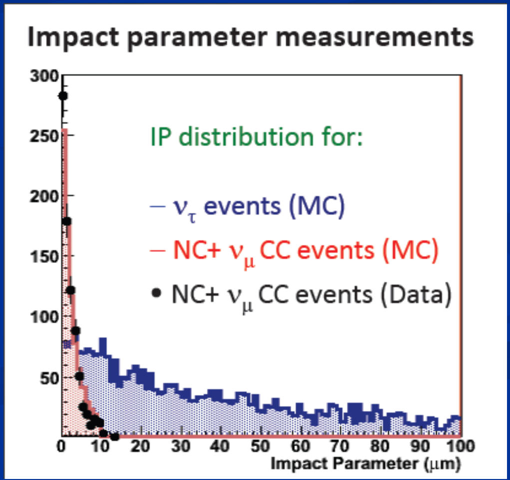
Momentum resolution dependece on number of emulsion plate transversed



Linearity of momentum center
Pion Test Beam – MC comparison



Soft muons momentum measured inside the brick and compared with one measured by electronic detector



Detection of decay topologies triggered by large IP wrt primary vertex or by kink/trident topologies

Physics Results

Analysis released on 2008-2009 subsample of 1088 (187 NC) events corrisponding to 1.85 10^{19} POT

- Expected charm events 16.0 ± 2.9
- Expected tau events ~ 0.5

New data will be released soon

Charm Candidate events

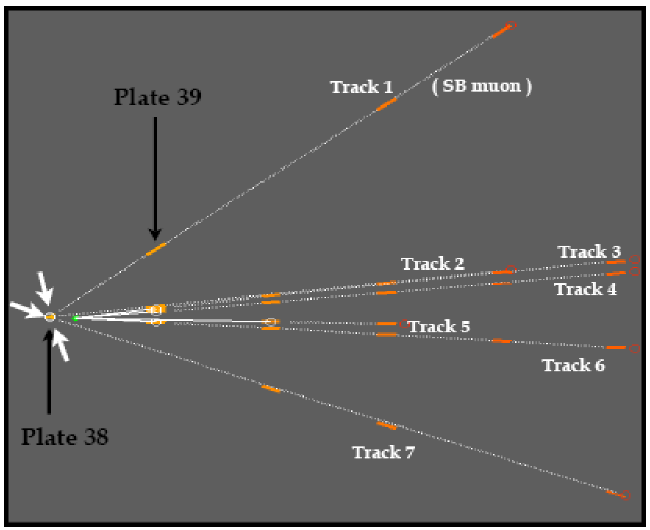
Proof of τ efficiency

- 20 charm events selected
  (3 events with 1-prong kink topology)
- ~ 2 BG events expected

Event 234654975

Brick 85405

All units are in microns!



VERTEX 1

	Impact Parameter
Track 1	1,36
Track 2	0,88
Track 7	0,51

X	66716,60
Y	49892,8
Z	90,9

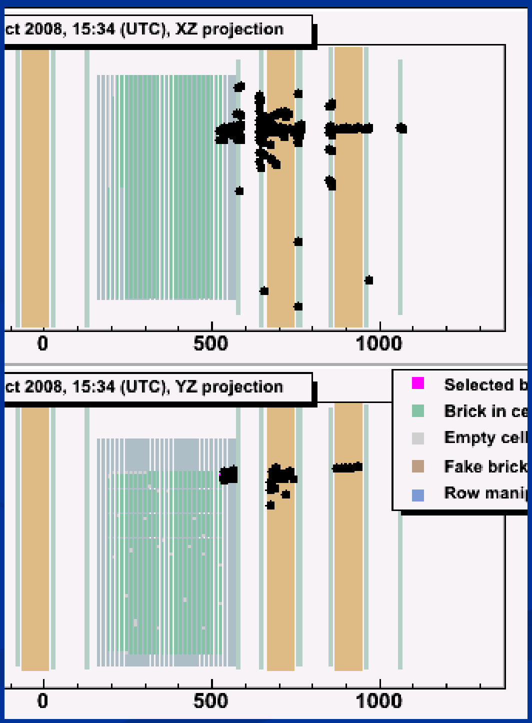
VERTEX 2

	Impact Parameter
Track 3	1,13
Track 4	1,81
Track 5	1,99
Track 6	1,39

X	66710,10
Y	49899
Z	403,9

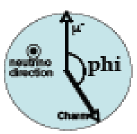
Primary vertex

Decay vertex



D^0

Tx	Ty	Flight Length (μm)	phi	minimum mass (GeV/c²)
-0,0207	0,0198	313,1	173,2°	1,7



The first ν_τ candidate

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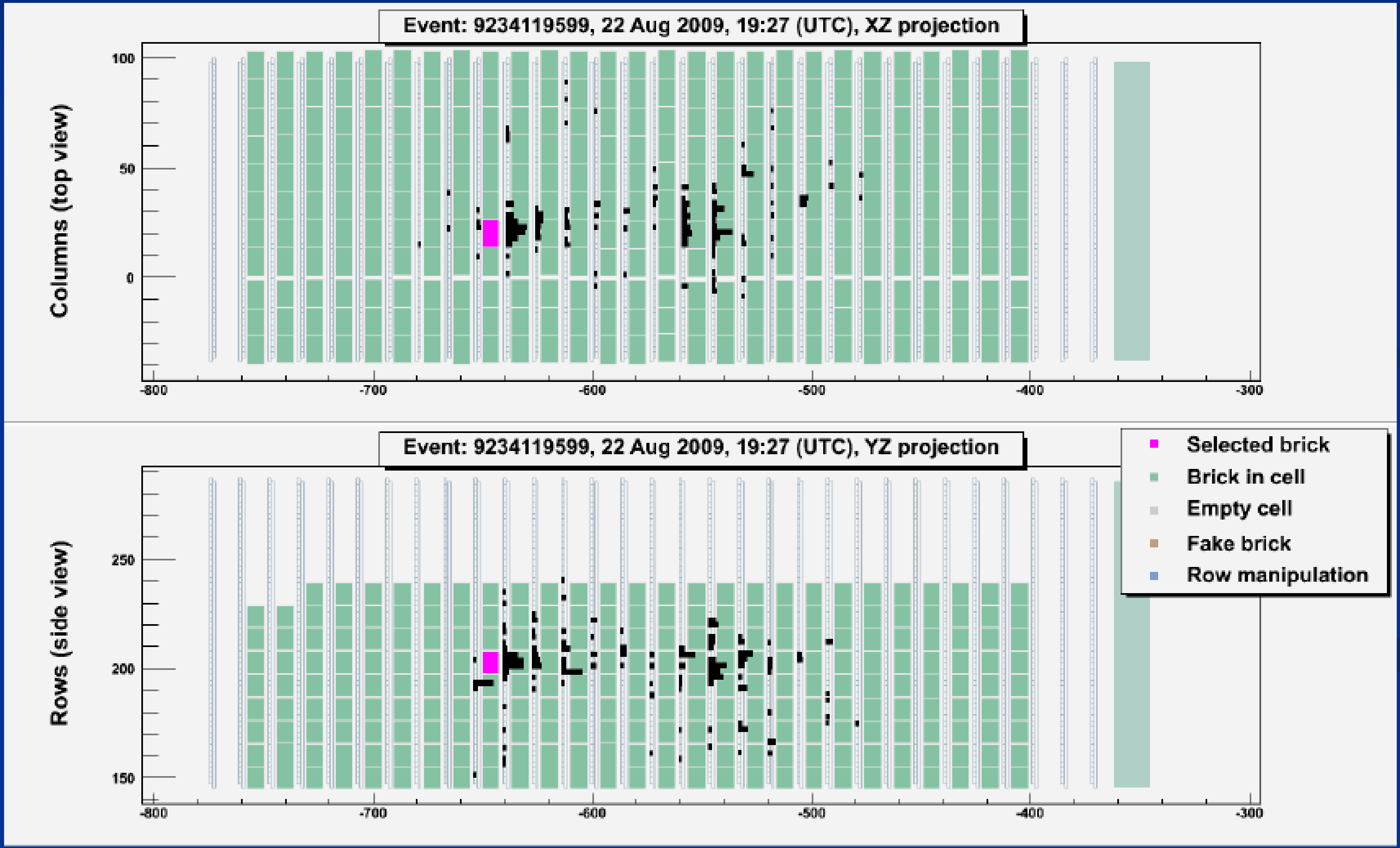
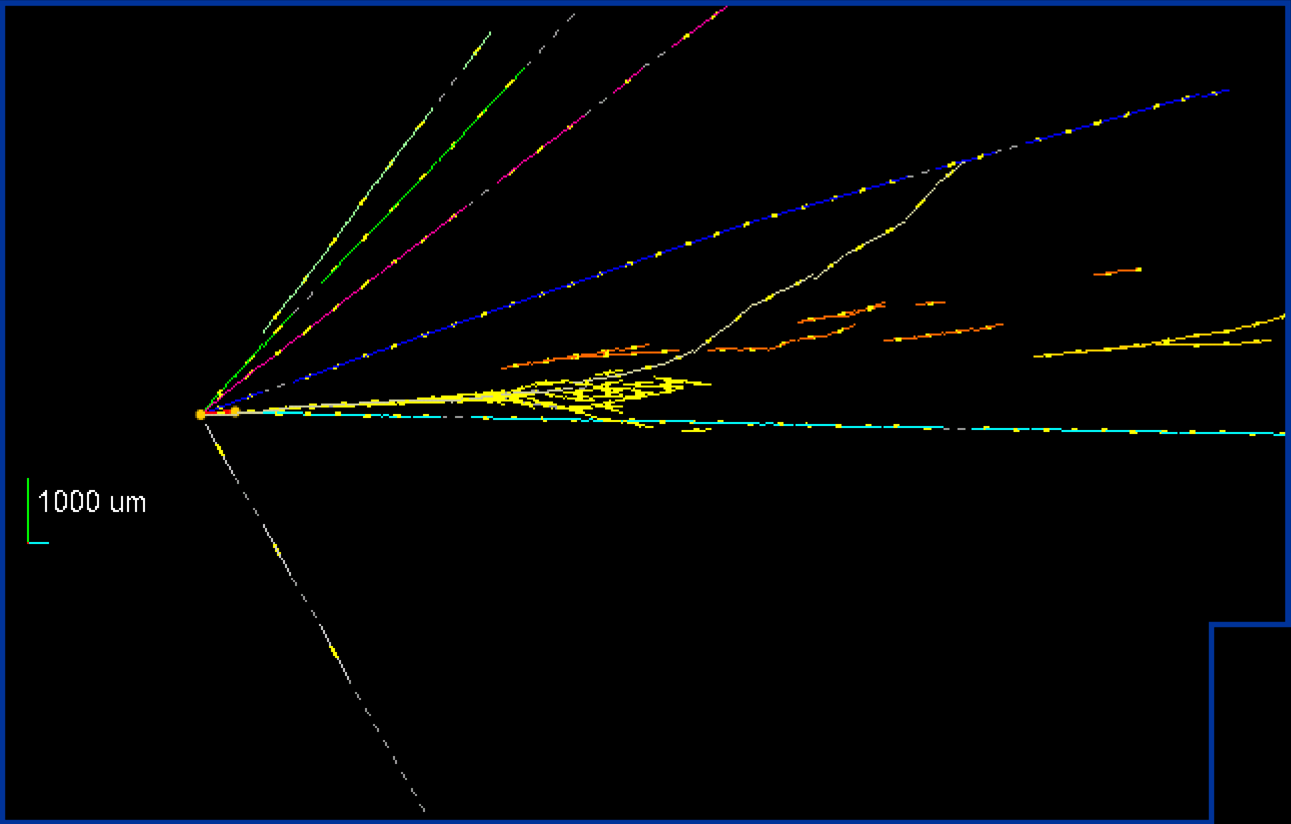
Observation of a first ν_τ candidate event in the OPERA experiment in the CNGS beam

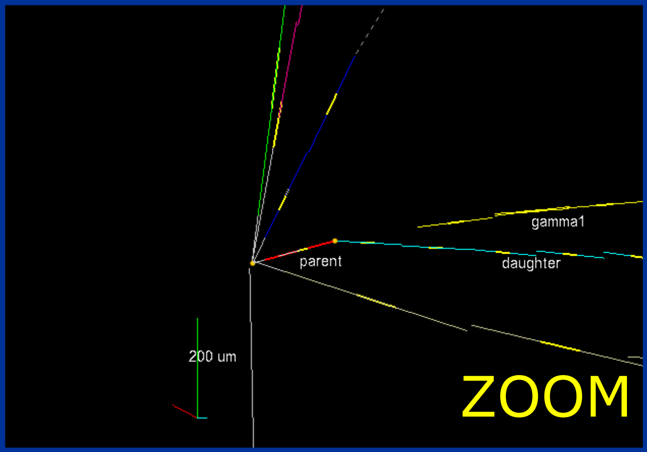
Event number: 9234119599 taken on 22nd of August, 19:27 (UTC)

ν_τ event recorded by the Electronic Detector

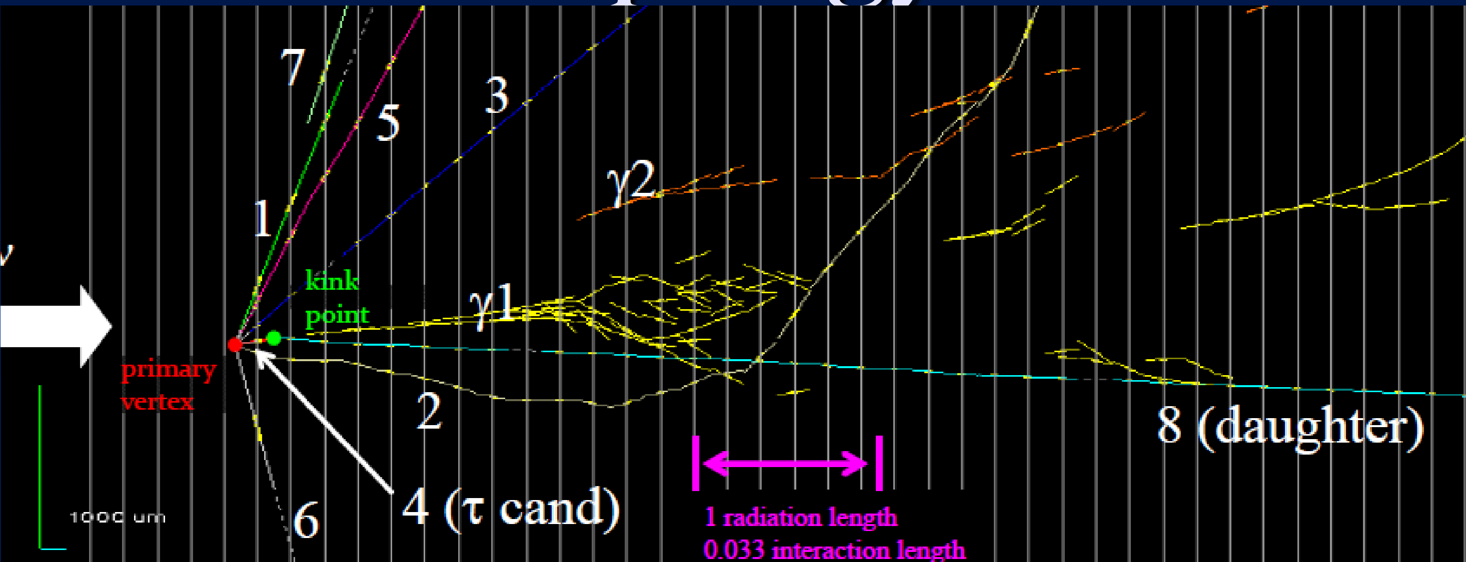


The first ν_τ candidate





Event topology and kinematics



Track	PID	Probability	tan Θ_X	tan Θ_Y	P (GeV/c)
1	HADRON range in Pb/emul=4.1/1.2 cm	Prob(μ)≈10^{-3}	0.177	0.368	0.77 [0.66,0.93]
2	PROTON	range, scattering and dE/dx	-0.646	-0.001	0.60 [0.55,0.65]
3	HADRON	interaction seen	0.105	0.113	2.16 [1.80,2.69]
4 (PARENT)			-0.023	0.026	
5	HADRON: range in Pb/emul=9.5/2.8 cm	Prob(μ)≈10^{-3}	0.165	0.275	1.33 [1.13,1.61]
6	HADRON: range in Pb/emul=1.6/0.5 cm	Prob(μ)≈10^{-3}			
7	From a prompt neutral particle		0.430	0.419	0.34 [0.22,0.69]
8 (DAUGHTER)	HADRON	interaction seen	-0.004	-0.008	12 [9,18]

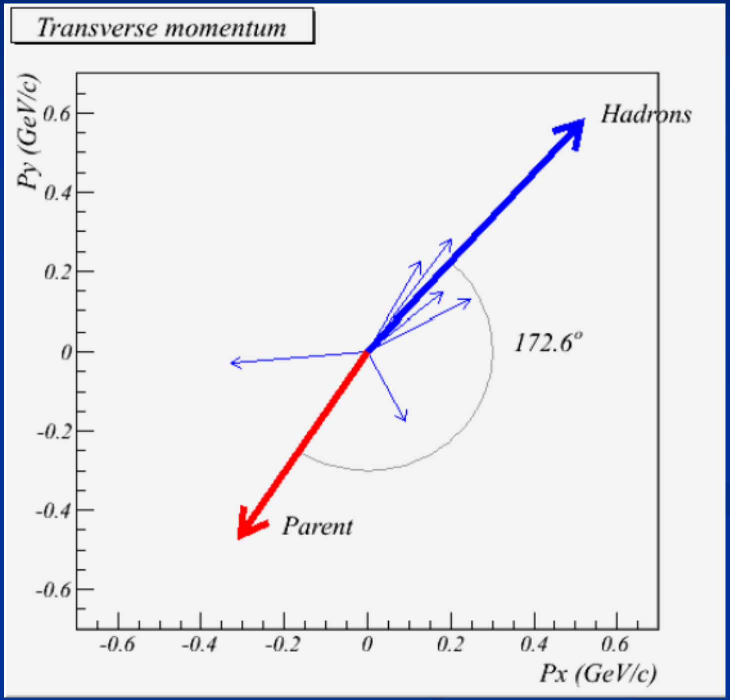
γ_1 : 5.6 ± 2.7 GeV/c
γ_2 : 1.2 ± 0.8 GeV/c

Vertex tracks followed down (through several bricks) to assess the muon-less nature of the event.

→ MC residual probabilty to be ν_μ CC event ~ 1% (undetected very large angle muon), 5% assumed

Kinematical variables

VARIABLE	Measured	Selection criteria
Kink (mrad)	41 ± 2	>20
Decay length (μm)	1335 ± 35	Within 2 plates
P daughter (GeV/c)	12^{+6}_{-3}	>2
Pt daughter (MeV/c)	470^{+240}_{-120}	>300 (γ attached)
Missing Pt (MeV/c)	570^{+320}_{-170}	<1000
φ (deg)	173 ± 2	>90



γ_1 and γ_2 are both attached to 2^{ry} vertex

Event nature and invariant mass reconstruction

- The event passes all cuts, with the presence of at least 1 gamma pointing to the secondary vertex, and is therefore a candidate to the $\tau \rightarrow$ 1-prong hadron decay mode.

- The invariant mass of the two detected gammas is consistent with the π^0 mass value (see table below).

- The invariant mass of the $\pi^- \gamma \gamma$ system has a value (see below) compatible with that of the ρ(770). The ρ appears in about 25% of the tau decays: $\tau \rightarrow \rho\,(\pi^- \pi^0)\,\nu_\tau$.

π^o mass	ρ mass
$120 \pm 20 \pm 35$ MeV	$640\,^{+125}_{-80}\,^{+100}_{-90}$ MeV

Background sources

- Prompt ν_τ:~ 10^{-7} / CC
- Decay of charmed particles produced in ν_e interactions: ~ 10^{-6} / CC
- Double charm production: ~ 10^{-6} / CC

Main sources:

- Decay of charmed particle produced in ν_μ interactions (CC & NC): ~ 10^{-5} / CC
- Hadronic interactions (CC & NC) ~ 10^{-5} / CC

Statistical significance

We observe 1 event in the 1-prong hadron τ decay channel,
with a background expectation (~ 50% error for each component) of:

0.011 events (reinteractions)
0.007 events (charm)

0.018 ± 0.007 (syst) events 1-prong hadron

all decay modes: 1-prong hadron, 3-prongs + 1-prong μ + 1-prong e :

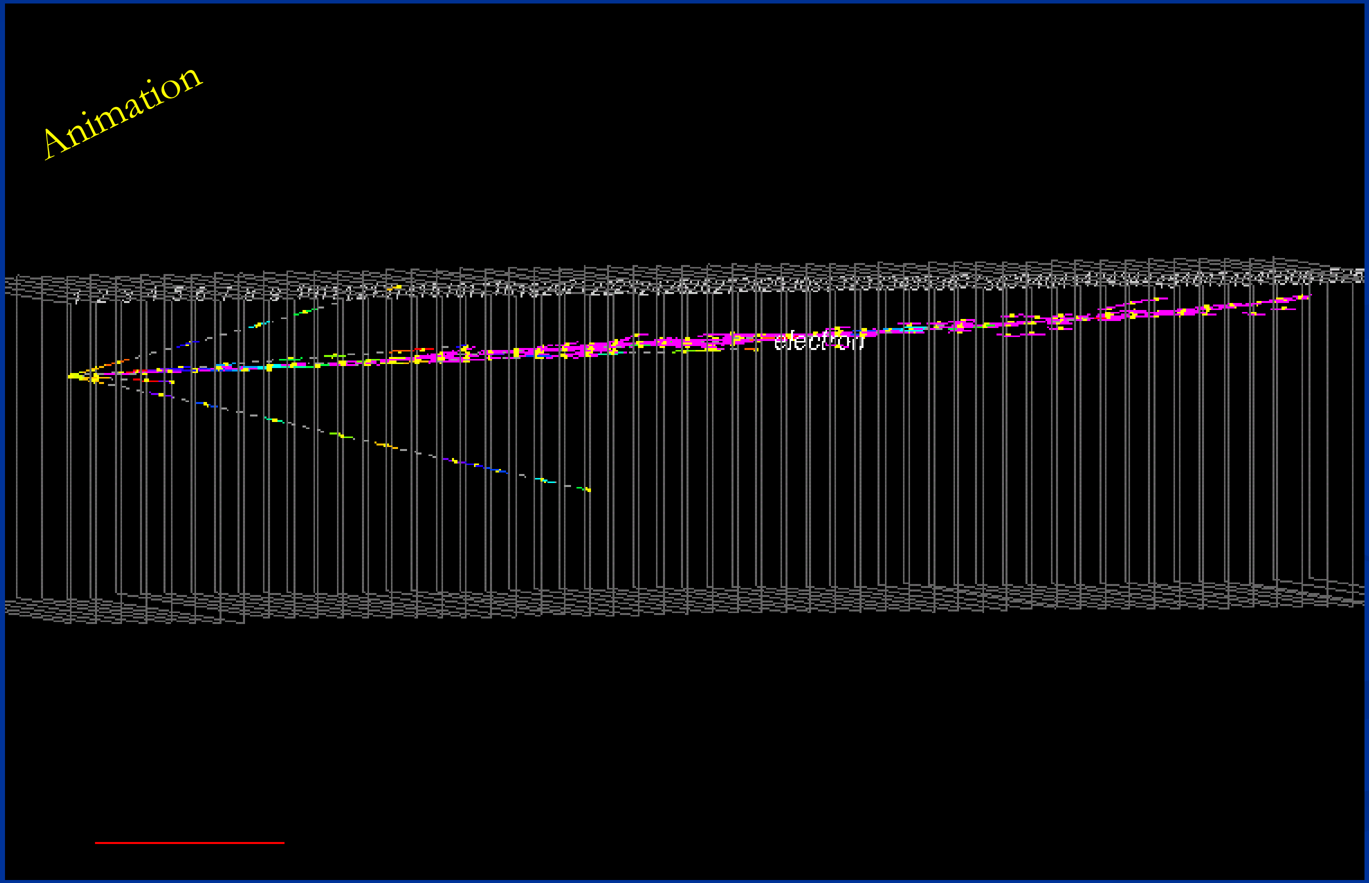
0.045 ± 0.020 (syst) events total BG
(here we add up the errors linearly)

By considering the 1-prong hadron channel only, the probability to observe 1 event due to a background fluctuation is 1.8%, for a statistical significance of 2.36 σ on the measurement of a first ν_τ candidate event in OPERA.

If one considers all τ decay modes which were included in the search, the probability to observe 1 event for a background fluctuation is 4.5% correspondig to a significance of 2.01 σ.

ν_e observation

- 13 ν_e candidate events have been observed



-Electron momentum:
$9.5_{-2.0}^{+2.0}$ GeV
-Missing momentum at primary vertex:
$1.1_{-0.8}^{+14.6}$ GeV/c
-Total energy of the event:
$18.9_{-8.4}^{+68.1}$ GeV

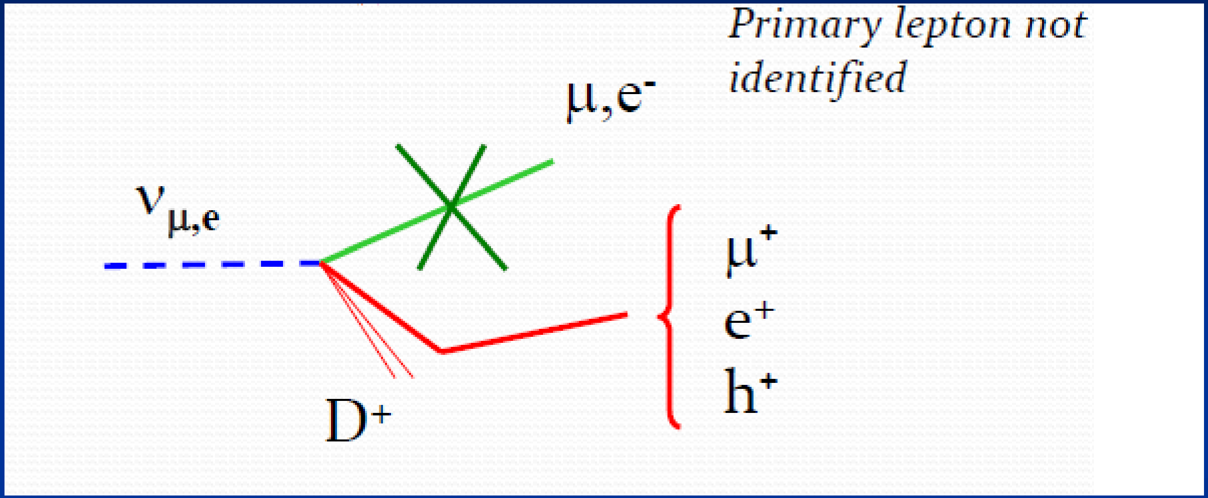
Compatible with ν_e from beam contamination

Conclusions

- The OPERA experiment is aimed at the discovery of neutrino oscillations in appearance mode through the study of $\nu_\mu \rightarrow \nu_\tau$ channel;
- Analyzing a subsample of 2008-2009 data taking ($1.85\ 10^{19}$ pot):
  - Decay topologies due to charmed particles observed in good agreement with expectation;
  - Events induced by ν_e due to the beam contamination has been observed
  - 1 muon-less event candidate for $\tau \rightarrow$ 1-prong hadron decay topology has been detected

Spare Slides

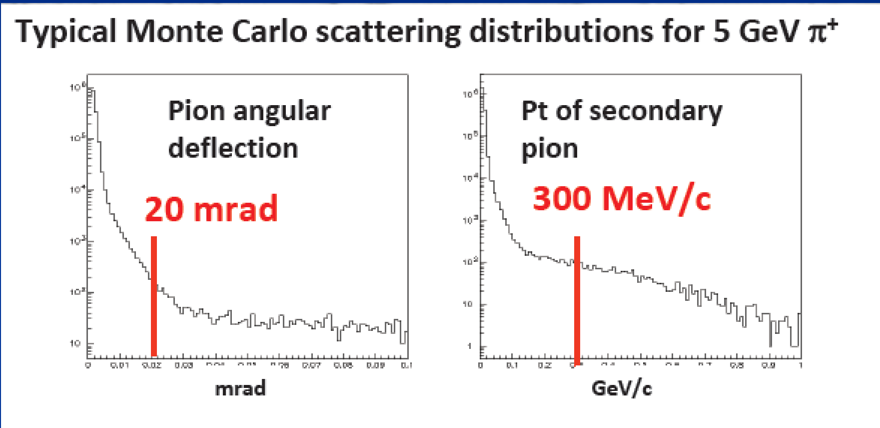
Charm background



-Since the muon ID ~ 96% this background can be suppressed identifying the primary lepton;
- For 1-prong hadronic channel 0.007 ± 0.004 (syst.) BG events are expected for the analyzed statistics

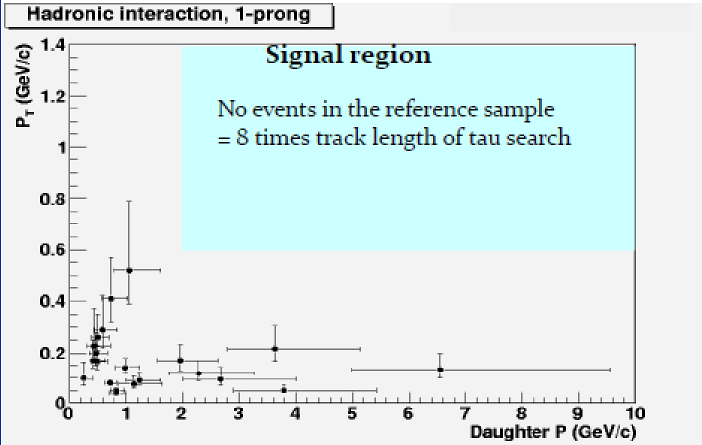
Hadronic interactions

- Simulation: 160 millions event (0.5 – 15 GeV) of $\pi^+ \pi^- K^+ K^- p$ (impinging 1 mm of lead) equivalento to 160 km of hadronic track lenght produced with FLUKA



Kink probability integrated ove the ν_μ NC hadronic spectrum after 2 mmPb and taking into account the cuts on the event global kinematics (3.8 ± 0.2) 10^{-5} kink/NC

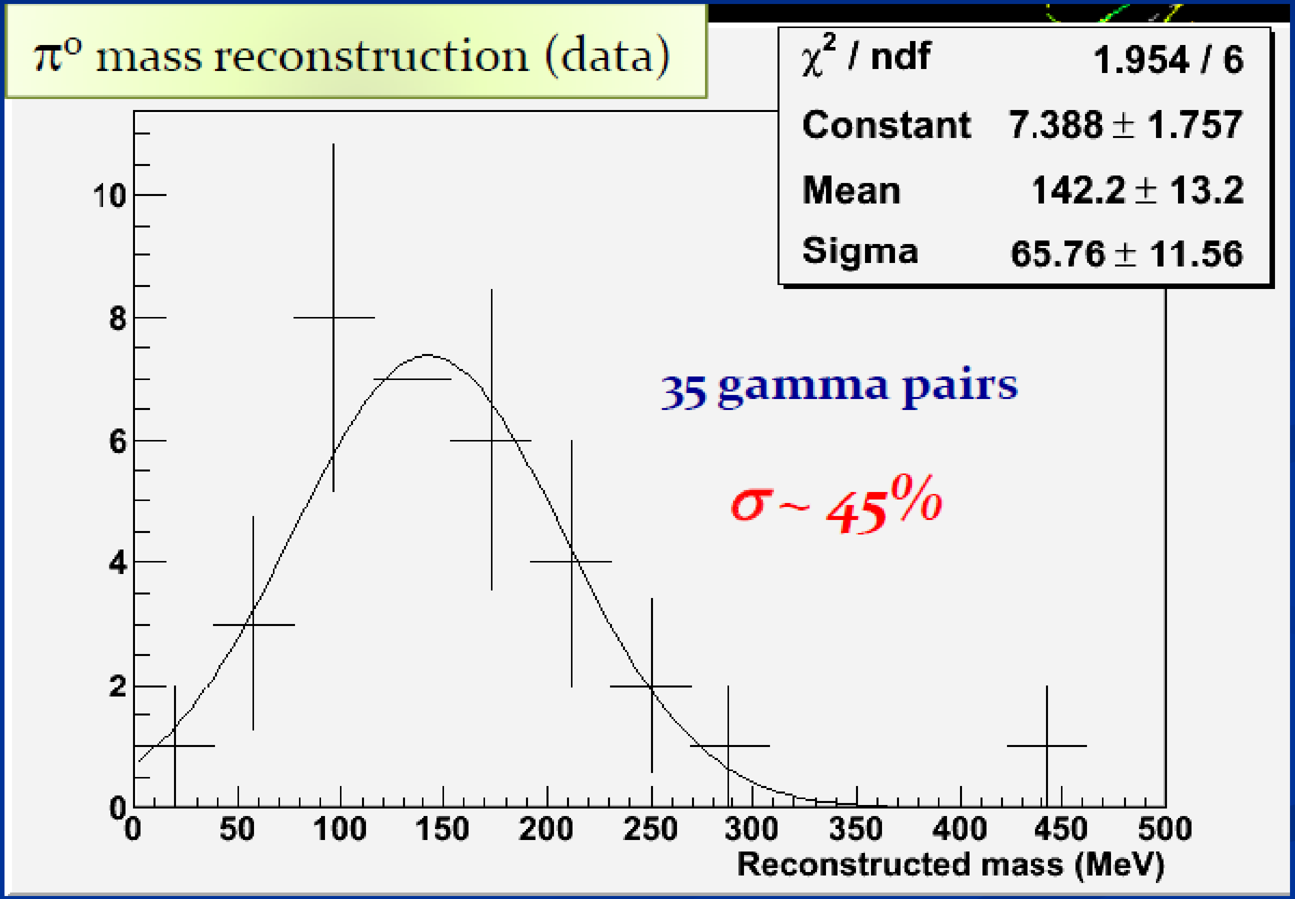
- Hadronic interactions background in OPERA data:



Search for "decay-like" interactions track far from the primary vertex

No background-like interactions has been found in the signal region
→ 90% CL upper limit of 1.54 10^{-3} kinks/NC event

π^0 mass reconstruction

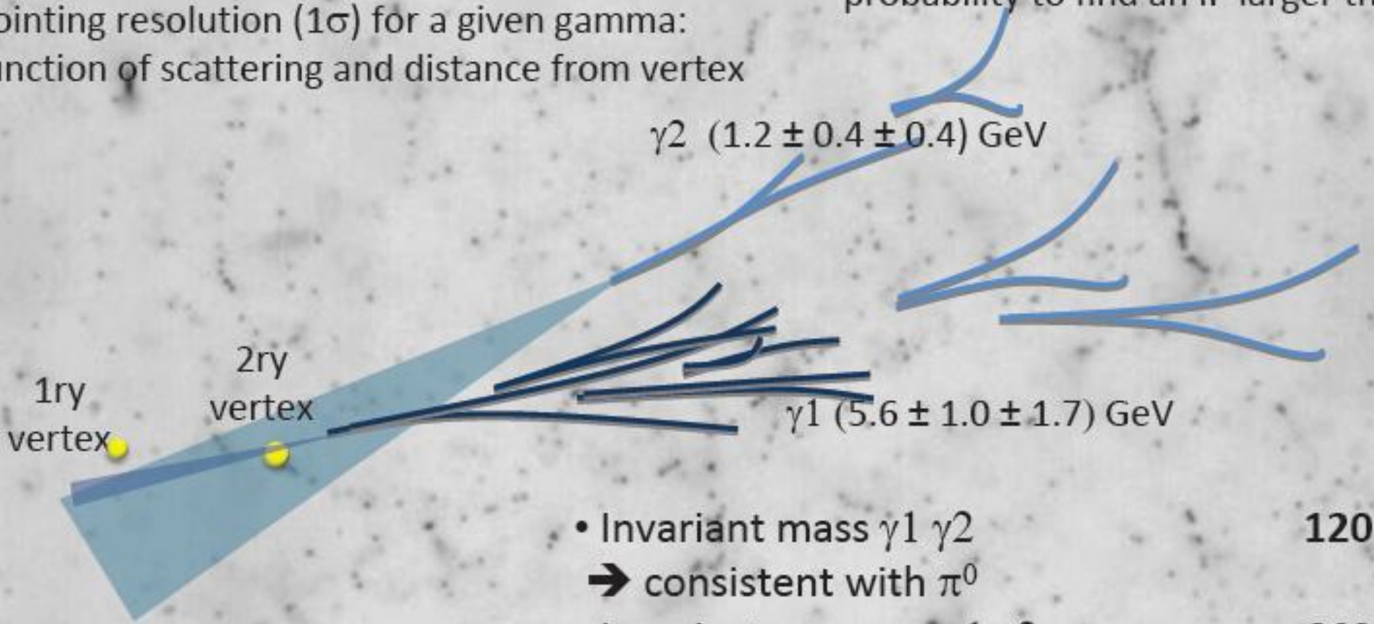


γ pointing

	Distance from 2ry vertex (mm)	IP to 1ry vertex (μm) <resolution>	IP to 2ry vertex (μm) <resolution>	**Prob. of attach. to 1ry vtx***	**Prob. of attach. to 2ry vtx***	**Attachment hypothesis**
1^{st} γ	2.2	45.0 <11>	7.5 <7>	**$<10^{-3}$**	**0.32**	**2ry vertex**
2^{nd} γ	12.6	85.6 <56>	22 <50>	**0.10**	**0.82**	**2ry vertex (favored)**

* probability to find an IP larger than the observed one

Pointing resolution (1σ) for a given gamma: function of scattering and distance from vertex

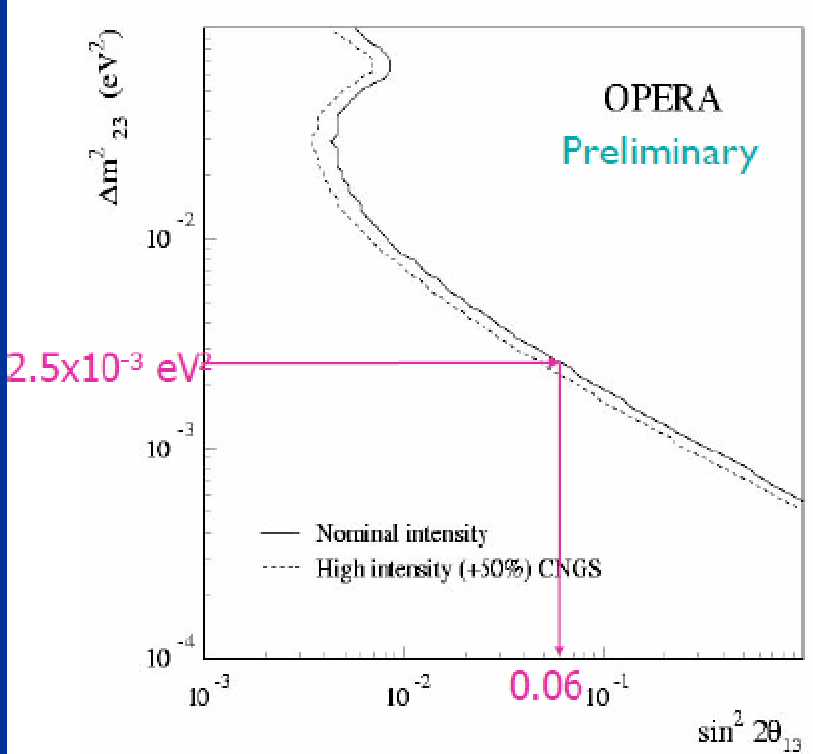


- Invariant mass $\gamma 1$ $\gamma 2$ — $120 \pm 20 \pm 35$ *MeV*
  ➔ consistent with π^0
- Invariant mass $\pi^- \gamma 1$ $\gamma 2$ — $640^{+125}_{-80}{}^{+100}_{-90}$ *MeV*
  ➔ consistent with $\rho(770)$

(Branching ratio $\tau \rightarrow \rho\ (\pi^- \pi^0)\ \nu_\tau$ ~ 25%)

Sensitivity to Θ_{13}

Simultaneous fit on:
E_e, missing p_T and visible energy



full mixing, 5 years run @ 4.5×10^{19} pot / year

Θ_{13} (deg)	Signal $\nu_\mu \to \nu_e$	Background			
		$\tau \to e$	ν_μCC	ν_μNC	ν_eCC beam
9	9.3	4.5	1.0	5.2	18
7	5.8	4.5	1.0	5.2	18
5	3.0	4.5	1.0	5.2	18

Limits at 90% CL for
$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 full mixing

	$\sin^2 2\Theta_{13}$	Θ_{13}
CHOOZ	<0.14	11°
OPERA	<0.06	7.1°

Charm in data