Search for $\nu_\mu \rightarrow \nu_\tau$ oscillations with the OPERA experiment

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on behalf of the OPERA Collaboration

QFTHEP - 2013

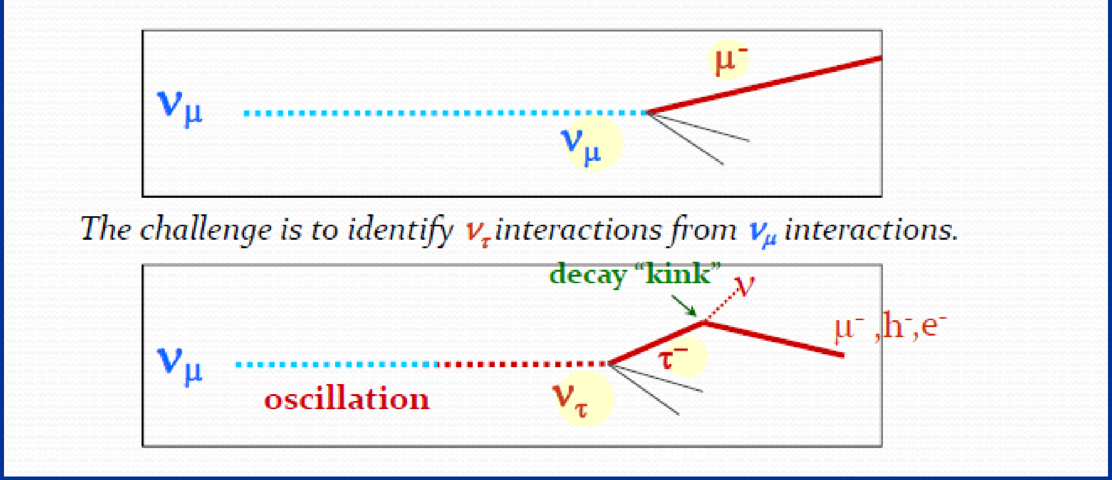
Outline

- The OPERA experiment
  - Requirements
  - CNGS neutrino beam
  - OPERA detector
- Physics Results
  - Charm control sample
  - ν_τ candidates
  - Background sources
- Conclusions.

The OPERA experiment

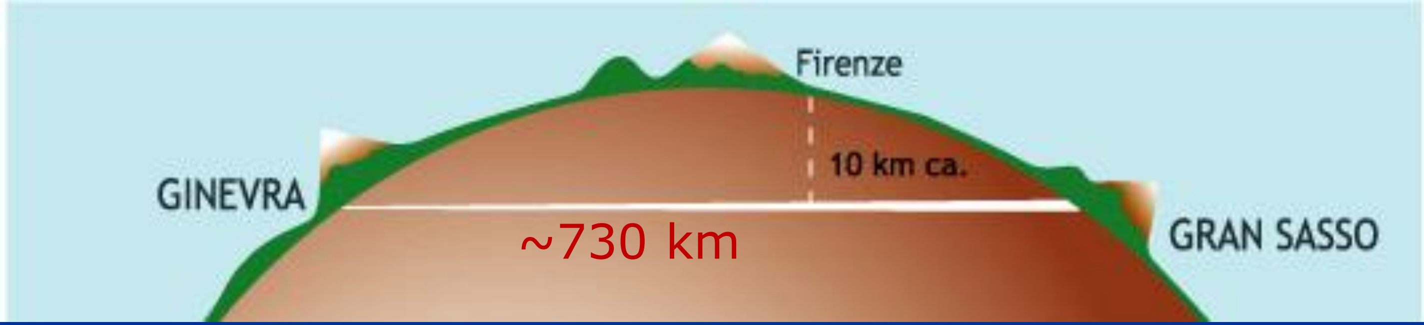
Oscillation Project with Emulsion-tRacking Apparatus

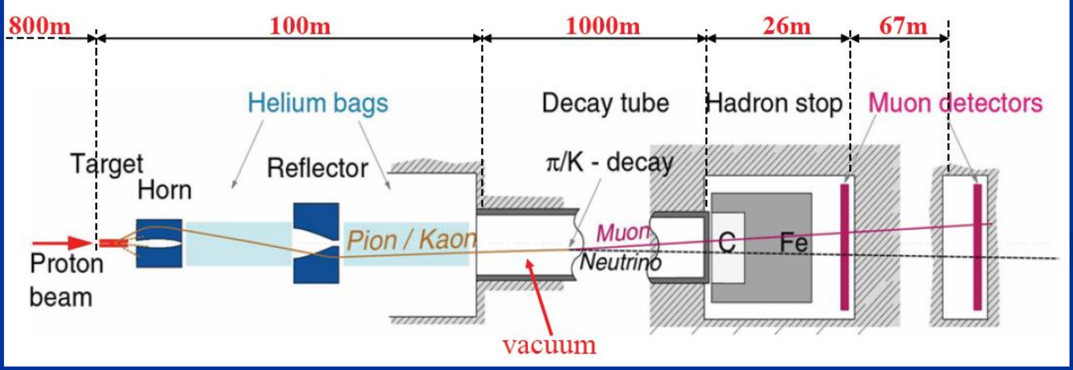
ν_τ appearance from an initially relatively pure ν_μ high energy artificial beam through the ν_τ CC interaction with the target mass.



- 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 background)

The CNGS neutrino beam





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

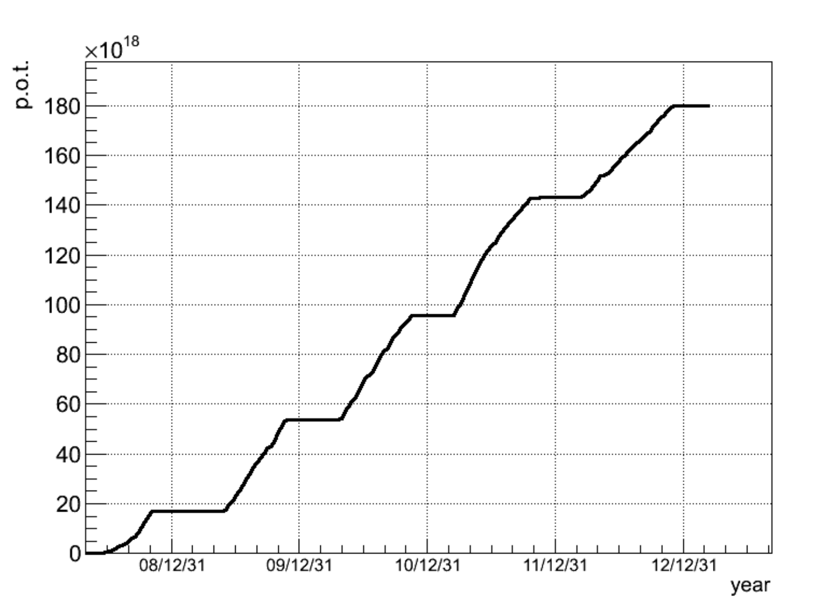
$\langle E\nu_\mu \rangle$	17 GeV
$(\nu_e+\bar{\nu}_e)/\nu_\mu$	0.8% (*)
$\bar{\nu}_\mu / \nu_\mu$	2.1% (*)
ν_τ prompt	Negligible (*)

(*) 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)

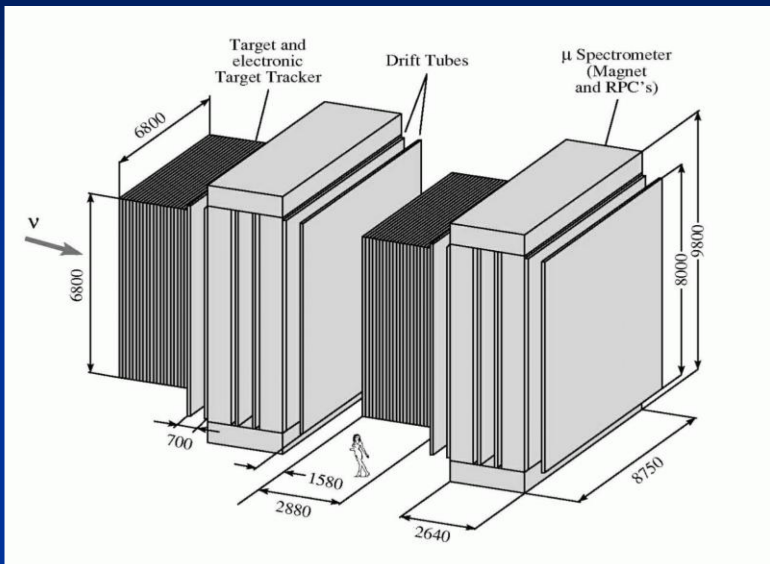
CNGS performances

Year	Proton On Target	Run
2006	0.076×10^{19}	Commissioning
2007	0.082×10^{19}	Commissioning
2008	**1.74×10^{19}**	**First physics run**
2009	**3.53×10^{19}**	**Physics run**
2010	**4.09×10^{19} pot**	**Physics run**
2011	**4.75×10^{19} pot**	**Physics run**
2012	**3.86×10^{19} pot**	**Physics run**



Total: $17.97\ 10^{19}$ pot
20% less than the proposal value ($22.5\ 10^{19}$)

The OPERA detector



Detector elements:

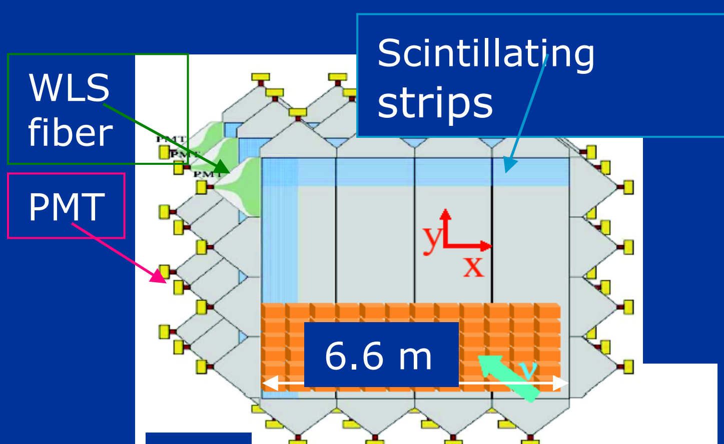
-Electronic detectors

-Muon spectrometers

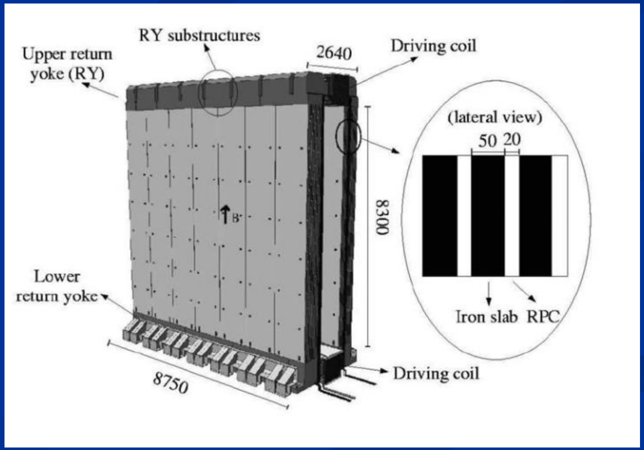
-Emulsion Cloud Chamber

1 SuperModule:

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

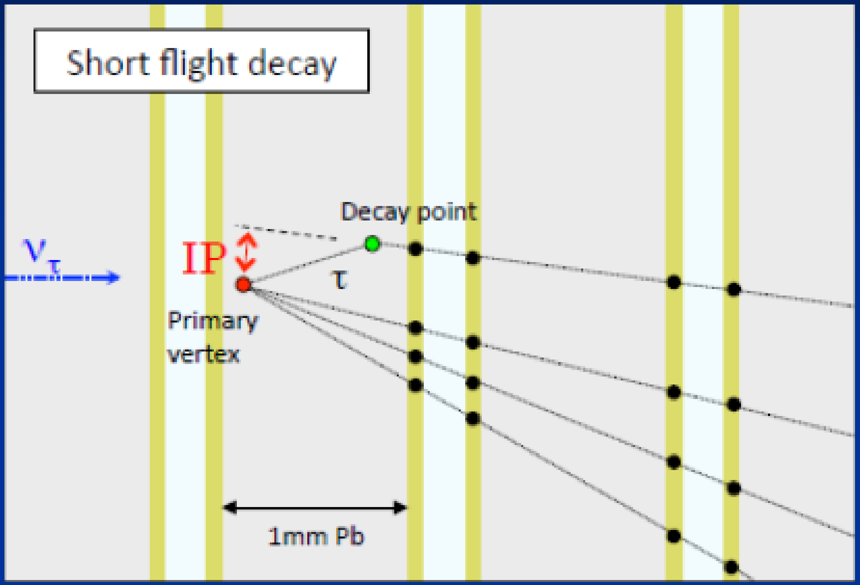


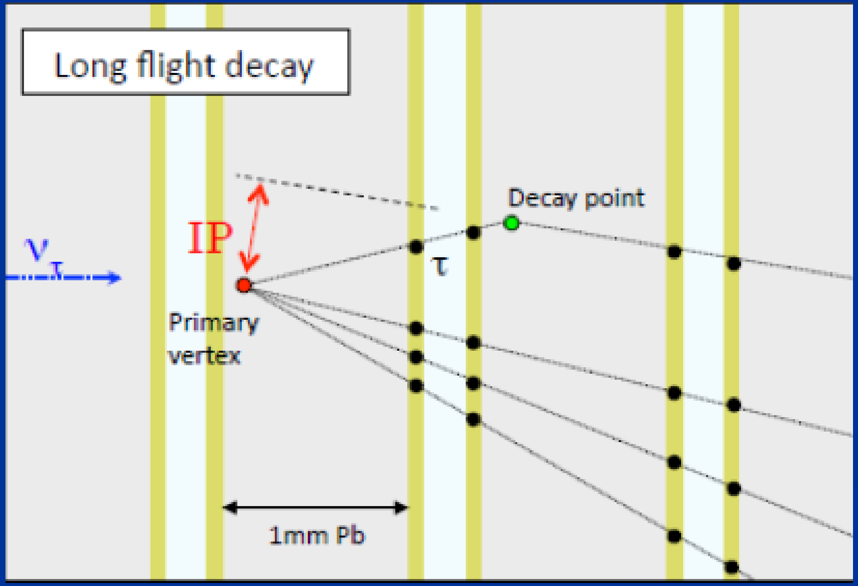
Strip granularity: 2.6 x 2.6 cm^2

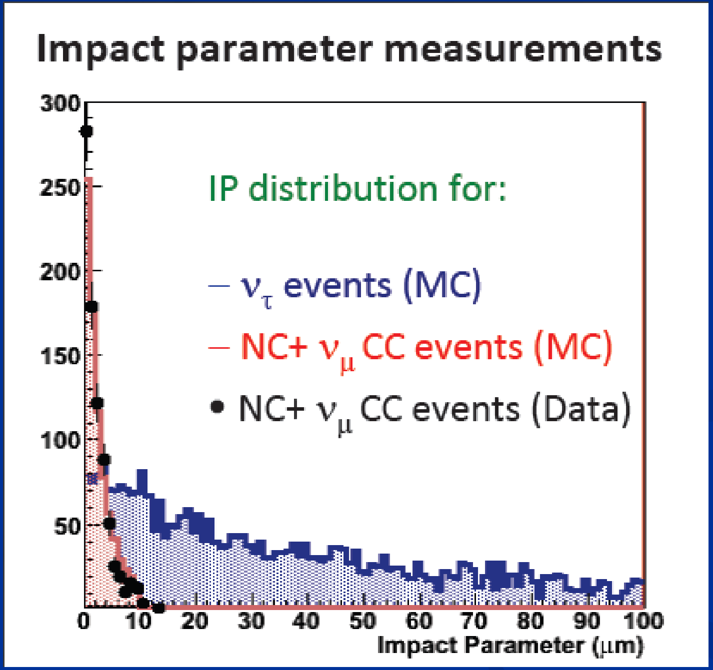


Measured magnetic field: 1.52 T

ν_τ detection





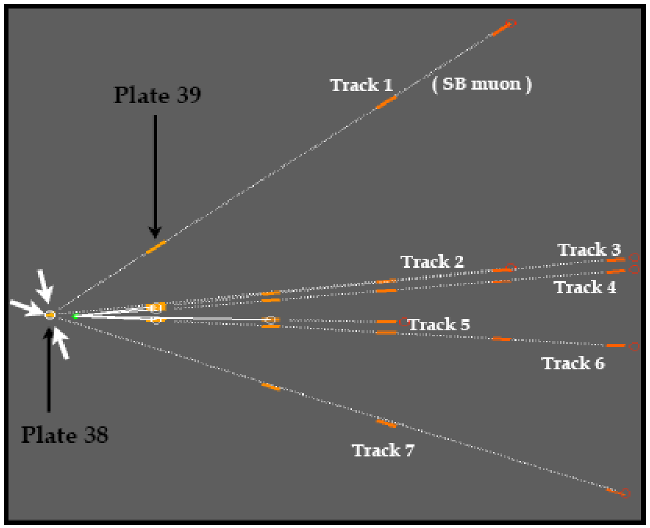


Detection of decay topologies triggered by large IP wrt primary vertex or by kink/trident topologies

Charm candidate events

Event 234654975

Brick 85405



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

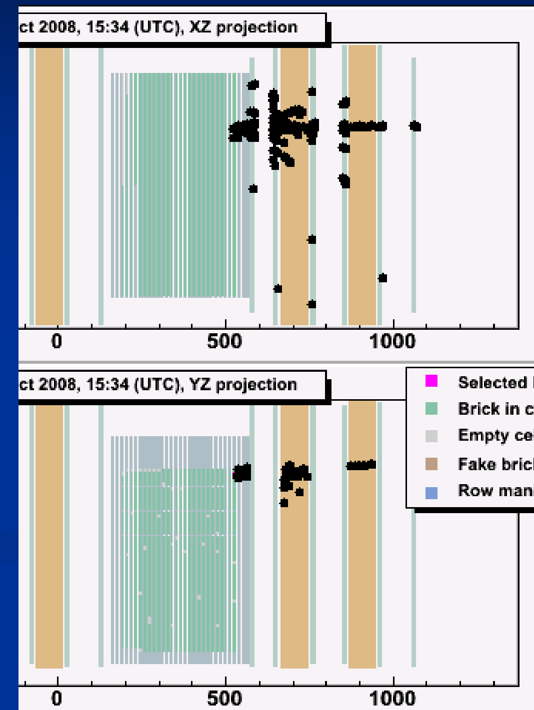
VERTEX 2

	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

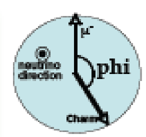
Primary vertex

Decay vertex

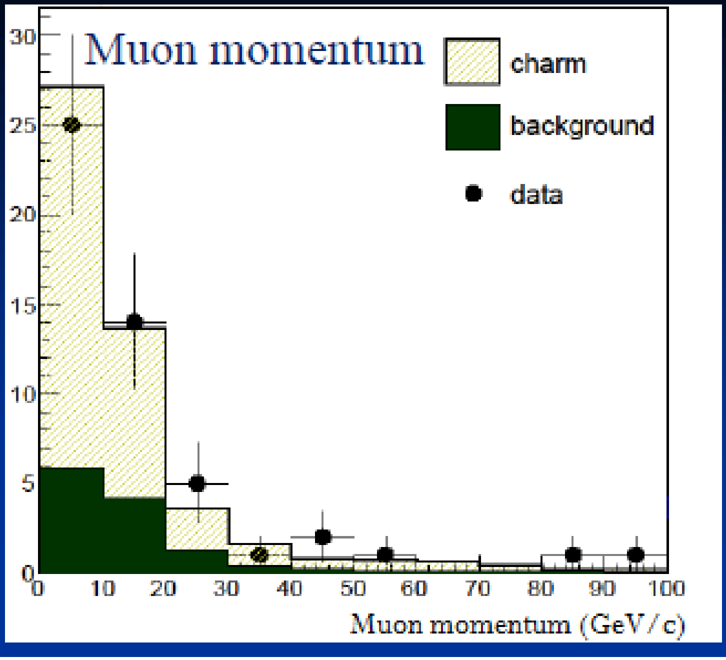


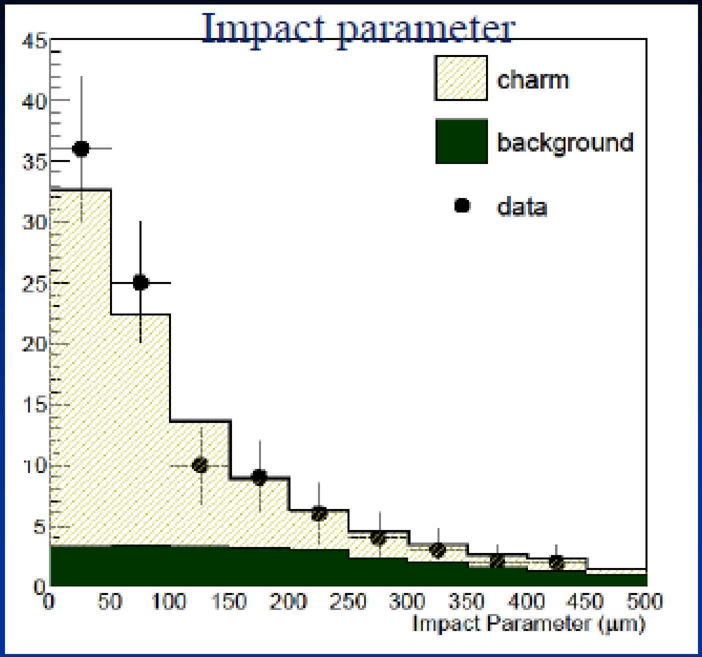
D^0

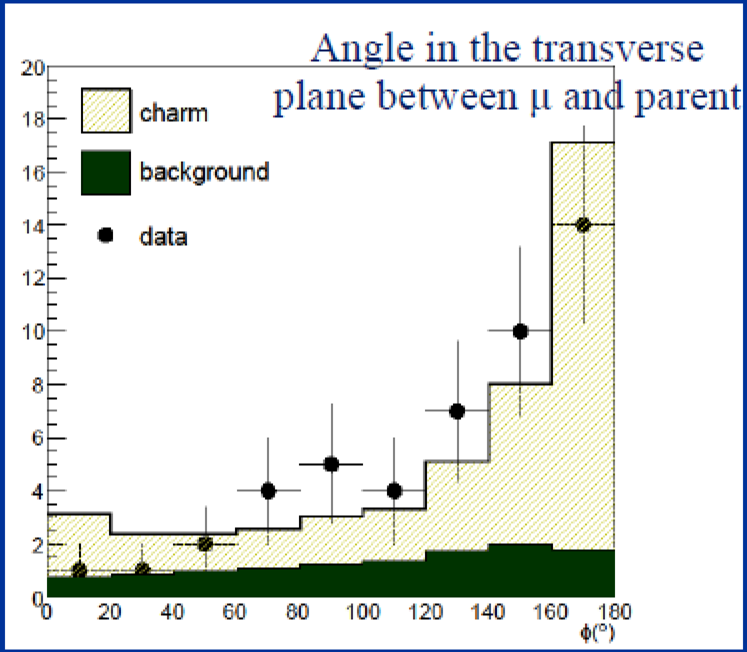
Tx	Ty	Flight Length (µm)	phi	minimum mass (GeV/c^2)
-0,0207	0,0198	313,1	173,2°	1,7

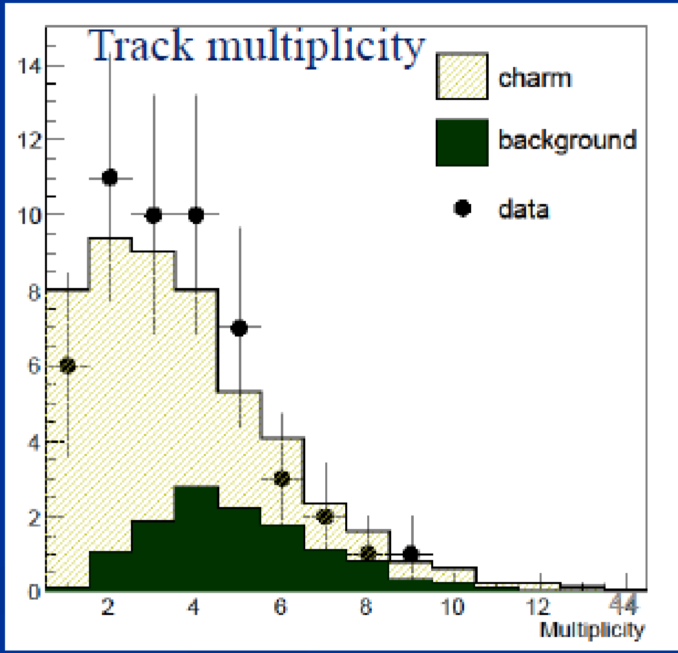


Check of the tau detection efficiency: similar life-time and decay topology (but with muon at the primary vertex)









Kolmogorov test > 0.99 for all plots

The first ν_τ candidate

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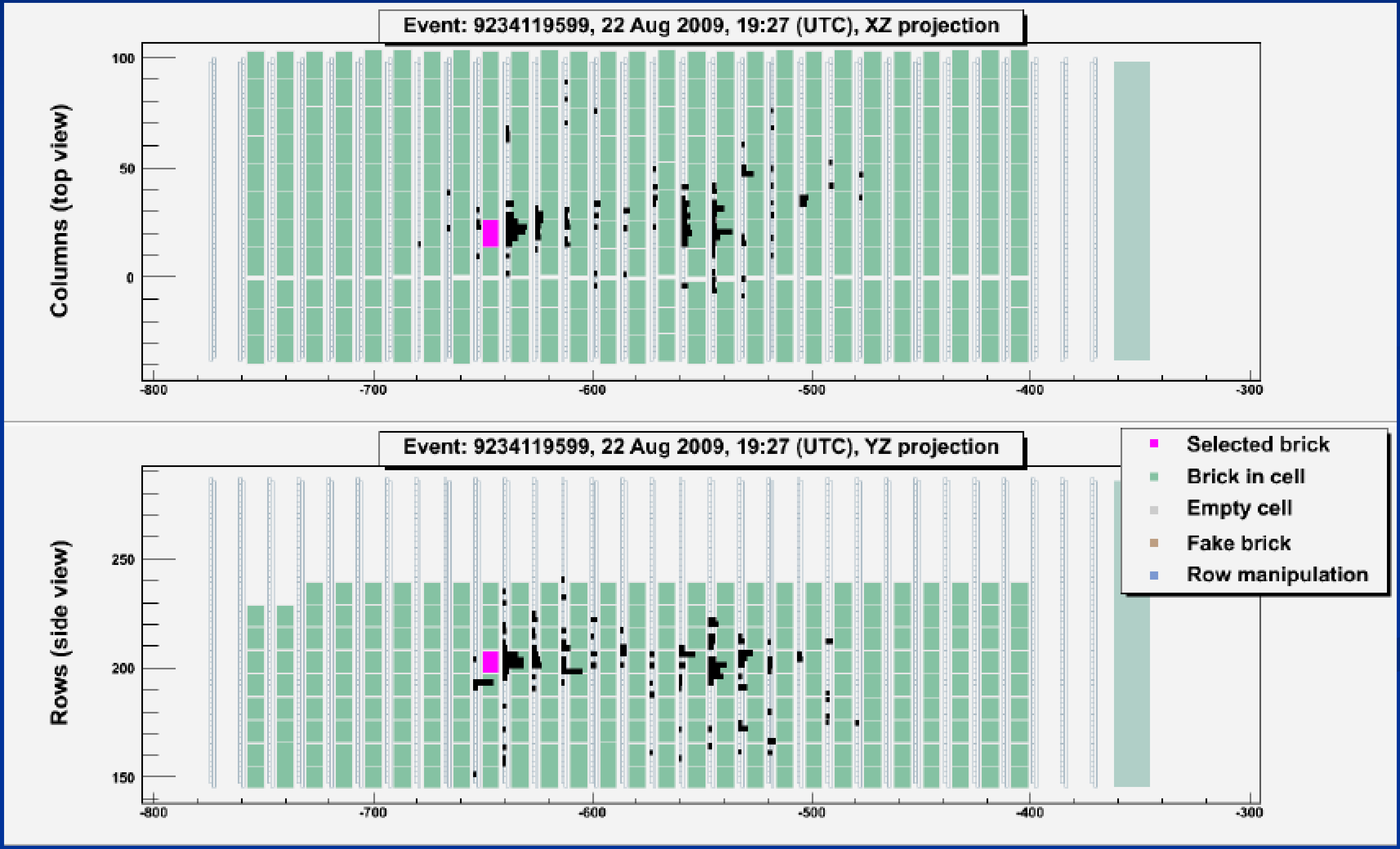
ELSEVIER

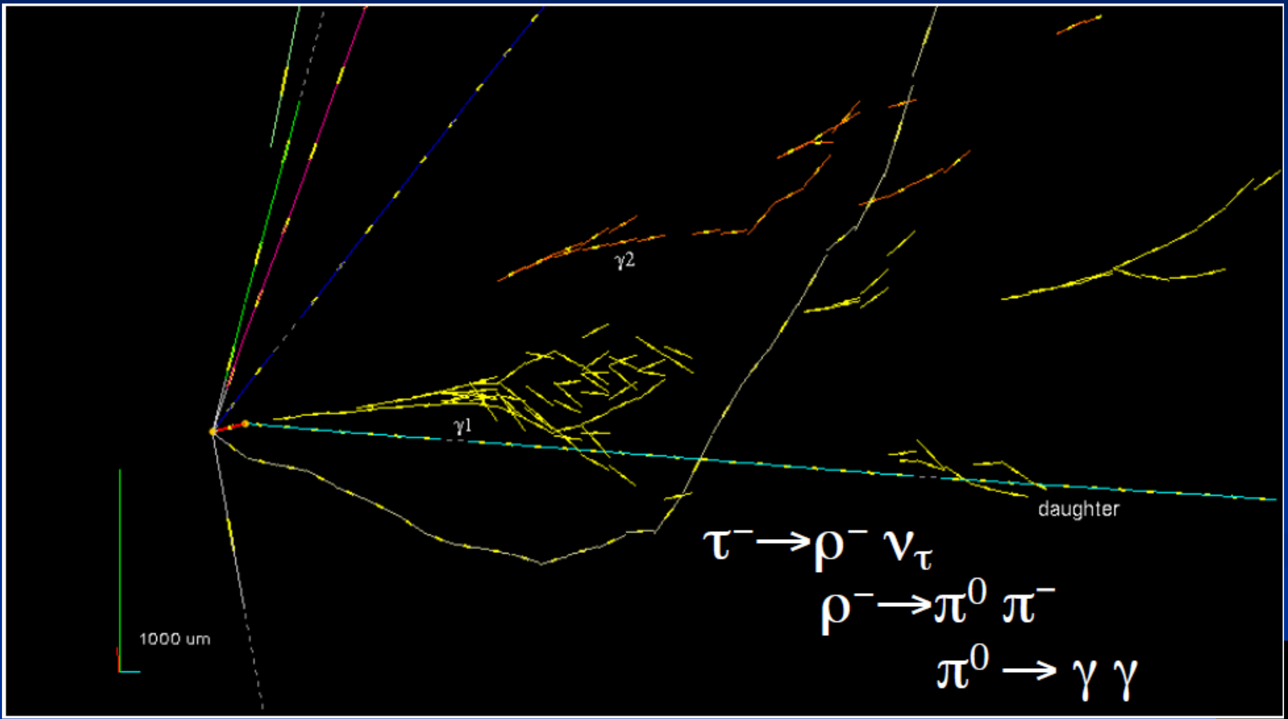
Observation of a first ν_τ candidate event in the OPERA experiment in the CNGS beam

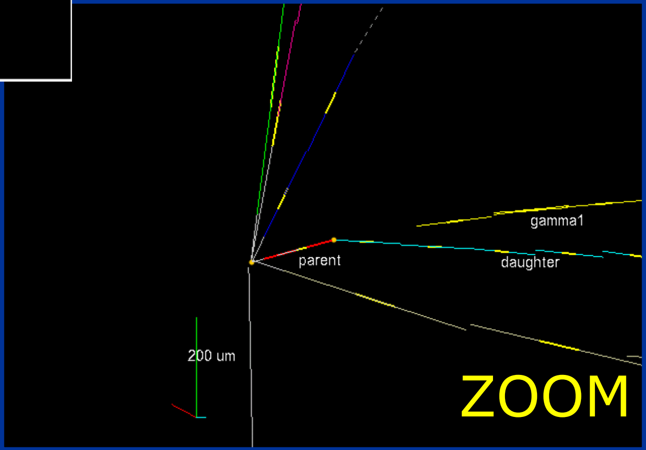
Event number: 9234119599 taken on 22nd of August, 19:27 (UTC)

ν_τ event recorded by the Electronic Detector



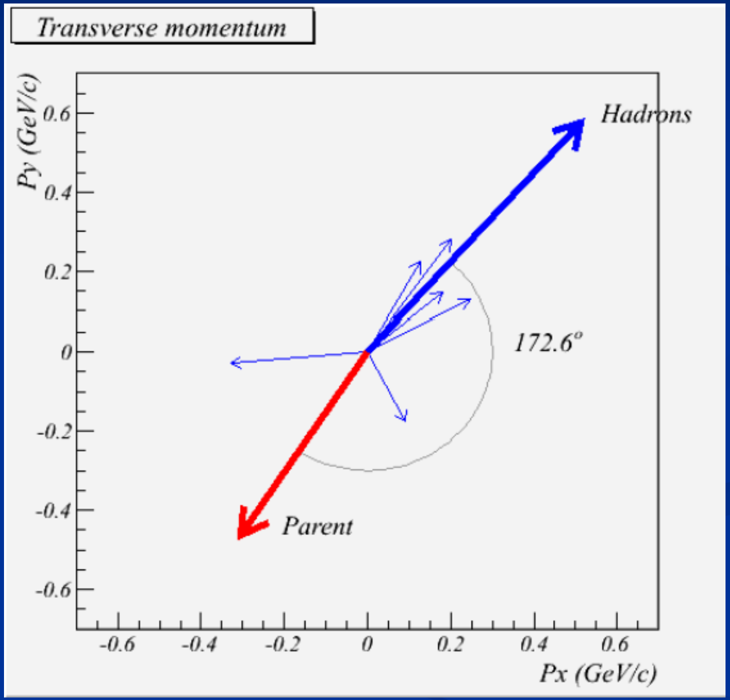
The first ν_τ candidate





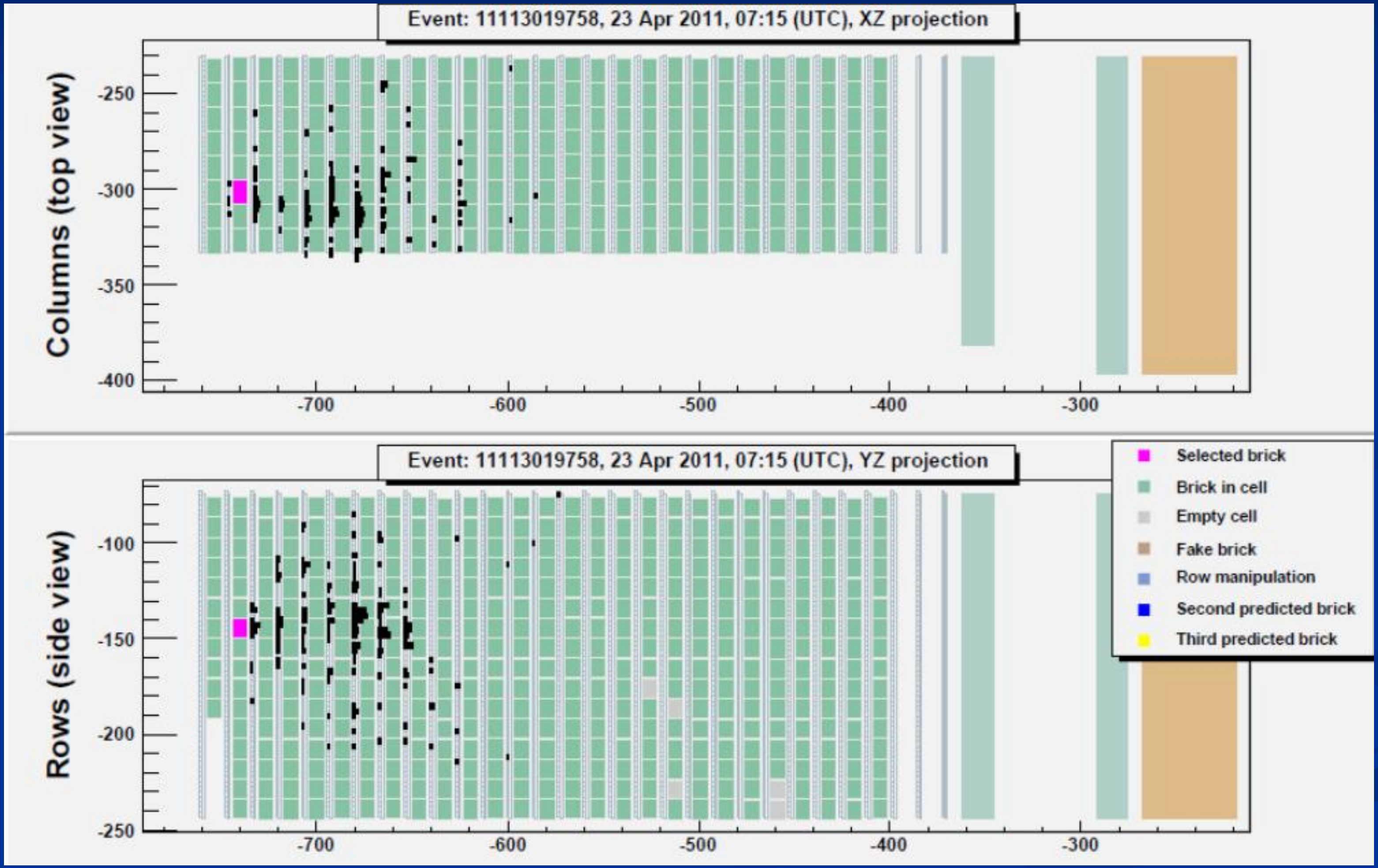
Kinematical variables

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**

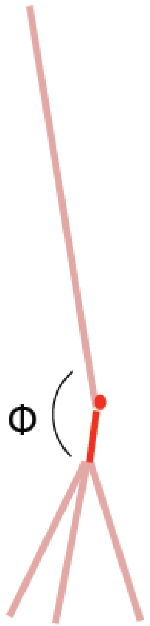


γ_1 and γ_2 are both attached to 2^{ry} vertex

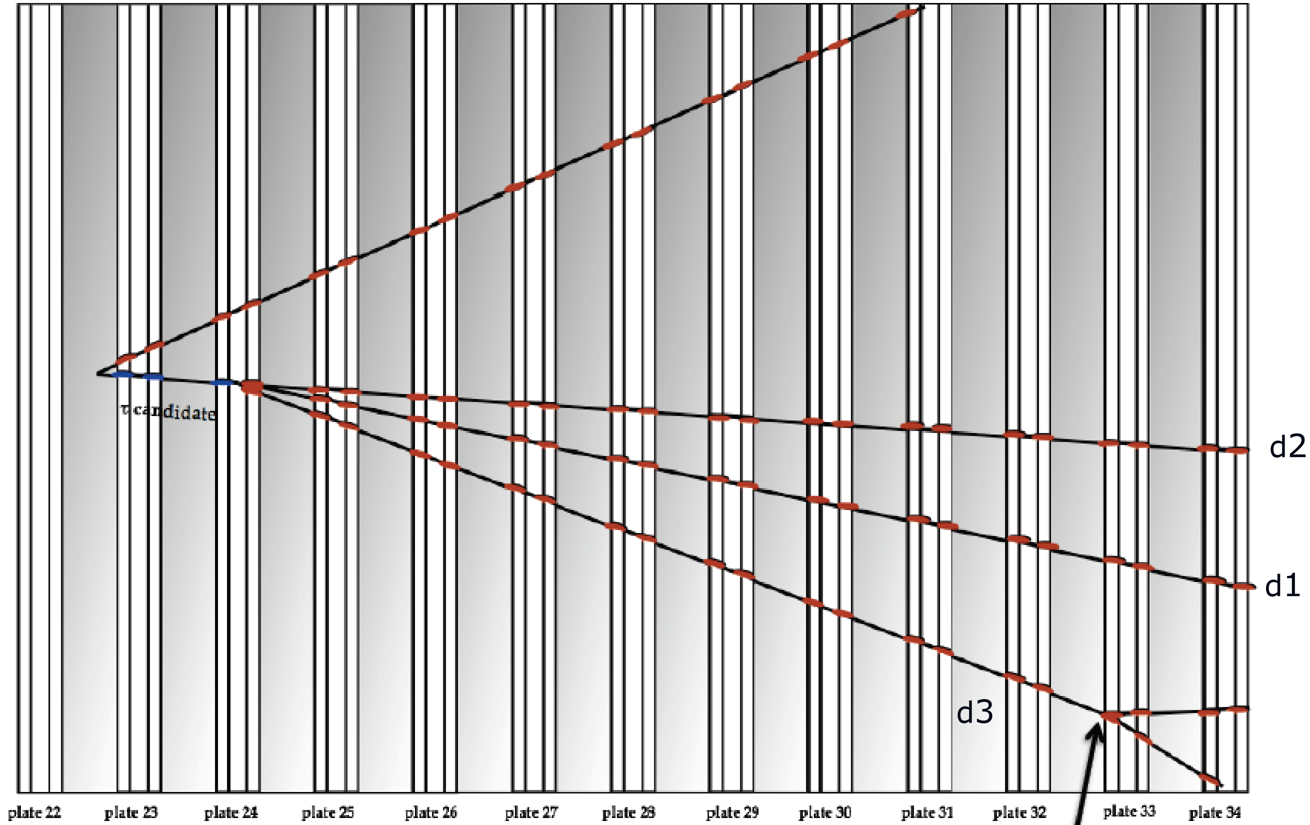
The second ν_τ candidate



Schematics of the event



Beam View
Φ=167°



Secondary Interaction
In Emulsion
With four Nuclear fragments

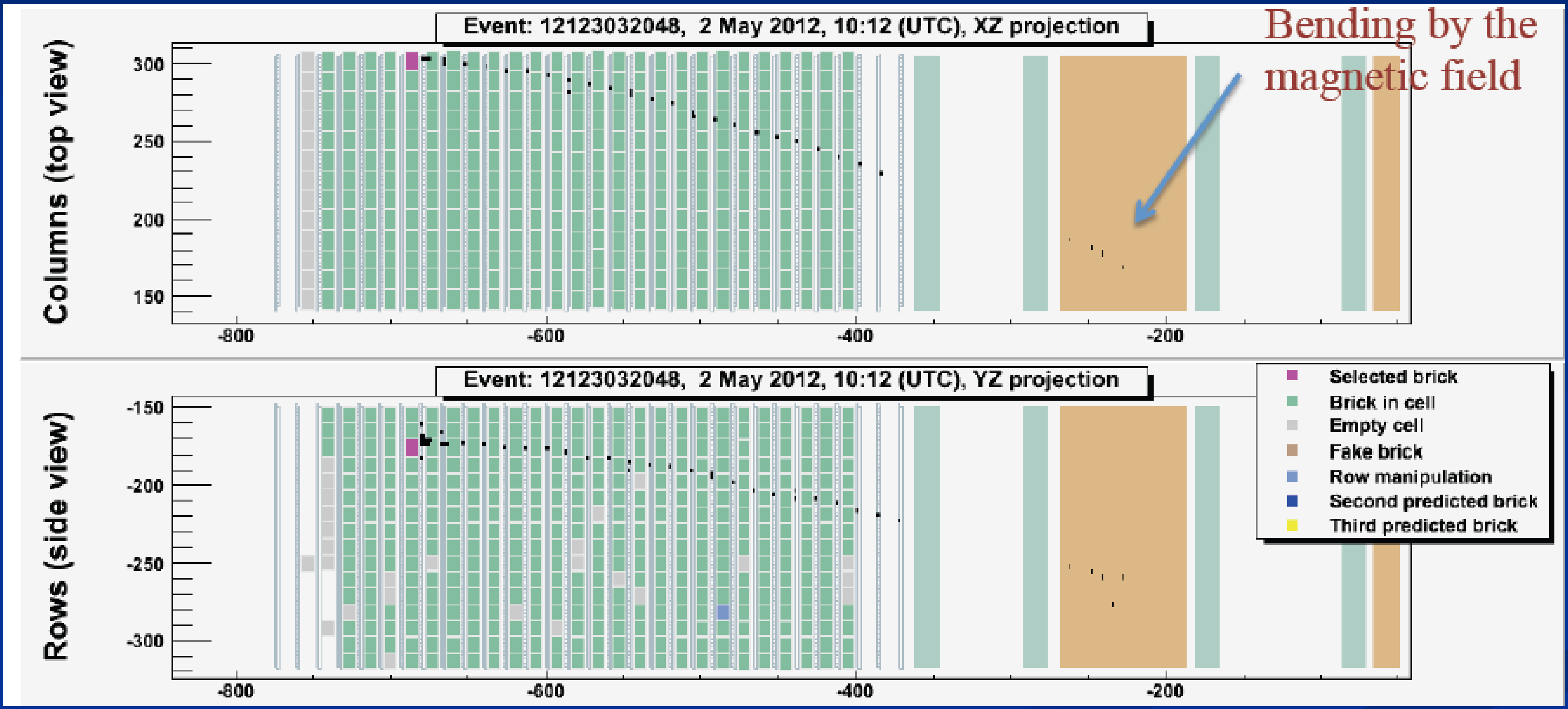
Momentum measurement and particle identification of event tracks

Track#	Momentum (1σ interval) [GeV/c]	Particle ID	Method / Comments
Primary	2.8 (2.1-3.5)	Hadron	• Momentum-Range Consistency Check Stops after 2 brick walls. Incompatible with muon (26÷44 brick walls)
d1	6.6 (5.2 - 8.6)	Hadron	• Momentum-Range Consistency Check
d2	1.3 (1.1 -1.5)	Hadron	• Momentum-Range Consistency Check
d3	2.0 (1.4 - 2.9)	Hadron	Interaction in the Brick @ 1.3cm downstream

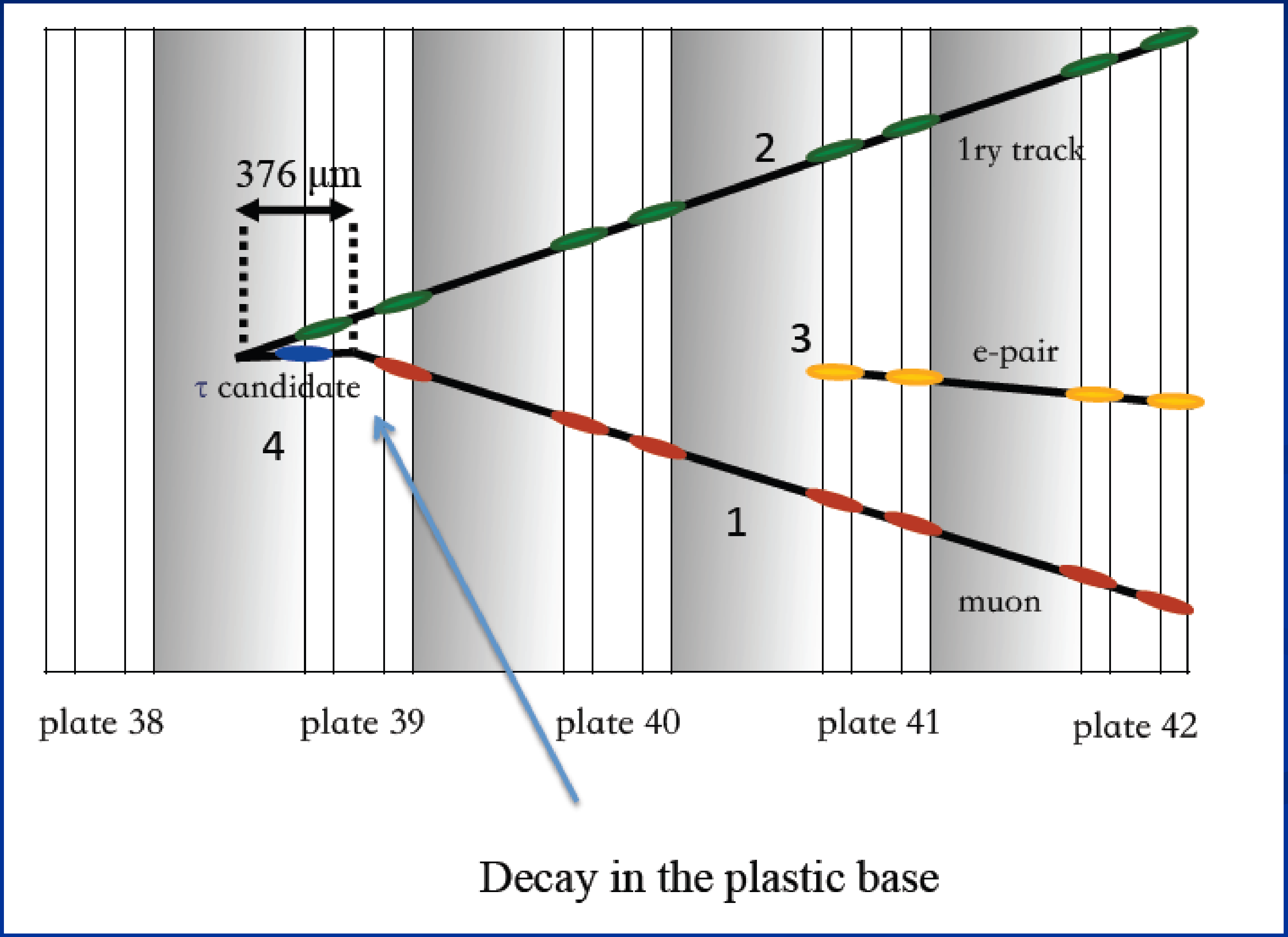
Kinematical variables

	Cut	Value
φ (Tau - Hadron) [degree]	>90	167.8±1.1
average kink angle [mrad]	< 500	87.4±1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4±1.7
Min Invariant mass [GeV/c²]	0.5 < < 2.0	0.96±0.13
Invariant mass [GeV/c²]	0.5 < < 2.0	0.80±0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31±0.11

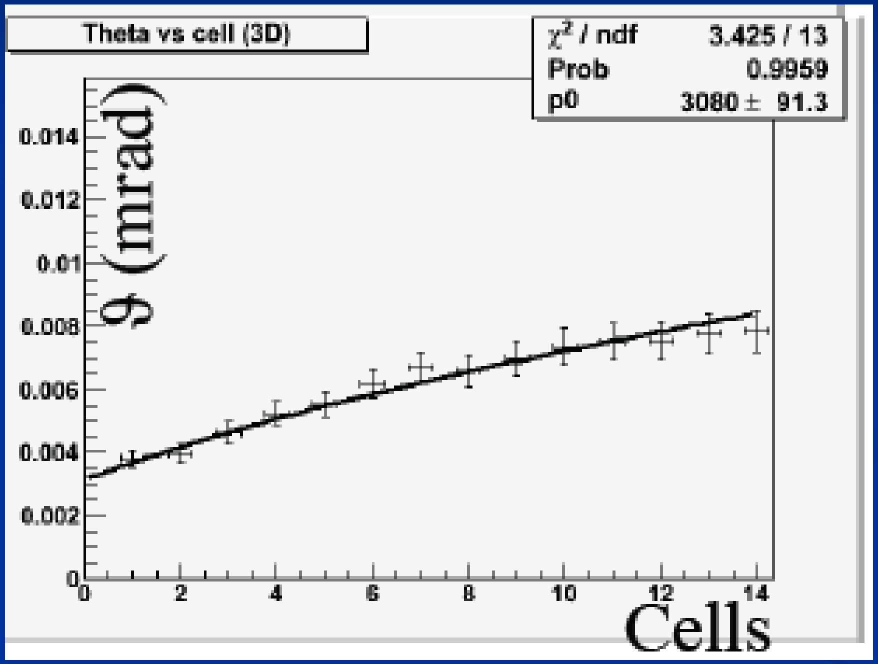
The third ν_τ candidate



Topological sketch



Muon momentum reconstruction

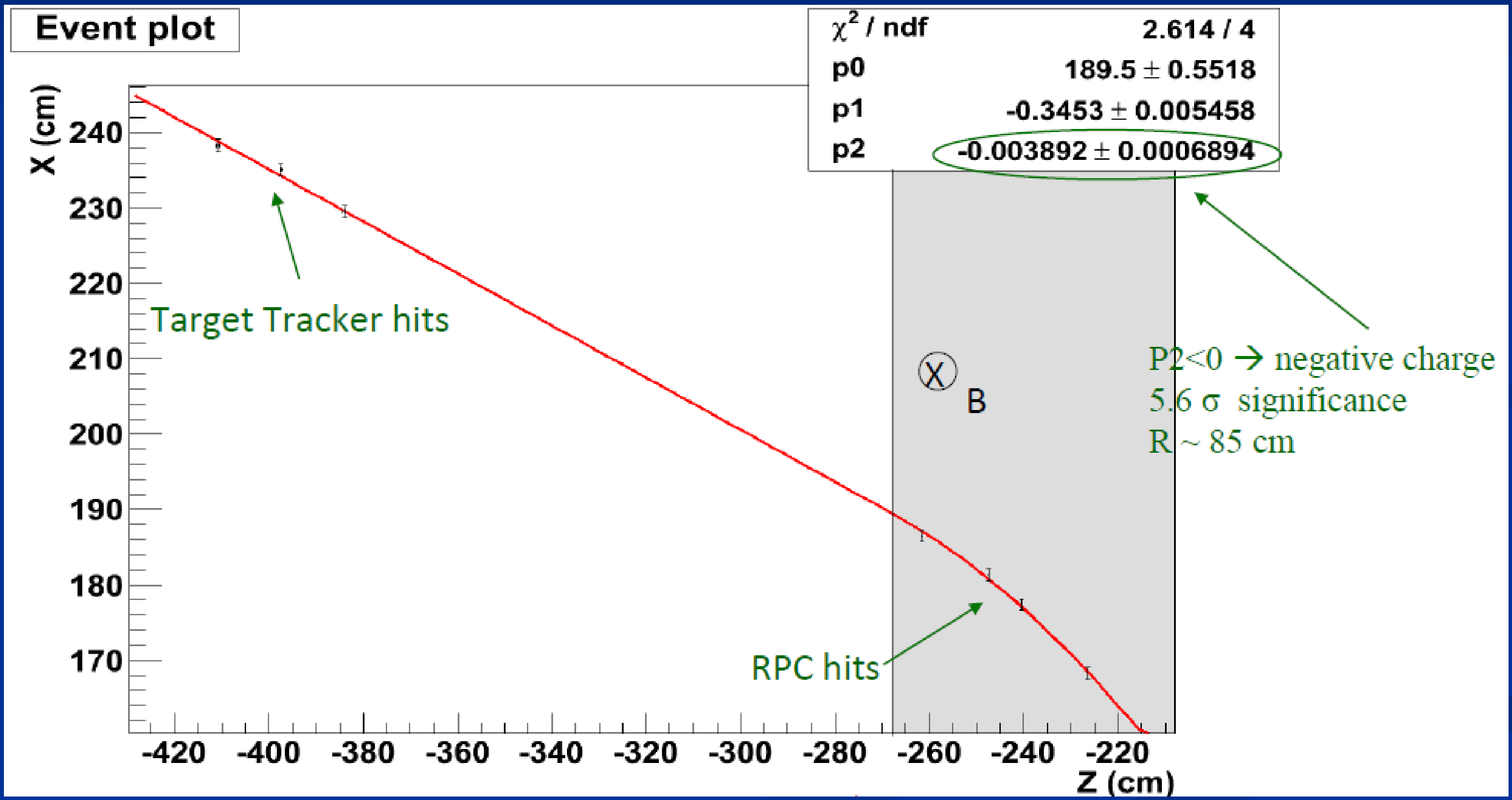


The muon momentum evaluated:

-by range in electronic detector is: 2.8 ± 0.2 GeV

-by MCS in brick: 3.1 [2.6, 4.0] GeV

Muon charge reconstruction

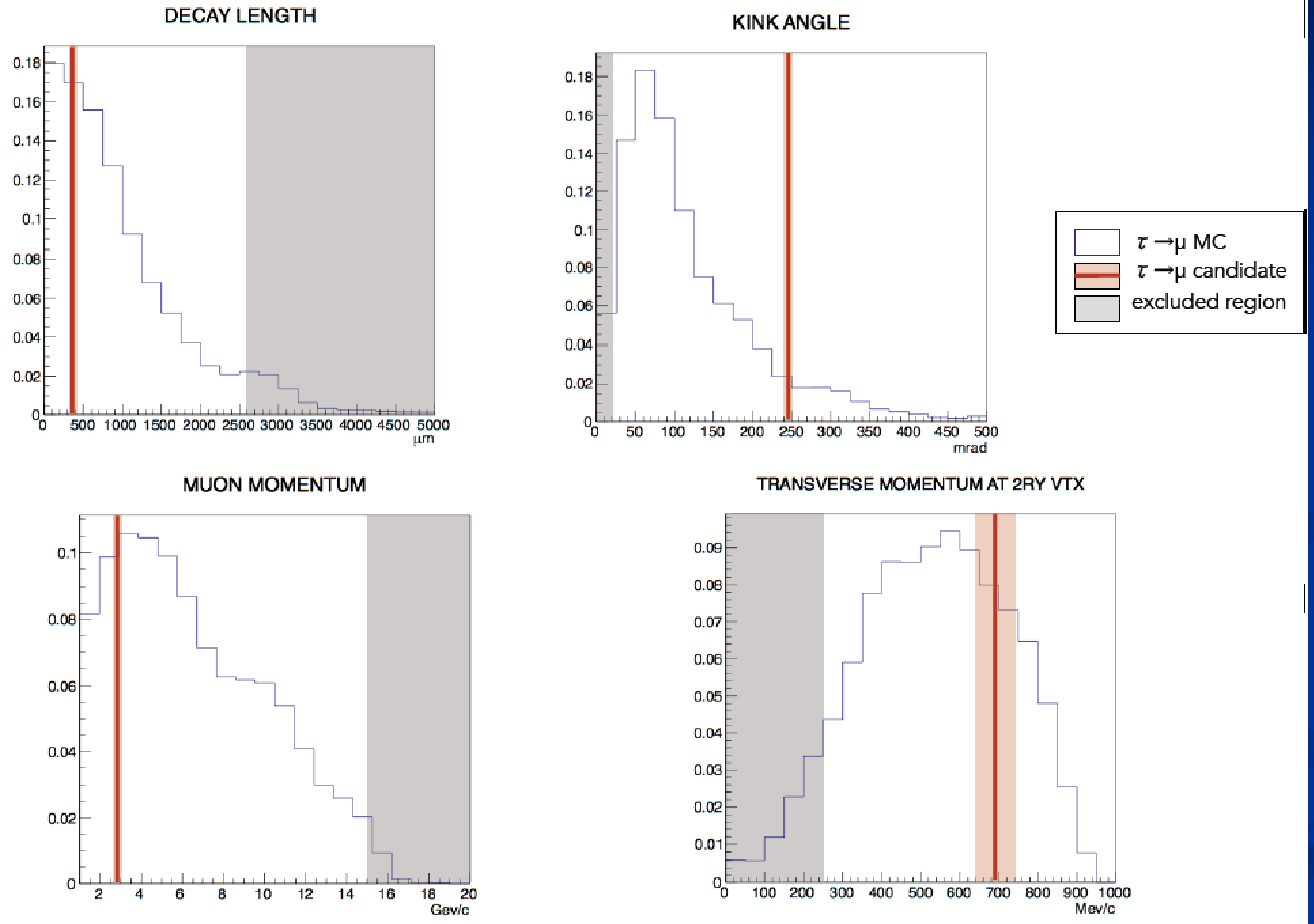


By MC estimation the probability to reconstruct a $\mu+$ stopping in the 7^{th} iron layer with p2 < -0.00389 is 0.063%

Kinematical variables

VARIABLE	AVERAGE
Kink angle (mrad)	**245 ± 5**
decay length (μm)	**376 ± 10**
Pμ (GeV/c)	**2.8±0.2**
Pt (MeV/c)	**690±50**
ϕ (degrees)	**154.5 ± 1.5**

Kinematical variables. All cuts passed: $\tau \rightarrow \mu$ candidate

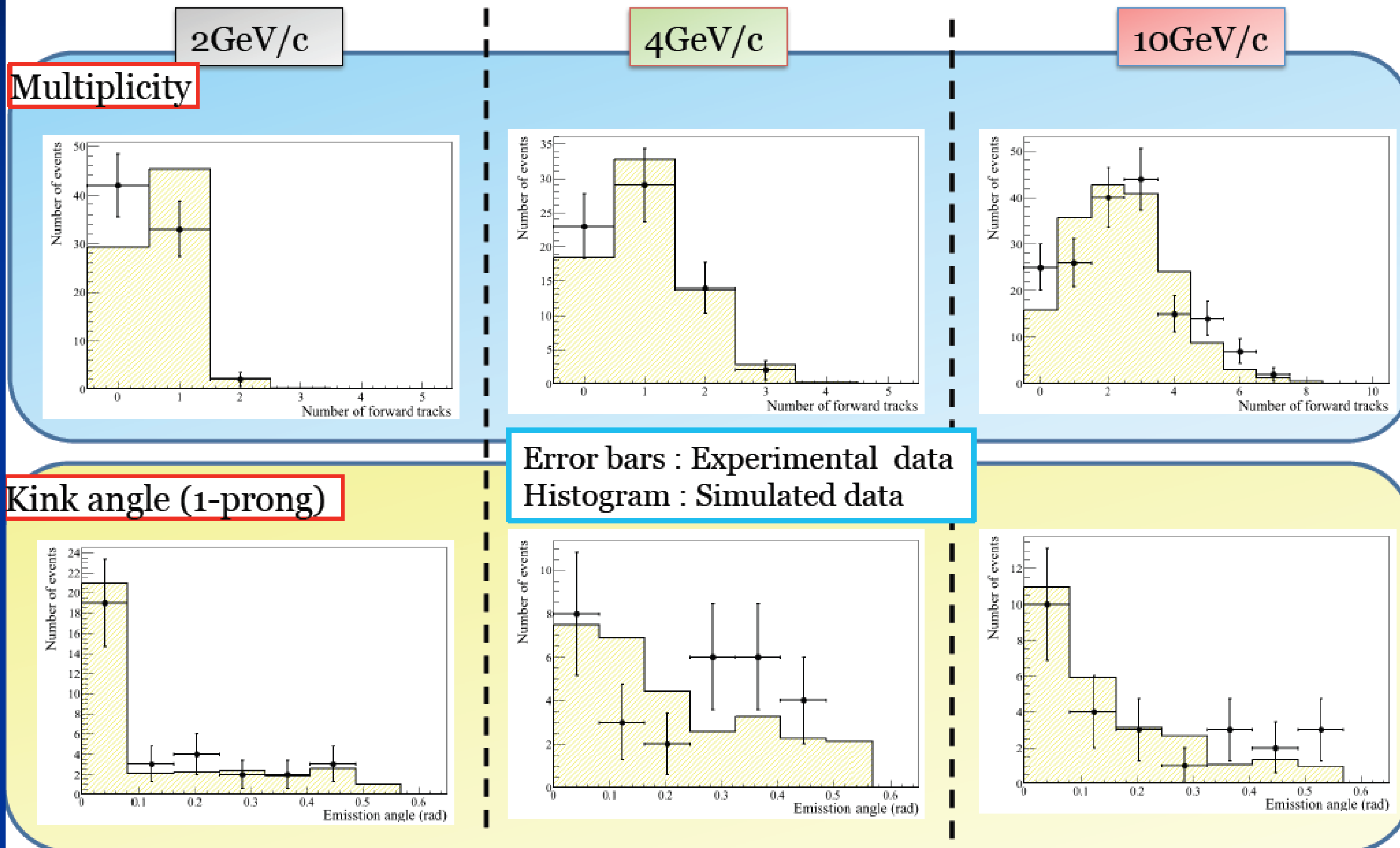


Background sources

- Hadronic interaction (nuclear fragment detection);
- μ^- at primary vertex not identified by ED at very large angle;
- Large angle muon scattering

Hadronic interaction

Secondary track emission

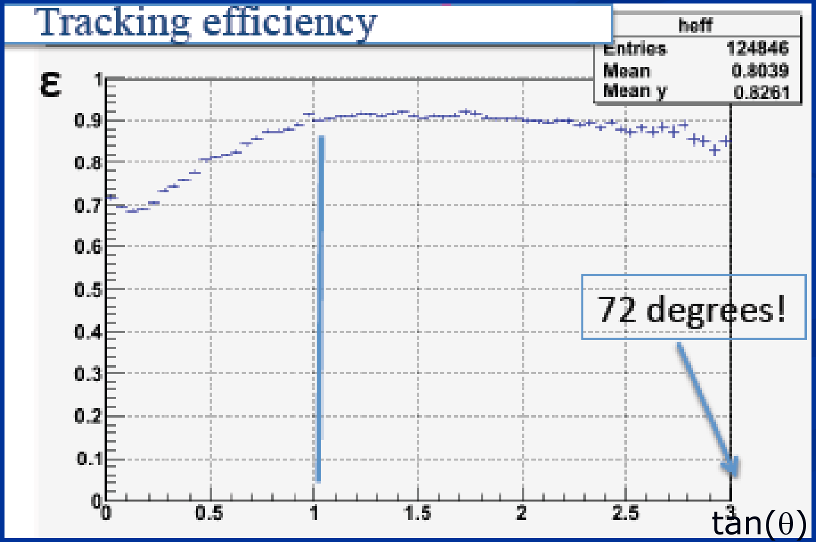


Good agreement within the statistical error: systematic error reduced to 30%

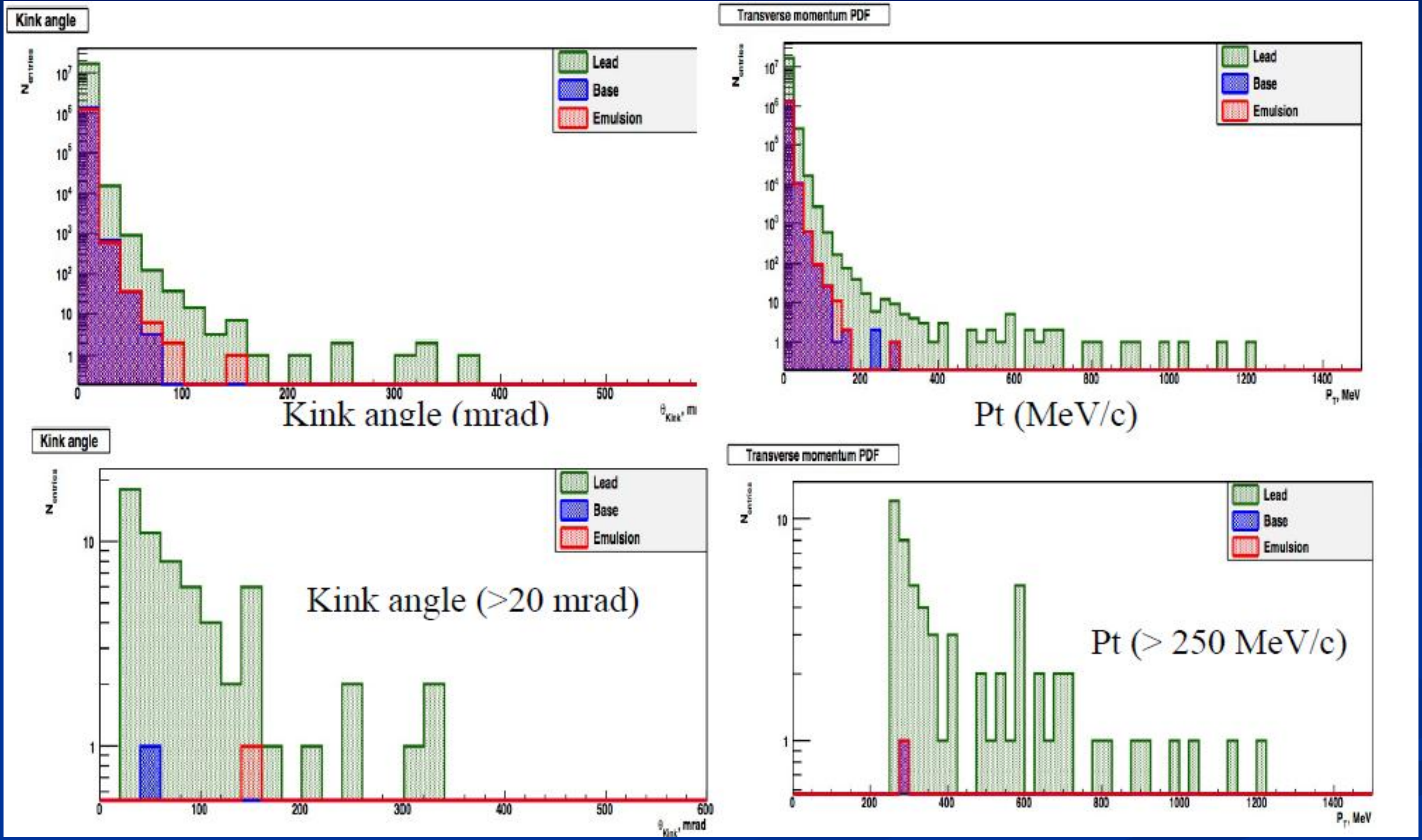
Comparison between Fluka simulation and test beam pion

Large angle tracks measurements

- Improvements on background rejection:
  - Undetected soft and large angle muons are source for charm background;
  - Detection of particles and nuclear fragments in hadronic interactions.



Large angle muon scattering



Rate in lead $O(10^{-6})$ and even less in emulsion/base ($10^{-8} \rightarrow 10^{-7}$)

Statistical considerations

Channel	Signal	Background	Charm	μScattering	Had. Inter.
$\tau \rightarrow h$	0.66	0.045	0.029		0.016
$\tau \rightarrow 3h$	0.61	0.090	0.087		0.003
$\tau \rightarrow \mu$	0.56	0.026	0.008	0.018	
$\tau \rightarrow e$	0.49	0.065	0.065		
total	2.32	0.226	0.19	0.018	0.019

By a simple counting method the probability that the observed 3 events in the 3 channels can be explained as background is 7.29 10-4.

→ 3.2 σ significance of non-null observation

Conclusion

- The OPERA experiment is aimed at the discovery of neutrino oscillations in appearance mode through the study of $\nu_\mu \rightarrow \nu_\tau$ channel;
- Decay topologies due to charmed particles observed in good agreement with expectation;
- 3 tau candidate events have been found in the channel $\tau \rightarrow h$, $\tau \rightarrow 3h$, $\tau \rightarrow \mu$ for an overall significance of 3.2 σ

BACKUP

Introduction

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

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

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

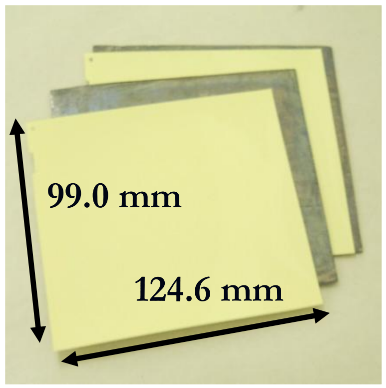
$$c_{ij}=\cos\theta_{ij},\quad s_{ij}=\sin\theta_{ij}$$

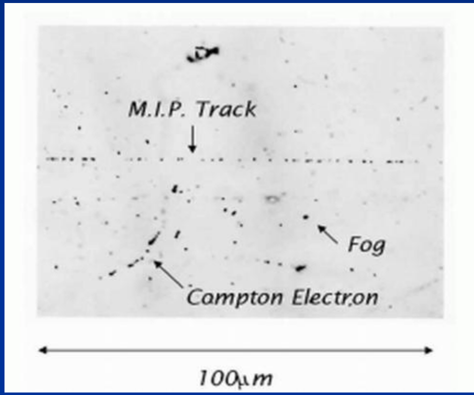
-CHOOZ (1997): The main oscillation channel responsible for atmospheric neutrino disappearance is not $\nu_\mu \rightarrow \nu_e$;
-SK (1998): The main oscillation channel responsible for atmospheric neutrino anomaly is not $\nu_\mu \rightarrow \nu_s$ and can be interpreted as $\nu_\mu \rightarrow \nu_\tau$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

Emulsion Cloud Chamber (ECC)

ECC: series of emulsions sheets interspaced with lead plates.

- Provide high resolution and large mass in a modular way

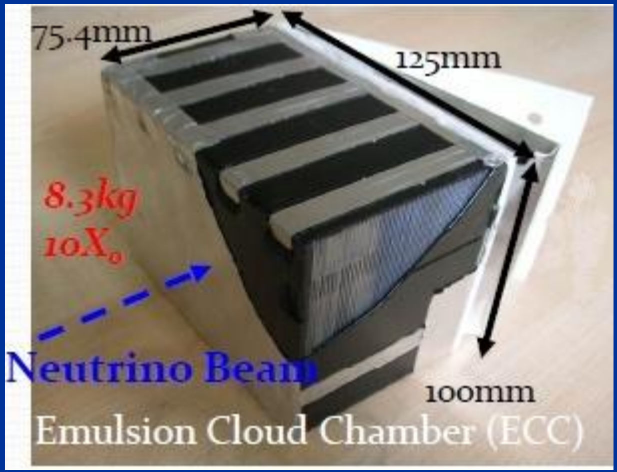


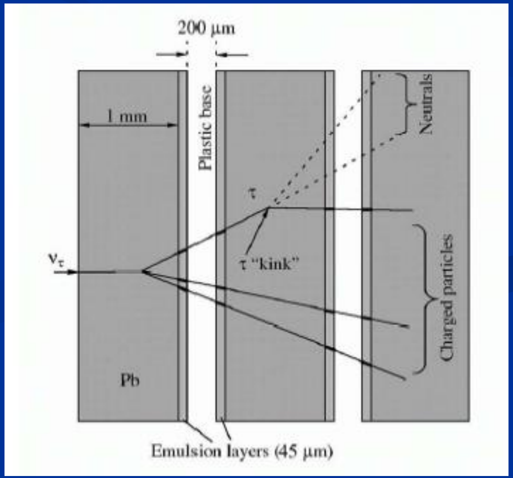


Emulsion resolution:
dx = 1 μm
dθ = 2 mrad

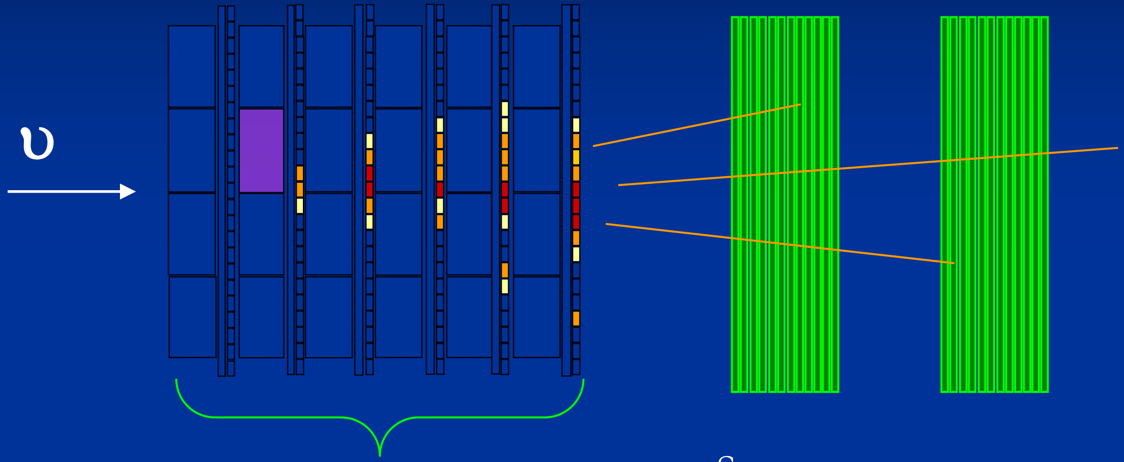
Brick: is the target basic component

- 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





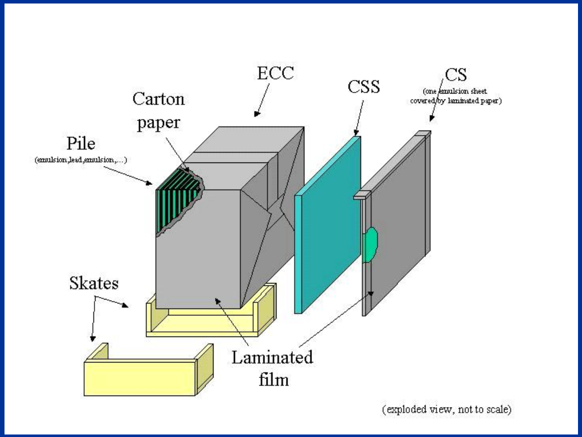
Detector working principle



TT : identifies the brick with the candidate interaction

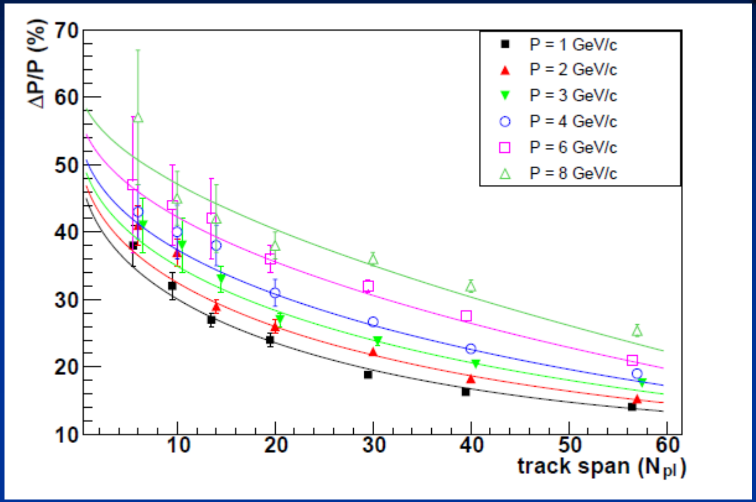
Spectrometer:
μ identification , measurement of charge and momentum

The Brick Manipulator System extracts the candidate brick from the wall

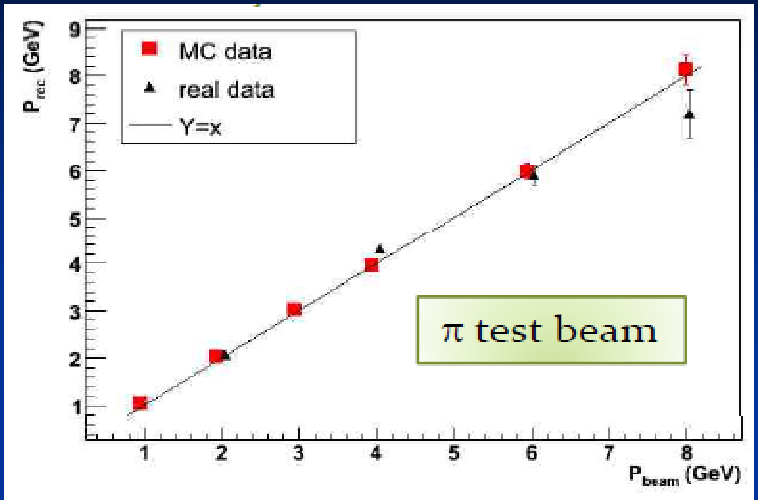


- CS developed in the cavern;
- CS measured half at LNGS half in Japan (scanning area depending on event type);
- If CS-TT tracks found → Brick exposed to Cosmic rays (12 h);
- Brick assigned to a lab for locating the neutrino interaction → see next slides

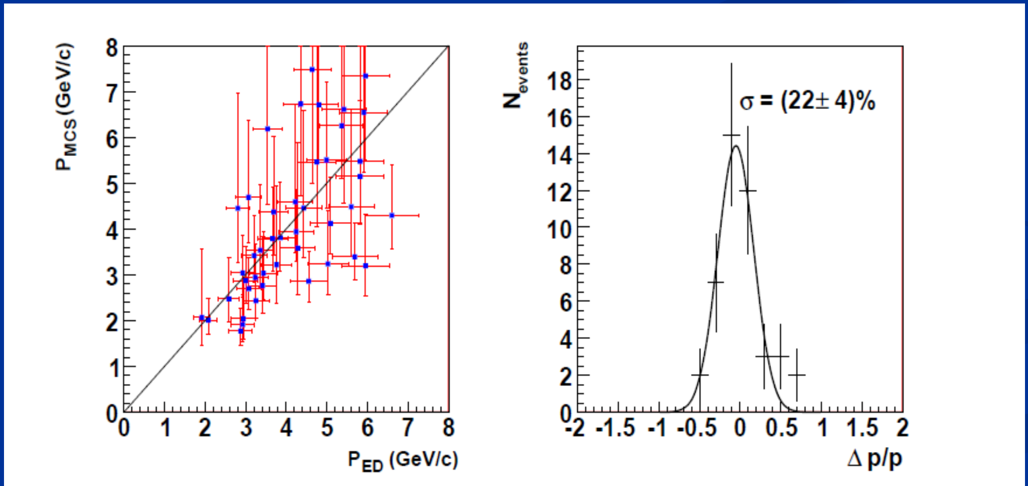
ECC performances



Momentum resolution dependece on number of emulsion plate transversed



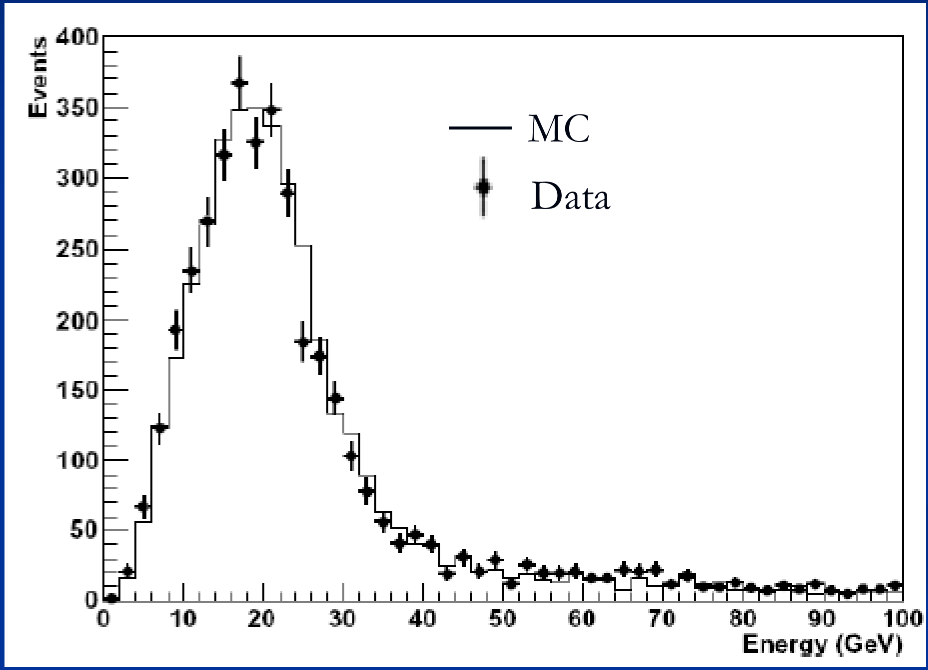
Linearity of momentum center
Pion Test Beam – MC comparison



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

Electronic Detector Performances

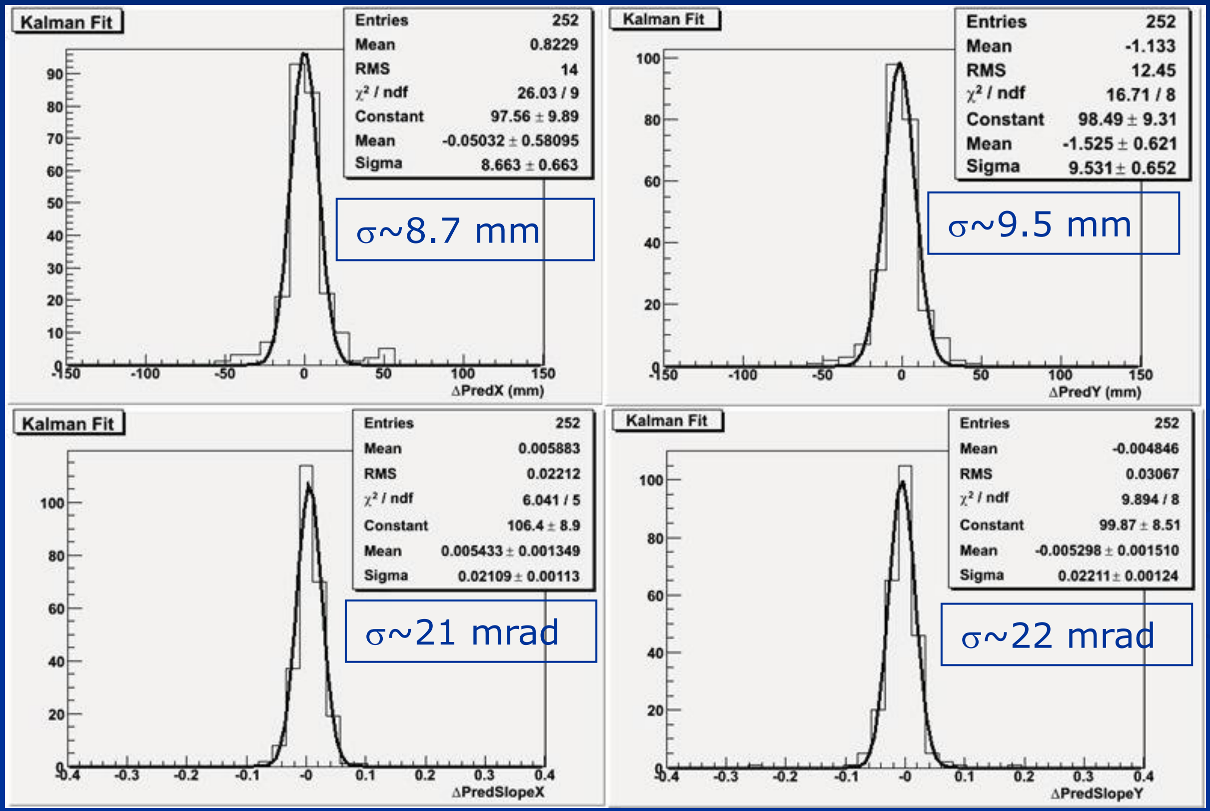
- Energy deposit in the Target Tracker



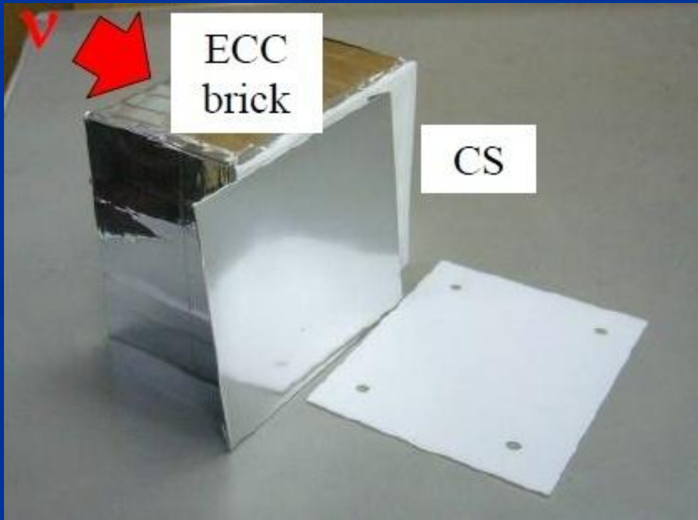
- Overall efficiency (Trigger + reconstruction) for CC events > 97.5%
- Charge id efficiency > 96% (2.5 GeV/c < |P| < 45 GeV/c)
- Momentum resolution (MC computation): 10% at 2.5GeV/c

  20% at 25 Gev/c
- Transverse spatial resolution < 1 mm

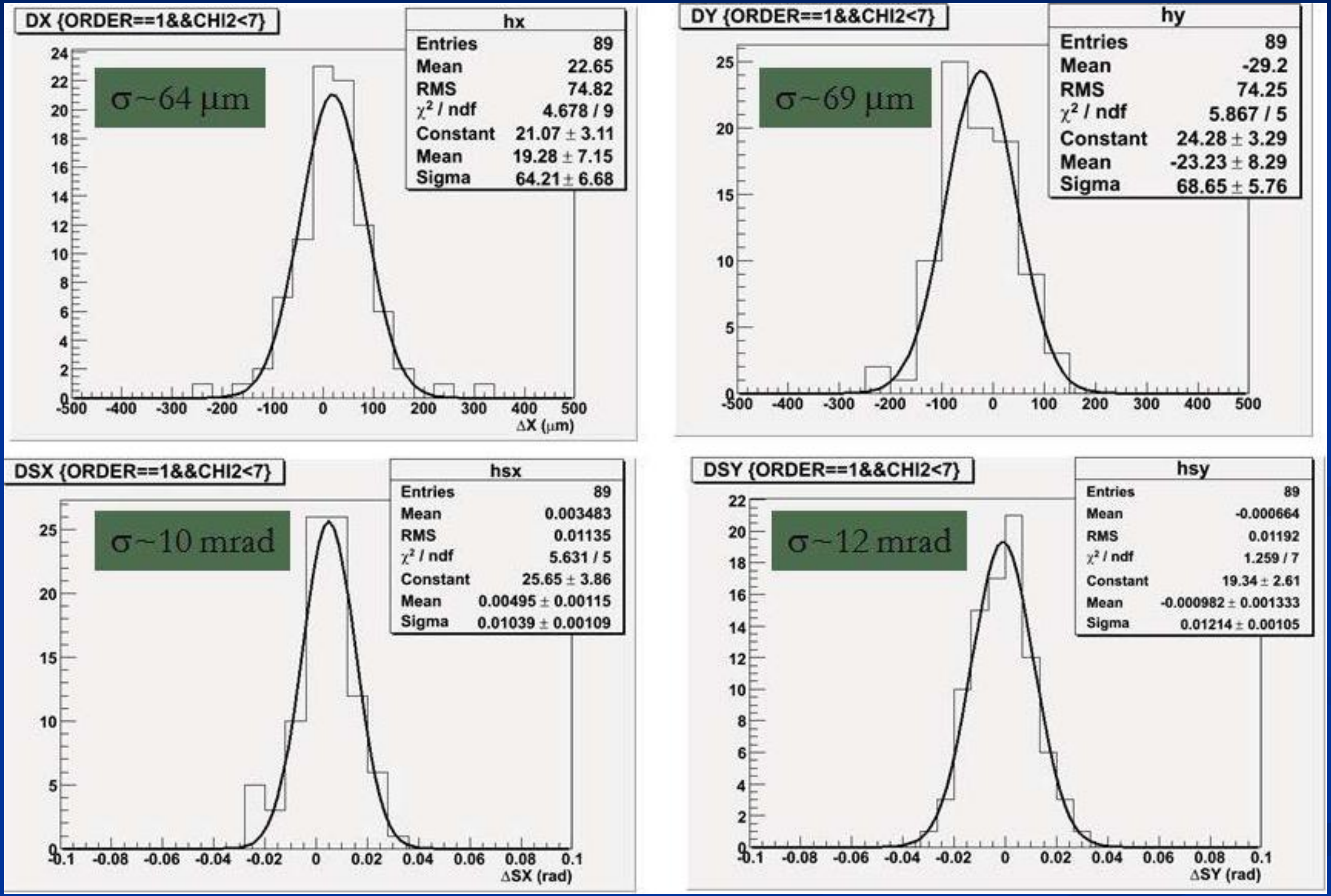
Changeable Sheets interface between ED and ECC



-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

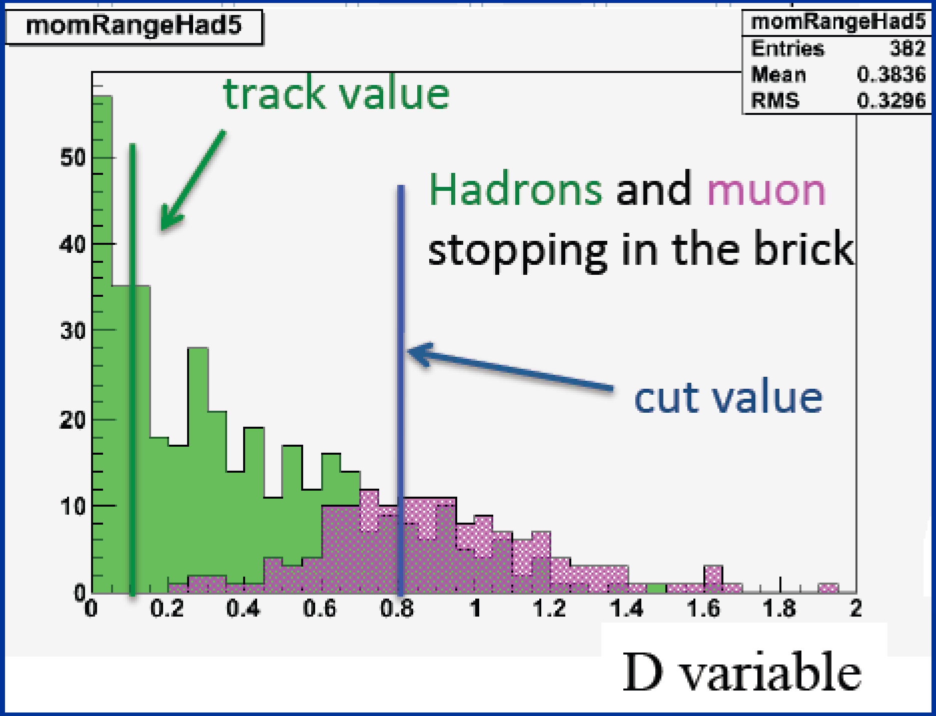


Tracks connected are not only muons.

Track follow – down of trk #2

$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{lead}}{\rho_{average}}$$

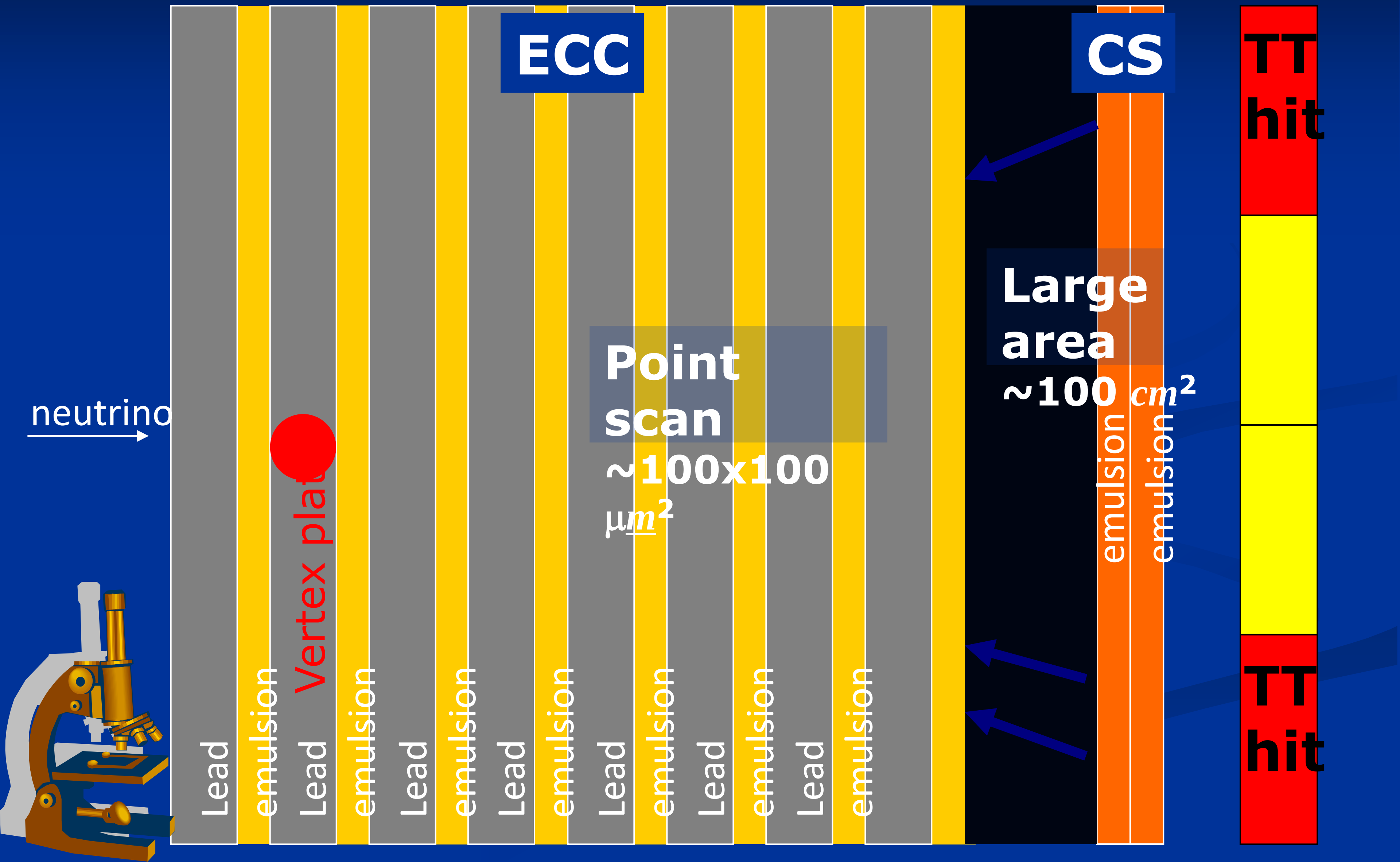
L = track length
R_{lead} = μ range
$\rho_{average}$ = average density
ρ_{lead} = lead density
p = momentum in emulsion



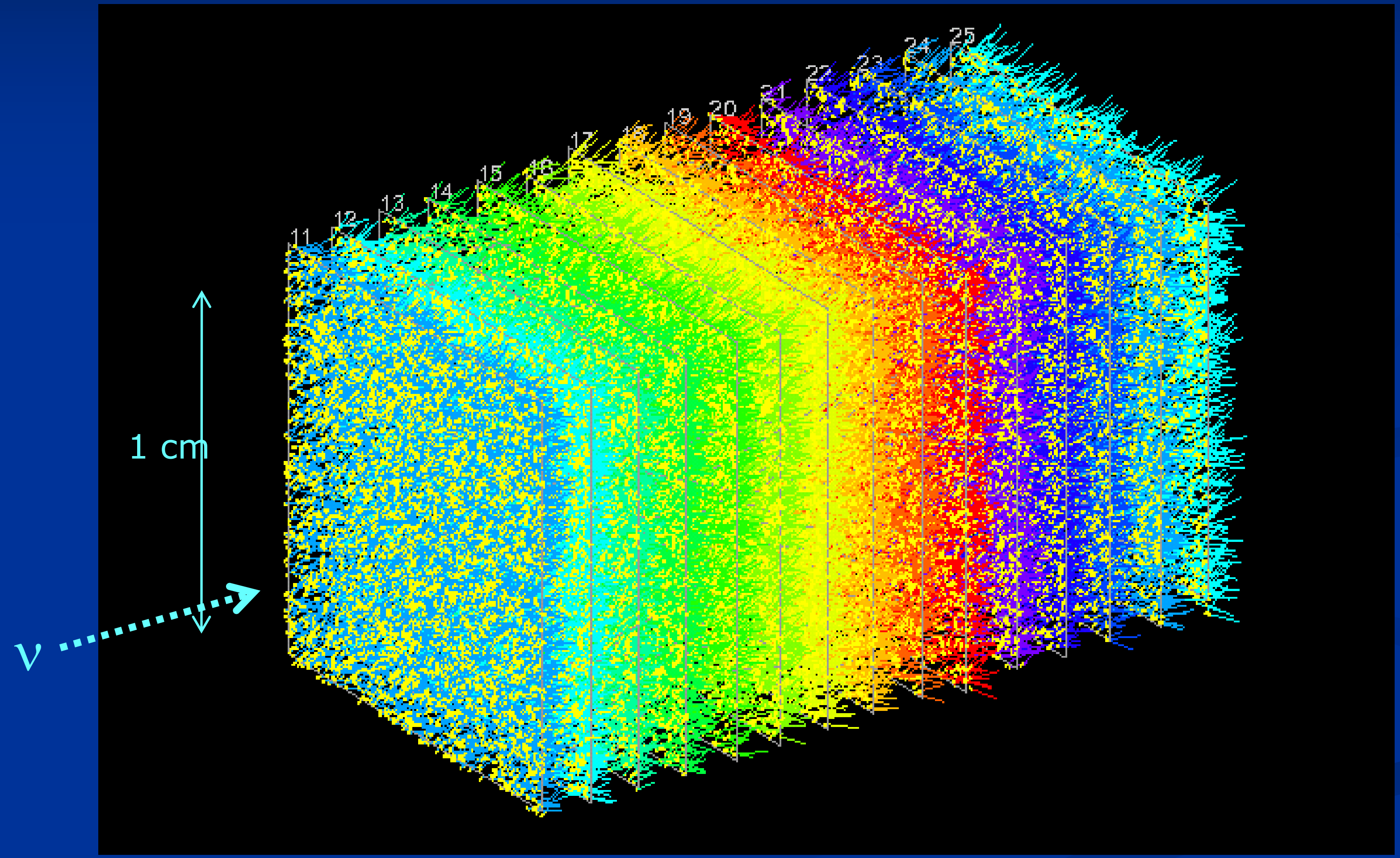
Momentum/range comparison
is inconsistent
with muon hypotesis

Interaction location in ECC brick

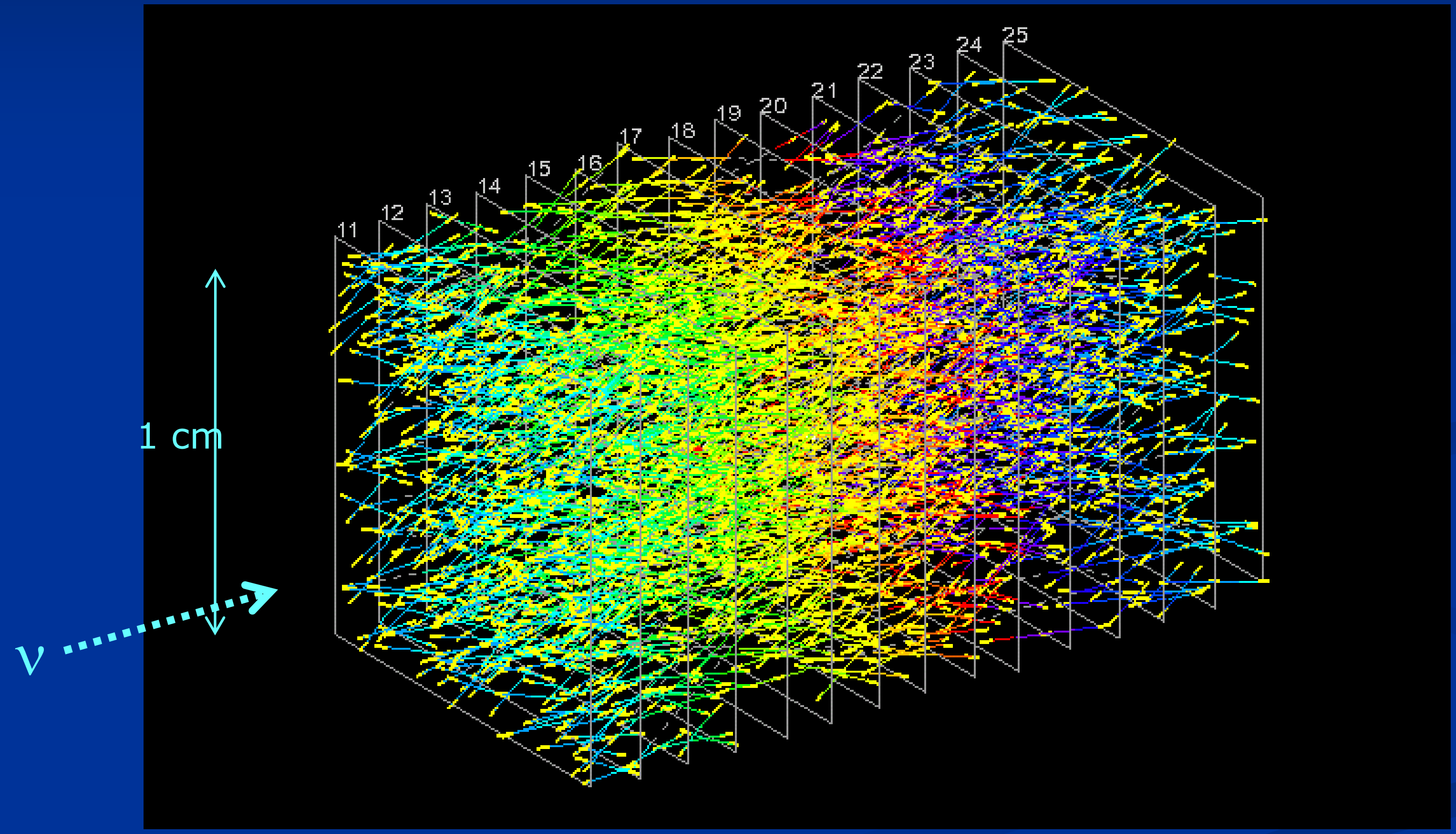
1. Follow back in brick tracks found in CS until they disappear: vertex plate



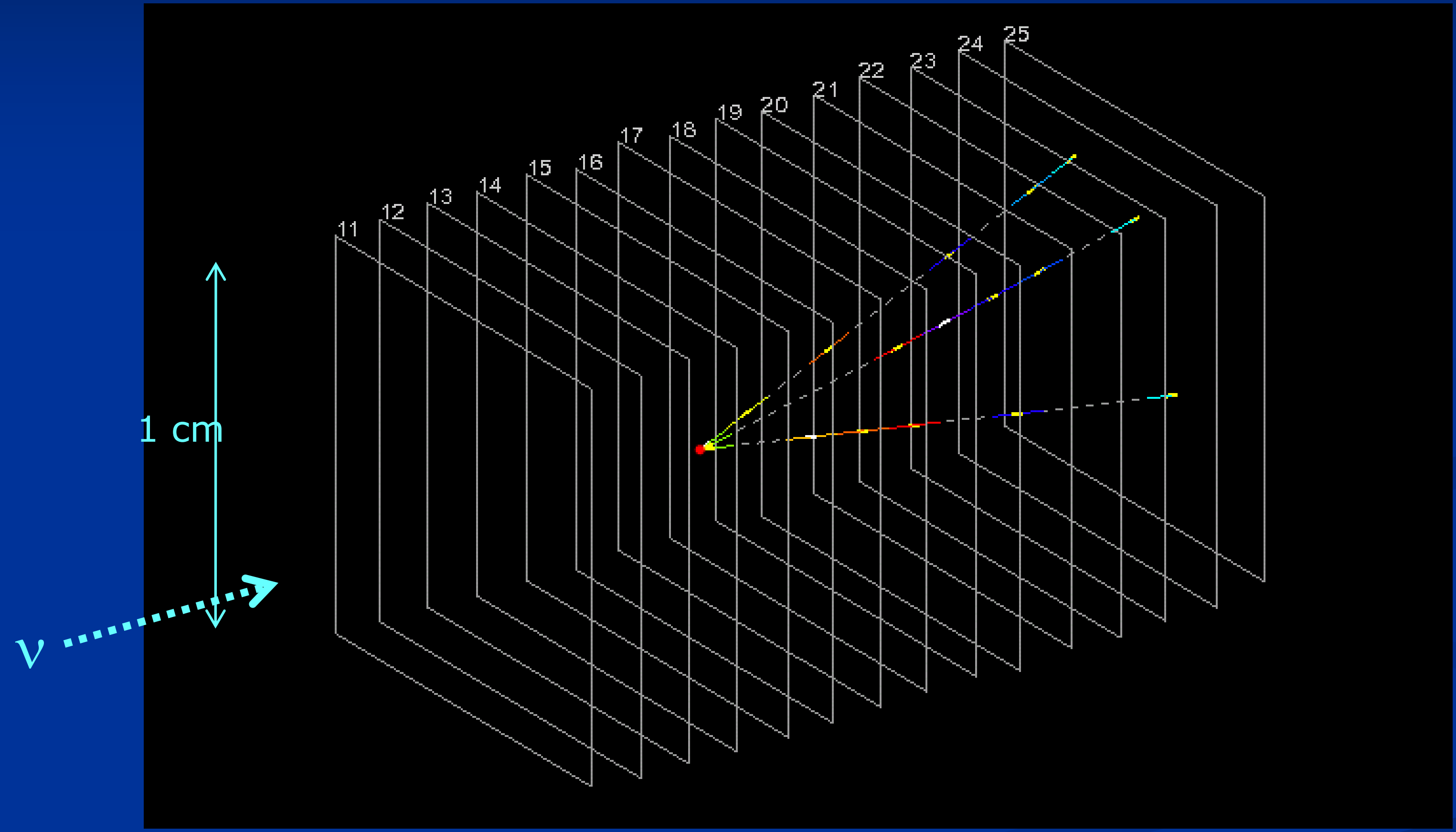
2. Search for all track segments in volume of $1 \times 1\ cm^2 \times 15$ films around plate where scanned back tracks disappear.



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