Locating the neutrino interaction vertex with the help of electronic detectors in the OPERA experiment

S.Dmitrievsky
Joint Institute for Nuclear Research, Dubna, Russia

LNGS seminar, 2015/04/08

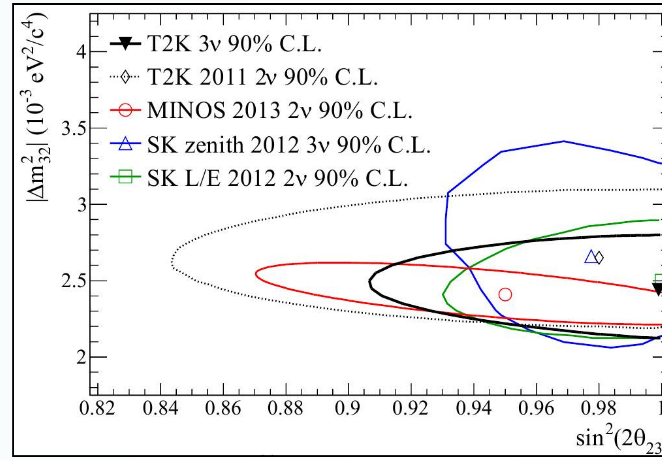
Outline

- **OPERA experiment and its hybrid detector**
- **Main characteristics of a Target Tracker detector**
- **Procedure of location the ν interaction vertex (Brick finding)**
- **Conclusions and outlook**

Motivation and main goal of the experiment

Neutrino oscillations have been mostly studied in **disappearance** mode.

Proof of different flavor ν **appearance** is required for the ultimate confirmation of the phenomenon.

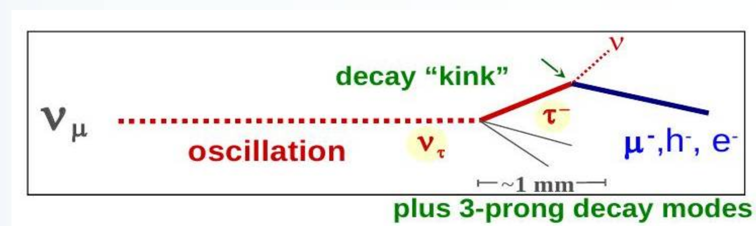


*Chin. Phys. C, **38**, 090001 (2014)*

Main goal of OPERA:

The first direct observation of ν_τ **appearance** in a nearly pure ν_μ beam through the **event-by-event** detection of the short-lived τ leptons produced in the ν_τ CC interactions.

$$P(\nu_\mu \rightarrow \nu_\tau) \cong \sin^2(2\theta_{23})\cos^4(\theta_{13})\sin^2\left(\frac{1.27\Delta m^2_{32}L(Km)}{E(GeV)}\right)$$



Requirements

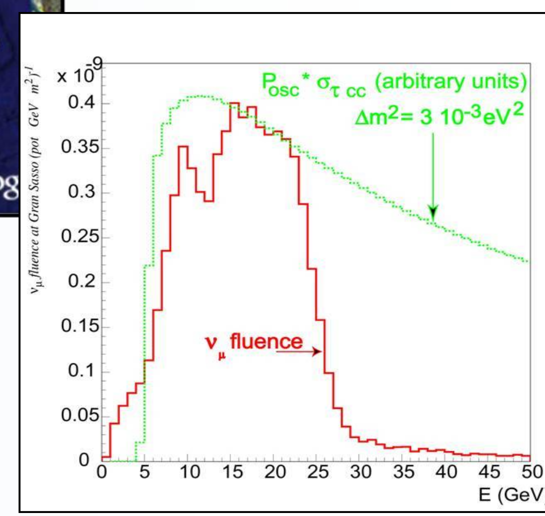
for ν beam: high neutrino energy, high intensity, long baseline

for detector: large mass, micrometric resolution, low background (underground location)

ν beam: CERN neutrinos to Gran Sasso

$< E_{\nu_\mu} >$	17 GeV
$(\nu_e + \overline{\nu}_e)/\nu_\mu$	0.9%*
$\overline{\nu}_\mu/\nu_\mu$	2.0%*
ν_τ prompt	negligible

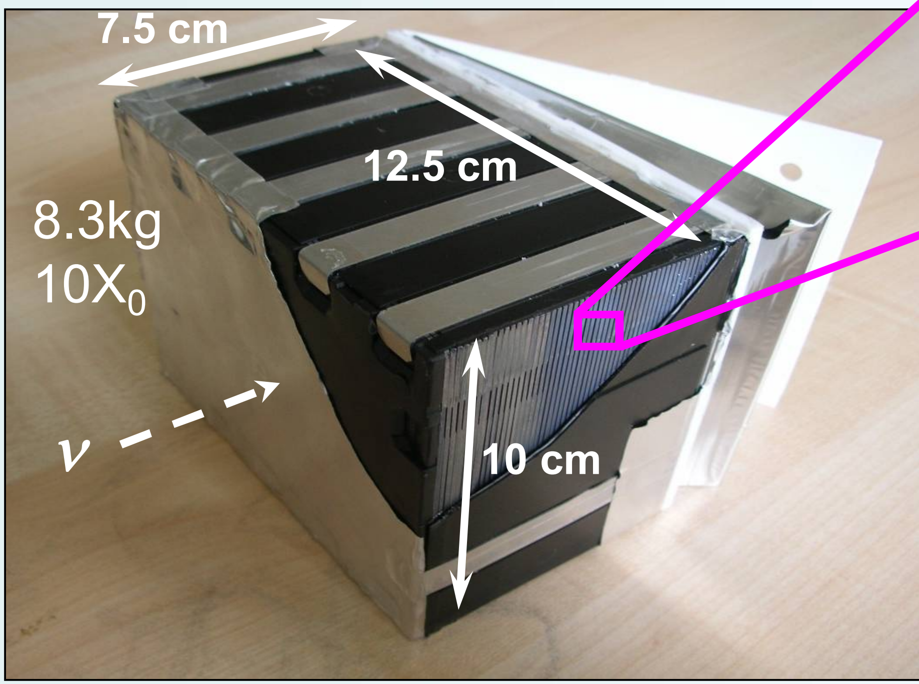
* interaction rate @ LNGS



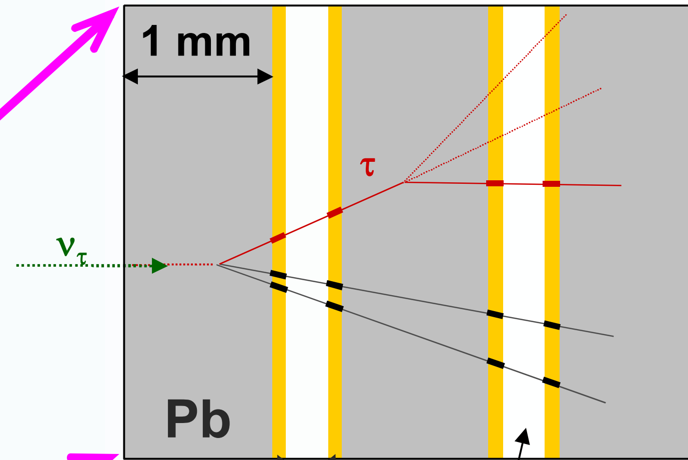
The beam was optimized to maximize the number of ν_τ CC interactions in the detector

OPERA target unit: ECC-brick

Basic unit of the OPERA detector is an Emulsion Cloud Chamber module (**ECC brick**): sandwich of 57 emulsion films interleaved with lead plates + a separate box with a removable pair of films (CS doublet).



Schematic view of a ν interaction in ECC

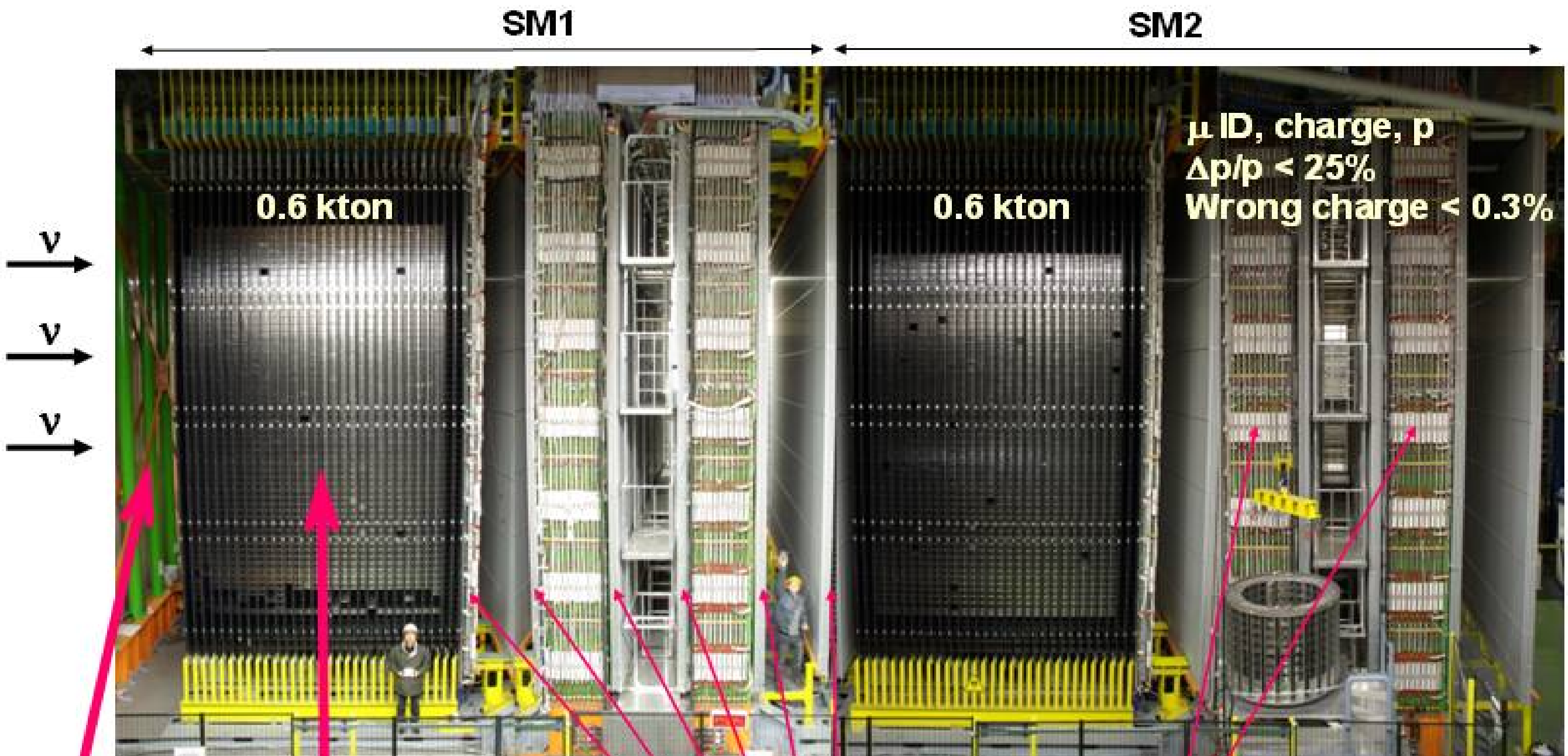


2 emulsion layers (44 μm thick) poured on a 200 μm plastic base

OPERA target:

Number of bricks:	**~150’000**
Total mass:	**~1.2 kton**
Total film surface:	**~111’000 m^2**

OPERA hybrid detector



Veto plane (RPC)

Target and Target Tracker $(6.7\,m)^2$

- Target/SM : ~75000 bricks, 29 walls
- Target tracker : 31 XY doublets of 256 scintillator strips + WLS fibres + multi-anodes PMT for
  - Trigger
  - Brick selection
  - Calorimetry

Muon spectrometer ($8 \times 10\ m^2$)

Instrumented dipole magnet

- 1.53 T
- 22 XY planes of RPC in both arms
- 2 XPC planes rotated by 42.6°

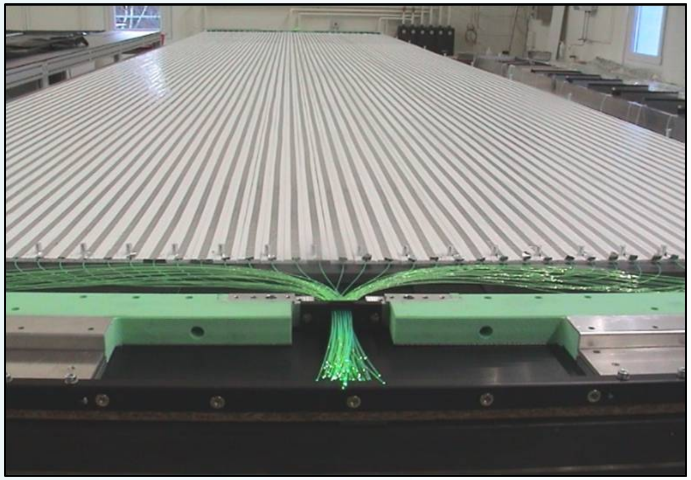
High precision tracker

- 6 4-fold layers of drift tubes

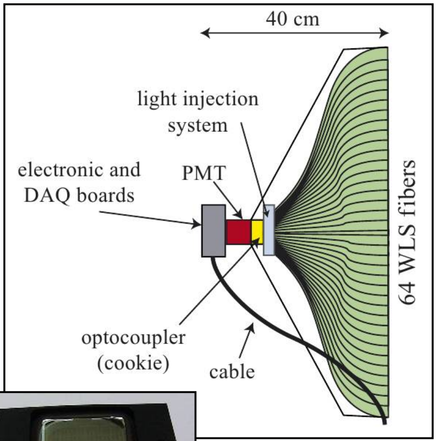
Target Tracker (TT) electronic detector

TT is a main tool for registration of ν interaction in real time and for vertex brick location. It consists of 496 modules each of 64 plastic scintillator (PS) strips read on both sides by WLS-fibers and multi-anode photomultiplier tubes (PMT).

A TT module made of 64 PS strips

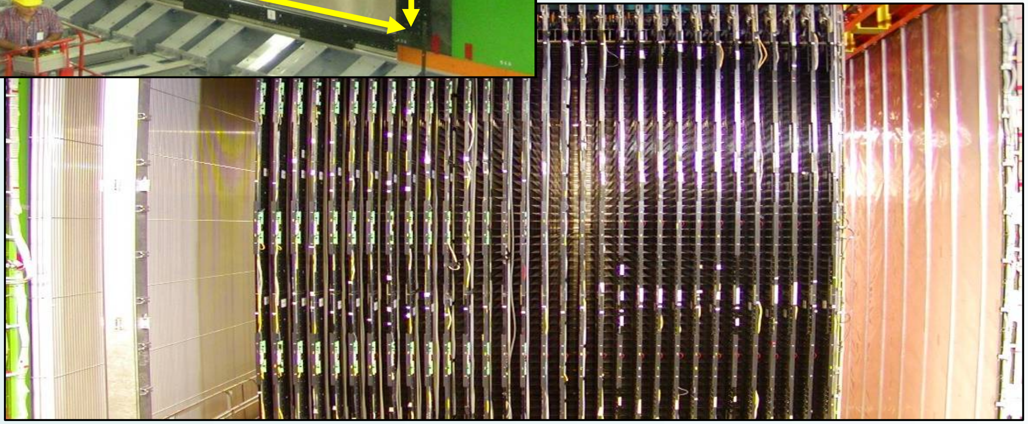


End-cup of a TT module

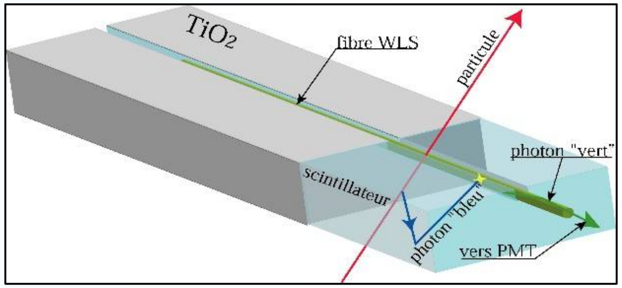


Hamamatsu M64 PMT

31 TT walls in each SM



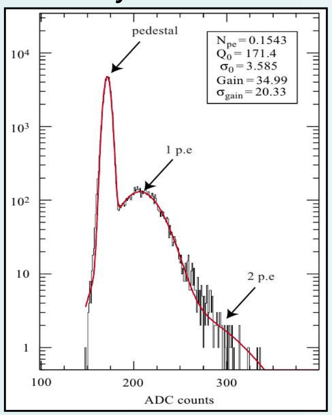
Particle detection principle in a strip



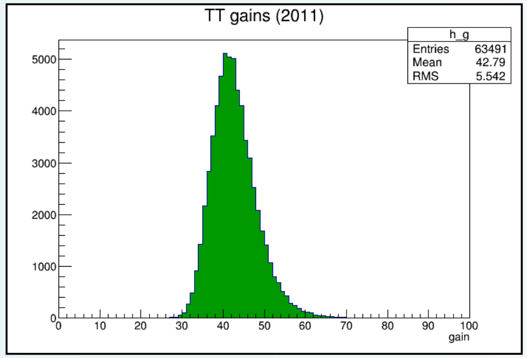
length=6.7m, width=2.6cm, thickness=1cm

Calibration of TT modules

Charge distribution recorded by a PMT channel

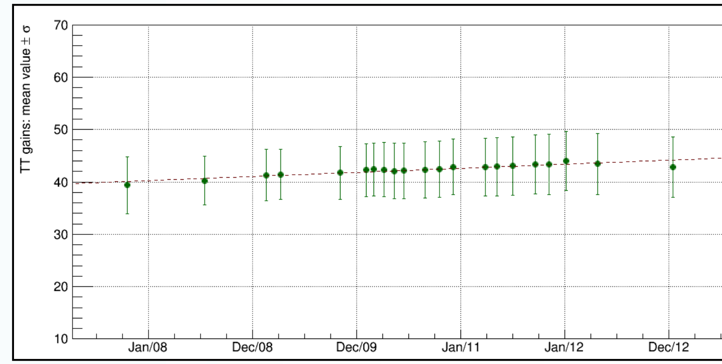


Fit by Poisson ⊗ Gaussian



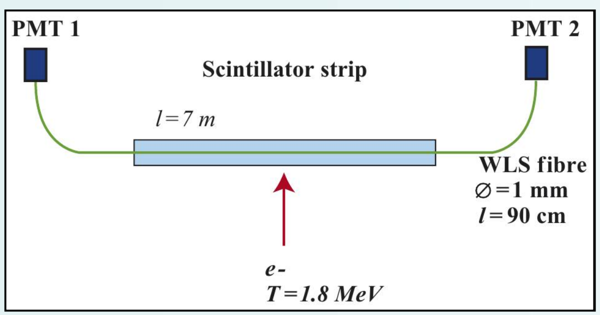
PMT gains are measured to convert ADC counts to a number of photoelectrons (p.e.)

Evolution of a mean gain of all PMTs in time



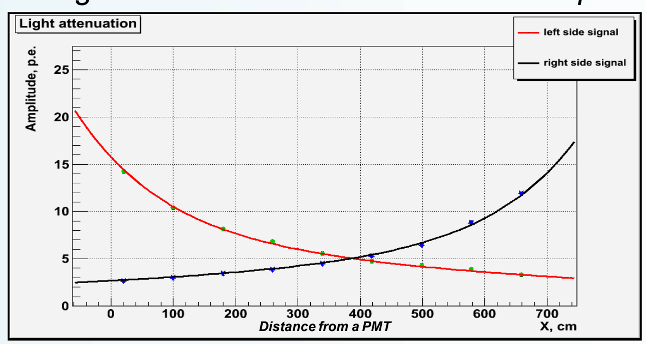
Almost a linear increase of ~2%/year

Study of signal attenuation in TT strips with help of electrons from a β source



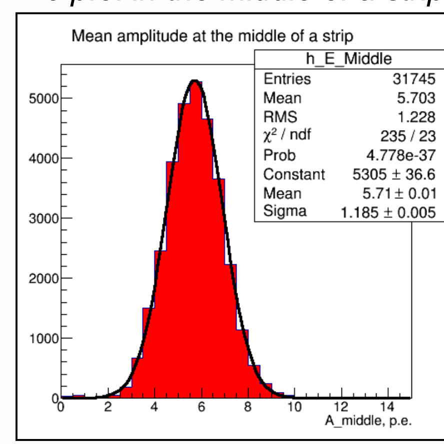
Average energy loss of a minimum ionizing particle (mip) crossing 1 cm of plastic scintillator is 2.15 MeV.

Signal attenuation curves for a TT strip



$$\begin{cases} A_{left} = A_0\left(\alpha e^{-\frac{\Delta x}{\lambda_s}} + (1-\alpha)e^{-\frac{\Delta x}{\lambda_l}}\right) \\ A_{right} = \beta A_0\left(\alpha e^{-\frac{L_0-\Delta x}{\lambda_s}} + (1-\alpha)e^{-\frac{L_0-\Delta x}{\lambda_l}}\right) \end{cases}$$

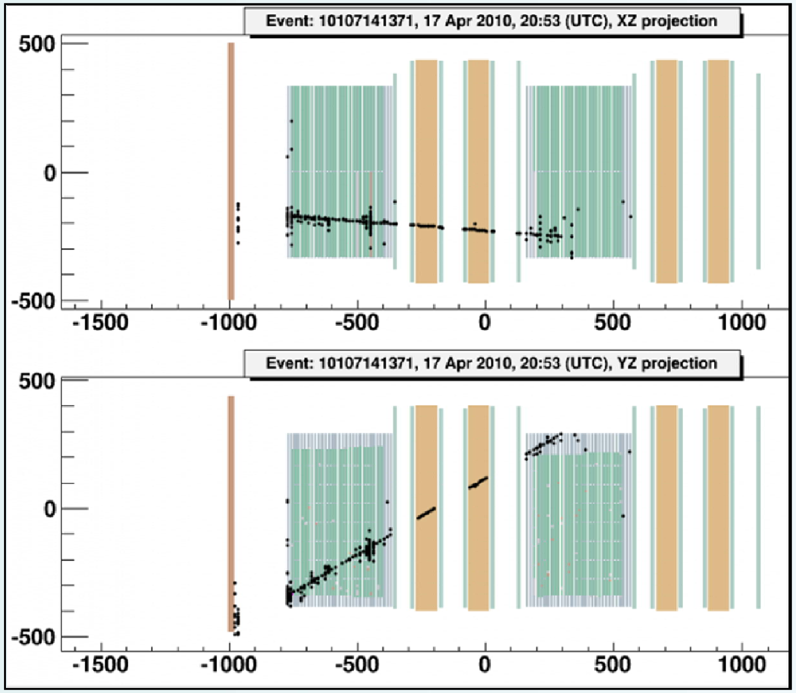
~6 p.e. in the middle of a strip

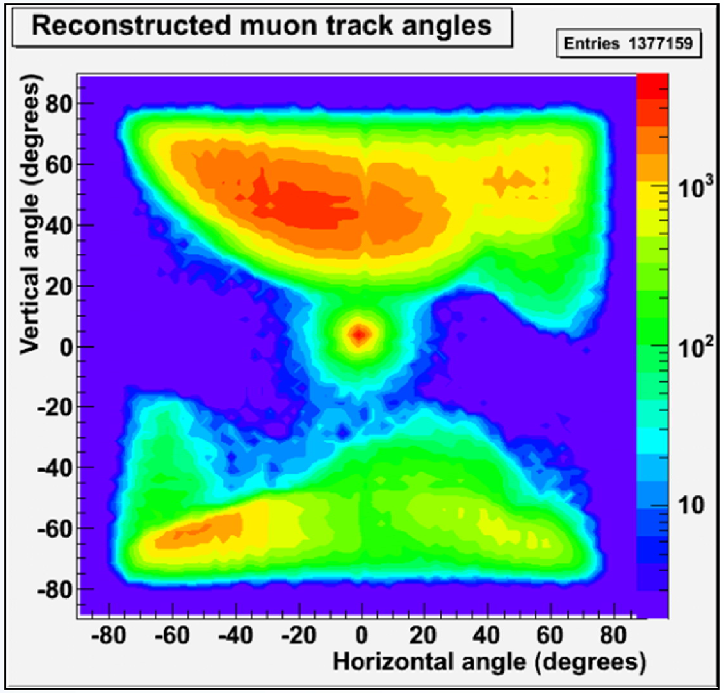


TT monitoring with help of muons

Cosmic muons as well as muons from the CNGS beam were used for TT response stability and registration efficiency monitoring.

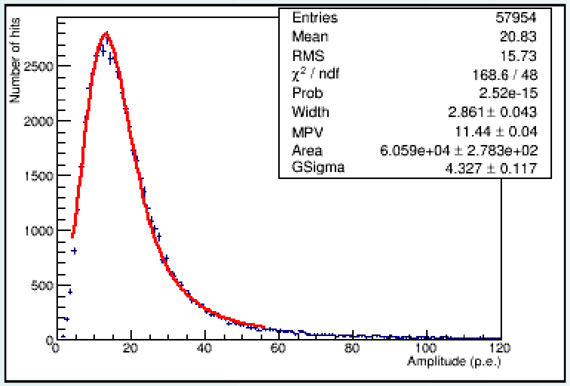
>10^6 of **3D muon tracks** have been reconstructed in TT for 2006-2013 period using a method of linear **Hough transform**.





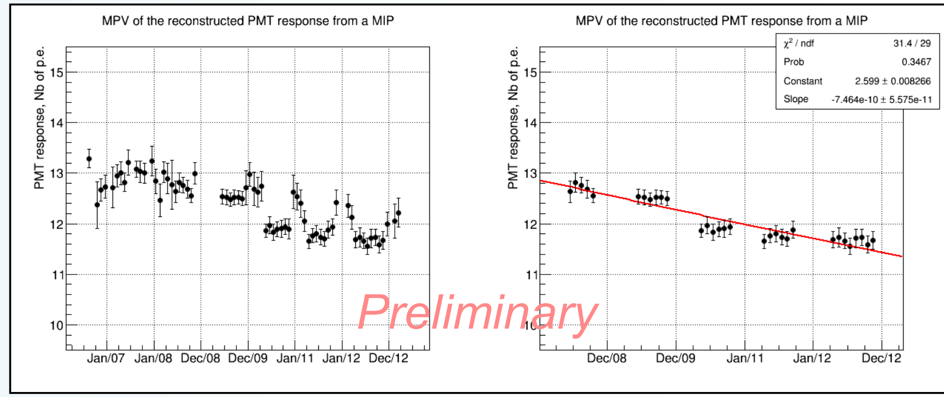
TT response stability and registration efficiency

Reconstructed TT response for muon track hits (for one month)



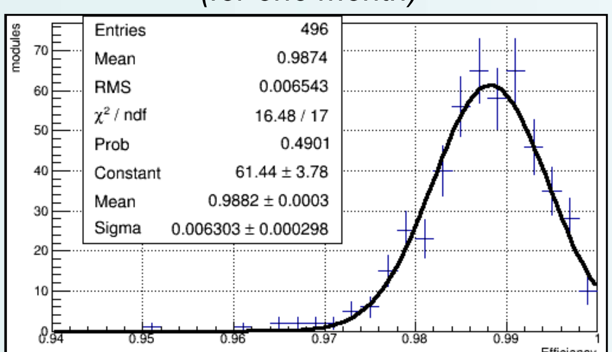
Fit by Landau ⊗ Gaussian

Evolution of MPV of TT response for low angle muon track hits



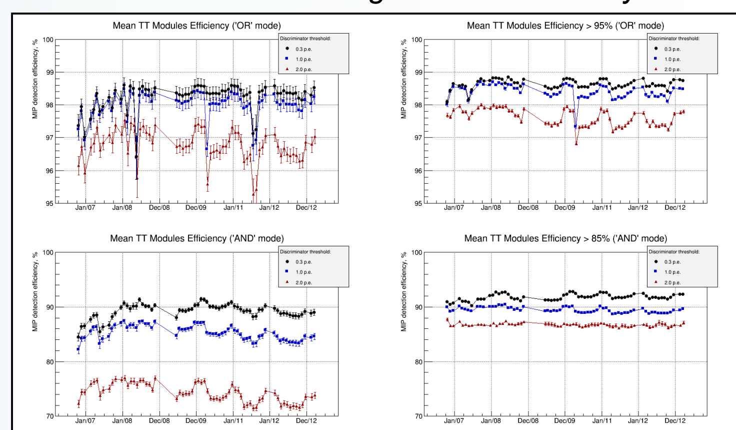
Decrease of ~2%/year due to ageing of scintillator

Registration efficiency of TT modules (for one month)



Efficiency is of ~99% in 'OR' mode (if signal at least from one side of a strip is present)

Evolution of TT registration efficiency



Threshold applied for raw TT signals = 1/3 p.e. (black curves)

Data analysis chain in OPERA

Reconstruction of interaction events

Association of events with the CNGS beam (selection of ***on-time*** events)

Track reconstruction and muon identification

Recognition of events originated in the target (selection of ***internal*** events)

Brick finding – location of the brick containing the neutrino interaction vertex

in electronic detectors

Confirmation of the selected brick by analysis of its interface emulsion films

Location of the neutrino interaction vertex in the brick (if it was confirmed)

Decay search – analysis of the ν event topology

Kinematic selection

in emulsion

Main difficulties of the vertex brick location

Fake and isolated hits (or small groups of hits)

Such hits present in an event due to several reasons: neutral particles interaction in the detectors, natural radioactivity background, PMT noise and channels cross-talks, etc. They can complicate event topology and affect performance of algorithms.

Restricted spatial resolution of the electronic detectors (ED)

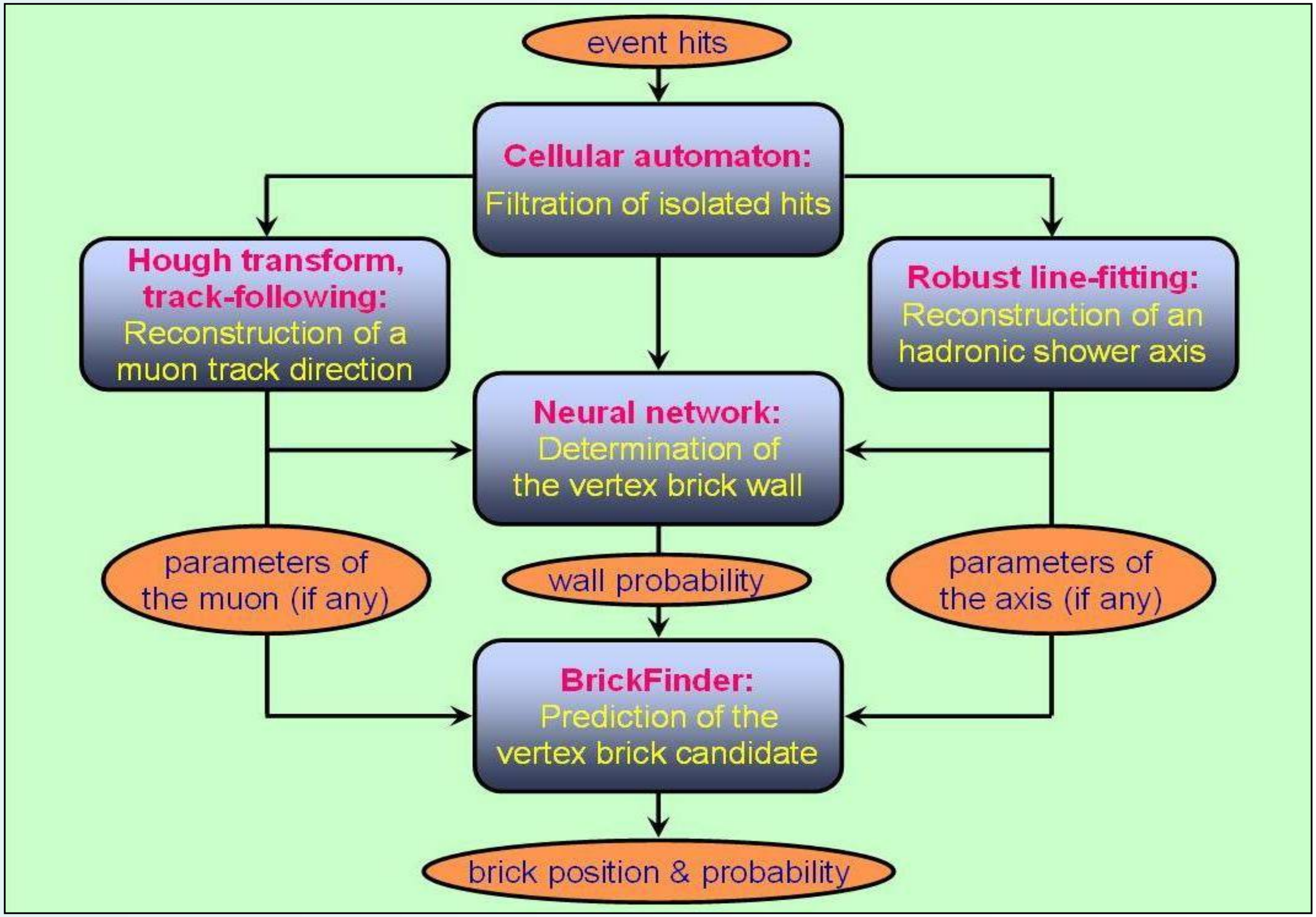
In most cases the ED resolution (~1 cm) doesn't allow to distinguish separate tracks, especially in showers, → it is difficult to reconstruct direction to the vertex using just hit positions. Deposited energy can help!

Back-scattering (BS)

BS particles can leave hits in the upstream (wrt the ν beam direction) TT walls of the vertex brick which makes impossible direct vertex brick wall identification as the first hit wall.

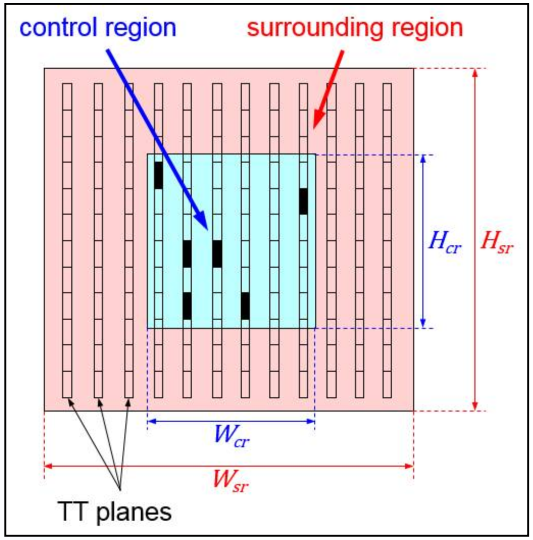
Brick finding (BF) strategy

High BF efficiency was needed in order to **reduce the emulsion processing load** (the most time-consuming part of data analysis) and to **minimize the target mass loss** (analyzed bricks were not replaced by the new ones).

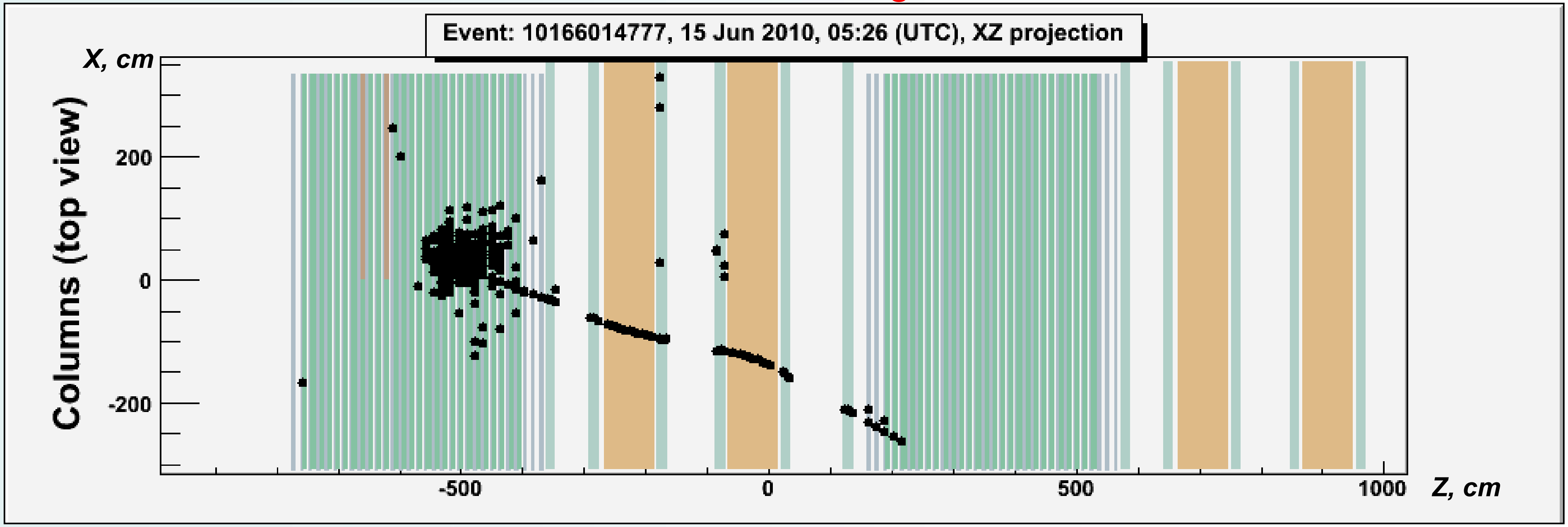


Event filtering – suppression of isolated TT hits

Principles of ***cellular automata*** were used to estimate the ***"isolation factor"*** of TT hits. The ***"solitaries"*** (those hits that had too few or no neighbors in the surrounding TT region) were excluded from the further analysis without distorting the event topology because tracks and showers were not affected by the procedure.

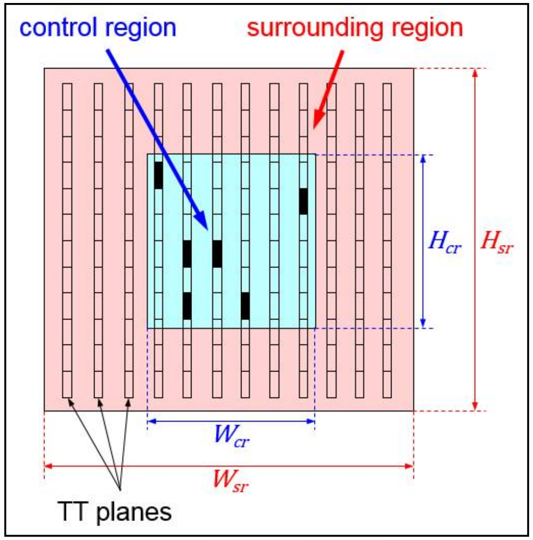


before cleaning

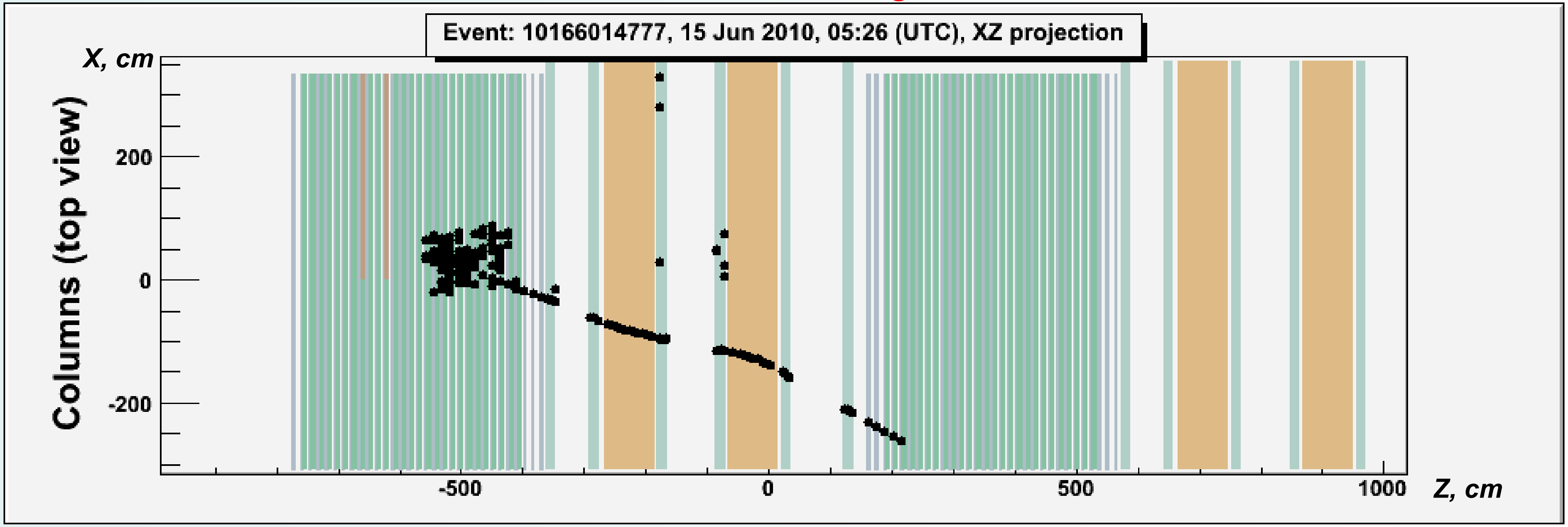


Event filtering – suppression of isolated TT hits

Principles of ***cellular automata*** were used to estimate the ***"isolation factor"*** of TT hits. The ***"solitaries"*** (those hits that had too few or no neighbors in the surrounding TT region) were excluded from the further analysis without distorting the event topology because tracks and showers were not affected by the procedure.



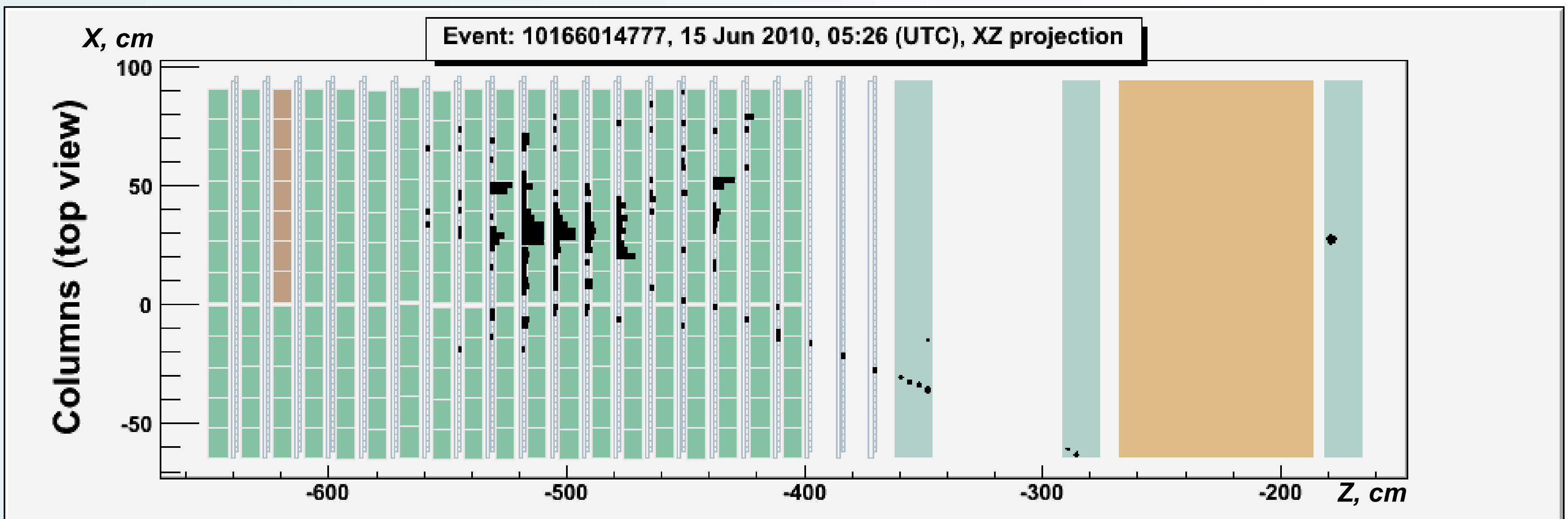
after cleaning



Reconstruction of a muon track direction

Three different ***pattern recognition*** techniques (***method based on a cellular automaton approach***, ***method of Hough transform,*** and ***track-following method***) were applied in order to reconstruct muon track direction in the beginning of the event.

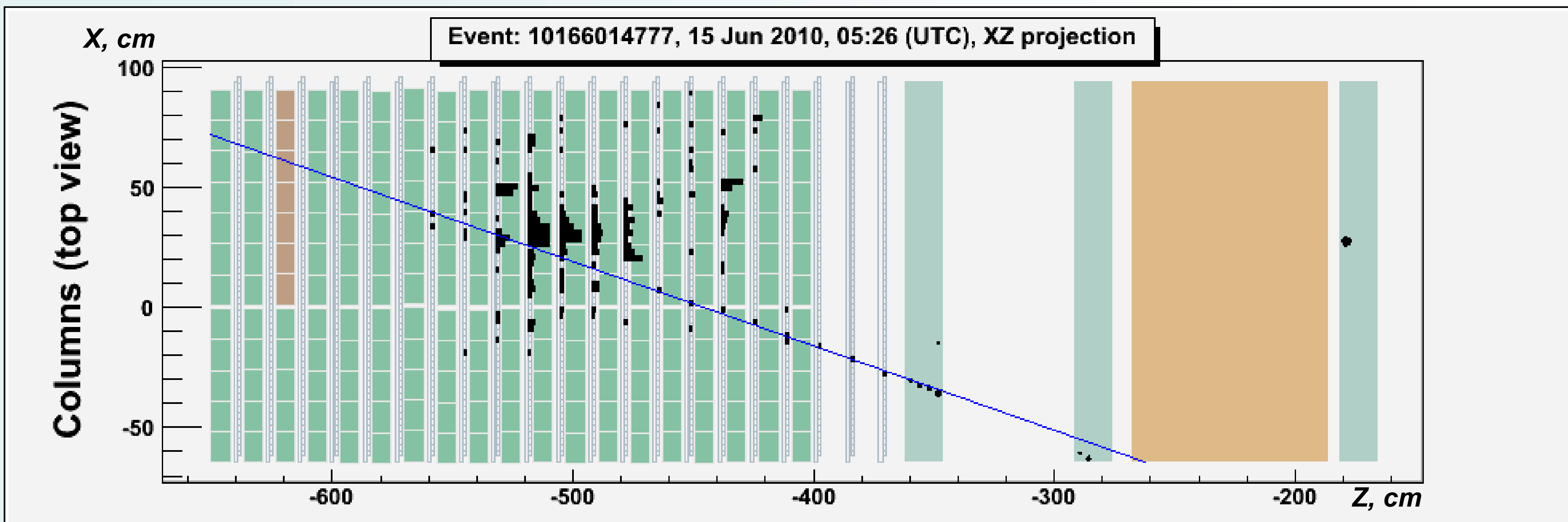
In simple cases (e.g., in ν_μ QE events) results of the reconstruction by different methods were practically the same. In more complicated situations (big showers, low momentum tracks) either the result of only one method was used for brick prediction or all the results were discarded (the decision was based on MC simulations).



Reconstruction of a muon track direction

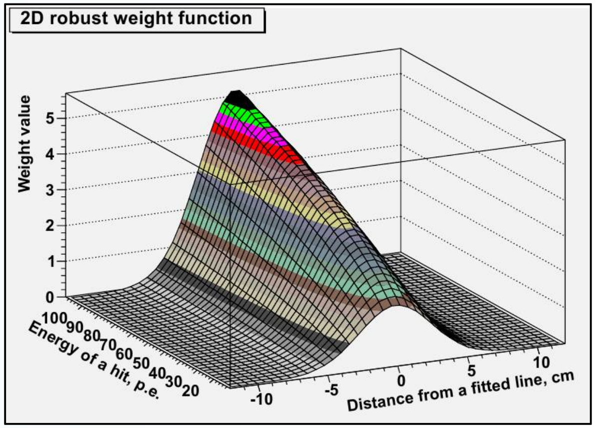
Three different ***pattern recognition*** techniques (***method based on a cellular automaton approach***, ***method of Hough transform,*** and ***track-following method***) were applied in order to reconstruct muon track direction in the beginning of the event.

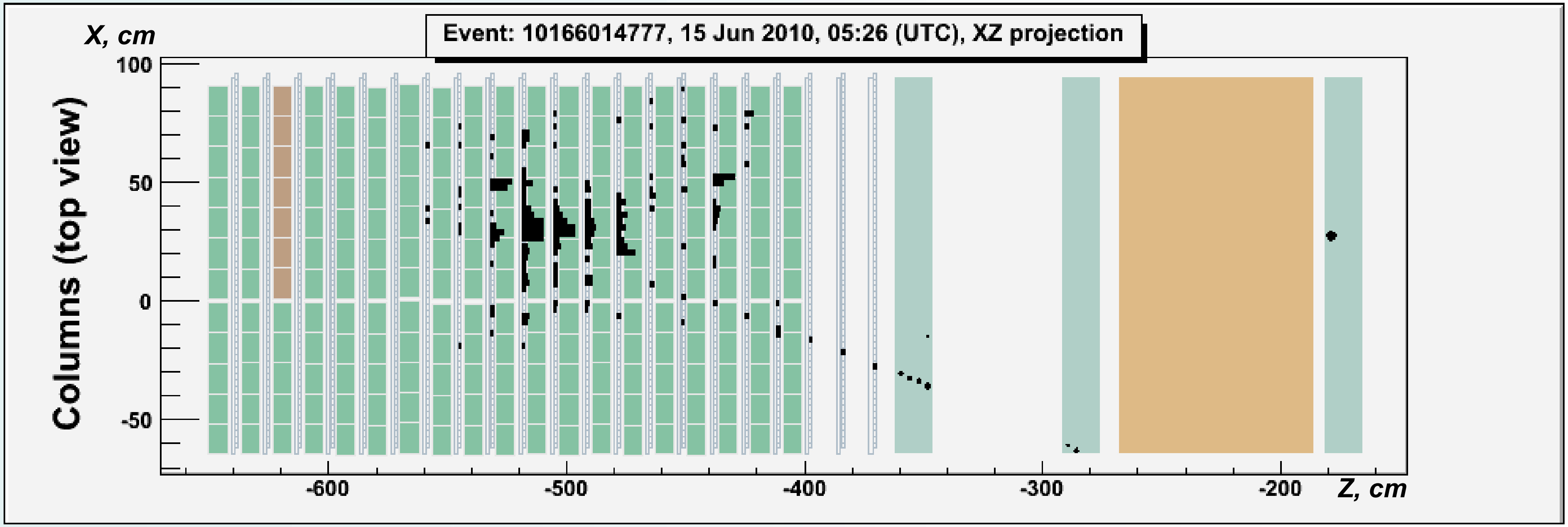
In simple cases (e.g., in ν_μ QE events) results of the reconstruction by different methods were practically the same. In more complicated situations (big showers, low momentum tracks) either the result of only one method was used for brick prediction or all the results were discarded (the decision was based on MC simulations).



Reconstruction of an hadronic shower axis

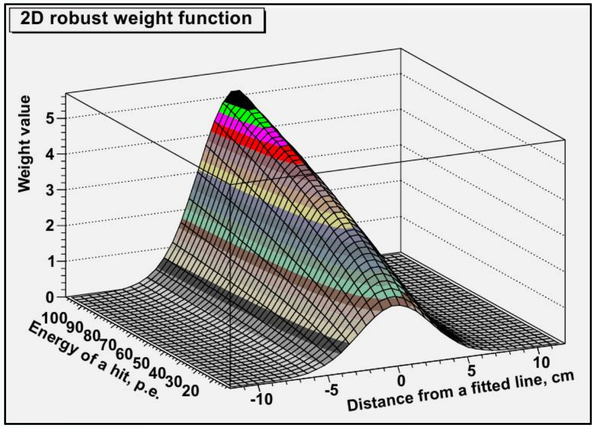
In some events, like the ν NC interaction ones, there was no separate track to point to the vertex. In this case reconstruction of an hadronic shower axis could help. For this purpose a ***robust line-fitting method*** was applied. The method was similar to the ***method of least squares***, but it estimated the parameters of the fitted line in iterative procedure by introducing weights for the measured points.

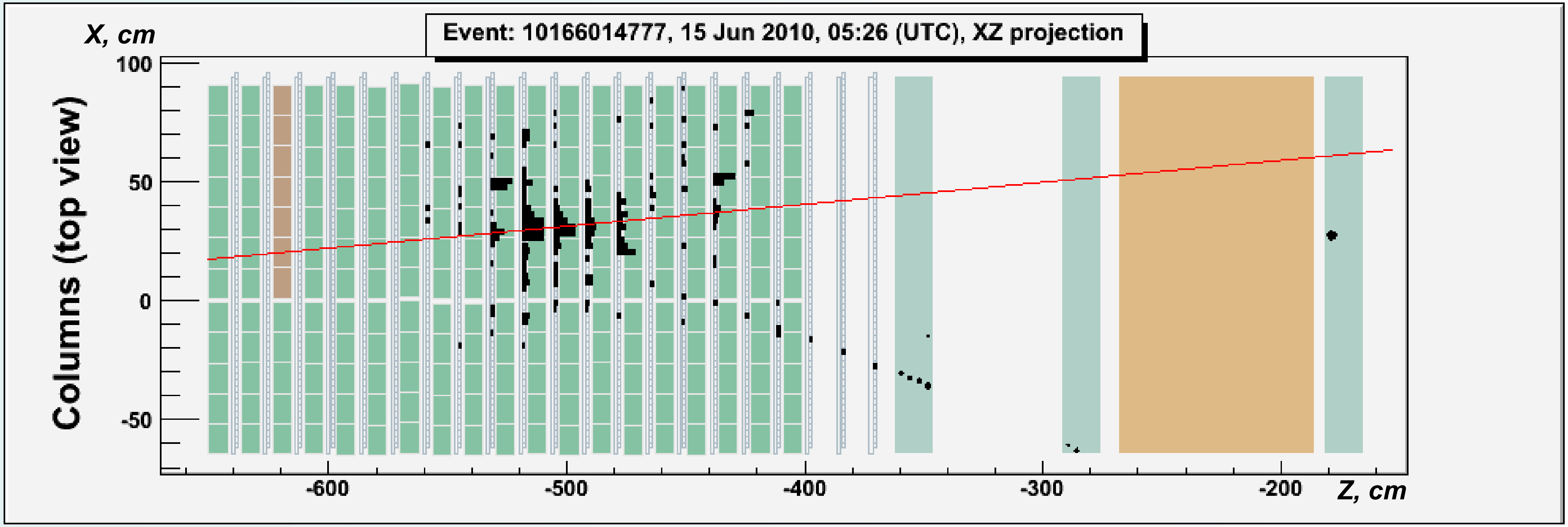




Reconstruction of an hadronic shower axis

In some events, like the ν NC interaction ones, there was no separate track to point to the vertex. In this case reconstruction of an hadronic shower axis could help. For this purpose a ***robust line-fitting method*** was applied. The method was similar to the ***method of least squares***, but it estimated the parameters of the fitted line in iterative procedure by introducing weights for the measured points.



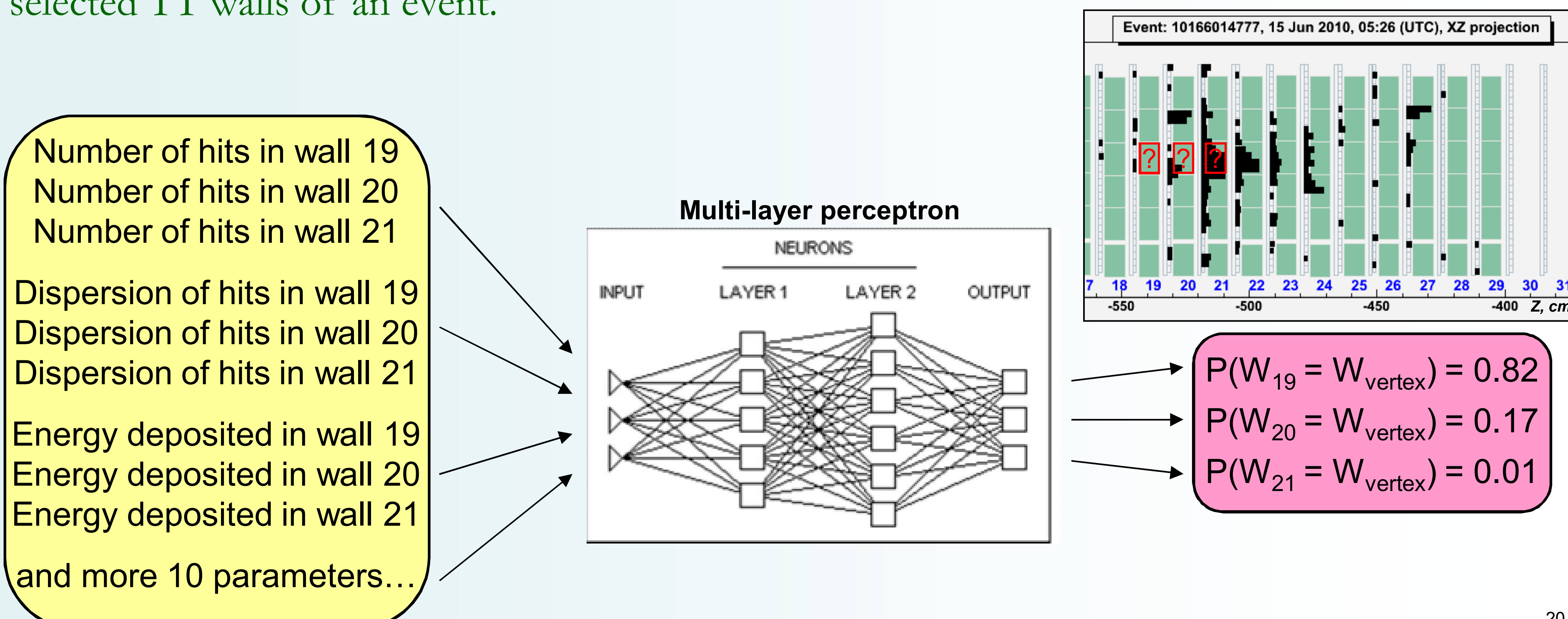


Determination of the vertex wall candidates

Presence of back-scattered (BS) particles could significantly expand the region of the vertex brick location. Big amount of information to be analyzed (number of hits in several walls, their amplitudes, geometrical distributions, etc.) in order to identify the vertex brick wall made it very difficult to elaborate any linear ('if-then') recognition algorithm. That's why an ***artificial neural network*** (***multi-layer perceptron, MLP***) was used for this purpose.

Task of the MLP was to classify an event according to presence of BS in the analyzed target walls. Simulated data were used for selection of input parameters and training of the MLP.

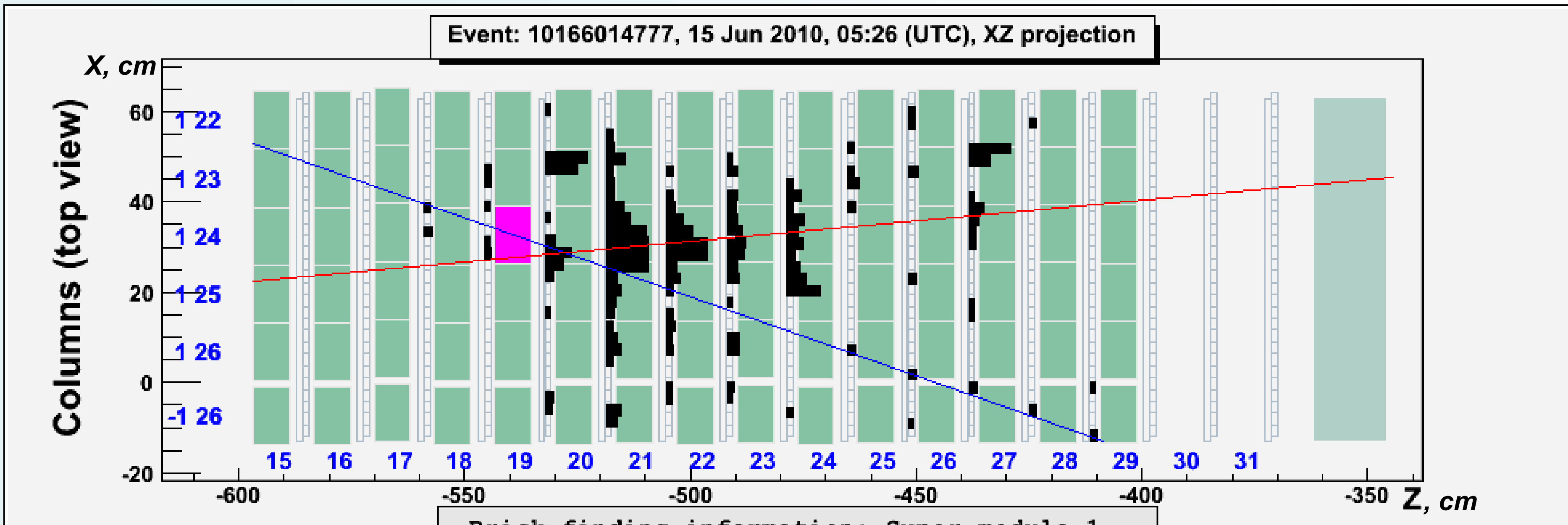
The output of the trained MLP was probabilities to contain the vertex brick for three pre-selected TT walls of an event.



Prediction of the vertex brick candidates

After the reconstruction of a muon track or/and an hadronic shower axis their parameters as well as the wall probabilities (obtained from the MLP) were used for location of a set of bricks that most likely contained a neutrino interaction vertex.

The calculation of brick probabilities took into account the real positions of all bricks inside the detector at the time of the event registration in accordance with the brick maps provided by the Brick Manipulator System.

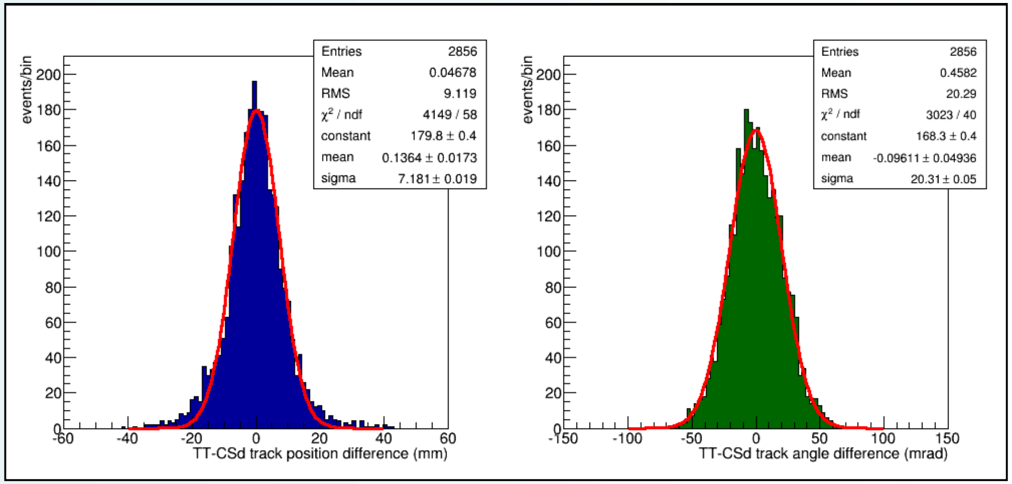


Brick finding information: Super module 1

	BrickId	Wall	Side	Column	Row	Prob
brick 1:	1059176	19	1	24	49	0.58
brick 2:	1059204	19	1	24	48	0.20
brick 3:	1060660	20	1	24	49	0.12

Accuracy of ED predictions and efficiency of BF

Comparison of muon track direction parameters reconstructed in ED and in the interface emulsion films



Brick finding efficiency for simulated OPERA events

Number of extr. bricks	ε_{BF}, CC	ε_{BF}, NC	ε_{BF}, CC/NC/QE
1 brick	77.5%	58.5%	74.1%
2 bricks	91.3%	75.4%	88.0%
3 bricks	94.8%	82.3%	92.2%
4 bricks	96.7%	86.1%	94.4%

Conclusions

- Overview of the procedure of the vertex brick finding (BF) with the help of electronic detectors in the OPERA experiment has been presented.

- The described BF algorithms were integrated by JINR group in the standard OPERA software and were successfully tested during 2009 run. Starting from 2010 they were used for the analysis of all OPERA neutrino events (up to 4 bricks were extracted for each event). BF efficiency for the 1st brick estimated with simulated data was ~74%.

- Target Tracker electronic detector of the hybrid OPERA setup has demonstrated good performance and stability. Its high detection efficiency (~99% for a mip) was stable since TT installation in 2006; no significant ageing of plastic scintillator was observed.

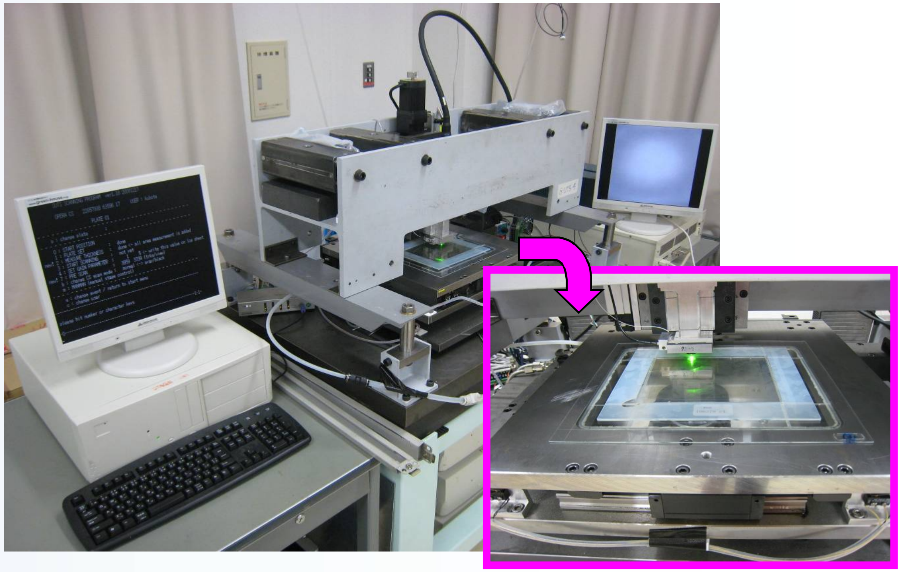
Backup slides

Emulsion scanning stations

EU: ESS (European Scanning System)

- Scanning speed/system: ~20 cm^2/h
- Customized commercial optics and mechanics
- Asynchronous DAQ software

Japan: S-UTS (Super Ultra Track Selector)



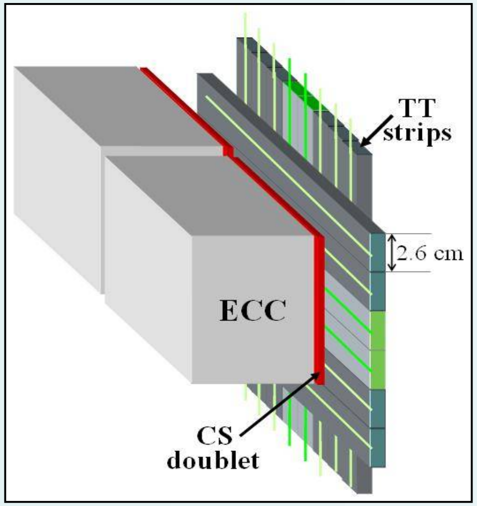
- Scanning speed/system: ~50 cm^2/h
- High speed CCD camera (3 kHz), Piezo-controlled objective lens
- FPGA Hard-coded algorithms

<u>Both systems demonstrate:</u>

- ~0.3 μm spatial resolution
- ~2 mrad angular resolution
- ~95% base track detection efficiency

Analysis of Changeable Sheets (CS)

Changeable Sheets (or **CS doublet**) is a pair of emulsion films attached on the downstream face of each brick used as interface between the ED and ECC detectors.



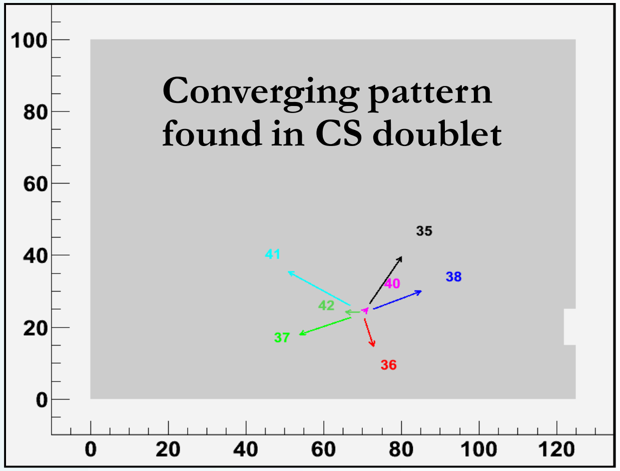
The predicted brick is approved for dismantling, development, and analysis if at least:

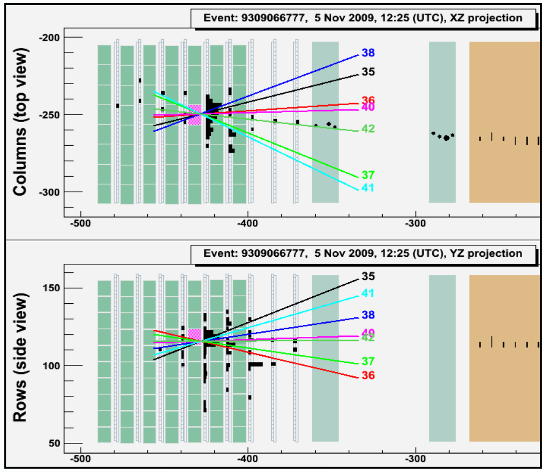
- a CS track compatible with the ED muon track within 60 mrad
- a CS track matching an isolated ED track
- two or more CS tracks possibly converging towards a common origin in the brick

CSd alignment by Compton electrons: **~2.5 μm**

Position accuracy of ED predictions: **~8 mm**

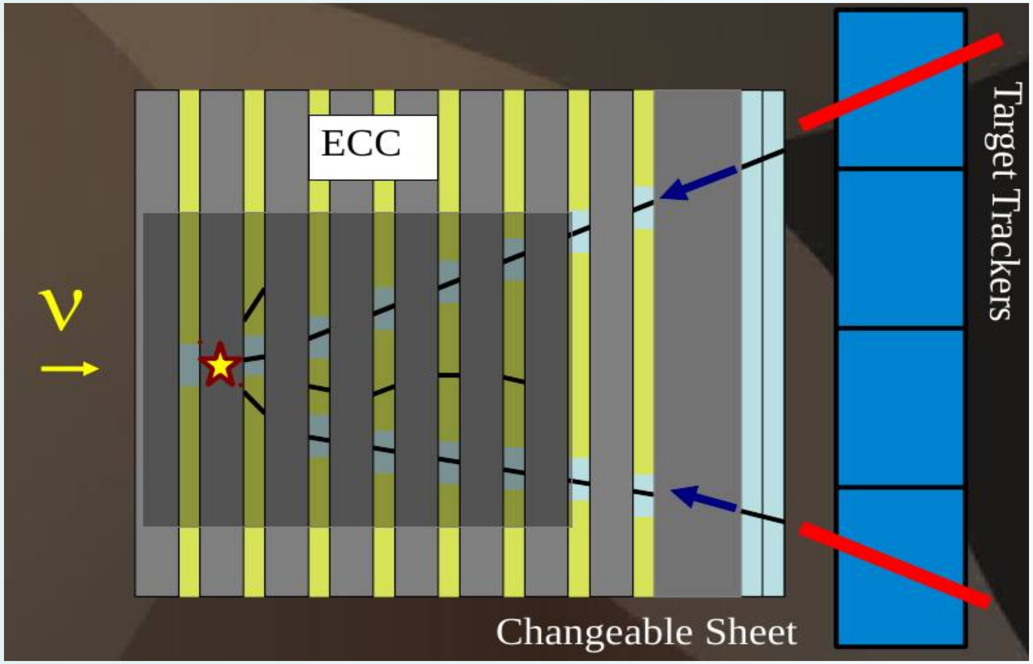
Angular accuracy of ED predictions: **~20 mrad**





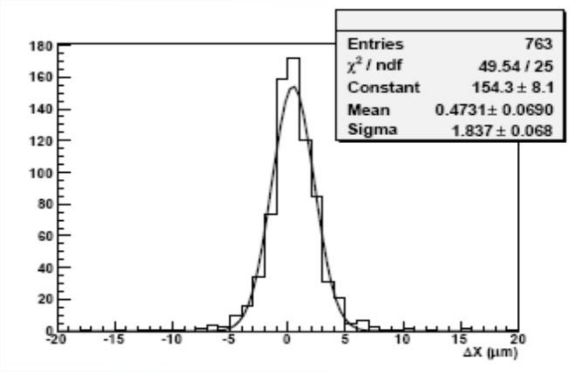
Analysis of ECC: scan-back procedure

- Search for track segments connected to the CS tracks in the most downstream films of the brick.
- Follow back of the found tracks in the upstream films of the brick until stopping point (signature of a vertex) is found.



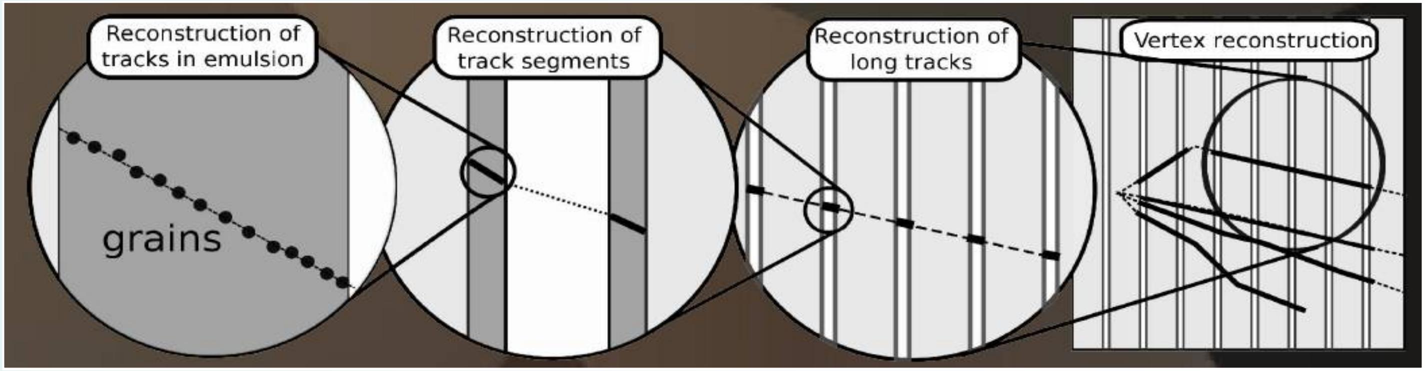
CSd-ECC alignment by X-ray marks: ~10 μm

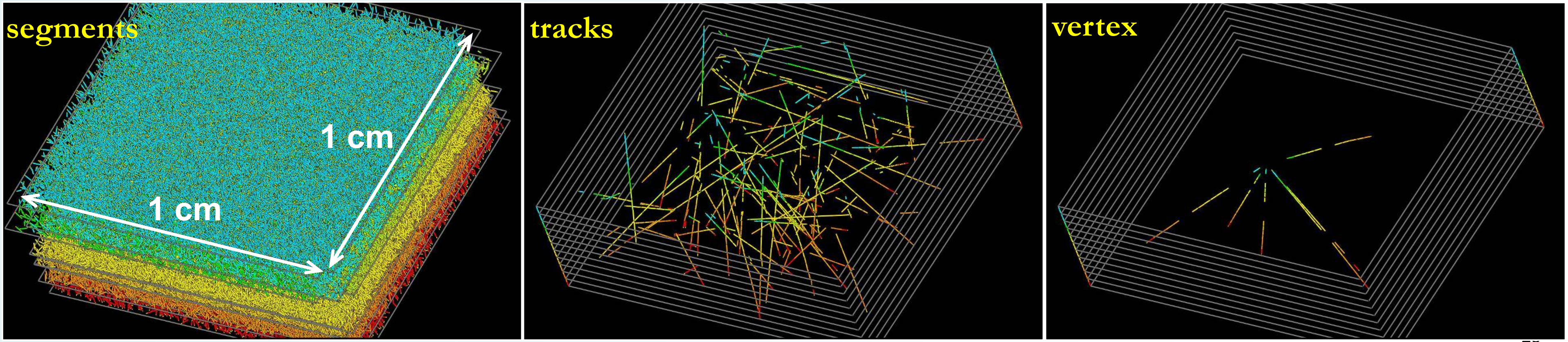
ECC films alignment by cosmic rays: ~2 μm



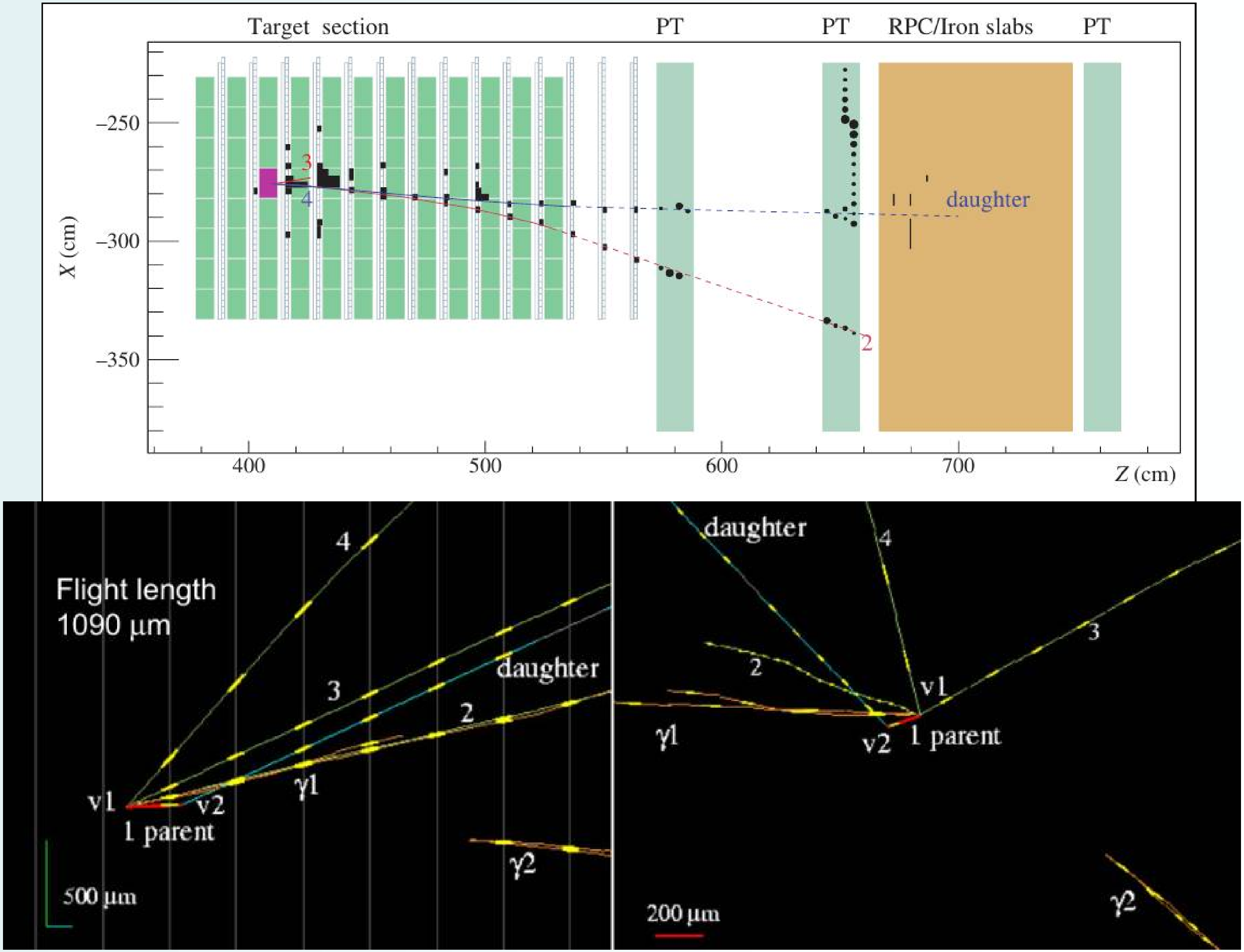
Location of a neutrino interaction vertex in ECC

- Search for converging tracks (or tracks matching the TT hits) in CS.
- Search for track segments connected to the CS tracks in the downstream films of the brick.
- Follow back of the found tracks in the upstream films of the brick until their stopping point.
- Scanning of a large volume (~2 cm^3 around the stopping point).



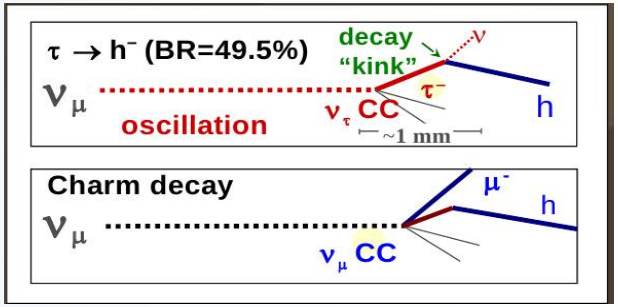


OPERA 4th ν_τ-candidate event ($\tau \rightarrow 1h$)

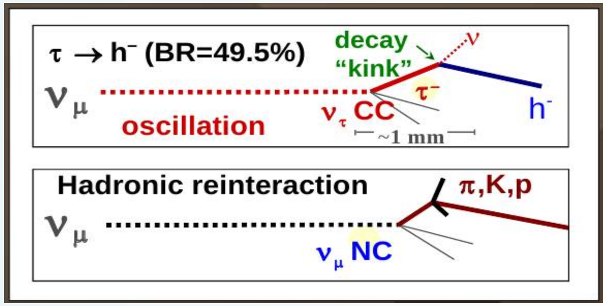


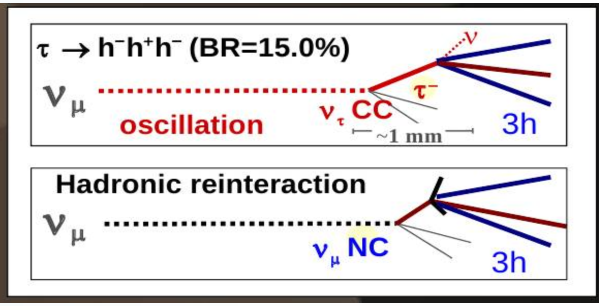
Main sources of background

Charmed particle decays:

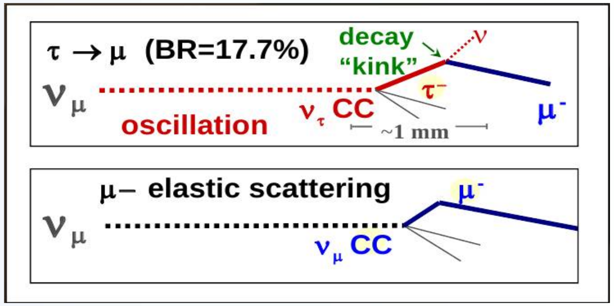


Hadronic re-interactions:

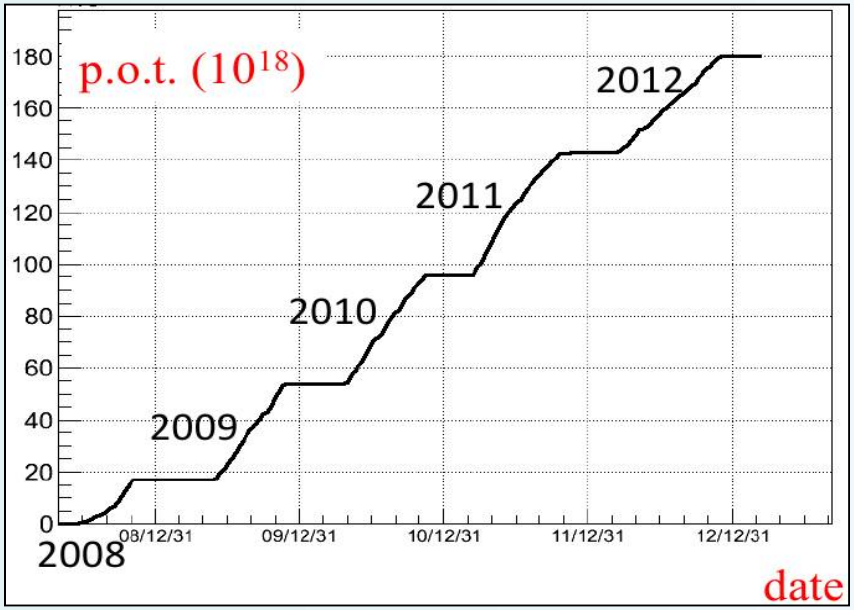


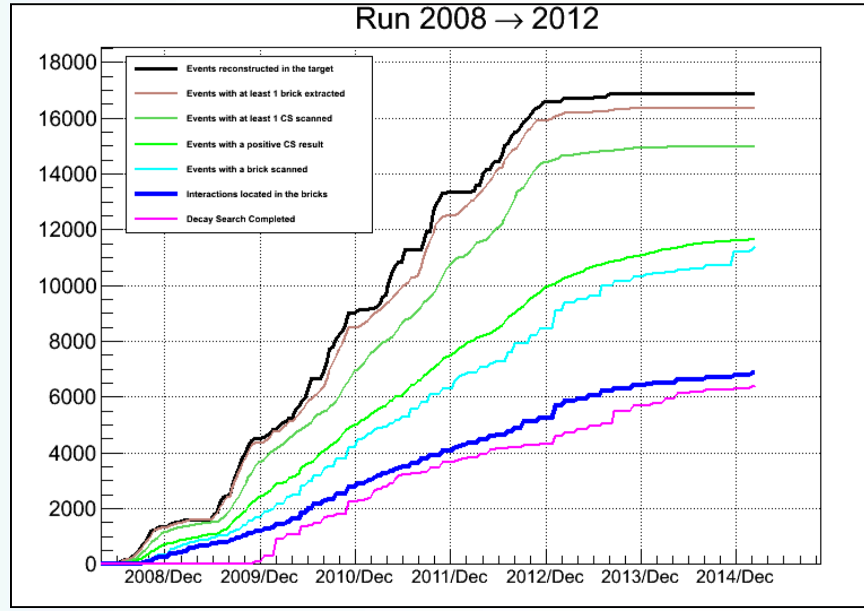


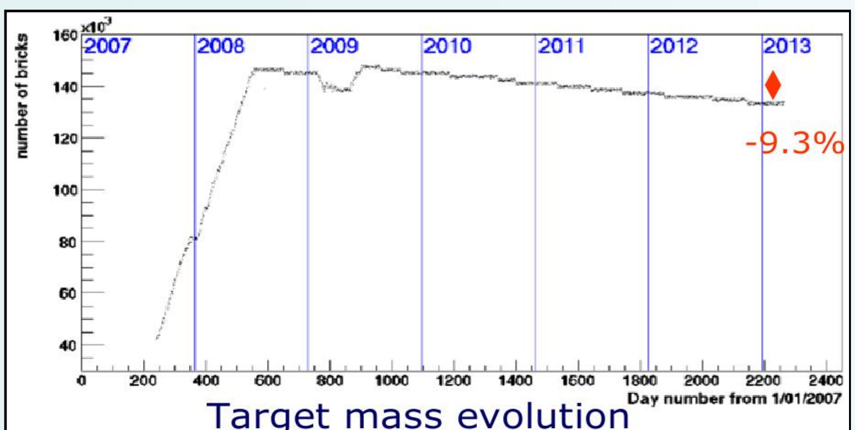
Large-angle scattering of muons:



Status of OPERA data analysis







Year	P.O.T. x 10^{19}	Events reconstructed in the target
2008	1.74	1'757
2009	3.53	3'590
2010	4.09	3'932
2011	4.75	4'311
2012	3.86	3'281
Total	**17.97** *	**16'871**

* Nominal value: **22.5 x 10^{19}** pot

Statistical considerations

Decay channel	Expected* signal	Observed	Expected background: Total	Charm decays	Hadronic re-interactions	Large-angle muon scattering
$\tau \to 1h$	0.41 ± 0.08	2	0.033 ± 0.006	0.015 ± 0.003	0.018 ± 0.005	–
$\tau \to 3h$	0.57 ± 0.11	1	0.155 ± 0.030	0.152 ± 0.030	0.002 ± 0.001	–
$\tau \to \mu$	0.52 ± 0.10	1	0.018 ± 0.007	0.003 ± 0.001	–	0.014 ± 0.007
$\tau \to e$	0.62 ± 0.12	0	0.027 ± 0.005	0.027 ± 0.005	–	–
Total	2.11 ± 0.42	4	0.233 ± 0.041	0.198 ± 0.040	0.021 ± 0.006	0.014 ± 0.007

* expectations for full mixing and $\Delta m^2_{32} = 2.32\text{x}10^{-3}$ eV^2

Probability to be explained by background ~ 10^{-5}

This corresponds to 4.2 σ significance of non-null observation