Status and updated results of the OPERA experiment Search for ν_μ and ν_τ oscillations

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Outline

- Data analysis chain in OPERA
- Main sources of background
- Results on $\nu_\mu \rightarrow \nu_\tau$ oscillation search
- Conclusions

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 *contained* events)

Brick Finding: localization of the brick containing the neutrino interaction vertex

in electronic detectors

Confirmation of the selected brick by analysis of the interface emulsion films (CS)

Location of a neutrino interaction vertex

Decay search: analysis of event topology

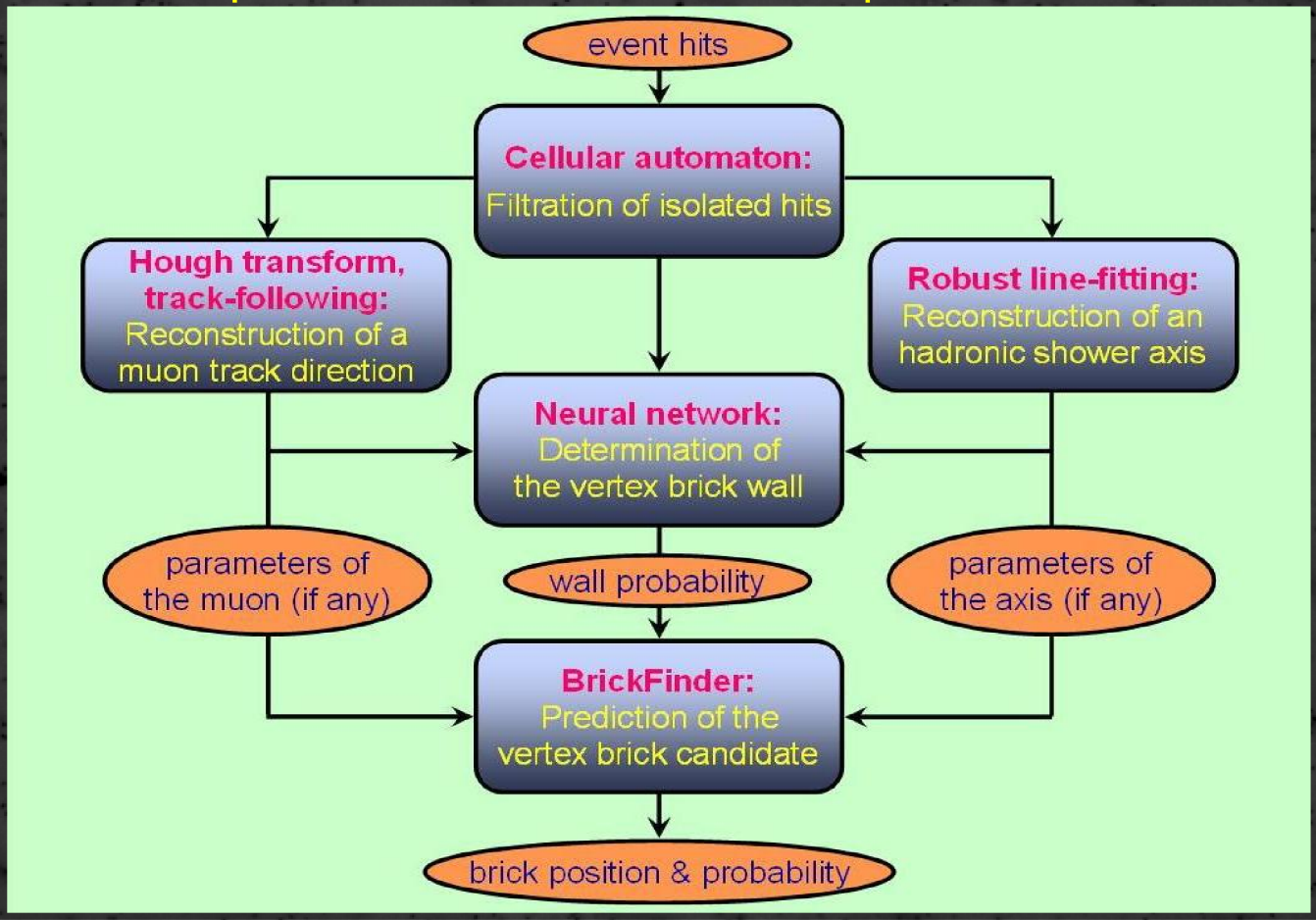
Kinematic selection

in emulsion

Brick Finding (BF)

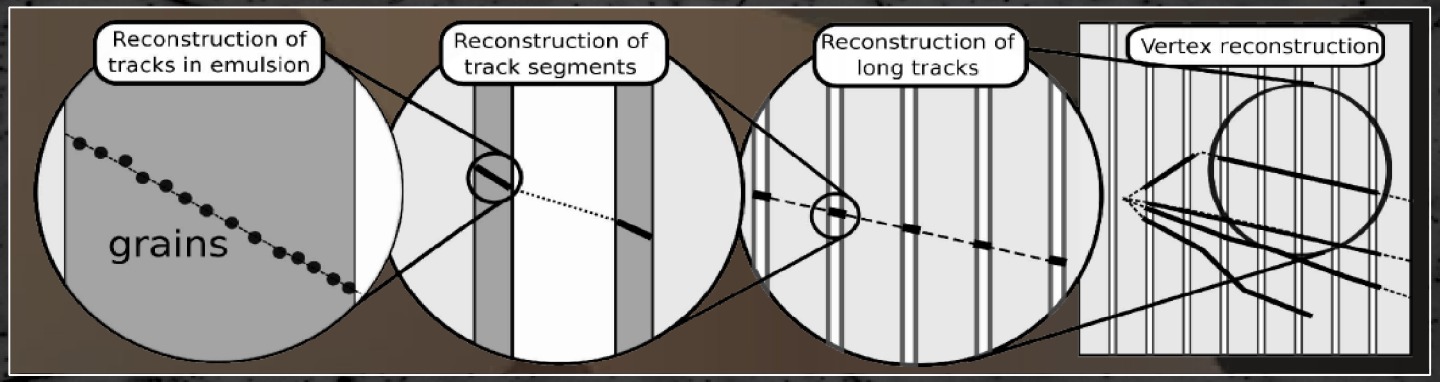
The most important task of the Target Tracker (TT) electronic detector is to localize the ECC brick where the neutrino interaction occurred. A high BF efficiency is needed in order to reduce the emulsion processing load and to minimize the target mass loss.

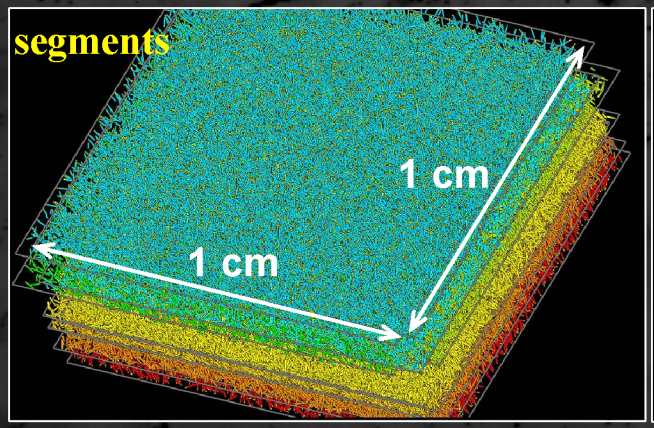
procedure of a vertex brick prediction

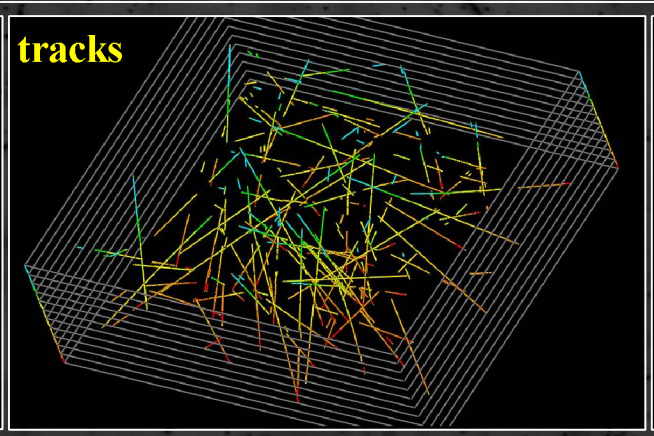


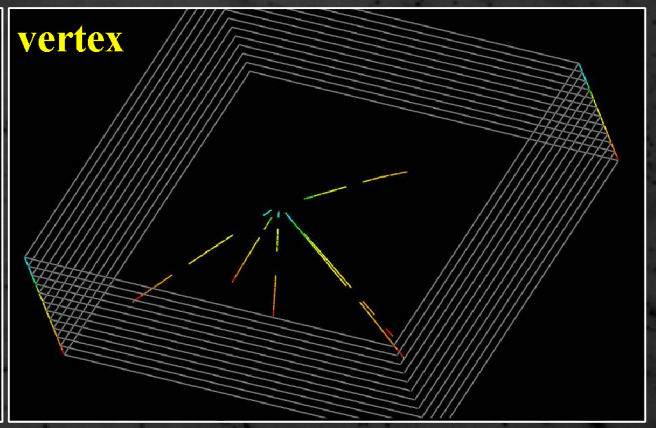
Location of a neutrino interaction vertex

- 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).



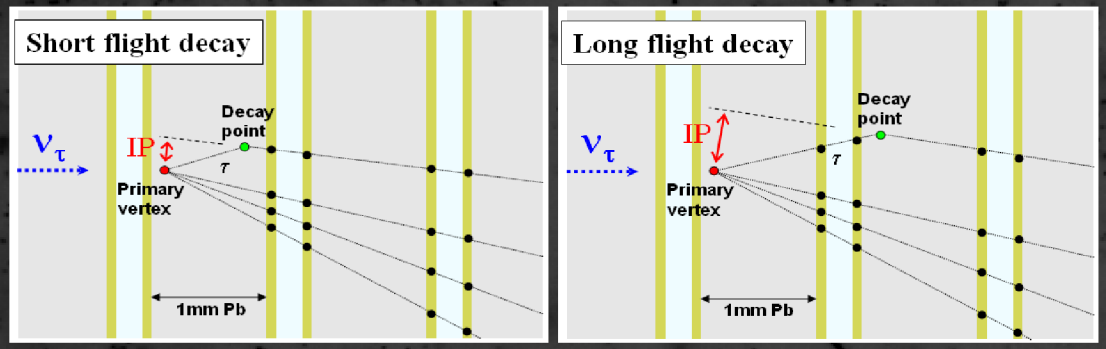


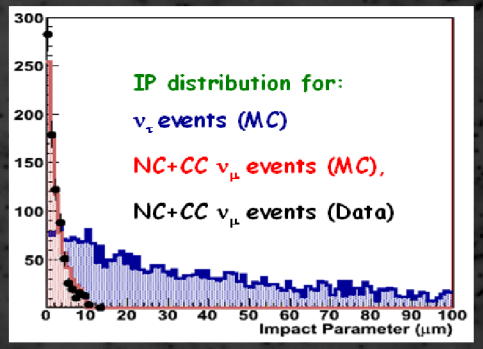




Decay search

Detection of decay or interesting topologies on tracks attached to the primary vertex





Impact parameter (IP) evaluation

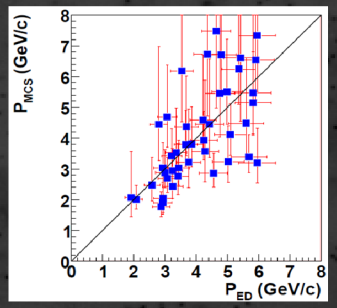
Momentum measurement by multiple Coulomb scattering (MCS)

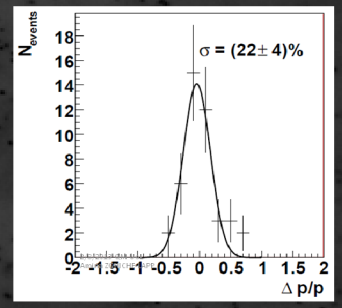
Search for significant kink/trident topology

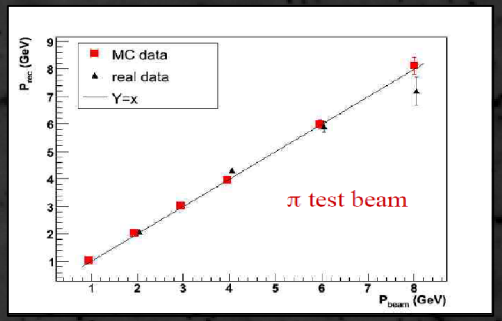
Additional track search

E.m. shower detection and energy measurement

Detection of nuclear fragments

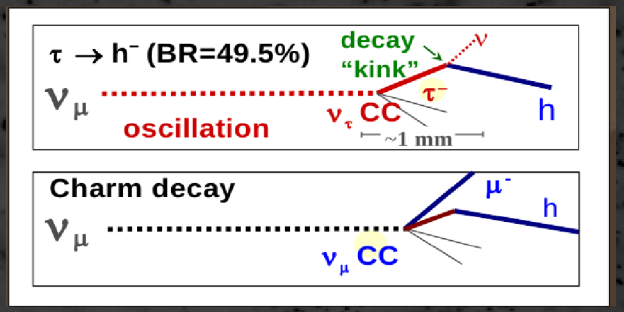




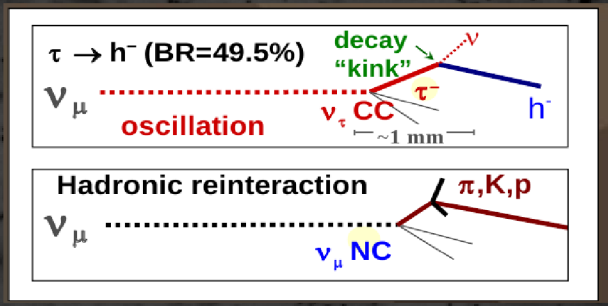


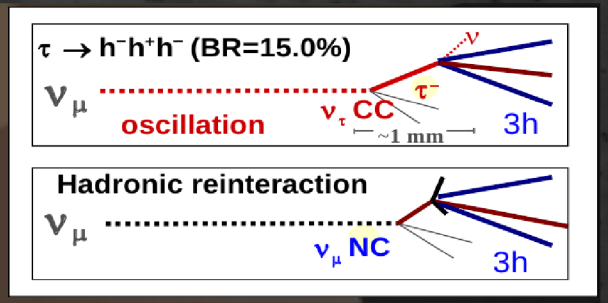
Main sources of background

Charmed particle decays:

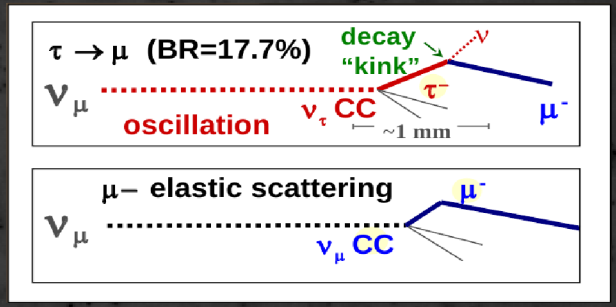


Hadronic re-interactions:





Large-angle scattering of muons:



Charmed particle decays

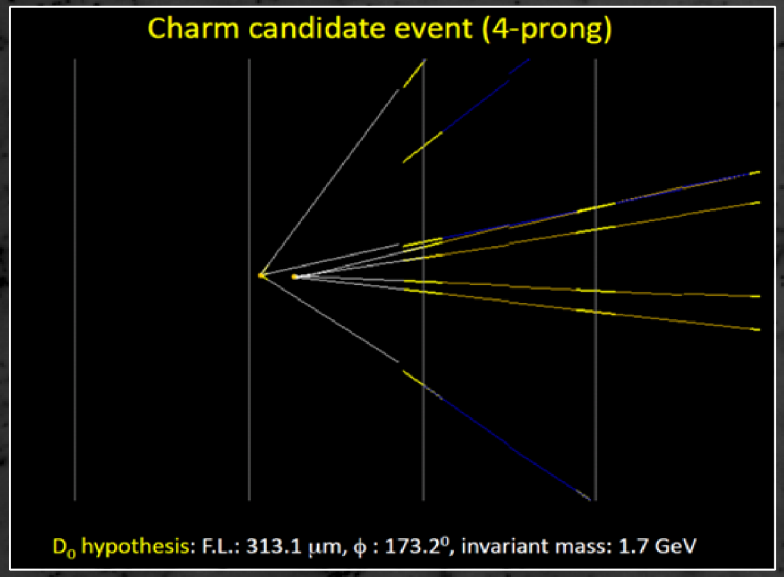
Charmed hadrons, produced in ν_μ DIS on nucleus, have similar mass, lifetime and decay modes as τ:

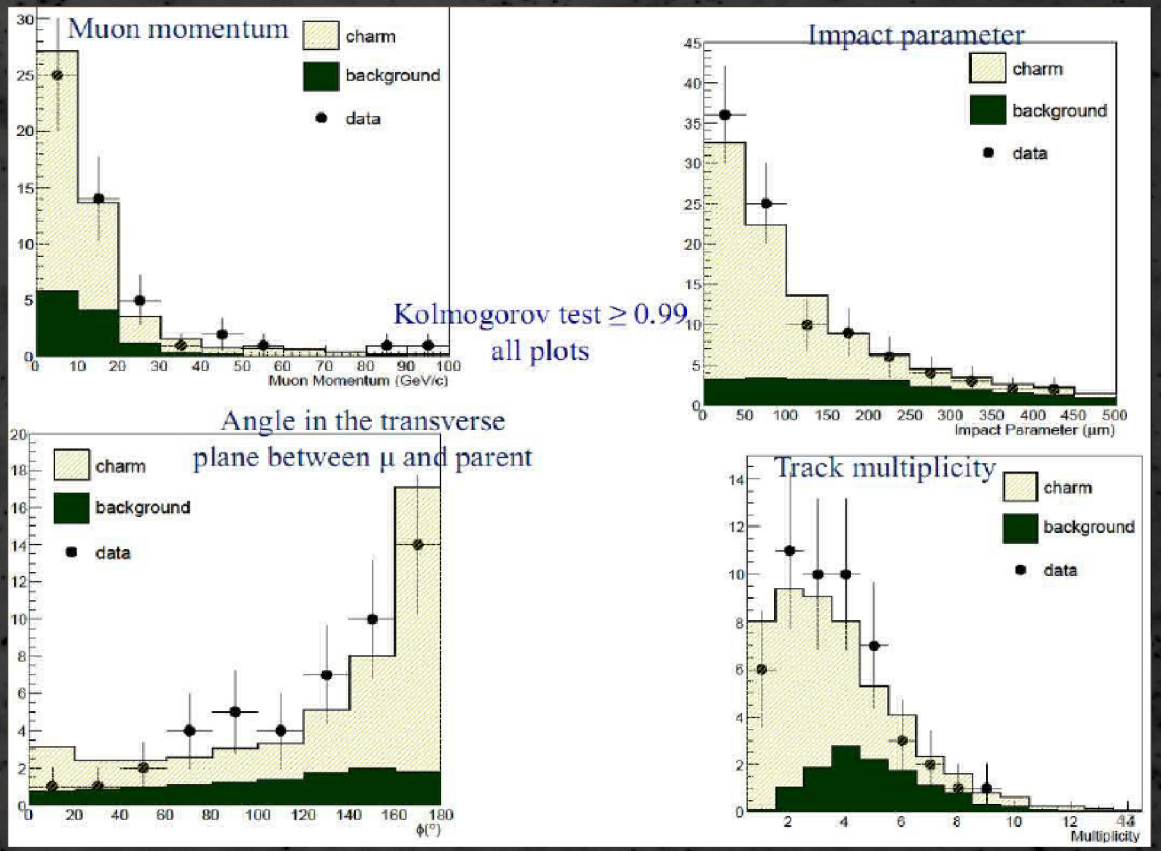
- Main source of background
- Reference sample to verify the understanding of τ detection efficiency

2008 ÷ 2010 data sample

Expected events: 55 ± 5

Observed events: 50



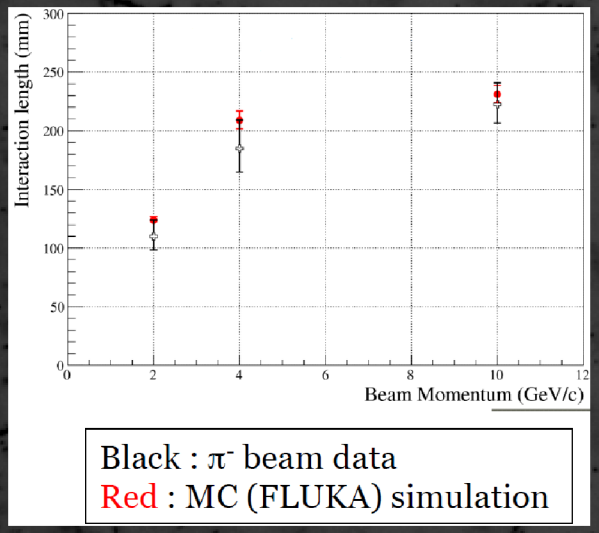


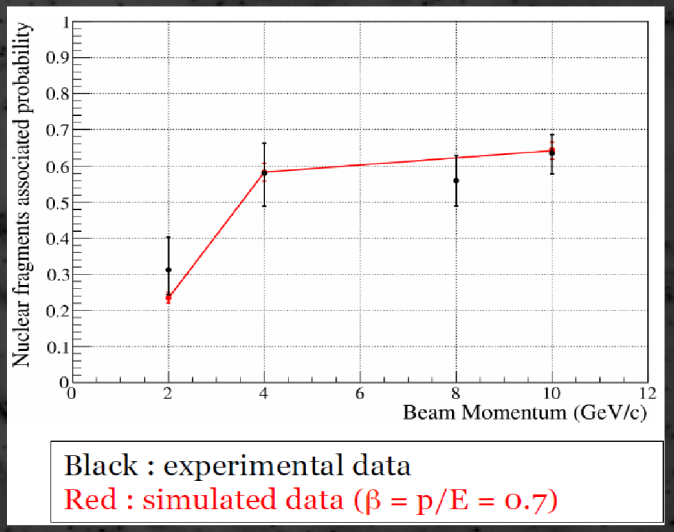
Hadronic re-interactions

Re-interactions in the lead of hadrons produced in ν_μ NC and ν_μ CC interactions.

This background was estimated by a FLUKA-based MC simulation. Several data-driven checks of FLUKA hadronic models for OPERA bricks were performed.

A good agreement between data and simulation is observed for different data-sets.





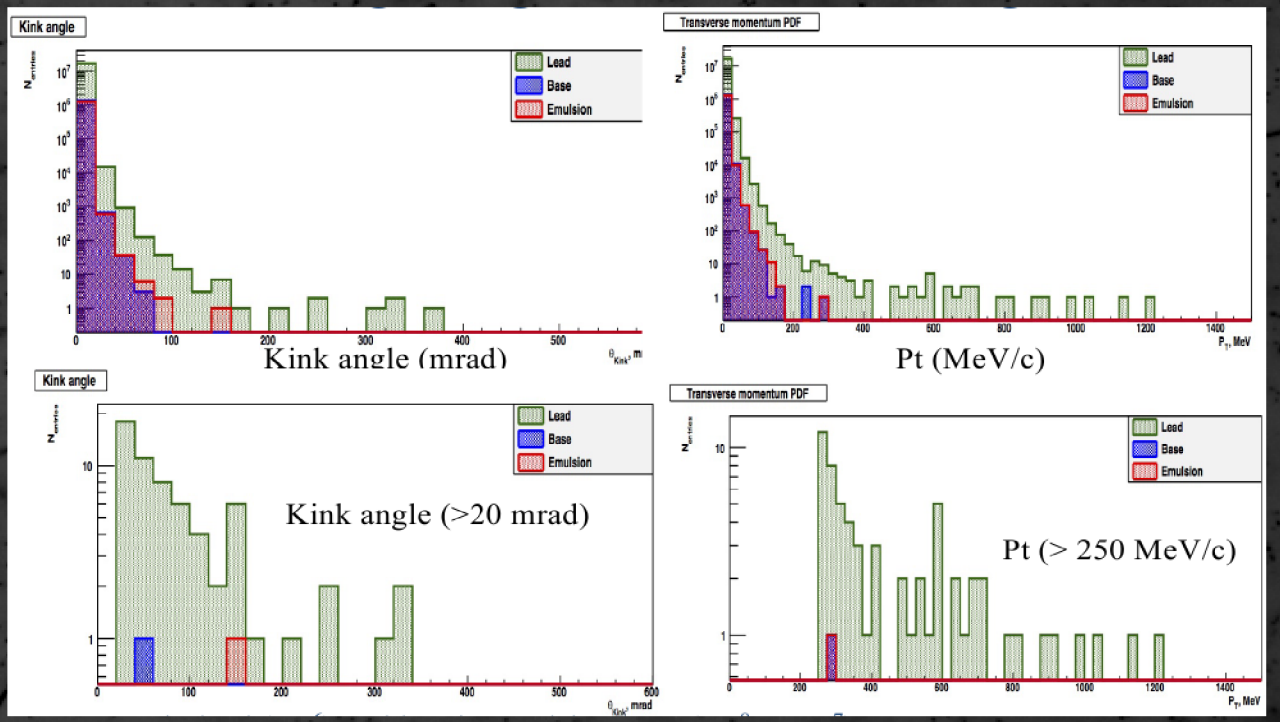
Accuracy of the background predictions: ~30%

Uncertainty in the rate of emission of high-angle nuclear fragments: ~10%

Large-angle scattering of muons

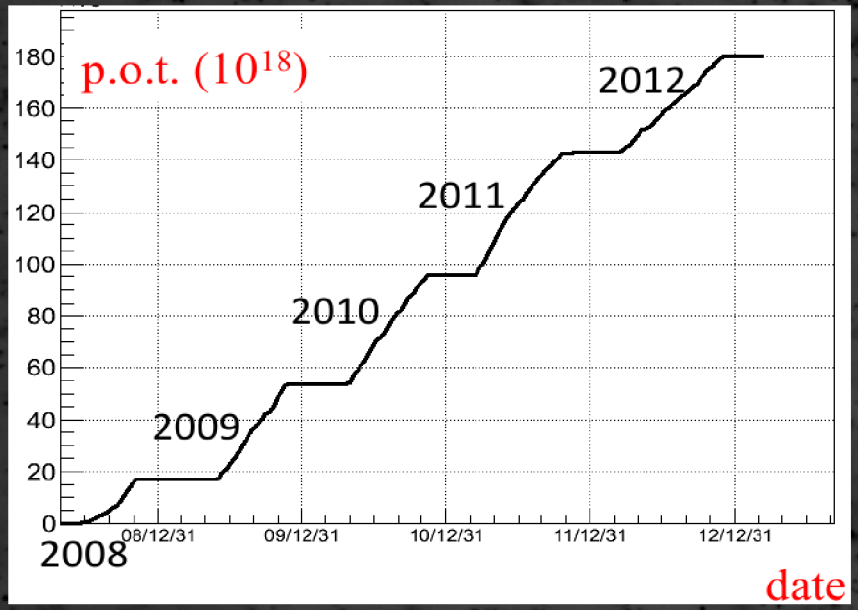
Measurements in progress to better constrain the muon large-angle scattering rate in thin (~0.1X_0) lead plates.

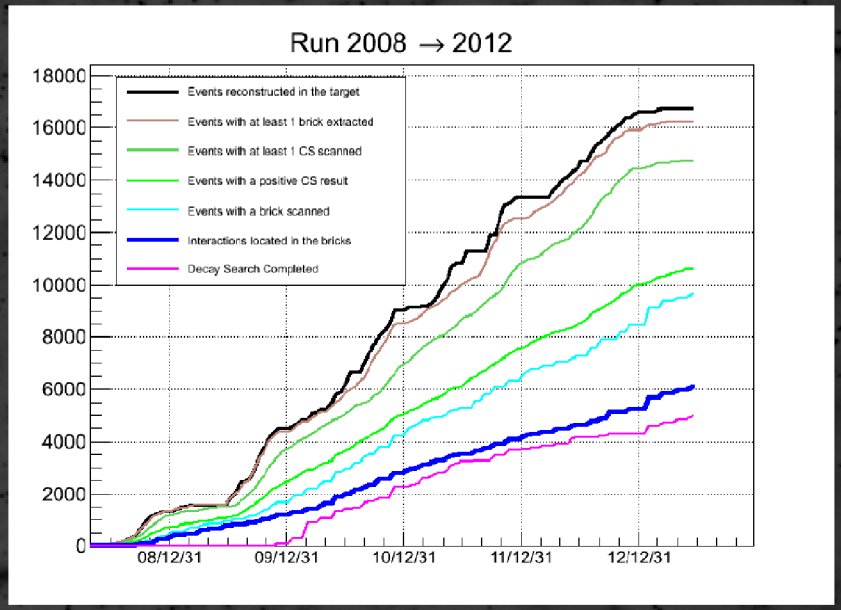
Geant 3.21 based MC simulation (with modifications to take into account the nuclear form factor of lead and inelastic interactions) predicts a rate of 2×10^{-6}.

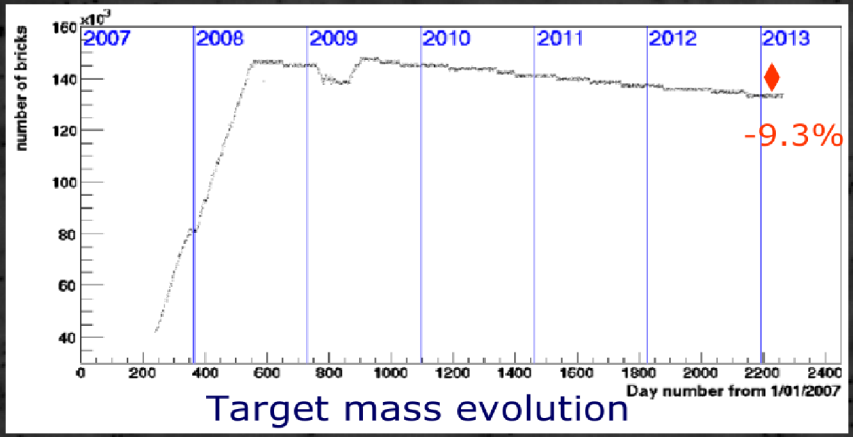


So far an upper limit from extrapolation of measurements on copper or nuclear emulsions (10^{-5}) is used for the analysis.

Status of data taking







Year	P.O.T. x 10^{19}	Events reconstructed in the target
2008	1.74	1'732
2009	3.53	3'580
2010	4.09	3'921
2011	4.75	4'283
2012	3.86	3'260
Total	**17.97** *	**16'776**

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

Data analysis strategy

2008-2009 data

Conservative approach: get confidence on the detector performances

No kinematical cut for event selection

Slower analysis speed (signal/noise not optimal)

Good data/MC agreement

Status: finished

2010÷2012 data

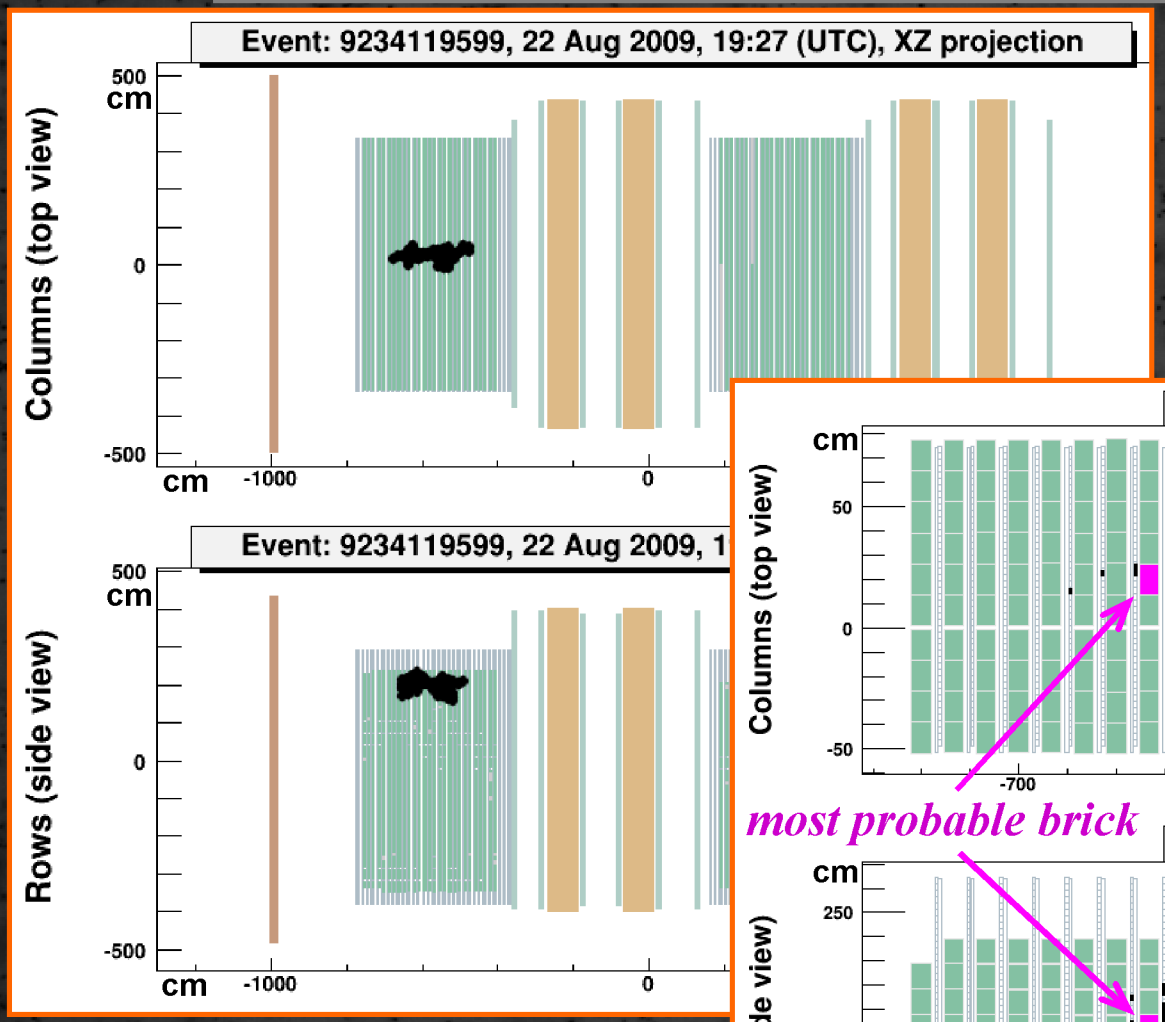
Kinematical selection of CC-like events: $P_{\mu}<15$ GeV

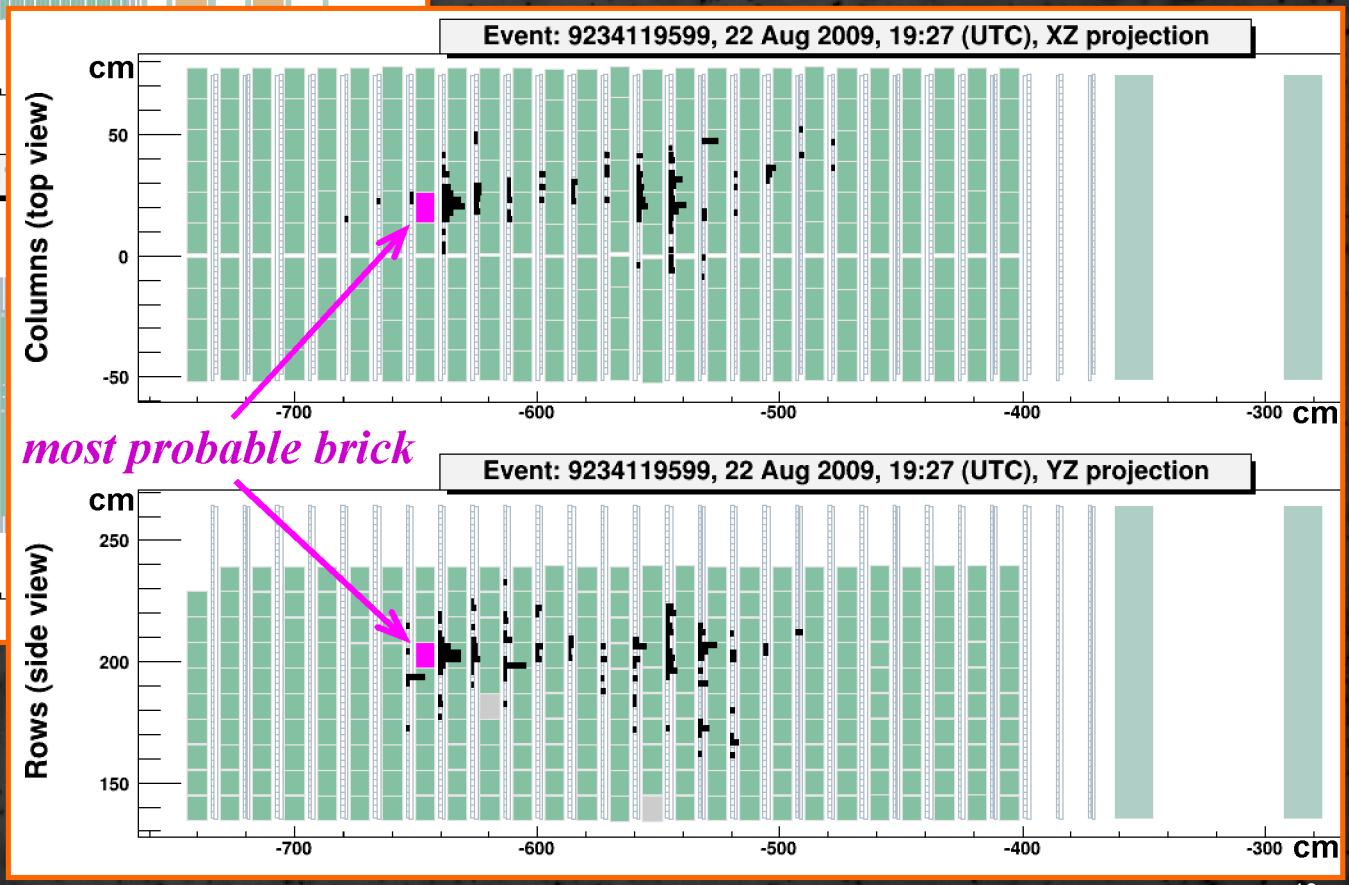
Anticipation of the analysis of the most probable brick before moving to the next one(s) (optimal ratio between efficiency and analysis time)

Anticipate the analysis of NC-like events

Status: in progress

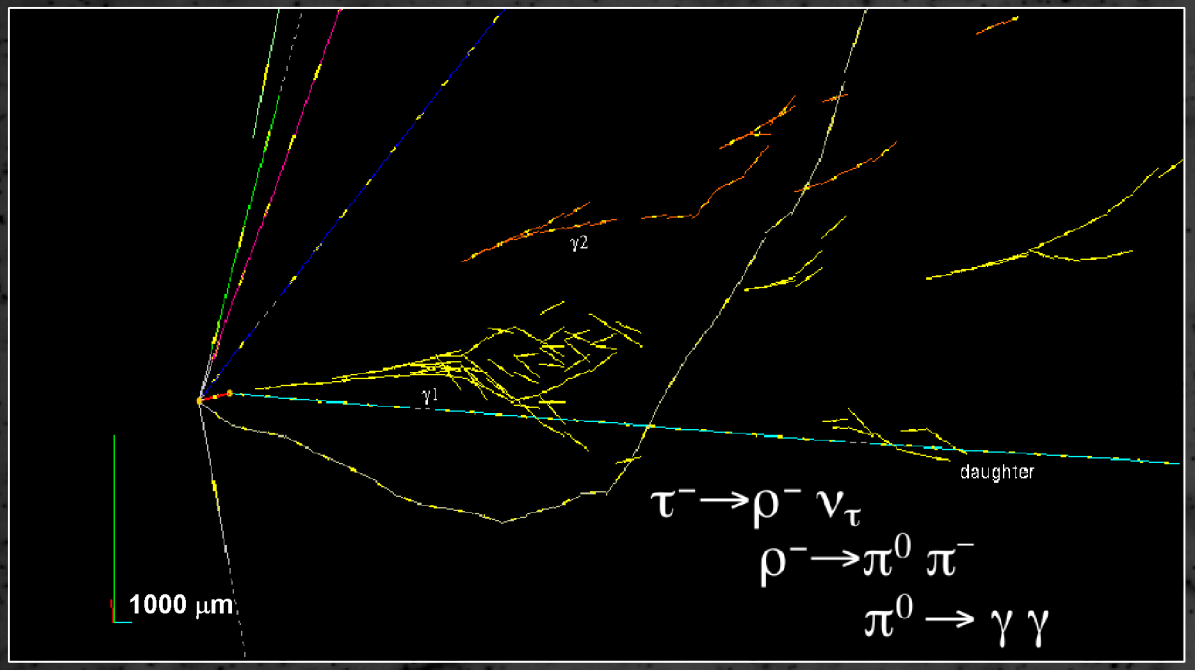
The 1st ν_τ candidate event: ED display

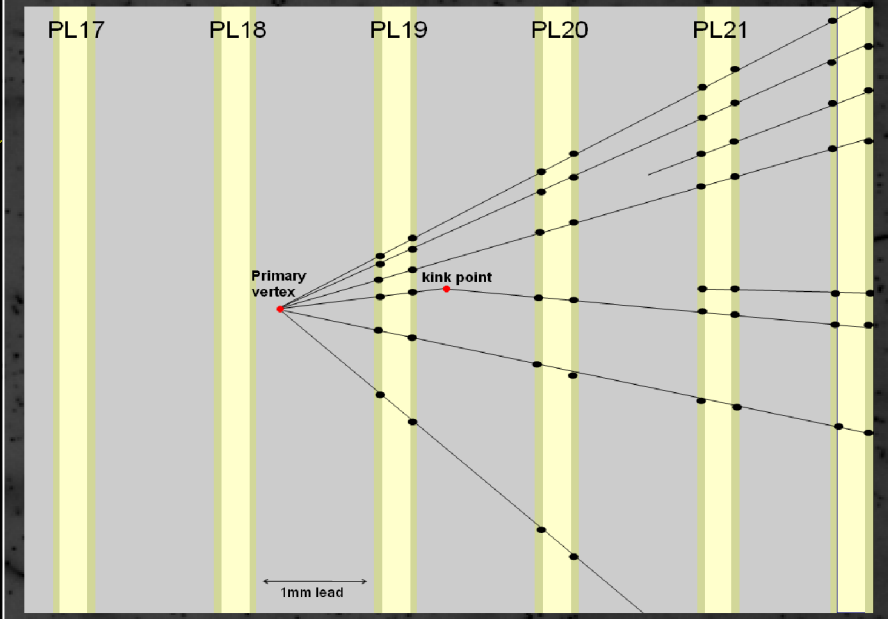




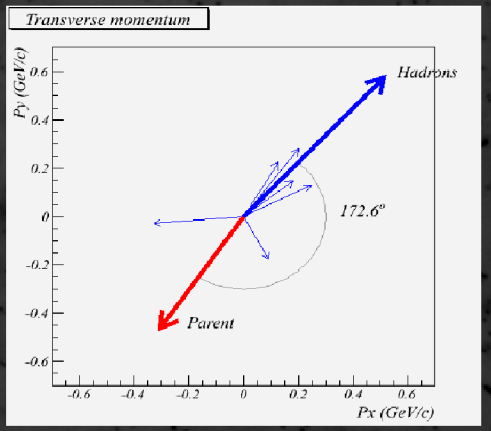
The 1st ν_τ candidate event

2008-2009 decay searched data, released in 2010 (Phys. Lett. B (2010) 138)

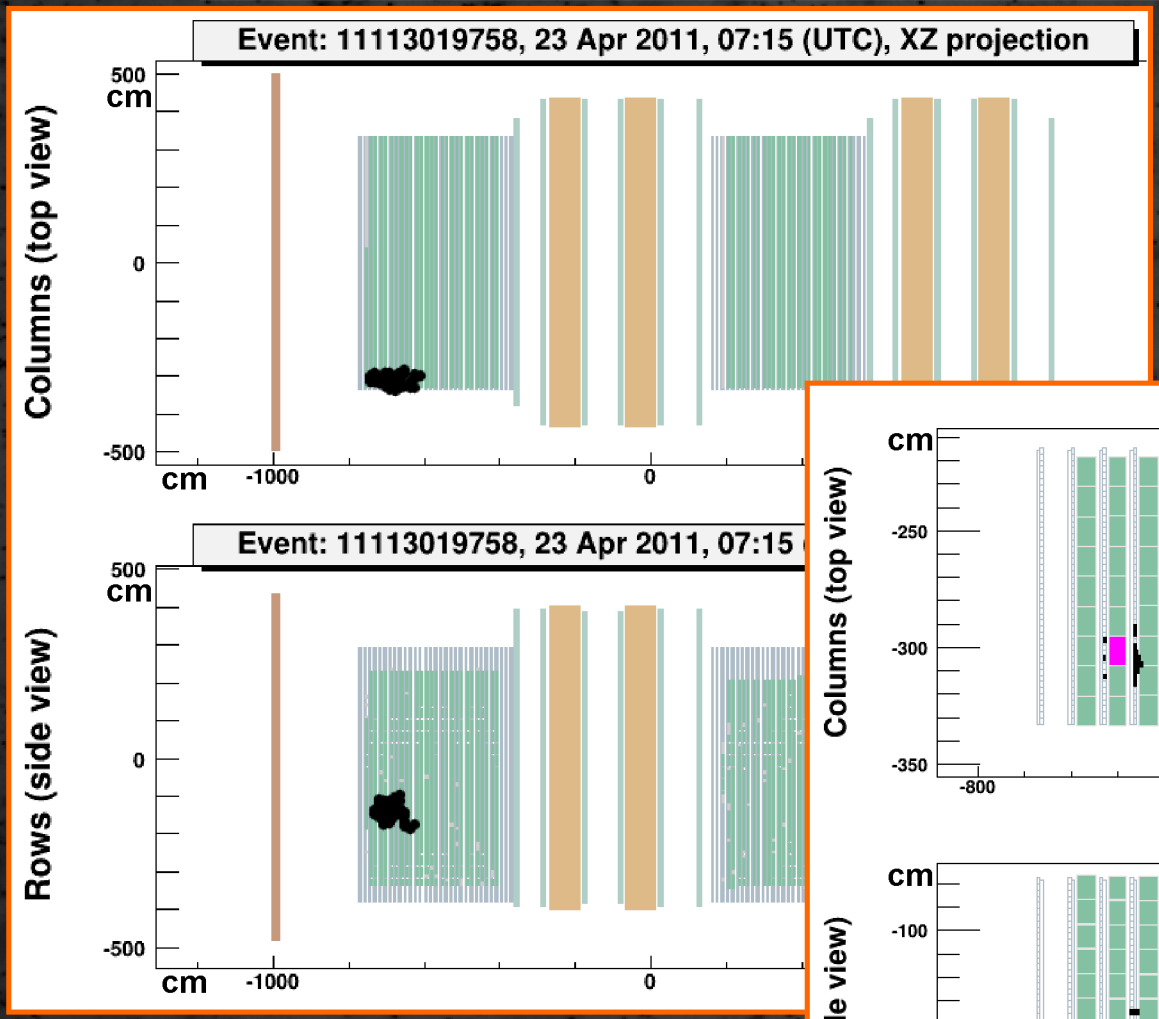


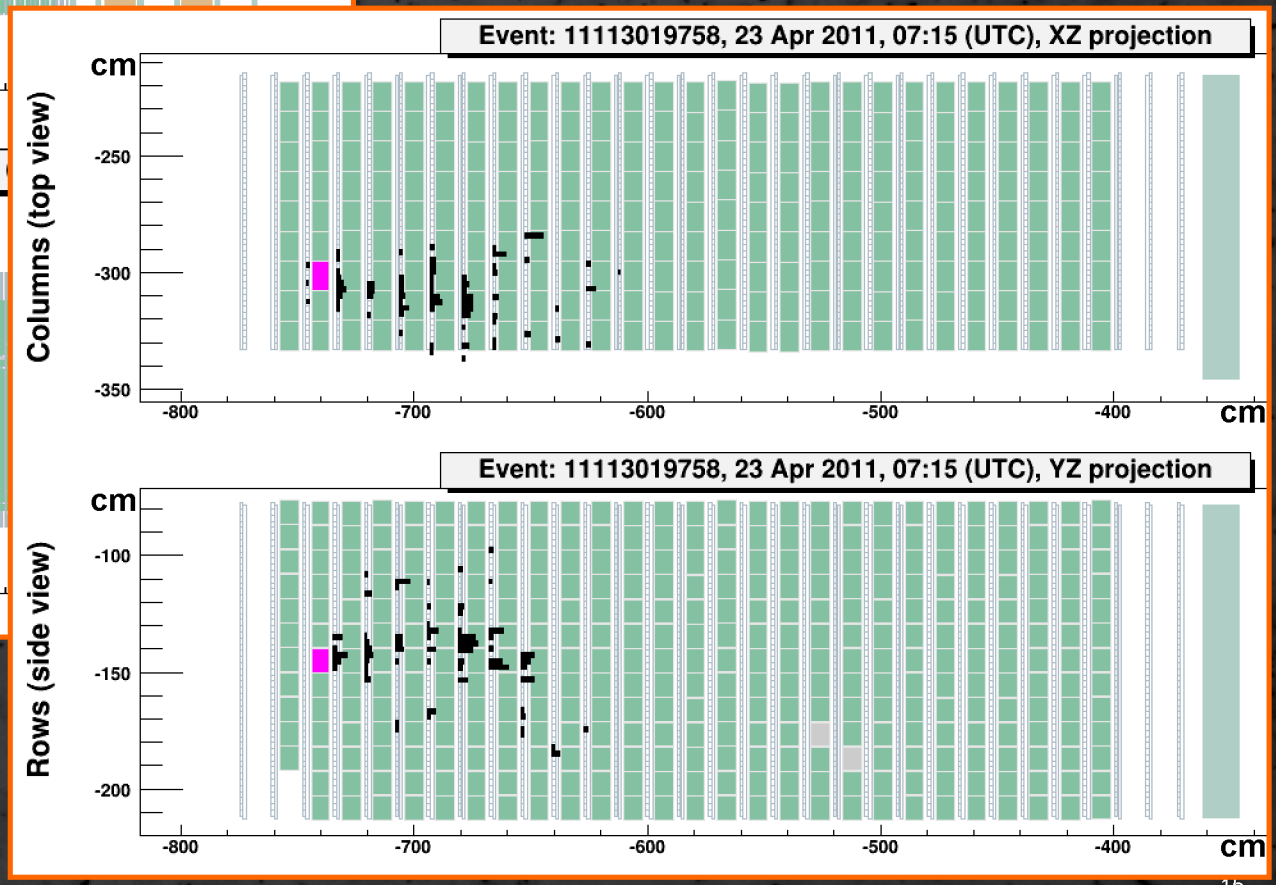


VARIABLE	AVERAGE	Selection criteria
kink (mrad)	41 ± 2	>20
decay length (μm)	1335 ± 35	within 2 lead plates
P daughter (GeV/c)	12^{+6}_{-3}	>2
Pt (MeV/c)	470^{+230}_{-120}	>300 (γ attached)
missing Pt (MeV/c)	570^{+320}_{-170}	<1000
ϕ (deg)	173 ± 2	>90



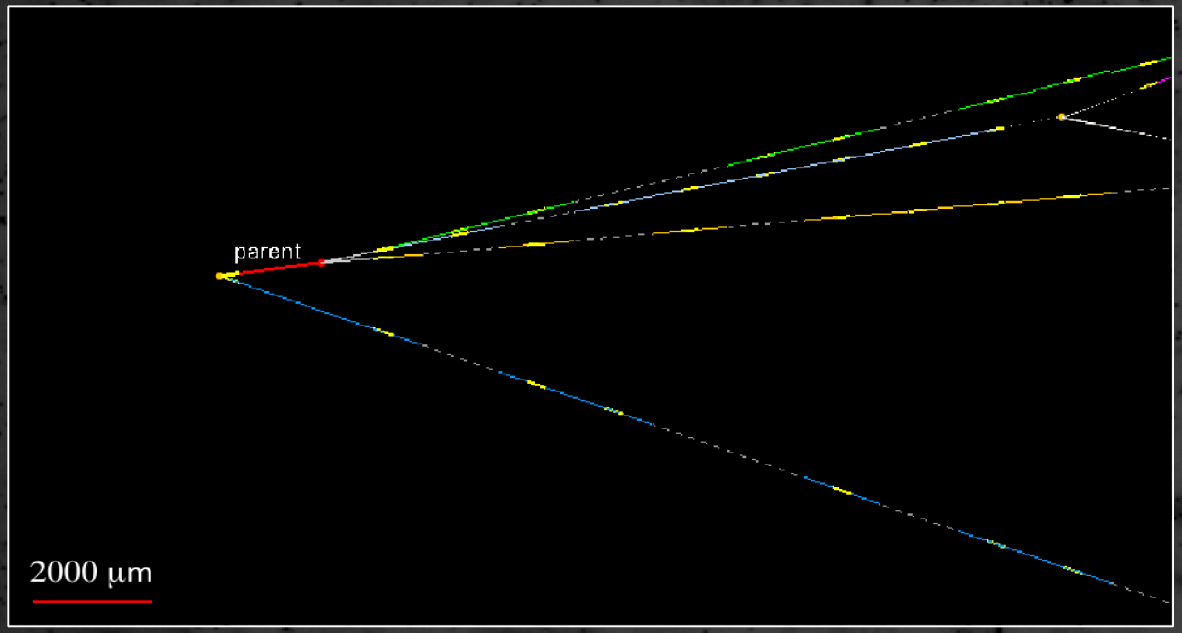
The 2nd ν_τ candidate event: ED display

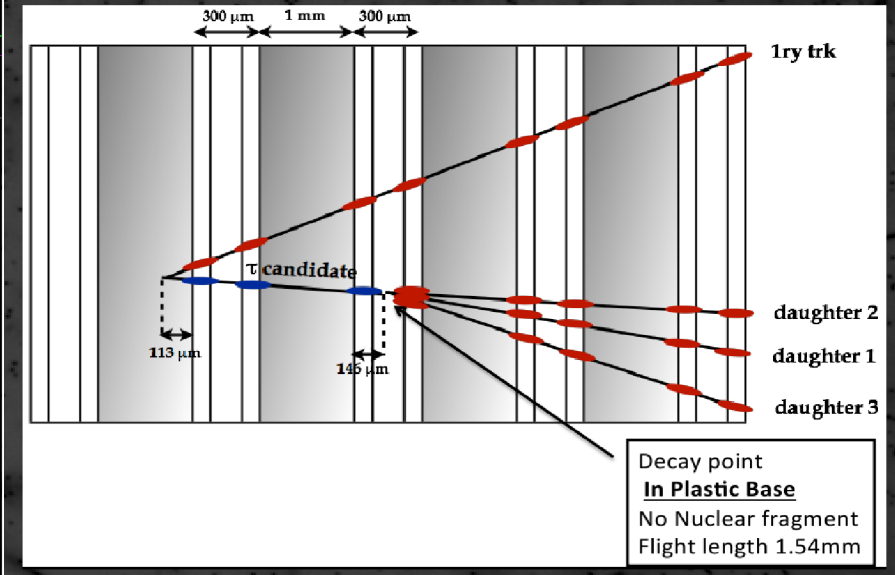




The 2nd ν_τ candidate event

2011 decay searched data, submitted to JHEP (arXiv:1308-2553)



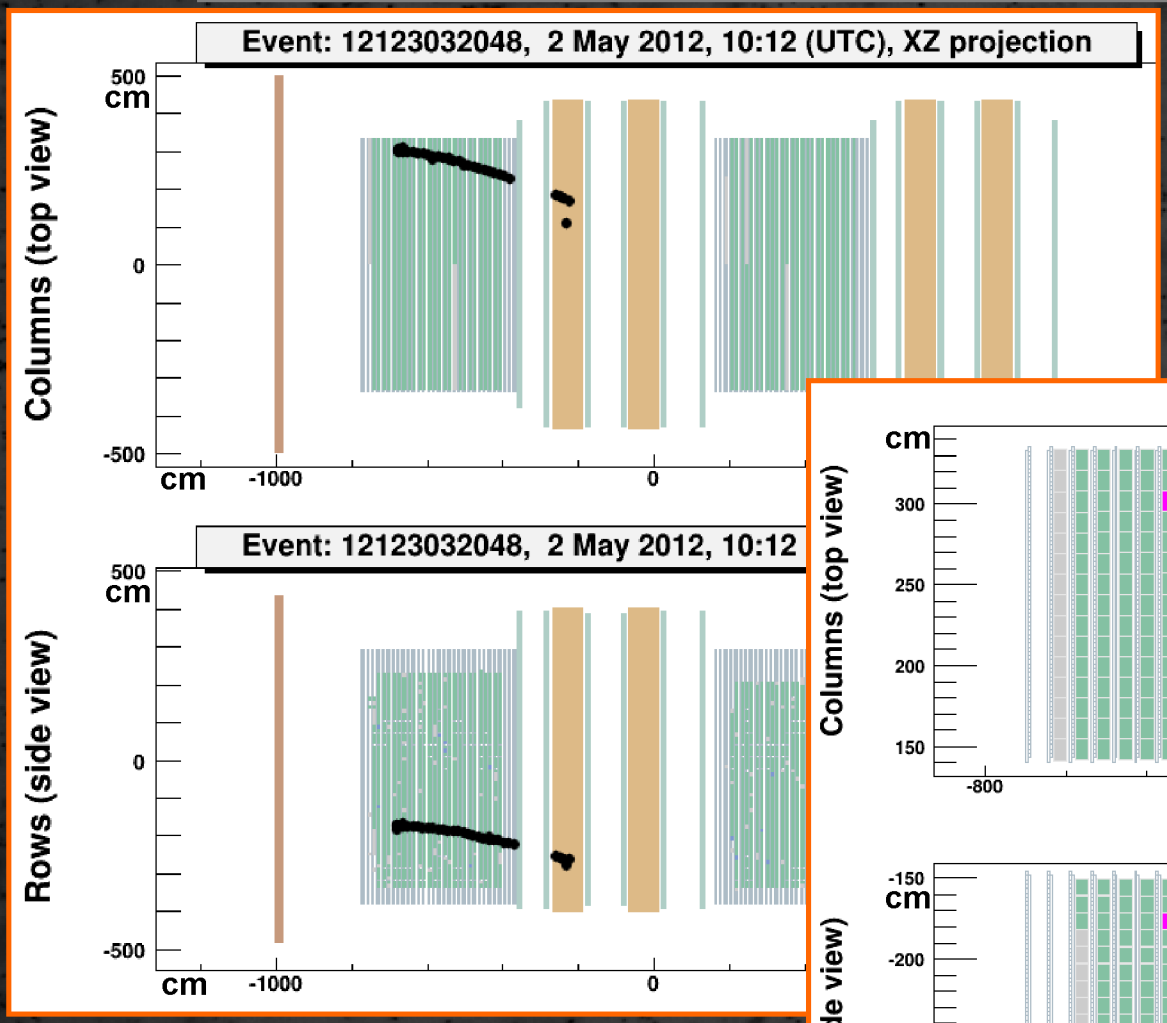


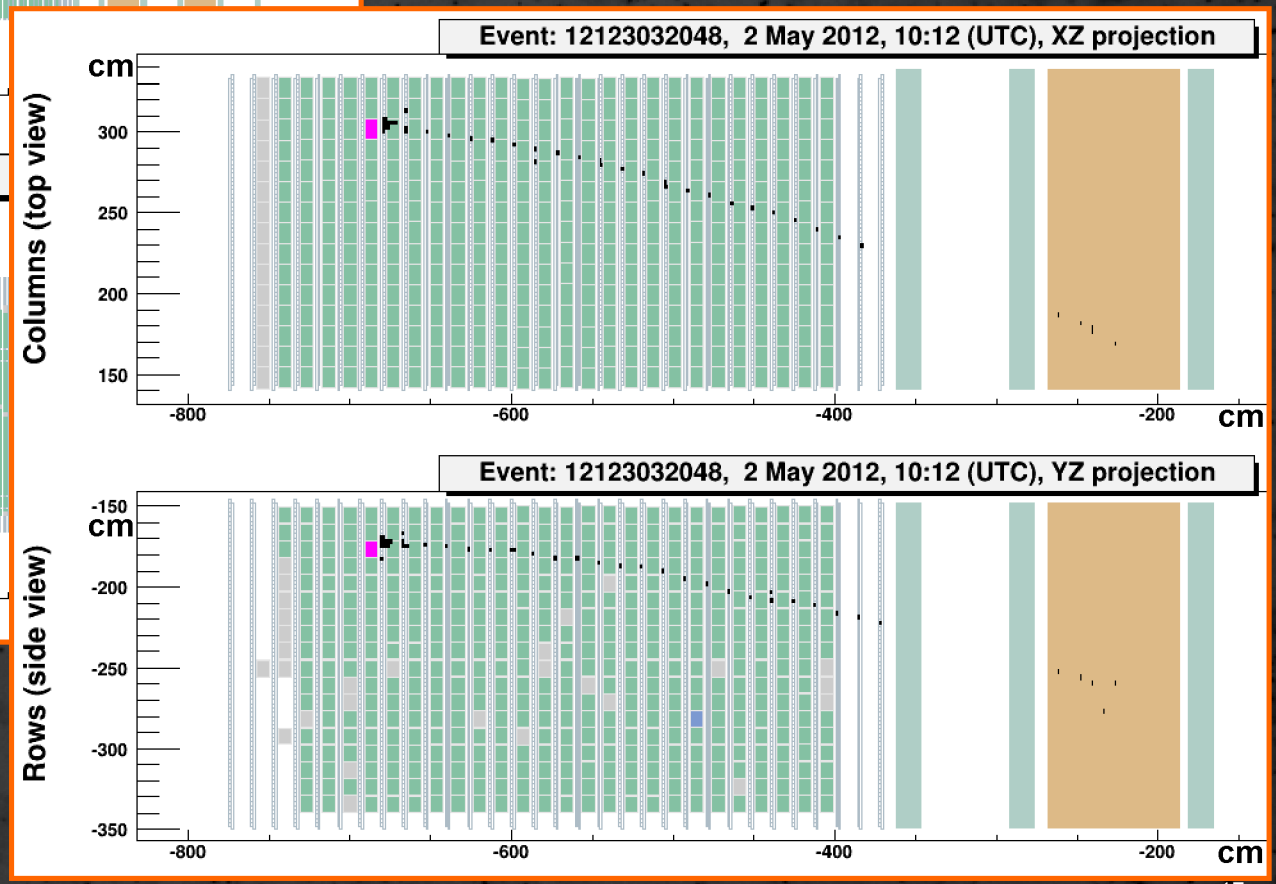
	Cut	Value
φ (Tau - Hadron) [degree]	>90	167.8±1.1
average kink angle [mrad]	< 500	87.4±1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4±1.7
Min Invariant mass [GeV/c²]	0.5 < < 2.0	0.96±0.13
Invariant mass [GeV/c²]	0.5 < < 2.0	0.80±0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31±0.11

All tracks were identified as hadrons

The event satisfies criteria for $\tau \rightarrow 3h$ channel

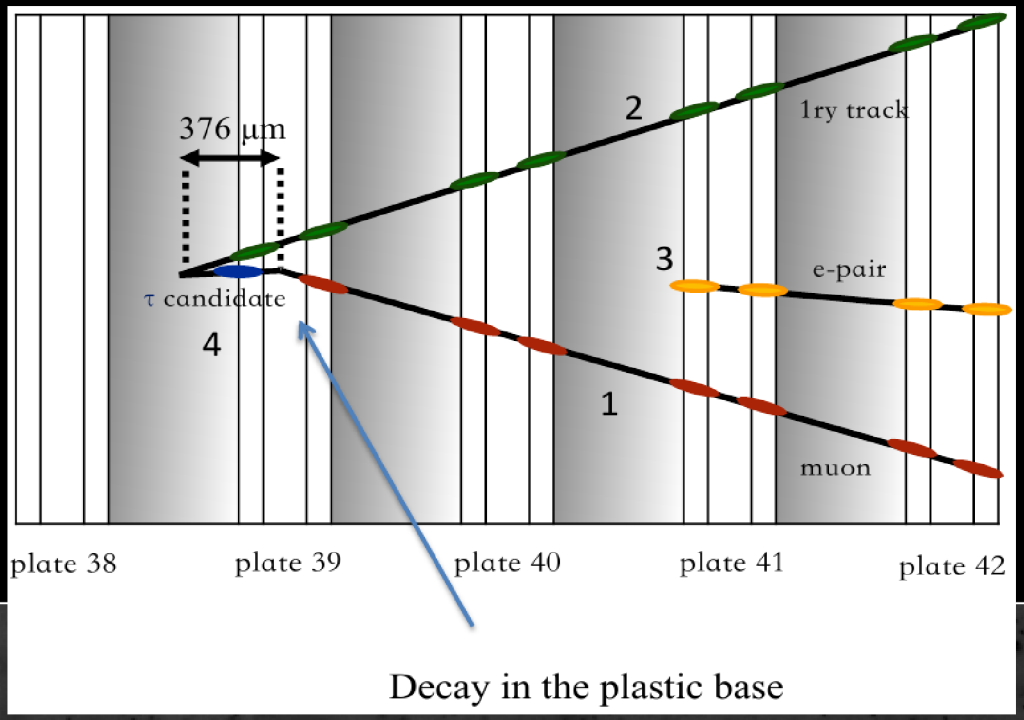
The 3rd ν_τ candidate event: ED display





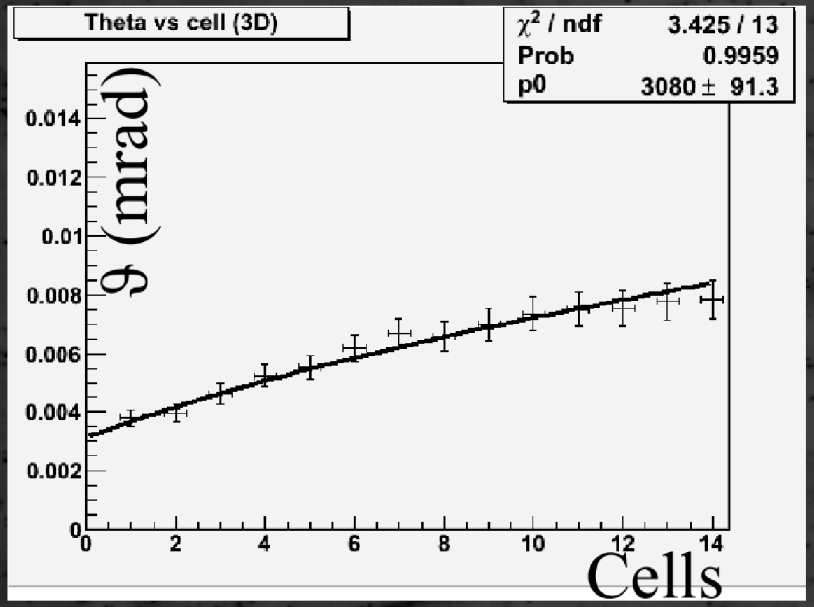
The 3rd ν_τ candidate event

1000 μm



Reconstruction of the muon parameters

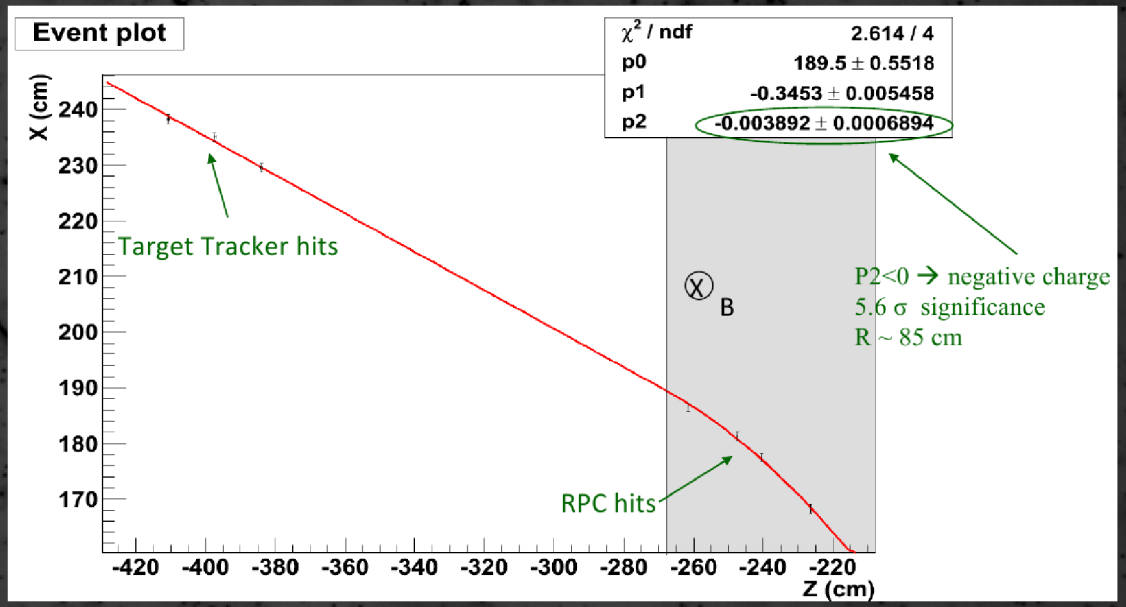
μ momentum



by range in ED: 2.8 ± 0.2 GeV

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

μ charge



By MC estimation the probability to reconstruct a μ+ stopping in the 7th iron layer with p2 < -0.00389 is 0.063%

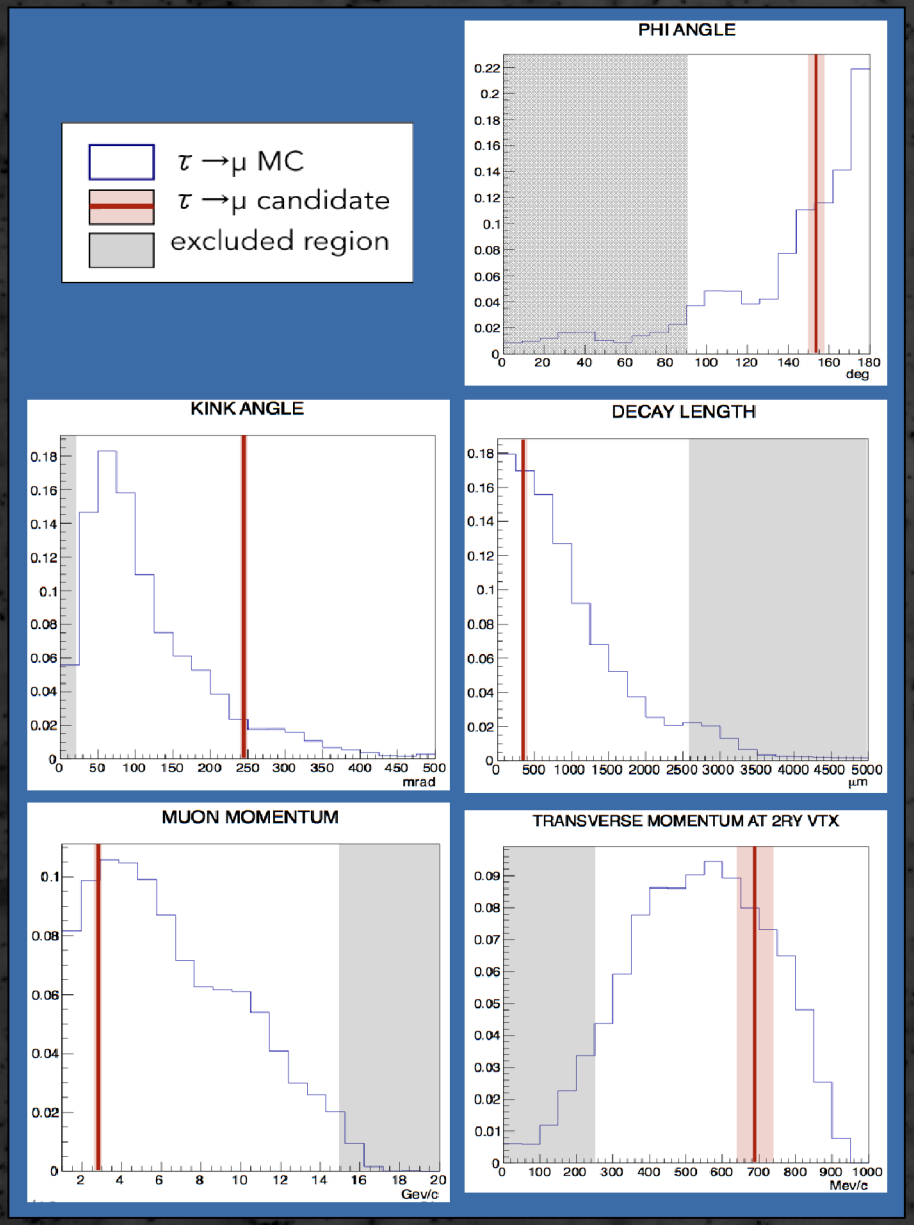
Event tracks' features

TRACK NUMBER	PID	MEASUREMENT 1			MEASUREMENT 2		
		Θ_X	Θ_Y	P (GeV/c)	Θ_X	Θ_Y	P (GeV/c)
1 DAUGHTER	MUON	-0.217	-0.069	3.1 [2.6,4.0]MCS	-0.223	-0.069	2.8±0.2 Range (TT+RPC)
2	HADRON Range	0.203	-0.125	0.85 [0.70,1.10]	0.205	-0.115	0.96 [0.76,1.22]
3	PHOTON	0.024	-0.155	2.64 [1.9,4.3]	0.029	-0.160	3.24 [2.52,4.55]
4 PARENT	TAU	-0.040	0.098		-0.035	0.096	

γ attachment

	$\delta\theta_{RMS}$ (mrad)	DZ (mm)	Measured IP (μm)	IP resolution (μm)	ATTACHMENT
1ry vertex	6	3.1	18.2	13.6	OK
2ry vertex	6	2.8	68.7	12.2	EXCLUDED

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**

All cuts passed: τ→μ candidate

Statistical considerations

	Signal*	Background	Charm	Had. re-int.	μ scattering
$\tau \to \mu$	0.56	0.026	0.0084	-	0.018
$\tau \to e$	0.49	0.065	0.065	-	-
$\tau \to h$	0.66	0.045	0.029	0.016	-
$\tau \to 3h$	0.61	0.090	0.087	0.003	-
Total	**2.32**	**0.226**	**0.189**	**0.019**	**0.018**

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

Observed in data: 3 events in the $\tau \to h$, $\tau \to 3h$, and $\tau \to \mu$ channels

Probability to be explained by background = 7.29×10^{-4} *(simple counting method)*

This corresponds to 3.2 σ significance of non-null observation

Conclusions

The OPERA experiment is aimed at the discovery of neutrino oscillations in direct appearance mode through the study of $\nu_\mu \rightarrow \nu_\tau$ channel.

CNGS program is completed. Data sample corresponding to 17.97×10^{19} pot (~80% of the nominal value) has been collected by the detector.

Event analysis of 2008-2009 runs is finished. Analysis of 2010-2012 data is ongoing with optimized strategy.

3 tau candidate events have been found up to now with 2.32 signal and 0.23 background events expected in the analyzed sample.

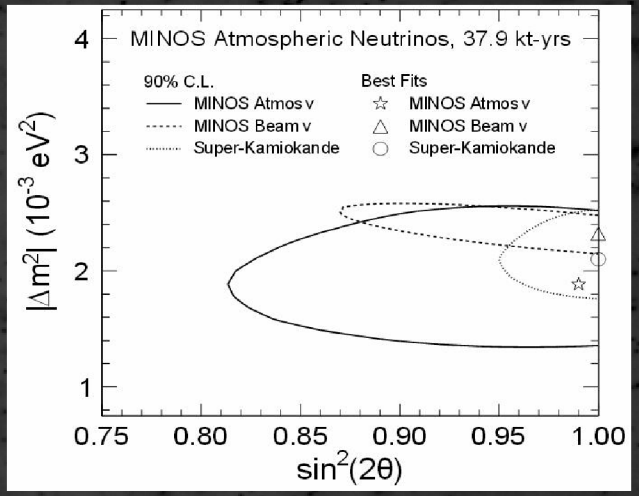
Significance of the observation is 3.2 σ determined by a simple counting method, with the meaning of an ***evidence*** of ν_τ appearance in the CNGS beam.

The current significance can be increased by extending the analysis to next-priority bricks and by improving of background rejection.

Backup slides

Physics motivation of the experiment

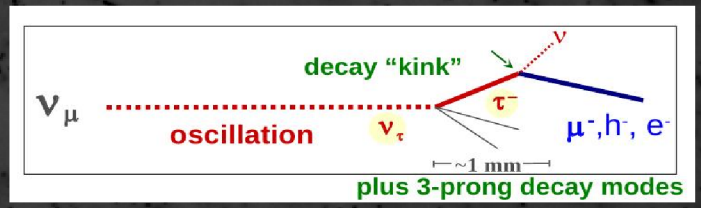
Discovery of *neutrino oscillations* made by Super-K with atmospheric neutrinos was later confirmed by experiments with accelerator ν beams in *disappearance* mode.



The observation of the *appearance* of oscillated neutrinos consistent with the disappearance results is a very important issue.

The challenge of OPERA is the *first direct observation* of ν_τ appearance in a pure ν_μ beam through the detection of the short-lived τ leptons produced in the charged-current (CC) tau neutrino interactions.

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

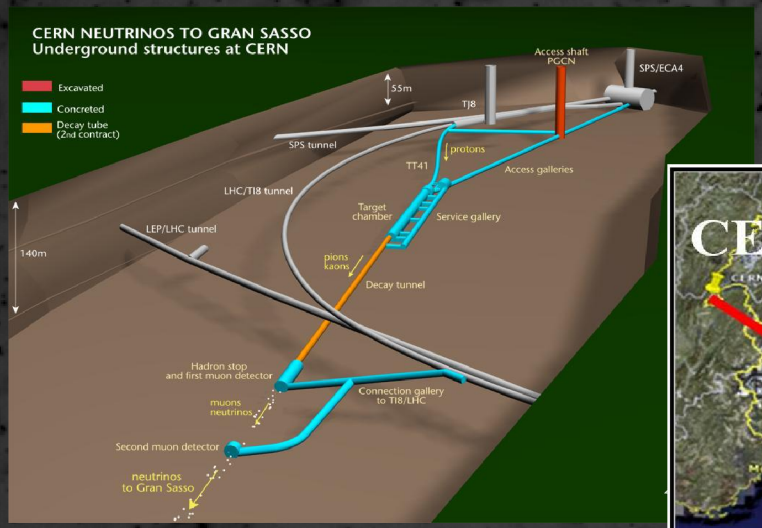


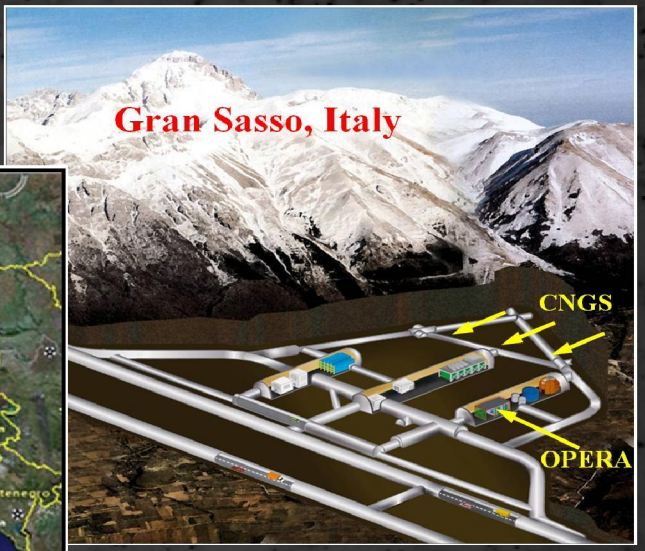
Requirements

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

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

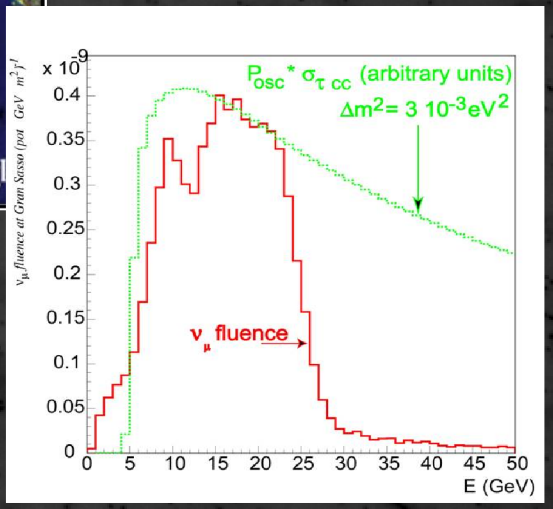
ν beam: CERN neutrinos to Gran Sasso





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

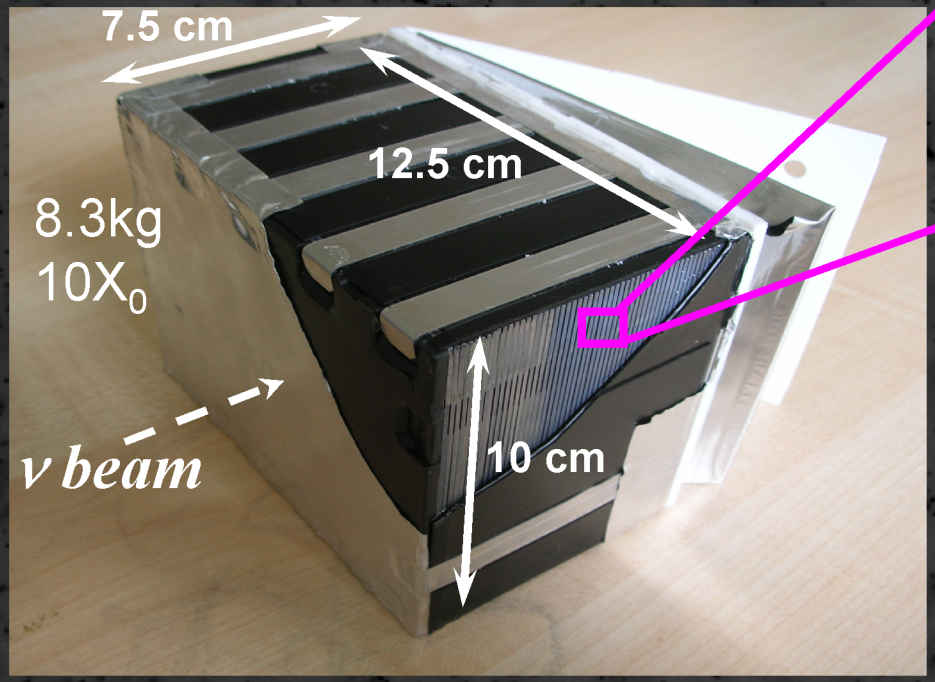
* Interaction rate @ LNGS

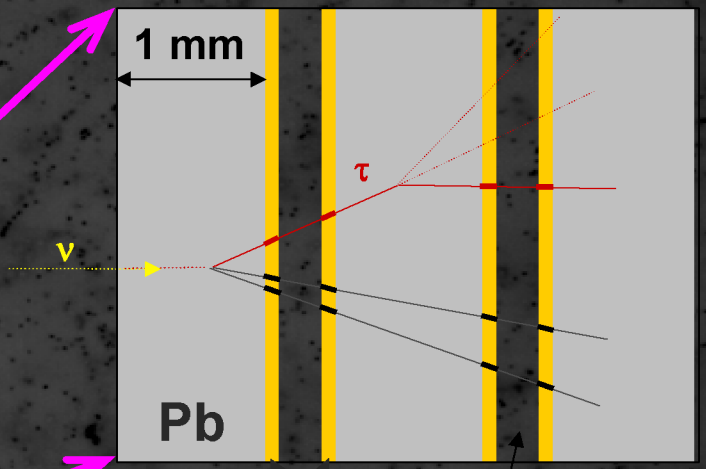


The beam is optimized to maximize the number of CC ν_τ interactions in the detector

OPERA 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 (CSd)



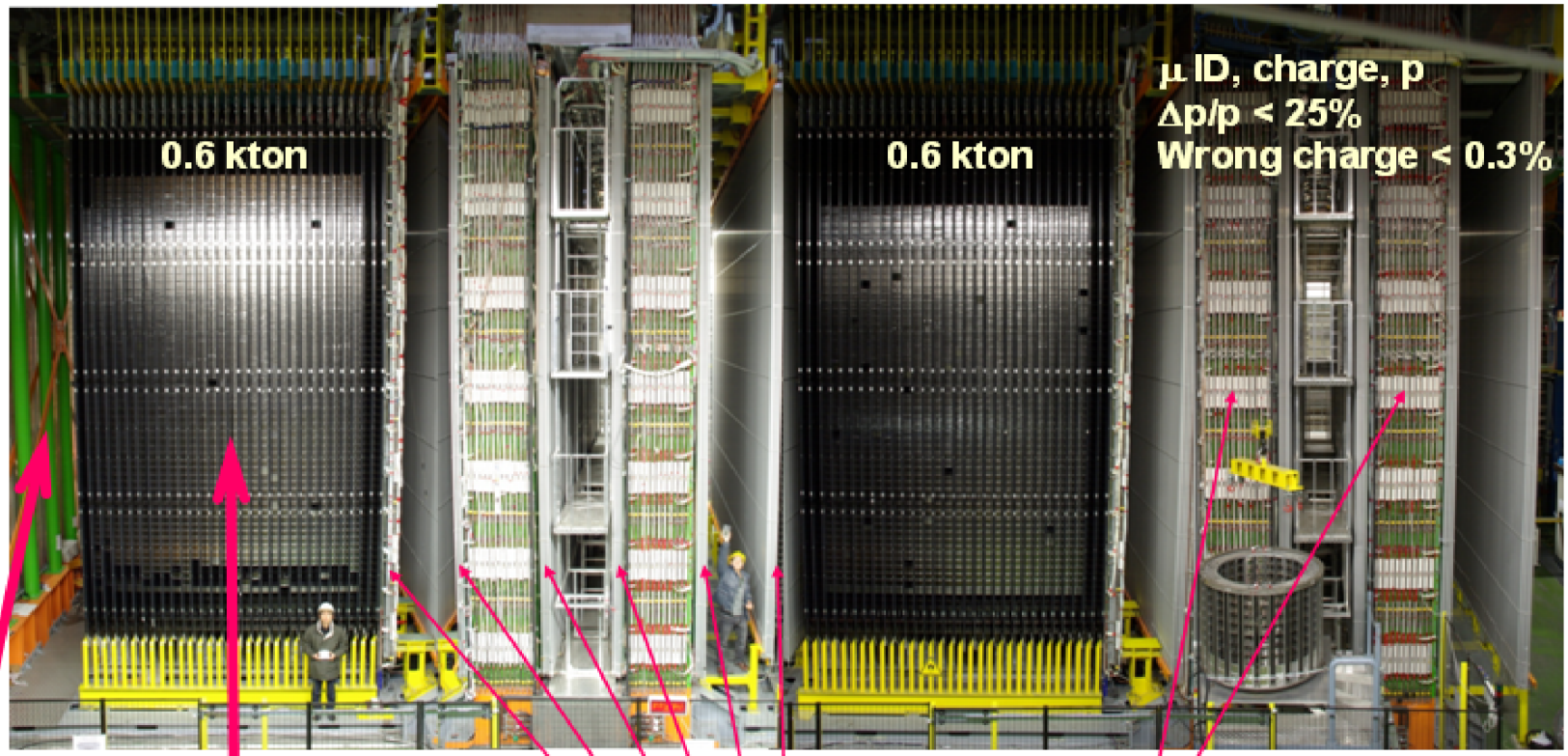


2 emulsion layers (44 μm thick) poured on a 200 μm plastic base

The OPERA target

Number of bricks:	~150'000
Total mass:	~1.2 kton
Total film surface:	~111'000 m²

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

High precision tracker
- 6 4-fold layers of drift tubes

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

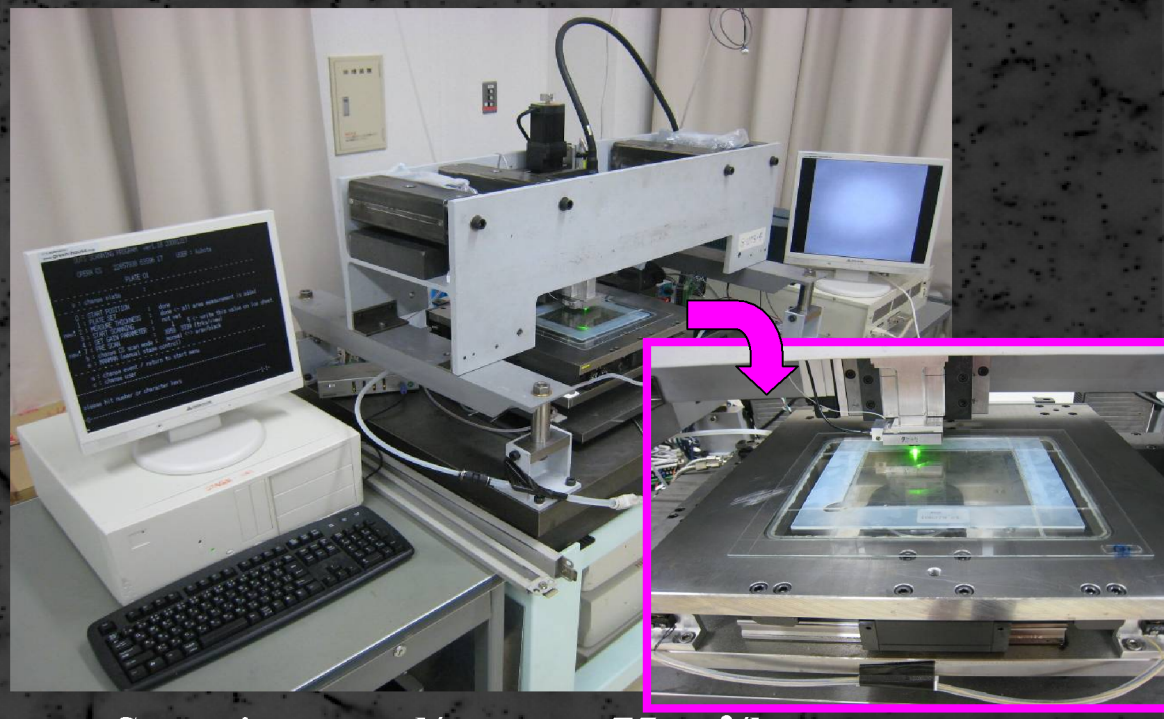
Muon spectrometer $(8\times10\ m^2)$

Emulsion scanning stations

EU: ESS (European Scanning System)

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

Japan: S-UTS (Super Ultra Track Selector)



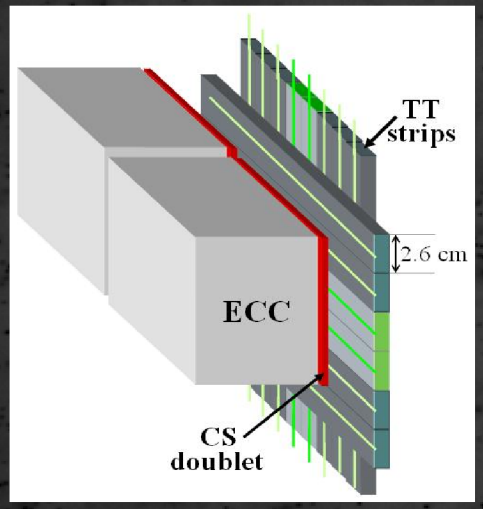
- Scanning speed/system: 75cm^2/h
- High speed CCD camera (3 kHz), Piezo-controlled objective lens
- FPGA Hard-coded algorithms

Both systems demonstrate:

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

Analysis in the 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:
~15 mrad