Latest results of OPERA

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On behalf of the OPERA collaboration

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OPERA collaboration

IIHE ULB
Bruxelles

IRB Zagreb

Bari
Bologna
LNF Frascati
L'Aquila
LNGS
Napoli
Padova
Roma
Salerno

LAPP Annecy
IPHC Strasbourg

OPERA is an international collaboration made of ~ 140 physicists from 28 institutions and 11 countries.

Aichi
Toho
Kobe
Nagoya
Utsunomiya

Hamburg

Jinju

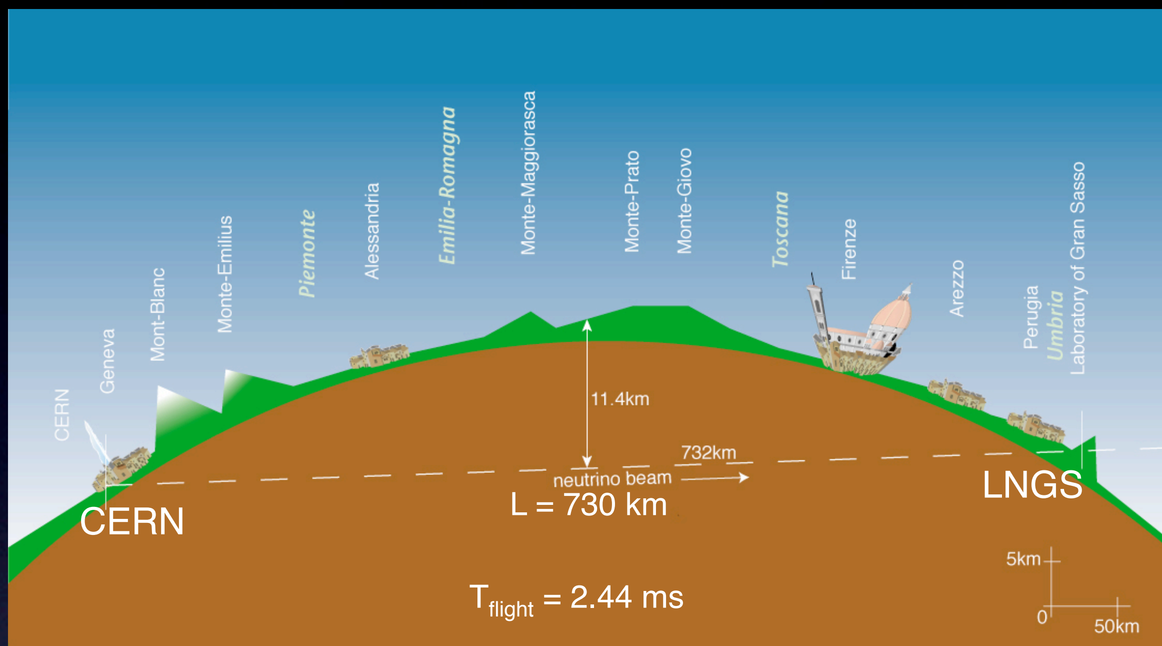
Technion Haifa

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

Bern

METU Ankara

OPERA experiment

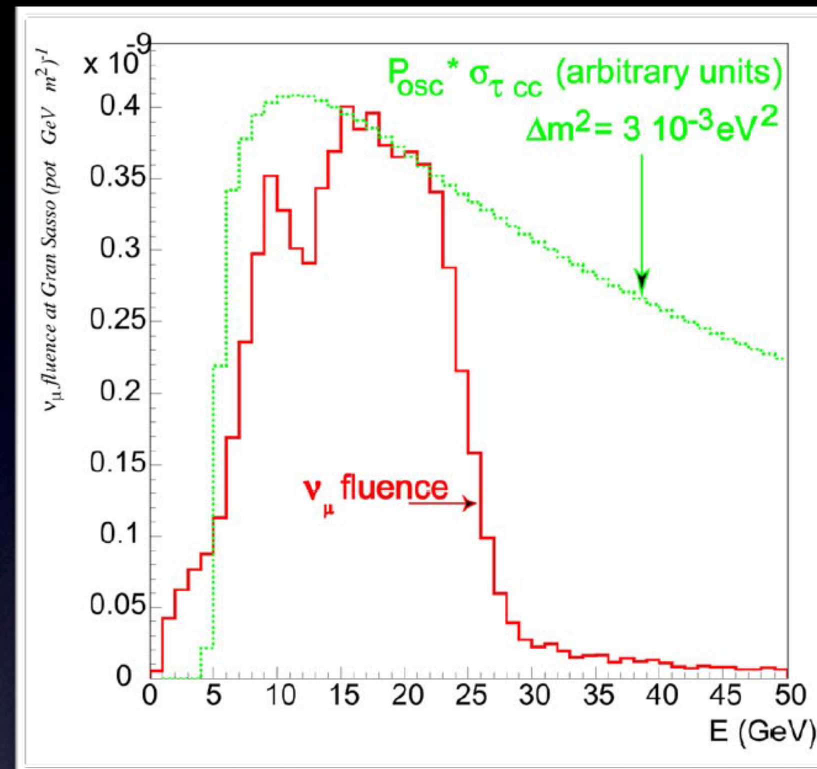


LNGS underground laboratory

- OPERA (Oscillation Project with Emulsion tRacking Apparatus) is a long baseline neutrino oscillation experiment.
- The "conventional" CNGS (CERN Neutrinos to Gran Sasso) neutrino beam is produced at CERN and measured by the OPERA detector at the LNGS laboratory, at a distance of 730 km.
- The goal of the experiment, using an almost pure ν_μ beam, is the measurement for the first time of the $\nu_\mu \rightarrow \nu_\tau$ **transition detecting the τ lepton** created in Charged Current (CC) interactions (**neutrino oscillation in an appearance mode**).

CNGS beam

- The beam is optimized for ν_τ appearance in the atmospheric oscillation region i.e. $\Delta m_{23}^2 \approx 2.4\times10^{-3}$ eV^2 and $\sin^2 2\theta_{23} \approx 1.0$ (as measured by SK, K2K and MINOS).

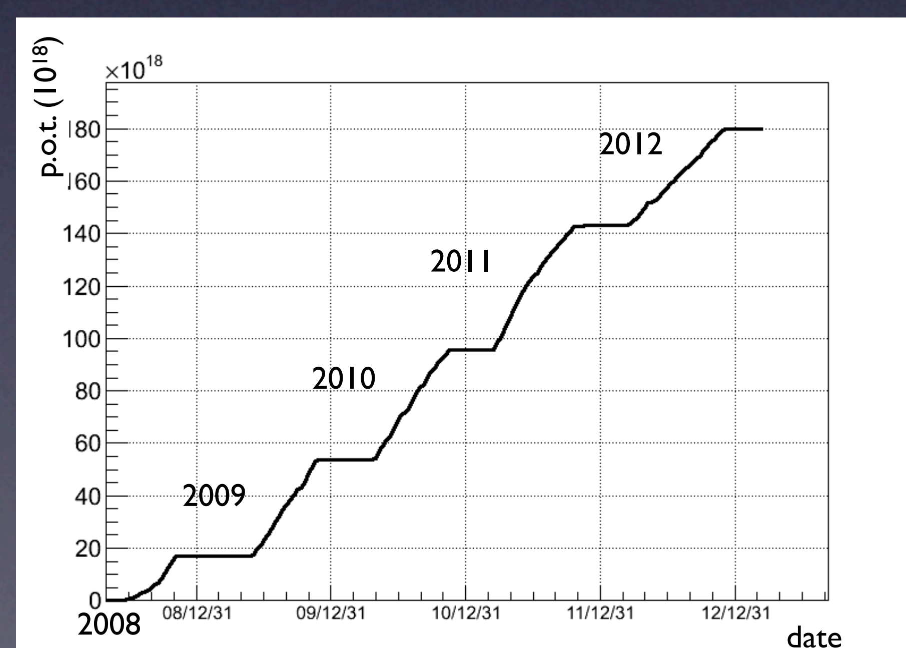


Beam parameters

<$E_{\nu\mu}$>	17 GeV
$(\nu_e+\overline{\nu}_e)/\nu_\mu$	0.87%
$\overline{\nu}_\mu/\nu_\mu$	2.1%
ν_τ prompt	negligible
nominal p.o.t./year	4.5x10^{19}
ν_μ CC/kton/year	~2900
ν_τ CC/kton/year	~18.5

Contaminations given in terms of interactions in the OPERA detector

- Best performance obtained in 2011.
- Overall p.o.t. 20% less than the proposal value (22.5 x 10^{19}).

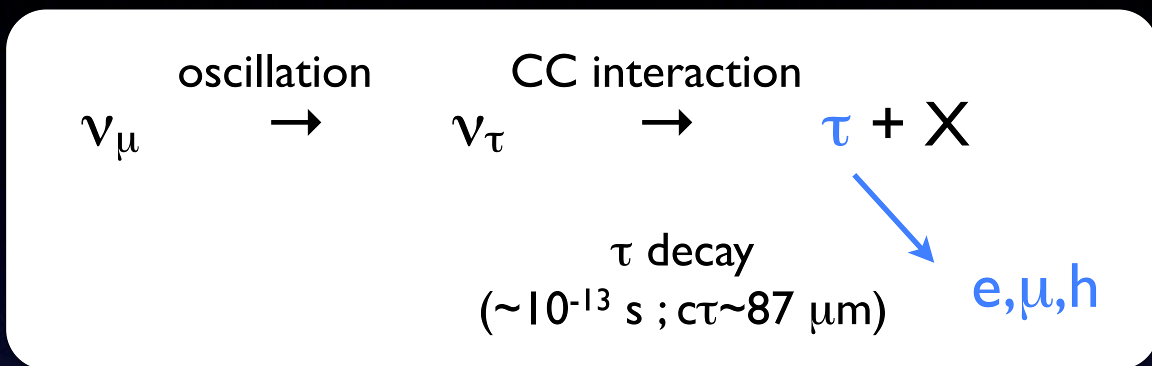


Beam performance

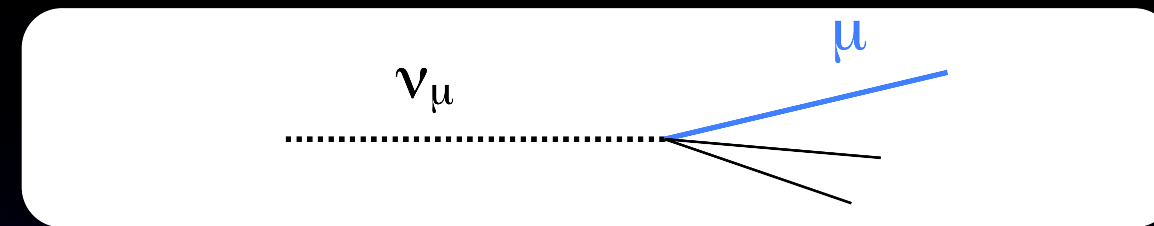
Year	Beam days	p.o.t (10^{19})
2008	123	1.74
2009	155	3.53
2010	187	4.09
2011	243	4.75
2012	257	3.86
Total	**965**	**17.97**

Detection principle

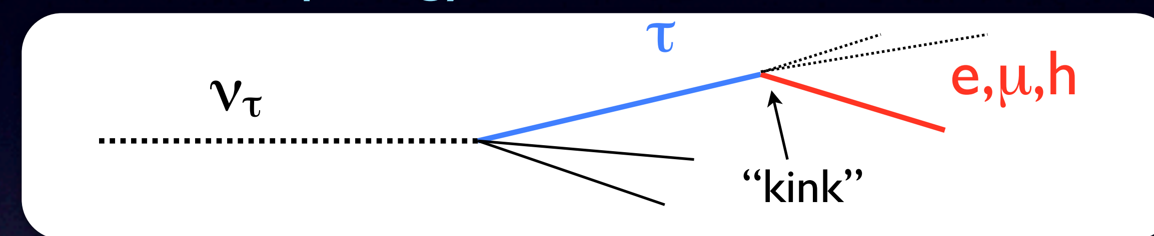
Physics process



Topology: ν_μ CC interaction



Topology: ν_τ CC interaction



- The detection of the τ lepton requires an identification of the "kink".
- The detector must fulfil the following requests:

1. Large mass due to small CC cross section (lead target).
2. Micrometric resolution to observe the kink (photographic emulsions).
3. Select neutrino interactions (electronic detectors).
4. Identify muons to reduce charm background (electronic detectors).

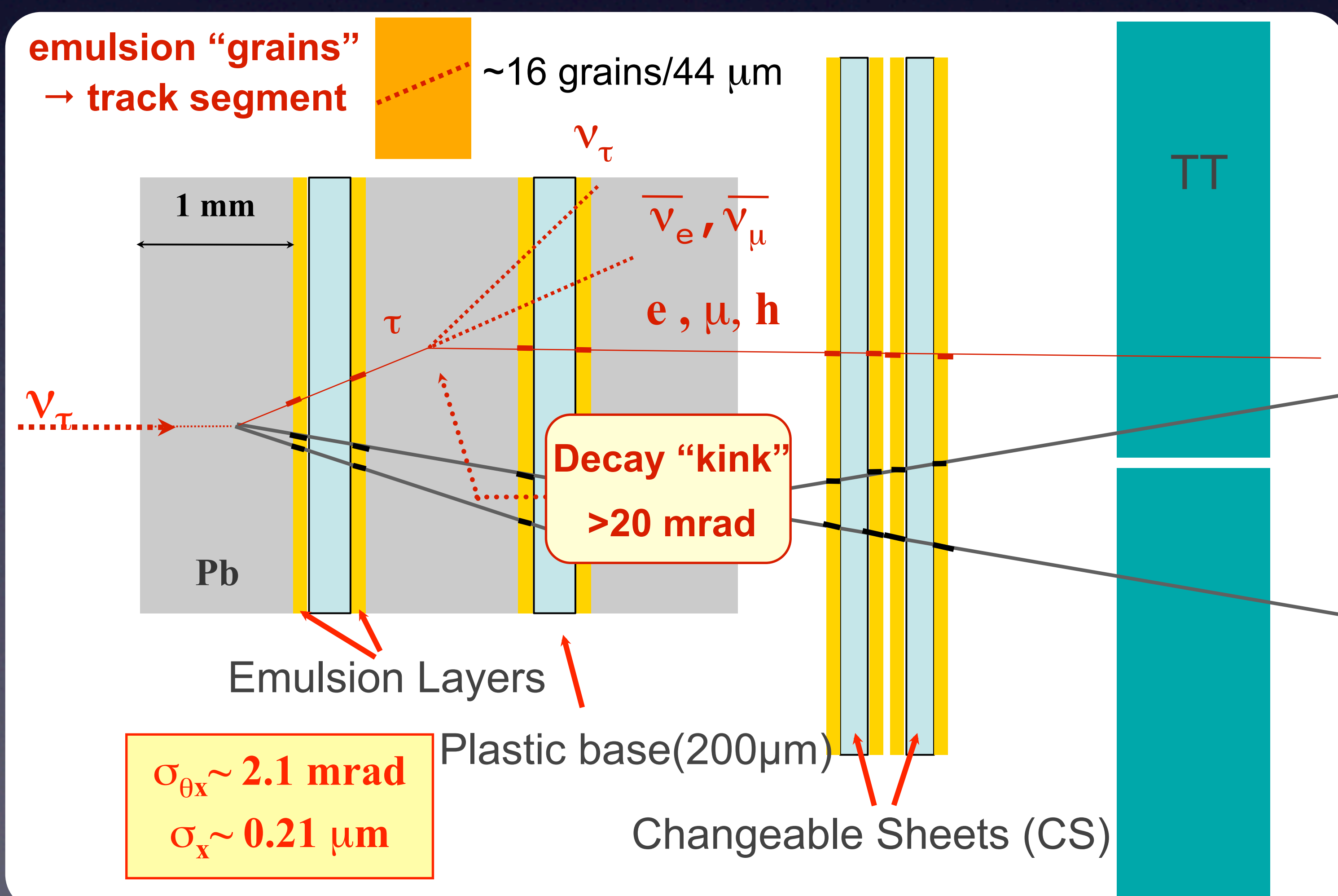
↓

OPERA: hybrid detector (emulsions + electronic detectors)

τ identification

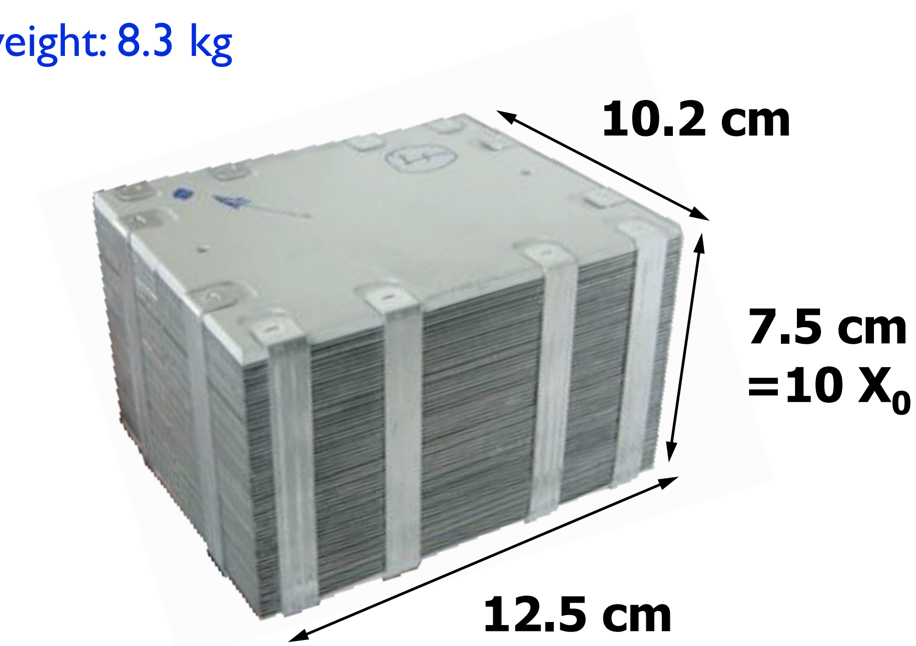
- The identification is done in the lead-emulsion target, which is divided in structures called “bricks”.
- The high granularity (300 hits/mm) of emulsions allows for an unambiguous measurement of the kink.

Lead-emulsion layers in brick



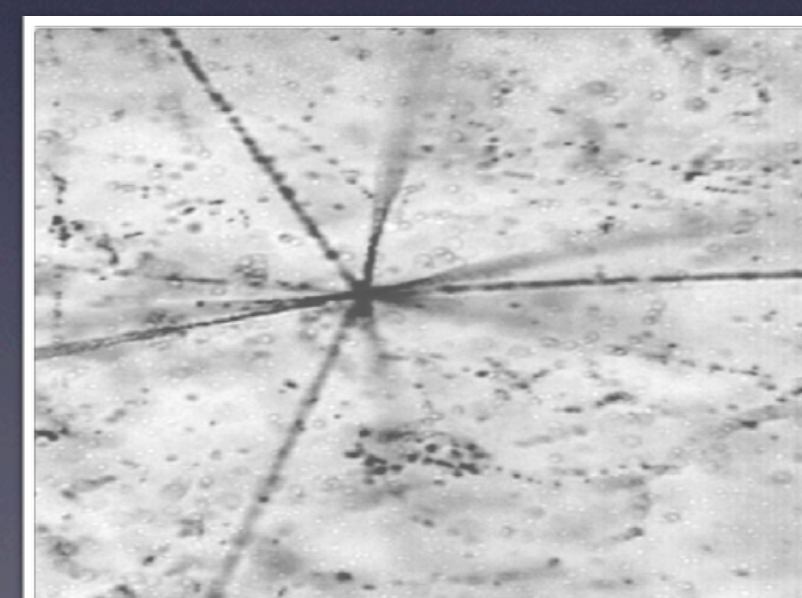
Brick structure

Brick weight: 8.3 kg



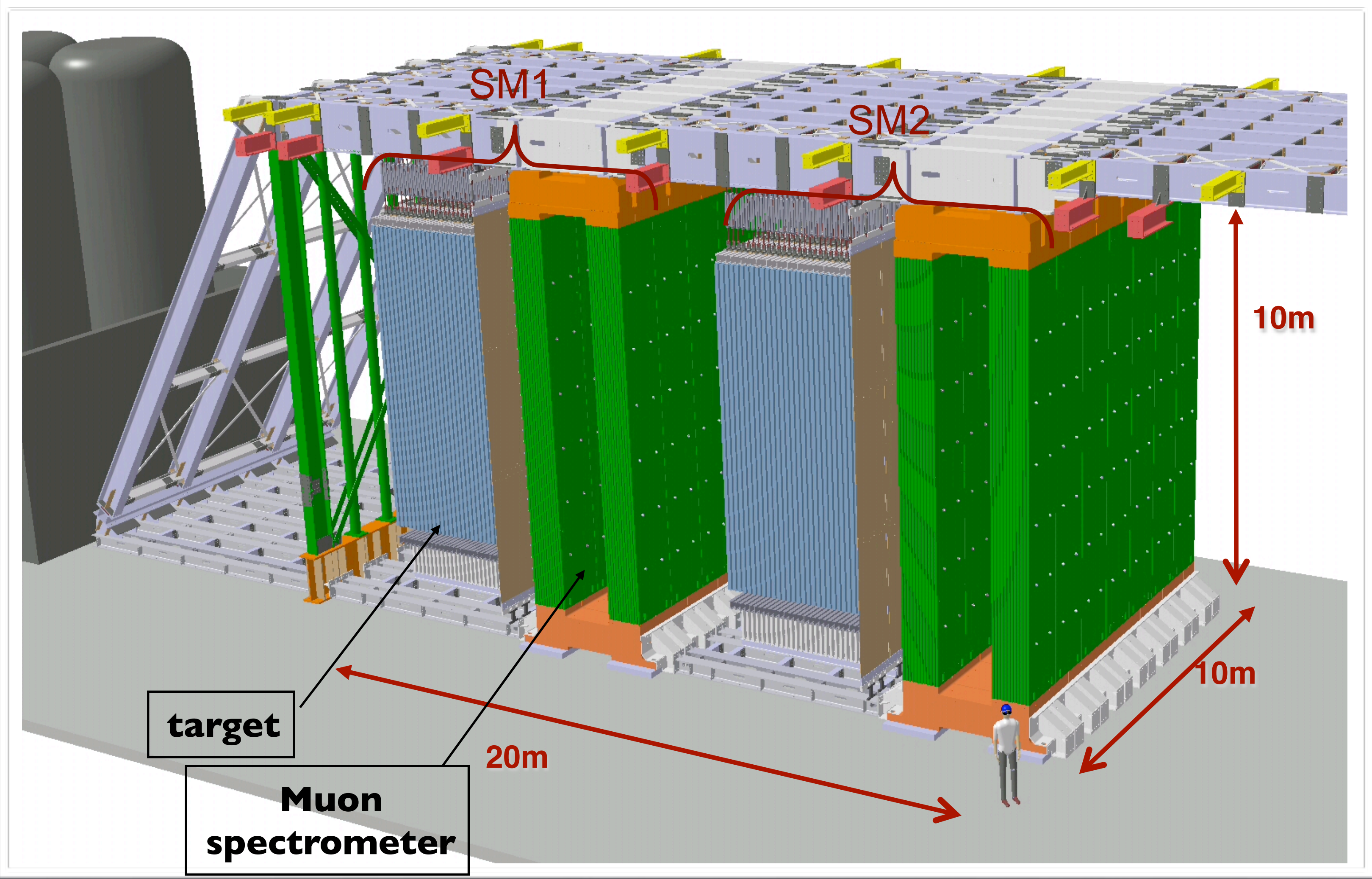
Sandwich of 56 (1mm) Pb sheets
+ 57 FUJI films (base + 2 emulsion layers)
+ 2 changeable sheets

Event reconstruction in emulsions

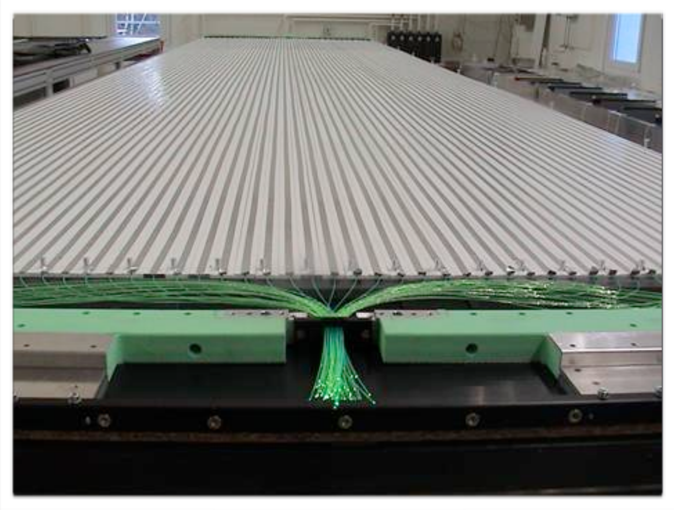


The OPERA detector

Detector design



- The total target mass is 1.25 kton (about 150000 bricks).
- Each target consists of 27 lead-emulsion brick walls alternated with scintillator planes (Target Tracker) used mainly for the identification of the brick to be extracted.
- The TT is made of plastic scintillator + wave length shifting fiber + 64 channel multi-anode Hamamatsu PM.
- At least 5 p.e. are detected for a mip with a detection efficiency of ~ 99%.



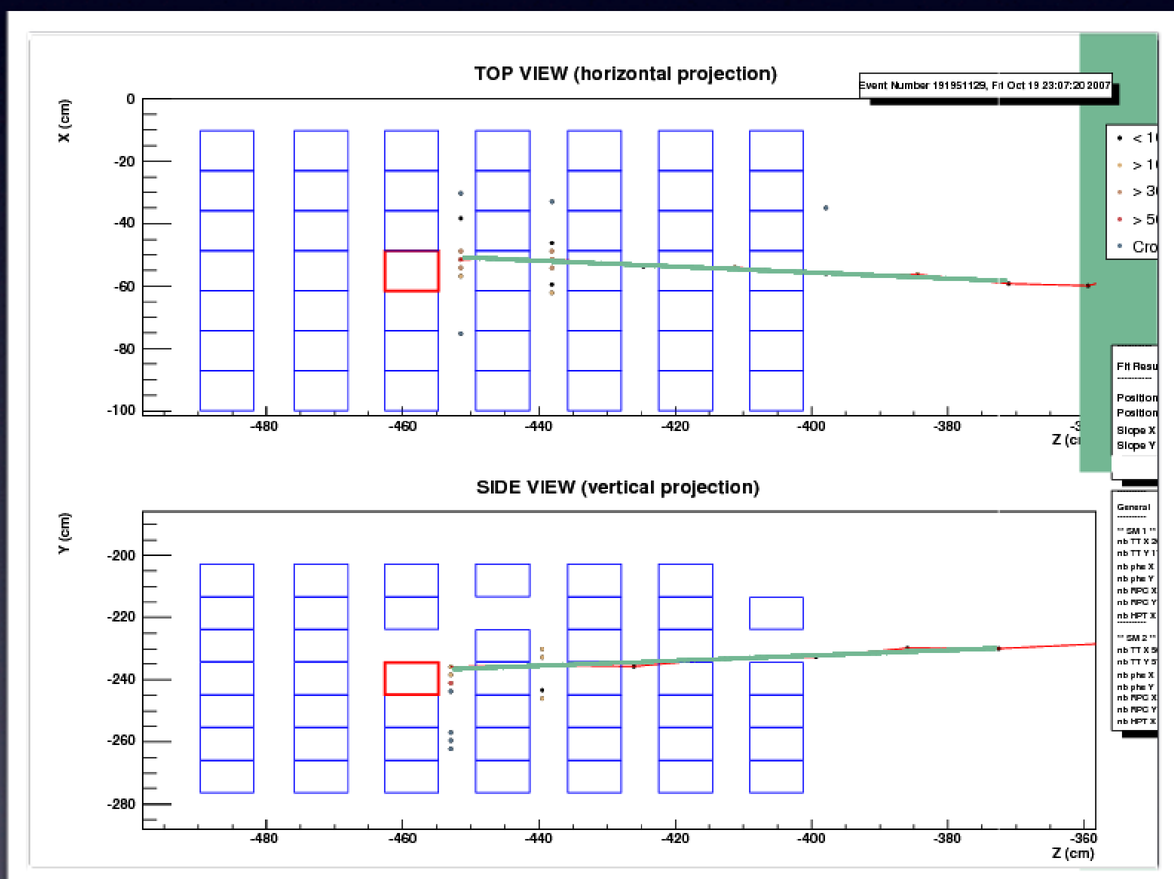
- Each spectrometer consists of 22 RPC planes in magnetic field (1.5 T) and 6 Drift Tubes planes, to identify muons and measure charge and momentum, in order to reduce charm background.

$\Delta p/p$ (<50 GeV/c)	~ 20%
μ ID (with TT)	~ 95%

OPERA working chain

1. Trigger on event "on time" with CNGS and selection of the brick using electronic detectors information (brick finding algorithm).

Brick selection



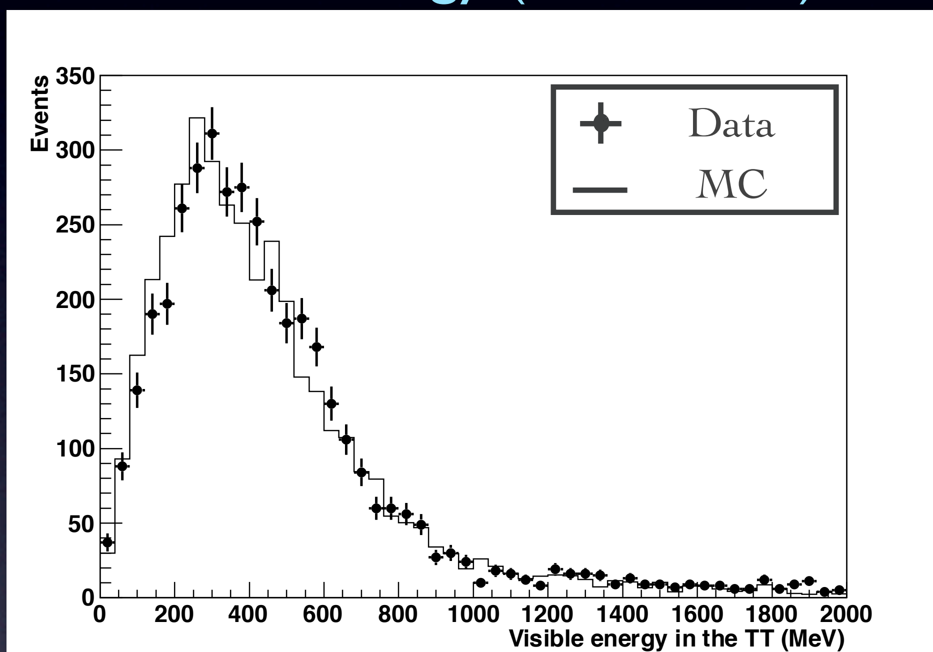
2. Brick removed by BMS (Brick Manipulating System).
3. The CS are developed and tracks validating the corresponding brick are searched for.
4. If a track matching the TT reconstruction is found in the CS, the brick is exposed to cosmic rays for sheets alignment.
5. The brick is disassembled and the emulsion films are developed and sent to scanning labs.

Up to 50 bricks can be extracted each day.

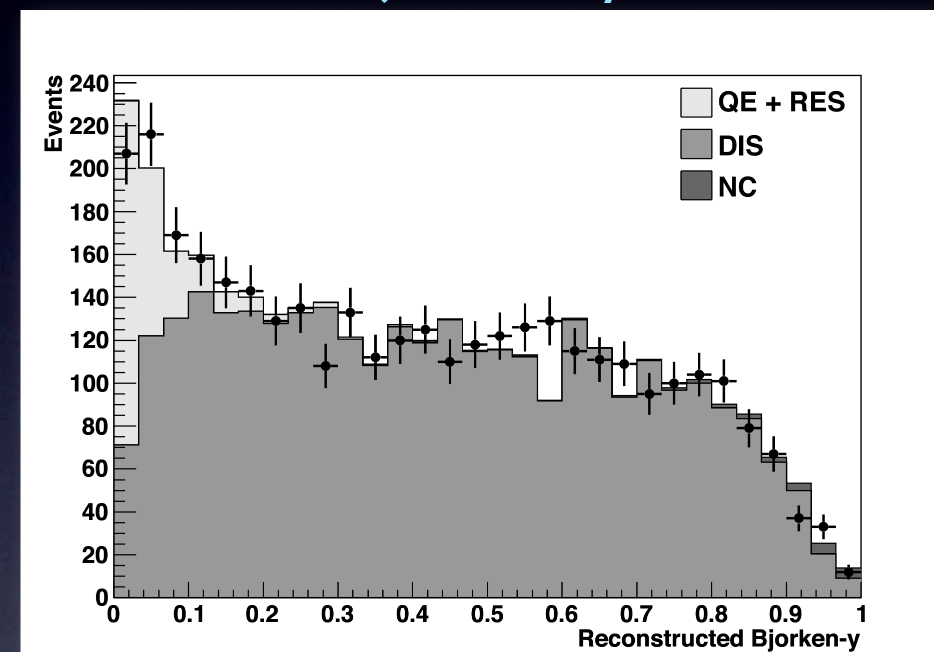
ED Data / MC comparison

- The electronic detectors (ED) simulation has been benchmarked against the large available data, showing a rather good agreement (*New J.Phys. 13 (2011) 053051*).

Visible energy (CC events)



Bjorken - y



Muon charge ratio

	μ^+/μ^-
Data	(3.92 ± 0.37) %
MC	(3.63 ± 0.13)%

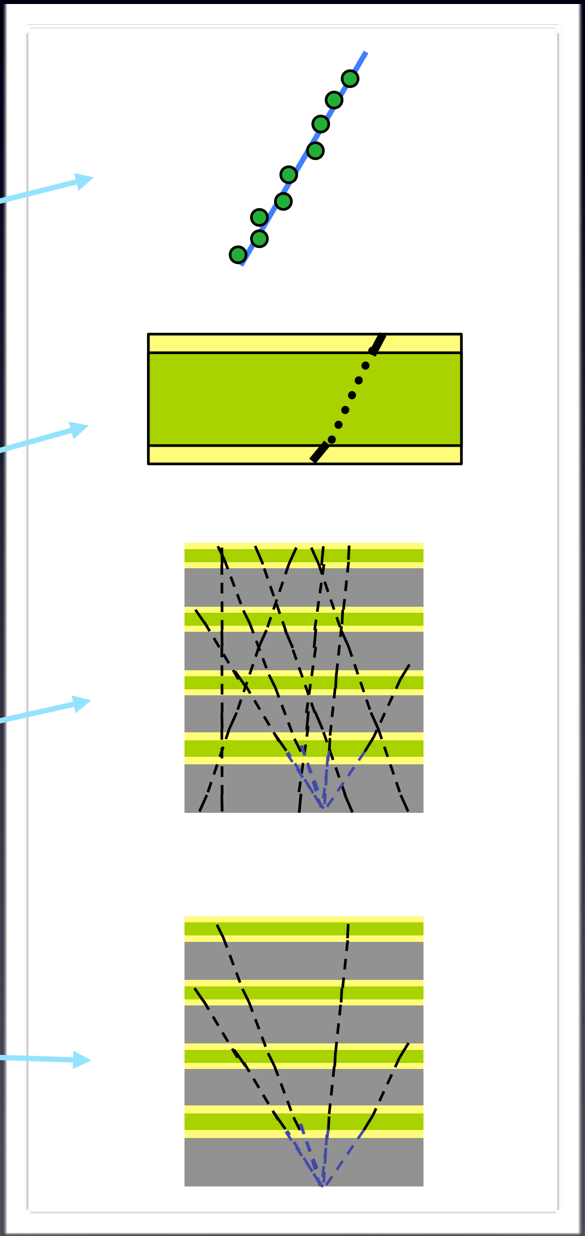
NC/CC ratio

	NC/CC
Data	0.228 ± 0.008
MC	0.257 ± 0.031

Scanning

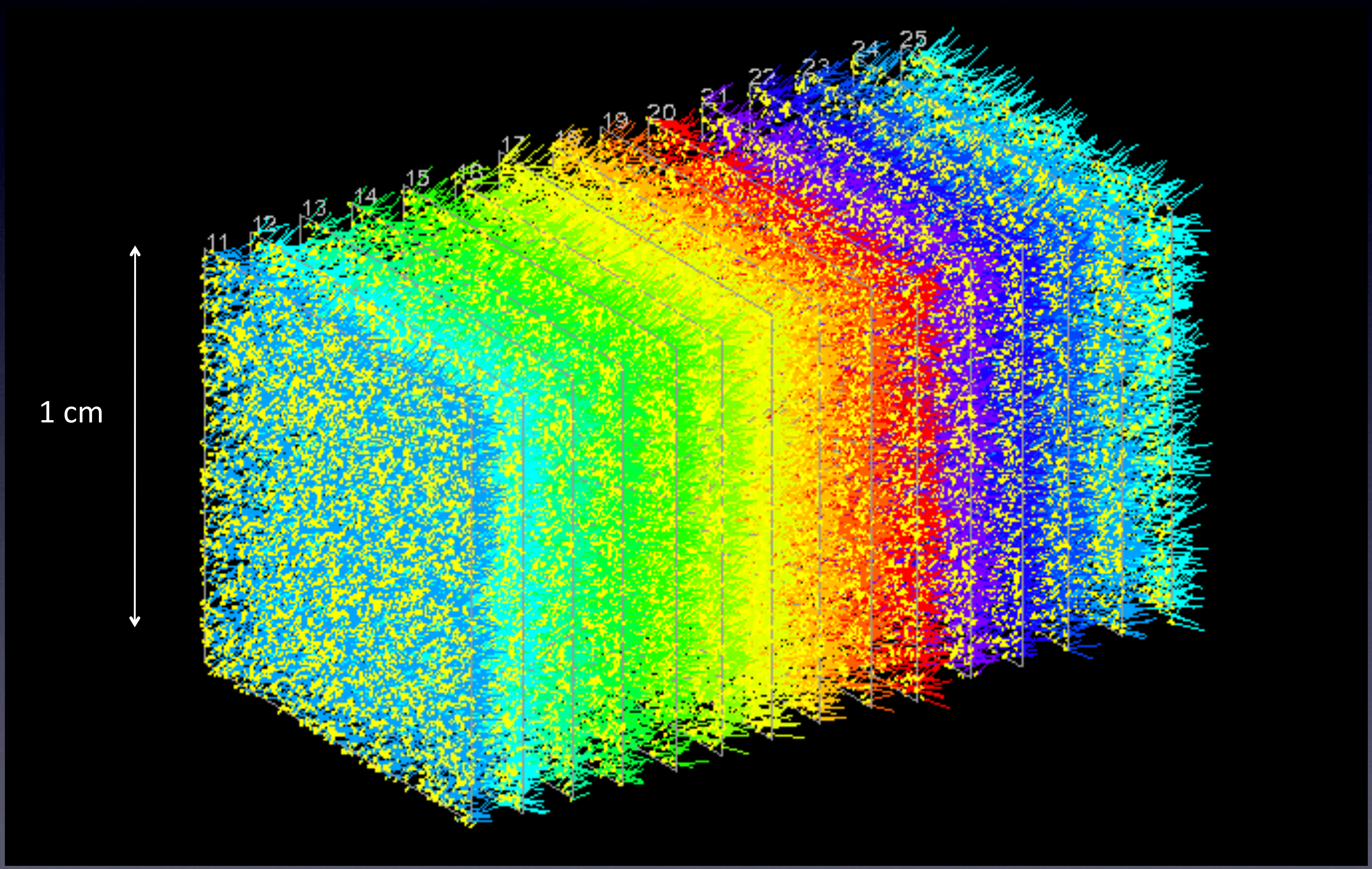
- The goal of scanning is to reconstruct the interaction vertex, measure particles momentum via multiple scattering and identify possible kinks.
- The scanning speed by automatic microscopes is about 20 cm^2/h.
- The procedure is the following:

1. Reconstruct microtracks (16 tomographic images in each emulsion layer).
2. Align microtracks through the plastic base and reconstruct basetracks.
3. Connect basetracks from several emulsions.
4. Reconstruct vertex and possible decay kinks.



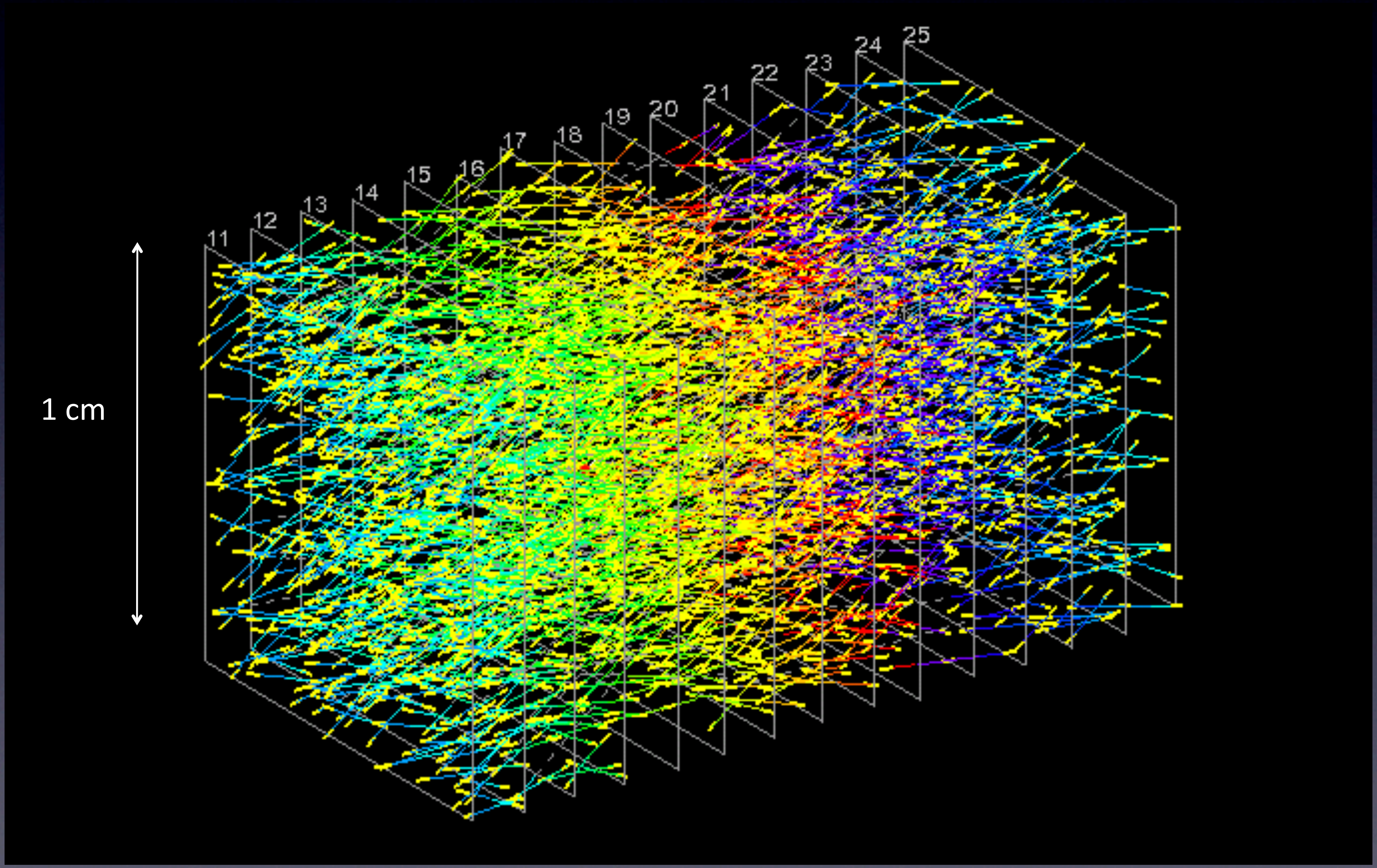
Vertex location

- Volume scan (about 2 cm^3) around the tracks stopping point.



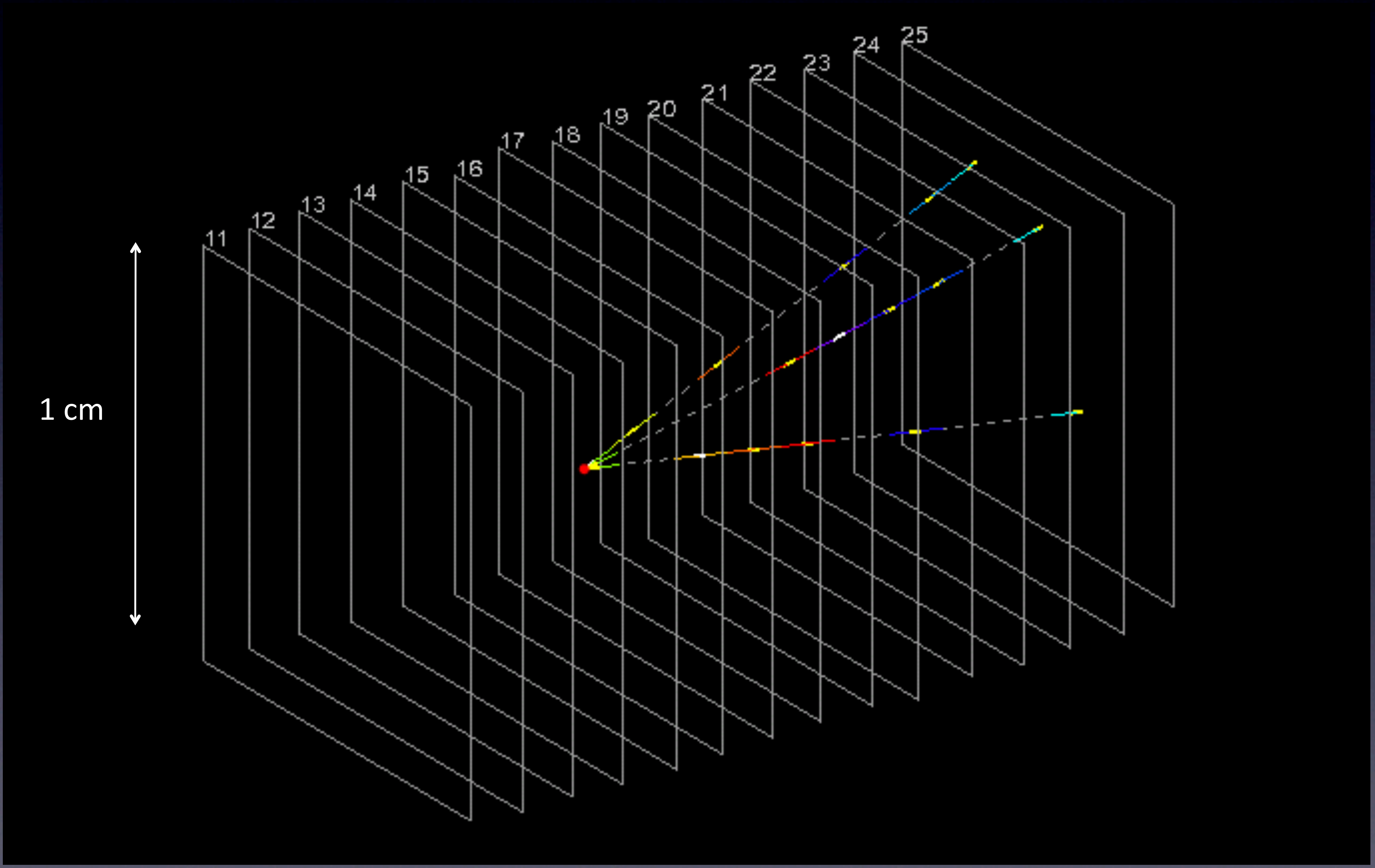
Vertex location

- Film to film connection.



Vertex location

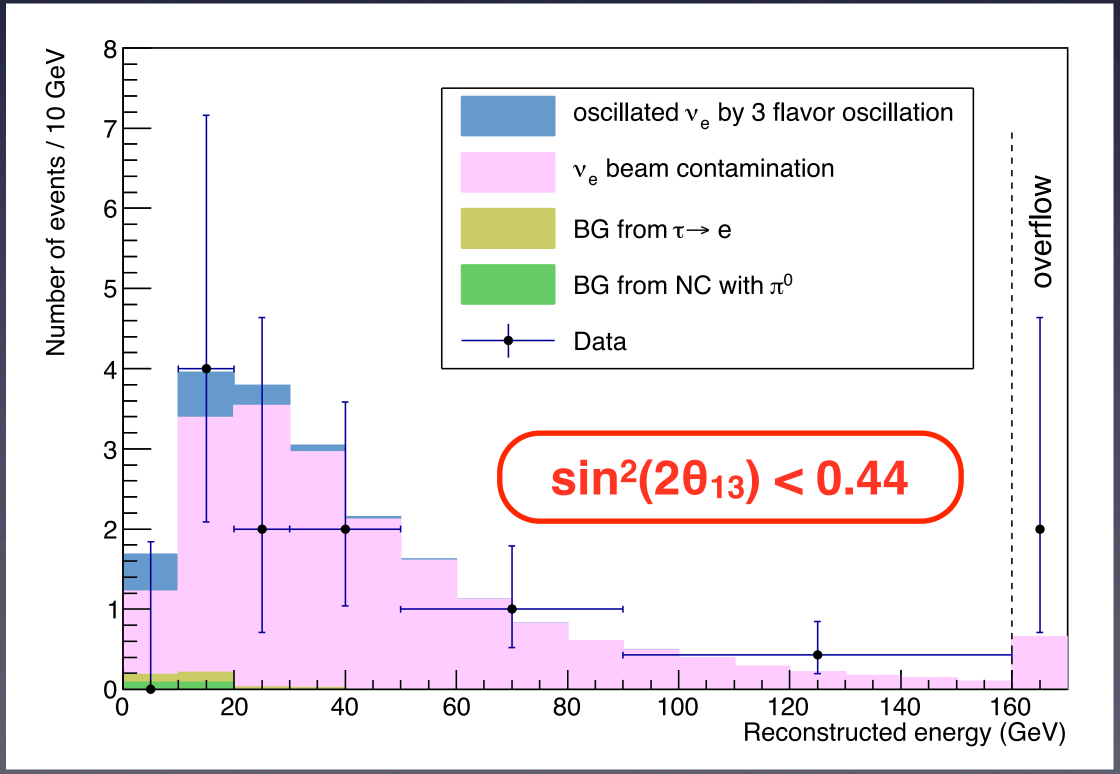
- Converging tracks (in agreement with the CS).



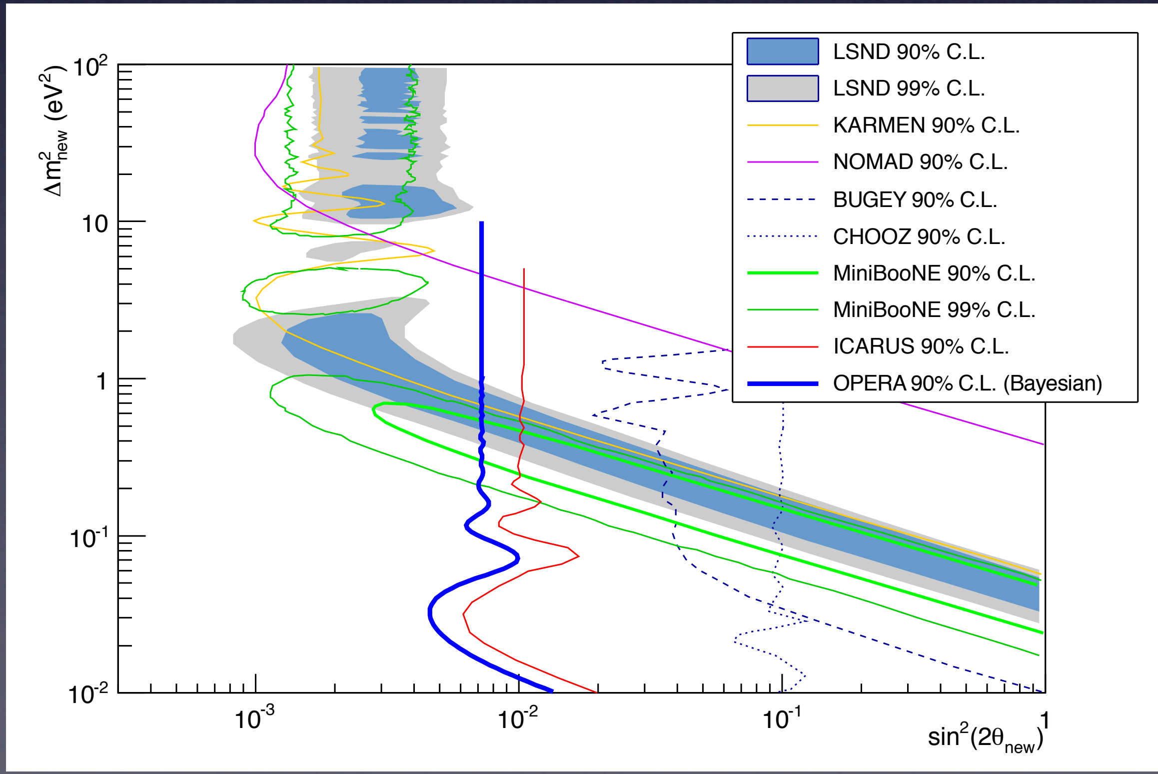
$\nu_\mu \rightarrow \nu_e$ Analysis

- In the 2008 and 2009 runs a dedicated ν_e search was performed.
- Out of 505 neutrino events without muon 19 candidates were found.
- In the standard 3 flavour scenario, the observation is compatible with a background-only hypothesis.
- A specific analysis for non-standard oscillation at large Δm^2 resulted in a competitive limit (*arXiv:1303.3953* submitted to JHEP).

Standard scenario



Non-standard oscillations



$\nu_\mu \rightarrow \nu_\tau$ Analysis

- In the 2008 and 2009 runs analysis a conservative approach was used to get confidence on the detector performance: no kinematical cuts and a slow analysis speed with a signal/noise ratio not optimized.

- For the 2010 - 2012 runs kinematical selections were applied:

1. Muon momentum of less than 15 GeV.

2. Most probable brick analyzed for all events before moving to the other ones to optimize the ratio between efficiency and analysis time.

3. Anticipation of the analysis of 0μ events (NC like ones with no muon detected)

- For results in the 2012 summer conferences the following runs were analyzed: all samples for 2010 run, 0μ sample for 2011 run and run 2012 not analyzed.

- Now the remaining samples are being analyzed (about 60% of the events have been analyzed so far).

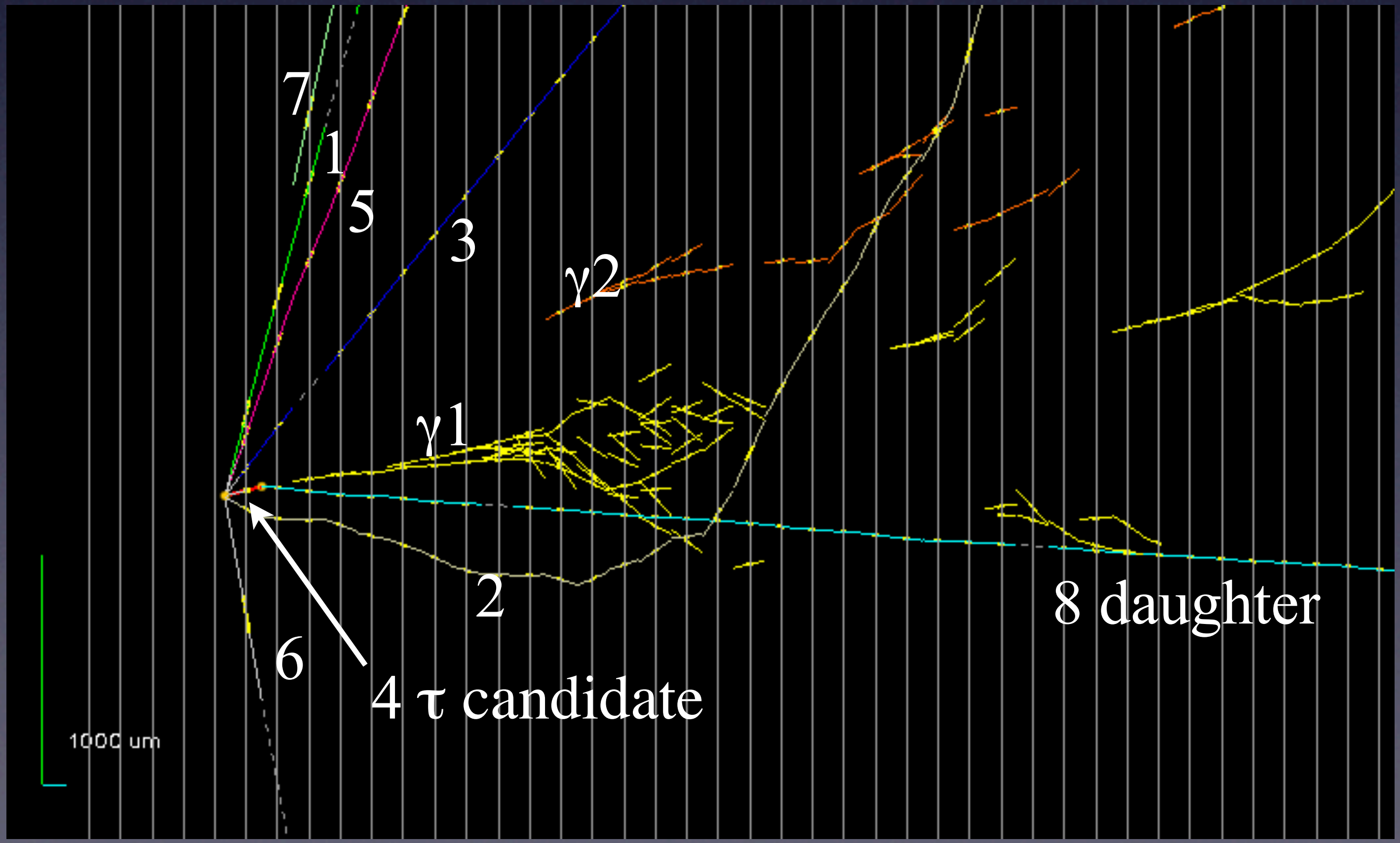
So far 3 candidates have been observed

First candidate

- In the decay search of 2008 and 2009 data we found a ν_τ candidate (*Phys. Lett. B 691 (2010) 138*).
- The event passes all selection criteria for the signal and it is classified as a possible decay of a τ into 1 prong hadron.
- The decay mode is compatible with $\tau \rightarrow \rho\ (\pi^-\pi^0)\ \nu_\tau$ which has a branching ratio of 25%.

Kinematical variables

Variable	Observed	Cut
Kink angle (mrad)	41 ± 2	>20
Decay length (μm)	1335 ± 35	< 2 lead plates
P daughter (GeV/c)	12^{+6}_{-3}	>2
Daughter Pt (MeV/c)	470^{+230}_{-120}	>300
Missing Pt (MeV/c)	570^{+320}_{-170}	<1000
Φ angle (deg)	173 ± 2	>90

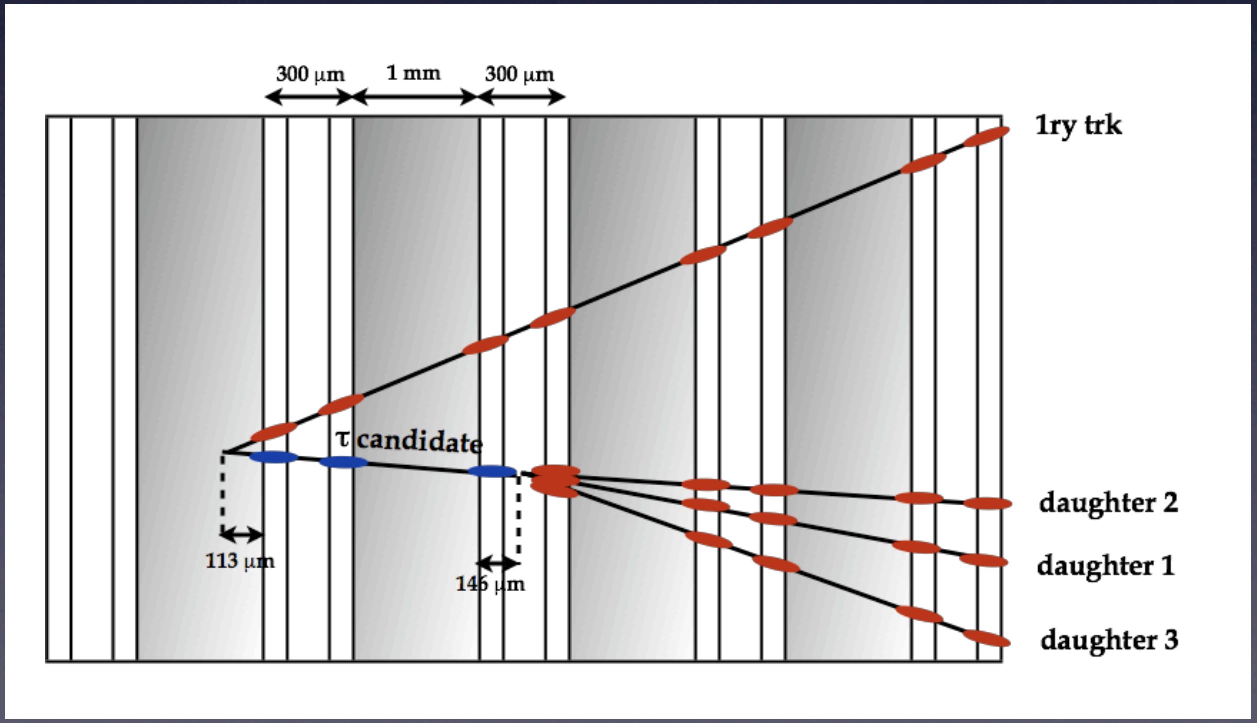


Second candidate

- In the decay search of 2011 data we found a second ν_τ candidate.
- The event passes all selection criteria for the signal and it is classified as a possible decay of a τ into 3 prong hadrons (branching ratio of 15%).
- The decay point is in the plastic base and no nuclear fragment is observed.

Kinematical variables

Variable	Observed	Cut
Kink angle (mrad)	87.4 ± 1.5	>20 & <500
Decay length (μm)	1540	< 2 lead plates
P daughter (GeV/c)	8.4 ± 1.7	>3
Min. invariant mass (MeV/c^2)	960 ± 130	>500 & <2000
Invariant mass(MeV/c^2)	800 ± 120	>500 & <2000
Missing Pt (MeV/c)	310 ± 110	<1000
Φ angle (deg)	167.8 ± 1.1	>90

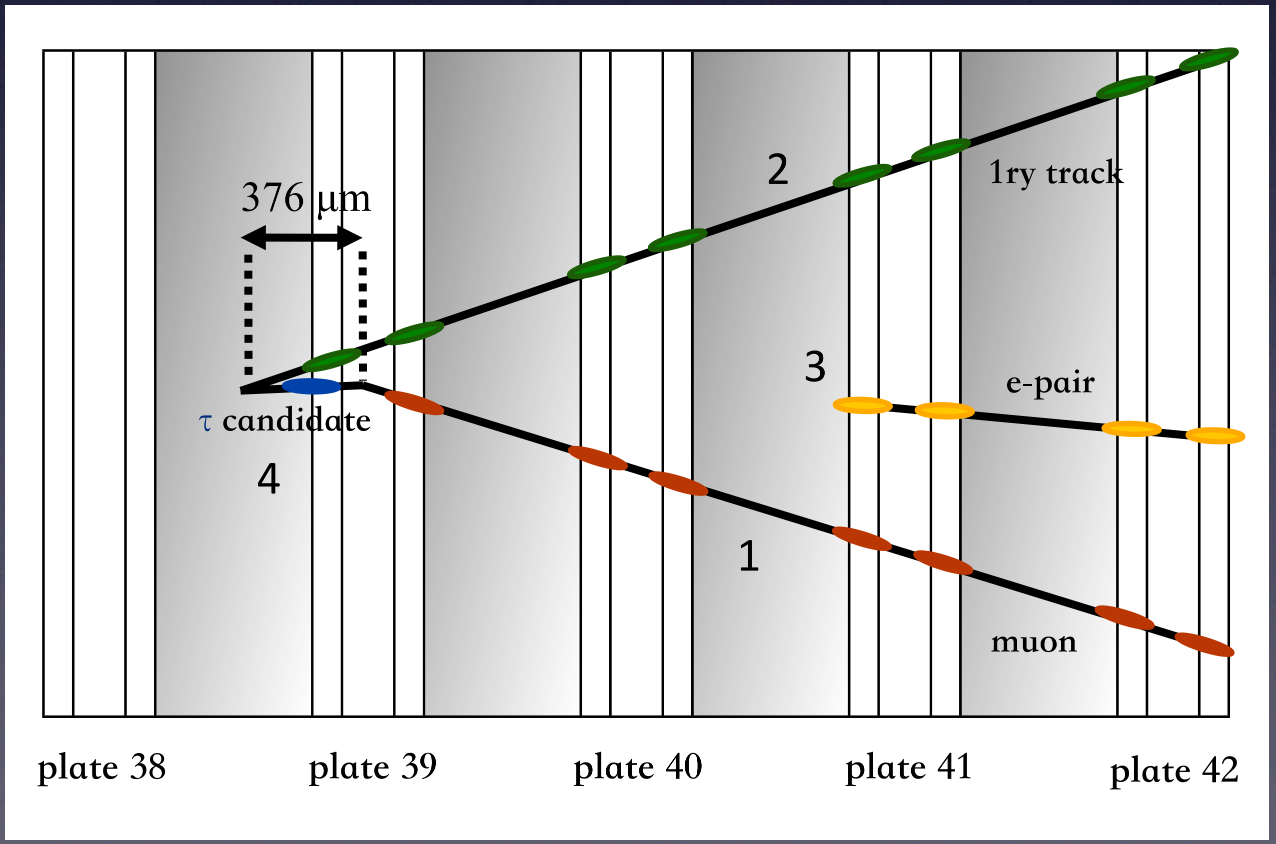


Third candidate

- In the decay search of 2012 data we found a third ν_τ candidate.
- The event passes all selection criteria for the signal and it is classified as a possible decay of a τ into μ (branching ratio of 17.7%).
- The γ attachment to the decay vertex is excluded.
- The momentum/range correlation is inconsistent with track 2 being a muon, and the muon (track 1) charge is negative at 5.6 sigmas.

Kinematical variables

Variable	Observed	Cut
Kink angle (mrad)	245 ± 5	>20 & <500
Decay length (μm)	376 ± 10	< 2 lead plates
P μ (GeV/c)	2.8 ± 0.2	<15
Daughter Pt (MeV/c)	690 ± 50	>250
Φ angle (deg)	154.5 ± 1.5	>90



Significance

- The expected number of events for the scanned statistics is:

Decay channel	Signal	Background			
		All	Charm	μ scattering	Hadronic interaction
$\tau \rightarrow h$	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	0.0084	0.018	
$\tau \rightarrow e$	0.49	0.065	0.065		
All	**2.32**	**0.226**	**0.19**	**0.018**	**0.019**

- 3 observed events in the $\tau \rightarrow h$, $\tau \rightarrow 3h$ and $\tau \rightarrow \mu$ channels.
- The probability to be a background fluctuation is 7.29×10^{-4}.
- This corresponds to a **3.2 σ significance** of non-null observation.

Conclusions

- The OPERA detector has been taking physics data successfully for 5 years (2008 - 2012).
- The detector is still running for cosmic muons data taking.
- In the analyzed data **three τ candidates have been observed**.
- Background studies showed good agreement between data and MC.
- A significance of 3.2 σ of non-null observation has been obtained (simple counting method).
- A significance of 4 σ is within reach.