Latest results of OPERA

A.Meregaglia - IN2P3/CNRS - IPHC Strasbourg
On behalf of the OPERA collaboration

11th June 2016 - Capri

OPERA collaboration

IIHE ULB
Bruxelles

IRB Zagreb

Bari
Bologna
LNF Frascati
LNGS
Napoli
Padova
Roma
Salerno

LAPP Annecy
IPHC Strasbourg

OPERA is an international collaboration made of ~ 140 physicists from 26 institutions and 11 countries.

Aichi
Toho
Kobe
Nagoya
Nihon

Hamburg

Jinju

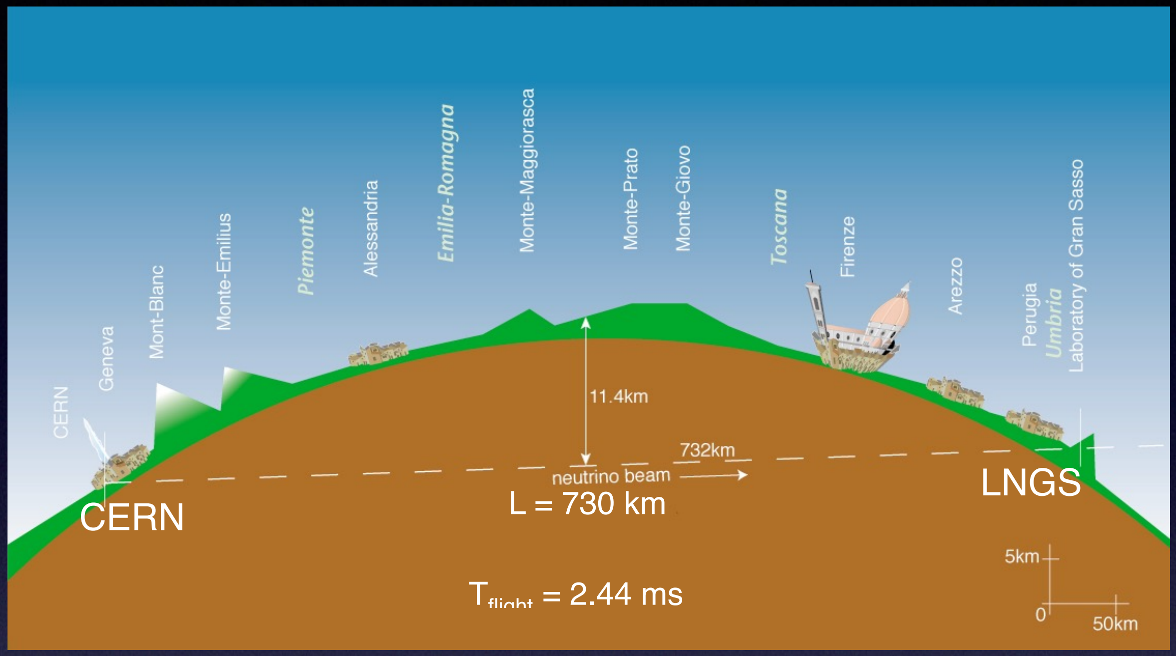
Technion Haifa

INR RAS Moscow
LPI RAS Moscow
SINP MSU Moscow
JINR Dubna

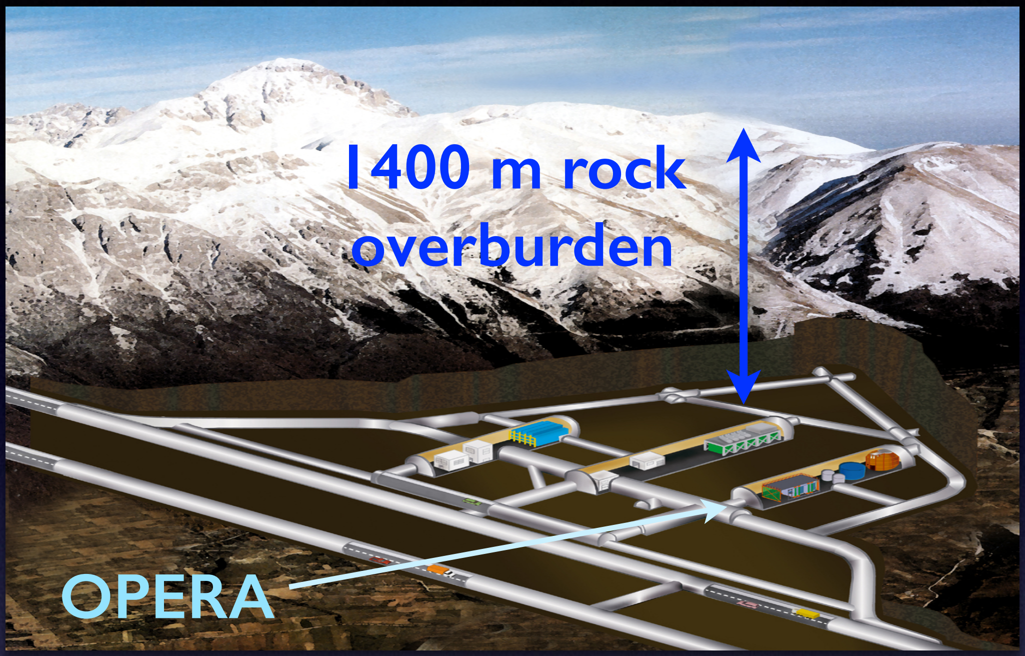
Bern

METU Ankara

OPERA experiment



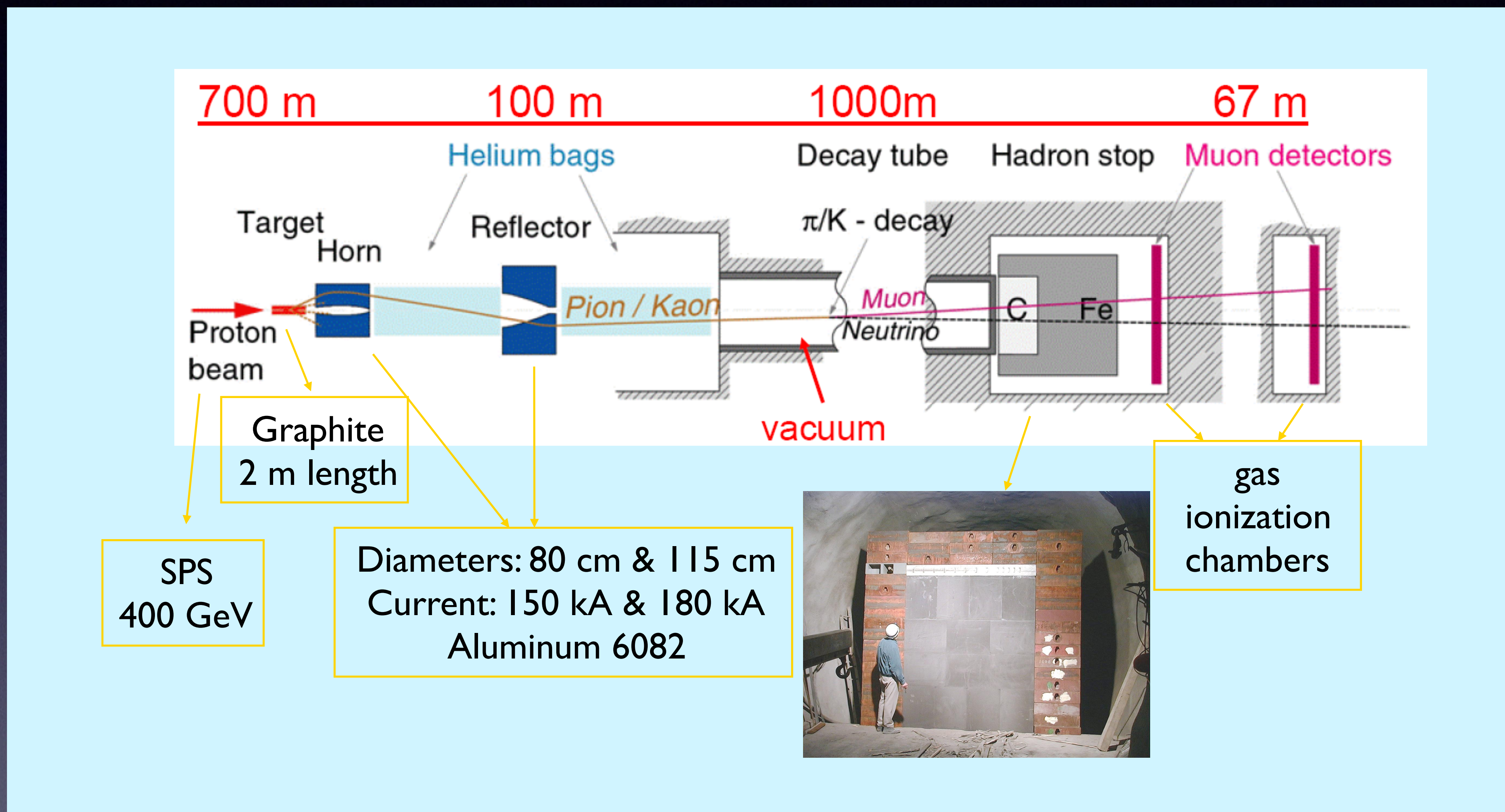
LNGS underground laboratory



- OPERA (Oscillation Project with Emulsion tRacking Apparatus) is a long baseline neutrino oscillation experiment which took data from 2008 till 2012.
- The "conventional" CNGS (CERN Neutrinos to Gran Sasso) neutrino beam was produced at CERN and reached 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 (1)

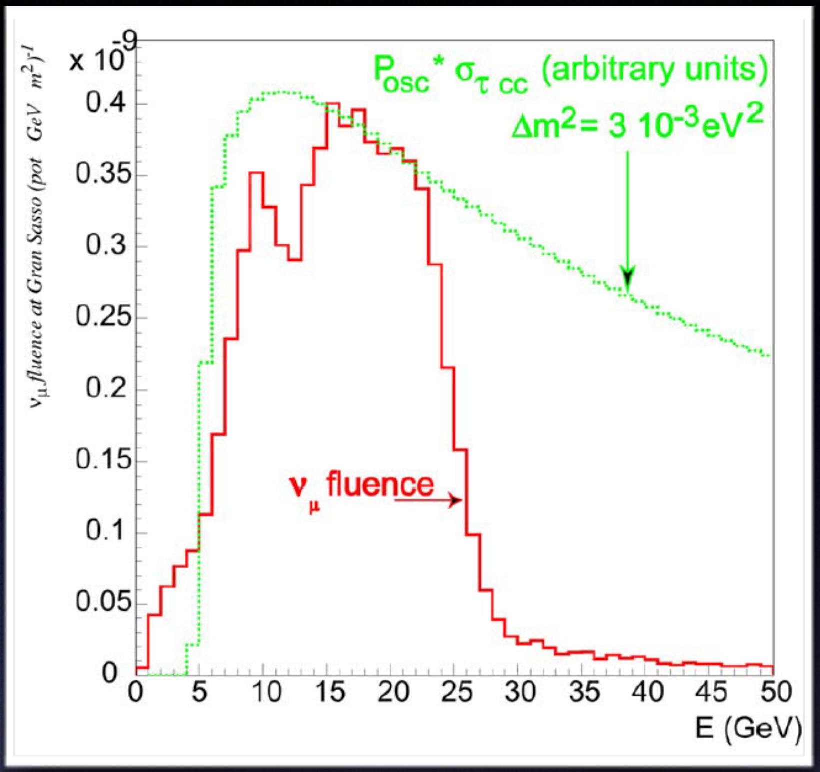
- The CNGS was a conventional neutrino beam: 400 GeV/c protons from the CERN SPS hit a graphite target producing pions and kaons which decayed in flight and produced neutrinos.



- 2 extractions separated by **50 ms**
- Pulse length: **10.5 μs**
- Beam nominal intensity: **2.4×10^{13} protons/extraction**
- Expected performance: **4.5×10^{19} pot/year**

CNGS beam (2)

- The beam was optimized for ν_τ appearance in the atmospheric oscillation region i.e. $\Delta m^2_{23} \approx 2.4 \times 10^{-3}$ eV^2 (as measured by SK, K2K and MINOS).
- Although the maximum of oscillation probability at 730 km is at about 1.5 GeV, we need to take into account the ν_τ CC cross section and the production threshold of 3.5 GeV.

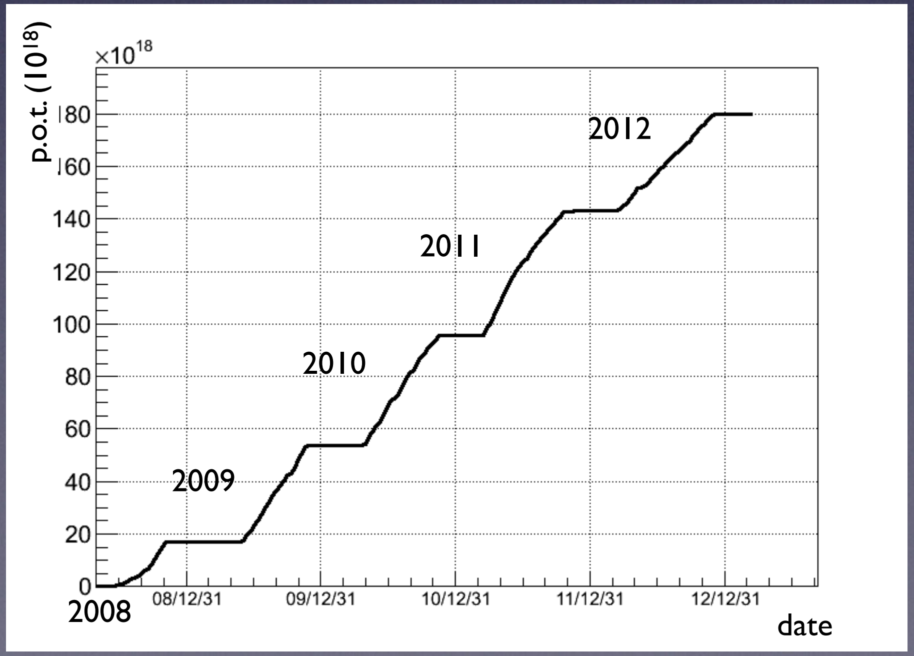


Beam parameters

<$E_{\nu\mu}$>	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}).

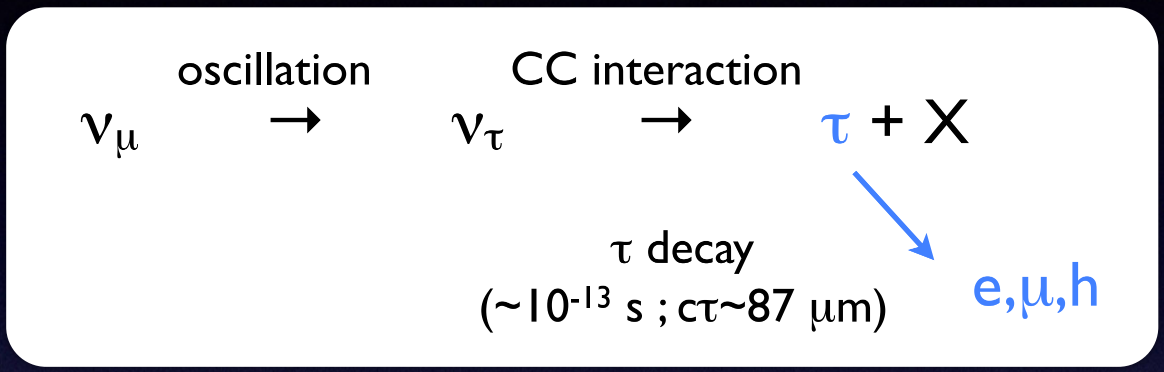


Beam performance

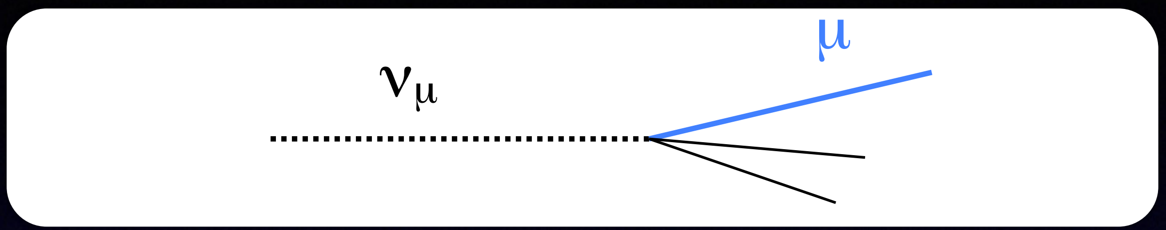
Year	Beam days	p.o.t (10^{19})
2008	123	1.74
2009	155	3.53
2010	187	4.09
2011	243	4.75
2012	257	3.86
Total	965	17.97

Detection principle

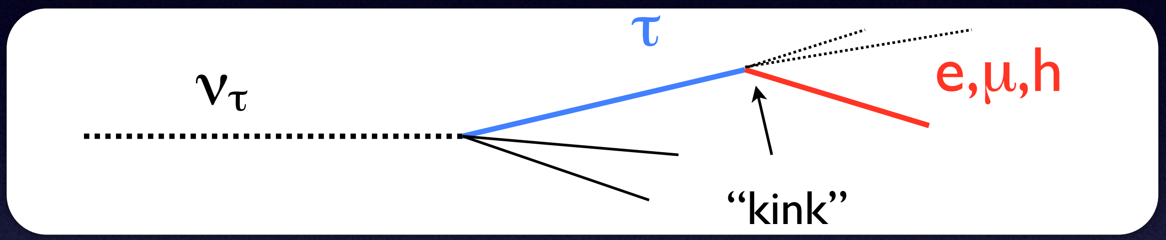
Physics process



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

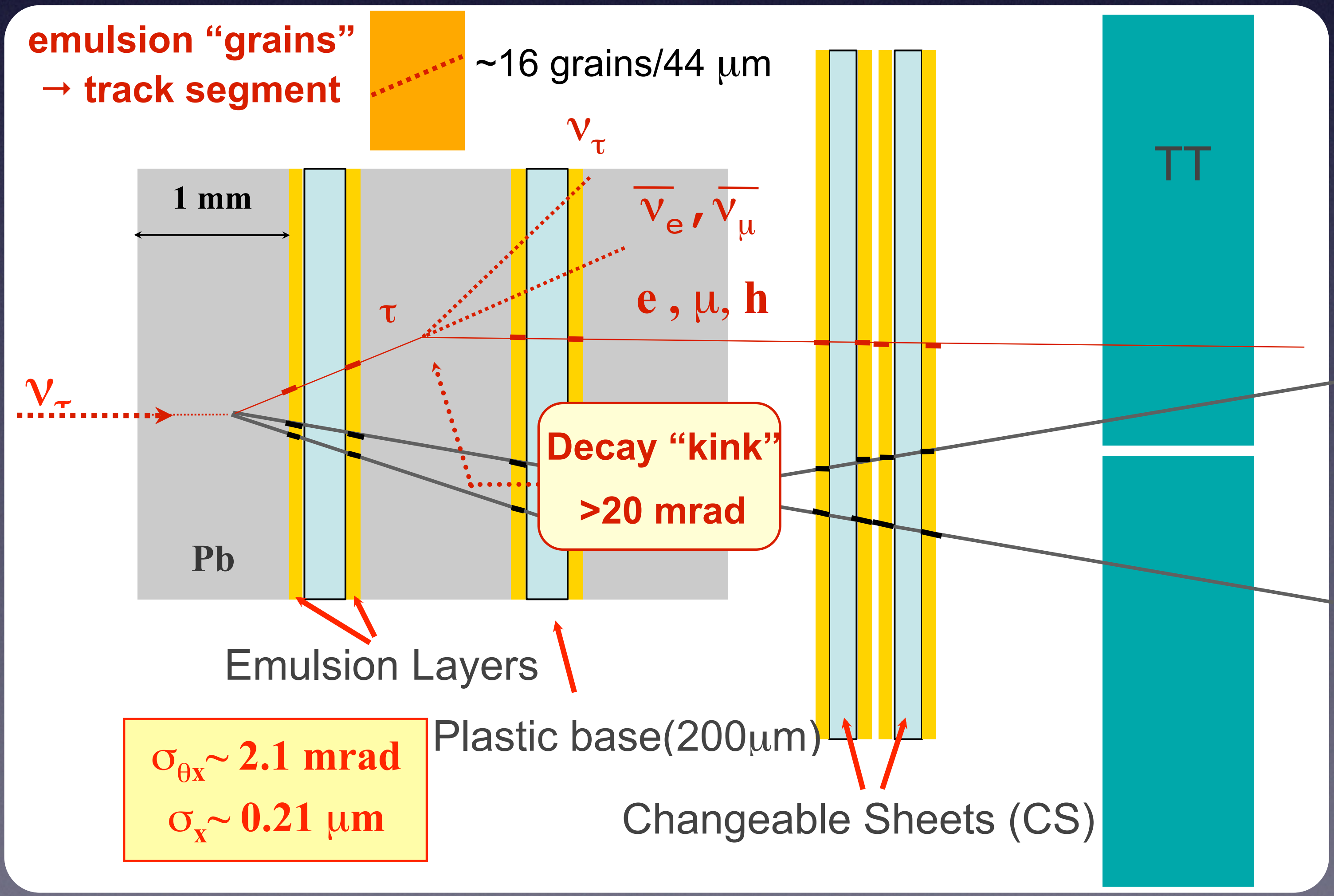
↓

OPERA: hybrid detector (emulsions + electronic detectors)

τ identification

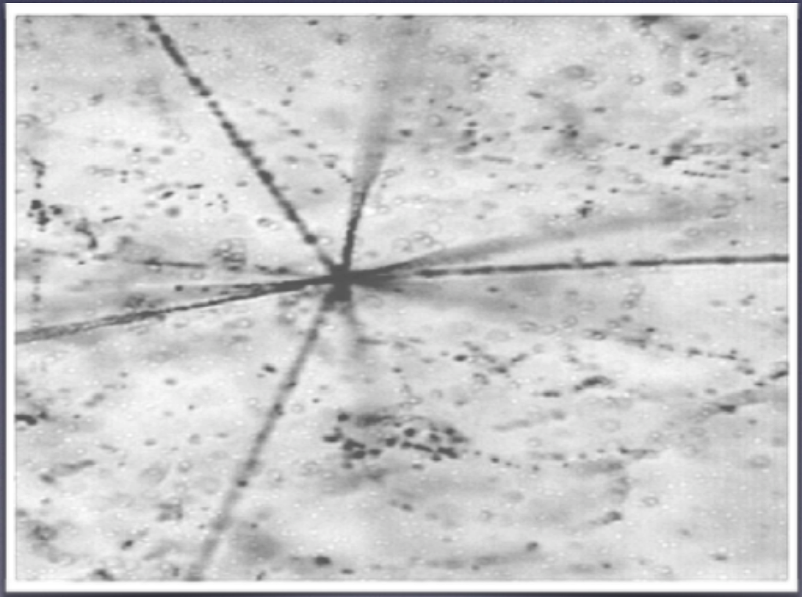
- The identification is done in the lead-emulsion target, which is segmented in units called "bricks".
- The high granularity (300 hits/mm) of emulsions allows for an unambiguous identification of the kink.

Lead-emulsion layers in brick



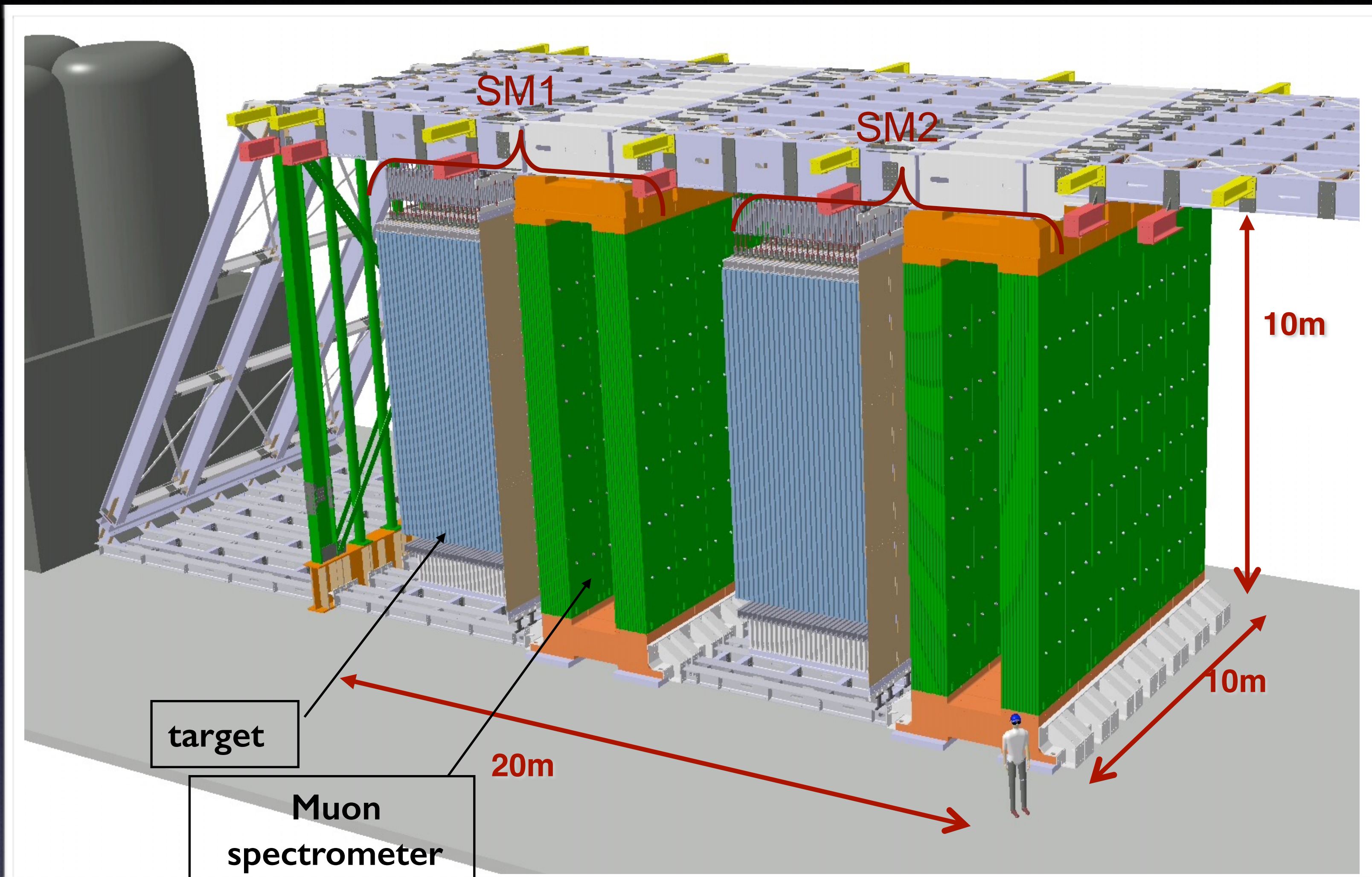
Brick structure

Event reconstruction in emulsions



The OPERA detector (1)

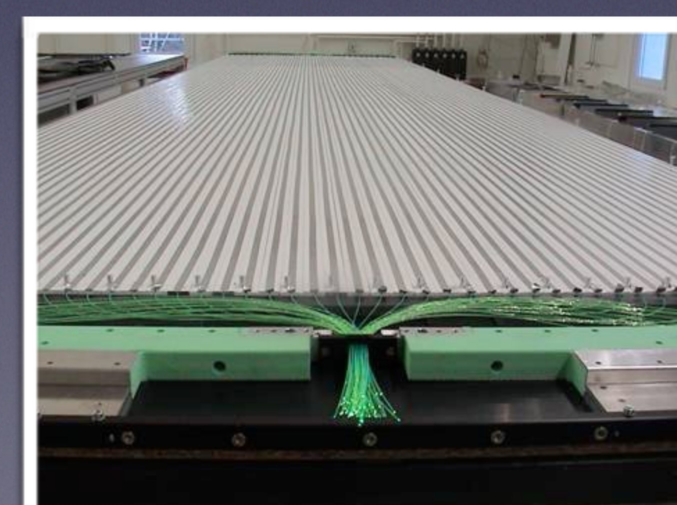
Detector design



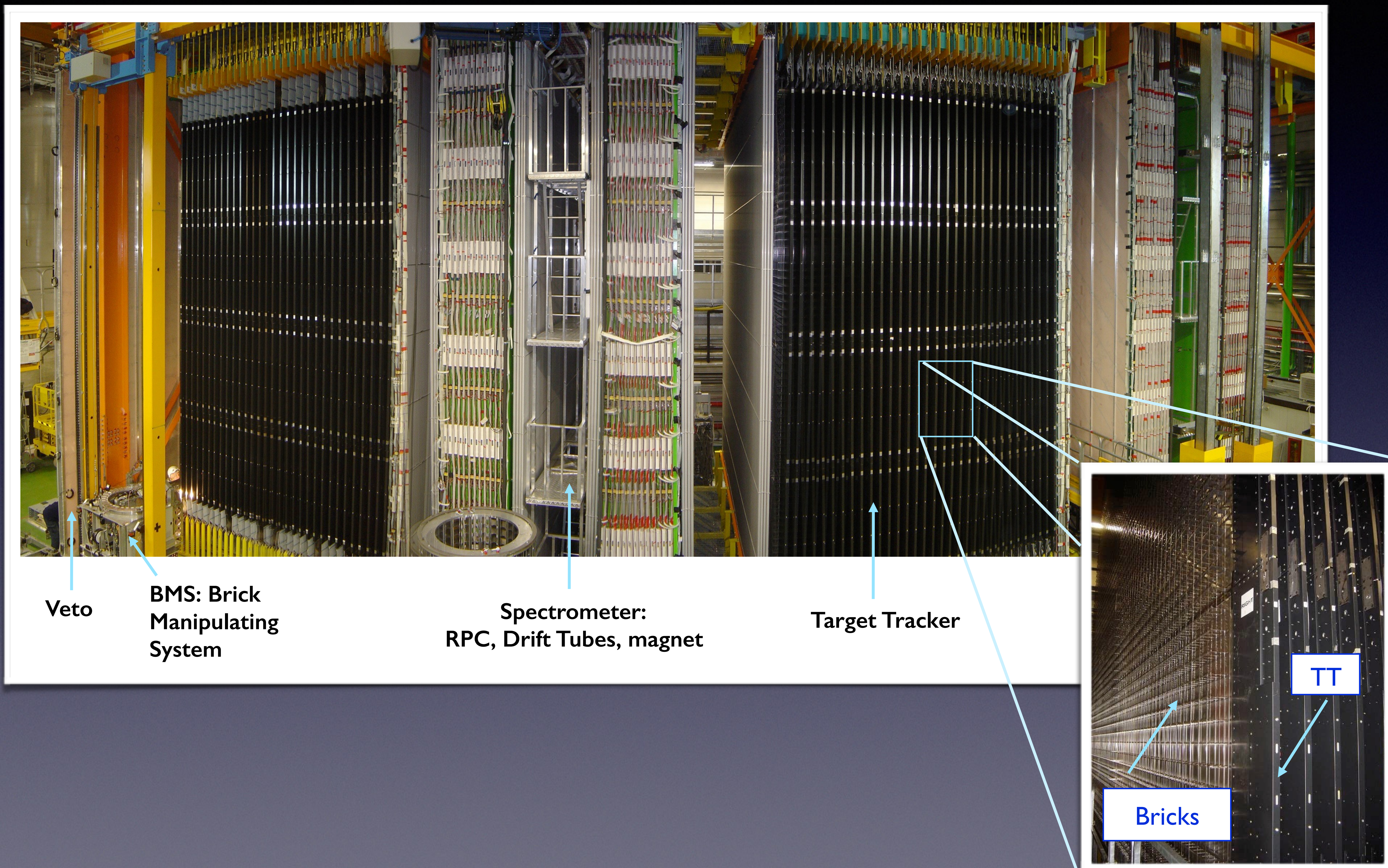
- The total target mass was 1.25 kton (about 150000 bricks).
- Each target consisted of 27 lead-emulsion brick walls alternated with scintillator planes (Target Tracker) used mainly for the identification of the brick to be extracted.
- The Target Tracker (TT) was made of plastic scintillator + wave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

- Each spectrometer consisted 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%



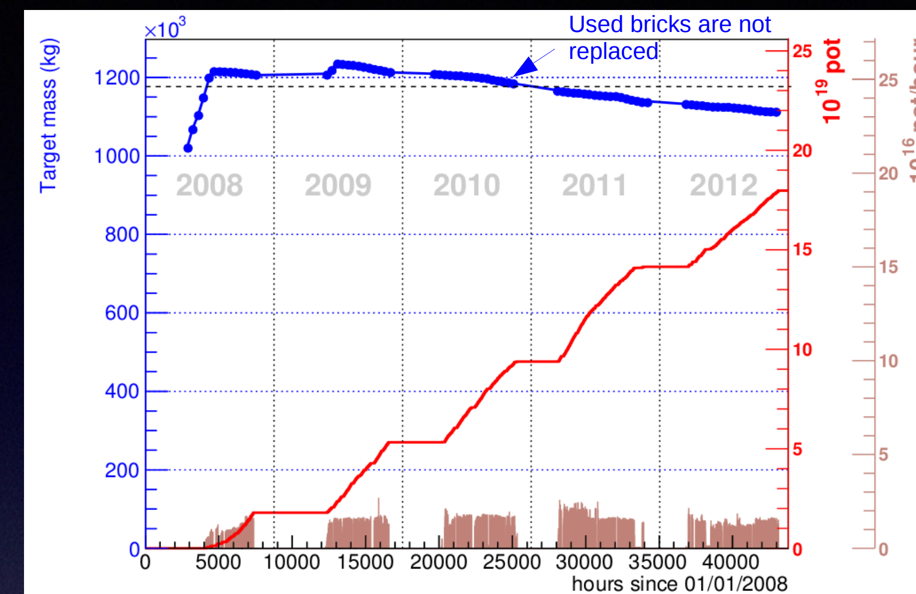
The OPERA detector (2)



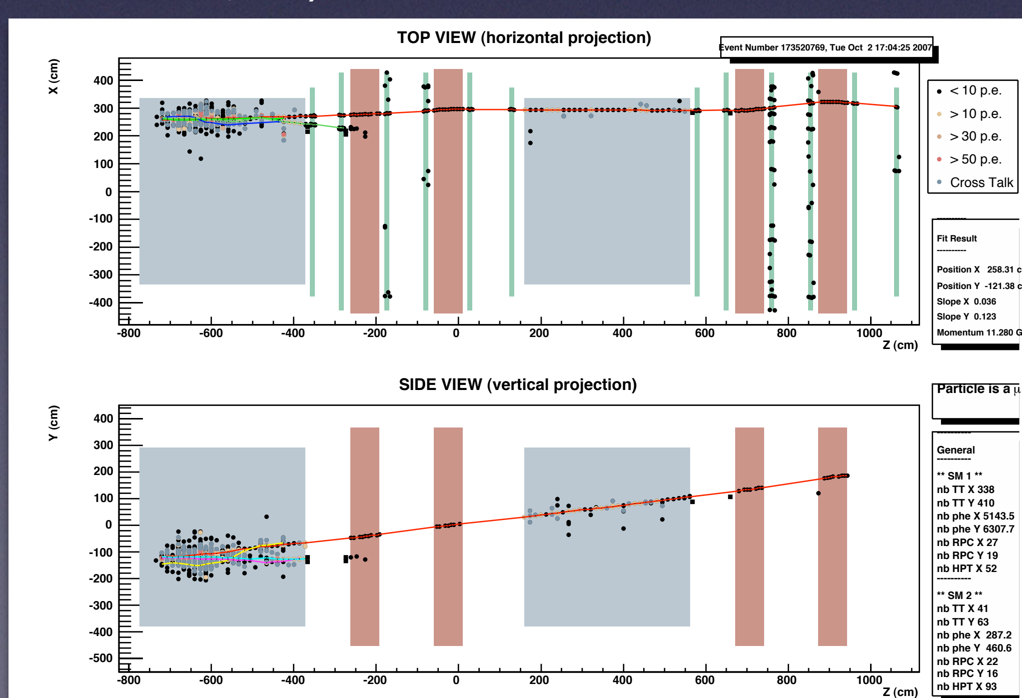
Data collection and analysis

- 19505 neutrino interactions recorded in the emulsion target.

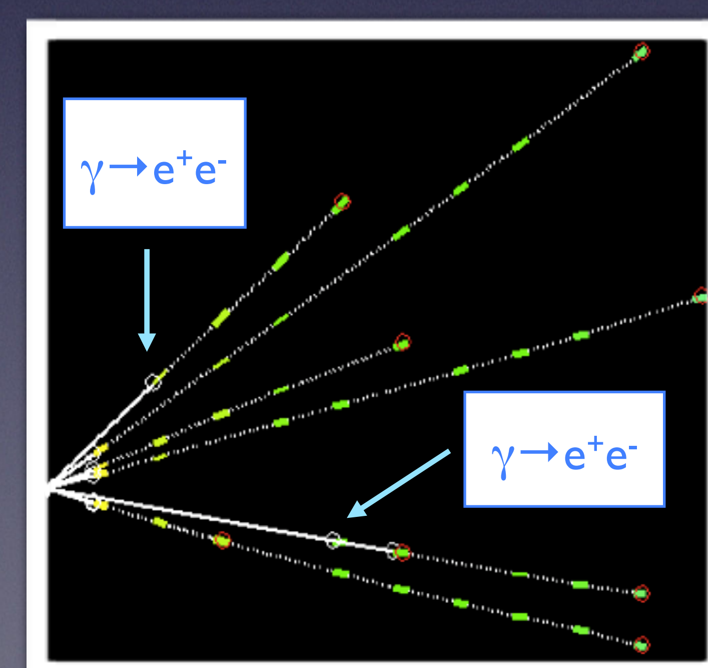
Year	Beam days	p.o.t (10^{19})	ν interactions
2008	123	1.74	1698
2009	155	3.53	3693
2010	187	4.09	4248
2011	243	4.75	5131
2012	257	3.86	3923
Total	965	17.97	19505



- The OPERA analysis chain is not trivial since we have to merge information from the electronic detectors (resolution of order of 1 cm) and from the emulsions (resolution of order of few μm) → **critical role of the CS**.



Reconstruction in electronic detectors of a ν_μ CC



Reconstruction in emulsions of a ν_μ CC

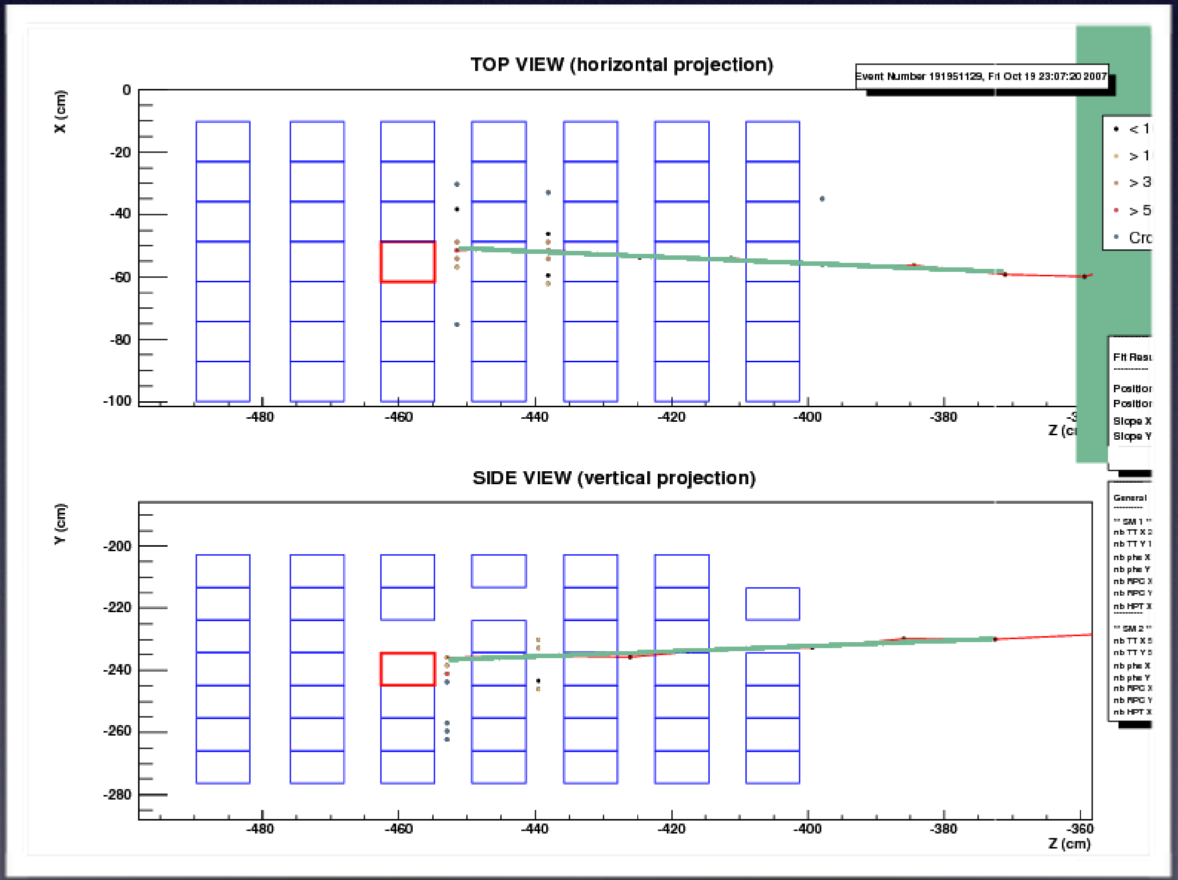
Analysis chain (1)

- The first phase of the analysis consists in the **brick selection** using electronic detectors and CS information.

Brick selection

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

- Brick removed by BMS (Brick Manipulating System).



- The CS are developed and tracks confirming the correctness of the brick are searched for.

- If a track matching the TT reconstruction is found in the CS, the brick is exposed to cosmic rays for sheets alignment.

- The brick is disassembled and the emulsion films are developed and sent to scanning labs.

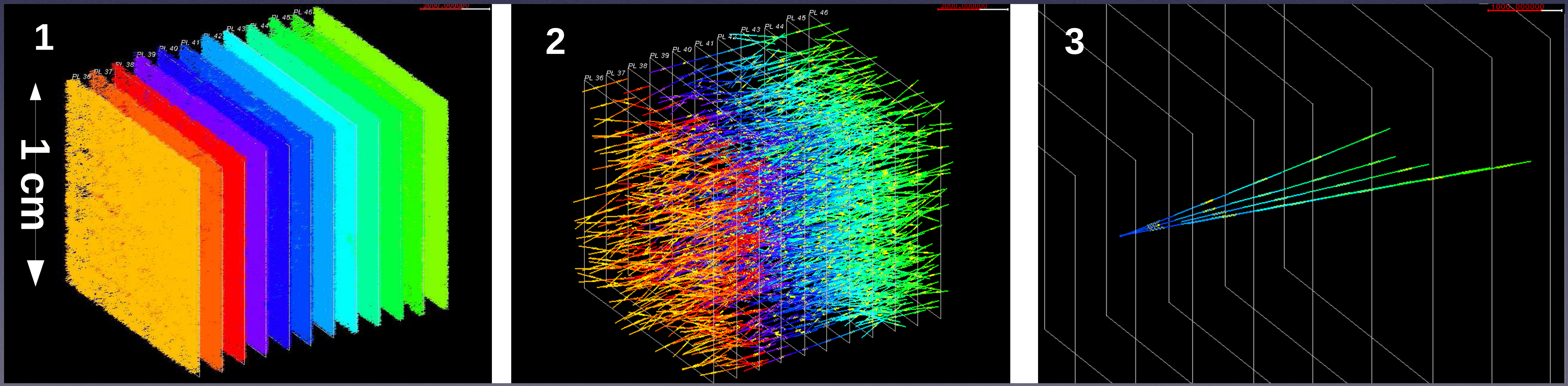
Up to 50 bricks were extracted each day.

Analysis chain (2)

- The second phase of the analysis consists in the **scanning** of the emulsions to reconstruct the interaction vertex, measure particles momentum via multiple scattering and identify possible kinks.

Scanning

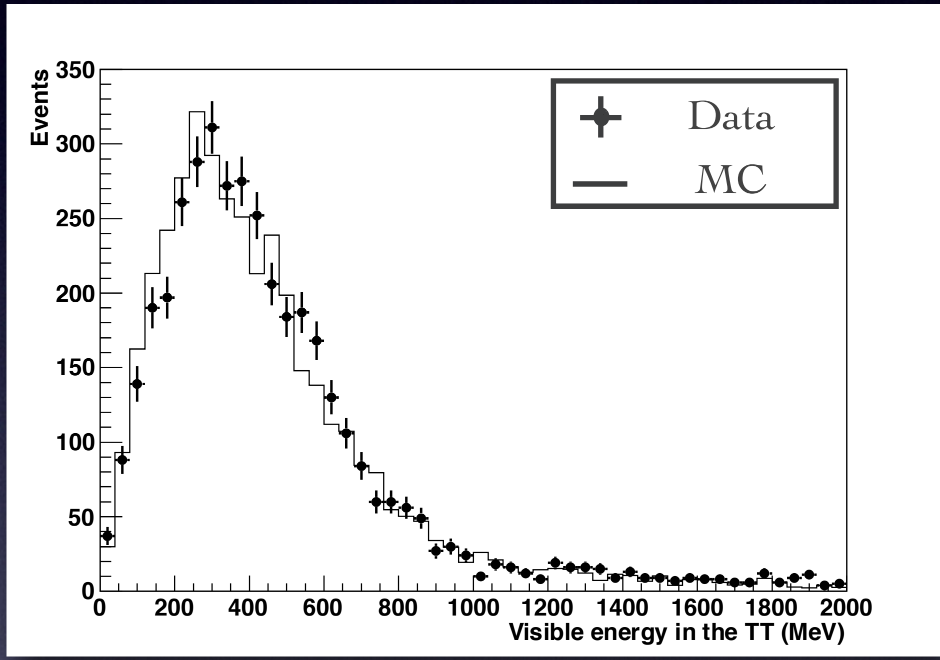
- Tracks tagged in the **CS films** are **followed upstream** until a **stopping point** is found.
- Base-tracks in the 12 films of the **volume centered in the stopping point** are reconstructed.
- Cosmic ray tracks (from a dedicated exposure) are used for the fine **alignment** of films.
- Passing-through tracks discarded → **vertexing algorithm**.



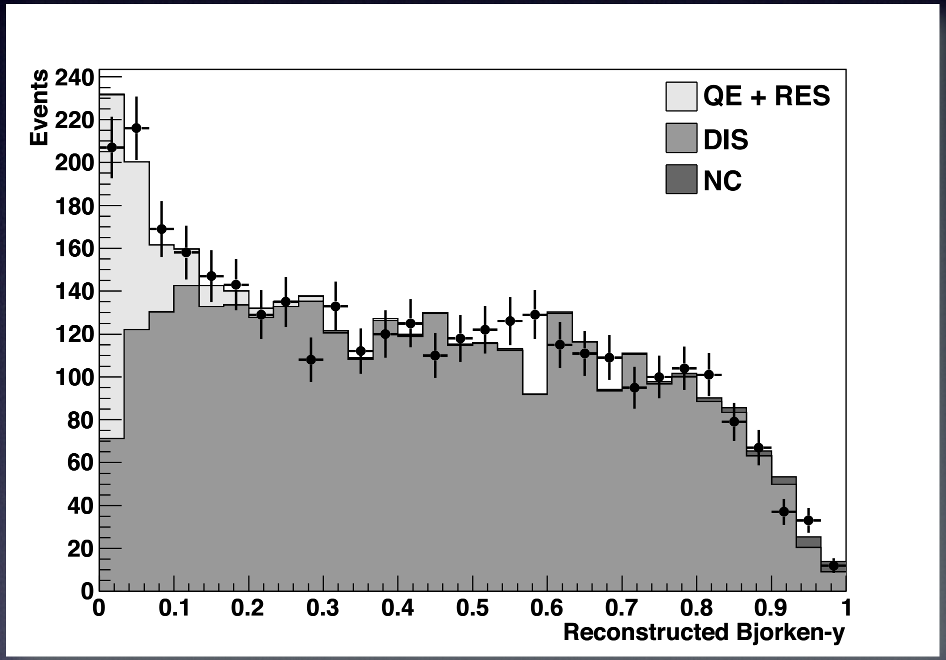
ED Data / MC comparison

- The electronic detectors (ED) simulation was 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

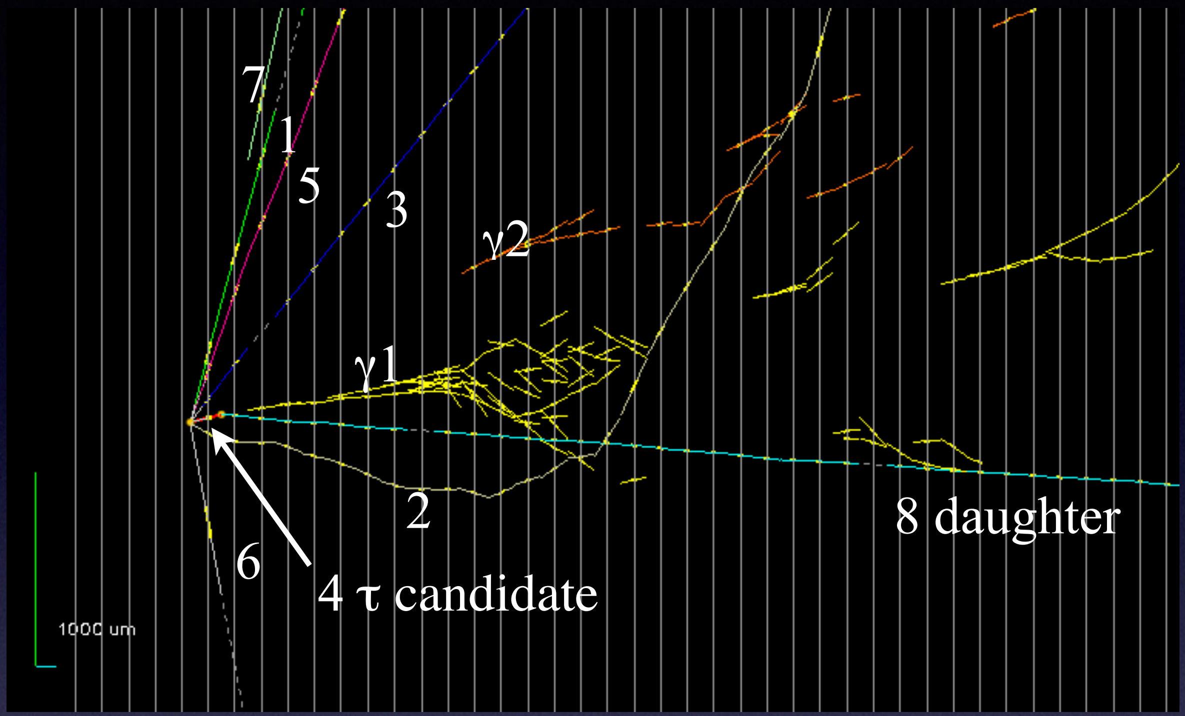
$\nu_\mu \rightarrow \nu_\tau$ analysis

- Different strategies were used in different periods:
  - 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: muon momentum of less than 15 GeV, most probable brick analyzed for all events before moving to the other ones and anticipation of the analysis of 0μ events (NC like ones with no muon detected) to optimize the ratio between efficiency and analysis time.
- The decay search procedure was applied to all the 17057 contained events (first and second most probable brick for 2008-2012 data and up to 4th most probable for 2008-2009 data) and **5 candidates were found** corresponding to a **5.1 σ significance** of non-null observation.

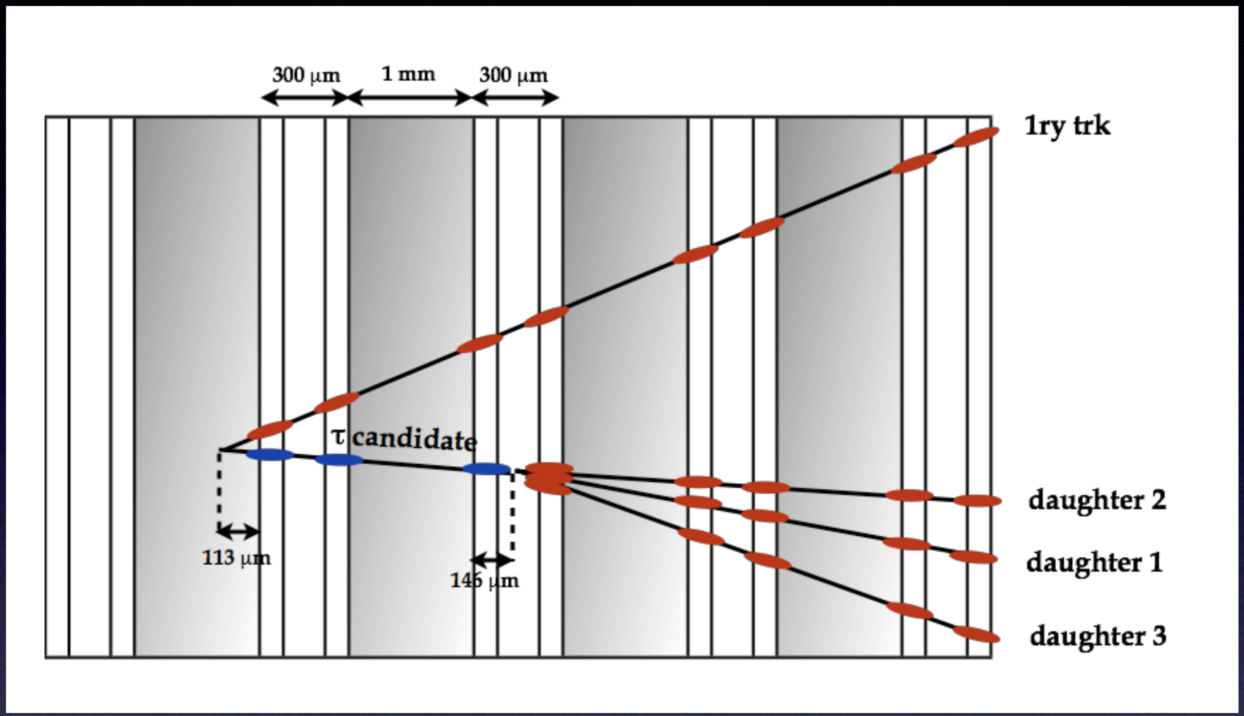
channel	Expected signal	Observed signal	Background	Charm	μ scattering	Hadronic interactions
$\tau \rightarrow$h	0.52 ± 0.10	3	0.04 ± 0.01	0.017 ± 0.003	-	0.022 ± 0.006
$\tau \rightarrow$3h	0.73 ± 0.14	1	0.17 ± 0.03	0.17 ± 0.03	-	0.003 ± 0.001
$\tau \rightarrow \mu$	0.61 ± 0.12	1	0.004 ± 0.001	0.004 ± 0.001	0.0002 ± 0.0001	-
$\tau \rightarrow$ e	0.78 ± 0.15	0	0.03 ± 0.01	0.03 ± 0.01	-	-
total	2.64 ± 0.53	5	0.25 ± 0.05	0.22 ± 0.04	0.0002 ± 0.0001	0.02 ± 0.01

ν_τ candidates

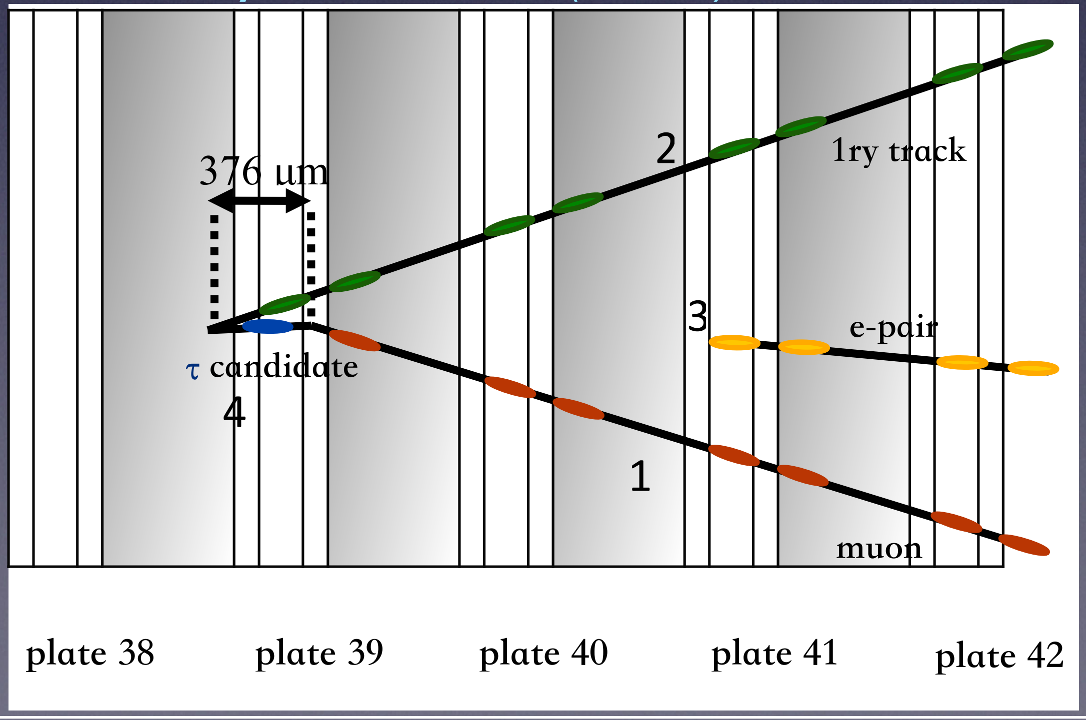
1st candidate (2010): $\tau \to \rho\ (\pi^- \pi^0)$
Phys. Lett. B 691 (2010) 138



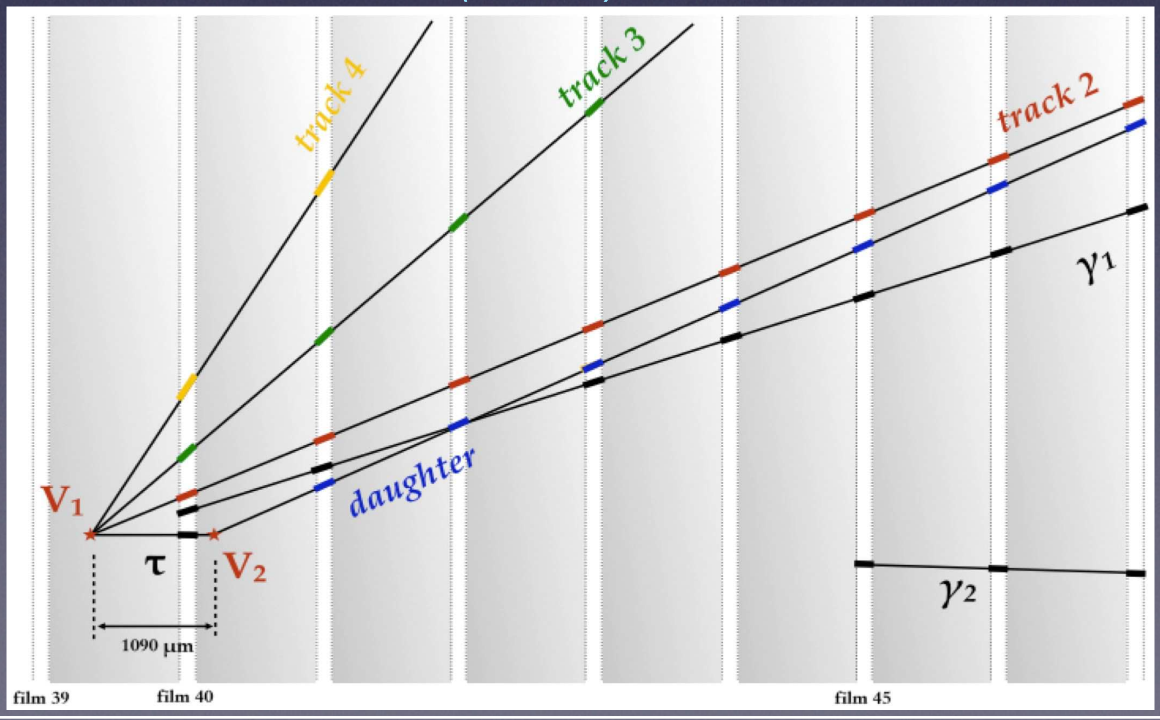
2nd candidate (2012): $\tau \to 3h$
JHEP 11 (2013) 036



3rd candidate (2013): $\tau \to \mu$
Phys. Rev. D 89 (2014) 051102



4th candidate (2014): $\tau \to 1h$
PTEP (2014) 101C01

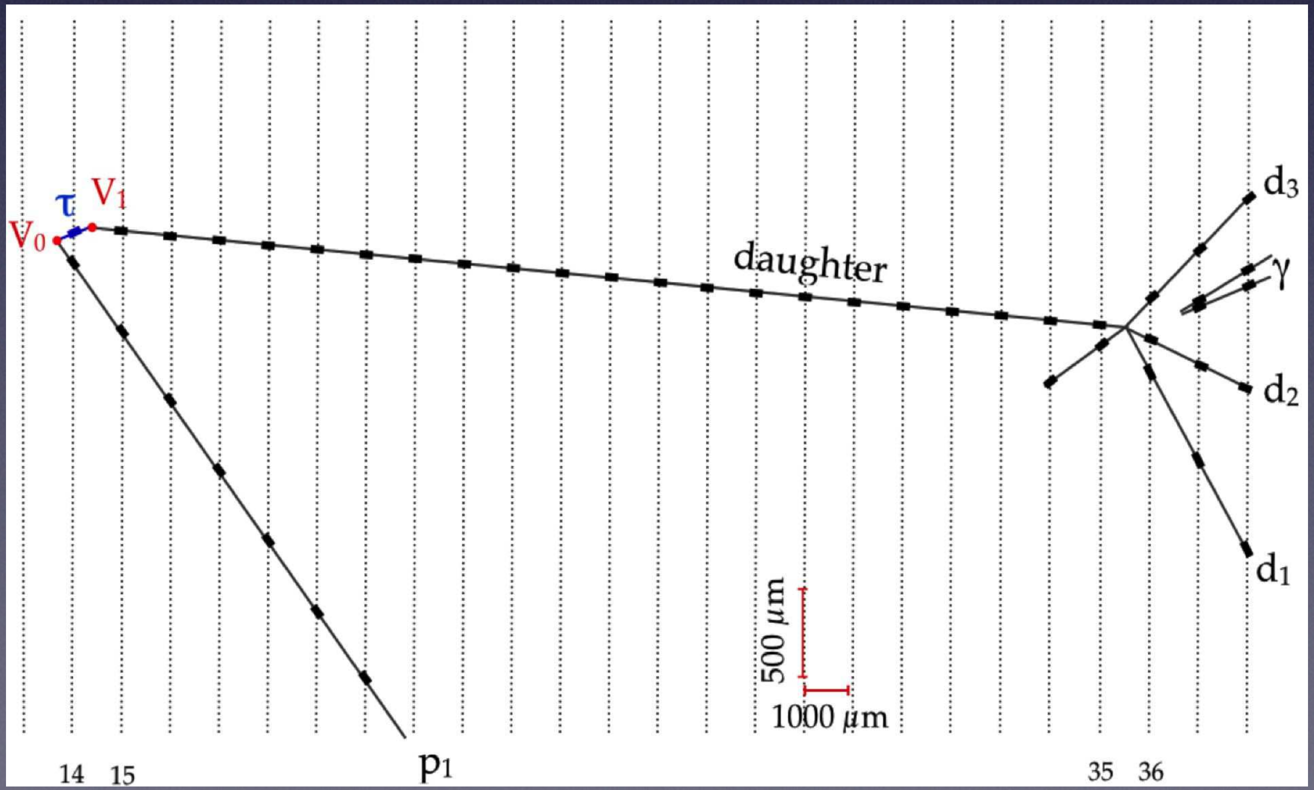


Fifth candidate

- In the decay search of 2012 data we found a fifth ν_τ candidate (*Phys. Rev. Lett. 115 (2015) 121802*).
- The event passes all selection criteria for the signal and it was classified as a possible decay of a τ into 1 prong hadron.
- Only one additional track attached to the primary vertex, identified as a hadron due to its reinteraction in the downstream brick.
- The daughter was unambiguously identified as a hadron due to its interaction after 22 planes.

Kinematical variables

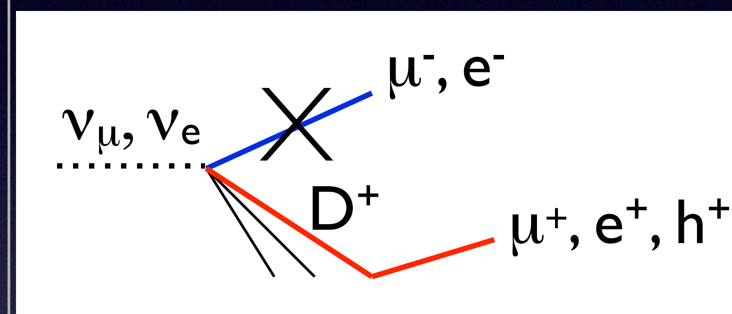
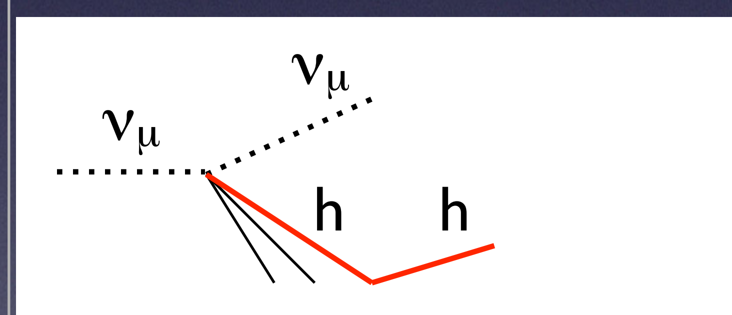
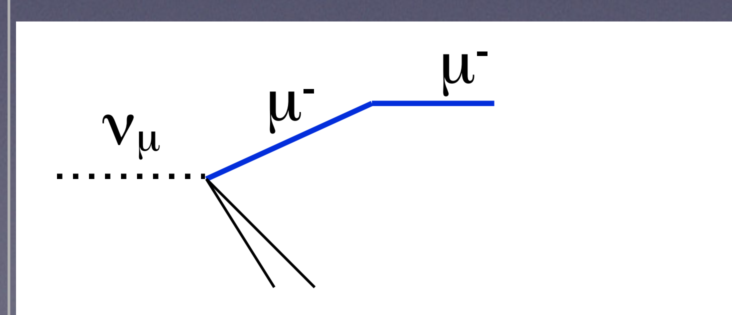
Variable	Observed	Cut
Kink angle (mrad)	90 ± 2	>20
Decay length (μm)	634 ± 30	< 2 lead plates
P daughter (GeV/c)	11^{+14}_{-4}	>2
Daughter Pt (MeV/c)	1000^{+1200}_{-400}	>600
Missing Pt (MeV/c)	300 ± 100	<1000
Φ angle (deg)	151 ± 1	>90



Background

- The MC simulation of the different backgrounds was benchmarked with different control samples.

Less relevant

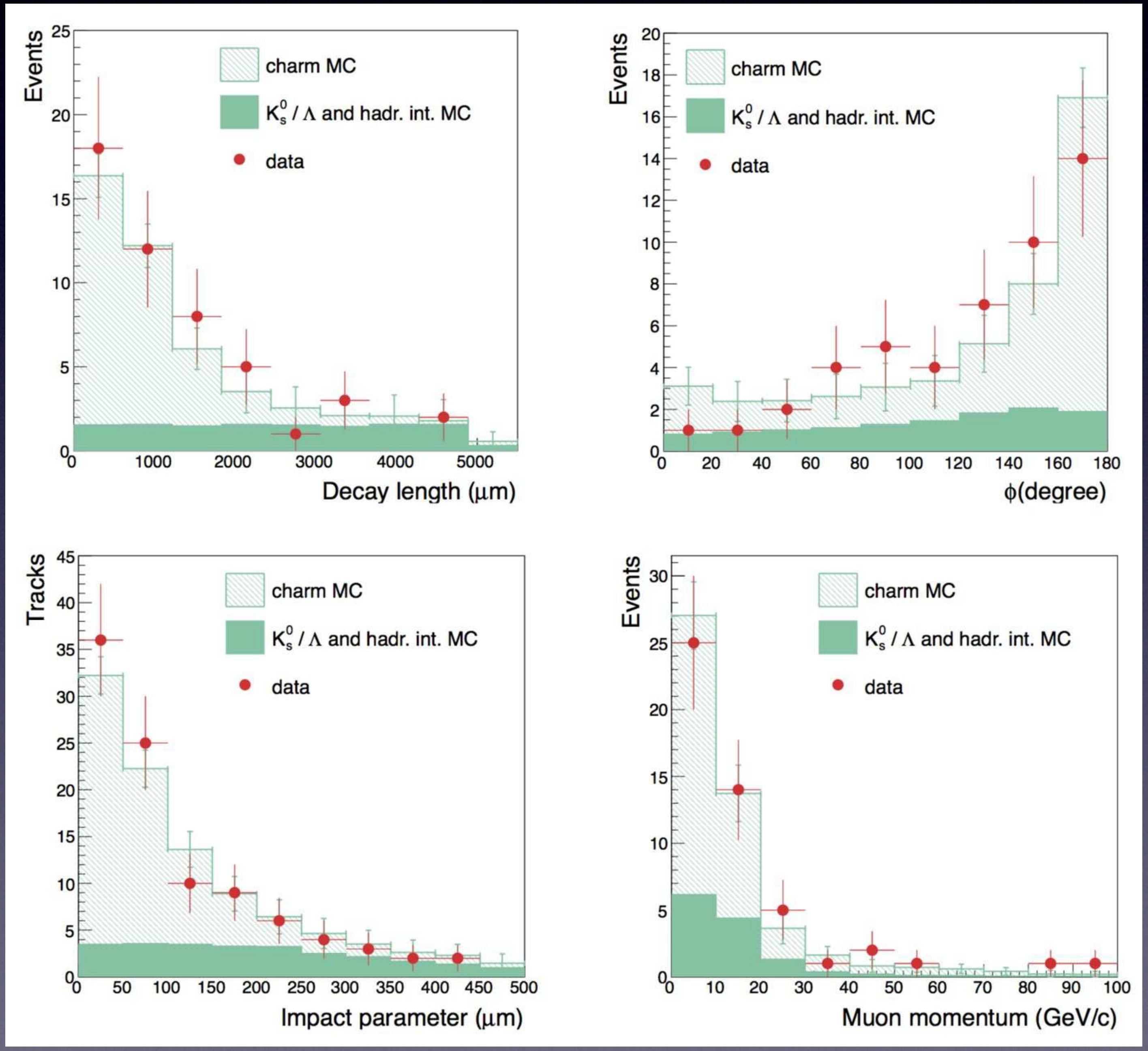
Type of BG	BG for…	Scheme	Benchmark and reduction
CC with Charm production	All channels if primary lepton is not detected and the charge of the daughter is not (or is incorrectly) measured		MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events. (*Eur. Phys.J. C74 (2014) 2986*) **Reduced by track follow down and large angle scanning**
Hadronic interactions	Background for $\tau \to h$		FLUKA + pion test beam data. (*PTEP9 (2014) 093C01*) **Reduced by large angle scanning and nuclear fragment search**
Large angle muon scattering	Background for $\tau \to \mu$		Improved knowledge bringing this contribution to a **negligible level**: GEANT4 simulation benchmarked on real data from the literature. (*IEEE Trans. Nucl. Sci. 62,5, 2216-2225*)

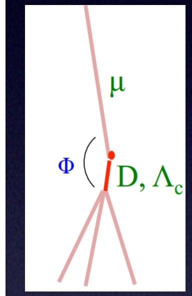
Charm validation

- The charm lifetime and decay topologies are similar to the ones of the τ lepton.

- Charm events can therefore be used as a control sample to benchmark the τ decay finding efficiency and kinematical variables reconstruction.

- Studying the 2008-2010 data sample **50** charm events where **observed** against an **expectation** value **of 54 ± 4** (*Eur.Phys.J. C74 (2014) no.8, 2986*) confirming our understanding of the detector efficiencies.





$\nu_{\mu} \rightarrow \nu_{\tau}$ + sterile neutrinos (I)

- The appearance probability is modified by one possible extra (sterile) state (3+1 scheme).

- This could result into an **increase or decrease** of the number of expected tau neutrinos observed.

$$\begin{vmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{vmatrix}$$

Full oscillation probability

$$\begin{aligned} P_{\mu\tau} = & -4\sum_{j=1}^{4}\sum_{i>j}^{4} \Re\left(U^*_{\mu i}U_{\tau i}U_{\mu j}U^*_{\tau j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) \\ & +2\sum_{j=1}^{4}\sum_{i>j}^{4} \Im\left(U^*_{\mu i}U_{\tau i}U_{\mu j}U^*_{\tau j}\right)\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right) \end{aligned}$$

Approximation

$$\begin{aligned} & \Delta m^2_{21} \ll \Delta m^2_{31} \ll \Delta m^2_{41} \\ & \Delta m^2_{31} \approx \Delta m^2_{32} \\ & \Delta m^2_{41} \approx \Delta m^2_{42} \approx \Delta m^2_{43} \end{aligned}$$

$$\begin{aligned} P_{\mu\tau} = & -4\,\Re\left(U^*_{\mu 2}U_{\tau 2}U_{\mu 1}U^*_{\tau 1}\right)\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) \\ & +2\,\Im\left(U^*_{\mu 2}U_{\tau 2}U_{\mu 1}U^*_{\tau 1}\right)\sin\left(\frac{\Delta m^2_{21}L}{2E}\right) \\ & +4\,|U_{\mu 3}|^2|U_{\tau 3}|^2\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) \\ & +4\,\Re\left(U^*_{\mu 3}U_{\tau 3}U_{\mu 4}U^*_{\tau 4}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) \\ & -2\,\Im\left(U^*_{\mu 3}U_{\tau 3}U_{\mu 4}U^*_{\tau 4}\right)\sin\left(\frac{\Delta m^2_{31}L}{2E}\right) \\ & +4\,|U_{\mu 4}|^2|U_{\tau 4}|^2\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right) \end{aligned}$$

$\nu_\mu \to \nu_\tau$ + sterile neutrinos (I)

- The appearance probability is modified by one possible extra (sterile) state (3+1 scheme).
- This could result into an **increase or decrease** of the number of expected tau neutrinos observed.

$$\begin{vmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{vmatrix}$$

Full oscillation probability

$$P_{\mu\tau} = -4\sum_{j=1}^{4}\sum_{i>j}^{4}\Re\left(U^*_{\mu i}U_{\tau i}U_{\mu j}U^*_{\tau j}\right)\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{j=1}^{4}\sum_{i>j}^{4}\Im\left(U^*_{\mu i}U_{\tau i}U_{\mu j}U^*_{\tau j}\right)\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

Approximation

$$\Delta m^2_{21} \ll \Delta m^2_{31} \ll \Delta m^2_{41}$$
$$\Delta m^2_{31} \approx \Delta m^2_{32}$$
$$\Delta m^2_{41} \approx \Delta m^2_{42} \approx \Delta m^2_{43}$$

$$\begin{aligned} P_{\mu\tau} = & -4\,\cancel{\Re\left(U^*_{\mu 2}U_{\tau 2}U_{\mu 1}U^*_{\tau 1}\right)\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)} \\ & +2\,\cancel{\Im\left(U^*_{\mu 2}U_{\tau 2}U_{\mu 1}U^*_{\tau 1}\right)\sin\left(\frac{\Delta m^2_{21}L}{2E}\right)} \\ & +4\,|U_{\mu 3}|^2|U_{\tau 3}|^2\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) \\ & +4\,\Re\left(U^*_{\mu 3}U_{\tau 3}U_{\mu 4}U^*_{\tau 4}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) \\ & -2\,\Im\left(U^*_{\mu 3}U_{\tau 3}U_{\mu 4}U^*_{\tau 4}\right)\sin\left(\frac{\Delta m^2_{31}L}{2E}\right) \\ & +4\,|U_{\mu 4}|^2|U_{\tau 4}|^2\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right) \end{aligned}$$

Negligible for CNGS

Standard physics

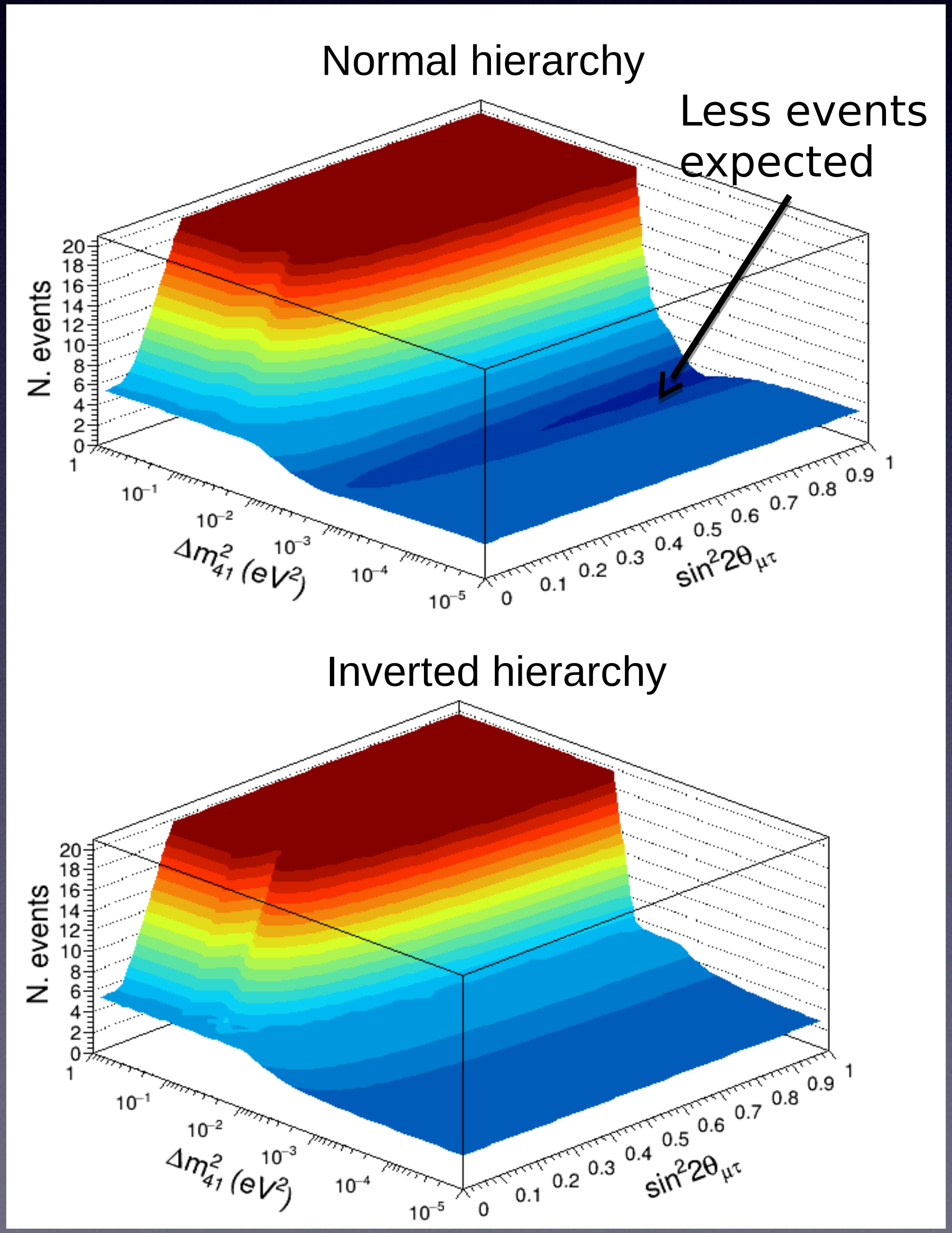
Interference

Exotic physics

$\nu_\mu \rightarrow \nu_\tau$ + sterile neutrinos (2)

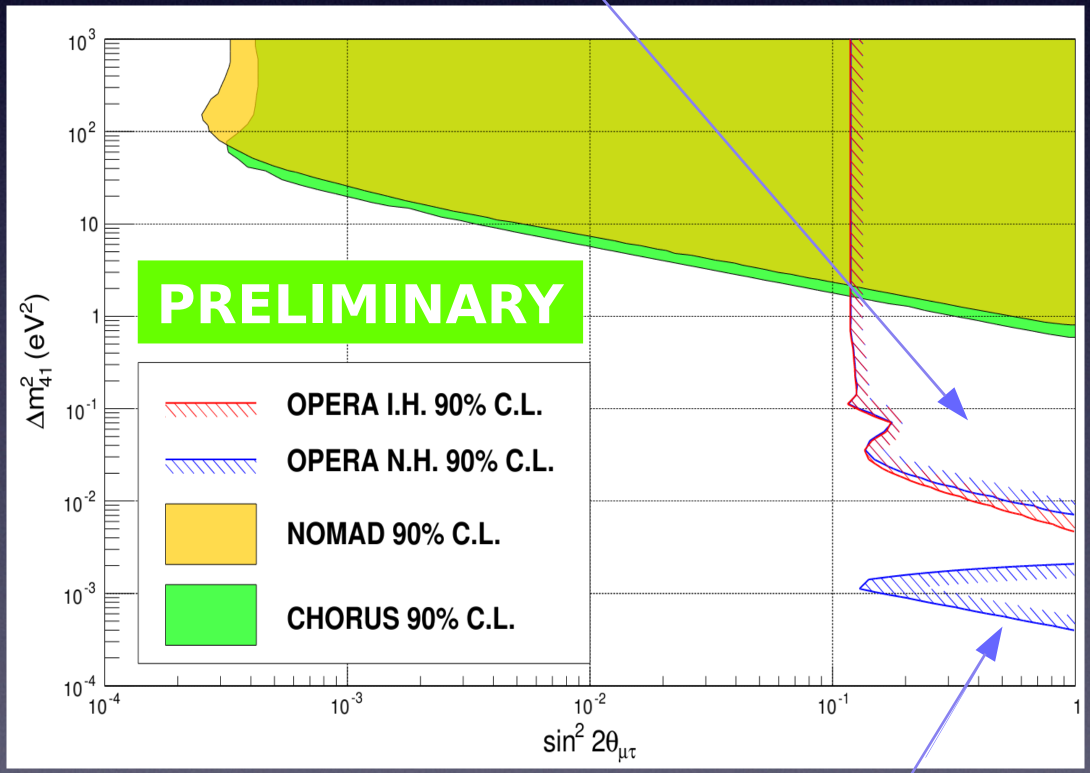
- Event rate only analysis was performed.

Expected ν_τ events



A wide range of Δm^2_{41} from 10^{-3} to 1 is excluded for $\sin^2 2\theta_{\mu\tau} > \sim 0.1$.

Exclusion regions

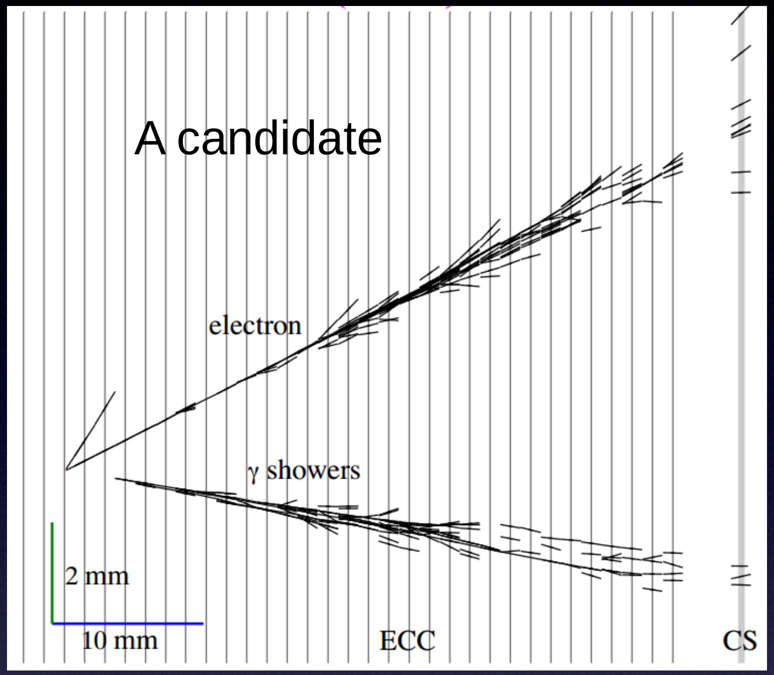


$$\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$$

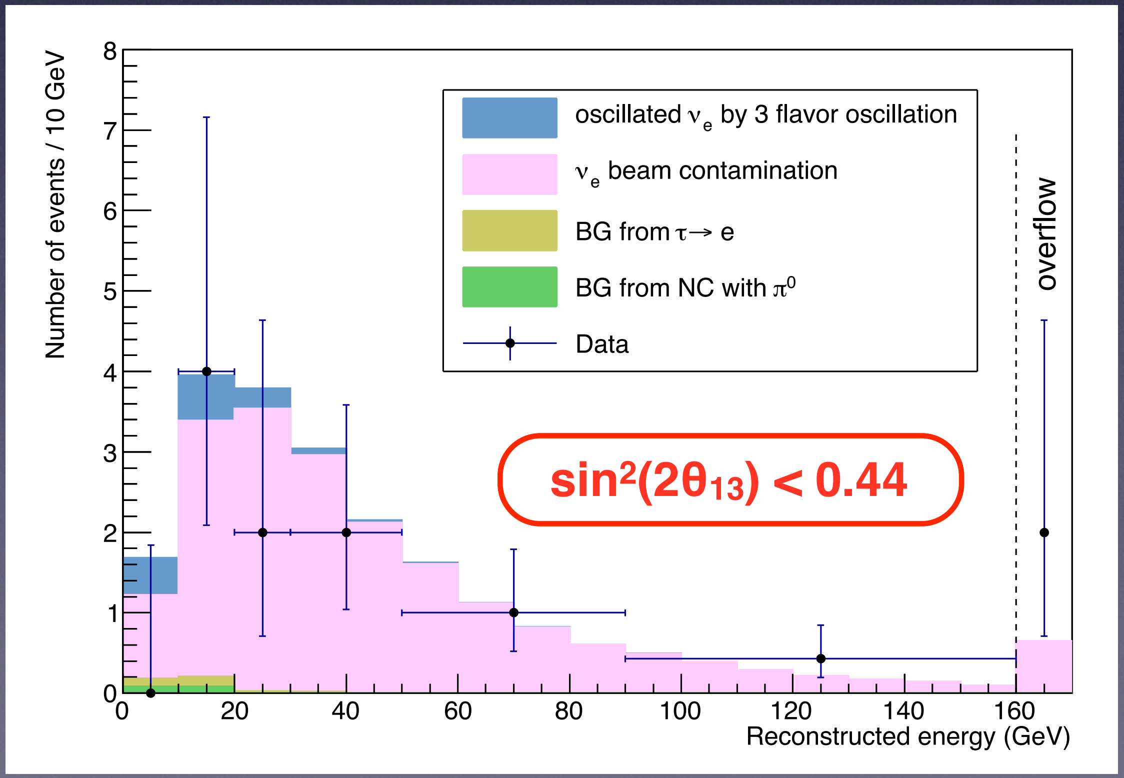
In case of N.H. for a sterile neutrino with mass close to m3 a reduction well below the observed 5 events would be expected.

$\nu_\mu \rightarrow \nu_e$ analysis (1)

- Thanks to the dense brick structure and the high granularity provided by the nuclear emulsions, the OPERA detector is also suited for electron and γ detection.
- Despite OPERA was not meant to observe the $\nu_\mu \rightarrow \nu_e$ transition, given the "large" value of θ_{13} an excess of ν_e could be observed.
- In the 2008 and 2009 runs a dedicated ν_e search was performed.
- Out of 505 neutrino events without muon 19 ν_e candidates were found.
- In the standard 3 flavour scenario, the observation is compatible with a background-only hypothesis.



Standard scenario



$\nu_\mu \rightarrow \nu_e$ analysis (2)

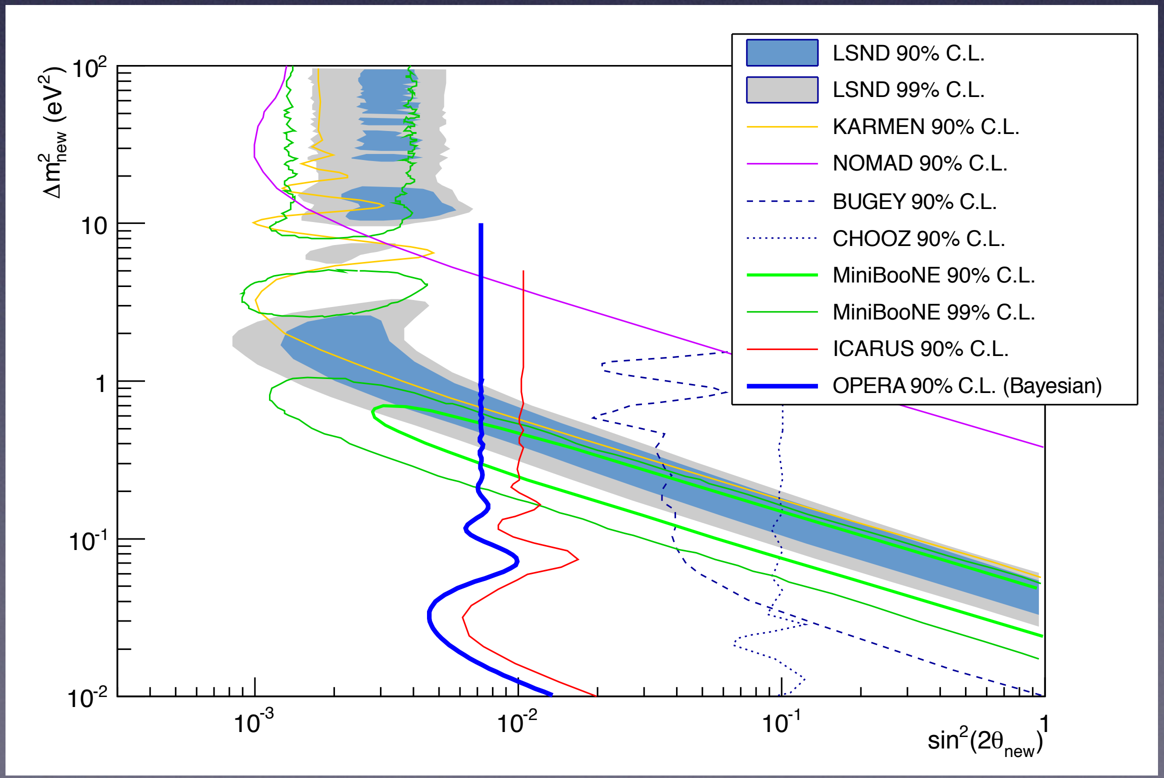
- Assuming a new sterile neutrino state and working in one mass scale dominance approximation, the new oscillation probability can be written as:

$$P = \sin^2(2\theta_{new}) \sin^2(1.27\Delta m^2_{new} L[km]/E[GeV])$$

- A specific analysis for non-standard oscillation at large Δm^2 resulted in a competitive limit (*JHEP 1307 (2013) 085*).
- Full statistics analysis is ongoing (factor of 2.5 increase) and a rigorous treatment of the 3+1 scheme will be applied.

Energy cut		20 GeV	30 GeV	No cut
BG common to both analyses	BG (a) from π^0	0.2	0.2	0.2
	BG (b) from $\tau \rightarrow e$	0.2	0.3	0.3
	ν_e beam contamination	4.2	7.7	19.4
Total expected BG in 3-flavour oscillation analysis		4.6	8.2	19.8
BG to non-standard oscillation analysis only	ν_e via 3-flavour oscillation	1.0	1.3	1.4
Total expected BG in non-standard oscillation analysis		5.6	9.4	21.3
Data		4	6	19

Non-standard oscillations



Conclusions

- OPERA took data from 2008 till 2012 and the $\nu_\mu \rightarrow \nu_\tau$ **oscillation** was observed with a confidence level of **5.1 σ** outreaching the proposal expectations and allowing to claim **discovery of ν_τ appearance**.
- Searches for **anomalies** in $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ channels are ongoing.
- First **preliminary limits** on $|U_{\mu 4}|^2$ $|U_{\tau 4}|^2$ were computed from direct measurement of ν_τ.
- Results on $\nu_\mu \rightarrow \nu_e$ with full statistics and correct treatment of the 3+1 scheme soon.
- Despite the experiment is currently being dismounted, scanning and analysis is still ongoing to study marginal events (failing the cut based selection) with still a significant ν_τ purity.

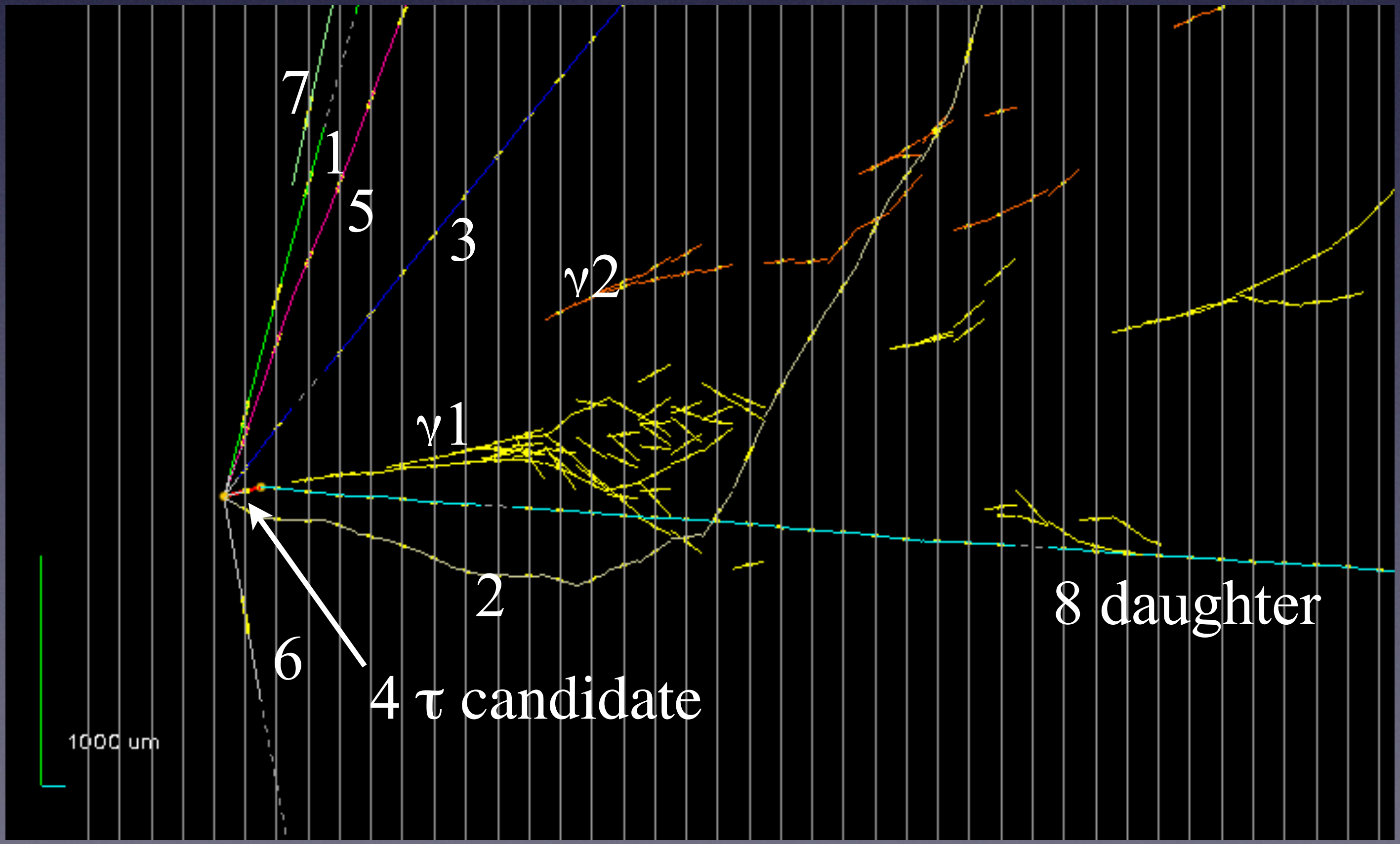
BK

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

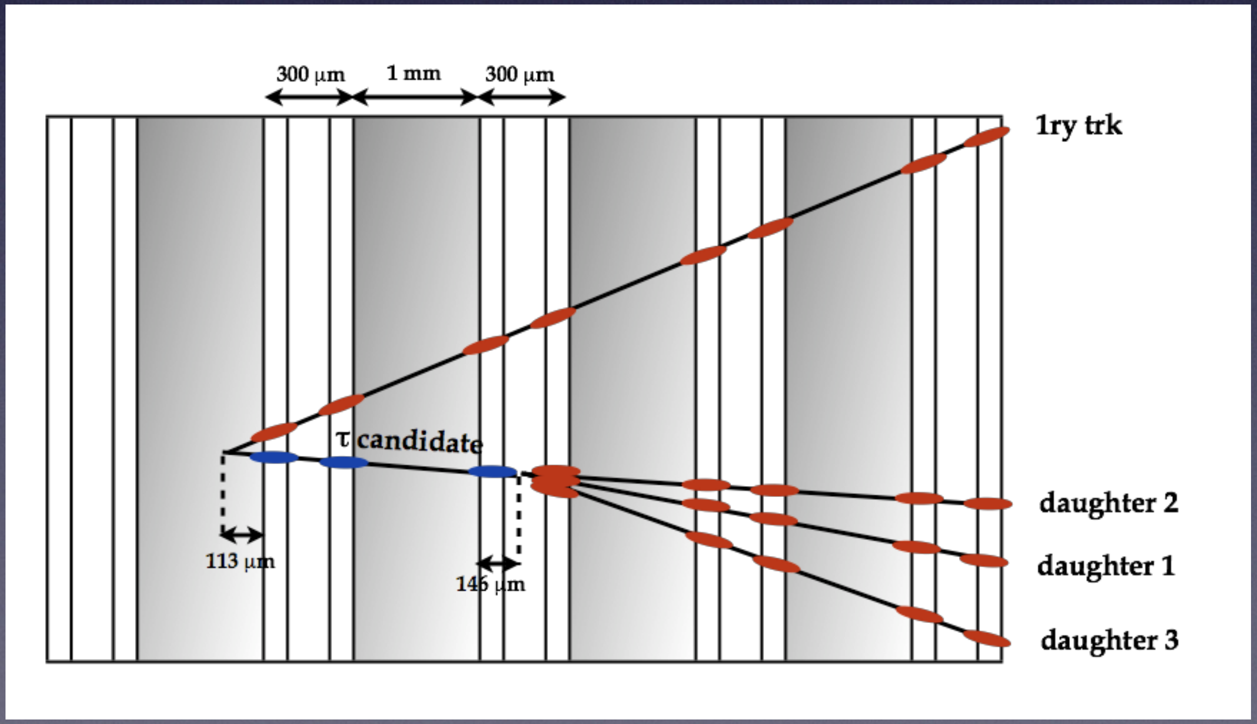


Second candidate

- In the decay search of 2011 data we found a second ν_τ candidate (*JHEP 11 (2013) 036*).
- 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

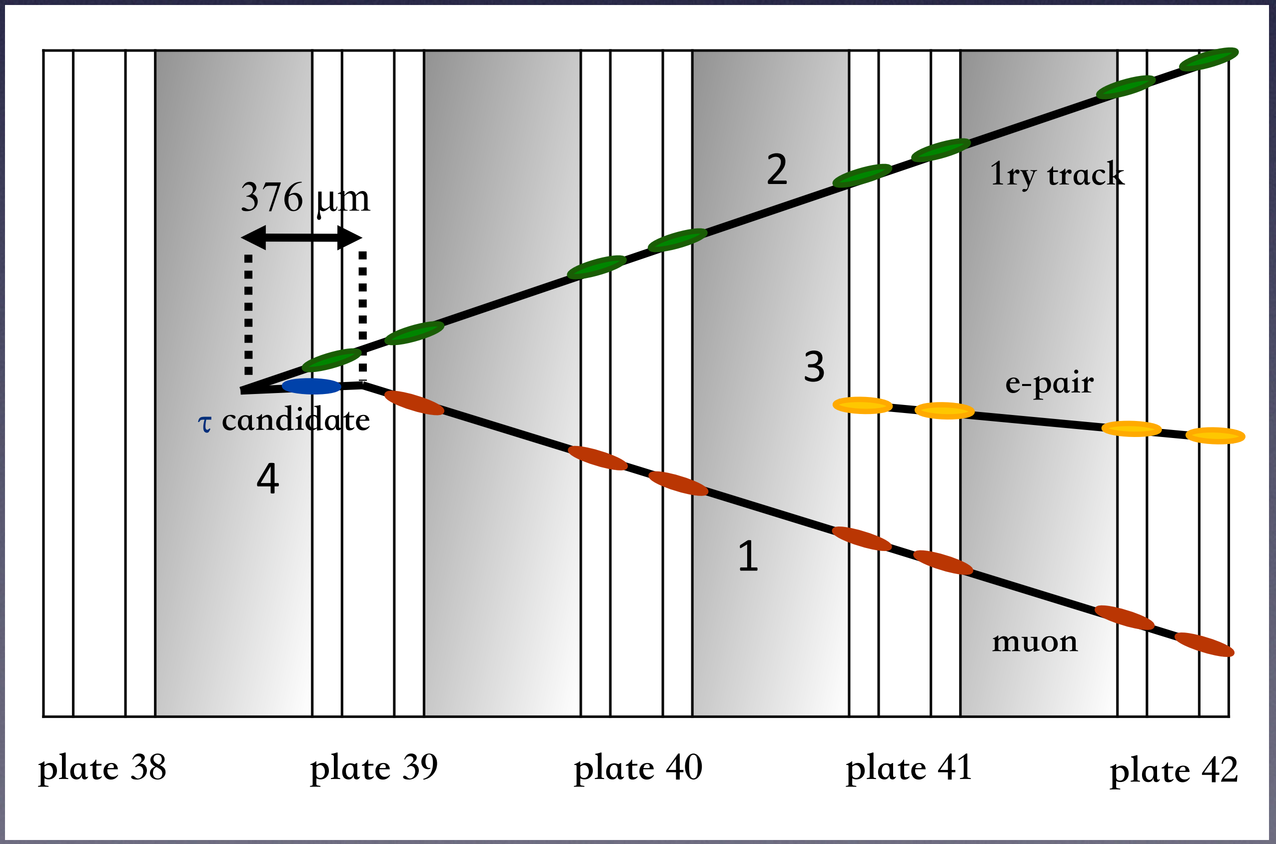


Third candidate

- In the decay search of 2012 data we found a third ν_τ candidate (*Phys. Rev. D 89 (2014) 051102*).
- 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

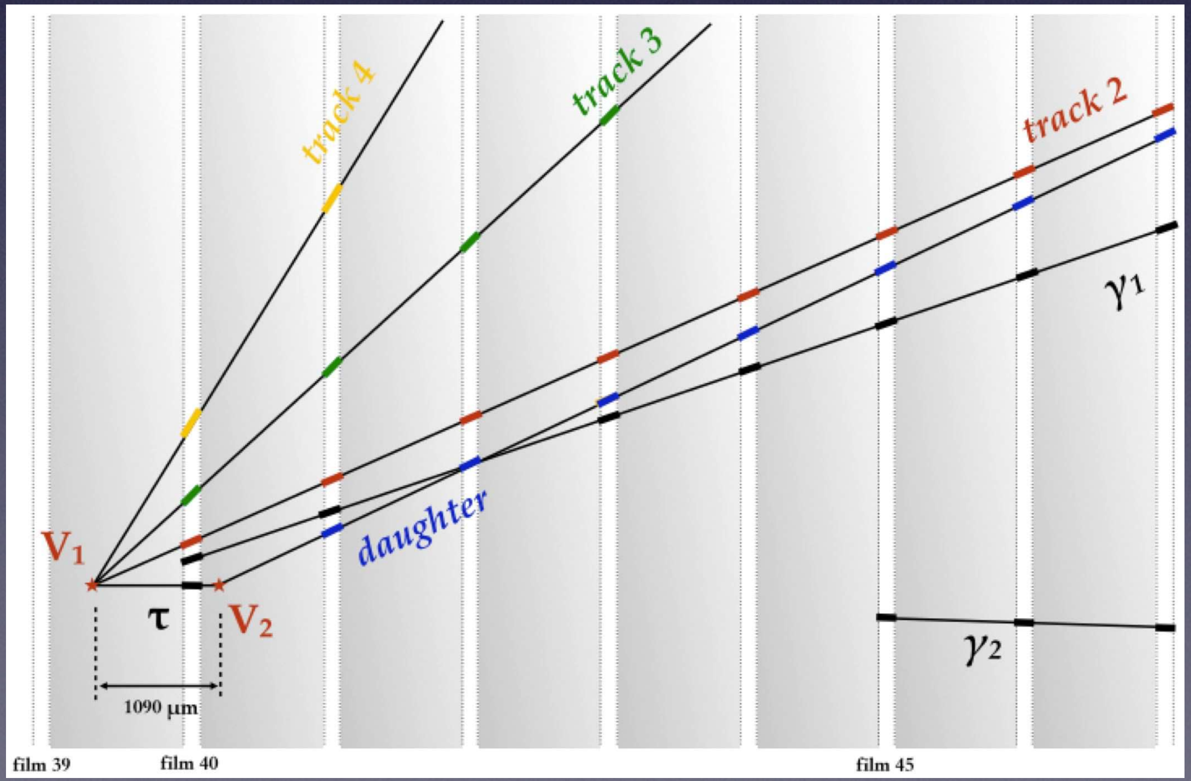


Forth candidate

- In the decay search of 2012 data we found a forth ν_τ candidate (*PTEP (2014) 101C01*).
- The event passes all selection criteria for the signal and it is classified as a possible decay of a τ into 1 prong hadron.
- Three additional tracks are attached to the primary vertex are reconstructed as hadrons for their reinteraction or for the momentum/range correlation.
- A γ attached to the primary vertex is also seen.

Kinematical variables

Variable	Observed	Cut
Kink angle (mrad)	137 ± 4	>20
Decay length (μm)	1090 ± 30	< 2 lead plates
P daughter (GeV/c)	$6^{+2.2}_{-1.2}$	>2
Daughter Pt (MeV/c)	820^{+300}_{-160}	>600
Missing Pt (MeV/c)	550^{+300}_{-200}	<1000
Φ angle (deg)	166^{+2}_{-31}	>90



Fifth candidate

- In the decay search of 2012 data we found a fifth ν_τ candidate (*Phys. Rev. Lett. 115 (2015) 121802*).
- The event passes all selection criteria for the signal and it is classified as a possible decay of a τ into 1 prong hadron.
- Only one additional track attached to the primary vertex, identified as a hadron due to its reinteraction in the downstream brick.
- The daughter is unambiguously identified as a hadron due to its interaction after 22 planes.

Kinematical variables

Variable	Observed	Cut
Kink angle (mrad)	90 ± 2	>20
Decay length (μm)	634 ± 30	< 2 lead plates
P daughter (GeV/c)	11^{+14}_{-4}	>2
Daughter Pt (MeV/c)	1000^{+1200}_{-400}	>600
Missing Pt (MeV/c)	300 ± 100	<1000
Φ angle (deg)	151 ± 1	>90