Results from the OPERA experiment in the CNGS beam

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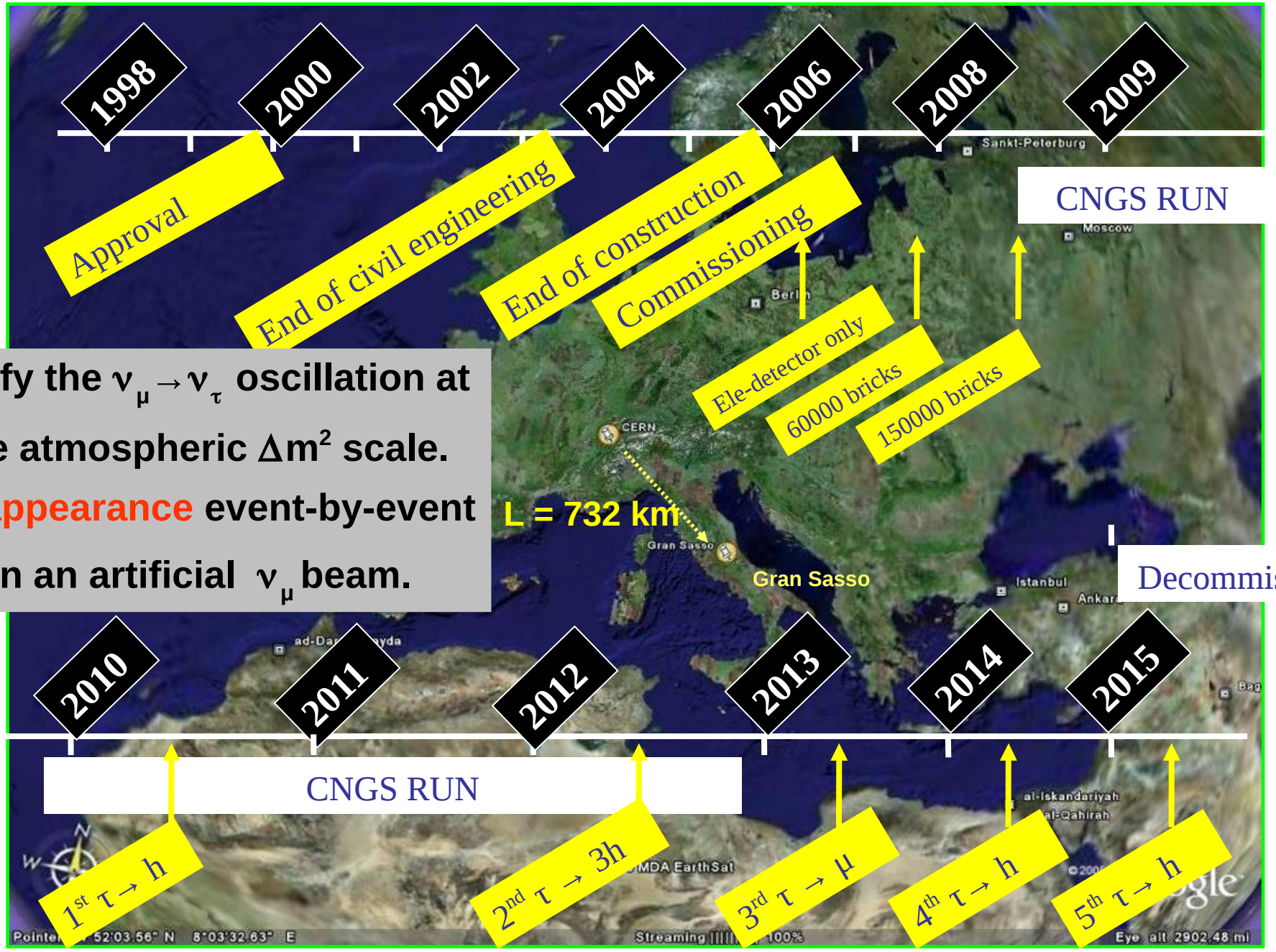
on behalf of the OPERA collaboration

NUFACT 2016

Quy Nhon, 23 August 2016

140 physicists, 11 countries, 28 institutions

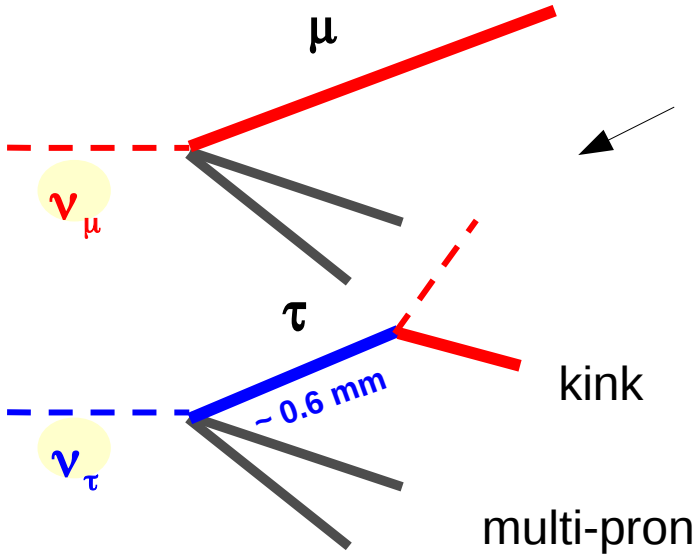
The OPERA project



Verify the $\nu_\mu \rightarrow \nu_\tau$ oscillation at the atmospheric Δm^2 scale.

ν_τ appearance event-by-event in an artificial ν_μ beam.

The ν_τ detection technique



Detect a few ν_τ^{CC} from the bulk of ν_μ^{CC}

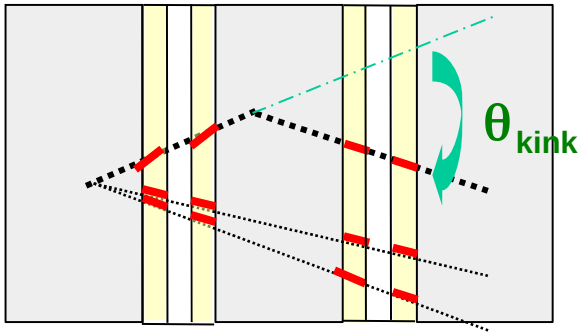
kink

$\tau^- \rightarrow \mu^- \nu_\tau \nu_\mu$	17 %
$\tau^- \rightarrow e^- \nu_\tau \nu_e$	18 %
$\tau^- \rightarrow h^- \nu_\tau n(\pi^0)$	50 %

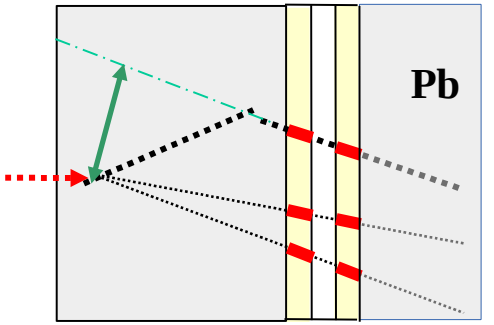
multi-prong

$\tau^- \rightarrow \pi^+\pi^-\pi^- \nu_\tau n(\pi^0)$	14 %

"long" decays: kink

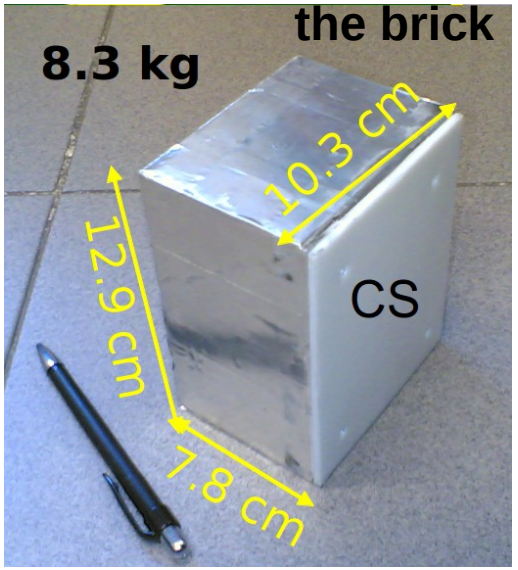


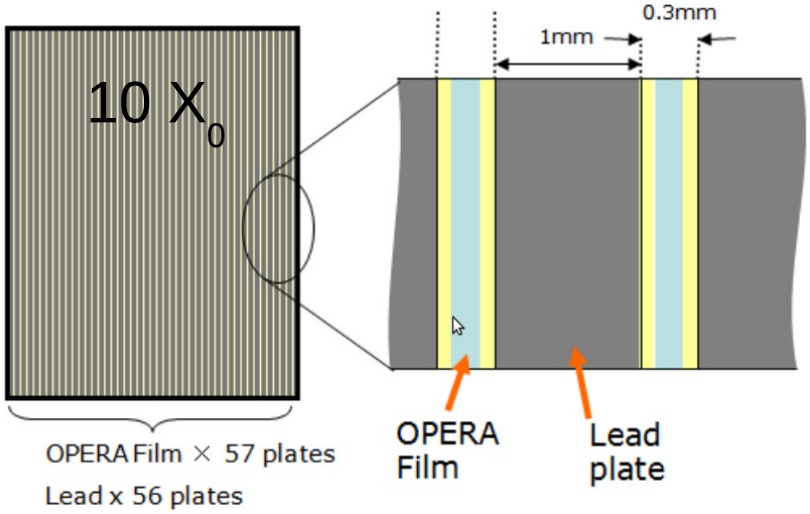
"short" decays: I.P.



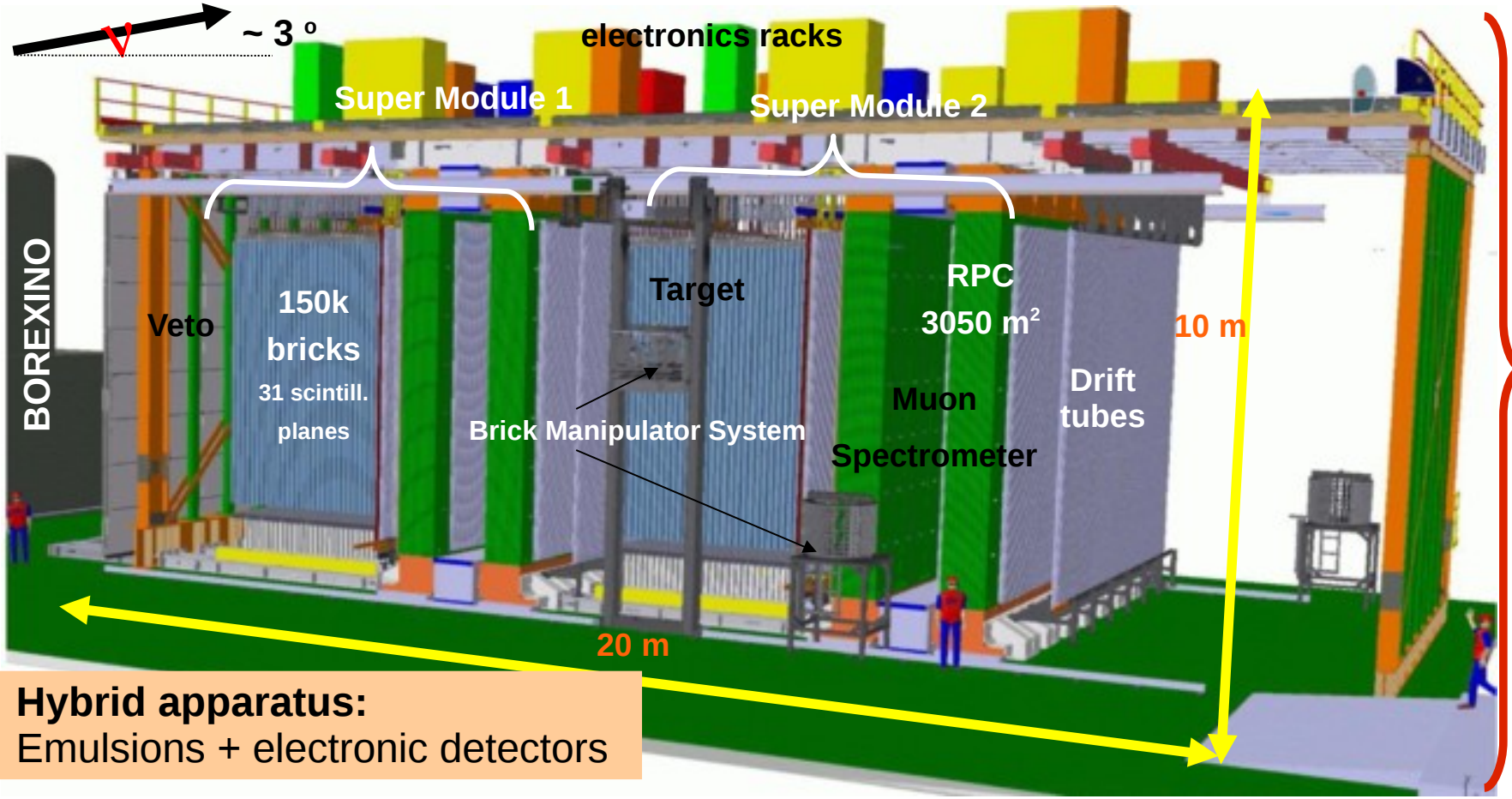
Modular detector of "Emulsion Cloud Chambers" (or bricks)
Reconciles the needs for:

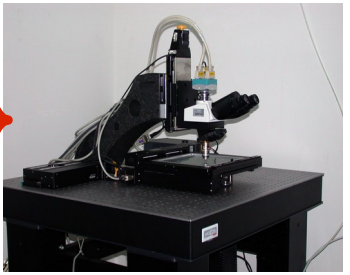
- **Large mass**
  - $N_\tau \propto (\Delta m^2)^2 M_{target}$
- **Extreme granularity**
  - μm space resolution

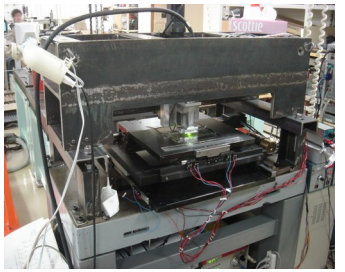




The OPERA experiment

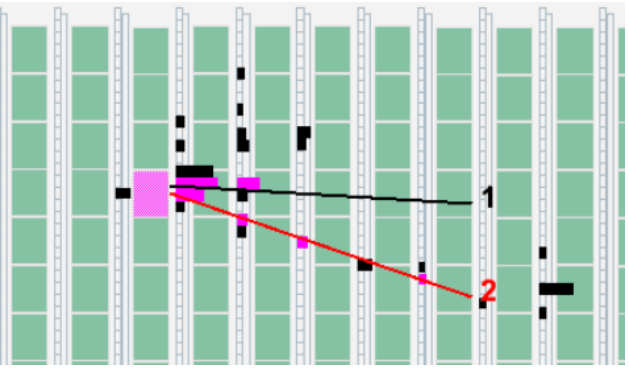






Hybrid apparatus:
Emulsions + electronic detectors

``Brick-finding"



+ several ancillary facilities "off-site":

- **Assembly/disassembly of bricks (LNGS)**
- **Brick Manipulator System (LNGS)**
- **Labelling and X ray marking (LNGS)**
- **Automatised development (LNGS)**
- **Scanning of CS doublets (LNGS+JP)**
- **Scanning bricks (Europe + JP)**

CERN Neutrinos to Gran Sasso

The oscillation peak for L= 732 km at ~ 1.5 GeV (similar to NuMI) but the beam is designed to observe τ leptons:

$< E_\nu >$	*17 GeV*
$L / < E_\nu >$	*43 km/GeV*

$N(\tau) \sim Pr(\nu_\mu \rightarrow \nu_\tau) \times \sigma_{\nu(\tau)CC}(E) \times$ flux

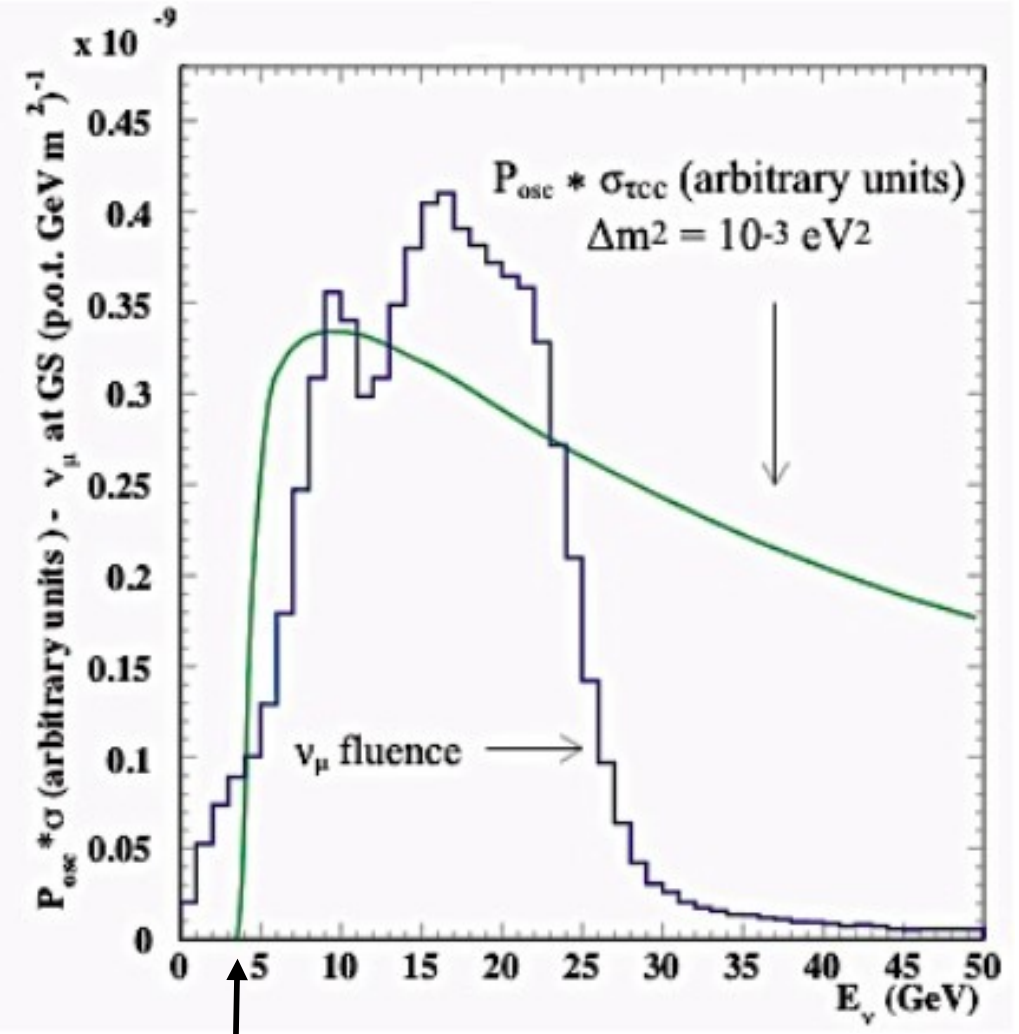
Fluxes:

$(\nu_e + \bar{\nu}_e) / \nu_\mu$	**0.9 %**
$\bar{\nu}_\mu / \nu_\mu$	**2.1 %**
ν_τ **prompt (from** D_s**)**	**negligible**

Interaction rates (1.8 x 10^{20} pot):

~ 20k ν_μ CC+NC

66.4 ν_τ CC (not efficiency corrected)



Threshold for τ at ~ 3.5 GeV.

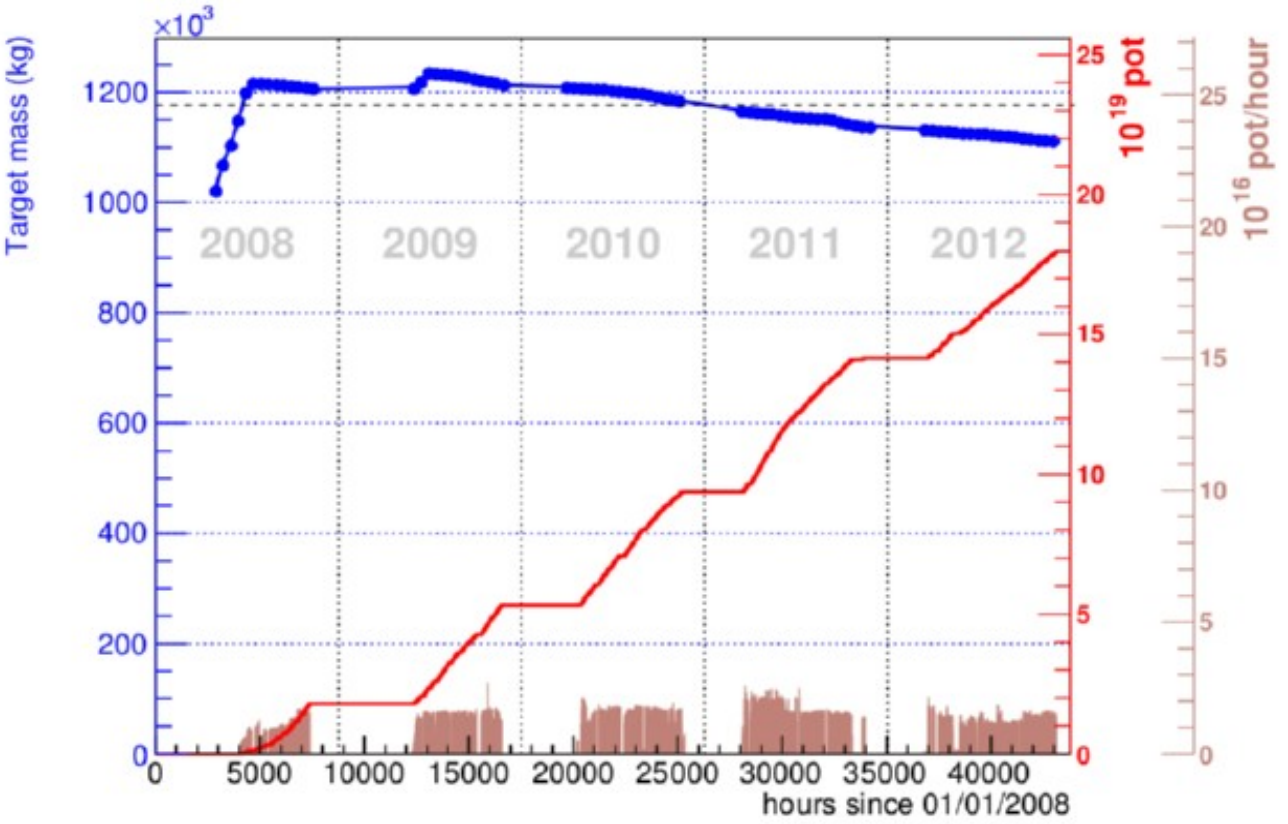
Collected data samples

The 5 year long CNGS run has ended in 2012.

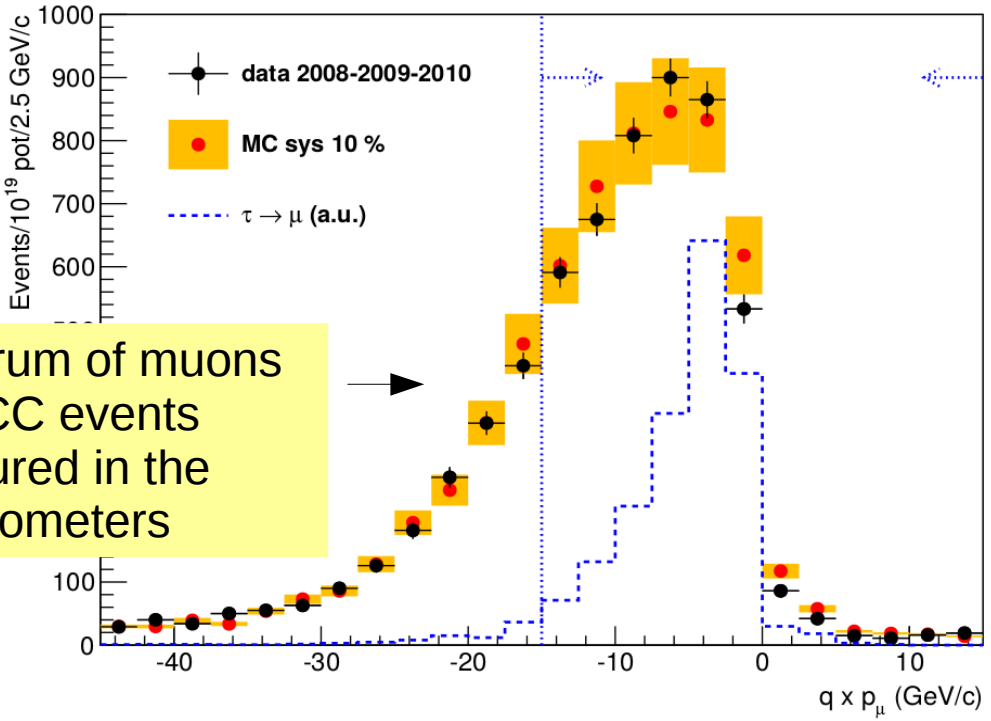
1.8 x 10^{20} p.o.t. collected
80% of the design (2.25 x 10^{20})

1.25 kton initial target mass
(150 k bricks)

19505 neutrino interactions in the emulsion targets.



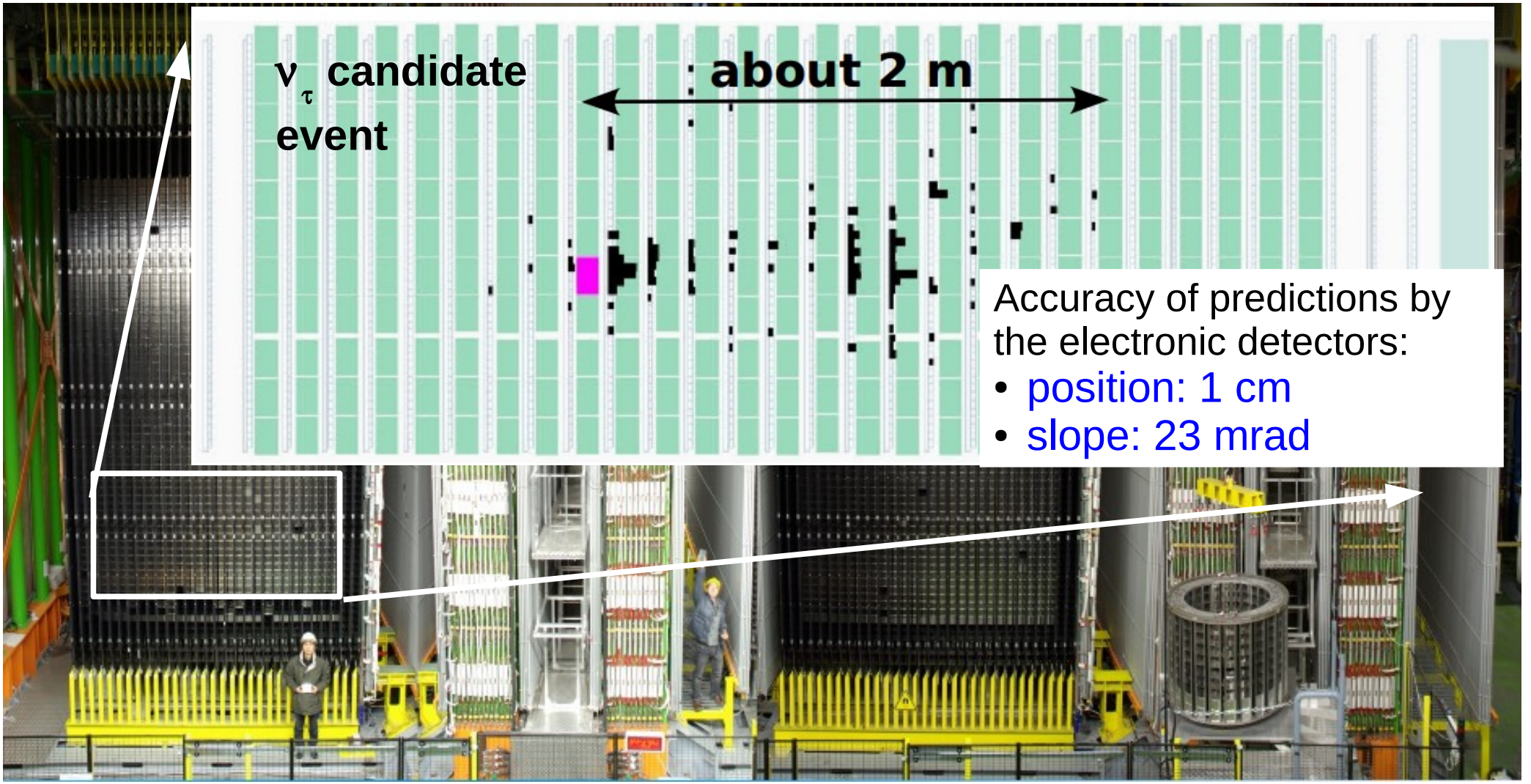
Year	Days	p.o.t. (10^{19})	ν interactions
2008	123	1.74	1698
2009	155	3.53	3693
2010	187	4.09	4248
2011	243	4.75	5131
2012	257	3.86	3923
tot	**965**	**17.97**	**19505**



Spectrum of muons from CC events measured in the spectrometers

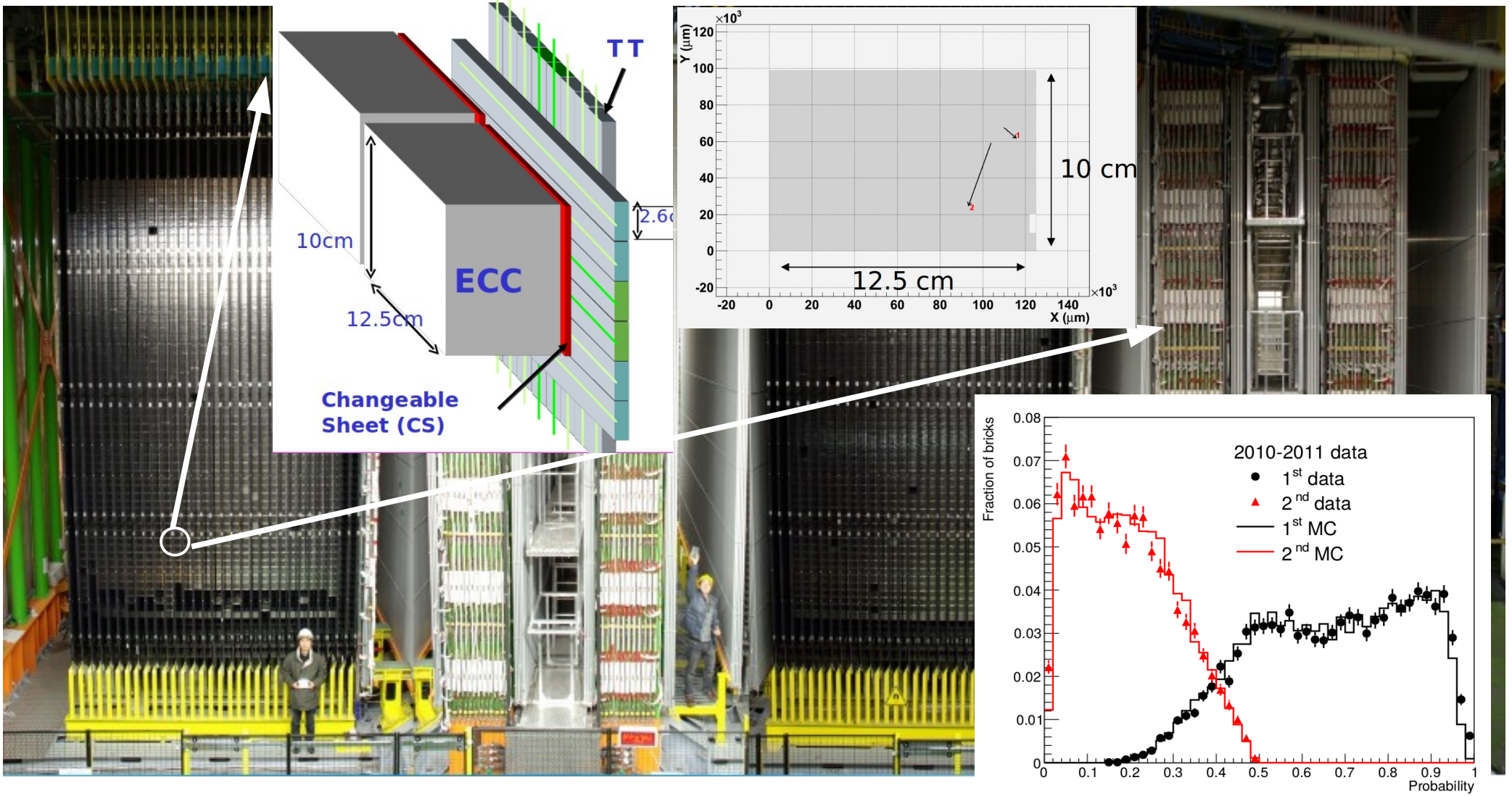
Brick finding

OPERA is a hybrid apparatus.
Electronic detectors predictions to locate bricks with neutrino interactions.



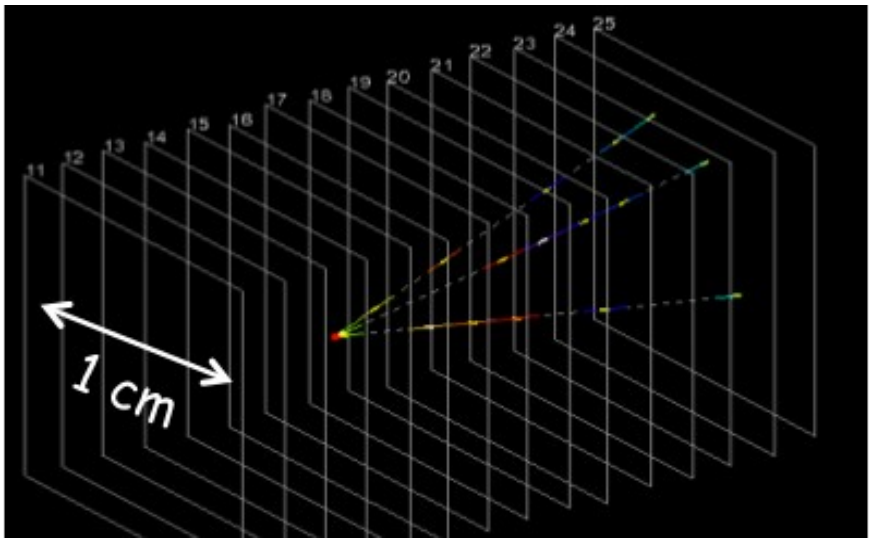
Brick finding

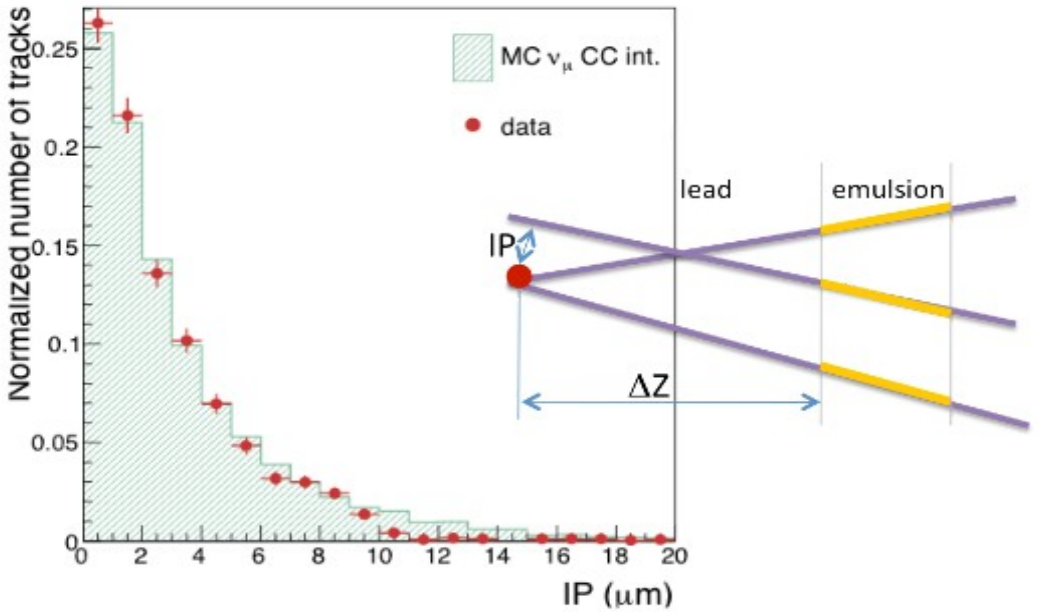
Changeable Sheets: the “bridge” from the cm scale of electronics detectors to μm scale of emulsions.
Electronic detector predictions to be confirmed by scanning of CS doublet.
Up to 4 bricks ranked in probability are considered for τ research.

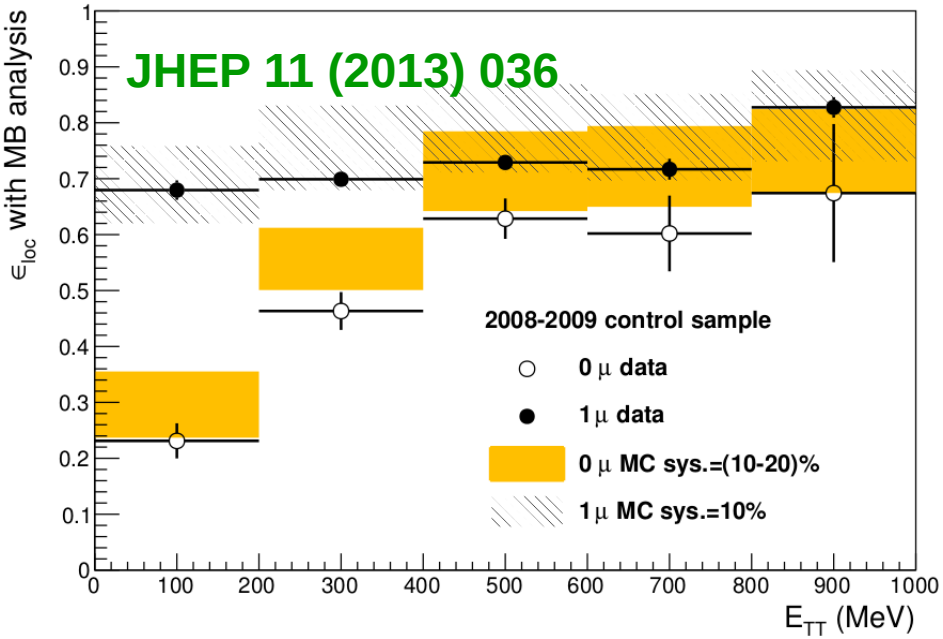


Vertex location and topology decay search in the brick

Tracks in the CS are followed upstream until a stopping point is found.
Vertex reconstruction by apposite algorithms.
Search of decay topologies (e.g. large impact parameters IP).





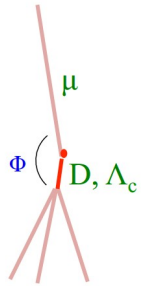


Full MC simulation of 0 μ and 1 μ samples.
Data/MonteCarlo in reasonable agreement.

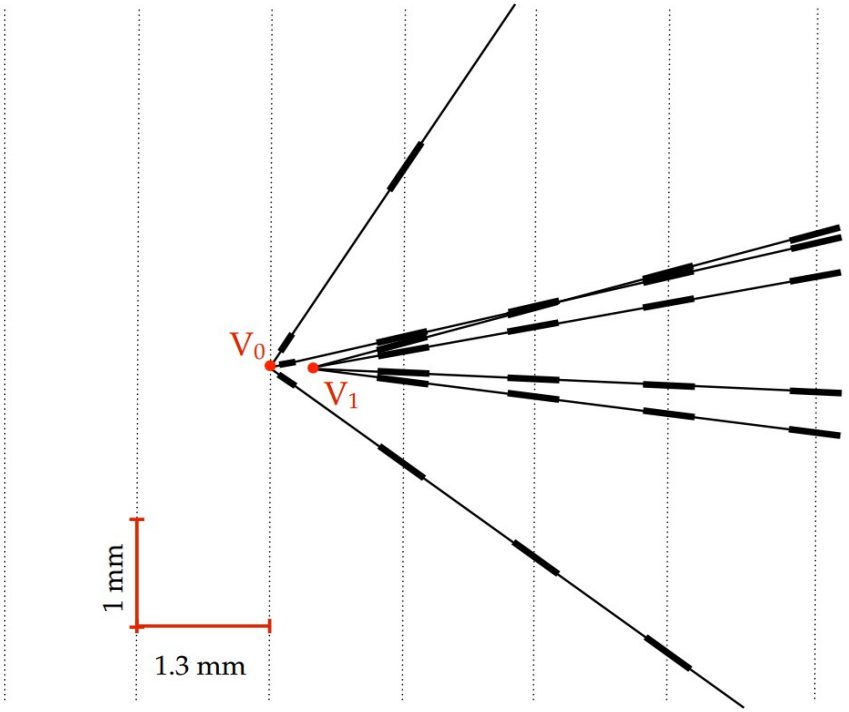
Validation with the CNGS charm events sample

Charmed hadrons produced in ν_μ CC events (μ at the primary vertex)

Charm and τ decays are topologically similar.
Test for: reconstruction efficiencies, description of kinematic variables, charm background.



2008-2010 data sample:
54 ± 4 expected events
50 observed events



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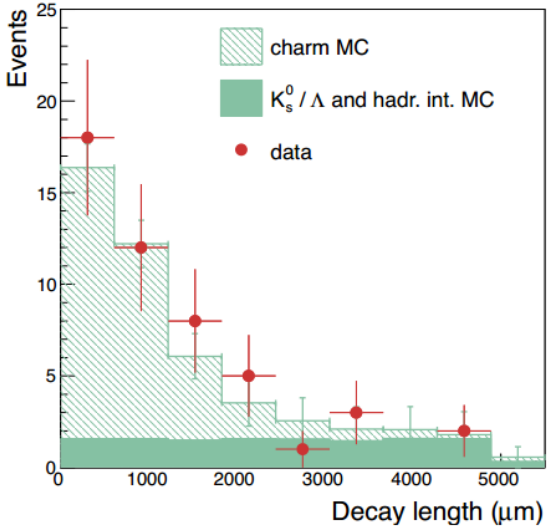
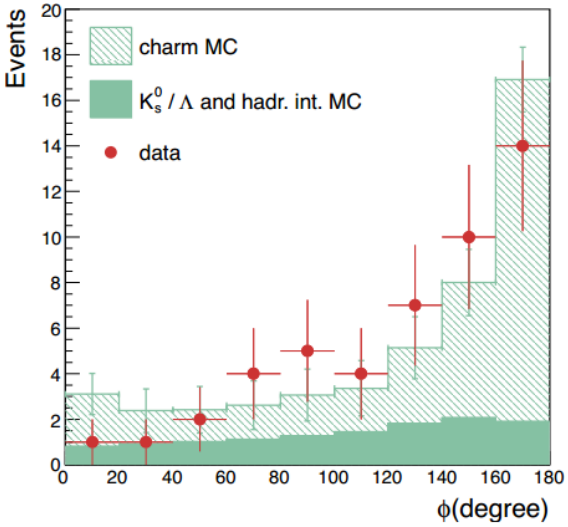
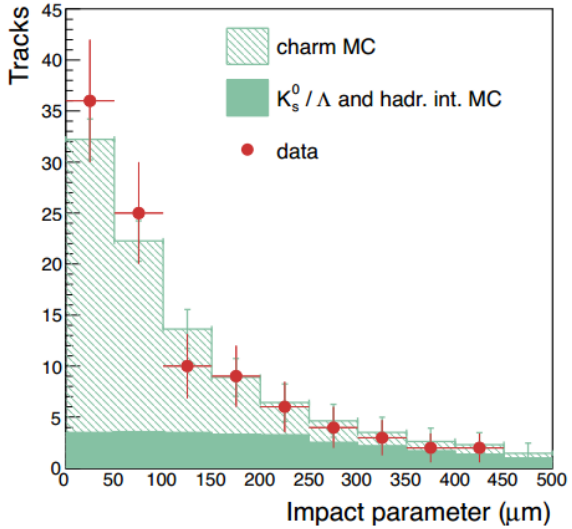
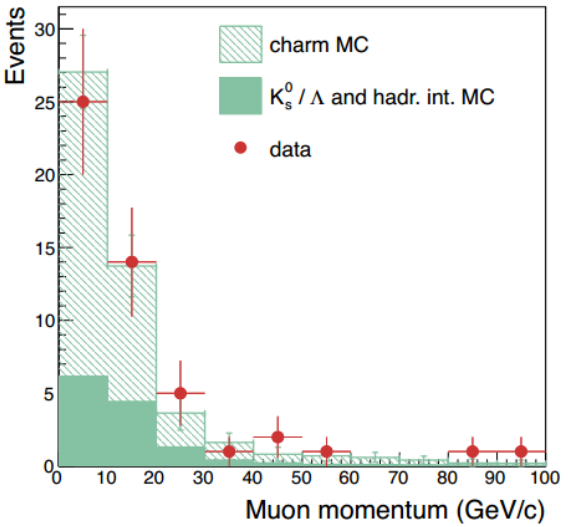




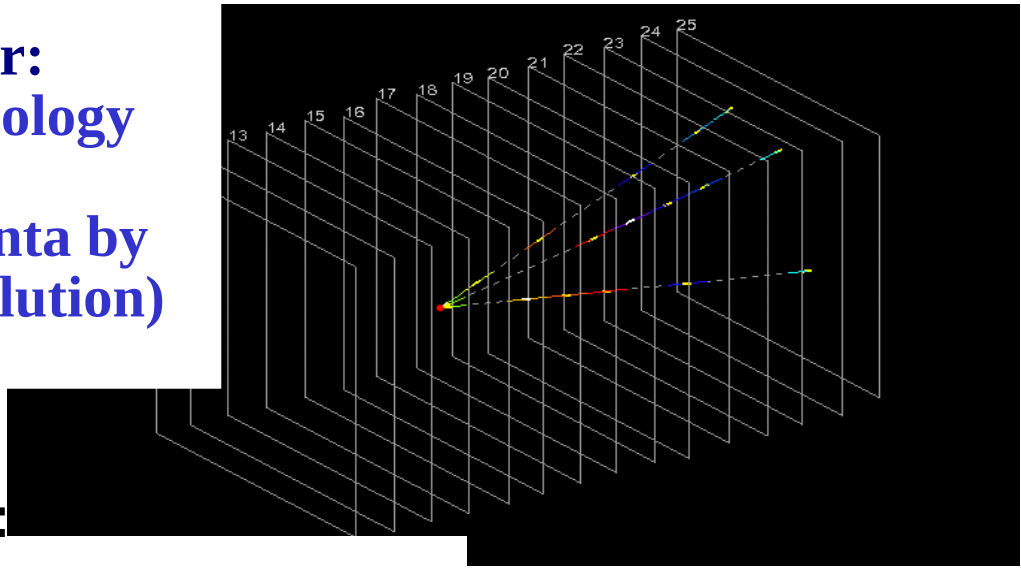




ν_τ candidate identification

The brick is a complete stand-alone detector:

- **Neutrino interaction vertex and decay topology reconstruction**
- **Measurement of charged particles' momenta by Multiple Coulomb Scattering (20-30% resolution)**
- **e/γ separation and energy measurement**



Kinematical cuts to increase S/B ratio:

variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
lepton-tag		No μ or e at the primary vertex		
z_{dec} (μm)	$[44, 2600]$	< 2600	$[44, 2600]$	< 2600
p_T^{miss} (GeV/c)	$< 1^\star$	$< 1^\star$	/	/
ϕ_{lH} (rad)	$> \pi/2^\star$	$> \pi/2^\star$	/	/
p_T^{2ry} (GeV/c)	$> 0.6(0.3)$*	/	> 0.25	> 0.1
p^{2ry} (GeV/c)	> 2	> 3	> 1 and < 15	> 1 and < 15
θ_{kink} (mrad)	> 20	< 500	> 20	> 20
m, m_{min} (GeV/c^2)	/	> 0.5 and < 2	/	/

0.3 GeV/c in presence of γ in the decay vertex

For candidate events, Track Follow Down (TFD) procedure:
All reconstructed event tracks followed from brick to brick,

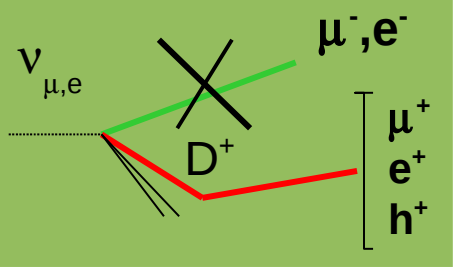
- **to enhance μ-identification (99%)**
- **improve μ/h discrimination (range measurement and nuclear interaction detection)**

$\nu_\mu \rightarrow \nu_\tau$ background characterization

Monte Carlo simulation benchmarked on control samples.

In order of decreasing relevance

CC with charm production (all channels) IF the primary lepton is not identified and the daughter charge is not (or incorrectly) measured

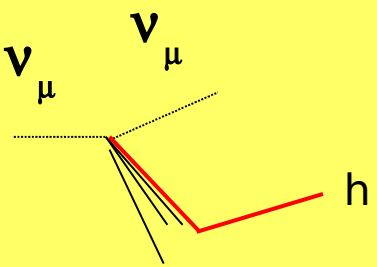


MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

Reduced by "track follow down" procedure and large angle scanning

Hadronic interactions

Background for $\tau \rightarrow$ h

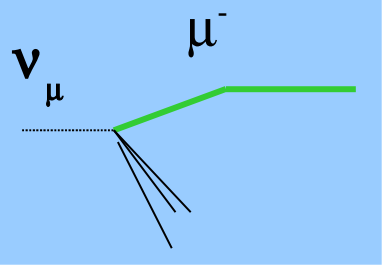


FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

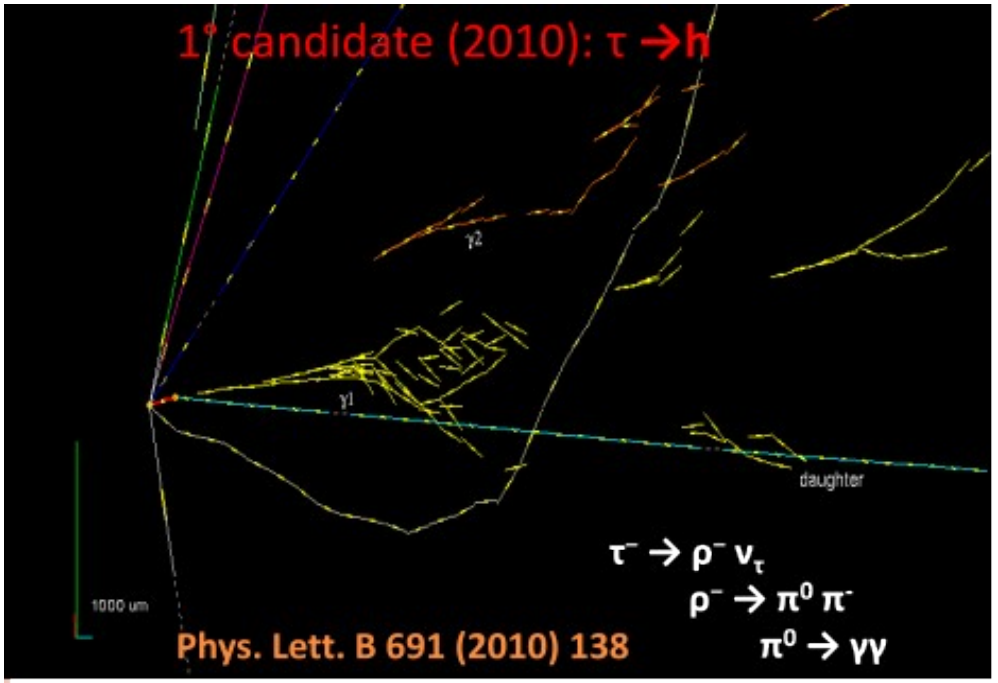
Large angle muon scattering

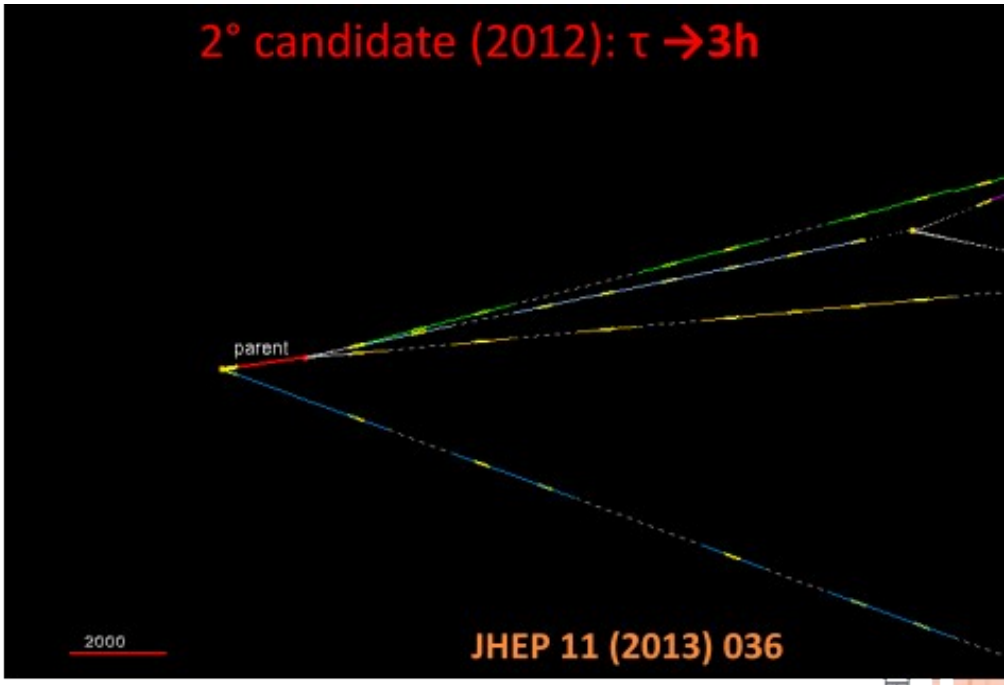
Background for $\tau \rightarrow \mu$

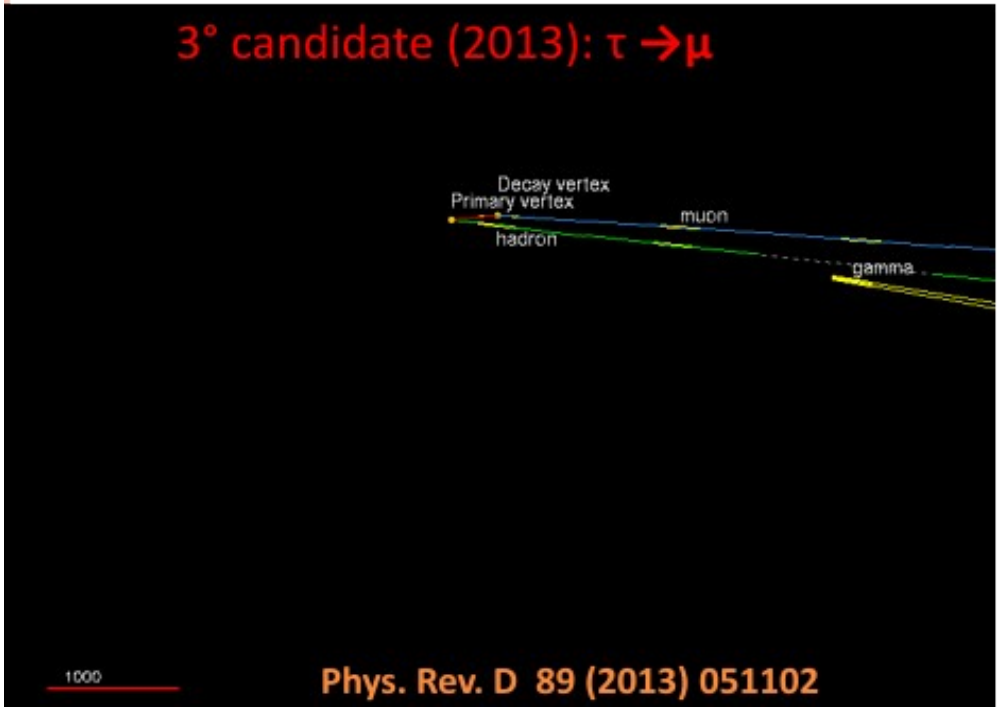


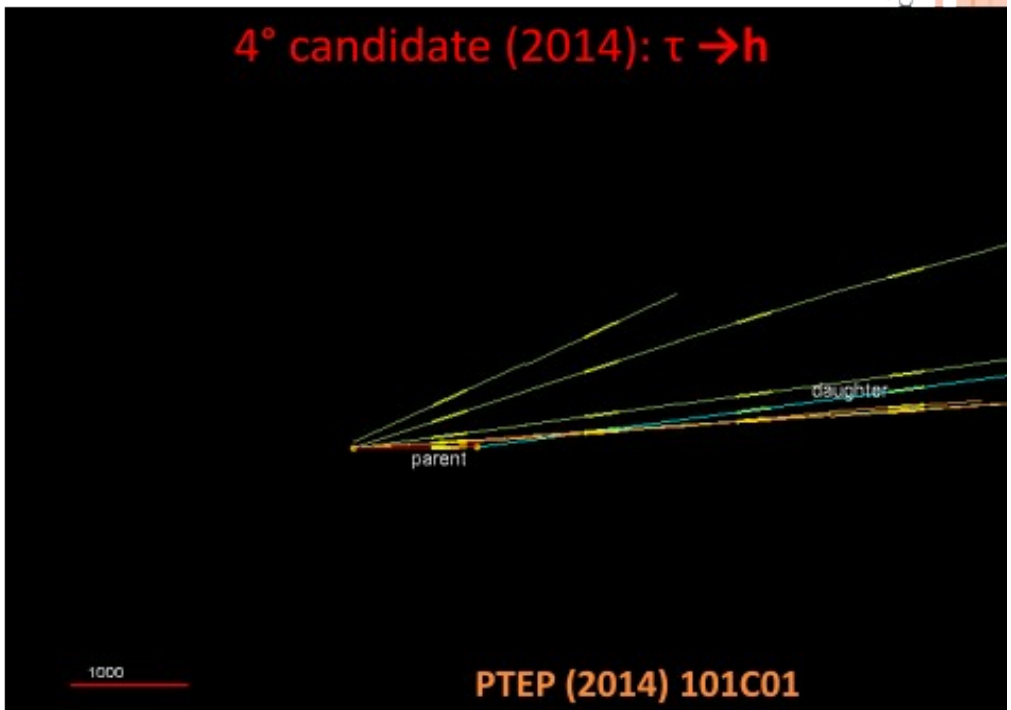
Measurements in the literature (Lead form factor), improved MC simulations

ν_τ events observed in OPERA

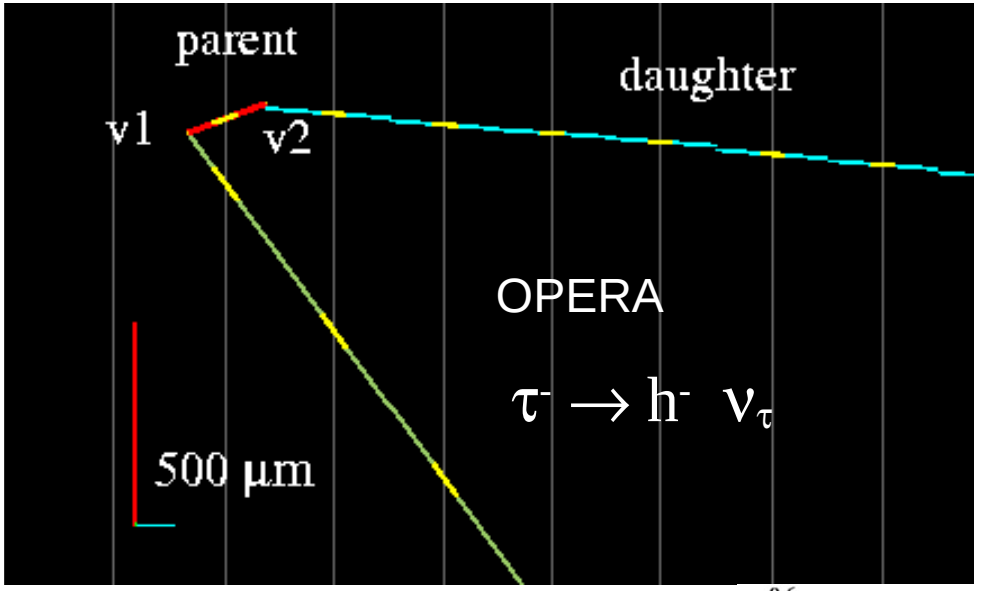


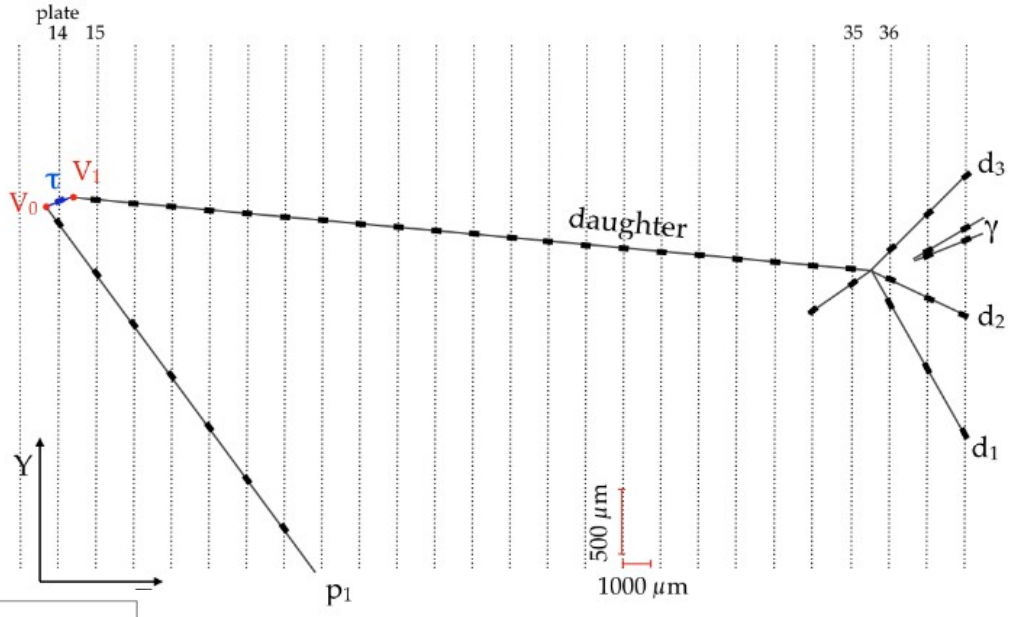


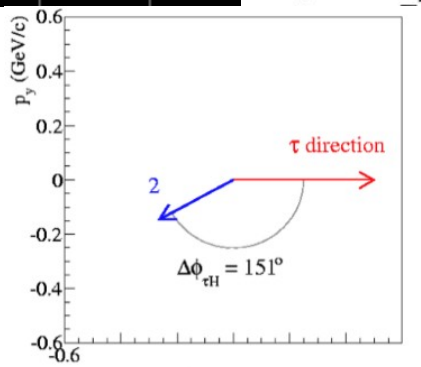




Fifth ν_τ candidate: discovery of ν_τ appearance







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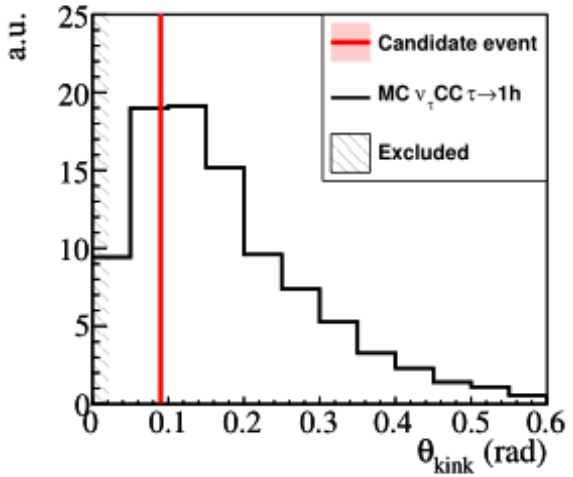
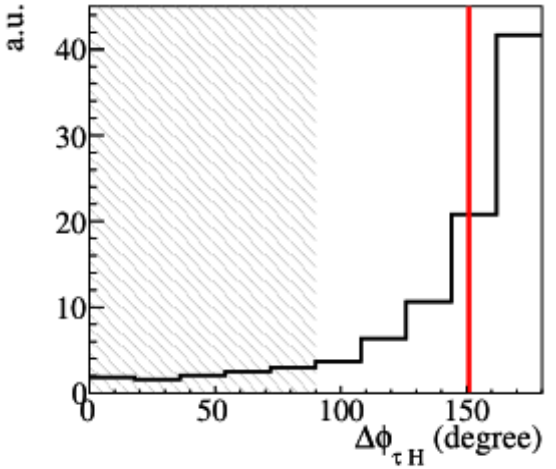
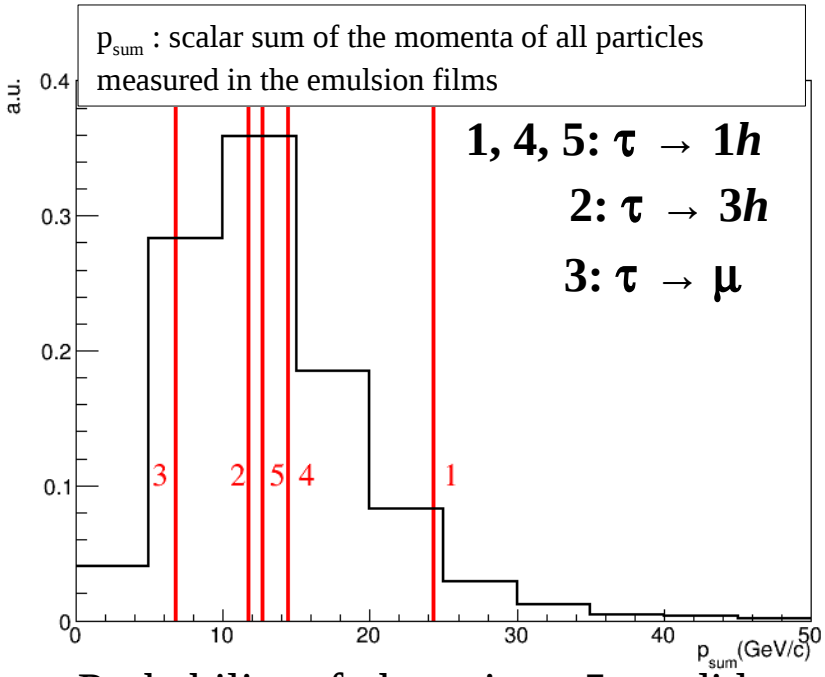
VARIABLE	VALUE
Kink angle (mrad)	**90 ± 2**
decay length (µm)	**634 ± 30**
P^{2ry} (GeV/c)	**11^{+14}_{-4}**
$P^{miss}t$ (GeV/c)	**0.3±0.1**
ϕ (degrees)	**151 ± 1**





$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis results

Decay channel	Expected background				expected signal events $\Delta m^2 = 2.44\times10^{-3}$ eV^2	Observed events
	Charm	*Had. Re-interaction*	*Large μ scattering*	*Total*		
$\tau \rightarrow 1h$	0.017±0.003	0.022±0.006	-	0.04±0.01	0.52±0.10	3
$\tau \rightarrow 3h$	0.17±0.03	0.003±0.001	-	0.17±0.03	0.73±0.14	1
$\tau \rightarrow \mu$	0.004±0.001	-	0.0002±0.0001	0.004±0.001	0.61±0.12	1
$\tau \rightarrow e$	0.03±0.01	-	-	0.03±0.01	0.78±0.16	0
Total	0.22±0.04	0.02±0.01	0.0002±0.0001	0.25±0.05	2.64±0.53	5



Probability to be explained by background fluctuation p = 1.1×10^{-7}

No oscillation hypothesis excluded at 5.1 σ

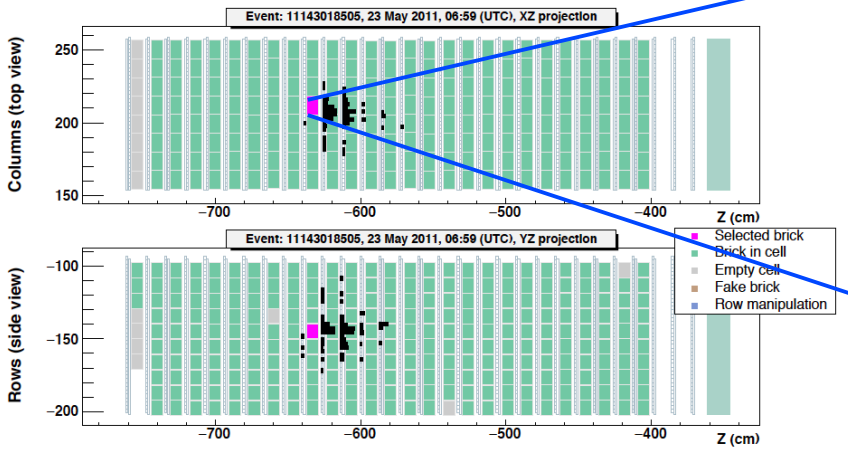
$\Delta m_{23}^2 = 3.3 \times 10^{-3}$ eV^2 with a 90% confidence interval [2.0, 5.0] x 10^{-3} eV^2 (assuming full mixing)

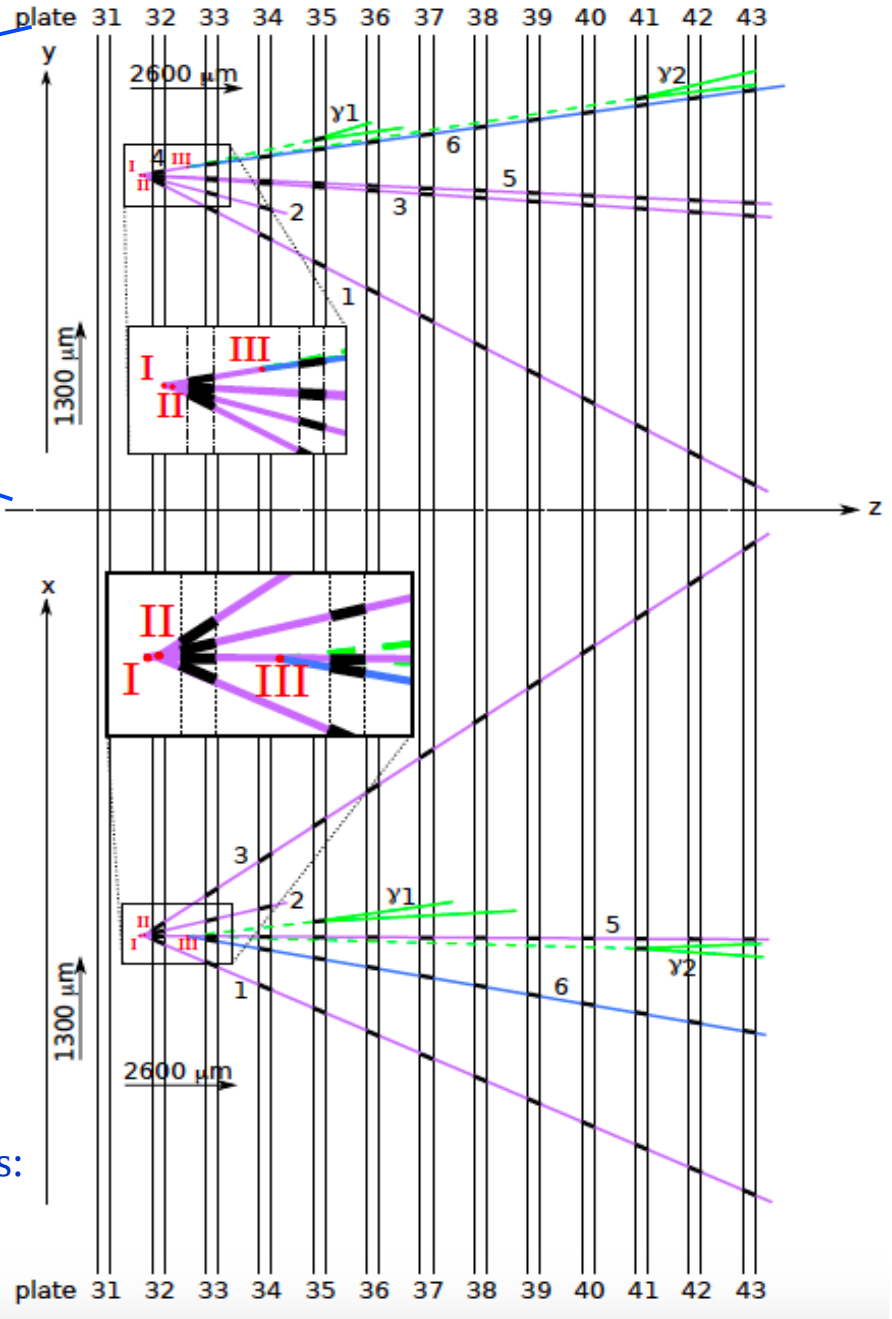
Probability of observing ≥5 candidates (2.9 S+B events expected): 17%

Frequency of configurations being less probable than the observed one: 6.4%

A ν event with 3 vertices: description

Muonless event





A primary and two secondary vertices found in emulsic
Electromagnetic activity (γ's) at the kink point.

Vertex ID	Attached tracks	x (μm)	y (μm)	z (μm)
I (primary)	2, 4, 5	15077.0	59157.9	-33081.8
II (secondary)	1, 3	15085.9	59149.9	-32979.2
III (kink)	4, 6	15073.9	59262.4	-31926.4

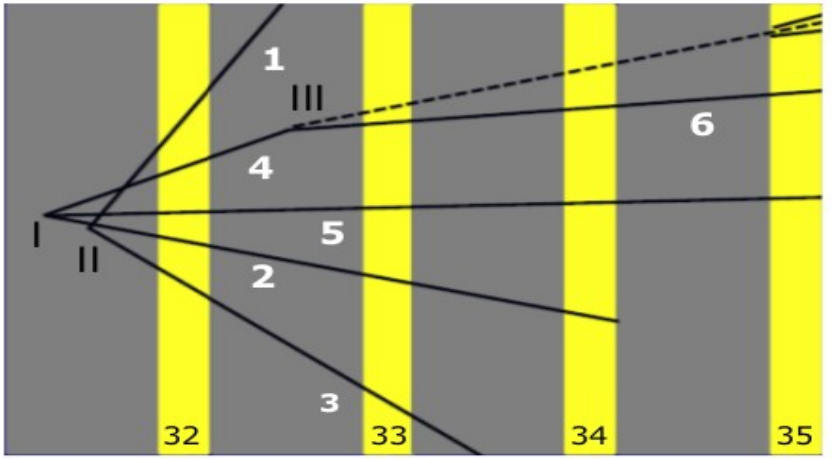
Track ID	p best fit (GeV/c)	68 % p range (GeV/c)
1	2.1	[1.6 ; 3.1]
3	4.3	[3.1 ; 7.1]
5	0.54	[0.45 ; 0.68]
6 (daughter)	2.7	[2.1 ; 3.7]

Flight lengths:
II: 103 µm
III: 1160 µm

Invariant masses at both secondary vertices larger than 1 GeV.

A ν event with 3 vertices: analysis

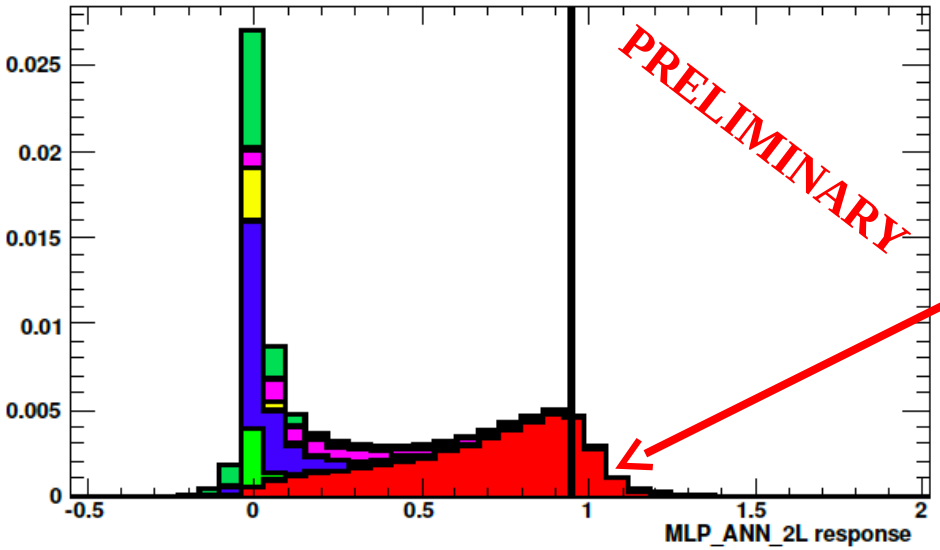
Vertex 2 can be a charmed particle decay.
Vertex III not classified as ν_τ interaction by standard selection cuts.
Dedicated simulations and Artificial Neural Network (ANN) analysis have been performed.

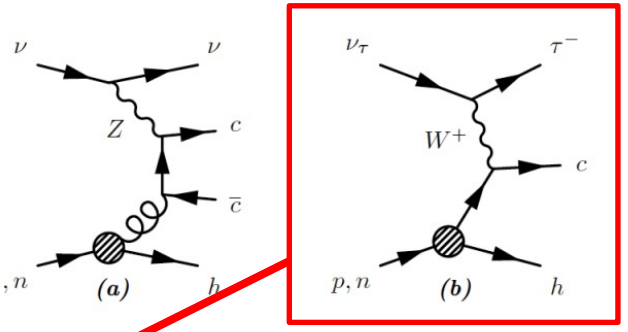


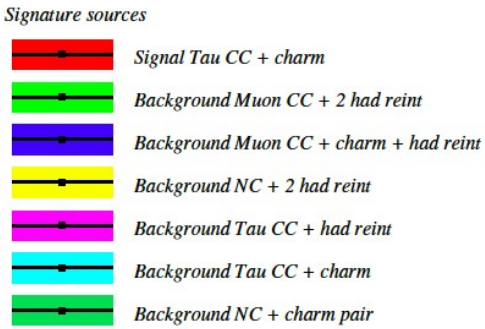
Sample	Expected events (10^{-3})
DIS ν_μ CC	4.0 ± 0.5
DIS ν_μ CC + charm	20.5 ± 0.5
DIS ν NC	3.8 ± 0.3
DIS ν NC + $c\bar{c}$ pair	12.59 ± 0.02
DIS ν_τ CC	9.0 ± 0.1
DIS ν_τ CC + charm	44.5 ± 0.1
Total	94.4

Event classified as ν_τ interaction with charm production (first topology of this kind).
3.5 σ CL with respect to bkg only hypothesis.

In total, less than 0.1 expected event.





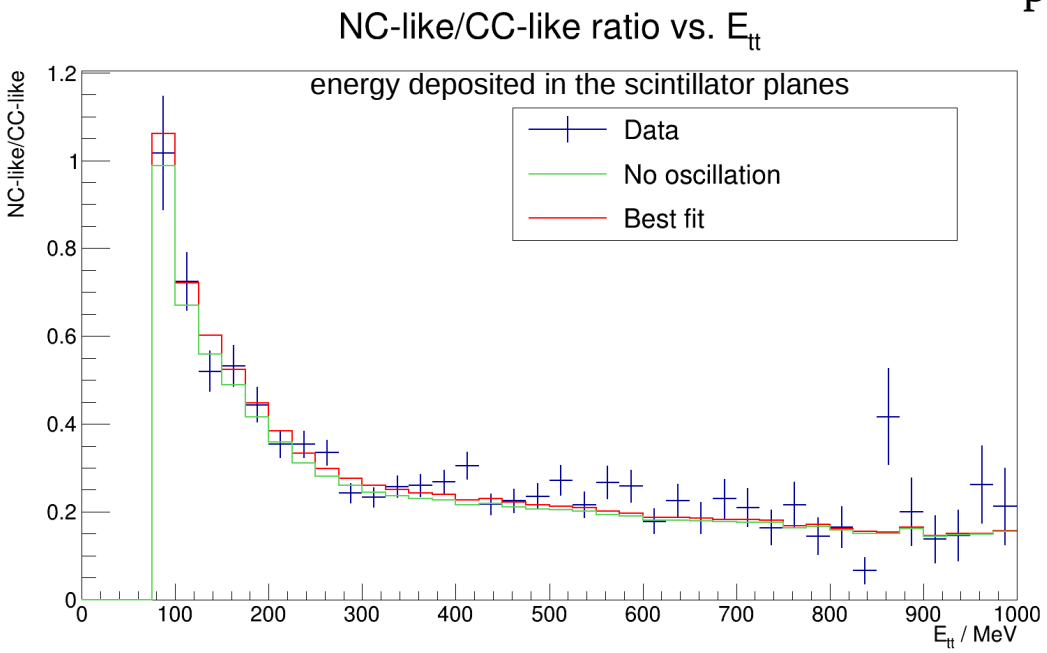


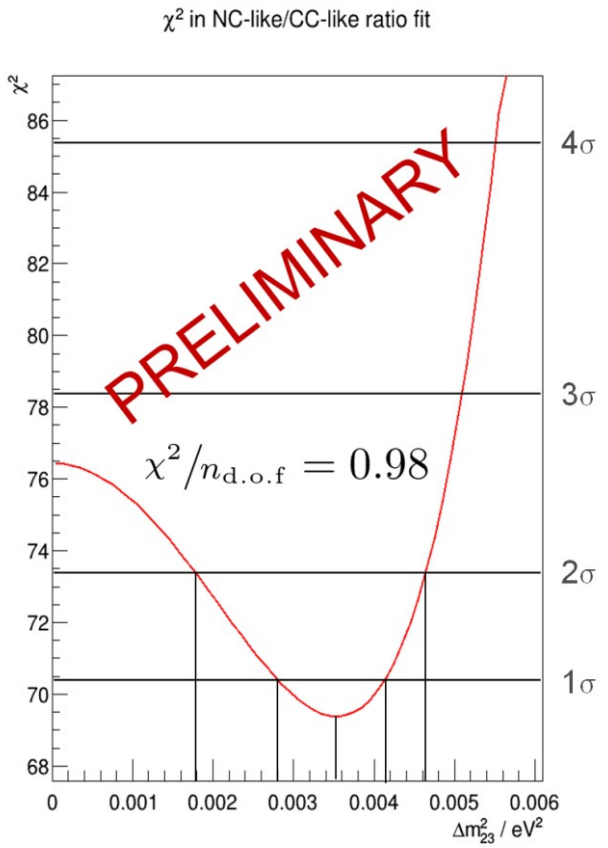
More details at ICNFP 2016

ν_μ disappearance

- Full data sample (2008-2012)
- Use of electronic detector data only and separation between CC and NC like events

Fit using NC-like/CC-like ratio in which all mixing parameters are fixed to the PDG values **but Δm_{32}^2**





reweighting MC according to oscillation probability and minimizing χ^2 between MC and data

To reduce systematic effects coming from the beam uncertainty (no near detector), NC like over CC like ratio is used

systematics under study

⇒Preliminary measurement of Δm_{32}^2

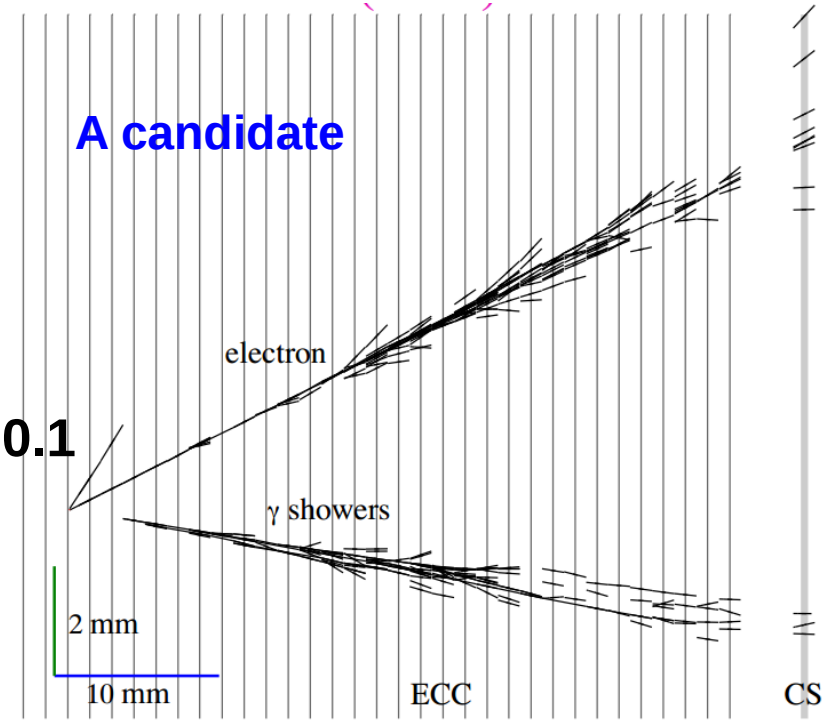
⇒consistent with the world average and the internal OPERA appearance results

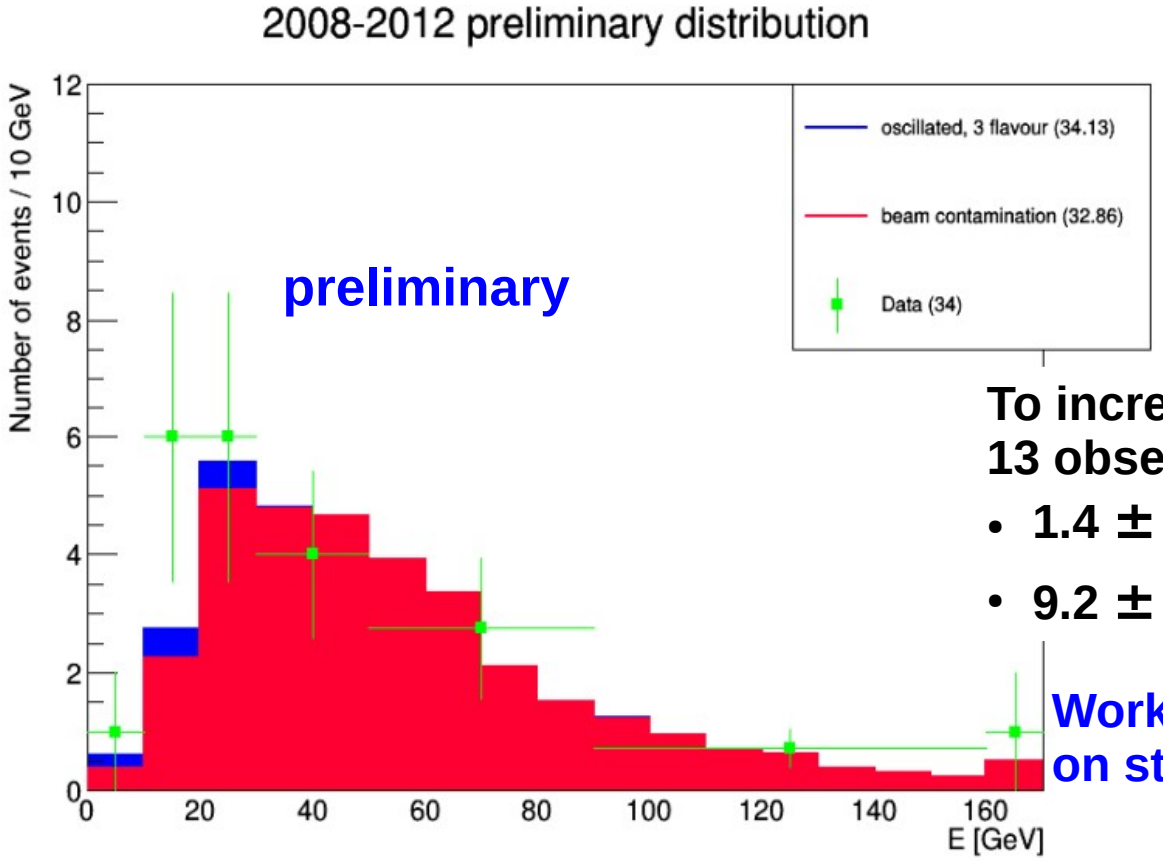
$\nu_\mu \rightarrow \nu_e$ oscillation analysis

2008-2012 Fulls sample (17.97×10^{19} p.o.t.):
34 ν_e events observed.

Expected number of events:

- **$\nu_\mu \rightarrow \nu_e$ oscillation: 2.9 ± 0.4**
- **ν_e beam contamination: 36.7 ± 5**
- **Other backgrounds ($\tau \rightarrow e$ and π^0 mis-id): 1.2 ± 0.1**





To increase signal/bkg ratio, E<30 GeV cut:
13 observed events for

- **1.4 ± 0.2 events from $\nu_\mu \rightarrow \nu_e$ oscillation**
- **9.2 ± 1 events from background**

Work in progress to extract exclusion limits on sterile neutrino according to 3+1 model.

$\nu_\mu \rightarrow \nu_\tau$: preliminary results on sterile ν

3+1 model

standard

$$P(\nu_\mu \rightarrow \nu_\tau) = 4\left|U_{\mu 3}^{\ 2}\right|\left|U_{\tau 3}^{\ 2}\right|\sin^2\frac{\Delta_{31}}{2}$$

(normal hierarchy)

exotic

$$+4\left|U_{\mu 4}^{\ 2}\right|\left|U_{\tau 4}^{\ 2}\right|\sin^2\frac{\Delta_{41}}{2}$$

$$+2\Re\left[U_{\mu 4}^{*}U_{\tau 4}U_{\mu 3}U_{\tau 3}^{*}\right]\sin\Delta_{31}\sin\Delta_{41}$$

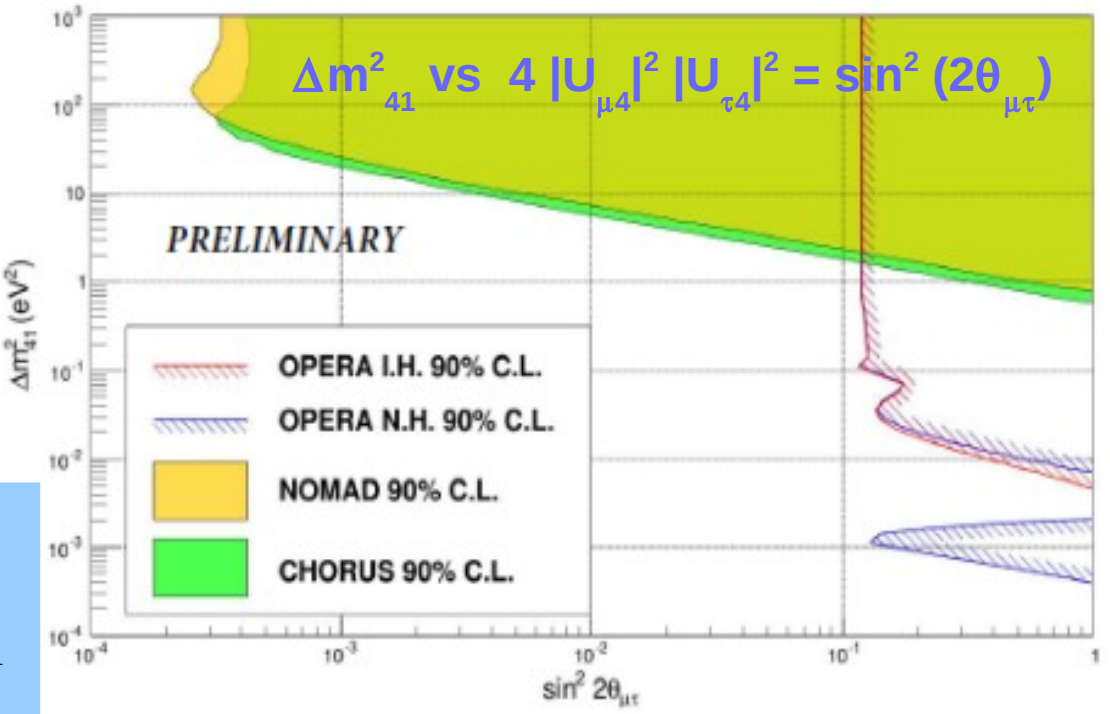
$$-4\Im\left[U_{\mu 4}^{*}U_{\tau 4}U_{\mu 3}U_{\tau 3}^{*}\right]\sin^2\frac{\Delta_{31}}{2}\sin\Delta_{41}$$

$$+8\Re\left[U_{\mu 4}^{*}U_{\tau 4}U_{\mu 3}U_{\tau 3}^{*}\right]\sin^2\frac{\Delta_{31}}{2}\sin\frac{\Delta_{41}}{2}$$

$$+4\Im\left[U_{\mu 4}^{*}U_{\tau 4}U_{\mu 3}U_{\tau 3}^{*}\right]\sin\Delta_{31}\sin\frac{\Delta_{41}}{2}$$

Interference term

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{2E}$$

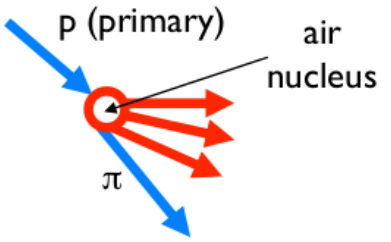


- 90% CL exclusion limit on Δm^2_{41} lowered down to 10^{-2} eV^2 for $\sin^2(2\theta_{\mu\tau}) > 0.5$

- At large Δm^2_{41} : $\sin^2(2\theta_{\mu\tau}) < 0.119$ at 90% CL

Update of JHEP 1506 (2015) 069

Cosmic rays: $R = N_{\mu+}/N_{\mu-}$

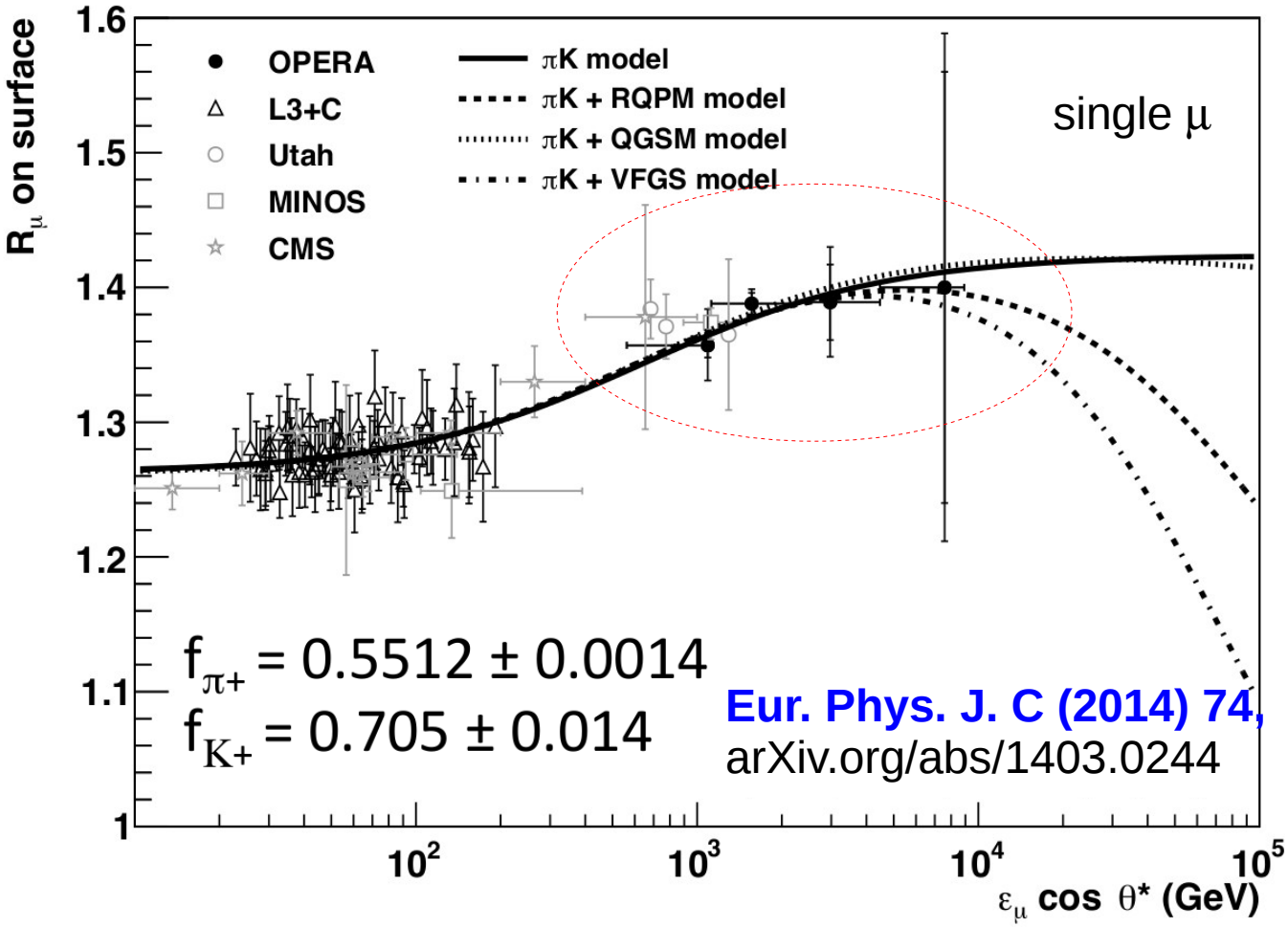


- Highest-E region reached!
- opposite magnet polarities runs → lower systematics
- Strong reduction of the charge ratio for multiple muon events

1 μ	1.377 ± 0.006
Multi-μ	1.098 ± 0.023

- Results compatible with a simple π-K model
- No significant contribution of the prompt component up to $E_\mu \cos\theta^* \sim 10$ TeV
- Validity of Feynman scaling in the fragmentation region up to $E_\mu \sim 20$ TeV ($E_N \sim 200$ TeV)

$$\phi_{\mu\pm} \propto \frac{a_\pi f_{\pi\pm}}{1 + b_\pi \mathcal{E}_\mu \cos\theta/\epsilon_\pi} + R_{K\pi} \frac{a_K f_{K\pm}}{1 + b_K \mathcal{E}_\mu \cos\theta/\epsilon_K}$$



Conclusions

- 1.8 x 10^{20} pot by CNGS from 2008-12 (80% of design).
- 5 ν_τ candidates so far with 0.25 expected background events.
- No oscillation hypothesis excluded at **5.1 σ.**
- In addition to the standard analysis, observed also a τ neutrino interaction with charm production.

- Study on $\nu_\mu \rightarrow \nu_e$ sub-dominant oscillation channel in progress.
- First results from ν_μ disappearance analysis shown.
- Sterile neutrino: limits on $|U_{\mu 4}|^2|U_{\tau 4}|^2$ from ν_τ appearance results.
- Cosmic ray physics: atmospheric μ^+/μ^- in the highest energy region to date.