Latest results from the OPERA experiment

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on behalf of the OPERA collaboration

XVI International Workshop on Neutrino Telescopes

Venezia, 3 March 2015

140 physicists, 11 countries, 28 institutions

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
Frascati
L'Aquila,
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoyn
Nihon

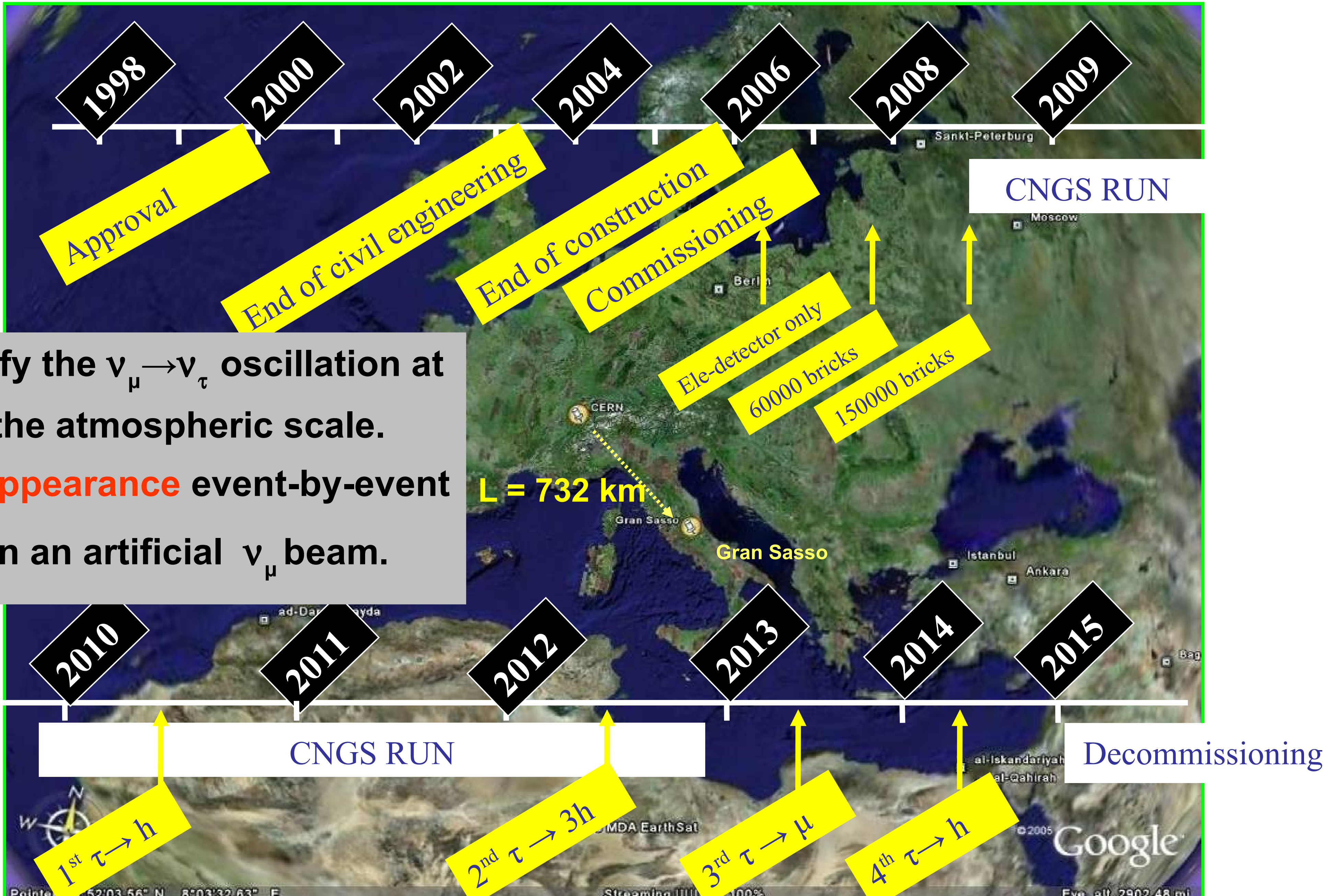
Korea
Jinju

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

Switzerland
Bern

Turkey
METU, Ankara

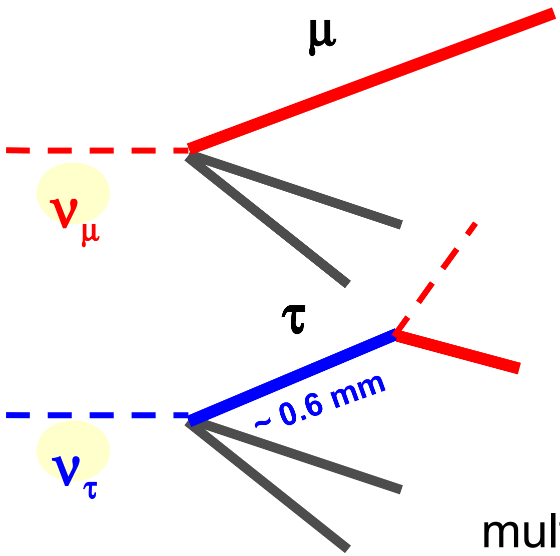
The OPERA project



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

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

The ν_τ detection technique



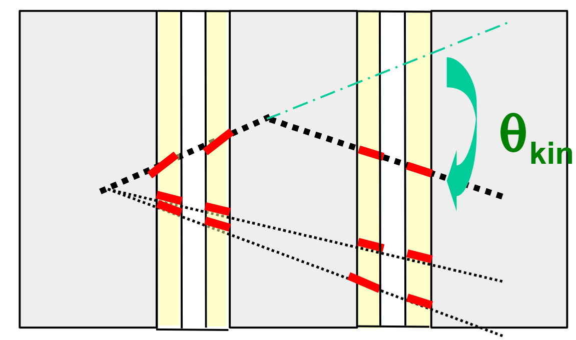
Detect a few ν_τ^{CC} from the bulk of ν_μ^{CC}

kink

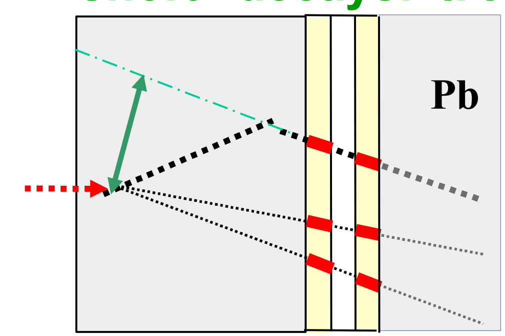
$\tau^- \rightarrow \mu^- \nu_\tau \nu_\mu$	17 %
$\tau^- \rightarrow e^- \nu_\tau \nu_e$	18 %
$\tau^- \rightarrow h^- \nu_\tau \, n(\pi^0)$	50 %
$\tau^- \rightarrow \pi^+ \pi^- \pi^- \nu_\tau n(\pi^0)$	14 %

multi-prong

"long" decays: kink

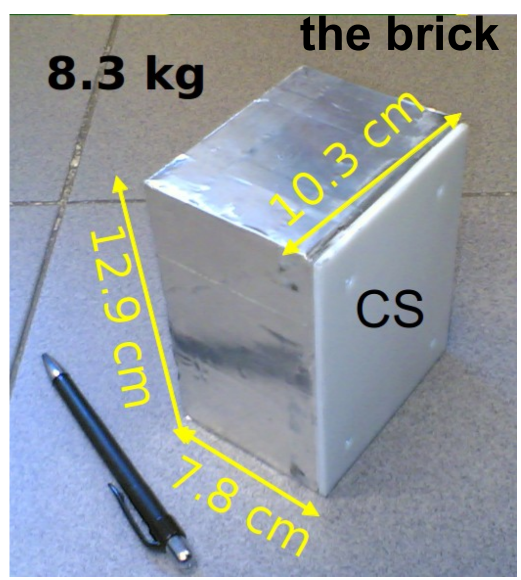


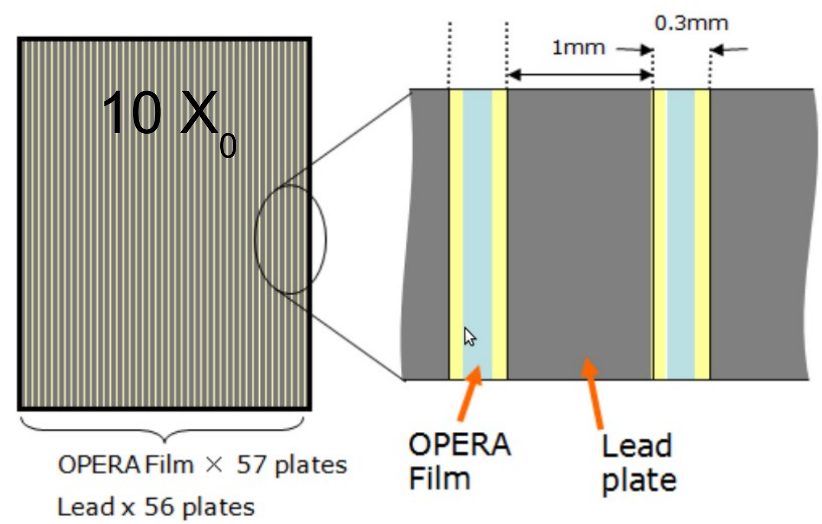
"short" decays: I.P.



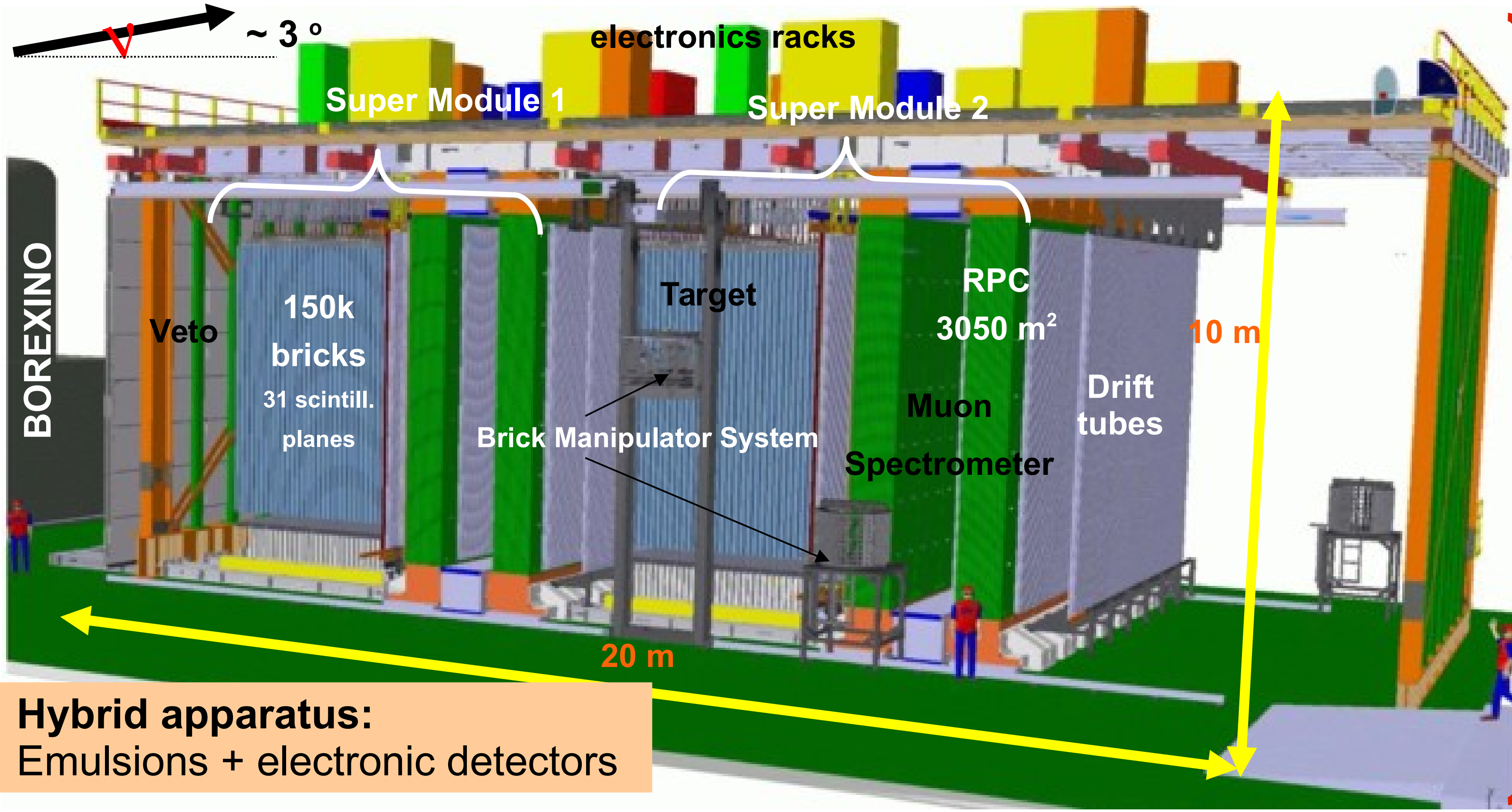
Modular detector of "Emulsion Cloud Chambers" (or bricks)
Reconciles the needs for:

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

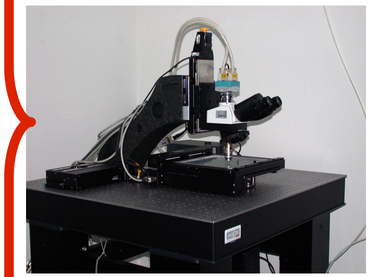


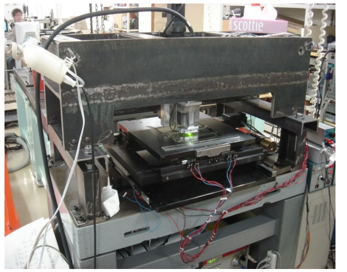


The OPERA experiment

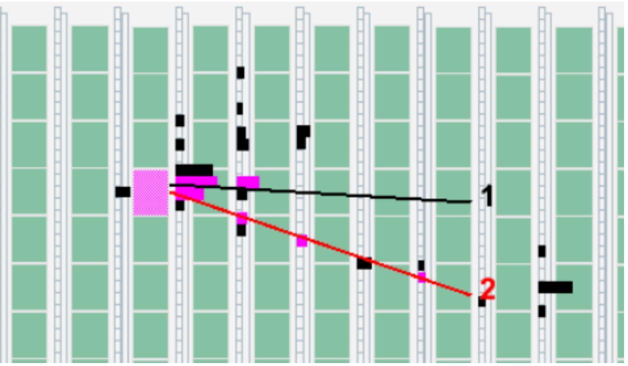


Hybrid apparatus:
Emulsions + electronic detectors





``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

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

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

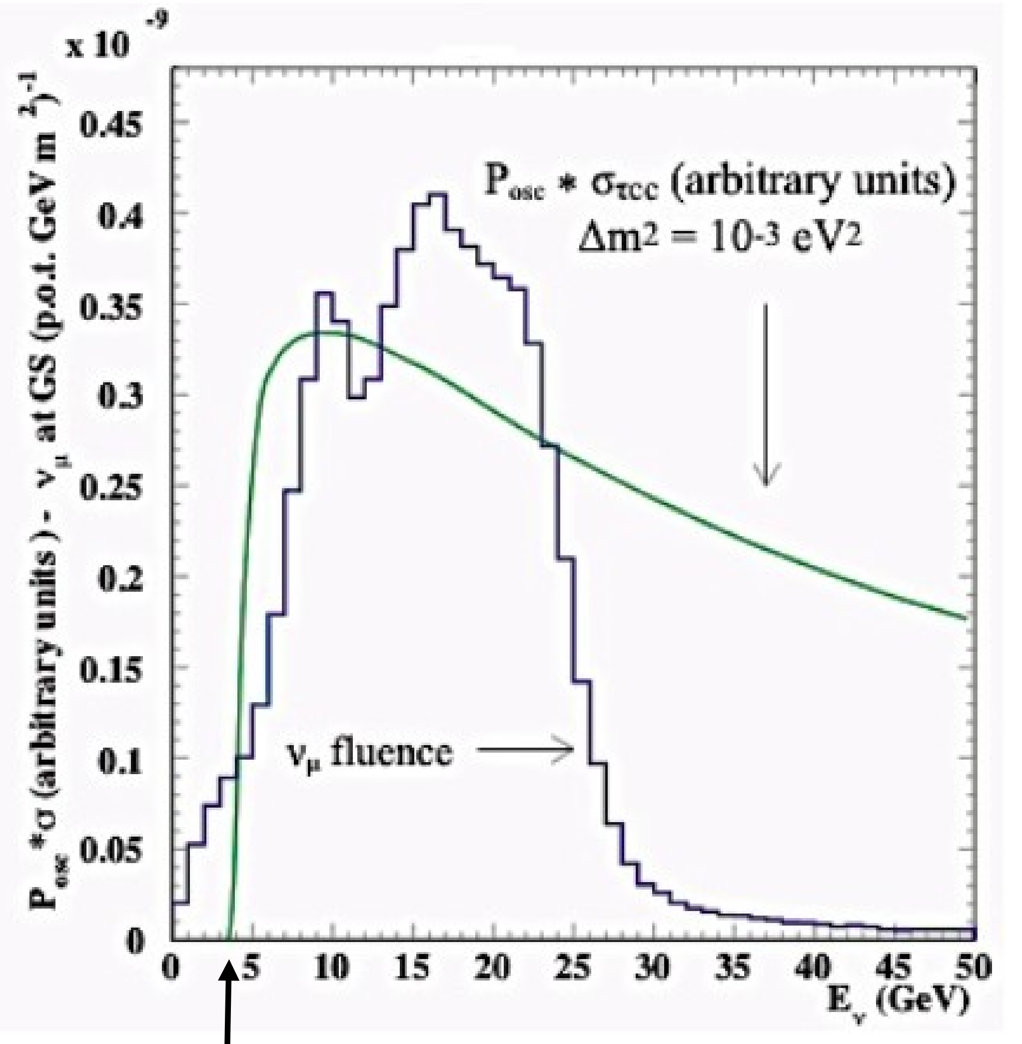
$N(\tau) \sim Pr(\nu_\mu \rightarrow \nu_\tau) \times \sigma_{\nu(\tau)CC}(E) \times flux$

Fluxes:

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

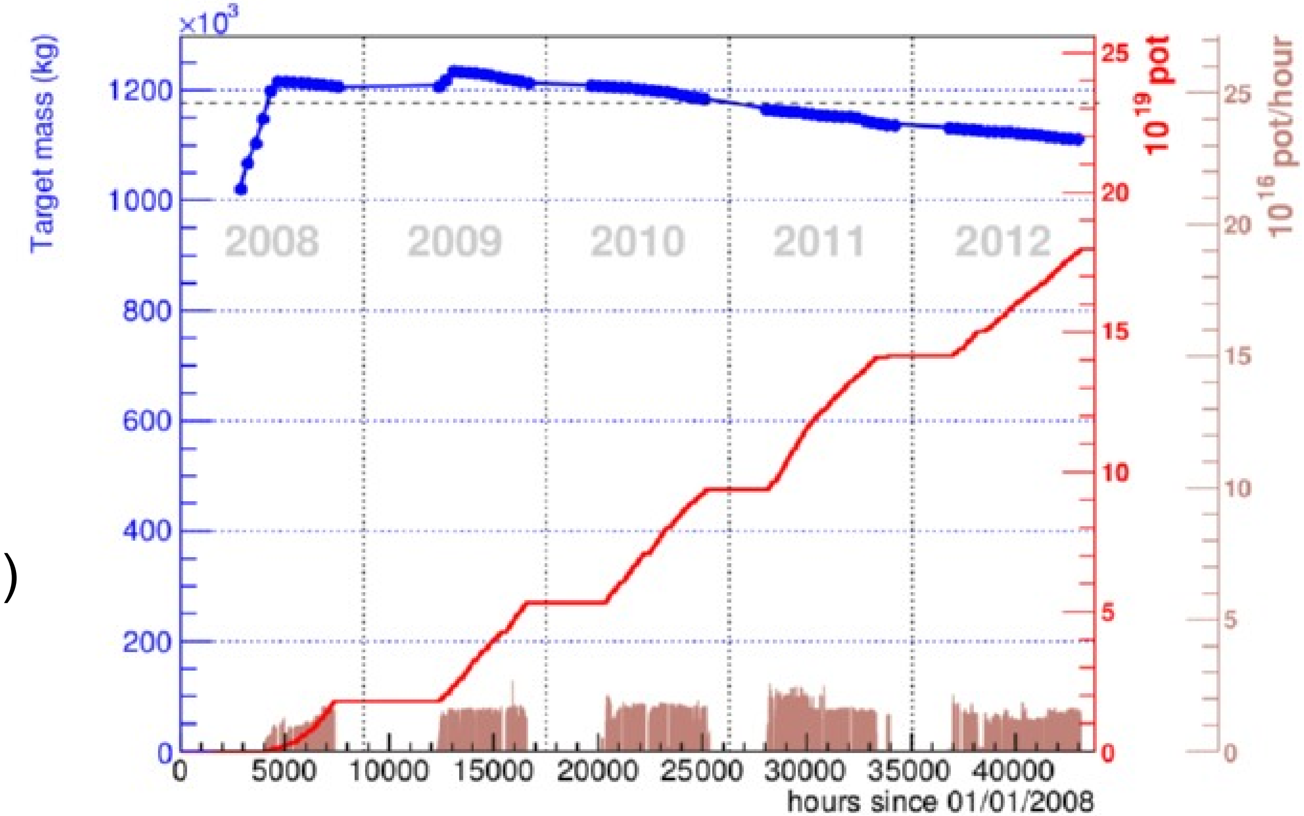
Interaction rates (1.8×10^{20} pot):

~ 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.

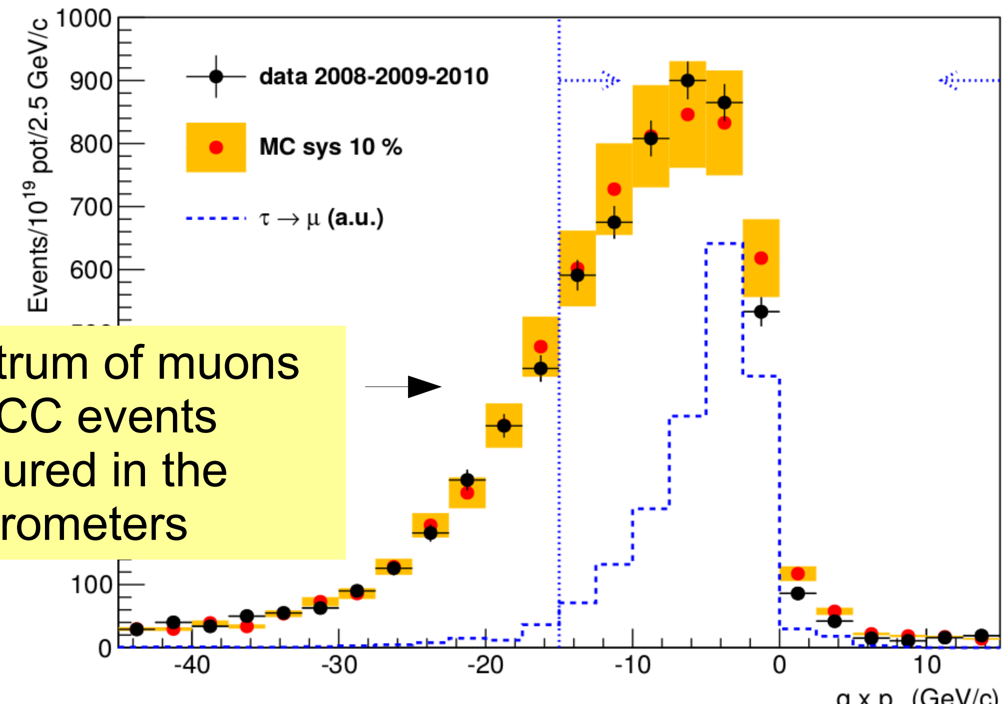
1.8×10^{20} p.o.t. collected
80% of the design (2.25×10^{20})

1.25 kton initial target mass
(150 k bricks)

19505 neutrino interactions in the emulsion targets.

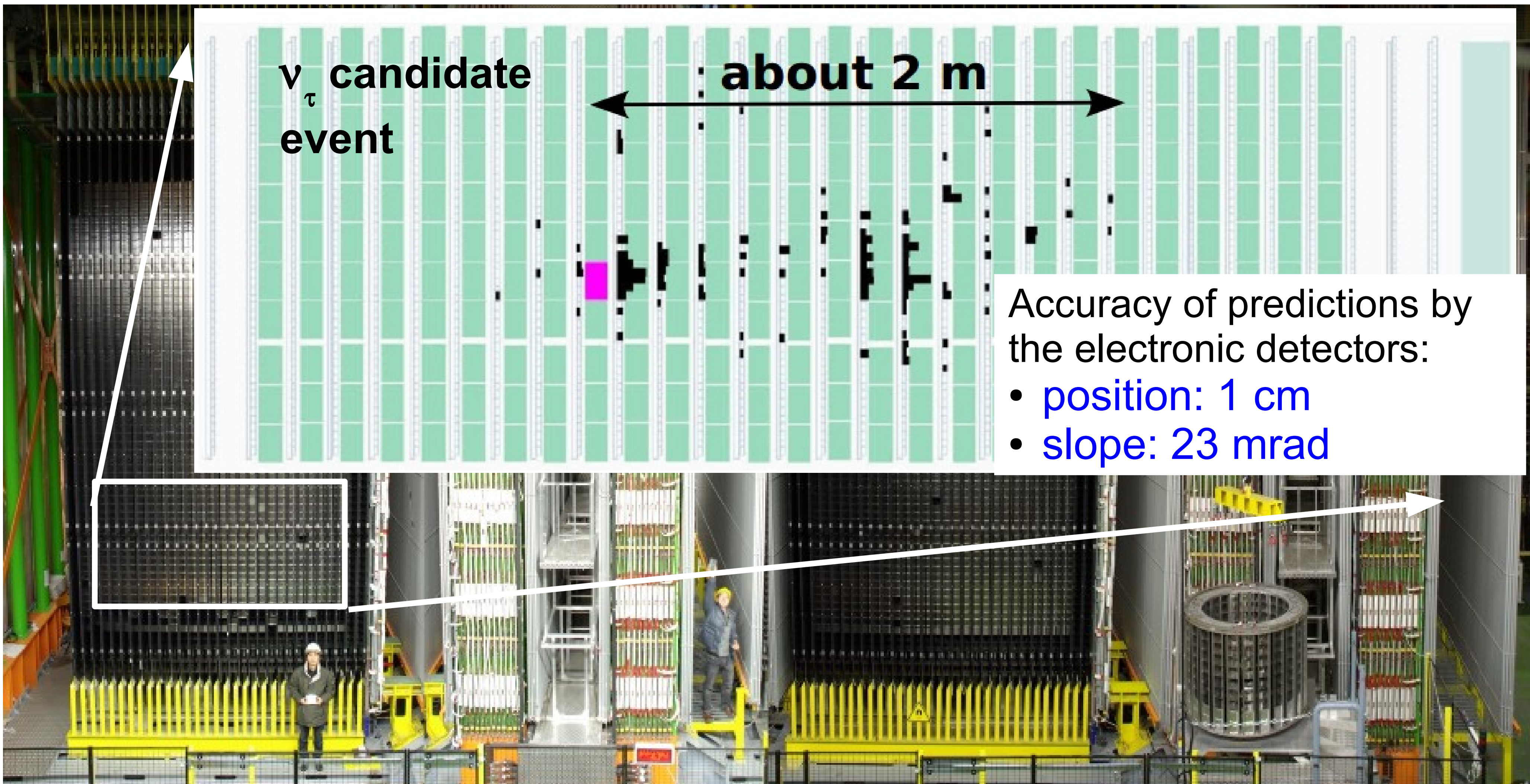
Year	Days	p.o.t. (10^{19})	ν interactions
2008	123	1.74	1698
2009	155	3.53	3693
2010	187	4.09	4248
2011	243	4.75	5131
2012	257	3.86	3923
tot	**965**	**17.97**	**19505**

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.

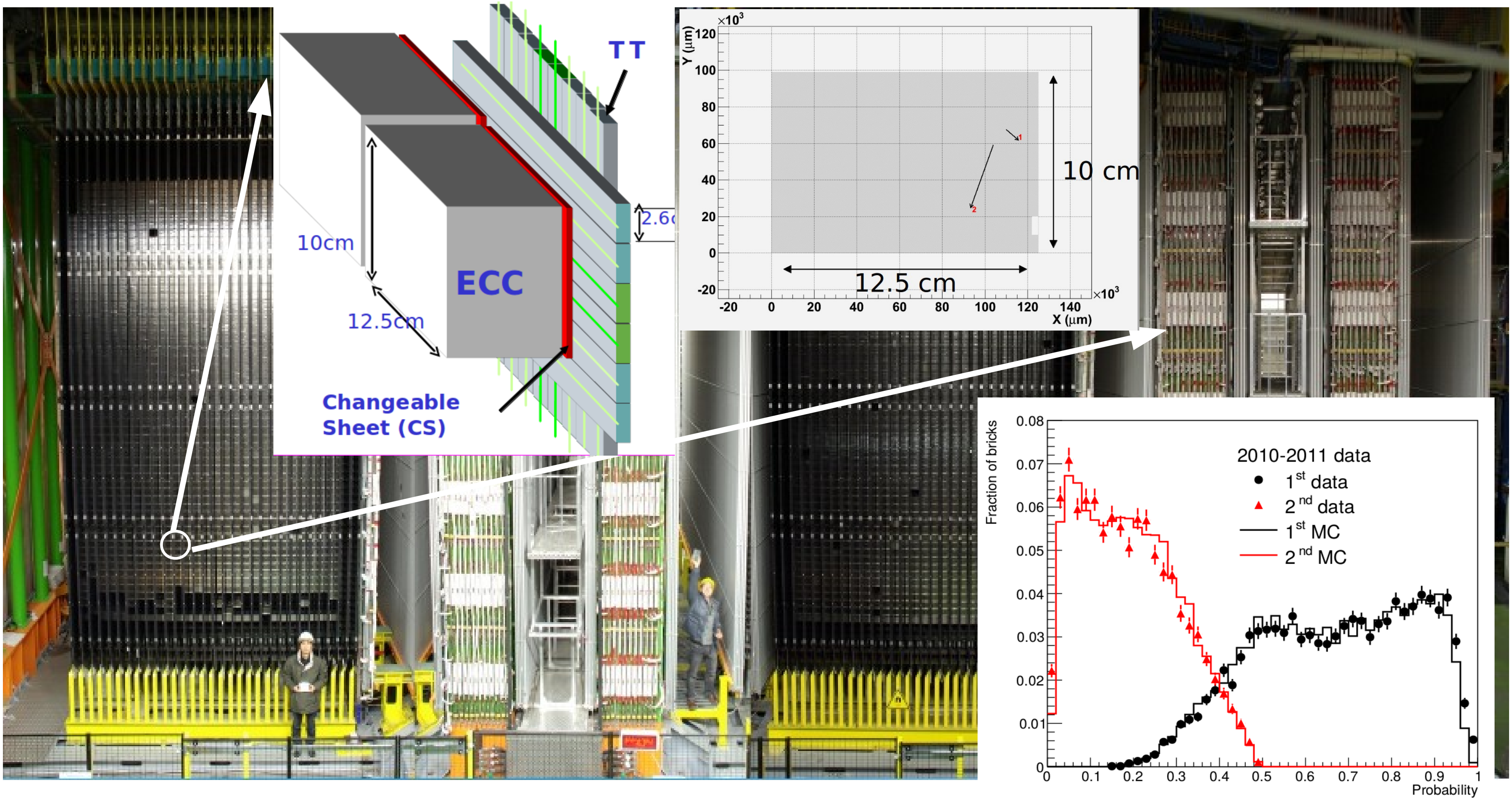


Brick finding

Changeable Sheets: the “bridge” from the cm scale of electronics detectors to μm scale of emulsions.

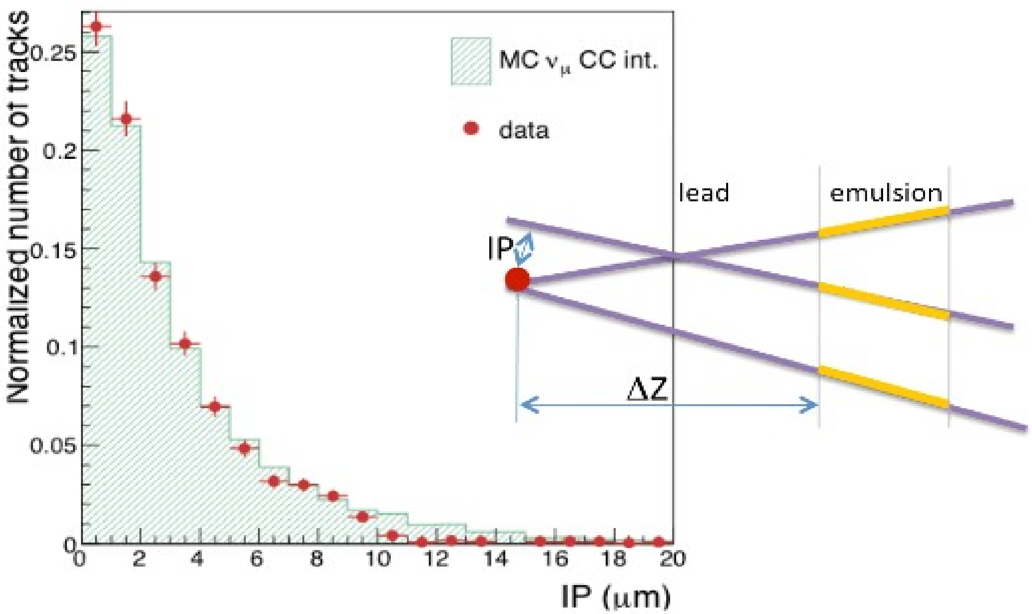
Electronic detector predictions to be confirmed by scanning of CS doublet.

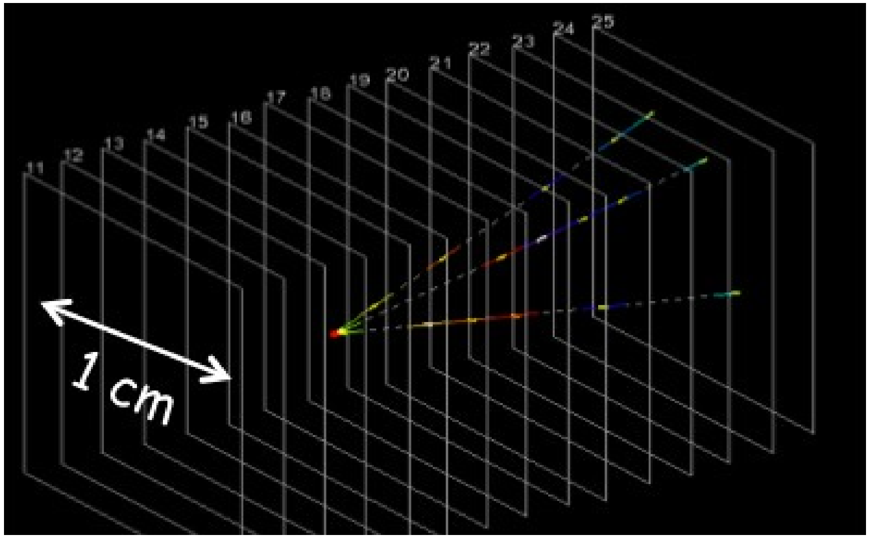
Up to 4 bricks ranked in probability are considered for τ research.

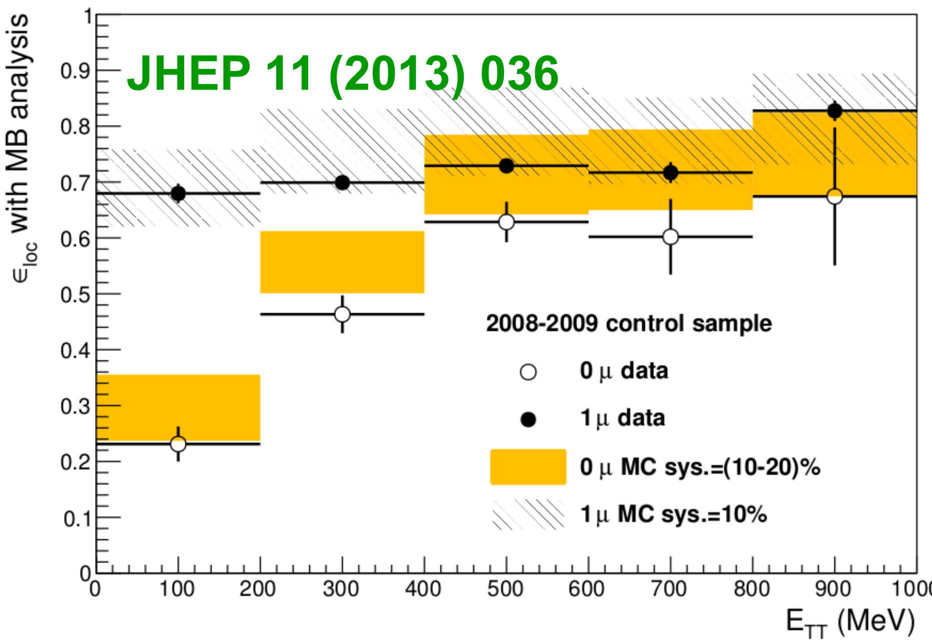


Vertex location and topology decay search in the brick

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).





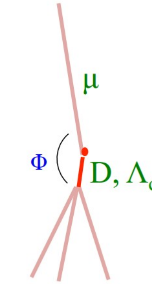


Full MC simulation of 0 μ and 1 μ samples.
Data/MonteCarlo in reasonable agreement.

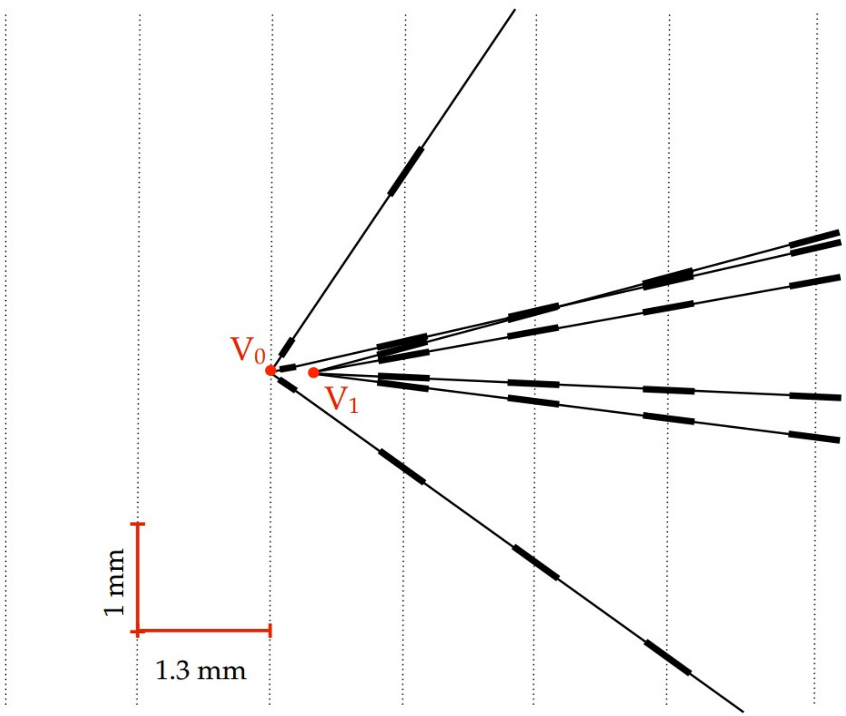
Validation with the CNGS charm events sample

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

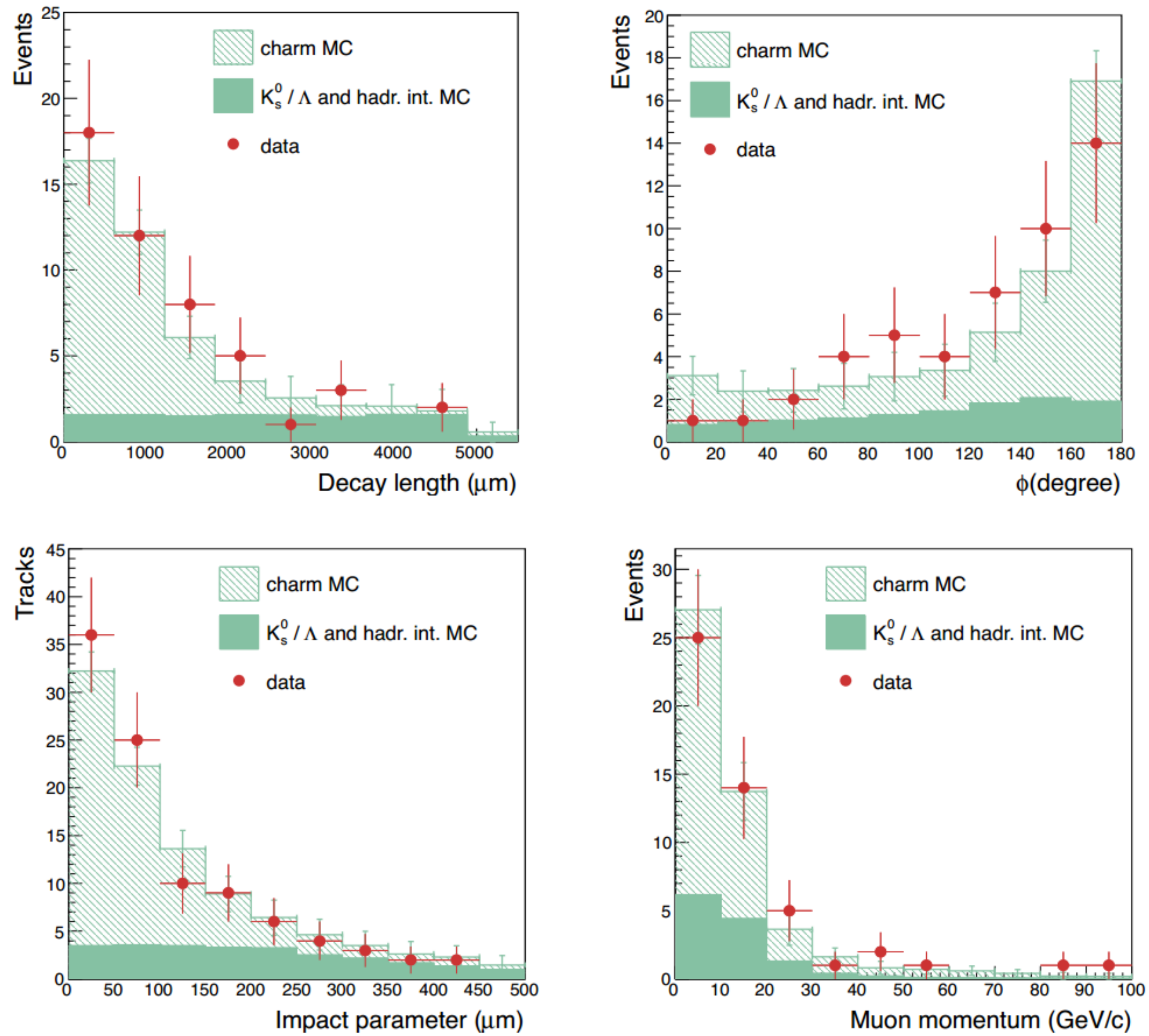
Charm and τ decays are topologically similar.
Test for: reconstruction efficiencies, description of kinematic variables, charm background.



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



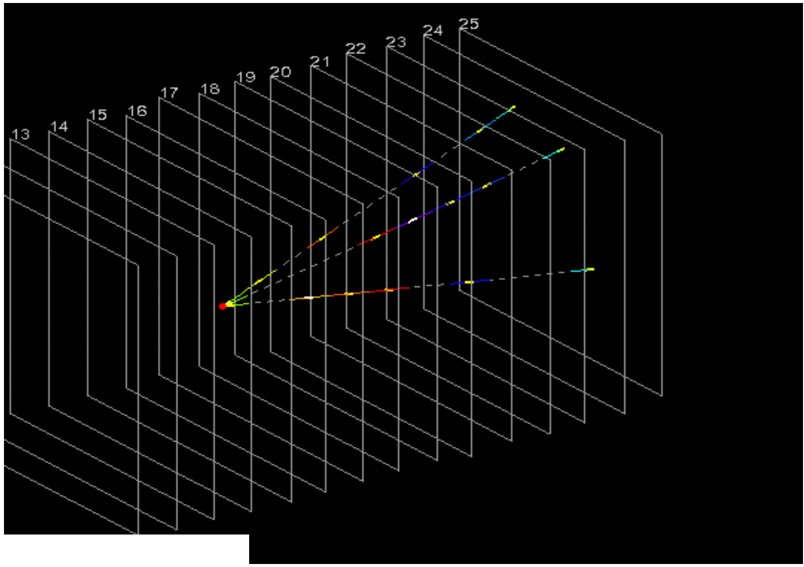
Eur.Phys.J. C74 (2014) 8, 2986



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)**

The 1st candidate ($\tau \rightarrow 1h$)

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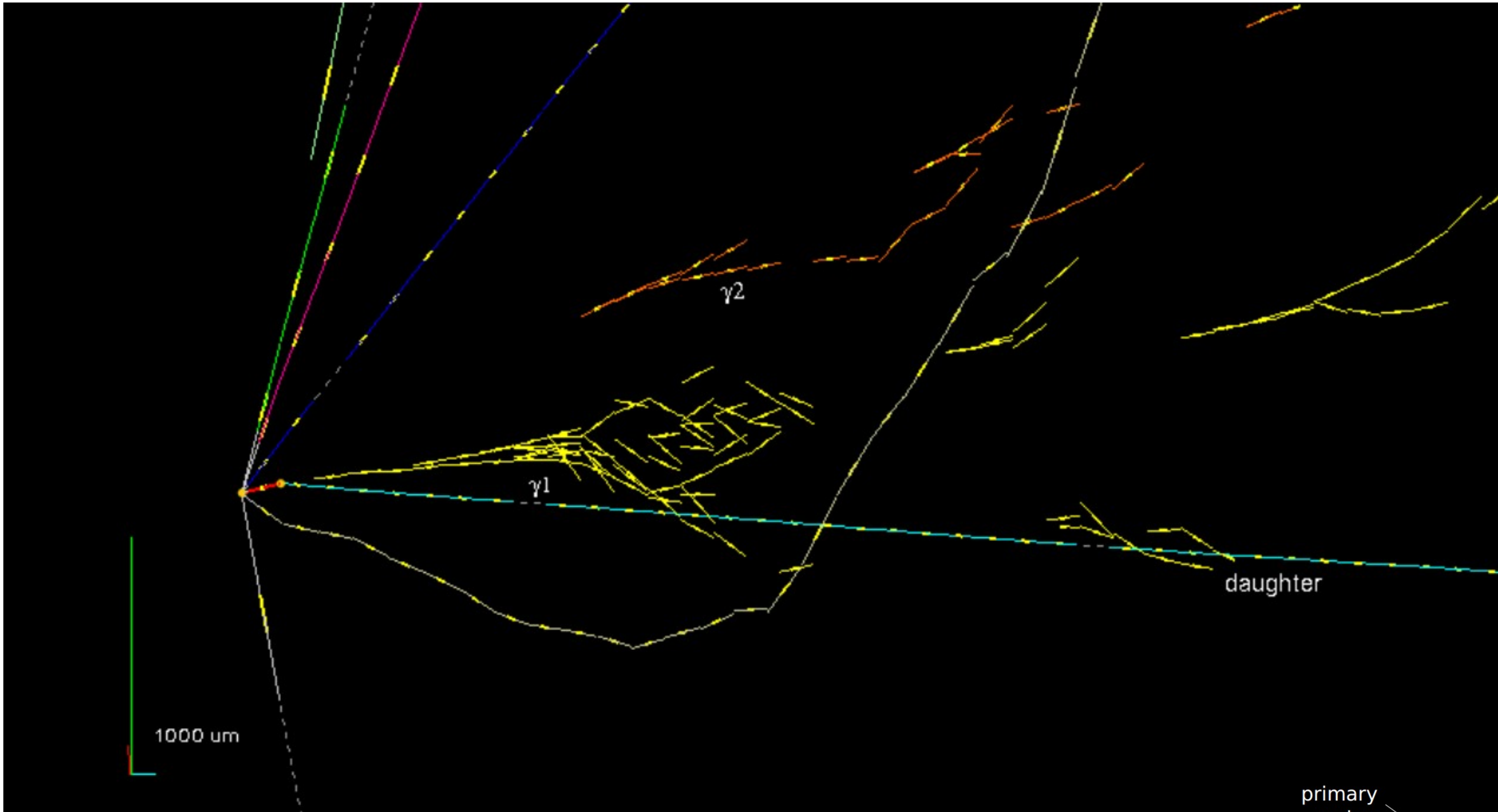
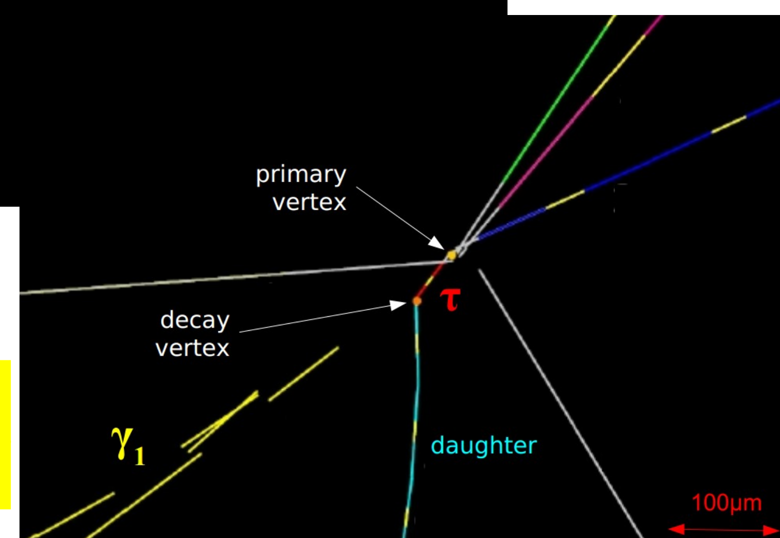




$\tau^- \rightarrow \rho^- + \nu_\tau$ (B.R. ~25%)

$\rho^- \rightarrow \pi^0 + \pi^-$

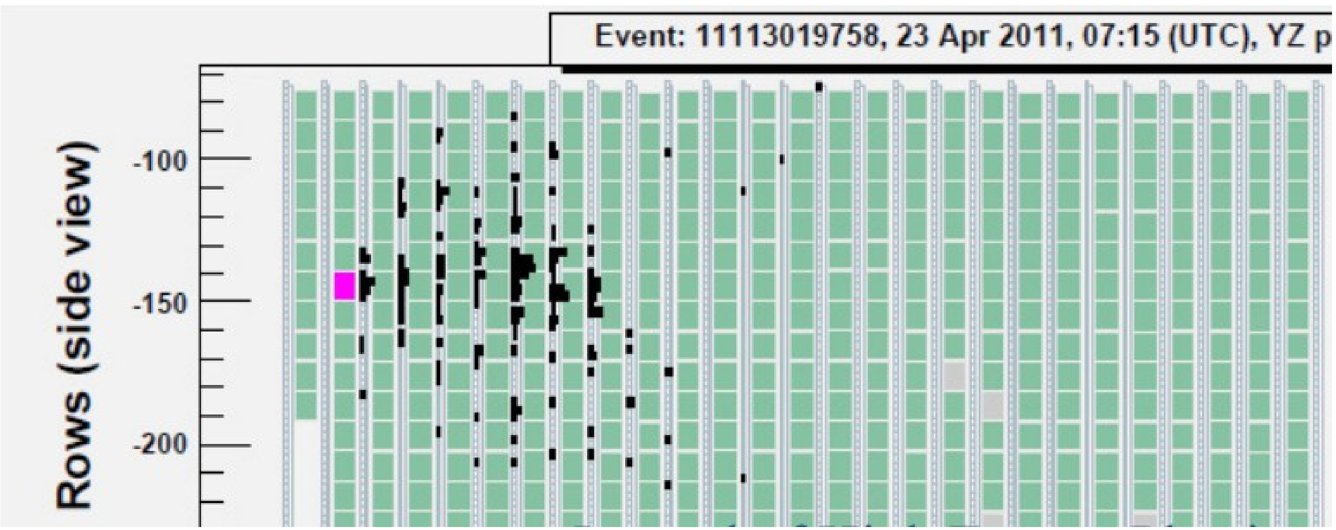
$\pi^0 \rightarrow \gamma\gamma$

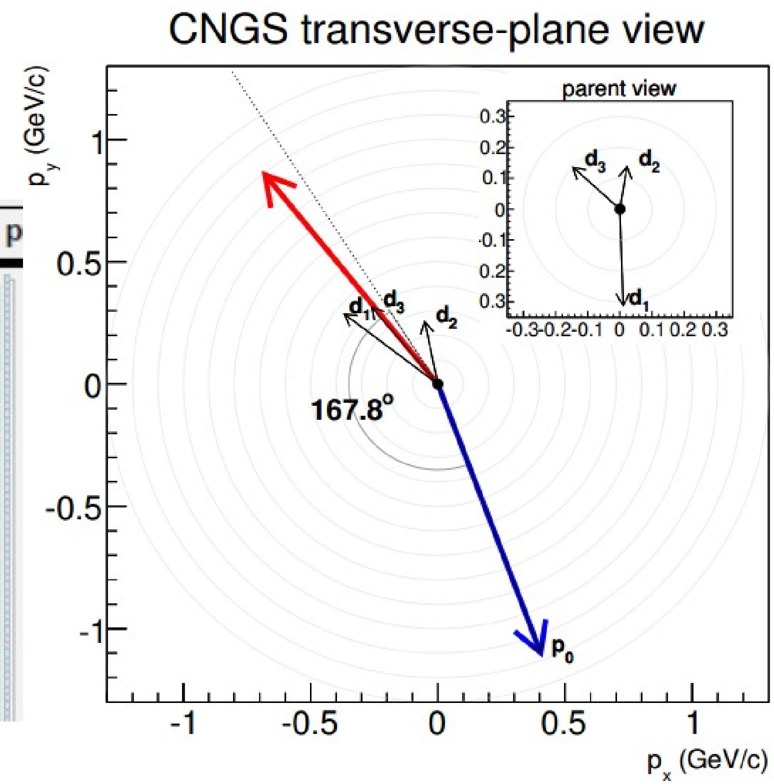
640^{+125}_{-80} (stat.)$^{+100}_{-90}$ (sys.) MeV/c^2

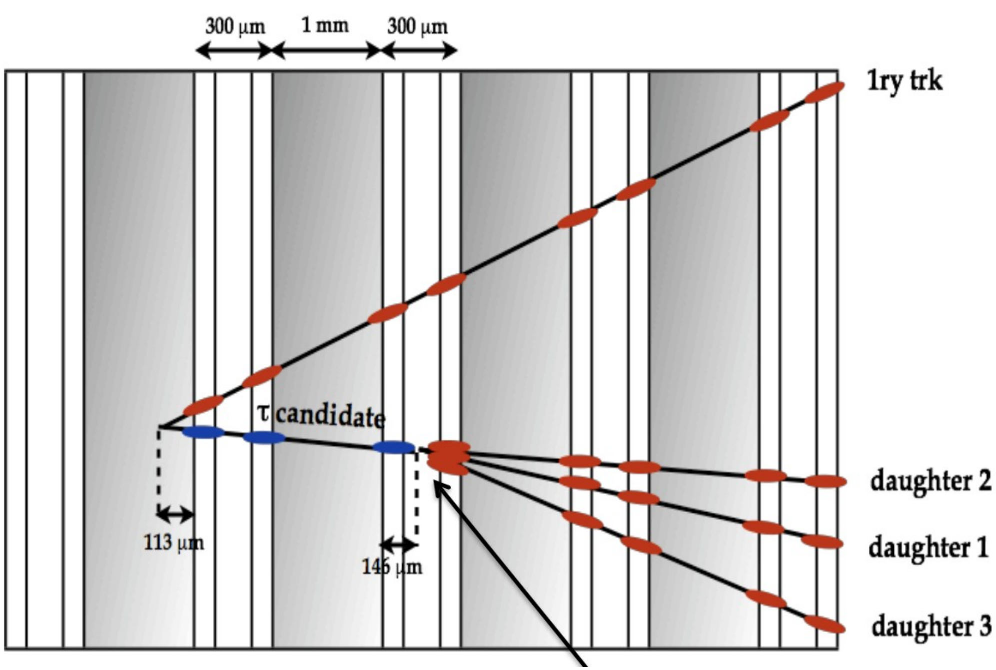
120 ± 20(stat.) ± 35(sys.) MeV/c^2

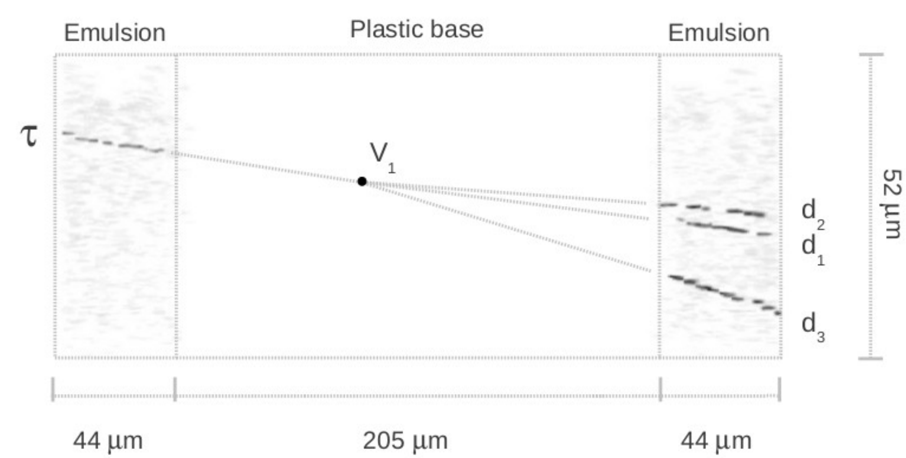
JHEP 11 (2013) 036

The 2nd candidate ($\tau \rightarrow 3h$)









The 3rd candidate ($\tau \rightarrow \mu$)

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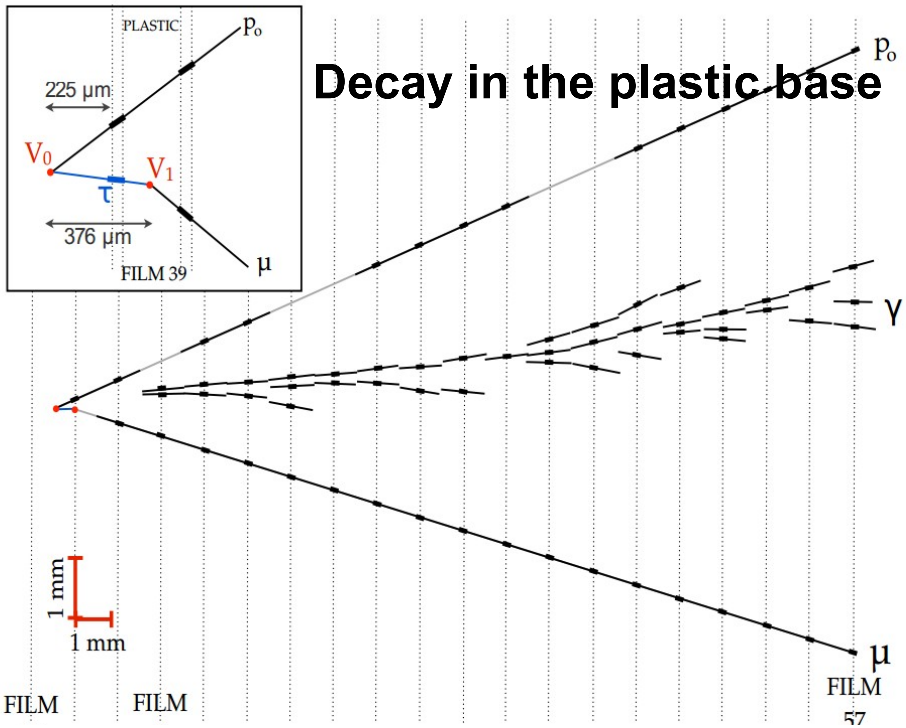
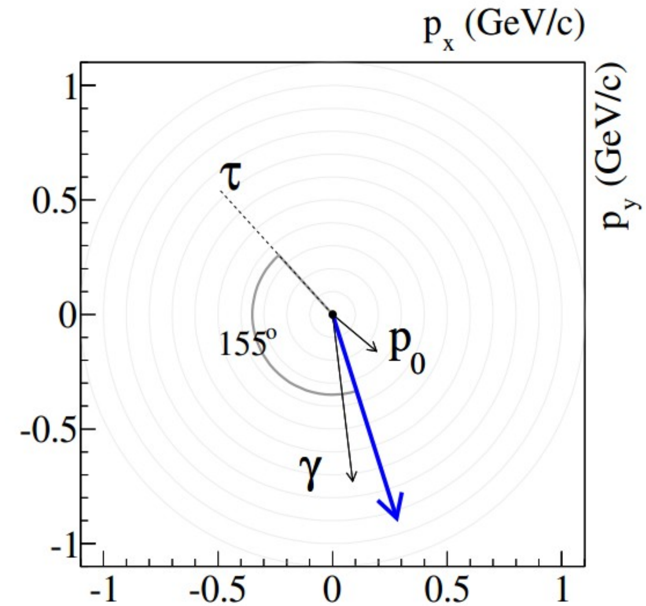
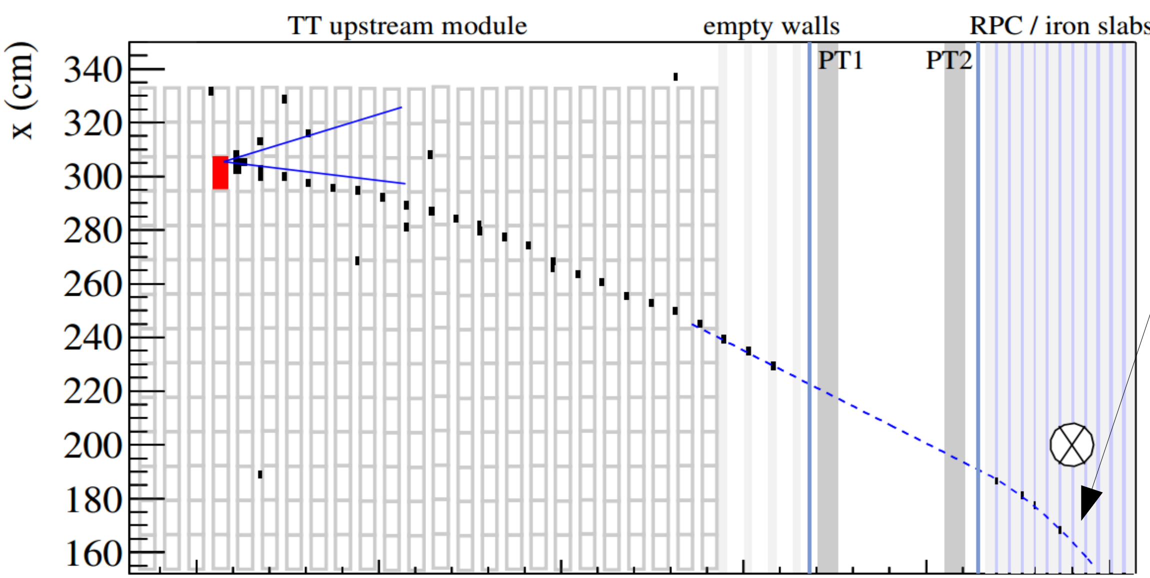
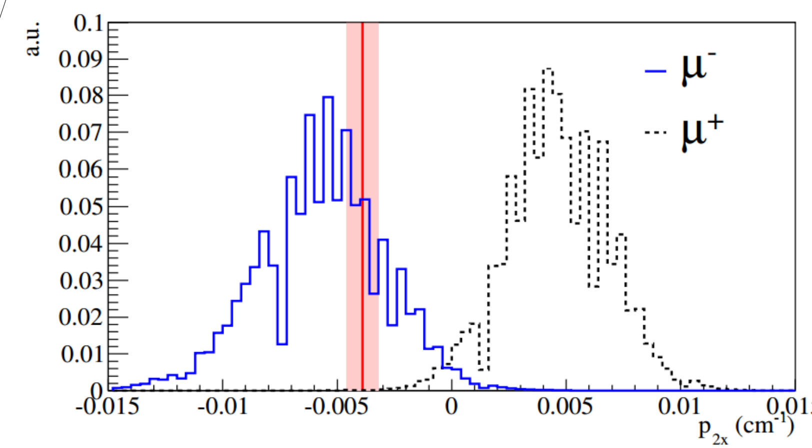
Decay in the plastic base







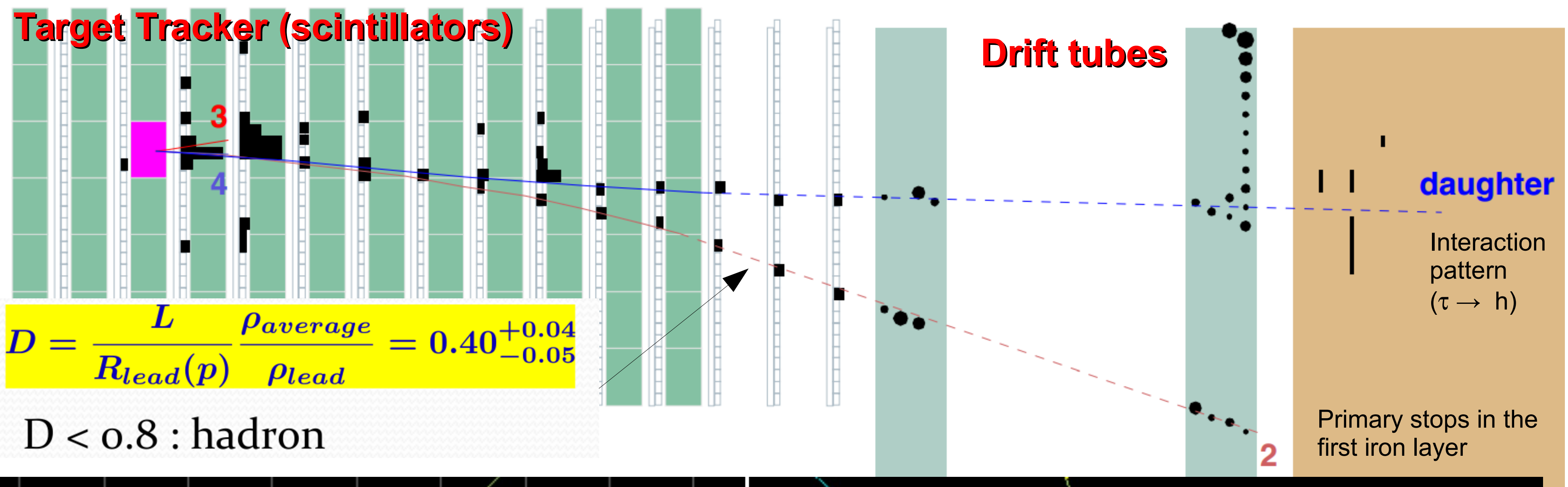
Negative charge of daughter muon measured by bending in the iron with RPC detectors



First measurement of lepton charge in appearance mode.

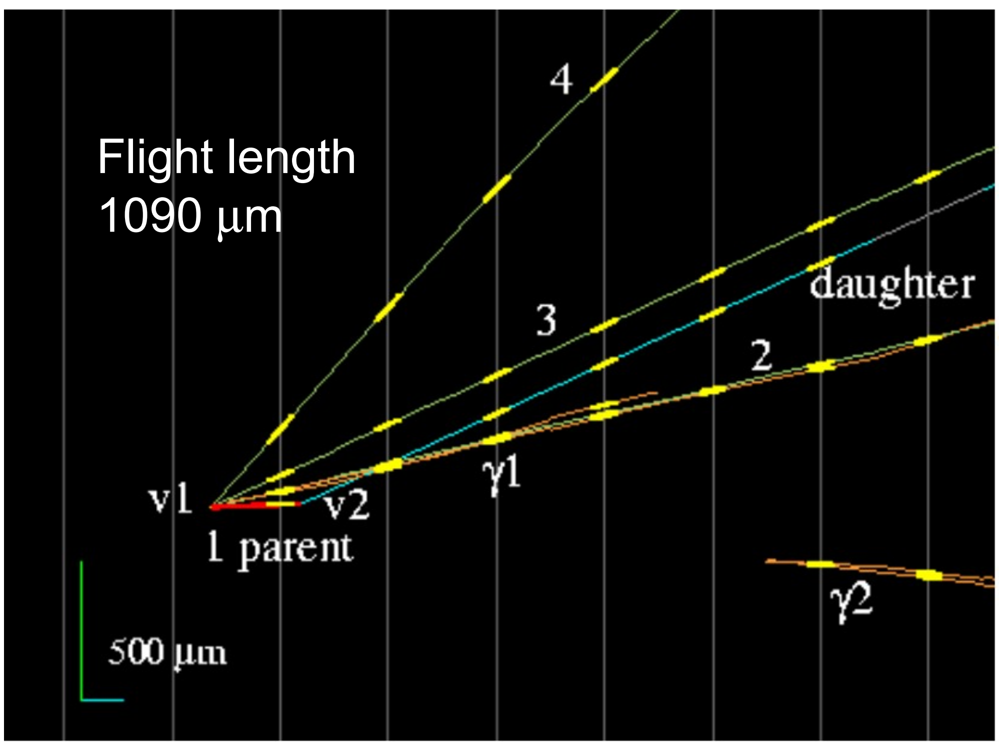
The 4th candidate ($\tau \rightarrow 1h$)

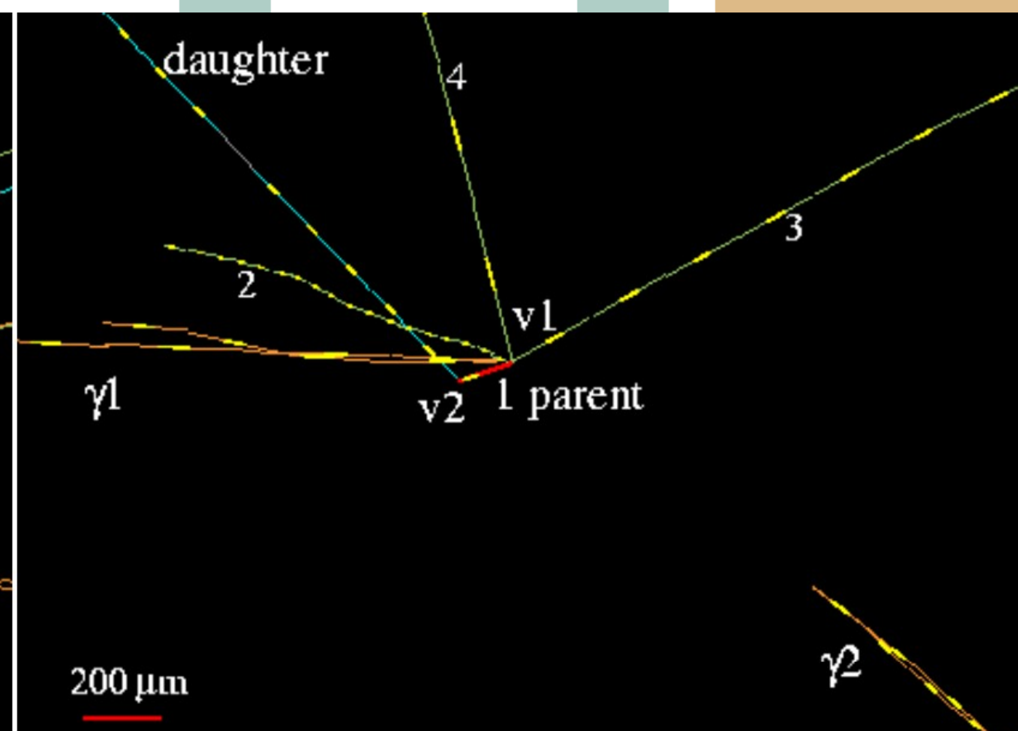
PTEP 2014 (2014) 10, 101C01



$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{average}}{\rho_{lead}} = 0.40^{+0.04}_{-0.05}$$

D < 0.8 : hadron



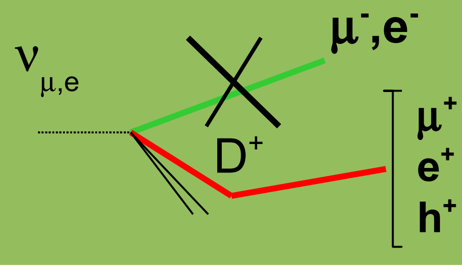


$\nu_\mu \rightarrow \nu_\tau$ background characterization

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

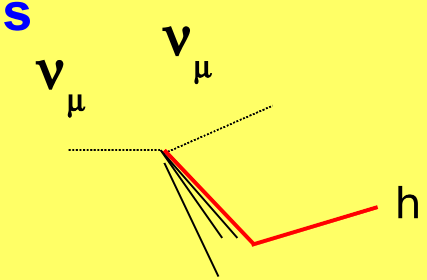


MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

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

Hadronic interactions

Background for $\tau \rightarrow h$

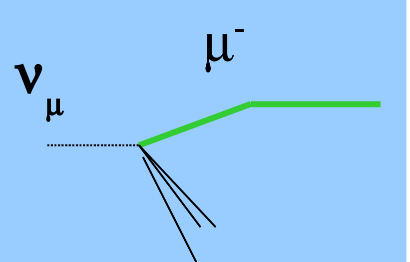


FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

Large angle muon scattering

Background for $\tau \rightarrow \mu$

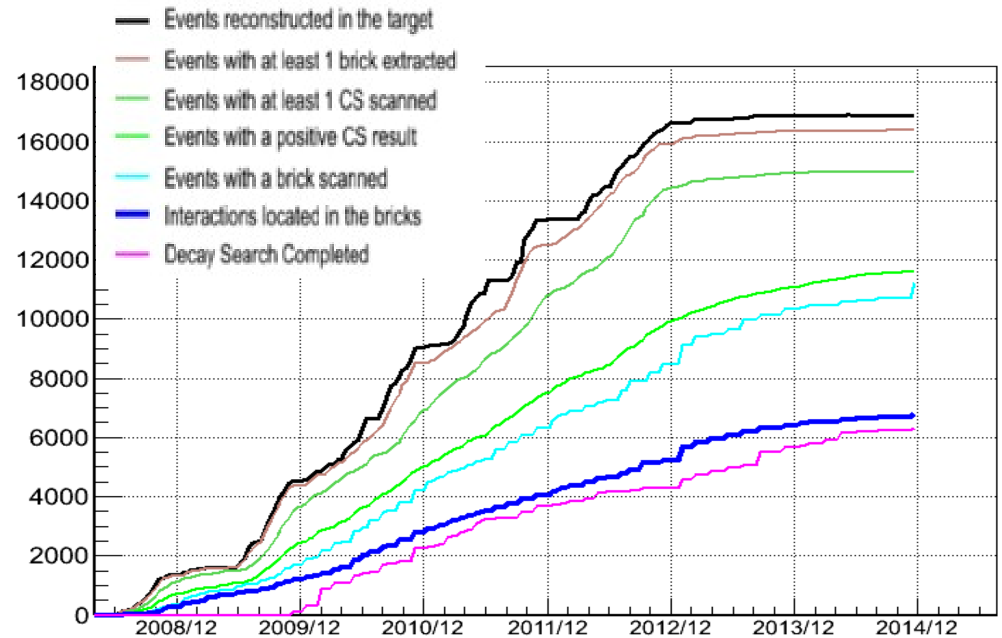


Measurements in the literature (Lead form factor), simulations and dedicated test-beams (in progress)

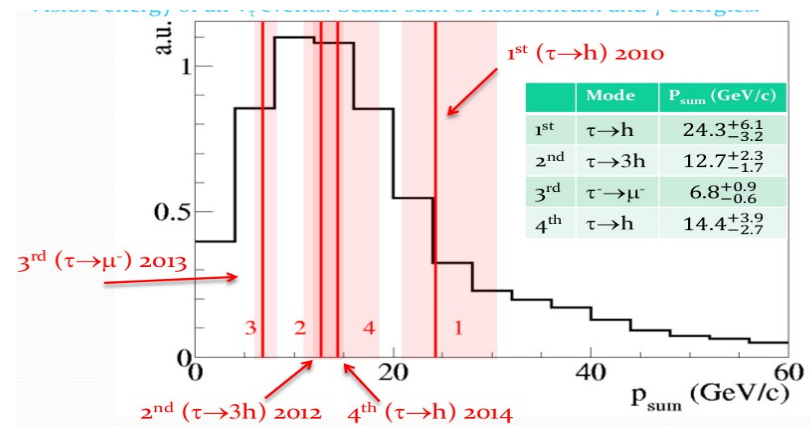
ν_τ analysis results

Status of the analysis:
The presented results correspond to about 70% of the total sample
2008-2009: 1st and 2nd brick completed
2010-2012: 1st brick completed

Analysis in progress.
Updates in summer conferences.



Decay channel	Expected signal $\Delta m_{23}^2 = 2.32$ meV^2	Total background	Observed
$\tau \to h$	0.41 ± 0.08	0.033 ± 0.006	2
$\tau \to 3h$	0.57 ± 0.11	0.155 ± 0.030	1
$\tau \to \mu$	0.52 ± 0.10	0.018 ± 0.007	1
$\tau \to e$	0.62 ± 0.12	0.027 ± 0.005	0
Total	2.11 ± 0.42	0.233 ± 0.041	4

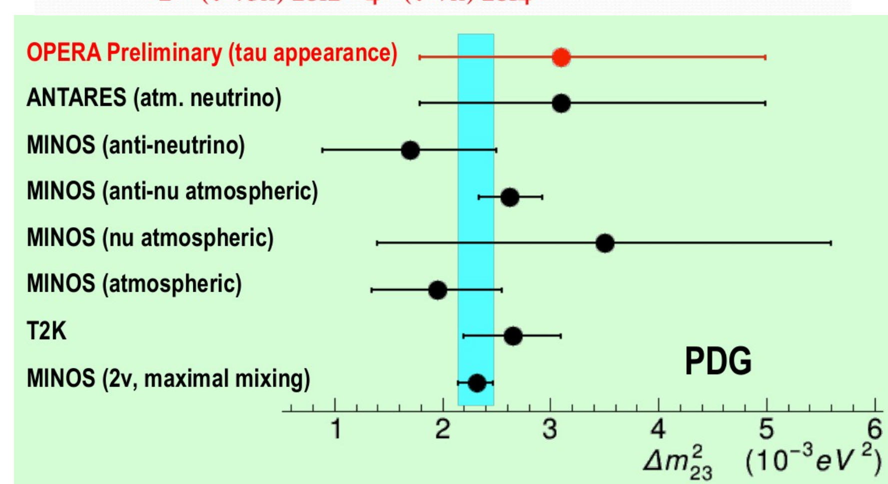


3 hadronic + 1 muonic candidates observed

Exclusion of null hypothesis: 4.2 σ

p-value = 1.03×10^{-5}

- Fisher combination of single channel p-value
- Likelihood ratio



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

standard

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

(normal hierarchy)

exotic

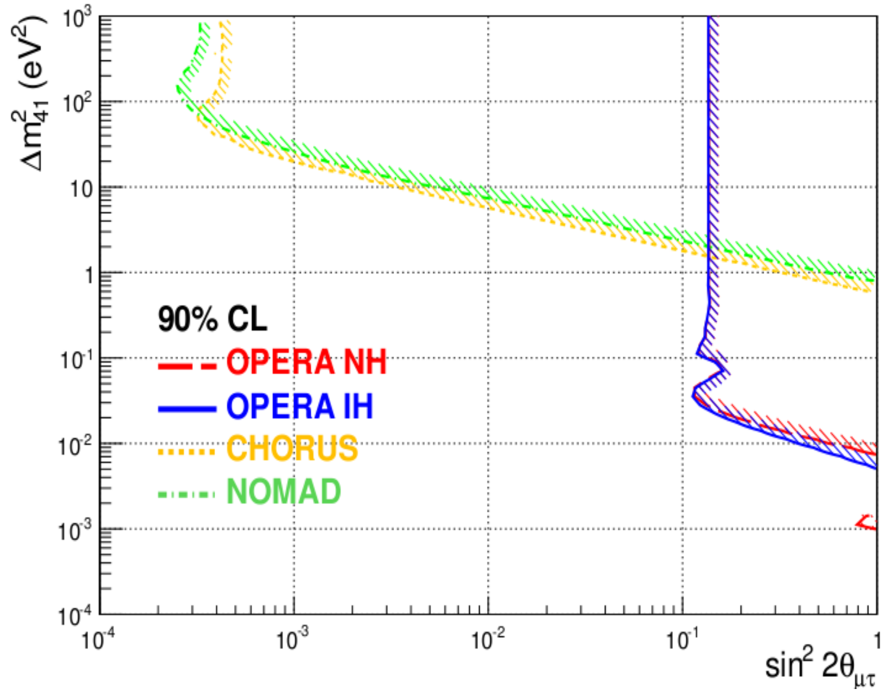
$$+4|U_{\mu 4}|^2 |U_{\tau 4}|^2 \sin^2 \frac{\Delta_{41}}{2}$$

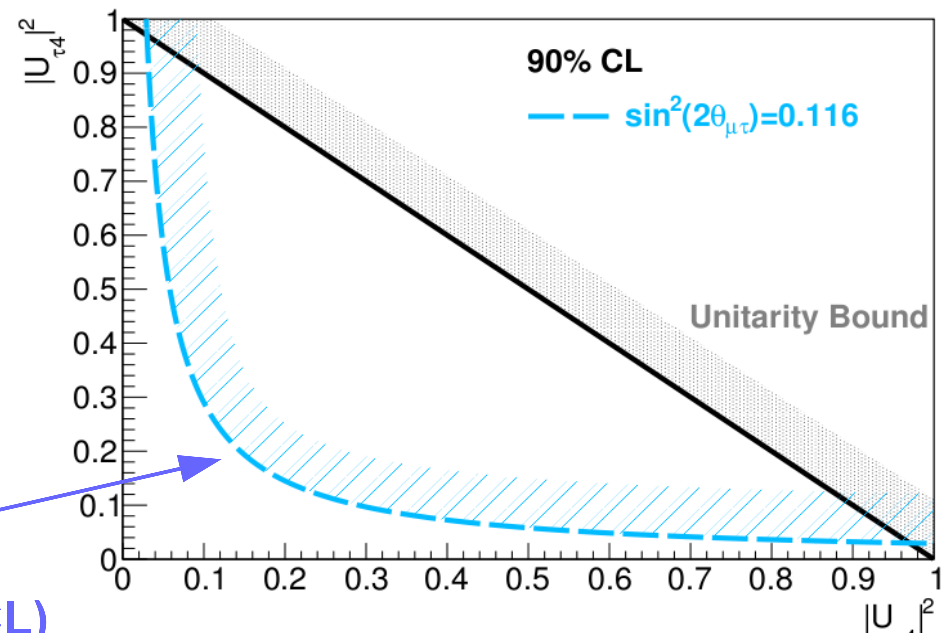
$$+2\Re[U_{\mu 4}^* U_{\tau 4} U_{\mu 3} U_{\tau 3}^*] \sin\Delta_{31} \sin\Delta_{41}$$
$$-4\Im[U_{\mu 4}^* U_{\tau 4} U_{\mu 3} U_{\tau 3}^*] \sin^2 \frac{\Delta_{31}}{2} \sin\Delta_{41}$$
$$+8\Re[U_{\mu 4}^* U_{\tau 4} U_{\mu 3} U_{\tau 3}^*] \sin^2 \frac{\Delta_{31}}{2} \sin\frac{\Delta_{41}}{2}$$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

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

Interference term

Profile likelihood on τ number



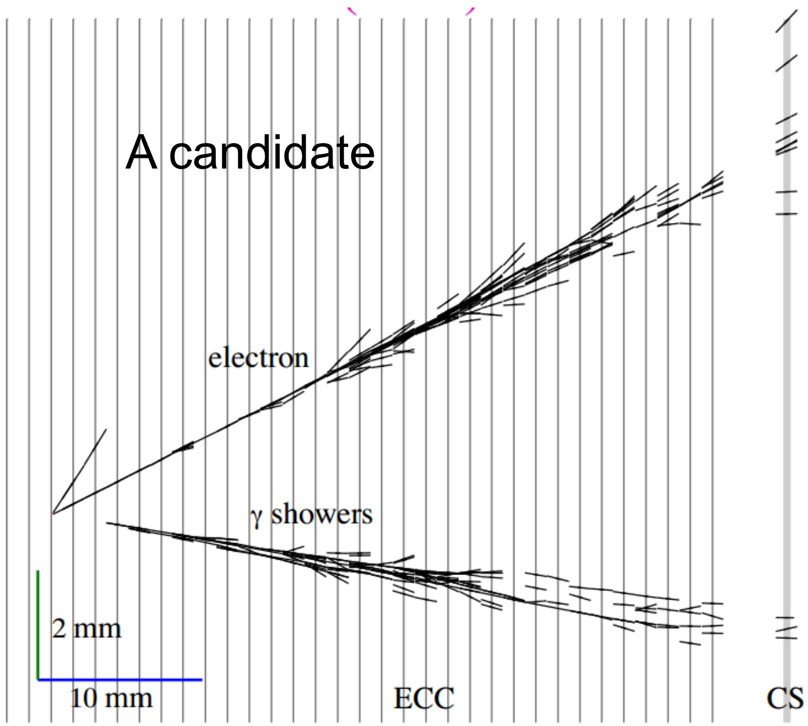


@ Δm^2_{41} > 1 eV² (3+1 model)

$4\,|U_{\mu 4}|^2\,|U_{\tau 4}|^2 = \sin^2(2\theta_{\mu\tau}) < 0.116$ (90% CL)

$\nu_\mu \rightarrow \nu_e$

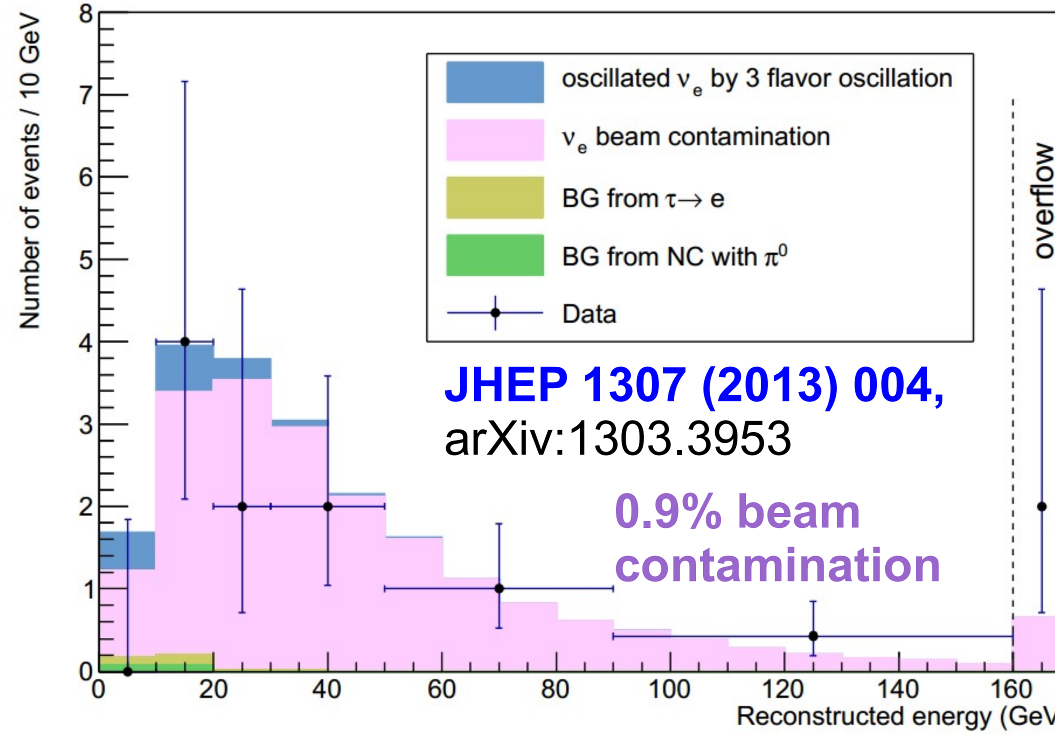
2008+2009 0μ interactions: 505 events
(~30% of the final sample)

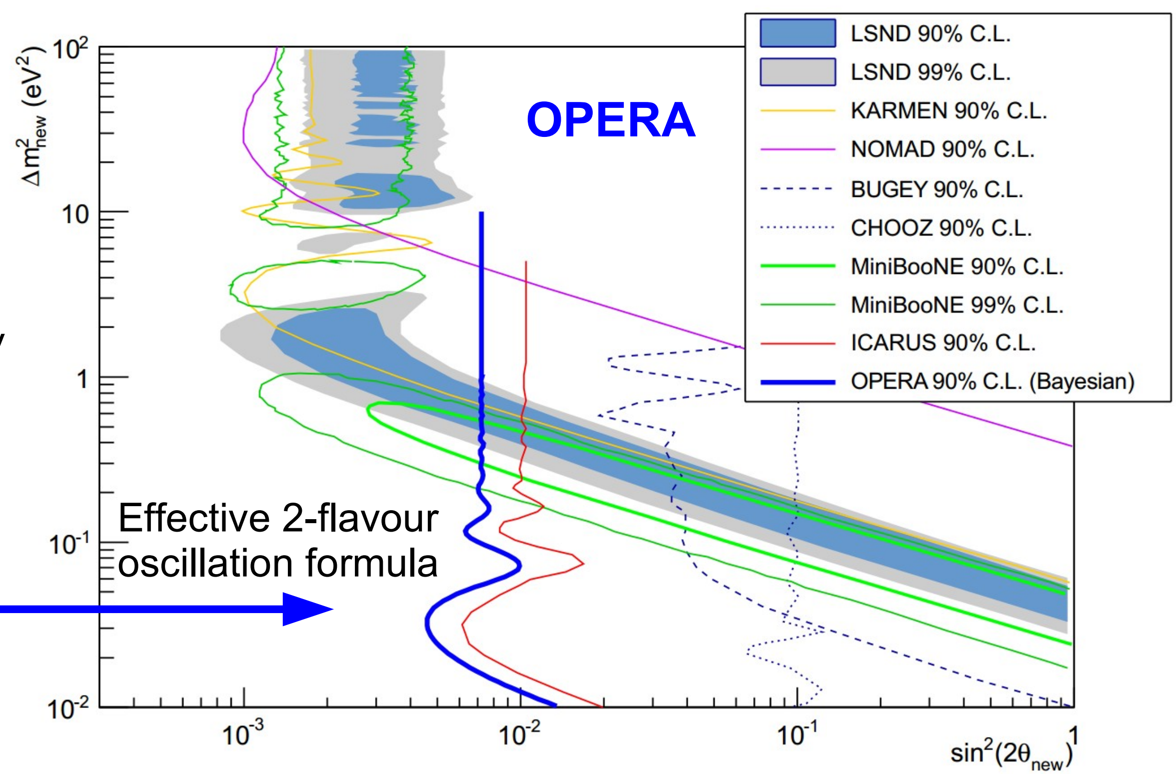


		E < 20 GeV
ν_e candidates	19	4
Background	19.8 ± 2.8 (sys.)	4.6

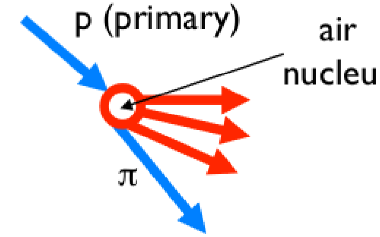
$\sin^2 2\theta_{NEW} < 7.2 \times 10^{-3}$ (90% CL)

$\sin^2 2\theta_{13} < 0.44$ (90% CL) (standard 3ν)





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

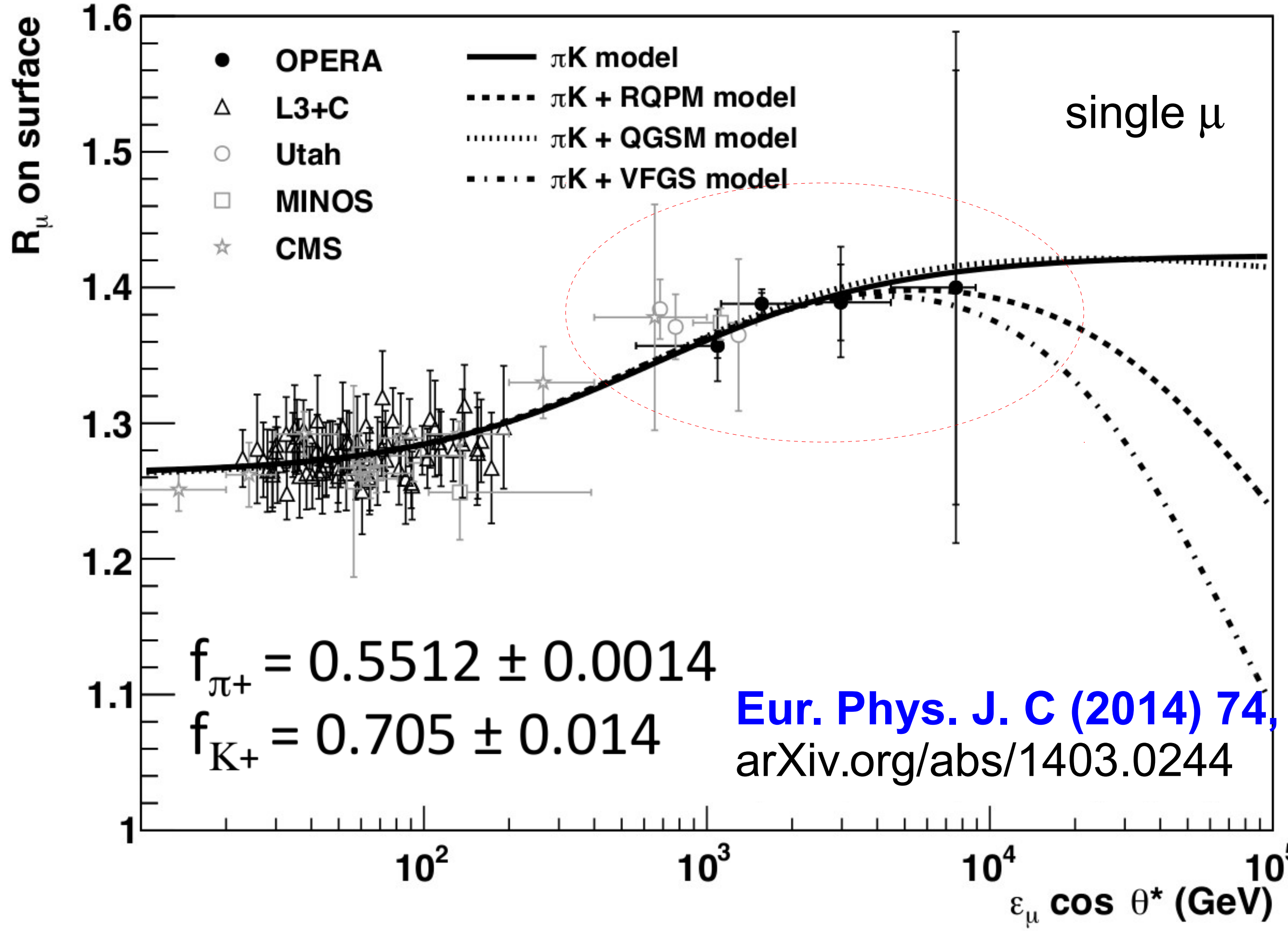


- Highest-E region reached!
- opposite magnet polarities runs → lower systematics
- Strong reduction of the charge ratio for multiple muon events

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

- 1.8×10^{20} pot by CNGS from 2008-12 (80% of design).
- 4 ν_τ candidates so far with a 0.23 event background.
- No oscillation hypothesis excluded at **4.2 σ.**

- Study on $\nu_\mu \rightarrow \nu_e$ sub-dominant oscillation channel.
- 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.

OPERA posters at XVI International Workshop on Neutrino Telescopes:

"Search for sterile neutrino mixing in the muon neutrino to tau neutrino appearance channel with the OPERA detector" - M. Tenti
"Appearance of rare physics phenomena in the OPERA neutrino experiment" - M .Roda
"The Muon-Tracking-System of the OPERA experiment" - B. Buttner
"Energy measurement of electromagnetic showers for the detection of the τ–>e channel in the OPERA search for neutrino oscillations" - B. Hosseini