More results from the OPERA experiment

Nicoletta Mauri
(University of Bologna and INFN)
on behalf of the OPERA Collaboration

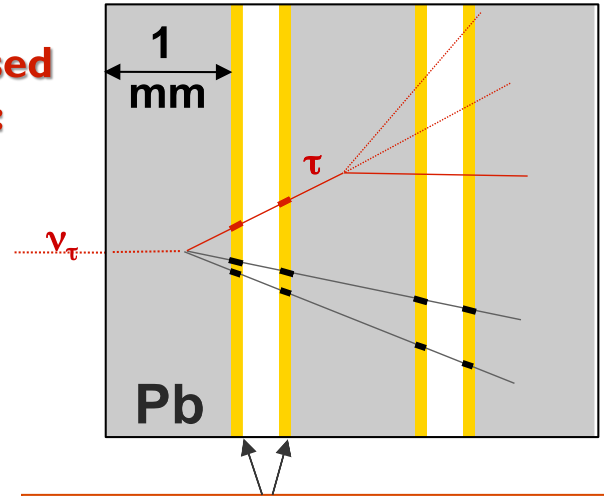
15th International Conference on Topics in Astroparticle and Underground Physics, TAUP2017
Sudbury, Canada, July 25th, 2017

The Oscillation Project with Emulsion tRacking Apparatus

- Long baseline neutrino oscillation experiment located in the CNGS (CERN Neutrinos to Gran Sasso) ν_μ beam
- Direct search for $\nu_\mu \rightarrow \nu_\tau$ oscillations detecting the τ lepton produced in ν_τ CC interactions (appearance mode)

Direct appearance search in OPERA: on event-by-event basis

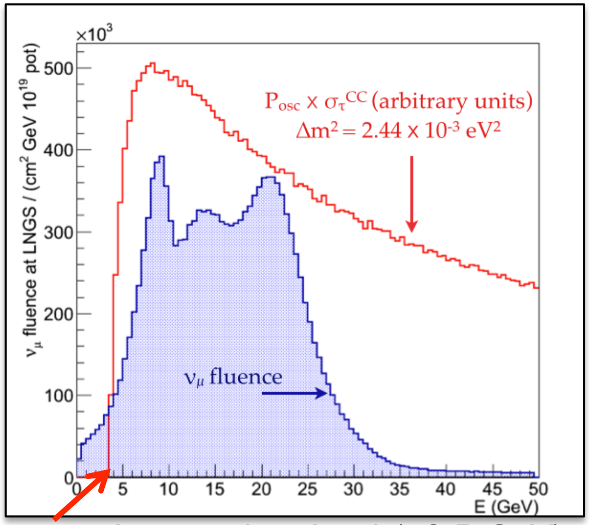
Emulsion based active target: ECC



57 × 2 emulsion layers (42 μm thick) poured on a 200 μm plastic base

CNGS beam: optimized for ν_τ appearance at LNGS (at 730 km)

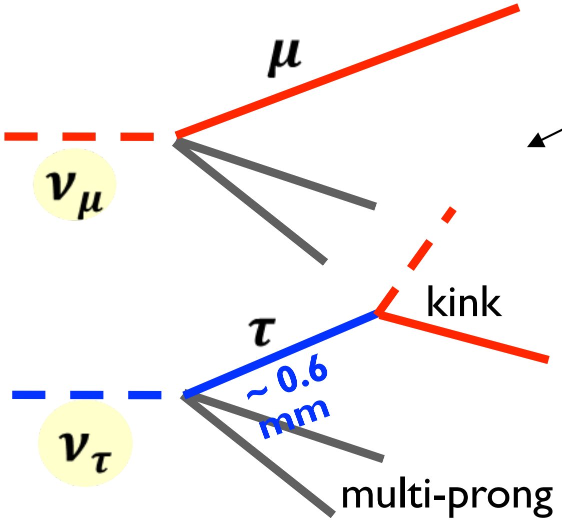
→ Maximize the number of ν_τ CC interactions at LNGS



τ production threshold (~3.5 GeV)

→ high energy beam $<E_\nu>$ ~ 17 GeV

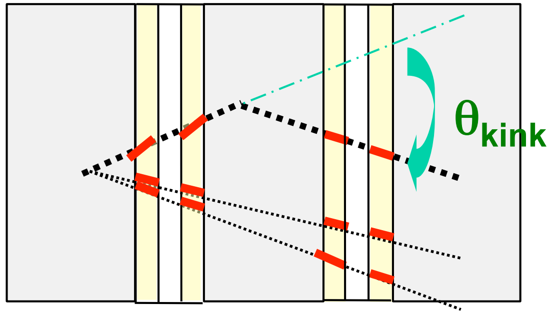
The ν_τ detection technique



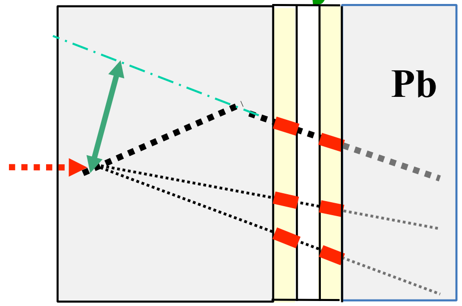
Detect a few ν_τ^{CC} from the bulk of ν_μ^{CC}

$\tau^- \rightarrow \mu^- \nu_\tau \nu_\mu$	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 %

"long" decays: kink



"short" decays: I.P.



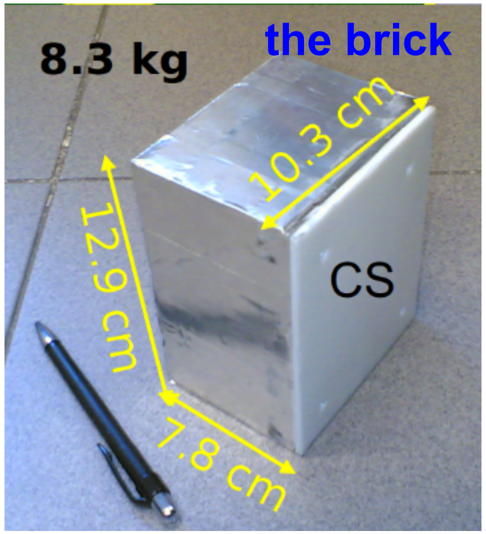
Modular detector of "Emulsion Cloud Chambers" (or bricks)

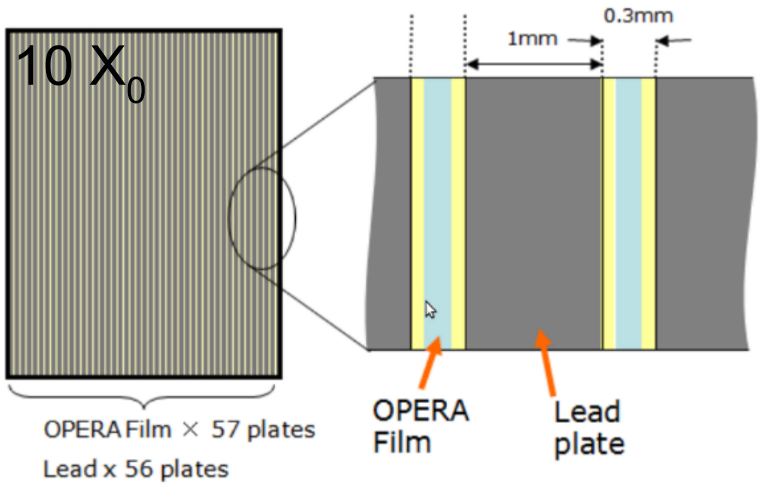
Large mass

$$N_\tau \propto (\Delta m^2)^2 M_{target}$$

Extreme granularity

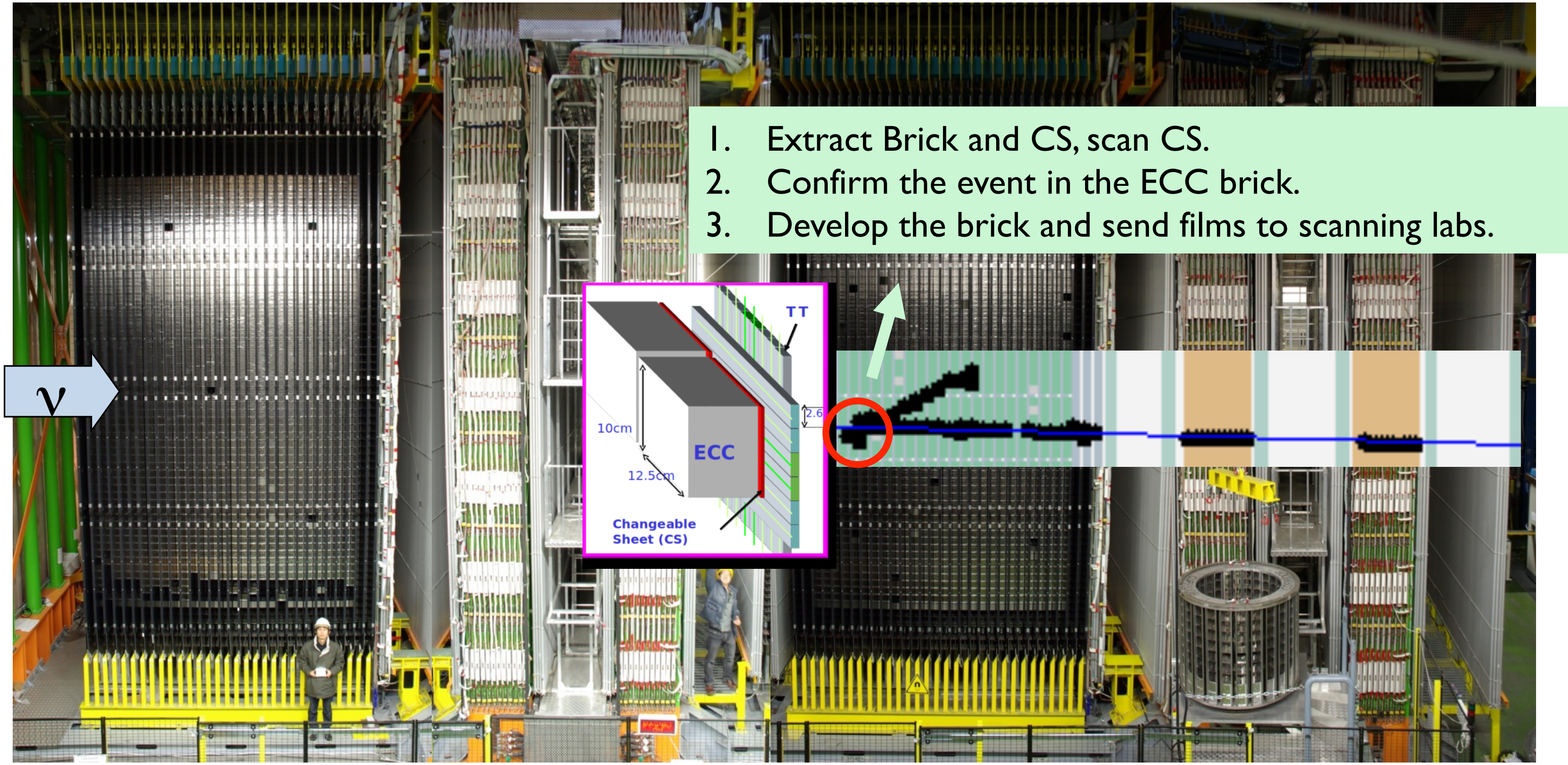
$\sim\mu$m space resolution





The OPERA hybrid detector

SM 1 | SM 2



Target
bricks walls + Target Tracker

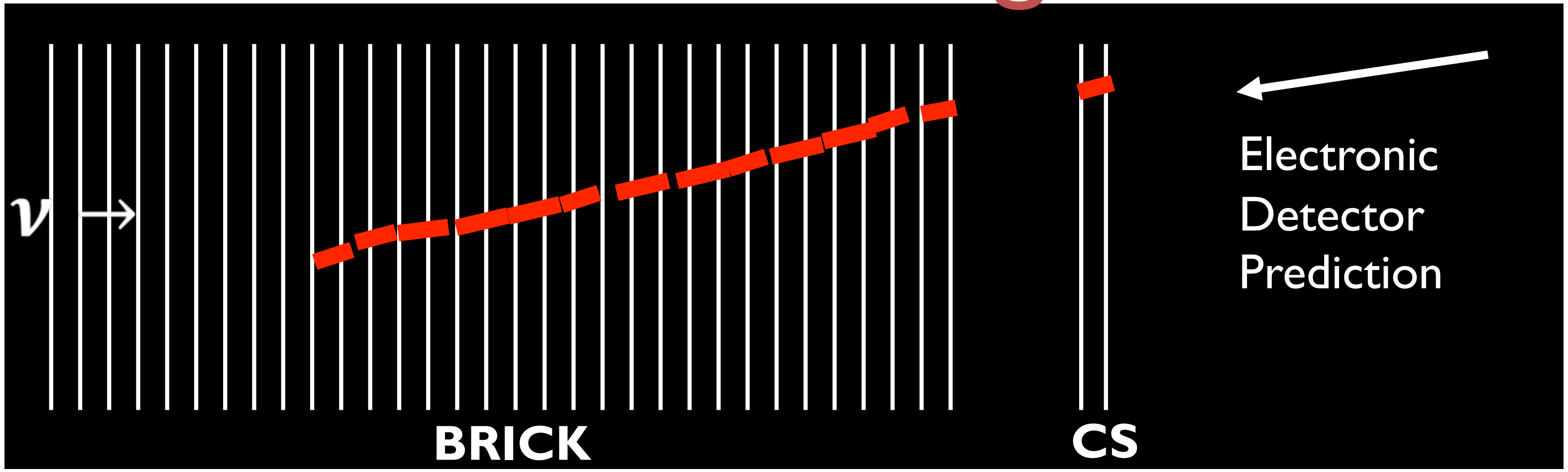
Spectrometer
RPC + drift tubes

Target
bricks walls + Target Tracker

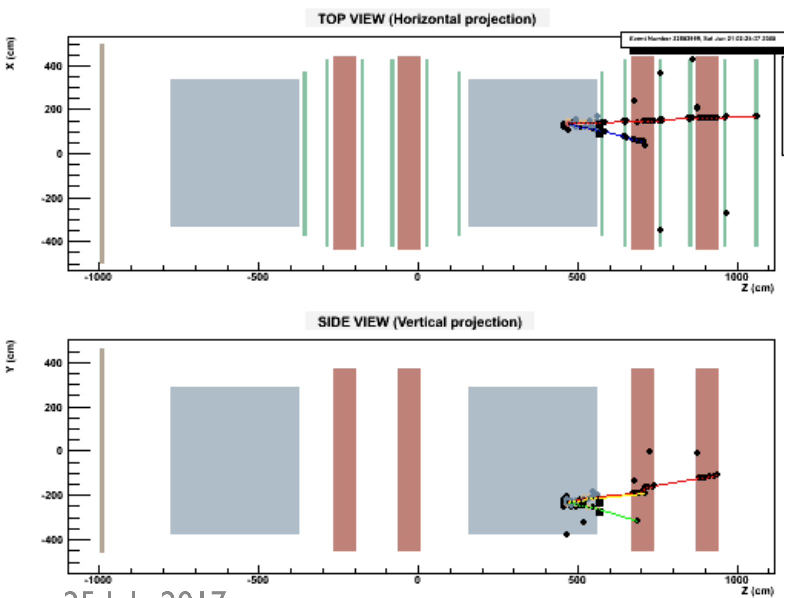
Spectrometer
RPC + drift tubes

~ 150.000 bricks in total
1.25 kt mass

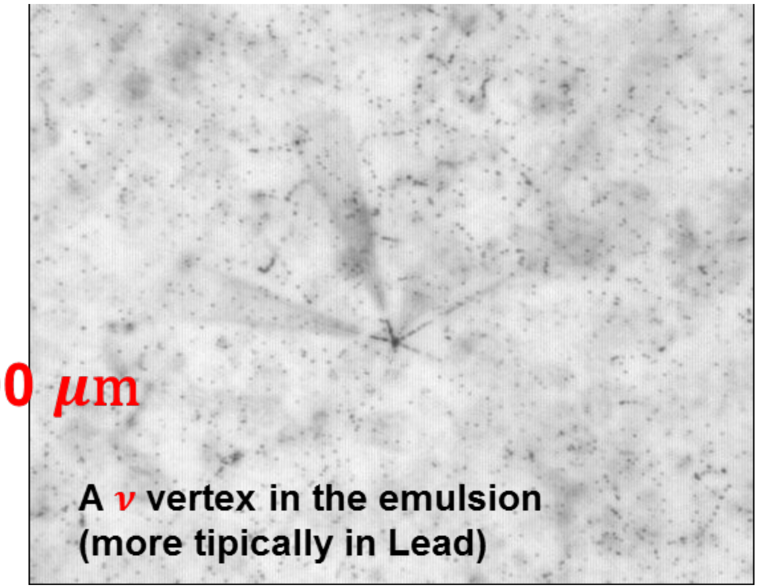
Vertex hunting in the brick



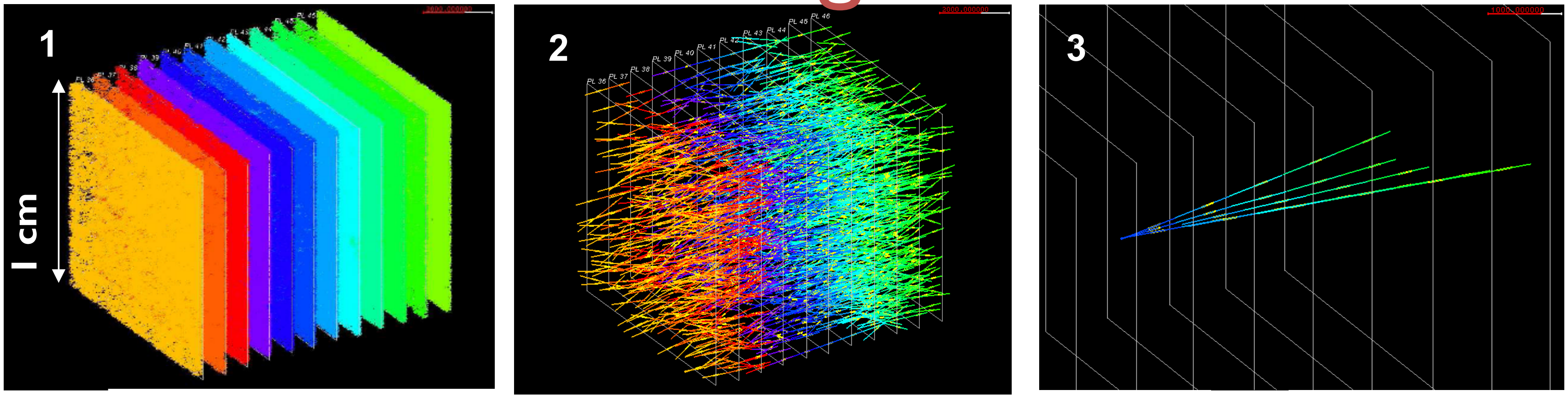
0) all tracks tagged in the **CS films** are **followed upstream** until a stopping point is found



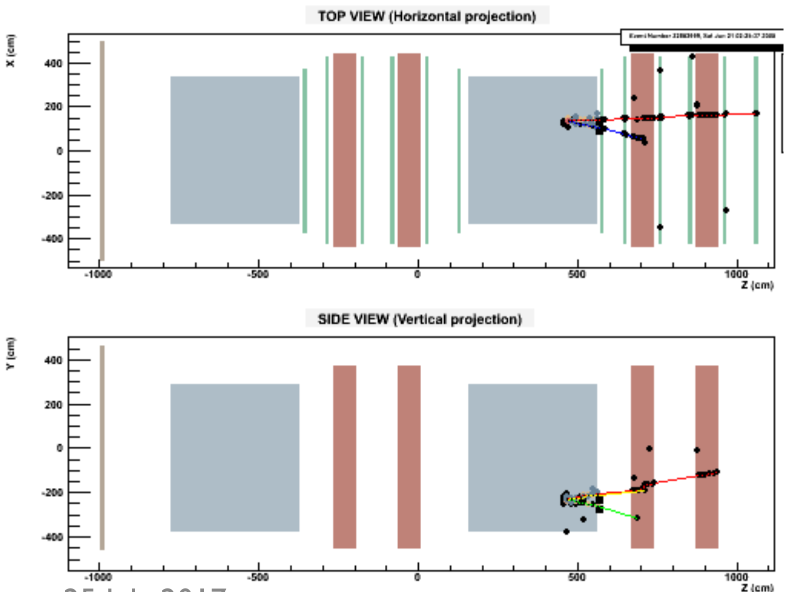
20 m →100 μm
(essential role of CS films)



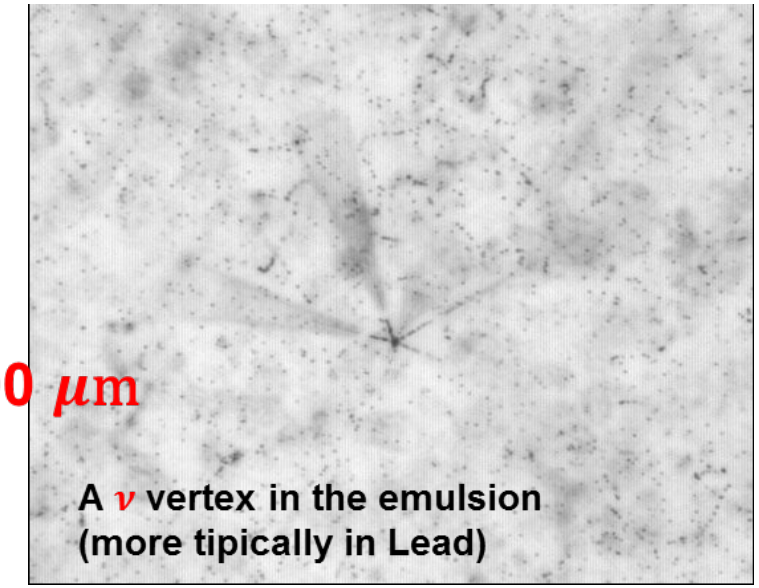
Vertex hunting in the brick



0) all tracks tagged in the **CS films** are **followed upstream** until a stopping point is found
1) a ~ 1 cm³ **volume centered in the stopping point** is scanned and tracks are reconstructed
2) cosmic ray tracks (from a dedicated exposure) are used for the fine **alignment** of films
3) passing-through tracks are discarded and the **vertexing algorithm** reconstructs the vertex.



20 m →100 μm
(essential role of CS films)



$\nu_\mu \rightarrow \nu_\tau$ appearance discovered

The 5 years long CNGS run

- **1.8×10^{20} p.o.t.** collected (**80%** of the design)
- **19505** ν interactions in the emulsion targets.
- **5 candidate events** fulfill kinematical selection **[S/B ratio ~10]**

Observed Data: 4 hadronic + 1 muonic candidates

Channel	Expected background	Expected signal	Observed
$\tau \rightarrow 1h$	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \rightarrow 3h$	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \rightarrow \mu$	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \rightarrow e$	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.25 ± 0.05	2.64 ± 0.53	5

Signal Background Modelization

- *Multichannel (uncorrelated) counting model based on Poisson Statistics*
- *Gaussian for Background Uncertainties*

$$\mathcal{L} = \prod \mathrm{Pois}(n_i, \mu s_i + b_i)\, \mathrm{Gaus}(b_{0i}, b_i, \sigma_{bi})$$

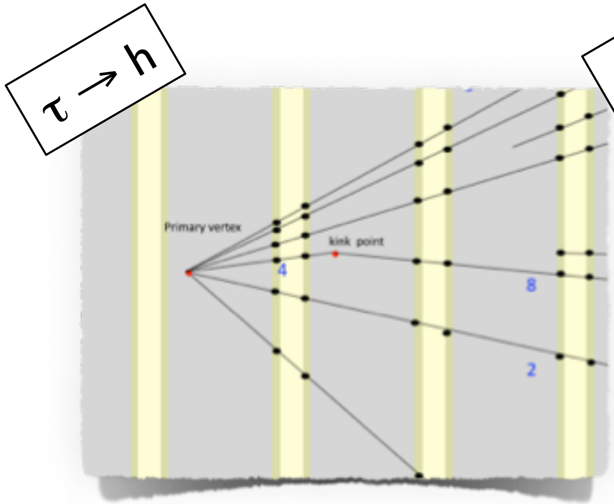
$\mu \rightarrow$ **strength of the signal** (parameter of interest)
with $\boldsymbol{\mu} = \mathbf{0}$: **background-only** hypothesis
and $\boldsymbol{\mu} = \mathbf{1}$: **nominal signal+background**

test statistics:
i) Profile Likelihood Ratio;
ii) Fisher's rule ($\mu = 0$) .

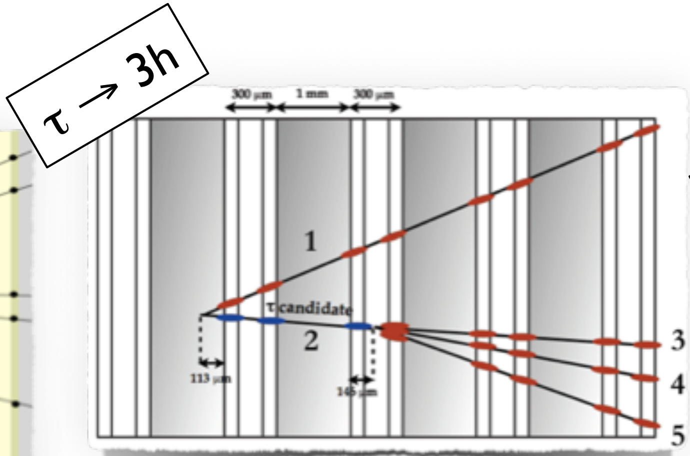
Background-only hypothesis:
- p-value = 1.1×10^{-7}
- **excluded at 5.1σ significance**

PRL 115, 121802 (2015)

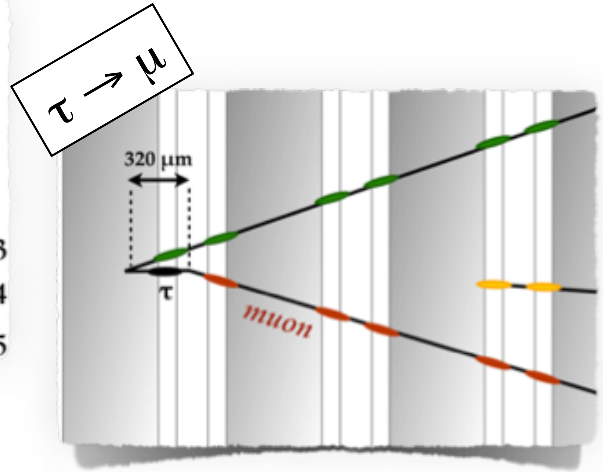
The 5 ν_τ candidate events



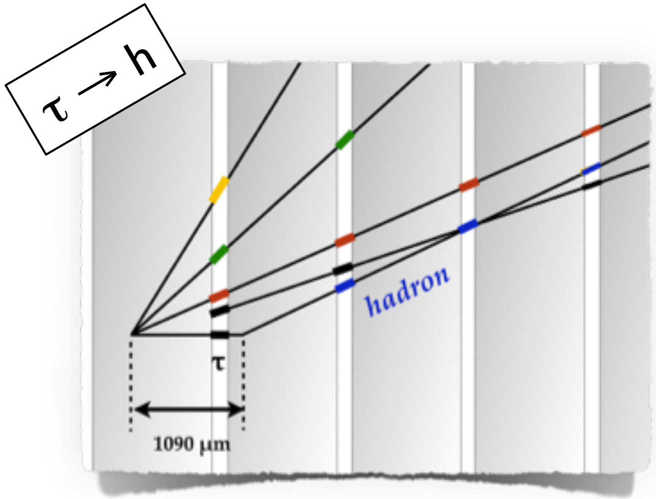
Phys. Lett. B 691 (2010) 138



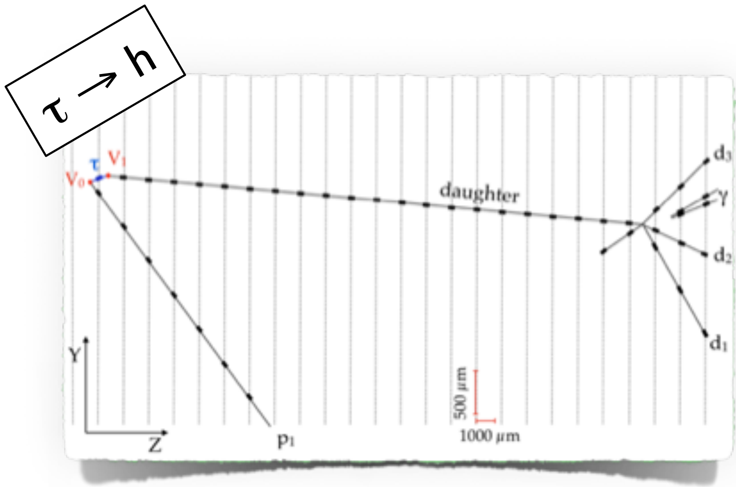
JHEP 11 (2013) 036



Phys. Rev. D 89 (2014) 051102



PTEP 2014 (2014) 10, 101C01



Phys.Rev.Lett. 115 (2015) no.12, 121802

Event selection with looser kinematical cuts

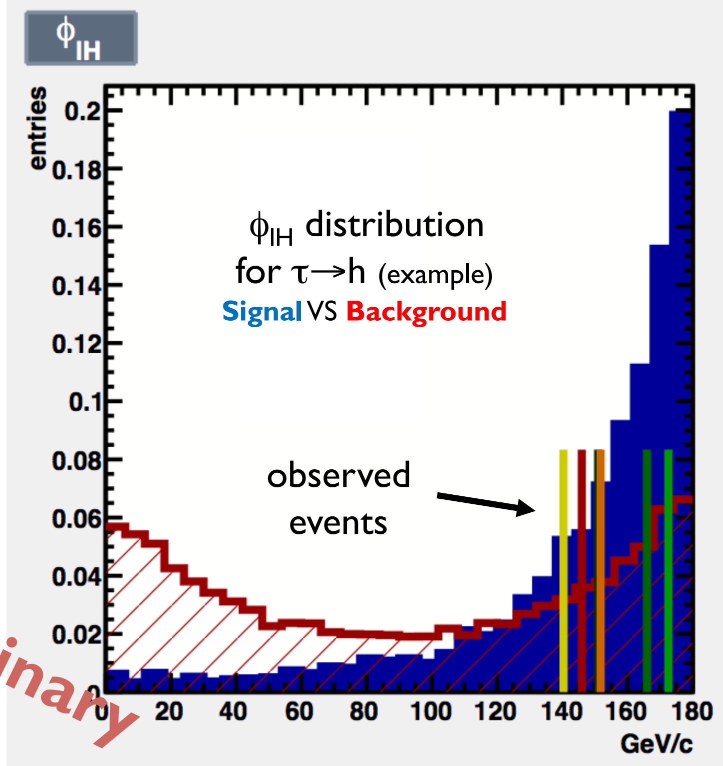
Loose kinematical cuts:

- **Minimum selection** to limit contribution from had. int. and large angle scattering bkg
- **Negligible additional background** from K/π decays

→Increase the statistics and apply a multivariate analysis

- **Boost Decision Tree**
  Use kinematical, topological variables and their **correlations**

Variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
z_{dec} (μm)	<2600	<2600	<2600	<2600
θ_{kink} (rad)	>0.02	>0.02	>0.02	>0.02
p_{2ry} (GeV/c)	>1	>1	>1	>1
p^T_{2ry} (GeV/c)	>0.15	/	>0.1	>0.1



- ✓ **5 more ν_τ candidates (increased statistics: ×2)**
- ✓ **S/B reduced from ~10 to ~3**
- ✓ **improvement in Δm^2_{23} measurement, the first in appearance mode**

Expected Signal	Expected Background	Observed ν_τ	Δm^2_{23} (10^{-3} eV^2)
6.8	2.0	10	2.7 ± 0.6 68% C.L

Preliminary

Measurement of Δm^2_{23}

$$N_{\nu_\tau} \propto \int \phi(E) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \epsilon(E)\sigma(E) dE$$
$$\propto (\Delta m^2_{32})^2 L^2 \int \phi(E)\epsilon(E)\frac{\sigma(E)}{E^2} dE$$

$\left({}^{L}/_{\langle E \rangle} \right)_{opera} \sim 43$ km/GeV

$\left({}^{L}/_{\langle E \rangle} \right)_{PEAK} \sim 500$ km/GeV

"Steep" Δm^2_{23} dependence

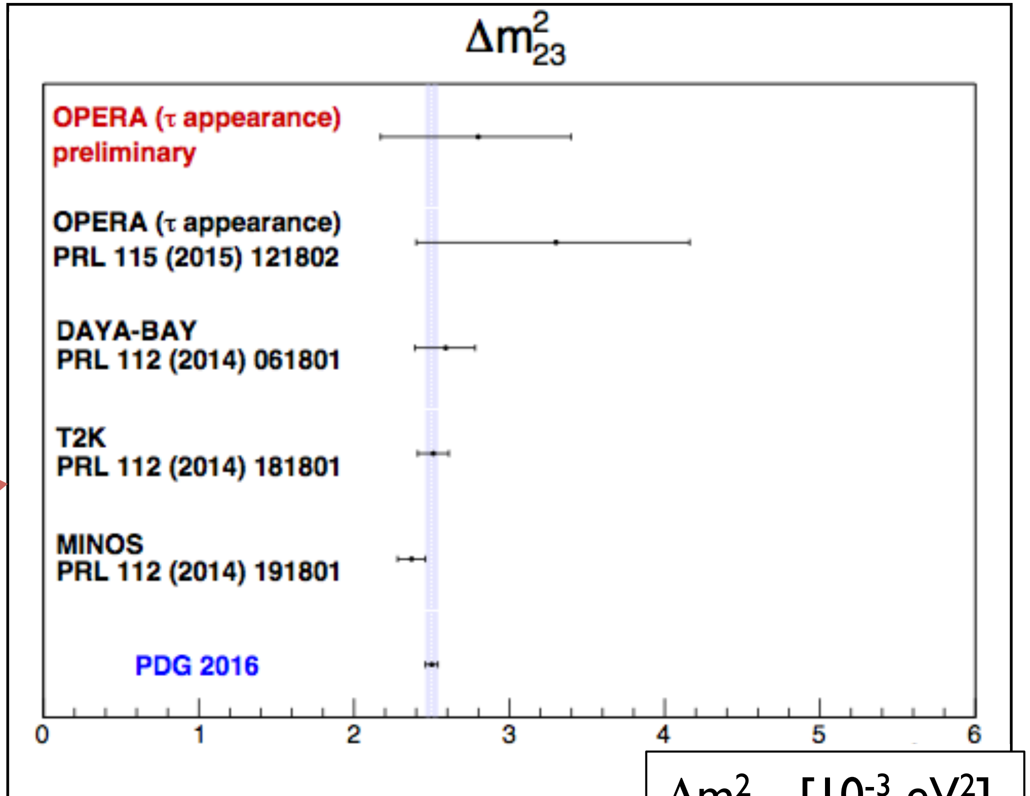
→ counting based measurement

90% C.L. interval
by Feldman & Cousins method

$\Delta m_{23}{}^2 = [2.1 - 3.3]\ 10^{-3}\ eV^2$

(assuming full mixing)

Preliminary



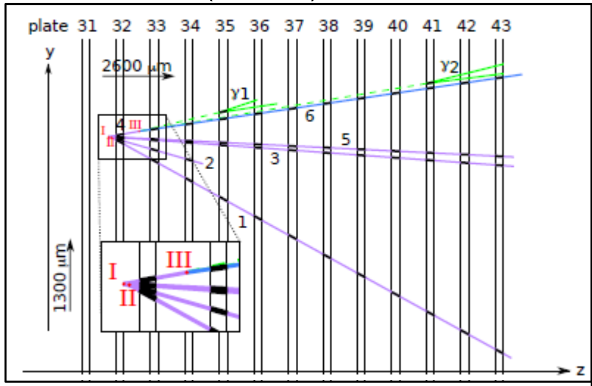
Δm^2_{23} [10^{-3} eV^2]

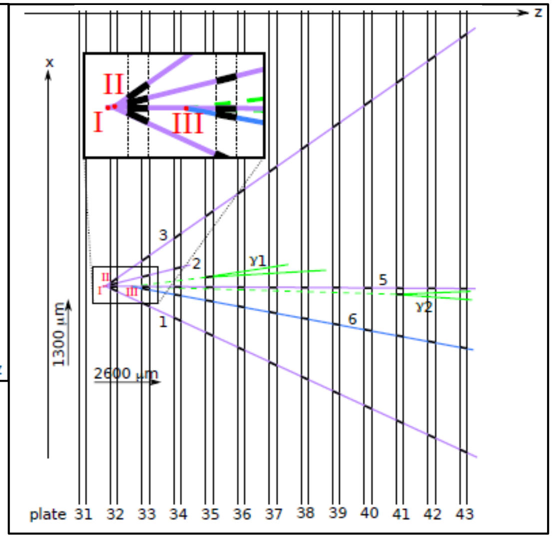
Peculiar muon-less event

- Muon-less neutrino event
- Most probable topology:
  ν interaction vertex + 2 decay vertices
- **Rare topology** not considered in the experiment proposal
  (0.1 events expected in full data sample)
- Ad **hoc simulations + ANN** (2 Layers MLP) to distinguish between possible interpretations:

yz view
(vertical)

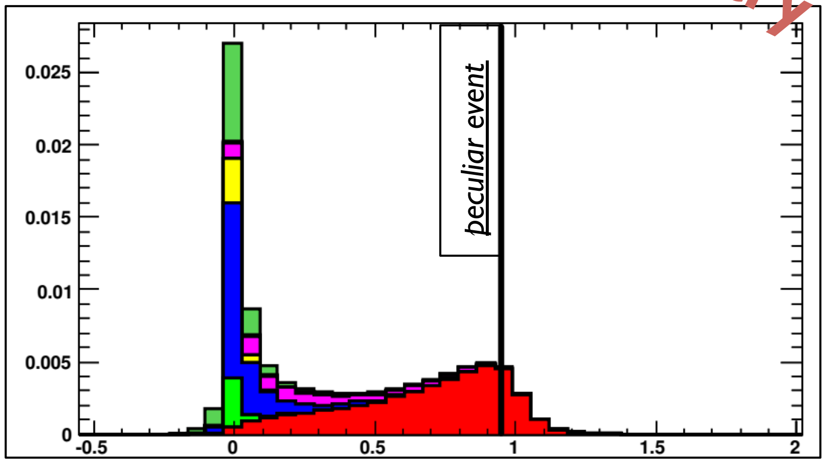
yz view
(horizontal)

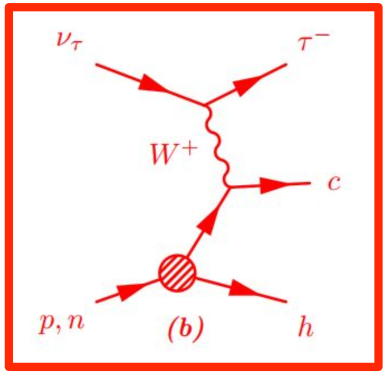




Preliminary

- $\nu_\tau CC + c$
- $\nu_\mu CC + c + had.\ int.$
- $\nu_\mu NC + c\bar{c}$
- $\nu_\tau CC + had.\ int.$
- $\nu_\mu CC + 2\ had.\ int.$
- $\nu_\mu NC + 2\ had.\ int.$

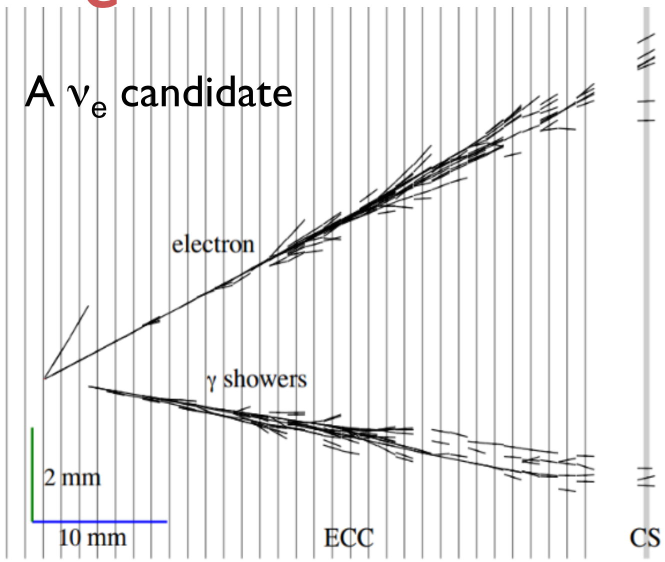




$\nu_\tau CC + charm$

Assuming the event not being ν_τ CC + charm: p-value ~ 10^{-4} → Significance = 3.5 σ

Subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

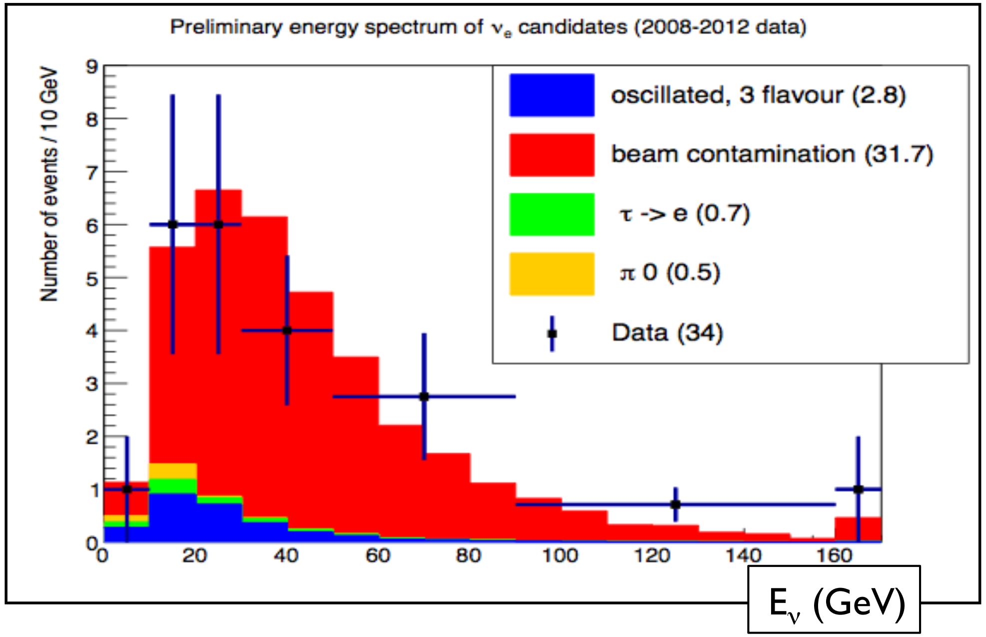


- OPERA ECC granularity allows e.m. shower id → **ν_e search**
- **A dedicated procedure**, balancing time need vs efficiency

0.9% ν_e beam contamination

Preliminary

Contribution	# events for 19.97 x 10^{19} pot
ν_e beam	***31.7***
τ (unidentified) → e	**0.7**
$\pi^0 \rightarrow \gamma$ (misidentified)	**0.5**
$\nu_\mu \rightarrow \nu_e$ oscillations	***2.8***
Total	*35.7 (32.9 w/o osc.)*
observed	*34*



Sterile neutrino mixing searches

OPERA can test the sterile neutrino hypothesis

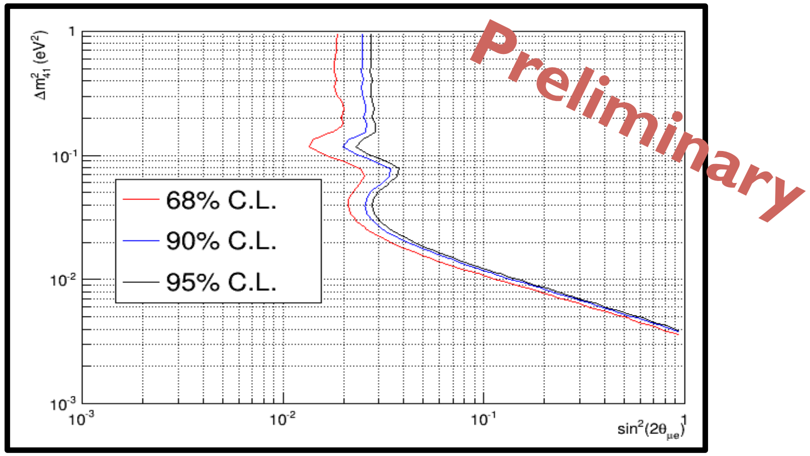
3+1 model:
parameters of interest

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

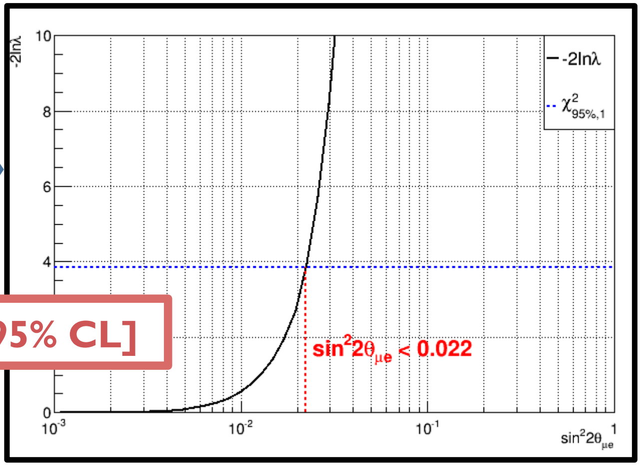
ν_e appearance

ν_τ appearance

ν_e appearance

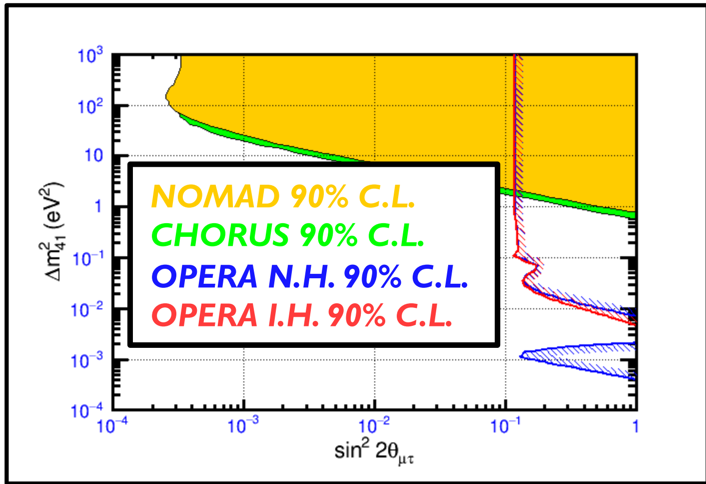


At high Δm^2_{41}

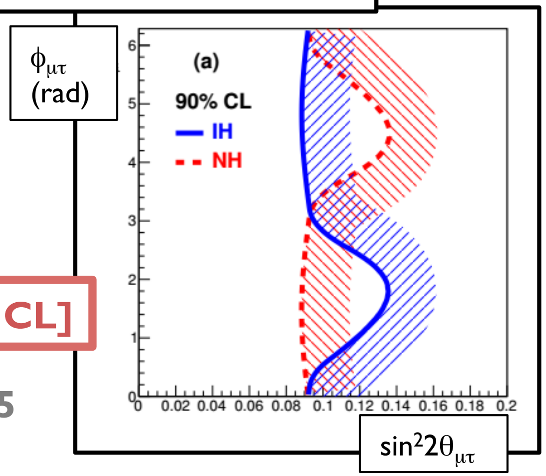


$\sin^2 2\theta_{\mu e} < 0.022$ [95% CL]

ν_τ appearance



At high Δm^2_{41}

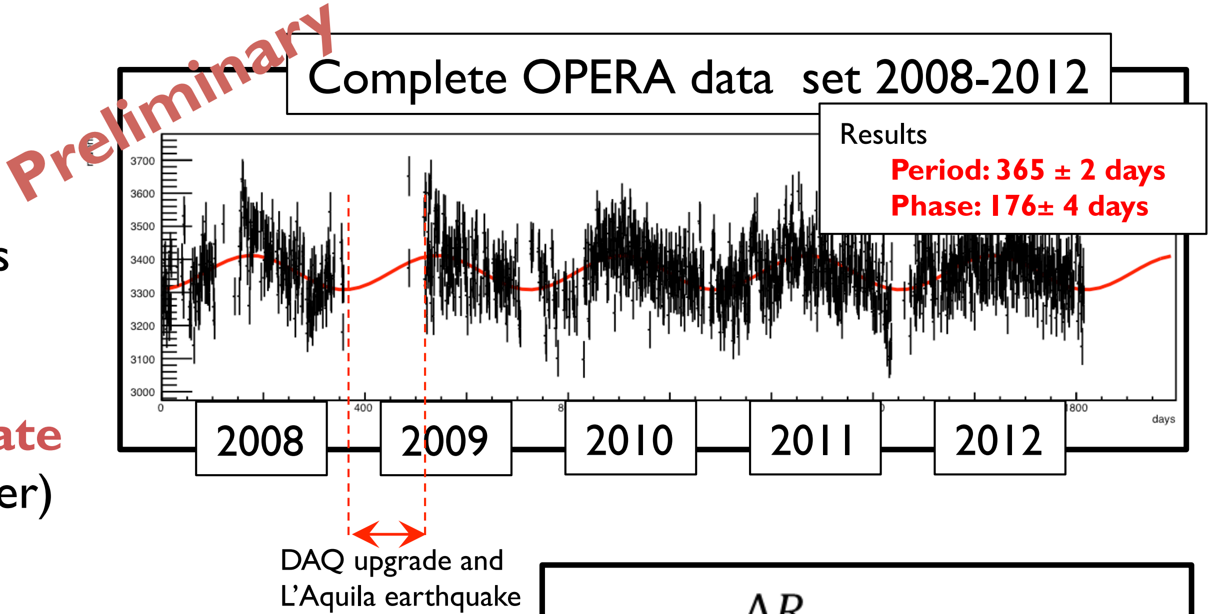


$\sin^2 2\theta_{\mu\tau} < 0.116$ [90% CL]

[JHEP 074 (2015) 0315

Annual modulation of muon rate

ΔT in the upper atmosphere
→ variation in atmospheric density
→ variation in π/K interaction length
→ variation in the fraction of mesons decaying before interacting

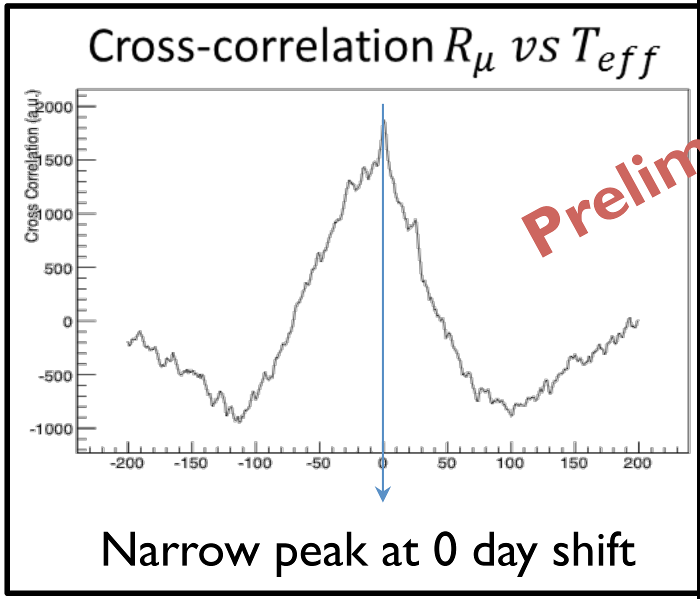


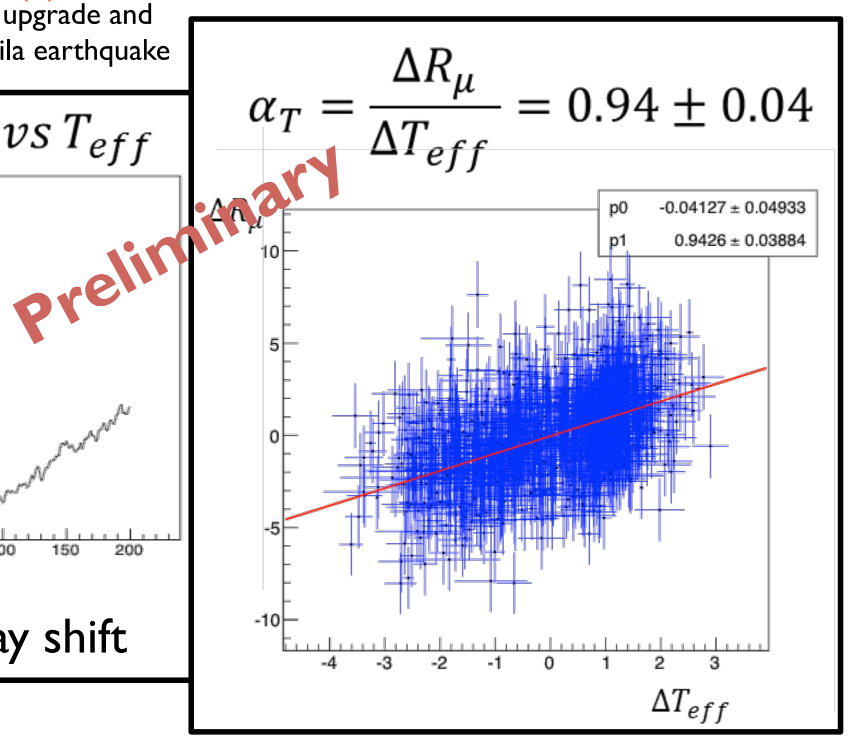
→ Annual modulation of muon rate
(more muons in summer than in winter)

Comparison with Dark Matter modulated signals and other experiments

Correlation between R_μ and the effective temperature T_{eff}

→ measurement of α_T





Conclusions

- **Discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance** in the CNGS neutrino beam: 5.1 σ

- Loose selection analysis to increase the number of ν_τ candidates $\Rightarrow$ improve OPERA **measurement of Δm^2_{23} (first measurement in appearance mode)**

- Muon-less **double decay event**
  Favored interpretation: ν_τ CC interaction with charm production

- **$\nu_\mu \rightarrow \nu_e$ oscillation search**

- Constraints on **sterile neutrinos**
  from $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ with the 3+1 flavor model

- Non-oscillation Physics: **annual modulation of atmospheric muons**

- ***PERSPECTIVES***: Exploit OPERA unique feature of identifying all three flavors:

  - ν_τ appearance
  - ν_e appearance
  - ν_μ disappearance

to constrain oscillations parameters with one single experiment

Thank you for your attention!

Image taken using an **OPERA nuclear emulsion film**
with a pinhole hand made camera
courtesy by Donato Di Ferdinando

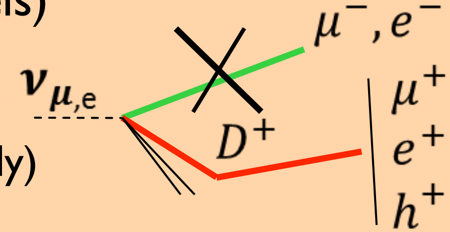
Back Up

$\nu_\mu \to \nu_\tau$ background characterization

Monte Carlo simulation benchmarked on control samples.

In order of decreasing relevance

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

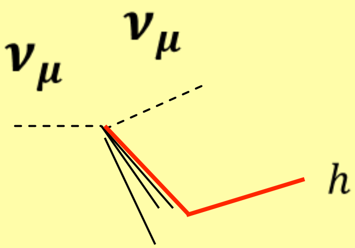


MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

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

[Eur.Phys.J. C74 (2014) 2986]

Hadronic interactions
Background for $\tau \to h$

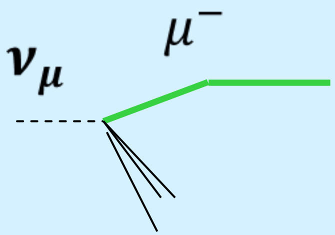


FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

[PTEP9 (2014) 093C01]

Large angle muon scattering
Background for $\tau \to \mu$



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

[IEEE Trans.Nucl.Sci. 62 (2015) no.5, 2216]

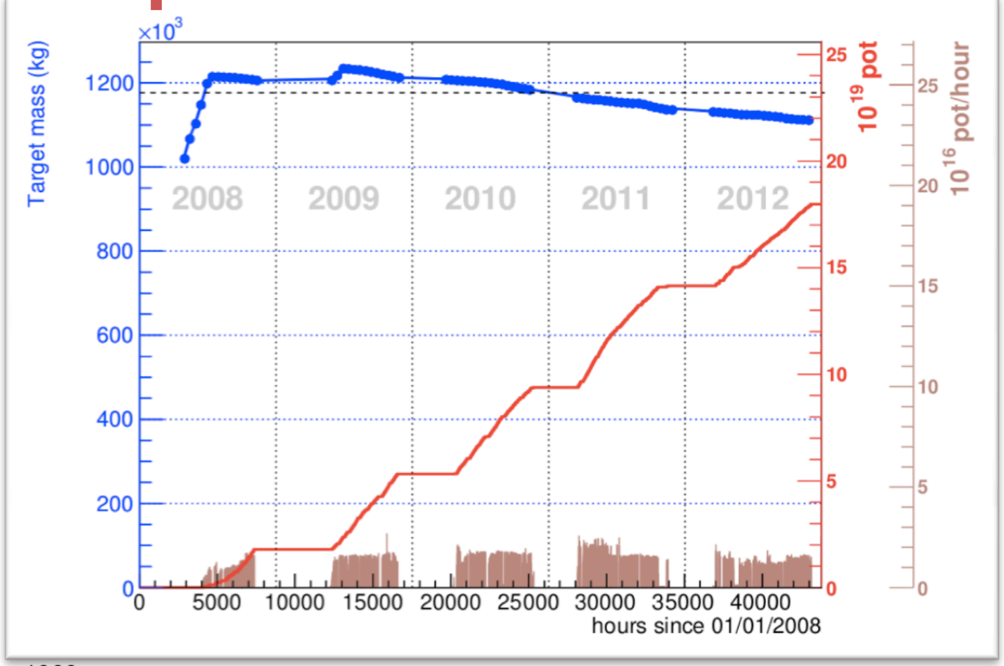
Data samples

The 5years long CNGS run ended in 2012.

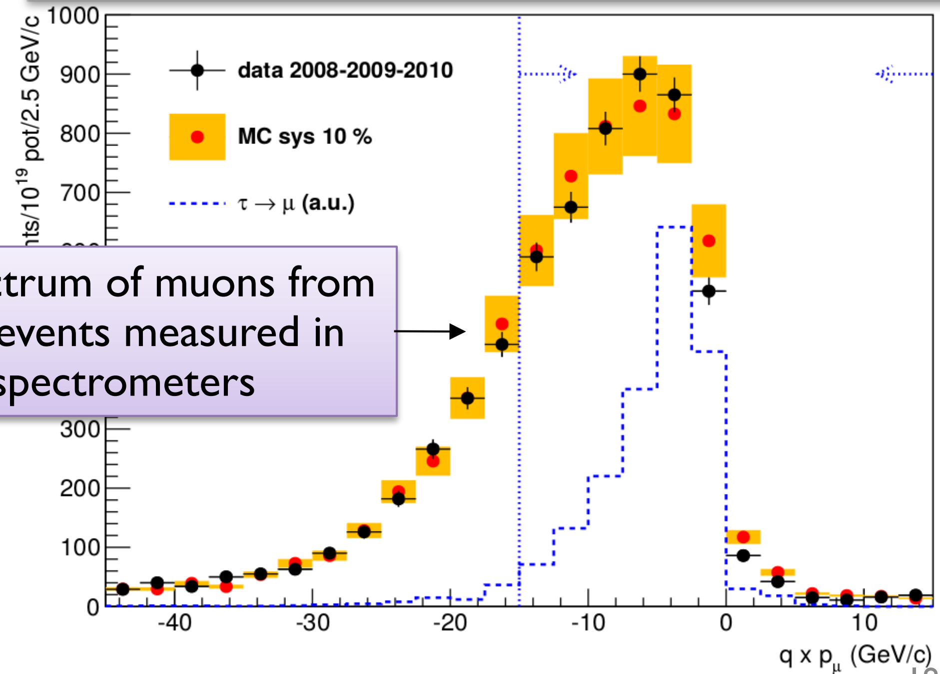
$1.8 \cdot 10^{20}$ p.o.t. collected
(80% of the design)

1.25 kton initial target mass
(150 k bricks)

19505 neutrino interactions
in the emulsion targets.

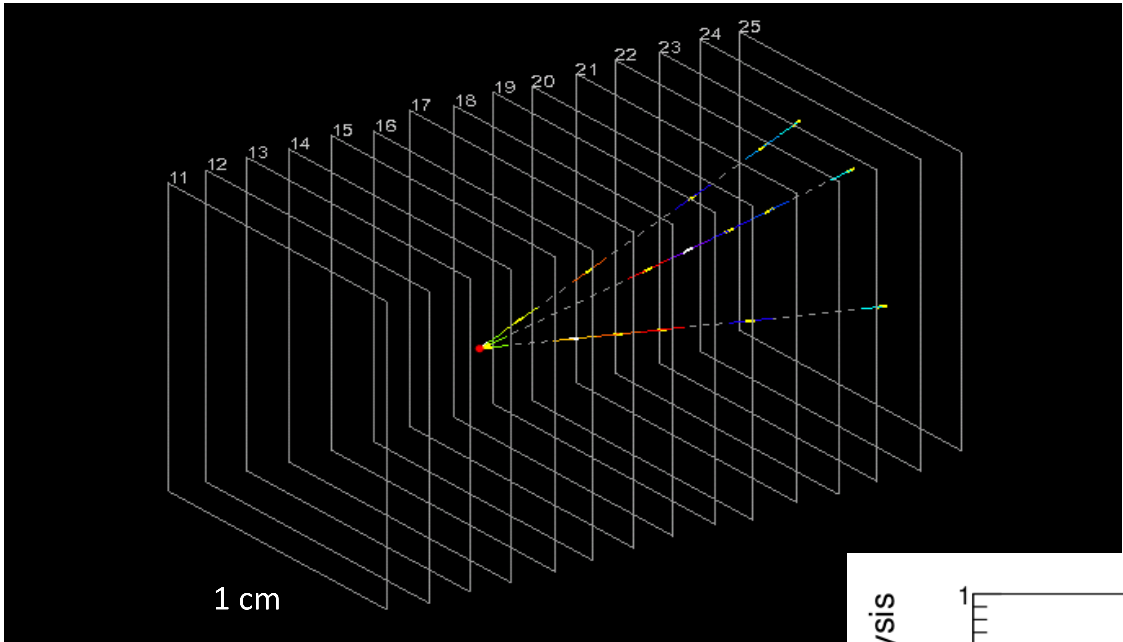


Year	Days	p.o.t. (10^{19})	ν interactions
2008	123	1.74	1698
2009	155	3.53	3693
2010	187	4.09	4248
2011	243	4.75	5131
2012	257	3.86	3923
tot	**965**	**17.97**	**19505**



Spectrum of muons from CC events measured in the spectrometers

Location efficiency

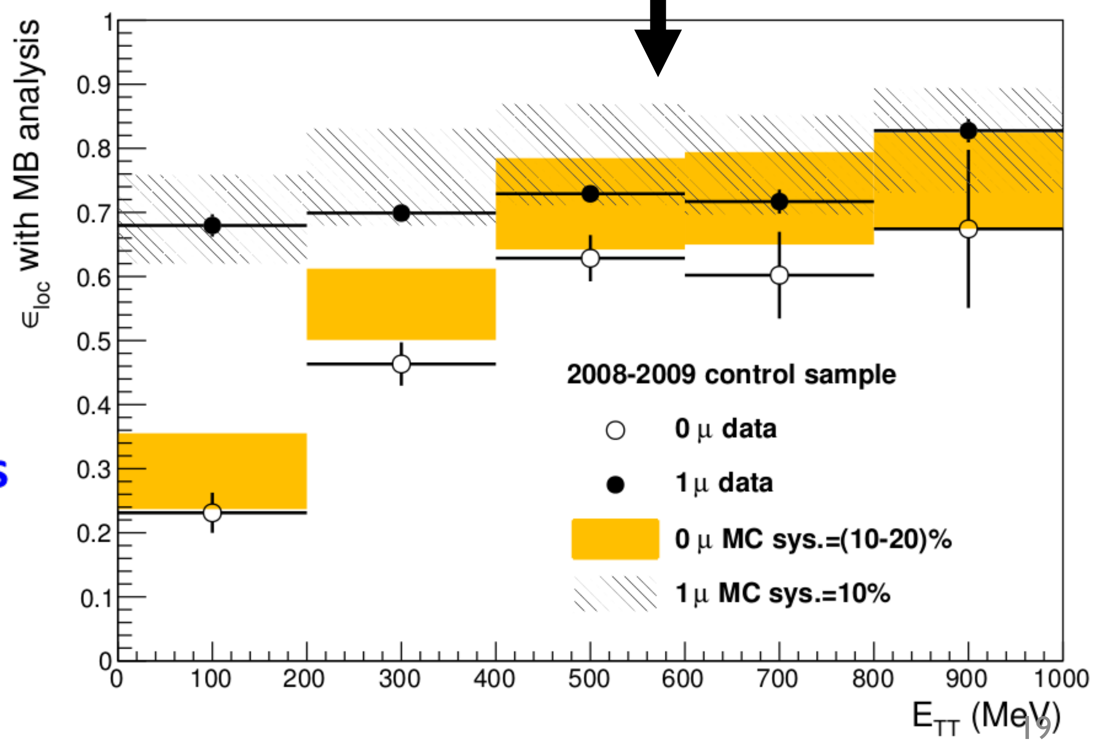


[JHEP 11 (2013) 036]

0μ−like and **1μ-like** samples

Data-Monte Carlo comparison of the **location efficiency** as a function of the visible energy in the target scintillators

Hybrid detector:
a complex simulation!
Reasonable agreement.



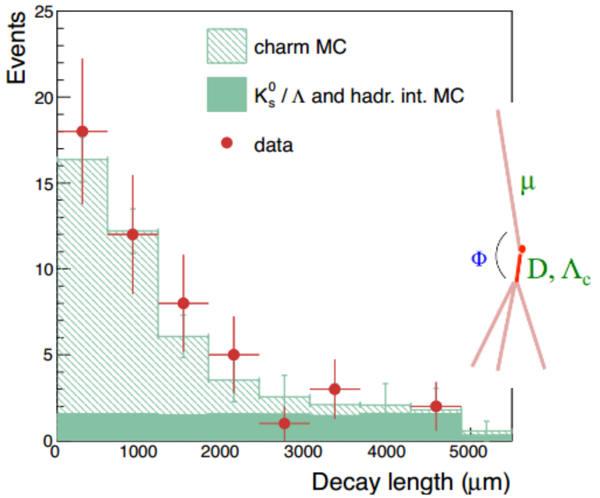
The **prediction for the τ signal** and **backgrounds** is based on **efficiencies** derived from the observed **0μ−like** and **1μ-like** samples

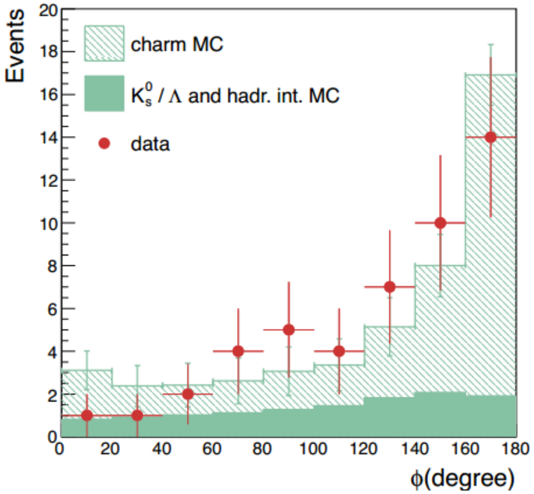
Validation with the charm events sample

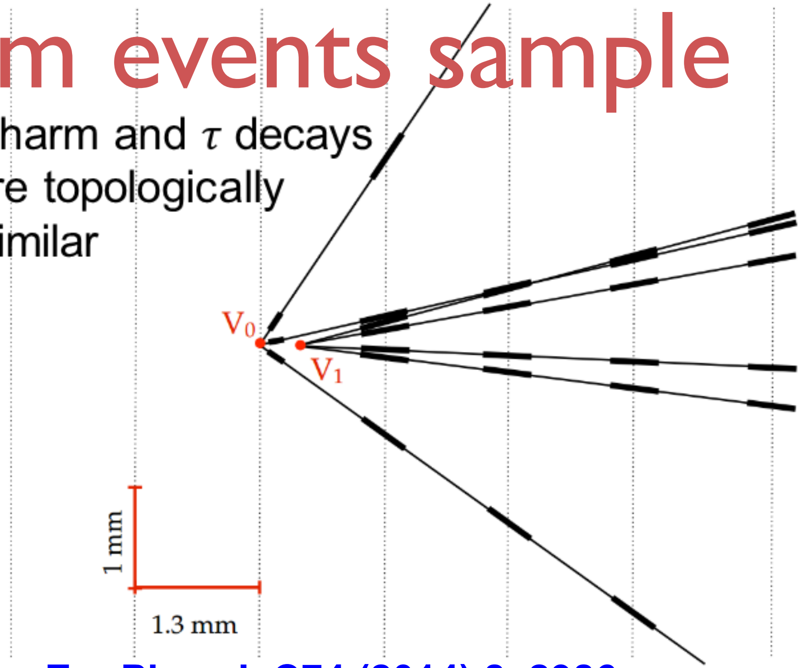
Test for: reconstruction efficiencies, description of kinematical variables, charm background.

54 ± 4 expected ↔ 50 observed

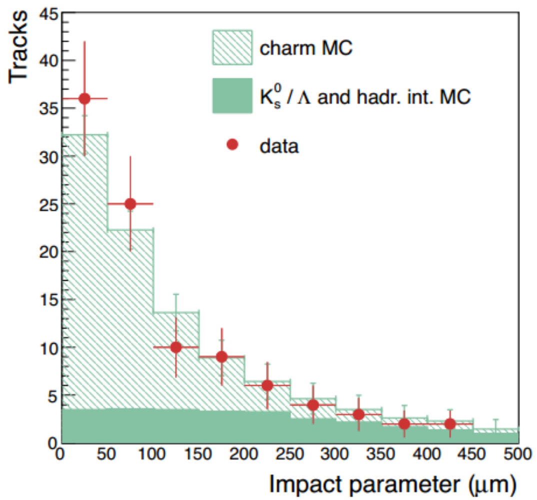
Charm and τ decays are topologically Similar

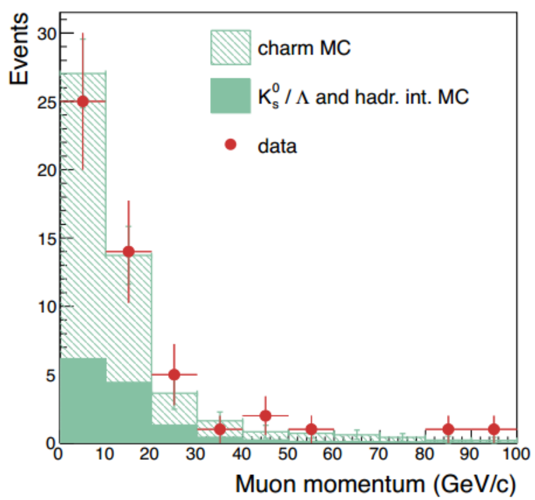


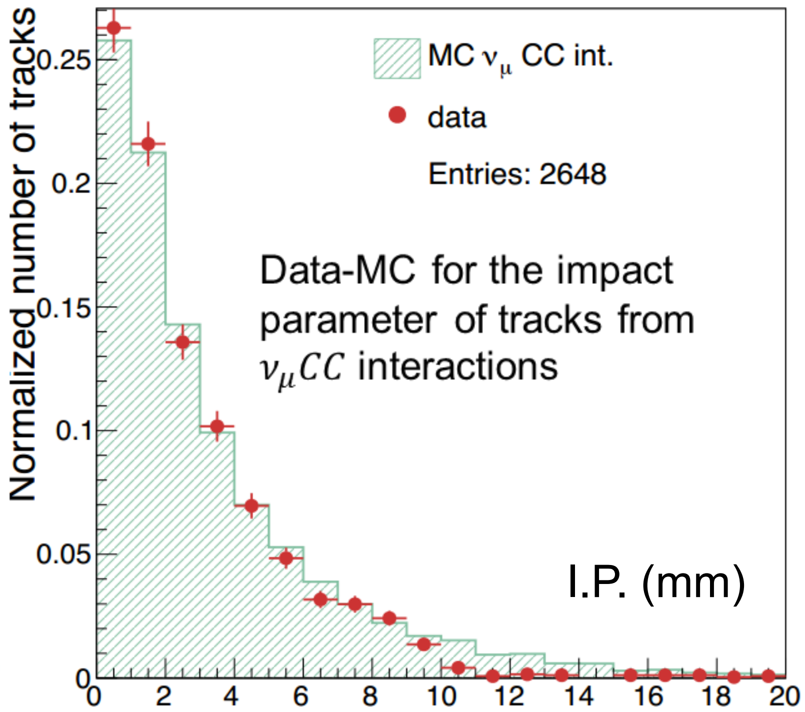




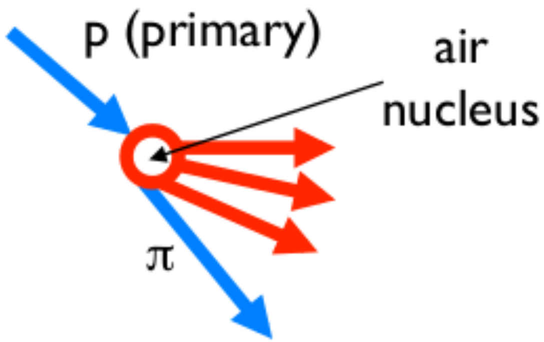
Eur.Phys.J. C74 (2014) 8, 2986







Atmospheric muon charge ratio



Eur. Phys. J. C74 (2014) 2933

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

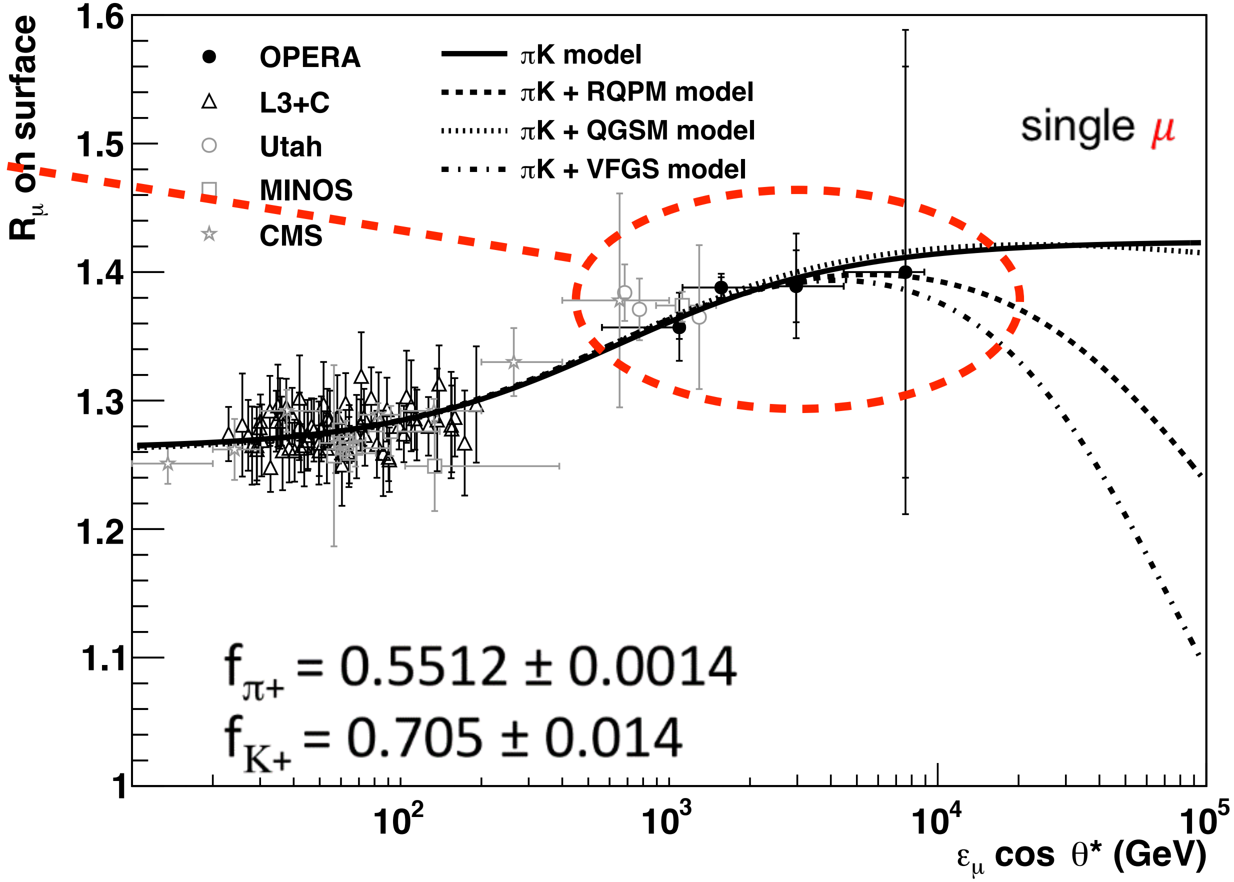
Highest-E region reached!

opposite magnet polarities runs → lower systematics

Strong reduction of the charge ratio for multiple muon events

1μ	1.377 ± 0.006
multi$-\mu$	1.098 ± 0.023

Results compatible with a simple $\pi - K$ model

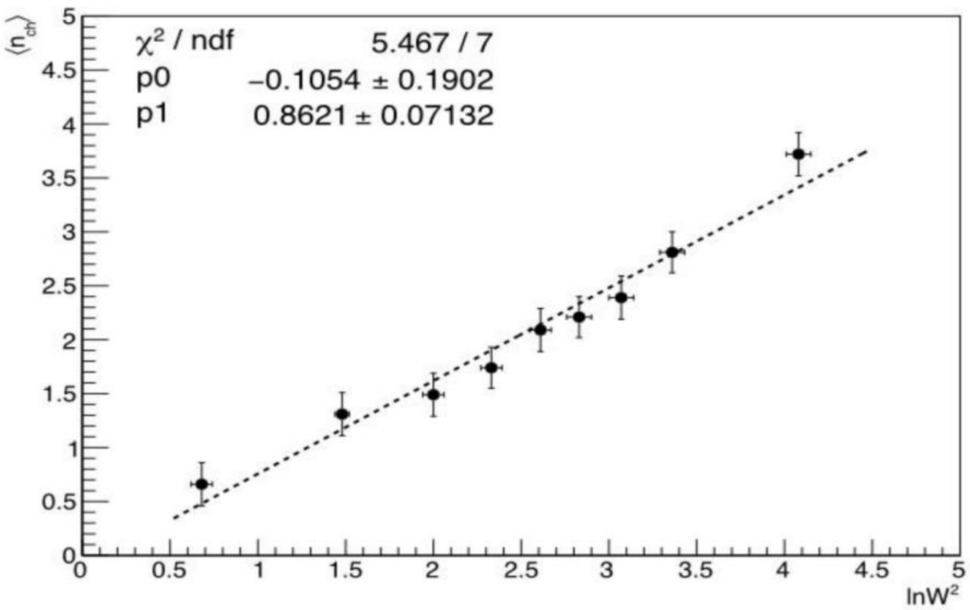


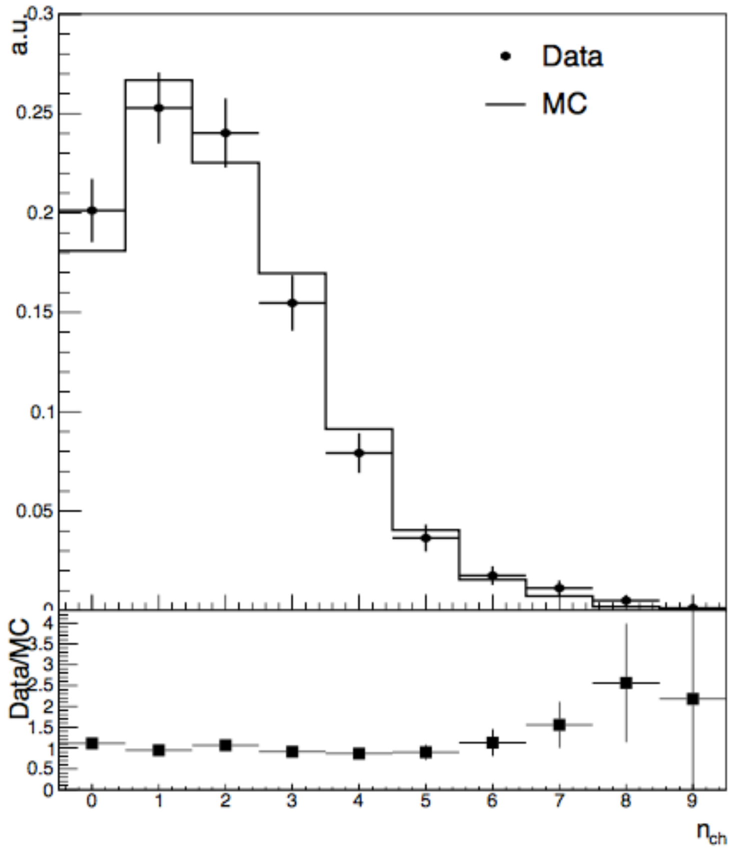
Primary Cosmic Ray composition at ~10^{13} ÷ 10^{14} eV/nucleon: proton excess δ_0 = 0.61 ± 0.02

Multiplicity studies in neutrino-lead scattering

The average charged particles multiplicity at primary vertex was measured.

- ✓ Test for phenomenological and theoretical models
- ✓ Provides data to tune MC event generators.
- ✓ Test KNO Scaling





submitted to EPJC and arXiv (http://arxiv.org/abs/1706.07930)