New results from the OPERA experiment in the CNGS neutrino beam

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

Istituto Nazionale di Fisica Nucleare

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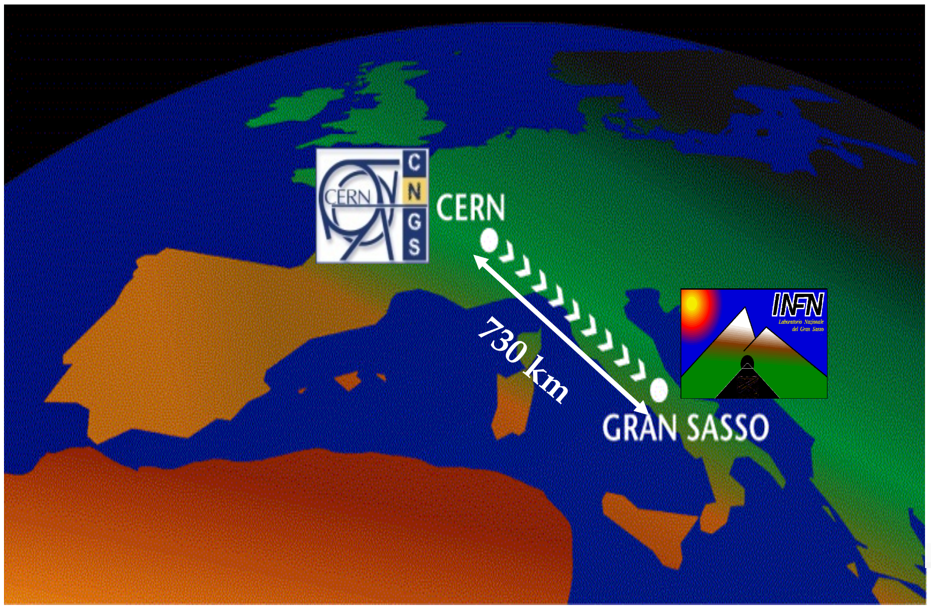
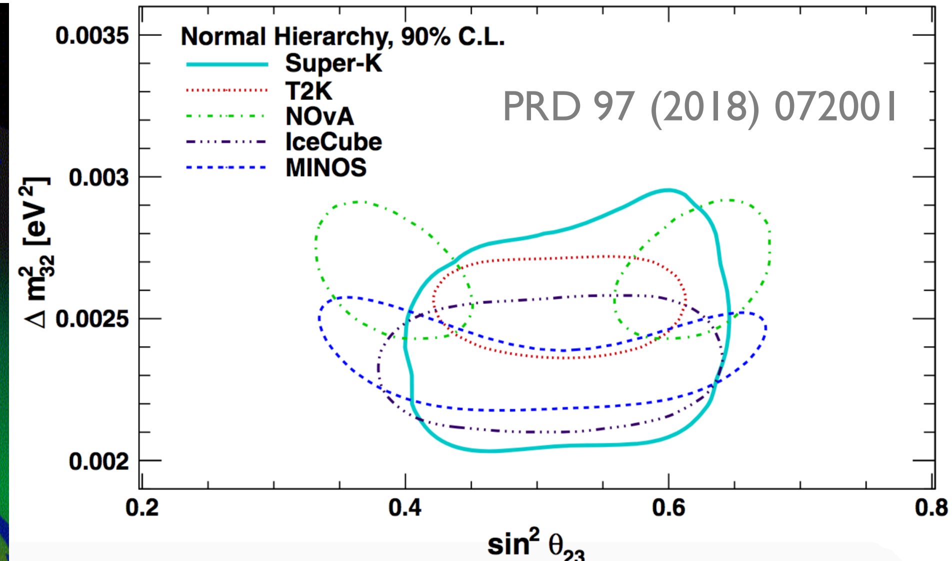
Outline

- The OPERA experiment
  - **detector and physics case**
- Appearance results
  - **$\nu_\mu \rightarrow \nu_\tau$ appearance channel**
  - **$\nu_\mu \rightarrow \nu_e$ appearance channel**
- Sterile neutrino mixing search
  - **3+1 model**
- Non-oscillation physics results
- Conclusions

The OPERA experiment

Main physics goal: **first direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode**



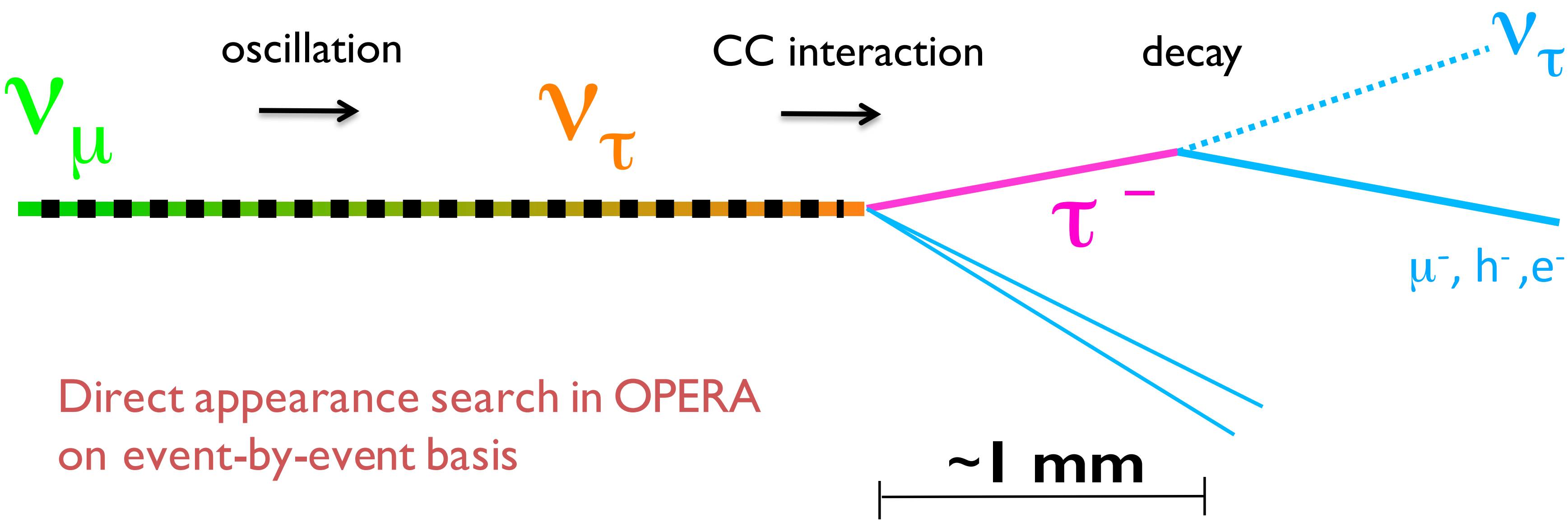


Full coverage of the parameter space for the atmospheric neutrino sector

- 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)

Appearance detection

Direct observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation



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

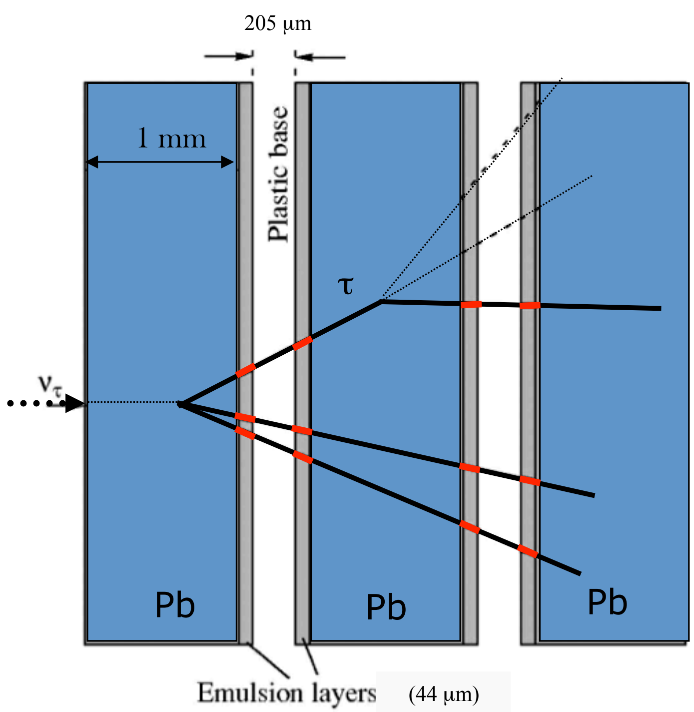
$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2(\Delta m^2_{23} L/4E)$$

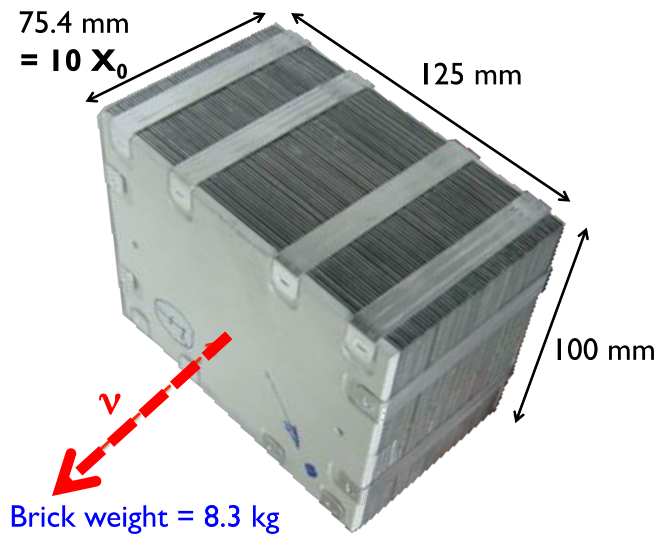
- $N(\tau) \propto M_{target}\, P(\nu_\mu \rightarrow \nu_\tau)$ → Large mass ~O(kton)
- detection of τ lepton production and decay → High granularity ~1 μm resolution

➡ **Emulsion Cloud Chamber**

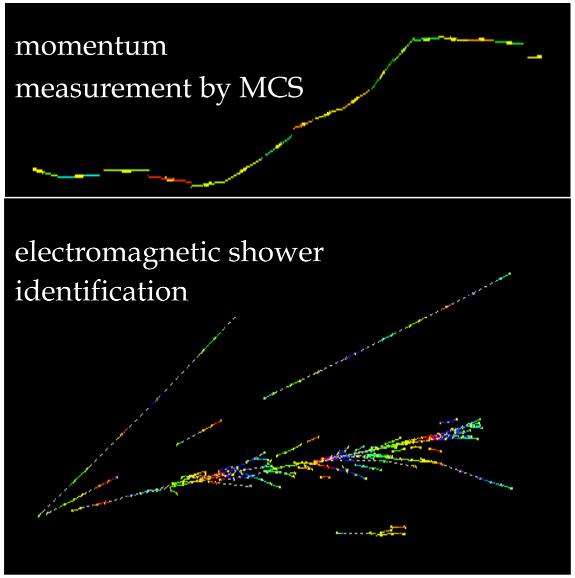
Neutrino interaction detector (ECC)

- Target basic unit: brick of 57 nuclear emulsions interleaved by lead plates + 2 interface emulsions (CS)
→ high resolution and large mass in a modular way
- unambiguous measurement of the kink





- "stand-alone" detector



The CNGS beam

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

→ Maximize the number of ν_τ CC interactions at LNGS

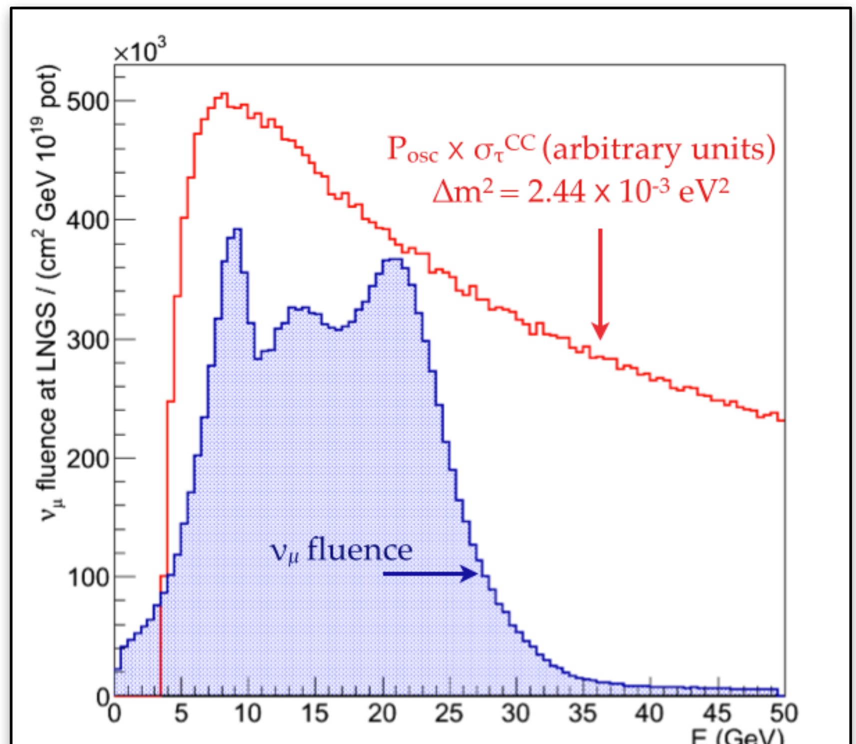
τ production threshold at ~3.5 GeV
+ ν_τ CC cross section
→ high energy beam $\langle E_\nu \rangle$ ~ 17 GeV

- ν_μ flux "off peak" w.r.t the maximum oscillation probability (~1.5 GeV)

$$N(\tau) \sim P(\nu_\mu \rightarrow \nu_\tau)\, \sigma_{\nu_\tau^{CC}}(E)\, \text{Flux}(E)$$

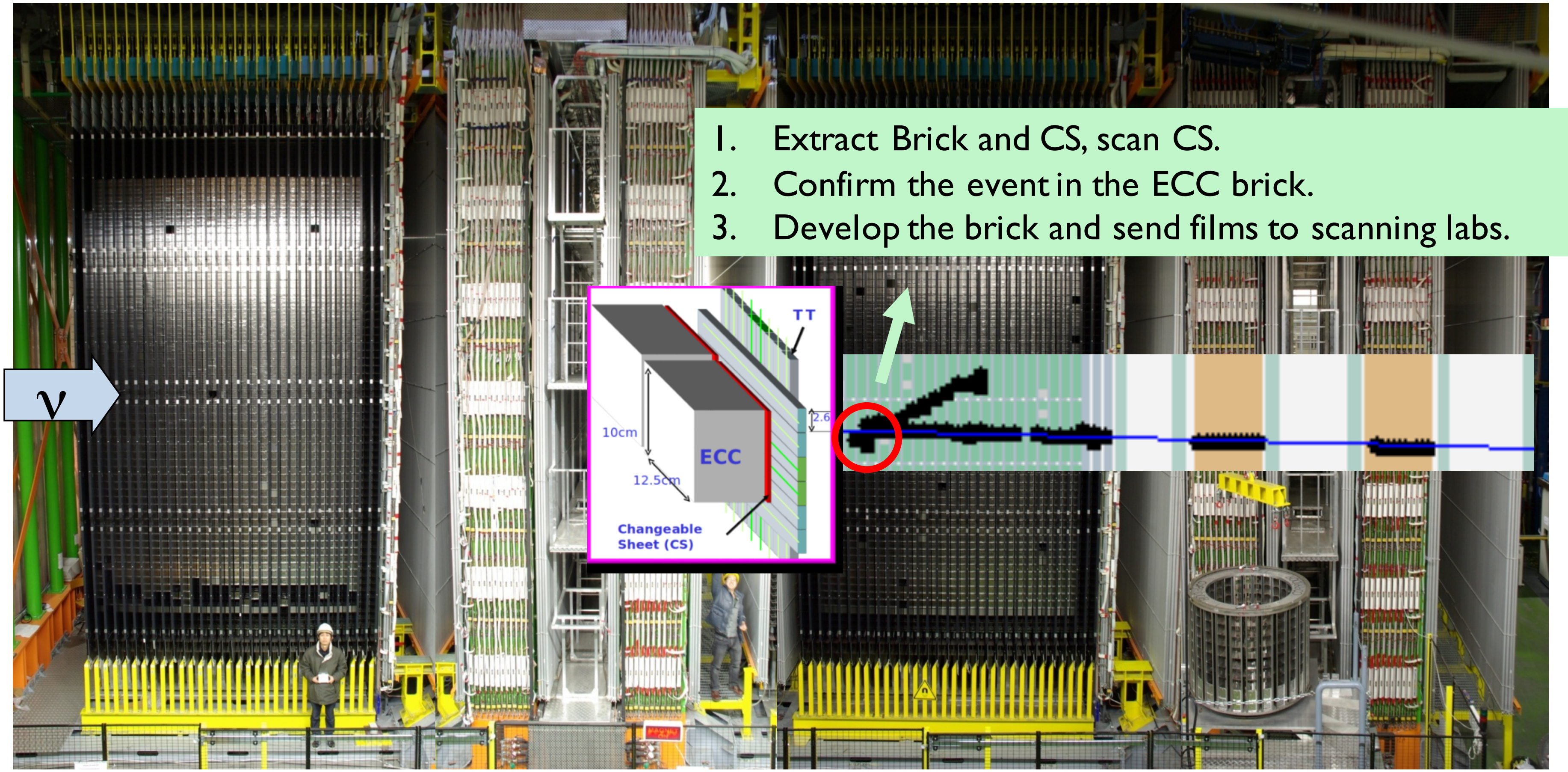
CC interactions in OPERA:

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



The OPERA hybrid detector

SM 1 | SM 2



1. Extract Brick and CS, scan CS.
2. Confirm the event in the ECC brick.
3. Develop the brick and send films to scanning labs.

Target
bricks walls + Target Tracker

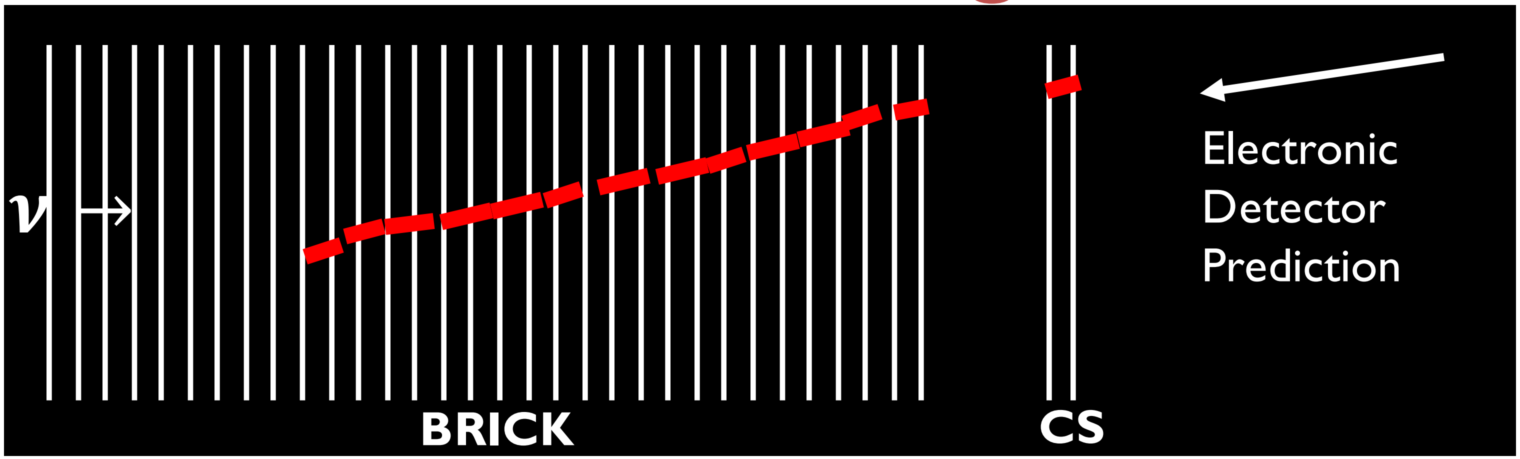
Spectrometer
RPC + drift tubes

Target
bricks walls + Target Tracker

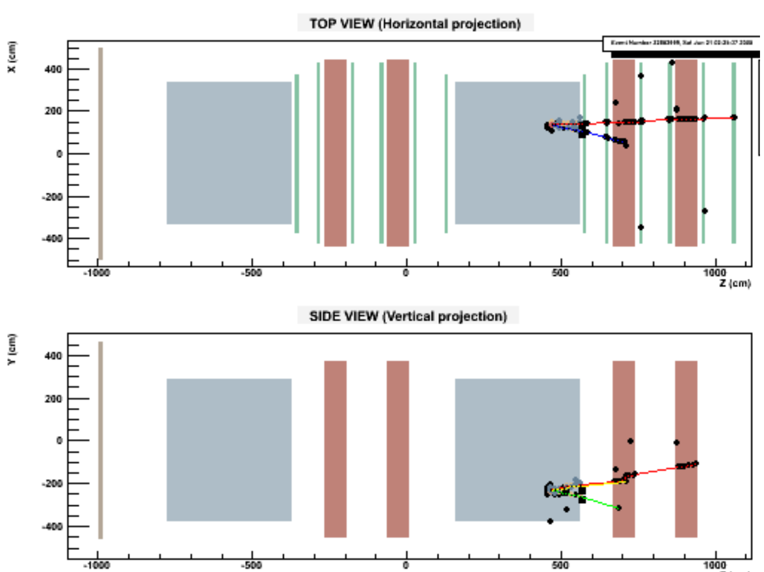
Spectrometer
RPC + drift tubes

~ 150.000 bricks in total
1.25 kt mass

Vertex hunting in the brick

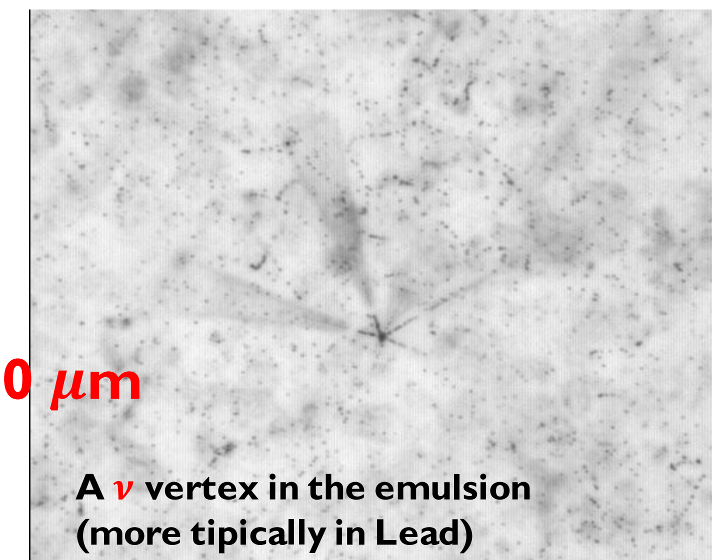


0) all tracks tagged in the **CS films** are **followed upstream** until a stopping point is found

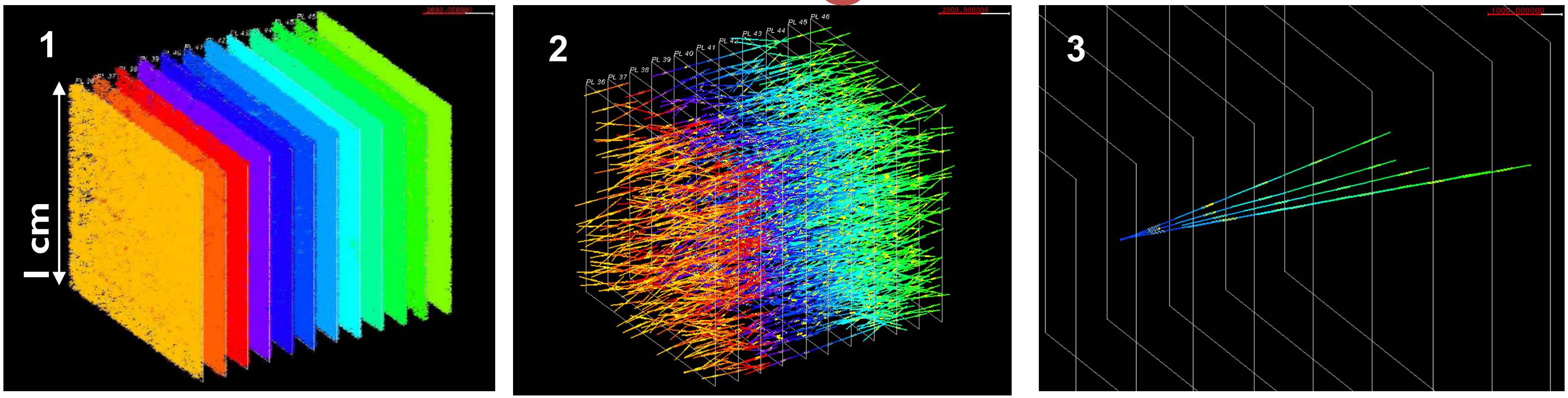


20 m → 100 μm

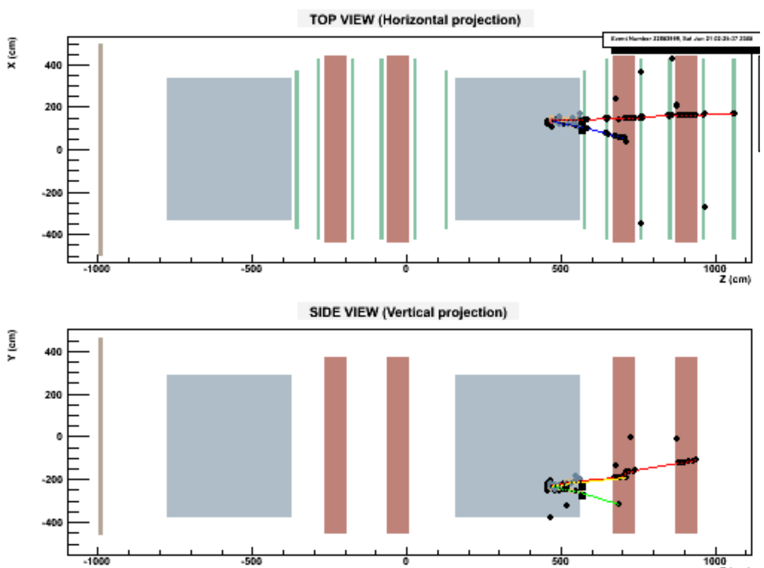
(essential role of CS films)



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
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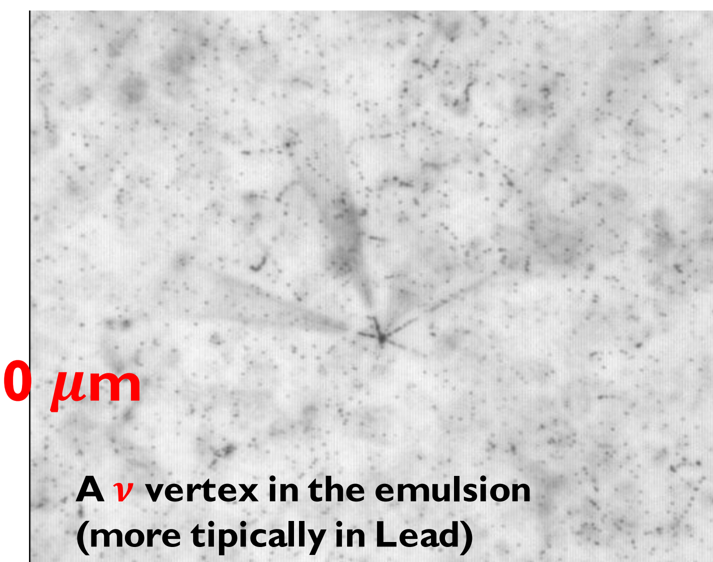


$\nu_\mu \rightarrow \nu_\tau$ appearance discovery

The 5 years long CNGS run (2008 → 2012)

- **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]**

Signal Background Modelization

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

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

μ → **strength of the signal** (parameter of interest)
with $\mu = 0$: **background-only** hypothesis
and $\mu = 1$: **nominal signal+background**

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

Observed Data: 4 hadronic + 1 muonic candidates

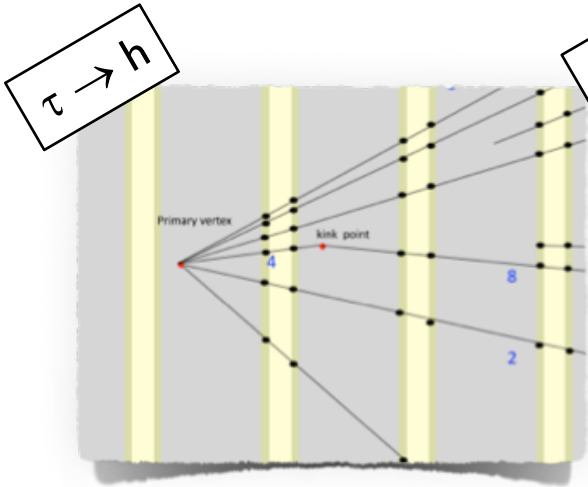
Channel	Expected background	Expected signal	Observed
$\tau \rightarrow 1h$	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \rightarrow 3h$	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \rightarrow \mu$	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \rightarrow e$	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.25 ± 0.05	2.64 ± 0.53	5

Background-only hypothesis:

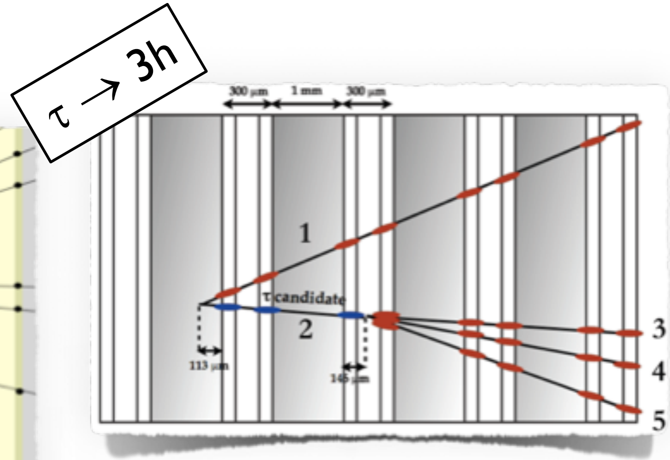
- p-value = 1.1×10^{-7}
- **excluded at 5.1σ significance**

PRL 115 (2015) 121802

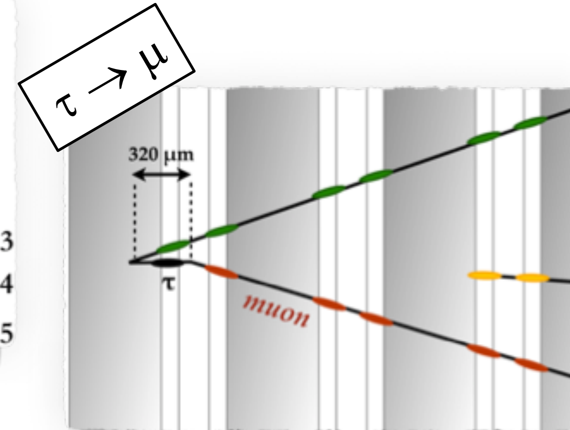
The 5 ν_τ candidate events



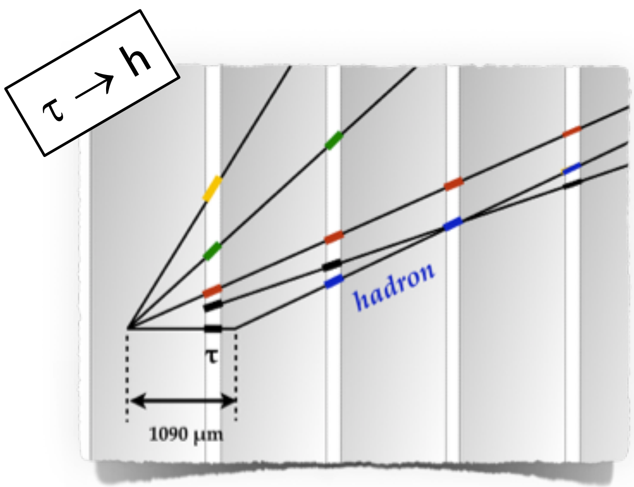
Phys. Lett. B 691 (2010) 138



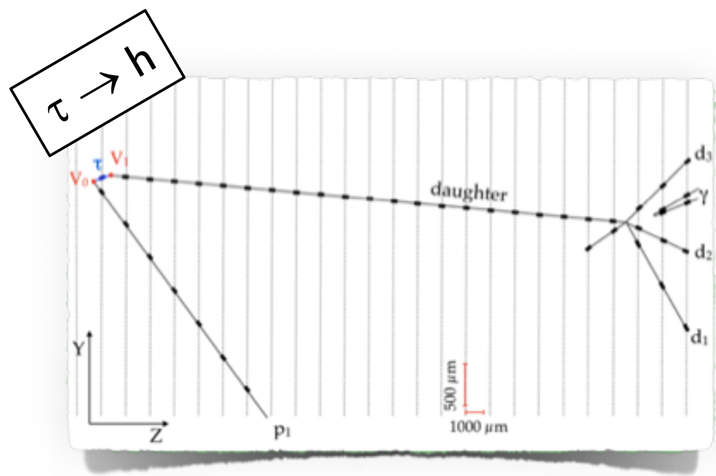
JHEP 11 (2013) 036



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

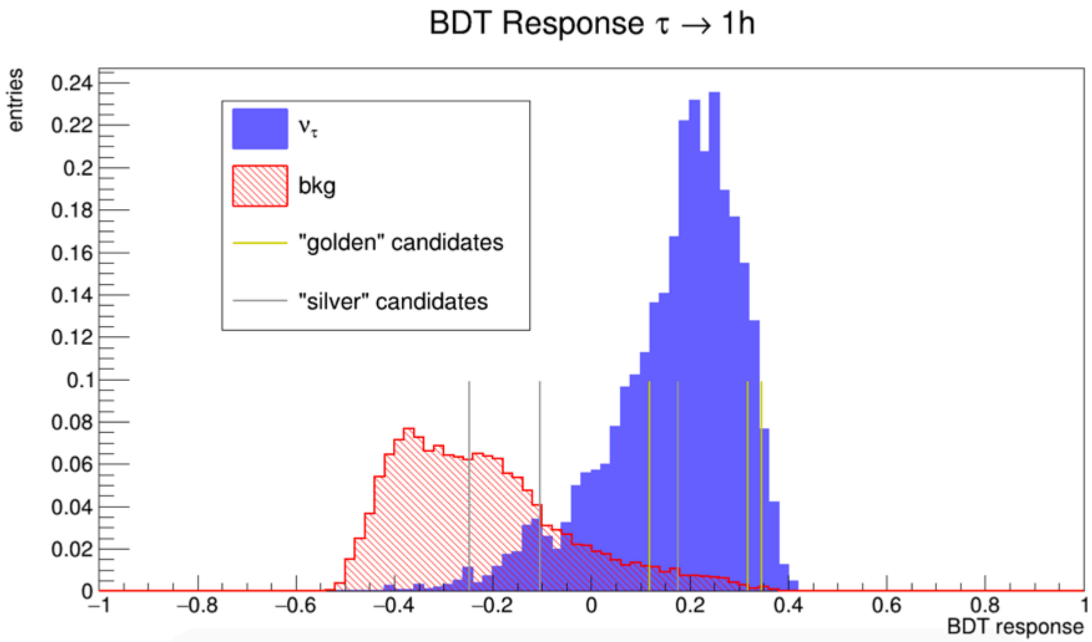
- ✓ **5 more ν_τ candidates (increased statistics: ×2)**
- ✓ **S/B reduced from ~10 to ~3**

PRL 120 (2018) 211801

10 events observed, 8.8 expected

Channel	Expected background: Charm	Hadron reinteraction	Large μ scattering	Total	ν_τ expected	Observed
$\tau \to 1h$	0.15 ± 0.03	1.28 ± 0.38		1.43 ± 0.39	2.96 ± 0.59	6
$\tau \to 3h$	0.44 ± 0.09	0.09 ± 0.03		0.52 ± 0.09	1.83 ± 0.37	3
$\tau \to \mu$	0.008 ± 0.002		0.016 ± 0.008	0.024 ± 0.008	1.15 ± 0.23	1
$\tau \to e$	0.035 ± 0.007			0.035 ± 0.007	0.84 ± 0.17	0
Total	0.63 ± 0.10	1.37 ± 0.38	0.016 ± 0.008	2.0 ± 0.4	6.8 ± 1.4	10

Final results on ν_τ appearance



PRL 120 (2018) 211801

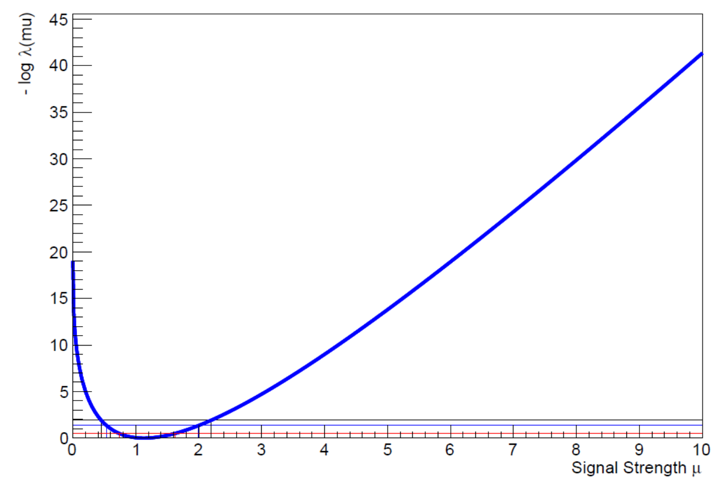
"golden" → tight selection cuts
"silver" → looser cuts

Test statistic: Likelihood ratio

Results: $\mu = 1.1^{+0.5}_{-0.4}$

$p_{value} = 4 \cdot 10^{-10}$

Significance = 6.1 σ



Measurement of Δm^2_{23}

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

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

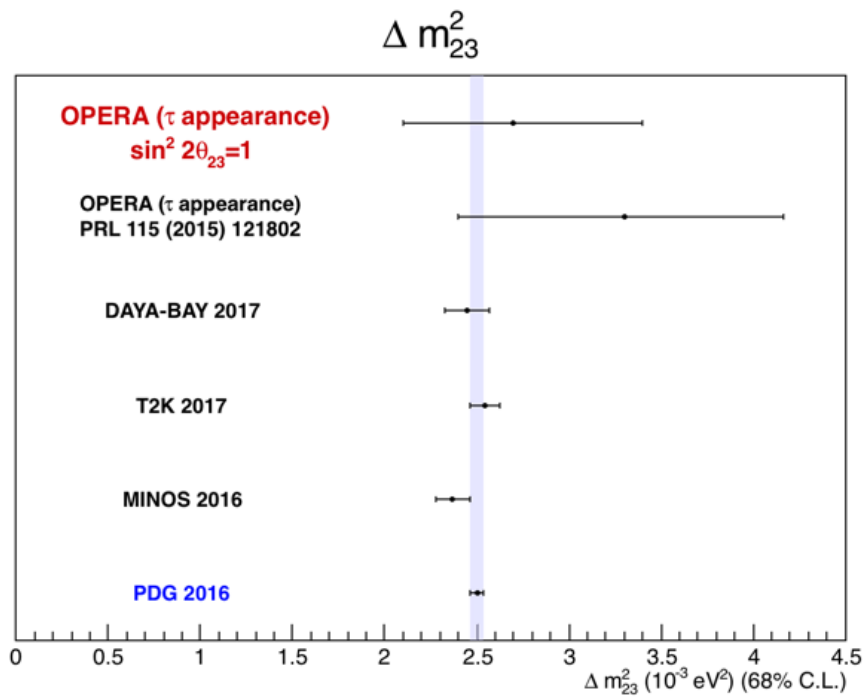
$\left({}^{L}/_{\langle E\rangle}\right)_{PEAK}$ ~500 km/GeV

"Steep" Δm^2_{23} dependence
$\longrightarrow$ counting based measurement

Assuming maximal mixing and
ν_τ CC interaction cross section (Genie):

$$|\Delta m^2_{23\ \mathrm{meas}}| = 2.7^{+0.7}_{-0.6} \cdot 10^{-3}\mathrm{eV}^2$$

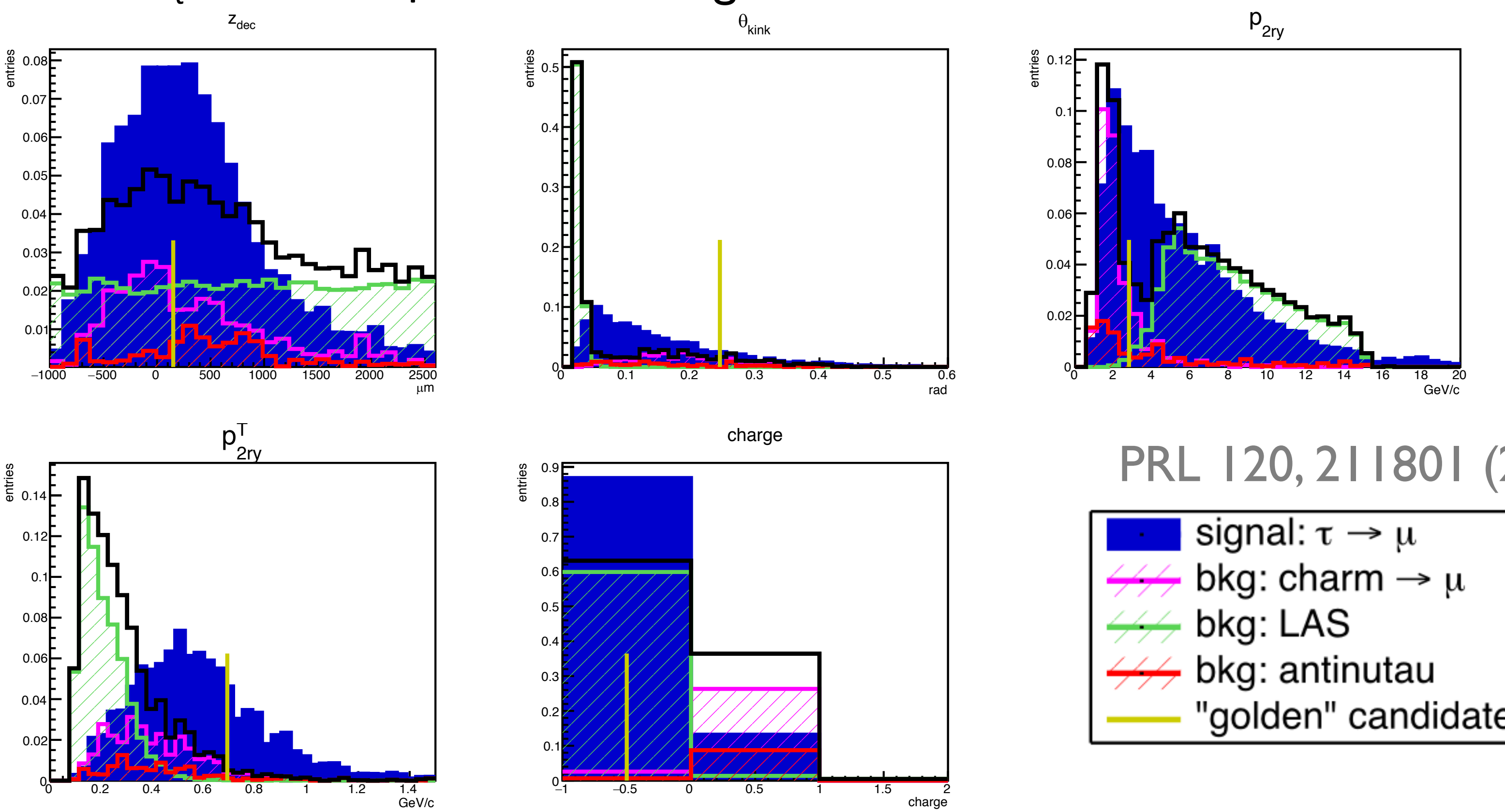
PRL 120 (2018) 211801



ν_τ lepton number

CNGS beam: 2% contamination of anti-ν_μ CC interactions

Expected anti-ν_τ with $\tau^+ \rightarrow \mu^+$ and its charge misidentified or not meas. = 0.0024 ± 0.0005



PRL 120, 211801 (2018)

Significance of having observed a $\tau^- \rightarrow \mu^-$: 3.7σ

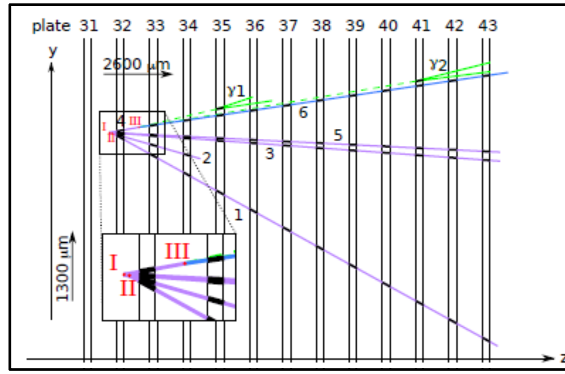
Assumption: lepton number is conserved in the neutrino interaction

<u>First direct evidence for the ν_τ lepton number</u>

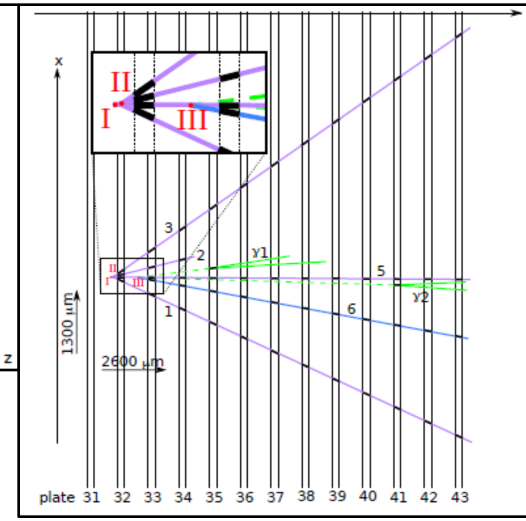
Peculiar muon-less event

- 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)

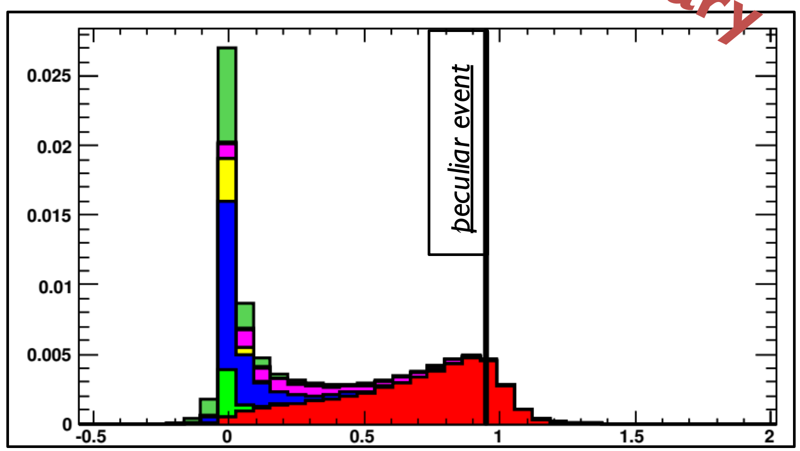


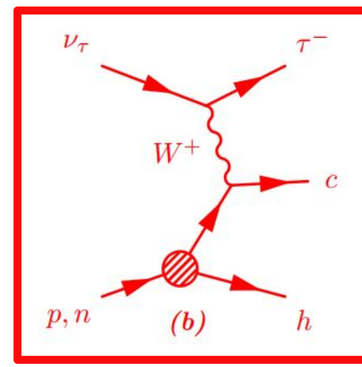
yz view
(horizontal)



Preliminary

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



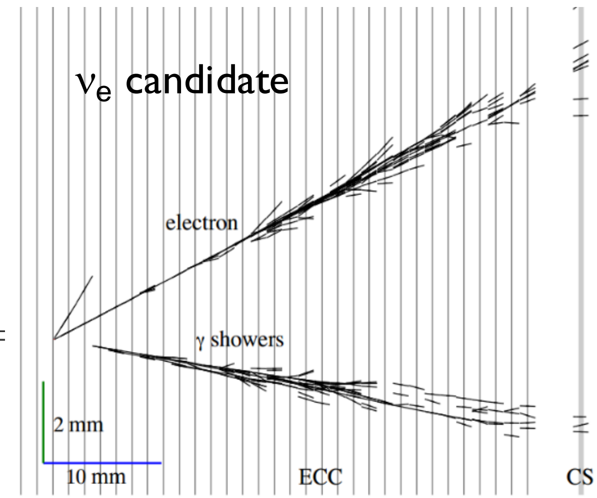


$\nu_\tau CC + charm$

Assuming the event not being ν_τ CC + charm: p-value ~ 10^{-4} → Significance = 3.4 σ

$\nu_\mu \to \nu_e$ oscillation search

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



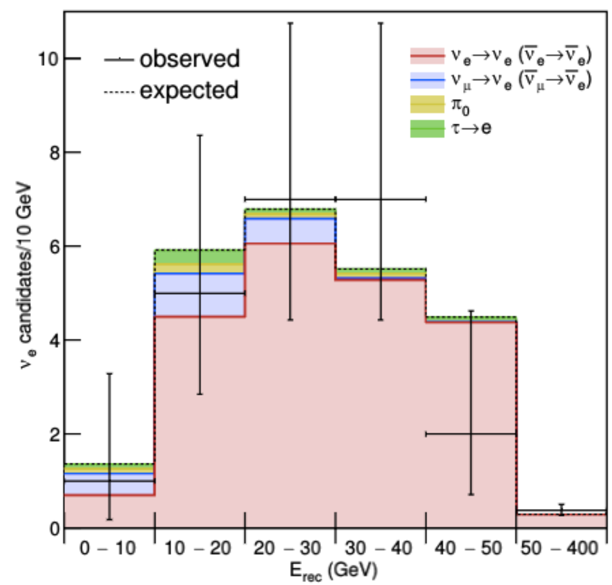
ν_e, $\bar{\nu}_e$ from beam contamination	30.7 ± 3.1 (syst.)
π^0	0.5 ± 0.5 (stat.)
ν_τ from 3-flavour oscillations ($\tau \to e$ channel)	0.7 ± 0.2 (syst.)
Total expected bkg	31.9 ± 0.5 (stat.) ± 3.1 (syst.)
Expected spectrum in case of 3-flavour oscillations	34.3 ± 0.5 (stat.) ± 3.4 (syst.)
Data	35

0.9% ν_e beam contamination

Energy distribution to constrain the parameter space: shape analysis

arXiv 1803.11400

Accepted by JHEP



Sterile neutrino mixing searches

OPERA can test the sterile neutrino hypothesis

3+1 model:

parameters of interest

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

ν_e **appearance**

ν_τ **appearance**

Sterile neutrino mixing searches

OPERA can test the sterile neutrino hypothesis

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

3+1 model:

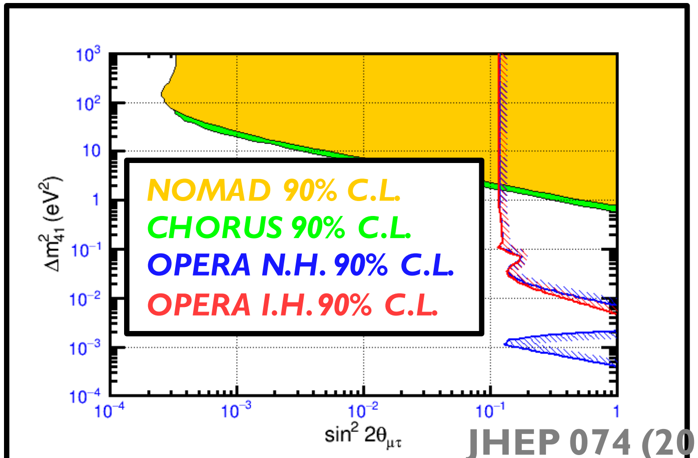
parameters of interest

ν_τ appearance

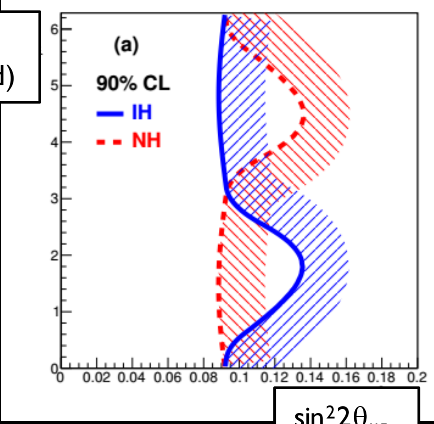
~ standard oscillation | pure exotic oscillation

$$P(Energy) = C^2 \sin^2 \frac{\Delta_{31}}{2} + \sin^2 2\theta_{\mu\tau} \sin^2 \frac{\Delta_{41}}{2}$$
$$+ \frac{1}{2} C \sin 2\theta_{\mu\tau} \cos\phi_{\mu\tau} \sin\Delta_{31} \sin\Delta_{41}$$
$$- C \sin 2\theta_{\mu\tau} \sin\phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin\Delta_{41}$$
$$+ 2C \sin 2\theta_{\mu\tau} \cos\phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2}$$
$$+ C \sin 2\theta_{\mu\tau} \sin\phi_{\mu\tau} \sin\Delta_{31} \sin^2 \frac{\Delta_{41}}{2}$$

interference terms



JHEP 074 (2015) 0315



<u>Effective mixing</u>

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

$$C = 2|U_{\mu3}||U_{\tau3}|$$
$$\phi_{\mu\tau} = Arg(U^\star_{\mu3} U^\star_{\tau3} U^\star_{\mu4} U^\star_{\tau4})$$
$$\sin 2\theta_{\mu\tau} = 2|U_{\mu4}||U_{\tau4}|$$

At high Δm^2_{41}

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

Sterile neutrino mixing searches

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

~standard oscillation — Exotic oscillation

$$P_{\nu_\mu \to \nu_e} = C^2 \sin^2 \Delta_{31} + \sin^2 2\theta_{\mu e} \sin^2 \Delta_{41}$$

Interference term:

$$+ 0.5\, C \sin 2\theta_{\mu e} \cos \phi_{\mu e} \sin 2\Delta_{31} \sin 2\Delta_{41}$$
$$- C \sin 2\theta_{\mu e} \sin \phi_{\mu e} \sin^2 \Delta_{31} \sin 2\Delta_{41}$$
$$+ 2\, C \sin 2\theta_{\mu e} \cos \phi_{\mu e} \sin^2 \Delta_{31} \sin^2 \Delta_{41}$$
$$+ C \sin 2\theta_{\mu e} \sin \phi_{\mu e} \sin 2\Delta_{31} \sin^2 \Delta_{41}$$

$$C = 2|U_{\mu 3} U_{e3}^*|$$

$$\Delta_{ij} = \frac{1.27 \Delta m_{ij}^2 L}{E}$$

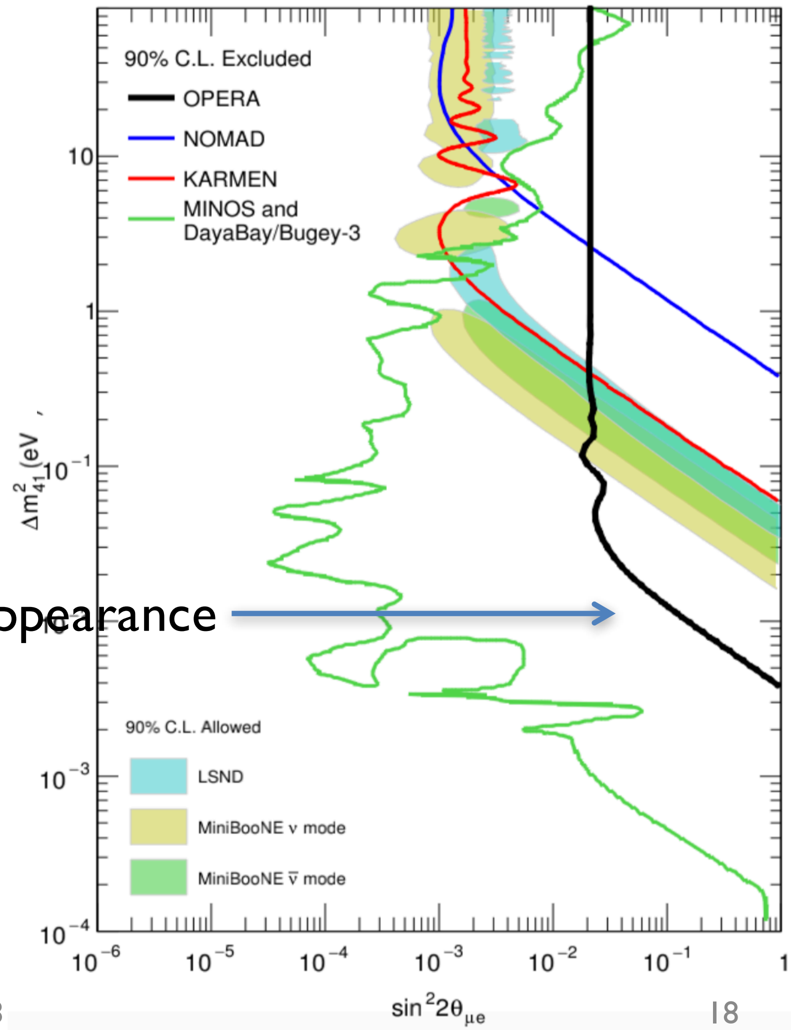
$$\phi_{\mu e} = Arg(U_{\mu 3} U_{e3}^* U_{\mu 4}^* U_{e4})$$

$$\sin^2 2\vartheta_{\mu e} = 4|U_{\mu 4}|^2 |U_{e4}|^2$$

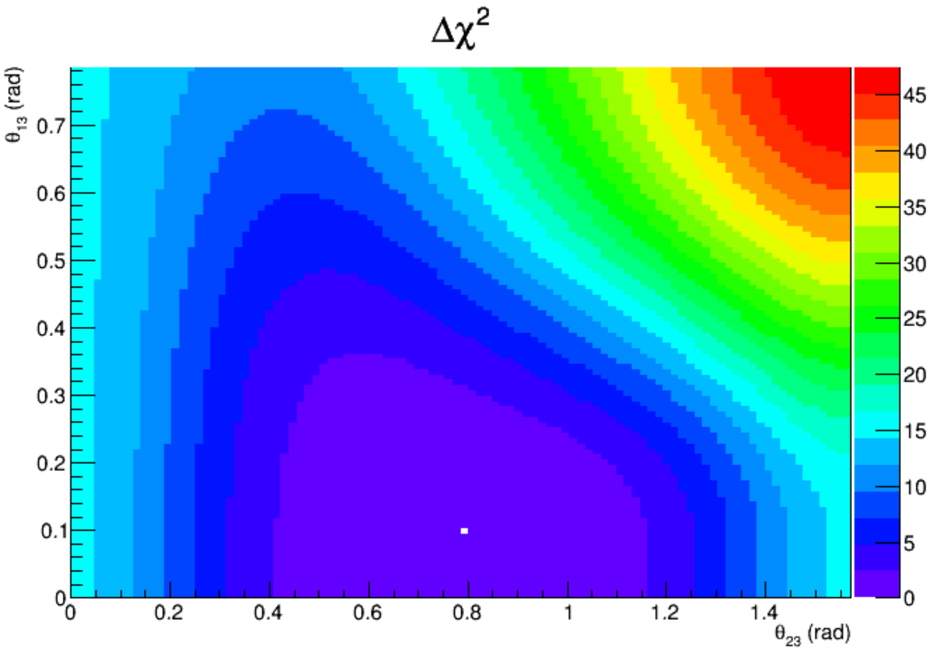
At high Δm^2_{41} → **$\sin^2 2\theta_{\mu e} < 0.021$ [90% CL]**

arXiv 1803.11400

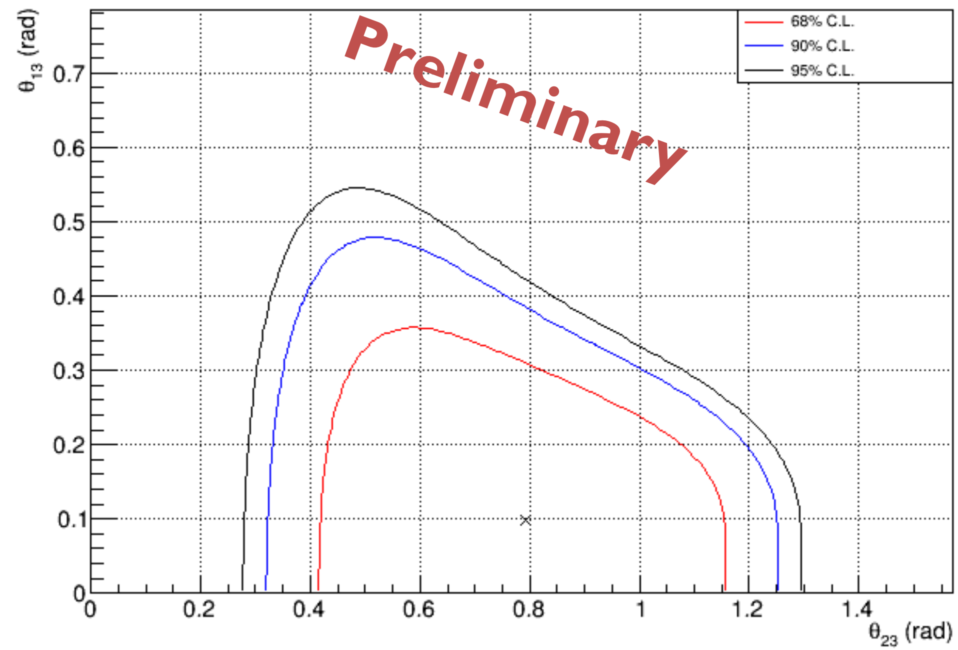
Unique in appearance



Combining $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ searches



10 ν_τ candidates
35 ν_e candidates



$\Delta m^2_{31} = (2.50 \pm 0.04) \times 10^{-3}$ eV^2

$\Delta m^2_{21} = 7.37 \times 10^{-5}$ eV^2

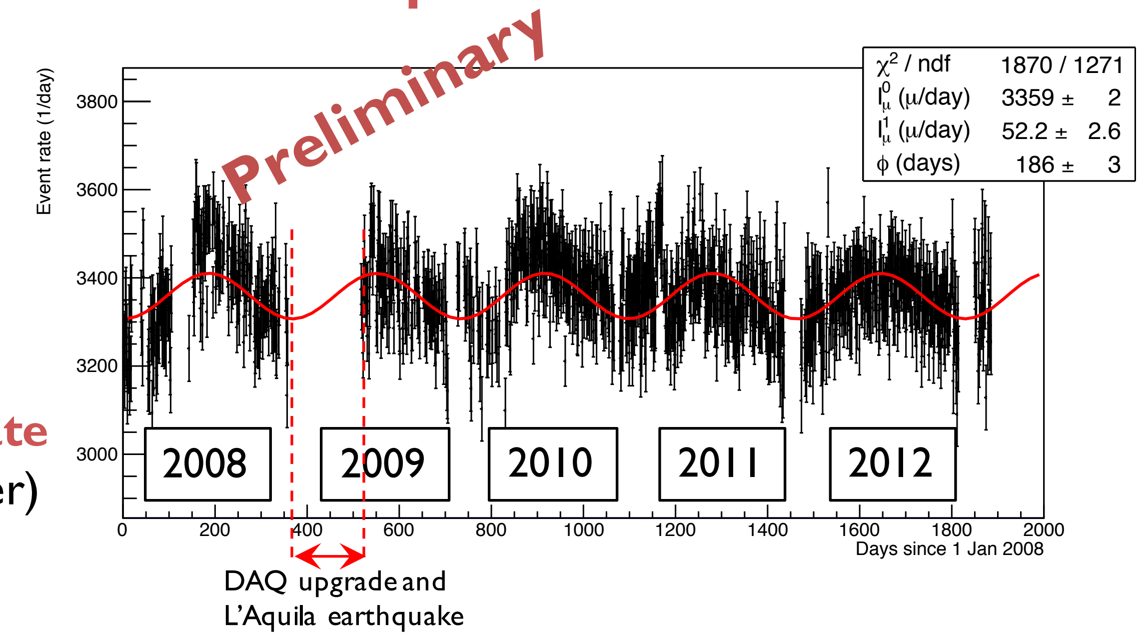
Standard 3 flavour scheme

Best fit: $(\theta_{23}, \theta_{13}) = (0.79, 0.10)$ [rad]
going to constrain also the 3+1 model

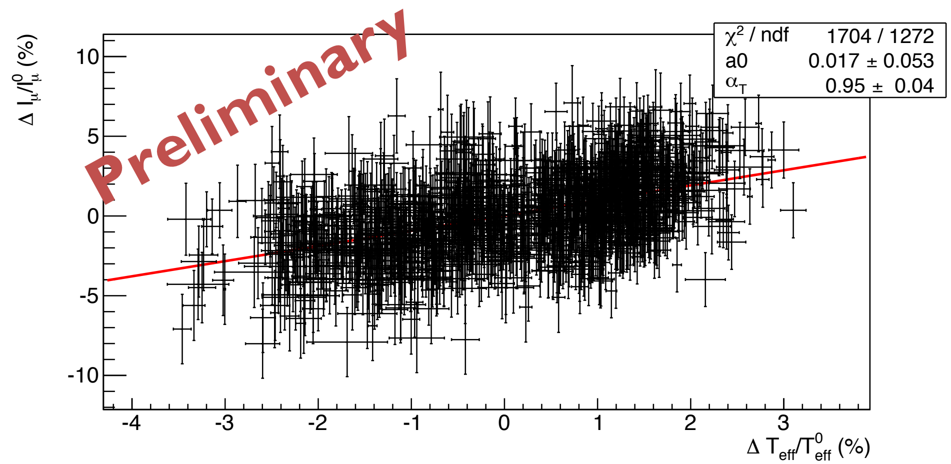
Seasonal variations of atmospheric muon rate

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} → α_T

$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\rm eff}}{T_{\rm eff}}$$

$\alpha_T = 0.95 \pm 0.04$

Conclusions

OPERA at LNGS in the CNGS beam played a unique role to prove the neutrino oscillation mechanism in appearance mode

- **$\nu_\mu \rightarrow \nu_\tau$ appearance** in the CNGS neutrino beam

  - New analysis with machine learning multivariate approach:
    6.1 σ significance in the discovery of ν_τ appearance

- **$\nu_\mu \rightarrow \nu_e$ 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 on final combined analysis***:
  exploit OPERA unique feature of identifying all three flavours:

  - ν_τ appearance
  - ν_e appearance
  - ν_μ disappearance

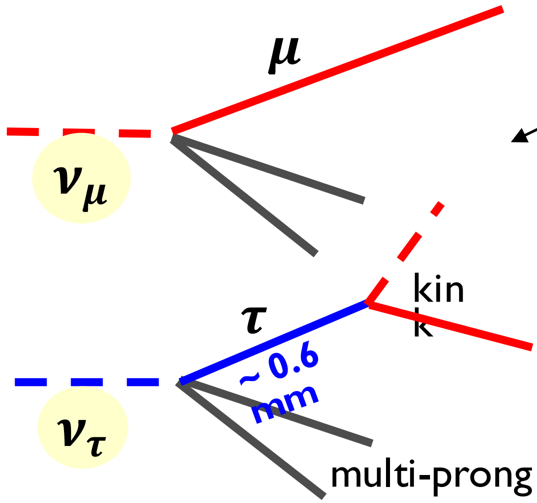
  to constrain oscillations parameters with one single experiment

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

The ν_τ detection technique

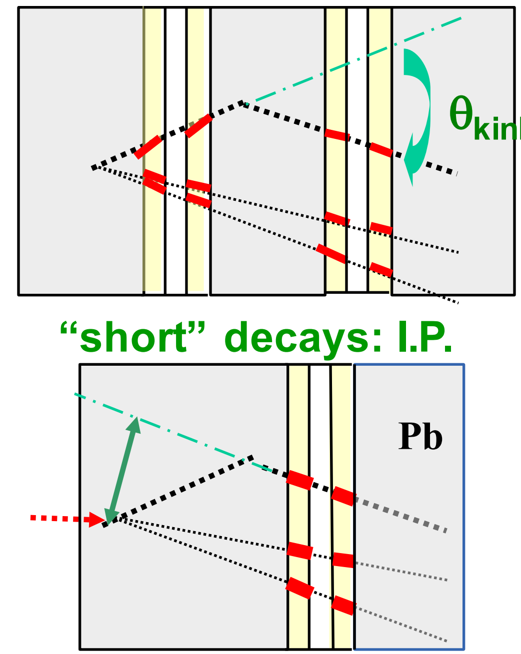


Detect a few ν_τ^{CC} from the bulk of ν_μ^{CC}

$\tau^- \rightarrow \mu^- \nu_\tau \, \nu_\mu$	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.



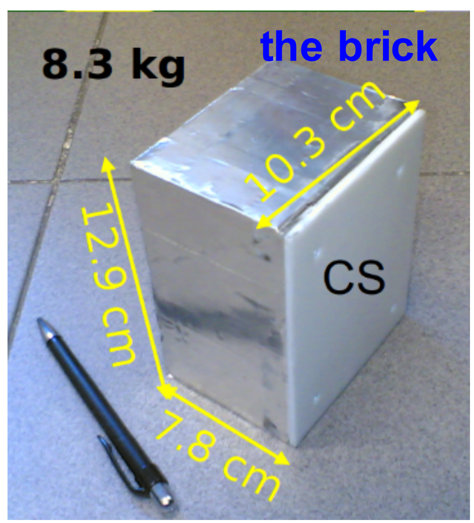
Modular detector of "Emulsion Cloud Chambers" (or bricks)

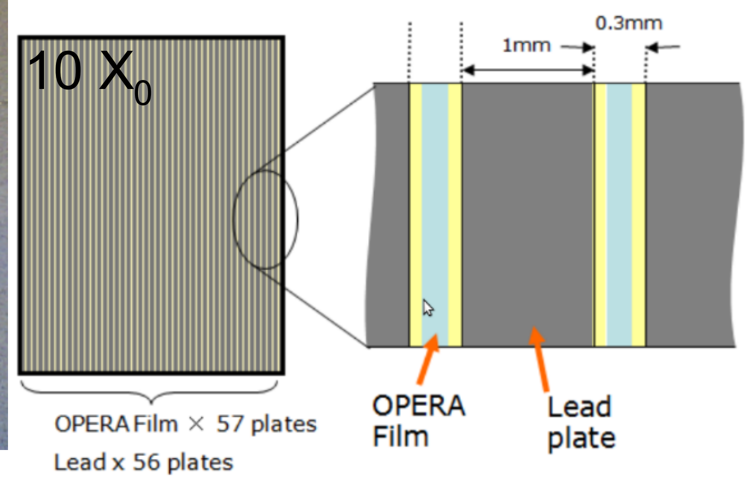
Large mass

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

Extreme granularity

$\sim \mu$m space resolution



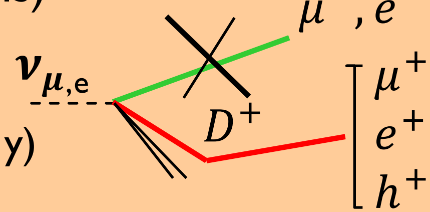


$\nu_\mu \rightarrow \nu_\tau$ background characterization

Monte Carlo simulation benchmarked on control samples.

In order of decreasing relevance

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

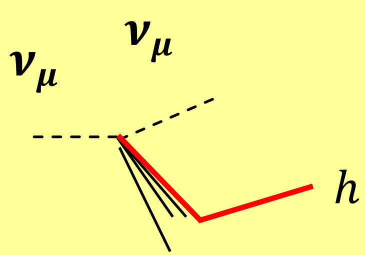


MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

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

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

Hadronic interactions
Background for $\tau \rightarrow h$

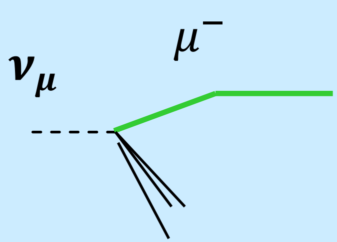


FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

[PTEP9 (2014) 093C01]

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



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

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

Data samples

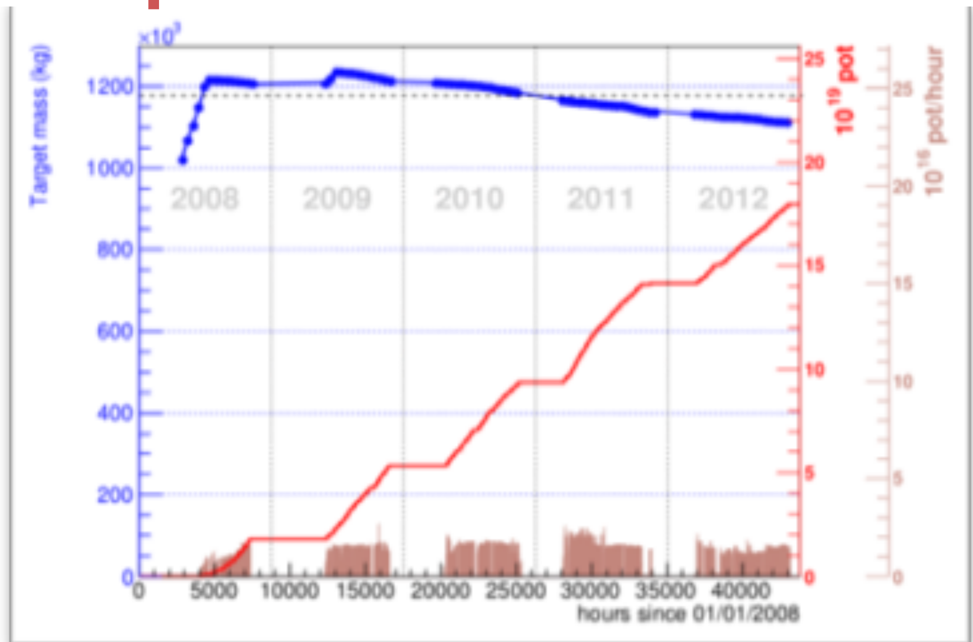
The 5years long CNGS run ended in 2012.

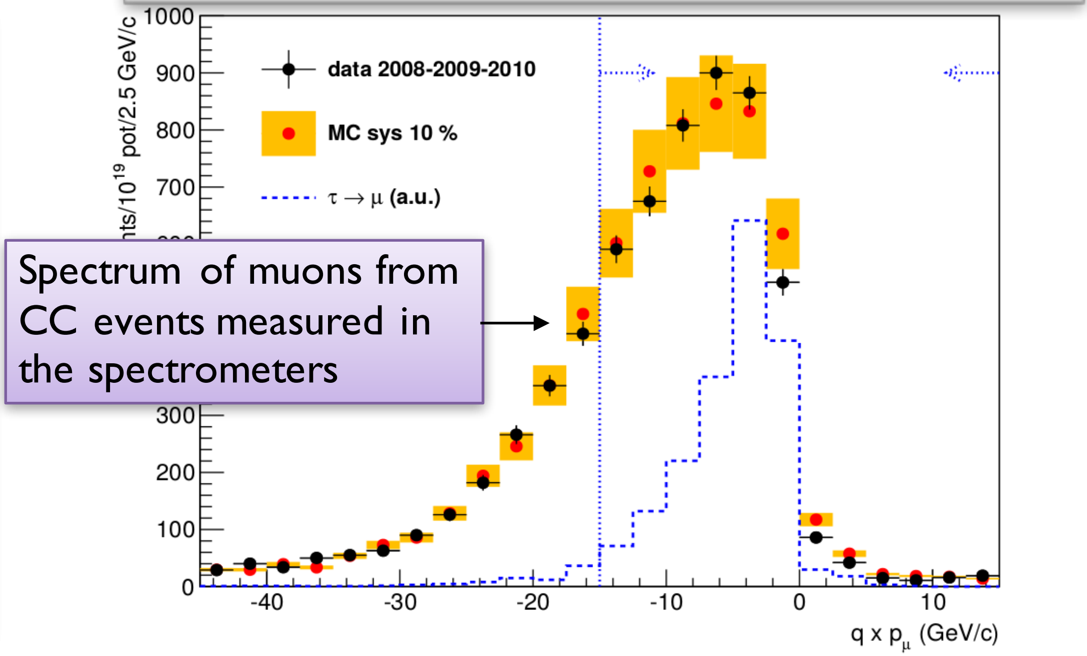
$1.8 \cdot 10^{20}$ p.o.t. collected (80% of the design)

1.25 kton initial target mass (150 k bricks)

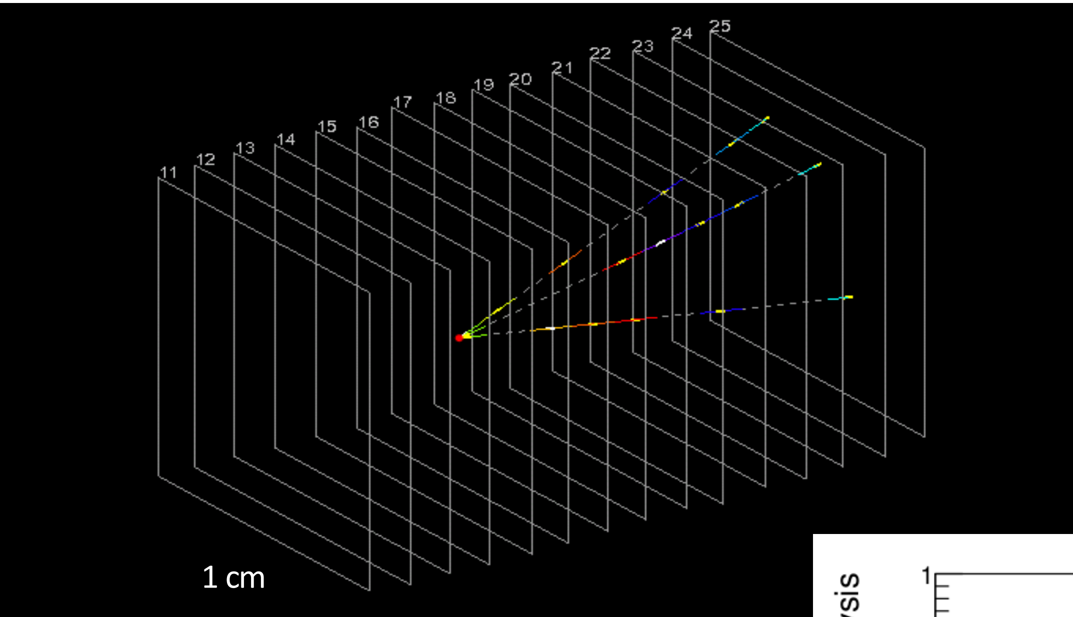
19505 neutrino interactions in the emulsion targets.

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**





Location efficiency

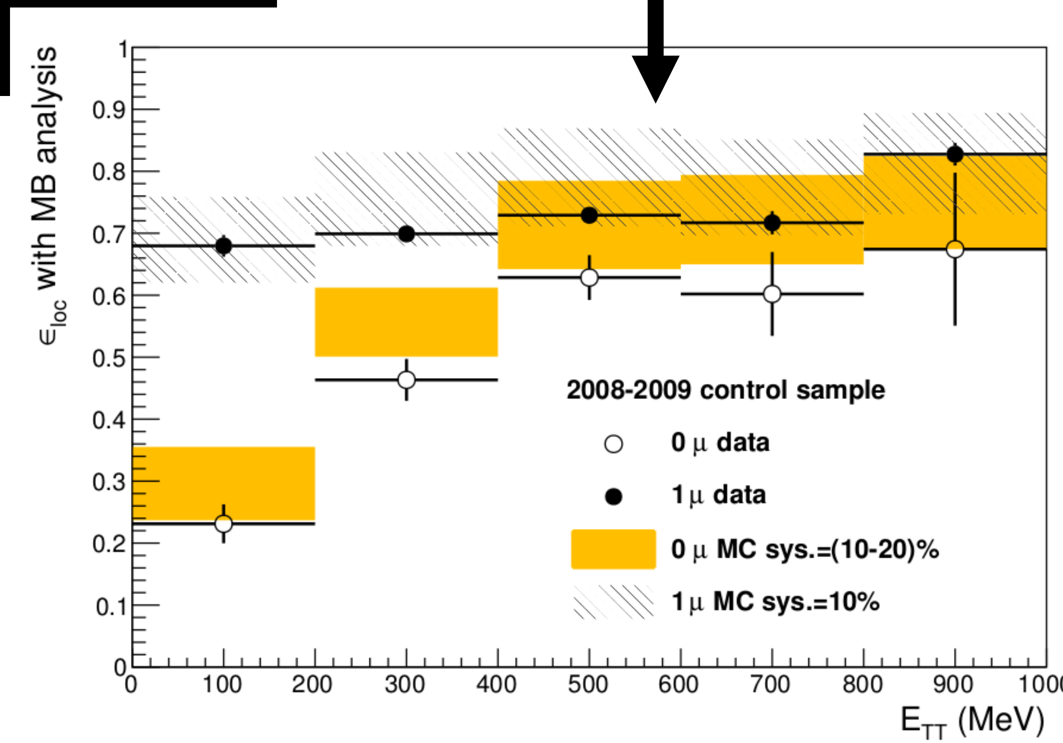


[JHEP 11 (2013) 036]

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.



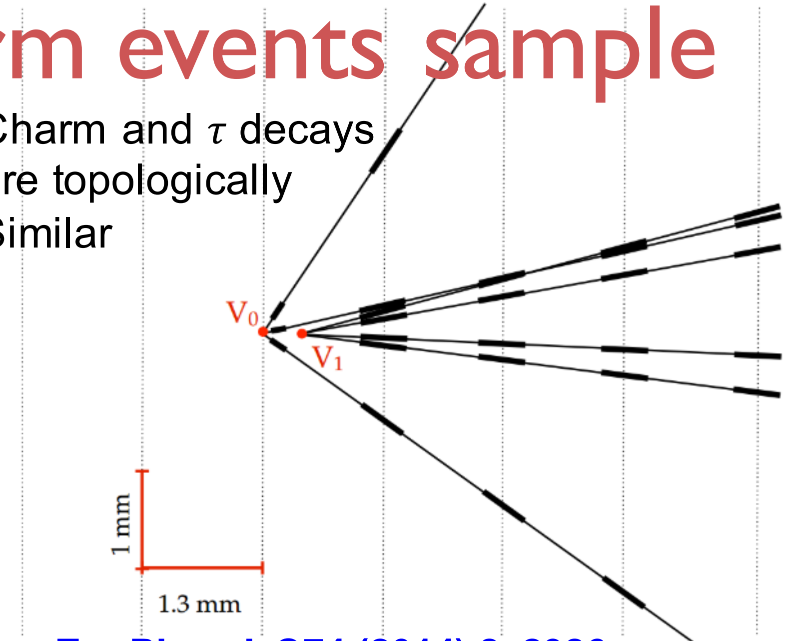
The **prediction for the τ signal** and **backgrounds** is based on **efficiencies** derived from the observed **0μ−like** and **1μ-like** samples

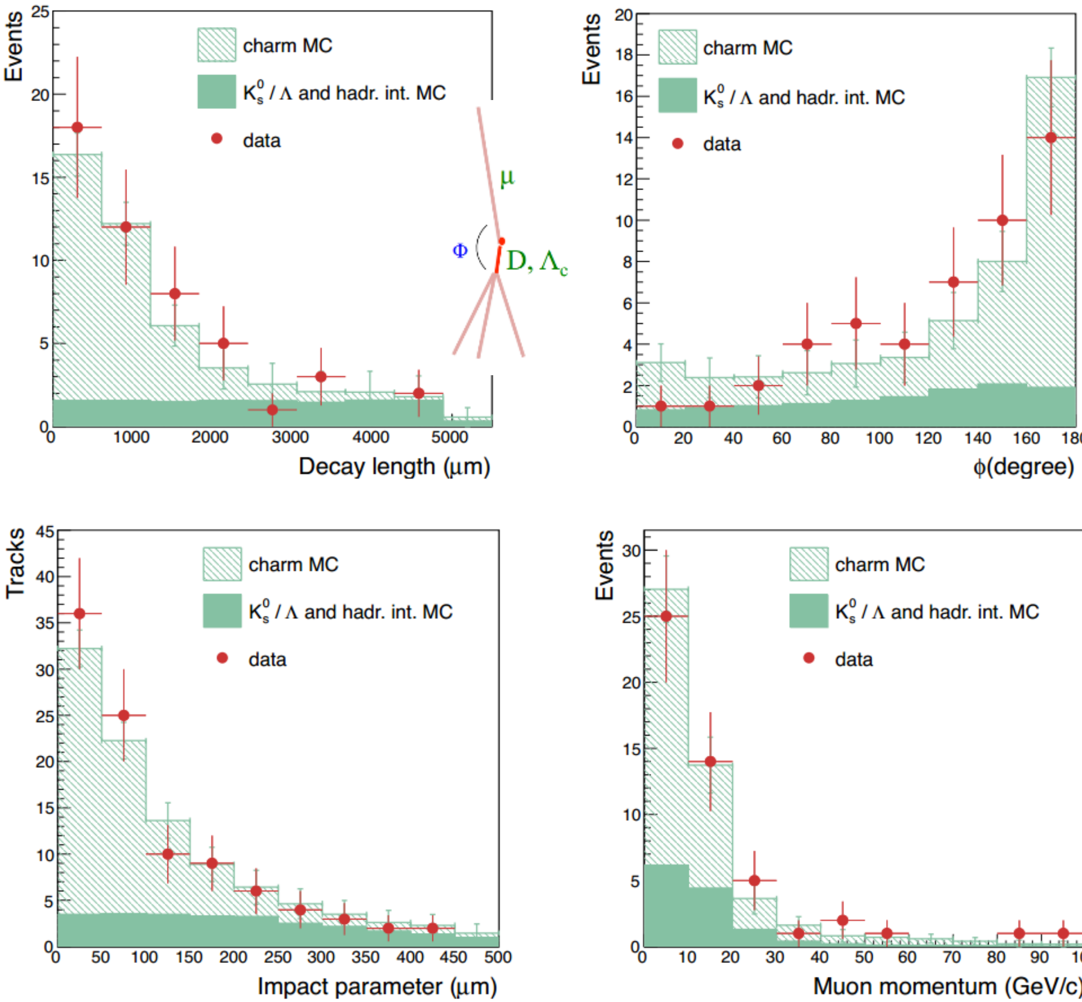
Validation with the charm events sample

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

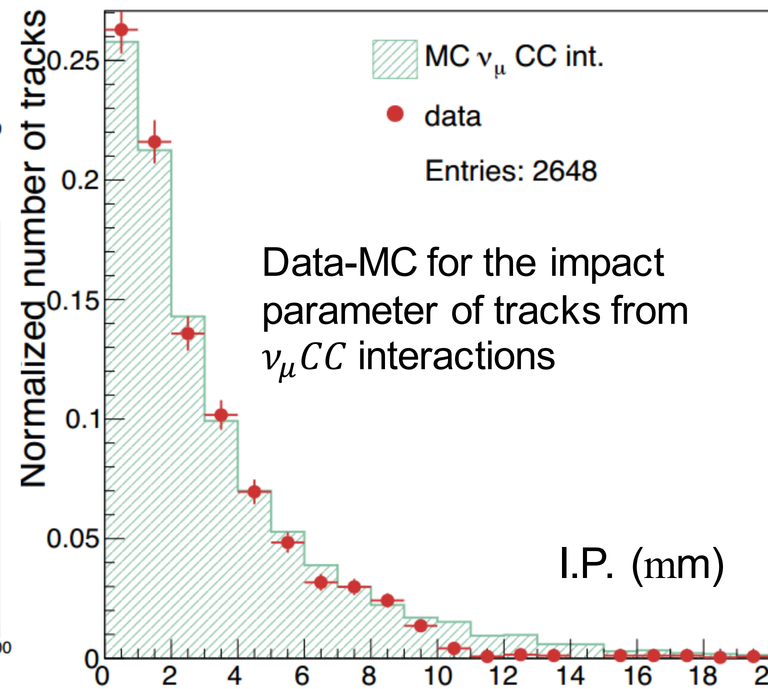
54 ± 4 expected ↔ 50 observed

Charm and τ decays are topologically Similar





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



ν_τ CC cross section

$$\langle\sigma\rangle_{meas} = \frac{(N^{obs} - N^{expB})/(\epsilon N_T)}{\int \Phi_{\nu_\mu}(E)\mathcal{P}_{\nu_\mu\to\nu_\tau}(E)dE}$$

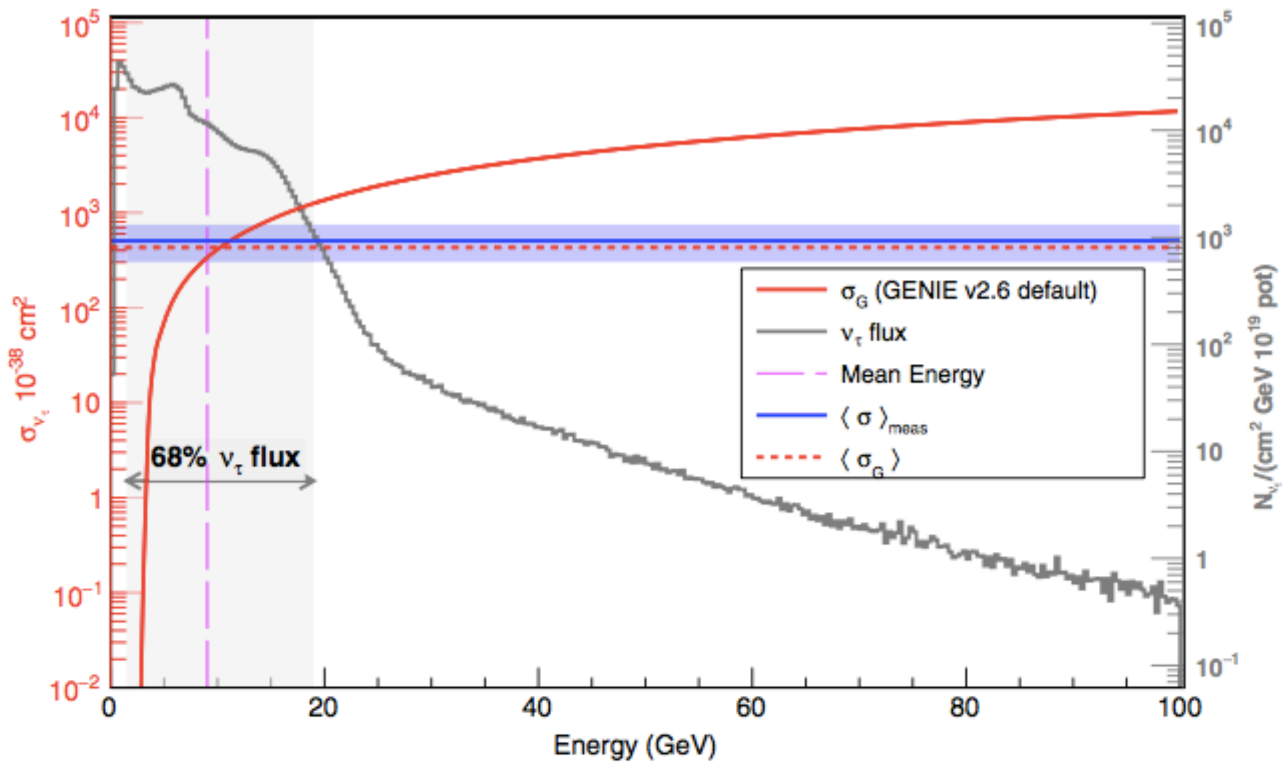
ϵ overall efficiency

N_T lead nuclei in the fiducial volume

$$\Delta m^2_{23\ \mathrm{PDG}} = (2.50 \pm 0.04)\cdot 10^{-3}\mathrm{eV}^2$$

PRL 120 (2018) 211801

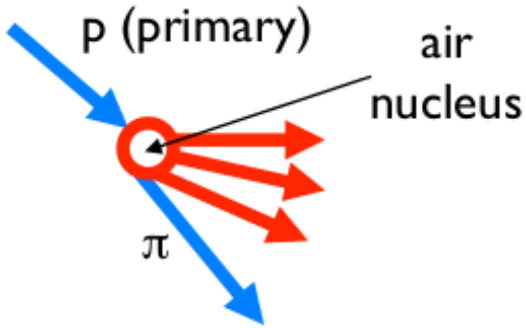
First measurement with negligible contamination from anti-ν_τ



$$\langle\sigma\rangle_{\mathrm{meas}} = (5.1^{+2.4}_{-2.0}) \times 10^{-36}\ \mathrm{cm}^2$$

$$\langle\sigma\rangle_{meas} = (1.2^{+0.6}_{-0.5})\ \langle\sigma_G\rangle$$

Atmospheric muon charge ratio



Eur. Phys. J. C74 (2014) 2933

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

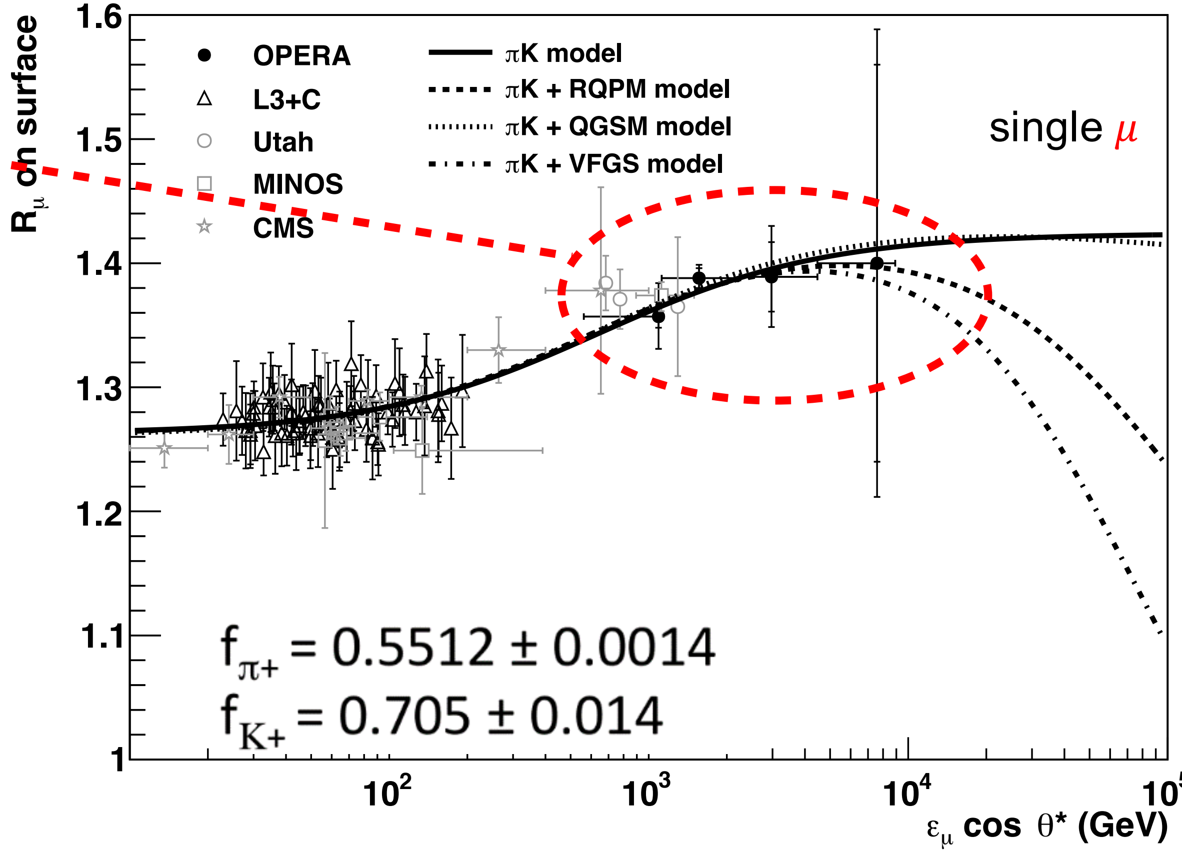
Highest-E region reached!

opposite magnet polarities runs → lower systematics

Strong reduction of the charge ratio for multiple muon events

1μ	1.377 ± 0.006
multi−μ	1.098 ± 0.023

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

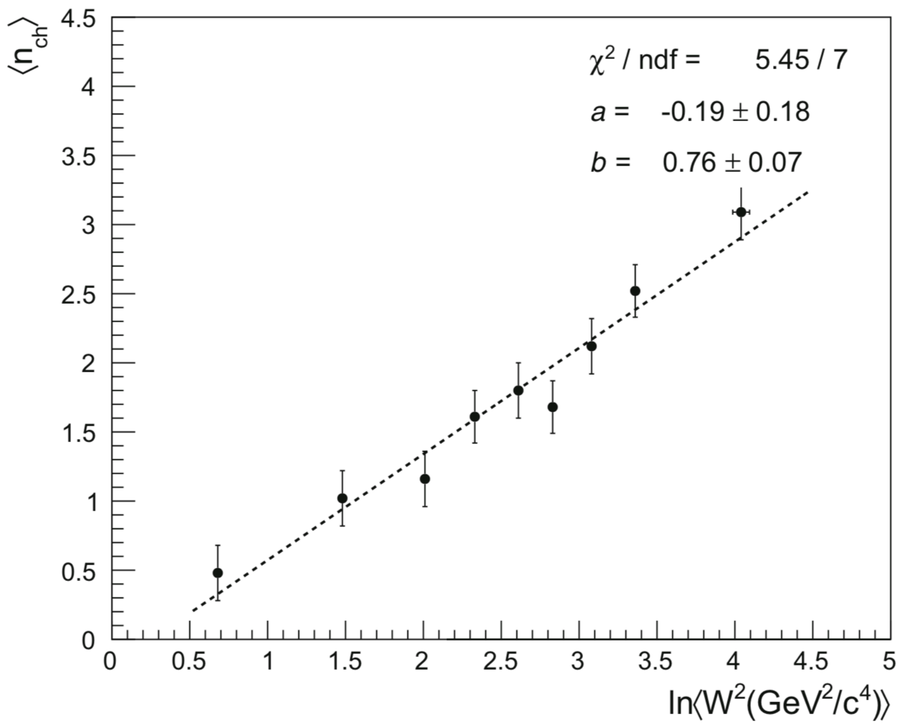


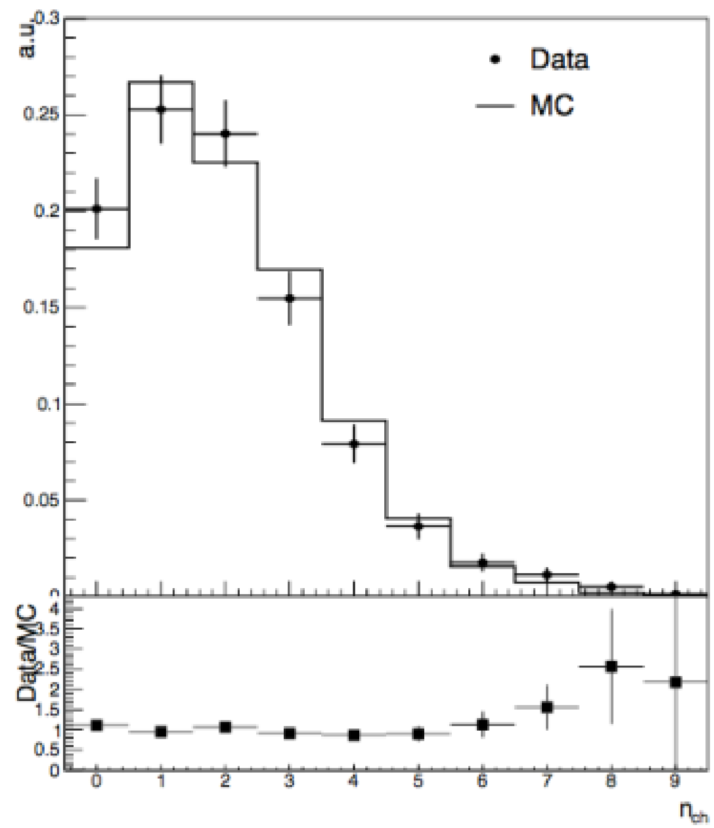
Primary Cosmic Ray composition at ~$10^{13} \div 10^{14}$ eV/nucleon: proton excess $\delta_0 = 0.61 \pm 0.02$

Multiplicity studies in neutrino-lead scattering

Measurement of the average charged particles multiplicity at primary vertex

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





EPJC C78 (2018) no.1, 62