*DISCRETE 2014*
King's College London, Strand Campus
2-6 December 2014

**A. Longhin,** INFN Frascati


On behalf of the OPERA Collaboration

# Results from OPERA

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

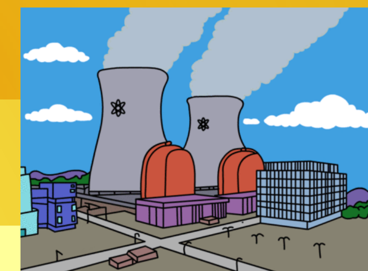
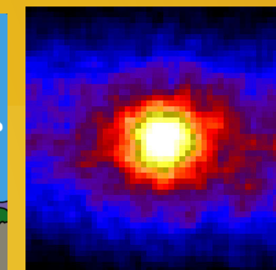
**Switzerland**
Bern

**Turkey**
METU, Ankara

- Appearance: $\nu_\mu \rightarrow \nu_\tau$
- Exotic $\nu_\mu \rightarrow \nu_e \nu_\mu \rightarrow \nu_\tau$
- Cosmic ray physics

# The long way to "appearance"

- $\nu_\mu$ **disappearance**: a “leading” effect: deficit of atmospheric $\nu$ (1998)
  - Discovery of $\nu$-oscillations Super-KAMIOKANDE, MACRO
- On the other hand … **appearance:**

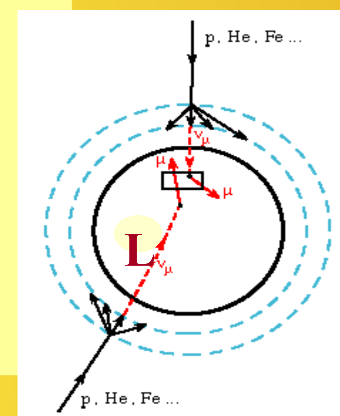
At the **solar scale**. Reactors and solar $\nu$.

$\nu_e \rightarrow \nu_\mu$ $\mu$ is below threshold!

At the **atmospheric scale**. Atmospheric-$\nu$, artificial beams.

$\nu_\mu \rightarrow \nu_e$ "RARE"... $\theta_{13}$ suppression ?

$\nu_\mu \rightarrow \nu_\tau$ “DIFFICULT” ! (mass suppression, small $c\tau$)




**Today's perspective (after the … “2013 appearance revolution”)**

$\nu_\mu \rightarrow \nu_e$

- Disappearence of anti-$\nu_e$ at reactors (2012, Daya-Bay, RENO, DCHOOZ). $\theta_{13}$ is indeed BIG !
- Appearance seen by T2K at the JPARC beam (→ talk by Y. Petrov)

## $\nu_\mu \rightarrow \nu_\tau$ Event-by-event detection: achieved by OPERA

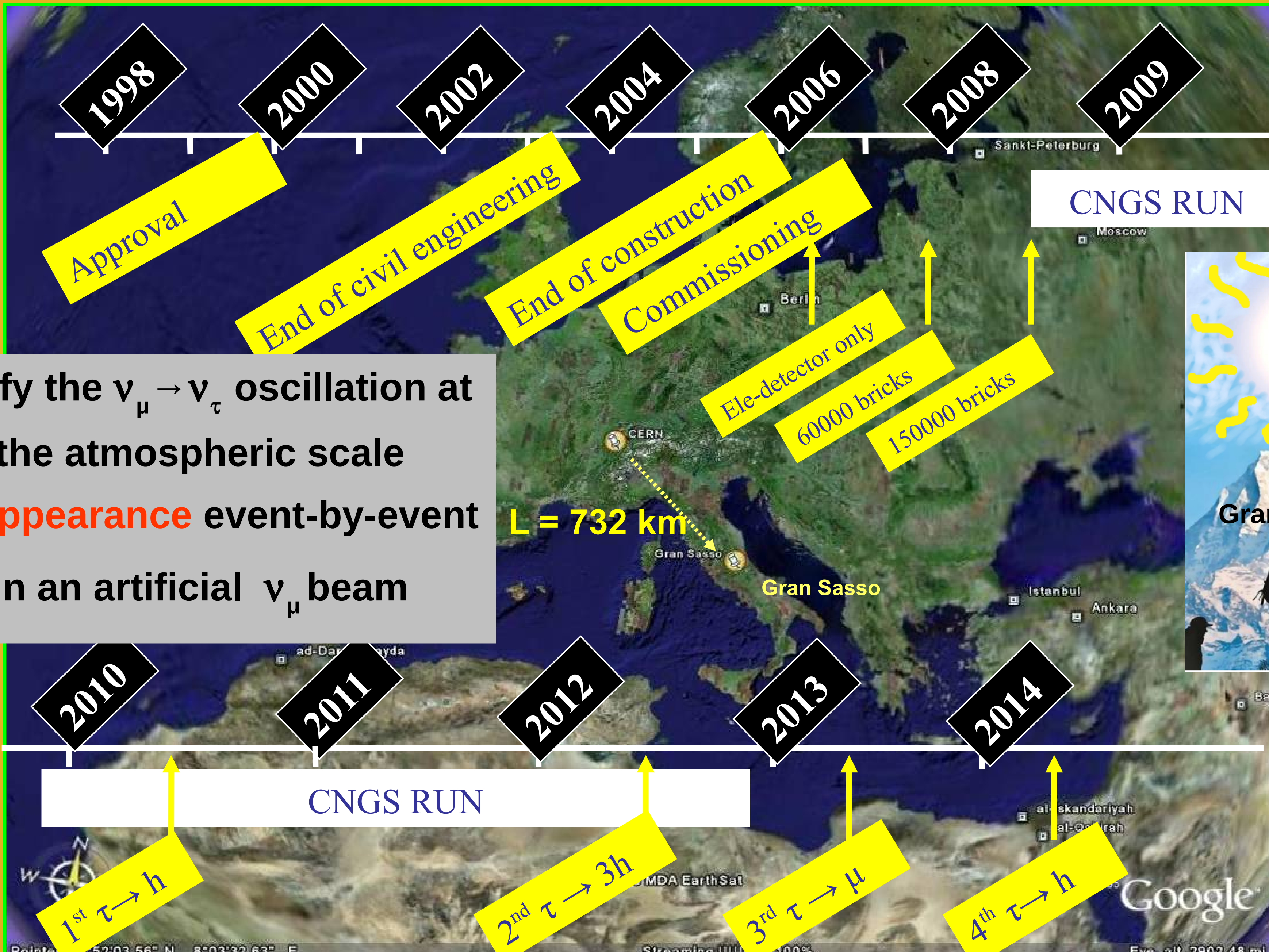
An experimental and technological challenge. 732 km baseline. Beam O(10) more energetic (17 GeV) than any other LBL (m($\tau$)). A “fine-grained” detector O(100) more massive (1.25 kt) than the precursors SBL (i.e. CHORUS).

# The OPERA road map

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

$\nu_\tau$ appearance event-by-event

in an artificial $\nu_\mu$ beam




# The CNGS beam for $\nu_\mu \rightarrow \nu_\tau$

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

**The oscillation peak for L= 732 km at ~ 1.5 GeV (similar to NuMI) but here the goal is to produce τ leptons → unbalance at higher energies**

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

Fluxes:

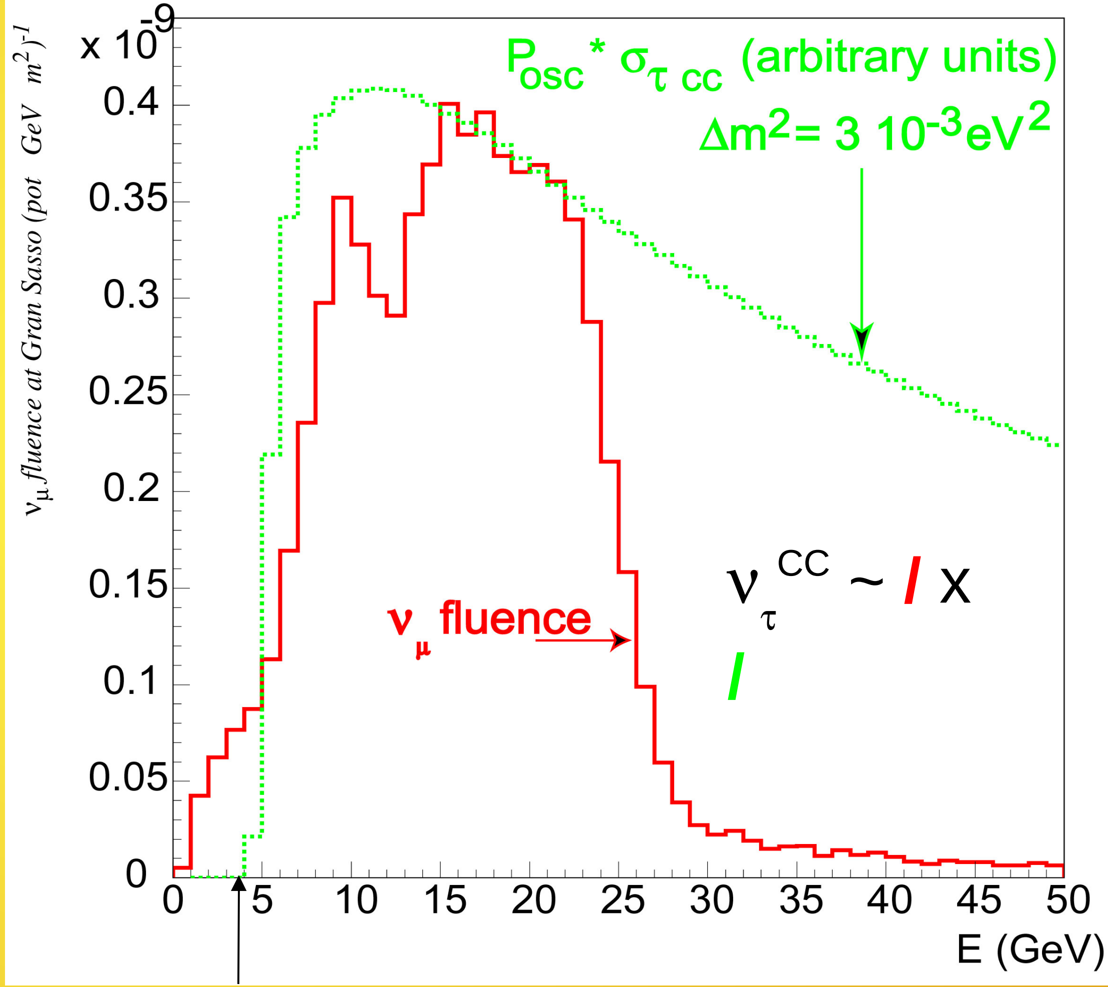
| | |
|---|---|
| $(\nu_e+\overline{\nu}_e)/\nu_\mu$ | **0.9 %** |
| $\overline{\nu}_\mu / \nu_\mu$ | **2.1 %** |
| **$\nu_\tau$ prompt (from $D_s$)** | **negligible** |

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

~ 20k $\nu_\mu$ CC+NC

66.4 $\nu_\tau$ CC (not efficiency corrected)

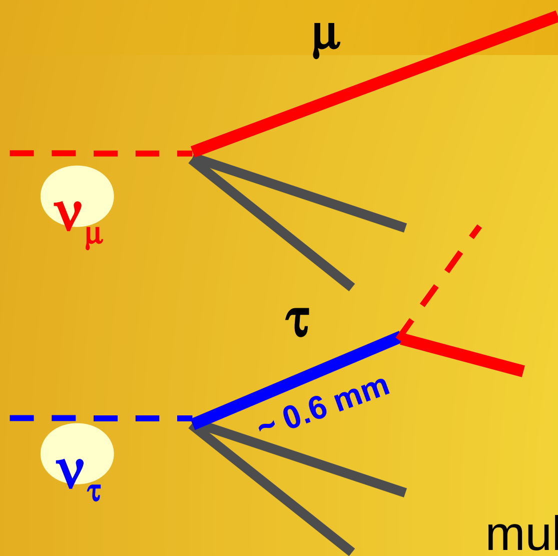
**DESIGN: 4.5·$10^{19}$ pot/year, 200 days/y per 5 y**




**Threshold for τ at ~ 3.5 GeV.**

**Slow rise.**

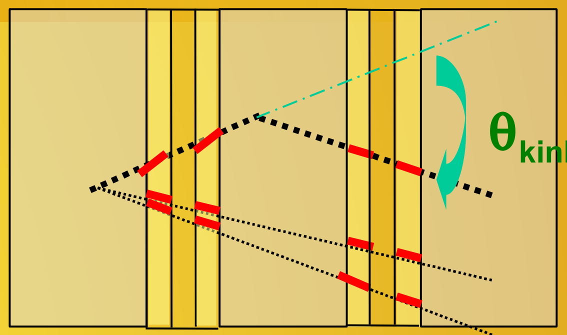
# The $\nu_\tau$ detection challenge



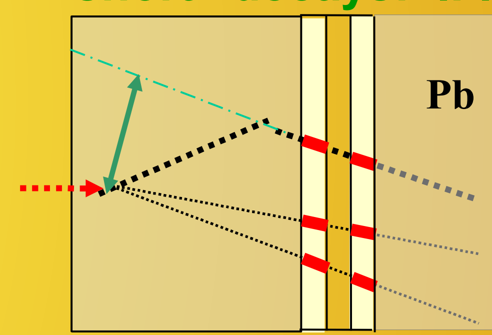

Detect a few $\nu_\tau^{CC}$ from the bulk of $\nu_\mu^{CC}$

| | | |
|---|---|---|
| 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

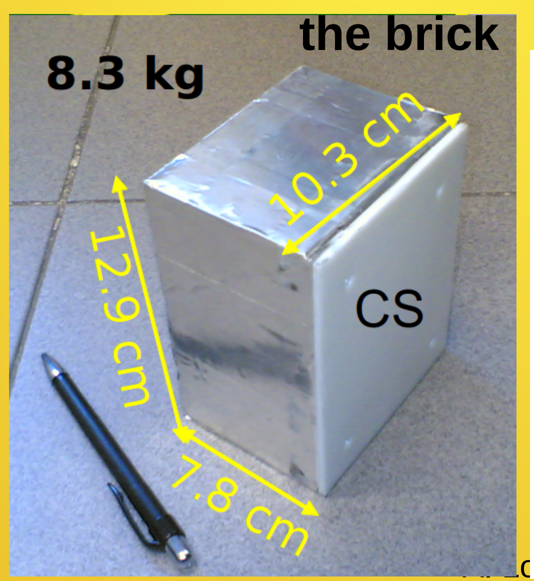


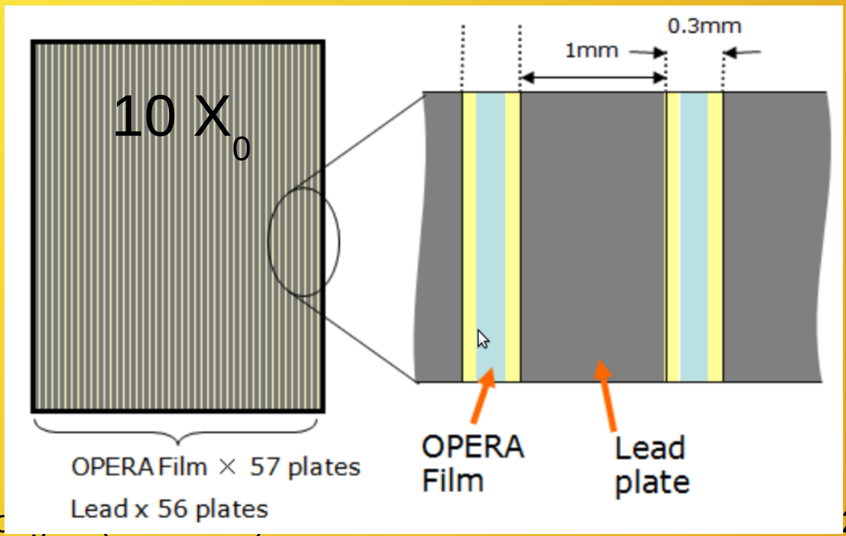

"short" decays: I.P.




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

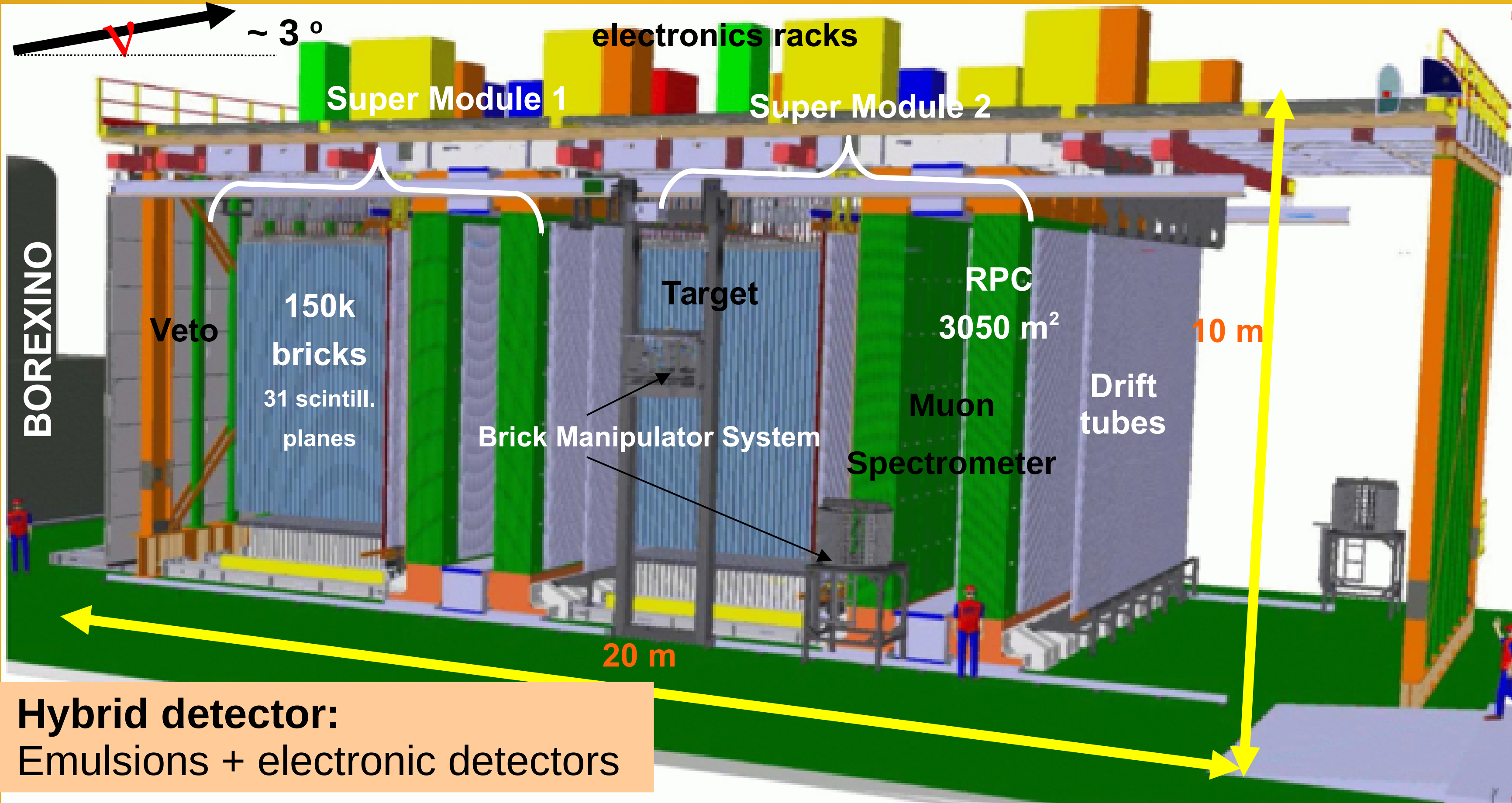
- **Large mass**
  - $N_\tau \propto (\Delta m^2)^2 M_{target}$
- **Extreme granularity**
  - $\sim \mu m$



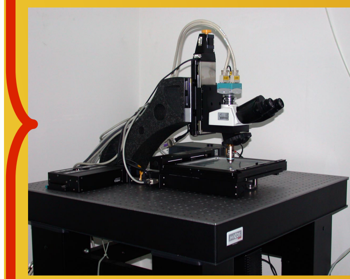



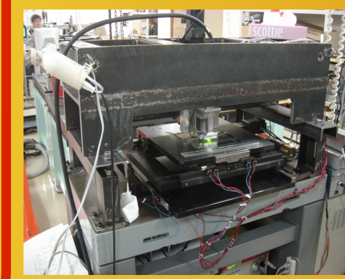
# The OPERA detector

**O(µm) resolution over a "dense" macroscopic volume O(100m$^3$)**

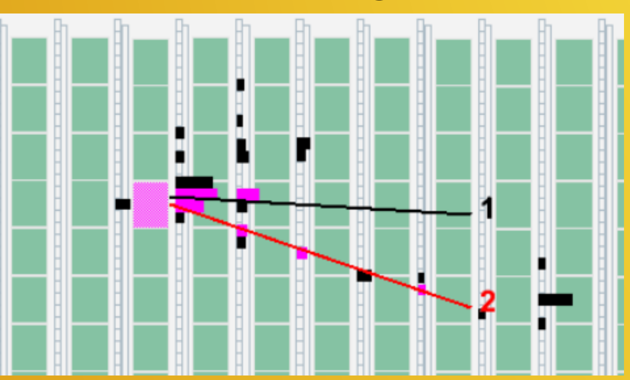



**Hybrid detector:**
Emulsions + electronic detectors





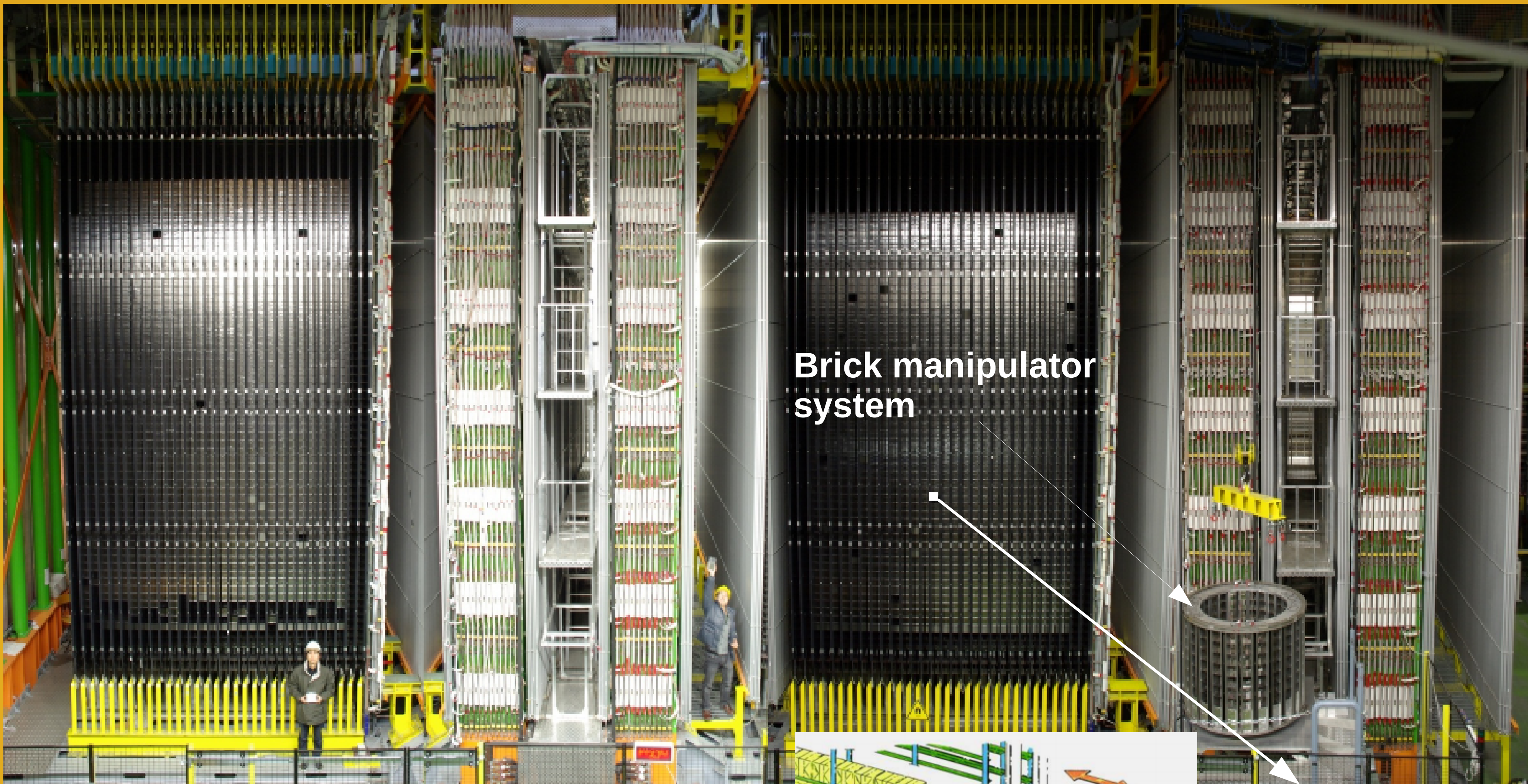
**``Brick-finding''**




**+ several ancillary facilities “off-site”:**

- **Emulsions “refreshing” (JP e LNGS)**
- **Assembly/disassembly of bricks (LNGS)**
- **Labelling and X ray marking (LNGS)**
- **Automatised development (LNGS)**
- **Scanning of CS doublets (LNGS)**
- **Scanning bricks (Europe + JP)**

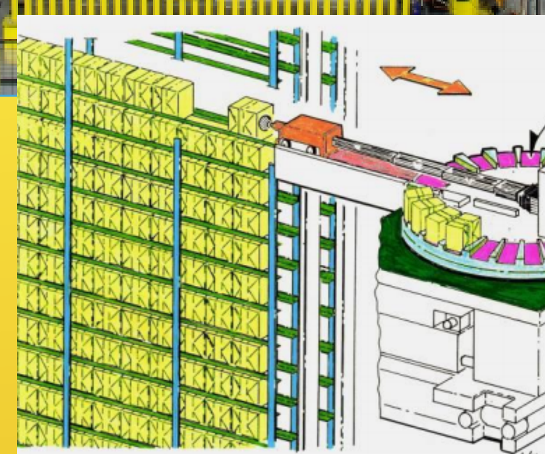
Super Module 1 Super Module 2

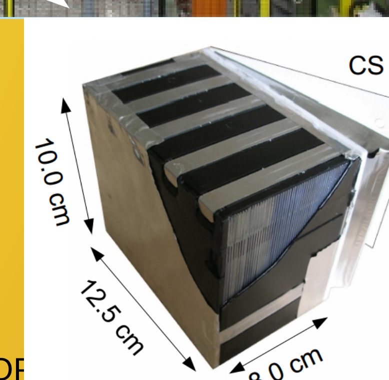



Target area

μ spectrometer

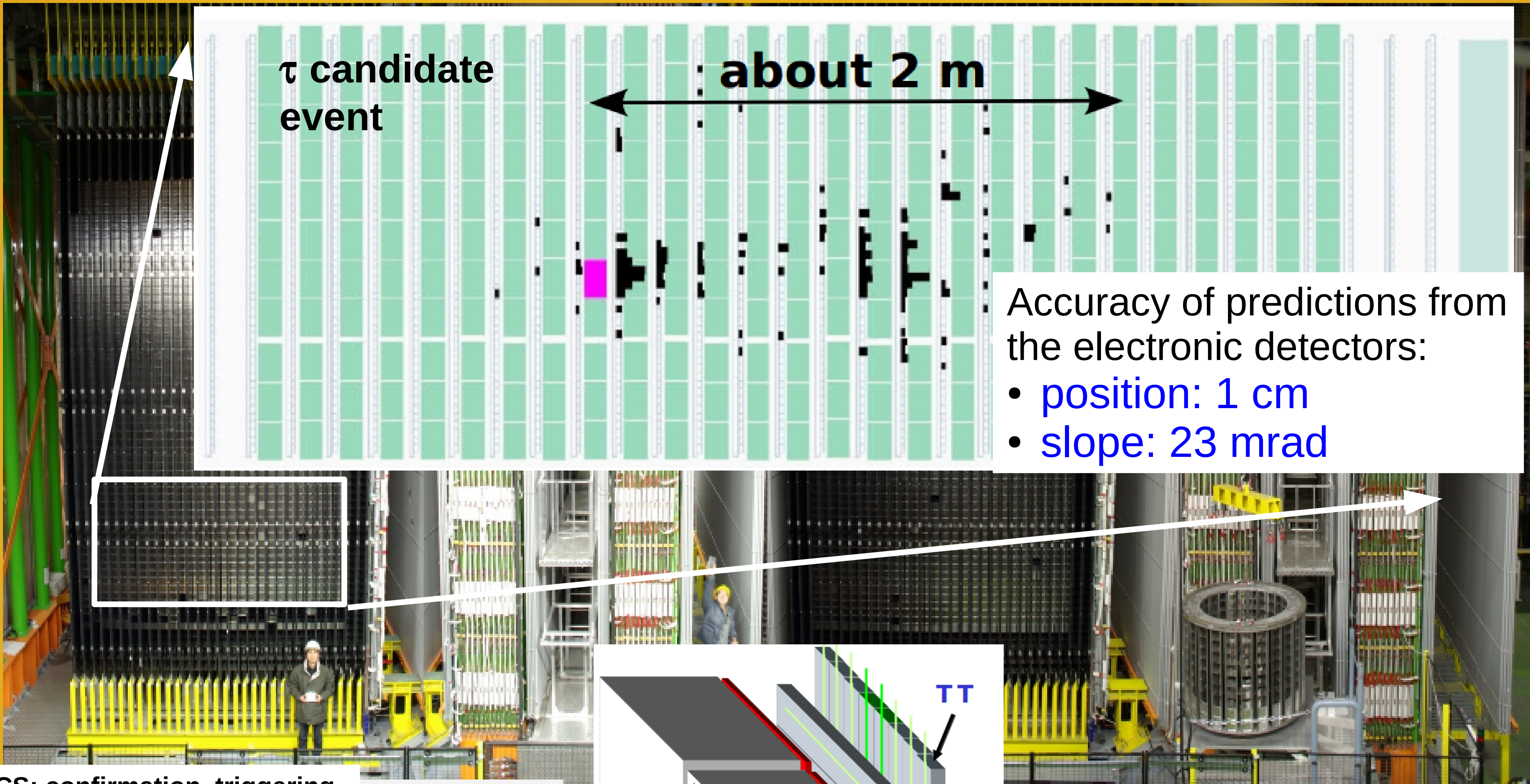
~ 150.000 bricks in total.
1.25 kt mass






rom OP

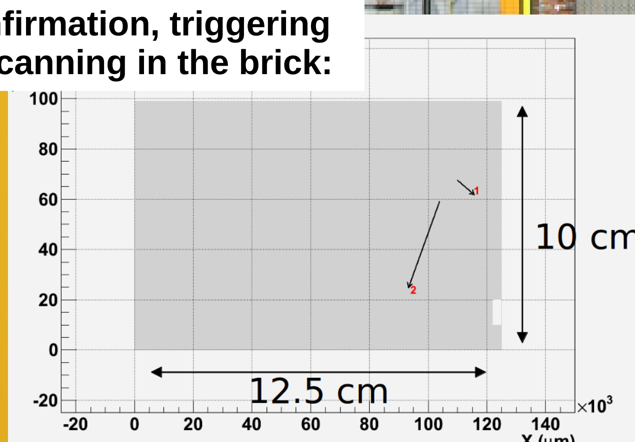
Super Module 1 Super Module 2

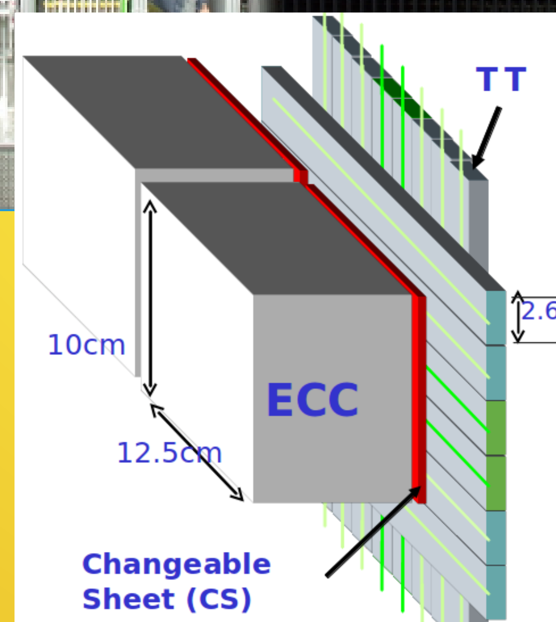



Accuracy of predictions from the electronic detectors:

- position: 1 cm
- slope: 23 mrad

CS: confirmation, triggering of the scanning in the brick:




**Location efficiency:**

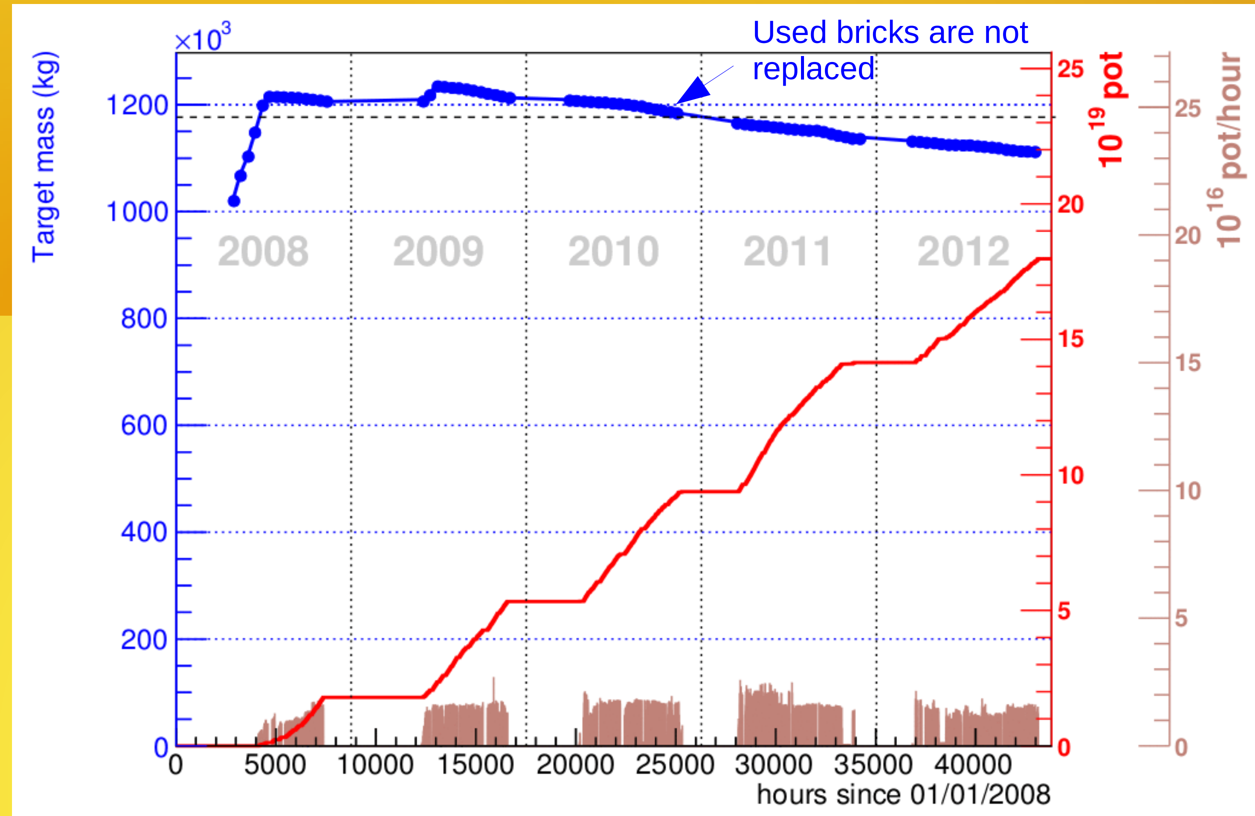
- CC: 74 %
- NC: 48 %

# Collected samples

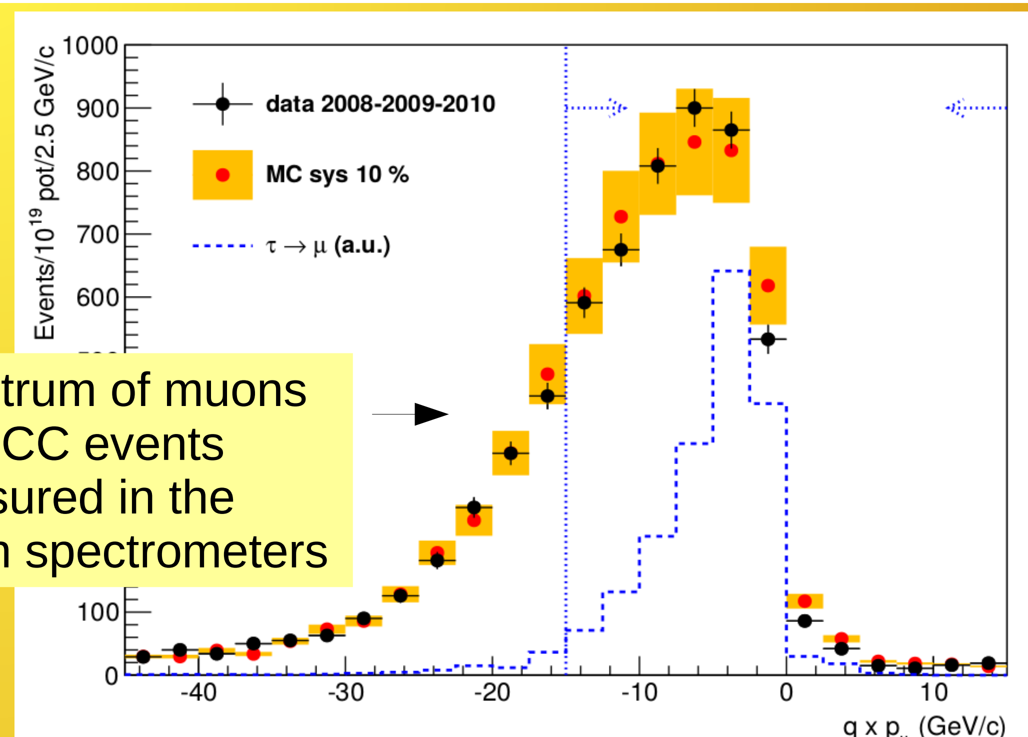
The 5 year long CNGS run has ended in 2012.

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

19505 neutrino interactions in the emulsion targets.



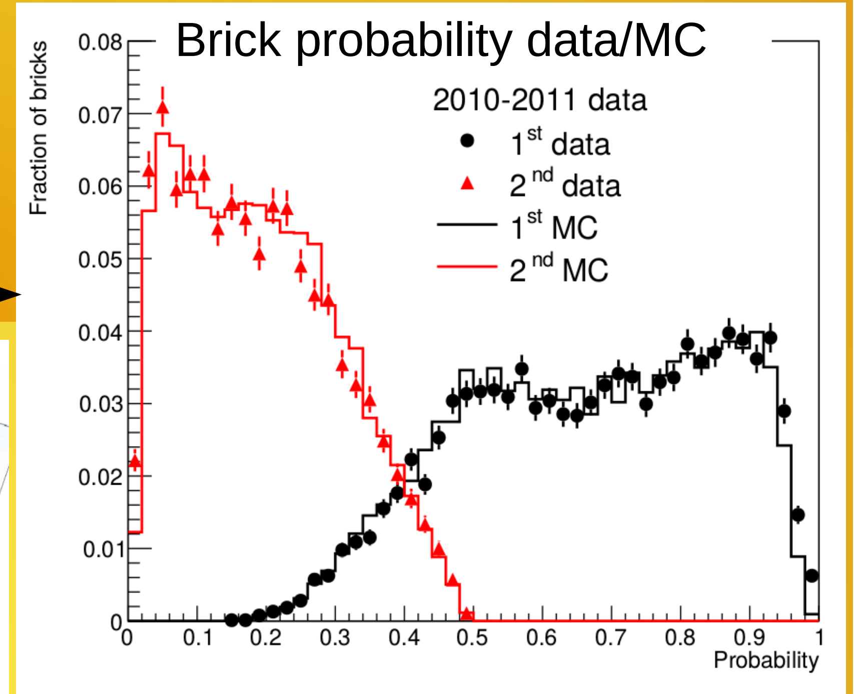

| Year | Days | p.o.t. ($10^{19}$) | ν interactions |
|---|---|---|---|
| 2008 | 123 | 1.74 | 1698 |
| 2009 | 155 | 3.53 | 3693 |
| 2010 | 187 | 4.09 | 4248 |
| 2011 | 243 | 4.75 | 5131 |
| 2012 | 257 | 3.86 | 3923 |
| **tot** | **965** | **17.97** | **19505** |




Spectrum of muons from CC events measured in the muon spectrometers

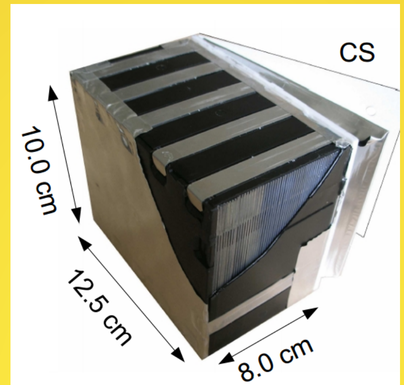
# Progress in the analysis of the emulsion films

Bricks are ordered according to their probability of containing the interaction vertex.

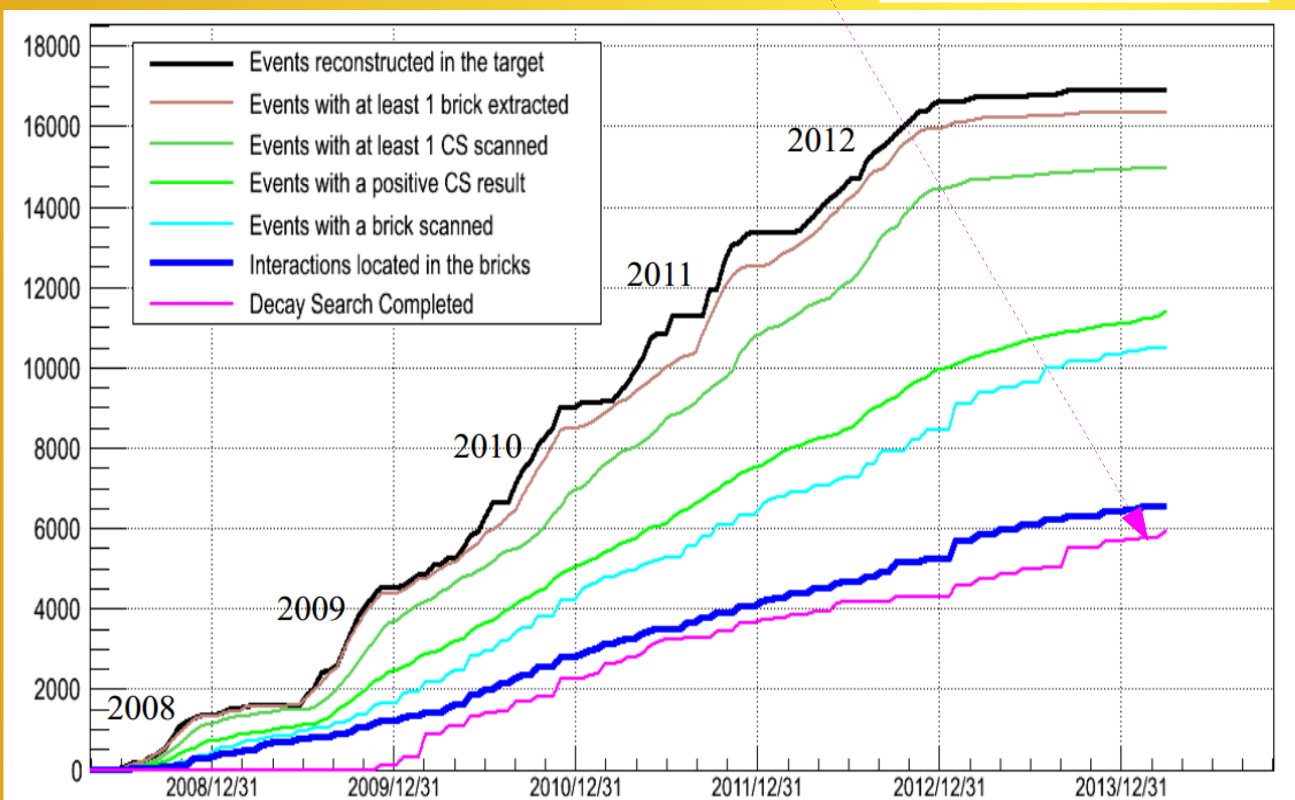


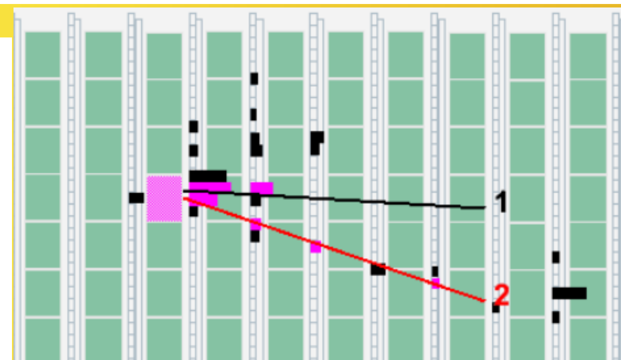

Analysis status:

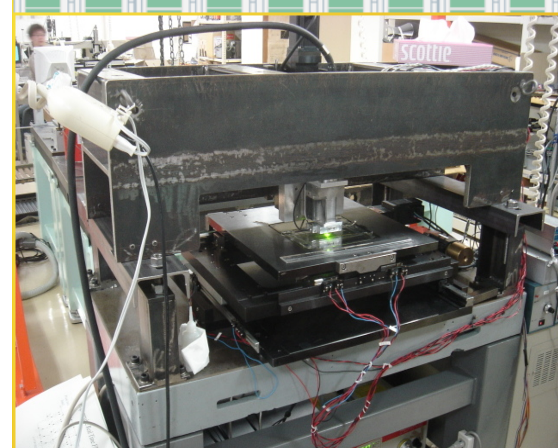
- **2008-09** 1st and 2nd bricks completed
- **2010-12** 1st bricks completed



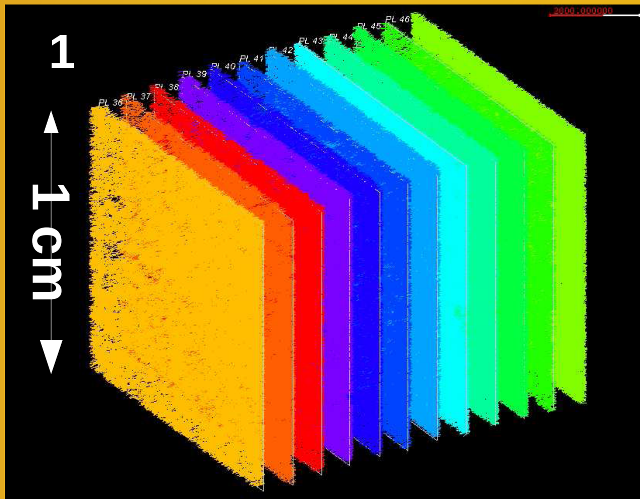

**> 6000 fully analysed bricks**

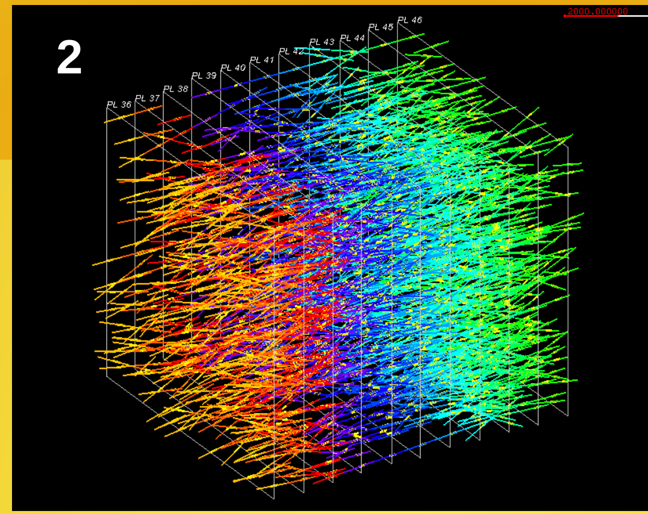


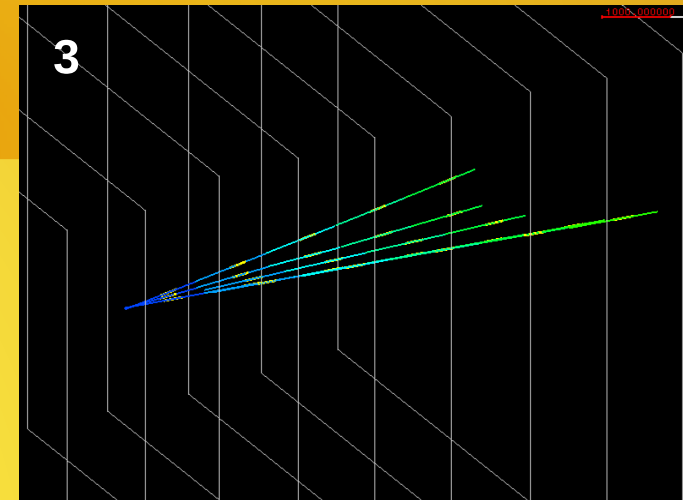



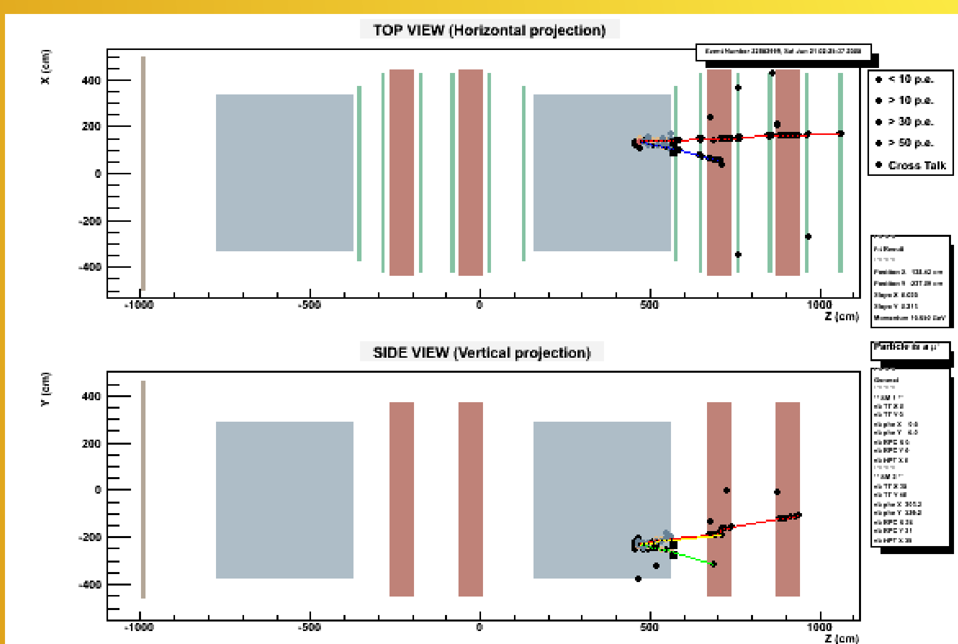
# Vertex hunting in the brick



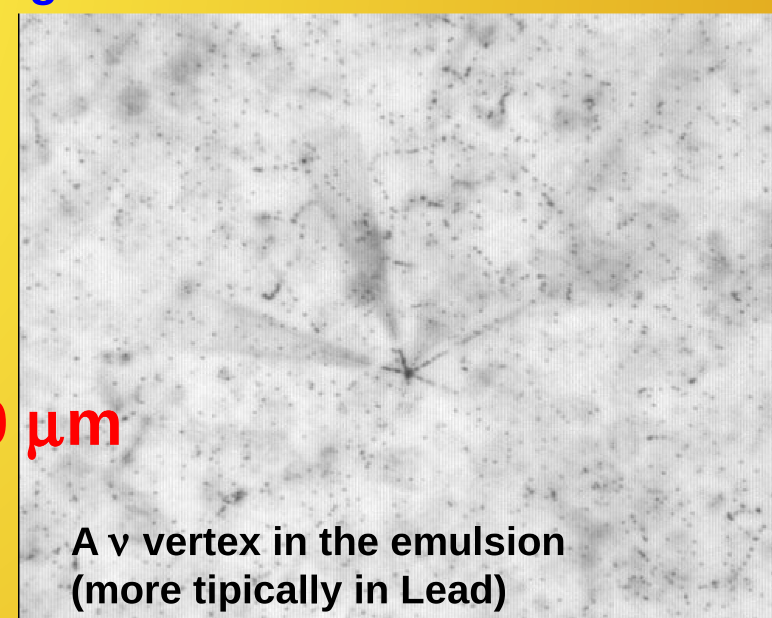




**0)** all tracks tagged in the **CS films** are **followed upstream** until a stopping point is found
**1)** base-tracks in the 12 films of the a **volume centered in the stopping point** are reconstructed
**2)** cosmic ray tracks (from a dedicated exposure) are used for the fine **alignment** of films
**3)** passing-through tracks are discarded and the **vertexing algorithm** reconstructs the vertex.




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



# Location efficiency

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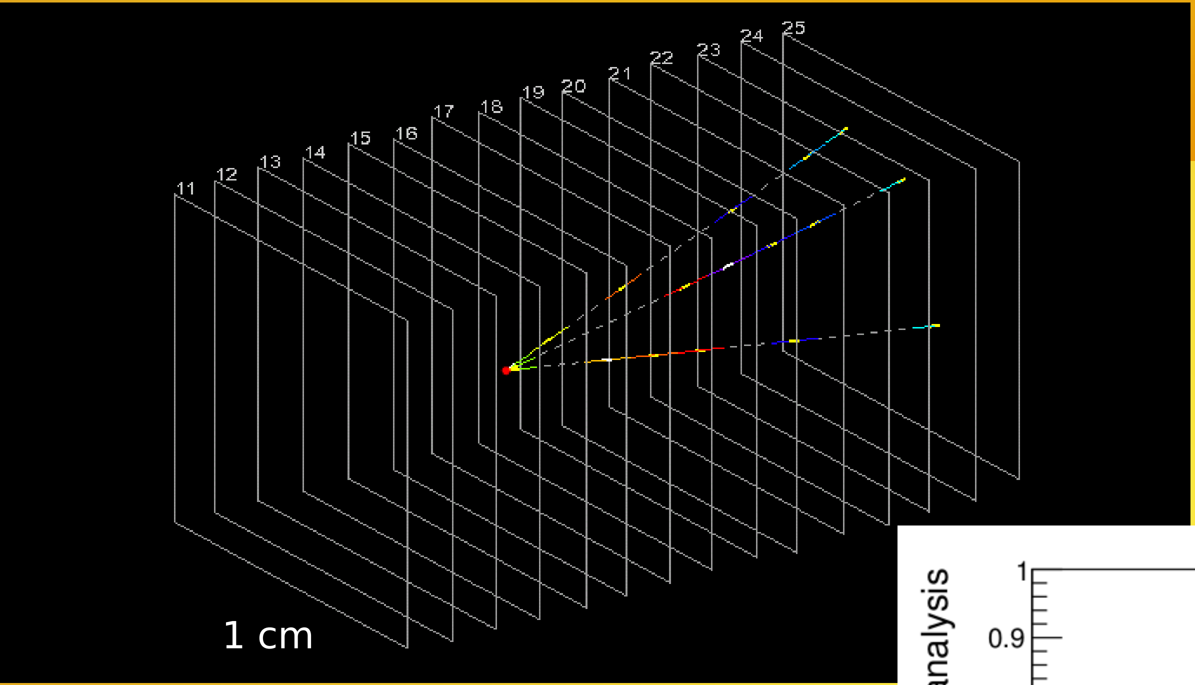
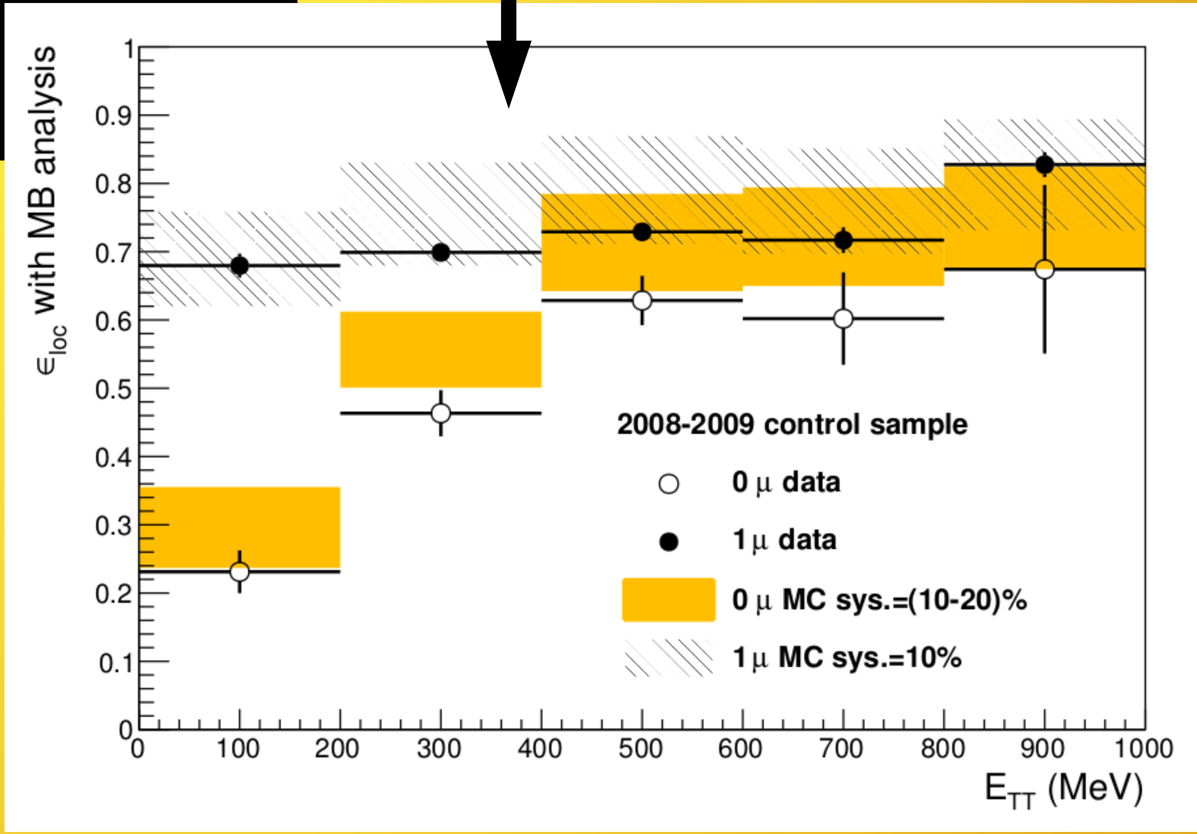



0μ and 1μ samples

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.

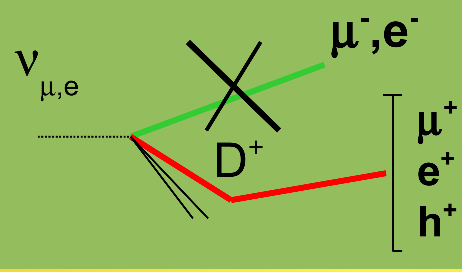
The prediction for the τ signal and backgrounds is based on efficiencies derived from the observed 0μ and 1μ samples

# $\nu_\mu \to \nu_\tau$ background characterisation

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

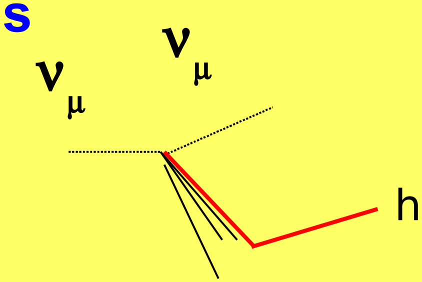



MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

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

**Hadronic interactions**

Background for $\tau \to h$

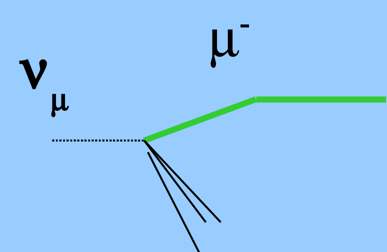



FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

**Large angle muon scattering**

Background for $\tau \to \mu$

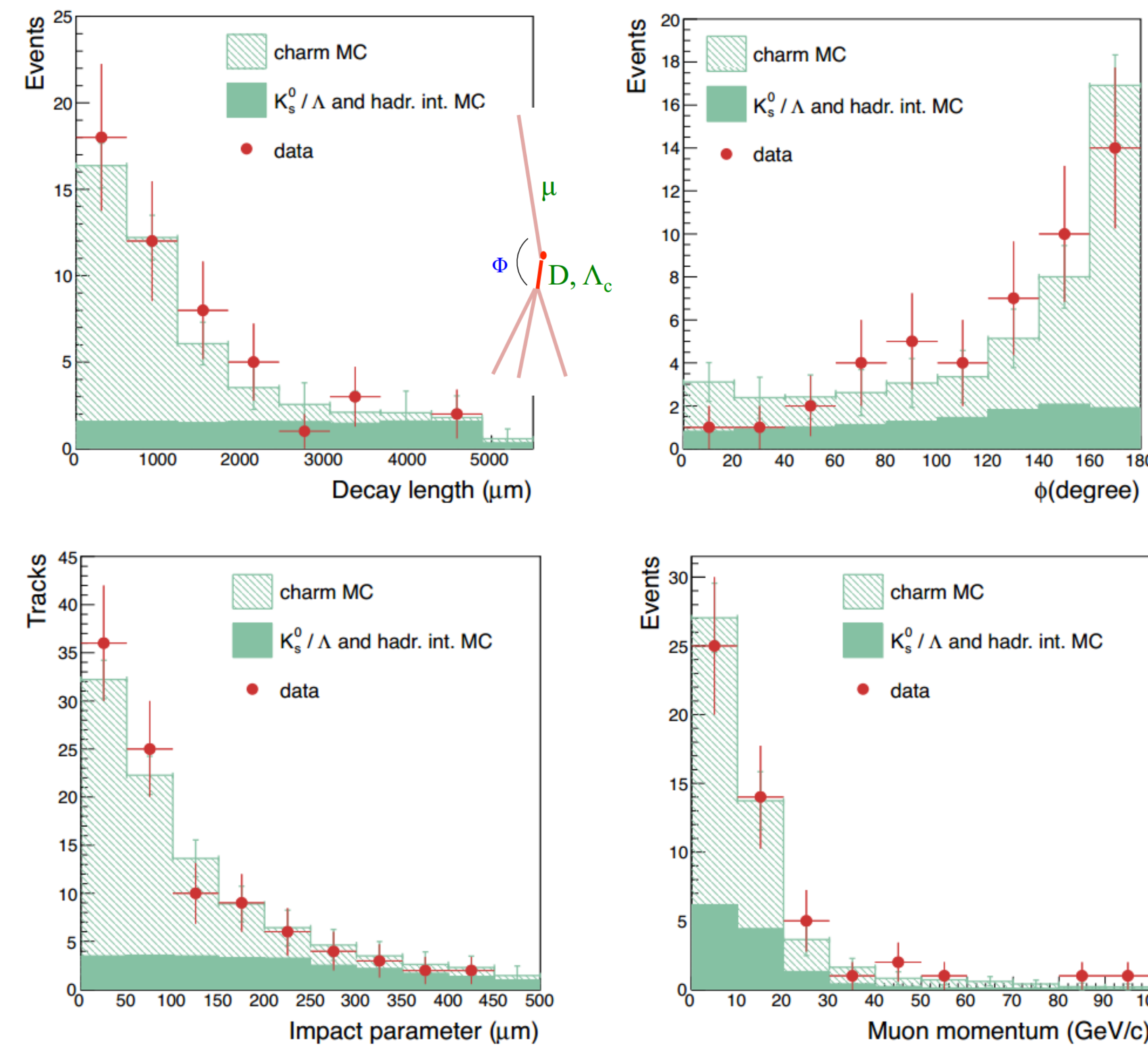


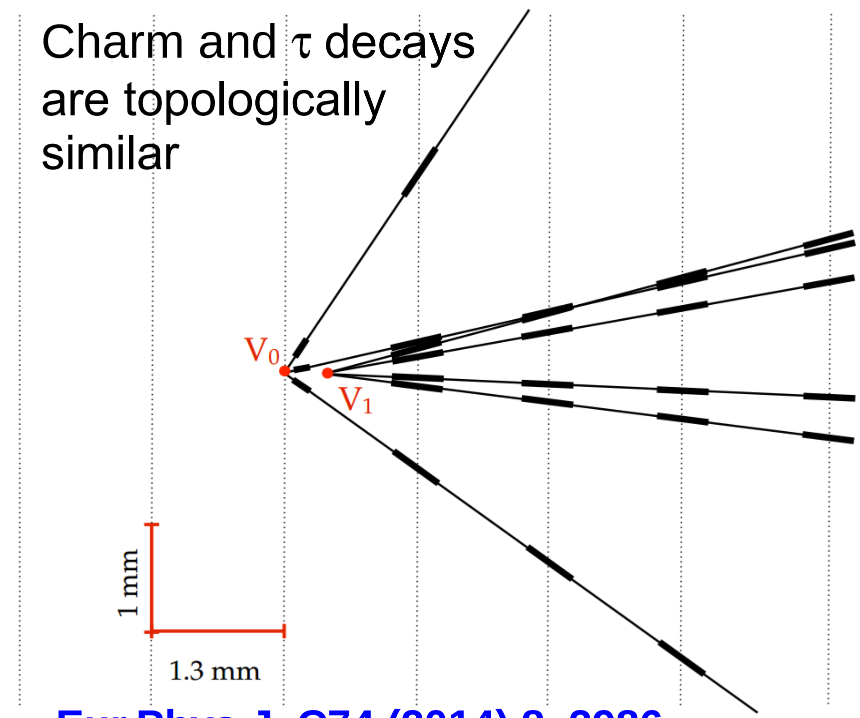

Measurements in the literature (Lead form factor), simulations and dedicated test-beams (in progress)

# Validation with the CNGS charm events sample

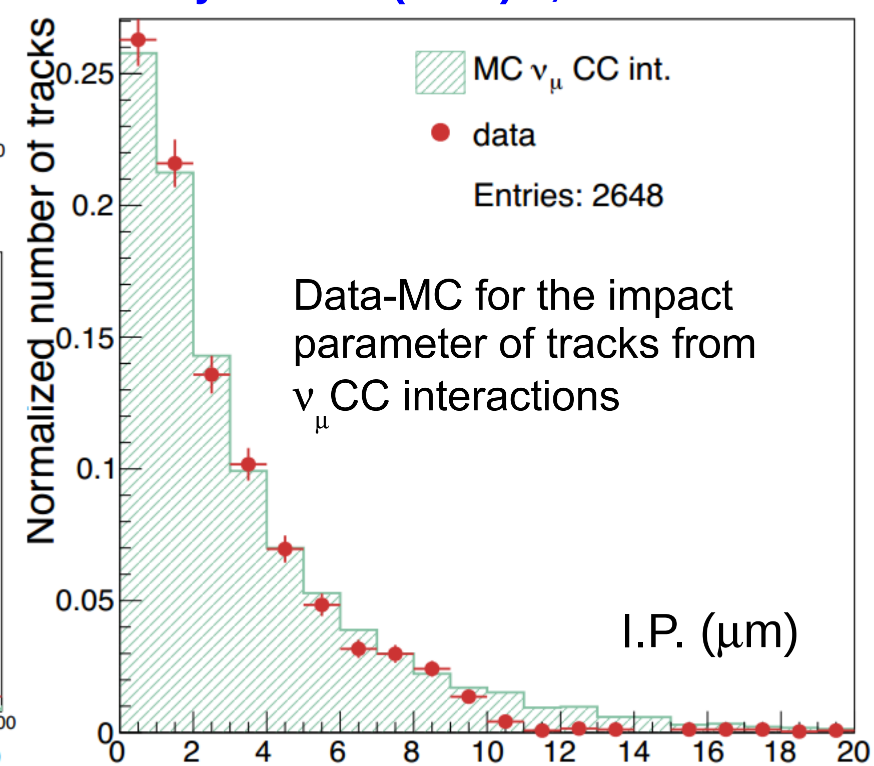
Test for: reconstruction efficiencies, description of kinematical variables, charm background.

**54 ± 4 expected ↔ 50 observed**

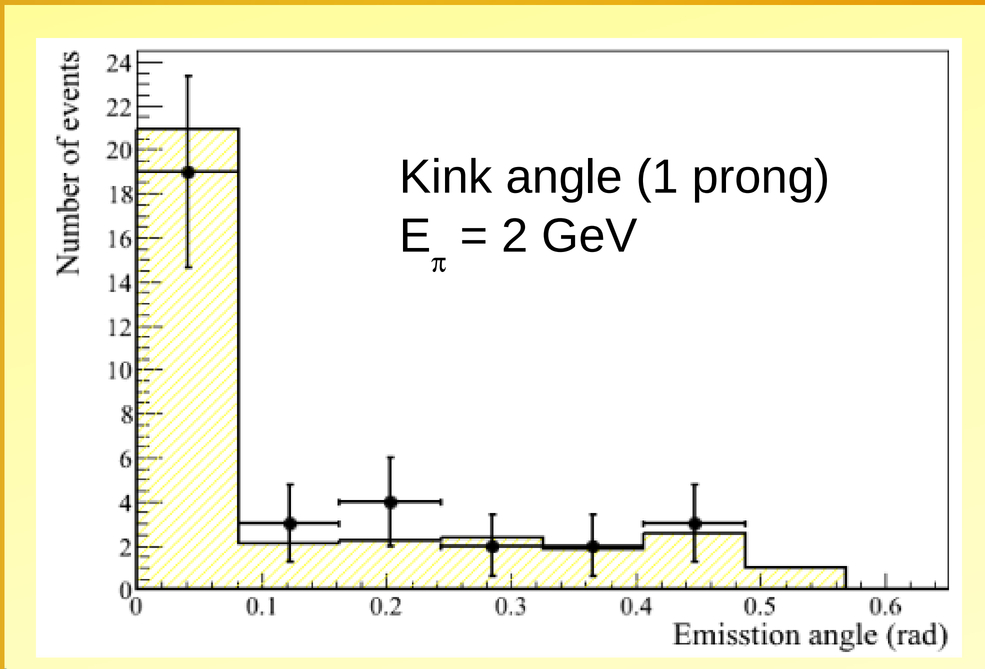


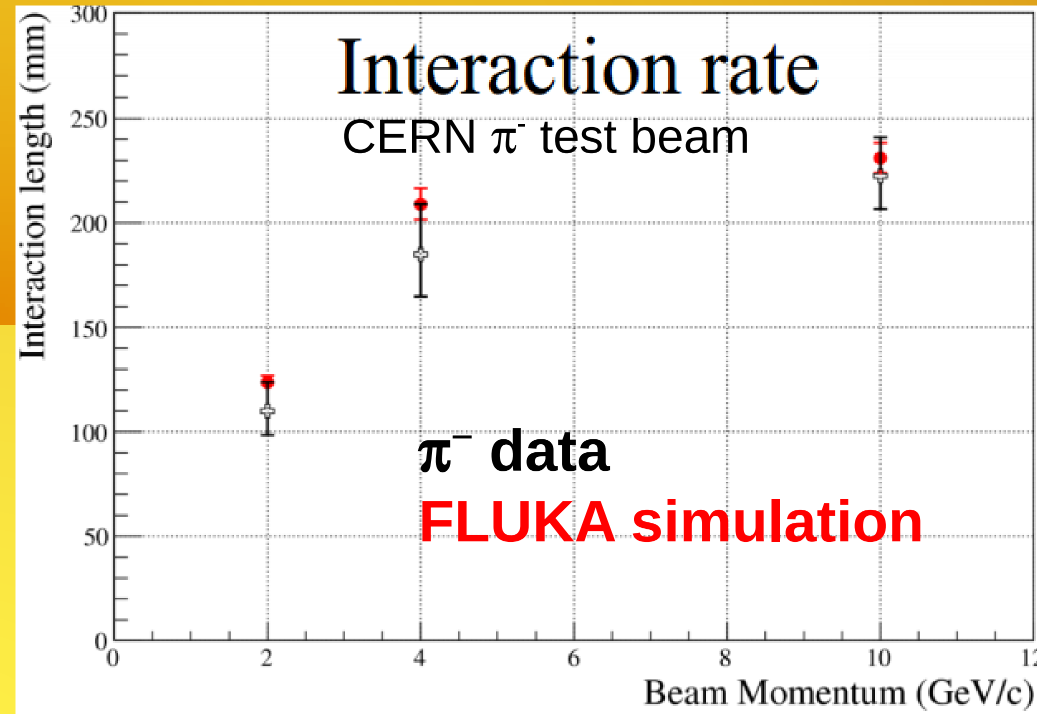




**Eur.Phys.J. C74 (2014) 8, 2986**

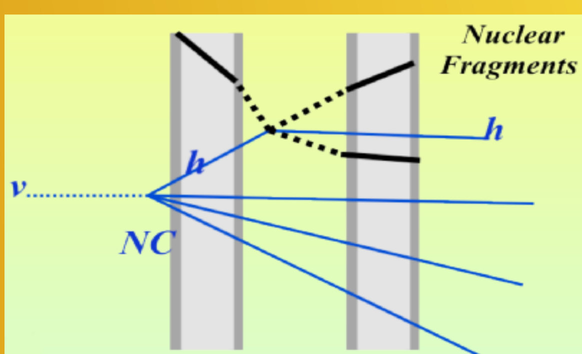


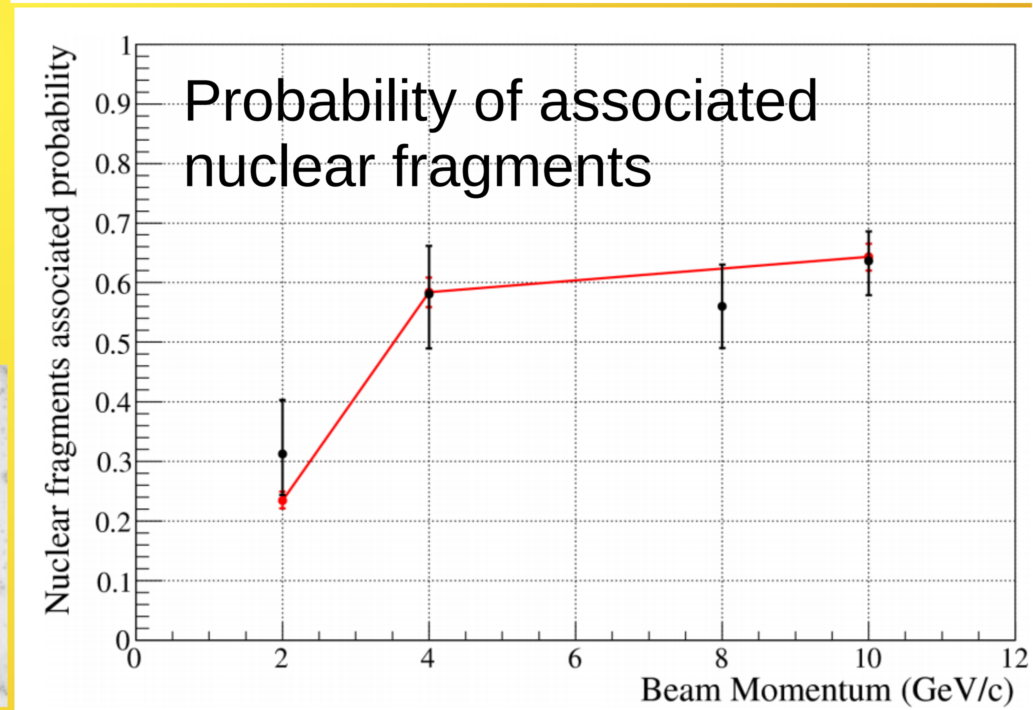
# Hadronic background: π test beams




**Nuclear fragments:** a smoking gun for the occurrence of an π interaction instead of a decay.




Hadronic background rate per located event: $\tau \rightarrow (3)h = (1.5)3.09 \times 10^{-5}$

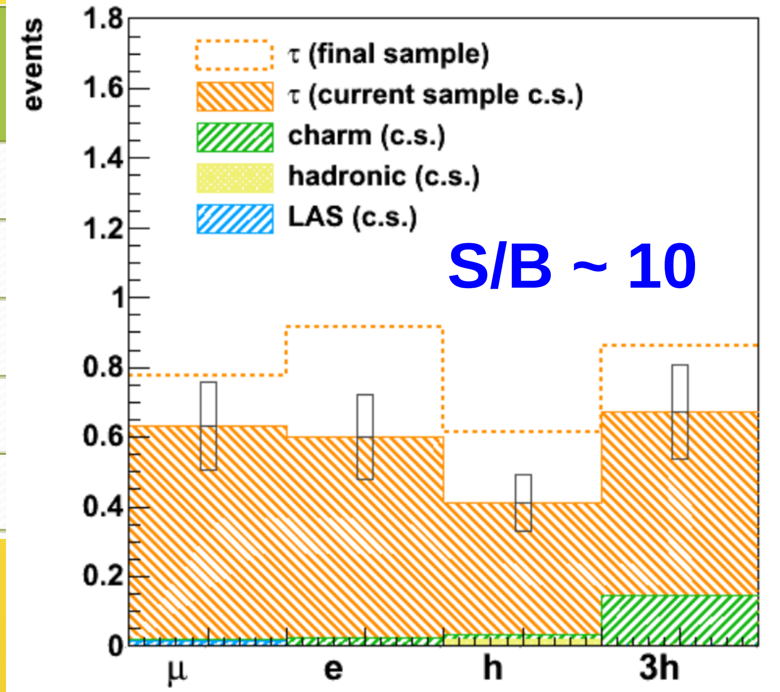
# $\nu_\tau$ analysis results

**Candidate events have to fullfil kinematical cuts:** →

defined in the experiment proposal to enhance the S/B ratio

| variable | $\tau \to 1h$ | $\tau \to 3h$ | $\tau \to \mu$ | $\tau \to e$ |
|---|---|---|---|---|
| lepton-tag | No $\mu$ or $e$ at the primary vertex | | | |
| $z_{dec}$ ($\mu$m) | $[44, 2600]$ | $< 2600$ | $[44, 2600]$ | $< 2600$ |
| $p_T^{miss}$ (GeV/$c$) | $< 1^\star$ | $< 1^\star$ | / | / |
| $\phi_{lH}$ (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 $< 15$ |
| $\theta_{kink}$ (mrad) | $> 20$ | $< 500$ | $> 20$ | $> 20$ |
| $m, m_{min}$ (GeV/$c^2$) | / | $> 0.5$ and $< 2$ | / | / |

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




**3 hadronic + 1 muonic candidates observed**

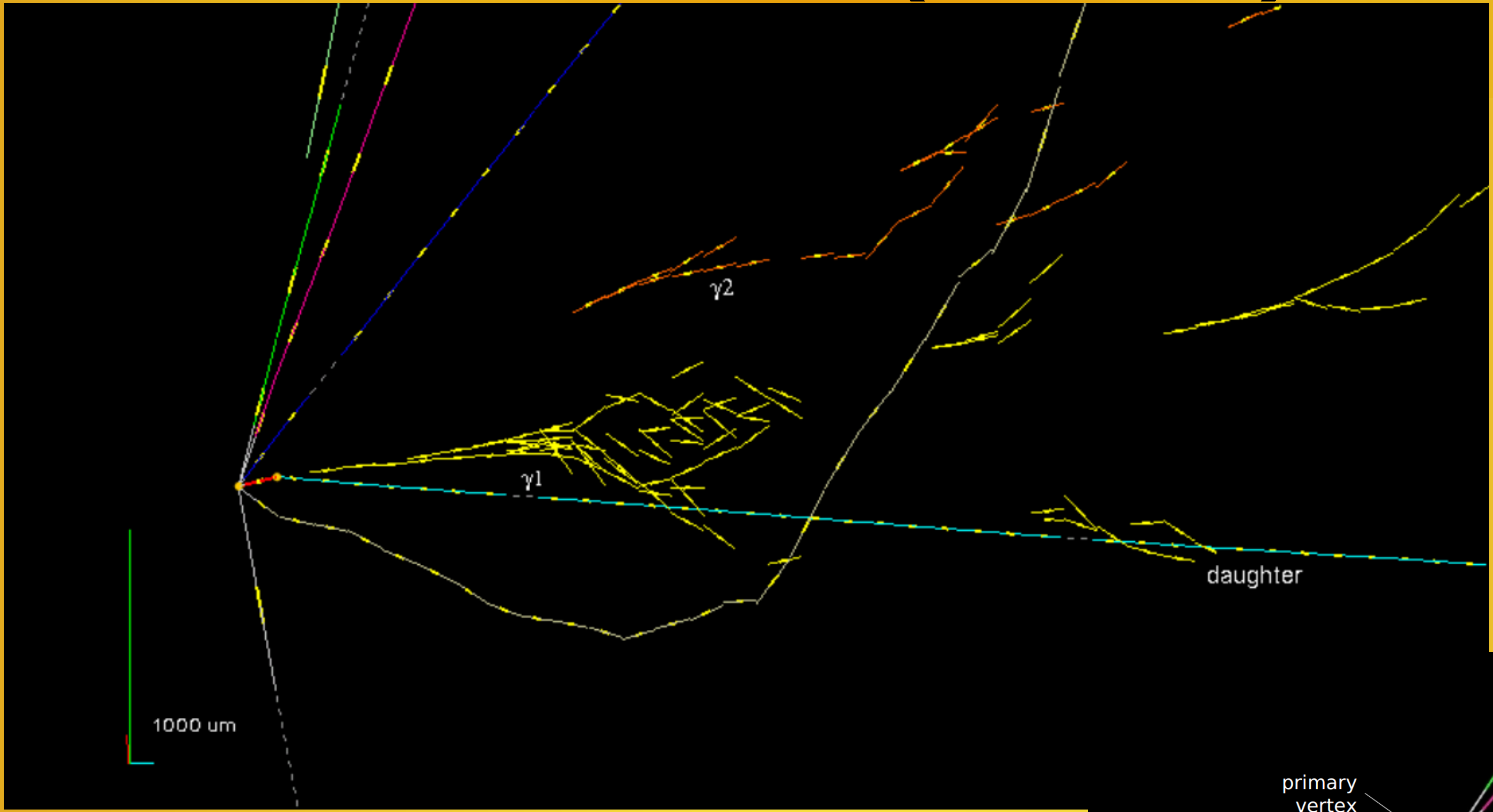
**Exclusion of null hypothesis: 4.2 σ**

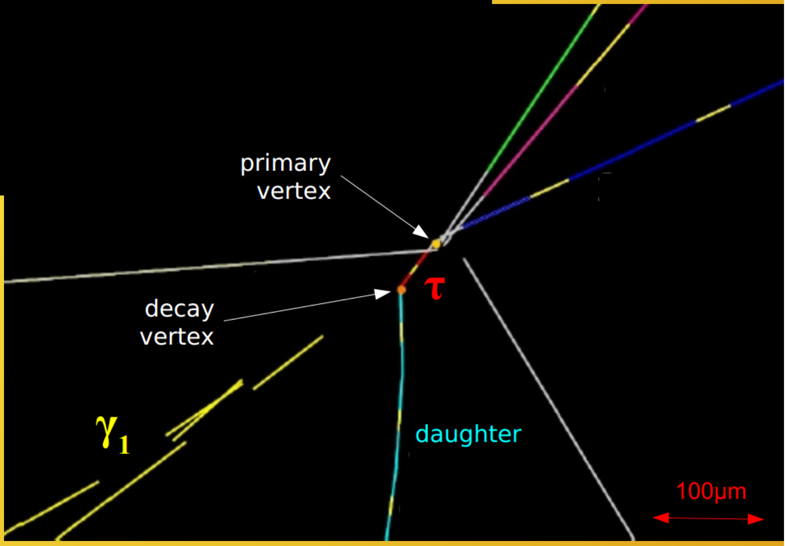
- Fisher combination of single channel p-value
- Likelihood ratio

*p*-value = $1.03 \times 10^{-5}$

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

Phys. Lett. B691 (2010) 138




$\tau^- \rightarrow \rho^- + \nu_\tau$ (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/$c^2$

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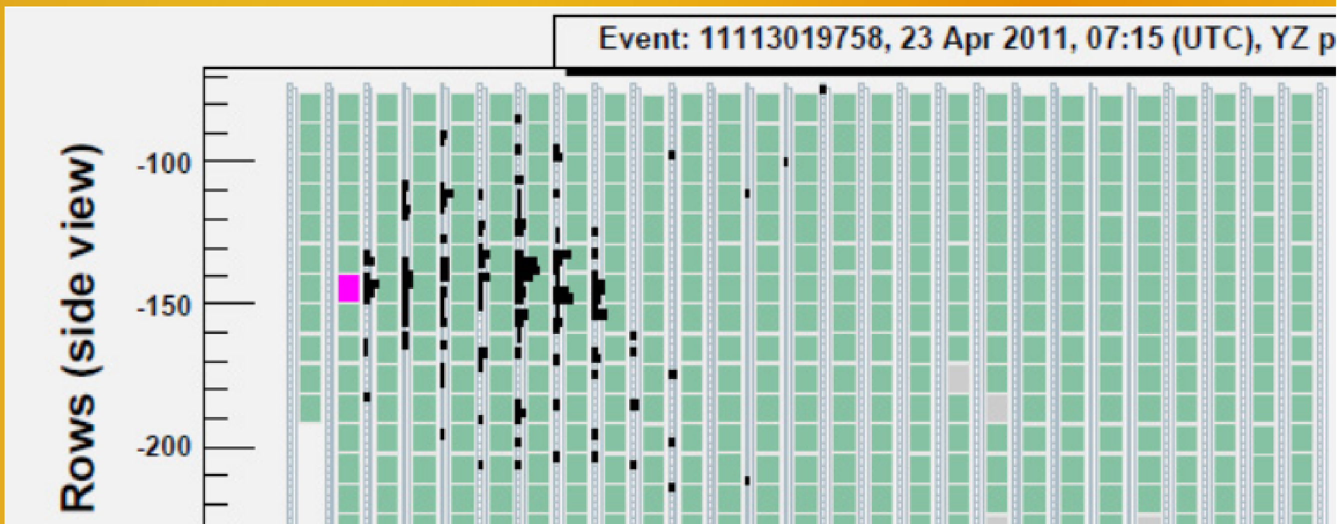
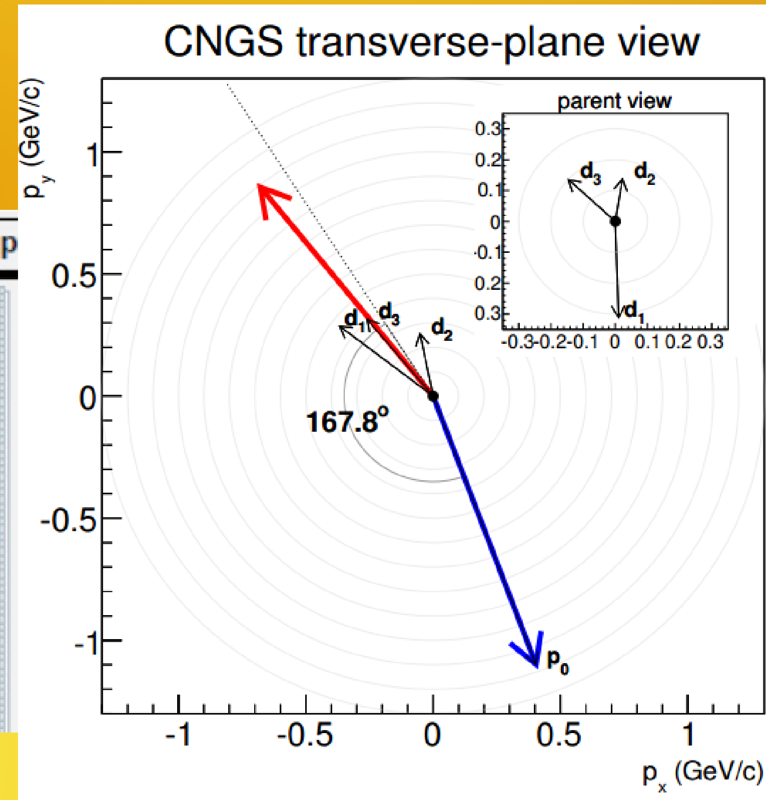
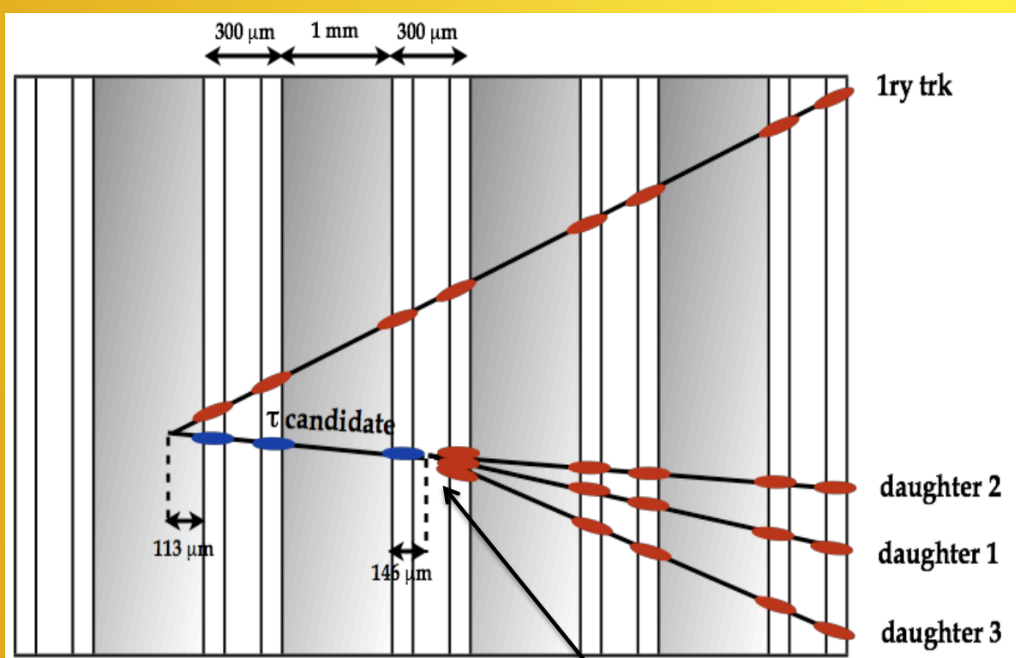
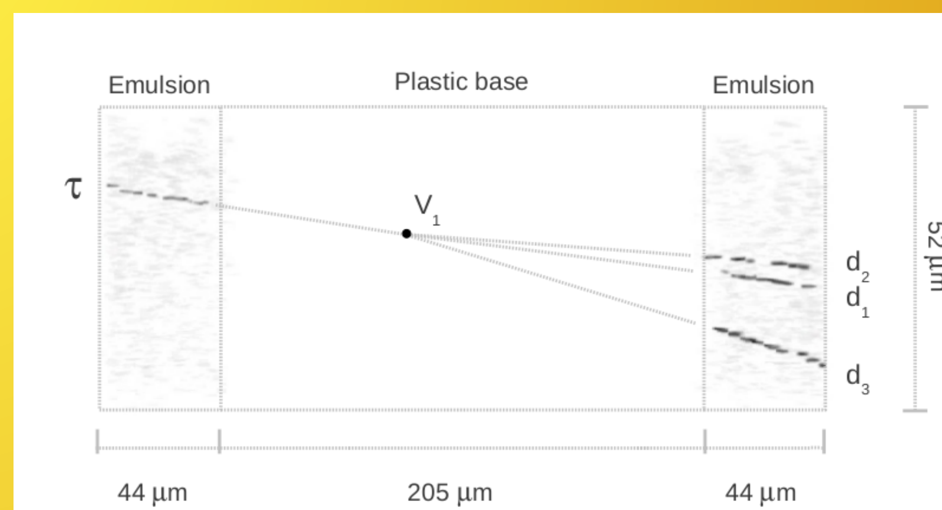
# The 2nd candidate ($\tau \rightarrow 3h$)



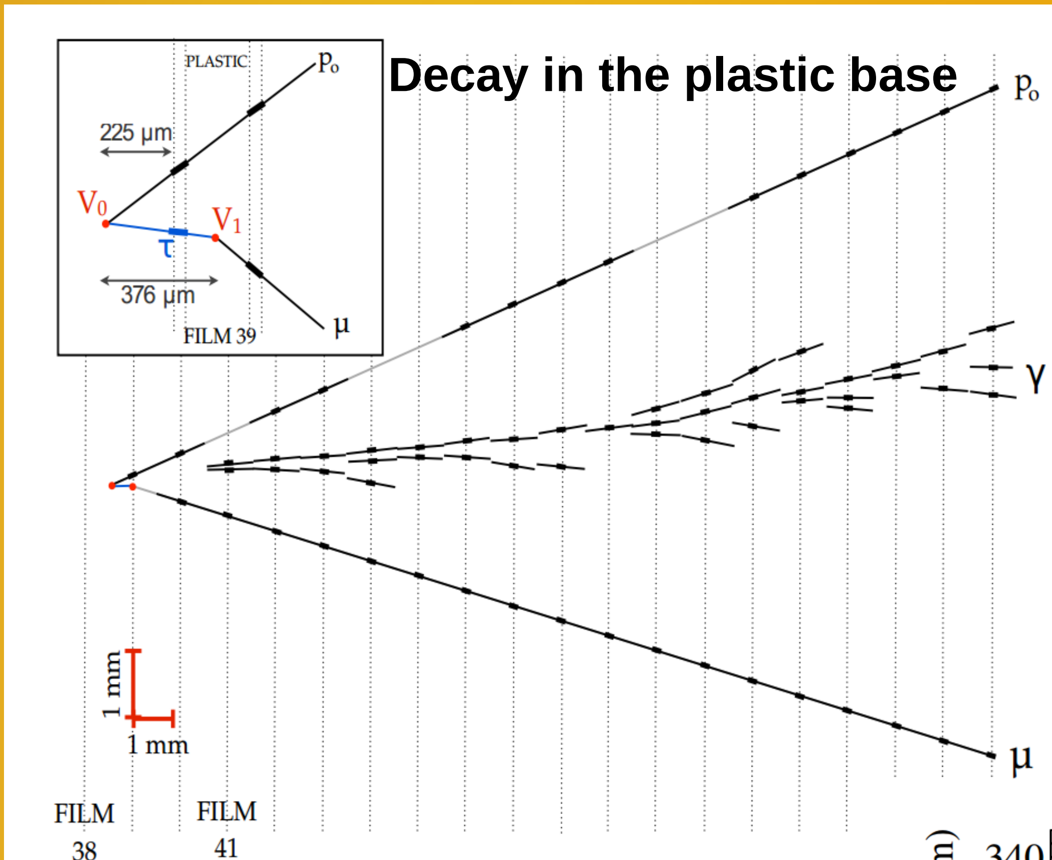



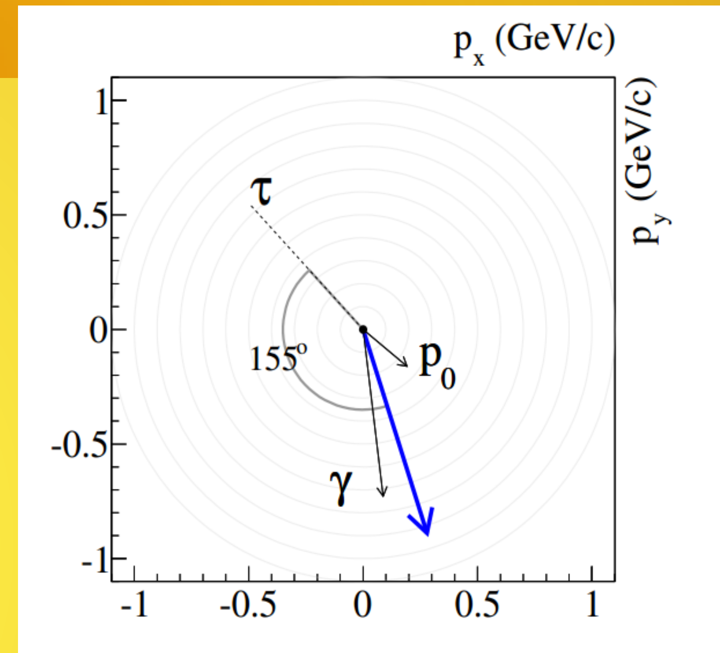



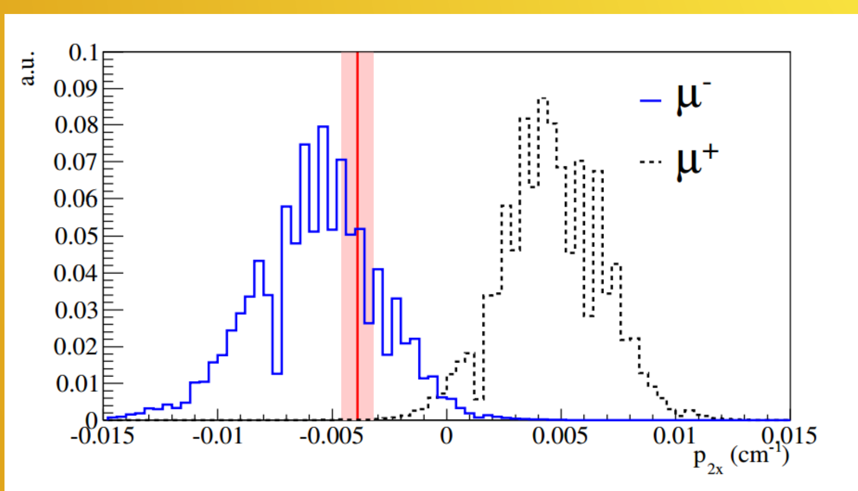

**Decay in the plastic base**

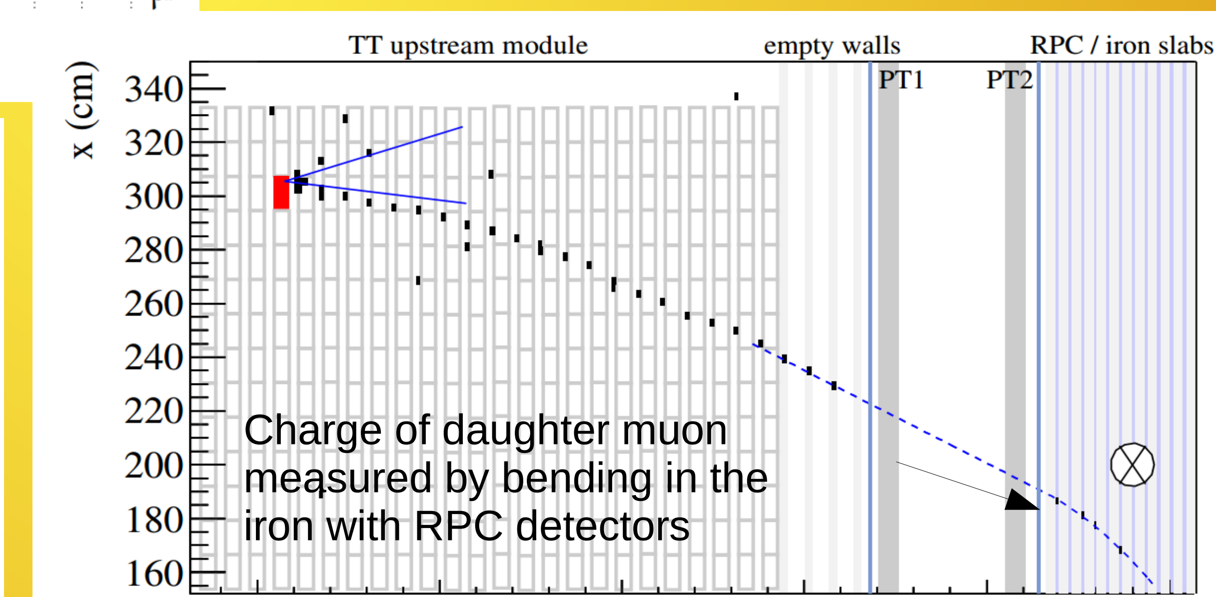
# The 3rd candidate ($\tau \rightarrow \mu$)

Phys. Rev. D 89 (2014) 051102(R)



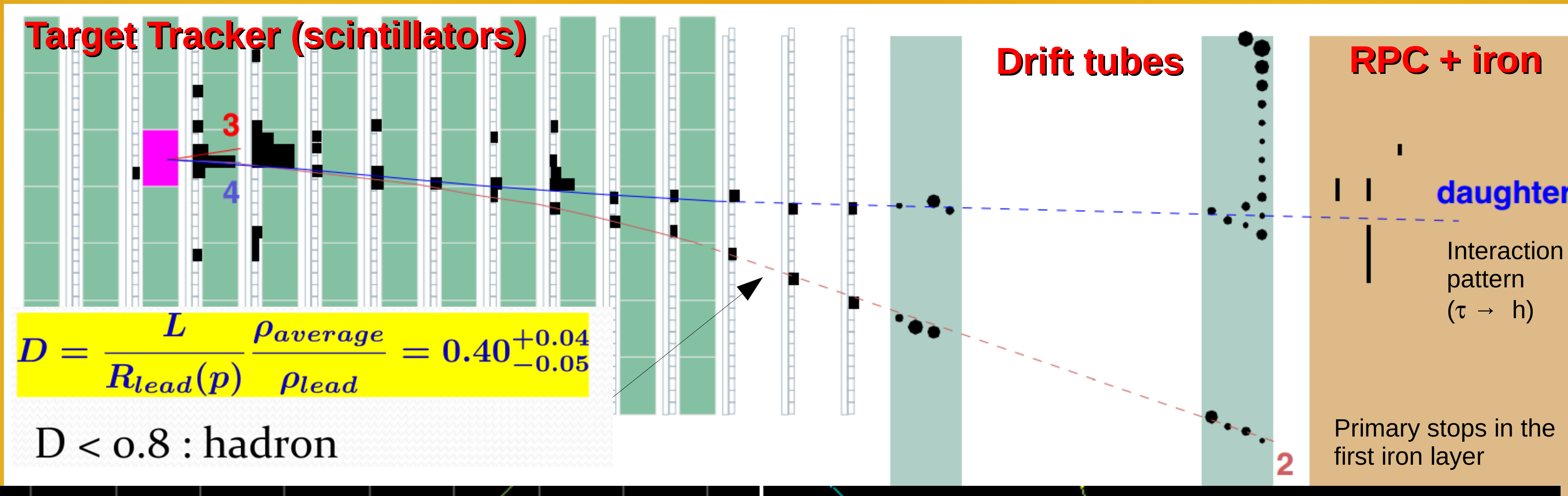



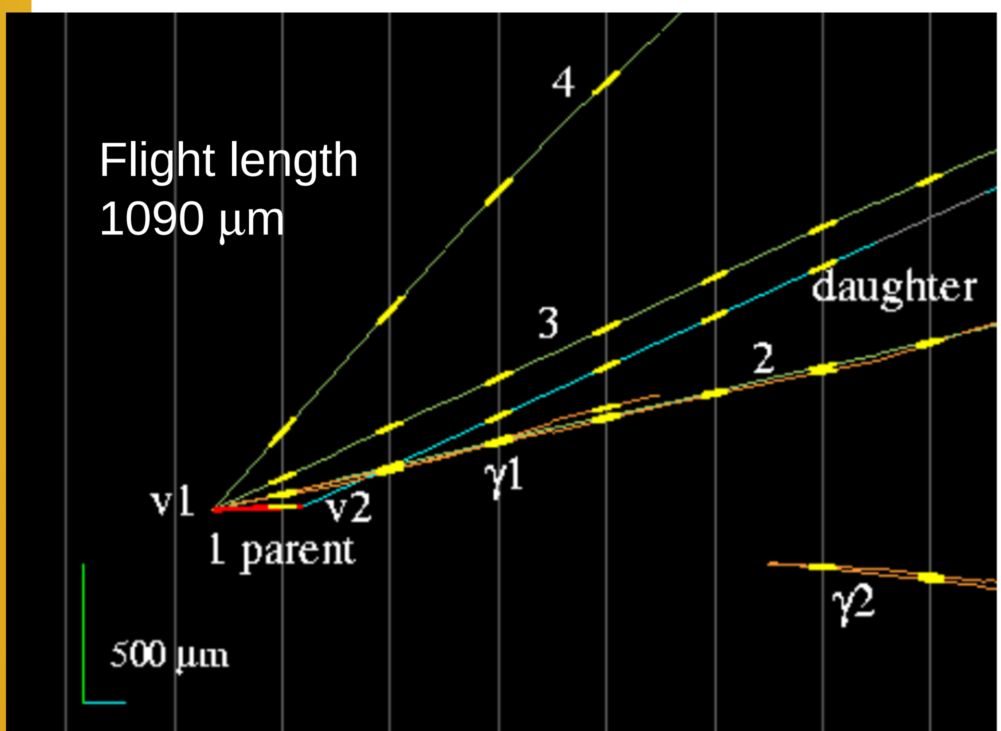
# The 4th candidate ($\tau \rightarrow 1h$)

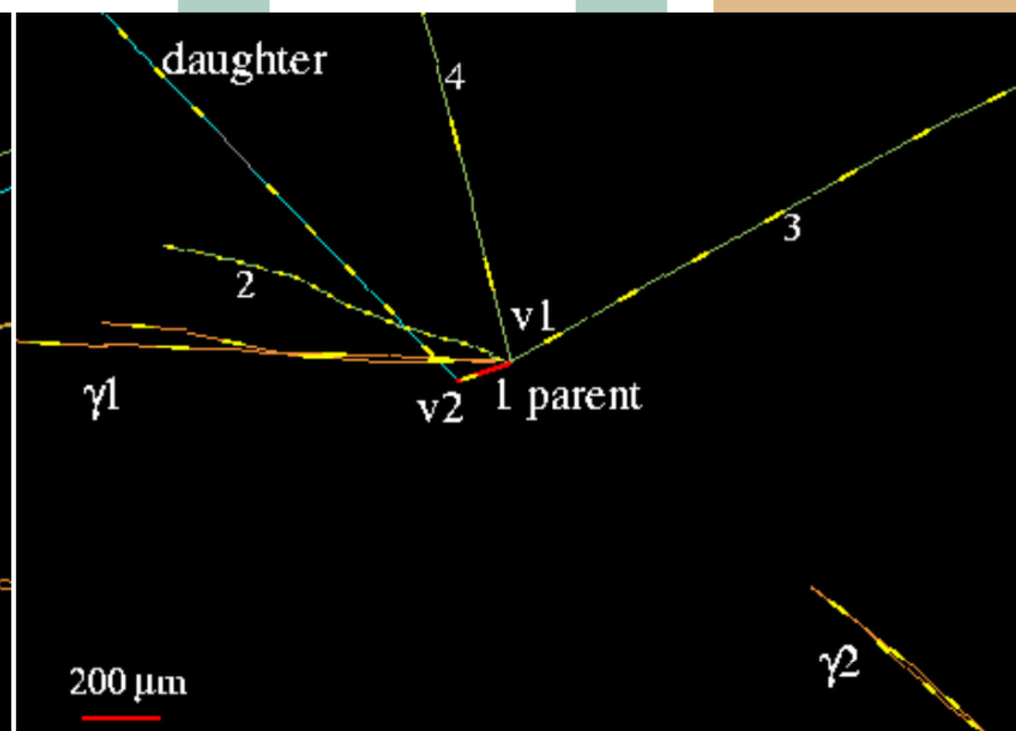
PTEP 2014 (2014) 10, 101C01




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

D < 0.8 : hadron



# Measurement of $\Delta m^2_{32}$

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

$$\propto (\Delta m^2_{32})^2 L^2 \int \phi(E)\epsilon(E)\frac{\sigma(E)}{E^2} dE$$

(L/<E>)$_{OPERA}$ ~ 43 km/GeV

(L/<E>)$_{peak}$ ~ 500 km/GeV

\`\`Steep'' $\Delta m^2$ dependence

→ counting based measurement

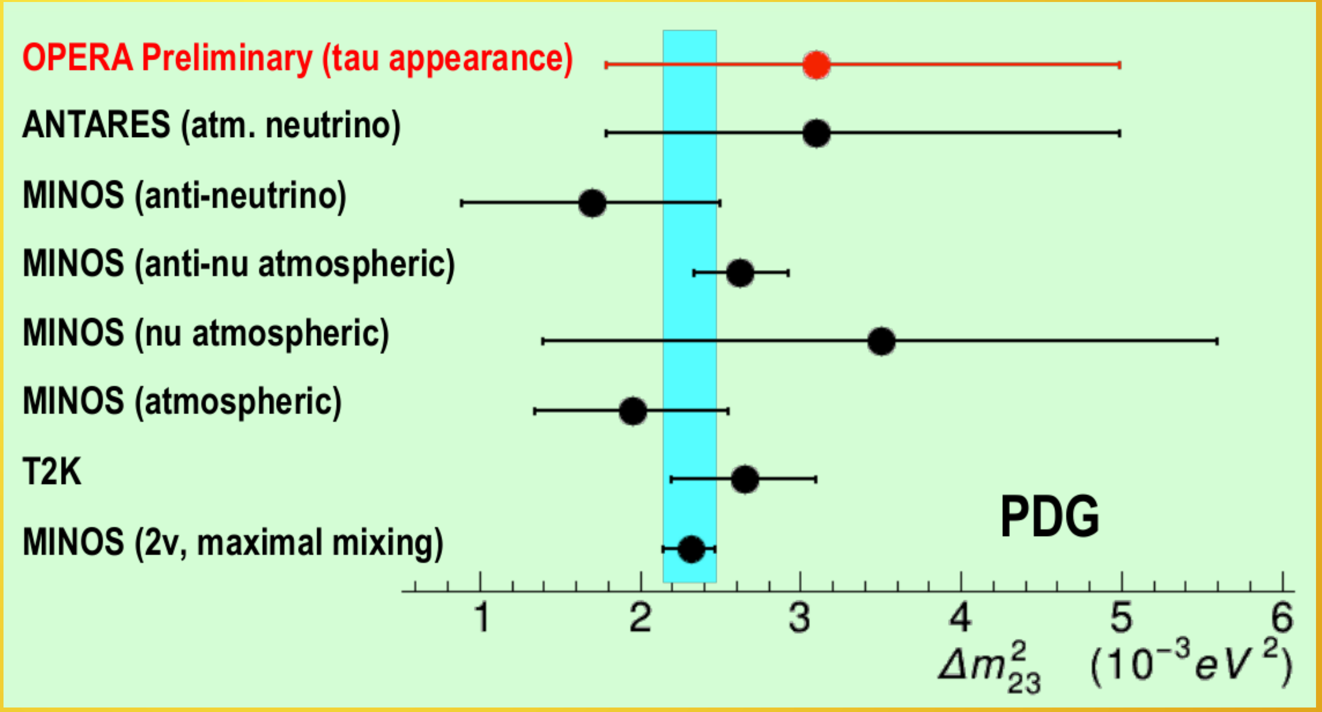
Feldman & Cousins

$\Delta m^2_{32}$ = [1.8, 5] x $10^{-3}$ $eV^2$

Bayesian

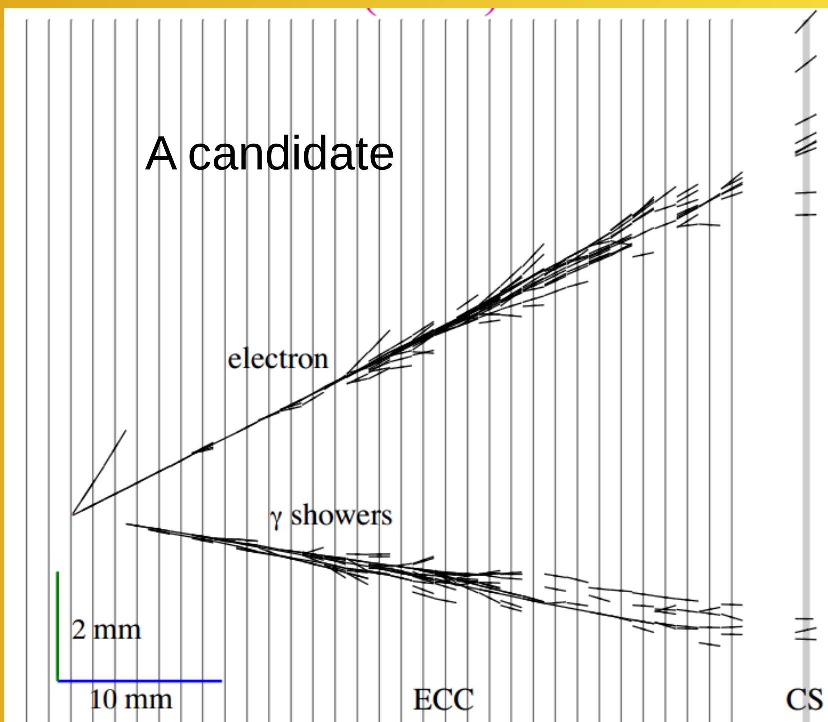
$\Delta m^2_{32}$ = [1.9, 5] x $10^{-3}$ $eV^2$

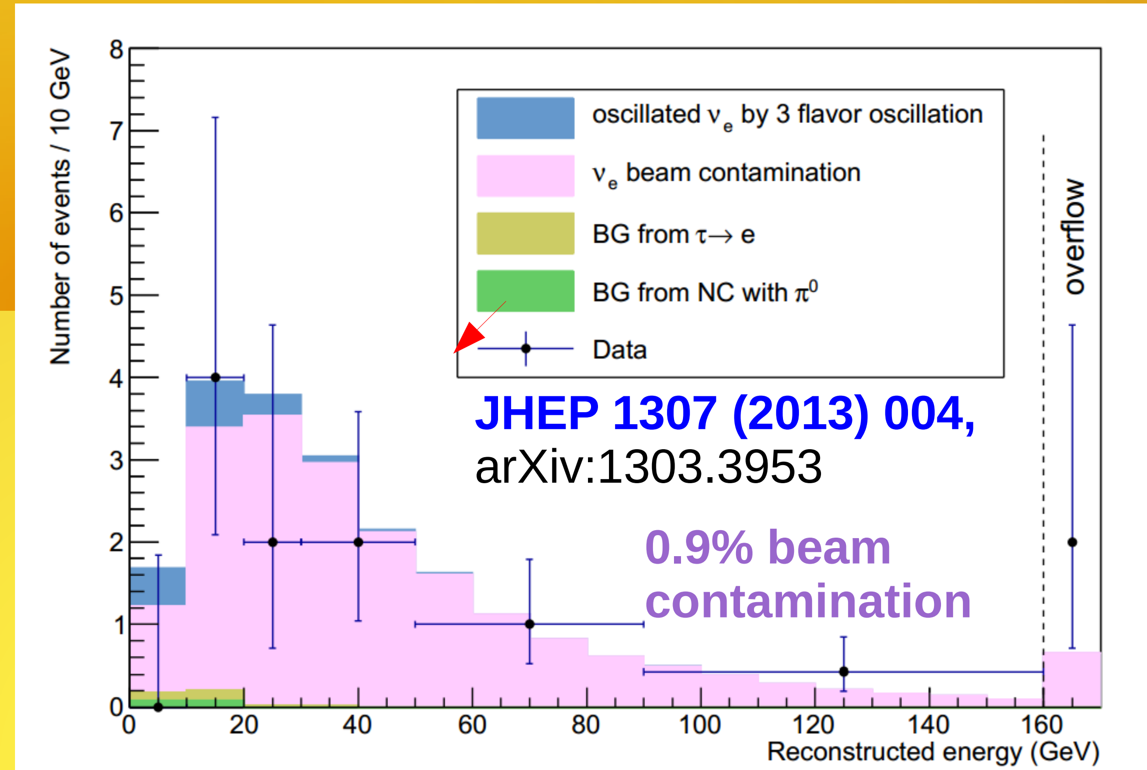
@ 90 % C.L.



# $\nu_\mu \rightarrow \nu_e$

0μ interactions: 505
(~ half of the final sample)

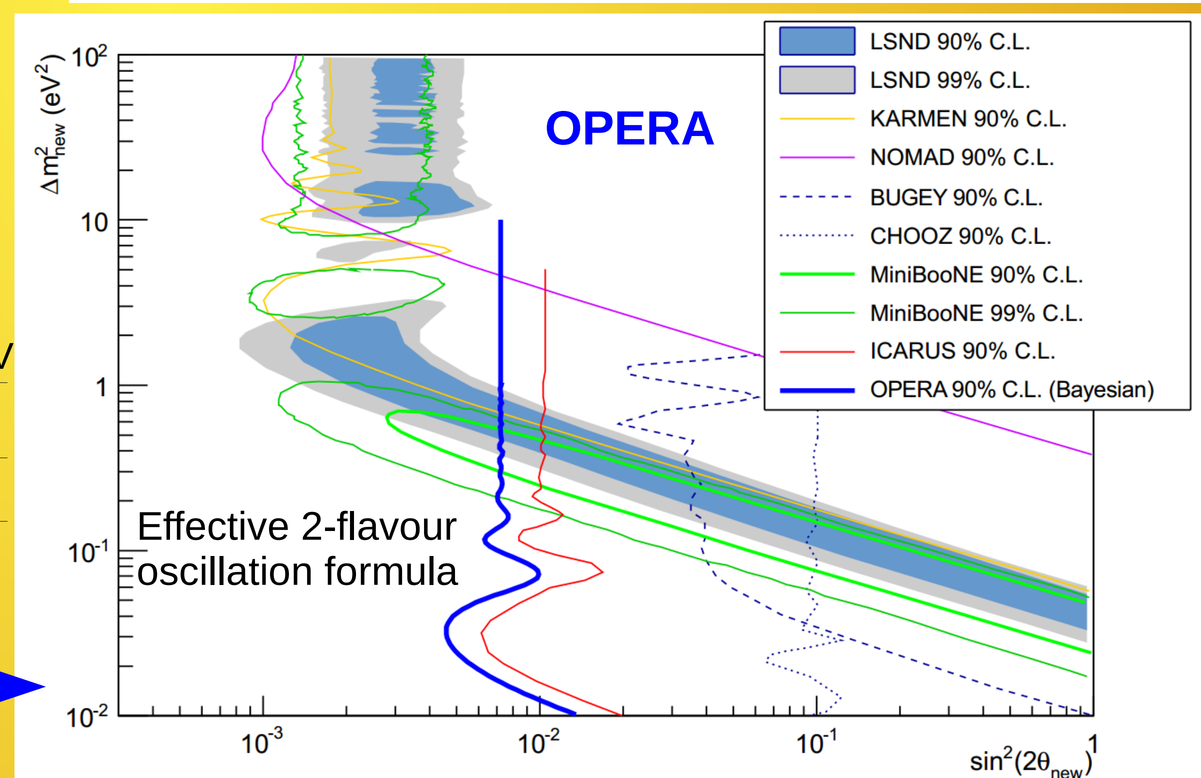



| | | E < 20 GeV |
|---|---|---|
| $\nu_e$ candidates | 19 | 4 |
| Background | 19.8 ± 2.8 (sys.) | 4.6 |

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

**$\sin^2 2\theta_{13} < 0.44$ (90% CL)** →



# $\nu_\mu \rightarrow \nu_\tau$ : effect of a sterile ?

How is the appearance probability is modified by one possible extra (sterile) state (3+1 scheme) ?

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

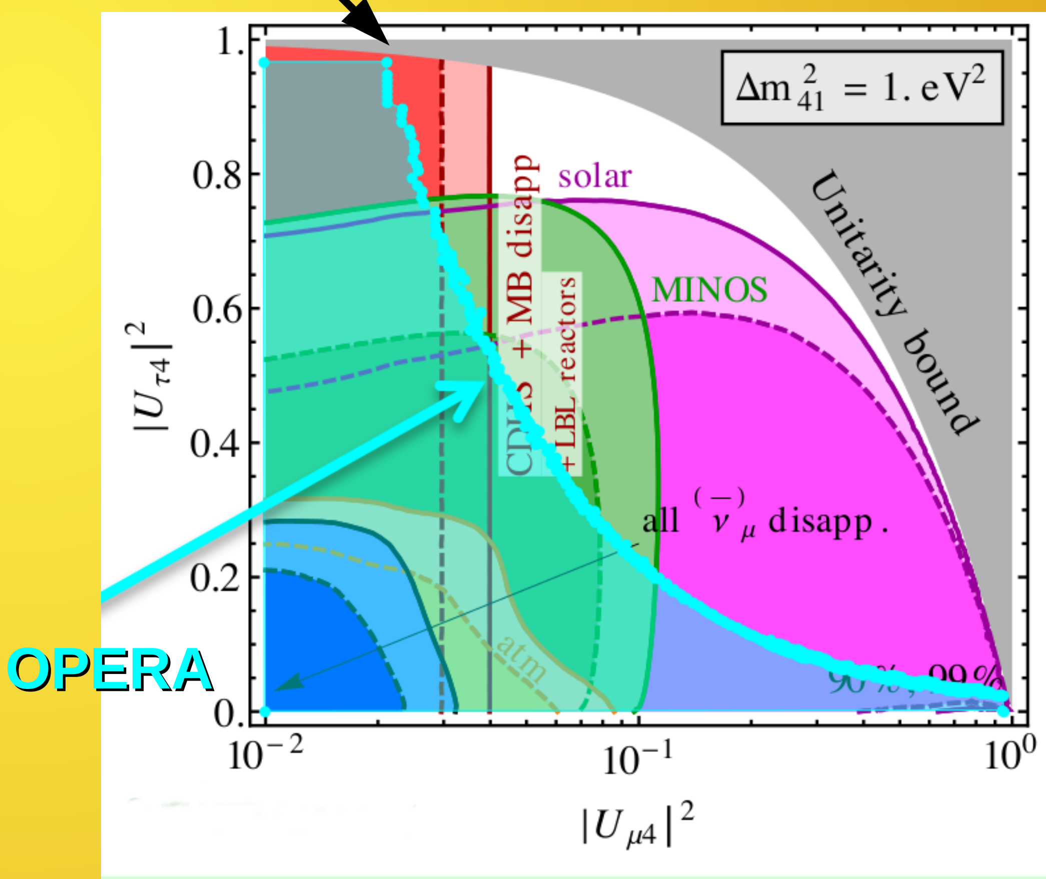
$$+4|U_{\mu 4}|^2|U_{\tau 4}|^2 \sin^2\frac{\Delta_{41}}{2}$$

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

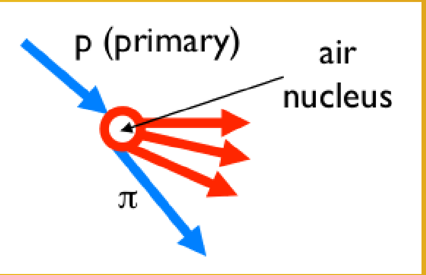
$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{2E}$$

Interference term

- Rich structure. Can result in an increase or decrease of expected number of $\nu_\tau$ events.
- Profile likelohood using $\nu_\tau$ rate only.
- Results in the $|U_{\tau 4}|^2$ - $|U_{\mu 4}|^2$ plane show complementarity with disappearance experiments.



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

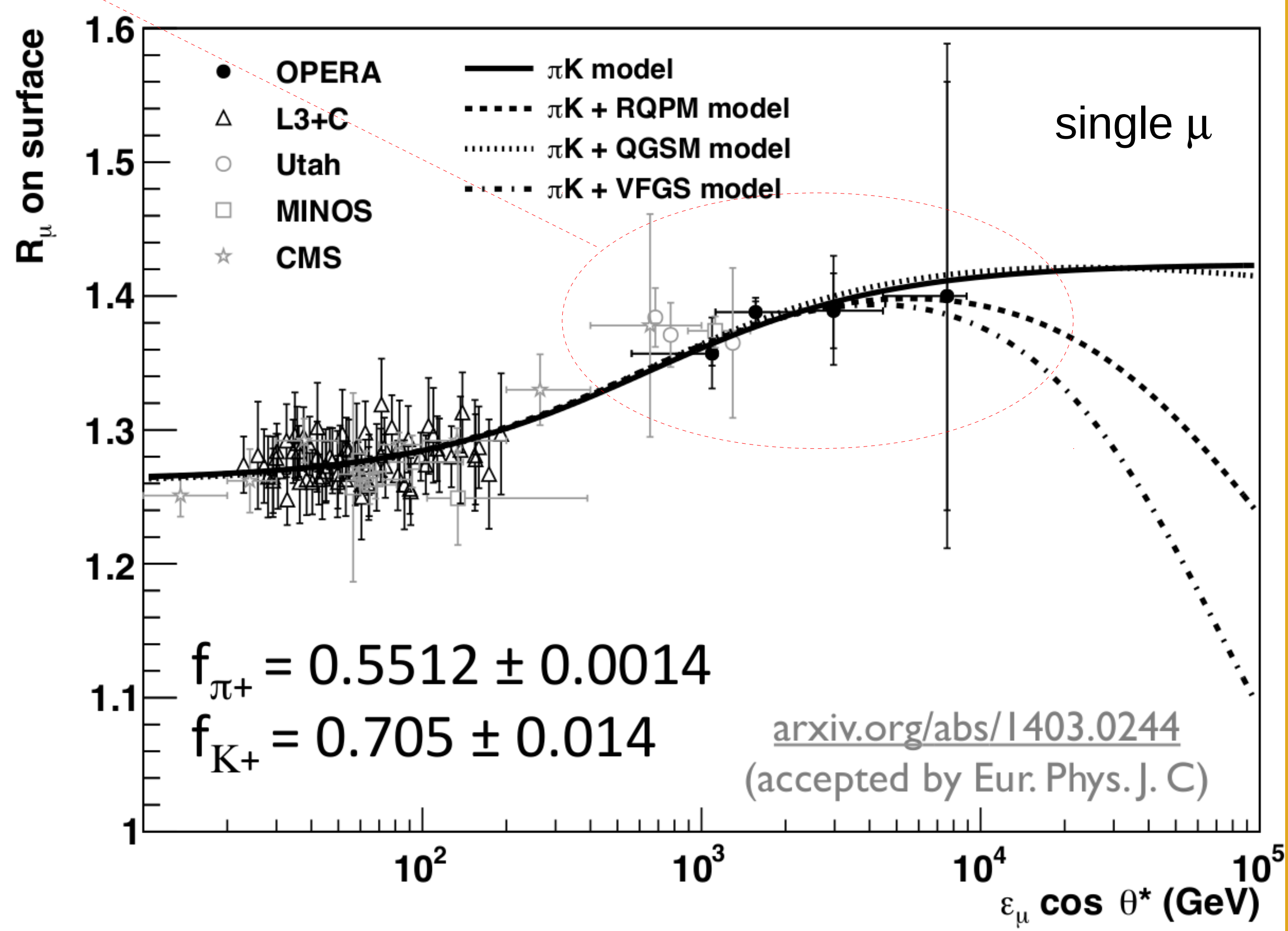



$$\phi_{\mu^\pm} \propto \frac{a_\pi f_{\pi^\pm}}{1 + b_\pi \mathcal{E}_\mu \cos\theta/\epsilon_\pi} + R_{K\pi}\frac{a_K f_{K^\pm}}{1 + b_K \mathcal{E}_\mu \cos\theta/\epsilon_K}$$

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

| | |
|---|---|
| 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)




$f_{\pi+} = 0.5512 \pm 0.0014$

$f_{K+} = 0.705 \pm 0.014$

arxiv.org/abs/1403.0244

(accepted by Eur. Phys. J. C)

# Conclusions

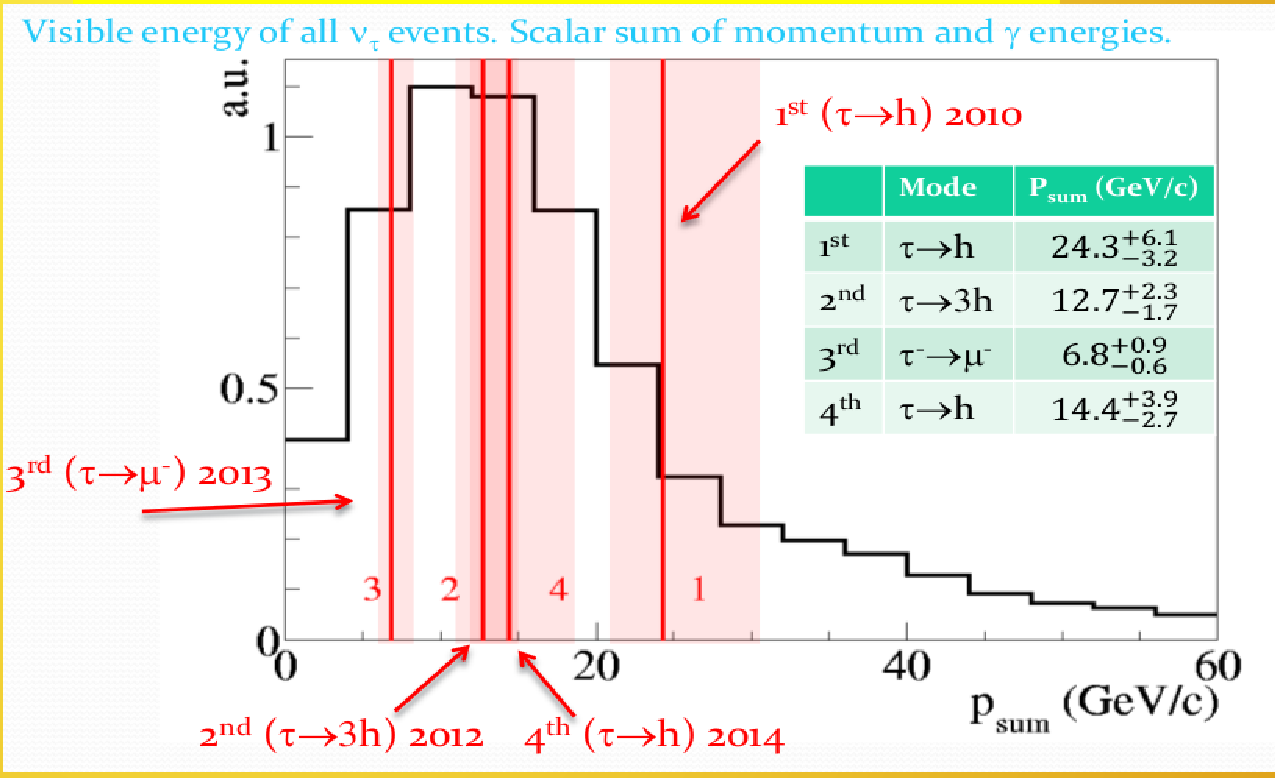
- $1.8 \times 10^{20}$ pot by CNGS from 2008-12 (80% of design)
- 4 $\nu_\tau$ candidates so far with a 0.23 event background
- No oscillation hypothesis excluded at **4.2 σ**

**Observation of $\nu_\tau$ appearance !**

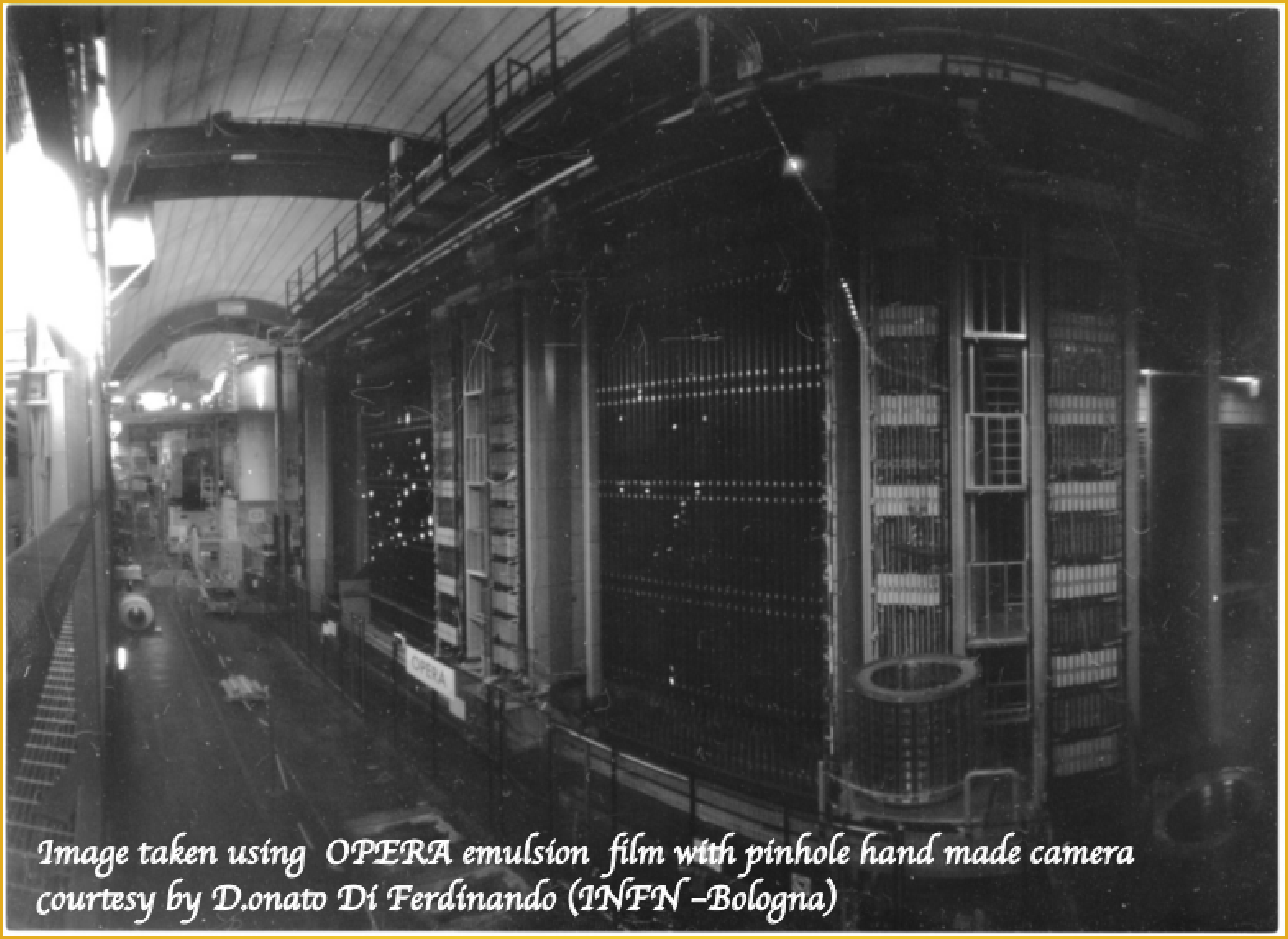
$\Delta m^2_{31}$ = [1.8, 5.0] x $10^{-3}$ eV$^2$ (90% CL)

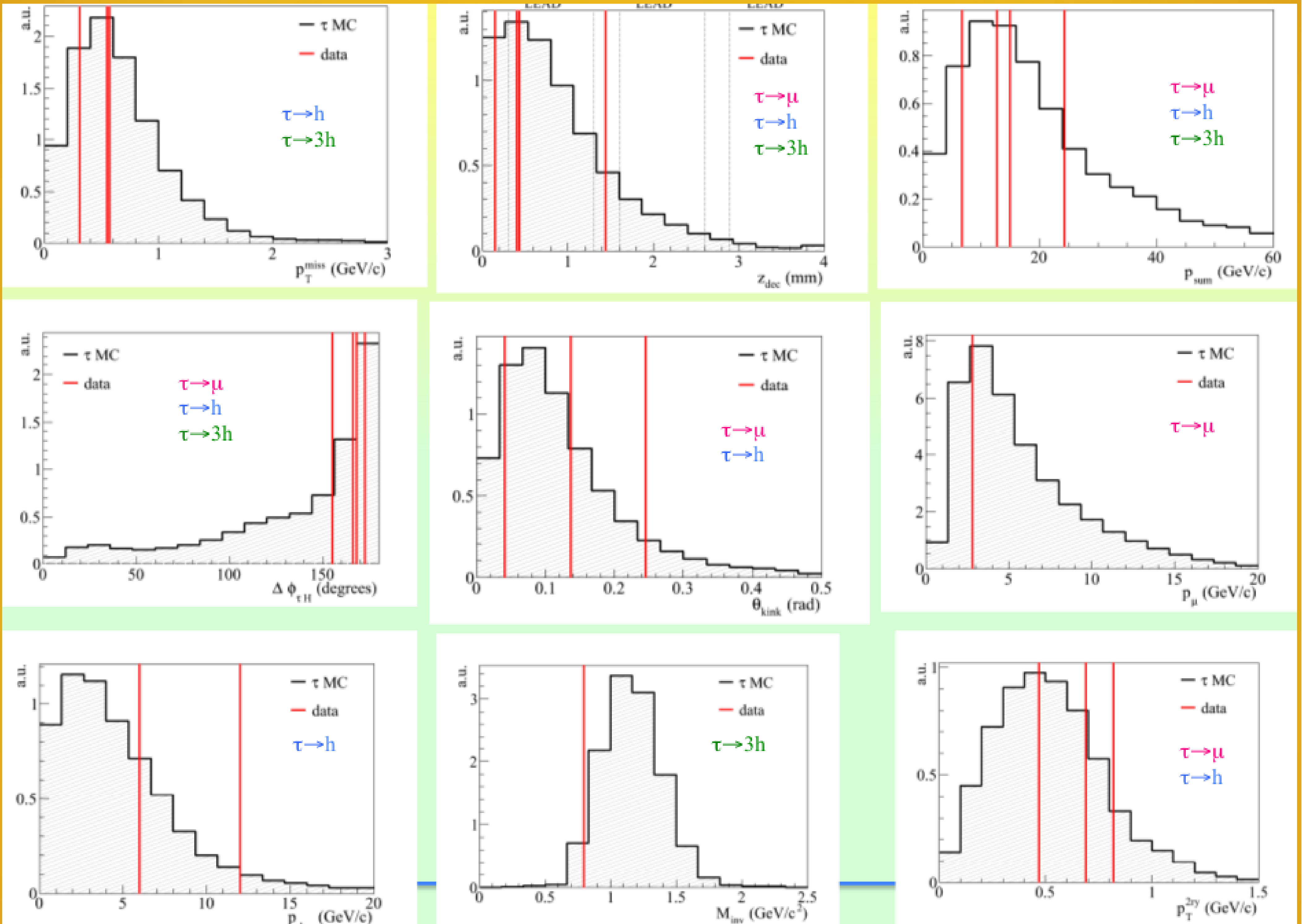
- Search for anomalies in $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ at a peculiar L/E. First limits on $|U_{\mu 4}|^2|U_{\tau 4}|^2$ from direct measurement of $\nu_\tau$

- Interesting cosmic ray physics results (muon charge ratio)

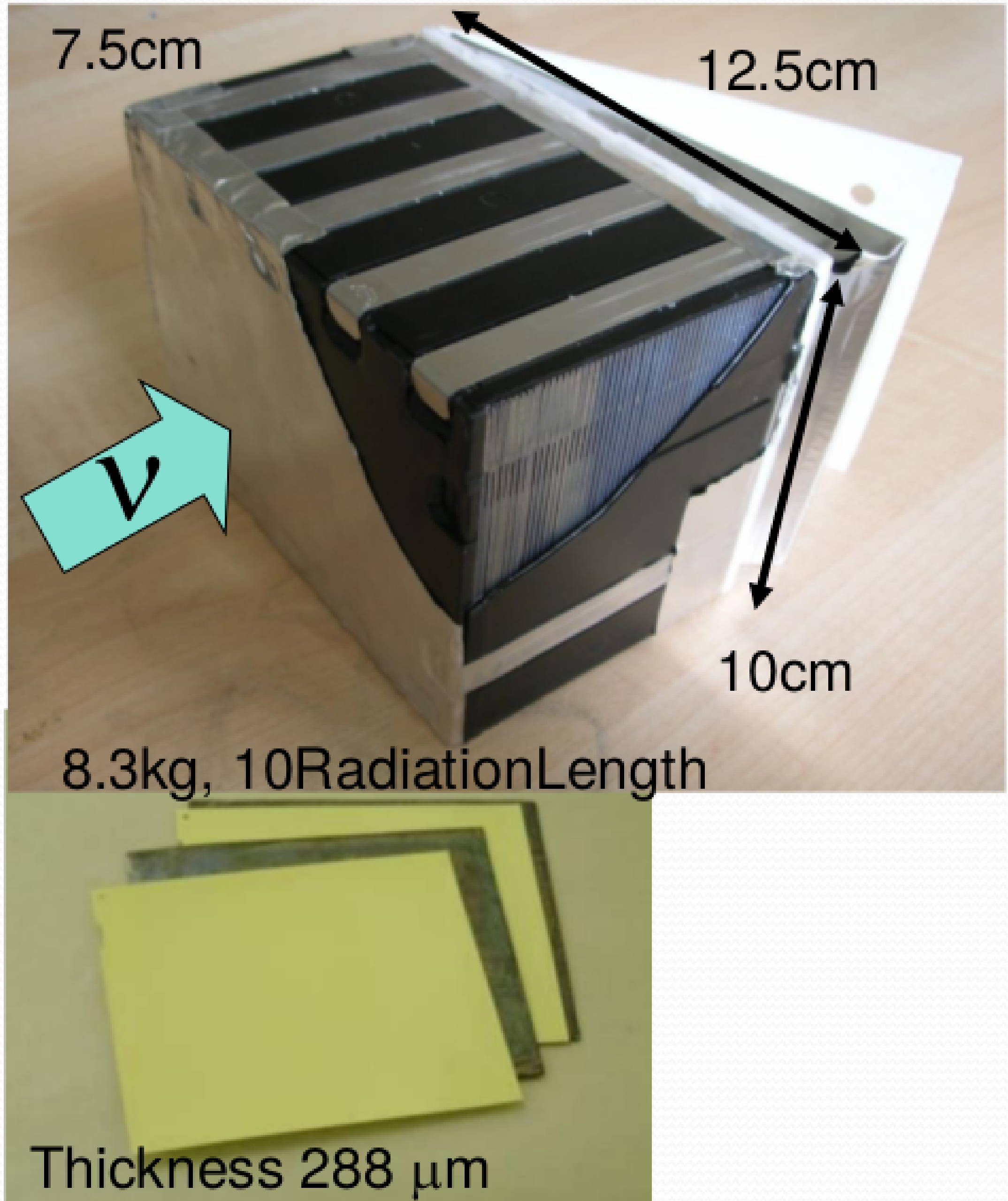


# OPERA taking a "selfie"... Thank you!




τ MC
data
τ→h
τ→3h
(GeV/c)
τ→μ
z (mm)
p (GeV/c)
Δ φ (degrees)
θ (rad)
(GeV/c)
M (GeV/c²)
a.u.

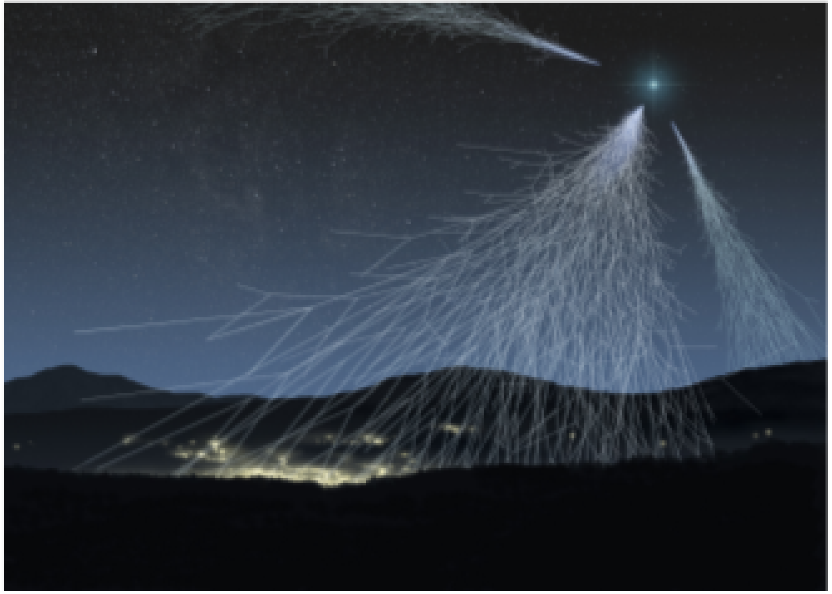
# The ECC




- ECC properties
  - 56 of 1mm thick lead plates interleaved with 57 emulsion films.
  - 8.3kg / brick
  - 10 radiation length
- 150,000 ECC bricks
  - 1.25 ktons
  - 9 million films
- Capability
  - Micrometric accuracy vertex analysis
  - Kinematical analysis
    - Momentum measurement by MCS.
    - EM energy measurement

# The atmospheric muon charge ratio

- The atmospheric muon charge ratio $R_\mu \equiv N_{\mu+}/N_{\mu-}$ is being studied and measured since many decades
  - Depends on the **chemical composition** and energy spectrum of the primary cosmic rays
  - Depends on the **hadronic interaction features**
  - At high energy, depends on the **prompt component**
- Possibility to check HE hadronic interaction models (E>1TeV) in the fragmentation region (phase space complementary to collider's one)
- Atmospheric muons are kinematically related to atmospheric neutrinos (same sources) → $R_\mu$ provides a benchmark for atmospheric ν flux computations (e.g. background for neutrino telescopes)



5 July 2014 N. Mauri, ICHEP 2014 2