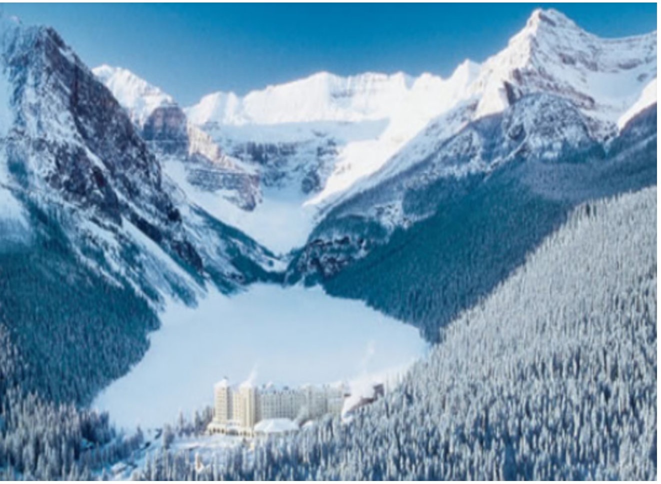


Winter Institute 2016,
Lake Louise, 7-14 Feb 2016

A. Longhin, INFN Frascati

On behalf of the OPERA Collaboration

Latest results from OPERA

- $\nu_\mu \rightarrow \nu_\tau$ appearance
- Sterile ν searches

The long way to appearance

- **Disappearance** a “leading” effect: deficit of atmospheric ν_μ →
  - 1998 discovery of ν-oscillations by Super-K, MACRO, K2K ...
- **Appearance** on the other hand:

• At the **solar scale**. Reactors and solar ν.

$\nu_e \rightarrow \nu_\mu$ "IMPOSSIBLE": μ is below threshold

• At the **atmospheric scale**. Atmospheric-ν, artificial beams.

$\nu_\mu \rightarrow \nu_e$ "RARE"

θ_{13} suppression ?

$\nu_\mu \rightarrow \nu_\tau$ “DIFFICULT” !

mass suppression, small cτ

Today's perspective

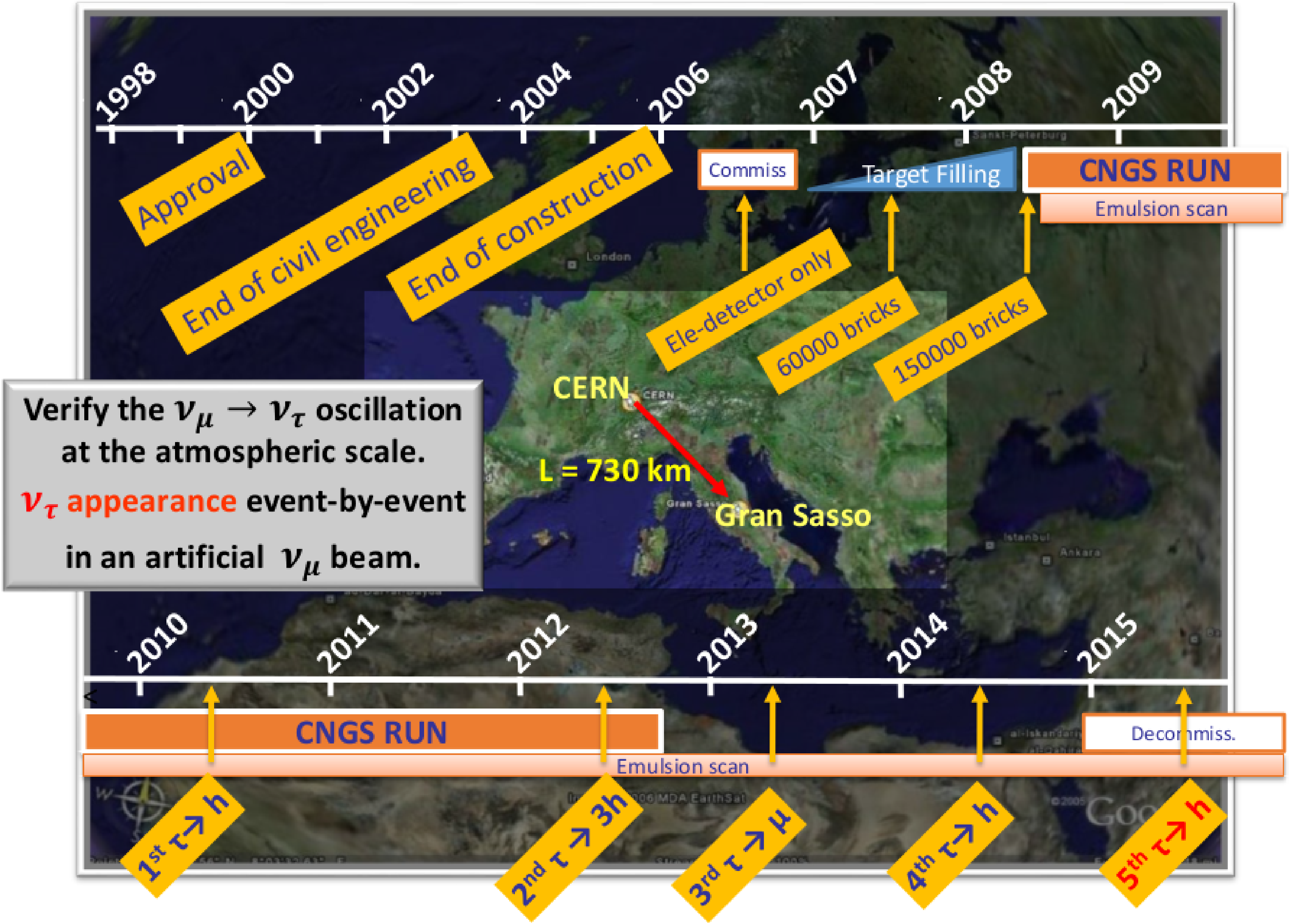
- Reactors: **no... θ_{13} is BIG !**
- Appearance seen by **T2K** and **NOνA** (with few POT)

Confirmed difficult, but event-by-event detection achieved by **OPERA** & **SK** (with a much lower S/B)

The OPERA road map

An experimental and technological challenge:

- **Beam:** O(10) more energetic (17 GeV) than any other LBL (m_τ). 732 km baseline
- **Detector:** "fine-grained" O(100) more massive (1.25 kt) than SBL precursors (CHORUS)



The CNGS beam for $\nu_\mu \to \nu_\tau$

$< E_\nu >$	*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

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

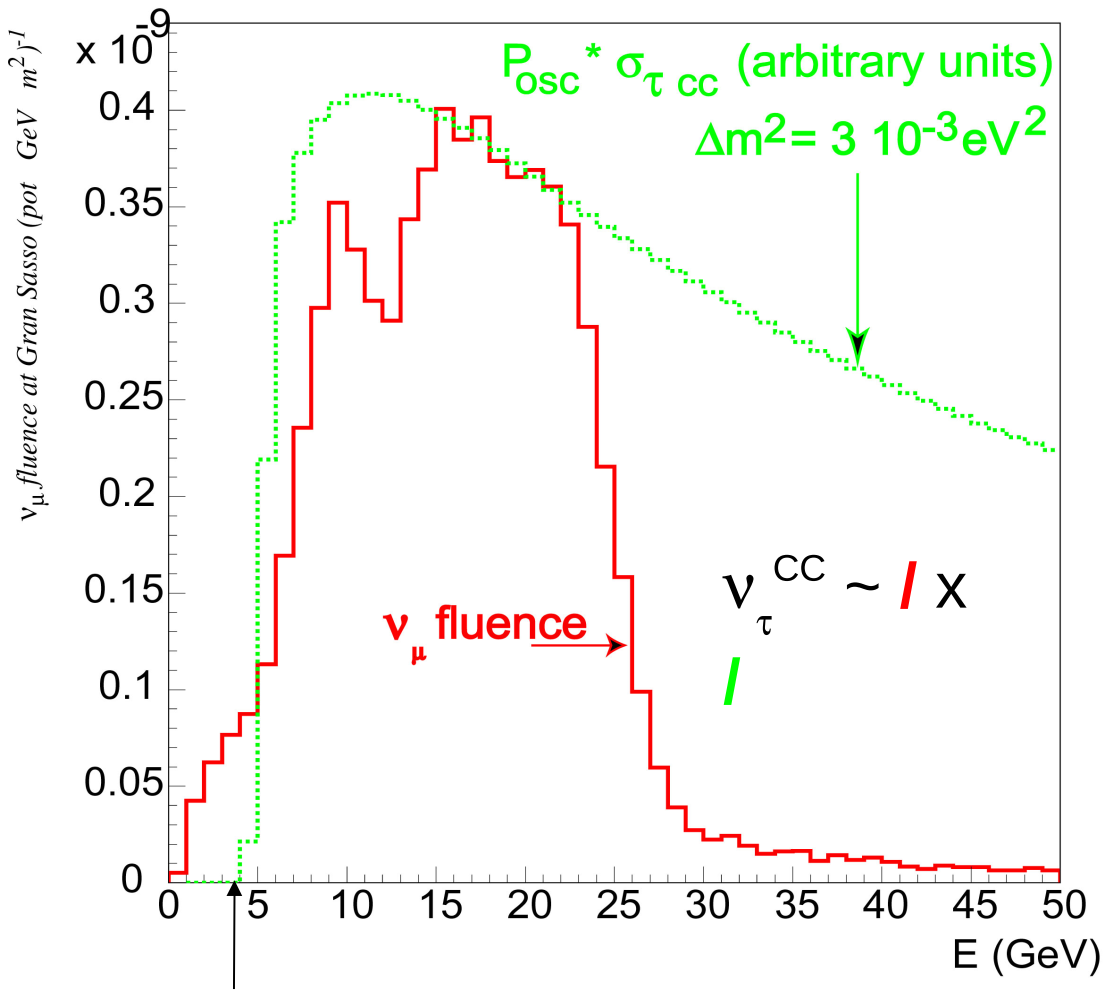
Fluxes:

$(\nu_e + \bar{\nu}_e) / \nu_\mu$	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)

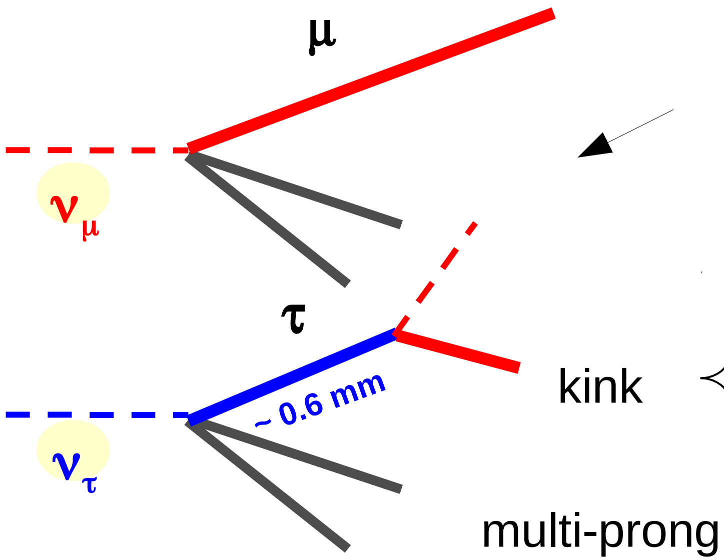
DESIGN: $4.5 \cdot 10^{19}$ pot/year, 200 days/y per 5 y



Threshold for τ at ~ 3.5 GeV.

Slow rise.

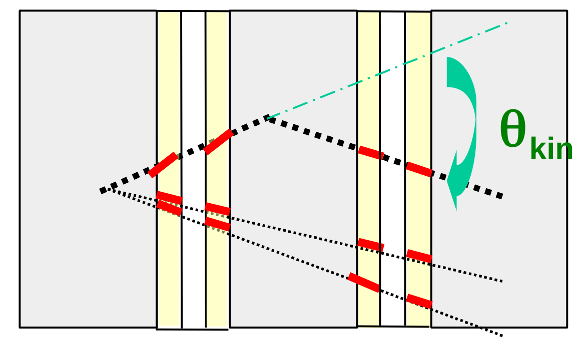
The ν_τ detection challenge



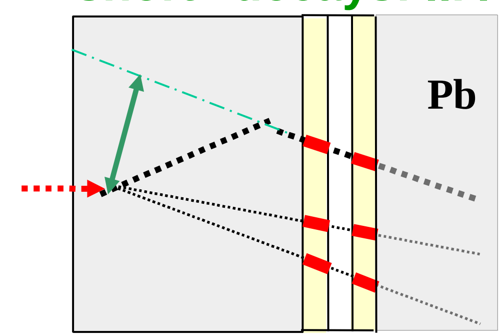
Detect a few ν_τ^{CC} from the bulk of ν_μ^{CC}

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



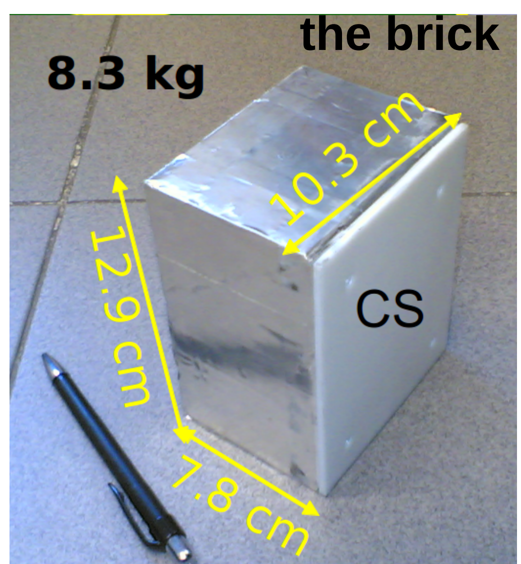
"short" decays: I.P.

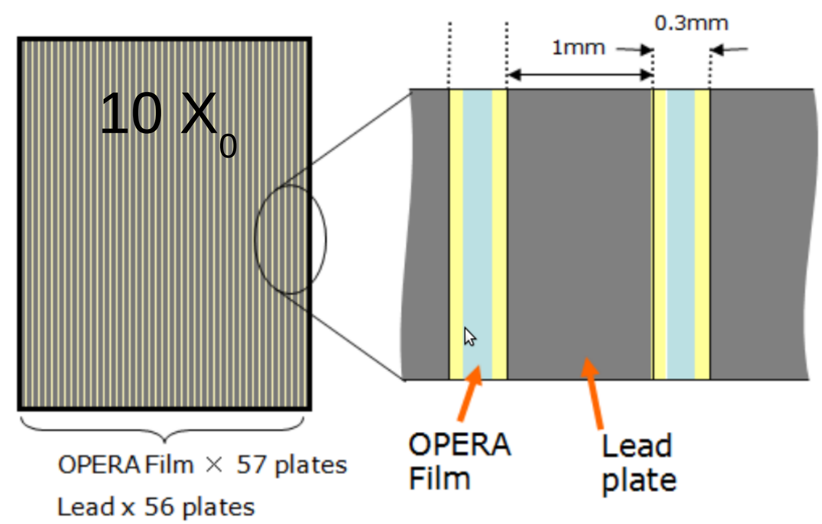


Modular detector of "Emulsion Cloud Chambers" (or bricks)

Reconciles the need for:

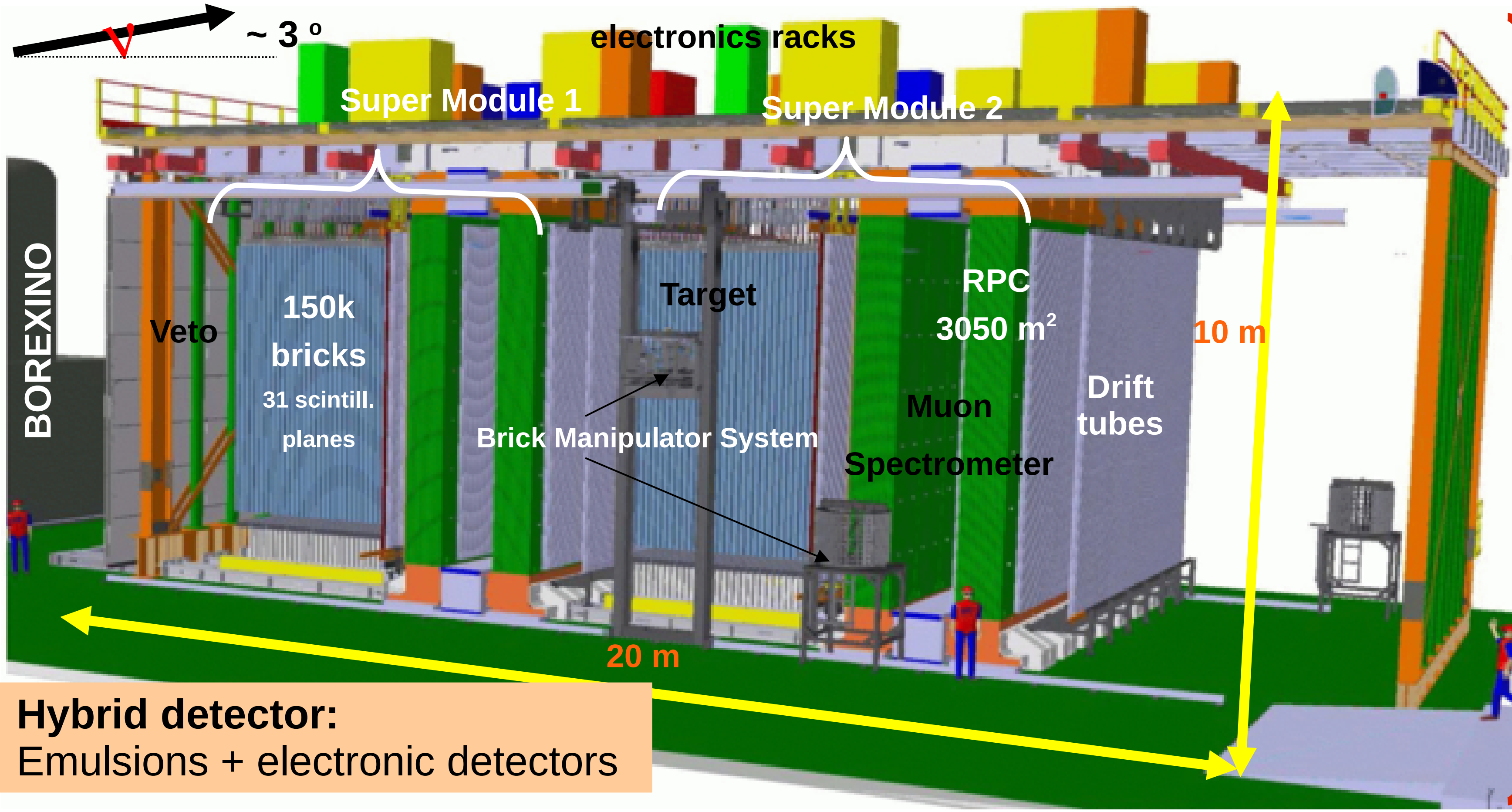
- **Large mass**
  - $N_\tau \propto (\Delta m^2)^2 M_{target}$
- **Extreme granularity**
  - ~ μm



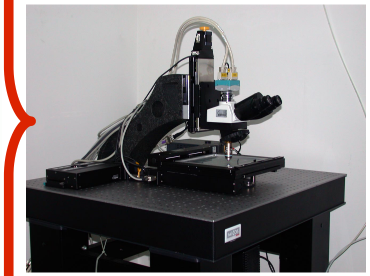


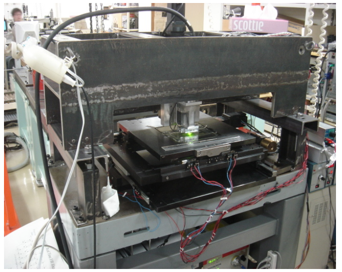
The OPERA detector

O(µm) resolution over O(100m³) !!!

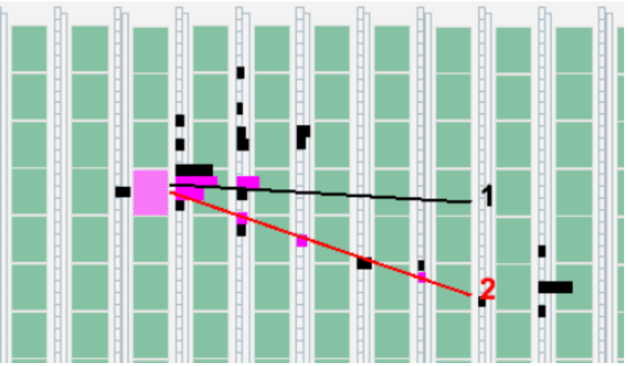


Hybrid detector:
Emulsions + electronic detectors



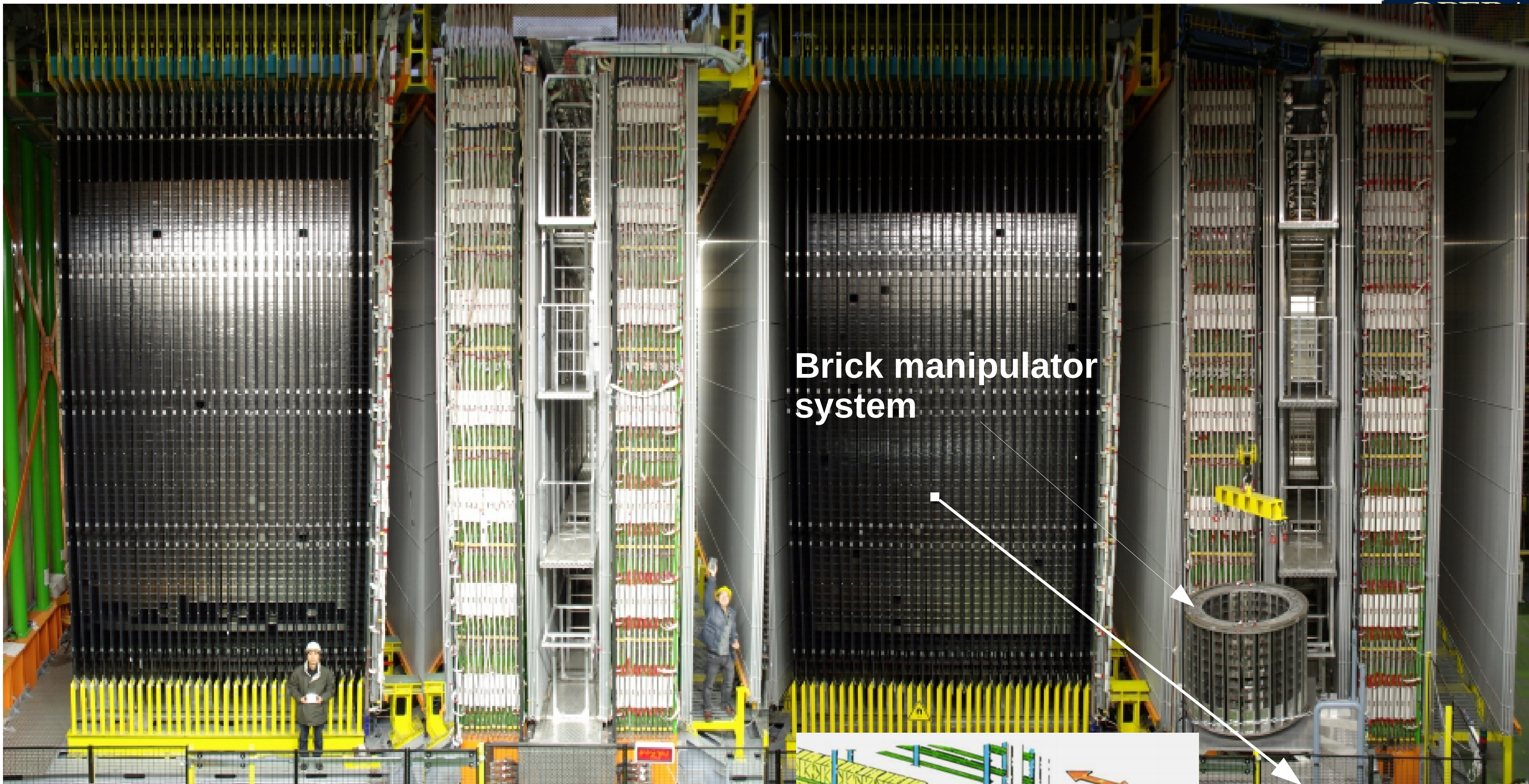


``Brick-finding''

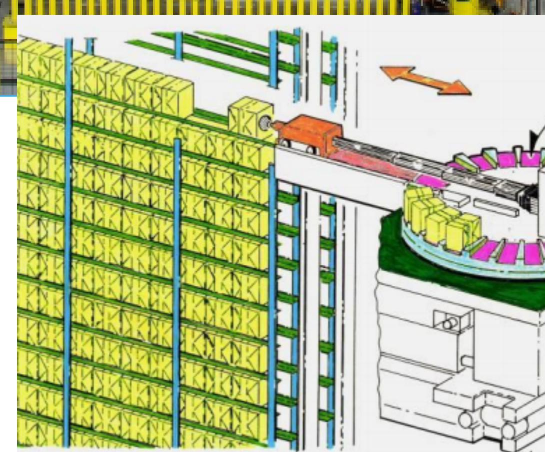


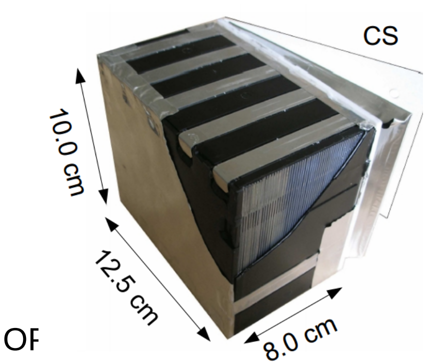
+ several ancillary facilities "off-site":

- Emulsions "refreshing" — JP & Gran Sasso
- Assembly/disassembly of bricks — Gran Sasso
- Labelling and X ray marking — Gran Sasso
- Automatised development — Gran Sasso
- Scanning of CS doublets — Gran Sasso
- Scanning of bricks — EU & JP

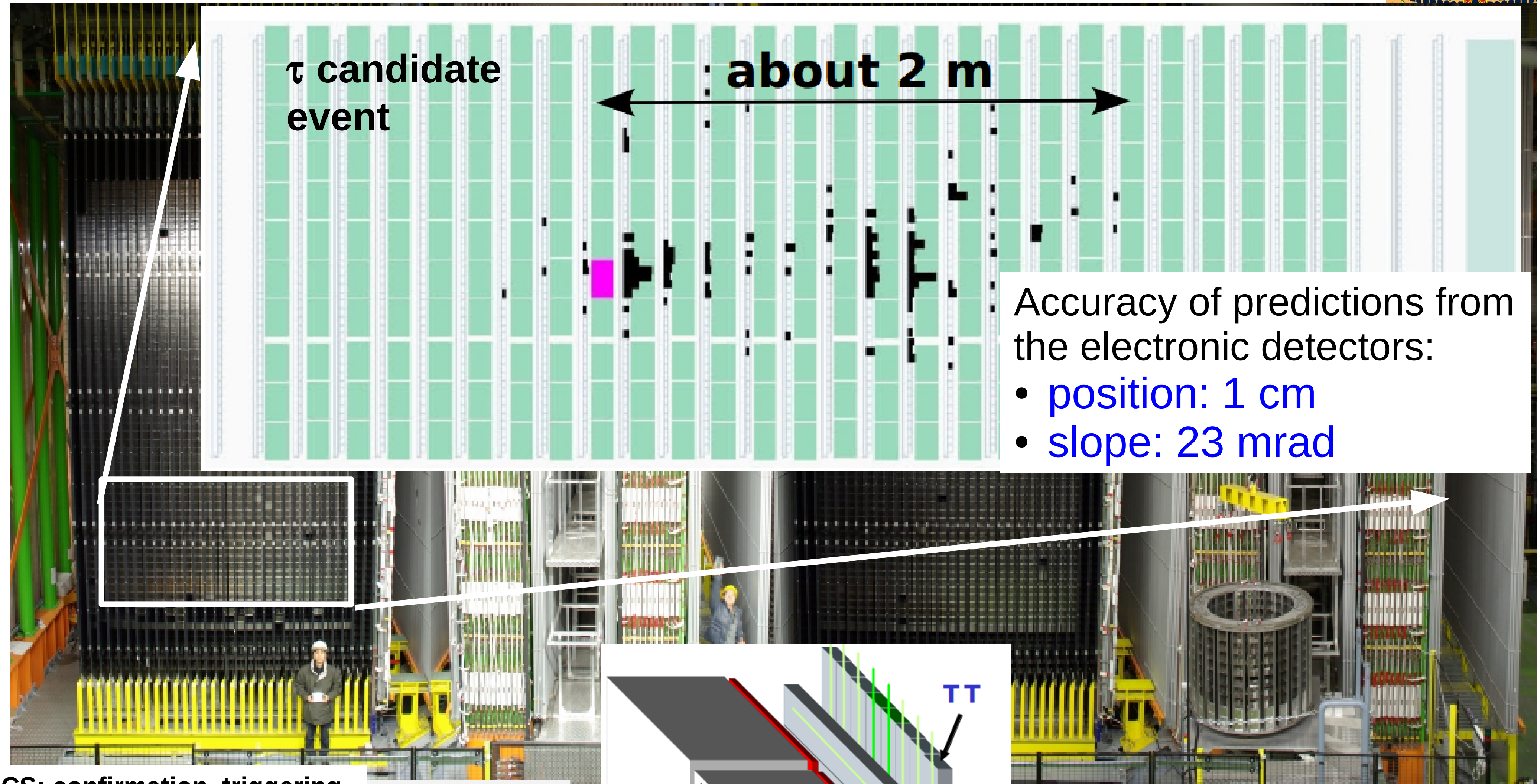


~ 150.000 bricks in total.
1.25 kt mass



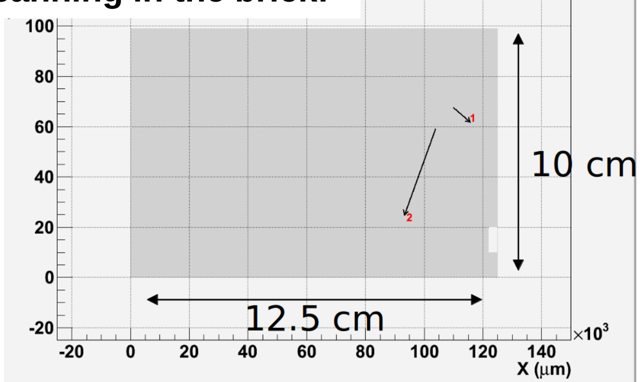


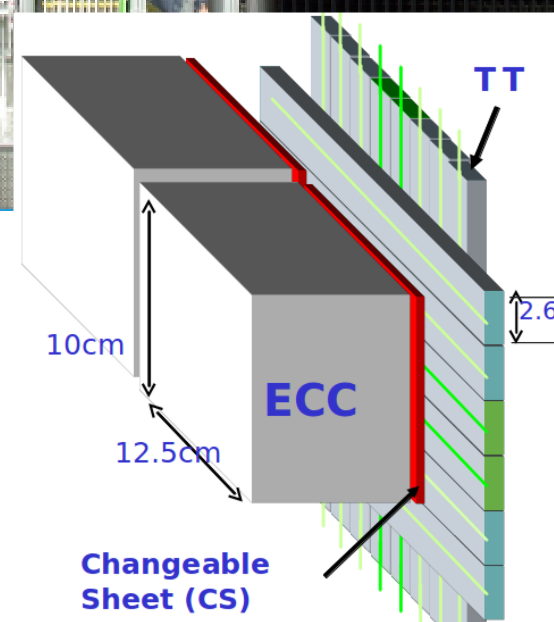
Super Module 1 — Super Module 2



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 %

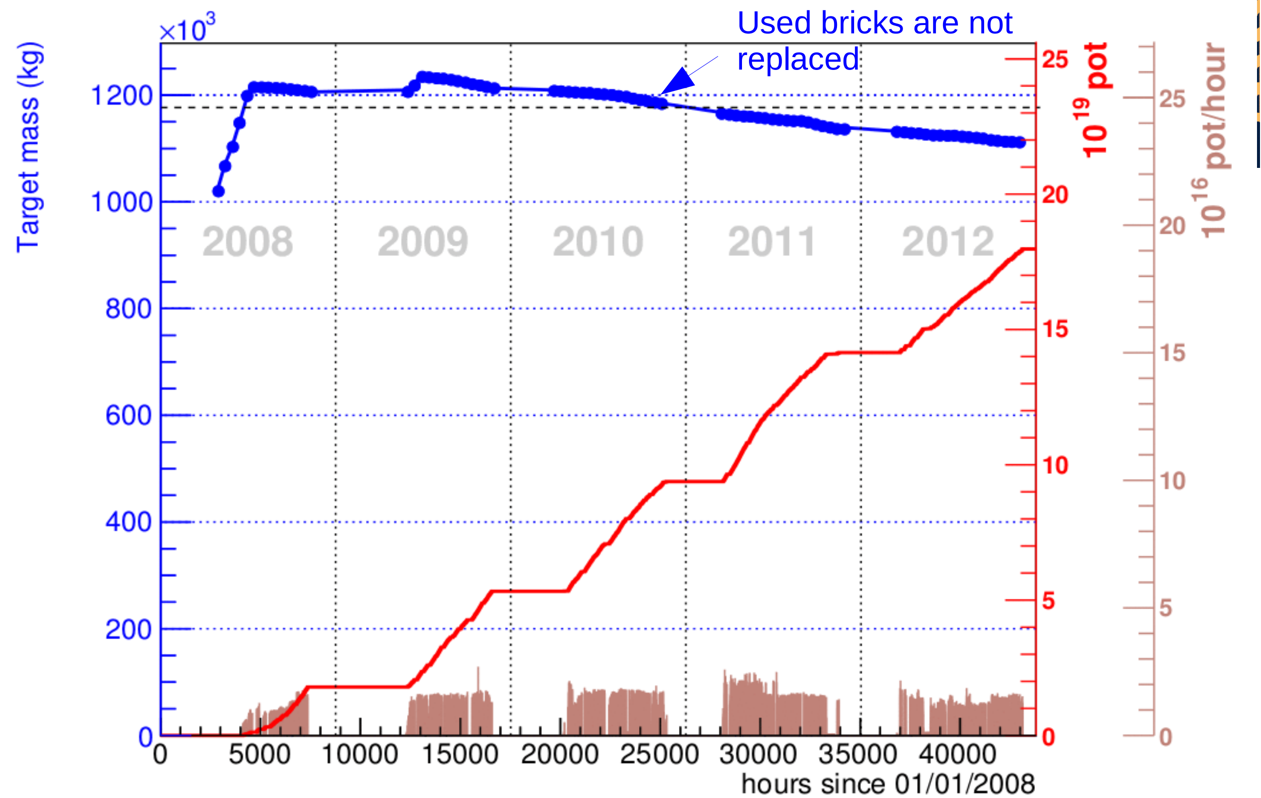
Collected samples

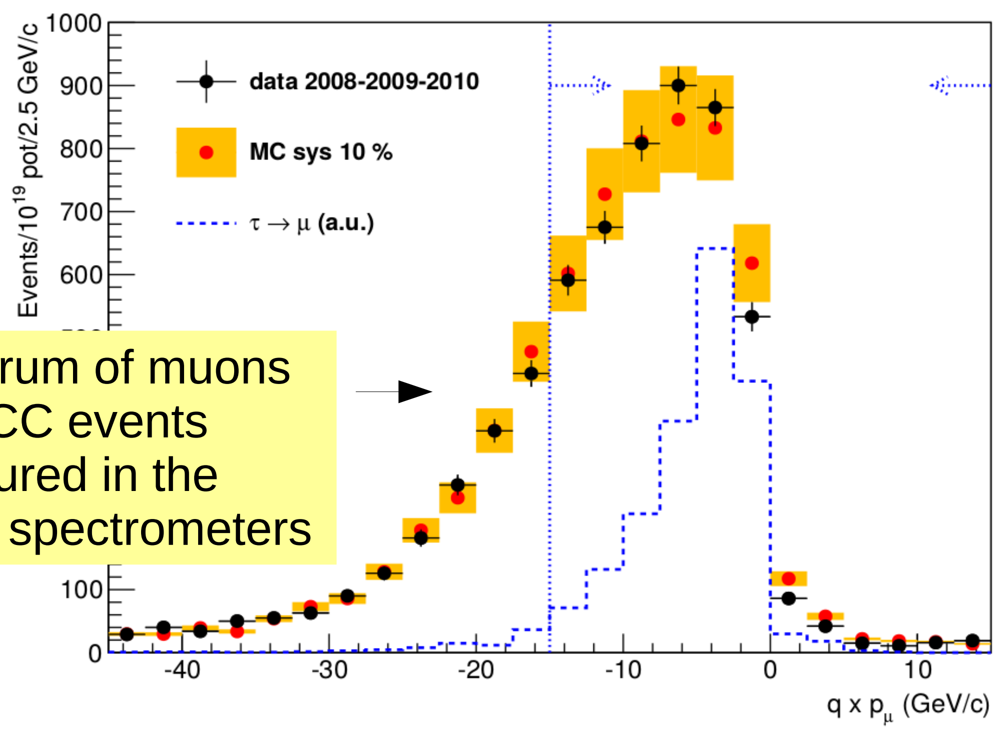
The 5 year long CNGS run has ended in 2012.

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**

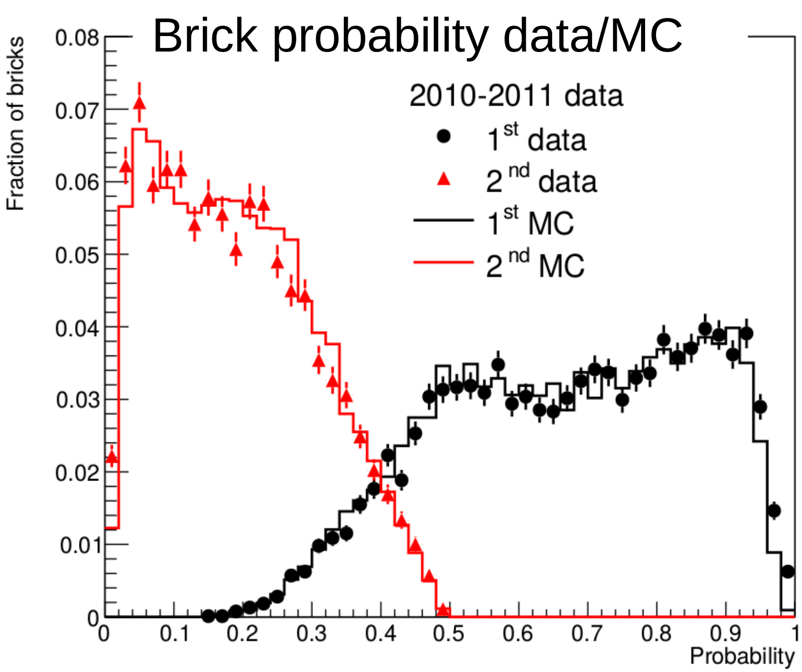


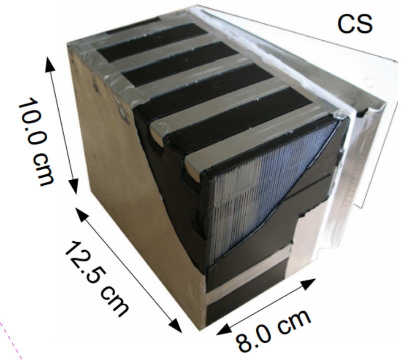


Spectrum of muons from CC events measured in the muon spectrometers

Progress in the analysis of the emulsion films

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

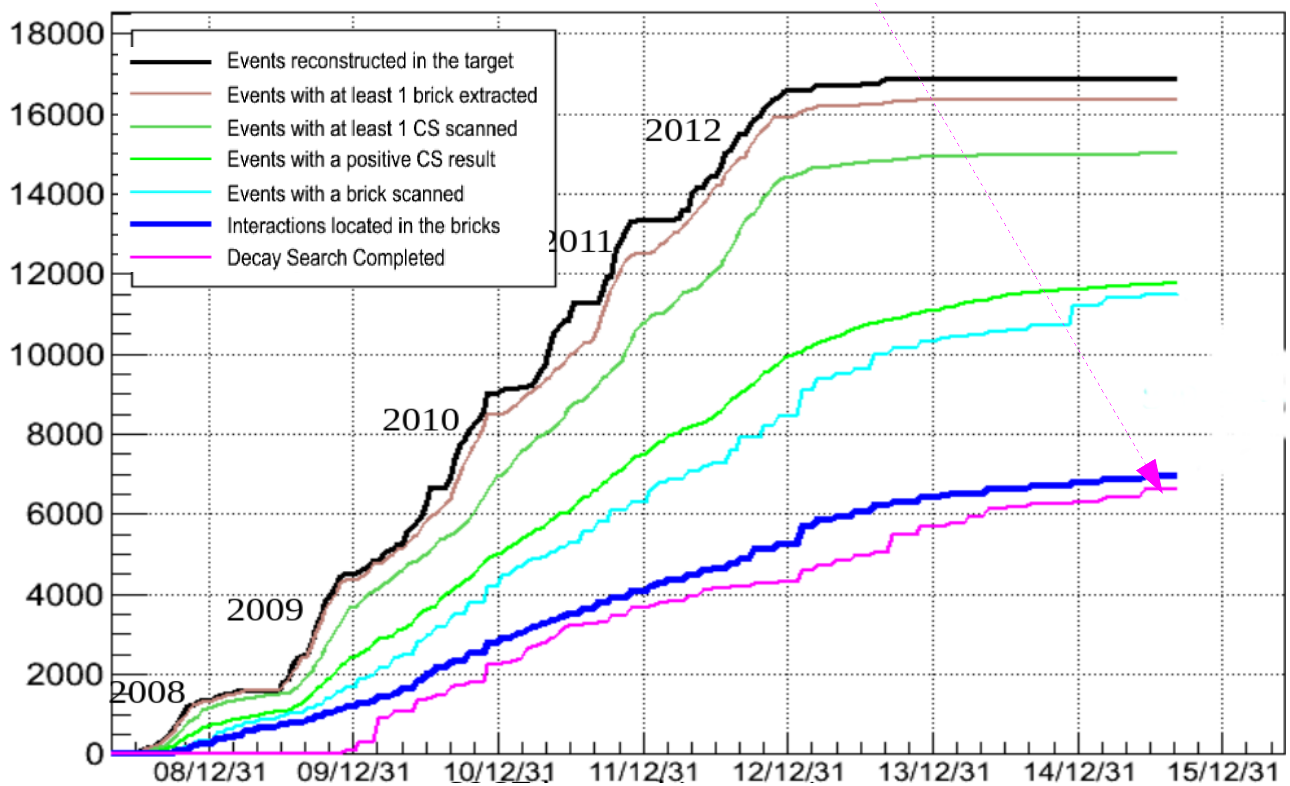


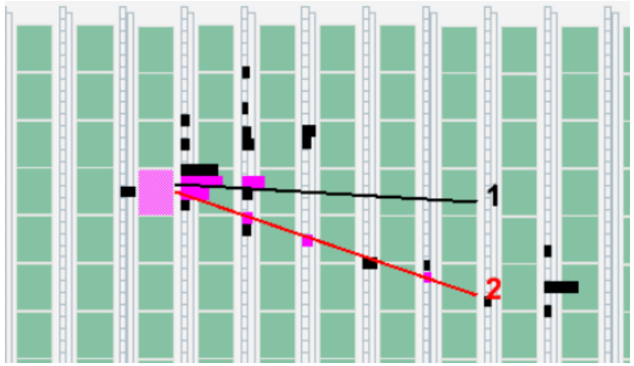


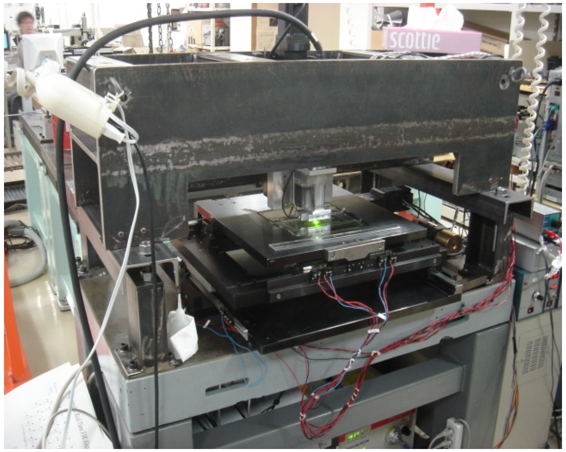
Analysis status:

- 2008-2009 completed up to 4th brick
- 2010-2012 completed up to 2nd bricks

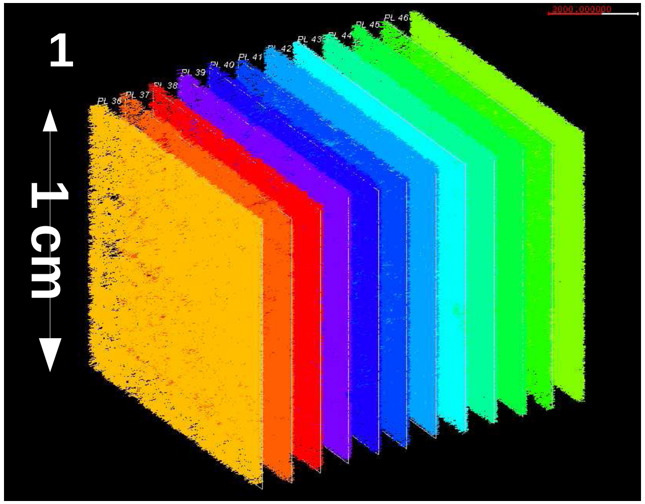
> 6600 fully analysed bricks

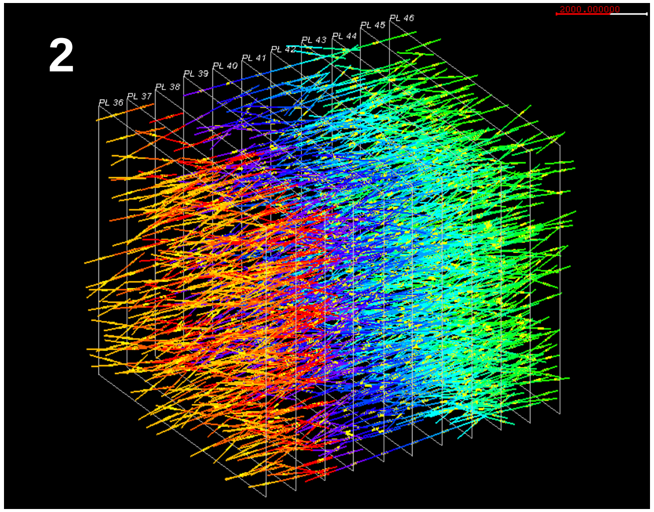


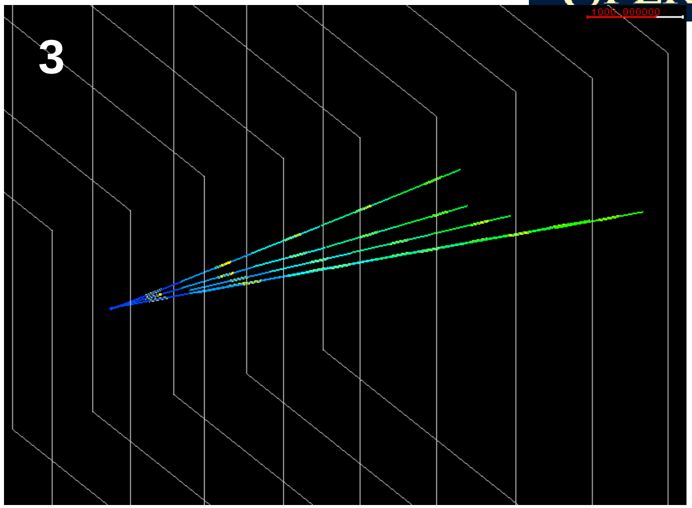




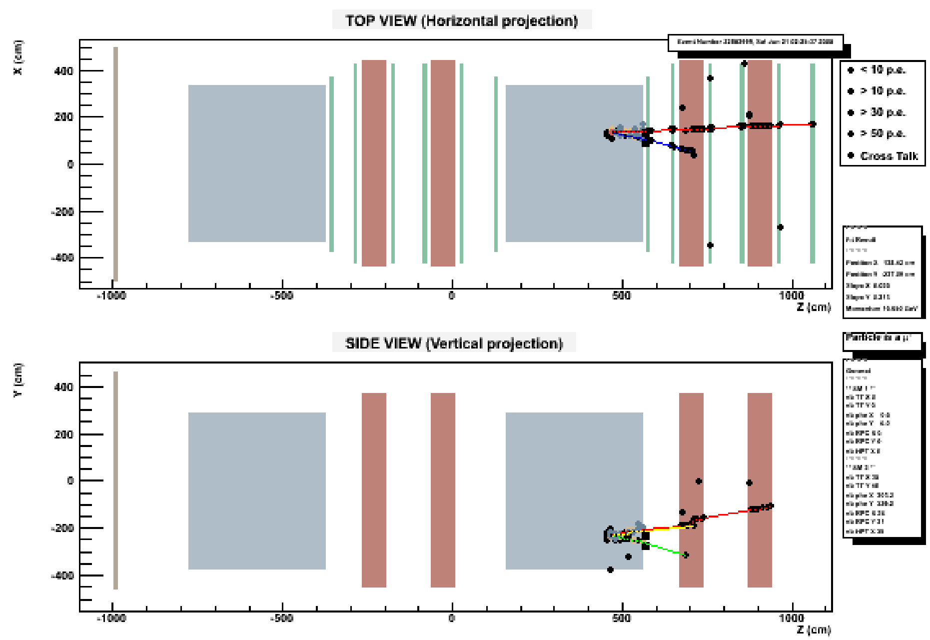
Vertex hunting in the brick



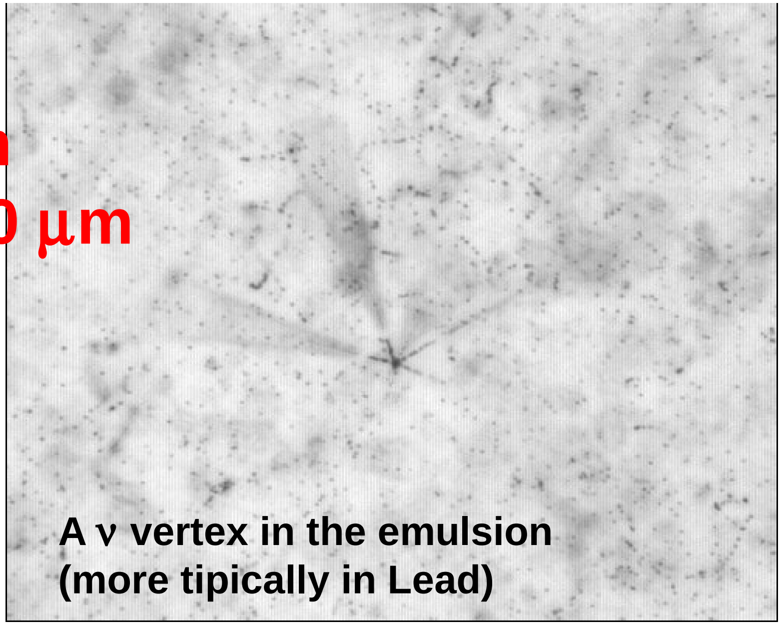




0) tracks tagged in the **CS films** are **followed upstream** until a **stopping point** is found
1) base-tracks in the 12 films of the a **volume centered in the stopping point** are reconstructed
2) cosmic ray tracks (from a dedicated exposure) are used for the fine **alignment** of films
3) passing-through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

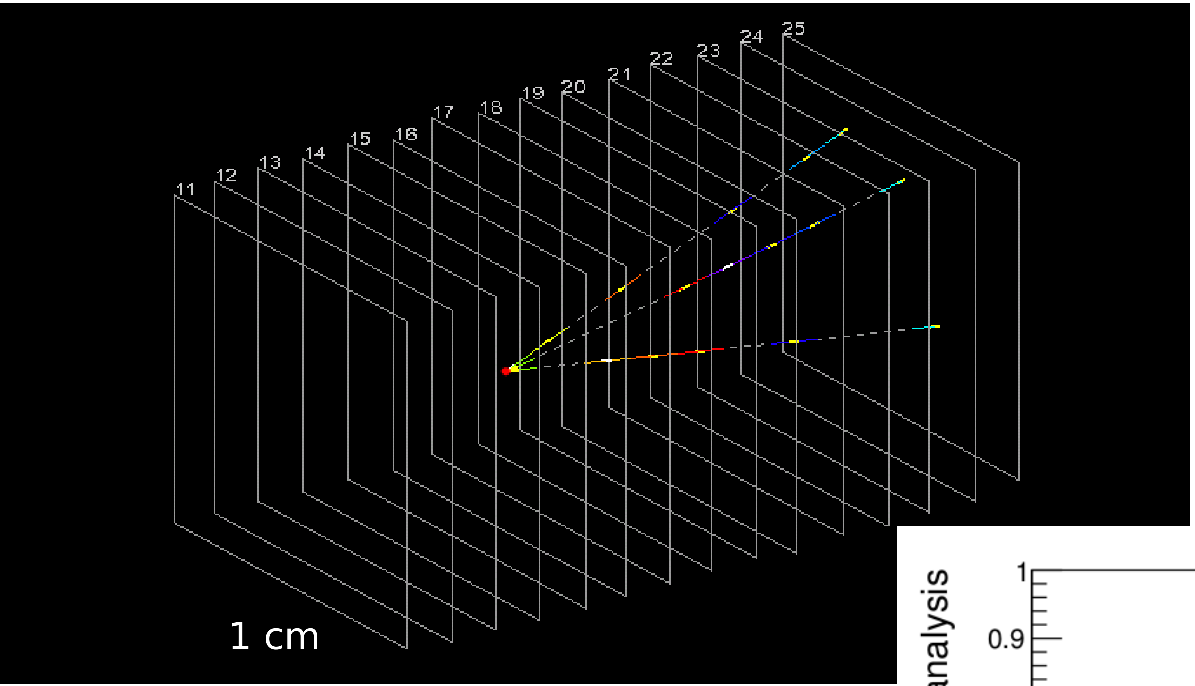


Leap from 20 m → 100 μm
(essential role of CS films)



Location efficiency

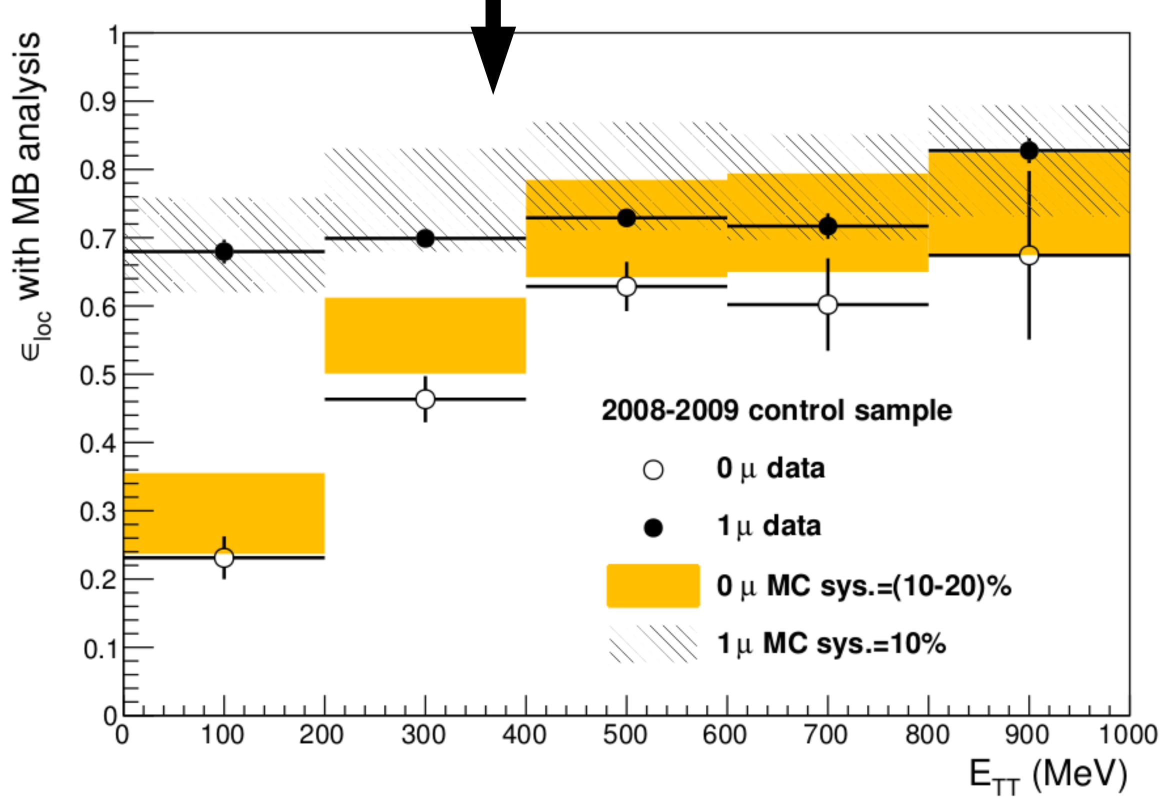
JHEP 11 (2013) 036



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.



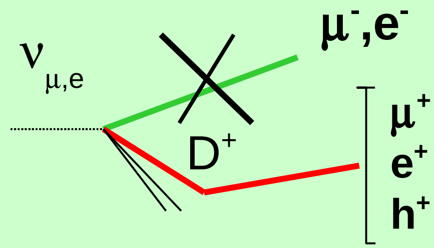
The prediction for the τ signal and backgrounds relies on the efficiencies as measured in real data

$\nu_\mu \rightarrow \nu_\tau$ 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



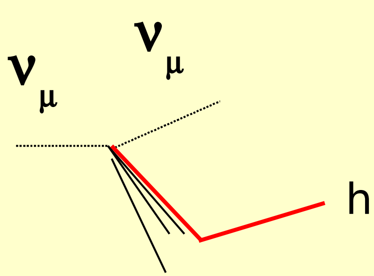
MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

Eur. Phys.J. C74 (2014) 2986

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

Hadronic interactions

Background for $\tau \rightarrow h$



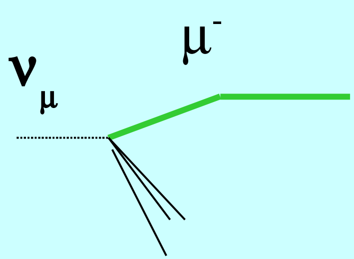
FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

PTEP9 (2014) 093C01

Large angle muon scattering

Background for $\tau \rightarrow \mu$



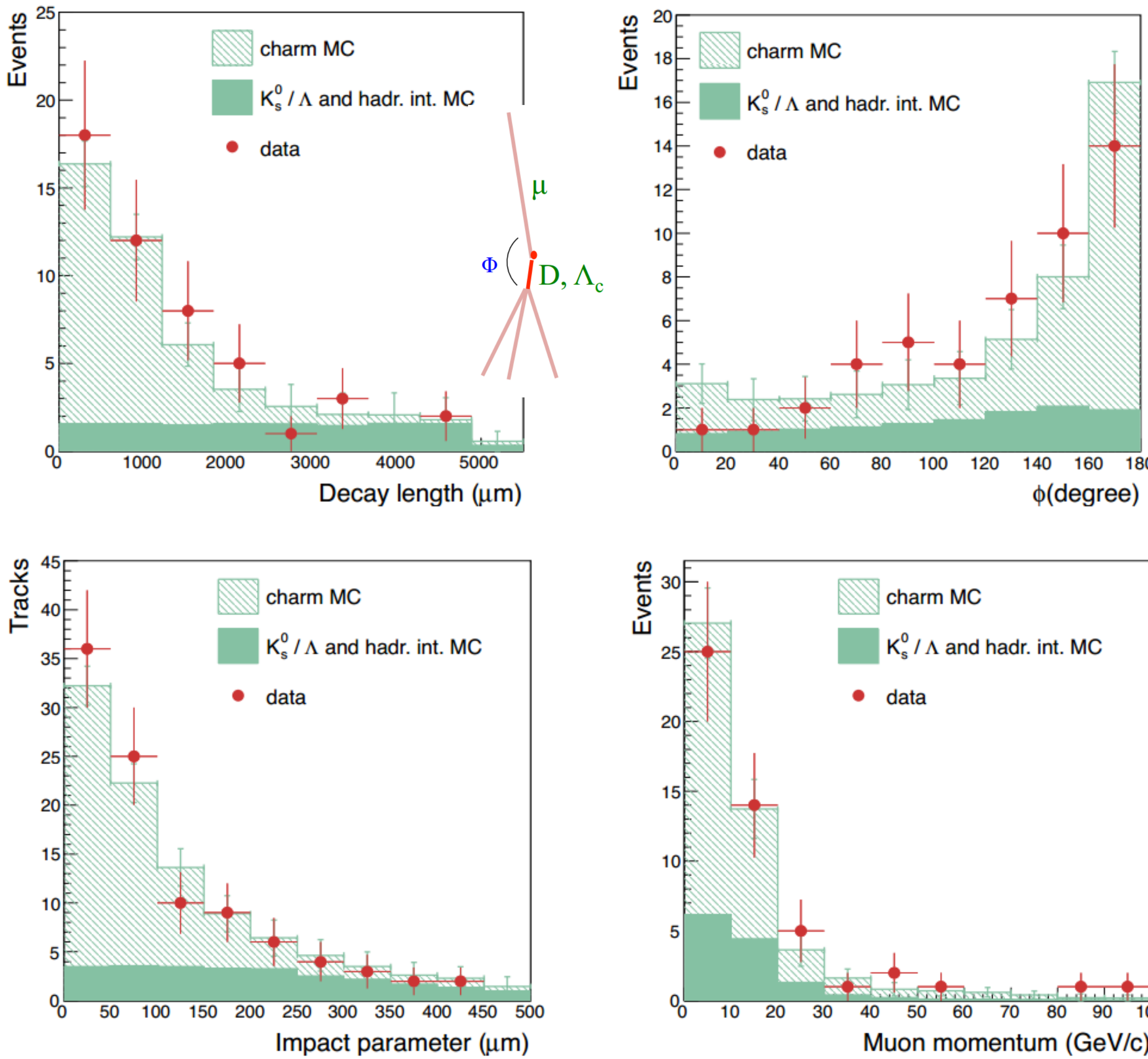
Improved knowledge bringing this contribution to a negligible level: GEANT4 simulation benchmarked on real data from the literature.

IEEE Trans. Nucl. Sci. 62,5, 2216-2225

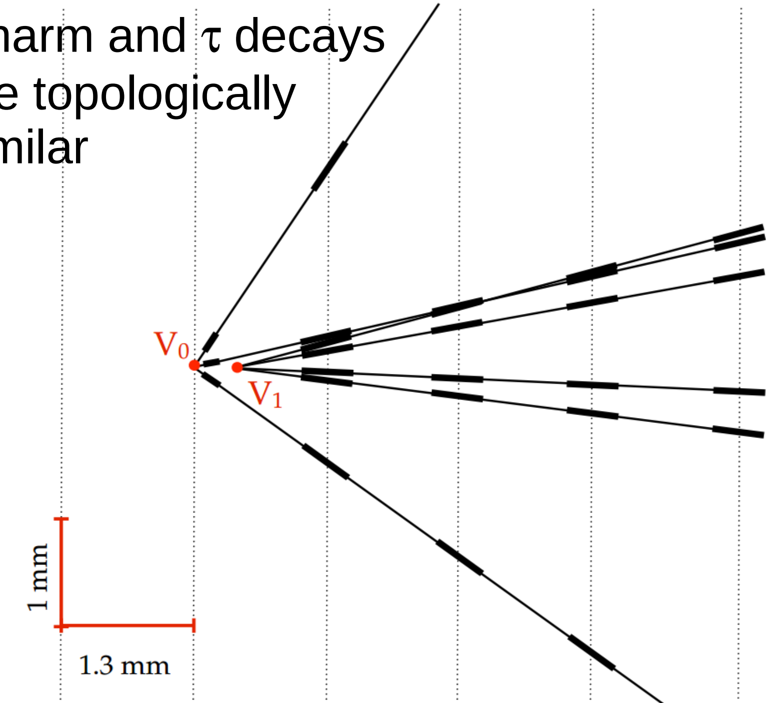
Validation with the CNGS charm events sample

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

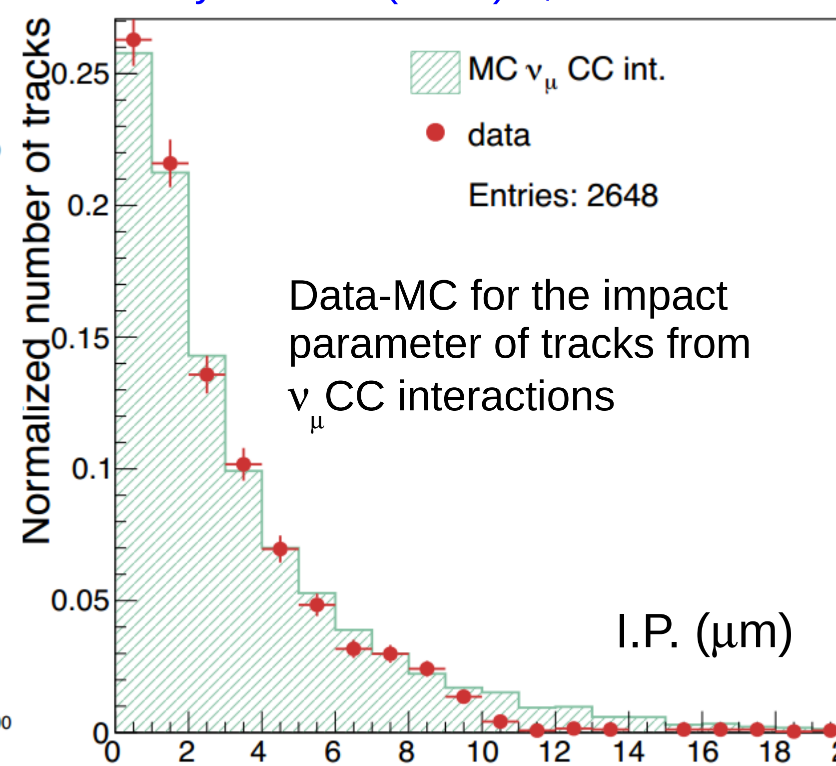
54 ± 4 expected ↔ 50 observed



Charm and τ decays are topologically similar



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



OPERA ν_τ appearance

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

Signal/background ~10

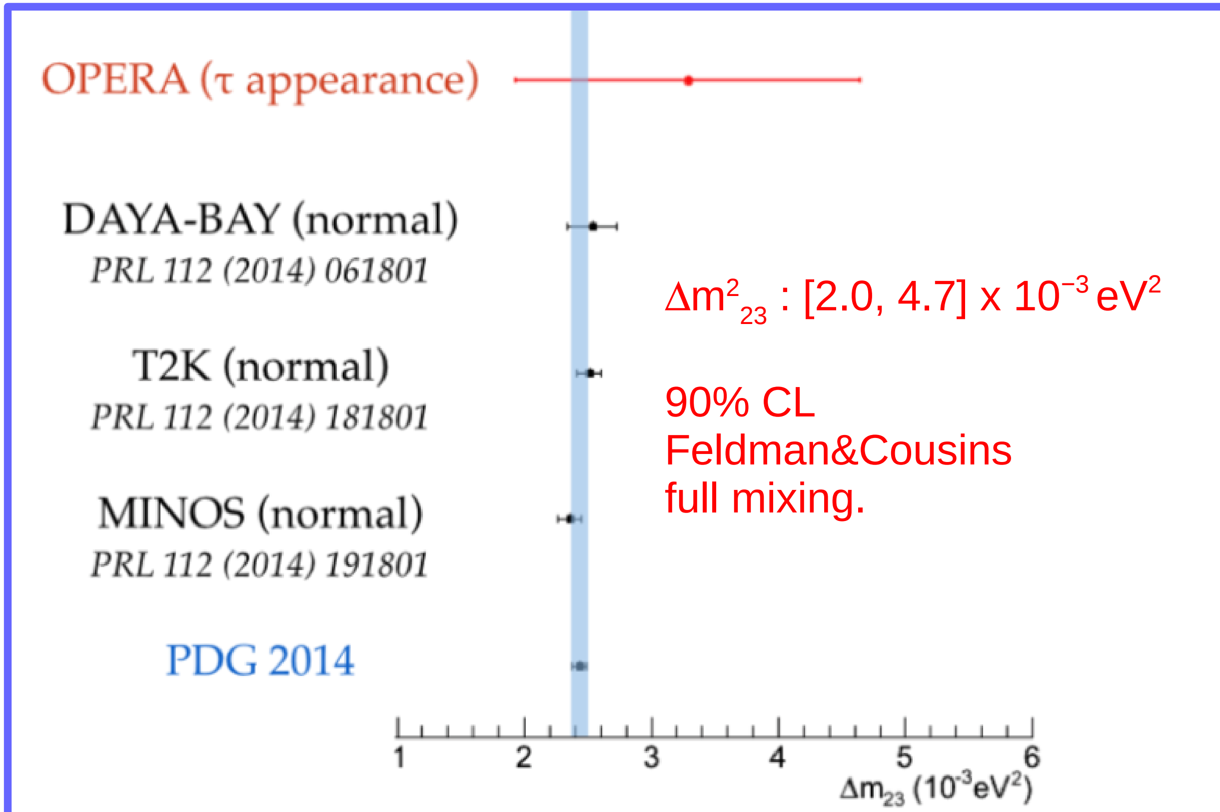
$$N_\tau \propto (\Delta m^2_{32})^2 L^2 \int \phi(E)\epsilon(E)\frac{\sigma(E)}{E^2}dE$$

5 candidates (1 leptonic+4 hadronic) fulfilling the kinematic selection defined in the experiment proposal

→

5.1 σ exclusion of the background-only hypothesis

[PRL 115 (2015) 12, 121802]



$\nu_\mu \rightarrow \nu_\tau$: steriles?

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

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

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

(normal hierarchy)

standard

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

exotic

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

interference

[JHEP 06 (2015) 069]

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

A rich structure:

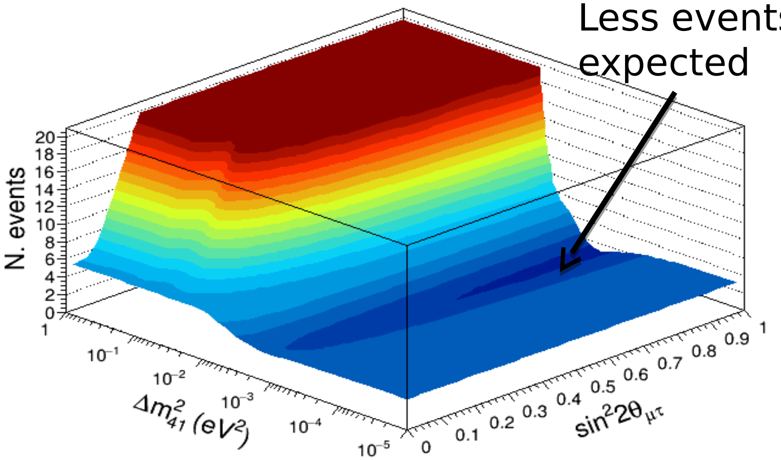
- can result in an increase or decrease of expected number of ν_τ events
- sensitive to new CPV phases + mass hierarchy (unlike short-baseline exp.)

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

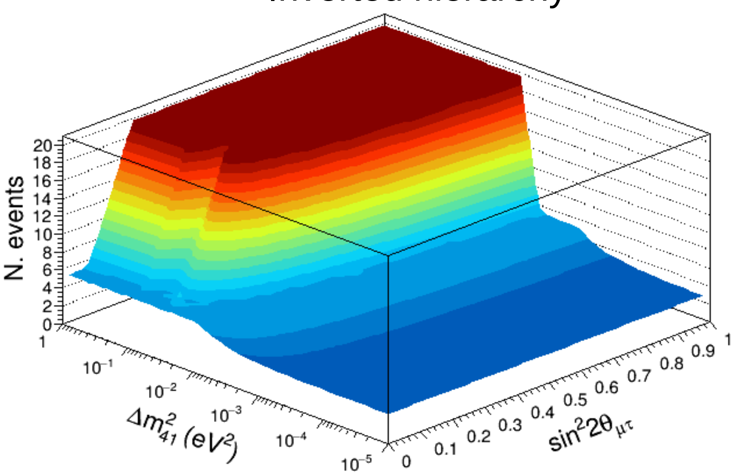
ν_τ rate only analysis

Expected ν_τ events

Normal hierarchy

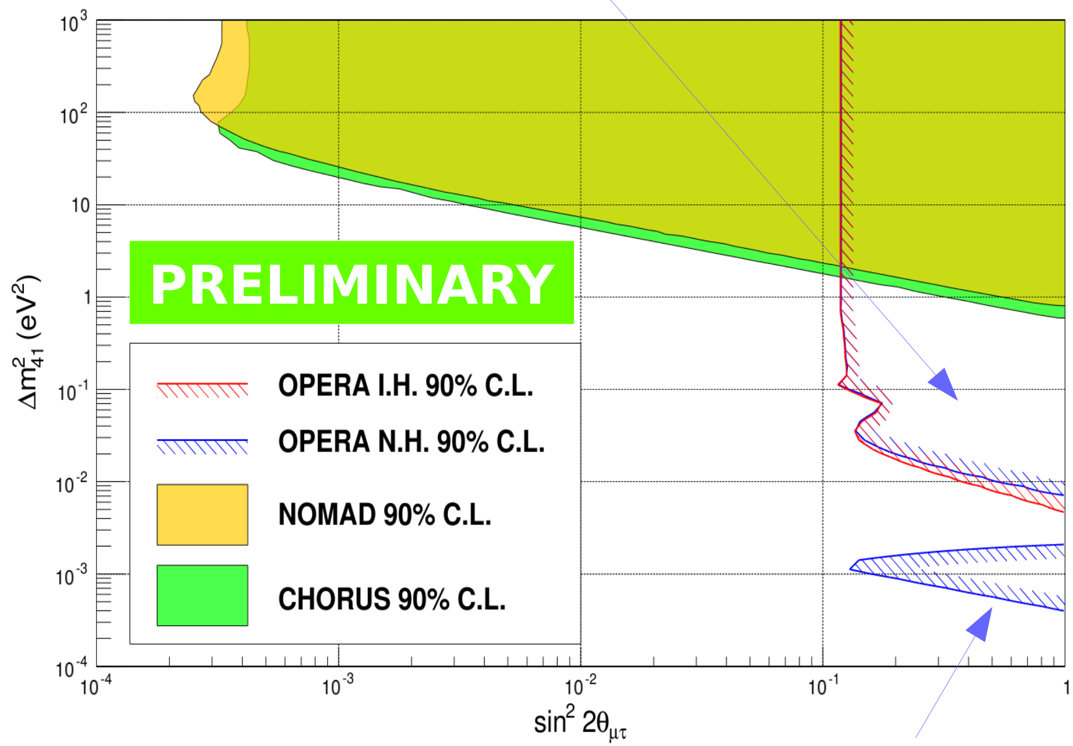


Inverted hierarchy



Long baseline, high-E:

a wide range of Δm^2_{41} from 10^{-3} to 1 excluded for $\sin^2 2\theta_{\mu\tau} > O(10^{-1})$



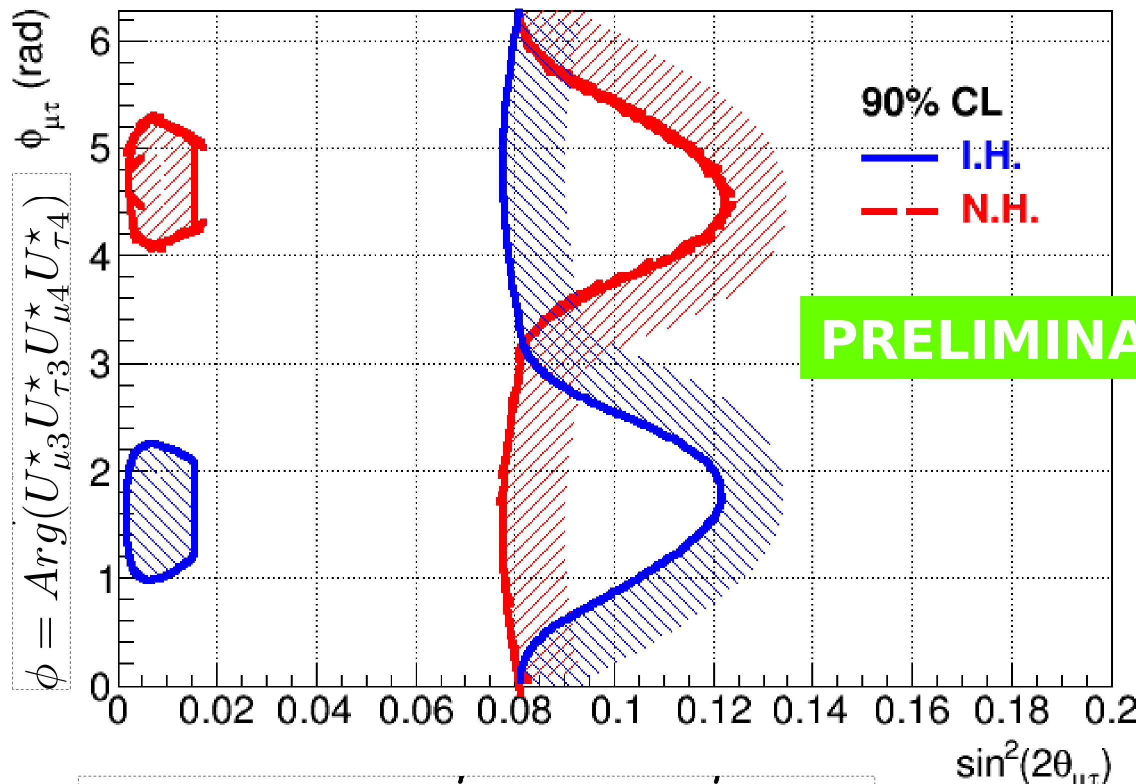
$$\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$$

With normal hierarchy a sterile neutrino close enough to m_3 would suppress ν_τ appearance well below the 5 observed events

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

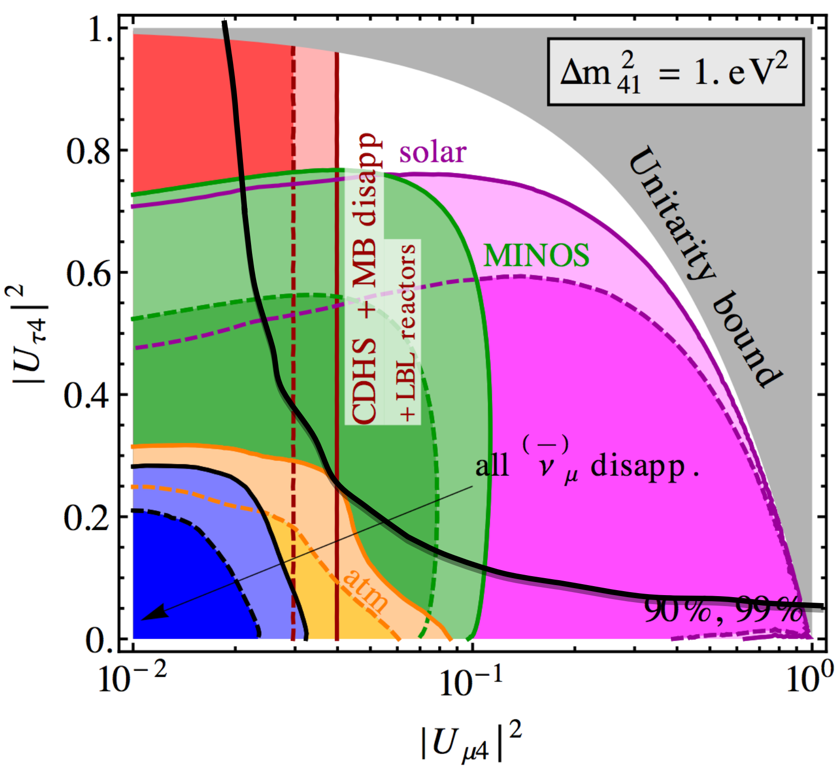
- For $|\Delta m^2_{41}| > 1$ eV^2
- Dependence on the new CP violating new phase ϕ
  - Peculiar of long-baseline

$$\phi = Arg(U^\star_{\mu 3} U^\star_{\tau 3} U^\star_{\mu 4} U^\star_{\tau 4})$$



$$\sin 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$$

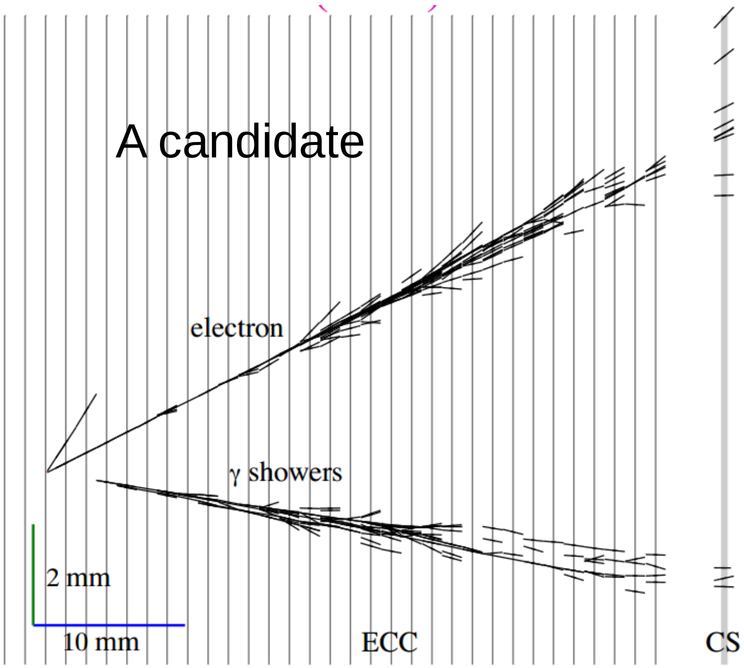
OPERA



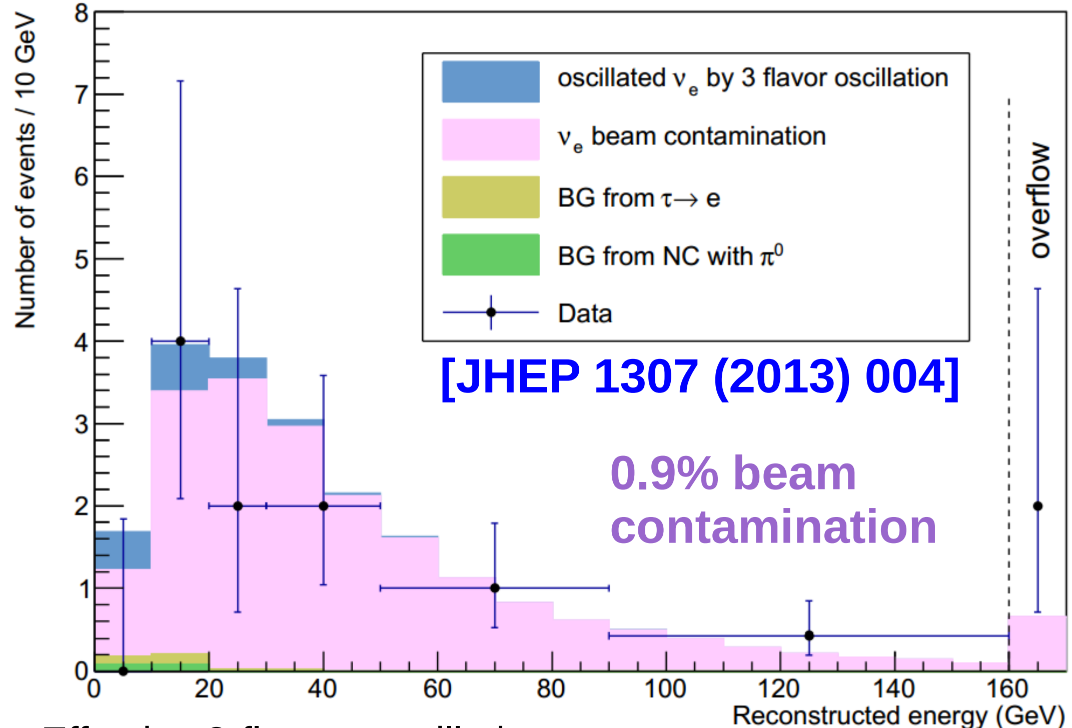
- $\sin^2 2\theta_{\mu\tau} < 0.119$ at 90% CL integrating over ϕ
- in the $|U_{\tau 4}|^2$ vs $|U_{\mu 4}|^2$ plane: complementarity with disappearance experiments (MINOS) is visible

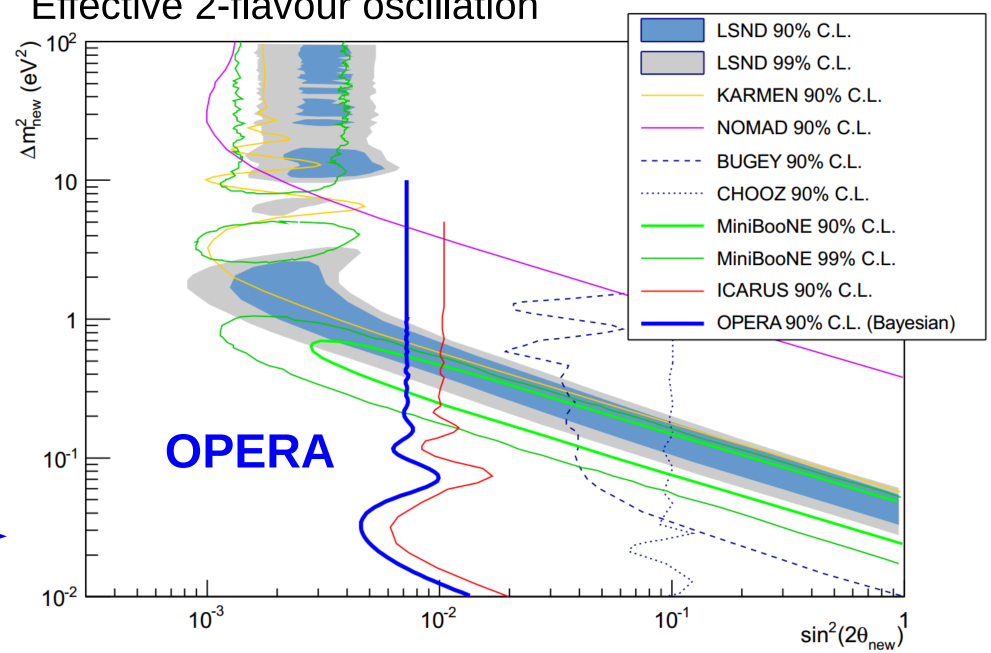
$\nu_\mu \rightarrow \nu_e$

505 0μ interactions (2008-09 runs)



		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) →

Final analysis with the full data sample close to completion (× 2.5 increase in sample)

Will include rigorous 3+1 treatment – A. Palazzo PRD 91, 91301R (2015)

Conclusions

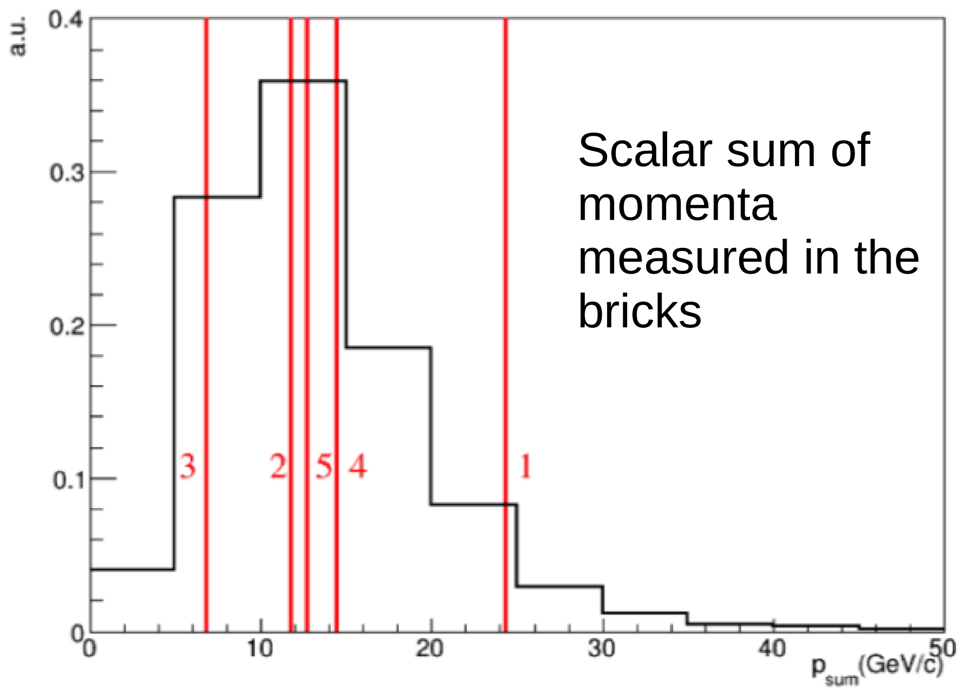
- $5\ \nu_\tau$ candidates with a 0.25 event background
- No oscillation hypothesis excluded at **5.1 σ**

discovery of ν_τ appearance

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

Outlook

- Emulsion analysis ~ complete
- Results $\nu_\mu \rightarrow \nu_e$ with full statistics soon
- Ongoing characterisation of events failing the cut-based appearance analysis (marginal events) still having a significant ν_τ purity



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

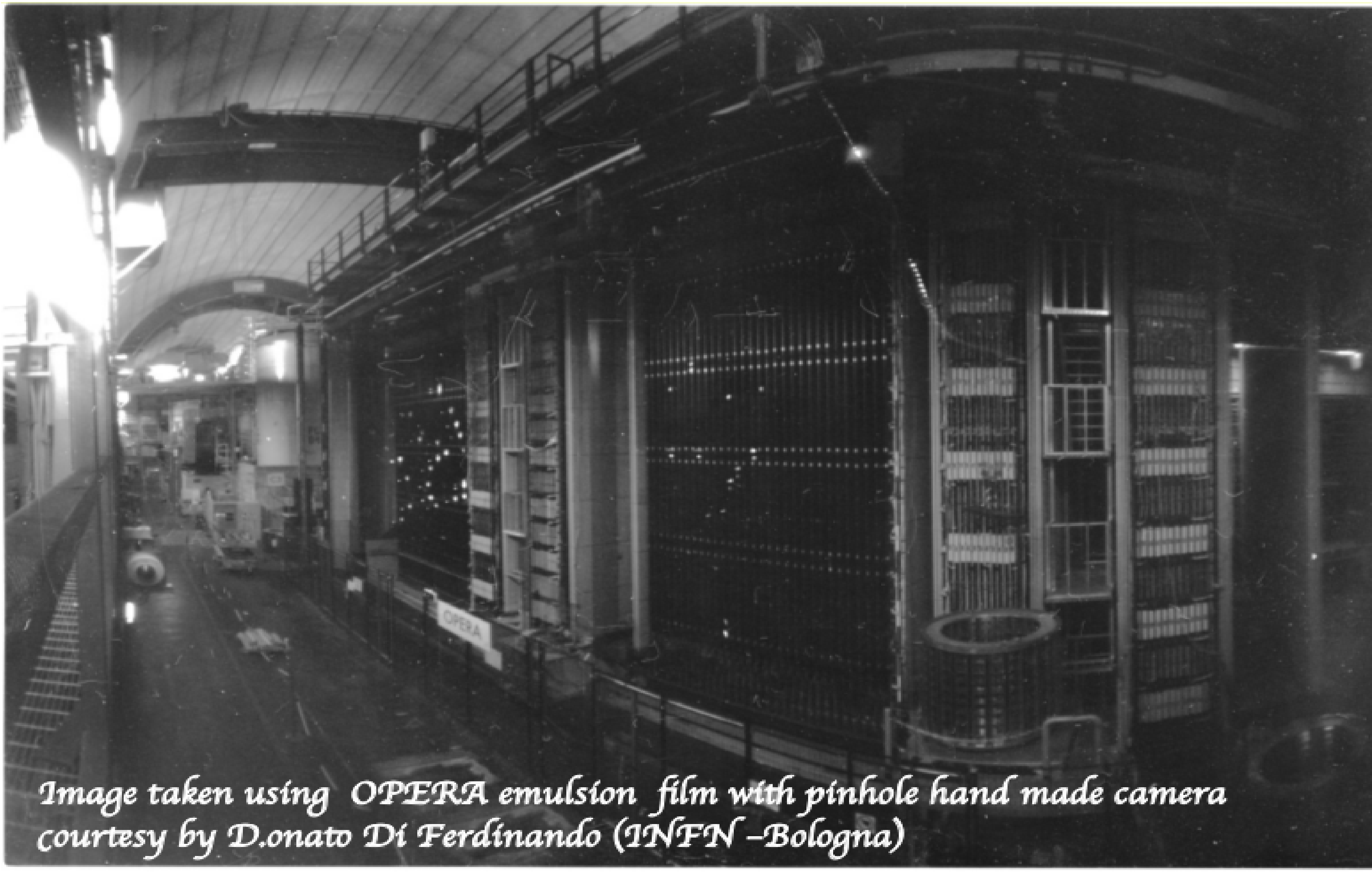


Image taken using OPERA emulsion film with pinhole hand made camera
courtesy by D.onato Di Ferdinando (INFN –Bologna)

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

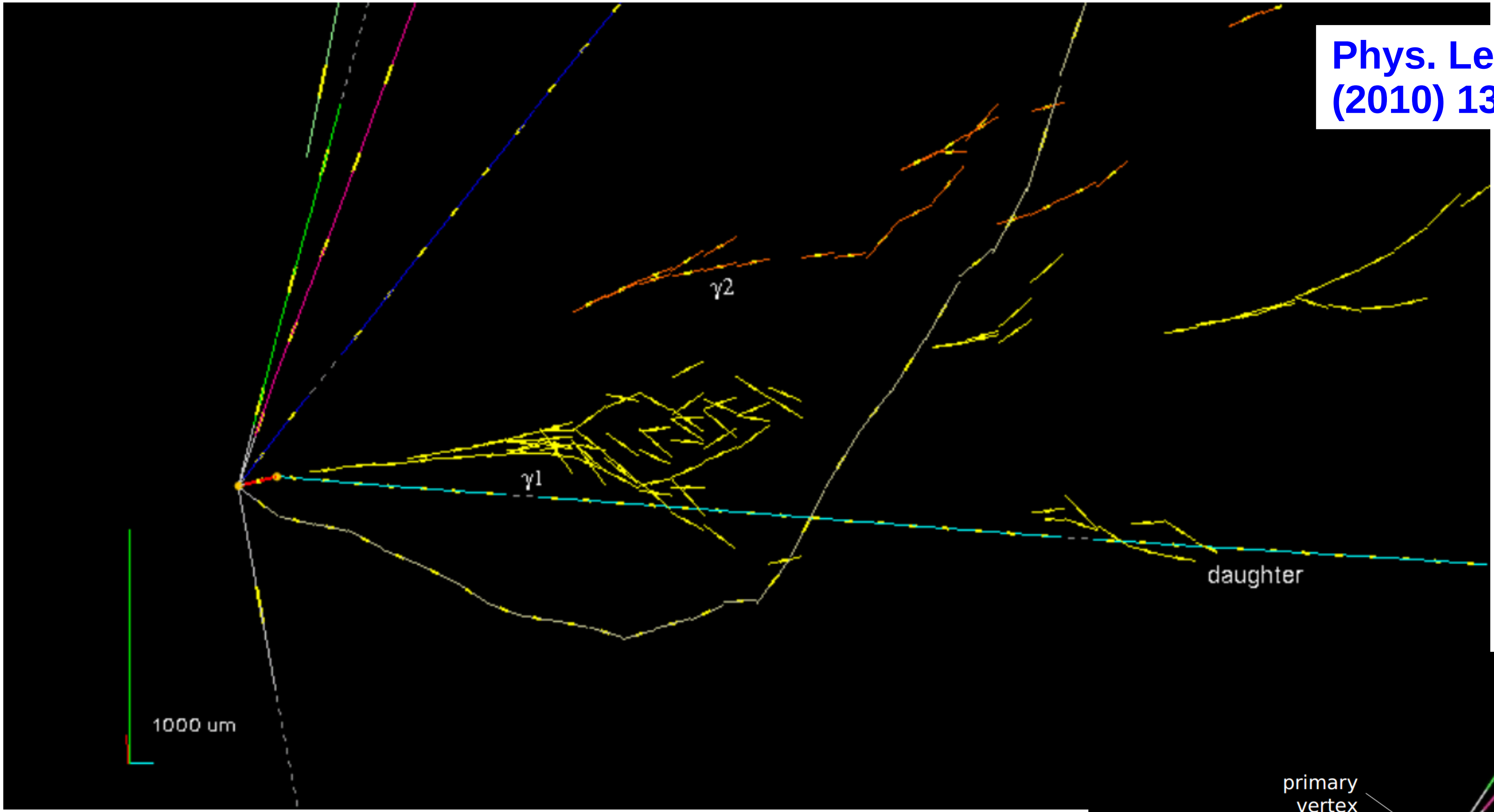
Korea
Jinju

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

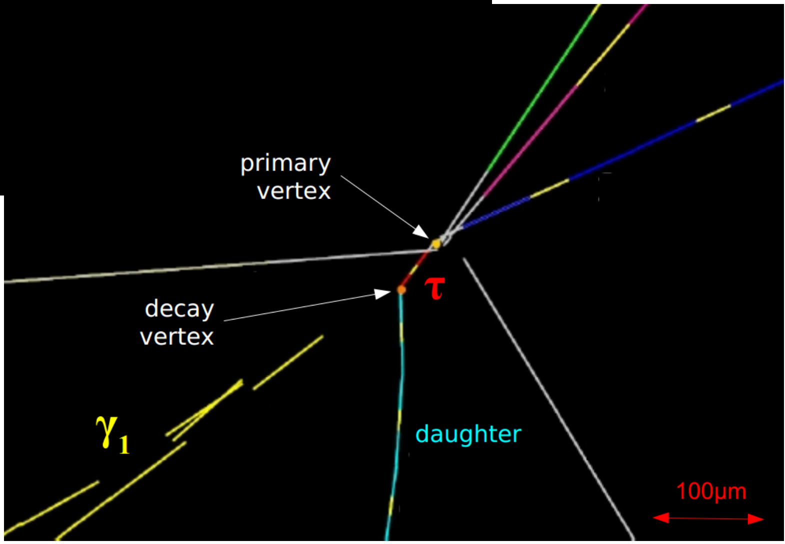
Switzerland
Bern

Turkey
METU, Ankara

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



Phys. Lett. B691 (2010) 138



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

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

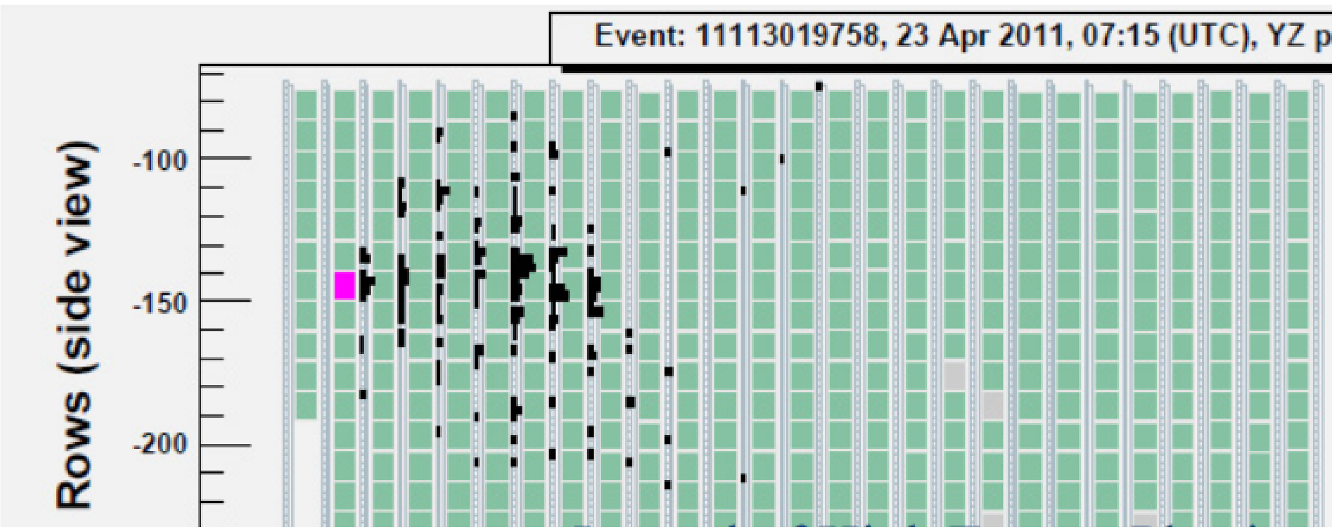
$\pi^0 \rightarrow \gamma\gamma$

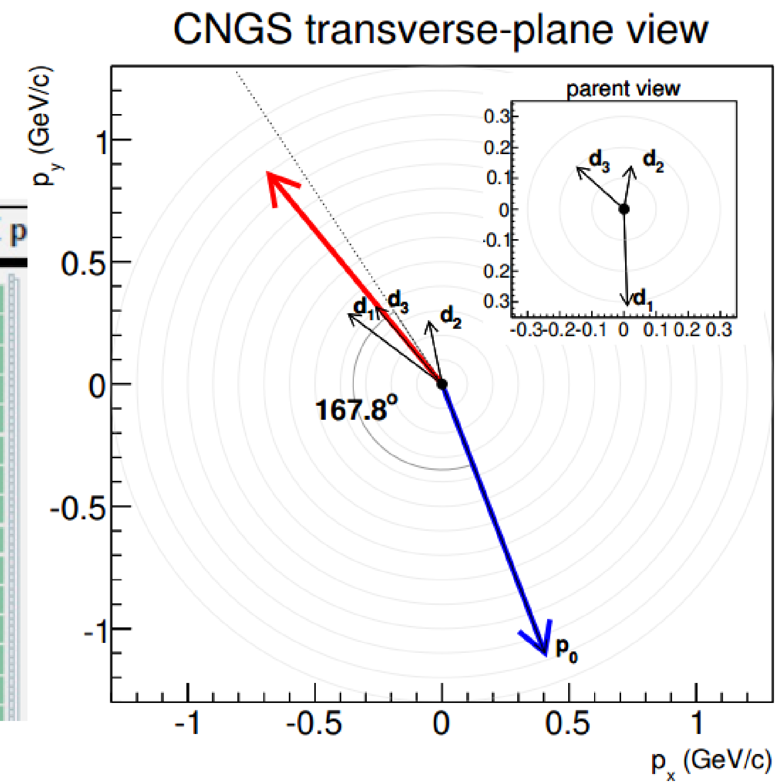
640^{+125}_{-80} (stat.) $^{+100}_{-90}$ (sys.) MeV/c^2

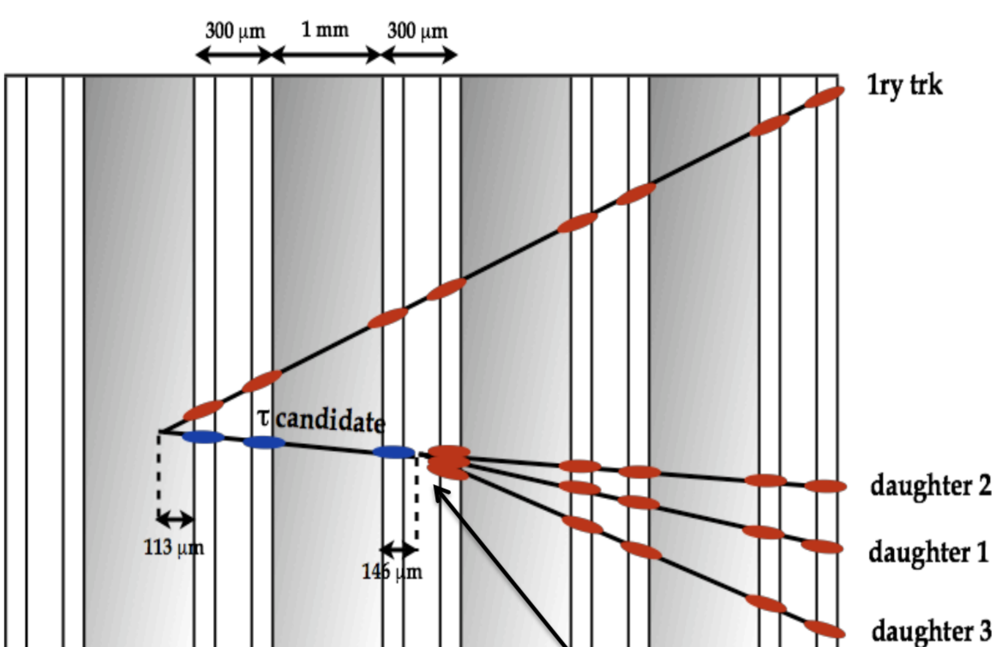
120 ± 20(stat.) ± 35(sys.) MeV/c^2

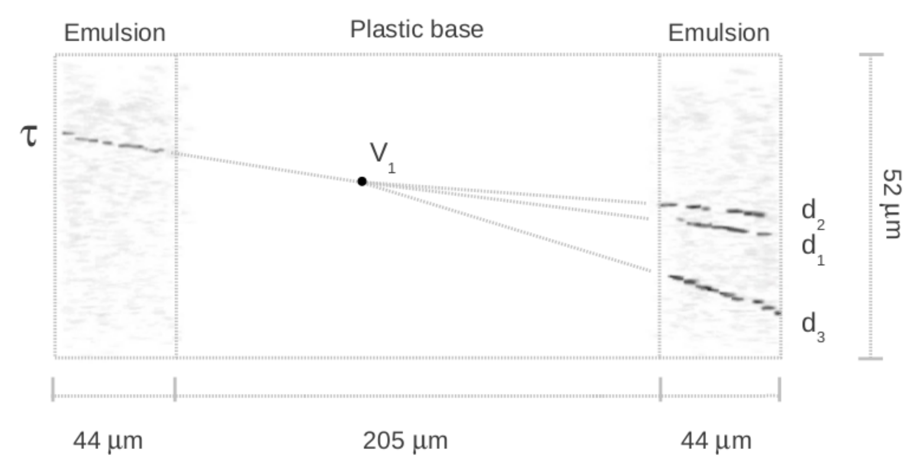
JHEP 11 (2013) 036

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







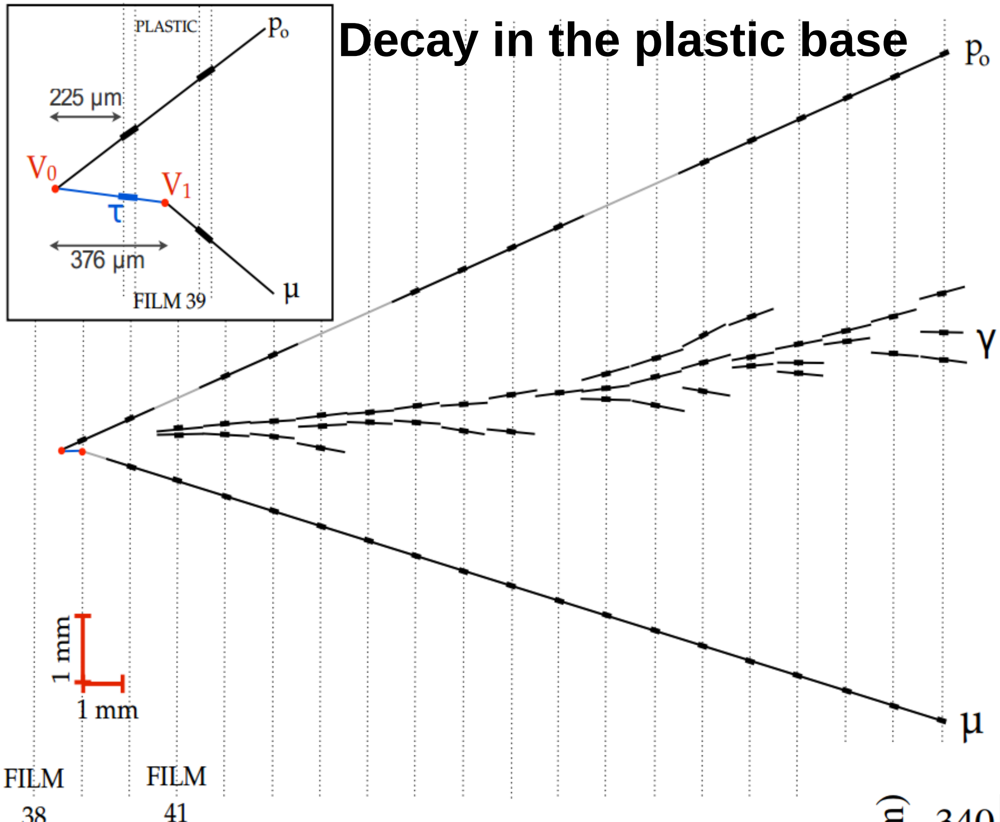


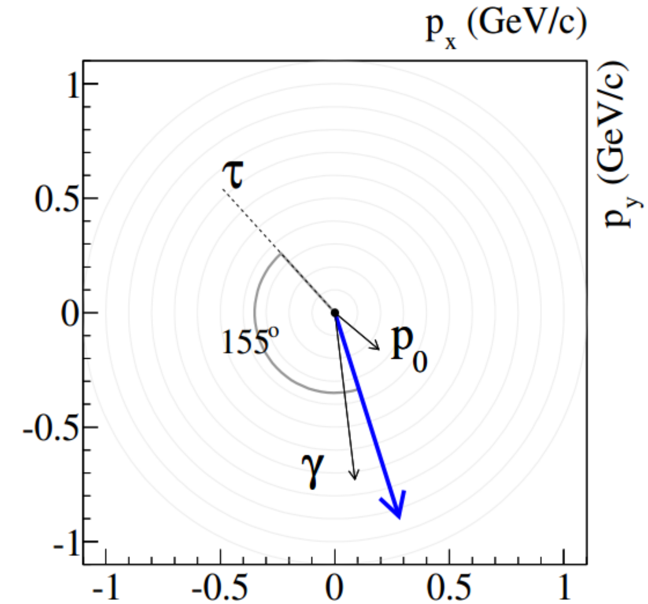
Decay in the plastic base

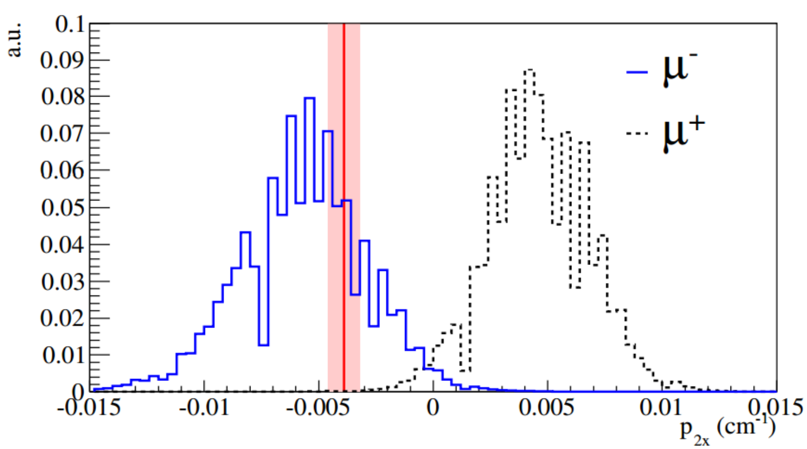
The 3rd candidate ($\tau \rightarrow \mu$)

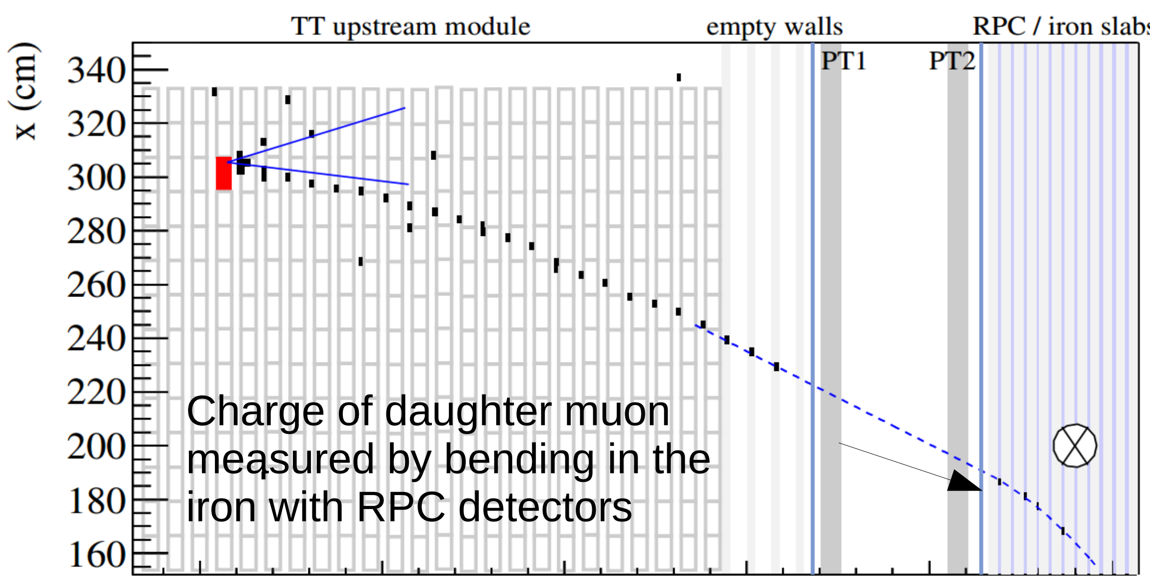
Phys. Rev. D 89 (2014) 051102(R)

Decay in the plastic base



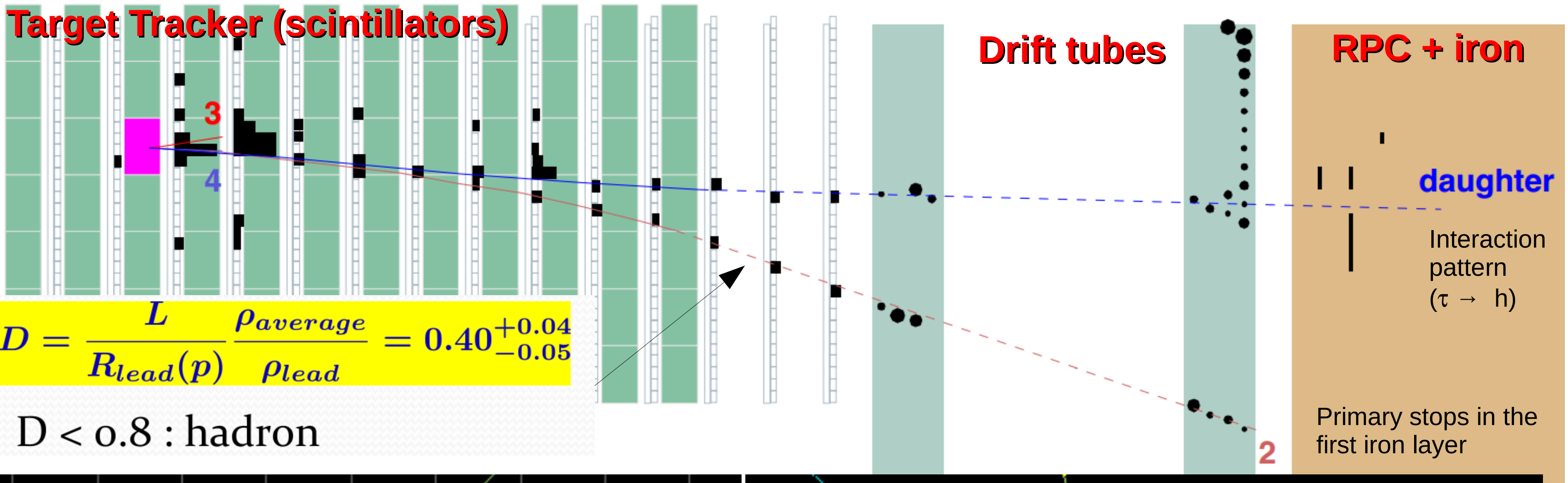






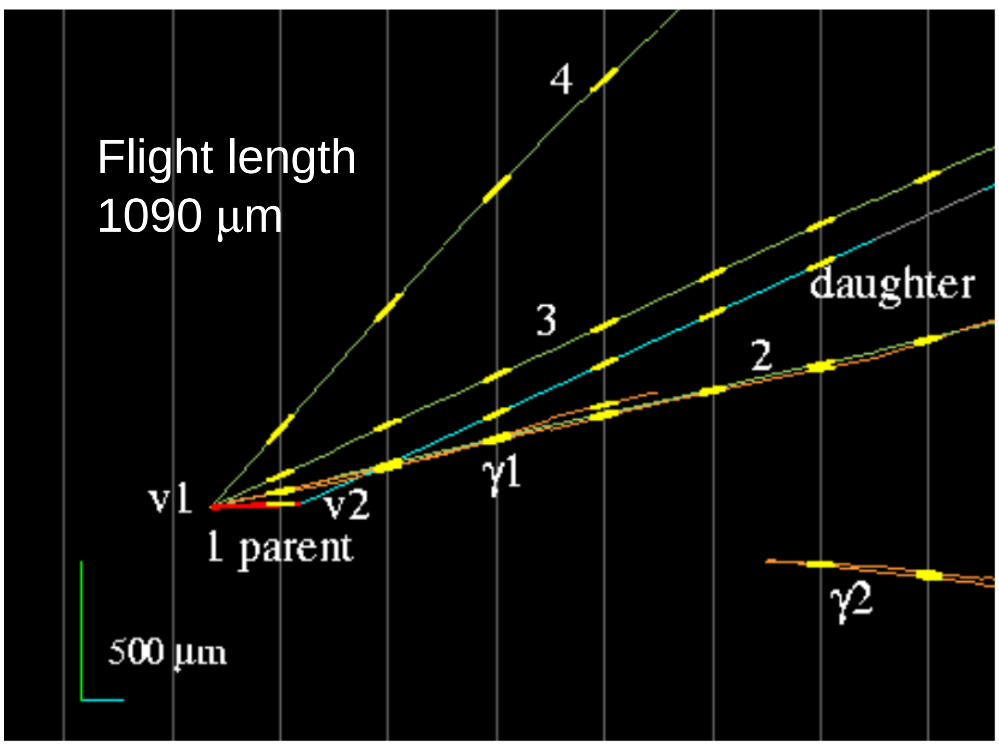
PTEP 2014 (2014) 10, 101C01

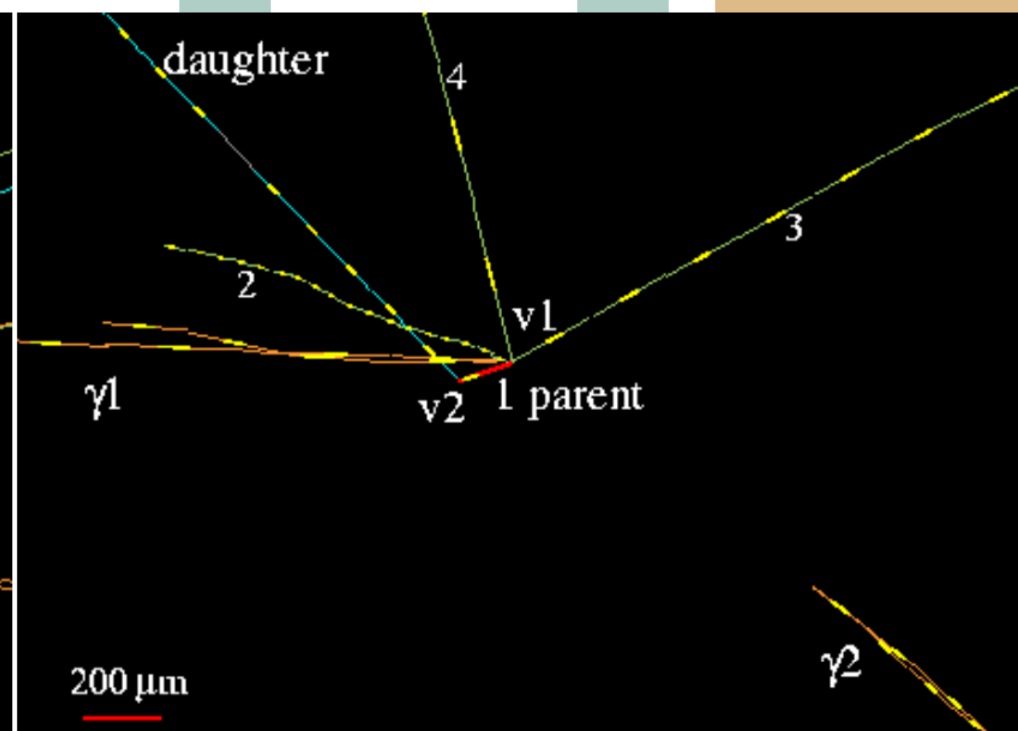
The 4th candidate ($\tau \rightarrow$ 1h)



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

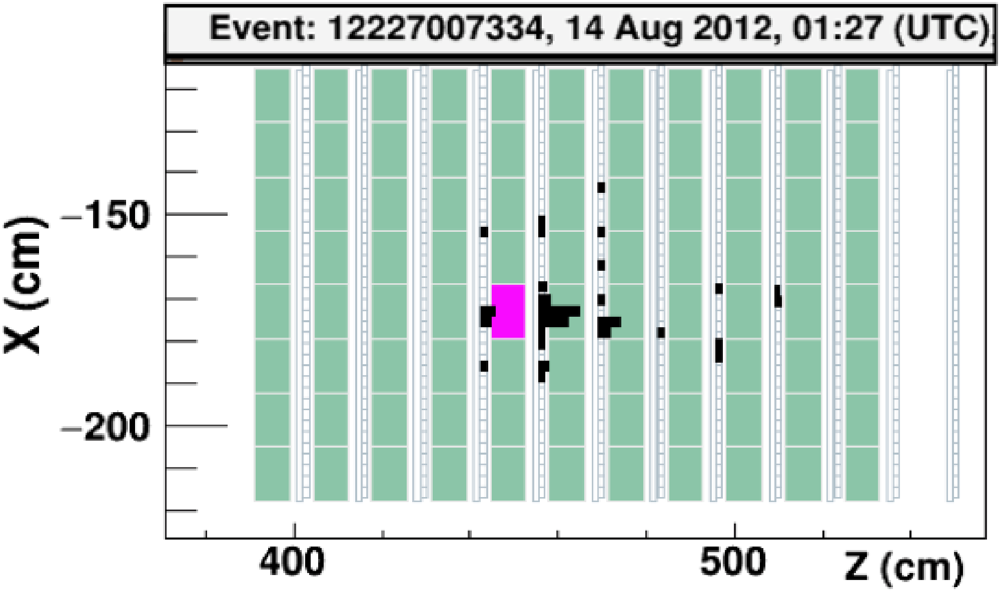
D < 0.8 : hadron

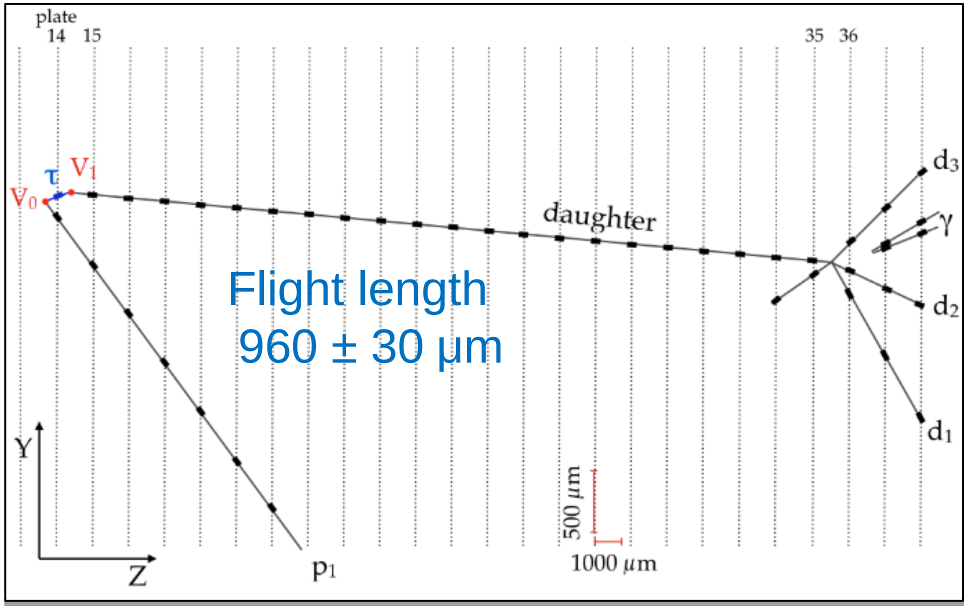




The 5th candidate ($\tau \rightarrow$ 1h)

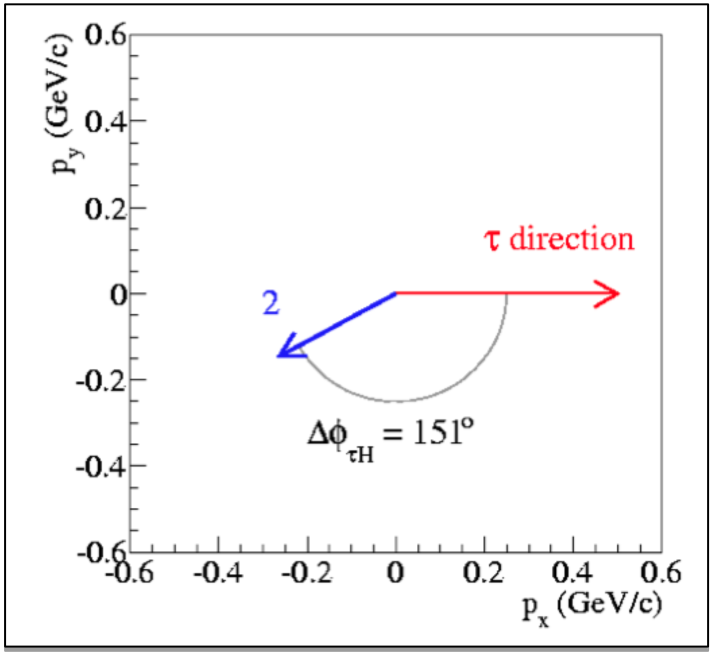
[Phys. Rev. Lett. 115 (2015) 12, 121802]

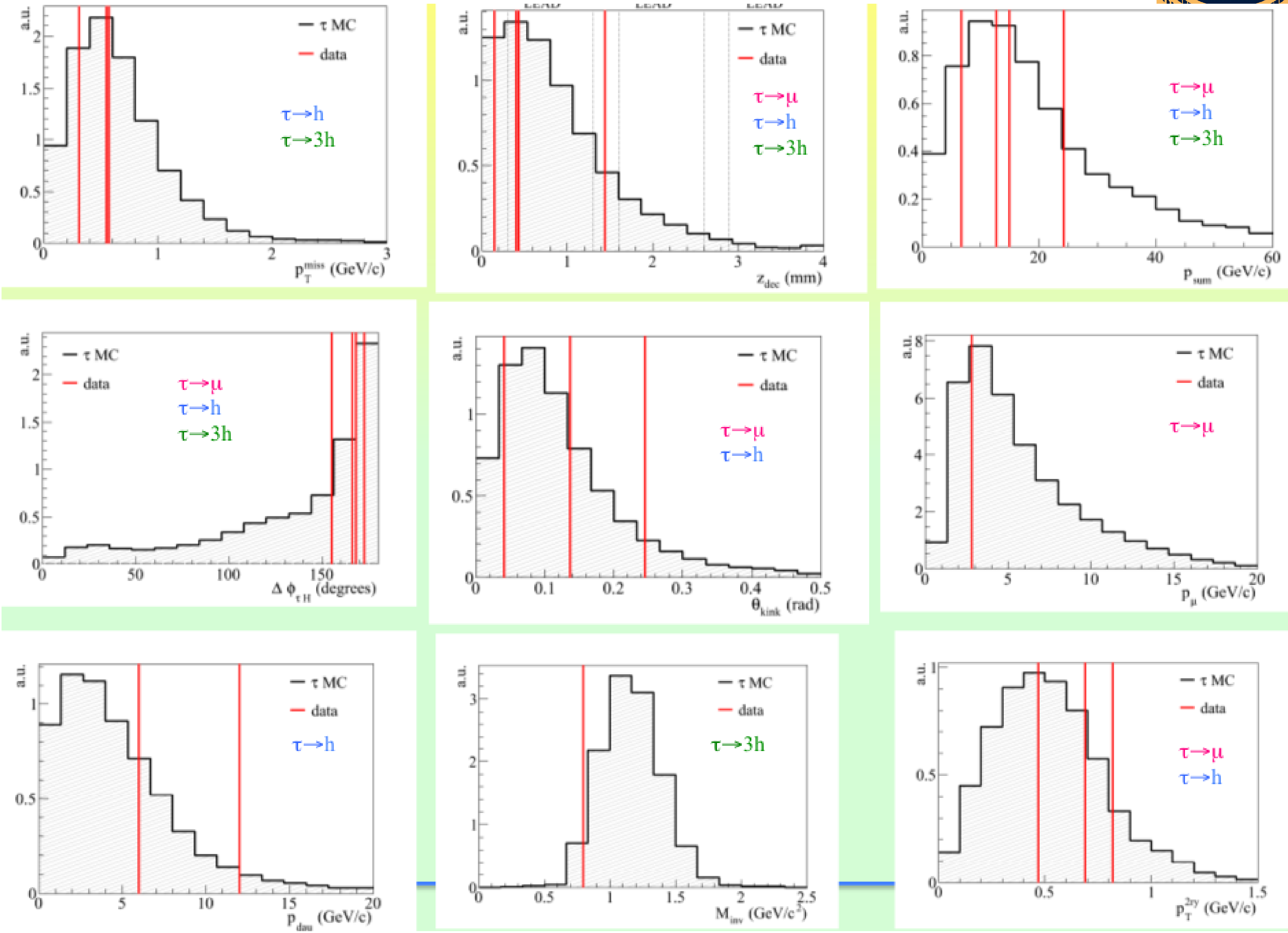




Kinematical variables

Parameter	Measured value	Selection Criteria
$\Delta\phi_{\tau H}$ (^{o})	151±1	>90
p_T^{miss} (GeV/c)	0.3 ± 0.1	<1
θ_{kink} (mrad)	90 ± 2	>20
z_{dec} (μm)	634 ± 30	[44, 2600]
p^{2ry} (GeV/c)	11^{+14}_{-4}	>2
p_T^{2ry} (GeV/c)	$1.0^{+1.2}_{-0.4}$	>0.6 (no γ attached)




τ MC
data
τ→h
τ→3h
a.u.
p_T^{miss} (GeV/c)
τ MC
data
τ→μ
τ→h
τ→3h
a.u.
z_{dec} (mm)
τ→μ
τ→h
τ→3h
a.u.
p_{sum} (GeV/c)
τ MC
data
τ→μ
τ→h
τ→3h
a.u.
$\Delta \phi_{\tau H}$ (degrees)
τ MC
data
τ→μ
τ→h
a.u.
θ_{kink} (rad)
τ MC
data
τ→μ
a.u.
p_μ (GeV/c)
τ MC
data
τ→h
a.u.
p_{dau} (GeV/c)
τ MC
data
τ→3h
a.u.
M_{inv} (GeV/c^2)
τ MC
data
τ→μ
τ→h
a.u.
p_T^{2ry} (GeV/c)

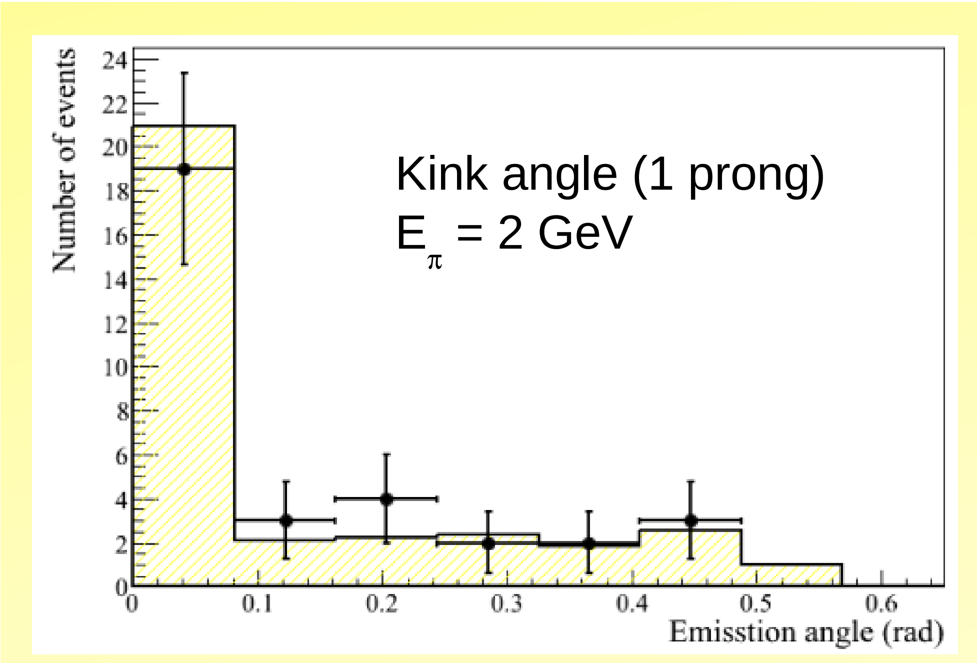
ν_τ kinematic analysis

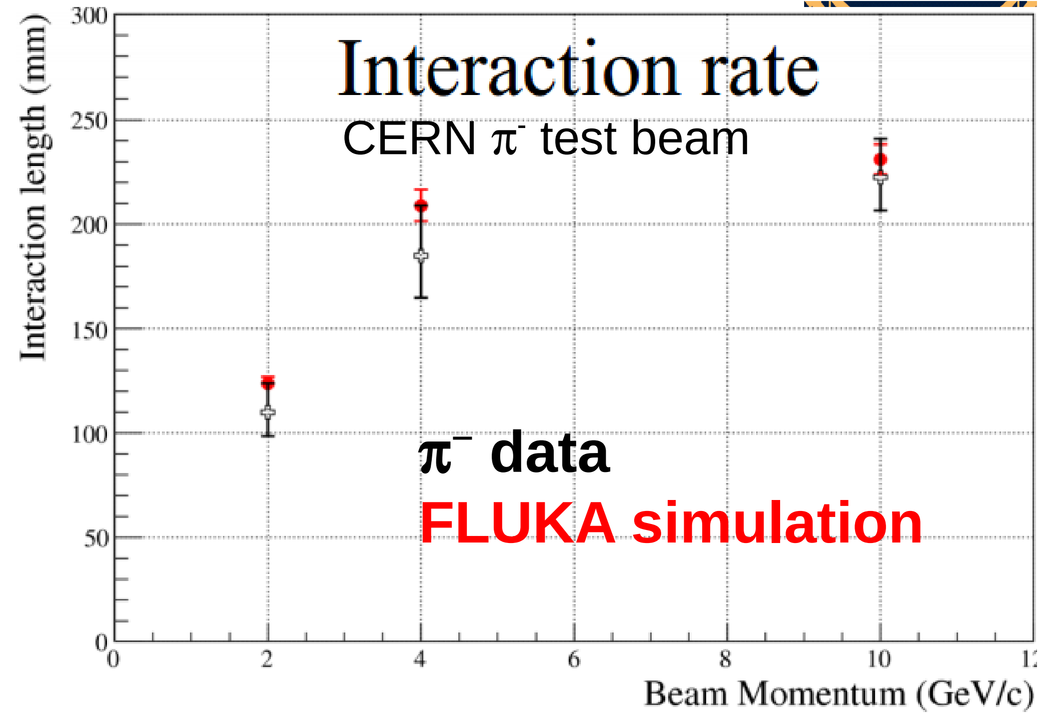
Candidate events have to fullfil kinematical cuts: →

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

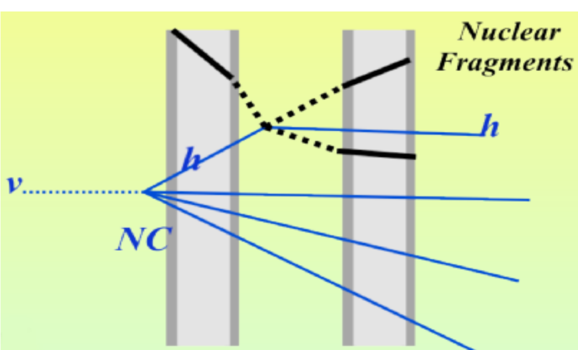
variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
lepton-tag	No μ or e at the primary vertex			
z_{dec} (μm)	$[44, 2600]$	< 2600	$[44, 2600]$	< 2600
p_T^{miss} (GeV/c)	$< 1^\star$	$< 1^\star$	/	/
ϕ_{lH} (rad)	$> \pi/2^\star$	$> \pi/2^\star$	/	/
p_T^{2ry} (GeV/c)	$> 0.6(0.3)*$	/	> 0.25	> 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	/	/

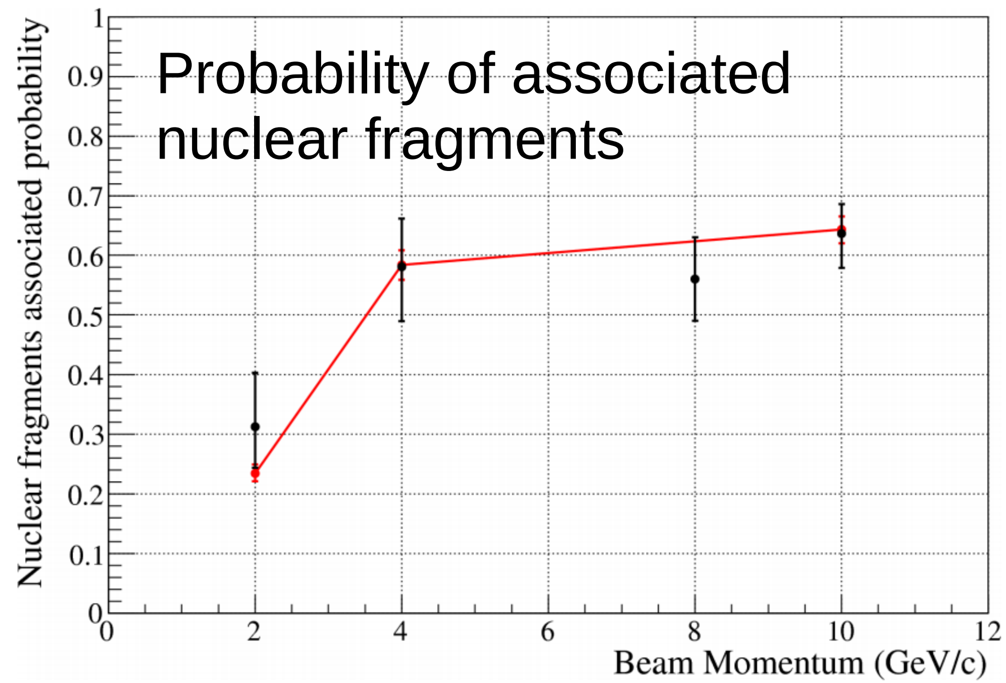
Hadronic background: π test beams





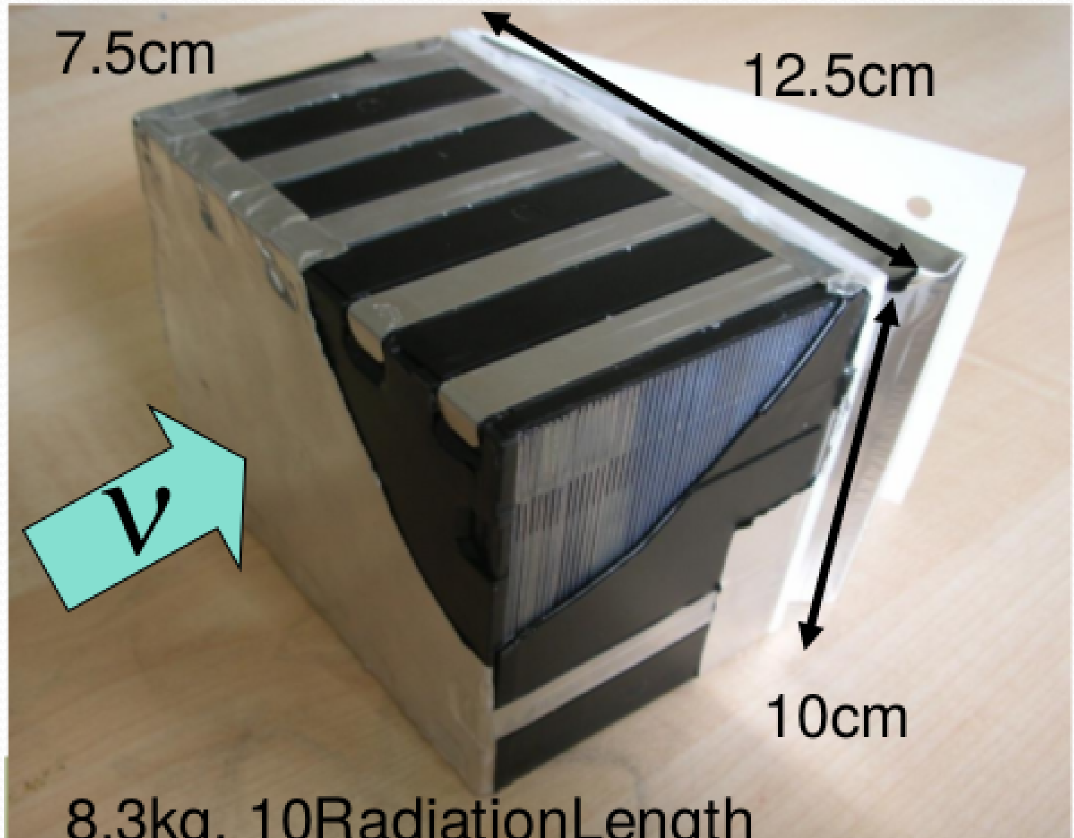
Nuclear fragments: a smoking gun for the occurrence of an π interaction instead of a decay.

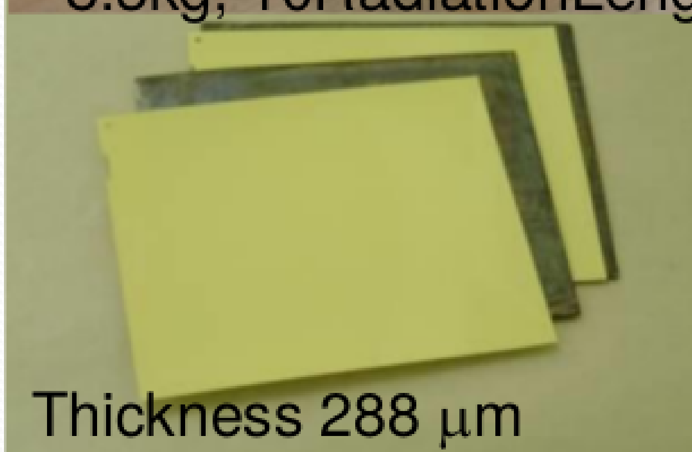




Hadronic background rate per located event: $\tau \rightarrow$ (3)h = (1.5)3.09 x 10^{-5}

The ECC

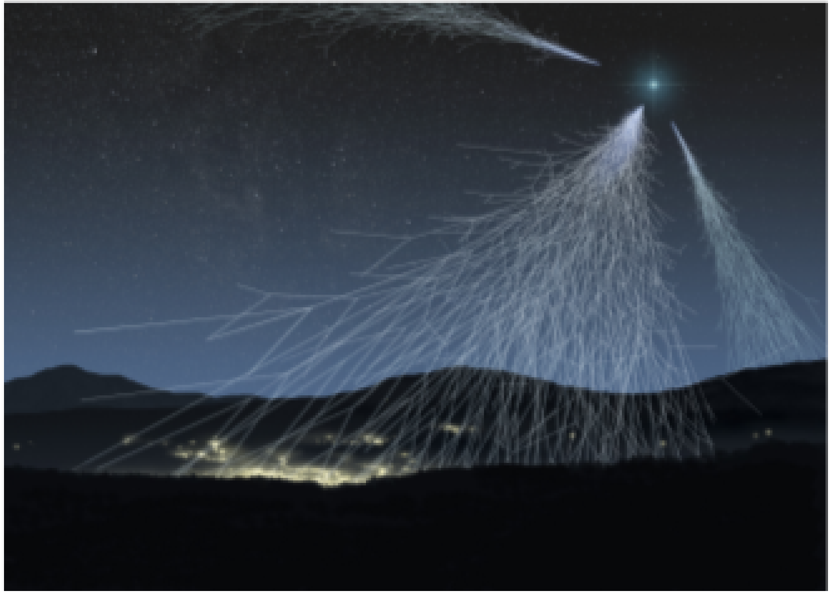




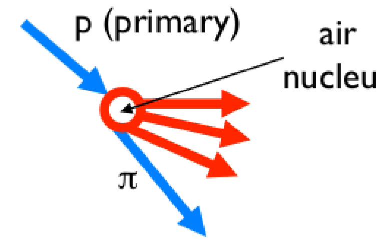
- ECC properties
  - 56 of 1mm thick lead plates interleaved with 57 emulsion films.
  - 8.3kg / brick
  - 10 radiation length
- 150,000 ECC bricks
  - 1.25 ktons
  - 9 million films
- Capability
  - Micrometric accuracy vertex analysis
  - Kinematical analysis
    - Momentum measurement by MCS.
    - 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_μ provides a benchmark for atmospheric ν flux computations (e.g. background for neutrino telescopes)



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)

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