Results from the OPERA experiment at the CNGS beam

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on behalf of the OPERA Collaboration

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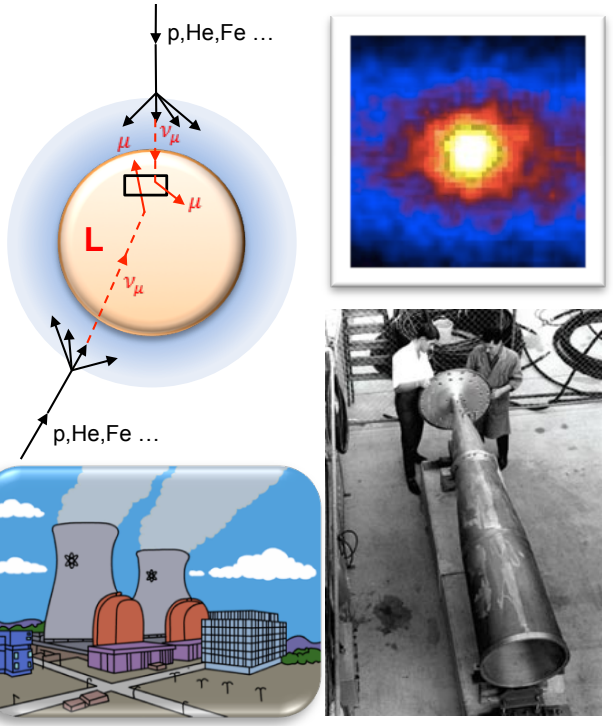
The long way to appearance

ν_μ disappearance: a "leading" effect

deficit of atmospheric ν (Super-K, MACRO 1998)

→ Discovery of ν-oscillations



On the other hand , the **appearance: a challenging effort…!**

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

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

At the **atmospheric scale**. Atmospheric-μ, artificial beams.

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

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

Today's perspective:

$\nu_\mu \rightarrow \nu_e$

Disappearence of anti-ν_e at reactors (2012, Daya-Bay, RENO, DCHOOZ). → θ_{13} is indeed BIG !

Appearance seen by T2K at the JPARC beam

$\nu_\mu \rightarrow \nu_\tau$ **Tau neutrino event-by-event detection achieved by OPERA**

An experimental and technological challenge. 730 km baseline.

- Beam O(10) more energetic (17 GeV) than any other LBL (m_τ) .
- "fine-grained" detector O(100) more massive (1.25 kt) than the precursors SBL (i.e. CHORUS).

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

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

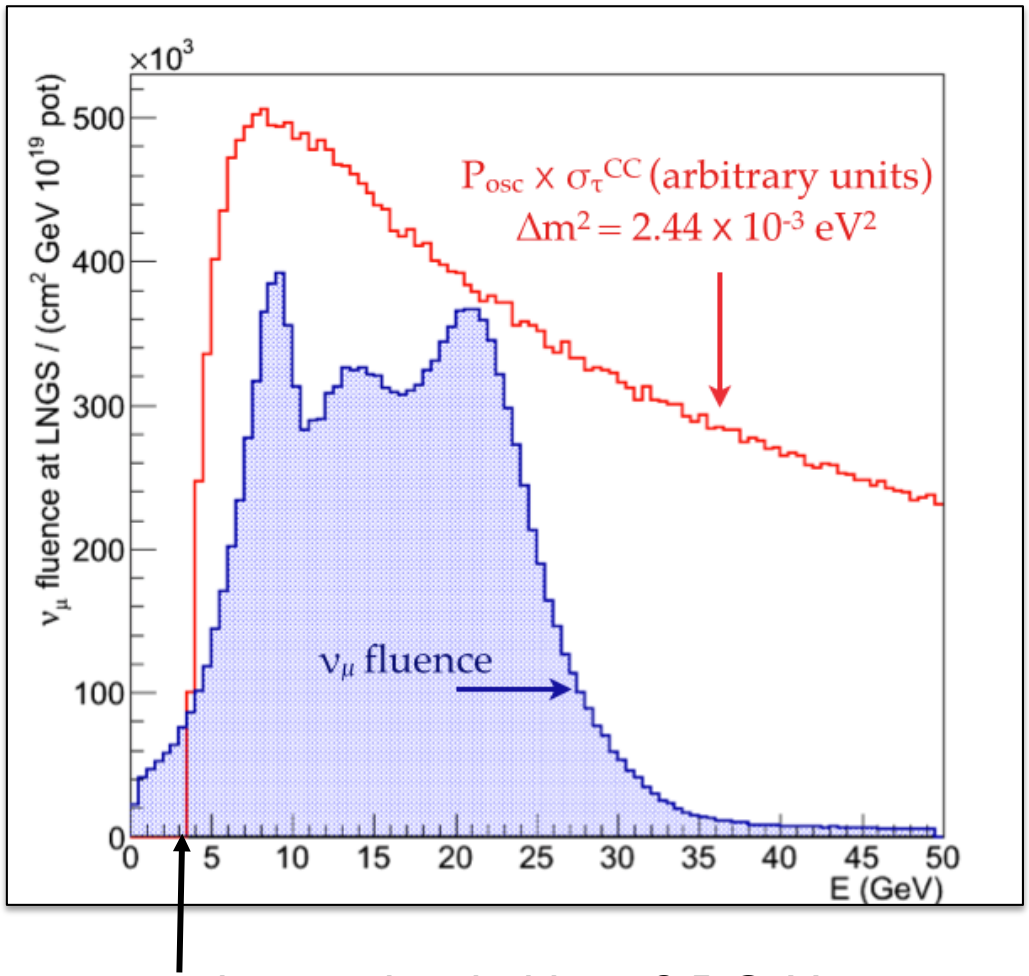
Fluxes:

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

Interaction rates ($1.8 \cdot 10^{20}$ p.o.t.):

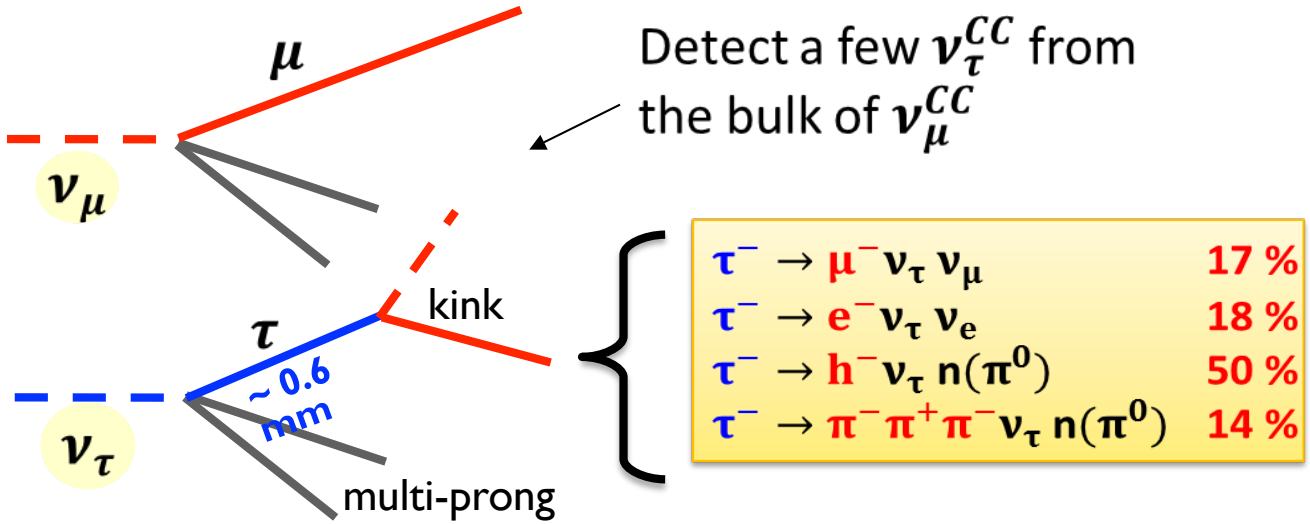
~ 20k ν_μ CC+NC

66.4 ν_τ CC (not efficiency corrected)



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

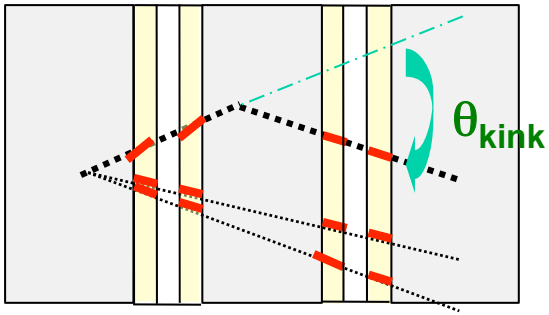
The ν_τ detection challenge



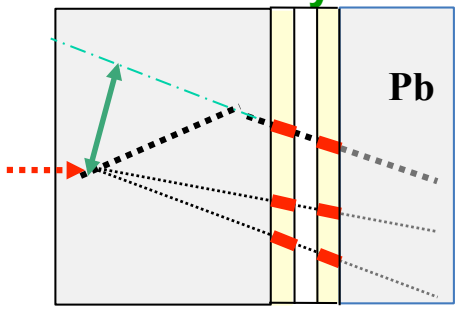
Detect a few ν_τ^{CC} from the bulk of ν_μ^{CC}

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



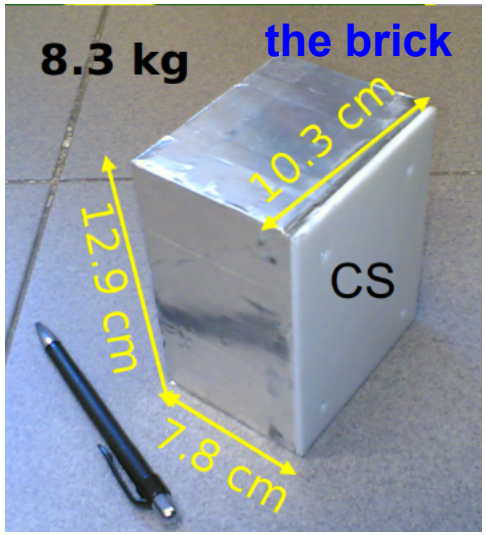
Modular detector of "Emulsion Cloud Chambers" (or bricks)

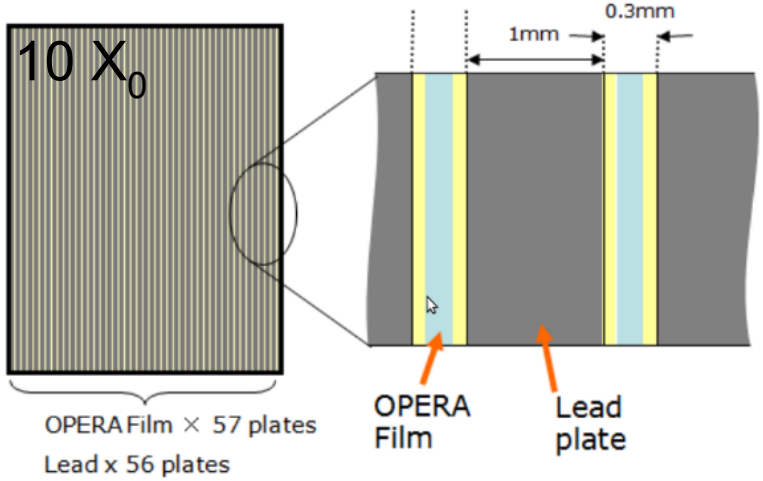
Large mass

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

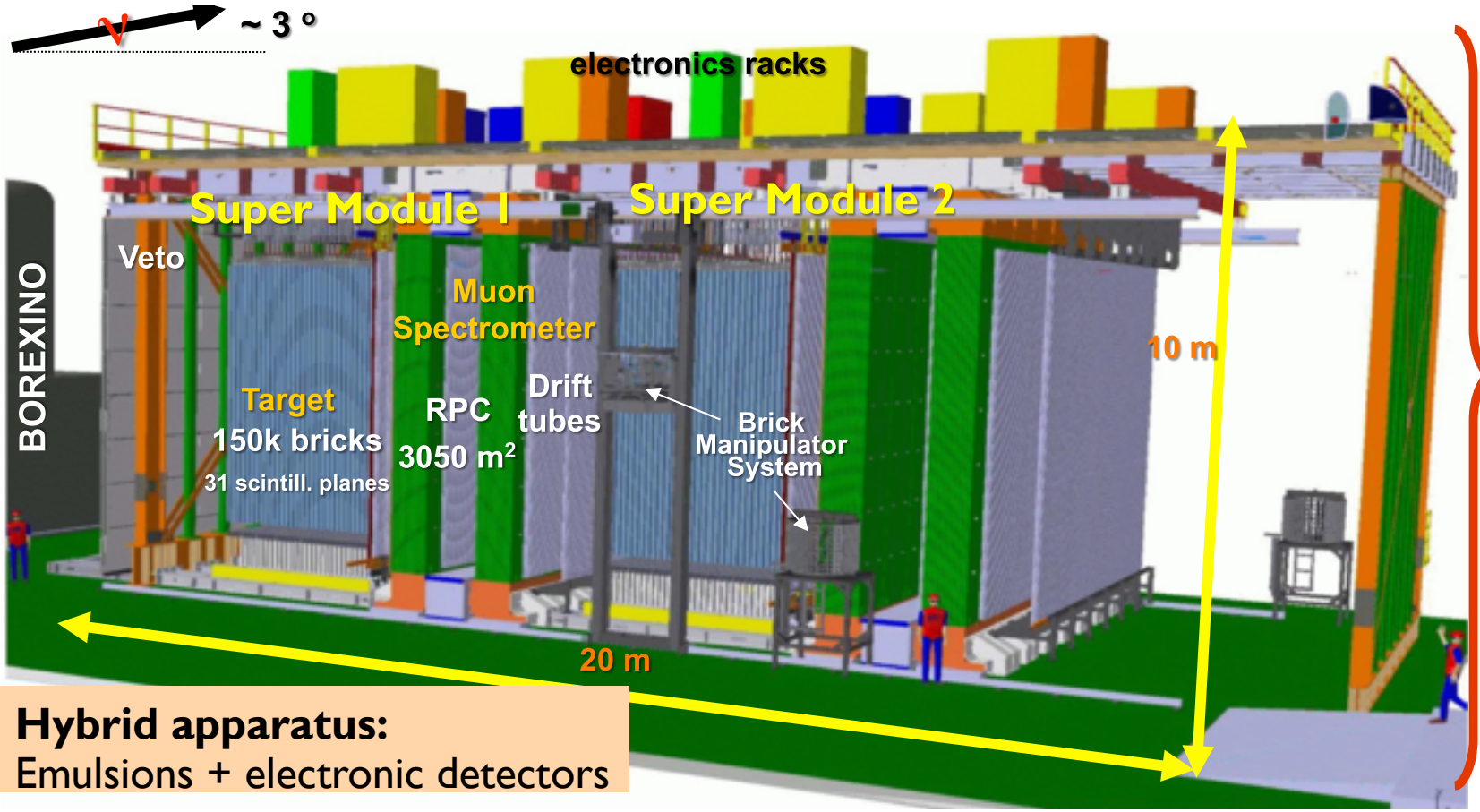
Extreme granularity

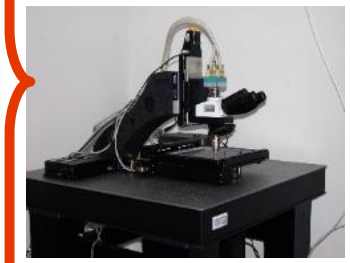
$\sim \mu$m space resolution

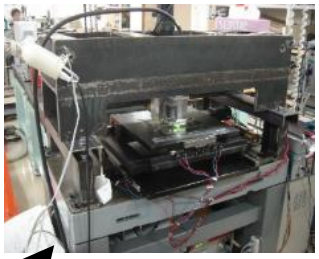




The OPERA detector

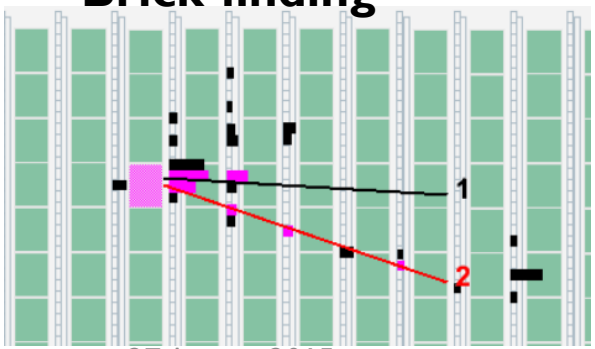






Hybrid apparatus:
Emulsions + electronic detectors

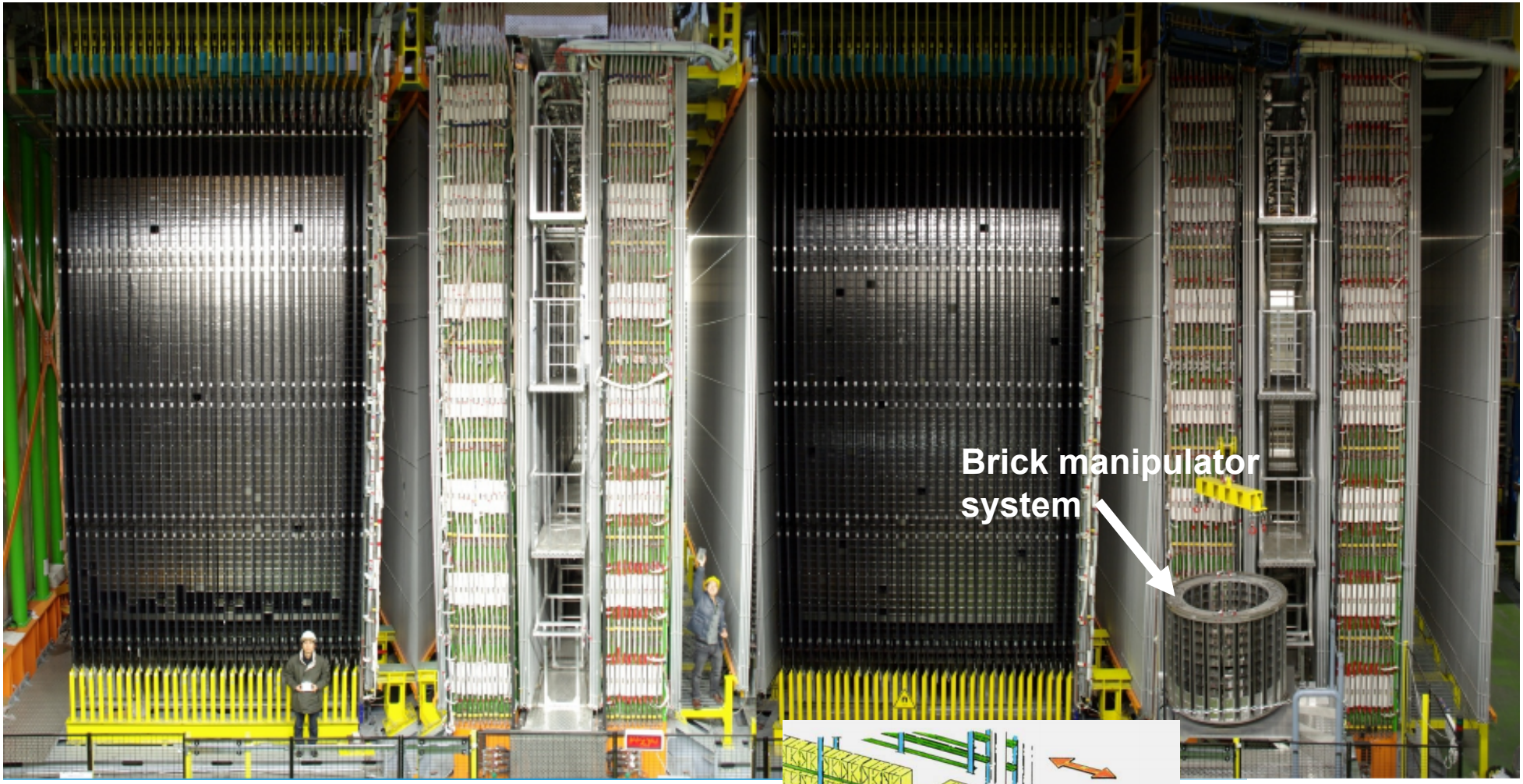
"Brick-finding"



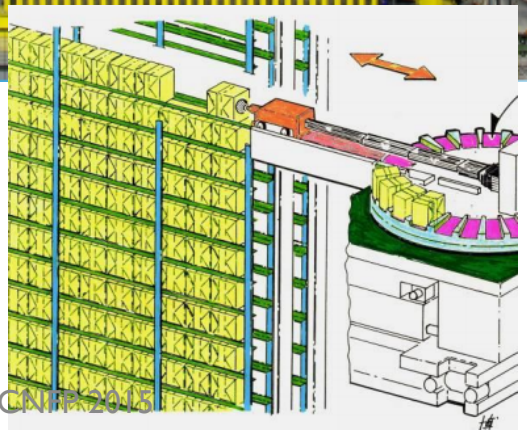
+ several ancillary facilities "off-site":

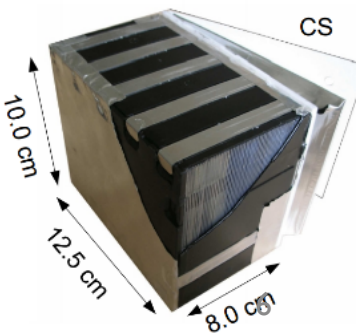
- **Assembly/disassembly of bricks (LNGS)**
- **Brick Manipulator System (LNGS)**
- **Labelling and X ray marking (LNGS)**
- **Automatised development (LNGS)**
- **Scanning of CS doublets (LNGS+JP)**
- **Scanning bricks (European Labs + JP)**

Super Module 1 Super Module 2



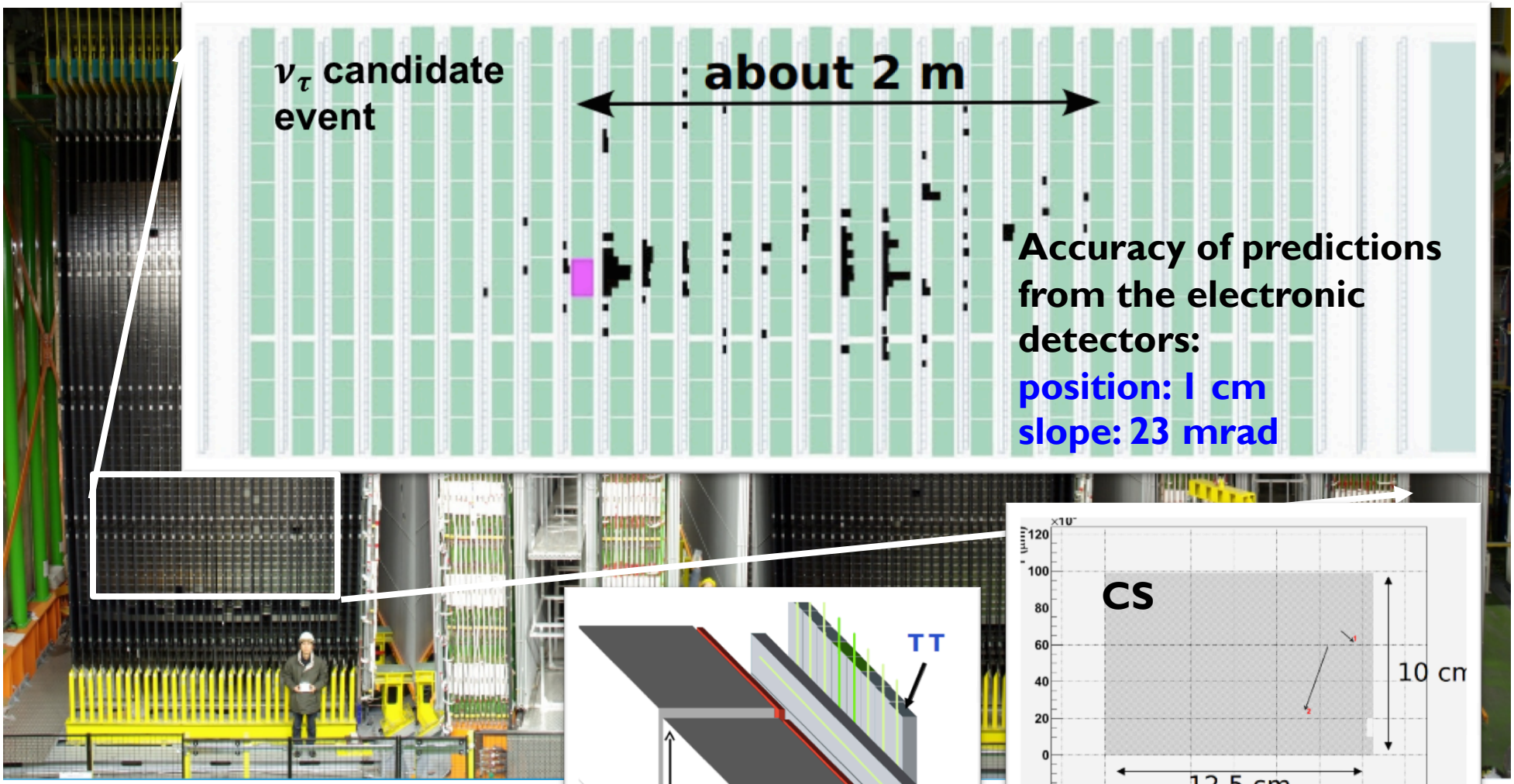
Target Muon spectrometer

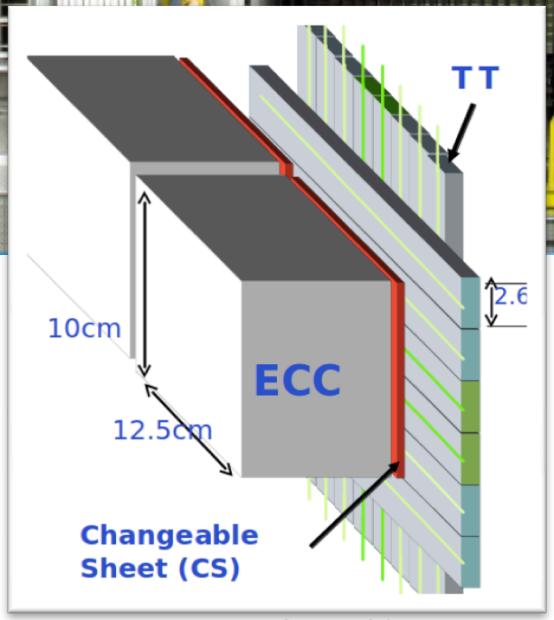




~ 150.000 bricks in total
1.25 kt mass

Super Module 1 — Super Module 2

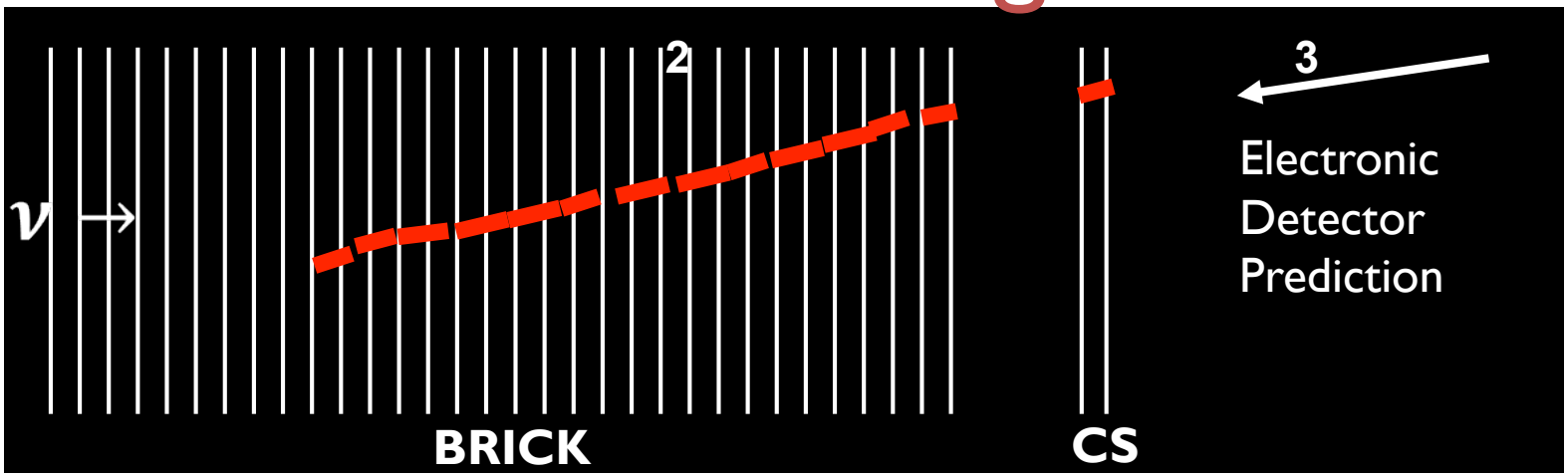




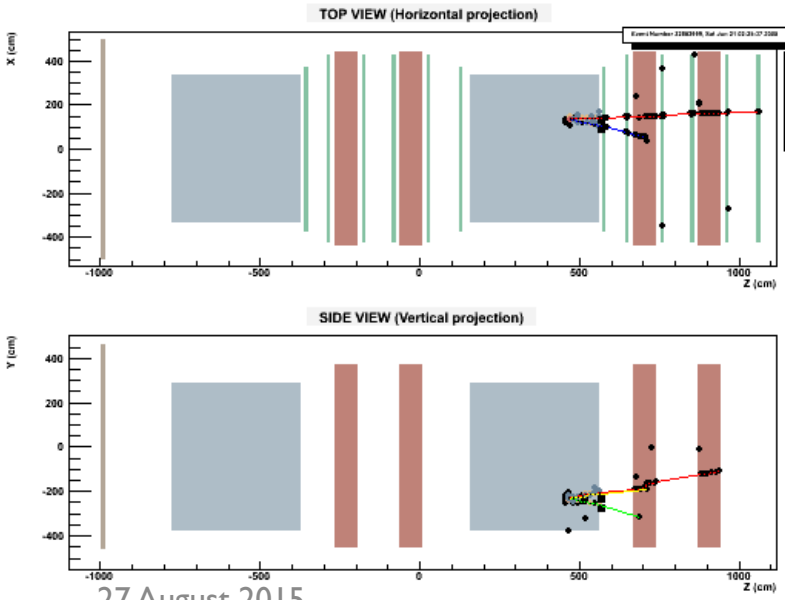
Changeable Sheets (CS) :
the "bridge" from the cm scale of electronics detectors to μm scale of emulsions.

Location efficiency:
CC: 74 %
NC: 48 %

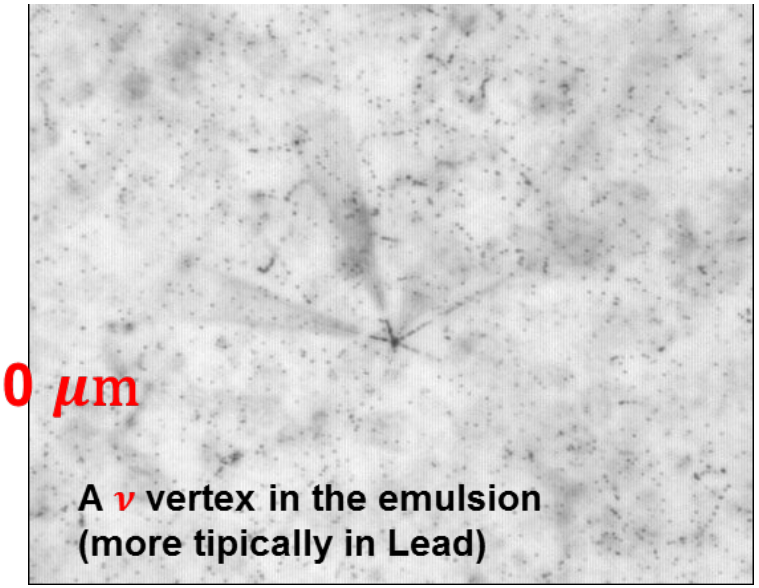
Vertex hunting in the brick



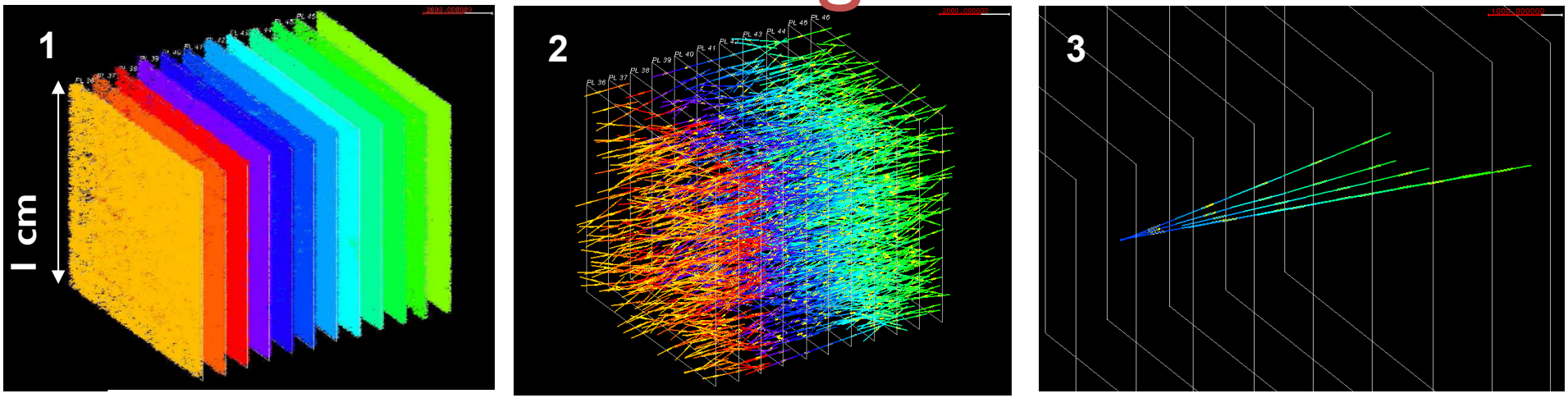
0) all tracks tagged in the **CS films** are **followed upstream** until a stopping point is found



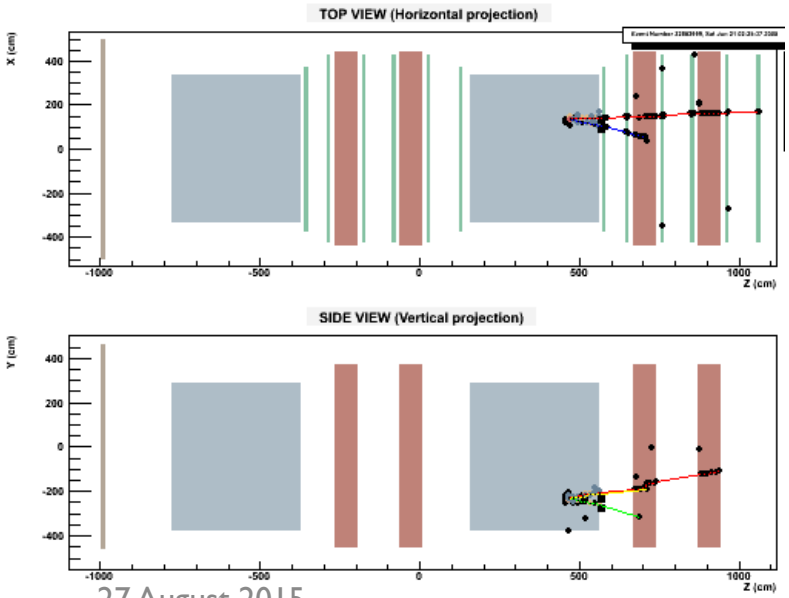
20 m →100 μm
(essential role of CS films)



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.



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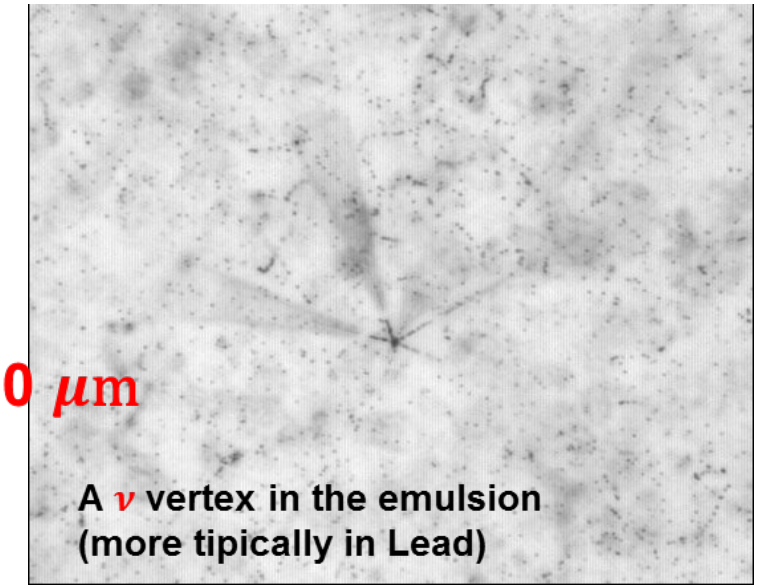


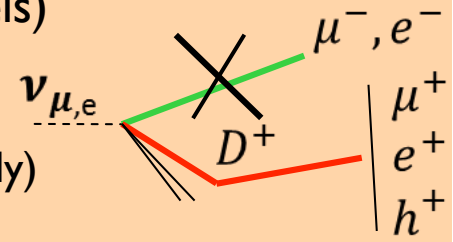
$\nu_\mu \rightarrow \nu_\tau$ background characterization

Monte Carlo simulation benchmarked on control samples.

In **red** some improvements…

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

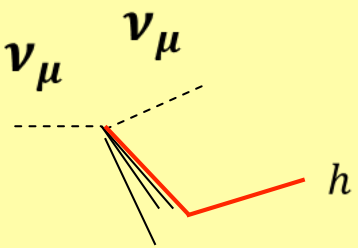


MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

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

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

Hadronic interactions
Background for $\tau \rightarrow h$

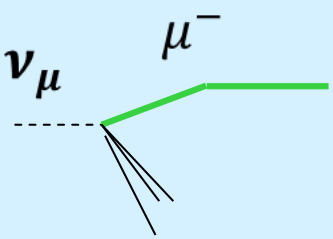


FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

[PTEP9 (2014) 093C01]

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



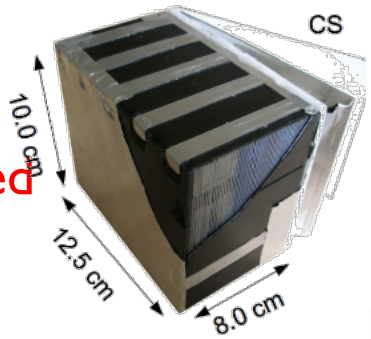
Measurements in the literature (Lead form factor), simulations and dedicated test-beams

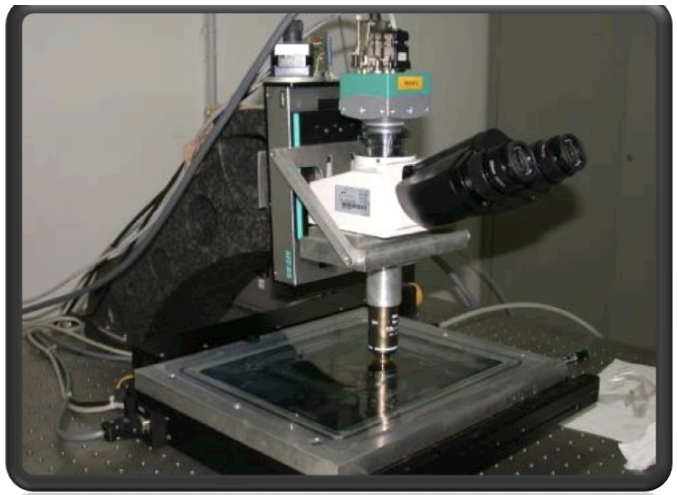
[arXiv:1506.08759]

Analysis of the emulsion films

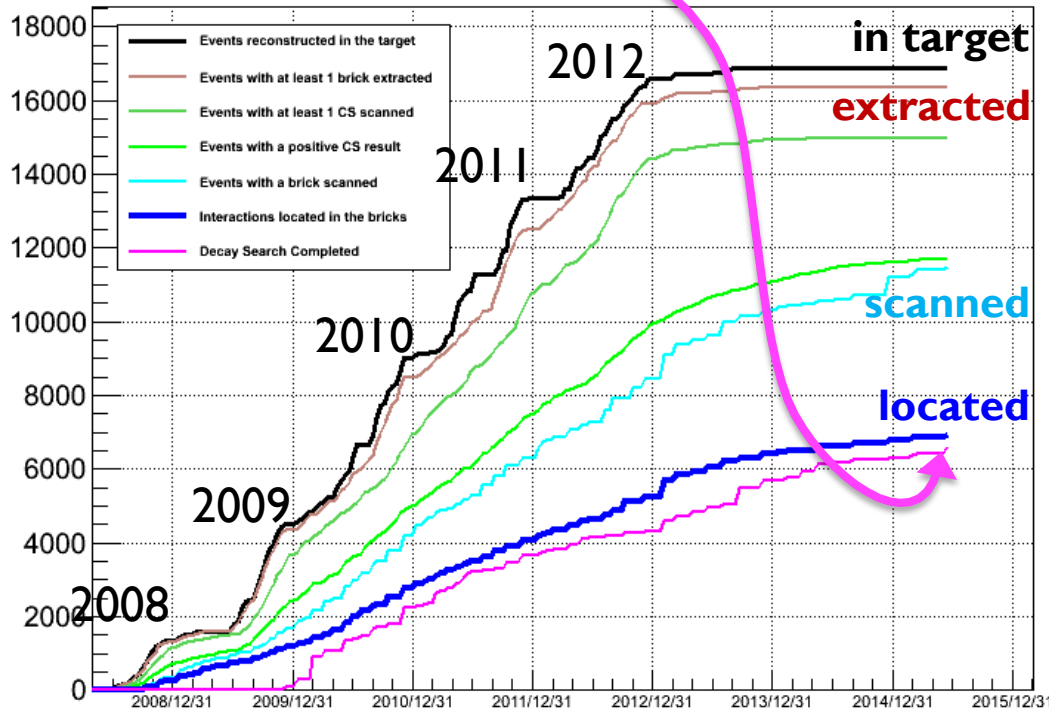
Bricks are **ordered** according to their probability of containing the interaction vertex.

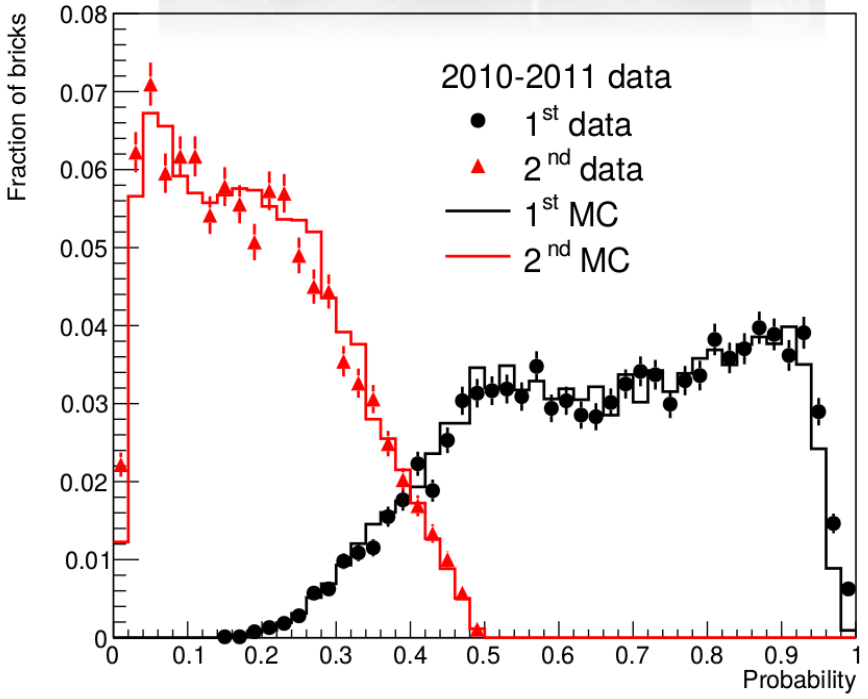
Analysis status:
2008-09 completed up to 4th brick
2010-12 1st and 2nd bricks completed





> 6600 fully analysed bricks





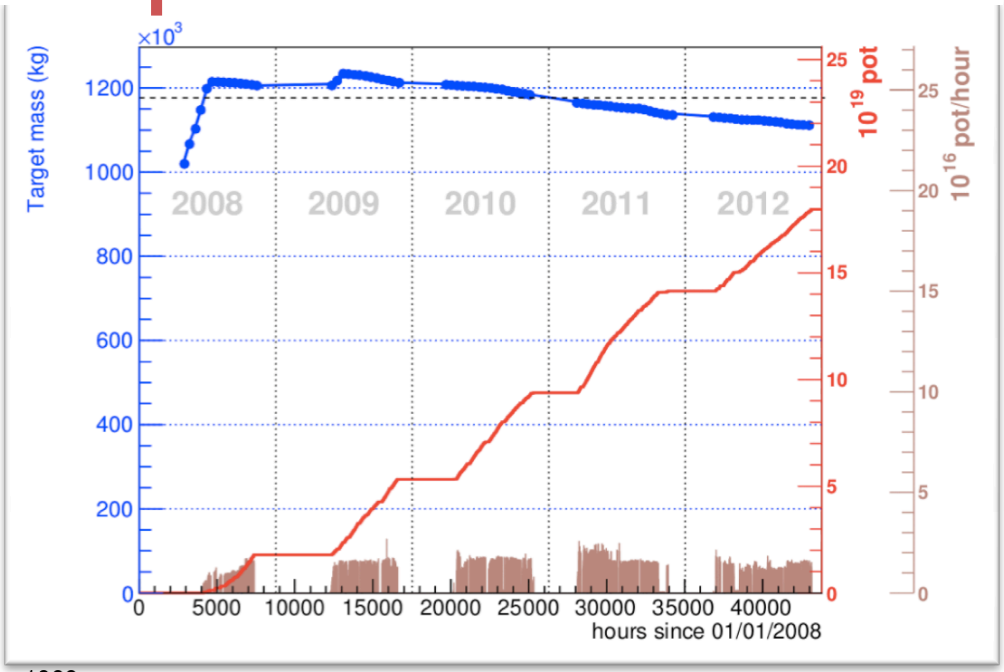
Data samples

The 5years long CNGS run ended in 2012.

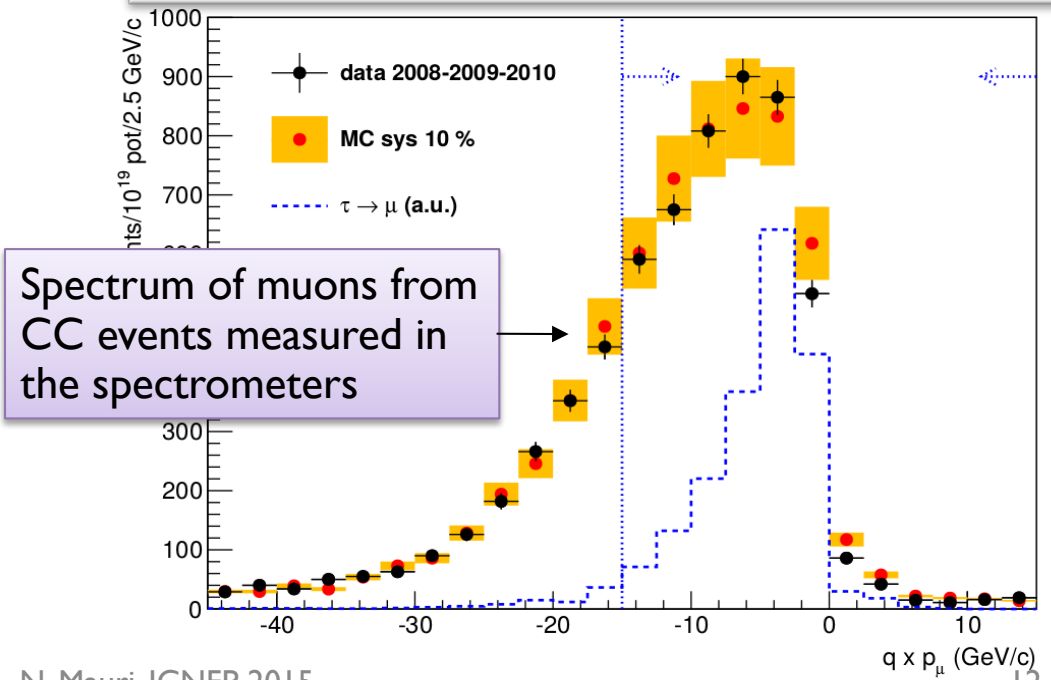
$1.8 \cdot 10^{20}$ p.o.t. collected
(80% of the design)

1.25 kton initial target mass
(150 k bricks)

19505 neutrino interactions
in the emulsion targets.



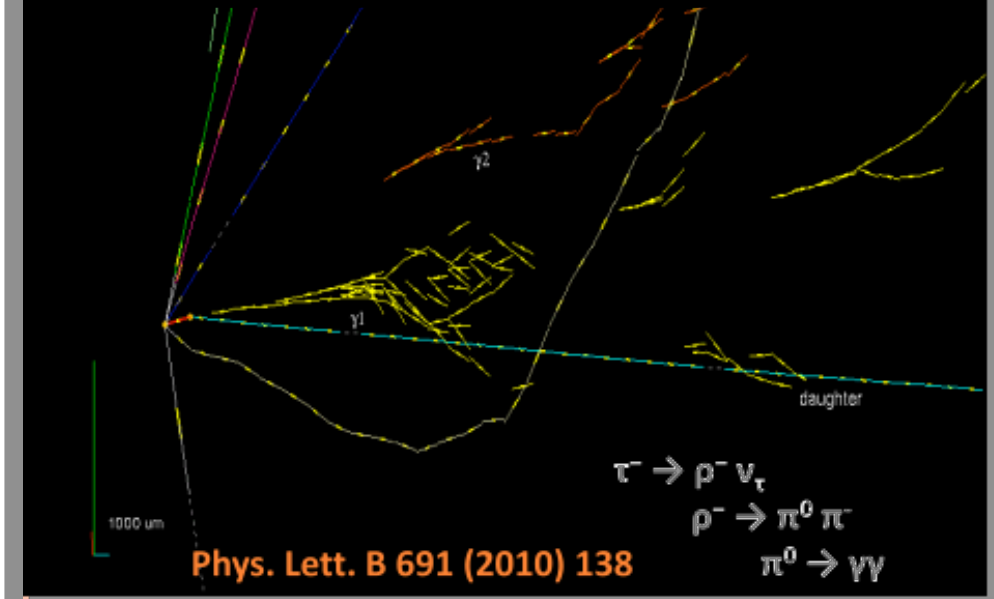
Year	Days	p.o.t. (10^{19})	ν interactions
2008	123	1.74	1698
2009	155	3.53	3693
2010	187	4.09	4248
2011	243	4.75	5131
2012	257	3.86	3923
tot	**965**	**17.97**	**19505**



Spectrum of muons from CC events measured in the spectrometers

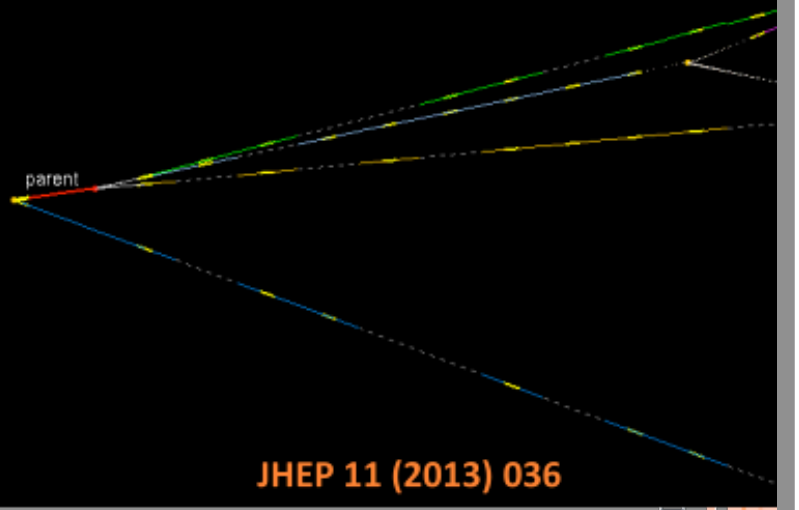
$\nu_\mu \rightarrow \nu_\tau$ search: signal candidates

1st candidate (2010): $\tau \rightarrow h$



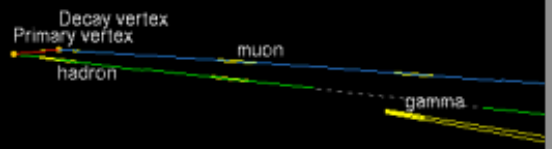
Phys. Lett. B 691 (2010) 138

2nd candidate (2012): $\tau \rightarrow 3h$



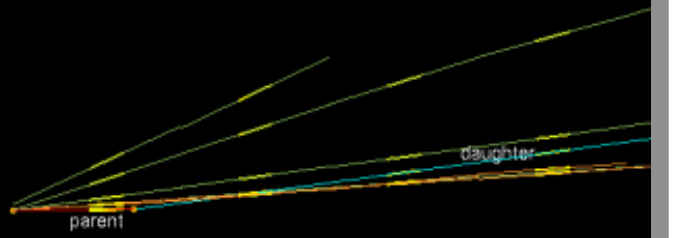
JHEP 11 (2013) 036

3rd candidate (2013): $\tau \rightarrow \mu$



Phys. Rev. D 89 (2013) 051102

4th candidate (2014): $\tau \rightarrow h$

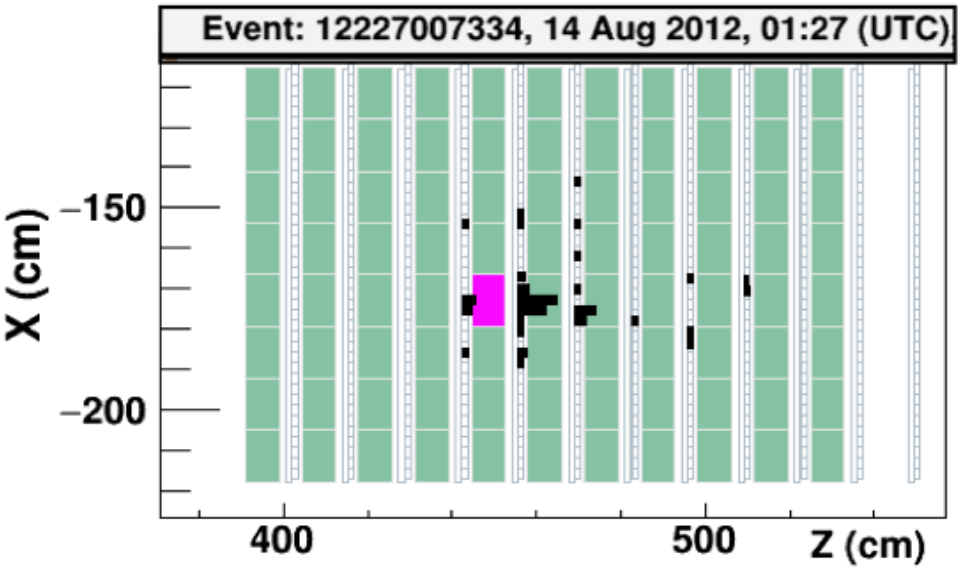


PTEP (2014) 101C01

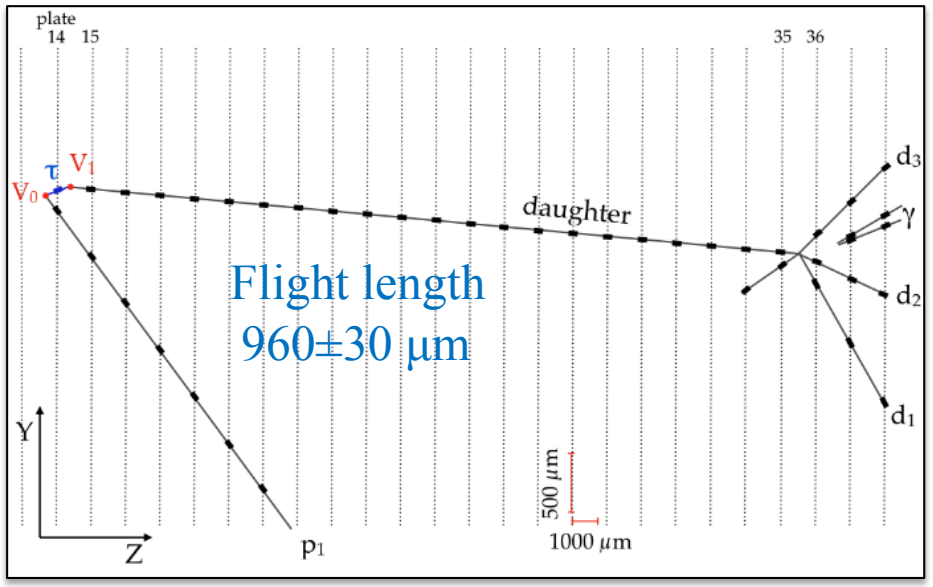
The 5th ν_τ candidate

Accepted by PRL, arXiv:1507.01417

As seen by the electronic detectors…

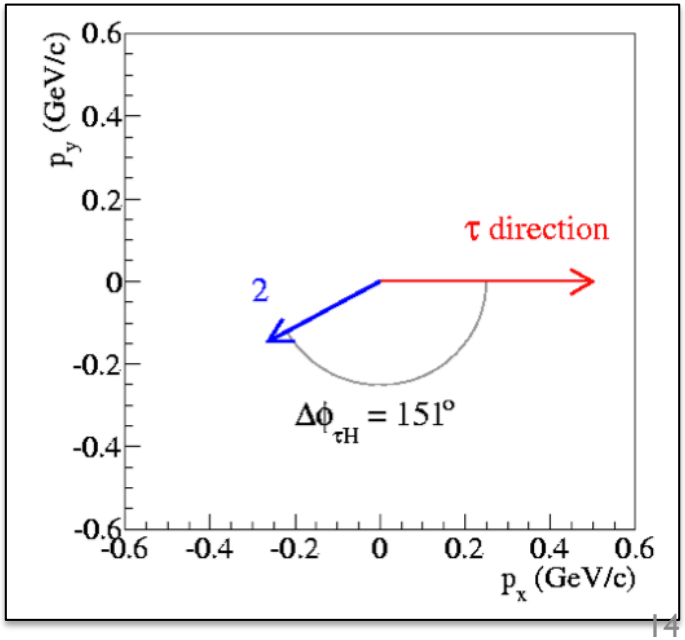


..and in the brick



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)



ν_τ analysis result

Accepted by PRL, arXiv:1507.01417

Candidate events have to fulfill 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	/	/

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** hypo.

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
$\tau \to 1h$	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

P-value $= 1.1 \cdot 10^{-7}$

Exclusion of background-only hypothesis: 5.1 σ

Measurement of Δm^2_{23}

Accepted by PRL, arXiv:1507.01417

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

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

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

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

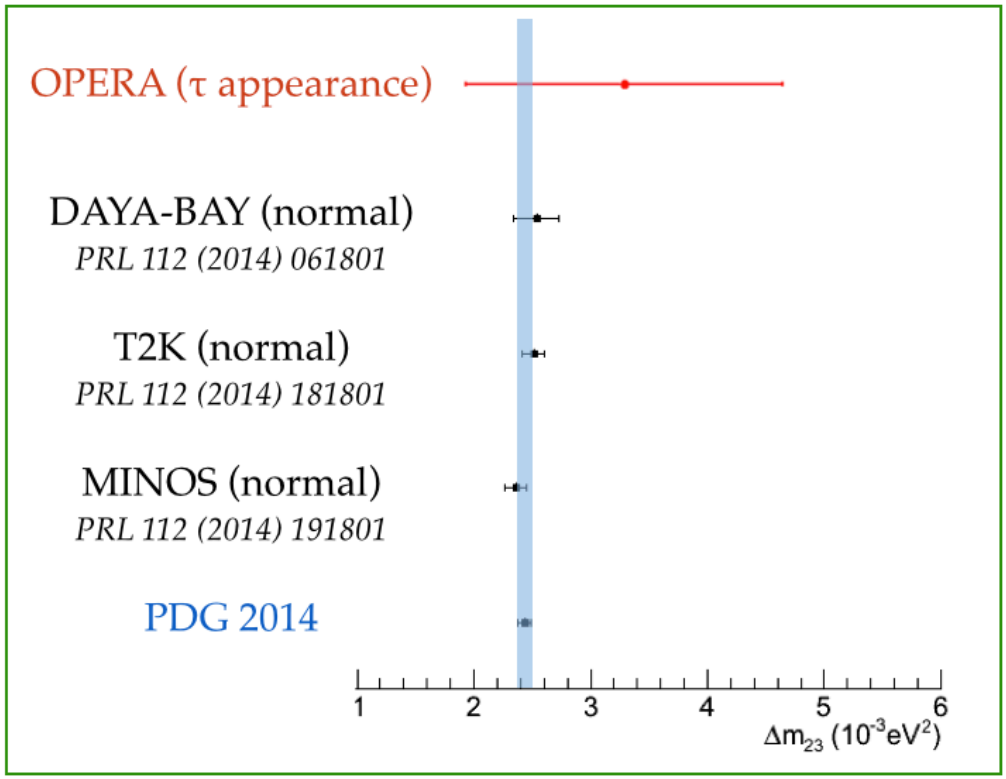
"Steep" Δm^2_{23} dependence

→ counting based measurement

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

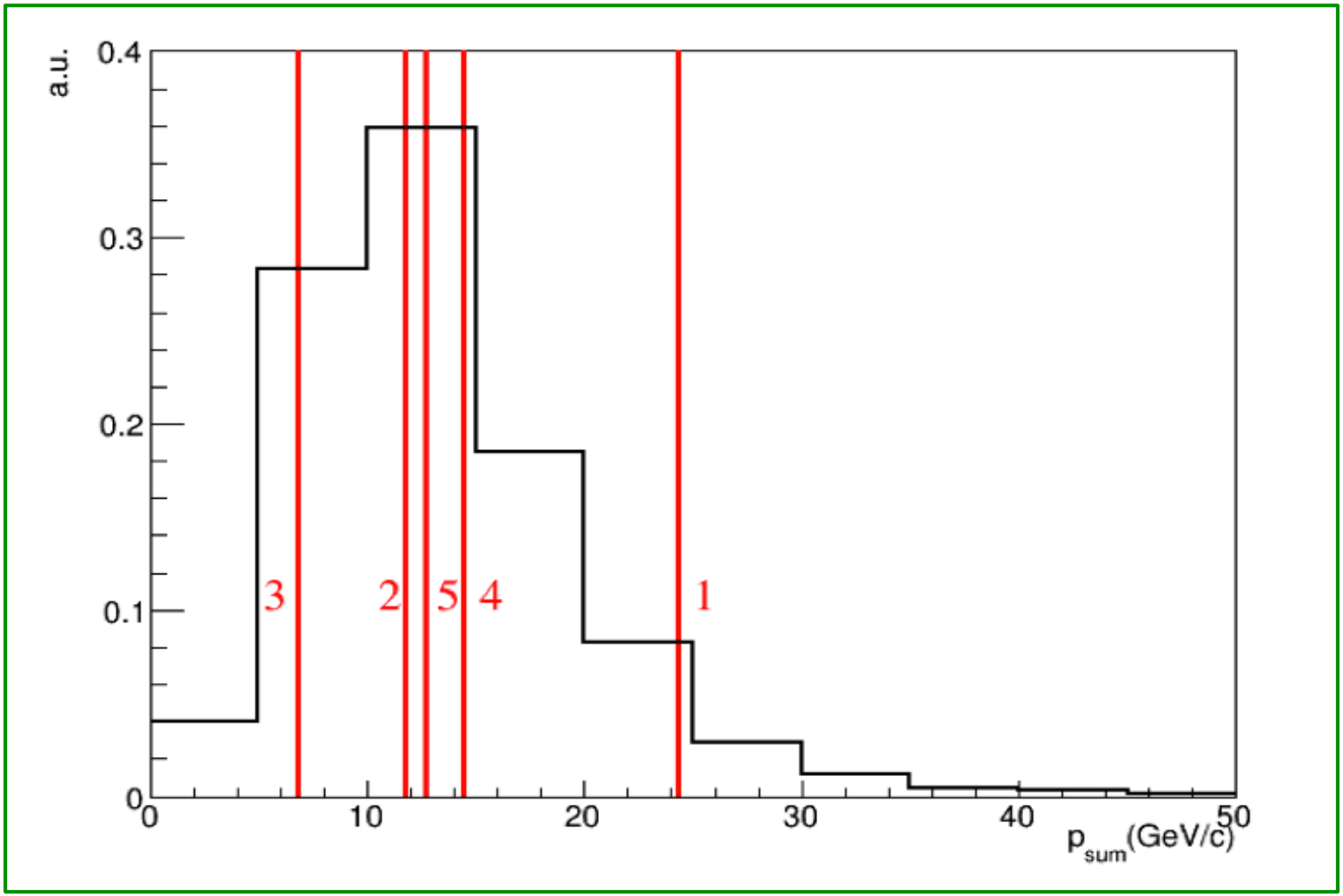
$$\Delta m^2_{23} = [2.0 - 4.7]\ 10^{-3}\ \text{eV}^2$$

(assuming full mixing)



Visible energy of all the candidates

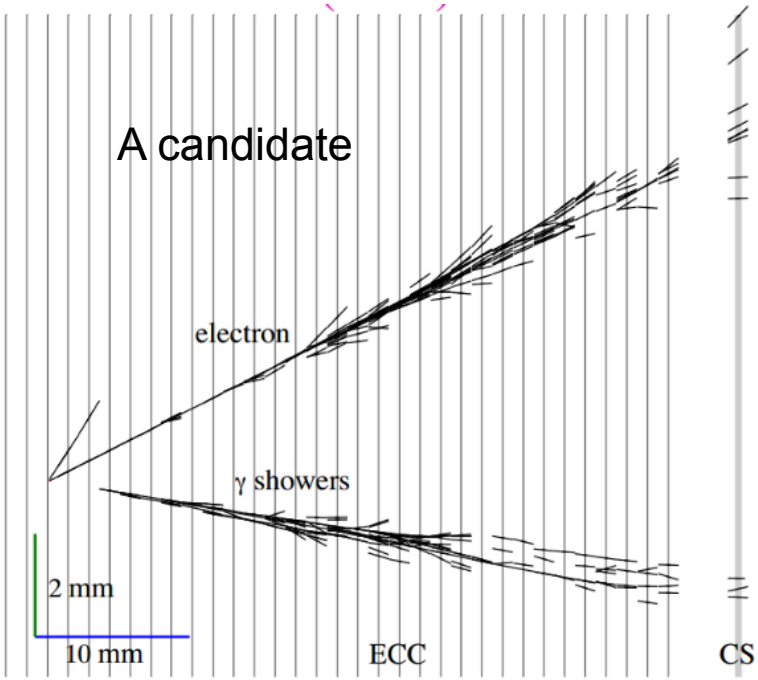
Sum of the momenta of charged particles and γ's measured in emulsion

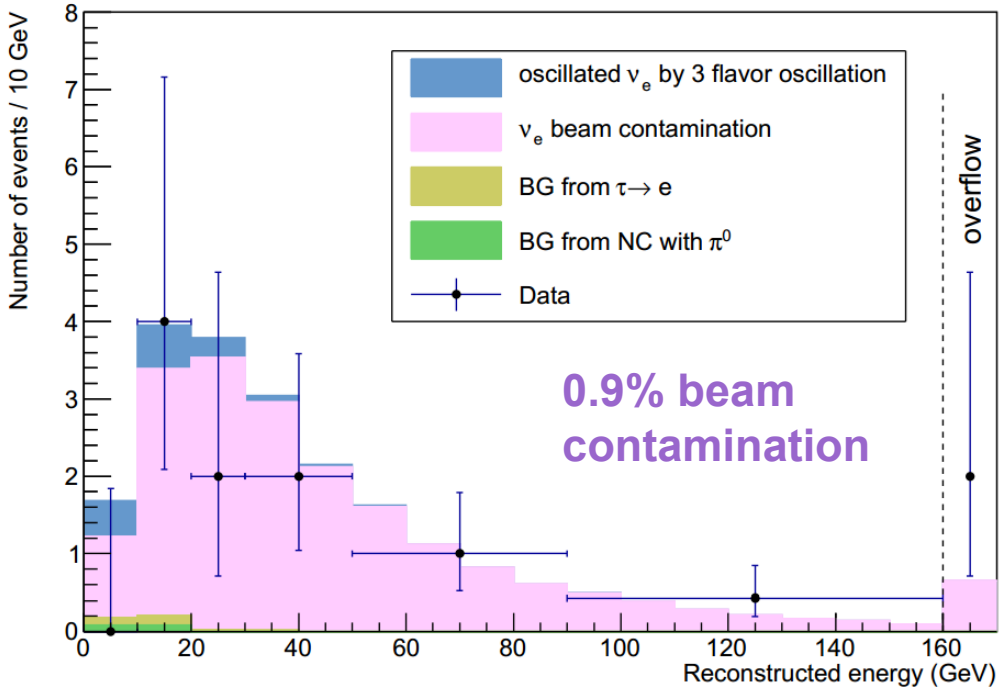


Subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

[JHEP 1307 (2013) 004]

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





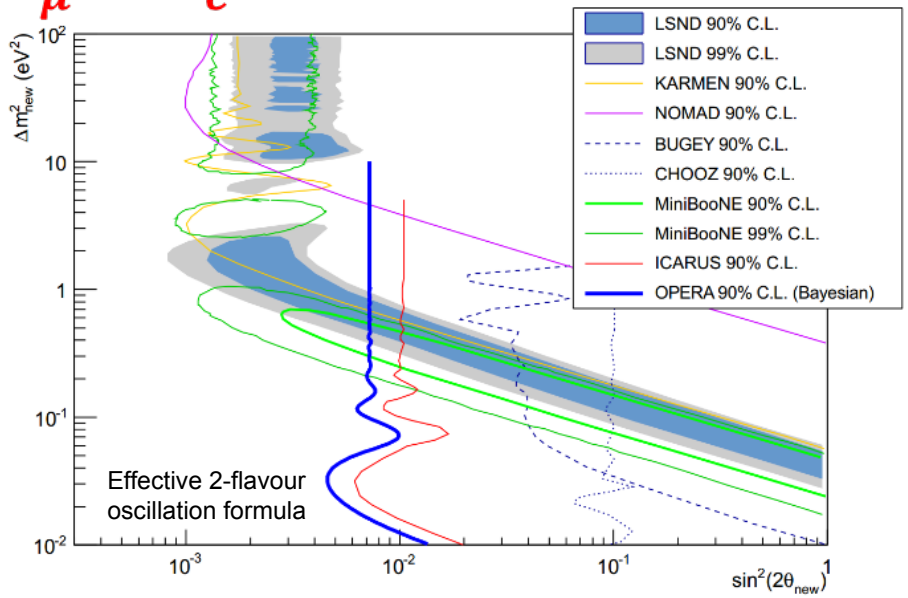
		E < 20 GeV
ν_e candidates	19	4
Background	19.8 ± 2.8 (sys.)	4.6

$$\sin^2 2\theta_{13} < 0.44 \text{ (90\% C.L.)}$$

Sterile neutrino mixing searches

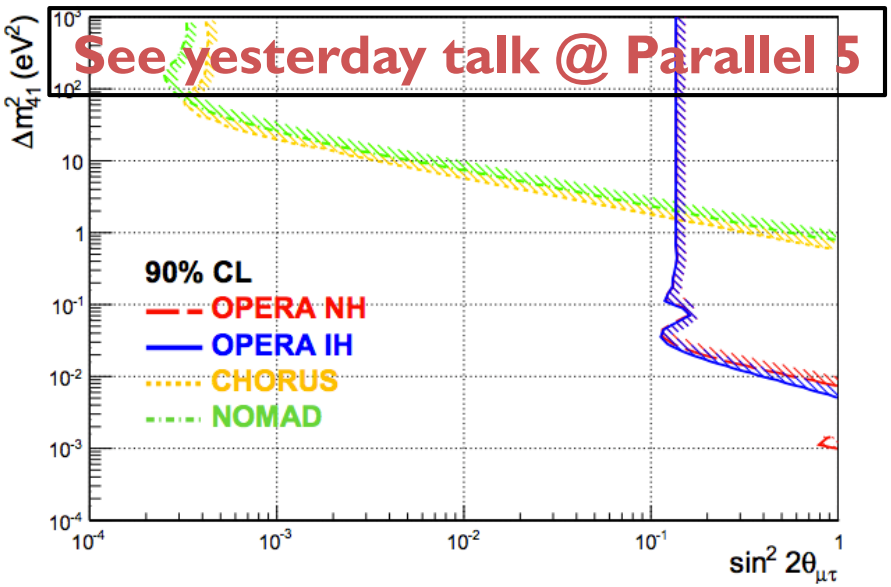
How the appearance probability is modified by one possible extra sterile state (3+1 scheme)?

$\nu_\mu \rightarrow \nu_e$



[JHEP 1307 (2013) 004]

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

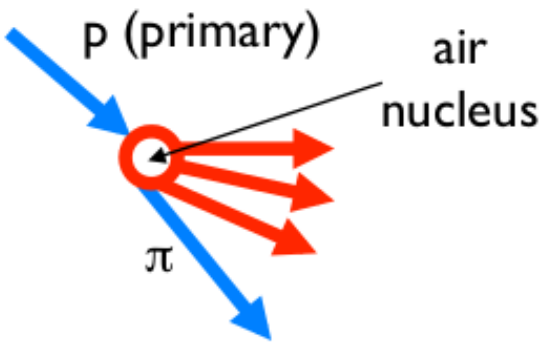


[JHEP 074 (2015) 0315]

Rich structure. Can result in an increase or decrease of expected number of ν_τ events.

First limits on $|U_{\mu 4}|^2 |U_{\tau 4}|^2$ from direct measurement of ν_τ .

Atmospheric muon charge ratio



Eur. Phys. J. C74 (2014) 2933

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

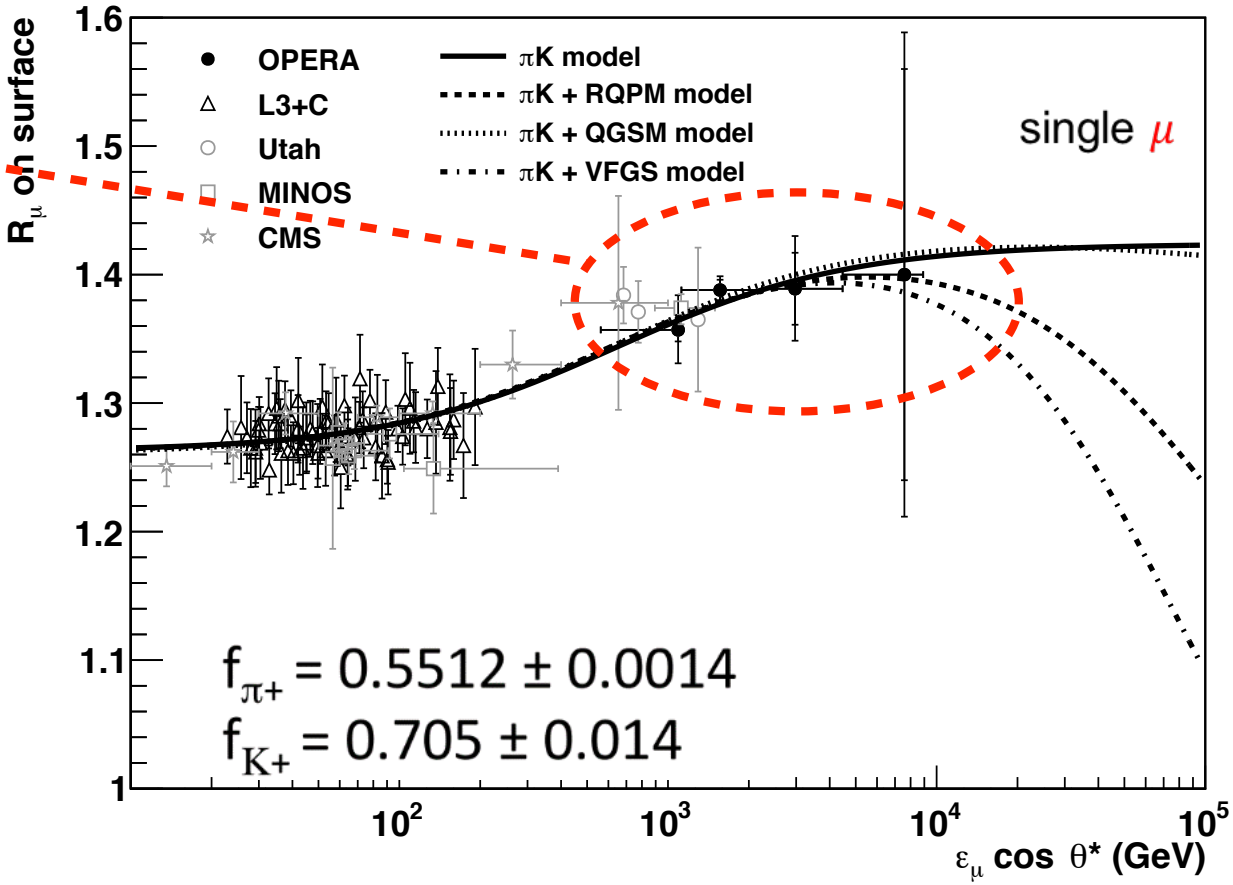
Highest-E region reached!

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 $\delta_0 = 0.61 \pm 0.02$

Conclusions

- 1.8 x 10^{20} pot by CNGS from 2008-12 (80% of design).
- Detector successfully measuring ν_e , ν_μ and ν_τ
- Analysis of an extended data sample. Improved background evaluation
- **5 ν_τ candidates** so far with a 0.25 event background
- No oscillation hypothesis excluded at **5.1 σ.**

  → discovery of ν_τ appearance in the CNGS beam

- 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 ν_τ .
- Interesting cosmic ray physics results (muon charge ratio in the highest energy region)

Thank you for your attention!

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

BACK UP

The OPERA Collaboration

Bari
Bologna
LNF Frascati
L'Aquila
LNGS
Napoli
Padova
Roma
Salerno

LAPP Annecy
IPHC Strasbourg

LHEP Bern

IHE Brussels

Hamburg

IRB Zagreb

INR Moscow
NPI Moscow
ITEP Moscow
SINP NSU Moscow

JINR
Dubna

METU Ankara

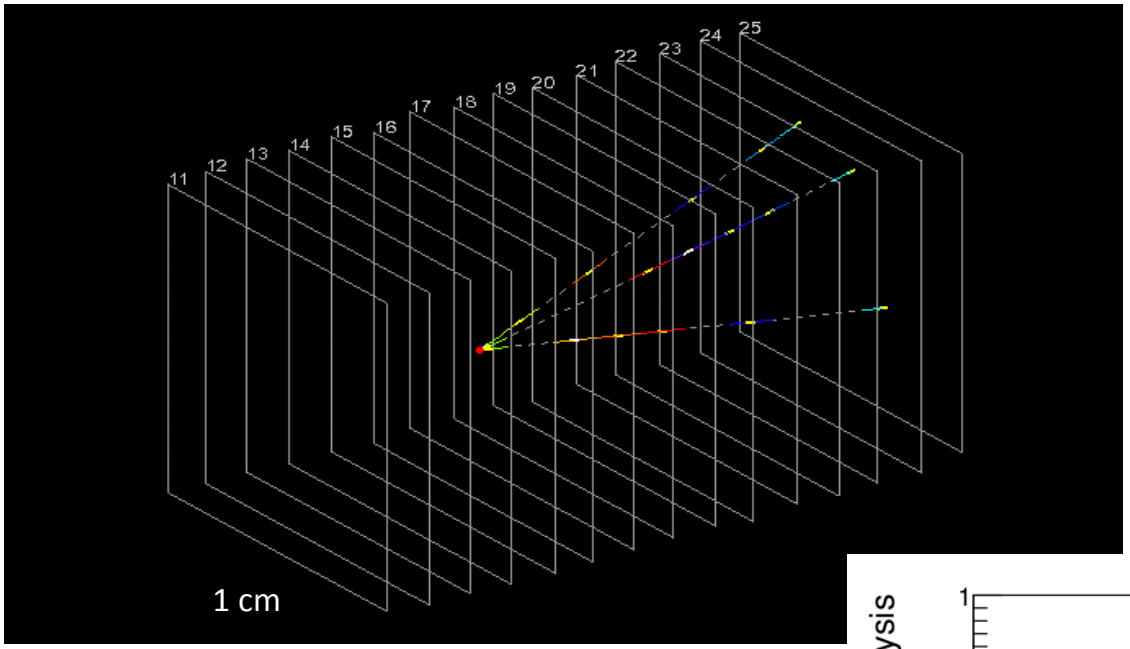
Technion Haifa

Aichi
Toho
Kobe
Nagoya
NIhon

Jinjiu

~ 140 physicists
from 28 institutions and 11 countries

Location efficiency



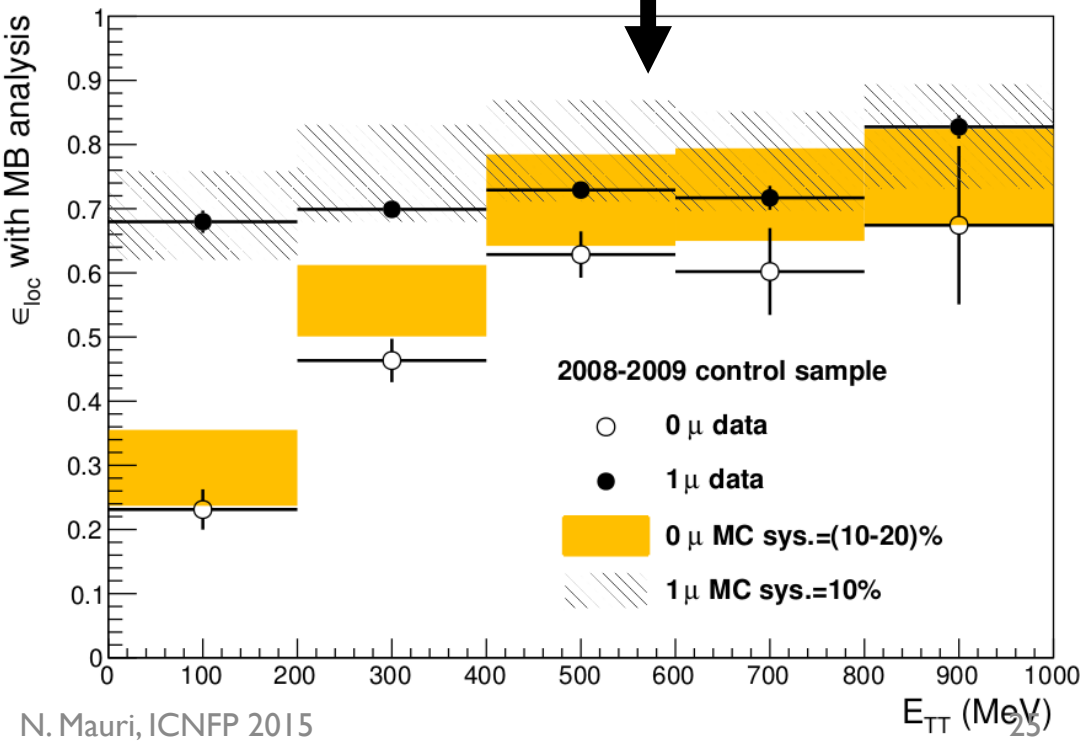
[JHEP 11 (2013) 036]

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



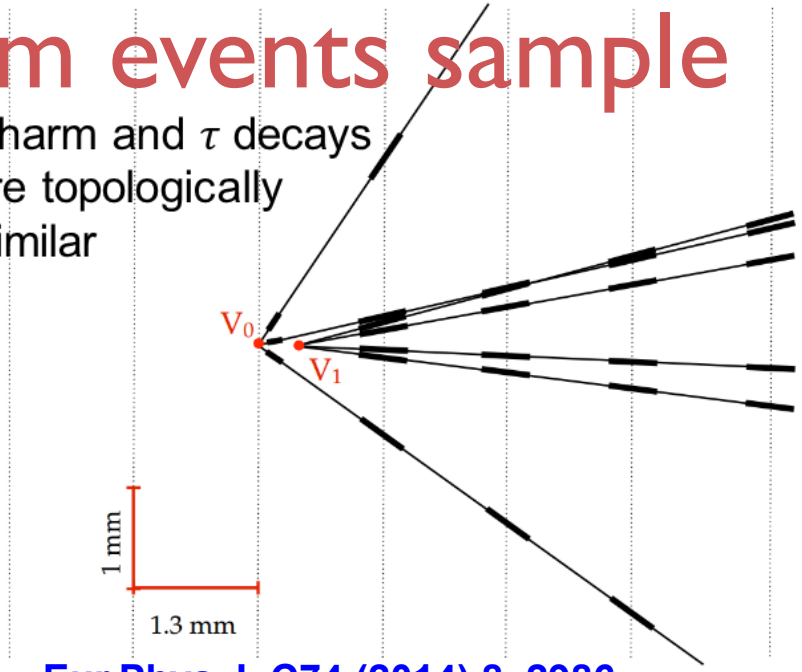
BACK UP
- BACKGROUND

Validation with the charm events sample

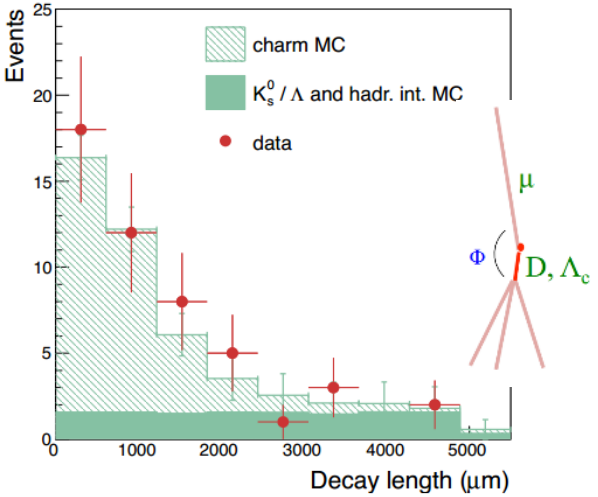
Test for: reconstruction efficiencies, description of kinematical variables, charm background.

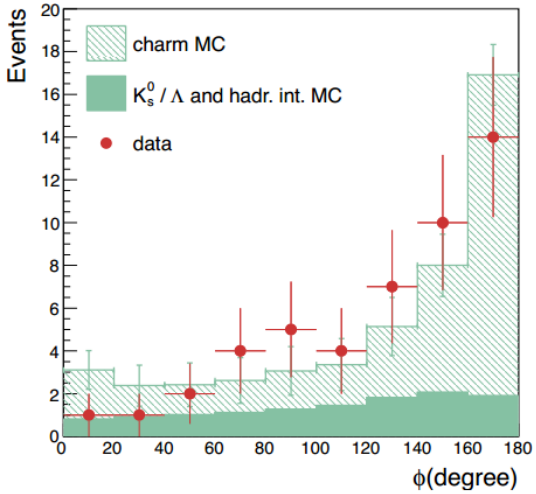
54 ± 4 expected ↔ 50 observed

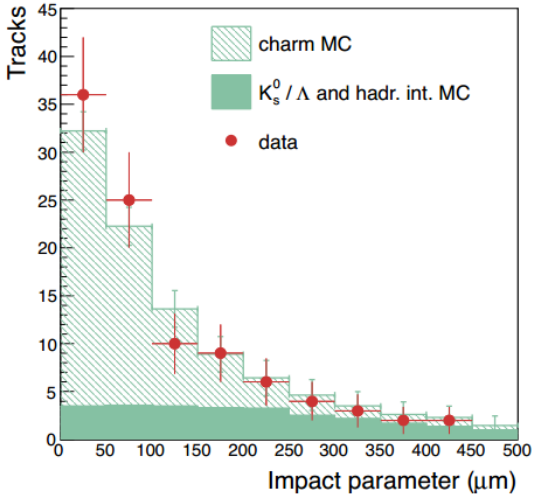
Charm and τ decays are topologically Similar

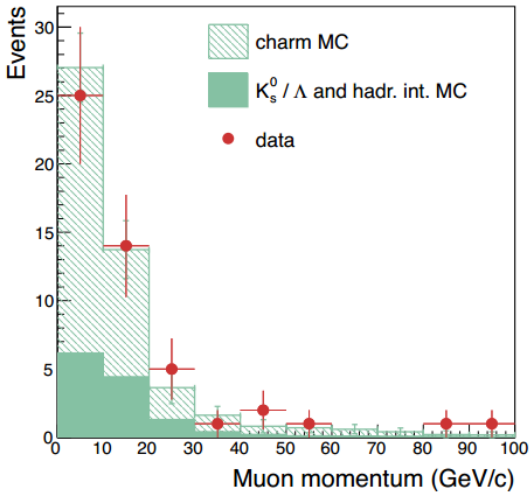


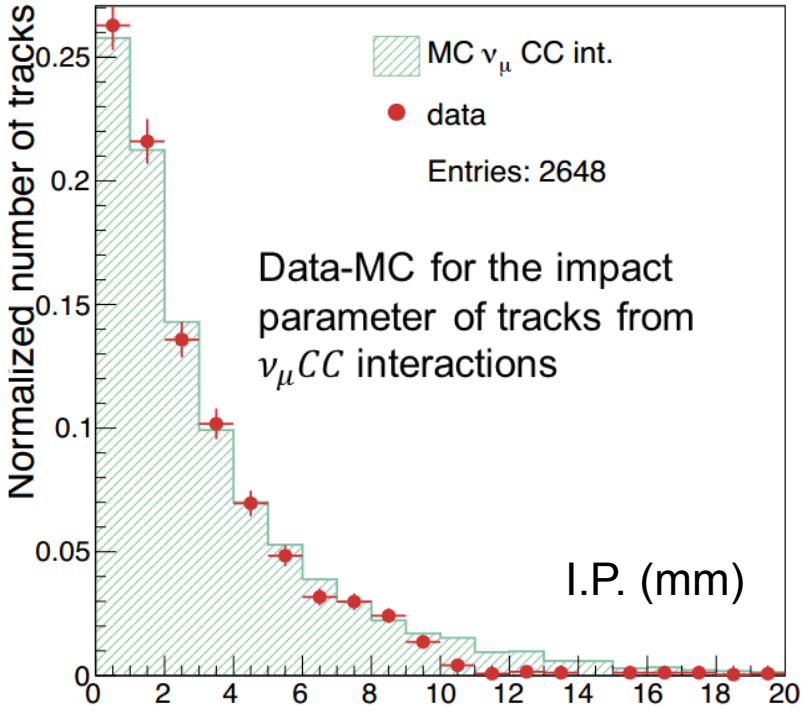
Eur.Phys.J. C74 (2014) 8, 2986







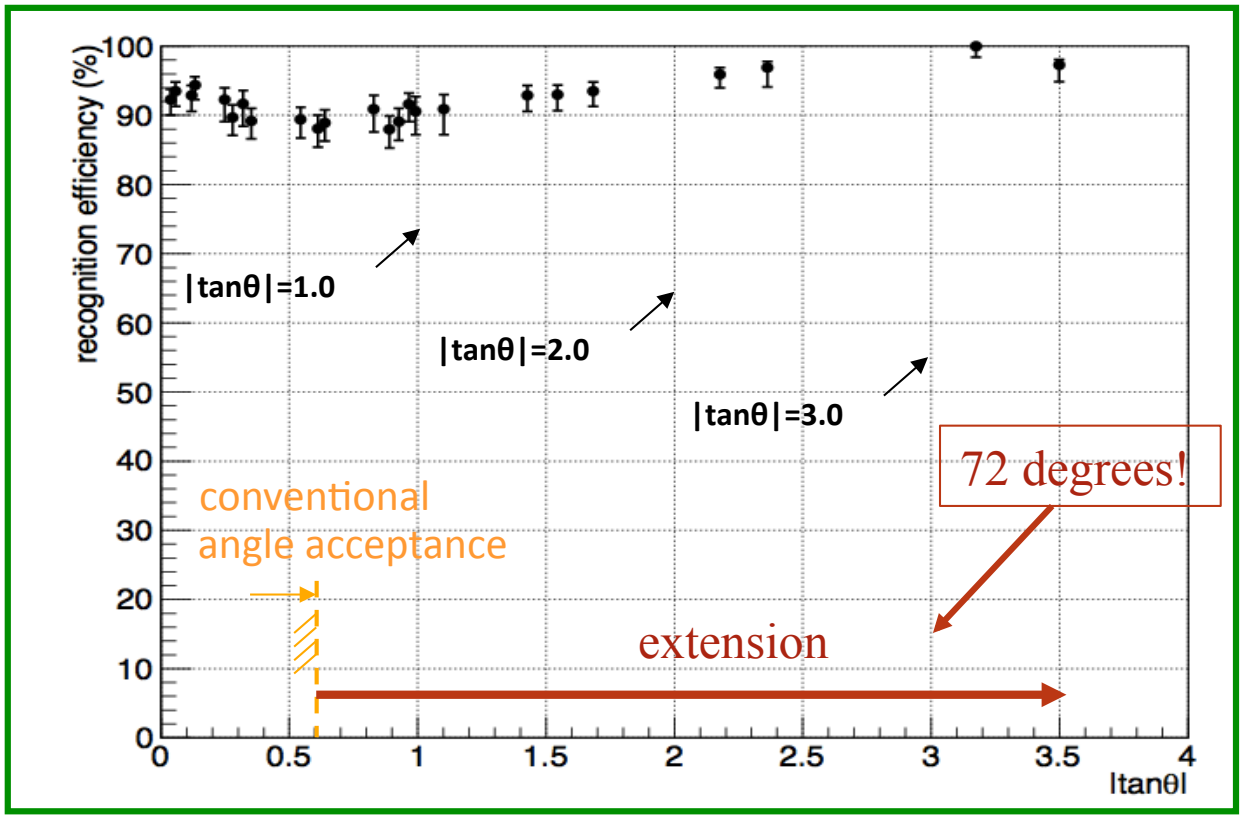


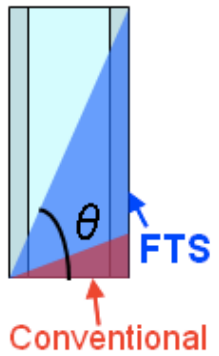


Improvement on the background rejection

Large angle track detection

Undetected soft and large angle muons are the source of charm background
Detection of particles and nuclear fragments in hadronic interactions

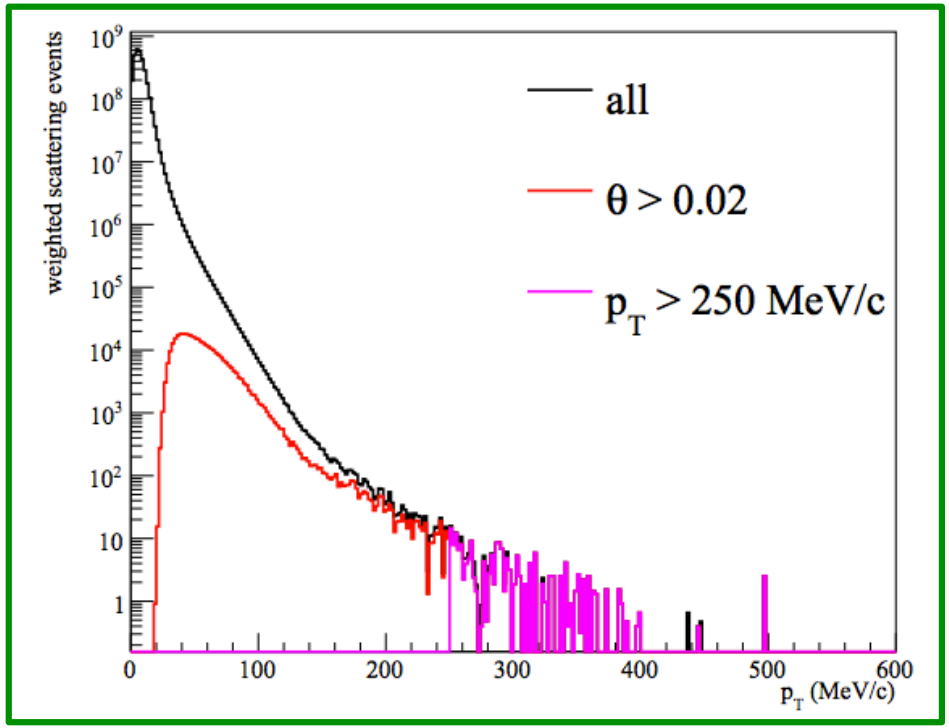




JINST 9 (2014) P12017

Large angle μ scattering

CNGS ν_μ CC muons on Lead $1 < p_\mu < 15$ GeV/c



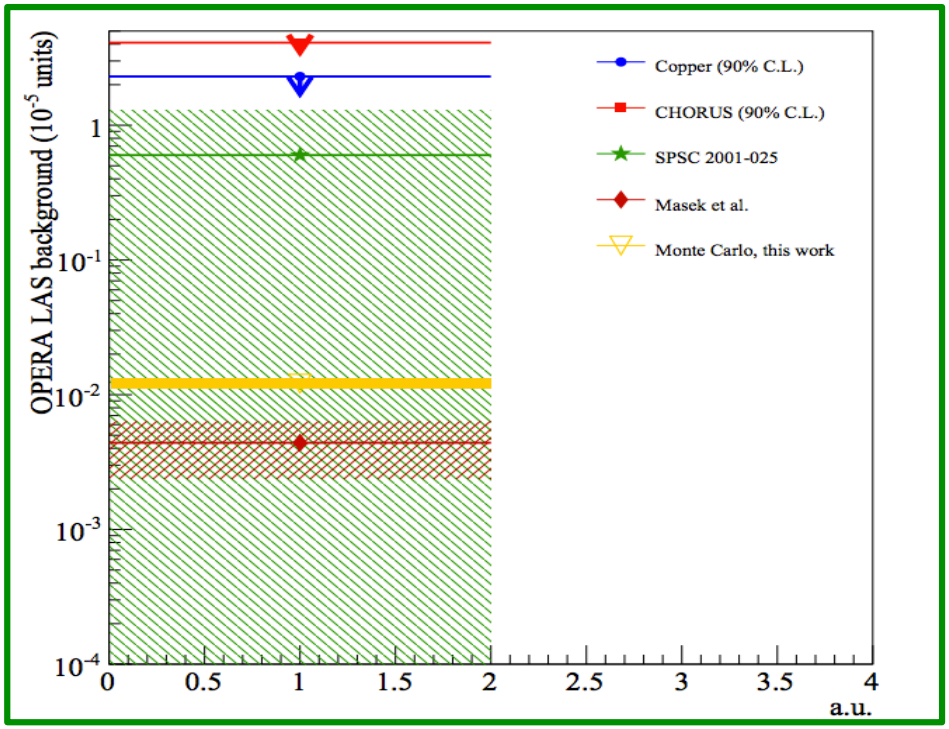
Main background in the τ →μ decay channel when using upper limits in the past

LAS background estimation

$$(1.2 \pm 0.1) \times 10^{-7} / \nu_\mu^{CC}$$

well below the values considered so far

IEEE Transactions on Nuclear Science

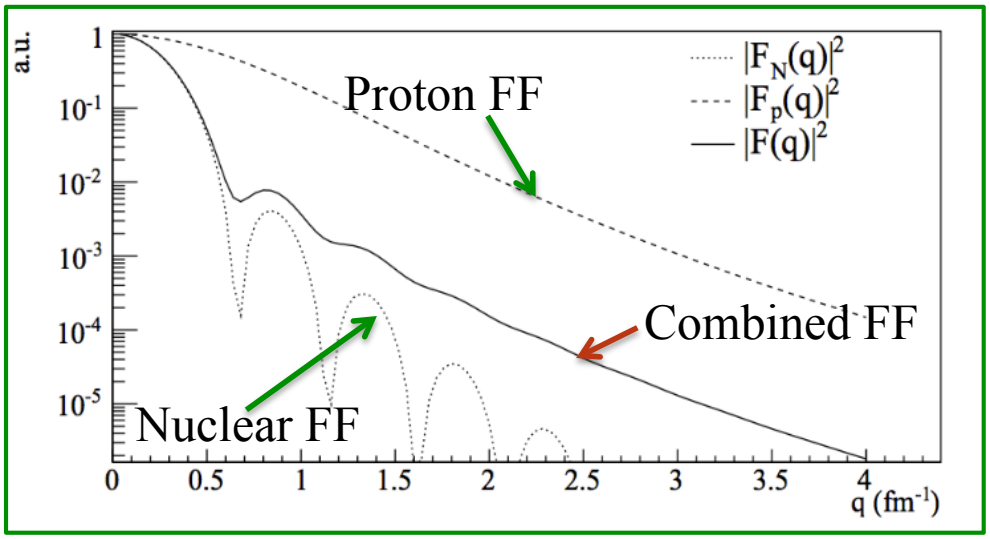


Large angle μ scattering

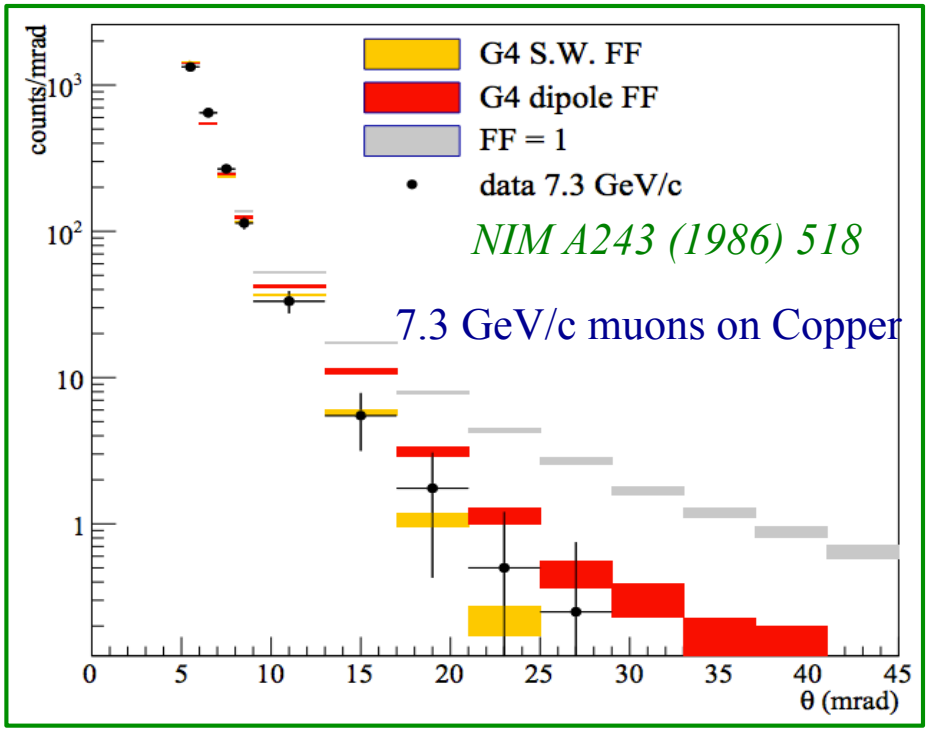
New estimate based on GEANT4
- Simulation modified by introducing form factors (FF) for Lead
(Saxon-Woods parameterization)

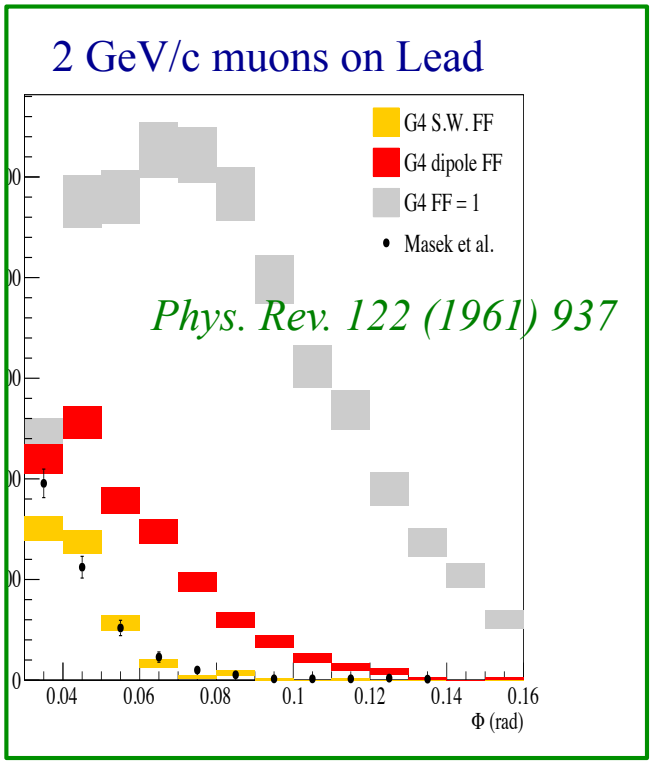
$$\rho_{SW}(r) = \rho_0 \left(1 + e^{\frac{r-b}{a}}\right)^{-1}$$

IEEE Transactions on Nuclear Science



MC predictions compared to available data

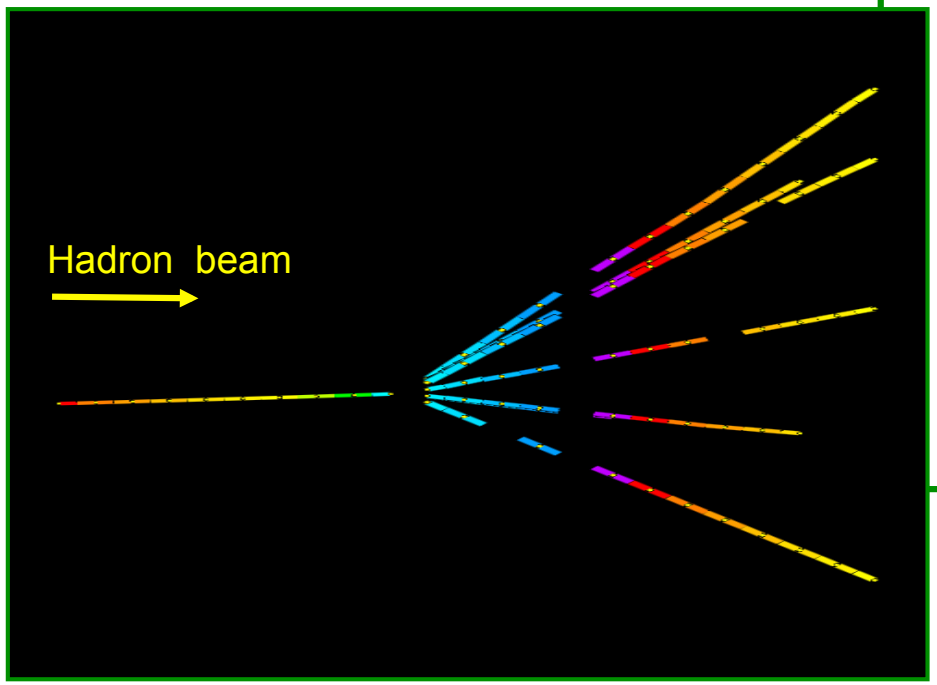


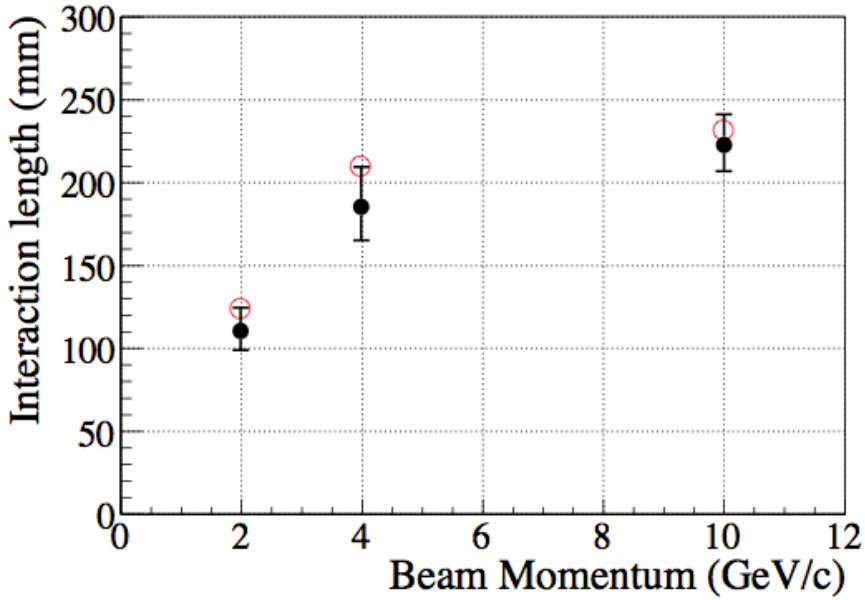


Background studies: hadronic interactions

Comparison of large data sample (π^- beam test at CERN) with Fluka simulation
→ check the agreement and estimate the systematic uncertainty

Track length analysed in the brick:
- 2 GeV/c : 8.5 m
- 4 GeV/c : 12.6 m
- 10 GeV/c : 38.5 m

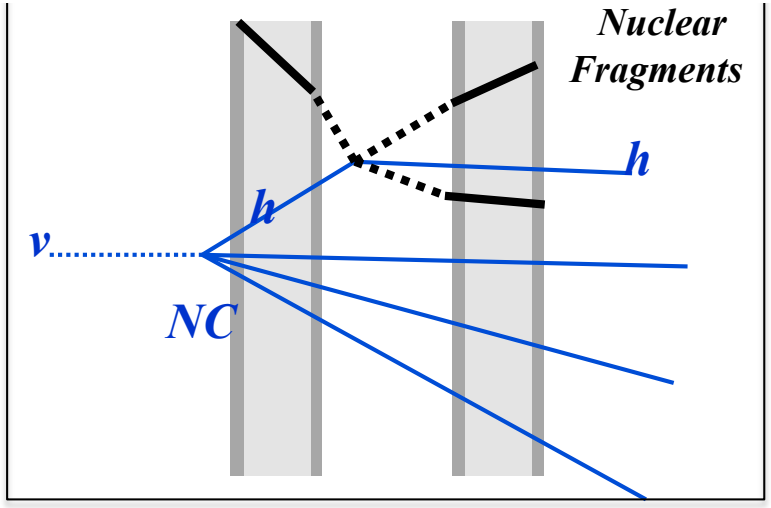




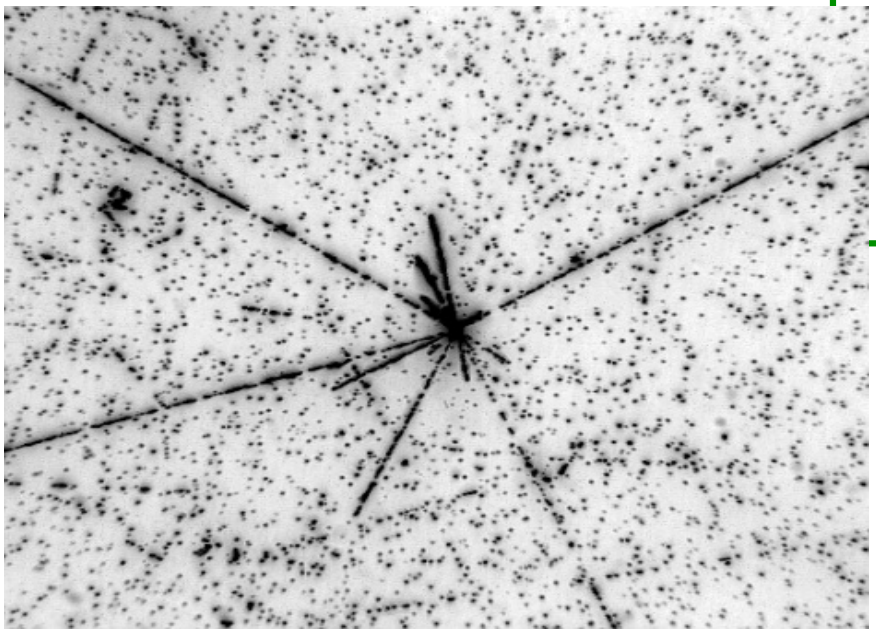
Black : π^- beam data
Red : MC (FLUKA) simulation

PTEP 9 (2014) 093C01

Nuclear fragments emission probability

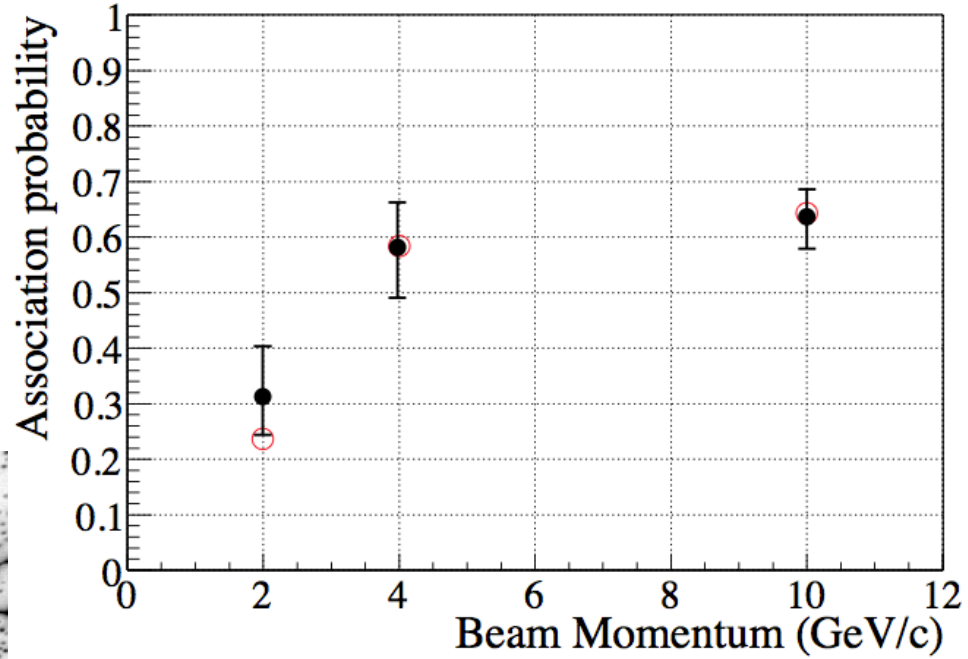


Highly ionizing fragments



150 μm

Additional background reduction



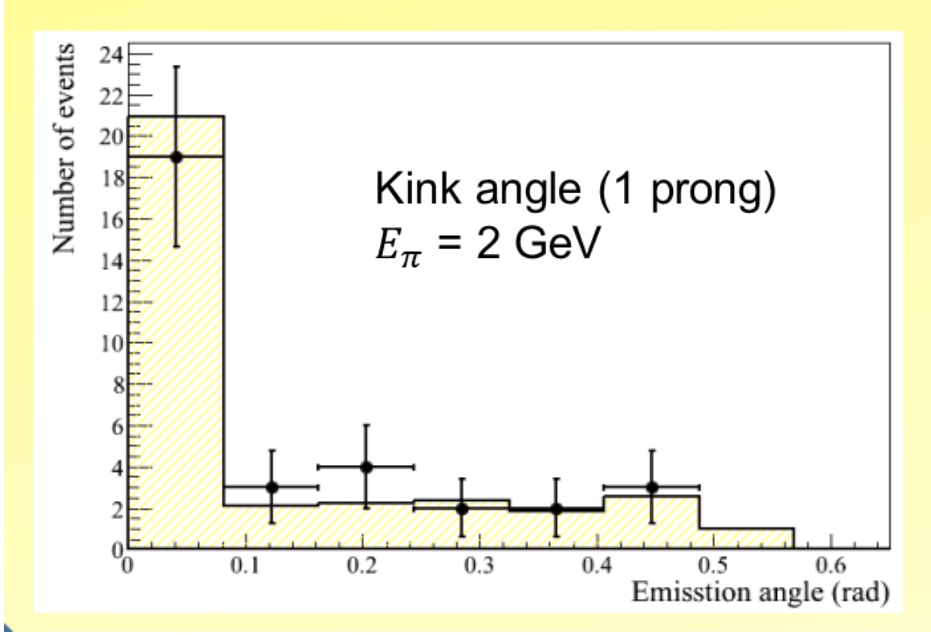
Black : experimental data

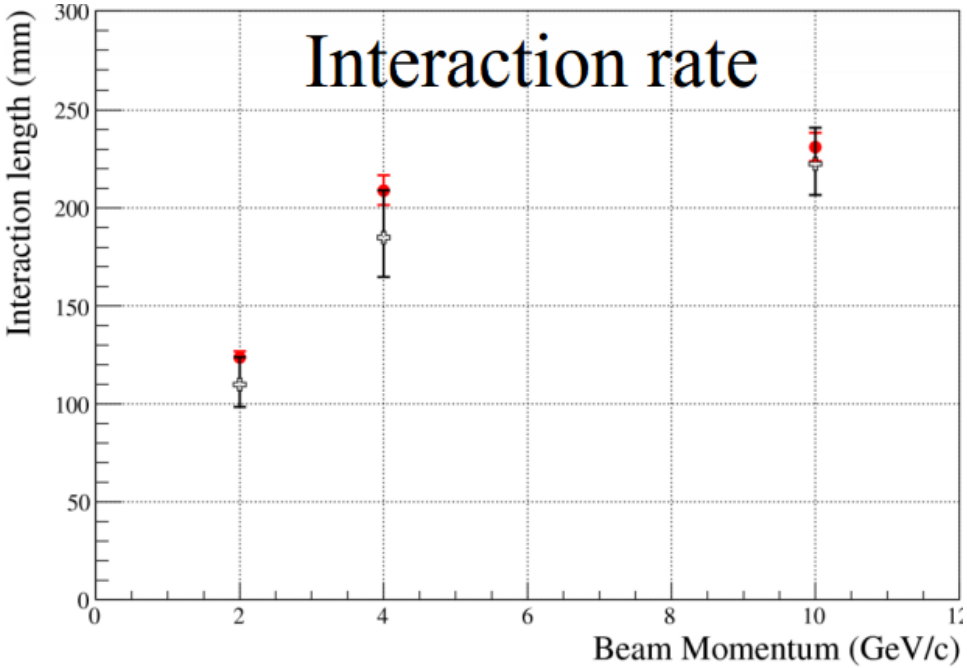
Red : simulated data (β= p/E = 0.7)

PTEP 9 (2014) 093C01

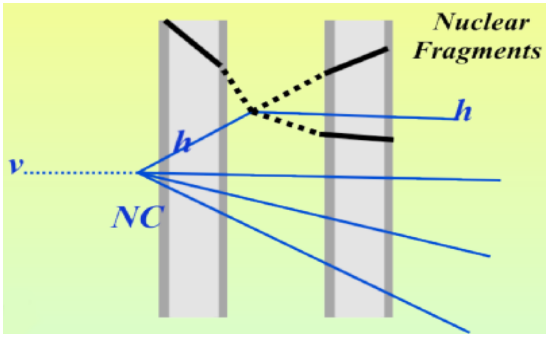
Hadronic background: π test beam

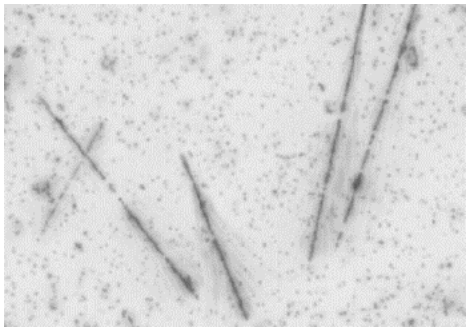
CERN π test beam

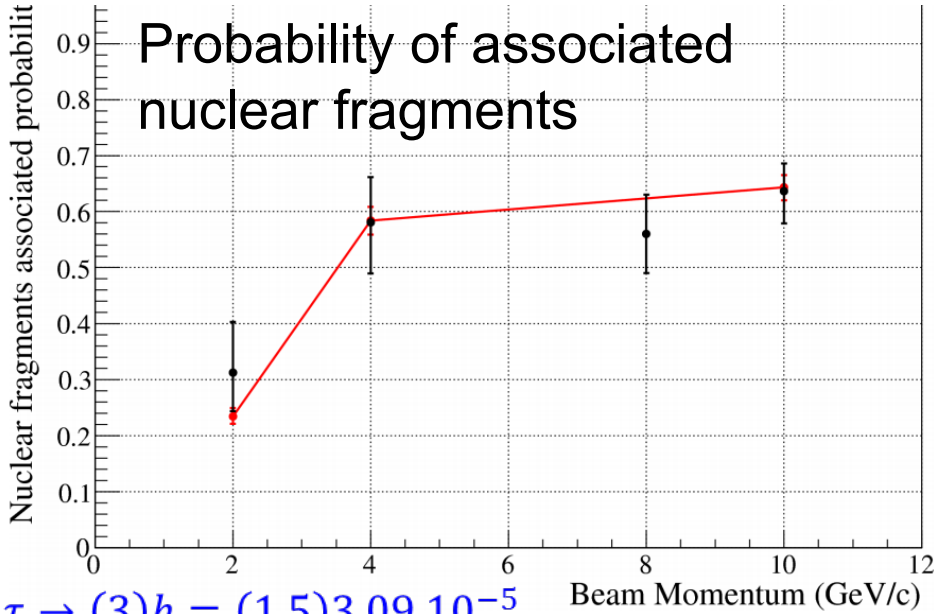




Nuclear fragments: a smoking gun for the occurrence of an π interaction instead of a decay.





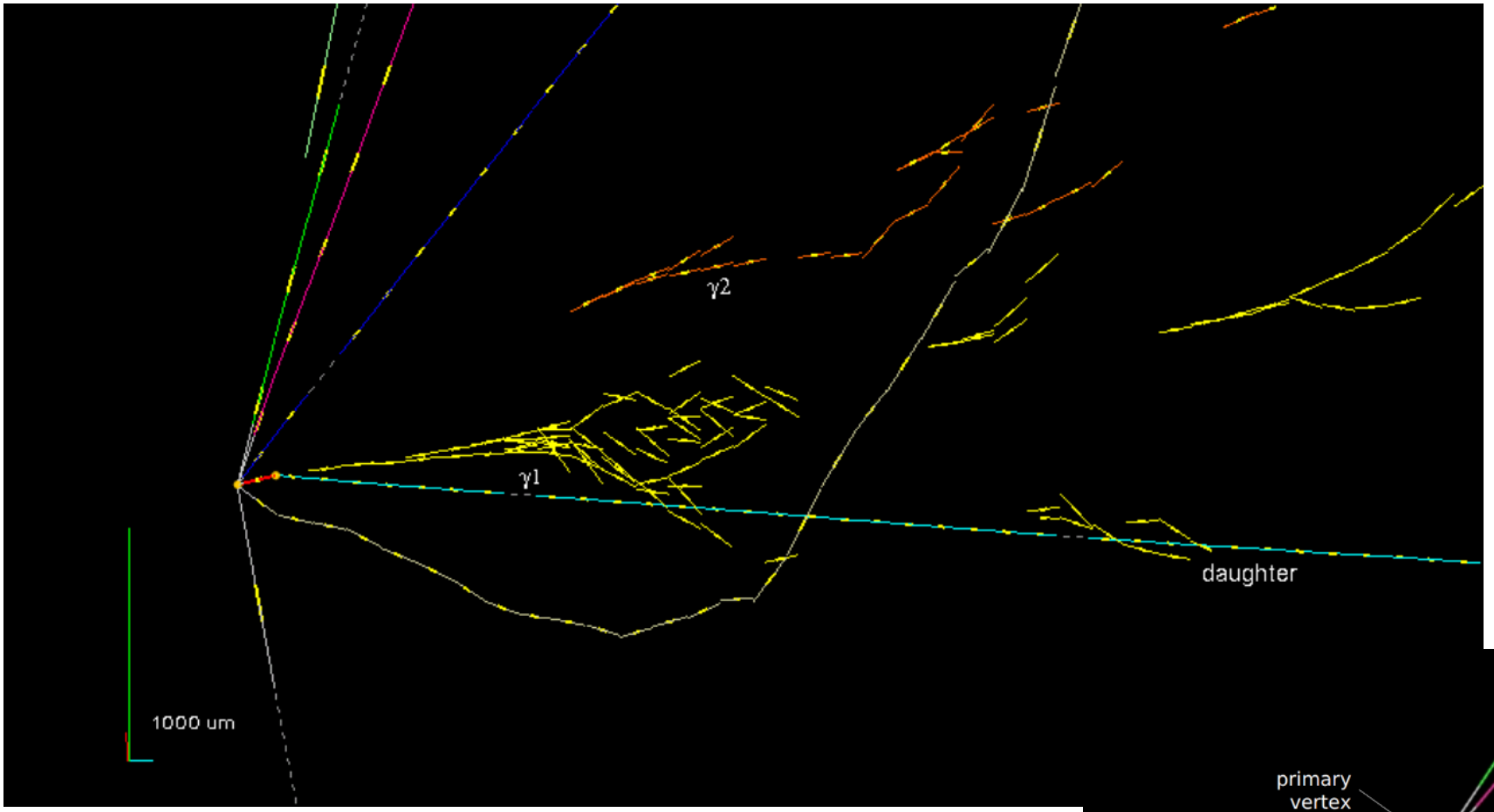


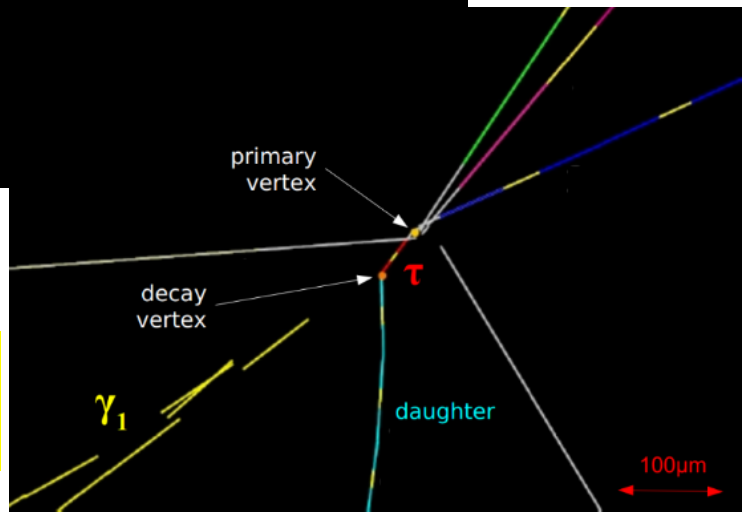
Hadronic background rate per located event: $\tau \rightarrow (3)h = (1.5)3.09\ 10^{-5}$

BACK UP
- NU TAU CANDIDATES

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

Phys. Lett. B691(2010) 138





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

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

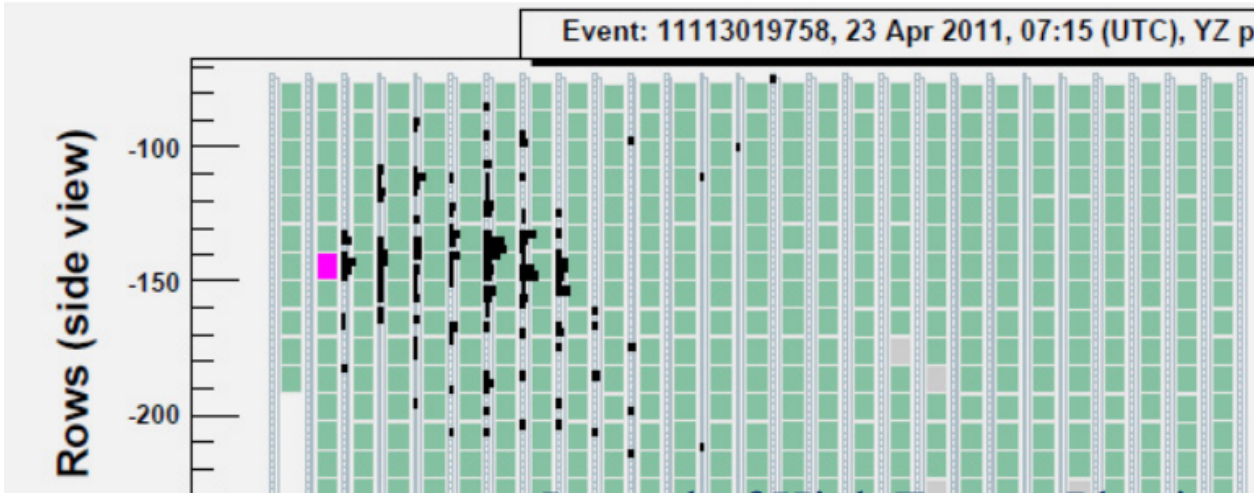
$\pi^0 \rightarrow \gamma\gamma$

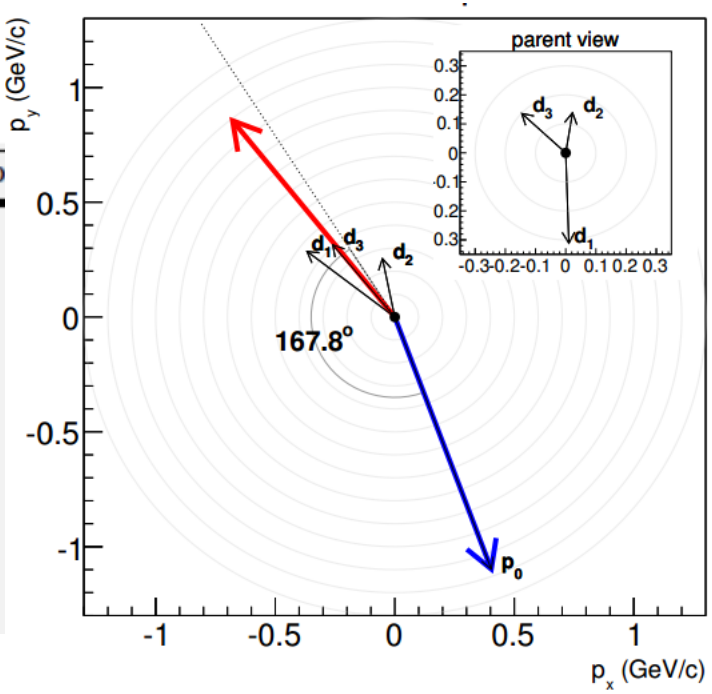
640^{+125}_{-80} (stat.)$^{+100}_{-90}$ (sys.) MeV/c^2

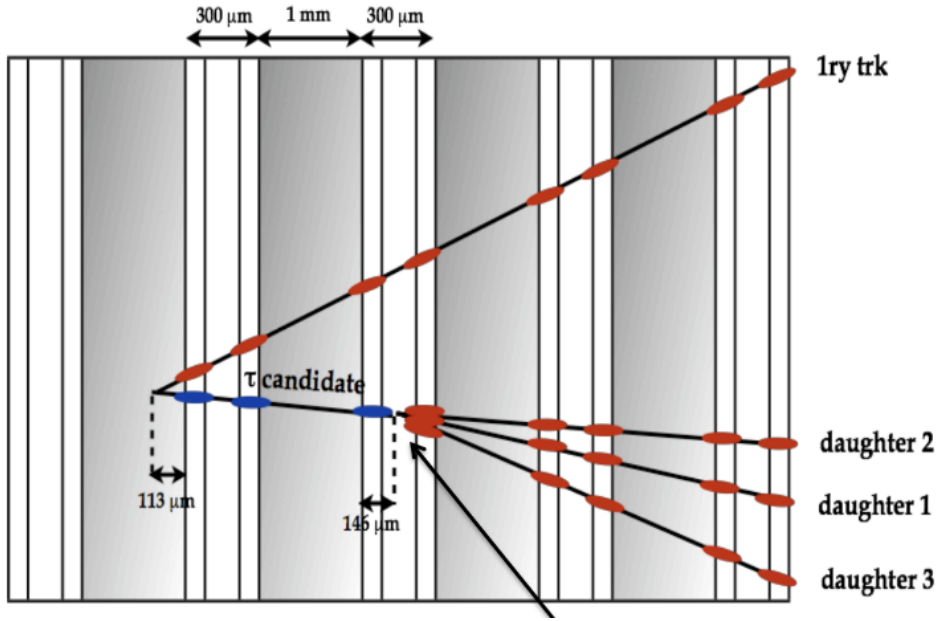
120 ± 20(stat.) ± 35(sys.) MeV/c^2

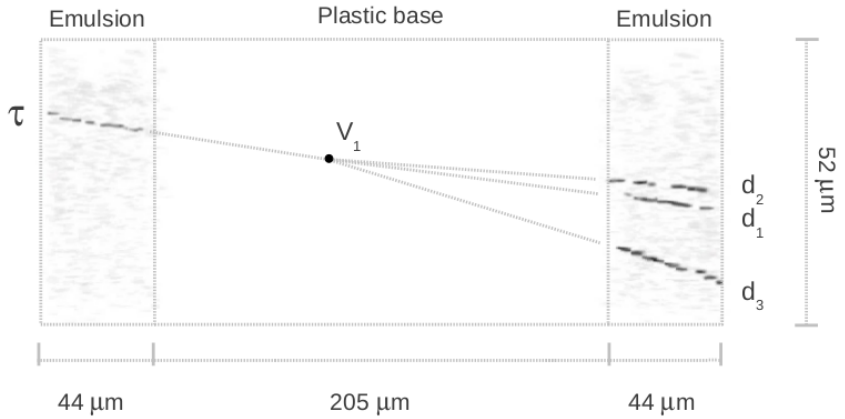
The 2nd candidate ($\tau \rightarrow 3h$)

JHEP 11 (2013) 036

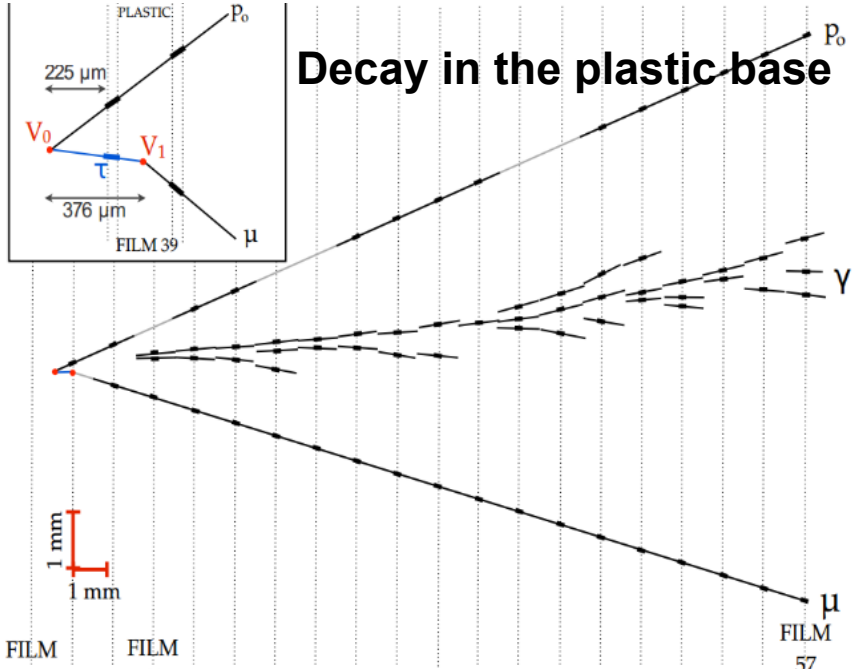






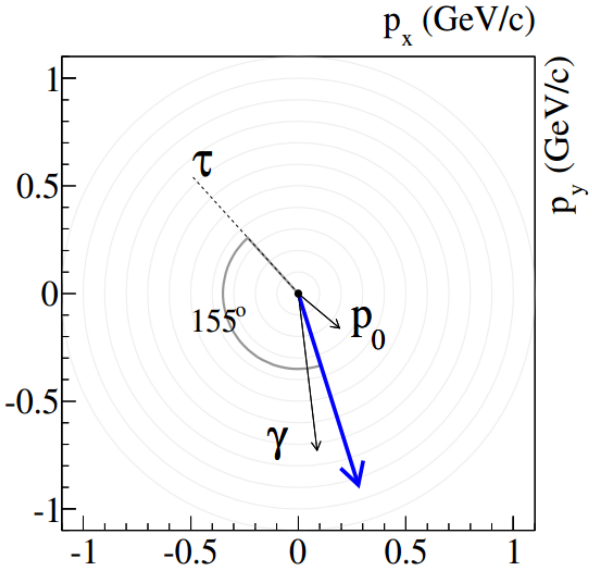


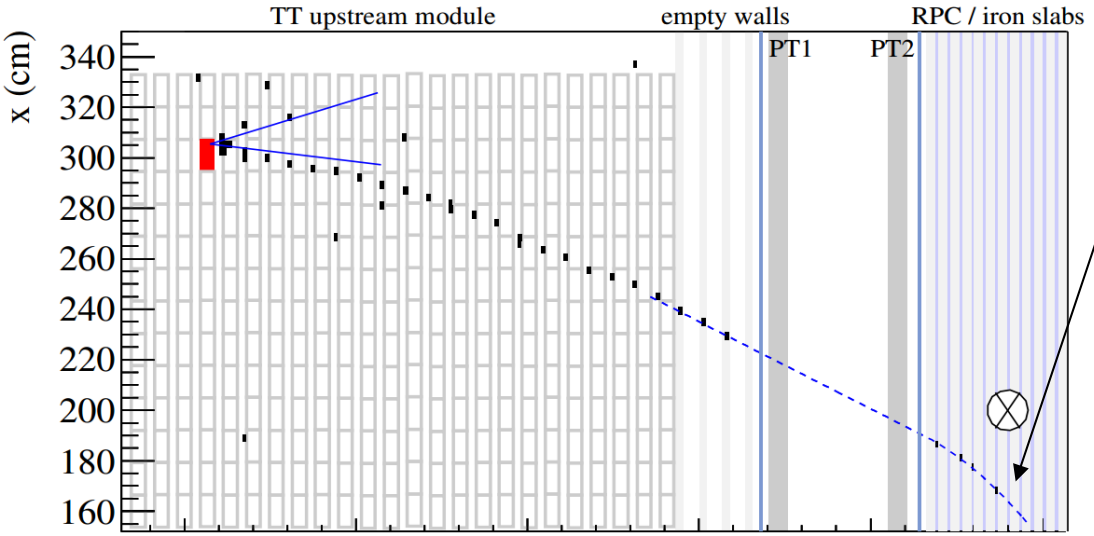
The 3rd candidate ($\tau \rightarrow \mu$)



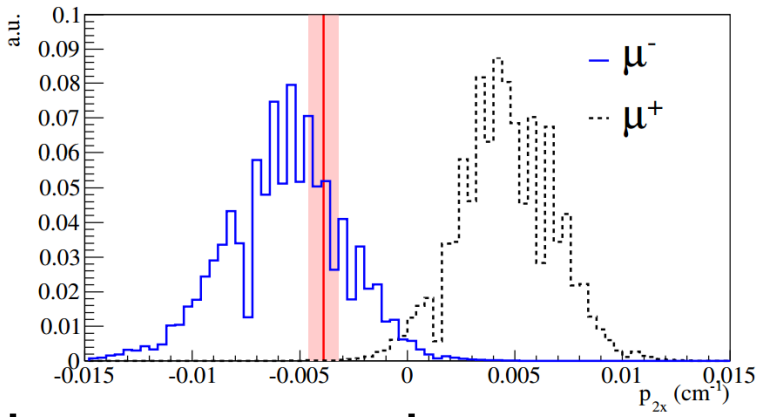
Decay in the plastic base

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



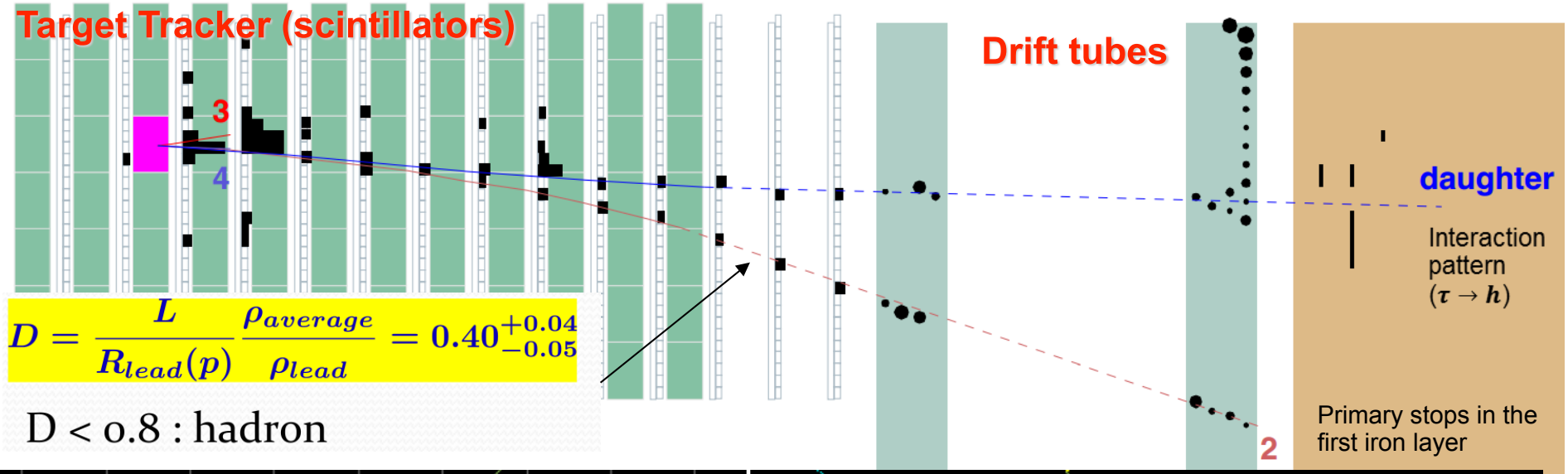


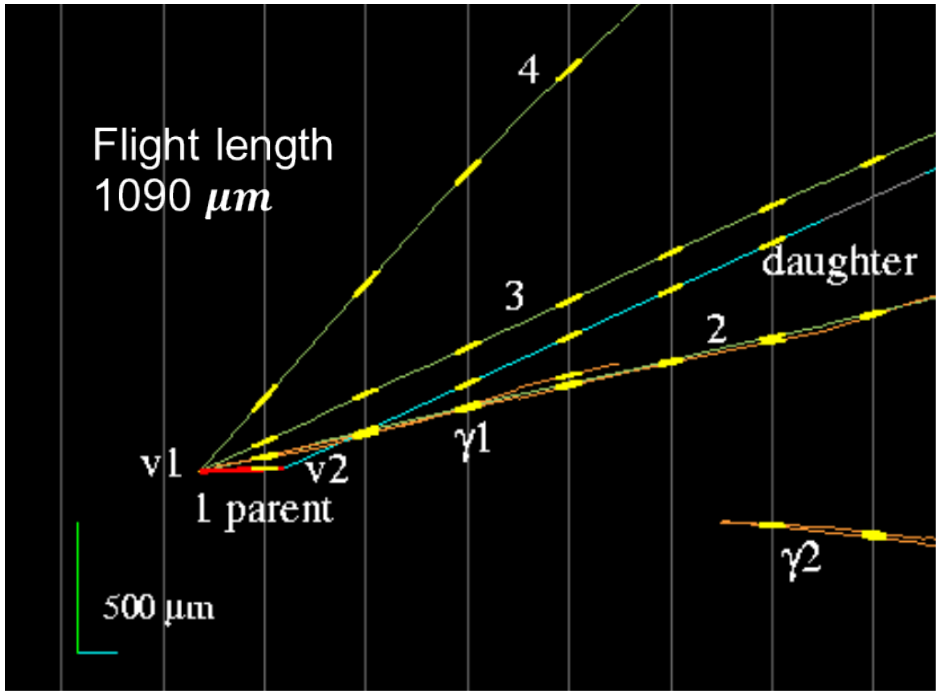
Negative charge of daughter muon measured by bending in the iron with RPC detectors

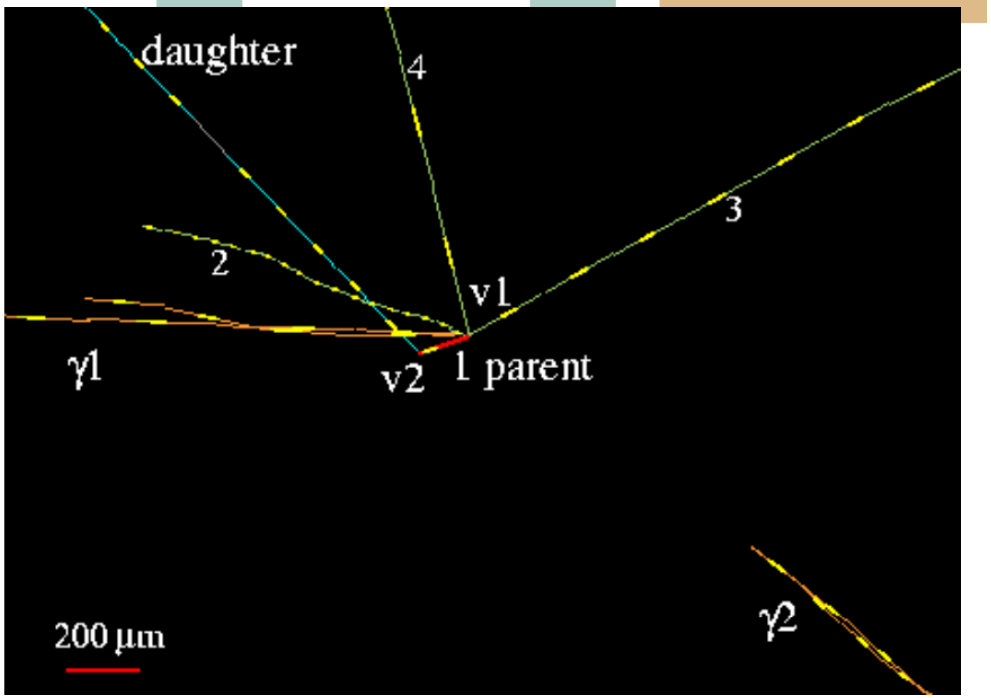


First measurement of lepton charge in appearance mode.

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

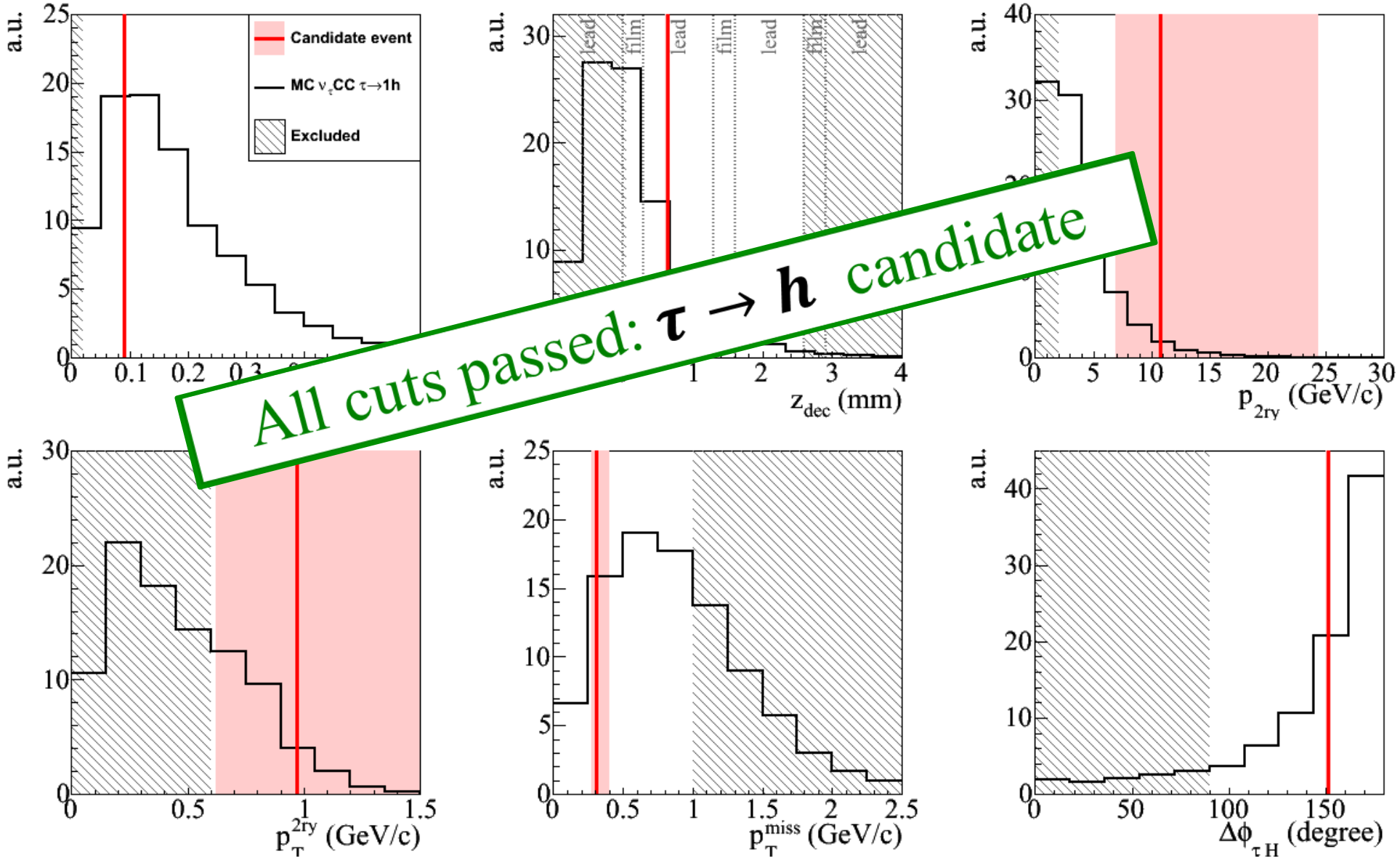


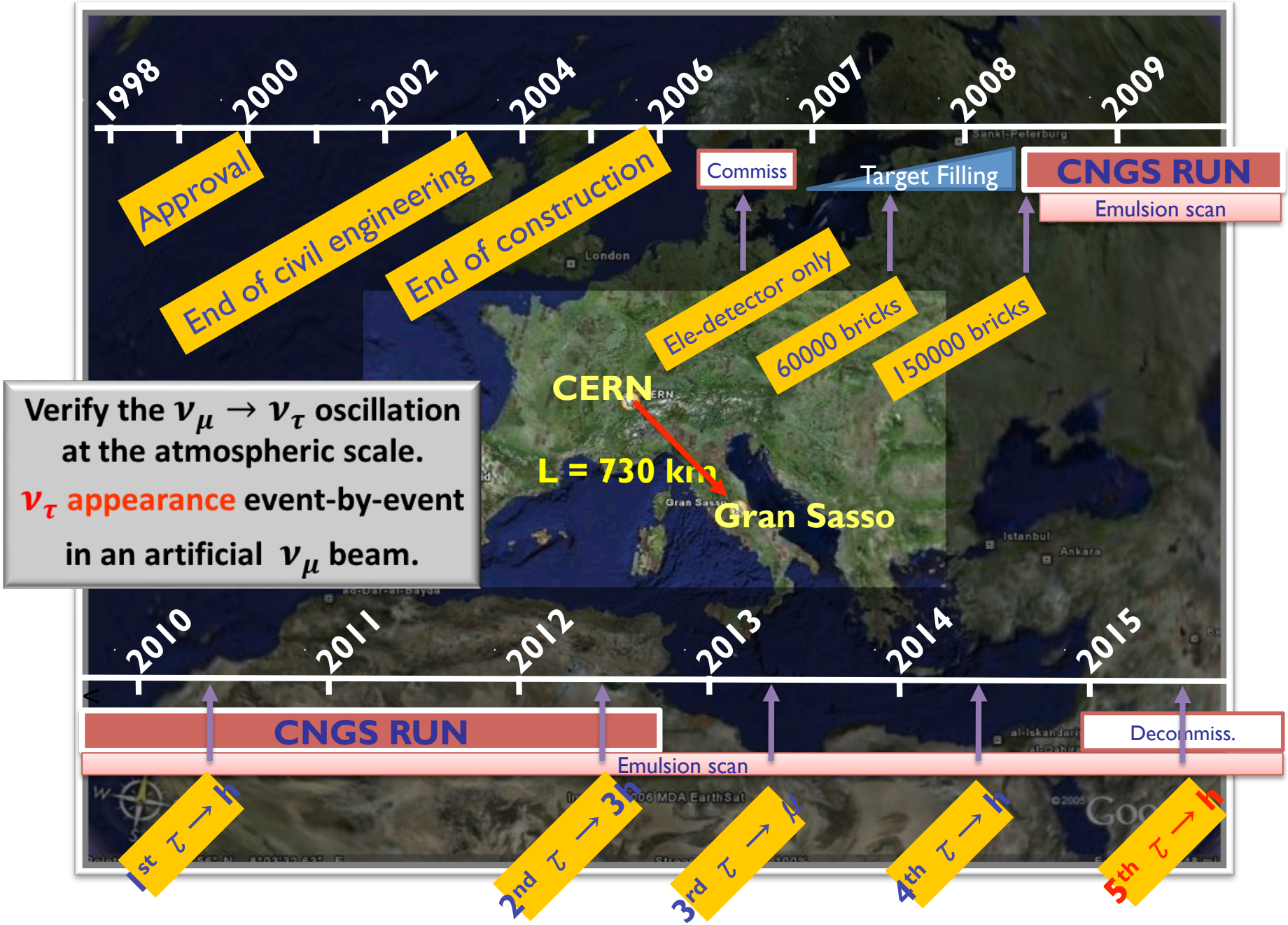




The 5th ν_τ candidate

Kinematical variables




1998
2000
2002
2004
2006
2007
2008
2009
Approval
End of civil engineering
End of construction
Commiss
Target Filling
CNGS RUN
Emulsion scan
Ele-detector only
60000 bricks
150000 bricks
CERN
L = 730 km
Gran Sasso
Verify the $\nu_\mu \rightarrow \nu_\tau$ oscillation at the atmospheric scale.
ν_τ appearance event-by-event in an artificial ν_μ beam.
2010
2011
2012
2013
2014
2015
CNGS RUN
Emulsion scan
Decommiss.
1st $\tau \rightarrow h$
2nd $\tau \rightarrow 3h$
3rd $\tau \rightarrow \mu$
4th $\tau \rightarrow h$
5th $\tau \rightarrow h$