

Results from the OPERA experiment in the CNGS beam

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on behalf of the OPERA Collaboration



Discovery of ν_τ appearance in the CNGS neutrino beam with the OPERA experiment

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[arXiv:1507.01417]
6 JUL 2015
submitted to PRL



Bari
Bologna
LNF Frascati
LNGS
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LAPP Annecy
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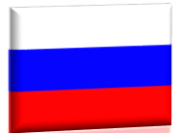
METU Ankara



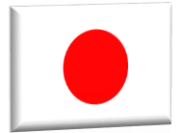
Jinjiu



28 institutions
140 physicists



INR Moscow
LPI Moscow
SINP MSU Moscow
JINR Dubna



Aichi
Toho
Kobe
Nagoya
Nihon

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 (after the ... “2013 appearance revolution”)

$\nu_\mu \rightarrow \nu_e$

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

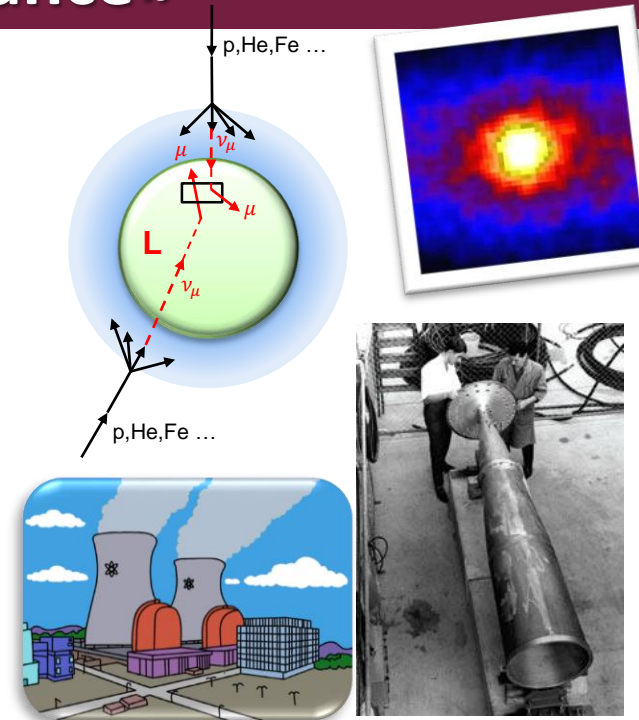
Appearance seen by T2K at the JPARC beam

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

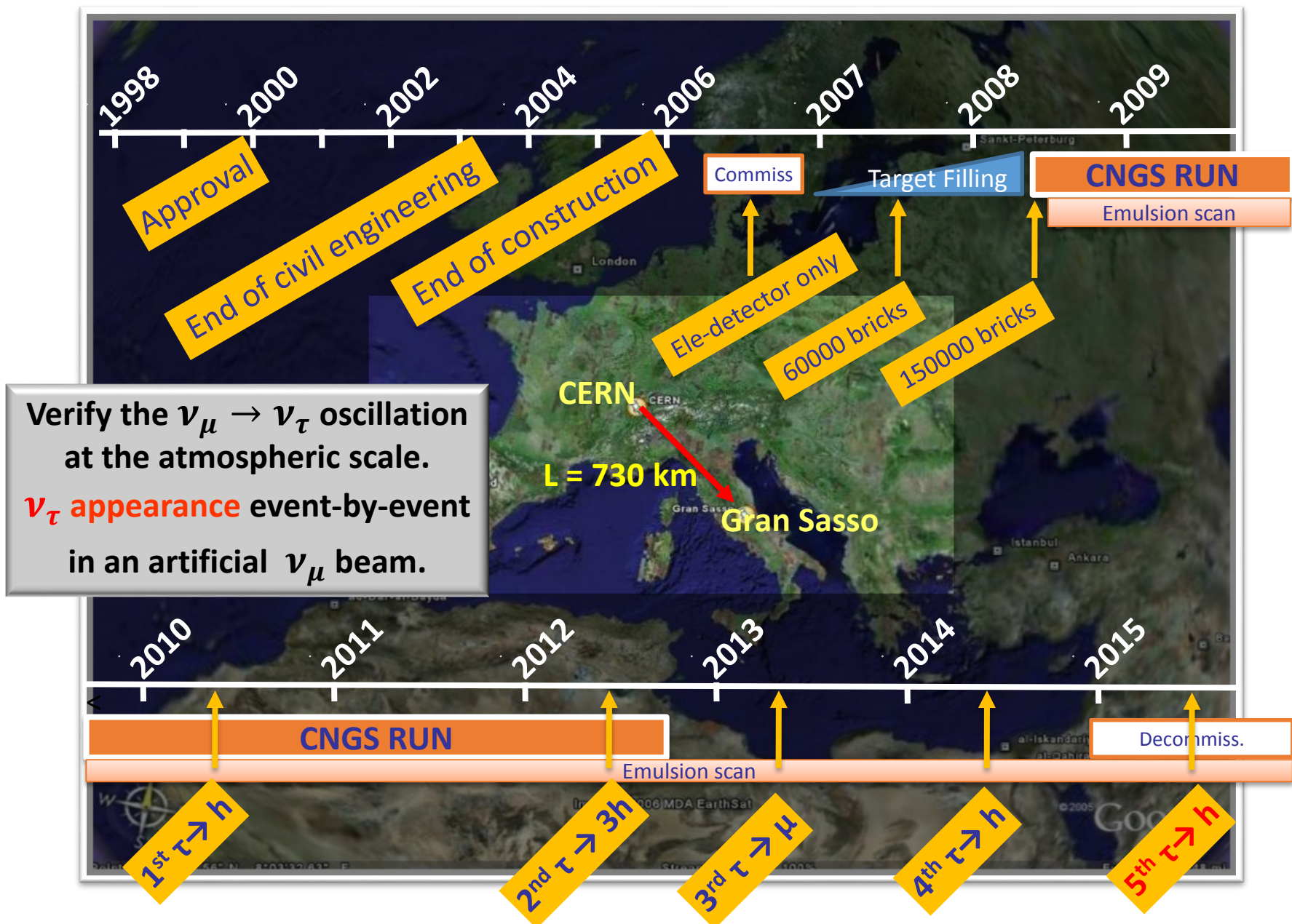
An experimental and technological **challenge**. 730 km baseline.

- 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 OPERA project



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

$\langle E_\nu \rangle$	17 GeV
$L / \langle E_\nu \rangle$	43 km/GeV

The oscillation peak for $L = 730$ km at ~ 1.5 GeV (similar to NuMI) but the **beam is designed to observe τ leptons** \rightarrow unbalance at higher energies

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

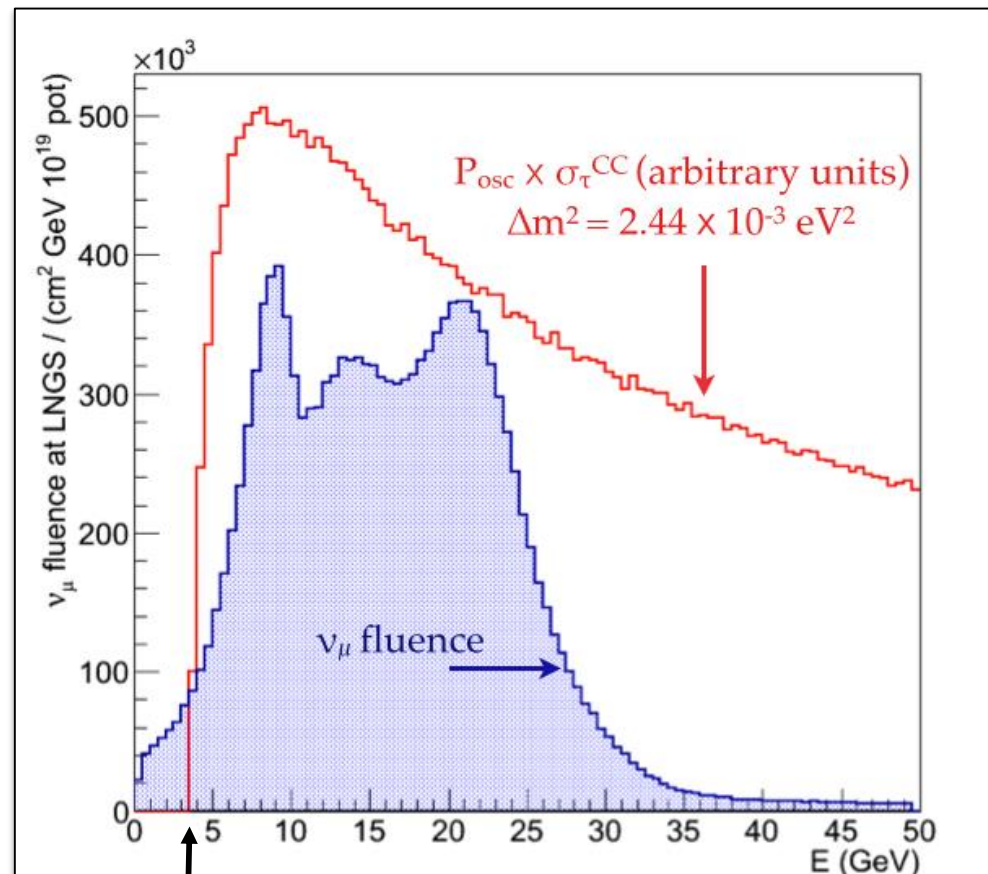
Fluxes:

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

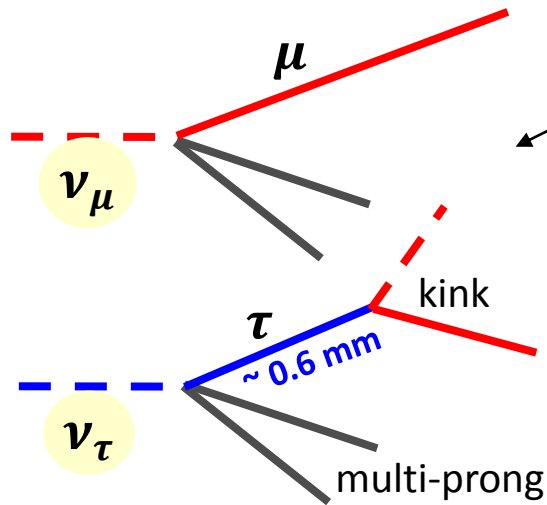
$\sim 20\text{k } \nu_\mu \text{ CC+NC}$

66.4 ν_τ CC (not efficiency corrected)



Threshold for τ at ~ 3.5 GeV.

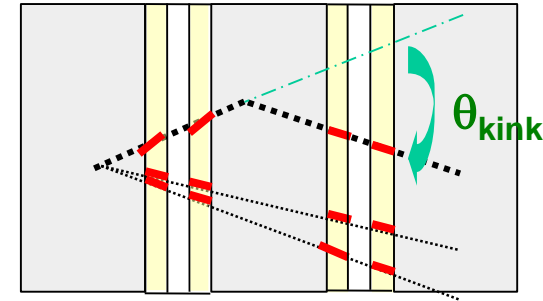
The ν_τ detection challenge



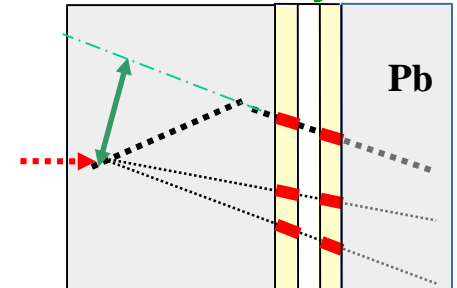
Detect a few ν_τ^{CC} from the bulk of ν_μ^{CC}

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

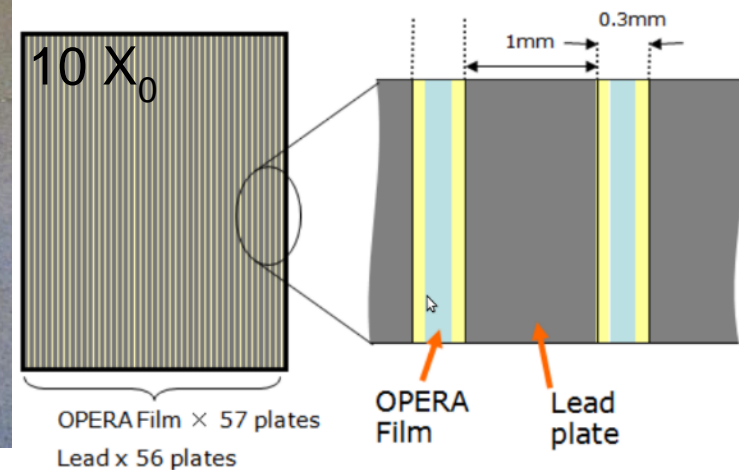
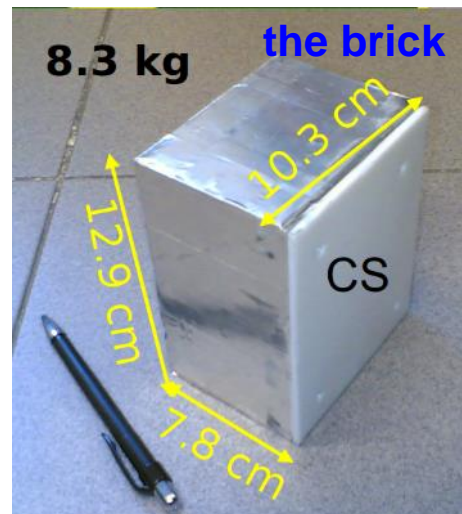
Reconciles the needs for:

Large mass

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

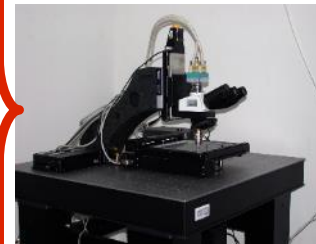
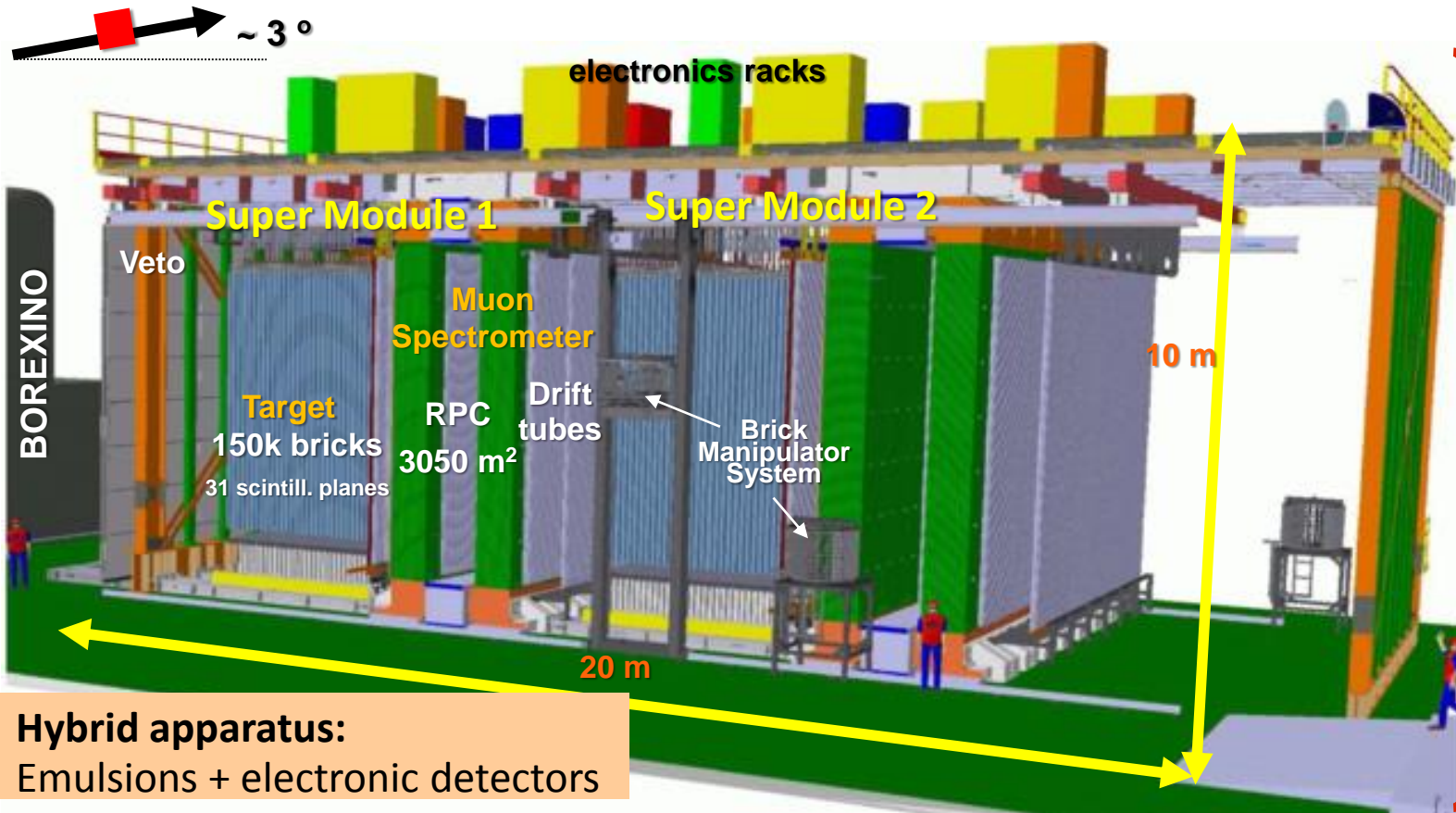
Extreme granularity

$\sim \mu\text{m}$ space resolution



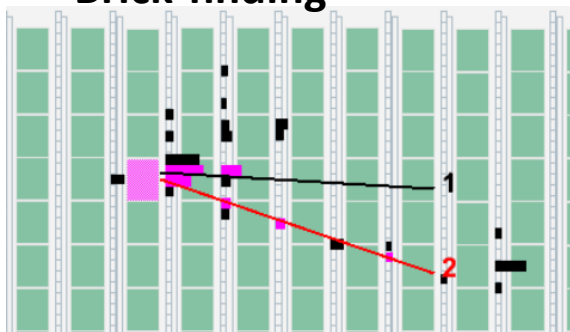
The OPERA detector

$O(\mu\text{m})$ resolution over a “dense” macroscopic volume $O(100\text{m}^3)$



Hybrid apparatus:
Emulsions + electronic detectors

“Brick-finding”

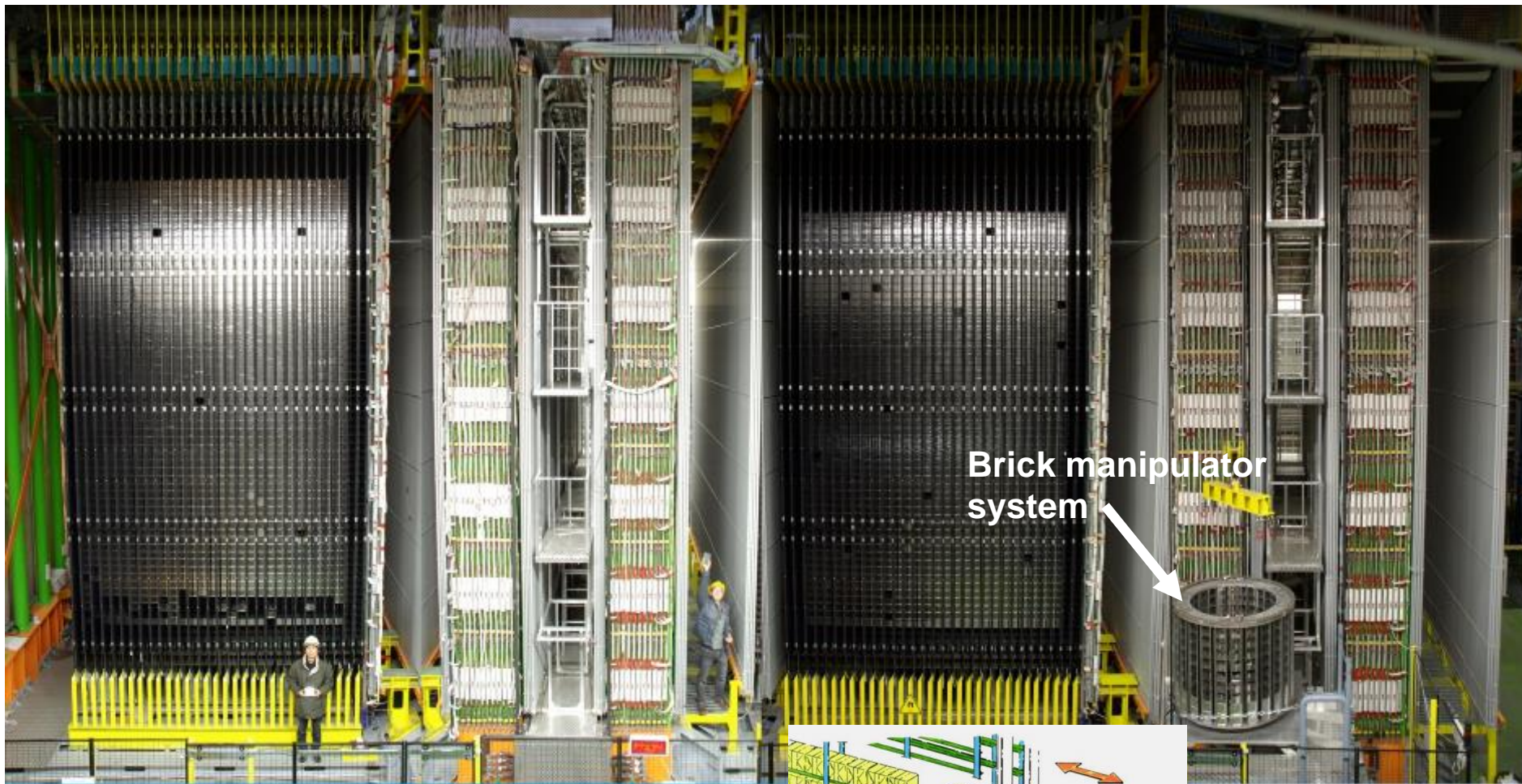


+ several ancillary facilities “off-site”:

- 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 →

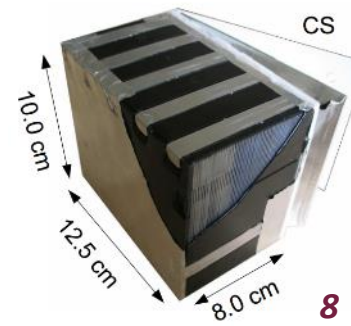
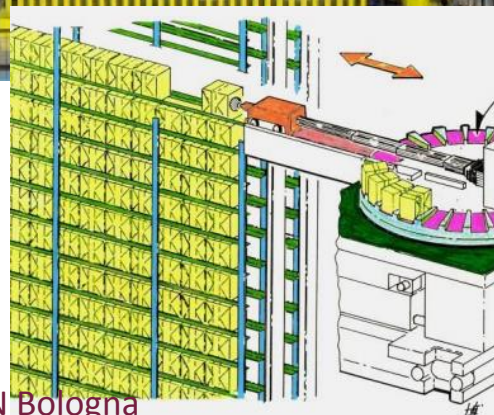
← Super Module 2 →



Target

Muon spectrometer

~ 150.000 bricks in total.
1.25 kt mass



ν_τ candidate event

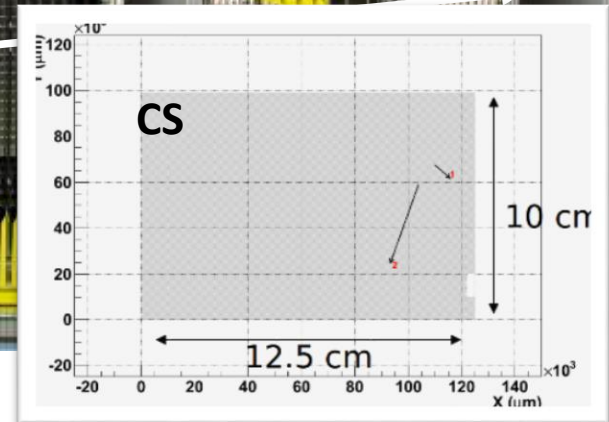
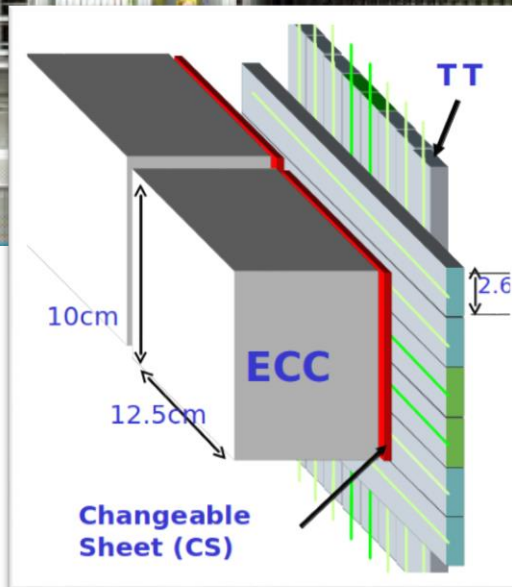
about 2 m

Accuracy of predictions from the electronic detectors:

position: 1 cm

slope: 23 mrad

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

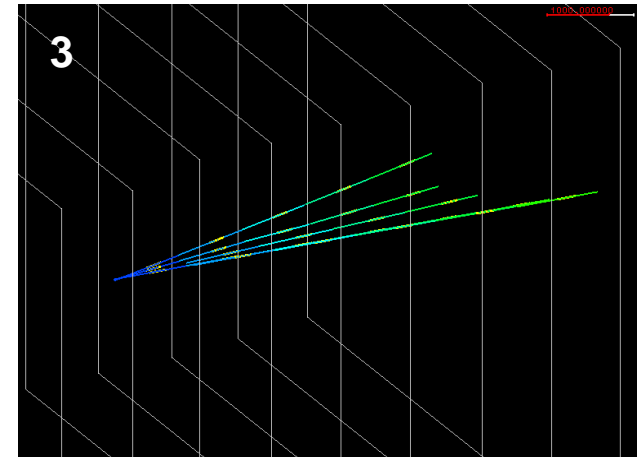
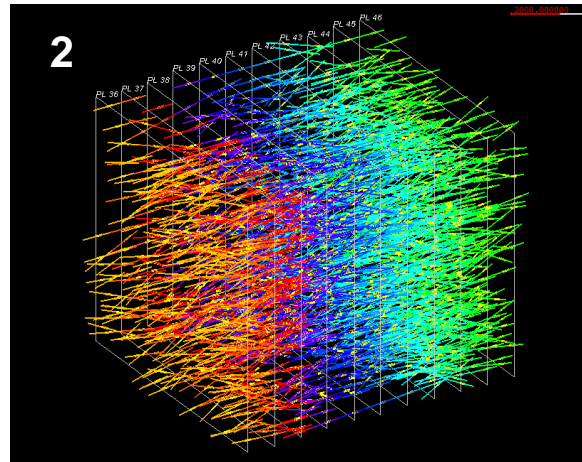
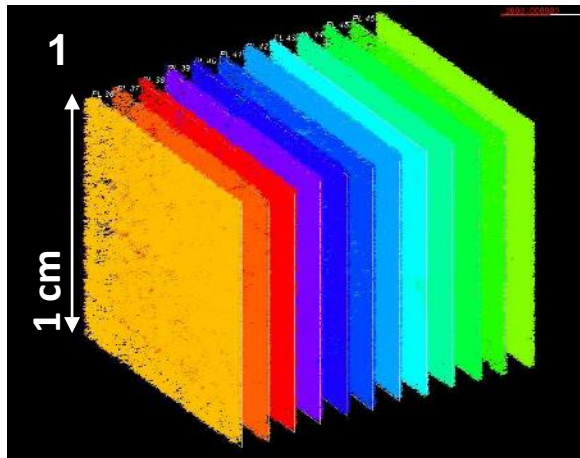


Location efficiency:

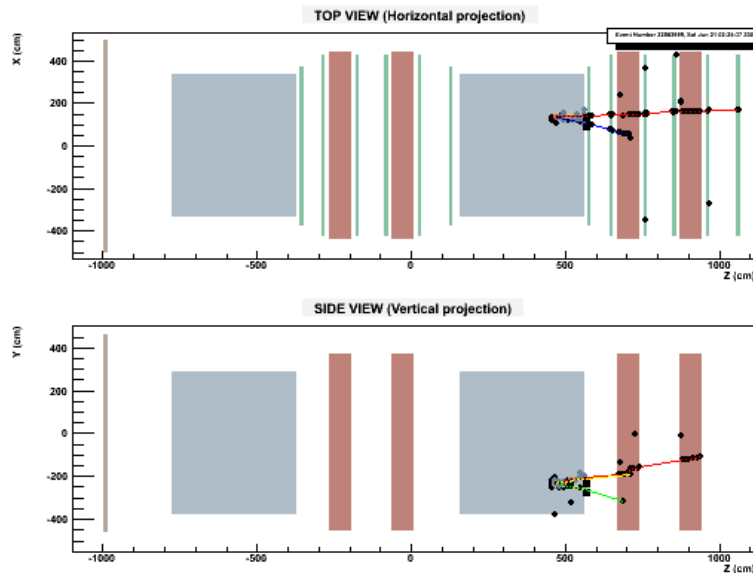
CC: 74 %

NC: 48 %

Vertex hunting in the brick

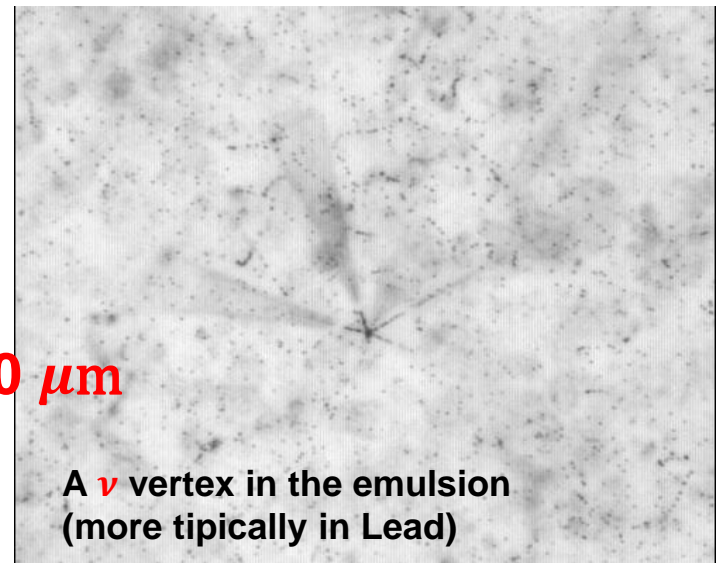


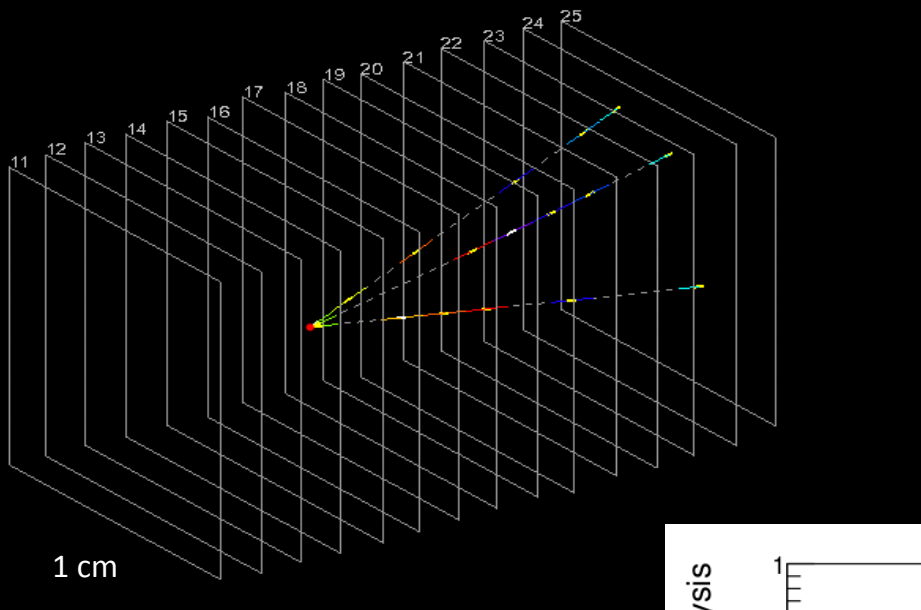
- 0) all tracks tagged in the **CS films** are **followed upstream** until a **stopping point** is found
- 1) a $\sim 1 \text{ cm}^3$ **volume centered in the stopping point** is scanned and tracks are reconstructed
- 2) cosmic ray tracks (from a dedicated exposure) are used for the fine **alignment**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



20 m \rightarrow 100 μm

(essential role
of CS films)



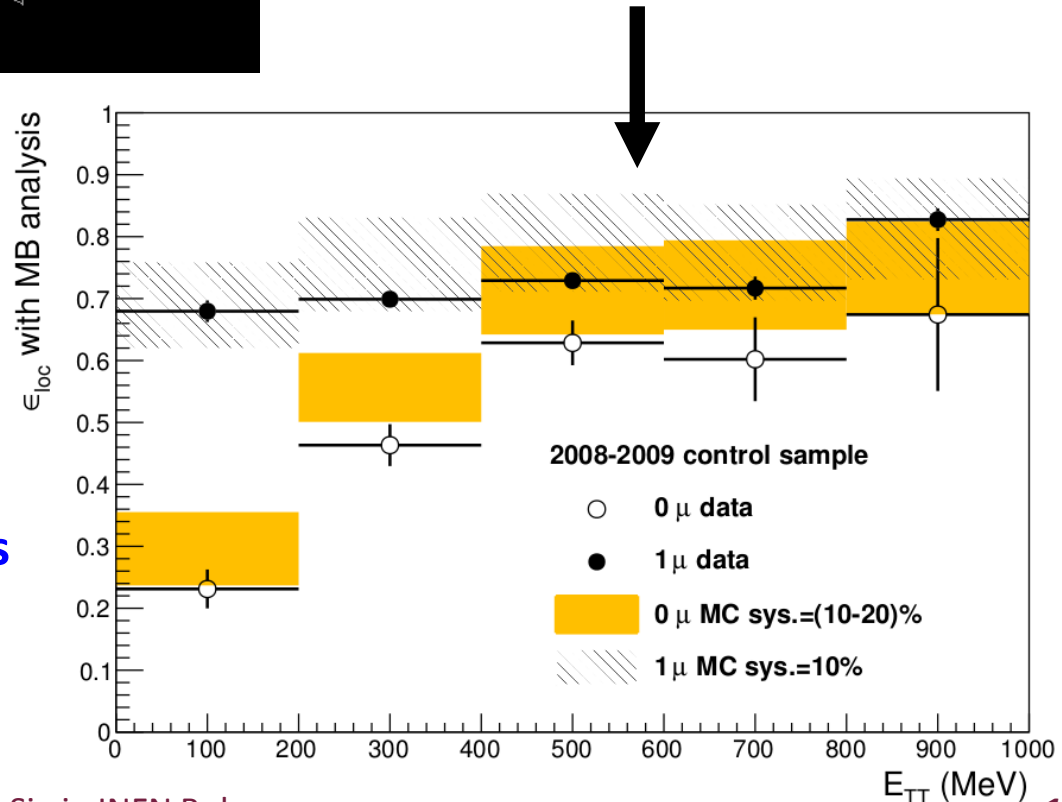


Hybrid detector:
a complex simulation!
Reasonable agreement.

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

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



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

Monte Carlo simulation benchmarked on control samples.

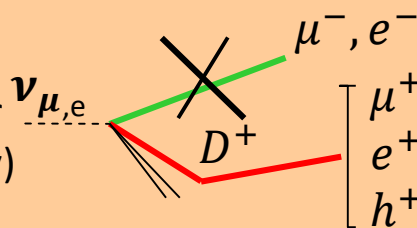
In red some improvements...

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



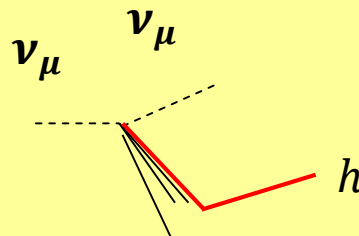
MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

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

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

Hadronic interactions

Background for $\tau \rightarrow h$



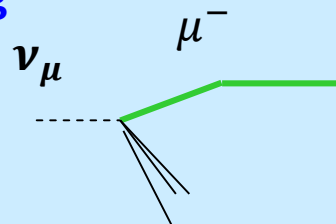
FLUKA + pion test beam data

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]

Progress in the analysis of the emulsion films

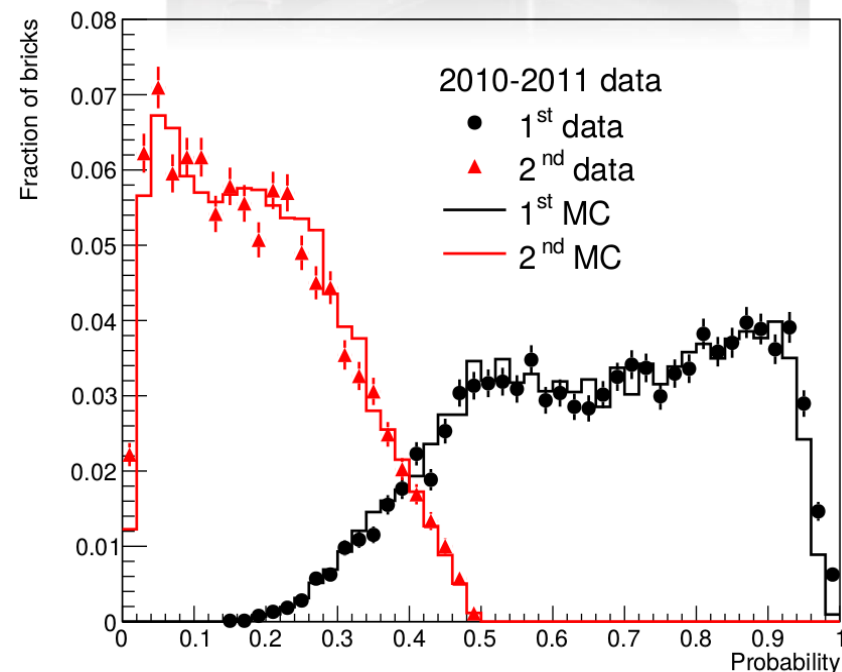
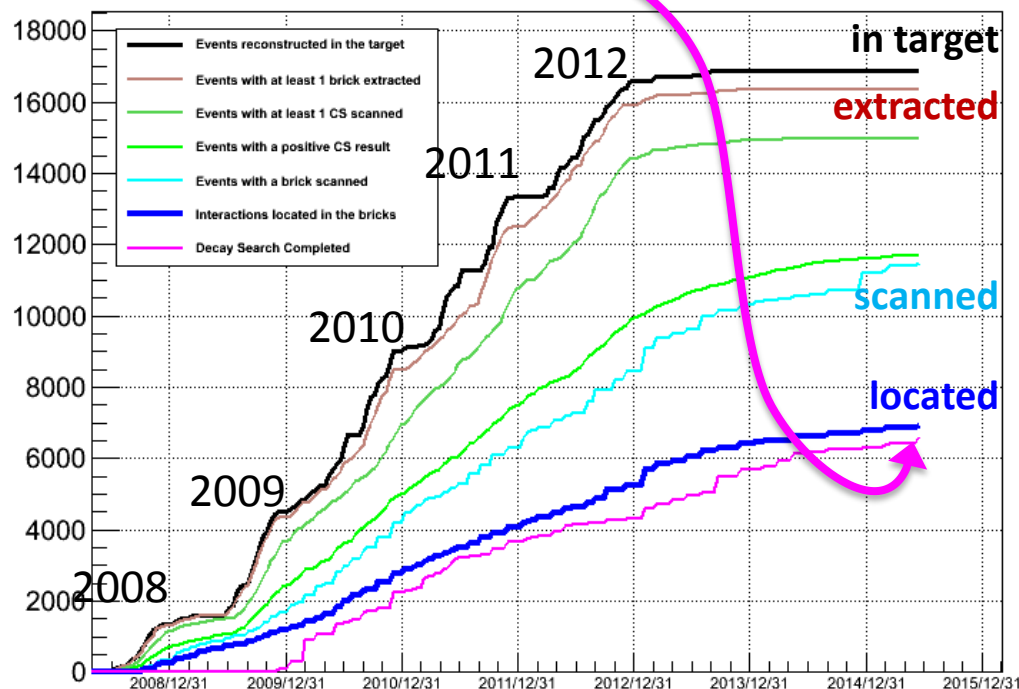
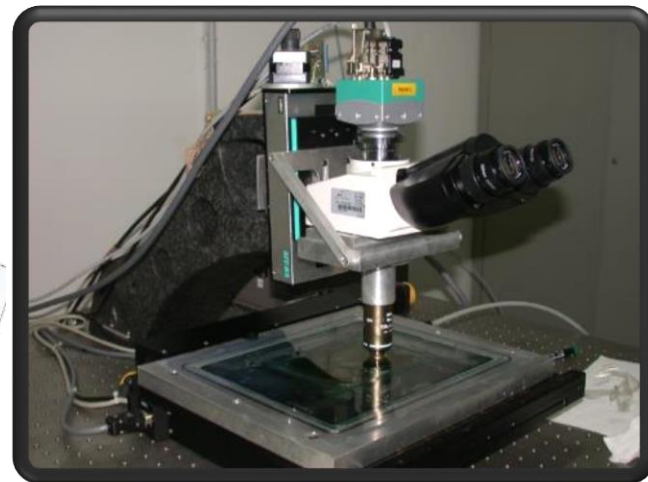
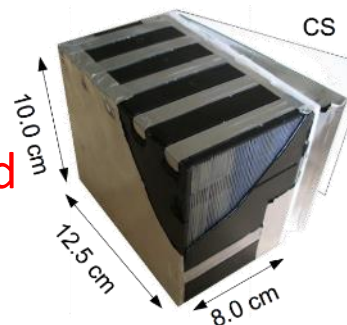
Bricks are **ordered** according to their probability of containing the interaction vertex.

Analysis status:

2008-09 completed up to 4th brick

2010-12 1st and 2nd bricks completed

> 6600 fully analysed bricks



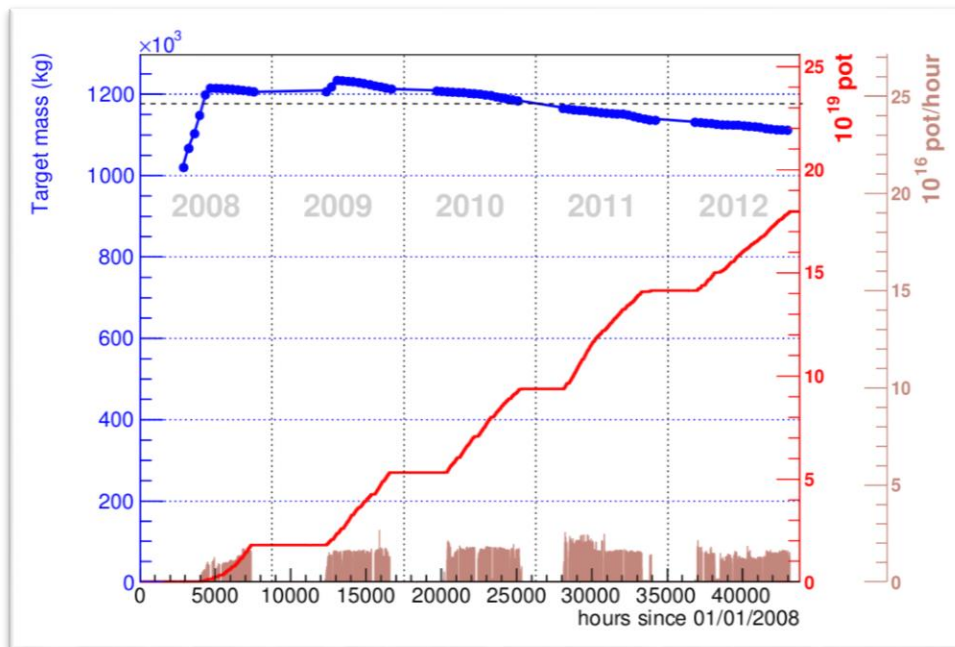
Collected data samples

The 5 years long CNGS run ended in 2012.

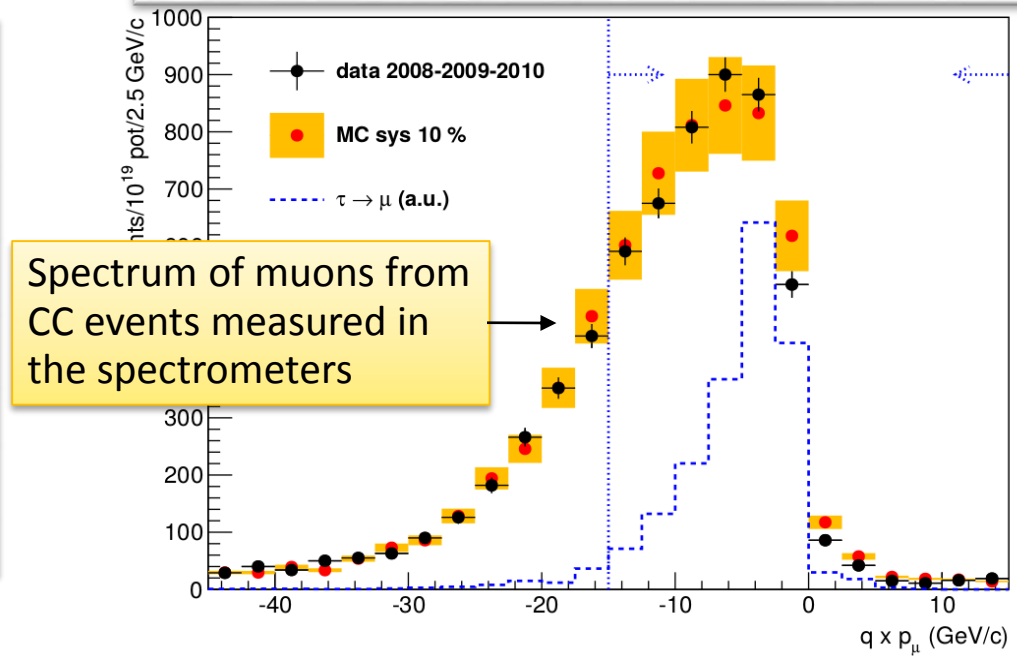
$1.8 \cdot 10^{20}$ p.o.t. collected
(80% of the design)

1.25 kton initial target mass
(150 k bricks)

19505 neutrino interactions
in the emulsion targets.

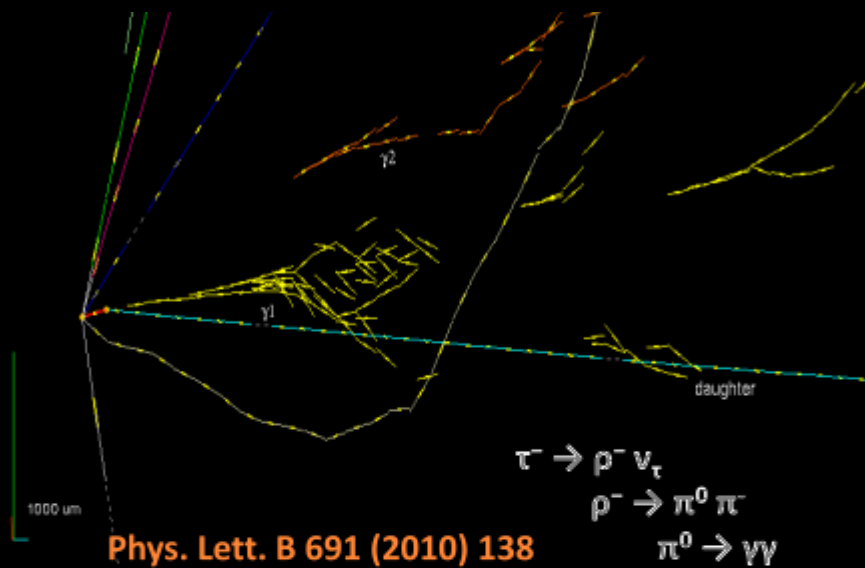


Year	Days	p.o.t. (10^{19})	ν interactions
2008	123	1.74	1698
2009	155	3.53	3693
2010	187	4.09	4248
2011	243	4.75	5131
2012	257	3.86	3923
tot	965	17.97	19505

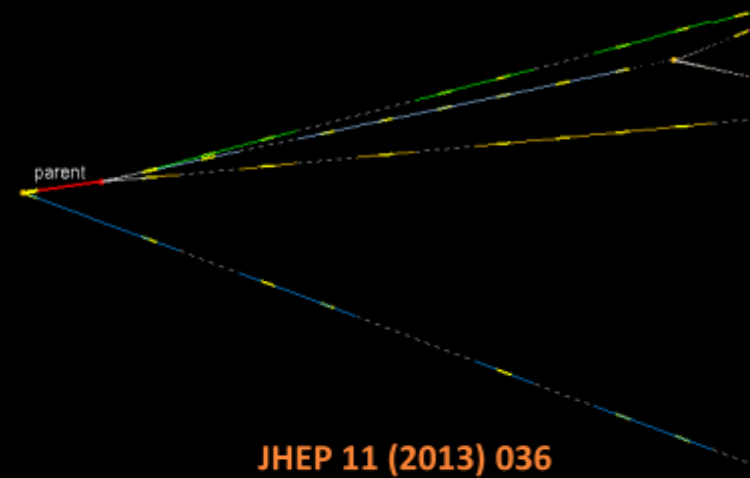


ν_τ GALLERY

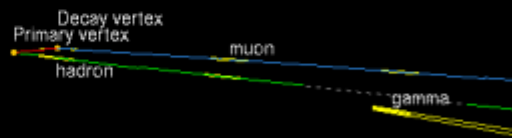
1st candidate (2010): $\tau \rightarrow h$



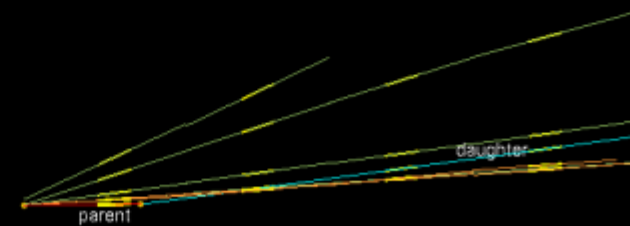
2nd candidate (2012): $\tau \rightarrow 3h$



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



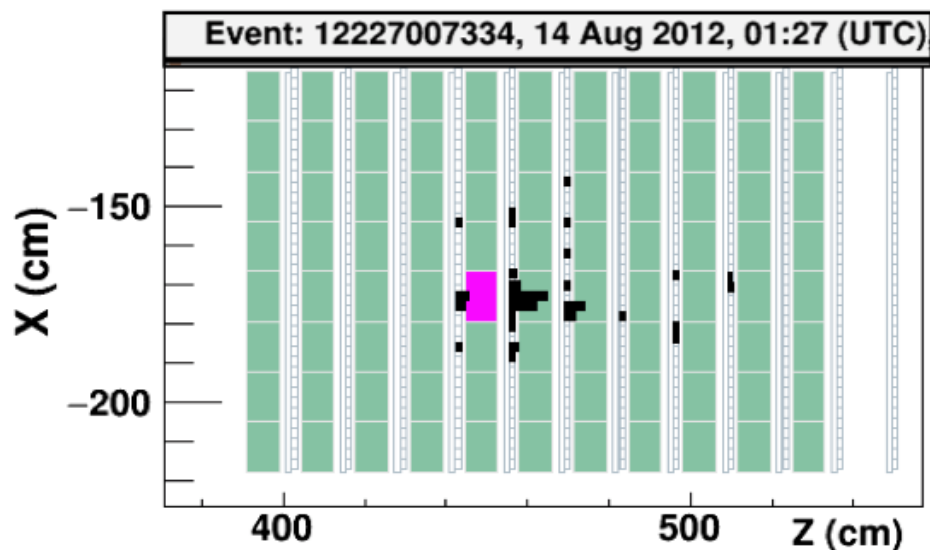
4th candidate (2014): $\tau \rightarrow h$



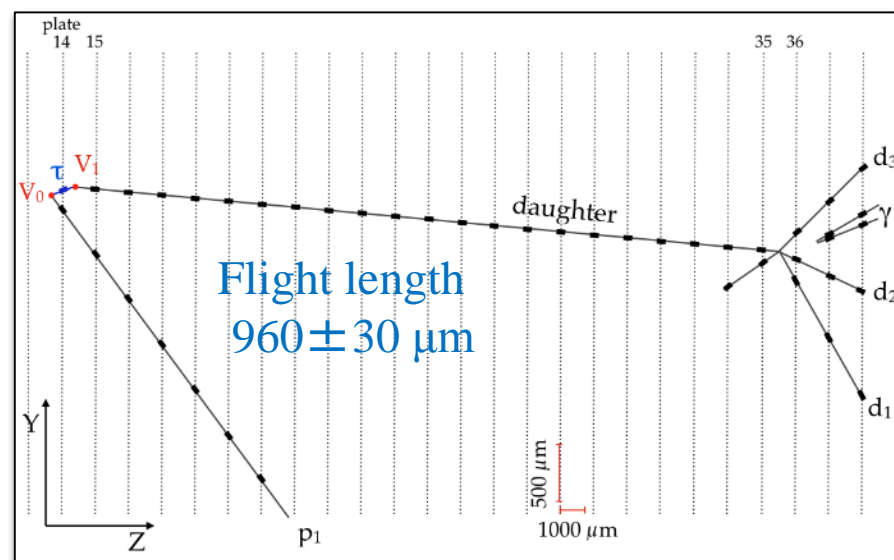
The 5th candidate ($\tau \rightarrow h$)

[arXiv:1507.01417]
6 JUL 2015

As seen by the electronic detectors...

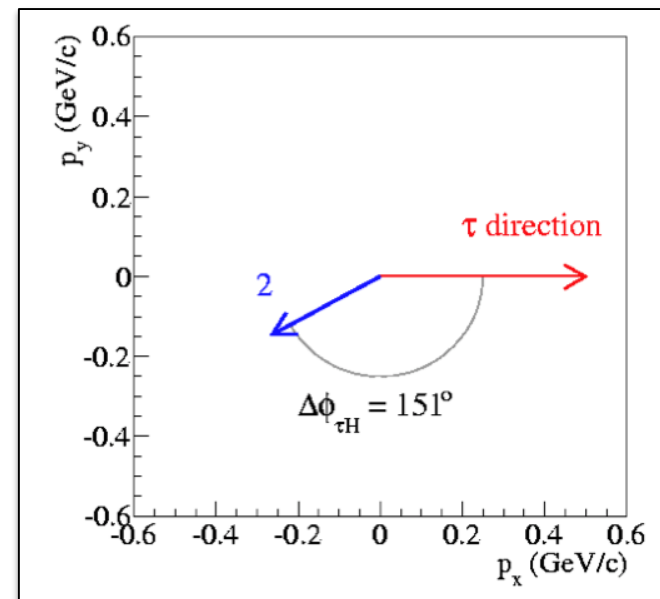


.. and in the brick



Kinematical variables

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



Candidate events
have to fulfill

kinematical cuts: →

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

variable	$\tau \rightarrow 1h$	$\tau \rightarrow 3h$	$\tau \rightarrow \mu$	$\tau \rightarrow e$
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*	< 1*	/	/
ϕ_{lH} (rad)	> $\pi/2^*$	> $\pi/2^*$	/	/
p_T^{2ry} (GeV/c)	> 0.6(0.3)*	/	> 0.25	> 0.1
p_T^{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

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

$\mu \rightarrow$ 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
$\tau \rightarrow 1h$	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

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

Exclusion of background-only hypothesis: 5.1 σ

Measurement of Δm_{23}^2

[arXiv:1507.01417]
6 JUL 2015

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

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

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

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

"Steep" Δm_{23}^2 dependence

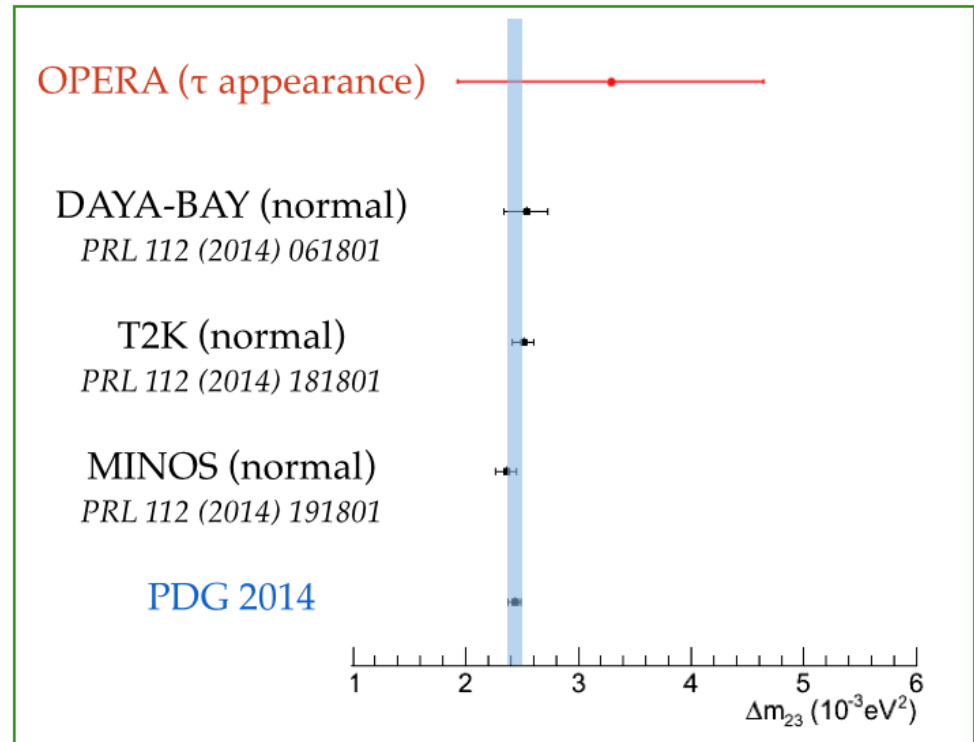
→ counting based measurement

90% C.L. intervals

by Feldman & Cousins method

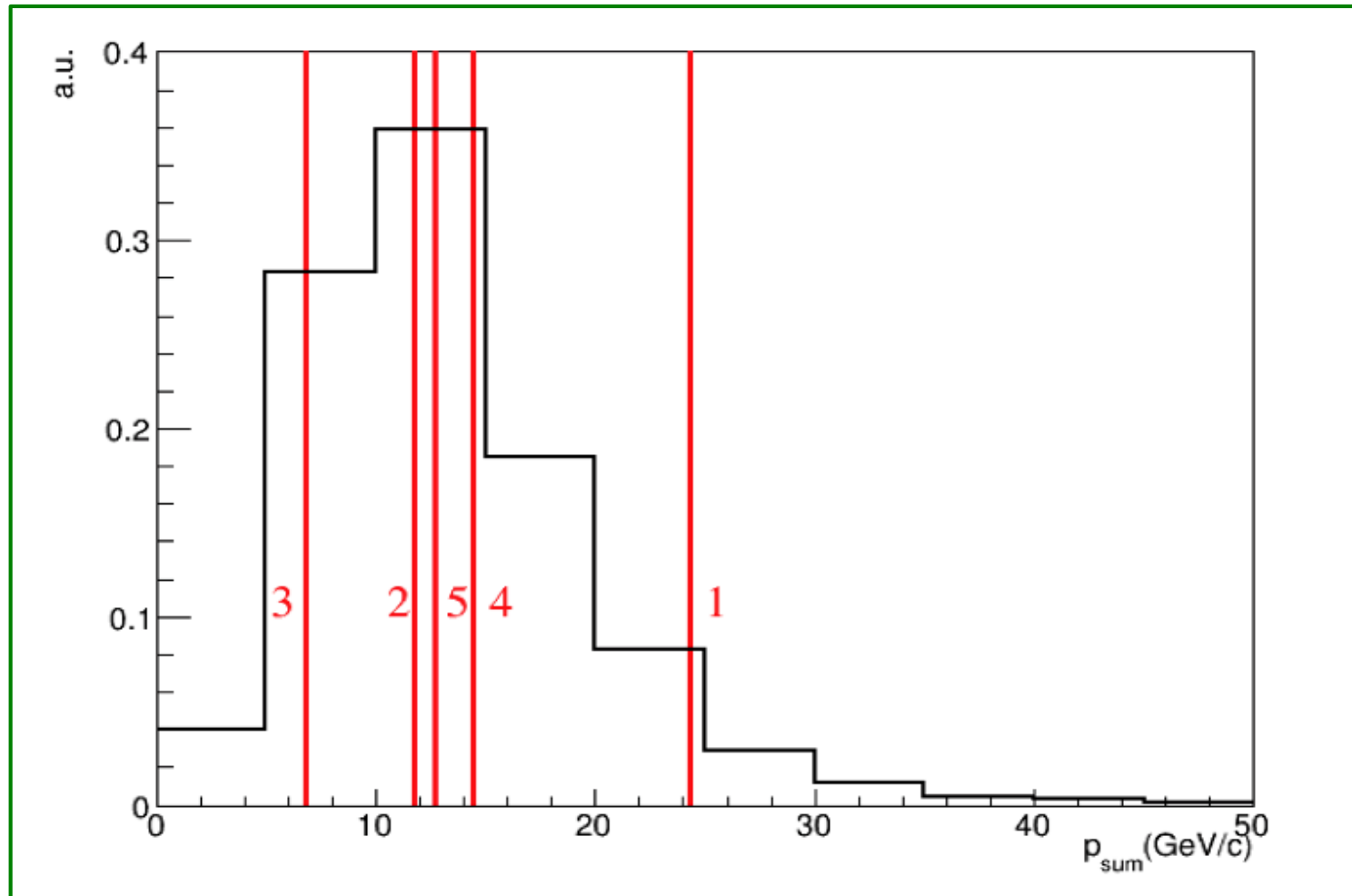
$$\Delta m_{23}^2 = [2.0 - 4.7] 10^{-3} \text{ eV}^2$$

(assuming full mixing)



Visible Energy Of All The Candidates

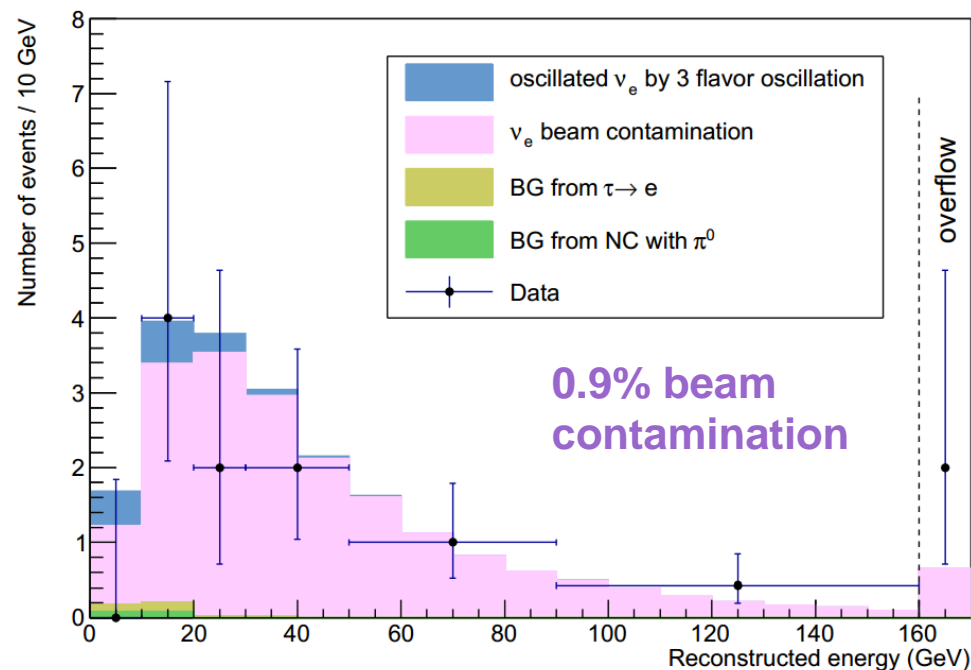
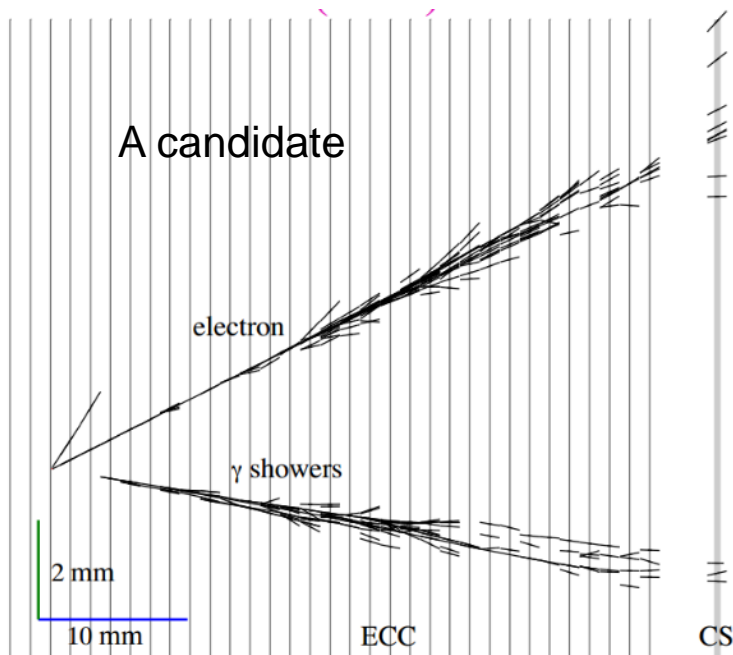
Sum of the momenta of charged particles and γ 's measured in emulsion



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

[JHEP 1307 (2013) 004]

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



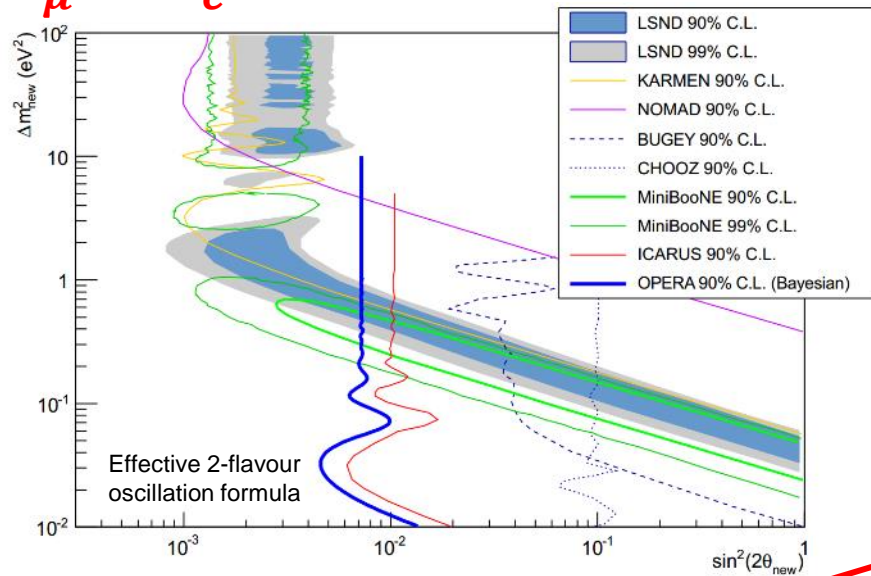
		E < 20 GeV
ν_e candidates	19	4
Background	19.8 ± 2.8 (sys.)	4.6

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

sterile neutrino?

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

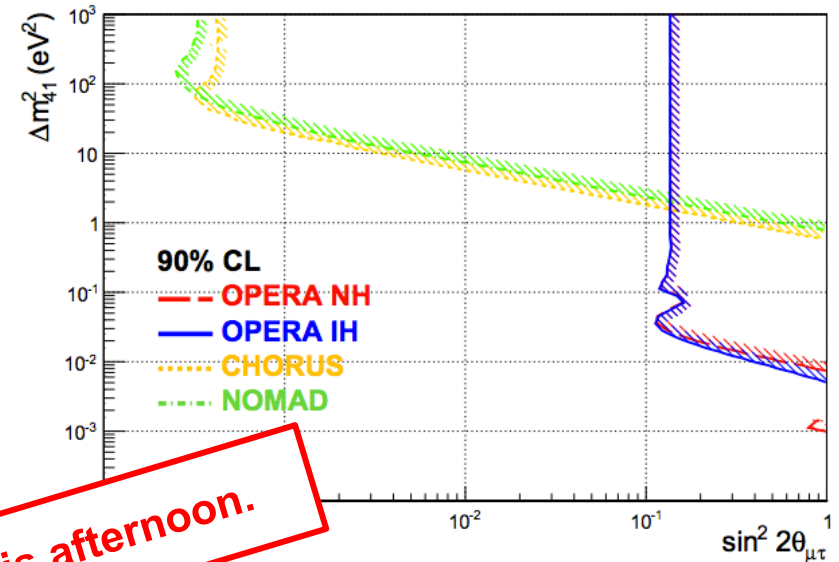
$$\nu_\mu \rightarrow \nu_e$$



[JHEP 1307 (2013) 004]

See talk by L. Stanco this afternoon.

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



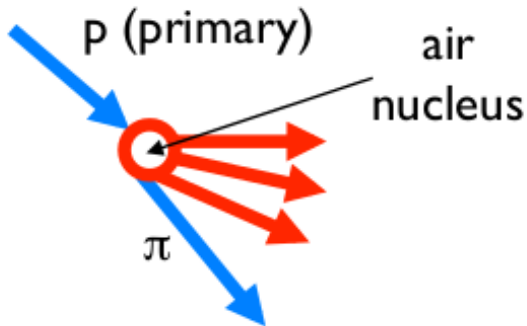
[JHEP 074 (2015) 0315]

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 .

Cosmic rays: $R_\mu = N_{\mu^+}/N_{\mu^-}$

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

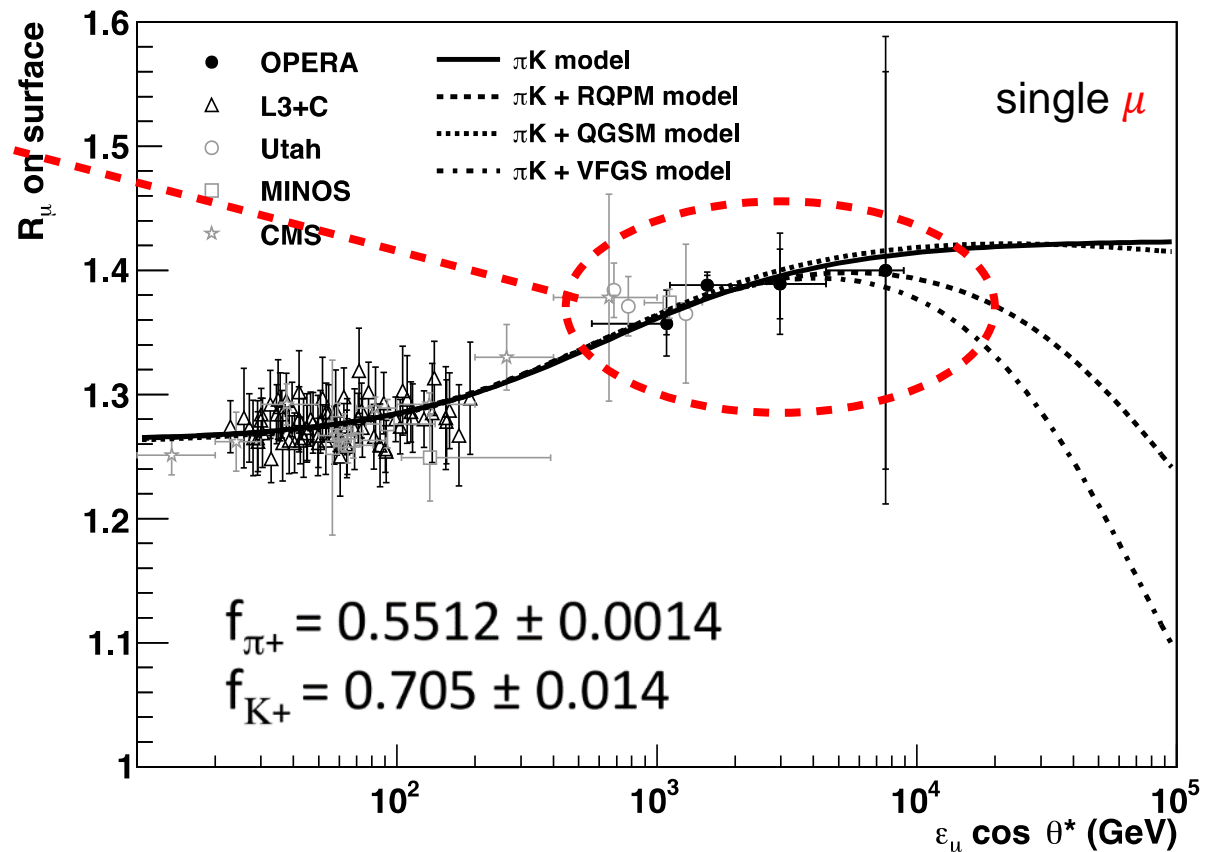
1μ

$$1.377 \pm 0.006$$

multi- μ

$$1.098 \pm 0.023$$

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



Conclusions

- 1.8×10^{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)

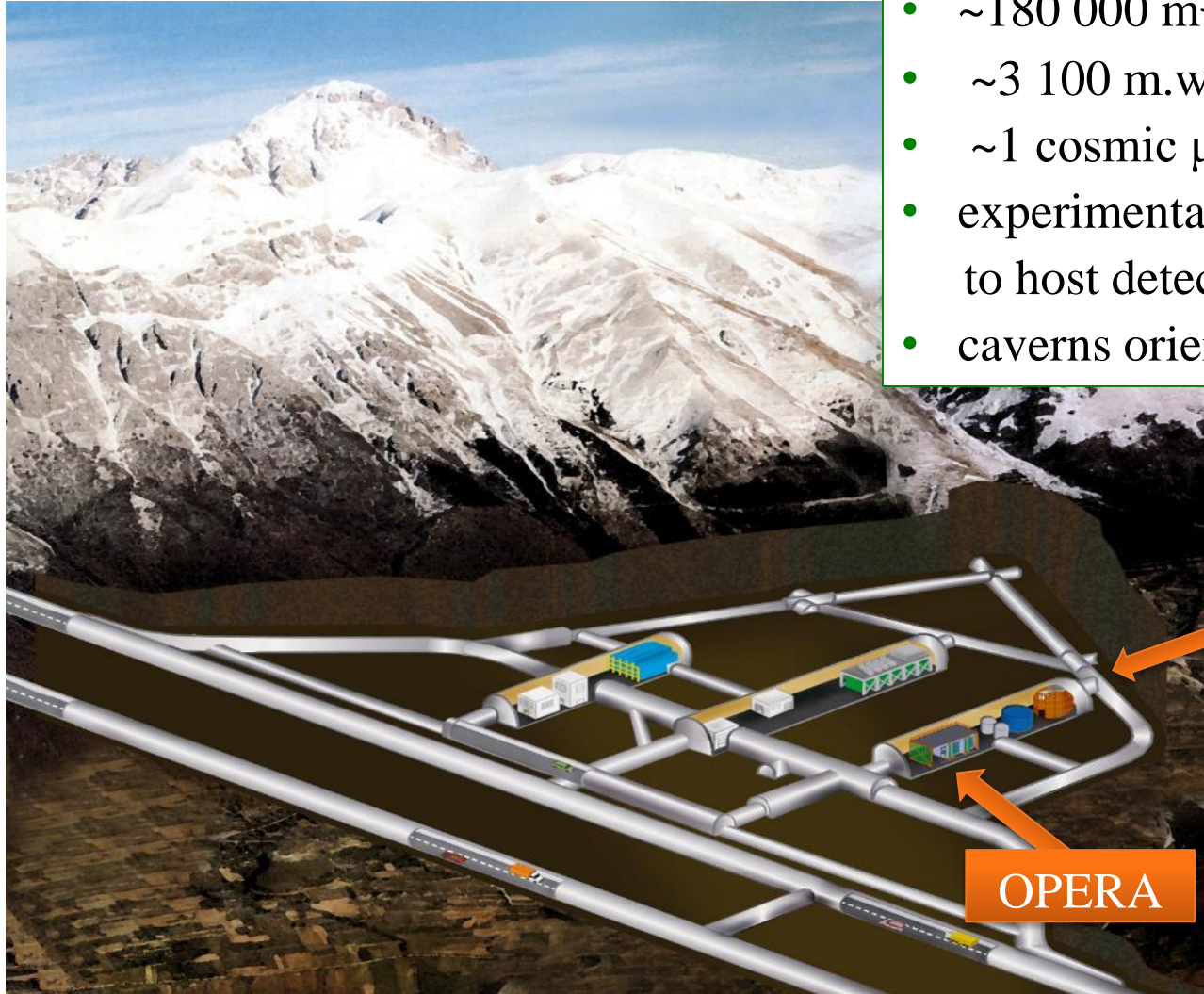
OPERA taking a "selfie"... Thank you!

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

BACKUP

LNGS of INFN

The world largest underground physics laboratory



- $\sim 180\,000\text{ m}^3$ caverns' volume
- $\sim 3\,100\text{ m.w.e.}$ overburden
- $\sim 1\text{ cosmic } \mu / (\text{m}^2 \times \text{hour})$
- experimental infrastructure suitable to host detector and related facilities
- caverns oriented towards CERN

CNGS

OPERA

OPERA Collaboration



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



METU Ankara



Technion Haifa



LAPP Annecy
IPHC Strasbourg



LHEP Bern



IHE Brussels



Hamburg

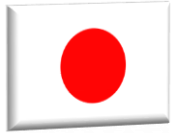


IRB Zagreb



INR Moscow
NPI Moscow
ITEP Moscow
SINP NSU Moscow

JINR Dubna



Aichi
Toho
Kobe
Nagoya
Nihon



Jinju



~ 140 physicists
from 28 institutions and 11 countries

BACKUP

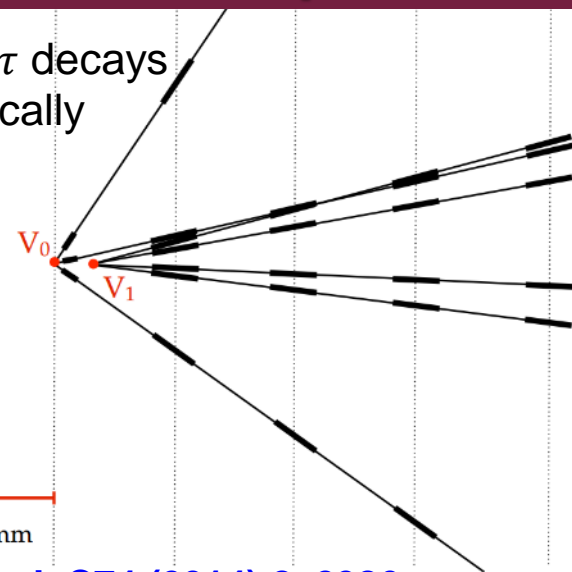
- BACKGROUND

Validation with the CNGS charm events sample

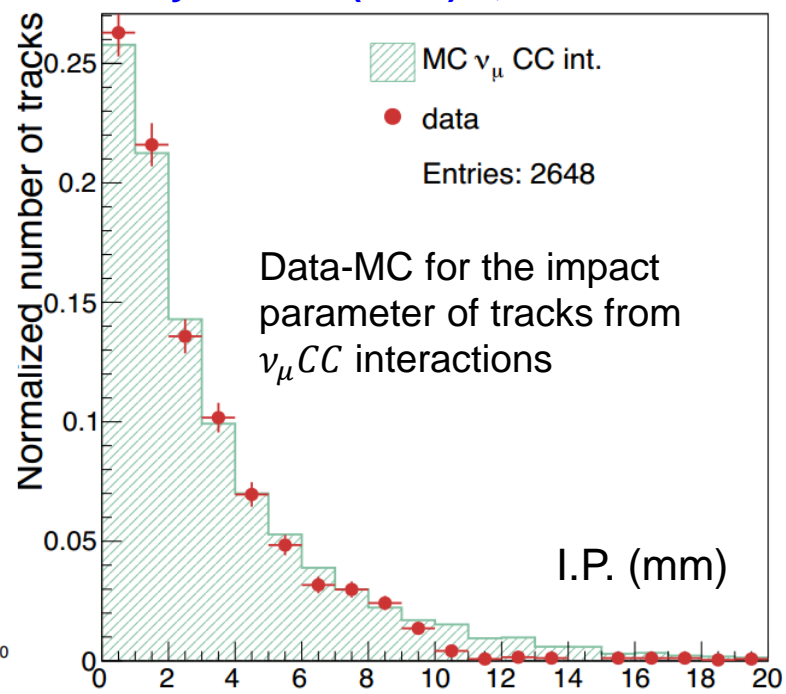
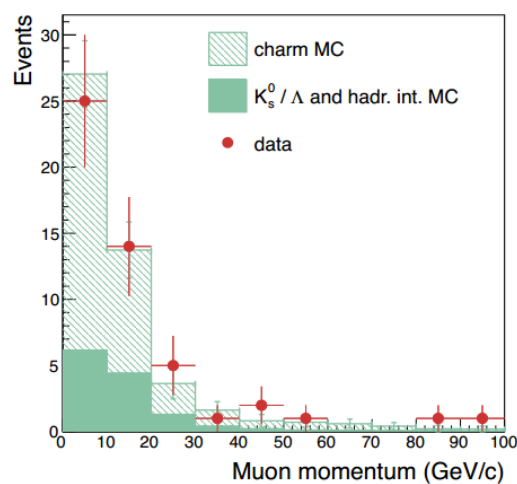
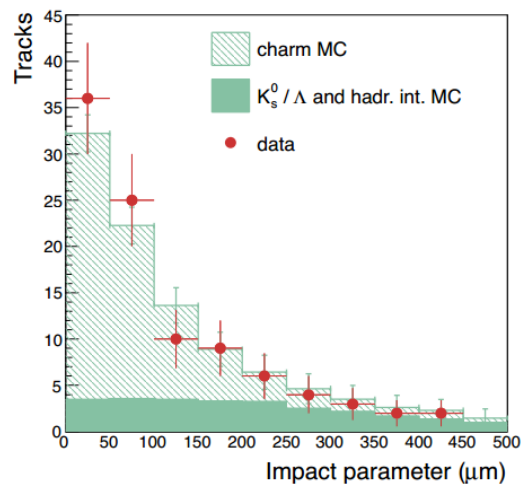
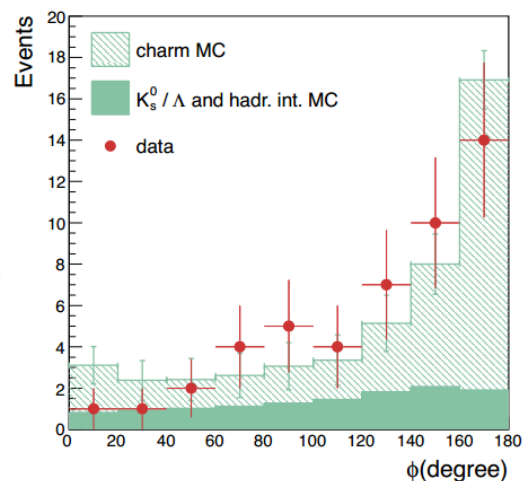
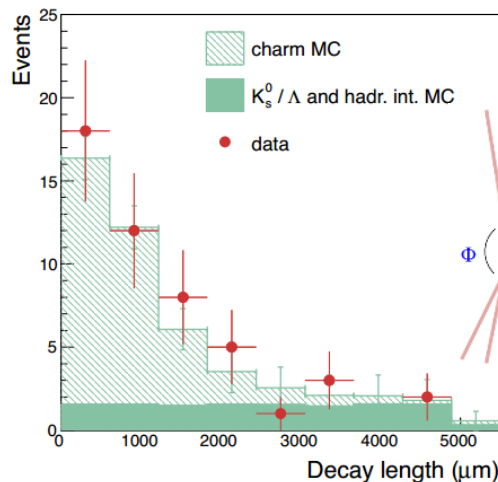
Test for: reconstruction efficiencies, description of kinematical variables, charm background.

54 ± 4 expected \leftrightarrow 50 observed

Charm and τ decays
are topologically
Similar



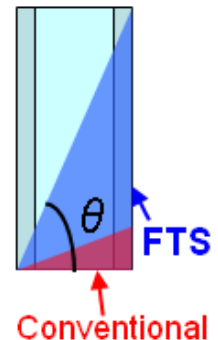
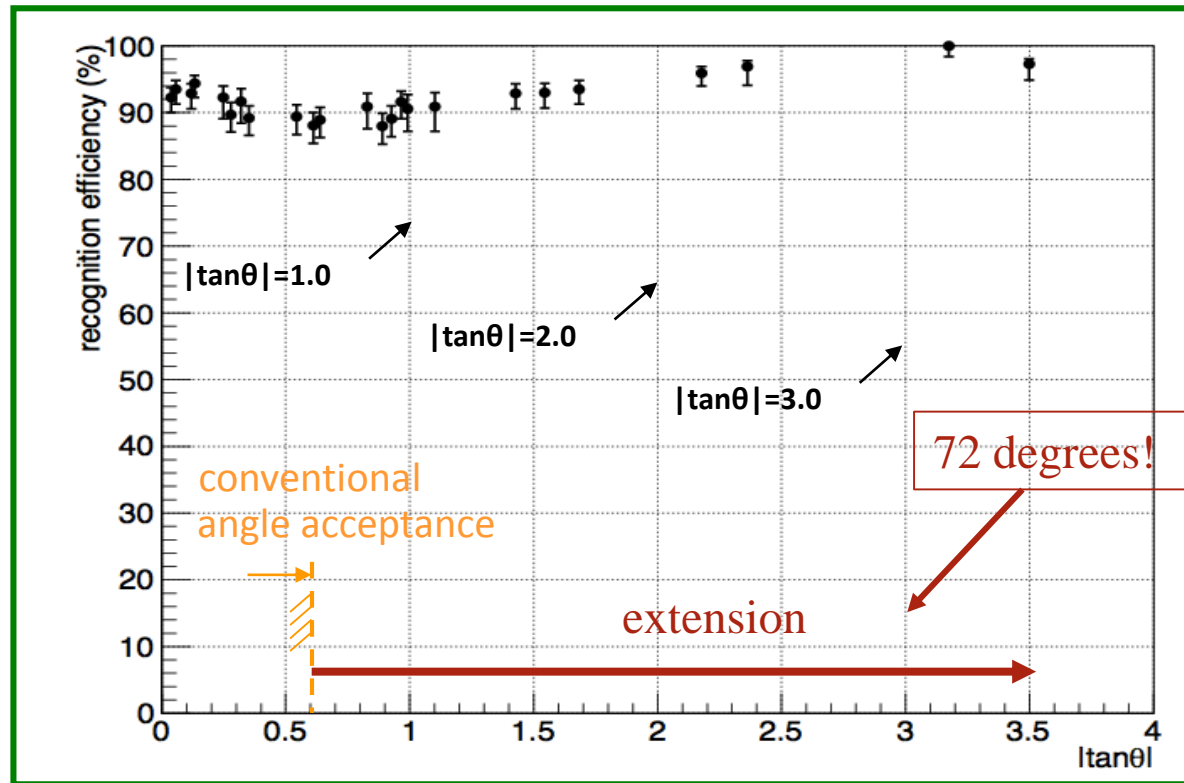
Eur.Phys.J. C74 (2014) 8, 2986



Improvements On The Background Rejection

Large angle track detection

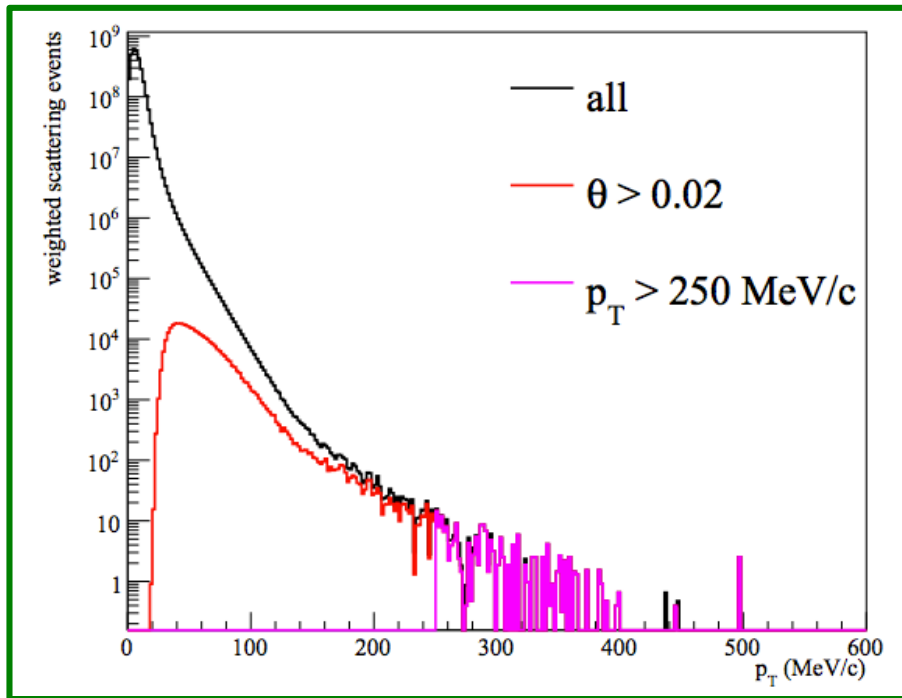
Undetected soft and large angle muons are the source of charm background
Detection of particles and nuclear fragments in **hadronic interactions**



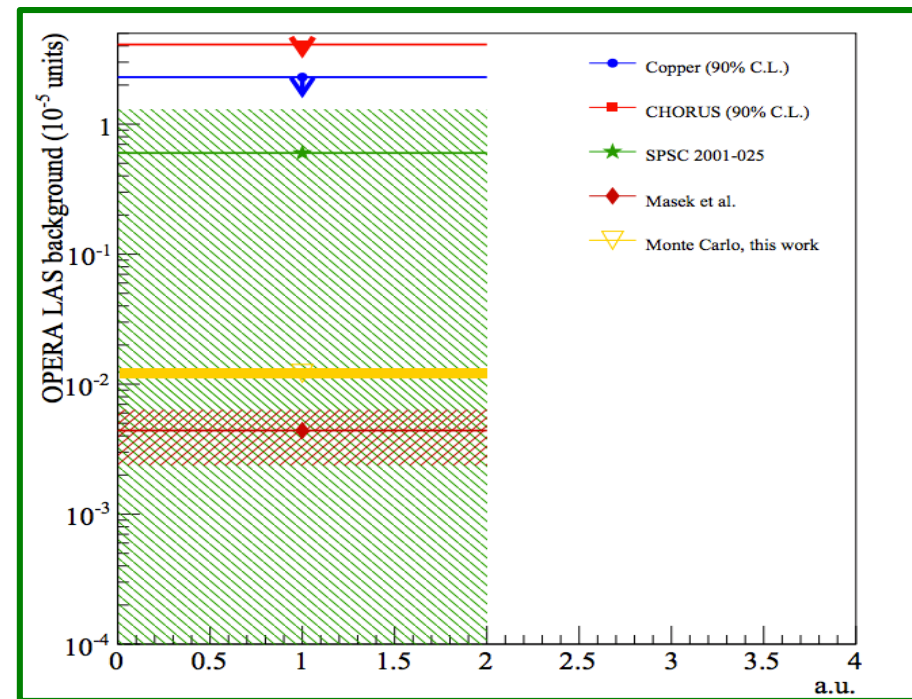
JINST 9 (2014) P12017

Large angle μ scattering

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



Main background in the $\tau \rightarrow \mu$ 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

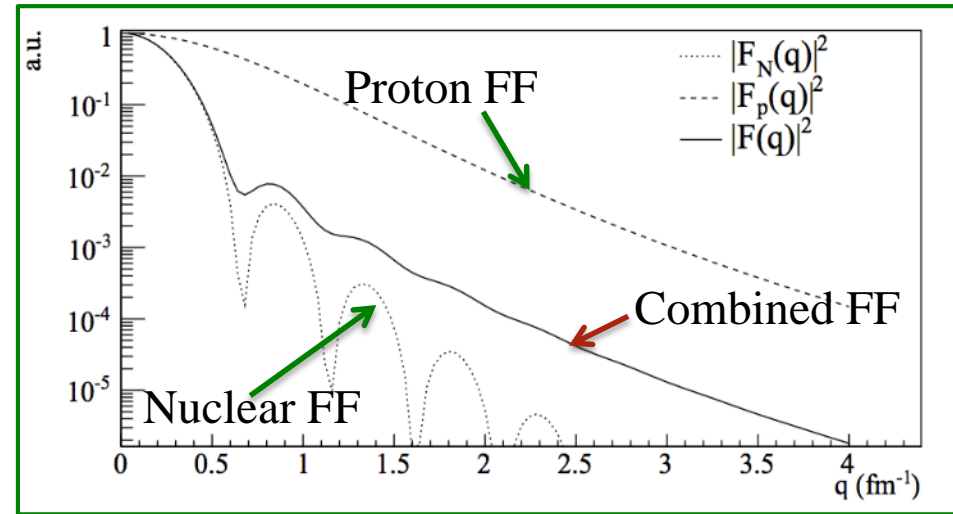
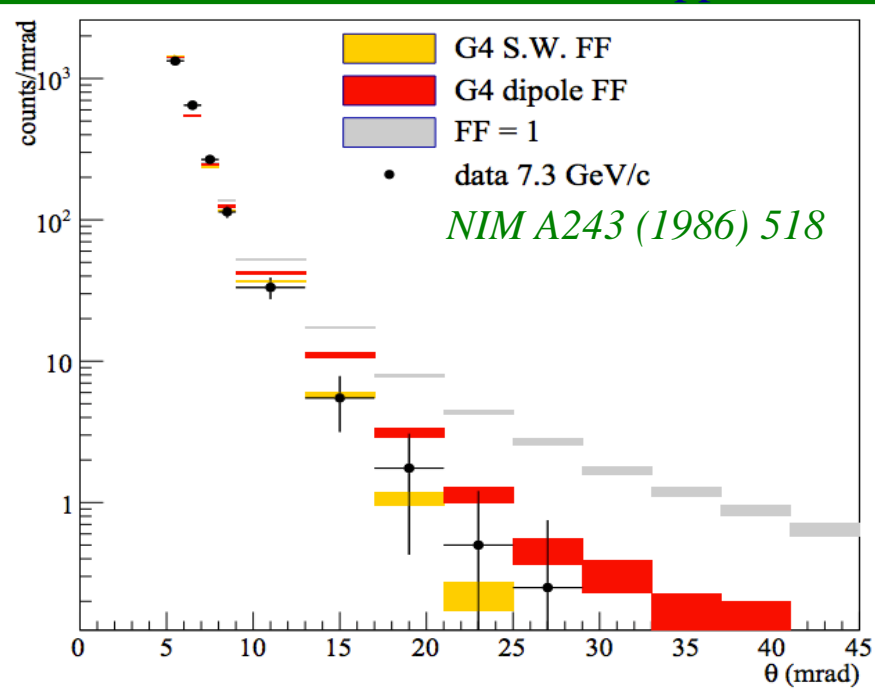
New estimate based on GEANT4
 - Simulation modified by introducing
 form factors (FF) for Lead
 (Saxon-Woods parameterization)

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

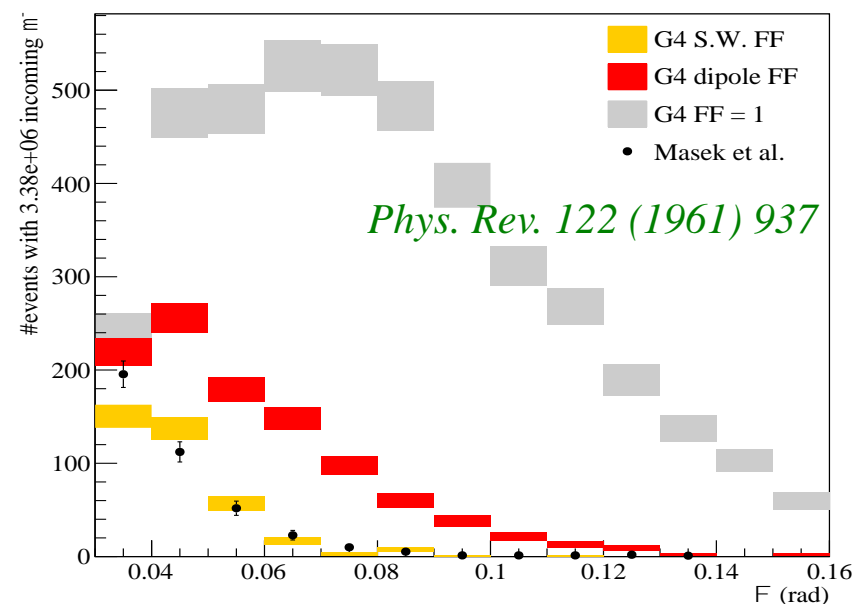
IEEE Transactions
 on Nuclear Science

MC predictions compared to available data

7.3 GeV/c muons on Copper



2 GeV/c muons on Lead

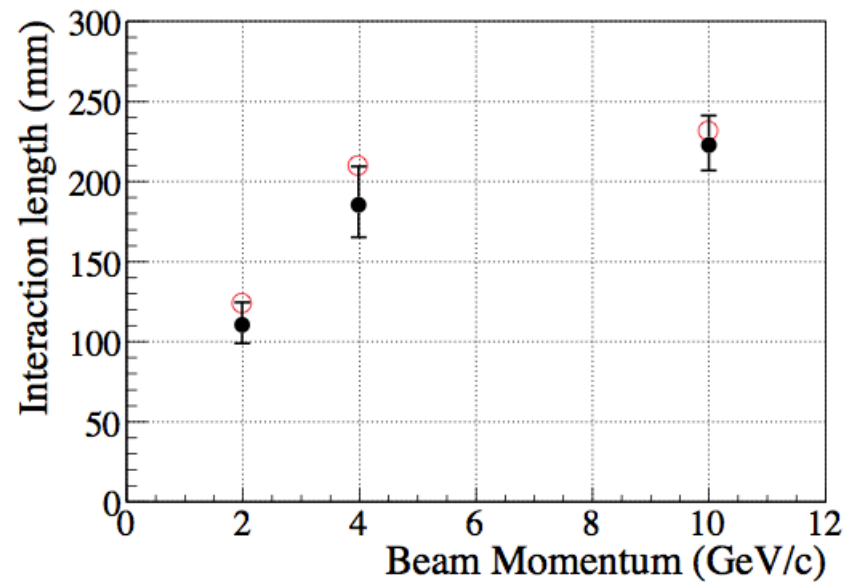
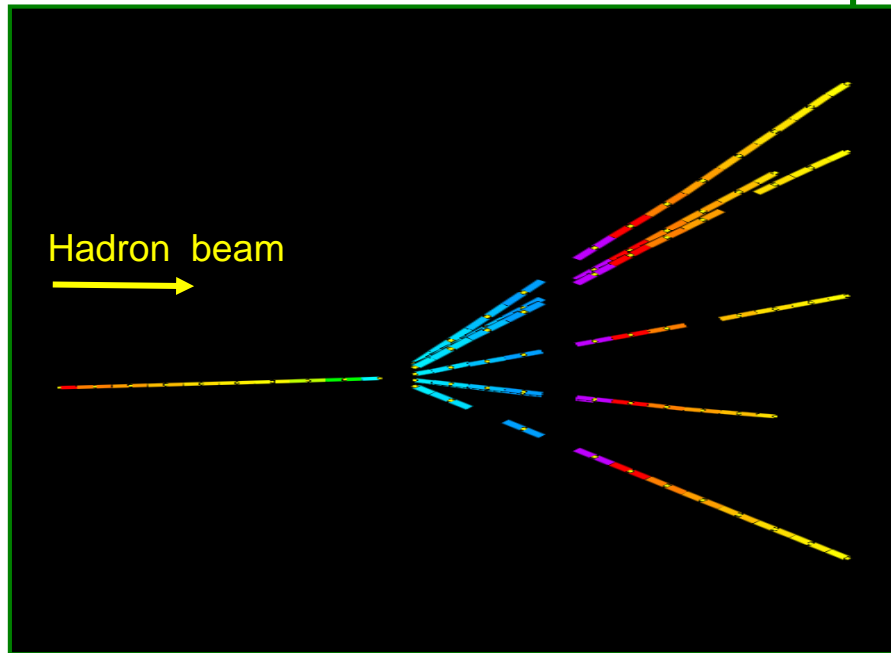


Background Studies: Hadronic Interactions

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

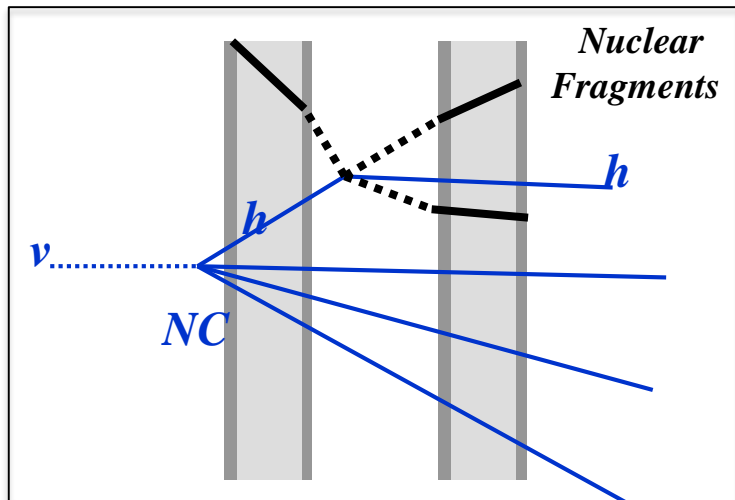


Black : π^- beam data

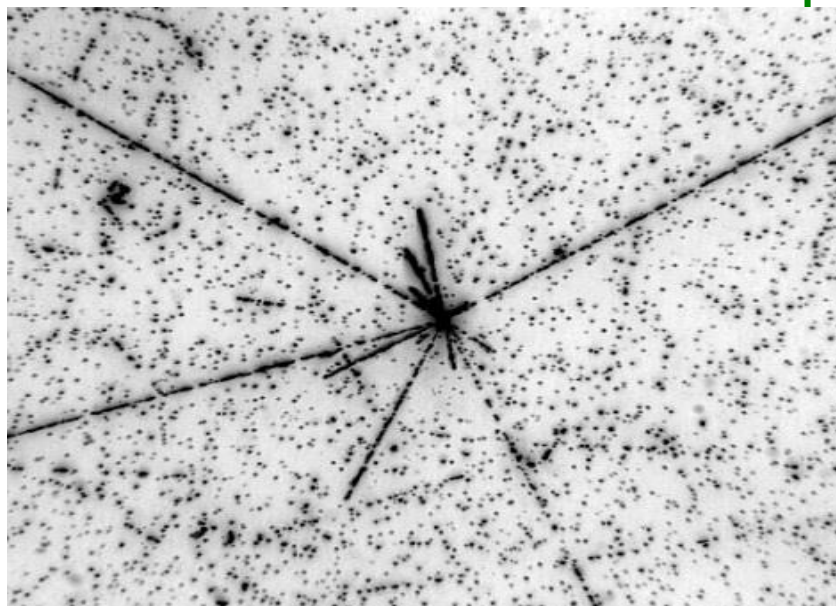
Red : MC (FLUKA) simulation

PTEP 9 (2014) 093C01

Nuclear Fragments Emission Probability

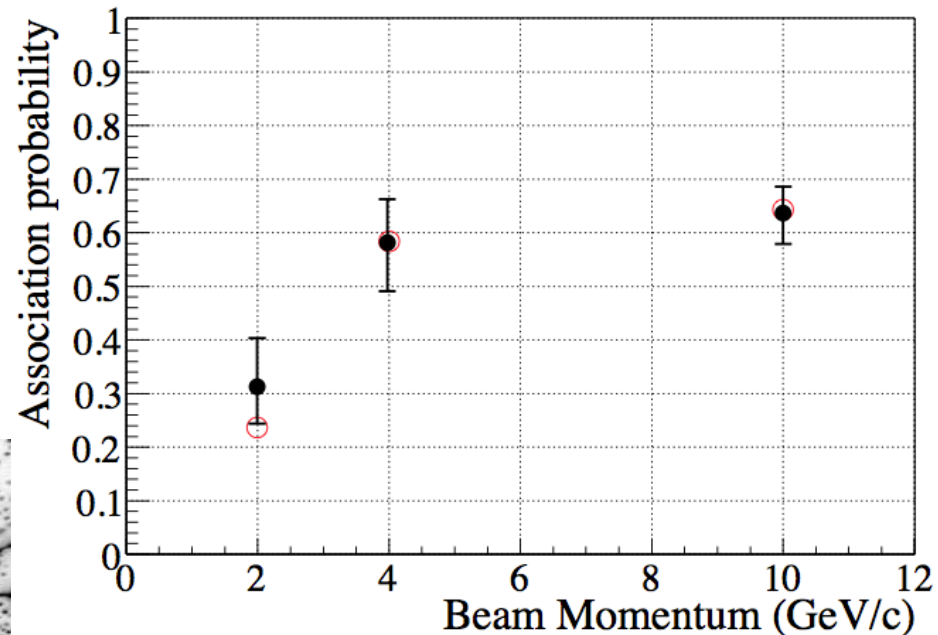


Highly ionizing fragments



150 μm

Additional background reduction



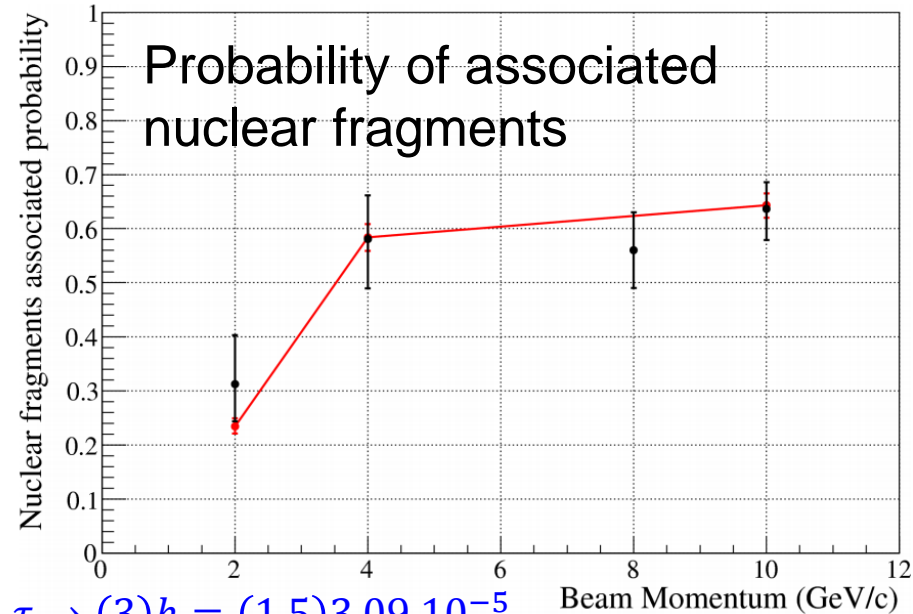
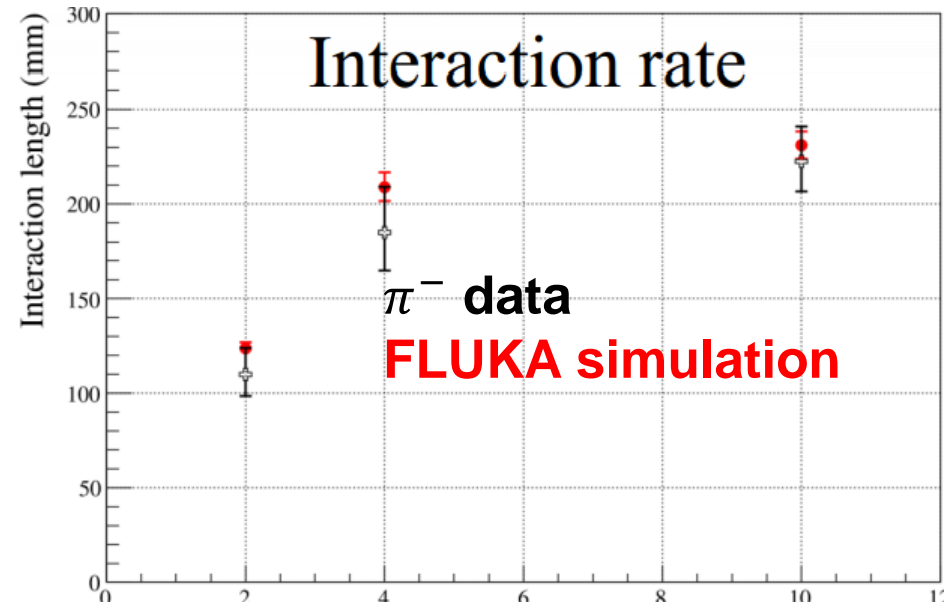
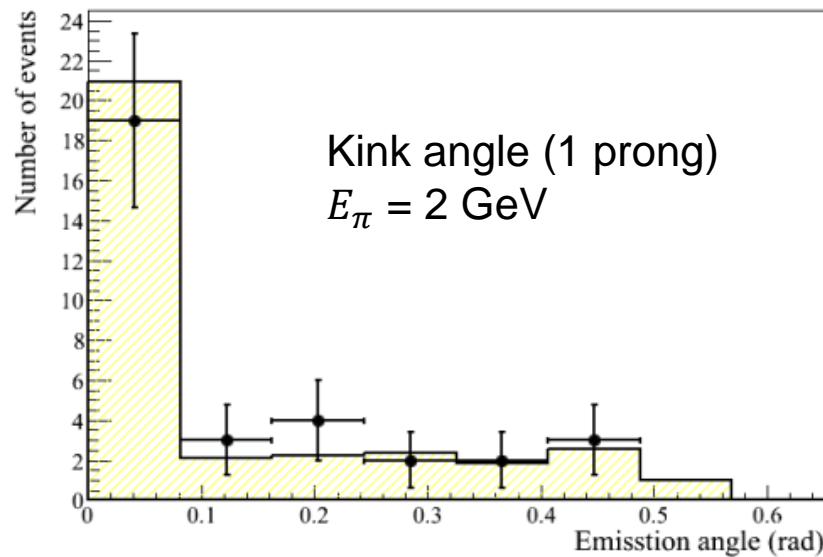
Black : experimental data

Red : simulated data ($\beta = p/E = 0.7$)

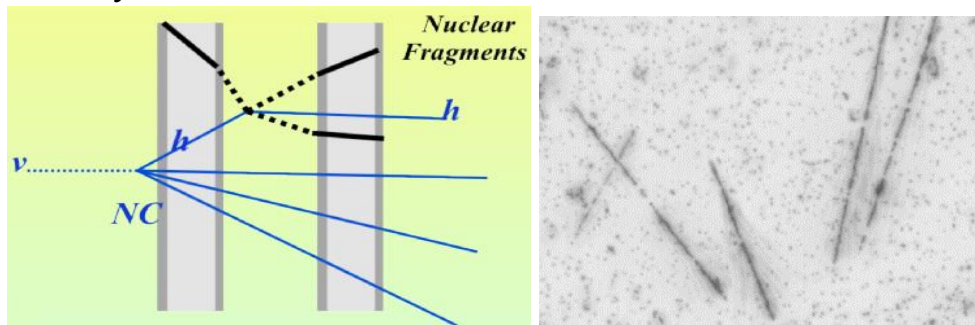
PTEP 9 (2014) 093C01

Hadronic background: π test beams

CERN π^- test beam



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



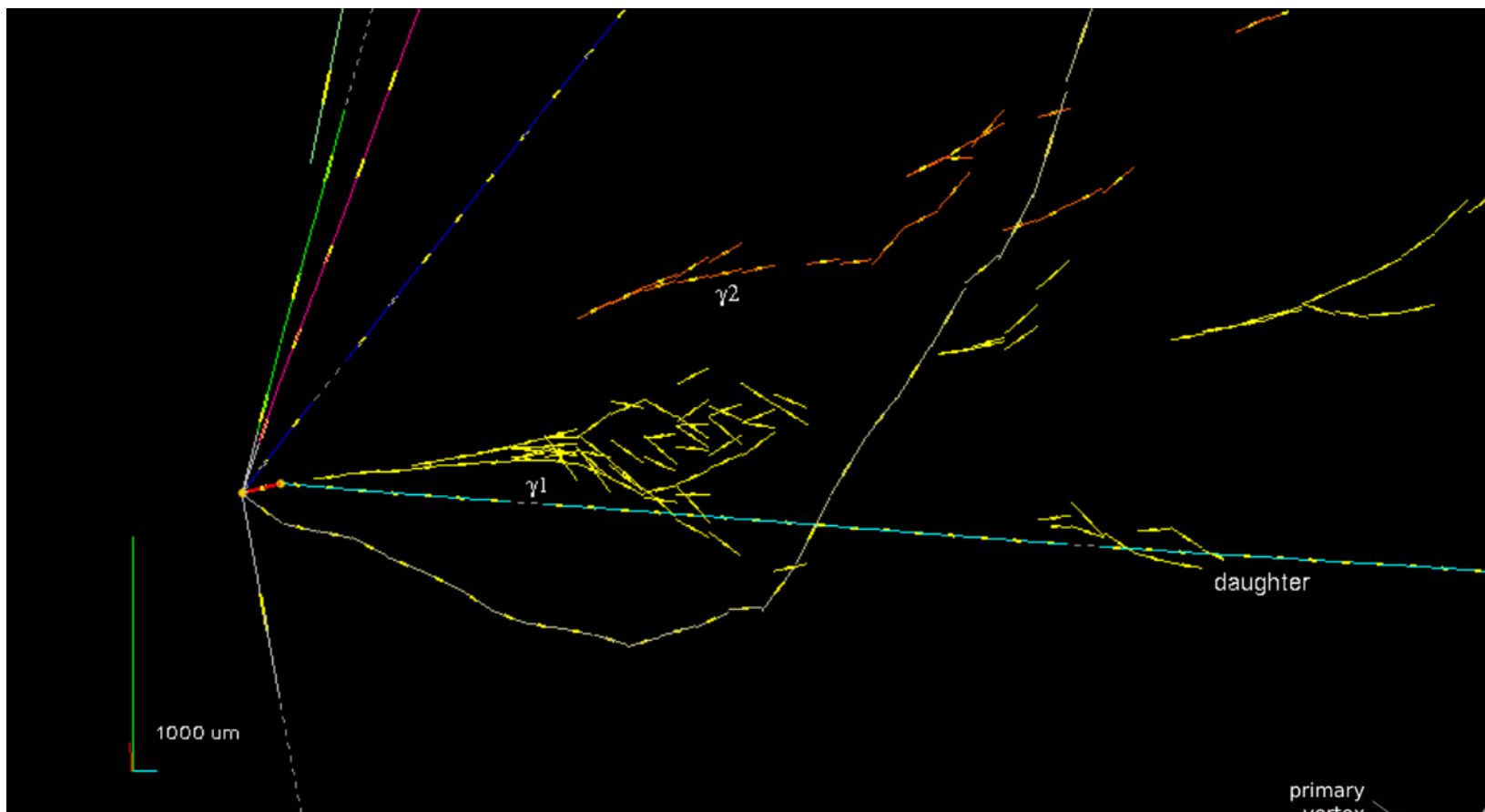
Hadronic background rate per located event: $\tau \rightarrow (3)h = (1.5)3.09 \cdot 10^{-5}$

BACKUP

- NU TAU CANDIDATES

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

Phys. Lett. B691(2010) 138



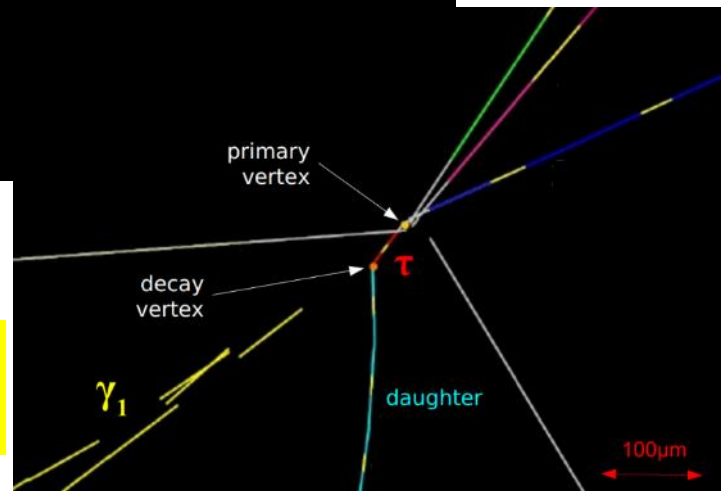
$$\tau^- \rightarrow \rho^- + \nu_\tau \quad (\text{B.R.} \sim 25\%)$$

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

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

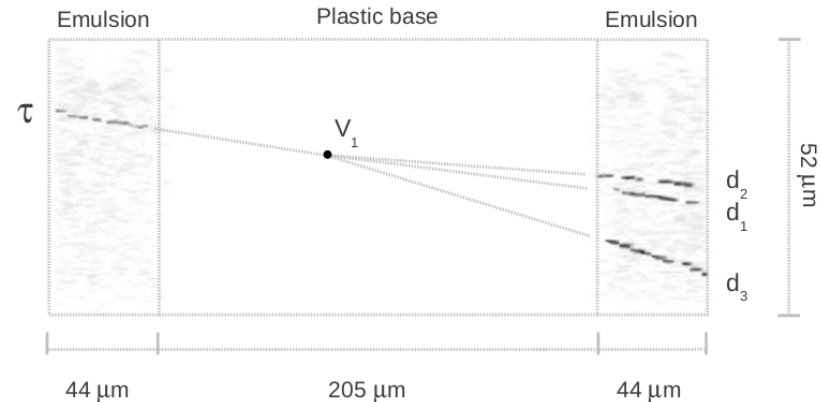
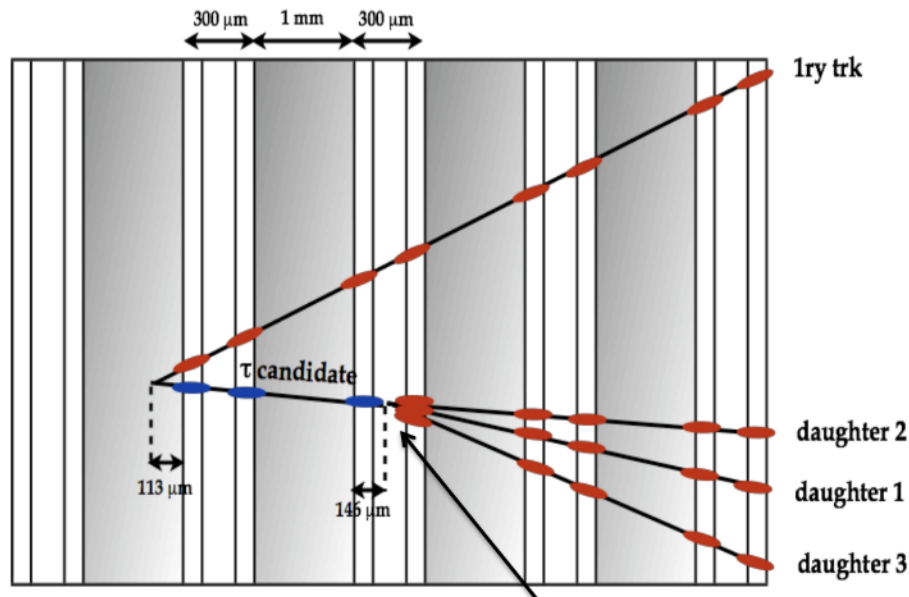
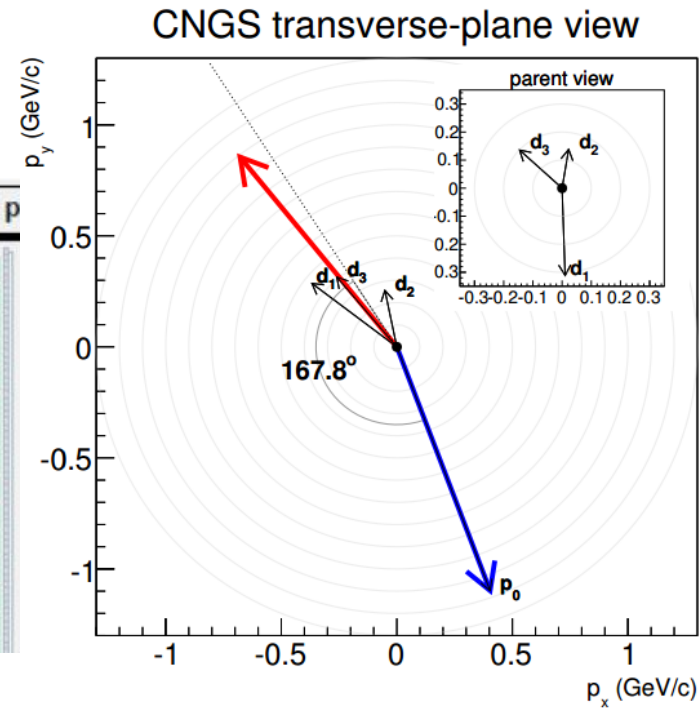
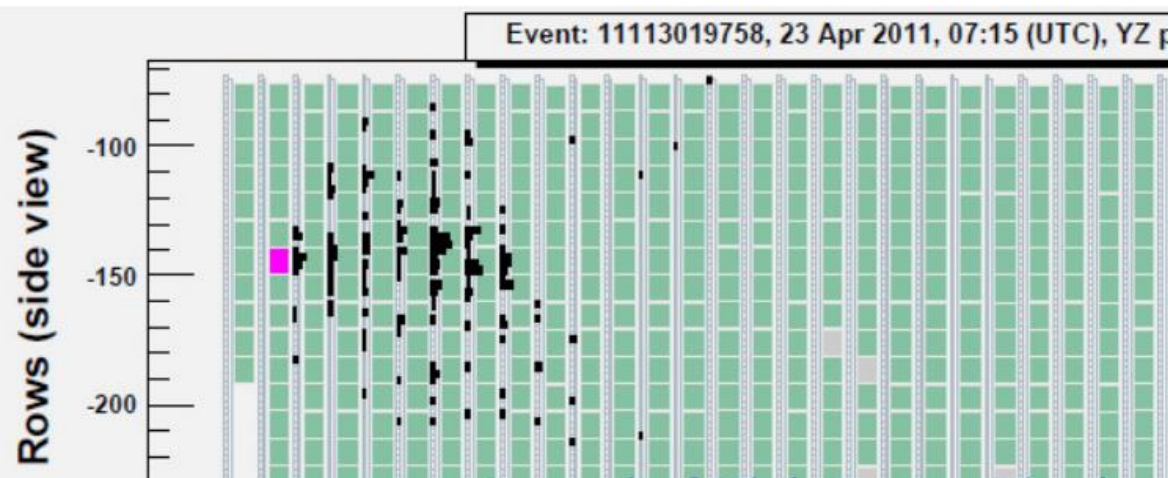
$$640^{+125}_{-80} (\text{stat.})^{+100}_{-90} (\text{sys.}) \text{ MeV}/c^2$$

$$120 \pm 20(\text{stat.}) \pm 35(\text{sys.}) \text{ MeV}/c^2$$

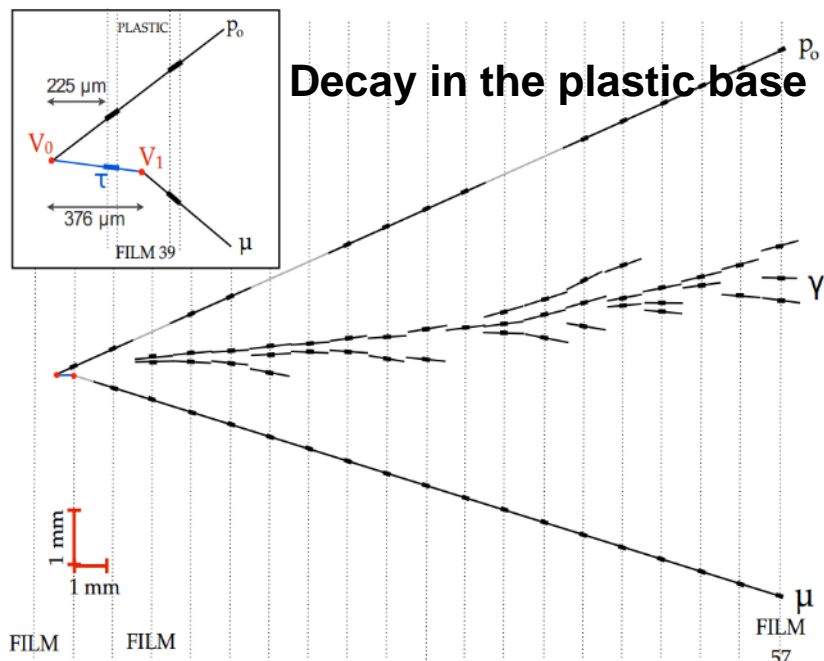


The 2nd candidate ($\tau \rightarrow 3h$)

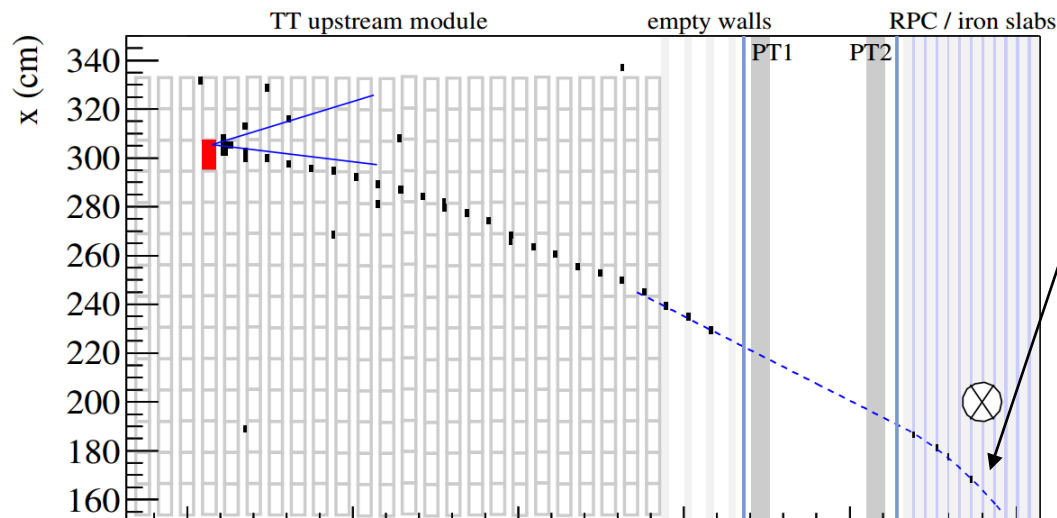
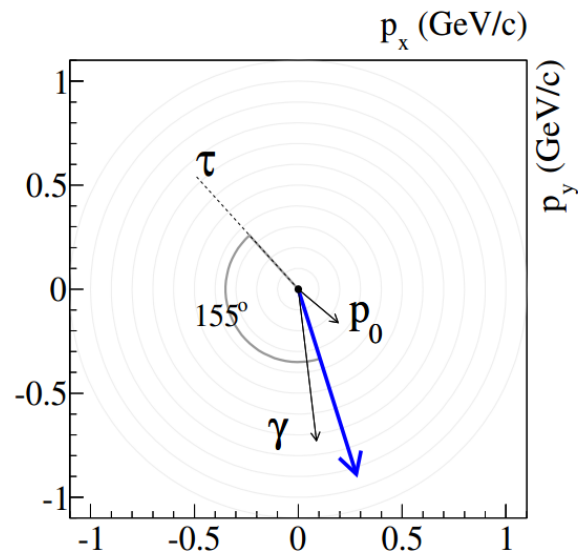
JHEP 11 (2013) 036



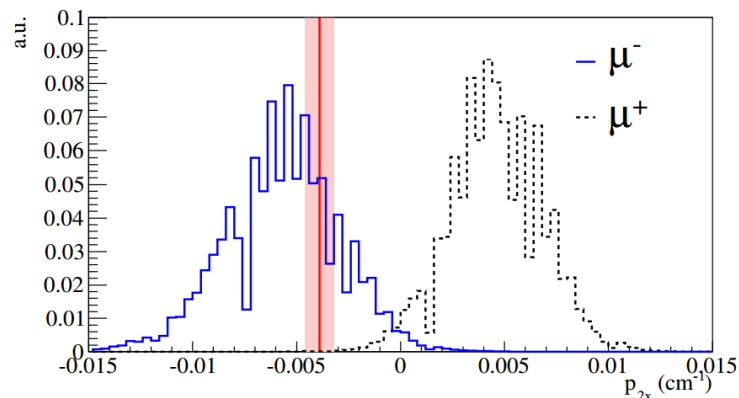
The 3rd candidate ($\tau \rightarrow \mu$)



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



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



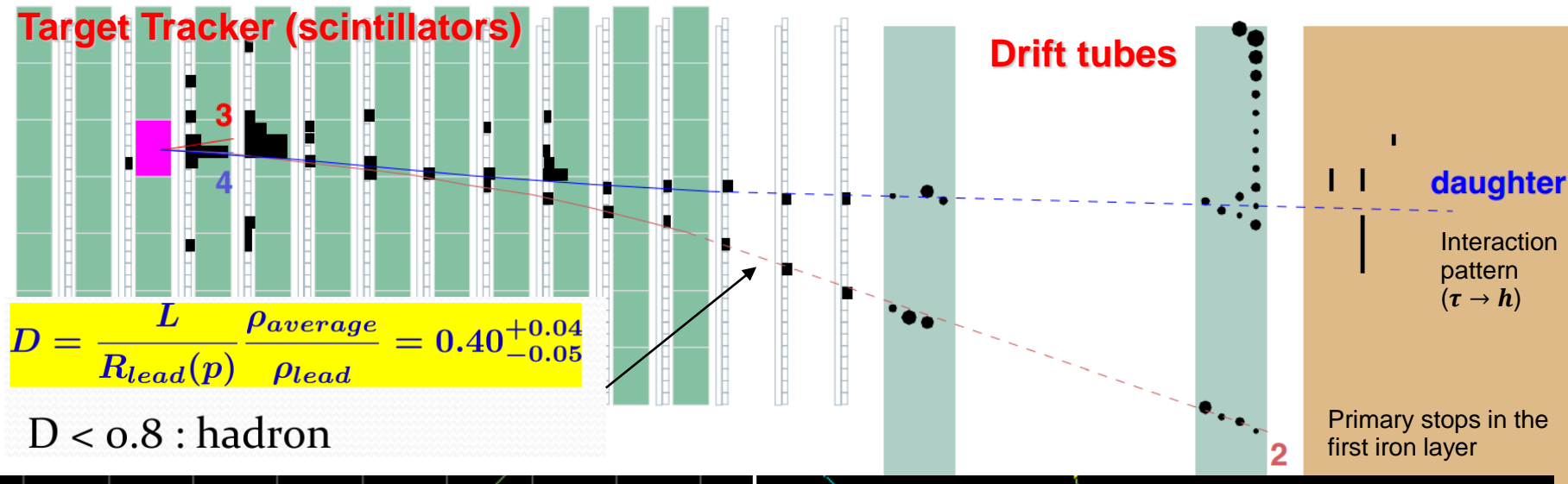
First measurement of lepton charge in appearance mode.

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

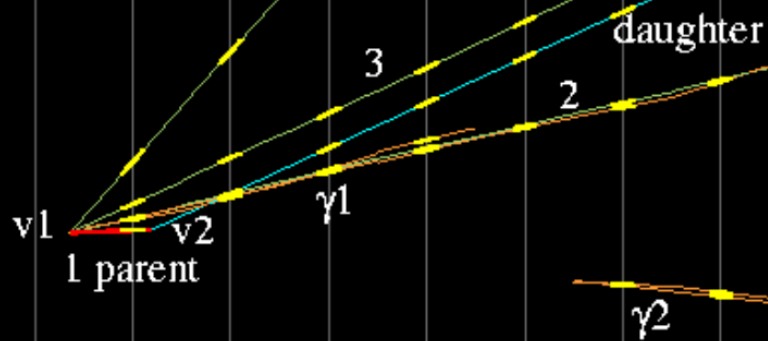
PTEP 2014 (2014) 10, 101C01

Target Tracker (scintillators)

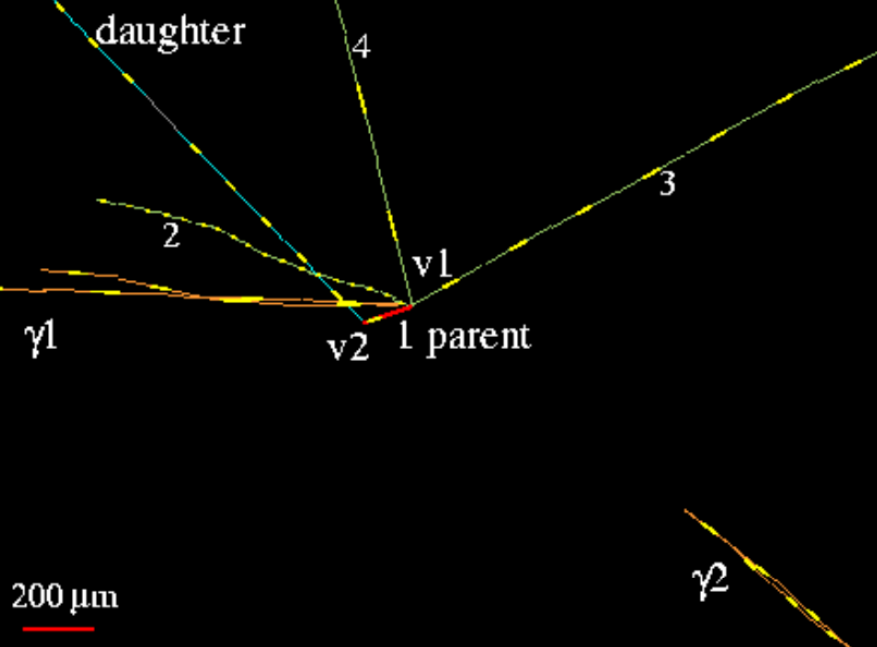
Drift tubes



Flight length
1090 μm



daughter



The Fifth ν_τ Candidate

Kinematical variables

