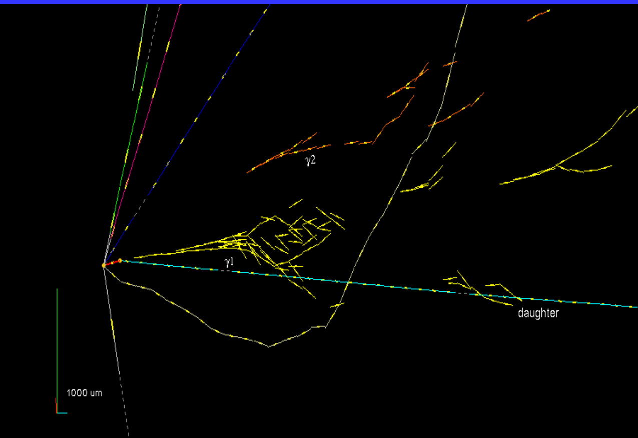
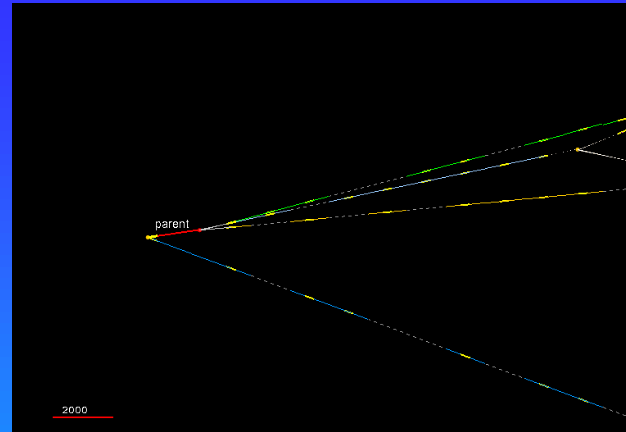
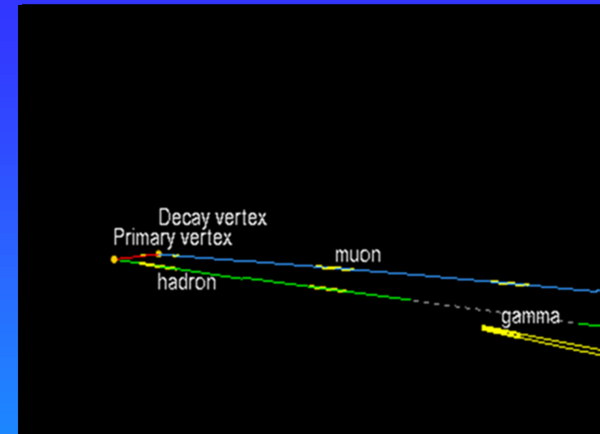
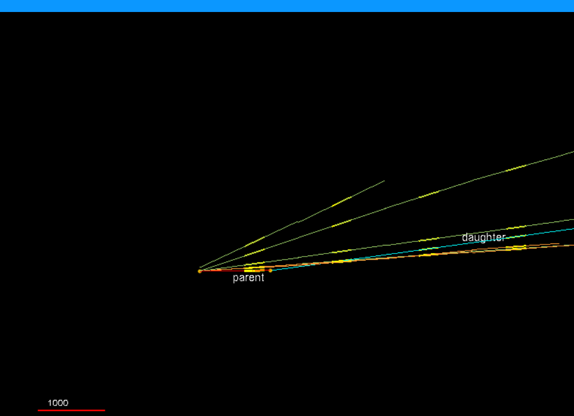






Discovery of ν_τ Appearance and Recent Results from OPERA



Tsutomu Fukuda
Toho Univ. Japan
for the OPERA Collaboration

OPERA

La Thuile 2016, 7th Mar. 2016, Aoste, Italy

OPERA collaboration

11 countries, 26 institutions, 140 physicists

Bari
Bologna
LNF
LNGS
Napoli
Padova
Roma
Salerno

LAPP Annecy
IPHC Strasbourg

INR-RAS Moscow
LPI-RAS Moscow
SINP MSU Moscow
JINR Dubna

Aichi
Toho
Kobe
Nagoya
Nihon

Technion Haifa | LHEP Bern | IHE Brussels | Hamburg | IRB Zagreb | METU Ankara | Jinjiu

Motivation of OPERA

- Neutrino oscillations have been studied in disappearance mode.
  - Atmospheric sector : Super-Kamiokande, MACRO, MINOS, K2K, T2K,…

  → Long way to appearance
  - Super-Kamiokande : ν_τ appearance in atmospheric neutrino data (statistical separation in background-dominated sample)
  - T2K, NOvA : ν_e appearance in ν_μ beam

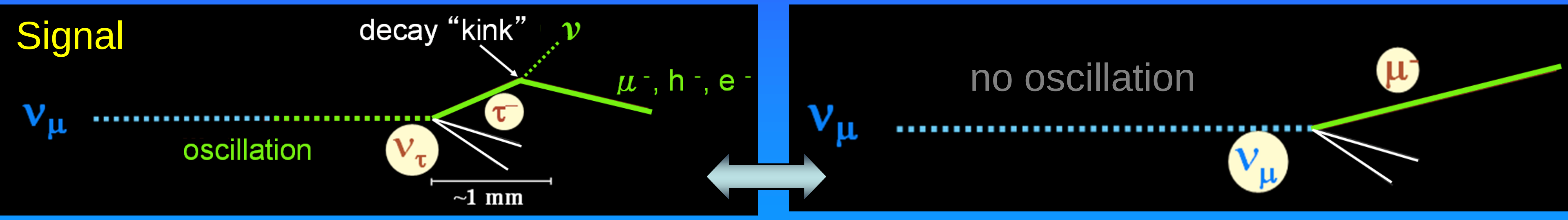
- Main goal of OPERA
  Verify the $\nu_\mu \rightarrow \nu_\tau$ oscillation at the atmospheric scale in appearance mode (S/N ~ 10).

Oscillation **P**roject with **E**mulsion t**R**acking **A**pparatus

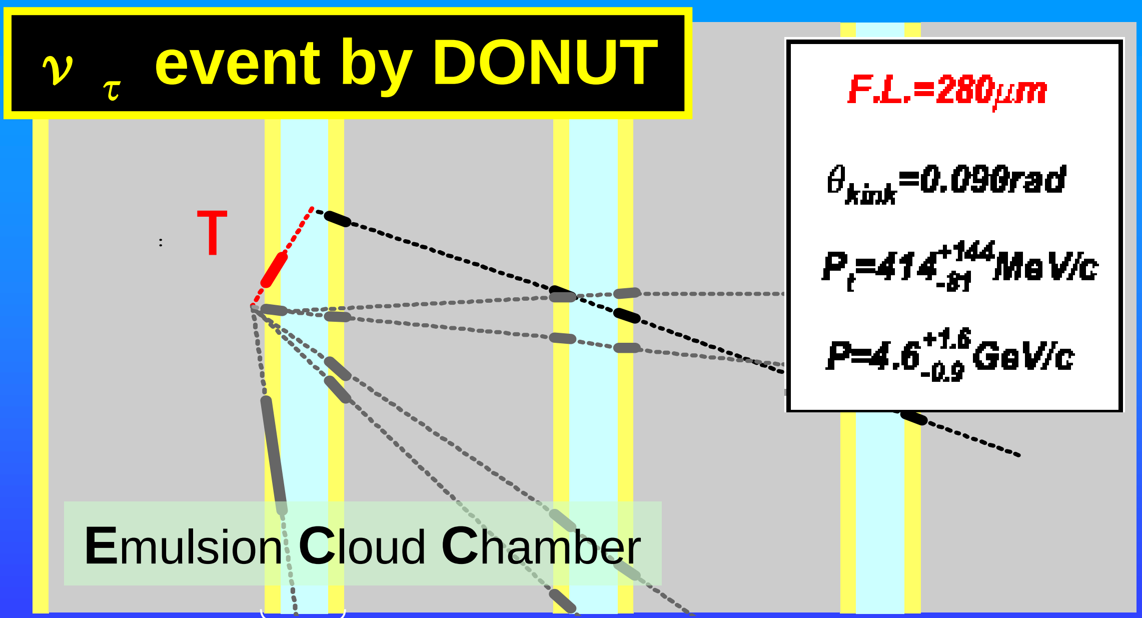
ν_τ detection

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_\tau + N \rightarrow \tau^- + X$$

Search for τ decay topology on an event by event basis.



plus 3-prong decay modes



emulsion film

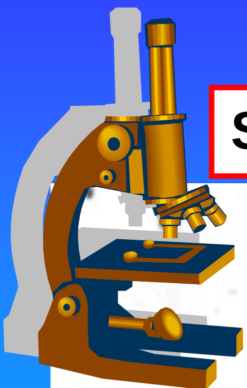
1mm Iron plate

Decay mode	BR (%)
$\tau^- \rightarrow \mu^- \nu_\mu \overline{\nu}_\tau$	17.36
$\tau^- \rightarrow e^- \nu_e \overline{\nu}_\tau$	17.85
$\tau^- \rightarrow h^-(n\pi^0)\, \overline{\nu}_\tau$	49.52
$\tau^- \rightarrow 2h^-h^+(n\pi^0)\, \overline{\nu}_\tau$	15.19

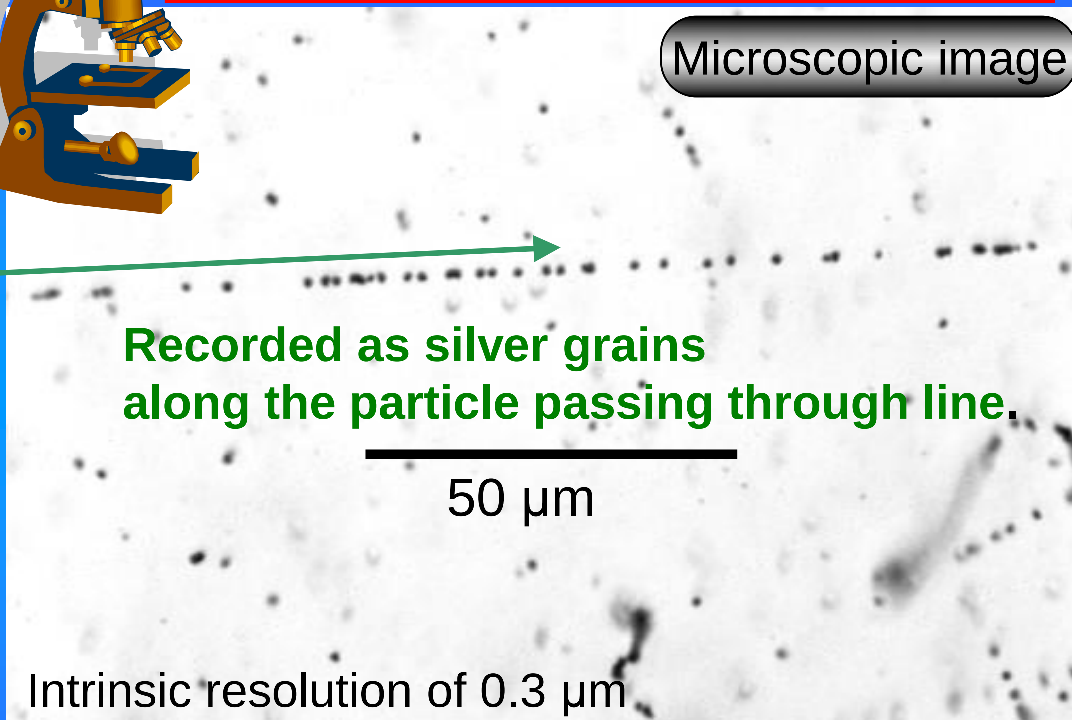
Direct observation of ν_τ using emulsion technology

Phys. Lett. B 504 (2001) 218

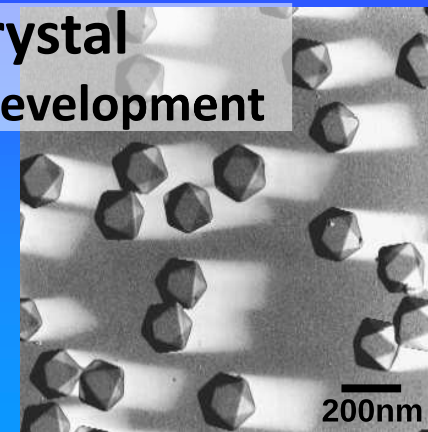
Nuclear emulsion



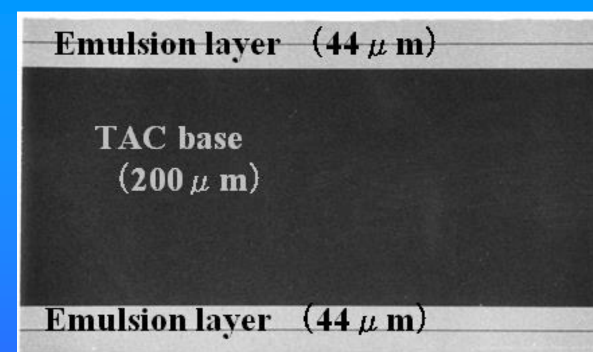
Sub micron resolution 3D tracker



AgBr crystal
before development



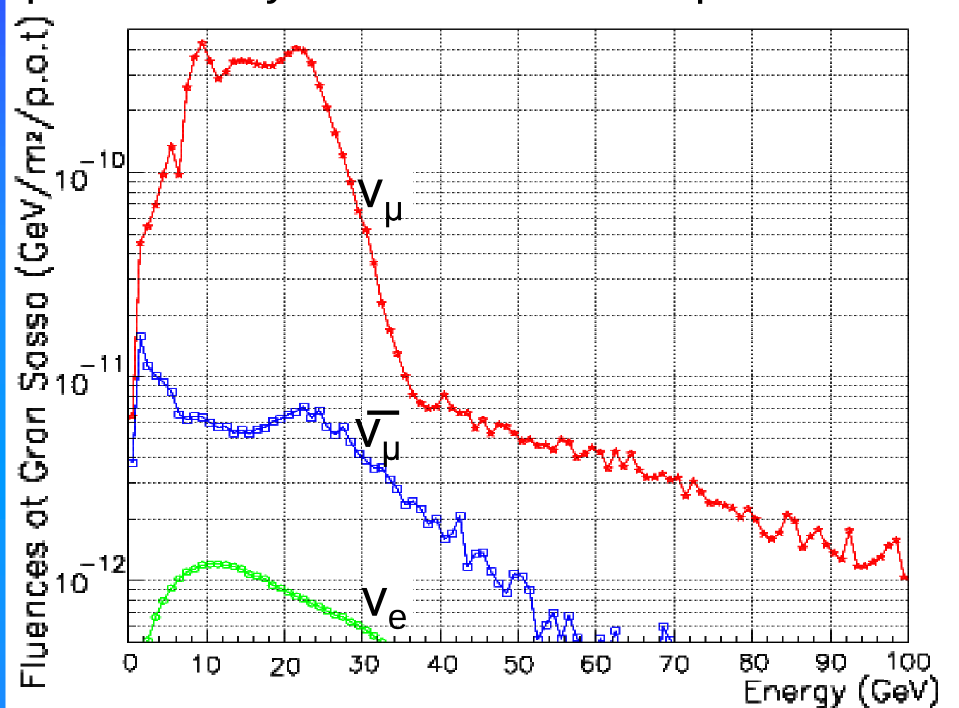
Cross-section view of emulsion film



- Nuclear Emulsion is a special photographic film
  : AgBr micro crystal semiconductor
- Signal is amplified by chemical process (development).

CNGS neutrino beam

produced by the SPS 400 GeV proton beam



conventional ν beam

< Eν > (GeV)	17
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87 %*
$\bar{\nu}_\mu$ / ν_μ	2.1 %*
ν_τ prompt	Negligible*

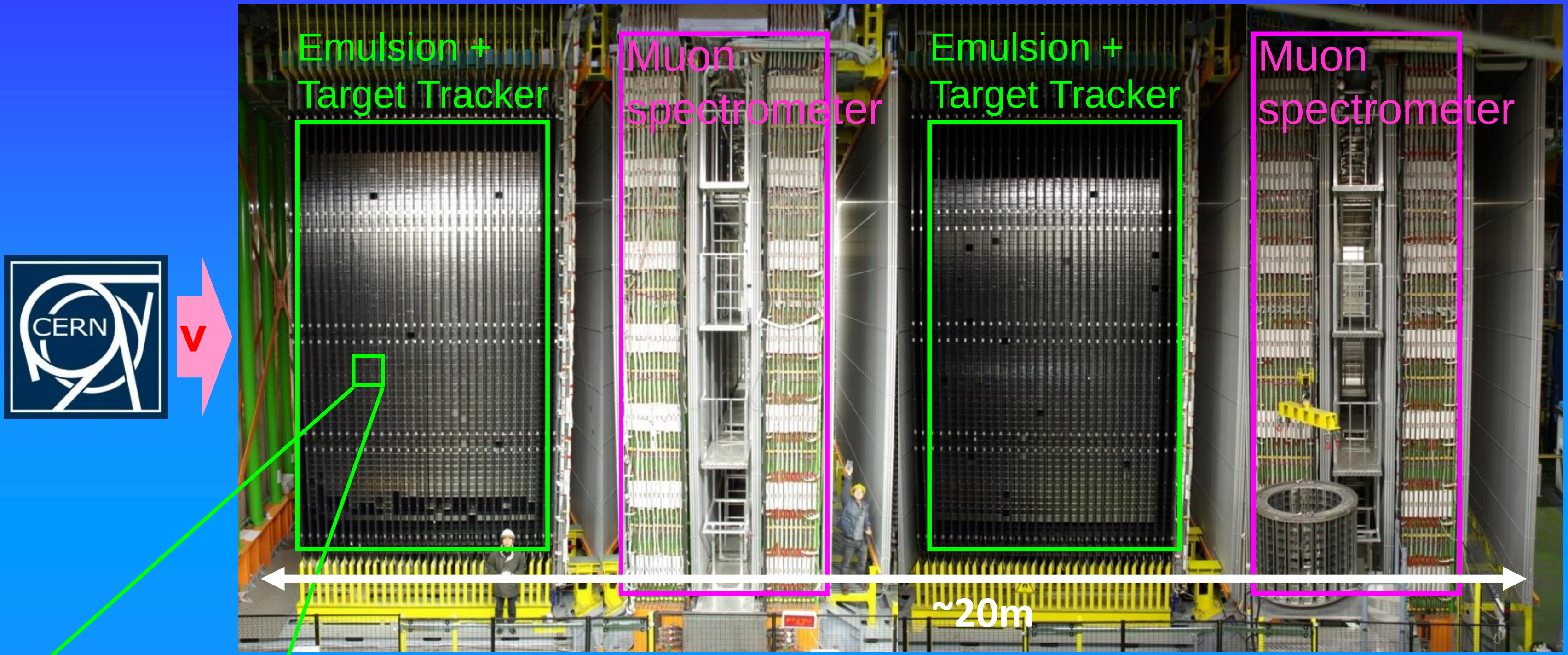
* Interaction rate at LNGS

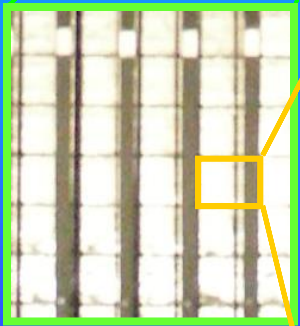
Beam is designed to observe τ leptons.

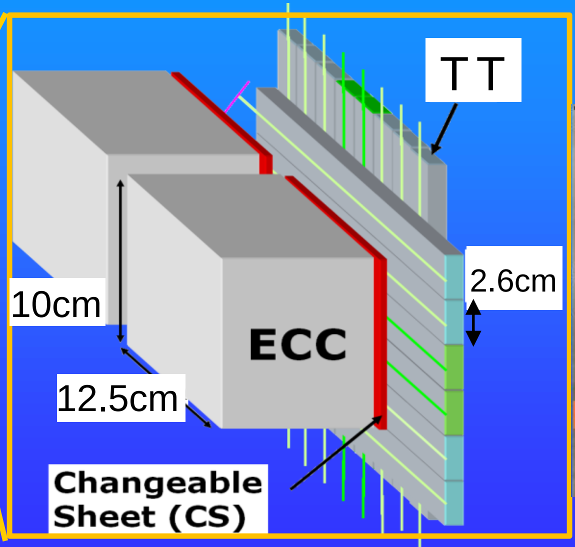
Interaction rates @1.8×10^{20} p.o.t.

→ ~20kν_μCC+NC and 66.4ν_τCC (not efficiency corrected)

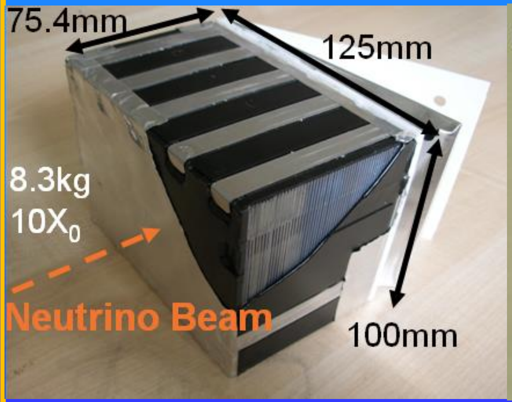
The OPERA Detector

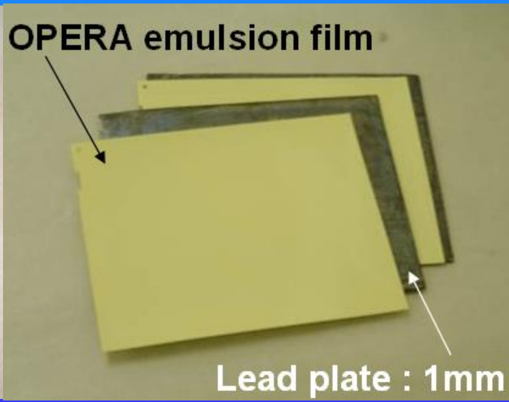






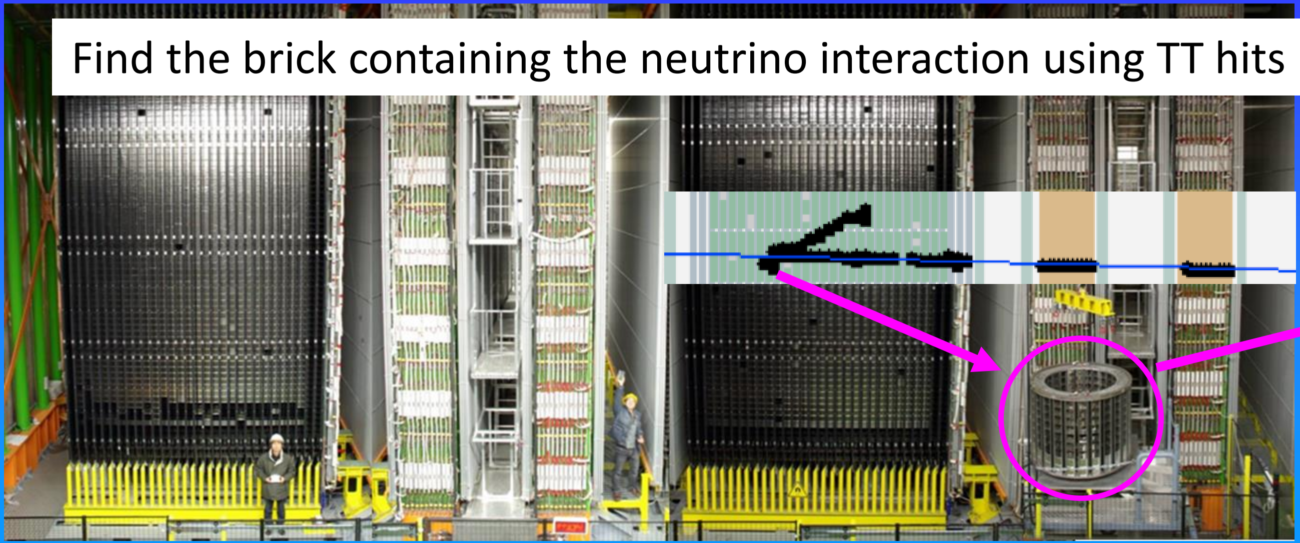
ECC: ~150,000 bricks (1.25 kton)

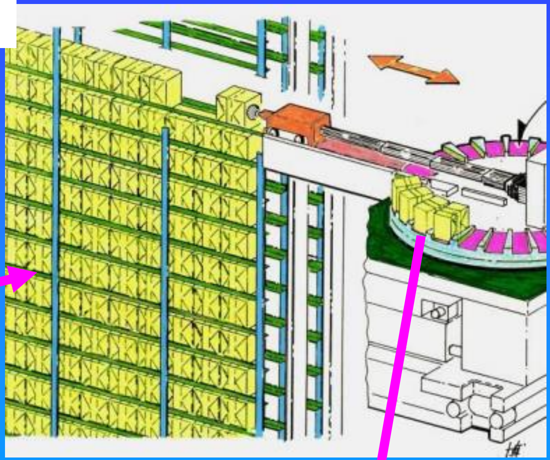


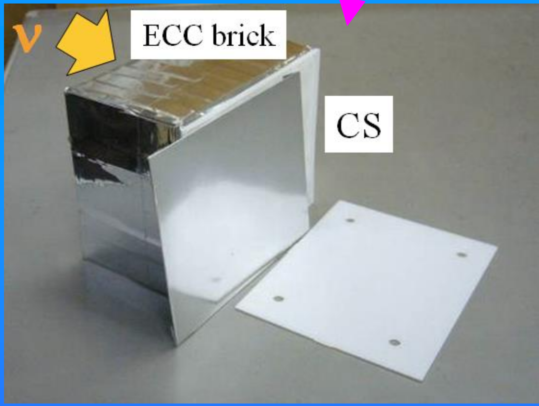


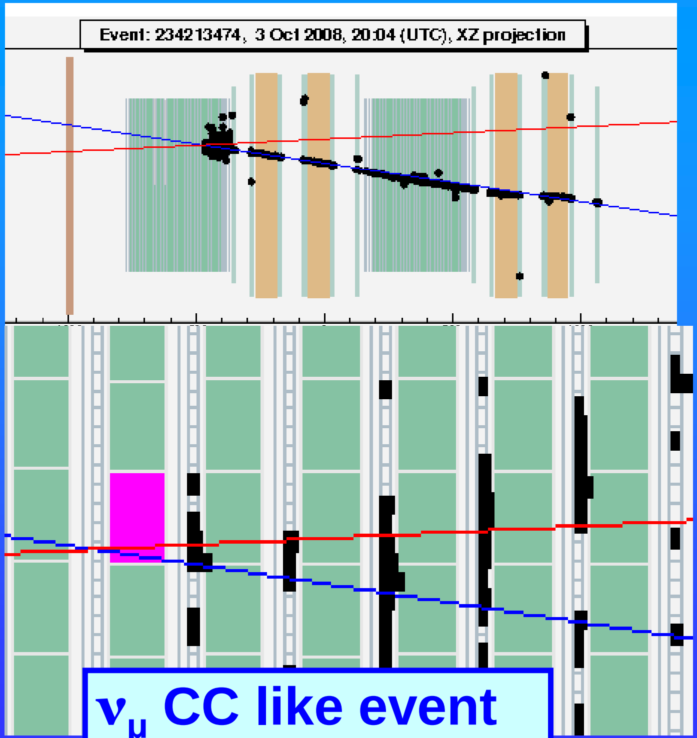
NIM A556 (2006) 80

The OPERA detector

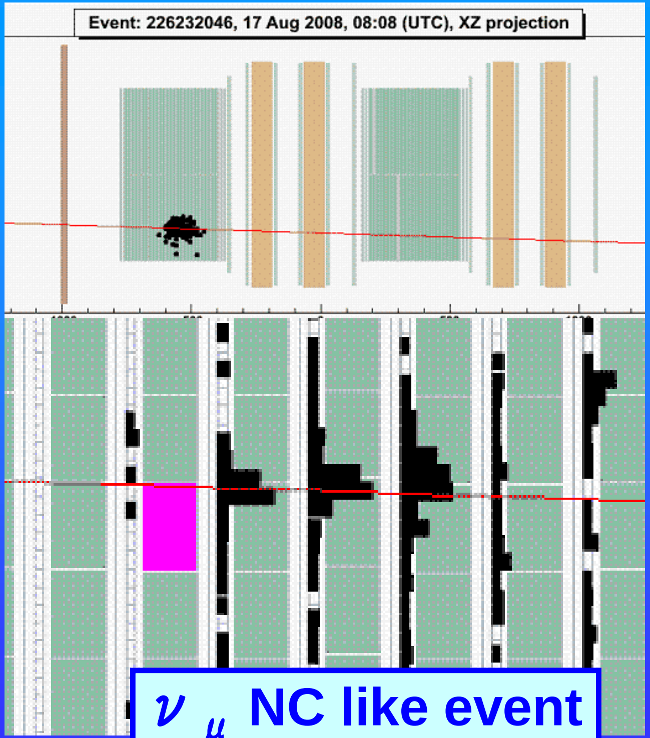








ν_μ CC like event



ν_μ NC like event

Only CS is analyzed at first.

Neutrino event analysis

- Experimental requirements

✓ Long baseline
✓ High neutrino energy ⇨ CNGS beamline

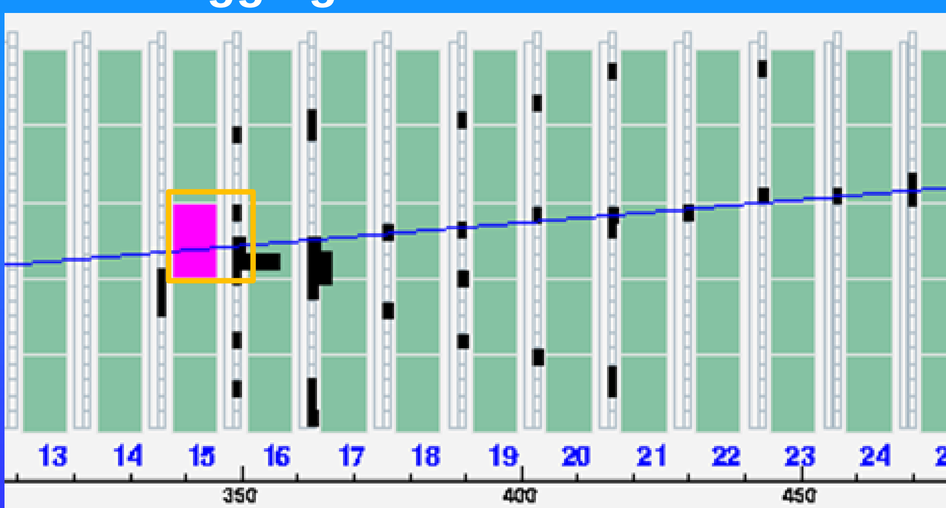
✓ High spatial resolution (ν_τ detection capability)
✓ Large target mass ⇨ OPERA detector

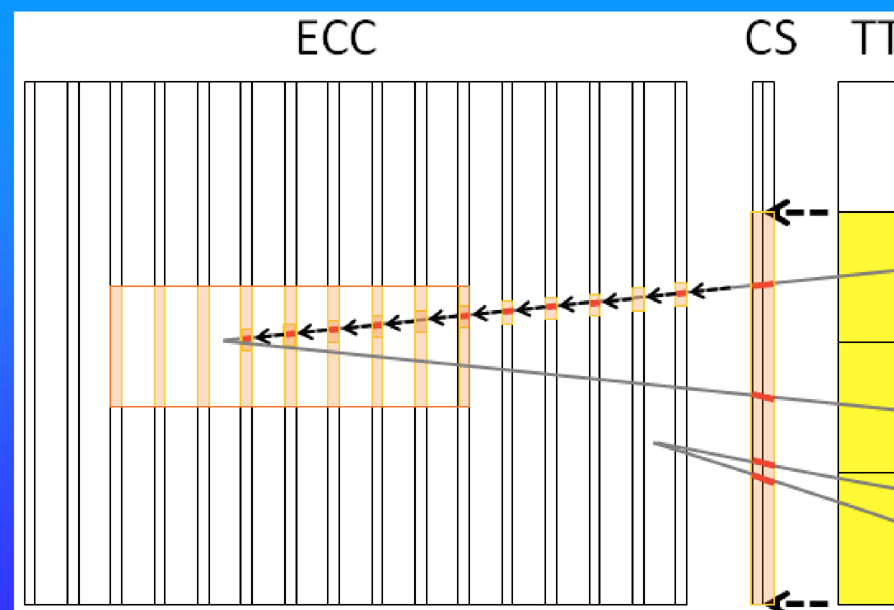
Challenge in OPERA

⇩

Large amount of emulsion analysis

Brick tagging and Scan back location





Technical improvements

High speed scanning x 20-75

Japanese Scanning System

Scanning speed : 75cm²/h

JINST **5:P04011, (2010)**

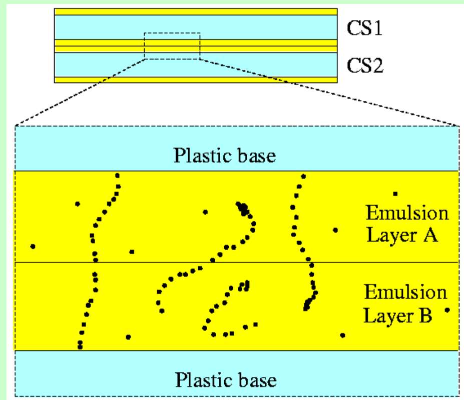
European Scanning System

Scanning speed : 20cm²/h

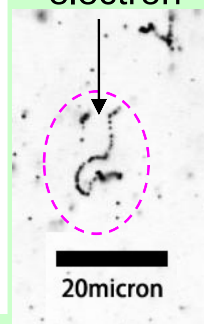
NIM **A551 (2005) 261**

Precision alignment (Compton alignment)

S/N x 10



100keV electron



With noise tracks connected both side of emulsion layer

Alignment accuracy:
σ=7.6μm ➡ σ=2.0μm

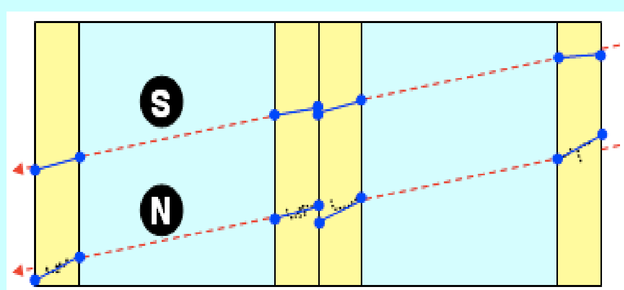
Reduce chance coincidence noises

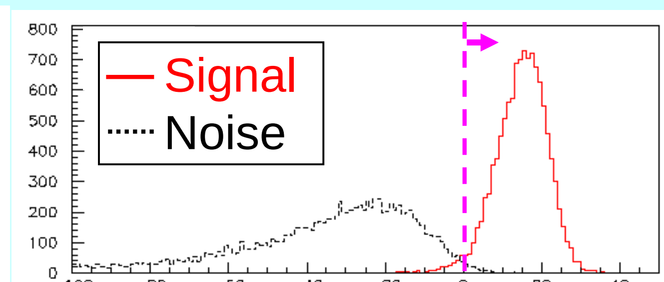
NIM **A575 (2007) 466**

High S/N discrimination (Track Ranking)

S/N x 100

Likelihood analysis with the linearity and blackness of each tracks

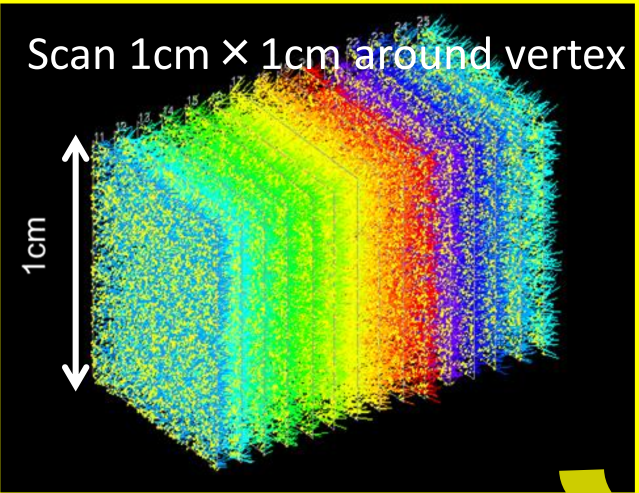


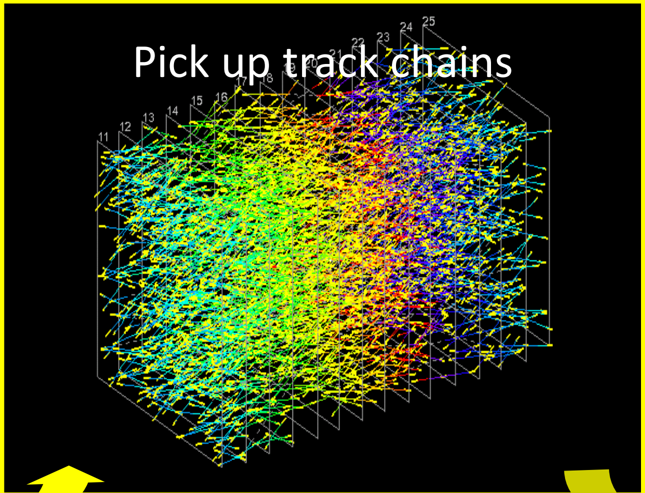


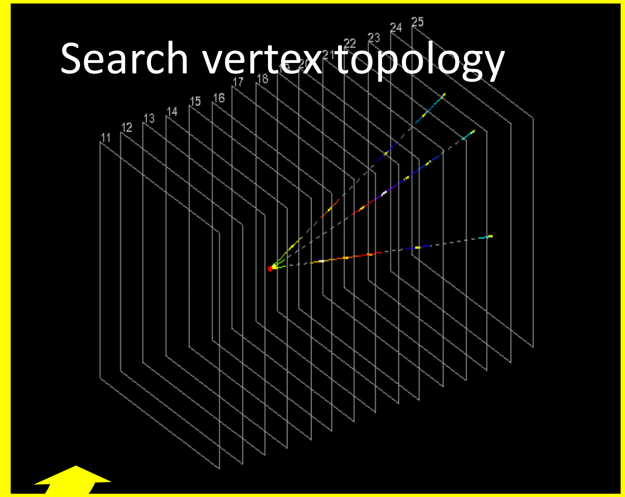
JINST **5:P04009, (2010)**

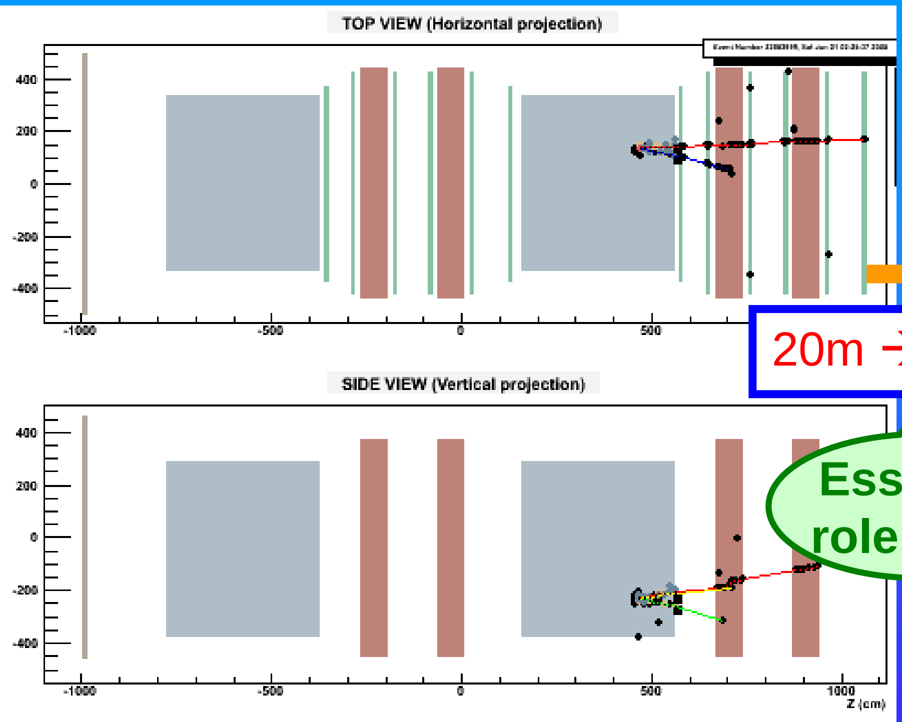
Signal 98%, Noise 1%

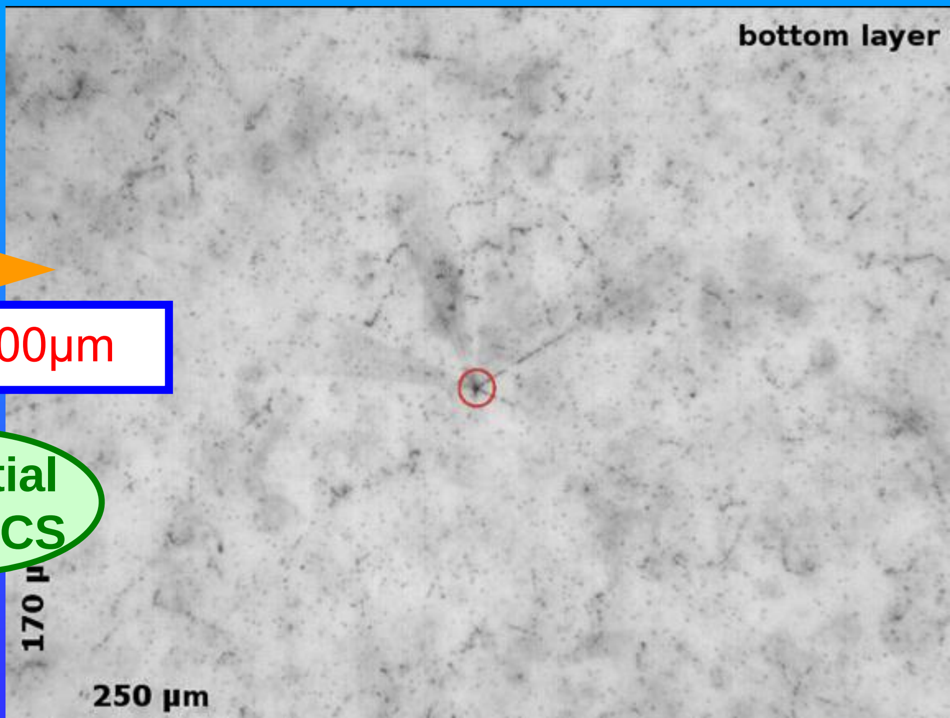
Neutrino event analysis









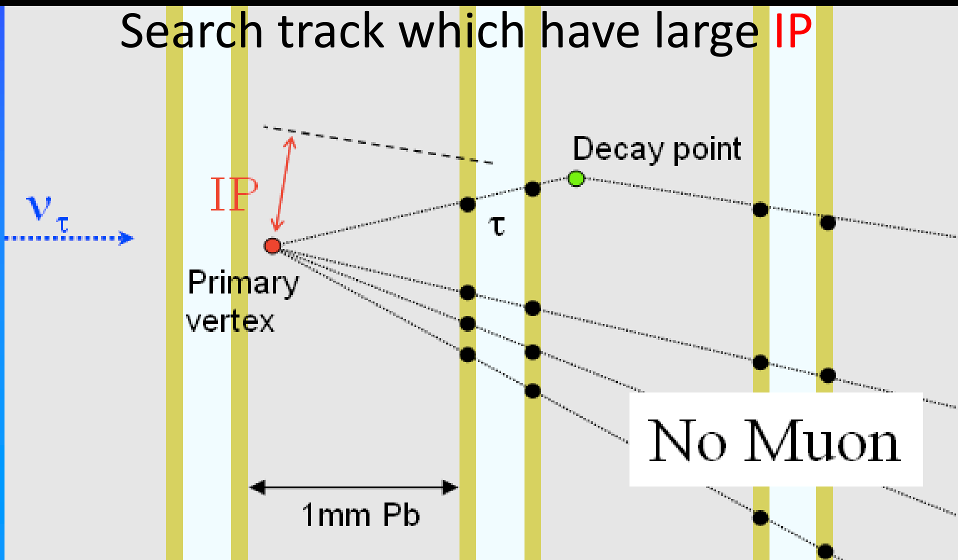


20m → 100μm

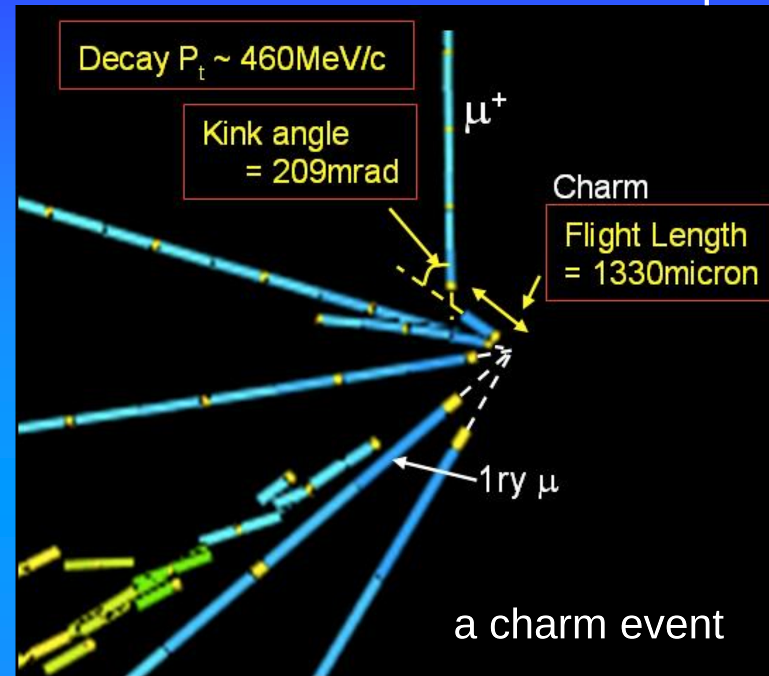
Essential role of CS

Neutrino event analysis

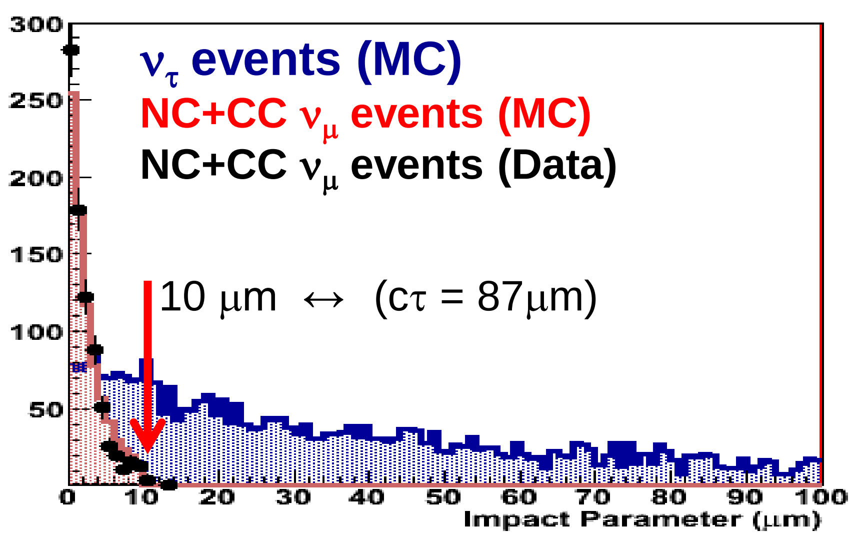
- **Decay topology search**



Charm events as a control sample



Impact Parameter distribution

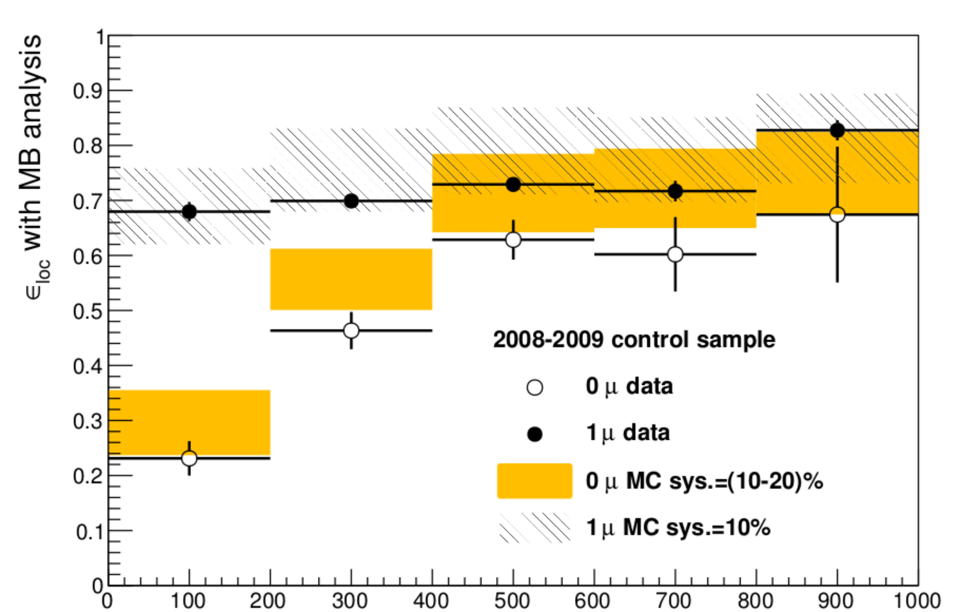


Decay topology	Events			
	Expected charm	Expected background	Expected total	Observed
1-prong	21 ± 2	9 ± 3	30 ± 4	19
2-prong	14 ± 1	4 ± 1	18 ± 1	22
3-prong	4 ± 1	1.0 ± 0.3	5 ± 1	5
4-prong	0.9 ± 0.2	–	0.9 ± 0.2	4
Total	40 ± 3	14 ± 3	54 ± 4	50

Eur.Phys.J. C74 (2014) 2986

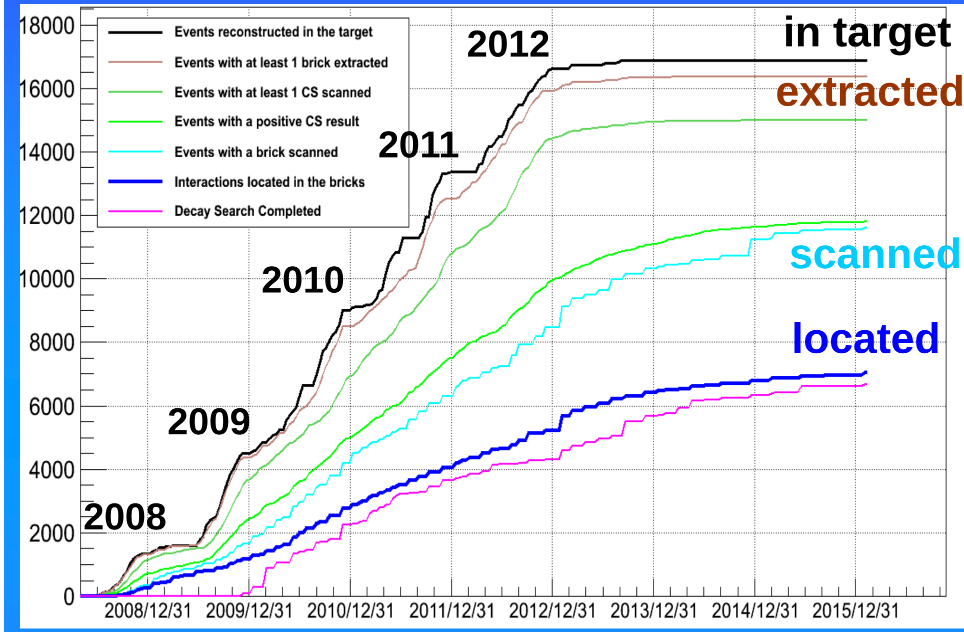
Data taking

Location efficiency



0μ-like and 1μ-like samples

Analysis status



Data-Monte Carlo comparison of the location efficiency as a function of the visible energy in the target scintillators

JHEP 11 (2013) 036

17.97×10^{19} POT (~80 % of expected)

Current status

~19600 event registered
~7000 events located
~6700 events fully analyzed

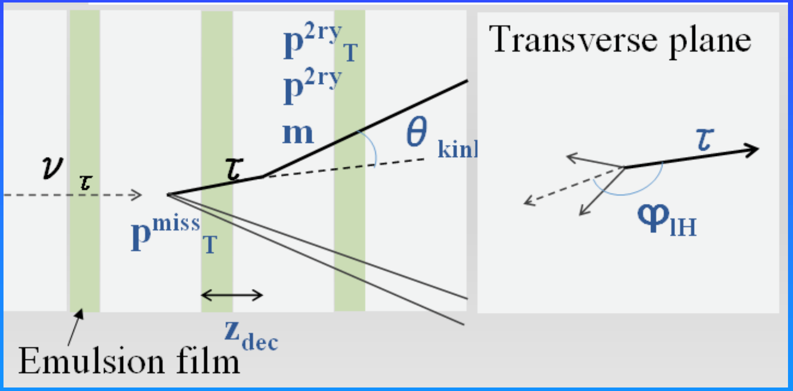
Hybrid detector:
a complex simulation
Reasonable agreement

ν_τ analysis

Kinematical selection

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	/	/

Cuts fixed since the beginning of the experiment



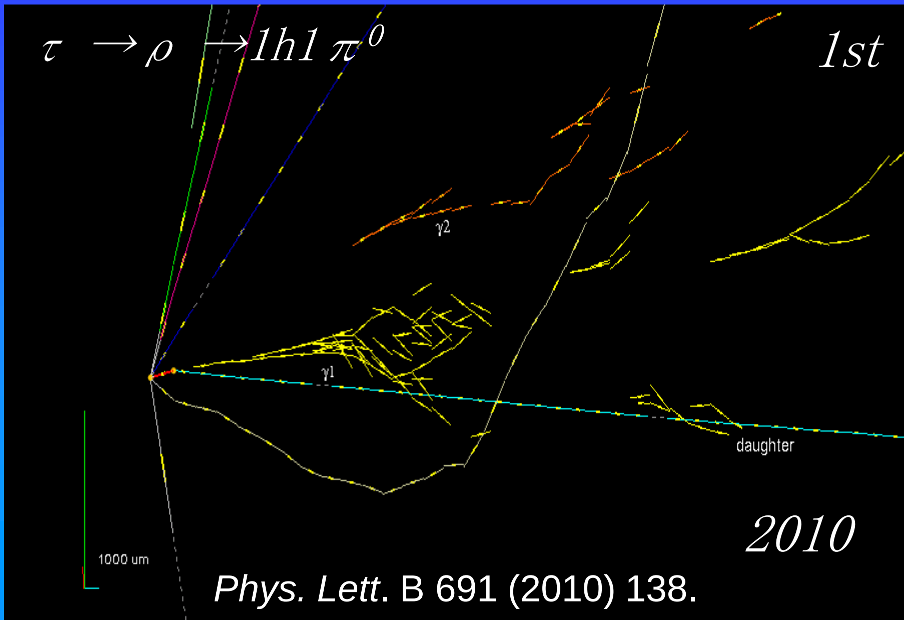
p^{miss}_T: vectorial sum of the transverse momenta of primaries (except the parent) and daughters wrt beam direction

p^{2ry}_T: transverse momentum of the daughter wrt parent direction

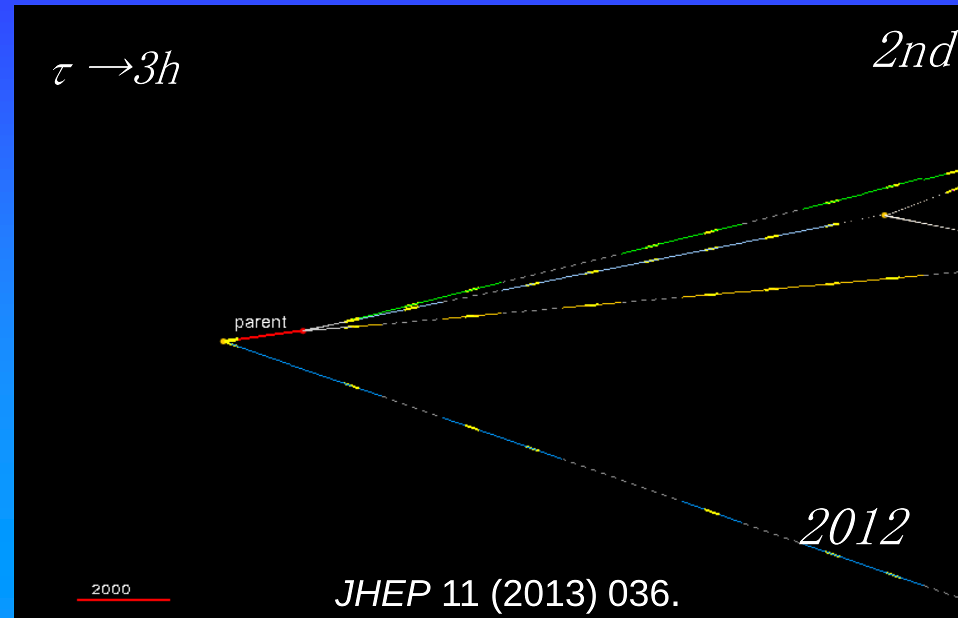
Data sample : The 1st and 2nd most probable bricks for all runs

	2008	2009	2010	2011	2012	Total
p.o.t. (10^{19})	1.74	3.53	4.09	4.75	3.86	17.97
0μ events	149	253	268	270	204	1144
1μ events (p_μ <15 GeV/c)	542	1020	968	966	768	4264
Total events	691	1273	1236	1236	972	5408
Detected ν_τ candidates	-	1	-	1	3	5

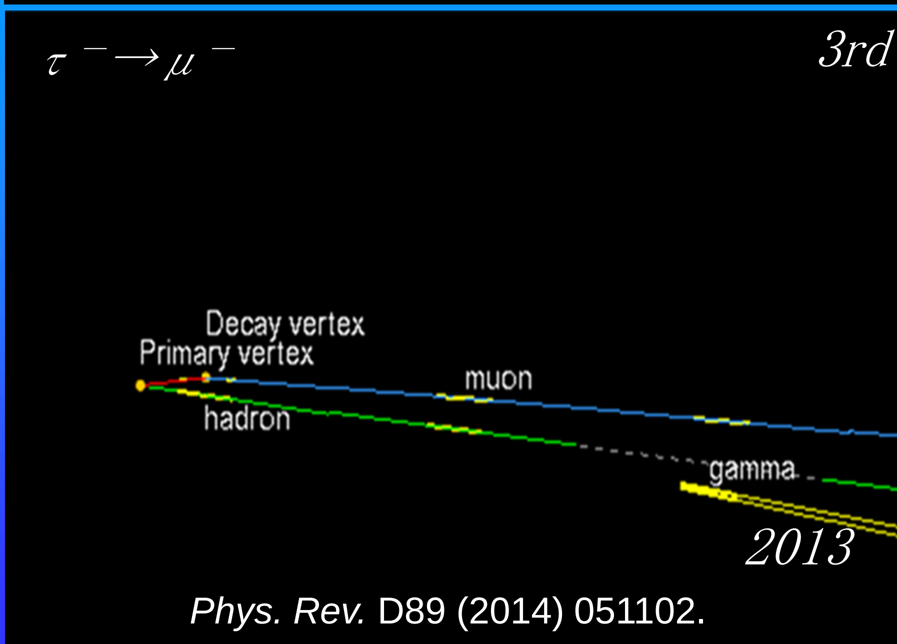
ν_τ candidate events



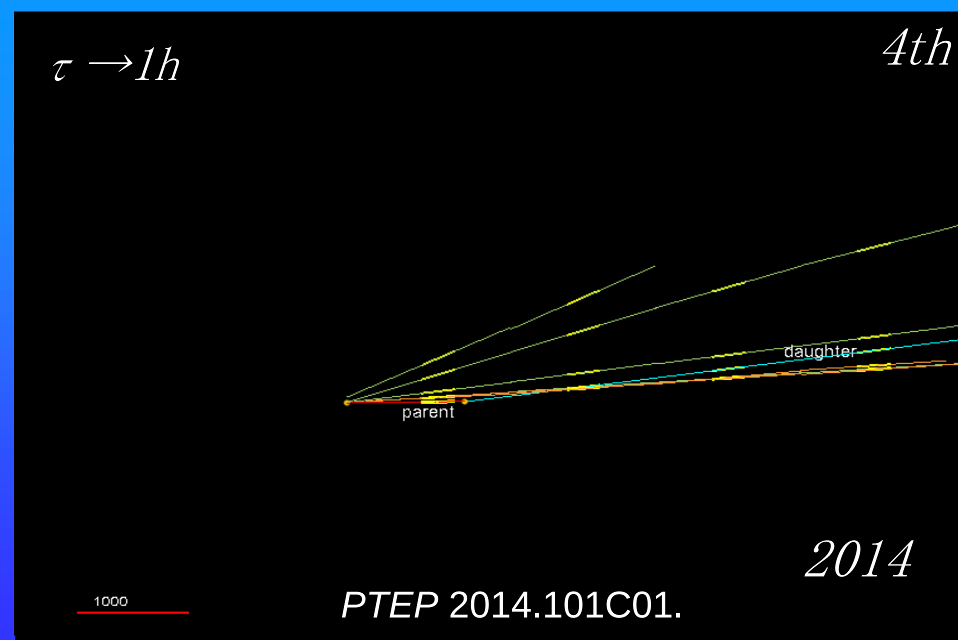
Phys. Lett. B 691 (2010) 138.



JHEP 11 (2013) 036.

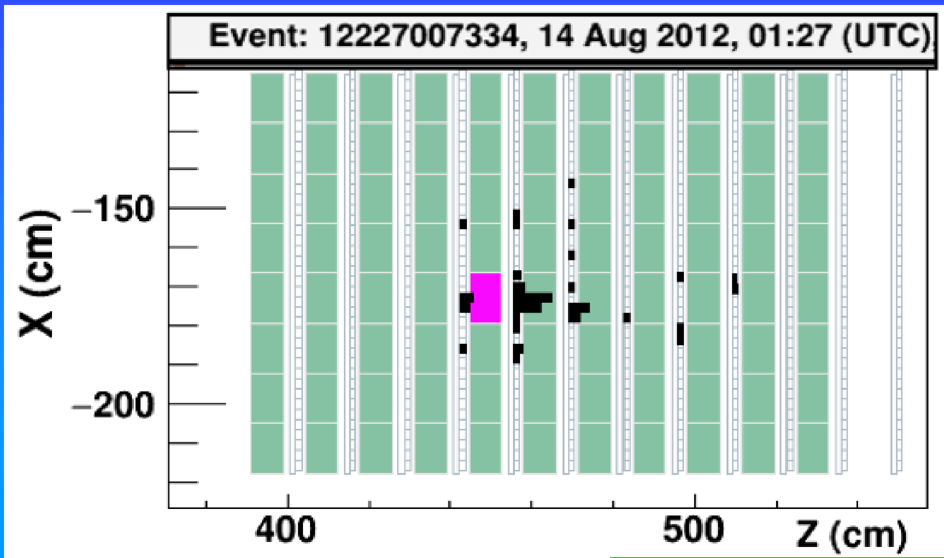


Phys. Rev. D89 (2014) 051102.

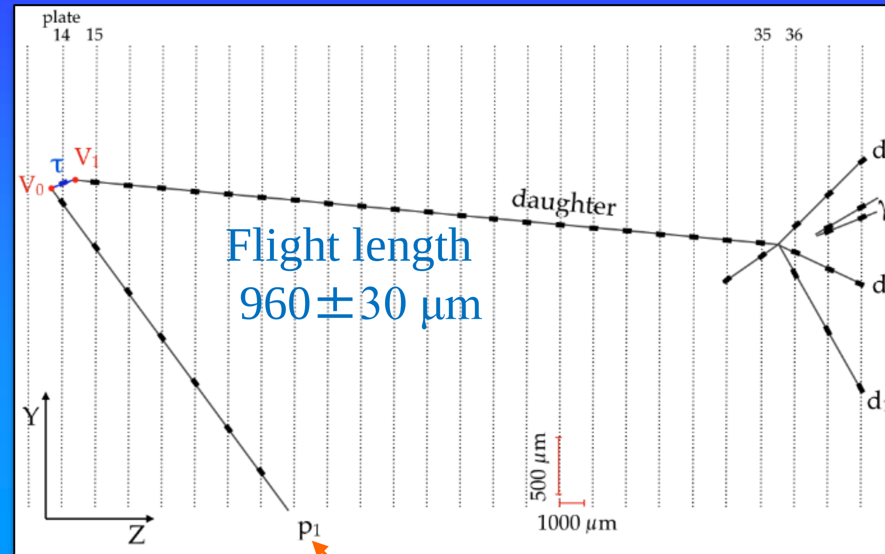


PTEP 2014.101C01.

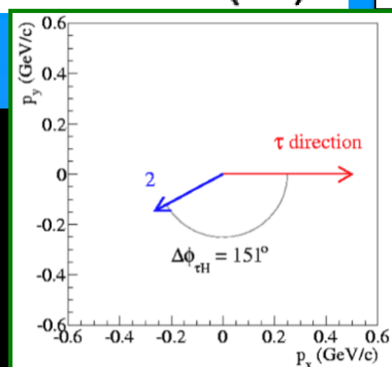
The 5th ν_τ event

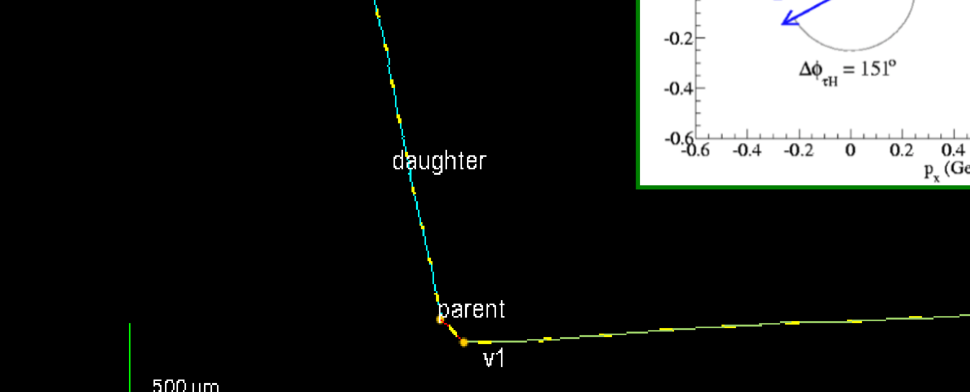


Electronic detectors → No muon



identified as a proton by dE/dx analysis





Phys. Rev. Lett. 115, 121802 (2015).

2015

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)

All variables passed the cuts

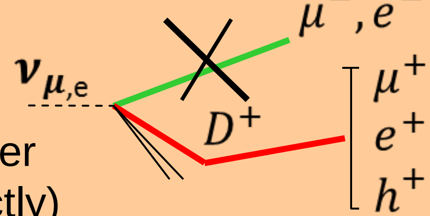
Background sources

Monte Carlo simulation benchmarked on control samples.

*In **yellow** improvements wrt former analyses*

CC with charm production (all channels)

If primary lepton is not identified and the daughter charge is not (or incorrectly) measured



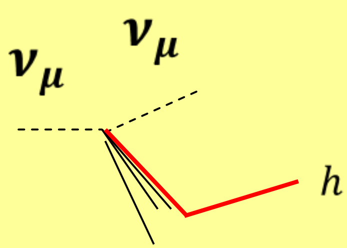
MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

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

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

Hadronic interactions

Background for $\tau \rightarrow h$



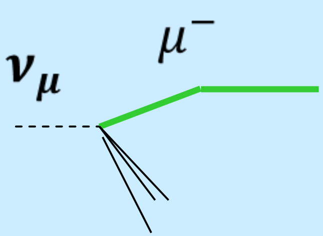
FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

[PTEP 2014, 093C01 (2014)]

Large angle muon scattering

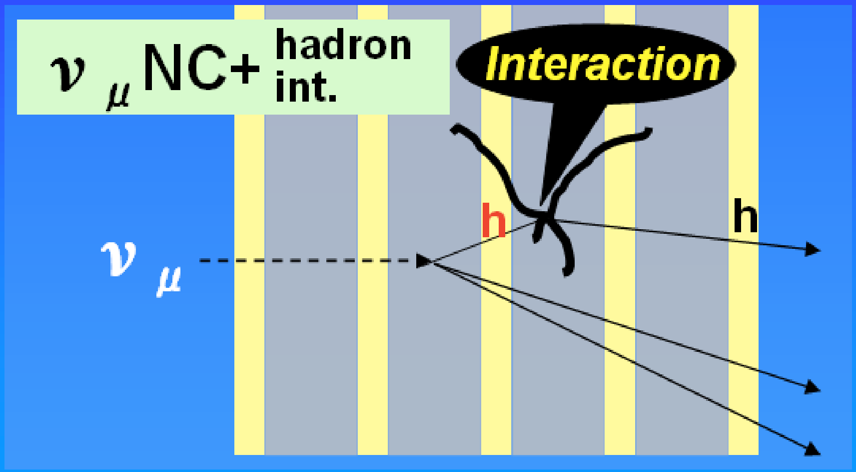
Background for $\tau \rightarrow \mu$



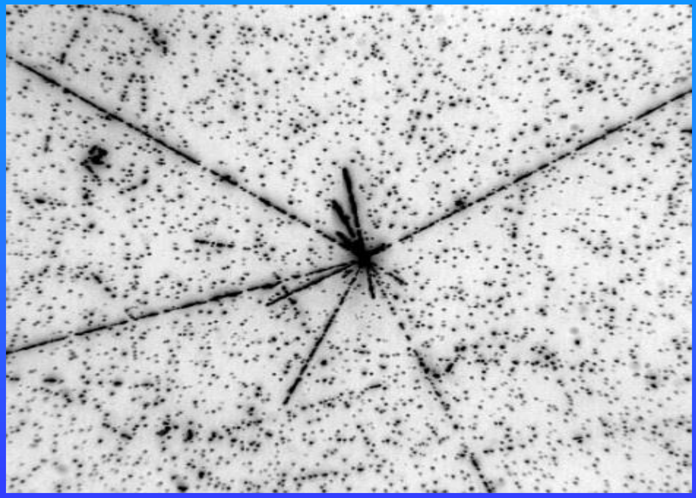
Measurements in the literature (Lead form factor), simulations and dedicated test-beams

[IEEE Transactions on Nuclear Science, vol.62 5]

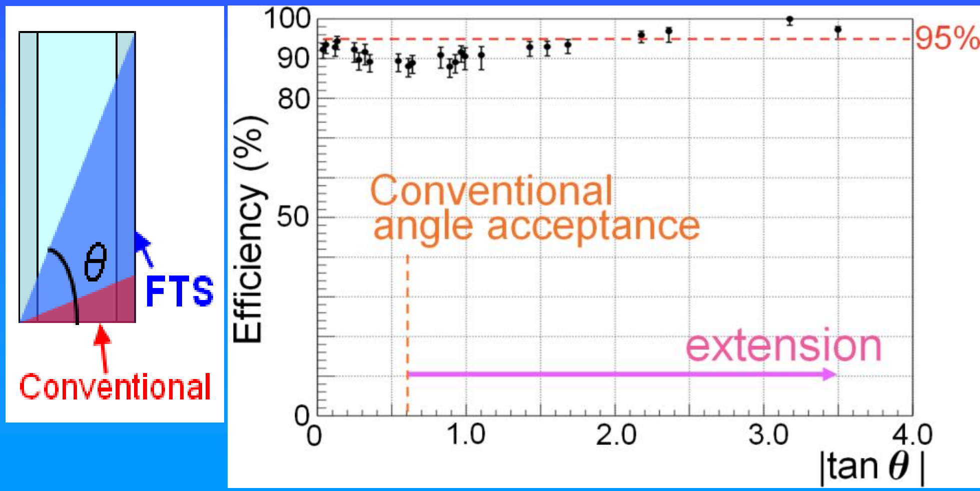
Hadronic background reduction



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

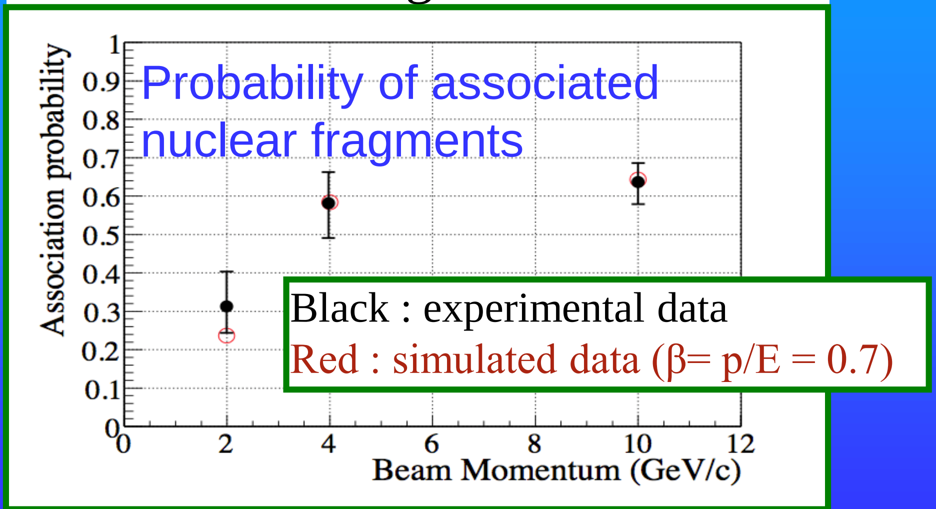


Large angle scanning technique



JINST 8:P01023, (2013), *JINST* 9:P12017, (2014)

Additional background reduction



PTEP 2014, 093C01 (2014)

ν_τ analysis result

Expected signal and background events for the analyzed data sample

Channel	Expected background				Expected signal	Observed
	Charm	Had. re-interac.	Large μ-scat.	Total		
$\tau \to 1h$	0.017 ± 0.003	0.022 ± 0.006	–	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.003 ± 0.001	–	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001	–	0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \to e$	0.03 ± 0.01	–	–	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.22 ± 0.04	0.02 ± 0.01	0.0002 ± 0.0001	0.25 ± 0.05	2.64 ± 0.53	5

5 observed events with **0.25 background**

Probability to be explained by background: 1.1×10^{-7} (Fisher, Profile likelihood)

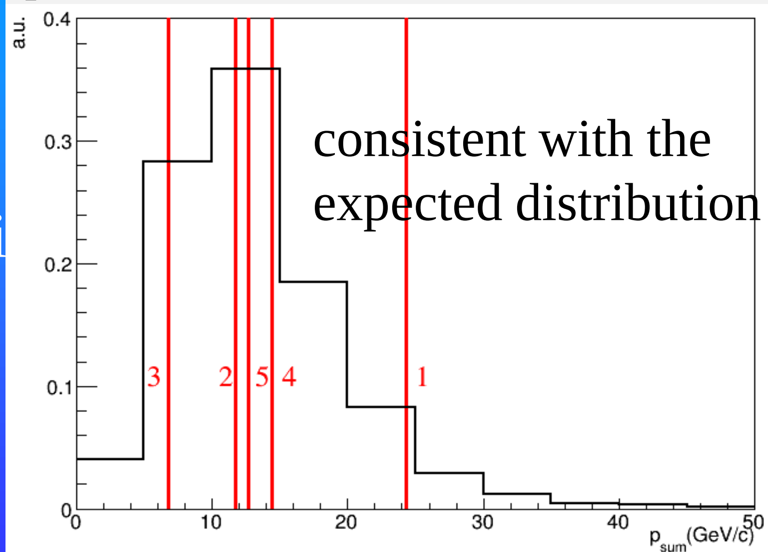
Corresponding to **5.1 σ** exclusion of the background-only hypothesis

Discovery of ν_τ appearance

→ Estimation of Δm^2_{23} (90% C.L.)

$[2.0, 5.0] \times 10^{-3}$ eV^2 (assuming full mixing)

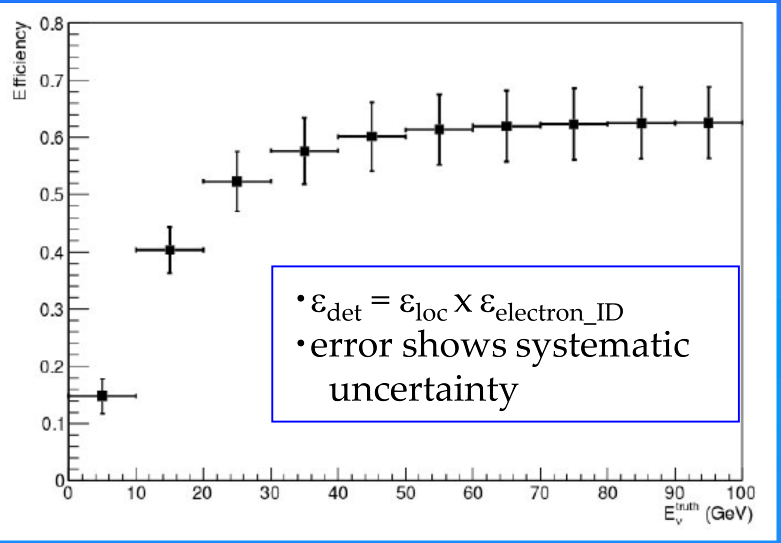
the scalar sum of the momenta of all particles measured in ECC



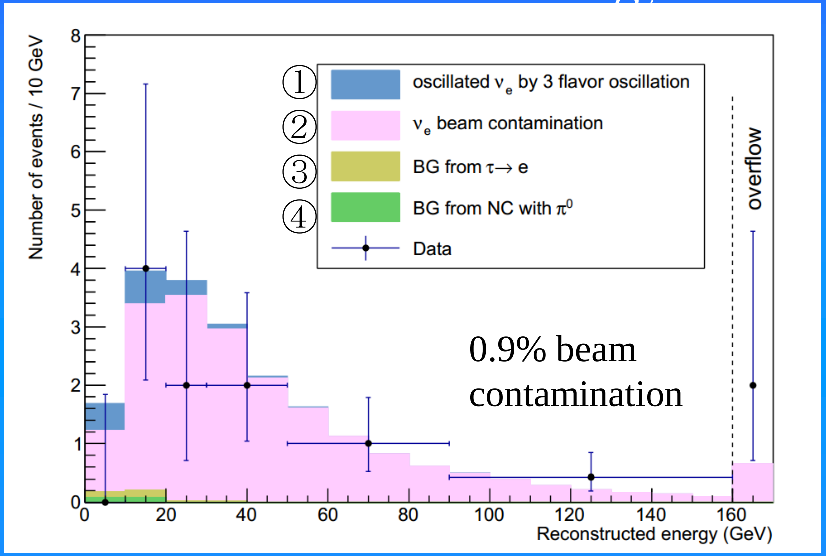
$\nu_\mu \rightarrow \nu_e$ oscillations

Results of 2008 – 2009 data sample (analysis for only 1st brick)

Detection efficiency



Reconstructed energy



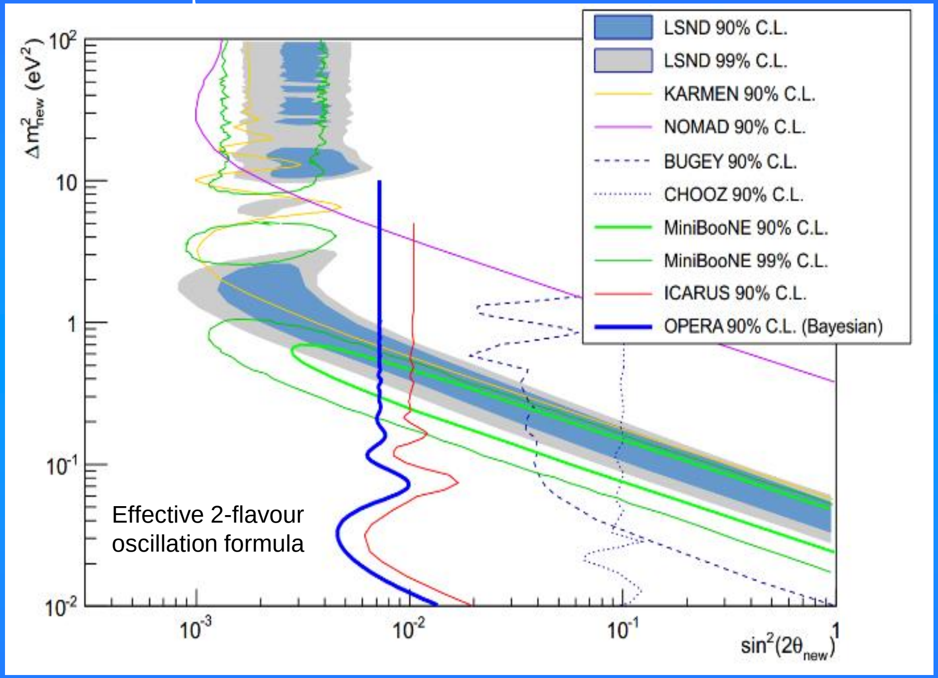
	no cut	E<20GeV(3 flavor)
observed νe	19	4
expected BG	19.8±2.8 (sys.)	4.6±0.7 (②+③+④)
Results (90% C.L.)		$\sin^2(2\theta_{13})<0.44$

$\sin^2(2\theta_{13}) = 0.098$, $\sin^2(2\theta_{23}) = 1$, $\Delta m^2_{32} = \Delta m^2_{31} = 2.32 \times 10^{-3}$ eV^2, $\delta_{CP} = 0$, matter effects are negligible

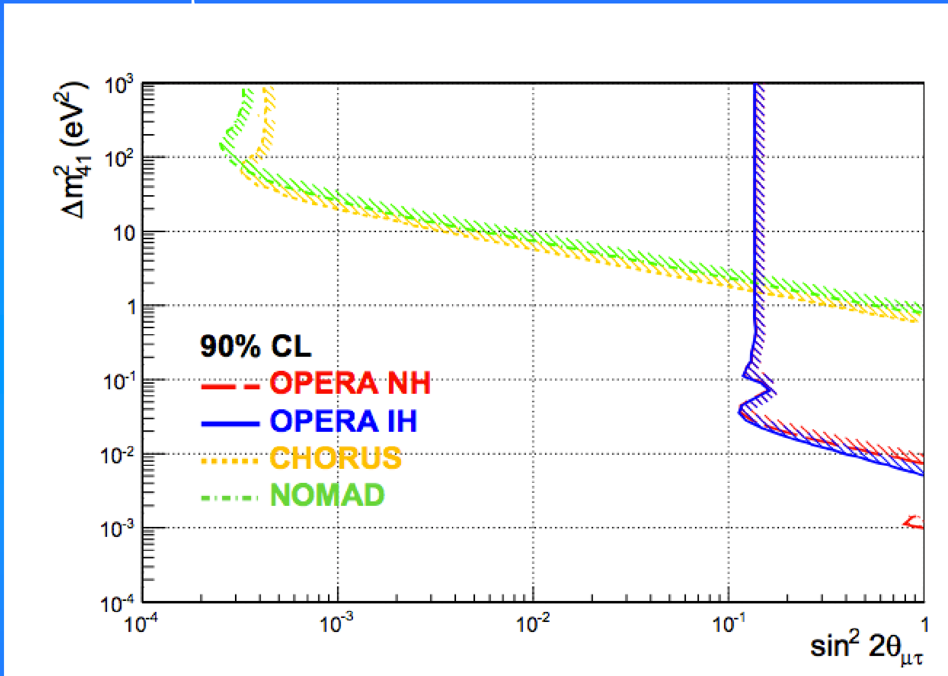
Non–standard oscillations

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]



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

Analysis in the 1st and 2nd bricks of the whole OPERA data sample.

→ 52 ν_e candidates found (Preliminary)

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

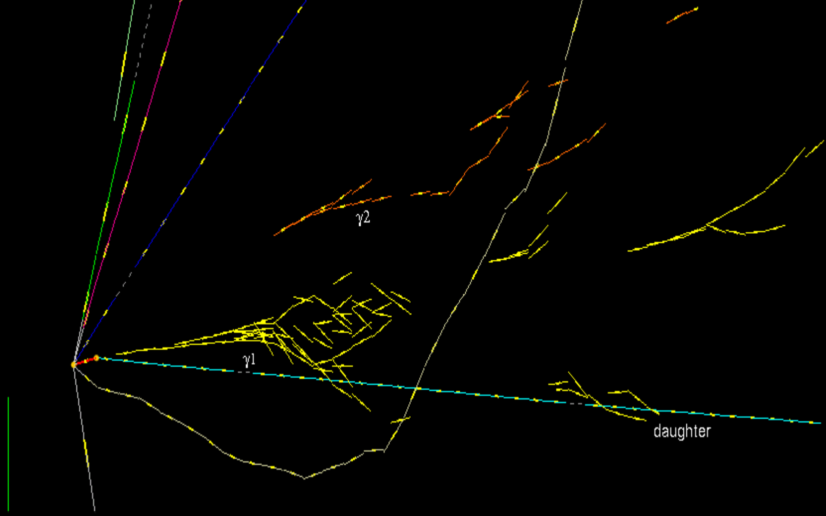
First limits on $|U_{\mu 4}|^2|U_{\tau 4}|^2$ from direct measurement of ν_τ

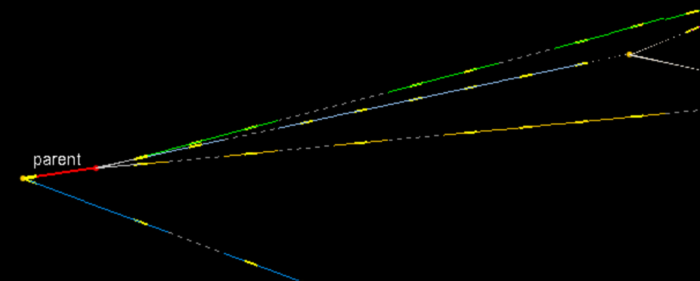
Conclusions

- 1.8×10^{20} pot by CNGS from 2008 to 2012 (80% of design).
- Analysis technique largely improved and detector successfully measuring ν_e, ν_μ and ν_τ.
- Analysis of extended data sample. Improved background evaluation.
- 5 ν_τ candidate events found with 0.25 background.
- Background-only hypothesis excluded at 5.1 σ.

  → Discovery of ν_τ appearance in the CNGS beam

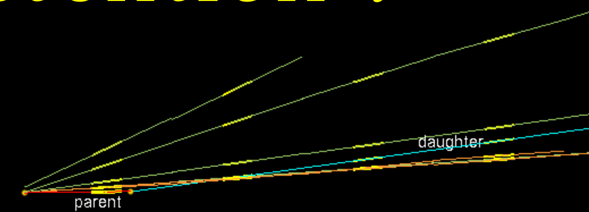
- Measurement of $\Delta m^2_{23} = [2.0\text{-}5.0] \times 10^{-3}\ \mathrm{eV}^2$.
- Upper limit for $\sin^2(2\theta_{13})<0.44$ and $\sin^2(2\theta_{new})<7.2\times10^{-3}$ by 19 ν_e events found in 2008-2009 data sample.
- ν_e analysis on going for all year run data and final analysis with the full data sample close to completion (x 2.5 increase in sample).
- Search for anomalies in $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$.
  First limits on $|U_{\mu4}|^2|U_{\tau4}|^2$ from direct measurement of ν_τ.

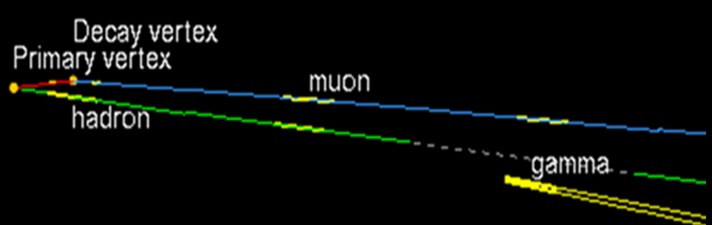


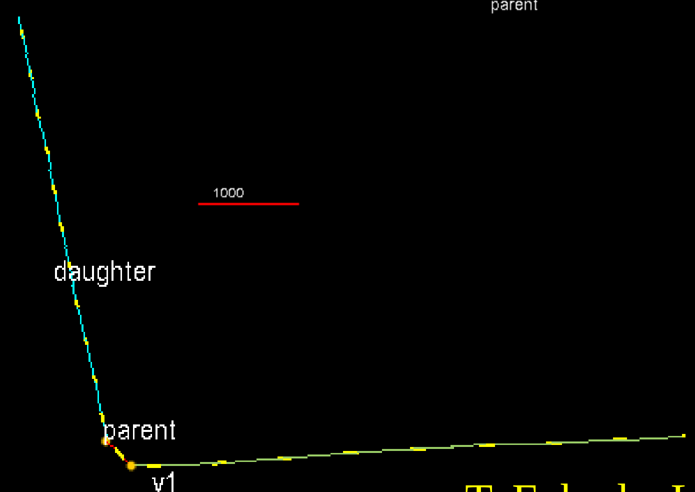


Thank you for your kind attention !

2000







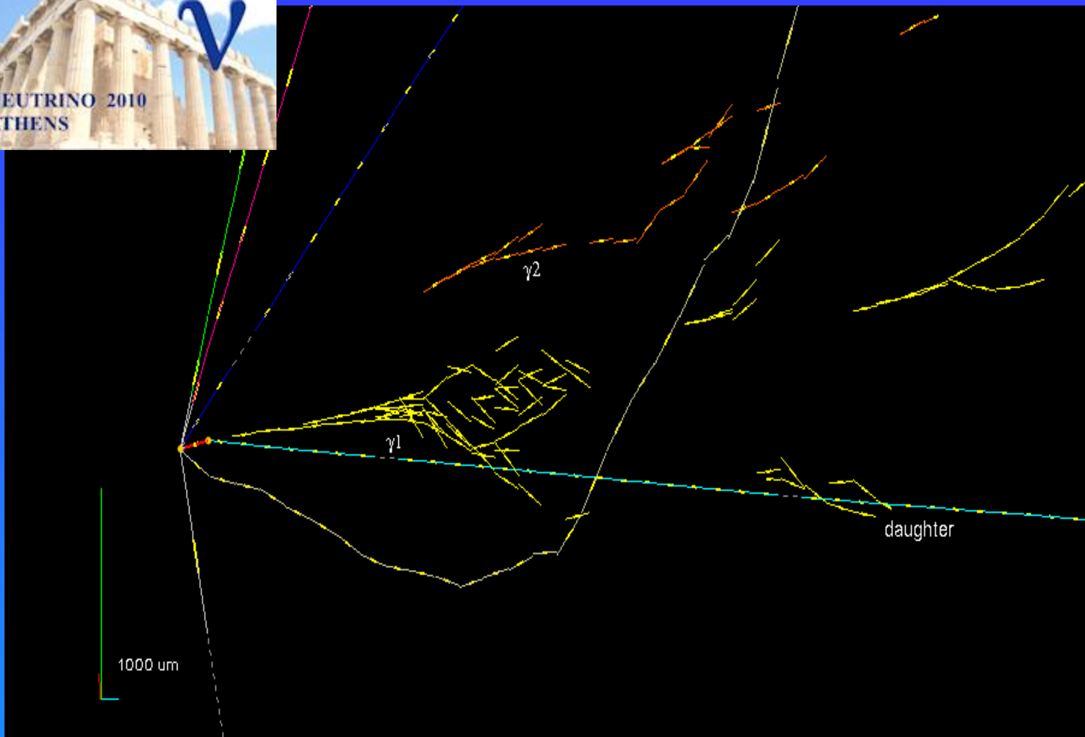
OPERA

500 um

T. Fukuda, La Thuile 2016

Supplements

The first ν_τ “appearance” candidate



Event Kinematics

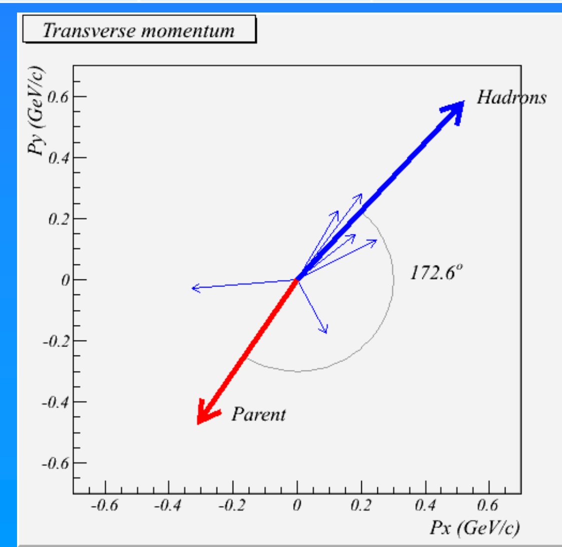
VARIABLE	Measured	Selection criteria
Kink (mrad)	41 ± 2	>20
Decay length (μm)	1335 ± 35	Within 2 lead plates
P daughter (GeV/c)	12^{+6}_{-3}	>2
Pt daughter (MeV/c)	470^{+230}_{-120}	>300 (γ attached)
Missing Pt (MeV/c)	570^{+320}_{-170}	<1000
φ (deg)	173 ± 2	>90

First detection of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode

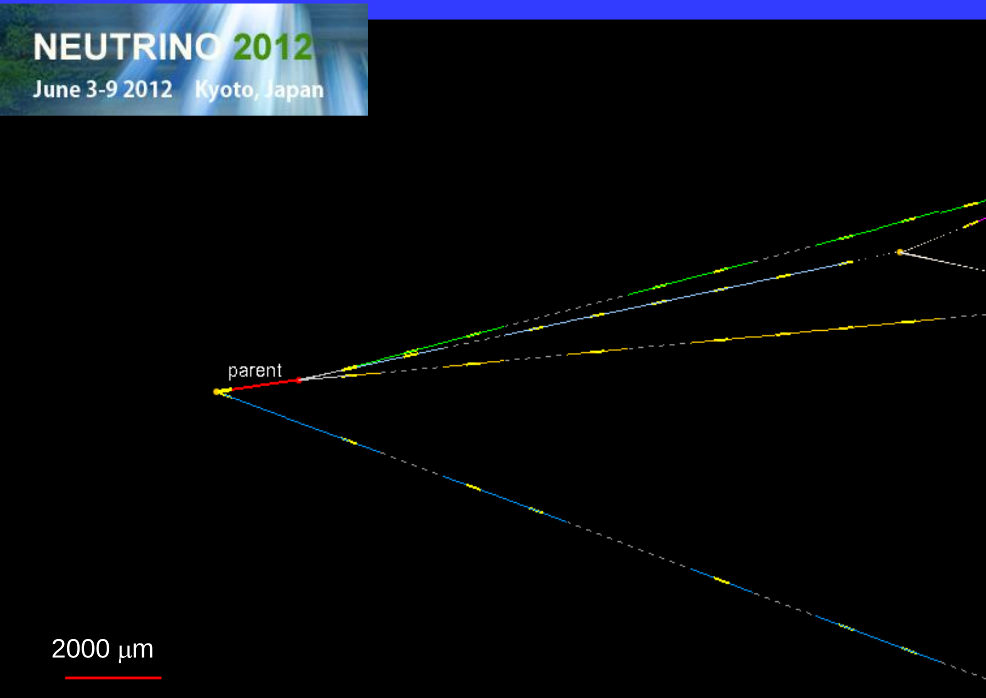
Reported in May 2010

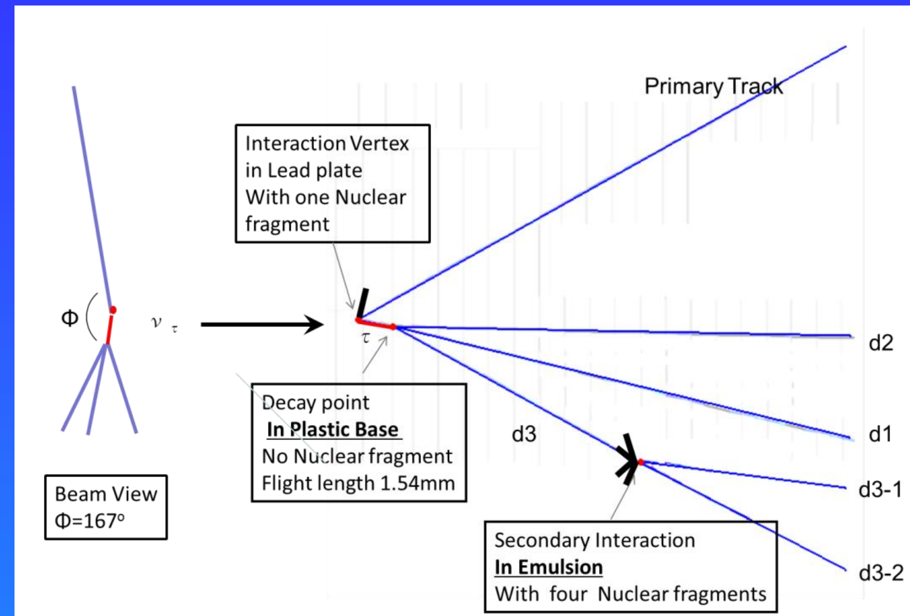
Decay channel: $\tau \rightarrow$ 1h

Phys. Lett. B 691 (2010) 138



The 2nd ν_τ candidate





All tracks other than τ were identified as hadrons.
Decay in plastic base.

Reported in June 2012

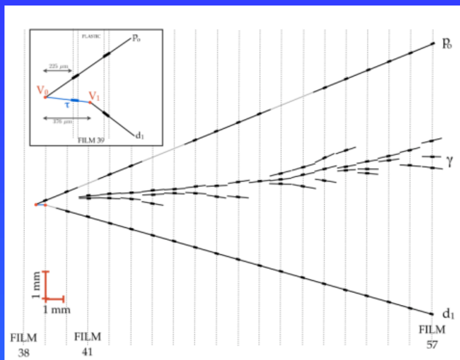
Decay channel: τ → 3h

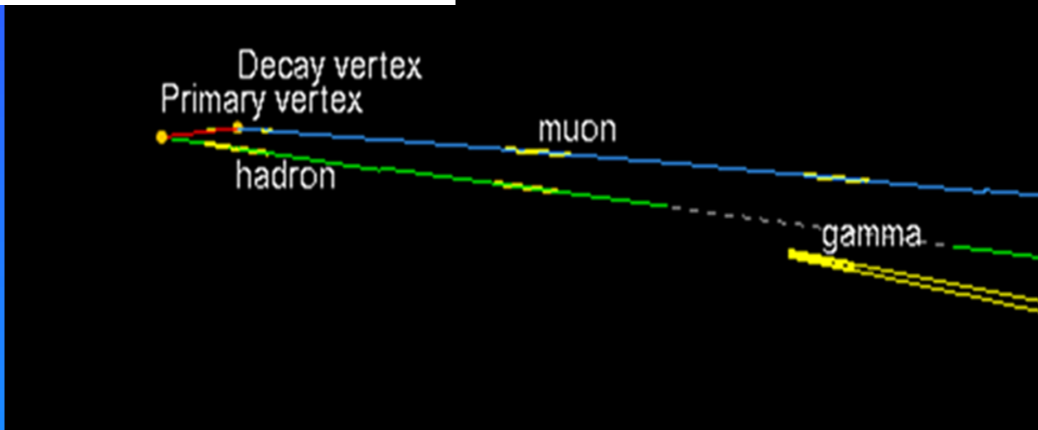
JHEP 11 (2013) 036

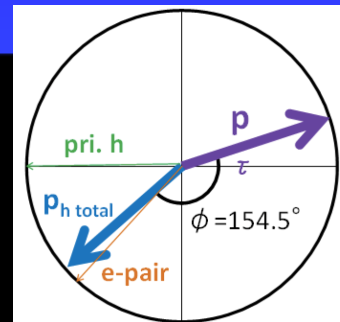
Event Kinematics

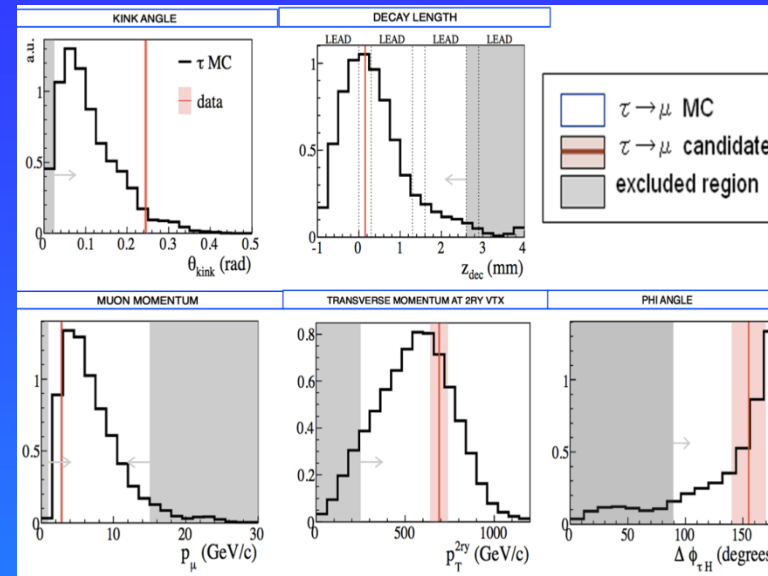
	Cut	Value	Error
Phi (Tau - Hadron) [degree]	>90	167.8	± 1.1
average kink angle [mrad]	< 500	87.4	± 1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4	± 1.7
Min Invariant mass [GeV/c²]	0.5 < < 2.0	0.96	± 0.13
Invariant mass [GeV/c²]	0.5 < < 2.0	0.80	± 0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31	± 0.11

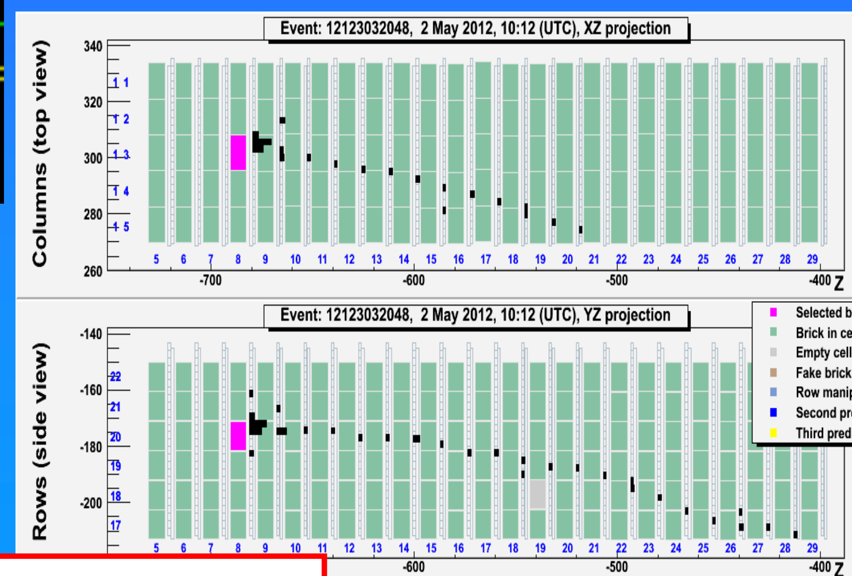
The 3rd ν_τ candidate











Decay daughter was identified as a muon because of its high penetrability.

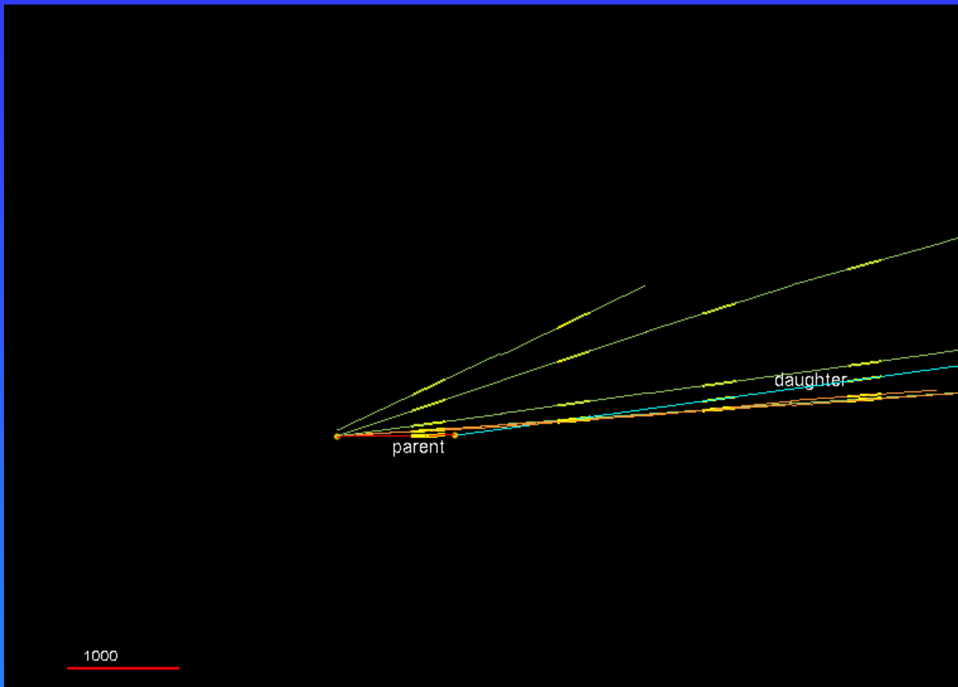
Reported in March 2013

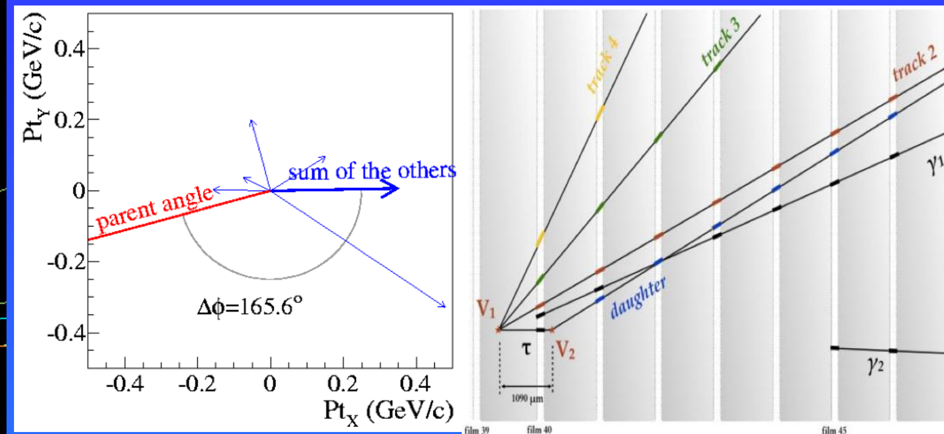
Decay channel: τ → μ

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

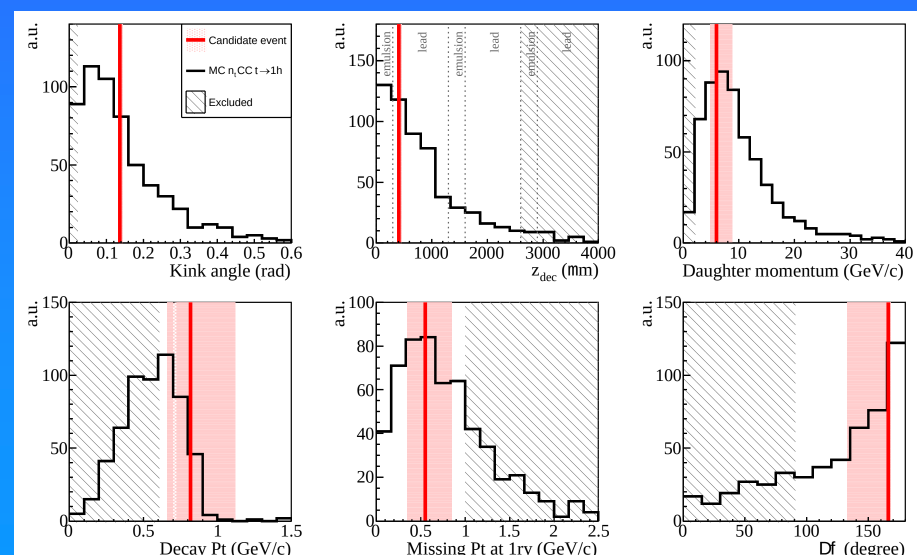
First leptonic decay

The 4th ν_τ candidate





Event Kinematics



Reported in March 2014

Decay channel: τ → 1h

Prog. Theor. Exp. Phys. (2014) 101C01

PTEP

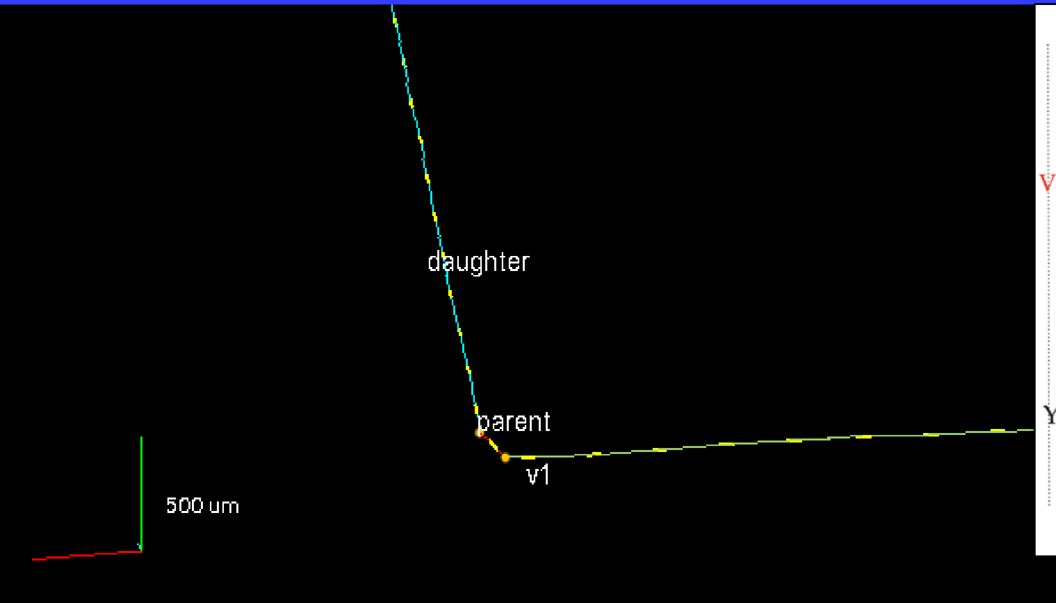
Prog. Theor. Exp. Phys. **2014**, 101C01 (10 pages)
DOI: 10.1093/ptep/ptu132

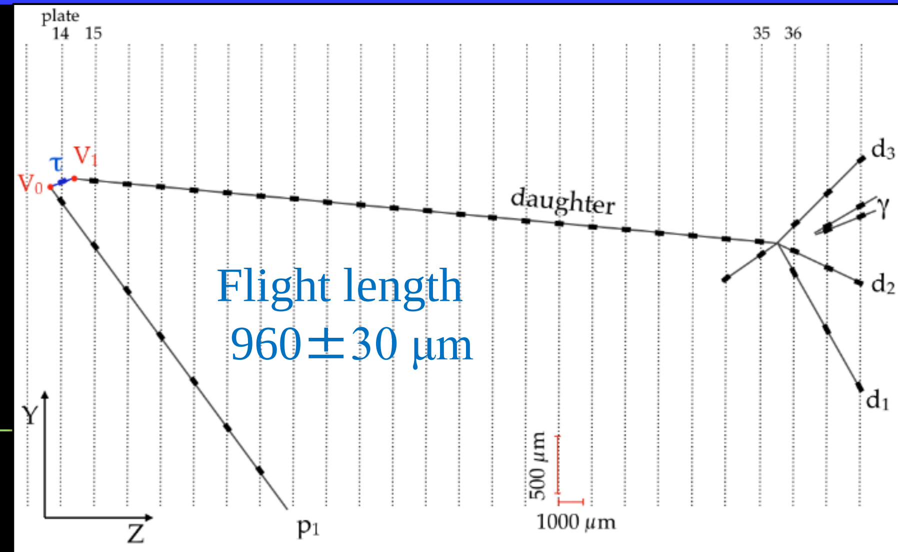
Letter

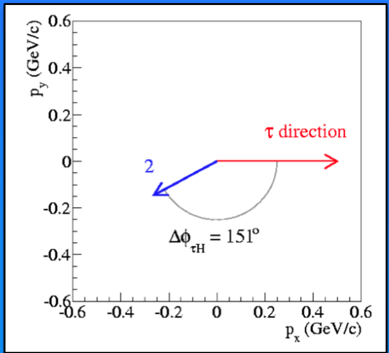
Observation of tau neutrino appearance in the CNGS beam with the OPERA experiment

OPERA Collaboration

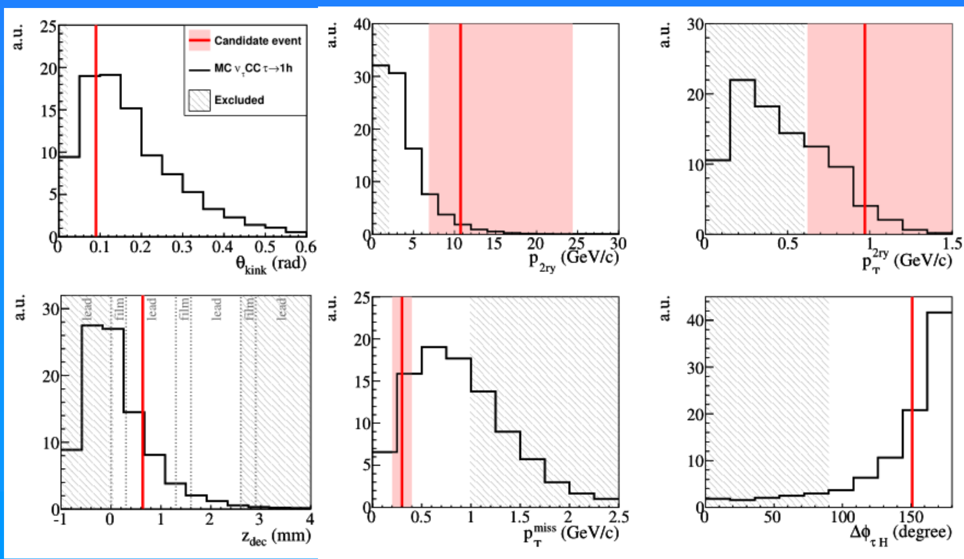
The 5th ν_τ candidate







Event Kinematics



Reported in June 2015

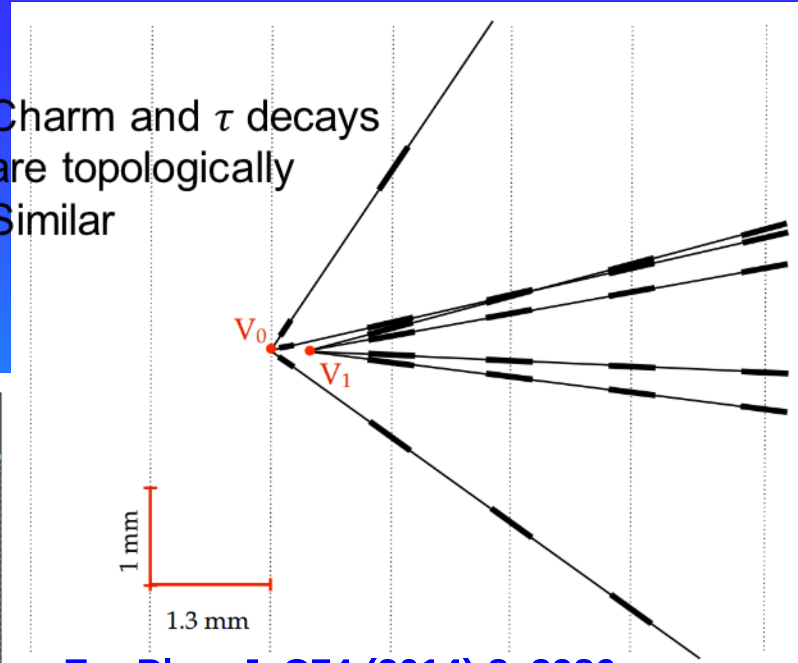
Decay channel: τ → 1h

Phys. Rev. Lett. 115 (2015) 121802

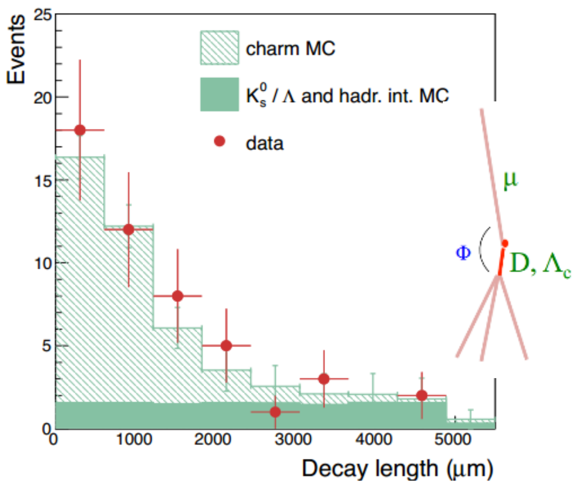
Validation with the CNGS charm events sample

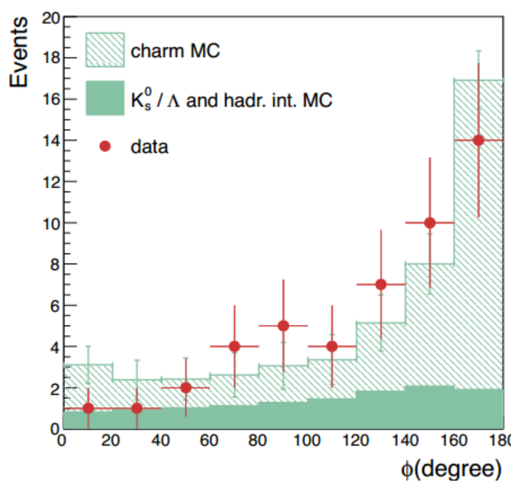
Test for: reconstruction efficiencies, description of kinematical variables, charm background.

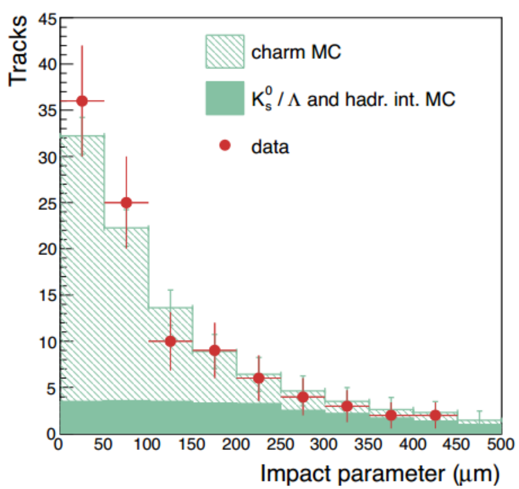
54 ± 4 expected $\leftrightarrow$ 50 observed

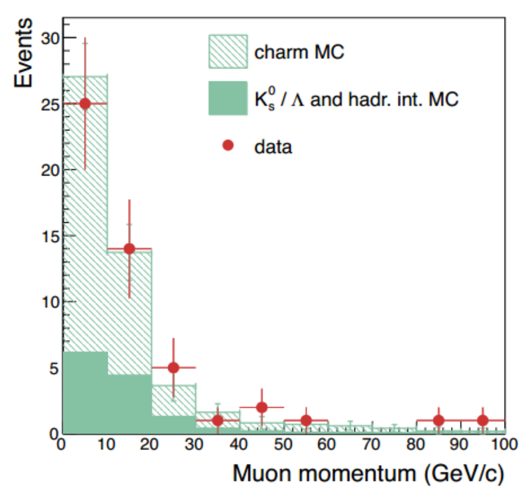


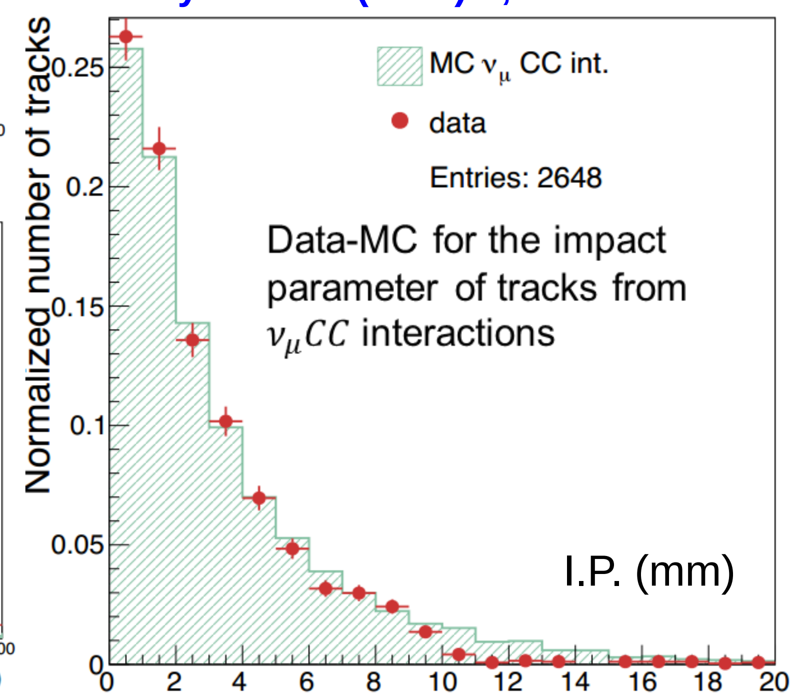
Eur.Phys.J. C74 (2014) 8, 2986





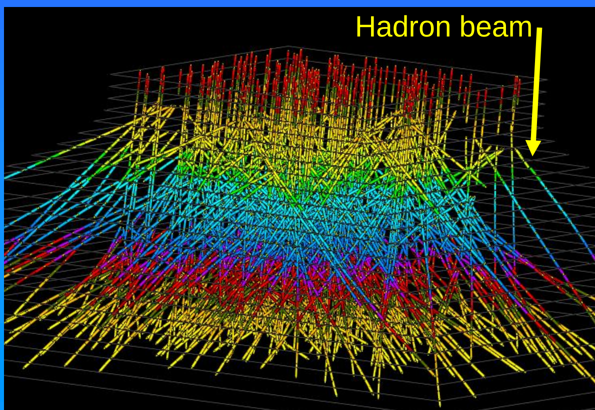






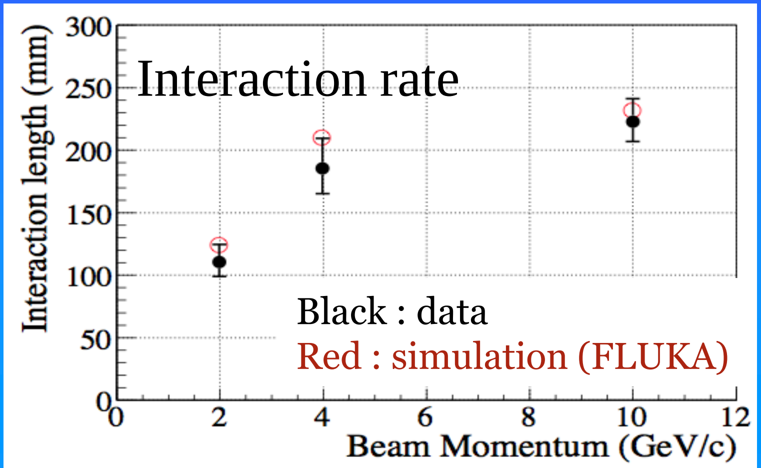
Validation of the hadronic background by test beams

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

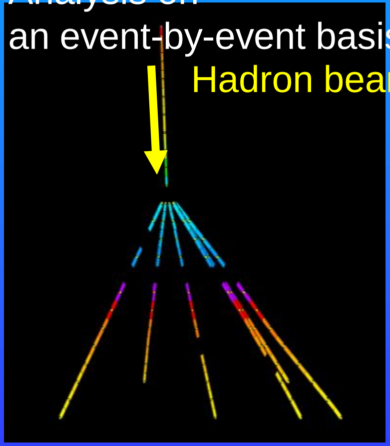


Track length analysed in the brick:

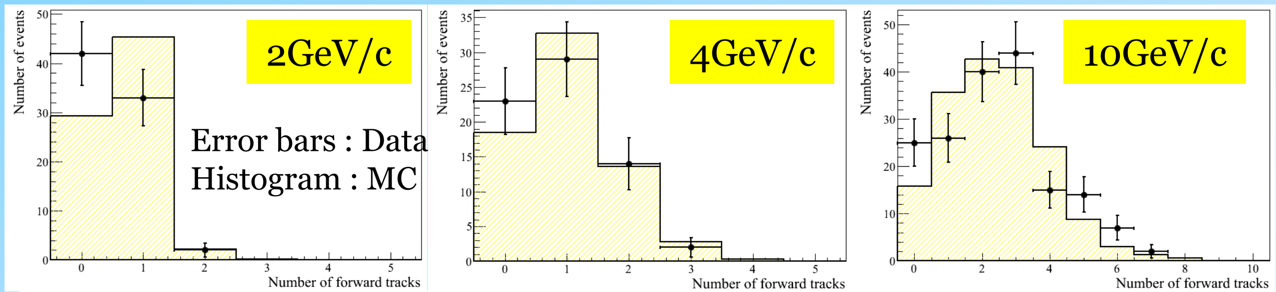
- 2 GeV/c : 8.5 m
- 4 GeV/c : 12.6 m
- 10 GeV/c : 38.5 m



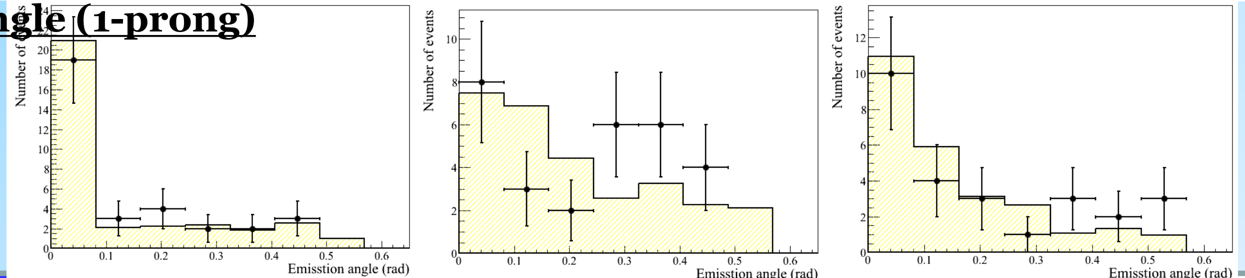
Analysis on
an event-by-event basis



Multiplicity Topological analysis of hadron interactions in an ECC brick



Kink angle (1-prong)

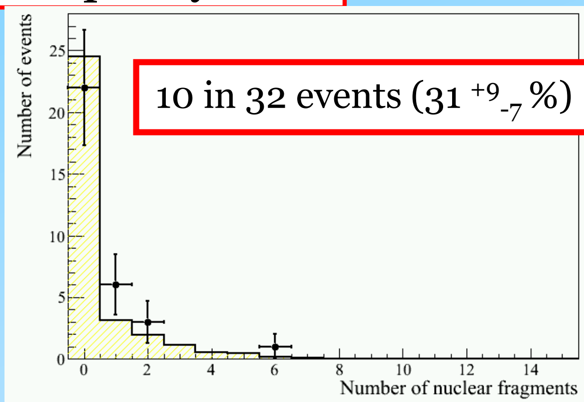


Nuclear fragments in 1 and 3 prong interactions

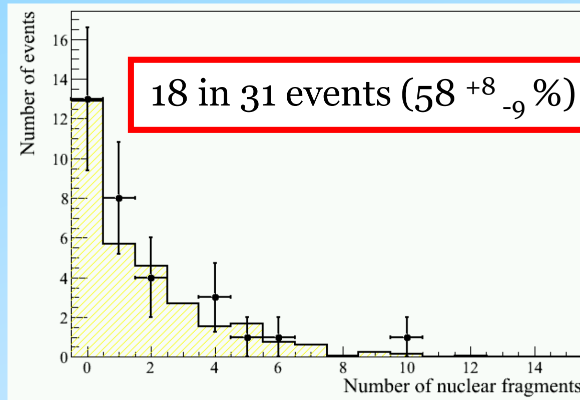
2GeV/c | 4GeV/c | 10GeV/c

Multiplicity

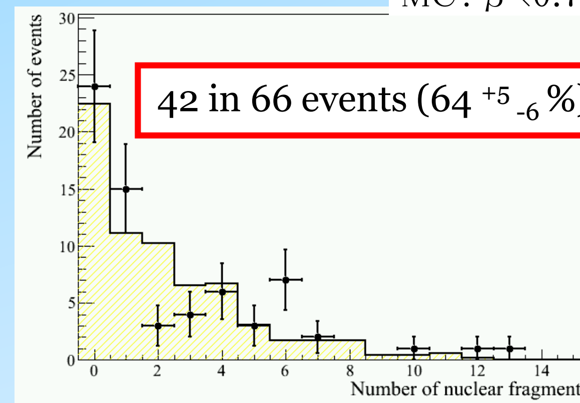
MC : $\beta < 0.7$



10 in 32 events (31^{+9}_{-7} %)



18 in 31 events (58^{+8}_{-9} %)

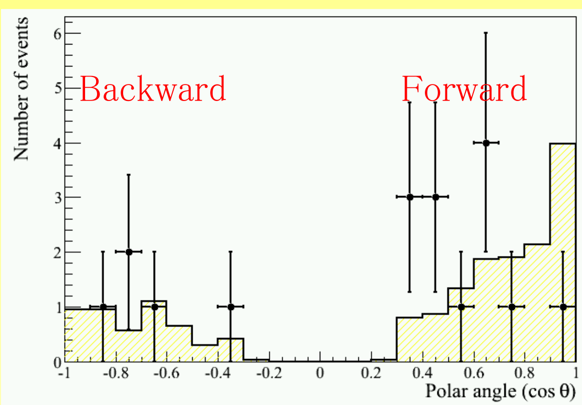


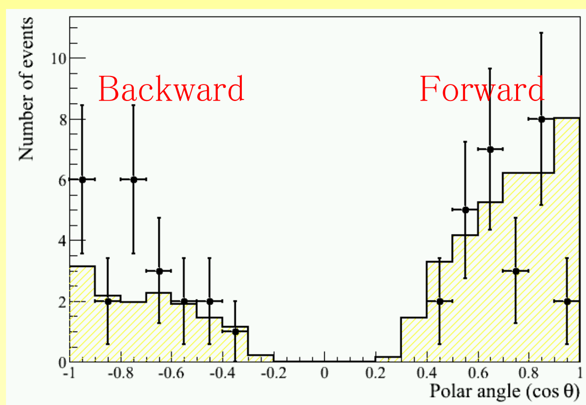
42 in 66 events (64^{+5}_{-6} %)

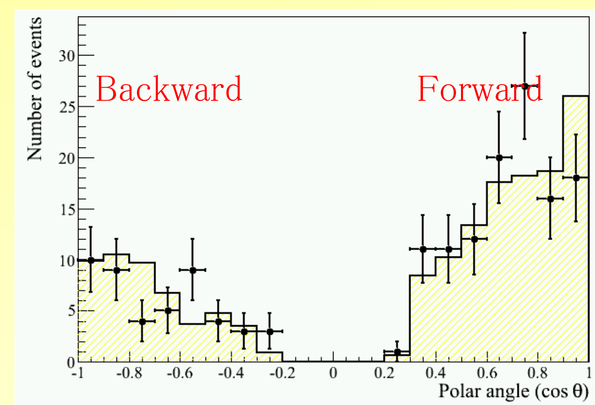
Error bars : Experimental data
Histogram : Simulated data

2, 4 GeV/c : IP < 100 + 0.01dz
10 GeV/c : IP < 50 + 0.01dz

Emission angle (cosθ)







Agreement with statistical error : Systematic error is 10%.