Results from the OPERA experiment in the CNGS beam

13/07/2016 PASCOS 2016

N. Kitagawa (Nagoya Univ.)
on behalf of the OPERA collaboration

Outline

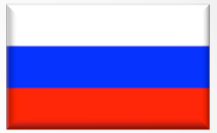
- Experimental technique and the detector
- Tau search
- Physical results
  - Tau appearance
  - ν_μ disappearance
  - $\nu_\mu \rightarrow \nu_e$ oscillations
  - sterile ν search
- Conclusions

OPERA collaboration

26 institutions, 140 physicists

Bari
Bologna
LNF Frascati
LNGS
Napoli
Padova
Roma
Salerno

LAPP Annecy
IPHC Strasbourg



INR Moscow
LPI Moscow
SINP MSU Moscow
JINR Dubna

Aichi
Toho
Kobe
Nagoya
Nihon

Technion Haifa

LHEP Bern

IHE Brussels

Hamburg

IRB Zagreb

METU Ankara

Jinjiu

Experimental proposal(2000) -> Start construction in LNGS (2003)
-> Start physics run (2008) -> End of physics run (2012)

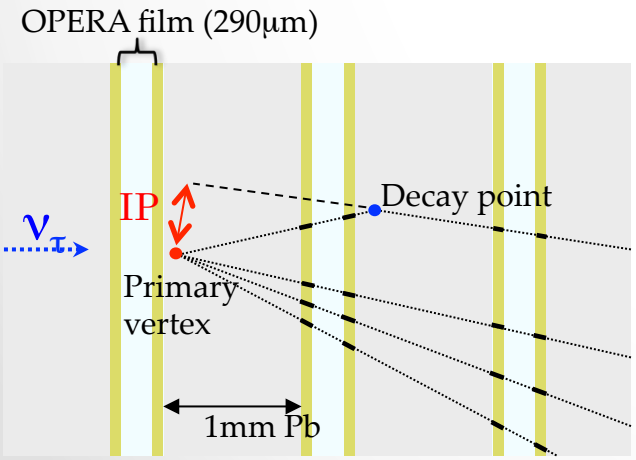
Motivation and ν_τ detection

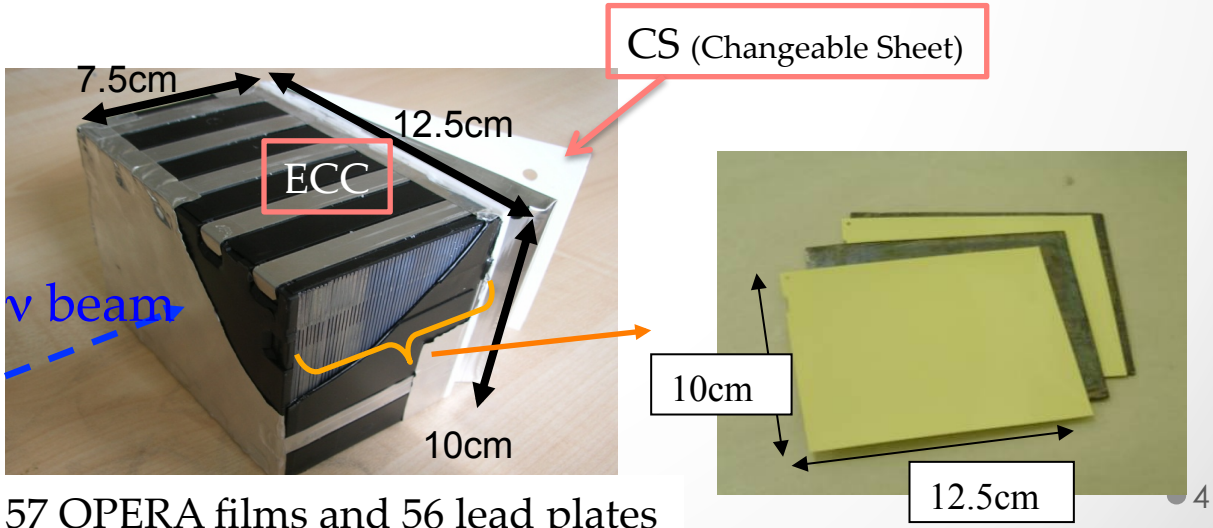
Many experiments observed oscillation phenomenon in disappearance mode.

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

For the detection of a short-lived tau lepton decay ($c\tau \sim 87\mu m$) produced in ν_τ CC interactions

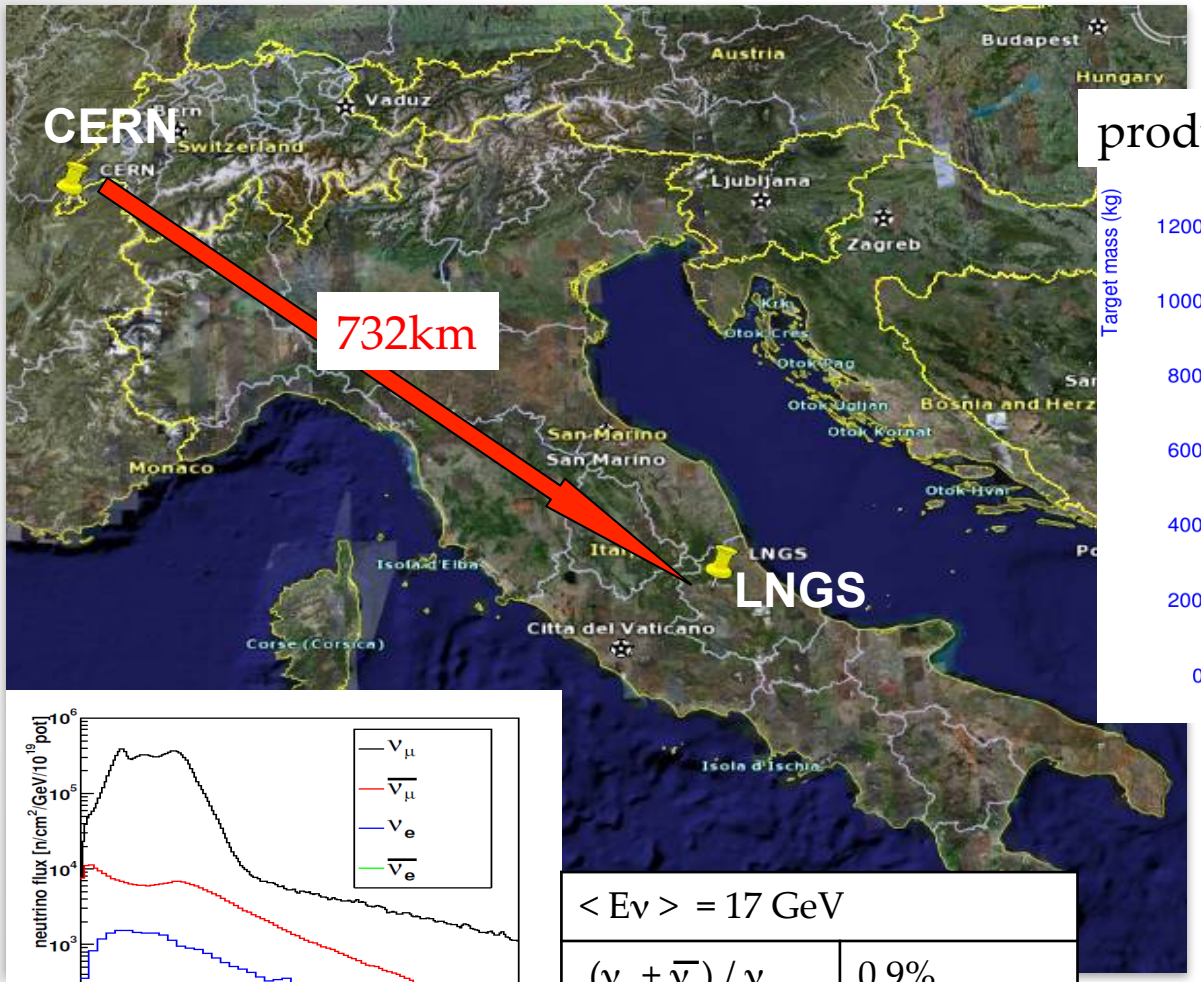
1: micrometric resolution ⟹ nuclear emulsion films
2: large target mass ⟹ 150,000 ECC bricks = 1.25 kton in total are required.



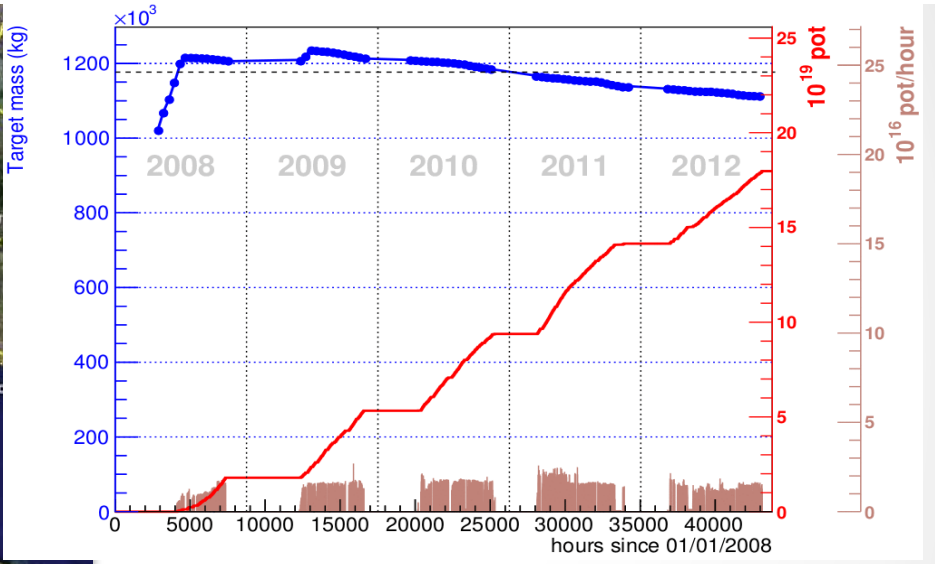


57 OPERA films and 56 lead plates

CNGS neutrino beam



produced by the SPS 400 GeV proton beam



< Eν > = 17 GeV	
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.9%
$\bar{\nu}_\mu / \nu_\mu$	2.1%
ν_τ prompt	negligible

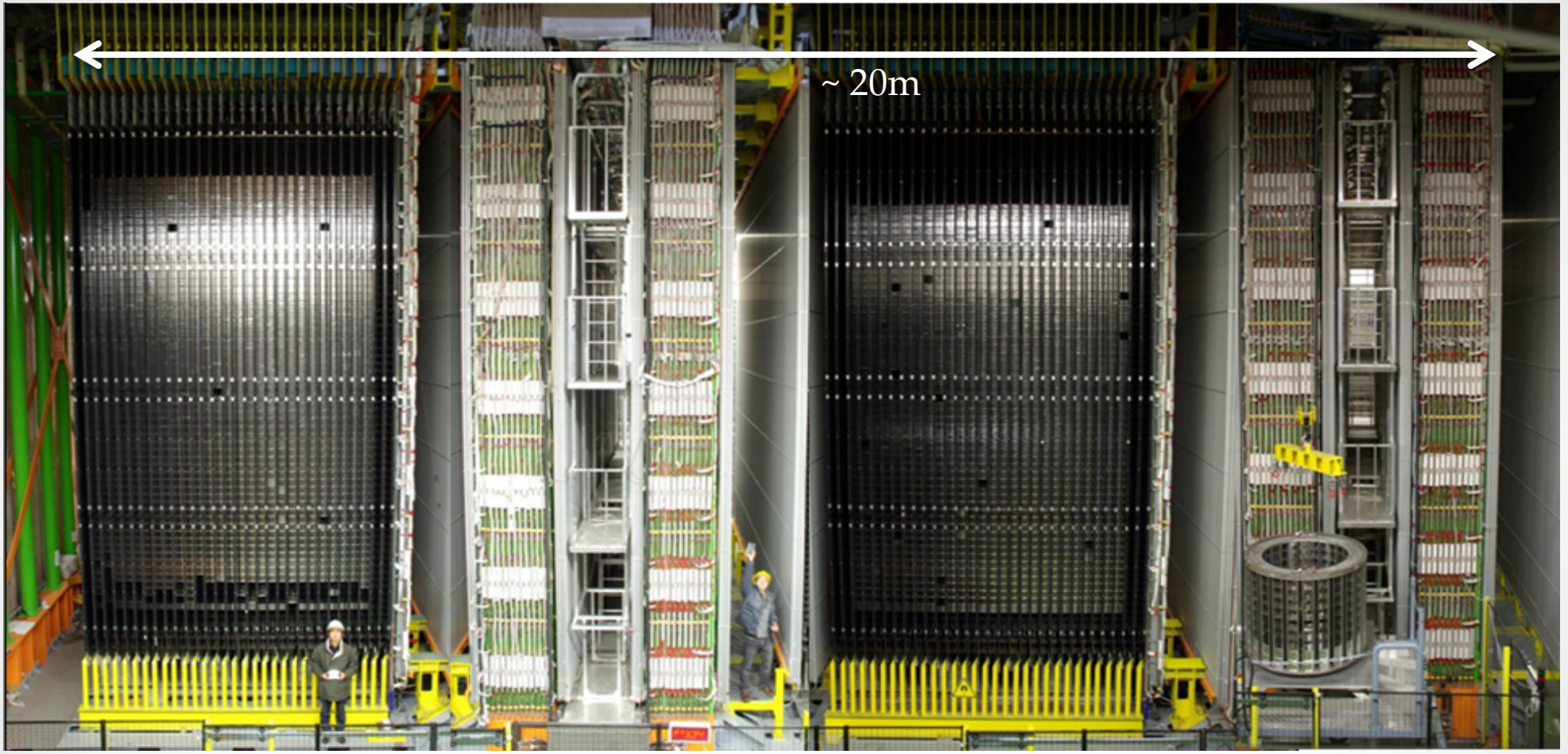
* interaction rate at LNGS

5 years CNGS run ended in 2012.

1.8x10^{20} p.o.t collected
(80% of the proposal value)

19505 neutrino interactions recorded in the emulsion targets

The OPERA detector @LNGS



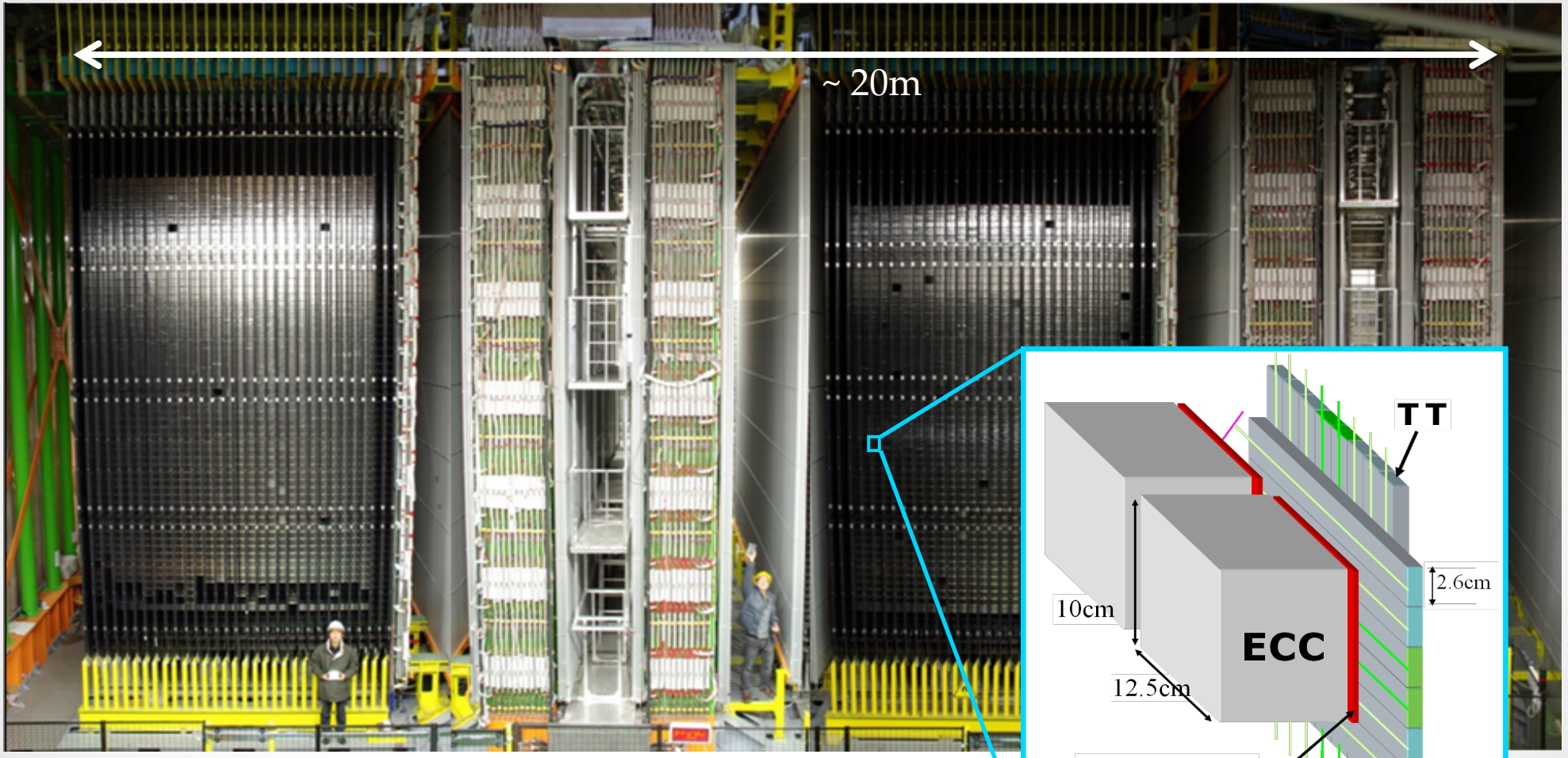
Target area
(ECC+ Target Tracker(TT))

Muon spectrometer

Δp/p (<50GeV/c)	~20%
μID (withTT)	~95%

- Total target mass ~ 1.25kton

The OPERA detector @LNGS



Target area
(ECC+ Target Tracker(TT))

Muon spectrometer

Δp/p (<50GeV/c)	~20%
μID (withTT)	~95%

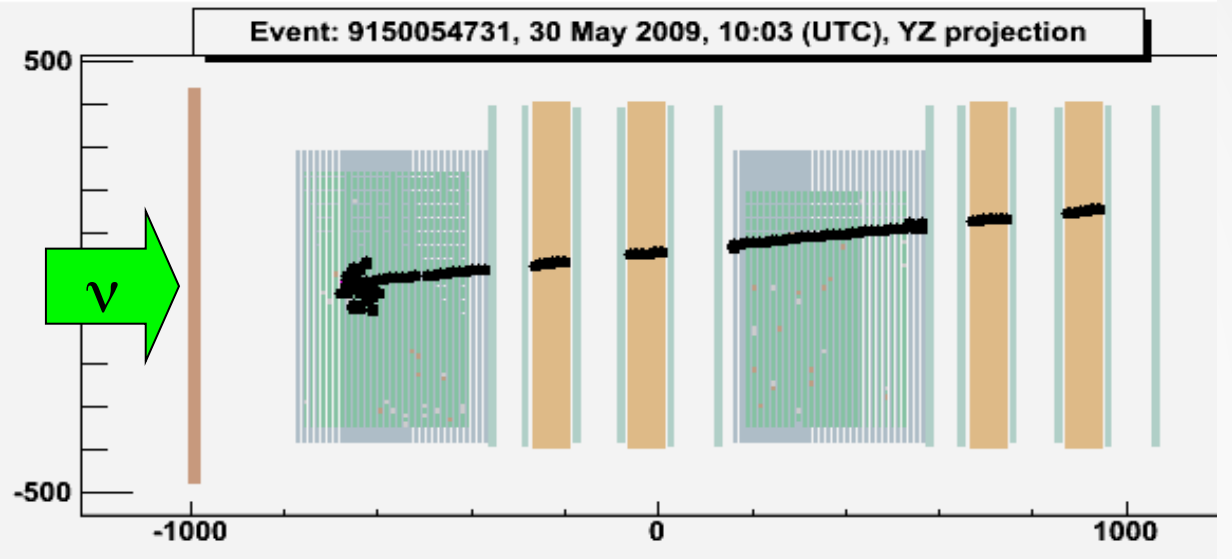
- Total target mass ~ 1.25kton

Classification of neutrino interactions

With μ

Define:1μ event

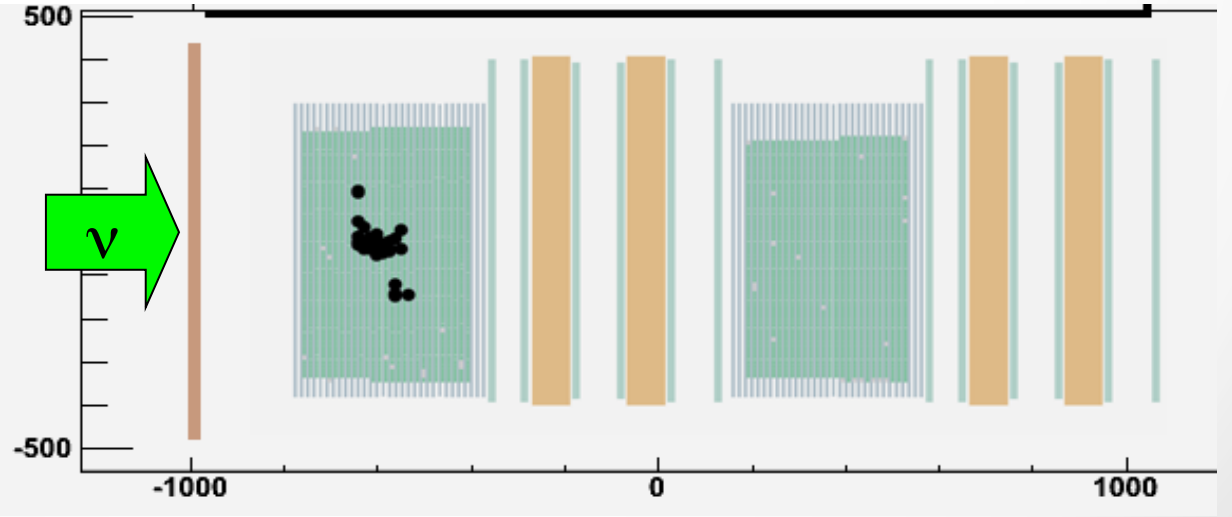
ν_μ CC
ν_τ CC : $\tau \rightarrow \mu$ (17.7%)



Without μ

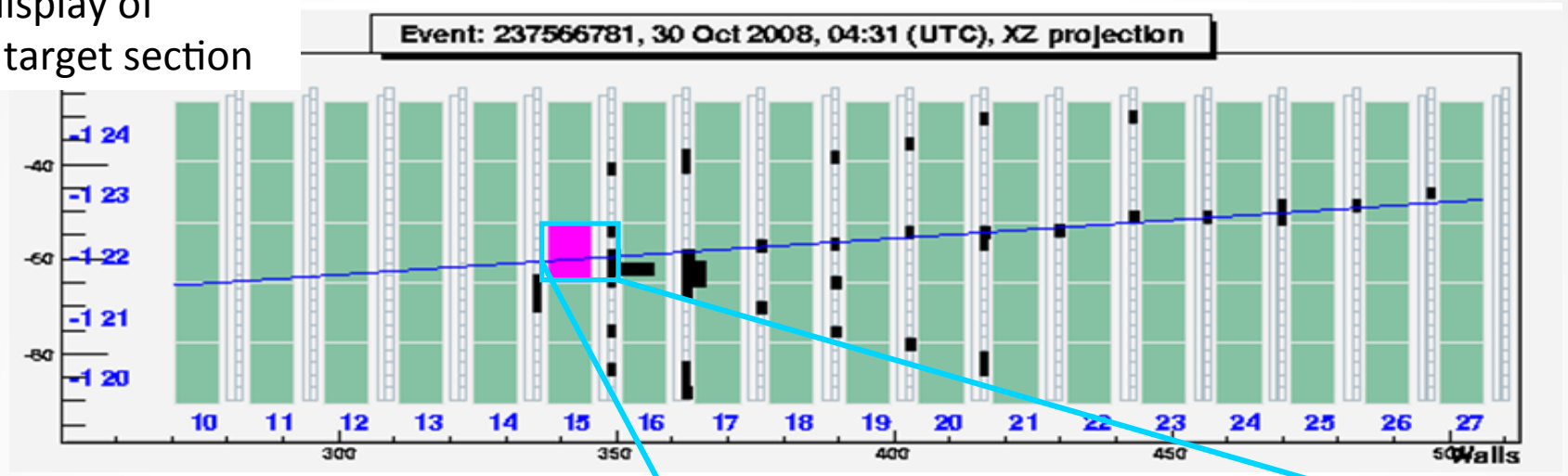
Define: 0μ event

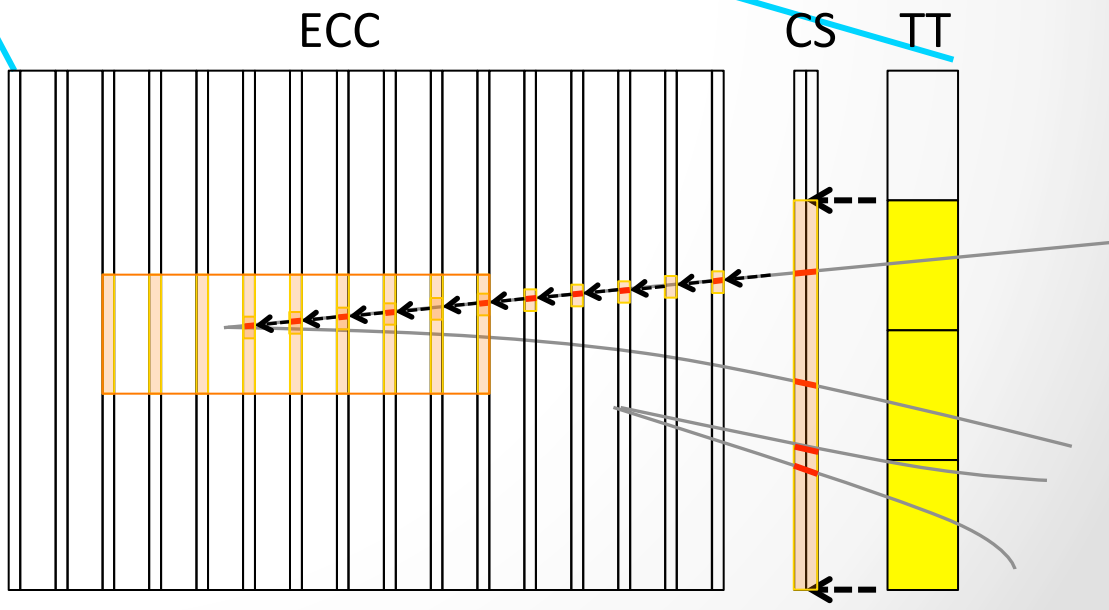
ν NC
ν_τ CC : $\tau \rightarrow e$ (17.8%)
ν_τ CC, :$\tau \rightarrow h,3h$ (64.5%)
ν_e CC



Location of neutrino interactions in ECC

Event display of
OPERA target section



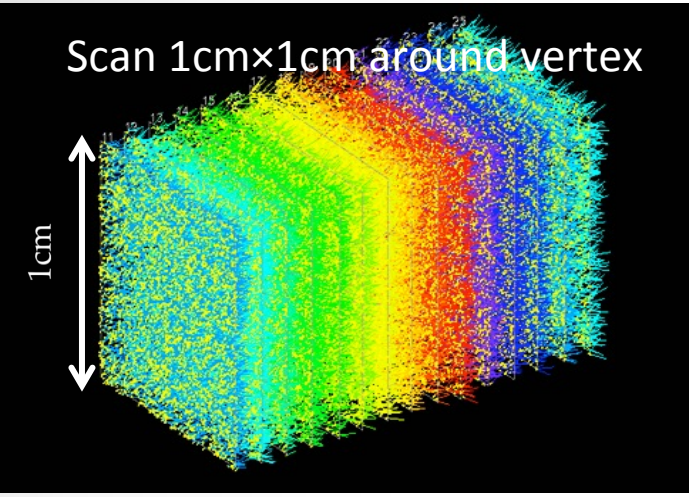


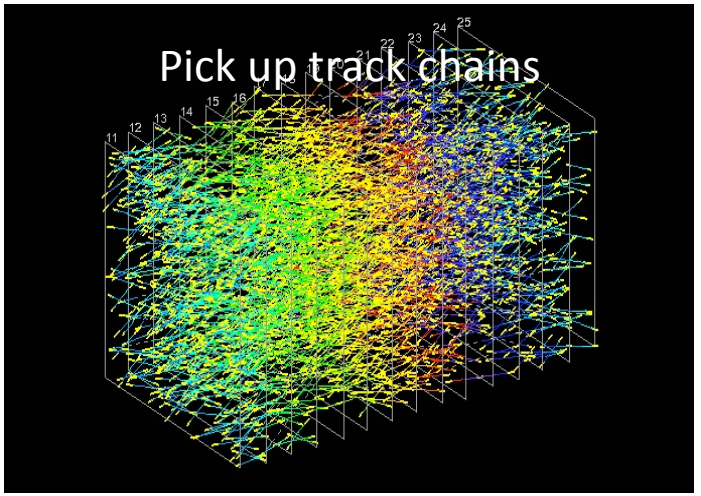
1. Select the most probable ECC containing the ν interaction using TT hits
2. Check CS to confirm the ECC and find tracks coming from ν interaction

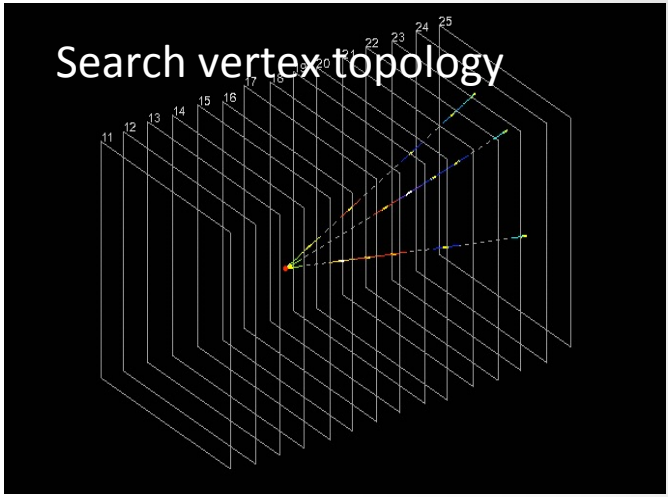
If no track found in CS, above 2 processes are repeated for the next ECC.

3. Follow back tracks to interaction vertex in the ECC
4. Scan 10 films around interaction vertex

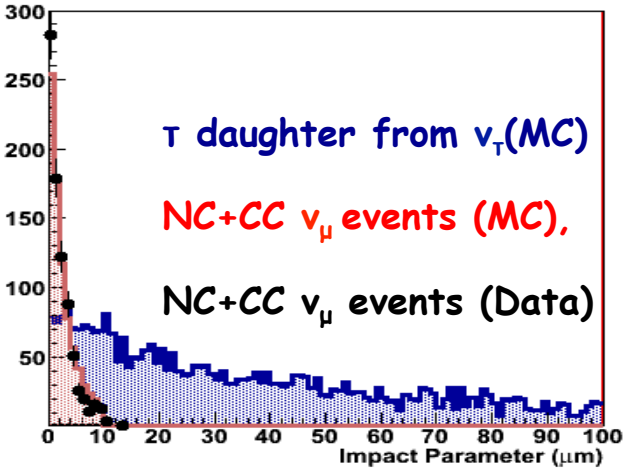
Search for decay topologies

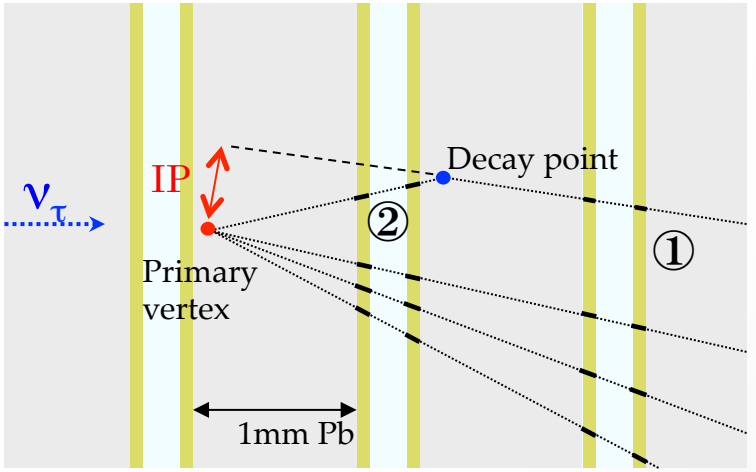






IP distribution





① Search track which have large Impact Parameter (IP)
② Search parent track

Data sample for ν_τ analysis

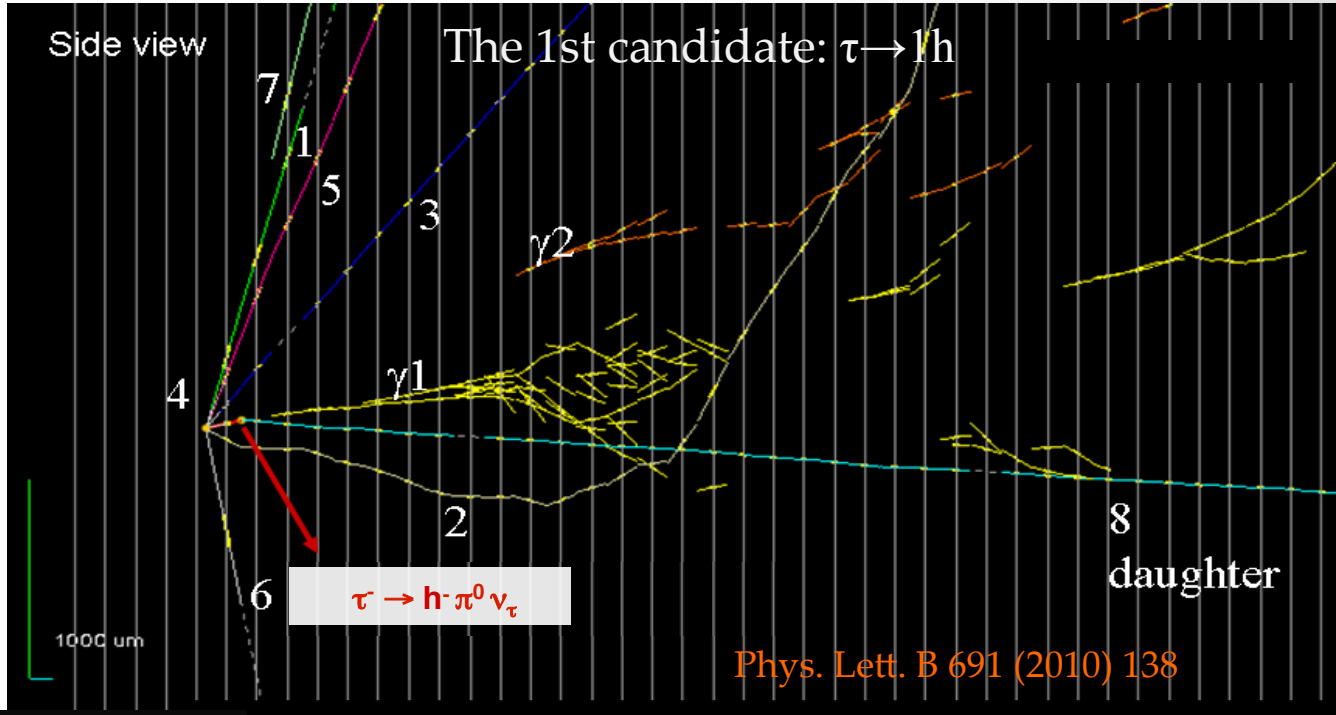
The 1st and 2nd most probable bricks for all runs

Number of events used in the analysis

	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 ($p\mu < 15$ GeV/c)	542	1020	968	966	768	4246
Total events	691	1273	1236	1236	972	5408
Observed ν_τ events	-	1	1	-	3	5

5408 events analyzed and 5 events observed

ν_τ events



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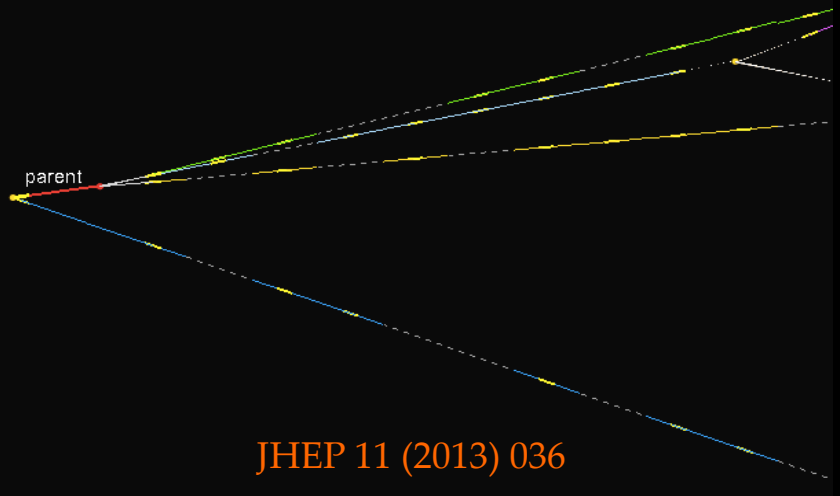
The 2nd candidate: τ→3h

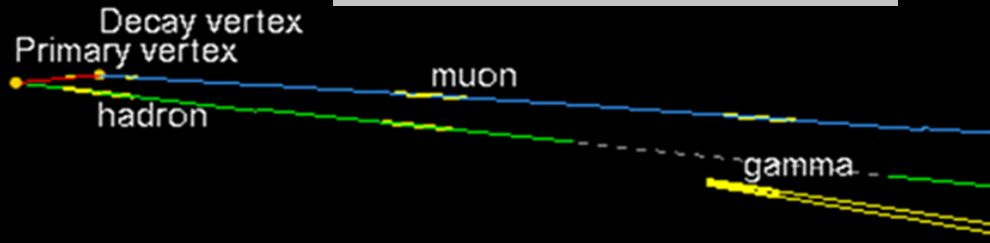


JHEP 11 (2013) 036

The 3rd candidate: τ- →μ−

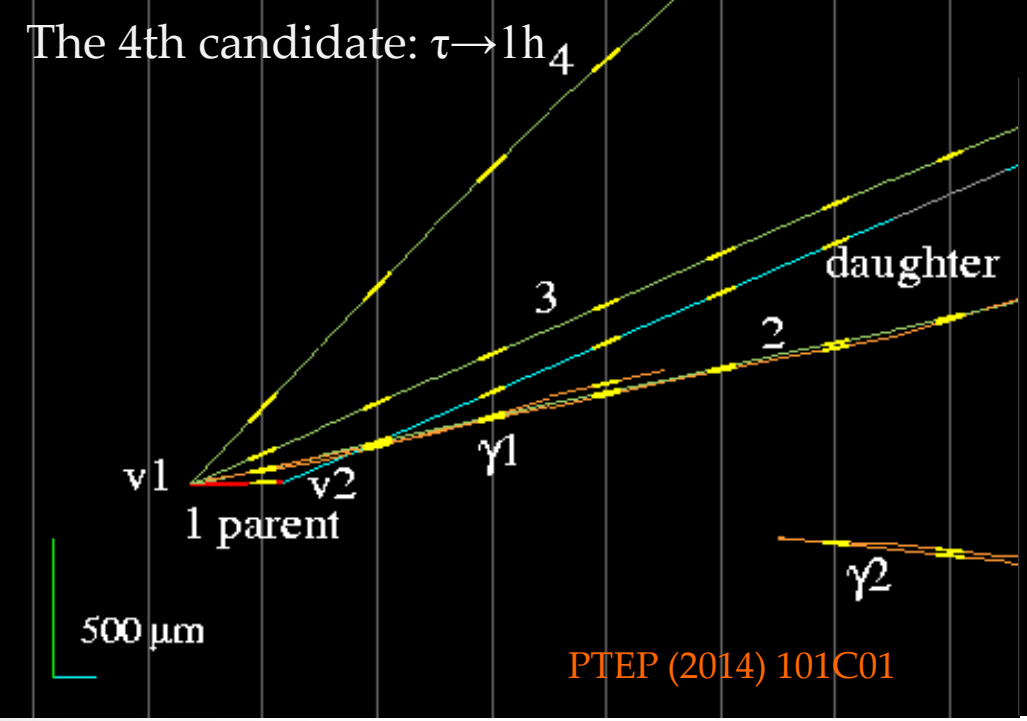
Indicate $\nu_\mu \rightarrow \nu_\tau$ oscillation

not $\nu_\mu \rightarrow \bar{\nu}_\tau$



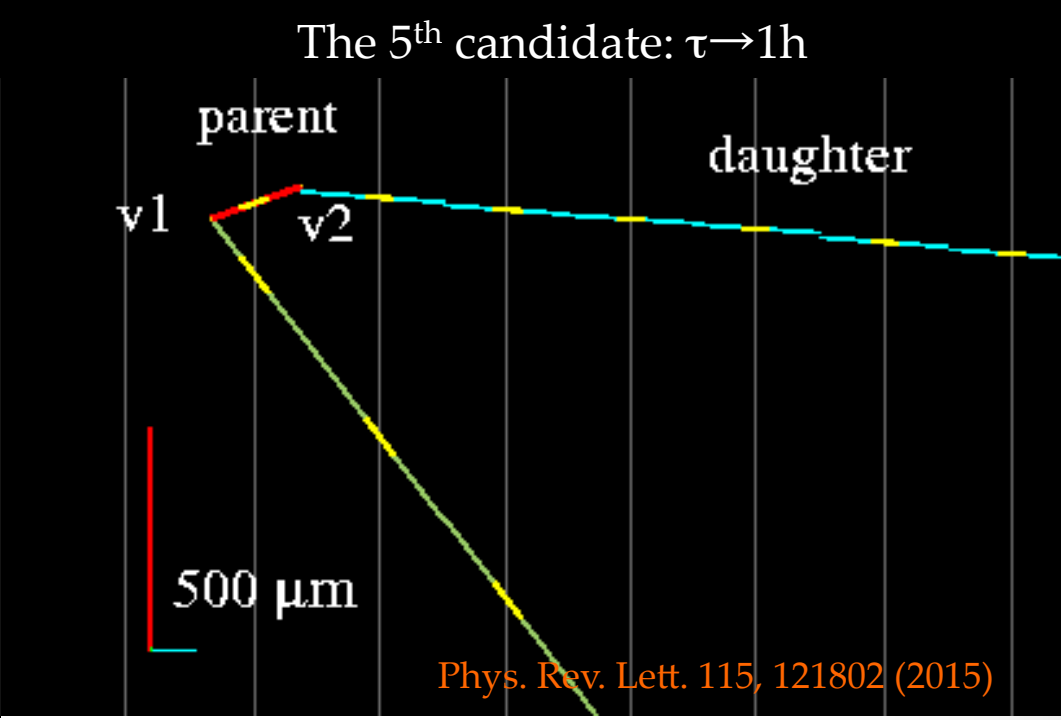
Phys. Rev. D 89 (2013) 051102

The 4th candidate: $\tau \rightarrow 1h_4$



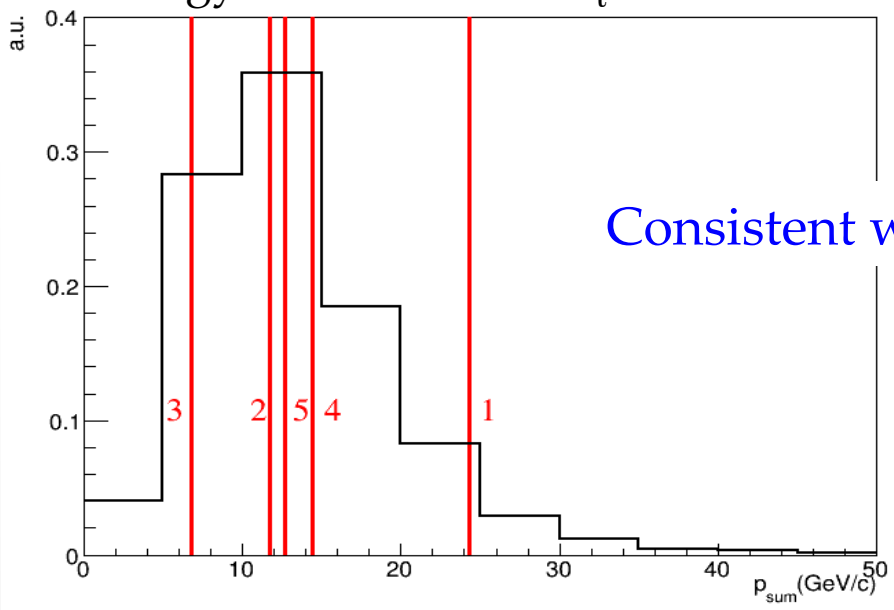
PTEP (2014) 101C01

The 5th candidate: $\tau \rightarrow 1h$



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

Energy distribution of ν_τ candidates



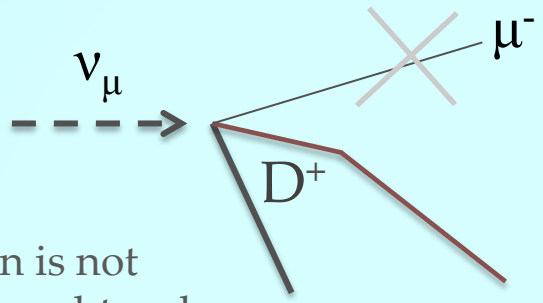
Consistent with the expected distribution

p_{sum} : the scalar sum of the momenta of all particles measured in the emulsion films

Background sources

1) CC interactions with charm production

(4% of CC)



if the primary lepton is not identified and the daughter charge is not measured

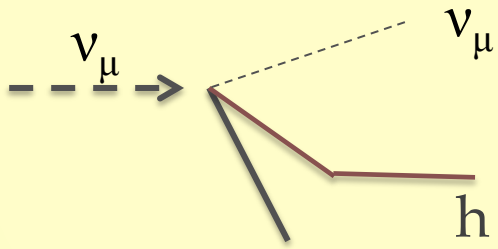
Monte Carlo simulation tuned on CHORUS data

Reduced by multi-brick tracking

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

2) Hadronic interactions

(0.2% of NC)

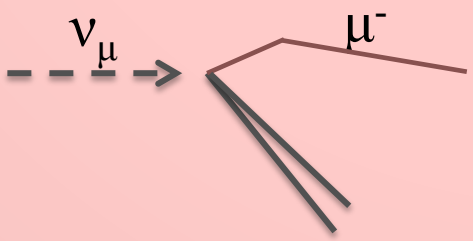


FLUKA and test beam data

Reduced by nuclear fragment search and large angle scanning

[PTEP9 (2014) 093C01]

3) Large angle μ scattering



Estimate by implementing a proper form factor for Lead

Simulation bench-marked on experimental data

[IEEE Trans. Nucl. Sci. 62, 2216 (2015)]

Significance

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

(for $\Delta m^2 = 2.44 \times 10^{-3}$ eV^2)

5 observed events with 0.25 background events expected

Probability to be explained by background fluctuation = 1.1×10^{-7}

Corresponding to 5.1 σ exclusion of the background-only hypothesis

Discovery of ν_τ appearance in the CNGS beam

$\Delta m^2_{23} = 3.3 \times 10^{-3}$ eV^2
with a 90% C.L. interval $[2.0, 5.0] \times 10^{-3}$ eV^2
(assuming full mixing)
First measurement by ν_τ appearance

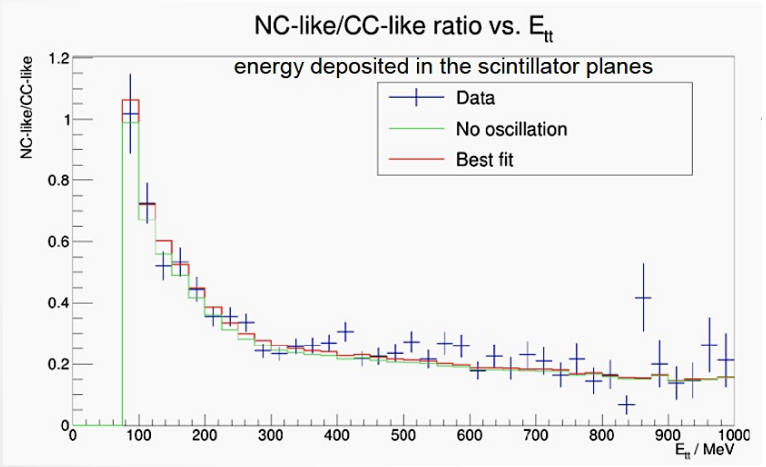
[PRL 115 (2015) 121802]

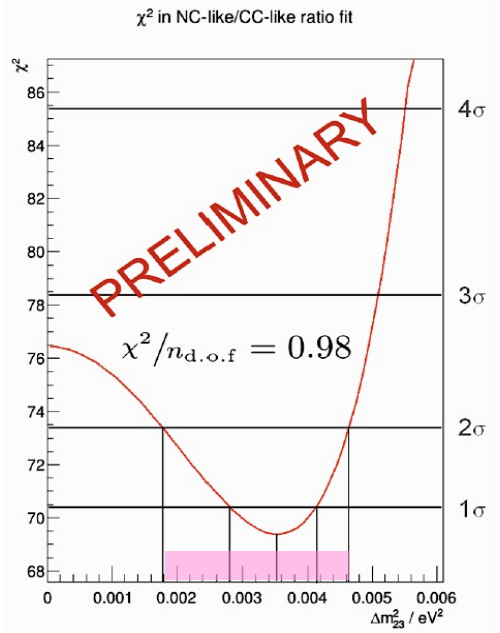
ν_μ disappearance

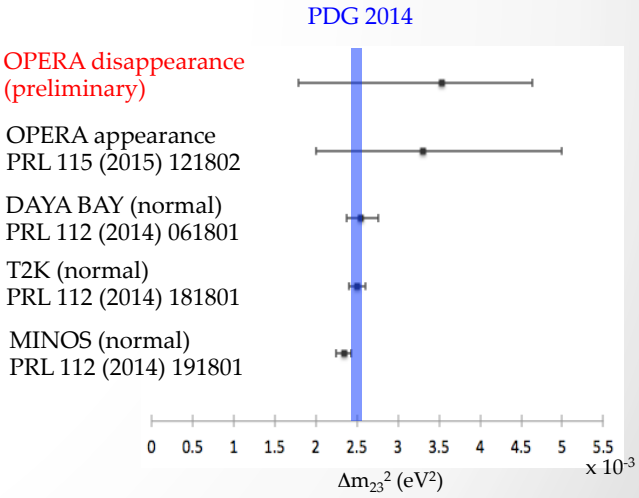
- Use electronic detector data for 5 years run
- Separate between ν_μCC-like and NC-like events
  - CC-like : reconstructed clear muon track in the spectrometers
  - NC-like : without any muon track
- Compare CC-like / NC-like event rate
  to reduce beam uncertainty because of no near detector

Parameters but Δm_{23}^2 are fixed to the PDG values.

Reweighting MC according to oscillation probability and minimizing $\chi 2$ between MC and data.



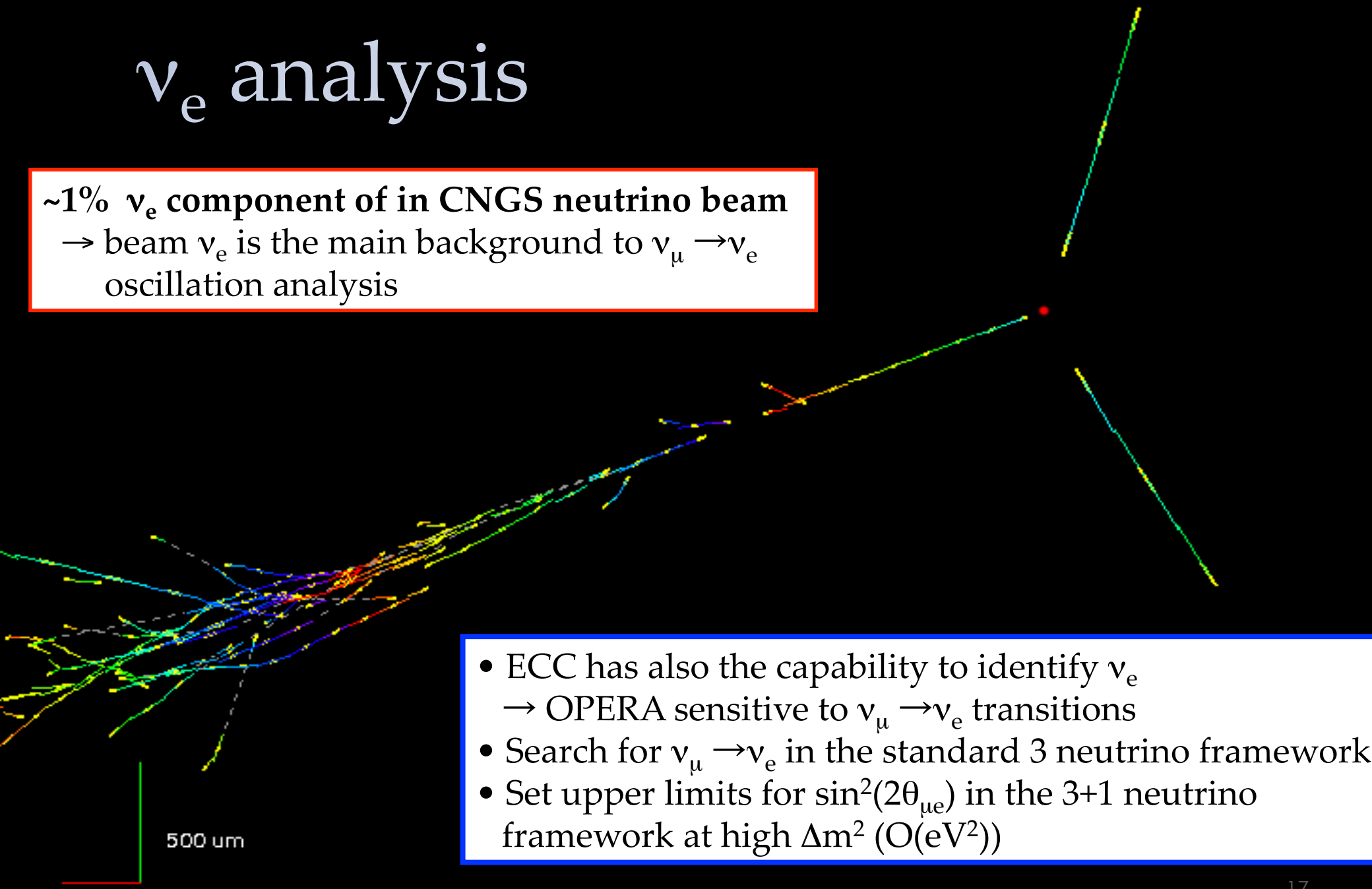




- Preliminary measurement Δm_{23}^2
- Our results consistent with the world average and the internal OPERA appearance results

ν_e analysis

~1% ν_e component of in CNGS neutrino beam
→ beam ν_e is the main background to $\nu_\mu \rightarrow \nu_e$ oscillation analysis

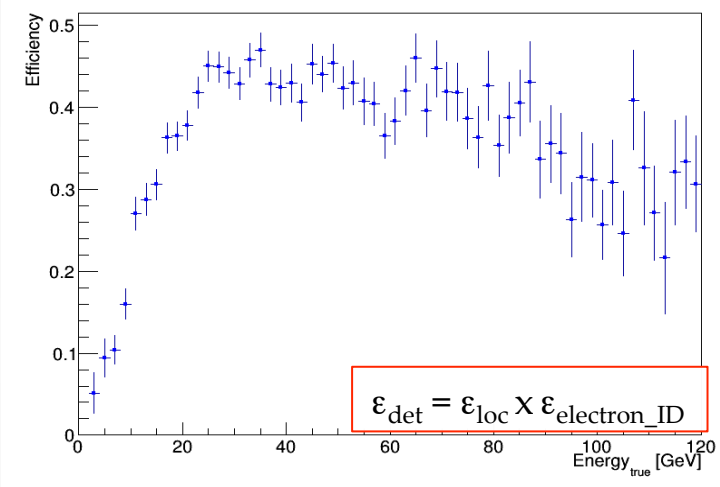


- ECC has also the capability to identify ν_e
  → OPERA sensitive to $\nu_\mu \rightarrow \nu_e$ transitions
- Search for $\nu_\mu \rightarrow \nu_e$ in the standard 3 neutrino framework
- Set upper limits for $\sin^2(2\theta_{\mu e})$ in the 3+1 neutrino framework at high Δm^2 ($O(eV^2)$)

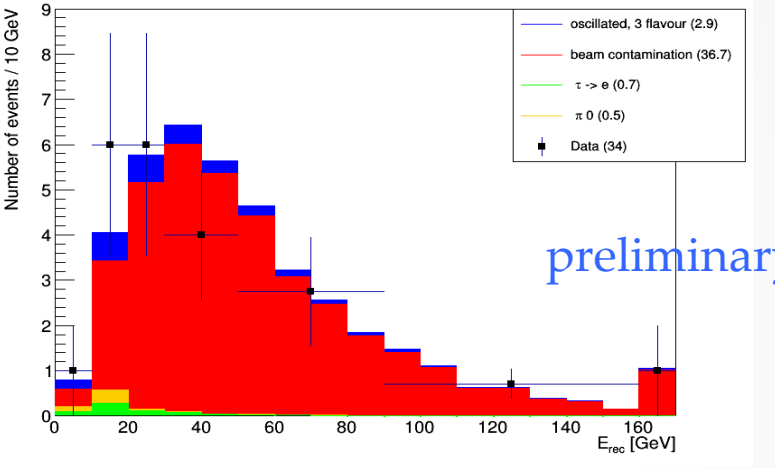
$\nu_\mu \rightarrow \nu_e$ oscillations

Results of 2008 – 2012 data sample (analysis for 1st+2nd brick)

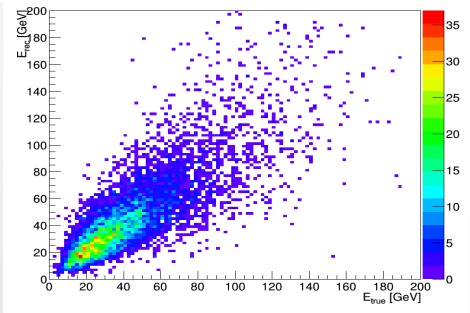
Location efficiency

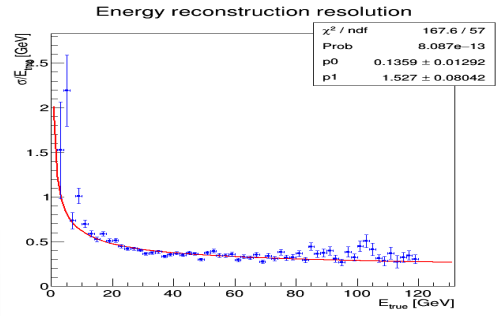


Reconstructed energy distribution



Reconstructed E vs True E (MC)





Observed νe events		34
Expected νe events	ν_e beam contamination	36.7±5
	BG ($\tau \rightarrow e$, mis-ID π^0)	1.2±0.1
	3-flavour oscillation	2.9±0.4

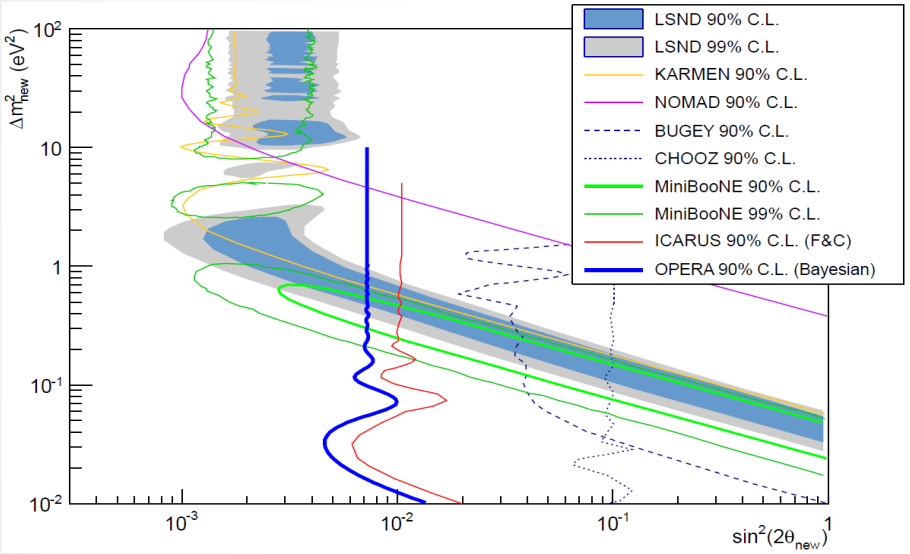
Work in progress to extract exclusion limits on sterile search

Sterile neutrino search

appearance probability modified by one possible extra (sterile) state (3+1 scheme)

$\nu_\mu \rightarrow \nu_e$

2008+2009 data



[JHEP07 (2013) 004]

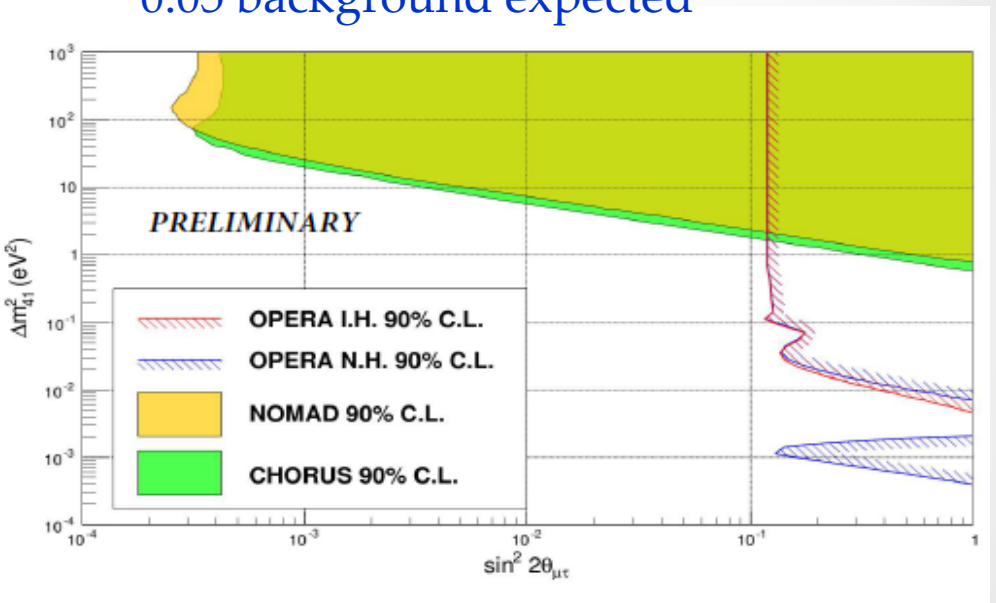
Upper limit on non standard ν oscillations $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ 90% CL

where $P = \sin^2(2\theta_{new})\ \sin2(1.27\ \Delta m^2_{new}\ L/E)$

Analysis to be updated with full ν_e sample and 3+1 framework

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

→ Observed 5 ν_τ events with 0.25 ± 0.05 background expected



- 90% CL exclusion region on Δm^2_{41} lowered down to 10^{-2} eV^2 for $\sin^2(2\theta_{\mu\tau}) > 0.5$

- At large Δm^2_{41} : $\sin^2(2\theta_{\mu\tau}) < 0.119$ at 90% CL

Update of JHEP 1506 (2015) 069

Conclusion and outlook

- OPERA runs from 2008 to 2012 were successfully carried out
- 1.8 x 10^{20} POT collected (about 80% of proposal value)
- 5ν_τ events found

No oscillation hypothesis excluded at 5.1σ
Discovery of ν_τ appearance in the CNGS beam

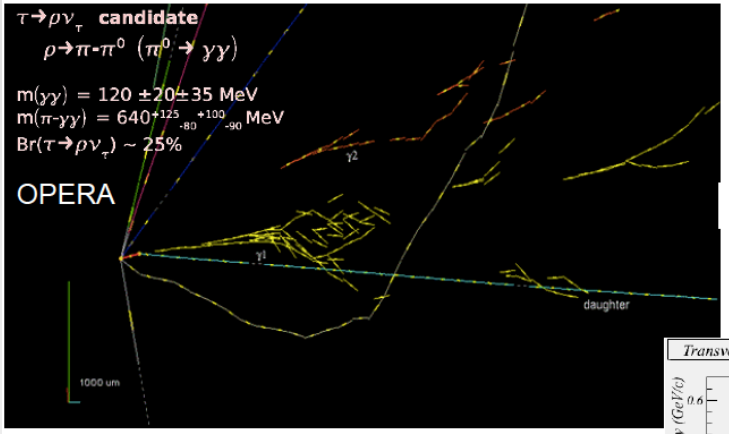
First Δm_{23}^2 measurement by ν_τ appearance

- Preliminary measurement Δm_{23}^2 from ν_μ disappearance analysis consistent with the world average and internal appearance result
- 34 ν_e events found for all year data
  latest result would be updated soon
- Sterile ν oscillation constraints from ν_e and ν_τ studies

Exploiting all three neutrino flavours:
ν_τ appearance + ν_e appearance + ν_μ disappearance data
=> **Constraints on the oscillation parameters with one single experiment**

back up

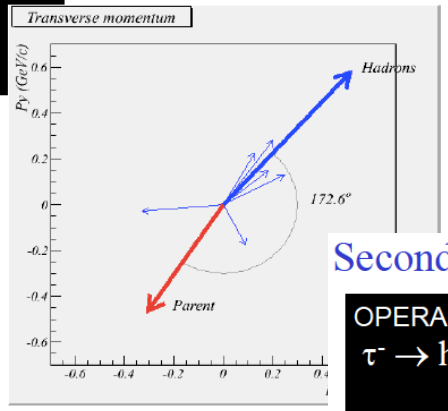
First ν_τ candidate



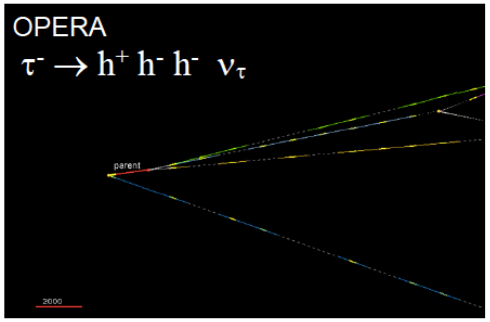
- In 2010 OPERA has published the first candidate based on the analysis of 35% of 2008/2009.

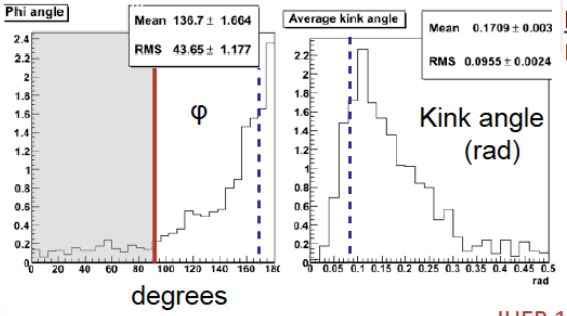
Phys. Lett. B 691 (2010) 138-145

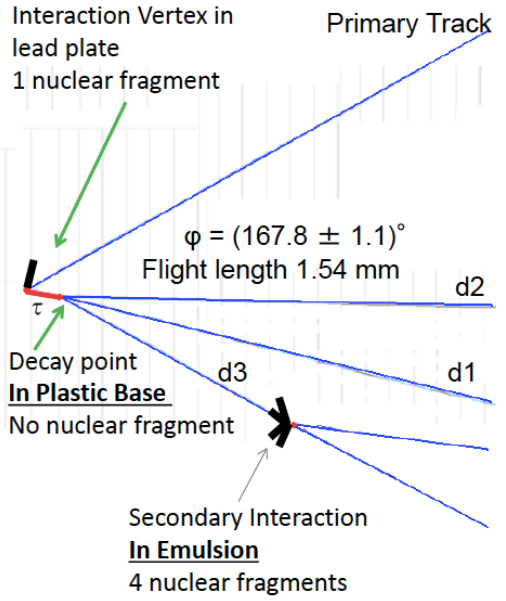
VARIABLE	Measured	Selection criteria
Kink (mrad)	41 ± 2	>20
Decay length (μm)	1335 ± 35	Within 2 plates
P daughter (GeV/c)	12^{+6}_{-3}	>2
P_T daughter (MeV/c)	470^{+230}_{-120}	>300 (γ attached)
Missing P_T (MeV/c)	570^{+320}_{-170}	<1000
ϕ (deg)	173 ± 2	>90



Second ν_τ candidate







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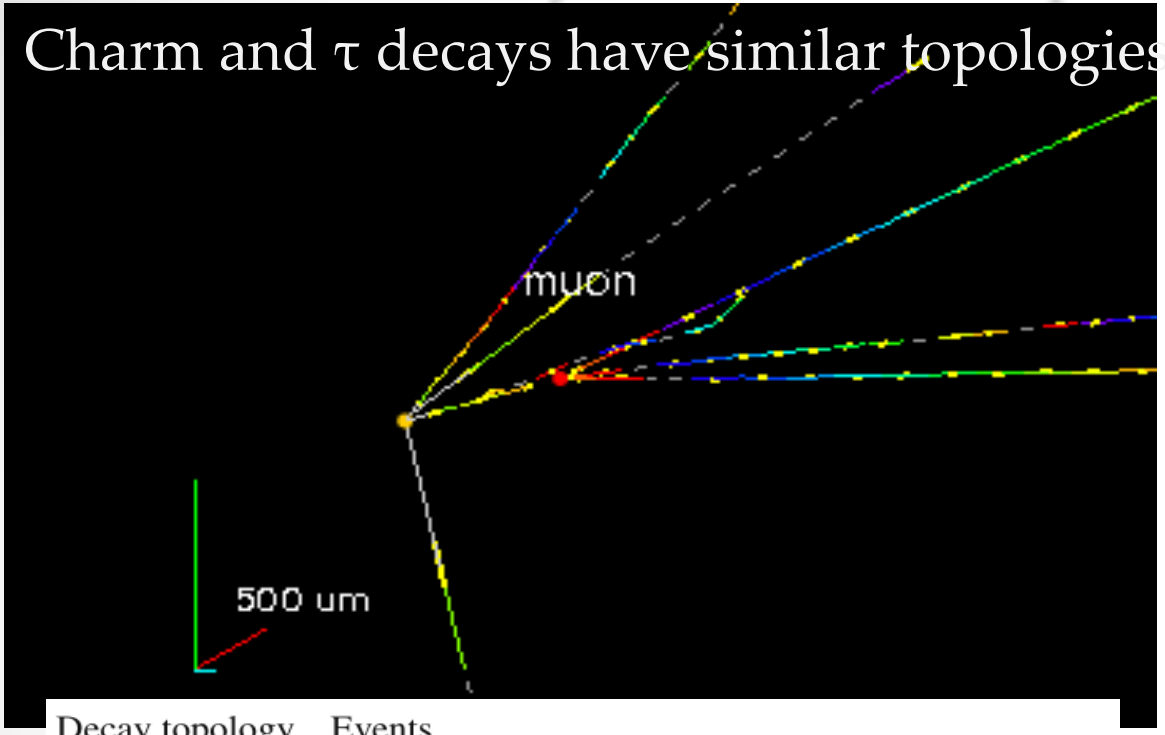
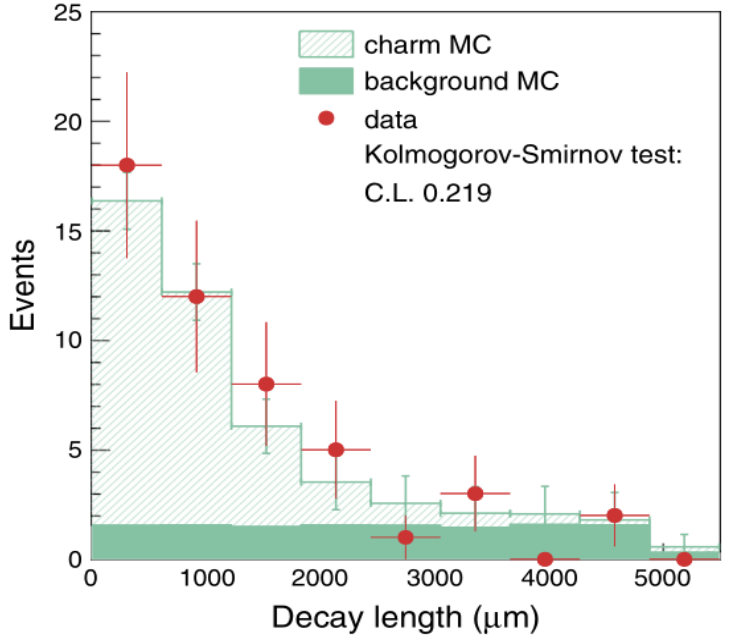
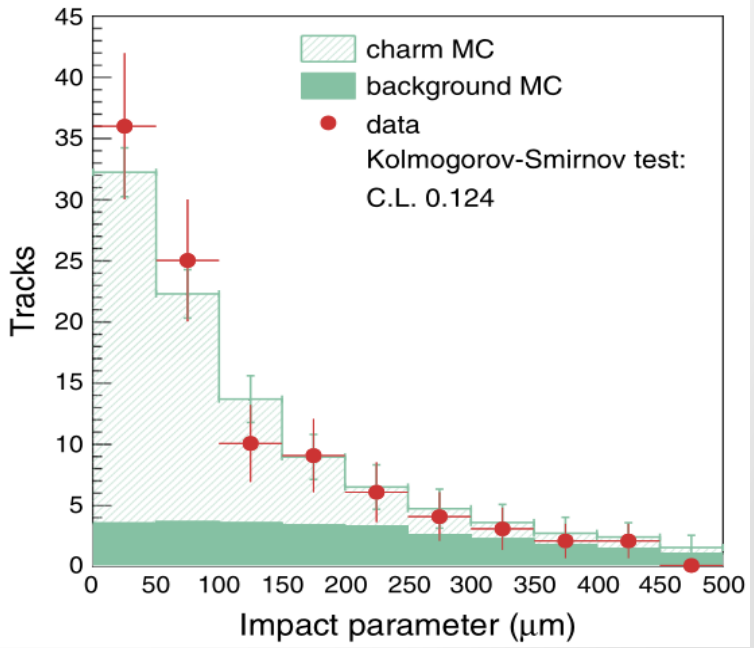
Charm decays: control sample for the τ decay search



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





Good agreement between data and expectations

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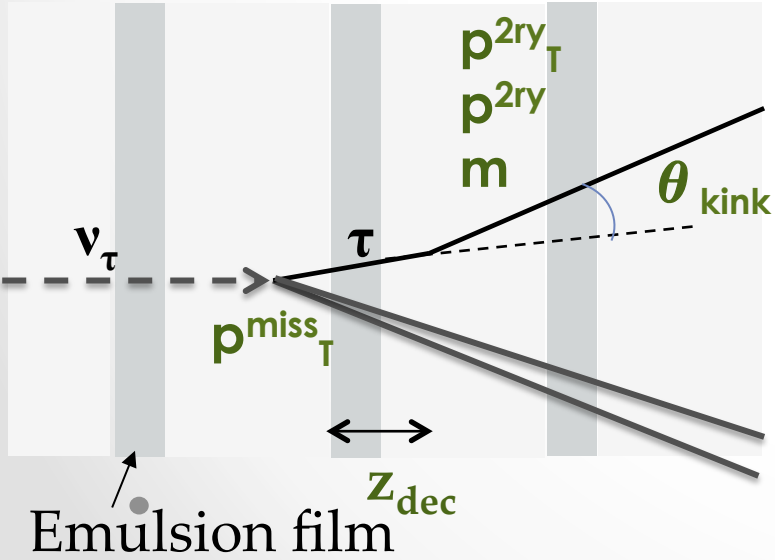
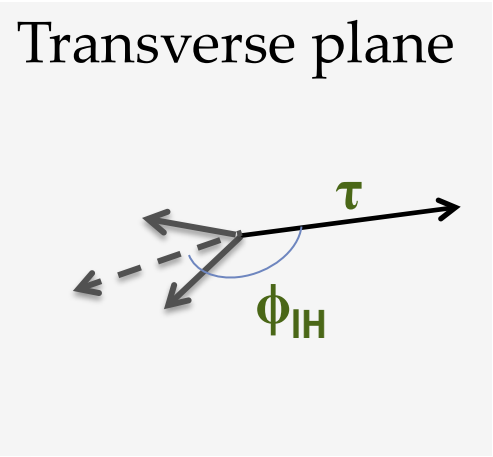
ν_τ analysis: kinematical selection

Cuts fixed since the beginning of the experiment

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

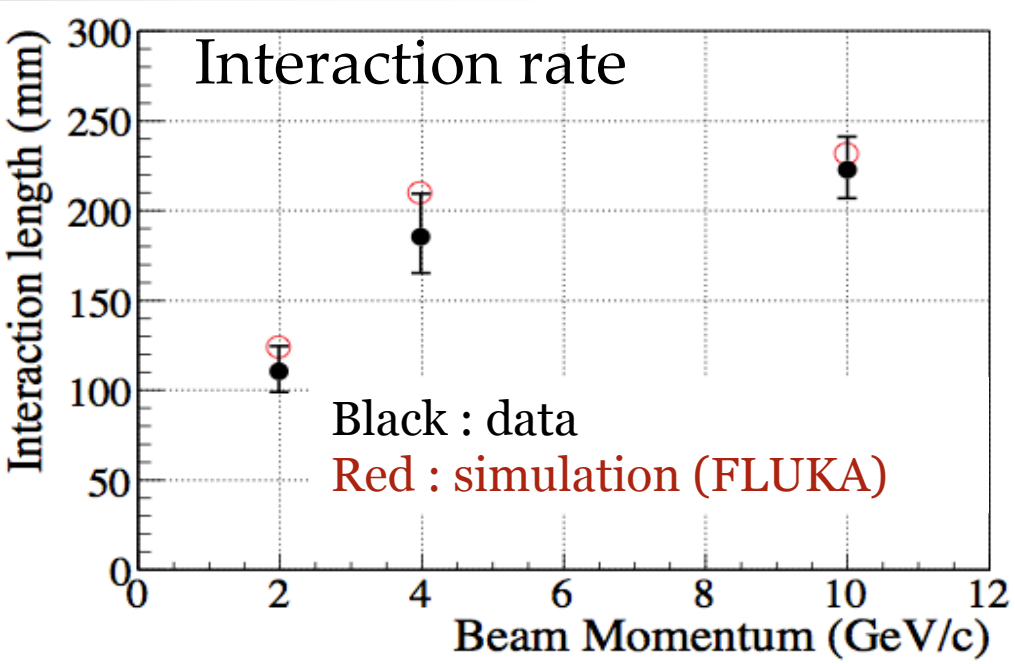




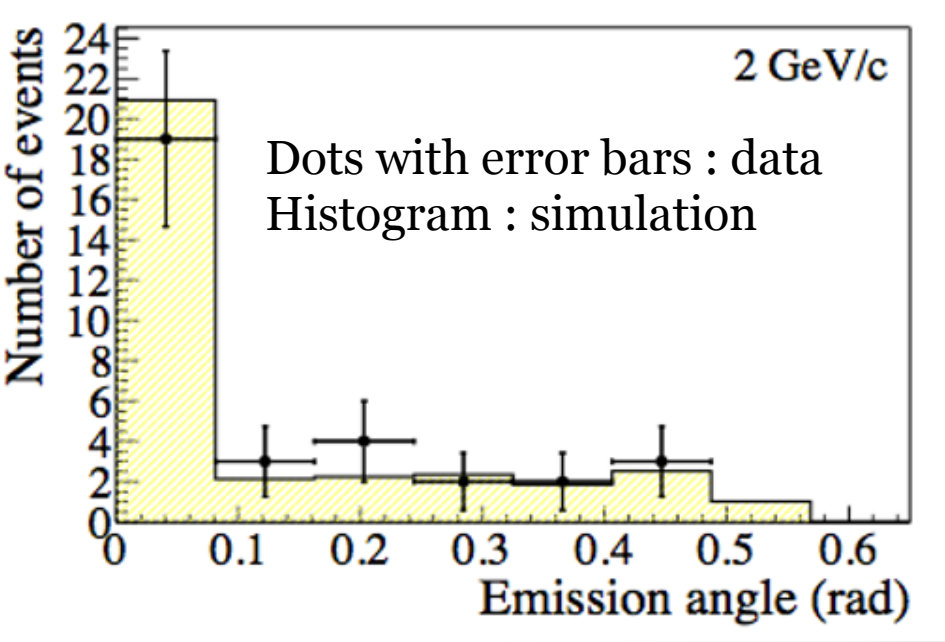
p^{miss}_T : vectorial sum of the transverse momenta of primaries (except the parent) and daughters wrt beam direction

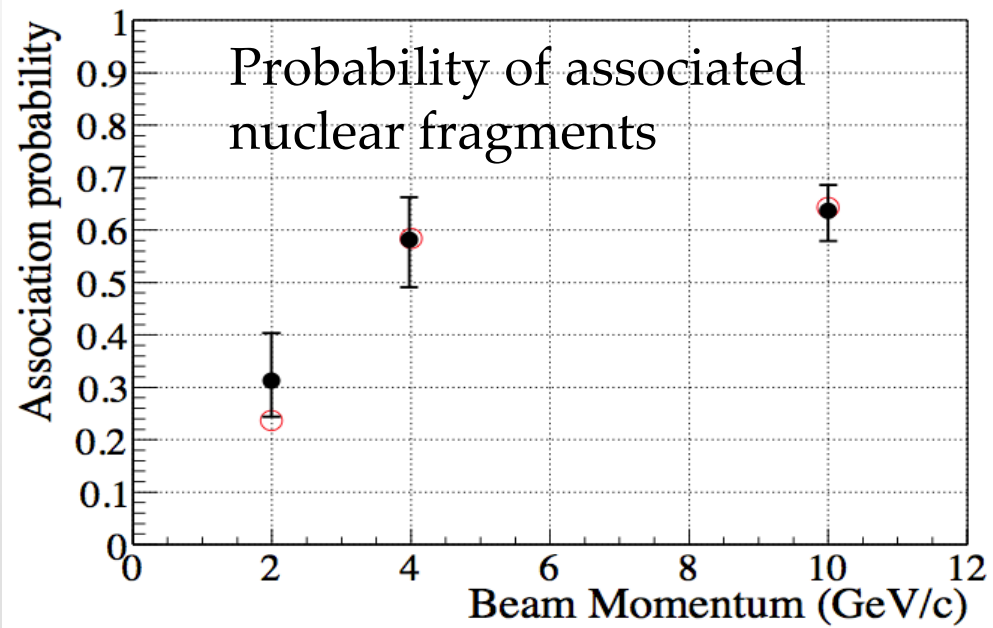
p^{2ry}_T : transverse momentum of the daughter wrt the parent direction

Validation of the hadronic background by test beams



Kink angle (1-prong events)



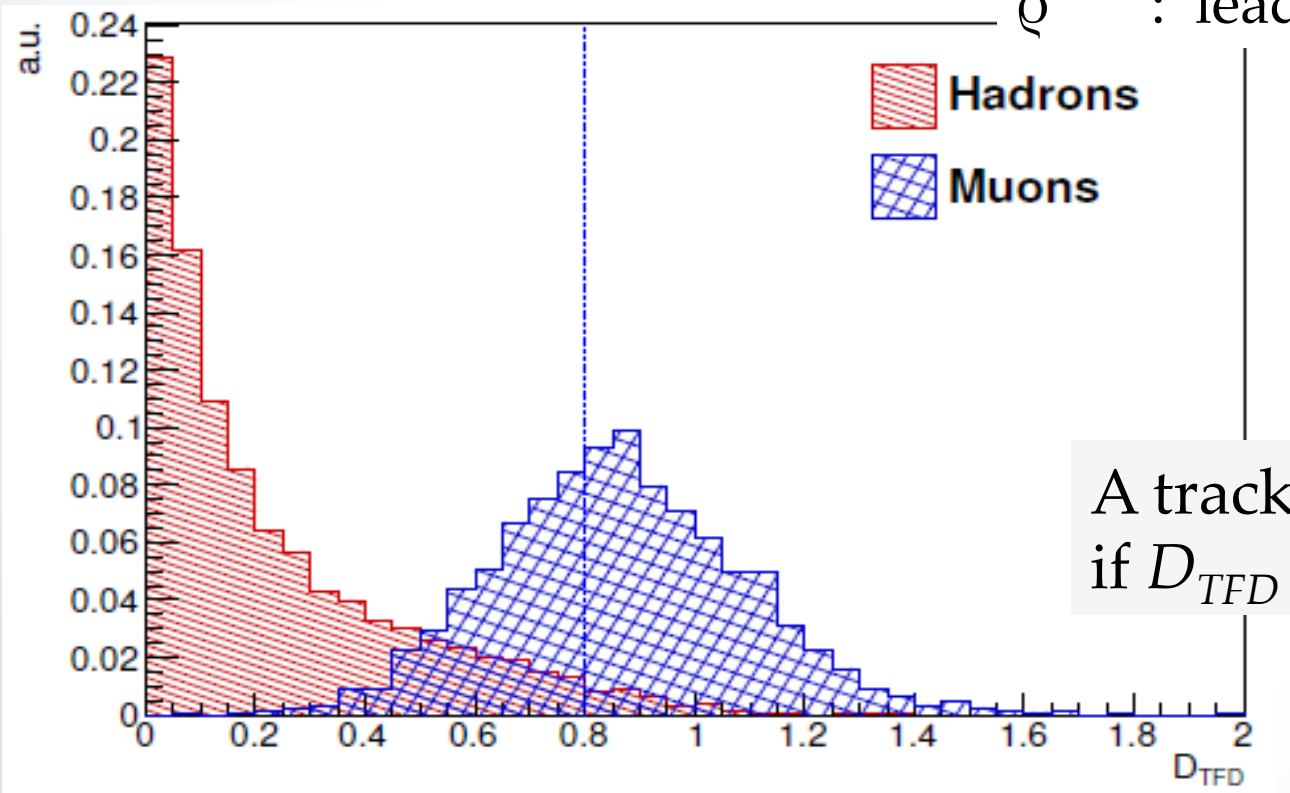


Muon/hadron separation by "track follow-down"

(primary tracks are followed until the stopping point)

$$D_{TFD} = \frac{L}{R(p)} \frac{\langle \rho \rangle}{\rho}$$

L : track length
R(p) : range in lead of a muon
<ϱ> : average density along the path
ϱ : lead density

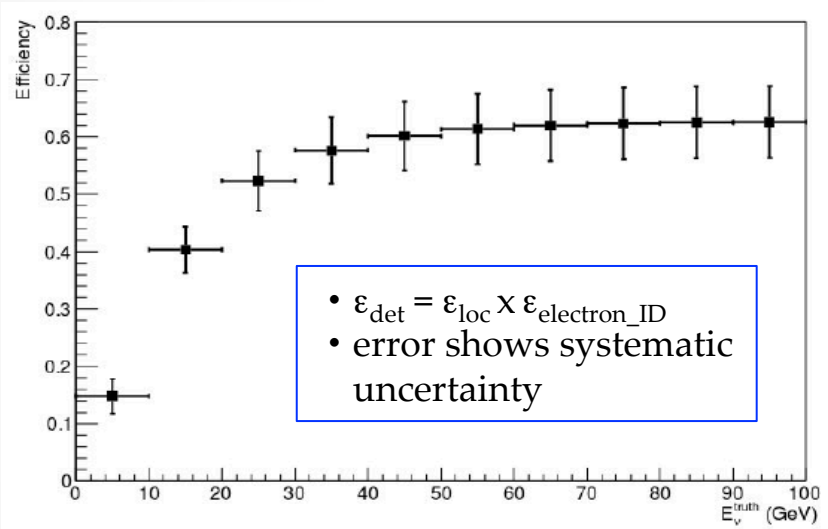


A track is classified as a muon if D_{TFD} is above 0.8

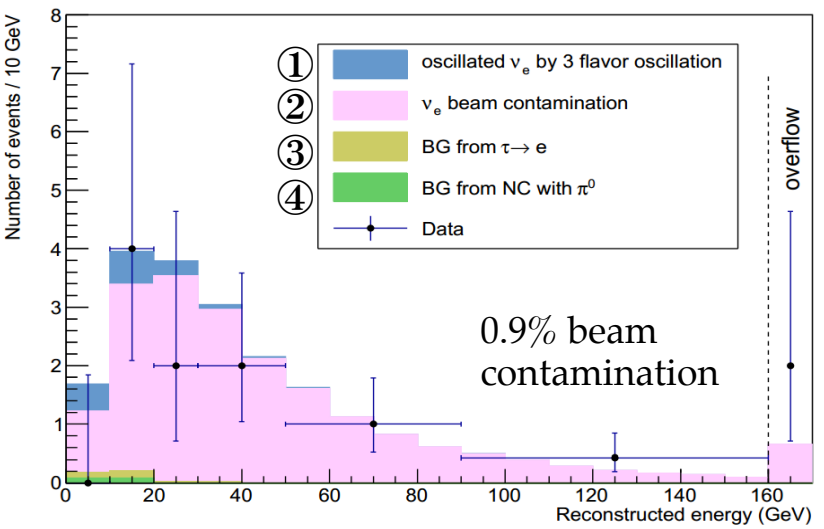
$\nu_\mu \rightarrow \nu_e$ oscillations

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

Detection efficiency



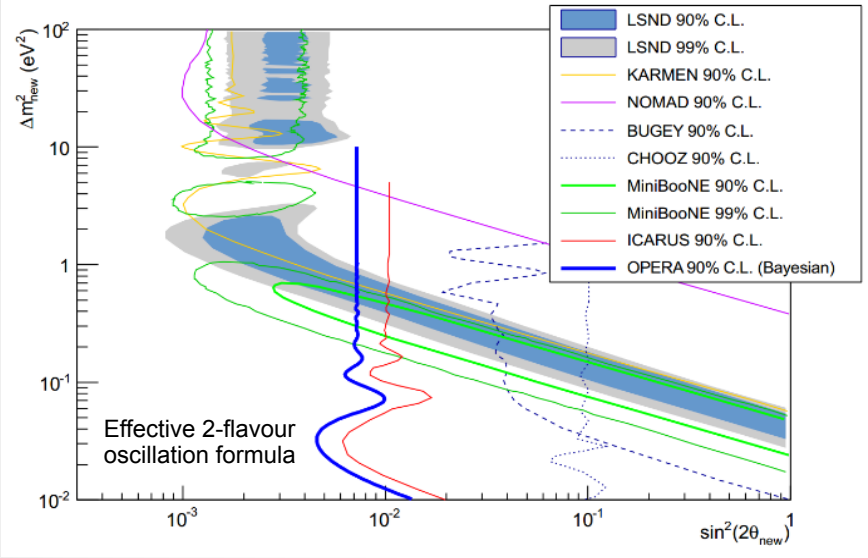
Reconstructed energy



	no cut	E<20GeV(3 flavor)	E<30GeV(non-standard)
observed νe	19	4	6
expected BG	19.8±2.8 (sys.)	4.6±0.7 (②+③+④)	9.4±1.4 (①+②+③+④)
Results (90% C.L.)		$\sin^2(2\theta_{13})<0.44$	$\sin^2(2\theta_{new})<7.2\times10^{-3}$

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

$\nu_\mu \rightarrow \nu_e$ oscillations



[JHEP 1307 (2013) 004]

	2008-2009 (previous paper)	2008-2012
#of data sample for ν_e search	505	1223
observed	19	34
observed (Eν<30GeV)	6	13
analysis method	2-flavour oscillation formula	(3+1) scheme

* selection criteria is slightly different from previous paper and all year analysis

In the range of Eν<30GeV,
Expected BG events (9.2±1) + Signal events (1.4±0.2)
is consistent with 13 observed events

Latest result to be updated soon