Latest results from the OPERA experiment

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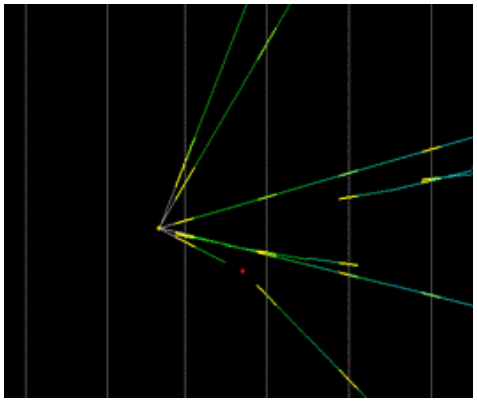
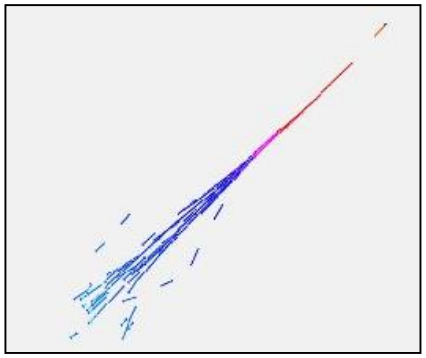
LAPP/CNRS, Université Savoie Mont-Blanc

On behalf of the OPERA Collaboration

- Introduction
- Experimental setup: CNGS and detector
- Data Analysis and Oscillation results
  - ν_τ appearance
  - ν_μ disappearance
  - ν_e appearance search
- Conclusions





September 16th 2016

XII th Rencontres du Vietnam
Gặp gỡ khoa học tại Việt Nam lần thứ 12
XXXVI Physics in Collision
ICISE, QUY NHON, VIETNAM, SEPTEMBER 13 - 18, 2016

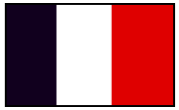
The OPERA collaboration

~ 140 physicists, 26 institutes, 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

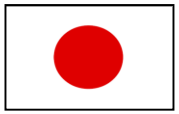


Germany
Hamburg

Israel
Technion Haifa

Italy
LNGS Assergi
Bari
Bologna
LNF Frascati
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Nihon



Korea
Jinju

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

Switzerland
Bern

Turkey
METU Ankara

- July 2000: Experiment proposal
- May 2003: start construction at LNGS
- summer 2006: 1st run with cosmics and CNGS commissioning
- autumn 2007: CNGS beam commissioning: ν interactions seen in the OPERA target
- July 2008: Emulsion target completed: start of ν physics run
- Dec. 2012: End of ν physics run

CNGS/OPERA: European long baseline ν project:

- motivated by the **atmospheric ν disappearance** results and the evidence of neutrino oscillation in 1998
- 3-flavour oscillation formalism (PMNS matrix) describes with success the major results from solar, atmospheric, reactor and neutrino beam experiments
  - ➢ Many results from ν disappearance (ν_e, ν_μ, $\bar{\nu}_\mu$, $\bar{\nu}_e$)

  => Oscillation picture should be tested in **different ν flavour appearance mode**

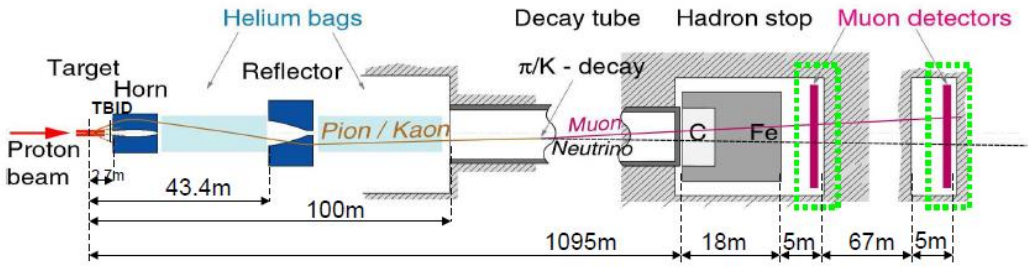
In the CERN high energy ν_μ beam (CNGS):

$$P(\nu_\mu \rightarrow \nu_\tau) \approx \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \sin^2\left(1.27 \frac{\Delta m^2_{23} L}{E}\right)$$

- search for direct ν_τ appearance at the Gran Sasso underground laboratory (730 km from CERN)

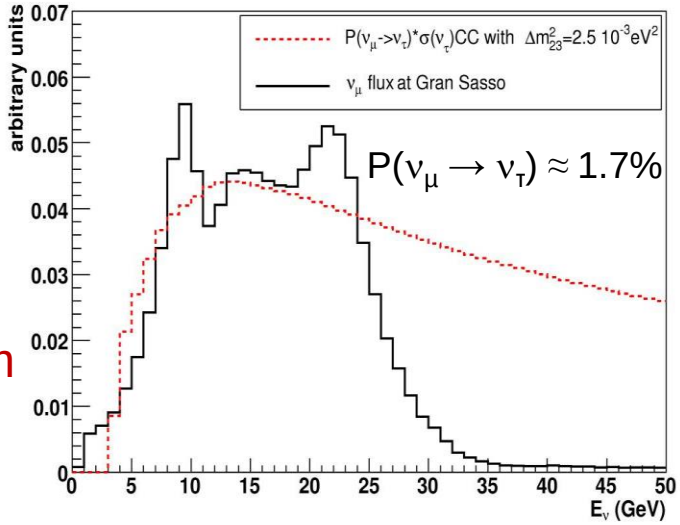
- by-product analysis: search for $\nu_\mu \rightarrow \nu_e$ and put constraints on non standard oscillation

CNGS: CERN Neutrinos to Gran Sasso



ν to Gran Sasso

L=730 km

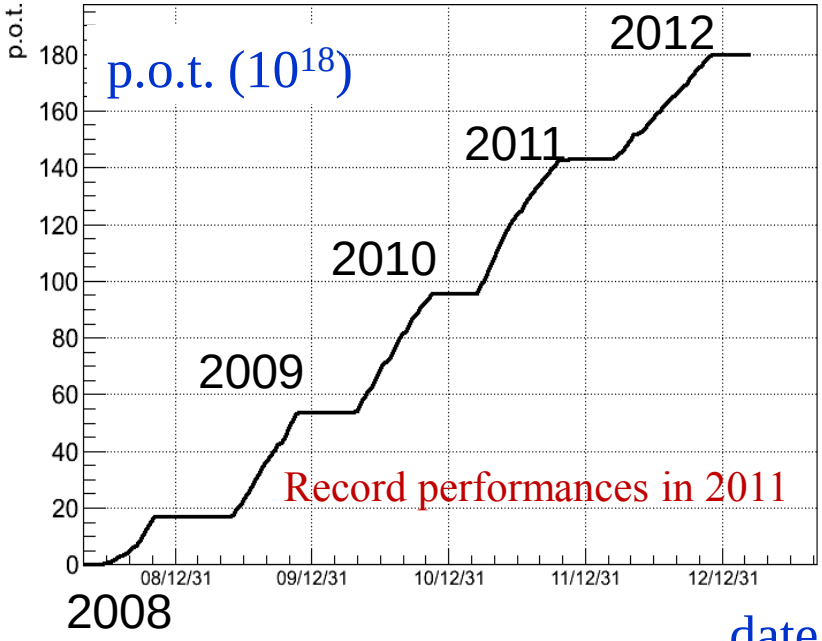


Conventional ν beam: 400 GeV protons from SPS

- 2 fast extractions (10.5 μs), separated by 50 ms / SPS cycle (6 s) => 2 10^{13} protons/extraction

=> Average beam power: 160 kW (peak: 480 kW)

ν_μ flux optimized to maximize the ν_τ charged current interactions



$< E >_\nu$	**17 GeV**
$(\nu_e + \overline{\nu}_e)CC$ / $\nu_{\mu CC}$	**0.9 %**
$\overline{\nu}_\mu$ CC/ ν_μ CC	**2.1 %**
ν_τ prompt	**negligible**

CNGS operation: 2008 => 2012

total intensity delivered:

1.8 x10^{20} p.o.t.

LNGS: Gran Sasso National Laboratory (Italy, 120 km from Rome)

Underground laboratory:

good cosmic ray shielding

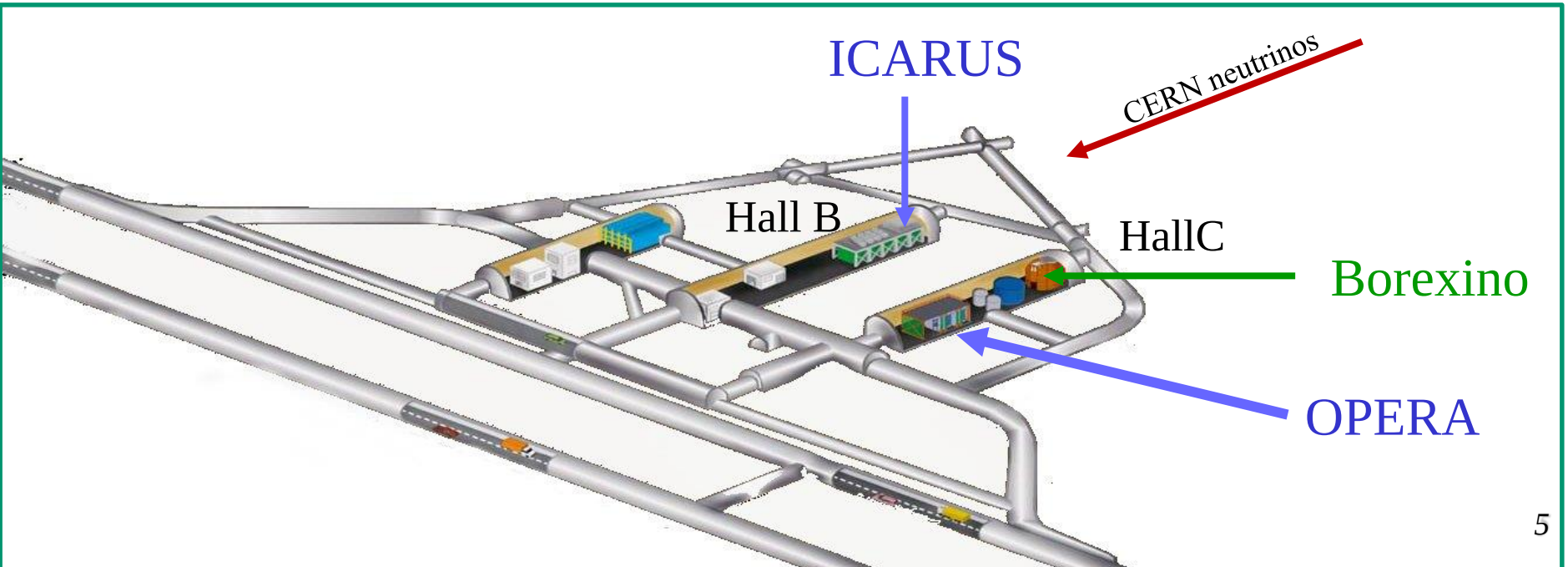
1 cosmic $\mu/m^2/hr$

3 large experimental halls

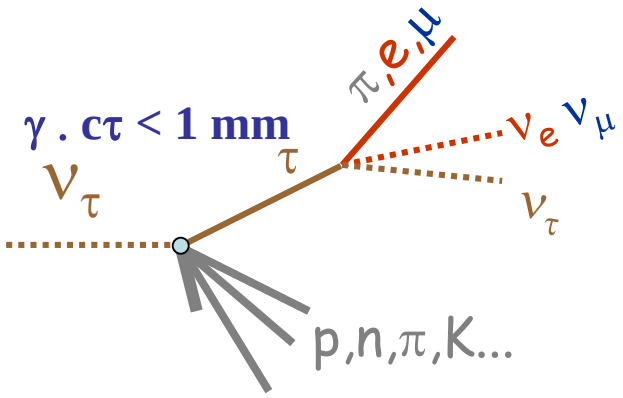
(100 m x 20 m x 18 m)

directed towards CERN

3800 mwe



Experimental signature for ν_τ appearance:



τ decay modes:

	BR
$\mu^- \nu_\tau \bar{\nu}_\mu$	17.4 %
$h^- \nu_\tau n\pi^o$	49.5 %
$e^- \nu_\tau \bar{\nu}_e$	17.8 %
$h^+ h^- h^- \nu_\tau n\pi^o$	15.2 %

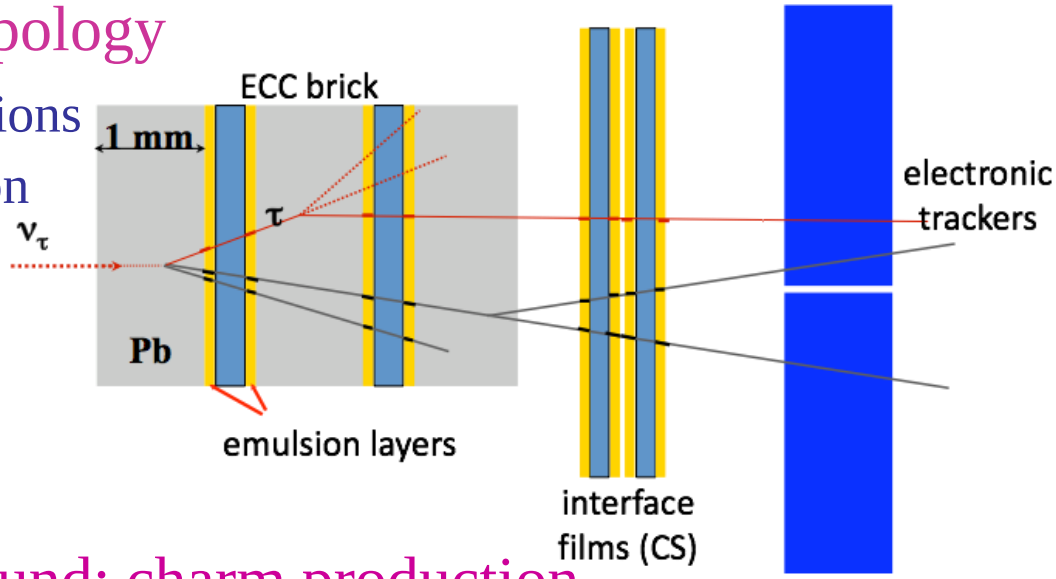
→ detect and identify the ν_τ charged current (CC) events

OPERA principle: hybrid detector with modular structure

direct observation of τ decay topology

→ μm resolution: photographic emulsions

→ large target mass: alternate emulsion films and lead sheets



reject main topological background: charm production

→ good muon id and charge reconstruction: use electronic detectors also for trigger and event localisation

1.25 kton detector at Gran Sasso (Hall C)

2 identical
Super Modules (SM)

Veto plane
(glass RPC)

Target and Target Tracker (6.7*m*)^2

- **Target : 74500 bricks, 26 walls**
- **Target tracker : 31 XY doublets of 256 scintillator strips + WLS fibres + multi-anodes PMT**

Δp/p (<25 GeV/c)	~20%
μ ID (with TT)	~95%

JINST 4(2009) p04018

High precision tracker
- **6 4-fold layers of drift tubes**

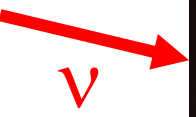
Instrumented dipole magnet
- **1.53 *T***
- **22 XY planes of RPC**

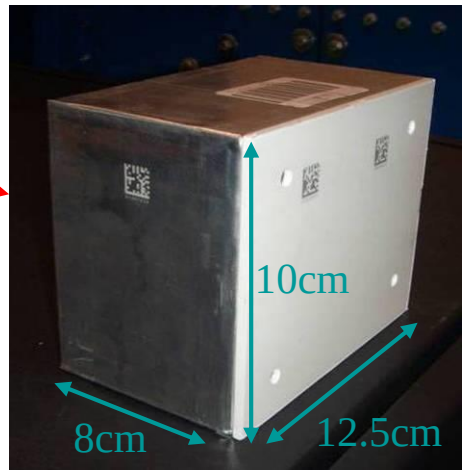
Muon spectrometer (8×9 *m*^{2})

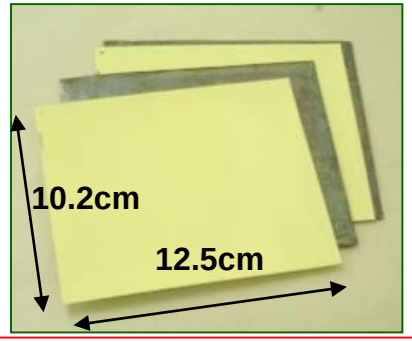
OPERA target: Modular detector: basic unit brick

56 Pb plates (1mm) + 57 FUJI emulsion films +1 changeable sheet doublet (CS)

8.3 kg
$10X_0$

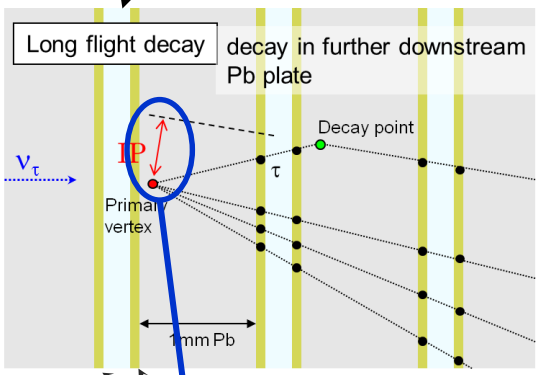






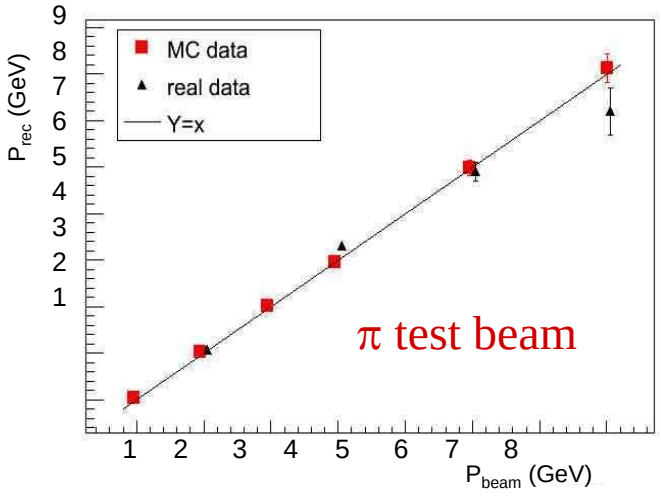
Track segment resolution:
σ(angle) = 2.1 mrad
σ (position) = 0.21 μm

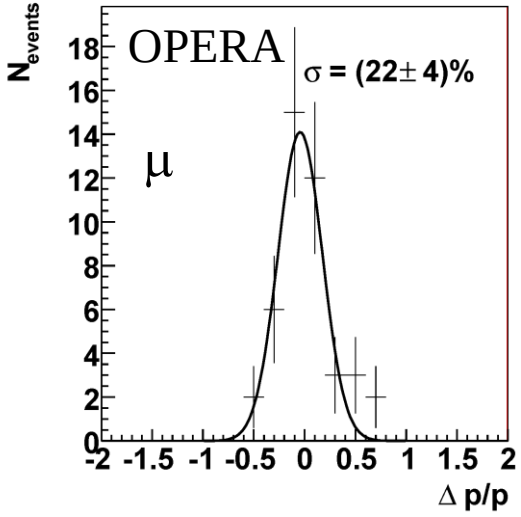
plastic base 200 μm thick

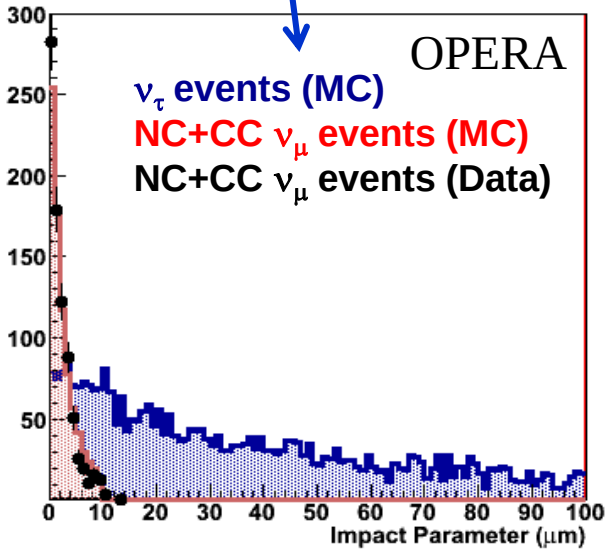


emulsion layers (44 μm thick)

Measurement of particle **momentum** by Multiple Coulomb Scattering in lead NJP 14 (2012) 013026

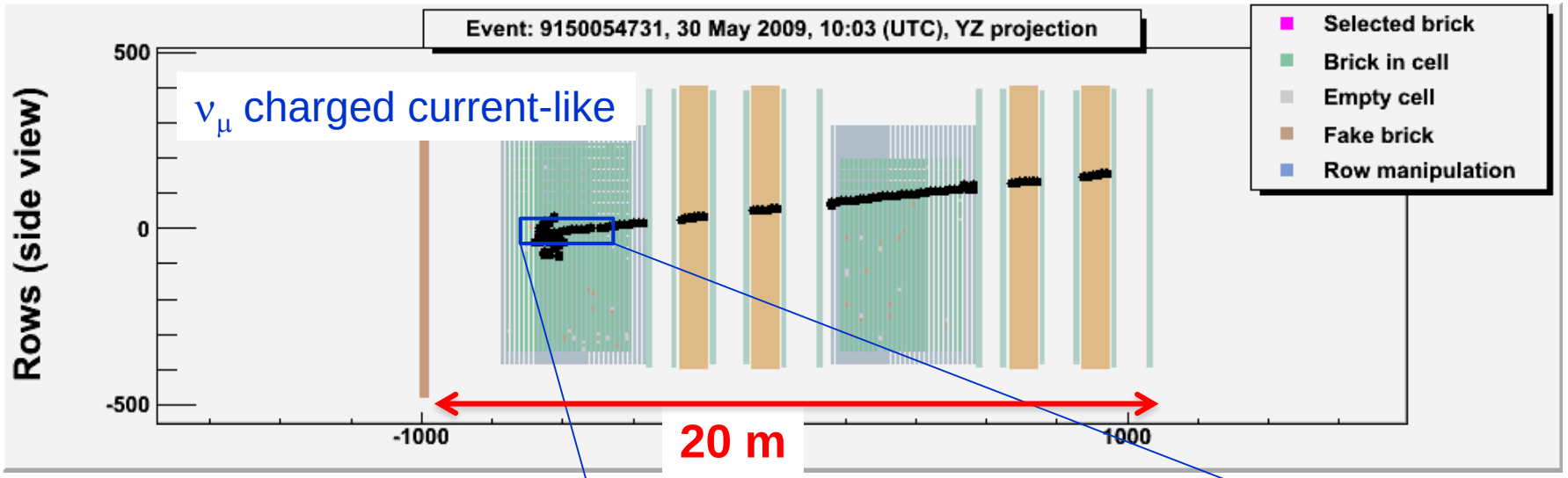






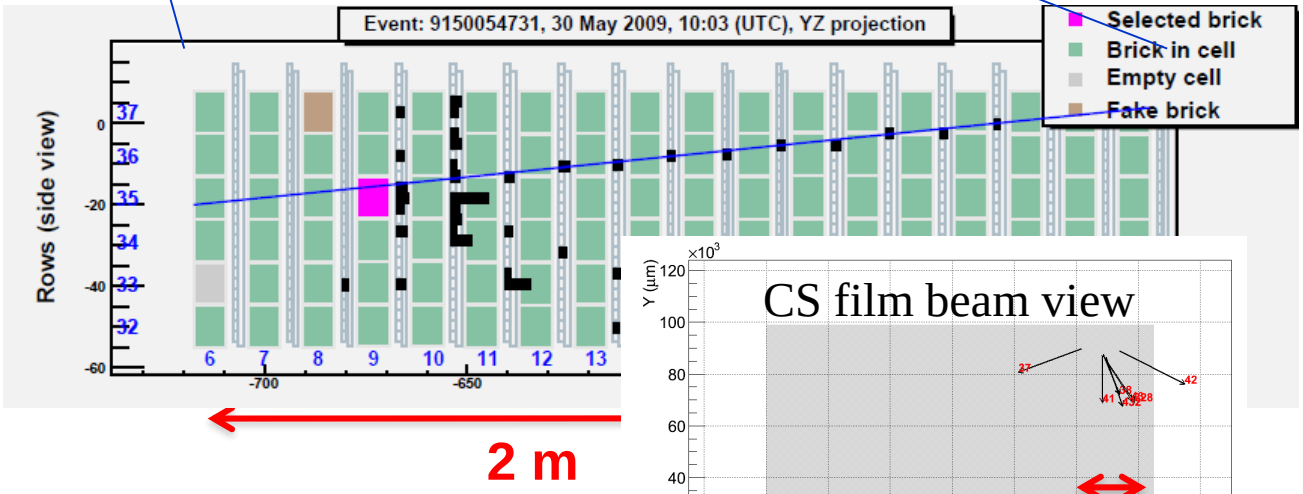
Vertex position resolution :
~1μm in transverse plane

OPERA event analysis



ν_μ charged current-like

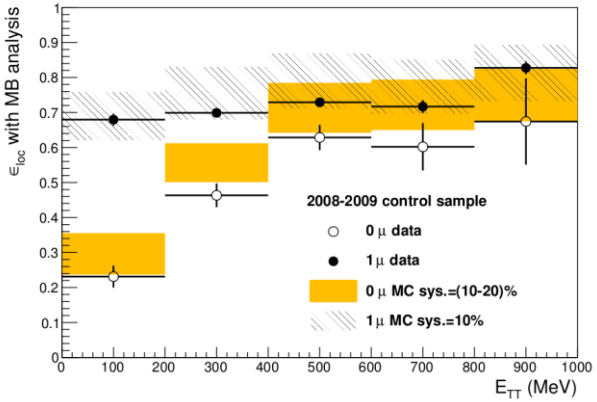
- Beam on time event
  DAQ: trigger, selection
- Electronic detector
  reconstruction



- Brick Finding

- CS scanning and brick validation
- Send brick to development
- Emulsion scanning

Interaction location and vertex reconstruction

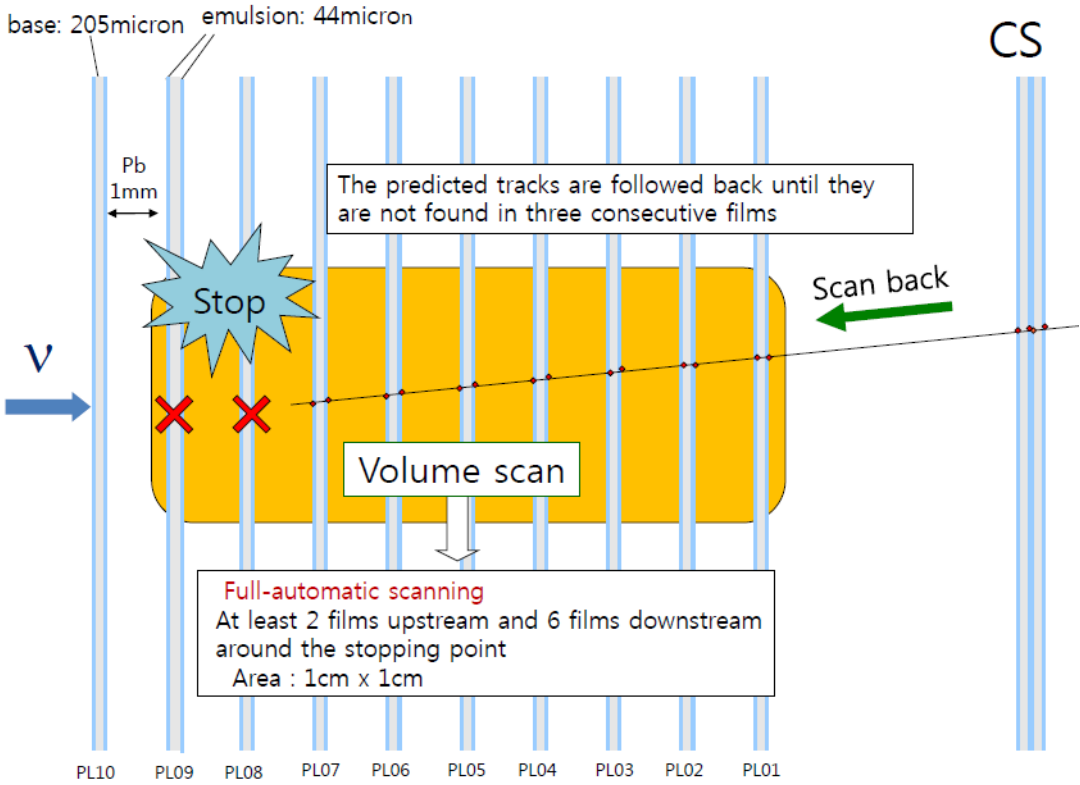


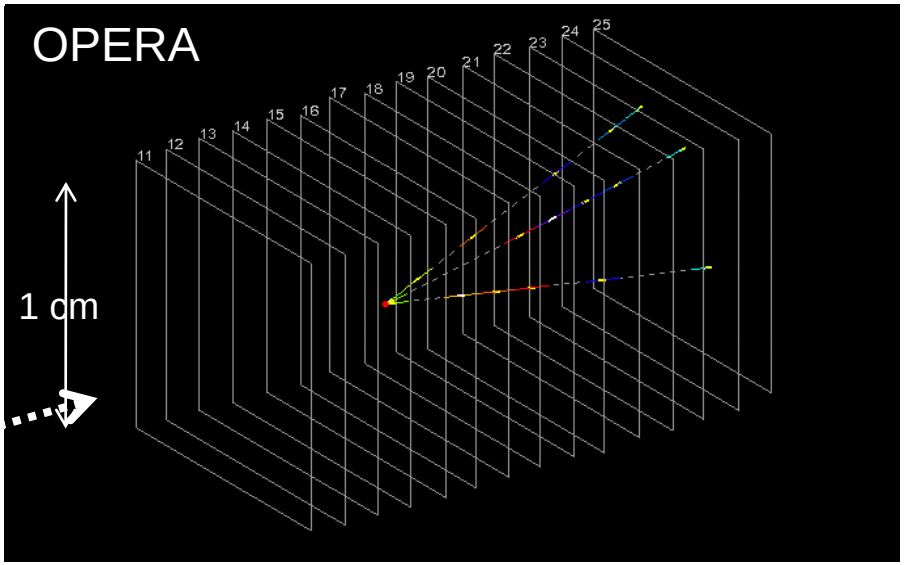
Vertex location efficiency:

74% CC

48% NC

JHEP 11 (2013) 036





Scan about 10 films around vertex:
Track reconstruction in several films

Reject passing-through and short tracks

Search tracks pointing to an interaction vertex
→ Decay Search procedure

Data sample

total intensity collected: 17.97×10^{19} p.o.t.

Year	Protons on target	SPS Eff.	Beam days	ν interactions
2008	1.74×10^{19}	61%	123	1931
2009	3.53×10^{19}	73%	155	4005
2010	4.09×10^{19}	80%	187	4515
2011	4.75×10^{19}	79%	243	5131
2012	3.86×10^{19}	82%	257	3923

20% less than the experiment proposal value (22.5×10^{19} p.o.t.)

$\varepsilon_{trigger} = 99\%$

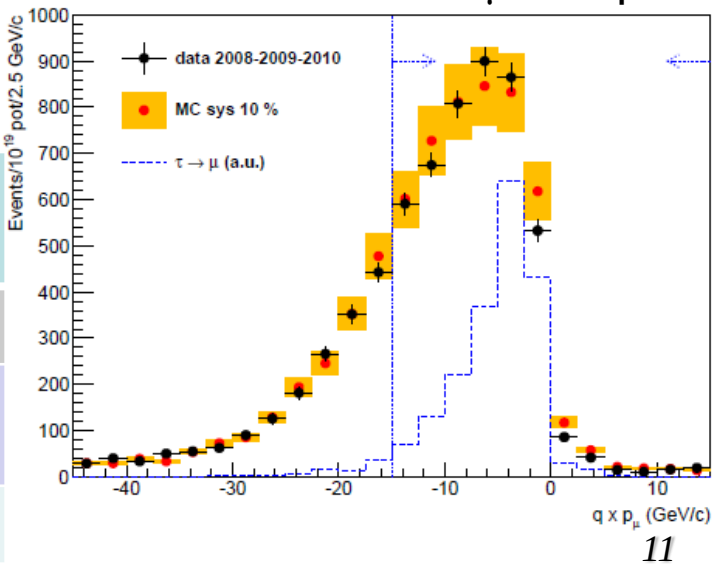
- 106 422 on time events recorded
- 60% are external rock events
- 20% are spectrometer interactions

19505 recorded ν interactions in the OPERA target

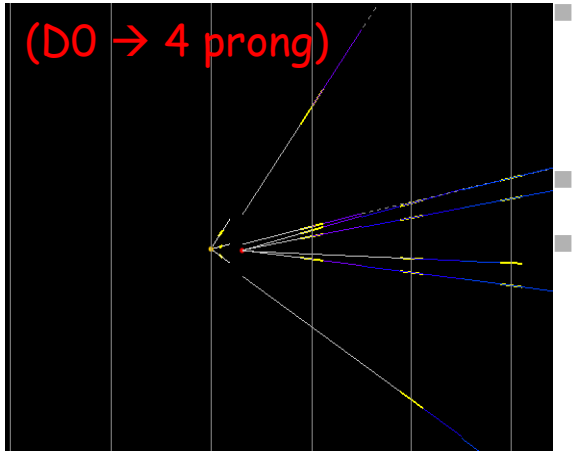
83% are reconstructed in the target

Event classification	Performed analysis	# of Decay Searched events
0μ	$1^{st}+2^{nd}$ brick	1144
1μ (P_μ < 15 GeV)	$1^{st}+2^{nd}$ brick	4264
All		5408

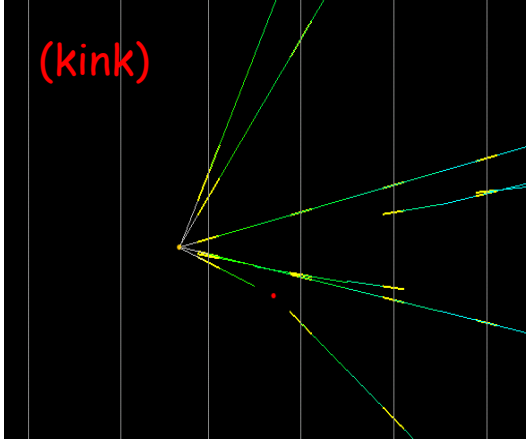
P distribution for 1 μ sample



Charmed hadron production



- Charm topology similar to τ (decay modes and lifetime) but μ at interaction vertex
- Control sample for decay search and ε
- Background, mostly from hadronic interactions

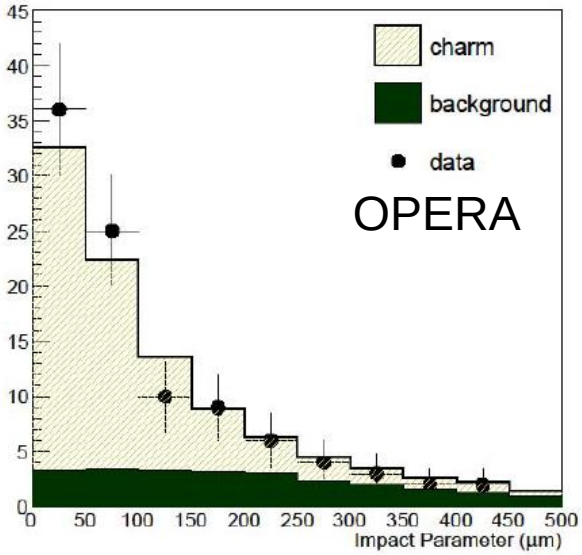


2008-2010 data analysis

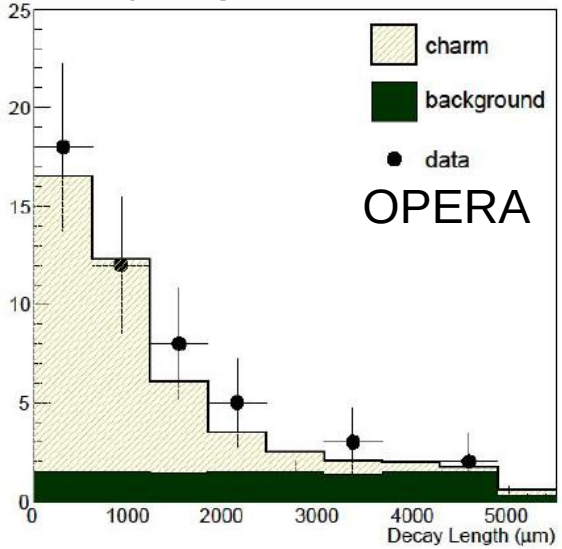
Eur.Phys.J. C74 (2014) 2986

Topology	Observed events	Expected events		
		Charm	Background	Total
Charged 1-prong	**19**	21 ± 2	9 ± 3	**30 ± 4**
Neutral 2-prong	**22**	14 ± 1	4 ± 1	**18 ± 2**
Charged 3-prong	**5**	4 ± 1	1.0 ± 0.3	**5± 1**
Neutral 4-prong	**4**	0.9 ± 0.2	<0.1	**0.9 ± 0.2**
Total	**50**	40±3	14±3	**54±4**

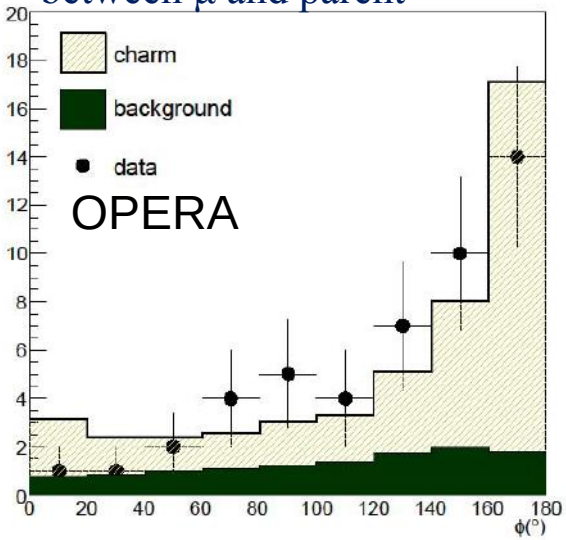
Impact parameter



Decay length



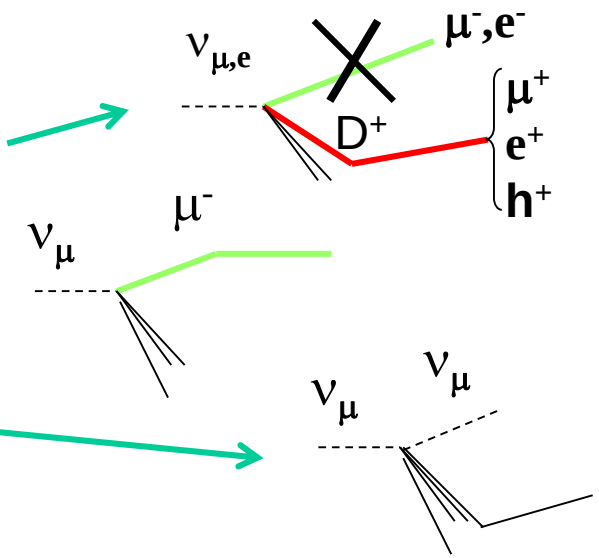
Angle in the transverse plane between μ and parent



$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis:

Background

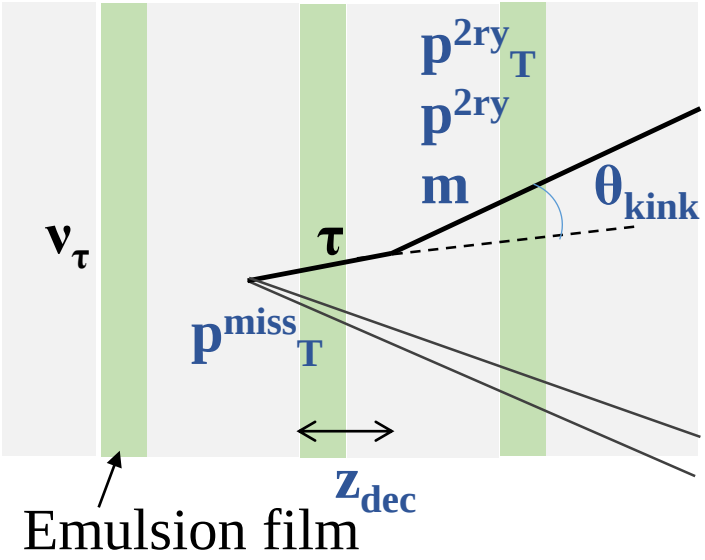
- ν_μ CC charm production (4% of CC), with μ mis-id'd (similar lifetime, missing E_T decays)
- Large-angle coulomb scattering of μ
- nuclear interactions of hadrons (0.2% of NC)

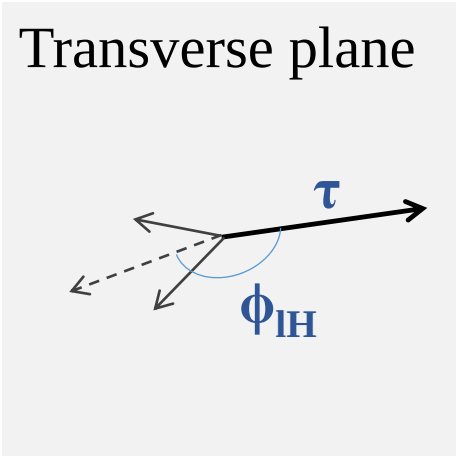


Kinematical analysis

variables to reduce background:

- Flight length
- Total p_T of τ daughters wrt τ direction
- Missing p_T at primary vertex
- Φ = angle of τ wrt hadronic shower in transverse plane to beam



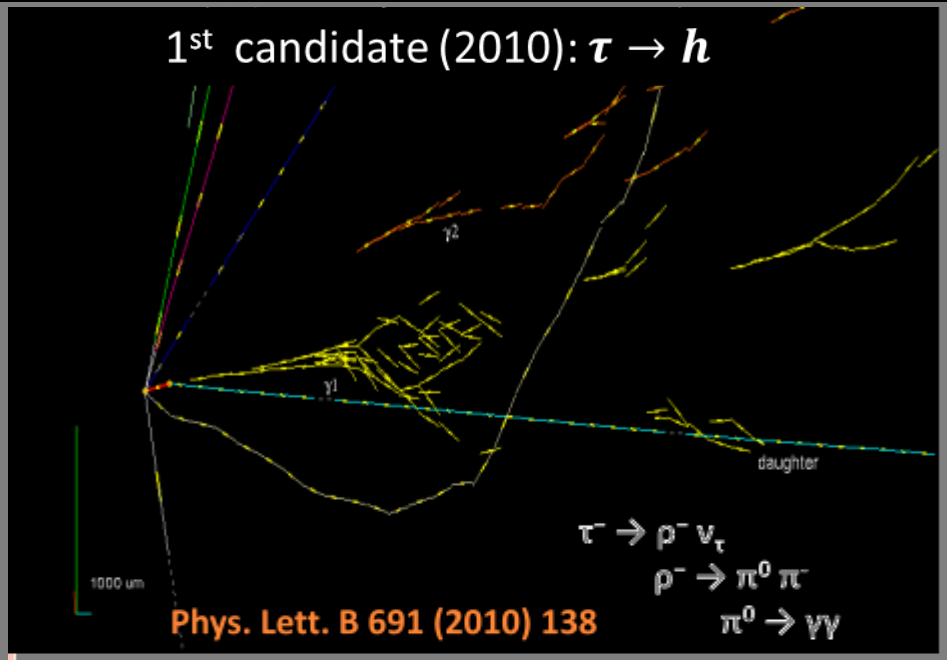


$p^{miss}{}_T$: vectorial sum of the transverse momenta of primaries (except the parent) and daughters wrt beam direction

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

ν_τ events observed in OPERA

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



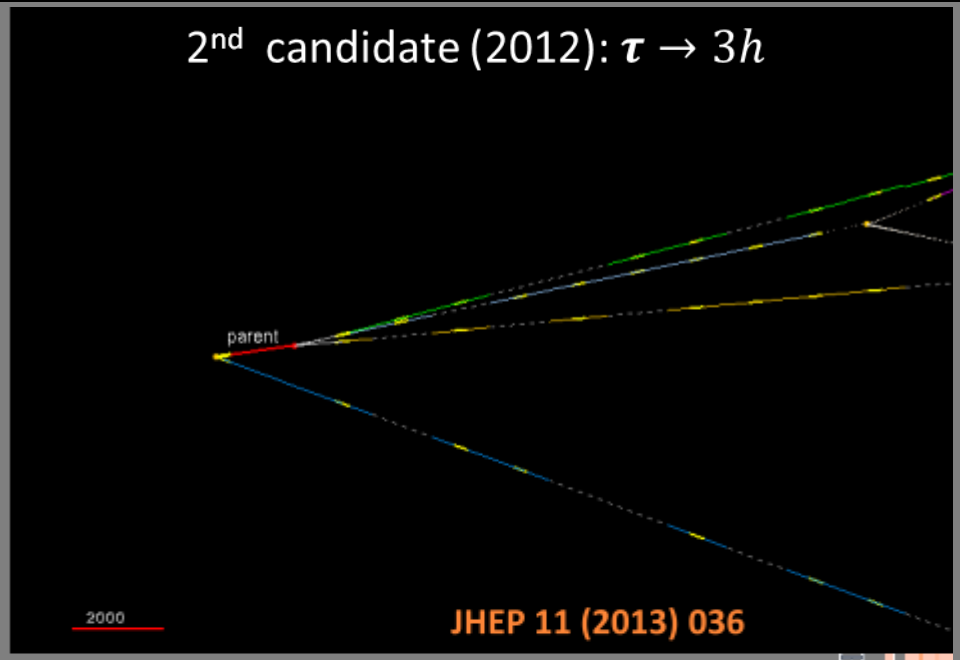
$\tau^- \rightarrow \rho^- \nu_\tau$

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

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

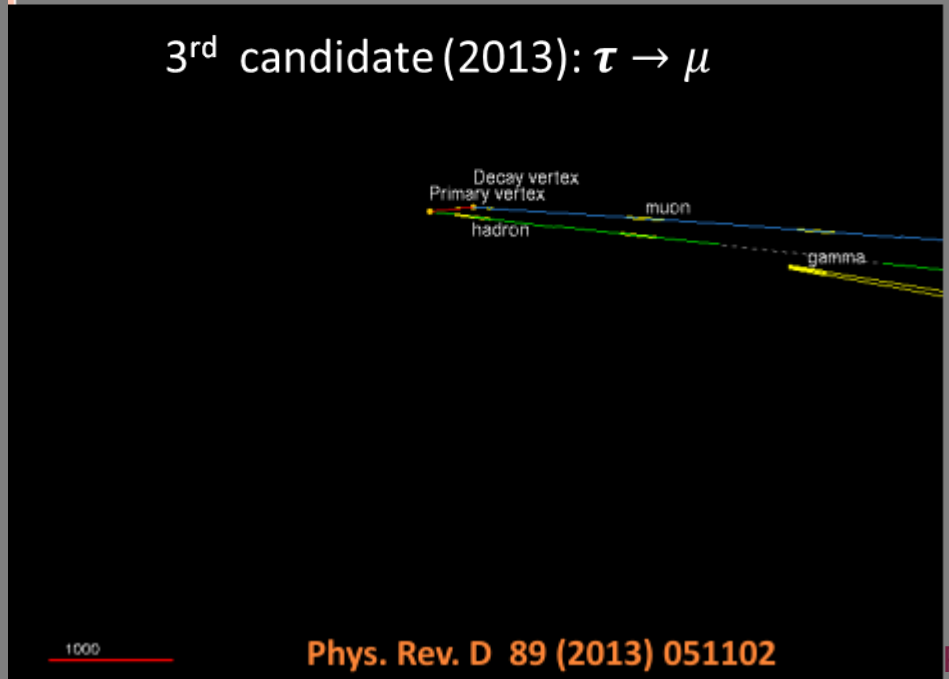
Phys. Lett. B 691 (2010) 138

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



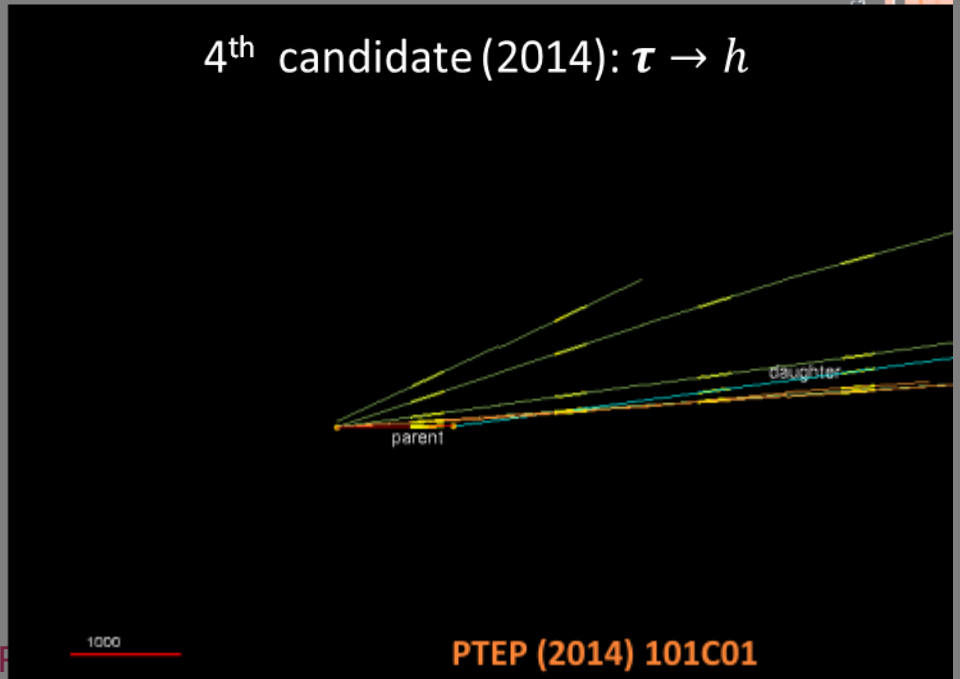
JHEP 11 (2013) 036

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



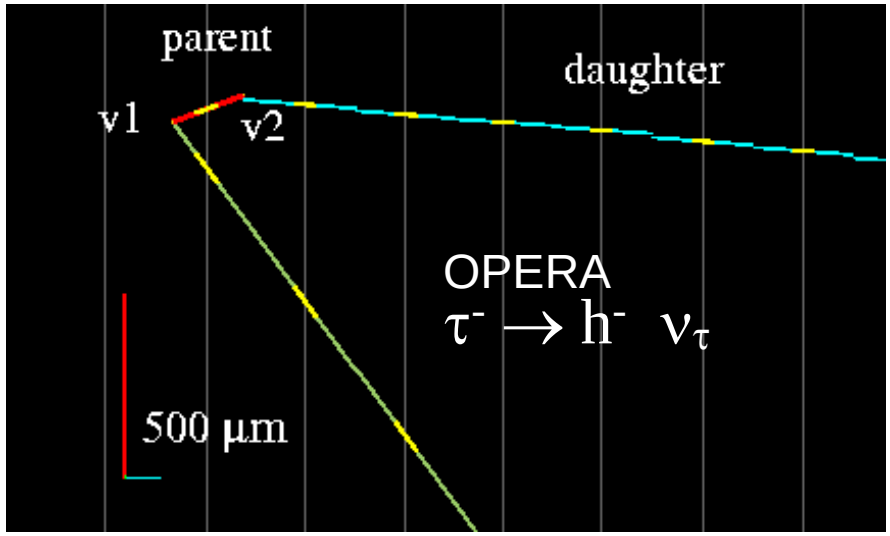
Phys. Rev. D 89 (2013) 051102

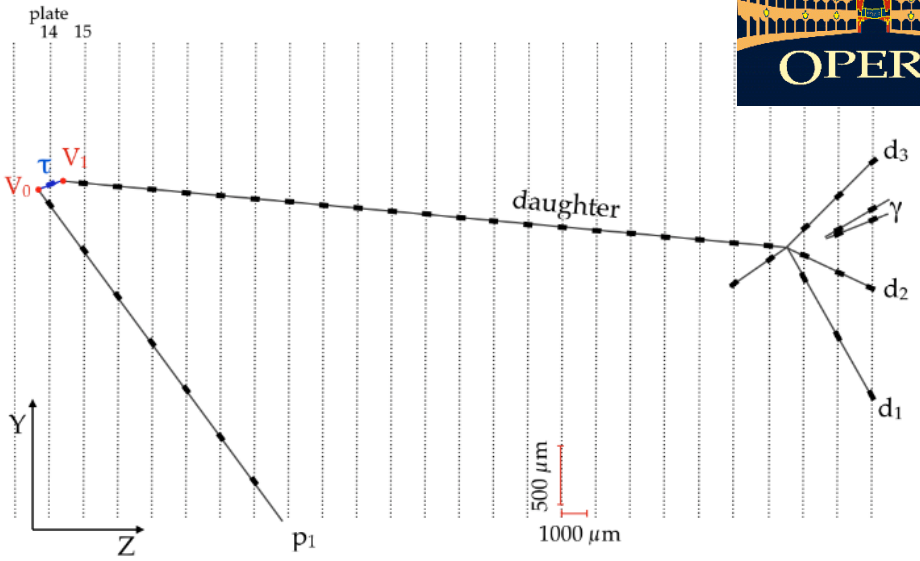
4th candidate (2014): $\tau \rightarrow h$

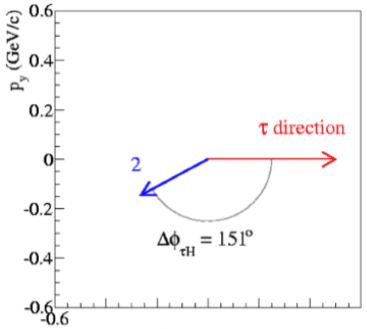


PTEP (2014) 101C01

Fifth ν_τ candidate => discovery of ν_τ appearance

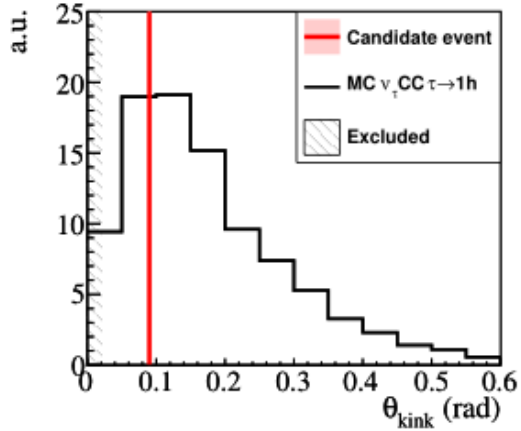


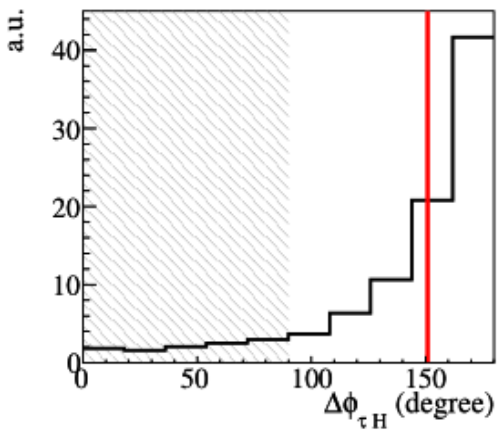




Phys. Rev. Lett. 115 (2015) 121802

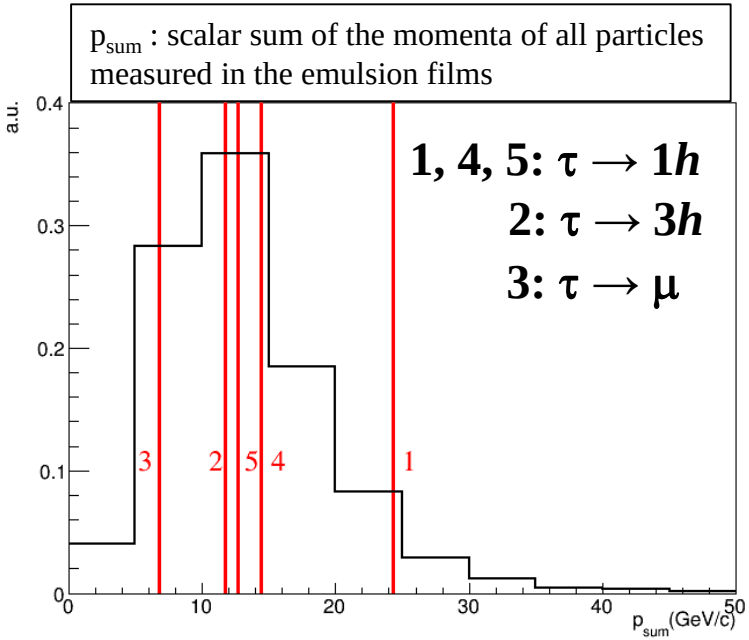
VARIABLE	VALUE
Kink angle (mrad)	**90 ± 2**
decay length (μm)	**634 ± 30**
P^{2ry} (GeV/c)	**11^{+14}_{-4}**
$P^{miss}t$ (GeV/c)	**0.3±0.1**
ϕ (degrees)	**151 ± 1**





$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis results:

Decay channel	Expected background				expected signal events $\Delta m^2 = 2.44 \times 10^{-3}$ eV^2	Observed events
	Charm	*Had. Re-interaction*	*Large μ scattering*	*Total*		
$\tau \rightarrow 1h$	0.017±0.003	0.022±0.006	-	0.04±0.01	0.52±0.10	3
$\tau \rightarrow 3h$	0.17±0.03	0.003±0.001	-	0.17±0.03	0.73±0.14	1
$\tau \rightarrow \mu$	0.004±0.001	-	0.0002±0.0001	0.004±0.001	0.61±0.12	1
$\tau \rightarrow e$	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



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

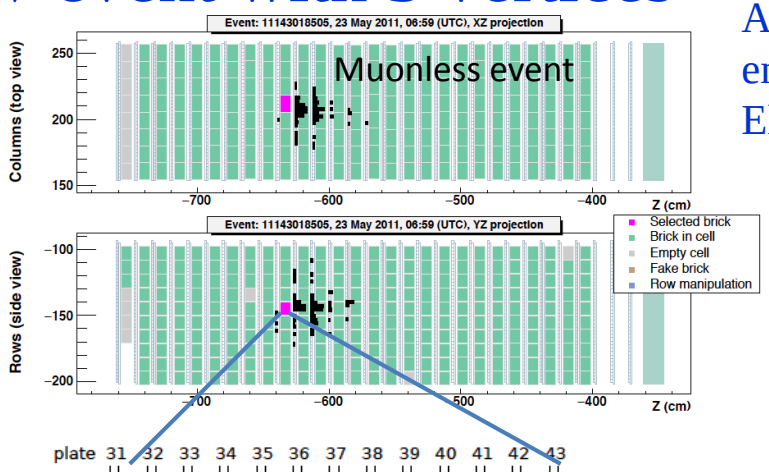
No oscillation hypothesis excluded at 5.1 σ

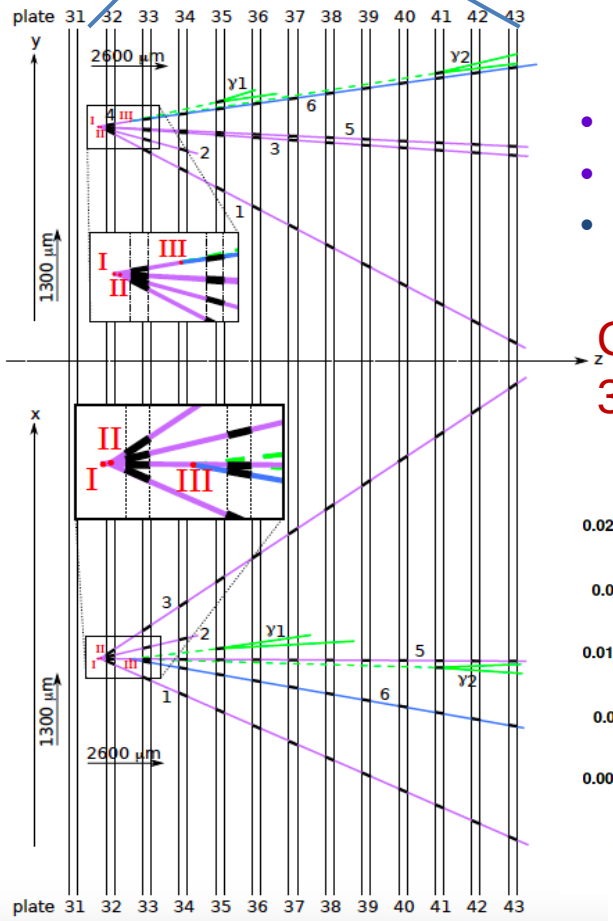
$\Delta m_{23}^2 = 3.3 \times 10^{-3}$ eV^2 with a 90% confidence interval [2.0, 5.0] x 10^{-3} eV^2 (assuming full mixing)

Probability of observing ≥5 candidates (2.9 S+B events expected): 17%

Frequency of configurations being less probable than the observed one: 6.4%

ν event with 3 vertices





A primary and two secondary vertices found in emulsion,
Electromagnetic activity (γ's) at the kink point.

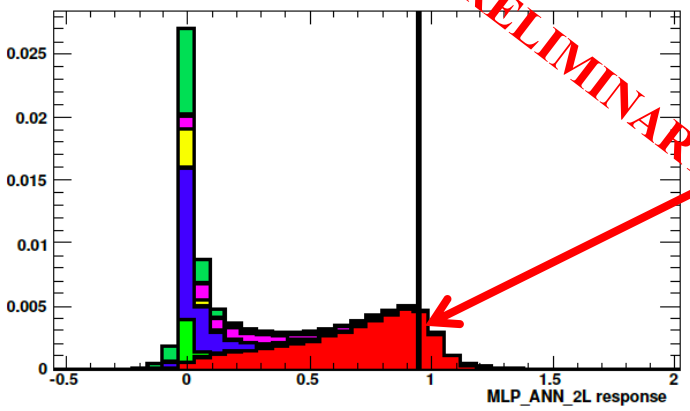
Vertex ID	Attached tracks	x (μm)	y (μm)	z (μm)
I (primary)	2, 4, 5	15077.0	59157.9	-33081.8
II (secondary)	1, 3	15085.9	59149.9	-32979.2
III (kink)	4, 6	15073.9	59262.4	-31926.4

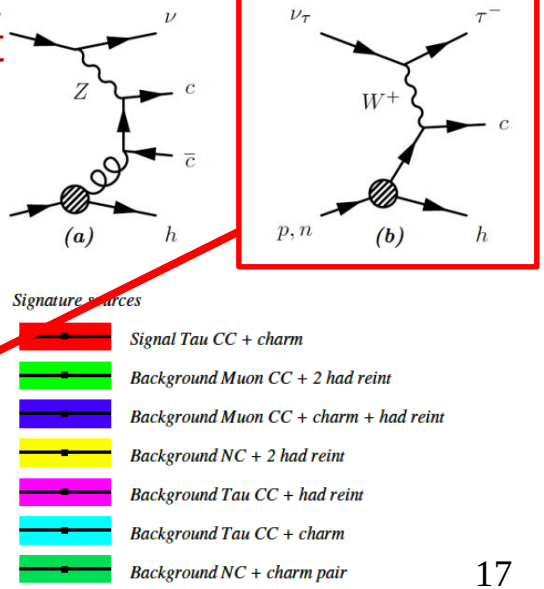
Flight lengths:
II: 103 μm
III: 1160 μm

Track ID	p best fit (GeV/c)	68 % p range (GeV/c)
1	2.1	[1.6 ; 3.1]
3	4.3	[3.1 ; 7.1]
5	0.54	[0.45 ; 0.68]
6 (daughter)	2.7	[2.1 ; 3.7]

- Invariant massses at both secondary vertices are larger than 1 GeV.
- Event not classified as ν_τ interaction candidate by standard analysis.
- Ad hoc simulations and multivariate analysis performed to distinguish between possible interpretations.

Compatible with a τ –charm event
3.5σ wrt background only

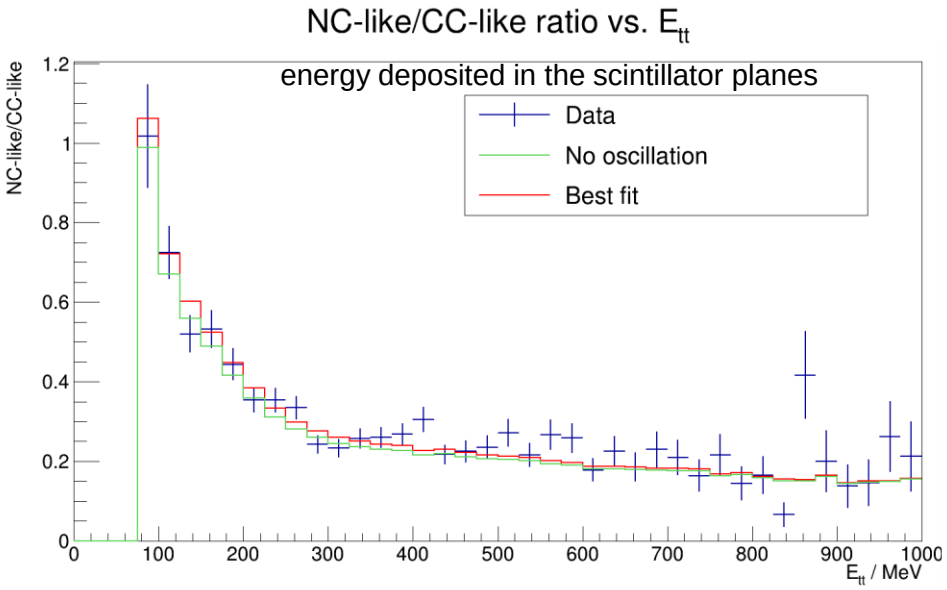


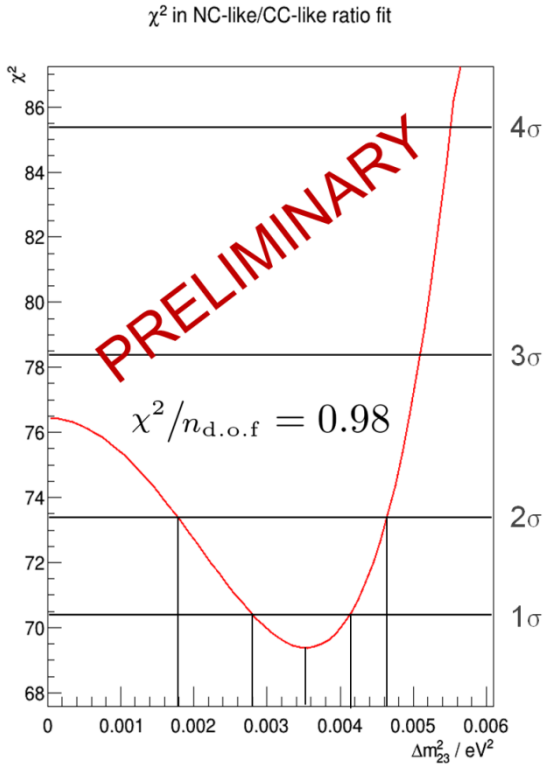


ν_μ disappearance

- Full data sample (2008-2012)
- Use of electronic detector data only and separation between CC and NC like events

a fit using NC-like/CC-like ratio in which all mixing parameters are fixed to the PDG values **but Δm_{23}^2**





reweighting MC according to oscillation probability and minimizing χ^2 between MC and data

To reduce systematic effects coming from the beam uncertainty (no near detector), NC like over CC like ratio is used

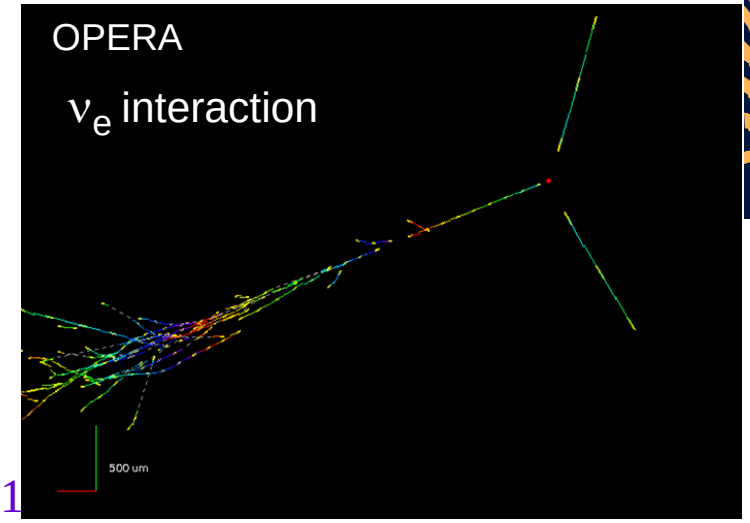
systematics under study

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

ν_e appearance search

2008-2012 sample (17.97 x 10^{19} p.o.t.)

→ Observed 34 ν_e events



Expected ν_e events :

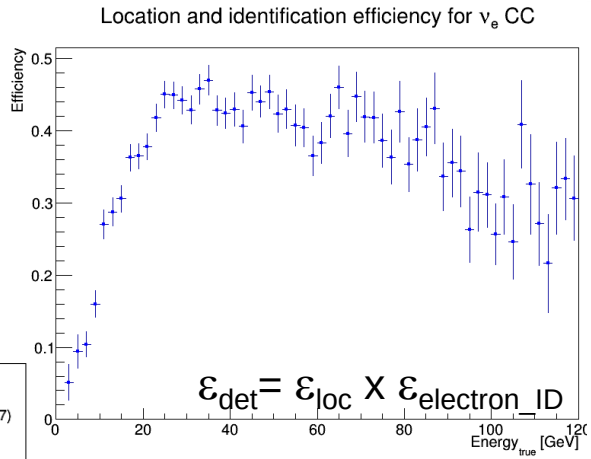
ν_e beam contamination 36.7 ± 5

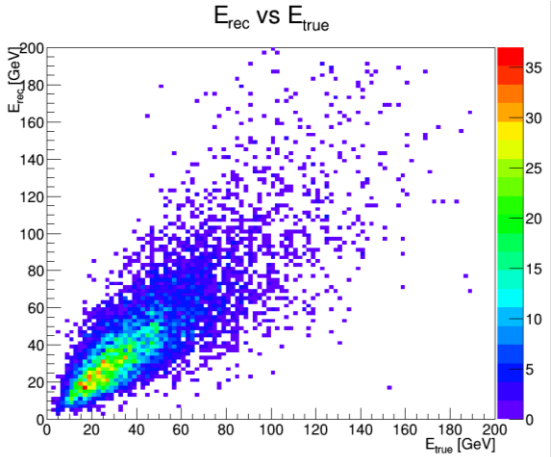
Background $\tau \rightarrow e$ + mis-id'd π^0 1.2 ± 0.1

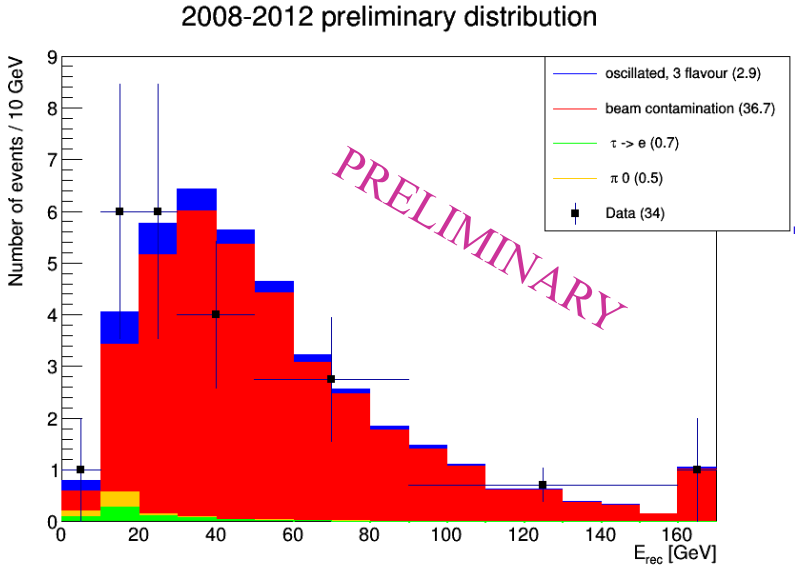
From 3-flavour oscillation:

$\nu_\mu \rightarrow \nu_e$ 2.9 ± 0.4 evts

($\sin^2(2\theta_{13}) = 0.098$)







Numbers are preliminary.

To increase signal-to-background ratio: E < 30 GeV

13 observed events for

9.2 ± 1 background expected + 1.4 ± 0.2 (from $\nu_\mu \rightarrow \nu_e$)

=> Work in progress to extract exclusion limits on sterile search

sterile neutrino search

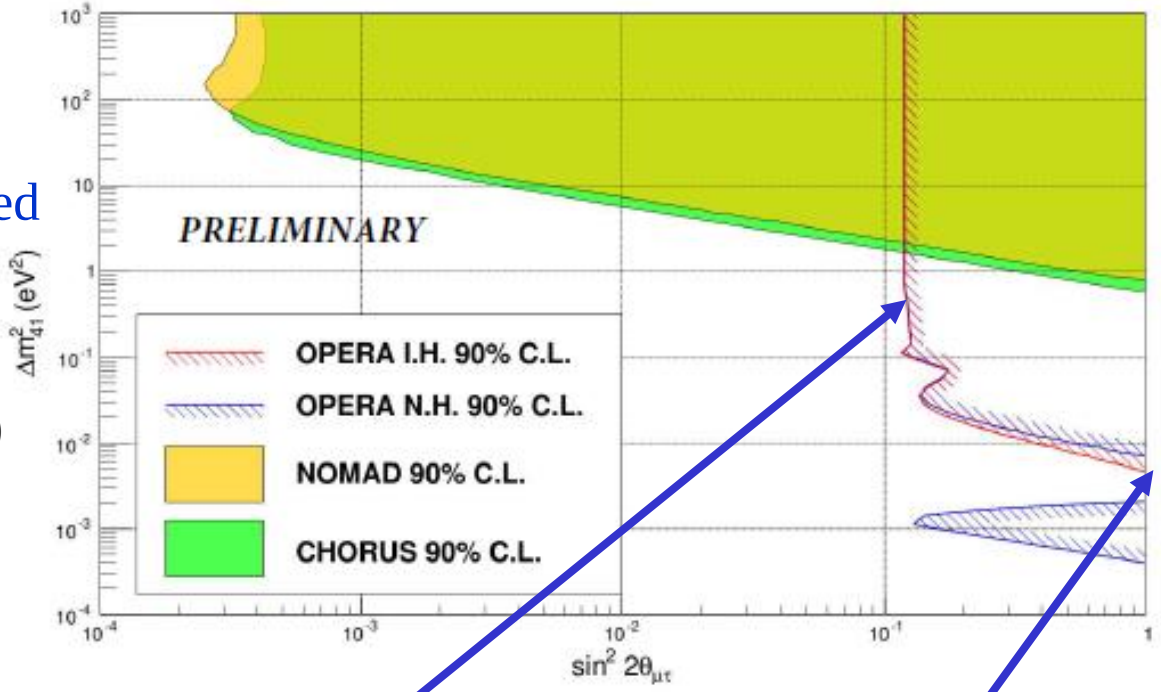
appearance probability modified by one possible extra (sterile) state (3+1 scheme)

$\nu_\mu \rightarrow \nu_e$

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

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

→ Observed 5 ν_τ events with 0.25 ± 0.05 background expected



Update of JHEP 1506 (2015) 069

Limits on
$\sin^2(2\theta_{\mu\tau}) = 4|U_{\mu 4}|^2 . |U_{\tau 4}|^2$

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

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

Summary and outlook

- OPERA has recorded events corresponding to 18.0 x 10^{19} p.o.t. delivered by the CNGS beam from 2008 to 2012 (80% of the nominal)
- Scanning ("second data-taking") and analysis mostly completed!

- $\nu_\mu \rightarrow \nu_\tau$ oscillation analysis: 5 candidates observed for 0.25 background expected
  => discovery with 5.1 σ significance (PRL 115 (2015) 121802)
  => $\Delta m_{23}^2 = 3.3 \times 10^{-3}$ eV^2 with a 90% confidence interval [2.0, 5.0] x 10^{-3} eV^2

- ν_μ disappearance analysis: => preliminary Δm_{32}^2 consistent with world average

- $\nu_\mu \rightarrow \nu_e$ oscillation search:
  Number of events observed in agreement with expected background + standard oscillation

- Sterile ν oscillation constraints from ν_e and ν_τ studies

- **Prospects:**
  - re-analysis of the data with looser selection and multivariate analysis: more signal and background but significant statistical gain
    => estimation of oscillation parameters and couplings with the tau appearance

  - Exploiting the unique feature of being able to identify all three neutrino flavours: ν_τ appearance + ν_e appearance + ν_μ disappearance data
    => Constraints on the oscillation parameters with one single experiment

The end

$\nu_\mu \rightarrow \nu_\tau$: preliminary results on sterile ν

3+1 model

standard

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

(normal hierarchy)

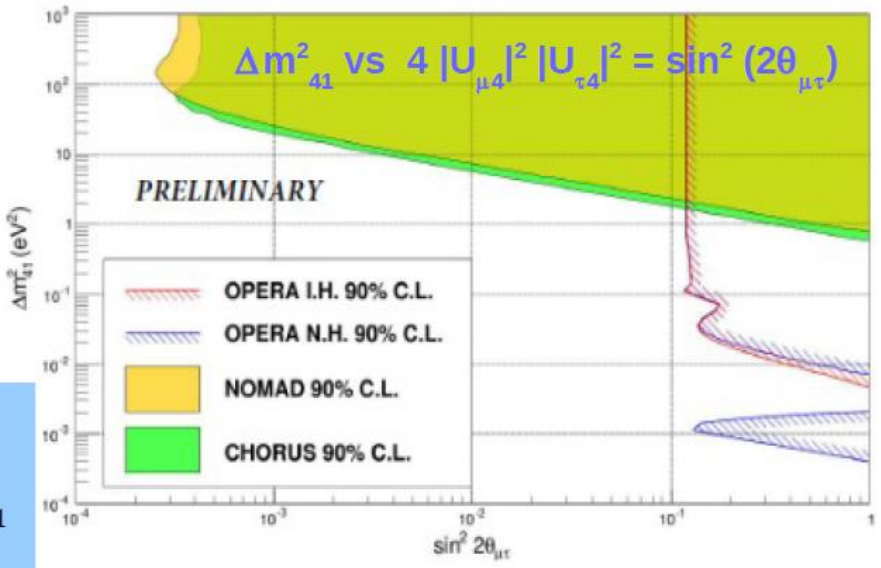
exotic

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

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

Interference term

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



- 90% CL exclusion limit 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

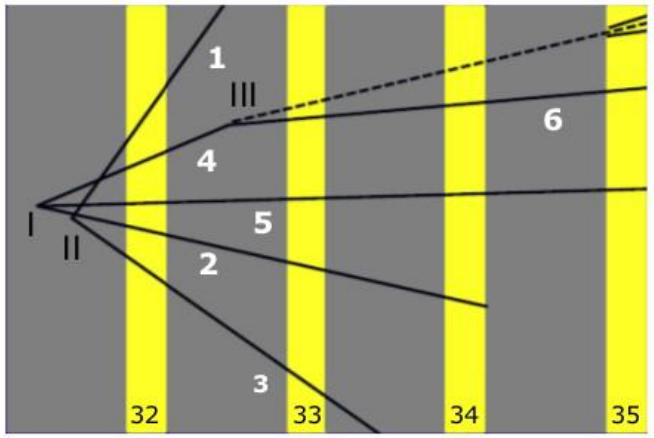
Update of JHEP 1506 (2015) 069

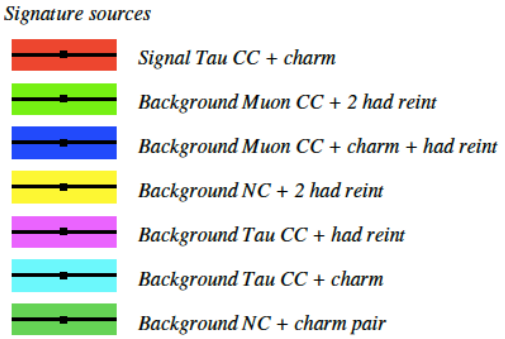
ν event with 3 vertices

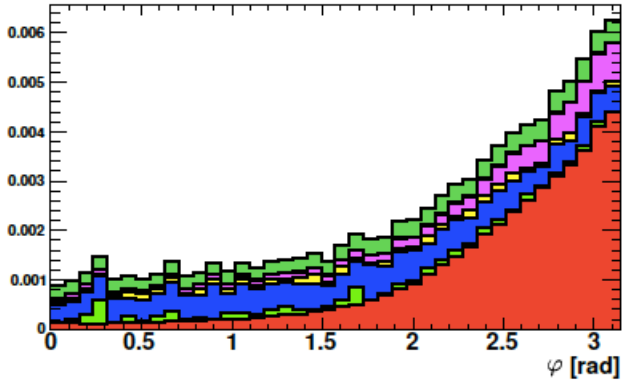
Sample	Expected events (10^{-3})
ν_τ CC + charm	45
ν_μ CC + charm + $h_{\rm int}$	21
ν_μ NC + $c\bar{c}$	13
ν_τ CC + $h_{\rm int}$	9
ν_μ CC + $2h_{\rm int}$	4
ν_μ NC + $2h_{\rm int}$	4
Total	100

Rates after topological selection (a first short decay in two prongs and the a long decay in one prong)

variable	value
1pr-like daughter momentum	2.7 GeV/c
1pr-like daughter transverse momentum	0.242 GeV/c
Kink angle	90 mrad
1pr-like flight length	1.16 mm
2pr-like daughters momentum	6.17 GeV/c
2pr-like daughters transverse momentum	0.542 GeV/c
2pr-like invariant mass	1.86 GeV/c^2
2pr-like flight length	103 μm
Total EM energy	12.5 GeV
φ angle	2.41 rad
Missing transverse momentum	0.944 GeV/c
Other hadronic momentum	0.850 GeV/c
ANN output	**0.946**

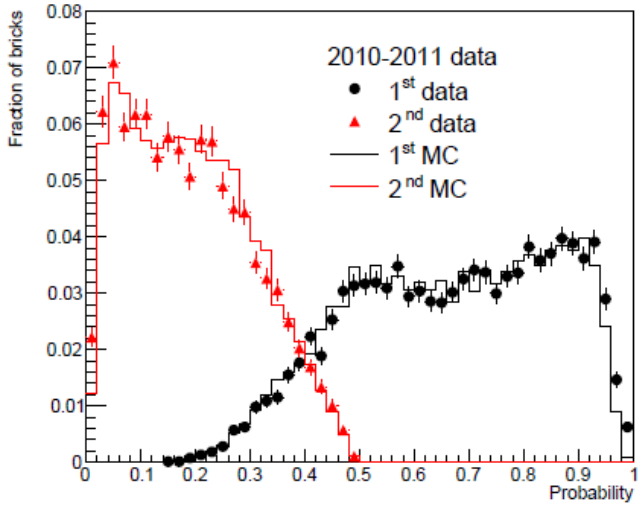




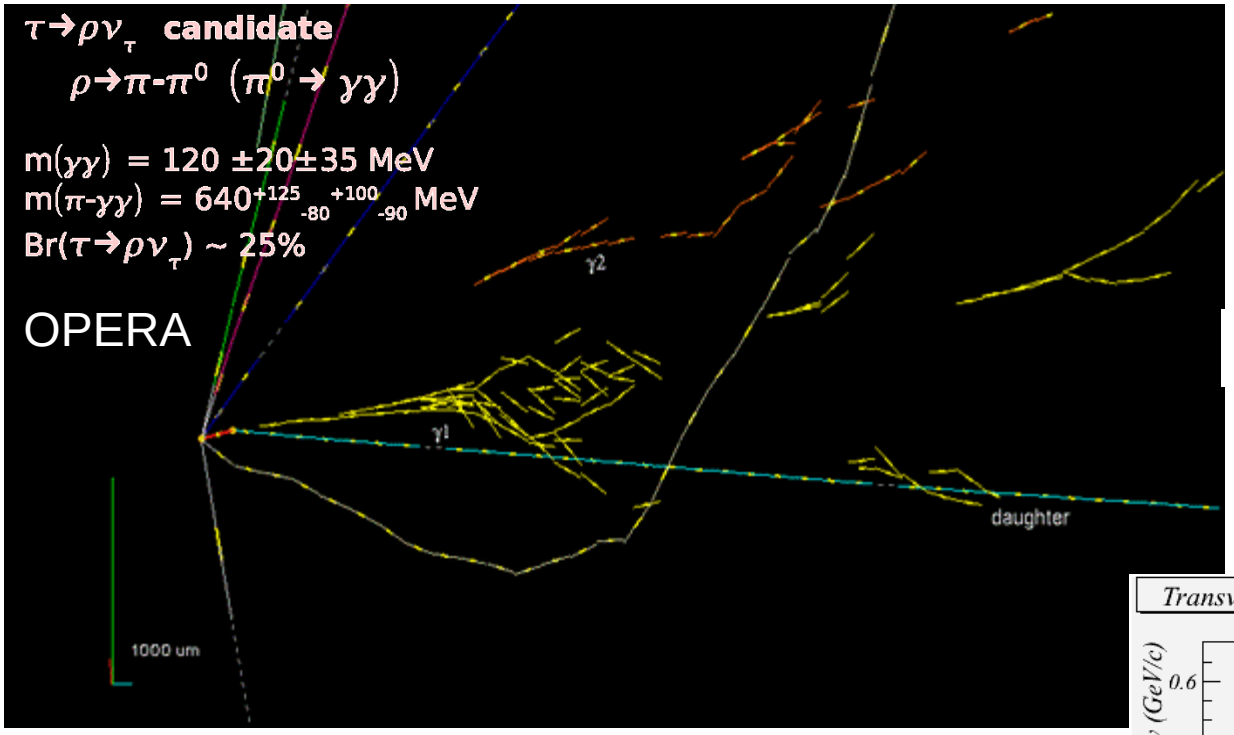


ν_τ analysis: kinematical selection

variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
lepton-tag	No μ or e at the primary vertex			
$z_{\rm dec}$ (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	/	/



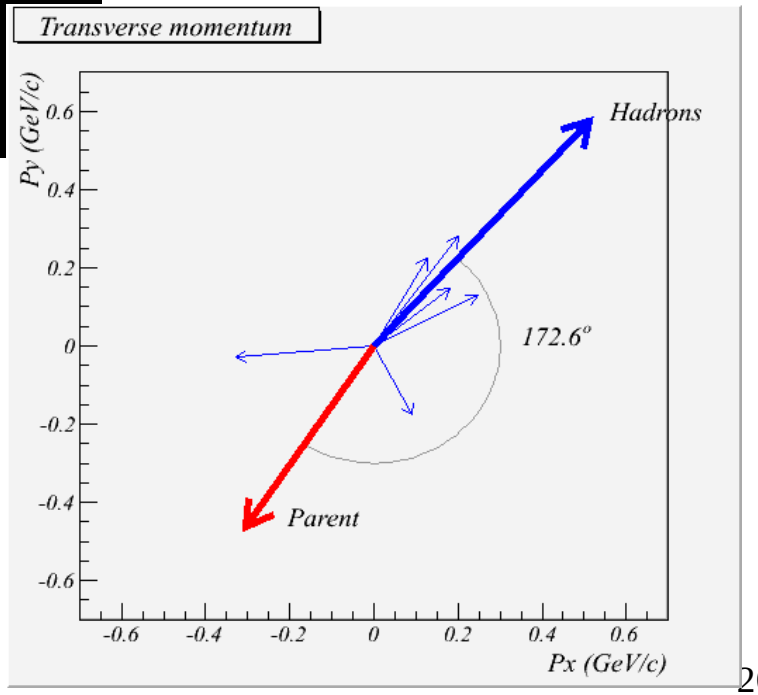
First ν_τ candidate (event 9234119599, taken on 22/08/2009)



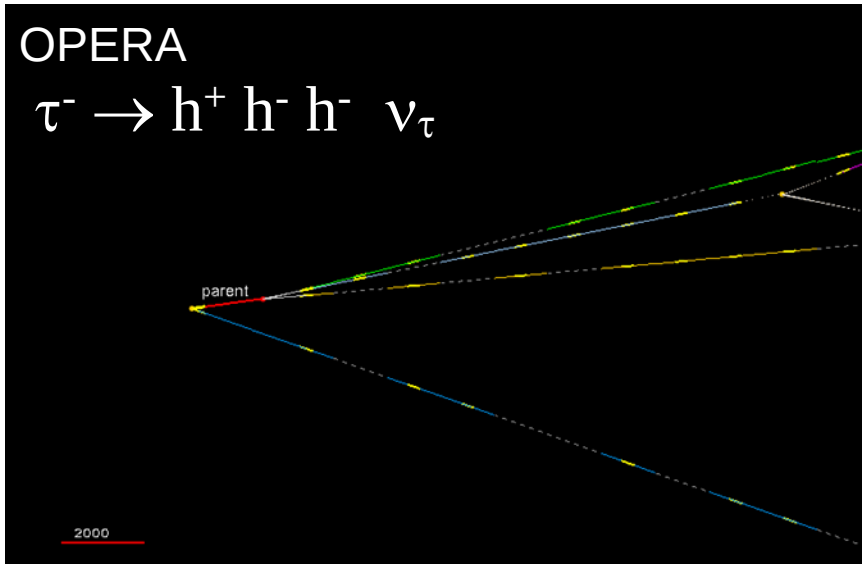
- In 2010 OPERA has published the first candidate based on the analysis of 35% of 2008/2009.

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 (event 11113019758, taken on 23/04/2011)



Interaction Vertex in lead plate
1 nuclear fragment

Primary Track

$\varphi = (167.8 \pm 1.1)^\circ$
Flight length 1.54 mm

d2

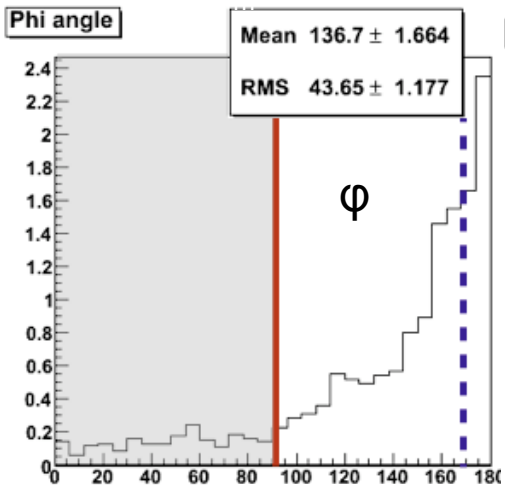
τ

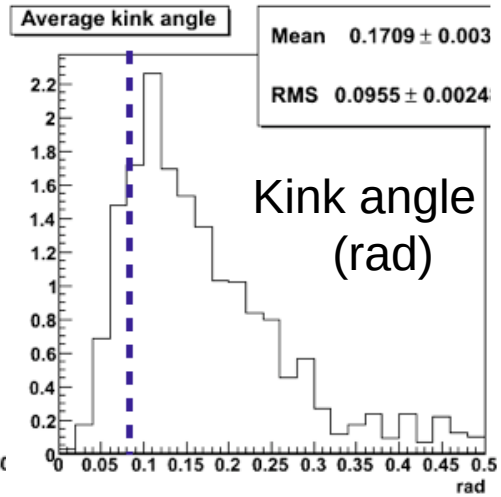
Decay point
In Plastic Base
No nuclear fragment

d3

d1

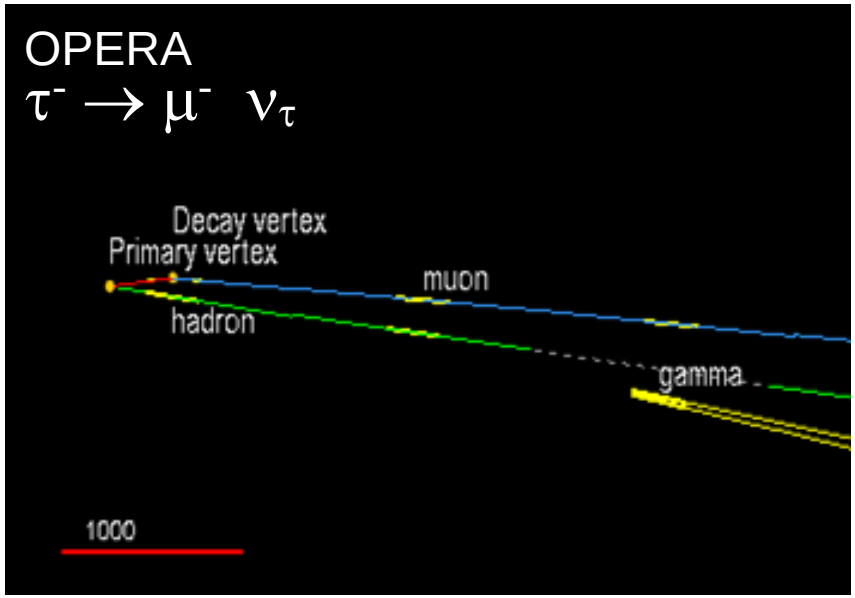
Secondary Interaction
In Emulsion
4 nuclear fragments

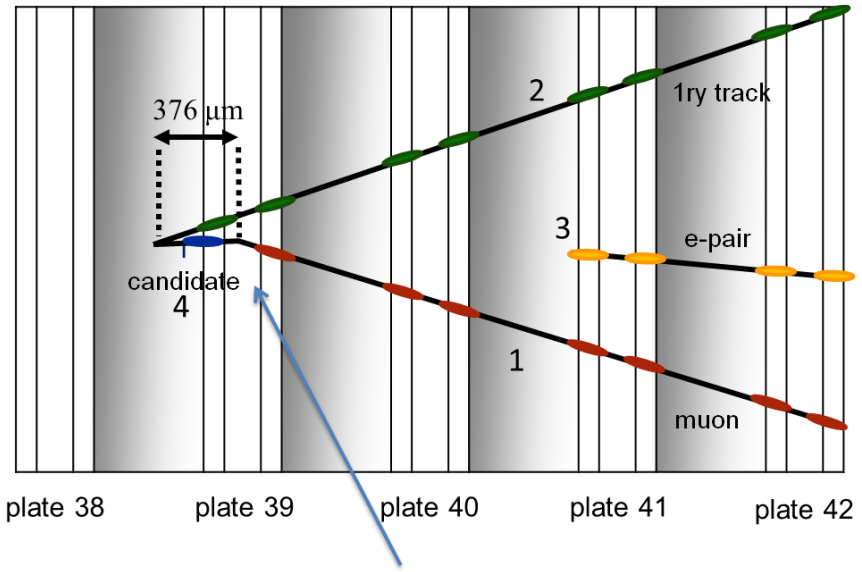




JHEP 11 (2013) 036

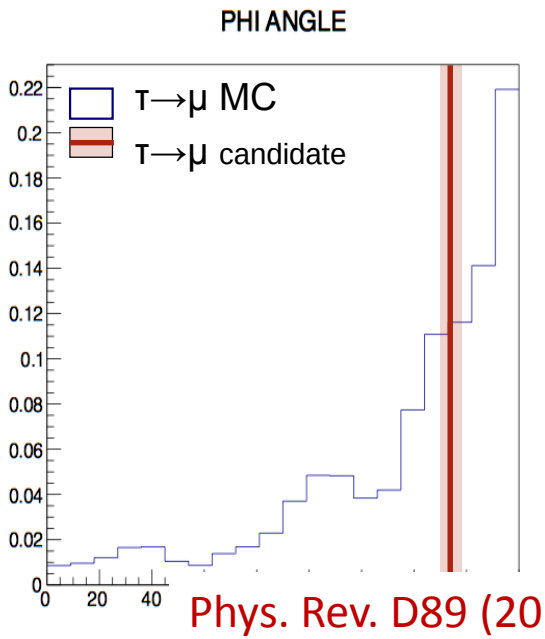
Third ν_τ candidate (event 12123032048, taken on 2/05/2012)

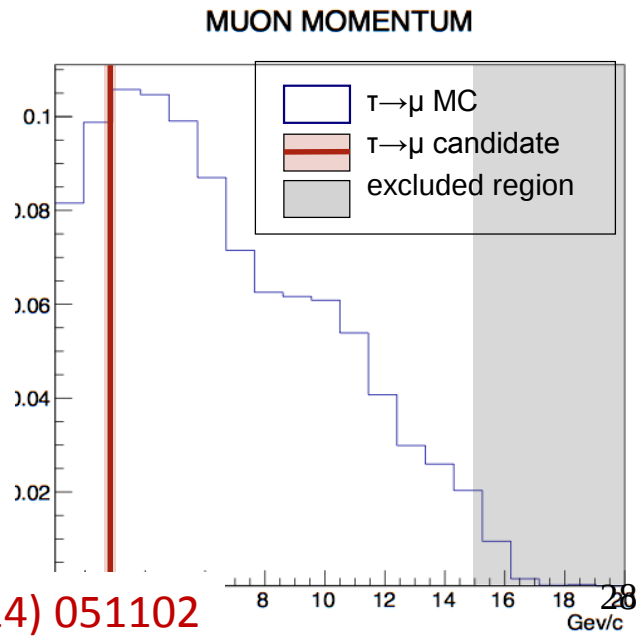




Decay in the plastic base

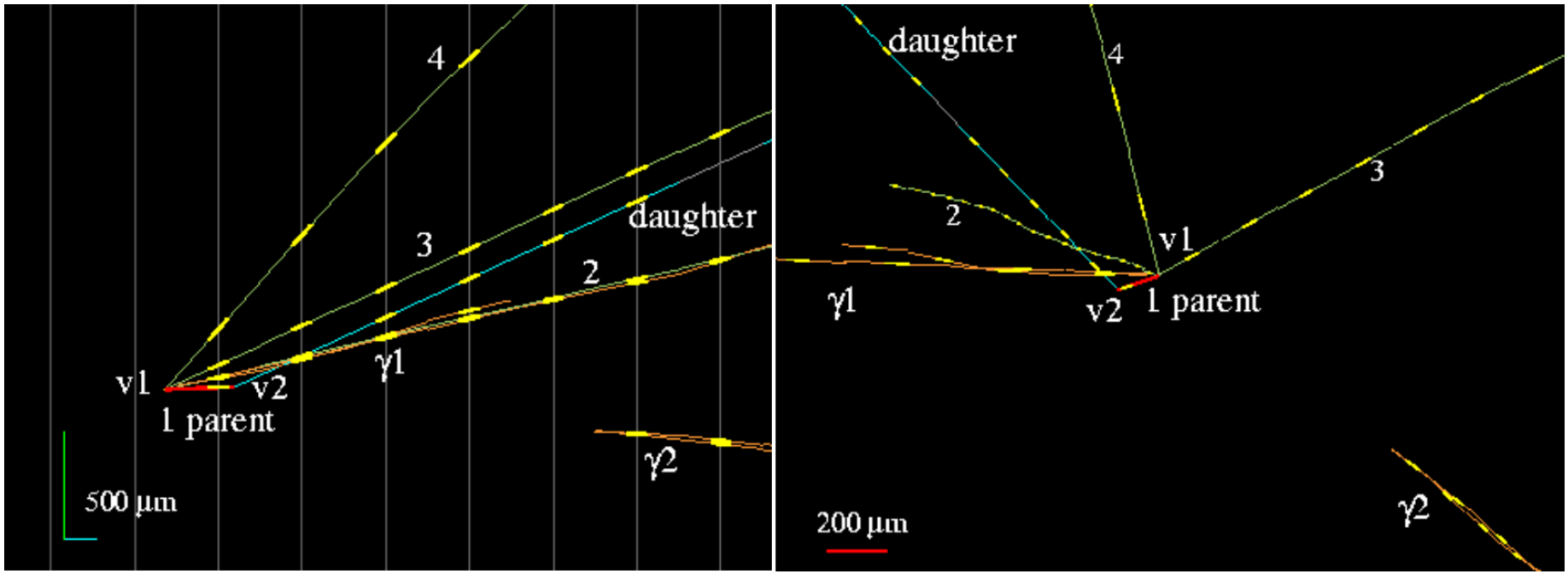
VARIABLE	VALUE
Kink angle (mrad)	245 ± 5
decay length (μm)	376 ± 10
Pμ (GeV/c)	2.8±0.2
Pt (MeV/c)	690±50
ϕ (degrees)	154.5 ± 1.5





Phys. Rev. D89 (2014) 051102

Fourth ν_τ candidate



VARIABLE	AVERAGE
Kink angle (mrad)	**245 ± 5**
decay length (μm)	**376 ± 10**
Pμ (GeV/c)	**2.8±0.2**
Pt (MeV/c)	**690±50**
ϕ (degrees)	**154.5 ± 1.5**

PTEP (2014) 101C01

$\nu_\mu \rightarrow \nu_\tau$ oscillation analysis results:

$\Delta m_{23}^2 = 3.3 \times 10^{-3}$ eV with a 90% confidence interval [2.0, 5.0] x 10^{-3} eV^2 (assuming full mixing)

using profile likelihood, Feldman-Cousins, Bayesian statistics, the difference among the methods negligible