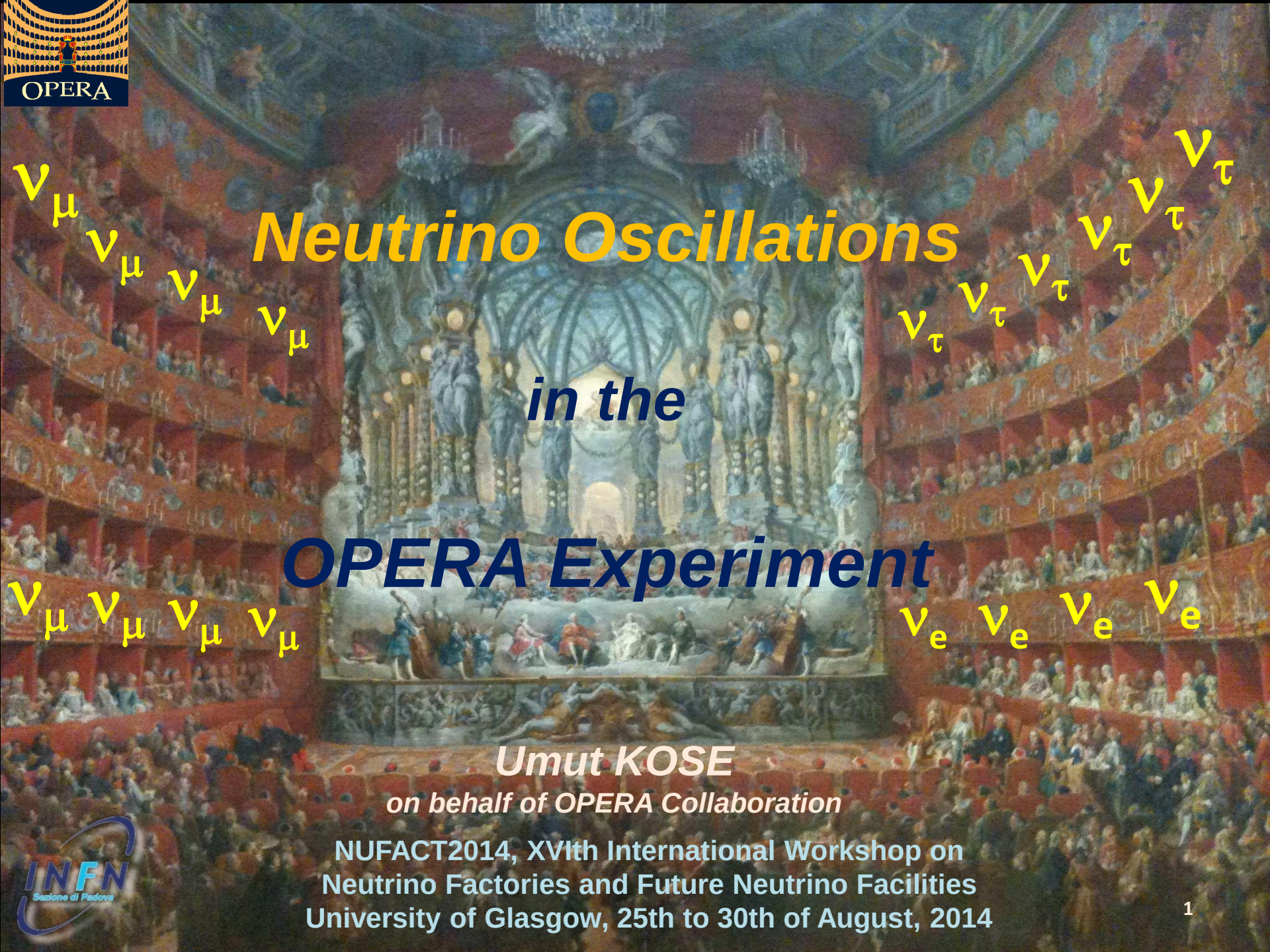


Neutrino Oscillations

in the

OPERA Experiment

Umut KOSE

on behalf of OPERA Collaboration

NUFACT2014, XVIth International Workshop on
Neutrino Factories and Future Neutrino Facilities
University of Glasgow, 25th to 30th of August, 2014

The OPERA Collaboration

140 physicists, 28 institutions in 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
LNF Frascati
L'Aquila
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Nihon

Korea
Jinju

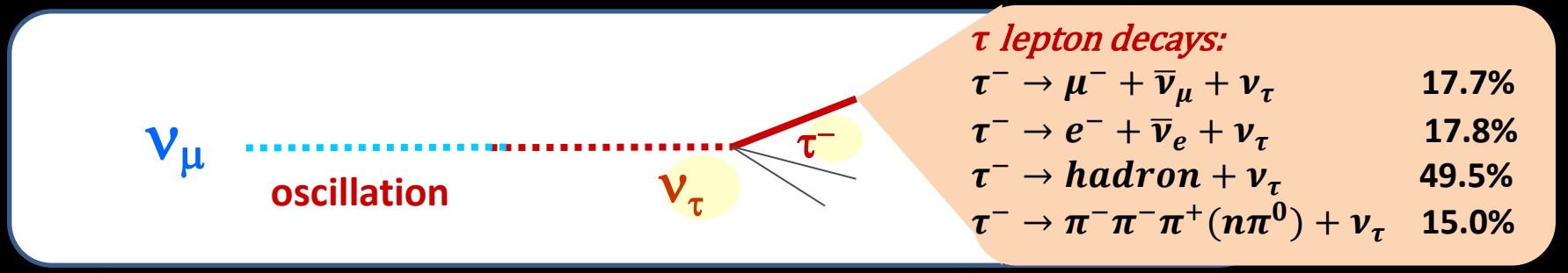
Russia
INR RAS Moscow
LPI RAS Moscow
ITEP Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern

Turkey
METU Ankara

Oscillation Project with Emulsion-tRacking Apparatus

Aim: establish neutrino oscillations in direct appearance mode in the $\nu_\mu \rightarrow \nu_\tau$ channel at atmospheric scale, through detection of the tau lepton produced in ν_τ Charged Current (CC) interaction on event-by-event basis. Full coverage of the parameter space indicated by SK, T2K and MINOS.



τ lepton decays:

$\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$	17.7%
$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$	17.8%
$\tau^- \rightarrow hadron + \nu_\tau$	49.5%
$\tau^- \rightarrow \pi^-\pi^-\pi^+(n\pi^0) + \nu_\tau$	15.0%

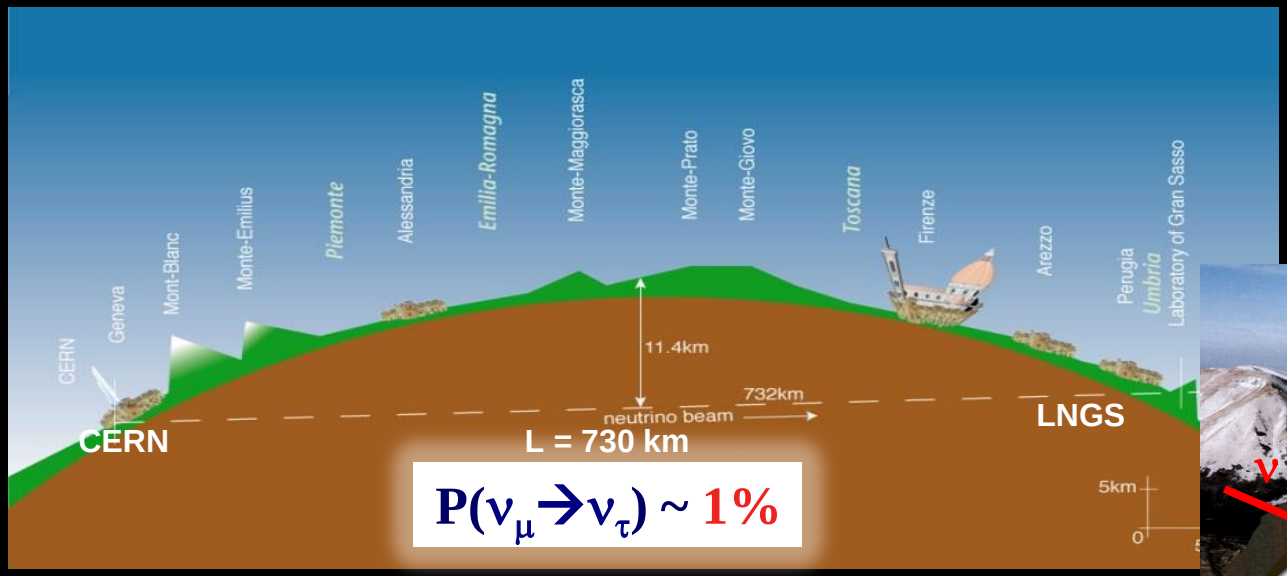
$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2(\Delta m^2_{23} L/4E)$$

Requirements:

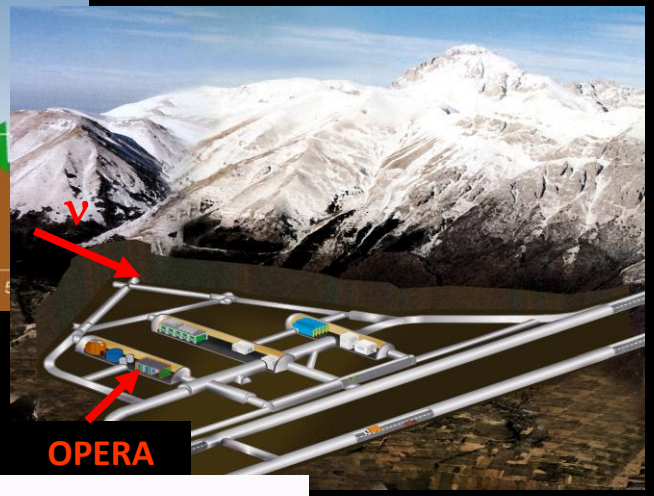
- ✓ *High energy and high intensity neutrino beam*
  Conventional ν_μ beam optimized for ν_τ appearance
- ✓ *Long baseline*
- ✓ *Large target mass and submicron resolution*
- ✓ Detector capability to identify short-lived τ lepton

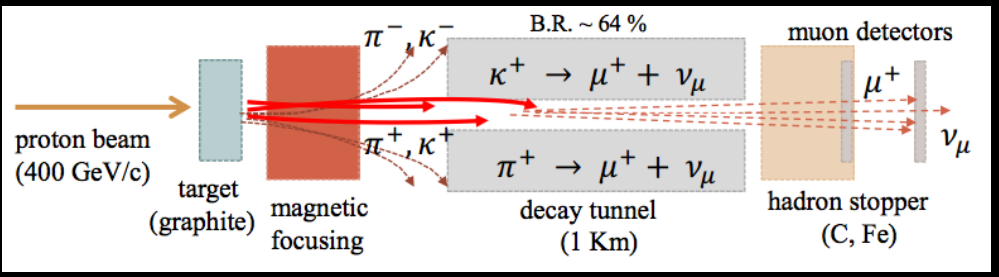
CERN Neutrino to Gran Sasso Beam

http://proj-cngs.web.cern.ch/proj-cngs/



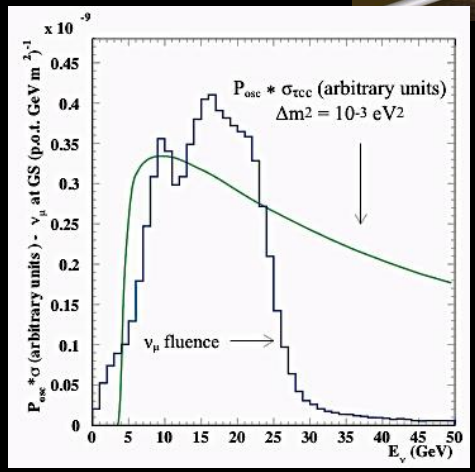
Gran Sasso National Laboratory:
1400 m rock shield
(cosmic μ flux reduction by a factor 10^6 w.r.t. surface)





$< E_\nu >$	17 GeV
L	730 km
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.87 % *
$\bar{\nu}_\mu/\nu_\mu$	2.1 % *
ν_τ prompt	Negligible *

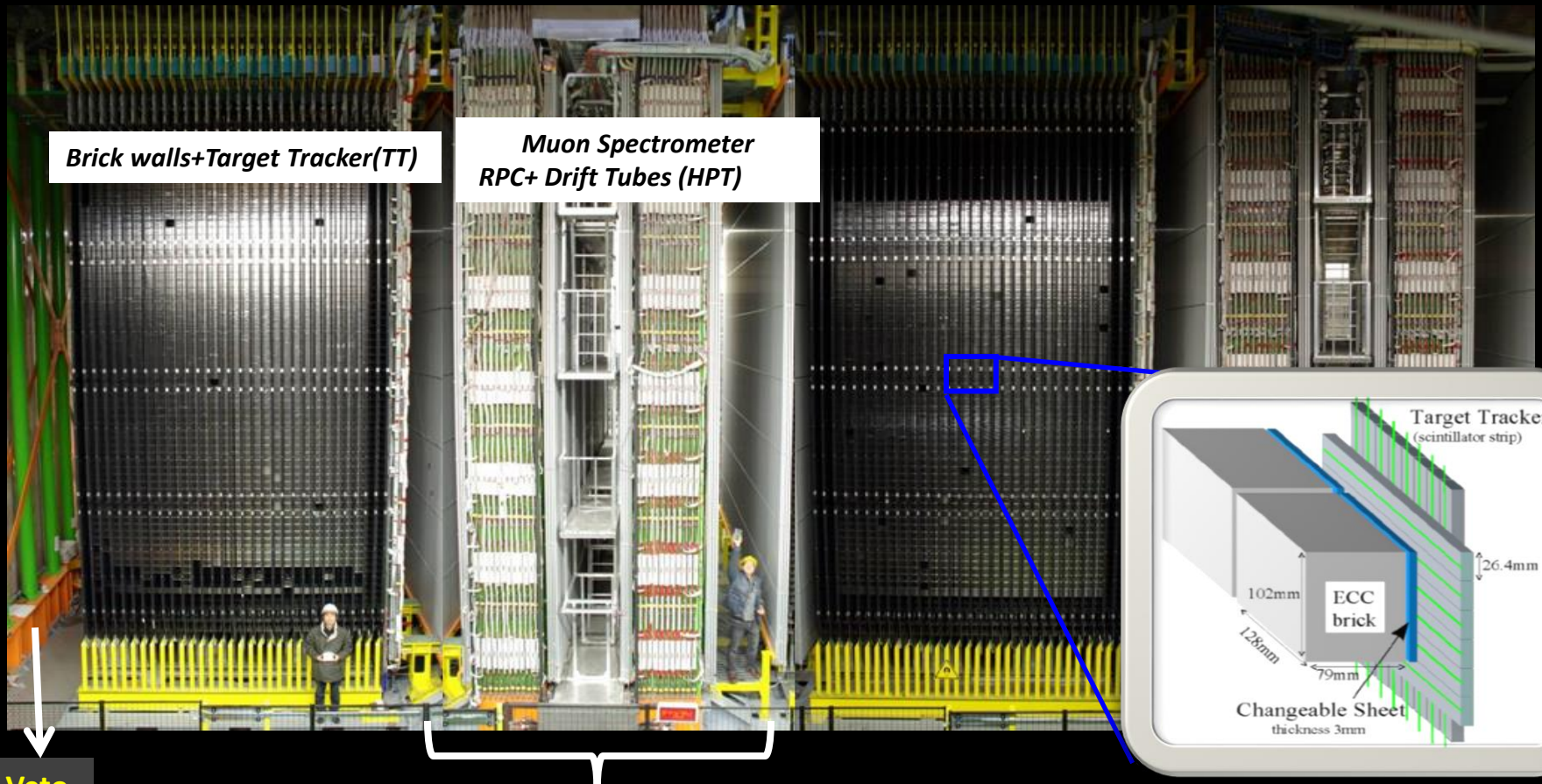
* Interaction rate at LNGS



Optimised to maximise ν_τ CC interactions at LNGS

OPERA detector*

*JINST **4 P04018, 2009.**



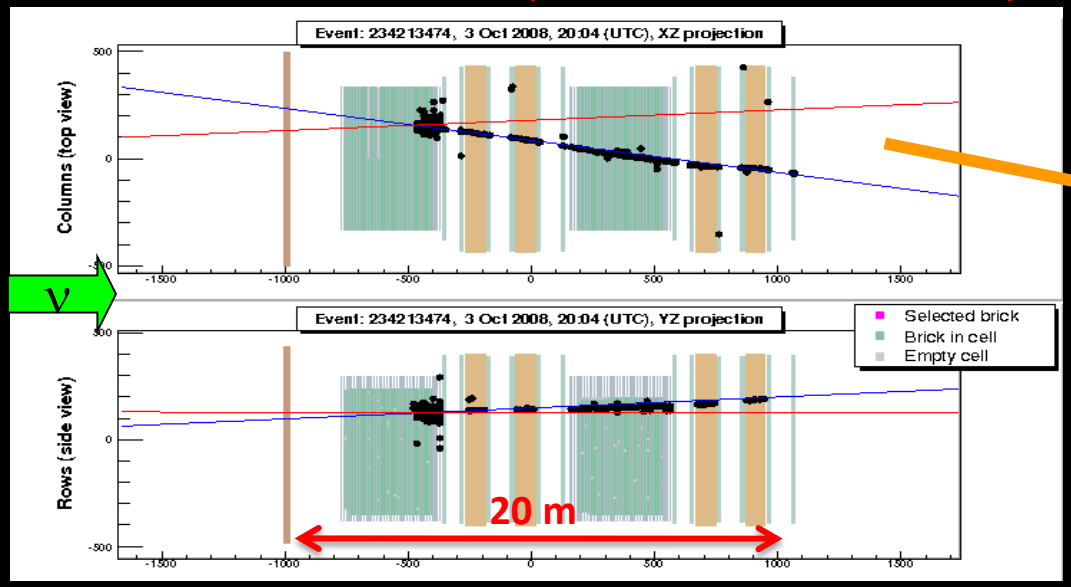
- μ id efficiency ~ 95% (with TT)
- Δp/p < 20% , p < 50 GeV/c
- misidentified μ charge prob. : 1.2%

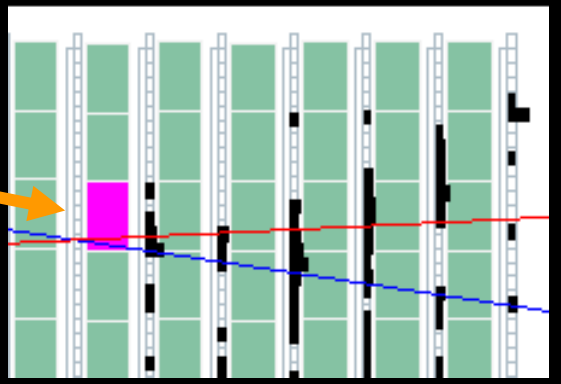
Each brick wall followed by a plane of Scintillator strips in X/Y direction. Target Tracker used for localization of Interaction brick.

- Trigger efficiency > 99%
- Brick finding : ε ≈ 60÷80%

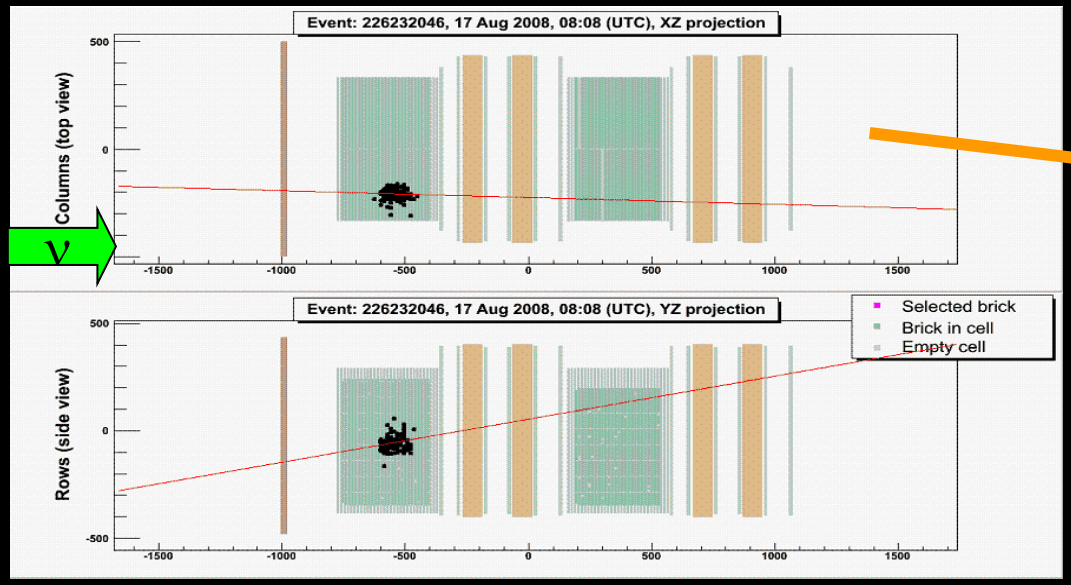
ECC brick= 56 lead plates + 57 films ~8kg ($10X_0$)

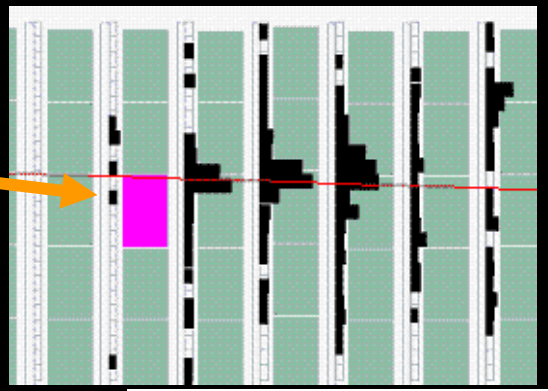
Typical ν_μ CC-like and ν_μ NC-like events





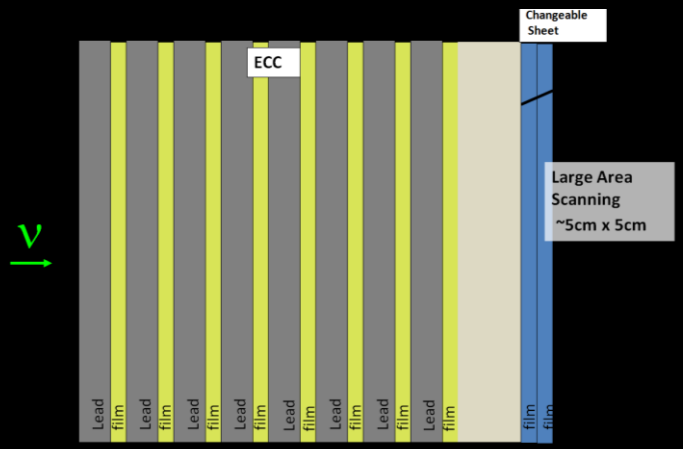
ν_μ CC
ν_τ CC, $\tau \to \mu$ (17.7%)

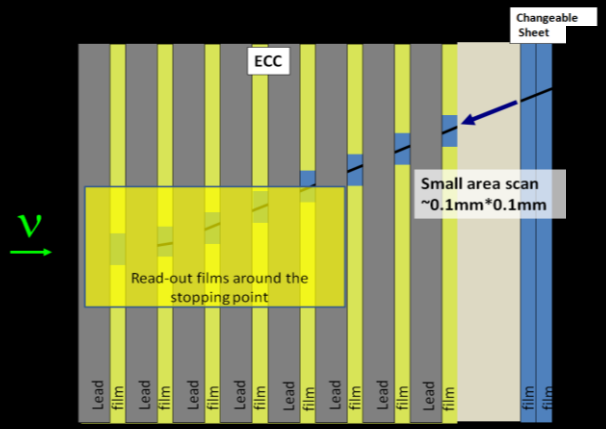


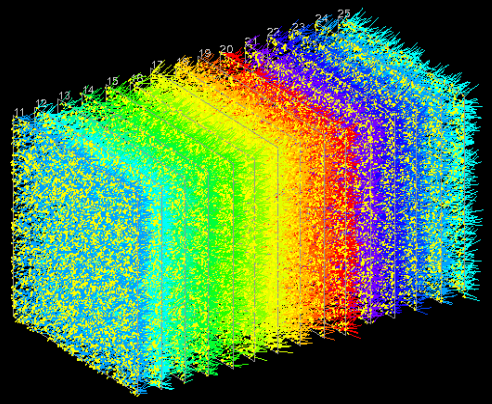


ν NC
ν_τ CC, $\tau \to e$ (17.8%)
ν_τ CC, $\tau \to h$, 3h (64.5%)
ν_e CC

Neutrino interaction location in ECC

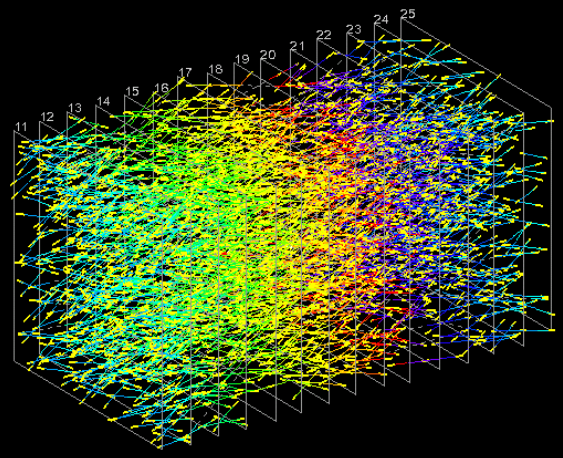


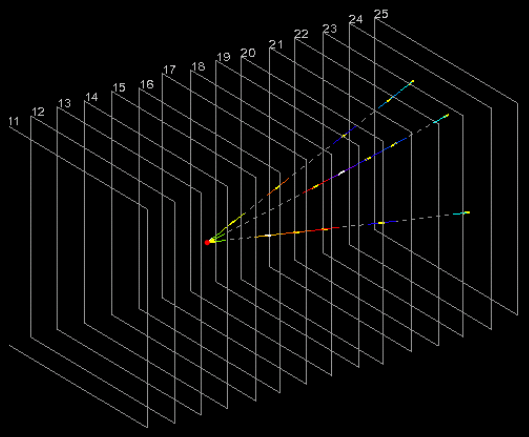




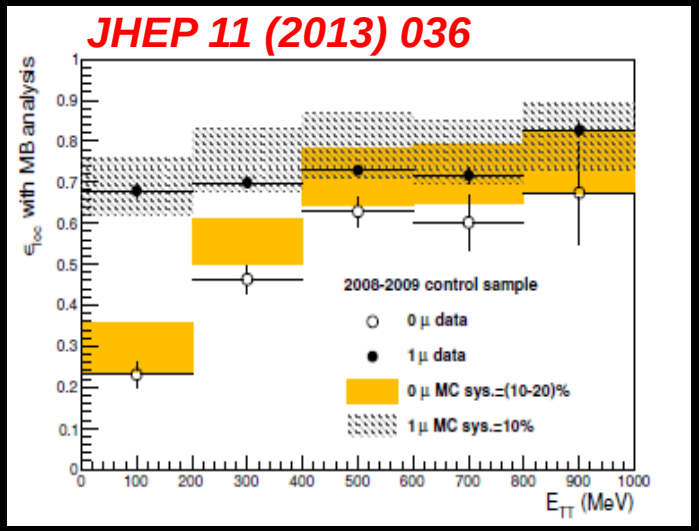
Step 1: *CS scanning → confirmation of ν interaction, predictions for brick analysis*

Step 2-4: *CS-ECC connection, ScanBack procedure, Volume data taking*





Step 5-6: *Validation of neutrino interaction vertex*



Location efficiency vs event energy

Decay search

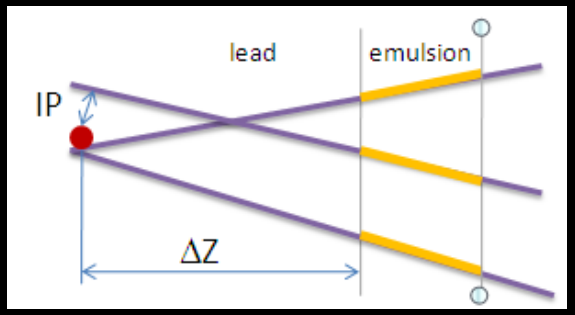
Eur. Phys. J. C 74 (2014) 2986.

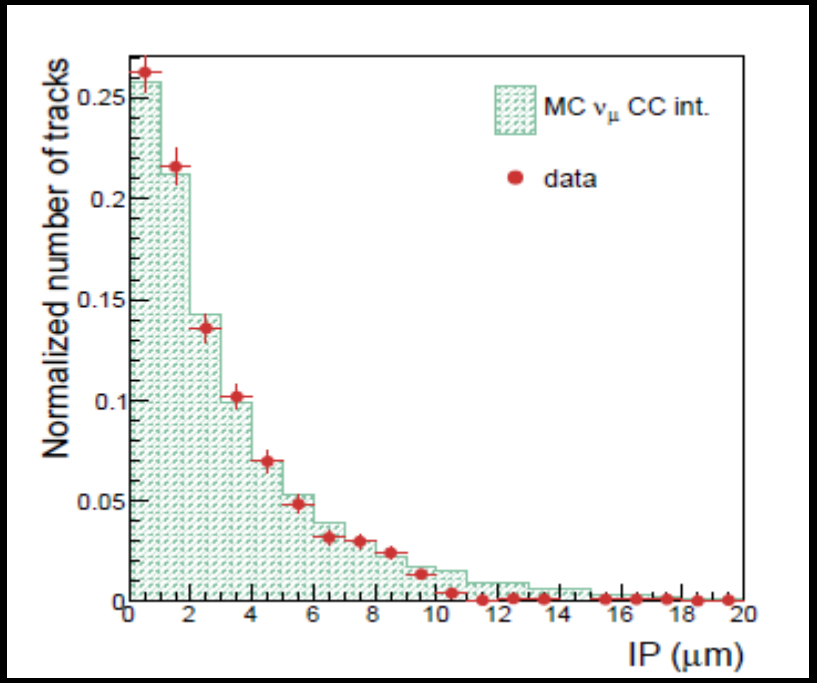
Impact Parameter evaluation

→ *crucial point to detect decay topology*

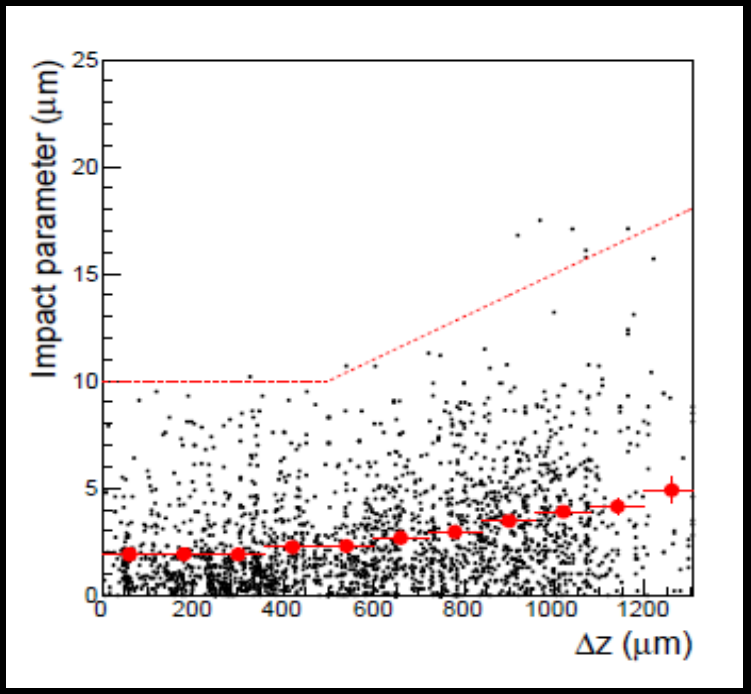
Kink search

Parent search





Impact parameter of tracks w.r.t. reconstructed ν interaction vertices



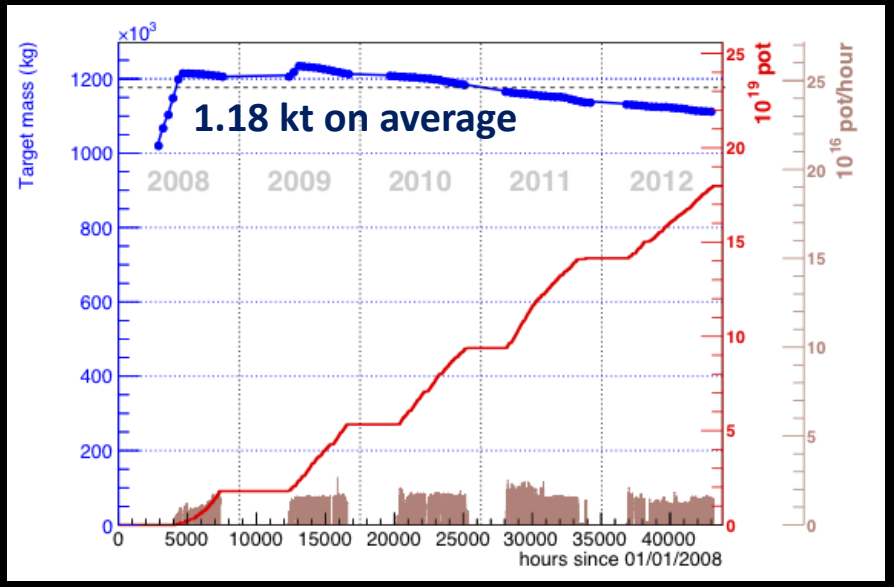
Impact parameter vs. longitudinal distance from reconstructed ν interaction vertex

Status of the Analysis

Run	p.o.t. (10^{19})	SPS efficiency	Beam days	ν interactions
2008	1.7	61%	123	1931
2009	3.53	73%	155	4005
2010	4.09	80%	187	4515
2011	4.75	79%	243	5131
2012	3.86	82%	257	3923
Total	**17.97**	77%	965	**19505**

↳ 80% of the design

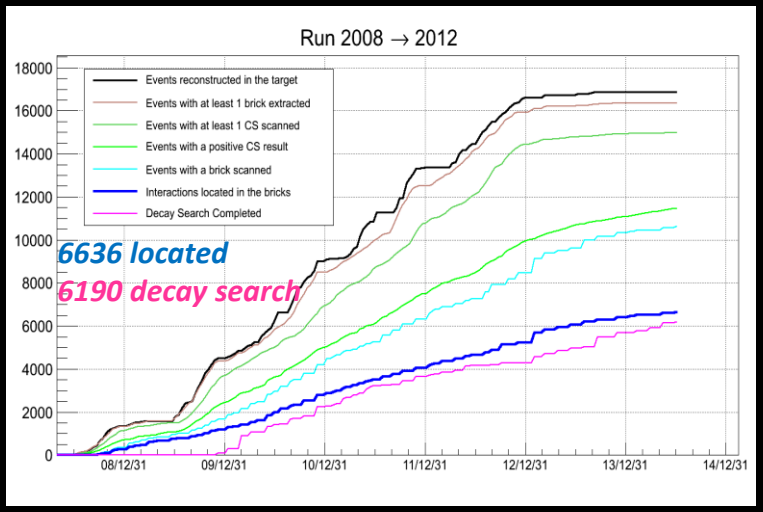
↳ ~87% predicted in the bricks



Analysis strategy

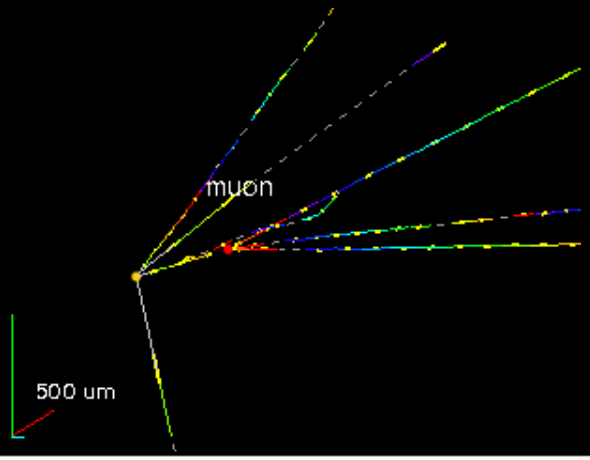
Bricks ordered by the probability to contain the neutrino interaction

- **Runs 2008-2009:** 1st and 2nd most probable bricks
- **Runs 2010÷2012:** 1st brick analysed so far. Extension to less probable bricks in progress.



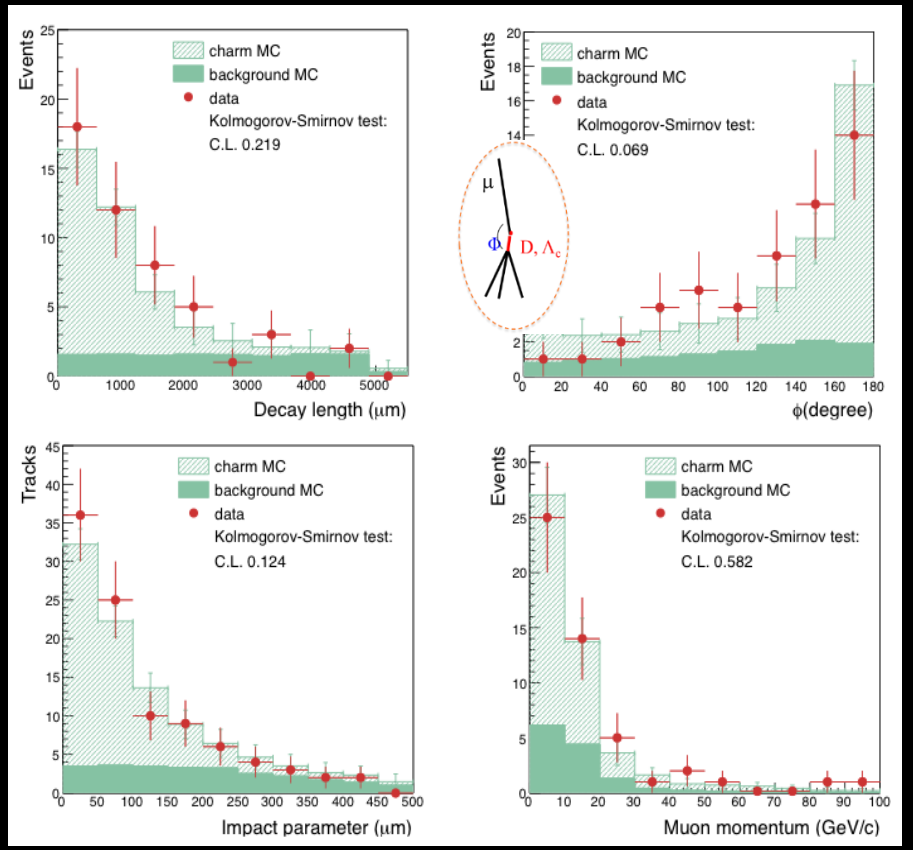
Search for short-lived particle decays: charmed hadrons as control sample

Eur. Phys. J. C ***74 (2014) 2986.***



Charmed hadrons produced by ν_μCC interactions
→ muon at the primary vertex
Mass and lifetime charmed hadrons ~ tau lepton
→ similar decay topology

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



2008-2010 OPERA data set

54 ± 4 charm events expected

50 observed in control sample

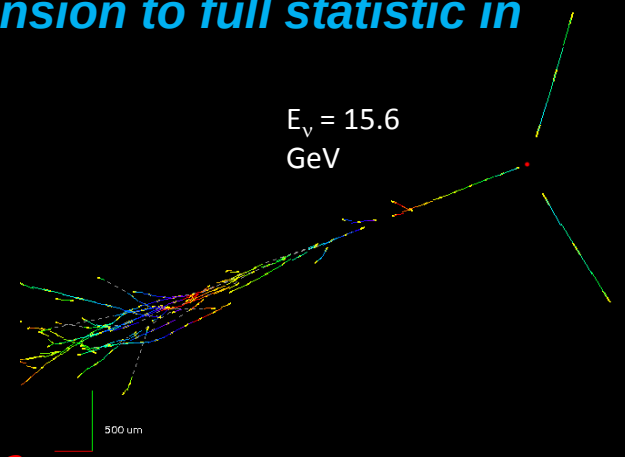
Good agreement between data and MC.

$\nu_\mu \rightarrow \nu_e$ oscillation results

JHEP 1307 (2013) 004

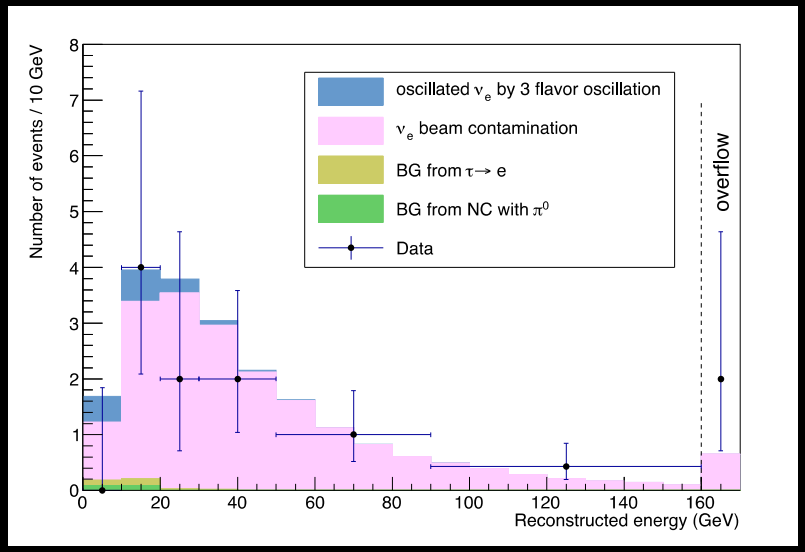
ν_e searched in 505 (data of 2008-2009 run ~ 50% full statistics) neutrino interaction without the muon in the final state. Extension to full statistic in progress.

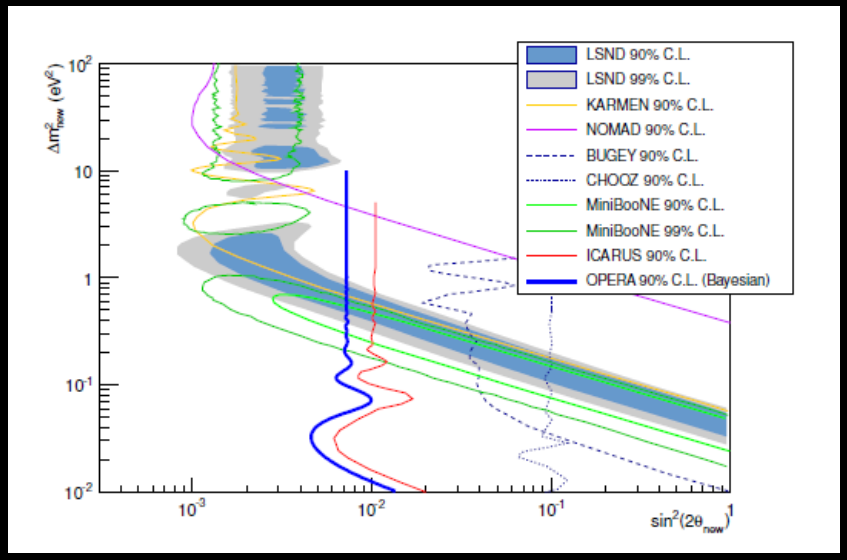
Energy cut		20 GeV	30 GeV	No cut
BG common to both analyses	BG (a) from π^0	0.2	0.2	0.2
	BG (b) from $\tau \rightarrow e$	0.2	0.3	0.3
	ν_e beam contamination	4.2	7.7	19.4
Total expected BG in 3-flavour oscillation analysis		4.6	8.2	19.8
BG to non-standard oscillation analysis only	ν_e via 3-flavour oscillation	1.0	1.3	1.4
Total expected BG in non-standard oscillation analysis		5.6	9.4	21.3
Data		4	6	19



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

$sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ @ 90% C.L.





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

Data sample: ***4685 located and fully analysed ν interactions***

	2008	2009	2010	2011	2012	Total
pot (10^{19})	1.74	3.53	4.09	4.75	3.86	17.97
0μ events	148	250	209	223	149	979
1μ events ($p_\mu < 15$ GeV/c)	534	1019	814	749	590	3706
Total of events	682	1269	1023	972	739	4685

Kinematical selection cuts kept fixed since beginning of the experiment.

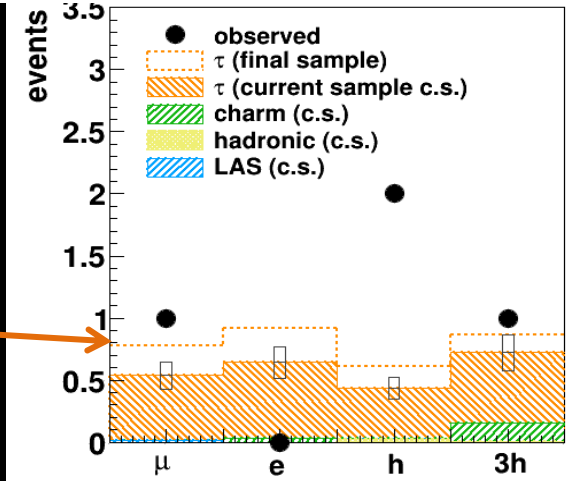
variable	$\tau \rightarrow 1h$	$\tau \rightarrow 3h$	$\tau \rightarrow \mu$	$\tau \rightarrow e$
lepton-tag		No μ or e at the primary vertex		
z_{dec} (μm)	$[44, 2600]$	< 2600	$[44, 2600]$	< 2600
p_T^{miss} (GeV/c)	$< 1^\star$	$< 1^\star$	/	/
ϕ_{lH} (rad)	$> \pi/2^\star$	$> \pi/2^\star$	/	/
p_T^{2ry} (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	/	/

Expected ν_τ events: 2.1 ± 0.4

($\Delta m^2 = 2.32 \times 10^{-3}$ eV^2, $\theta_{23} = \pi/4$)

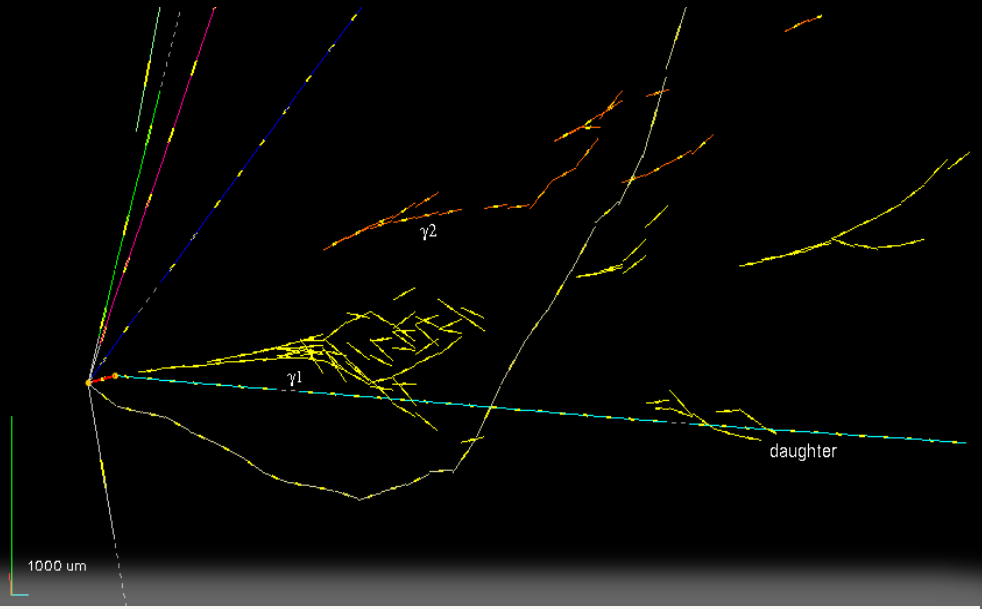
Observed ν_τ events: 4

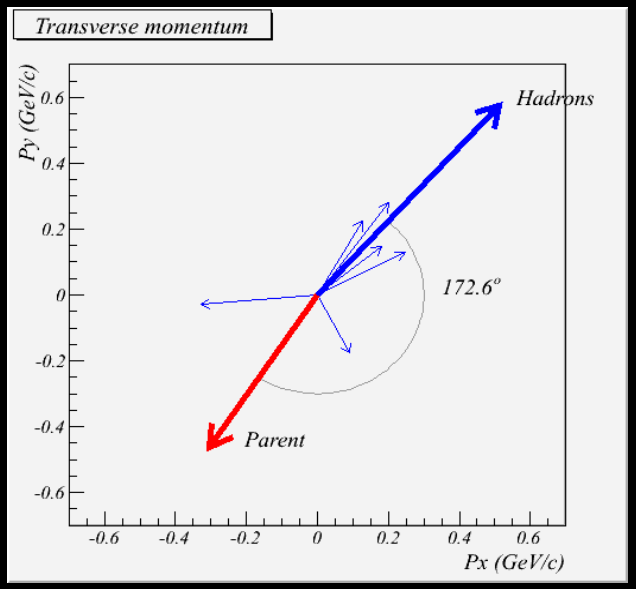
After completion of 2nd bricks for 2010 ÷ 2012 runs, expected events : 3.2 events



The first ν_τ candidate event

Phys. Lett. B (2010) 138





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

$\gamma 1 + \gamma 2$ $\quad 120 \pm 20 \pm 35$ MeV

$\pi^- + \gamma 1 + \gamma 2$ $\quad 640\ ^{+125}_{-80}\ ^{+100}_{-90}$ MeV

$\nu_\tau + N \rightarrow \tau^- + \text{hadrons}$

$\quad \hookrightarrow \rho^- + \nu_\tau$

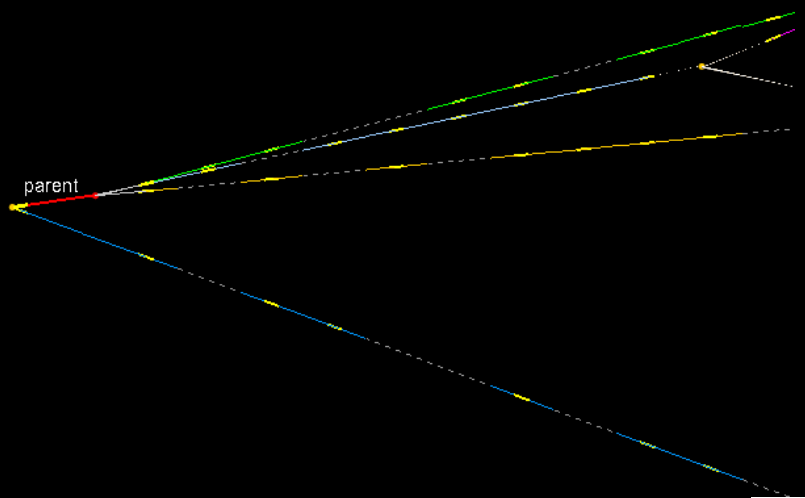
$\quad\quad \hookrightarrow \pi^- + \pi^0$

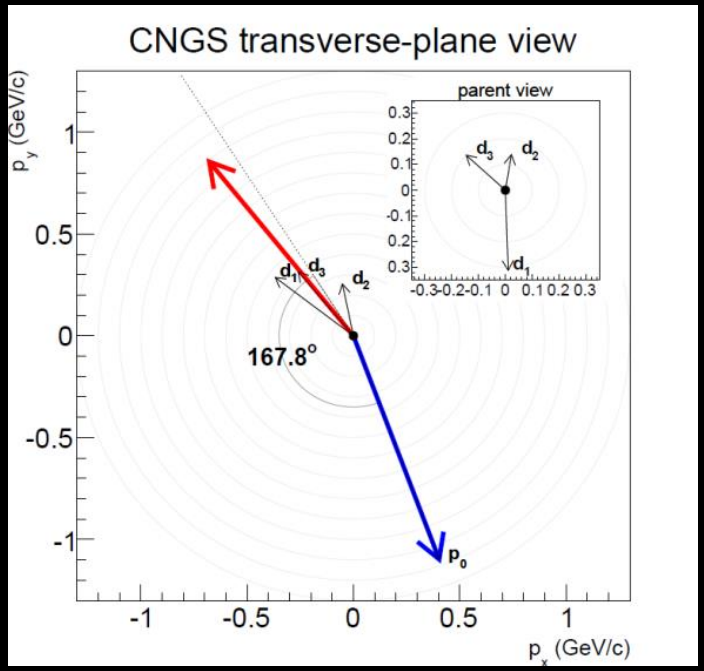
$\quad\quad\quad \hookrightarrow \gamma\gamma$

Variable	Value
Kink angle (mrad)	41 ± 2
Decay length (μm)	1335 ± 35
P daughter (GeV/c)	$12\ ^{+6}_{-3}$
Pt (MeV/c)	$470\ ^{+230}_{-120}$
Missing Pt at 1ry vertex (MeV/c)	$570\ ^{+320}_{-170}$
φ (deg)	173 ± 2

The second ν_τ candidate event

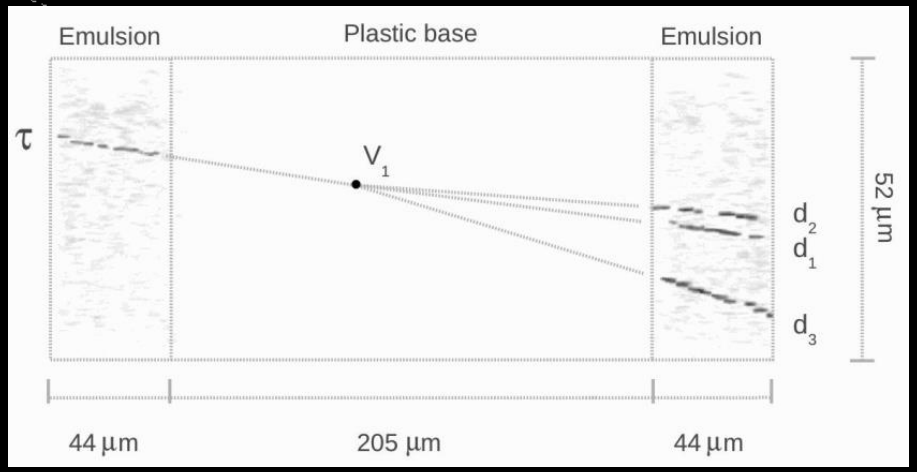
JHEP 11 (2013) 036





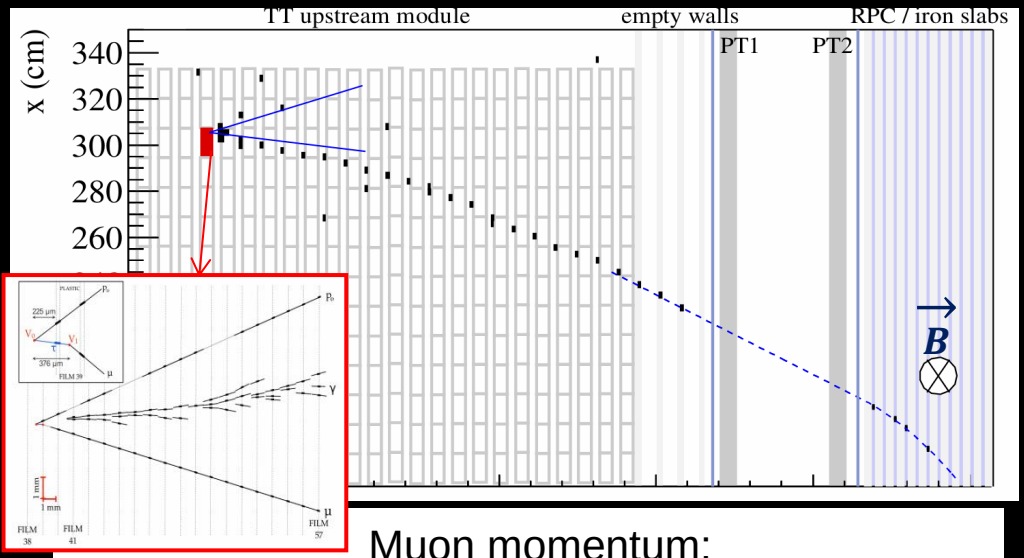
$\nu_\tau + N \rightarrow \tau^- + \text{hadrons}$

$\hookrightarrow h^+ h^- h^- \nu_\tau$



The third ν_τ candidate event

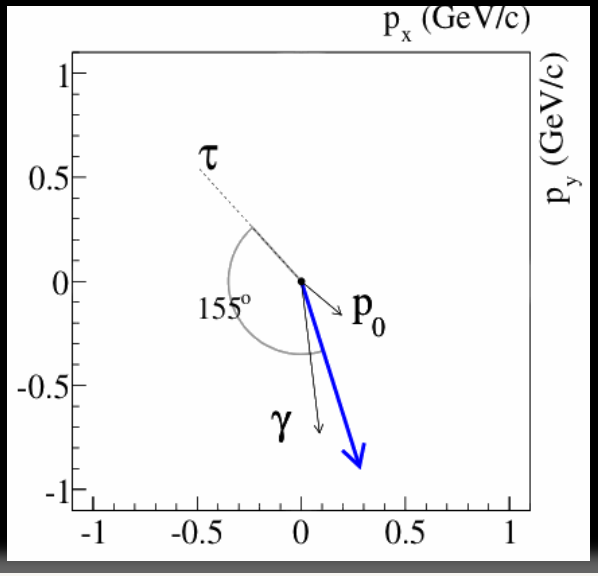
Phys. Rev. D 89 (2014) 051102(R)



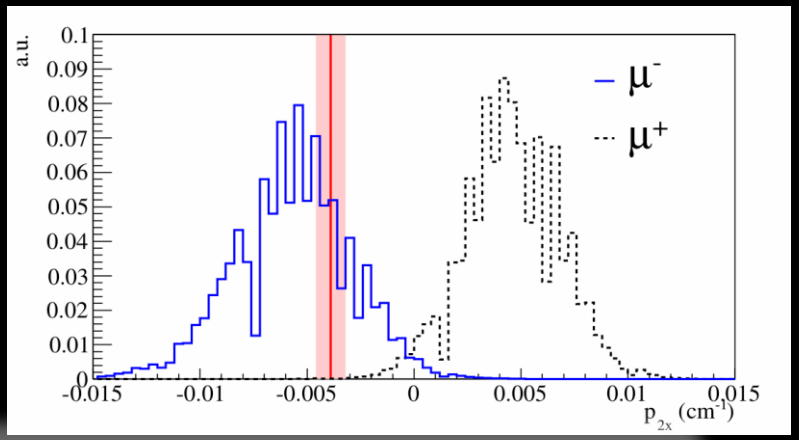
$\nu_\tau + N \rightarrow \tau^- + \text{hadrons}$

$\hookrightarrow \mu^- \nu_\tau \bar{\nu}_\mu$

Muon momentum:
by range (electronic detectors) 2.8 ± 0.2 GeV/c
by MCS in emulsion 3.1 [2.6, 4.0] GeV/c



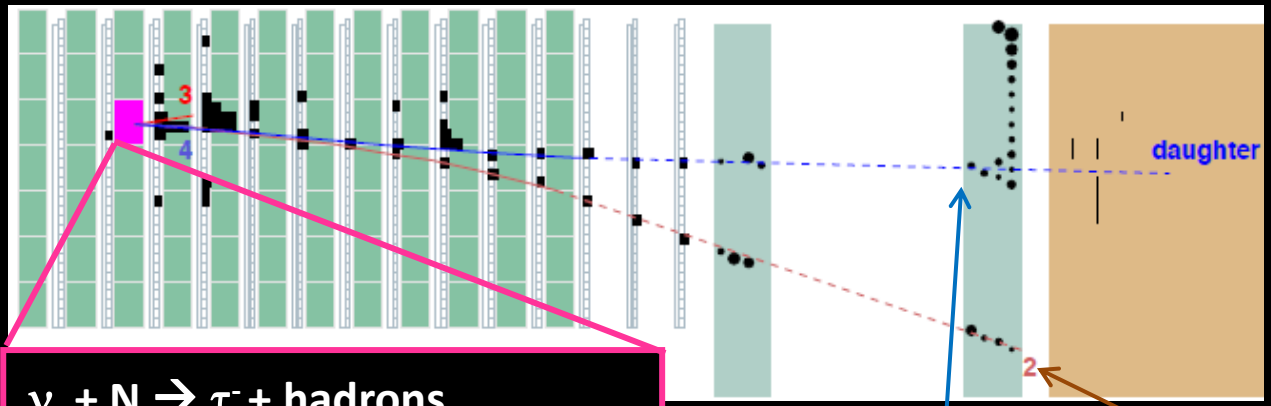
Negative muon measured in the muon spectrometer



First measurement of the lepton charge in appearance mode

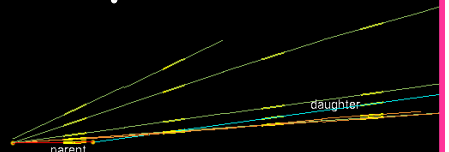
The fourth ν_τ candidate event

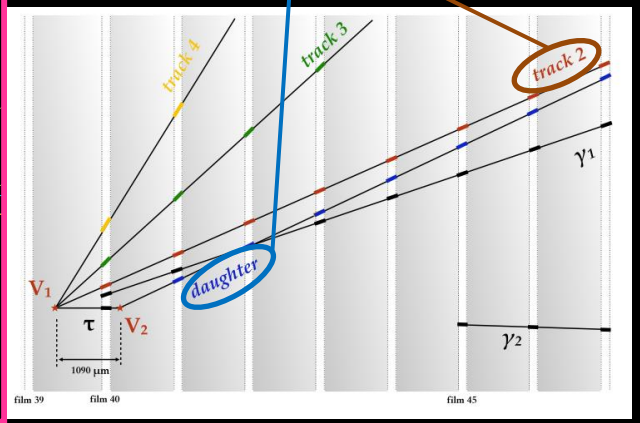
arXiv 1407.3513 - Submitted to PTEP



$\nu_\tau + N \rightarrow \tau^- + hadrons$

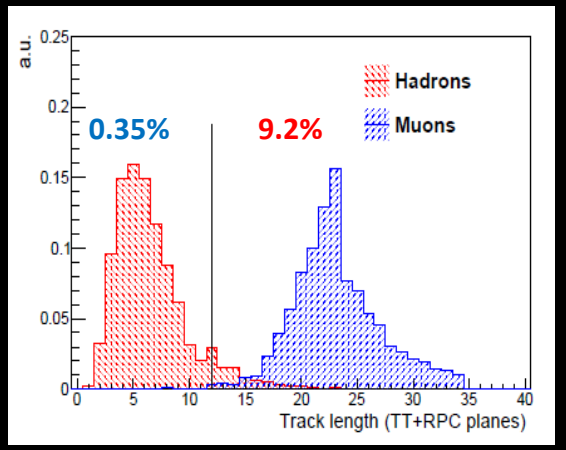
$\pi^- \nu_\tau$

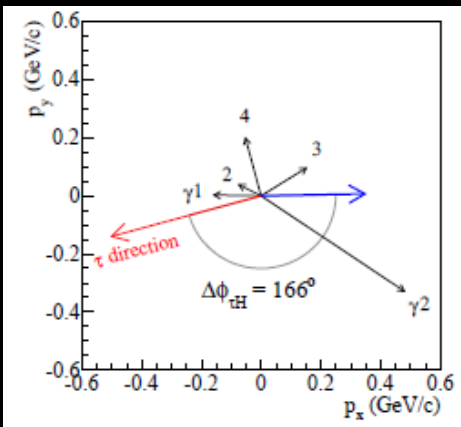




***Track 3** visible interaction in downstream brick #2*
***Track 4** crosses 1 wall; identified as a proton based on its ionization*

***Track 2** from neutrino interaction vertex,*
p = 1.9 GeV crossing 9 wall and stopping in first iron slab of the magnet.



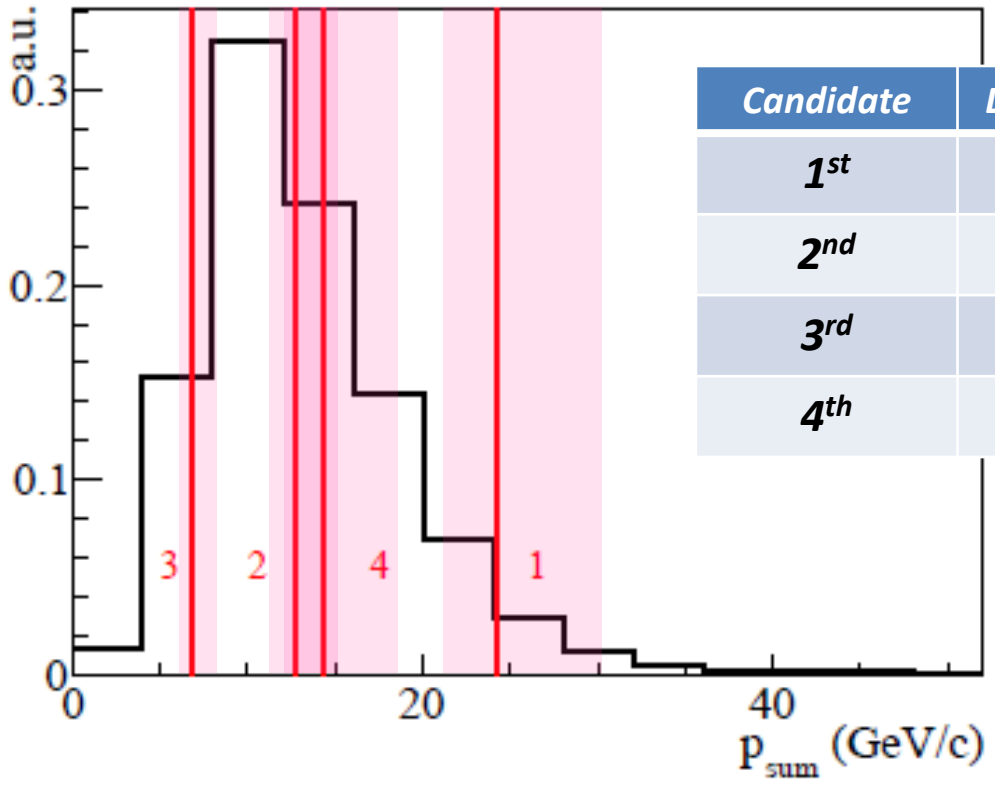


Variable	Selection	Measured value
θ_{kink} (mrad)	> 20	137 ± 4
z_{dec} (μm)	< 2600	406 ± 30
p_{2ry} (GeV/c)	> 2	$6.0^{+2.2}_{-1.2}$
p_T^{2ry} (GeV/c)	> 0.6 (0.3*)	$0.82^{+0.30}_{-0.16}$
p_T^{miss} (GeV/c)	< 1	$0.55^{+0.30}_{-0.20}$
$\Delta\phi_{\tau H}$ (degrees)	> 90	166^{+2}_{-31}

Summary of four events

Visible energy of all ν_τ events:

Scalar sum of momentum and γ energies



Candidate	Decay Mode	Psum(GeV/c)	year
1st	$\tau \to h$	$24.3^{+6.1}_{-3.2}$	2010
2nd	$\tau \to 3h$	$12.7^{+2.3}_{-1.7}$	2012
3rd	$\tau \to \mu^-$	$6.8^{+0.9}_{-0.6}$	2013
4th	$\tau \to h$	$14.4^{+3.9}_{-2.7}$	2014

Significance

The expected signal and background is normalized to the number of located events

$$n^{0\mu}(\nu_\tau^{CC}) = \frac{\langle \sigma(\nu_\tau^{CC}) \rangle}{\langle \sigma(\nu_\mu^{CC}) \rangle} \frac{\langle \epsilon^{0\mu}(\nu_\tau^{CC}) \rangle}{\langle \epsilon^{0\mu}(\nu_\tau^{CC}) \rangle + \alpha \langle \epsilon^{0\mu}(\nu_\tau^{NC}) \rangle} n^{0\mu} \qquad \alpha = \frac{NC}{CC}$$

Decay channel	Expected signal $\Delta m_{23}^2 = 2.32$ meV^2	Total background	Observed
τ→h	0.41 ± 0.08	0.033 ± 0.006	2
τ→3h	0.57 ± 0.11	0.155 ± 0.030	1
τ→μ	0.52 ± 0.10	0.018 ± 0.007	1
τ→e	0.62 ± 0.12	0.027 ± 0.005	0
Total	2.11 ± 0.42	0.233 ± 0.041	4

Two statistical methods

- Fisher combination of single channel → p-value = 1.24×10^{-5}
- Likelihood ratio → p-value = 1.03×10^{-5}

Observation of tau appearance with 4.2σ

First measurement of Δm^2_{32} in appearance experiment

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

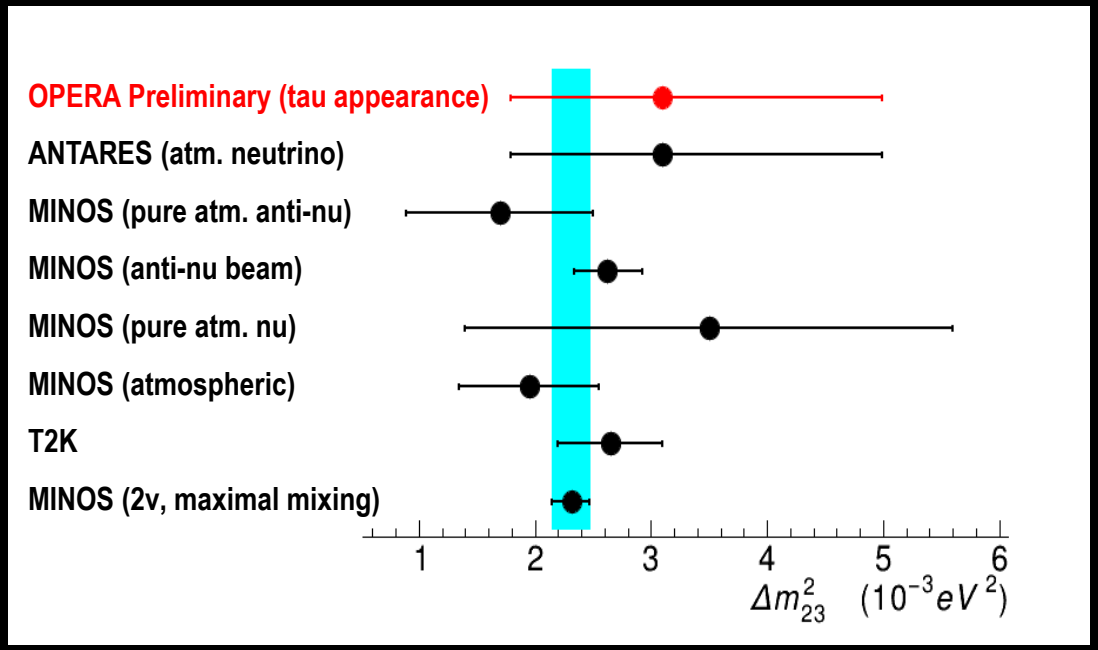
$$\propto (\Delta m^2_{32})^2 L^2 \int \phi(E) \epsilon(E) \frac{\sigma(E)}{E^2} dE$$

OPERA Off-peak
L/<E> ~ 43 Km/GeV
$(L/<E>)_{peak}$ ~ 500 Km/GeV

→ Strong dependence on Δm^2 → measure Δm^2 with counting experiment

90% CL intervals on Δm^2_{32} assuming $sin^2(2\theta_{23}) = 1$

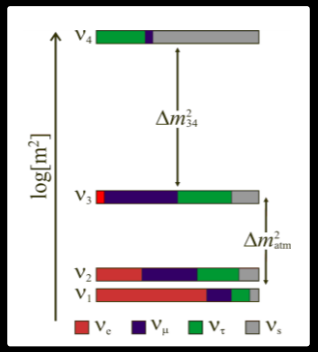
Feldman & Cousin
[1.8 – 5] x 10^{-3} eV^2
Bayesian
[1.9 – 5] x 10^{-3} eV^2



Sterile neutrino searches through $\nu_\mu \to \nu_\tau$ oscillation

- *Assume there is an additional sterile neutrino and an additional mass scale*
- *Mixing matrix is extended to:*

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



(3+1) model

$\Delta m^2_{41} > |\Delta m^2_{31}|$

$\Delta m^2_{32} = 2.32 \times 10^{-3}\ eV^2$

PRELIMINARY

For $L = 730$ km and $< E_\nu > = 17$ GeV
$P_{\nu_\mu \to \nu_\tau}$ independent from Δm^2_{21} since

$$\frac{\Delta m^2_{21} L}{E} \sim 0$$

$$\sin^2 2\theta_{\mu\tau} = \sin^2 2\theta_{24} \sin^2 \theta_{34}$$

$$P_{\nu_\mu \to \nu_\tau} = 4|U_{\mu 3}|^2|U_{\tau 3}|^2 \sin^2 \frac{\Delta_{31}}{2} + 4|U_{\mu 4}|^2|U_{\tau 4}|^2 \sin^2 \frac{\Delta_{41}}{2}$$
$$+2\Re[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}] \sin\Delta_{31} \sin\Delta_{41}$$
$$-4\Im[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}] \sin^2 \frac{\Delta_{31}}{2} \sin\Delta_{41}$$
$$+8\Re[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}] \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2}$$
$$+4\Im[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}] \sin\Delta_{31} \sin^2 \frac{\Delta_{41}}{2}$$

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

$$\hat{\delta} = \arg[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}]$$

$$4\Im[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}] = 4\sqrt{|U_{\mu 4}|^2|U_{\tau 4}|^2|U_{\mu 3}|^2|U_{\tau 3}|^2} \sin\hat{\delta} = 2\sin\theta_{\mu\tau}\sqrt{|U_{\mu 3}|^2|U_{\tau 3}|^2} \sin\hat{\delta}$$

$$8\Re[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}] = 8\sqrt{|U_{\mu 4}|^2|U_{\tau 4}|^2|U_{\mu 3}|^2|U_{\tau 3}|^2} \cos\hat{\delta} = 4\sin\theta_{\mu\tau}\sqrt{|U_{\mu 3}|^2|U_{\tau 3}|^2} \cos\hat{\delta}$$

An upper limit on $sin^2(2\theta_{\mu\tau})$ at high Δm^2_{41} values*

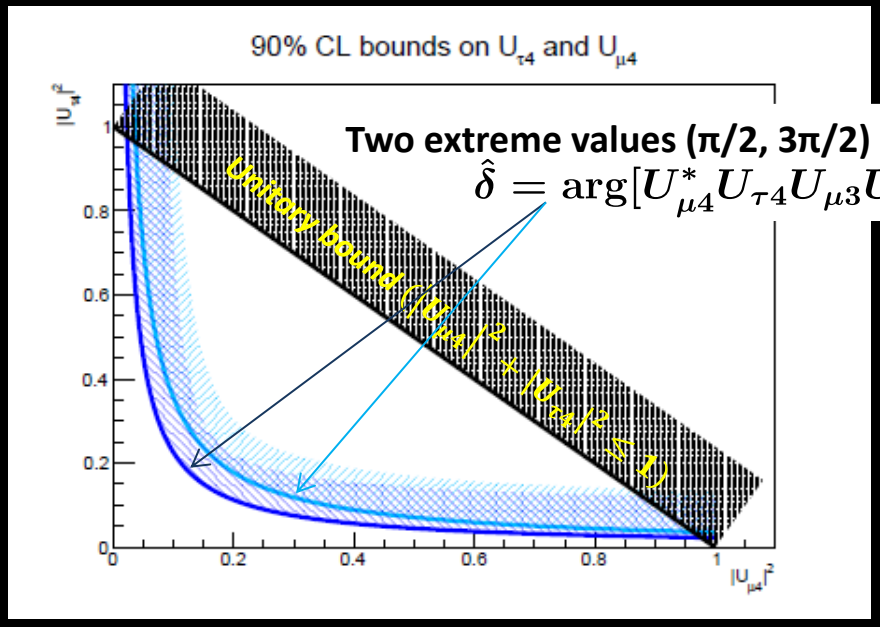
PRELIMINARY

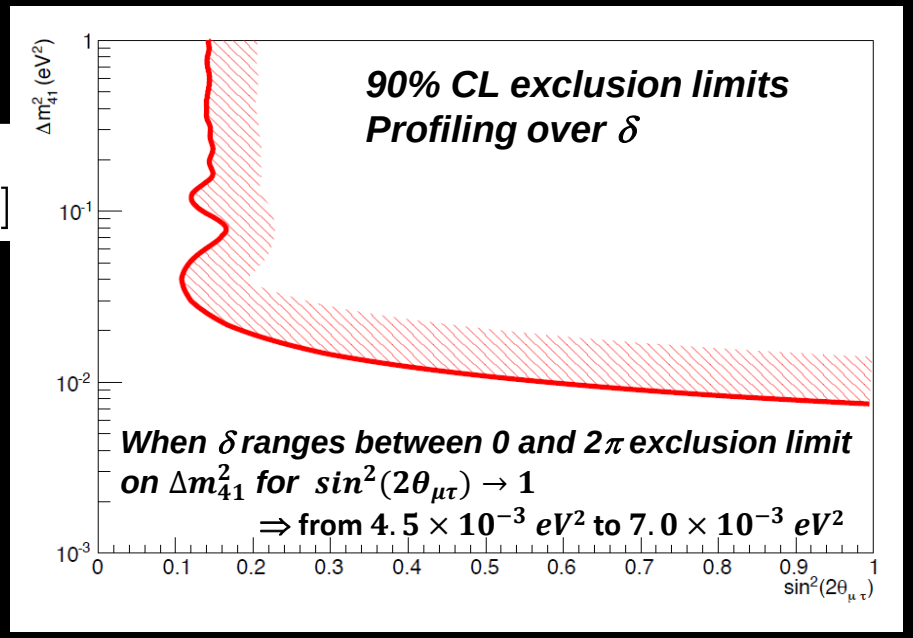
Profile likelihood $\tilde{L}(\delta, sin^2(2\theta_{\mu\tau}))$ →maximazing $L(\delta, sin^2(2\theta_{\mu\tau}), C^2) = \frac{\mu^n}{n!}e^{-\mu}$ on C^2 between 0 and 1, $C = 2|U_{\mu 3}U^*_{\tau 3}|$, n number of candidate events (4), μ is the expected number of events given by

$$\mu = N_b + \int A\phi(E)\, P_{\nu_\mu \to \nu_\tau}(E)\sigma(E)\epsilon(E)dE$$

Expected number of background (0.23), Normalization factor, neutrino flux, oscillation probability, CC ν_τ cross-section, tau detection efficiency.

$$\chi^2 = -2ln(\tilde{L}(\delta, sin^2(2\theta_{\mu\tau}))/L_0) \text{ where } L_0 = \frac{n^n}{n!}e^{-n}$$





*Paper in preparation.

Conclusions

- **OPERA experiment:**
  successful data taking from 2008 to 2012, 17.97 10^{19} pot collected.
- $\nu_\mu \rightarrow \nu_e$ analysis:
  - 19 events (4 events with E_{rec}<20GeV) observed with an estimation of 19.8±2.8 (4.6 with E_{rec}<20GeV) events.
  - At large Δm^2 region, 6 events observed with an estimation of 9.4 ±1.3 events gives an upper limit of 7.2 10^{-3} at 90% C.L. on $\sin^2(2\theta_{new})$.

- $\nu_\mu \rightarrow \nu_\tau$ analysis:
  - 4685 located events fully analysed
  - 4 ν_τ candidates observed so far with an expectation of 2.1±0.4 events and 0.23 background.
  - No oscillation hypothesis excluded at 4.2 σ

  Observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode
- First measurement of Δm^2_{32} in appearance mode ($\nu_\mu \rightarrow \nu_\tau$ oscillations) :
  - Δm^2_{32} = [1.8 – 5] x 10^{-3} eV^2 (90% C.L.) for $\sin^2(2\theta_{23}) = 1$
- Sterile neutrino search in $\nu_\mu \rightarrow \nu_\tau$: **PRELIMINARY**
  - First limits on $|U_{\mu 4}|^2 |U_{\tau 4}|^2$ from direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillation.

Image taken using OPERA emulsion film with pinhole hand made camera by D. Diferdinando