The OPERA experiment

analysis status and recent results on $\nu_\mu \rightarrow \nu_e$ oscillations

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on behalf of the OPERA collaboration

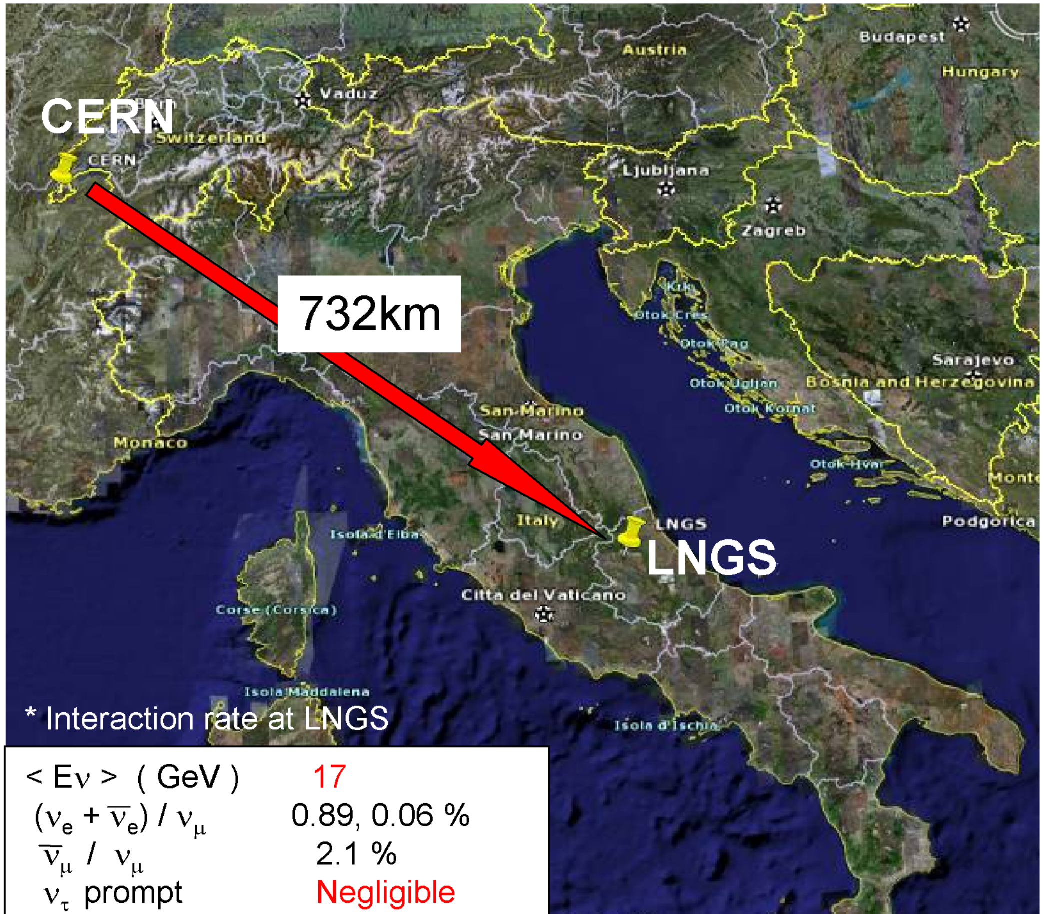
16th Lomonosov Conference
Moscow, 22-28 August,2013

Outline

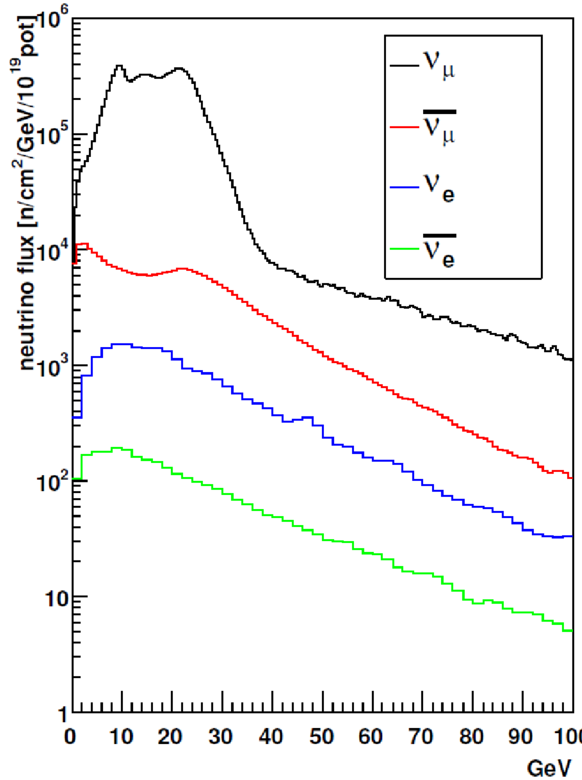
- The OPERA experiment
- Status of neutrino events analysis
- Recent result of $\nu_\mu \to \nu_e$ oscillation search
- Conclusions

The OPERA Experiment

Direct observation of ν_τ appearance from ν_μ oscillation



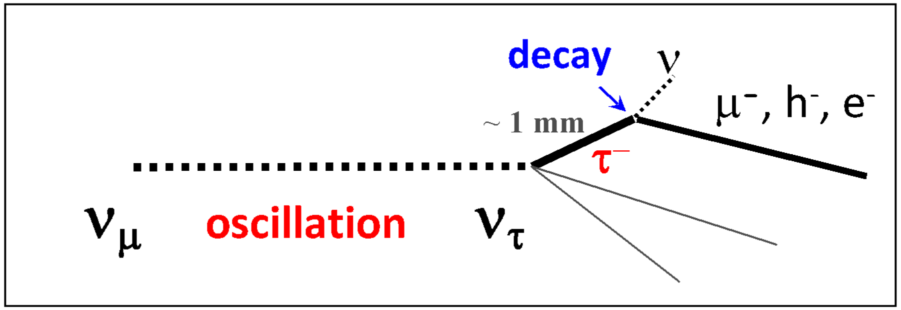
< Eν > (GeV)	17
$(\nu_e + \overline{\nu}_e) / \nu_\mu$	0.89, 0.06 %
$\overline{\nu}_\mu$ / ν_μ	2.1 %
ν_τ prompt	Negligible



$$P(\nu_\mu \to \nu_\tau) \sim \sin^2(2\theta_{23}) \cdot \sin^2\left(1.27 \cdot \Delta m^2_{23} \cdot \frac{L}{E}\right) \sim 1.7\%$$

$\sin^2 2\theta_{23} = 1.0$, $\Delta m_{23}^2 = (2.32+0.12-0.08) \cdot 10^{-3}\ eV^2$ [PRL 106:181801 (2011)]

Emulsion Cloud Chamber (ECC)



To detect tau lepton decay, micrometric resolution is required.

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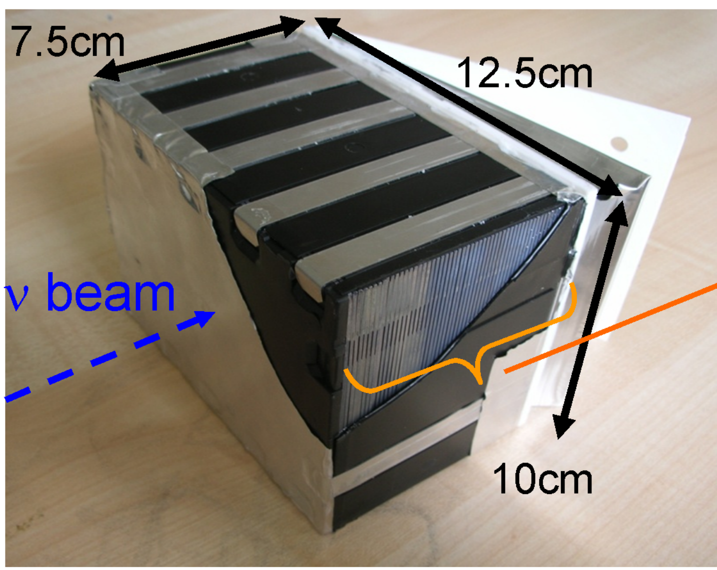
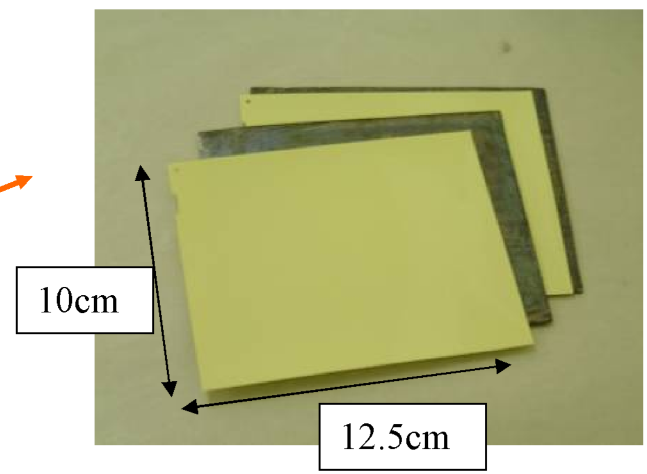
Nuclear emulsion (OPERA film)

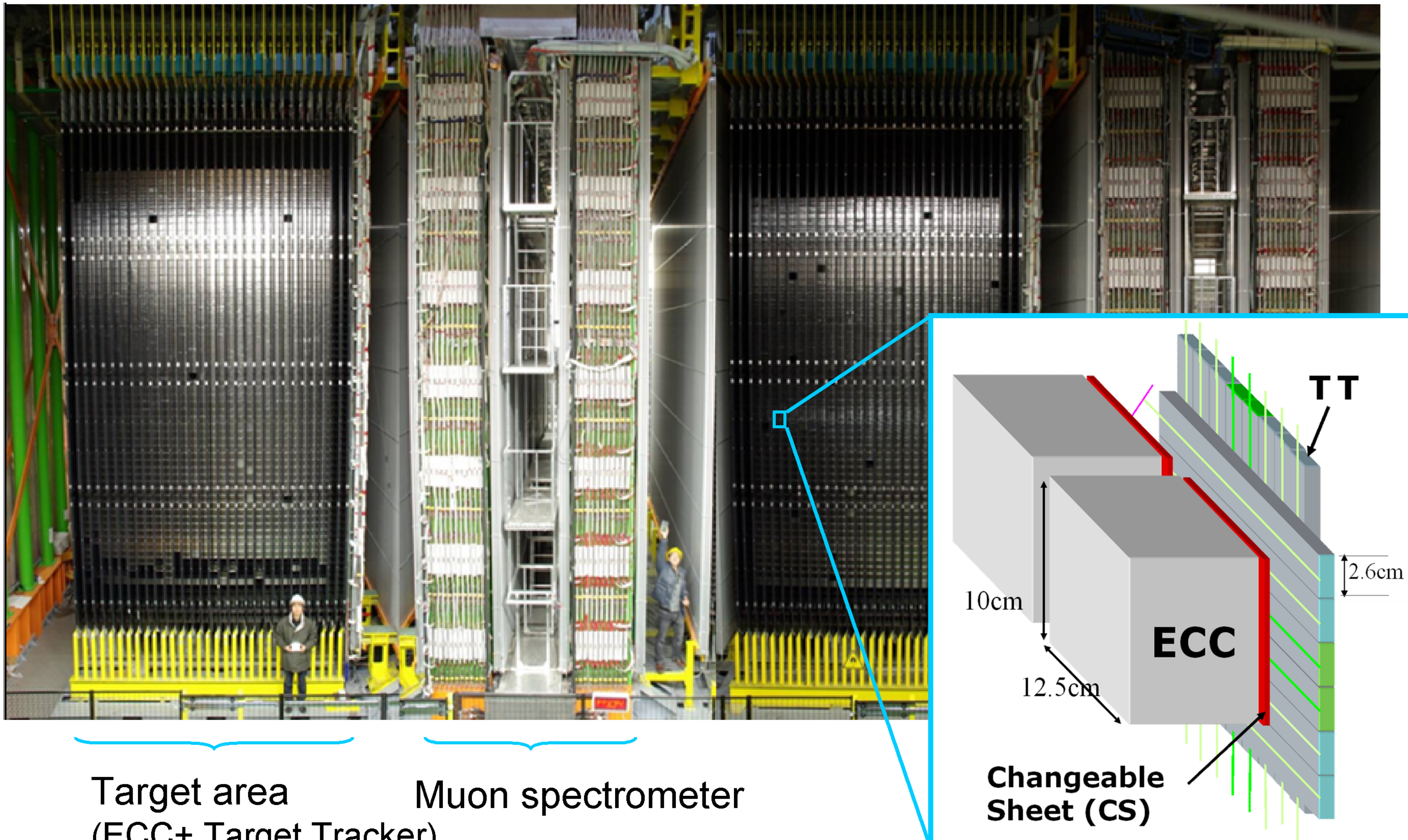


Emulsion Cloud Chamber (ECC)



- 57 films interleaved with 1mm-thick lead plates
- 8.3kg/1ECC -> 10 radiation length (X_0)

The OPERA detector @LNGS



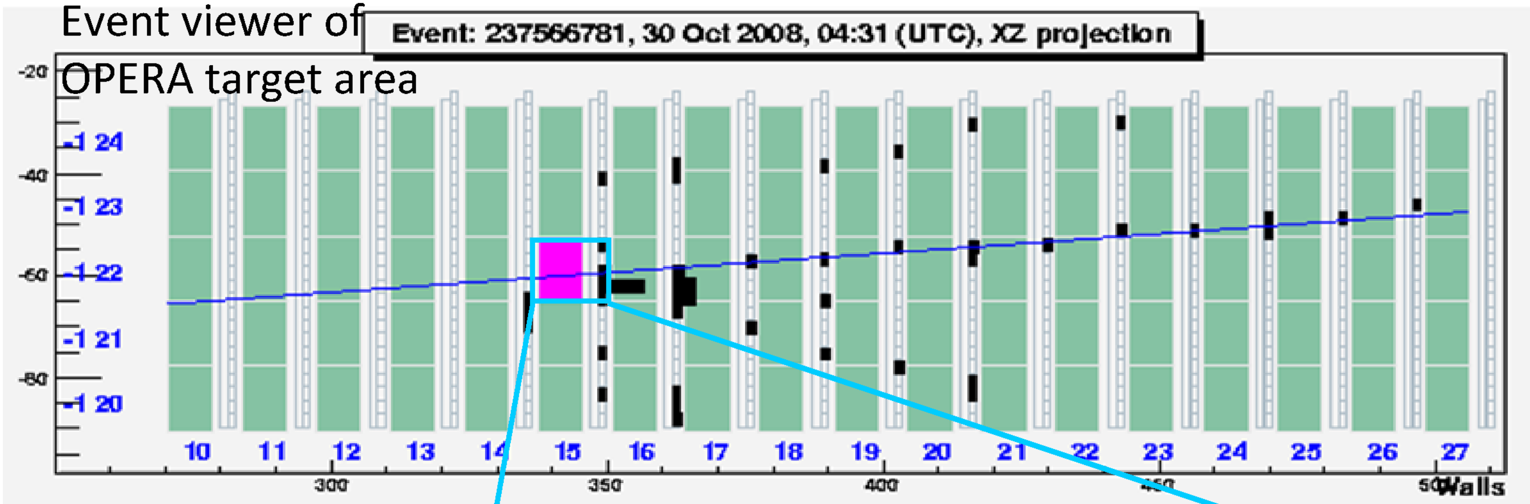
Target area
(ECC+ Target Tracker)

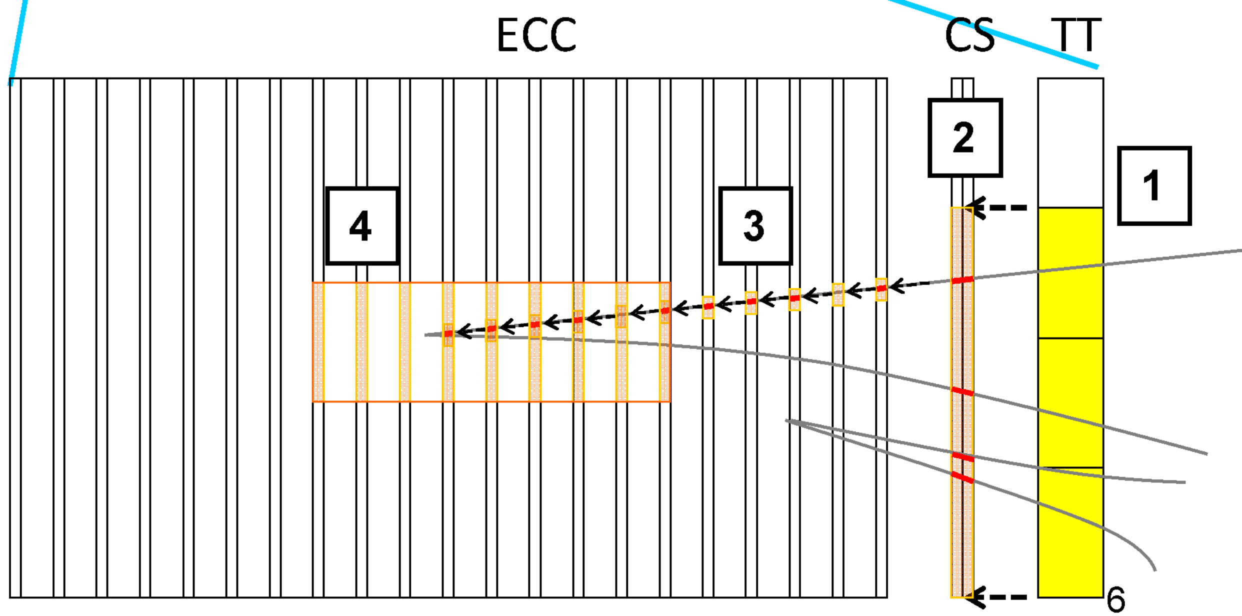
Muon spectrometer

Total target mass ~ 1.25kton

Location of neutrino interactions in ECC

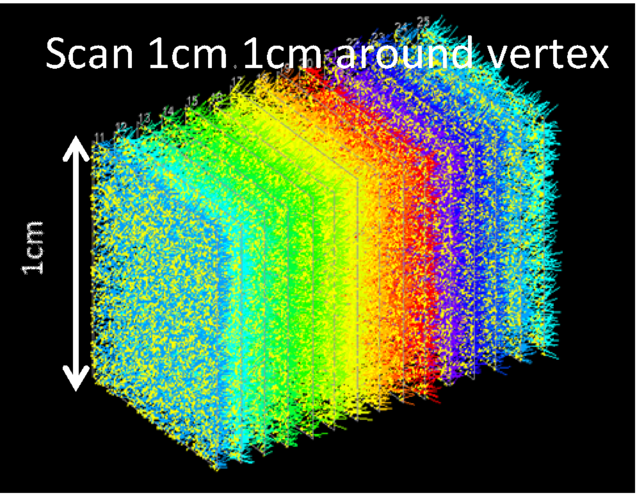
Event viewer of OPERA target area

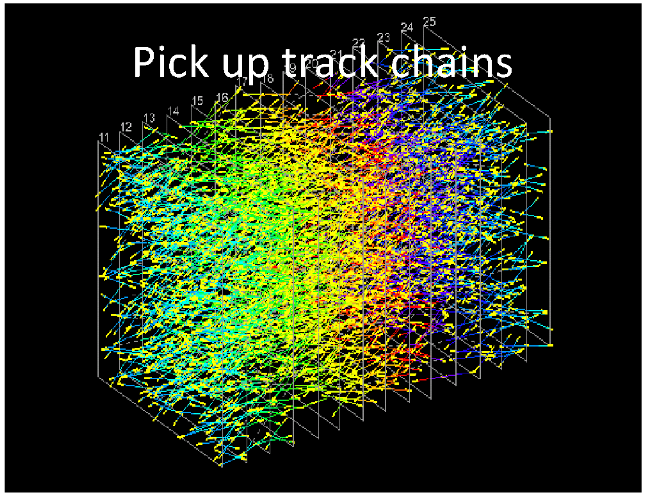


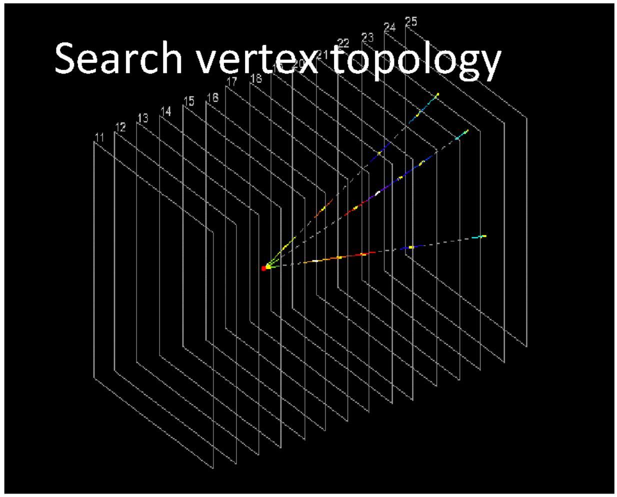


1. Select the most probable ECC containing the ν interaction using TT hits
2. Check CS to confirm the ECC and find tracks coming from ν interaction
3. Follow back tracks to interaction vertex in the ECC
4. Scan 10 films around interaction vertex

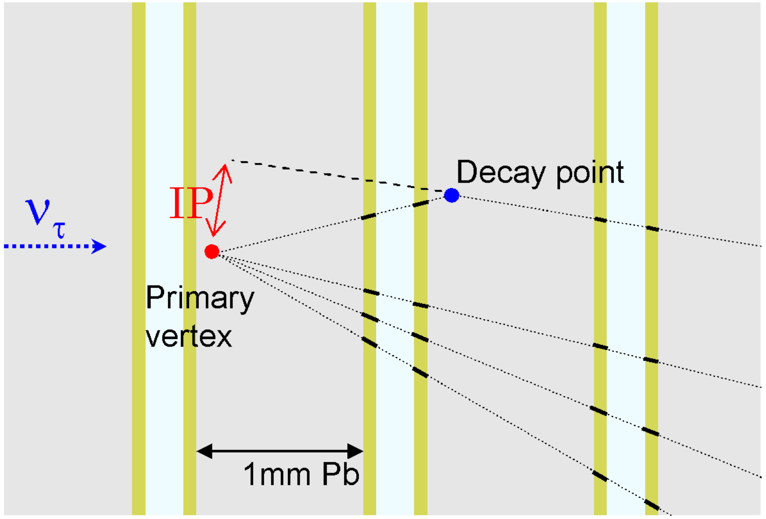
Search for decay topologies



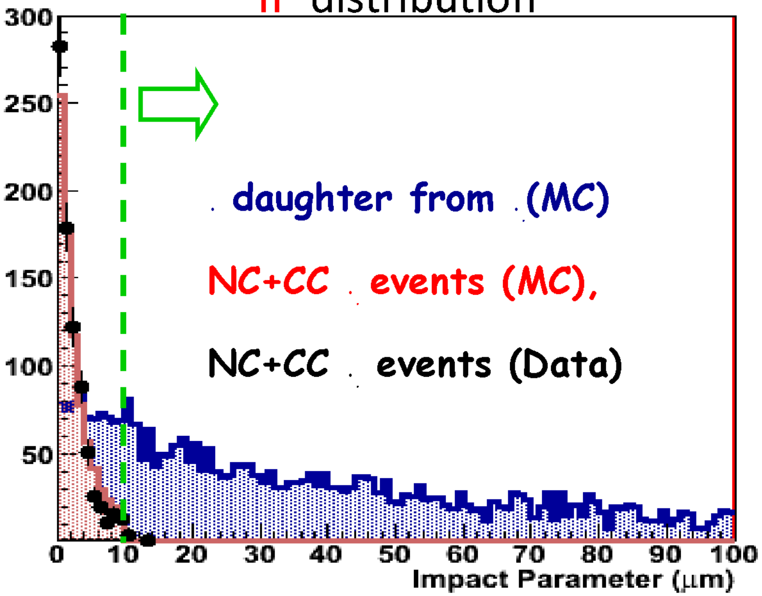




Search track which have large Impact Parameter (IP)

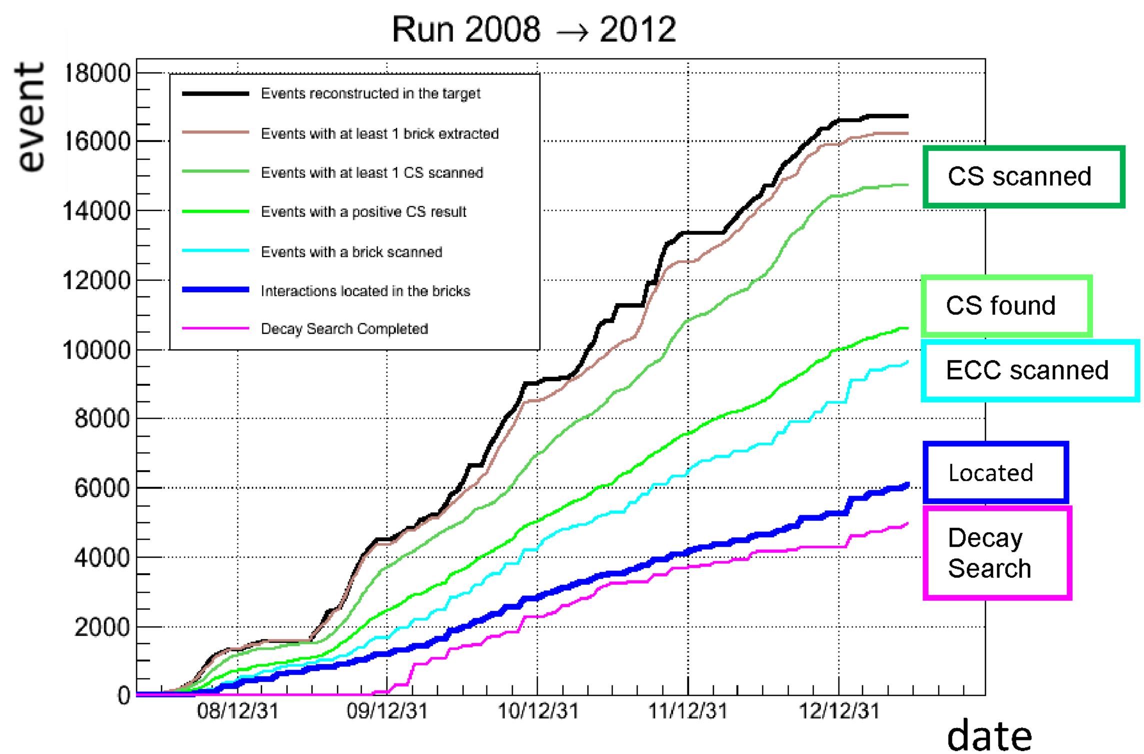


IP distribution



Beam exposure and analysis status

year	POT
2008	1.74×10^{19}
2009	3.53×10^{19}
2010	4.09×10^{19}
2011	4.75×10^{19}
2012	3.86×10^{19}
Total	17.97×10^{19}



- 5 years run was successfully done
- Total POT is 80% of the proposal value (22.5×10^{19} POT)

- 2008 and 2009 data samples are completely analyzed
- 2010-12 data are on going with optimised strategy
- Located: 6067, Decay search: 4969

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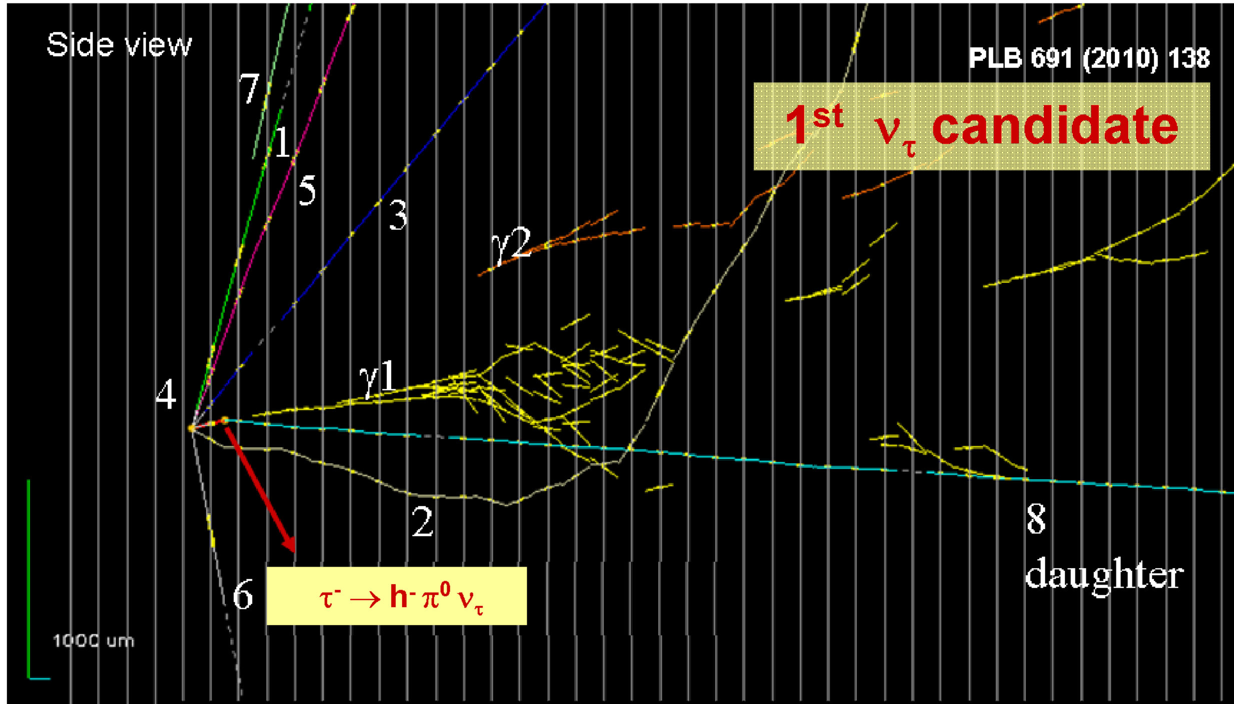
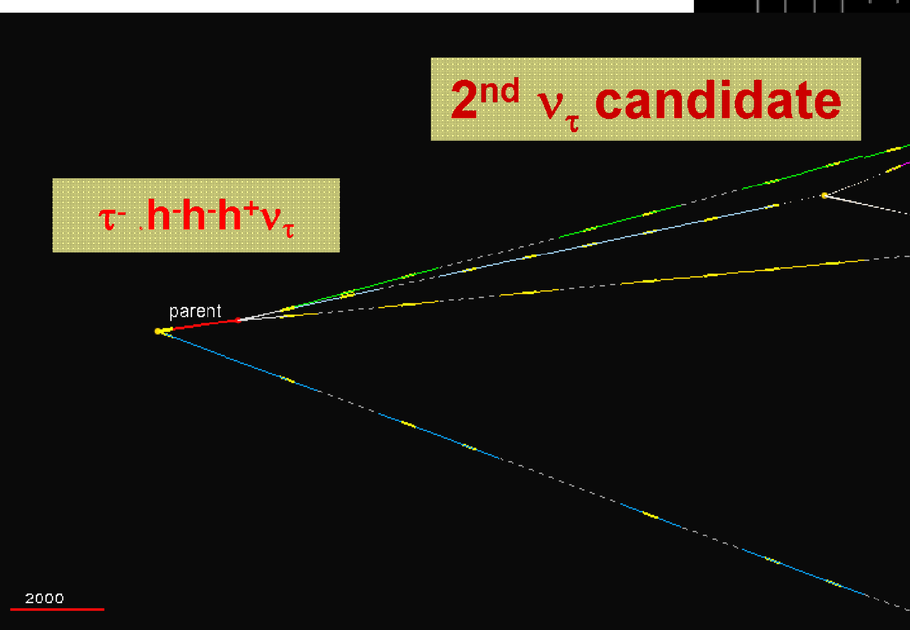
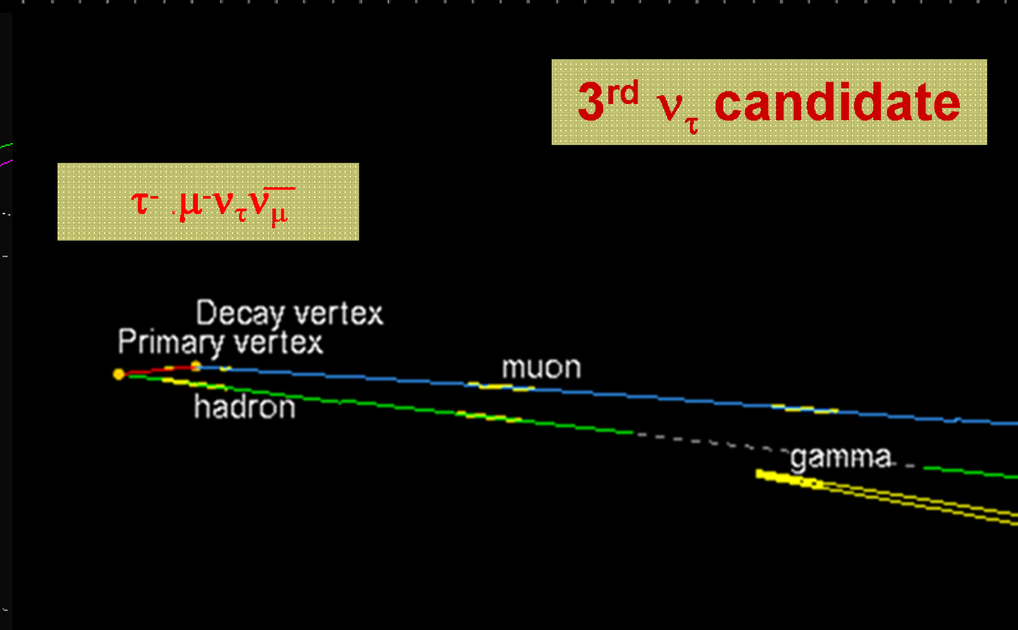
ν_τ events

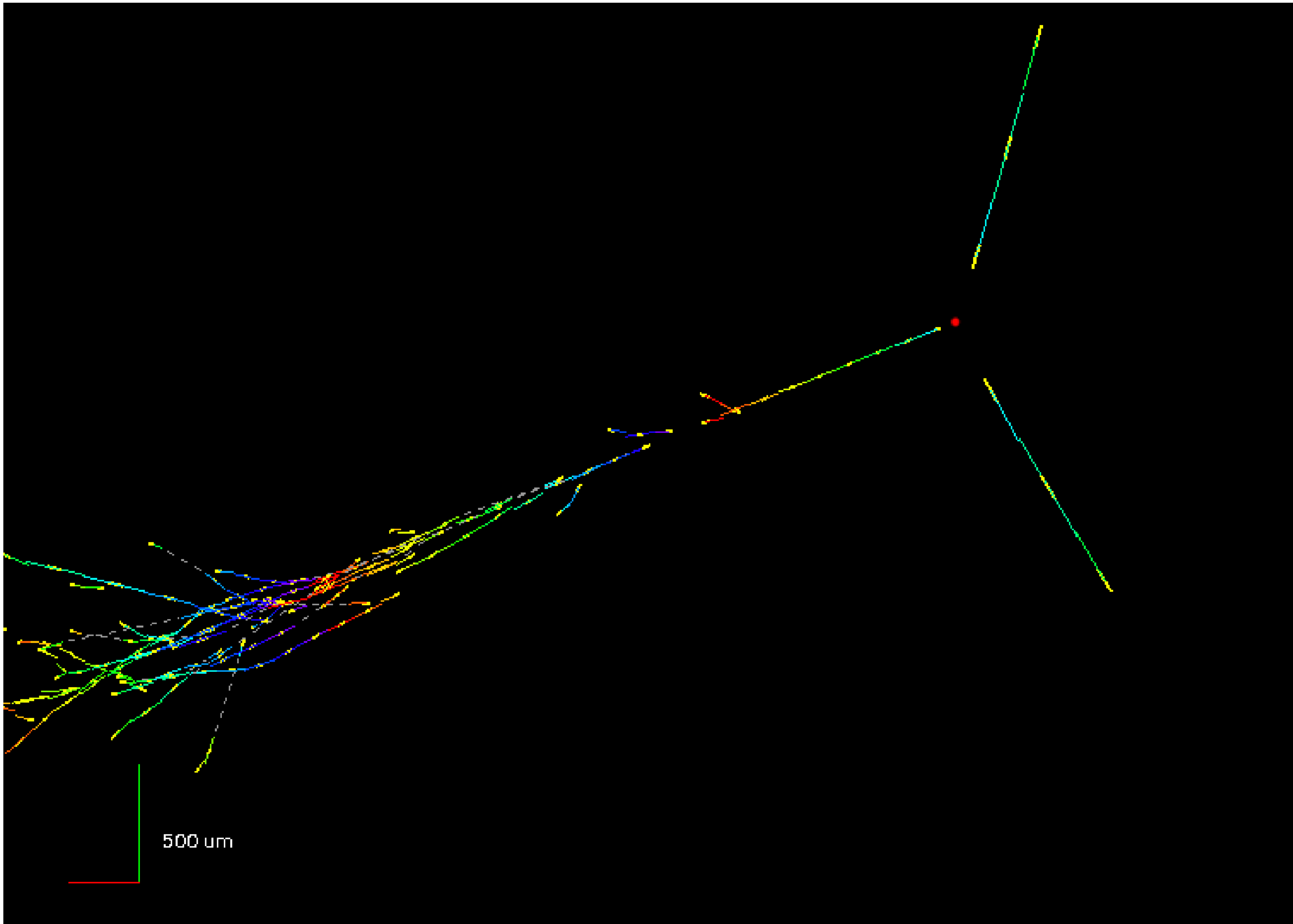
The recent results of ν_τ search will be reported by the next speaker, S.Dmitrievsky.





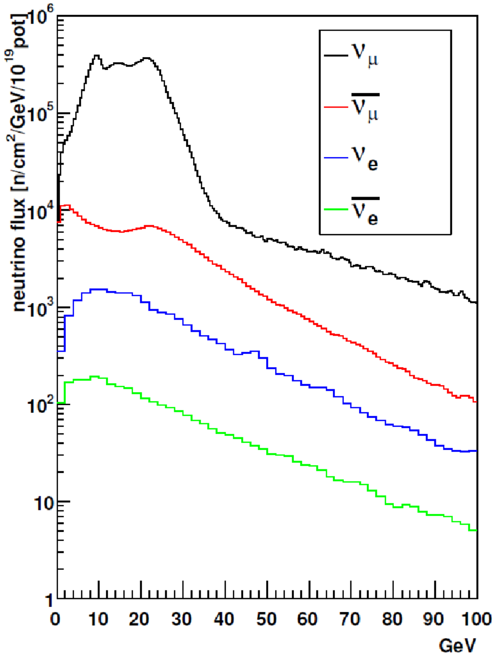


$\nu_\mu \rightarrow \nu_e$ oscillation analysis in OPERA



$\nu_\mu \rightarrow \nu_e$ oscillation analysis in OPERA

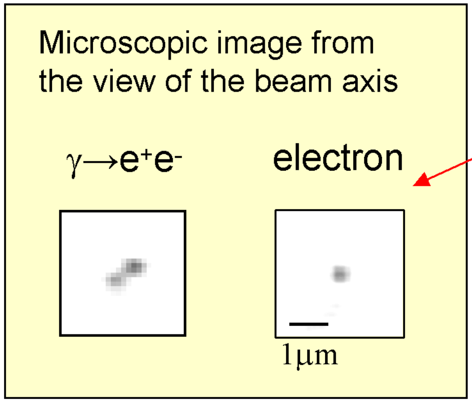
- prompt ν_e contamination of CNGS neutrino beam is ~1%
  –> prompt ν_e is the main background for oscillation analysis
  –> optimize energy region

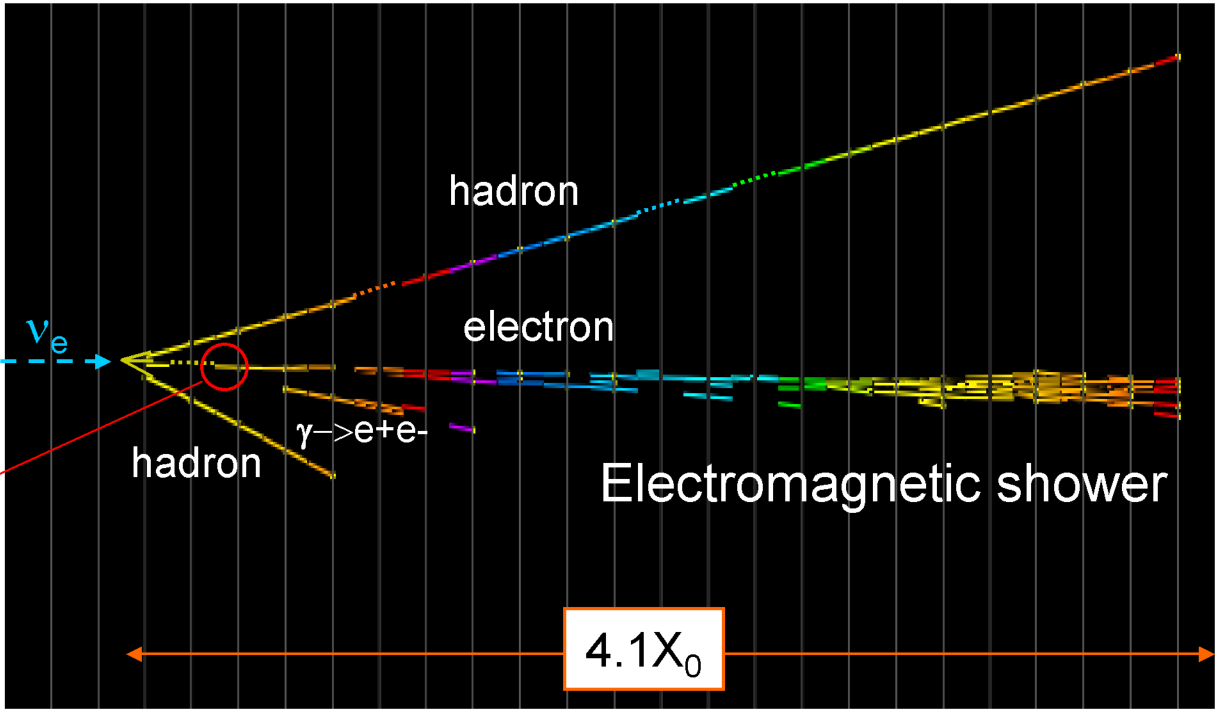


- CNGS neutrino beam is wide-band spectrum
  –> sensitive to high Δm^2 region

Search for ν_e events in the 505 located events which didn't have no muon identified by the electronic detector (0μ events) of 2008-2009 data set

Electron Identification in ECC





- Primary electron track observed as an isolated track, not pair tracks

fine position resolution of nuclear emulsion and fine segmentation (track reconstruction each 1mm lead plate ($0.18X_0$)) in ECC
–> separate electron from γ–>e+e-

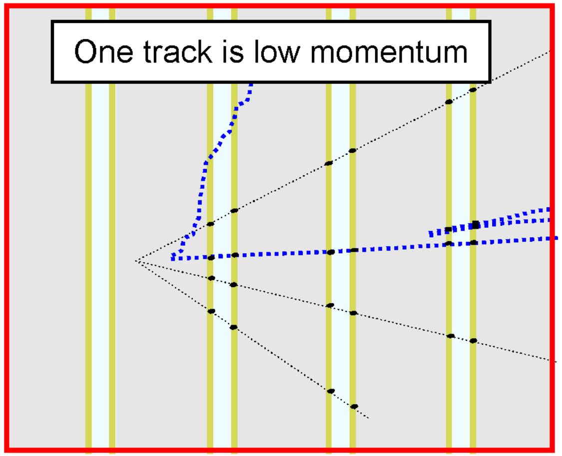
- Electromagnetic shower developed in ECC

–> separate electron from pion

Background estimation
(misidentified as ν_e)

- π^0 decay

  γ conversion nearby the vertex and e+e- are not observed pair track



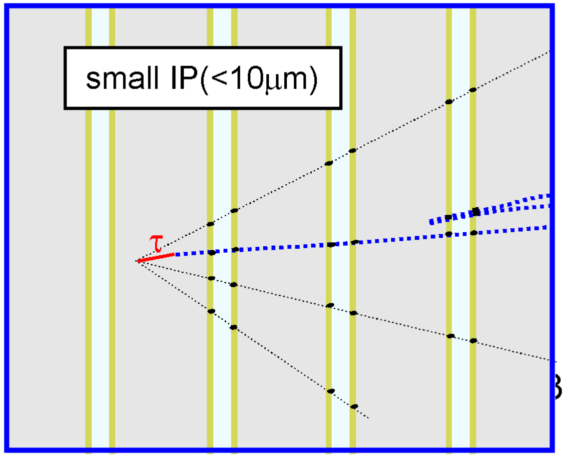
→Estimate from the data sample

γ converting in the second and third lead plates after the interaction vertex were searched in the 1106 ν interactions

0.2 ± 0.2 (inclusive)

- τ–>e decay

  the electron track has small impact parameter (IP<10μm) to the primary vertex



→Estimate from MC simulation

0.3 ± 0.1 (inclusive)

ν_e energy estimation

- Reconstruct the energy deposition (E_{vis}) in Target Tracker.
- Obtain the fitting parameter from E_{vis} to reconstructed ν_e energy ($E_{\nu e\_rec}$) through the MC simulation.

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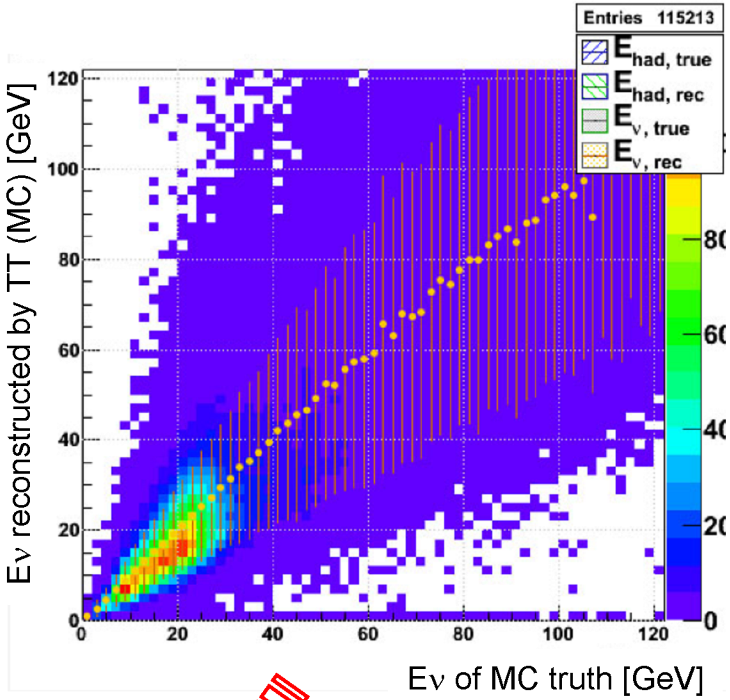
Estimate the $E_{\nu e\_rec}$

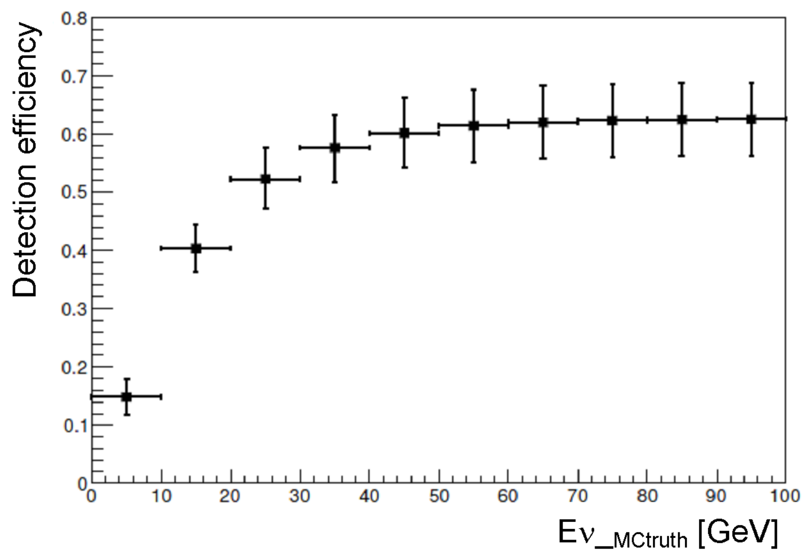


Energy resolution

$$\Delta E / E = 0.37 + 0.74 / \mathrm{sqrt}(E)$$

Estimation of detection efficiency

Detection efficiency is estimated by the full simulation (based on GEANT3), reproduces the analysis procedure for the data.

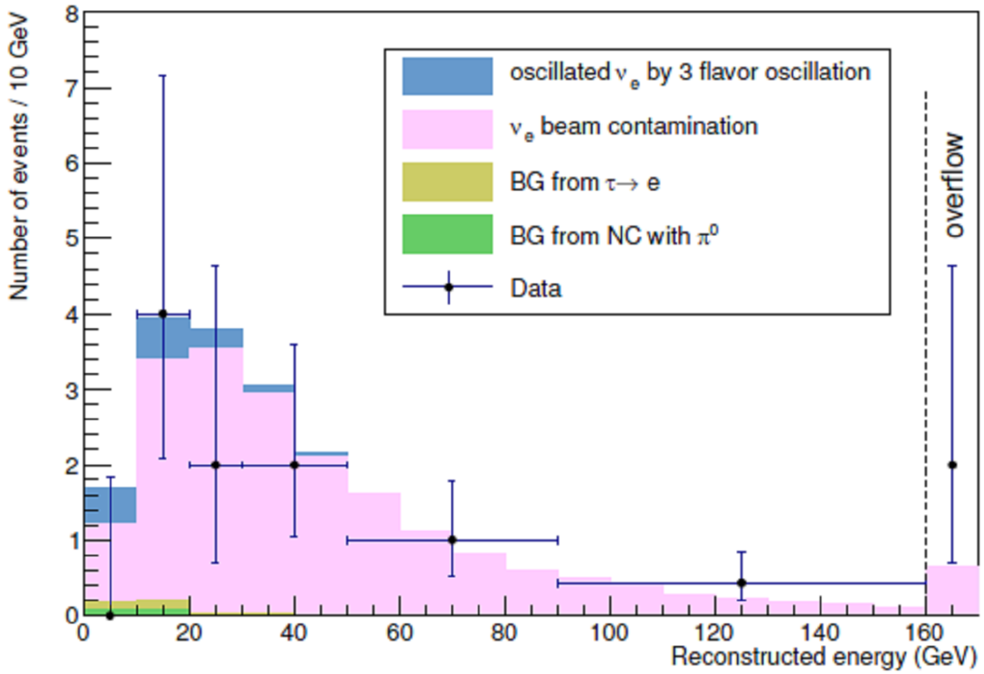


By considering all analysis strategies tuned along the years,
Set the uncertainty 20% (Eν<10GeV) and 10% (Eν>=10GeV)

Analysis of 2008-2009 data sample

(5.27x10^{19} POT)

19 ν_e events observed out of 505 0μ events



Systematic Uncertainty

1. Beam flux 10%
2. Detection efficiency
   10%(Eν>=10GeV)
   20%(Eν<10GeV)

Expected number of background ν_e events :19.8 ± 2.8(sys)

prompt ν_e, NC with π^0, τ->e

-> Observation agrees with background expectation

ν_μ->ν_e oscillation analysis

- 3 flavor mixing model

$$P_{\nu\mu\rightarrow\nu e} = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Delta_{31} + (higher\ order)$$

$\sin^2\theta_{23} = 0.5,\ \sin^2\theta_{12} = 0.311, \Delta m_{32}^2 = 2.32\times10^{-3} eV^2, \Delta m_{21}^2 = 7.50\times10^{-5}(eV^2)$
assuming $\delta = 0$, Normal Hierarchy and neglecting matter effects

- non-standard oscillation
  (analysis for LSND-MiniBooNE observation results)

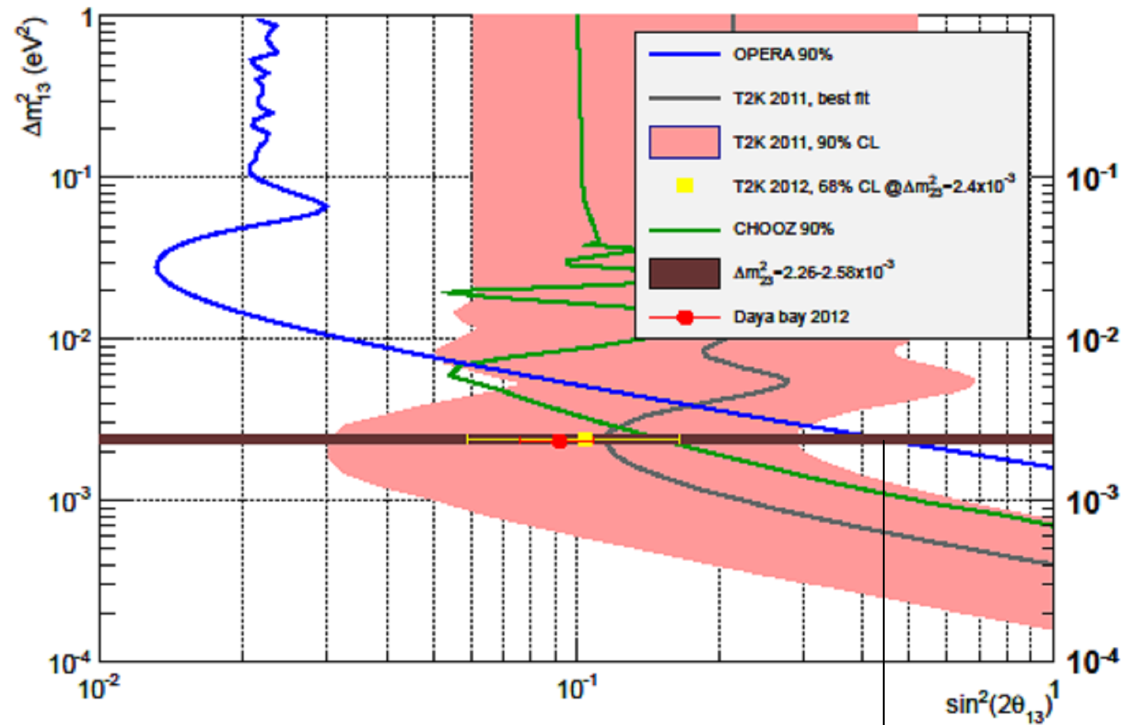
  in the one mass scale dominance approximation

$$P_{\nu\mu\rightarrow\nu e} \sim \sin^2(2\theta)\cdot\sin^2(1.27\cdot\Delta m^2\cdot L/E)$$

OPERA $\nu_\mu \to \nu_e$ oscillation results

(in 2008+2009 data set)

3 flavor mixing model for standard oscillation



Upper limit (90%C.L.) @$\Delta m^2_{13}=2.32\times10^{-3}$ eV^2

$\sin^2(2\theta_{13}) = 0.44$

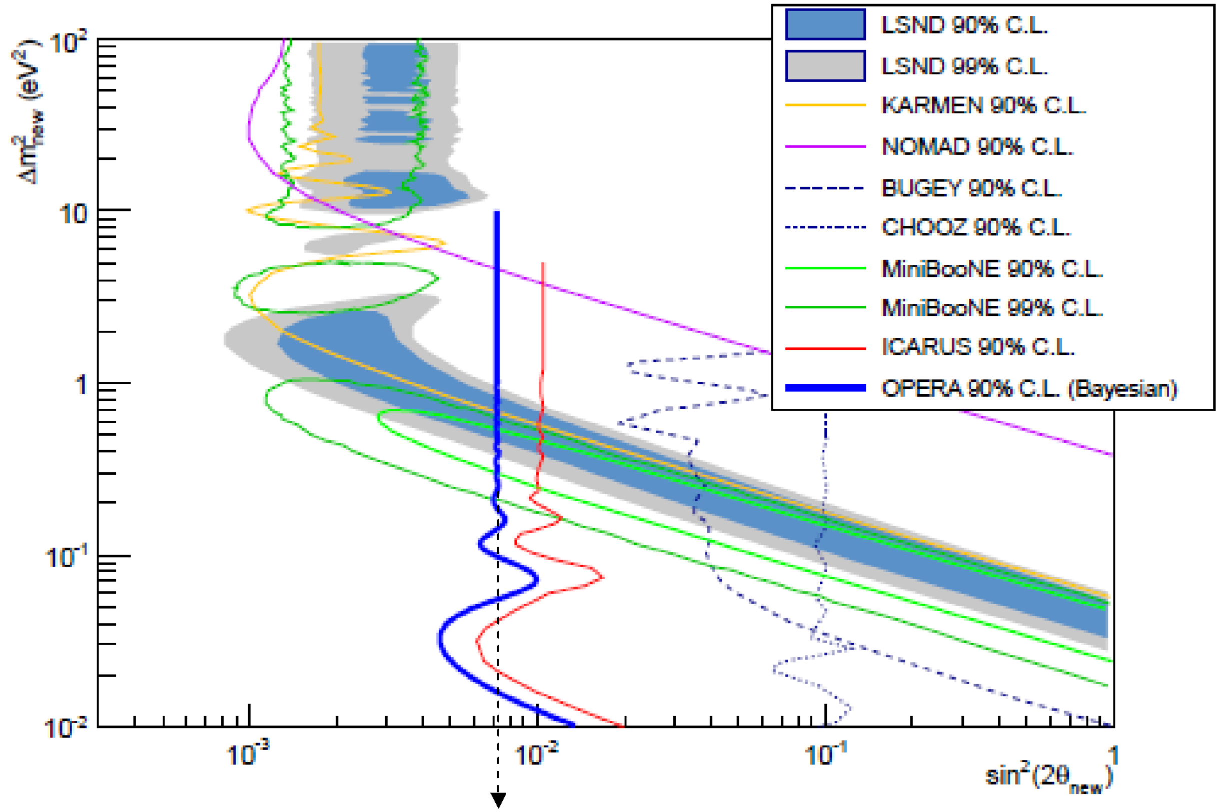
$N_{expBG} = 4.6 \pm 0.7$(sys), $N_{obs} = 4$ (E_{ν_rec}<20GeV)

Observation is compatible with non-oscillation hypothesis

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

(in 2008+2009 data set)

2 flavor mixing model for non-standard oscillation with a dominant mass scale



$N_{expBG} = 9.4 \pm 1.3$(sys)

$N_{obs} = 6$

(E_{ν_rec}<30GeV)

Upper limit (90%C.L.) @largeΔm^2

$\sin^2(2\theta) = 7.2\text{x}10^{-3}$

Conclusions

<Analysis status>

- OPERA runs from 2008 to 2012 were successfully carried out.
- 17.97 x 10^{19} POT collected, about 80% of proposal value 22.5 x 10^{19} POT.
- 3 ν_τ events have been found up to now.

<ν_μ–>ν_e oscillation search>

- 19 ν_e events observed in 2008-2009 data set
- in the 3 flavor mixing model

  4 events observed vs 4.6 ± 0.7 expected (E_{rec}<20GeV)

  –> upper limit (90%C.L.) $\sin^2(2\theta_{13}) < 0.44$ @ $\Delta m^2_{13}=2.32\times10^{-3}eV^2$
- non-standard oscillations

  6 events observed vs 9.4 ± 1.3 expected (E_{rec}<30GeV)

  –> upper limit (90%C.L.) $\sin^2(2\theta) < 7.2\times10^{-3}$

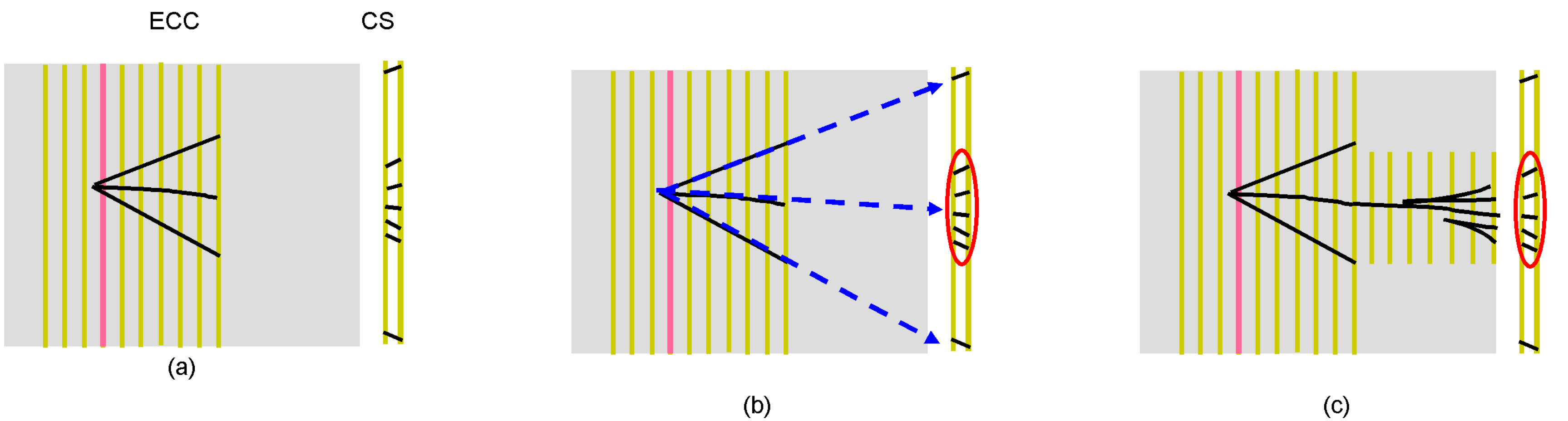
Statistics increase x3.4 for 5 years run's data set

In addition, considering an improvement of energy resolution and detection efficiency

Back Up

Event Trigger

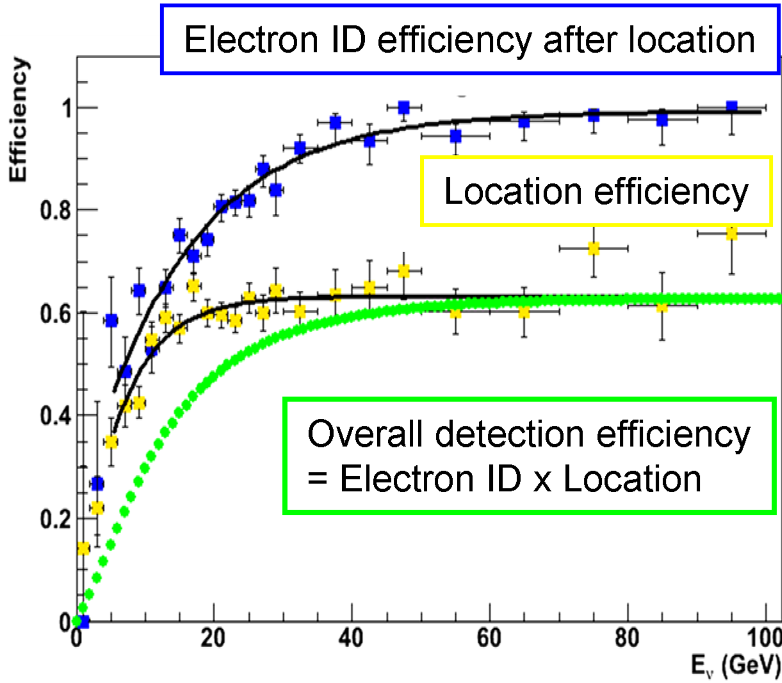
CS shower tracks



To improve the location efficiency of low energy neutrino events

- Shower track search in ECC instead of CS
- Full emulsion plates scanning of ECC, and then reconstruct VTX and identify the electron

Estimation of detection efficiency



CS shower hint

Scan Back
(normal procedure
for location)

	C.L.	Upper limit F&C	Upper limit Bayes	Sensitivity F&C	Sensitivity Bayes
Number of oscillated ν_e events	90%	3.1	4.5	6.1	6.5
	95%	4.3	5.7	7.8	7.9
	99%	6.7	8.2	10.7	10.9
$\sin^2(2\theta_{\mathrm{new}})$ at large Δm^2	90%	5.0×10^{-3}	7.2×10^{-3}	9.7×10^{-3}	10.4×10^{-3}
	95%	6.9×10^{-3}	9.1×10^{-3}	12.4×10^{-3}	12.7×10^{-3}
	99%	10.6×10^{-3}	13.1×10^{-3}	17.1×10^{-3}	17.4×10^{-3}

Energy cut	Upper limit F&C	Upper limit Bayes	Sensitivity F&C	Sensitivity Bayes
20 GeV	8.5×10^{-3}	10.4×10^{-3}	14.2×10^{-3}	14.2×10^{-3}
30 GeV	5.0×10^{-3}	7.2×10^{-3}	9.7×10^{-3}	10.4×10^{-3}
No cut	8.6×10^{-3}	9.5×10^{-3}	10.8×10^{-3}	11.0×10^{-3}