Status of studies of an ICANOE-like detector at the Neutrino Factory

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ICANOE at the Neutrino Factory

ICANOE is one of the two large detectors proposed for the CERN-Gran Sasso beam.

- Liquid Argon target for fine-grained event imaging
- Calorimeter modules for tail-catching and muon charge+momentum determination

→Good detector for a Neutrino Factory

Possible baselines

With the high fluxes foreseen at the Neutrino Factory we can think of very long baselines:

Ring location	Distance to GS	Mean density
CERN	732 km	2.8 g/cm^3
Canary	2900 km	3.2 g/cm^3
FNAL	7400 km	3.7 g/cm^3
KEK	8815 km	4.0 g/cm^3

Event rates for a 10 kton detector

Rates				
		L=732 km	L=2900 km	L=7400 km
μ^- 10^{20} decays	ν_μ CC	226000	14400	2270
	ν_μ NC	67300	4120	680
	$\bar{\nu}_e$ CC	87100	5530	875
	$\bar{\nu}_e$ NC	30200	1990	300
μ^+ 10^{20} decays	$\bar{\nu}_\mu$ CC	101000	6380	1000
	$\bar{\nu}_\mu$ NC	35300	2240	350
	ν_e CC	197000	12900	1980
	ν_e NC	57900	3670	580

E_μ=30 GeV

No oscillations

No polarization

No beam divergence

Neutrino Oscillations

Experimentally, we can study in principle 12 independent processes:

$\mu^- \rightarrow e^-$	$\bar{\nu}_e$	ν_μ		
		$\nu_e \rightarrow e^-$		appearance
		$\nu_\mu \rightarrow \mu^-$		disappearance
		$\nu_\tau \rightarrow \tau^-$		appearance
	$\bar{\nu}_e \rightarrow e+$			appearance
	$\bar{\nu}_\mu \rightarrow \mu+$			disappearance
	$\bar{\nu}_\tau \rightarrow \tau+$			appearance

Plus their charge conjugates with μ^+ beam

Oscillation probabilities:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta_{13} \Delta_{32}{}^2$$

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta_{13} \sin^2 \theta_{23} \Delta^2{}_{32}$$

$$P(\nu_e \rightarrow \nu_\tau) = \sin^2 2\theta_{13} \cos^2 \theta_{23} \Delta^2{}_{32}$$

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4\cos^2 \theta_{13} \sin^2 \theta_{23} (1 - \cos^2 \theta_{13} \sin^2 \theta_{23}) \Delta^2{}_{32}$$

$$P(\nu_\mu \rightarrow \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \Delta^2{}_{32}$$

$$P(\nu_\tau \rightarrow \nu_\tau) = 1 - 4\cos^2 \theta_{13} \cos^2 \theta_{23} (1 - \cos^2 \theta_{13} \cos^2 \theta_{23}) \Delta^2{}_{23}$$

$$\Delta_{32}{}^2 = \sin^2(1.27 \Delta m_{32}{}^2 L / E)$$

Event classes in ICANOE-like detector

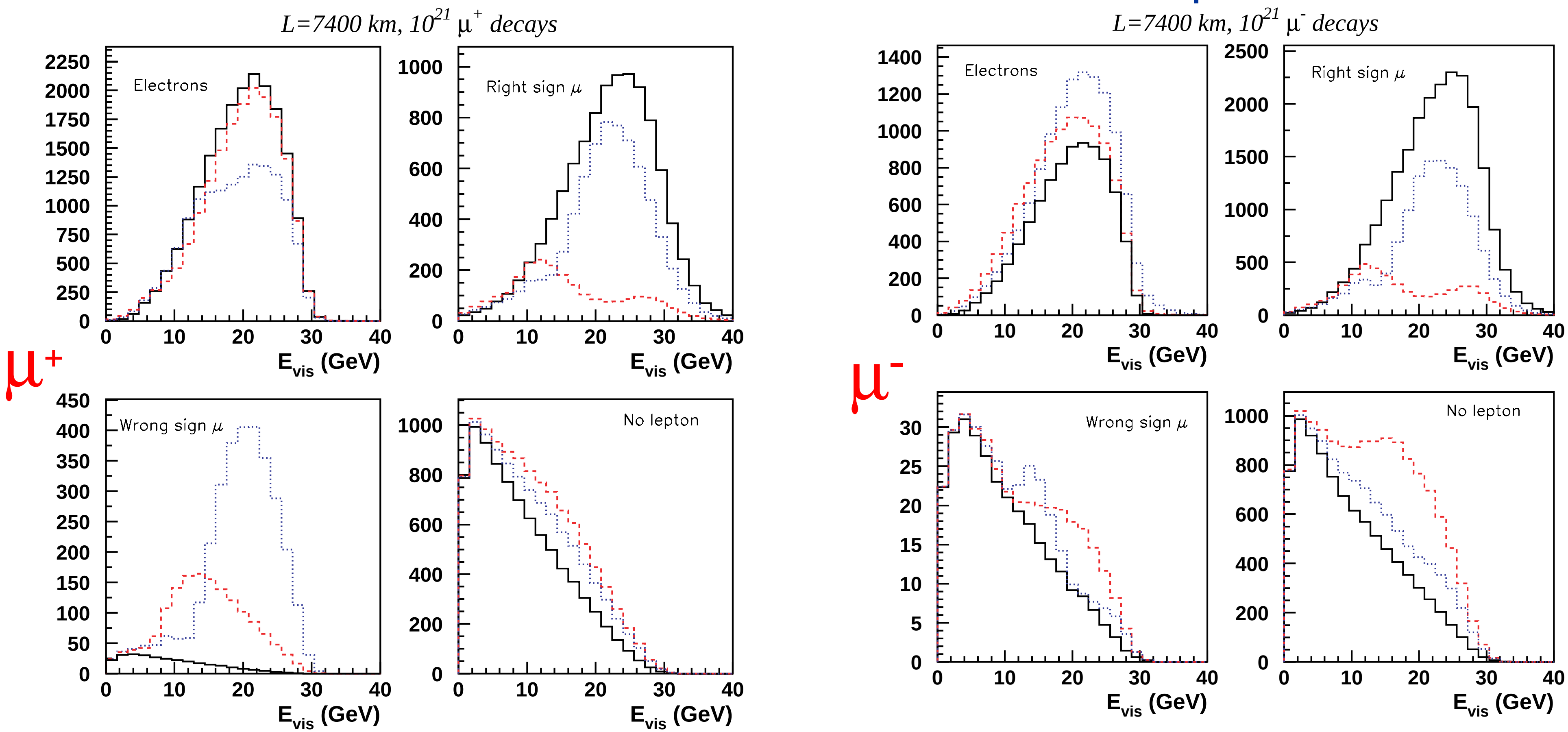
Detector able to identify γ, e, μ and hadrons,
charge is measured only for muons.

Events can be classified into four classes, according to the leading particle:

- ✯Electron of any charge
- ✯Muons of same sign as those circulating in ring
- ✯Muons of opposite sign (oscillation, or bg)
- ✯No leading leptons

Observed Spectra

Neutrino oscillations visible in the spectra:



No oscillation

$\Delta m^2 = 3.5\ 10^{-3}\ eV^2$

$\Delta m^2 = 7\ 10^{-3}\ eV^2$

$\theta_{23} = \pi/4$

$\sin^2\theta_{13} = 0.05$

ICANOE fast simulation

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Detector simulation

ICANOE fully simulated for CNGS studies.

For this study, events fully simulated and passed through ICANOE fast simulation.

$$\frac{\sigma(E)_{e.m.}}{E} = \frac{3\%}{\sqrt{E(GeV)}} \qquad \frac{\sigma(E)_{had}}{E} = \frac{20\%}{\sqrt{E(GeV)}} \qquad \frac{\sigma(P_\mu)}{P_\mu} = 20\%$$

$$\frac{\sigma(\theta)}{\theta} = 130 mrad / \sqrt{p(GeV)}$$

Proper neutrino cross section used

Charged $\pi^\pm$,$K^\pm$ decay into $\mu^\pm$ for BG treatment

Fitting procedure

Parameters are determined by fit of visible energy from the different classes.

We use:

- χ^2 for $>$40 events in bin
- -log **L** $<$40 events in bin

Beam systematics: 2% uncorrelated (25 bins)

Background added in fit

Earth density and oscillation parameters can vary in the fit or be fixed to reference value

Parameters used

For this study, we consider as our default:

- $2*10^{20}$ decays of 30 GeV $(\mu^+ + \mu^-)$
- 3-family mixing with:
  - $\Delta m^2_{23}=(3.5, 5, 7) * 10^{-3}$ eV^2
  - $\sin^2\theta_{23}=0.5$
  - $\sin^2 2\theta_{13}=0.05$
- 10 kton ICANOE-like detector

Goals of Experiments at NUFACT

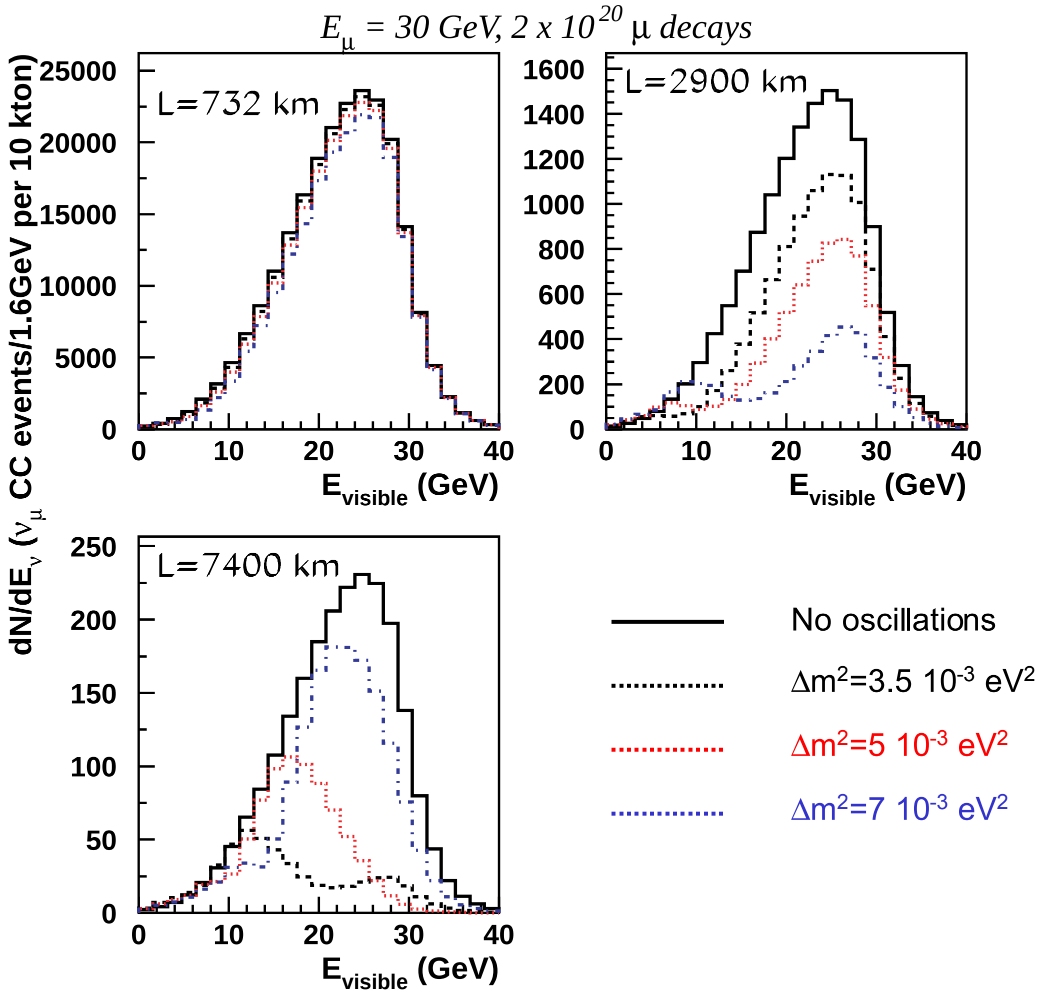
For second generation long baseline experiments, the main goals will be:

- ✯ Precise determination of Δm^2_{23} and Θ_{23}
- ✯ Measurement of Θ_{13}
- ✯ Study of matter effects
- ✯ Study of CP violation

Precise determination of $\Delta m^2_{23}, \Theta_{23}$

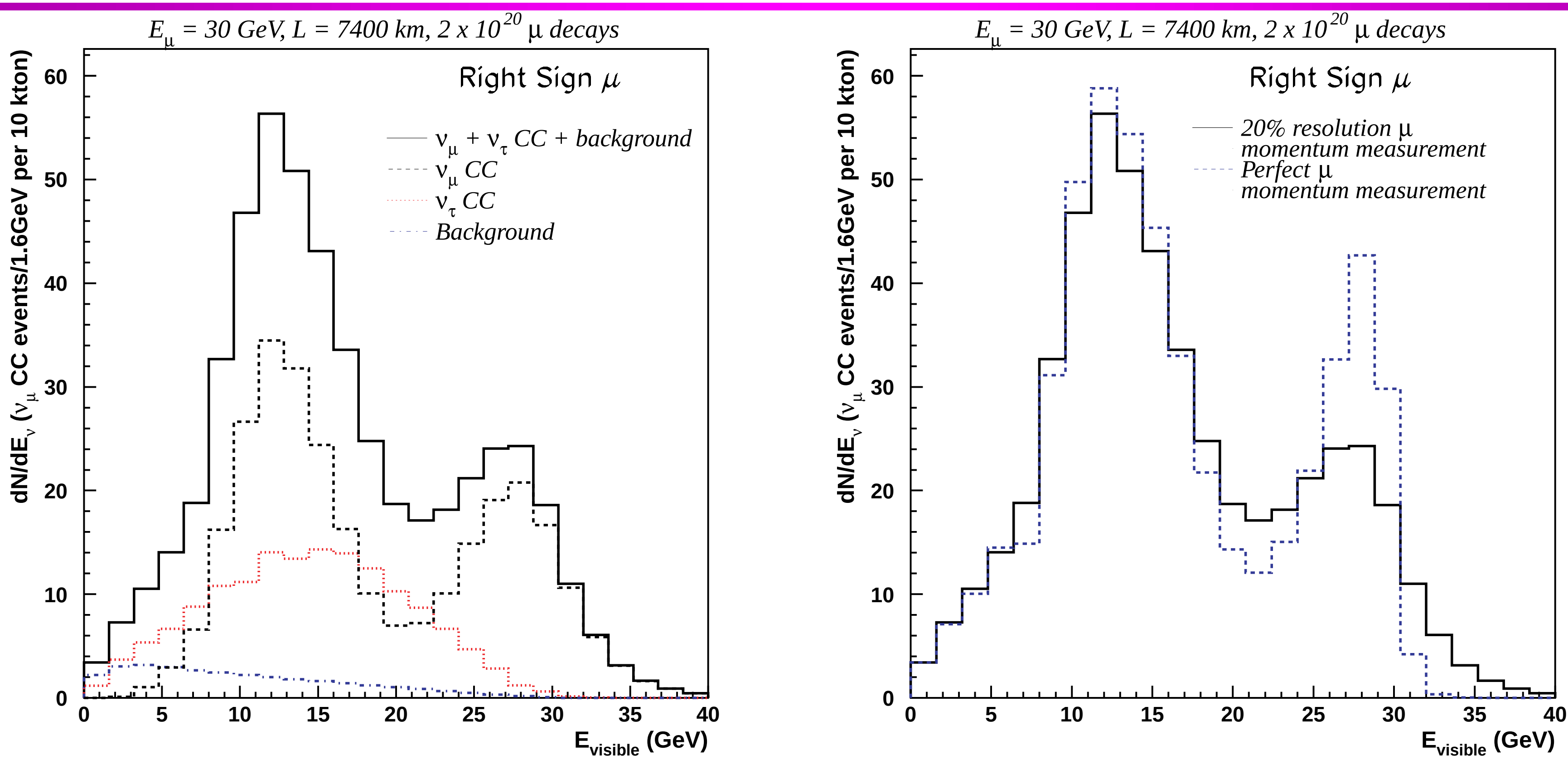
Assume $\Theta_{13} = 0$ ⇨ 2-family $\nu_\mu \rightarrow \nu_\tau$ oscillations

Disappearance dip
at large distances
for right-sign μ :



- Position: Δm^2_{23}
- Height: Θ_{23}

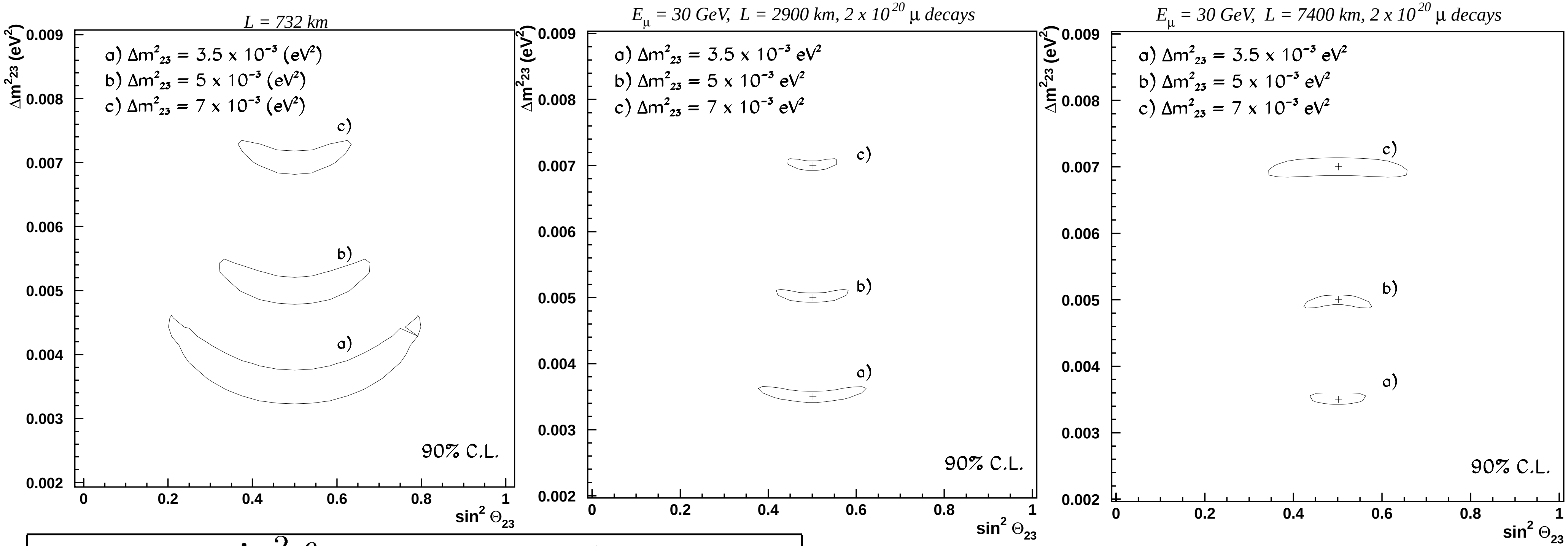
Right–sign muon disappearance



Contributions to events in the dip:

- Resolution
- $\nu_\mu \rightarrow \nu_\tau \rightarrow \tau \rightarrow \mu$ decays
- background

Sensitivity for $\Delta m^2_{23},\theta_{23}$ measurements



$\sin^2\theta_{23}$ measurement		
Δm^2_{23} (eV^2)	L=2900 km	L=7400 km
7×10^{-3}	0.50 ± 0.11	0.50 ± 0.04
5×10^{-3}	0.50 ± 0.06	0.50 ± 0.06
3.5×10^{-3}	0.50 ± 0.05	0.50 ± 0.09

Event simulation includes:
- Background
- Exclusive τ decays
- Resolution

2% Beam systematics

Consistent with Barger et al. hep-ph/9911524

Error on Δm^2_{23}=1%

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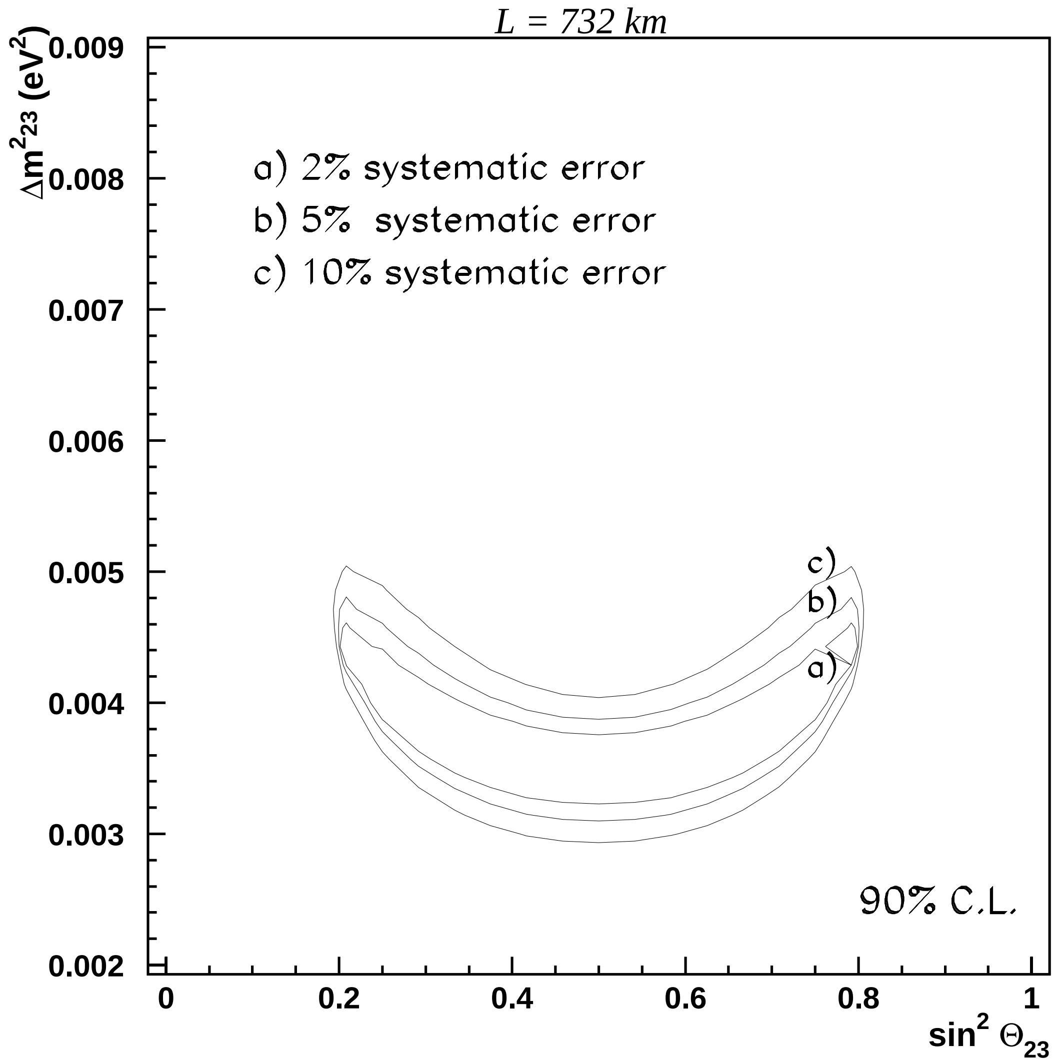
Beam systematic

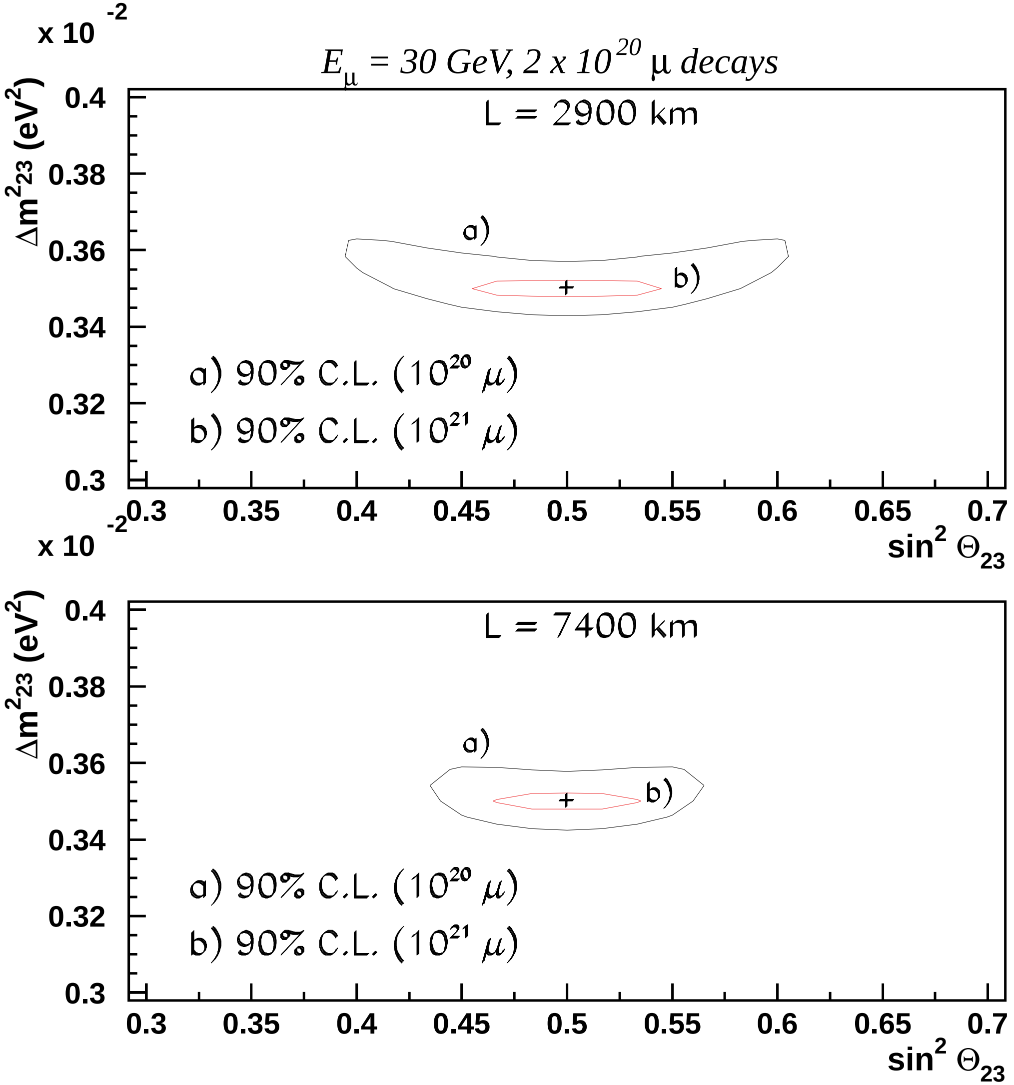
Systematic error on flux only relevant for L=732 km, where oscillation effect is small



Statistical improvements

A factor 10 more statistics can still improve the measurement at very long distances

(2% systematics)



3–family mixing

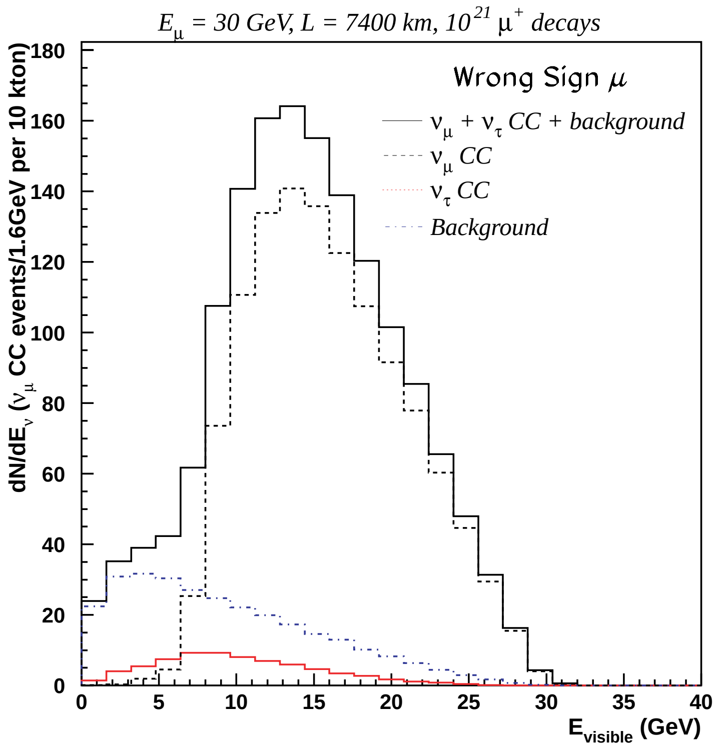
With $\Theta_{13} \neq 0$, all flavors mix.

Assuming $\Delta m^2_{23} > 0$, oscillations involving ν_e ($\bar{\nu}_e$) are enhanced (suppressed) by MSW interactions with matter

Effect can be spectacular for wrong-sign muons

Contributions to wrong-sign muons:

- $\nu_e \rightarrow \nu_\mu$
- $\nu_e \rightarrow \nu_\tau \rightarrow \tau \rightarrow \mu$



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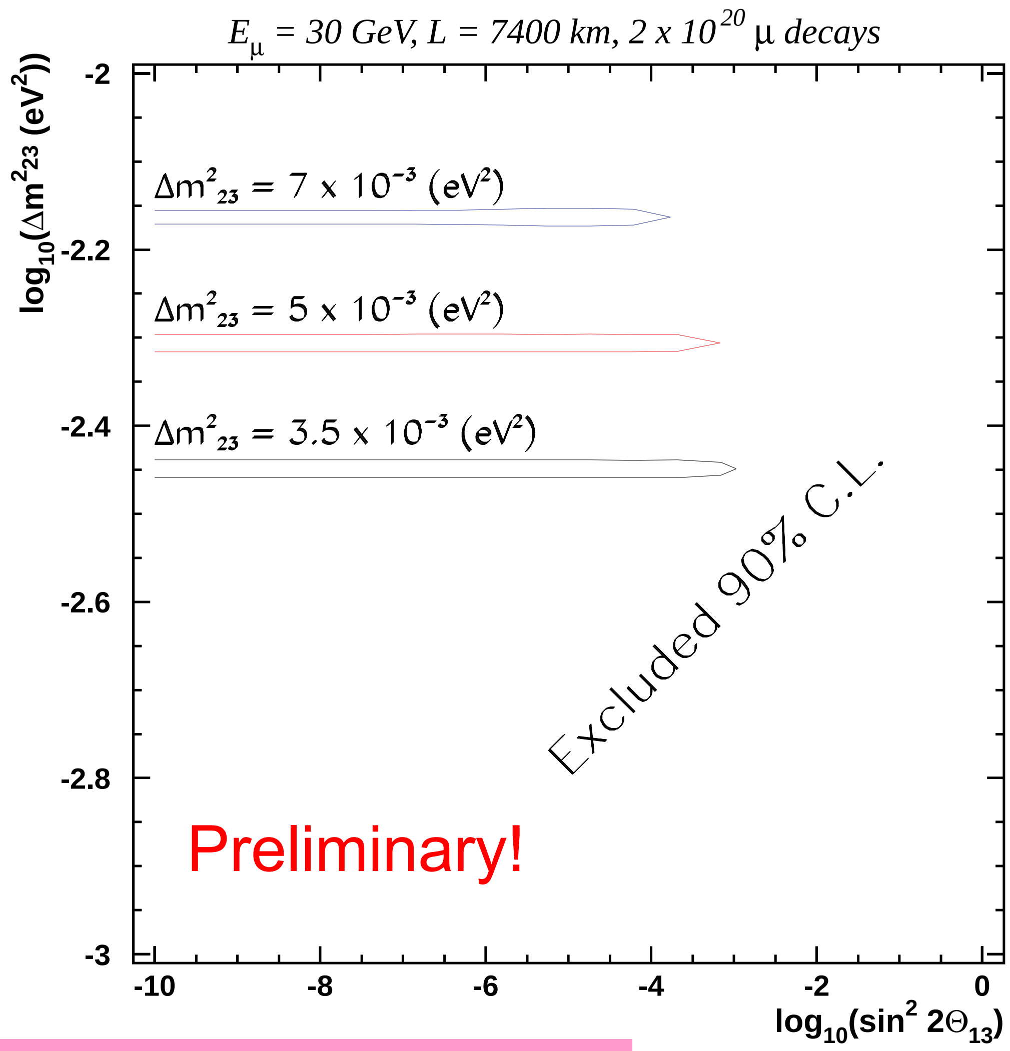
Sensitivity to θ_{13}

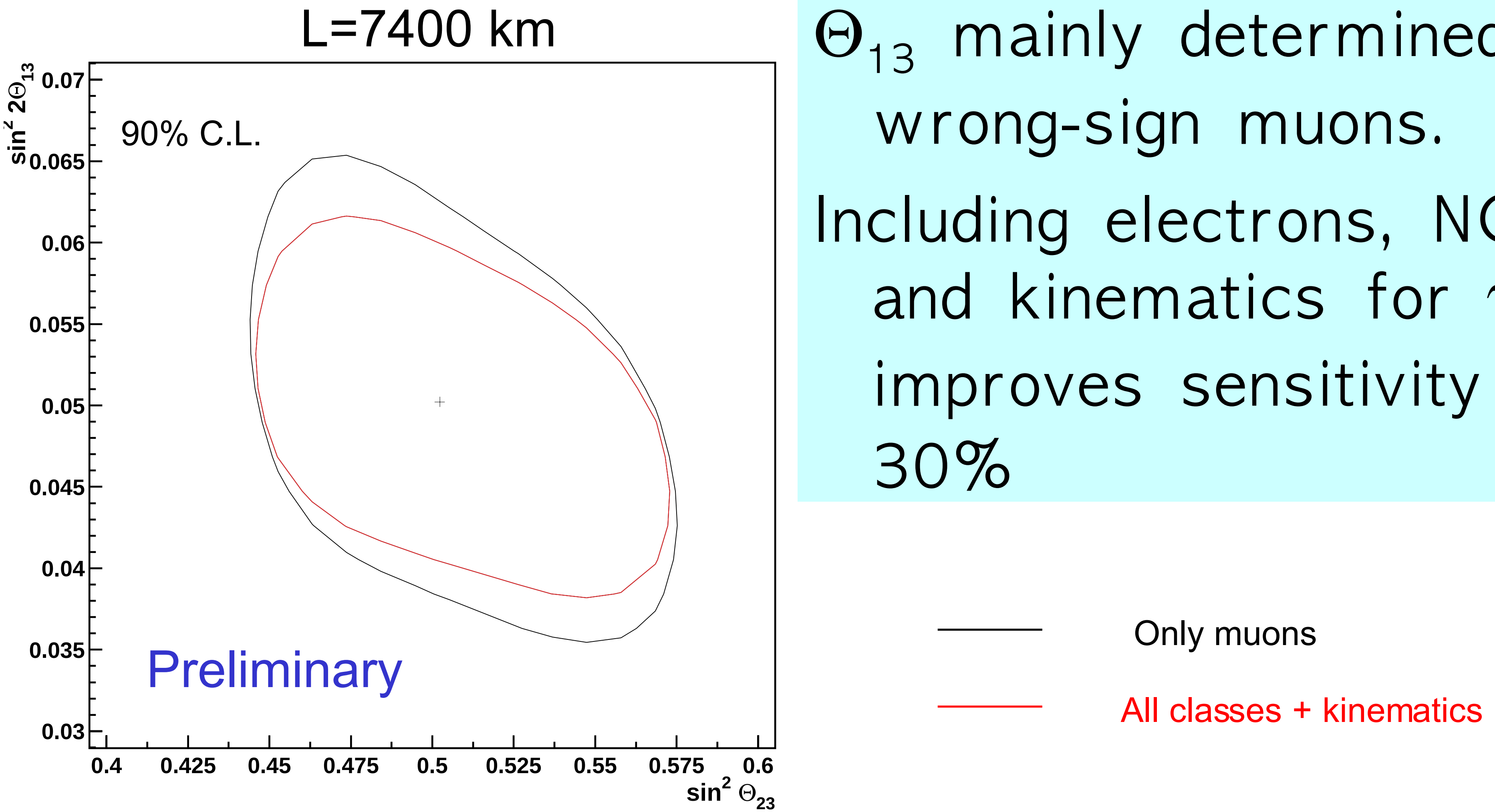
Sensitivity to Θ_{13} for different values of Δm^2_{23}, using all classes and kinematics.

Similar sensitivity for L=2900 km.



2 orders of magnitude better than ICANOE at CNGS

Measurement of Θ_{13}



Θ_{13} mainly determined by wrong-sign muons.

Including electrons, NC and kinematics for τ improves sensitivity by 30%

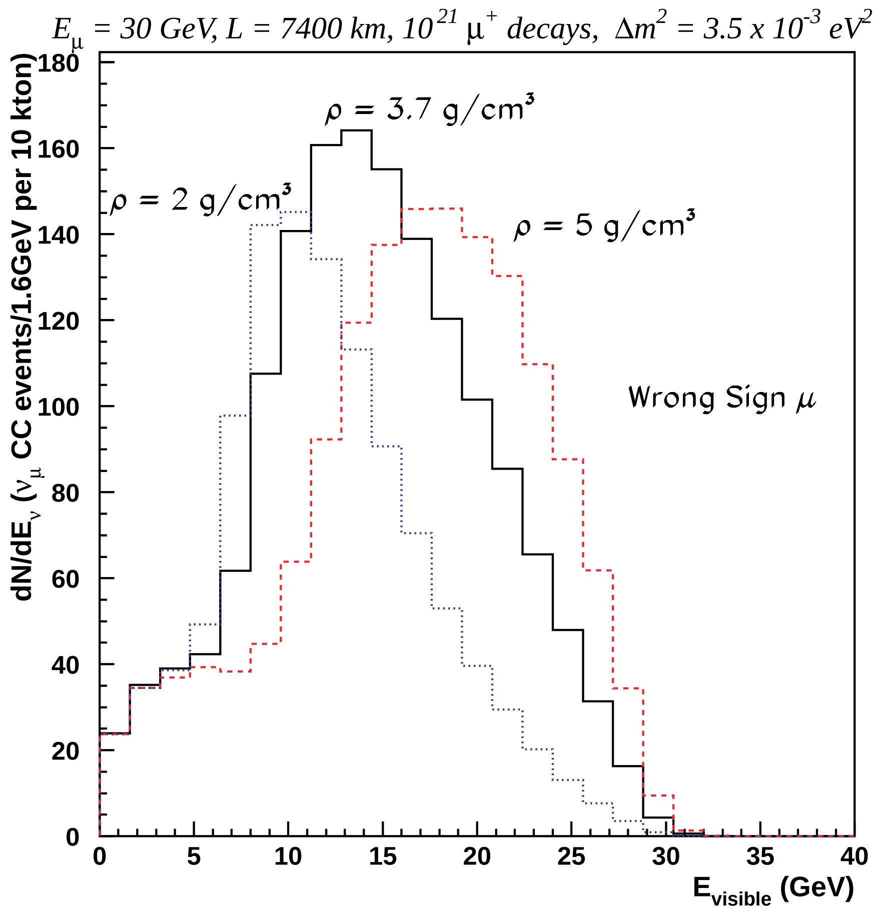
Earth density

Resonance position depends on $\Theta_{13} \Delta m^2_{13}, \rho$

$$E_\nu^{res} \approx \frac{1.32 \times 10^4 \cos 2\theta_{13} \Delta m_{23}{}^2 (eV^2)}{\rho(g/cm^3)}$$

- For small θ_{13}, $\cos 2\theta_{13} \approx 1$
- Δm^2_{23} measured independently by right-sign muon disappearance

→ The resonance position, visible in wrong-sign muons, gives a measurement of the mean density



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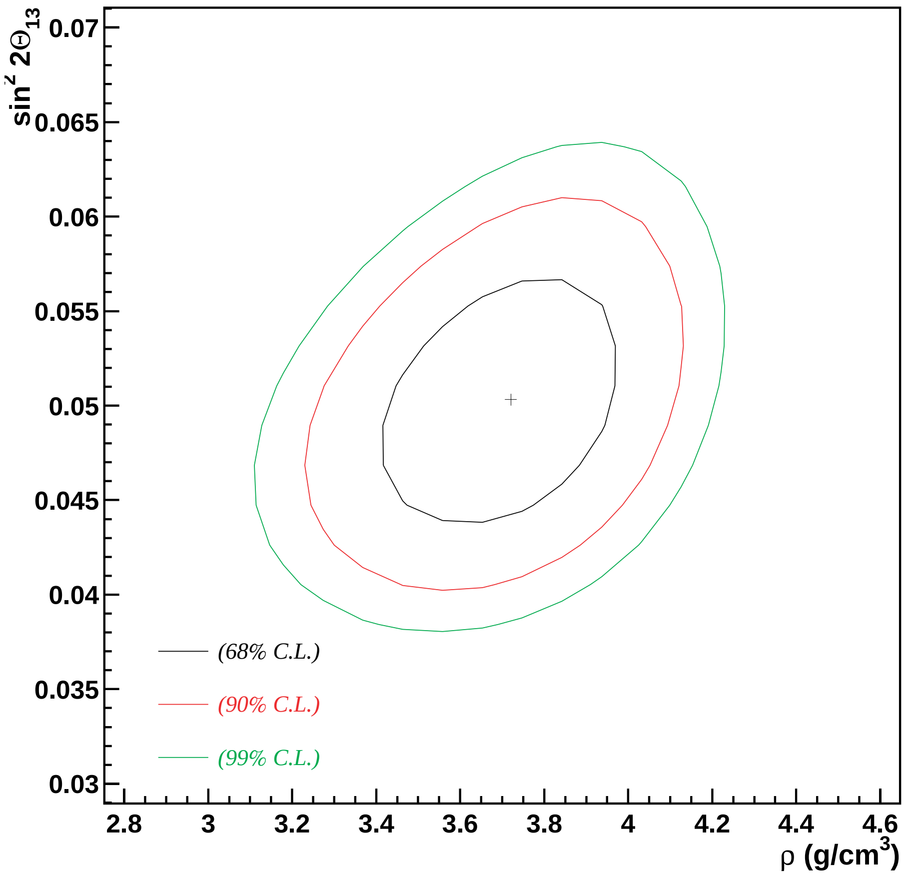
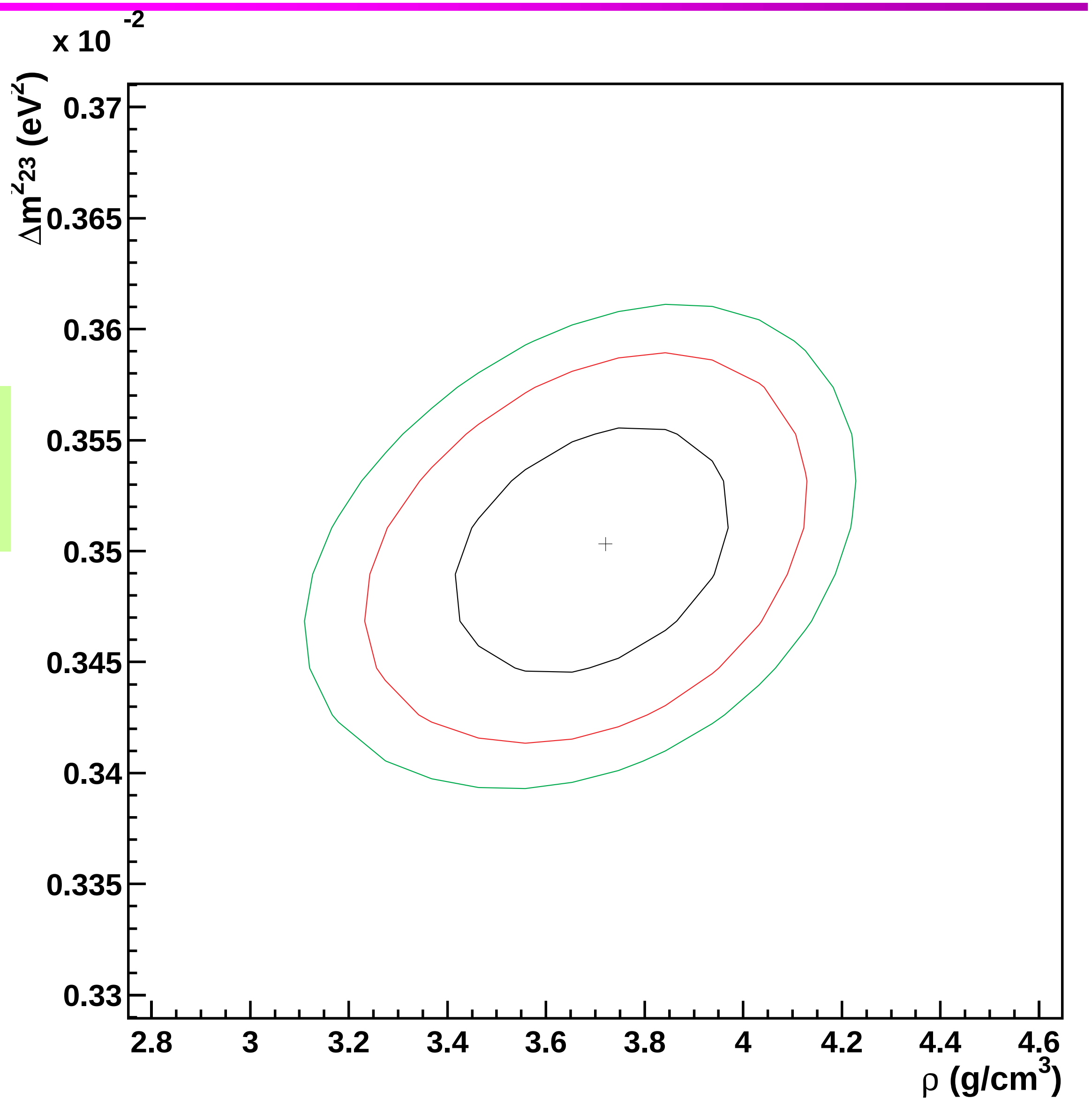
Determination of ρ and Θ_{13}

The determination of ρ is not very correlated to that of the other oscillation parameters, e.g. θ_{13}



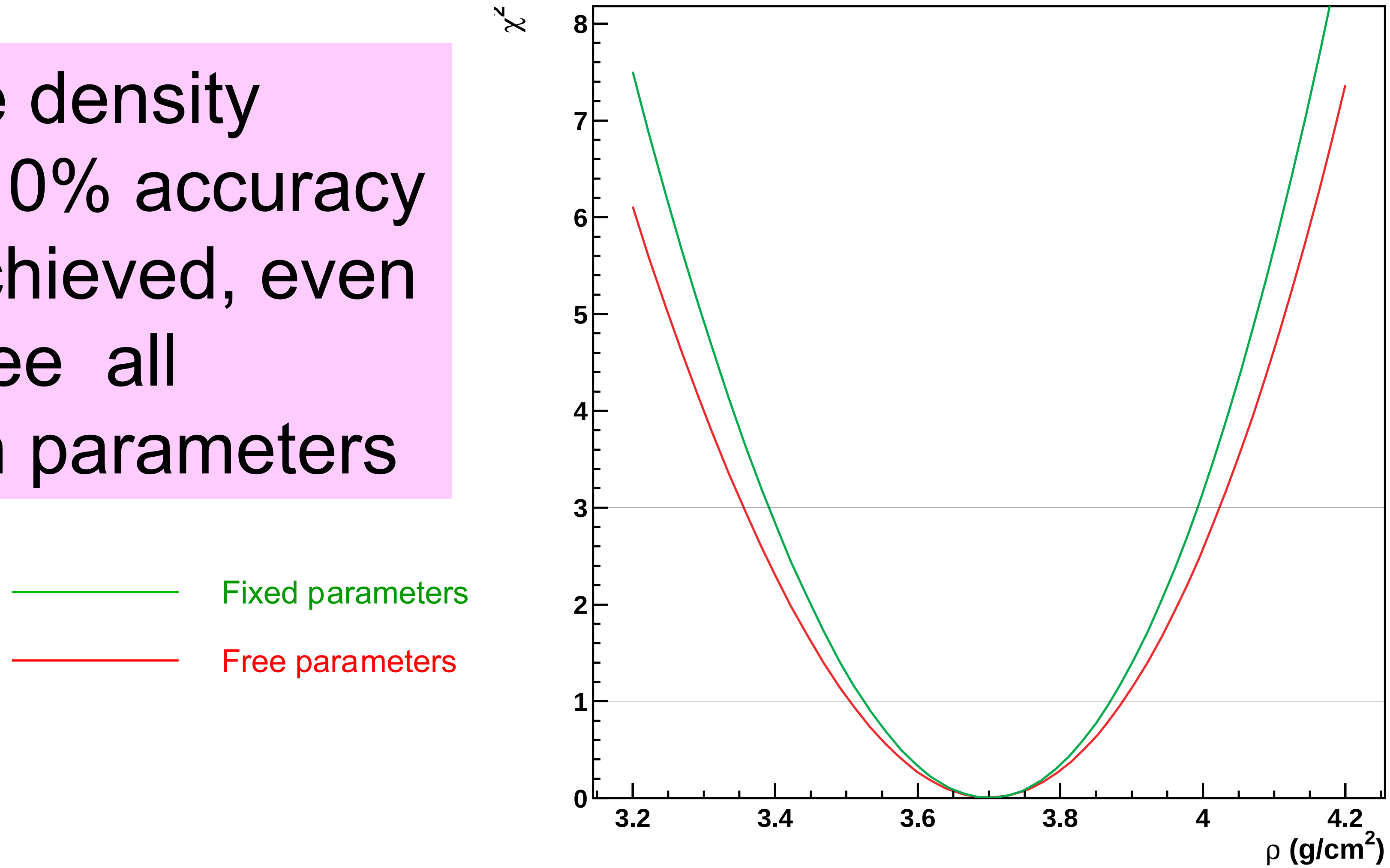
Determination of ρ and Δm^2_{23}

...or $\Delta m_{23}{}^2$



Density determination

Fitting the density alone, a 10% accuracy can be achieved, even leaving free all oscillation parameters

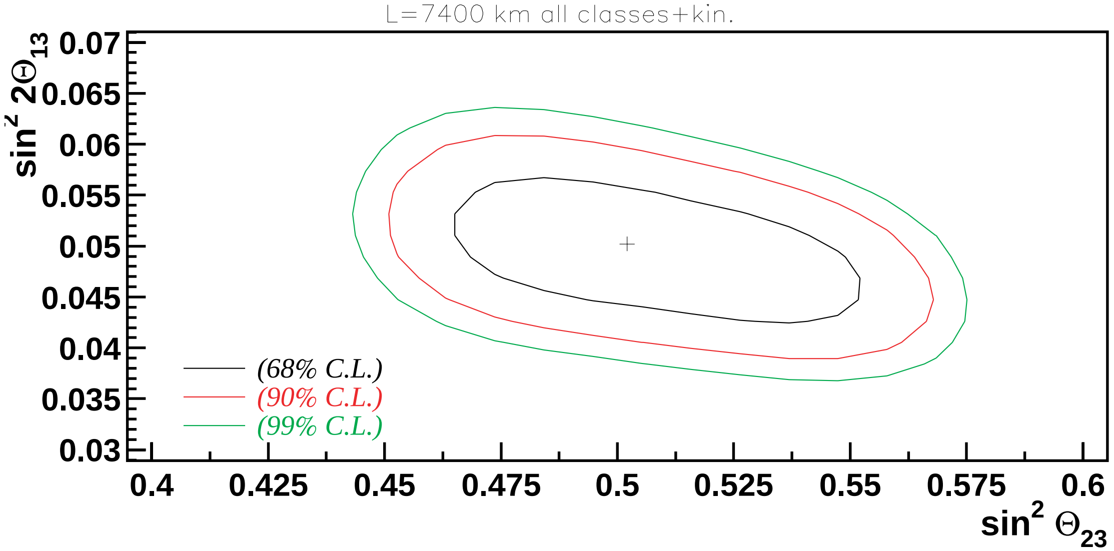


Influence of density

Density fixed to true value:

$\sigma(\sin^2 2\theta_{13})=0.0071$

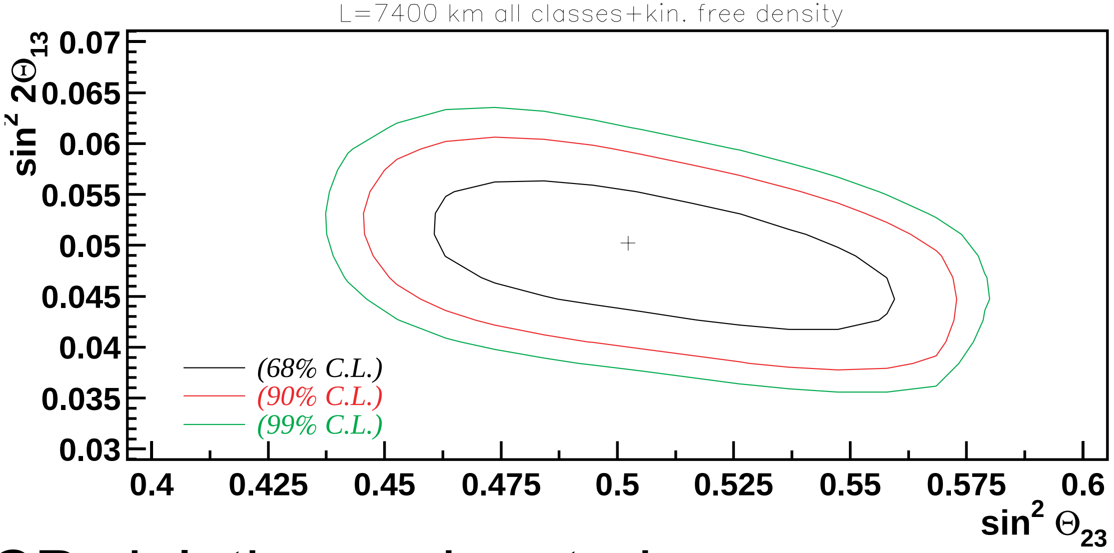
$\sigma(\sin^2\theta_{23})=0.044$



Density left free in the fit:

$\sigma(\sin^2 2\theta_{13})=0.0074$

$\sigma(\sin^2\theta_{23})=0.050$



Influence of matter on CP violation under study

Conclusions

- An ICANOE-like detector at the Neutrino Factory, provides:
  - →Identification of different event classes
  - →Precise determination of Δm^2_{23} and θ_{23}
  - →Improved sensitivity or a measurement of θ_{13}
  - →Study of matter effects and determination of ρ
- Event simulation done with background, exclusive τ decays, beam systematics
- Matter effect can be directly measured
- Work in progress for CP violation studies