Physics potential at the Neutrino Factory: Can we benefit from more than just detecting muons?

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Neutrino Oscillations at the NuFactory

In a Neutrino Factory we can study in principle 12 independent processes:

$\mu^- \to e^- \; \bar{\nu}_e \; \nu_\mu$

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

Plus their charge conjugates with μ^+ beam

Oscillation probabilities:

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

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

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

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

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

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

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

How to get most of the potential?

Experimentally, it is not possible to disentangle exactly all 12 oscillation processes.

However, we believe that once such a powerful machine is built, one should try to extract most of the information, with a detector as versatile as possible

LAr TPC 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 technology for a Neutrino Factory

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

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

No oscillations

E_μ=30 GeV

No polarization

No beam divergence

Detector simulation

ICANOE fully simulated for CNGS studies.

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

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

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

Proper neutrino cross section used

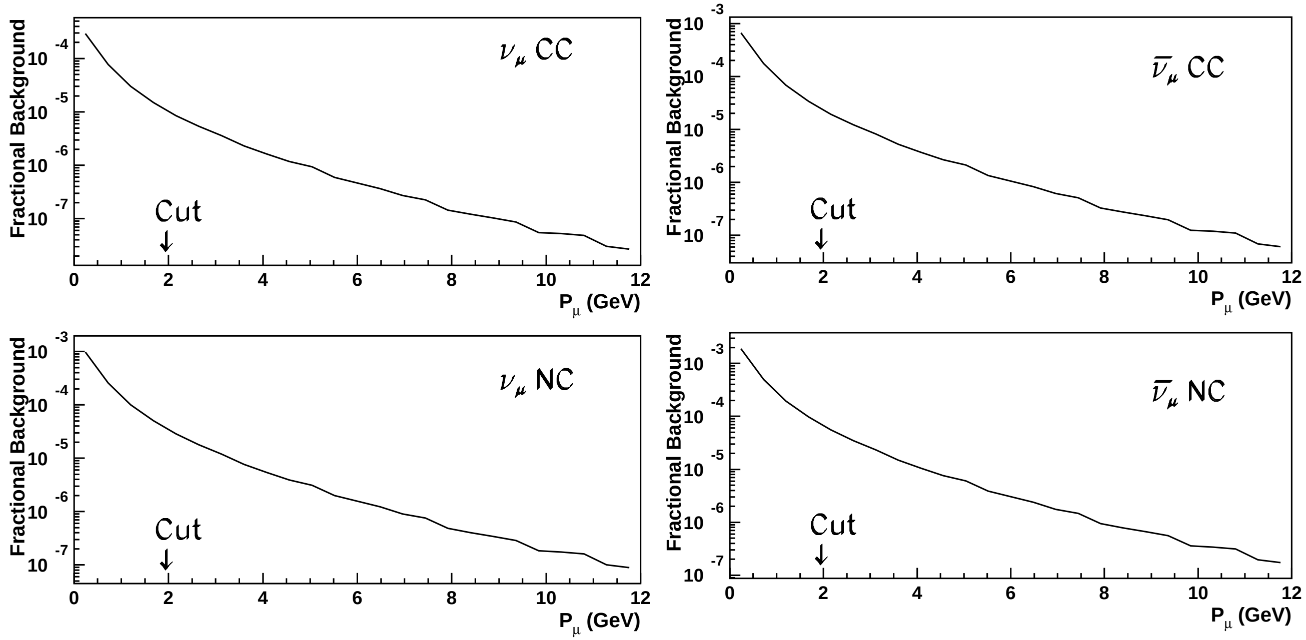
Charged $\pi^{\pm}$,$K^{\pm}$ decay into $\mu^{\pm}$ for BG treatment

Background treatment

Hadron decays can produce "fake" wrong-sign muon events.

We are not aiming at large background rejection factors.

Simple momentum cut P_μ>2 GeV applied



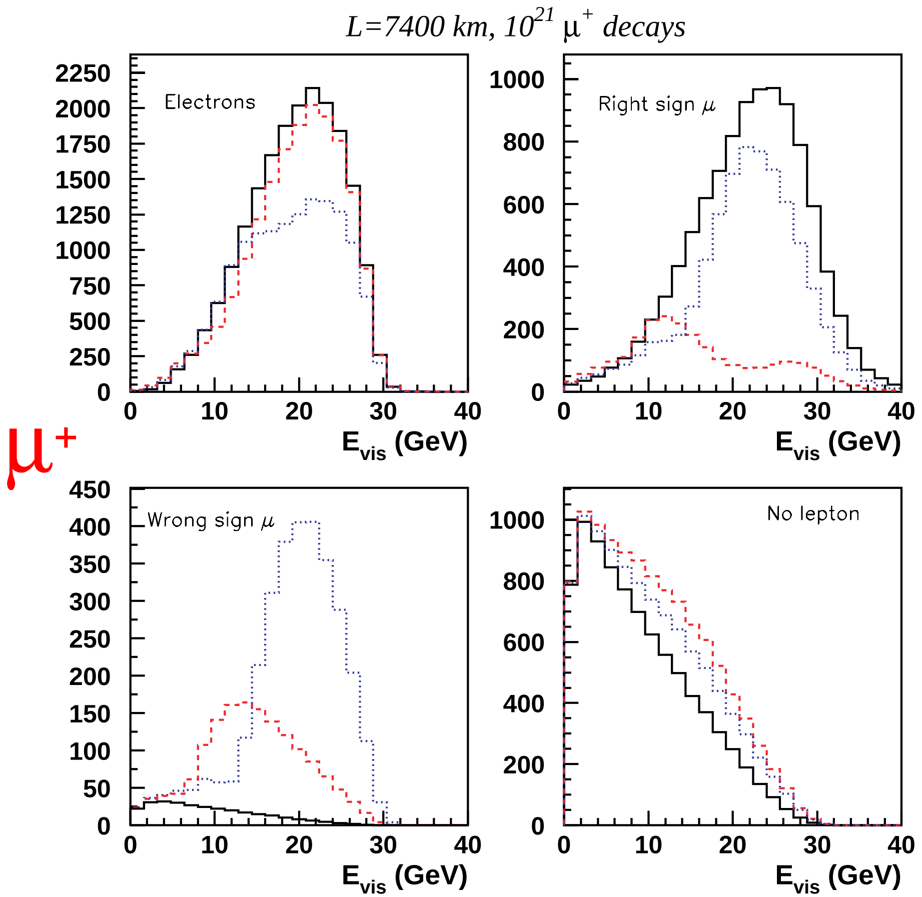
Parameters used

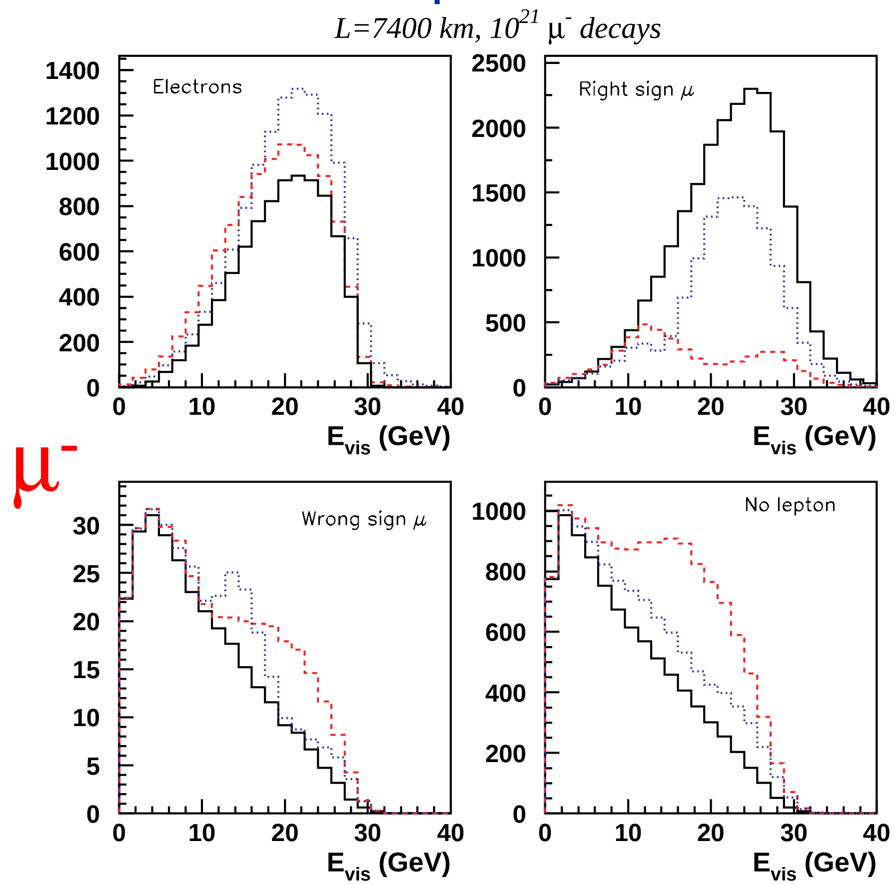
For this study, we consider as our default:

- ✯ $2*10^{20}$ 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

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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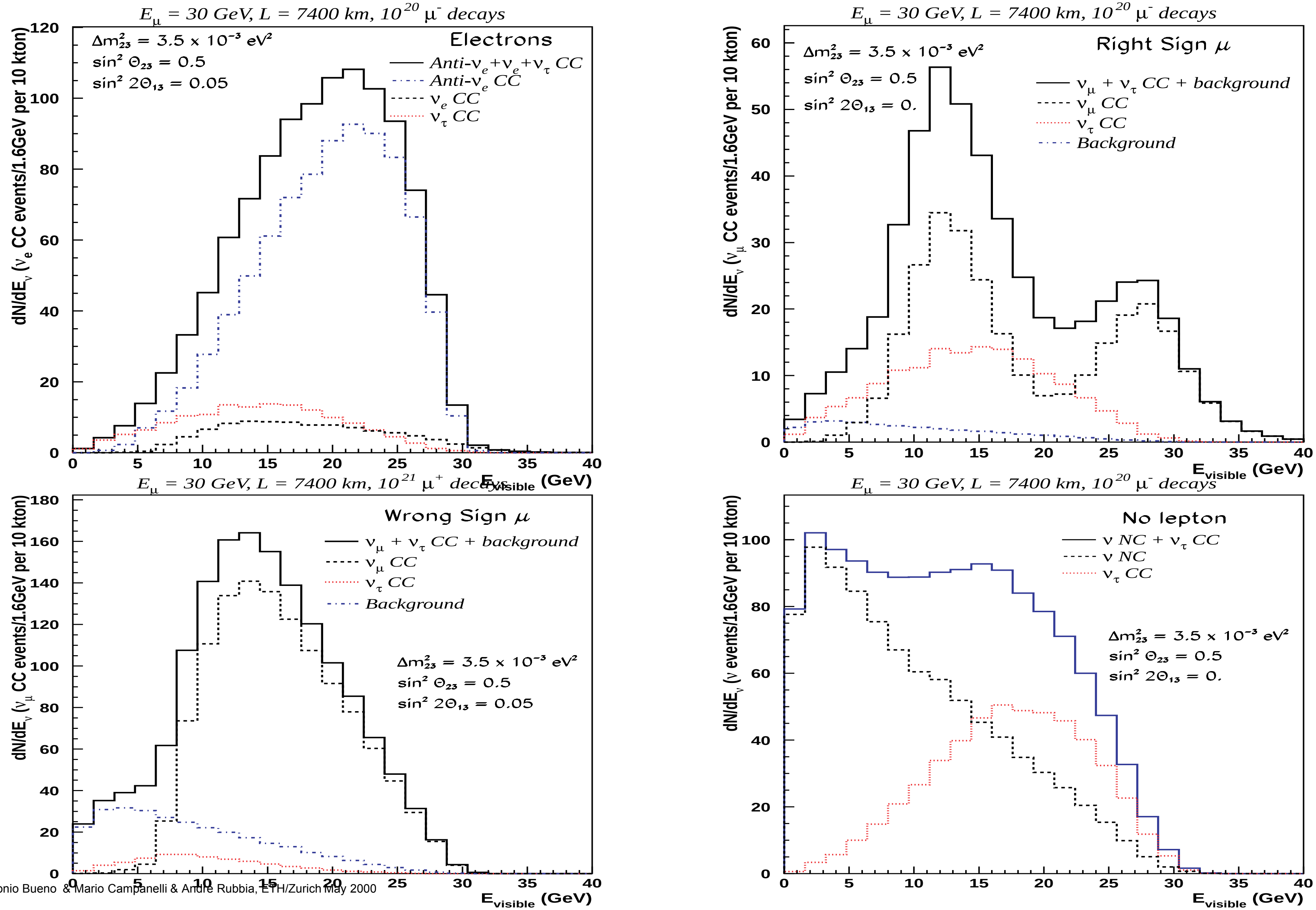
A closer look to different event classes



ν_τ appearance

ICANOE has been designed to perform ν_τ appearance searches at the CNGS.

A similar detector at the Neutrino factory would benefit from the better signal/BG ratio given by the longest baselines:

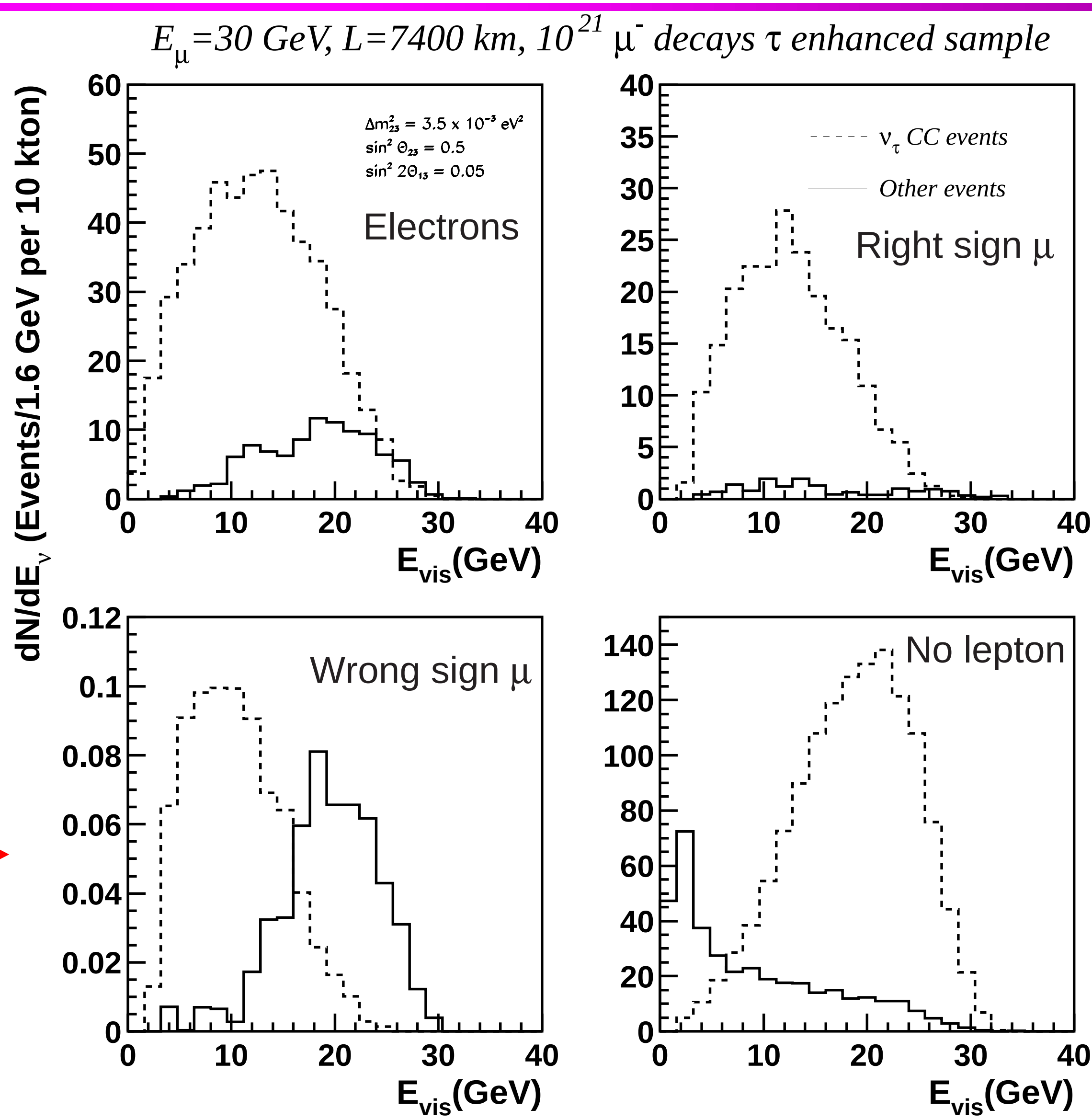
$\nu_\mu \to \nu_\tau$ appearance search					
Cuts	$\tau \to l$	CC background	Cuts	$\tau \to h$	NC background
Initial	100%	100%	Initial	100%	100%
Loose cuts					
$P_T^l < 0.5$GeV	50%	14%	$P_T^{miss} < 1$GeV	72%	40%
$P_T^{miss} > 0.6$GeV	40%	0.5%	$Q_T > 0.5$GeV	30%	2%
Tight cuts					
$P_T^l < 0.5$GeV	50%	14%	$P_T^{miss} < 1$GeV	72%	40%
$P_T^{miss} > 1$GeV	20%	0.08%	$Q_T > 1$GeV	6%	0.07%

1 event background

τ–enhanced sample

Tau contribution enhanced for all event classes

$\nu_e \rightarrow \nu_\tau$ oscillations!!



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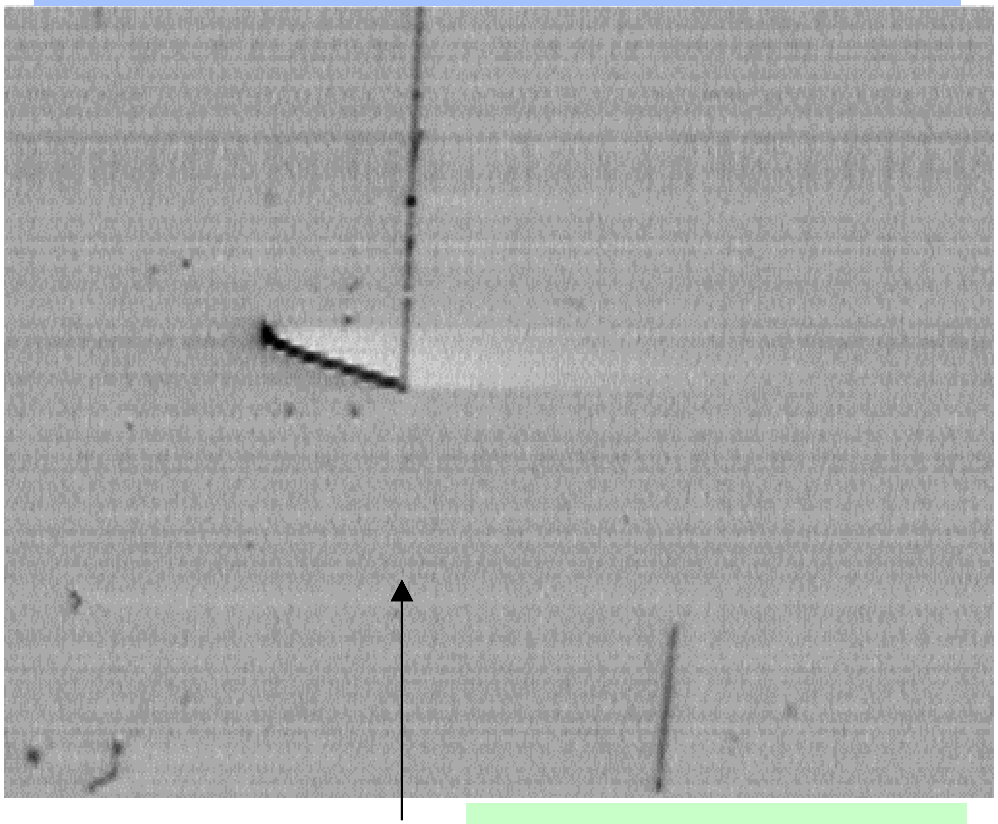
Quasi-elastic events

Provide ν-$\bar{\nu}$ separation for all flavors:

- $\nu_l + n \rightarrow l^- + p$
- $\bar{\nu}_l + p \rightarrow l^+ + n$

Only way to determine helicity of electron neutrino without explicit electron charge measurement

Real ν event
in the 50 liter LAr TPC in
CERN WANF beam



CERN ν-beam

$$\nu_\mu + n \rightarrow \mu^- + p$$

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

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 for** <40 events in bin

Beam systematics: 2% uncorrelated (25 bins)

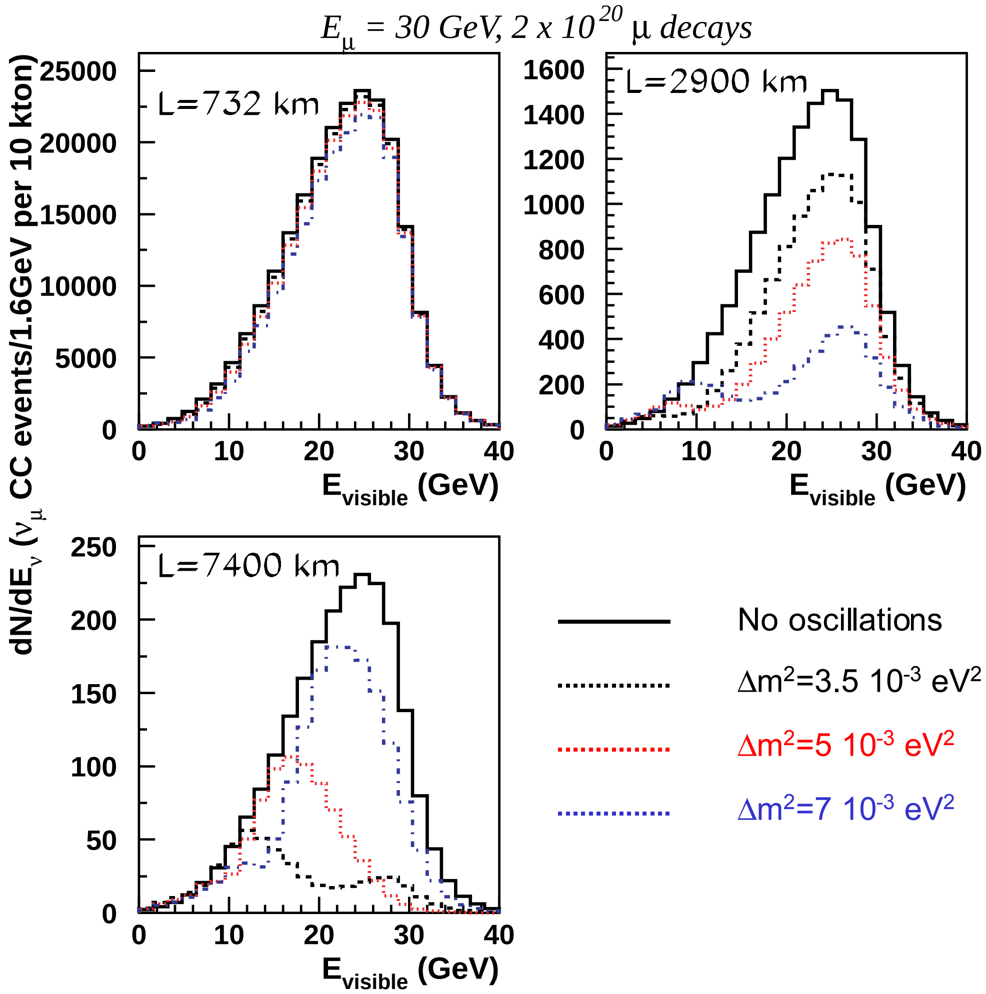
Background added in fit

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

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

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

Measurement dominated by disappearance dip at large distances for right-sign μ :



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

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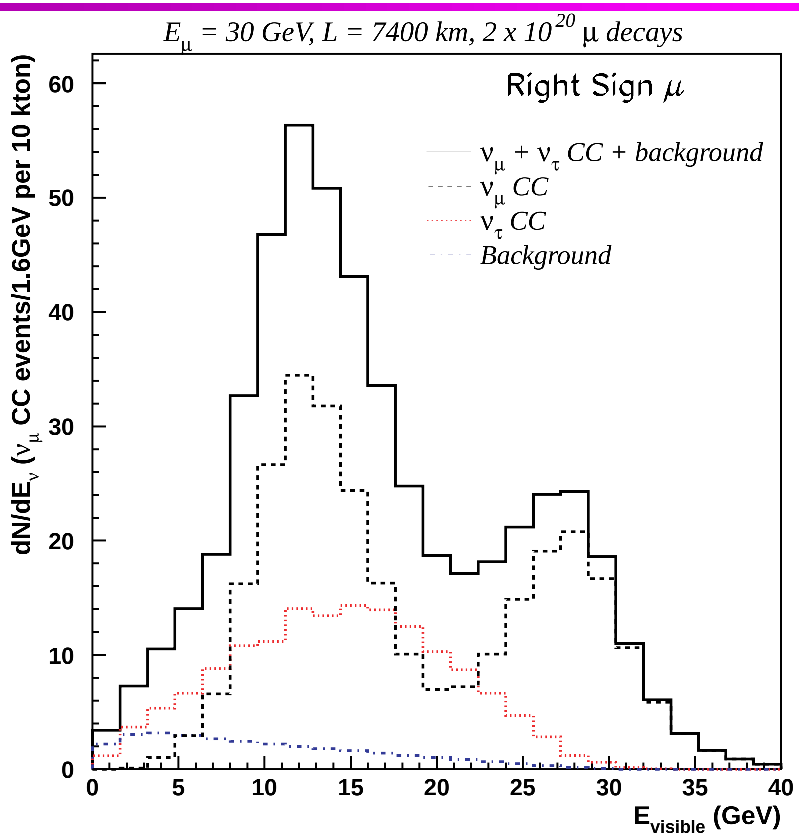
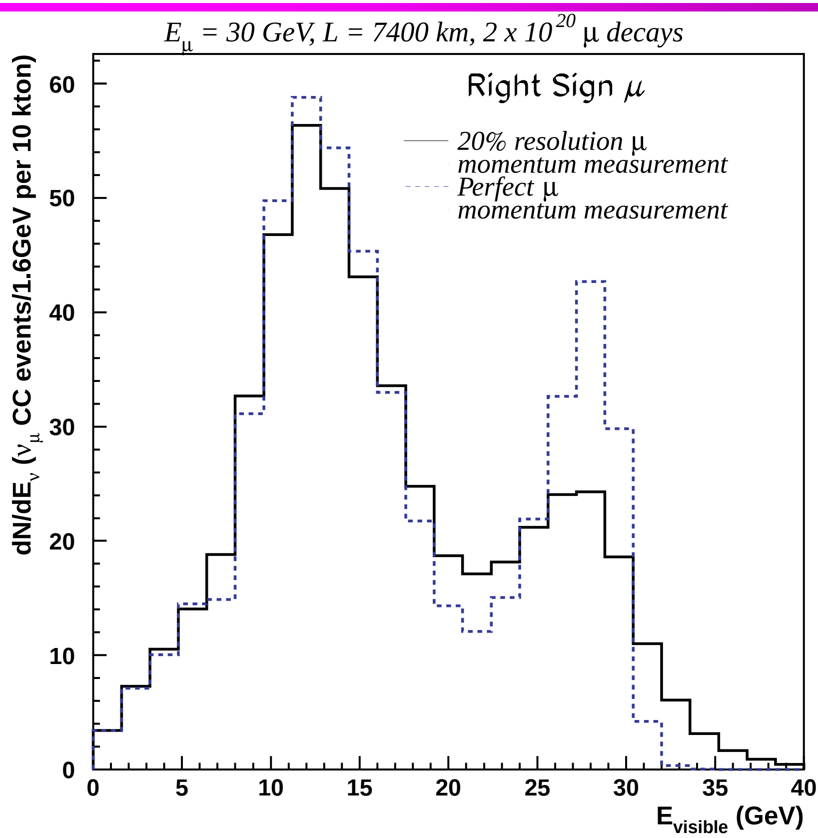
Right-sign muon disappearance

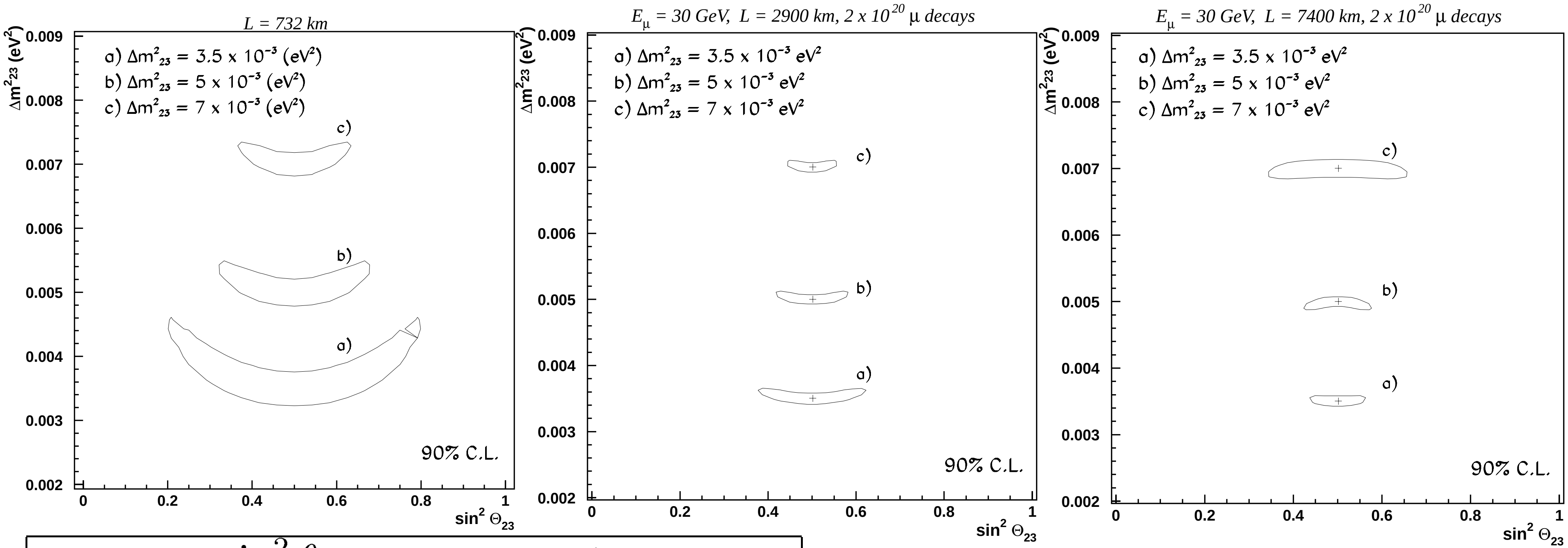




Contributions to events in the dip:

- Resolution
- $\nu_\mu \to \nu_\tau \to \tau \to \mu$ 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

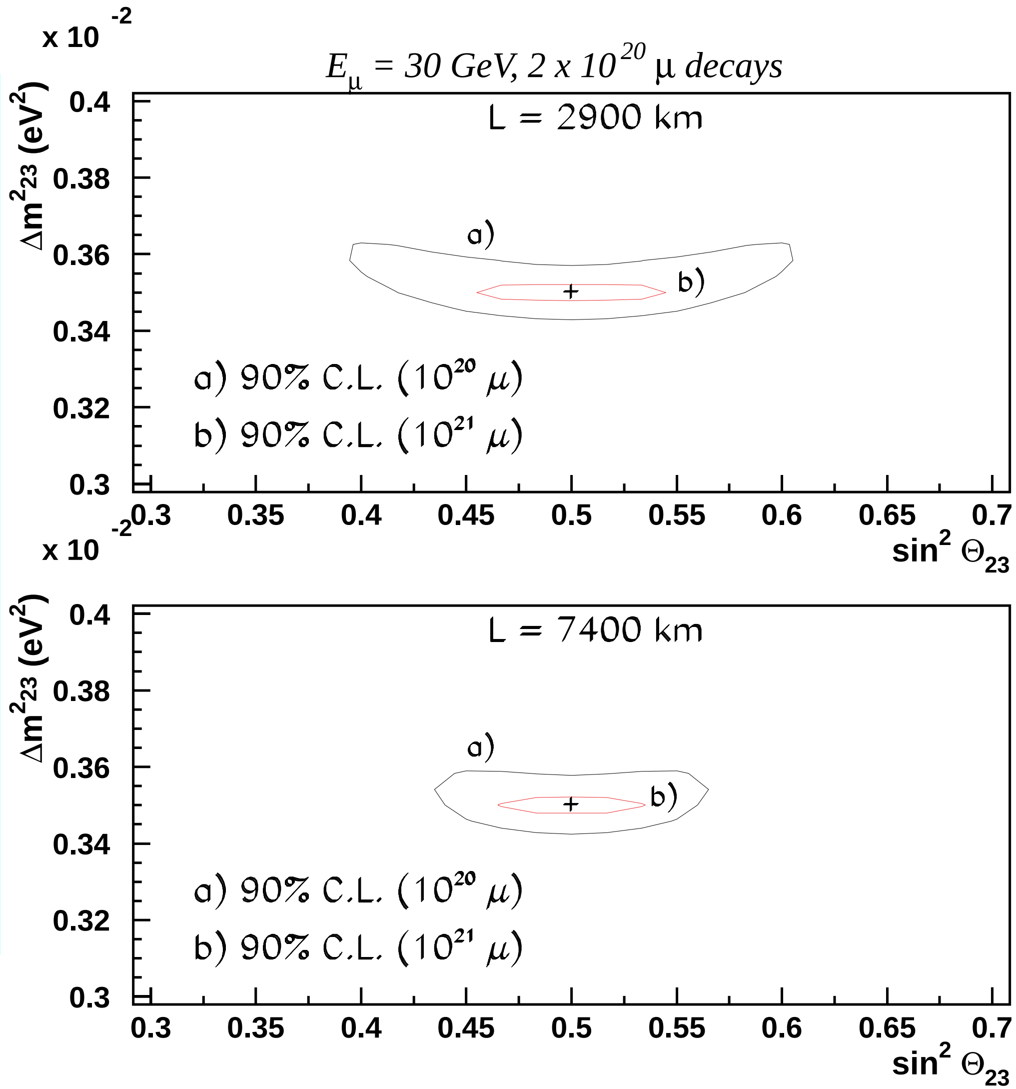
Consistent with Barger et al. hep-ph/9911524

Error on Δm^2_{23}=1%

Statistical improvements

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

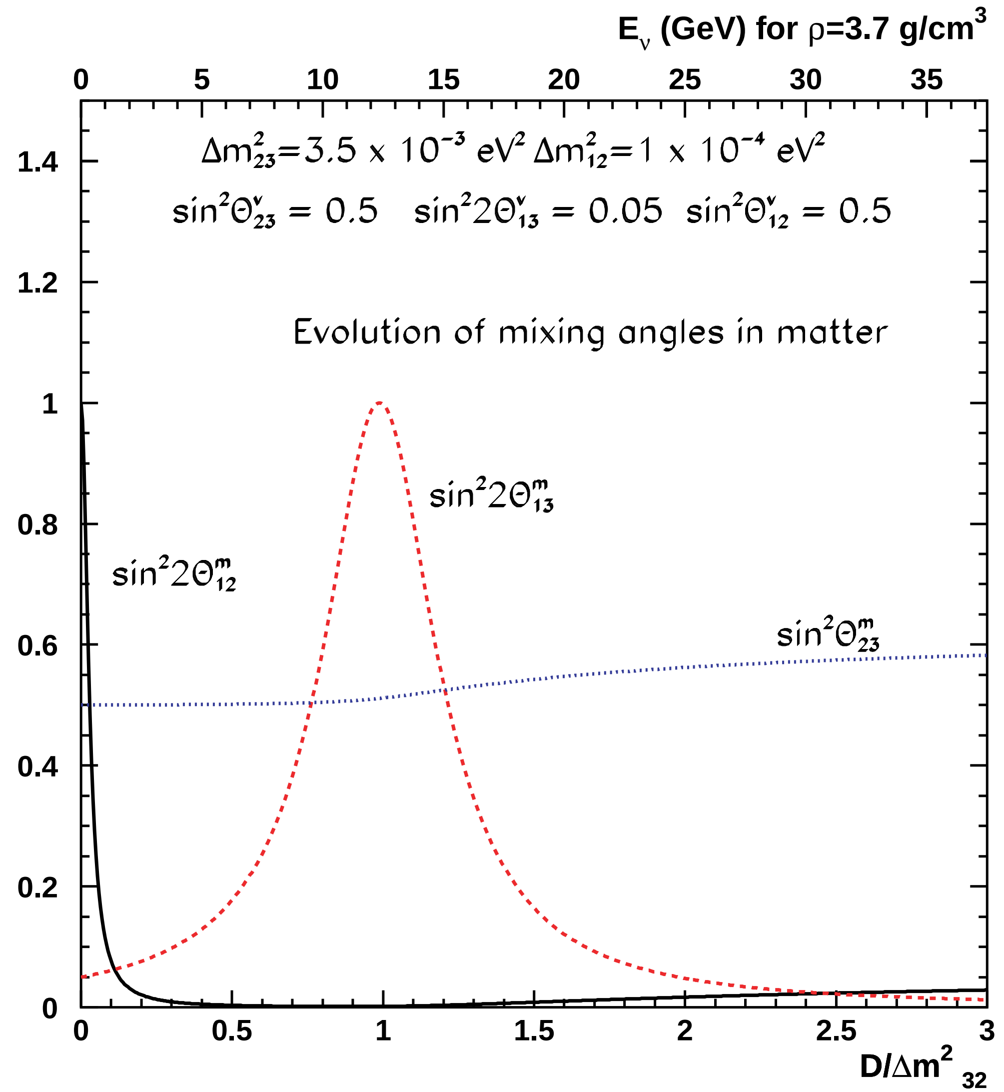
(2% systematics)



3–family mixing

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

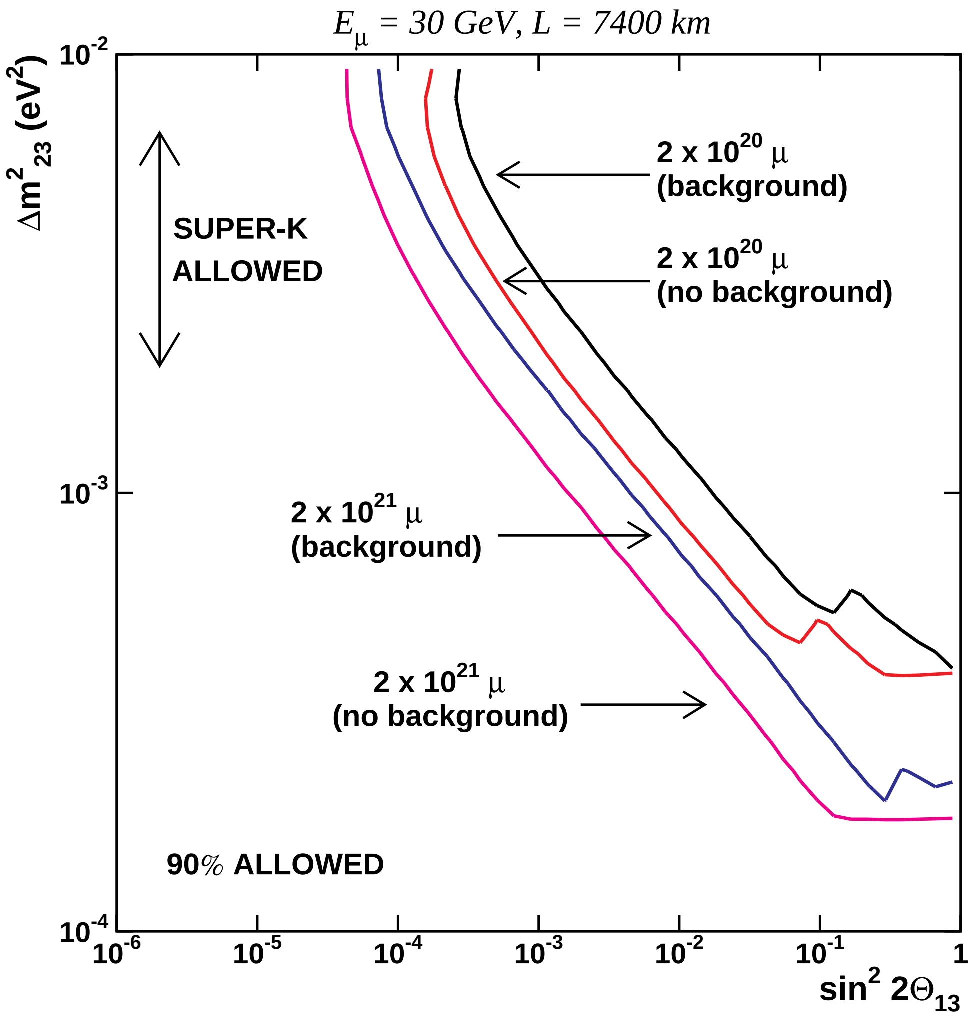
Assuming $\Delta m^2_{23}>0$, oscillations involving ν_e ($\bar{\nu}_e$) are enhanced (suppressed) by MSW interactions with matter



Sensitivity to θ_{13}

Sensitivity to Θ_{13} strongly depends on background level assumed for wrong-sign muons

Negligible contribution from other classes



2 orders of magnitude better than ICANOE at CNGS

Quasi-elastics

Quasi-elastic events can confirm discovery of $\nu_\mu \rightarrow \nu_e$ oscillations. For $\sin^2 2\theta_{13}=0.05$:

ν_e appearance search with quasi-elastic Electron Class: Events for 10^{21} μ^- decays						
	$\bar{\nu}_e$ CC		$\nu_\mu \rightarrow \nu_e$ CC		$\nu_\mu \rightarrow \nu_\tau$ CC, $\tau \rightarrow e$	
Baseline	Total	Elastic	Total	Elastic	Total	Elastic
$L = 732$ km	860000	43000	2090	84	3990	110
$L = 2900$ km	54300	2700	1720	70	3300	90
$L = 7400$ km	8300	410	960	40	1450	40

Measurement of Θ_{13}

Three-family mixing $\sin^2\theta_{23} = 0.5$, $\sin^2 2\theta_{13} = 0.05$				
	All classes χ^2_{all}		Only muons $\chi^2_{rs\mu} + \chi^2_{ws\mu}$	
	L=2900 km	L=7400 km	L=2900 km	L=7400 km
$\Delta m^2_{32} = 3.5 \times 10^{-3}$ eV^2,				
$\delta(\Delta m^2_{32})$	1.4%	0.9%	1.4%	0.9%
$\delta(\sin^2\theta_{23})$	14%	8%	16%	9%
$\delta(\sin^2 2\theta_{13})$	15%	10%	17%	15%
$\Delta m^2_{32} = 5 \times 10^{-3}$ eV^2				
$\delta(\Delta m^2_{32})$	0.4%	0.8%	0.4%	0.8%
$\delta(\sin^2\theta_{23})$	11%	8%	10%	12%
$\delta(\sin^2 2\theta_{13})$	11%	9%	14%	16%
$\Delta m^2_{32} = 7 \times 10^{-3}$ eV^2				
$\delta(\Delta m^2_{32})$	0.4%	0.6%	0.4%	0.6%
$\delta(\sin^2\theta_{23})$	7%	8%	8%	18%
$\delta(\sin^2 2\theta_{13})$	8%	6%	9%	20%

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

Including electrons, NC and kinematics for τ can improve precision by more than 30%

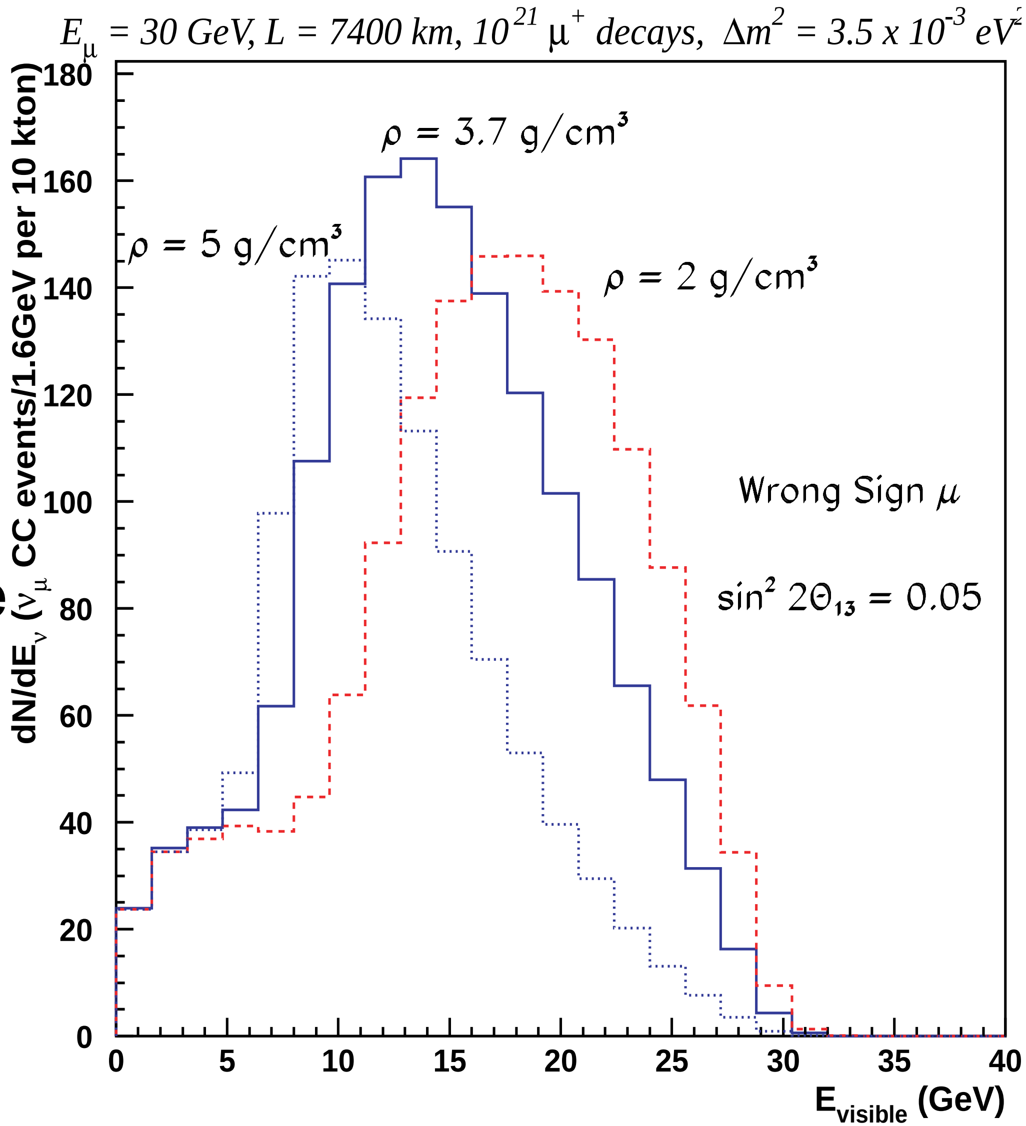
Earth density

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

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



Influence of density

Density fixed to true value:

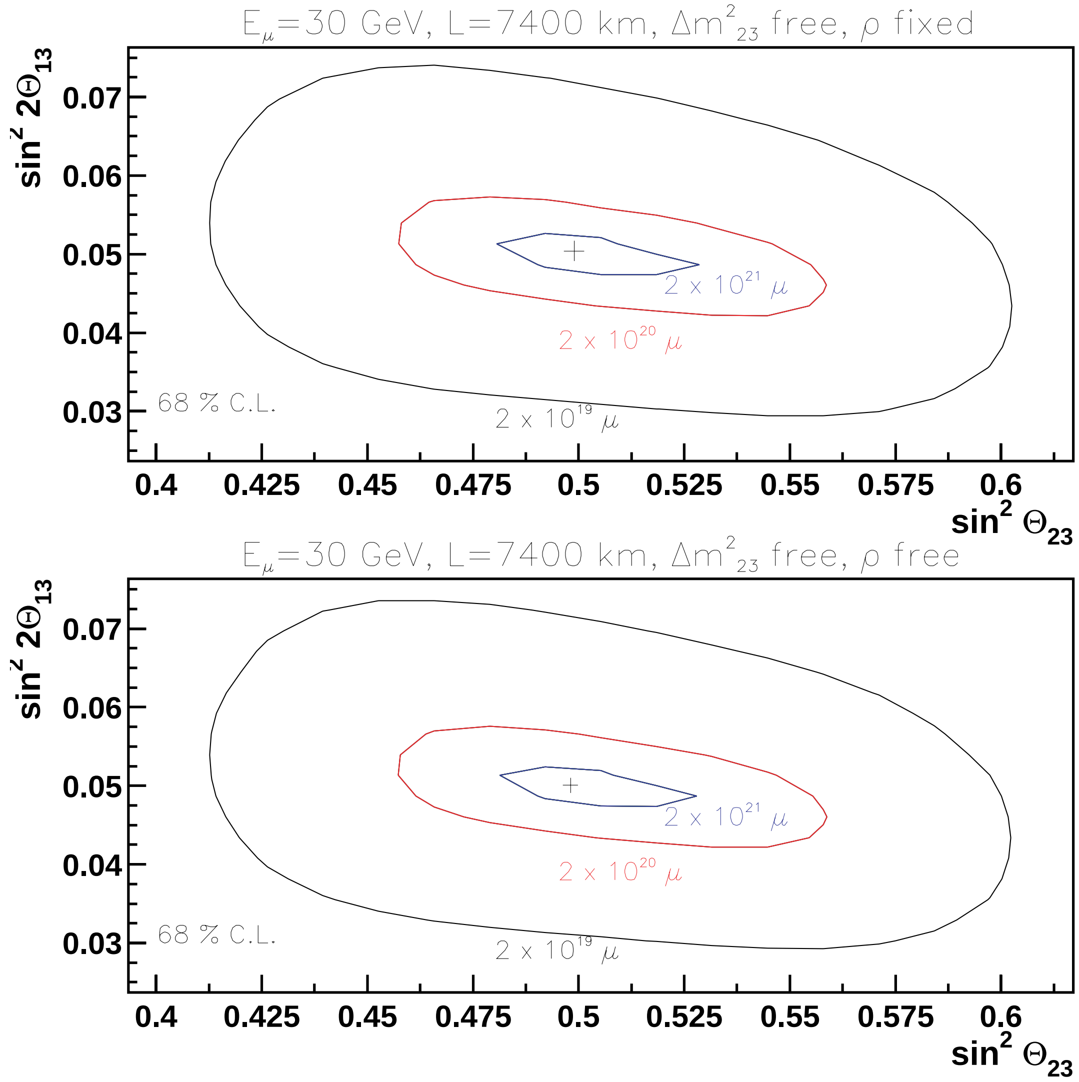
$\sigma(\sin^2 2\theta_{13})=0.0071$

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

Density left free in the fit:

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

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



Over–constraining the oscillation

For 3 active neutrinos: $\sum_{x=e,\mu,\tau} P(\nu_x \to \nu_y) = 1$

Assuming new phenomena in oscillations to τ neutrinos, probabilities would change:

$P(\nu_\mu \to \nu_\tau) \to \alpha\, P(\nu_\mu \to \nu_\tau)$

$P(\nu_e \to \nu_\tau) \to \beta P(\nu_e \to \nu_\tau)$

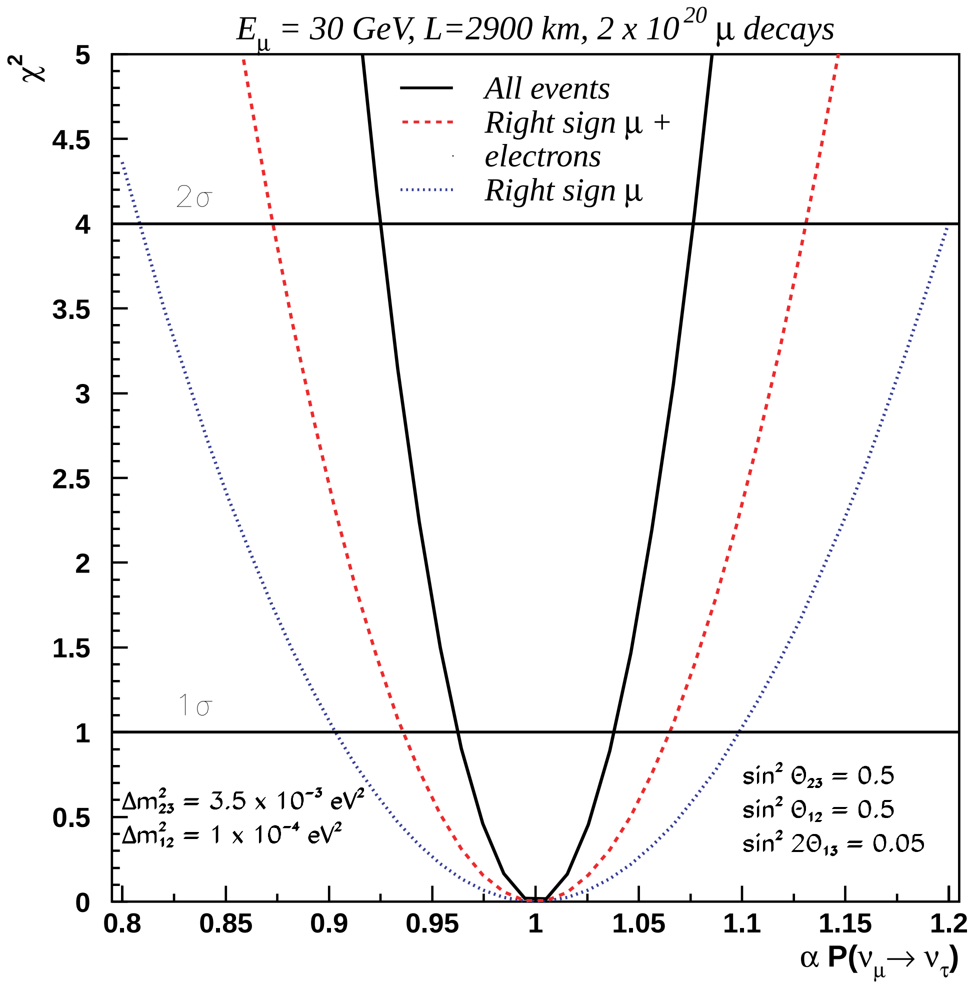
Precision on α: O(1%)

Precision on β: O(20%)

Appearance/disappearance test				
Baseline	Δm^2_{32} ($\times 10^{-3}$ eV^2)	$10^{20}\mu^\pm$	$10^{21}\mu^\pm$	$10^{22}\mu^\pm$
Precision on $\alpha \Rightarrow \alpha \times P(\nu_\mu \to \nu_\tau)$				
7400 km	3.5	5.5%	2%	0.6%
	5	6%	2%	0.6%
	7	11%	3%	1%
2900 km	3.5	4%	2%	0.6%
	5	3%	1%	0.4%
	7	2.5%	1%	0.4%
Precision on $\beta \Rightarrow \beta \times P(\nu_e \to \nu_\tau)$				
7400 km	3.5	60%	20%	7%
	5	35%	10%	5%
	7	25%	7%	2%
2900 km	3.5	75%	25%	9%
	5	25%	15%	5%
	7	30%	10%	4%

Over-constraining the oscillation

As expected, all event classes contribute to over-constrain the oscillation to ν_τ



Effects of CP Violation

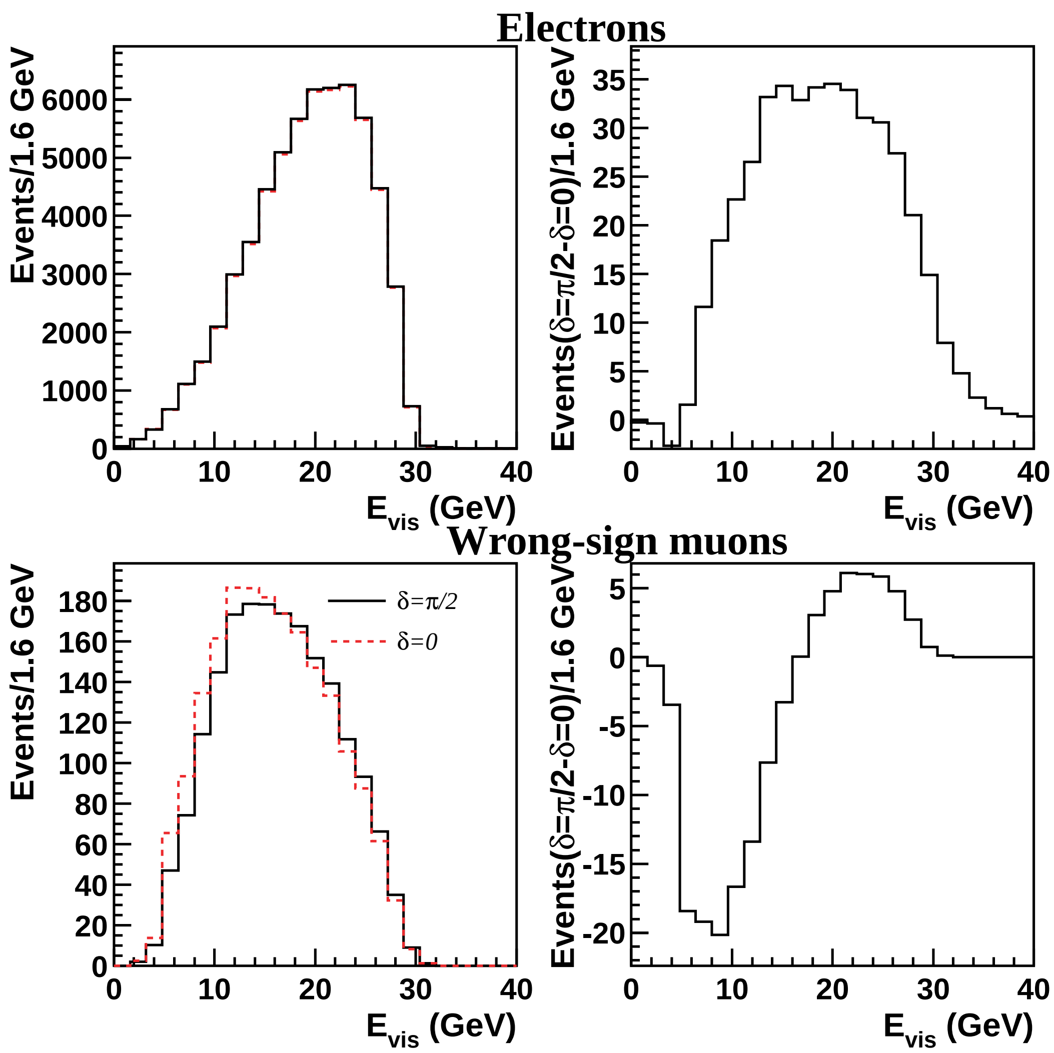
L=2900 km, $\Delta m^2_{12}=10^{-4}eV^{2,}$ $\Delta m^2_{23}=3.5*10^{-3}eV^2$, $\sin^2\theta_{23}=\sin^2\theta_{12}=0.5$, $\sin^2 2\theta_{13}=0.05$

Increase number of electrons

(large, but drawn in the BG)

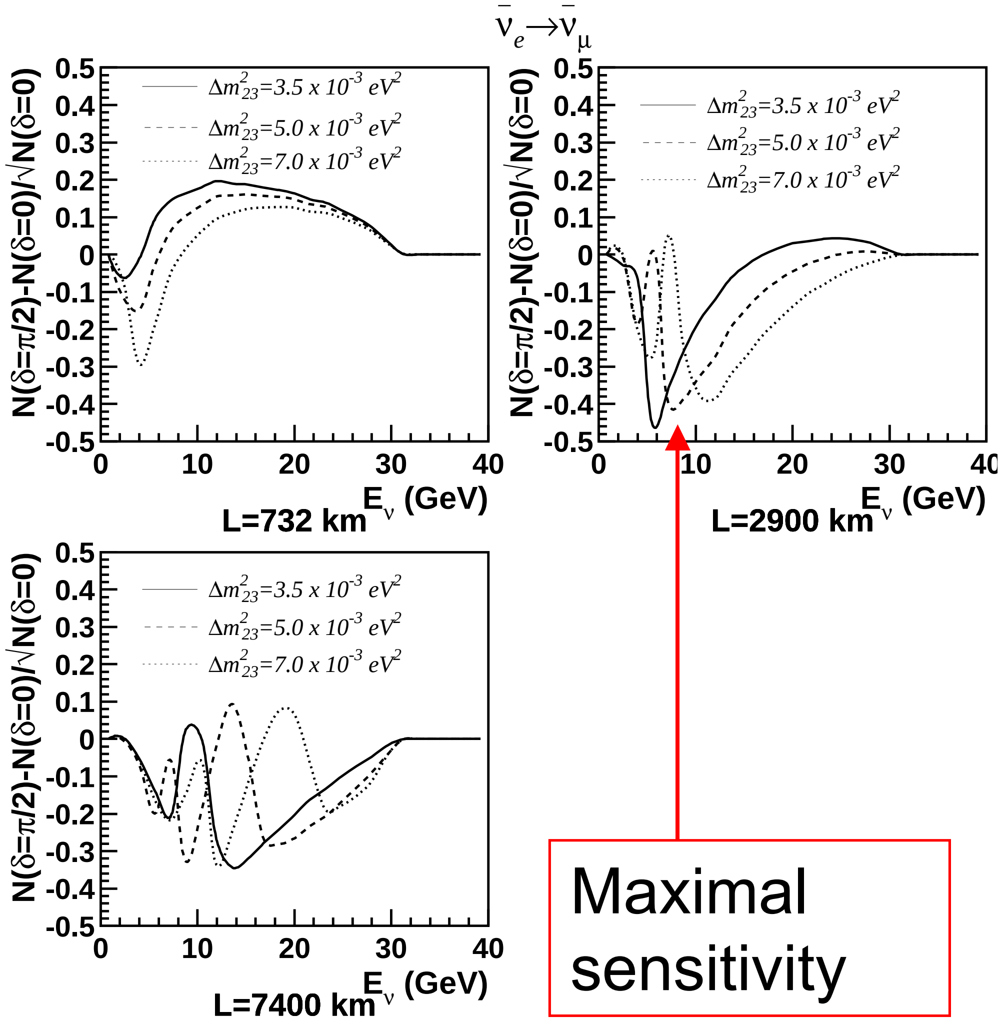
Change shape in wrong-sign muons

(smaller but much cleaner)



Sensitivity to CP violation

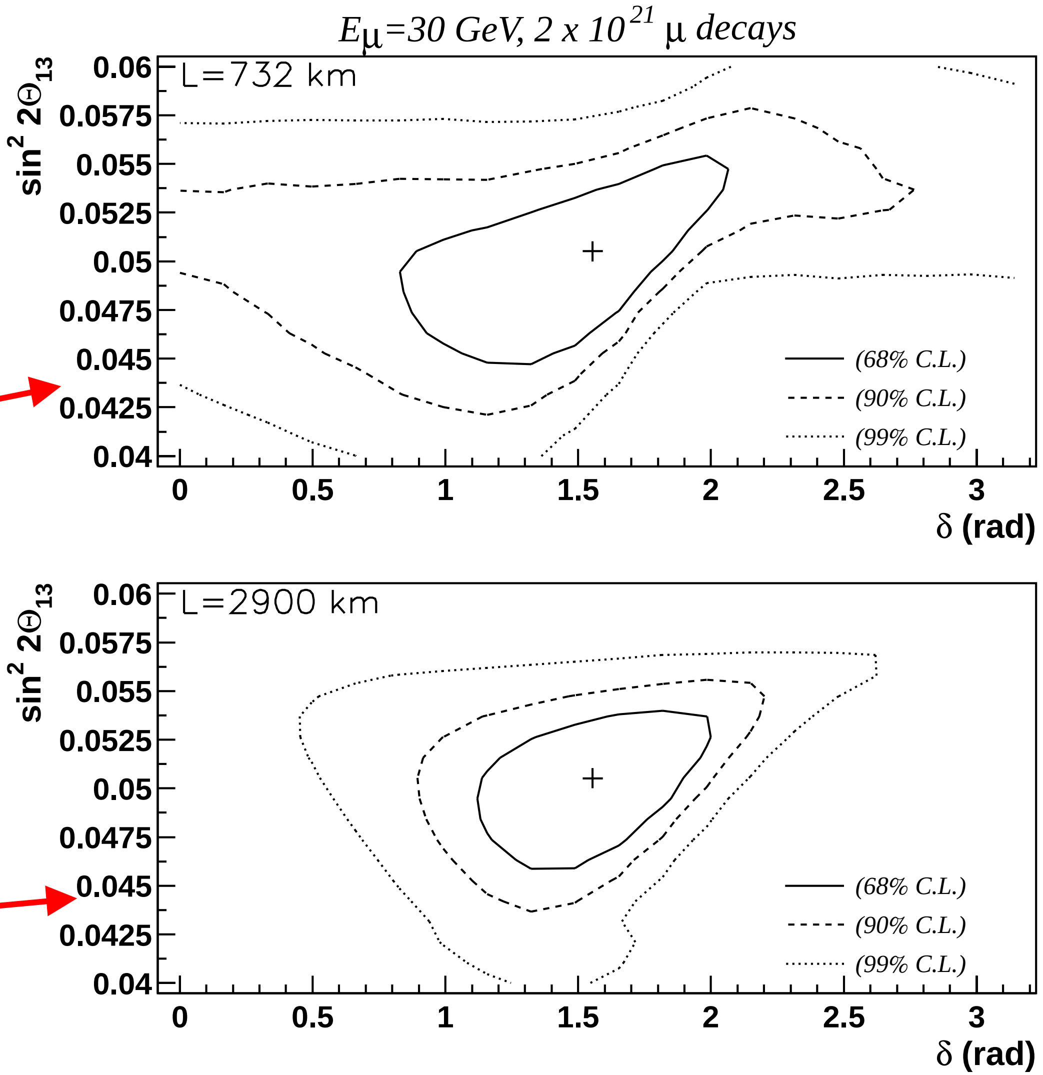
Sensitivity to CP for wrong-sign muons is maximal at L=2900 km, for neutrino energies around 10 GeV



δ vs θ_{13}

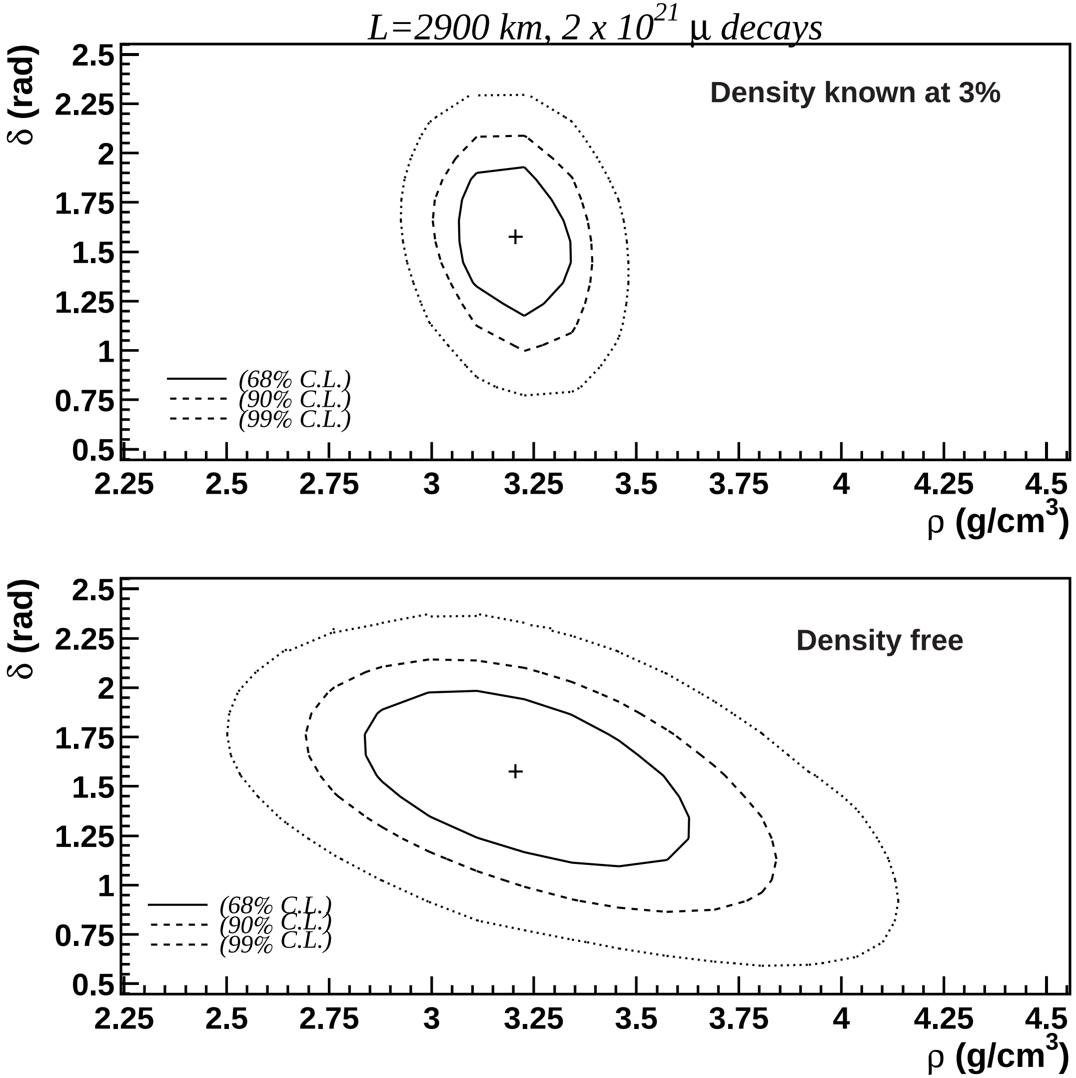
When CP violation only leads to a normalization factor, the effect is very correlated to a variation in θ_{13}

Correlation is much smaller when also a shape change occurs



δ vs ρ

In a global fit, even a complete ignorance of the matter density does not spoil the determination of CP



No need for more baselines!

Use of quasi-elastic events

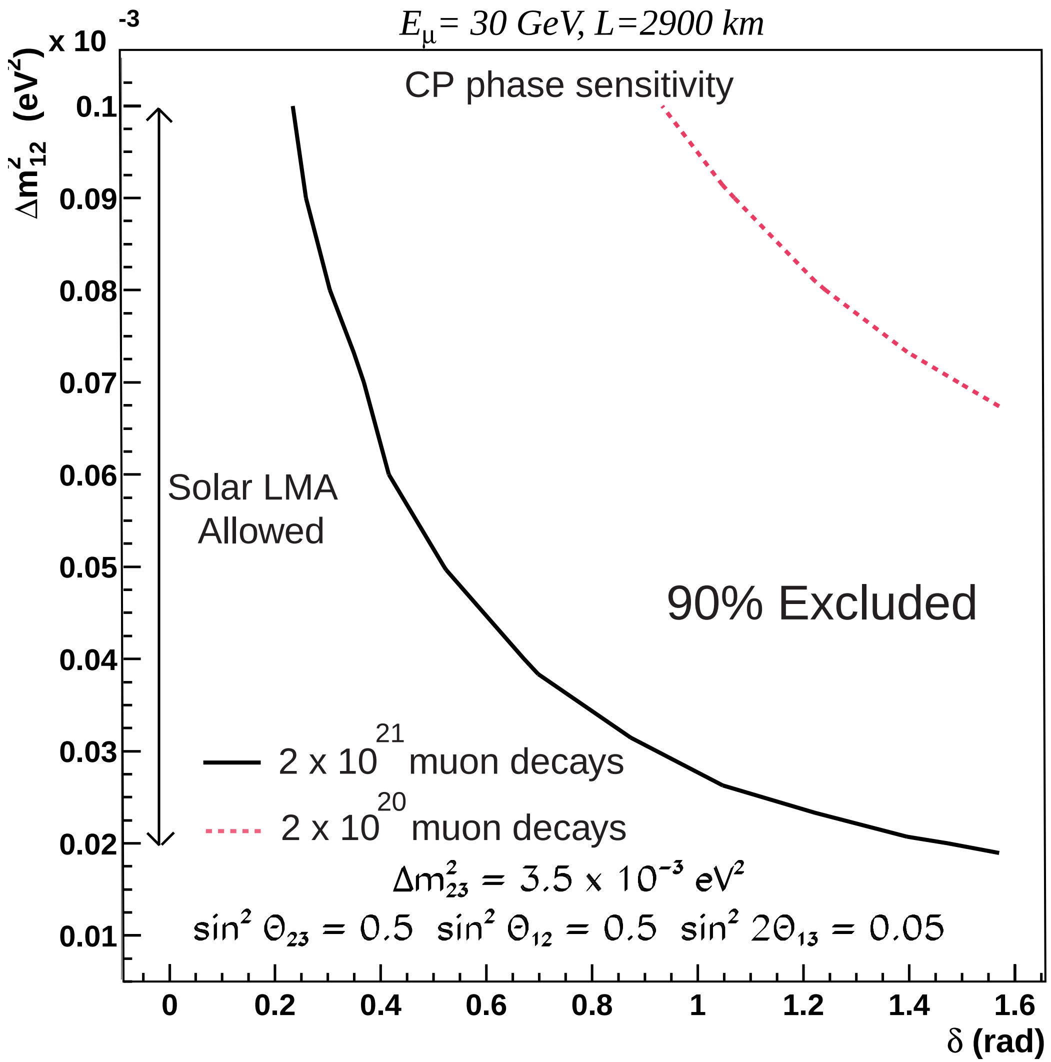
The CP violation effect is large for the electrons, but is hard to see due to ν_e background from the beam. Clean signal in quasi-elastic events

CP-violation with quasi-elastic events				
L=2900 km		N_{ele} ($\delta = 0$)	N_{ele} ($\delta = \pi/2$)	Stat. significance
$\Delta m^2_{32} = 3.5 \times 10^{-3} eV^2$	$10^{21}\ \mu^\pm$	35	26	1.5σ
$\sin^2\theta_{23} = 0.5$, $\sin^2 2\theta_{23} = 0.05$	$5 \times 10^{21}\ \mu^\pm$	175	130	3.4σ
$\Delta m^2_{12} = 10^{-4}$ eV^2, $\sin^2\theta_{12} = 0.5$	$10^{22}\ \mu^\pm$	350	260	4.8σ
$\Delta m^2_{32} = 7 \times 10^{-3}$ eV^2	$10^{21}\ \mu^\pm$	96	85	1.1σ
$\sin^2\theta_{23} = 0.5$, $\sin^2 2\theta_{23} = 0.05$	$5 \times 10^{21}\ \mu^\pm$	480	425	2.5σ
$\Delta m^2_{12} = 10^{-4}$ eV^2, $\sin^2\theta_{12} = 0.5$	$10^{22}\ \mu^\pm$	960	850	3.6σ

Sensitivity to δ

Amplitude of CP-violating effects strongly depends on all oscillation parameters, in particular Δm^2_{12}.

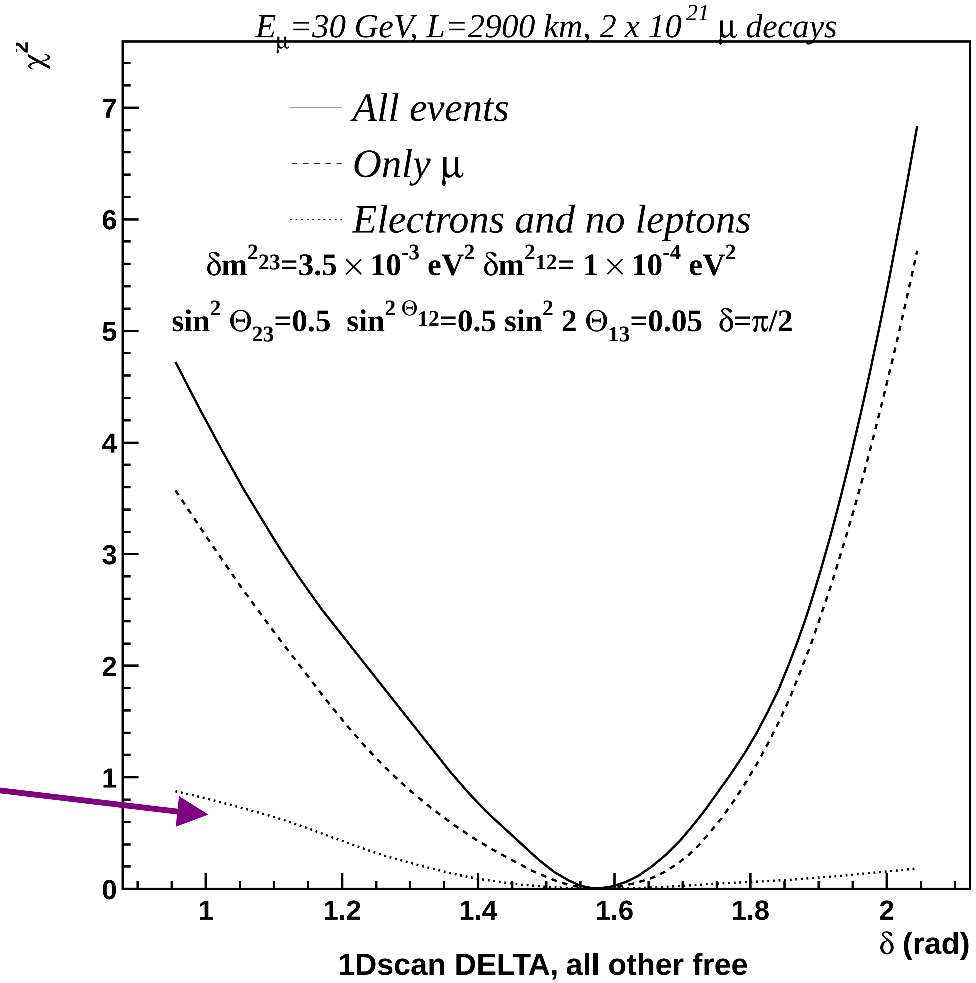
High fluxes needed, apart from a little corner of the parameter space



Measurement of CP violation

In the most favorable case, the phase δ can be measured with a 20% accuracy at L=2900 km.

Electron and NC-like events also contribute, albeit marginally, to the fit



Conclusions

- Neutrino factory allows simultaneous study of many oscillation phenomena
  - ➜A general-purpose detector is needed for:
    - – Electrons
    - – Tau identification
    - – Quasi-elastic events
    - – Neutral current-like events.
- These events contribute to the main measurements:
  - ➜θ_{13}, $\nu_e \rightarrow \nu_\tau$, CP violation

  and provide essential cross-checks
- To look for new phenomena, we need to over-constrain the oscillation pattern