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

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Hep-ph/0005007

# Neutrino Oscillations at the NuFactory

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

$\mu^- \rightarrow e^- \bar{\nu}_e$	$\nu_\mu$	
	$\nu_e \rightarrow e^-$	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  $\mu^+$  beam

Oscillation probabilities:

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

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

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

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

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

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

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

# How to get most of the potential?

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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

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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

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Detector able to identify  $\gamma$ , e,  $\mu$  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

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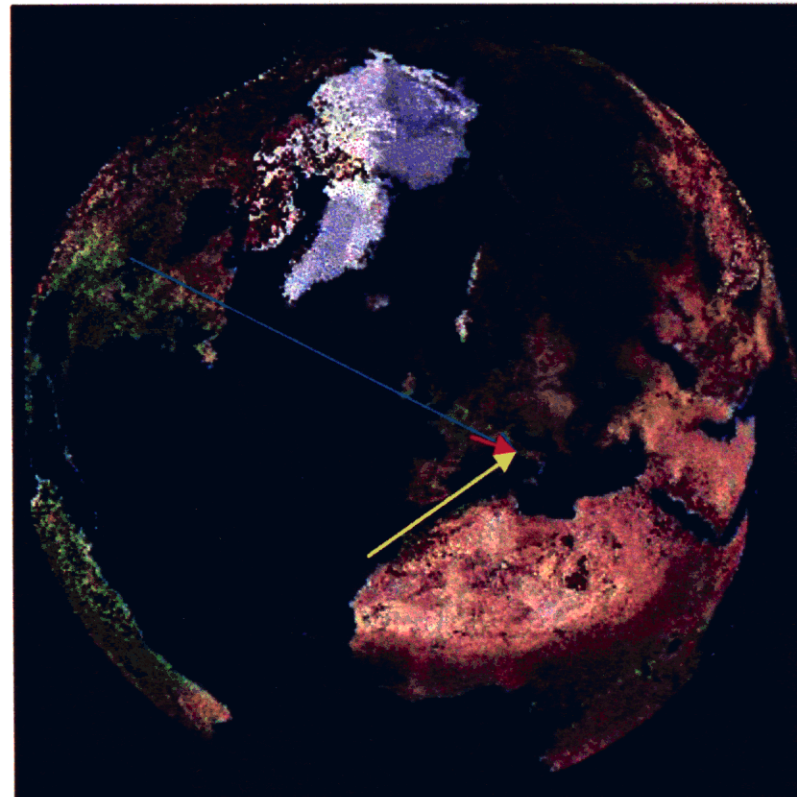
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# Possible baselines

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 <sup>3</sup>
Canary	2900 km	3.2 g/cm <sup>3</sup>
FNAL	7400 km	3.7 g/cm <sup>3</sup>
KEK	8815 km	4.0 g/cm <sup>3</sup>



# Event rates for a 10 kton detector

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

**No oscillations**

$E_\mu = 30$  GeV

No polarization

No beam divergence



# Detector simulation

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ICANOE fully simulated for CNGS studies.

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

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

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

Proper neutrino cross section used

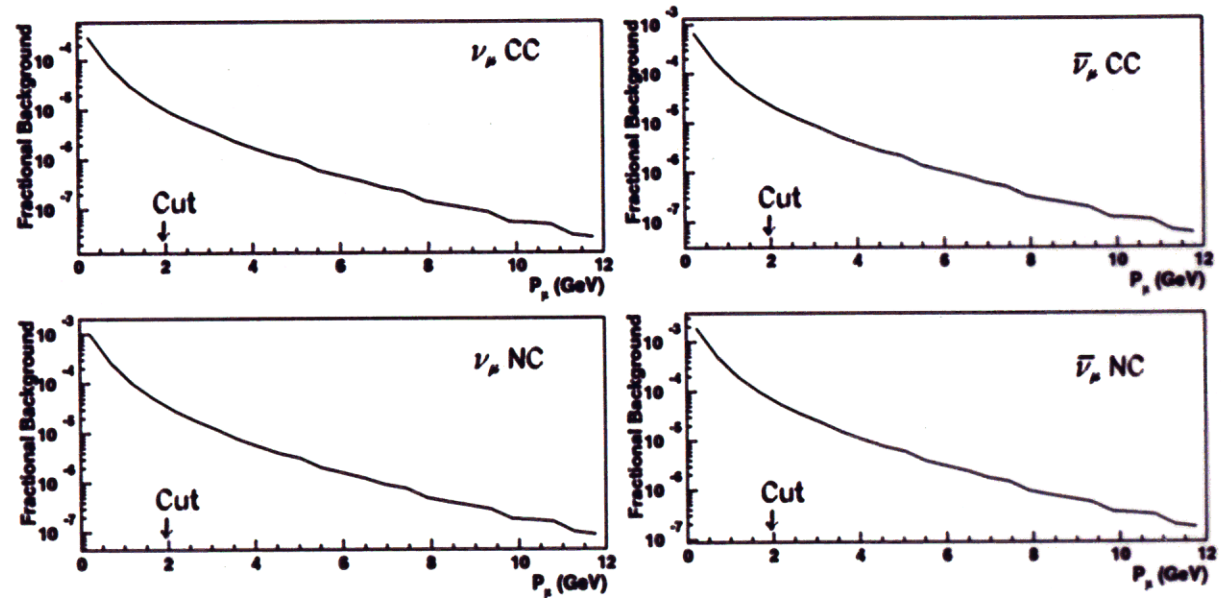
Charged  $\pi^\pm, K^\pm$  decay into  $\mu^\pm$  for BG treatment

# Background treatment

Hadron decays can produce “fake” wrong-sign muon events.

We are not aiming at large background rejection factors.

Simple momentum cut  $P_{\mu} > 2$  GeV applied



# Parameters used

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For this study, we consider as our default:

★  $2 \cdot 10^{20}$  decays of 30 GeV ( $\mu^+ + \mu^-$ )

★ 3-family mixing with:

→  $\Delta m_{23}^2 = (3.5, 5, 7) \cdot 10^{-3} \text{ eV}^2$

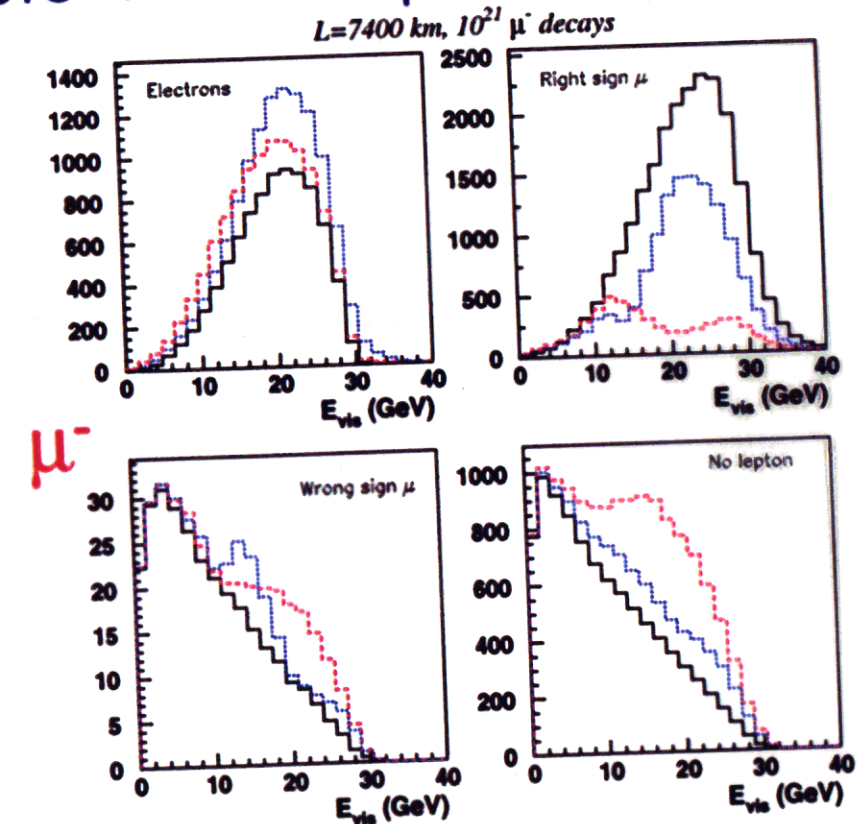
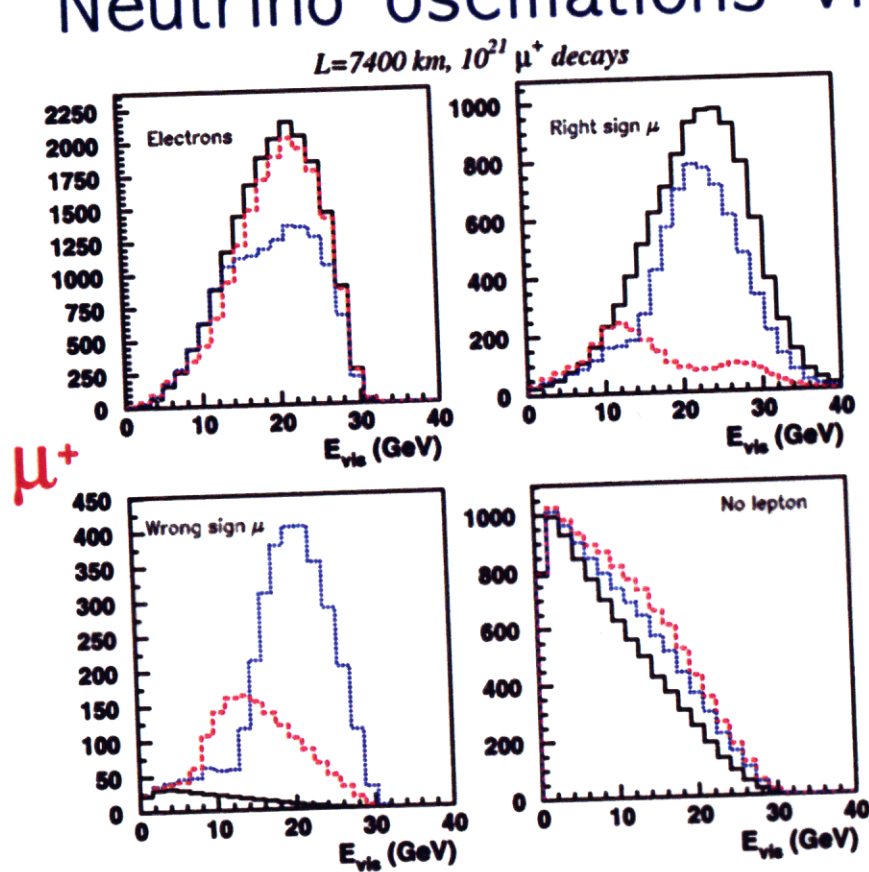
→  $\sin^2 \theta_{23} = 0.5$

→  $\sin^2 2\theta_{13} = 0.05$

★ 10 kton ICANOE-like detector

# Observed Spectra

Neutrino oscillations visible in the spectra:

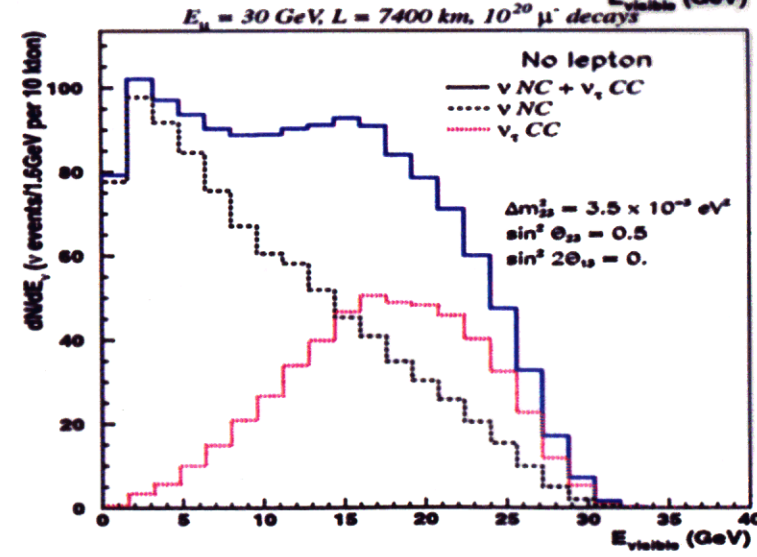
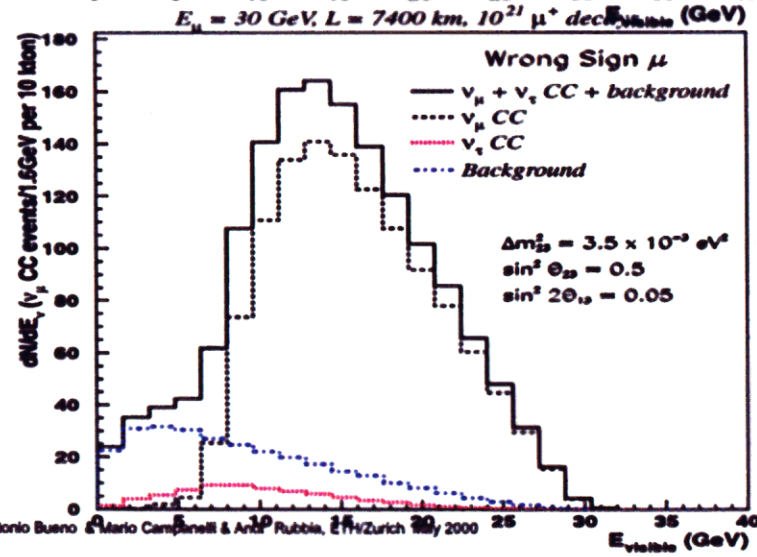
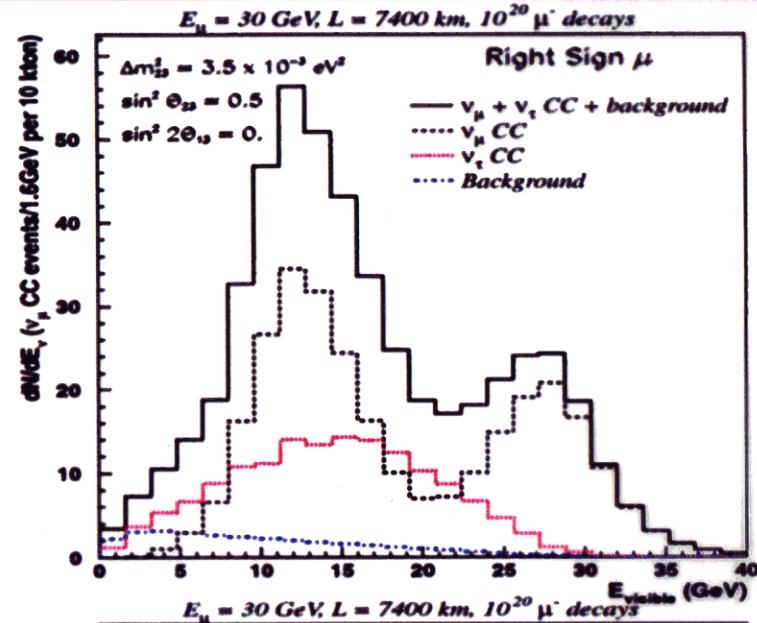
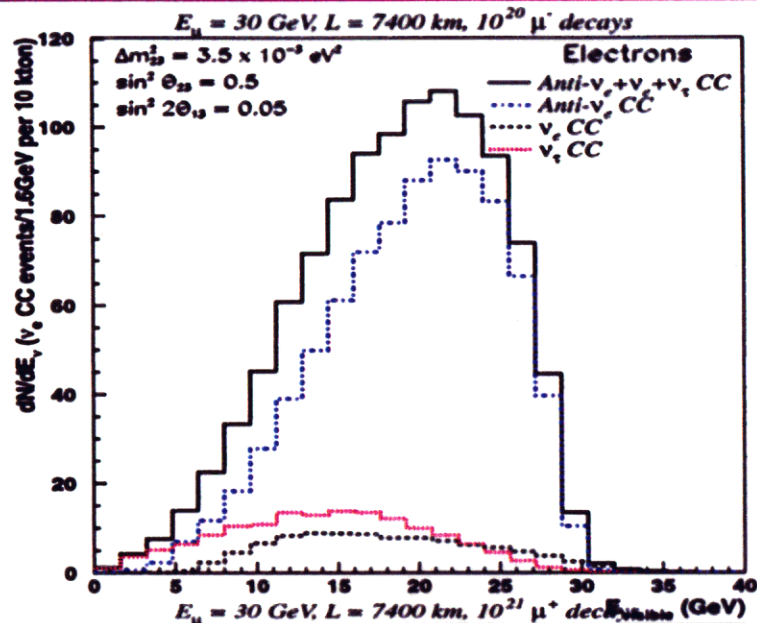


ICANOE fast simulation

— No oscillation  
 - - -  $\Delta m^2 = 3.5 \cdot 10^{-3} \text{ eV}^2$   
 - - -  $\Delta m^2 = 7 \cdot 10^{-3} \text{ eV}^2$

$\theta_{23} = \pi/4$   
 $\sin^2 \theta_{13} = 0.05$

# A closer look to different event classes



# $\nu_\tau$ appearance

ICANOE has been designed to perform  $\nu_\tau$  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:

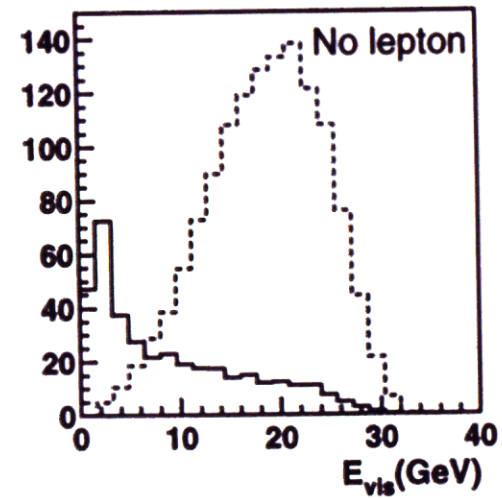
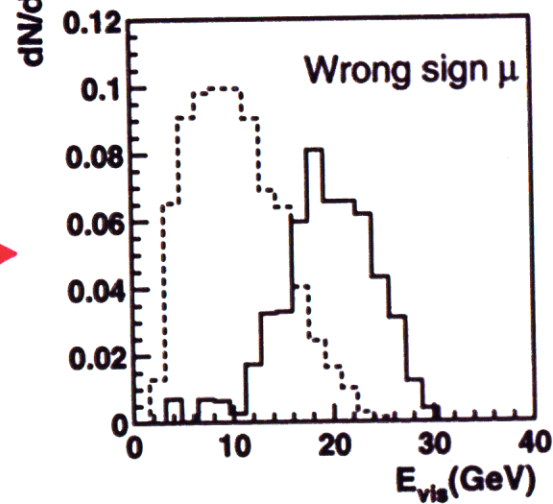
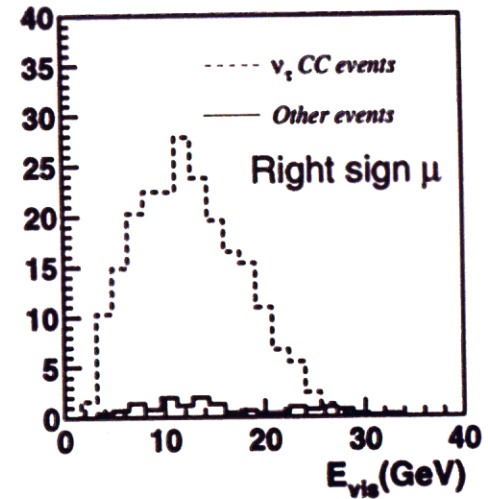
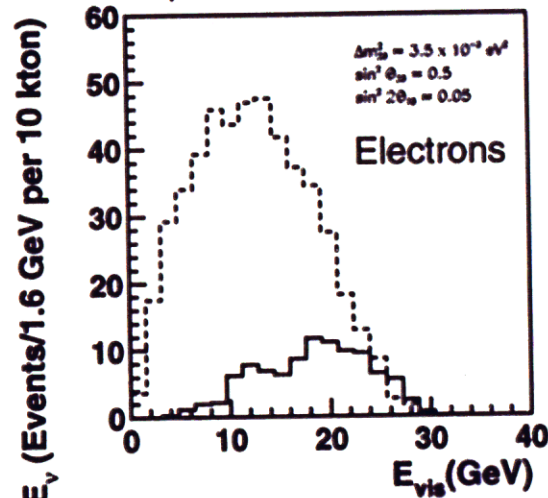
$\nu_\mu \rightarrow \nu_\tau$ appearance search					
Cuts	$\tau \rightarrow l$	CC background	Cuts	$\tau \rightarrow h$	NC background
Initial	100%	100%	Initial	100%	100%
Loose cuts					
$P_T^l < 0.5\text{GeV}$	50%	14%	$P_T^{\text{miss}} < 1\text{GeV}$	72%	40%
$P_T^{\text{miss}} > 0.6\text{GeV}$	40%	0.5%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

1 event  
background

# $\tau$ -enhanced sample

Tau contribution enhanced for all event classes

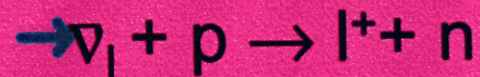
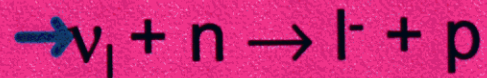
$E_\mu = 30 \text{ GeV}, L = 7400 \text{ km}, 10^{21} \mu^- \text{ decays } \tau \text{ enhanced sample}$



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

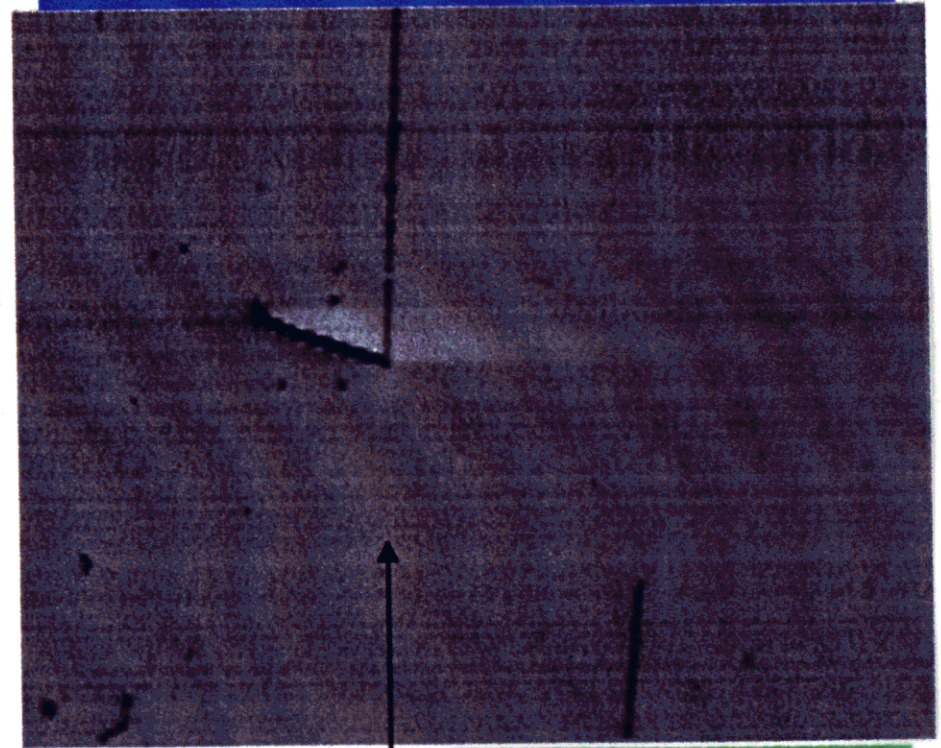
# Quasi-elastic events

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

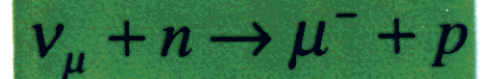


Only way to determine helicity of electron neutrino without explicit electron charge measurement

Real  $\nu$  event  
in the 50 liter LAr TPC in  
CERN WANF beam



CERN  $\nu$ -beam





# Goals of Experiments at NUFACT

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

- ★ Precise determination of  $\Delta m^2_{23}$  and  $\Theta_{23}$
- ★ Measurement of  $\Theta_{13}$
- ★ Study of matter effects
- ★ Study of CP violation

# Fitting procedure

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

We use:

- ★  $\chi^2$  for  $>40$  events in bin
- ★  $-\log \mathbf{L}$  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

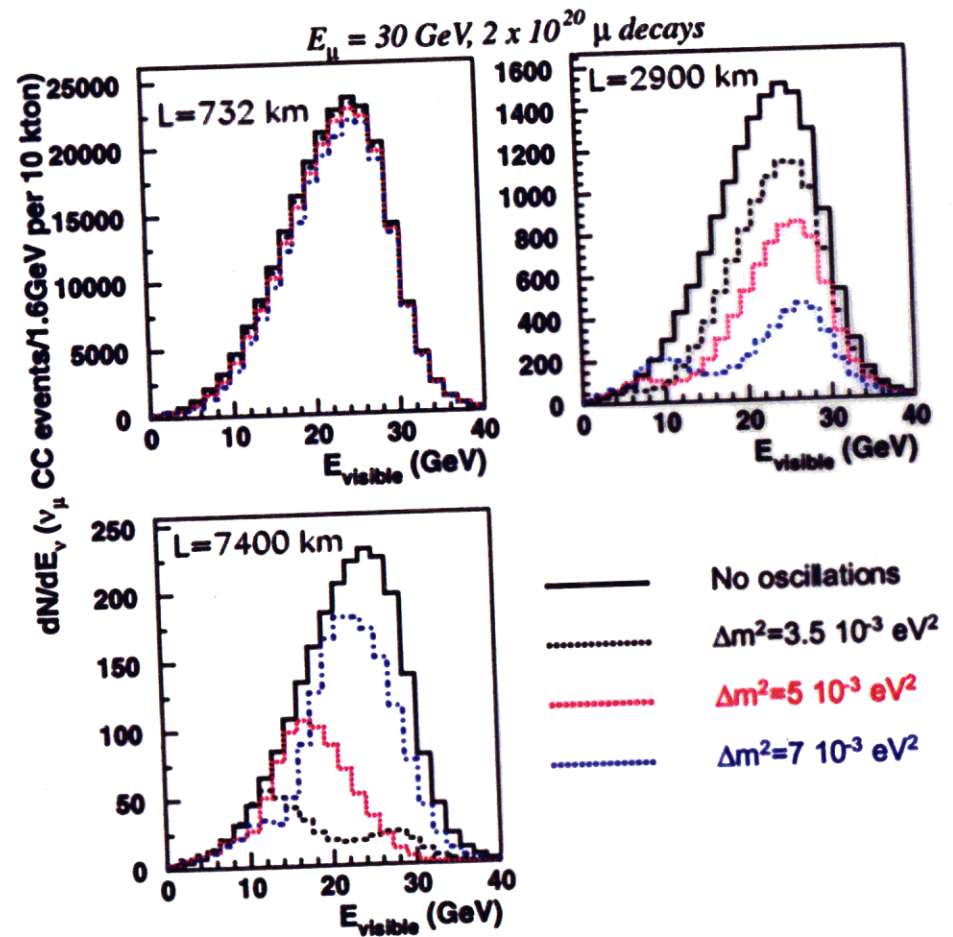
# Precise determination of $\Delta m^2_{23}, \Theta_{23}$

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

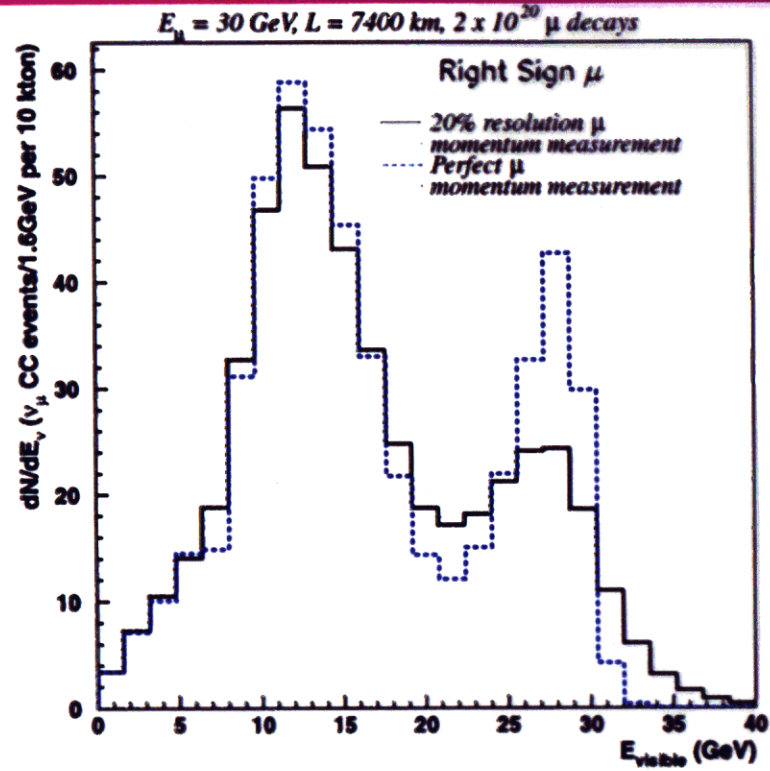
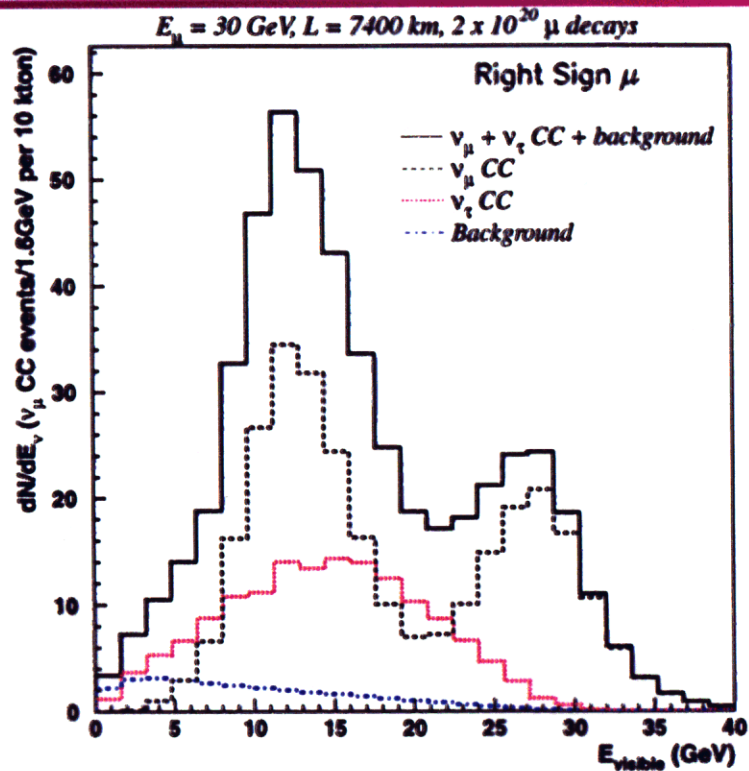
Measurement dominated by disappearance dip at large distances for right-sign  $\mu$  :

★ Position:  $\Delta m^2_{23}$

★ Height:  $\Theta_{23}$



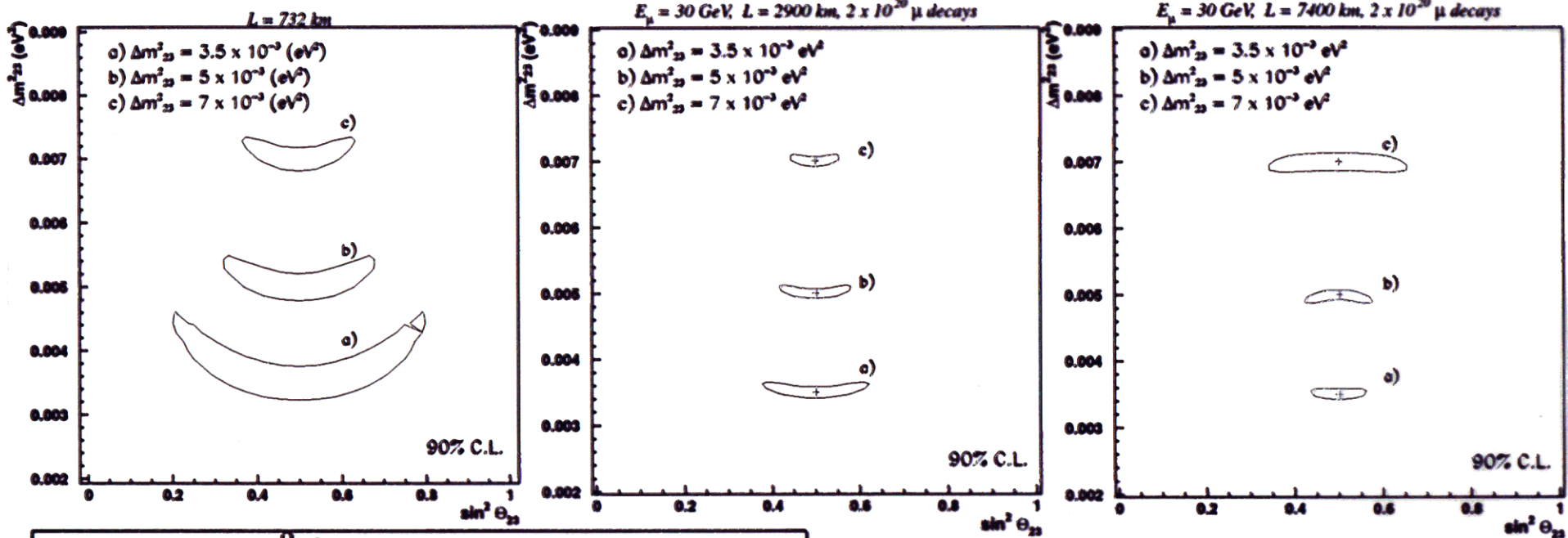
# Right-sign muon disappearance



Contributions to events in the dip:

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

# Sensitivity for $\Delta m_{23}^2, \theta_{23}$ measurements



$\sin^2 \theta_{23}$ measurement		
$\Delta m_{23}^2$ ( $eV^2$ )	L=2900 km	L=7400 km
$7 \times 10^{-3}$	$0.50 \pm 0.11$	$0.50 \pm 0.04$
$5 \times 10^{-3}$	$0.50 \pm 0.06$	$0.50 \pm 0.06$
$3.5 \times 10^{-3}$	$0.50 \pm 0.05$	$0.50 \pm 0.09$

Event simulation includes:  
 ✎Background  
 ✎Exclusive  $\tau$ decays  
 ✎Resolution  
 2% Beam systematics

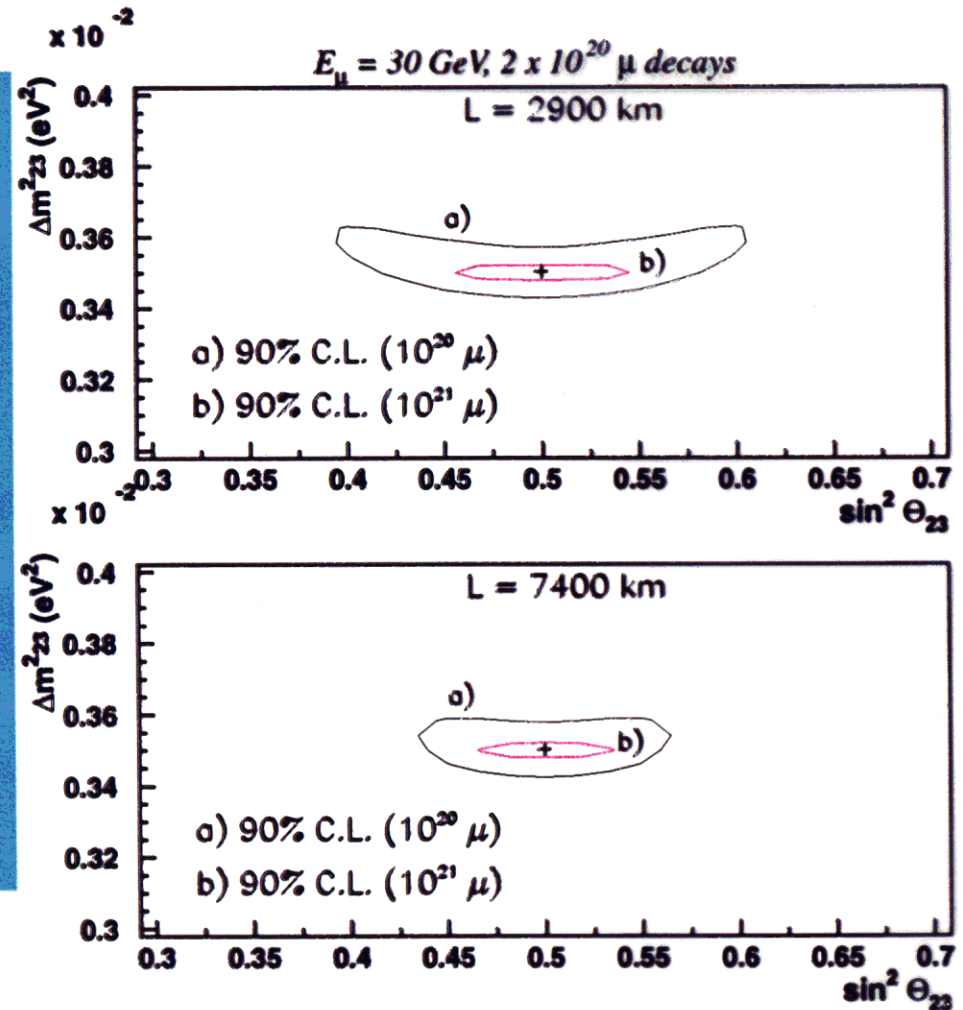
Consistent with Barger et al. hep-ph/9911524

Error on  $\Delta m_{23}^2 = 1\%$

# Statistical improvements

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

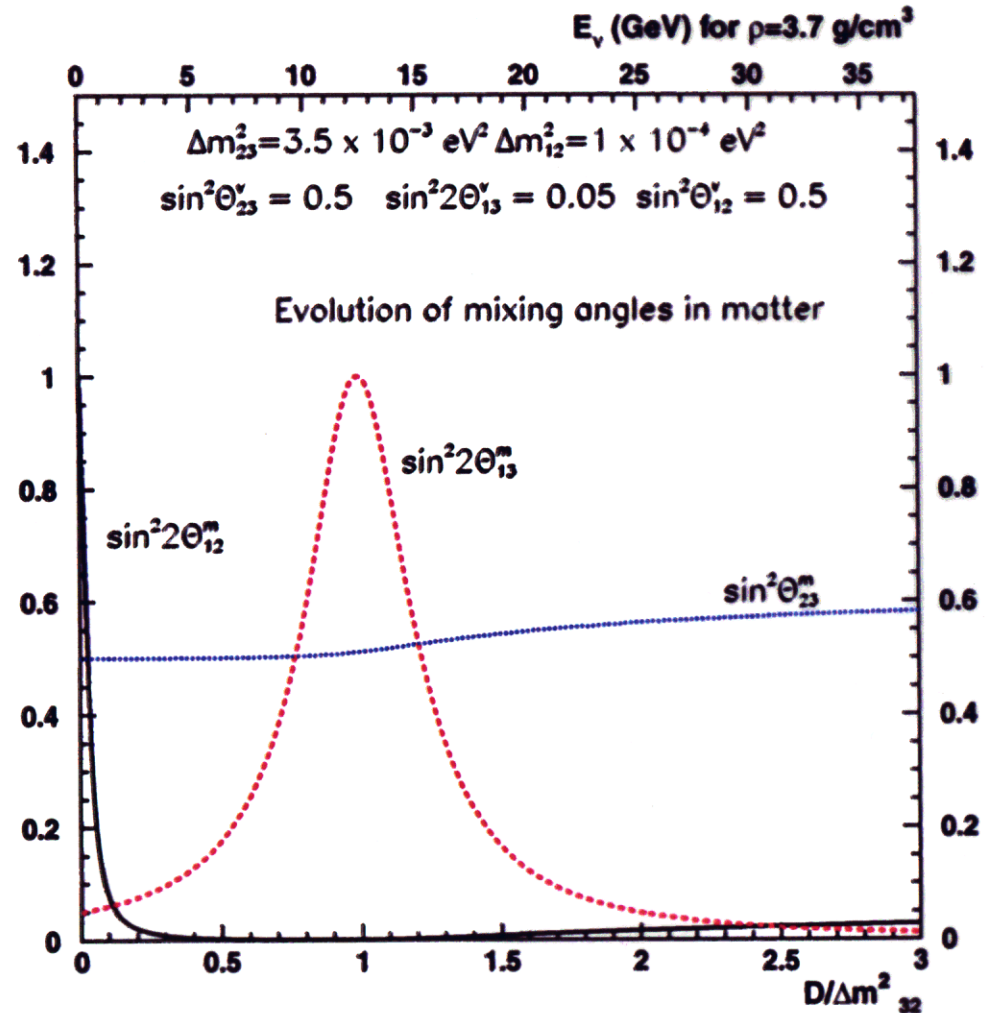
(2% systematics)



# 3-family mixing

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

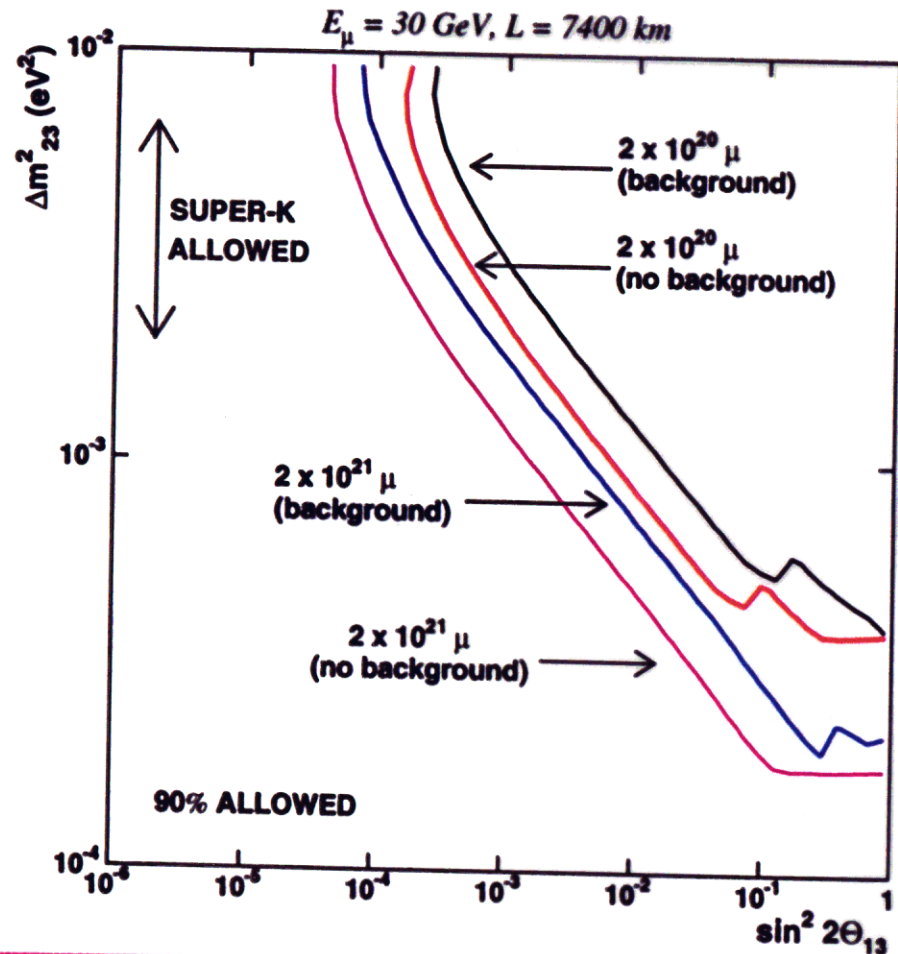
Assuming  $\Delta m_{23}^2 > 0$ , oscillations involving  $\nu_e$  ( $\bar{\nu}_e$ ) are **enhanced** (suppressed) by MSW interactions with matter



# Sensitivity to $\theta_{13}$

Sensitivity to  $\theta_{13}$  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-elastic

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

$\nu_e$ appearance search with quasi-elastic Electron Class: Events for $10^{21} \mu^-$ decays						
Baseline	$\bar{\nu}_e$ CC		$\nu_\mu \rightarrow \nu_e$ CC		$\nu_\mu \rightarrow \nu_\tau$ CC, $\tau \rightarrow e$	
	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 $\Theta_{13}$

Three-family mixing $\sin^2 \theta_{23} = 0.5, \sin^2 2\theta_{13} = 0.05$				
	All classes $\chi_{all}^2$		Only muons $\chi_{\tau\mu}^2 + \chi_{\nu\mu}^2$	
	L=2900 km	L=7400 km	L=2900 km	L=7400 km
$\Delta m_{32}^2 = 3.5 \times 10^{-3} \text{ eV}^2,$				
$\delta(\Delta m_{32}^2)$	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%
$\Delta m_{32}^2 = 5 \times 10^{-3} \text{ eV}^2$				
$\delta(\Delta m_{32}^2)$	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%
$\Delta m_{32}^2 = 7 \times 10^{-3} \text{ eV}^2$				
$\delta(\Delta m_{32}^2)$	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%

$\Theta_{13}$  mainly determined by wrong-sign muons.

Including electrons, NC and kinematics for  $\tau$  can improve precision by more than 30%

# Earth density

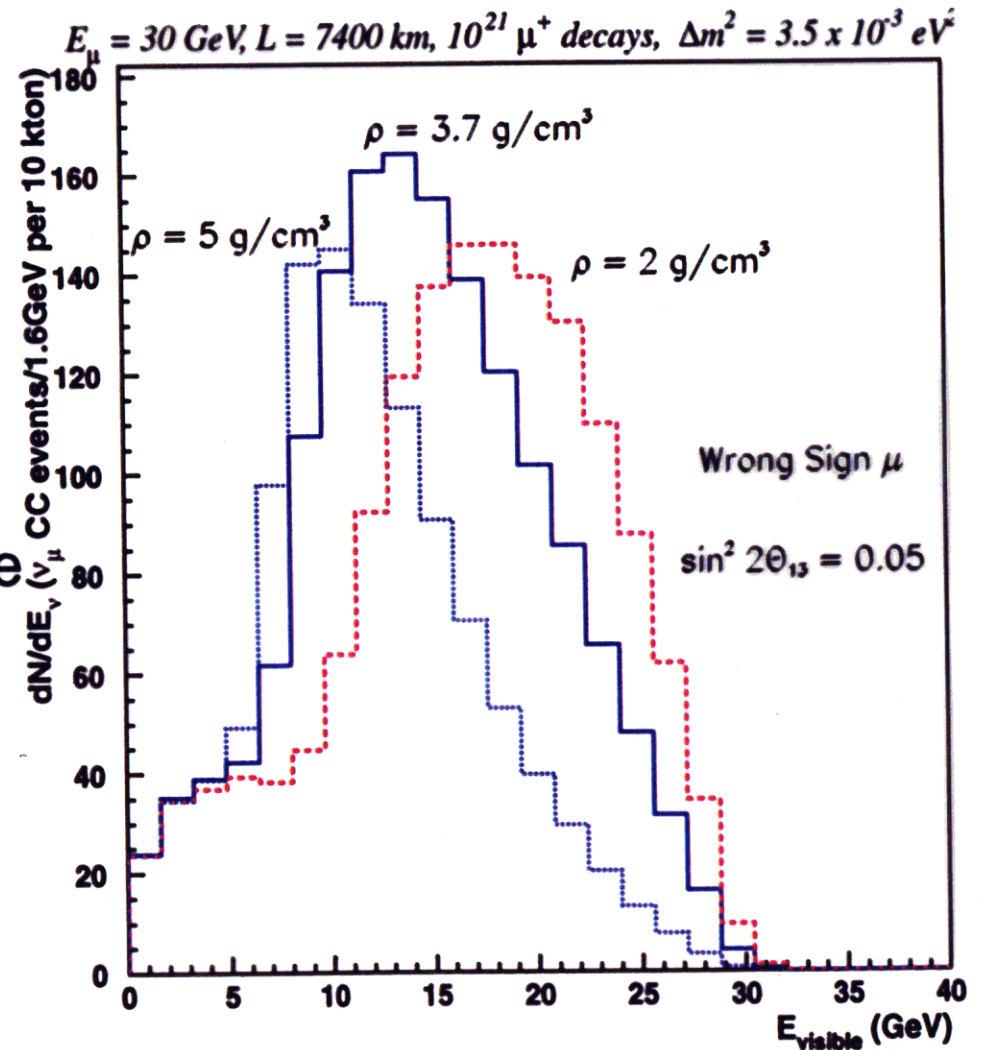
Resonance position depends on  $\Theta_{13}\Delta m^2_{13}, \rho$

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

¥ For small  $\theta_{13}$ ,  $\cos 2\theta_{13}^{-1}$

¥  $m_{23}^2$  measured independently by right-sign muon disappearance

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



# Influence of density

Density fixed to true value:

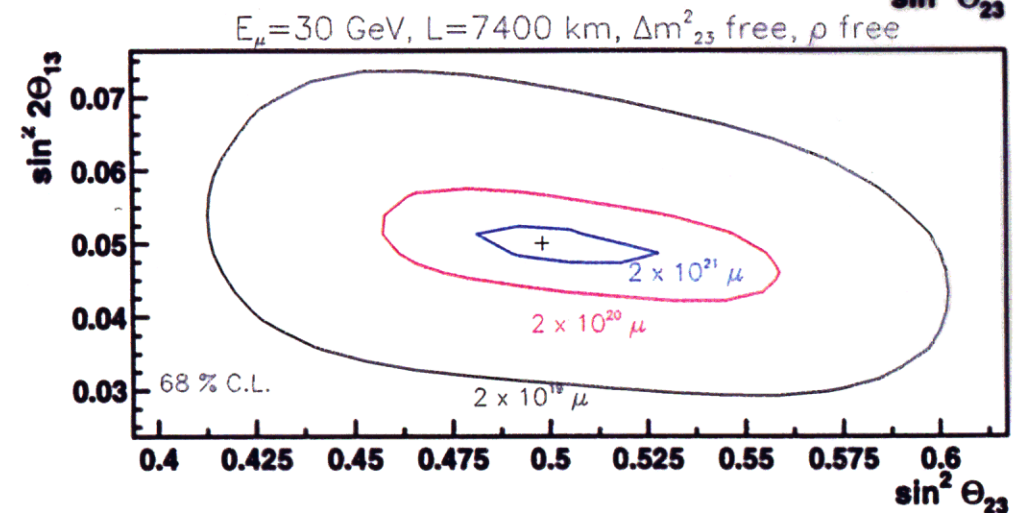
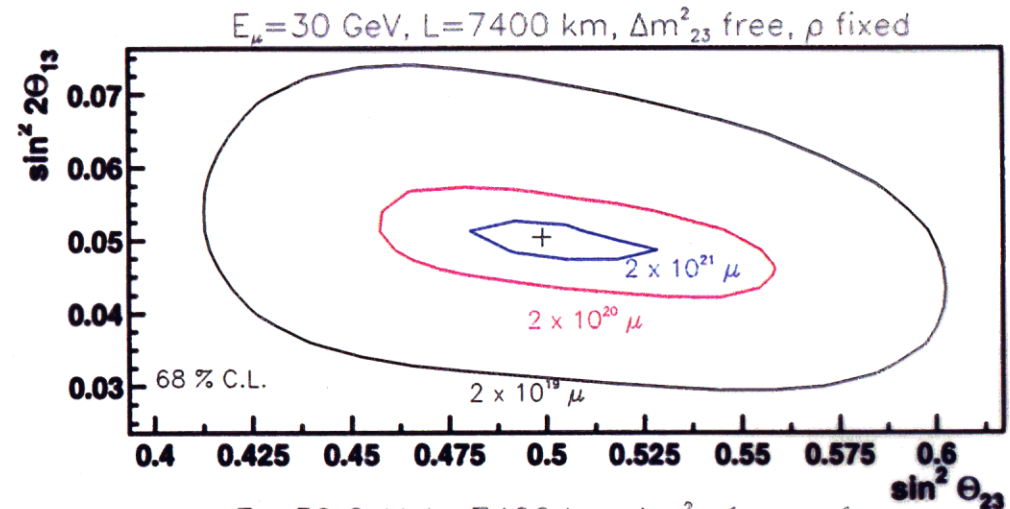
$$\sigma(\sin^2 2\theta_{13}) = 0.0071$$

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

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:

$$\sum_{x=e, \mu, \tau} P(\nu_x \rightarrow \nu_y) = 1$$

Assuming new phenomena in oscillations to  $\tau$  neutrinos, probabilities would change:

$$P(\nu_\mu \rightarrow \nu_\tau) \rightarrow \alpha P(\nu_\mu \rightarrow \nu_\tau)$$

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

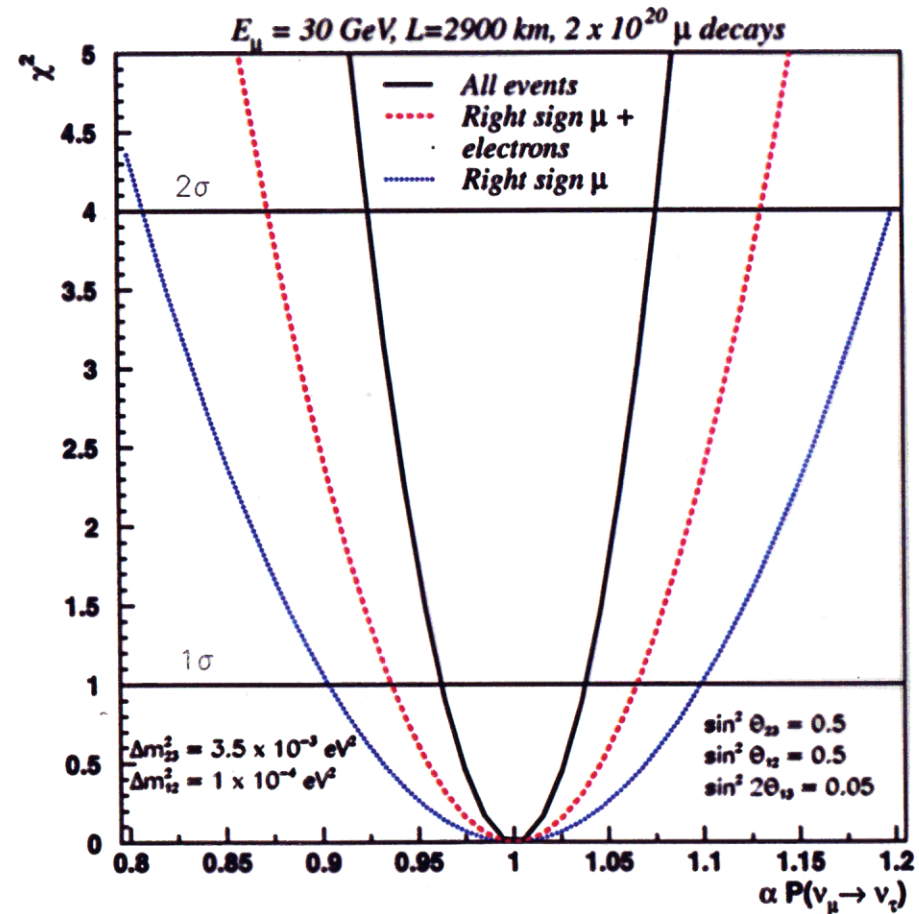
Precision on  $\alpha$ : O(1%)

Precision on  $\beta$ : O(20%)

Appearance/disappearance test				
Baseline	$\Delta m_{32}^2$ ( $\times 10^{-3}$ eV <sup>2</sup> )	$10^{20} \mu^\pm$	$10^{21} \mu^\pm$	$10^{22} \mu^\pm$
Precision on $\alpha \Rightarrow \alpha \times P(\nu_\mu \rightarrow \nu_\tau)$				
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 $\beta \Rightarrow \beta \times P(\nu_e \rightarrow \nu_\tau)$				
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  $\nu_\tau$

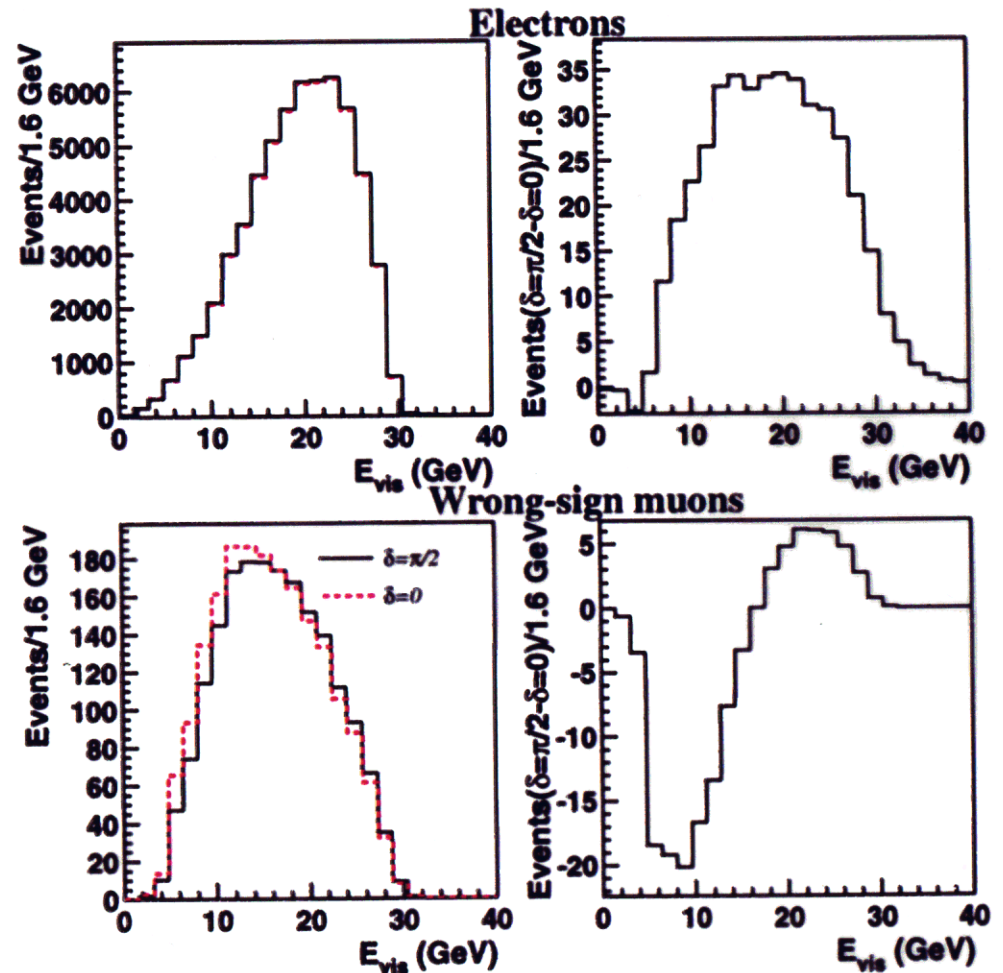


# Effects of CP Violation

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

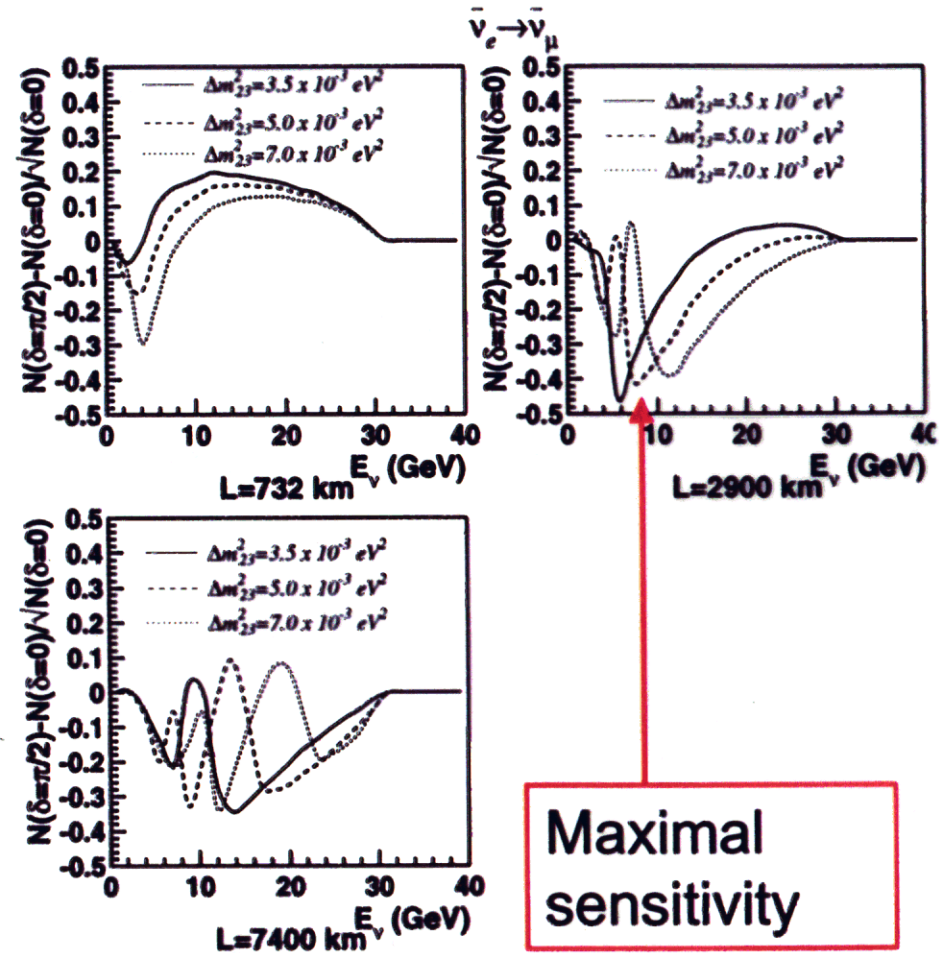
Increase number of electrons  
(large, but drawn in the BG)

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

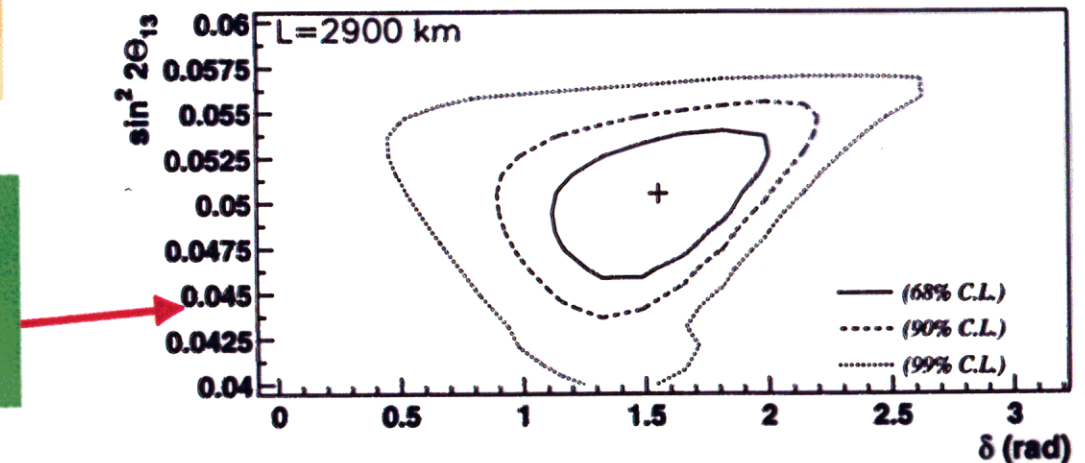
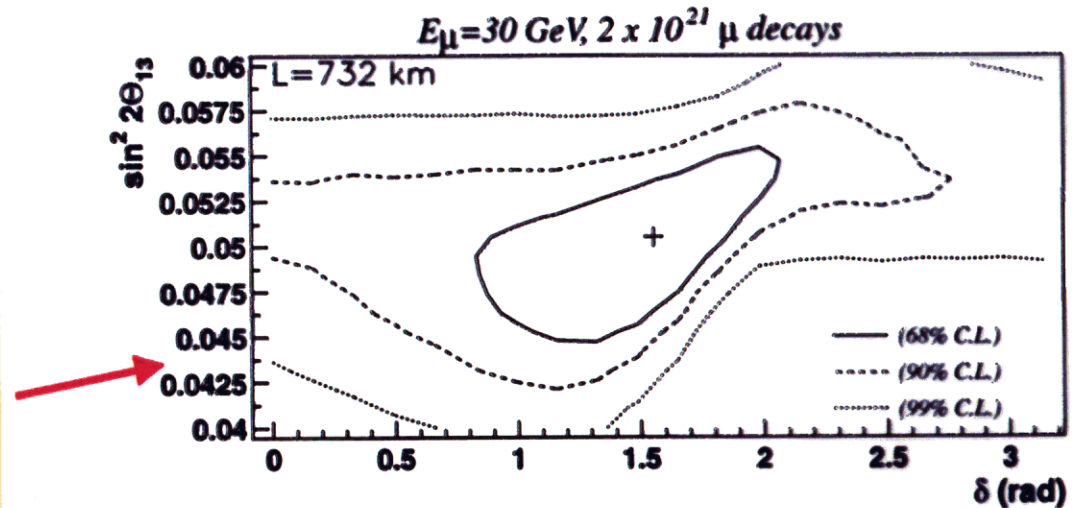




# $\delta$ vs $\theta_{13}$

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

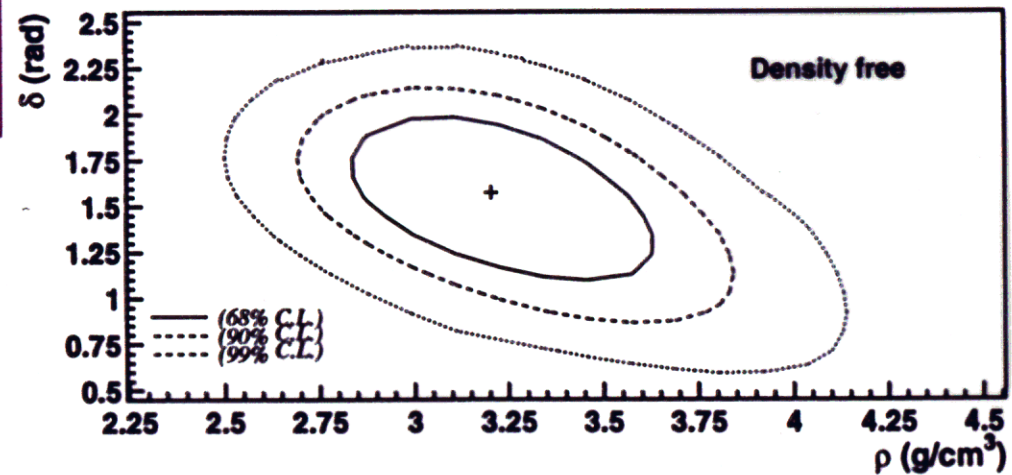
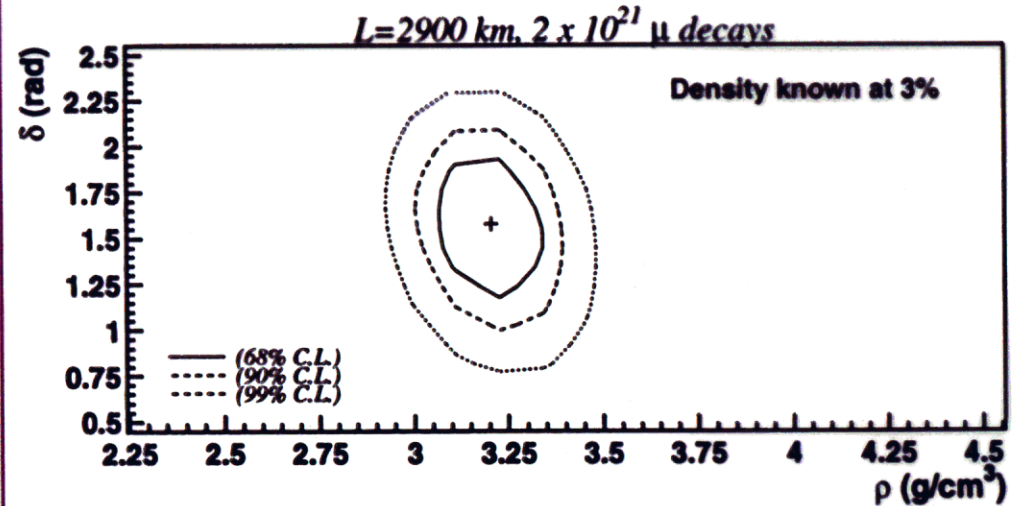
Correlation is much smaller when also a shape change occurs



# $\delta$ vs $\rho$

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

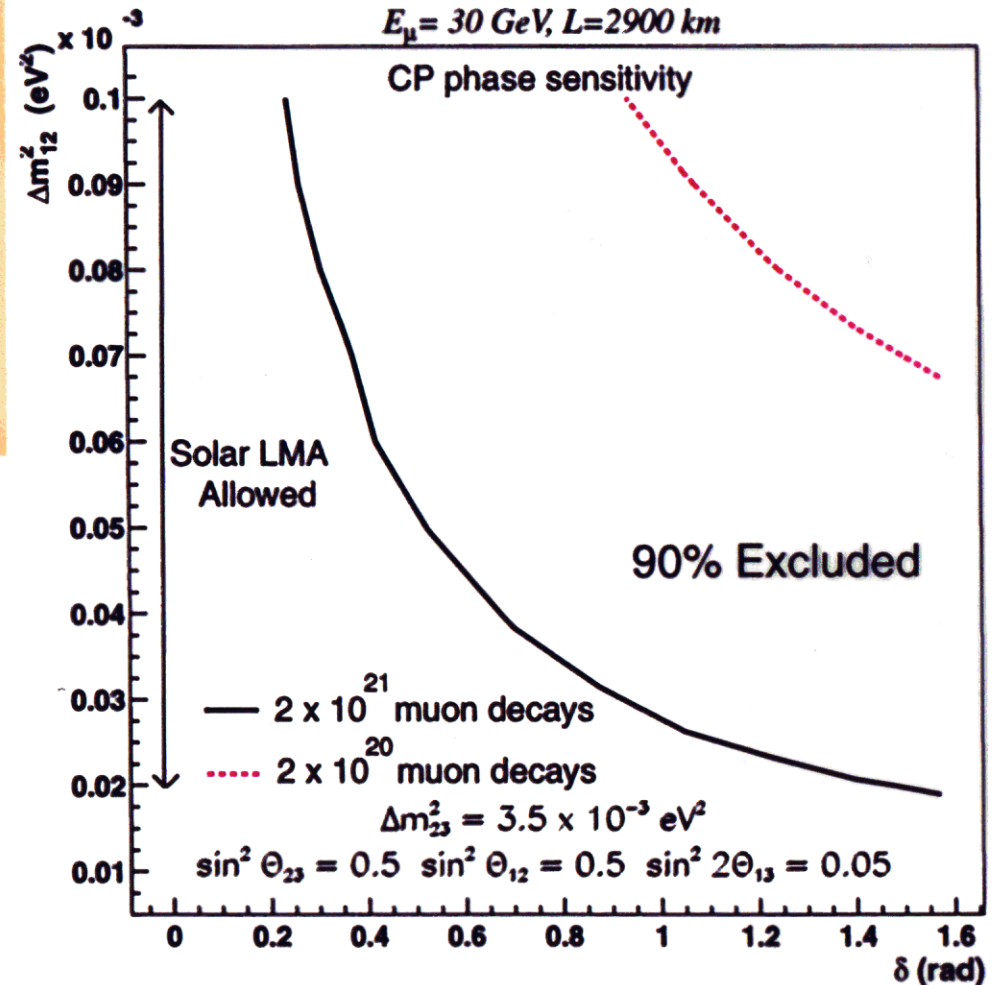
The CP violation effect is large for the electrons, but is hard to see due to  $\nu_e$  background from the beam. Clean signal in quasi-elastic events

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

# Sensitivity to $\delta$

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

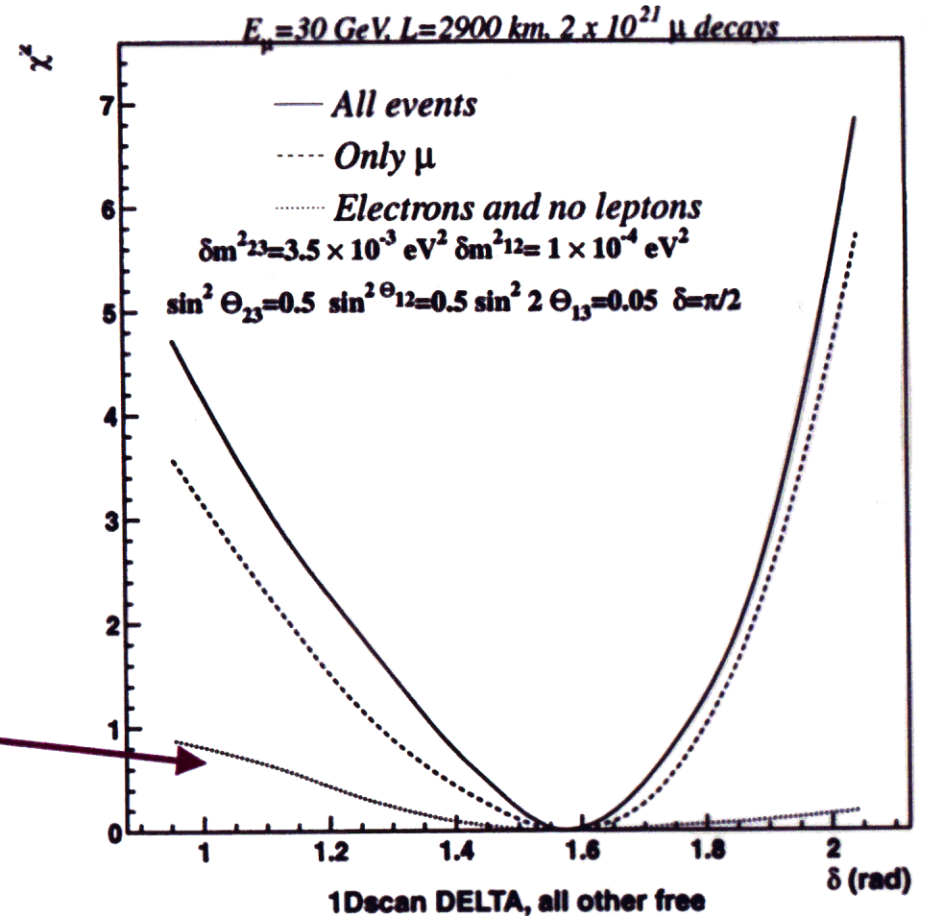
High fluxes needed, apart from a little corner of the parameter space



# Measurement of CP violation

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

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



# Conclusions

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- ★ 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:
  - $\theta_{13}$ ,  $\nu_e \rightarrow \nu_\tau$ , CP violation
  - and provide essential cross-checks
- ★ To look for new phenomena, we need to over-constrain the oscillation pattern