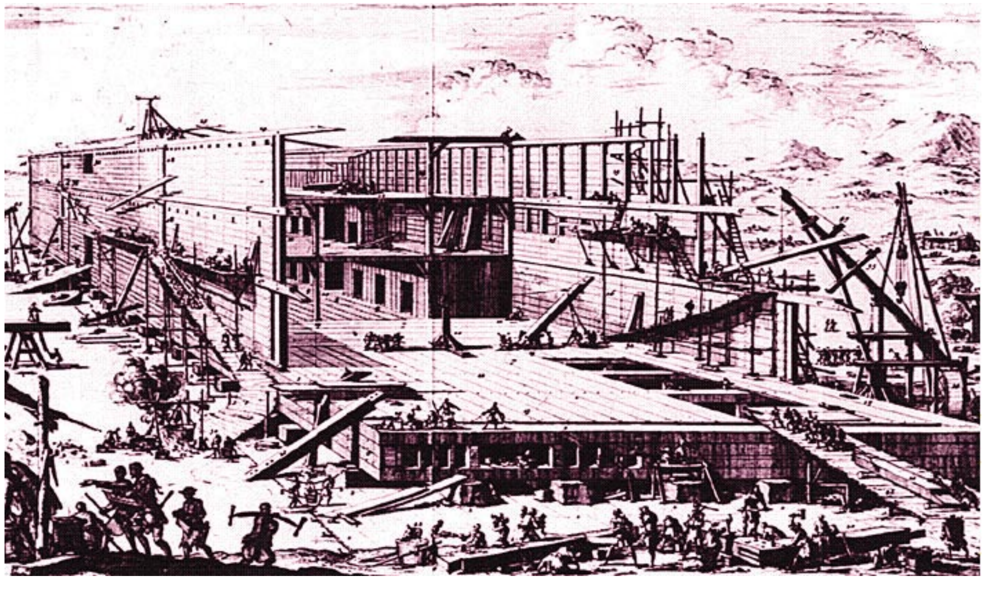
Status of physics studies of an ICANOE-like detector at the neutrino factory



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NuFact Neutrino Oscillation Working Group

29/2/2000

The ICANOE detector

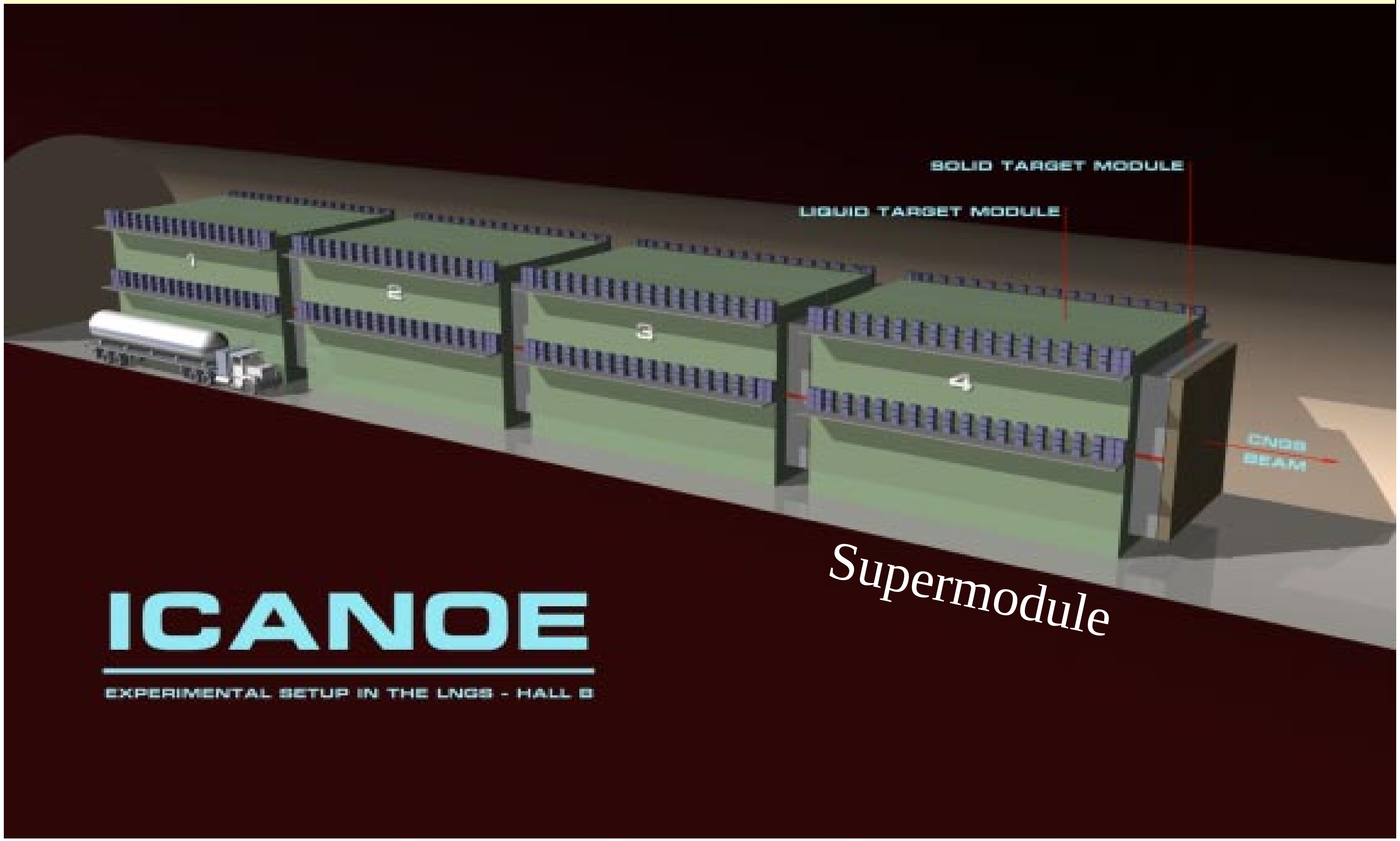
- Merging of two technologies:
  - *Low density* **liquid target**: ICARUS liquid argon imaging (bubble chamber quality)
  - *High density* **solid target**: magnetized fine grained NOE calorimeter
- Capable of detecting and measure final state *e*,γ,μ and *hadrons*, also provides μ charge discrimination
- Isotropic detector suitable to study atmospheric as well as ν beam from accelerators

Proposed experiment at CNGS

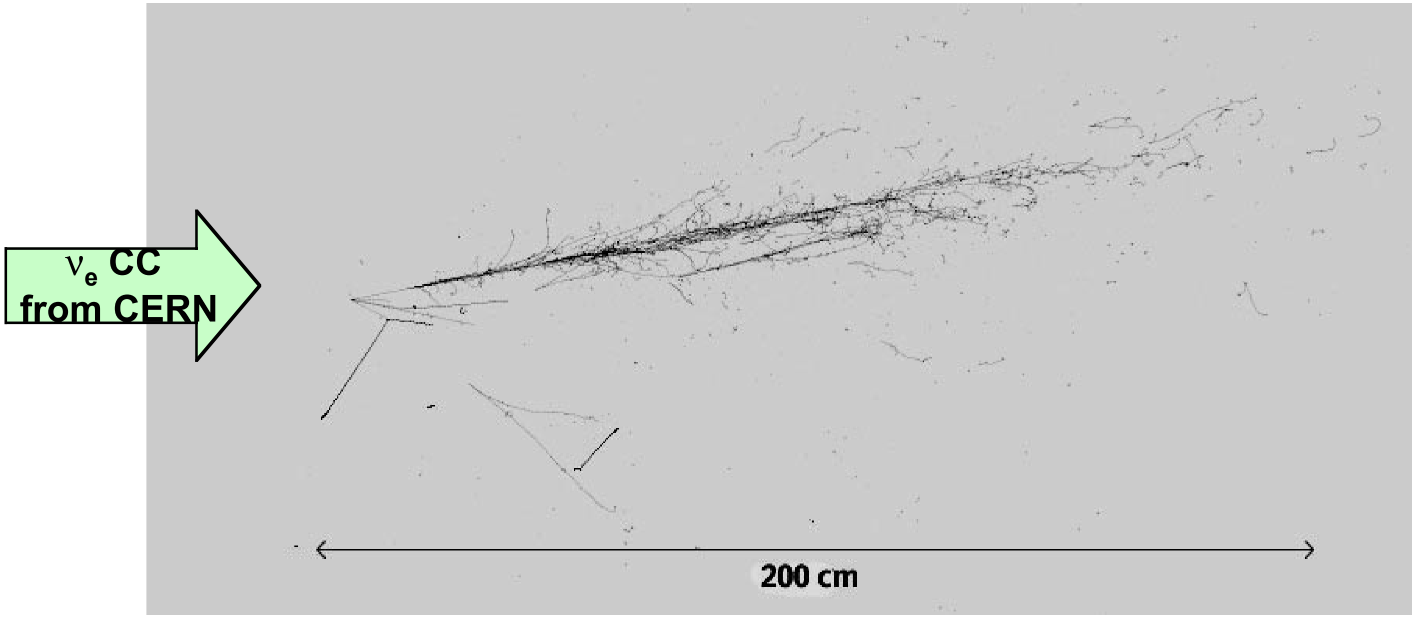
LNGS-P21/99 CERN/SPSC 99-40 SPSC/P314

The ICANOE detector at CNGS

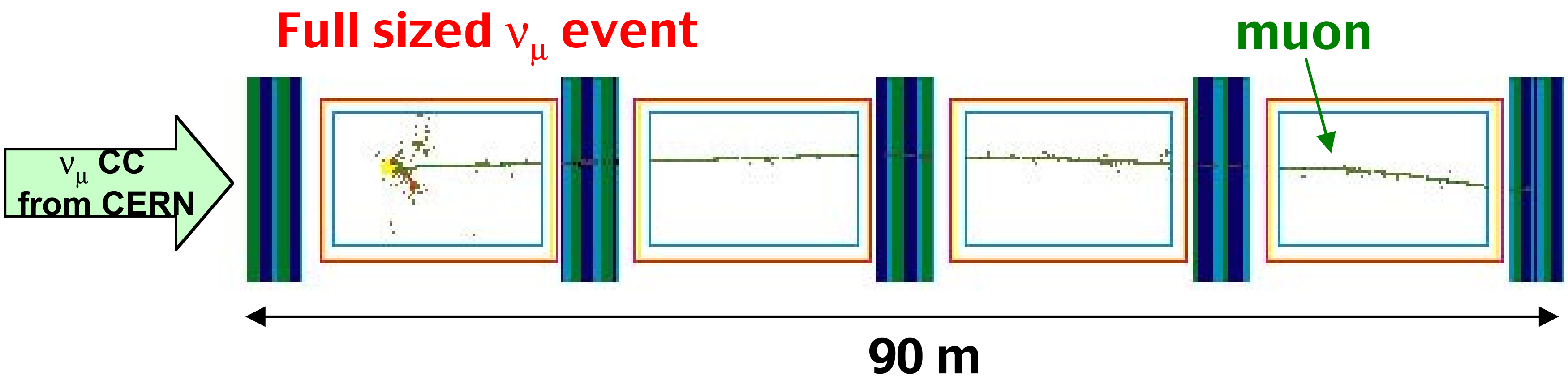
Liquid Target module : 1.4 (1.9) kton active (total) mass
Solid Target module: 0.8 kton mass



ICANOE: typical beam ν events



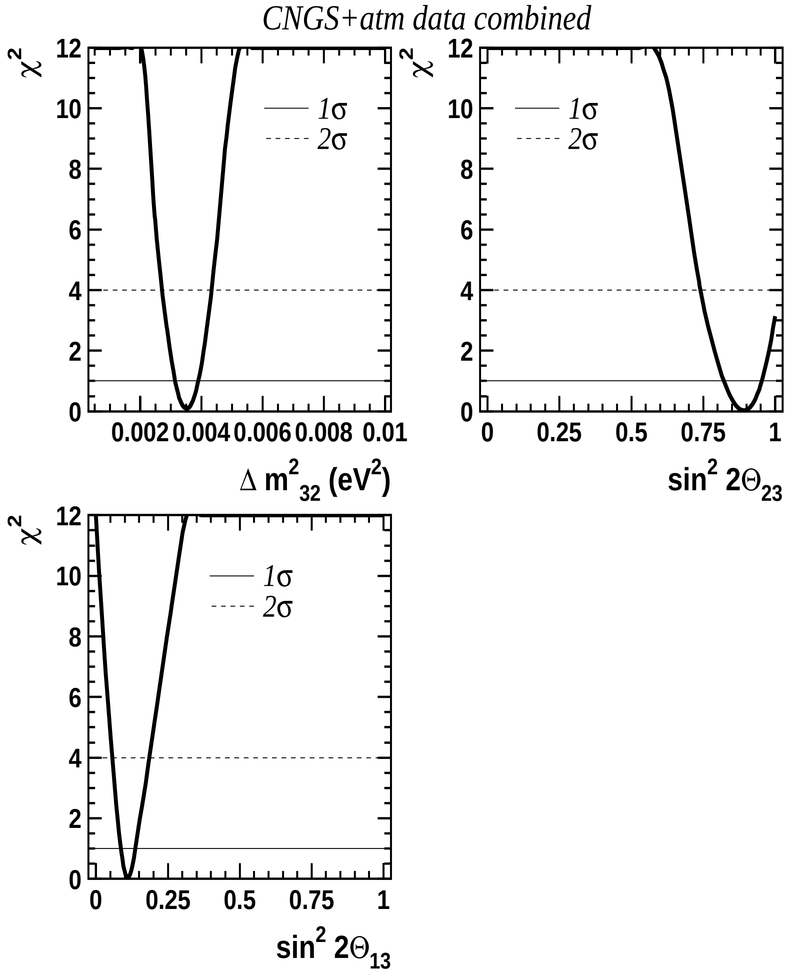
LAr Imaging



First generation LBL oscillation measurements

- Simultaneous measurement of
  - Events from LBL conventional ν beams from meson decays
  - ν originating from cosmic ray interactions in the atmosphere

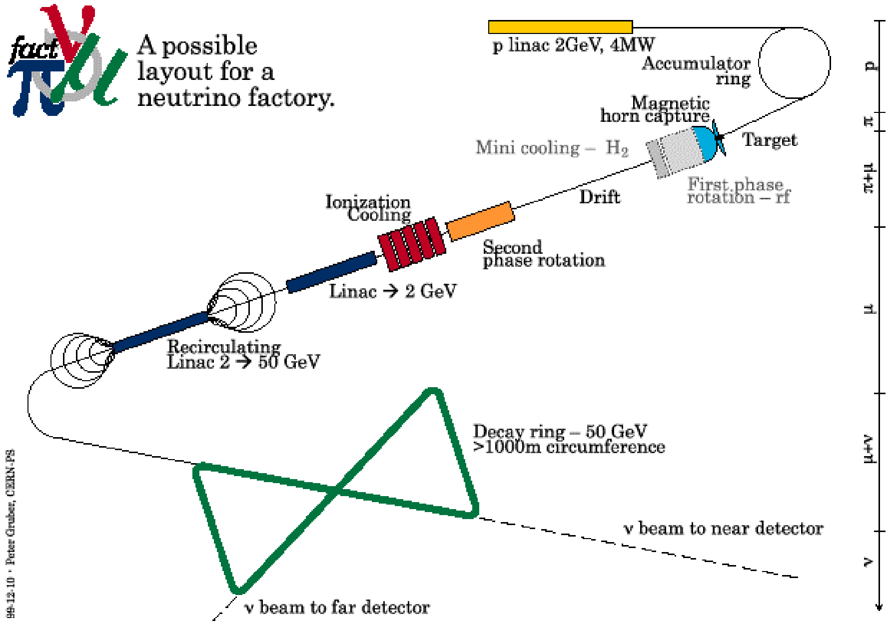
$\sin^2 2\theta_{13} = 0.10 \pm 0.04$
$\sin^2 2\theta_{23} = 0.90 \pm 0.12$
$\Delta m^2_{32} = (3.5 \pm 0.4) \times 10^{-3}\ \mathrm{eV}^2$



Precision of O(10%) on the oscillation parameters

Second generation LBL experiments: the NuFact

- By the time this facility becomes operational we presume that ν oscillations experimentally established beyond any doubt
- Main goals:
  - Accurate determination of Δm^2_{23} , Θ_{23} and especially Θ_{13}
  - Matter effects
  - CP violation



Long and Very Long Baseline Experiments

NuFact location	Distance to Gran Sasso	Mean density
CERN	732 km	2.8 g/cm^3
Canary Islands	2900 km	3.2 g/cm^3
FNAL	7400 km	3.7 g/cm^3
KEK	8815 km	4.0 g/cm^3

R > 3500 km & R< 4500 km

→ $\rho\ (g/cm^3) = 7.25 - 5 * 10^{-4} * R$

R > 4500 km & R < 6360 km

→ $\rho\ (g/cm^3) = 7.74 - 7 * 10^{-4} * R$

R > 6360 km

→ $\rho = 2.8\ g/cm^3$

Neutrino Event Rates

- Assume for this study:
  - **10 kton detector** (fiducial)
  - **E_μ = 30 GeV**
  - No polarization
  - No beam divergence

Rates (no oscillations)

		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

Event Classes

- Electron (no charge discrimination)
- Right sign muons
- Wrong sign muons
- NC-like events (no prompt lepton identified)

Therefore,we can study

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

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

Plus their charge conjugates with μ^+ beam

Oscillation probabilities

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

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

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

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

$$1 - \sin^2 2\theta_{23} \Delta^2{}_{32} \qquad \mathit{for} \;\; \theta_{13} << 1$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4 \theta_{13} \sin^2 2\theta_{23} \Delta^2{}_{32} \approx \sin^2 2\theta_{23} \Delta^2{}_{32} \qquad \mathit{for} \;\; \theta_{13} << 1$$

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

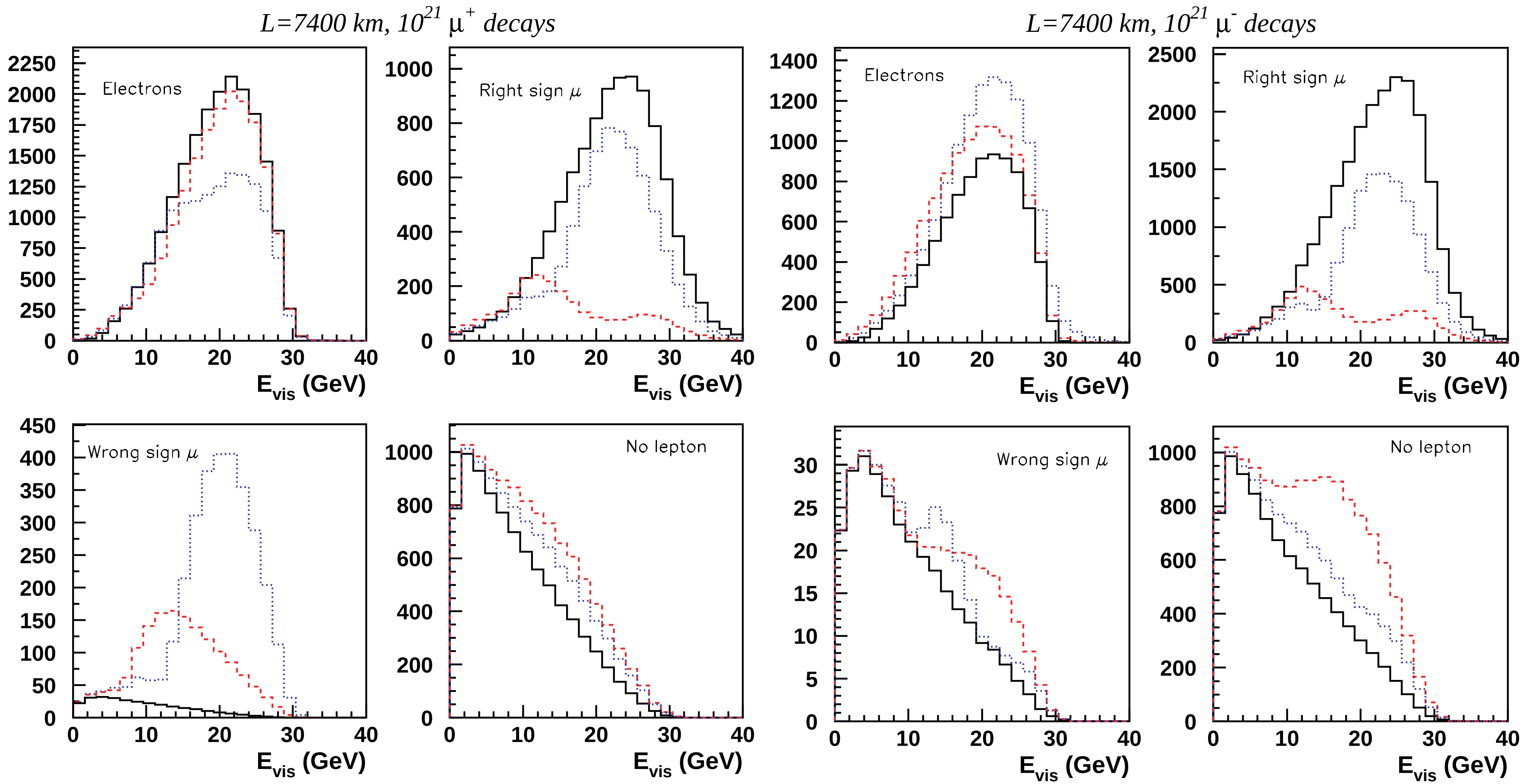
CKM-like parametrization

$$\theta_{13} \in \left[0, \frac{\pi}{4}\right] \Rightarrow \sin^2 2\theta_{13} \in [0,1]$$

$$\theta_{23} \in \left[0, \frac{\pi}{2}\right] \Rightarrow \sin^2 \theta_{23} \in [0,1]$$

$\sin^2 \Theta_{23} = 0.5$
maximal mixing

Example of event classes



No oscillation

$\Delta m^2_{23} = 3.5 * 10^{-3}\ eV^2$

$\Delta m^2_{23} = 7 * 10^{-3}\ eV^2$

$\sin^2\Theta_{23} = 0.5$

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

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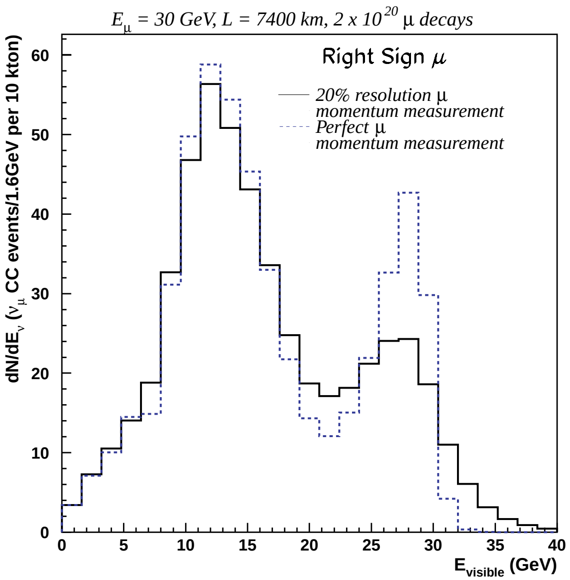
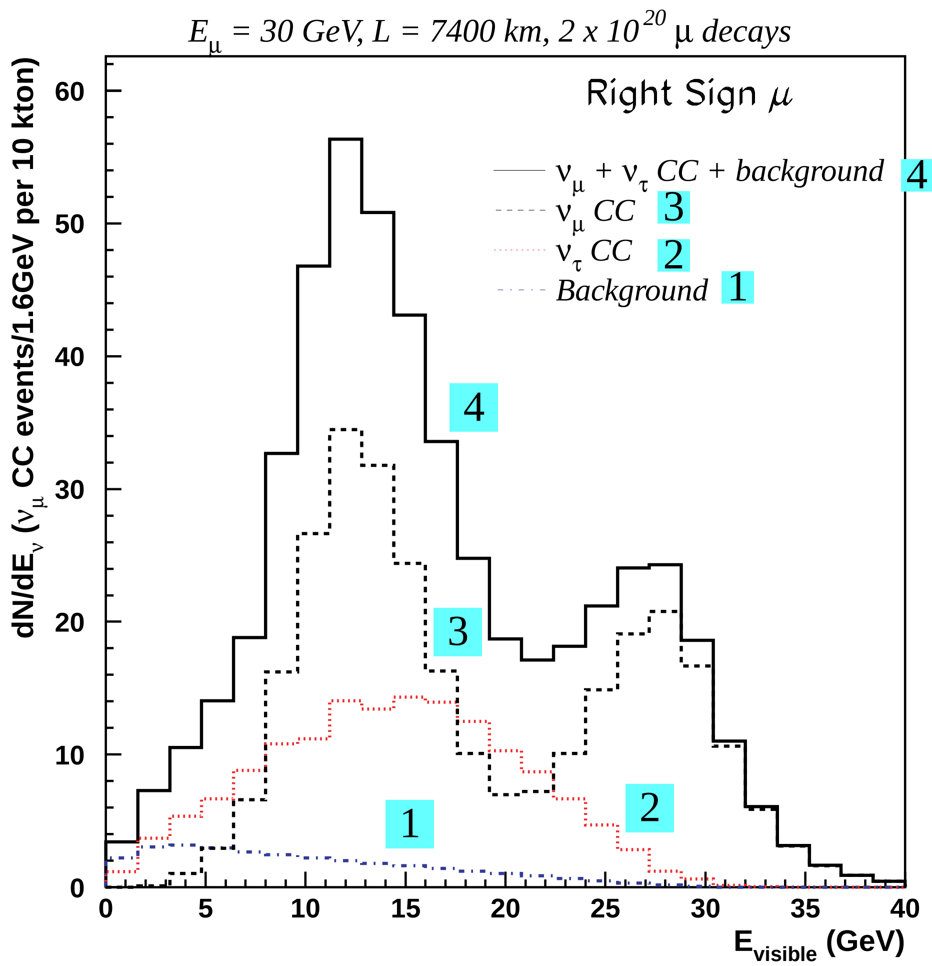
ICANOE fast simulation

- Proper neutrino cross section used
- Momentum and angular resolution parameterized from fully simulated events used for CNGS studies



- Charged meson decays to study backgrounds for wrong and right sign muons

$\Delta m^2{}_{23} = 3.5 * 10^{-3}\ eV^2$



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Parameter fit

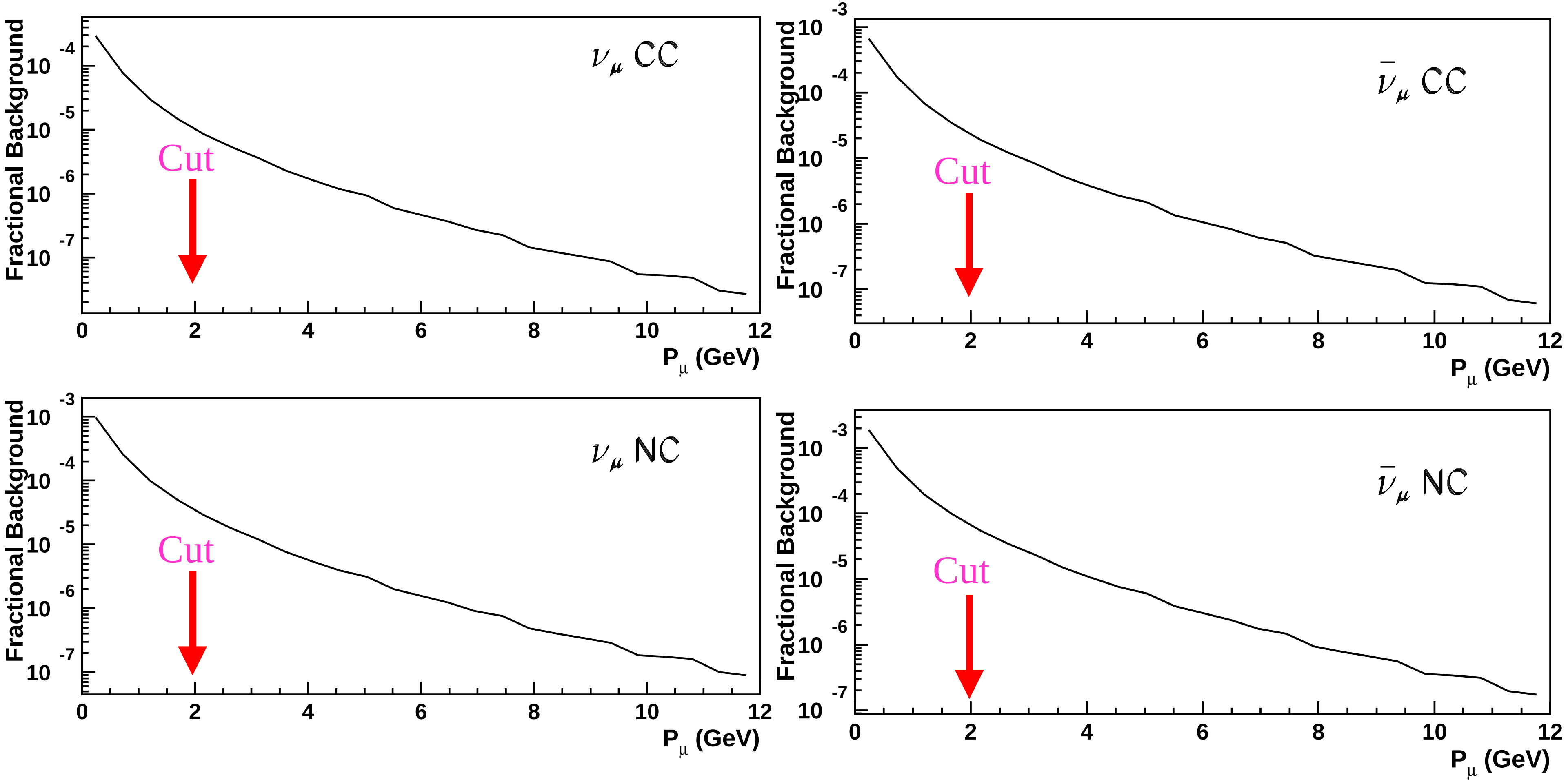
- Fit visible energy distributions (25 bins) for all event classes and the two μ polarities
- Beam systematics: 2% uncorrelated bin to bin
- Background reduction: $p_{\mu} > 2$ GeV cut
- Fit procedure:
  - Poisson distributed data (*bin with less than 40 events*)

Maximize -ln L

  - Gaussian distributed data (*bin with more than 40 events*)

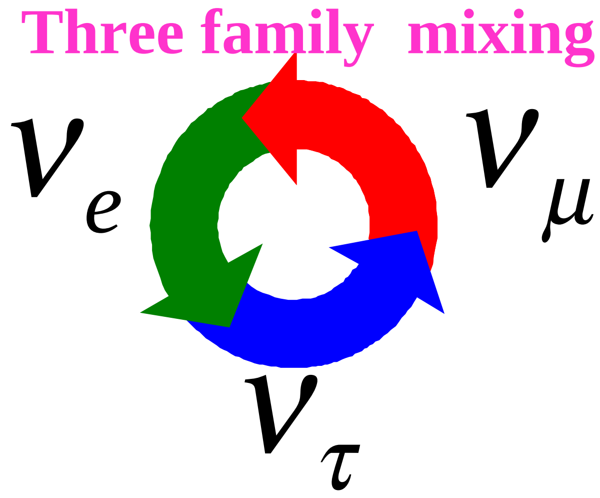
Minimize χ^2

Background contamination



The “data”

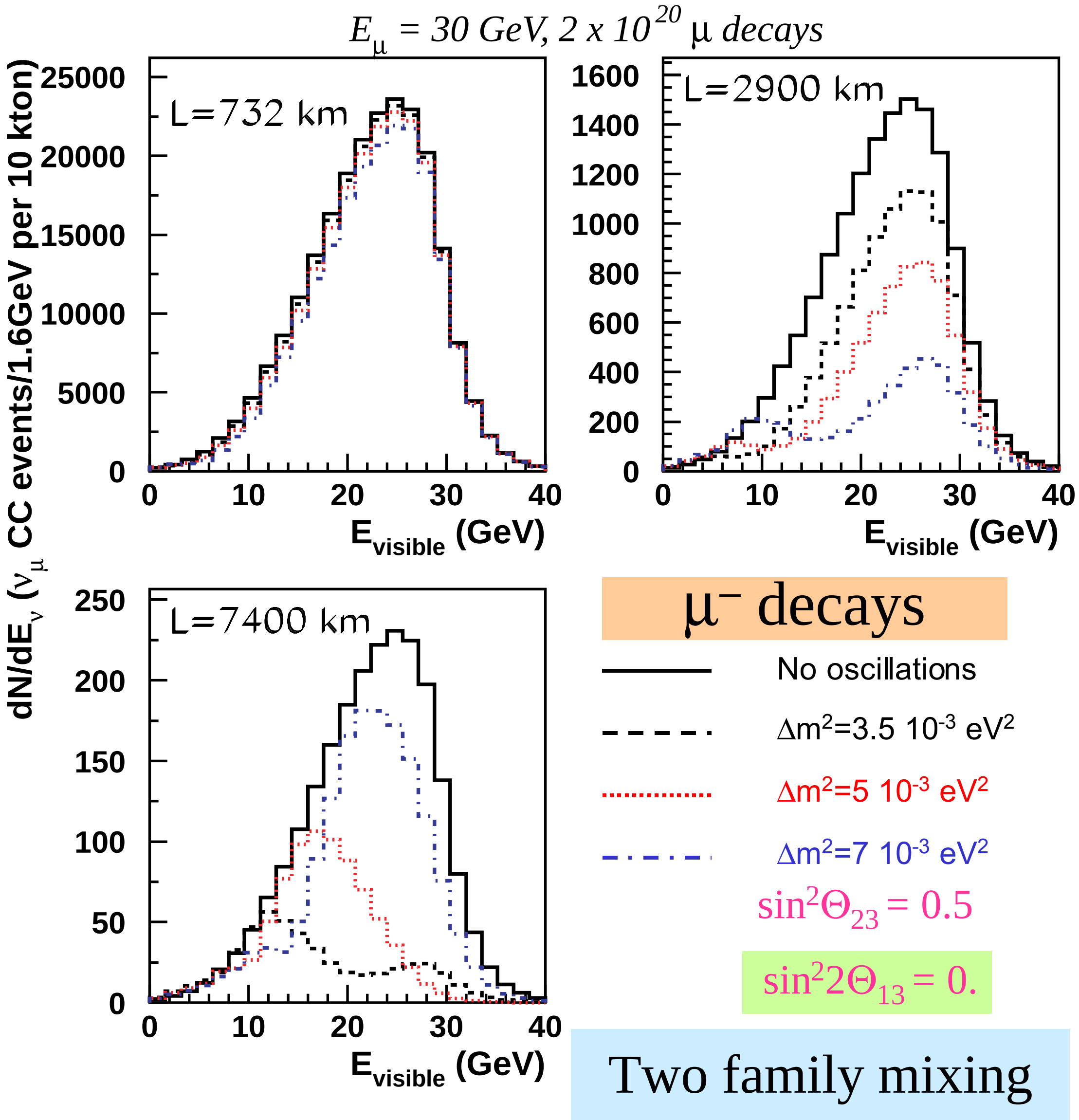
- Reference values used for fits
  - $\Delta m^2_{23} = 3.5\ ,\ 5\ ,\ 7 * 10^{-3}\ eV^2$
  - $\sin^2\Theta_{23} = 0.5 \qquad \Theta_{23} = 45\ ^0$
  - $\sin^2 2\Theta_{13} = 0.05 \quad \Theta_{13} = 6.5\ ^0$



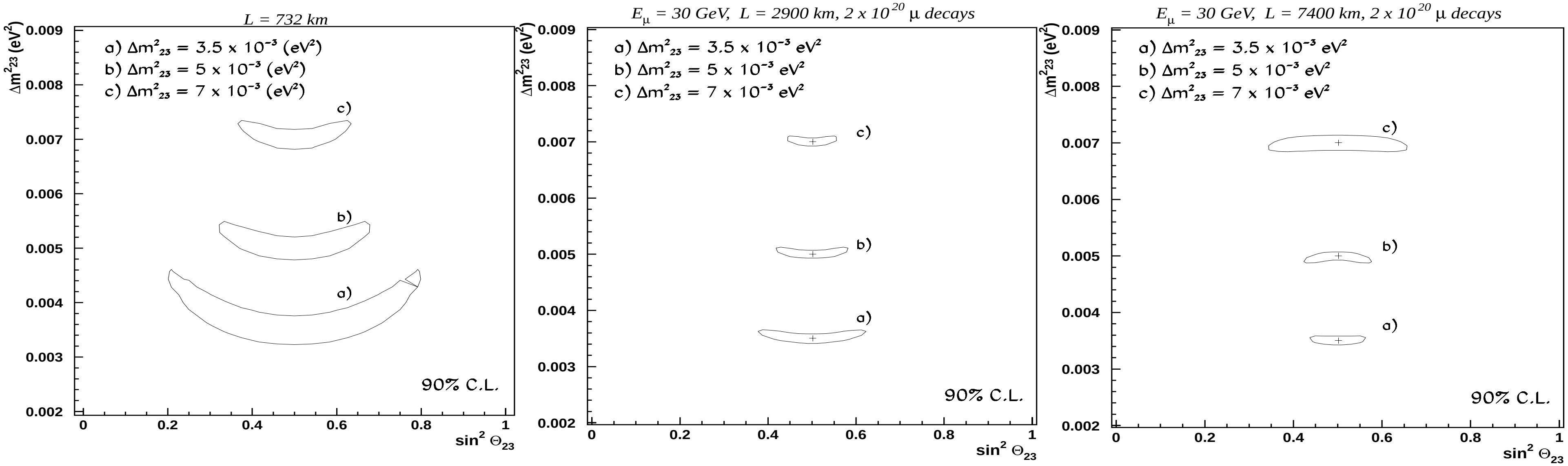
- And as already pointed out:
  - Three different baselines: **732, 2900, 7400 km**
  - **E_μ = 30 GeV**
  - **$2 * 10^{20}$ μ** decays of each polarity
  - **10 kton** detector (fiducial)

Precise measurement of Δm^2_{23} and $\sin^2\Theta_{23}$

- Disappearance dip allows to measure
  - Δm^2_{23} ⇨ dip location
  - $\sin^2\Theta_{23}$ ⇨ dip depth
- Visible at large distances



Two family mixing



$\sin^2 \theta_{23}$ measurement		
Δm^2_{23} (eV^2)	L=7400 km	L=2900 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

Measurements consistent with Barger et al.

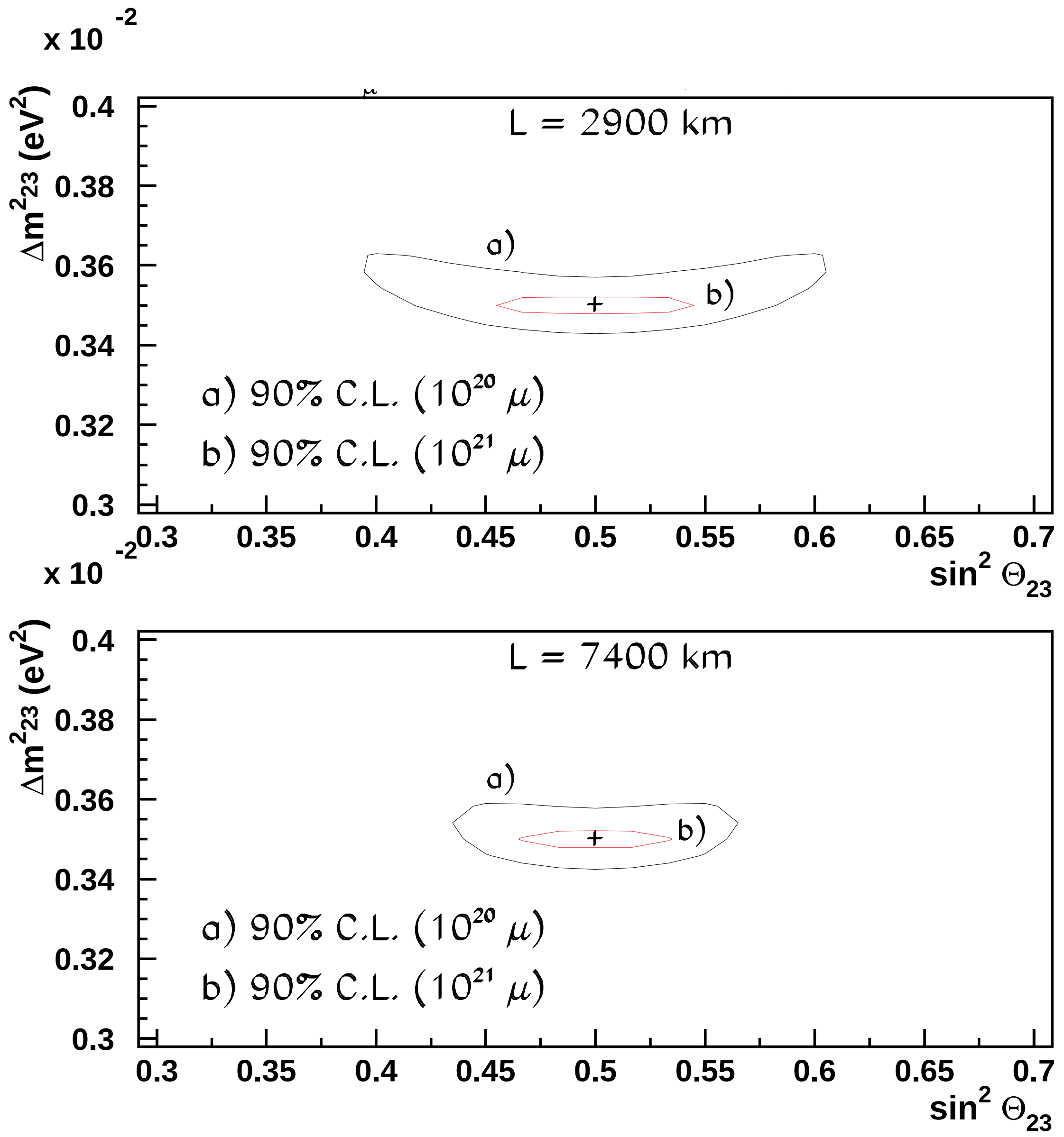
hep-ph/9911524

Error on Δm^2_{23} = 1%

Large distances required for precise measurements

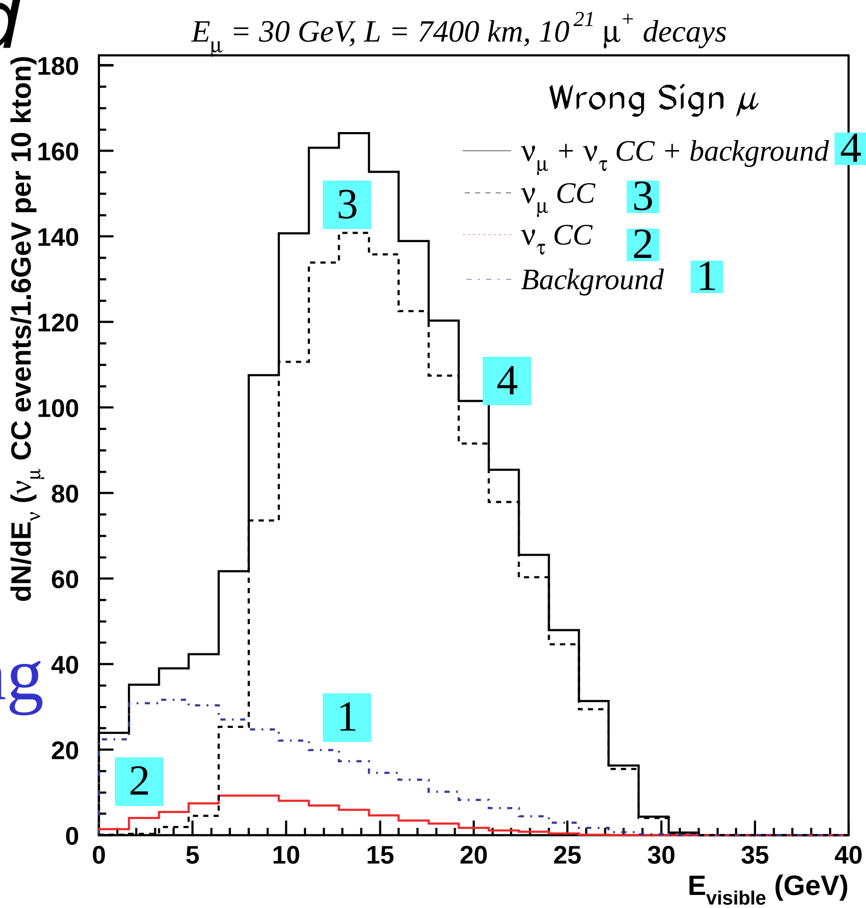
Improved statistics

- Two family mixing
- Black contour:
  - 10^{20} μ decays
- Red contour
  - 10^{21} μ decays



Three neutrino mixing

- One mass scale approximation: Δm^2_{23} *and* Δm^2_{12} *effects decouple*
- Matter effects included in our calculations
  - $\Delta m^2_{23} > 0 \rightarrow \nu_e$ ($\bar{\nu}_e$) oscillation enhanced (suppressed) by MSW
  - Striking appearance of wrong sign muons for μ^+ decays since
    - $\nu_e \rightarrow \nu_\mu$ $\nu_e \rightarrow \nu_\tau \rightarrow \tau \rightarrow \mu$ allowed for $\Theta_{13} \neq 0$



$\Delta m^2_{23} = 3.5 * 10^{-3}$ eV^2

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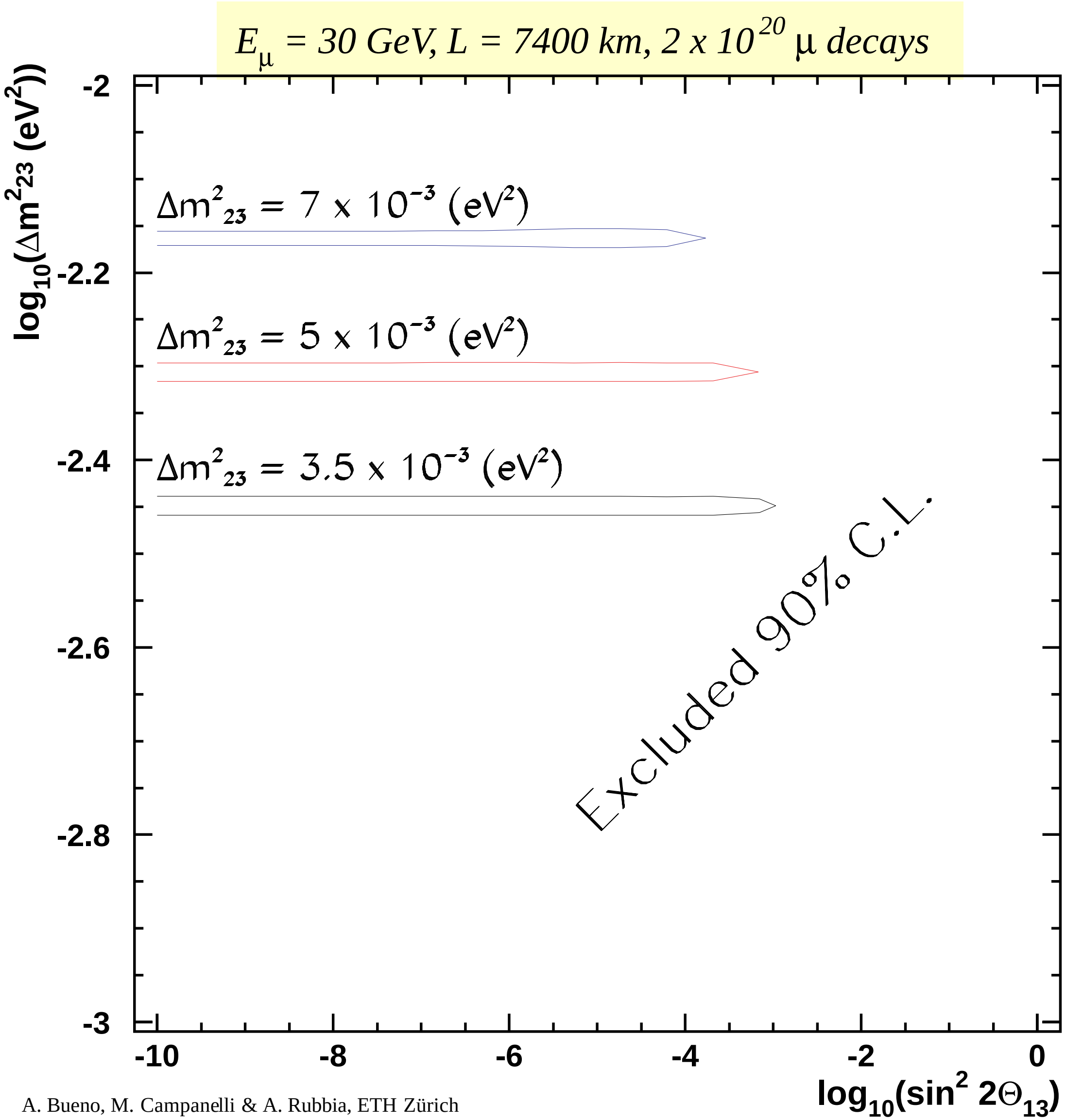
Θ_{13} Sensitivity



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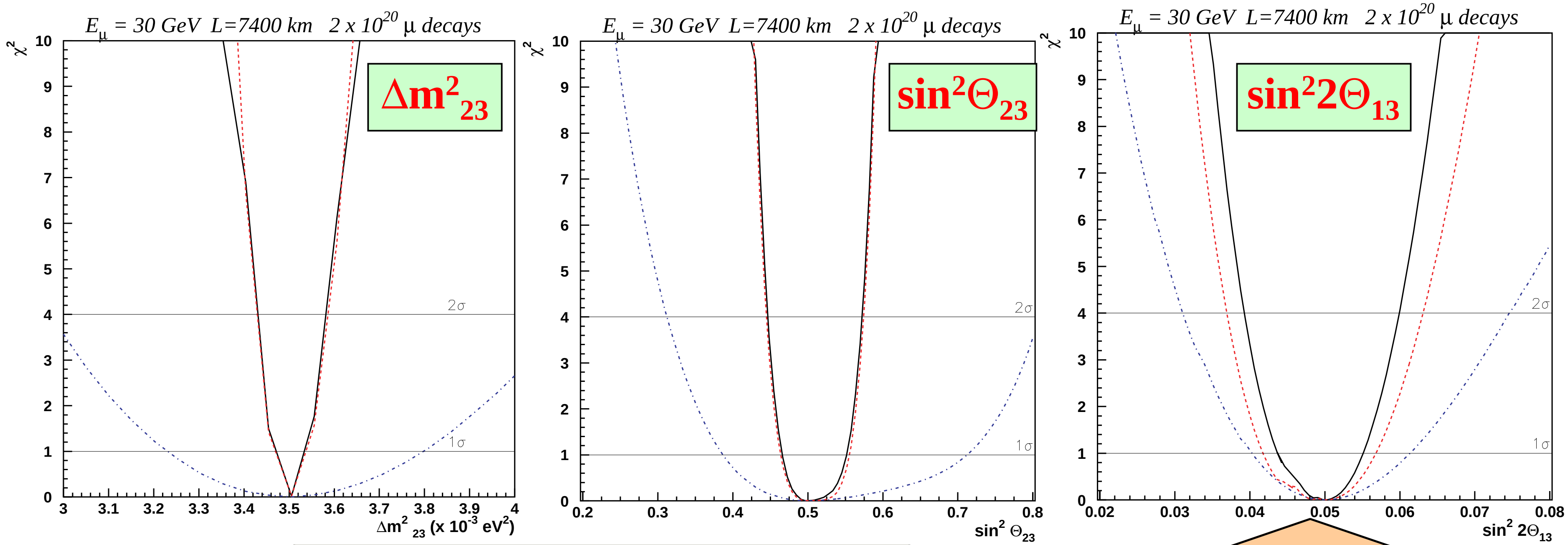
Two orders of magnitude improvement with respect to ICANOE at CNGS

If background disregarded and 10^{21} μ decays considered, results consistent with *A. Cervera et al. hep-ph/0002108*

Oscillation parameters measurement (I)



L=7400 km, **$\Delta m^2_{23} = 3.5 * 10^{-3}$ eV^2**
Disappearance dip visible

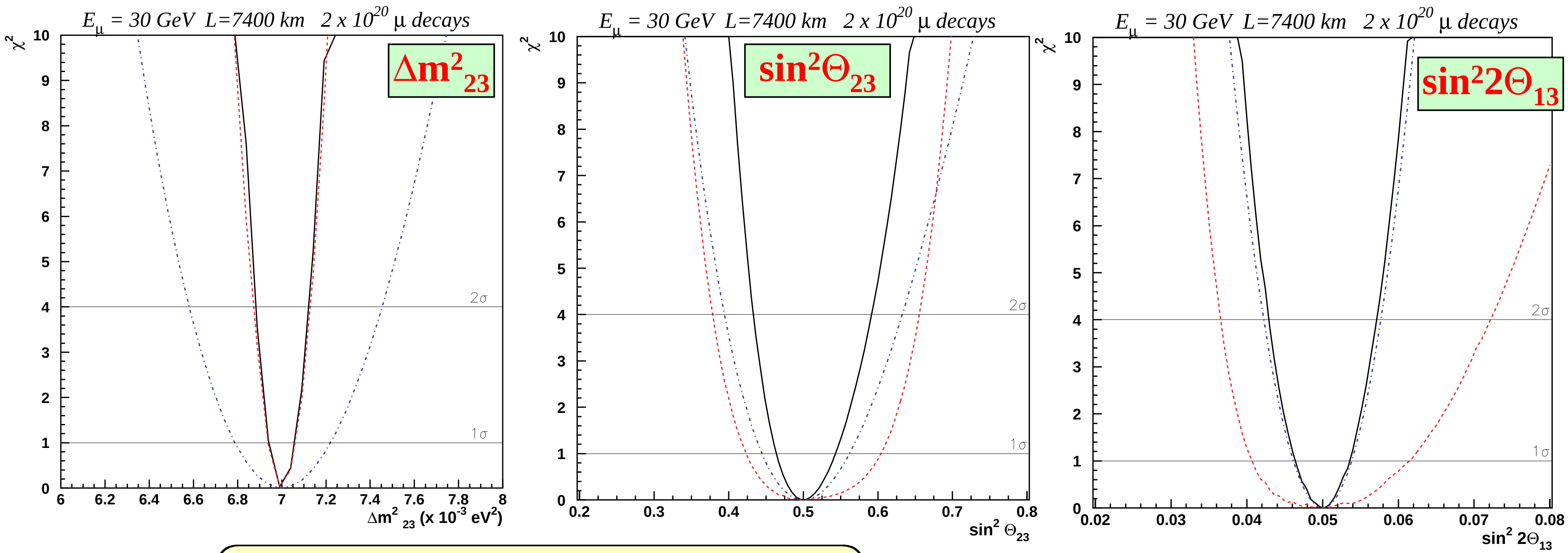
Use of all event classes improves Θ_{13} measurement

- - - - Fit with electrons only

.... Fit with wrong and right sign muons only

—— Fit with all event classes

Oscillation parameters measurement (II)



L=7400 km, $\Delta m^2_{23} = 7*10^{-3}$ eV^2

Disappearance dip not visible

- Fit with electrons only
- Fit with wrong and right sign muons only
- Fit with all event classes

Improved determination of mixing angles if all classes used

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Parameter measurement summary

	L=2900 km	L=7400 km
Δm^2_{23} $(10^{-3}$ eV$^2)$	3.50 ± 0.05	3.50 ± 0.03
$\sin^2\theta_{23}$	0.50 ± 0.07	0.50 ± 0.04
$\sin^2 2\theta_{13}$	$0.050^{+0.006}_{-0.009}$	0.050 ± 0.005
Δm^2_{23} $(10^{-3}$ eV$^2)$	7.00 ± 0.03	7.00 ± 0.05
$\sin^2\theta_{23}$	0.50 ± 0.03	0.50 ± 0.04
$\sin^2 2\theta_{13}$	$0.050^{+0.003}_{-0.005}$	0.050 ± 0.003

- *Very long baselines required to measure oscillation parameters at the per cent level*
- ICANOE ability to measure all events classes minimizes the impact of
  - The selected baseline
  - The primary muon energy chosen

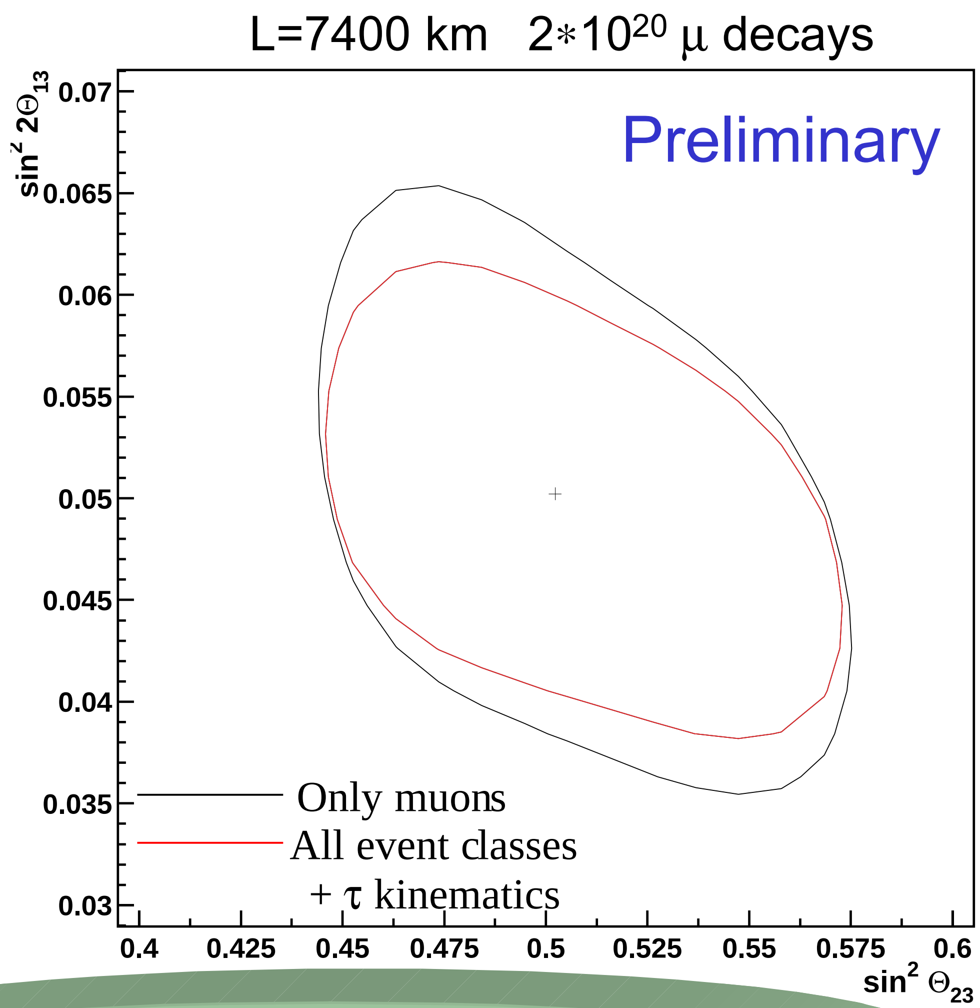
  to achieve a very precise measurement of mixing angles and mass differences

Θ_{13} improved measurement

- Measurement proceeds in steps:
  - Use wrong and right sign muons
  - Include all classes
  - Take advantage of tau kinematics

$\tau \rightarrow$ lepton: $\cancel{P}_T > 0.5$ GeV, $P^{\tau}_T < 1$ GeV

$\tau \rightarrow$ hadron: $Q_T > 0.5$ GeV



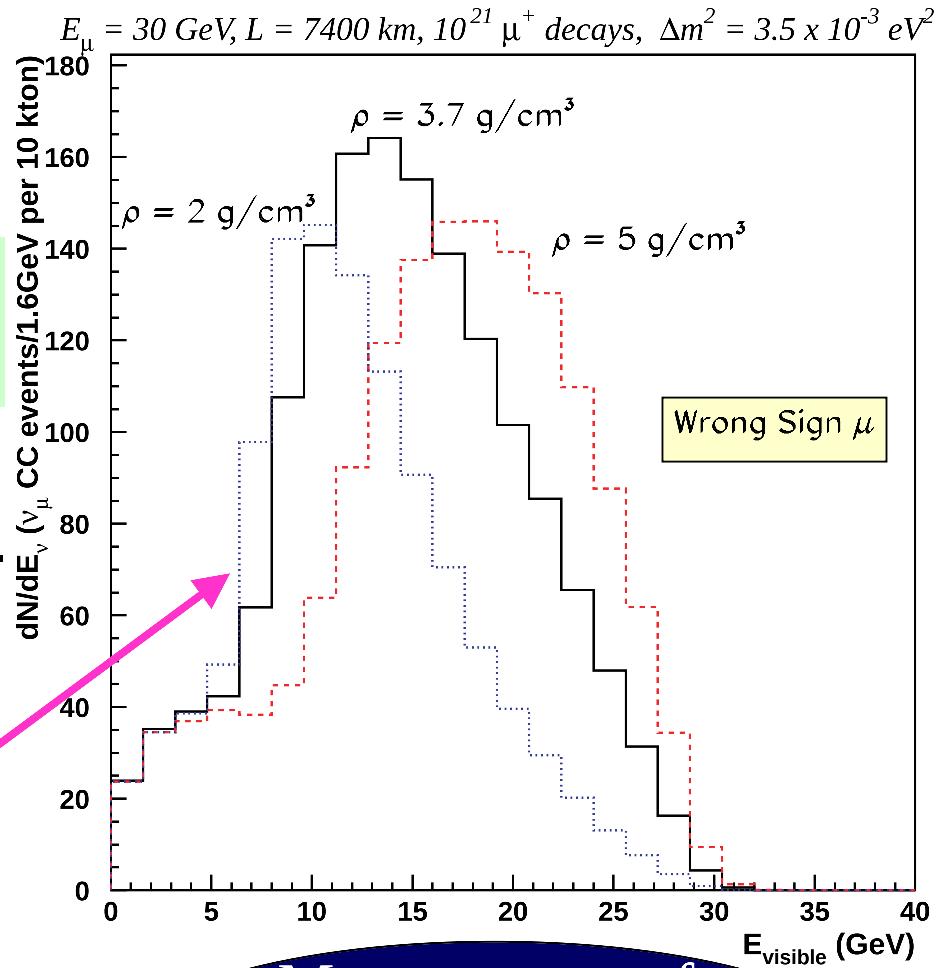
Improves sensitivity by 30%

Neutrino propagation in matter

- Maximal oscillation amplitude at resonant energy

$$E_\nu^{res} \approx \frac{1.32\times10^4 \cos 2\theta_{13} \Delta m_{23}^{\ 2}(eV^2)}{\rho(g/cm^3)}$$

- Δm^2_{32} accurately measured thanks to right-sign μ disappearance
- Θ_{13} known to be small
- For fixed Δm^2_{32}, resonance peak location is a function of Earth's density



Measurement of mean Earth density feasible

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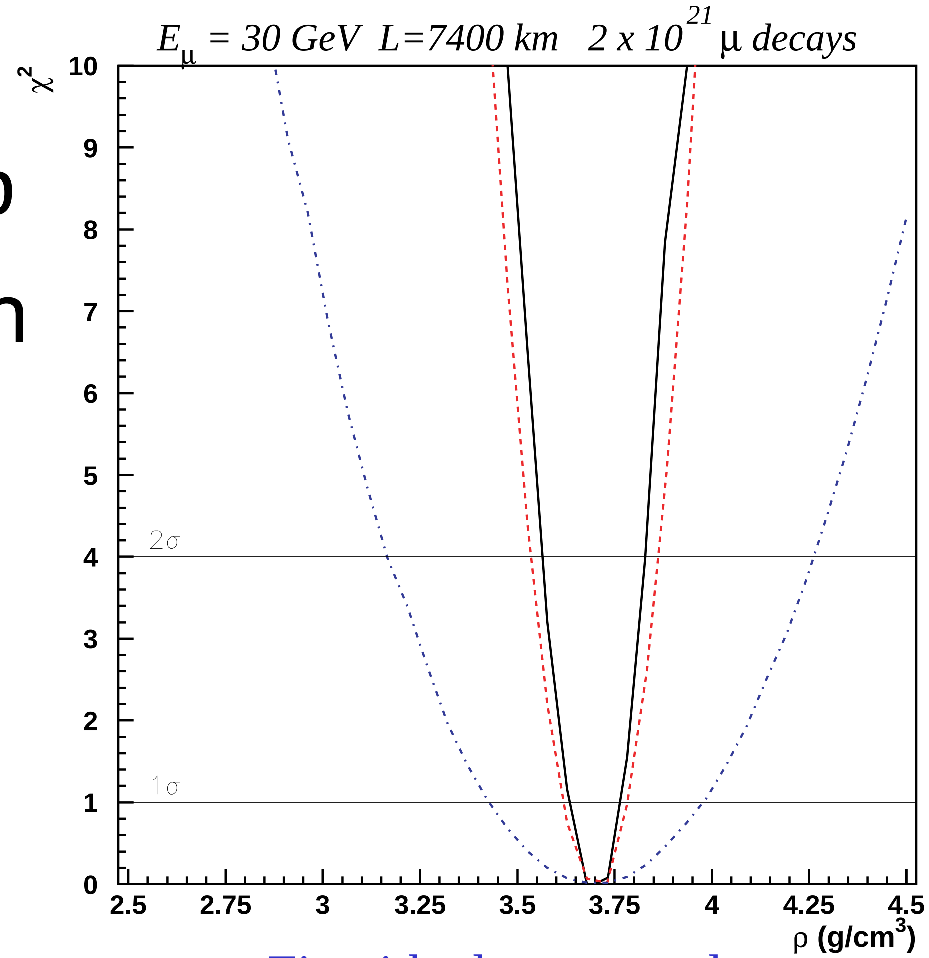
Earth's density measurement

- Fit leaving all parameters free but ρ
- Precise determination

$$\rho = 3.70 \pm 0.07\ g/cm^3$$

~2% accuracy

- 10% accuracy when only electrons are used



Fit with electrons only

Fit with wrong and right sign muons only

Fit with all event classes

Density influence on fits

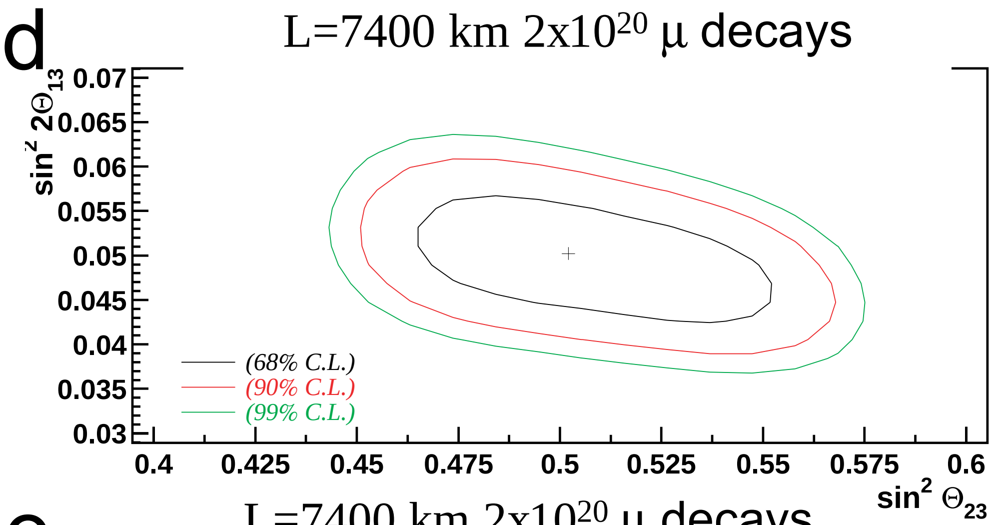
- All event classes used
- Fit with fixed density

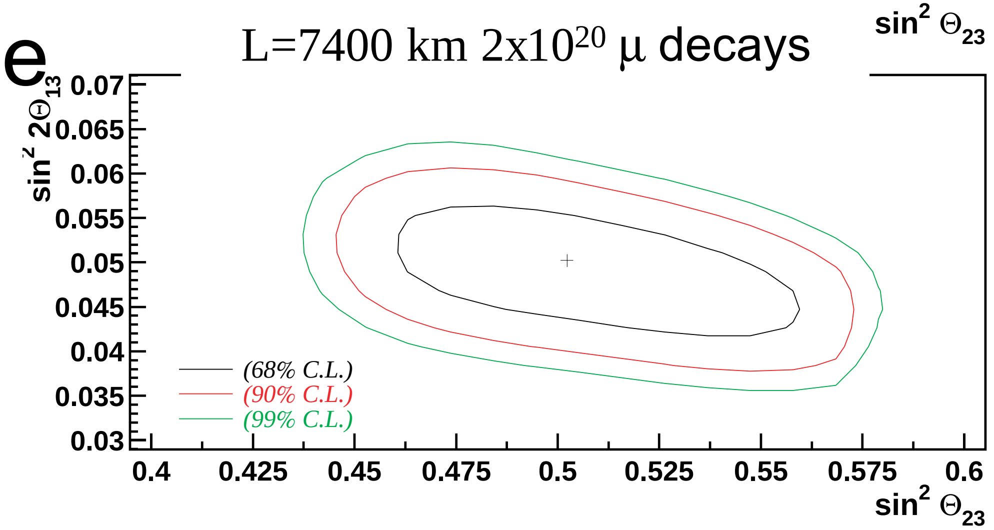
  $\sigma(\sin^2 2\theta_{13})=0.0071$

  $\sigma(\sin^2\theta_{23})=0.044$
- Fit with density as free parameter

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

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





Conclusions

- ICANOE-like detector identifies all event classes
- Oscillation measurements not so crucially dependent on μ energy and baseline (provided it is very large)
- Measure mixing angle and mass differences with accuracy at the level of the per cent
- Matter effects can be detected and Earth's density precisely measured
- *CP violation studies in progress*