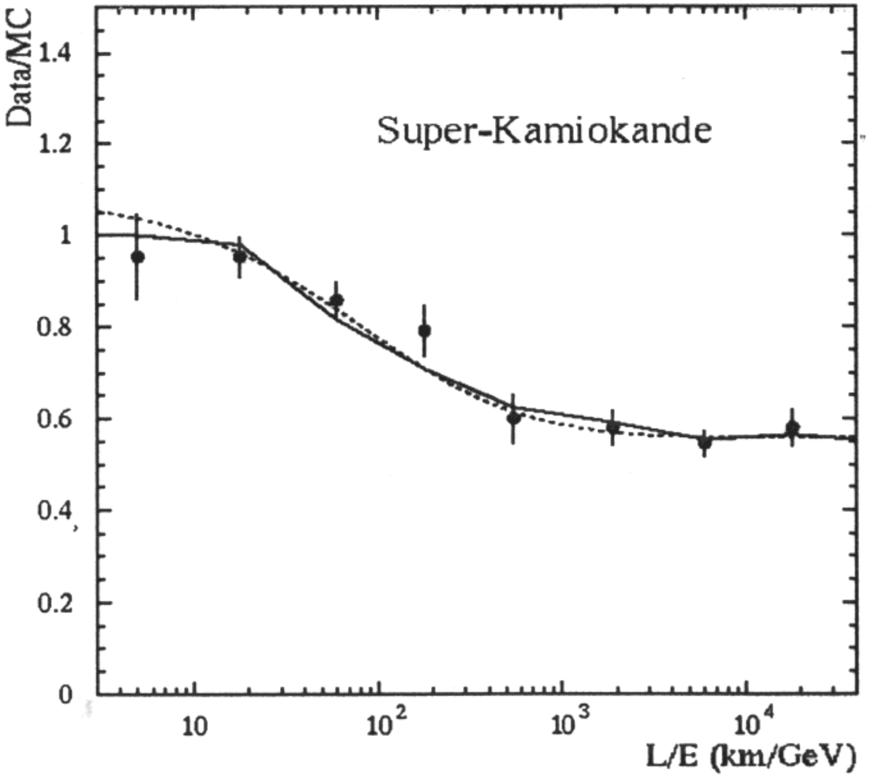
Physics motivations

- SK data interpreted as 2ν oscillations in the $\nu_\mu \longleftrightarrow \nu_\tau$ channel
  - Supported by MACRO, SOUDAN2,CHOOZ,Palo Verde

- Dynamics of ν_μ disappearance not established

- Limited precision on oscillation parameters
  Need for precision measurements
  ("Neutrino stoichiometry")

Dynamics of ν_μ disappearance



- L/E resolution of SuperKamiokande not sufficient to detect oscillations.
- Viable alternative hypotheses.
  - Decay.
  - Decoherence.
  - Large extra dimensions.
- At least one oscillation cycle has to be detected to prove oscillations (disprove alternative hypotheses).

More than two neutrinos?

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•Scenarios involving more than 2 states (3ν or 4ν mixing) not fully constrained

➡ MATTER EFFECTS:

•Modify the ν_μ survival probability

(exploited by SK to exclude maximal ν_μ/ ν_s mixing)

•Introduce an asymmetry in the transition probabilities of ν_μ and anti-ν_μ

➡ detector with charge identification

Physics goals

Atmospheric muon neutrinos:

Explicit observation of the oscillation pattern.

Proof of oscillations.

Precise determination of Δm^2 and $\sin^2(2\Theta)$.

Test admixture of electron (3ν) and sterile (4ν) neutrinos searching for matter-induced effects.

Sign of Δm^2, constraints on U^2_{e3}, ...

Other topics:

CNGS beam, ν-factories, cosmic rays...

Why atmospheric neutrinos?

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- Wide L/E range and very long baselines

  Unique sensitivity to small Δm^2

  Possibility to test matter-induced effects

- Up/down symmetry of fluxes

  (Robust prediction for E_ν>1-2 GeV)

  For $\Delta m^2 < 10^{-2}$ eV^2 and E_ν>1.5 GeV, downgoing neutrinos unaffected by oscillations

Near/Far identical sources

(Ideal case for disappearance experiments: detailed knowledge of fluxes not needed)

A detector for precision measurements of L/E

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The *L/E* resolution is determined by the capability of the experiment to reconstruct the ν energy and the ν direction of flight (L ~ 2R cosθ$_\nu$):

$$\frac{\sigma^2_{L/E}}{(L/E)^2} = \frac{\sigma^2_E}{E^2} + \frac{\sigma^2_L}{L^2} \simeq \frac{\sigma^2_{E_\mu}}{E^2_\mu}(1-y)^2 + \frac{\sigma^2_{E_h}}{E^2_h}y^2 + \tan^2\theta\sigma^2_\theta$$

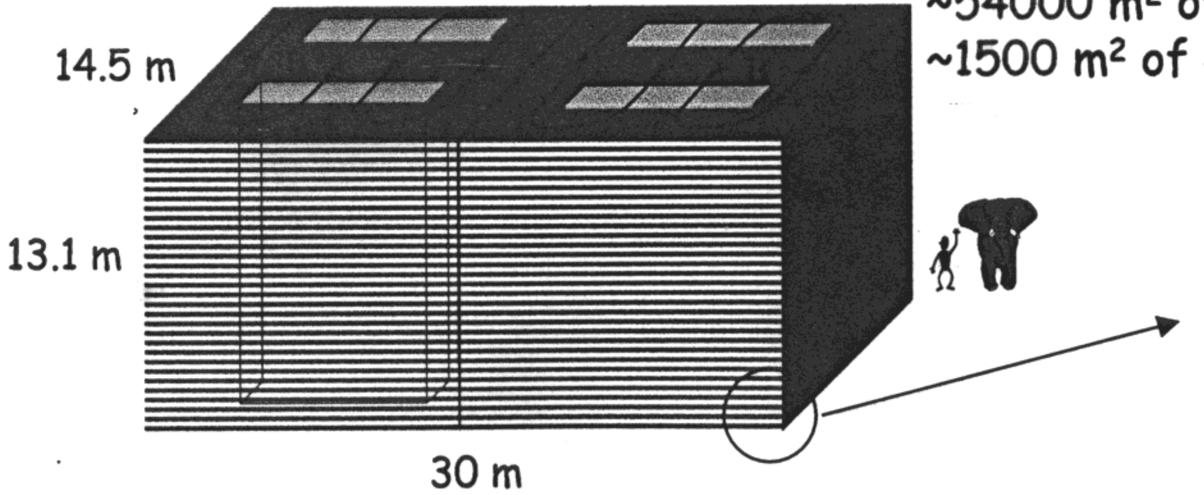
- Near the horizon resolution is spoiled by the $\tan^2\theta$ term
- Low L/E values *must* be obtained with high *E*
- Extend the detector efficiency toward the HE component of the ν spectrum and provide a good momentum resolution for muons

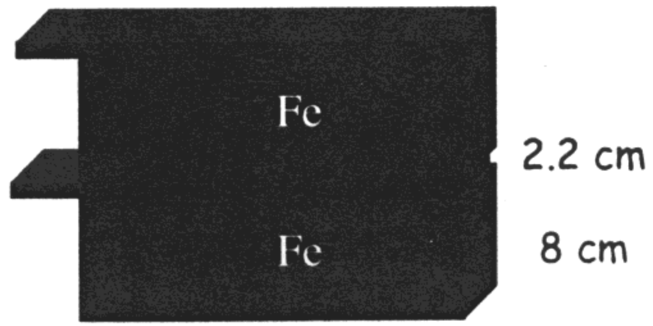
The MONOLITH Detector

Large mass		~ 35 kton
Magnetized Fe spectrometer		B = 1.3 Tesla
Space resolution		~ 1 cm (rms on X-Y coordinates)
Time resolution		~ 1 ns (for up/down discrimination)
Momentum resolution	σ_p/p	~ 20% from track curvature for outgoing m
		~ 6% from range for stopping muons
Hadron E resolution	σ_{E_h}/E_h	~ $90\%/\sqrt{E_h} \oplus 30\%$

$8.0 \times 3000 \times 1450\ cm^3 \times 7.87\ g/cm^3$ = 285 ton/plane   130 planes

~54000 m^2 of detector : Glass Spark Counters
~1500 m^2 of external veto: Scintillator Counters





Event selection

Event selections developed to optimise the *observation of the oscillation pattern*

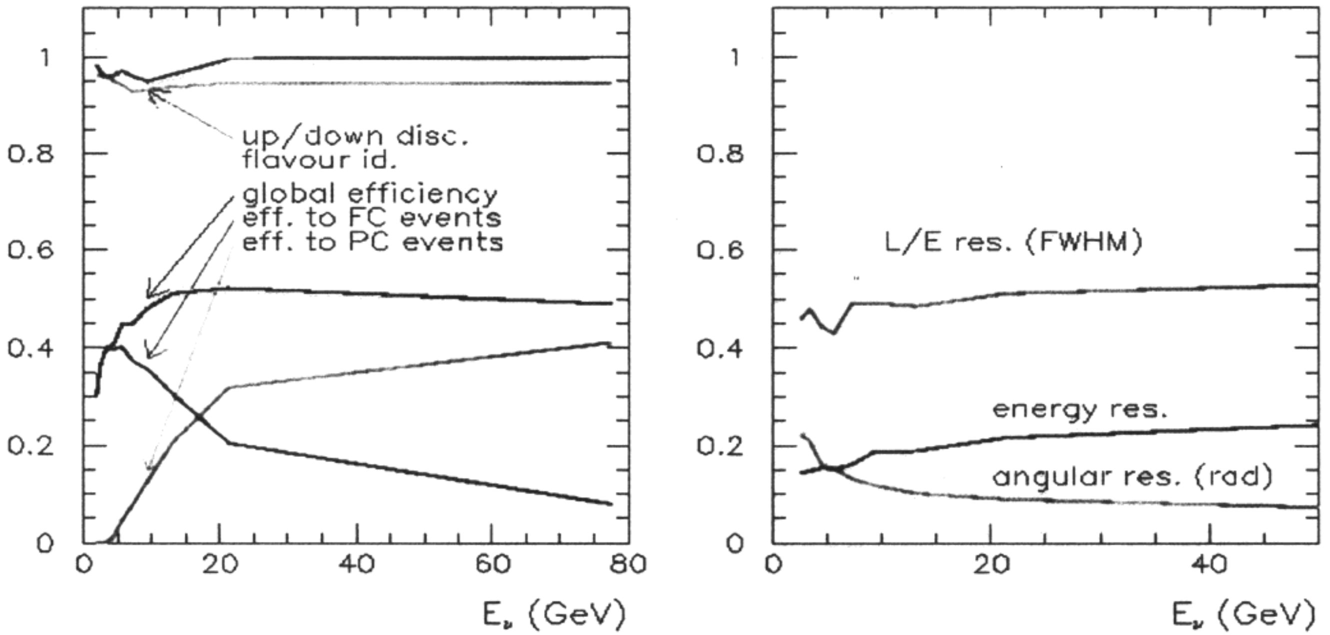
(keep under control the relative L/E resolution)

1. $E_\mu > 1.5$ GeV
2. Fiducial selection of 40 cm on each side

   FC events: inside fiducial volume

   PC events: one single outgoing track with Range(μ_{out}) > 4 m
3. Nb. of fired layers > 6
4. Selection on combinations of the observables E_μ, θ_μ, E_h to ensure the required *L/E* resolution

Efficiencies and resolutions

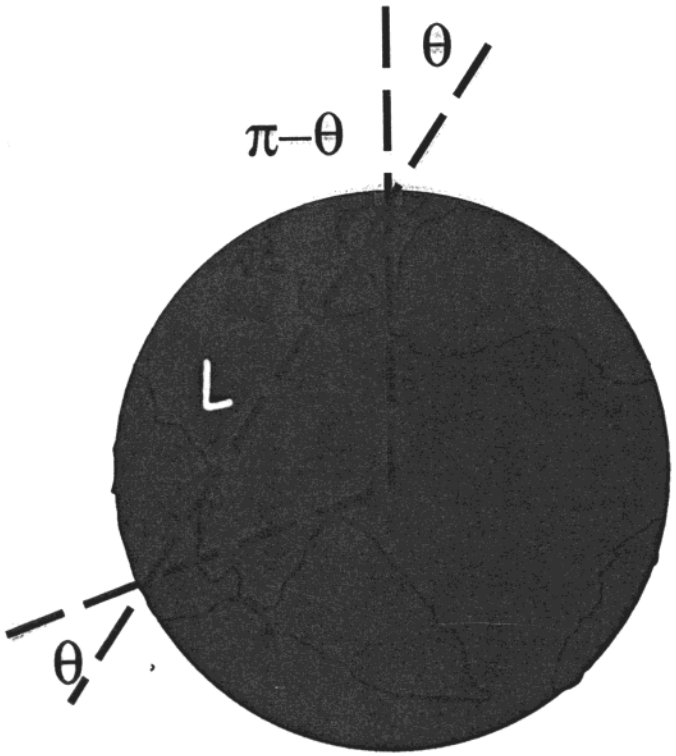


- $E_\nu = E_\mu + E_h$
- $\theta_\nu = \theta_\mu$

Selected ν_μ CC (downgoing only!) after 4 y of data taking:

Fully contained:	931
Partially contained:	259
Total:	1190

Measurement of oscillation parameters



Make a reference L/E distribution with downgoing neutrinos:

- $L(\theta_{up}) = 2R\cos(\theta_{up})$
- $L'(\theta_{down}) = L(\pi - \theta_{down})$

Compare to upgoing neutrinos

An oscillation pattern shuold appear in the up/down ratio of observed events:

$$\frac{N_{up}(L/E)}{N_{down}(L'/E)} = 1 - \sin^2(2\Theta)\,\sin^2(1.27\,\Delta m^2\, L/E)$$

Measurement of oscillation parameters (2)

Definition of the likelihood:

$$\mathcal{L} = \Pi_i \left(e^{-\mu_i} \mu_i^{D_i}/D_i!\right) \left(e^{-P_i\mu_i} P_i\, \mu_i Ui/U_i!\right)$$

Where μ is the expected rate of downgoing neutrinos (free in the fit)

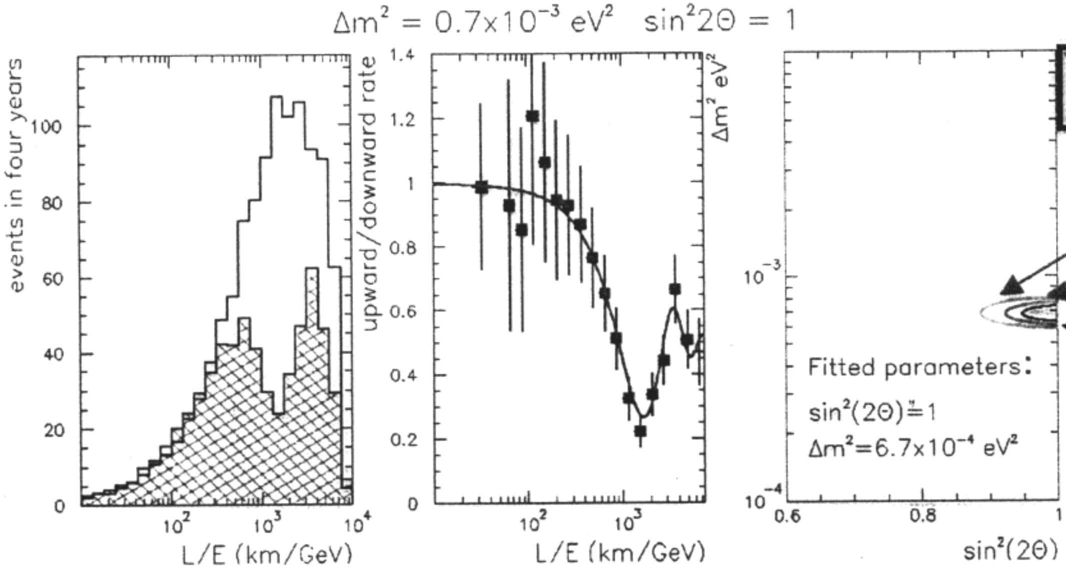
$P = P(\Delta m^2, \sin^2 2\Theta)$ * resolution function (parametric form free in the fit)

U and D are the observed rate in each bin

Test statistics:

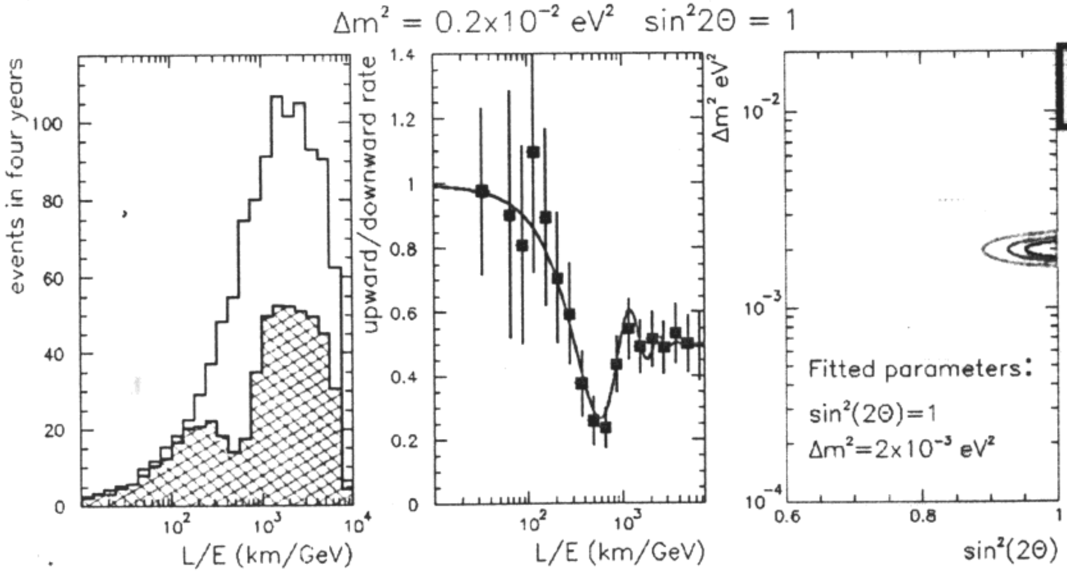
$$-2\ln \frac{\mathcal{L}(\mu_i, r, \Delta m^2, \sin^2(2\Theta_{23});\ \sin^2(2\Theta_{23}) \text{ and } \Delta m^2 \text{ fixed})}{\mathcal{L}(\mu_i, r, \Delta m^2, \sin^2(2\Theta_{23}))}$$

Expected L/E distributions (1)



$\Delta m^2 = 7\times10^{-4}$ eV²

99% C.L
90% C.L.
68% C.L.



$\Delta m^2 = 2\times10^{-3}$ eV²

Central value in each bin is obtained with a 26 years statistics.
Event rates, error bars and contour lines correspond to 4 years.

Expected L/E distributions (2)

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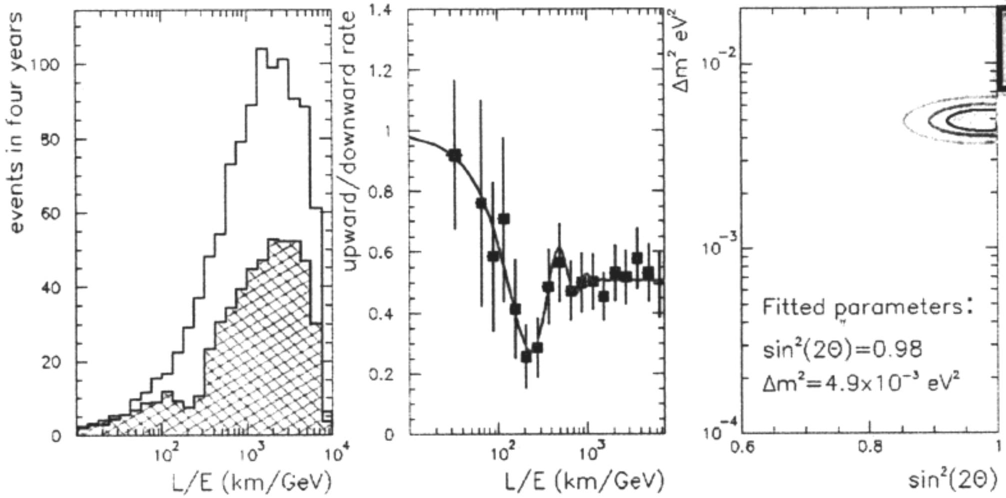
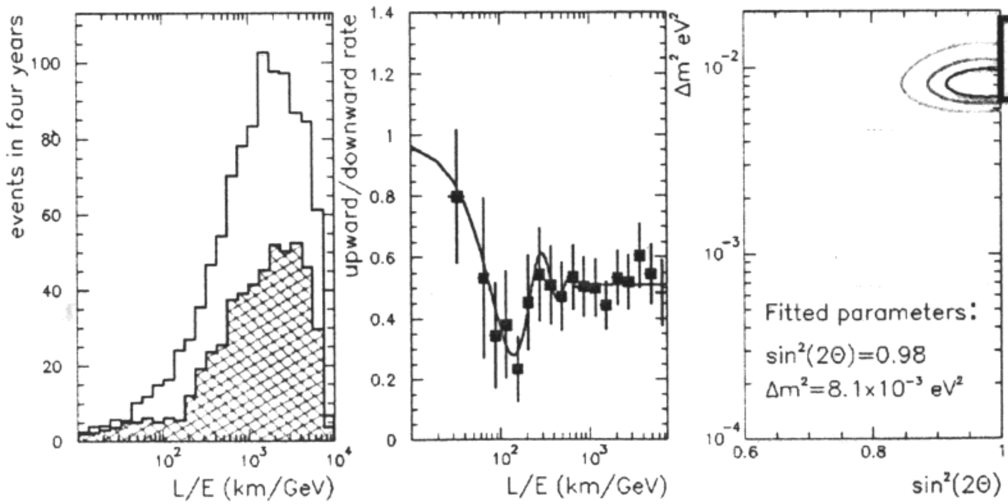
$\Delta m^2 = 0.5\times10^{-2}$ eV^2 $\sin^2 2\Theta = 1$



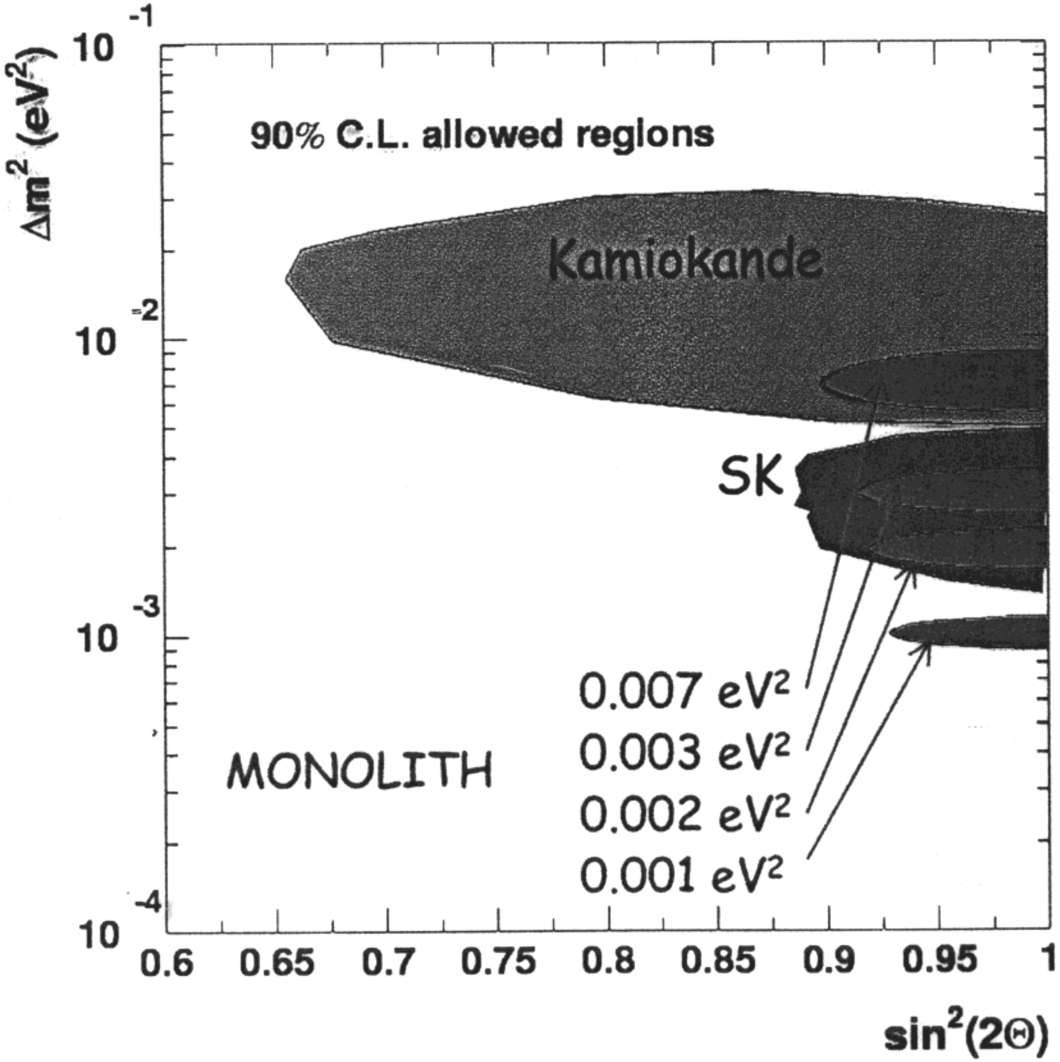
$\Delta m^2 = 5\times10^{-3}$ eV^2

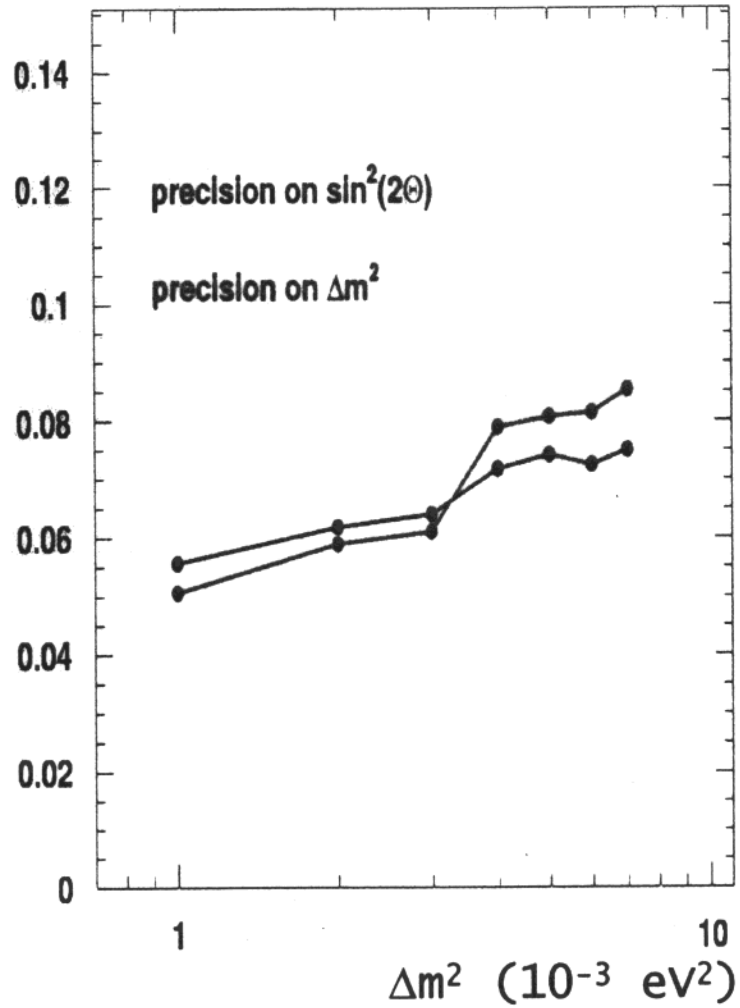
$\Delta m^2 = 0.8\times10^{-2}$ eV^2 $\sin^2 2\Theta = 1$



$\Delta m^2 = 8\times10^{-3}$ eV^2

Monolith sensitivity (4 years)





Matter effects (a case study)

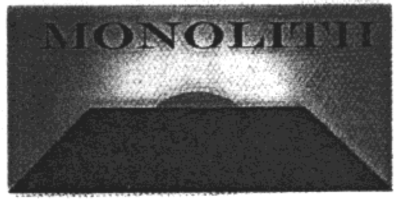
"One mass scale dominance" scenario for atmospheric neutrinos:

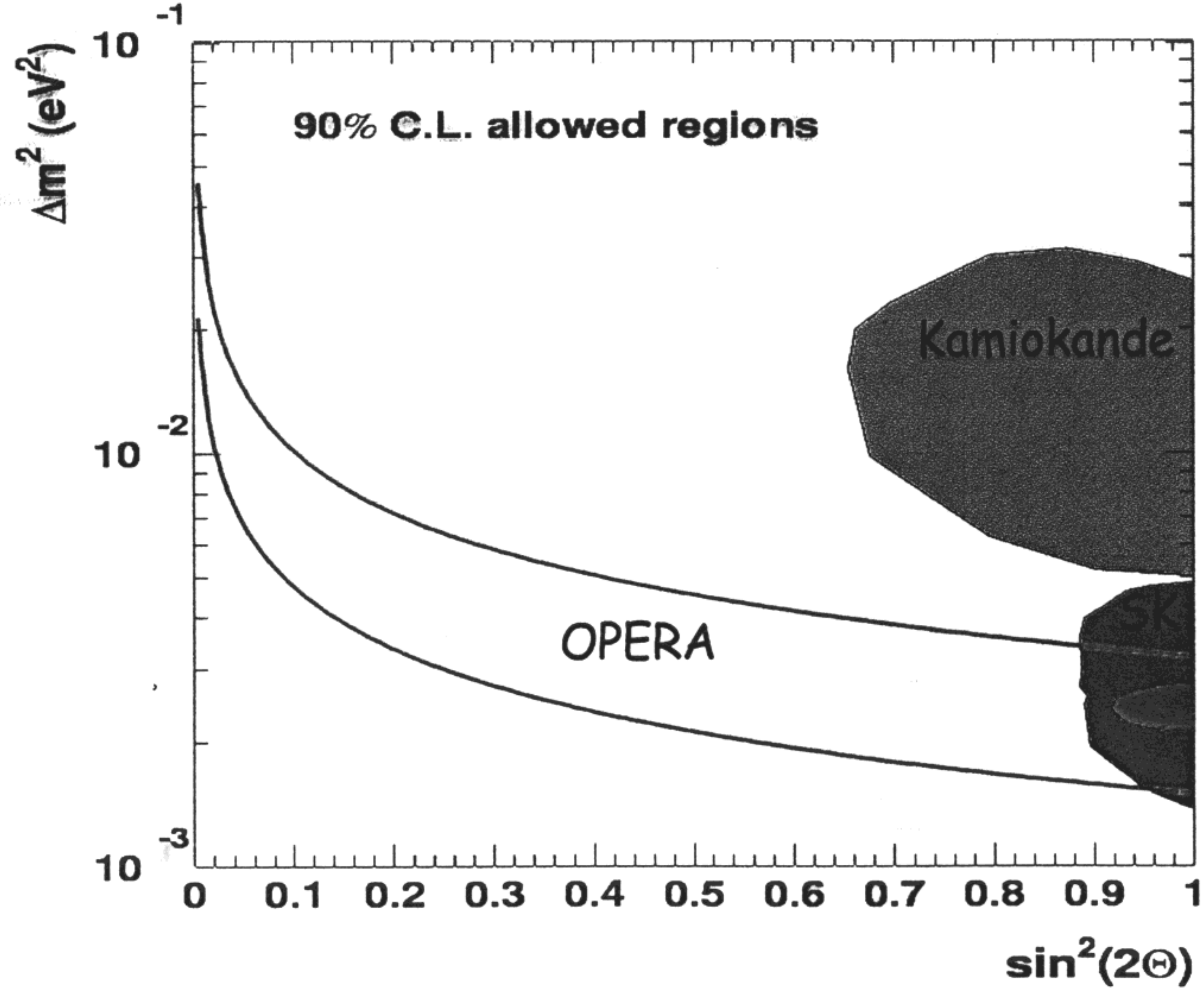
- $\Delta m^2_{Atm} = \Delta m^2_{23} \quad \gg \quad \Delta m^2_{Sun} = \Delta m^2_{12}$
- $\Delta m^2_{12}\, L/E \ll 1$ and the sector (1,2) is inoperative
- the CP-phase is unobservable

oscillation described by three parameters: Θ_{13}, Θ_{23} and Δm^2_{23}

- The mixing (1,3) is bound to be small (CHOOZ: $\sin^2(2\Theta_{13}) < 0.1$), but the (1,3) transition can become resonant in the Earth:

MONOLITH sensitivity



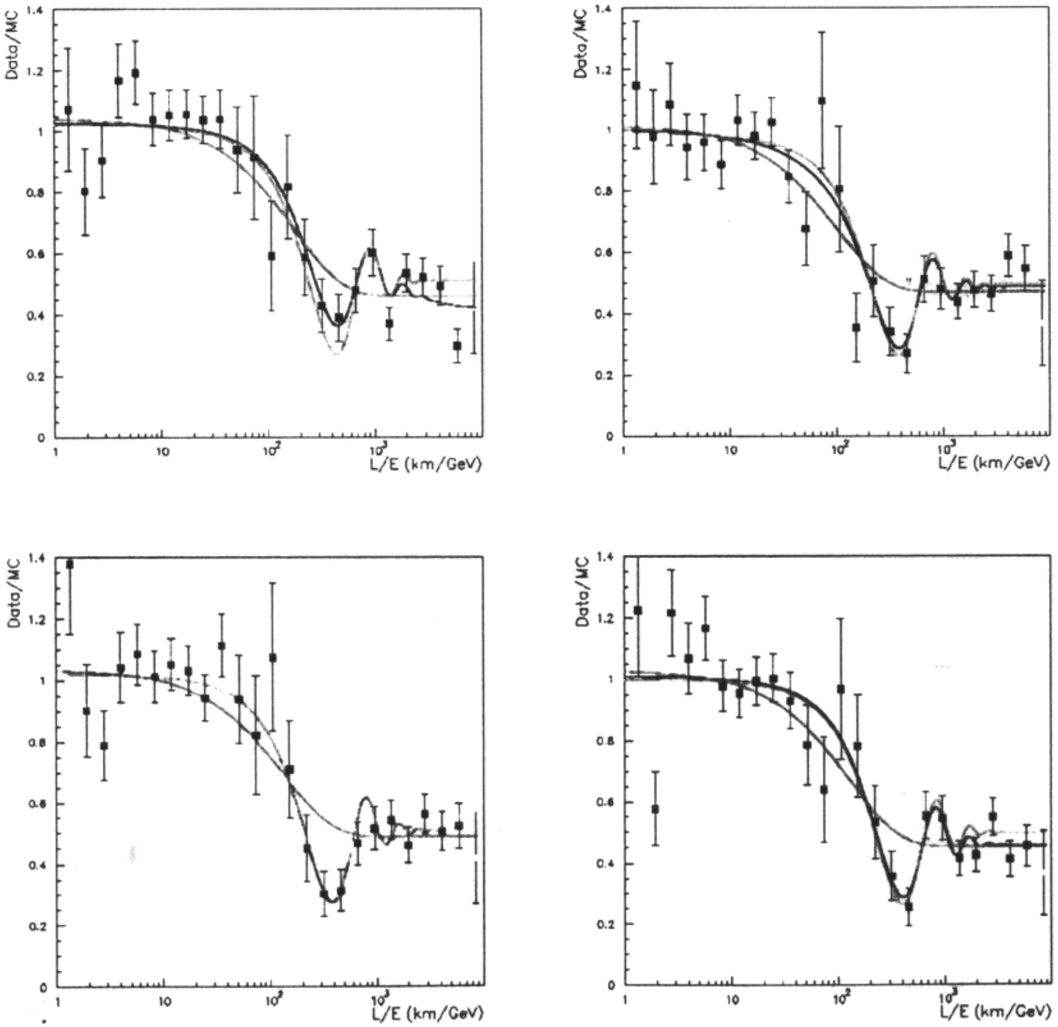


Δm^2=0.0025 eV^2
(current best fit of SK data)

MONOLITH (4 y)

Test of ν_μ disppearance dynamics

MONOLITH



Four simulated experiments of 4 years with $\Delta m^2 = 0.003\ eV^2$

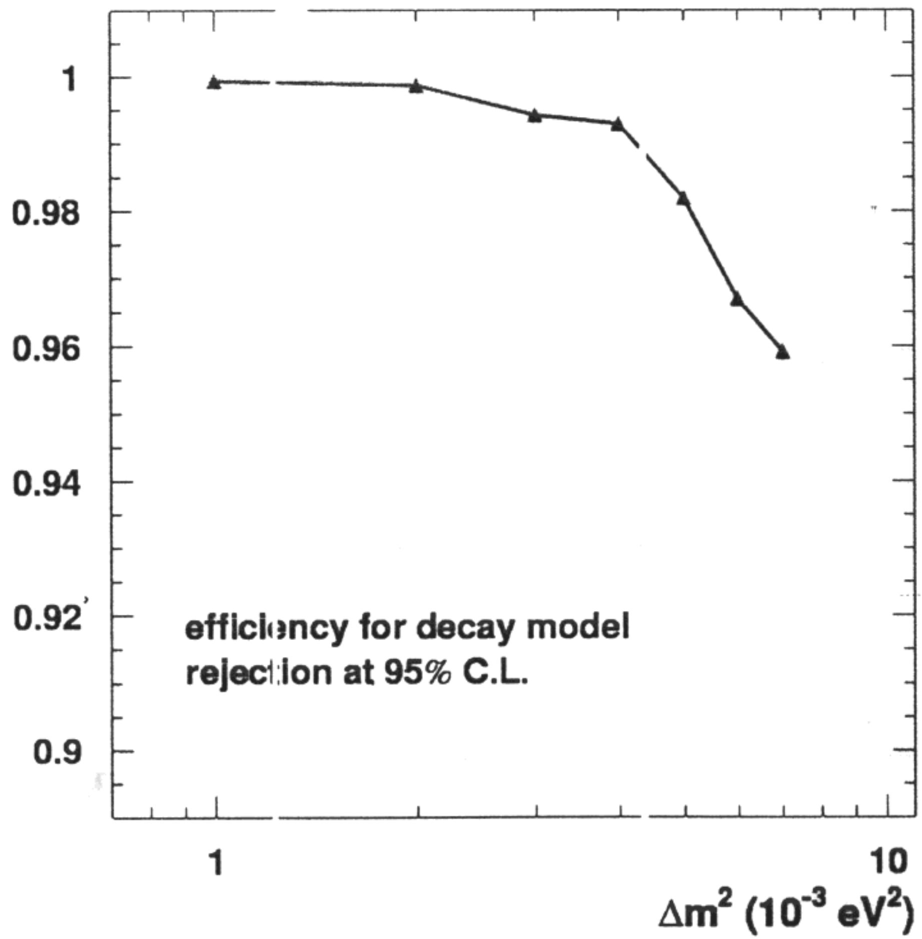
- best fit to oscillation
- best fit to decay
- best parametric fit (linear combination of both)

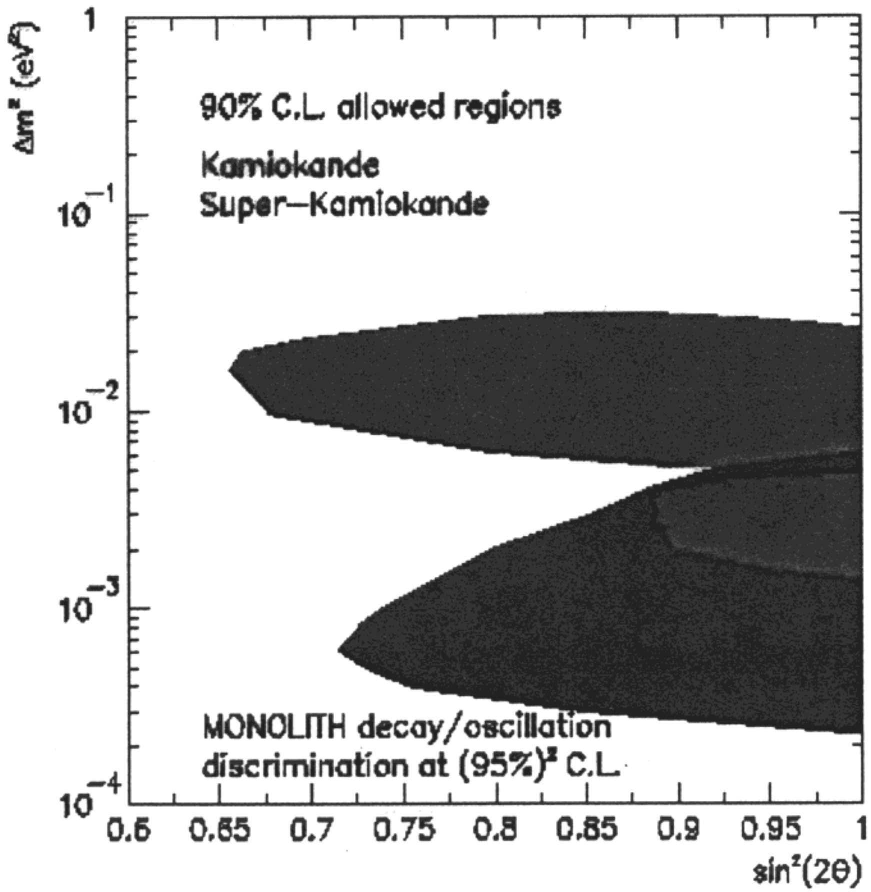
Test statistics:

$$-2\ln \frac{\mathcal{L}(a\,P_{decay} + (1-a)\,P_{osc},\ a=0,1)}{\mathcal{L}(a\,P_{decay} + (1-a)\,P_{osc})}$$

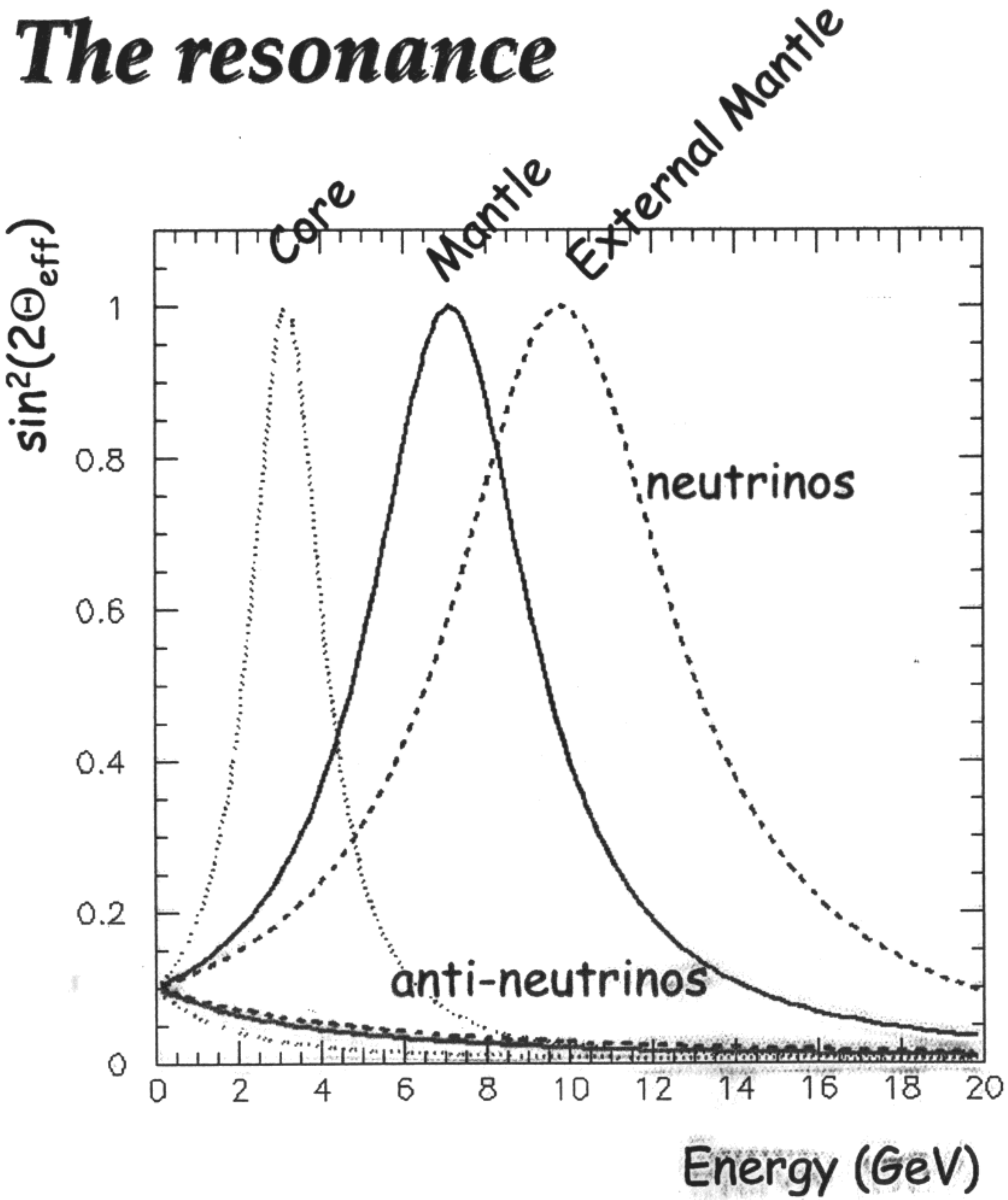
Decay model rejection

SK 90% C.L. region



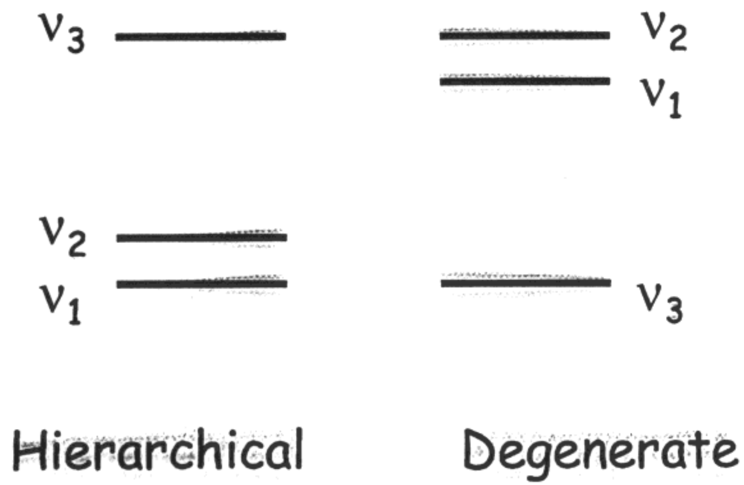


The resonance



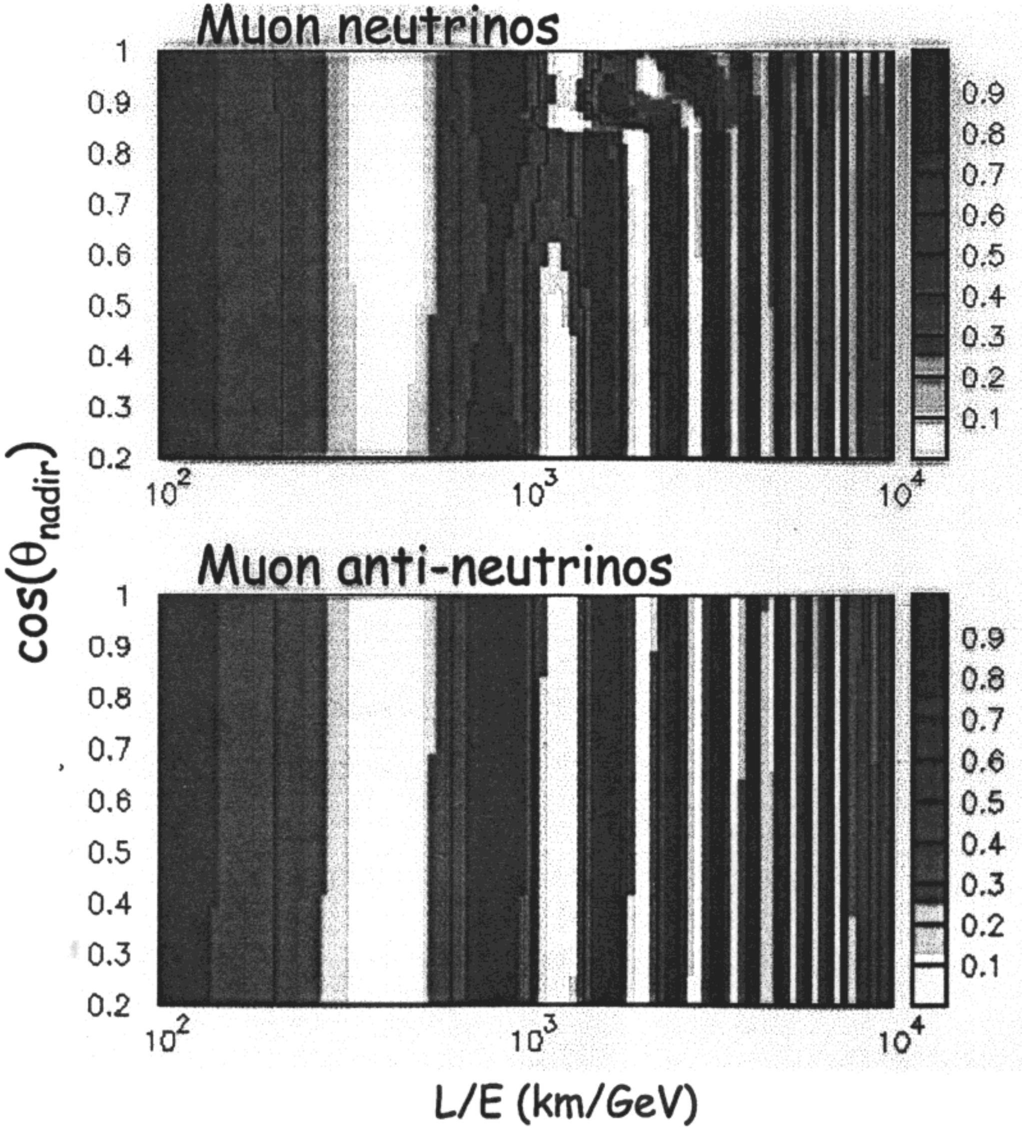
Examples for $\Delta m^2 = +0.003\ eV^2$ and $\sin^2(2\Theta_{13}) = 0.1$

- $E_R = \pm\cos(2\Theta_{13})\ \Delta m^2/(2\sqrt{2}G_F N_e)$
- $\Gamma_R = 2\sin(2\Theta_{13})\ \Delta m^2/(2\sqrt{2}G_F N_e)$



Example of oscillation patterns

MONOLITH



Spectral distortions relevant around 50° and for energies from3 GeV to 15 GeV.

Optimal baseline ~ 9000 km

For different Δm^2, this pattern shifts along log(L/E)

Survival probabilities calculated for $\sin^2(2\Theta_{13}) = 0.1$ and $\Delta m^2 = +0.003$ eV^2

MONOLITH at a ν-Factory

A ν-Factory beam is a pure beam of either
ν_μ + anti-ν_e or anti-ν_μ + ν_e

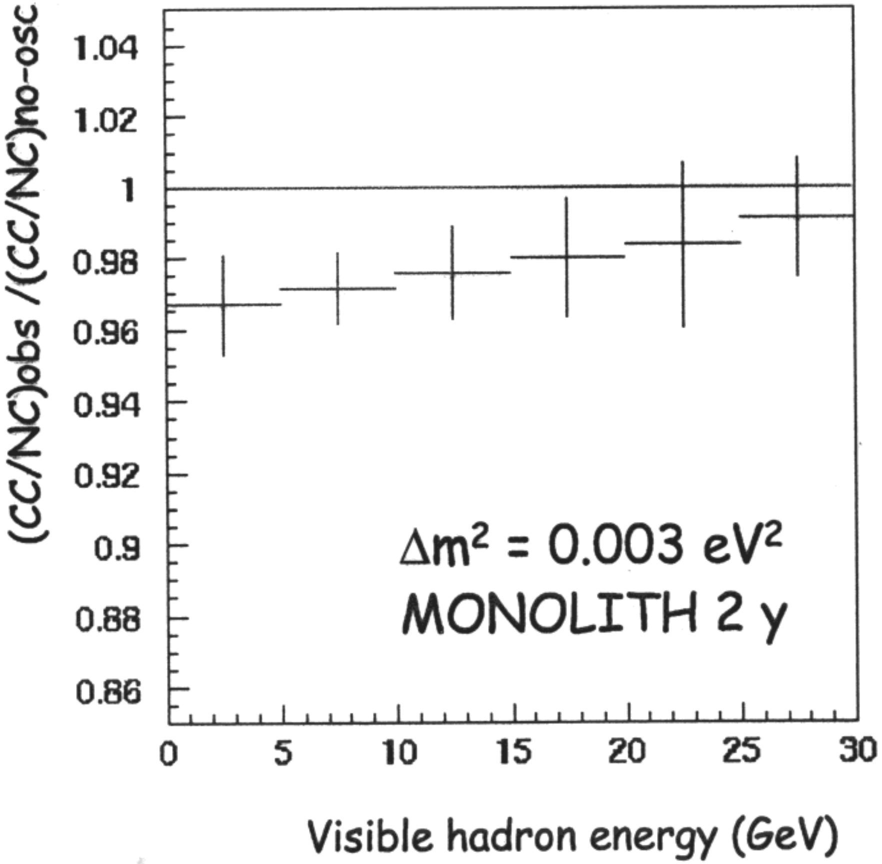
Signature for ν_e oscillation:

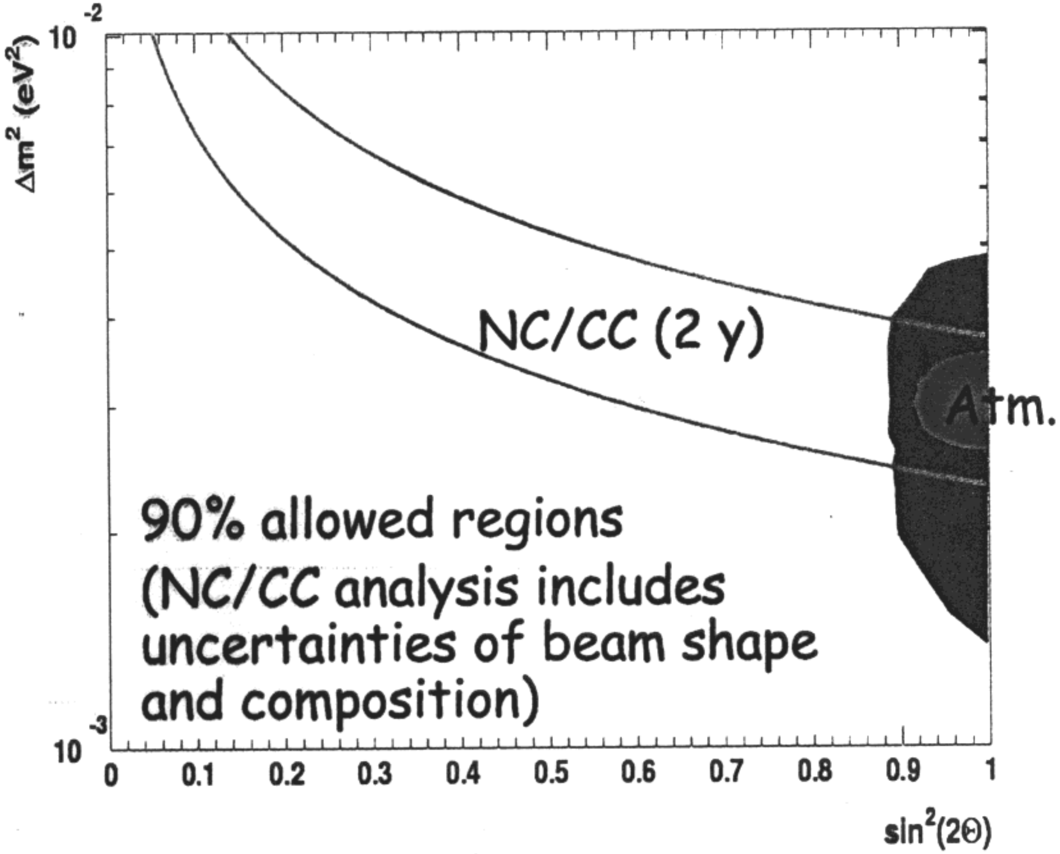
WRONG SIGN MUONS!

A large mass magnetized calorimeter is considered as candidate detector

MONOLITH matches the charge id. and angle resolution requirements for this measurement

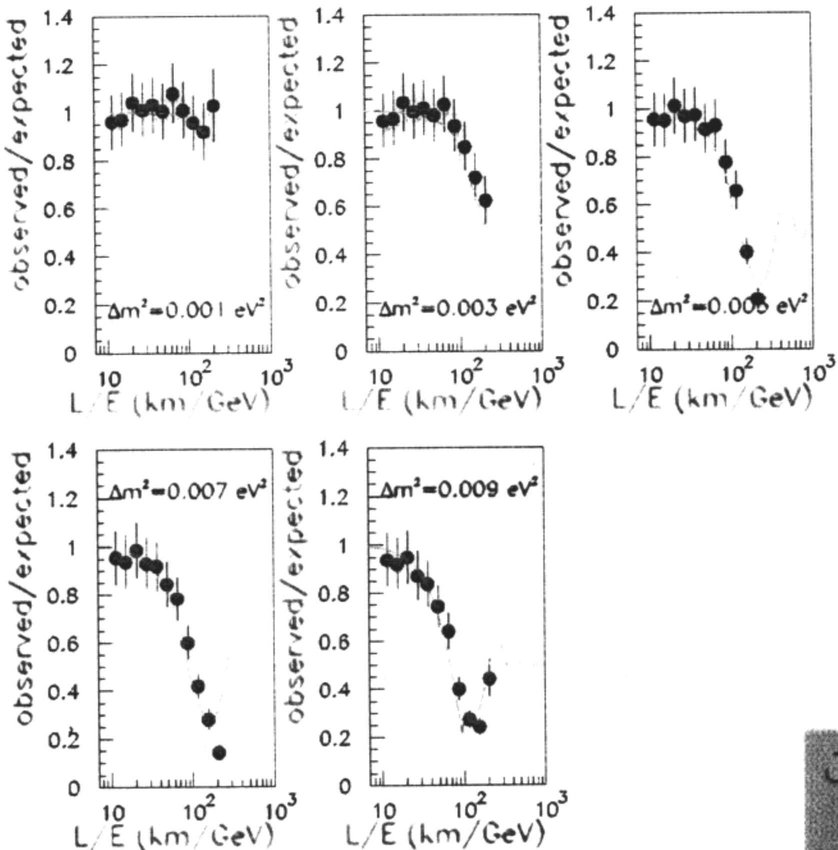
MONOLITH on CNGS (2)





Can supplement atmospheric data at large Δm^2

Monolith on CNGS beam



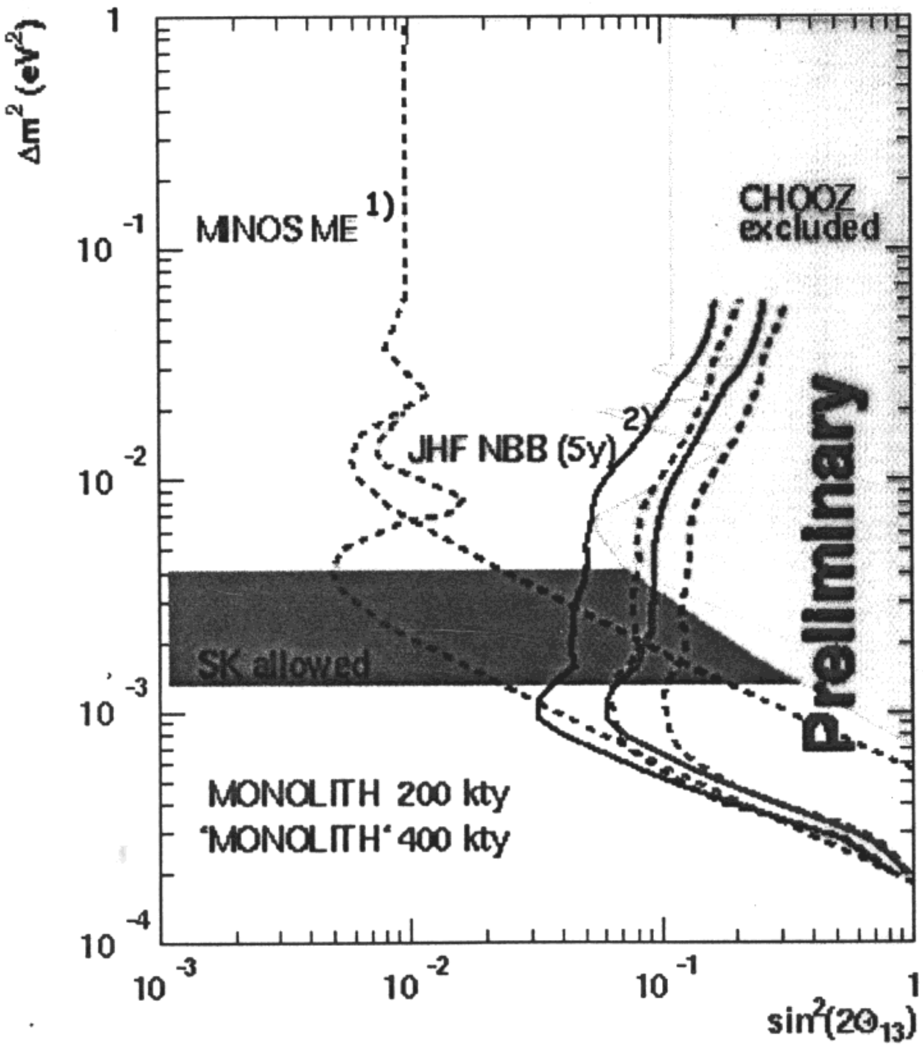
- J CNGS beam will cover with very high statistics the region L/E < 100 km/GeV: ~ 40,000 events/year ν_μ CC after selections vs. ~ 200 events/year from up-going atmospheric.
- J Resolution is OK.

L **Systematic effects: a tough job!**

- J NC/CC ratio less sensitive to systematic effects related to the beam shape. Short/Long event ratio with ~ 60,000 (20,000) ν_μ CC (NC) events/year after selections

Sensitivity to $sin^2(2\Theta_{13})$

ν_μ / ν_e - 90% C.L. expected limit



Sensitivity curves computed assuming 15% uncertainty on flux predictions and perfect knowledge of the resolution function

Exclusion regions if no effect observed for positive (continuous line) and negative (dashed line) sign of Δm^2

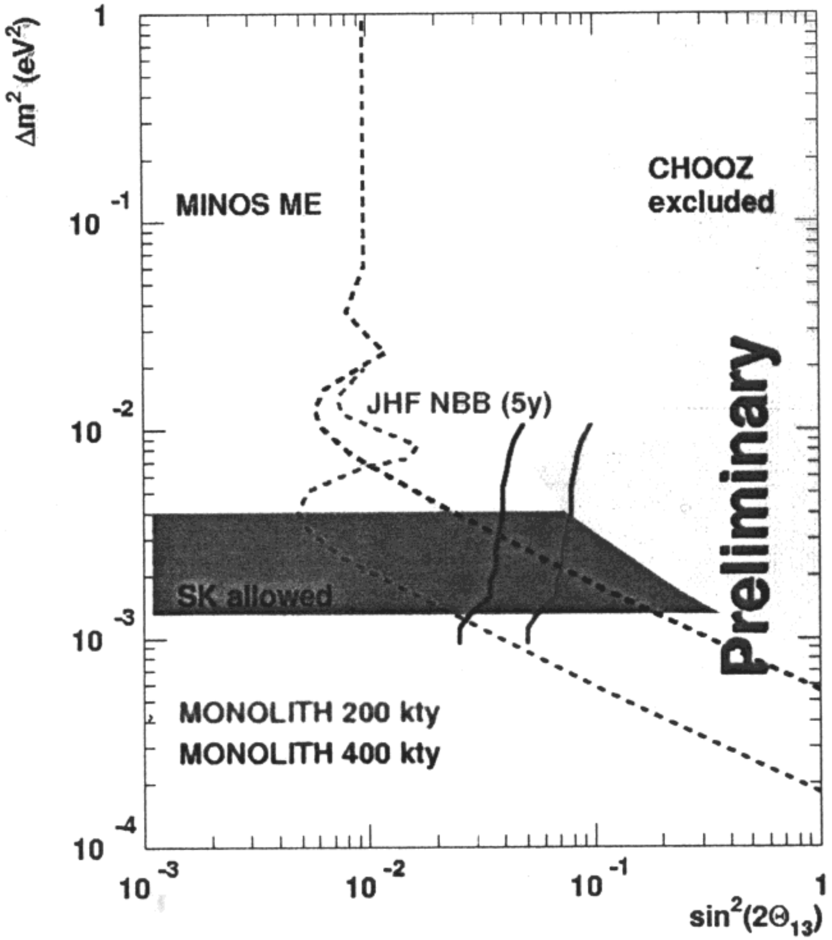
Test statistics:

$$-2\ln \frac{\mathcal{L}(A,\Delta m^2, sin^2(2\Theta_{23}), sin^2(2\Theta_{13})=0)}{\mathcal{L}(A,\Delta m^2, sin^2(2\Theta_{23}), sin^2(2\Theta_{13}))}$$

1) A. Para, hep-ph/0005012
2) T. Kobayashi, talk in La Thuile, 2001

Sensitivity to the sign of Δm^2

sign of Δm^2 - expected sensitivity at 90% C.L.



Region over which the sign of Δm^2 can be determined assuming that $\sin^2(2\Theta_{13})$ be known with a relative error of 100%

(Measurement difficult for mixing below 0.01: the optimal baseline exceeds the Earth diameter)

NB: MINOS and JHF cannot measure the sign of Δm^2!

SENSITIVITY TO OSCILLATION PARAMETERS OF A MAGNETIZED (MONOLITH-LIKE) ATMOSPHERIC-ν DETECTOR

	osc	Δm^2_{23}	$\sin^2 2\vartheta_{23}$ *	$\sin^2 2\vartheta_{13}$	sign(Δm^2)	δ_{CP}
MONOLITH 200 kt·y	yes	$\pm 1.5 \cdot 10^{-4}$ eV^2	4.5%	if $\gtrsim 0.08$	if $\sin^2 2\vartheta_{13} \geq 0.08$	no
MEGALITH 1600 kt·y	yes	$\pm 0.5 \cdot 10^{-4}$	1.5%	$\gtrsim 0.01$	≥ 0.01	no

$$* \doteq \left(1 - \frac{1}{2}\sin^2 2\vartheta_{13}\right) \sin^2 \vartheta_{23}$$

Conclusions

MONOLITH

MONOLITH can significantly contribute to precision measurements of neutrino mixing and masses

The superior *L/E* resolution of MONOLITH will allow detection of the first oscillation period:

- test of ν_μ disappearance dynamics
- precision measurement of Δm^2 and mixing

Its capability to measure the muon charge will allow to test admixture of ν_s and ν_e searching for matter-induced effects

Sign of Δm^2, constraints on U^2_{e3}, ...

Its large mass will allow to exploit CNGS beam for disappearance and NC/CC measurements

In the long term, it can be used for measurements at a ν-Factory