ICHEP 2000

F Ronga
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Atmospheric neutrino results from:

MACRO at GRAN SASSO

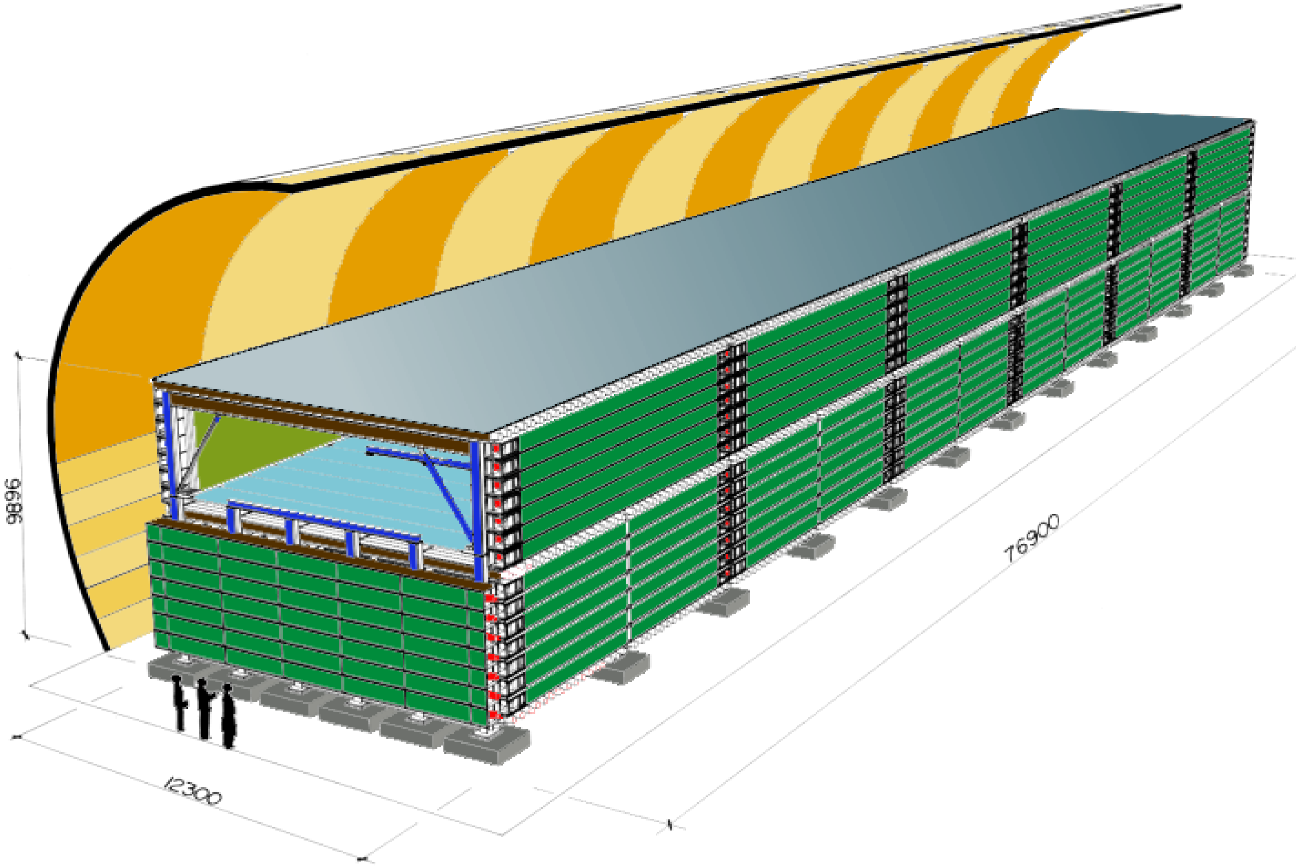
M onopole , **A** strophysics , and **C** osmic **R** ay **O** bservatory

Bari, Bologna, Boston, Caltech, Drexel, Indiana, Frascati, Gran Sasso , L'Aquila, Lecce, Michigan, Napoli, Pisa, Roma I, Texas, Torino

Summary:

- Upward- Going Through-Going Muons
- Sterile Vs Tau Neutrino with matter effects
- Low energy Events
- Conclusions

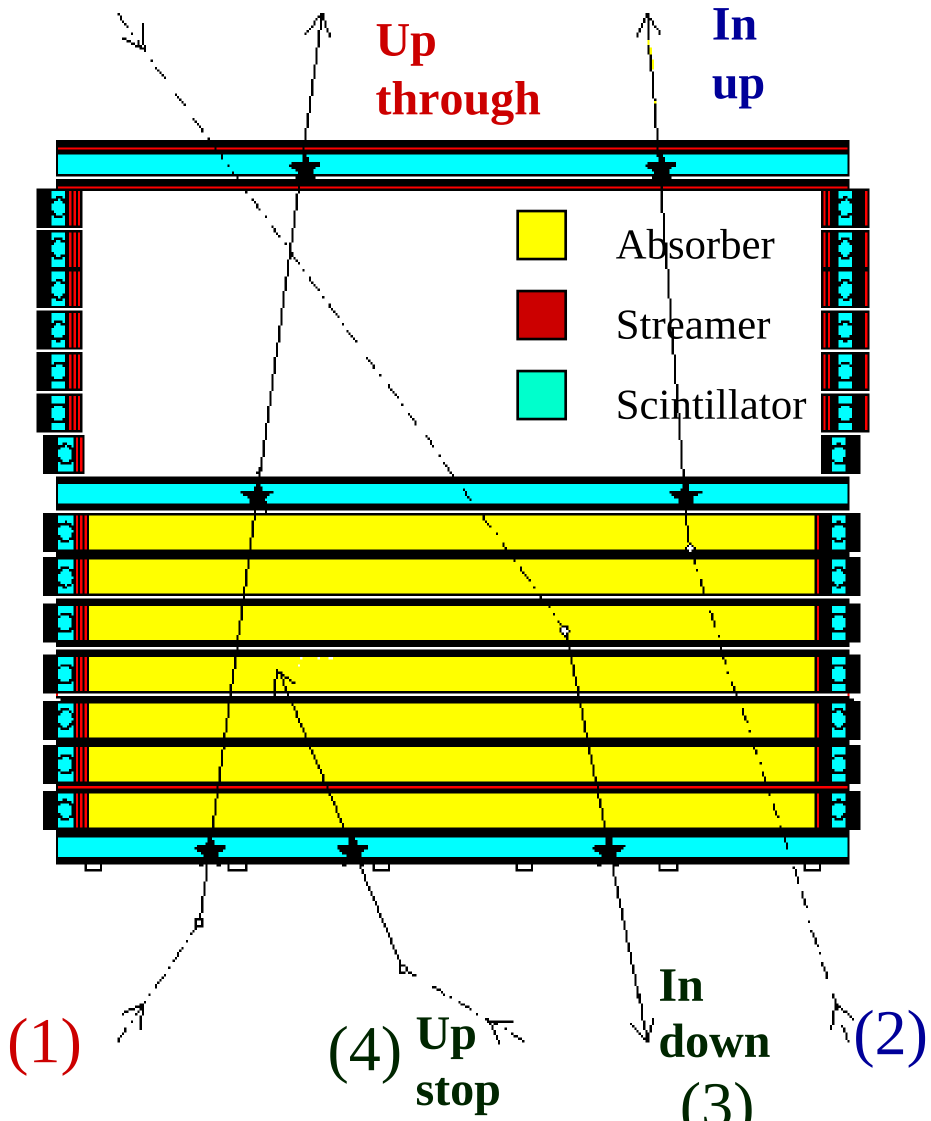
Main features of Macro as ν detector



- Large acceptance (~10000 m^2sr for an isotropic flux)
- Low downgoing μ rate (~10^{-6} of the surface rate)
- ~600 tons of liquid scintillator to measure T.O.F. (time resolution ~500psec)
- ~20000 m^2 of streamer tubes (3cm cells) for tracking (angular resolution < 1°)

More details in Nucl. Inst. and Meth. A324 (1993) 337.

Neutrino event topologies in MACRO



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Detector mass ~ 5.3 kton

(1) Up throughgoing μ (ToF) ~140 Ev/y $E_{median} \approx 50GeV$

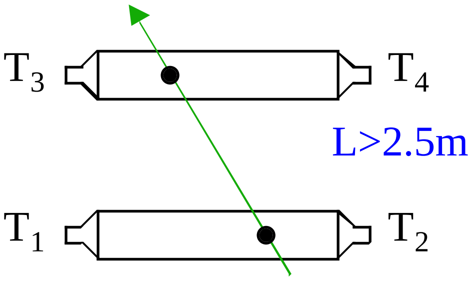
(2) Internal Upgoing μ (ToF) ~ 25/y $E_{median} \approx 3.5GeV$

(3) Internal Downgoing μ (no ToF) ~ 22y $E_{median} \approx 4.2GeV$

(4) UpGoing Stopping μ (no ToF) ~ 22/y

Upward Going Muons (Through) Data Set

data selection based on the time-of fligth measured with the scintillators



$$\frac{1}{\beta} = \frac{(T_1 + T_2 - T_3 - T_4)c}{2L} = \begin{cases} +1 & \mu\downarrow \\ -1 & \mu\uparrow \end{cases}$$

1) streamer track in agreement in the scintillator counters with the position from the times at the ends

2) -1.25 < 1/beta < -0.75

3) 2m (≈ 200gr/cm2 of absorber crossed to reduce at 1% level the backward due to π's produced by downward-going muons (Astrop Phys 9 (1998) 105)

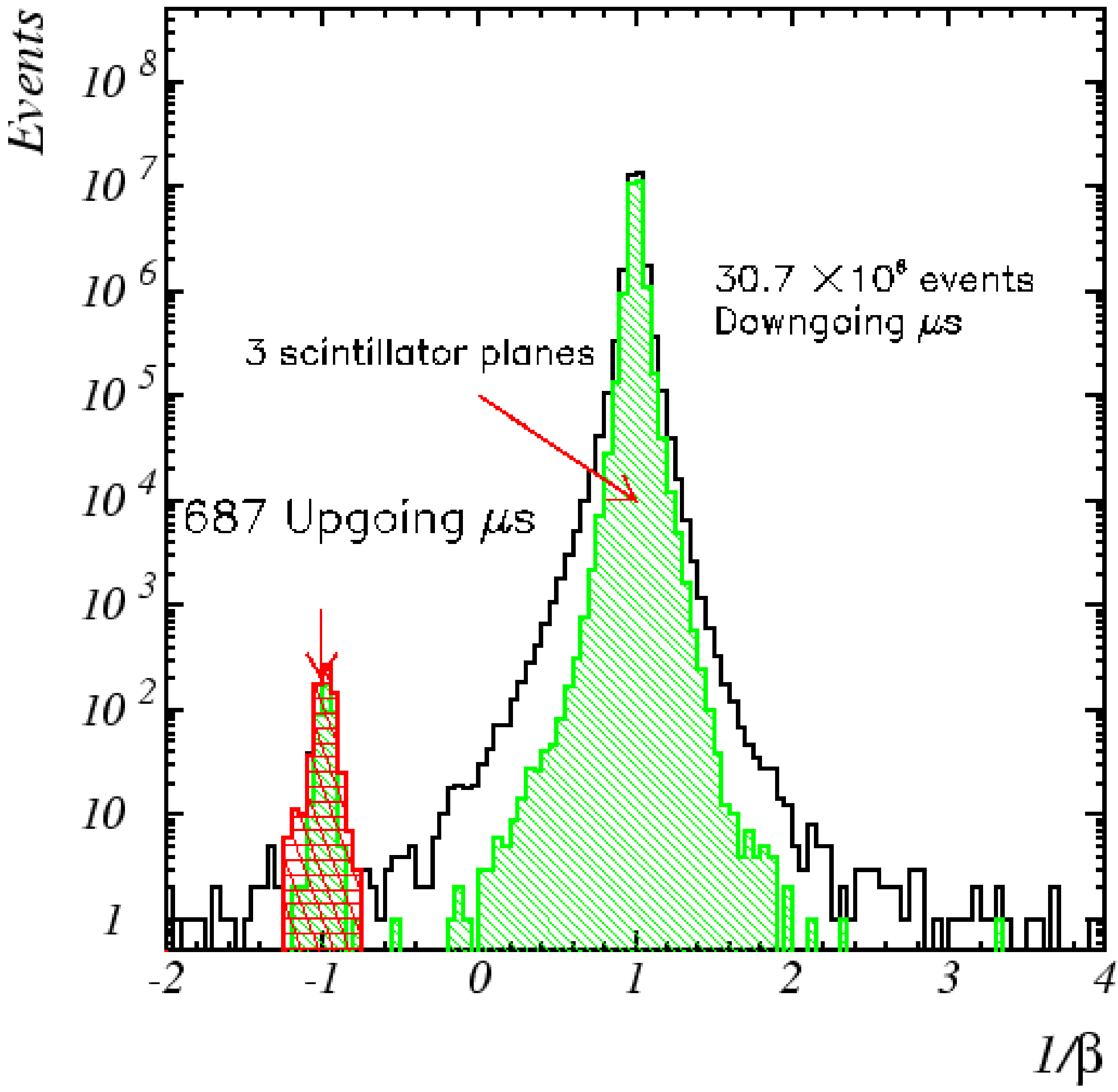
- Data selection only by software. (No scanning)

- 768 neutrino induced through-going upward muons during

Mar 89-Nov 91 (1/6 lower detector, 1.38 y)
Dec 92-Jun 93 (lower detector, 0.41 y)
Phys. Lett. B357 (1995) 481
29 Apr 94 –5 Mar 2000 (complete detector) 4.8y
(Phys.Lett. B434 (1998) 451 until Nov 98)

Upward Going Muons

1/β distribution



Upward Going Muons (Through) Results

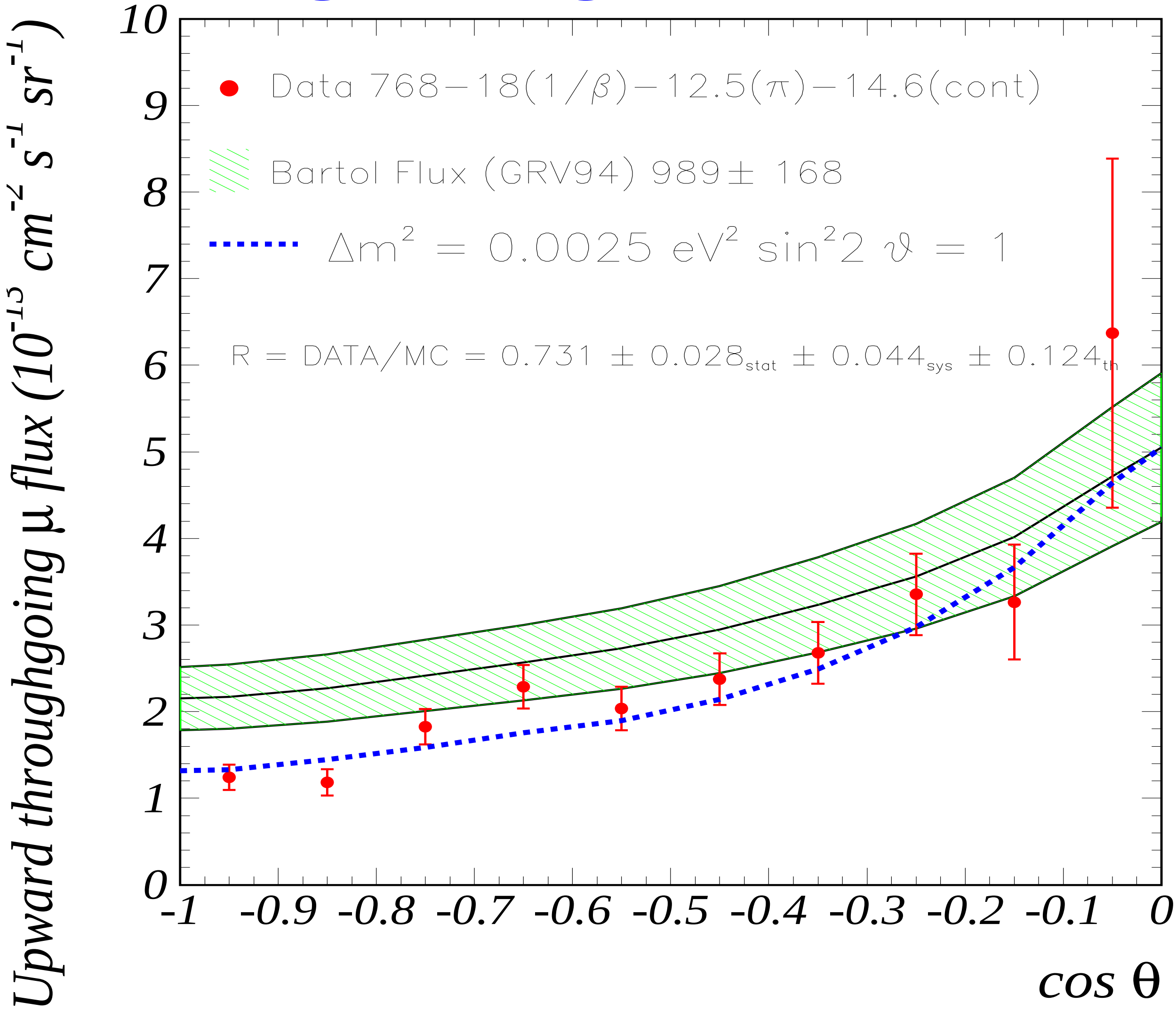
Total number of events:	**768**
background (wrong b)	**18**
background (pion from muon)	**12.5**
Internal neutrino interactions	**14.6**
Total	**723**
Prediction	**989±17%**

Bartol neutrino Flux ±14%
GRV94 cross section 9%
Lohmann muon energy loss 5%

R=data/prediction= 0.73

±0.028(stat)±0.044(systemat.)±0.12(theoretical)

Upward Going Muons (Through) Angular Distribution



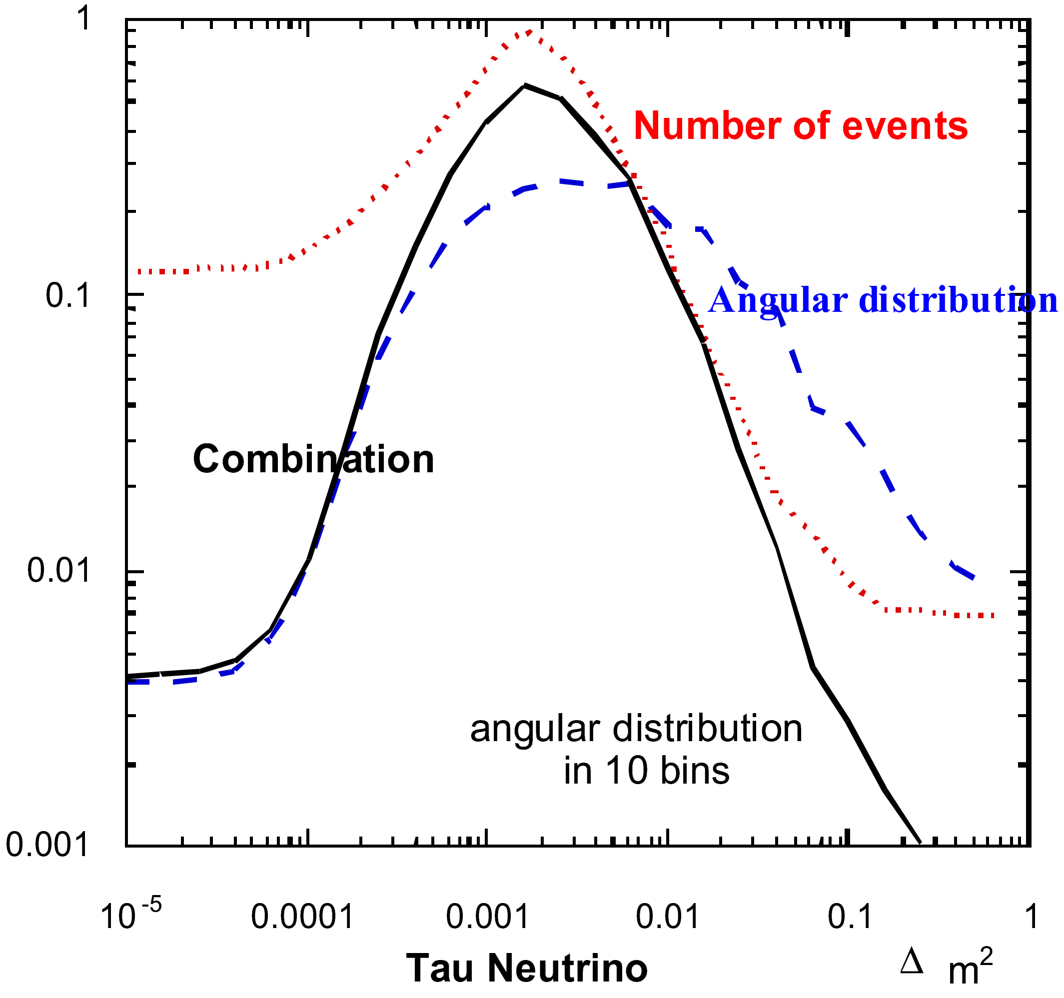
$\chi 2$ test on the angular distribution (10 bins) with prediction normalized to data :

- $\chi 2$ = **11.2/9 d.o.f.** for $\nu_\mu \Rightarrow \nu_\tau$ with maximum mixing and $dm^2 \sim 0.0025\ eV^2$ P = 26 %
- $\chi 2$ = **24.3/9 d.o.f.** for no - oscillations P = 0.9 %

(since <Eμ thresh>≈ 1 GeV MACRO should be compared with the SuperKamiokande Through-going + Stopping muons)

Probabilities for maximum mixing and $\nu_\mu \rightarrow \nu_\tau$ oscillations

Peak probability from the angular distribution: 26%
from the combination: 57%



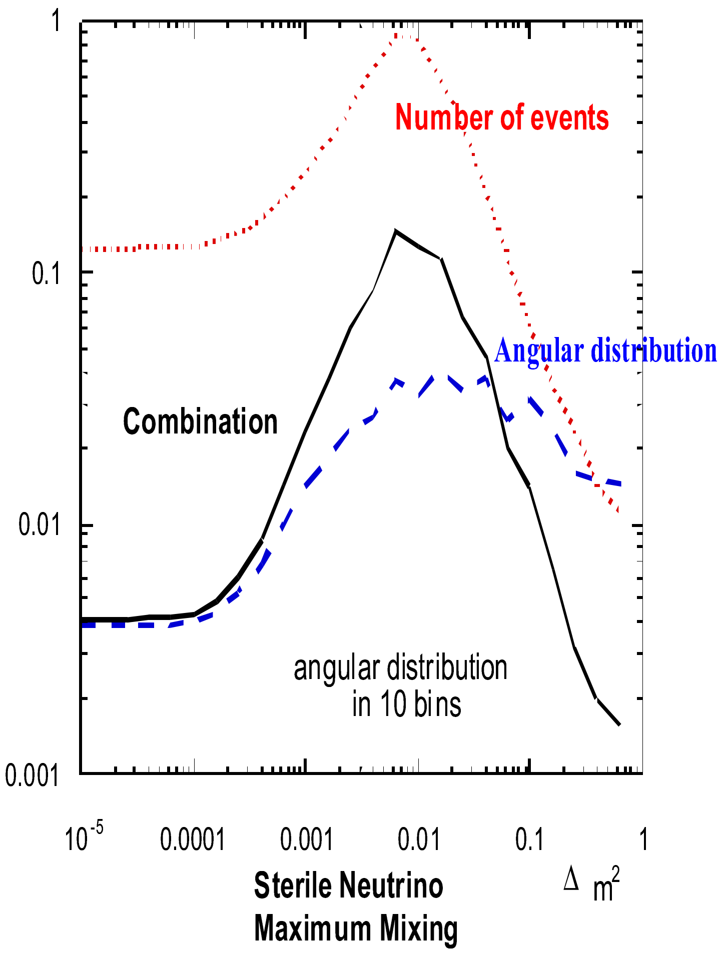
• The peak probability from the angular distribution alone is in the same region of the peak probability from the total number of events

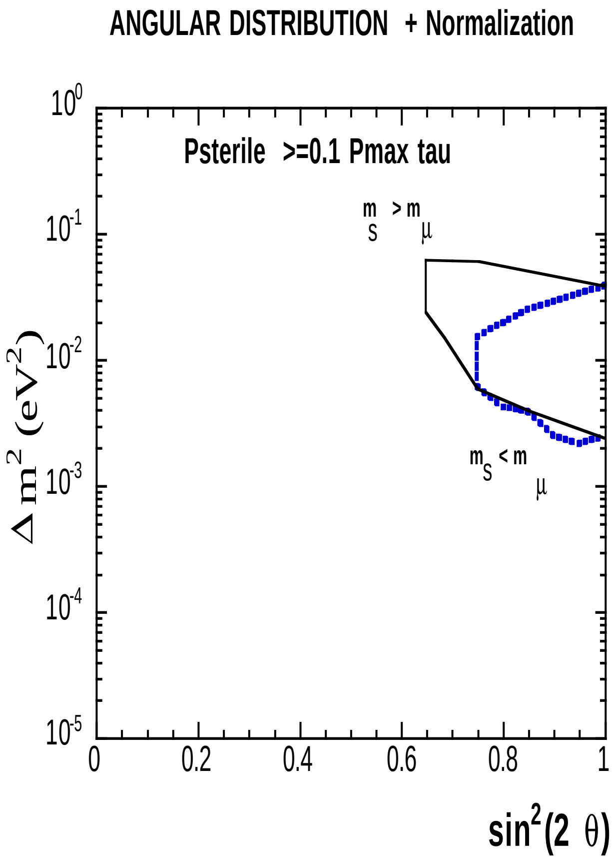
• Probability for no-oscillation: ~ 0.4 %

MACRO UPMU
Probability for sterile neutrinos oscillations

• sterile neutrino ==>> matter effects ==> reduction of the angular distortion

Peak probability from the angular distribution: 4.1%
from the combination: 14.5%





Peak probabilities lower than that for tau neutrinos:

• **from the angular distribution:** 4.1 %

• **from combination:** 14.5 %

MACRO UPMU : matter effect with the ratio vertical/horizontal

• This ratio (*Lipari -Lusignoli (Ph Rev D 57 1998)*) can be statistically more powerful than a chi-square test for two reasons:

1) the ratio is sensitive to the sign of the deviation

2) there is gain in statistical significance grouping data in two bins

• As disadvantage you could lost **some data structure** in the angular distribution

• Ratio or chi-square in 10 bins ? Several authors prefer chi-square.
Chi-square in 10 (or more) bins **no strong discrimination between tau and sterile neutrino** oscillations (for SK also)
(Foot hep-ph/0007065 , Fornengo et al hep-ph/0002147)

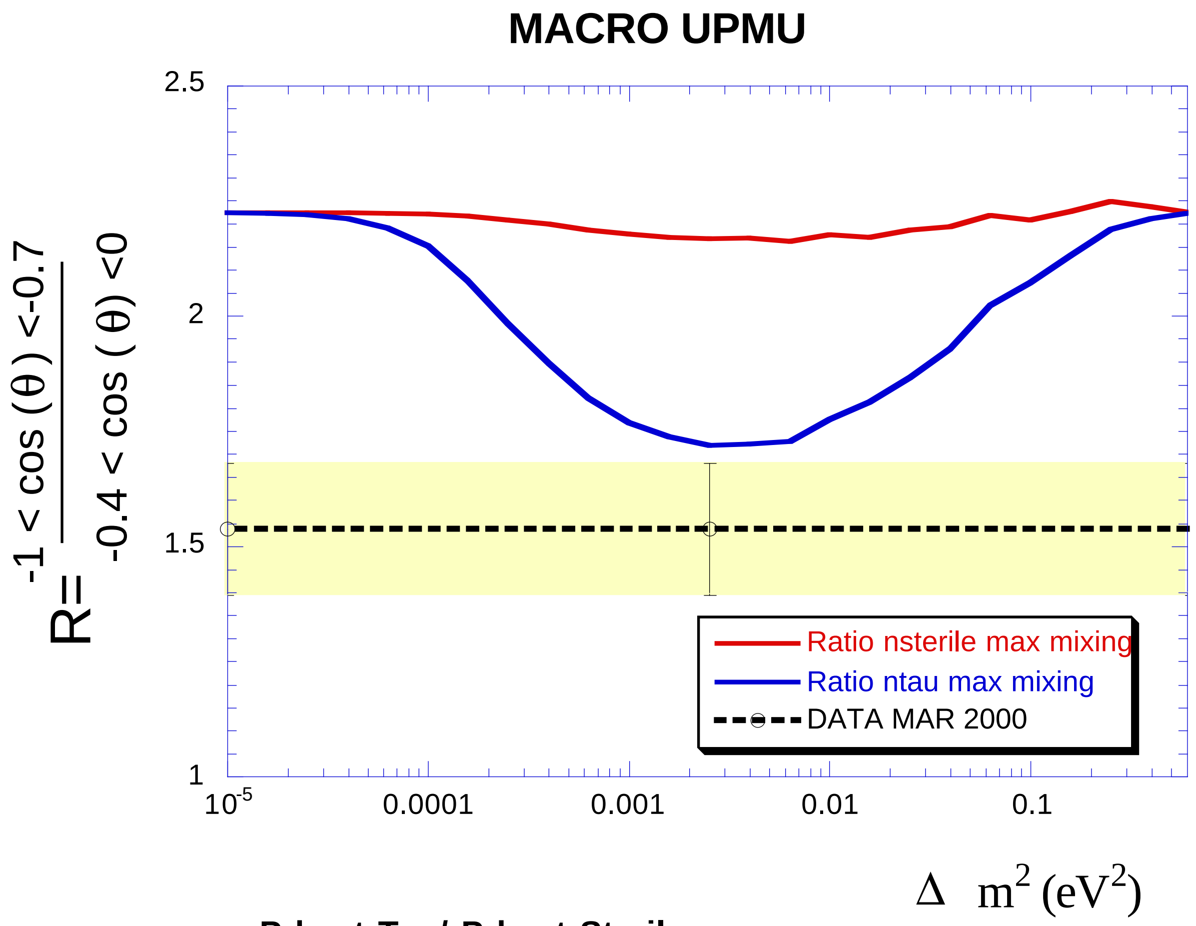
• **Recently : optimization of the ratio**

Result (for MACRO) for the best bin combination

$$R = \frac{N(\cos(\theta) < -0.7)}{N(\cos(\theta) > -0.4)}$$

Obtained from a ***Montecarlo simulation*** *to minimize the probability for sterile neutrino assuming tau neutrino oscillations with* dm^2*=0.0025* eV^2

Ratio vertical/horizontal Montecarlo Optimized



P best Tau/ P best Sterile =
70 (5% systematic in each bin)
413 (no systematic error)

- **The plot is for** Maximum mixing**. But similar results for mixing < 1**

- **Sterile neutrino disfavored respect to tau at >98%** (5% systematic in each bin)

Errors on the ratio vertical/horizontal

• neutrino flux (Lipari neutrino 2000) :

the ratio depend from the K / π ratio and decay
Ldecay K ≈ 0.75 (EGeV/100) Km
Ldecay π ≈ 5.6 (EGeV /100) Km
two sources of uncertainty :
a) Spectral Index in the energy spectrum of the primary $E^{-\alpha}$
b) The calculation of the K/π fraction in the cosmic ray cascade (**largest contribution**)

$$\frac{\delta R}{R} \approx 3\%$$

• uncertainty in the neutrino cross section as function of the energy:

from the comparison of different cross sections (MACRO)

$$\frac{\delta R}{R} \approx 2\%$$

• uncertainty in the detector acceptance :

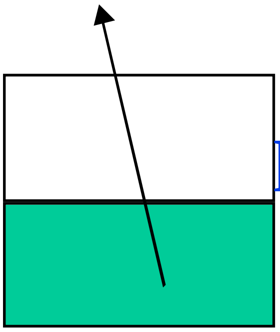
from a study of the down-going muons in MACRO we obtain 5% in each bin (used in the likelihood ratio calculation) ==> (if not correlated)

$$\frac{\delta R}{R} \approx 7.1\%$$

• uncertainty in the background in the bin near the horizontal:

Foot hep-ph/0007065

negligible in MACRO : small number of events and conservative cut (exclusion of 50% solid angle cos(θ)>-0.1)



Internal Upgoing partially contained events (IU)

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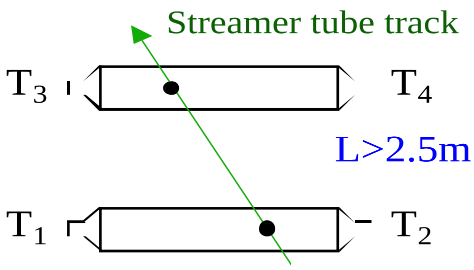
Identified by:

time-of-fligth between central / upper SC layers

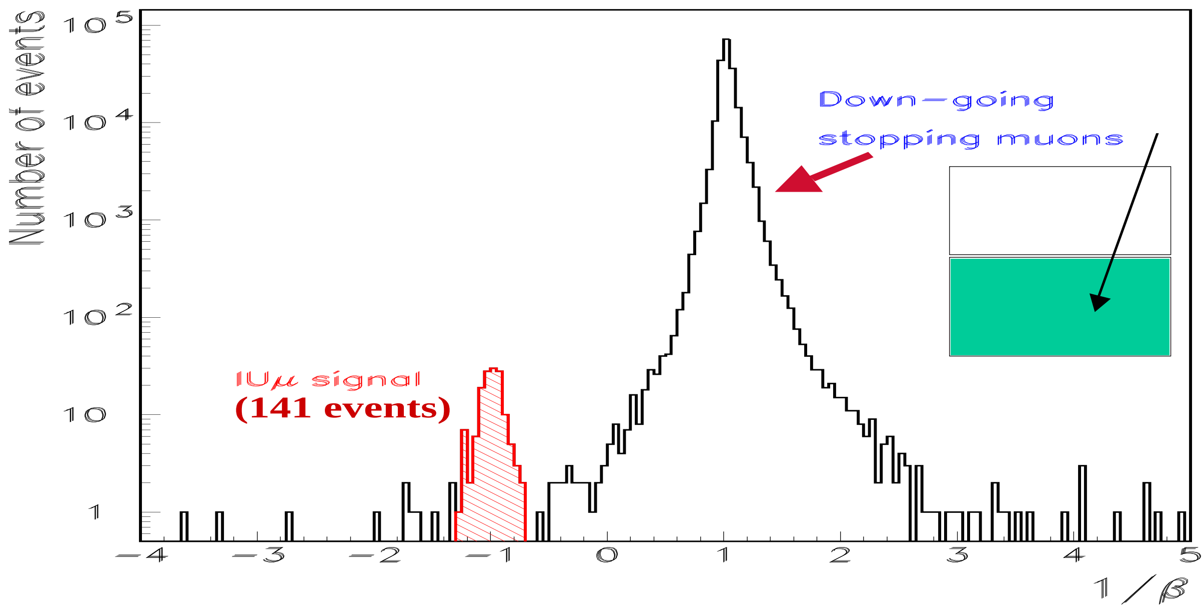


$$\frac{1}{\beta} = \frac{(T_1 + T_2 - T_3 - T_4)c}{2L} = \begin{cases} +1 & \mu\downarrow \\ -1 & \mu\uparrow \end{cases}$$

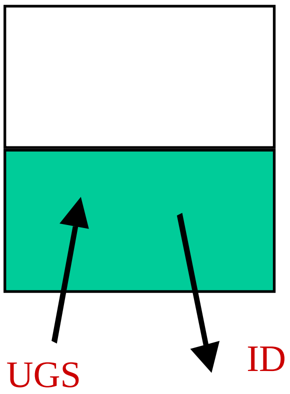
and **topological criteria for**

vertex containment inside lower detector

to remove upward-throughgoing muons (~1 % after this cut)



DATA - Bck(1/β) = 135 events



Internal Downgoing (ID) and UpwardGoing Stopping (UGS) partially contained events

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Selection criteria:

- No T.o.F. measurement
- topological constraints for the track (bottom SC layer + track inside fiducial volume)
- visual scan procedure (on real and simulated events) for final selection
- > 100 g cm^{-2} of material crossed in the detector to reduce background of upward π from μ

From MC simulation:

- $E_\nu \sim 4$ GeV
- Mixture of ~ 50% UGSμ + ~ 50% IDμ
- ~ 87% from ν_μ -C.C. interactions

DATA: 5.1 live-y

- From Apr. 1994 up to Mar. 2000

DATA - Bck = 229 events

MONTE CARLO PREDICTIONS

- GEANT based program for the simulation of detector response
- **Simulated events processed through the same analysis chain as the data**

$$\Phi_{\nu_\mu \to \mu} = \Phi_\nu \otimes \sigma_\nu \otimes \varepsilon\left(E_\mu, \theta_{zenith}\right)$$

- Φ_ν: Bartol ν flux with geomagnetic cutoffs (error ~ 20%)
- σ_ν = Q.E. + 1π (Lipari et al., PRL**74** (1995) 4384) + DIS (GRV-LO-94 PDF) (error ~ 15%)
- $\varepsilon(E_\mu,\theta_{zenith})$: detector response and acceptance (systematic error ~ 10 %)

▼

Internal Up	MC:	$247 \pm 25_{sys} \pm 62_{the}$
	DATA:	$135 \pm 12_{stat}$
Idown + UGStop	MC:	$329 \pm 33_{sys} \pm 82_{the}$
	DATA:	$229 \pm 15_{stat}$

- Using the NEUGEN code (MINOS experiment):

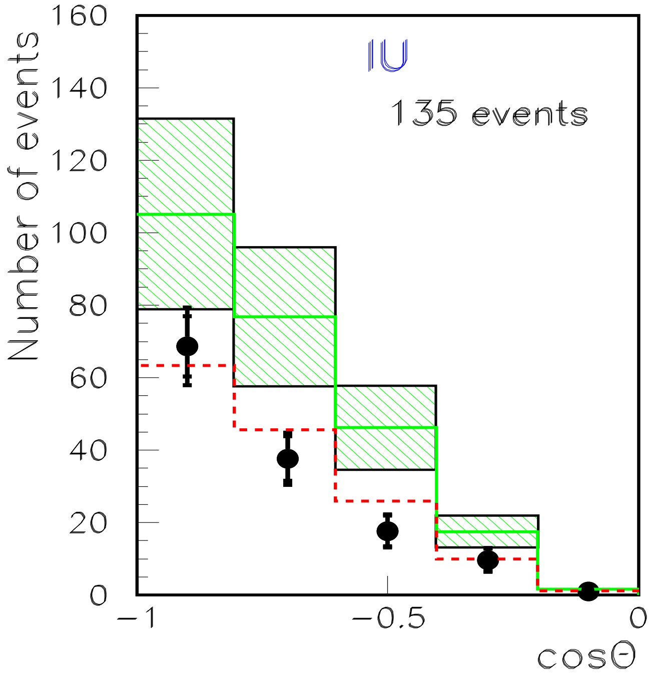
→ 6% difference in the expectations

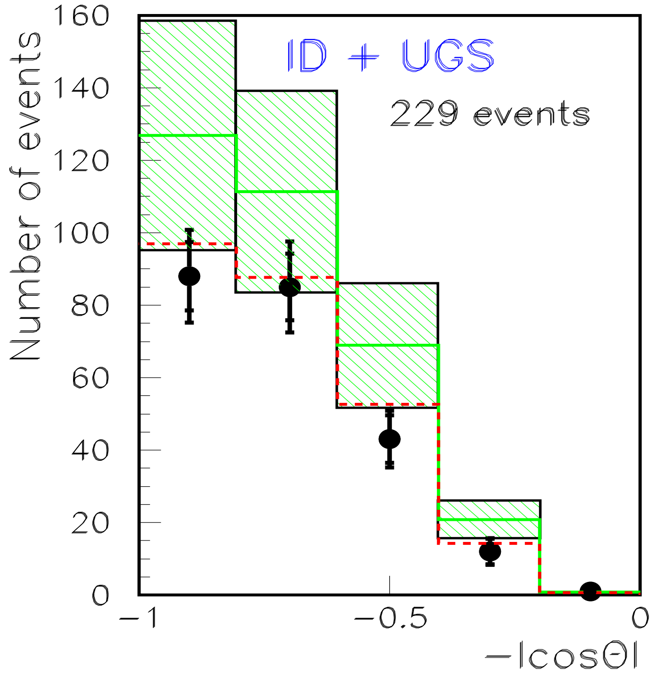
ANGULAR DISTRIBUTIONS

LOW ENERGY EVENTS

$$\frac{Data}{MC}_{(IU)} = 0.55 \pm 0.04_{stat} \pm 0.06_{sys} \pm 0.14_{th}$$

$$\frac{Data}{MC}_{(ID+UGS)} = 0.70 \pm 0.04_{stat} \pm 0.07_{sys} \pm 0.18_{th}$$





MC expectation (no oscillations)

maximal mixing , $\Delta m^2 = 2.5 \times 10^{-3}$ eV ^{2}

- Data consistent with a **constant deficit** in all **zenith angle** bins (IU: χ^2 /d.o.f. = 3.1/4 on shape)

UP-DOWN ASYMMETRY

$$\textbf{Ratio}\ \ R = \frac{\text{In Up}}{\text{In Down + UpG Stop}}$$

- **Most of the theor. uncertainties canceled (<5%)**
- **Systematic errors reduced** (~6%)

Data: $R = 0.59 \pm 0.07_{stat}$

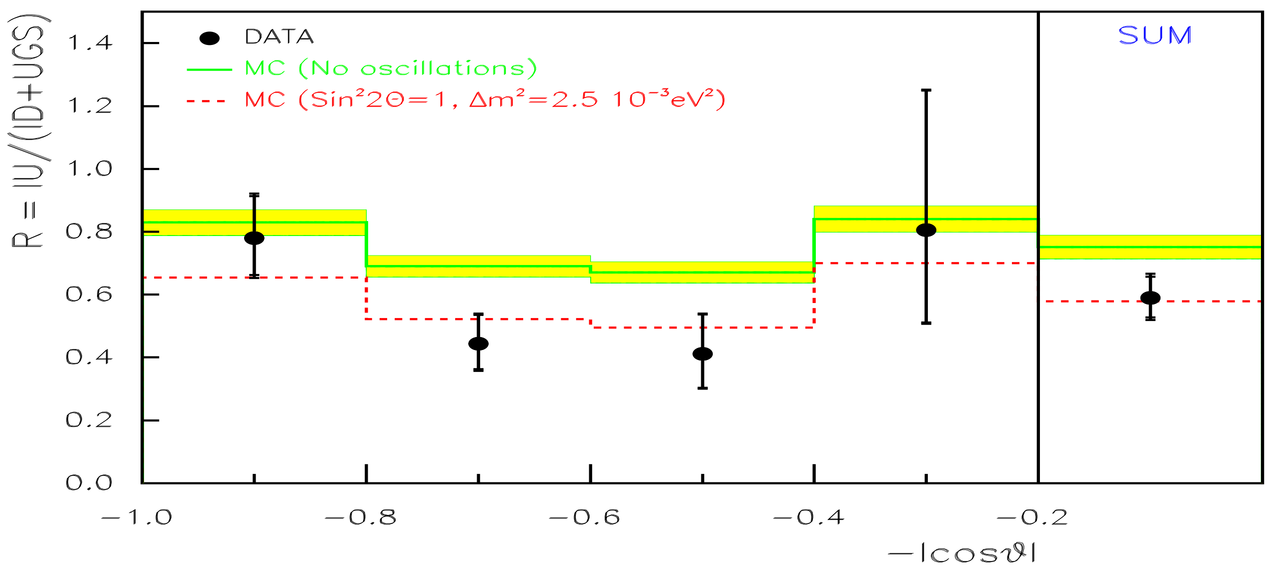
Expected (No oscillations): $R = 0.75 \pm 0.04_{sys} \pm 0.04_{th}$

→ **compatibility ~ 2.7%**

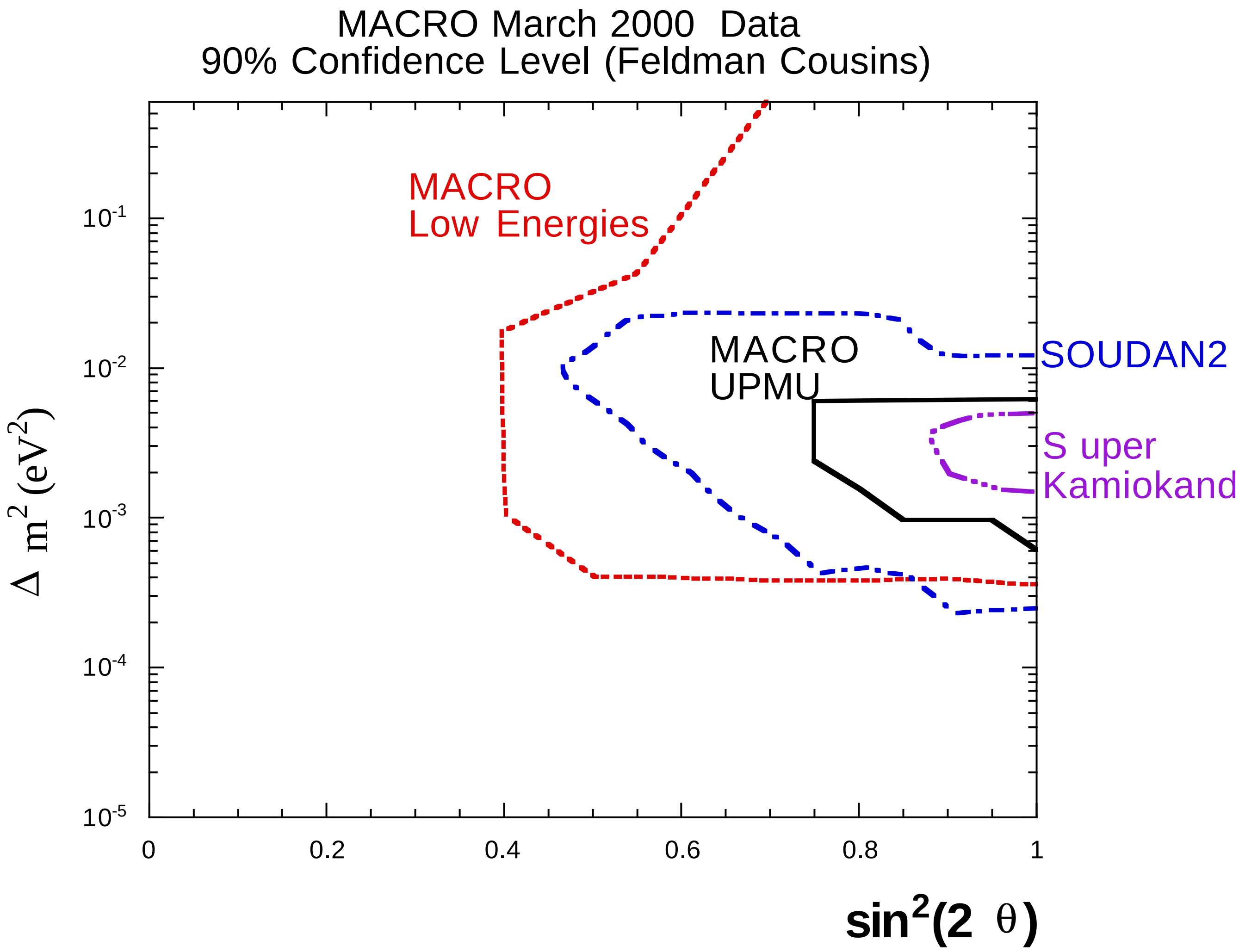
Expected with

$\nu_\mu \rightarrow \nu_\tau$ oscillations $R = 0.58 \pm 0.03_{sys} \pm 0.03_{th}$

(maximal mixing and $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$)



Confidence level regions
(ν_μ - -> ν_τ oscillations)



Conclusions

1)High energy events

(Upward Through-Going Muons)

Angular distributions **more regular** than in the past (Only statistics, no change in the data analysis in the last 3 years!)

χ^2 = **11.2/9 d.o.f.** for $\nu_\mu \rightarrow \nu_\tau$

Good agreement with the $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximum mixing and Δm^2 around 0.0025 eV^2 :

2)Sterile Neutrino and Matter effects:

Two flavor sterile neutrino oscillations disfavored at > 98% respect $\nu_\mu \rightarrow \nu_\tau$ with maximum mixing

(from the ratio test and 5% systematic error in each bin)

3)Low energy events:

event deficit,no zenith angle distortion,

Up-Down asymmetry (≈3%)==>

agreement with the $\nu_\mu \rightarrow \nu_t$ oscillations with maximum mixing and Δm^2 around 0.0025 eV^2 :