# Atmospheric Neutrino Induced Muons

MACRO

at GRAN SASSO

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


**USA-ITALY Collaboration**

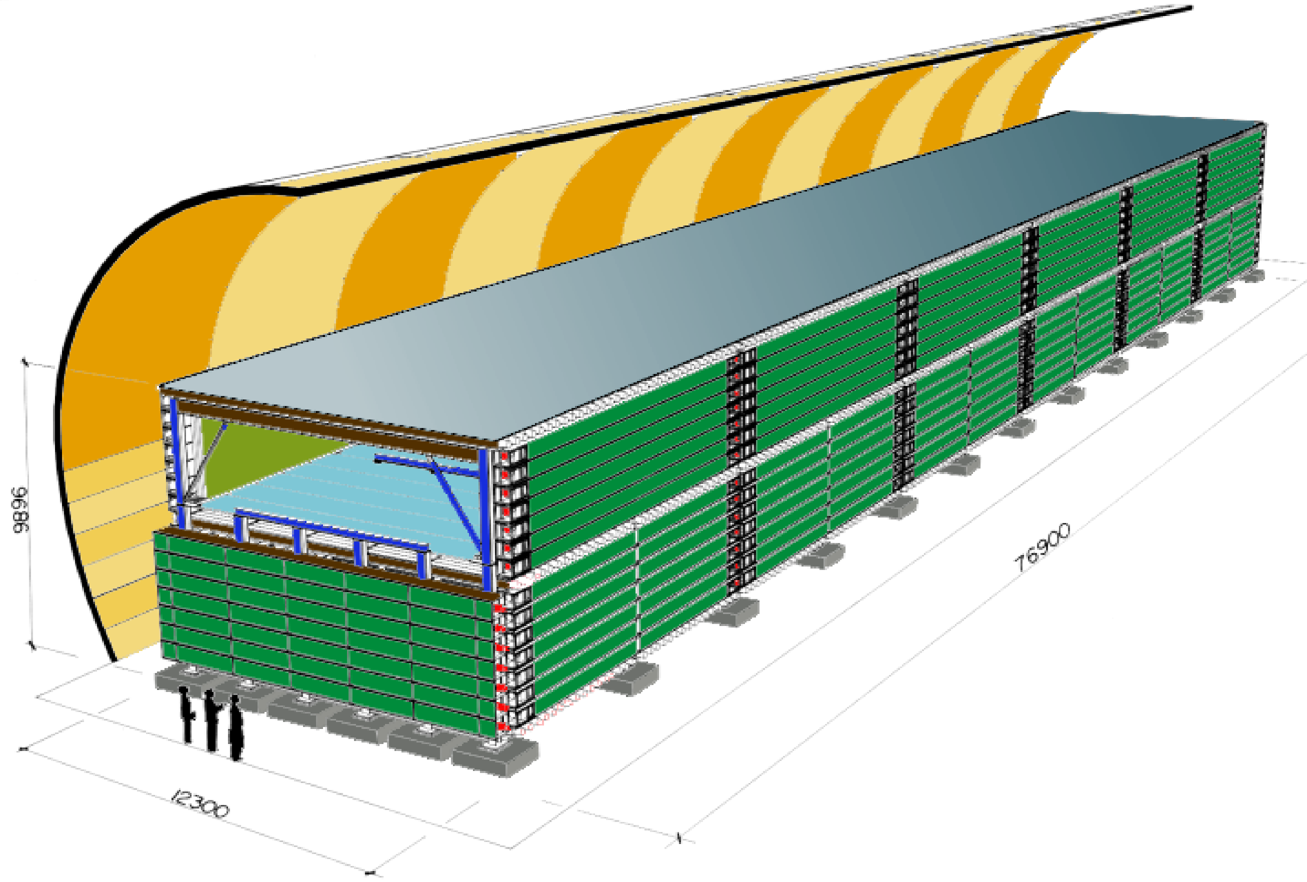
**Bari,Bologna,Boston,Caltech,Drexel,Indiana,Frascati,Gran Sasso,L'Aquila,Lecce,Michigan,Napoli,Pisa, Roma I, Texas,Torino**


## Summary:

- Upward-going (through-going) muons produced by neutrino interactions in the rock below the detector.  
MACRO and other experiments

- Muons produced by neutrino interactions inside the detector or stopping muons

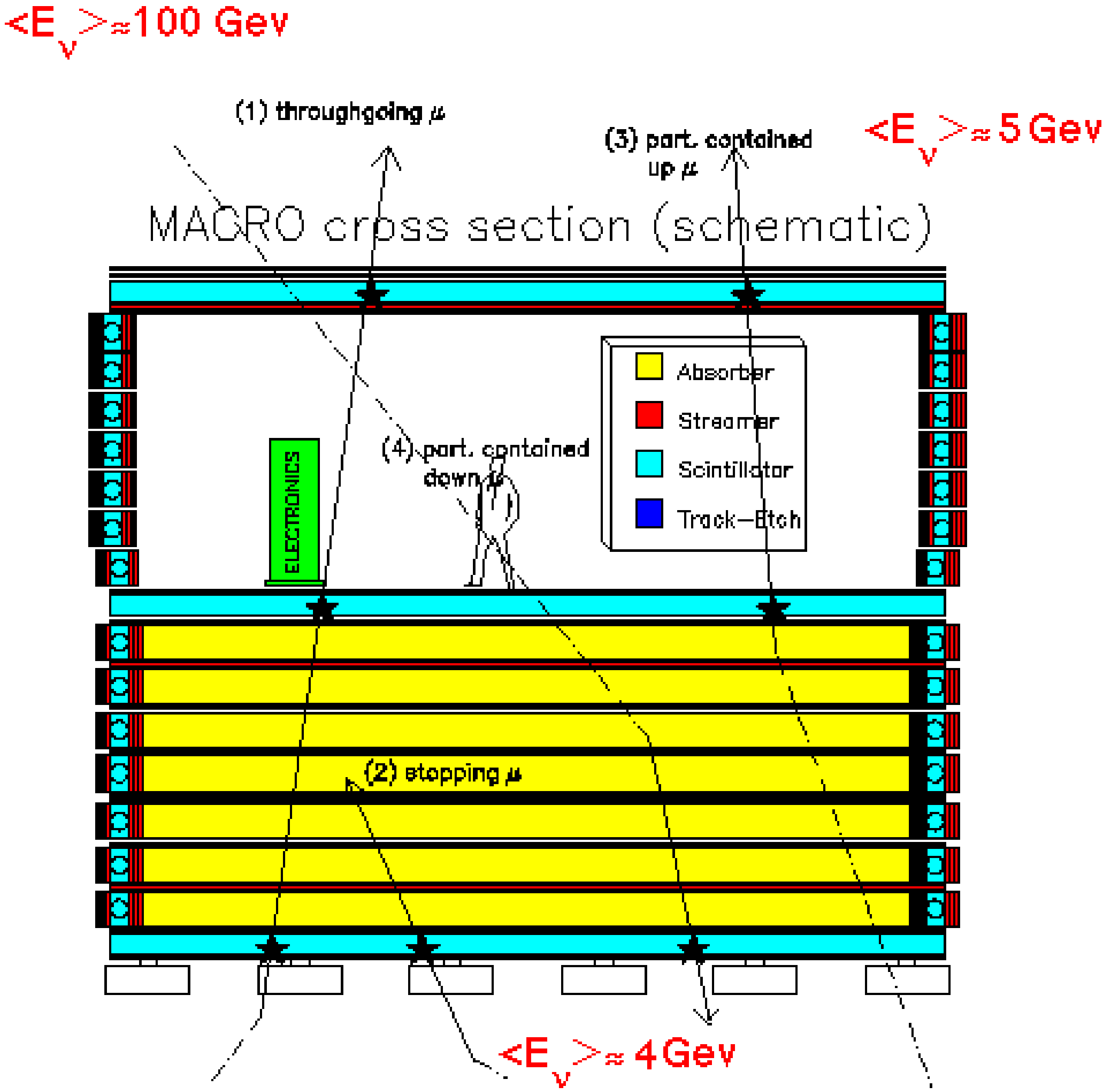
# Main features of Macro as ν detector



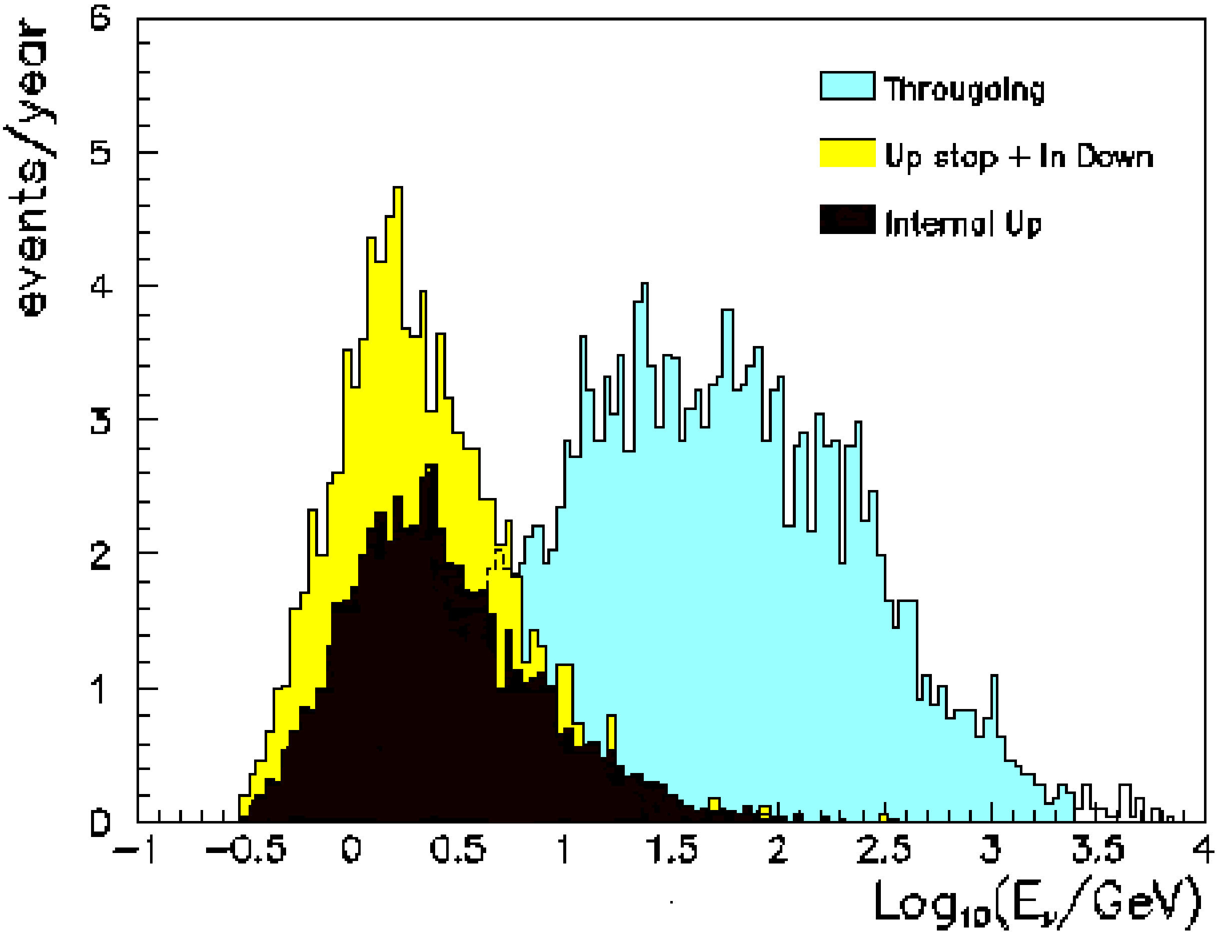

- Large acceptance (~10000 $m^2$sr for an isotropic flux)
- Low downgoing μ rate (~$10^{-6}$ of the surface rate )
- ~600 tons of liquid scintillator to measure T.O.F. (time resolution ~500psec)
- ~20000 $m^2$ of streamer tubes (3cm cells) for tracking (angular resolution < 1° )

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

• MACRO can detect different categories of Neutrino produced Muons.



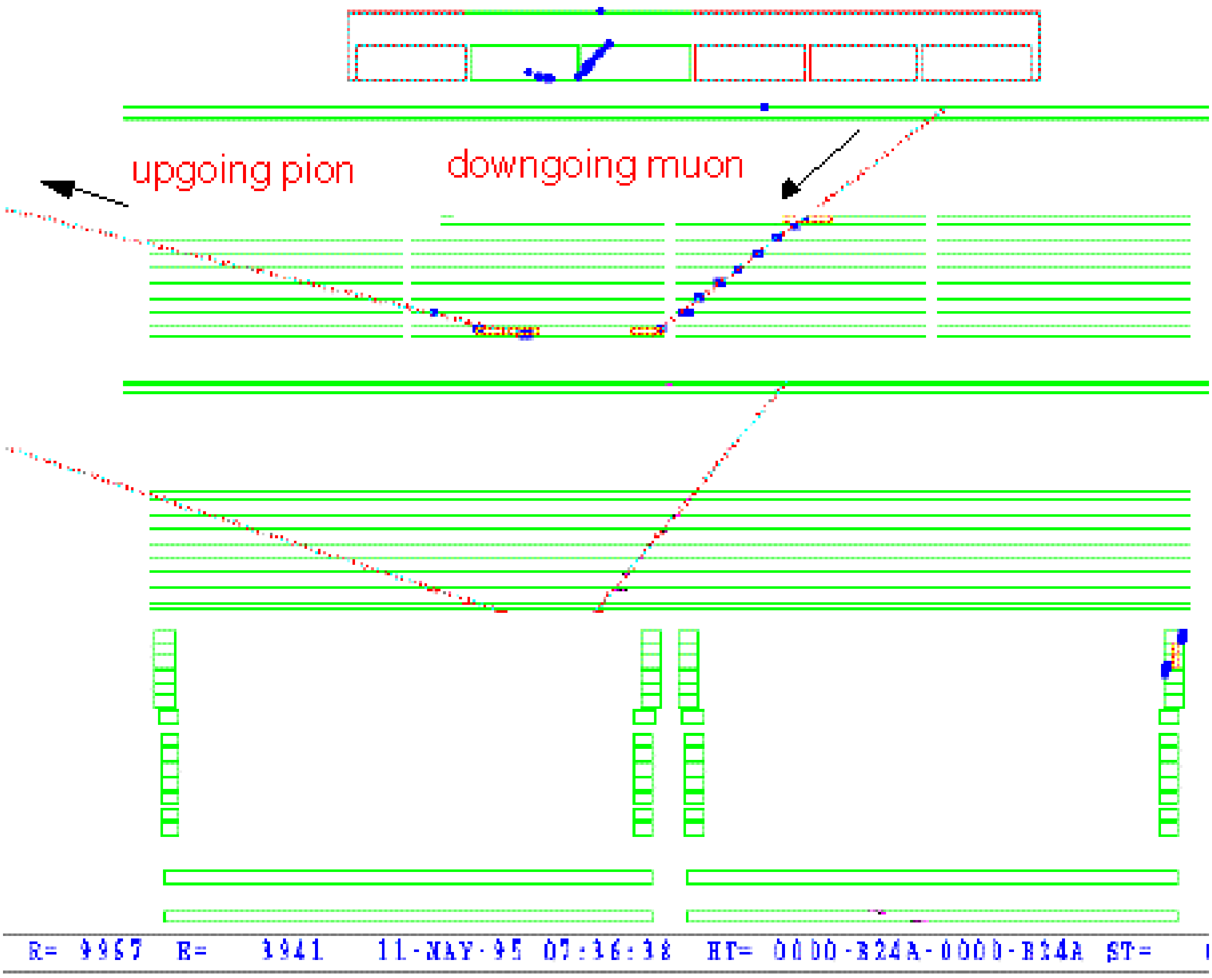
# Parent Neutrino Energy for different event topology



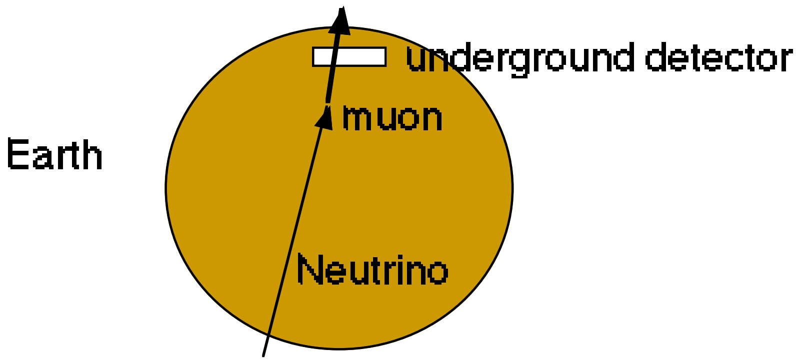
# Pion production at large angle

- Pions produced at large angle from muon interaction in the rock around the detector are a possible source of background for stopping and throughgoing upgoing muons
- 243 upgoing particles + downgoing muons were found in 13.600 h

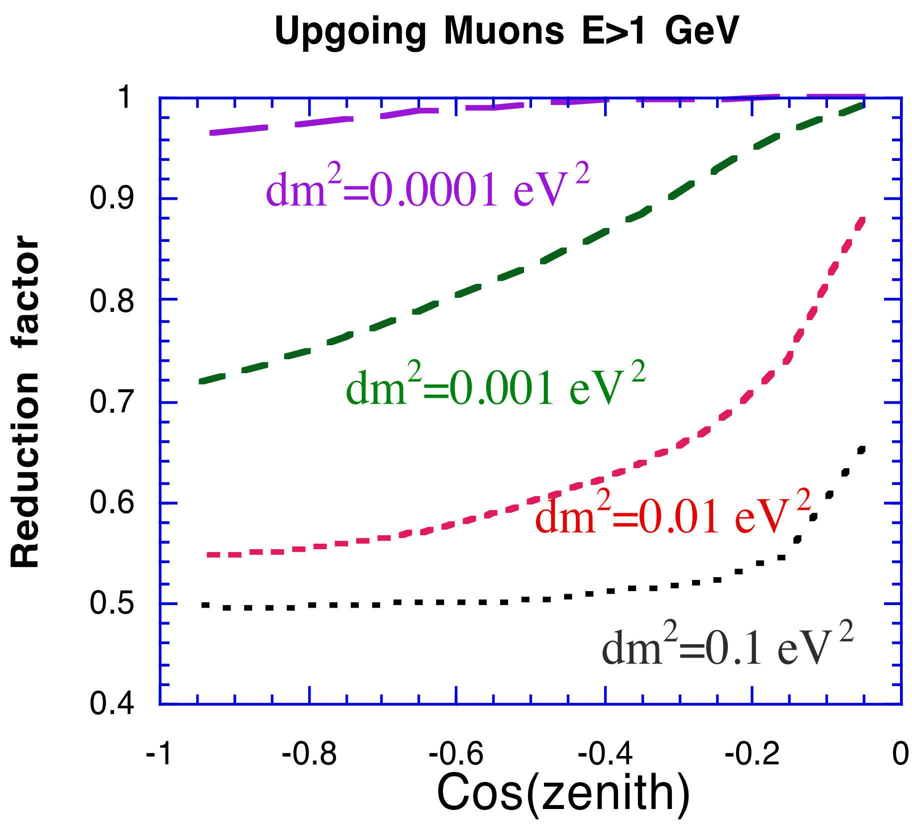
background in the stopping muon search (5%) and in the through-goind (2%)



# Upward-going (through-going) muons and neutrino oscillations




- Reduction factor for $\nu_\mu \varnothing \nu_\tau$ oscillations with maximum mixing



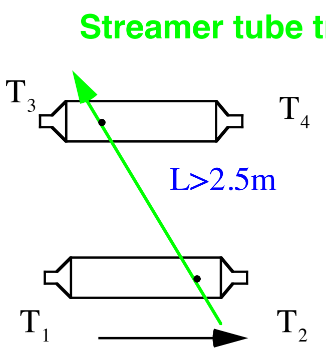
# Upgoing muons - data set

| 1st SMD | construction | 6 SMD | | ATTICO |
|---|---|---|---|---|
| Mar '89 – Nov '91 | | Dec '92 – Jun '93 | | Apr '94 – Dec '97 |
| 1.4 yr | | 0.43 yr | | 2.89 yr |
| ~2.3x10⁶ μ↓ | | 3x10⁶ μ↓ | | ~18x10⁶ μ↓ |
| 26 μ↑ | | 51 μ↑ | | 398 μ↑ |

# DATA ANALYSIS

- **Four independent analyses**

- **β evaluation:**

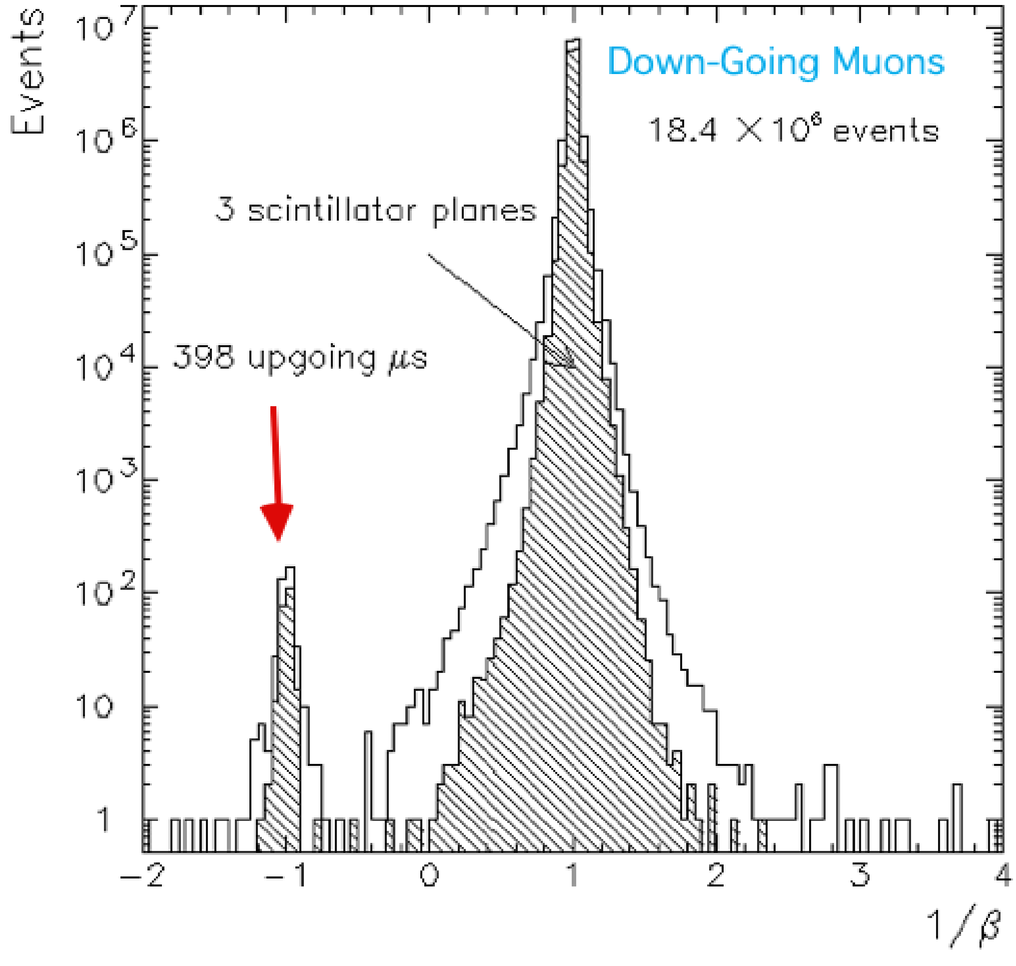



$$\frac{1}{\beta} = \frac{(T_1 + T_2 - T_3 - T_4)c}{2L} = \begin{cases} +1 & \mu\downarrow \\ -1 & \mu\uparrow \end{cases}$$

**Z (Main cut : agreement z-streamer and z-TOF)**

- **when 3 counters are intercepted (~50% of tracks) : β from linear fit of times vs position ⇨ $\chi^2$ cut**
- **for 2 counters events additional background cuts ( mainly to cut multiple and showering muons)**

# Upward-going (through-going) muons - 1/β distribution



# Upward-going (through-going) muons - Results

**Total number of events: 479**

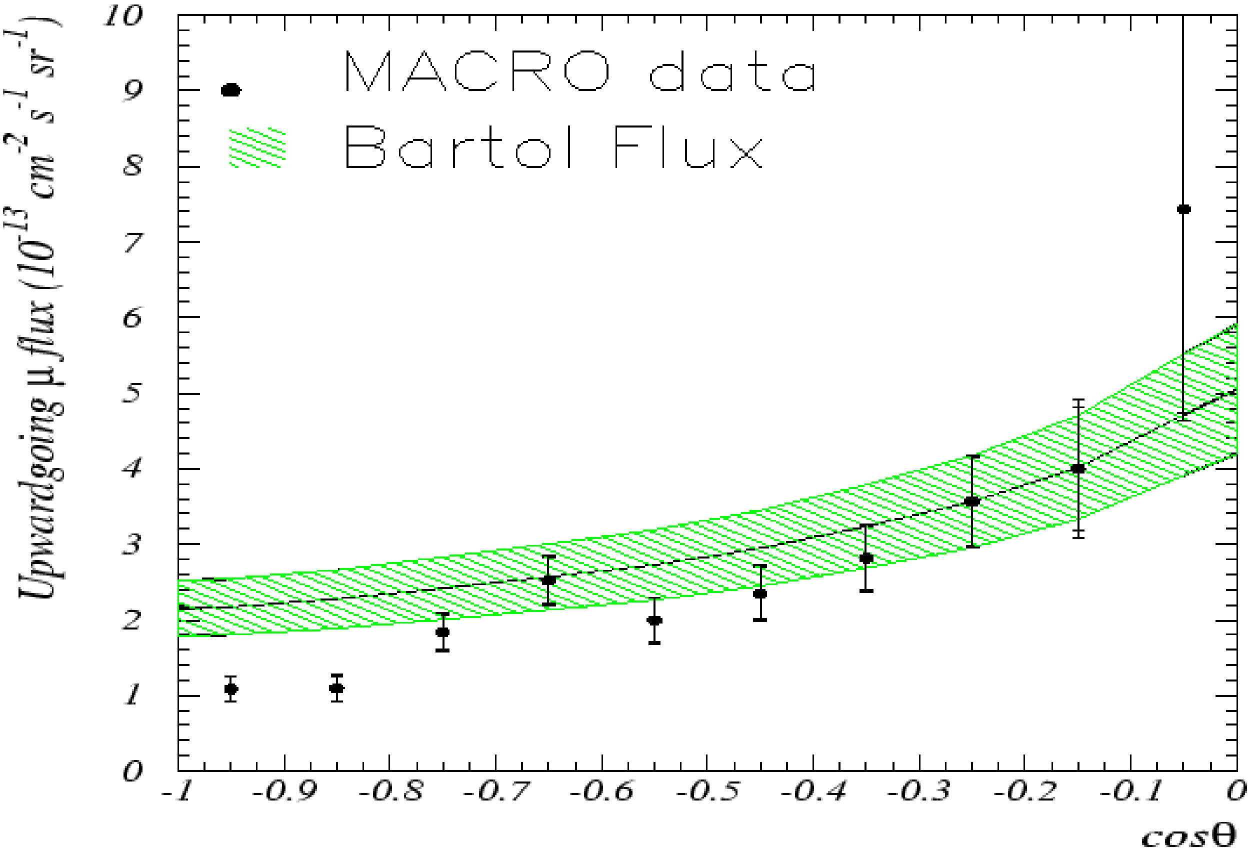
| | |
|---|---|
| **background (wrong β)** | **9** |
| **background (pion from muon)** | **8** |
| **Internal neutrino interactions** | **11** |
| | |
| **Total** | **451** |
| | |
| **Prediction** | **612±17%** |

**Bartol neutrino Flux ±14%**
**Morfin Tung cross section 9%**
**(better agreement experimental data 100 GeV )**
**Lohmann muon energy loss 5%**

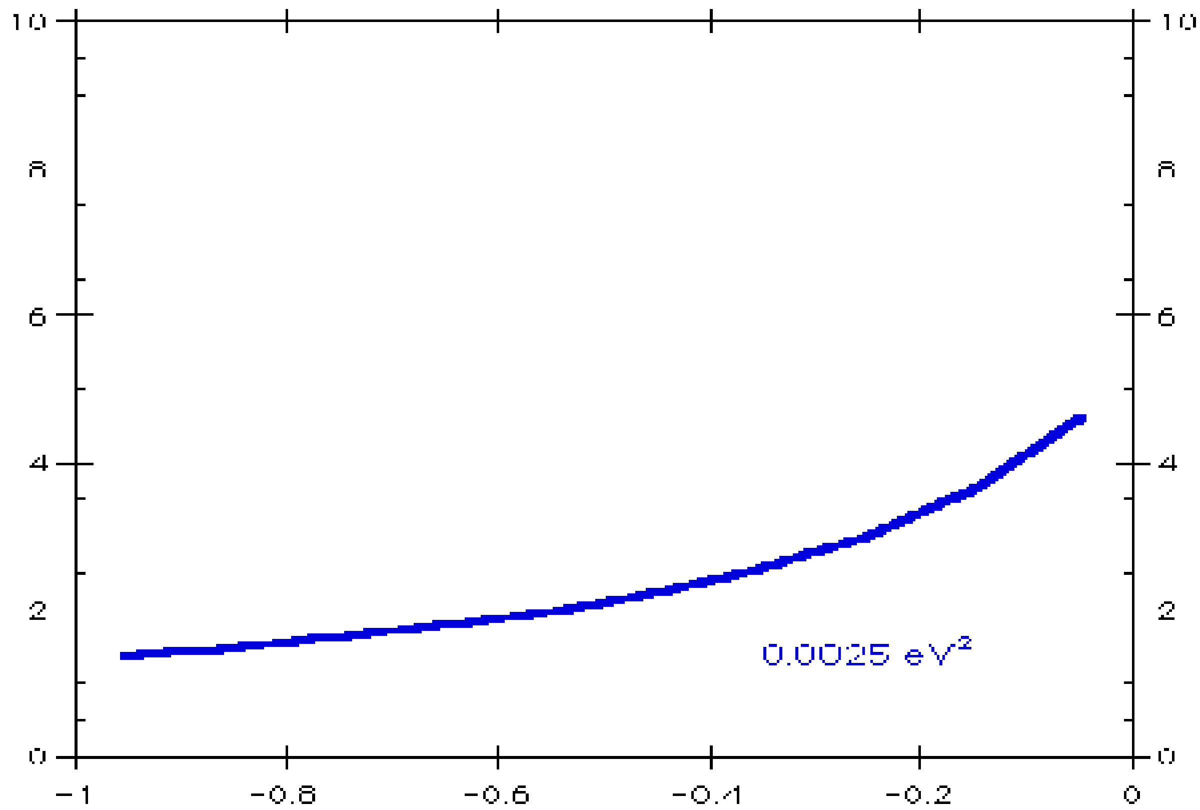
**R=data/prediction= 0.74**

**±0.0035(stat)±0.04(systemat.)±0.13(theoretical)**

Eμ>1 GeV



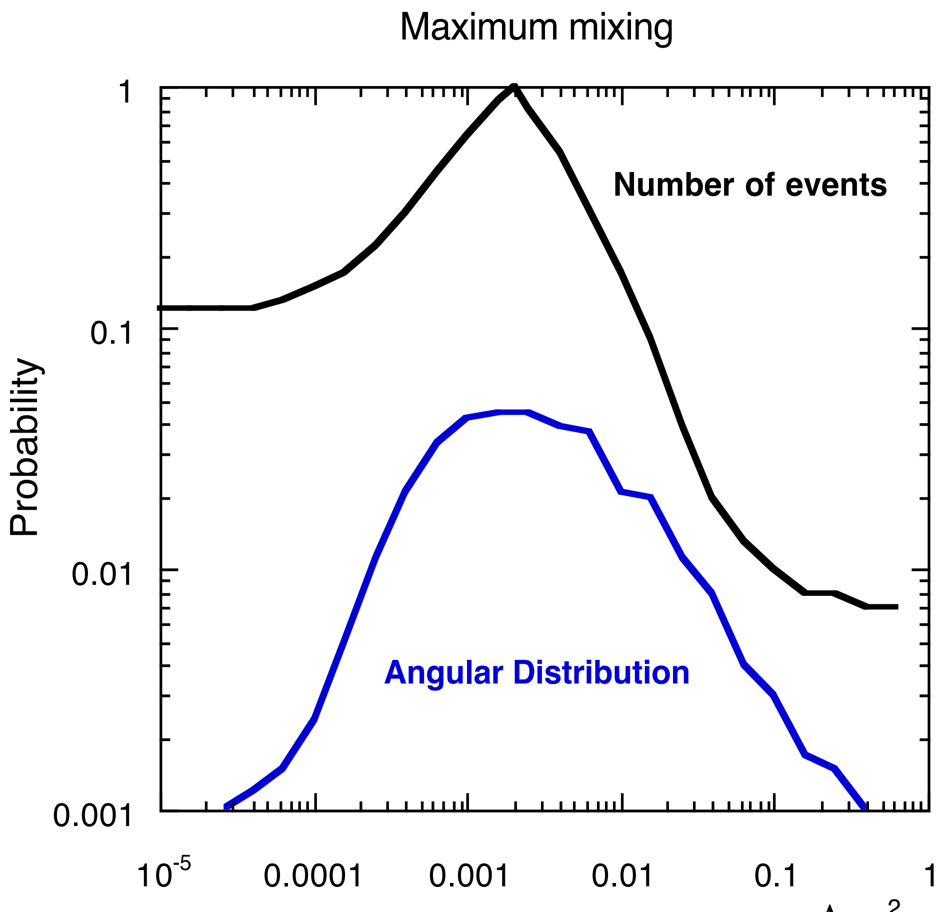
MACRO data
Bartol Flux
Upwardgoing μ flux (10^-13 cm^-2 s^-1 sr^-1)
cosθ
10
9
8
7
6
5
4
3
2
1
0
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0




$\chi^2$ test on the angular distribution on the first 9 bins with
prediction normalized to data :

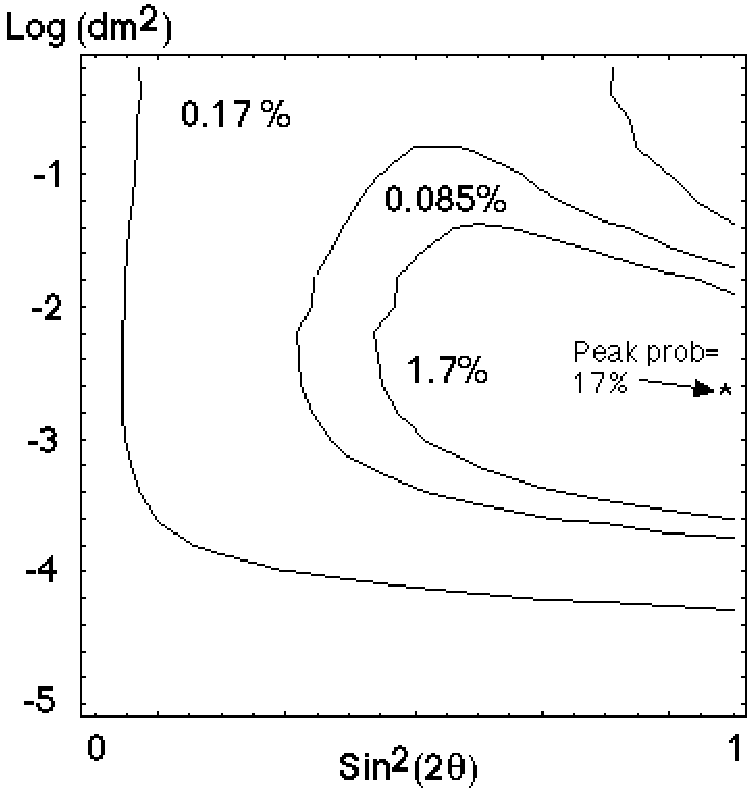
- $\chi^2$ minimum in the physical region =**15.8** for maximum mixing and $\Delta m^2$ around 0.002 $eV^2$ ($\nu_\mu$ -->> $\nu_\tau$ )
- $\chi^2$ minimum in the non physical region =12.5 (mixing>1)
- $\chi^2$ =**26.1** for no -oscillations

# Probability from angular distribution and total number of events $\nu_\mu \to \nu_\tau$




• The Peak probabilities (for maximum mixing) are in the same regions

# Combined Probability angular distribution and total number of events ($\nu_\mu$ --> $\nu_\tau$)




**Equal-probability plot**

- Peak probability $\nu_\mu$ --> $\nu_\tau$ **17%**
- Probability for No oscillations **0.1%**
- Similar Plot for $\nu_\mu$ --> sterile neutrino (Liu-Smirnof 1997) best probability **2%**

# Confidence regions for oscillation parameters

- Problem of the physical boundaries

**$\sin^2(2\theta)$ bounded by zero and 1**

- No "standard" approach up to now

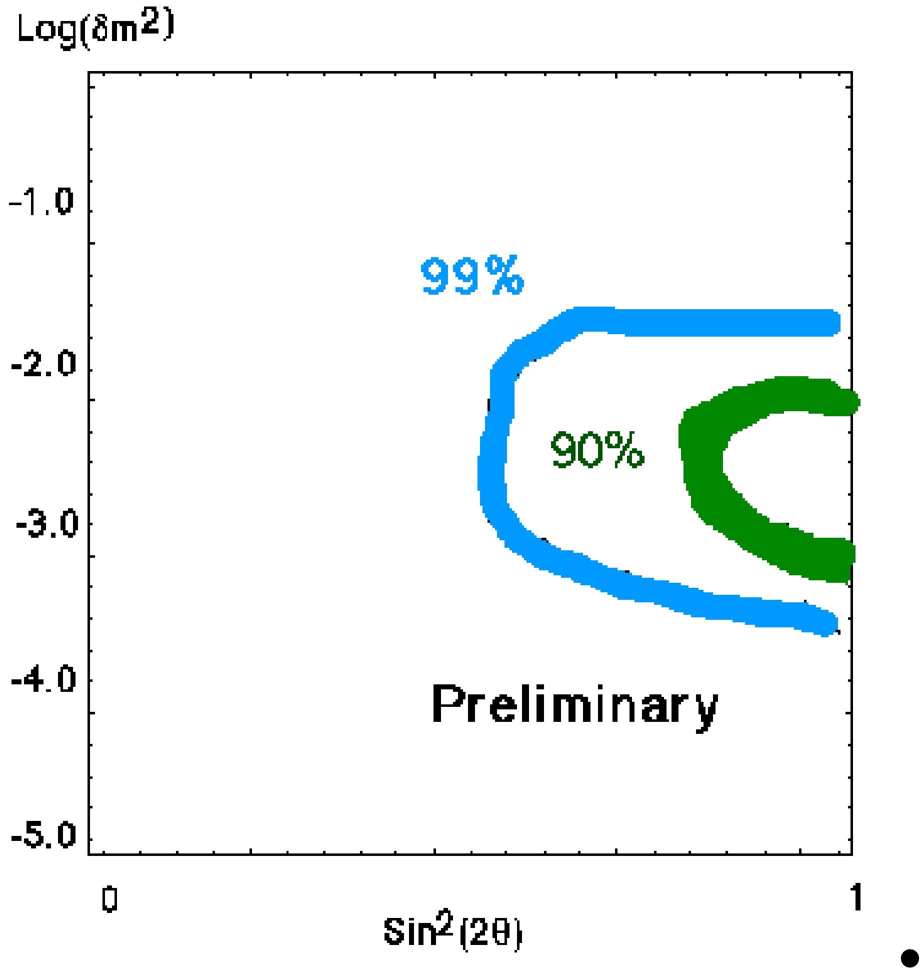
- **Feldman- Cousins** Phys Rev D 57 (April 1998):

Rules for setting confidence intervals based on Montecarlo simulations.

**Example in the paper : neutrino oscillations**

- The confidence regions with this method are different from past methods (and generally smaller).

# Confidence regions for oscillation parameters (Feldman-Cousins)

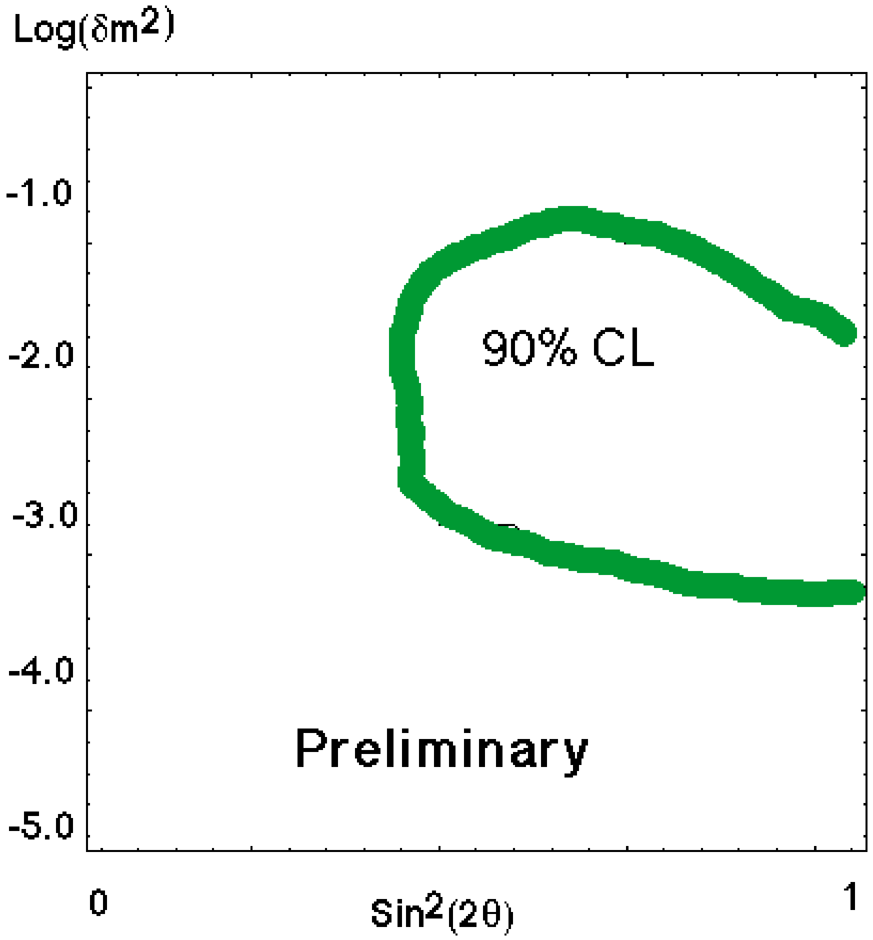



• Note : In this kind of plots there is **no information** on the goodness of the agreement of data with the hypothesis You assume that the model is correct (Pbest=17%).

- The regions are smaller than the one expected from the "sensitivity" (statistical fluctuation?)

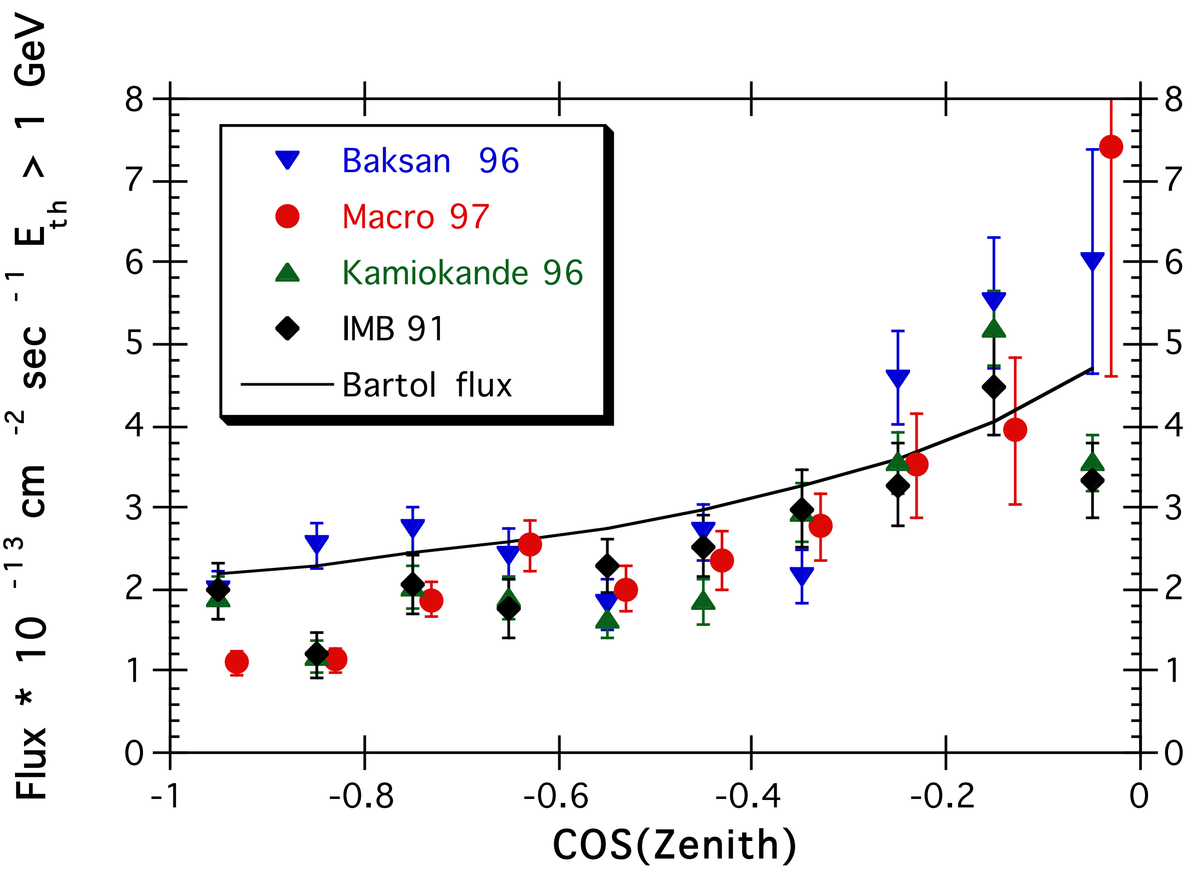
# Confidence regions
# Sensitivity

90% Contour for an experiment like MACRO Assuming oscillations in the best point and assuming to detect the number of events predicted (a sort of "Sensitivity")



# Upmu in Other Experiments

| Experiment | Depth m water | Muon Rate resp MACRO | UPMU # | Eth. (GeV) |
|---|---|---|---|---|
| Baksan | 850 | 96 | 558 | 1 |
| IMB | 1570 | 23 | 430 | 1.8 |
| Kamiokande | 2700 | 4 | 364 | 3 |
| Macro | 3700 | 1 | 451 | 1 |



# Upmu in Other Experiments

- To compare data flux are scaled to a common threshold (1 GeV) using the **theoretical prediction for neutrino flux and assuming no neutrino oscillations.**

- This correction could be quite large (for Superkamiokande factor 1.7)

- Some difference in the data near the vertical. The reason could be due to the background (up to almost 2 order of magnitude of difference due to the different rock depths)

# Upmu in Other Experiments
# Angular Distribution

• Lipari -Lusignoli (Ph Rev D 57) :
the shape of the angular distribution is quite stable for different neutrino fluxes and interaction cross sections

$$S = \frac{\int_{-1/2}^{0} f(\cos(\theta))d\cos(\theta)}{\int_{-1}^{-1/2} f(\cos(\theta))d\cos(\theta)}$$

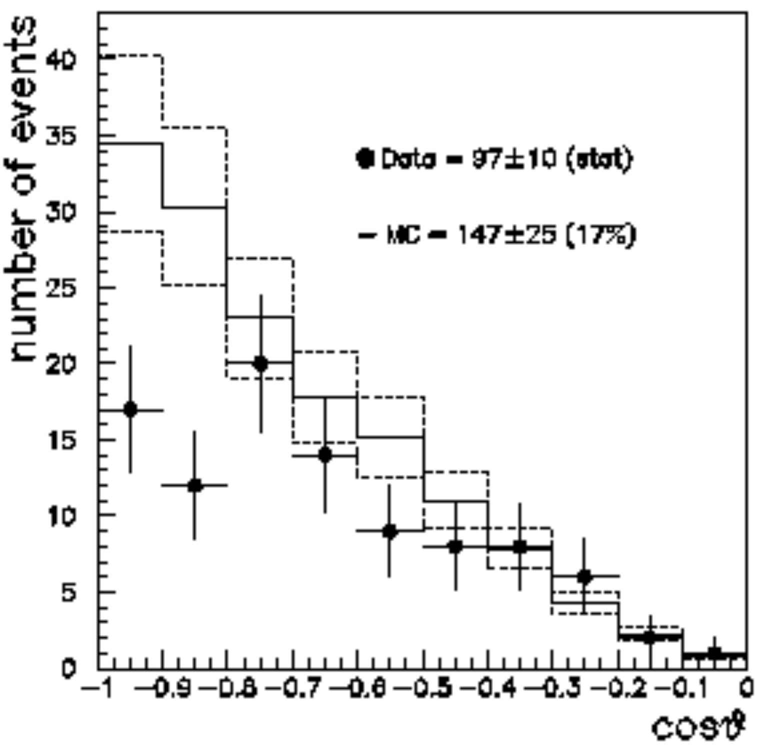
• **S in the data is bigger the one predicted**

| | Data | Prediction |
|---|---|---|
| **Baksan** | **1.82±0.18** | **1.50** |
| **IMB** | **1.79±0.18** | **1.53** |
| **Kamiokande** | **1.91±0.21** | **1.56** |
| **MACRO 97** | **2.01±0.46** | **1.50** |

# Upward-going (through-going) muons - checks on the systematics

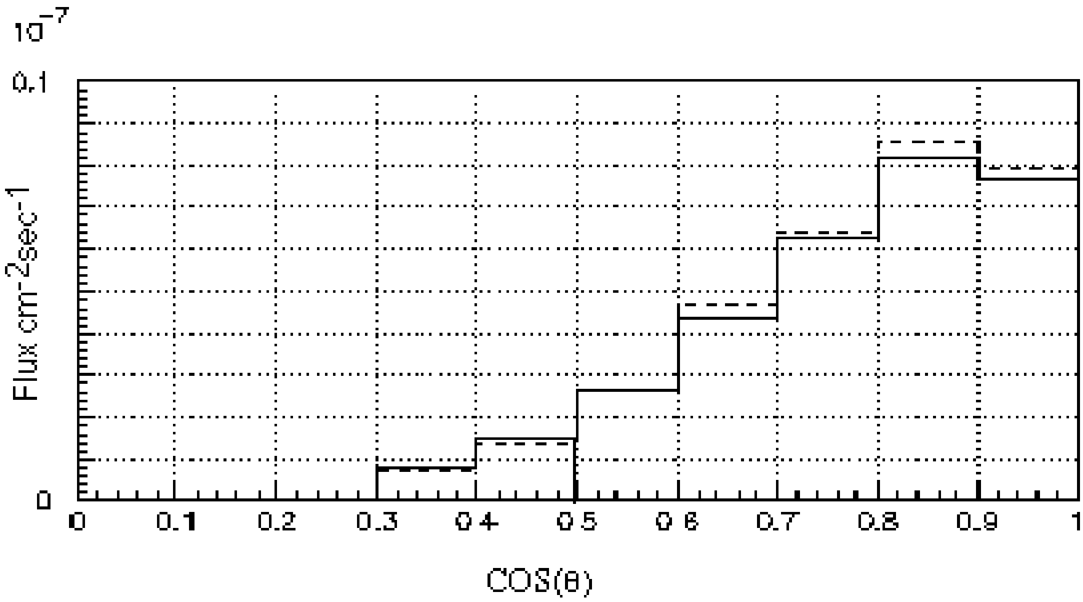
• Several independent analyses

• Check with a separate electronics/acquisition system (the one for neutrino stellar collapse) for the event with 3 counters. No track required. ==>> **Almost another experiment!!**



# Upward-going (through-going) muons - checks on the systematics

• Measurement of the down-going muon rate with the same cuts for the upgoing-muons and check with the predicted I(h)




Continous line : flux measured previously and predicted from I(h)

Dotted line : flux mesured with the upgoing-muon cuts (except beta)

# Upward-going muons (Internal)

• Similar cuts used in the through-going muon analysis with the addiction of :

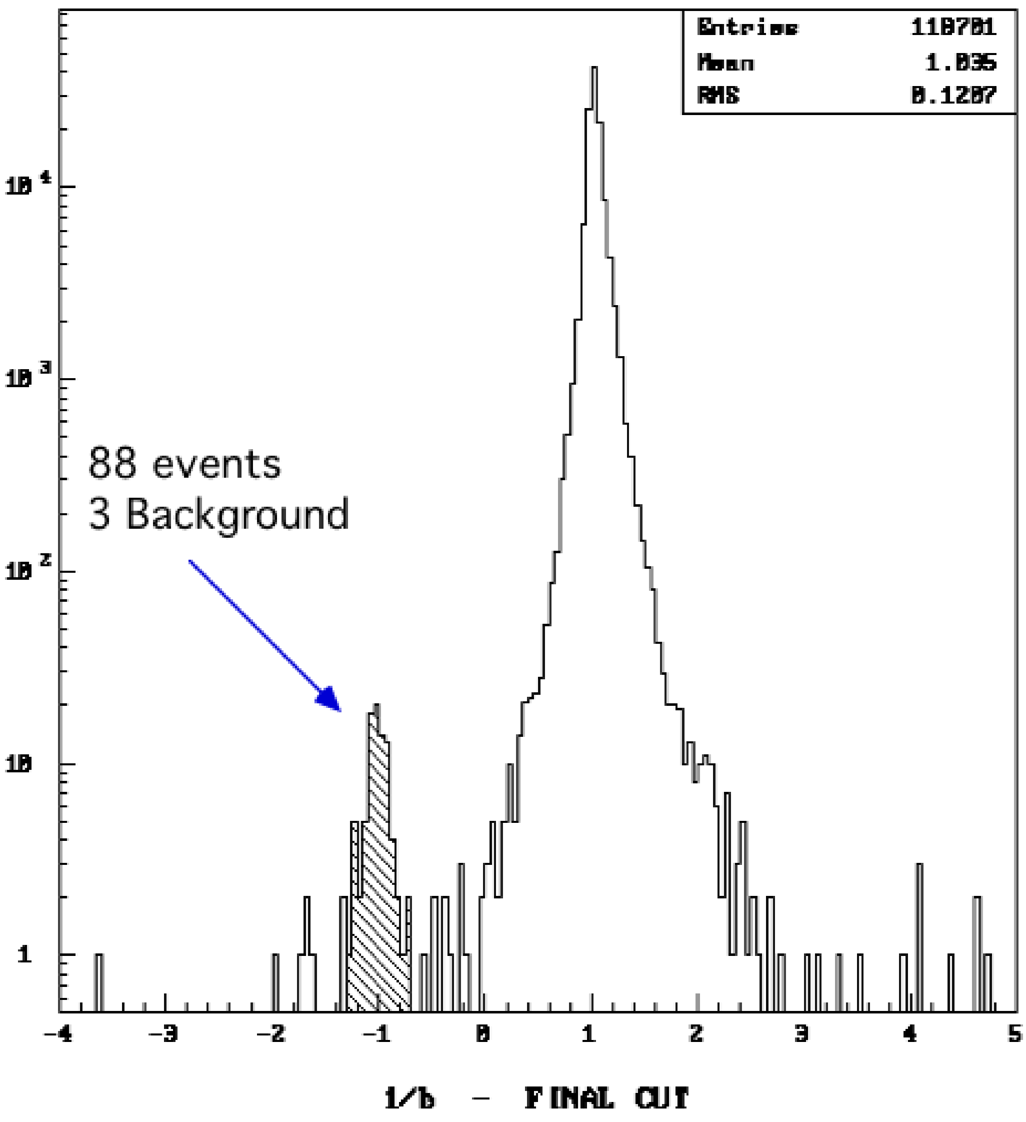
**Vertex containement cut**

in order to remove the normal upward-going through-going muons (1% after this cut)

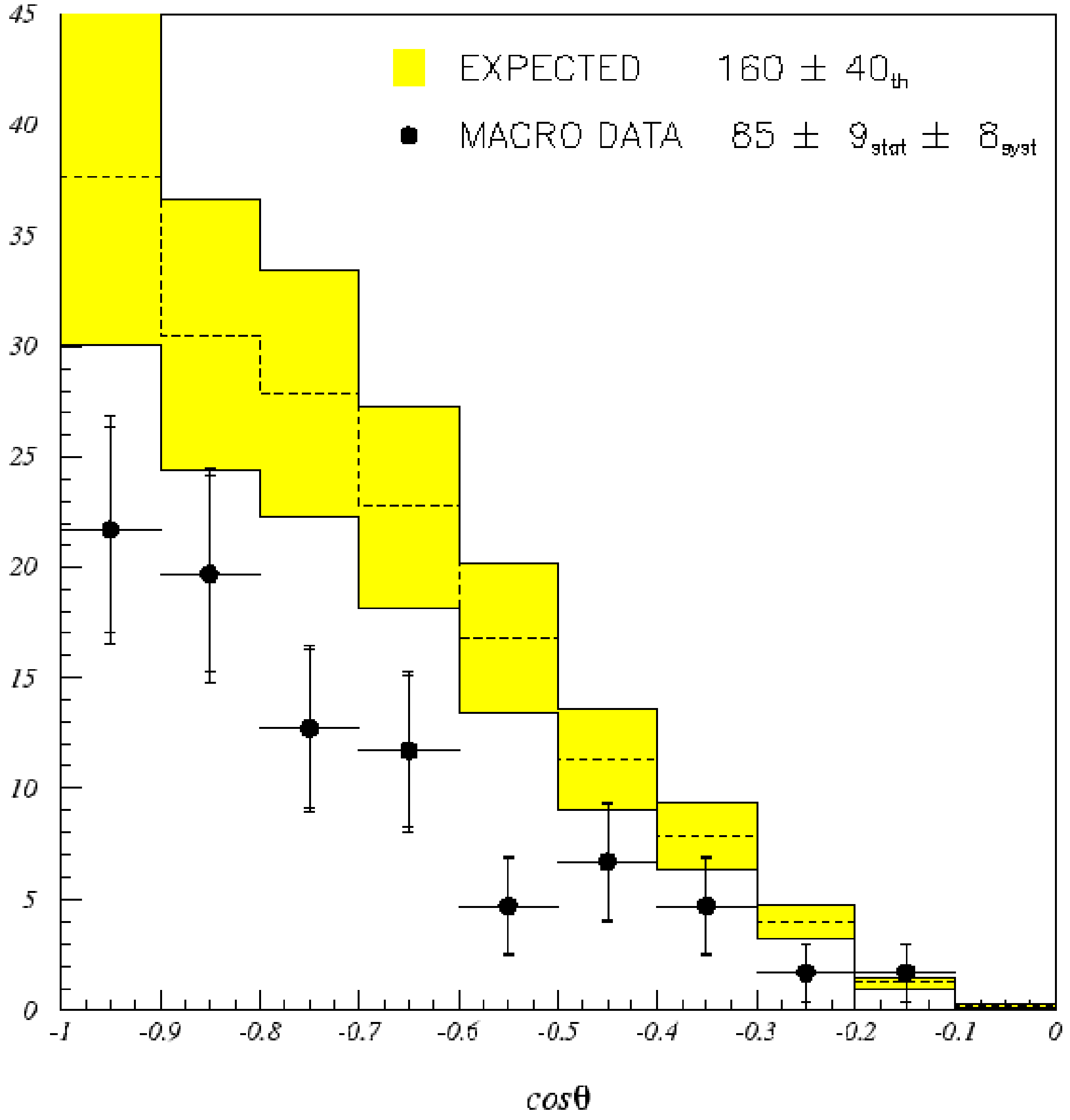
• From the montecarlo simulation the event sample is an almost pure sample of single muon events

**89% of the events are due to $\nu_\mu$**

# Upward-going muons (Internal) - 1/β distribution



# Upward-going muons (Internal) - Angular Distribution



# Upward-going muons (Internal)

• **Ratio between data and prediction**

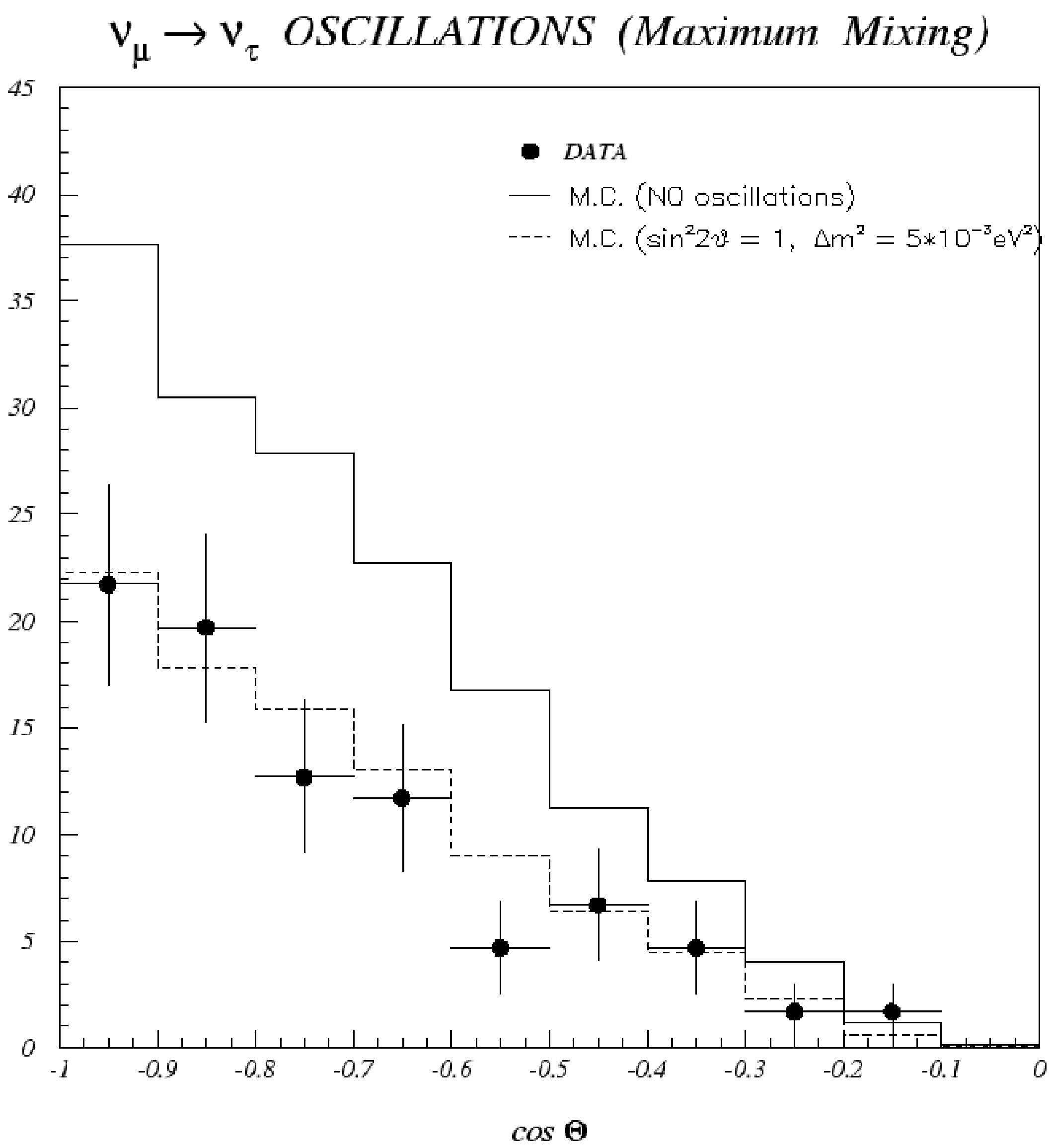
**R= 85/160 events=**
**0.53 ± 0.06 (stat) ± 0.05(syst) ± 0.13 (theoretical)**

(Bartol neutrino flux 20 % uncertainty-
Lipari et al low energy cross sections 13% uncertainty)

• The shape of the angular distribution is in agreement with prediction (no "deficit" on the vertical)

• all this is in agreement with a model of oscillation with maximum mixing and $\delta m^2$ bigger than a few units in $10^{-4}$ $eV^2$

# Upward-going muons (Internal) - Angular Distribution



# Down-going muons (Internal) - and stopping muons

- The internal Down-Going and the stopping muons topologies inside MACRO are similar: one scintillator in the bottom layer and >=3 streamer tube layers giving a **track**.

- Fiducial volume cut in order to avoid edge effects

- Final selection based on scanning on a randomly mixed sample of data events and simulated events

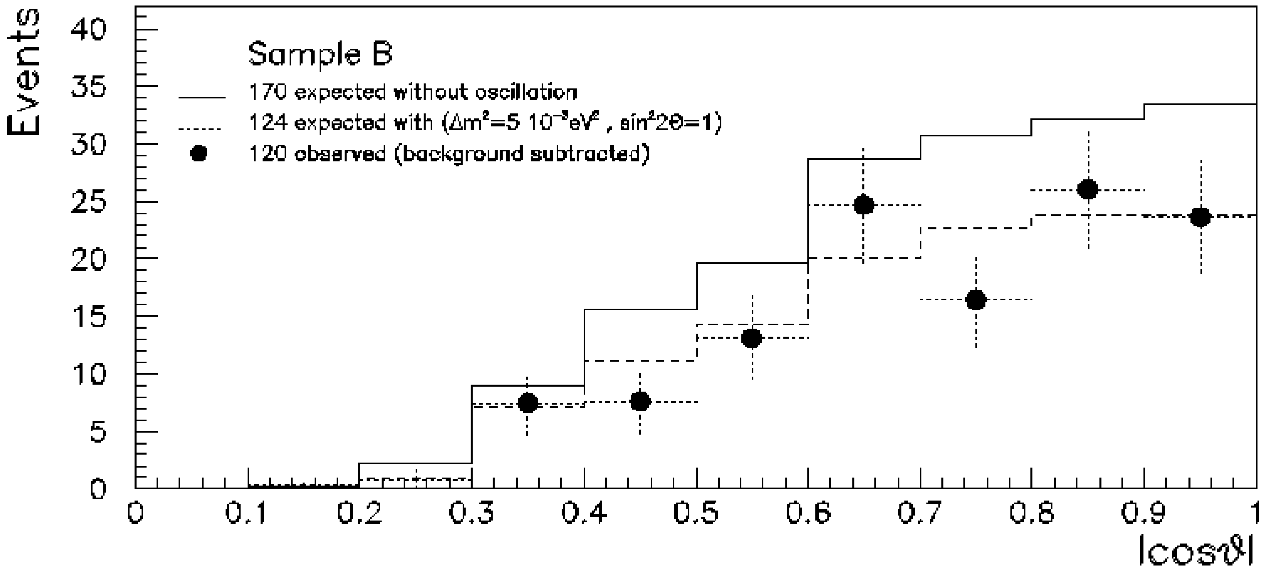
- Two samples (the difference is in the minimum amount of material)

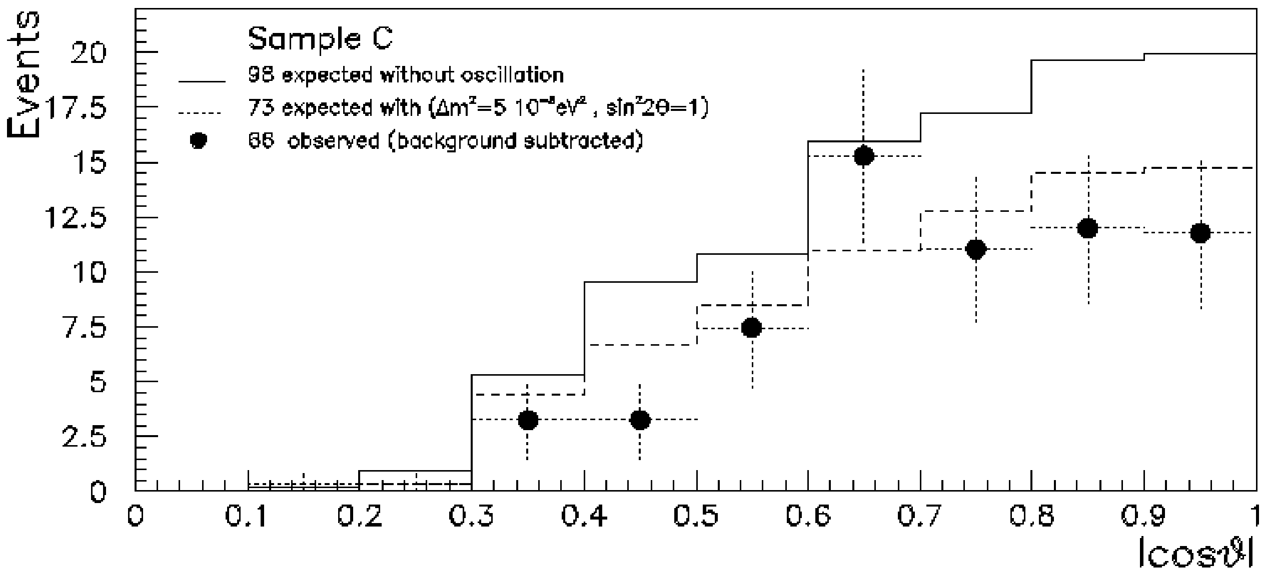
| Sample | R min gr/cm2 | $\nu_\mu$ | data | Background (pion ) | data-background | Expected |
|---|---|---|---|---|---|---|
| B | 100 | 90% | 125 | 5 | 120 | 170 |
| C | 160 | 94% | 66 | 1 | 65 | 98 |

R (sample B) =

**0.71** $\pm$ 0.07 (statist) $\pm$ 0.07 (sys)$\pm$ 0.18 (theor)

## Down-going muons (Internal) - and stopping muons- Angular distribution




- Shape of the angular distributions in agreement with expectations

# Conclusions

MACRO **Upgoing Muons** (Through-going) :
$E\nu \approx 100$ GeV

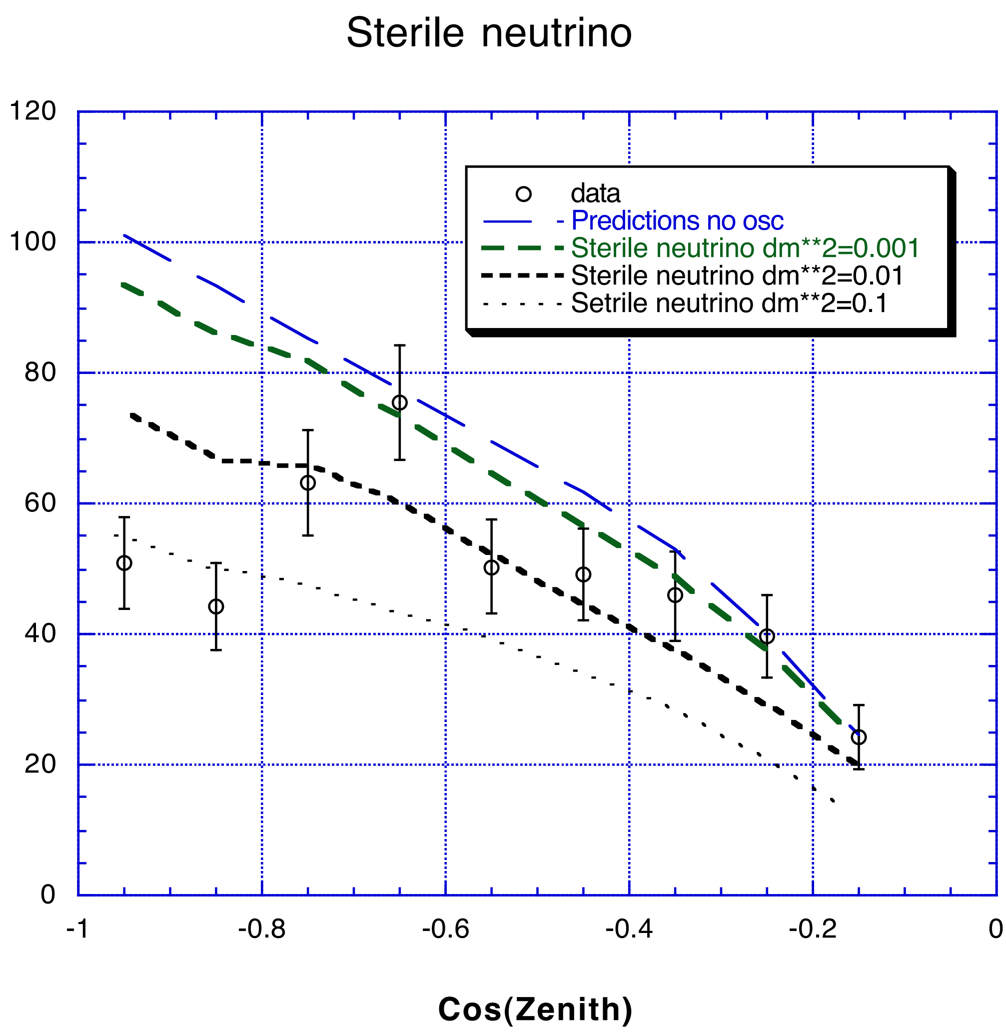
- Peak probability $\nu_\mu \rightarrow \nu_\tau$ **17%**
- Probability for No oscillations **0.1%**
- Peak Probability $\nu_\mu \rightarrow \nu$ sterile **2%**

**Low energy events**:
$E\nu \approx 5$ GeV

| | R=data/predict No Oscil | No oscillations | With oscillations $10^{-3}<\delta m^2<10^{-2}$ |
|---|---|---|---|
| Internal Up | 0.53±0.15 | 1 | 0.56 |
| Internal Down + Stopping Up | 0.71±0.21 | 1 | 0.73 |

**Conclusion: a $\nu_\mu \rightarrow \nu_\tau$ oscillation with maximum mixing and $\delta m^2 \approx$ a few units in $10^{-3}$ $eV^2$ is consistent with all the MACRO Data**

**Only Warning :**
**The peak probability for the angular distributions of the Upgoing Muons (Through-going) is low (4.6%) ==>>**
**Statistical Fluctuation or Hidden Physics?**



Sterile neutrino
120
100
80
60
40
20
0
-1
-0.8
-0.6
-0.4
-0.2
0
Cos(Zenith)
data
Predictions no osc
Sterile neutrino dm**2=0.001
Sterile neutrino dm**2=0.01
Setrile neutrino dm**2=0.1