Atmospheric Neutrinos

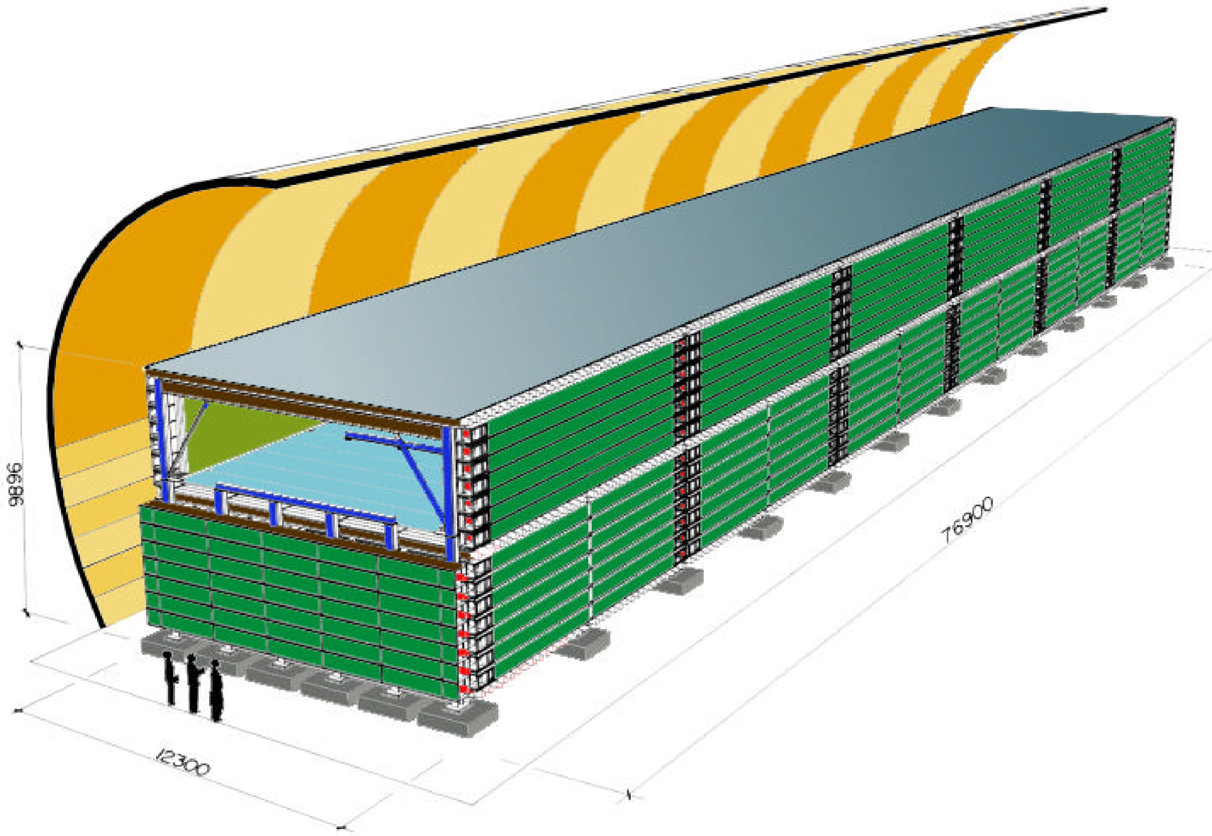
MACRO

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

Barry Barish

XIX International Conference on Neutrino Physics & Astrophysics
Sudbury, Canada June 16 - 21, 2000

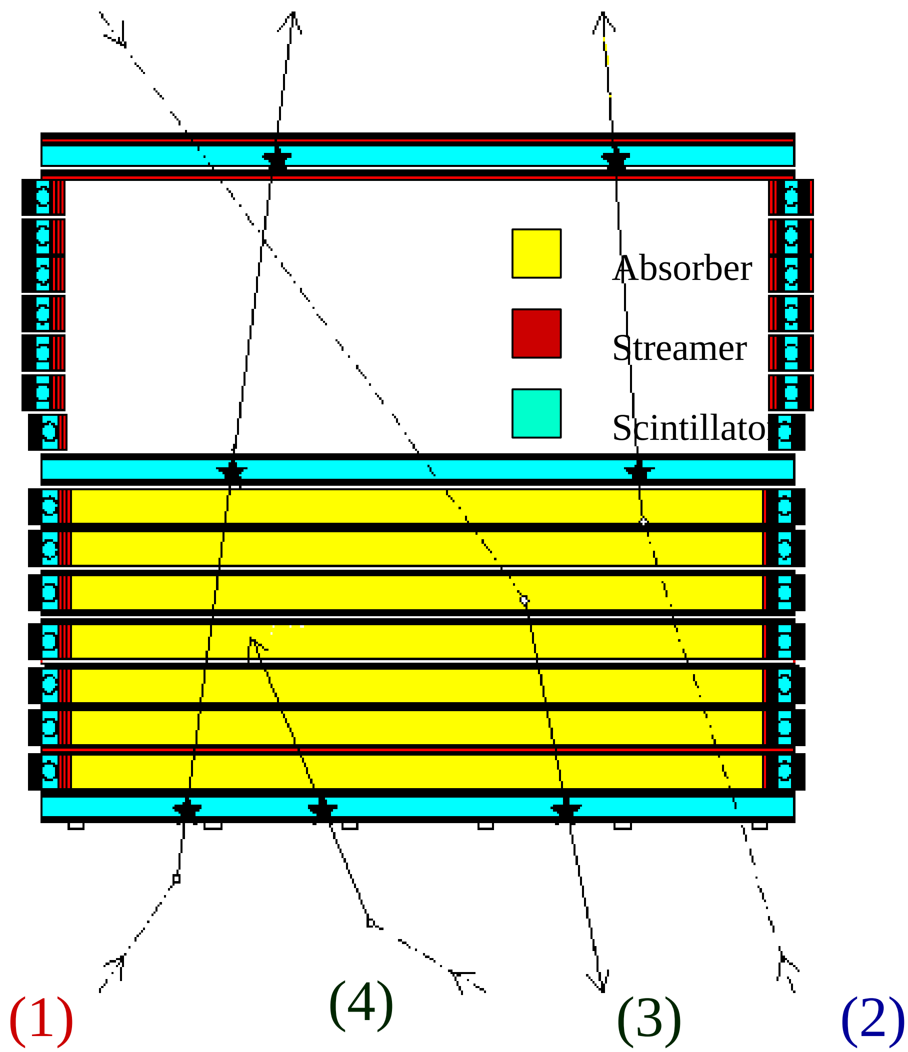
Main features of Macro as ν detector



- 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



Detector mass ~ 5.3 kton

Event Rate:

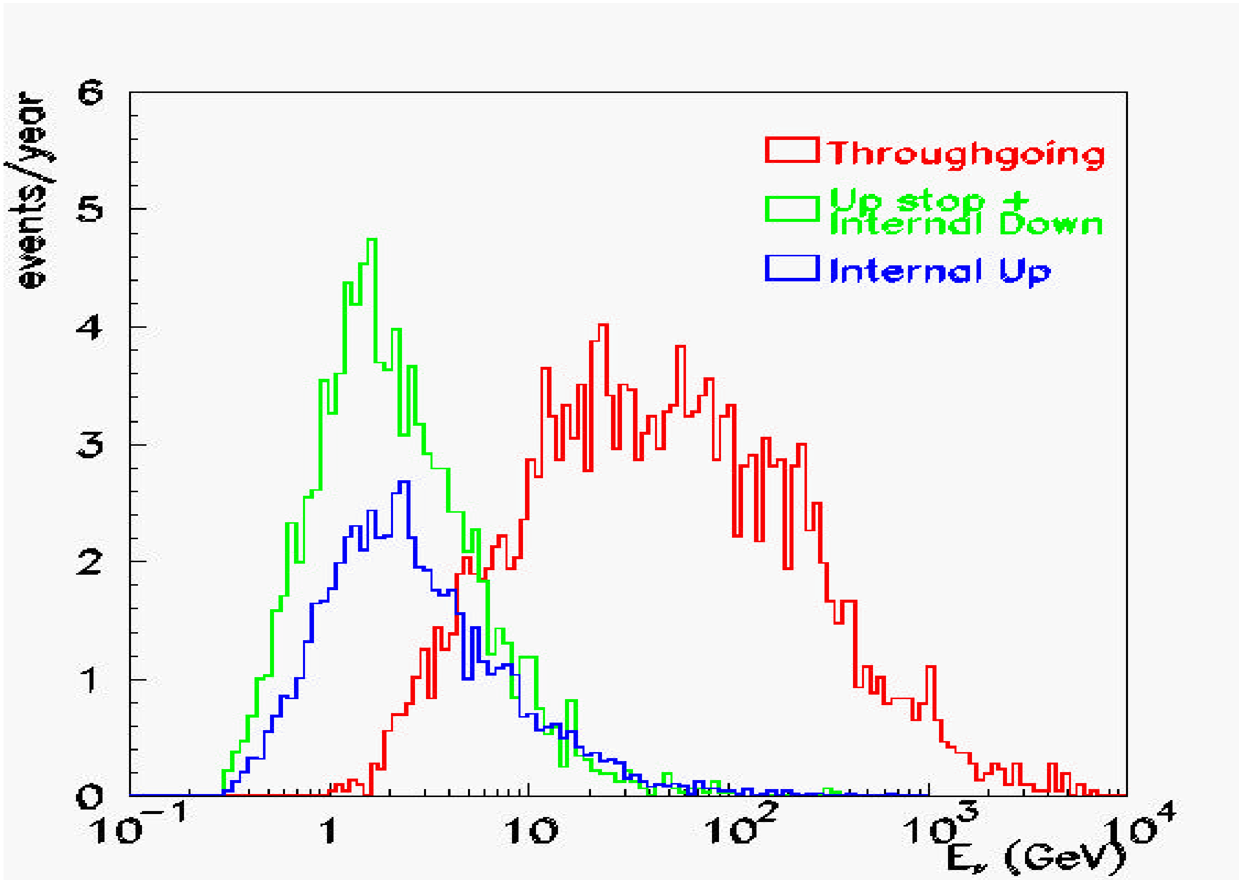
(1) up throughgoing μ (ToF) ~160 /y

(2) internal upgoing μ (ToF) ~ 50/y

(3) internal downgoing μ (no ToF) ~ 35/y

(4) upgoing stopping μ (no ToF) ~ 35/y

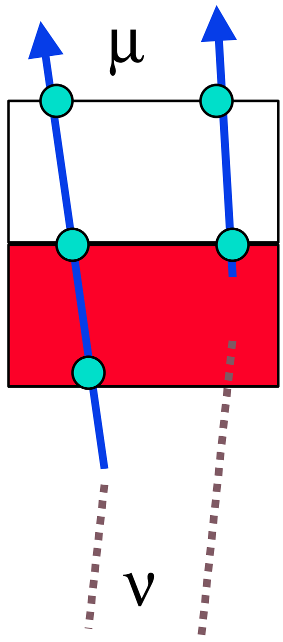
Energy spectra of ν events detected in MACRO



- **<E> ~ 100 GeV for throughgoing μ**
- **<E> ~ 5 GeV for internal upgoing μ**
- **<E> ~ 4 GeV for internal downgoing μ**

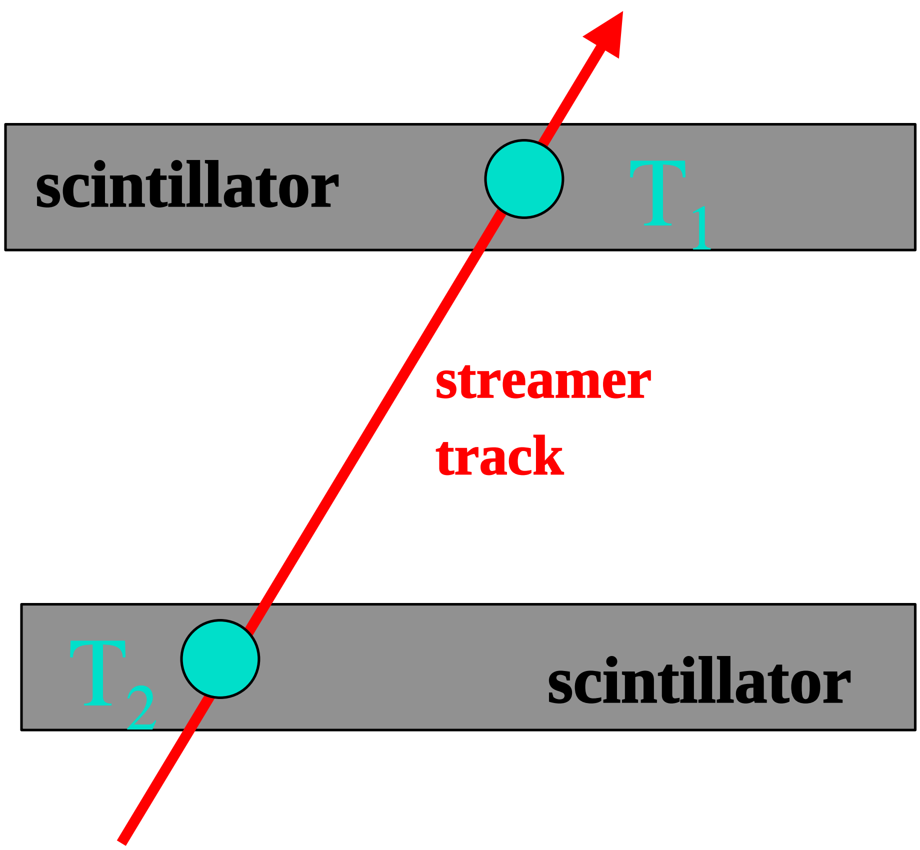
  and for upgoing stopping μ

- Low energy events allow us to investigate the ν oscillation parameter space **independently** of the throughgoing muon data

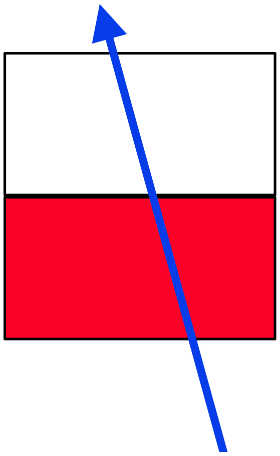


Neutrino induced upward-going muons

identified by the time-of-flight method



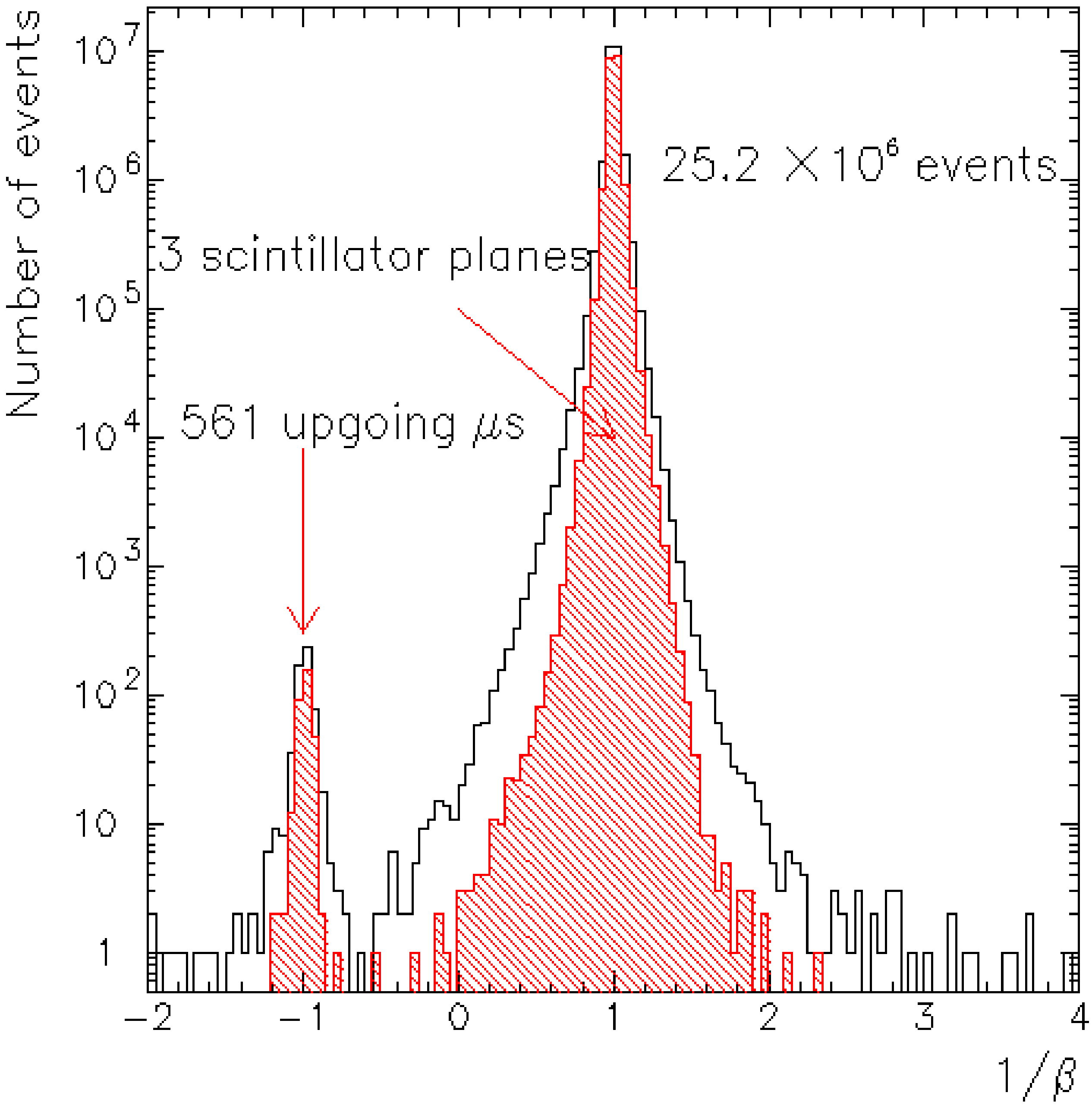
$$1/\beta = (T_2 - T_1) * c / l$$



Upward throughgoing muons

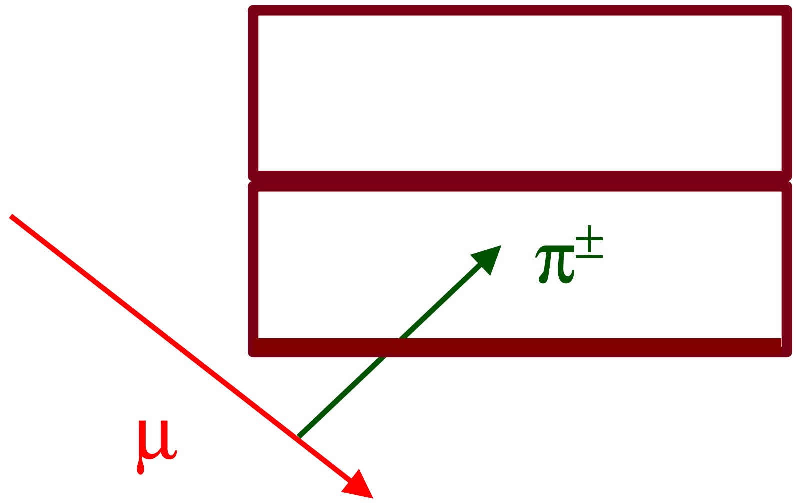
External ν-interactions 768 events

upward vs downward muons



Background source for ν_μ events: pion production by downward μ's

(MACRO Collab., Astroparticle Phys. 9('98)105)



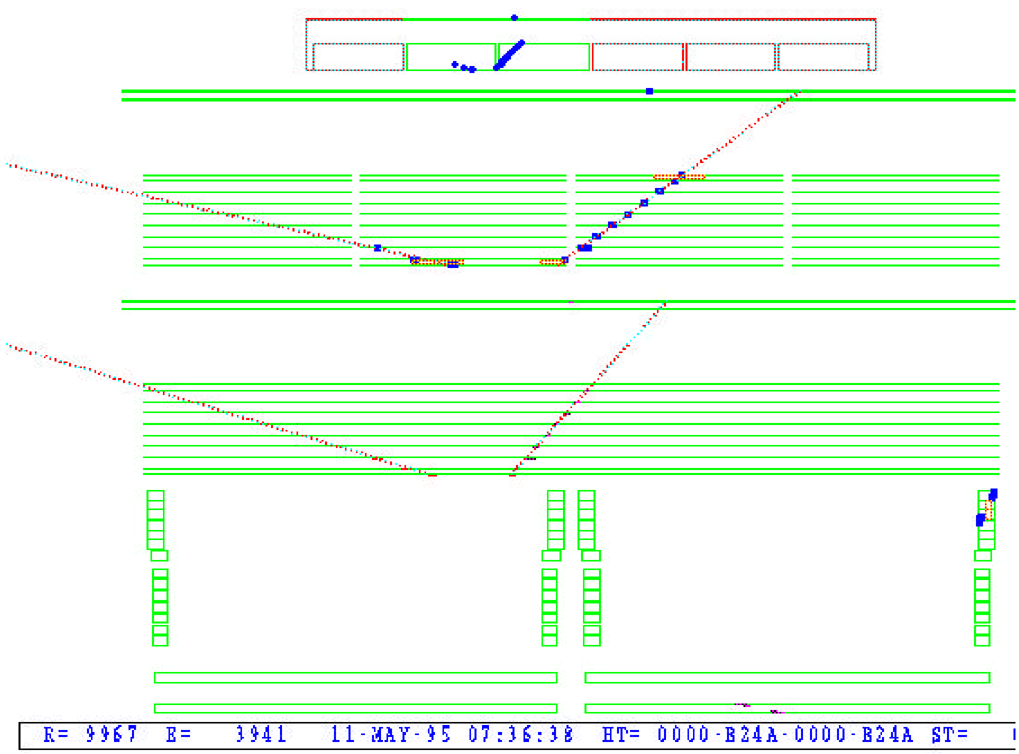
- **rate of downgoing μ's ~10^5x rate of upgoing μ's**

- background mainly **pions produced at large angles** by μ interactions in the rock around the detector ($\mu + N \longrightarrow \mu + \pi^{\pm} + X$)

- Estimated background in MACRO:
  ~ 5% for the stopping muon sample
  *(MACRO Coll., PL **B478** ('00) 5)*
  ~ 1% for the up-throughgoing m (>200 g/cm^2 cut)
  *MACRO Coll., PL **B434** ('98) 451)*

Pion production at large angle

- upgoing charged π produced by μ interactions in the rock under the detector
- a background source for upward stopping and throughgoing muons
- studied 243 events with downgoing μ plus upgoing particles



- Estimated background
  - upward throughgoing μ's: ~1%
  - low energy events: ~5%

Total observed flux and comparison with Monte Carlo

Data		
	number of events:	**768 events**
	background (wrong β)	18
	background (π's from muons)	12.5
	Internal neutrino interactions	14.6
Total		**723 events**

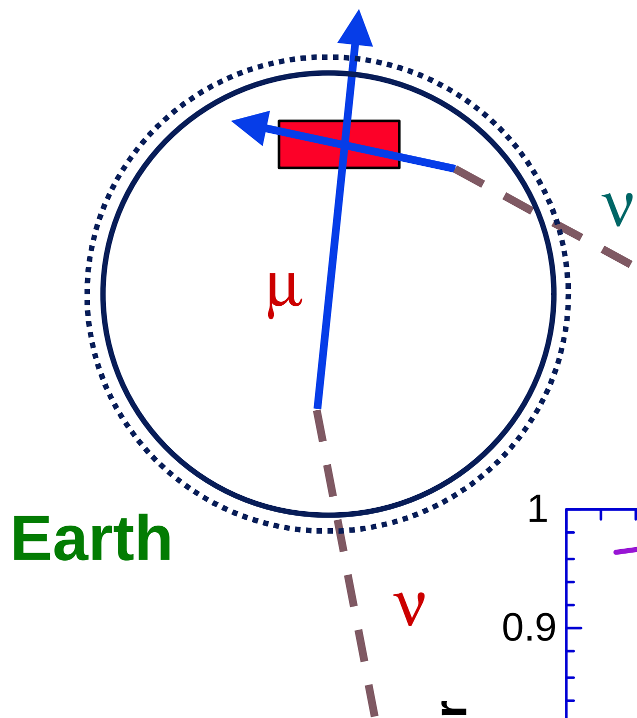
Prediction (Monte Carlo)		**989 ± 17%**
	Bartol neutrino Flux	(±14%)
	GRV-LO-94 cross section	(± 9%)
	Lohmann muon energy loss	(± 5%)

data/prediction **R = 0.731**

$\pm 0.028_{stat} \pm 0.044_{syst} \pm 0.124_{theor}$

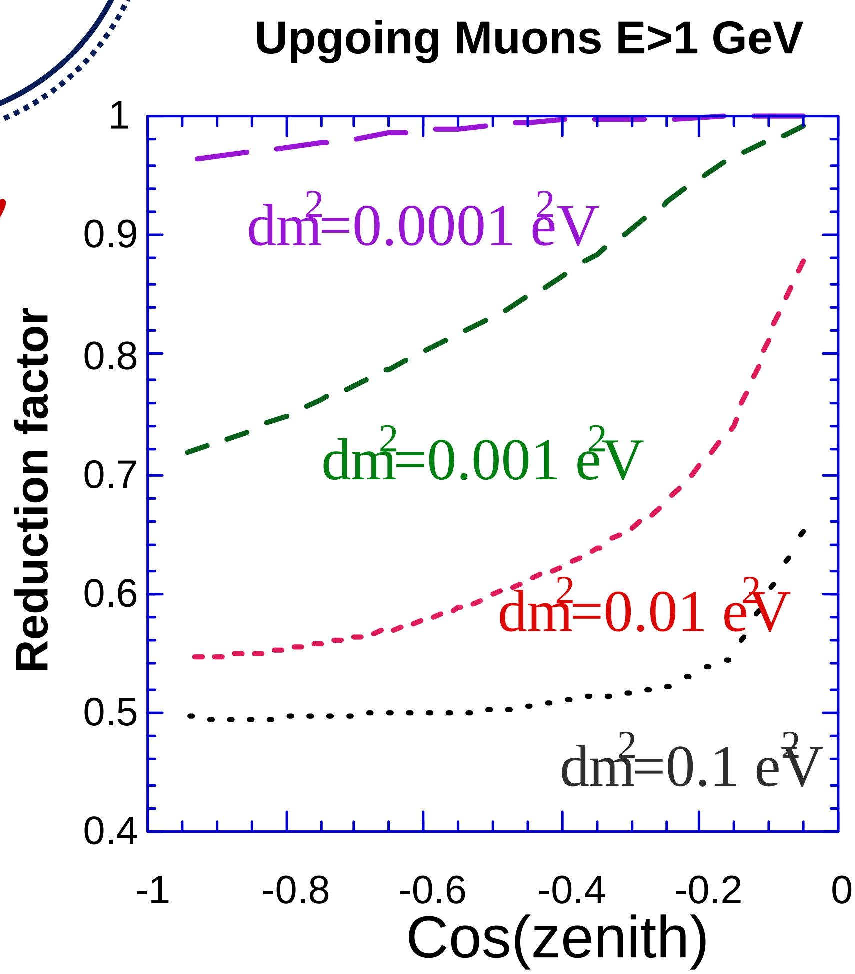
Effects of ν_μ oscillations on MACRO events

→ Flux reduction depending on zenith angle for the upward throughgoing events



underground detector

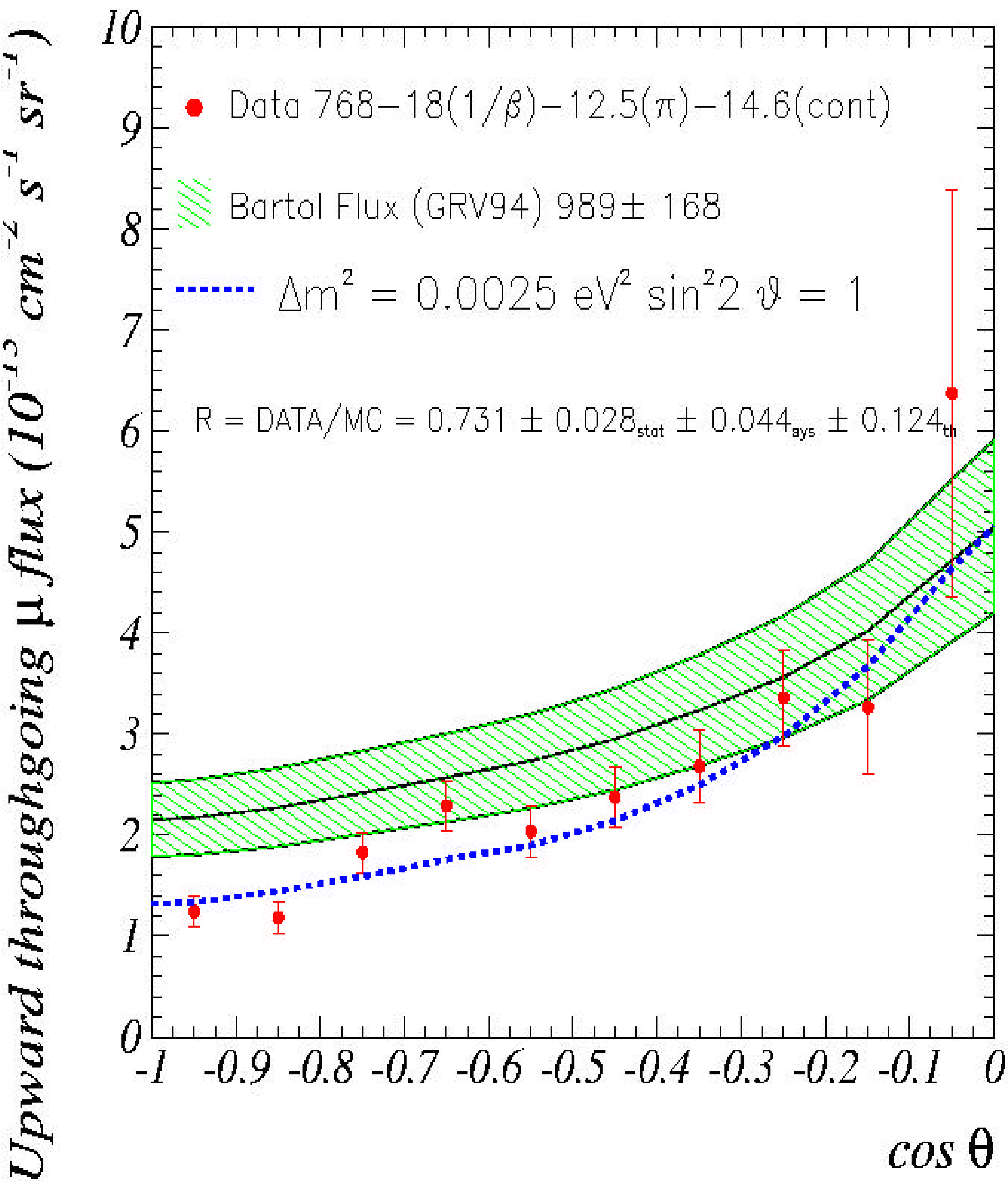
$L_\nu \sim 10 - 10^4$ km



distortion of the angular distribution

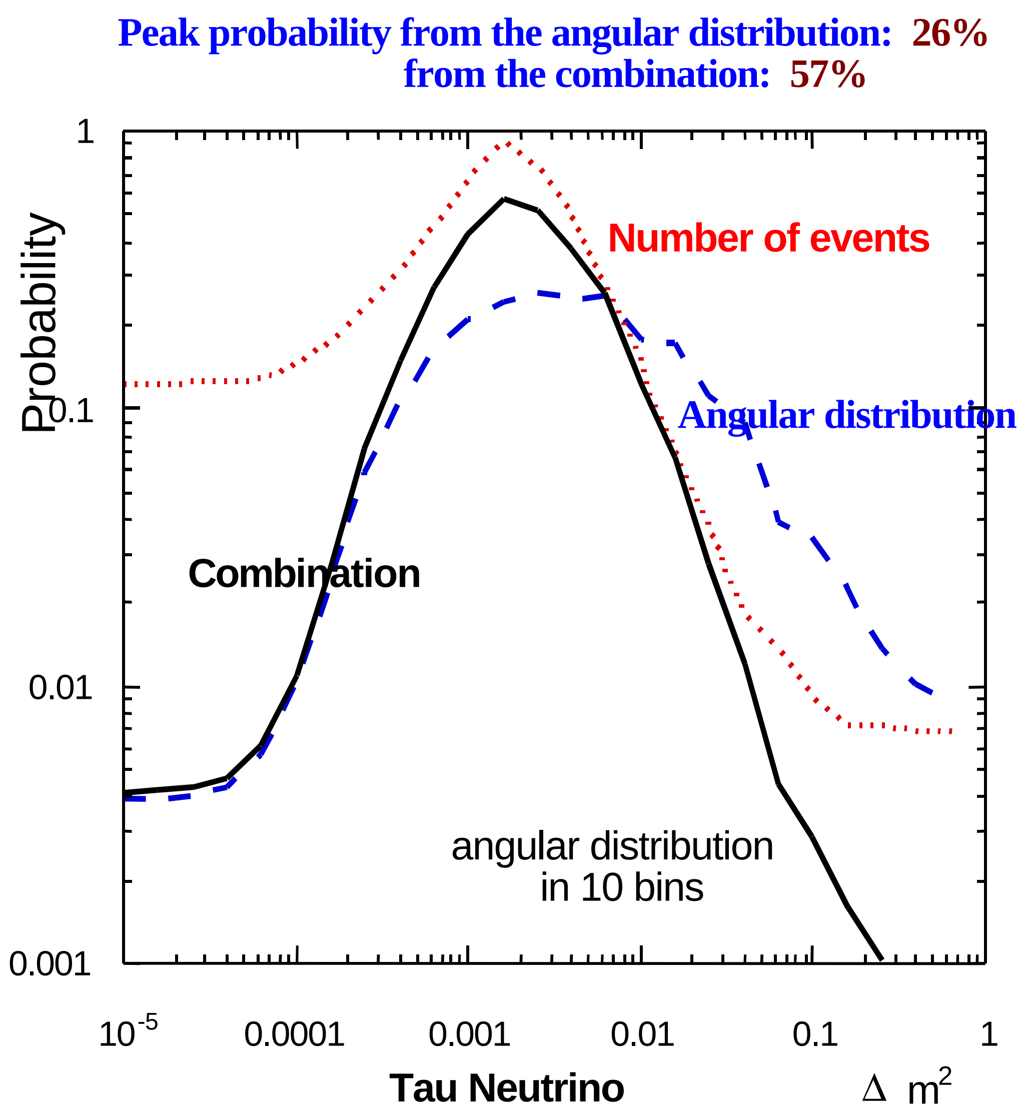
Zenith angle distribution

$E_\mu > 1$ GeV



Probabilities of $\nu_\mu \rightarrow \nu_\tau$ oscillations

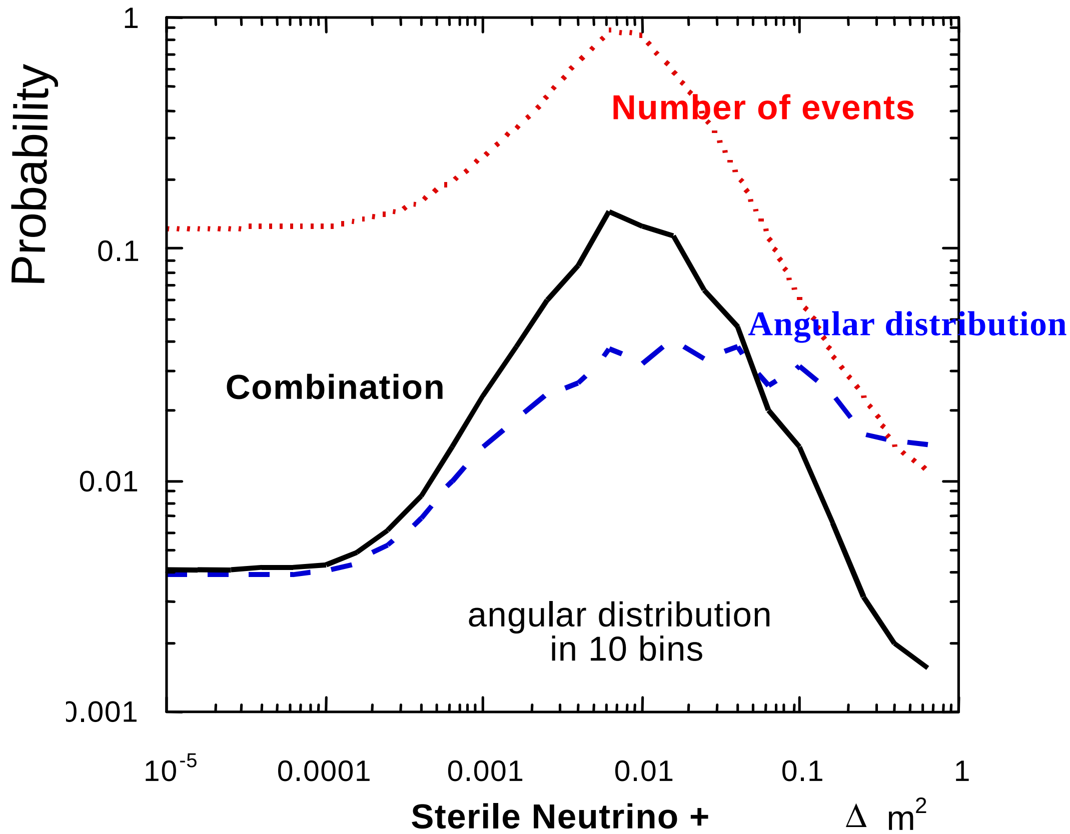
(for maximal mixing)



• The peak probability from the angular distribution agrees with the peak probability from the total number of events

• Probability for no-oscillation: ~ 0.4 %

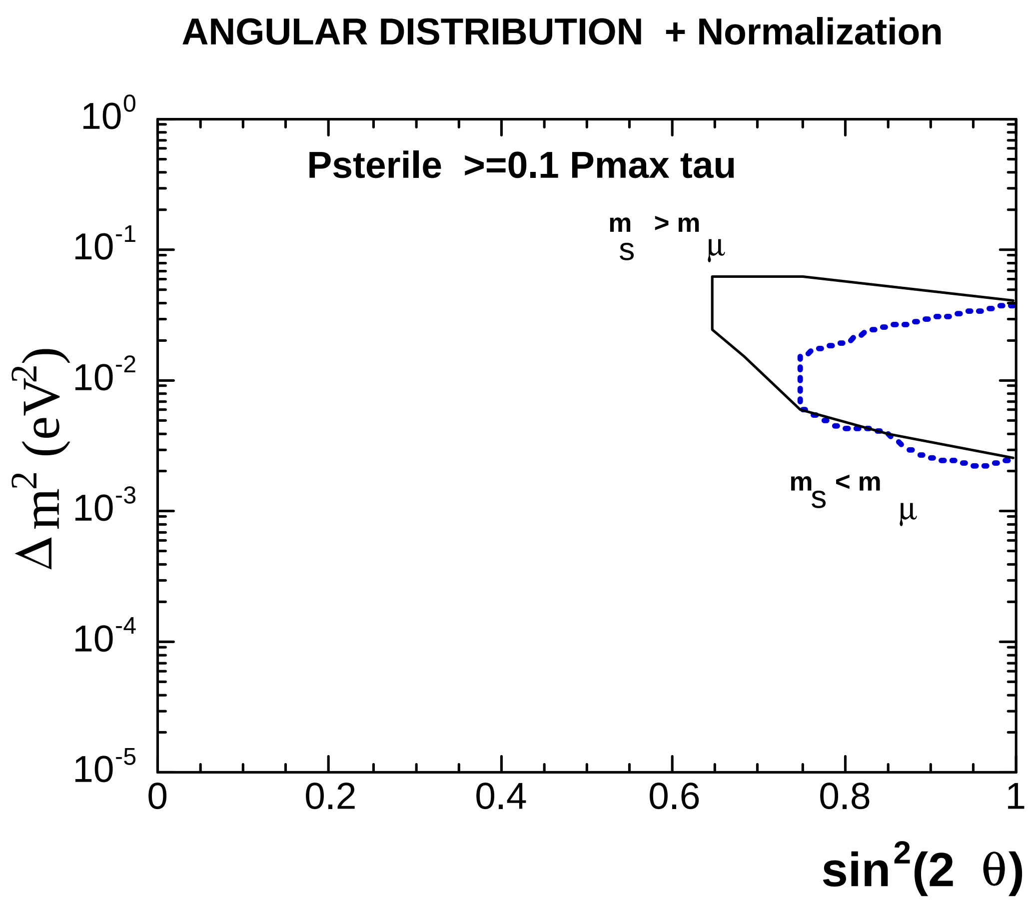
Probabilities for sterile neutrino oscillations with maximum mixing



Peak probabilities lower than that for tau neutrinos:

- from the angular distribution: **4.1 %**
- from combination: **14.5 %**

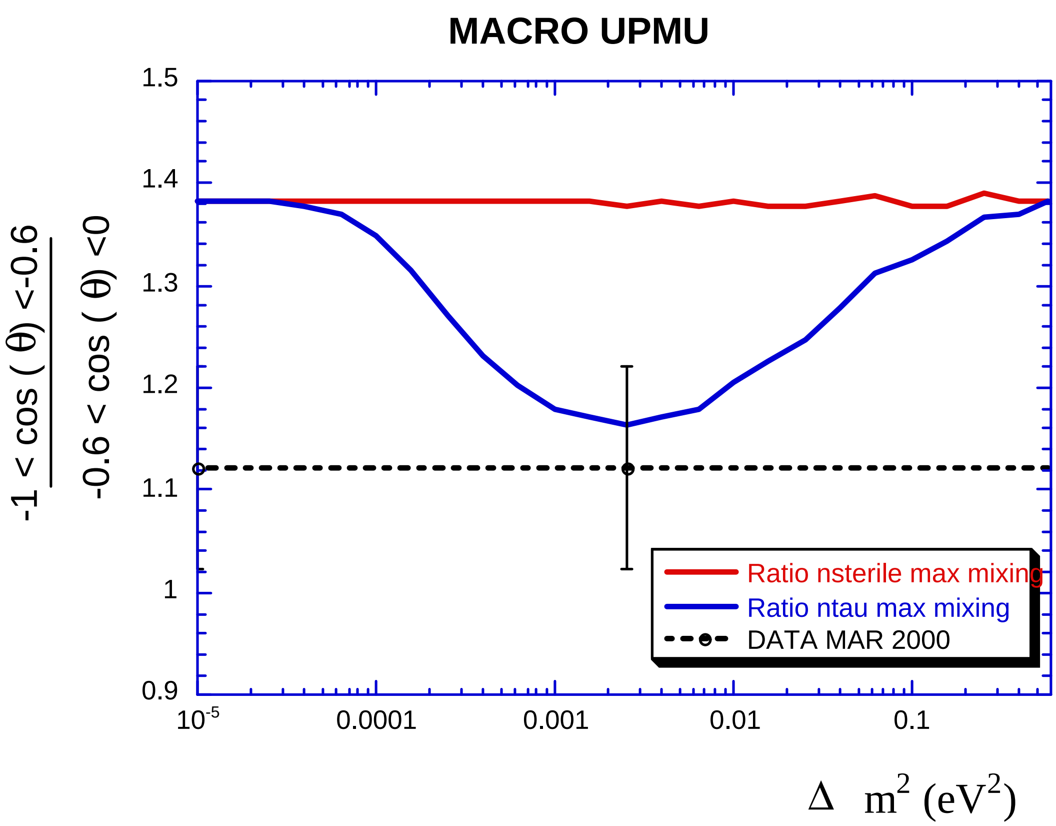
Probabilities for sterile neutrino oscillations



Test of oscillations with the ratio vertical / horizontal

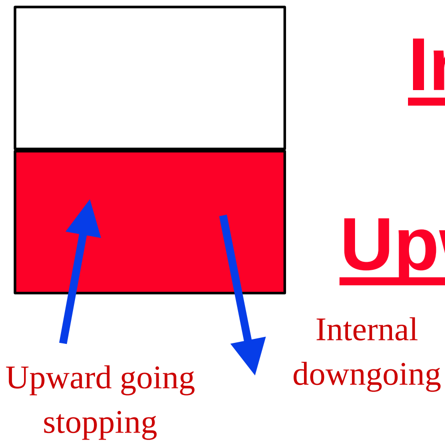
- Ratio *(Lipari- Lusignoli, Phys Rev D57 1998)* can be statistically more powerful than a χ^2 test:
  1) the ratio is sensitive to the sign of the deviation
  2) there is gain in statistical significance

- Disadvantage: the structure in the angular distribution of data can be lost.



P best Tau/ P best Sterile = 15 (5% systematic in each bin)

Measured value ~ 2 σ (and one sided) from the expected value for sterile neutrino



Internal Downgoing μ's and Upward Going Stopping μ's

from MC simulation:

- E_ν ~ 4 GeV
- mixture
  - upward going stopping μ ~ 50%
  - internal downgoing μ ~ 50%
- ~ 87% from ν_μ –charged current events

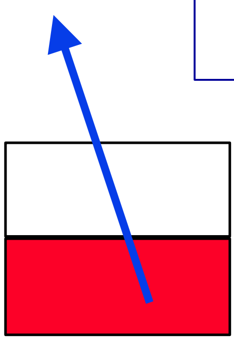
DATA - Background = 229 events

Data vs Monte Carlo Predictions

Low Energy Neutrino Events

- 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 %)

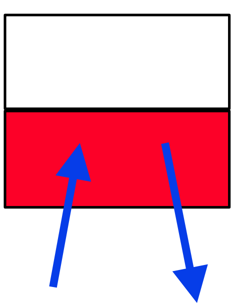
Internal upward going μ's



MC: $247 \pm 25_{sys} \pm 62_{theo}$

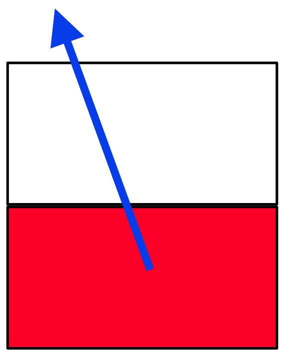
DATA: $\mathbf{135 \pm 12_{stat}}$

Internal down + Upgoing stop



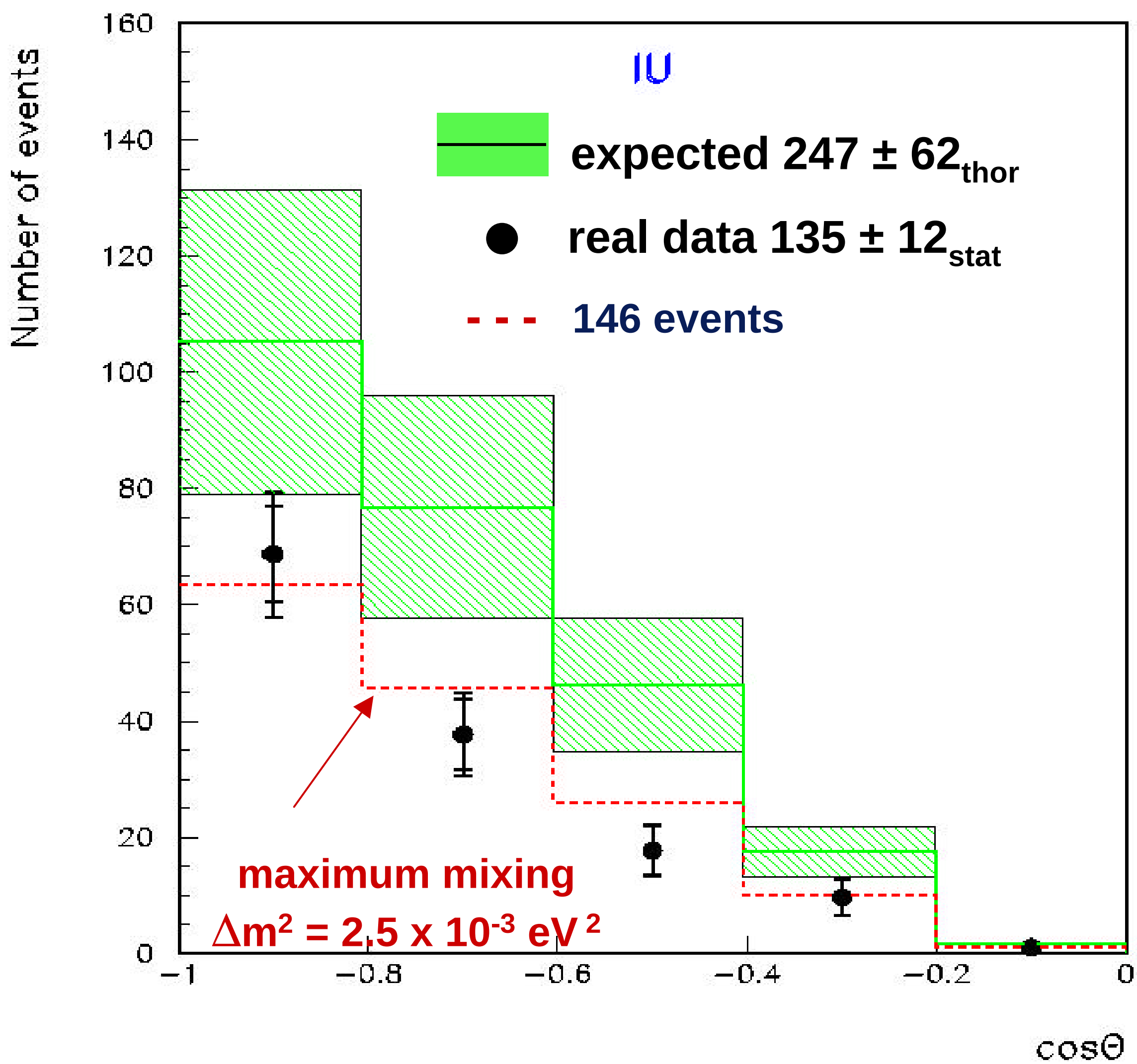
MC: $329 \pm 33_{sys} \pm 82_{theo}$

DATA: $\mathbf{229 \pm 15_{stat}}$

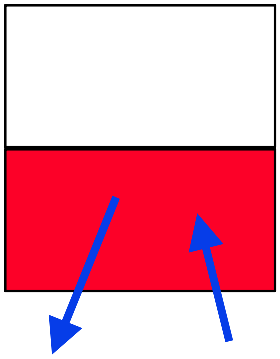


Internal upward events

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

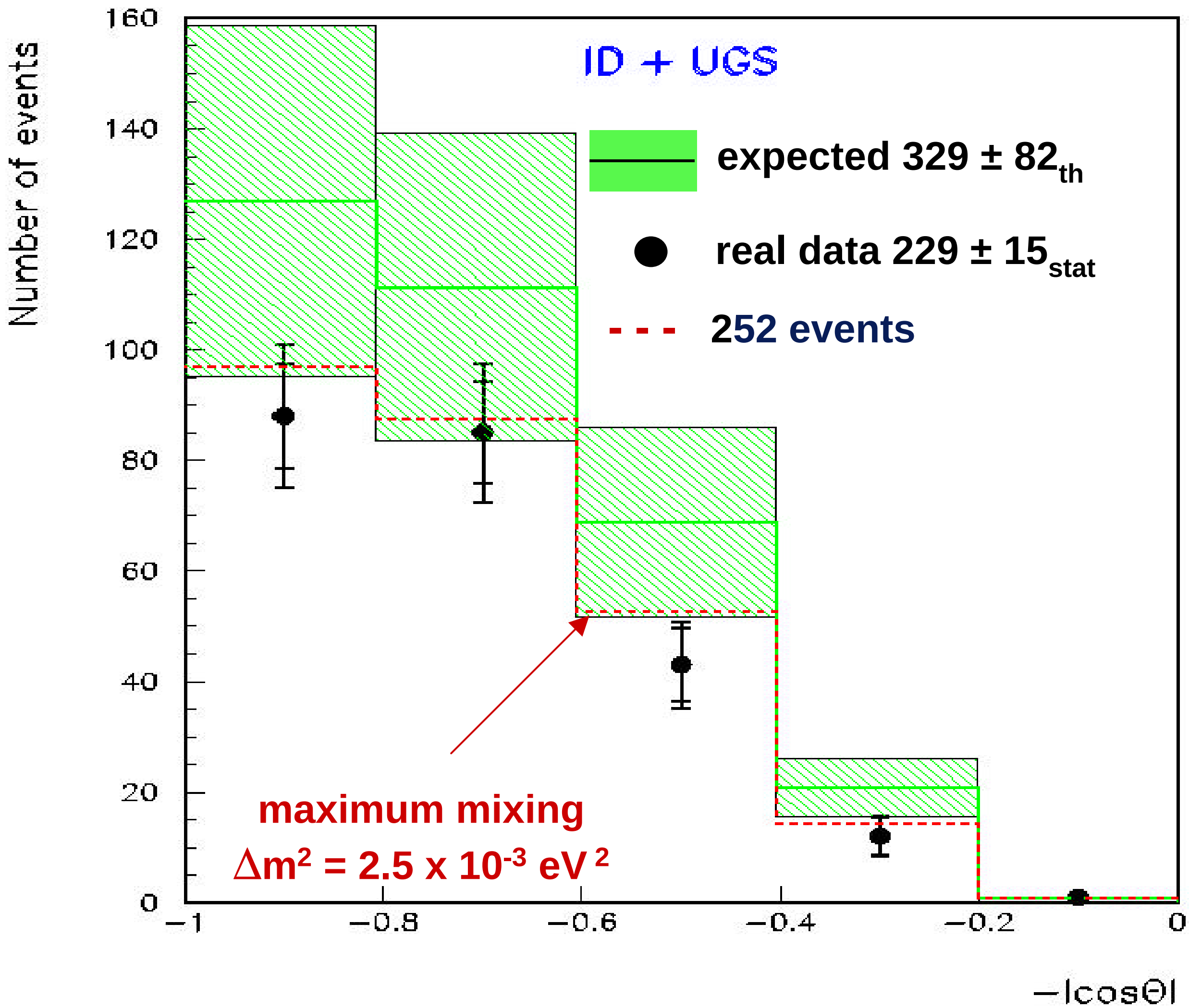


- Data consistent with a **constant deficit** in all **zenith angle** bins (χ^2 /d.o.f. = 3.1/4 on shape)
- Probability for NO oscillations: ~ **4.3%** (one side)



Internal downward + Upward stopping events

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



- Data consistent with a **constant deficit** in all **zenith angle** bins
- Probability for NO oscillations: ~ **12%** (one side)

Ratio of event types at low energy

(Internal upward) / (Internal downward + Upward stopping)

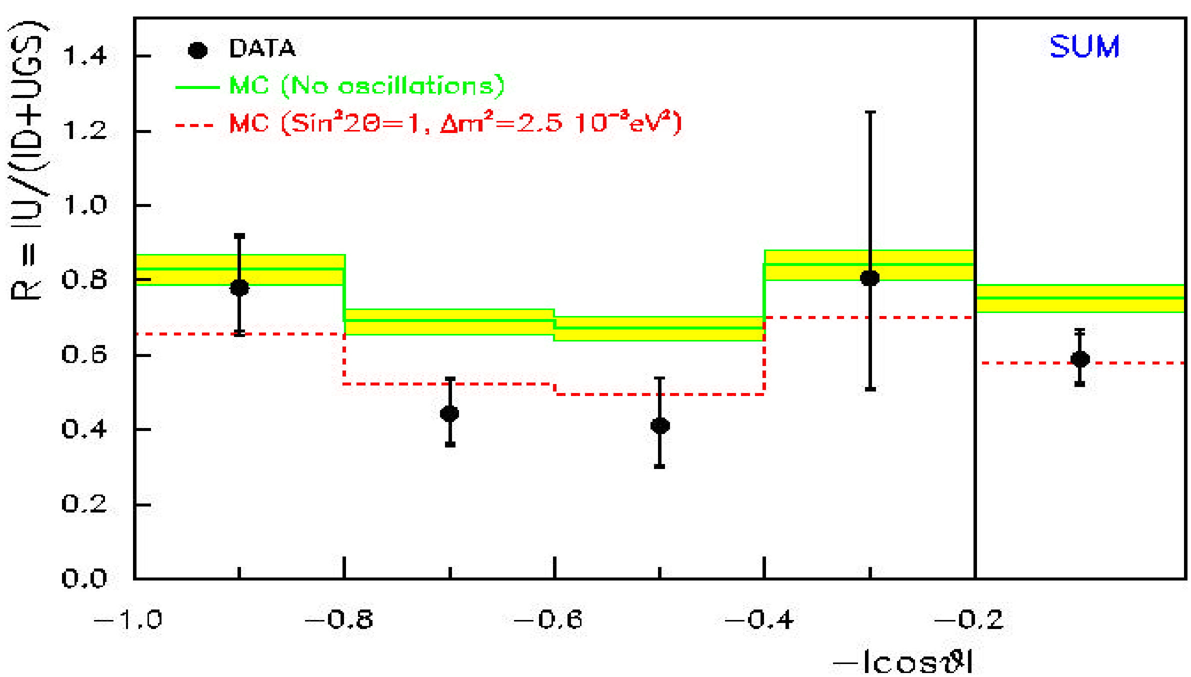
- **Most of the theor. uncertainties canceled (<5%)**
- **Systematic errors reduced** (~6%)

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

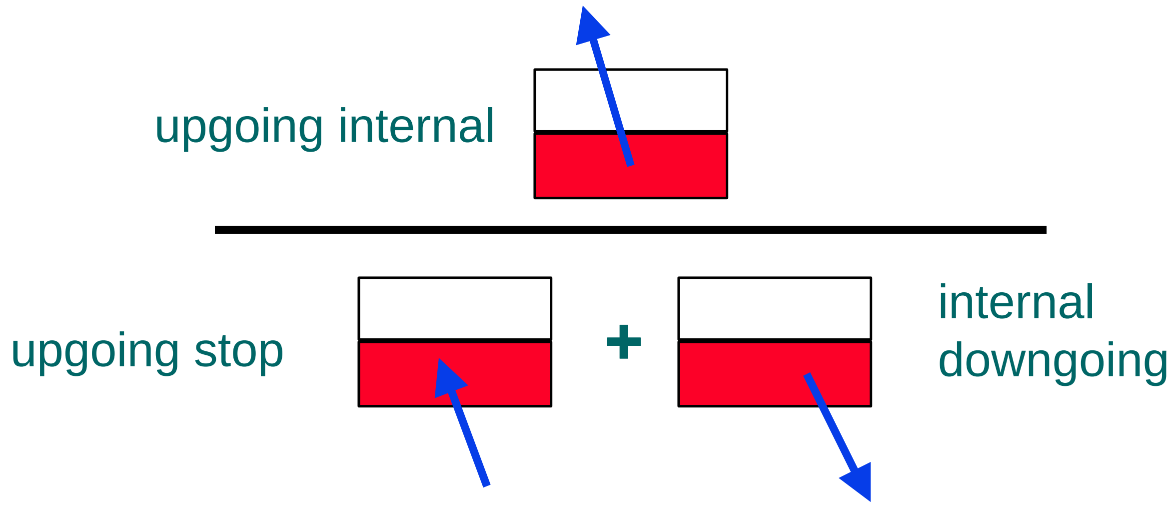
Expected (No oscillations): $R = 0.75 \pm 0.04_{sys} \pm 0.04_{th}$

compatibility ~ 2.7%

Expected $\nu_\mu \rightarrow \nu_\tau$ oscillations $R = 0.58 \pm 0.03_{sys} \pm 0.03_{th}$
(maximal mixing and $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$)



Ratio of event types at low energy

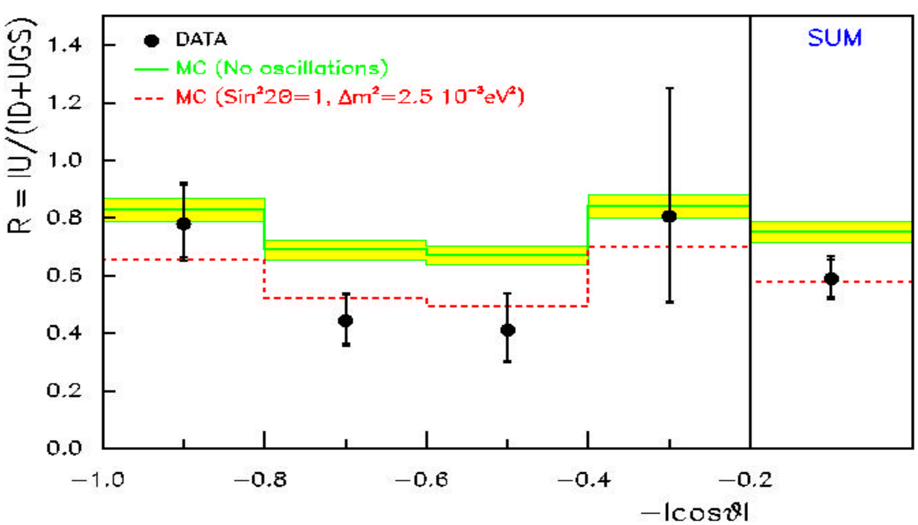


- Most of the theor. uncertainties canceled $< 5\%$
- Systematic errors reduced $\sim 6\%$

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

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

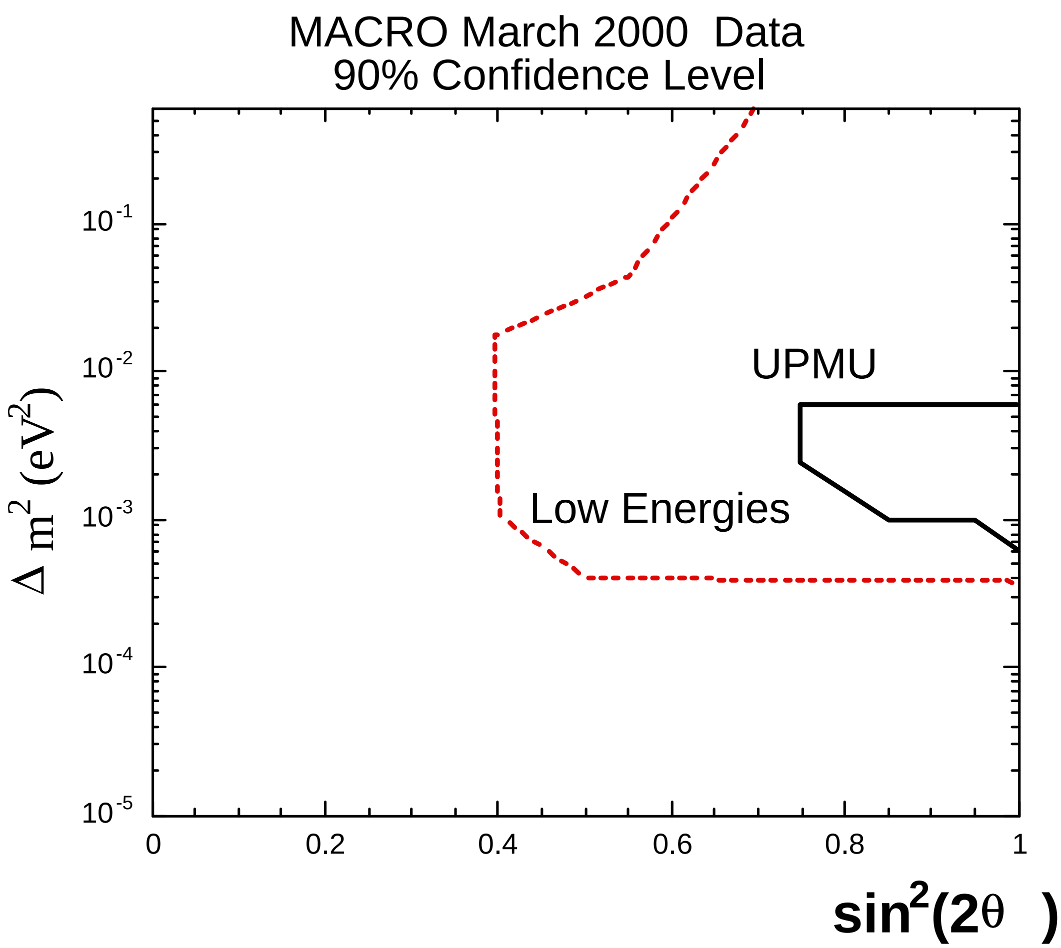
Expected $\nu_\mu \rightarrow \nu_\tau$ oscillations $R = 0.58 \pm 0.03_{sys} \pm 0.03_{th}$



maximal mixing

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

MACRO ν events: confidence level regions for $\nu_\mu \rightarrow \nu_\tau$ oscillation



Summary and Conclusions

- **High energy events:**

  - $\nu_\mu \longrightarrow \nu_\tau$ oscillation favoured with large mixing angle and $\Delta m^2 \sim 2.5 x 10^{-3}$ eV^2
  - sterile ν disfavoured at $\sim 2\,\sigma$ level

- **Low energy events:**

  - event deficit with respect to expectation different for Internal upward, and internal downward + Uuward going stopping
  - no zenith angle distortion
  - compatibility between result and expectation (no oscillations) with a probability < 3 %
  - agreement with hypothesis of oscillation with large mixing angle and $10^{-3} < \Delta m^2 < 2x10^{-2}$ eV^2

- **A consistent scenario arises from both high and low energy MACRO ν events**