MACRO results on ν oscillations

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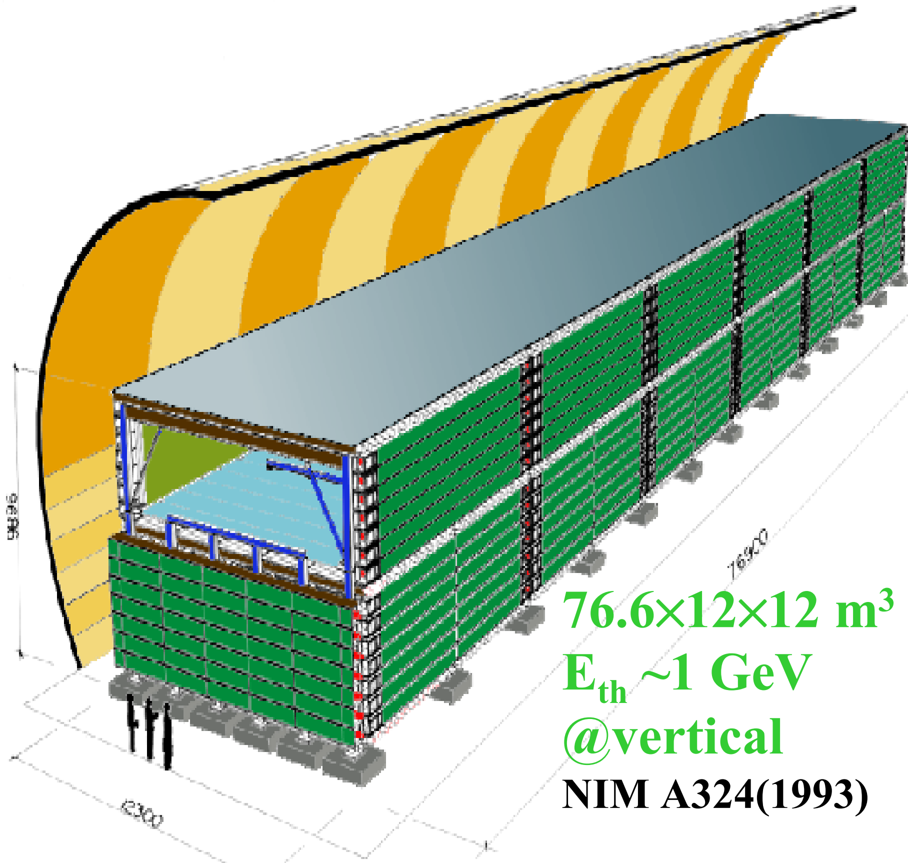
for the MACRO Collaboration

Les Houches, 18-22 June 2001 - Neutrino Masses and Mixings

Outline

- Neutrino detection in MACRO @ Gran Sasso updated to acq end (19 Dec 2000)
- Results on through-going upward muons: matter effects $\nu_\mu \rightarrow \nu_\tau$ **or** $\nu_\mu \rightarrow \nu_\tau$
- Low energy topologies
- Multiple scattering

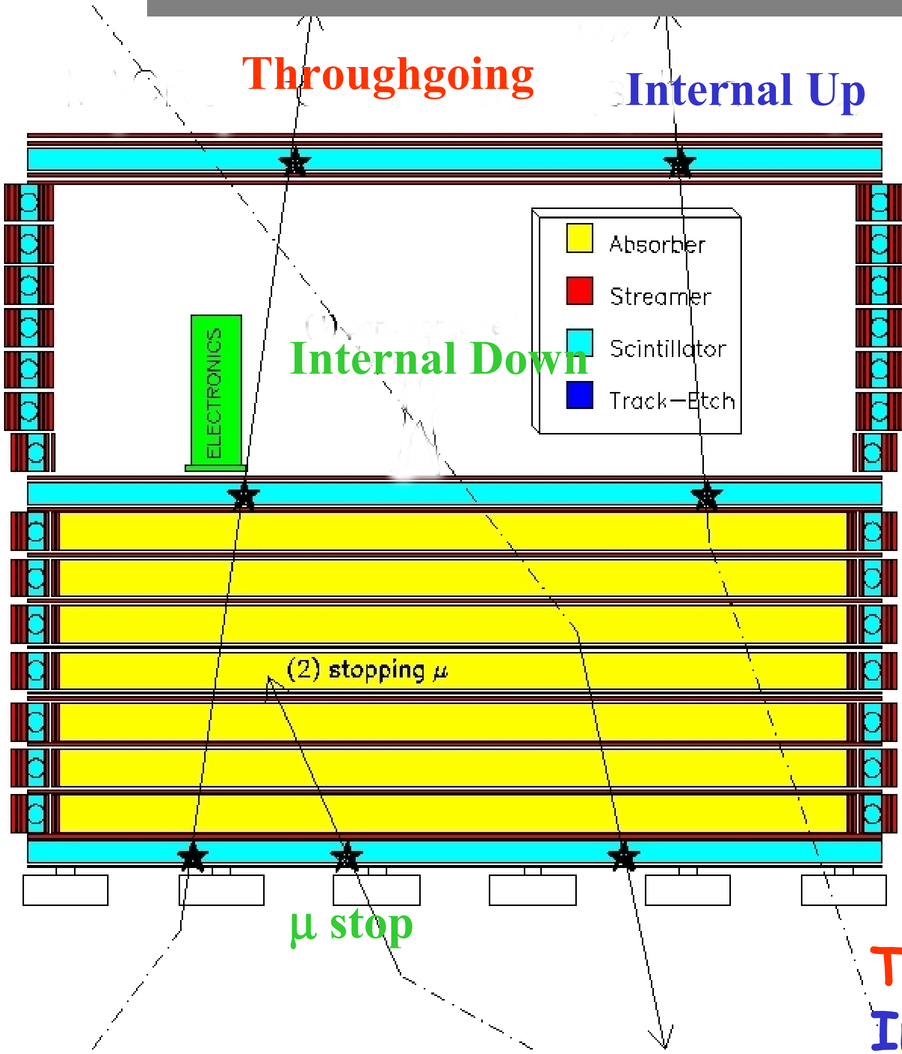


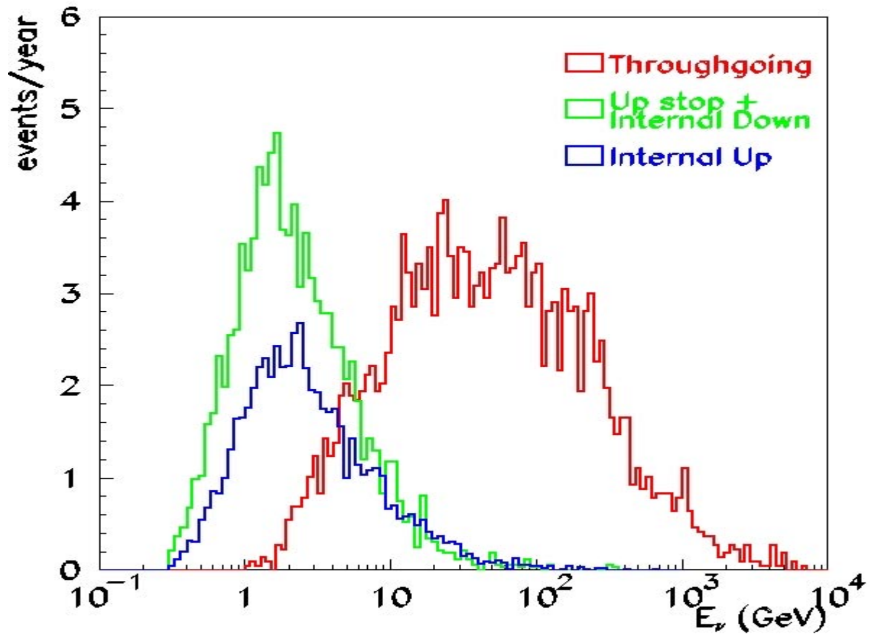
$76.6 \times 12 \times 12$ m^3
E_{th} ~1 GeV
@vertical
NIM A324(1993)

Different technique than SK clear event topologies, different energies, fully automatic analysis, no rejection of events at trigger level (efficiency, acceptance, backgrounds can be studied using atm. muons)

- Min rock coverage 3150 hg/cm^2
- 600 ton liquid scintillator (600 ps), 20000 m^2 streamer tubes (< 1°)

ν event topologies

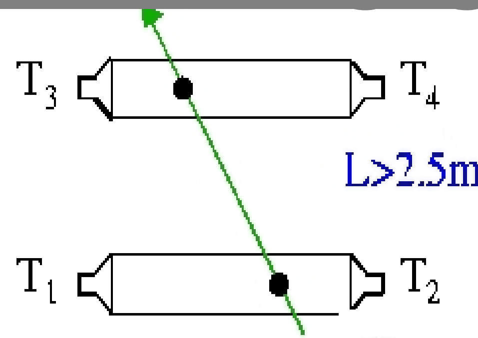




Throughgoing: Emedian~50 GeV 180/yr
Internal Up: Emedian~3.5 GeV 50/yr
Internal Down+Stopping μ:
Emedian~4.2 GeV 35+35/yr (expected)

Upward throughgoing μ analysis

T.o.F. technique:



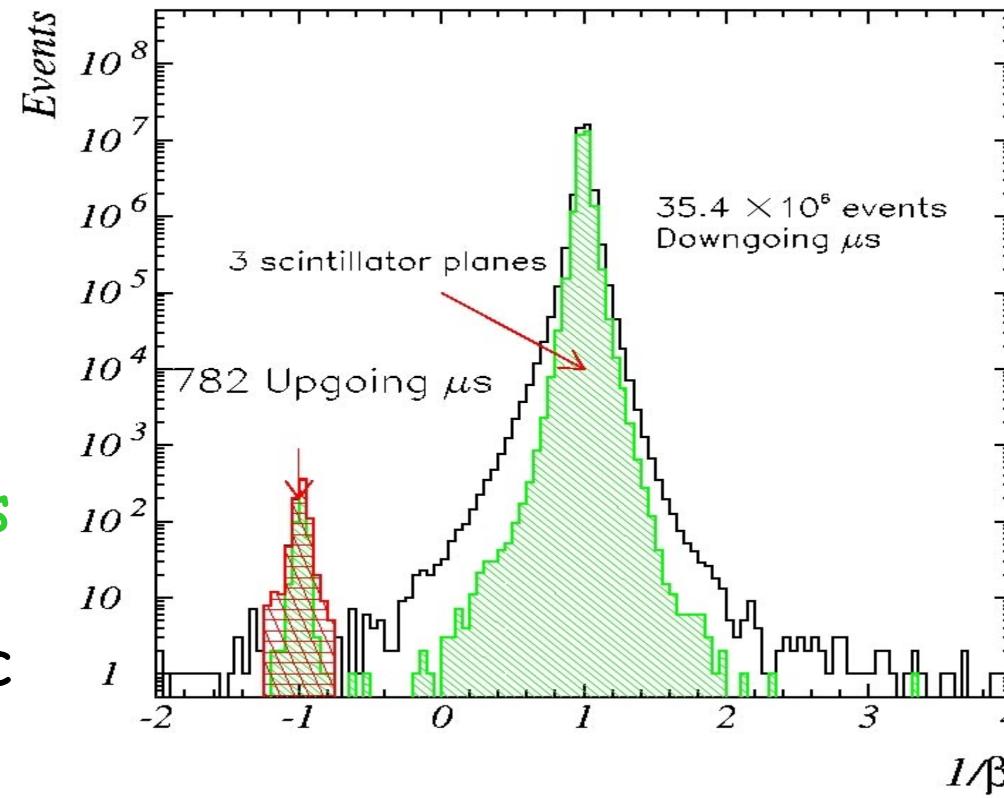
$$\frac{1}{\beta} = \frac{(T_1 + T_2 - T_3 - T_4)c}{2L} = \begin{cases} +1 & \mu\downarrow \\ -1 & \mu\uparrow \end{cases}$$

Main cut:
position along scint. counter from ST track in agreement inside 70 cm with that from ToF

~200 gr/cm^2 in rock Absorber to reduce at 1% Background from upgoing πs

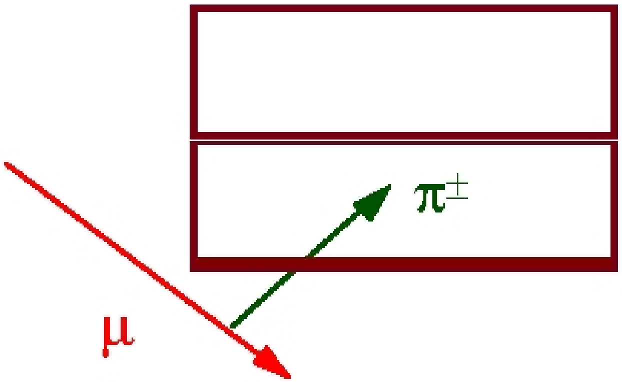
No scanning, fully automatic

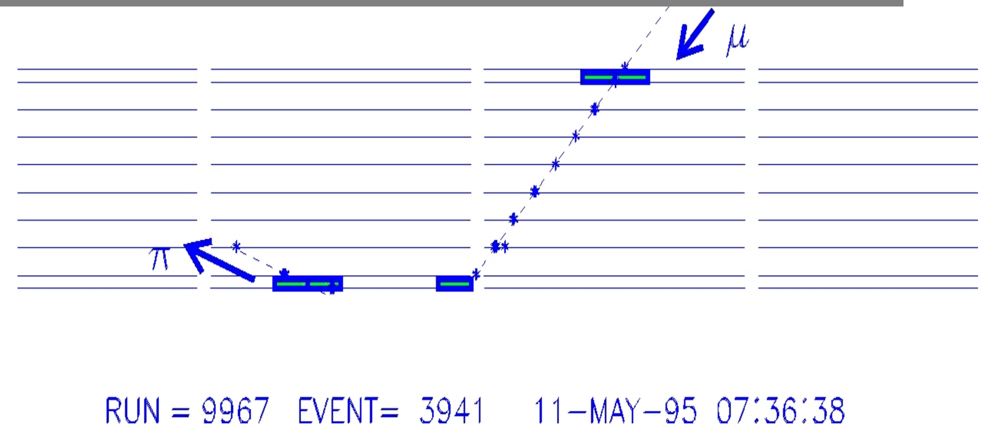
-1.25 < 1/β < -0.75



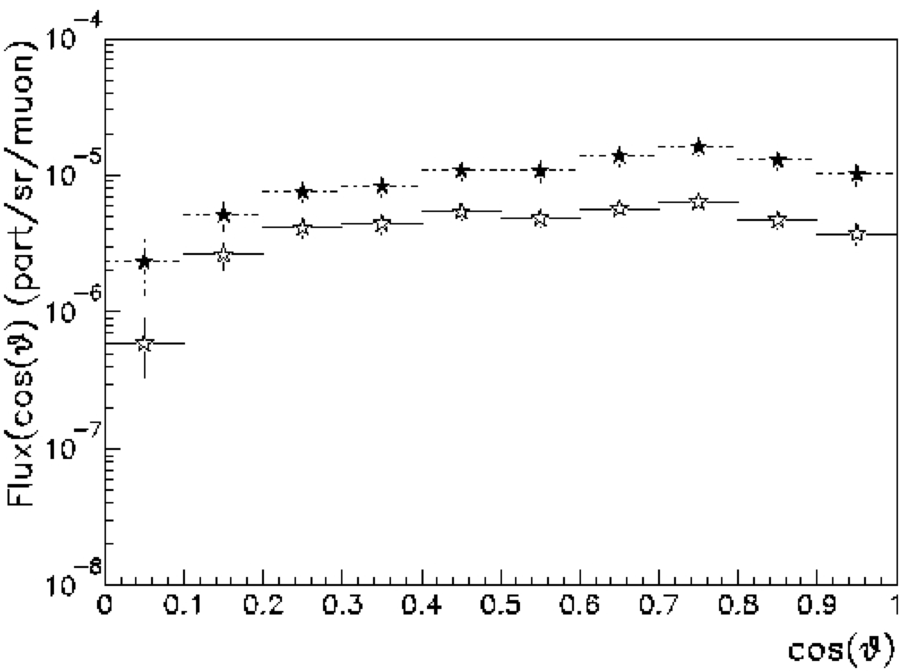
1/β distribution (full detector)

The backgrounds





MACRO Coll., Astr. Phys 9 (1998)



Physical background from atm. μ ↓ photonuclear interactions producing upgoing soft particles

Important for shallow detectors (Baksan, IMB while SK and Soudan2 have vetos)

243 upgoing particles between $12.2 \cdot 10^6$ μs ↓ ⇨ ~10^{-4} π/μ ↓

~1% in throughgoing μs↑

~5% in stopping μs

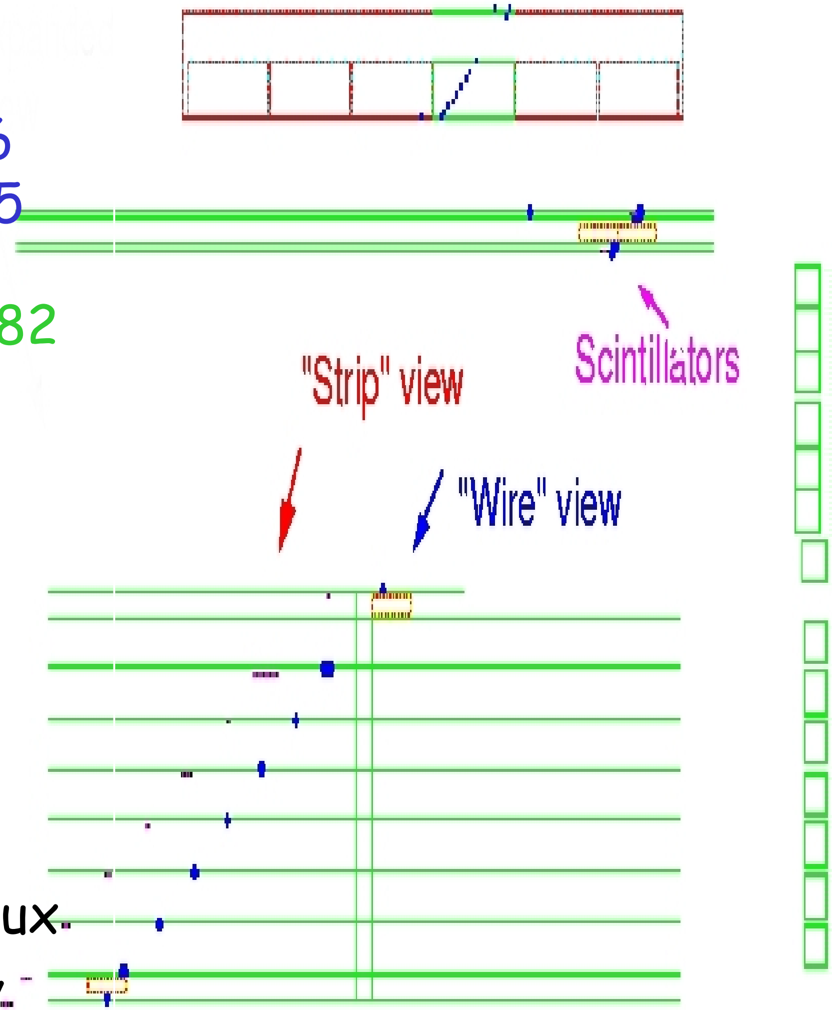
Results for Upward throughgoing μs

Data taking period	Detector configuration	Livetime (eff. includ.)	μ↑
Mar89-Nov91	1/6 lower part	1.38 yr	26
Dec 92-Jun93	lower part	0.41 yr	55

PLB357 (1995)

Apr 94-Dec 00	full detector	5.51 yr	782

PLB434 (1998)



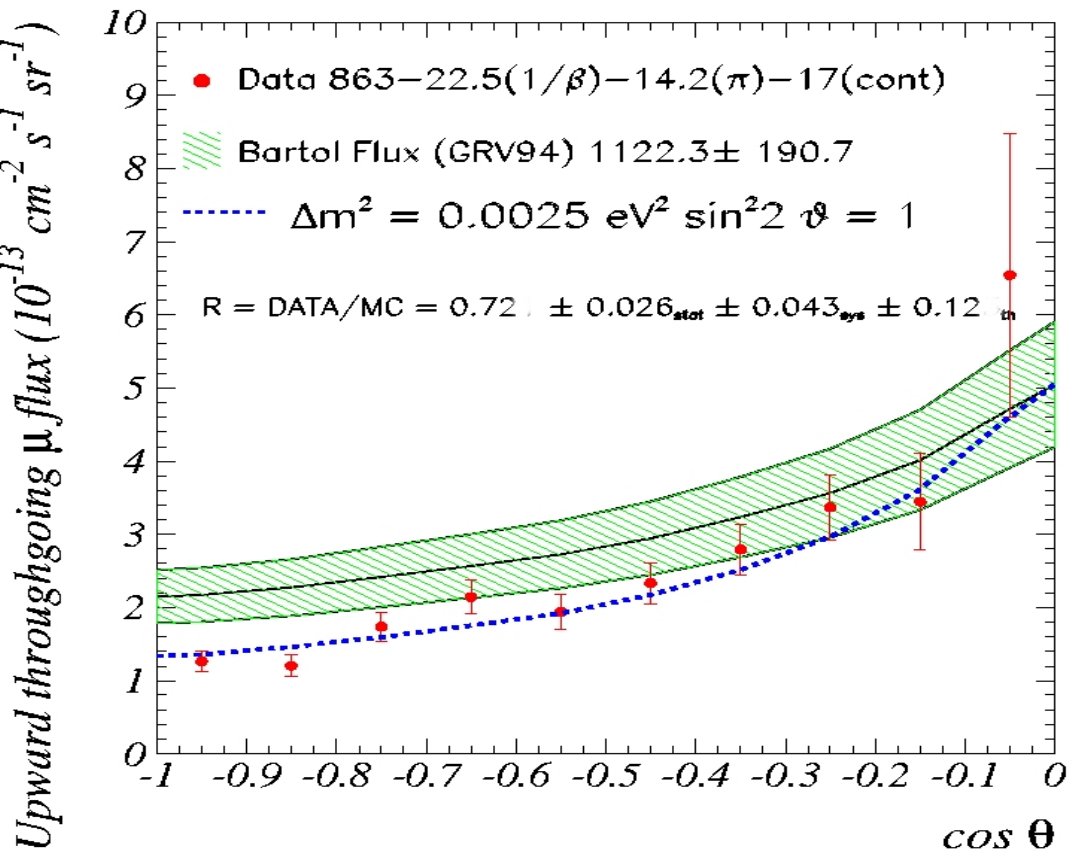
23 Dec 1994

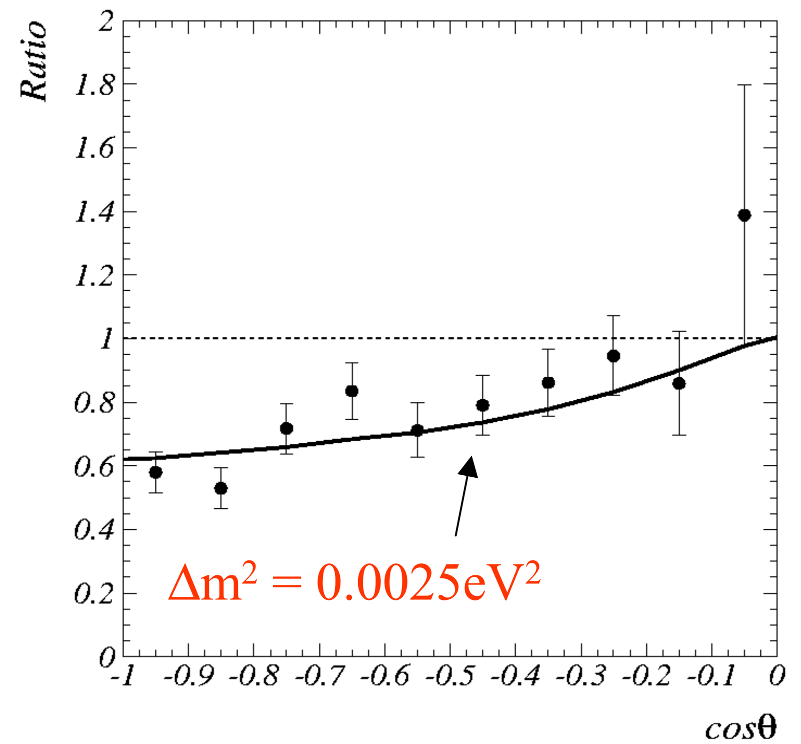
Total n. of events	863
Backgrounds	
Incorrect β	22.5
Soft upgoing π	14.2
Internal ν interactions	17
Measured	**809**
Expected	**1122 ± 17%**

(Bartol flux 14%, cross sections (GRV94) 9%, μ energy Loss 9% (Lohmann et al.)

R = 0.72 ± 0.026stat±0.043sys± 0.12theor

μ↑ flux angular distribution



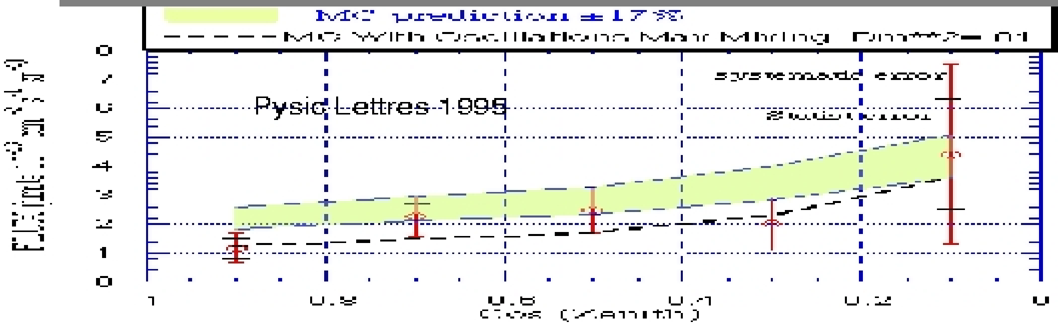


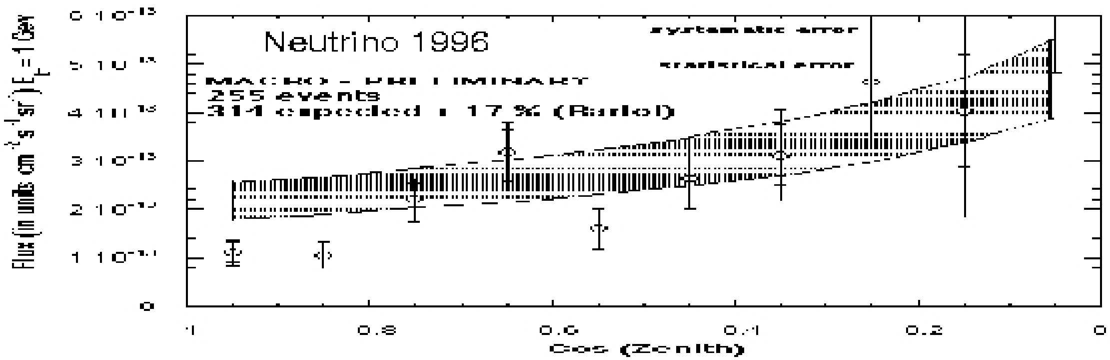
χ^2 test on the angular distribution (10 bins) with prediction normalized to data:

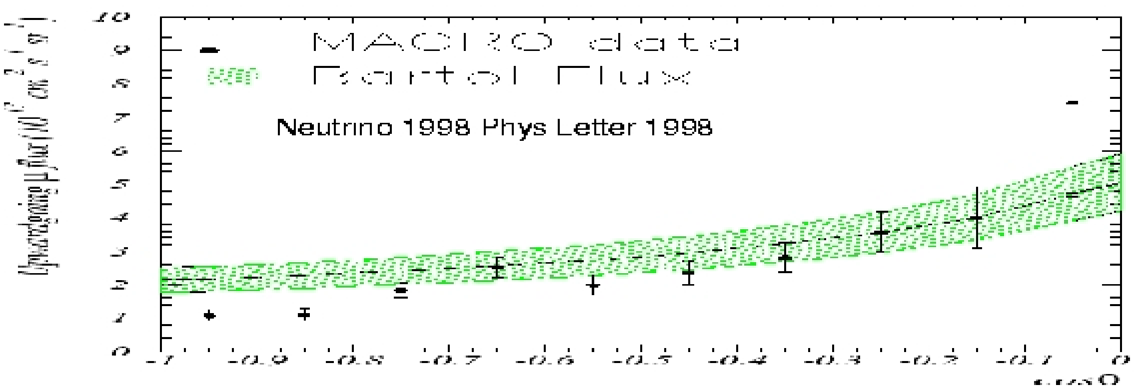
χ^2/dof=25.9/9 for no-oscillations ⇨P = 0.2%

χ^2/dof=9.6/9 for $\nu_\mu \rightarrow \nu_\tau$ (Δm^2 = 0.0025 eV^2 $\sin^2 2\theta$=1) ⇨P = 37%

μ↑ flux angular distribution during time

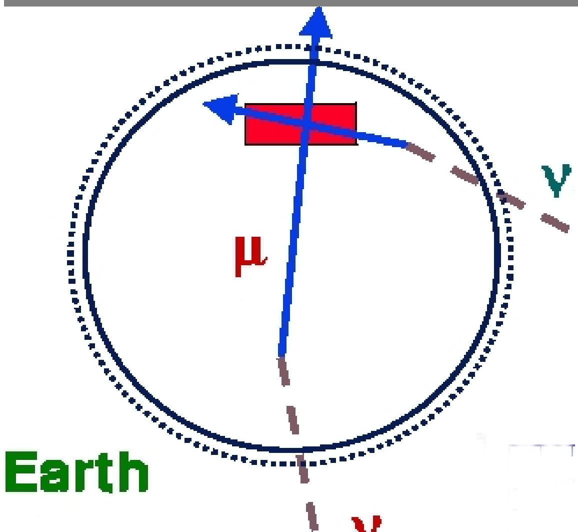






Since 1994 to now the angular distribution has become more regular

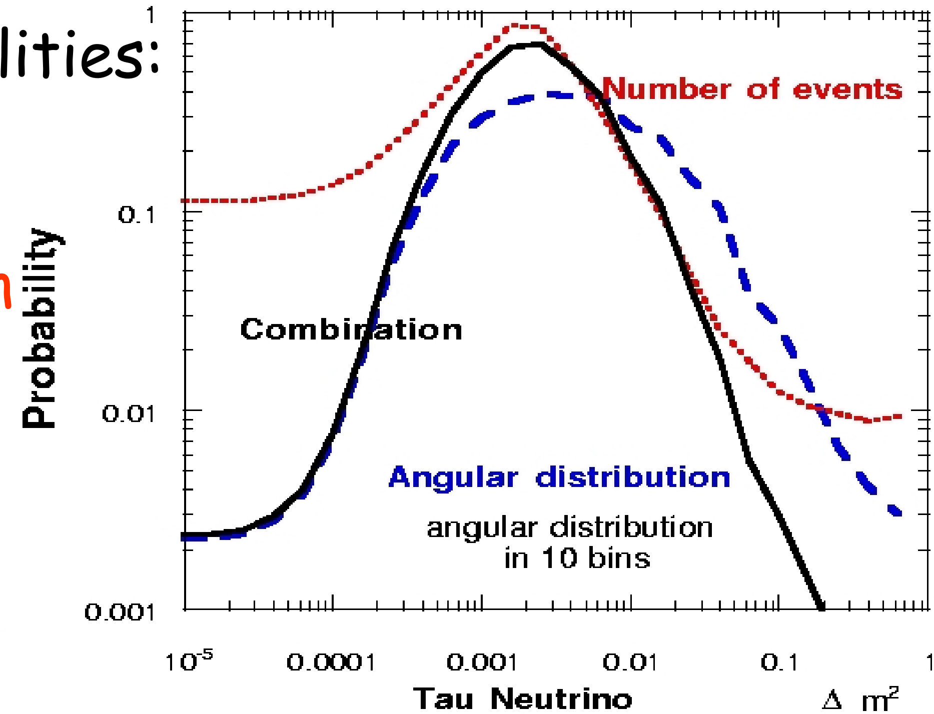
νμ→ντ oscillations in upward throughgoing μ

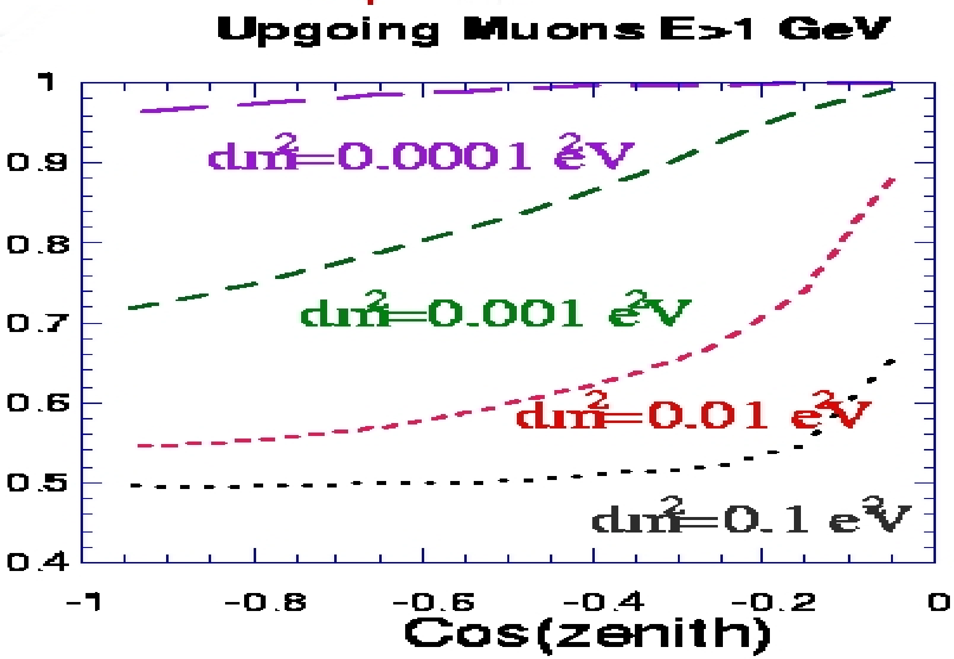


Peak probabilities:

37% shape

66% shape × normalization



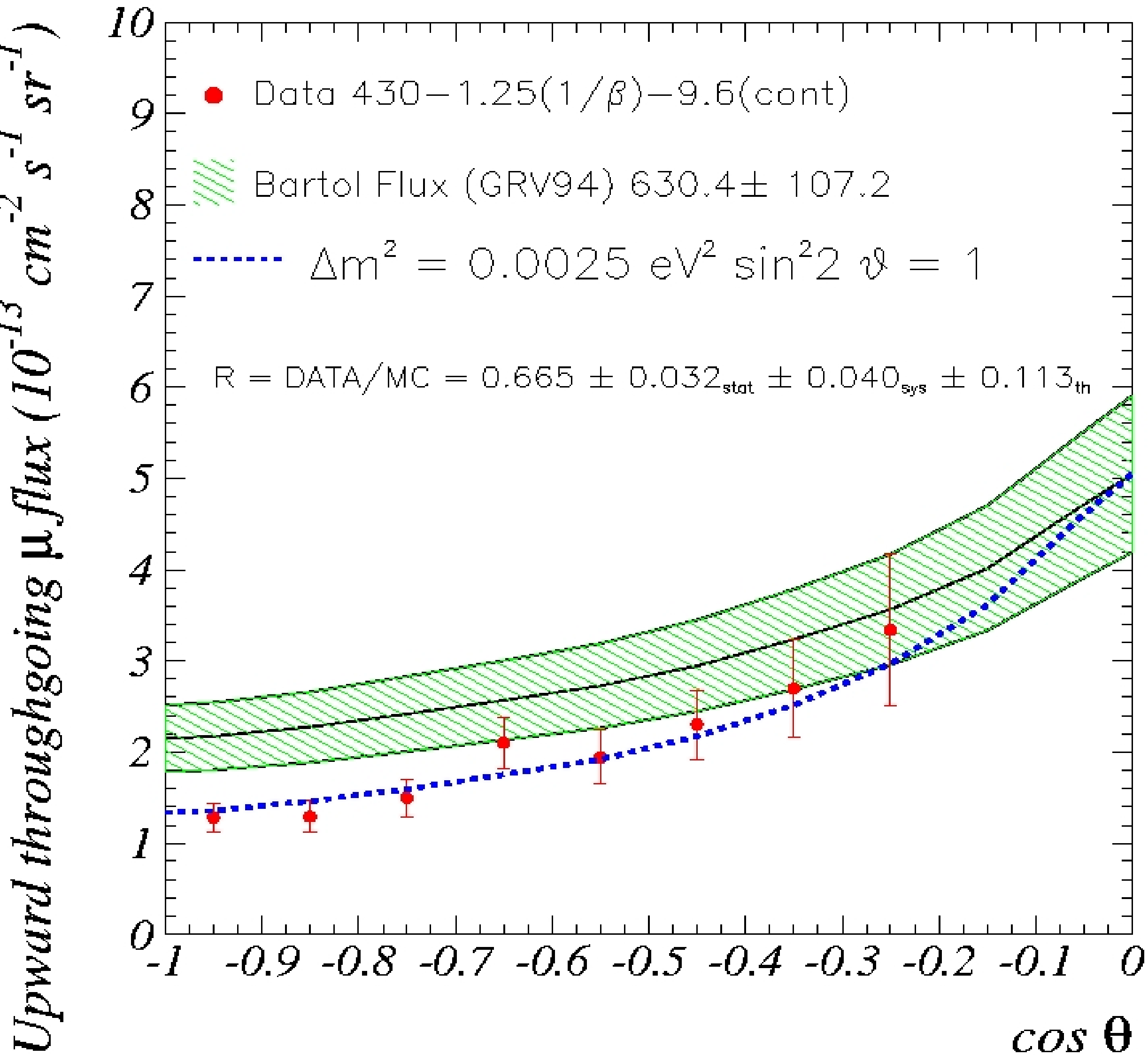


Reduction factors for

νμ→ντ

MACRO threshold ~1 GeV more sensitive to vertical deficit than SK (average threshold ~6 GeV)

Angular distribution for selected sample

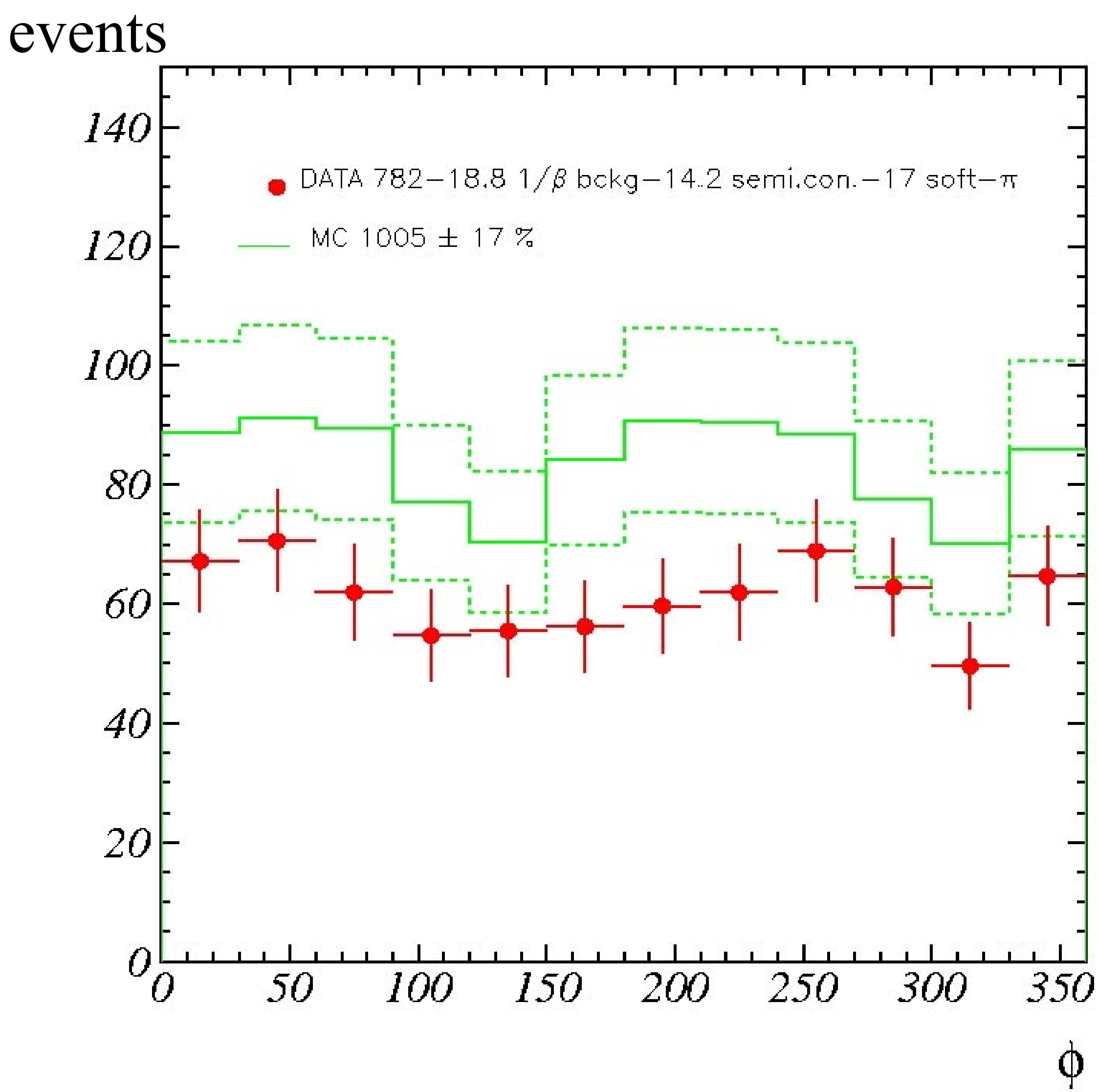


3 box events (redundant time measurement) Same shape of full sample

χ^2/dof=9.4/7 for no-oscillations ⇨ P = 22.8%

χ^2/dof=3.7/7 for $\nu\mu \rightarrow \nu\tau$ (Δm^2 = 0.0025 eV^2 $\sin^2 2\theta$=1) ⇨ P = 81.5%

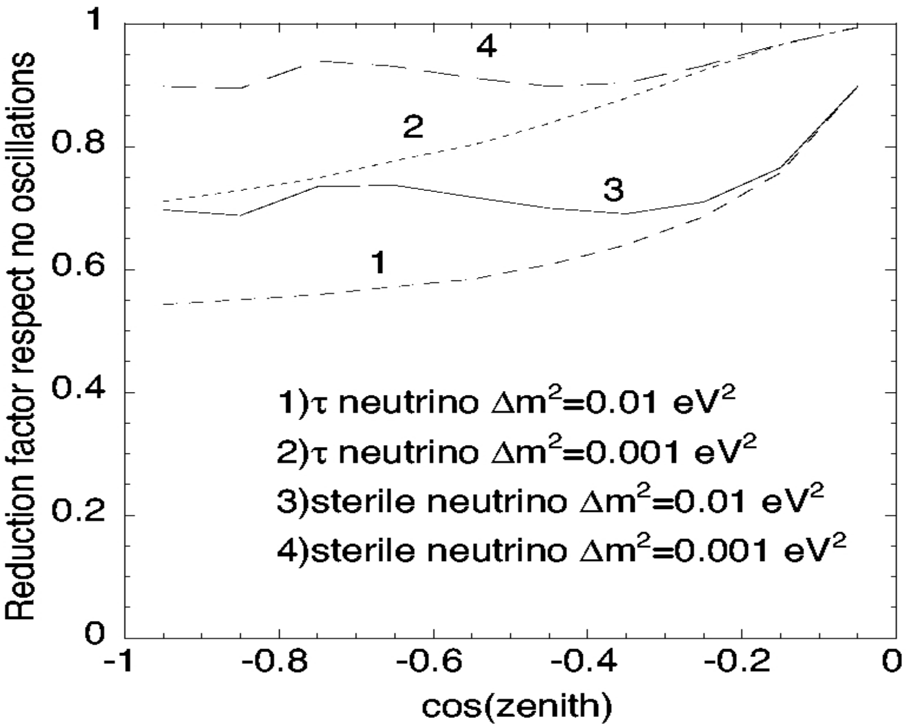
Angular distribution for selected sample



Oscillations do not affect azimuth angular distribution

χ^2/dof=2.8/11 normalizing prediction to data⇨ P = 0.99

Matter effects in upward throughgoing μs



When ν flavors involved in oscillations have different weak potential in matter

$$V_{weak} = \frac{\pm G_F n_B}{2\sqrt{2}} \times \begin{cases} -2Y_n + 4Y_e & \nu_e \\ -2Y_n & \nu_\mu, \nu_\tau \\ 0 & \nu_{sterile} \end{cases}$$

+ for ν, - for $\bar{\nu}$ n_B = barion density

Yn,e = n, e/barion

Matter effects can be important for νμ→νe,νsterile not for νμ → ντ

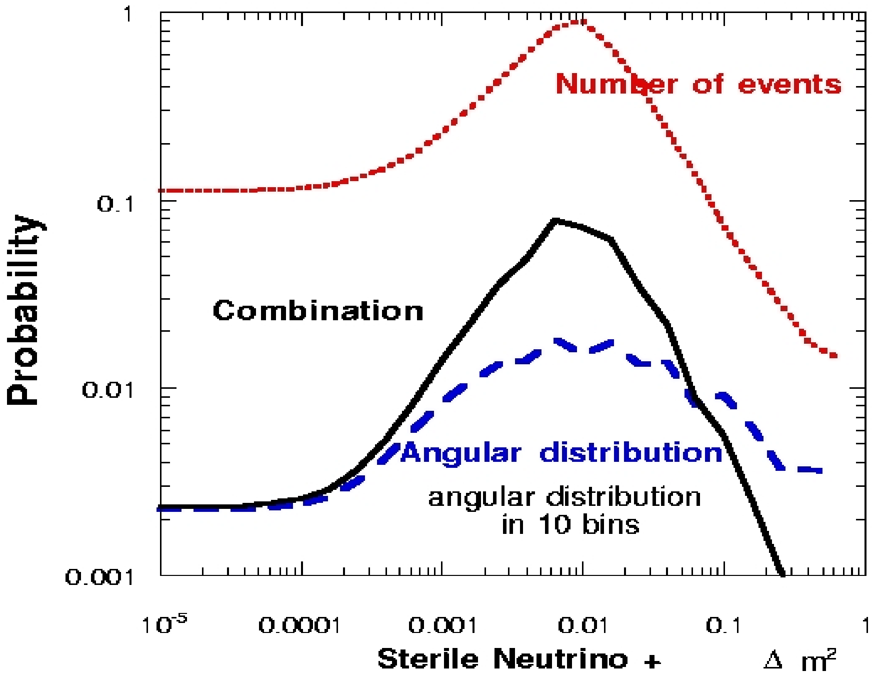
$E\nu/\Delta m^2 \geq 10^3$ GeV/eV² ⇨for HE up-throughgoing μs

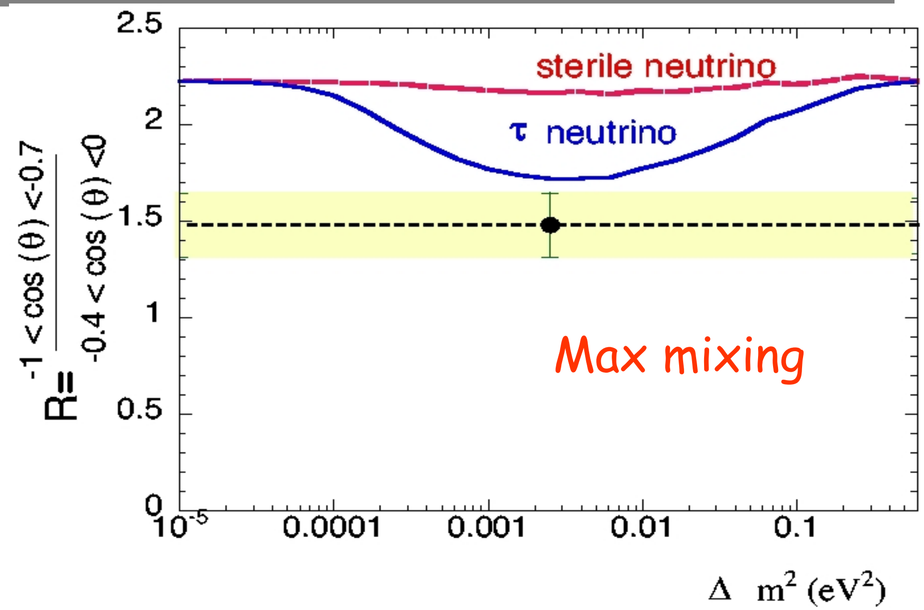
For maximal mixing matter effect produces a reduction of oscillation effect ⇨ closer to predicted with no oscillations

For mixing <1 enhancement for some values of parameters (MSW)

Sterile or tau ν oscillations?

Peak probability for shape 1.8%
Peak probability for shape×normalization = 8%





Vertical/horizontal more powerful test than χ^2

P. Lipari&M. Lusignoli, PRD57(1998)

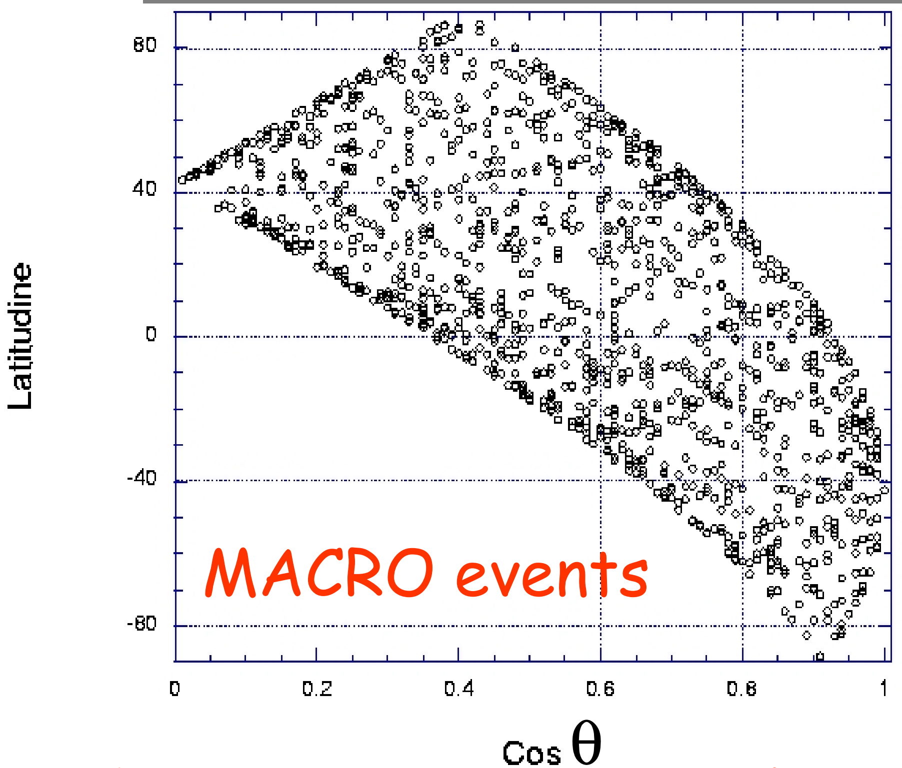
Psterile= 0.033%/Pτ = 8.4%=254

$\nu_\mu \rightarrow \nu_{sterile}$ excluded at ~99% c.l.

Ratio: sensitive to sign of deviation, gain in statistical significance (2bins) but some feature of angular shape could be lost

MACRO bin choice through simulation (MACRO Coll., hep-ex/0106049)

Systematic errors in the ratio



•Neutrino flux sources of uncertainty:
P. Lipari, Nucl. Phys. Proc Supp.91(2001)
1) K/π fraction
2) Energy specrum spectral index $E^{-\alpha}$
⇨δR/R ~3%

• From comparison of different cross sections ⇨δR/R ~2%

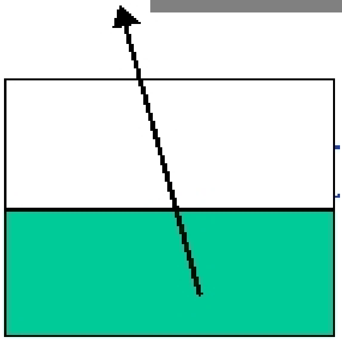
•Detector acceptance + background in horizontal region
⇨δR/R ~4.6%

Other uncertainties: seasonal variations ⇨dR/R ~1.3%
+ US atmosphere profile ⇨dR/R ≤1%

MACRO upgoing μs: variation in vertical/horizontal ratio
R(Nov-Apr) - R(May-Oct)=≈0.19±0.17stat

Seasonal effect difficult to calculate because neutrinos come from meson and muon decays and from all over the Earth

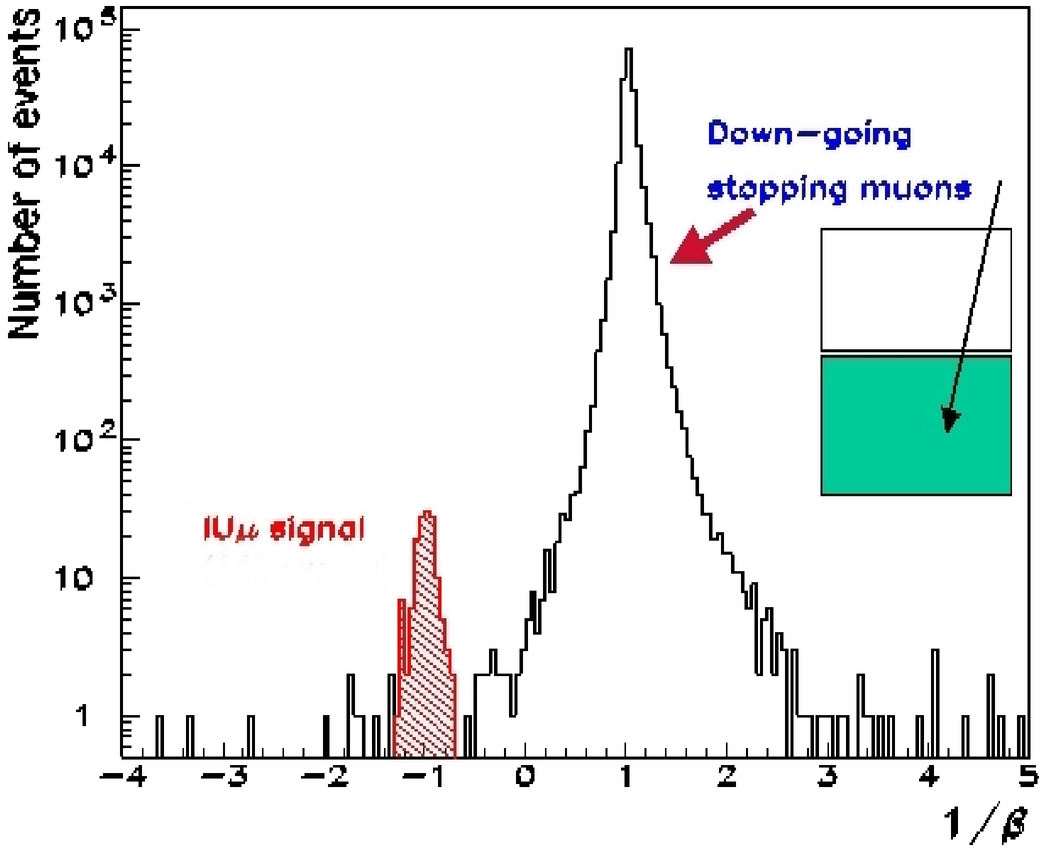
Internal Up events

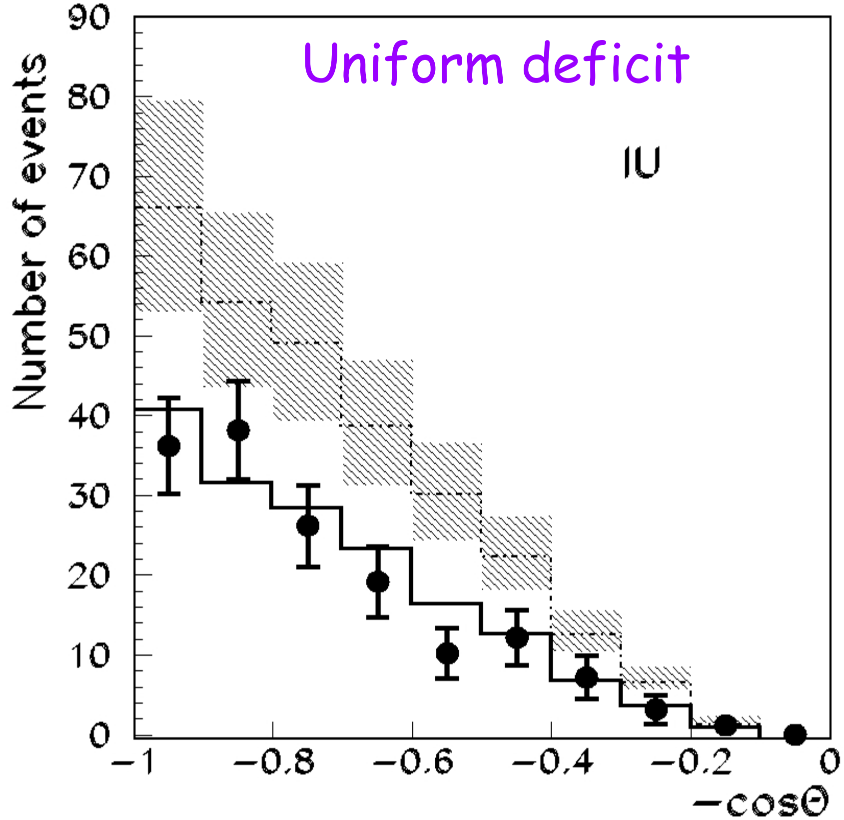


ToF between central and upper scintillator layers+ containment cuts to reject up-throughgoing μs (1% backg)

DATA 161 with -1.3< 1/β <-0.7 (eff. livetime 0.58yr)

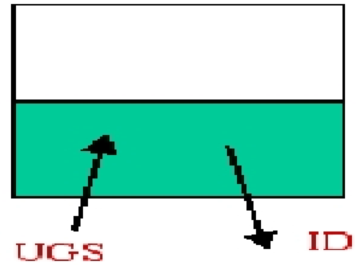
Backgrounds (wrong β, secondary hits) = 7 ⇨ 154





Internal Down + Upward Stopping

Selected using topological cuts
Tracks inside fiducial volume crossing bottom scintillator layer ending in lower part, visual scanning (real+simulated events), ≳100 gr/cm^2: background due to soft πs (~5%)



DATA: 272 events (5.6 yr), background 10 events ⇨ 262

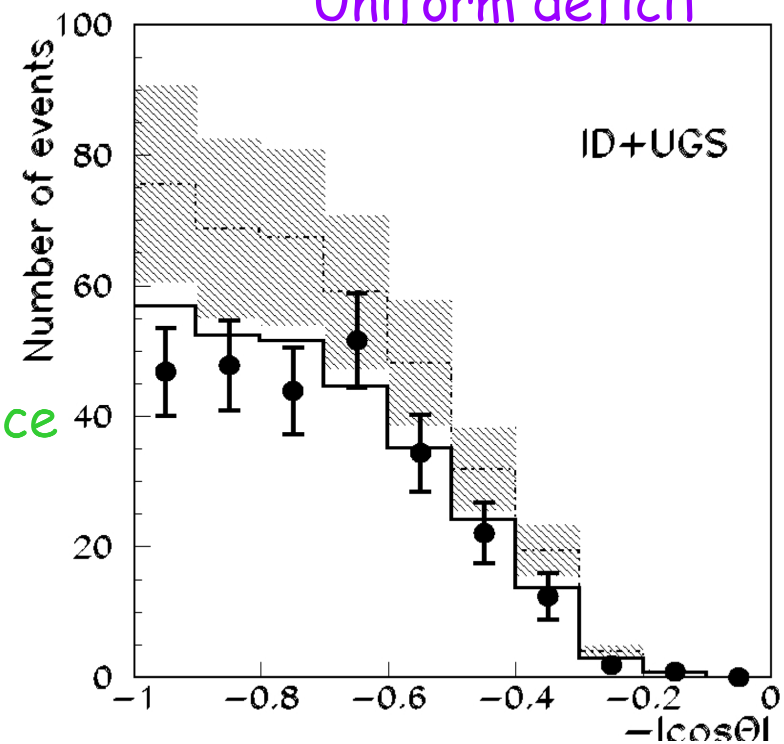
Predictions: $\Phi = \Phi\nu \otimes \sigma\nu \otimes \varepsilon(E\mu,\theta)$

$\Phi\nu$ = Bartol ν flux (~20%)

$\sigma\nu$ = Qel+1π+DIS(GRV94-LO) (~15%)
Lipari et al., PRL74(1995)
25% error in MC normalization

$\varepsilon(E\mu,\theta)$ = detector responce and acceptance (~10%)
6% difference respect to MINOS Neugen
IU and ID+UGS mainly due to CCνμ
NC and νe (~13% IU and 10% UGS+ID)

Uniform deficit



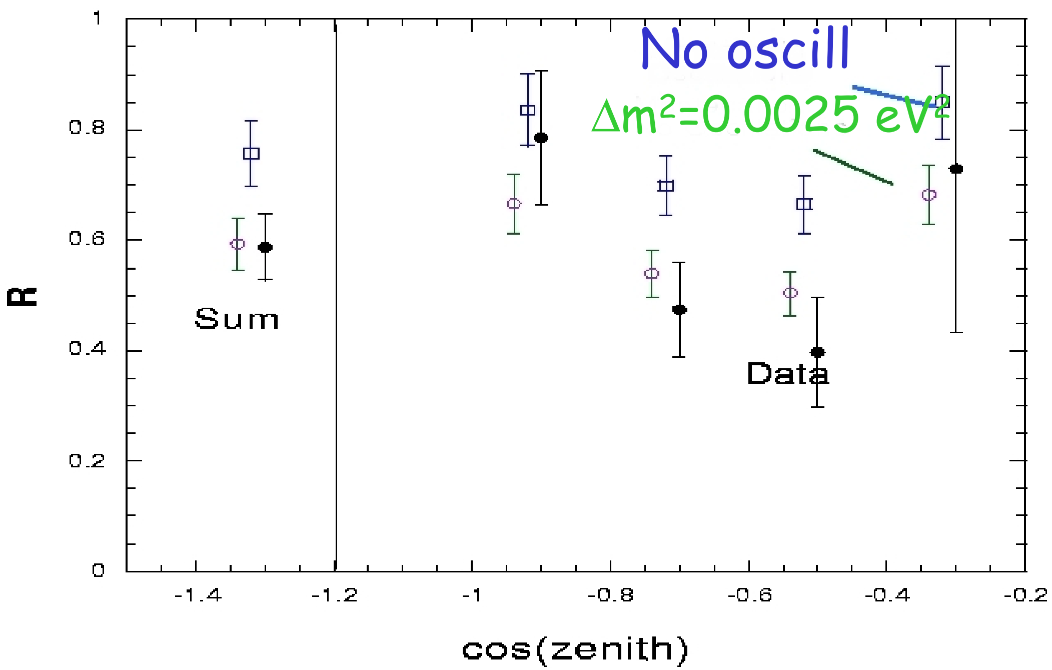
Double Ratio

	IU	ID+UGS
DATA	154 ± 12stat	262 ±16stat
MC (no osc)	285 ± 28sys±71th	375 ±37sys ±94th
R=DATA/MC(no osc)	0.54 ± 0.13tot	0.70 ± 0.19tot
MC (Δm^2=0.0025 eV^2)	168	284

$R=IU/(ID+UGS)_{DATA}$ =0.59 ± 0.060stat $R=IU/(ID+UGS)_{MC}$ = 0.76 ± 0.059sys

$R=IU/(ID+UGS)_{MC}$ (Δm^2=0.0025 eV^2) = 0.59 ± 0.046sys

R_{IU} and R_{ID+UGS} not same reduction ⇨ deficit not due to theor. overestimate of ν flux/cross sections (both topologies <Eν>~4 GeV)



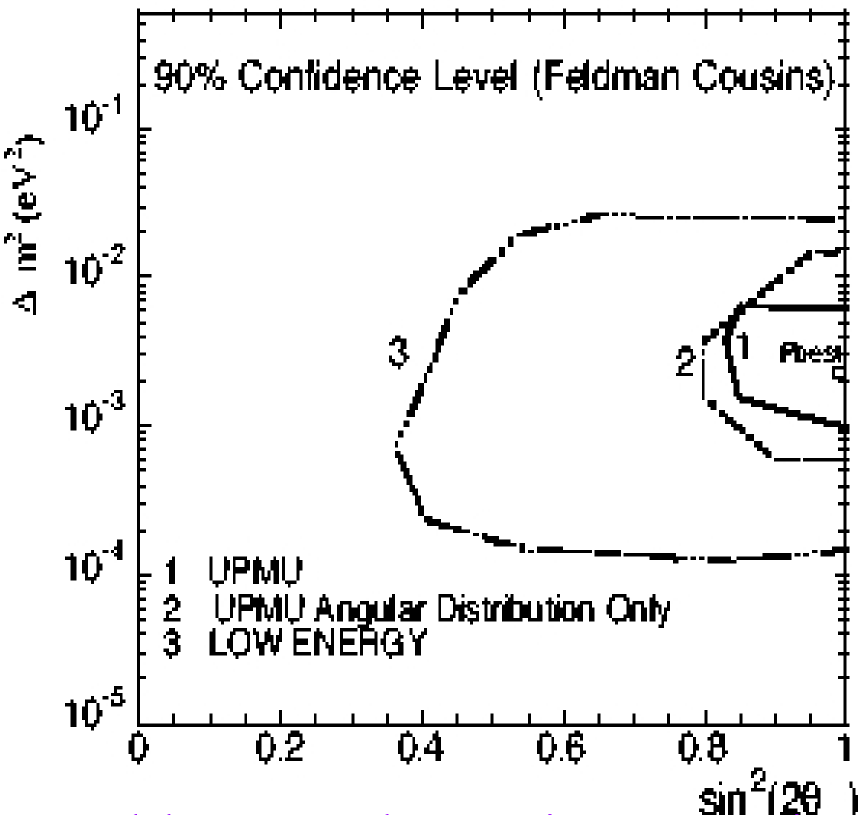
Expected reductions for Δm^2 ~1-10 ×10^{-3} eV^2 $\sin^2 2\theta=1$

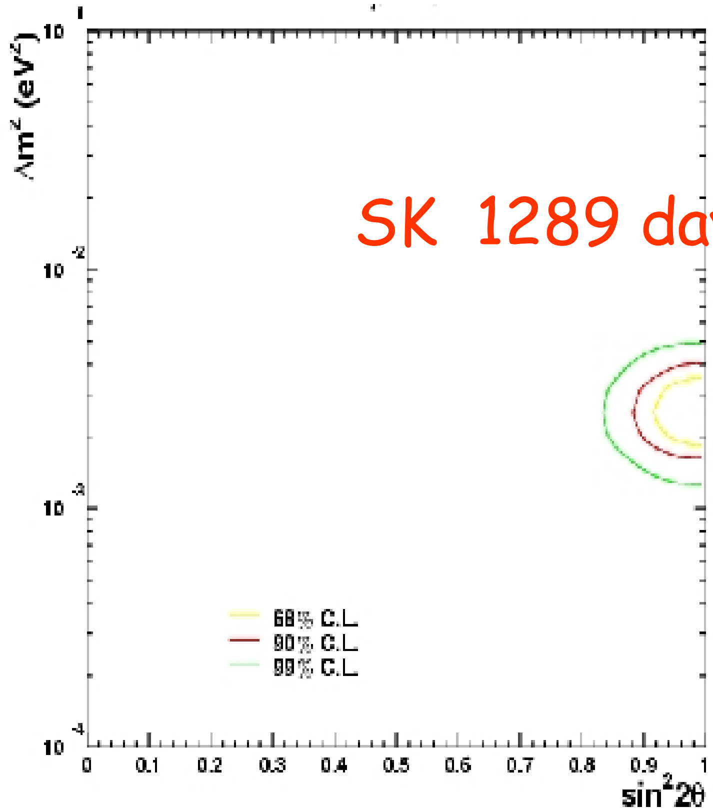
1/2 for IU 1/4 for ID+UGS

Probability to obtain double ratio so far from expected is 2.2%

(including non-gaussian shape of the uncertainty of the ratio)

Allowed regions $\nu_\mu \to \nu_\tau$





Feldman and Cousins prescription
PRD57(1998)

Contained + upward muons

Max prob for throughgoing μs (66%) 0.0024eV^2
for low energy (87%)

Multiple Scattering

Upgoing muon energy estimate through multiple scattering in 25 radiation lengths of MACRO using ST system ⇨ L/E

2 analysis:

1) Angular and space difference between lower track (1-8 planes) upper track (6:14)

MACRO ST 3 cm cells (digital information)⇨

$\sigma \sim 3\text{cm}/\sqrt{12} \sim 1\text{cm}$ ⇨ residual Eμ 10GeV/ $\sqrt{\cos\vartheta}$

2) ST Space resolution improved by a factor 3.5 to 3mm using TDC analogue information (150 ns) ⇨

muon residual energy up to 40 GeV (Eν~200 GeV)

Given preferred oscillation parameter $\Delta m^2 \sim O(10^{-3}\ eV^2)$ oscillation effects should be stronger at Eμ≤10 GeV and disappear at E> 100 GeV

Results (positive) will be presented at ICRC

Conclusions

1) High energy events: angular distribution more regular than in the past
χ^2/dof=9.6/9 for $\nu_\mu \to \nu_\tau$ (Δm^2 = 0.0025 eV^2 $\sin^2 2\theta$=1)
⇨P = 37% (only from shape) 66% (shape + normalization)
Two flavor sterile ν oscillations disfavored respect to $\nu_\mu \to \nu_\tau$ @ 99% c.l. for max mixing

2) Low energy events: flat angular distribution deficit, up/down asymmetry P~2% (no oscillation) independent on theoretical errors
Confirm HE μs preferred parameters

3) Multiple scattering analysis provides residual μ energy information and L/E indication