F Ronga INFN Laboratori Nazionali Frascati Italy

Summary of results obtained by the MACRO experiment

1989-2000

MACRO at GRAN SASSO

Monopole, **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

The Gran Sasso Laboratory under the central Appenines(ITALY)

The MACRO detector

The search for magnetic monopoles, free quarks and other exotic particles

Study of the high energy muons and cosmic ray composition at the "knee" (10^{15} eV)

Neutrino mass and oscillations in the atmospheric neutrino beam: neutrino conference 1998 evidence for oscillations from Superkamiokande, MACRO and Soudan2

Neutrino astronomy

The Gran Sasso Laboratory in the central Appennines

ITALY

beside the Gran Sasso Tunnel (10.4 km long) on the highway connecting Teramo to Rome, at about 6 km from the west entrance at 963 m over the sea level and the maximum thickness of the rock **overburden is 1400 m, corresponding to 3800 m.w.e.**

Why This Laboratory?

Cosmic ray muons at sea level ~ 100 Hz / m^2

In the Gran Sasso Laboratory **~ 3 10^{-4} Hz / m^2**

Emuon > 1.4 TeV

Important for "low noise experiments"

Astrophysical neutrinos ,dark matter , proton decay, monopole searches…….

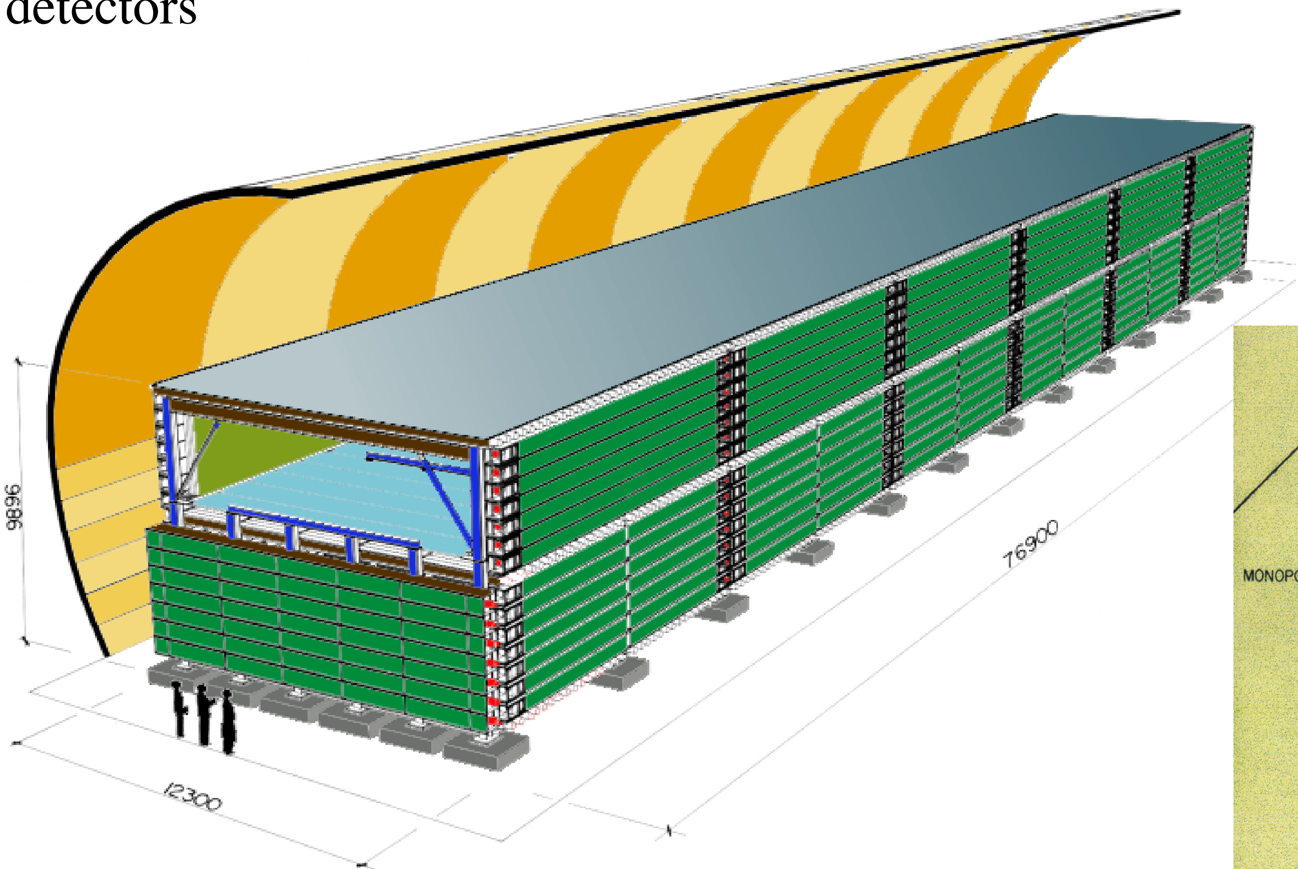
First Generation experiments : started in 1989

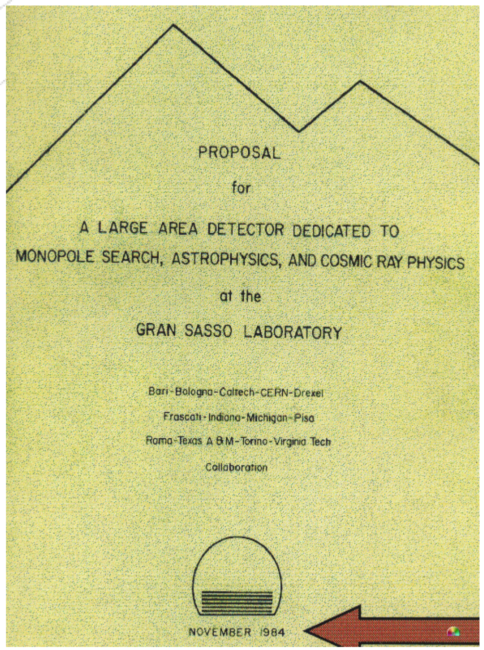
Gallex (solar neutrinos), **MACRO**, **LVD** (neutrino from stellar collapse), double beta decay experiments, **EAS-TOP,** (showers on the top of the mountain)

The MACRO detector in hall B of the Gran Sasso Laboratory - proposed in 1984

dimensions 76.9 x 12.3 x9.9 m^3

Detectors : liquid scintillator counters (in green), streamer tube chambers, CR39 plastic detectors






MACRO

1987

(a)

1990

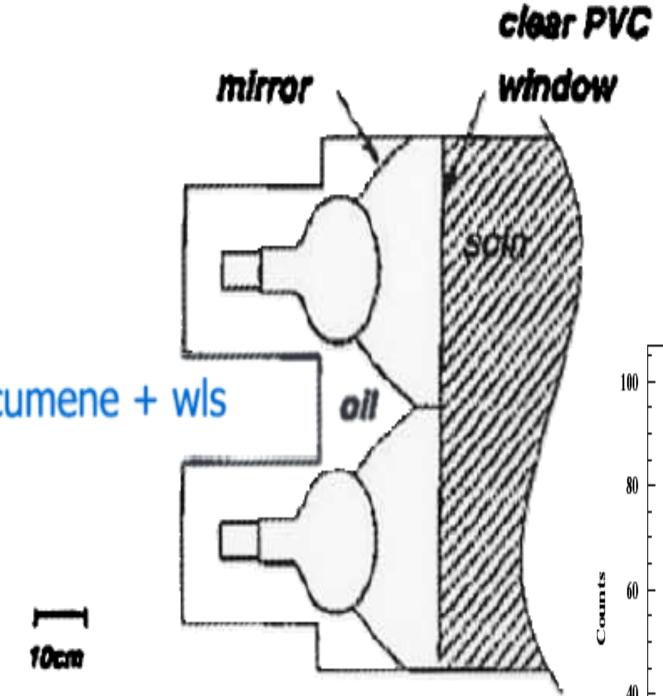
(b)

1995

2001
Waiting for
ICARUS

Scintillators

- Liquid scintillator: mineral oil+ pseudocumene + wls
- Total mass 600 t
- Time resolution: ~750 ps
- Calibration tools: cosmic muons, LED's, UV laser



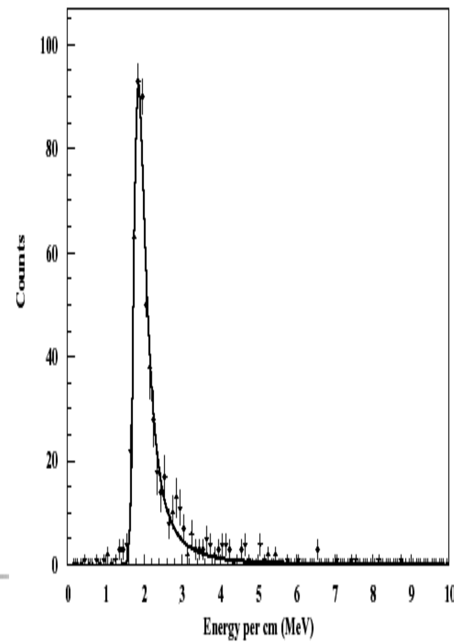
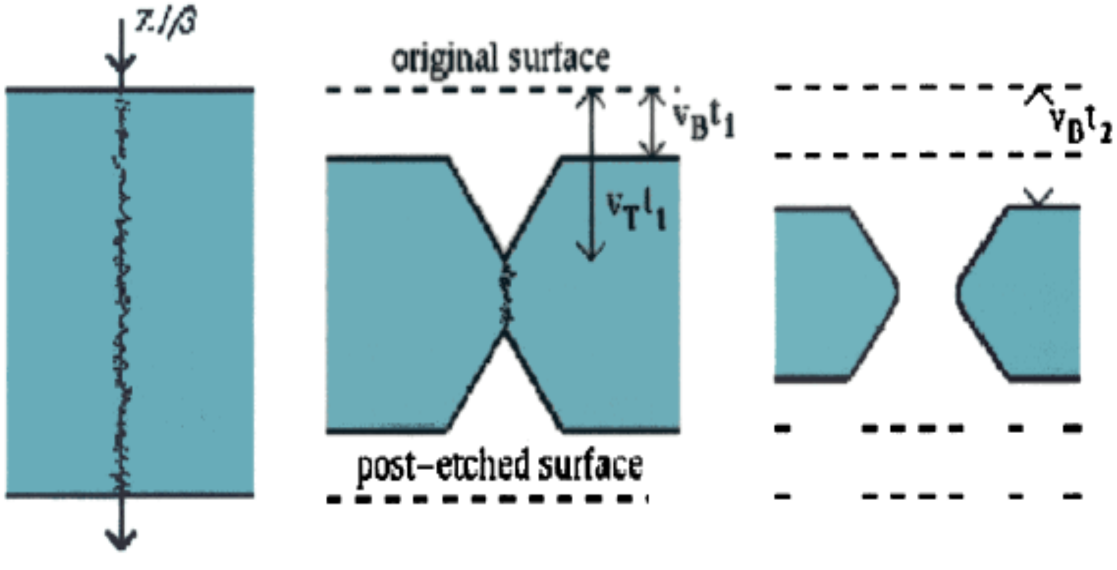


Fig. 3. Typical energy loss rate in a MACRO liquid scintillation

- ✓ 200 MHz WFD for pulse shape analysis
- ✓ Energy Reconstruction Processor (ERP): ADC/TDC system
- ✓ PHRASE: dedicated hardware for ν burst detection from SN

Track-etch detectors

- CR39/Lexan/CR39/Lexan/Al/CR39/Lexan wagons
- (24.5 x 24.5) cm^2 wagons
- Total surface : ~ 1263.2 m^2 (~ 7100 m^2 sr)
- Calibrated with slow and fast ions



(a)

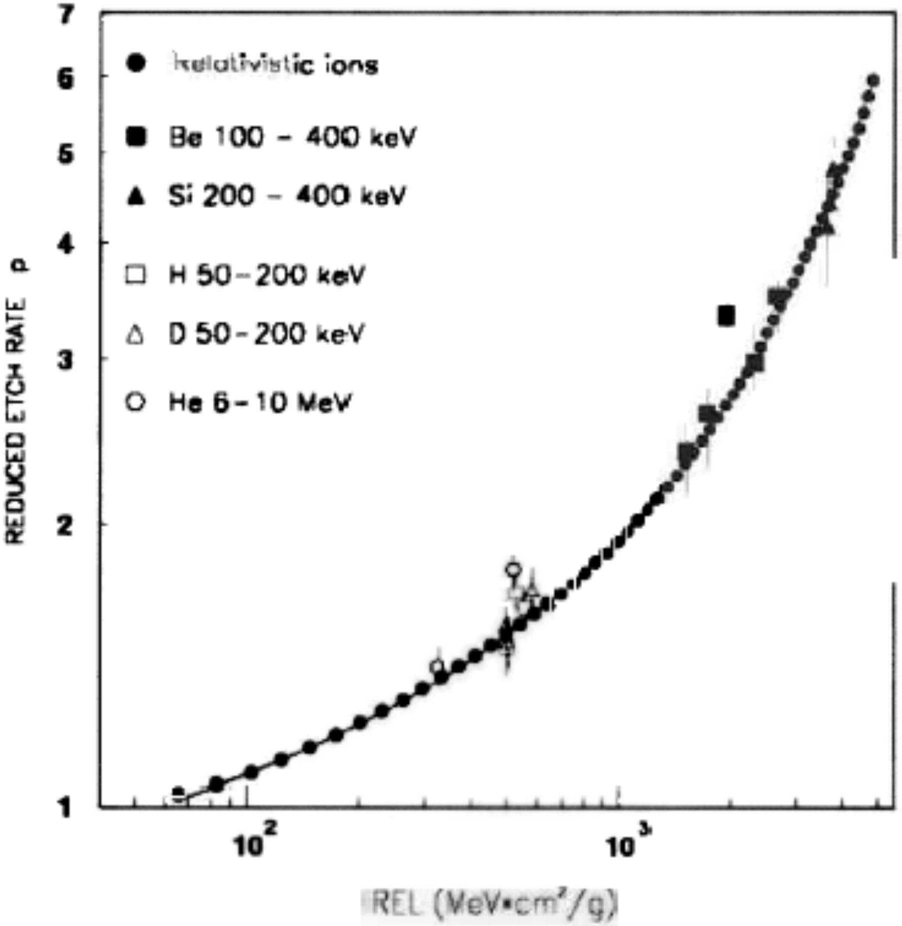
The reduced etch rate

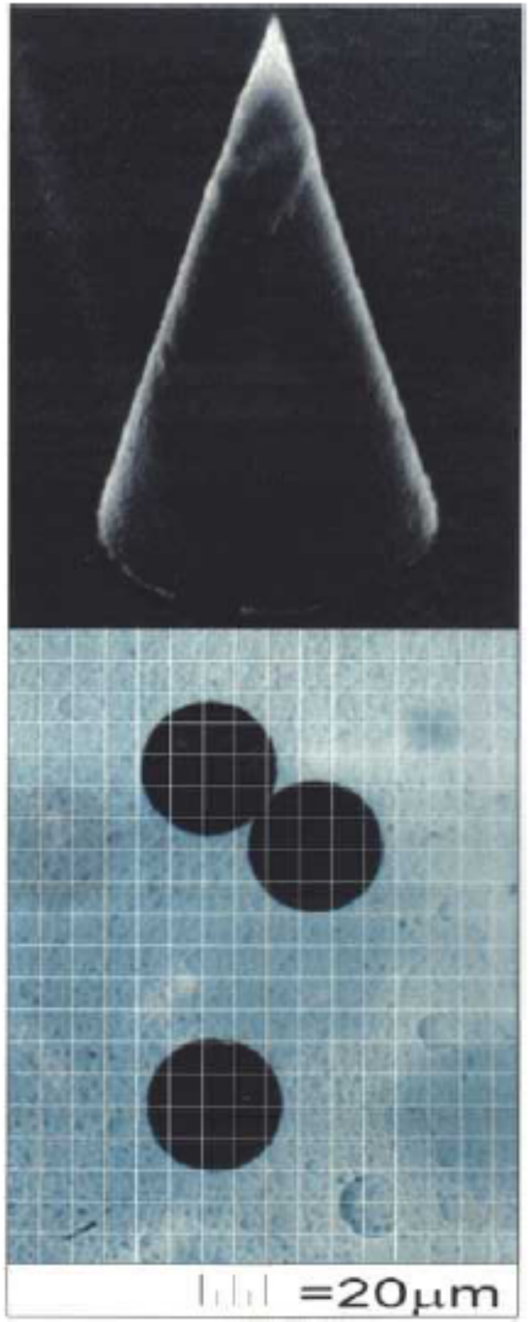
$$p = V_T/V_B$$

is simply related to the Restricted Energy Loss (REL)

$$REL = (dE/dX)_{E<Emax}$$

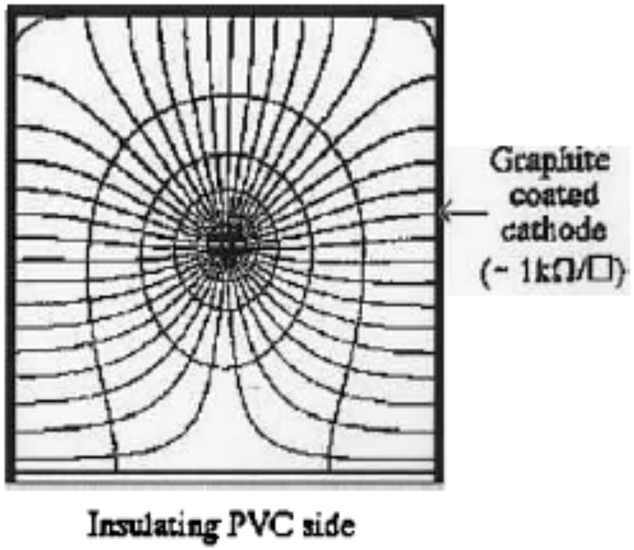
CR39 calibrations





Streamer Tubes

- (3 cm x 3 cm x 12 m) cell with 100μm Cu-Be wire
- Gas mixture: He (73%) + n-pentane (27%)
- Total surface : ~ 19000 m^2
- Maximum time jitter: 600 ns
- Pick-up strips for stereo track reconstruction
- Angular resolution: 0.2°



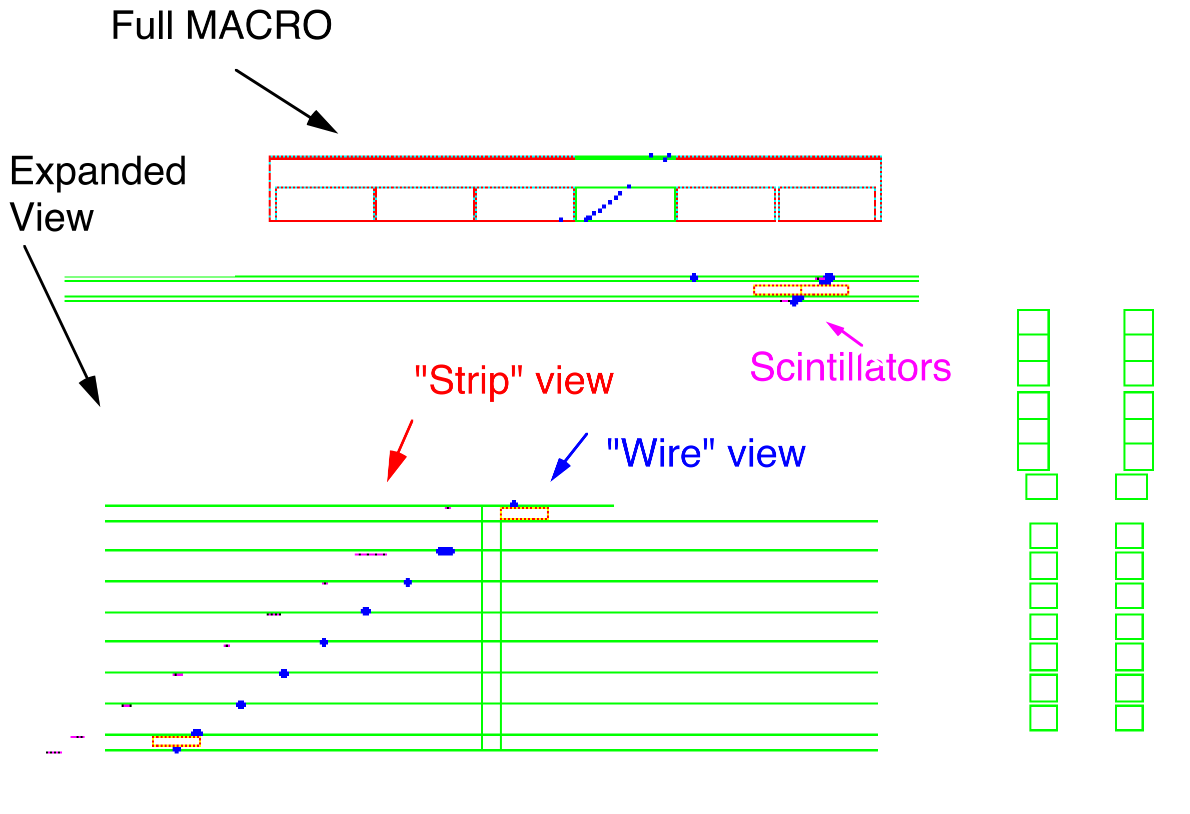
✓ Digital and analogic (OR of few ch's) readout

✓ Two temporal windows: FAST (10μs) and SLOW (500μs)

✓ Charge and Time Processor (QTP): ADC + 150ns sampling

Upgoing muon with 3 scintillator planes

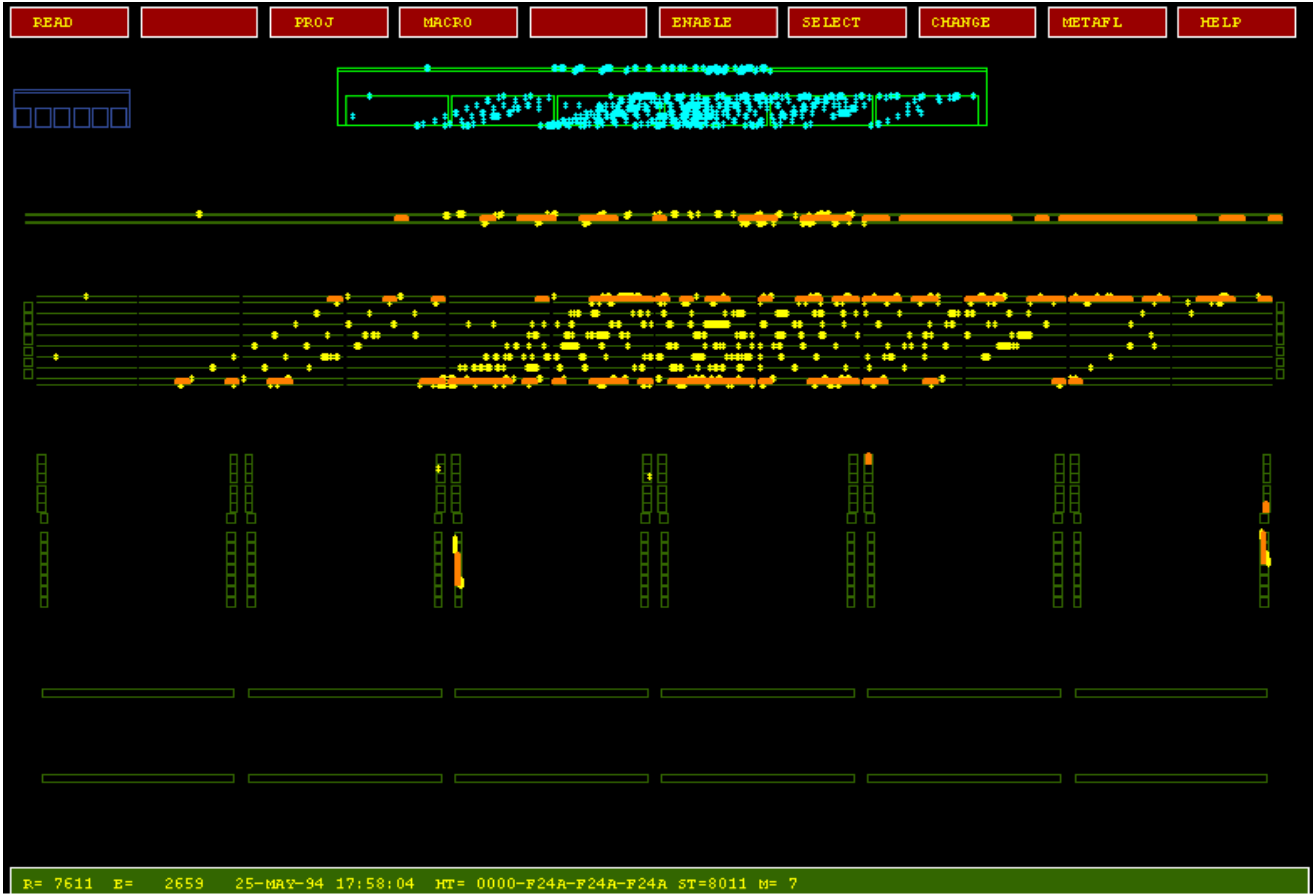
(produced by a CC neutrino interaction in the rock under MACRO)



$1/\beta = -1.01 \quad \chi^2 = 1.6$

R= 9000 E= 11864 28-DEC-94 21:32:39 HT= 0000-124A-0000-0000 ST= 0 M= 0

A big muon bundle (E>50000 GeV)



Magnetic monopole

- very old question (Pierre de Maricourt ≈ 1200)
- 1931 **Dirac: the magnetic charge g** should be multiple of

$$g = \frac{1}{2}\frac{h}{c}e$$

e is the elementary charge

Numerically g=68.5 e

A moving monopole produces an electric field $E = \frac{v}{c} \wedge B$

At high v/c $\frac{dE}{dx} \propto g^2 = 68.5^2 e^2$

Very large signals in detectors!

At low v/c : more complicated situation (kinematical thresholds to have ionization ecc.)

1974 `t Hooft, Polyakov

Magnetic monopoles in GUT's

- Produced as intrinsically stable topological defects during phase transitions in the Early Universe.
- Huge mass of the order of the energy scale of the symmetry breaking transitions. Unpredicted flux.
- Velocity expected around $\beta \sim 10^{-3}$ if gravitationally bound to the Galaxy. Larger velocity reached due to acceleration in magnetic fields.
- Astrophysical bounds to the monopole flux (e.g. the Parker bound)
- U.H.E.C.R. events above the GZK cut-off explained as due to monopole induced showers or to energy release in monopole-antimonopole annihilation.

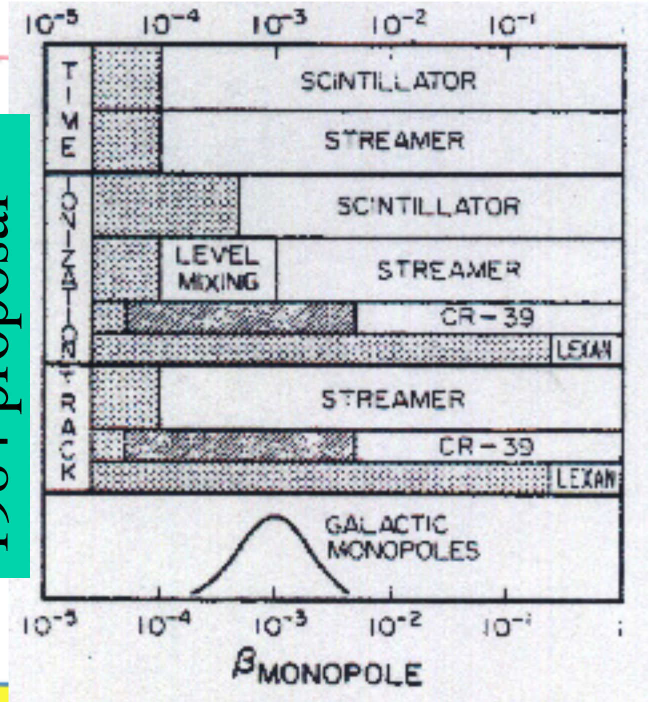
1982 1 event detected? Cabrera (superconductive loop)

Magnetic monopole searches in MACRO

Different analysis techniques are used in different β ranges:

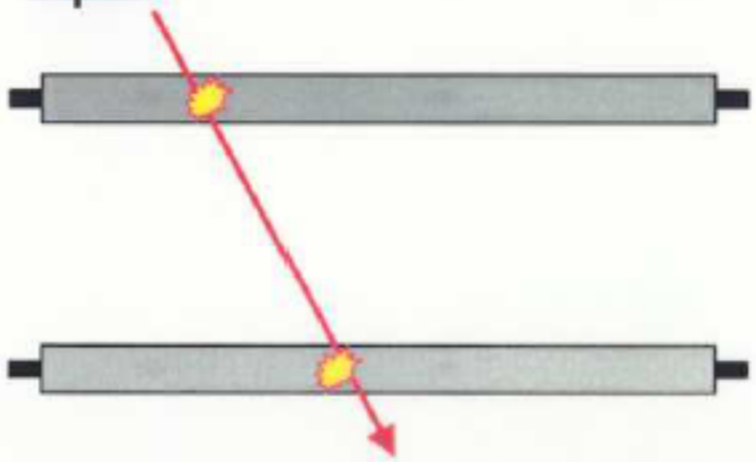
- ✓ searches with scintillators alone
- ✓ searches with streamer tubes alone
- ✓ searches with nuclear track-etch
- ✓ combined searches

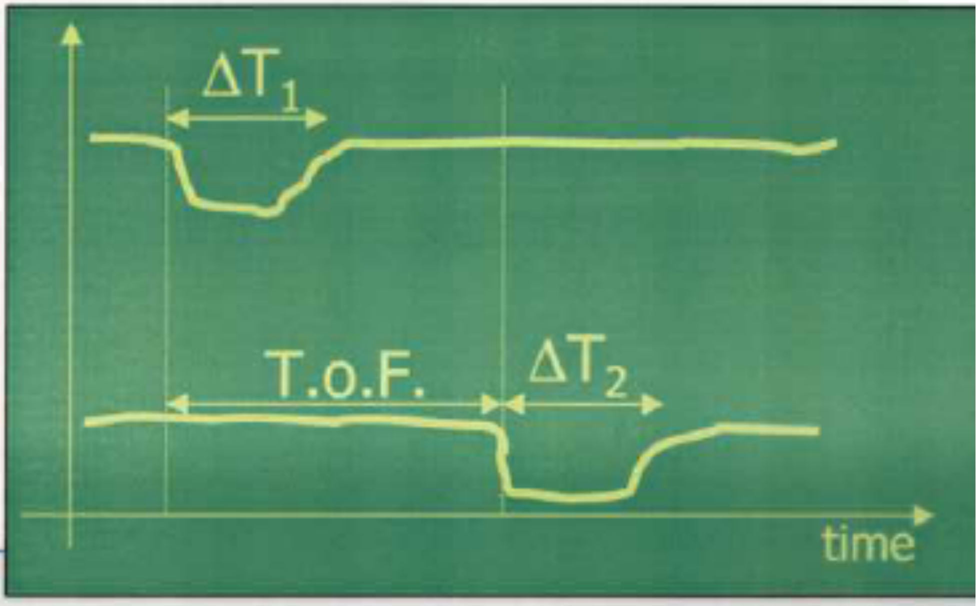
1984 proposal



Redundancy & Complementarity

Search with scintillators alone





✓ Study of the PMT pulse

✓ Measurement of the light yield

✓ Consistency check between the box crossing time and the ToF across MACRO

For slow monopoles the PMT pulse might reduce to a train of single photoelectrons.

Dedicated hardware: trigger + WFD

Search with streamer tubes alone

Velocity range: $10^{-4} \leq \beta \leq 5 \cdot 10^{-3}$

- Sensitivity down to $\beta \sim 10^{-4}$ allowed by the Drell effect on He
- Sensitivity for $\beta > 5 \cdot 10^{-3}$ forbidden by the huge muon background

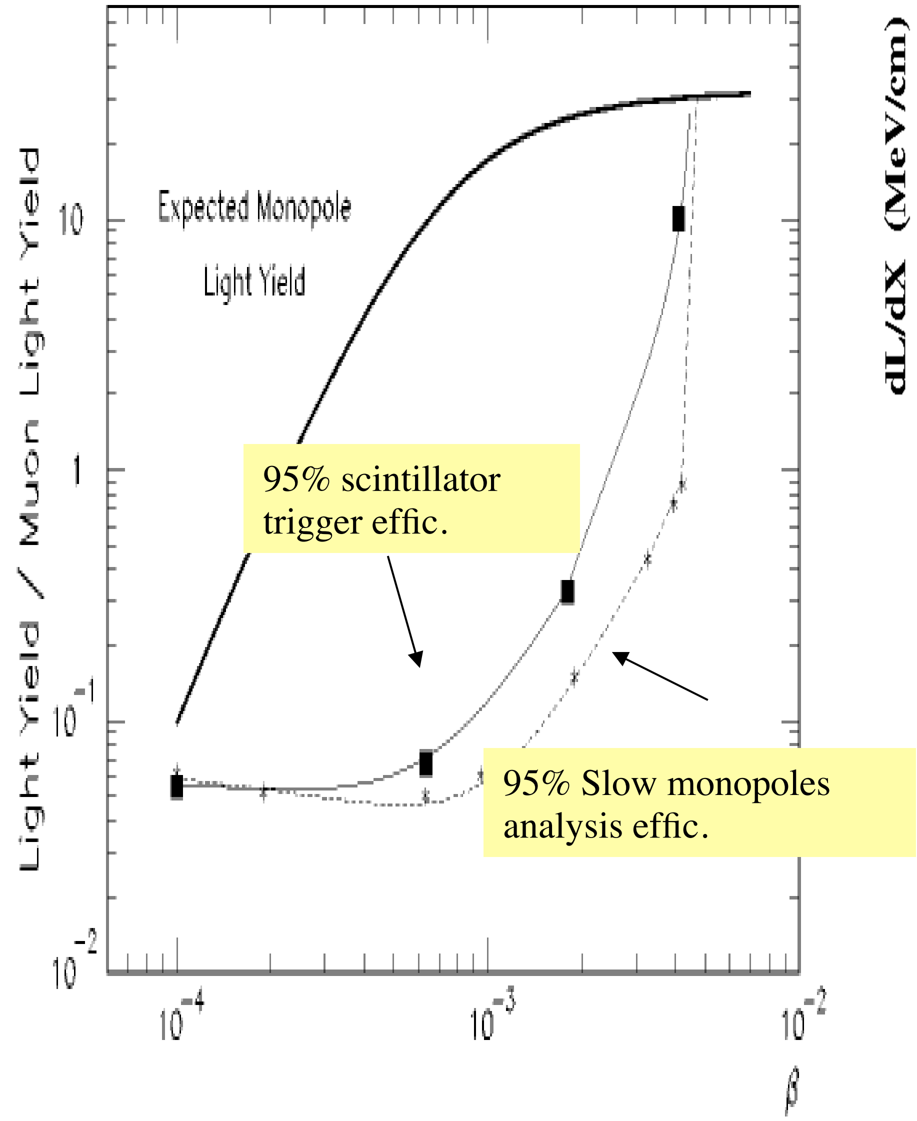
Analysis strategy:

- look for slow particles crossing MACRO with constant β

Background:

- Accidental coincidences of radioactivity background hits ($\sim 40 Hz/m^2$)
- Electronic noise, pick-up, cross-talk

Magnetic monopole combined search using the 3 detectors



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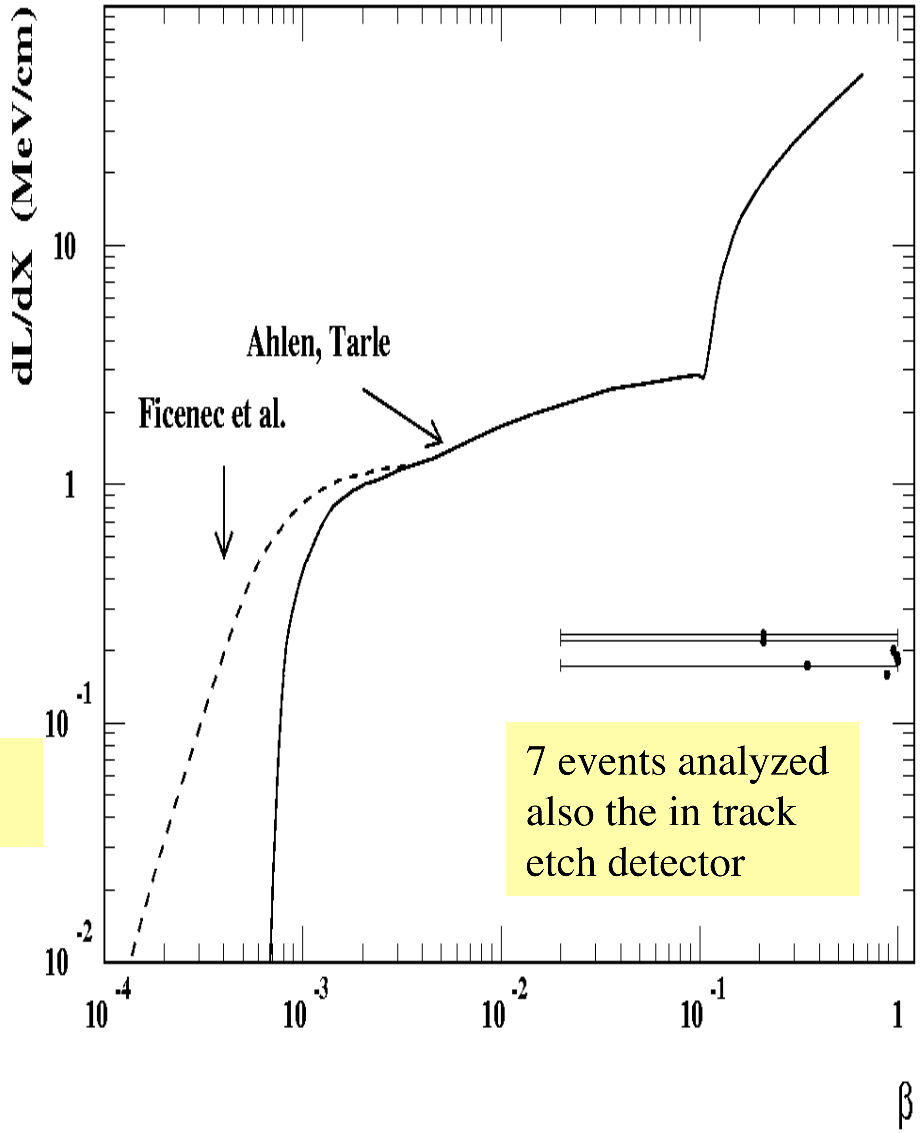
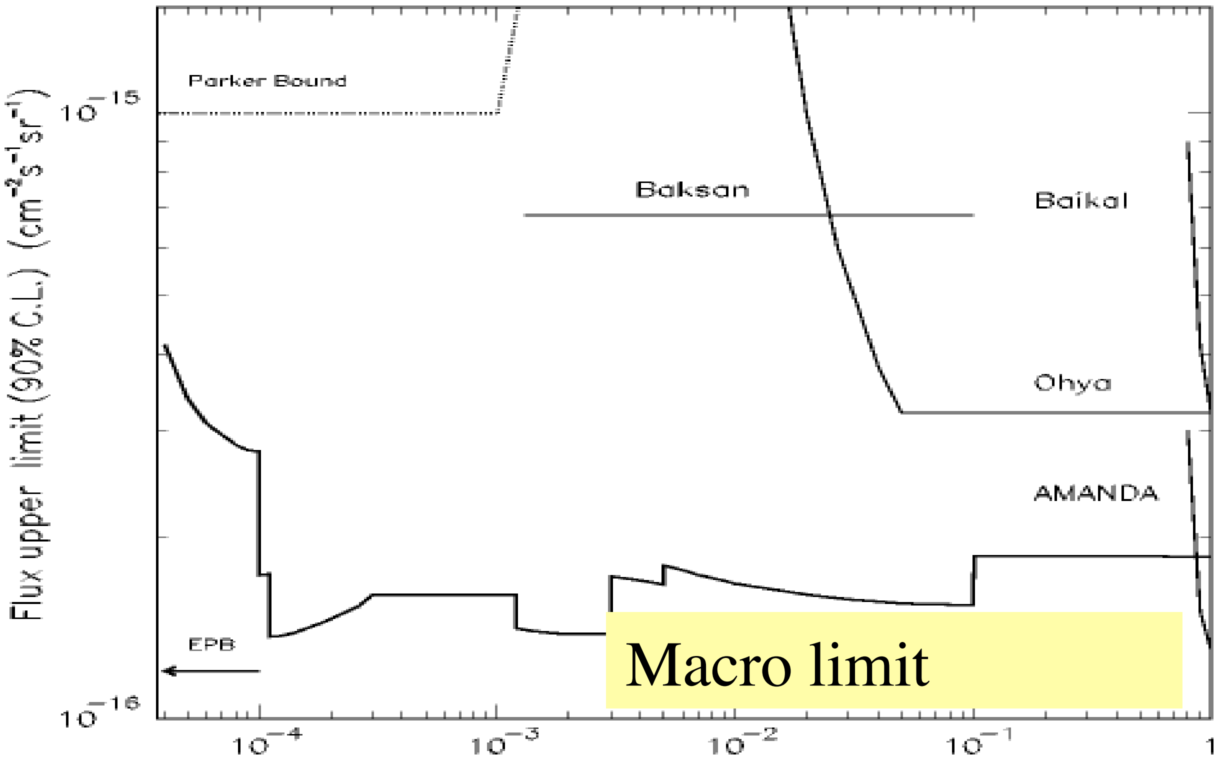
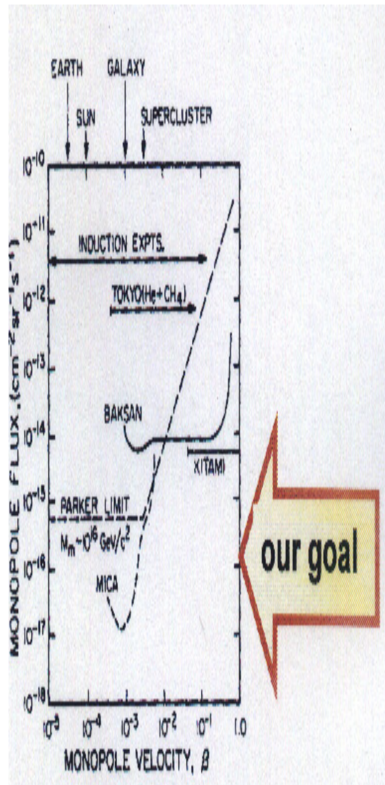


Limits to the monopole flux





1984 proposal

Fig. 9. The global MACRO limit for an isotropic flux of bar

magnetic monopoles, with $m \geq 10^{17}$ GeV/c^2, $g = g_D$ and $\sigma_{cat} <$ few mb. For comparison, we present also the flux limits from other experiments.

Search for other massive exotic particles

NUCLEARITES: aggregates of SQM (Strange Quark Matter)

(E.Witten PRD30 (1984) 272 - A.De Rujula and S.L.Glashow Nature 312 (1984) 734)

Look for signatures (large energy release) in Scintillators and Track-etch.

Acceptance depends on SQM mass and velocity.

Discovered ? See http://www1.msfc.nasa.gov/NEWSROOM/news/releases/2002/02-082.html

Q-balls: aggregates of squarks, sleptons and Higgs fields

(S.Coleman NPB262 (1985) 293 – A.Kusenko & M.Shaposhnikov PLB417 (1998) 99)

Search for electrically charged Q-balls by means of their substantial energy release along a straight track with no attenuation throughout the detector.

Scintillators, streamer tubes and track-etch detectors are sensitive to Q-balls in different β ranges.

Limits to the nuclearite flux

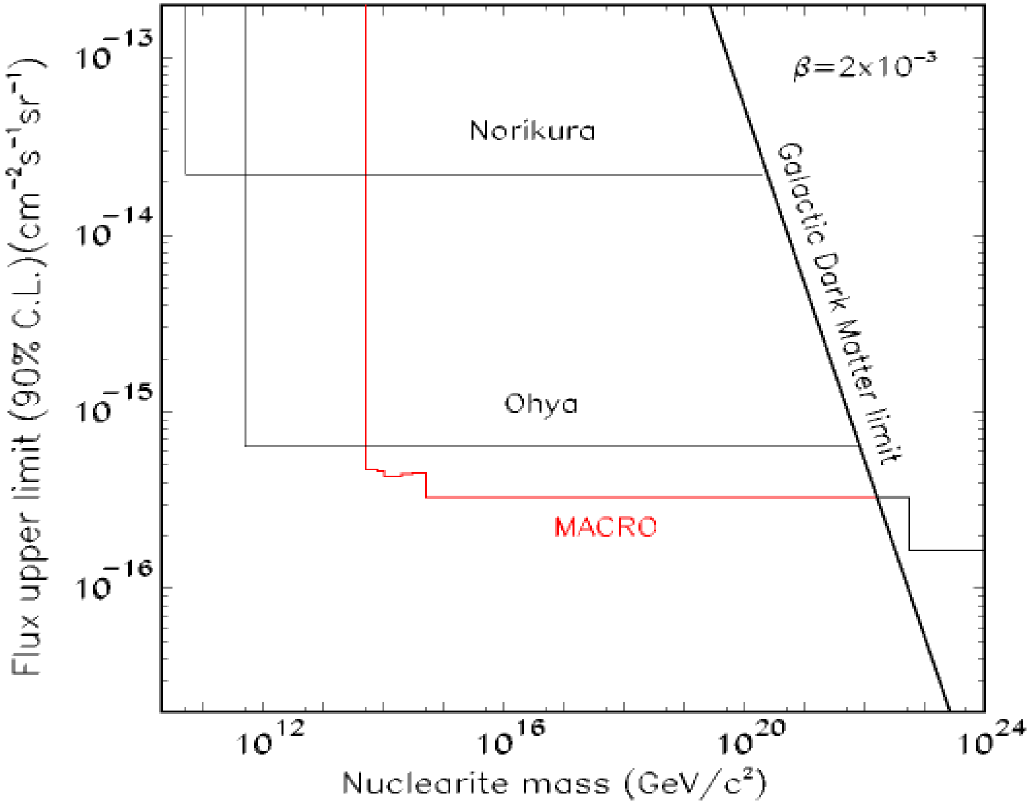
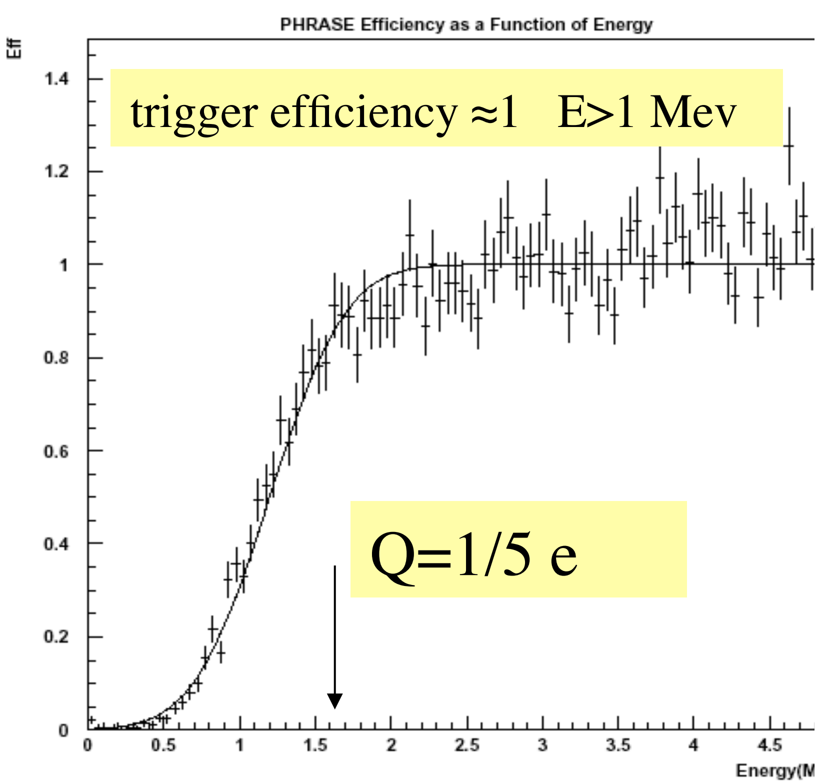


Figure 14: 90% c.l. flux upper limits vs. mass for nuclearites with $\beta = 2 \cdot 10^{-3}$ at ground level. Nuclearites of such velocity could have galactic or extragalactic origin. The MACRO direct limit (solid line) is shown along with the other direct limits [70, 71]; the indirect mica limits of [73, 74] are at the level of $2 \cdot 10^{-20} cm^{-2} s^{-1} sr^{-1}$. The limits for nuclearite masses larger than $5 \cdot 10^{22}$ GeVc^{-2} correspond to an isotropic flux.

Search for lightly ionizing particles (free quarks etc)



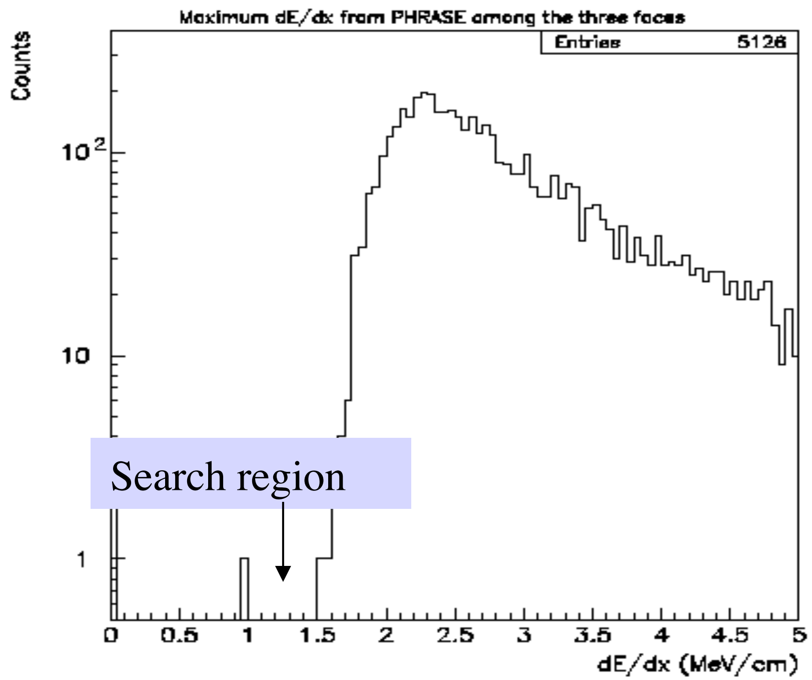


Fig. 1. The measured efficiency of triggering the low-en PHRASE trigger and the LIP trigger as a function of the en released in the liquid scintillation counters. Some measured ciencies were greater than 100 % because the normalization fa used was an estimate of the true normalization as a function o ergy.

Fig. 2. Energy loss as measured by PHRASE for the 5126 LIP events that passed the track quality and geometry cuts and satisfied the requirement of a maximum energy loss rate (measured by ERP) less than 1.1 MeV/cm. The signal region is in the [0, 1.4] MeV/cm interval. For the events in the signal region, see the text.

Flux limit ≈ **1.6 10^{-15} cm^{-2} sec^{-1} sr^{-1} for Q 1/5 : 2/3 *e*** to be improved with full statistics

Cosmic Rays : a few remarks

Cosmic Rays at Sea Level are due to secondaries produced in the interactions of a primary (proton or nucleon) in the Atmosphere

Energy Spectra (of primaries) in the range of energies up to 1000 Tev $\alpha \approx 2.7$,after 1000 Tev α increases **(“knee”)**

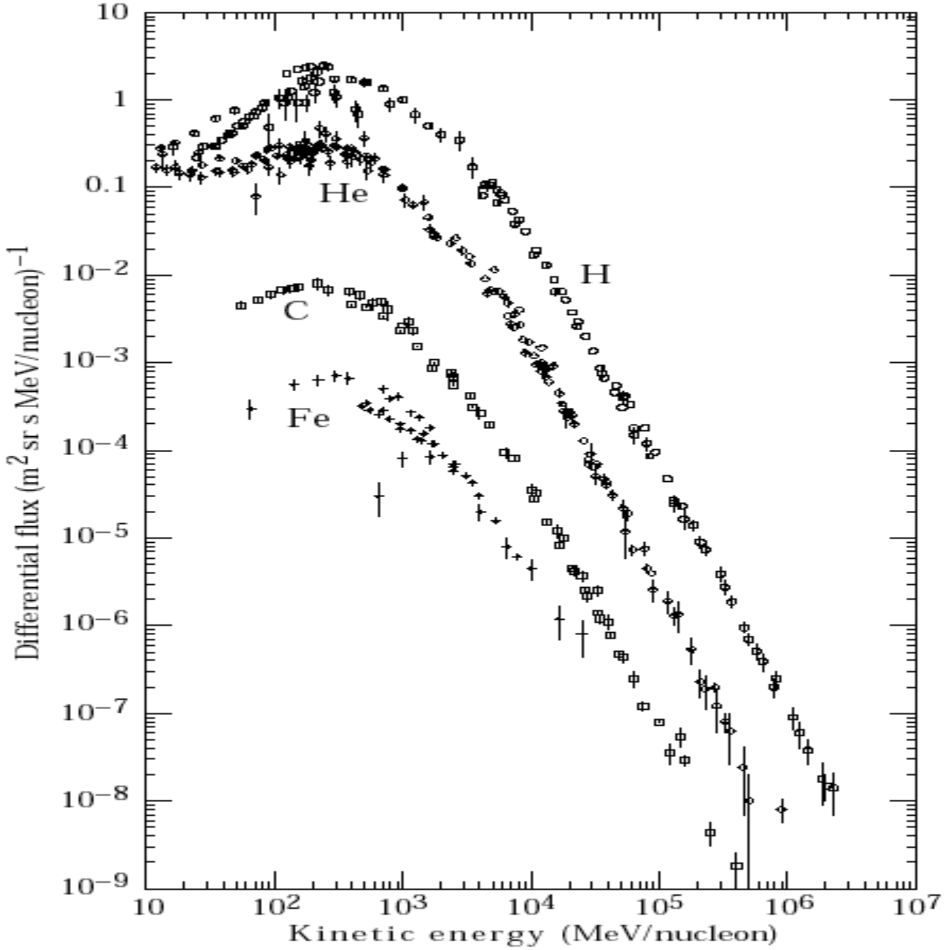
$$I_N(E) \approx 1.8\, E^{-\alpha} \frac{\text{nucleons}}{\text{cm}^2 \ \text{s} \ \text{sr} \ \text{GeV}}$$

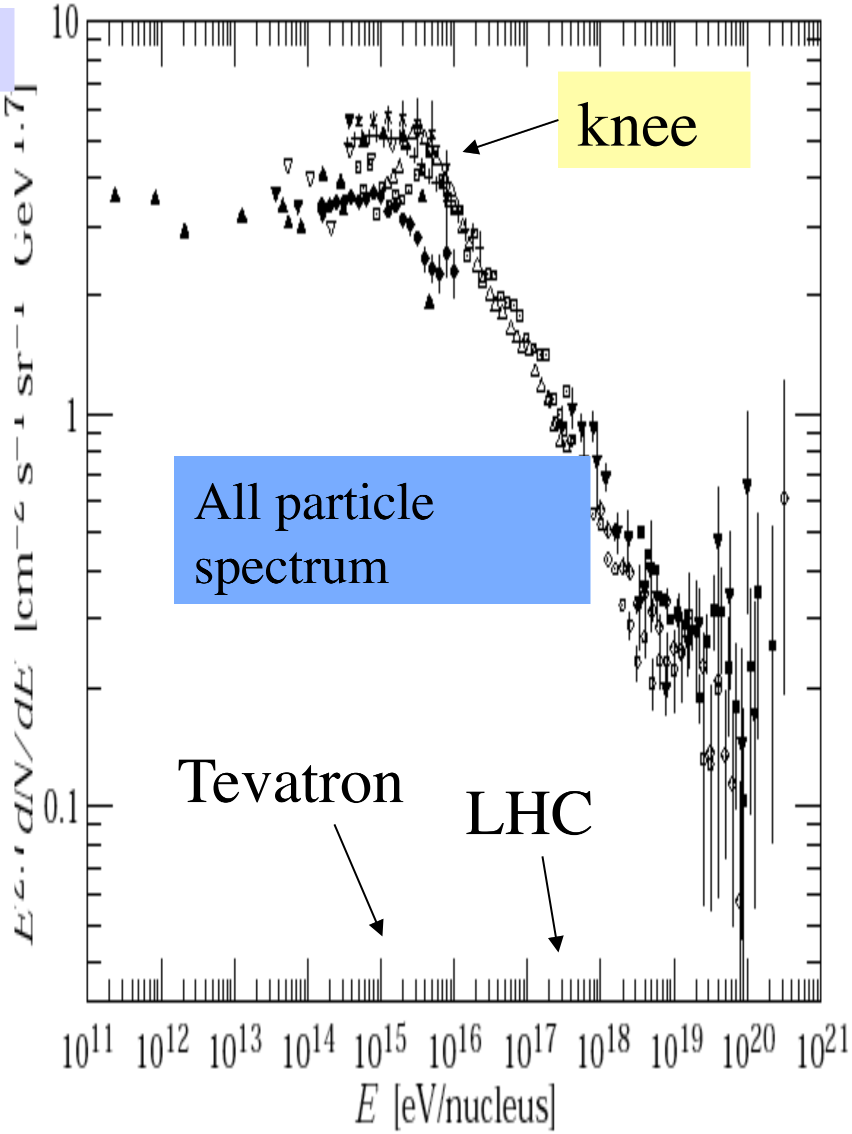
The Cascade is a **Complex Phenomena** not fully understood . Complicated Montecarlo Calculations are in a continuos Development. The detailed Simulation of the Cascade is **Difficult.** Kinematical region not explored by accelerator experiments

At the sea level three main components : electrons (+ photons), muons, hadrons. Only muons and neutrinos undergorund **At energy < 1000 TeV cosmic ray produced probably in the supernavae shock waves. Open problem at higher energy.**

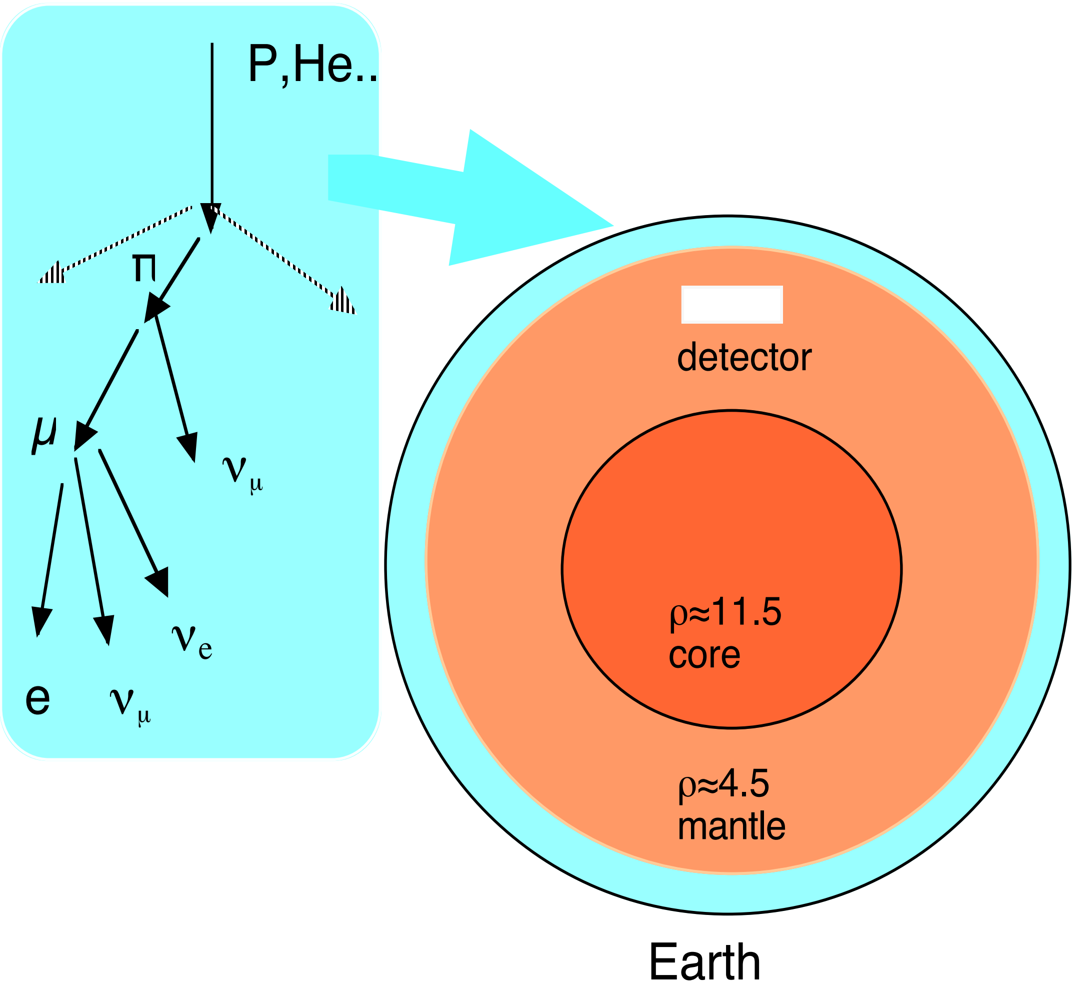
Cosmic Rays - a few remarks - Composition

Direct measurements only at low energy

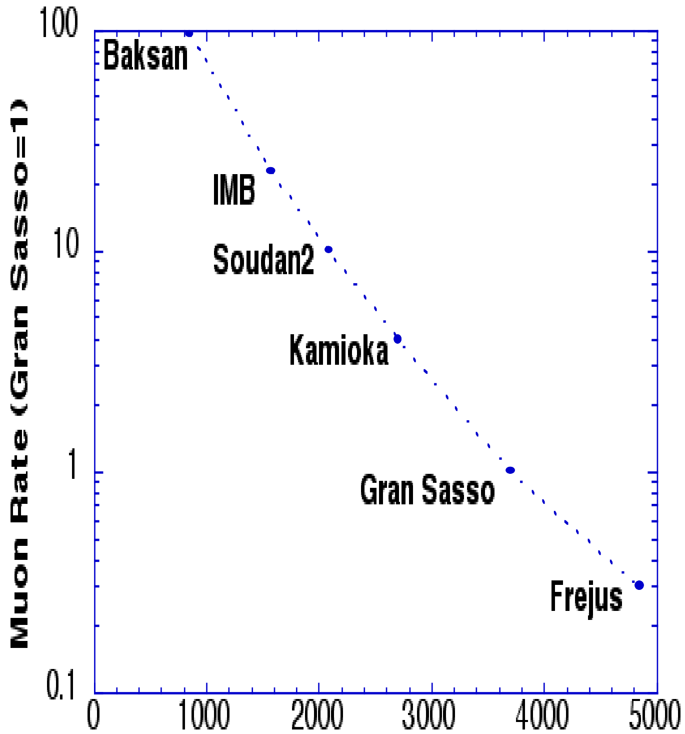




Cosmic Rays : the hadronic cascade

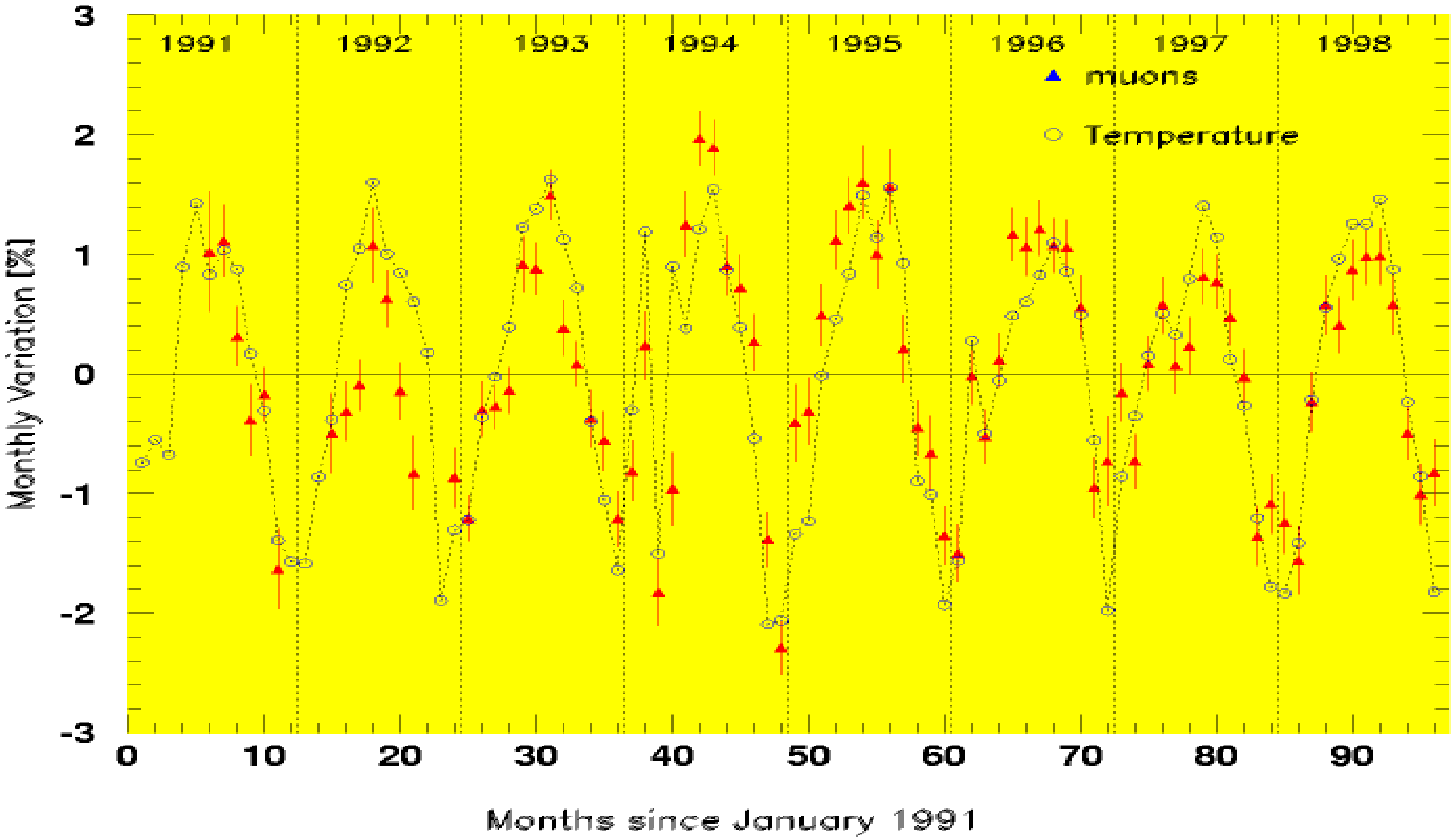


Muon rate underground



MACRO Cosmic Rays study :
Down-going Muon rate and Seasonal Effect

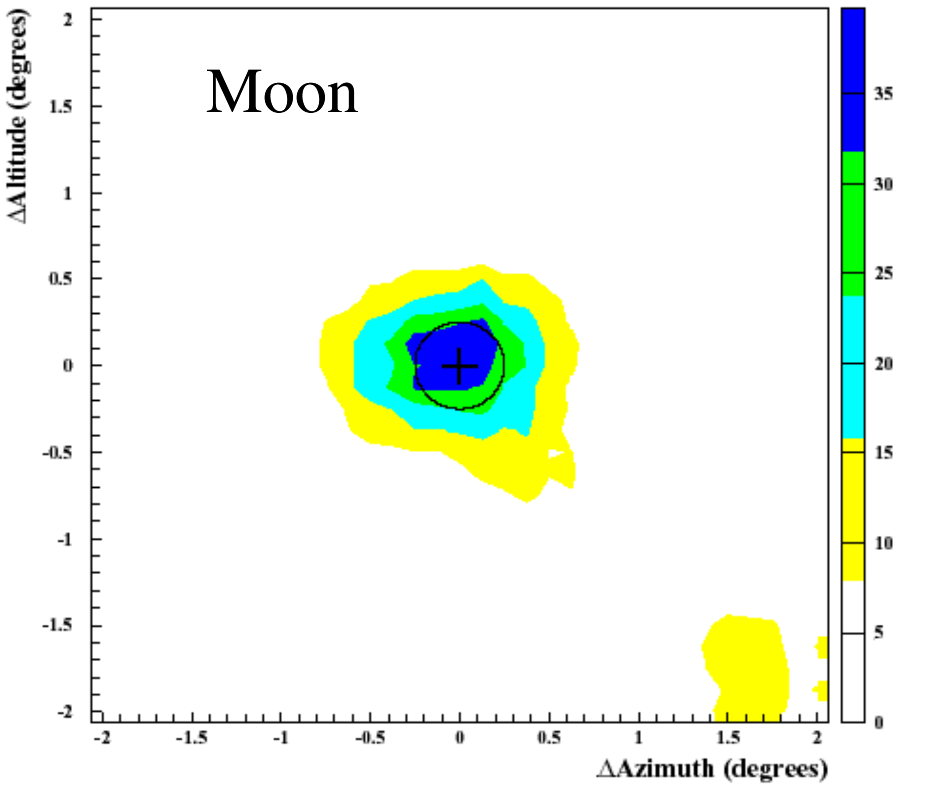
Study of the seasonal effect: the muon rate is a function of the atmosphere profile dependent from the temperature



Cosmic Rays study : Astronomy with Down-going Muons

Found (in an expensive way!) **the moon and the sun** (as event deficit)

All sky search : no positive signal detected (as expected : charged particles are deflected by the galactic magnetic field)



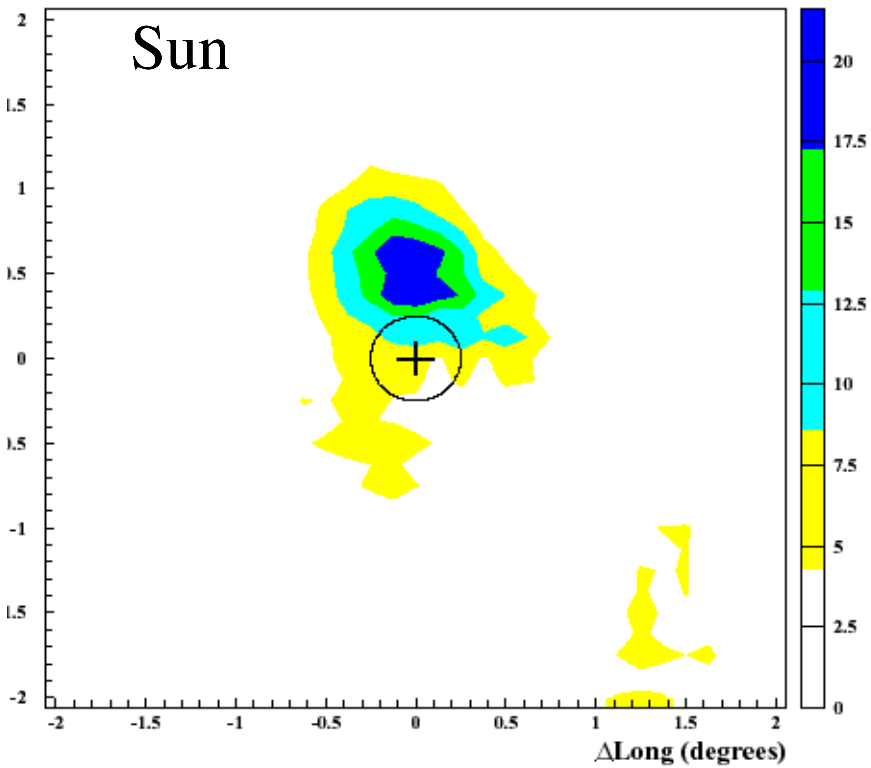


Fig. 1. χ^2 levels in the sky windows centered on the Moon position. The maximum value of χ^2 is 39.7 at (+0.°,+0.1°) corresponding to more than 6 σ signal.

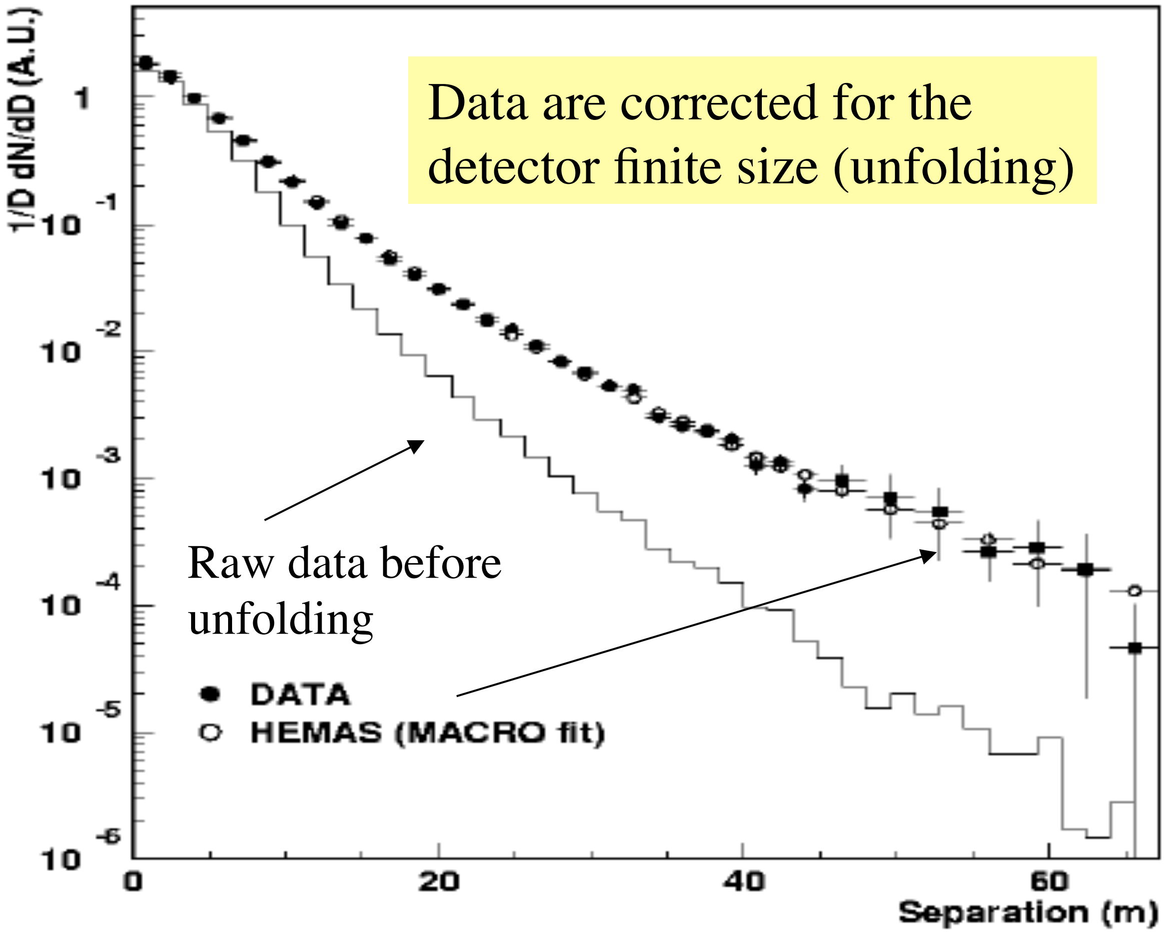
. **4.** χ^2 levels in the sky windows centered on the Sun position ıg ecliptic coordinates. The maximum value of χ^2 is 21.6 at °,+0.625°) corresponding to more than 4.5 σ signal.

Cosmic Rays : check of the models for the cascade development at the "knee"

For example:

Study of the muon distance in muon bundles

"decoherence"



Cosmic Rays: cosmic ray composition at "knee" MACRO EAS-TOP Coincidences

EXPERIMENTAL DATA

SIMULTANEOUS EAS MEASUREMENTS OF:

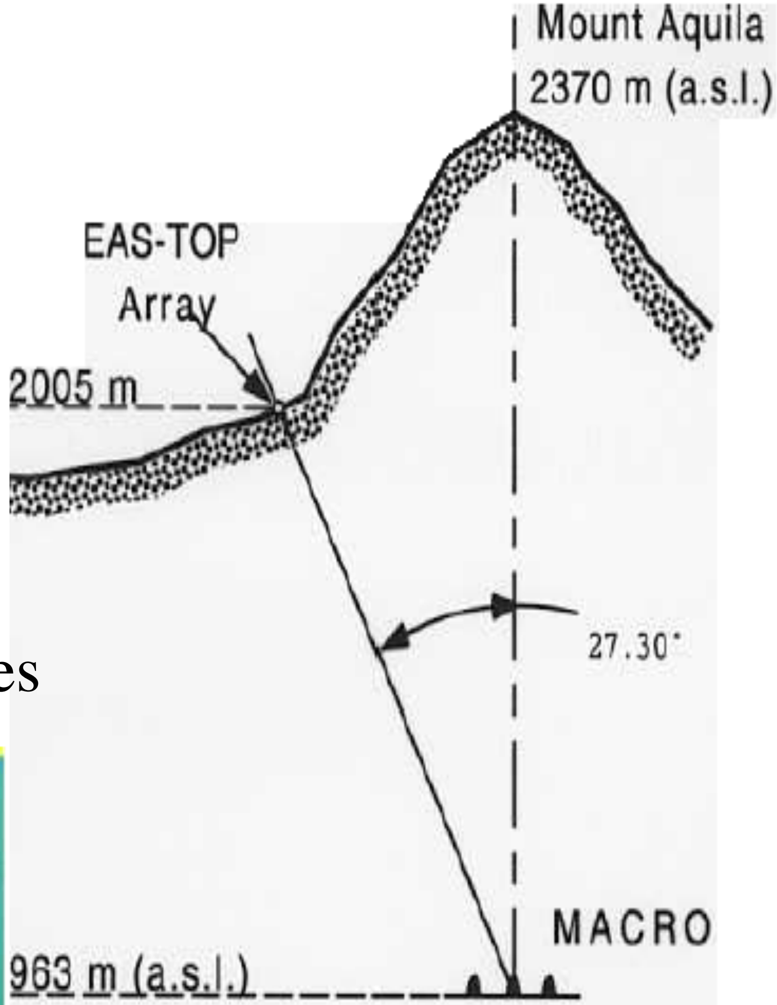
SHOWER SIZE AT 2000 m a.s.l.
by EAS-TOP (Campo Imperatore)
35 x 10 m^2 scintillator modules, Aeff = 10^5 m^2

TeV MUON NUMBER AT 3100 m w.e.
by MACRO (Deep underground Gran Sasso Labs.)
6 x 120 m^2 tracking modules, Aeff= 920 m^2

23043 h live time 28160 coincidences

SECONDARIES PRODUCED IN CM KINEMATIC REGION:

Y - Ybeam ~ - 4.5 @ Ybeam ~ 7.5



...re 1: National Gran Sasso Laboratories: relative location of EAS-TOP and MACRO.

Cosmic Rays : cosmic ray composition at “knee” MACRO EAS-TOP Coincidences

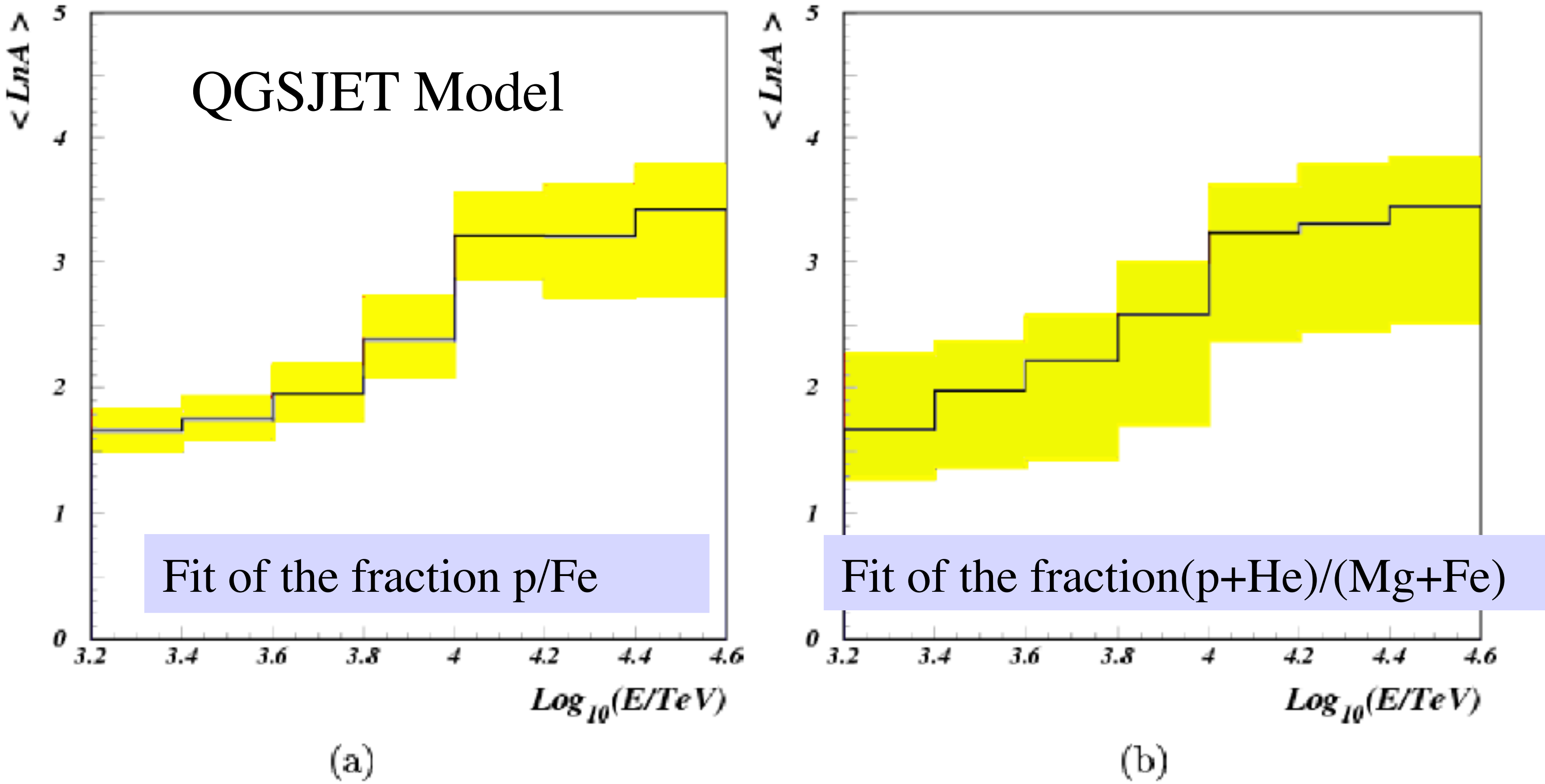


Figure 21: EASTOP-MACRO coincidences. $\langle lnA \rangle$ vs primary energy for: (a) p/Fe and (b) $Light/Heavy$ compositions. The histograms (black lines) are obtained from the data, the shaded areas include the uncertainties discussed in the text.

Cosmic Rays study : cosmic ray composition at "knee" MACRO EAS-TOP Coincidences

The change of composition support the idea of different origin of cosmic ray above the knee

However the result depends strongly from the interaction model

Similar results obtained by several experiment at sea level (Kascade - Casa Mia…Eμ>≈a few GeV). MACRO is the only one with Eμ>≈ 1.4 TeV.

This data could be used in future combined analysis of all experiments

Milestones in the Oscillating Neutrino

1930 Pauli : the "neutrons" to explain the missing energy

1934 Fermi : theory of beta decay and the word "neutrino"

1956 Reines and Cowan et al.: first direct detection of electron neutrino

1957 Pontecorvo : suggestion of neutrino oscillations

1963 Lederman Schwartz Steinberg detection of muon neutrino

1965 (Reines in South Africa and the KGF experiment in India) : first detection of atmospheric neutrinos

1968 Davis et al.: first detection of neutrinos from the SUN. Flux lower than expected. $\delta m^2 \approx 10^{-10}$ (vacuum solut.) or $\delta m^2 \approx 10^{-5}$ eV^2

1986 Beginning of the Atmospheric Neutrino Anomaly (IMB - Usa and then Kamiokande Japan) $\delta m^2 \approx 10^{-3} \div 10^{-2}$ eV^2

1995 LSND experiment anomaly(Los Alamos) $\delta m^2 \approx 0.1 \div 1$ eV^2

Milestones in the Oscillating Neutrino

1998 Evidence for Oscillations in the Atmospheric Neutrinos? (Superkamiokande, Soudan2,MACRO,...)

2002 SNO : evidence for muon neutrino appareance in the path from the SUN to the Earth and matter effect in the earth

The Oscillating Neutrino

- **Pontecorvo suggestion :**

if we postulate

1) Neutrino have different masses
2) The Weak eigenstate is a mixture of Mass Eingenstate then:

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos(\theta) & e^{i\delta}\sin(\theta) \\ -e^{-i\delta}\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

and the survival probability for ν_μ neutrinos is :

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

L in Km, E in GeV, $\Delta m^2 = m_1^2 - m_2^2$ in $(eV/c^2)^2$

The Oscillating Neutrino: Matter effects

Oscillating Neutrino crossing the Sun/Earth could have a "Matter Effect" (MSW).
This occurs when the two oscillating neutrinos have different interactions in the matter (for example ν_e has interaction with electrons in the matter different from ν_μ)

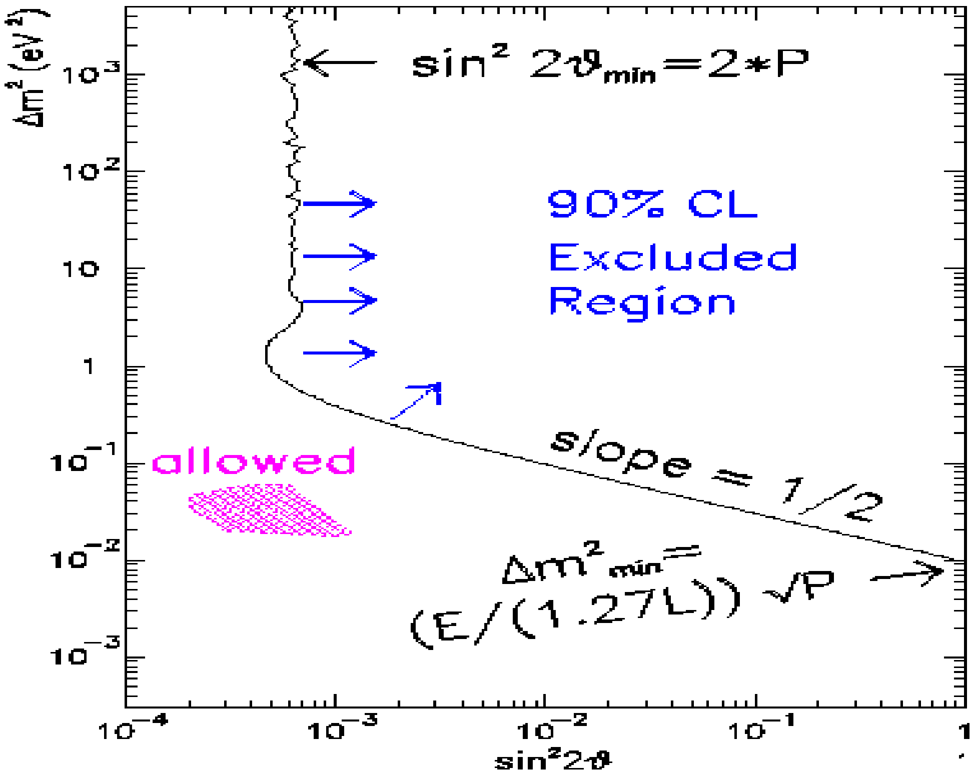
$$V_{weak} = \frac{\pm G_f n_B}{2\sqrt{2}} \times \begin{cases} -2Y_n+4Y_e & \text{for } \nu_e \\ -2Y_n & \text{for } \nu_\mu,\nu_\tau \\ 0 & \text{for } \nu_s \end{cases}$$

+ sign for neutrinos, n_B= barion density, Y_n,Y_e= neutrons (electrons) for one barion

quite important in the three flavor oscillation analysis and in the sterile neutrino analysis

for mixing=1 the effective mixing is reduced for the matter effect
for mixing<1 enhancement for particular values of parameters (MSW resonance)

The Oscillation Plot



the line is defined typically by $\chi^2 = \chi^2 min + x$ (x=4.6..). X depends from the "physical region"

Not well defined (Feldman Cousins) *also called exclusion plot*)

This plot has no information on the goodness of one of the two hypotheses (oscill. in a given flavor /no oscill) should be done only with a good χ^2min.

- ***large*** Δm^2 **due to the energy spread of a typical neutrino beams** $Posc = \frac{\sin^2(2\theta)}{2}$
- ***small*** Δm^2 $Posc = \sin^2(2\theta)\left(1.27\Delta m^2 \frac{L}{E}\right)^2$

Neutrino Oscillations was one of the motivation for the MACRO proposal (1984)!!

Neutrino Oscillation Studies (from the proposal)

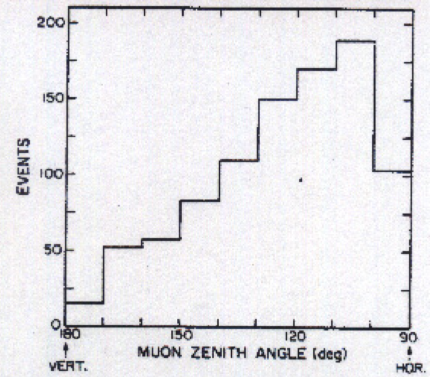


Fig. (2)11 Expected angular distribution of upward-going muons for 2.5 years of operation assuming no oscillations.

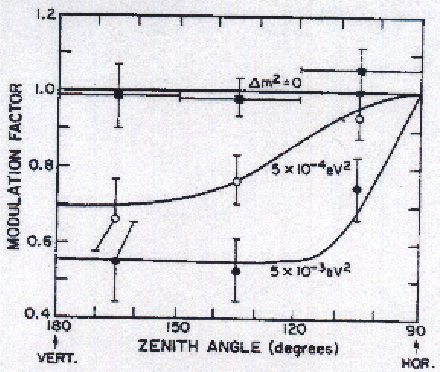


Fig. (2)12 Modulation factor of upward-going muons as a function of zenith angle. Solid lines are based on 50,000 simulated events. The data points indicate the results of a simulated experiment of two years duration.

In 1984, proposal anticipates MACRO sensitivity and contribution to neutrino oscillations ....

Hence, in two years of operation, our experiment can set a 3σ limit for neutrino oscillations for mass differences in excess of 10^{-3} eV^2 for maximal mixing. In Fig. (2)13, this limit (shaded region) is compared with the present limits set by other neutrino oscillation experiments. For $\sin^2 2\theta > 0.6$, the experiment should yield nearly an order of magnitude improvement for the limit on Δm^2.

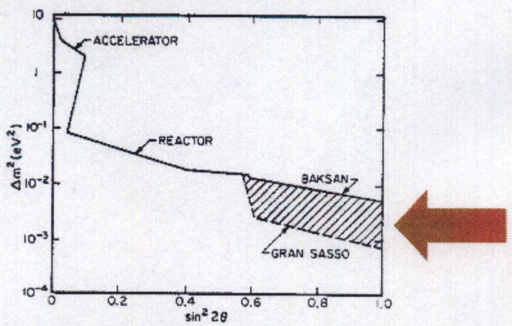
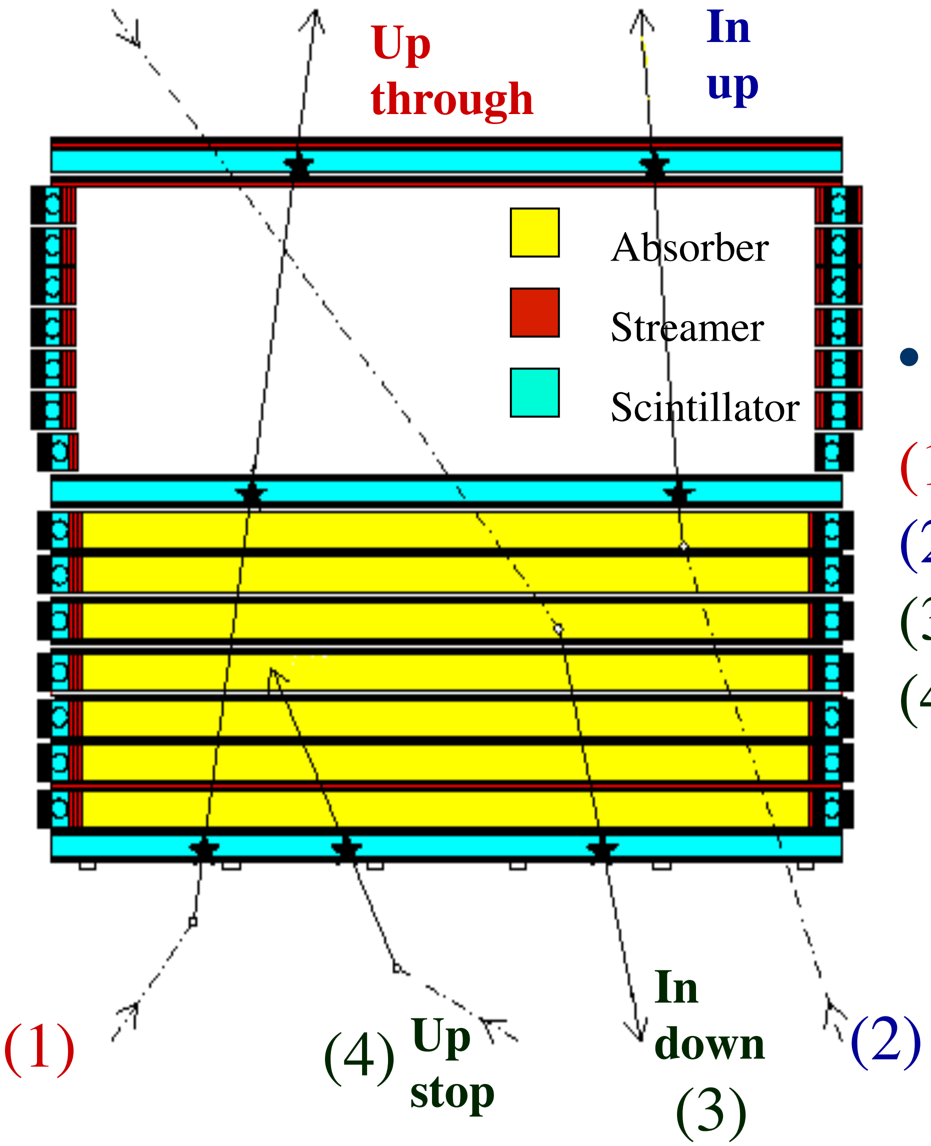


Fig. (2)13 Present best limits on Δm^2 vs. $\sin^2 2\theta$. The shaded region represents the improvement obtainable with our experiment.

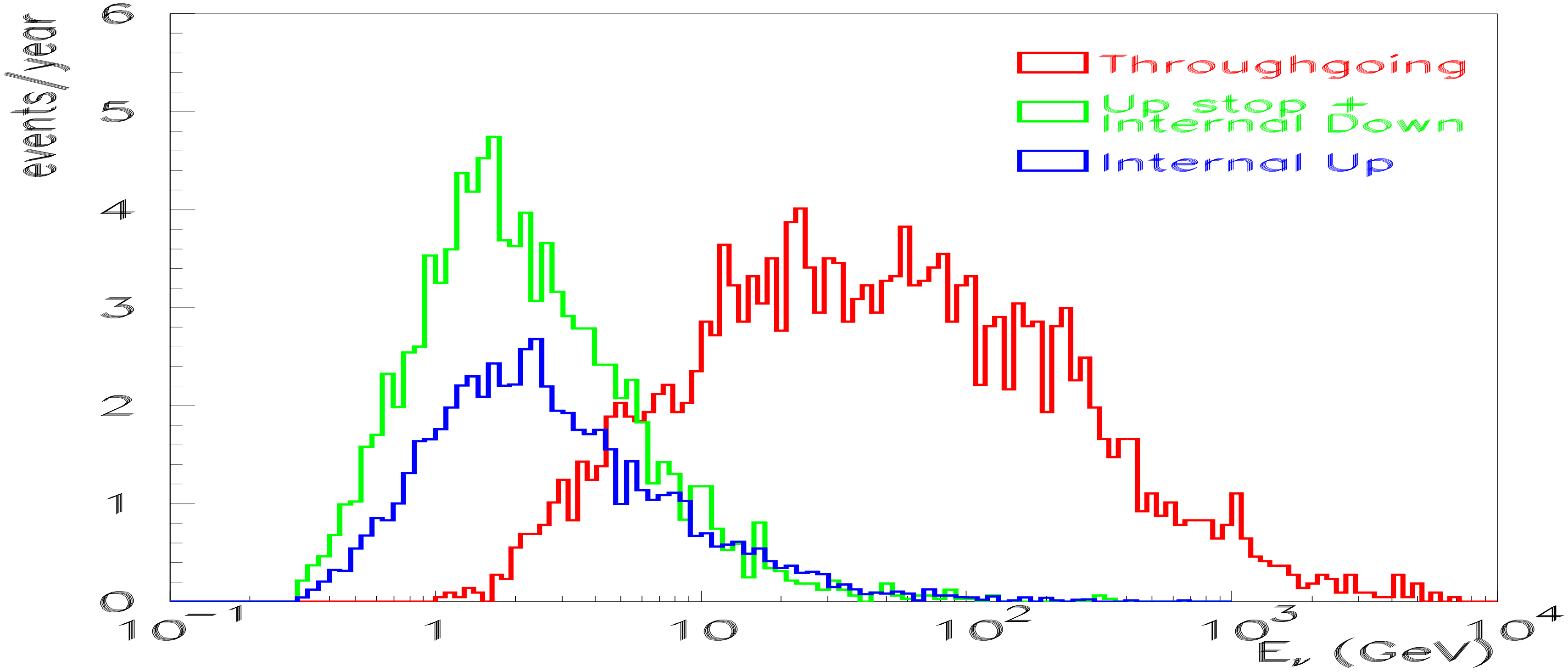
Neutrino event topologies in MACRO



- **Detector mass ~ 5.3 kton**

(1) Up throughgoing μ (ToF)
(2) Internal Upgoing μ (ToF)
(3) Internal Downgoing μ (no ToF)
(4) UpGoing Stopping μ (no ToF)

Energy spectra of ν events detected in MACRO

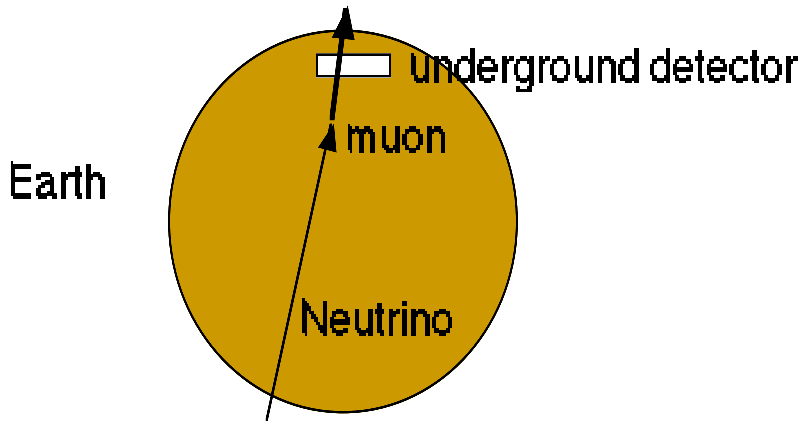


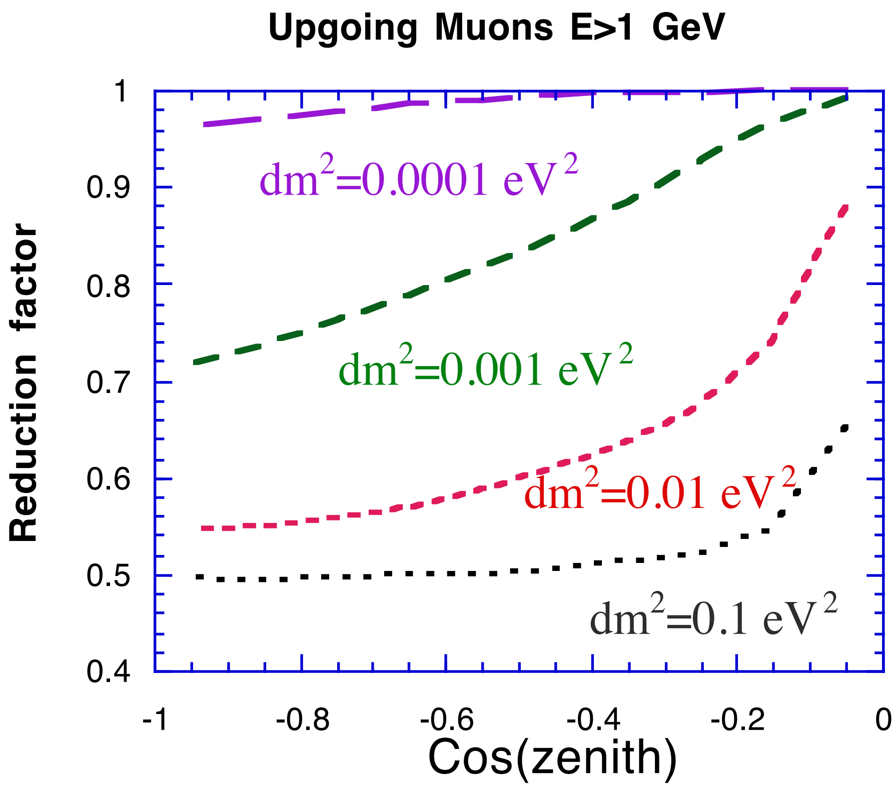
- E_{median} ~ 50 GeV for Throughgoing muons;
- E_{median} ~ 4.5 GeV for Internal Upgoing (IU) μ;
- E_{median} ~ 3.5 GeV for Internal Downgoing (ID) μ and for UpGoing Stopping (UGS) μ;

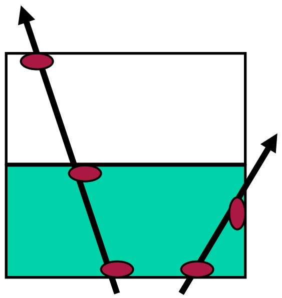
Low energy events (IU, ID+UGS) allow to investigate the ν oscillation parameter space <u>independently</u> from throughgoing muons

UP Going Muons (Through-going)

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



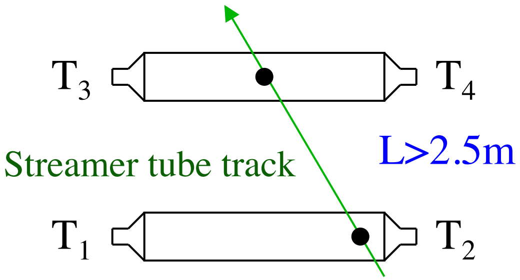




Neutrino Induced Upward Throughgoing muons

Event selection based on *time-of-flight method*

* β evaluation:

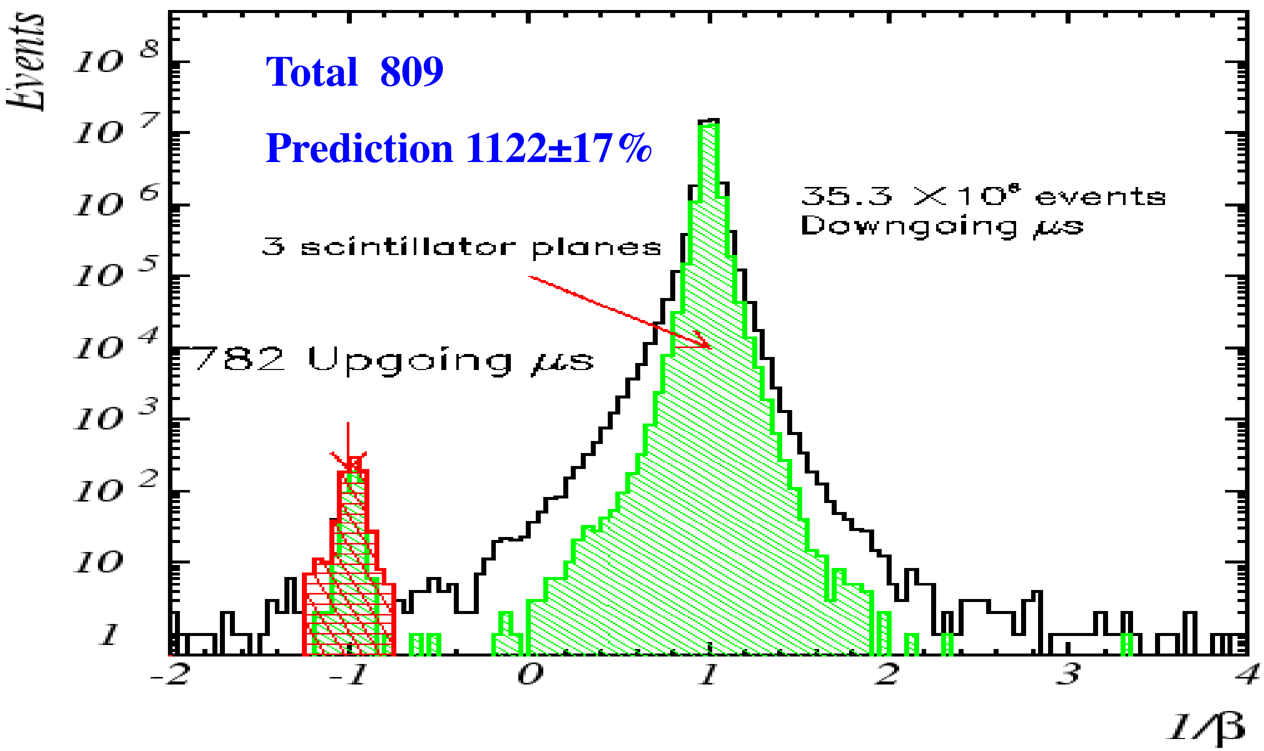


$$\frac{1}{\beta} = \frac{(T_1 + T_2 - T_3 - T_4)c}{2L} = \begin{cases} +1 & \mu \uparrow \\ -1 & \mu \downarrow \end{cases}$$

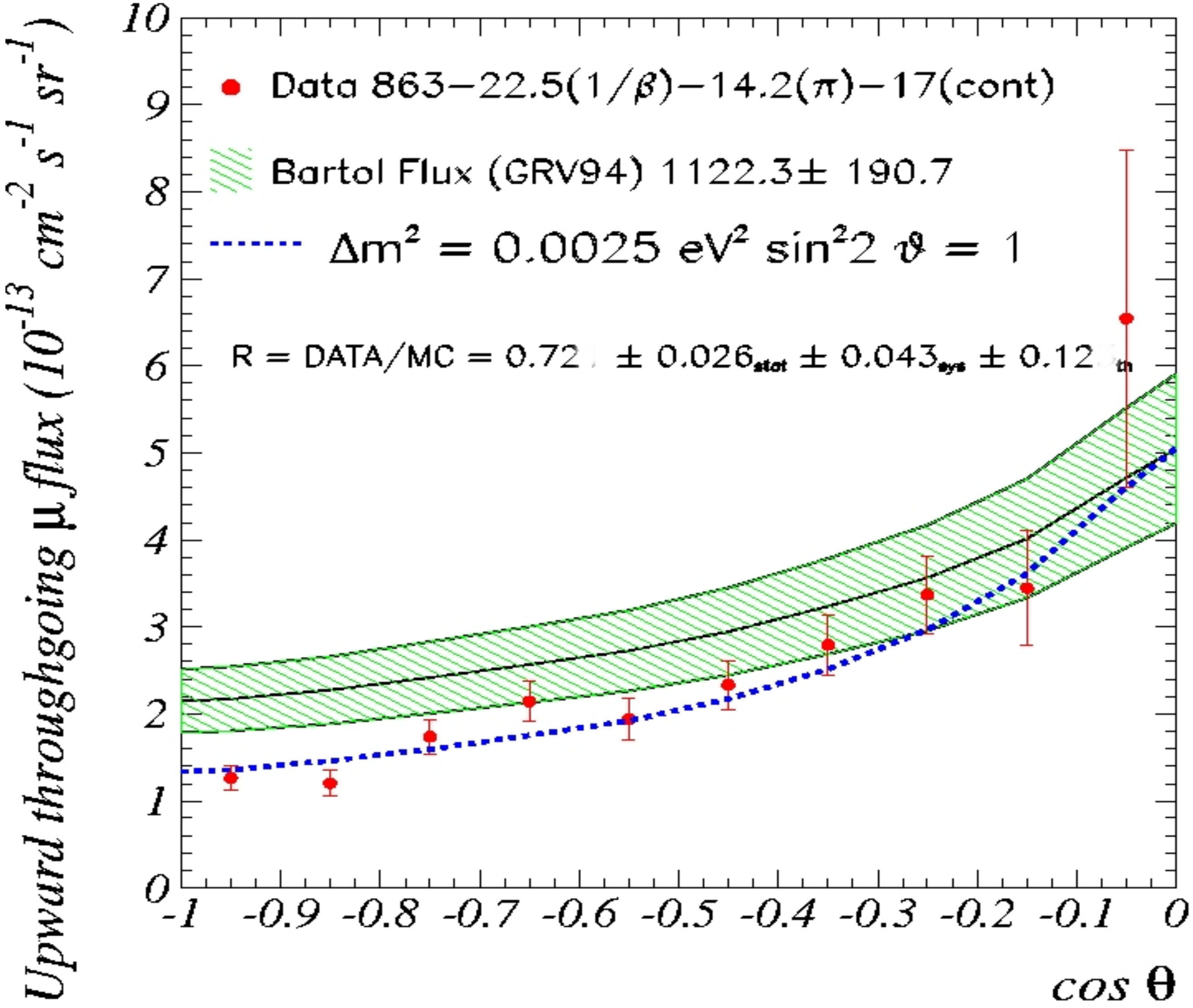
Total : 809 ev

R=data/prediction= 0.72 ±0.026(stat)±0.043 (systemat.)±0.12(theor)

Event deficit?



Neutrino in MACRO : Evidence of oscillations from the UPMU angular distributions angular distribution



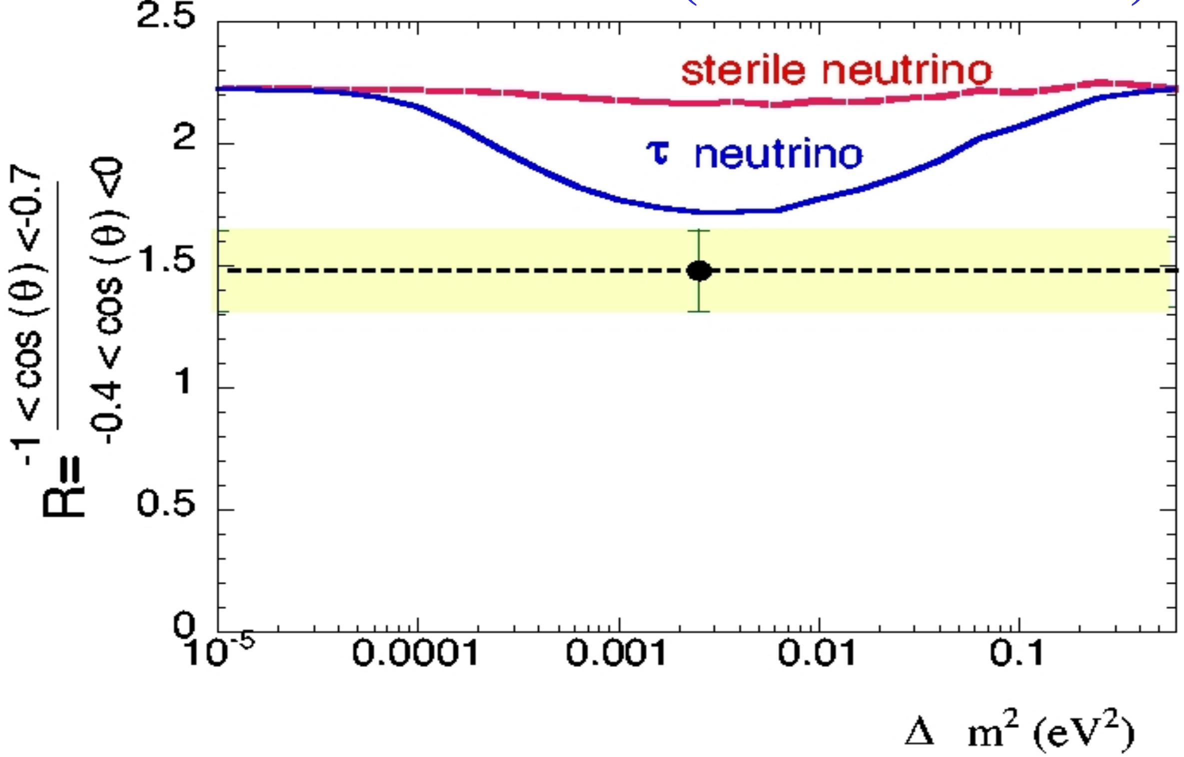
χ^2 test on the angular distribution (10 bins) with prediction normalized to data :

- **χ^2 = 9.6/9 d.o.f** for ν_μ ν_τ with maximum mixing and $\Delta m^2 \sim 0.0025$ eV^2 **P = 37 %**

- **χ^2 = 25.9/9 d.o.f.** for no - oscillations **P = 0.2 %**

Ratio vertical / horizontal

• to discriminate sterile neutrino oscillations(matter effects) and
τ neutrino oscillations (no matter effect)

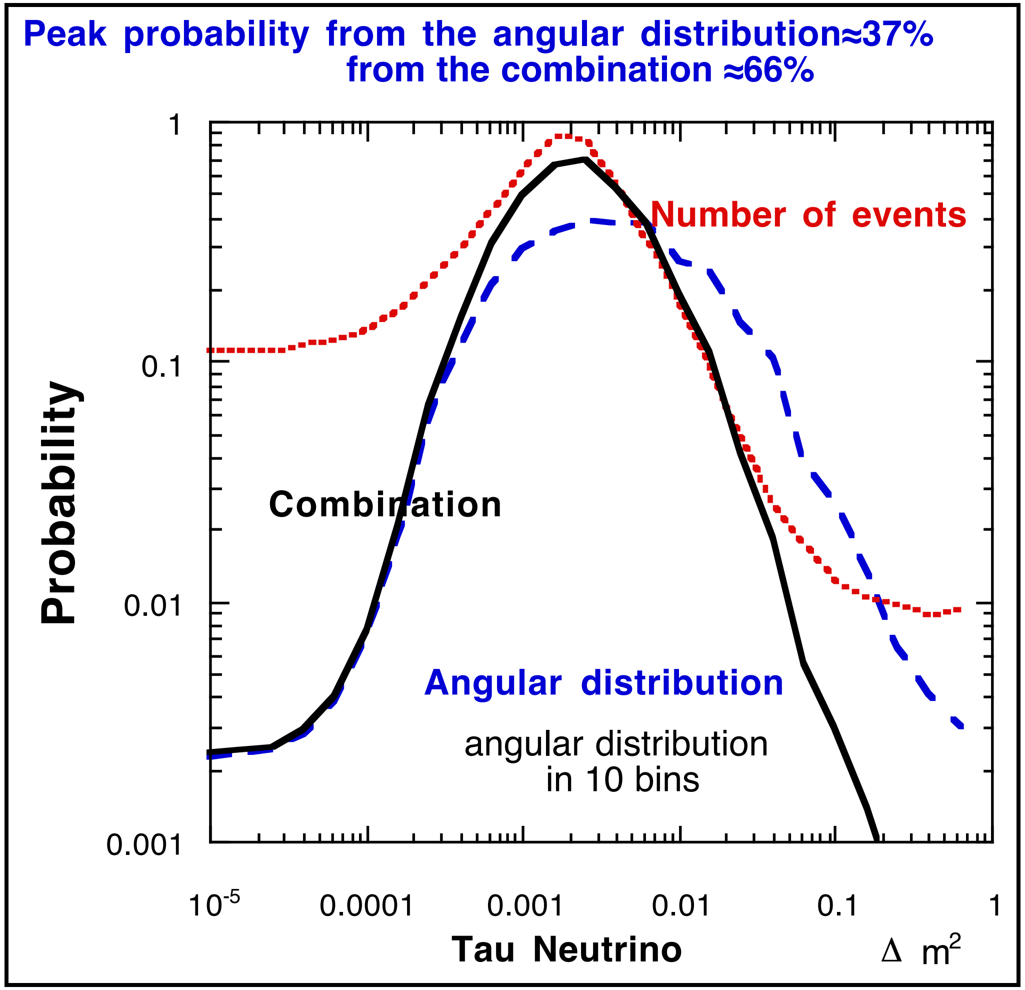


$$R = \frac{N(\cos(\theta) < -0.7)}{N(\cos(\theta) > -0.4)}$$

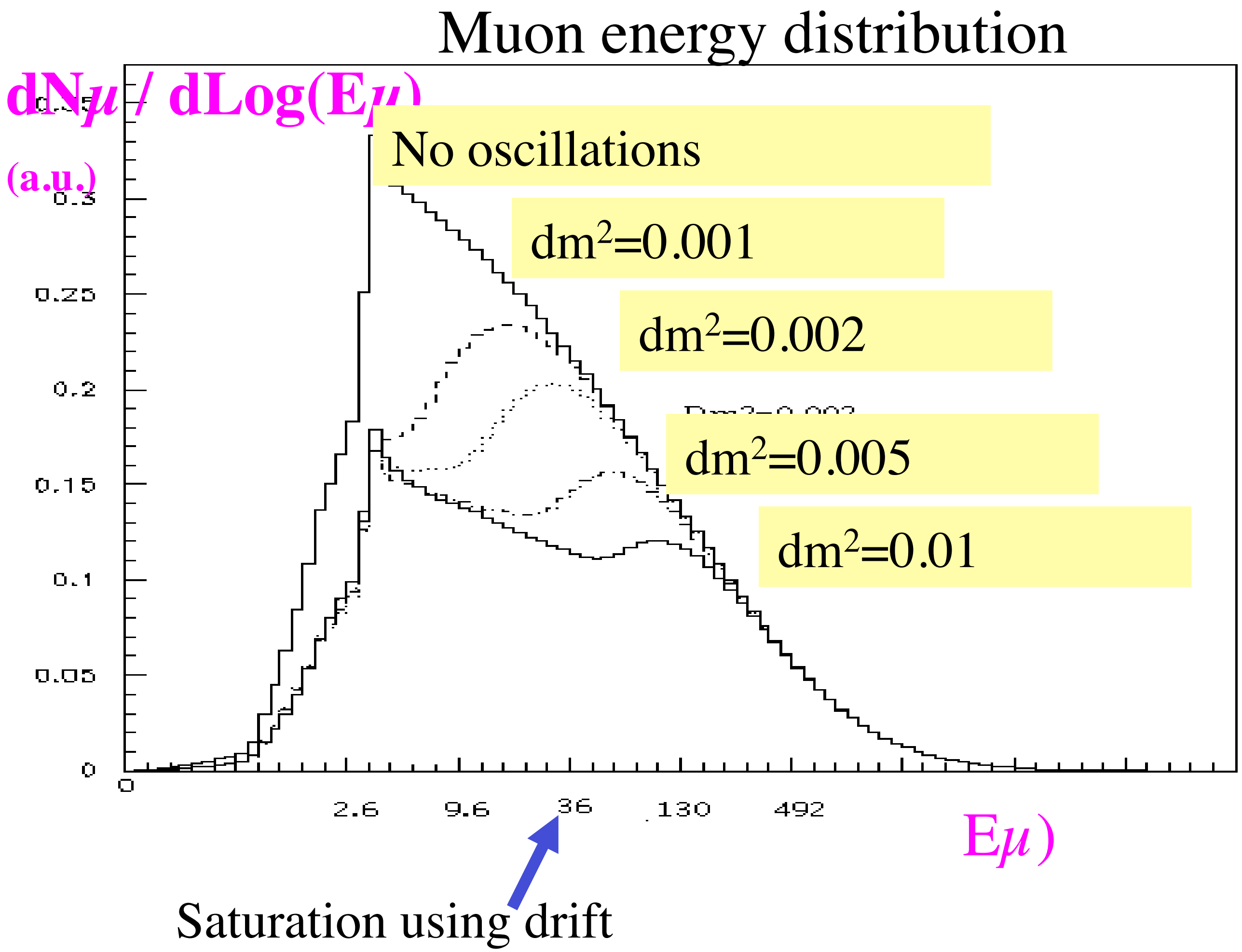
• **The plot is for maximum mixing**
P(sterile) = 0.033% **P(τ) = 8.4%**

• **Sterile neutrino disfavored with respect to τ at >99% C.L. for any mixing** (7% systematic on the ratio)

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



Recently : additional information coming from the muon energy measurement using the multiple coulomb scattering



Macro ≈ 25 X_0

Streamer tube spatial resolution:

σ ≈1 cm digit (3x 3 cm cells)

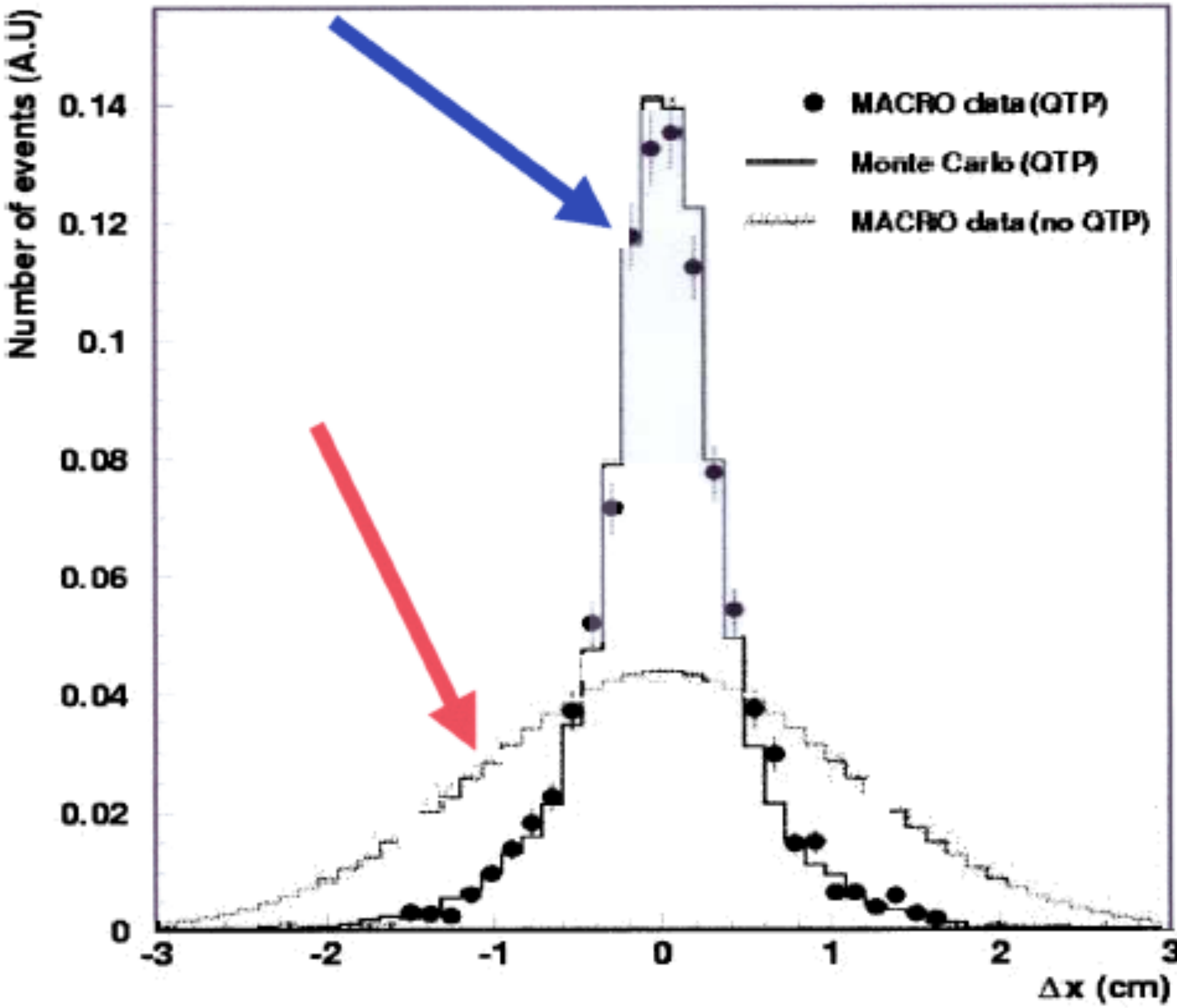
σ ≈ 0.3 cm measuring the drift time

The test beam showed a correct performance of the electronics:

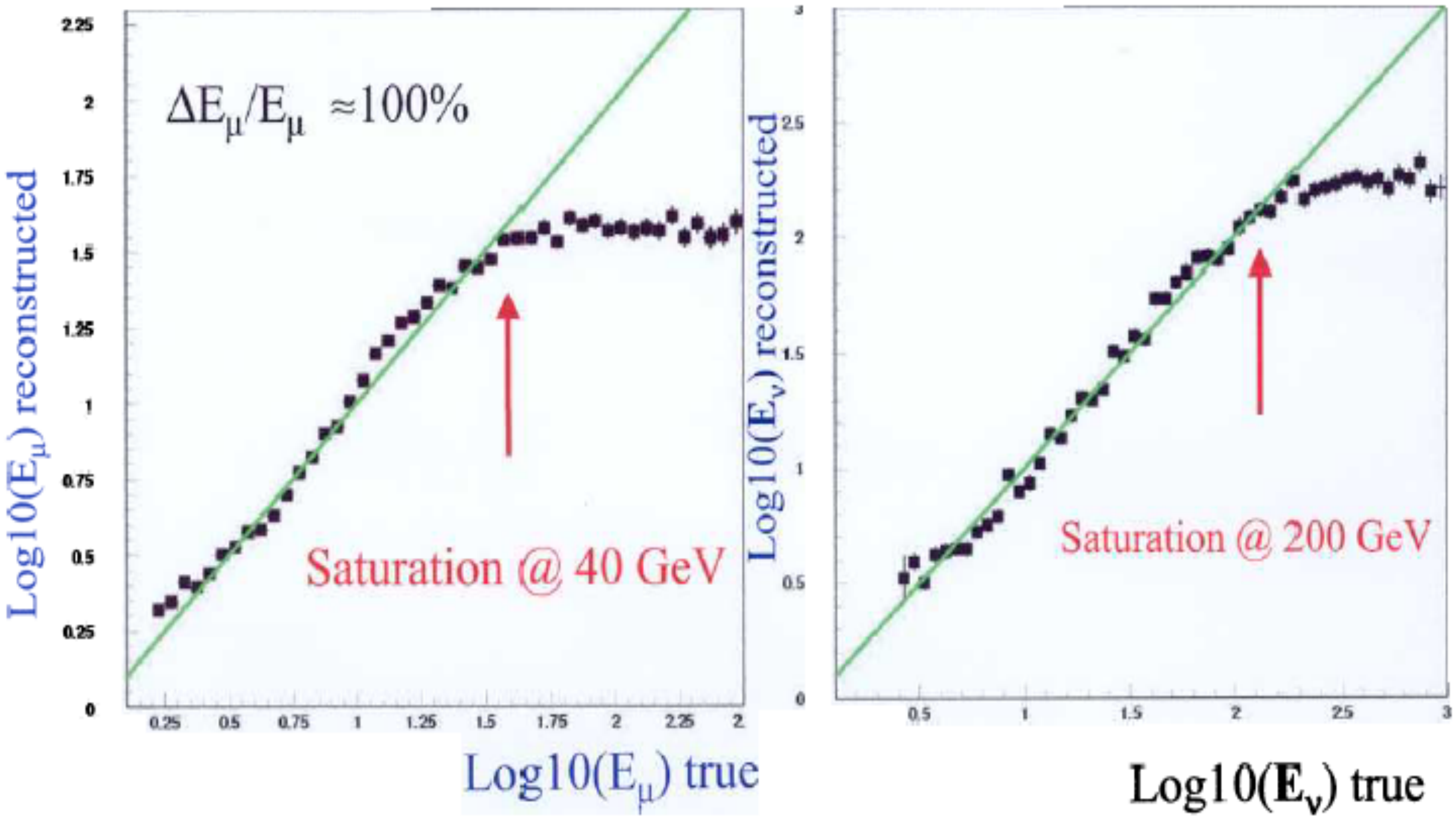
Method appplied to MACRO DATA:

DOWN GOING MUON RESIDUALS DISTRIBUTION

With QTP σ ~ 3 mm NO QTP (streamers in digital mode) σ ~ 1 cm

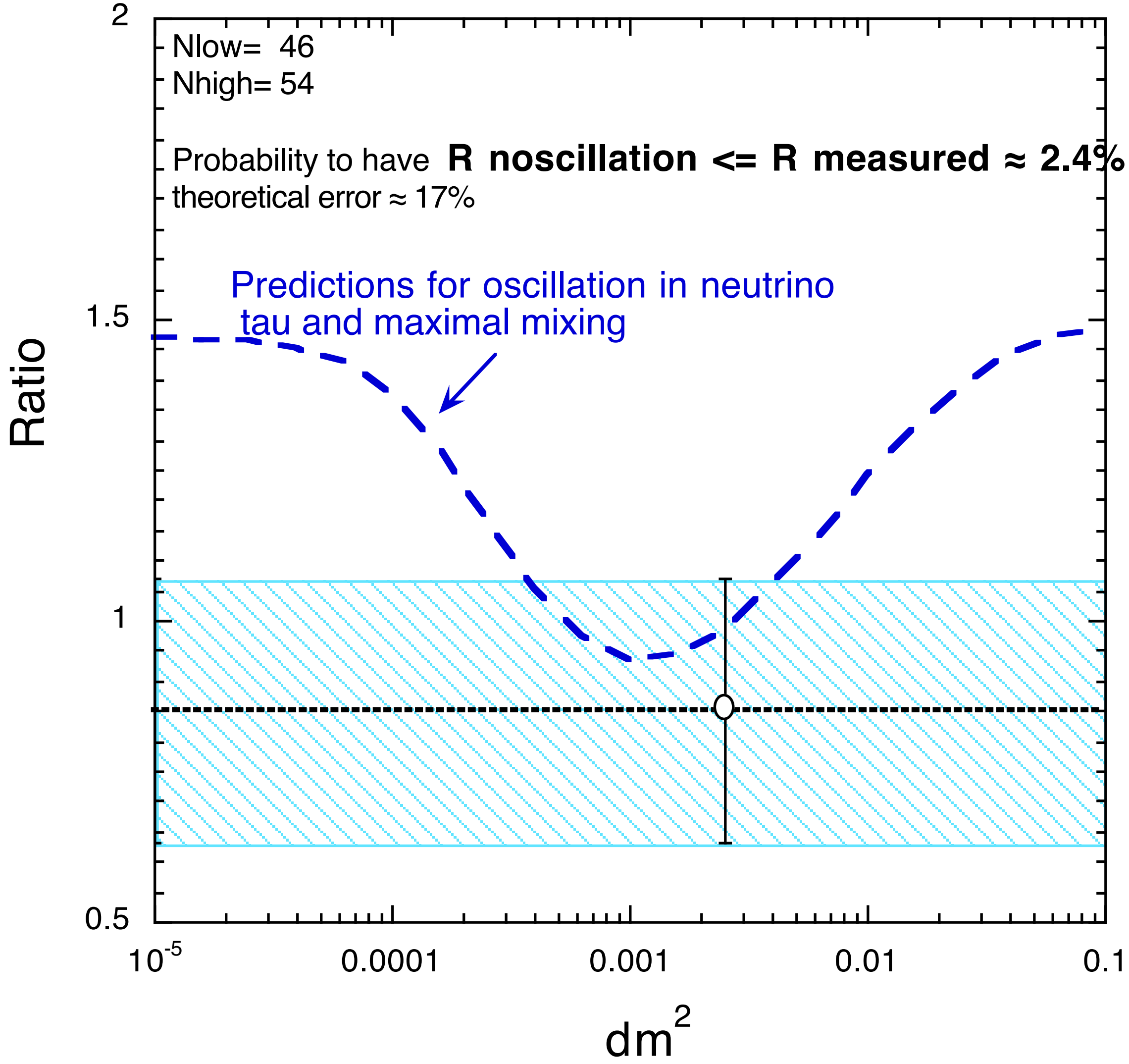


An improvement of a factor 3.5 !



. MACRO can easily measure L_ν, by tracking the muon.

Upward Going Muons
Ratio E low / E high using multiple coulomb scattering



$E\ low_\nu \approx 15$ GeV

$E\ high_\nu \approx 170$ GeV

Neutrino :Low energy results

Internal Upward going μ's

DATA: $154 \pm 12_{stat}$

MC: $285 \pm 28_{sys} \pm 57_{theo}$

MC (Δm^2=0.0025 eV^2): $168 \pm 17_{sys} \pm 34_{theo}$

Internal down + Upgoing stopping μ's

DATA: $262 \pm 16_{stat}$

MC: $376 \pm 38_{sys} \pm 76_{theo}$

MC (Δm^2=0.0025 eV^2): $284 \pm 28_{sys} \pm 57_{theo}$

$$\frac{Data}{MC}_{(IU)} = 0.54 \pm 0.04_{stat} \pm 0.05_{sys} \pm 0.11_{th}$$

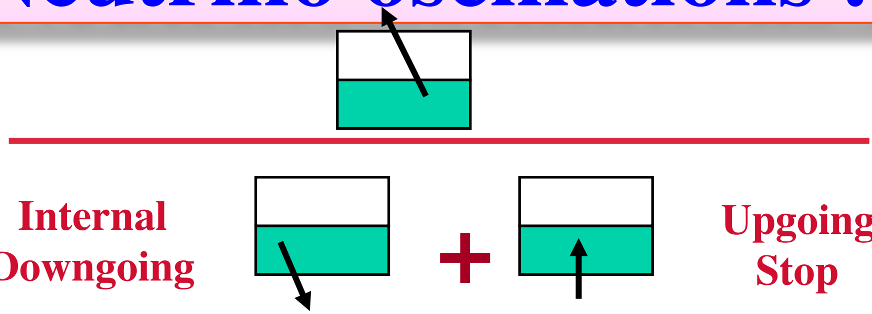
$$\frac{Data}{MC}_{(ID+UGS)} = 0.70 \pm 0.04_{stat} \pm 0.07_{sys} \pm 0.14_{th}$$

- Zenith angular distributions → **constant deficit**
- R_{IU} and R_{ID+UGS} not same reduction →

deficit not due to theor. overestimate of ν flux/cross sections

IU and ID+UGS have <Eν> ~ 4 GeV

Neutrino oscillations : Double Ratio

R = 
Internal Downgoing + Upgoing Stop

Expected reductions for

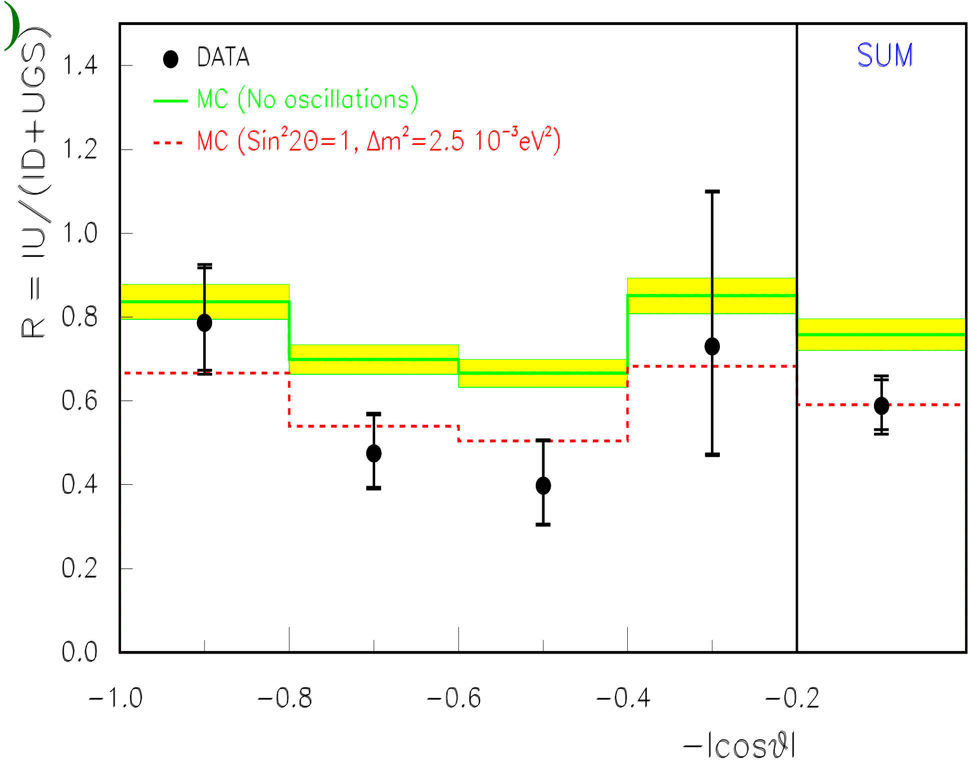
$\Delta m^2 \sim 1\text{-}10 \times 10^{-3}\ eV^2$ $\sin^2 2\theta = 1$

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

- **Most of the theor. err. cancel (<5%)**
- **Systematic err. reduced (~6%)**

Data: **$R = 0.59 \pm 0.06_{stat}$**

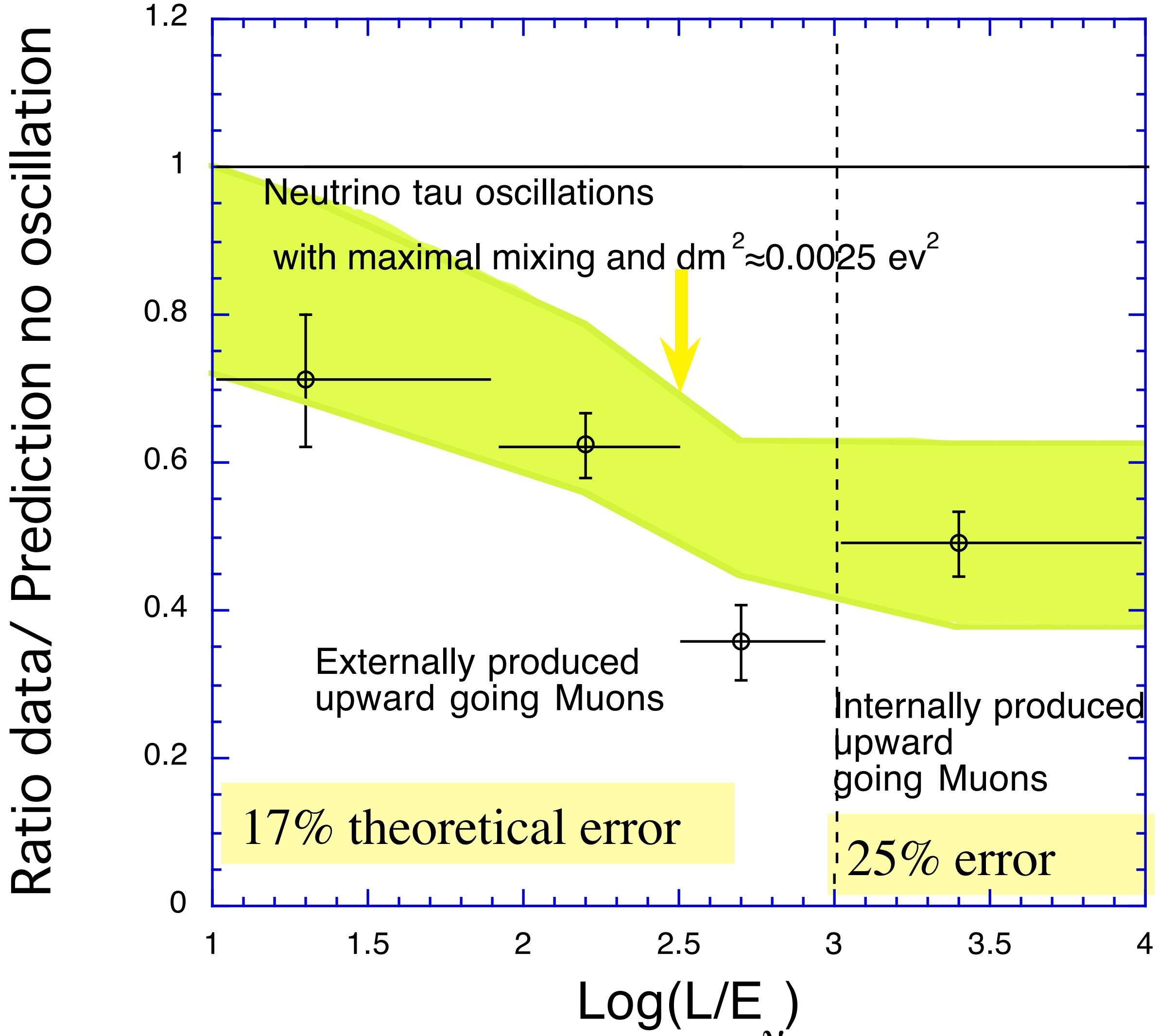
Expected (No oscillations):
$R = \mathbf{0.76} \pm 0.04_{sys} \pm 0.04_{th}$



Probability to obtain double ratio so far from expected is ~2%

===>>>> UP /Down Asimmetry

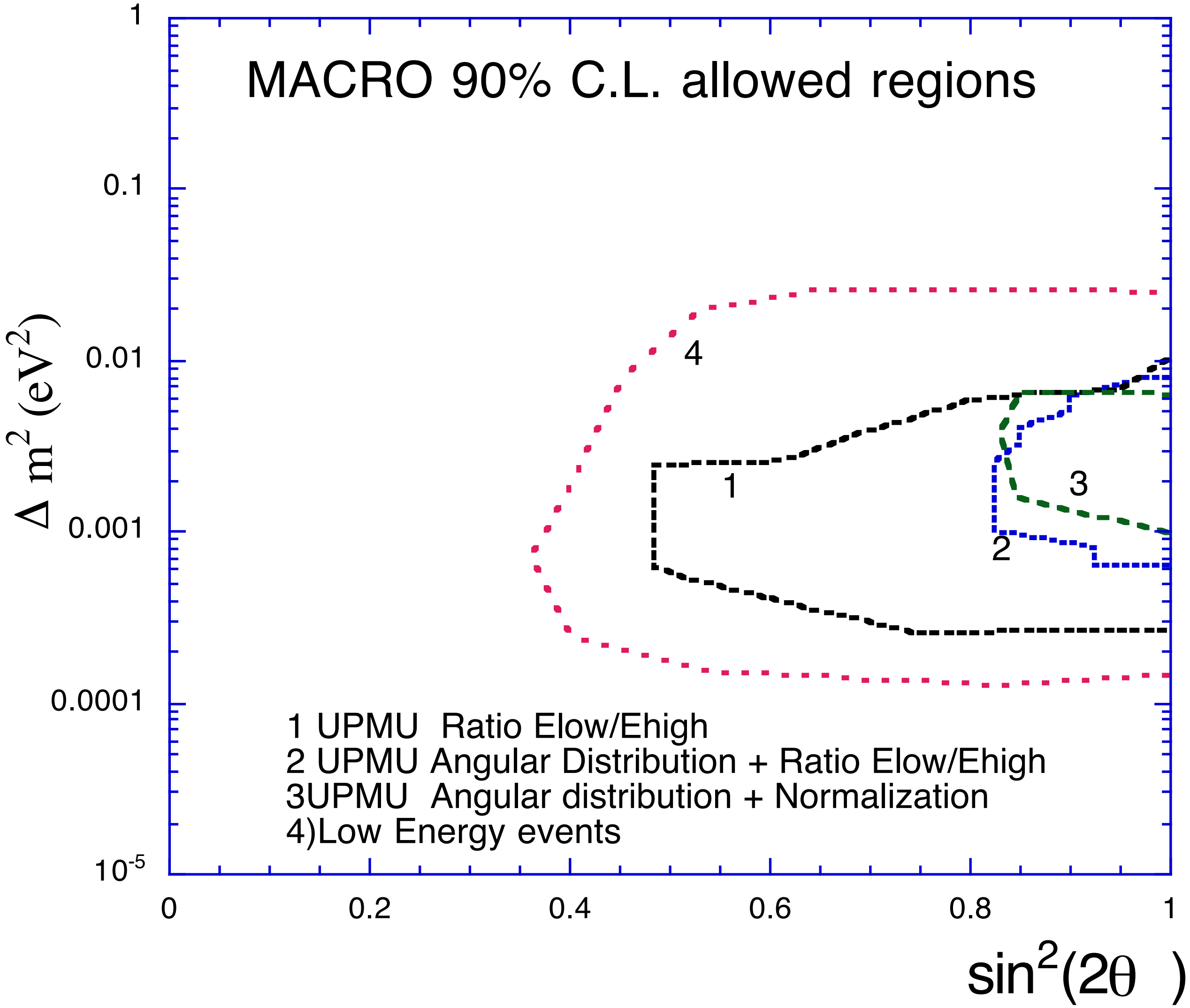
The physical quantity for 2 flavor neutrino oscillatons is L/E$_\nu$



L =path length

E=neutrino energy measured using the multiple coulomb scattering (external events)

MACRO 90% allowed region for different event samples

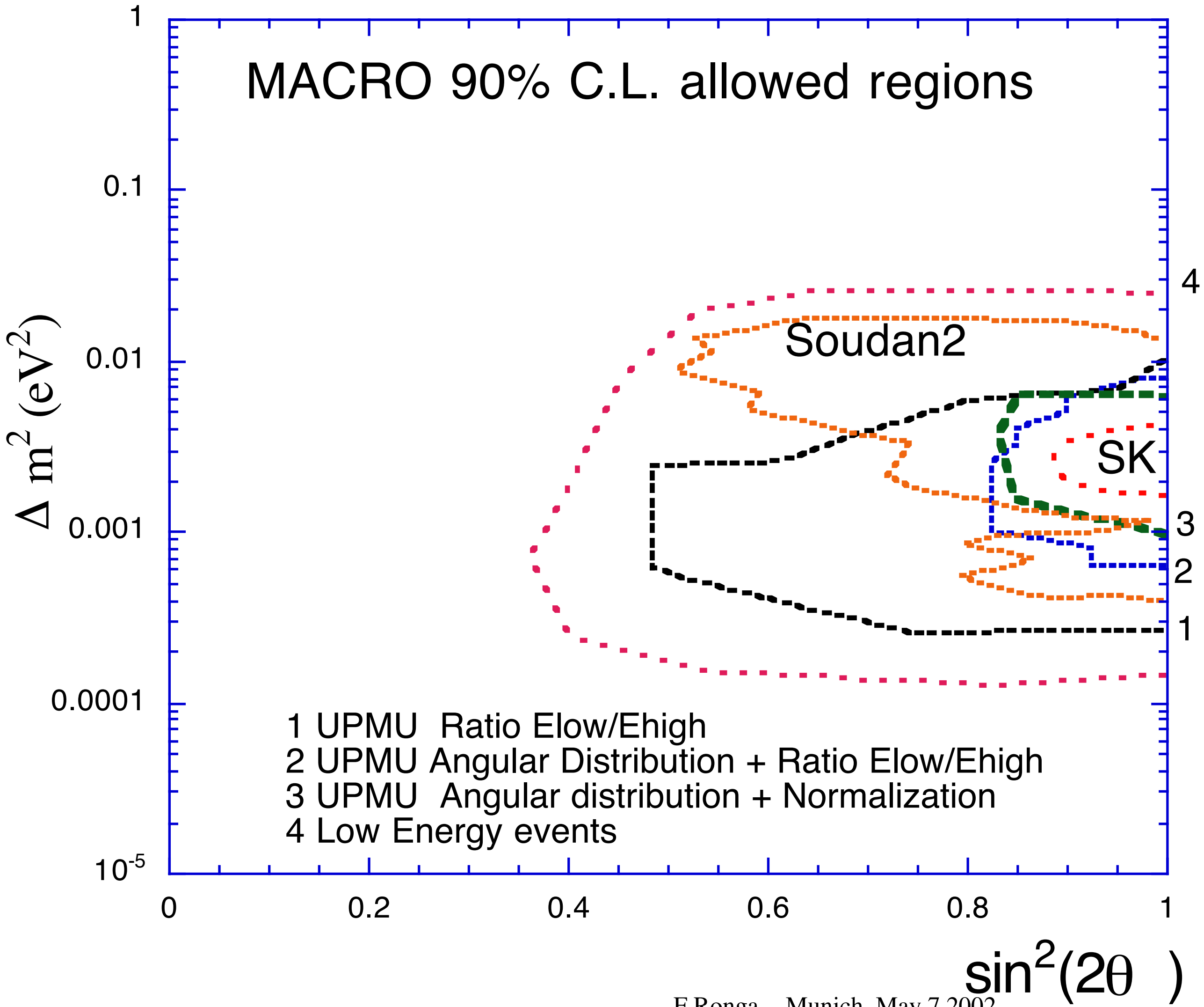


Everything consistent with $\nu_\mu \dashrightarrow \nu_\tau$ oscillations

- Angular distribution
- Up Down Asymmetry
- Energy distribution
- Event rate

Evidence for oscillations $\approx 10^5 : 1$

MACRO 90% allowed region, SuperKAmiokande and Soudan2



Best point for MACRO $dm^2=0.0025eV^2$

(no change since 1998)

Same as SK

Neutrino astronomy

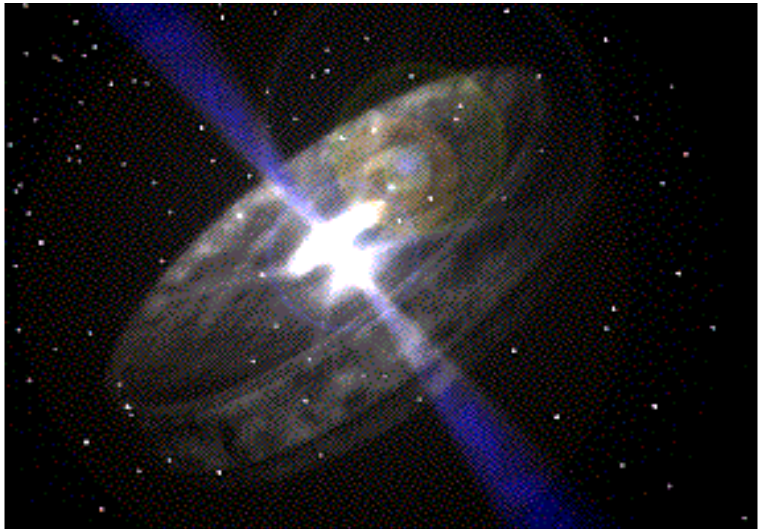
Proposed around 1960 (Greisen) *Neutrino are not deflected by magnetic fields and not absorbed by matter*

Detection : Upward going muons

Possible neutrino sources:

Galactic binary systems and Supernova remnants (Crab nebula..)

Active Galactic Nuclei



Gamma Burst Sources……...

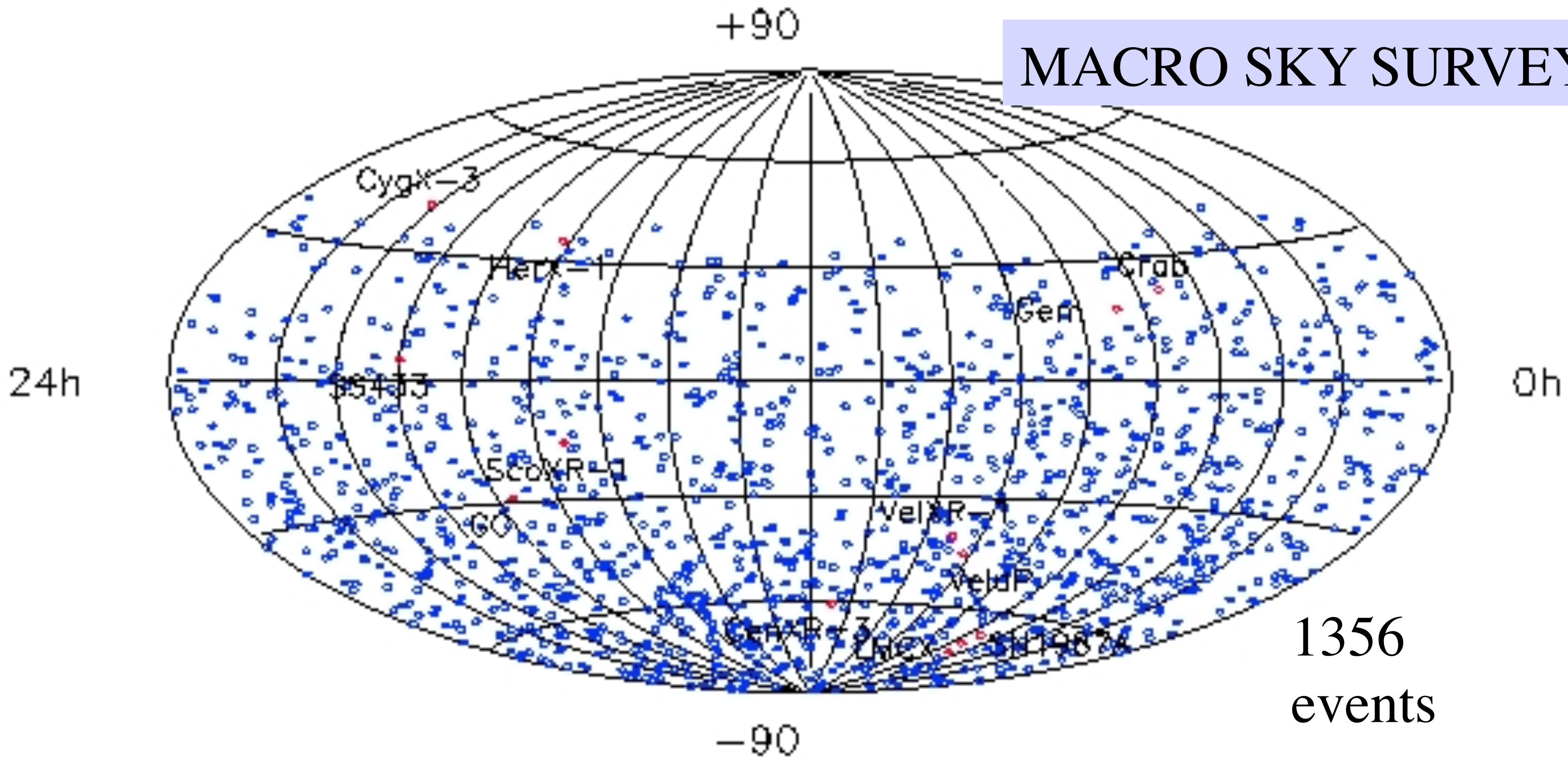
Expected signals < 0.1 ev/yr/1000m^2

Neutrino astronomy

Neutrino are produced in the cascade produced at the source by the primary protons. Spectral index ≈ 2.1.

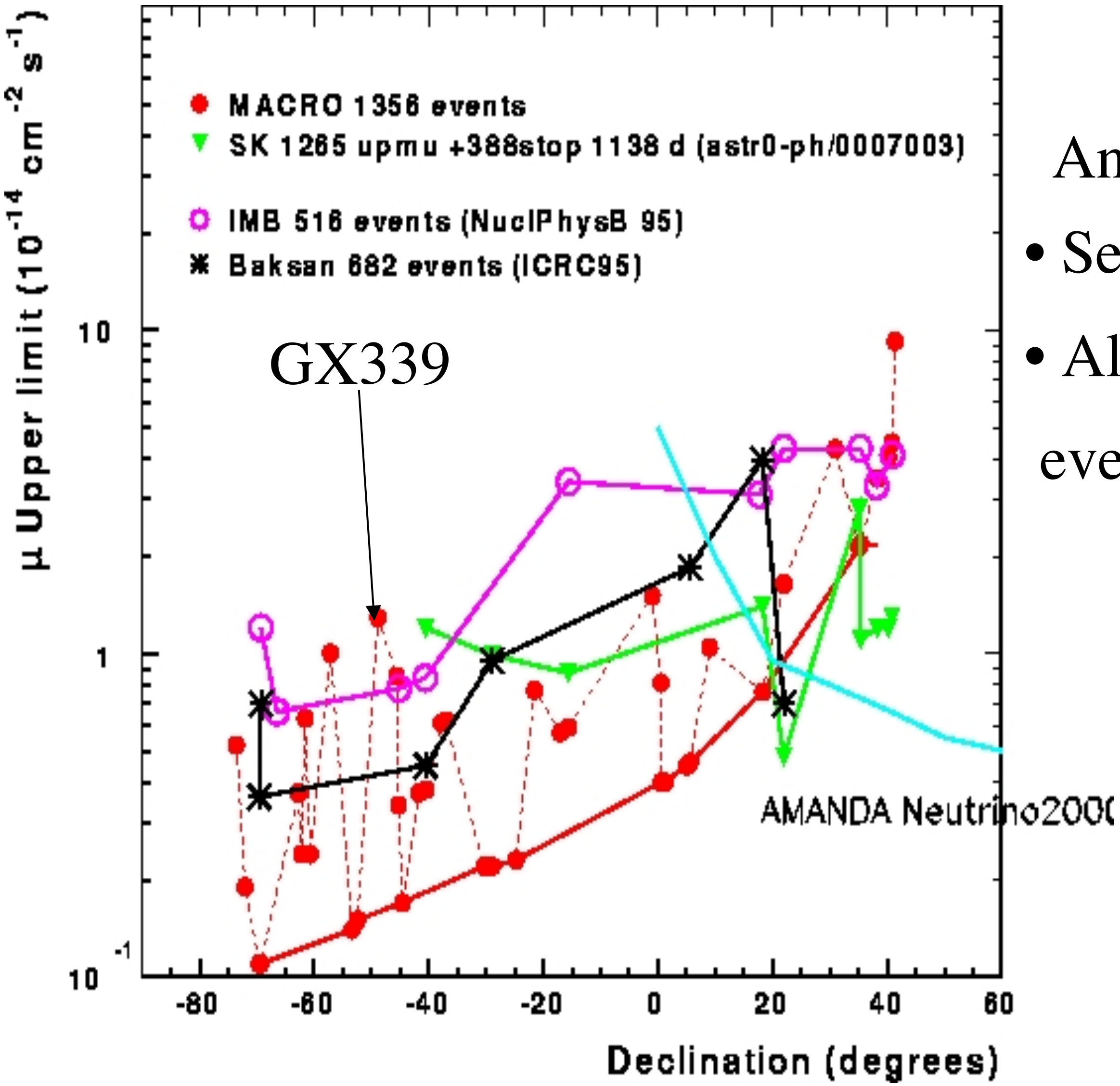
Atmospheric neutrinos are a background for this search, but spectral index ≈ 3

MACRO SKY SURVEY



1356
events

Neutrino astronomy :search for point like sources



Angular cone 3 degrees

- Search around know sources
- All sky search for cluster of events

Upper limits for 42 selected sources

(Astr Journ 546 1038 2001)

Neutrino astronomy: Galactic MicroQuasars

High interest in the last months: microquasars (galactic objects with a mini-balck hole in the center) could be very interesting sources of neutrinos

Ev/year/1km^2

Source name	Δt (days)	N_μ
CI Cam	0.6	0.05
XTE J1748-288	20	2.5
Cygnus X-3	3	4.8
LS 5039	persistent	0.2
GRO J1655-40	6	1.8
GRS 1915+105	6	0.5
Circinus X-1	4	0.2
LS I 61°303	7	0.1
LS I 61°303	20	0.1
XTE J1550-564	5	0.04
V4641 Sgr	0.3	0.03
V4641 Sgr	0.3	3.9
Scorpius X-1	persistent	0.9
SS433	persistent	252
GS 1354-64	2.8	0.02
GX 339-4	persistent	183.4
Cygnus X-1	persistent	2.8
GRO J0422+32	$1 \div 20$	$0.1 \div 2$
XTE J1118+480	$30 \div 150$	$6 \div 30$

NEUTRINO FLUX PREDICTIONS FOR KNOWN GALACTIC MICROQUASARS.
By C. Distefano (Catania U. & INFN, LNS), D. Guetta (Arcetri Observatory), E. Waxman (Weizmann Inst.), A. Levinson (Tel Aviv U.).
Feb 2002. 17pp. : **astro-ph/0202200**

The largest excess in MACRO is from GX339-4

7 events (1.9 background)

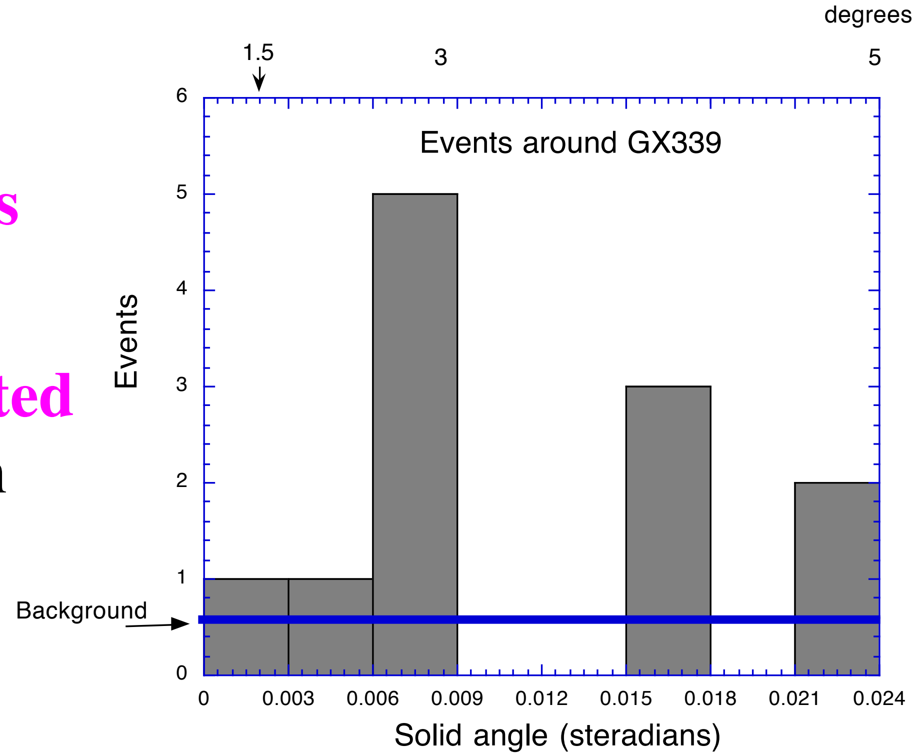
Prob≈1% (42 sources exam.)

Neutrino astronomy: Galactic MicroQuasars

True signal or statistical fluctuation?

Con:

- **we have 1 event in an 1.5 degrees cone (expected ≈ 60%)**
- **signal 10 time larger than expected** (but inside the typical errors of such calculation)



Wait for future experiments..

Neutrino astronomy: diffuse high energy neutrino flux from extragalactic source

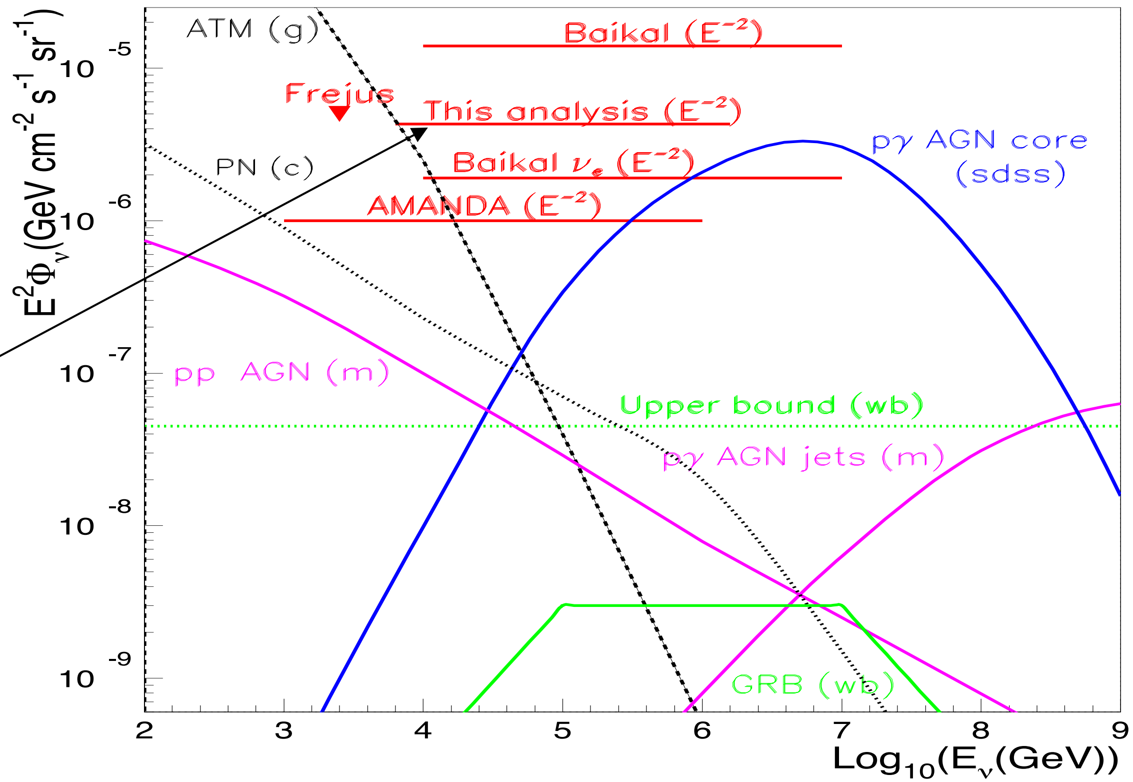
Search for TeV events with a very high energy deposition in the scintillators and streamer tube;

2 events found

1 expected from atmospheric neutrinos

MACRO limit

Baikal and Amanda unpublished



Other MACRO neutrino negative searches

Search for dark matter (WIMPS) from the center of the SUN or EARTH, this search uses the upgoing muons

Search for burst of neutrinos from galactic Supernova (1989-2000)

Summary and Future (1)

All the goal of the proposal reached

- Magnetic monopole and exotic particle search :

the best limit in the world; complementary technique to identify a single monopole; Not easy to improve this search

- Cosmic ray physics and composition around the knee:

several experiments are working (one of the best is Kascade in Germany); however the MACRO and EAS-TOP data will remain unique ($E\mu > 1.4$ TeV).

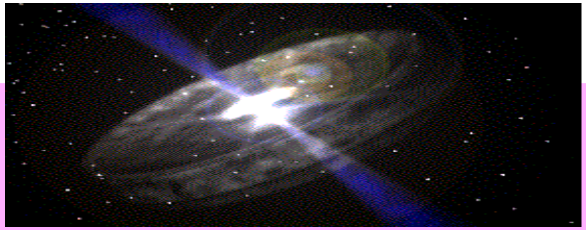
- Atmospheric Neutrino Oscillations

The most interesting result. Unfortunately obtained only in 1998, MACRO had the potentiality to claim atmospheric neutrino oscillations without the SuperKamiokande data.

Summary and Future (2)

• Atmospheric Neutrino Oscillations

No future atmospheric neutrino experiment planned. The future is in the long base line beams (Fermilab-Soudan,CERN-Gran Sasso, KEK - Kamioka)



• Neutrino Astronomy.

Currently the MACRO data set is the best in the world (angular resolution better than SuperKamiokande). The future is already started with the under-ice and under-water experiments (Amanda, Antares, Nemo, Baikal) It will be interesting to see if the Microquasar signal is real