ATMOSPHERIC NEUTRINO OSCILLATIONS IN MACRO

1. INTRODUCTION
2. EXPERIMENTAL
3. UP-THROUGOING μ
4. SEMICONTAINED μ
   UP-STOPPING μ
5. $\nu_\mu \to \nu_\tau$, $\nu_\mu \to \nu_s$
6. L/E_ν DISTRIBUTIONS
7. CONCLUSIONS

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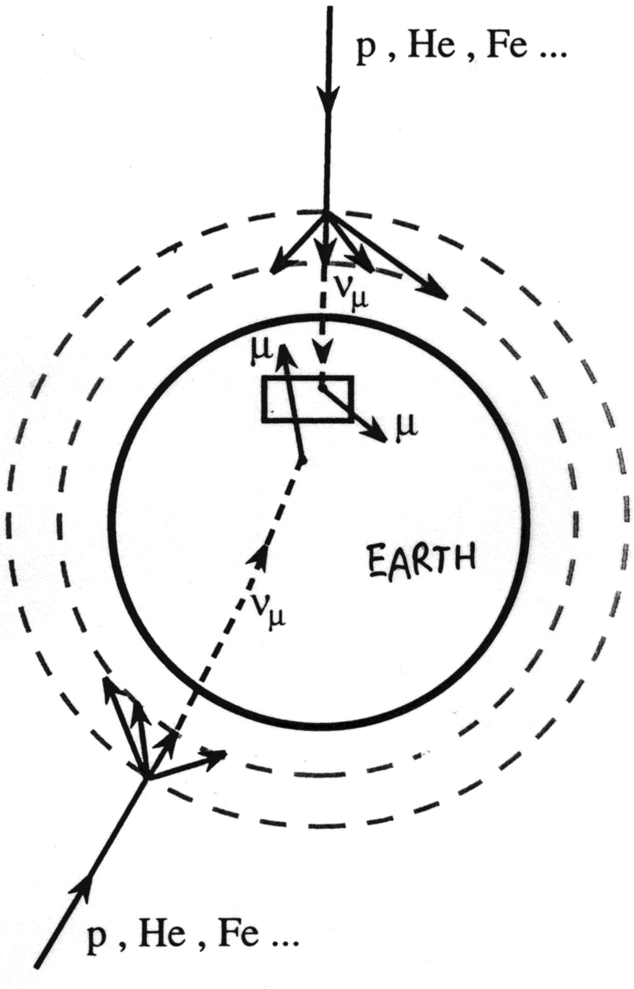
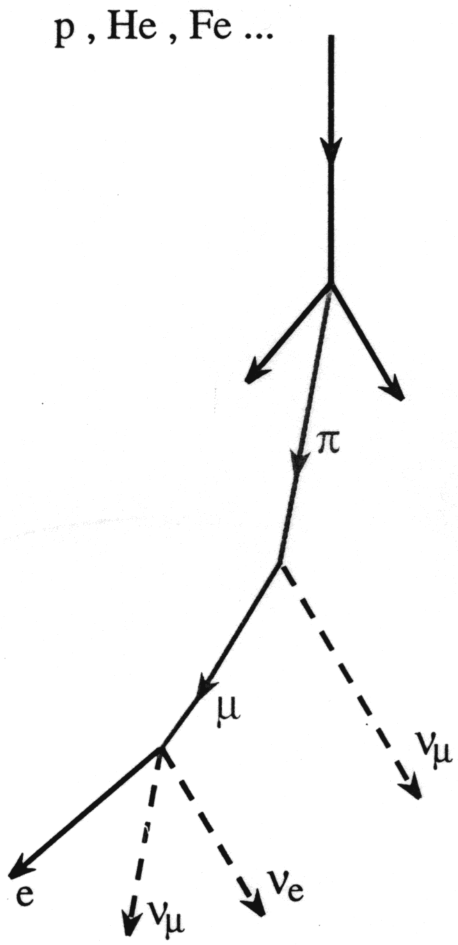
VENEZIA
25-7-01


p , He , Fe ...
ν_μ
μ
μ
EARTH
ν_μ
p , He , Fe ...


p , He , Fe ...
π
μ
ν_μ
e
ν_μ
ν_e

2. ν-OSCILLATIONS

WEAK FLAVOUR EIGENSTATES $\nu_e \quad \nu_\mu \quad \nu_\tau$
MASS EIGENSTATES $\nu_1 \quad \nu_2 \quad \nu_3$

DECAYS, INTERACTIONS $\pi^+ \to \mu^+ \nu_\mu$, $\nu_\mu n \to \mu^- p$
PROPAGATION $\nu_1(t) = \nu_1(0)\, e^{-E_1 t}$

MIXING $\nu_\ell = \sum_{m=1}^{3} U_{\ell m}\, \nu_m$

2-FLAVOUR MIXING
$$\begin{cases} \nu_\mu = \nu_2 \cos\theta_{\mu\tau} + \nu_3 \sin\theta_{\mu\tau} \\ \nu_\tau = -\nu_2 \sin\theta_{\mu\tau} + \nu_3 \cos\theta_{\mu\tau} \end{cases}$$

IF $\theta_{e\mu} \simeq \theta_{e\tau} \simeq \theta_{\mu\tau} \ll$ (SMALL) $\Rightarrow \nu_e \simeq \nu_1$, $\nu_\mu \simeq \nu_2$, $\nu_3 \simeq \nu_\tau$

$m_{\nu_1} \ll m_{\nu_2} \ll m_{\nu_3}$

IF $\theta \gg$ (LARGE) SITUATION IS DIFFERENT

OSCILLATIONS IN VACUUM (DISTANCE L)

DISAPPEARANCE $P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{\mu\tau} \sin^2\left(\frac{1.27\, \Delta m^2 L}{E_\nu}\right)$
APPEARANCE $P(\nu_\mu \to \nu_\tau) = 1 - P(\nu_\mu \to \nu_\mu)$

$\Delta m^2 = m^2_{\nu_3} - m^2_{\nu_2}$

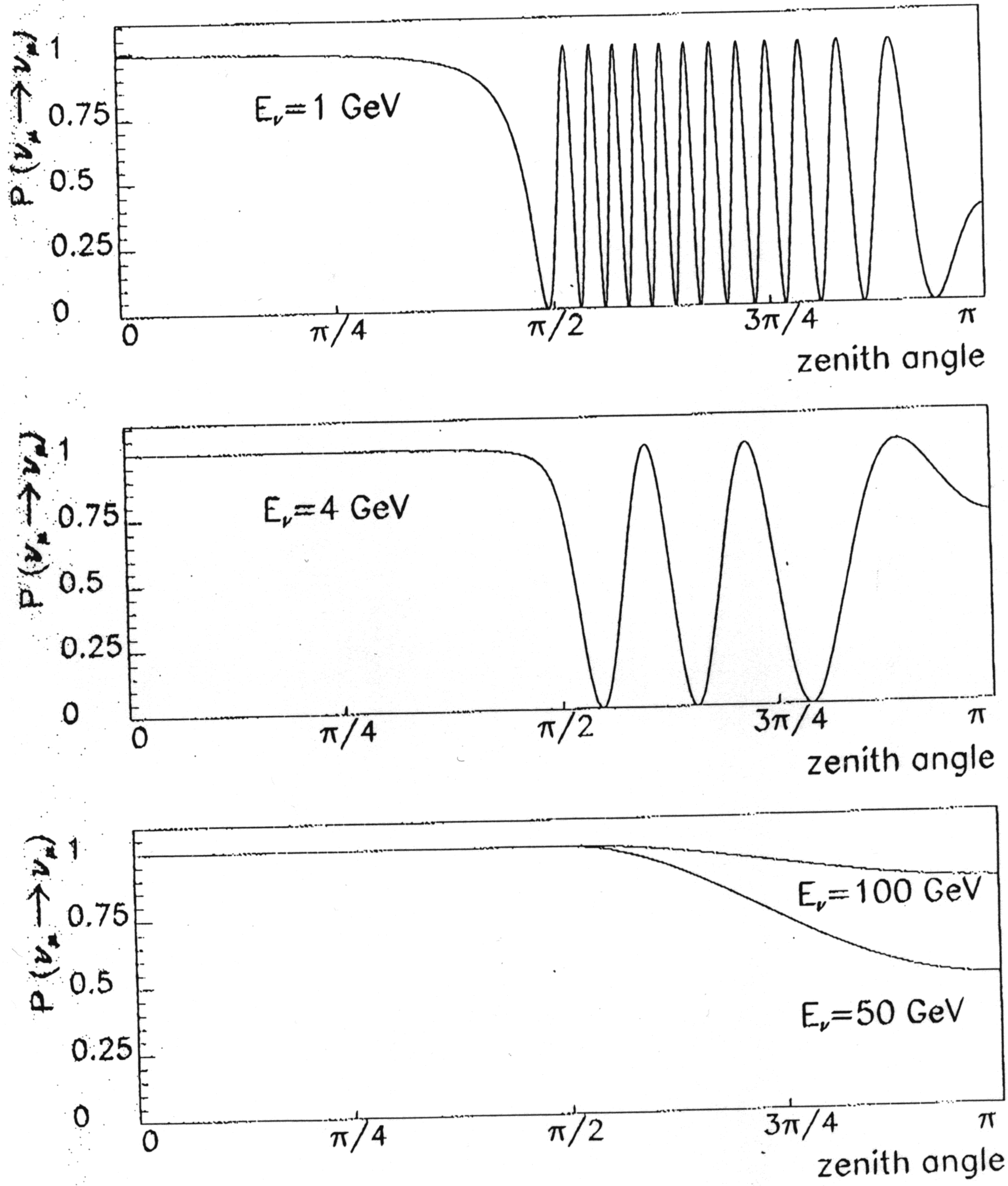
SIMPLE FORMULAE MODIFIED BY
- ADDITIONAL FLAVOUR OSCILLATION
- MATTER EFFECTS

IN CASE OF OSCILLATIONS
- NEUTRINOS HAVE MASSES $m_\nu \neq$
- L_e, L_μ, L_τ VIOLATION
- NEUTRINO DECAYS ?

"STERILE" ν's

$P(\nu_\mu \rightarrow \nu_\mu)$

$(\Delta m^2, \text{sen}^2(2\vartheta_{mixing})) = (2.5*10^{-3}eV^2, 1)$



13'000 Km

+1 0 -1

$\cos\vartheta$

hep-ex/0106049
PHYS LETT B434 (1998) 451
" " B478 (2000) 5
hep-ex/0105087
ICRC 2001 CONF

5. MACRO

GENERAL PURPOSE DETECTOR . MASS = 5.1 Kt
76.6 m x 12 m x 9.3 m $S\Omega_I \simeq 9600\ m^2 sr$, $S\Omega_\nu \simeq 3100\ m^2 sr$
AT GRAN SASSO   3700 mwe

OPTIMIZED FOR MMs SEARCHES (GUT)

RESULTS ON COSMIC RAYS (SEASONAL VARIATION, MOON SHADOW (POINTING ACCURACY), BACKGROUND STUDIES, ...)

ATMOSPHERIC NEUTRINOS

- UP-THROUGOING μ , $\langle E_\nu \rangle \simeq 50$ GeV   809 events

MC SIMULATION: BARTOL ν_μ FLUX, μ $\frac{dE}{dx}$ BY LOHMAN, GRV94 DEEP INELASTIC PARTON DISTRIBUTIONS

- UP-SEMICONTAINED μ $\langle E_\nu \rangle \simeq 4$ GeV   154 events

- UP-STOPPING μ " "   262 events
  +DOWN SEMICONTAINED

OPTIMIZATION YIELDS (OF UP-THROUGOING)
$$\begin{cases} \Delta m^2 = 2.5 \times 10^{-3}\ eV^2 \\ \sin^2 2\theta = 1 \end{cases}$$

$\nu_\mu \to \nu_\tau$ OR $\nu_\mu \to \nu_s$?

$\nu_e, \nu_\mu, \nu_\tau + \nu_s$ COULD EXPLAIN THE RESULTS FROM SOLAR, ATMOSPHERIC AND LSND ACCELERATOR NEUTRINOS

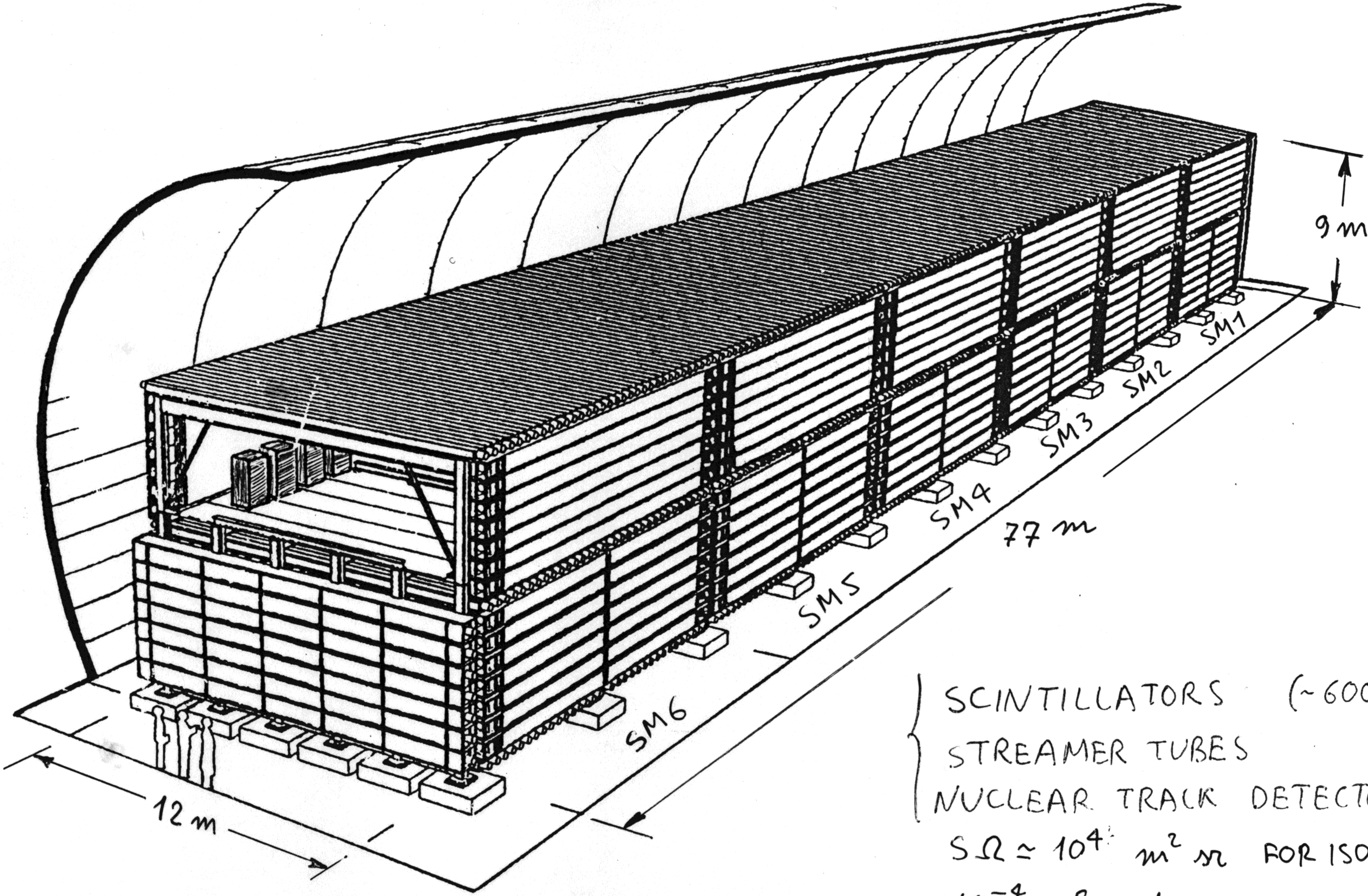
MATTER EFFECTS CAN BE SEEN IN H.E. SAMPLE

$$R = \frac{N(-1 < \cos\theta < -0.7)}{N(-0.4 < " < 0)} = \frac{305}{206} = 1.48 \pm 0.13_{STAT} \pm 0.10_{SYST}$$

(MOST OF THE UNCERTAINTIES DROP OUT)

$\nu_\mu - \nu_s$ EXCLUDED AT 99% CL COMPARED TO $\nu_\mu \to \nu_\tau$

MACRO



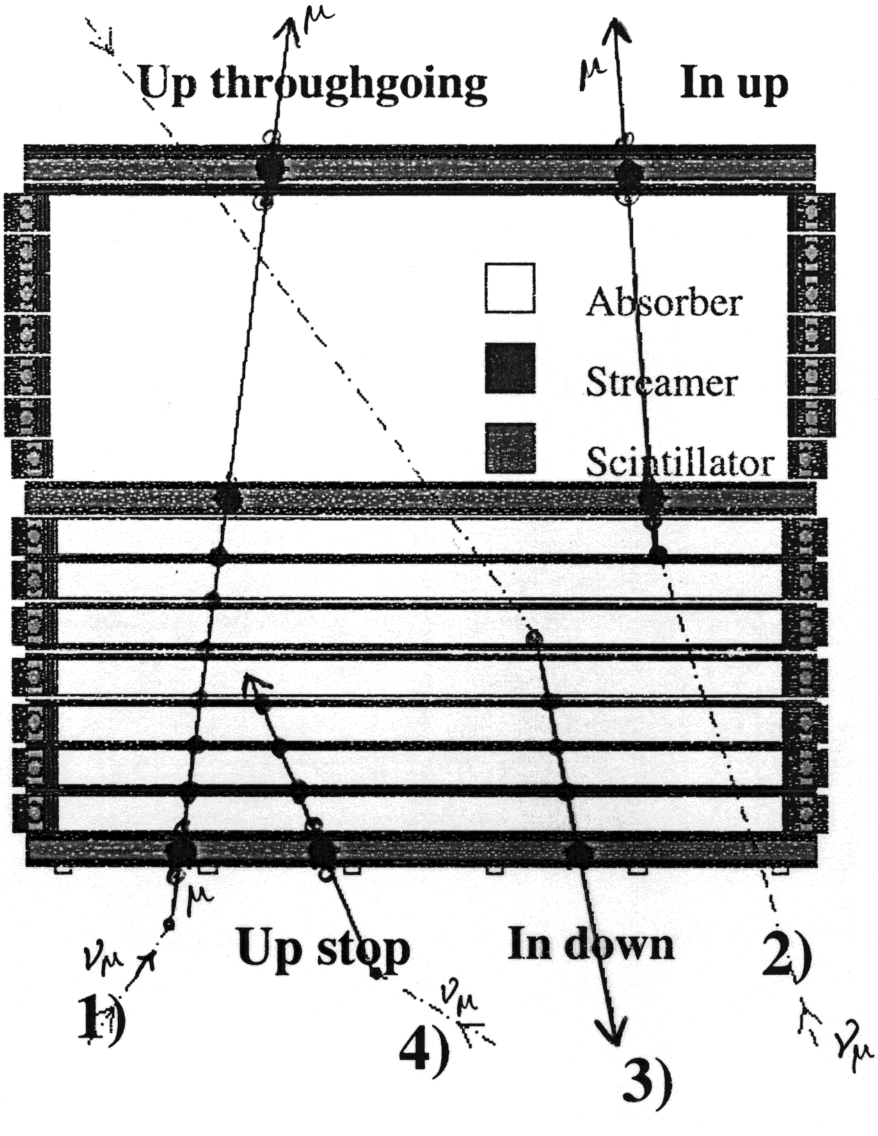
SCINTILLATORS (~600 t)
STREAMER TUBES
NUCLEAR TRACK DETECTORS

$S\Omega \simeq 10^4\ m^2\ sr$ FOR ISOTROPIC FLUX

$10^{-4} \lesssim \beta \lesssim 1$

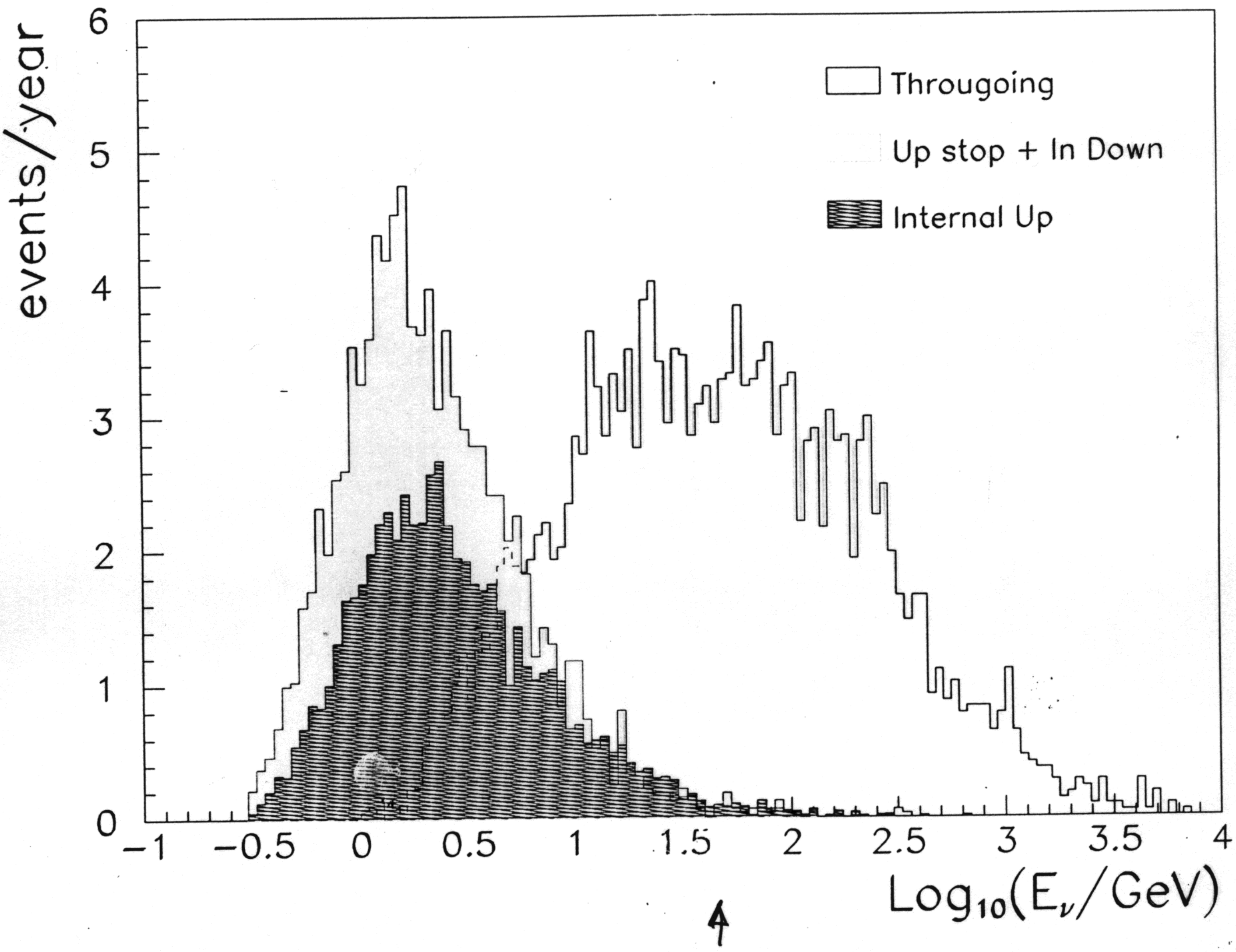
Neutrino event topologies in MACRO

Detector mass ~ 5.3 kton



Event category	<Eν>	Rate
1) up throughgoing μ	~ 50 GeV	160/y
2) internal upgoing μ	~ 5 GeV	50/y
3) internal downgoing μ	~ 4 GeV	35/y
4) upgoing stopping μ	~ 4 GeV	35/y

MACRO

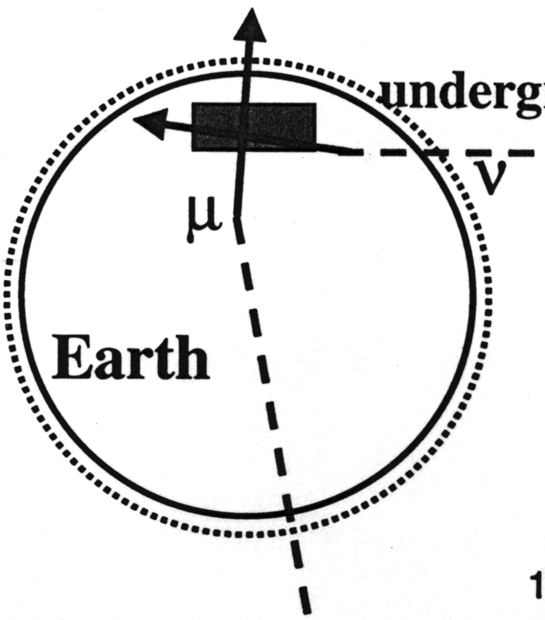


↑ ⟨Eν⟩ ≈ 50 GeV

↑ ⟨Eν⟩ ~ 4 GeV

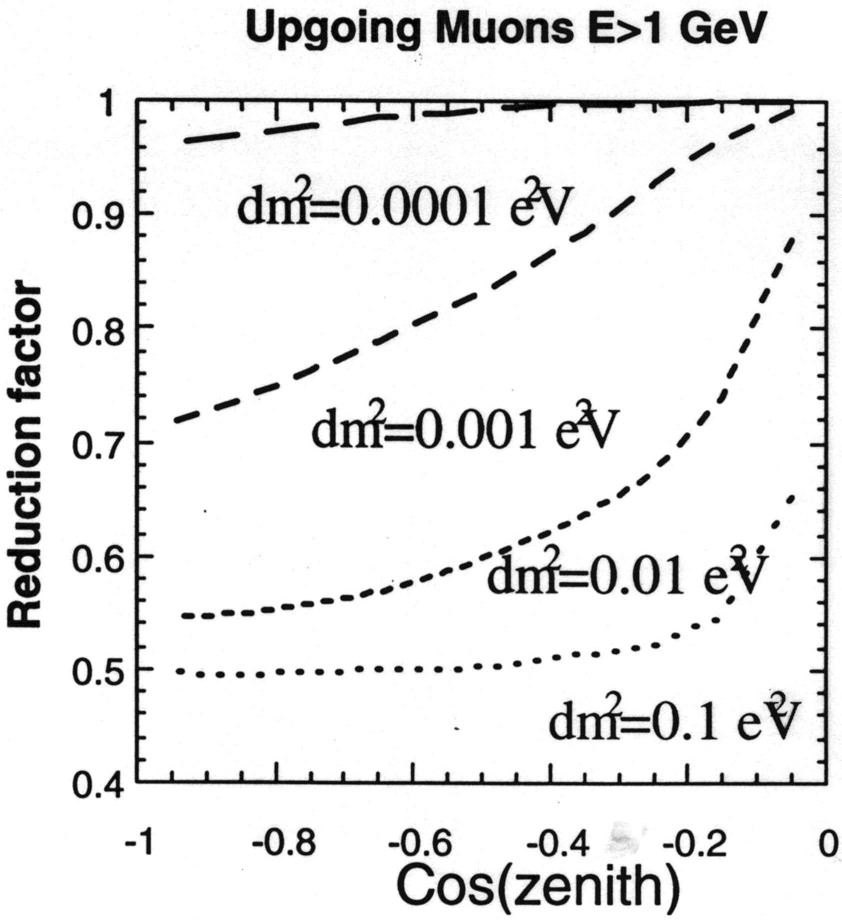
Effects of ν_μ oscillations on up throughgoing events

→ **Flux reduction** depending on **zenith angle** for the high energy events

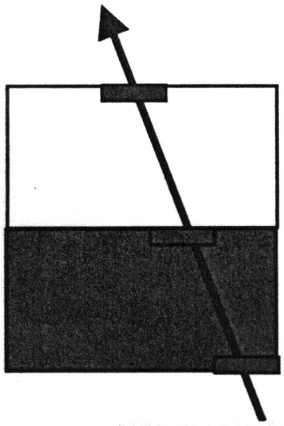


$E_\nu \sim$ 50÷ ~~100~~ GeV

$L_\nu \sim 10^2 - 10^4$ km

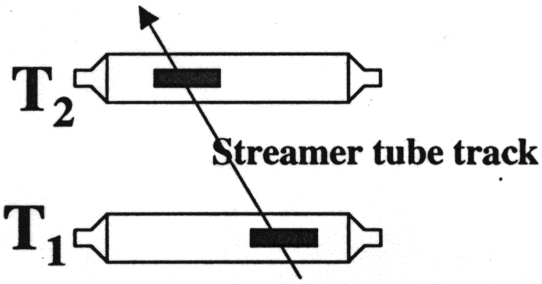


From MC: distortion of the angular distribution



Neutrino induced upward throughgoing muons

Identified by the time-of-flight method



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

$\Delta t \sim 0.5$ n sec , Δ(position) ~ 1 cm

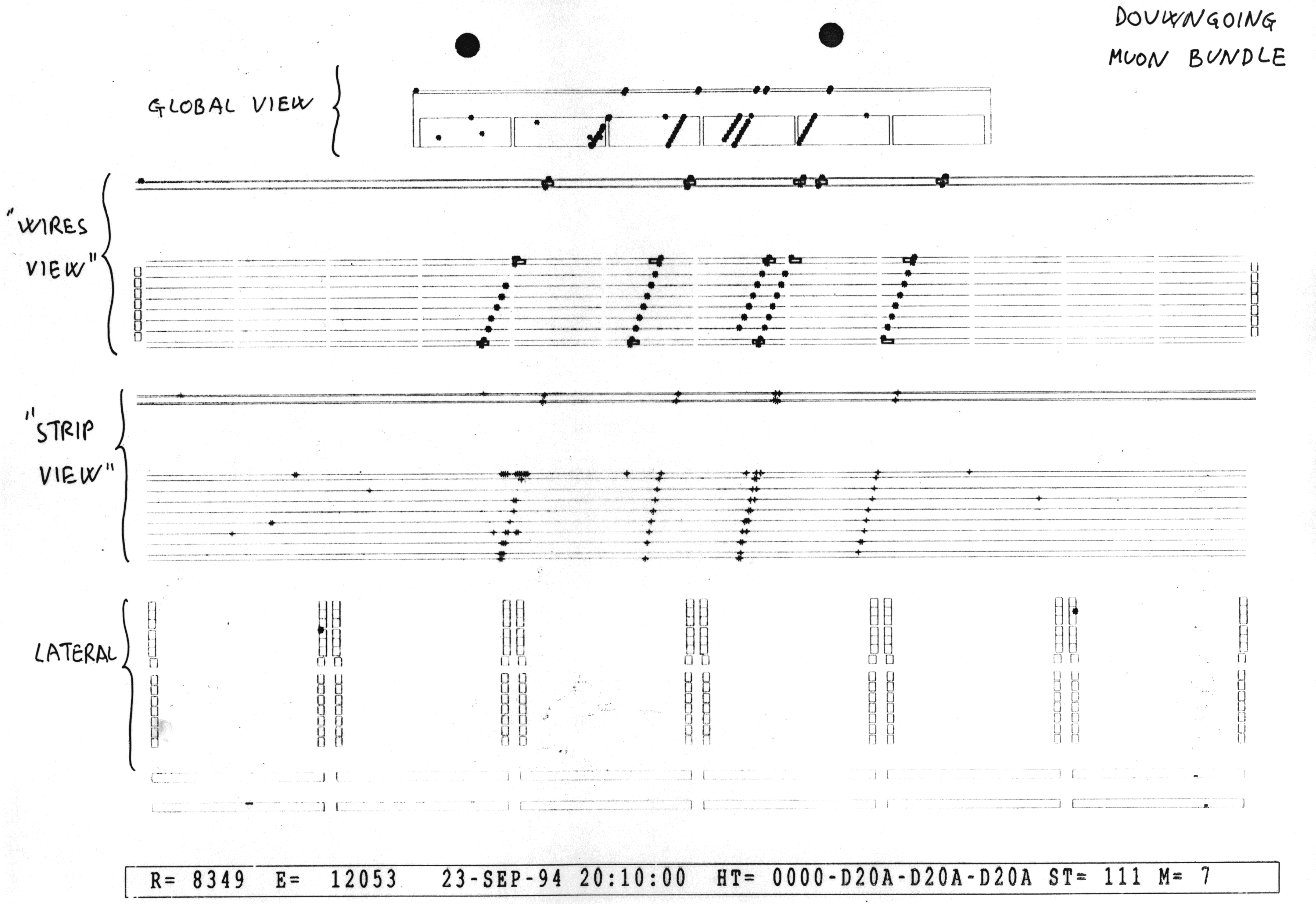
Background rejection cuts:

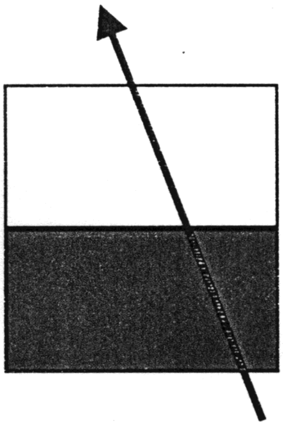
- agreement between **streamer track** and **scintillator hits**

- >200 g/cm^2 of absorber crossed to minimize the background due to $\uparrow\pi$' s produced by $\downarrow$ **muons**
  (Astroparticle Physics **9** (1998) 105)

- **automated data** selection procedure (no visual scan)

- several independent analyses


DOUWNGOING
MUON BUNDLE
GLOBAL VIEW
"WIRES VIEW"
"STRIP VIEW"
LATERAL
R= 8349 E= 12053 23-SEP-94 20:10:00 HT= 0000-D20A-D20A-D20A ST= 111 M= 7



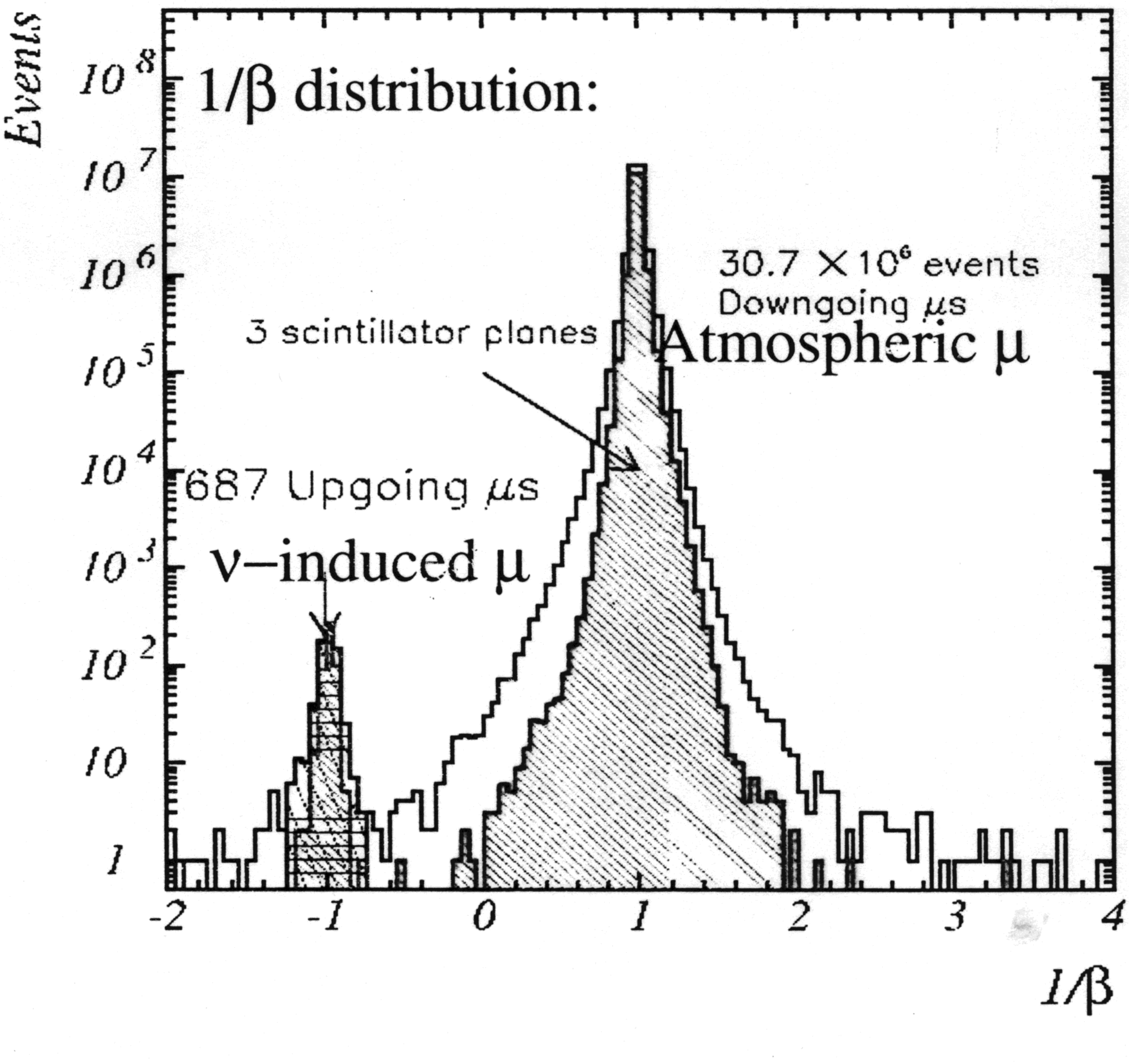
Upward throughgoing muons: the data set

1st SMD — construction — 6 SMD — ATTICO

3/89 11/91 12/92 6/93 4/94 3/00

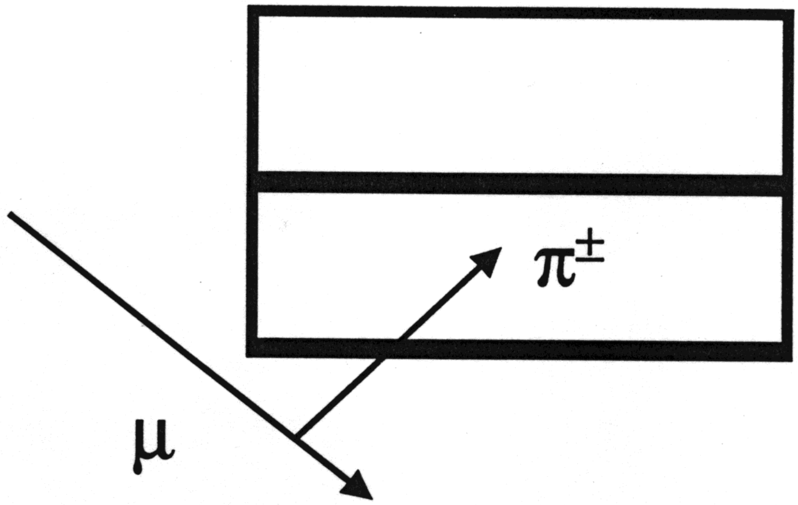
1st SMD	6 SMD	ATTICO
1.4 y	0.4 y	5.1 y
26 ↑μ	51 ↑μ	691 ↑μ

Phys. Lett. B357 (1995) 481   *Phys. Lett. B434 (1998) 451*



Background source for the ν_μ events: pion production by atmospheric muons

MACRO Collab., Astroparticle Phys. 9(1998),105



- Mainly **pions produced at large angles** by μ interactions in the rock around the detector ($\mu + N \rightarrow \mu + \pi^\pm + X$)

- **$\uparrow\pi$ Rate ~ 10^{-5} × Atmospheric $\mu\downarrow$**

- Estimated background in MACRO:

  ~ **5%** for the stopping muon sample

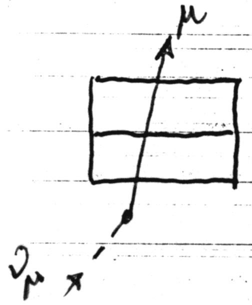
  *(MACRO Coll., PL **B478** (2000),5)*

  ~ **1%** for the up-throughgoing μ (>200 g/cm^2 cut)

  *(MACRO Coll., PL **B434** (1998),451)*

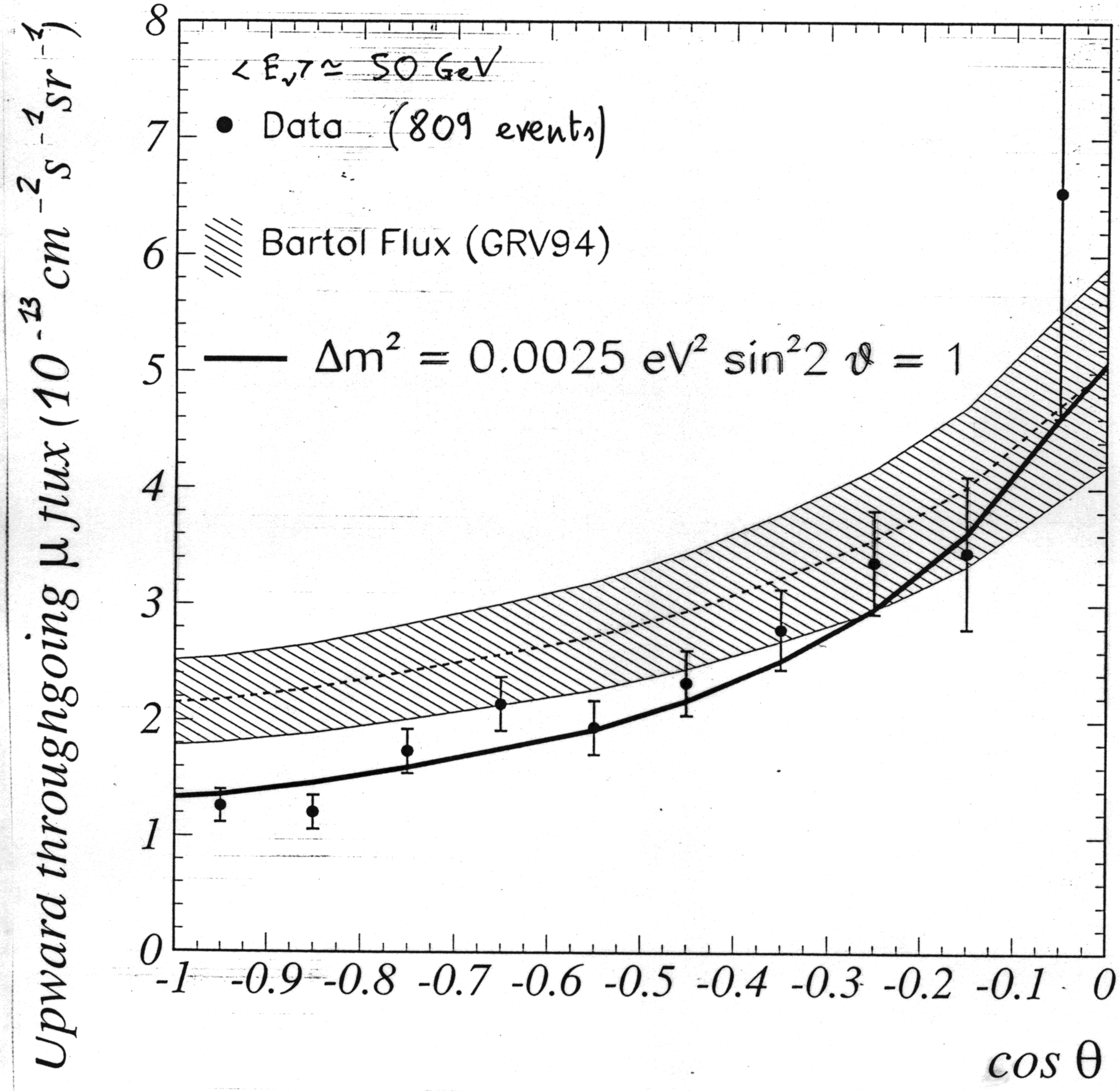
MACRO

ICRC 2001



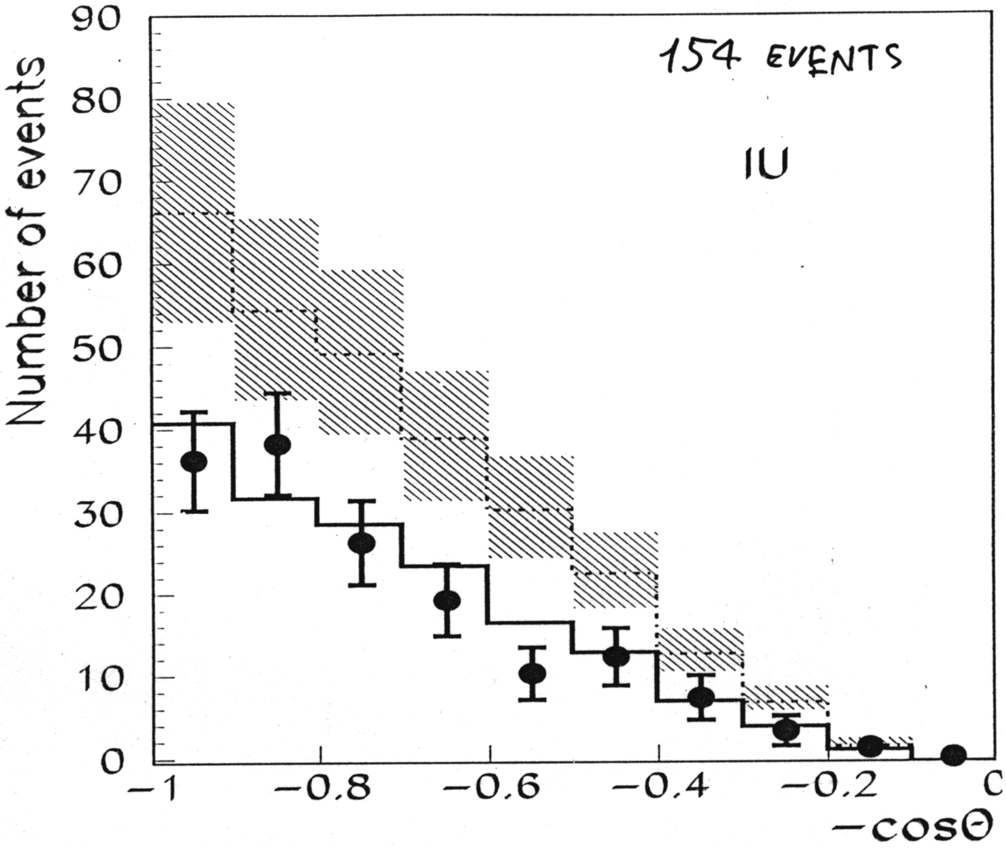
$$R_{-1<\cos\theta<0} = \frac{DATA}{MC} = 0.721 \pm 0.026_{STAT} \pm 0.043_{SYST} \pm 0.123_{TH}$$

$$\frac{809_{ev}}{1122_{MC}}$$

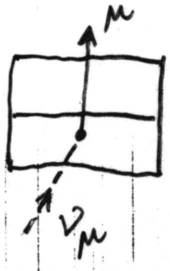


MACRO

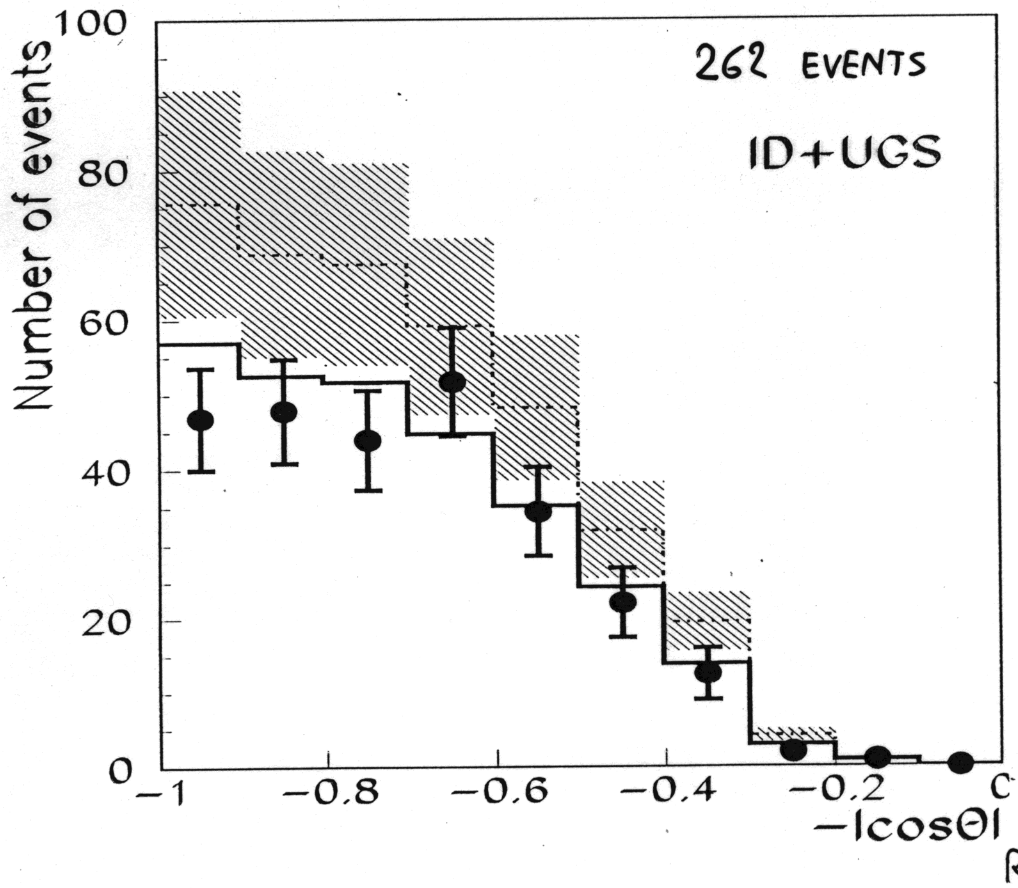
$E_\nu \simeq 4$ GeV

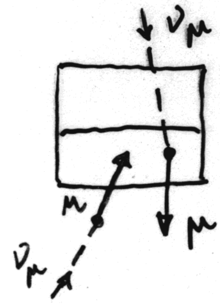


UP-SEMICONTAINED



$R = \frac{\text{MEASURED}}{\text{EXPECTED}} = \frac{154}{285} = \simeq 0.54 \pm 0.04_{STAT} + 0.15$

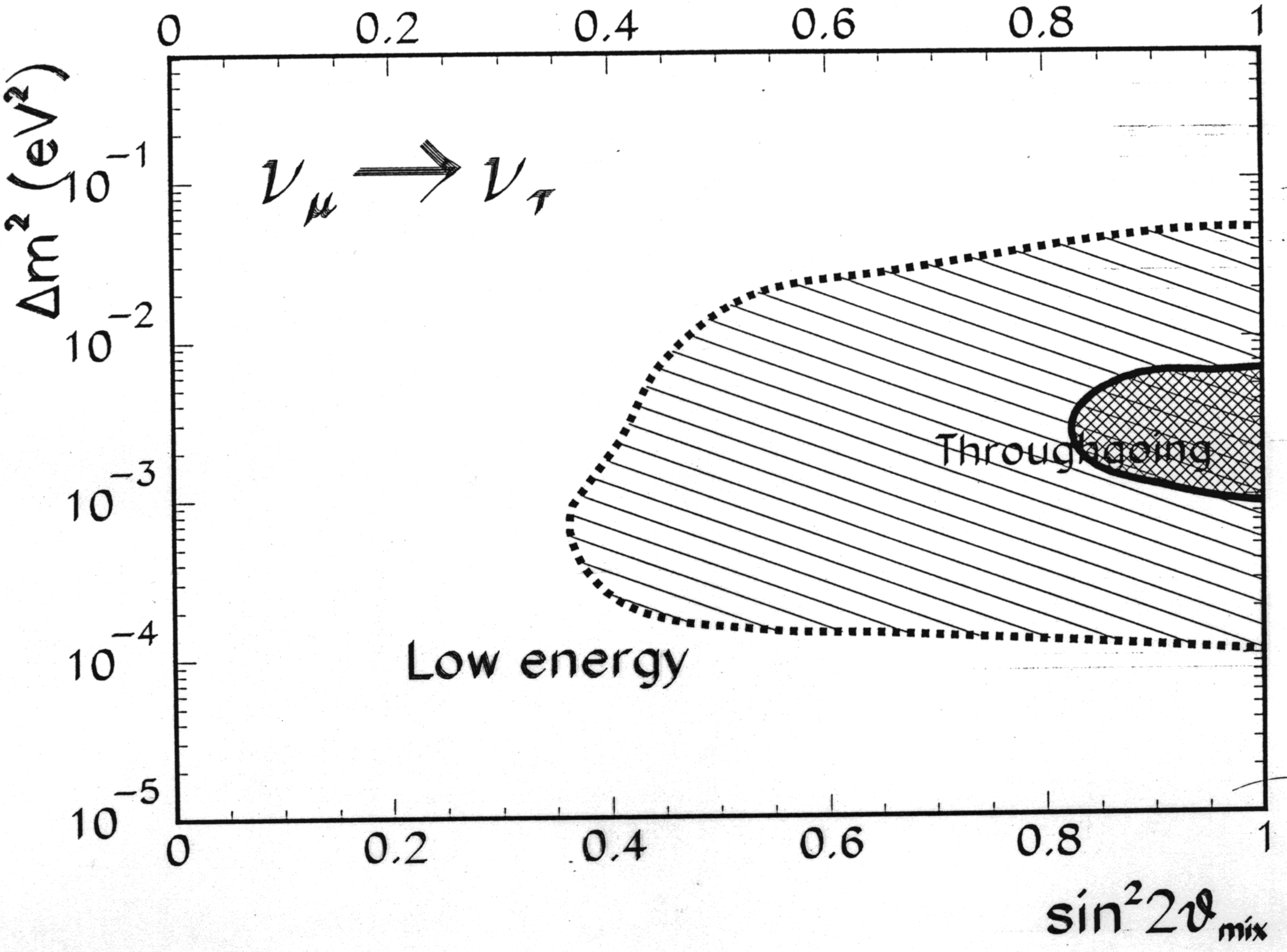




UPSTOPPING +
+ DOWN SEMICONTAINED

$R = \frac{\text{MEASURED}}{\text{EXPECTED}} = \frac{262}{375} \simeq$
$\simeq 0.70 \pm 0.04_{STAT} \pm 0.02_{SYS} \pm 0.17_{TH}$

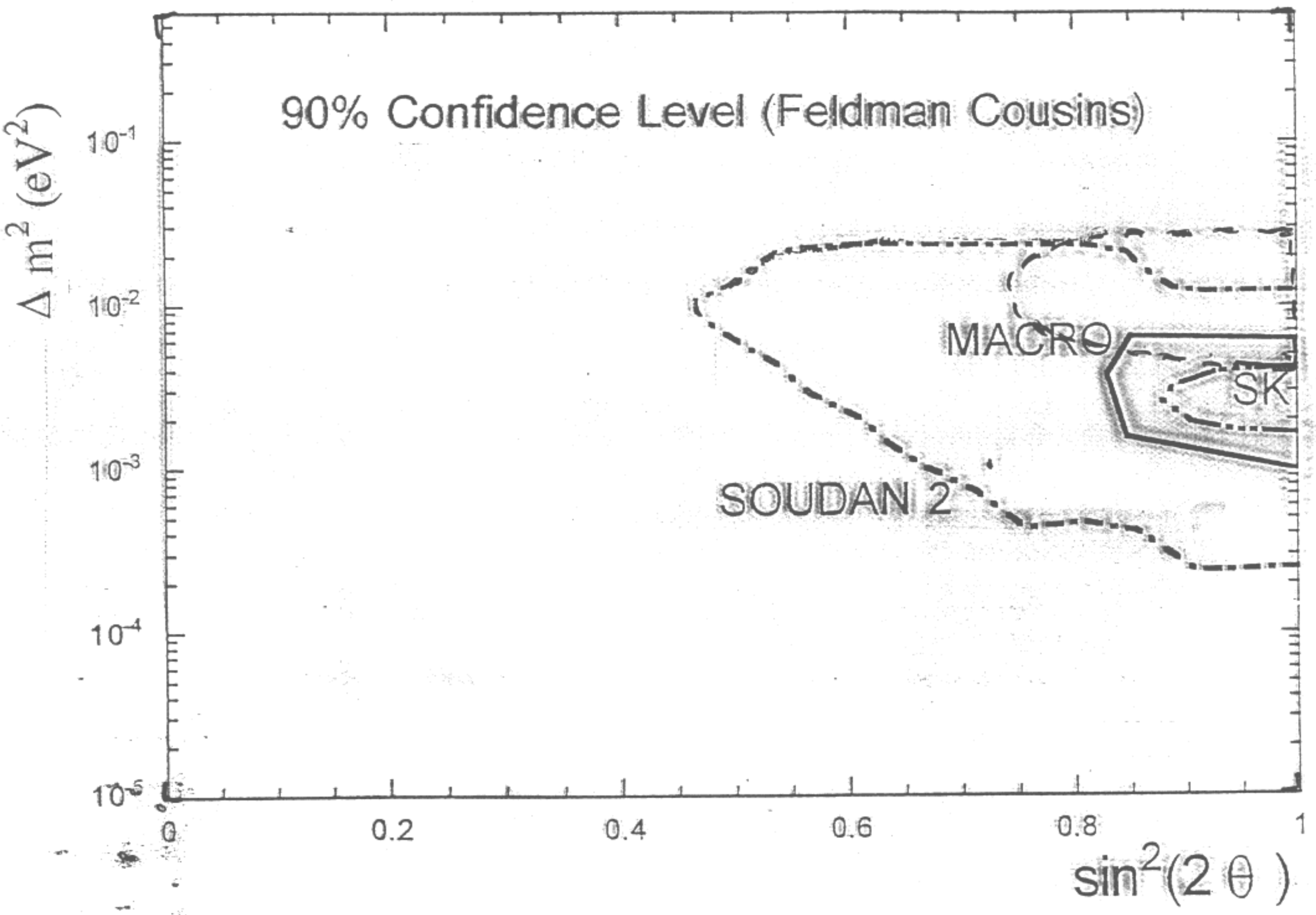
90% CL



0
0.2
0.4
0.6
0.8
1
Δm^2 (eV²)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$\nu_\mu \rightarrow \nu_\tau$
Throughgoing
Low energy
$\sin^2 2\vartheta_{mix}$

Confidence level regions
(ν_μ--> ν_τ oscillations)

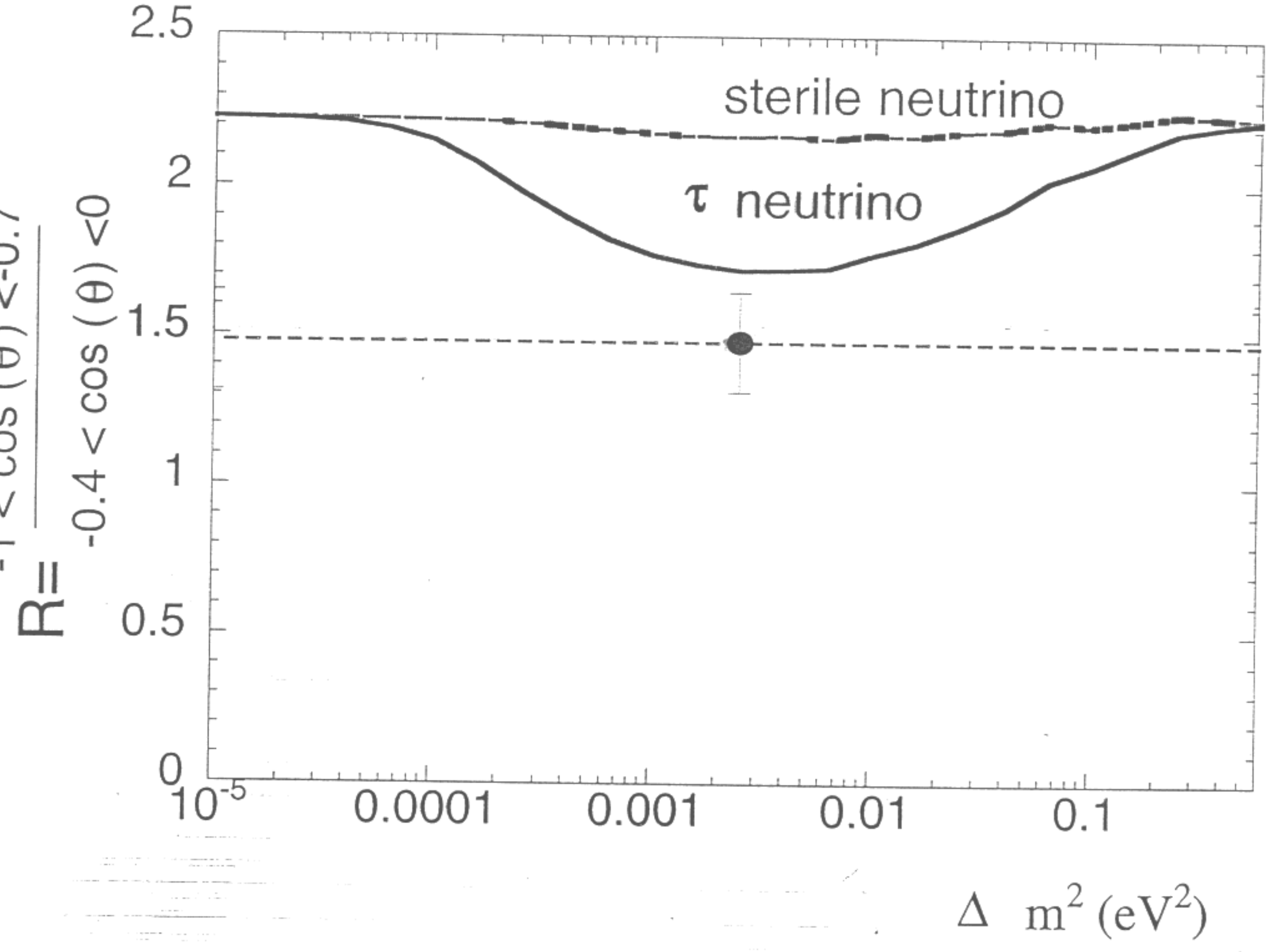
KAMIOKANDE



$\sin^2 2\theta = 1$

$\Delta m^2 = 0.0025\ eV^2$

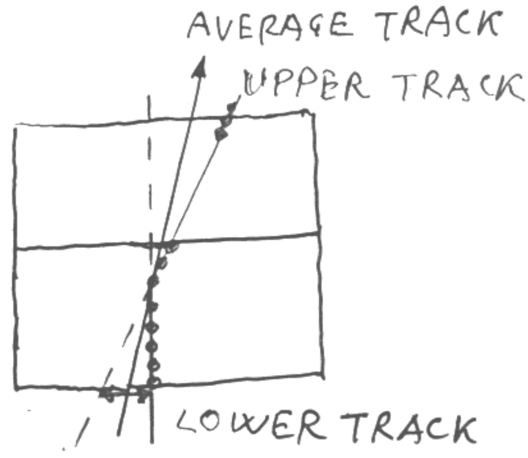
MACRO
hep-ex/0106049

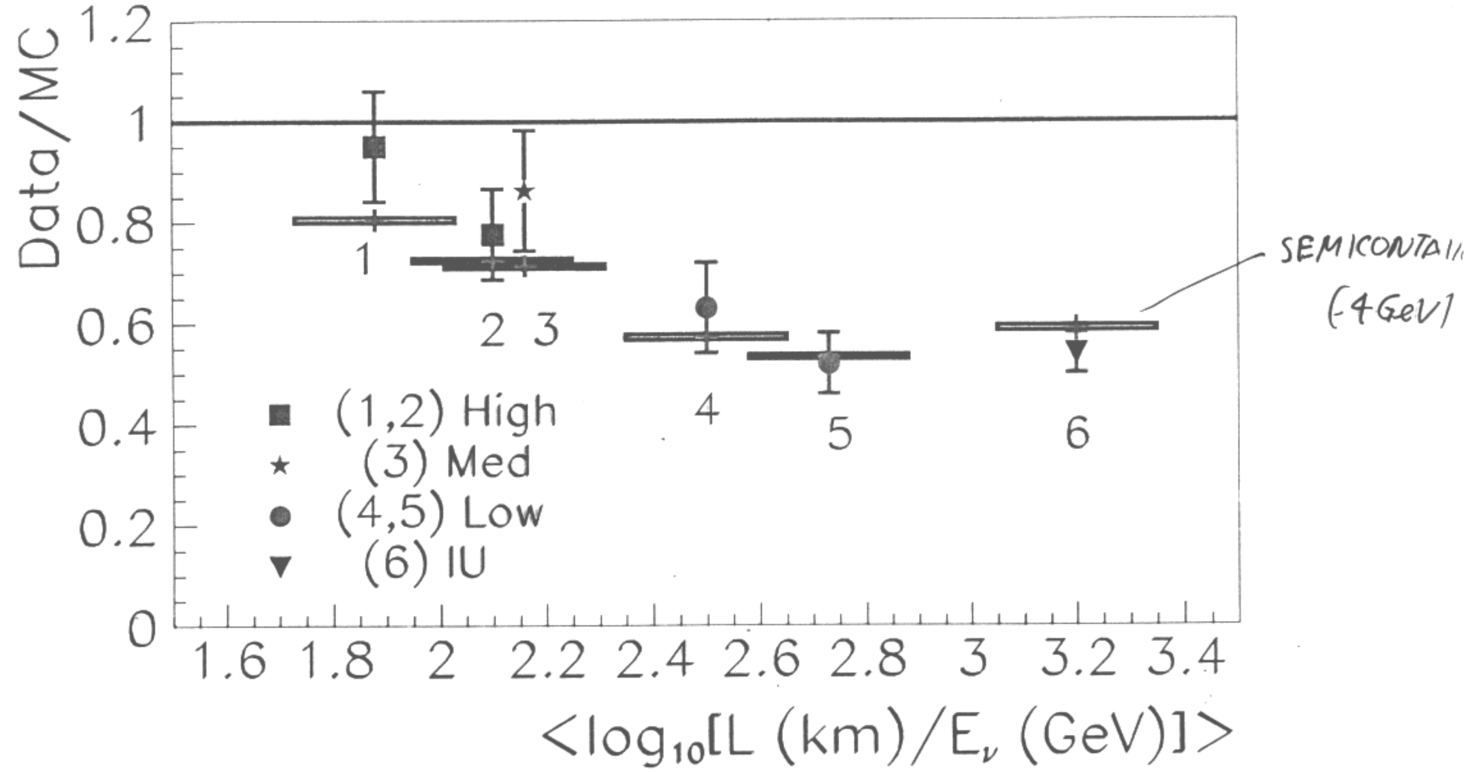


μ ENERGY ESTIMATE FROM MULTIPLE COULOMB SCATTERING

SIMPLER METHOD

R ~ 1 cm





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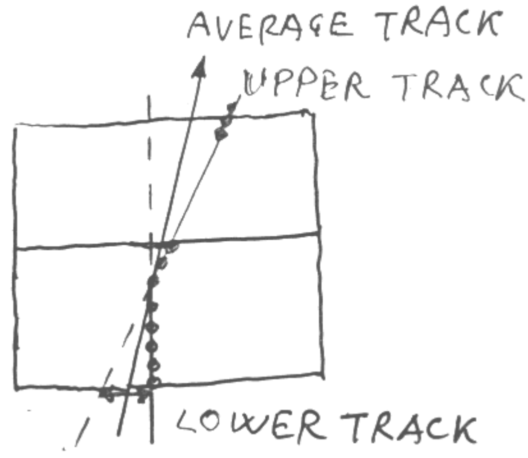
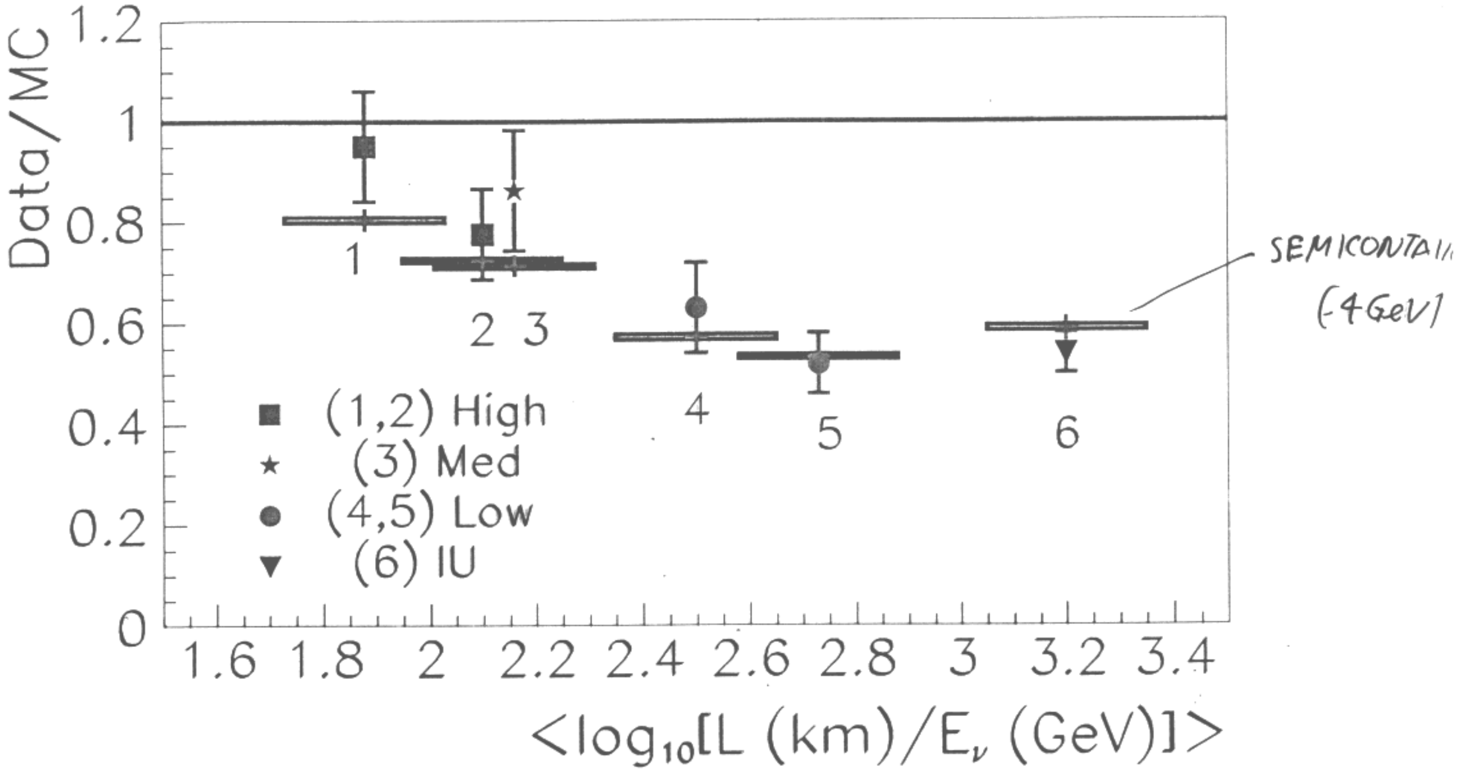
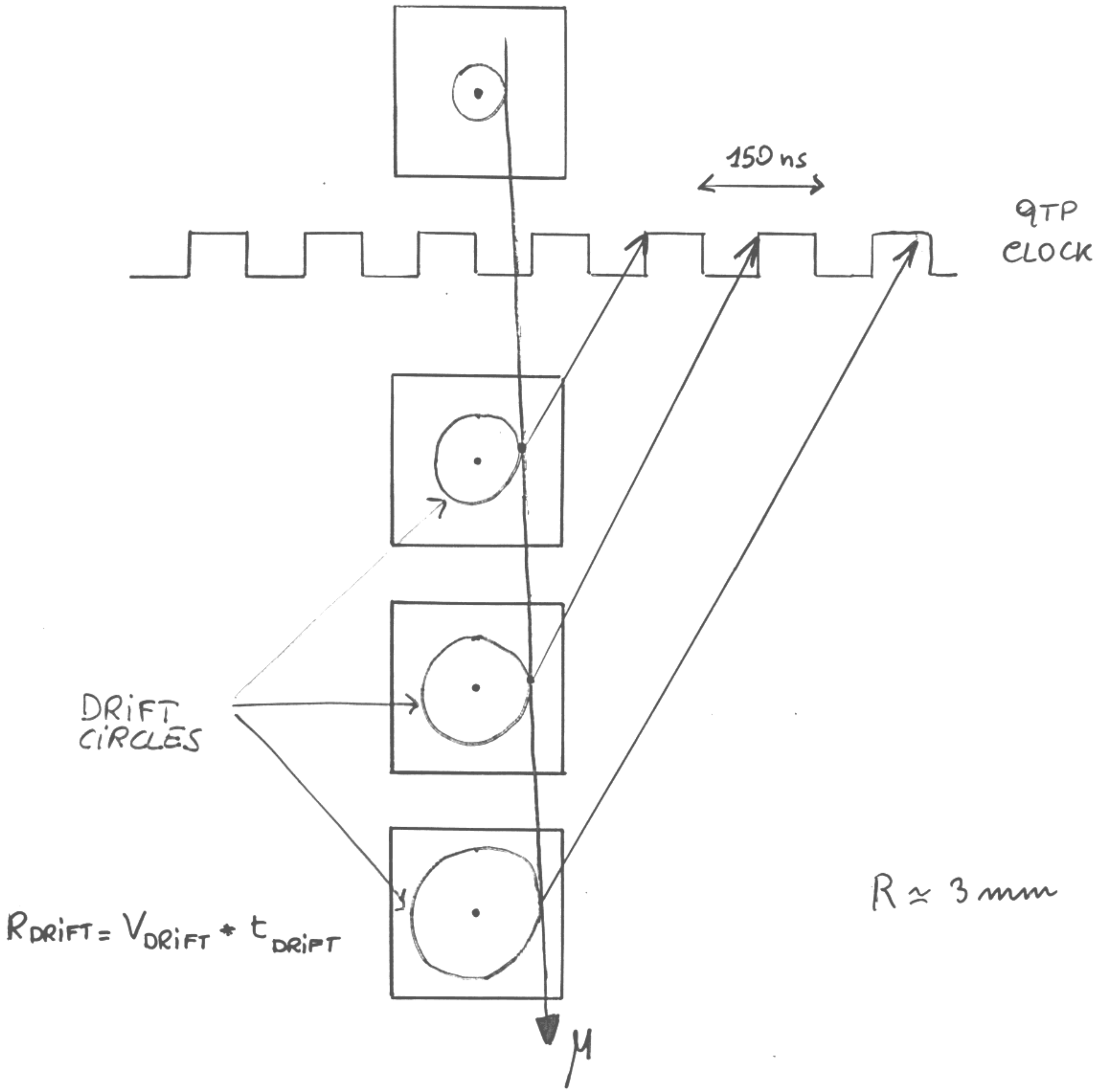
R ~ 1 cm





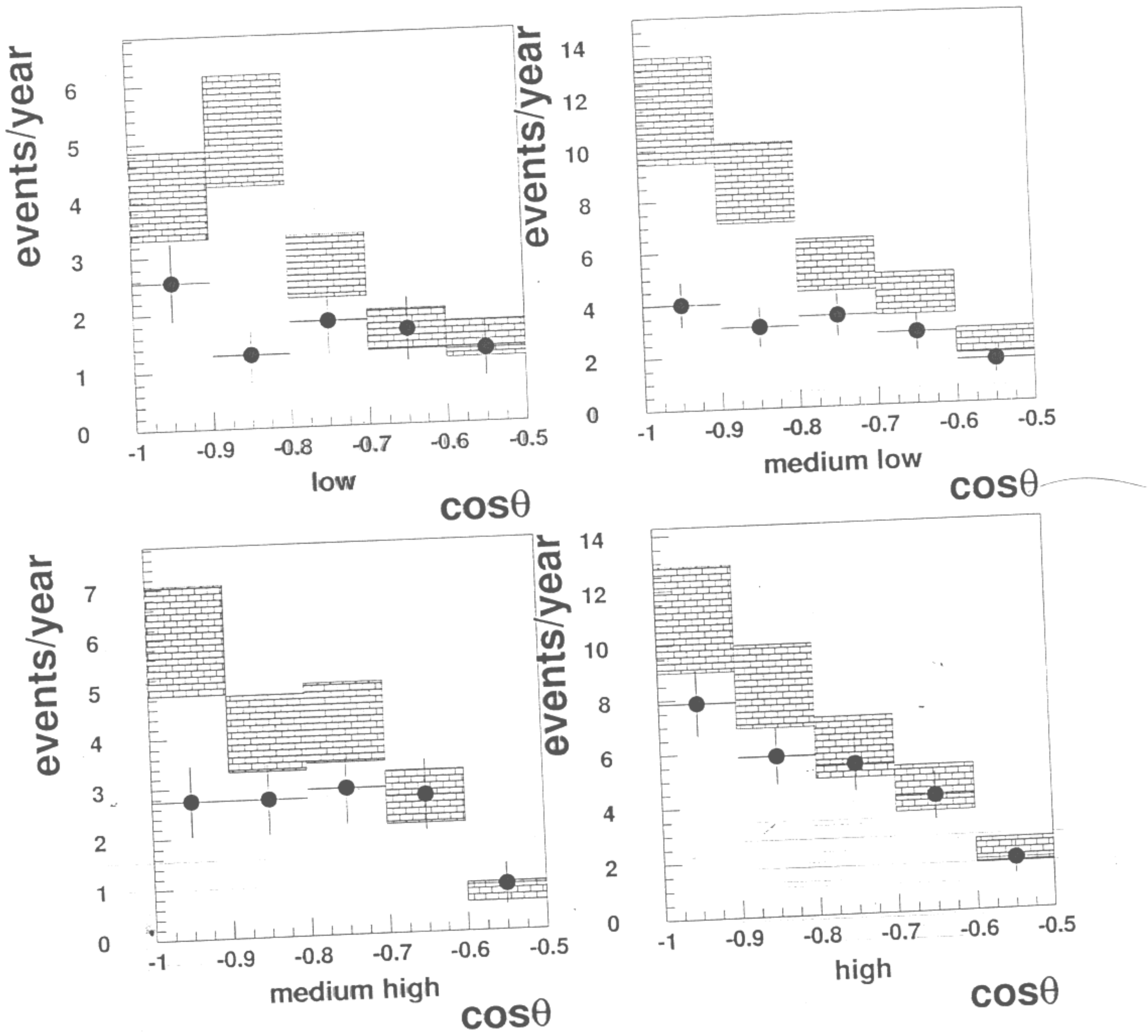
μ ENERGY ESTIMATES FROM MULTIPLE COULOMB SCA

① STREAMER TUBES USED IN DRIFT MODE
USING QTP (CHARGE AND TIME PROCESSOR) WHICH MEASUR ARRIVAL TIME, DURATION AND CHARGE OF STREAMER TUBE SIGNALS



THE TRACK IS RECONSTRUCTED PERFORMING A FIT OF THE DRIFT CIRCLES OF THE TRIGGERED TUBES

MACRO


events/year
low
cosθ
events/year
medium low
cosθ
events/year
medium high
cosθ
events/year
high
cosθ

SCAP 29/6/01

MACRO

μ-ENERGY ESTIMATE FROM COULOMB MULTIPLE SCATT: