F. Ronga

NEUTRINO Physics in the MACRO detector

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

MACRO at GRAN SASSO

Monopole, Astrophysics, and Cosmic Ray Observatory

Outline

- The MACRO detector
- Search for ν from stellar collapses
- π produced at large angle : possible background for atmospheric neutrinos
- upgoing muons : flux
- upgoing muons : neutrino astronomy

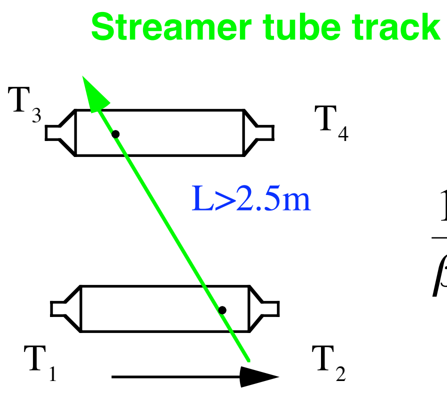
Upgoing muons - data set

1st SMD	construction	6 SMD		6SMD +ATTICO
Mar '89 – Nov '91		Dec '92 – Jun '93		Apr '94 – Dec '95
1.4 yr		0.43 yr		1.24 yr
~2.3x10^6 μ↓		3x10^6 μ↓		~8x10^6 μ↓
26 μ↑		51 μ↑		188 μ↑

DATA ANALYSIS

- **Four independent analysis**

- **β evaluation:**



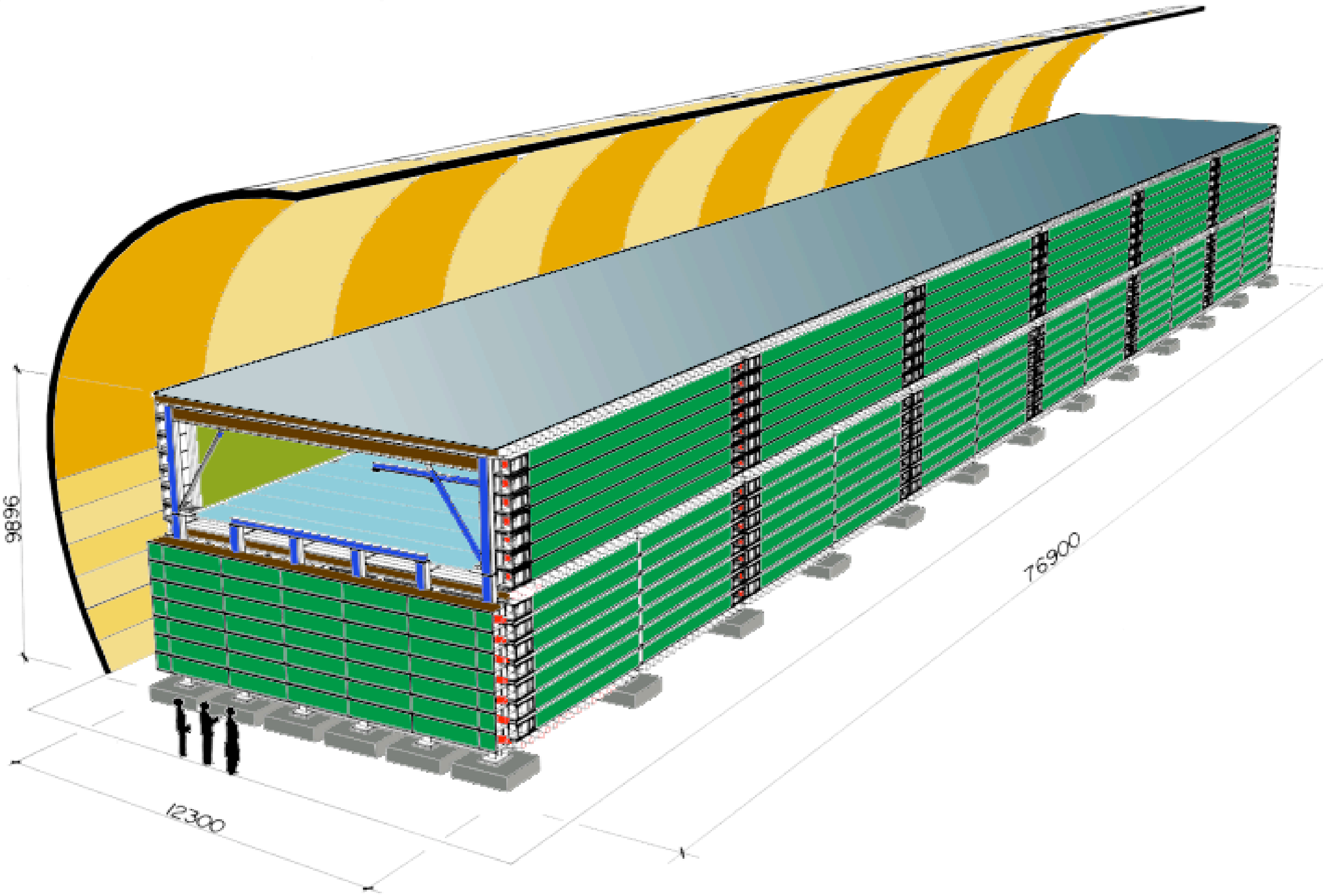
$$\frac{1}{\beta} = \frac{(T_1 + T_2 - T_3 - T_4)c}{2L} = \begin{cases} +1 \ \mu\downarrow \\ -1 \ \mu\uparrow \end{cases}$$

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 Í χ^2 cut**

- for 2 counters events **additional background cuts (mainly to cut multiple and showering muons)**

Main features of Macro as ν detector

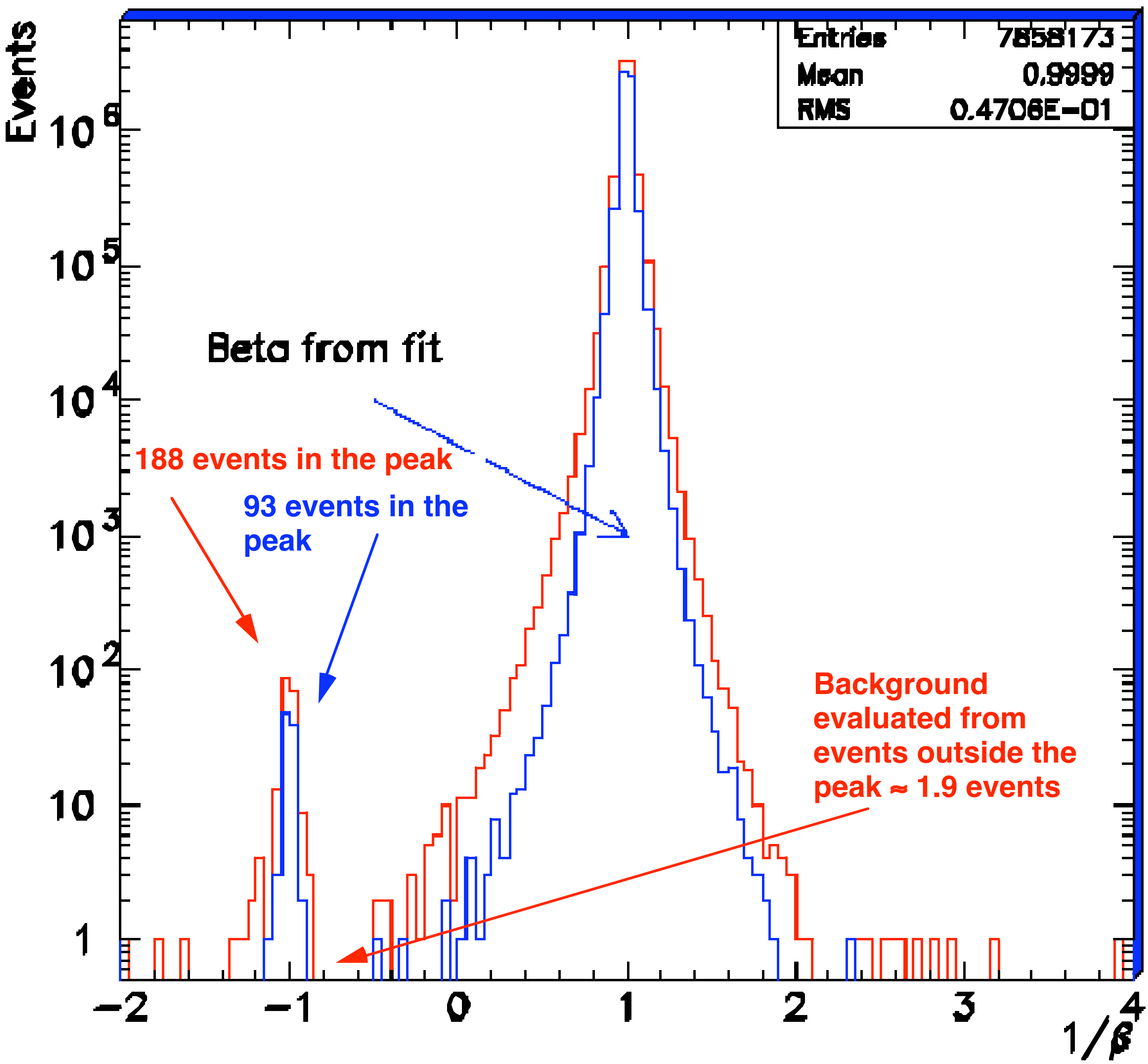


- Large acceptance (~10000 m^2sr for an isotropic flux)
- Low downgoing μ rate (~10^{-6} of the surface rate)
- ~600 tons of liquid scintillator to measure T.O.F. (time resolution ~500psec)
- ~20000 m^2 of streamer tubes (3cm cells) for tracking (angular resolution < 1°)

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

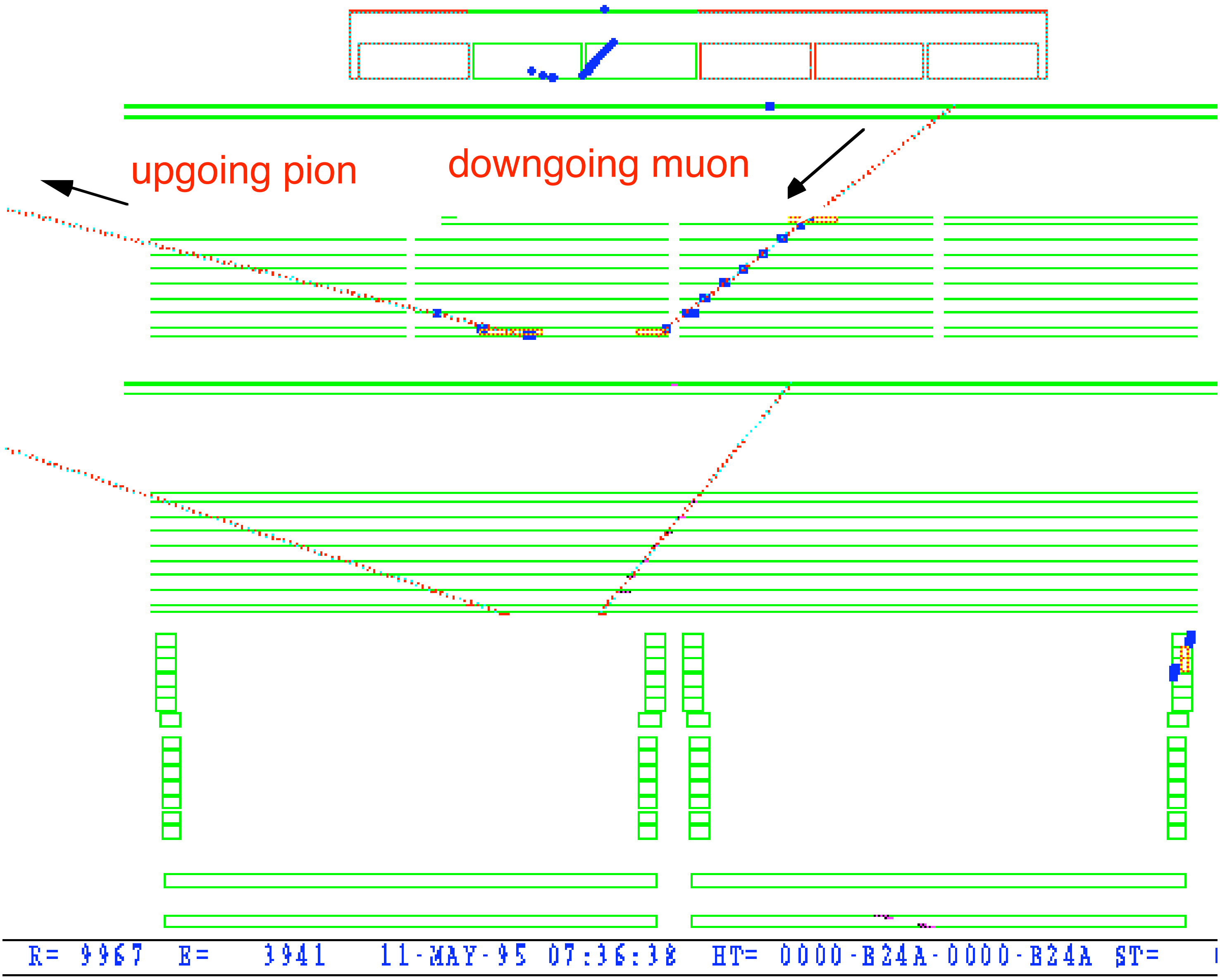
Upgoing muons - final cuts for flux measurement

- $L_{\text{lower MACRO}} > 2\text{m}$ $(Emin_{\mu} \gtrsim .5\text{GeV}, \; \langle E_{\mu} \rangle \approx 1.5 \text{ GeV})$
- $-1.25 < 1/\beta < -0.75$



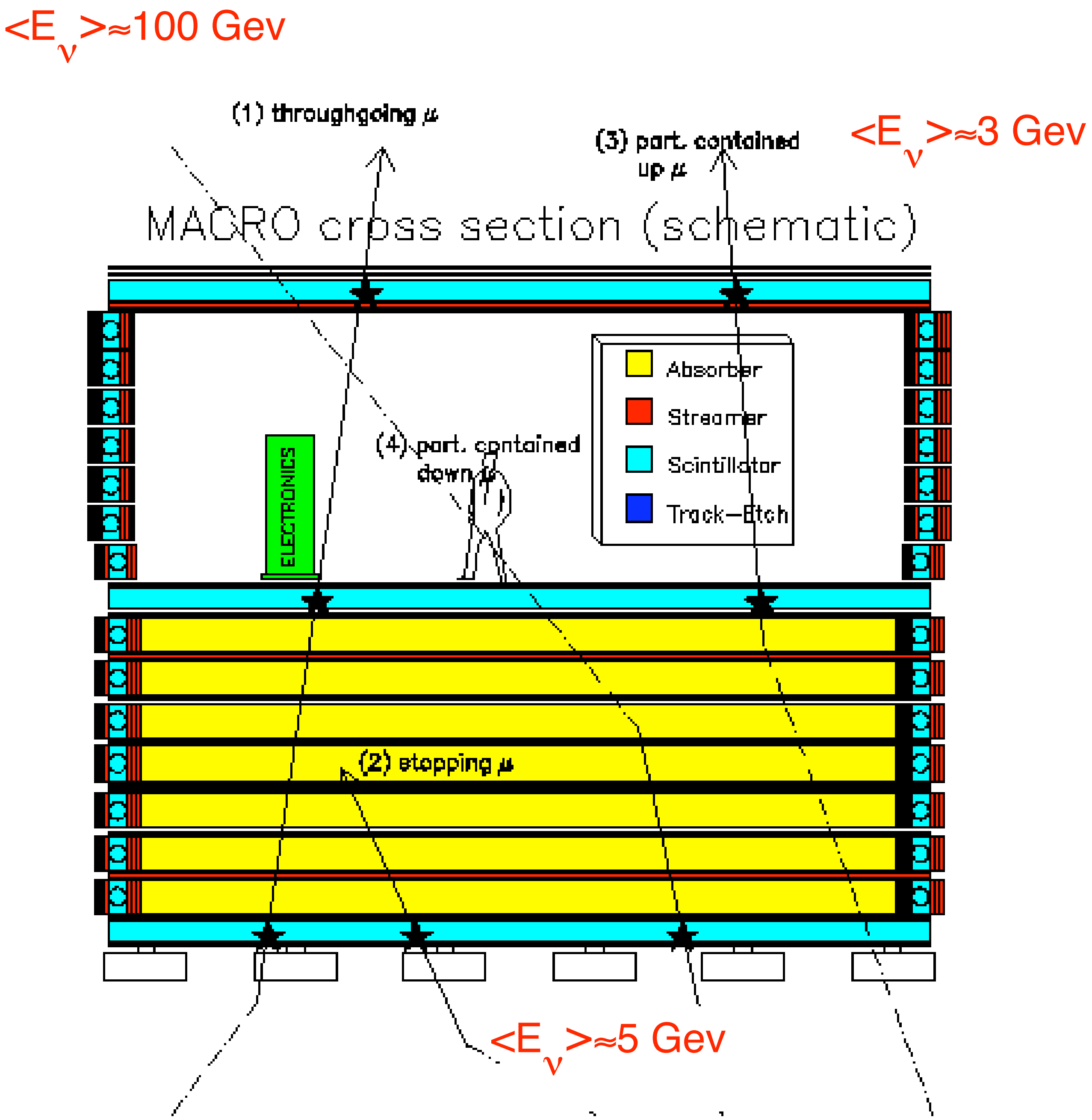
Pion production at large angle

- 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
- 230 upgoing particles + downgoing muon were found in 1.07 year of livetime with attico and 0.48 year with only lower MACRO
- possible background in the stopping muon search ≈ 10%

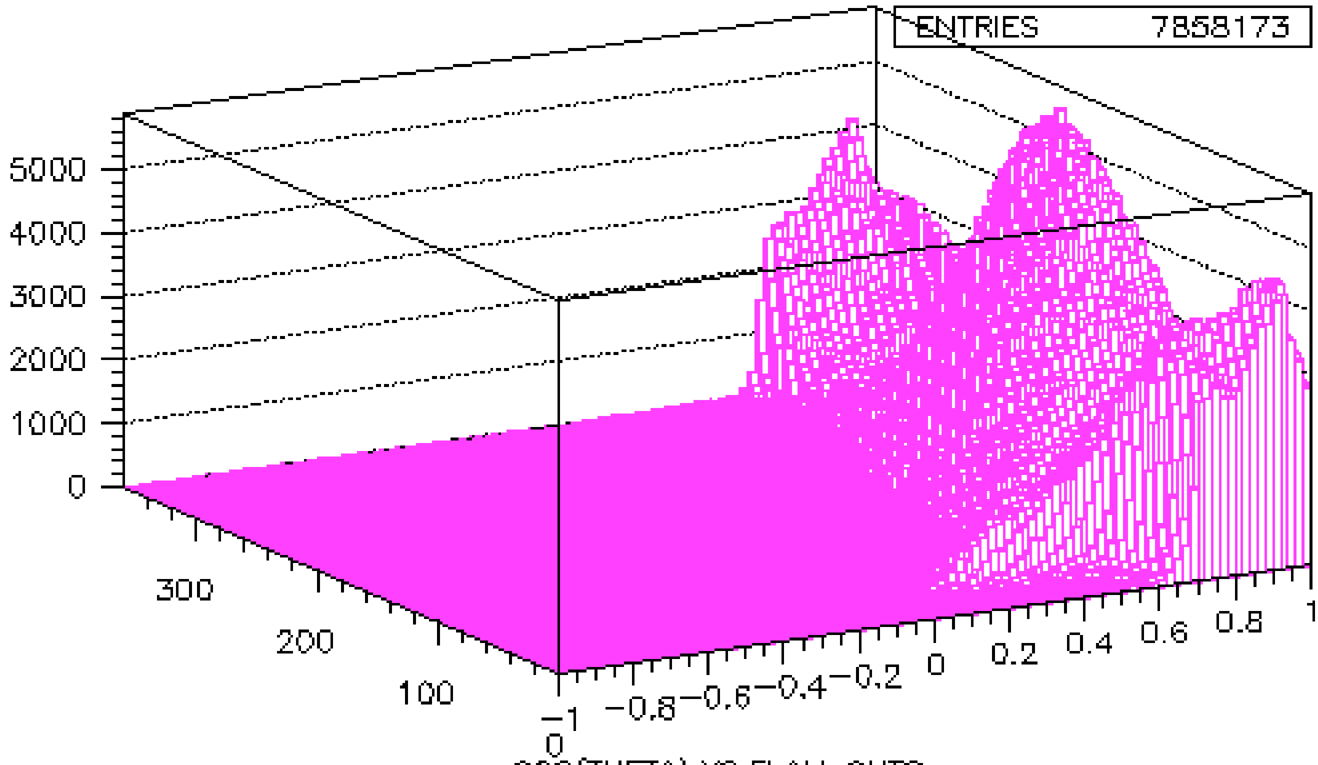


Neutrino event topologies in MACRO

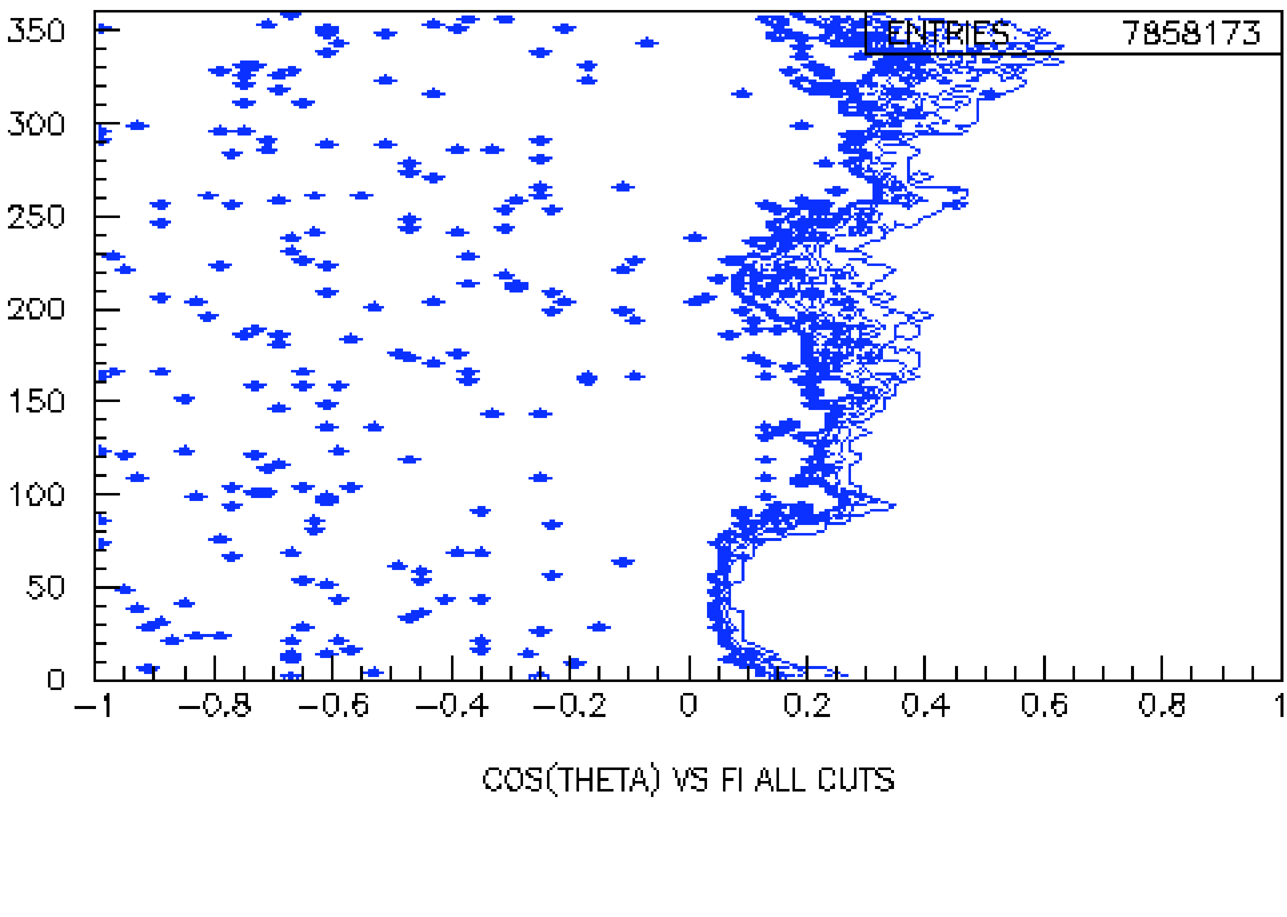
• MACRO can detect different categories of Neutrino produced Muons.



Angular Distribution of Upgoing and downgoing muons

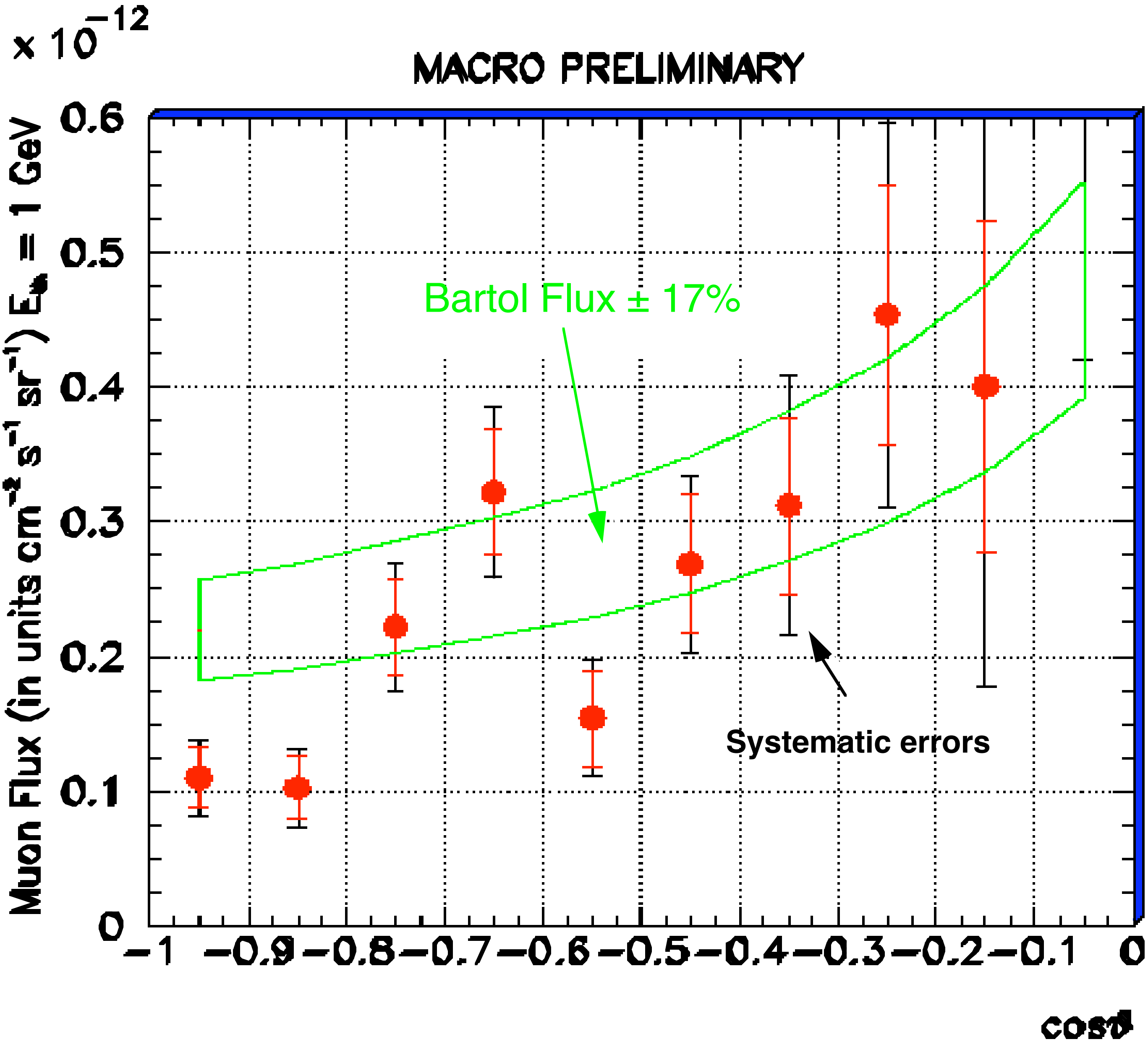


COS(THETA) VS FI ALL CUTS



COS(THETA) VS FI ALL CUTS

Angular distribution



flux in the bin of cos(zenith)< -0.8 too low?

- best acceptance for MACRO
- effect of material :
  - -15 % for water (compared to rock)
  - +10 % for Fe
- χ^2/d.o.f. = 16/9 assuming a theoretical error of 17% for each bin, χ^2/d.o.f. = 23/8 with scaling in the flux (0.8) and 0 theoretical error

Events measured and expected

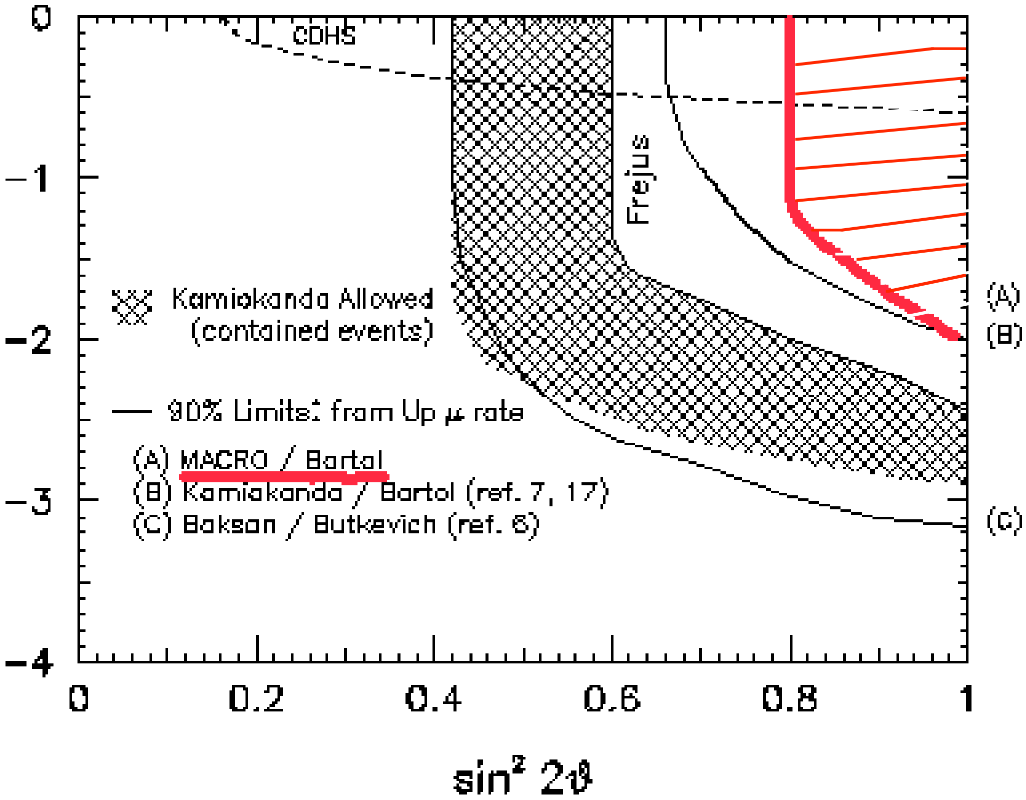
• data	266
• background	4.9
• MC internally produced	6.4
• Data- Background - MC internally produced	254.7
• MC Upgoing muons (Bartol flux)	314.5 ±17%
Butkevich flux	323
Mitsui flux	288
Volkova	286

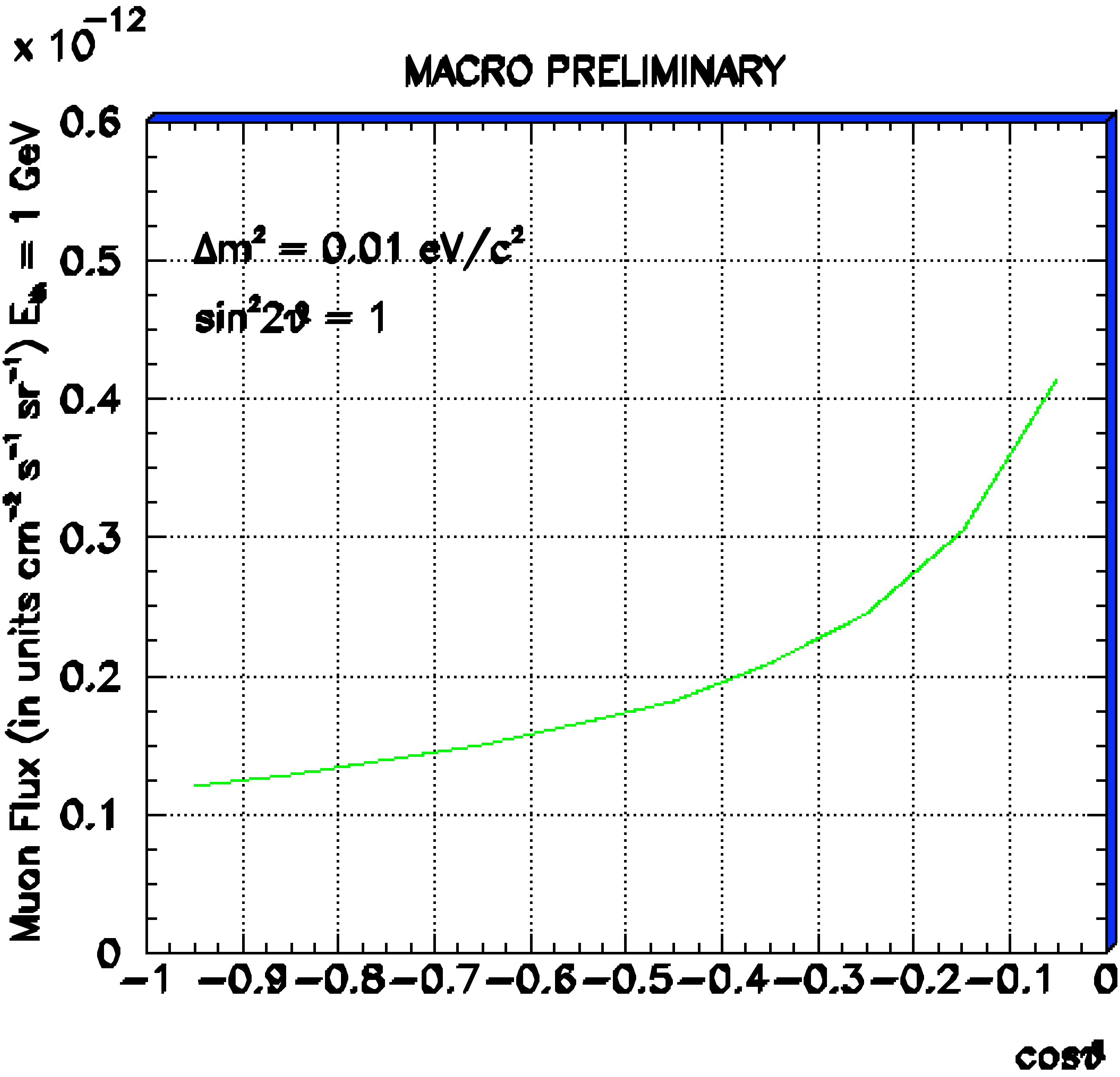
- **R = Nfound/Nexpected(Bartol flux) =0.81 ± 0.05 (statist) ± 0.06 (system.) ± 0.14 (theoretical) = 0.81 ± 0.16 (errors in quadrature)**

Exclusion plot computed from R (90% c.l.)

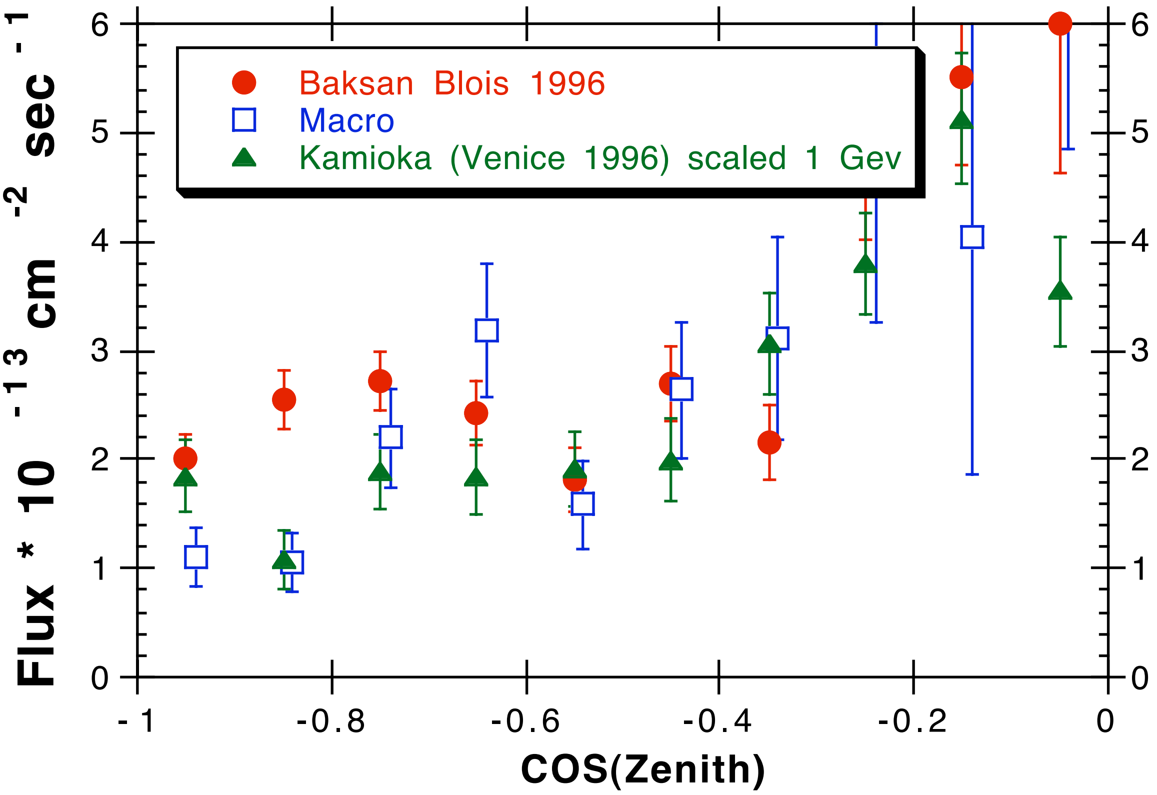
Log(Dm²)

$\nu_\mu \rightarrow \nu_\tau$:




x 10^-12
MACRO PRELIMINARY
Δm² = 0.01 eV/c²
sin²2ϑ = 1
Muon Flux (in units cm⁻² s⁻¹ sr⁻¹) E_th = 1 GeV
0.6
0.5
0.4
0.3
0.2
0.1
0
−1 −0.9 −0.8 −0.7 −0.6 −0.5 −0.4 −0.3 −0.2 −0.1 0
cosϑ

Flux compared to other experiments



Conclusions

- MACRO is taking data in the final configuration
- Very reliable operation for stellar collapse
- Possible background in the stopping muons due to upward-going pions produced from down-going muons
- About 150 upgoing muons/year for flux measurement
- Measured flux about 80% of the predicted (Bartol neutrino flux)
- Zenith angular distribution ?
- No evidence for neutrino point sources. Combined flux limits now in the range of a few units in 10^{-15} cm^{-2} sec^{-1}

Summary

- MACRO as neutrino detector
- Large angle scattered pions as possible background to stopping and throughgoing muons
- Upgoing throughgoing muon analysis
- Neutrino astronomy

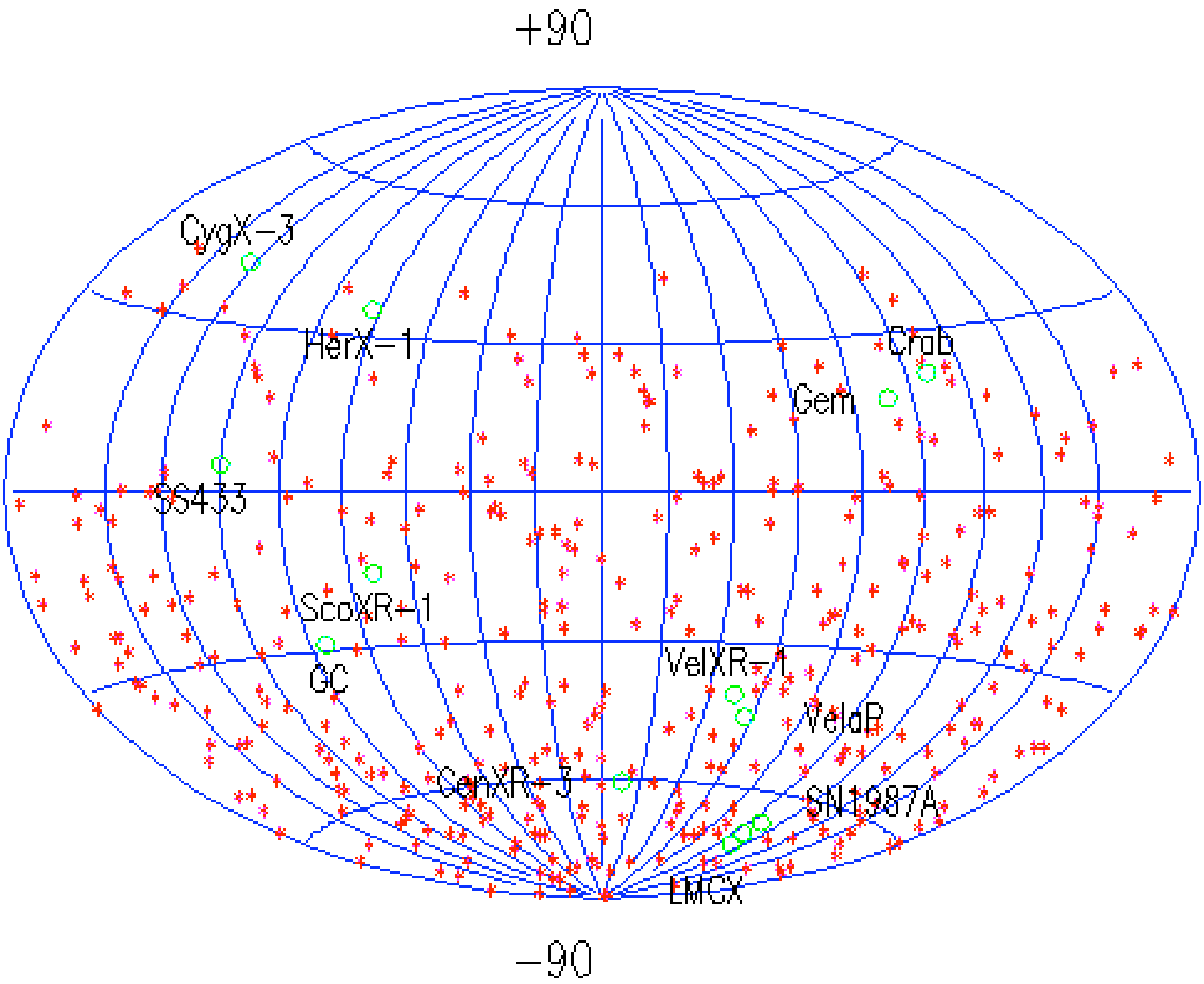
Neutrino Astronomy

- **392 Events. Larger sample. No cut on the path in lower MACRO (no requirement on the material crossed) . Inclusion of events taken during construction periods.**

- **Pointing accuracy and resolution checked with the shadow of the Moon in the down-going muons events**

- **Search window 3° (about 90% of the signal for a neutrino spectral index 2.1).**

- **No statistically significant cluster**



Acceptance study with down-going muons

- Comparison of the down-going muons data (analyzed with same cuts as for up-going muons) with the Montecarlo simulation of down-going muons : Main difference with previous experiments

Cut	Data	MC	Difference
streamer track matching 2 scin boxes + L >2.5 m	79.5%	81.7%	2.2%
cuts to remove background	96.2%	98.0%	1.8%
L > 2m lower MACRO	84.5%	83.7%	-0.8%
Total			3.2%

- The differences in function of the zenith angle are used to estimate the systematic errors on the acceptance for upward-going muons,

even if some of the differences are due to the MC generator and to the Gran Sasso map

Monte Carlo simulation of upgoing muons

- Calculation of the upgoing muon flux:

  Atmospheric neutrino flux: BARTOL flux

  (Phys. Rev. D48(1993)1140)

  uncertainty on upgoing muon flux with E> 3 GeV = ±13% with atmospheric muon flux normalization

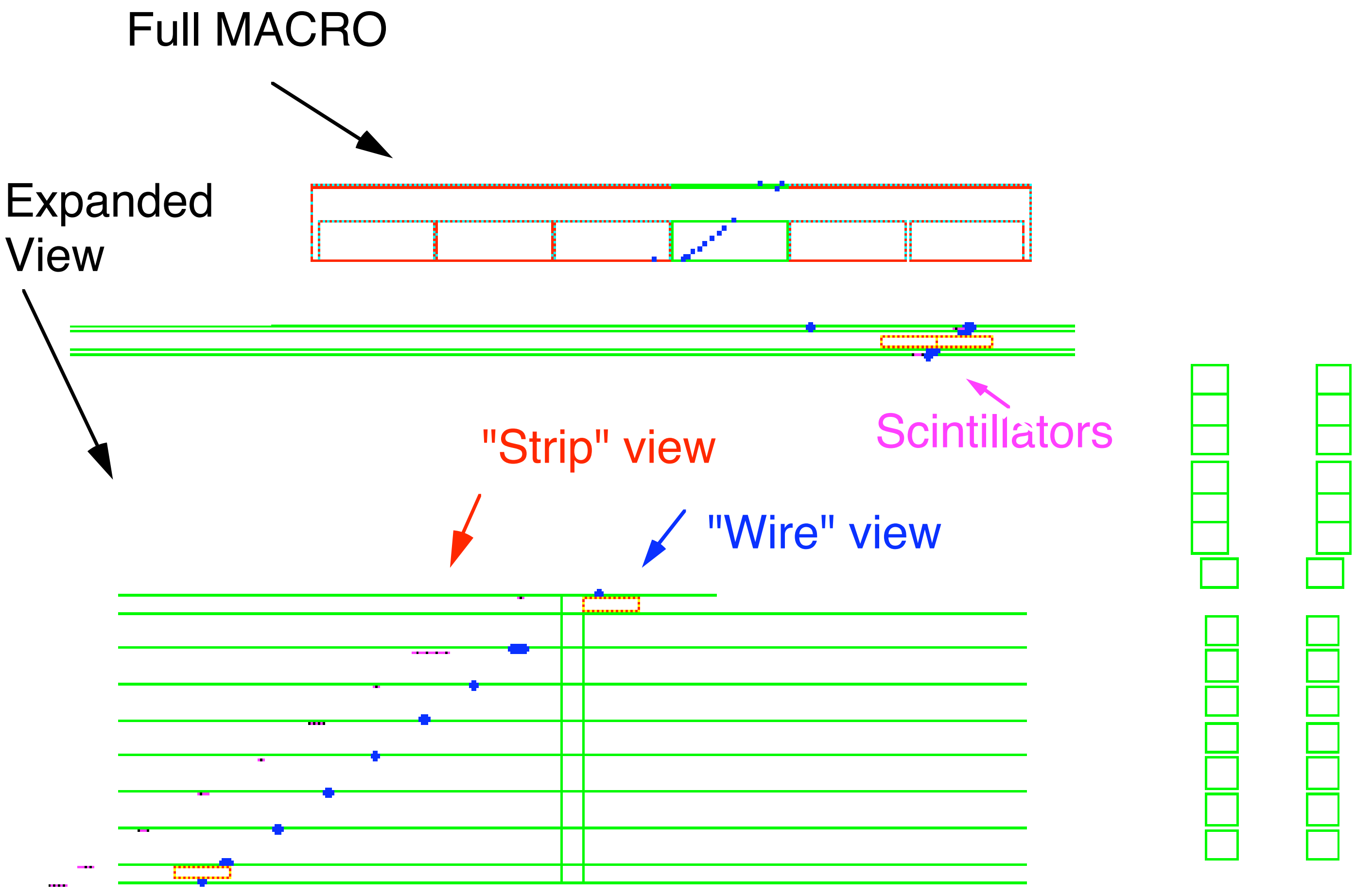
  Neutrino interaction cross section: Morfin and Tung DIS parton distributions (Z. Phys. C52 (1991) 13)
  uncertainty = ± 9 %

  Lohmann et al. muon energy loss calculation (CERN-EP/85-03)
  uncertainty = ± 5%

  Total uncertainty = ± 17%

- GEANT based simulation of the apparatus

Upgoing muon with 3 scintillator planes



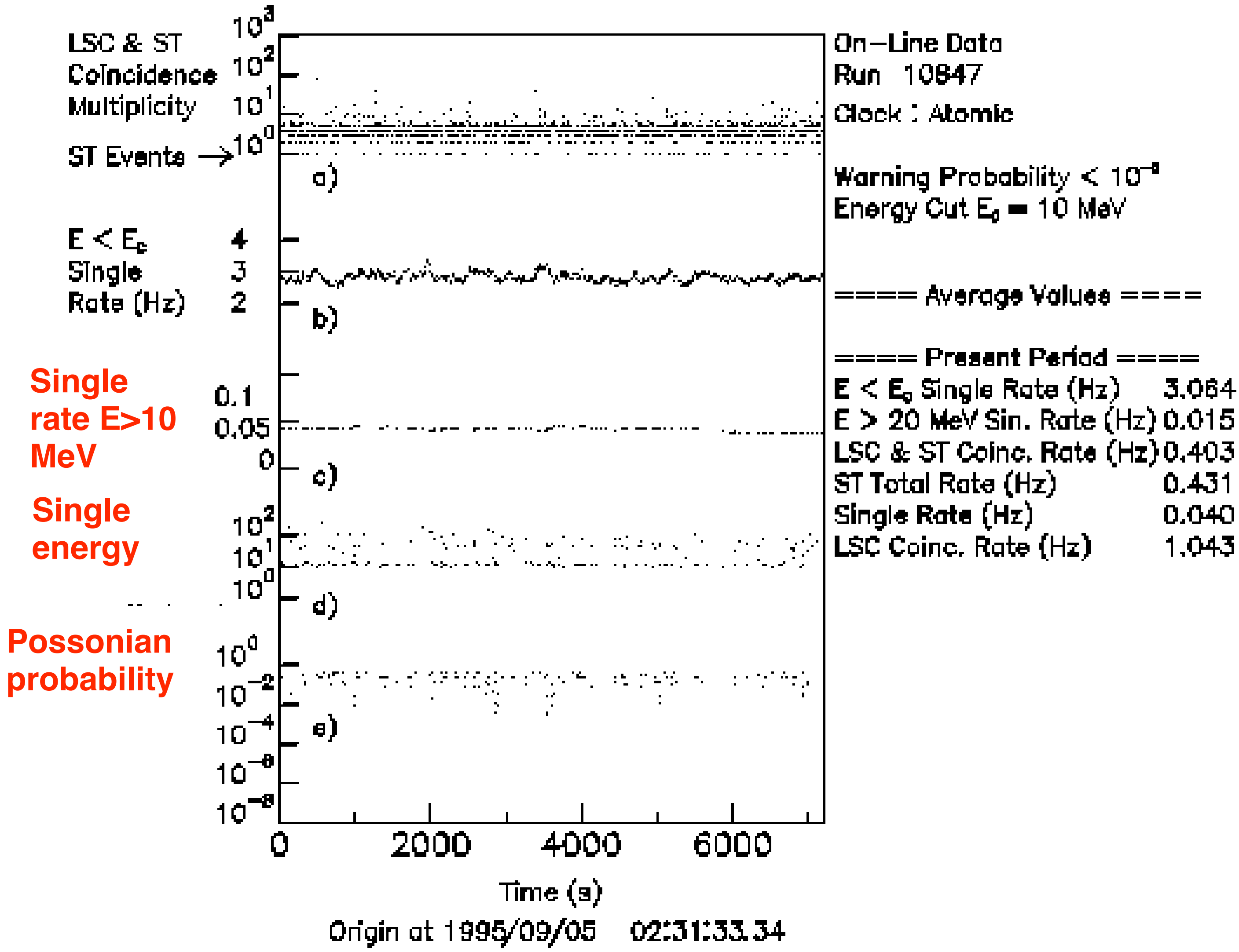
$1/\beta = -1.01 \quad \chi^2 = 1.6$

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

Search for neutrino bursts from stellar collapses

- ≈580 Tons of liquid scintillator
- calibration with muons (≈ 34 MeV) + natural γ line from ^{208}Tl (2.6 MeV)
- 110 events (ν_e + p -> e^+ + n from a supernova in the galactic center)
- 40 mHz background rate ==>> fluctuation of 20 events in 2 sec <<10^{-5} in 10 years (supernova like SN1987A ≈ 20 events)

Online monitor programs : very stable rate

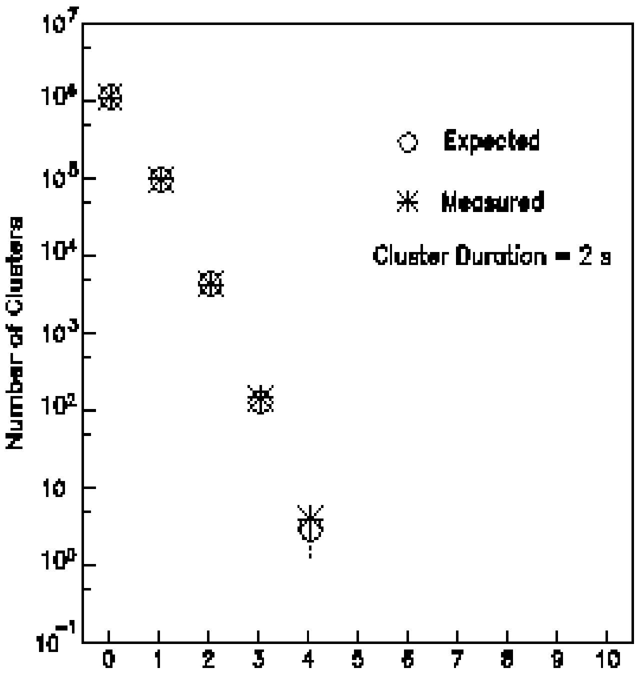


Search for neutrino bursts from stellar collapses

- **MACRO is running for this search from 1989 (with lower mass)**

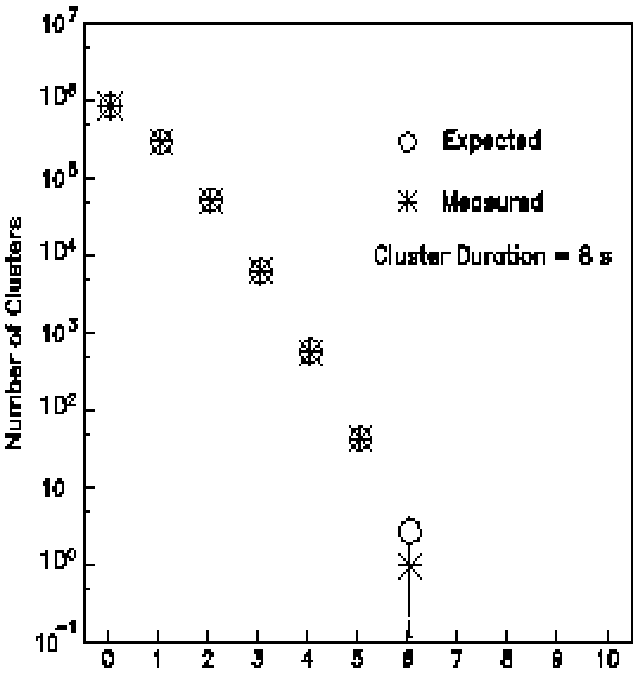
Data of February 1995-February 1996

Cluster duration 2 sec



Events in a cluster

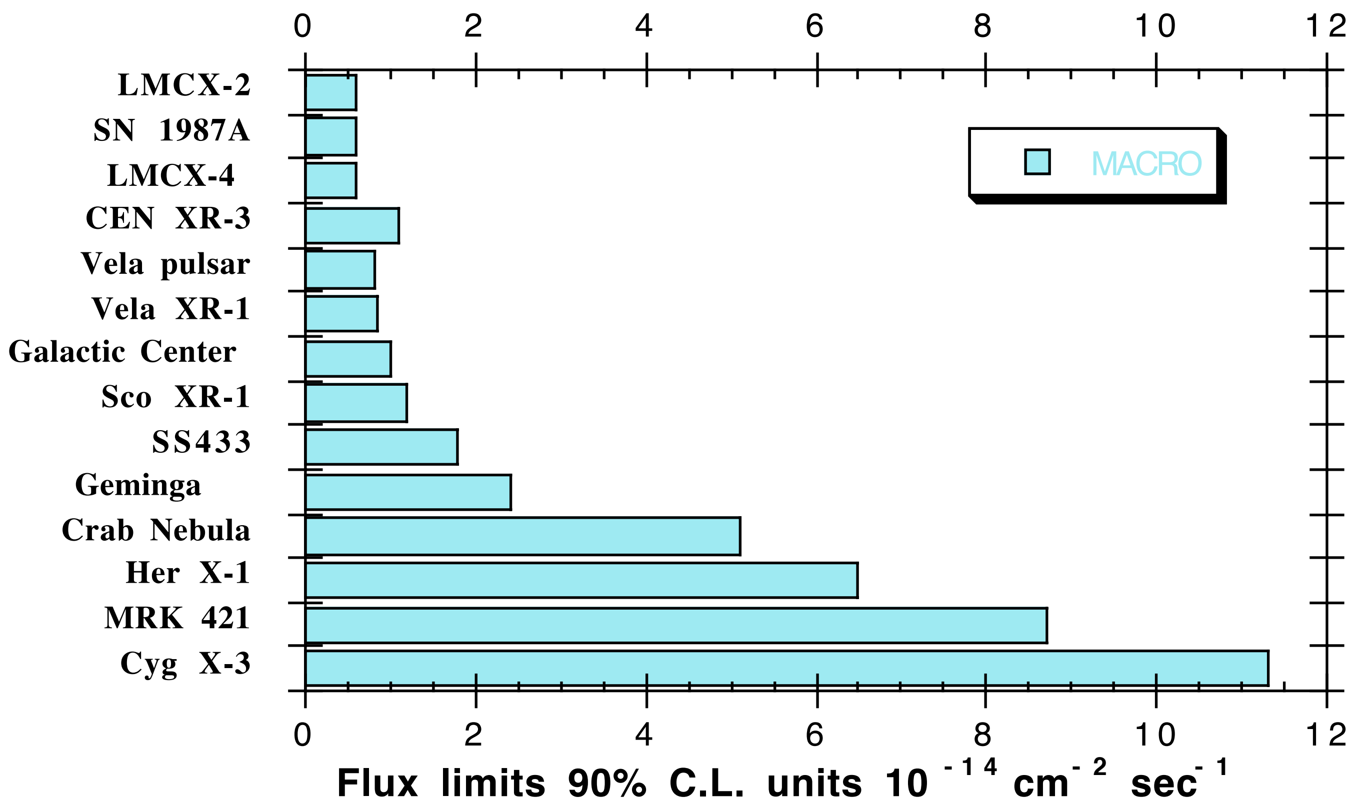
Cluster Duration 8 s



Events in a cluster

Neutrino Astronomy- Flux limits

Source	Events in 1.5 °	Events in 3°	Background in 3°
Cyg X-3	0	0	0.06
Mrk 421	0	0	0.06
Her X-1	0	0	0.08
Crab Nebula	0	1	0.18
Geminga	0	0	0.14
SS433	0	0	0.2
Sco XR-1	0	0	0.3
Galactic Center	0	0	0.32
VELA XR-1	0	0	0.41
VELA pulsar	0	0	0.45
CEN XR-3	0	1	0.67
LMCX-4	0	0	0.9
SN 1987A	0	0	0.91
LMCX-2	0	0	0.72



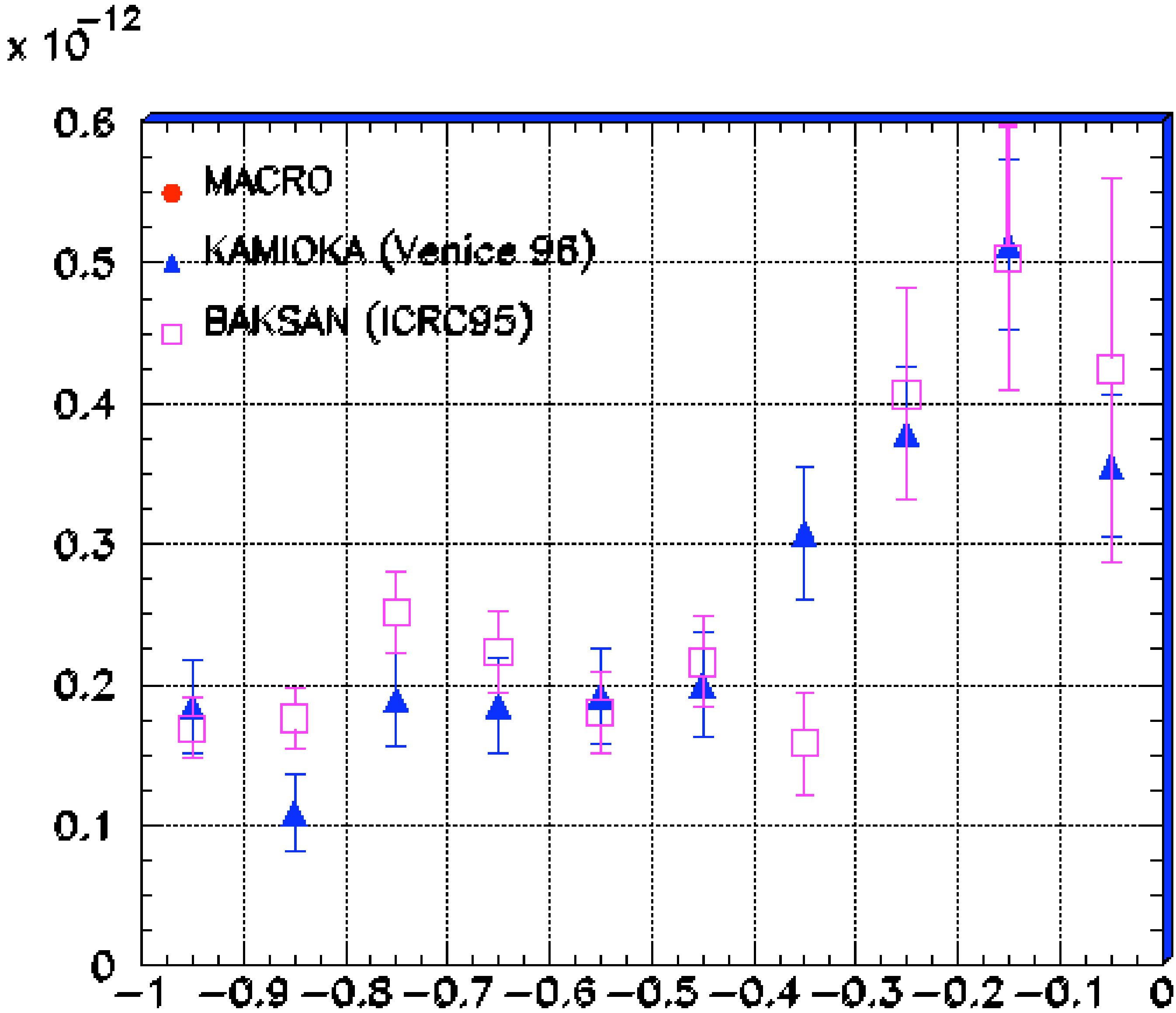
Flux limits for selected sources
(90% C. L., units 10^{-14} cm^{-2} sec^{-1})

	MACRO	Baksan(1995)	IMB(1994)	Kamioka(1989)	KGF(1995)
Cyg X-3	11.3		4.1	9.9	4.3
MRK 421	8.7		3.3		13.8
Her X-1	6.5		4.3	14.4	10.1
Crab Nebula	5.1	2.6	4.3	6.6	5.8
Geminga	2.4	4.	3.1	6.3	9.3
Sco XR-1	1.2		3.4		
Galactic Center	0.99	.95	1.6	7	8.1
Vela XR-1	0.84	0.45	0.84	3.4	3.8
Vela pulsar	0.8		0.78		
CEN XR-3	1.1		0.98		
LMCX-4	0.6	0.36	0.66	2.6	2.6
SN 1987A	0.6	1.15	1.2		

Red : X-Ray Binaries
Magenta : pulsar
Green : Galaxies
Black : others

Baksan 1995 : R Boliev et al 24th ICRC (Rome) 1-722
Kamioka 1989 : Y Oyama et al. Phys Rev D39 (1989) 1481
KGF 1995 : H Adarkar et al. 24th ICRC (Rome) 1-820
IMB 1994 : R Becker-Szendy Nucl. Phys B38 (1995) 331

Flux - Other Experiments



"Kamioka scaled" from 3 GeV to 1 Gev (Bartol flux)

Title

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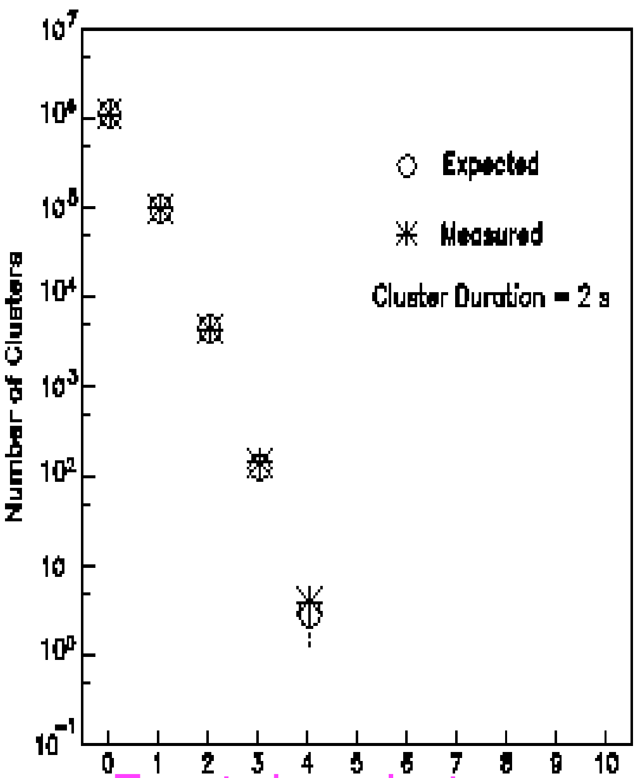
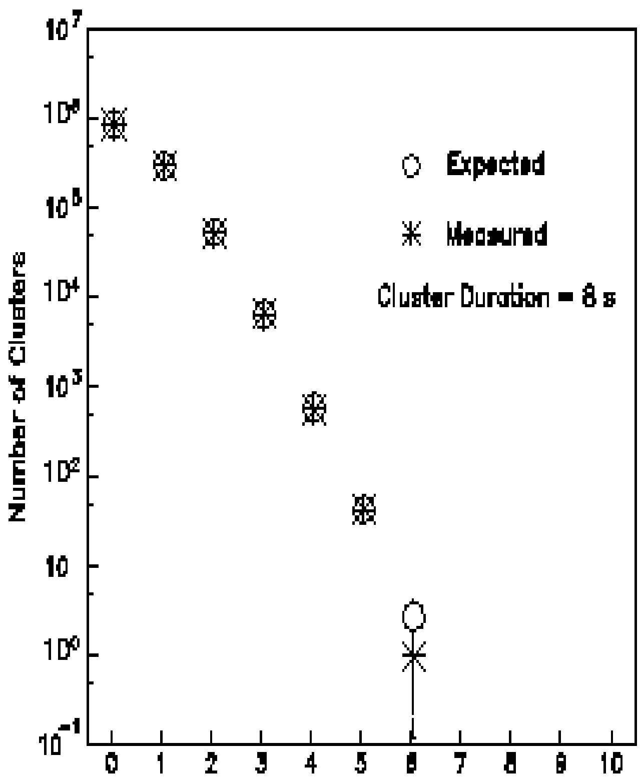


Events in a cluster

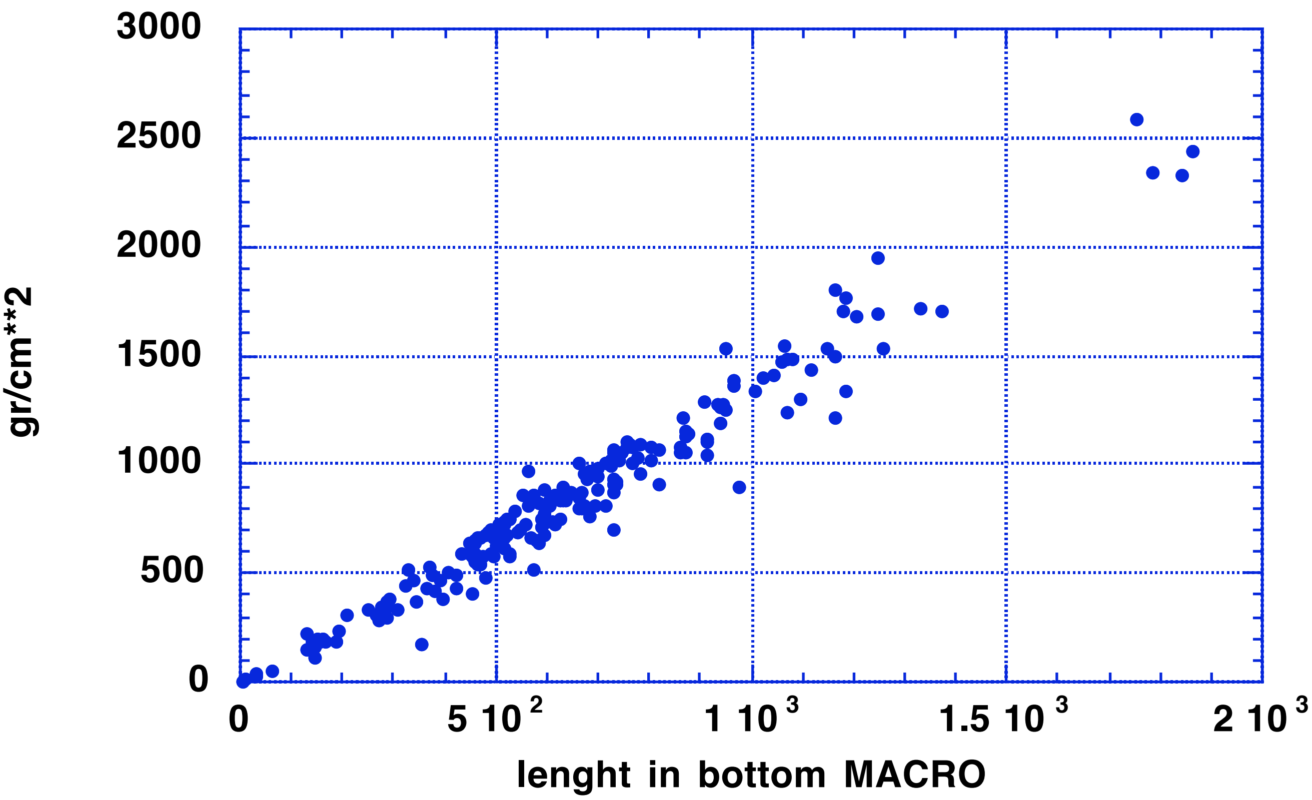
Cluster Duration 8 s



Events in a cluster

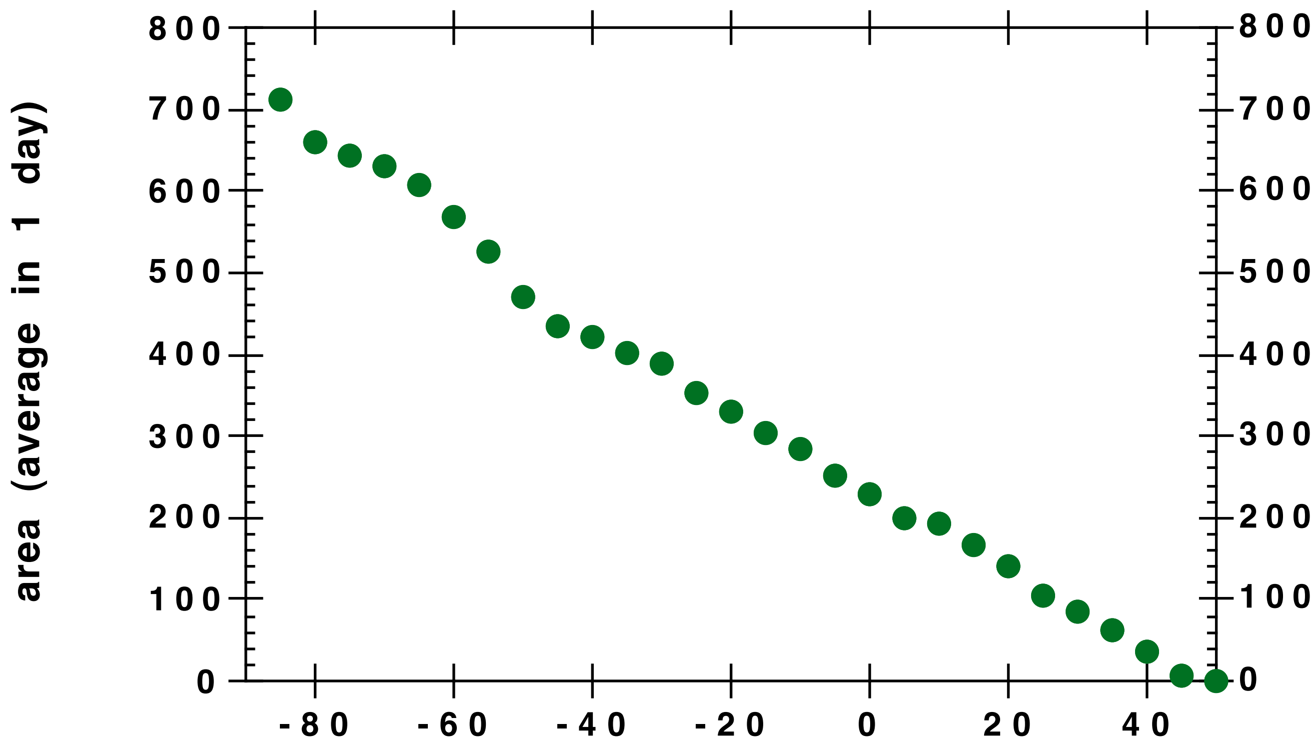
Title

- Body text

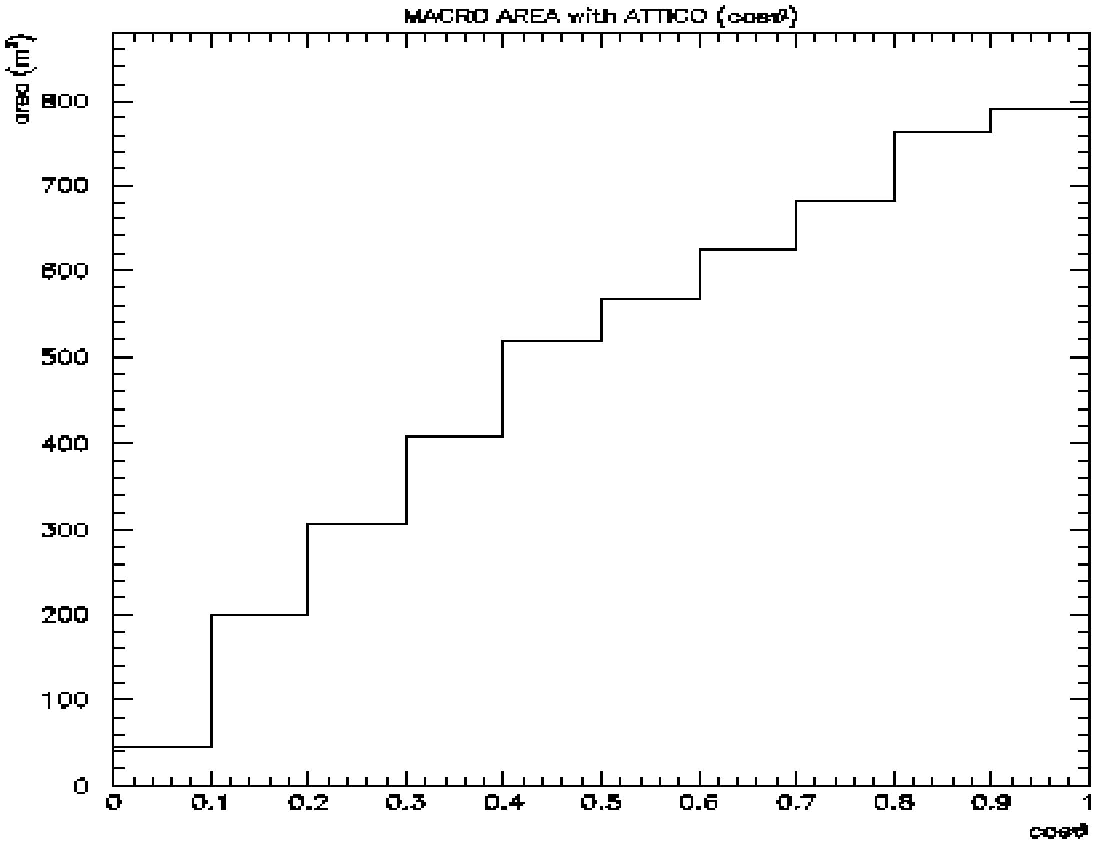


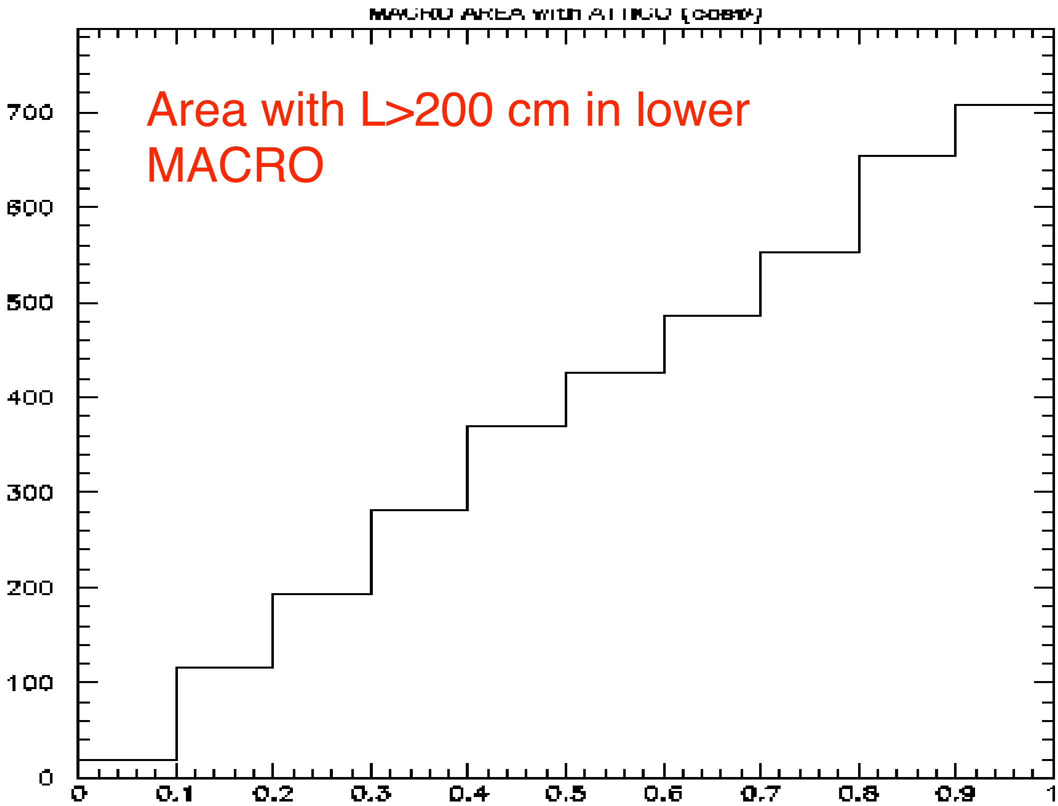
Title

- Body text



MACRO AREA


MACRO AREA with ATTICO (cosθ)
area (m²)
0
100
200
300
400
500
600
700
800
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
cosθ


MACRO AREA with ATTICO (cosθ)
Area with L>200 cm in lower MACRO
0
100
200
300
400
500
600
700
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Very High Energy Muons from AGN

• details in ICRC 1995 (Rome) 1 pag 800

- Method : linear combination of the energy released in the scintillators and in the streamer tubes
- Background : atmospheric neutrinos (for upward-going particles)
- optimization on the cut in "energy" to optimize the signal respect to background

Events/year MACRO lower part only

"energy (a.u.)"	Atmospheric	Atmos.+AGN [1]	Atmos.+AGN [2]
40	3.3	6.6	4
50	1.3	3.1	1.7
60	0.6	2.2	0.85

- 1 event in .4 year of live time with energy >40 (a.u.)

  1.4 expected from atmospheric neutrinos

  2.9 from atmospheric neutrinos + model 1

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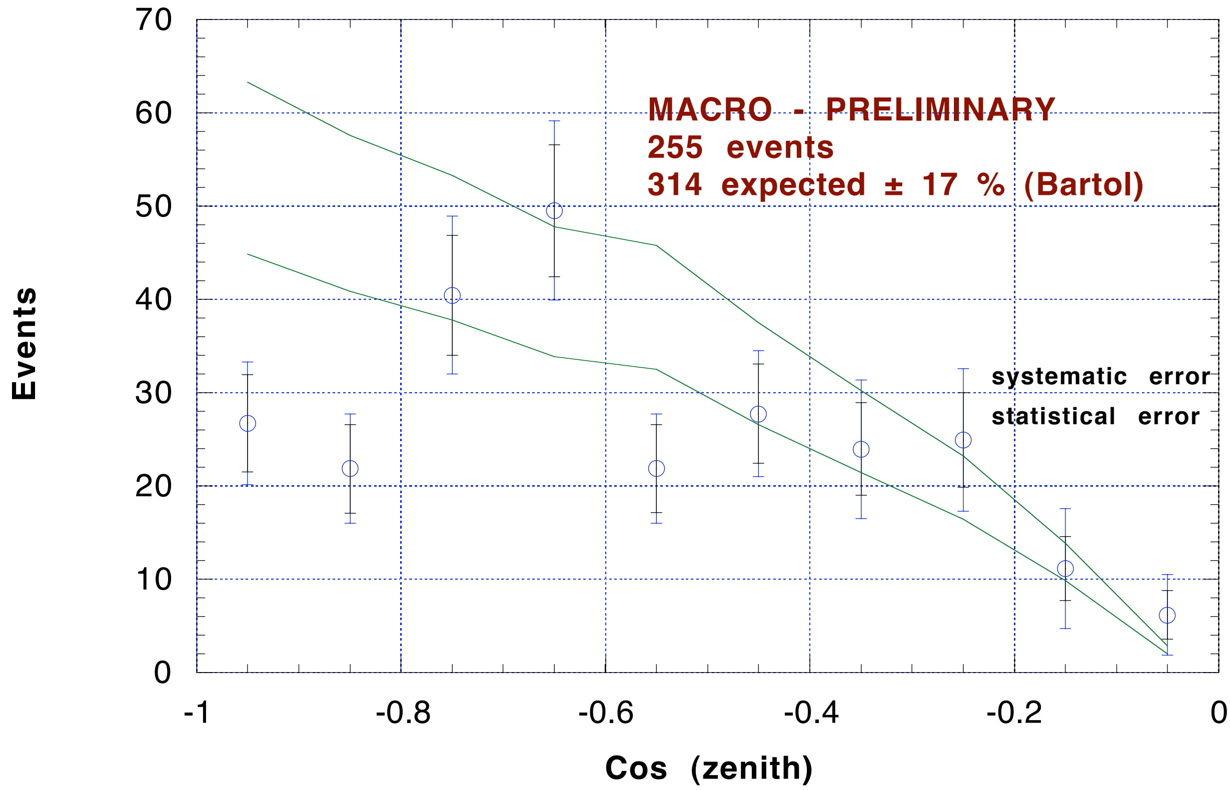
1) Protheroe Szabo High Energy Neutrino Astronomy World Scientific p 24
2) Stecker et al. Phys Rev Lett 66 (1991) and 69(1992)

Angular distribution - Events



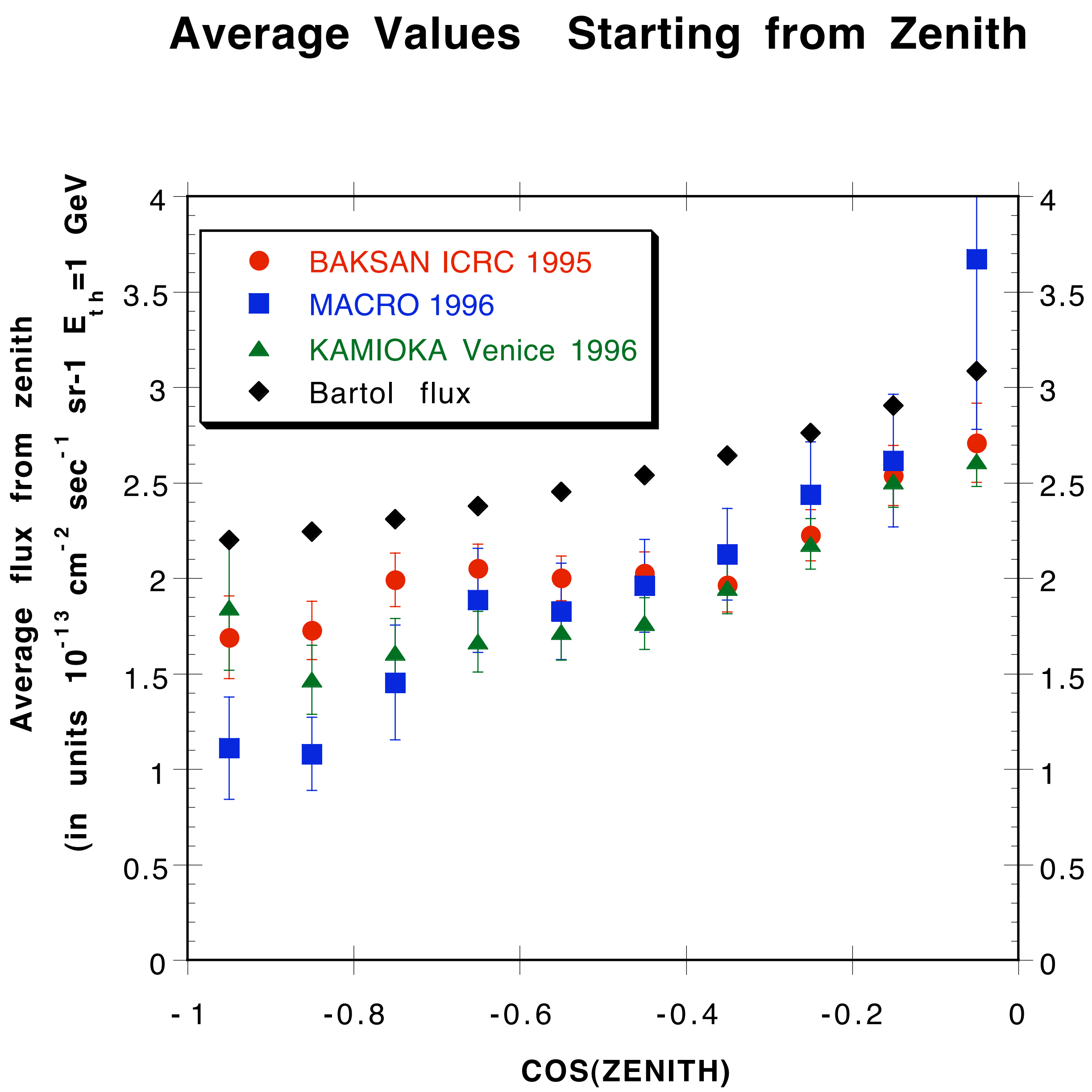
Title

- Body text

Comparison with other experiments

$$\langle F_N \rangle = \Sigma_{i=1,N} F_i / N$$

(i=1 vertical)



Title

- Body text