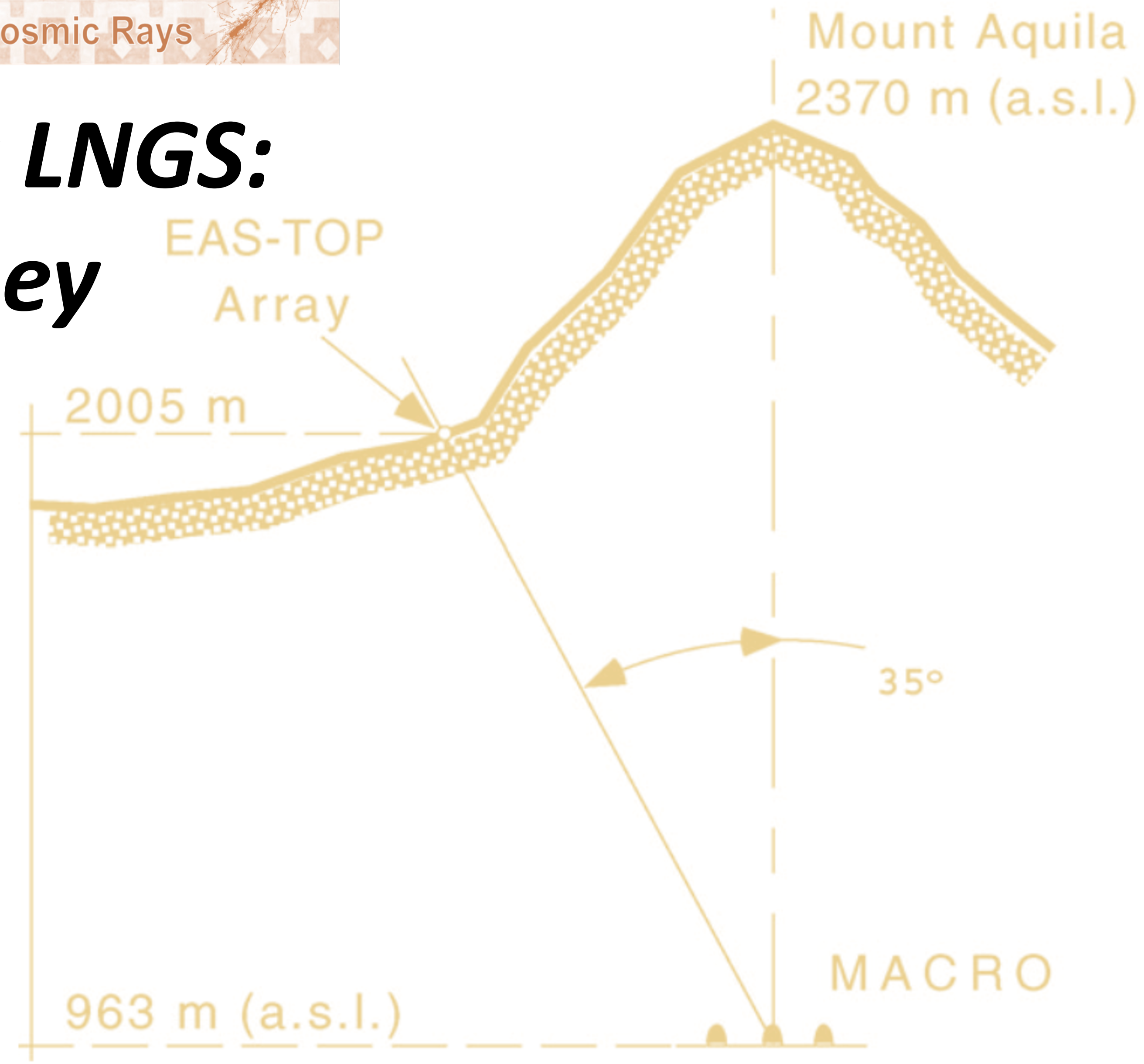
UHECR2022:
6th International Symposium on Ultra High Energy Cosmic Rays

Cosmic Ray Physics at LNGS: a historical journey

Sergio Petrera – GSSI and LNGS-INFN



The birth of Underground Laboratories

- Underground labs are needed to reduce `noise’
- R. Davis ^{37}Cl Experiment (1960’s) on solar neutrinos probably the father of all large UG labs
- In the late 1970’s a strong boost to build UG experiments from **Grand Unified Theories (GUT)**
- GUT’s (from Georgi & Glashow, 1974) predict **nucleon instability**: expected decay times ~10^{30} yr for SU(5), larger $10^{32}÷10^{34}$ yr for SO(10), SUSY-GUT
- Many experiments with sensitivity $\mathcal{O}$ (kt-yr) since early 80’s searching for proton-decay
- Two classes:
  - Fine grained tracking calorimeters: Kolar GF (India), Nusex, Frejus (Europe), Soudan (USA)
  - Water Cherenkov: IMB, HPW (USA), Kamioka (Japan)
- All hosted in disused mines or in side-halls of road tunnels

The birth of Gran Sasso Laboratory (LNGS)

1979: Proposal by A. Zichichi to Italian Parliament

Initial ideas for new detectors. Two main directions: solar neutrinos, proton decay

1982: Approval of LNGS construction

New collaborations formed, new detector designs

Symposium on Underground Physics, Saint-Vincent, Italy, April 1985

1987: Construction completed

1989: Start data taking of first large experiment (MACRO)

1982-1990

- St. Vincent 1985 started the process of selection of experiments

Approved:

- GALLEX (Gallium Experiment) solar neutrinos
- LVD (Large Volume Detector)
- MACRO (Monopole, Astrophysics and Cosmic Ray Observatory)

+ EAS-TOP shower array at Campo Imperatore

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Rationale:

- Solar neutrinos (more than a promise): Chlorine to Gallium provides lower threshold with better capability to investigate the reduced ν rate (Chlorex)
- GUT is still the promised land, but proton decay more & more unreachable (IMB, Kam-I, Soudan,…)
- Two detectors with complementary merits: *Large volume* vs. *Large area*
- Large volume focused on neutrinos
- Large area to search for the last unexplored GUT prediction: relic monopoles *(after t'Hooft & Polyakov, 1974)*

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Two unexpected events:

1983 Cygnus X-3
1987 SN1987A

Rationale:

- Solar neutrinos (more than a promise): Chlorine to Gallium provides lower threshold with better capability to investigate the reduced ν rate (Chlorex)
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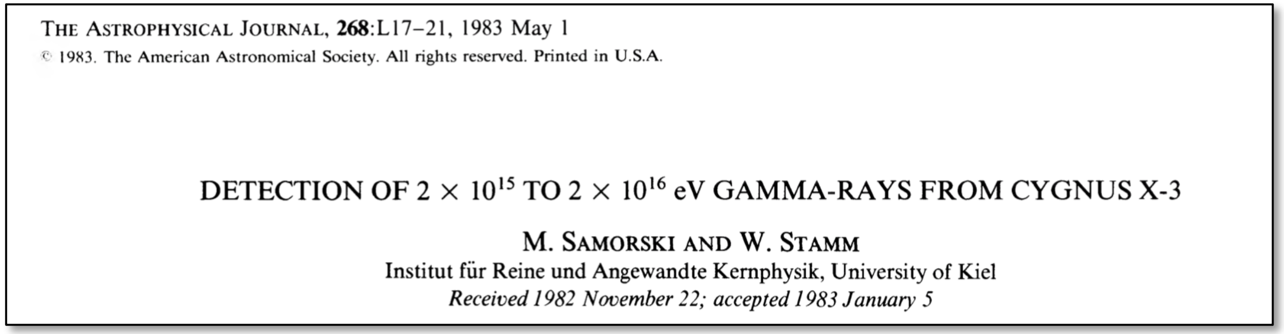
1983 Cygnus X-3



The Astrophysical Journal, **268**:L17–21, 1983 May 1
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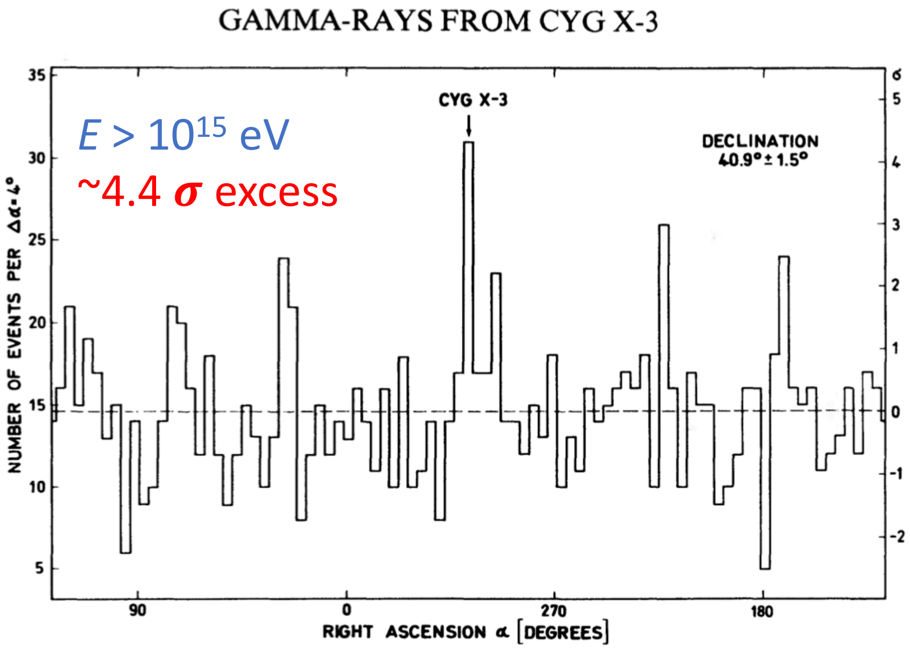
DETECTION OF 2 × 10^{15} TO 2 × 10^{16} eV GAMMA-RAYS FROM CYGNUS X-3

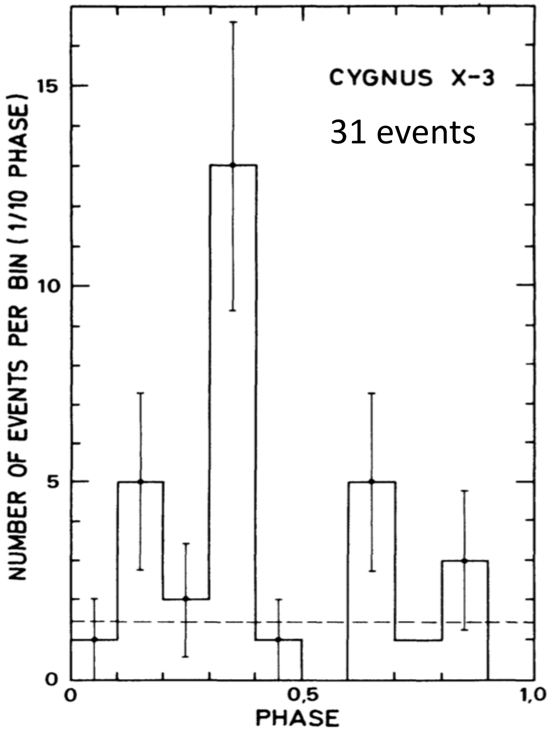
M. Samorski and W. Stamm
Institut für Reine und Angewandte Kernphysik, University of Kiel
Received 1982 November 22; accepted 1983 January 5

- X-ray emitting binary system, *R. Giacconi et al., ApJ (1967)*
- X-rays modulated 4.8 h
- Observed also in TeV range



E > 10^{15} eV

~4.4 σ excess



31 events

4.8 hours

1983 Cygnus X-3

- X-ray emitting binary system, *R. Giacconi et al., ApJ (1967)*
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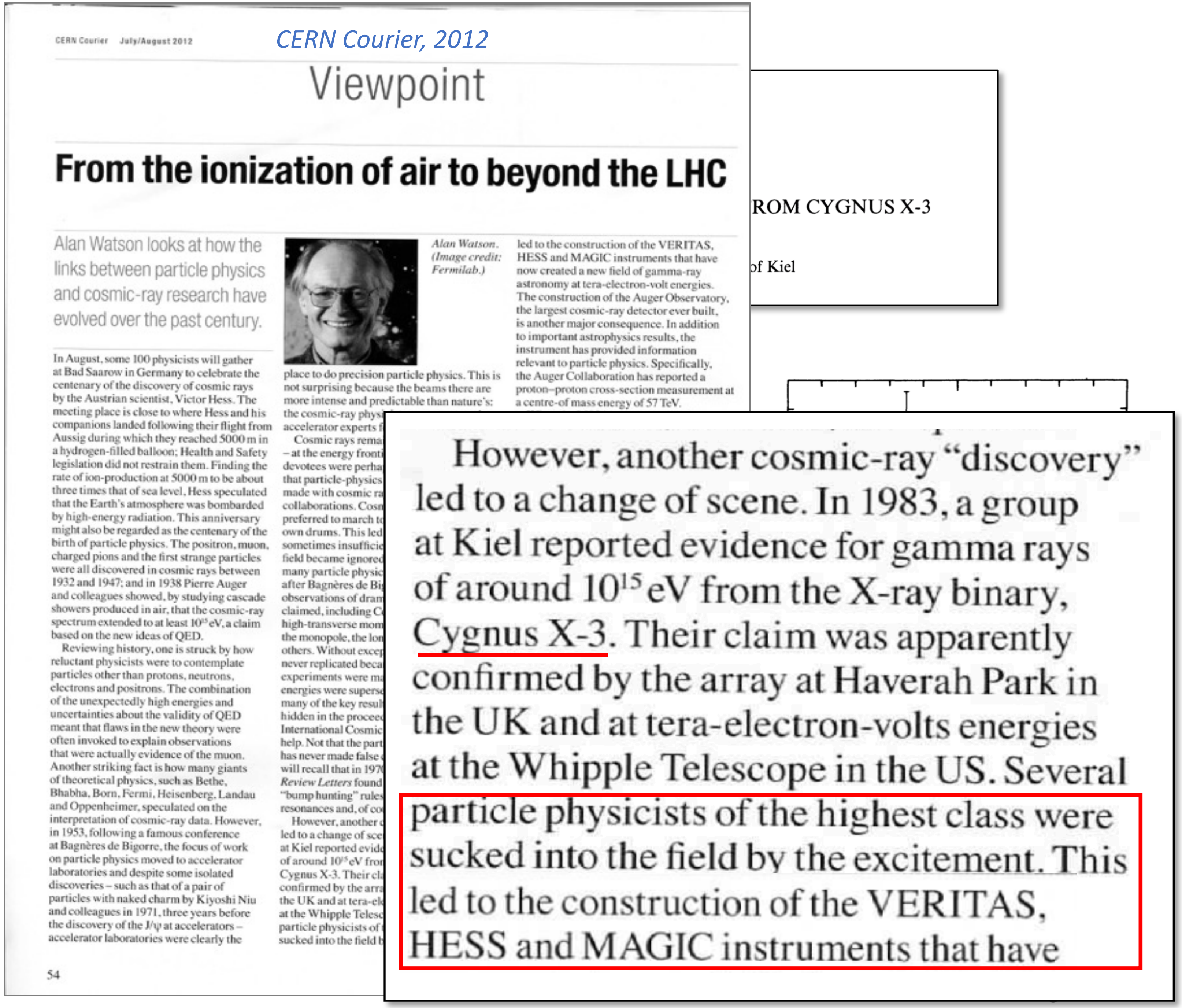
- Observed also in TeV range



CERN Courier, 2012

CERN Courier July/August 2012

Viewpoint

From the ionization of air to beyond the LHC

Alan Watson looks at how the links between particle physics and cosmic-ray research have evolved over the past century.

Alan Watson. (Image credit: Fermilab.)

In August, some 100 physicists will gather at Bad Saarow in Germany to celebrate the centenary of the discovery of cosmic rays by the Austrian scientist, Victor Hess. The meeting place is close to where Hess and his companions landed following their flight from Aussig during which they reached 5000 m in a hydrogen-filled balloon; Health and Safety legislation did not restrain them. Finding the rate of ion-production at 5000 m to be about three times that of sea level, Hess speculated that the Earth's atmosphere was bombarded by high-energy radiation. This anniversary might also be regarded as the centenary of the birth of particle physics. The positron, muon, charged pions and the first strange particles were all discovered in cosmic rays between 1932 and 1947; and in 1938 Pierre Auger and colleagues showed, by studying cascade showers produced in air, that the cosmic-ray spectrum extended to at least 10^{15} eV, a claim based on the new ideas of QED.

Reviewing history, one is struck by how reluctant physicists were to contemplate particles other than protons, neutrons, electrons and positrons. The combination of the unexpectedly high energies and uncertainties about the validity of QED meant that flaws in the new theory were often invoked to explain observations that were actually evidence of the muon. Another striking fact is how many giants of theoretical physics, such as Bethe, Bhabha, Born, Fermi, Heisenberg, Landau and Oppenheimer, speculated on the interpretation of cosmic-ray data. However, in 1953, following a famous conference at Bagnères de Bigorre, the focus of work on particle physics moved to accelerator laboratories and despite some isolated discoveries – such as that of a pair of particles with naked charm by Kiyoshi Niu and colleagues in 1971, three years before the discovery of the J/ψ at accelerators – accelerator laboratories were clearly the

place to do precision particle physics. This is
not surprising because the beams there are
more intense and predictable than nature's:
the cosmic-ray physi
accelerator experts f
Cosmic rays remai
– at the energy fronti
devotees were perha
that particle-physics
made with cosmic ra
collaborations. Cosm
preferred to march t
own drums. This led
sometimes insufficie
field became ignored
many particle physic
after Bagnères de Bi
observations of dram
claimed, including C
high-transverse mom
the monopole, the lon
others. Without excep
never replicated beca
experiments were ma
energies were superse
many of the key resul
hidden in the procee
International Cosmic
help. Not that the part
has never made false
will recall that in 197
Review Letters found
"bump hunting" rules
resonances and, of co
However, another
led to a change of sce
at Kiel reported evide
of around 10^{15} eV fro
Cygnus X-3. Their cl
confirmed by the arra
the UK and at tera-el
at the Whipple Telesc
particle physicists of
sucked into the field b

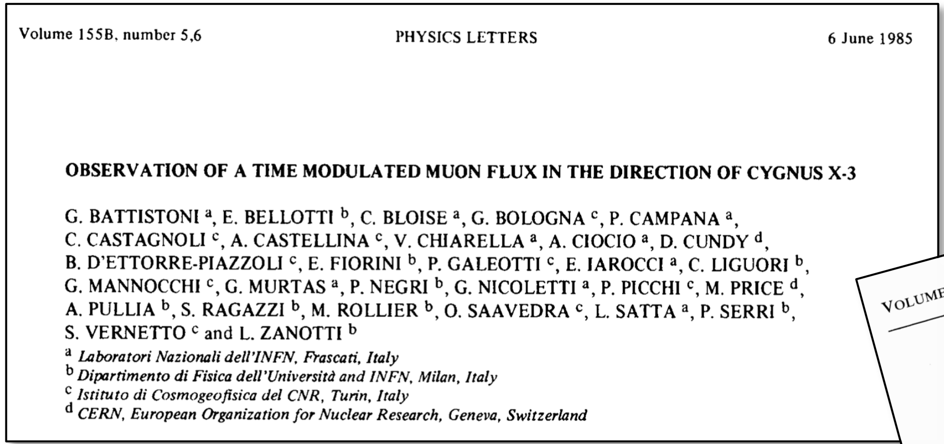
led to the construction of the VERITAS, HESS and MAGIC instruments that have now created a new field of gamma-ray astronomy at tera-electron-volt energies. The construction of the Auger Observatory, the largest cosmic-ray detector ever built, is another major consequence. In addition to important astrophysics results, the instrument has provided information relevant to particle physics. Specifically, the Auger Collaboration has reported a proton–proton cross-section measurement at a centre-of mass energy of 57 TeV.

54

ROM CYGNUS X-3

of Kiel

However, another cosmic-ray "discovery" led to a change of scene. In 1983, a group at Kiel reported evidence for gamma rays of around 10^{15} eV from the X-ray binary, Cygnus X-3. Their claim was apparently confirmed by the array at Haverah Park in the UK and at tera-electron-volts energies at the Whipple Telescope in the US. Several particle physicists of the highest class were sucked into the field by the excitement. This led to the construction of the VERITAS, HESS and MAGIC instruments that have



Volume 155B, number 5,6 PHYSICS LETTERS 6 June 1985

OBSERVATION OF A TIME MODULATED MUON FLUX IN THE DIRECTION OF CYGNUS X-3

G. BATTISTONI [a], E. BELLOTTI [b], C. BLOISE [a], G. BOLOGNA [c], P. CAMPANA [a], C. CASTAGNOLI [c], A. CASTELLINA [c], V. CHIARELLA [a], A. CIOCIO [a], D. CUNDY [d], B. D'ETTORRE-PIAZZOLI [c], E. FIORINI [b], P. GALEOTTI [c], E. IAROCCI [a], C. LIGUORI [b], G. MANNOCCHI [c], G. MURTAS [a], P. NEGRI [b], G. NICOLETTI [a], P. PICCHI [c], M. PRICE [d], A. PULLIA [b], S. RAGAZZI [b], M. ROLLIER [b], O. SAAVEDRA [c], L. SATTA [a], P. SERRI [b], S. VERNETTO [c] and L. ZANOTTI [b]

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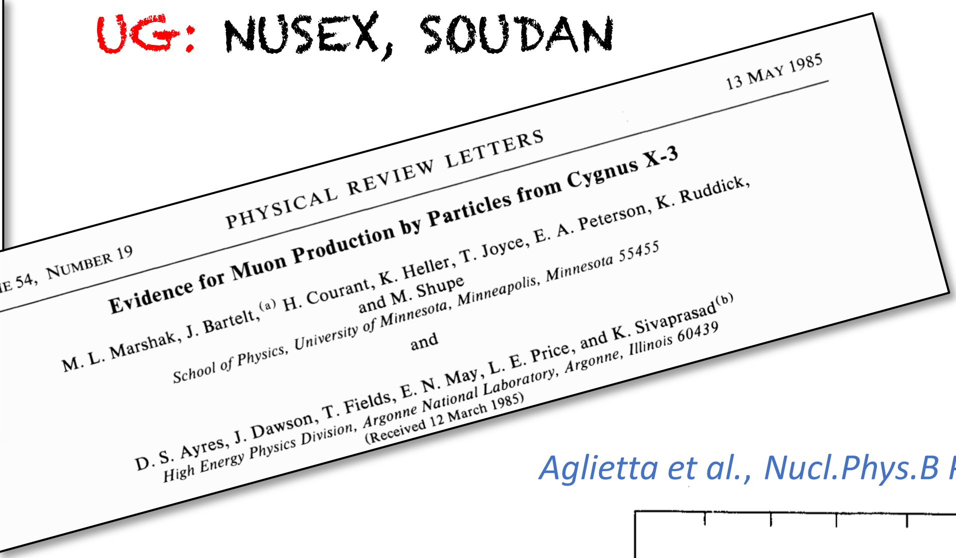
[b] *Dipartimento di Fisica dell'Università and INFN, Milan, Italy*
[c] *Istituto di Cosmogeofisica del CNR, Turin, Italy*
[d] *CERN, European Organization for Nuclear Research, Geneva, Switzerland*

UG: NUSEX, SOUDAN



VOLUME 54, NUMBER 19 PHYSICAL REVIEW LETTERS 13 MAY 1985

Evidence for Muon Production by Particles from Cygnus X-3

M. L. Marshak, J. Bartelt,(a) H. Courant, K. Heller, T. Joyce, E. A. Peterson, K. Ruddick, and M. Shupe
School of Physics, University of Minnesota, Minneapolis, Minnesota 55455
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D. S. Ayres, J. Dawson, T. Fields, E. N. May, L. E. Price, and K. Sivaprasad(b)
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

(Received 12 March 1985)

1985 Cygnus X-3

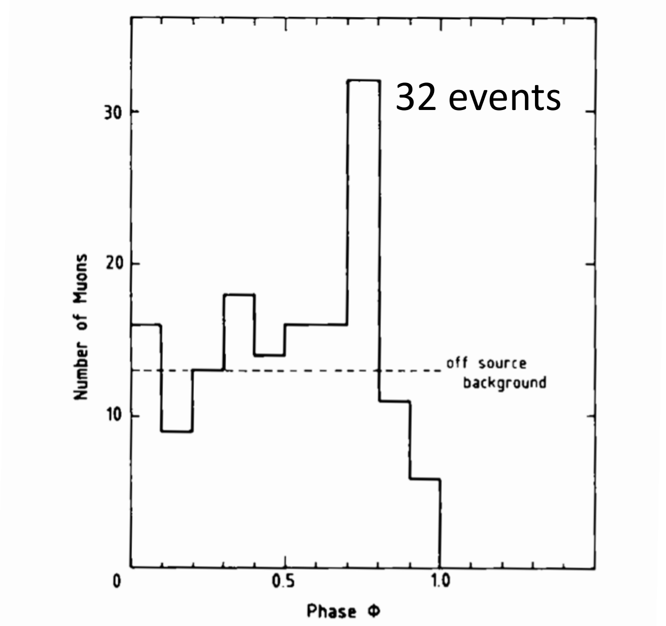
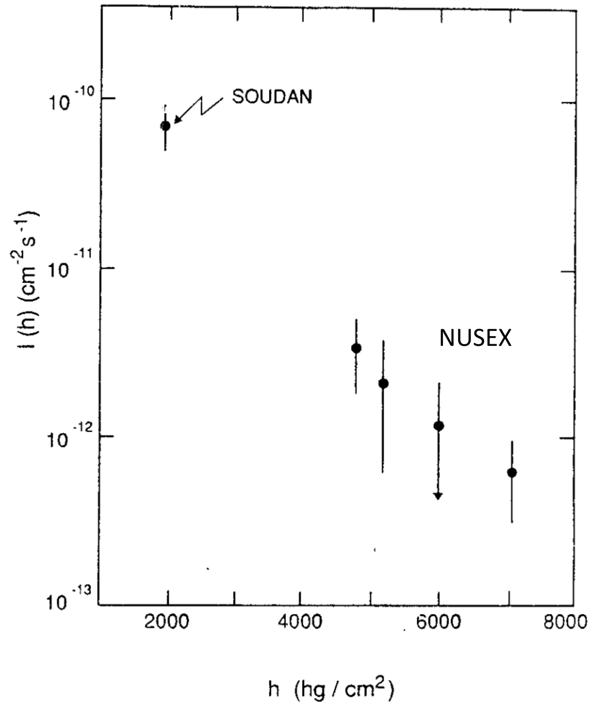
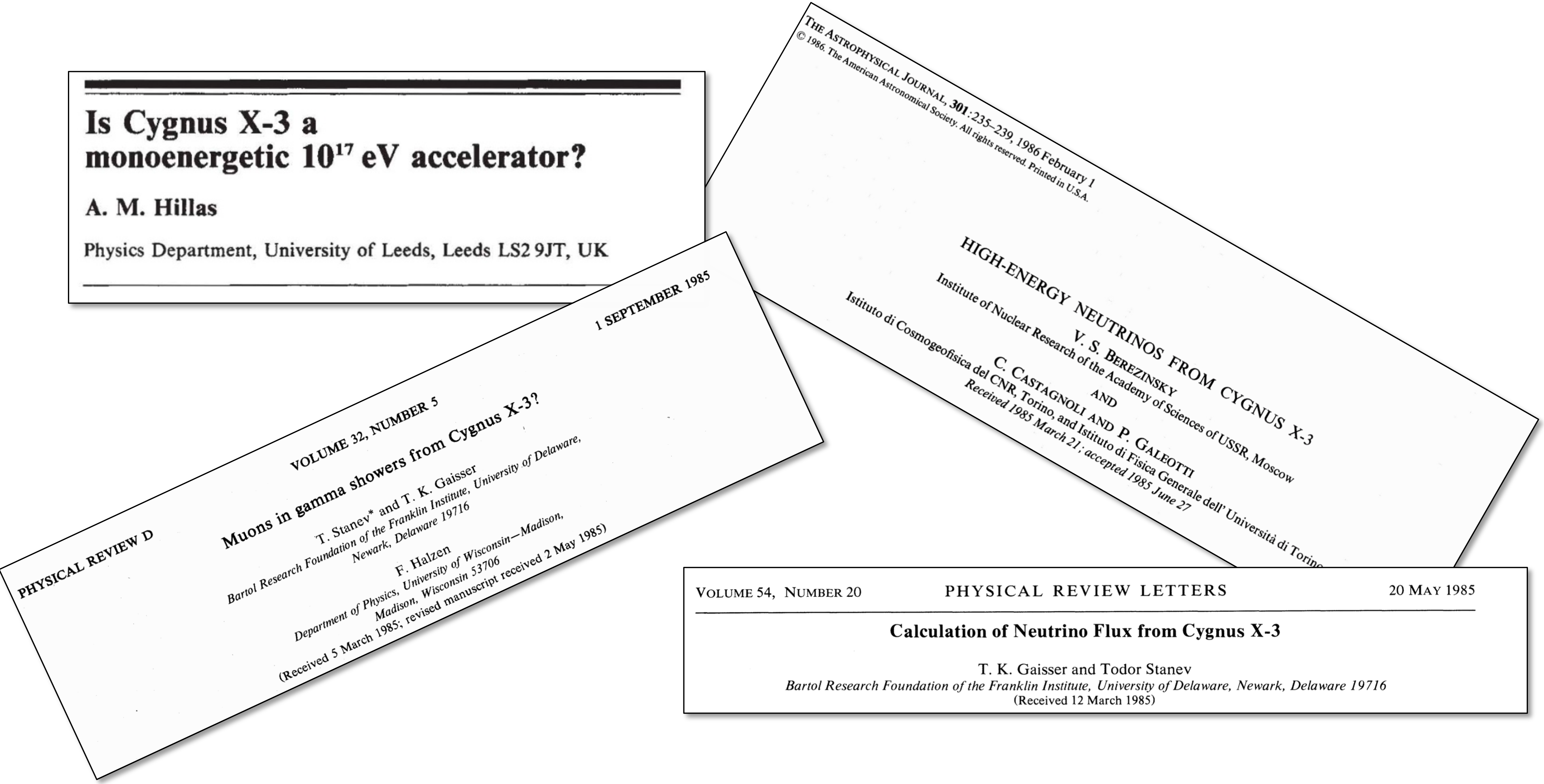


Fig. 1. Phase distribution for muons coming from an observation window of 10° × 10° centred on Cygnus X-3.

Aglietta et al., Nucl.Phys.B Proc.Suppl. (1990)





Is Cygnus X-3 a monoenergetic 10^{17} eV accelerator?

A. M. Hillas

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PHYSICAL REVIEW D VOLUME 32, NUMBER 5 1 SEPTEMBER 1985

Muons in gamma showers from Cygnus X-3?

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(Received 5 March 1985; revised manuscript received 2 May 1985)

THE ASTROPHYSICAL JOURNAL, **301**:235–239, 1986 February 1
© 1986. The American Astronomical Society. All rights reserved. Printed in U.S.A.

HIGH-ENERGY NEUTRINOS FROM CYGNUS X-3

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AND

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Istituto di Cosmogeofisica del CNR, Torino, and Istituto di Fisica Generale dell' Università di Torin
Received 1985 March 21; accepted 1985 June 27

VOLUME 54, NUMBER 20 PHYSICAL REVIEW LETTERS 20 MAY 1985

Calculation of Neutrino Flux from Cygnus X-3

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Bartol Research Foundation of the Franklin Institute, University of Delaware, Newark, Delaware 19716
(Received 12 March 1985)

Photons behaving like hadrons?

Cygnets:

SUSY

Strange nuggets

...

Volume 164B, number 1,2,3 PHYSICS LETTERS 5 December 1985

CAN A LIGHT GLUINO SOLVE THE CYG X3 PUZZLE?

G. AURIEMMA, L. MAIANI and S. PETRARCA

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Received 2 September 1985

Fermi National Accelerator Laboratory

FERMILAB-Conf-85/134-A
September 1985

SEARCHING FOR CYGNETS *

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PHYSICS LETTERS B 22 May 1986

DIFFICULTIES WITH INTERPRETATIONS OF UNDERGROUND MUONS FROM CYGNUS X-3

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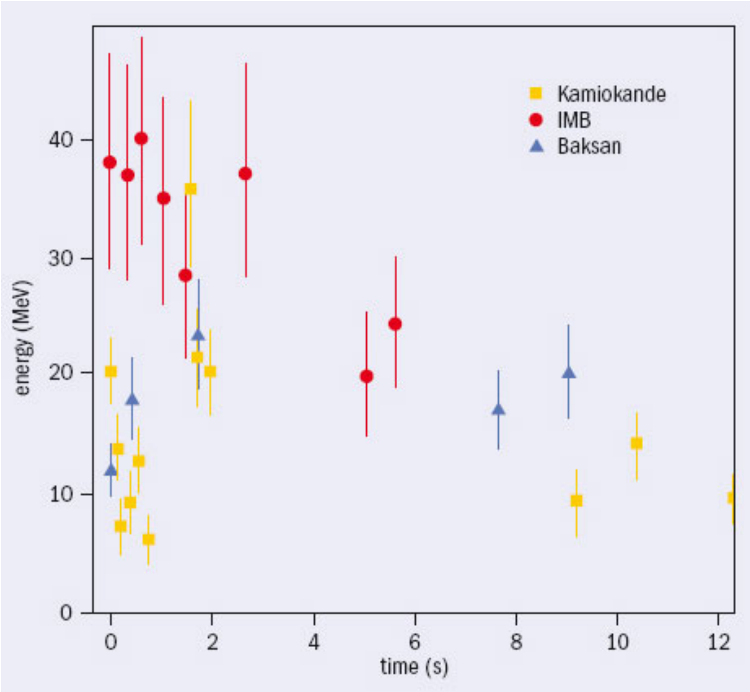
Received 4 March 1986

SN 1987A



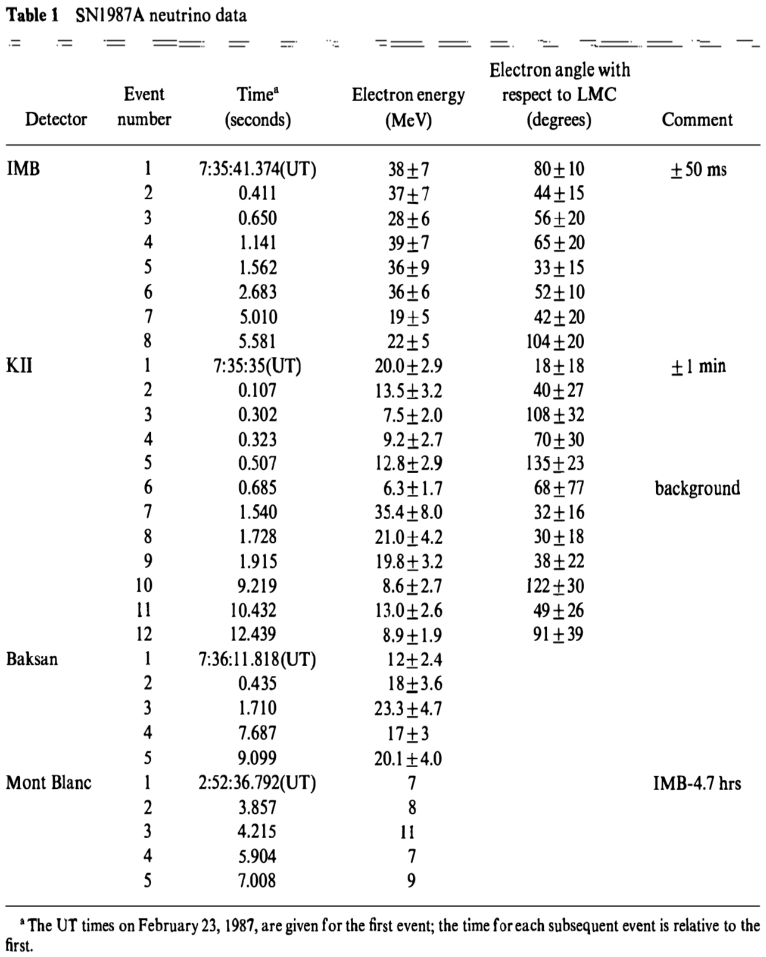


Table 1 SN1987A neutrino data

Detector	Event number	Time[a] (seconds)	Electron energy (MeV)	Electron angle with respect to LMC (degrees)	Comment
IMB	1	7:35:41.374(UT)	38±7	80±10	±50 ms
	2	0.411	37±7	44±15	
	3	0.650	28±6	56±20	
	4	1.141	39±7	65±20	
	5	1.562	36±9	33±15	
	6	2.683	36±6	52±10	
	7	5.010	19±5	42±20	
	8	5.581	22±5	104±20	
KII	1	7:35:35(UT)	20.0±2.9	18±18	±1 min
	2	0.107	13.5±3.2	40±27	
	3	0.302	7.5±2.0	108±32	
	4	0.323	9.2±2.7	70±30	
	5	0.507	12.8±2.9	135±23	
	6	0.685	6.3±1.7	68±77	background
	7	1.540	35.4±8.0	32±16	
	8	1.728	21.0±4.2	30±18	
	9	1.915	19.8±3.2	38±22	
	10	9.219	8.6±2.7	122±30	
	11	10.432	13.0±2.6	49±26	
	12	12.439	8.9±1.9	91±39	
Baksan	1	7:36:11.818(UT)	12±2.4		
	2	0.435	18±3.6		
	3	1.710	23.3±4.7		
	4	7.687	17±3		
	5	9.099	20.1±4.0		
Mont Blanc	1	2:52:36.792(UT)	7		IMB-4.7 hrs
	2	3.857	8		
	3	4.215	11		
	4	5.904	7		
	5	7.008	9		

[a] The UT times on February 23, 1987, are given for the first event; the time for each subsequent event is relative to the first.

A. Burrows, Annu. Rev. Nucl. Part. Sci., 1990

- Both CygX3 and SN1987 strongly impacted the designs of LV and LA detectors
- LVD strongly focused on neutrinos (SN, astrophysical, atmospheric): 1 kton Liq.Sc. but poor tracking capabilities → improved tracking system (+ streamer tubes)
- MACRO good tracker on wide area (77×12 m^2) (needed for monopoles) → + `attico' for increased Liq. Scint. mass (SN), tot. 0.56 kton and up/down discr. (atm-ν)

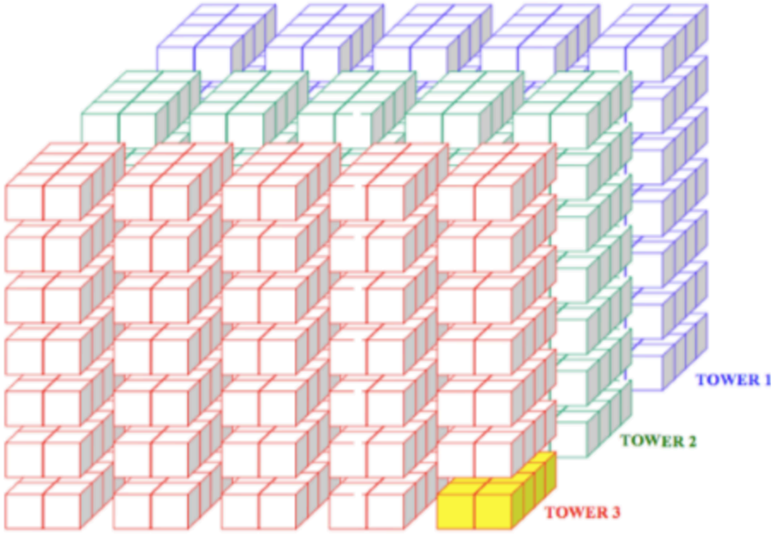
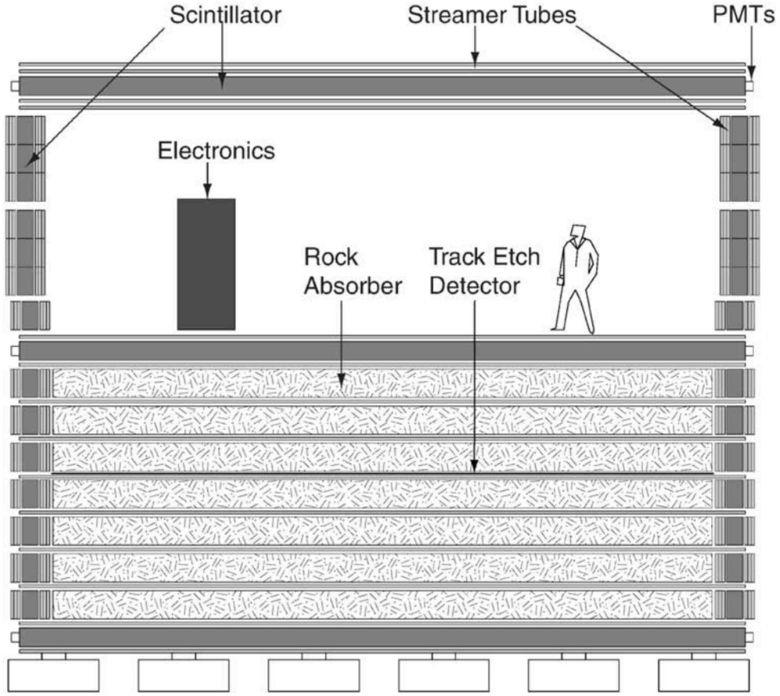


Figura 1: scheme of the arrangement of the counters in LVD

M. Ambrosio et al. / Nuclear Instruments and Methods in Physics Research A 486 (2002) 663–707

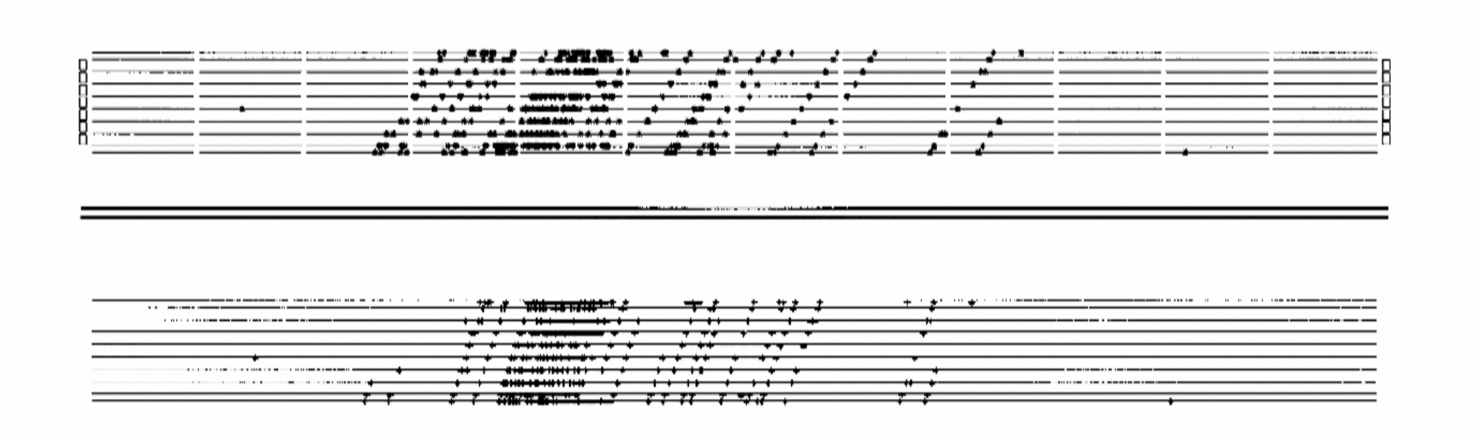


A short detour to personal memories

- My previous activity in Particle Physics at accelerators
- After announcement of GS Lab, contacts with NUSEX towards a `super-NUSEX’ for proton-decay
- But… frustration from running p-decay experiments!
- New idea: GUT monopoles !!! Strong interest from US groups (B. Barish, +…)
- Need of a large area tracking system with dedicated trigger for low-β

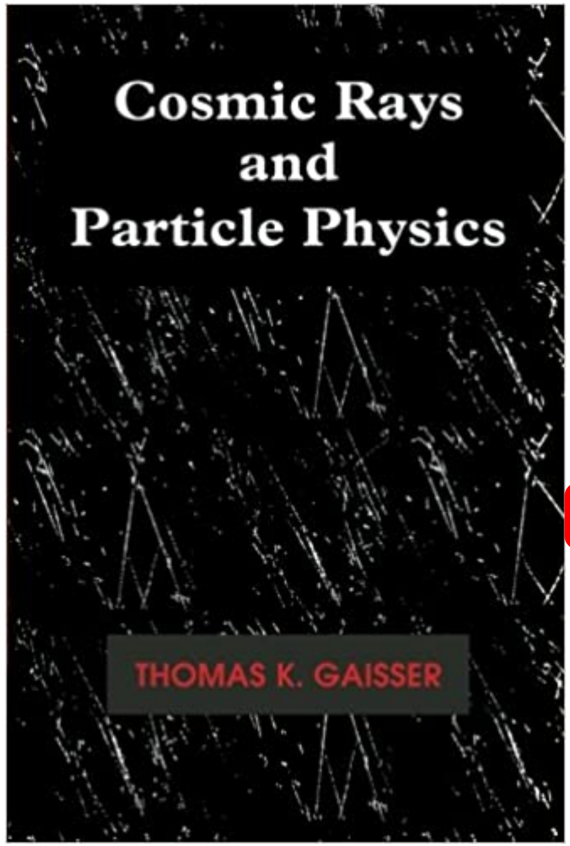
MACRO

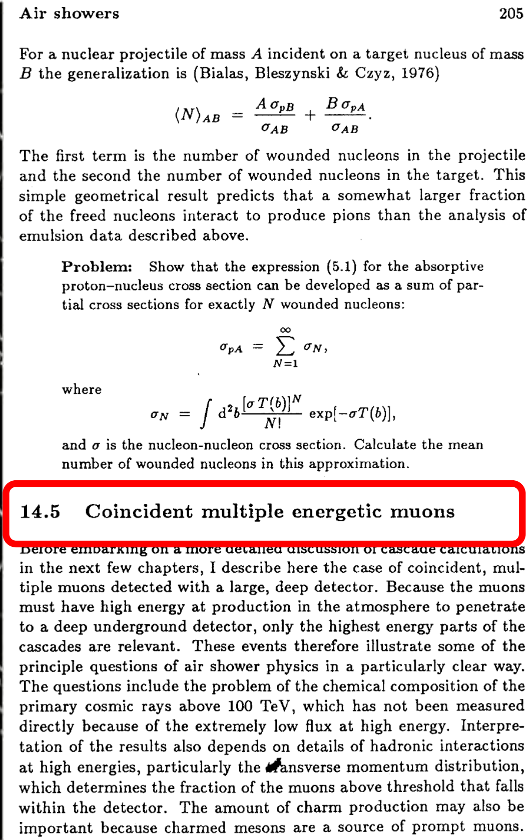
- An excellent tracker (50,000 ST) for UG muons, multimuons ⇒ **Cosmic Rays**



$\langle R_\mu \rangle \approx 3$ m
muon count unbiased

My approach to Cosmic Rays





Air showers 205

For a nuclear projectile of mass A incident on a target nucleus of mass B the generalization is (Bialas, Bleszynski & Czyz, 1976)

$$\langle N \rangle_{AB} = \frac{A\,\sigma_{pB}}{\sigma_{AB}} + \frac{B\,\sigma_{pA}}{\sigma_{AB}}.$$

The first term is the number of wounded nucleons in the projectile and the second the number of wounded nucleons in the target. This simple geometrical result predicts that a somewhat larger fraction of the freed nucleons interact to produce pions than the analysis of emulsion data described above.

Problem: Show that the expression (5.1) for the absorptive proton–nucleus cross section can be developed as a sum of partial cross sections for exactly N wounded nucleons:

$$\sigma_{pA} = \sum_{N=1}^{\infty} \sigma_N,$$

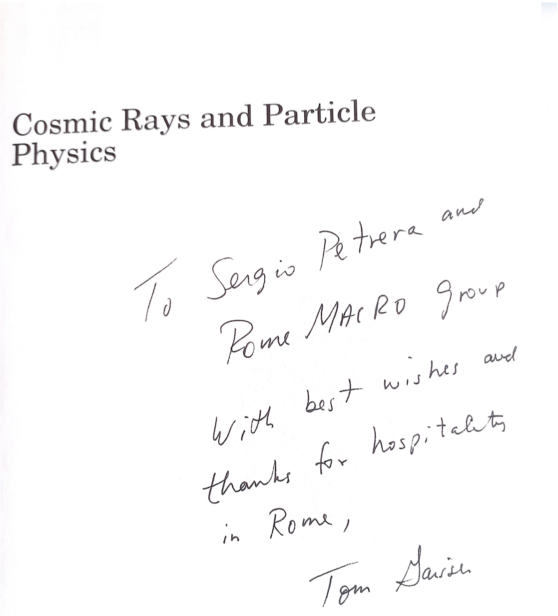
where

$$\sigma_N = \int d^2b \frac{[\sigma T(b)]^N}{N!} \exp[-\sigma T(b)],$$

and σ is the nucleon-nucleon cross section. Calculate the mean number of wounded nucleons in this approximation.

14.5 Coincident multiple energetic muons

Before embarking on a more detailed discussion of cascade calculations in the next few chapters, I describe here the case of coincident, multiple muons detected with a large, deep detector. Because the muons must have high energy at production in the atmosphere to penetrate to a deep underground detector, only the highest energy parts of the cascades are relevant. These events therefore illustrate some of the principle questions of air shower physics in a particularly clear way. The questions include the problem of the chemical composition of the primary cosmic rays above 100 TeV, which has not been measured directly because of the extremely low flux at high energy. Interpretation of the results also depends on details of hadronic interactions at high energies, particularly the transverse momentum distribution, which determines the fraction of the muons above threshold that falls within the detector. The amount of charm production may also be important because charmed mesons are a source of prompt muons.

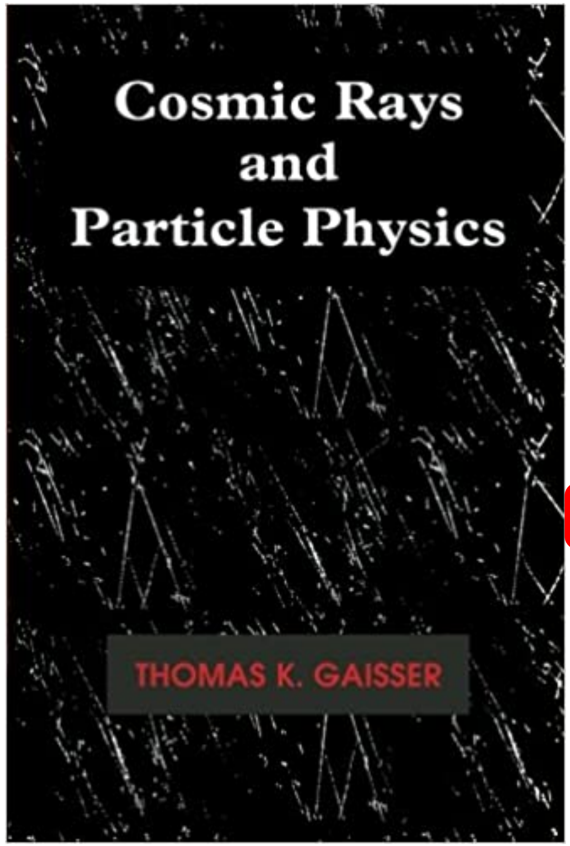


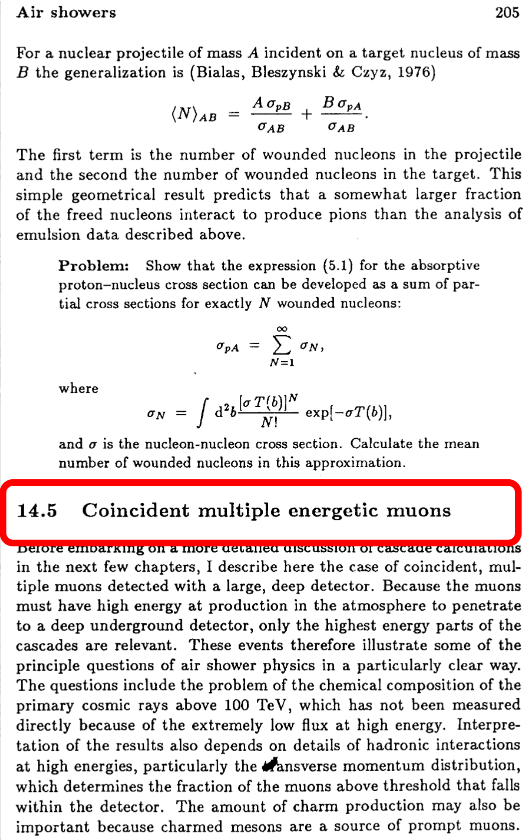
Cosmic Rays and Particle
Physics

To Sergio Petrera and
Rome MACRO group
With best wishes and
thanks for hospitality
in Rome,

Tom Gaisser

From UG muons to Cosmic Rays





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E_μ (thresh) ≈ 1.4 TeV at LNGS

Originate from CR's around the `knee' region

Multimuons sensitive to composition

Gaisser & Stanev, NIM, 1985

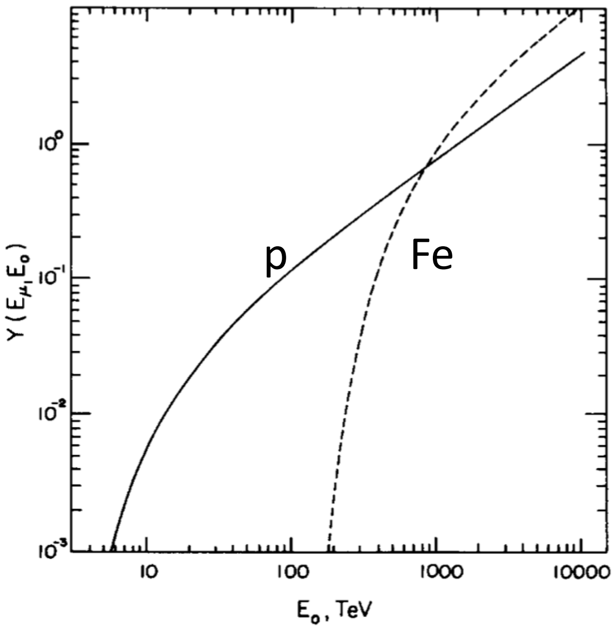
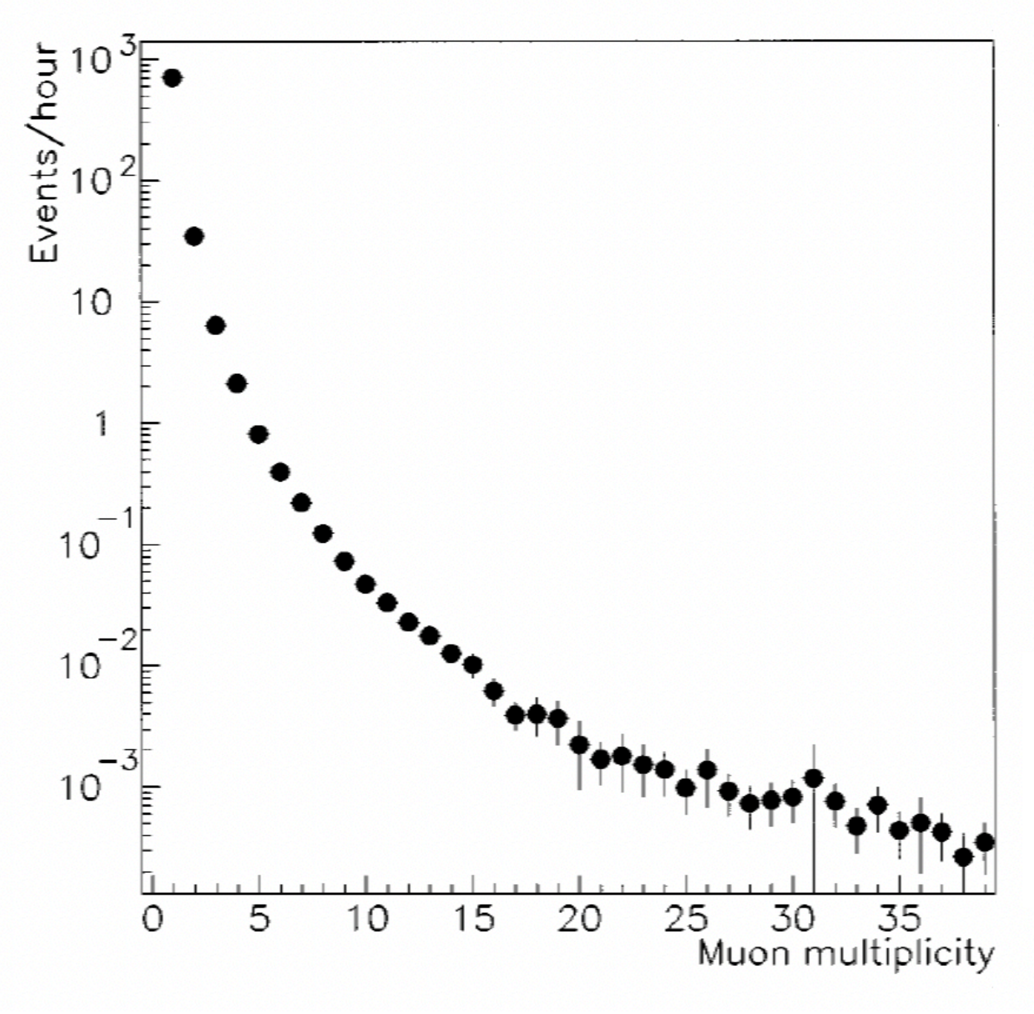


Fig. 5. Muon yields from primary protons (solid line) and iron nuclei (dash line) at depth of 4 km.w.e.

A selection of CR results from Gran Sasso Lab

- Spectrum and composition from MACRO multimuons
- EAS-TOP-MACRO results
- Other UG muon results
- Atmospheric neutrinos

Fit of spectrum and composition from multimuon



$$R(N_\mu)=\Omega S\sum_A \int dE\ \ \Phi_A(E)\cdot D_A(E,N_\mu)$$

D_A(E, N_μ) probability for a primary of mass *A* and energy per nucleus *E* to be reconstructed as an event with N_μ muons in MACRO. Obtained from MC detector simulation using HEMAS (Forti et al., PRD, 1990) as UG muon generator.

Comparison with Sibyll: largest differences for single muons.

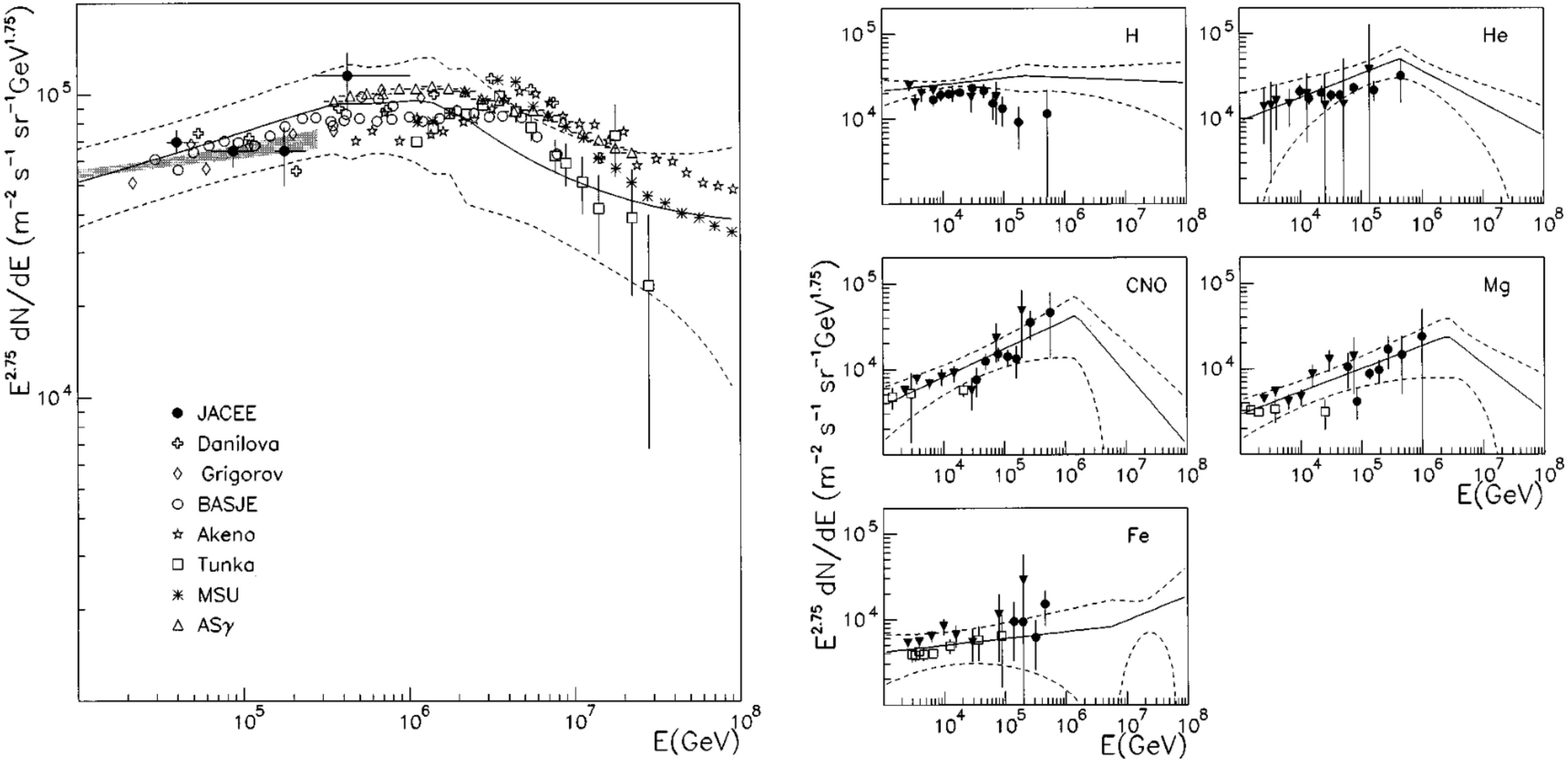
Parametric fluxes to fit

$$\Phi_A(E)=K_1(A)E^{-\gamma_1(A)} \quad \text{for} \quad E<E_{\rm cut}\ (A),$$

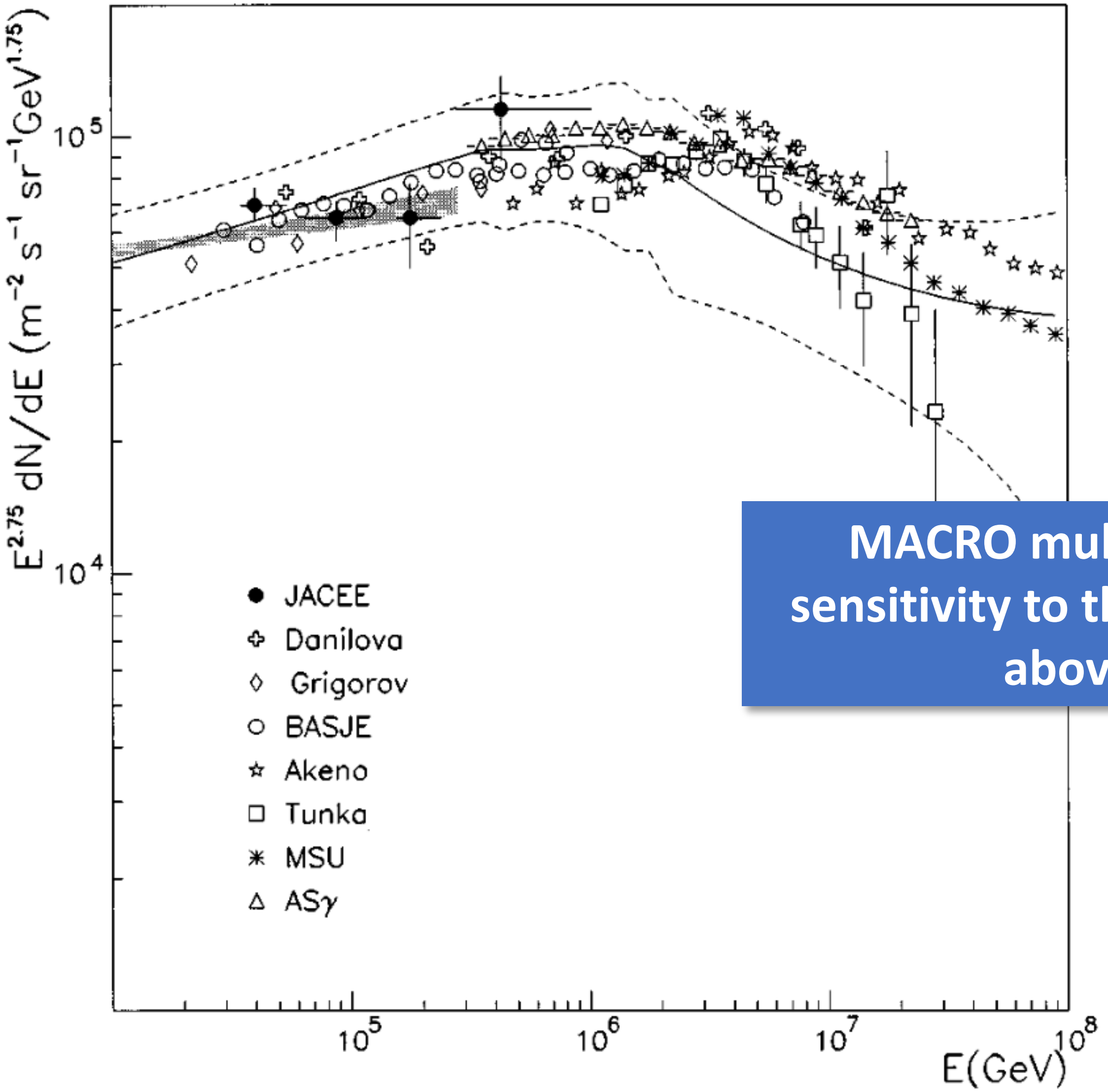
$$\Phi_A(E)=K_2(A)E^{-\gamma_2(A)} \quad \text{for} \quad E>E_{\rm cut}\ (A),$$

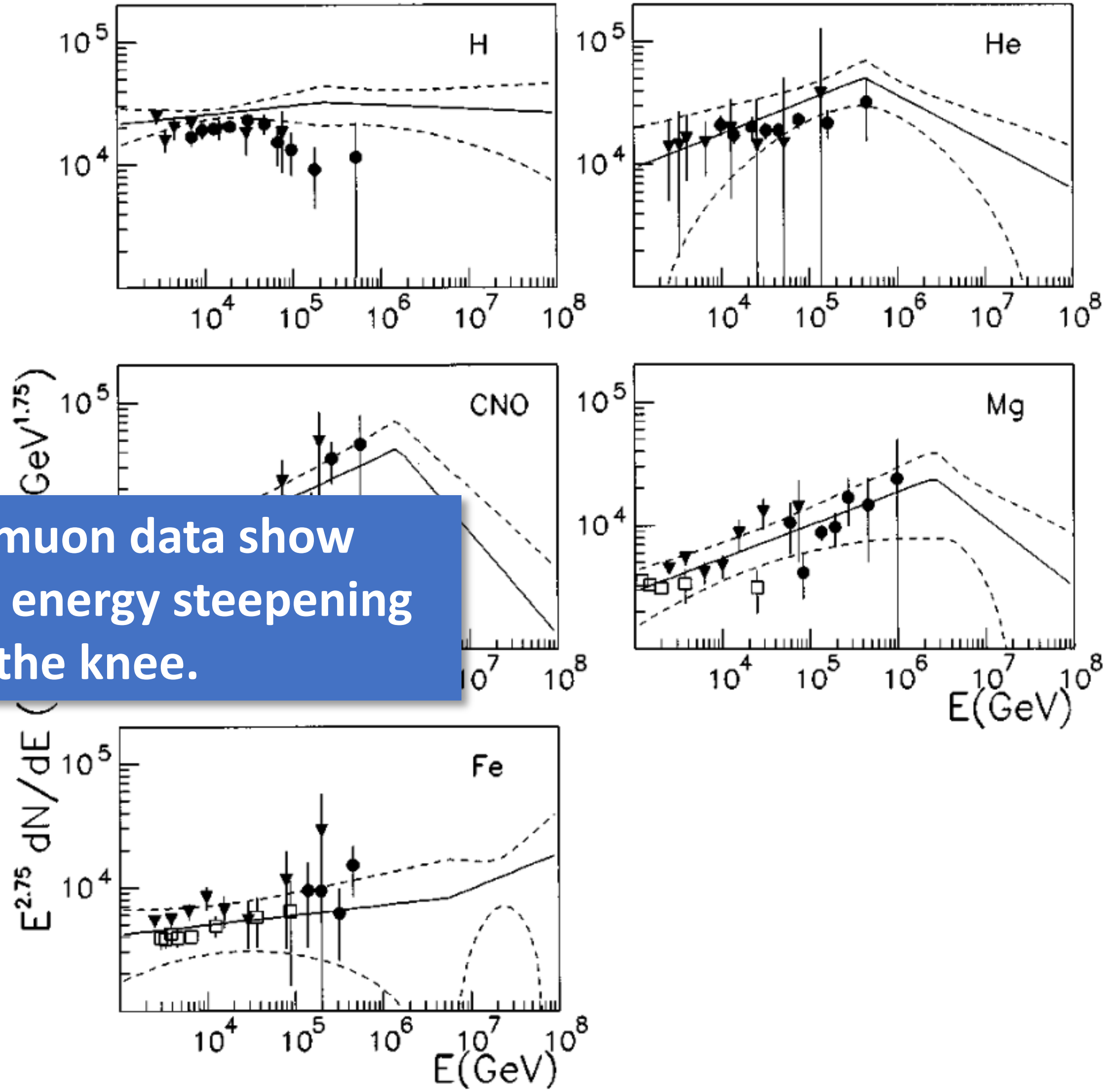
$$\text{with}\ K_2=K_1 E_{\rm cut}^{\gamma_2-\gamma_1} \qquad E_{\rm cut}\ (Z)=E_{\rm cut}\ ({\rm Fe})\cdot Z/26$$

MACRO Coll., PRD, 1997



MACRO Coll., PRD, 1997

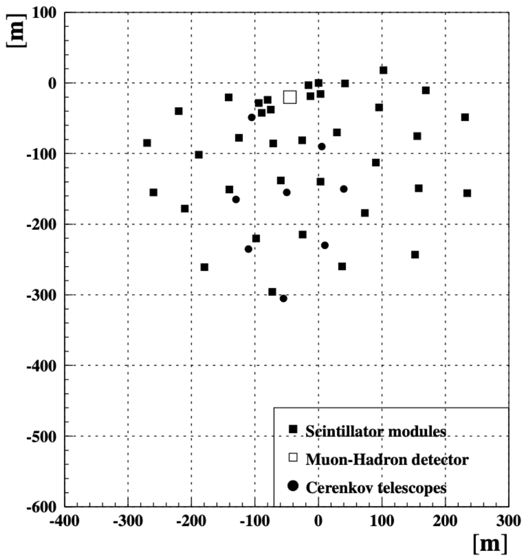


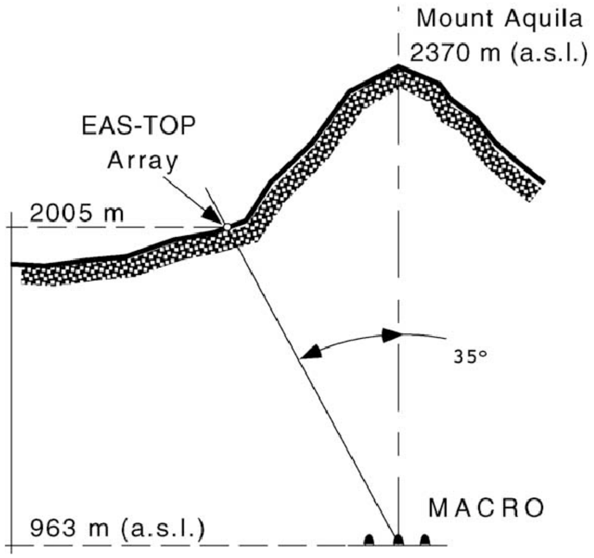


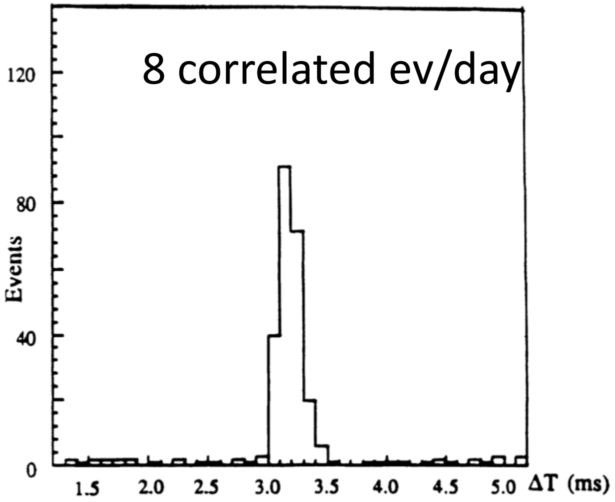
MACRO multimuon data show sensitivity to the energy steepening above the knee.

EAS-TOP-MACRO

Correlating EAS-TOP sizes N_e to MACRO UG muon multiplicities N_μ

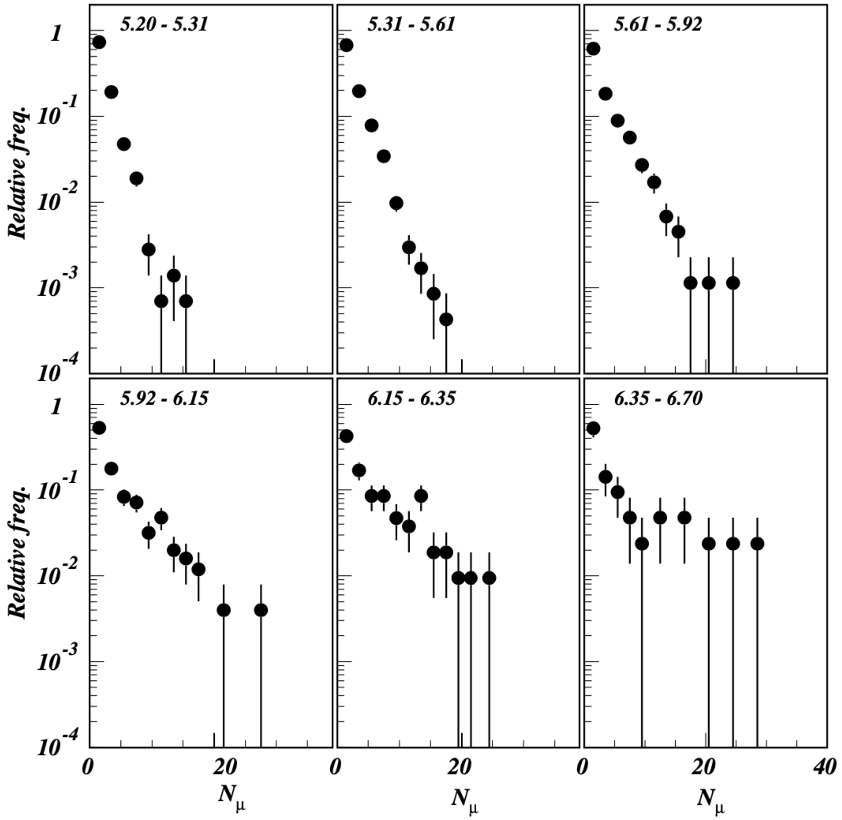






8 correlated ev/day

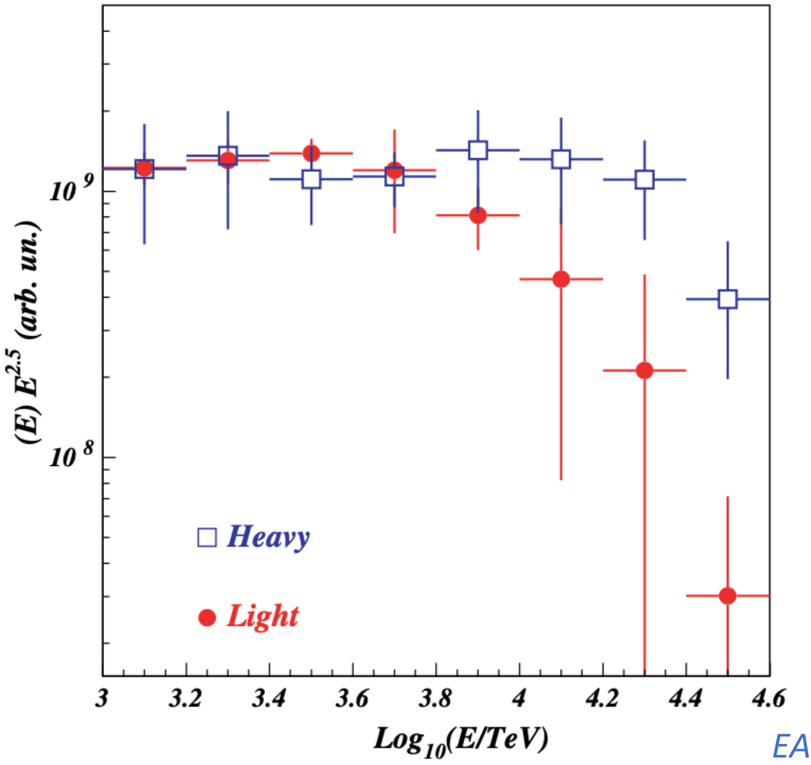
M. Aglietta et al. / Astroparticle Physics 20 (2004) 641–652

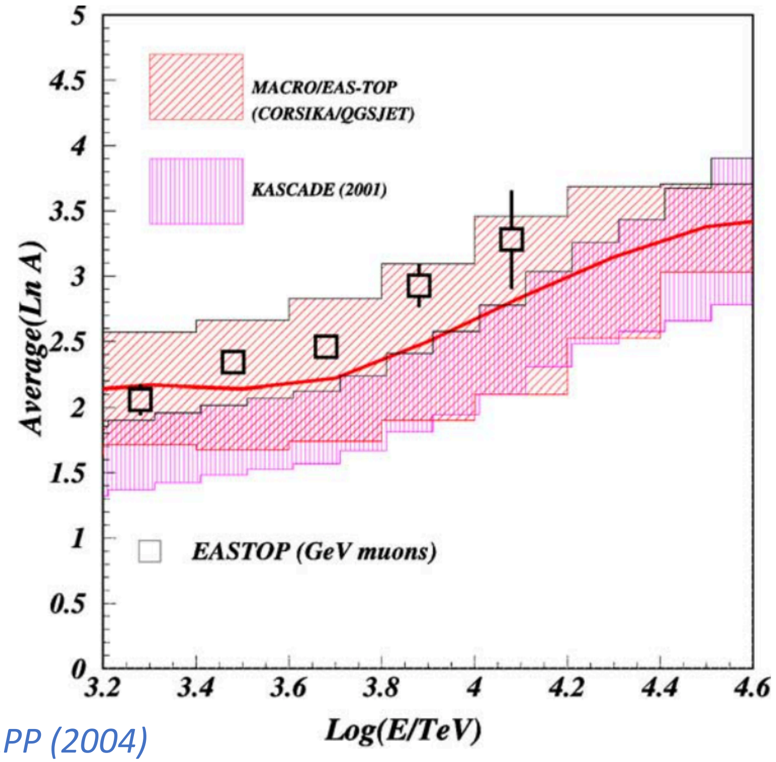


CORSIKA simulation. Five samples with different nuclear masses have been generated:

- grouped into [L] proton + helium and [H] magnesium + iron

$$\xi^2 = \sum_i \frac{(N_i^{\mathrm{exp}} - p_{\mathrm{L}} N_i^{\mathrm{L}} - p_{\mathrm{H}} N_i^{\mathrm{H}})^2}{\sigma_{i,\mathrm{exp}}^2 + (p_{\mathrm{L}}\sigma_{i,\mathrm{L}})^2 + (p_{\mathrm{H}}\sigma_{i,\mathrm{H}})^2}$$





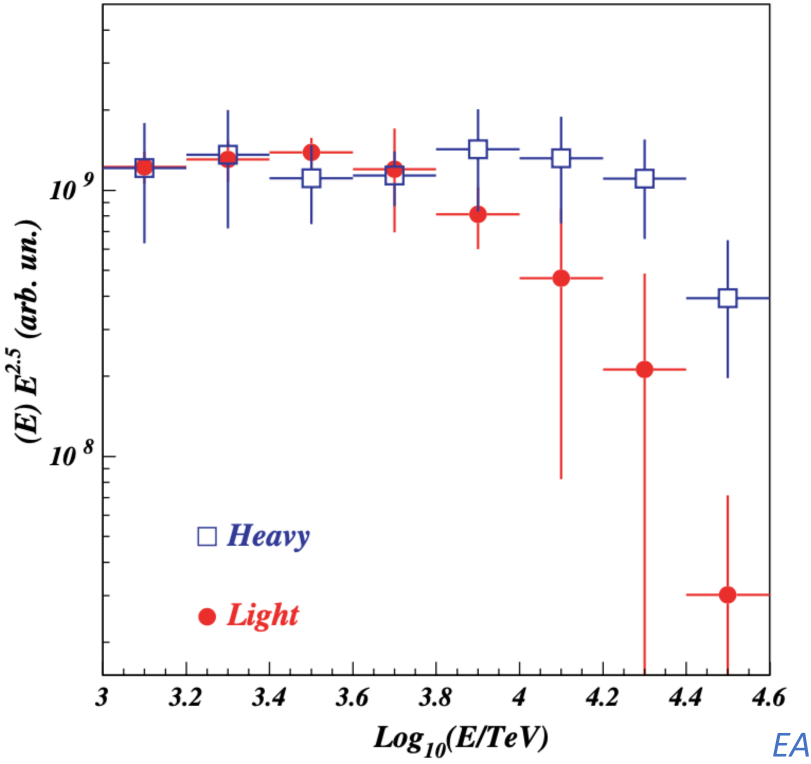
EAS-TOP-MACRO Coll., APP (2004)

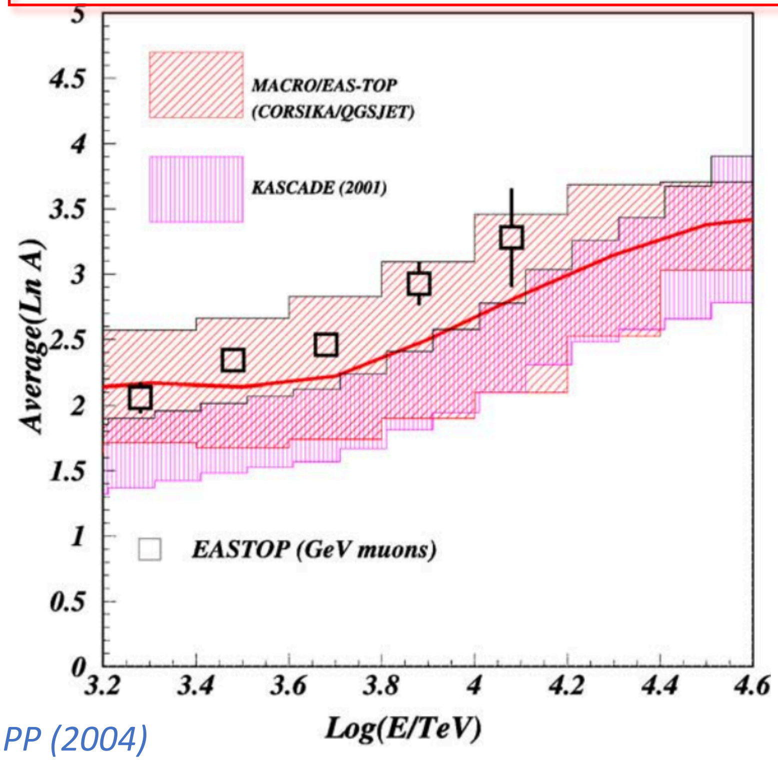
CORSIKA simulation. Five samples with different nuclear masses have been generated:

- grouped into [L] proton + helium and [H] magnesium + iron

$$\xi^2 = \sum_i \frac{(N_i^{\mathrm{exp}} - p_{\mathrm{L}} N_i^{\mathrm{L}} - p_{\mathrm{H}} N_i^{\mathrm{H}})^2}{\sigma_{i,\mathrm{exp}}^2 + (p_{\mathrm{L}}\sigma_{i,\mathrm{L}})^2 + (p_{\mathrm{H}}\sigma_{i,\mathrm{H}})^2}$$

Also correlation of EAS-TOP Cherenkov light to MACRO UG muons exploited to get spectrum for p+He (80 TeV) and p+He+CNO (250 TeV)

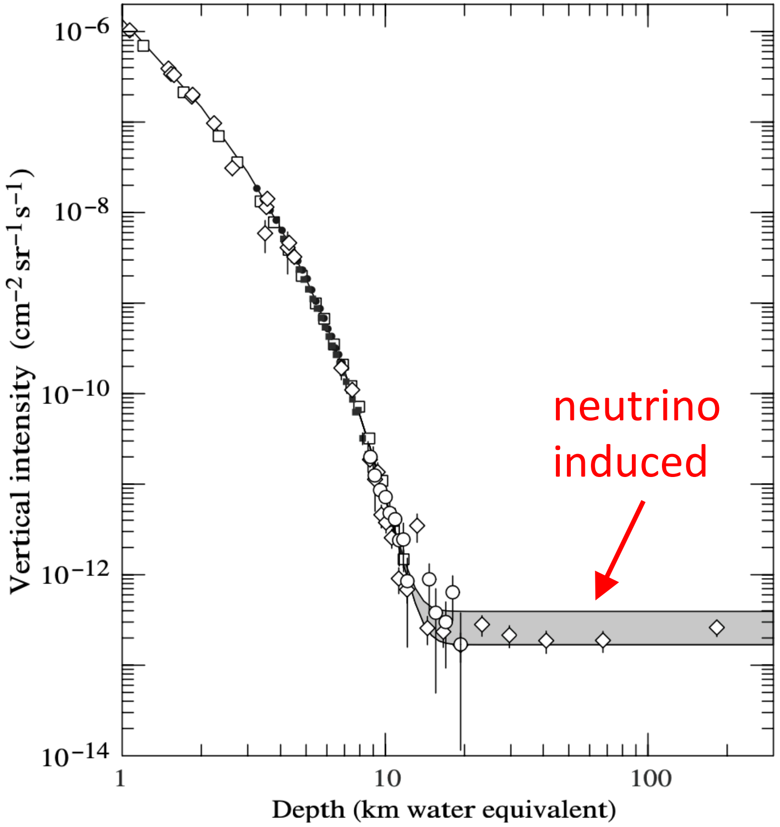




EAS-TOP-MACRO Coll., APP (2004)

Other UG muons results

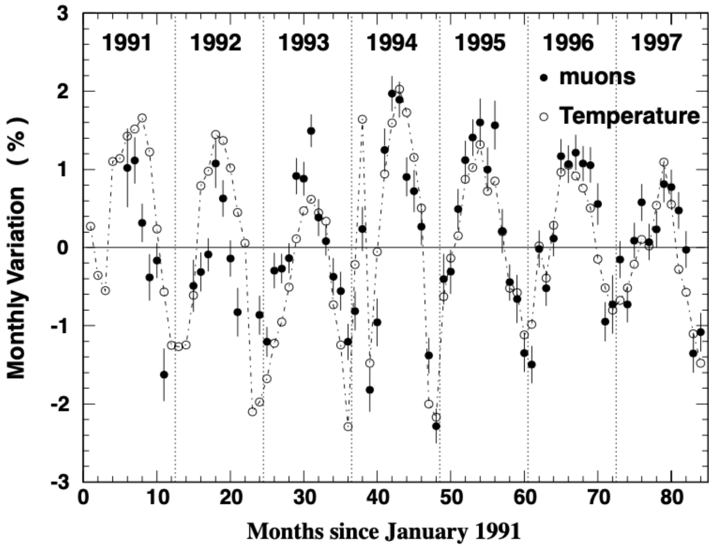
Vertical muon intensity



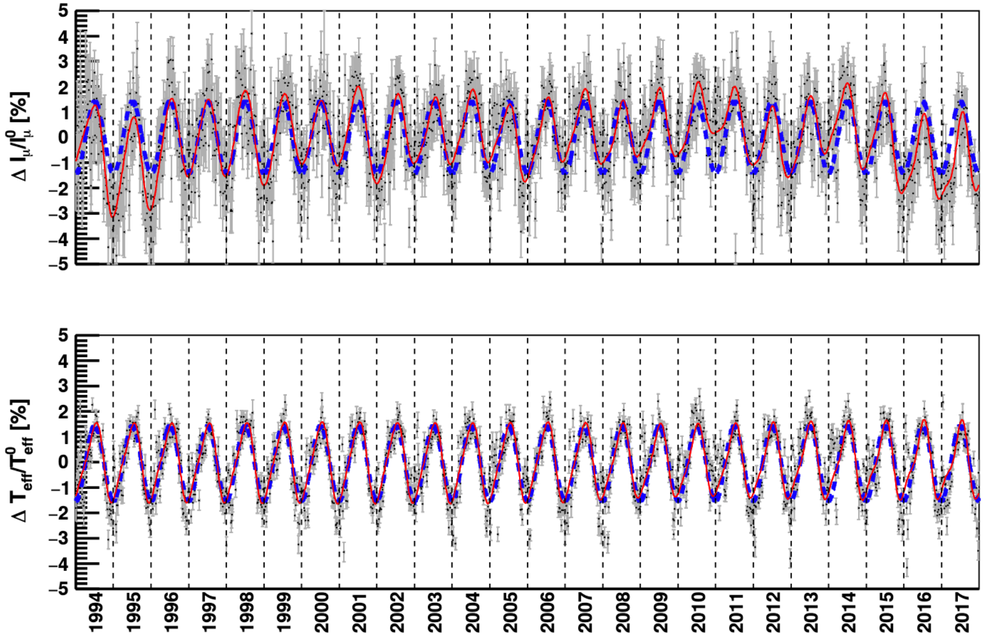
neutrino induced

Figure 24.5: Vertical muon intensity vs depth (1 km.w.e. = 10^5 g cm^{-2} of standard rock). The experimental data are from: ◊: the compilations of Crouch [45], □: Baksan [46], ○: LVD [47], ●: MACRO [48], ■: Frejus [49]. The shaded area at large depths represents neutrino-induced muons of energy above 2 GeV. The upper line is for horizontal neutrino-induced muons, the lower one for vertically upward muons.

Muon rates vs temperature



MACRO

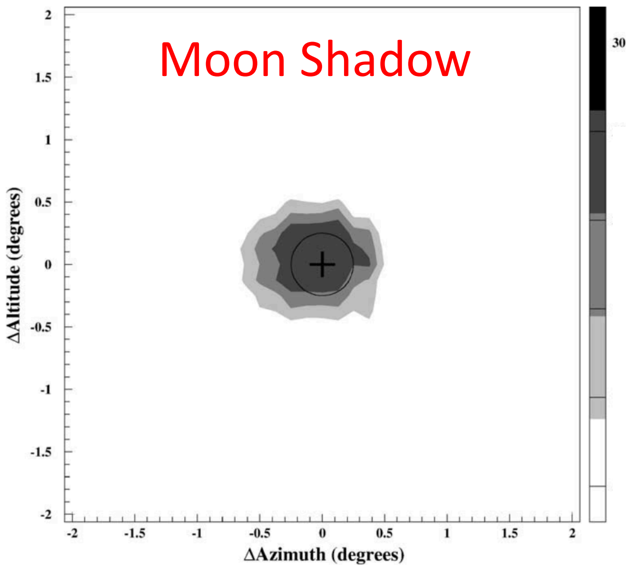


LVD

Muon astronomy

MACRO Coll., ApJ (1993)

M. Ambrosio et al. / Nuclear Instruments and Methods in Physics Research A 486 (2002) 663–707



Moon Shadow

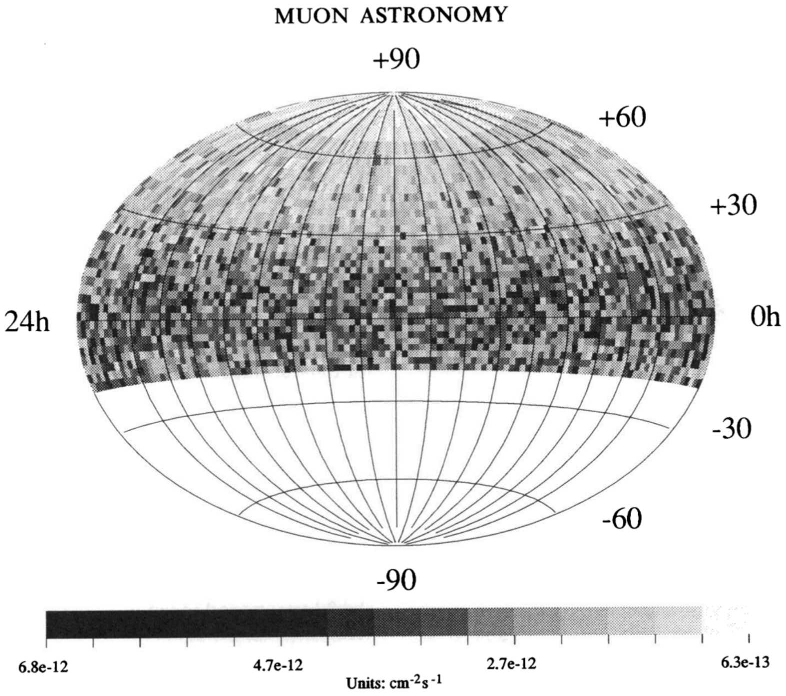


FIG. 7.—The 95% confidence limits on the muon flux for the all-sky survey in equatorial coordinates

TABLE 4

SEARCH FOR MODULATED MUON SIGNALS FROM POINT SOURCES

Source	P_0	Type	$W(\geq Z^2)$	$J_\mu^{mod}(95\%)$ ($cm^{-2}\ s^{-1}$)
4U 0115+63	24.32 days[a]	Orbital	0.79	$<8.9 \times 10^{-13}$
Crab	33.3 ms[b]	Pulsar	0.90	$<1.1 \times 10^{-12}$
Her X-1	1.70 days[c]	Orbital	0.98	$<9.4 \times 10^{-13}$
4U 1907+09	8.38 days[d]	Orbital	0.57	$<1.4 \times 10^{-12}$
Cyg X-1	5.60 days[e]	Orbital	0.68	$<9.0 \times 10^{-13}$
Cyg X-3	4.79 hr[f]	Orbital	0.06	$<1.1 \times 10^{-12}$

[a] Ricketts et al. 1981.
[b] Massaro et al. 1991.
[c] Ögelman 1987.
[d] Bolton 1975.
[e] Makishima et al. 1984.
[f] van der Klis & Bonnet-Bidaud 1989.

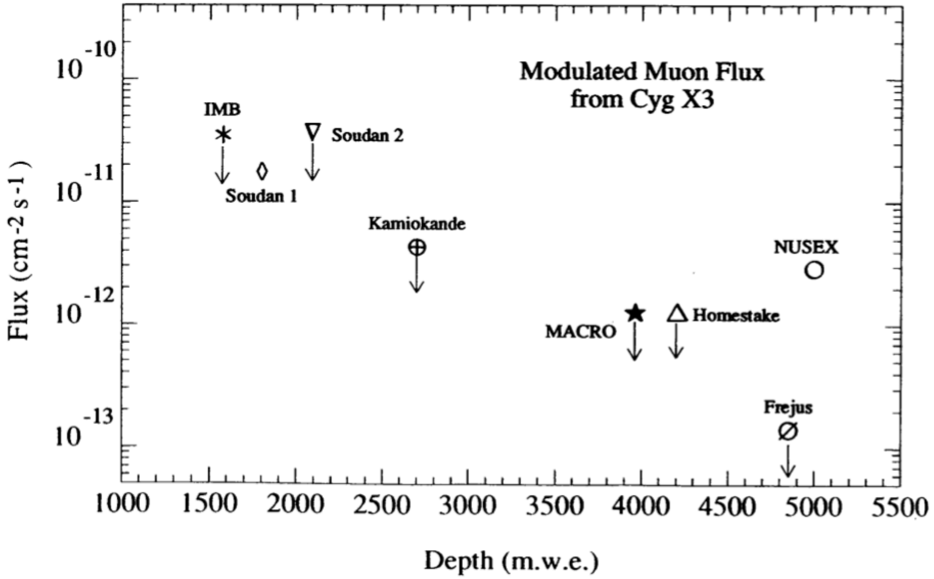
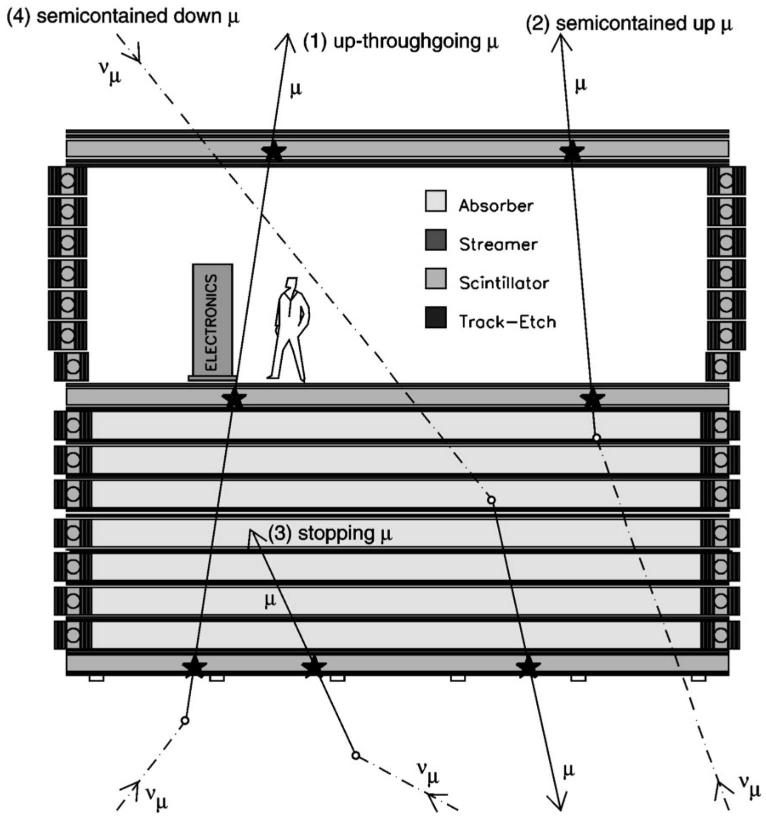
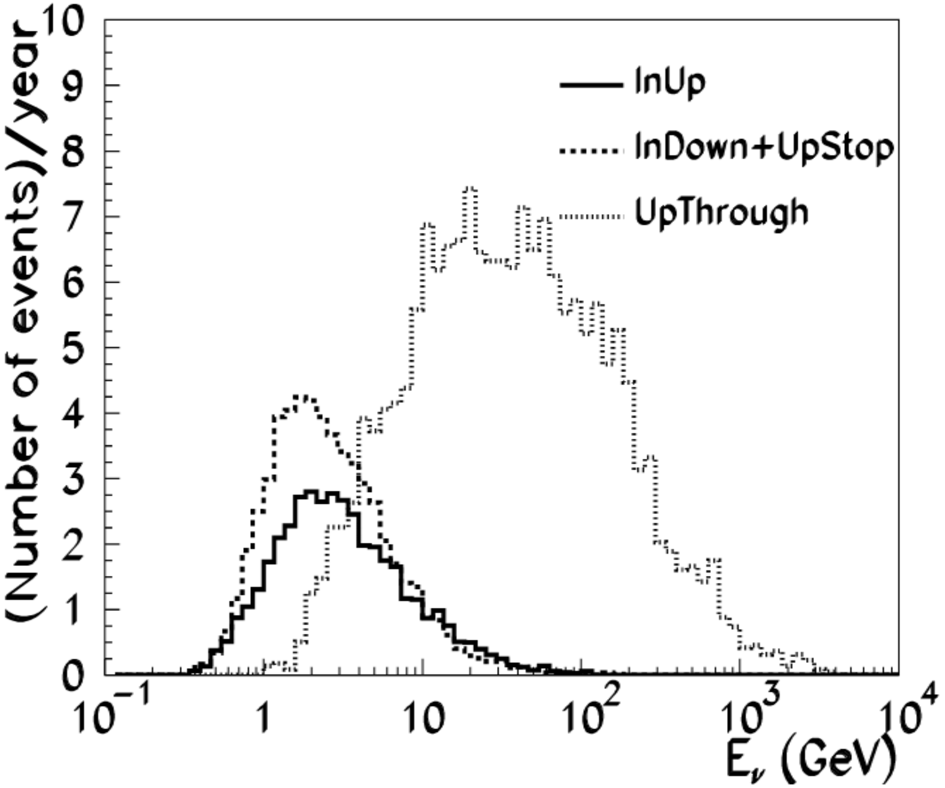


FIG. 9.—MACRO limit to the modulated muon flux from Cyg X-3 compared with the results from other underground detectors.

Atmospheric neutrinos

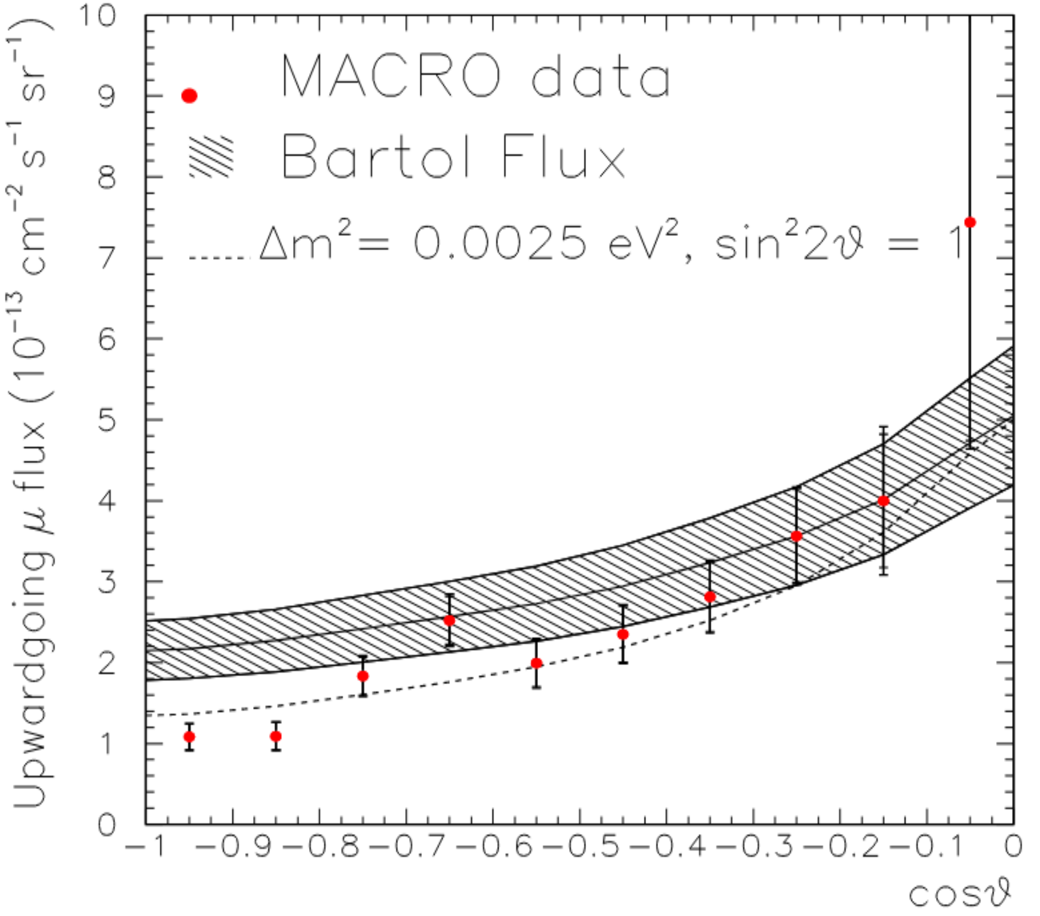
- Atmospheric neutrinos produced by CR interactions with air nuclei
- Search for neutrino oscillation in MACRO based on $\nu_\mu \rightarrow \mu$ events
- Flavor oscillation affects muon angular distribution
- Different topologies observed in MACRO: Upgoing, Stopping and Internal





UPGoing Muons

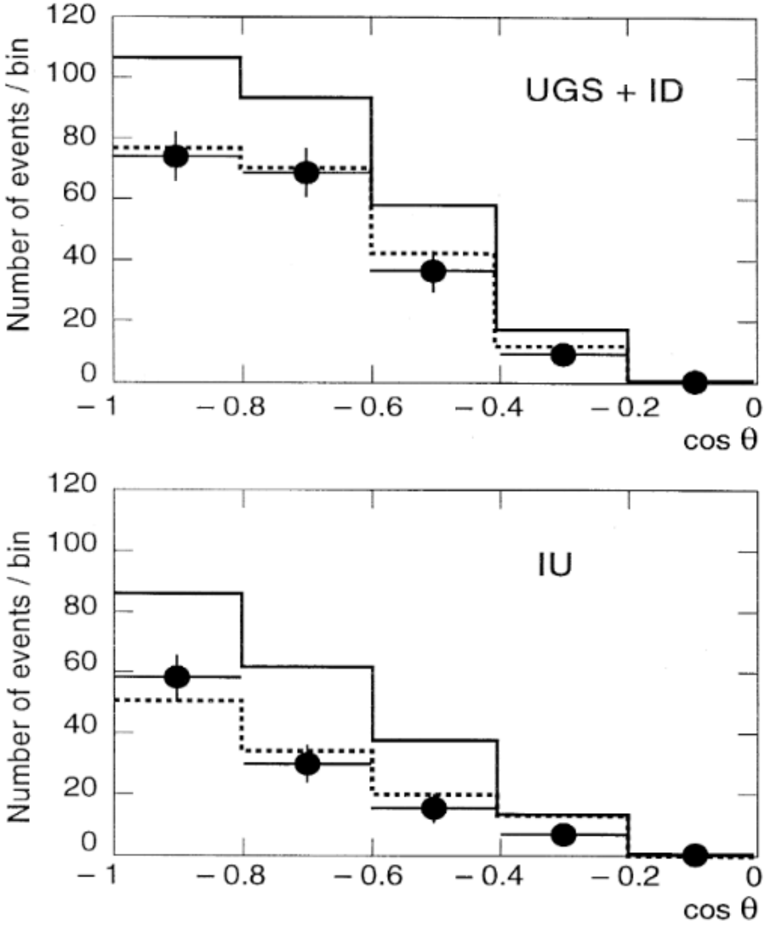
MACRO Coll., PLB (1998)



Bartol flux: *Agrawal, Gaisser, Lipari, Stanev Phys. Rev. D (1996)*

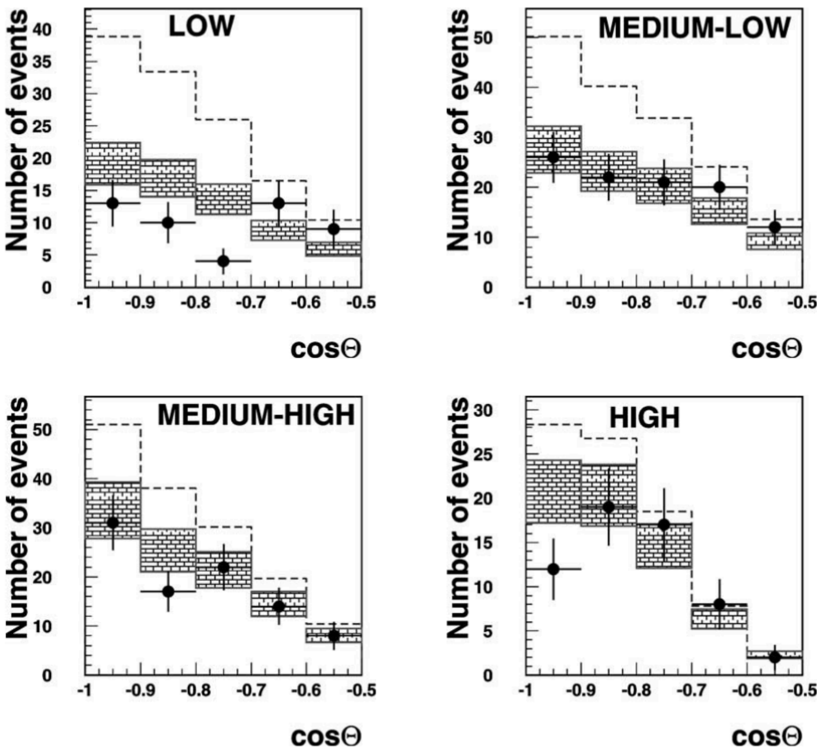
Stopping and Internal Muons

MACRO Coll., PLB (2000)

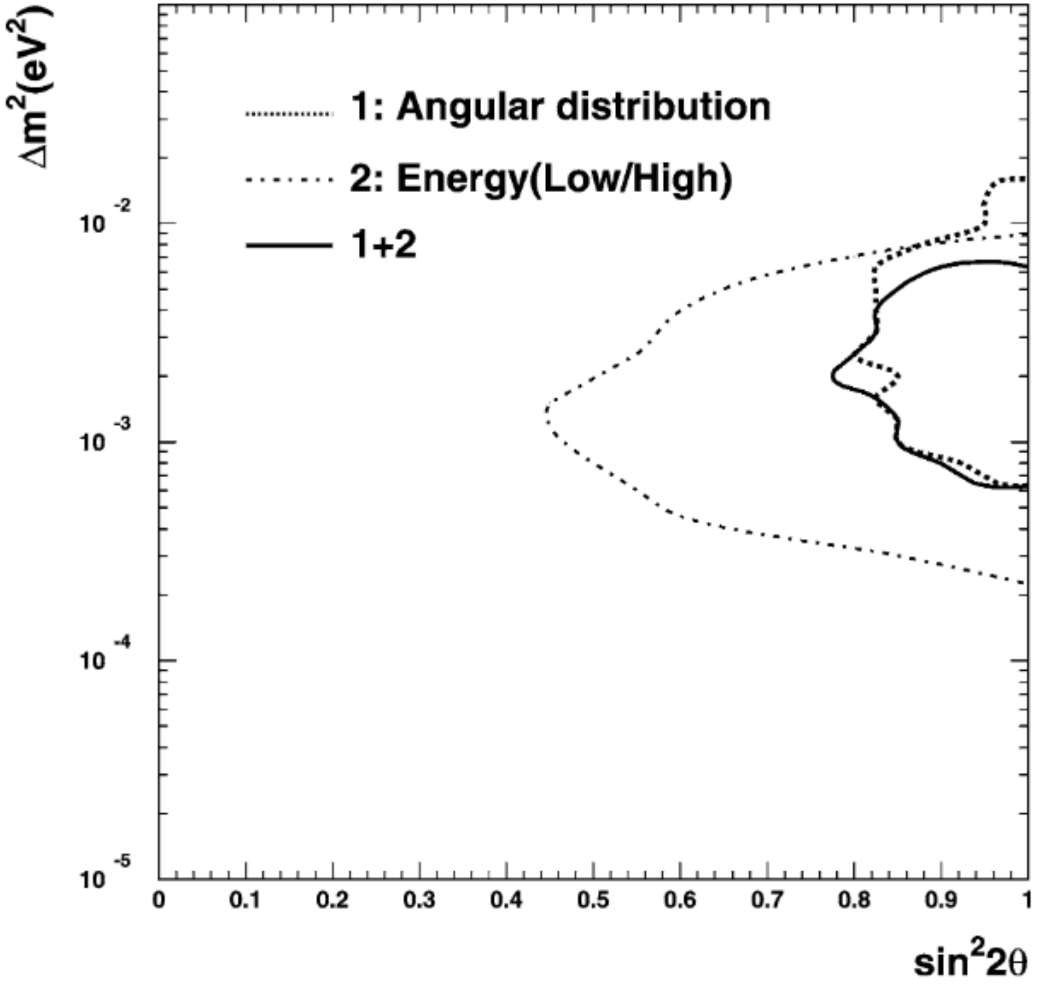


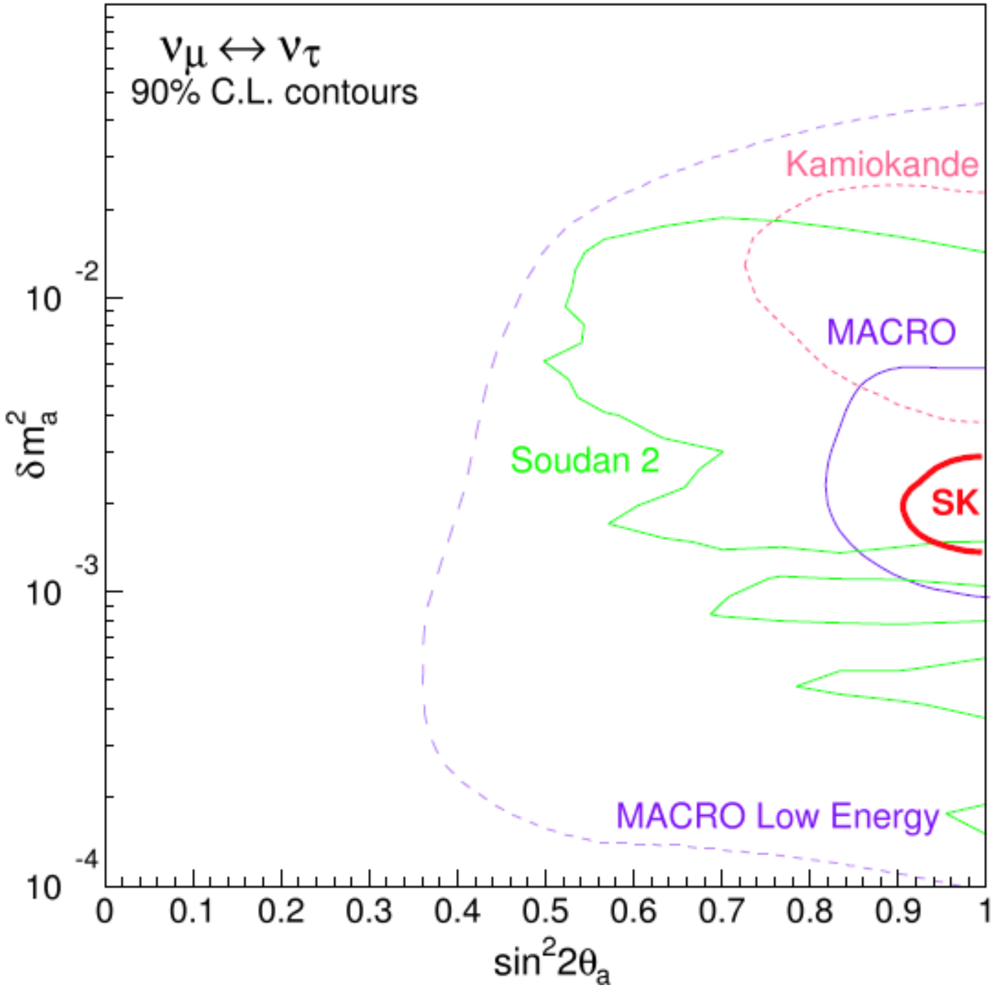
Muon Multiple Scattering for E separation

Sample	Energy cuts (GeV)	Median energy (GeV)
Low	$E_\nu^{\rm rec} < 30$	13
Medium–Low	$30 < E_\nu^{\rm rec} < 80$	36
Medium–High	$80 < E_\nu^{\rm rec} < 130$	88
High	$E_\nu^{\rm rec} > 130$	146

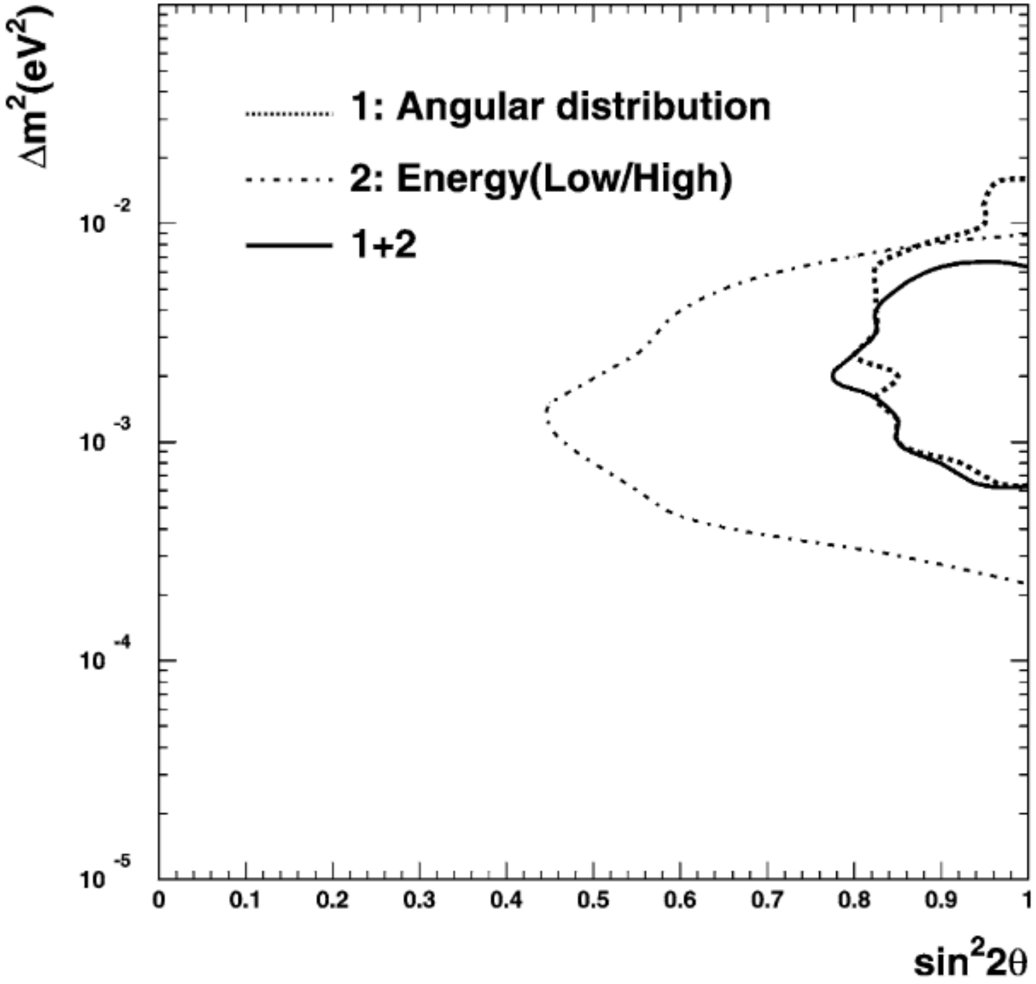


MACRO Coll., PLB (2003)





MACRO Coll., PLB (2003)



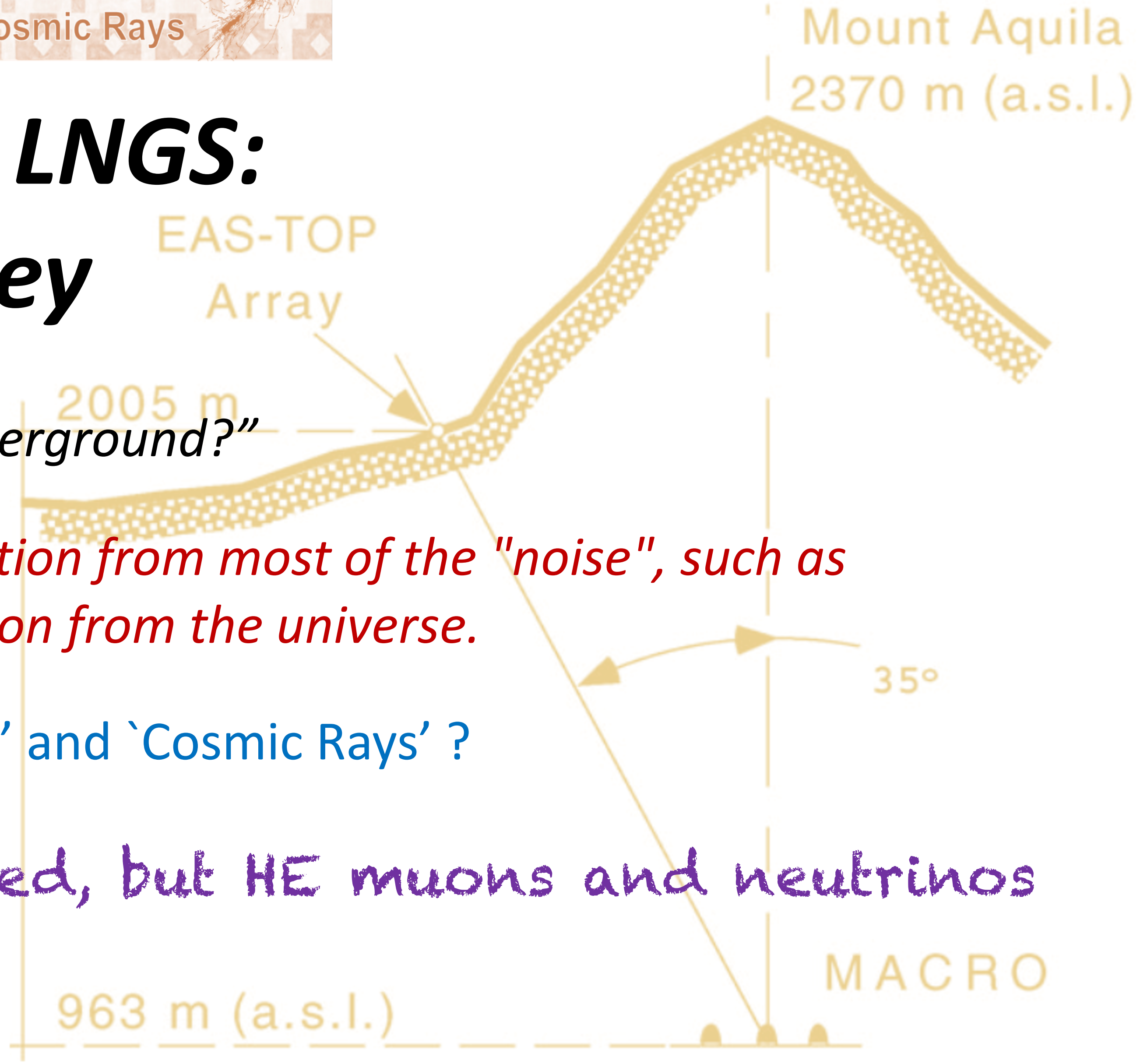
“…E quindi uscimmo a riveder le stelle”
“…And thence we came forth to see again the stars”
(Dante Alighieri, La Divina Commedia)

`Puccio' Bellotti: *first director of LNGS,*
for leaving an unforgettable
mark with his wisdom and
friendly attitude, in the start of
experimental operations.

Tom Gaisser: *for his crucial role in the*
study of underground muons
and their potential in CR physics.
Thanks for his papers, his books
and the enlightening discussions.

Backup slides

Cosmic Ray Physics at LNGS: a historical journey



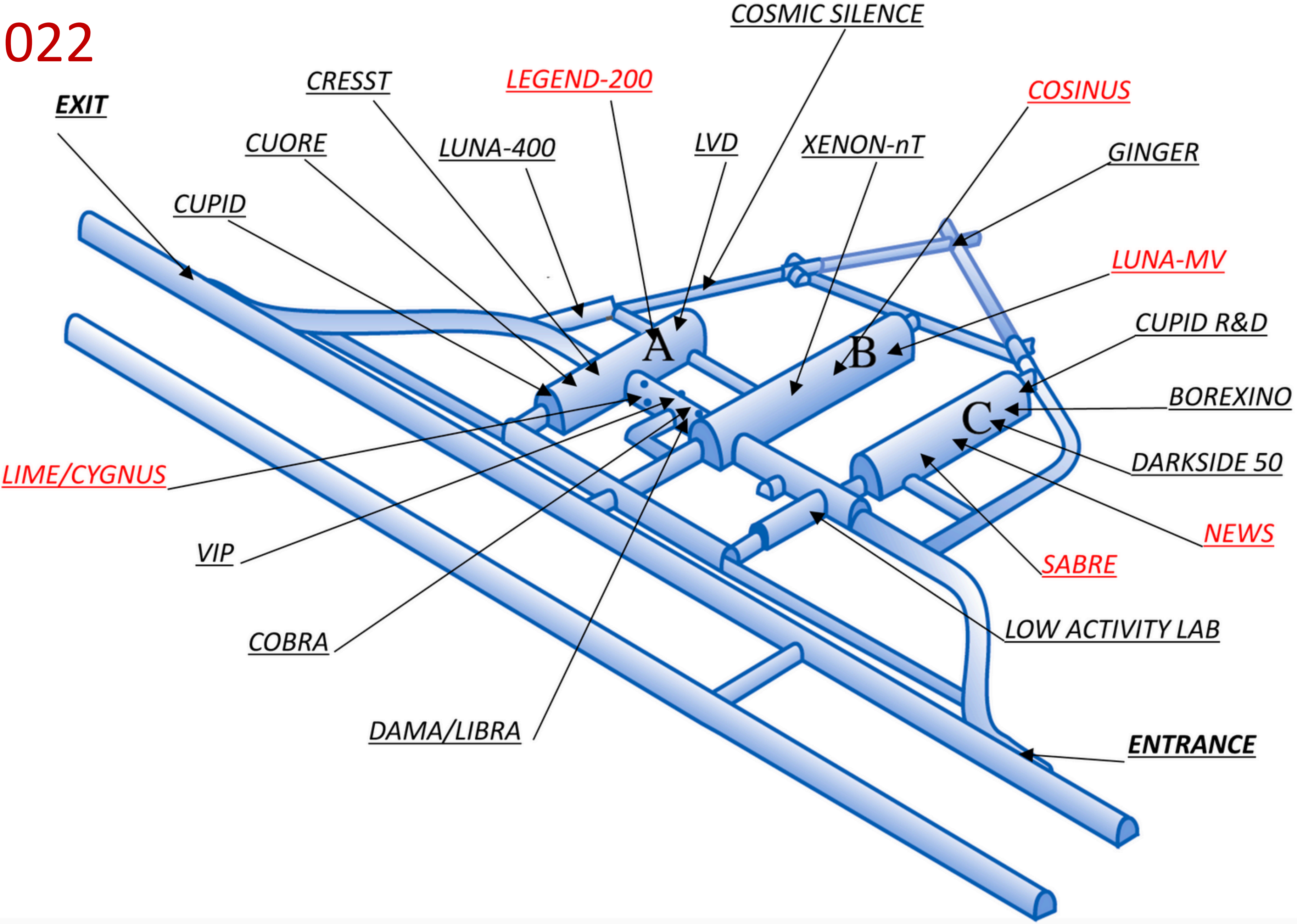
From the web: *“Why are laboratories underground?”*

*Being underground gives scientists protection from most of the "noise", such as **cosmic rays** and other background radiation from the universe.*

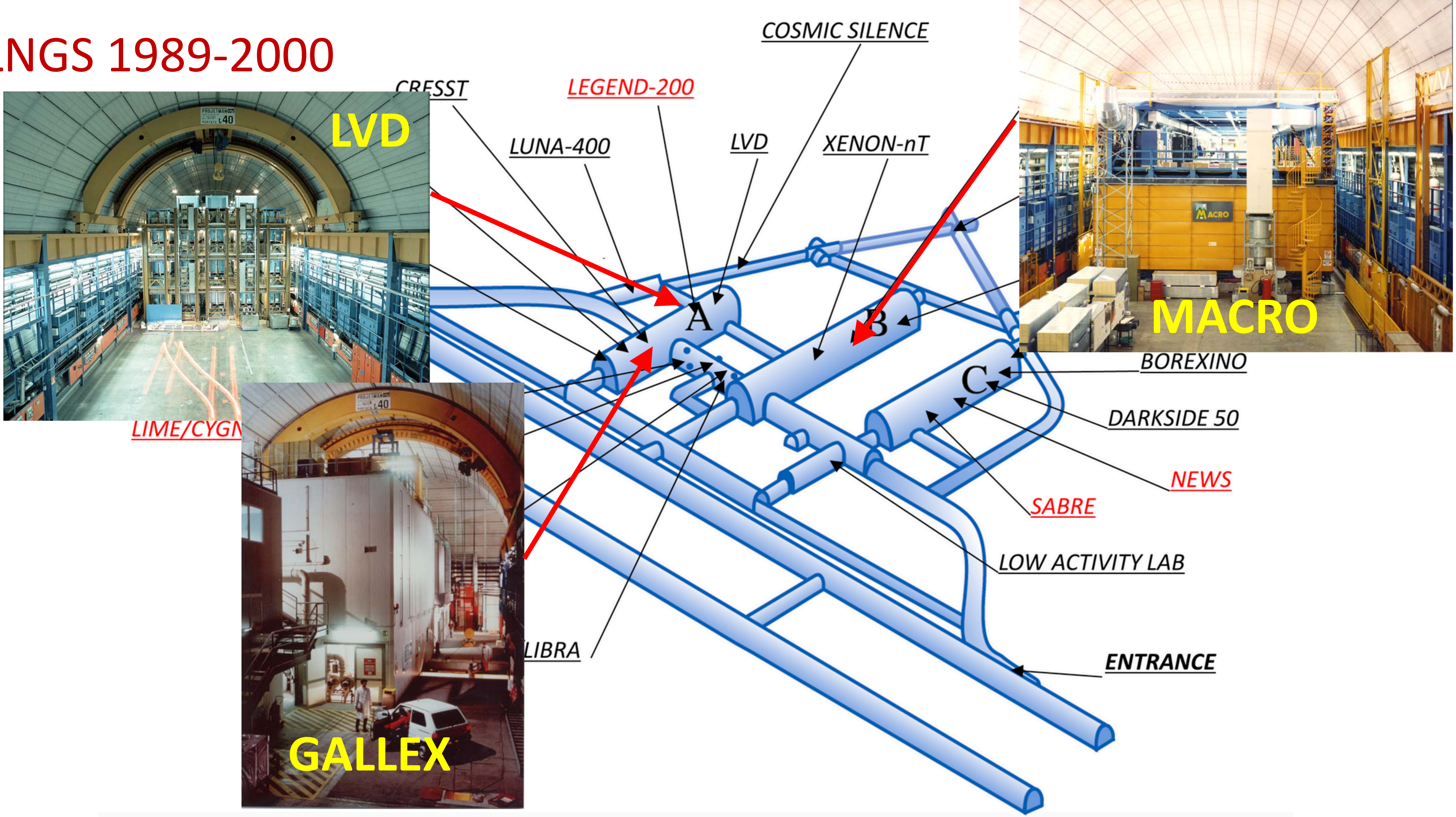
Contradiction between `Underground Lab’ and `Cosmic Rays’ ?

CR’s secondaries are suppressed, but HE muons and neutrinos still survive

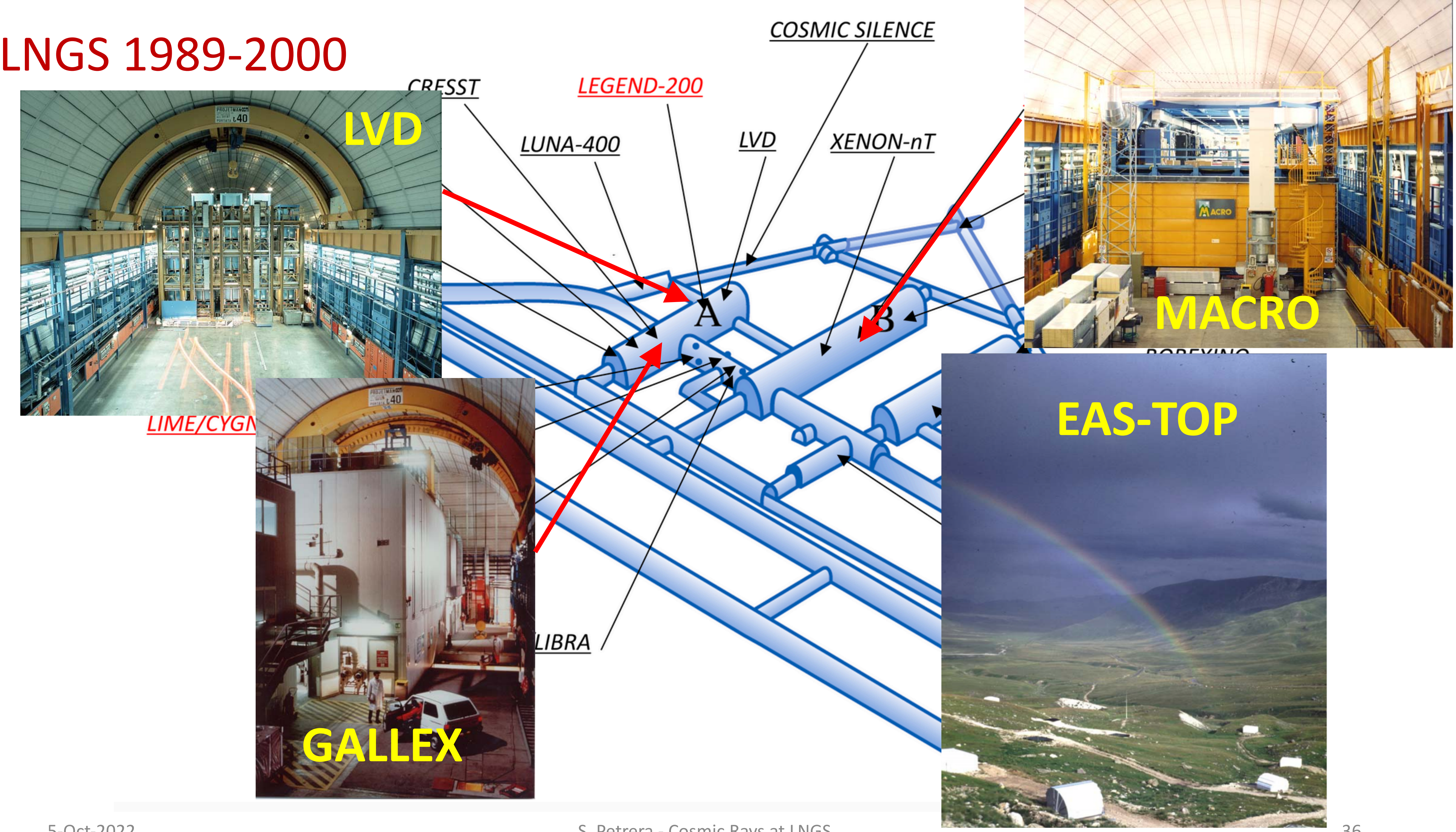
LNGS 2022


COSMIC SILENCE
CRESST
LEGEND-200
COSINUS
EXIT
CUORE
LUNA-400
LVD
XENON-nT
GINGER
CUPID
LUNA-MV
CUPID R&D
BOREXINO
DARKSIDE 50
LIME/CYGNUS
NEWS
VIP
SABRE
COBRA
LOW ACTIVITY LAB
DAMA/LIBRA
ENTRANCE
A
B
C

LNGS 1989-2000



LNGS 1989-2000



THE ASTROPHYSICAL JOURNAL, 412:301–311, 1993 July 20

MUON ASTRONOMY WITH THE MACRO DETECTOR

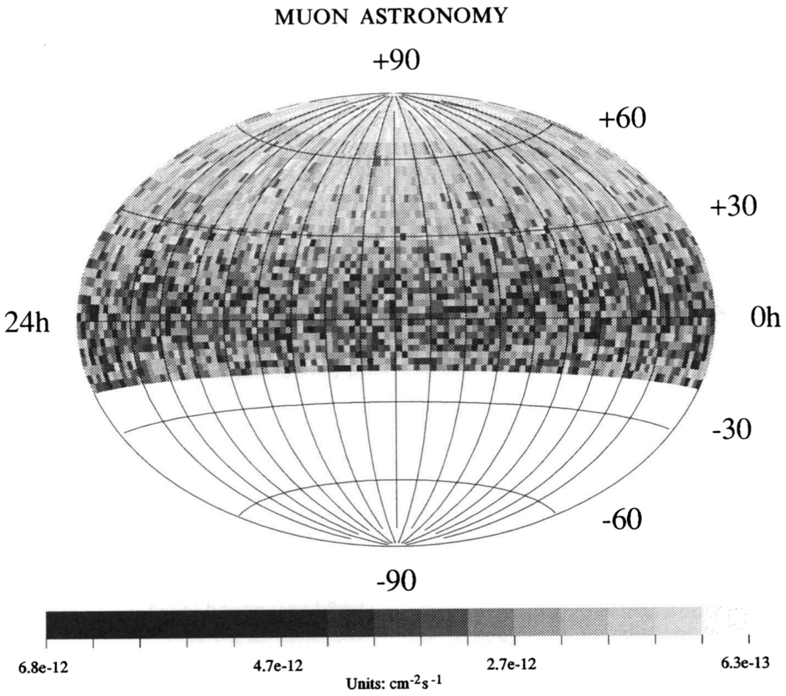
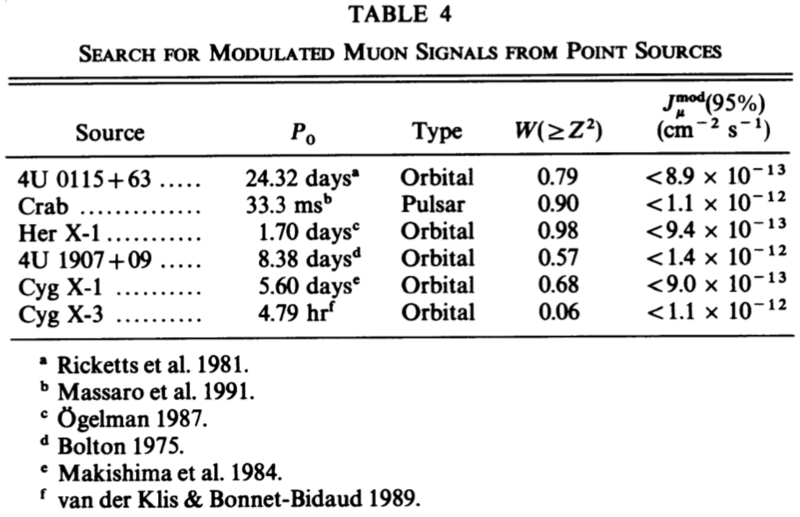


FIG. 7.—The 95% confidence limits on the muon flux for the all-sky survey in equatorial coordinates



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[e] Makishima et al. 1984.
[f] van der Klis & Bonnet-Bidaud 1989.

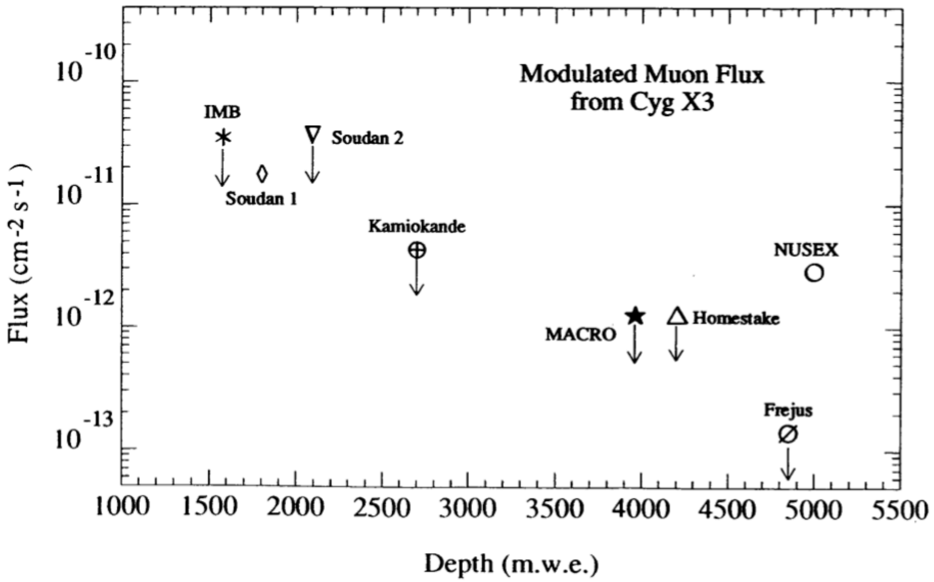


FIG. 9.—MACRO limit to the modulated muon flux from Cyg X-3 compared with the results from other underground detectors.

The Astrophysical Journal, 546:1038–1054, 2001 January 10

NEUTRINO ASTRONOMY WITH THE MACRO DETECTOR

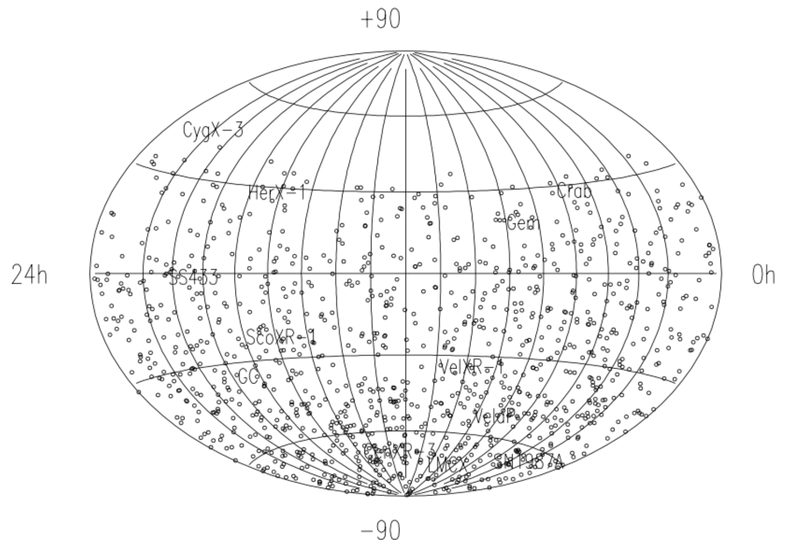


Fig. 9.—Upward-going muon distribution in equatorial coordinates (1100 events).

TABLE 5

Flux Upper Limits on Muon Fluxes from Neutrino Production from Various Catalogs

Catalog	Number of Sources	Average Exposure ($\times 10^{-14}$ cm^{-2} s^{-1})	ν-Induced μ-Flux Limit ($\times 10^{-16}$ cm^{-2} s^{-1})	ν-Flux Limit (cm^{-2} s^{-1})
MACRO list	42	4.67	3.06	5.79×10^{-8}
SNRs (Green catalog)[a]	220	2.35	2.63	5.00×10^{-8}
Blazars (Padovani & Giommi 1995)	181	2.77	5.44	1.03×10^{-7}
BATSE[b]	2527	3.37	1.68	3.17×10^{-8}
EGRET[c]	271	3.66	2.03	3.82×10^{-8}
BeppoSAX (E. Pian 1999, private communication)	32	3.41	6.84	1.27×10^{-7}
Novae X (N. Masetti 1999, private communication)	29	4.97	5.34	1.01×10^{-7}

Note.—Flux upper limits are at 90% c.l. for $E_\mu > 1$ GeV and for an assumed spectral index of the neutrino flux of $\gamma = 2.1$. The catalog, the number of souces in it, the average exposure (which is the denominator in eq. [11]), the muon flux upper limits, and the neutrino flux upper limits ($E_{\nu\mathrm{min}} = 1$ GeV) are given. Flux upper limits are calculated according to eqs. (12) and (13).

[a] Green, D. A. 1998, A Catalog of Galactic Supernova Remnants, available at the URL http://www.mrao.cam.ac.uk/surveys/snrs.

[b] Paciesas, W. S., et al. 1999, available at the URL http://gammaray.msfc.nasa.gov/batse.

[c] Hartman, R. C., et al. 1998, available at the URL ftp://gamma.gsfc.nasa.gov/pub/THIRD_CATALOG.

LVD Coll., Phys.Atom.Nucl. (2003)

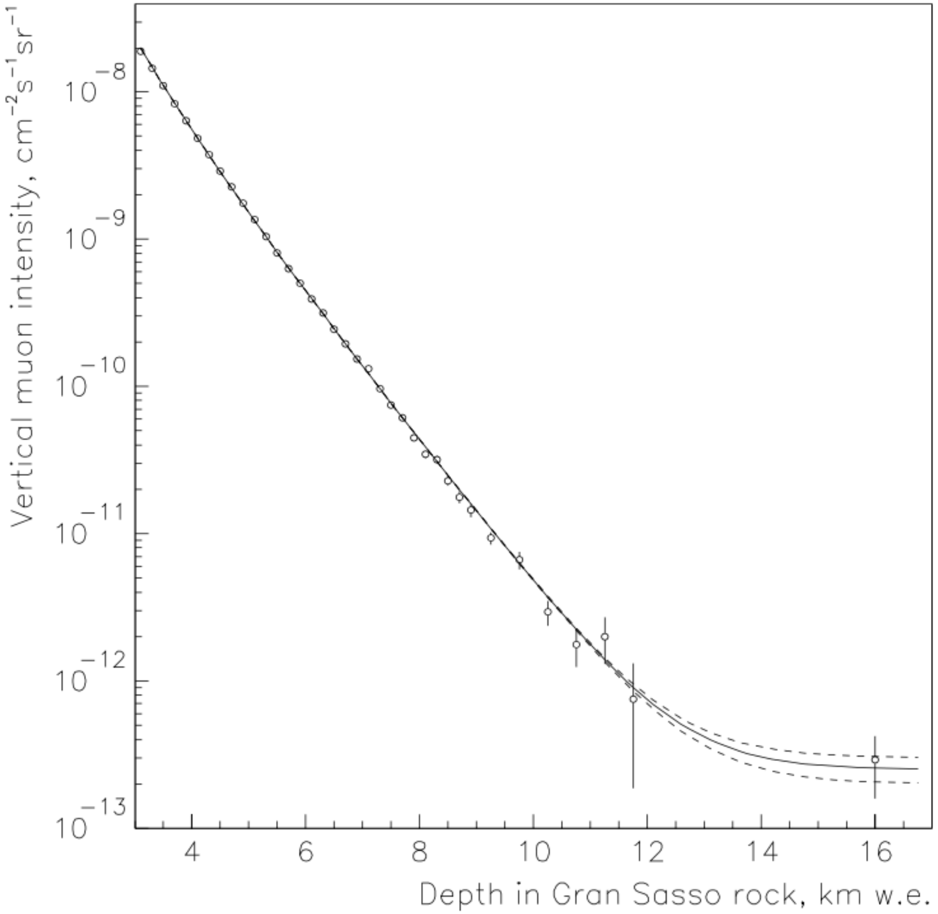
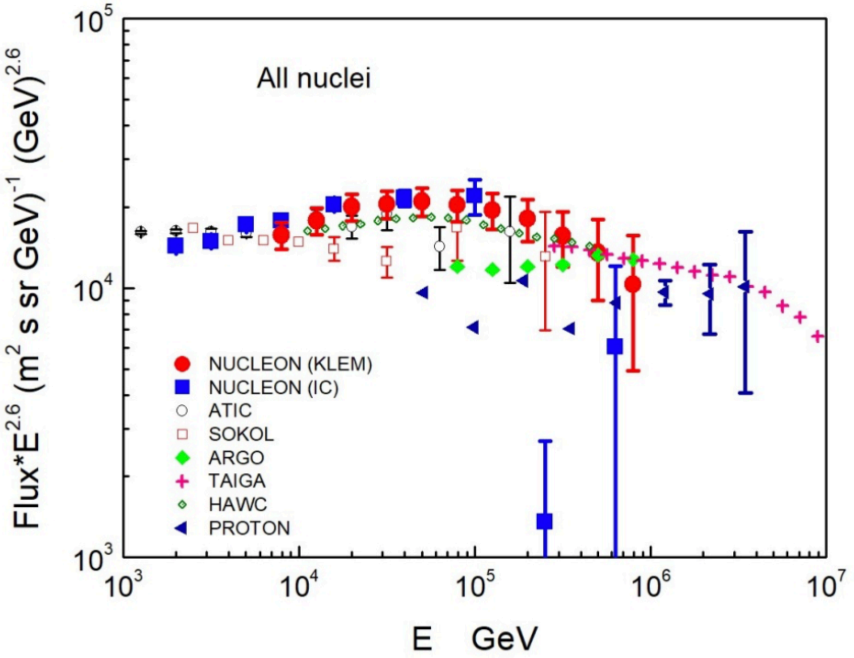
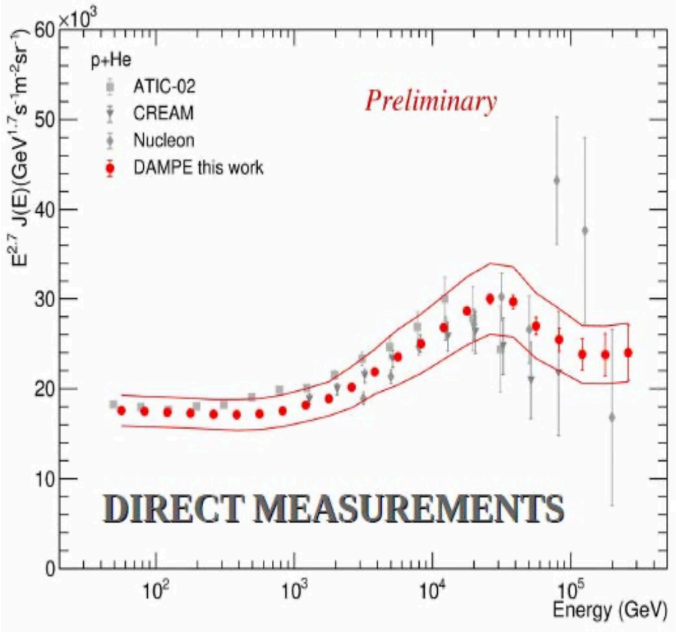
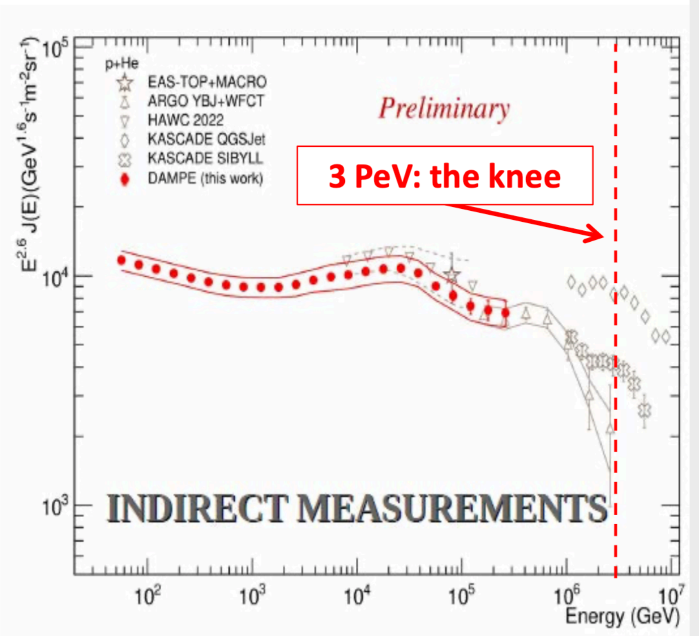


Figure 2: 'Depth – vertical muon intensity' relation in Gran Sasso rock. LVD data are presented together with the best fit (solid curve). Dashed curves show the calculated intensities for maximal and minimal contributions from neutrino-induced muons (see text for details).


All nuclei
Flux*E^2.6 (m^2 s sr GeV)^-1 (GeV)^2.6
E GeV
10^3
10^4
10^5
10^6
10^7
NUCLEON (KLEM)
NUCLEON (IC)
ATIC
SOKOL
ARGO
TAIGA
HAWC
PROTON


×10^3
E^2.7 J(E)(GeV^1.7 s^-1 m^-2 sr^-1)
p+He
ATIC-02
CREAM
Nucleon
DAMPE this work
Preliminary
DIRECT MEASUREMENTS
Energy (GeV)
0
10
20
30
40
50
60
10^2
10^3
10^4
10^5


E^2.6 J(E)(GeV^1.6 s^-1 m^-2 sr^-1)
p+He
EAS-TOP+MACRO
ARGO YBJ+WFCT
HAWC 2022
KASCADE QGSJet
KASCADE SIBYLL
DAMPE (this work)
Preliminary
3 PeV: the knee
INDIRECT MEASUREMENTS
Energy (GeV)
10^3
10^4
10^5
10^2
10^3
10^4
10^5
10^6
10^7

p+He

Correlation of EAS-TOP Cherenkov telescopes to MACRO N_μ

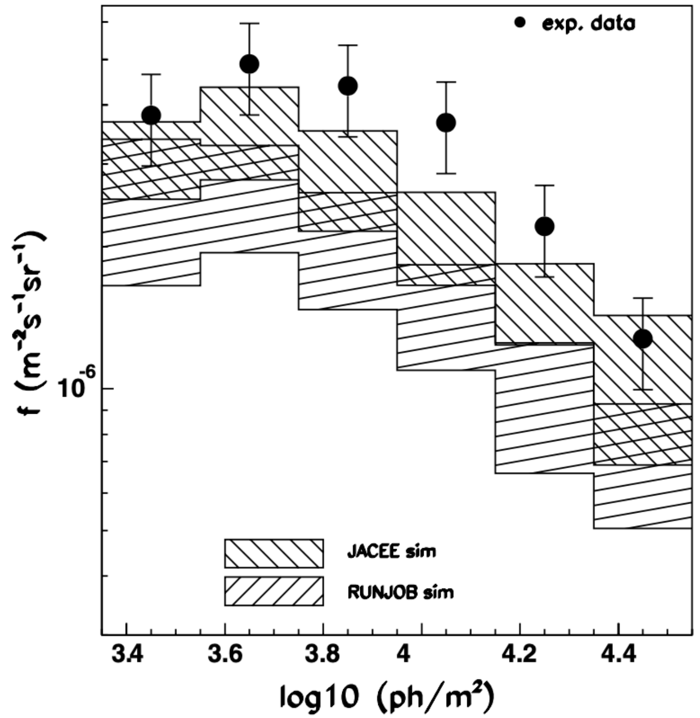


Fig. 12. Same as Fig. 11 in fixed intervals of photon density and scaling all core distances in the region $r \in [145, 185]$ m to $r \in [125, 145]$ m.

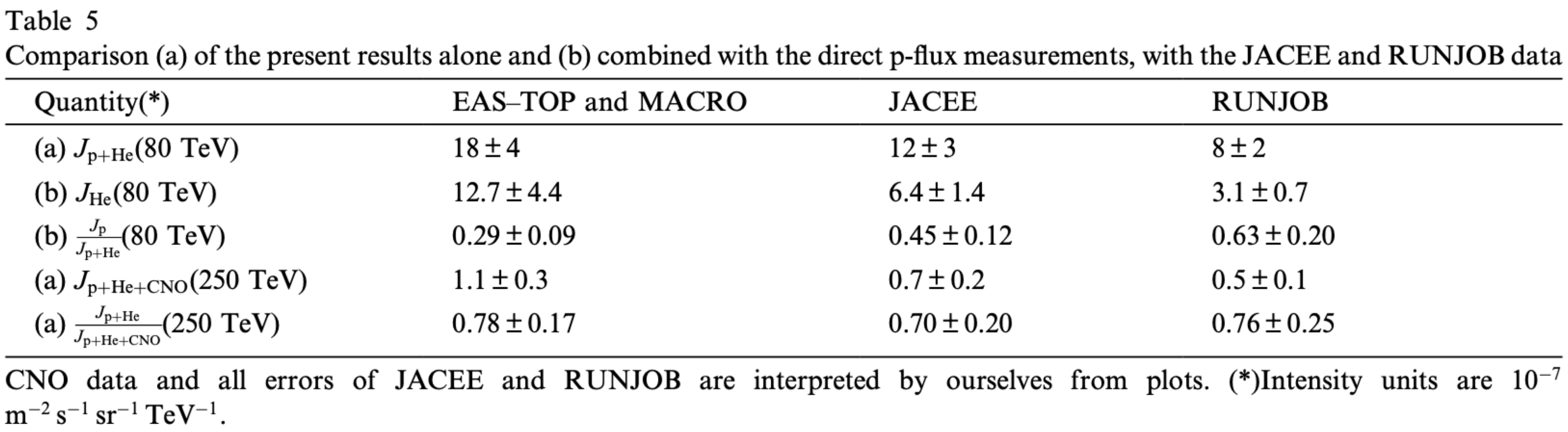


Table 5

Comparison (a) of the present results alone and (b) combined with the direct p-flux measurements, with the JACEE and RUNJOB data

Quantity(*)	EAS–TOP and MACRO	JACEE	RUNJOB
(a) $J_{\mathrm{p+He}}$(80 TeV)	18 ± 4	12 ± 3	8 ± 2
(b) J_{He}(80 TeV)	12.7 ± 4.4	6.4 ± 1.4	3.1 ± 0.7
(b) $\frac{J_{\mathrm{p}}}{J_{\mathrm{p+He}}}$(80 TeV)	0.29 ± 0.09	0.45 ± 0.12	0.63 ± 0.20
(a) $J_{\mathrm{p+He+CNO}}$(250 TeV)	1.1 ± 0.3	0.7 ± 0.2	0.5 ± 0.1
(a) $\frac{J_{\mathrm{p+He}}}{J_{\mathrm{p+He+CNO}}}$(250 TeV)	0.78 ± 0.17	0.70 ± 0.20	0.76 ± 0.25

CNO data and all errors of JACEE and RUNJOB are interpreted by ourselves from plots. (*)Intensity units are 10^{-7} $\mathrm{m^{-2}\,s^{-1}\,sr^{-1}\,TeV^{-1}}$.

MACRO Coll., Eur. Phys. J. C (2002)

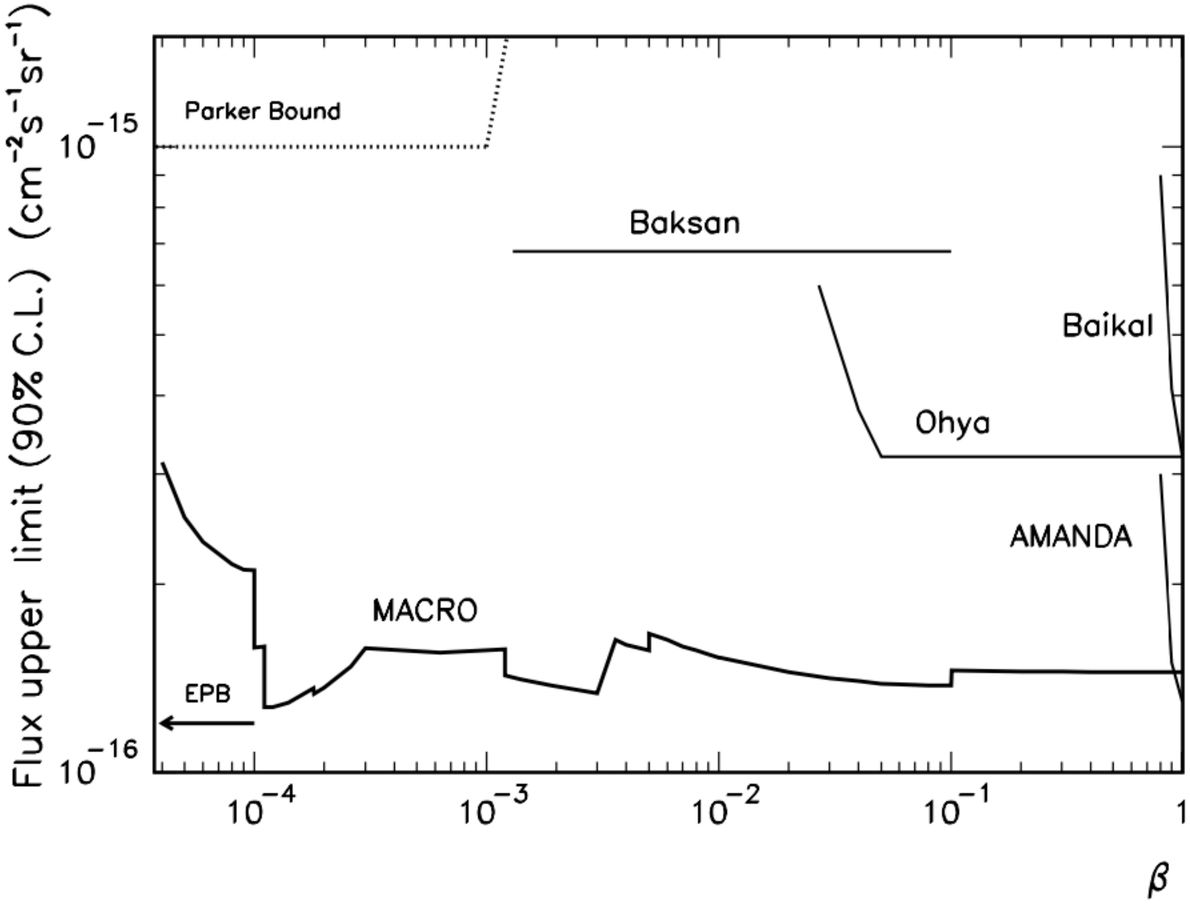


Fig. 9. The global MACRO limit for an isotropic flux of bare magnetic monopoles, with $m \geq 10^{17}$ GeV/c^2, $g = g_D$ and $\sigma_{cat} <$ few mb. For comparison, we present also the flux limits from other experiments [31]