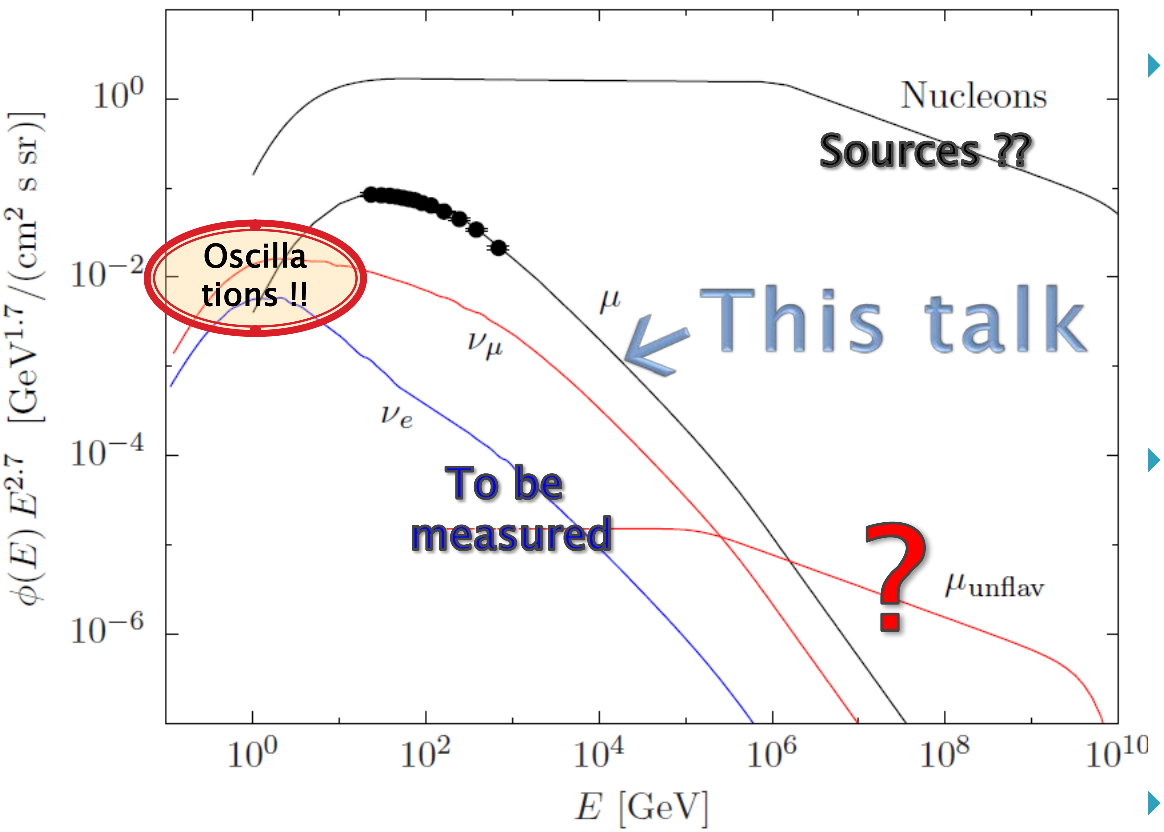
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

INFN
Istituto Nazionale di Fisica Nucleare

Atmospheric muons: experimental aspects

Maurizio Spurio
Department of Physics
University of Bologna and INFN

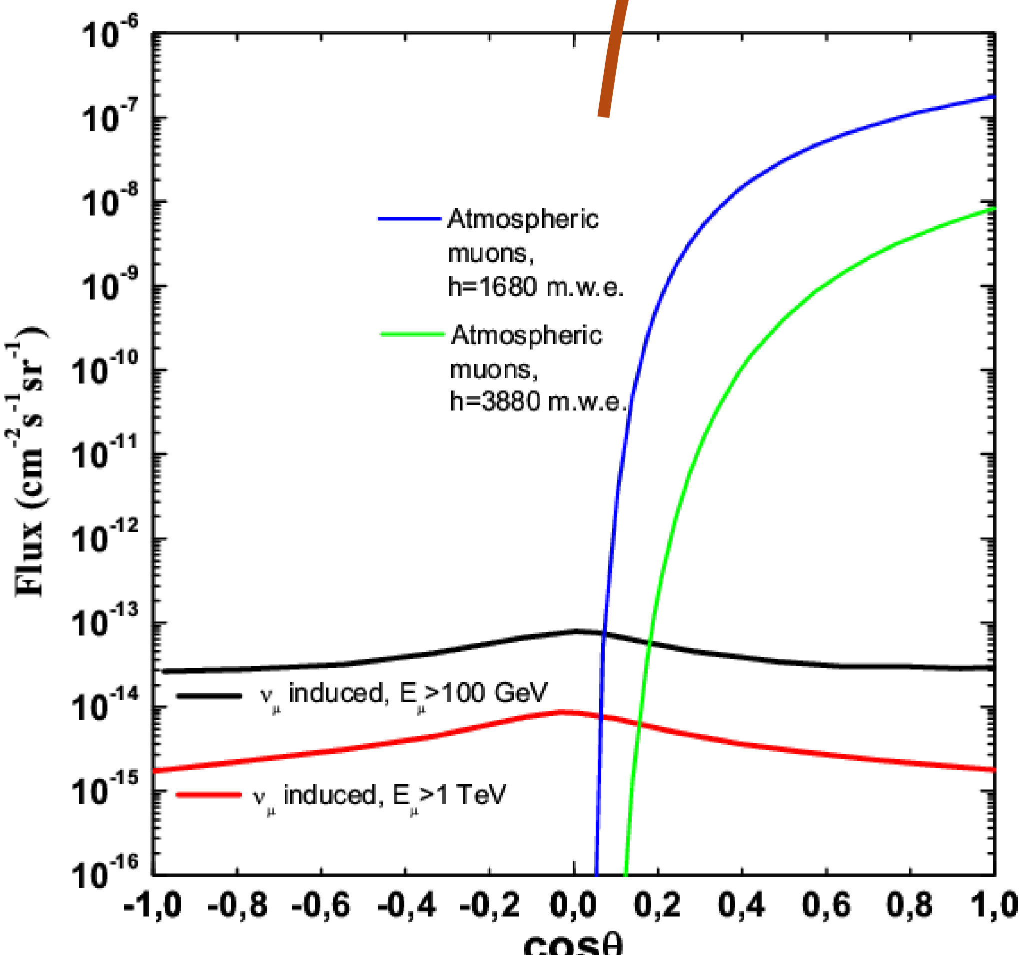
Origin and spectrum of atmospheric muons and neutrinos



J.I. Illana, arXiv:1010.5084v1

- Muons and neutrinos are both produced by the decay of charged mesons produced by CR interactions with atmospheric nuclei
- The meson production spectrum has the same power law of the primary CRs; $$\frac{dN_P}{dE_P} \propto E_P^{-\gamma}$$
- Competition for π,K between **decay** and **interaction**

Atmospheric muons and muons induced by neutrinos



- Different strategy to detect muons and ν_μ–induced μ
- The muon flux through a horizontal area amounts to ~ one particle/(cm^2 minute):

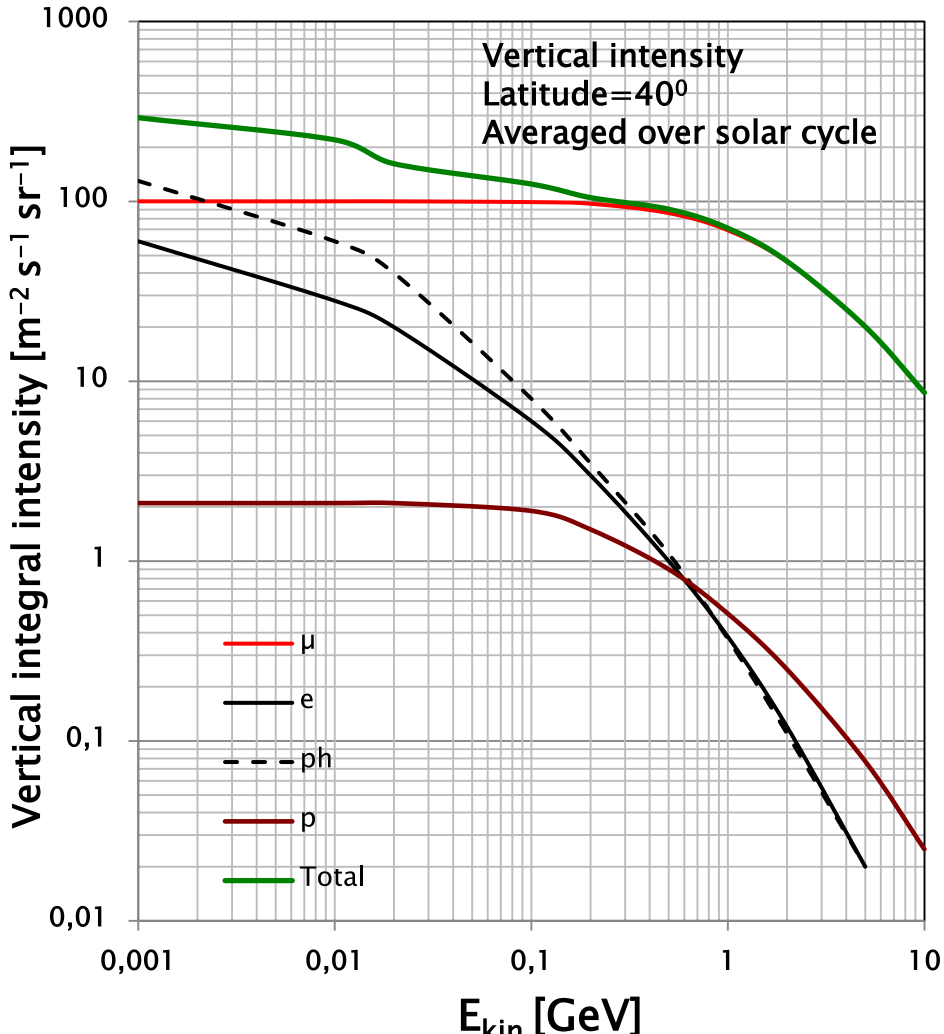
$$I_v(E_\mu > 1\,\mathrm{GeV}) \approx 70\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

- Huge detectors for neutrinos

Measuring muons

During the last 30 years the CR muon flux and energy spectrum has been studied in many experiments using different methods.

- Three techniques:
  1. direct measurements using magnetic spectrometers;
  2. measurements of muon cascades at shallow depth;
  3. measurement of the depth-intensity curve deep underground (water, ice)
- **Relevant quantities** that can be directly measured are:
  - The absolute muon intensity;
  - The muon momentum spectrum;
  - The charge ratio.

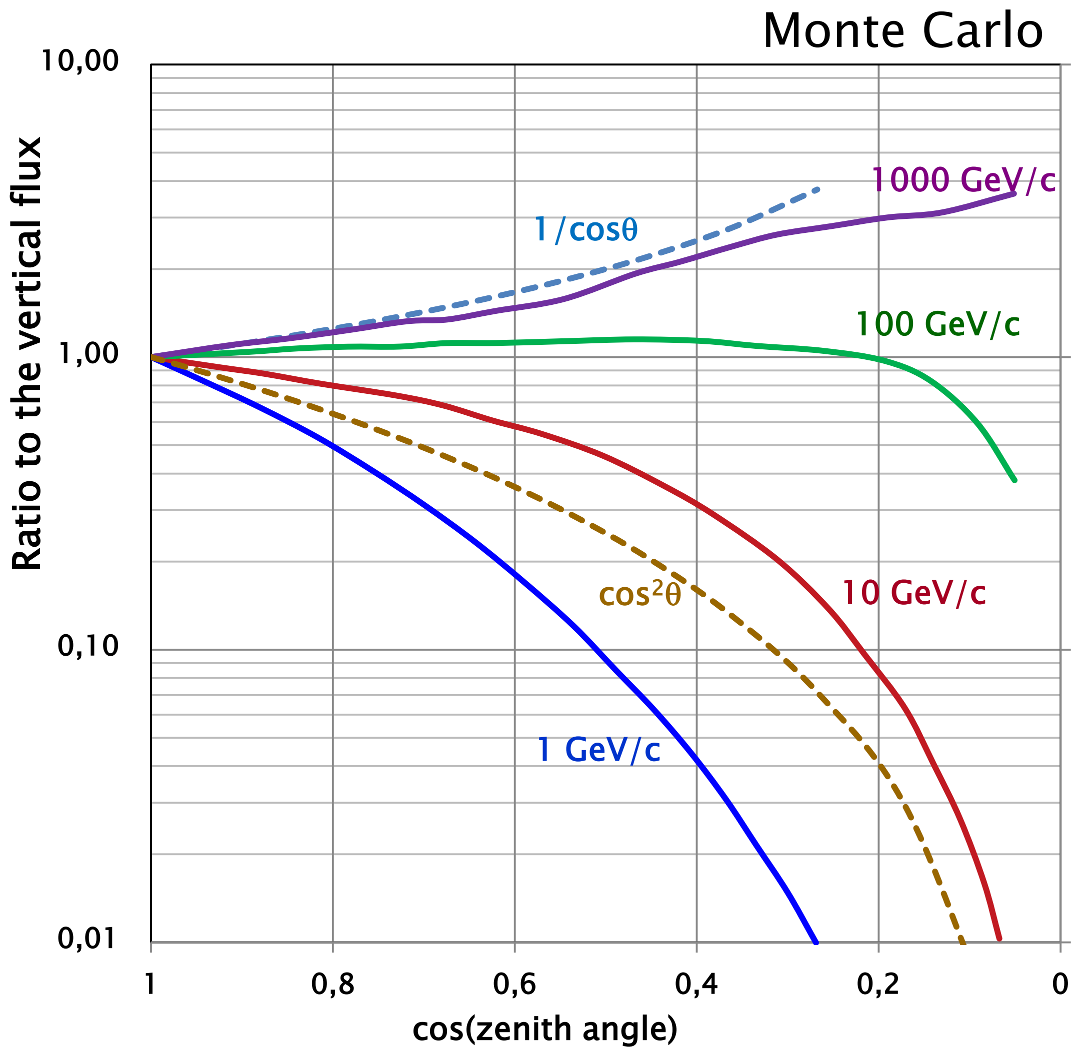


Relevant quantities

- **Critical energy** ε: the energy above which the interaction probability of secondary mesons is larger than that of decay;
- $\varepsilon_\pi = 115$ GeV , $\varepsilon_K = 850$ GeV from the vertical direction
- $\mathbf{E_\mu < \varepsilon_\mu = 1}$ **GeV**. μ decay and energy losses effects important
- $\boldsymbol{\varepsilon_\mu < E_\mu < \varepsilon_\pi, \varepsilon_K}$. Almost all mesons decay. The muon flux has the same power law of the parent mesons, and of the primary CRs.
- $\boldsymbol{E_\mu \gg \varepsilon_\pi, \varepsilon_K}$.HE region.
- The muon intensity varies (in different way as a function of $\mathbf{E_\mu}$) with:
  - **Altitude**: $\Phi(h) \sim exp(h/h_0)$ h_0 is a characteristic length
  - **Geomagnetic latitude**; effects are important for μ up to ~5 GeV
  - **Solar activity**. The 11 y cycle modulates CRs up to ~20 GeV
  - **Zenith, azimuth angles**
  - **Atmospheric conditions** (Pressure, Temperature)

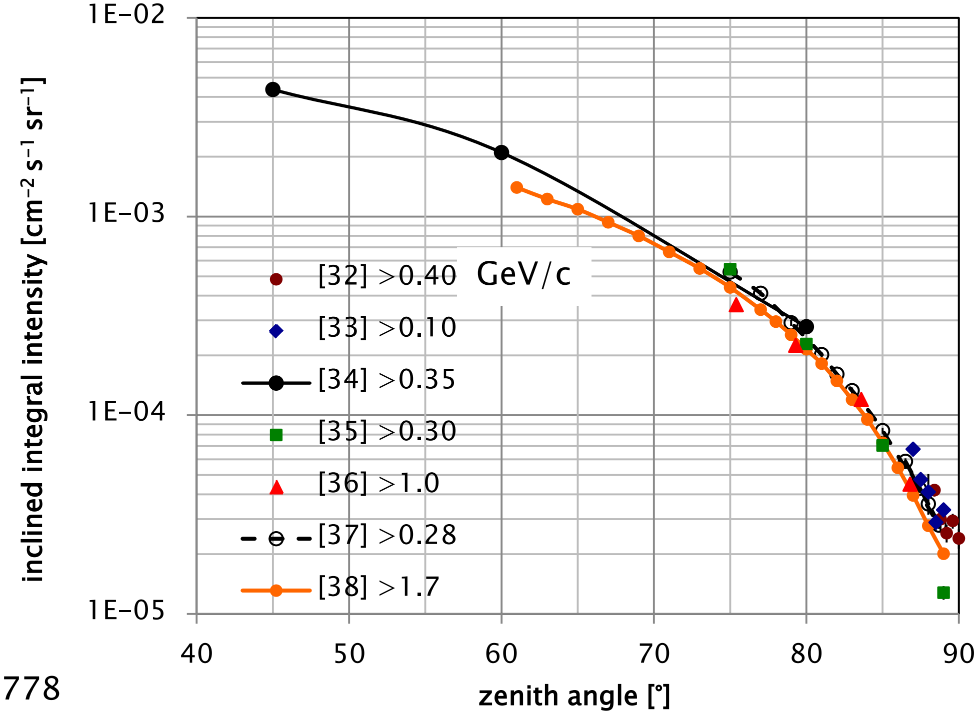
Zenith angle dependence

- **Low energy**: at 1 GeV, $d_\mu = \gamma \tau_\mu c = 6$ km; the muon flux at large zenith angles is suppressed due to the thicker atmosphere $\Phi \propto \cos^n\theta$, $n \sim 2 \div 3$
- The overall angular distribution of muons at the ground is $\sim\cos^2\theta$, which is characteristic of muons with $E \sim 3$ GeV
- **Intermediate energy**: the muon flux is almost independent on θ up to $\cos\theta \sim 0.2$;
- **High energy ($E_\mu \gg \varepsilon_K$)**: flux dependence $\sim 1/\cos\theta$



Zenith angle dependence

- Experimental data: muon intensity at sea level as a function of θ for p_μ>0.35 GeV/c at zenith> 45º at several geomagnetic latitude.



[32] Wada T. et al. Nucl. Phys. B 151(2006)465
[33] Wibberenz G., Z. Phys. 167 (1962) 284
[34] Barker P.R., Phys. Rev. 100 (1955) 860
[35] Carmichek H., Phys. Rev. 107 (1957) 1401
[36] Pugacheva G: et al., Geom. Y Aeron. 13(1973) 778
[37] Golden L.R. et al., J. Geophys. Res. 100(1995) 23515
[38] Beuermann K.P. et al.,Can. J. Phys. 46 (1968) 1034

High energy

- $E_\mu \gg \varepsilon_\pi, \varepsilon_K$. The rate of mesons decay steepen one power of E_μ since the pion and kaon decay probability is suppressed.
- The thickness of the atmosphere is not large enough for pions to decay. Mesons decay more easily in non-vertical directions.
- Muons at large angles have a flatter energy spectrum. The energy dependence is then $dN_\mu/dE_\mu = E_\mu^{-(\gamma+1)}$ and the zenith dependence is $dN_\mu/d\cos\theta \propto (\cos\theta)^{-1}$.

$$\frac{dN_\mu}{dE_\mu}(E_\mu, \vartheta) \cong AE_\mu^{-\gamma}\left[\frac{A_{\pi\mu}}{1+\dfrac{B_{\pi\mu}E_\mu\cos\vartheta^*}{\varepsilon_\pi}} + \frac{A_{K\mu}}{1+\dfrac{B_{K\mu}E_\mu\cos\vartheta^*}{\varepsilon_K}}\right]$$

A, γ = (adjustable) parameters

$\varepsilon_\pi, \varepsilon_K$ = characteristic critical energies

$A_{\pi(K)\mu}, B_{\pi(K)\mu}$ =(constant/fit)

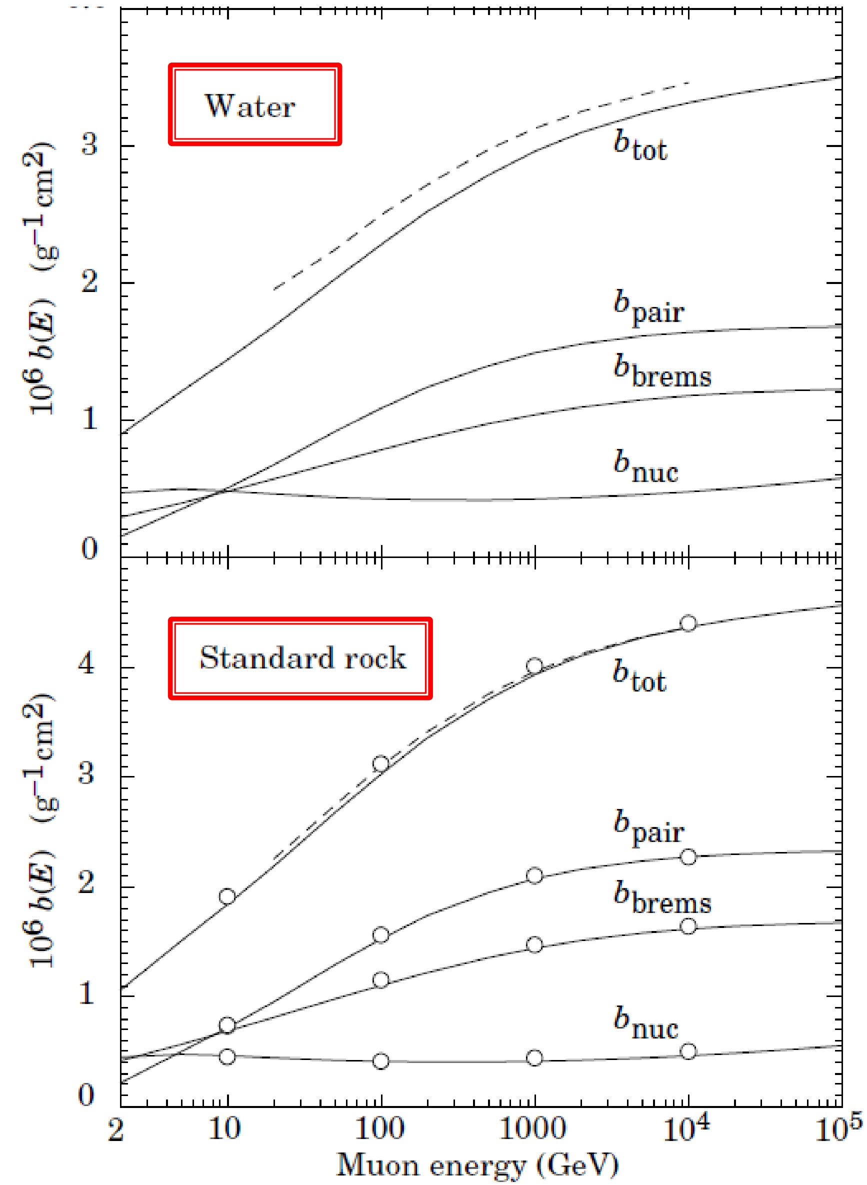
Muon energy losses

- Two terms: continuum and stochastic processes

$$\frac{dE}{dh} = a(E) + b(E)E\ ,\ \ \mathrm{MeV\ g^{-1}cm^{2}}$$

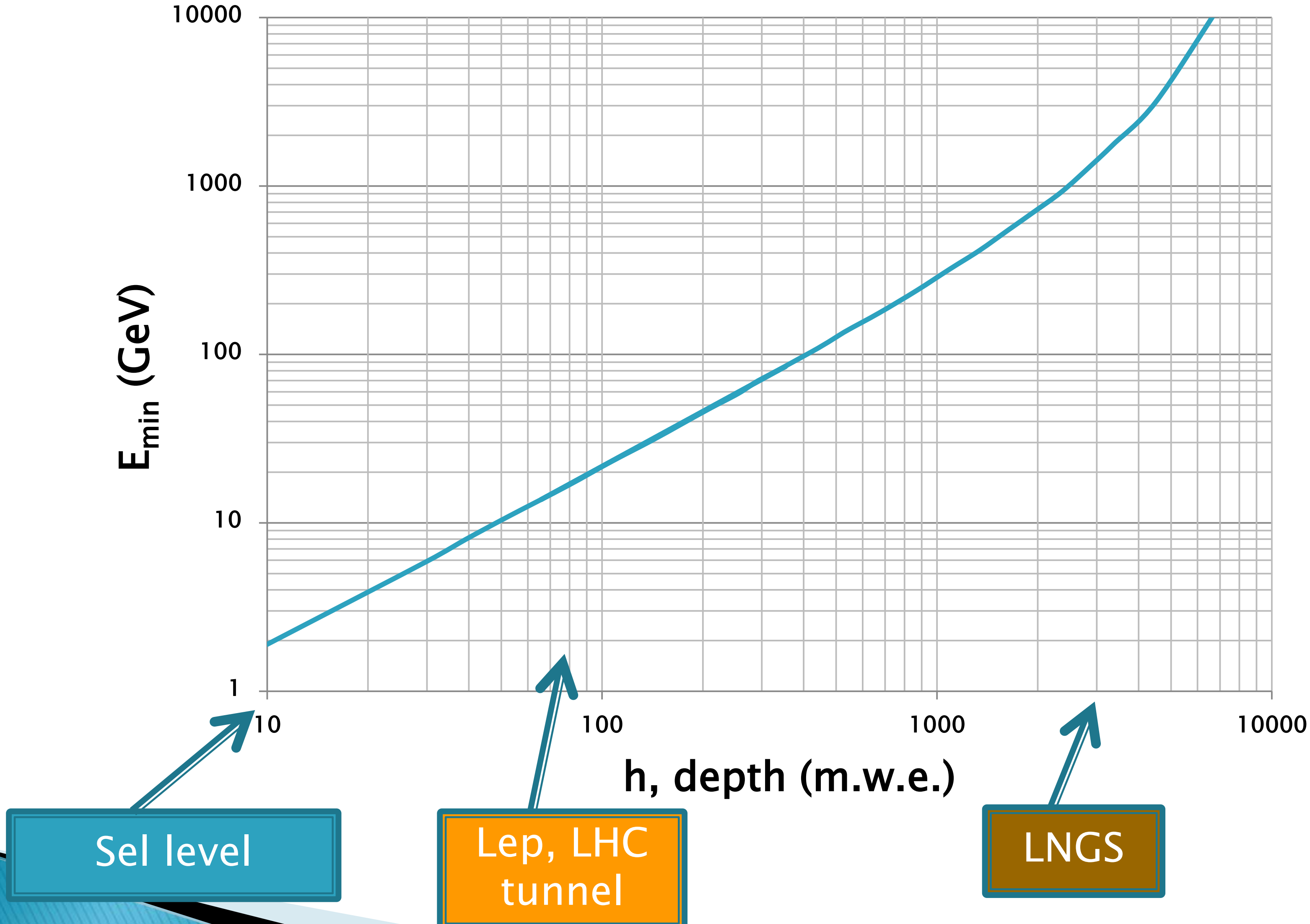
- $a(E)$~2 MeV g^{-1} cm^{2}
- In rough approximation:

$$\boxed{E_{\mu,\min} = \left(E_{\mu,res} + \frac{a}{b}\right)e^{bh} - \frac{a}{b}}$$



D. E. Groom, et al. Atomic and Nuc. Data tables, 76(2001)

Depth– μ energy relation



Measurements at sea level

- The muon intensity at sea level is measured through muon telescopes (limited solid angle, fixed E_μ^{thr}) or hodoscopes.
- To compare different muon observations at low energies (< 20 GeV/c) it is very important to know the year and location where the measurements were made
- Usually, the flux from the vertical direction is reported (units: $m^{-2}\ s^{-1}\ sr^{-1}$)

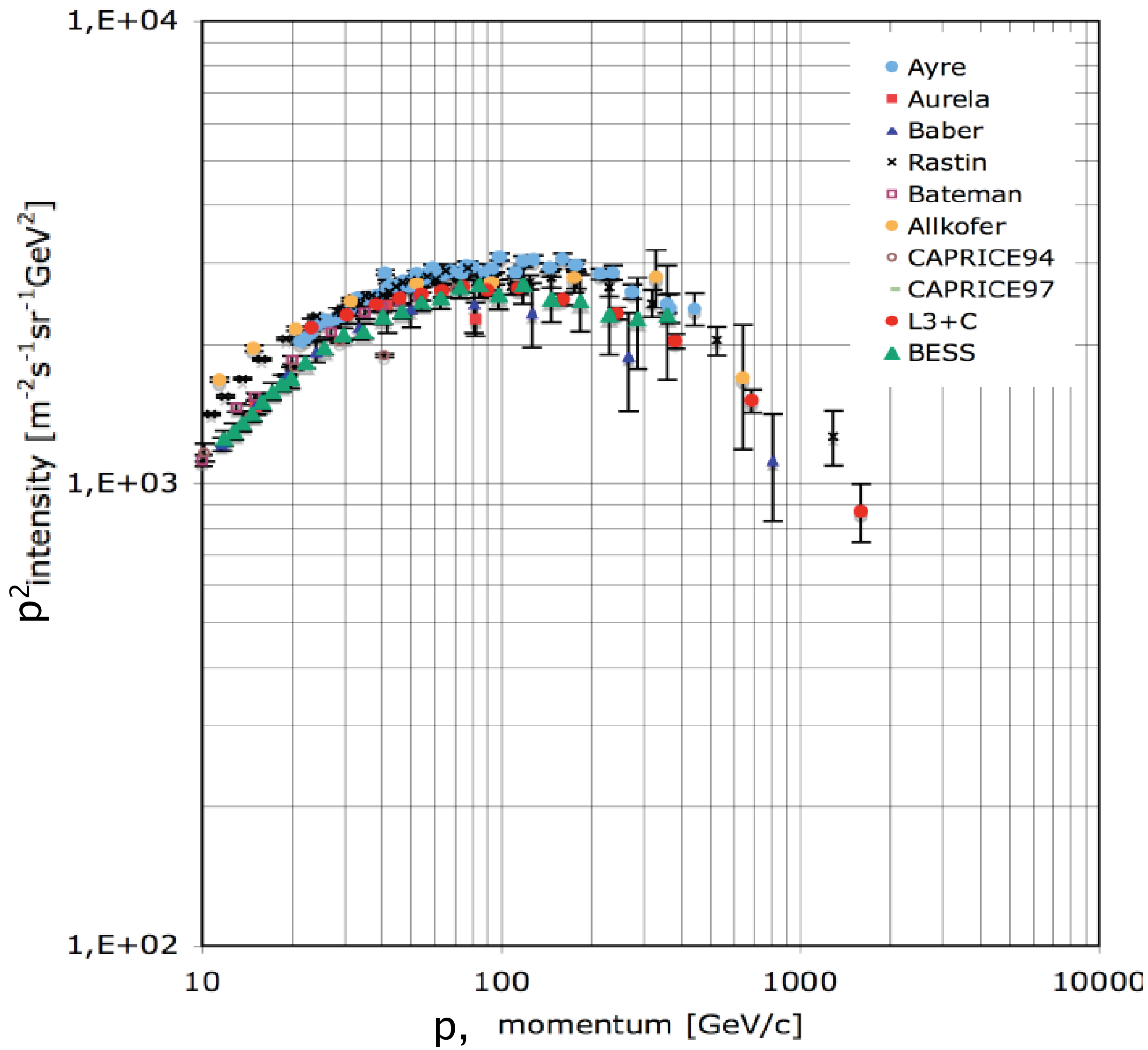
SEA LEVEL- Vertical intensity

Direct measurements			Momentum range [GeV/c]	"Bugaev" [1]	H & T	PDR [8]
1	Aurela et al, Proc. Phys. Soc. London 81 (1963) 593		15.1 – 82.1	X	X	
2	Ayre et al, J. Phys. G: Nucl. Phys. 5 (1975) 584		20 – 500	X		X
3	Baber et al, Nucl. Phys. B4 (1968) 539		11 – 810	X	X	
4	Rastin et al, J. Phys. G: Nucl. Phys. 10 (1984) 1609		3 – 3000	X	X	X
5	Bateman et al, Phys. Lett B36 (1971) 144		10 – 150	X	X	
6	Allkofer et al, Phys. Lett B36 (1971) 425		20 – 1000	X	X	X
7	De Pascale te al, J. Geophys. Res. 98 (1993) 3501		0.25 – 100	X	X	X
8	Kremer et al, Phys. Rev. Lett. 83 (1999) 4241	Caprice	0.2 – 120		X	X
9	Achard et al, Phys Lett B598 (2004) 15	L3+C	20 – 3000			
10	Haino et al, astro-ph/0403704	Bess-TeV	0.6 - 400			

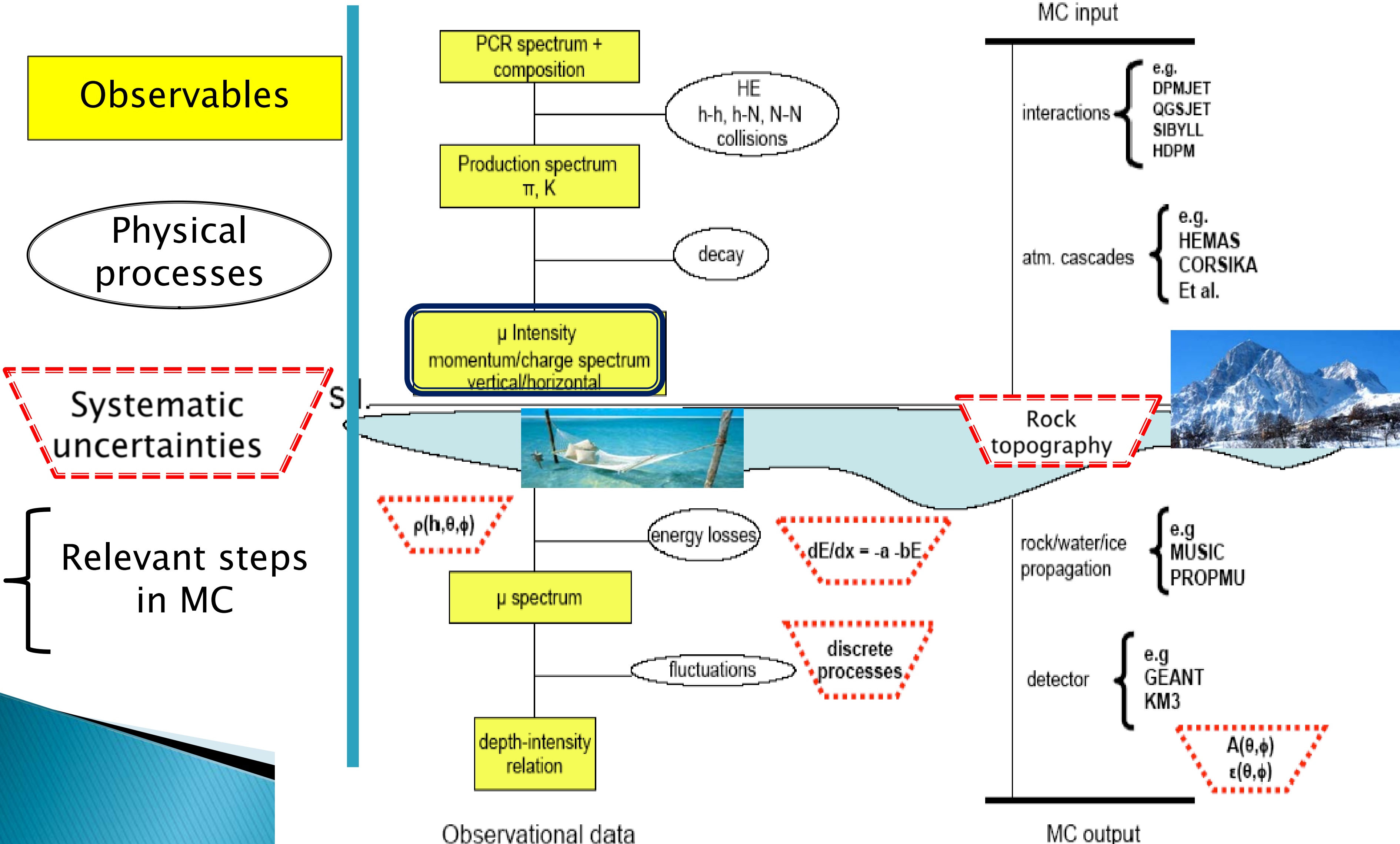
[1] Bugaev E.V. et al., astro-ph/9803488v3, Phys.Rev.D58(1998)05401
[7] H&T=Hebbeker T.,Timmermans C., Astropart. Phys., 18 (2002) 102
[8] PRD= Review of Particle Physics

Measurements at sea level: Data

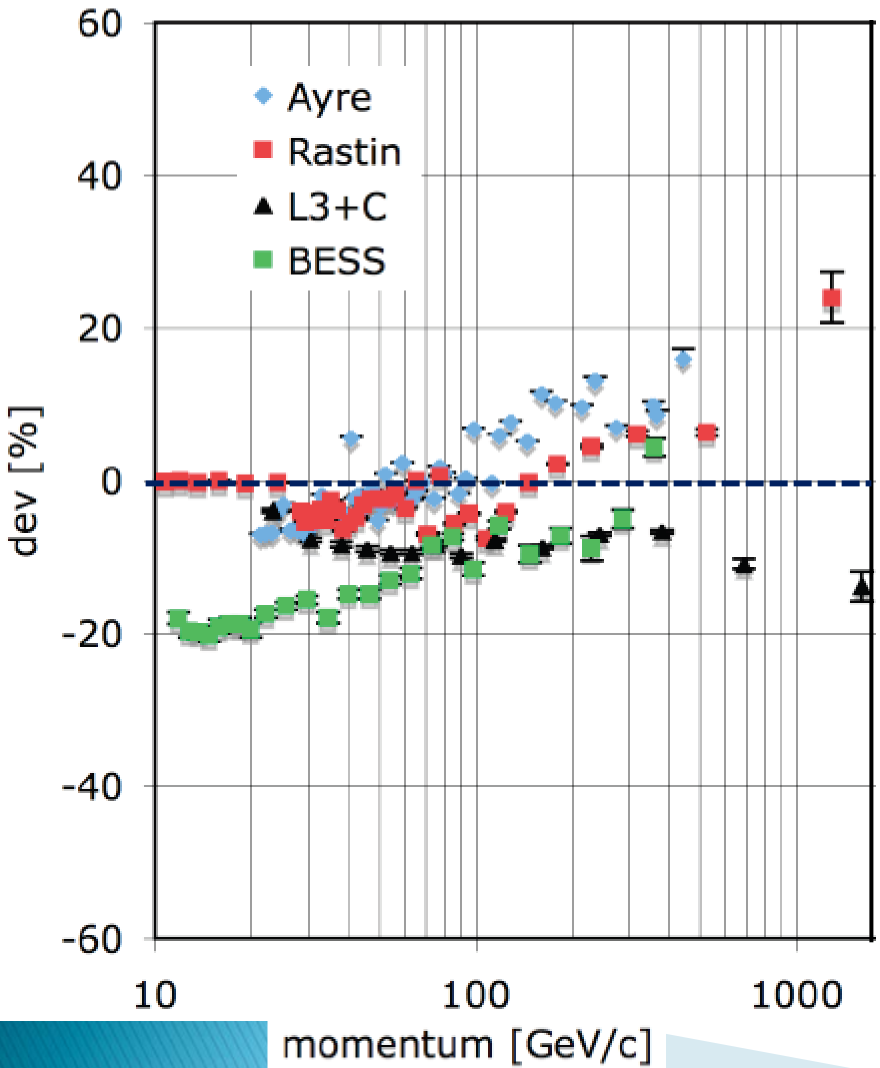
- ➢ Example of large magnetic spectrometers
- ➢In most cases, the flux of *single* muons is measured;
- ➢ Results of L3+C for the vertical direction
- ➢As a function of zenith



Measurements and simulation under-ground/ice/water



Modeling the differential muon flux



Two approaches:

- full Monte Carlo simulations (CORSIKA, FLUKA,…)
- Best-fit shape of particular parametric formula to muon flux data at sea level

Here, the deviations w.r.t. the Bugaev parameterization. -------- [astro-ph/9803488v3]

- Differences ±15-20% exist between data and parameterizations.
- Disagreements between different experiments as large as 30%

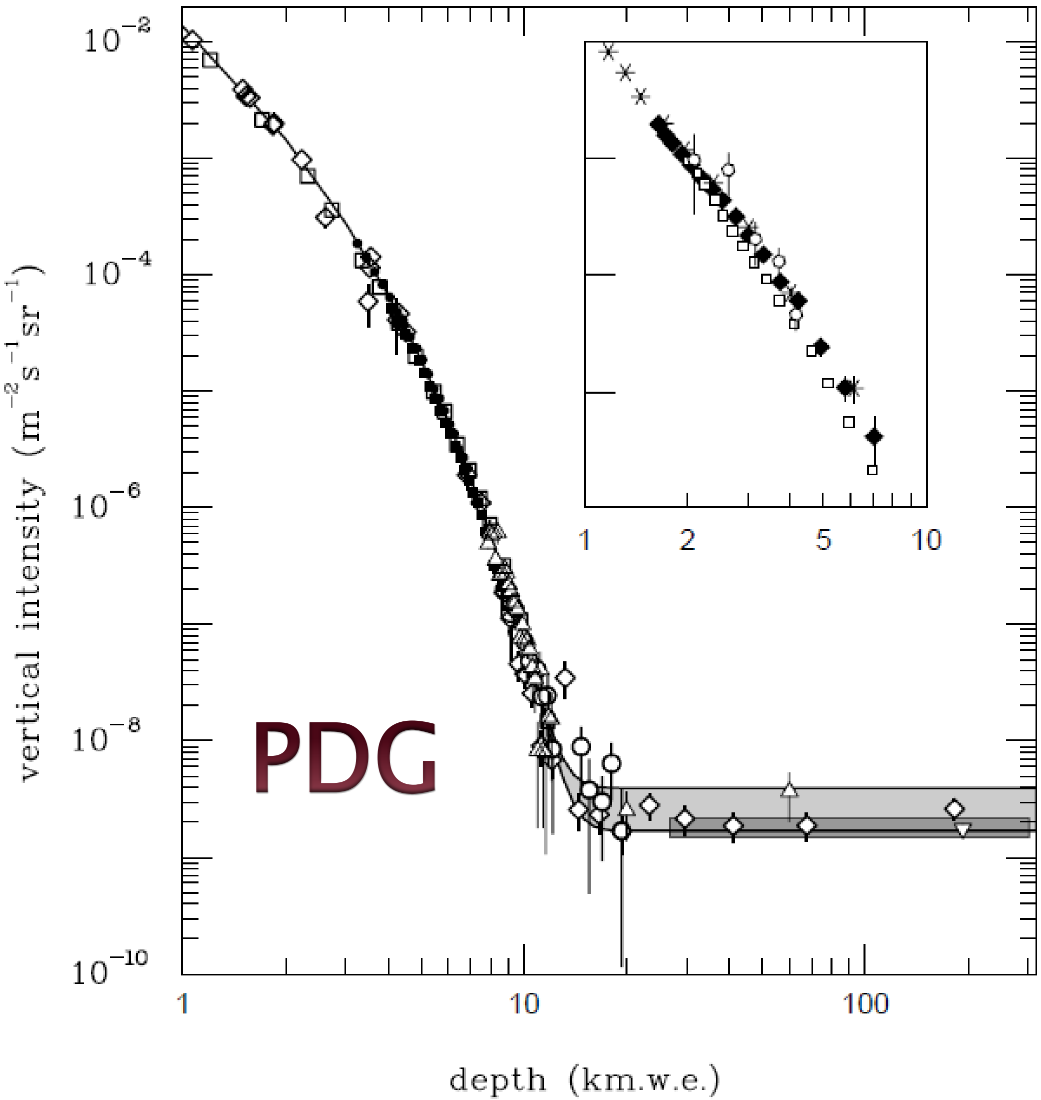
Toward higher energies

- "Ground" magnetic spectrometers fail to measure p_μ>1TeV/c
- Power low energy spectrum of HE muons;
- Underground detector ←→ selection of HE muons at surface.
- Muons at Gran Sasso (3000–12000 hg/cm^2) ←→ E_μ= 1.5–40 TeV at the sea level;
- The muon flux at large depth depends on the sea-level muon spectrum and on the ***P(E,h)*** = muon survival probability
- The "vertical" muon intensity, for a given direction θ and a corresponding rock slant depth *h* is expressed as:

$$I_\mu^V(h,\vartheta) = \left(\frac{1}{\Delta T}\right)\frac{\sum_i N_i m_i}{\sum_j \Delta\Omega_j A_j \epsilon_j / cos\theta_j}$$

- ΔT=livetime; N_i is the number of detected events with multiplicity m_i in the angular bin $\Delta\Omega_j$; A_j and ε_i the geometrical and intrinsic acceptance of the detector.
- Measured underground (Frejus, MACRO, LVD, SNO, Baksan)

The Depth–Intensity Relation

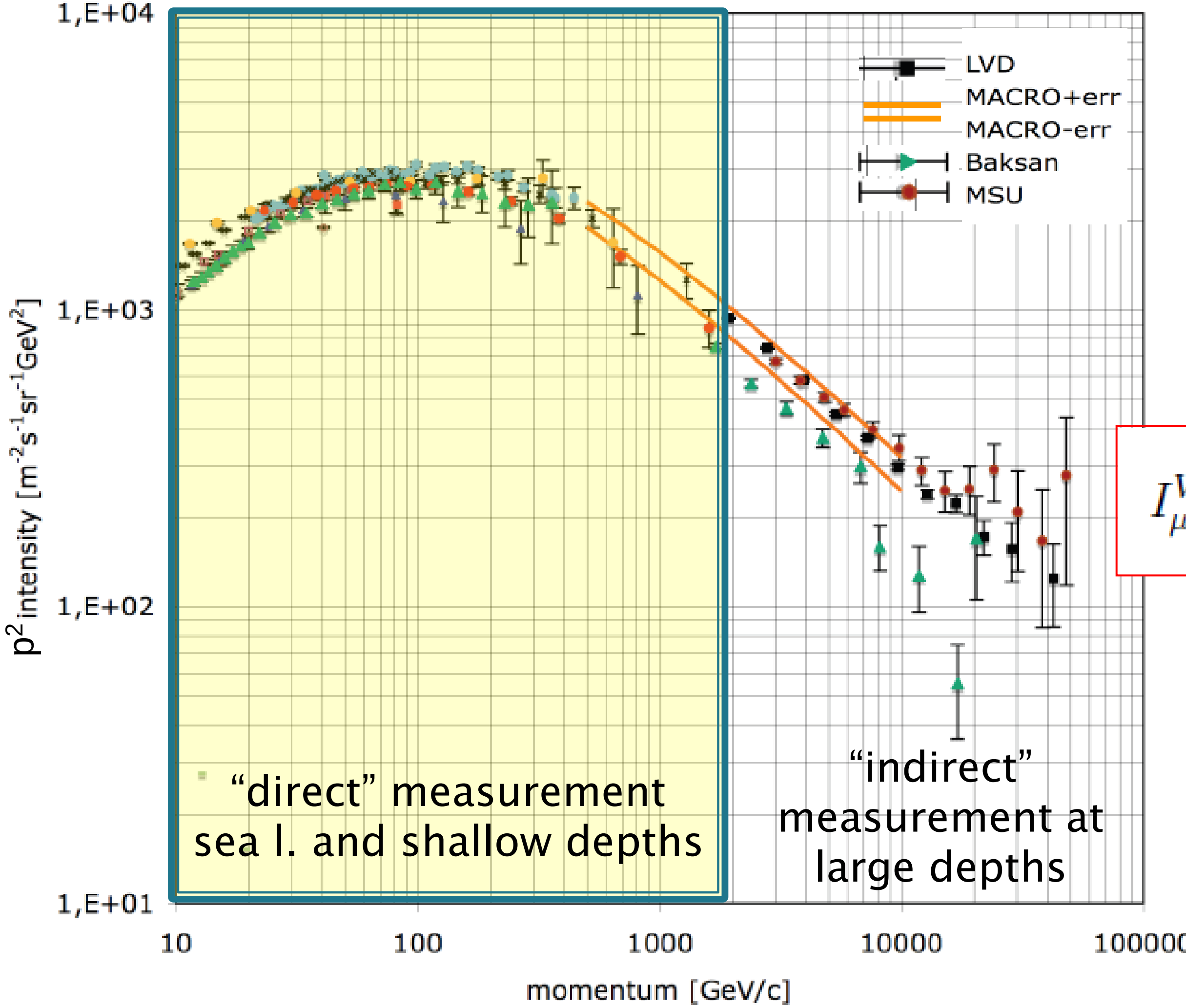


The experimental data are from: ◊: the compilations of Crouch [58], □: Baksan [63], ○: LVD [64], •: MACRO [65], ■: Frejus [66], and △: SNO [67].

- Muon intensity vs. standard rock thickness. The shaded area at large depths represents neutrino-induced muons of energy above 2 GeV.
- Inset: water/ice
- Different DIR functions. For instance:

$$I_\mu^V(h) \cong h^{-\alpha}\left(\frac{K}{h+H}\right)e^{-\beta h}$$

The sea-level spectrum from *I(h)*



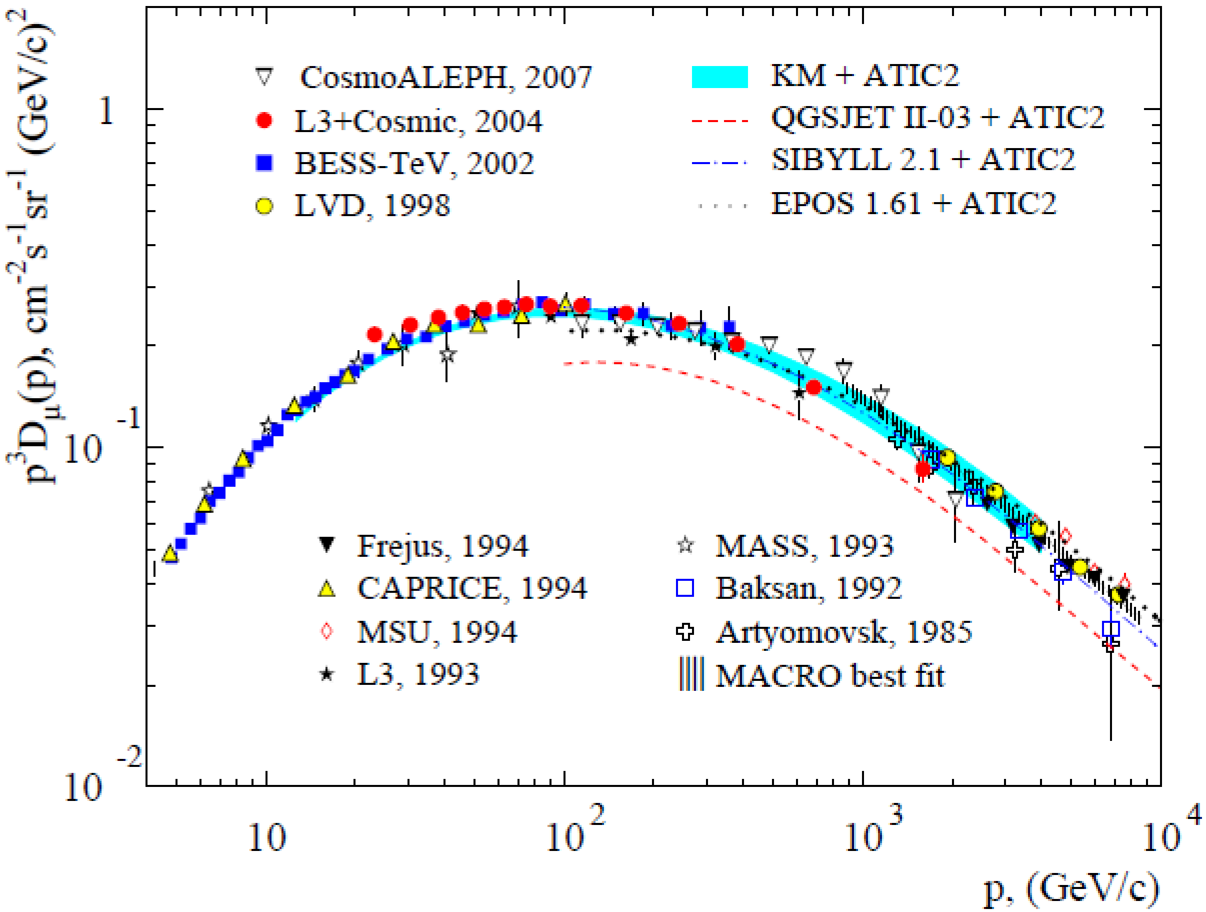
- The sea-level muon spectrum $\frac{dN_\mu}{dE_\mu}$ can be deconvoluted from $I^V_\mu(h)$:

$$I_\mu^V(h) = \int_0^\infty \frac{dN_\mu}{dE_\mu d\Omega} P(E_\mu, h) dE_\mu,$$

[Baksan] V.N. Bakatanov et al., Sov. J. Nucl. Phys. 55 (1992) 1169.
[MSU] G.T. Zatsepin et al., Izv. Ross. Akad. Nauk, Sez. Fiz. 58 (1994) 119.
[LVD] M. Aglietta et al., Phys.Rev. D58 (1998) 092005
[MACRO] M. Ambrosio et al., Phys. Rev D52 (1995) 3793.

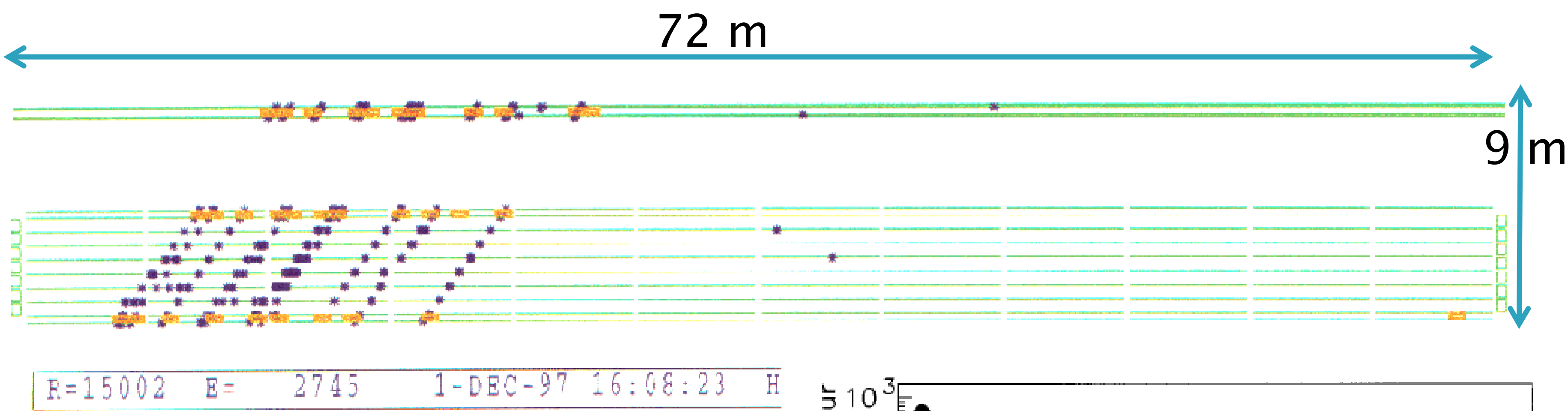
Comparisons with some models

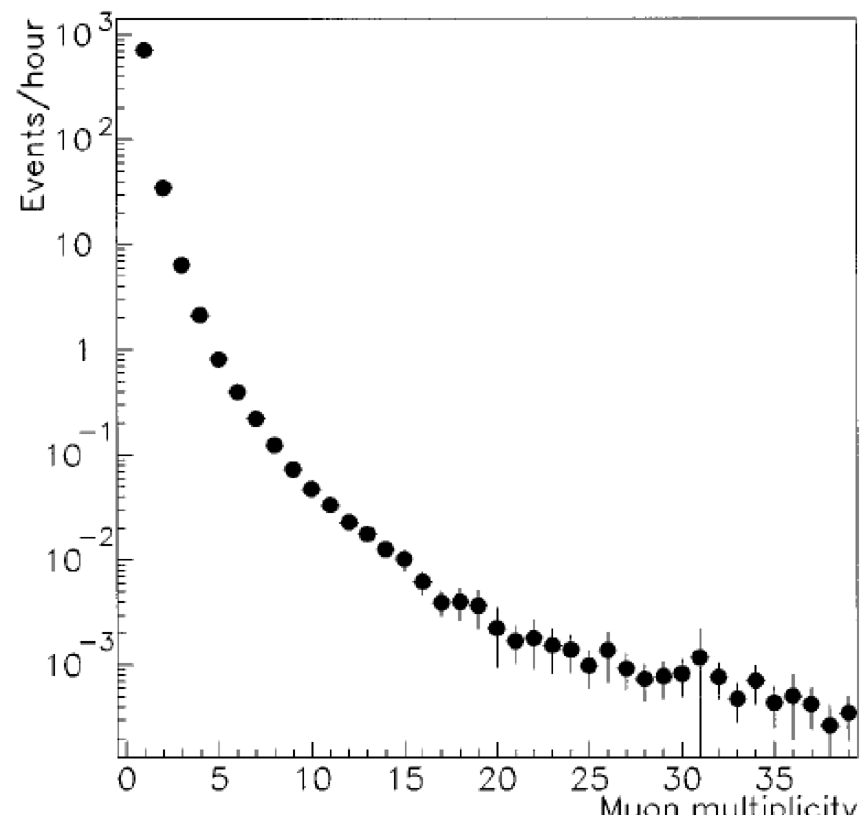
A. A. Kochanov et al., arXiv:0803.2943v2



- Energy spectrum of muons at ground level near the vertical.
- The curves are the calculations for the ATIC-2 primary CR spectrum and different hadronic models.

A muon shower under 3 km.w.e.

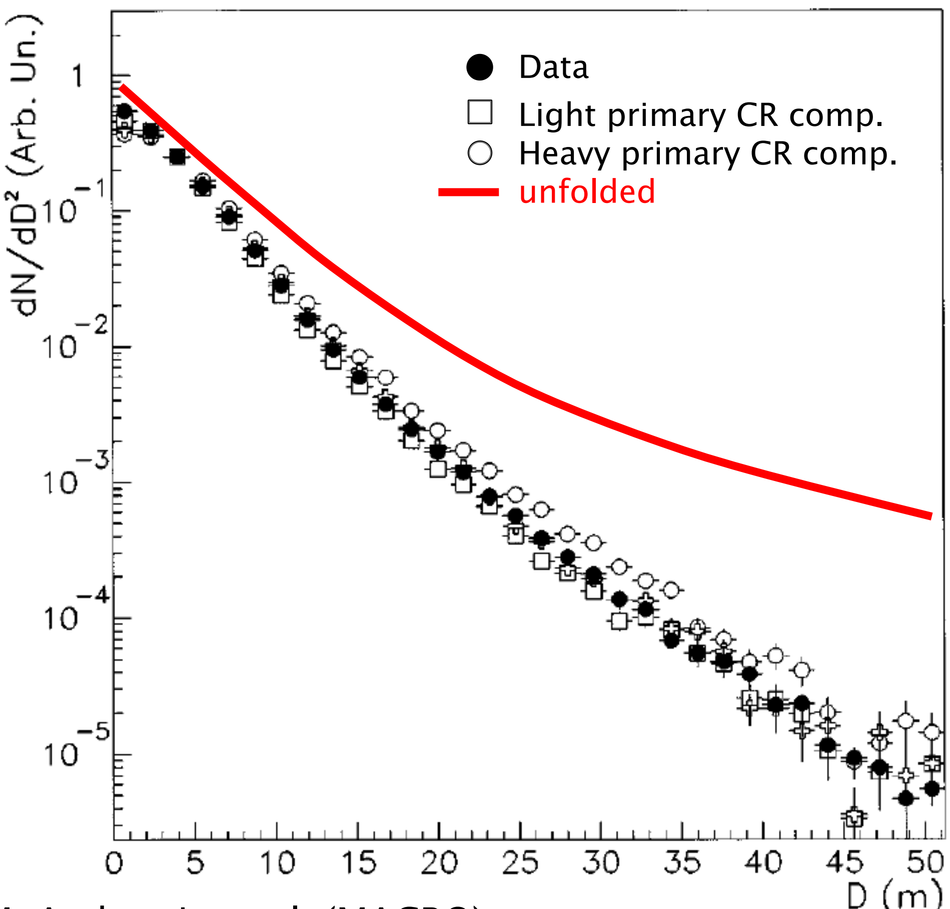




MACRO@Gran Sasso

Events underground = large fraction of multiple muon events

Testing the interaction models: distance between muon pairs



M. Ambrosio et al. (MACRO)
- Phys.Rev.D56:1407-1417 (1997);
- Phys.Rev.D56:1418-1436 (1997)
- Phys.Rev.D60:032001 (1999)

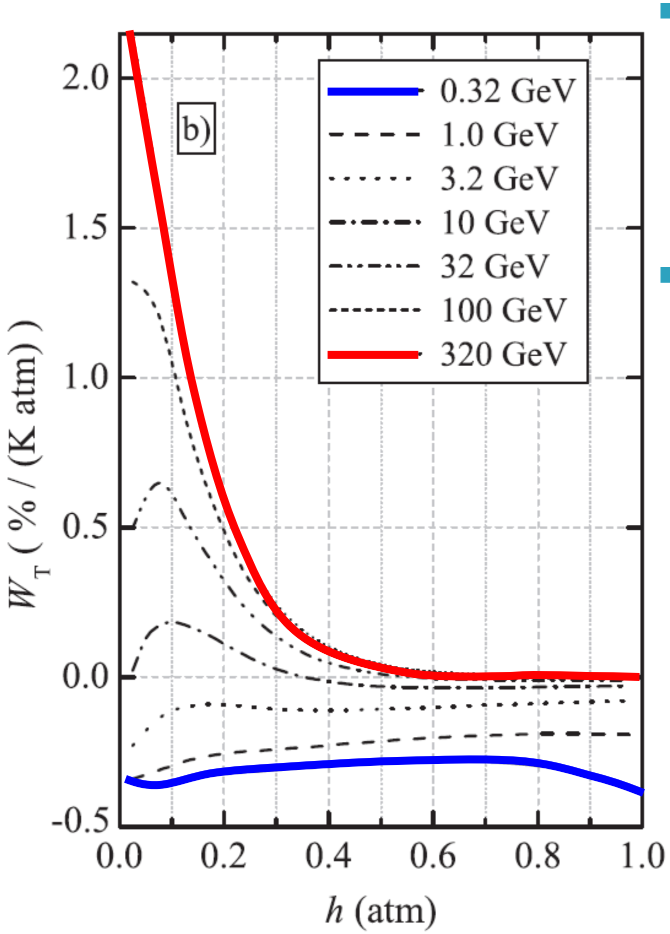
- Underground μ are originating mostly in kinematic regions (high rapidity and high $\sqrt{s}$) not completely covered by existing collider data;
- The lateral distribution is primarily sensitive to the interaction model rather than primary CRs energy/composition
- The separation D between muons is

$$\boxed{D \cong (P_\perp / E^{\pi,K}) H_{prod}}$$

- $P_\perp$ is the transverse momentum of π, K of energy $E^{\pi,K}$;
  H_{prod}= production height

Temperature effect – π,K and μ

- If atmospheric **temperature** at depth h is changed by $\Delta T(h)$, the muon flux $N(E_{min},X,h)$ at observation level X changes by $\Delta N(E_{min},X,h)$
- $\Delta N(E_{min},X,h)$ depends on T (at constant atm. P) and can be positive or negative depending on E_{min} due to two competition effects:



- **Mesons**: if T increases → atmosphere expands → air density decreases and the probability of the interaction of K and π becomes smaller
- **Muons**: if T increases → atmosphere expands → geometric path longer → higher number of muons decay

The differential temperature coefficient W_T

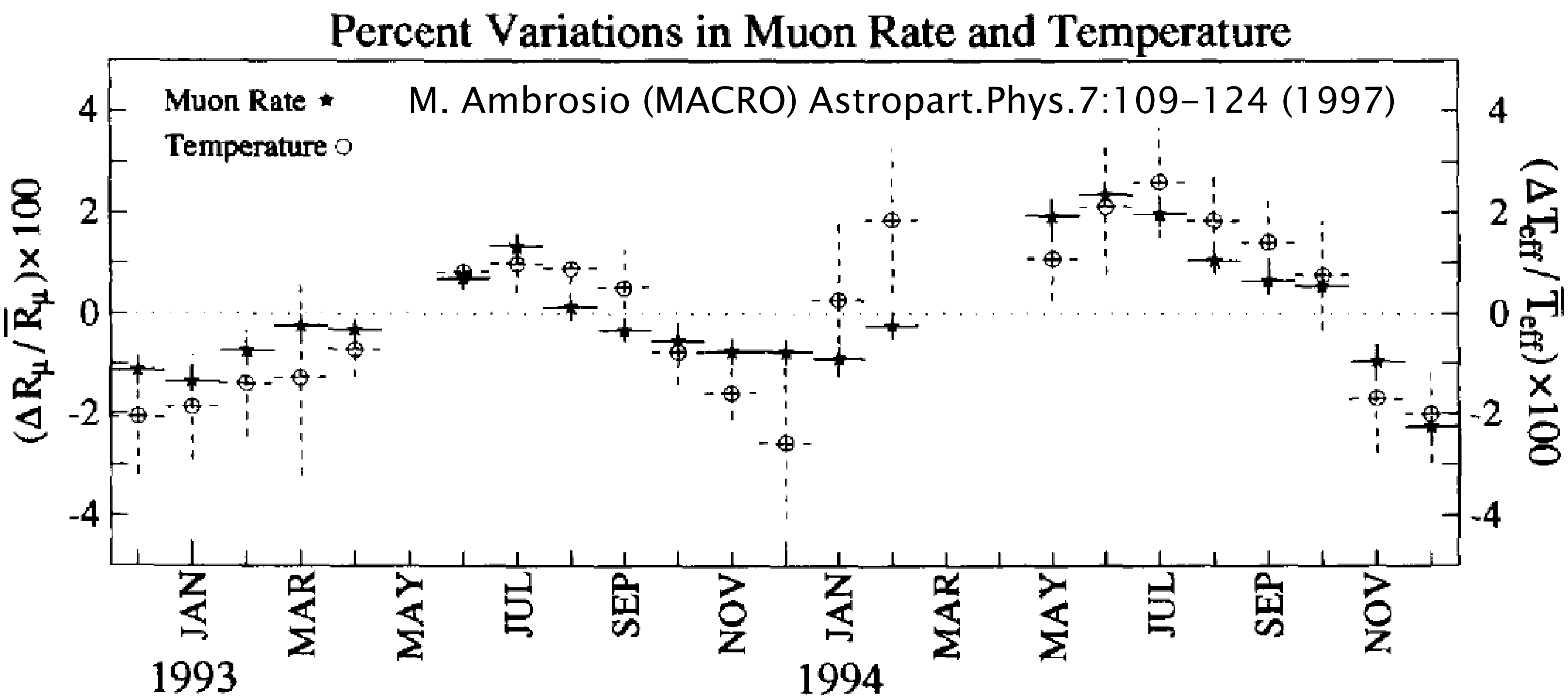
$$\Delta N(E_{min},X,h) \propto W_T \, \Delta T(h)$$

is negative for small E_{min} and positive for large E_{min}

A.N. Dmitrieva et al., Astroparticle Physics 34 (2011) 401

Temperature effect – underground μ

- The dependence of the critical energies $\varepsilon_{\pi,K}$ on temperature is the main source of the seasonal variation in HE muon rate
- Superposition of the monthly variation (%) in the muon rate and the mean monthly variation in the effective temperature measured from the MACRO experiment



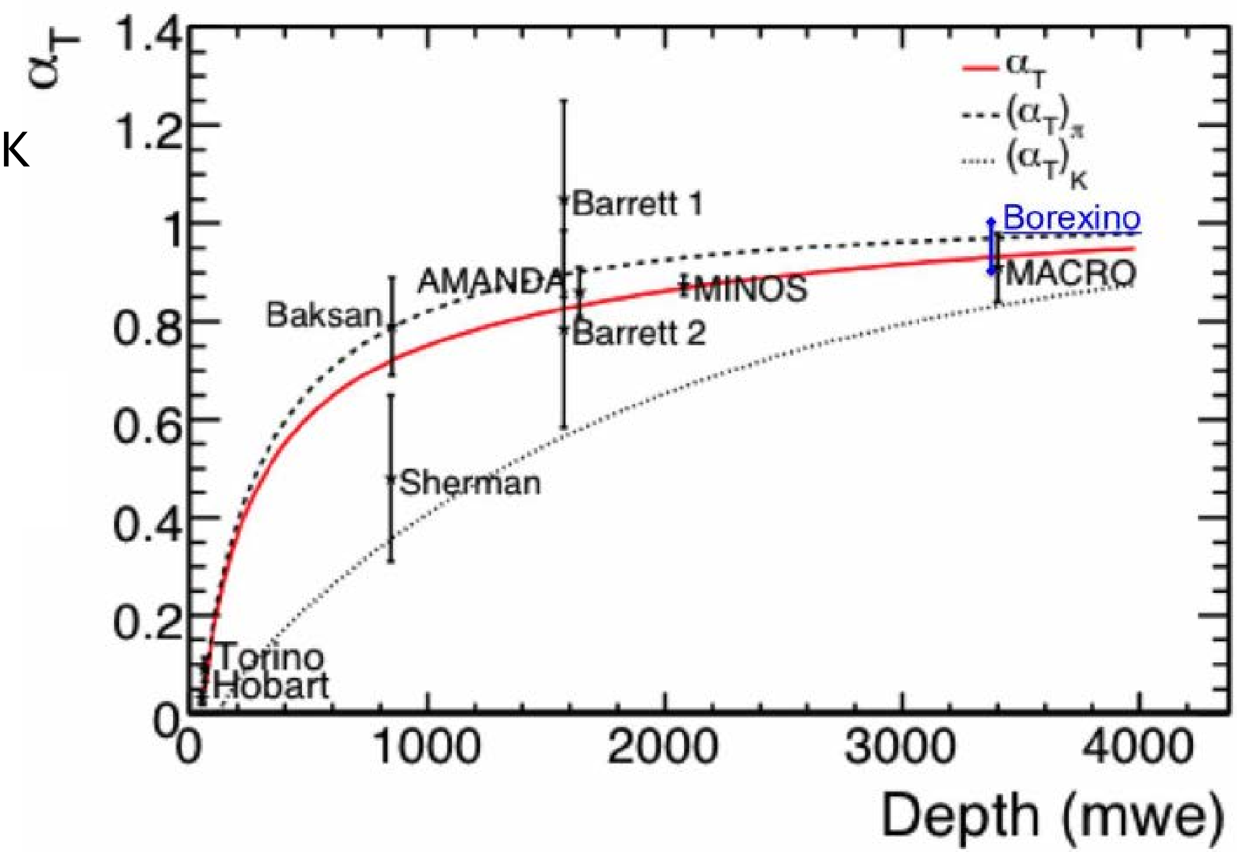
Temperature coefficient

- Experimental determination of the temperature coefficient α_T compared with that expected from $\pi \rightarrow \mu$ as a function of depth.

$$\frac{\Delta I_\mu}{I_\mu^0} = \int_0^\infty dX \alpha(X) \frac{\Delta T(X)}{T(X)} = \alpha_T \frac{\Delta T_{eff}}{T_{eff}} \approx \alpha_T (T_{eff} - \bar{T}_{eff})/\bar{T}_{eff},$$

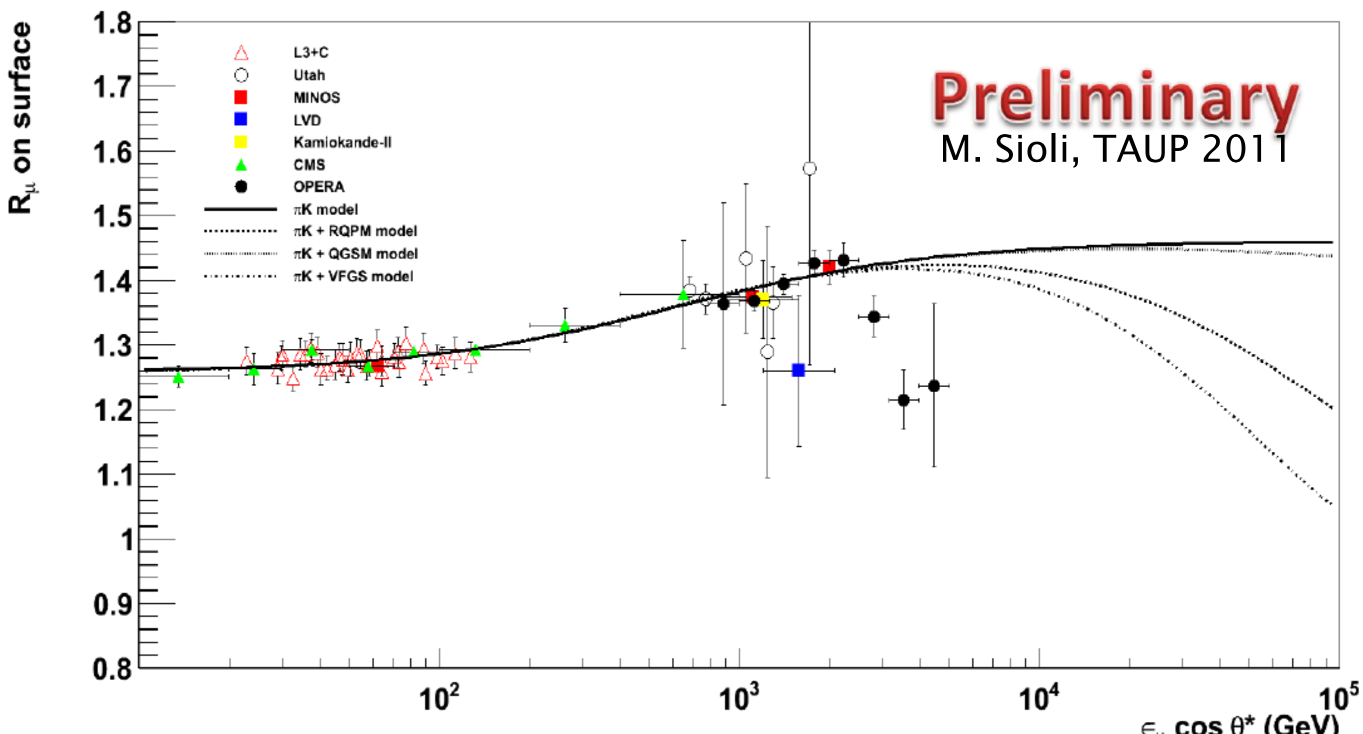
Used to estimate the π/K ratio in CR interactions

(MINOS) P. Adamson, *et al.*, *Phys.Rev., 2010, **D81,01200***
+ Borexino @ICRC 2011



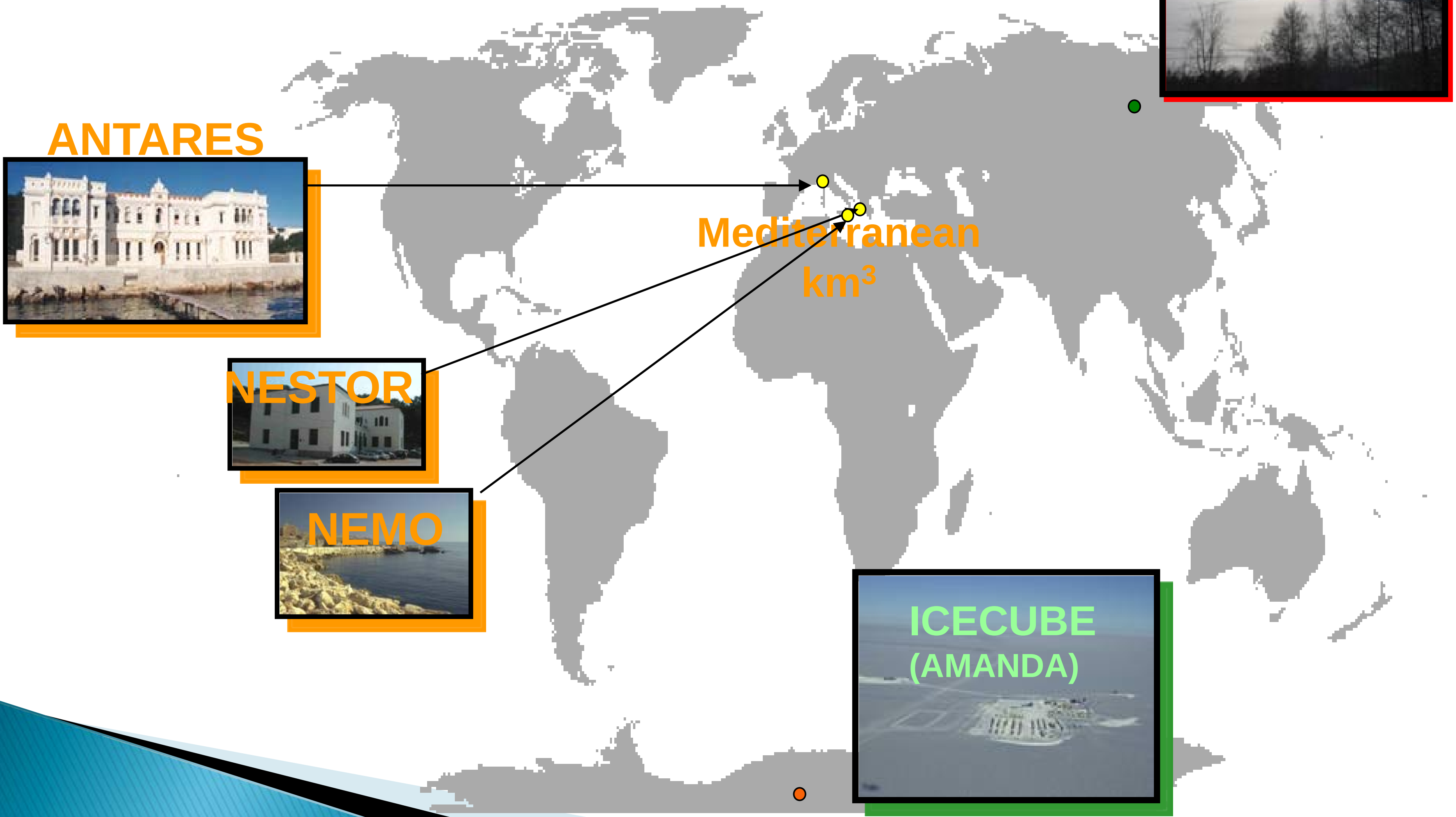
The muon charge ratio R_μ

- Since the cosmic ray primaries are positively charged, there are more π^+ than π^- and kaons in the hadronic showers.
- At high energies, several competing processes can affect R_μ .
- As energy increases, the fraction of muons coming from kaon decays also increases
- Strong interaction production channels lead to a K^+/K^- ratio higher than for π^+/π^- , R_μ is expected to rise with energy



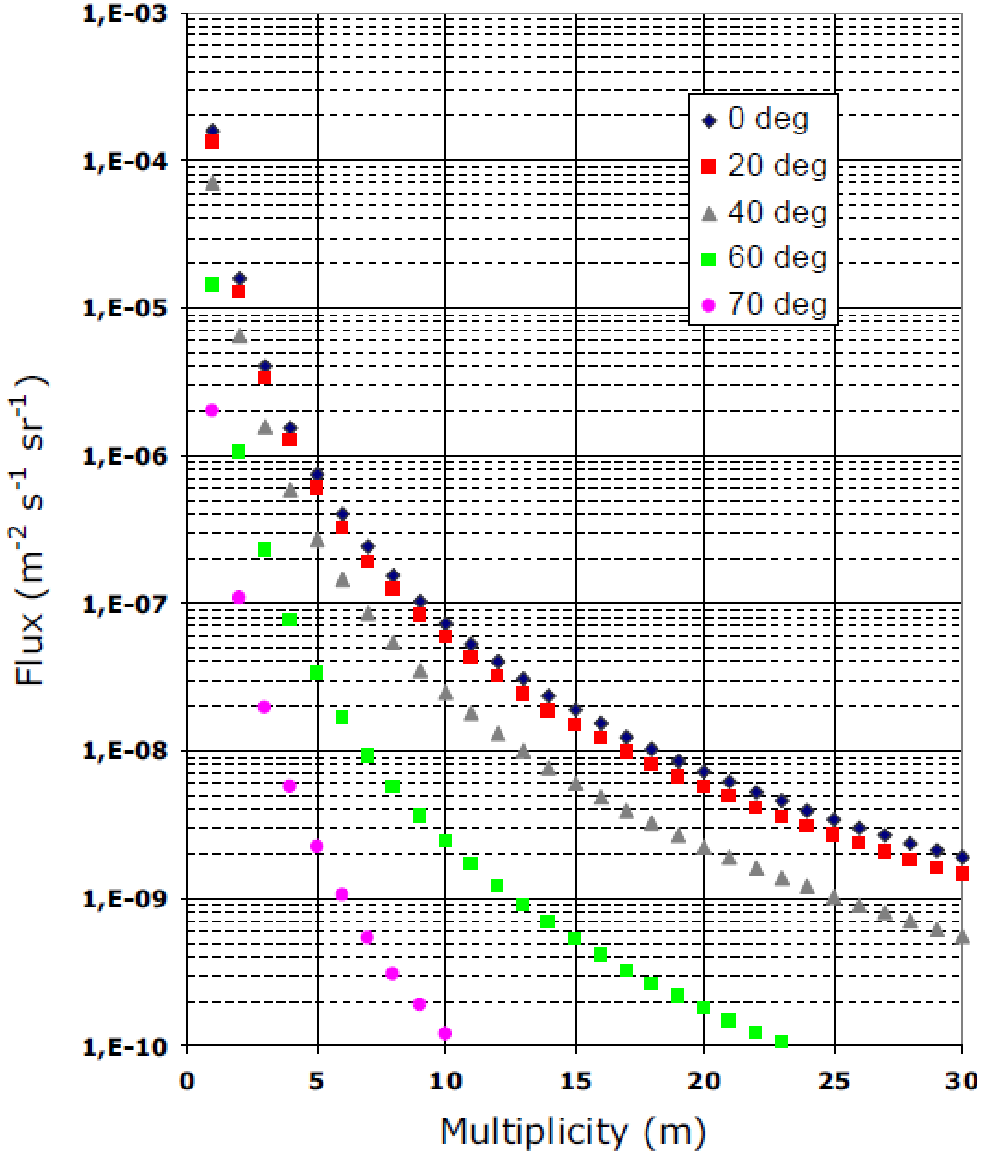
Muons in Neutrino Telescopes (NT)

- Neutrino telescopes: new research frontiers in HE physics and astrophysics



Muon bundles in NT

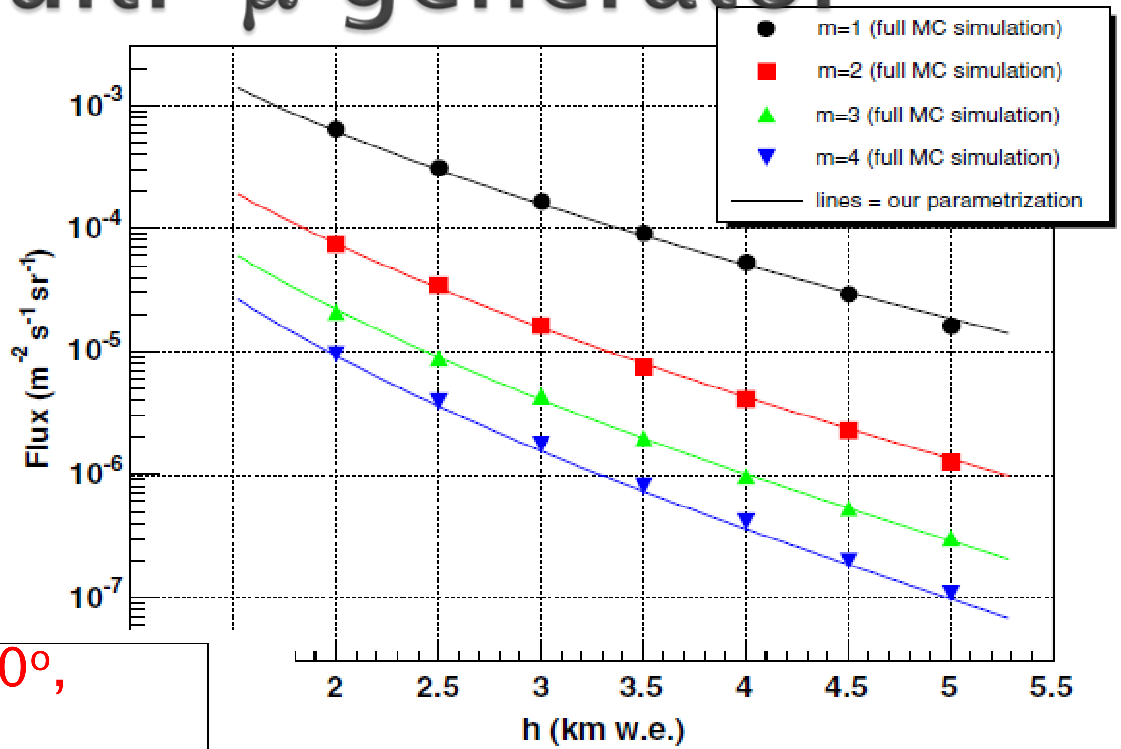
- Muons represent the major background and a tool to understand the NT systematics
- Due to the detector configuration, most triggered events are muons in bundle;
- Based on MACRO results, a parameterization of single and multi–μ in deep water was obtained –Y. Becherini et al., Astropart. Phys. 25 (2006) 1
- Differential energy spectrum vs. depth, zenith angle, multiplicity and distance between muons

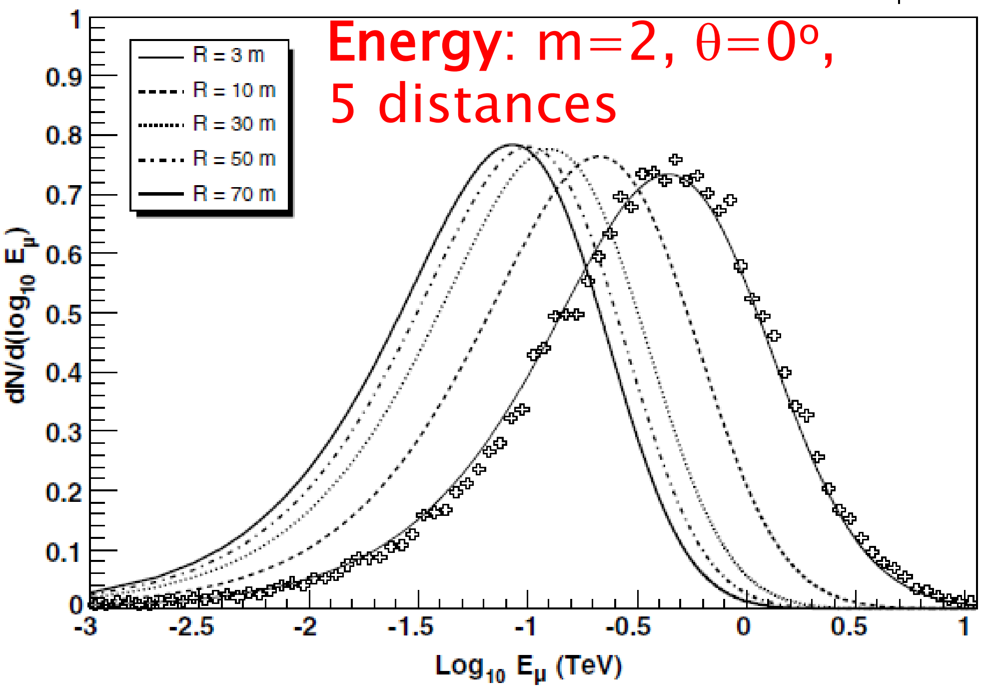


Expected multiplicity distribution of muons (E_μ> 1 GeV) in bundles for a detector at the vertical depth of 3 km.w.e. and for 5 different zenith angles

Single and Multi-μ generator

Y. Becherini et al.,
Astropart. Phys. 25 (2006) 1



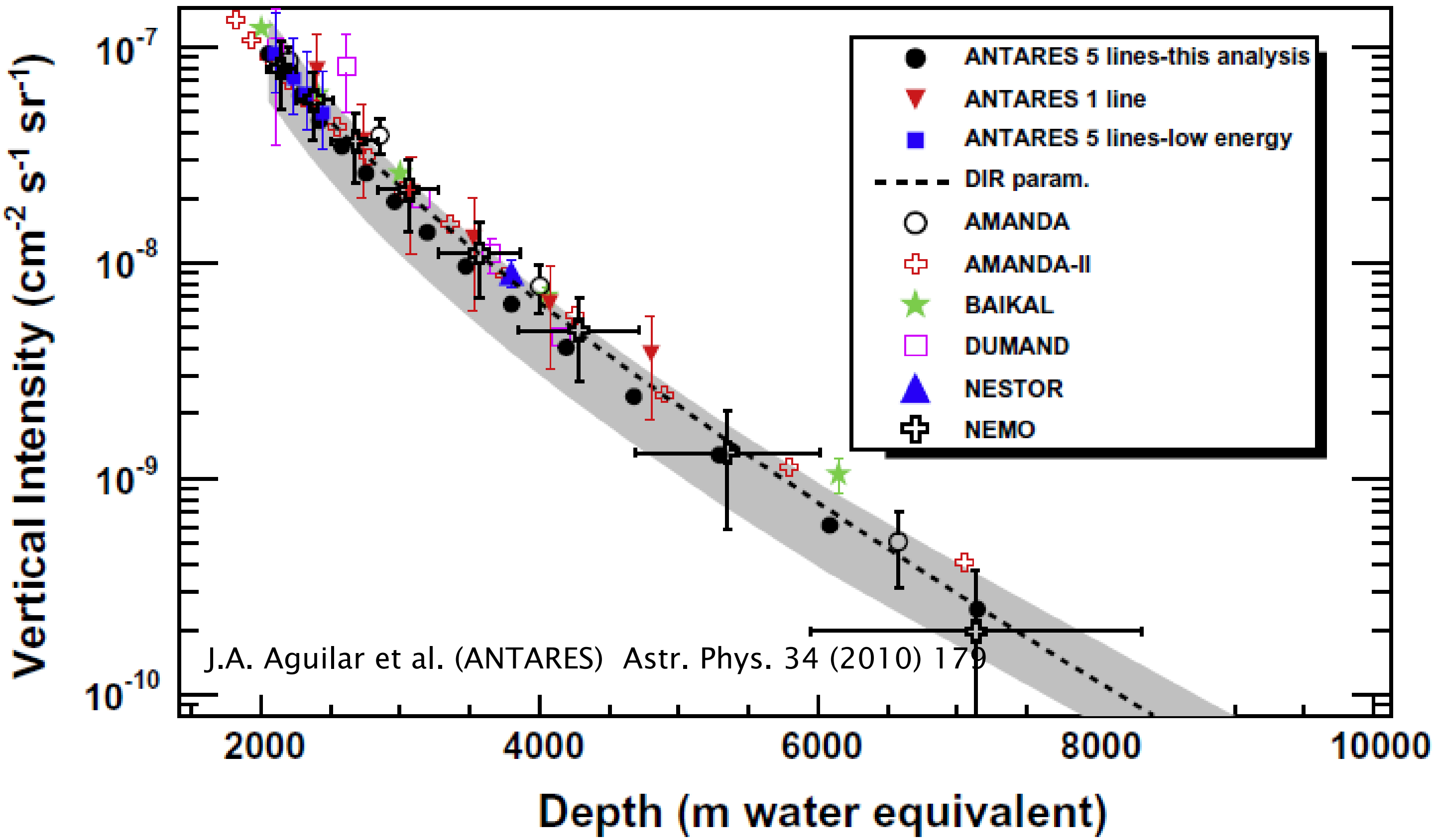


Energy: m=2, θ=0°, 5 distances

- Based on the MACRO experimental data (flux, multiplicity, distance between muon pairs, average energy)

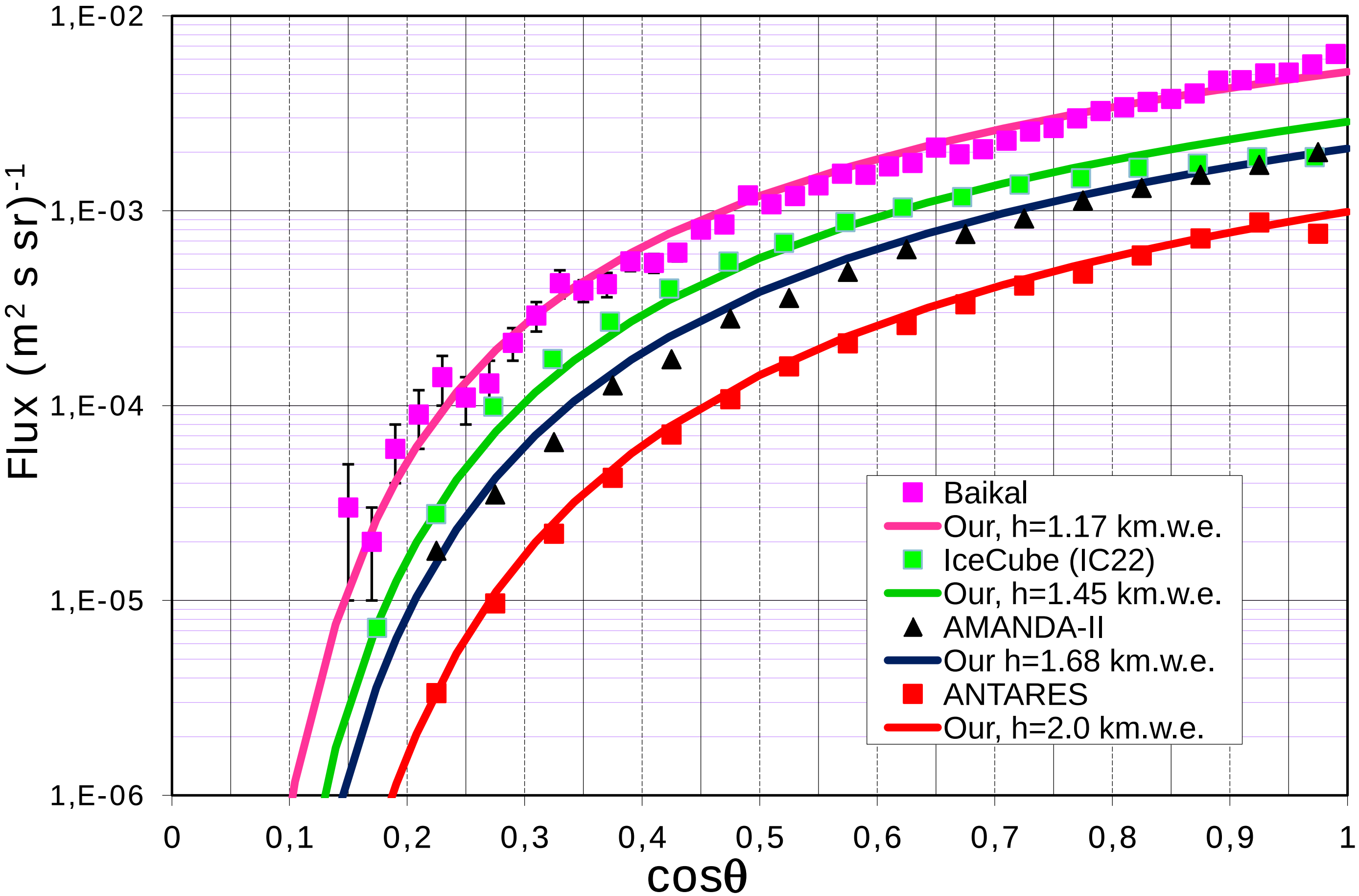
The DIR in underwater/ice NT

- Water: reduced systematic w.r.t. rock due to the medium knowledge
- But: an ANTARES storey is made of 3 Optical Modules which are looking downward, optimized to detect *upgoing* particles.
- Cherenkov light from downward going muons is seen with the "tail" of the PMT angular acceptance (large systematic uncertainty)



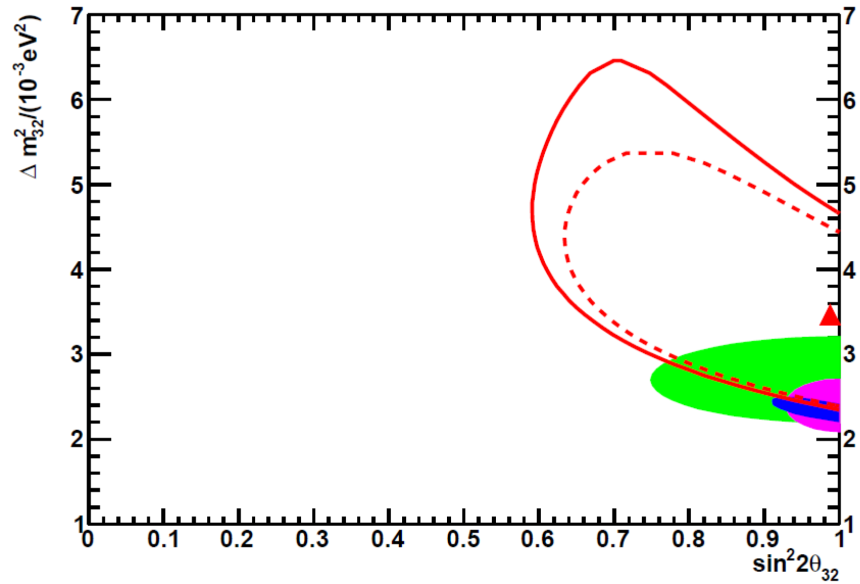
The muon flux underwater/ice

- Compilation of flux vs. zenith angle measured by underwater/ice neutrino telescopes
- Data compared with parametric formulas (APP 25 (2006) 1) at fixed depth

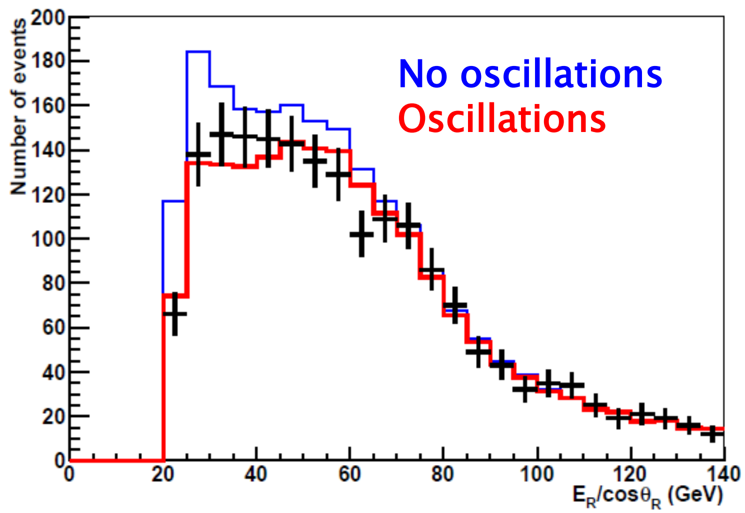


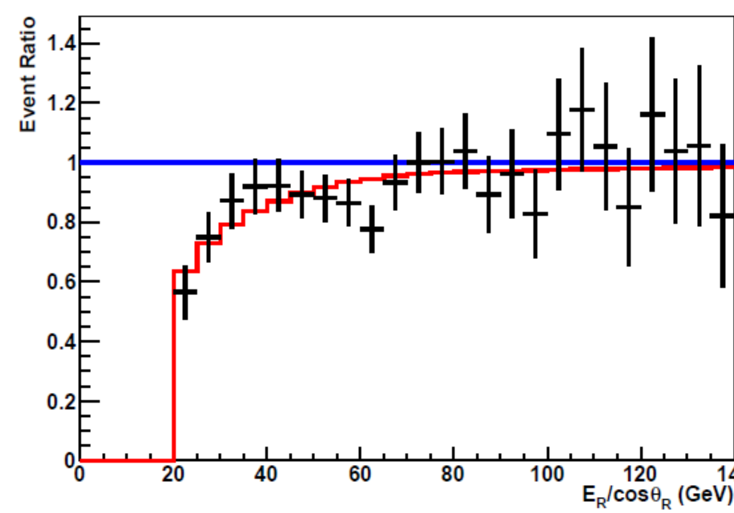
Baikal: 13th Neutrino Telescope
IC22: arXiv:0902.0021
AMANDA-II: 28th ICRC
ANTARES: APP 34 (2010) 179

Atmospheric ν_μ oscillation measurement with the ANTARES NT

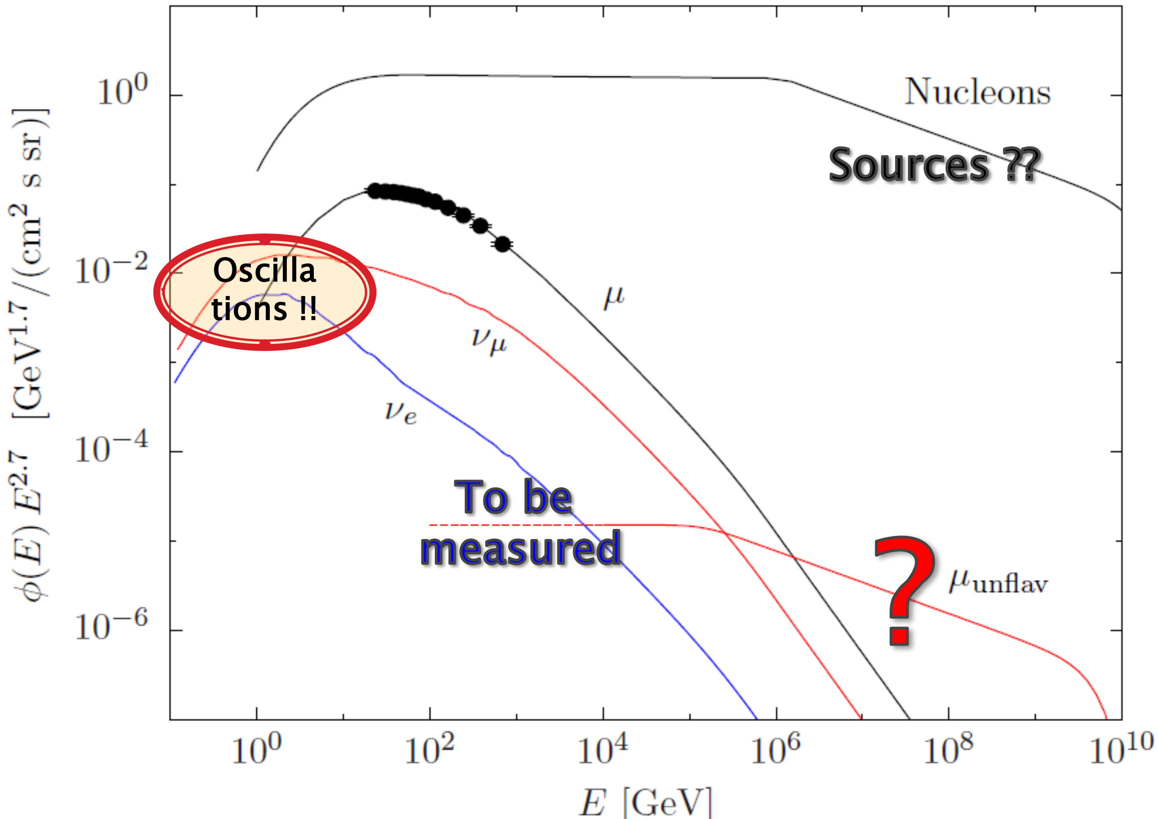


Preliminary





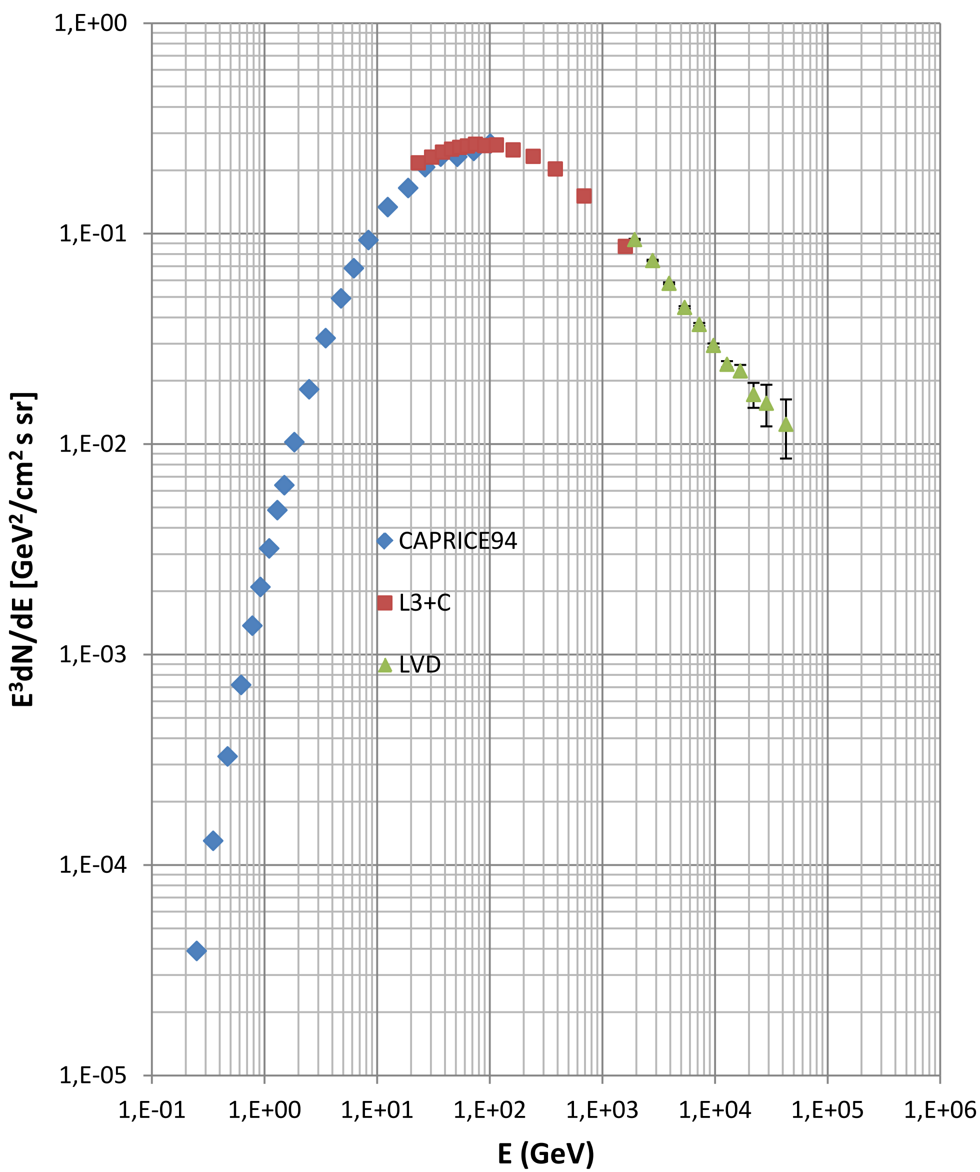
Conlusions



J.I. Illana, arXiv:1010.5084v1

Muon spectrum

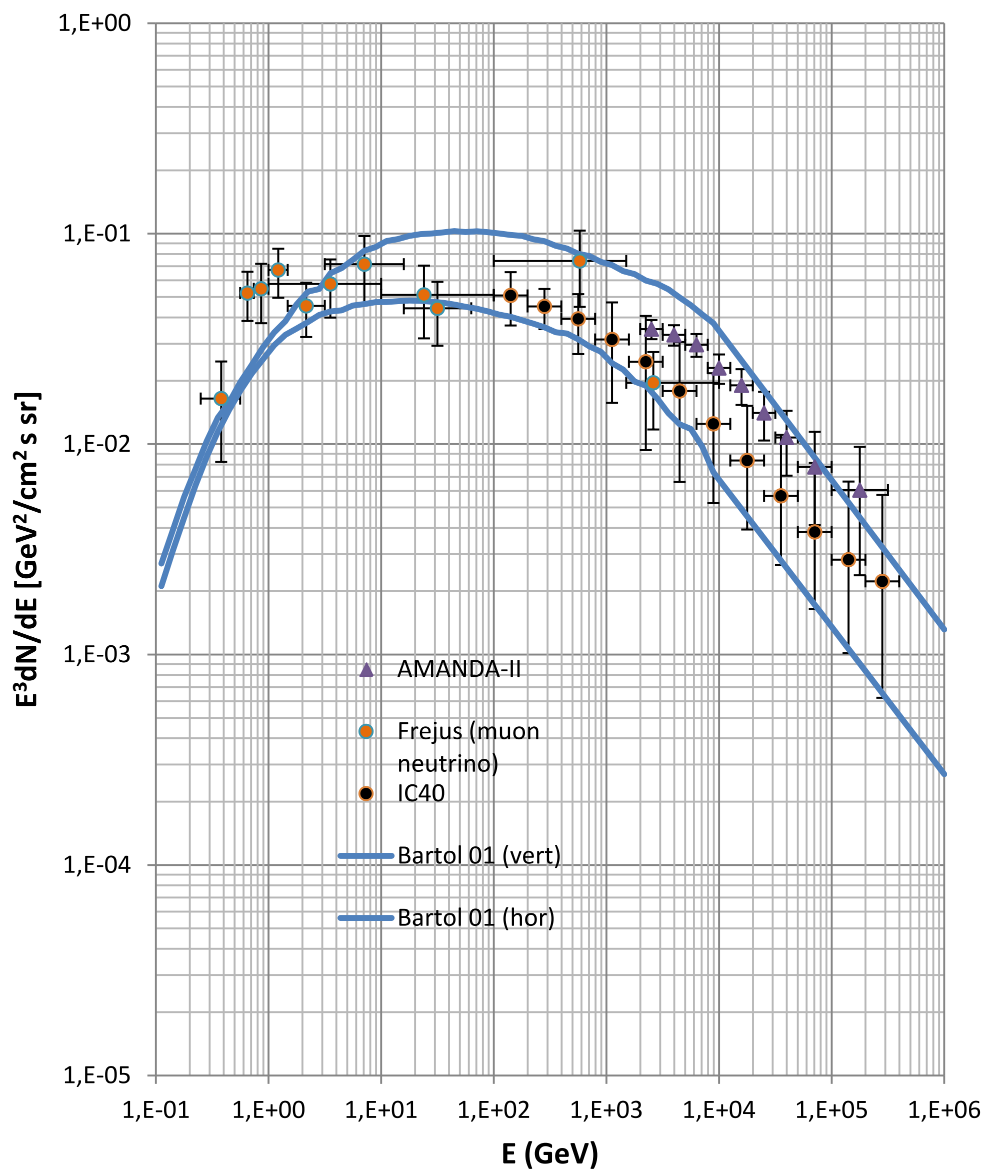
- Generated in the same processes as neutrinos
- Measured in ~6 decades of muon momentum
  - sea level, underground
- Disagreement between different experiments up to 30% due to systematics
- Indirect methods for higher energies
- Muon bundles underground



Muon neutrino spectrum

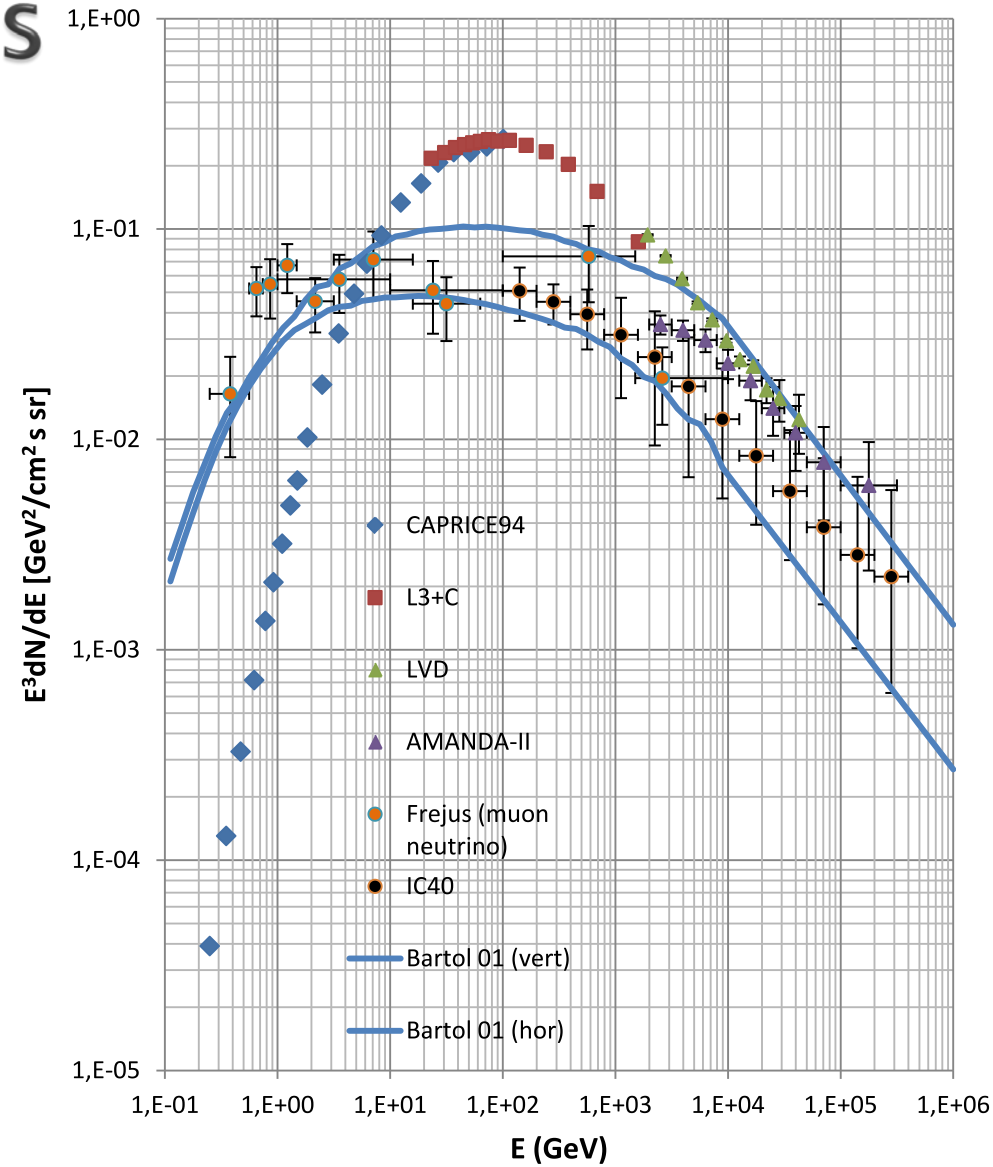
- Energetic spectrum of atmospheric ν_μ measured through the detection of upgoing muons
- Background for cosmic ν searches
- ν_e component to be accurately measured

[IC40] Abbasi R. et al., Phys.Rev.D83(2011)012001
[Frejus] K. Daum et al., Zeitschrift fur Physik C 66, 417 (1995).
[AMANDA-LE] R. Abbasi *et al.*, Phys. Rev. D79 (2009)102005.
[AMANDA-II] R. Abbasi et al., Astropart. Phys. 34, 48 (2010).



Muon and neutrino fluxes

- Fundamental for Earth Science purposes and muon imaging feasibility
  - characteristics of $\Phi\mu$
  - attenuation by rock
  - detector geometry
- "Prompt" component still undetected



- Many thanks to the conference organizers for the invitation
- Many thanks to the colleagues of the (MACRO), Opera and ANTARES collaborations in Bologna, and in particular to Stefano Cecchini

A low-energy muon telescope

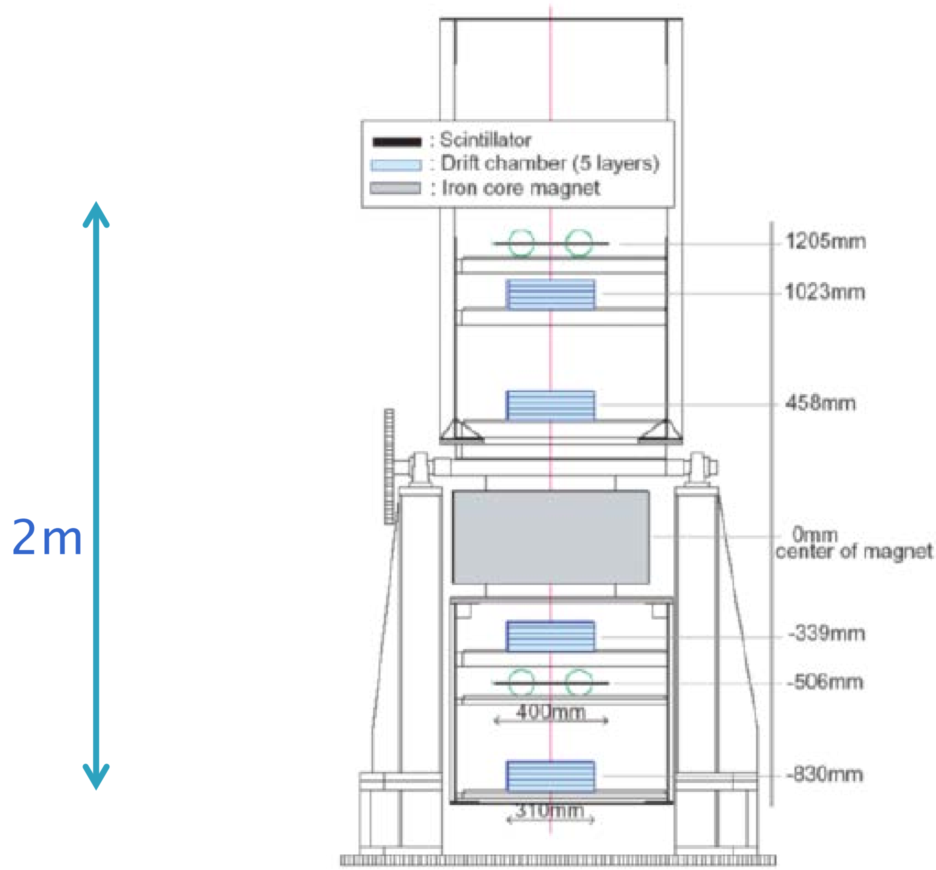
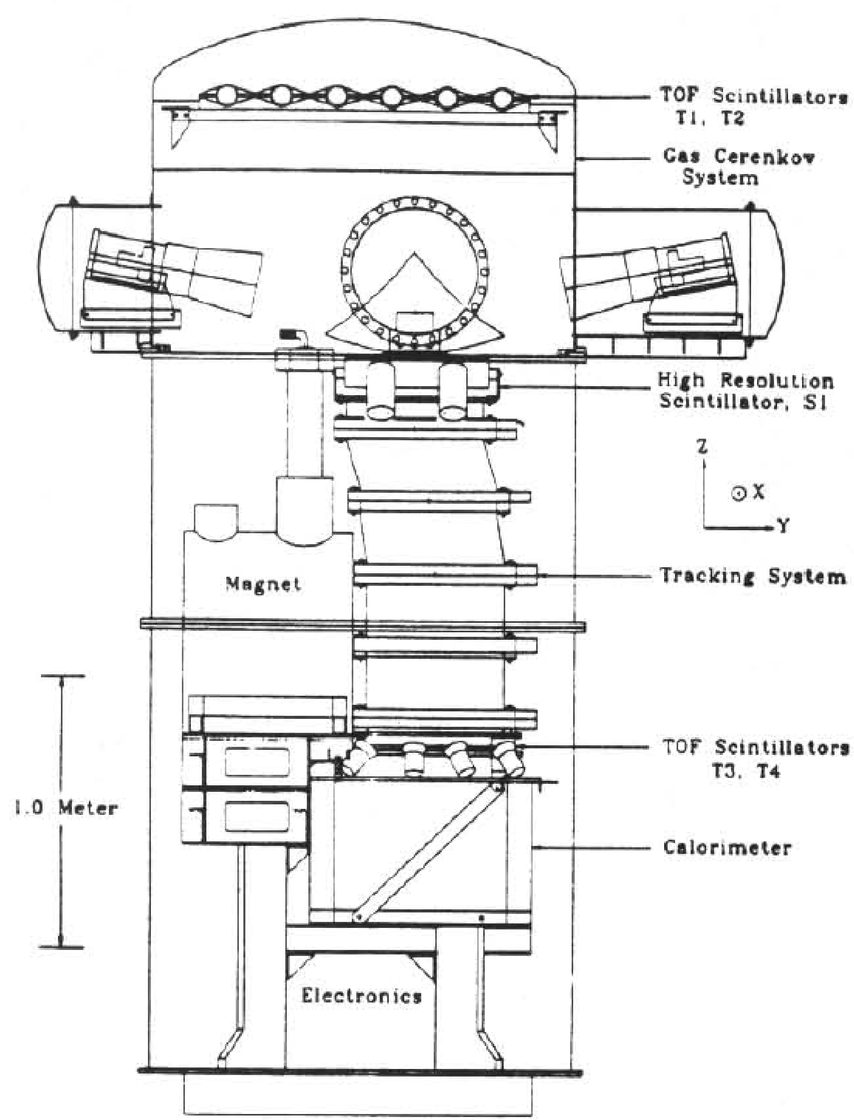


Figure 1. Schematic drawing of the OKAYAMA telescope. The central grey box is an iron core magnet. Scintillation counters and Drift chambers are located above and below the magnet.

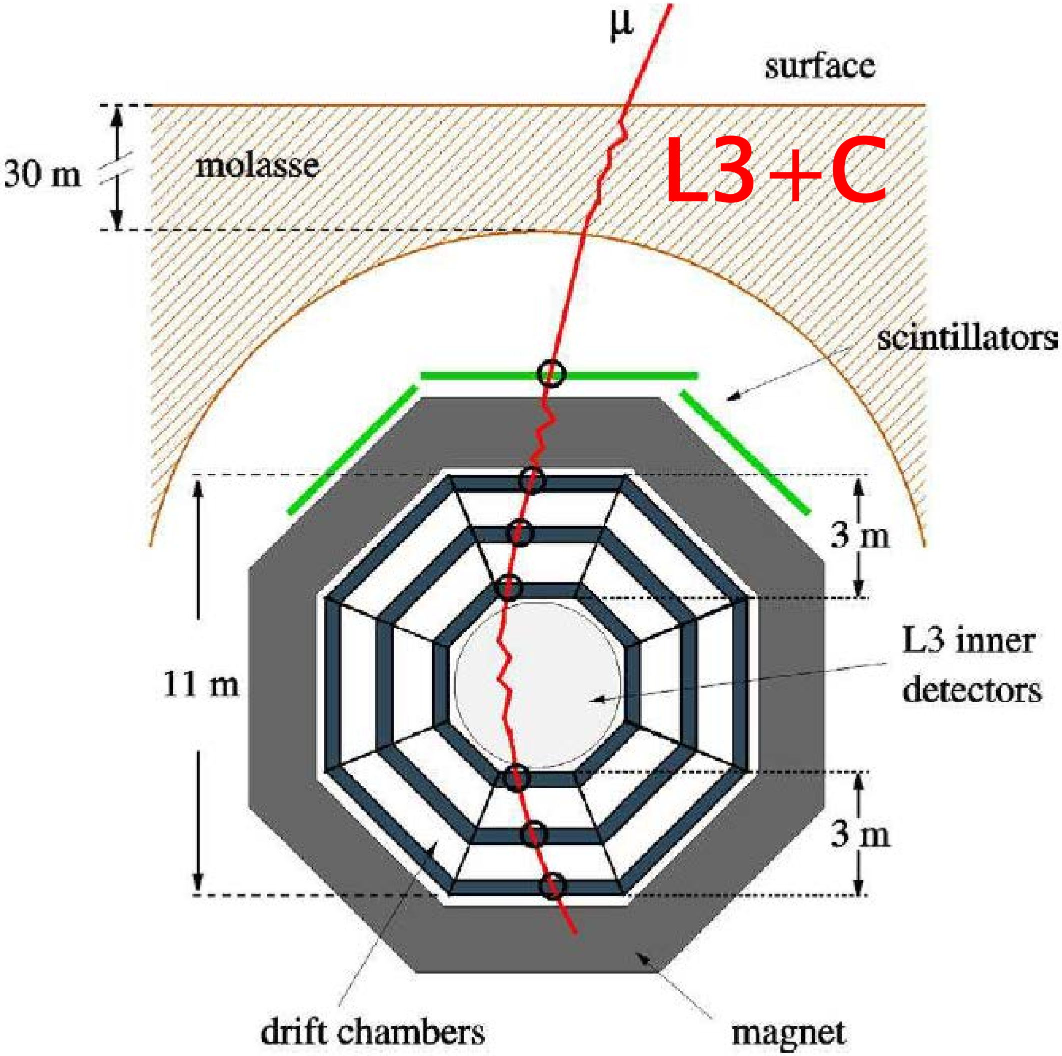
A low-energy muon telescope

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 98, NO. A3, PAGES 3501–3507, MARCH 1, 1993

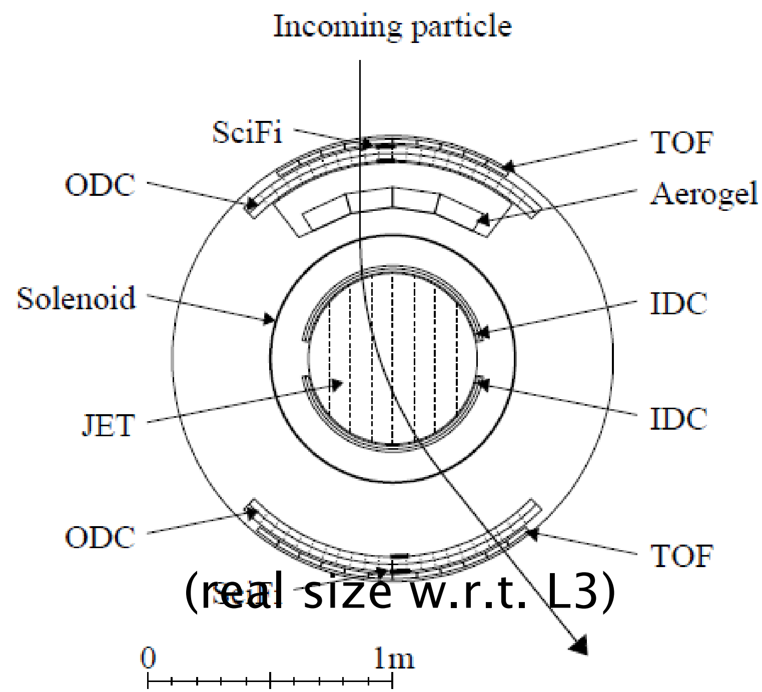


Example of large magnetic spectrometers

L3+C



BESS-TeV

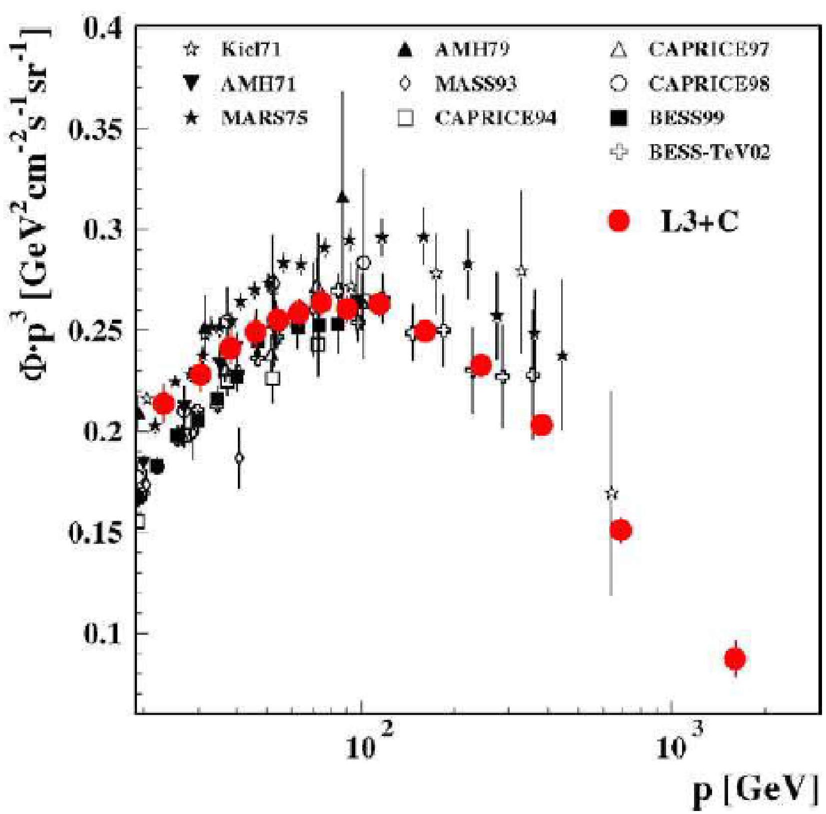


(real size w.r.t. L3)

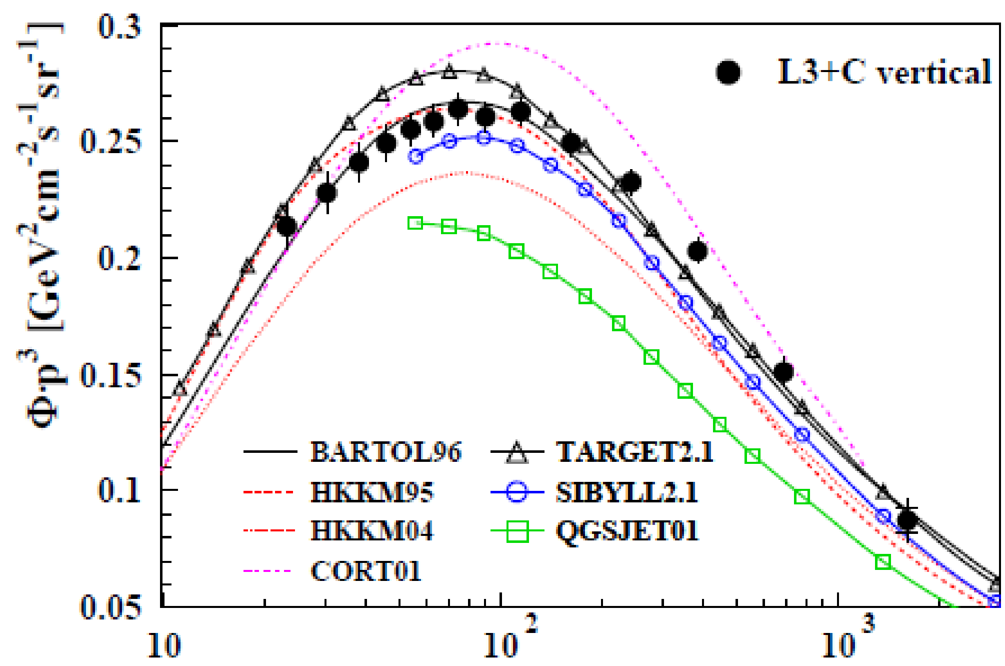
L3+C

P. Achard et al. (L3+C Coll) Physics Letters B 598 (2004) 15-32

Vertical muon spectrum compared to previous direct measurements extrapolated to sea level.



Vertical spectrum compared with different interaction models and primary fluxes

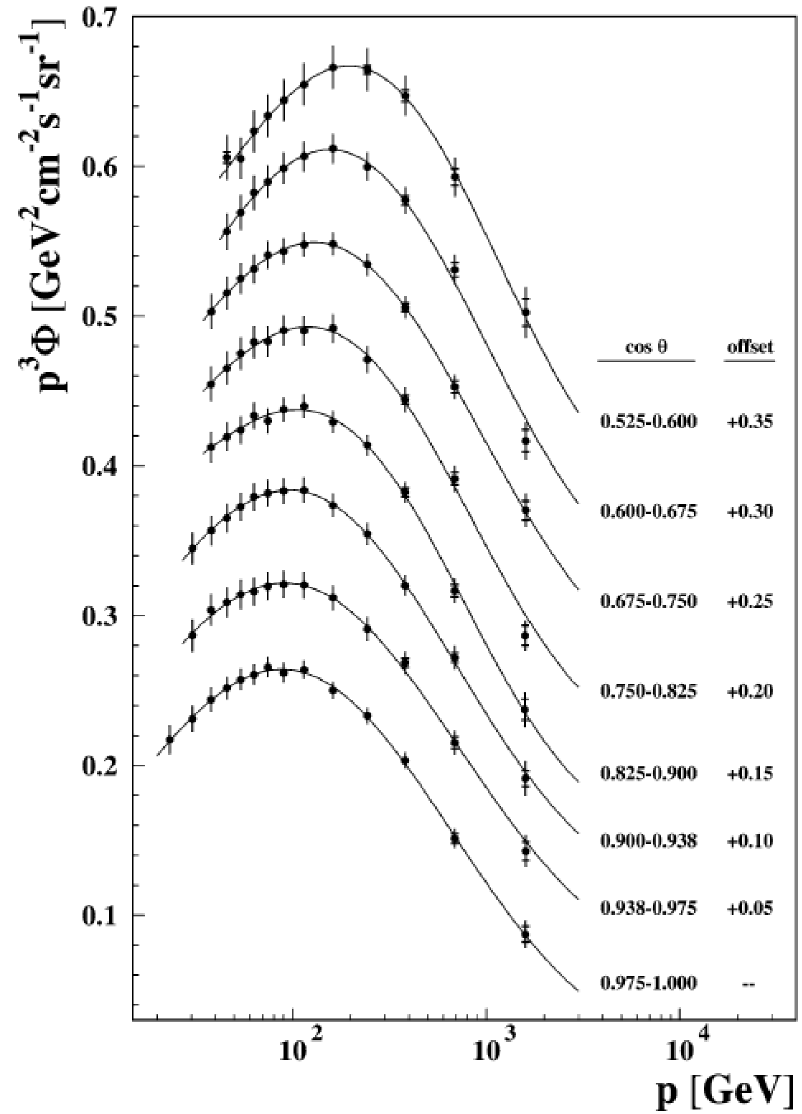


L3+C flux vs. zenith angle

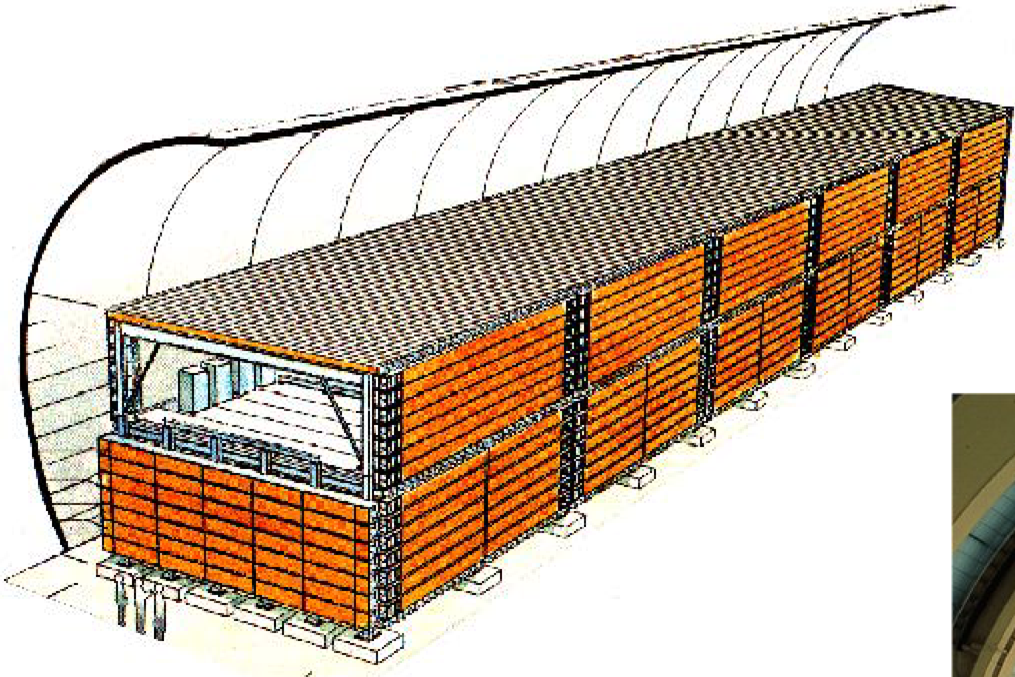
$$\frac{dN_\mu}{dE_\mu}(E_\mu, \vartheta) \cong A' E_\mu^{\ -\gamma} / \cos\vartheta$$

$$E_\mu > 1\,\mathrm{TeV}, \vartheta < 60^0$$

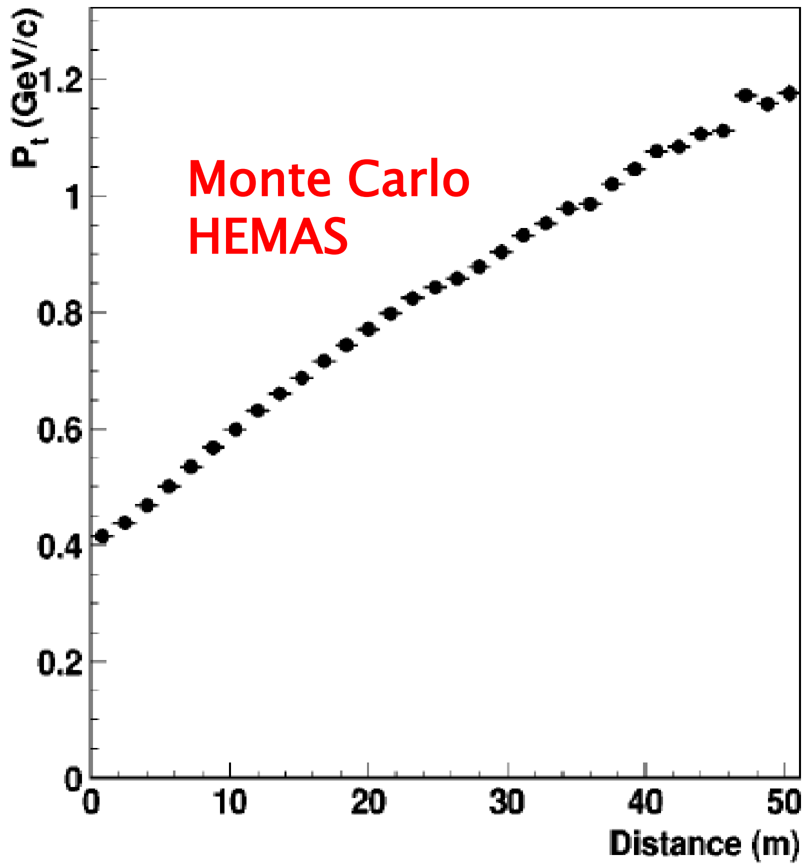
L3+C muon flux between 20 GeV –3 TeV for 8 zenith directions



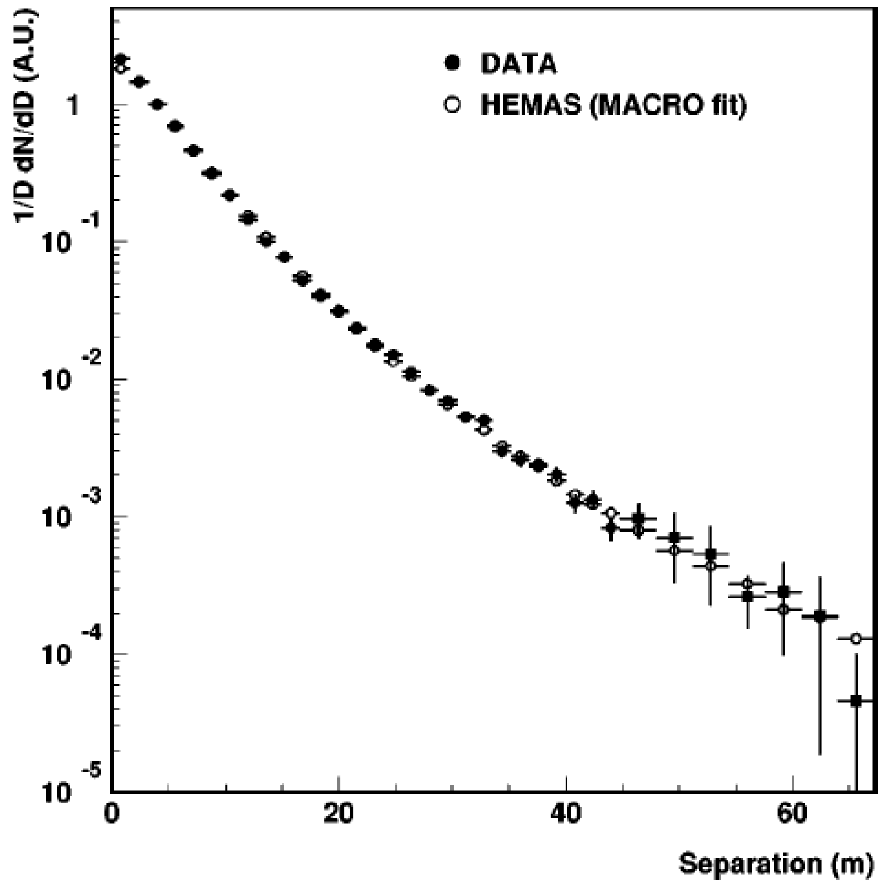
MACRO and LVD at Gran Sasso



Example of results



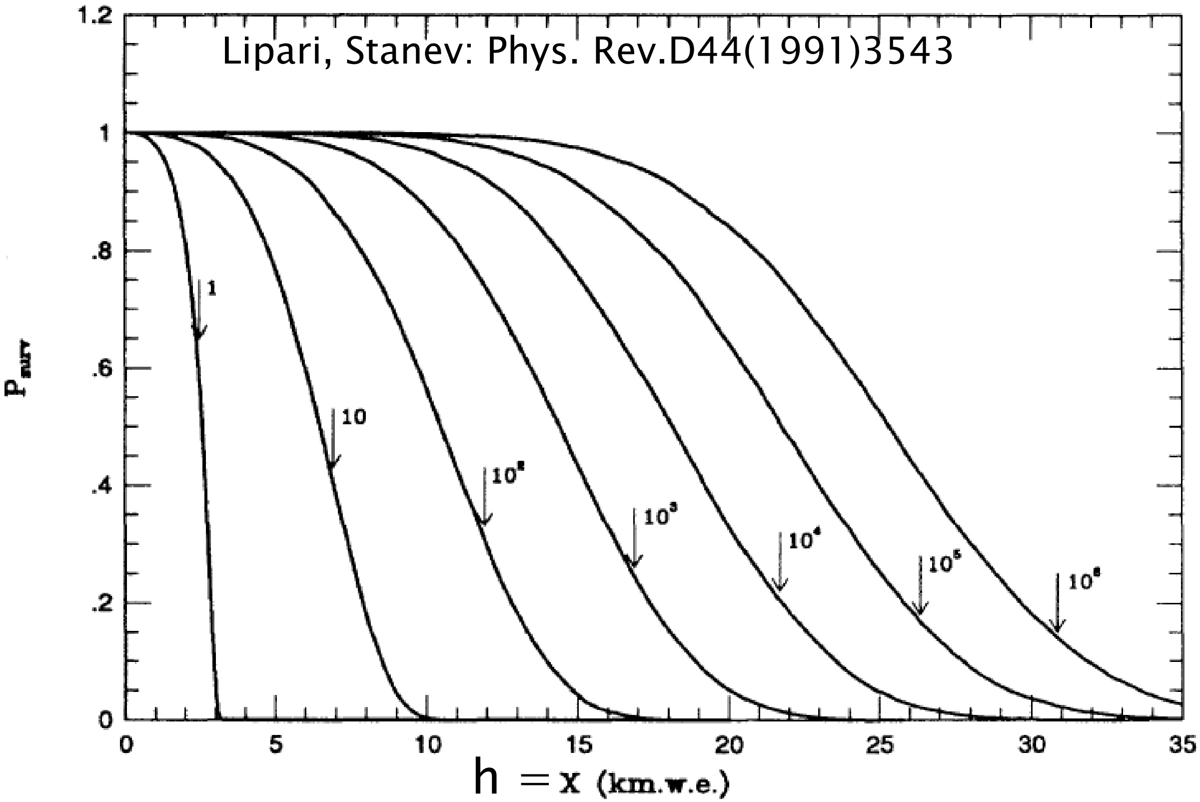
Average separation of underground muon pairs at Gran Sasso depth, as a function of $P_{\perp}$ of the parent mesons



Unfolded experimental decoherence distribution. Infinite-detector Monte Carlo expectation, computed with the HEMAS interaction and the MACRO-fit primary composition model

The muon survival probability

- ***P(E,h)*** is the probability that a muon of energy E survives after a depth h (km.w.e.). Figure for E from 1 to 10^6 TeV
- The curves become flatter with increasing E due to radiative energy loss and fluctuations
- The “range” of the average energy loss is also indicated
- Different computations for rocks/water/ice exists



Effective temperature

$$\int_0^\infty dX\alpha(X)\ \frac{\Delta T(X)}{T(X)} = \alpha_T\ \frac{\Delta T_{\mathit{eff}}}{T_{\mathit{eff}}} \approx \alpha_T (T_{\mathit{eff}} - \bar{T}_{\mathit{eff}})/\bar{T}_{\mathit{eff}},$$

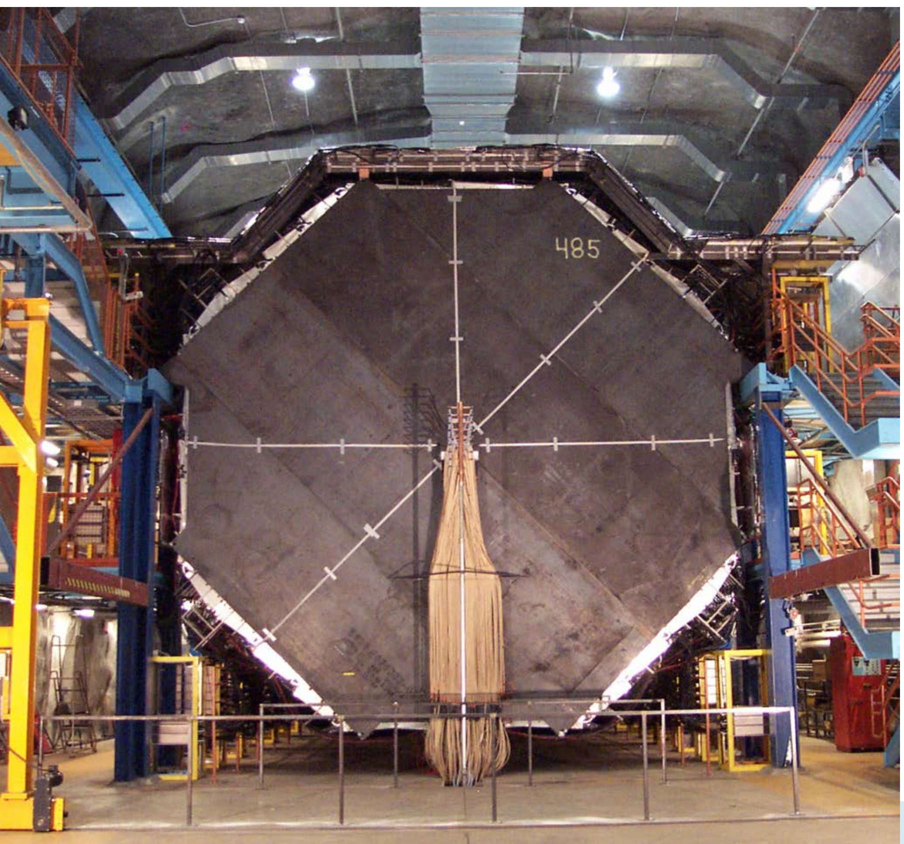
$$T_{\mathit{eff}} = \frac{\int T(X)\, dX/X\ \left[\exp(-X/\Lambda_\pi) - \exp(-X/\Lambda_N)\right]}{\int dX/X\ \left[\exp(-X/\Lambda_\pi) - \exp(-X/\Lambda_N)\right]}$$

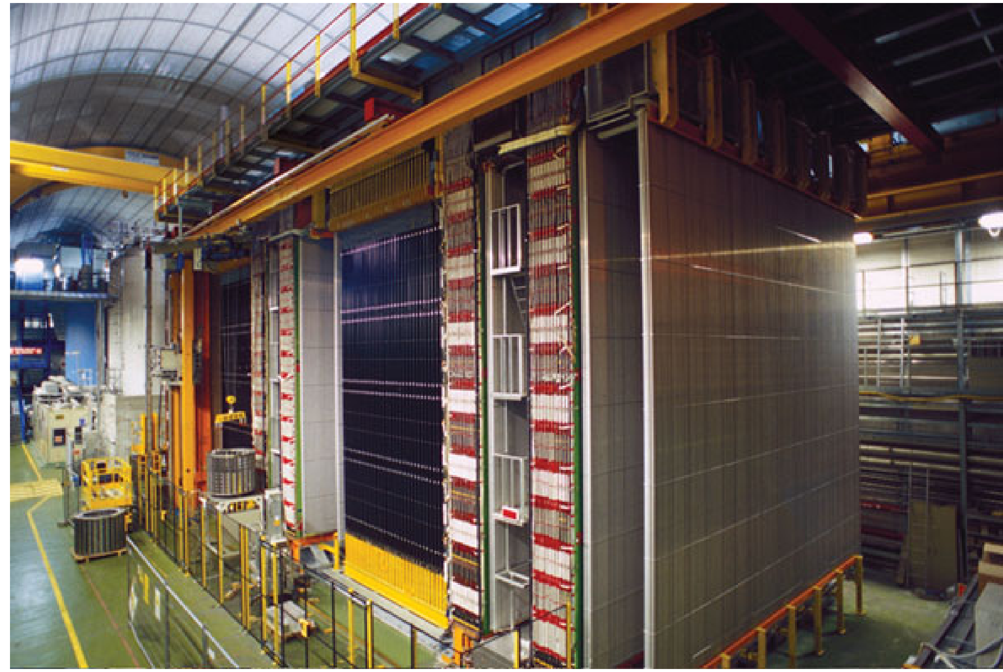
$$\approx \frac{\sum_i [T(X_i)/X_i]\ \left[\exp(-X_i/\Lambda_\pi) - \exp(-X_i/\Lambda_N)\right]}{\sum_i (1/X_i)\ \left[\exp(-X_i/\Lambda_\pi) - \exp(-X_i/\Lambda_N)\right]},$$

- The effective temperature coefficient reflects the fraction of mesons that are sensitive to atmospheric temperature variations

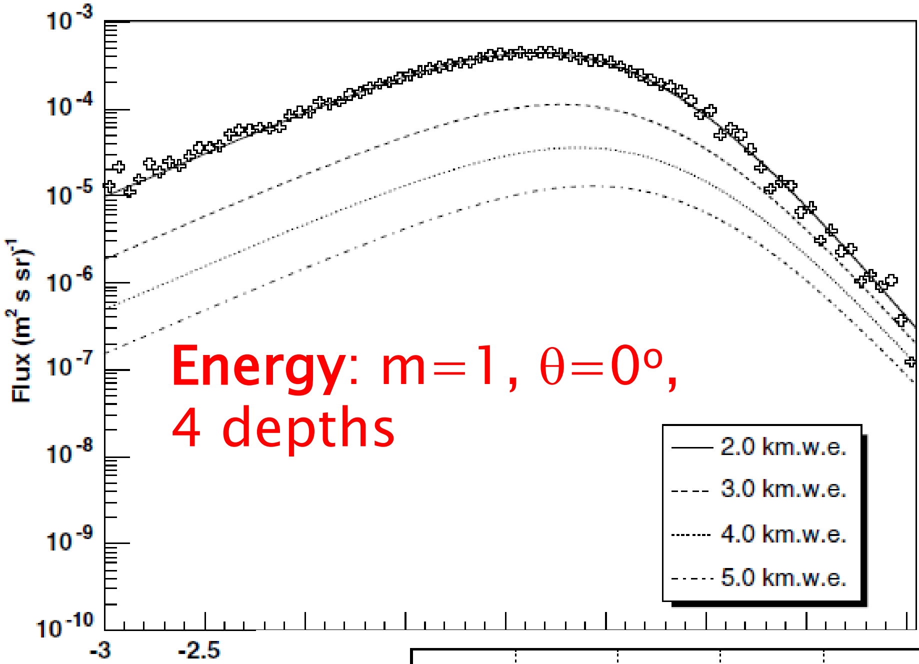
Minos and OPERA

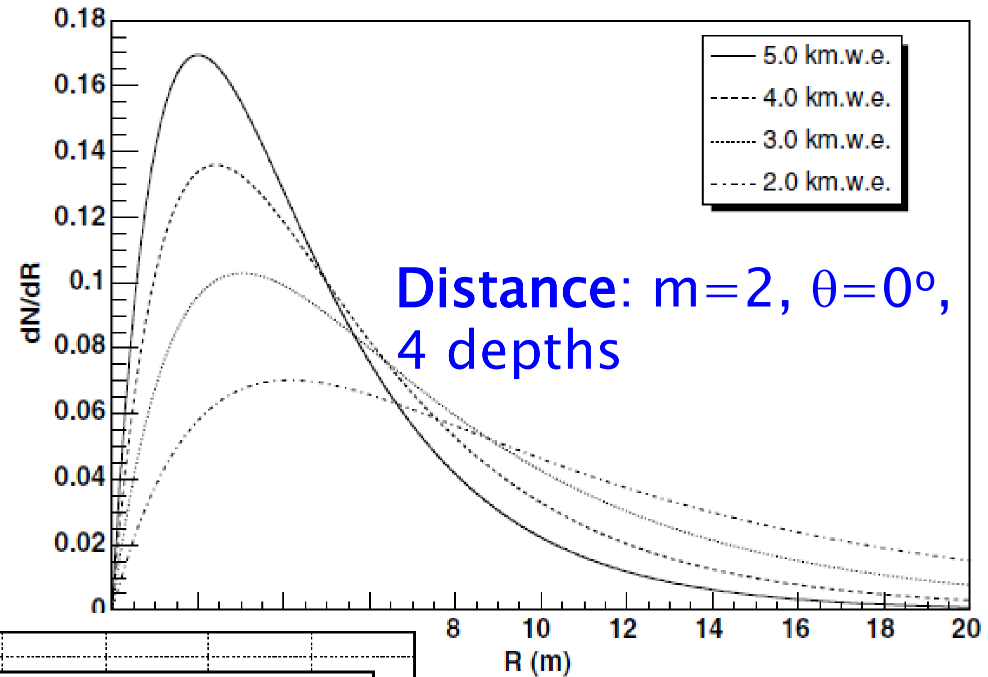
- **MINOS@Soudan mine**: steel-scintillator sampling calorimeter made out of alternating planes of magnetized steel and plastic scintillators

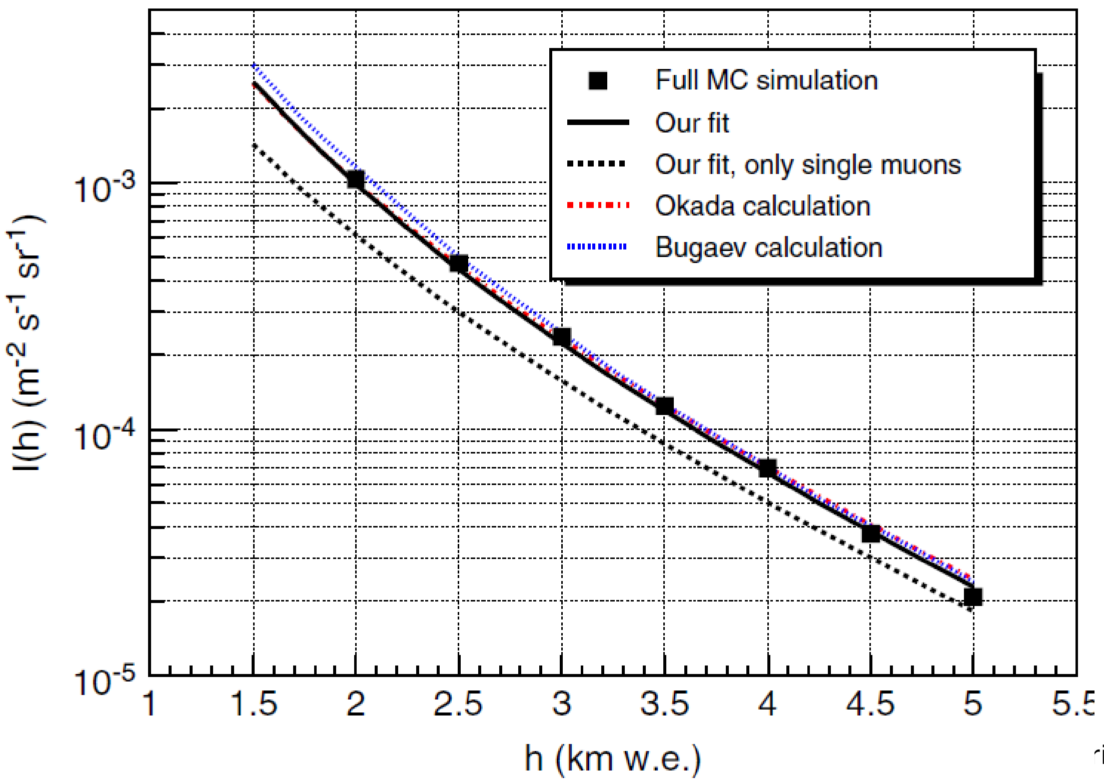




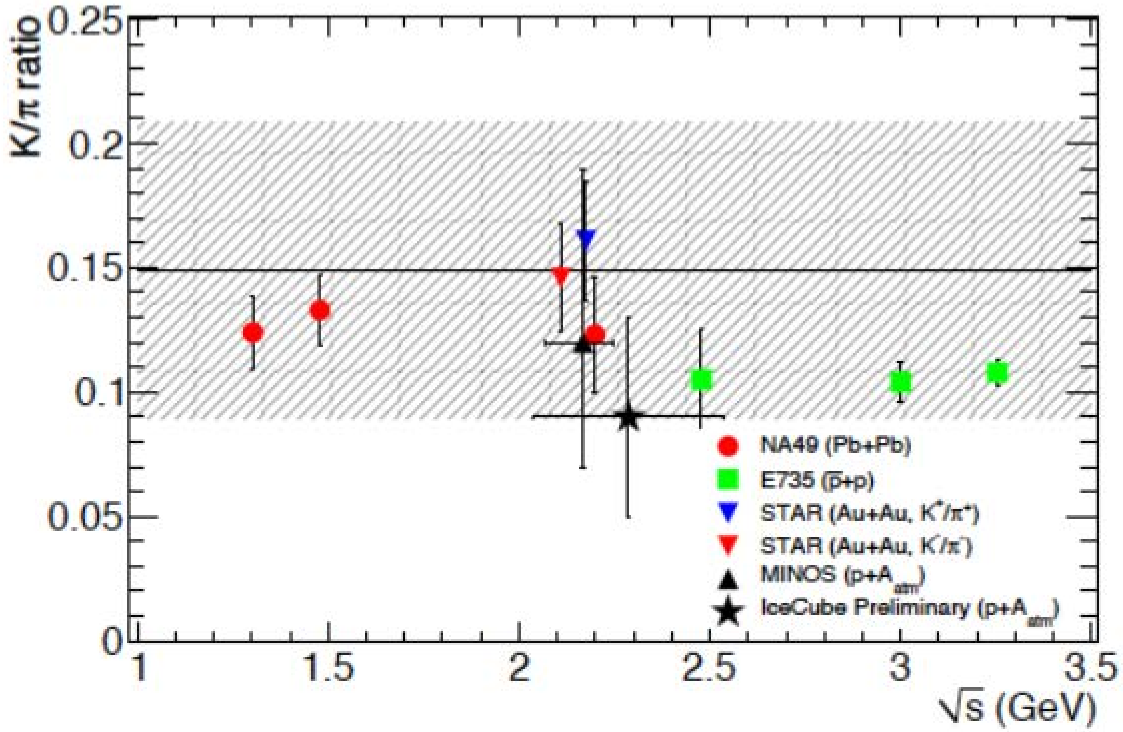
OPERA@Gran Sasso: The apparatus contains about 150000 *bricks* (photographic emulsion films interleaved with lead plates for tau-leptons observation) for a total mass of 1300 tons and it is complemented by electronic detectors (trackers and spectrometers)


Energy: m=1, θ=0º,
4 depths
Flux (m² s sr)⁻¹
2.0 km.w.e.
3.0 km.w.e.
4.0 km.w.e.
5.0 km.w.e.
-3
-2.5


Distance: m=2, θ=0º,
4 depths
dN/dR
R (m)
5.0 km.w.e.
4.0 km.w.e.
3.0 km.w.e.
2.0 km.w.e.


Full MC simulation
Our fit
Our fit, only single muons
Okada calculation
Bugaev calculation
I(h) (m⁻² s⁻¹ sr⁻¹)
h (km w.e.)

Measurement of the π/K ratio



IceCube and ANTARES