

# COSMIC RAY MUON PHYSICS

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## Abstract

We present a review of atmospheric and underground muon flux measurements. The relevance of these data for the atmospheric neutrino flux computation is emphasized. Possible sources of systematic errors in the measurements are discussed, focusing on the sea level muon data. Underground muon data are also reported.

## 1 Introduction

At sea level, together with neutrinos, muons are the most abundant particles originated by the interactions of primary cosmic rays at the top of the atmosphere. Due to their relative stability and small cross sections, these particles are able to arrive deep underground and/or deep underwater. As a consequence, their study covers many aspects of cosmic ray physics.

Recently, atmospheric muon flux measurements received attention in the context of the atmospheric neutrino anomaly [1, 2]. Because of the close relation between muon and neutrino production, it follows that the evaluation of the atmospheric muon flux can provide an important cross check on the atmospheric neutrino flux. Moreover, measurements of muon flux at all geomagnetic latitudes are crucial for the normalization of the calculated neutrino flux.

Measurements performed at different altitudes (sea level, at mountain level or in balloon born experiments) offer various advantages. First of all, a different set of measurements at different altitude values can provide information about the longitudinal development of the muon component in

cosmic ray showers. Moreover, the interpretation of data collected at the top of the atmosphere are not affected by the uncertainties inherent in particle production and propagation, since the muons (and the corresponding neutrinos) generated in the first stages of the cascade. Finally, the knowledge of high altitude muon data is crucial for sea level sub-GeV neutrinos: the corresponding sub-GeV muons originated in the same decay processes cannot reach the sea level, considering that the average muon energy loss in the atmosphere is of the order of 2 GeV; we are thus forced to take data at high altitudes.

On the other hand, measurements performed at ground level offer the advantage of a high stability, large collecting factor and a long exposure time due to the relatively favourable experimental conditions. They however suffer of an intrinsic difficulty in interpretation, since the muons that arrive at sea level are the last stage of a multi-step cascade process. This is true, in particular, for the measurements at high zenith angles, near the horizon, where the intermediate and high energy regions of the spectrum can be analysed ( $p_\mu = 10\text{-}100$  GeV/c). Nevertheless, for this reason, sea level data offer the possibility to perform a robust check of the reliability of existing Monte Carlo codes.

Finally, underground measurements offer the possibility to extend the energy range of the muon spectrum beyond 1 TeV. Such measurements are of an indirect type, but their link with the direct low-energy observations gives the possibility to complete the picture of muon spectra measurements and to cross-check the validity of the global set of data.

Most of the experiments devoted to the measurement of the muon momentum spectra and intensity have been carried in the '70s. The problem is that the results are often in disagreements with one another; the discrepancies are significantly larger than the experimental errors reported. Recently new instruments, mainly designed for balloon experiments, have been developed; they are able to give detailed information on the muon flux at different altitudes in the atmosphere [3]. Also new measurements deep underground [4, 5, 6, 7, 8] or by EAS arrays [9] have added new information at very high energies.

In this paper we summarize the observations of the muon flux at sea level and deep underground and discuss some of the systematics connected with such measurements. For more complete discussion one can refer to the recent papers [10, 11] and to books [12, 13].

## 2 Atmospheric muon production and propagation

Secondary muons are mainly produced in the decays of secondary mesons, mostly  $\pi^\pm$  and  $K^\pm$ . The most important decay channels, and their respective decay probabilities, are:

$$\begin{aligned} a) \quad \pi^\pm &\rightarrow \mu^\pm \nu_\mu && \sim 100\% \\ b) \quad K^\pm &\rightarrow \mu^\pm \nu_\mu && \sim 63.5\% \end{aligned}$$

in which the produced muons take on the average 79% and 52% of the energy of the  $\pi^\pm$  and  $K^\pm$ , respectively.

The contribution of  $K$  decays to muon production is a function of the energy and ranges from  $\sim 5\%$  at low energies to an asymptotic value of  $\sim 27\%$  for  $E \gtrsim 1$  TeV. At very high energies a small contribution arises from charmed particles. The analytical form of the muon production spectrum at a given height in the atmosphere can be derived by folding the two-body decay kinematics of the parent mesons with their production spectrum. The latter is generally expressed in terms of the so called “spectrum weighted” moments

$$Z_{p\pi^\pm} = \int_0^1 x^\gamma \frac{dN_{p\pi^\pm}}{dx} dx \quad (1)$$

where  $dN_{p\pi^\pm}/dx$  is the pion production spectrum ( $x = E_\pi/E_p$  and  $\gamma$  is the differential primary spectral index). A similar expression can be obtained for kaons. In general, the development of the meson and muon components in the atmosphere depends on the energy range we are considering. The competition between interaction and decay of the particles plays a crucial role and the relative importance of the two processes depends on the energy. We can distinguish three different energy regions in the muon spectrum:

a)  $E_\mu \gg \epsilon_{\pi,K}$ , where  $\epsilon_\pi = 115$  GeV and  $\epsilon_K = 850$  GeV are the critical energy beyond which meson reinteractions cannot be neglected. This is the typical muon energy range studied by underground detectors or by ground based experiments looking at high inclined directions. In this case, the meson production spectrum have the same power law dependence of the primary cosmic rays, but the rate of their decay has an extra  $E^{-1}$  dependence with respect to the primary and meson spectrum (a consequence of

the Lorentz time dilatation). The muon (and hence neutrino) flux takes the form:  $dN/dE_\mu = E_\mu^{-(\gamma+1)}$ , and a zenith dependence  $dN/d\cos\theta \propto (\cos\theta)^{-1}$ . It should be noted that, in this energy region, the enhancement of the  $K^\pm$  contribution to the secondary lepton production is particularly important in the neutrino flux calculation, as a consequence of the two-body decay kinematics [14]. This last remark does not hold for muons, for which the limited knowledge of meson production in this energy range is not so crucial as for neutrinos.

b)  $\epsilon_\mu \lesssim E_\mu \lesssim \epsilon_{\pi,K}$ , where  $\epsilon_\mu \simeq 1$  GeV. In this energy range, almost all the mesons decay, and the muon flux has a power law dependence with the same spectral index of the parent mesons (and hence of the primary cosmic ray, in the assumption of complete Feynman scaling validity) and is almost independent on the zenith angle. A compact form which expresses the low and high energy regions is [12]:

$$\frac{dN_\mu}{dE_\mu}(E_\mu, \theta) \simeq 0.14 E_\mu^{-2.7} \left[ \frac{1}{1 + \frac{1.1E_\mu \cos\theta}{\epsilon_\pi}} + \frac{0.054}{1 + \frac{1.1E_\mu \cos\theta}{\epsilon_K}} \right] \quad (2)$$

c)  $E_\mu \lesssim \epsilon_\mu$ . In this case, muon decays and the energy losses in the atmosphere cannot be neglected. Moreover, geomagnetic latitude and solar modulation now play an important role being the primary cosmic ray energy  $E_p < 20$  GeV.

We stress again the relevance of muon flux measurements for the knowledge of the neutrino flux. In principle, sea level neutrino flux computation can be derived directly from muon flux measurements high in the atmosphere ( $X < 37$  g/cm<sup>2</sup>) [15]. This approach gives good results, but only a complete Monte Carlo simulation can take into account second order effects. The main ingredients in Monte Carlo calculations (and the main sources of systematics) of atmospheric lepton production are the input primary cosmic ray spectrum and a detailed description of secondary multiparticle production in the atmosphere. The primary cosmic ray composition plays an important role only in the very high energy range; the composition is dominated by protons and  $\alpha$  particles at energies below 100 GeV.

Among various Monte Carlo codes now available, we recall [1] and [16] which are the ones used to interpret the atmospheric neutrino anomaly, and the new code based on the FLUKA interaction model [17] which takes into account 3-dimentional effects of secondary propagation in the atmosphere.

The comparison between the Monte Carlo evaluation of the muon flux at different altitudes and at sea level with the existing muon flux measurements constitutes one of the most powerful benchmark to assess the validity of the simulations.

### 3 Atmospheric muon flux measurements

Measurements of the absolute intensity, energy spectrum and positive-to-negative ratio of muons have been carried out many times in the past. Most of these observations were made at sea level and few at different mountain altitudes with counter telescopes separated by absorbers (Pb, Fe) and magnetic spectrometers. More recently, with the development of superconducting magnet, it has been possible to operate spectrometers also on board of balloons [18, 19, 20, 21, 22] which led to accurate measurements at different levels in the atmosphere.

Here we will consider mainly ground-based measurements and those made with detectors on balloons near the ground level or very close to it. The relevant quantities that can be directly measured and will be discussed here, are:

- absolute muon intensity
- muon momentum spectrum
- charge ratio

#### 3.1 Absolute intensity measurements

The vertical muon intensity at sea level is a quantity which varies with the geomagnetic latitude, altitude, solar activity and atmospheric conditions.

The geomagnetic field tends to prevent low energy cosmic rays from penetrating through the magnetosphere down to the Earth's atmosphere. At any point on the Earth one can define a threshold or cut-off rigidity,  $P_c$ , for cosmic rays arriving at a particular zenith and azimuth angle [23].

Primary nuclei having lower rigidity are excluded by the action of the geomagnetic field and do not contribute to production of secondaries in the atmosphere. The cut-off values range from less than 1 GV near the geomagnetic poles to about 16 GV for vertical particles near the equator [24]. It results that geomagnetic effects are important for sea level muons up to

about  $\sim 5$  GeV (Fig. 1). The effect is larger at higher altitudes; Conversi [25] found that the vertical flux of muons with momentum around 0.33 GeV/c at latitude 60 deg was 1.8 times higher with respect to the flux at the equator.

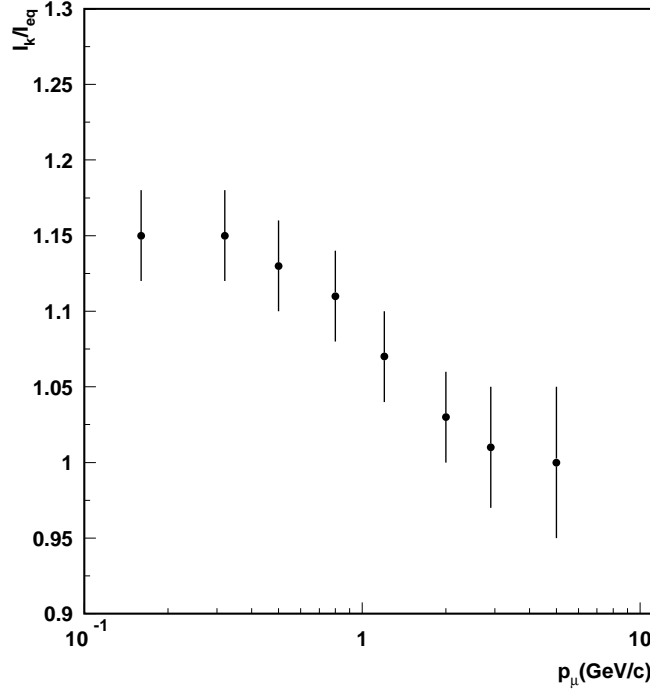


Figure 1: *The latitude effect on the integral muon intensity at sea level. It is shown the ratio between the intensity measured at Kiel  $I_K$  ( $Pc = 2.3$  GV), and the intensity measured near the equator  $I_{eq}$  ( $Pc = 14.1$  GV), with the same instrument <sup>26</sup>.*

Moreover, as cosmic ray primaries are predominantly positively charged particles, the flux and spectra in the East and West directions differ up to energies of about 100 GeV; the intensity from the West is stronger than that from the East. This effect increases with altitude.

In addition, the primary cosmic ray spectrum at the top of the atmosphere changes with the 11 year solar cycle as the configuration of the Interplanetary Magnetic Field (IMF) varies. It results that the cosmic ray flux is significantly “modulated” up to energies of about 20 GeV (Fig. 2).

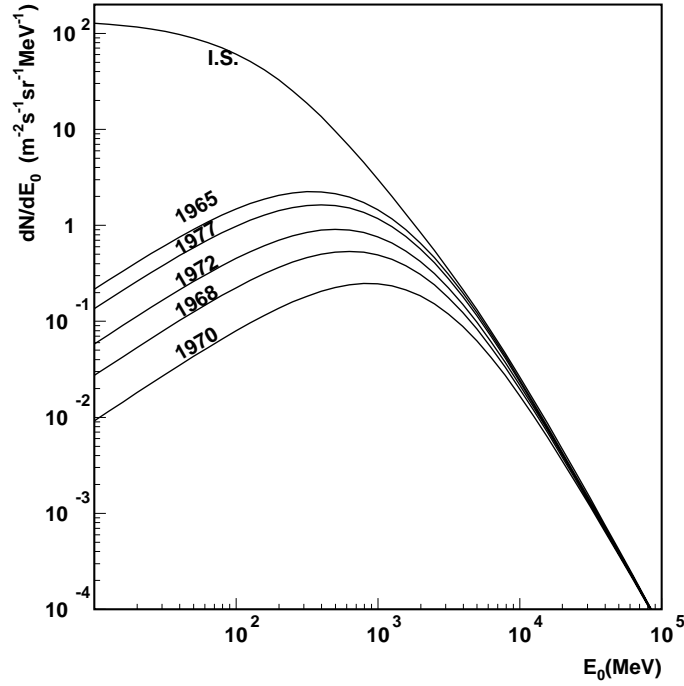


Figure 2: *Approximate solutions (the so called force-field solution) <sup>27,28</sup> that fit the observations of the primary proton spectrum at the top of the atmosphere at different years. Also shown is the assumed Interstellar Spectrum. Notice the extension of the solar modulation effect.*

In order to estimate how these changes in the primary spectrum influence the counting rate of a muon detector it is necessary to know the "differential response curve" [12]. Its shape varies significantly with the depth of observations, see Fig. 3. Their detailed calculations depend on the properties of nuclear cascades in the atmosphere; more precise descriptions can be found in [30, 31] At the standard momentum of 1 GeV/c and at high latitudes the modulation is 7% and 4.5% for the differential and the integral fluxes, respectively [32].

So in making a comparison of muon observations at low energies (less than 20 GeV) it is very important to know the year and the location the measurements were made. Figure 4 shows the neutron monitor counting rate

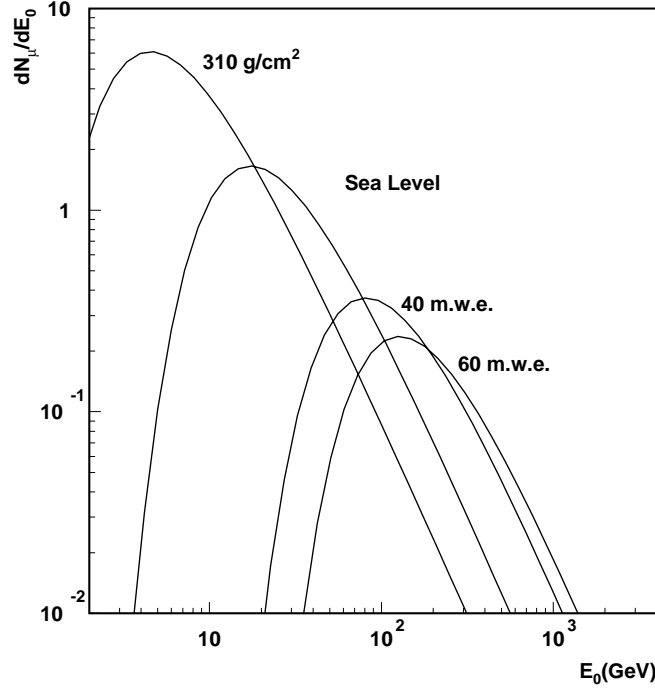


Figure 3: *Differential response functions for muons detected at different depths, after Mathews*<sup>29</sup>

recorded by a middle latitude station since 1953. No continuous recording of the same kind exists for muon monitors. By the comparison of the peak to peak variations during the interval 1965-1972 one can estimate that the total muon flux changes are usually a factor 3 to 5 smaller than the observed neutron flux variations [32, 33]

Finally, changes in pressure and, particularly, temperature above the instrument up to the point of muon production by pions and kaons, produce variations of different amplitude in different energy range. The most conspicuous for muons at higher energies is the seasonal variation [34, 35, 36] for which the results reported in the following have not been corrected for.

Classical definition of the hard component [37] is related to penetration characteristics, it is to say the capability of crossing  $167 \text{ g/cm}^2$ , equivalent to roughly 15 cm of Pb. As a matter of fact this component is made of muon



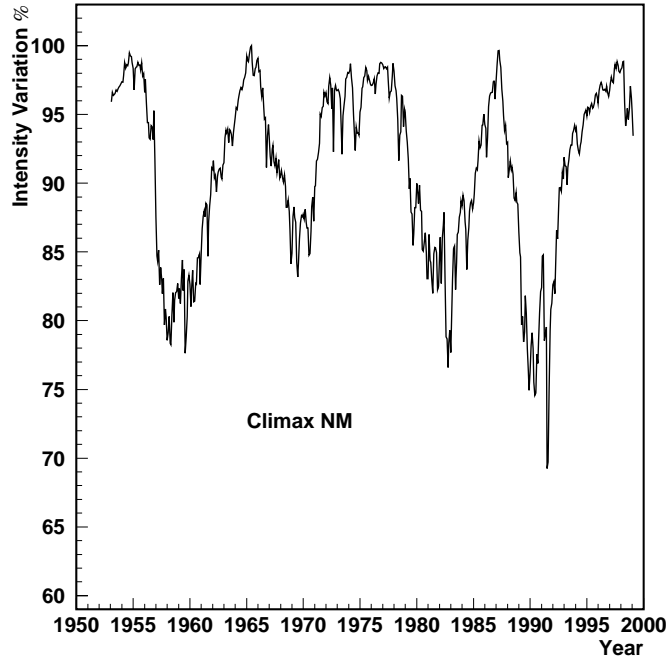


Figure 4: *Observed time variation in the monthly counting rate of the Climax Neutron Monitor ( $P_c = 3.03$  GV) normalized to 1965. The 11 year variation associated with solar sunspot cycle is easily recognizable. Pronounced minima occur during sunspot maxima. A complete record of the muon intensity variations during the same period is not available.*

with momenta  $p_\mu > 0.32$  GeV/c and less than 1% are protons, neutrons, electrons and pions.

Let us distinguish between vertical and horizontal integral muon fluxes. These latter are made in order to extend the range of the former beyond several tens of GeV/c, but usually they do not give absolute values of the vertical muon intensity. For this reason we will not discuss them here.

The first measurement of the integral vertical intensity was made by Greisen [38] at latitude  $50^\circ$  and altitude 259 m a.s.l. (corresponding to  $1007$  g/cm<sup>2</sup>) who found the value:  $0.83 \times 10^{-2} \pm 1\%$  cm<sup>-2</sup>s<sup>-1</sup>sr<sup>-1</sup>. Rossi [37] noticed that this value needed to be corrected in order to account for

showering and scattering of particles inside the apparatus. Successive measurements led to higher values. The observations made at different latitudes and during different years are presented in Fig. 5. Most measurements were made at high latitudes [39, 40, 41, 42, 43, 44], and only the few at low latitudes [45, 46]; were corrected for the geomagnetic effect. No corrections have been made for the solar modulation effects; the measurements are essentially grouped in the period 1967-1977, with one in 1998 [44]. The agreement between the measurements is fairly good (all the data within 10%) and one has to take into account that the largest contribution to the deviations are the systematic errors due to incorrect knowledge of the acceptance, efficiency of the counters and correction for the multiple scattering.

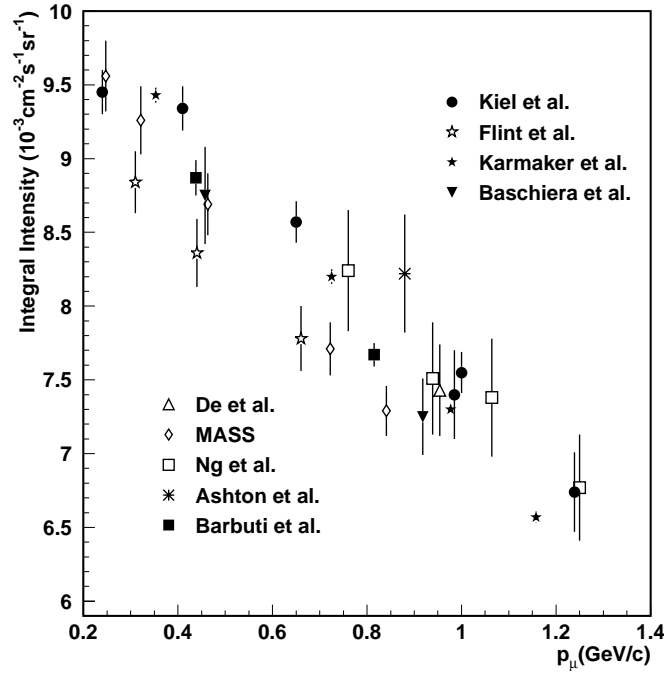


Figure 5: *Integral momentum spectrum of low energy muons at sea level. Data are taken from Kiel<sup>26,32</sup>, Flint et al.<sup>39</sup>, Karmakar et al.<sup>45</sup>, Baschiera et al.<sup>41</sup>, De et al.<sup>46</sup>, MASS<sup>44</sup>, Ng et al.<sup>40</sup>, Ashton et al.<sup>42</sup>, Barbuti et al.<sup>43</sup>.*

For energies  $E_\mu > 1$  TeV direct measurements of the muon flux were made

at highly inclined directions using large magnetic spectrometers [47, 48, 49], large emulsion chambers [50] and EAS arrays [9]. For the discussion of the results we refer to the recent paper [11].

## 3.2 Momentum spectra

These spectra have been measured many times for moments up to  $\sim 100$  TeV/c. Magnetic spectrometers are mainly used at low and intermediate energies, while observations at high energies are made close to the horizontal directions at ground level or deep underground. The latter are indirect measurements, since the ground level spectra have to be extracted from underground data. We will consider here only ground level and underground observations.

### 3.2.1 Ground level measurements

Direct measurements of momentum spectra for  $p_\mu < 1$  TeV/c are important for the comparison of nuclear cascade models with available data. Furthermore by extending the model results to higher energies one can hope to be able to evaluate prompt muon production and/or charm production. In the momentum region 10 GeV/c - 1 TeV/c: a) the production spectrum of the charged pions cannot be represented by a power law but has a maximum at an energy that depends on both the altitude and the latitude b) the energy loss and the decay of muons must be properly considered. In order to join low to high momentum spectra it is important to have single experiments that cover the widest energy range.

To better see the differences between the sea-level spectra we plot in Fig. 6 the percentage deviations of the data from the best fit spectrum obtained by [51]. Notice that even if individual errors are small (however increasing with momentum due to decreasing number of detectable particles and to the maximum detectable momentum), deviations up to  $\pm 20\%$  are observed probably because of systematic effects.

### 3.2.2 Underground measurements

From underground muon intensity measurements, informations about sea-level muon spectra can be obtained using different procedures (see for ex-

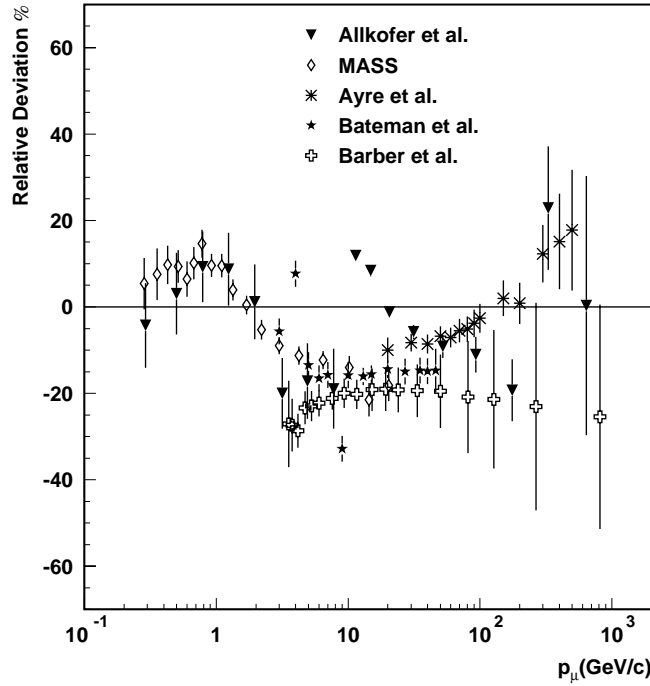


Figure 6: *Relative deviation of the differential muon spectra with respect to the Kiel fit* <sup>51</sup>. The data are taken from Allkofer et al. <sup>51</sup>, MASS <sup>44</sup>, Ayre et al. <sup>52</sup>, Bateman et al. <sup>53</sup>, Barber et al. <sup>54</sup>.

ample [5, 6]). Here and in the following, we assume a standard procedure applied from large area underground experiment [8, 7]. The vertical muon intensity, for a given direction  $\theta, \phi$  and a corresponding rock slant depth  $h$  can be expressed as:

$$I_\mu^V(h, \theta, \phi) = \left( \frac{1}{\Delta T} \right) \frac{\sum_i N_i m_i}{\sum_j \Delta \Omega_j A_j \epsilon_j / \cos \theta_j} \quad (3)$$

where  $\Delta T$  is the total livetime of the experiment,  $N_i$  is the number of detected events with multiplicity  $m_i$  in the angular bin  $\Delta \Omega_j$ ,  $A_j$  and  $\epsilon_j$  are, respectively, the geometrical and intrinsic acceptance of the detector. The relation between the measured  $I_\mu^V(h)$  and the sea-level muon spectrum can be expressed as:

$$I_\mu^V(h) = \int_0^\infty \frac{dN_\mu}{dE_\mu d\Omega} P(E_\mu, h) dE_\mu, \quad (4)$$

where  $P(E, h)$  is the muon survival probability function determined via Monte Carlo. Assuming for the sea-level muon spectrum an expression of the form (2), leaving as free parameters the muon spectral index and a normalization constant, it is possible to unfold sea level muon spectrum from the measured absolute muon intensity.

In Fig. 7 are reported the results of the fit of MACRO data [8] together with LVD [7], MSU [6] and Baksan [5] data. Data are presented multiplied by factor  $p^3$  to better observe the variation of the spectrum in the whole energy region and to strengthen a possible flattening in the tail of the spectrum due to charm production. The statistics is still too poor to allow any definite assessment on the existence of this effect at energies  $> 10$  TeV/c.

In indirect measurements, accurate estimates of the systematic errors are needed. The main sources of systematics in (4) are the knowledge of the rock density overburden and the treatment of hard processes in the energy loss of muons in the rock. In the MACRO fit, for example, their overall contribution has been estimated to be  $\sim 5\%$  and  $3\%$  in the determination of the normalization constant and muon spectral index respectively.

### 3.3 Charge ratio

In the primary cosmic rays there is an excess of positively charged particles (protons) with respect to the total number of nucleons. This excess is transmitted via nuclear interactions to pions and further to muons. By assuming that the primary composition is constant in the energy range considered, this ratio will remain constant with the exception of high energies, where the contribution from kaons starts to become sizeable. The muon charge ratio is expected to increase also with zenith angle as the depth is increasing and likewise the energy of the primaries that produce muons of a given momentum at ground. This quantity is important to study nucleon-nucleon interactions, composition and kaon contribution. Magnetic spectrographs are used for determining this ratio. Because of systematic effects in the momentum measurement the values are usually much spread out. Moreover limited statistics at high energy makes it difficult to appreciate the energy dependence. We report in Fig. 8 only the recent data from Mass [44] at lower momenta,

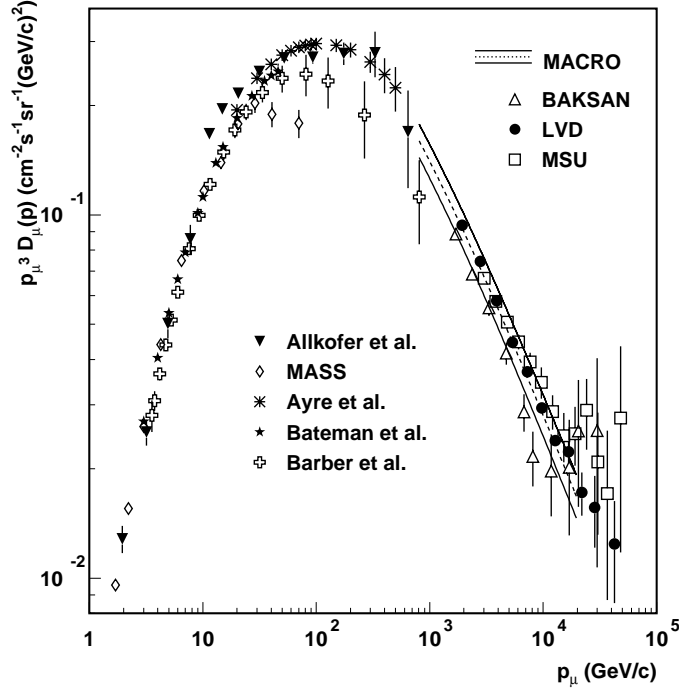


Figure 7: *Vertical differential momentum of muons at sea level. Direct data extend up to 1 TeV and are taken from [allkofer, depascale, barber, bateman, ayre]. Indirect data obtained from underground observations for  $E > 1$  TeV/c are taken from Baksan <sup>5</sup>, LVD <sup>7</sup>, MSU <sup>6</sup>, and MACRO fit <sup>8</sup>, with the two parallel lines indicating the range allowed by the errors of the fit parameters.*

and the two compilations made by [55]. It is clear more measurements with longer exposures are still needed.

## 4 Conclusions

Since atmospheric muons and neutrinos are generated in the same processes, the accuracy of the neutrino flux calculation can be improved by forcing the poorly known input parameters of the cascade model to fit the data on the muon flux.

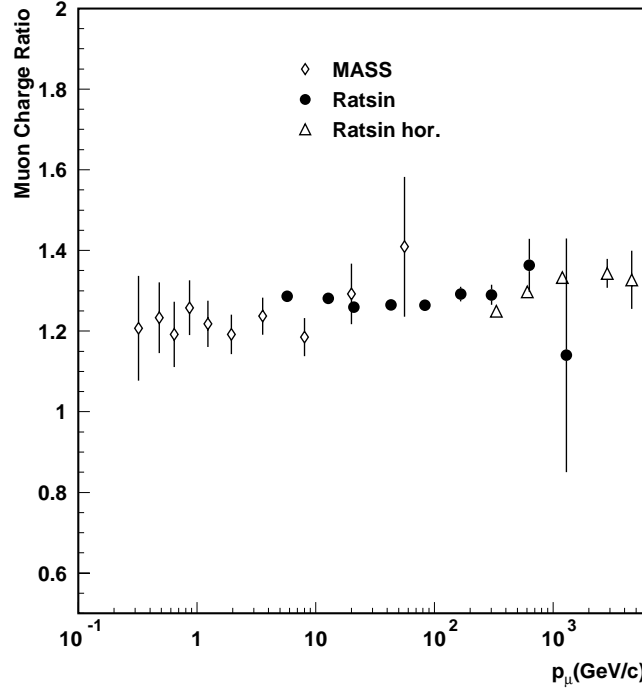


Figure 8: *Ratio  $\mu^+/\mu^-$  at sea level. The data have been taken from MASS <sup>44</sup>, Ratsin <sup>55</sup>.*

However, the data are still not sufficient for this purpose, since several sea level measurements of the vertical muon flux are in poor agreement with one another, even though each experiment has typically very good statistics.

Disagreement between the results of different experiments are present even if the quoted errors are relatively small in the majority of the experiments. It indicates the existence of significant systematic errors in some experiments by as much as 30-35% at momenta from 10 to 1000 GeV/c.

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