A new interpretation of the high energy atmospheric muon charge ratio

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Abstract. We present a review of past measurements of the vertical atmospheric muon charge ratio above 1 TeV. In particular we focus on the latest OPERA data which confirm with a higher statistical significance a drop of the charge ratio above $\sim 3$ TeV. We attempt to interpret the result in terms of possible physical mechanisms that could manifest itself in this energy region.

1. Phenomenological models

The atmospheric muon charge ratio at sea level $R_{\mu}$ is defined as the number of positive over negative muons. It was extensively studied in the past since it is an highly informative observable for cosmic rays and particle physics. Atmospheric muons are mainly generated by the decay of charged mesons (typically $\pi^\pm$ and $K^\pm$ mesons) which are produced in the hadronic cosmic ray interactions some tens of km above the sea level. The phenomenological description of the evolution of $R_{\mu}$ as a function of the muon energy is a quite complex process as it involves several ingredients at the same time. Since atmospheric neutrinos share the same production mechanisms with muons a careful study of the muon charge ratio may provide new information on the high energy part of the atmospheric neutrino spectrum.

Past derivations of the atmospheric muon charge ratio can be found in [1, 2] and more recently in [3]. The starting point is the so called “all-proton” and “all-neutron” spectra. Since at high energy collective nuclear effects can be neglected in the production of secondaries what really matters are the proton and neutron fluxes as a function of the energy per nucleon. Then one has to solve a set of coupled diffusion equations to obtain the meson fluxes which can be convoluted to the kinematics of two-body decay to obtain the final lepton fluxes (muon or neutrinos). A simplified expression for muons which takes into account both low and high energy approximations is derived in [4] and can be expressed as

$$\Phi_{\mu} = \frac{\Phi_N(\mathcal{E}_\mu)}{1 - Z_{NN}} \sum_{\text{par}} a_i Z_{Ni} \left( 1 + b_i \mathcal{E}_\mu / \epsilon_i(\theta) \right)$$

where $\Phi_N(\mathcal{E}_\mu) \simeq \Phi_0\mathcal{E}_\mu^{-(\gamma+1)}$ is the primary spectrum of nucleons (evaluated at the muon energy in the atmosphere $\mathcal{E}_\mu$) with a spectral index $\gamma + 1 \simeq 2.7$. For each of the $N_{\text{par}}$ muon parents ($\pi$, $K$, charmed particles etc.) the constants $a_i$ and $b_i$ contain the kinematical factors for the
decay into muons, $\epsilon_i(\theta)$ are the critical energies defined as the energies above which interaction processes dominate over decay. They depend on the ratio $m_i/\tau_i$ (mass over rest lifetime of the muon parent) and on the atmospheric profile density and therefore on the zenith angle $\theta$.

The angular dependence of the critical energies may be expressed as $\epsilon_i(\theta) = \epsilon_i(0)/\cos \theta^*$ where $\cos \theta^* = f(\theta)$ is the zenith angle evaluated at the muon production point. Using this expression in Eq. 1 it becomes clear that the proper variable which describes the evolution of $R_\mu$ with the energy is $E_\mu \cos \theta^*$ and not simply the muon energy.

The spectrum weighted moments are defined as:

$$Z_{ij} = \int_0^1 \frac{1}{\sigma_{ij}} \frac{d\sigma_{ij}}{dx_{lab}} (x_{lab})^{-1} dx_{lab}$$

where $\sigma_{ij}$ is the inclusive cross-section for the production of a particle $j$ from the collision of a particle $i$ with a nucleus in the atmosphere and $x_{lab} = E_j/E_i$ is the energy fraction carried by the secondary particle. Use of the $Z$ factors shows explicitly that particle production in cosmic ray cascades is concentrated in the forward fragmentation region at large $x_{lab}$. At this level it is important to note that the explicit form of Eq. 1 was obtained assuming the validity of the Feynman scaling which is known to hold with good approximation in the fragmentation region.

Neglecting for the moment the charm contribution in Eq. 1 we see that the $R_\mu$ evolution with the energy results from the competition of the pion and kaon decays as a function of the energy. At high energy the kaon contribution to muon production is larger due to their larger critical energies. On the other hand the kaon charge ratio is larger than the pion charge ratio since only positive kaons exhibits the associated strange production

$$p + \text{air} \rightarrow K^+ + \Lambda + X$$

which does not have a counterpart for negative kaons. The net result is that $R_\mu$ is predicted to mildly increase at high energy reaching an asymptotic plateau above some TeV.

2. Experimental data at high energy

We selected data from experiments which explicitly provided their results in terms of the variable $E_\mu \cos \theta^*$. Below 1 TeV we used data from L3+C [5], CMS [6] and MINOS-ND [7]. Above 1 TeV we used data from the underground Čerenkov detector Kamiokande-II [8], the liquid scintillator detector LVD [9], and the magnetic spectrometers of UTAH [10], MINOS-FD [11] and OPERA [12]. MINOS-FD data reported in [7] were grouped in two high energy bins. Data are jointly displayed in Fig. 1 with a fit to Eq. 1 with different models of charm production [13, 14].

OPERA data were updated with a threefold statistics with respect to Ref. [12]. Details of the analysis are in [15]. In that paper a comprehensive discussion and evaluation of the main sources of systematic errors is presented, namely the bias introduced by the alignment of the spectrometers (the dominant source) and the knowledge of the charge misidentification probability. A drop in the new OPERA $R_\mu$ data above a few TeV is still clearly visible with a larger statistical significance. In the next section we discuss three physical scenarios which could be responsible for this unexpected behaviour. In doing so we implicitly assume that the observed anomaly is not a detector artifact (e.g. related to the acceptance) nor it is due to an unaccounted systematic error.

3. Interpretation of the results

We focus on three potential sources of a sizeable decrease of the charge ratio value at high energy. What should also be considered here is the sharpness of the $R_\mu$ reduction which demands the sudden emergence of a physical process able to explain it.
Figure 1. The result of the fit of OPERA and CMS data to Eq. 1 is shown by the continuous line. The dashed, dotted and dash-dot lines are, respectively, the fit results with the inclusion of the RQPM, QGSM [13] and VFGS [14] models for prompt muon production in the atmosphere. Red line is a fit to function (4).

3.1. All-nucleon spectrum
One possibility is a sharp change in the primary cosmic ray composition above few tens of TeV/nucleon. Recent data from ATIC [16], CREAM [17] and PAMELA [18] suggest an increasing contribution of helium and heavier components in the range 10-100 TeV/n. About 80% of muons with \( E_\mu \cos \theta^* > \sim 3 \) TeV are generated in primary interactions in this energy range. When plotted as \( n/p \) ratio these data show a mild increase from 20% up to 30% which is unable to explain the drop in the OPERA charge ratio measurement.

Anti-protons in the primary radiation could also strongly affect the atmospheric muon charge ratio [19]. A sizeable anti-proton component in this energy region is excluded by ARGO-YBJ data which constrain the \( \bar{p}/p \) ratio below 5% around 10 TeV/n [20].

3.2. Feynman Scaling Violation
The asymptotically constant behavior of \( R_\mu \) follows from the assumption of a meson production cross section which does not depend from the energy itself but only on \( x_{\text{lab}} \). This assumption is strongly violated in the central region of the interaction but it is supposed to hold with good approximation in the forward fragmentation region up to the highest energies. Recent data from BRAHMS at RHIC [21] in a phase space region partially overlapping with the one of interest have become available. The charge separated \( \pi \)'s and \( K \)'s spectra at \( \sqrt{s} = 200 \) GeV up to rapidities \( \sim 3 \) are well reproduced by cosmic ray interaction models as DPMJET. In the past
several models of Feynman Scaling Violation (FSV) were evoked to explain some experimental data of atmospheric muon charge ratio (see e.g. [22]). Using a simplified model we found that the drop in the OPERA $R_\mu$ value could be reproduced only with a sharp artificial transition of the $Z_{NK^+}/Z_{NK^-}$ ratio from 2.2 down to 1.25 around $E_\mu \cos \theta^* \sim$3 TeV. A possible reason for this sudden drop would be a reduction of $K^+$ associated production in favour of heavier flavor production in the forward region.

3.3. Heavy flavors

The search for heavy flavor components in the atmospheric muon spectrum has a long history. Heavy flavors are dynamically suppressed with respect to lighter mesons and therefore their cross section (and Z-moments) are much smaller than for conventional mesons. Since they decay almost instantaneously they inherit the spectral index of the primary radiation which is a power law harder than for light mesons. Therefore at some energy a cross-over is expected between the conventional muon flux and the “prompt” muon component. Where this cross-over should occur is still largely uncertain. For charmed mesons it is expected to lie between 10 TeV and some hundreds of TeV depending on the model. The explanation of the OPERA $R_\mu$ drop in terms of prompt muon production would require a large charm contribution, even larger than the one predicted by models with Intrinsic Charm components [13]. On the other hand one may suppose a strong FSV in the charm sector with an enhanced production above a threshold energy. OPERA data can be reproduced using Eq. 1 with $Z_{N\pi}$ and $Z_{NK}$ taken from [12] and a trial function of the form

$$Z_{N-charm}(E_\mu) = \begin{cases} Z_{N-charm}^0 & \text{for } E_\mu < E_\mu^0 \\ Z_{N-charm}^0 \left[1 + (E_\mu - E_\mu^0)\Delta\gamma\right] & \text{for } E_\mu > E_\mu^0 \end{cases}$$

(4)

where $Z_{N-charm}^0 = 4 \times 10^{-4}$ is taken from [23], $\Delta\gamma = 1.6$ and $E_\mu^0 = 2.7$ TeV. This additional muon source should be observed as an enhancement of the overall atmospheric muon flux above some TeV, for which there exist some indications in the literature (see e.g. [24] and data compilation in [13]). Note however that the functional form and the values reported above would produce an unphysical muon flux already at energies as large as 10 TeV.

4. Discussion

We reviewed the present knowledge of the atmospheric muon charge ratio for $E_\mu \cos \theta^* > 1$ TeV. New data from OPERA confirm a mild transition between the pion and kaon regions with a sharp drop around 3 TeV. We speculated about possible physical sources of this observation. An interesting possibility could be a FSV for $K^+$ associated production in favor of the opening of charm production above some TeV. This conjecture should be confirmed by experiments measuring the overall muon flux above $\sim$100 TeV and in particular by an enhancement of the atmospheric neutrino flux in the same energy region. It should be noticed that this enhancement was recently excluded by the IceCube experiment which measured the atmospheric neutrino flux up to 400 TeV in agreement with the prediction assuming only the conventional neutrino flux [25].

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