The atmospheric muon charge ratio: a probe to constrain the atmospheric $\nu_\mu/\bar{\nu}_\mu$ ratio

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The atmospheric muon charge ratio, defined as the number of positive over negative charged muons, is an important observable to shed light on the physics of cosmic ray interactions in atmosphere. It allows studying the features of high-energy hadronic interactions in the forward region and the composition of primary cosmic rays. In particular, the TeV muon charge ratio provides sensitivity to the charge ratio of high energy kaons, the principal parents of atmospheric neutrinos. In this paper the results from the OPERA experiment in the TeV energy range are reviewed.

1 Introduction

The atmospheric muon charge ratio $R_\mu \equiv N_{\mu^+}/N_{\mu^-}$ is studied and measured since many decades over a wide muon energy range, from few GeV up to several TeV. It provides relevant information on both cosmic rays and particle physics through its dependence on several aspects: primary chemical composition and energy spectrum, hadronic interactions features and, at very high energy, production and prompt decays of charmed particles.

Atmospheric muons constitute the penetrating charged remnants of cosmic rays under the Earth's surface. They are produced when primary cosmic rays, typically protons, impinge on the Earth's atmosphere starting a particle cascade, in which secondary particles decay into muons (and muon neutrinos):

$$N + \mathrm{air} \rightarrow \pi^\pm, K^\pm(, D^0, D^\pm, \Lambda_C \ldots) \rightarrow \mu^\pm \overset{(-)}{\nu}_\mu$$

In the energy range up to $\sim$100 GeV atmospheric muons come mostly from the decay of secondary pions. At higher energies, the kaon contribution to the muon flux increases, reaching the asymptotic value of 27% at about 10 TeV [1]. The pion and kaon components constitute the *conventional* muon flux. At even higher energies, at $\mathcal{O}(100)$ TeV, also charmed hadron decays are expected to contribute (*prompt* muon component).

Atmospheric muon neutrinos share the mesonic origin with atmospheric muons, $\pi^\pm, K^\pm \rightarrow \mu^\pm\ \nu_\mu(\bar{\nu}_\mu)$, but the kaon and pion contributions are quite different due to the kinematics of their two-body decays. The muon carries most of the energy in pion decay ($m_\pi \gtrsim m_\mu$), so pions are the dominant parents for atmospheric muons (Fig. 1, left panel). Due to the different kaon decay phase space ($m_K \gg m_\mu$), kaons are more efficient than pions in producing neutrinos and their contribution is $\sim$ 80% above $\mathcal{O}(1)$ TeV (Fig. 1, right panel).

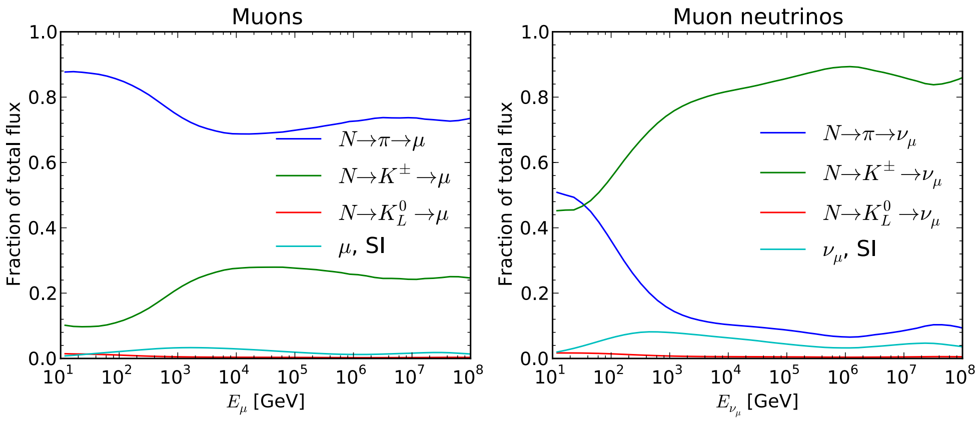

Figure 1: Conventional contributions to atmospheric muon and muon neutrino fluxes as a function of energy [2]. The steepness of the primary spectrum suppresses the contribution of secondary interactions (SI).

The results on the atmospheric muon spectrum and charge ratio are essential for a precise prediction of the atmospheric neutrino flux. This is needed both in the low energy range (from MeV to TeV) for detailed measurements of neutrino oscillations and mass hierarchy in atmospheric neutrino experiments and in the high energy range (from GeV to PeV) for background evaluation in the search for astrophysical neutrinos at neutrino telescopes. Moreover, the muon charge ratio in the TeV range allows to constrain the kaon production in a phase space inaccessible to collider and fixed target experiments, so it represents an important benchmark for neutrino flux calculations and the predicted $\nu_\mu/\bar{\nu}_\mu$ ratio.

In the following Secs. the key features of the atmospheric lepton flux parameterizations and charge ratio are recalled, then experimental results on the muon charge ratio in the TeV energy range are reviewed.

2 Inclusive production of atmospheric muons and neutrinos

The atmospheric leptons detected at the Earth's surface and underground are produced in the forward fragmentation region, with a large Feynman $x = E_{meson}/E_{nucleon} \approx E_{lepton}/E_{nucleon}$. Assuming scaling of particle production in the forward region, the inclusive fluxes of muons and muon neutrinos are well described by [1]

$$\Phi_l(E_l) = \frac{\Phi_N(E_l)}{1 - Z_{NN}} \sum_{i=1}^{N_{par}} \frac{a_{il}\, Z_{Ni}}{1 + b_{il}\, E_l \cos\theta^*/\varepsilon_i}$$

where $\Phi_N(E_l) \simeq \Phi_0 E_l^{-(\gamma+1)}$ is the spectrum of primary nucleons (evaluated at the lepton energy in the atmosphere E_l) with spectral index $\gamma + 1 \simeq 2.7$. The sum is over the contributions of lepton parents, i.e. charged pions, kaons, charmed particles, etc. The constants a_{il} and b_{il}

contain the kinematic factors for the i-th parent decay into lepton l. The critical energy $\varepsilon_i/\cos\theta^*$ is defined as the energy for meson i above which interaction processes dominate over decay, and θ^* is the zenith angle at the lepton production point.

The spectrum weighted moments for secondary particle production are defined as:

$$Z_{ij} = \frac{1}{\sigma_{ij}} \int_0^1 \frac{d\sigma_{ij}(x)}{dx} x^\gamma dx$$

where σ_{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 $x = E_j/E_i$ is the energy fraction carried by the secondary particle. In the scaling approximation the particle production depends only on x and not explicitly on the energy. The approximation is valid since it holds in the forward fragmentation region, which is enhanced by the x^γ weighting. Using the Z factors makes explicit that the particle production in cosmic ray cascades is concentrated in the forward fragmentation region at large x.

For each i-th contribution to the muon flux, at energies below the critical energy ε_i most mesons decay and the lepton flux follows the same power law of primary cosmic rays. For $E_\mu \gg \varepsilon_i(\theta)$, the meson interations dominate, so the energy spectrum steepens by one power and the relative contribution is suppressed. Therefore each contribution to the muon charge ratio produced by different muon parents can be disentangled by studying the muon charge ratio as a function of the "vertical surface energy" $E_\mu \cos\theta^*$.

Considering only the conventional π and K parent mesons, the inclusive muon flux separated for μ^+ and μ^- is given by

$$\Phi_{\mu^\pm}(E_\mu) \propto \left(\frac{a_\pi Z_{N\pi^\pm}}{1 + b_{\pi\mu} E_\mu \cos\theta^*/\varepsilon_\pi} + \frac{a_K Z_{NK^\pm}}{1 + b_{K\mu} E_\mu \cos\theta^*/\varepsilon_K} \right)$$

The increasing kaon contribution to the muon flux in the range between 100 GeV and the TeV, $\varepsilon_\pi < E_\mu \cos\theta^* < \varepsilon_K$, is therefore explained by the two energy scales which determine the pion and kaon contributions, $\varepsilon_\pi \simeq 115$ GeV and $\varepsilon_K \simeq 850$ GeV.

These energies have to be compared with the corresponding value for charmed particles, $\varepsilon_X > 10^7$ GeV. The prompt muon component is therefore isotropically distributed since the corresponding $\cos\theta^*$ factor is suppressed, at least in the TeV region.

2.1 Parameterization of the muon charge ratio

The atmospheric muon charge ratio is larger than unity because the primary cosmic rays are mostly protons, favoring the production of π^+ and K^+ over π^- and K^- in the forward region. Each meson is likely to have an energy close to the one of the primary nucleon (high x_F) and comes from its fragmentation (valence quarks, majority of u), therefore the positive charge excess is preserved.

Considering the pion component, the isospin symmetry $Z_{p\pi^+} = Z_{n\pi^-}$ (i.e. the inclusive π^+ spectrum from protons is equal to the π^- spectrum from neutrons) allows expressing the pion contribution to the muon charge ratio in terms of the fraction of positive pions f_{π^+}, depending only on Z factors and the primary proton excess $\delta_0 = (p-n)/(p+n)$ [3]. Assuming Feynman scaling, the charge ratio does not depend on the energy E_μ nor E_π. The constant value of the muon charge ratio measured over the 10–100 GeV energy range, where almost only pion contribute, is an experimental evidence of the validity of the Feynman scaling in the forward region, see Sec. 3.

The kaon component does not have the same isospin symmetry between positive and negative kaons. The associated production $N + \mathrm{air} \rightarrow \Lambda\, K^{+}(+\ \mathrm{anything})$, which has no analog for K^{-}, largely favors K^{+} over K^{-} ($Z_{pK^+} \gg Z_{nK^-}$), therefore the K^{+}/K^{-} ratio is larger than the π^{+}/π^{-} ratio [1]. Hence the muon charge ratio increases with the increasing kaon contribution. An analytical description of the contributions in terms of δ_0, f_{π^+} and kaon Z factors is given in Ref. [3], and used by the OPERA Collaboration to extract the Z_{pK^+} factor (see Sec. 3.1). The associated production process and Z_{pK^+} in particular cannot be constrained by accelerator experiments (high pseudo-rapidity regions), and the Monte Carlo predictions by various hadronic interaction generators differ up to several factors. This has a strong impact on the evaluation of the flux of TeV atmospheric neutrinos, which are dominated by kaon production.

Summarizing, in order to disentangle the different parent components to the muon flux (π, K, charm) the correct variable to describe the evolution of R_μ is the vertical surface energy $E_\mu \cos\theta^*$ [4], as seen in Sec. 2. This approach assumes a constant primary composition. If the energy dependence of the proton excess δ_0 in the primary cosmic rays is considered, the parameterization described in Ref. [3] should be used. Since δ_0 depends on the primary nucleon energy, which has an almost linear relation with the muon energy ($E_N \simeq 10\, E_\mu$ for TeV muons [3]), the dependency on the surface muon energy E_μ and the zenith projection $\cos\theta$ should be considered separately, see Sec. 3.1.

3 Measurements of the atmospheric muon charge ratio

In the pion dominated energy region ($E_\mu \lesssim 100$ GeV), the muon charge ratio R_μ has been measured by several experiments on surface, by balloon-borne detectors and at shallow depths [5]. Its value is constant, $R_\mu \simeq 1.27$, as expected assuming the validity of Feynman scaling in the fragmentation region [1].

The increasing kaon contribution from a few hundred GeV to a few TeV causes a smooth transition to a higher value of the muon charge ratio, $R_\mu \simeq 1.38$. Recent results were presented by the CMS [6], MINOS [7, 8] and OPERA [9, 10] Collaborations in this energy range, around vertical surface energy $E_\mu \cos\theta^* \sim 1$ TeV. Underground experiments naturally select high energy down-going muons and the minimum energy threshold is fixed by the rock overburden surrounding the detector. The evaluation of the muon surface energy E_μ depends on the rock depth crossed by the muon coming from a particular direction and therefore the distribution of $E_\mu \cos\theta^*$ is related to the shape of the overburden.

Key elements for the accurate determination of the muon charge and momentum in the $\mathcal{O}$(TeV) energy range are magnetized detectors and large depth. MINOS and OPERA are long-baseline neutrino experiments located deep underground, while CMS is a collider experiment located at shallow depth but provided with an intense magnetic field. In the following Section the results from the OPERA experiment will be reviewed.

3.1 OPERA results

The OPERA experiment is a hybrid electronic detector/emulsion apparatus exposed to the CNGS neutrino beam from 2008 up to 2012. It is located in the underground Gran Sasso laboratory, at an average depth of 1400 m of rock corresponding to 3800 m.w.e. OPERA is the deepest experiment able to measure charge-separated atmospheric muons. The minimum surface muon energy threshold is ∼1 TeV (1.4 TeV averaged over all the directions and rock depths). The detector is composed of two identical parts, called supermodules, each consisting of a target section and a magnetic spectrometer. The target consists of scintillator strips interleaved with Emulsion Cloud Chambers, the spectrometer is a large dipole iron magnet instrumented with Resistive Plate Chambers. The magnetic field is almost uniform, with intensity 1.53 T, and directed along the vertical axis with opposite orientations in the two magnet arms. A muon crossing the spectrometer is deflected in the horizontal plane. The deflection is measured by six stations of vertical drift tubes, the Precision Trackers (PT), grouped in 3 pairs placed upstream of the first arm, in between the two arms and downstream of the second arm. The charge and momentum reconstruction is performed for tracks crossing at least one magnet arm using the angle $\Delta\phi$ in the bending plane, i.e. the difference between the track directions reconstructed by two PT stations before and after each magnet arm. For nearly horizontal muons up to four bending angles can be measured in the two dipole magnets.

Cosmic ray induced events in OPERA are reconstruted with a dedicated software procedure effective at identifying single and multiple muon tracks (*muon bundles*). Due to the charge-symmetry of the dipole magnet, the acceptance for μ^+ and μ^- is the same and, depending on the track topology, the maximum detectable momentum varies from a few hundred GeV/c up to 1 TeV/c [11, 10]. Data were collected with both magnetic field polarities in order to minimize systematic errors due to misalignment of PT stations.

OPERA reported a first measurement of the atmospheric muon charge ratio using the 2008 Run data [9] and the final results using the complete statistics from 2008 up to 2012 [10]. In the latter analysis the two data sets collected with opposite magnet polarities were combined reaching the most accurate measurement to date of R_μ in the TeV energy region. The muon charge ratio was computed separately for single muons, $R_\mu(n_\mu = 1) = 1.377 \pm 0.006\,(stat.)^{+0.007}_{-0.001}\,(syst.)$, and for muon bundles, $R_\mu(n_\mu > 1) = 1.098 \pm 0.023\,(stat.)^{+0.015}_{-0.013}\,(syst.)$. This is the first observation of a decrease in the charge ratio of high multiplicity events with respect to single muon events. The dilution effect in R_μ is expected since the multiple muon sample selects events generated by heavier primary cosmic rays and secondaries with a low value of Feynman-x_F, coming from the central region [11]. Recently also the MINOS Collaboration provided a measurement of the multiple-muon charge ratio, $R_\mu(n_\mu > 1) = 1.104 \pm 0.006\,(stat.)^{+0.009}_{-0.010}\,(syst.)$ [12], in agreement with the OPERA result.

Thanks to the Gran Sasso orography, the amount of rock crossed by muons is not directly related to the zenith angle, and the high energy tail is not completely suppressed by the $\cos\theta$ factor. OPERA presented results on R_μ (for single muons) as a function of the vertical surface energy $E_\mu \cos\theta^*$, fitting data to the parameterized model described in Ref. [4]. The atmospheric muon charge ratio was measured in a large $E_\mu \cos\theta^*$ range, from 500 GeV up to $\sim$ 10 TeV, and plotted in Fig. 2. With an average value $\langle E_\mu \cos\theta^* \rangle \simeq 2$ TeV, OPERA is the magnetized experiment measuring the charge ratio at the largest vertical surface energy. The fit of OPERA and L3+C data, shown in Fig. 2, yields the fractions of charged mesons decaying into positive muons $f_{\pi^+} = 0.5512 \pm 0.0014$ and $f_{K^+} = 0.705 \pm 0.014$. The prompt muon component does not significantly contribute to R_μ up to $E_\mu \cos\theta^* \lesssim 10$ TeV.

Taking into account the possible variation of the primary cosmic ray composition requires to disentangle the energy and zenith angle dependencies [3], as seen in Sec. 2.1. The fit in two dimensions $(E_\mu, \cos\theta^*)$ yields the proton excess in primary cosmic rays $\delta_0 = (p - n)/(p + n) = 0.61 \pm 0.02$ at primary energy $\langle E_N \rangle \approx 20$ TeV/nucleon, and the spectrum weighted moment related to the associated kaon production, $Z_{pK^+} = 0.0086 \pm 0.0004$. The Z_{pK^+} factor, here

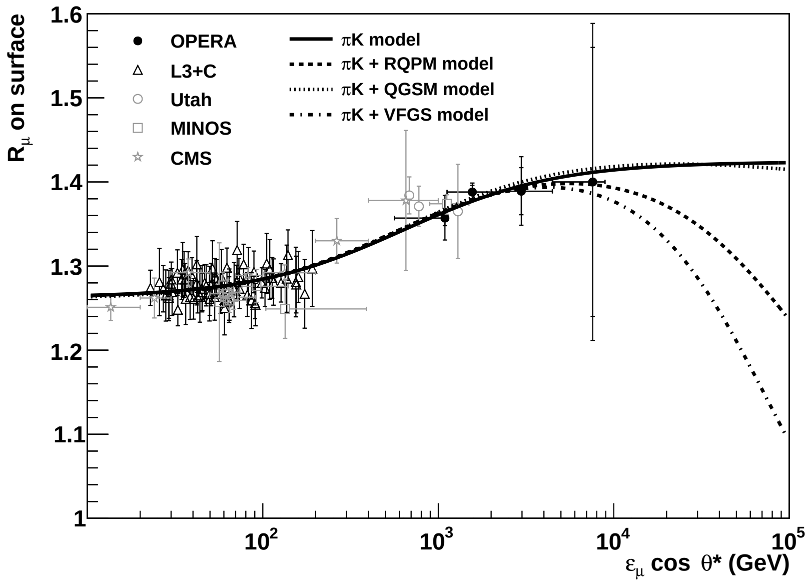

Figure 2: The atmospheric muon charge ratio measured by OPERA (*black points*) as a function of $E_\mu \cos\theta^*$. OPERA and L3+C data are fitted together and the fit result is shown by the continuous line [10]. Results from MINOS Near and Far Detectors [7, 8] and CMS [6] are also shown.

determined for the first time, allows to predict the atmospheric $\nu_\mu/\bar{\nu}_\mu$ ratio in the TeV range: the expected ratio for muon neutrinos increases from $\nu_\mu/\bar{\nu}_\mu \approx 1.5$ at low energy to ≈ 2.3 above a TeV [13].

4 Conclusions

The results on the atmospheric muon charge ratio from the OPERA, MINOS and CMS experiments show an increase of R_μ as a function of the vertical surface energy $E_\mu \cos\theta^*$ in the range between hundreds GeV and a few TeV. The measurements of OPERA in the TeV energy region are compatible with a simple parametric model where the rise is due to the increasing kaon contribution to the muon flux. No significant contribution from charm decay is observed up to energies ∼10 TeV. A future experimental measurement of R_μ in the region $E_\mu \cos\theta^* > 10$ TeV, with a new detector at very large depths, could shed light on the prompt component even before the crossover between conventional and prompt muon fluxes.

The OPERA measurement of R_μ in the highest energy range to date allows to constrain the associated kaon production $\Lambda\, K^+$ in high energy primary interactions in the forward region. The result attains to a phase space inaccessible to accelerator experiments (high $x_F \leftrightarrow$ high pseudo-rapidity). It determined for the first time the spectrum weighted moment Z_{pK^+}, fundamental to accurately predict the atmospheric $\nu_\mu/\bar{\nu}_\mu$ ratio [13]. The Z_{pK^+} factor was extracted together with the primary proton excess δ_0, which is consistent with direct measurements of the primary composition [3]. The energy behaviour of R_μ measured by OPERA above a few TeV, compatible with the plateau corresponding to the asymptotic kaon contribution, supports the validity of Feynman scaling in the fragmentation region up to primary energies/nucleon around 200 TeV.

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