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Impact of using the data-driven Daemonflux model on CORSIKA simulations of atmospheric muons in KM3NeT

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Muons, created in interactions of cosmic rays (CRs) with the Earth's atmosphere, are the main component of cosmic ray air showers which reach underwater or in-ice neutrino telescopes such as KM3NeT and IceCube. Measurements of such muons provide crucial information about the properties of cosmic rays, and their interactions with the atmosphere. The KM3NeT research infrastructure includes two telescopes in the Mediterranean Sea which are partially installed and already operational. The KM3NeT/ORCA detector is deployed at 2450 m depth near Toulon, France. The KM3NeT/ARCA telescope is located at 3500 m depth off-shore Capo Passero, Italy. Previous comparisons of the atmospheric muon rate between the data collected by KM3NeT/ORCA (KM3NeT/ARCA) and CORSIKA simulations show a 40% (up to 80%) disagreement, with the simulations underestimating the data. The simulations were performed using the Sibyll 2.3d model for high-energy hadronic interactions and the Global Spline Fit (GSF) model for the primary CR fluxes and mass composition. Recently, a data-driven model, known as Daemonflux, derived from cosmic ray, accelerator, and surface muon data was proposed to help ameliorate the disagreement. In this study, we estimate the impact of correcting the simulations using the muon flux obtained from the Daemonflux model. We show that these corrections significantly increase the atmospheric muon flux in CORSIKA simulations and can potentially alleviate the disagreement seen in previous comparisons between KM3NeT data and CORSIKA simulations.

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PoS(PIC2024)073

1. Introduction

The KM3NeT experiment employs two neutrino telescopes in the Mediterranean Sea, namely, KM3NeT/ORCA for neutrino oscillation and mass-ordering measurements, and KM3NeT/ARCA for neutrino astronomy studies [1]. For atmospheric muon studies, the key differences between the two detectors are the depths at which they are located, and their configuration, size and hence their energy thresholds. The KM3NeT/ORCA detector is located off the French shore about 40 km from Toulon and at a depth of about 2450 m. It is smaller and denser compared to the KM3NeT/ARCA detector, since the observation of neutrino oscillations and the determination of mass hierarchy require a lower energy threshold. KM3NeT/ARCA, on the other hand, is located at a depth of about 3500 m off the shore of Capo Passero in Italy. The primary goal of KM3NeT/ARCA is to study cosmic neutrinos in the TeV-PeV energy range. In the final configuration of the detector, KM3NeT/ARCA is designed to comprise two building blocks, whereas KM3NeT/ORCA is planned to be a single-block detector. The single-block configurations for the two detectors are denoted by ARCA115 and ORCA115, where 115 denotes the number of lines in the block. Both detectors are currently operational in the ORCA24 and ARCA33 configurations.

When cosmic rays interact with the Earth's atmosphere, muons are created. Muons created with sufficiently high initial energies reach the detectors. These atmospheric muons dominate the number of reconstructed events in both KM3NeT detectors. Precise measurements of these atmospheric muons can shed light on the composition of cosmic rays and their early interactions with the atmosphere. Given that atmospheric muons also form a dominant background for searches for neutrinos, it is imperative to simulate them with high precision and accuracy. A recent comparison between the ORCA6 and ARCA6[1] data and CORSIKA simulations [2] of atmospheric muons showed a disagreement of about 40% and 60%, respectively [3]. The main hypothesis to explain this deficit is an incomplete understanding of the primary flux and mass composition of CRs and their hadronic interactions with the atmosphere. In order to test this hypothesis, we study a data-driven flux of atmospheric muons at sea level, known as Daemonflux [4], and estimate its impact on the disagreement between data and simulations. In the following study, no new data is used in comparison to [3], but we show that the use of the Daemonflux model significantly improves the agreement between data and simulation, while also reducing the systematic uncertainties on the simulations.

2. Simulations of atmospheric muons in KM3NeT

For this work, the simulation of atmospheric muons is initiated in the upper atmosphere and terminated deep underwater. The initial step deals with the interaction of the primary CRs with the air nuclei, which progresses to an extensive air shower (EAS). This step is performed using the CORSIKA package. The two crucial inputs are the primary CR flux and mass composition, and the hadronic interaction model (HIM) which describes their interaction with the air nuclei. The five nuclei used as primaries in the CR flux are proton, helium, carbon, oxygen, and iron. All the other elements were accounted for by adjusting the flux weights of carbon, oxygen, and iron. The data-driven GSF [5] is used to describe the CR mass composition.

[1] ARCA6 and ORCA6 denote the configuration of the detectors with six working lines each.

PoS(PIC2024)073

Sibyll 2.3d [6] has been chosen as the second key ingredient, since it incorporates the most recent experimental constraints from the Large Hadron Collider. The differences between the different choices of the HIM are usually treated as systematic uncertainties. The output of the CORSIKA simulation is the muon flux at sea level. The muons are then propagated down to the detectors using the gSeaGen code [7] with PROPOSAL [8] as the muon propagator. The last step, which involves the simulation of the Cherenkov radiation, its detection by the optical modules of the detector, as well as the muon track reconstruction, is performed using internal KM3NeT software. While CORSIKA provides very detailed simulations for atmospheric muons, it is heavy on computing resources if large statistics of high energy muons need to be generated. In order to mitigate this, an alternative fast MC generator known as MUPAGE [9] is used in KM3NeT. It generates the kinematics of single-muon and multi-muon bundles at different zeniths, energies, and depths using parametric formulae. For this work, the MUPAGE parameters are adjusted to reproduce the CORSIKA expectations. Therefore, MUPAGE tuned on CORSIKA can be used as a quicker alternative to a full simulation with CORSIKA using Sibyll 2.3d and GSF.

3. Daemonflux-based corrections to CORSIKA

As seen above, an input for simulations is the primary flux and mass composition of the CRs, and their hadronic interactions with the atmosphere. The Daemonflux model provides a data-driven estimate of the atmospheric muon flux at sea level which covers the energy range from a few GeV to a few PeV. Furthermore, it also uses the rigorously-estimated uncertainties from these experiments in order to provide a systematic uncertainty on the atmospheric muon flux. For this work, we compare the atmospheric muon flux provided by Daemonflux and Sibyll 2.3c + GSF[2] [10] in a grid of energy spanning the range $1 - 10^6$ GeV, and zenith angle spanning the range $0 - 90$ deg. These calculations were performed using the MCEq package [11] which also includes the Daemonflux model. A generic atmospheric profile is used for these calculations, and only conventional atmospheric muon fluxes are considered. In the case of ORCA6, 90% of the events were found to lie in the primary CR energy range from 3 TeV to 320 TeV, while, for ARCA6, 90% of the events were contained in the range from 4 TeV to 1 PeV. On the other hand, the prompt component resulting from decays of charmed mesons is expected to be dominant only at muon energies larger than 10^6 GeV [12, 13] and hence, is not studied in this analysis. Furthermore, it is important to note that MCEq provides fluxes only for single-muon bundles while CORSIKA also provides the fluxes for multi-muon bundles. Using the comparison between Daemonflux and Sibyll 2.3c + GSF (denoted ScGSF below), we define correction factors as

$$CF = \frac{\text{Daemonflux}(E, \theta)}{\text{ScGSF}(E, \theta)} \tag{1}$$

These CFs are computed for the (E, θ) grid mentioned above. It is important to note that the fluxes can be significantly different for μ^+ and μ^-, as shown in Fig. 1. Fig. 1 also shows the μ^+ correction factors as a function of energy for various zenith angles. A 2-dimensional interpolation is then used to obtain a smooth set of CFs as a function (E, θ).

[2]The MCEq package does not provide Sibyll2.3d publicly yet.

PoS(PIC2024)073

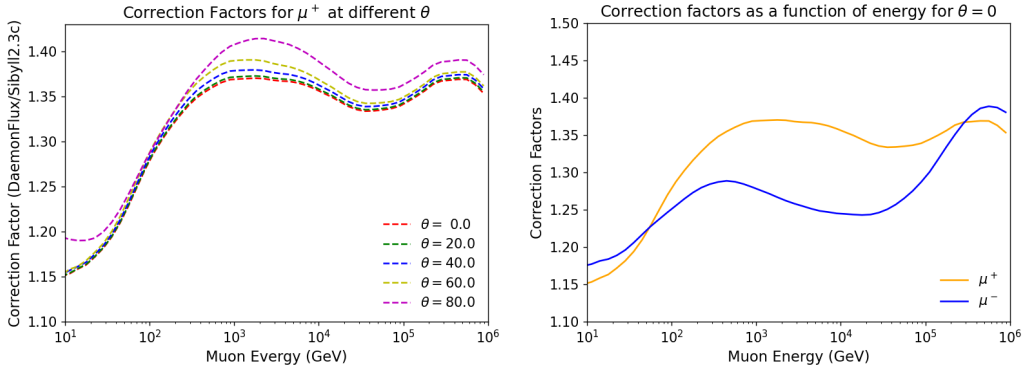

Figure 1: Correction factors as a function of energy for various zenith angles for μ^+(**left**) and a comparison of correction factors for μ^+ and μ^- at $\theta = 0$ as a function of energy (**right**).

The analysis for KM3NeT uses CORSIKA simulations for ORCA6 and ARCA6. All the events shown in the following results are required to pass quality cuts on reconstructed muons to reject optical backgrounds from bioluminescence and ^{40}K. For each event, a weight is introduced based on the energy and zenith of the muon with the highest energy (leading muon) at sea level. The requirement for this choice arises from the fact that MCEq does not provide fluxes for muon-bundles. Deriving the weight based on the total energy of all muons in a bundle instead of the leading-muon was found to have no significant impact on the results presented in Sec. 4. A comparison is performed between the event rates from the re-weighted CORSIKA (referred

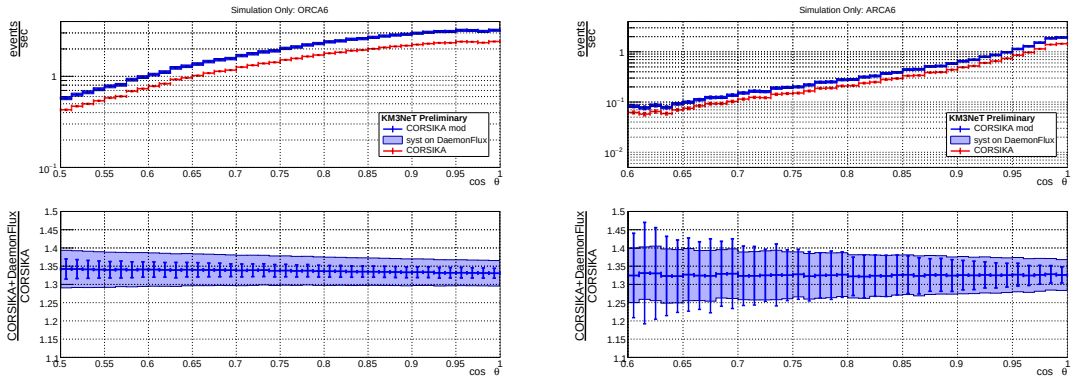

Figure 2: A comparison of the event rates as a function of cos θ between nominal CORSIKA and CORSIKA re-weighted using Daemonflux for ORCA6 (**left**) and ARCA6 (**right**).

to as CORSIKA MOD) and those from the nominal CORSIKA as used in [3]. The resulting correction on the nominal event rates is about 30 – 35%. Furthermore, the Daemonflux package also provides uncertainties on the flux of muons at sea level. Two additional sets of CFs are derived as $\mathrm{CF}_{\mathrm{up/down}}$ = (Daemonflux ± error)/(ScGSF). Using two additional 2-dimensional interpolations, a set of smooth upward and downward CFs are obtained as function of (E, θ). These are used to re-weight CORSIKA event-by-event to obtain systematic errors on the ratio of CORSIKA MOD to CORSIKA of around 7%. The impact of this re-weighting is shown in Fig. 2 for ORCA6 and ARCA6. It is important to note that this comparison is made for $\cos\theta > 0.5$ in the case of ORCA6

PoS(PIC2024)073

and $\cos\theta > 0.6$ in the case of ARCA6. Below these values of $\cos\theta$, there is a discrepancy between true and reconstructed muon populations due to the prevailing mis-reconstructed vertical muons [3].

4. Data and MC with systematics

The ratios obtained from the comparisons between CORSIKA MOD and nominal CORSIKA are then used to re-scale MUPAGE tuned on CORSIKA. The uncertainties of Daemonflux are propagated further as flux uncertainties on MUPAGE, thus replacing the uncertainties on GSF and Sibyll 2.3d. Two other sources for systematic errors are considered: uncertainties on the light absorption length in sea water and on the PMT quantum efficiency. The relative uncertainties on these two sources are the same as those in [3]. The result of correcting CORSIKA and hence MUPAGE is shown in Fig. 3. For ORCA6, the disagreements reduce from about 40% to less than 5% and the flux uncertainties are reduced from about 20% to around 5%. The disagreements for ARCA6 were as high as 80% in some bins. These are now reduced to under 20% and the flux uncertainties are down from around 20% to 7%. The dominant uncertainties are now related to light absorption and PMT efficiency. The disagreements between data and CORSIKA simulations using Daemonflux are well within the systematic uncertainties. It should further be noted that, as in [3], the ratio of data to simulation as well as the total uncertainty for ORCA6 are flat as a function of $\cos\theta$, as opposed to that for ARCA6, could be related to the simulation of water properties.

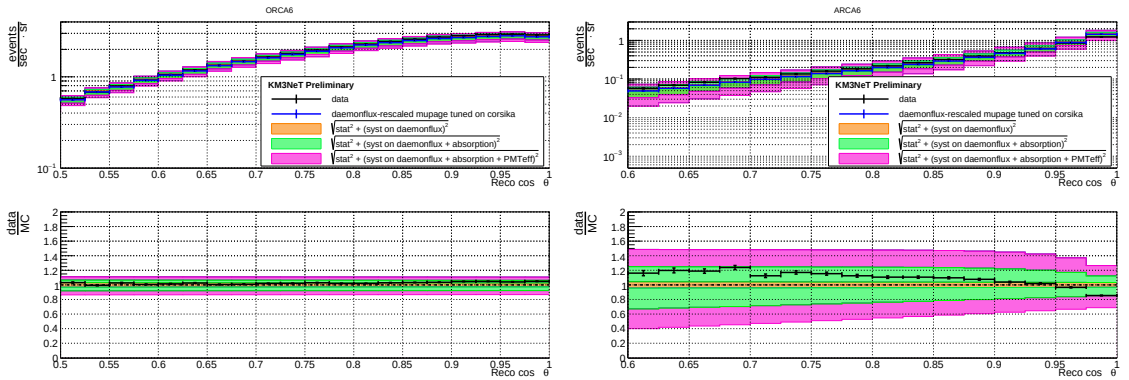

Figure 3: The reconstructed muon rate as a function of the cosine of the zenith angle (top panels) for ORCA6 (**left**) and ARCA6 (**right**). The data points are shown in black while the simulations, rescaled using Daemonflux, are shown in blue. The bottom panels show the ratio of the muon rate in data to that in simulations as a function of the cosine of the zenith angle for ORCA6 (**left**) and ARCA6 (**right**). Statistical uncertainties are shown as vertical error bars. The systematic uncertainties, shown in colored bands, are summed linearly.

To summarize, using the Daemonflux model to re-weight CORSIKA significantly improves the level of agreement with data while also reducing flux and hadronic interaction model uncertainties. The remaining disagreement with ARCA6 data may indicate that the detector response simulation, in particular the light attenuation, could be at the origin of the remaining differences between data and simulations. This study should benefit from using larger detector configurations already deployed in sea, in particular, since they provide a better reconstruction of the muon bundle properties. This study provides additional insights on the cosmic ray showers by testing atmospheric muons reaching

PoS(PIC2024)073

large depths underwater and thus exploring a very different phase space in energy and CR properties than ground-based detectors.

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PoS(PIC2024)073