PROCEEDINGS OF SCIENCE

Rescaling of the muon content of simulated air showers in the context of the Muon Puzzle

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Over the past two decades, multiple astroparticle physics experiments have observed an excess of muons in air shower measurements compared to predictions based on hadronic interaction models calibrated to LHC data. This discrepancy impacts the interpretation of mass composition studies and has deep implications regarding our understanding of hadronic processes at the highest energies. In this work, a Monte Carlo simulation method is proposed, where the longitudinal profiles of simulated and observed air showers are matched in order to estimate the quantity by which the muon content and the Heitler-Matthews β coefficient of a given model must be adjusted to describe the input data. This so-called "Top-Down" method is tested with a mockup dataset composed of air showers simulated at 10 EeV with the Sibyll$\star$ model, for different primaries, and reconstructed with the Pierre Auger Observatory software. Assuming the mass composition fraction measured by the Pierre Auger Observatory at this energy for the Sibyll 2.3d model, the quality of the recovery of the muon signal of the mockup dataset is investigated.

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1. Introduction

Ultra-high energy cosmic-ray (UHECR) experiments rely on several observables from extensive air showers (EAS) to infer on the properties of primaries, such as their mass, their energy or their arrival direction. More specifically, the measurement of the depth of maximum development of EAS $X_{\max}$ plays an important role in mass composition studies as EAS initiated by heavier primaries reach their maximum at shallower atmospheric depths [1]. However, the fluorescence light detection technique used by UHECR experiments to measure the longitudinal profile suffers from a low duty cycle (between 10 and 20%) and at the highest energies, the number of collected events rapidly decreases. To circumvent such a limitation, the 100% duty cycle of ground particle detectors can be taken advantage of to estimate the muon content of air showers, which can be used as another powerful mass discriminator, as heavier primaries generate EAS with a higher muon content [2]. The interpretation of such measurements strongly depends on the hadronic interaction models being considered [3, 4] and therefore, a clear understanding of the physics of EAS is necessary to perform accurate simulations. Nevertheless, since the measurement of the muon content of EAS with energies between 10^{17} and 10^{18} eV published by the HiRes collaboration in 2000 [5], this understanding has been challenged by the existence of a deficit in the number of muons predicted by various hadronic interaction models when compared to measurements. This discrepancy, also sometimes nicknamed Muon Puzzle, has since been firmly established through numerous analyses conducted by the Pierre Auger Collaboration [6–8], as well as by the WHISP group through a combined analysis of the data from multiple experiments [9, 10]. In this work, a top-down simulation scheme similar to the one described in [7] is proposed, which consists in finding simulated showers whose longitudinal profile match the one of observed showers. The underlying idea is that by constraining the longitudinal profile in simulations, we ensure the electromagnetic components of simulated and observed showers are similar. Consequently, any discrepancy in the ground detector signals must originate from the muon component, allowing for a muon rescaling of the simulations to be determined. This simulation scheme is here tested with a mockup dataset generated within the framework of the Pierre Auger Observatory, and produced with the Sibyll⋆ hadronic interaction model [11], which contains an artificially increased number of muons to mimic the observed muon excess. The Sibyll 2.3d model [12] is used to run the top-down simulations and evaluate whether this method accurately retrieves the true mass-dependent muon rescaling factors between the two models. The first section provides a general overview of the top-down simulation chain, followed by a brief description of the mockup dataset to be matched in the second section. Finally, the results concerning the accuracy of the muon content recovery is discussed, focusing on the calculation of the muon rescaling factors and the Heitler-Matthews β coefficient [13], which governs the evolution of the muon content of air showers as a function of the primary mass.

2. The Top-Down simulation chain

As briefly mentioned in the previous section, the main principle behind the top-down simulation approach is to find a simulated shower with a longitudinal profile that closely matches that of the observed shower, whose muon component must be characterized. Figure 1 provides a general overview of the simulation chain. For a given a shower, one-dimensional simulations and

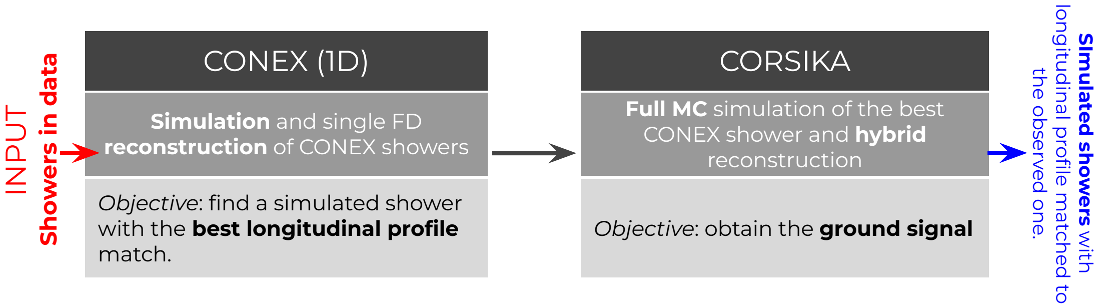

Figure 1: Schematic view of the top-down simulation chain.

reconstructions are performed to identify a shower with a matching profile, which is then resimulated with full three-dimensional information, including the particle distribution at the ground. However, such a method requires a few intermediary steps that are crucial to the validity of the comparison between observed and simulated showers ground signal:

- *Fitting of the atmosphere*: The development of EAS depends on atmospheric properties, which can vary throughout a night of observations. Therefore, top-down simulations must be performed under the same atmospheric conditions as the showers they aim to match. To run these simulations, the air shower simulation code CORSIKA 7.7440 [14] is used, where the atmosphere is modeled with five layers characterized by a set of coefficients. These coefficients are determined by fitting the atmospheric profile retrieved from GDAS database, using the profile measured closest to the observed shower's time and date.

- *Finding a matching profile*: To identify a simulated shower that matches the longitudinal profile of an observed one, numerous simulations are required, demanding significant computing resources. To accelerate this process, the CONEX option in CORSIKA [15] is taken advantage of. It models EAS development in one dimension by solving cascade equations. The observed shower arrival direction and energy, as well as the primary mass, serve as input parameters. In this work, each simulated shower has the same primary as the observed shower it is trying to match: proton showers with protons, helium showers with helium nuclei, and so on. The simulated londitudinal profiles are finally processed with the reconstruction software of the Pierre Auger Observatory and the best-matching CONEX shower is selected based on a χ^2 fit between the simulated and observed profiles.

- *Full Monte Carlo simulations*: Once a matching shower has been identified, it is resimulated using a Monte Carlo approach to obtain the particle distribution at the ground. The shower is reconstructed using the data from both the fluorescence telescopes and the Water-Cherenkow detectors (hybrid mode), and the asymmetry in the reconstruction of the core position is accounted for by performing multiple reconstructions. The same χ^2 fit procedure is applied to find the shower reconstruction with the most similar longitunal profile. From the lateral distribution function of the ground signal in all triggered detectors, the signal $S_{1000,\mathrm{tot}}$ at 1000 m from the shower core is derived and used as an estimator for the shower size.

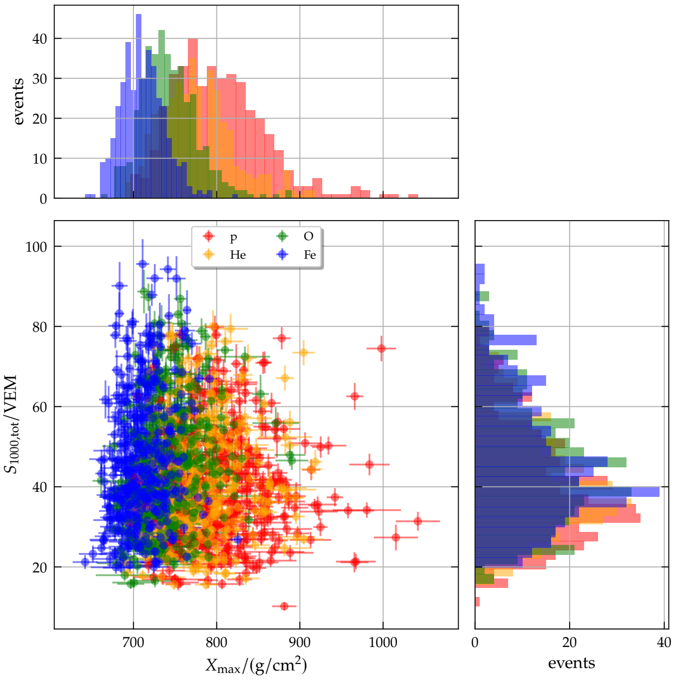

Figure 2: Total signal at 1000 m from the shower core $S_{1000,\mathrm{tot}}$ as a function of the depth of maximum shower development X_{max} for the Sibyll★ mockup dataset. The primaries found in this dataset are represented by different colors.

At the end of the top-down chain, each shower in the Sibyll★ mockup dataset will have a Sibyll 2.3d counterpart, with the same primary mass and a similar longitudinal profile.

3. The mockup dataset

The mockup dataset consists of air showers simulated with the muon-enhanced Sibyll★ hadronic model and processed through a hybrid reconstruction. The energy bin is constrained to the range $10^{18.8}$ to $10^{19.2}$ eV, and to showers with a zenith angle below 60°. To insure that the top-down simulations can effectively reproduce the longitudinal profiles found in this dataset, several quality cuts on the reconstructed profiles are applied: a profile measured over 300 g/cm^2, a Cherenkov fraction less than 20%, high-quality Gaisser-Hillas fit of the profile, and several others. In total, the mockup dataset is constituted of 1600 reconstructed EAS, equally splitted between proton, helium, oxygen, and iron primaries. Figure 2 shows the X_{max} and $S_{1000,\mathrm{tot}}$ distributions of the mockup dataset, heavier primaries producing shallower showers with larger ground signal.

4. Results

The mockup dataset is processed through each steps of the top-down simulation chain described in Section 2. Figure 3 illustrates how well the longitudinal profiles of this dataset are matched using Sibyll 2.3d simulations. Both X_{max} and the calorimetric energy E_{cal} are accurately recovered within the reconstruction uncertainties of the Pierre Auger Observatory (~ 20 g/cm^2 and

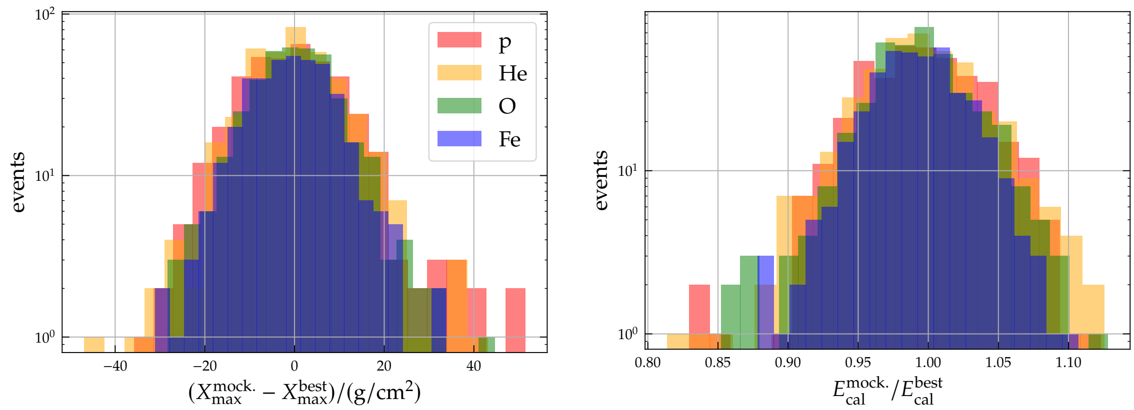

Figure 3: Difference in X_{max} (left) and calorimetric energy ratio (right) of the mockup dataset showers and their corresponding best matched simulations.

$\sim$ 14 %, respectively). At the end of the chain, the total signal at 1000 m $S_{1000,\text{tot}}$ of the simulated shower can be retrieved and compared to that of the shower it has matched. The difference between the two quantities corresponds to the difference in the muon content of the two showers (for the sake of clarity, the *1000* subscript is dropped):

$$S_{\text{tot}}^{\text{mock.}} - S_{\text{tot},i}^{\text{sim.}} = S_{\mu}^{\text{mock.}} - S_{\mu,i}^{\text{sim.}}, \tag{1}$$

where i is the primary mass for which the simulations were run. If the muon content of simulations needs be rescaled to accurately describe that of the mockup dataset, one can express this as:

$$S_{\mu}^{\text{mock.}} = r_{\mu,i} S_{\mu,i}^{\text{sim.}}, \tag{2}$$

where $r_{\mu,i}$ is the muon rescaling factor of a given primary. Combining these two equations gives:

$$r_{\mu,i} = 1 + \frac{S_{\text{tot}}^{\text{mock.}} - S_{\text{tot},i}^{\text{sim.}}}{S_{\mu,i}^{\text{sim.}}}. \tag{3}$$

The quantities in Equation 3 are fully accessible for both mockup datasets or for real hybrid events. Indeed, in simulated showers the muon signal can be directly obtained from the corresponding traces in the Water-Cherenkov detector photomultipliers. The first row of Table 1 presents the average rescaling factor values for all considered primaries, calculated using Equation 3. Depending on the primary, the muon content predicted by the Sibyll 2.3d model would have to be scaled by a factor between $\sim$ 1.40 and 1.45 to accurately describe the Sibyll★ mockup dataset. The advantage of

	proton	helium	oxygen	iron
$\langle r_\mu \rangle$	1.41 ± 0.04	1.40 ± 0.04	1.45 ± 0.04	1.44 ± 0.04
$\langle r_\mu^{\text{true}} \rangle$	1.41 ± 0.03	1.40 ± 0.03	1.43 ± 0.03	1.42 ± 0.03

Table 1: Rescaling factors and true muon signal ratios between Sibyll 2.3d and Sibyll★, as described in the text. The reported uncertainties are statistical.

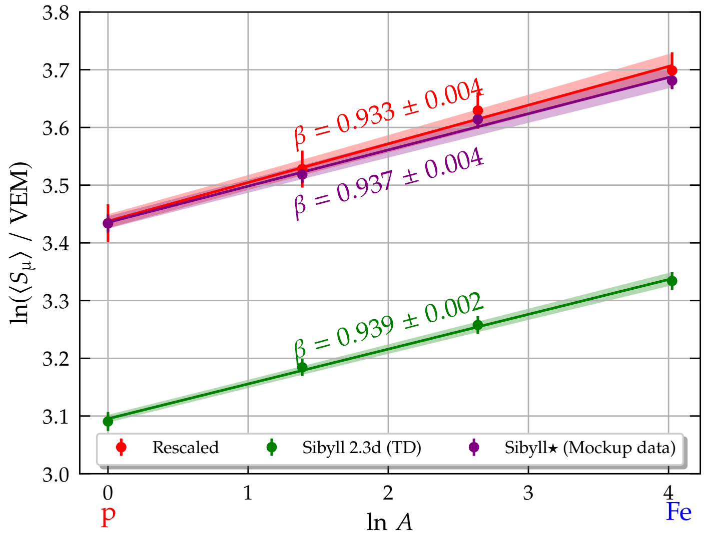

Figure 4: Evolution of the average muon signal as a function of the primary mass for the Sibyll⋆ mockup dataset (purple), the Sibyll 2.3d top-down simulations (green) and the rescaled Sibyll 2.3d top-down simulations (orange).

working with a mockup dataset is that the muon signal can be directly extracted from the showers, which is not possible when analizing real vertical hybrid events. This enables the true rescaling factors between the Sibyll 2.3d and the Sibyll⋆ models to be computed, defined as the ratio of the muon signals predicted by both models for a given primary. These ratios are presented in the last row of Table 1. Within statistical uncertainties, the true ratio and the rescaling factors obtained through the top-down method show remarkable agreement. Finally, in Figure 4, the evolution of the average muon signal as a function of the primary mass is shown for both the mockup dataset and the Sibyll 2.3d top-down simulations. The slope of this evolution corresponds to the Heitler-Matthews β coefficient introduced in Section 1. When the expectactions from the Sibyll 2.3d simulations are scaled by the rescaling factors listed in the first row of Table 1, the resulting trend (orange) closely matches the true trend from Sibyll⋆. Moreover, the excellent agreement between the true β value (purple) and the one obtained through the top-down method (orange) further highlights the robustness of this approach.

5. Summary and Outlook

A top-down simulation scheme was developed to quantify the rescaling of the muon content in air showers predicted by hadronic interaction models. When tested on a mockup dataset composed of air showers simulated with the muon-enhanced Sibyll⋆ mdodel, the method demonstrated excellent recovery of both the average muon signal and the Heitler-Matthews β coefficient. Ongoing work focuses on implementing a new approach to conceal the event-by-event composition of the mockup dataset, paving the way for the application of this method to real events, and to newly released hadronic interaction models.

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References

[1] Pierre Auger Collaboration, *Measurement of the mass composition of ultra-high-energy cosmic rays at the Pierre Auger Observatory*, *POS(ICRC2023)* **365** (2023).

[2] K. H. Kampert and M. Unger, *Measurements of the cosmic-ray composition with air shower experiments*, *Astroparticle Physics* **35(10)** (2012) 660

[3] R. Ulrich, R. Engel, and M. Unger, *Hadronic multiparticle production at ultrahigh energies and extensive air showers*, *Physics Review D* **83** (2011) 054026

[4] T. Pierog, *Hadronic Interactions and Air Showers: Where Do We Stand?*, *EPJ Web Conf.* **208** (2019) 02002

[5] T. Abu-Zayyad, *et al.*, *Evidence for Changing of Cosmic Ray Composition between* 10^{17} *and* 10^{18} *eV from Multicomponent Measurements*, *Physics Review Letters* **84** (2000) 1347

[6] Pierre Auger Collaboration, *Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events*, *Physics Review D* **91** (2015) 032003.

[7] Pierre Auger Collaboration, *Testing Hadronic Interactions at Ultrahigh Energies with Air Showers Measured by the Pierre Auger Observatory*, *Physics Review Letters* **117** (2016) 192001.

[8] Pierre Auger Collaboration, *Direct measurement of the muonic content of extensive air showers between* 2×10^{17} *and* 2×10^{18} *eV at the Pierre Auger Observatory*, *European Physical Journal* **80** (2020) 751.

[9] H. Dembinski, *et al.*, *Report on Tests and Measurements of Hadronic Interaction Properties with Air Showers*, *EPJ Web Conf.* **210** (2019) 02004

[10] D. Soldin, *et al.*, *Update on the Combined Analysis of Muon Measurements from Nine Air Shower Experiments*, *POS(ICRC2021)* **349** (2021).

[11] F. Riehn, A. Fedynitch, and R. Engel, *Sibyll★*, *Astroparticle Physics* **160** (2024) 102964

[12] F. Riehn, *et al.*, *Hadronic interaction model Sibyll 2.3d and extensive air showers*, *Physics Review D* **102** (2019) 063002

[13] J. Matthews, *A Heitler model of extensive air showers*, *Astroparticle Physics* **22(7-8)** (2005) 387

[14] D. Heck, *et al.*, *CORSIKA: a Monte Carlo code to simulate extensive air showers*, *Report FZKA 6019* (1998)

[15] T. Bergmann, *et al.*, *One-dimensional hybrid approach to extensive air shower simulation*, *Astroparticle Physics* **26(6)** (2007) 420