Rescaling of the muon content of air shower simulations in the context of the Muon Puzzle

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What is this study about?

Several UHECR experiments have reported a muon deficit in air shower simulations compared to measurements[1], requiring a model-dependent rescaling of the predicted muon content and known as the Muon Puzzle of extensive air showers. This work presents a simulation approach that matches the longitudinal profiles of an air shower dataset with simulations to identify the muons as sole responsible for any discrepancy found in the signal of particle ground detectors. Using a mock dataset of known composition simulated within the Pierre Auger Observatory[2] framework, and considering the Sibyll 2.3d[3] hadronic interaction model, we recover the true rescaling factors of said model, as well as the Heitler-Matthews β coefficient[4] of the mock dataset.

1. Top-Down simulation chain

The Top-Down (TD) method[5] involves matching the longitudinal profiles of an input and a simulated shower to achieve the same electromagnetic component in both. For each shower in the mock dataset, the steps are:

1. Extraction of the atmospheric profile.
2. Simulation and reconstruction of 1-D showers to find the best matching longitudinal profile.
3. Full Monte Carlo simulation and reconstruction of the best shower to obtain ground signal distribution.

Mock data shower →

CONEX

Simulation and **reconstruction** of 1-D showers

Objective: find a simulated shower with a **similar longitudinal profile** and save its parameters.

→

CORSIKA

Full MC simulation of the best CONEX shower and reconstruction

Objective: obtain the **ground signal** in particle detectors.

→ **Reconstructed shower** matched to the mock one.

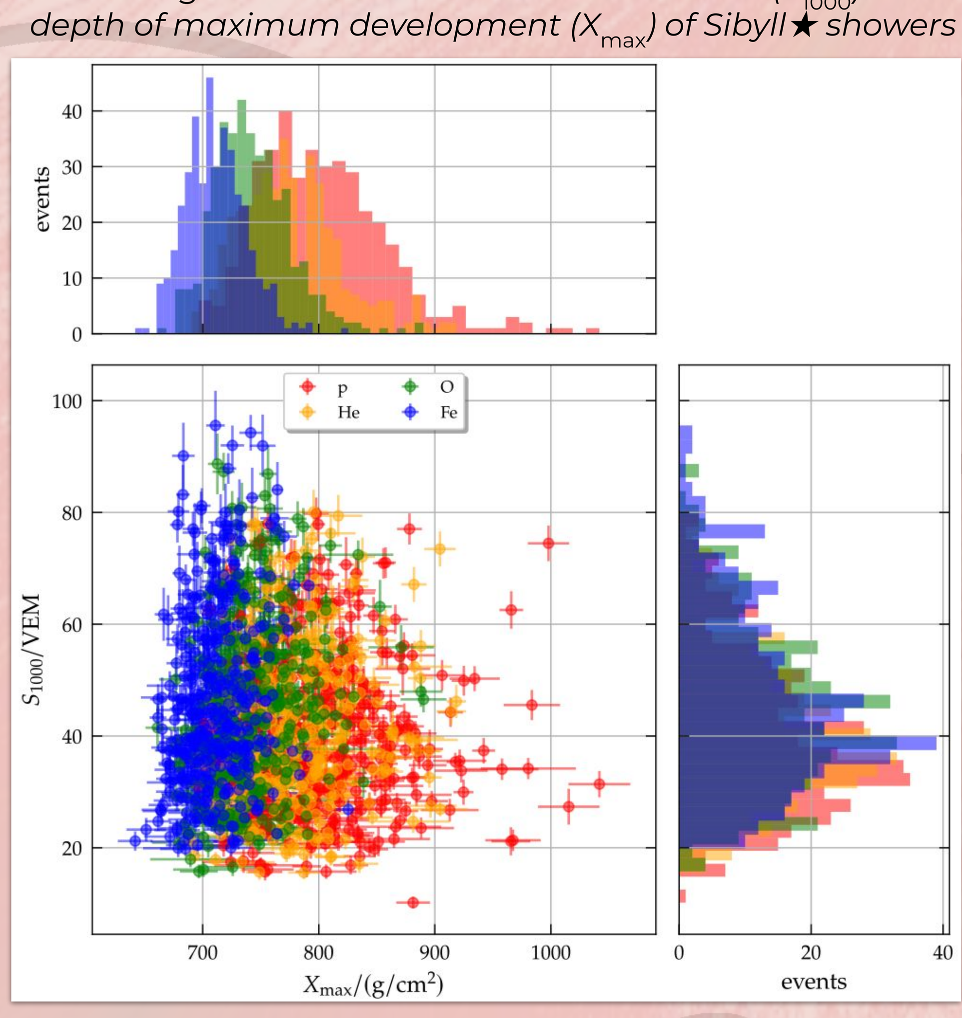
Flow chart of the Top-Down simulation chain

2. The Mock Dataset

The mock dataset consists of air showers simulated with the muon-enhanced Sibyll★ hadronic model[6] and reconstructed with the Pierre Auger Observatory.

- **Primaries**: proton, helium, oxygen and iron.
- **Energy**: 18.8 < lg(E/eV) < 19.2
- **Zenith angle**: below 60°
- **Atmospheres**: 4 seasons
- **1600 events** (400/primary)

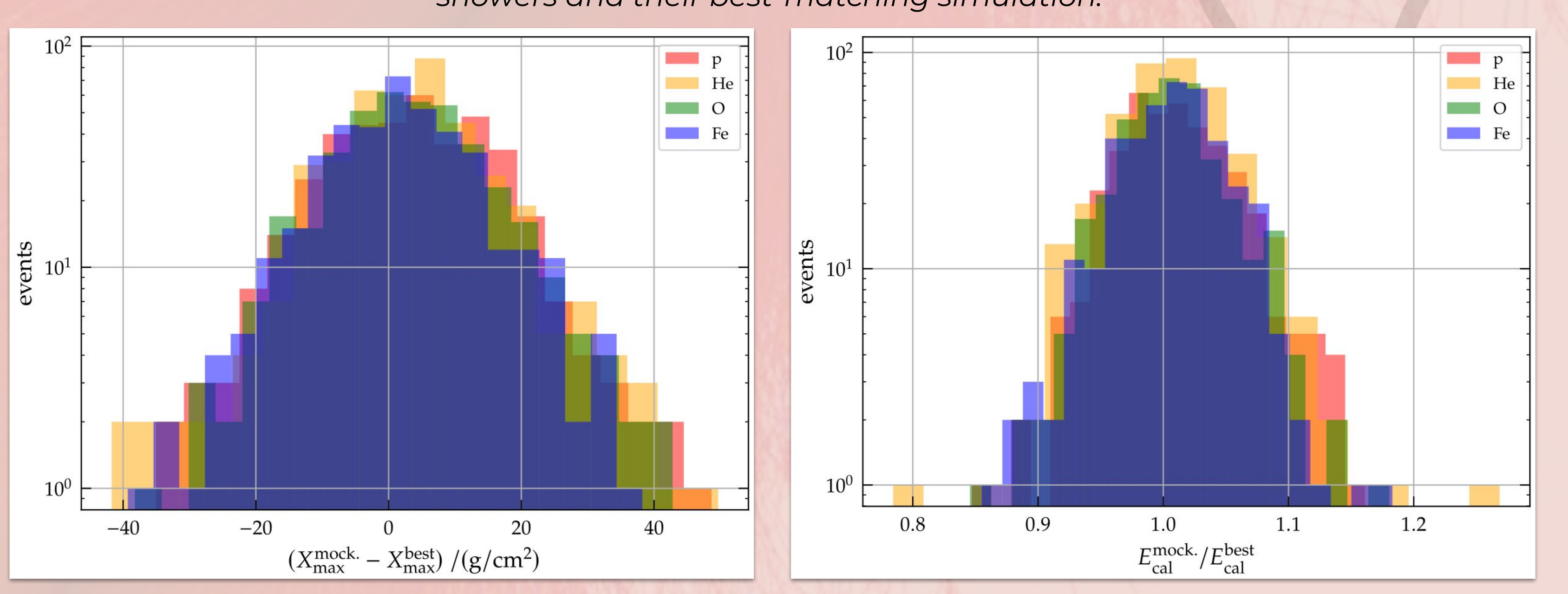
Total signal at 1000 m from the shower core (S_{1000}) vs. depth of maximum development (X_{max}) of Sibyll★ showers



3. Simulated air showers

The mock dataset is processed through the top-down simulation chain using CORSIKA 7.7440[7] and Sibyll 2.3d model, with the simulated primary matching that of the selected shower in the mock dataset. Asymmetry in the core reconstructions is accounted for.

Difference in reconstructed X_{max} (left) and calorimetric energy ratio (right) between the Sibyll★ mock showers and their best-matching simulation.



4. Muon signal and rescaling factors

The total (*left*) and muon (*right*) signals at 1000 m from the shower core are estimated from the lateral distribution fit and the station traces, respectively.

$\langle S_{1000,tot}\rangle$ [VEM]	proton	helium	oxygen	iron
Sibyll★ (mock.)	39.95 ± 0.70	41.91 ± 0.69	45.07 ± 0.74	46.78 ± 0.80
Sibyll 2.3d (MC)	30.95 ± 0.59	32.04 ± 0.56	33.31 ± 0.60	34.29 ± 0.61

$\langle S_{1000,\mu}\rangle$ [VEM]	proton	helium	oxygen	iron
Sibyll★ (mock.)	30.99 ± 0.49	33.73 ± 0.49	37.12 ± 0.43	39.69 ± 0.59
Sibyll 2.3d (MC)	21.99 ± 0.36	24.15 ± 0.36	25.99 ± 0.40	28.05 ± 0.43

➢ The top-down paradigm allows us to write the average rescaling factor of primary i as:

$$\langle r_{\mu,i}\rangle = 1 + \frac{\langle S^{mock.}_{1000,tot}\rangle - \langle S^{MC}_{1000,tot,i}\rangle}{\langle S^{MC}_{1000,\mu,i}\rangle}$$

True ratio: $$\langle r_{\mu,i}\rangle = \frac{\langle S^{mock.}_{1000,\mu,i}\rangle}{\langle S^{MC}_{1000,\mu,i}\rangle}$$

➢ We obtain an **excellent agreement** between true and TD factors.

Rescaling factors	proton	helium	oxygen	iron
True	1.41 ± 0.03	1.40 ± 0.03	1.43 ± 0.03	1.42 ± 0.03
From TD	1.41 ± 0.04	1.41 ± 0.04	1.45 ± 0.04	1.44 ± 0.04

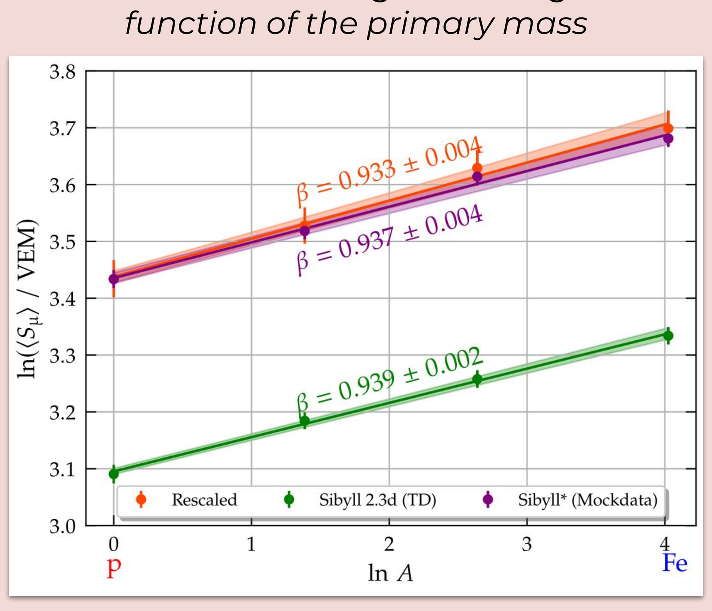
Statistical errors are reported in all tables.

5. Heitler-Matthews β coefficient

The **Heitler-Matthews β** coefficient represents the rate of change in muon content relative to the primary mass.

Key result: The β coefficient of the **mock dataset** is accurately recovered through the **rescaling** of the chosen **hadronic model** used in the TD chain.

Evolution of the average muon signal as a function of the primary mass



Summary & Outlook

➢ A top-down simulation scheme was developed to quantify the rescaling of the muon content of air showers predicted by hadronic interaction models.

➢ An excellent recovery of the average muon signal and of the Heitler-Matthews β coefficient is observed when testing the method on a mock dataset.

➢ Ongoing implementation of a new method allowing to 'hide' the event-by-event composition of the mock dataset.

➢ Application of the method to real events.

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