*Acta Physica Polonica B Proceedings Supplement* **18**, 5-A24 (2025)

# THE TOP–DOWN RECONSTRUCTION ALGORITHM AND ITS APPLICATION TO DEEP EXTENSIVE AIR SHOWERS*

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*Received 18 February 2025, accepted 4 April 2025,*

The Top–Down reconstruction chain is a Monte Carlo simulation scheme that focuses on reconstructing observed extensive air showers while accounting for the muon discrepancy between the observed and simulated events. With the help of this algorithm, we try to reconstruct a particularly unique air shower observed by the Pierre Auger Observatory. The uniqueness of this observation lies in the very large depth of its maximum. We have modified the Top–Down chain to accommodate this unique event and present the Top–Down simulated events, which are the best match to the air shower studied.

DOI:10.5506/APhysPolBSupp.18.5-A24

## 1. Introduction

The Pierre Auger Observatory employs hybrid detection for a deeper study of extensive air showers (EAS) produced by ultra-high-energy cosmic rays (UHECRs). In this study, I discuss the Top–Down reconstruction algorithm, in particular, a unique extensive air shower observed by the Observatory. In the end, the implications of the study and plans for further analysis are discussed.

## 2. Extensive air showers

When high-energy cosmic rays ($> 10^{15}$ eV) interact with the Earth's atmosphere, they produce cascades of particles called extensive air showers. Studying these EASs is beneficial for the understanding of cosmic rays. The Pierre Auger Observatory [1] aims at studying these EASs to better understand cosmic rays. It consists of fluorescence detectors (FDs), surface

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[*] Presented at the 31st Cracow Epiphany Conference on the *Recent LHC Results*, Kraków, Poland, 13–17 January, 2025.

detectors (an extensive array of water Cherenkov detectors and scintillator detectors), and other detectors. Some important observables about the EAS are as follows [2]:

— Energy of the primary particle: this energy can be estimated from the total energy deposited by the secondary particles.

— Arrival direction: this is reconstructed from timing information at the detector stations.

— Mass composition: this is determined from other important key observables such as the muon content and $X_{\mathrm{max}}$.

For this particular study, $X_{\mathrm{max}}$ is a significantly important observable. The rate at which the EAS develops in the atmosphere is dependent on the mean free path of the particles in the atmosphere. Therefore, as a parameter, we use the atmospheric depth (measured in g/cm$^2$) as an observable called $X$. Figure 1 refers to a hybrid detection by the Pierre Auger Observatory. The energy deposit as a function of the slant height is called the longitudinal profile of the shower. You may notice a peak in this longitudinal profile of the EAS. This peak corresponds to the maximum of the shower development. The depth, $X$, at which we notice this maximum development is called $X_{\mathrm{max}}$.

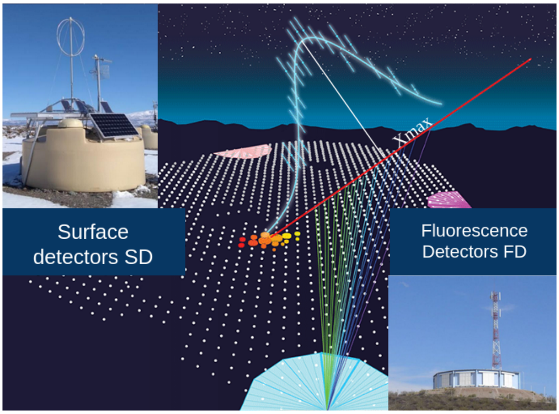


Fig. 1. Detection of a hybrid event by the Pierre Auger Observatory: The dots on the ground represent the array of surface detectors and the semi-circular structures are the fluorescence detectors. The FD measures the energy deposited by the EAS as it develops in the atmosphere. The depth at which it reaches the maximum development is called the $X_{\mathrm{max}}$.

## 3. Muon puzzle

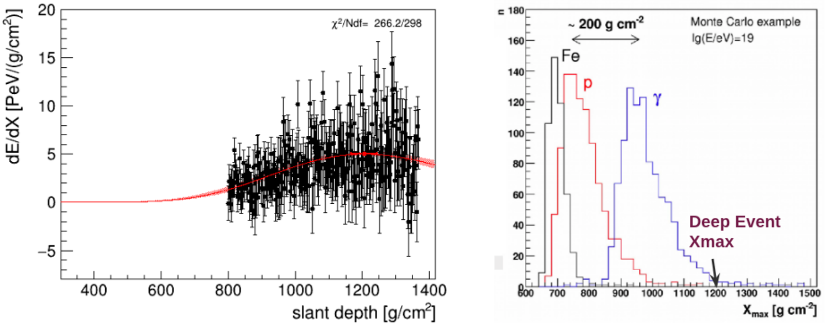
A significant issue that we encounter in our studies of EAS is the muon puzzle [3]. It has been noted that there is a discrepancy in the muon content between observations and predictions made by hadronic interaction models. The hadronic interaction models significantly underestimate the muon numbers, and the issue becomes significant at ultra-high energies. This discrepancy is known as the muon puzzle.

## 4. Top–Down reconstruction algorithm

Reconstructions of the EAS involve simulations, which implies that the muon puzzle is inherited in them. So, the objective of the Top–Down reconstruction algorithm [4] is to address this muon puzzle in its reconstruction process. For this, the algorithm depends on the fact that we understand the electromagnetic component of the EAS well. As mentioned in the previous section, fluorescence detectors measure the energy deposit of the air shower as it travels through the atmosphere. This energy deposit, which is visualized by the longitudinal profiles of the EASs, helps isolate the electromagnetic component of the EAS. For this, we simulate multiple longitudinal profiles and compare their chi-square values. The simulated profile that best matches the observed profile (least chi-square) is chosen. In addition, we do a full EAS simulation of this best-match simulation. The ground-based detectors, on the other hand, detect all the particles that make it to them (electromagnetic and muonic, both). Since we now have the electromagnetic component with high confidence (from the longitudinal profile match), we can subtract the electromagnetic component from the ground-based signals, and the remainder is the muonic component. Any discrepancy remaining between the observed and simulated signal can then be attributed to the muon puzzle. We use this algorithm [5] in this project to analyze a particular EAS.

## 5. The deep event

The EAS discussed below is very unique in nature. Its key features are given in figure 2 (a), alongside its longitudinal profile. The characteristic that makes it unique is its exceptionally large $X_{\max}$ value. From figure 2 (b), it can be noted that the $X_{\max}$ of the event is outside the range of $X_{\max}$ of hadronic primaries. This means *(i)* the EAS penetrated deep into the atmosphere, and its maximum development was observed at a greater depth than normal; *(ii)* it indicates unusual primary composition or even exotic physics. This makes it an interesting and important event to study.



(a) (b)

Fig. 2. Left: Longitudinal profile of the deep event: Energy — $(4.15 \pm 0.39 \pm 0.32) \times 10^{18}$ eV; angle of inclination — $(53.3 \pm 0.6, 355.0 \pm 0.6)$ deg; $X_{\mathrm{max}}$ — $(1205 \pm 38)$ g/cm$^2$. Right: Distribution of $X_{\mathrm{max}}$ for different primaries.

## 6. Reconstruction of the deep event using the Top–Down

For our analysis, we assume that the deep event was hadronic. To begin our analysis using the Top–Down method, the first step involves obtaining a match for the longitudinal profile. However, since we do not know which primary particle in particular it might be, we made 100 longitudinal simulations of different primary particles and compared their chi-square against $X_{\mathrm{max}}$ values. The lighter primaries penetrate deeper, producing larger $X_{\mathrm{max}}$ than the heavier ones. Figure 3 shows a comparison between the $X_{\mathrm{max}}$ values of the simulated longitudinal profiles and their chi-square values. As expected, for this deep event, the agreement is better for lighter primaries, specifically proton, than for heavier primaries. So, in the following analysis, we assume the proton as the primary particle of the event. From figure 3, it can also be observed that for 100 simulations, we were barely able to reach the $X_{\mathrm{max}}$ value of 900 g/cm$^2$. This implies that the Top–Down chain will need to be modified for the analysis of this event.

### *6.1. Modifications to Top–Down*

For an event as unique as this EAS, which is also difficult to simulate, only the chi-square as a quality cut seemed insufficient. So, additional quality cuts were applied to key features such as $X_{\mathrm{max}}$, $E_{\mathrm{cal}}$, d$E$ d$X$, *etc.*, to ensure that the best simulation closely matches the observed event. For reconstructing any typical hadronic event, we would do around 500 longitudinal profile simulations to find a match. However, since this particular event is statistically rare, achieving a satisfactory match in simulations also requires increasing the statistical sample. Therefore, the number of simulations was increased to 100,000 to obtain the best match.

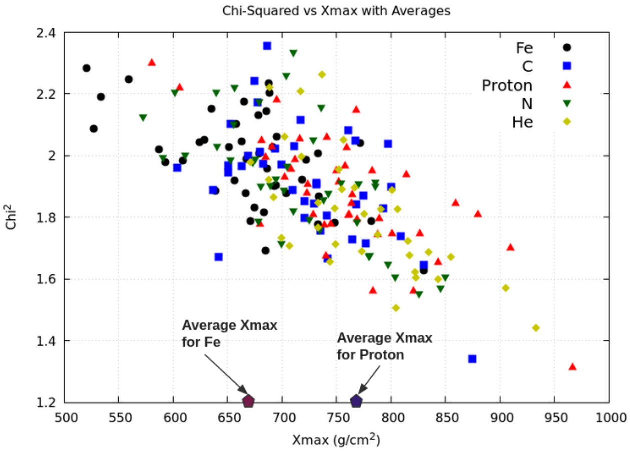


Fig. 3. chi-square *versus* $X_{\max}$ comparison of different primary particles for 100 longitudinal profile simulations.

### 6.2. *The best reconstruction*

Figure 4 shows the best reconstruction of the deep event using the Top–Down reconstruction chain. The $X_{\max}$ values for the reconstruction and the observed event are in agreement with each other. To get the best match for $X_{\max}$ value, 10,000 longitudinal profile simulations were enough. But to get the best match that met all the additional quality cuts mentioned in Section 6.1, we required 100,000 simulations.

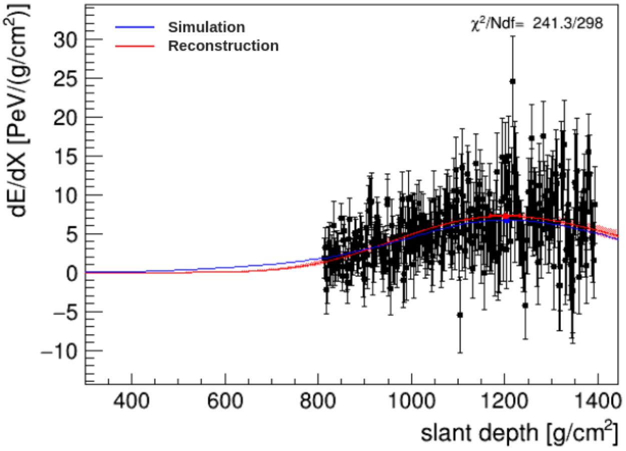


Fig. 4. The best reconstruction after analysis — $X_{\max}$ – $(1201 \pm 31)\,\mathrm{g/cm^2}$.

## 7. Implication of the results

As discussed previously, the deep event is very unique and may suggest some New Physics. However, establishing New Physics requires first ruling out the known physics. With this motivation, the EAS was analyzed using the Top–Down approach, assuming it to be hadronic in nature. We were able to get a satisfactory reconstruction of the event using a proton as the primary particle. This implies that, although less probable, there is still a possibility that the event was induced by a proton primary. Further analysis may include considering other nuclei as primary particles and evaluating the statistical likelihood of each of them being the true primary.

I acknowledge the support from the National Science Centre (NCN) Poland, grants No. 2020/39/B/ST9/01398 and 2022/45/B/ST9/02163 as well as from the Ministry of Science and Higher Education, Poland, grant No. 2022/WK/12.

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