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Nuclear and Particle Physics Proceedings 273–275 (2016) 1271–1275

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Questions and Answers in Extreme Energy Cosmic Rays – a guide to explore the data set of the Pierre Auger Observatory

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Abstract

The Pierre Auger Observatory is the largest extensive air shower detector, covering 3000 km^2 in Argentina. The Observatory makes available, for educational and outreach purposes, 1% of its cosmic ray data set, corresponding after 10 years of running to more than 35 000 cosmic ray events. Several different proposals of educational activities have been developed within the collaboration and are available. We will focus on the activity guide we developed with the aim of exploring the rich education and outreach potential of cosmic rays with Portuguese high school students. In this guide we use the Auger public data set as a starting point to introduce open questions on the origin, nature and spectrum of high energy cosmic rays. To address them, the students learn about the air-shower cascade development, data reconstruction and its statistical analysis. The guide has been used both in the context of student summer internships at research labs and directly in schools, under the supervision of trained teachers and in close collaboration with Auger researchers. It is now available in Portuguese, English and Spanish.

Keywords:
Cosmic Ray, Air Showers, Student Guide, Pierre Auger Observatory

1. Introduction

Cosmic rays are a powerful tool to introduce students to particle physics. They are appealing because they represent a new observation window to astrophysics and, because they cover a wide range of energies and fluxes, their main features can be demonstrated at low energy and then extrapolated to the extremely high energy frontier. In this contribution we focus on the measurements that can be done by students using data collected by a running experiment and made available specifically for outreach and education programs. We present a guide developed to help high school students explore the public data of the Pierre Auger Observatory on extreme energy cosmic rays. At this time there are versions in English, Portuguese and Spanish, that can be accessed on the web [1] or by contact with the authors; a teacher's guide with answers to the proposed questions is also available.

This contribution follows the structure of the guide, discussing the points that should be addressed with students and the reactions obtained from the first users. The first section deals with the general physics concepts and questions, next the Pierre Auger Observatory and its public data set are discussed, and lastly the data analysis is explained together with the expected results. Future plans for new versions and applications are discussed in the outlook section.

2. Cosmic Ray Spectrum and Cosmic Ray Shower Development

The guide starts by introducing the necessity for a large variety of experiments to cover the full cosmic ray spectrum, as shown in figure 1, insisting also on the use of logarithmic scales and proper units. The highest

http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.203

energy cosmic rays have collision energies well above the LHC, and macroscopic beam energies (corresponding to about 1 Joule, unit known to the students) and such low fluxes (of the order of 1/km^2/century) that they can only be detected indirectly, through the extensive air showers they produce in the Earth's atmosphere.

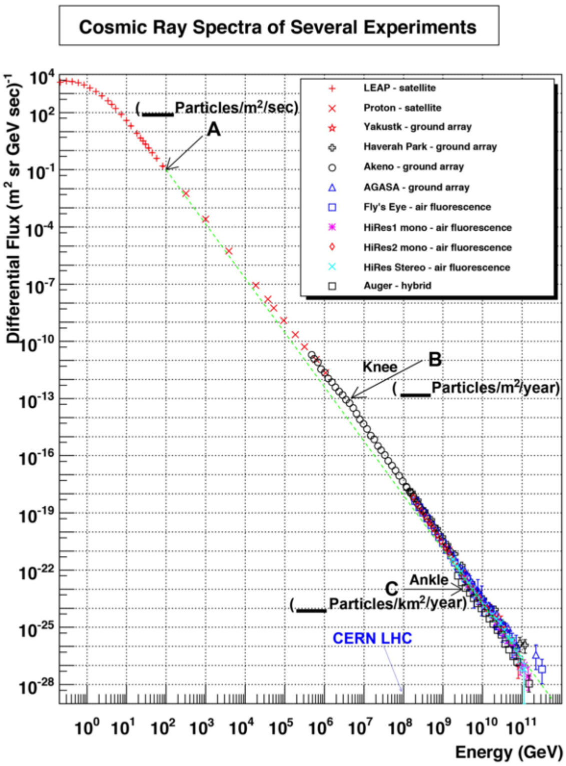


Figure 1: Compilation of experimental measurements of cosmic ray fluxes, from [2]. Students are asked to calculate the approximate fluxes in three different energy regions, labeled A, B and C.

Cosmic ray showering, the way these particle cascades develop by interaction in the Earth's atmosphere, is then briefly explained. To understand it, the basics of particle physics (presently not taught at high schools in Portugal) must be introduced, but this can be done at different levels. In fact, students using this guide independently at schools have asked for dedicated lectures and have then presented a description associating the bulk of the hadronic cascade to the strong interaction, the muonic component seen at ground to the weak interaction governing pion decay, and the large part of the shower energy transported by electrons and photons to the electromagnetic interaction.

To avoid the details, the guide introduces the concept of a toy-model, using for that the well-known Heitler formalism and its extensions, and also the superposition model for nuclei. Students should fill in a table (see figure 2) for the first steps of particle multiplication, getting a feeling for how the main shower variables depend on the properties of the primary particle. The dependence on primary energy and particle type of the main experimental observables (maximum number of particles in the shower, the atmospheric depth at which the shower maximum occurs, the number of muons at the ground) can be numerically inferred from those tables, even if the mathematics tools are not yet available for the students to make an analytical derivation.

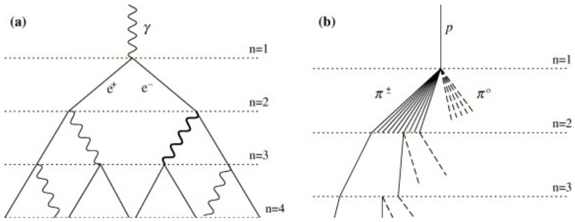
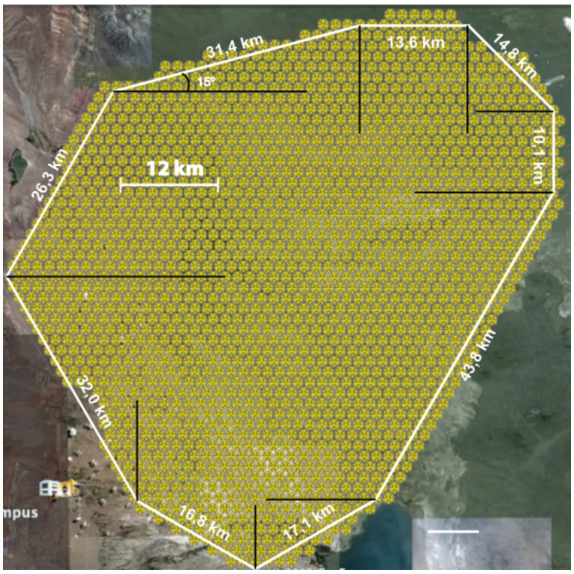


Figure 2: Representation of the Heitler model for (a) electromagnetic cascades and (b) its extension to hadronic cascades. Students are asked to fill in the value in tables similar to the ones shown below, and to then derive analytic expressions for the main shower observables, starting from the primary energy, E_o. For each interaction level the students calculate the corresponding atmospheric depth (X), the total number of particles, (N for the electromagnetic particles in (a), and N_{tot} and N_{ch}, for the total number of pions and of charged pions, respectively, in (b)) and the energy associated to each particle (E). In (b), the energy kept for further pion multiplication is given in E_{ch}.

n	X	N	E	n	N_{tot}	N_{ch}	E	E_{ch}
0	0	1	E_0	**0**	1	1	E_0	E_0
1	d	2	$E_0/2$	**1**	30	20	$E_0/30$	$2E_0/3$
2				**2**				
n				**n**				

3. The Pierre Auger Observatory and its Public Data Set

After the first sections, the students are ready to understand the principle of sampling detection which is central to the data analysis they are invited to do. The middle section of the guide - much lighter, to be done over the weekend during a two-week internship, for example - encourages the independent exploration of the web pages of the Pierre Auger Observatory with the aim of solving a number of games and reasonably easy questions (see figure 3, for an example). We expect this section to be complemented with visits to laboratories or museums to see working particle detectors as demonstrators. At present, one school has a planned visit to the Observatory itself.



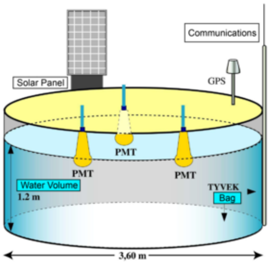


Figure 3: Representation of the surface detector of the Pierre Auger Observatory (top). Students are asked to calculate the approximate area, and compare it to the sensitive area of 1600 water Cherenkov tanks, as represented on the left.

The Pierre Auger Observatory is a hybrid observatory, with a sampling surface detector covering around 3000 km^2 and a fluorescence detector imaging the cascade development, with around 10%-15% duty-cycle. The surface detector consists of autonomous water Cherenkov detector stations separated by 1.5 km in a triangular grid. Its low energy extension adds extra stations with smaller spacing and higher elevation fluorescence telescopes. The Observatory is thoroughly described in [3].

1% of the cosmic ray showers recorded in the surface detector of the Pierre Auger Observatory are made public for outreach and education purposes. Events above a certain energy cut or with a zenith angle greater than 60 degree (for which the reconstruction must be changed) are, at present, removed from the public data samples. There are still around 35 000 public events that can be viewed, selected and downloaded from the web page [4] illustrated in figure 4, where a glossary with technical terms can also be found.

For each event, in addition to the reconstructed variables (detection time, shower core position, direction in local spherical coordinates and in galactic coordinates, and reconstructed energy), the station-by-station information, from which they are obtained, is also given. In fact, one can download the list of triggered stations, with their corresponding positions, the total signal and the timing associated with this event. Most events have 3 stations, the minimum for reconstruction, while the ones corresponding to higher energy or more inclined events can have more than 10 stations.

Figure 4: Public Event Display of the Pierre Auger Observatory [4]. The web page exists in several different languages.

4. Data Reconstruction and Data Analysis

The last two sections of the guide focus on the public data, first at the event-by-event level, then in a statistical analysis of the full available data set. Each of these brings different challenges and conveys different information to the students; they share, however, the importance of discussing systematic and statistical uncertainties, in addition to the excitement of dealing with real data to answer present-day scientific questions with high school level tools.

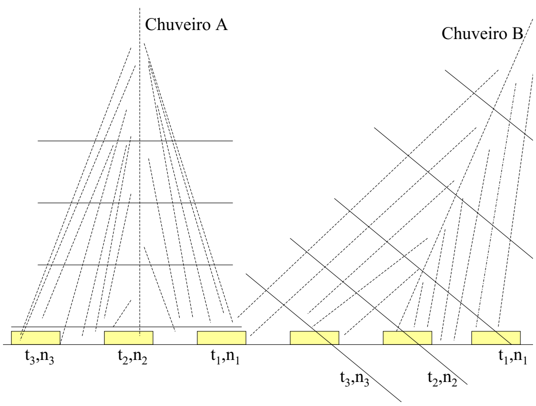


Figure 5: Schematic representation of extensive air showers at different zenith angles. The parallel lines represent surfaces of constant arrival time, assuming propagation at the velocity of light.

The station-by-station data of individual cosmic ray events is used to investigate how to reconstruct the event with relatively simple algorithms, with the hints given in the guide (see, as an example, figure 5). For some variables, the simplified reconstruction will lead to results very close to the official ones obtained by Auger, while in other cases the students can only get some sensitivity to what the more complex calculation will depend on. In all cases, the focus is on the selection of the most sensitive inputs for each calculation. While the students are, in general, motivated by the fact that they can do the reconstruction themselves, they tend to simply use the official results given by Auger to judge if their results are "right or wrong". This should be demystified by discussing the possible accuracy of different algorithms used by experimentalists, and the importance of the evaluation of uncertainties.

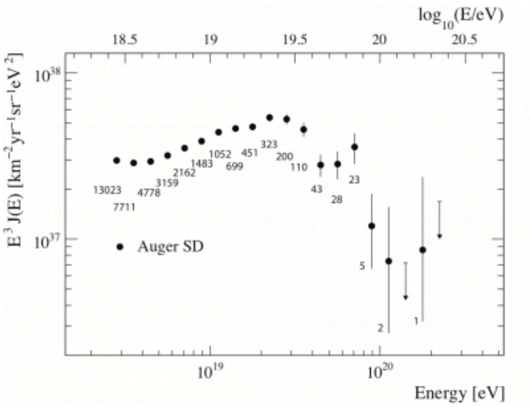


Figure 6: The energy spectrum measured with the Surface Detector of the Pierre Auger Observatory [6]. Although the highest energy events have been removed, the first break in the spectrum can be reproduced with the public data set. However, the most evident feature, to be discussed with and by the students, is the variation of the detection efficiency as a function of energy and angle.

Finally, the statistical analysis of the full reconstructed data set is proposed. A spreadsheet application (commonly used by the students and teachers) or a physics data analysis program (commonly used by researchers) may be preferred according to the conditions in which the guide is being explored. Dedicated tools can also be implemented, but the use of any tool should not distract users from the physics data analysis.

The notions of isotropy, acceptance and exposure, the detection and reconstruction efficiency as a function of energy and angle are discussed. In this section of the guide, the real physics results are obtained analyzing the observed spectrum and flux, explaining that the different slopes may come from different kinds of sources (galactic and extragalactic), that sources are only expected to be seen in galactic coordinates (the event arrival time must be used to correct directions) and at high energy and for low-charge primaries, due to magnetic fields.

Because only 1% of the full Auger data is available, statistical uncertainties are very important; the results must be critically compared with the published Auger ones, but many of the features are recognizable, as shown in figures 6 and 7. The data set is continuously increasing and plans to release a larger fraction of the data and to relax the cuts have been discussed and agreed upon by the Pierre Auger Collaboration.

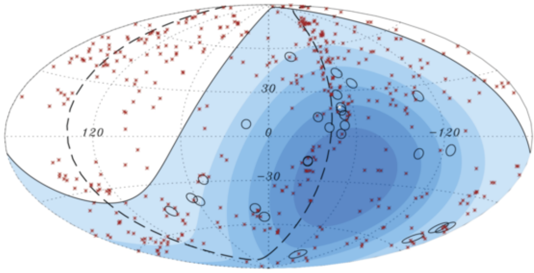


Figure 7: Arrival directions of the highest energy cosmic rays seen by the Pierre Auger Observatory (open circles) are compared to the directions of active galactic nuclei in the nearby sky [5]. This was one of the most famous Auger results. Although the arrival directions of the highest energy cosmic rays are not available in the public data set, the low energy data gives a good measurement of the sky exposure (corresponding to the shaded blue areas), fundamental for their interpretation.

5. Conclusions and Outlook

The central idea of this guide is to provide an end-to-end 21st century science exercise with high school level tools. In Portugal, at least, particle physics is absent from the high school programs and some of the mathematics used (exponentials and logarithms, for example) are taught in the last grade only, but the goal is that the guide allows students to follow the entire analysis process.

We have applied it in different contexts, but always with reasonably small groups of very motivated senior students. This was done, first in two-week summer internships at our home laboratory in Lisbon, with intensive learning and contact with other experimental activities, and then at science clubs at schools, where the students are accompanied by their teachers and contact with researchers is minimal. Science clubs have the advantage of doing long-term projects, without the pressure of grade-evaluation and involving different teachers, namely of physics and mathematics. Lastly, one of the teachers using the guide in Portugal proposed it in an international project with schools in Mexico, Spain and Uruguay. Although this project is not finished yet, it is already a successful activity, in terms of shared learning, in line with our goals to generalize the use of the guide and of the public Auger data.

The reactions have, in general, been positive even if the preferences for each section vary from student to student. For example, while some students find the introductory sections harder and would prefer to go sooner to the data analysis, others consider the modeling the most challeging and interesting part and deepen the study of the particle physics behind it. The input gathered from the several different users has been very helpful to improve successive versions. Our plans now include creating a shorter, simplified version which can be used more generally, even by younger students, and adding extra support material for the teachers, so that they can more easily introduce the most advanced parts. In fact, even if the contact with researchers is a plus in these programs, making the guide a fully standalone project that could bring a more significant number of students in contact with our research field would be a complementary goal.

A long term goal, which has not proven easy to implement, is to isolate specific questions that could be dealt with in an afternoon, in view of creating an activity similar to the International Masterclasses on Particle Physics, dealing with event-by-event reconstruction and/or final statistical analysis. Input from other users - and from our colleagues - will be helpful in this regard.

Acknowledgments

We thank all the students and teachers who gave valuable input about the use of the guide. We thank, in particular, the participants in the international project, *The Universe, a World to Discover*, in the person of Alexandra Forte, and the students who participated in the Summer Internships at LIP in the last years. We acknowledge the support of Ciência Viva - Agência Nacional para a Cultura Científica e Tecnológica, through the project CV-2012/PEC258, in the programme *Escolher Ciência*.

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