PROCEEDINGS OF SCIENCE

International Masterclasses as part of the Pierre Auger Observatory program of Outreach and Education

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The Pierre Auger Observatory is committed to bringing education and knowledge of cosmic rays to the public, with a strong focus on schools and students. Over the last few years, initiatives have been developed, such as the Science Fair, virtual visits, and participation in international activities on the subject of cosmic rays, including collaborations with external groups. Modern digital tools bringing novel ways of interacting with the public have been explored at these initiatives and also locally at a renewed Visitor Center in Malargüe. The development of tools for the public release of the Auger data, including standardized data formats, analysis notebooks, and a 3D interactive event display, led to the creation of a new activity directed to high-school students called Masterclasses. The participants are challenged to perform the reconstruction and selection of events using a graphical interface with 3D effects, then combined into a smoothed, exposure-corrected sky map of arrival directions. A final discussion takes place in which the students engage with peers and scientists, looking for answers about the origin of ultra-high-energy cosmic rays. The concept had a successful debut in 2022 and was included in the 2023 edition of the International Masterclasses on Particle Physics, reaching students worldwide.

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1. Introduction

The Pierre Auger Observatory has a rich program of Outreach and Education that comprises a strong presence online and a variety of initiatives taking place at the local, regional and international levels [1]. The online presence is established by a dedicated outreach web page with extensive explanatory content on cosmic rays and a virtual tour to the observatory, as well as by social network accounts with regular posts for a total of about 6 600 followers [2].

Two of the initiatives with highest impact to the students and populations of the region are the Malargüe Science Fair and the Visitor Center of the observatory. The Science Fair happens every two years and involves students of several ages, from primary to adult schools in Argentina, in the development and presentation of science projects. Selected projects are presented in Malargüe and discussed with scientists of the Pierre Auger Collaboration. The last edition took place on November 2022 and counted 21 projects and more than 600 visitors, as reported in Fig. 1.

The Auger Visitor Center, located at the observatory building in Malargüe, is permanently open to the public with an interactive exposition. The number of visitors, mainly from Argentina, has recovered in 2022 to pre-pandemic peak values of nearly 10 000 visitors per year. At the beginning of 2023, the center was renewed with additional exhibitors, such as an on-screen virtual assistant, new small-scale models of the observatory facilities, working detectors and a manned-balloon structure with goggles for a virtual-reality tour to the field.

The Auger Collaboration is also engaged with initiatives promoted by international institutions and taking place worldwide, such as the International Cosmic Day and the International Day of Women and Girls in Science. This global reach is strengthened by decentralized and regular efforts of organization, by the member institutions, of lectures and hands-on activities to schools and demonstrations to the general public. In this work, we report on the development and first realization of a new Outreach and Education activity of the Pierre Auger Observatory - the International Masterclasses with the Auger public data.

Figure 1: Poster advertisement and pictures of the eight edition of the Malargüe Science Fair.

2. International Masterclass with the Auger public data

2.1 Purpose, concept and framework

An *Astroparticle Masterclass* to bring experimental data and research methods into the classroom has been successfully introduced and realized in the past [3]. The idea to create a new Masterclass arose from the availability of a new set of tools and data-sets made by the public release of the Pierre Auger Observatory cosmic-ray data [4]. The release includes 10% of the data recorded with the surface detector (SD) until the end of August 2018, as pseudo-raw data in the JSON format and a summary file in CSV format. To visualize the data, plots of the events and an interactive 3D event display with 3D effects are provided. Additionally, python notebooks that re-implement published analyses are accessible online through the kaggle platform. A detailed account of the Auger open data may be found in [5].

The project was created with the purpose of developing an experimental activity for high-school students to learn about astroparticle physics, by challenging them to analyze the Auger public data using a friendly interface built from the existing tools. The aim was to reach students worldwide.

The concept was inspired by the program of International Masterclasses (IMC) promoted by the International Particle Physics Outreach Group (IPPOG). Under this program, students visit a research institution or university and are scientists for one day with the *hands on particle physics*, doing measurements with data mainly from collider experiments [6]. The program runs yearly, through several days, each session comprising both lectures and the experimental activity. It happens simultaneously with students at different locations and ends with a joint video-conference for discussing the results with scientists.

The program has been very successful, attracting more than 10 000 students every year from about 60 countries. In order to reach students worldwide, the Auger International Masterclass was proposed for and included into the framework of the IMC, benefiting from IPPOG's wide network of contacts of research institutions and schools, starting from the 19$^{\text{th}}$ edition of IMC, in 2023.

2.2 Implementation

The motivation of the measurement is an open question in today's science: *What is the origin of ultra-high-energy cosmic rays?* In order to find an answer, students must analyze the Auger data and search for anisotropy in the arrival directions of the highest-energy cosmic rays, reproducing the work of [7].

For that, independent data-sets with 50 public events are given, containing only the SD signal and arrival times as measured by the observatory. Students must reconstruct the arrival direction and energy of the events and apply selection criteria in order to keep only those for which the arrival direction points to the source location. The reconstructed arrival directions of the selected events are used for the production of a sky map of particle flux. The students then discuss their results by analyzing the observable flux patterns and comparing them with the location of known astrophysical structures, such as the Milky Way and nearby galaxies. The final interpretation aims at taking a conclusion about the origin of the particles detected.

To complete the exercise, the students work at computers and use the interface shown in Fig. 2. The interface is visually appealing and intuitive, having been built from the 3D display of the Auger

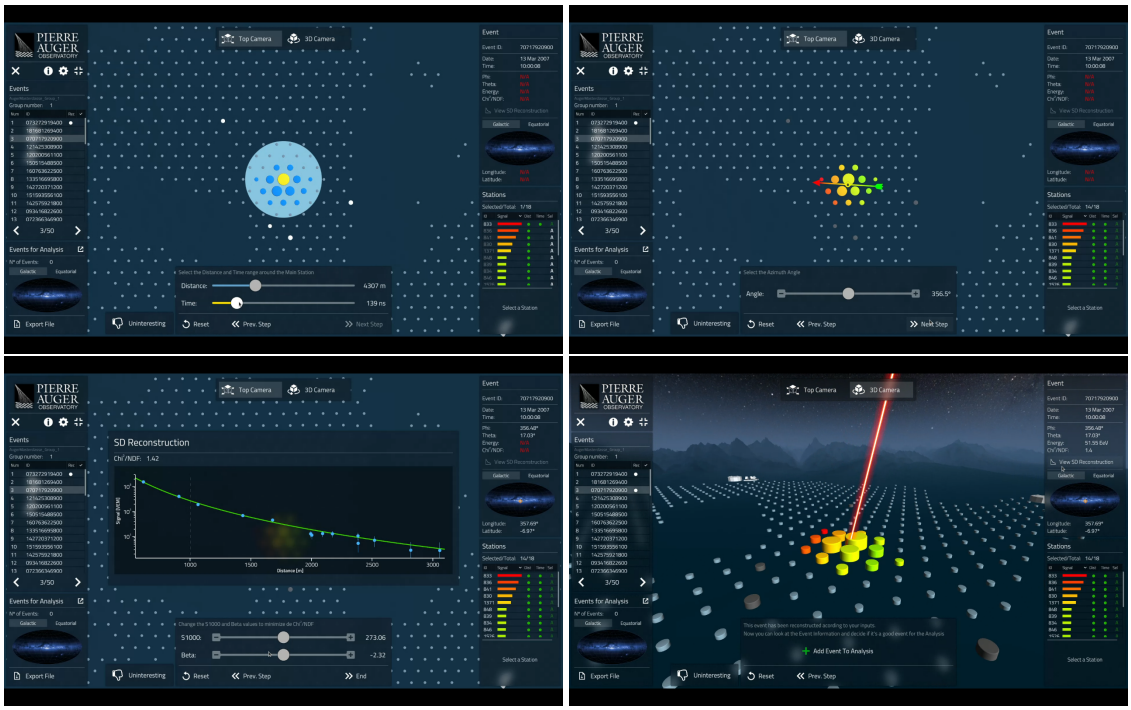

Figure 2: The Auger Masterclass interface with the steps of the analysis of single events. From top left to bottom right, the steps are: 1) station selection, 2) azimuth (and zenith) angle reconstruction, 3) fit of a lateral distribution function, 4) acceptance or rejection of the event based on selection criteria.

public data with the Unity engine [8]. It allows showing a top or 3D view of the SD with the event stations highlighted in color. There is also a left panel with the list of events and a right panel with more detailed information about the current event.

The analysis is performed on an event-by-event basis, starting from the selection of the SD stations with signal and rejection of those with background. For that, two scrolls are used, that control which SD stations of the event are considered based on their location and signal arrival-time. After completing that first step, the selected stations are colored according to the signal arrival time, and a direction must be visually adjusted to the color pattern in order to reconstruct the azimuth angle. The student must then select two stations on opposite sides of the event for the zenith angle to be computed from the respective signal arrival-times and assuming a shower front propagating as a plane wave at the speed of light. The reconstructed arrival direction in galactic and equatorial coordinates is also computed by the interface.

After the geometry reconstruction, the signals of the selected stations are plotted as a function of the distance to the reconstructed shower axis, and the students must fit a two-parameter lateral distribution function (LDF) to the data points, using two scrolls. The primary cosmic-ray energy is computed by the interface by reading the interpolated S(1000) value. Finally, criteria on the reconstructed energy, quality of the LDF fit, and topology of the event stations are applied to select the event for further analysis or to discard it.

Throughout the exercise, concepts such as event, signal, background, air shower extension and

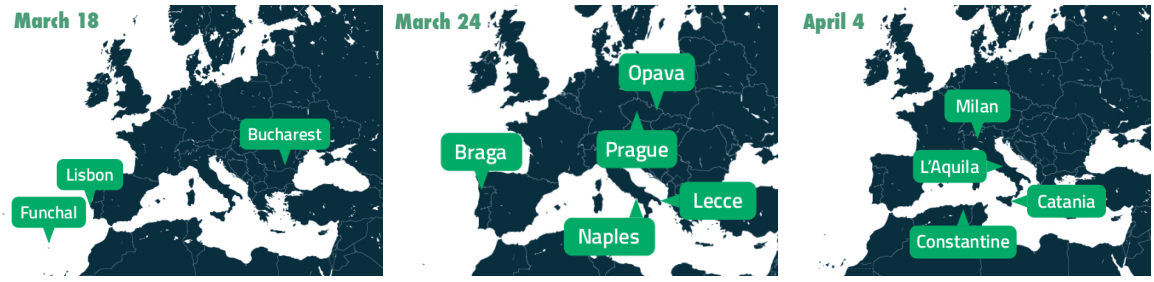

Figure 3: Dates and cities of the first three Auger Masterclass events at the IMC 2023.

duration scales, data fitting, and selection are worked out. Except for the shower core, for which the Auger value is used, all the reconstruction is performed by the students, and the output is the result of their actions and decisions.

After analyzing the data-set, students upload files with the reconstructed arrival directions of the selected events to the Masterclasses web page, which combines the results from all students and runs the python notebook of the large-scale anisotropy analysis [4]. Throughout the discussion, concepts such as sky map coordinates, propagation effects, statistical and systematic errors, and directional correlation are discussed.

3. Premier at the International Masterclasses 2023

After a successful pilot test of the activity with Italian and Portuguese students in May 2022, three Auger Masterclasses took place at the IMC 2023 in March and April. The organization involved more than 550 high-school students at 12 research institutions from 5 countries, mostly from Europe (Czech Republic, Italy, Portugal, Romania) but also from Africa (Algeria), as shown in Fig. 3.

The organization of the activity involved the realization of two preparatory meetings with the participating institutions and the preparation of a complete list of resources that include data-sets, software compatible with different operative systems, and support documentation. All these materials are centralized and freely available on the Masterclasses web page, which also includes the platform for the submission and analysis of the results [9]. Given that all the resources are open, the activity can also be organized as a single, small-scale event outside the context of IMC. In that case, with fewer students and data-sets involved, the final discussion of the results is expected to be based on small statistics.

Figure 4 shows photos reporting the several stages of the Auger Masterclasses that happened simultaneously at the different sites during the three dates. The typical number of students at a given site was ~30, but smaller (10) or bigger (>100) groups were also involved. During the mornings, lectures on astroparticle physics and detection, with a strong focus on the Pierre Auger Observatory, were given. Demonstrations with interactive content, such as the Auger virtual reality experience, were successful in reaching the audiences. After lunch, the hands-on activity was carried on for ~2 hours, with students, alone or in groups of two, working through their own data-set with the help of a printed activity guide and the presence of tutors in the room, typically one tutor for

Figure 4: For three days, the Auger Masterclasses joined high-school students and scientists across three continents in exploring the physics of ultra-high-energy cosmic rays.

every ten students. At the end, a joint video-conference took place among the participants and scientists working at the Pierre Auger Observatory, in Malargüe. The video-conferences included a discussion of the results, a virtual tour to the observatory, a session of questions and answers with the scientists, and a final quiz for the students to test their knowledge through a friendly competition using cell phones.

To assert that the realization of the Auger Masterclasses filled all its aims is not an overstatement, based on the wide and enthusiastic participation of high-school students from different countries,

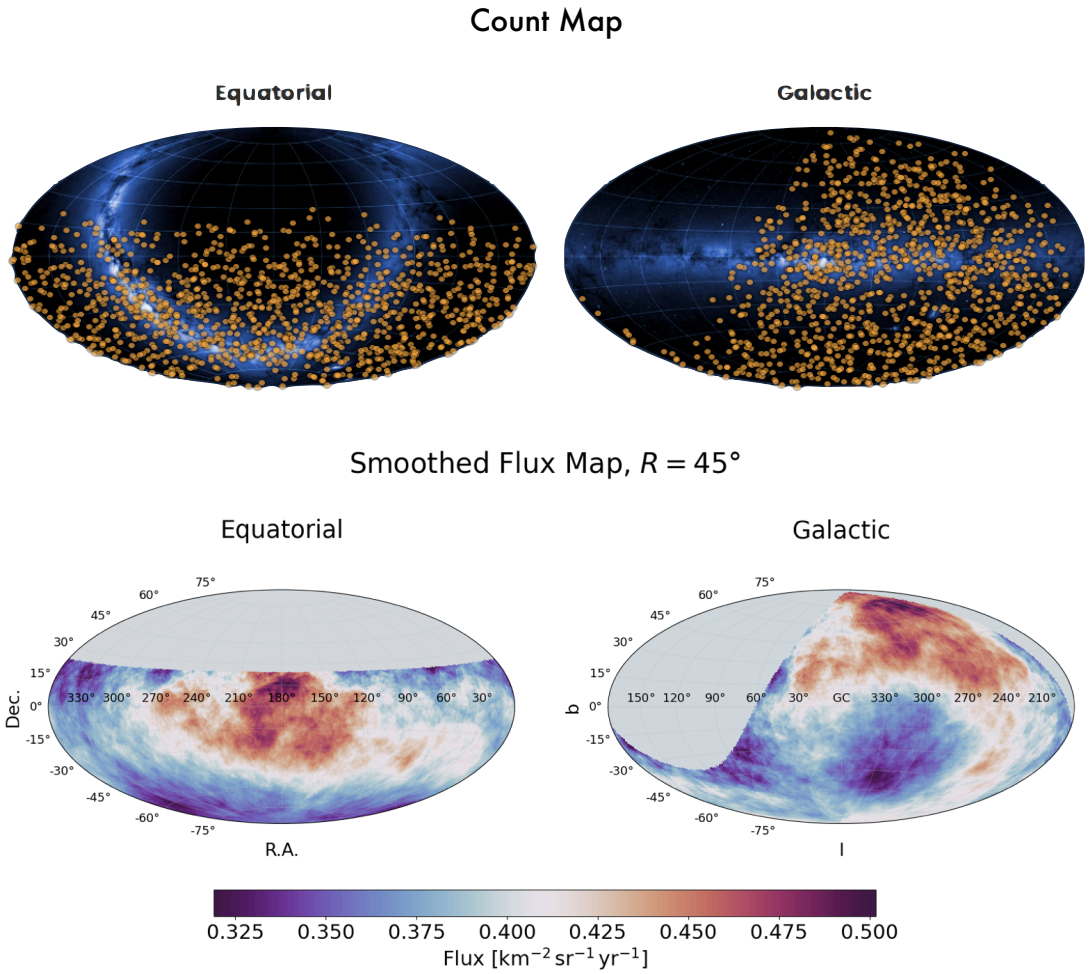

Figure 5: The sky maps resulting from the first Auger Masterclass session, built with the arrival directions of 1130 events reconstructed by the students.

as well as by the lively discussions that took place among students and scientists.

That the activity contributed to bringing education and knowledge of cosmic rays to the students may also be assessed from their performance in analyzing the data. To illustrate this point, the combined counts and smoothed-flux sky maps resulting from the first Masterclass day are shown in Fig. 5. It amounts to 1130 event arrival directions. The count maps show the region of the sky not accessible to the observatory for the public data with zenith-angle <60° and isotropy to a great extent. The resulting flux map, corrected for the declination-dependent exposure and smoothed by the application of a 45° radius top-hat function, shows a dipole pattern that is very similar to the Auger result using the open data [4].

4. Conclusions and outlook

The program of Outreach and Education at the Pierre Auger Observatory has been enriched with the development and realization of International Masterclasses with the Auger public data. The new activity was integrated into the framework of the IPPOG program to reach high-school students worldwide and made a successful debut at the IMC 2023 with the organization of three events. The participants had the opportunity to learn about astroparticle physics and detection, to analyze the Auger public data, to discuss the results with peers and scientists from other cities and countries, and to perform a guided virtual visit to the Pierre Auger Observatory.

It is foreseen that the activity will continue during the next IMC editions with participation enlarged to institutions and students from other continents beyond Europe and Africa. The feedback from this first edition, based on the results and on a questionnaire to participants, is under evaluation in order to improve the organization of future events. Additional features to the exercise that include hybrid or inclined SD data are being envisaged. A complete list of resources needed for the realization of the activity is publicly available, allowing for it to be arranged also in the context of outreach activities beyond the IMC.

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