INTERNATIONAL MASTERCLASSES
Experimental activity at the Pierre Auger Observatory

// Origin of ultra-high-energy cosmic rays

Training Guide   Person/Group _____

Goals:
- **Rebuild 50 events of the Pierre Auger Observatory**
- **Select the ones that contain directional information about their origin**
- **Discuss where in the Universe the cosmic rays of extreme energy are produced**

Before starting:

- Navigate to https://augermasterclasses.lip.pt/downloads and find *"NEXT ACTIVITIES DATASETS"*.

- Find you institution and download to your Downloads folder the dataset *AugerMasterClasse_X.augermc*, where *X* is the group number indicated above. Each person/group has their own unique dataset to use.

- In Auger's interactive event viewer, click on *"Read Events File"* in the upper left corner and select the data file in your Downloads folder with the extension *".augermc"*

- You are now ready to start analyzing events. Begin the process by selecting the first event from the left sidebar.

Step 1: Selecting the stations
Identify the surface detector stations that are part of the event, selecting stations with signal and removing stations with background.

- Click on *"Start Reconstruction"* and click on the event station that has the largest signal. The size and color of the station represent its signal; the exact value can be found in the right sidebar. Then click on *"Next Step"*.

- Select the remaining stations of the event according to the following criteria:

  - **distance to the station with the highest signal:** moving the distance bar allows you to select stations further and further away from the station with the highest signal;

  - **arrival time of shower particles:** moving the time bar allows you to select stations where the signal has been recorded with an increasing time difference with respect to the station with the highest signal;

  - it is also possible to add or remove individual stations from the selection by clicking the station *"Sel"* column on the right sidebar.

- After eliminating the stations far from the event, as well as the stations that recorded a time of arrival of the particles incompatible with the shower, complete the selection by clicking *"Next Step"*.

Step 2: Reconstruction of the arrival direction
Reconstruct the direction of arrival of the cosmic ray, determining the azimuthal angle _"Phi"_ between the direction of the cosmic ray projected onto the surface and the East-West axis, and the zenith angle _"Theta"_ between the cosmic ray direction and the vertical.

- Reconstruct the azimuthal angle according to the following criteria:

  - **Shower particles arrive first at stations on the arrival side of the cosmic ray**: orient the arrow to the surface according to the variation of the time of arrival of shower particles at stations, which is indicated by color (green is earlier, red/orange is later); then click on _"Next Step"_.

- Reconstruct the zenith angle according to the following criteria:

  - **Shower particles move (approximately) at the speed of light**; select two stations aligned in the azimuth direction and spaced as far apart as possible;

  - The cosmic ray direction is calculated automatically by the program based on the times of the selected stations. The respective value, as well as the arrival direction represented on the sky map, appear in the sidebar right after clicking _"Next Step"_.

Step 3: Rebuilding the energy
Rebuild cosmic ray energy by determining the profile (shape of the lateral distribution) and size of the surface shower.

- The graph presented illustrates the lateral distribution of shower particles, in which the dots represent the amount of signal from the selected stations as a function of the distance from the stations to the cosmic ray path that was reconstructed. **The signal at 1000 meters away is proportional (after corrections) to the energy of the cosmic ray.**

- Determine the function that best fits lateral distribution of the shower:

  - Adjust the *"S1000"* and *"Beta"* parameters by clicking the *"+"* or *"-"* buttons on the ends of the sliders in order to get the best fit of the function to the experimental points.

  - The quality of fit depends on the distance between the function and the points, and **is quantified by *"Chi2 /NDF"*.**

  - After obtaining the best fit you can, click on *"End"*.

- The reconstruction of the event is finished! The properties that were reconstructed are indicated in the right sidebar. An animation of the arrival of the cosmic ray at the observatory based on these properties is displayed. **The next step describes the criteria that determine whether this event is to be selected or not.**

Step 4: Selection Criteria
Select only events that contain directional information about the origin of extreme energy cosmic rays.

- Check whether the event simultaneously meets the following criteria:

  1) the reconstructed energy is **greater than or equal to 8 EeV**;

  2) the number of stations that have a signal, and that belong to the hexagon immediately around the station with the largest signal, is **greater than or equal to 5**;

  3) the quality of the fit to the lateral distribution of particles is good, indicated by a value of *"Chi 2 /NDF"* **less than or equal to 2**.

- If the criteria match, accept the event by clicking on *"Add Event to Analysis"* and the event arrival direction is added to the sky map in the sidebar left. If not, do not accept the event by clicking on *"Uninteresting"*.

- Start the analysis of the next event by selecting it in the sidebar sidebar.

After reviewing the events:

- In the lower left corner a sky map appears with the arrival directions of the selected events. Is it possible to draw conclusions?

- Export the results by clicking *"Export File"* in the lower right corner of the screen and saving the file with extension *".augermcexport"*.

- Access the link: https://augermasterclasses.lip.pt/activities and upload the file saved in the previous step by clicking on *"Upload File"*.