Search for upward-going air showers with the Fluorescence Detector of the Pierre Auger Observatory

Emanuele De Vito for the Pierre Auger Collaboration
Università del Salento, INFN Lecce

Introduction

The fluorescence detector (FD) of the Pierre Auger Observatory[1] is sensitive to upward-going air showers for energies above 10^{17} eV. Given its operation time and wide field of view, the FD has the potential to support or constrain the recent "anomalous" observations by the ANITA detector [2], interpreted as upward-going air showers of unexplained nature.
We have used 14 years of data collected by the FD to search for upward-going showers using a set of quality selection criteria defined using 10% of the full data sample. To distinguish candidates from false positives, calculate the exposure and obtain the expected background, dedicated simulations for signal (upward-going events) and background (downward-going events) have been performed. Results of the analysis after unblinding the data set are presented here.
Finally, the exposure and sensitivity for the specific scenario of a signal being ascribed to tau lepton decay are calculated and the corresponding upper limits are shown as a function of primary energy and in different zenith angle ranges.

Simulations

Upward-going protons have been simulated with $\log_{10}(E/\mathrm{eV}) \in [16.5, 18.5]$, zenith angle $\theta \in [90°, 180°]$ and a first interaction point $H_{fi} \in [4, 9]$ km.
Protons have been chosen because they can be easily adapted to fit any interesting scenarios such as neutrinos, Beyond Standard Models (BSM) particles [3].
Downward-going events can also mimic an upward-going track in the camera so events with $\log_{10}(E/\mathrm{eV}) \in [17, 20]$ and a zenith angle $\theta \in [0°, 90°]$ have also been simulated as a background.

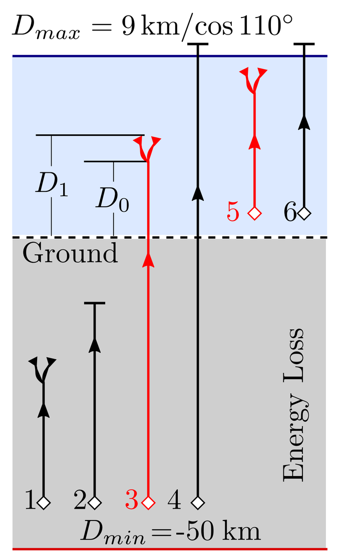

Figure 1: Representation of τ simulations. τ-decays which may trigger the FD are indicated in red.

Taus have been simulated 50 km inside the Earth up to $\simeq$ 26 km in the air with $\log_{10}(E/\mathrm{eV}) \in [16.5, 20]$.
Figure 1 shows all possible outcomes for the generated taus. Cases 3 and 5 where the tau decays in the FD field of view have been used to calculate the expected trigger rate for a tau air shower. Taus have been simulated with TAUOLA [4] considering all the decay branches with only $e^{\pm}$, $\pi^{\pm}$, π^0, $K^{\pm}$ and K^0 meaningfully contributing to the energy of the resulting atmospheric air shower.

References

[1] A. Aab et al. [Pierre Auger Coll.]. *Nucl. Instrum. Meth. A*, 798:172–213, 2015.

[2] P.W. Gorham et al [ANITA Coll.]. *Phys. Rev. Lett.*, 121:161102, 2018.

[3] I.A. Caracas for the Pierre Auger Coll. *PoS*, ICRC2021:1145, 2021.

[4] M. Chrzaszcz, T. Przedzinski, Z. Was, and J. Zaremba. *Comput. Phys. Commun.*, 232:220–236, 2018.

[5] M. Mastrodicasa for the Pierre Auger Coll. *PoS*, ICRC2021:1140, 2021.

Laser Cleaning

Upward-going lasers are used by the Collaboration for atmospheric monitoring. They are mainly shot by two facilities located in the middle of the array (CLF and XLF) and by 4 LIDARs located at each FD site. Lasers are mostly fired vertically and the large majority are rejected based on their known time stamp. However it may happen that some lasers leak into the data sample as genuinely upward-going events. An algorithm has been developed to identify and reject the remaining lasers by exploiting the time of each event and its position inside the array.

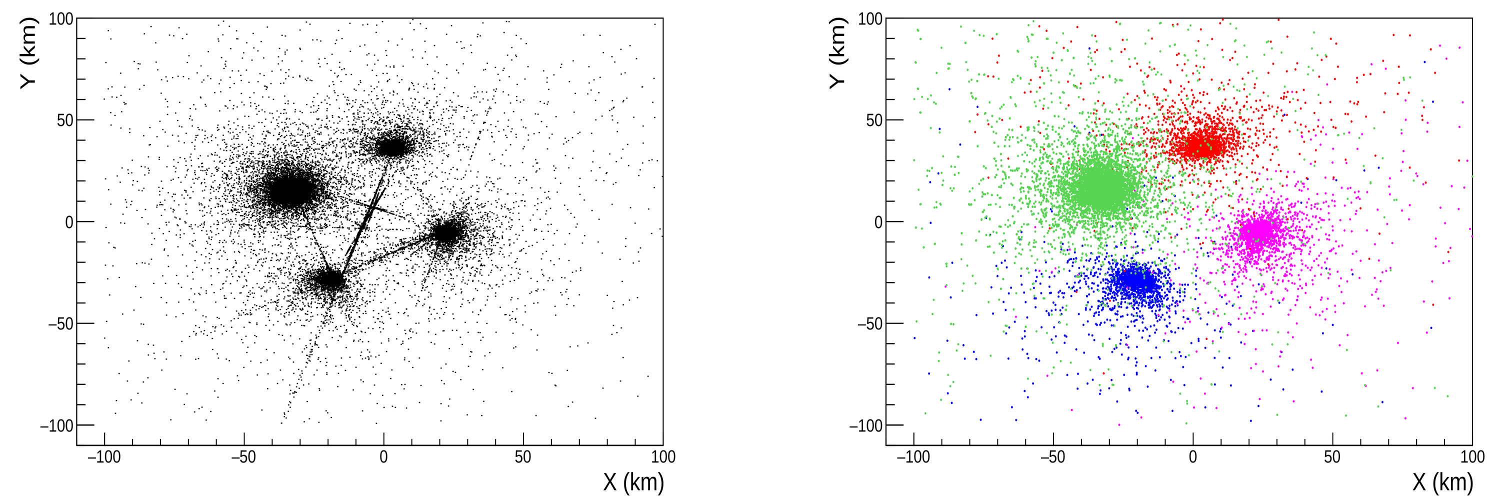

Figure 2: Distribution of the exit points for the events with $\theta > 90°$ before (left) and after (right) the laser cleaning. Lasers are clearly visible along the lines connecting the FD sites. The colour scheme refers to the site where each event has been observed. Data used here corresponds to 10% of the entire data sample.

Exposure

When simulating an upward-going shower the height of the first interaction point H_{fi} can significantly change the trigger efficiency of the FD. For this reason a double differential exposure has been calculated as

$$\frac{d\varepsilon}{dH_{fi}}(E_{cal}, H_{fi}) \simeq 2\pi \cdot S_{gen} \cdot \Delta T \cdot \sum_i \eta(E_{cal}, \cos\theta_i, H_{fi}) \cdot \frac{1}{\Delta H_{fi}} \cdot \cos\theta_i \cdot \Delta\cos\theta_i$$

where E_{cal} is the energy released by the shower in the air, S_{gen} is the surface area of generation (a square of 100×100 km^2), ΔT is the 14 years of operation of the FD, η is the fraction of events passing the selection and θ is the zenith angle (Figure 4, left).
By folding $d\varepsilon/dH_{fi}$ with the τ trigger efficiency, the double differential exposure to τ lepton air shower is derived. Finally, the FD exposure for the scenario of a τ lepton decay is calculated as a function of the initial energy of the τ by integrating over E_{cal} and H_{fi} (Figure 4, right).

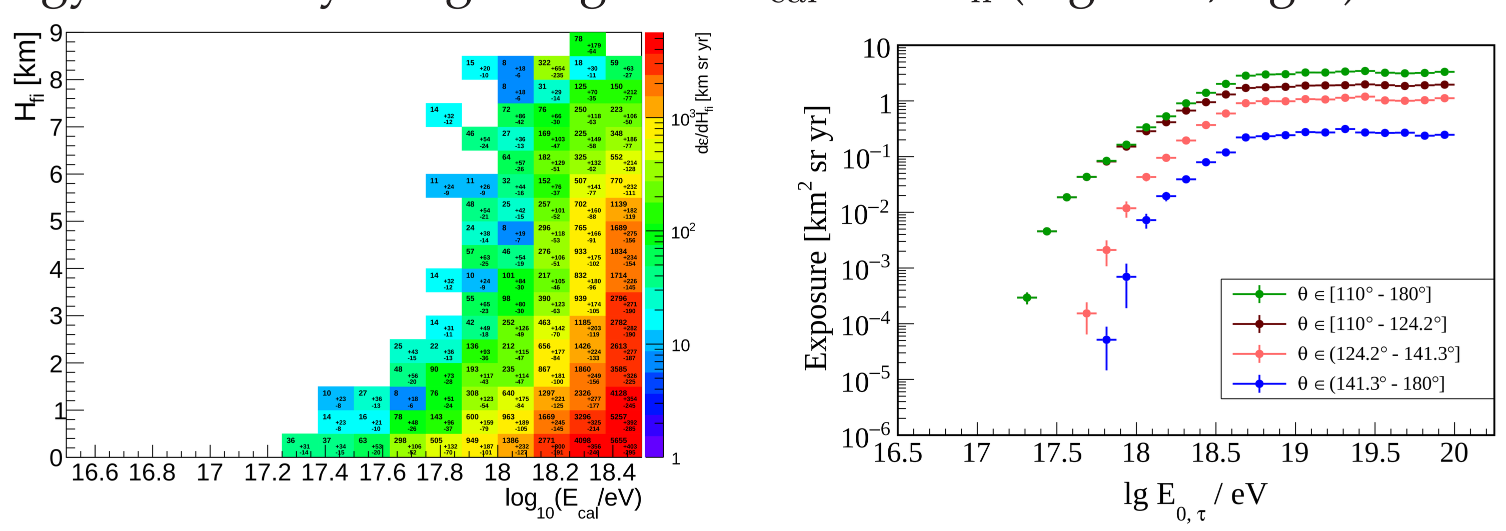

Figure 4: (Left) Double differential exposure with $\log_{10}(E_{cal}/\mathrm{eV})$ on the x-axis and the height of first interaction on the y-axis for upward-going events. (Right) FD exposure for decays of upward-going showers induced by τ decay as a function of the lepton energy, for the whole zenith range (green) and for three different zenith intervals.

Analysis Strategy

A blind analysis has been performed with 10% of data used to study the background [5]. After laser are rejected, a profile constrained geometry fit has been applied to remaining sample testing if any possible upward-going geometry can explain the event. In that case, downward geometries have been tested too. Variable $X = \mathrm{atan}(-2\log(\frac{L_{down}}{L_{all}})) \cdot 2/\pi$ has been defined to compare the likelihood of the two reconstructions. $X = 0$ means that the downward geometry is favoured, while $X = 1$ means that the upward solution is preferred.

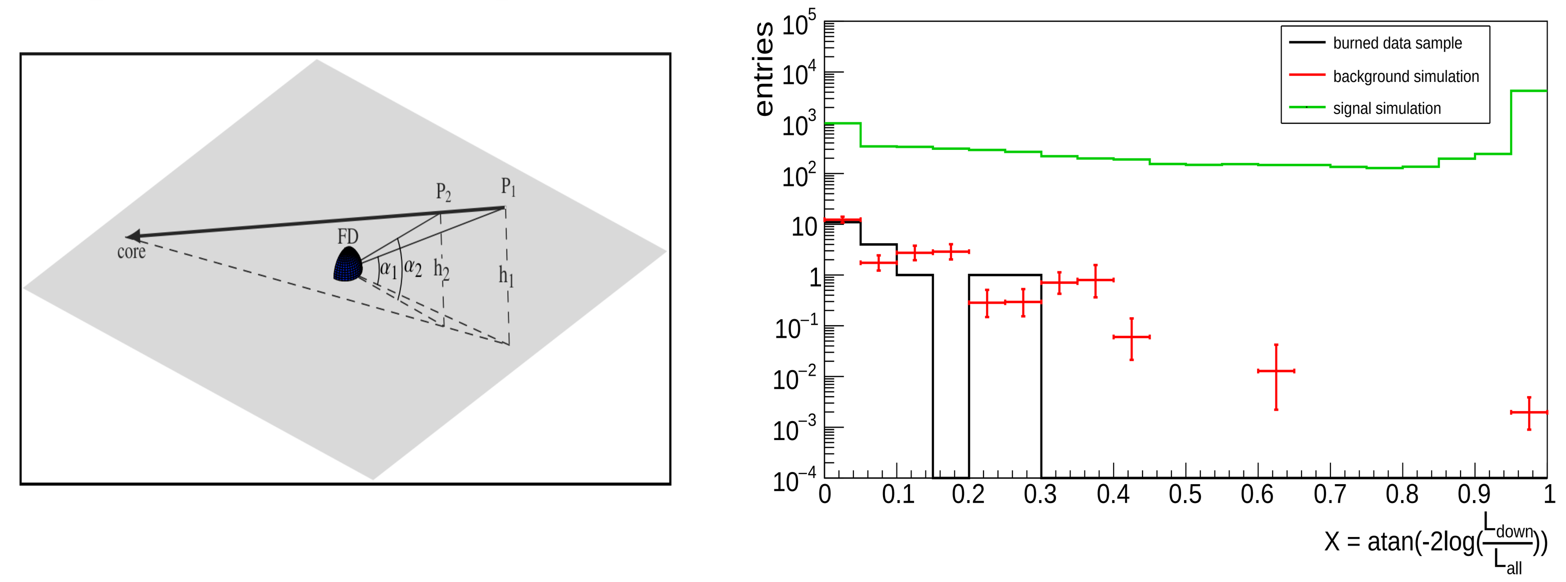

Figure 3: (Left) Graphical representation of a downgoing event landing behind the FD site that can mimic an upward-going event. (Right) Distribution of the X variable for the events from 10% of data (black), background simulations (red), signal simulations (green). We have set a cut value on X=0.55 to discriminate between background and signal region with an expected background of 0.5 events in the full data sample.

Unblinding and upper limits

The unblinding procedure led us to only one event passing all the cuts, compatible with the expected background. We set an integral upper limit to the flux of upward-going air shower at $3.6 \cdot 10^{-20}\mathrm{cm^{-2}sr^{-1}s^{-1}}$ ($8.5 \cdot 10^{-20}\mathrm{cm^{-2}sr^{-1}s^{-1}}$) by weighting the exposure with E_{cal}^{-1} (E_{cal}^{-2}).

The corresponding upper limit for the flux of upward-going τ leptons has been set for two different injection spectral indices and for three different zenith ranges. As expected from the exposure, the most horizontal zenith angles provide the best limits.

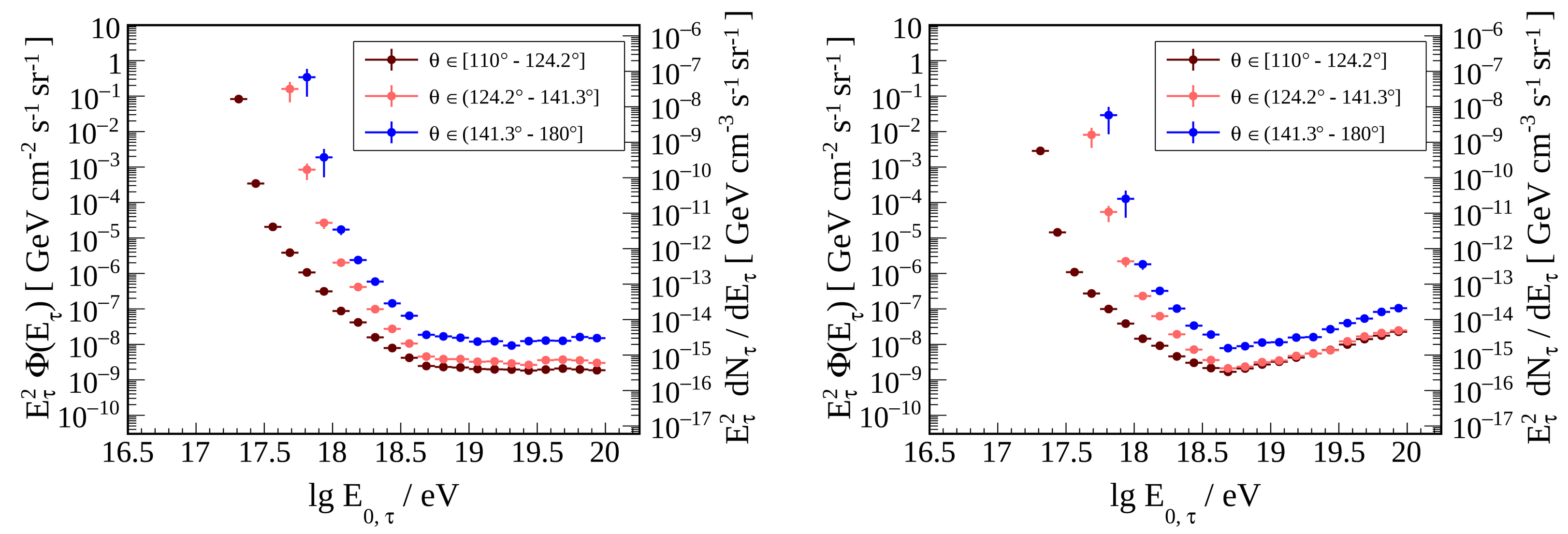

Figure 5: Upper limit set with the hypothesis of 1 background event and a spectral index equal to -1 (left) and -2 (right) for three different zenith intervals.

These results will be extended to be compared with the neutrino flux upper limit provided by ANITA or to test any interesting BSM scenario.