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Fluorescence and Hybrid Detection Aperture of the Pierre Auger Observatory

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The aperture of the Fluorescence Detector (FD) of the Pierre Auger Observatory is evaluated from simulated events using different detector configurations: mono, stereo, 3-FD and 4-FD. The trigger efficiency has been modeled using shower profiles with ground impacts in the field of view of a single telescope and studying the trigger response (at the different levels) by that telescope and by its neighbours. In addition, analysis cuts imposed by event reconstruction have been applied. The hybrid aperture is then derived for the Auger final extension. Taking into account the actual Surface Detector (SD) array configuration and its trigger response, the aperture is also calculated for a typical configuration of the present phase.

1. Introduction

One of the main objectives of the Pierre Auger Observatory [1] is the measurement of the flux of cosmic rays above 10^{18} eV. An accurate knowledge of the aperture is an important piece of this measurement, in particular in its different detection configurations: SD-only, FD-only and hybrid. For this purpose it is mandatory to use a detailed simulation to exploit dependences on the numerous parameters.

The detector aperture, integrated over solid angle, is given by

$$\mathcal{A} = \int_{\Omega} S_{eff}\; cos\theta \; d\Omega \quad , \quad \text{with} \qquad S_{eff} = \int_{A_{gen}} \epsilon_{trg} \cdot \epsilon_{rec} \, dS \tag{1}$$

where $d\Omega = dcos\theta d\phi$ and Ω are the differential and total solid angles respectively. Excluding inclined showers, θ varies from 0 to $60°$. S_{eff} is the effective area, ϵ_{trg} is the overall trigger efficiency and ϵ_{rec} is the reconstruction efficiency. dS and A_{gen} are the differential and total areas where shower events hit ground level. Equation (1) allows the calculation of aperture for different conditions and detector configurations. Single detector (SD or FD) apertures are obtained using the relevant detector efficiency functions for ϵ_{trg} and ϵ_{rec}. On the other hand, a hybrid aperture calculation has to include efficiencies of both detectors and therefore each efficiency function has to be read in (1) as the product $\epsilon^{SD} \times \epsilon^{FD}$[1].

2. The basic FD trigger function

Under the assumption that all six telescopes forming an FD eye have identical characteristics one can restrict the generation area to a slice with a vertex at a telescope, radius from 0 up to a maximum distance and azimuthal width equal to the telescope field of view (i.e. $\pm 15°$ around the telescope axis). Efficiency is calculated as a function of polar coordinates of shower impact points. Because of left-right symmetry, efficiency is a function of r and $\Phi = |\phi_G - \phi_G^{axis}|$, the absolute azimuthal distance of the impact point from the telescope axis azimuth. The assumption of identical telescopes is needed to extend the evaluation of $\epsilon_{trg}(r, \Phi)$ for $\Phi > 15°$, using the efficiency measured by the neighbouring telescopes. The simulation FDSim [2] was used

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[1] Hereafter, the upper index will be explicitly written only in case of ambiguity, when both detections are considered at the same time.

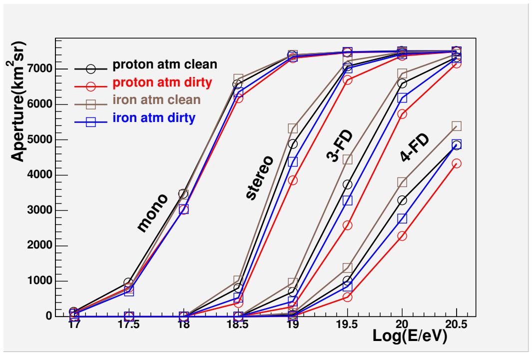

Figure 1. Estimated hybrid apertures in km^2·sr as a function of shower energy for different detector configurations, primary particles and atmospheric conditions.

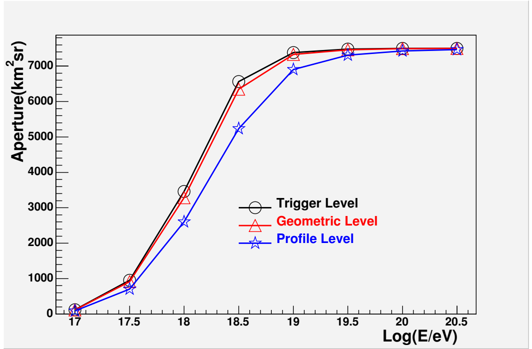

Figure 2. Estimated mono hybrid apertures in km^2·sr at various reconstruction levels as a function of shower energy for proton primaries in a "clean" atmosphere.

for generating showers from two primary types, protons and iron nuclei, in 8 energy bins from 10^{17} to $10^{20.5}$ eV. Two different atmospheres were used with vertical aerosol optical depth (VAOD) above the FD level of 0.03 and 0.06, respectively. These atmospheres will be referred to as "clean" and "dirty", having respectively lower and higher VAOD with respect to the typical Malargüe atmosphere[3].

In total 700,000 shower profiles have been generated. Trigger efficiency has been calculated in cells of $\Delta r = 2$ km times $\Delta\Phi = 1.5°$ for four separate cases: protons and iron nuclei in "clean" and "dirty" atmospheres. The basic trigger function $\epsilon_{trg}(r, \Phi)$ has been regularized and parameterised, at each energy, through a fit to an empirical function.

During the current period of data taking only some telescopes are fully equipped with a corrector ring (an optical device for increasing aperture) [1]. Therefore, for a selected configuration of primary and atmosphere (protons in "clean" atmosphere), we simulated 20,000 shower profiles with this optics, to study the differences between telescopes with or without a corrector ring.

3. The hybrid aperture in ideal case

Using the basic trigger function discussed in the previous section it is straightforward to evaluate the efficiency ϵ^{OR}_{trg} to trigger a shower by *at least one telescope in the eye*. This function is mapped onto the ground. For this purpose the ground area is divided into a grid of 0.5×0.5 km^2 cells and the corresponding polar coordinates $(r, \phi_G)_{eye}$ relative to each eye is calculated. This allows the evaluation of ϵ^{OR}_{trg} at the cell center as seen by each eye for the different detection configurations, i.e. *mono*, *stereo*, *3-FD* or *4-FD*. The corresponding aperture follows directly from the surface integral in eq. (1). The integral has been performed over a domain fully including the SD array in its final extension and assuming $\epsilon^{SD}_{trg} = 1$ within the array boundary and 0 outside. This represents the *effective hybrid area in the ideal case of a fully efficient SD at any energy*. Since a hybrid trigger requires only a SD single station trigger (SD-T1)[1], this condition turns out to be fulfilled as soon as the energy exceeds 10^{18} eV.

Then the aperture is $\mathcal{A} = \bar{S}_{eff} \times \pi(1 - cos^2\theta_{max}) \simeq 2.36\ sr \times \bar{S}_{eff}$, where the bar signs stand for the average over solid angle, with a $cos\theta\ dcos\theta$ distribution. In Fig. 1 the aperture calculated for different FD configurations is shown. The mono-hybrid aperture is practically independent of primary type, but is slightly sensitive to atmosphere parameters. The relative difference between the two atmospheres is about 15% at 10^{18} eV and vanishes at higher energies. For more demanding detection configurations (stereo, 3-FD and 4-FD), apertures tend to be more sensitive to both composition and atmosphere.

Apertures shown in Fig. 1 are trigger apertures. since the only requirement applied to showers is the fullfillment of trigger conditions. Other conditions have to be applied if showers are to be reconstructed. In Fig. 2 we show how the aperture changes when the Shower Detector Plane (SDP) (*Geometry Level*) and the shower profile (*Profile Level*) are reconstructed. In this figure, SDP reconstruction was assumed to be fulfilled with at least 5 pixels. The profile level requires a minimum number of 10 pixels and the shower maximum in the telescope field of view.

4. The hybrid aperture of the growing detector

The aperture shown so far is based on FD efficiency only and for the full Auger site as the generation area. However the Auger detector is not static, but is continually changing: at present, since new tanks are added and put into operation and, at completion, since individual detectors (SD tanks and/or FD telescopes) can be occasionally out of operation or excluded because of non standard performance. Therefore the actual hybrid aperture in the construction phase and also in the final configuration has to be calculated using both FD and SD trigger responses. The SD trigger efficiency has been extensively studied separately and in particular the use of a “Lateral Trigger Probability” (LTP) function has been proposed [4] for a complete description of the trigger features. These LTP functions have been parameterised as a function of distance at various energies.

Because in the current phase of data taking FD telescopes have different optical configurations (with and without corrector ring), the basic trigger functions were calculated accordingly. As shown in fig 4, the configuration with corrector ring allows more distant viewing at any angle.

In Fig. 3 the mono hybrid trigger efficiency is shown as a function of energy, for the site configuration of mid

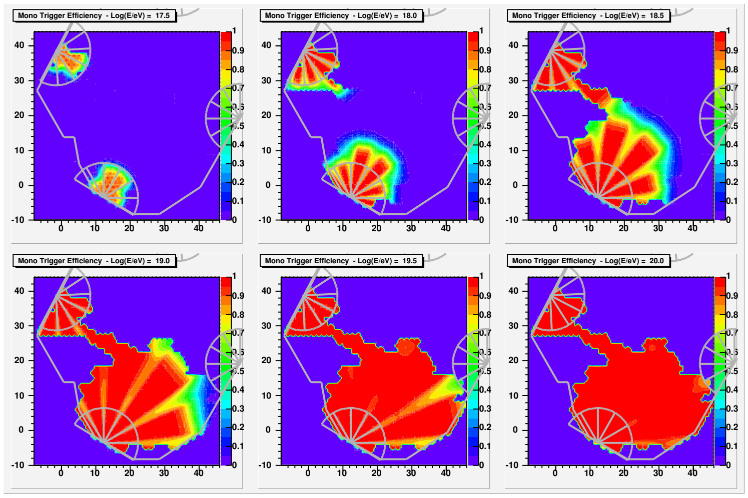

Figure 3. Mono hybrid trigger efficiency at mid October 2004, for proton primaries in “clean” atmosphere, at energies from $10^{17.5}$ to 10^{20} eV. Efficiency is represented following a color code from violet (0) to red (1). At this date, the two central telescopes (3 and 4) of both eyes were equipped with corrector ring lenses. The unusual shape of the domain where efficiency is greater than 0 is caused by the extent of the SD array at this date.

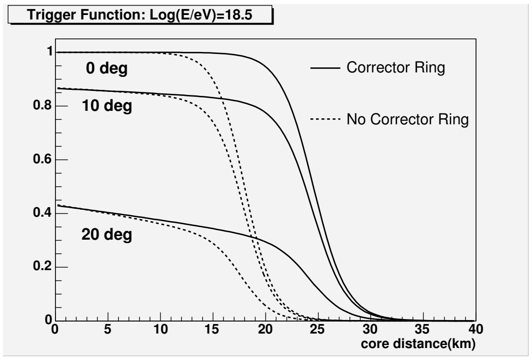

Figure 4. FD basic trigger function $\epsilon_{trg}(r,\Phi)$ at $10^{18.5}$ eV for three different Φ angles. The function parameters refer to proton primaries in a "clean" atmosphere.

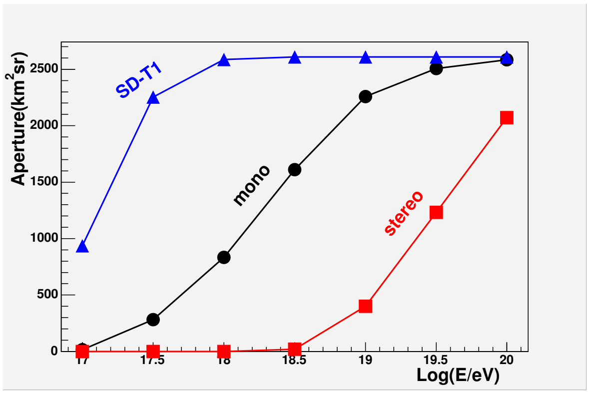

Figure 5. Hybrid Trigger aperture in km^2·sr for mono, stereo and SD-T1 detections.

October 2004. At lower energies the mono hybrid trigger accesses only the area covered by SD tanks just in front of each eye. In particular at $10^{17.5}$ eV the single tank are easily visible as red spots in the trigger patterns. At higher energies, when the LTP range exceeds the distance between contiguous tanks, the area accessed by the hybrid trigger is roughly the intersection of FD patterns with SD domain.

In Fig. 5 the hybrid trigger aperture is shown as a function of energy for mono and stereo detection as compared with SD-T1 detection[2] (SD-only single station trigger efficiency). It can be seen that mono detection approaches SD-T1 as energy increases. Stereo detection becomes sizable above 10^{19} eV and then rapidly increases.

5. Conclusions

The use of basic trigger functions for both SD and FD detectors allows a detailed study of the local trigger probability and aperture in the case of hybrid detection. This approach is particularly appealing since it limits the intensive CPU simulation to the generation of these functions, that can then be used very easily for aperture calculations. The advantage is still more evident if one takes into account that simulation studies are largely detector specific. Finally we have shown that this approach allows the continuous evaluation of apertures as new detectors are added in the field and put into operation.

References

[1] J. Abraham *et al.*, The Auger Collaboration, Nucl. Instr. Meth. A523 (2004) 50-95
[2] L. Prado jr, *et al.*, Nucl. Instr. Meth. A545 (2005) 632-642.
[3] R. Cester *et al.*, contribution to this conference.
[4] D. Allard *et al.*, contribution to this conference.

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[2] SD data are acquired at higher trigger level (namely T3) since trigger rates are too high at lower levels.