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Expected performances of the SWGO observatory to ultra high energy gamma-ray

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The Southern Wide-field Gamma-ray Observatory (SWGO) [1] will be a next generation ground array experiment probing the Southern sky in search of gamma-ray sources from the Galactic plane. The experiment will be located in the Atacama Astronomical Park at 4770 m above sea level. The observatory will be a wide field of view and high duty cycle (almost 100%) array measuring the Extensive Air Showers (EAS) generated by primaries of energy greater than 100 GeV. SWGO will rely on the Water Cherenkov Detector (WCD) technique to study the ground particle distribution of the secondary particles of the EAS, to reconstruct the characteristics of the primary gamma rays. Recently, the HAWC [2] and LHAASO [3] experiments detected various sources at energies greater than 100 TeV, both arrays being in the Northern hemisphere, and there is a clear lack of an observatory exploring the Southern hemisphere sky at these energies. In this contribution, we describe the expected performance of the current reference configuration (nearly 1 km^2 area with a dense core at the centre) of the SWGO observatory in the 30 TeV - 1 PeV energy range. The energy resolution is about 15% and the angular one is 0.1-0.15 degrees, showing an improvement with respect to current observatories. Gamma-hadron separation power and sensitivity are expected to be at least comparable with LHAASO and further studies with improved simulations will allow to refine the performance quantities.

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1. Introduction

The Southern Wide-field Gamma-ray Observatory (SWGO) [1] will be a next generation, water cherenkov detector array probing the southern sky in search of gamma-ray sources. It will probe the spectrum of gamma rays from 100 GeV to few PeV, being the first of its kind in the Southern hemisphere. SWGO will be built in Pampa La Bola in the Atacama Astronomical Park in Chile, at an altitude of 4770 m above the sea level.

The collaboration is considering several array layouts of water cherenkov detectors that are divided in multiple zones. An inner dense core (>60% fill factor) of at least $3 \cdot 10^4$ m^2 to study the lower energies, and one or more low density (<5% fill factor) outer zones covering roughly 1 km^2 of surface.

To evaluate the best candidate, a big simulation effort has been done by the collaboration. However, it soon became clear that simulating performance at Ultra High Energies (UHE) in the standard way is not feasible. Generally, the CORSIKA [4] software is used to produce a big sample of EASs at the observation level. Then, a GEANT4-based code is used to simulate the detector response.

By analyzing the simulations, it is possible to get effective area, background separation power, Point Spread Function (PSF) and all the standard parameters that are used to compare the different layouts. But in the UHE range, the requirements on gamma/hadron (g/h) separation and the computational time required to simulate a single event are so big that this procedure is not feasible.

To solve this issue, we have developed a fast simulation code that can make the GEANT4 [5] step much faster by parametrizing the tank response with a lookup-table. Basically, since the full description of the software is beyond the scope of this paper, we created a table (for each candidate tank we need to simulate) describing how the detector responds to specific particles (type, energy, entering point and direction), and then we use a multi-dimensional interpolation algorithm to interface with the CORSIKA particle list of the events and produce the tank response to shower particles.

2. UHE array response simulations

We have used a dataset containing photon and proton generated showers from 30 TeV to 10 PeV following a power law distribution (index -1 for photons and -2 for protons). A smaller slope was chosen for the photon dataset in order to have more statistic at higher energy in order to reduce the amount of required events to simulate.The azimuth direction of the primaries is uniform over 360° and the zenith angle follows a sinusoidal distribution between 0° and 52°.

The photon dataset contains $3 \cdot 10^5$ events, while the protons one $2 \cdot 10^6$, each proton event being thrown twice to increase the statistic further. Event core position has been selected uniformly inside a circle of radius 700 m from the center of the array, using the current SWGO reference configuration shown in figure 1 (left). The layout is divided in 3 constant fill factor zones:

- a core of radius 156 m and fill factor 70%,
- an intermediate ring of radii 156 m and 400 m with fill factor 4%,

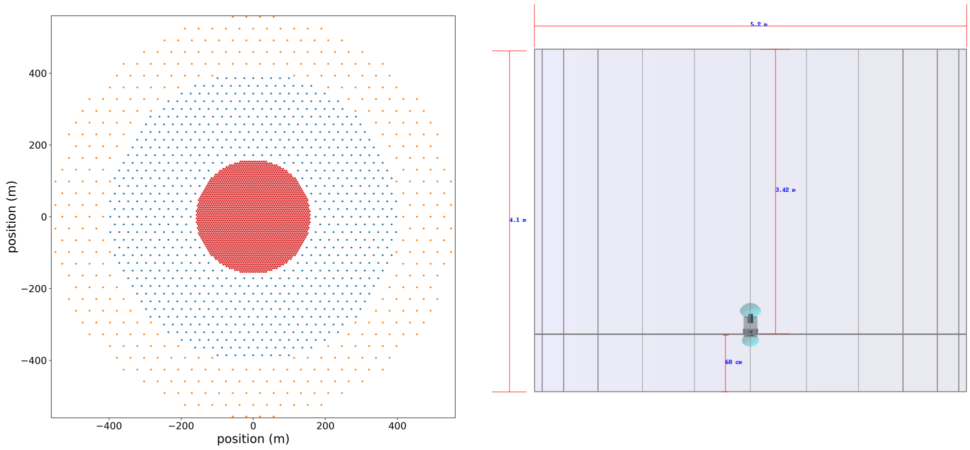

Figure 1: (left) Layout of the simulated array, an almost 1 km^2 solution divided in 3 zones with different fill factors. (right) Picture of the simulated tank model.

- an external ring of radii 400 m and 560 m with fill factor 1.7%,

The purpose of the inner region is to study the lower energies, which require a smaller collection area. On the other hand, the outer rings will be more sensitive to UHE events thanks to the larger effective area. In the reference configuration, all tanks are identical and their main characteristics are:

- Radius 2.6 m and height 4.1 m metal tanks
- Double layer polypropylene bladder containing the water
- Lower layer fully covered in Tyvek® for improved light output and a 8" HQE photomultiplier (PMT) looking downwards
- Upper layer covered in Tyvek® only on the lateral walls and equipped with a upper looking 10" PMT

Figure 1 (right) shows a profile picture of the tank used in the simulations. The idea of the double layer design is to use the upper one for timing and electromagnetic component measurements and the lower one for the muonic component. The lower layer is more sensitive to the muonic component thanks to the natural shield provided by the upper layer.

After simulating the events, we run our reconstruction/classification procedure, obtaining the results that will be discussed in the next section. This work is still preliminary, and the analysis (and this will become clear in the next section) still needs to be properly tuned for the UHE events.

3. Preliminary performance of SWGO at UHE

In this work, for the sake of brevity, we will present only the performance for events with reconstructed zenith angle $\leq$ 30° and core reconstructed inside the array. For most quantities, we will plot the results together with some reference values, which were obtained from a full-simulation dataset prepared by the collaboration to study the performance at lower energies [1]. Since the UHE statistic of this reference dataset is smaller, we have decided to not include reference values for the gamma/proton efficiency. For all the other quantities, cyan lines will be used for the reference data and orange ones for the results of this work.

First of all, we computed the total effective area of the layout, figure 2 shows the results (orange) together with the reference values (cyan) and the single array zone contributions.

In every plot shown the same code for identifying the zone will be used:

- 1: indicates the core of the layout (from 0 m to 156 m from the array center) and will be represented with solid lines
- 2: indicates the midway ring (from 156 m to 400 m from the array center) and will be represented with dashed lines
- 3: indicates the outer ring (from 400 m to 560 m from the array center) and will be represented with dash-dotted lines

Above 50 TeV, the effective area is already stable and saturating at roughly 80% of the physical area of the array (this also happens to the contributions of each zone). This is expected since we evaluate the g/h separation cut requiring an 80% gamma efficiency.

Figure 3 shows that the gamma efficiency is stable around 80% the testing dataset we used to compute the plots. This, together with the effective area, indicates that basically any event above 50 TeV is triggering the array and the reconstruction manages to return the main properties of the shower (we will discuss in the precision of such information further is this section).

We also tried to evaluate the proton efficiency, but unfortunately, the statistics is still insufficient. A preliminary result is shown in figure 3. In the plot, the data points with arrows are bins in which all protons were rejected by the g/h separation. We evaluated some sort of upper limit with one over the number of protons before applying the g/h separation. We could evaluate the separation power only in the first bin. Even in that bin the number of protons passing the cut is still small, which reflects in an high uncertainty in the separation power.

As g/h separation we have trained a multi layer perceptron in each analysis bin (we bin in zenith angle, core and energy), for this we used a python package developed by the collaboration. As input we used some basic event level information (reconstructed core, zenith angle and energy) and g/h separation variables (such as PINCness and LDFChi2 [7]) and the output of a graph neural network [8] and a transformer [9].

We used the 68% quantile of the angle between reconstructed direction and MonteCarlo direction as value of the angular resolution. Figure 4 shows the angular resolution (orange) together with the reference one (cyan). The increase above 300 TeV is under investigation. A fine tuning of the SWGO reconstruction code for high energy events is in progress.

We used a template-based algorithm [6] to reconstruct the core position and the energy of the events. The template we used was obtained by merging a low energy one (produced with the GEANT4-based full simulation) and a UHE one (generated with the fast simulation). Figure 5 shows the energy bias and resolution (orange) compared with the reference ones (cyan). The

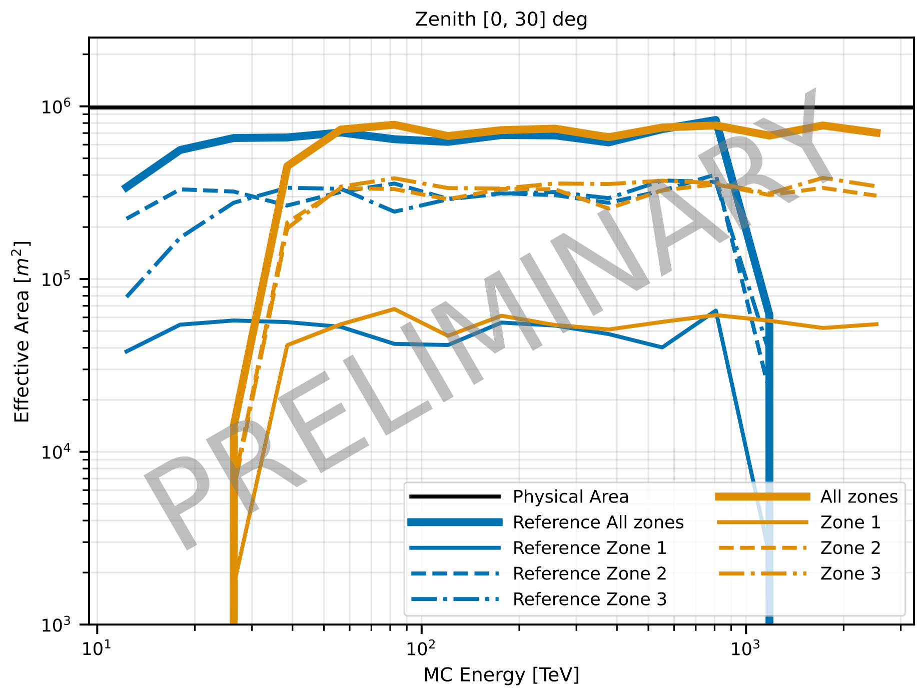

Figure 2: Total (bold line) effective area of the simulated array and its components. Solid lines indicate events reconstructed in the core region, dashed ones in mid zone and dash-dotted ones in the outer ring. Cyan lines are reference values from a full simulation dataset while orange data is the one produced with the fast simulation algorithm.

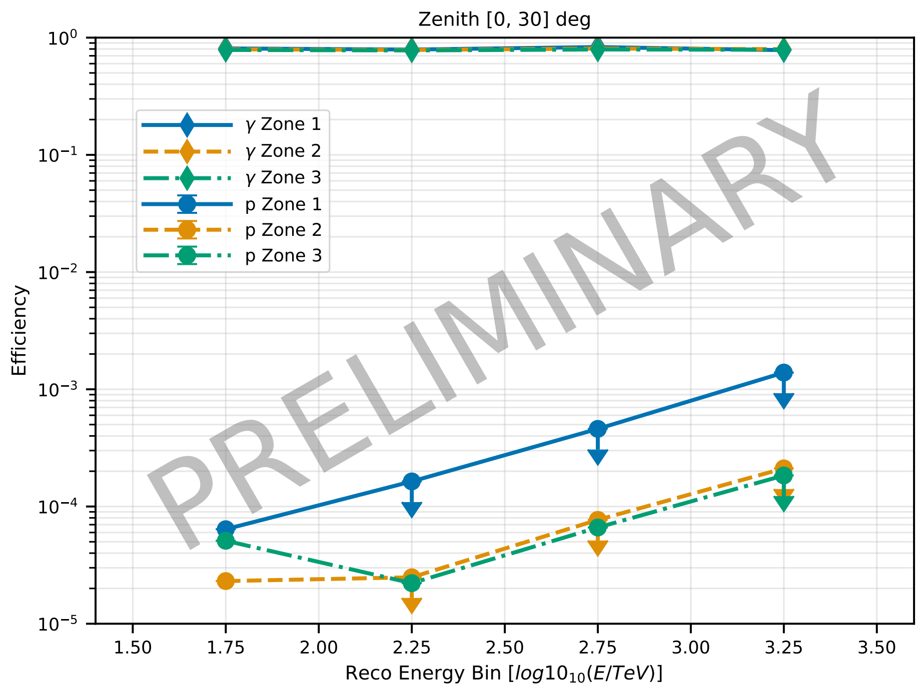

Figure 3: Proton (diamonds) and gamma (circles) efficiency of the simulated array. Solid cyan lines indicate events reconstructed in the core region, orange dashed ones in mid zone and green dash-dotted ones in the outer ring. Arrows show points in which all protons were rejected.

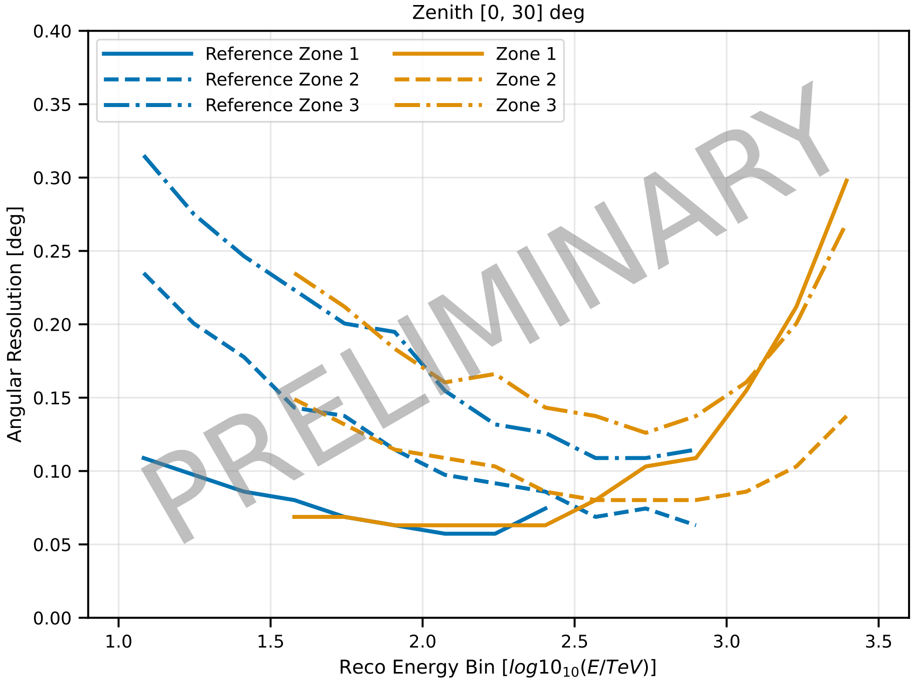

Figure 4: Angular resolution of the simulated array. Solid lines indicate events reconstructed in the core region, dashed ones in mid zone and dash-dotted ones in the outer ring. Cyan lines are reference values from a full simulation dataset while orange data is the one produced with the fast simulation algorithm.

negative values around 30 TeV are due to switching to the low energy reconstruction template but the value of the bias is comparable with the step of the template. On the other hand, the increase of the bias around 10 PeV is probably due to the reconstructed energy reaching the end of the template energy bins. The increase of the energy resolution above 1 PeV is still under investigation.

Figure 6 shows the core resolution (orange) compared with the reference one (cyan). It is smaller than 10 m at any energy above 30 TeV and for any core region.

Due to the too many missing points in the background evaluation, we could not compute the sensitivity of the array. We will do this calculation once we will have more statistics.

4. Concluding remarks

We have simulated the array response to UHE primaries (photons and protons) to evaluate the performance of a candidate layout for the SWGO experiment. Unfortunately, the proton sample is still limited and strong conclusions on background separation power and sensitivity cannot be taken. The data was large enough to evaluate the energy dependence of effective area, PSF and energy resolution.

The effective area is stable above 50 TeV and roughly equal to 80% of the physical area of the experiment. The PSF is $\leq 0.15°$ at least up to 1 PeV, then it starts to increase. The energy resolution is always smaller than 15% but again there is some effect to understand above 300 TeV.

Our conclusion is that we are moving in the direction of evaluating possible candidates for SWGO. The analysis needs to be improved and the statistics increased. Therefore we will continue

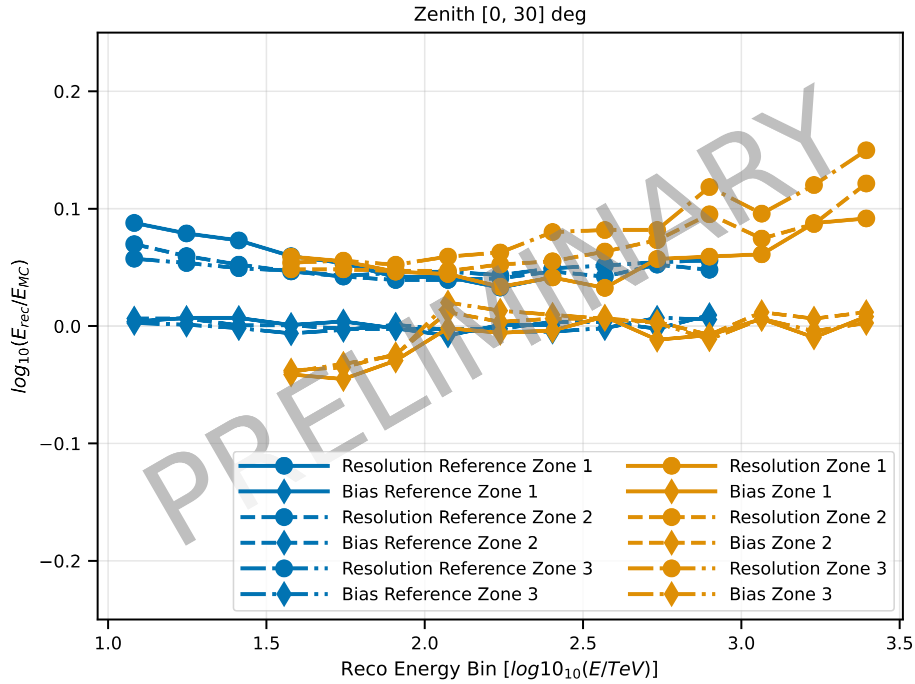

Figure 5: Energy bias (diamonds) and resolution (circles) of the simulated array. Solid lines indicate events reconstructed in the core region, dashed ones in mid zone and dash-dotted ones in the outer ring. Cyan lines are reference values from a full simulation dataset while orange data is the one produced with the fast simulation algorithm.

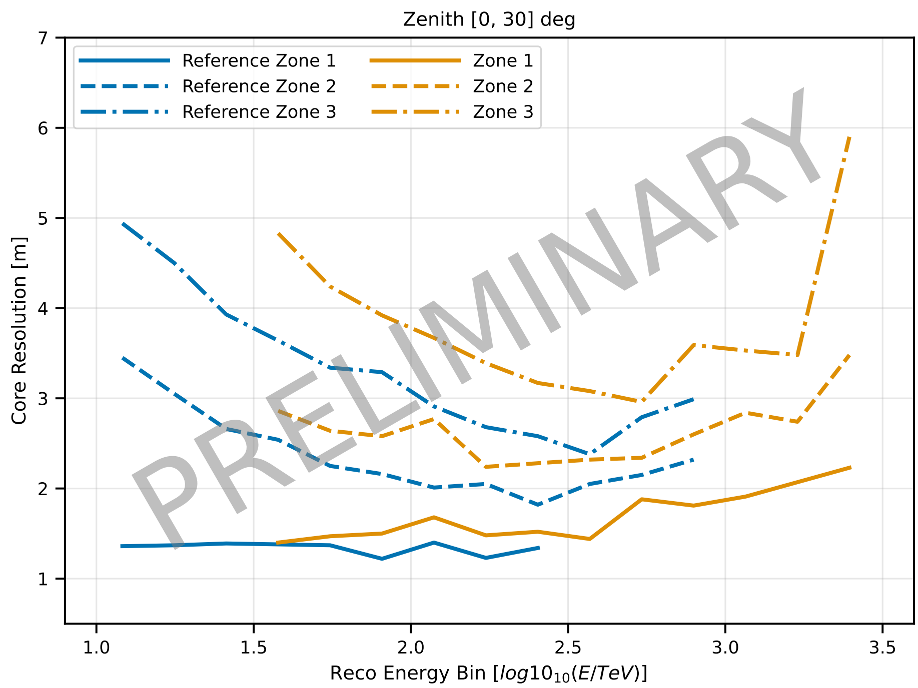

Figure 6: Core resolution of the simulated array. Solid lines indicate events reconstructed in the core region, dashed ones in mid zone and dash-dotted ones in the outer ring. Cyan lines are reference values from a full simulation dataset while orange data is the one produced with the fast simulation algorithm.

our work towards this objectives.

Acknowledgments

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