PROCEEDINGS OF SCIENCE

Simulation of PeV atmospheric showers for SWGO

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The recent discovery of PeV gamma-ray emission especially from the LHAASO observatory, located in the Northern hemisphere, boosted the relevance of observing the Southern sky at such energies. SWGO (Southern Wide-Field Gamma-Ray Observatory) is the largest proposed detector with sensitivity in the 100 TeV-1 PeV energy range. The baseline SWGO idea is a km^2 array of water tanks to be placed above 4,400 m a.s.l. in the Andes, South America. In this contribution, we have studied the particle content and the morphology of Extensive Air Showers (EAS) generated by photons and protons in the 0.1 to 10 PeV energy range. We have simulated over 10^6 gamma-rays and proton induced showers respectively with primary energy in the 0.1-10 PeV energy range. We also show the particle distribution at ground, the lateral profile, the muon content and the average particle properties at ground.

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1. Introduction

The recent results obtained by the LHAASO [1, 2] and HAWC [3] observatories opened the field of Ultra High Energy Gamma Ray Astronomy. LHAASO and HAWC are wide field-of-view (FOV) observatories both located in the Northern Hemisphere, there is therefore a clear lack of a detector with similar performance located in the Southern hemisphere. The SWGO collaboration [4] is proposing the construction of such an observatory. The main requirements of the SWGO observatory are:

- to cover the 100 GeV< E <1-10 PeV energy range,
- a baseline detection technique with Water Cherenkov Detectors (WCDs),
- placed at a latitude between 10° and 30° South,
- a location at an altitude above 4,400 m a.s.l.

Covering such a wide energy range might be obtained by an array with a central area ($\sim 8 \times 10^4$ m^2) with high fill factor (ideally $\geq$ 80%) to study the hundreds GeV energy range and a large external ring, $\geq$ 1 km^2 surface, with a smaller fill factor ($\leq$ 5%) dedicated to the energies above 100 TeV. Globally, between 5000 − 10000 detector units are to be deployed.

To optimize the layout of the external detector, we have performed a detailed study of the EAS morphology and particle content in the $0.1 < E < 10$ PeV energy range.

2. EAS Simulation

The full EAS simulation has been performed using the CORSIKA [5] Extensive Air Shower (EAS) Monte Carlo using the hadronic interaction models QGSJetII-04 [6] and UrQMD [7]; the EAS electromagnetic component is simulated using the EGS4 [8].

We simulated photon showers both with fixed energy and zenith angle and with energy sampled on a power law spectrum and with zenith angle θ between 0° and 65°. Proton showers were always simulated on a power law spectrum either with fixed or variables zenith angles. The summary of the simulated showers sample is reported in Table 1.

Particle	E [PeV]	ZD [deg]	N
γ	0.1/0.3/1/3/10	20/40	10^4
	0.1 − 10	0 − 65	10^5
p	0.1 − 10	20/40	2×10^5
	0.1 − 10	0 − 65	2×10^5

Table 1: CORSIKA production. Columns are primary particle type, energy, zenith angles and number of showers.

In the input cards for the CORSIKA code we defined the following energy threshold below which particles are ignored by the simulation: 5 MeV for photons and electrons, 0.1 GeV for muons and hadrons.

3. PeV Showers Studies

Ground Pattern The first result we checked is the pattern of the CORSIKA simulated showers on the ground. We counted the number of particles hitting the tanks of two possible layouts of the SWGO experiment: A1 (baseline) and A7 (the most extended, and better suited for PeV showers). In both of them the tanks are located on a triangular grid with circular pattern. The two layouts differ both for the total surface of the array ($\sim 2.8 \times 10^5 \text{m}^2$ and $\sim 1\text{km}^2$) and for the detector fill factor: (A1) 80% for $r < 160$ m, 5% for 160m $< r <$ 300m the first and (A7) 80% for $r <$ 100m, 2.5% for 100m $< r <$ 600m, 0.63% for 600m $< r <$ 1200m the second. All different simulated layouts (9 in total) share the total realization cost.

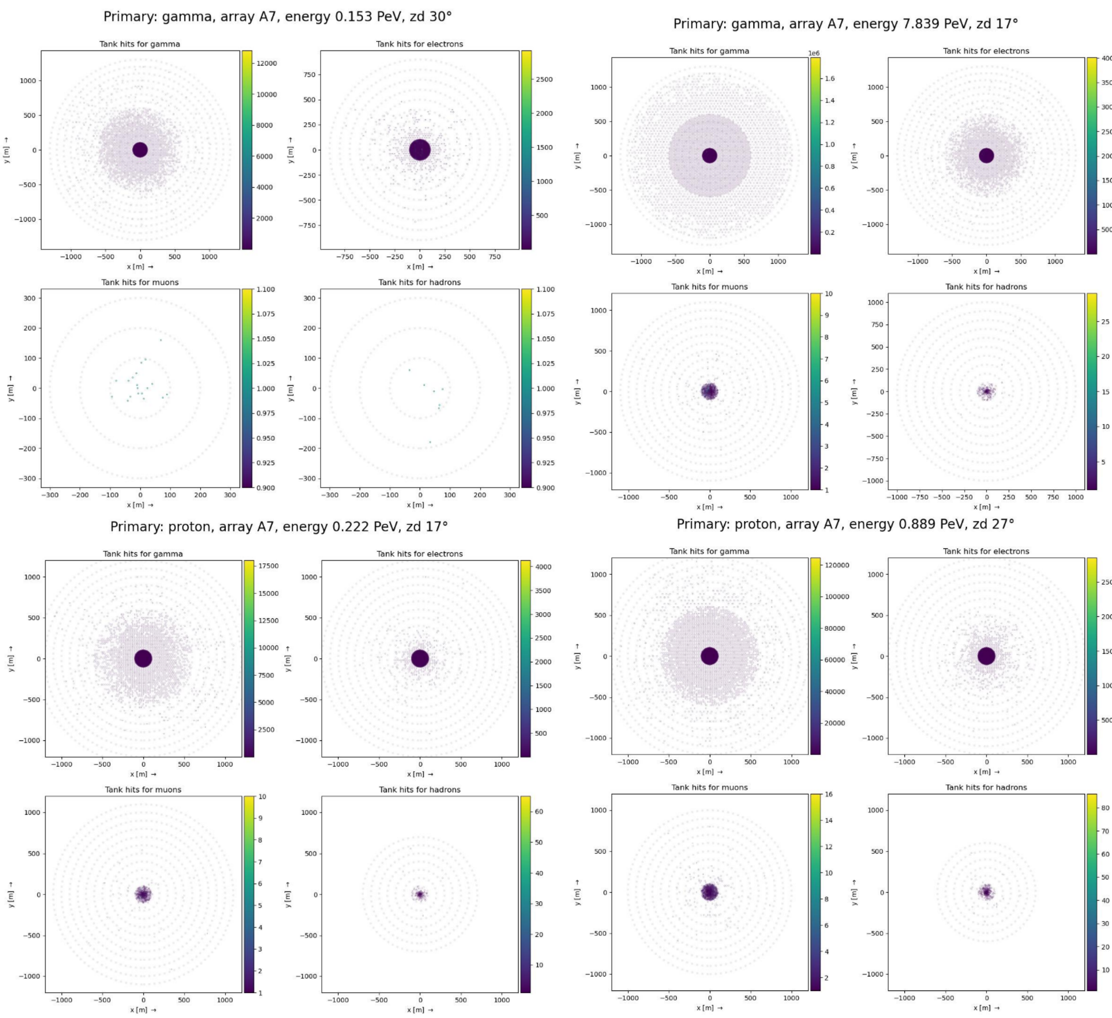

Figure 1: Ground particle distribution for A7 configuration. *Above*: Gamma ray at 0.1 PeV *(left)* and 10 PeV *(right)*. *Below*: Protonic ray at 0.1 PeV *(left)* and 1 PeV *(right)*. The zenith angle with which the primary particle enters the atmosphere is denoted by *zd*. Color bars on the side show the number of detected hits for each tank. Taken from [9].

In Figure 1, we report the pattern, for different EAS particles, of showers generated by PeV photons and protons. For all shown particle distributions the shower core is located in the center of the array. Comparing the pattern obtained for many showers we can observe that the number of photon in gamma-ray and proton showers (of similar energy) are comparable at all distances from the core. On the other hand electrons in gamma-ray showers are more numerous and spread apart. As expected we can see that in photon showers muons in the outermost layers of the experiment layout are rare and these few muons are concentrated at core distances smaller than $\sim$ 150 m. In a proton shower muons can be measured even at large core distances.

Lateral Distribution Surface arrays usually sample the EAS lateral distribution of each event and use this measurement to evaluate the EAS parameters (i.e. the shower size or number of particles at observation level or the particle density at fixed distance from the shower core) that are then used to determine the energy of the primary particle. Figure 2 shows the mean lateral distribution, obtained without considering a detector layout, of particles at SWGO observation level, for $E \sim 1$ PeV and $\theta = 20^{\circ}$ proton showers. In the top left panel we show the mean lateral distribution for all shower particles, without applying any energy cut. We further studied the EAS particle lateral distribution selecting only particles with energy greater than 250 MeV (top right panel), 500 MeV (bottom left panel) and 1 GeV (bottom right panel). We analyzed these plots that are relevant to study the particles that can contribute to the signals generated in a detector located below an absorber (as it is usually done to measure the muon shower component).

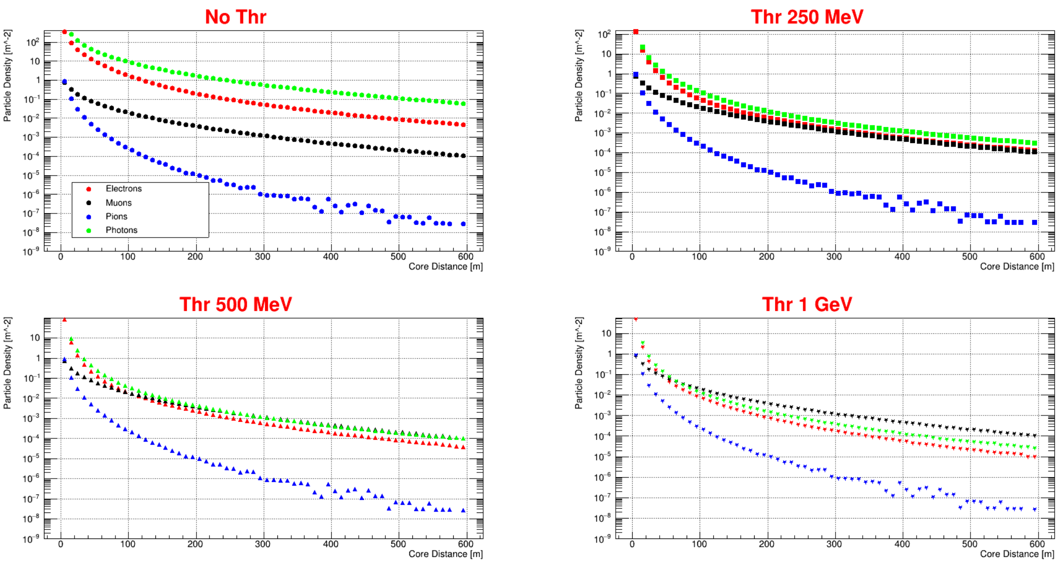

Figure 2: Mean Lateral distribution for showers initiated by $\sim 1PeV$ proton. The distributions are shown for all particles (*top left*) and for particles with energy: $E > 250$ MeV (*top right*), $E > 500$ MeV (*bottom left*), $E > 1$ GeV (*bottom right*)

We can see that from all shower secondary particles, photons are the more abundant at all core distances. Considering particles with energy greater than 250 MeV the electrons and muon densities are comparable for core distances larger than 200 m. Only using a 1 GeV threshold the electron density decreases quite rapidly with the core distance; already at core distances greater than 50 m from the shower core the muon density is much higher than the electron one.

Figure 3 shows the same lateral distributions for 1 PeV photon generated showers. As expected the trends are similar to those of the proton showers, and the muon and pion components are much less numerous.

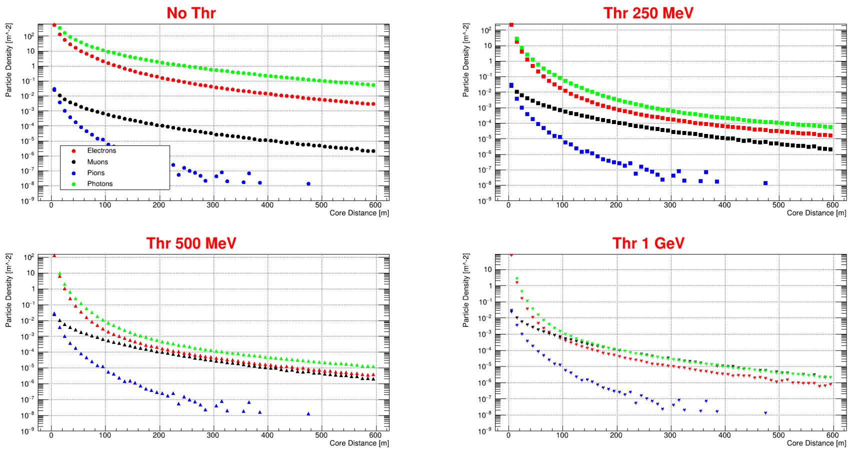

Figure 3: Mean Lateral distribution for showers initiated by $\sim 1PeV$ photon. The distributions are shown for all particles (*top left*) and for particles with energy: $E > 250MeV$ (*top right*), $E > 500MeV$ (*bottom left*), $E > 1GeV$ (*bottom right*)

EAS particle energy distribution An important parameter in the design of an EAS array is the shower particles energy. Figure 4 (*Top panel*) shows the energy spectra of photons, electrons, muons and pions in showers observed at 4700 m a.s.l. Showers are generated by photons of 1 PeV$< E <$10 PeV and zenith angle $0° < \theta < 50°$. The *bottom panel* of the same figure shows the particle energy spectra in showers generated by 0.1 PeV$< E <$1 PeV and $0° < \theta < 50°$ protons.

One can notice how the energy peak is independent on the primary energy and type. The width of the distribution is significant and this has important effects when detecting these particles in the tank. The cutoff on the left of the photon histogram is at the electron mass.

4. Conclusions and outlook

In this contribution, we have shown a selection of the main features of $\sim PeV$ photon and proton showers. The main features emerging from this simulation are as expected: photon are the more numerous particle in the showers, the muon component is a strong parameter to separate electromagnetic from hadronic showers, albeit gamma showers are contaminated by a significant number of muons, most of the electrons in the shower have energy near the critical one, the mean muon energy is around 10 GeV. These shower characteristics are of main importance in the project phase of the SWGO experiment, both for the detector design and for the definition of the gamma/hadron separation algorithm. All this is true considering all particle in the showers, while if we count particle numbers applying energy cuts we see that, at the high altitudes considered for SWGO, the muon and electron densities above hundred of MeV energies are comparable at all core distances. Only with a 1 GeV energy threshold the muon densities dominate the electron ones for core distances greater than $\sim 50m$.

In order to test a realistic response of SWGO for PeV showers, we plan to fully simulate the response with the simulation software of the tanks. This faces an issue related to the large number (hundreds of thousands) of particles at ground (see Figure 1): simulating all individual particles passage through the tank requires enormous CPU time. We found that 8 h are required for a single event. To cope with this, considering the fact that several particles tracks are realistically found several times in the array, we are preparing look-up-tables for particle type, hit position, hit direction, energy in order to speed up the simulation. After making use of this mesh-grid approach we plan to be able to obtain a factor 10-100 faster simulations.

References

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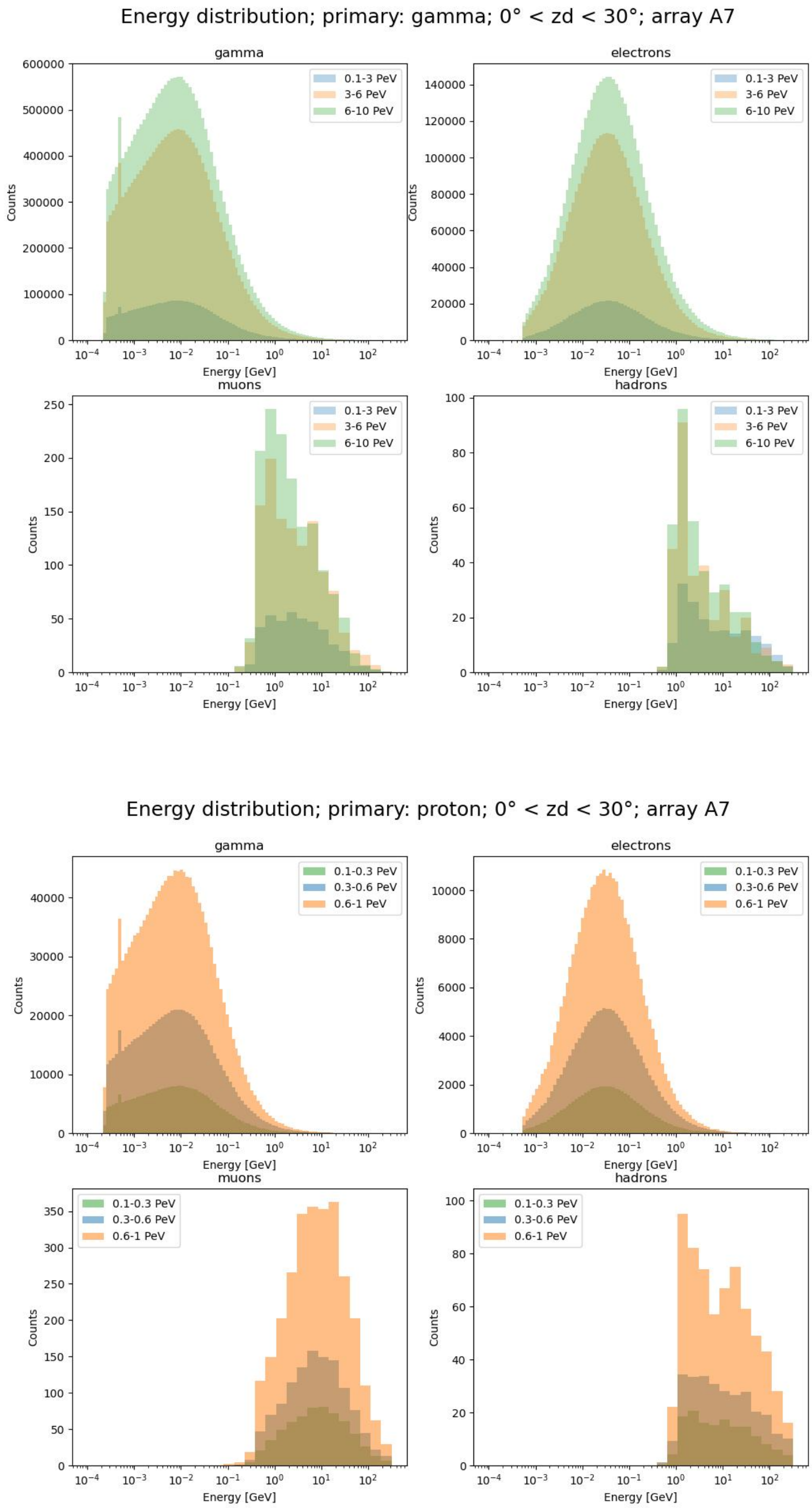

Figure 4: Energy spectra of the particles in photons (top) and protons (bottom) originated showers (0.1 PeV$< E <$1 PeV and $0^\circ < \theta < 50^\circ$) at 4700 m a.s.l.