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Hybrid concept of detection for a wide-field gamma-ray observatory using Cherenkov telescopes

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The hybrid detection approach in astroparticle physics has been successfully employed in cosmic-ray experiments and is currently being explored by gamma-ray observatories like LHAASO. We present a study on the hybrid detection concept for the future Southern Wide-field Gamma-ray Observatory (SWGO), integrating multiple Cherenkov telescopes represented in the analysis by Single-Mirror Small-Size imaging atmospheric Cherenkov Telescopes (SST-1M) located next to the surface array of water Cherenkov detectors (WCDs). We discuss the mutual benefits of this hybrid approach and present simulation-based results on key performances. Our findings points to the fact that the combination of wide field-of-view and continuous operation of WCDs with the high angular and energy resolution of Cherenkov telescopes could significantly improve the overall detection capabilities of the SWGO experiment.

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1. Introduction

While existing wide-field observatories of gamma rays, such as HAWC and LHAASO, are providing valuable information about the gamma ray sources in the Northern sky, no such experiment currently operates in the Southern hemisphere. The Southern Wide-field Gamma-ray Observatory (SWGO) [1] is a proposed next generation experiment designed to fill in this observational gap. The information that can be obtained from the continuous wide-field observations is a powerful tool to study gamma rays, but it has been demonstrated that a hybrid detection approach, combining measurements from Imaging Air Cherenkov Telescopes (IACT) with a surface detector array, can enhance the overall detection performance (see e.g. [2]).

As a first step towards the full hybrid detection approach, we study how a wide-field array of surface detectors can contribute to improving the operation and data analysis of SST-1M Cherenkov telescopes [3] placed inside the surface array. We perform a simulation-based analysis of a configuration with two identical[1] SST-1M telescopes working in stereo mode and present preliminary results on the key performances, including the gamma/hadron (γ/h) separation, flux sensitivity, and energy and angular resolution. The analysis follows a reconstruction pipeline similar to the standard SST-1M reconstruction procedure [4] with additional γ/h discrimination parameters LCm and $P^{\alpha}_{\rm tail}$ obtained from the array of surface detectors.

2. Method

2.1 Simulation settings

The presented study is based on three-step Monte Carlo (MC) simulations. First, particle interactions and Cherenkov light from air showers were simulated in `CORSIKA v7.7402` [5] employing as hadronic interaction models for low- and high-energy interactions `UrQMD` [6] and `QGSJet II-04` [7], respectively. Second, the attenuation of the light and the response of the SST-1M telescopes was calculated in `sim_telarray v2021-12-25` [8]. Finally, the response of the ground array to the particles produced in the first step was evaluated using the simplified parametric code [9].

The ground array, shown in Fig. 1, consisted of 9997 water-Cherenkov detectors (WCD), each covering 12.6 m^2, spread over an area of 1 km^2 and equipped with 3 PMTs. The fill factor of the array was 12.5%. The simulated altitude was 4700 m and the atmospheric density profile, together with the geomagnetic field, was adjusted to the Pampa la Bola site located in the Atacama Astronomical Park, Chile. Although the geographical position is tailored to the future SWGO site [10], main conclusions can be generalized to other high-altitude sites as well.

The SST-1M simulations were performed for low night-sky background with a photon rate of 72 MHz, the corresponding response of pixels was tuned to those conditions [4]. The atmosphere transmissivity was calculated using MODTRAN [11] for Pampa la Bola. Pointing direction of the telescopes was 20° zenith angle and showers came from the North to the South. The positions of the two SST-1Ms which were 110 m apart are depicted in orange in Fig. 1.

Monte Carlo sets of diffuse gamma rays, protons, and point-like gamma rays were simulated to train the Random Forests (RF) used in the reconstruction of showers in `sst1mpipe` [12], which

[1] Hardware configuration of the more recent prototype SST-1M-2 was used [4].

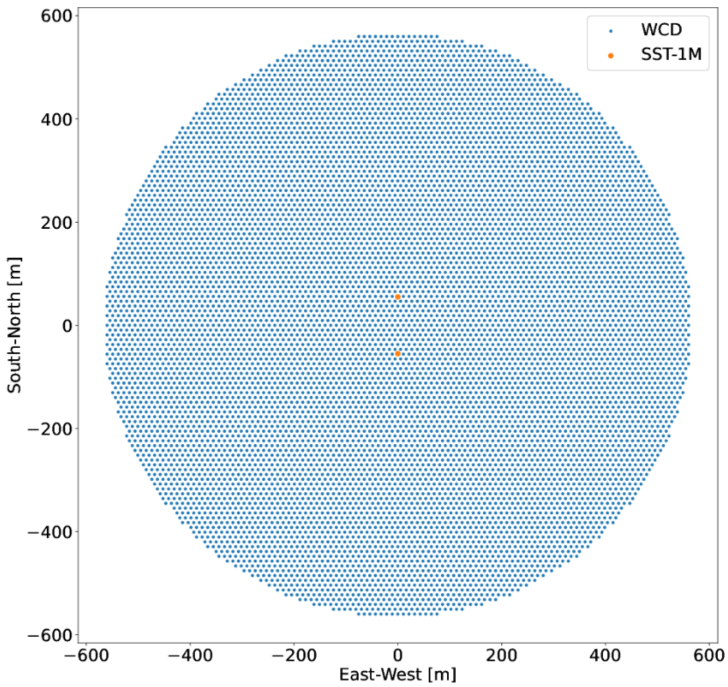

Figure 1: Sketch of the array of WCDs together with positions of 2 SST-1Ms.

is an open source software developed for calibration and shower reconstruction for SST-1M, and to directly evaluate the sensitivity to point-like source of gamma rays, respectively. The energy of the primaries was between 200 GeV and 631 TeV, and 400 GeV and 1100 TeV for gamma rays and protons, respectively, both simulated according to $\frac{\mathrm{dN}}{\mathrm{dE}} \propto E^{-2}$. In the case of diffuse samples, the opening angle of 10° was used to cover the entire field of view of SST-1M. Showers were thrown up to the impact distance of 1032 m from the ground array center. However, during the analysis, events with shower core positions above 565 m, the radius of the array, were discarded from the ground array-enhanced analysis, in order to explicitly confirm that the array size is sufficient to well cover the effective area of the SST-1M telescopes (only ~ 2% of reconstructed gammas were discarded).

2.2 LCm and P^{α}_{tail}

As mentioned above, the signal from the surface detector array was evaluated using a simplified code from [9]. The signal in the WCDs is calculated from the shower footprint at the ground level (4700 m a.s.l.) obtained from CORSIKA simulations. Two γ/h discrimination parameters, which can be easily obtained from an array of WCDs, are extracted from the simulated response of the ground array. For comparison, we also use the true number of muons N_μ from the CORSIKA simulations as an ideal reference case.

The first parameter obtained from the ground array is LCm, a γ/h discriminator first introduced in [9]. The LCm variable characterizes the azimuthal asymmetry of the ground-level shower footprint and has been shown to be a powerful discriminator between gamma and hadron-induced showers [9, 13, 14]. The second γ/h discriminator obtained from the surface array is the P^{α}_{tail} [15].

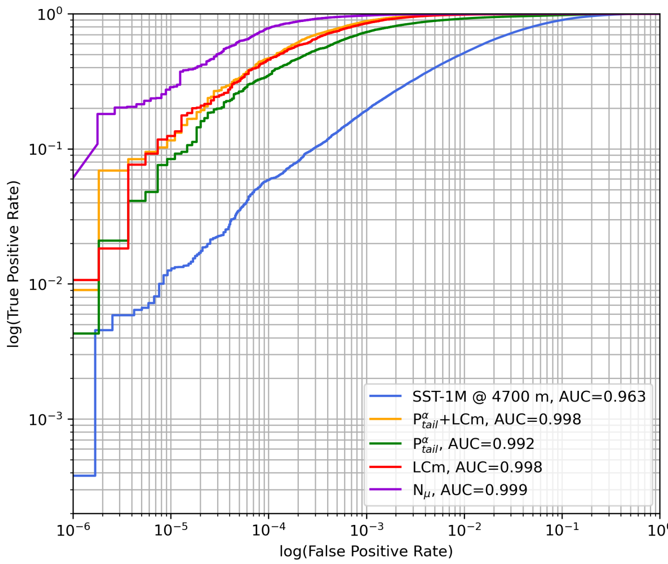

Figure 2: Receiver Operating Characteristics. Solely for SST-1M telescopes (blue) and for SST-1M telescopes with γ/h discrimination parameters obtained from the ground array added into the `sst1mpipe`, including the $P^{\alpha}_{\mathrm{tail}}$ (green), LCm (red), both $P^{\alpha}_{\mathrm{tail}}$ and LCm (orange) and true number of muons N_{μ} (purple). Those of LCm and $P^{\alpha}_{\mathrm{tail}}$ are shown for energies above 10 TeV only.

This variable is built from the total signal detected by the ground array of WCDs and shows a strong correlation with the total number of muons in the shower.

Both parameters, LCm and $P^{\alpha}_{\mathrm{tail}}$, are evaluated only for showers with energy above 10 TeV, which is the lower energy limit where these parameters can be evaluated with the software used and below which the meaning of the parameters starts to be problematic. The true number of muons is extracted for showers at all energies. The surface-array parameters were added to the features used for training of RF classifier for γ/h separation in `sst1mpipe`.

3. Results

The most significant improvement is obtained for the γ/h separation performance. This is demonstrated in Figure 2, which shows the receiver operating characteristics (ROC). The performance of the γ/h classifier is expressed as the integral of the ROC curve, area under the curve (AUC). With the addition of the LCm and $P^{\alpha}_{\mathrm{tail}}$ variables from the ground array, the achieved AUC is 0.998 compared to 0.963 from the telescopes only.

The Gini importance[2] of individual reconstruction parameters for different γ/h classifiers is shown in Figure 6. Different colors correspond to the sole SST-1M telescopes (blue) and analyses enhanced by ground-array information. In the case of pure SST-1M reconstruction, the largest importance exhibits `camera_frame_hillas_width`, a measure of the spread of a shower on camera, which is well known γ/h discriminator of IACTs [4]. When the true number of muons is included, the decision is heavily based on it, demonstrating the superior separation power of N_{μ}.

[2]The Gini importance is a measure of how much individual features contribute to the decision-making process of the Random Forrest. For more details, see `https://scikit-learn.org/stable/modules/tree.html`.

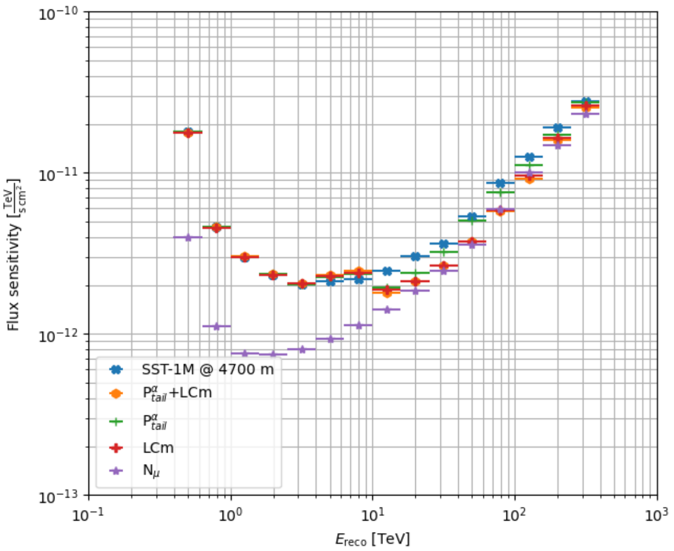

Figure 3: The flux sensitivity for the sole SST-1M telescopes (blue) and SST-1M telescopes with the additional information from the ground array (same as in Figure 2).

The interpretation of P^{α}_{tail} and LCm is slightly more complicated, because they contribute only at $E > 10$ TeV, while the figure shows importance over the full energy range. Nevertheless, both P^{α}_{tail} and LCm overall dominate the decision logic when used, and for their combination, LCm contributes more than P^{α}_{tail}, showing its better γ/h discrimination power at ultra-high energies [9, 13, 15].

Figure 3 shows the effect of the above-mentioned performance on the flux sensitivity of the telescopes. Incorporating the parameters from the ground array into the reconstruction improves the flux sensitivity by ~ 30% above 10 TeV. The ideal case with the use of N_{μ} would increase the sensitivity over the whole energy range. The fact that LCm even surpasses in efficiency N_{μ} [13] is visible in the energy bins around 100 TeV for which the calculation of LCm was optimized. In other bins N_{μ} works better, which is unexpected, although the RF classification may result in slightly different outputs than those investigated in [13]. However, these differences will be the subject of further investigation.

Interestingly, including the γ/h separation variables into the RF indirectly influences also the angular resolution, energy bias and energy resolution, but this is caused solely due to the selection effect that increases or decreases the amount of showers which pass the gamaness cut. Figure 4 shows the angular resolution of the SST-1M telescopes without and with the additional parameters from the ground array. In this case, the selection effect of including N_{μ} parameter causes worsening of the angular resolution at energies below few tens of TeV due to the incorporation of gamma events with poorer directional reconstruction.

The energy bias and energy resolution are shown in Figure 5. The energy resolution degrades at energies above ~ 300 TeV, which is partly related to the altitude of the telescope position site. This performance might be improved with additional information from the ground array, including the reconstructed shower core position and energy estimator.

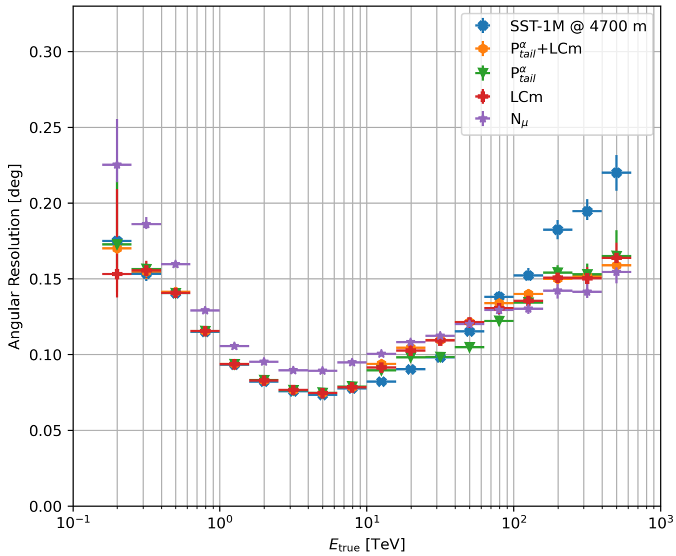

Figure 4: Angular resolution defined as 68% containment as function of true energy for point-like source gammas of the SST-1M telescopes (blue) and SST-1M telescopes with the additional γ/h separation parameters from the ground array (same as in Figure 2).

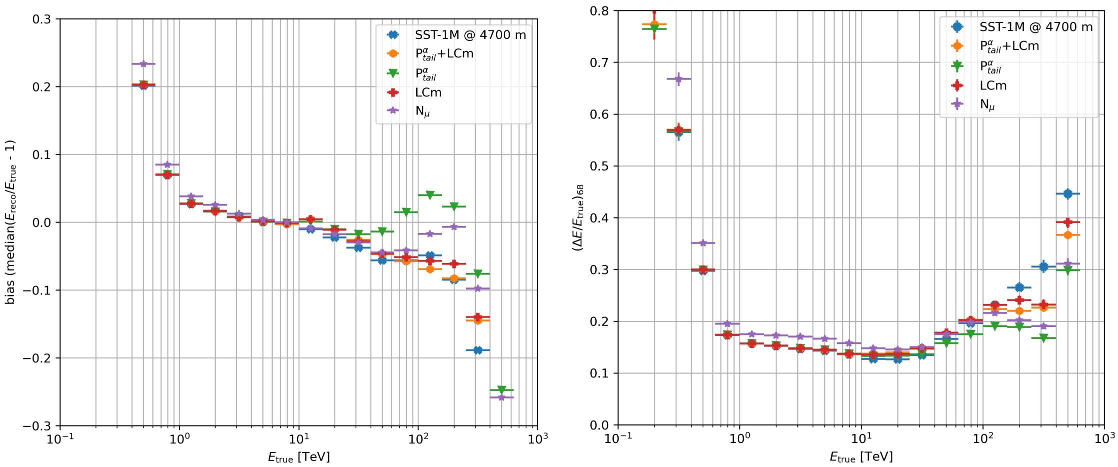

Figure 5: The energy bias (left) and energy resolution (right) for the sole SST-1M telescopes (blue) and SST-1M telescopes with the additional γ/h separation parameters from the ground array (same as in Figure 2).

4. Summary

In this study, we investigate the performance of a hybrid detection of gamma-rays combining two SST-1M imaging atmospheric Cherenkov telescopes with a dense surface array of water-Cherenkov detectors, similar to that proposed for SWGO. Using a simulation-based approach, we evaluate the performance of the angular and energy resolution, γ/h separation, and flux sensitivity of the SST-1M telescopes when taking into account γ/h separation variables obtained from the ground array, LCm and $P^{\alpha}_{\mathrm{tail}}$. We demonstrate that the inclusion of such parameters improves the reconstruction performance. Especially the γ/h separation power is significantly increased and,

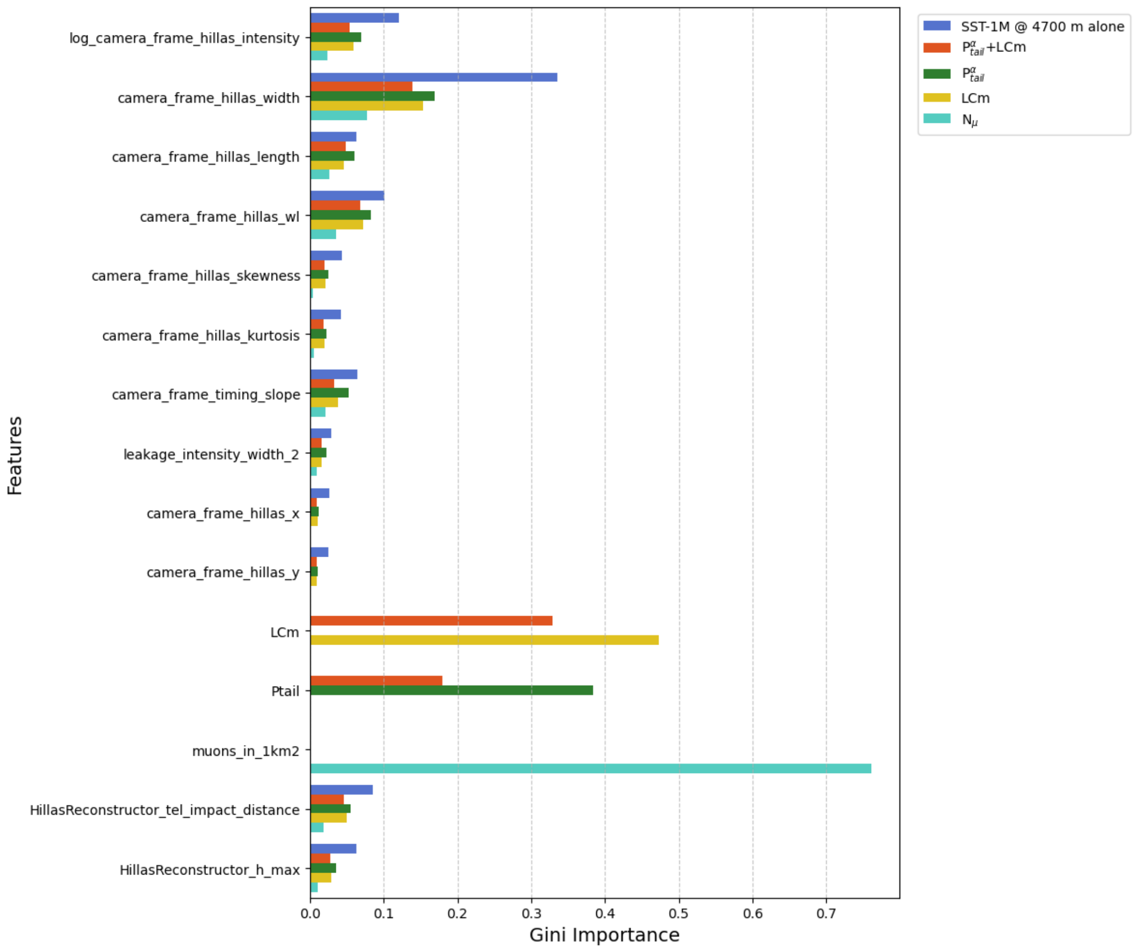

Figure 6: The Gini importance for γ/h Random Forests classifier of the sole SST-1M telescopes (blue) and of SST-1M telescopes with the additional information from the ground array: true N_{μ} (muons_in_1km2, cyan), LCm (yellow), P^{α}_{tail} (green) and P^{α}_{tail}+LCm (red). For the sole SST-1M telescopes the standard features which are used for the reconstruction: log of the intensity, width, length, width/length ratio, skewness, kurtosis, timing slope, leakage, coordinates of the shower center of gravity in the FoV (x,y). The parameters derived from stereo reconstruction the distance of the impact point from the telescope (impact dist) and the height of the shower maximum (h_{max}) were also used.

consequently, the flux sensitivity of the telescopes is improved by $\sim 30\%$ above 10 TeV.

We note, that these results are preliminary and only the γ/h discriminators from the ground array are taken into account. In future work, using more thorough analysis and simulation of the whole surface detector array response and reconstruction, additional improvements of the telescope performance might be achieved by incorporating more information from the ground array, such as the reconstructed shower core position and energy. Moreover, the information from the telescopes, with their precise angular and energy resolution might help with the energy calibration of the surface array.

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