Azimuthal fluctuations and number of muons at the ground in muon-depleted proton air showers at PeV energies

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Muon counting is an effective strategy for discriminating between gamma and hadron-initiated air showers. However, their detection, which requires shielded detectors, is highly costly and almost impossible to implement in large km^2 environmentally sensitive areas. This work shows that the gamma/hadron discriminators, based on the new LCm variable and the number of muons, have equivalent proton rejection levels at the PeV energies. It is, therefore, possible to build, at an affordable cost, a large, high performant wide field-of-view gamma-ray observatory.

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INTRODUCTION

Recently a new gamma/hadron discriminating variable, LCm, that quantifies the azimuthal non-uniformity in the pattern of the shower at the ground, was proposed [1]. This variable was shown to be strongly correlated with the number of muons observed at the ground, N_μ, which was known to be the best gamma/hadron (g/h) discriminator at energies above a few TeV and the only one to ensure rejection levels above 10^{-4} at the PeV energies. The success of such a strategy to discriminate gamma from hadron-induced Extensive Air Showers (EAS) is embodied by the LHAASO observatory, with the detection of gamma rays with energies up to the PeV [2]. It opened a new exciting and unexpected chapter in the field of ultra-high-energy gamma-ray astrophysics.

Nonetheless, the LHAASO strategy to absorb the electromagnetic component of the EAS burying large Water Cherenkov Detectors (WCDs) under a few meters of soil [3], although quite effective, is highly costly and impossible to implement in environmentally protected areas. A promising alternative would be to measure, using the WCDs, the azimuthal asymmetry with the newly introduced quantity, LCm. However, this variable was only tested using limited statistics $\mathcal{O}(10^4)$, not enough to claim the needed rejections levels at PeV energies.

In this work, a strategy to simulate and handle a very large EAS sample is developed and applied to study muon-depleted proton air showers with energies deposited at the ground equivalent to PeV gamma showers. These investigations are done considering detector array configurations with different fill factors (FF), and the implications of the obtained results in the design of large ground-array gamma-ray observatories are discussed.

SIMULATION SETS

To perform the study described in the previous section, 10^6 proton-induced showers were produced with energies between 1 and 2 PeV using CORSIKA (version 7.7410) [4]. The showers were simulated employing as hadronic interaction models for low and high energy interactions UrQMD [5, 6] and QGSJet II-04 [7], respectively. The zenith angle was fixed to 20° with respect to the vertical, while the azimuth angle was chosen from a uniform distribution. The shower secondary particles were collected at an altitude of 4700 m a.s.l.[8]

Following reference [1], a 2D histogram with cells with an area of $\sim 12\,\mathrm{m}^2$ emulated a ground detector array with a fill factor equal to one (FF=1). Smaller FFs were obtained by masking the 2D histogram with regular patterns. A bijective correspondence between cells and the WCD stations was established, and thus, the total signal in each station is given by the sum of the expected signals due to the particles that hit the corresponding histogram cell. The amount of signal deposited by the particles in a given cell was computed through a parametrization derived using a dedicated Geant4 simulation of the water Cherenkov detector considered in this work [9]. The parameterizations were derived for muons, electrons and protons. The latter two represent the electromagnetic and the hadronic shower component, respectively. The signal parameterizations as a function of the particle energy were built for the mean signal and its fluctuations. The fluctuations due to the stochastic processes of particle interactions and light collection and the fluctuations of the muon tracklengths in the station were considered.

Additionally, a set of 10^3 gamma-induced showers was simulated in the same conditions described for the protons, except for the energy. The energy was fixed to 1.6 PeV. Such was verified to be the mean energy for which proton and gamma showers have the same signal footprint at the ground. It is worth noting that the aim

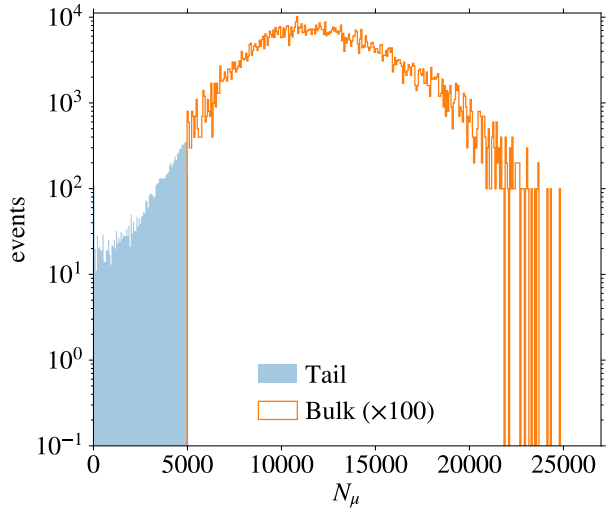

FIG. 1. Distribution of the number of muons at the ground in the proton EAS: the blue filled bins correspond to the proton muon-depleted sample; the bins with orange contours are the proton reduced set, multiplying the mean number of the events in each bin by one hundred (the inverse of the sampling factor).

of this study is to have a reference to compare LCm with N_μ and not to claim absolute rejection factors.

From the proton original set, too big to be easily handled, two sets were extracted: one with all the shower events below a fixed muon scale the proton muon-depleted set (*tail*); another, the proton reduced set (*bulk*), with about one-hundredth of the events not selected for the first set, chosen randomly. The threshold to this decision was set to $N_\mu = 5000$, where N_μ is the number of muons contained in one square kilometer. This value was verified with a smaller shower sample $\mathcal{O}(10^4)$ to be the number to select the 1% of showers with the lowest number of muons. The first of these sets preserves all the proton events more likely to be identified as gamma candidates if the main g/h discriminator relies on the number of muons at the ground. The second proton set is used to reconstruct the full shape of any distribution one may be interested in. As an example, in figure 1, it is shown for the proton showers the distribution of the number of muons at the ground putting together both sets. The size of the bin-to-bin fluctuations reflects the statistics of the corresponding samples.

In this work, the experimental proxy to N_μ is the total amount of signal recorded by the WCDs due to the passage of muons, S_μ. It is assumed that S_μ can be obtained without any uncertainty other than the signal and tracklenghts fluctuations mentioned before.

In figure 2, are shown the cumulative distributions of the S_μ (top) and LCm (bottom) variables, obtained assuming a detector array with a fill factor of 12.5%. The

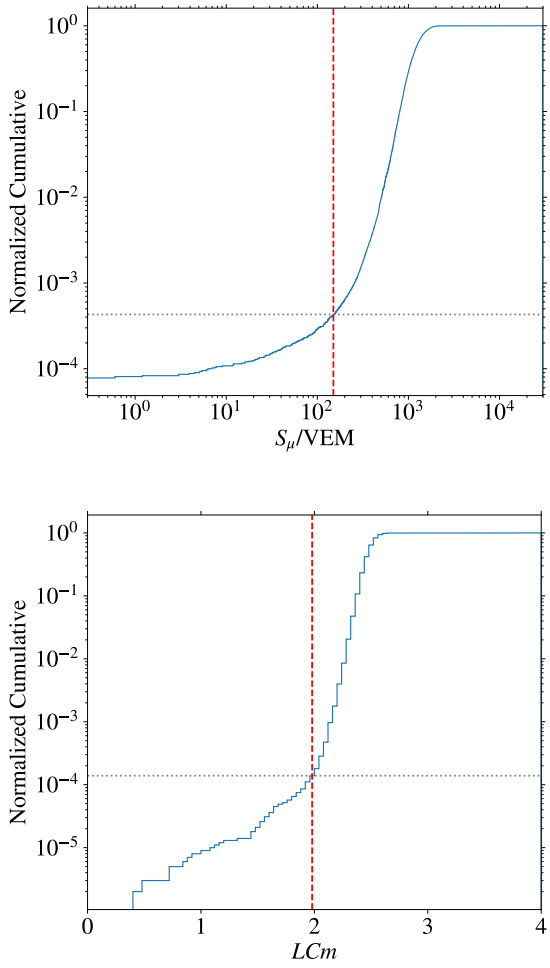

FIG. 2. Cumulative distributions for the S_μ (top) and LCm (bottom) distribution for events in the reference proton set (proton tail + proton bulk renormalized to the total number of showers simulated). The red (dashed) lines define the values of S_μ and LCm for which the gamma set has a selection efficiency of 90%.

values that, in each of these cumulative distributions, correspond to 90% of gamma shower selection efficiency are $S_\mu^g = 4.29 \times 10^{-4}$ and $LCm^g = 1.39 \times 10^{-4}$, respectively. Hence, the LCm has a lower residual background of protons for selecting gamma showers approximately a factor of 3 with respect to S_μ. The same study was done assuming a sparser array with FF= 1.4%. The proton selection efficiencies become now: $S_\mu^g = 9.33 \times 10^{-4}$ and $LCm^g = 6.10 \times 10^{-4}$, making LCm a slightly better discriminator ($\sim 50\%$).

LCm-N_μ CORRELATIONS

In this section, the correlation between the observed number of muons at the ground and the LCm vari-

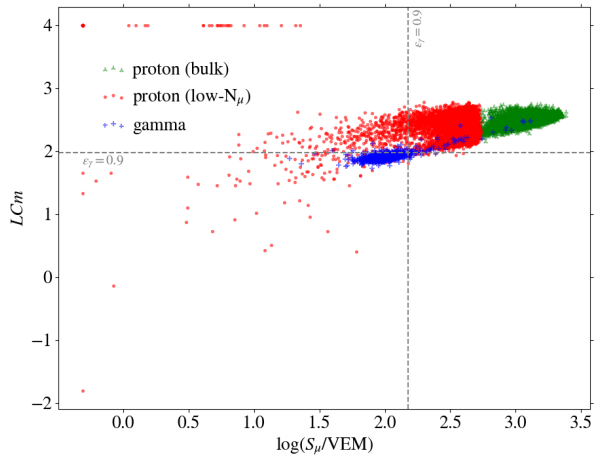

FIG. 3. Correlation between $\log(S_\mu)$ and LCm for the muon-depleted (red), proton bulk (green) and gamma (blue) events. The dashed grey lines indicate the cuts on N_μ and LCm to select 90% for the gamma showers. The discrimination quantities were computed assuming a detector array with a fill factor of 12.5%.

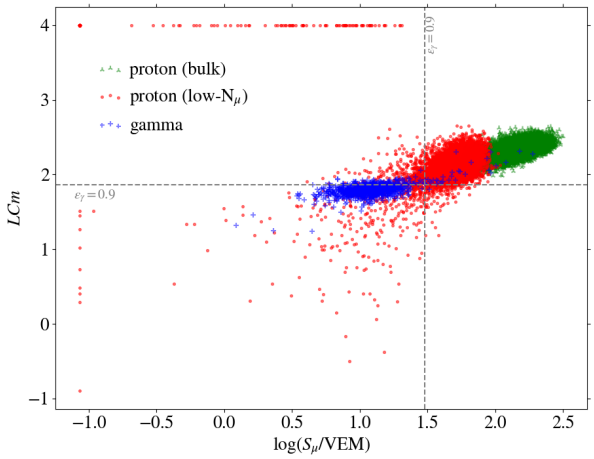

FIG. 4. Same plot as the one displayed in figure 3 but assuming a detector array with a fill factor of 1.4%.

able is discussed, focusing on the ability to distinguish PeV gamma-induced showers from the cosmic-ray background.

In figure 3, it is shown the observed LCm-S_μ correlation for the considered samples, assuming a detector array with FF= 12.5%. Shower events with $S_\mu = 0$ were placed at the extreme left of the plot, while events with poor quality to extract LCm are displayed at the top. The criteria used for the latter decision was to require that the azimuthal fluctuations of radial profile, built with radial bins of 30 m, had more than two degrees of freedom to fit LCm.

The lines indicate the values of S_μ^g and LCm^g, defined in the previous section (see figure 2), which delimit the regions that preserve 90% of the gamma events. These lines define four areas of interest:

- Region I - $S_\mu > S_\mu^g$ and $LCm > LCm^g$: rejected events using as g/h discriminator either the LCm or the S_μ;
- Region II - $S_\mu < S_\mu^g$ and $LCm > LCm^g$: accepted events using as g/h discriminator the S_μ but rejected if the g/h discriminator would be the LCm;
- Region III - $S_\mu < S_\mu^g$ and $LCm < LCm^g$: accepted events using as g/h discriminator either the LCm or the S_μ;
- Region IV - $S_\mu > S_\mu^g$ and $LCm < LCm^g$: rejected events using as g/h discriminator the S_μ but accepted if the g/h discriminator would be the LCm.

Considering the total simulated statistics of 10^6 proton showers, the fraction of events that would be in each of these regions, assuming FF= 12.5% are: Region I - 9.99×10^{-1}; Region II - 4.03×10^{-4}; Region III - 9.90×10^{-5}; Region IV - 1.00×10^{-5}.

A low FF is mandatory in a real detector array with a size able to collect useful statistics at the PeV energies. In these terms, the previous figures were redone considering now FF= 1.4% (figure 4). The fraction of events that would be in each of the above-defined regions are now: Region I - 9.99×10^{-1}; Region II - 4.09×10^{-4}; Region III - 3.52×10^{-4}; Region IV - 1.15×10^{-4}.

The potential impact of a signal threshold due to the station triggering probability was also investigated. The threshold was set as high as 10 photoelectrons [9] with no visible effect on the analysis.

Despite it being out of the scope of the paper, we would like to emphasize the high correlation between $\log(S_\mu)$ and LCm, which might be explored to probe the shower muon content without the need for dedicated muon counters.

Additionally, for all tested fill factors, the number of events in Region II is higher than the number of events in Region IV, implying that the shower can be discriminated through the azimuthal fluctuations even if the number of muons is compatible with those induced by a gamma primary with equivalent energy. This means that the electromagnetic shower component still contains information about the nature of the primary particle. In [1], it was shown already that LCm attains discrimination power even if only the electromagnetic shower component is considered. The result obtained in this work is therefore an additional confirmation of this interesting feature for the rare muon-depleted showers that constitute the primary background for accurately identifying showers at PeV energies.

Finally, one may note that this study used the quantity S_μ as a proxy for N_μ and might argue that a de-

tector other than a WCD might lead to different conclusions. To test this, LCm was computed for an array with FF= 12.5% and directly compared to the total number of muons at the ground in 1 km^2 (FF= 100%). In these conditions, unfeasible for a realistic experiment, the discrimination capability of LCm was verified to continue to surpass those of N_μ by a factor of 5.

DISCUSSION AND CONCLUSIONS

The number of muons produced in a high energy hadronic-induced shower that reaches the ground at a high altitude is an order of magnitude higher than that produced in a gamma-induced shower of the same reconstructed energy. Thus, N_μ is an excellent g/h discriminator, ensuring rejection levels of the order of 10^{-4} at the PeV energies. However, at these energies and altitudes, the number of EAS photons and electrons reaching the ground is many orders of magnitude higher than the number of their companion muons. In this way, directly counting muons requires the use of shielded detectors with some inert material such as earth (e.g. [3, 10, 11]), water (e.g. [12], [13]) or concrete and iron (e.g. [14], [15]). It is an effective but highly costly strategy to implement in large areas ($\sim$ few km^2) observatories.

Alternatively, the LCm variable, which quantifies the azimuthal non-uniformity in the pattern of the shower at the ground, was found to be highly correlated, at the level of the mean values, with N_μ [1], and it is easy to implement at a reasonable low cost.

In this work, a simulation strategy was conceived to analyse the rare muon-depleted shower events (main background source for gamma PeV showers), and with it, it was shown that the S_μ and LCm variable continue to have a high correlation, leading thus to equivalent rejection levels for both variables. This conclusion holds for all the tested array fill factors, which span from 50% down to 1.4%.

The findings in this work constitute a unique opportunity to build a cost-effective gamma-ray observatory, based on water Cherenkov detectors, able to cope with a wide energy range (from hundreds of GeV to many tens of PeV). In this optimised array, which would be able to sample the shower calorimetric footprint, both the FF and the number of PMTs in each WCD station would be higher in the inner regions and would become progressively lower towards the outer regions.

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[1] R. Conceição, L. Gibilisco, M. Pimenta, and B. Tomé, "Gamma/hadron discrimination at high energies through the azimuthal fluctuations of air shower particle distributions at the ground," JCAP **10**, 086 (2022), arXiv:2204.12337 [hep-ph].

[2] Cao, Zhen and et. al, "Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ ray Galactic sources," *Nature* ***594****, 33–36 (2021).*

[3] Xiong Zuo *et al.* (LHAASO), "Design and performances of prototype muon detectors of LHAASO-KM2A," Nucl. Instrum. Meth. A **789**, 143–149 (2015).

[4] D Heck, J Knapp, JN Capdevielle, G Schatz, and T Thouw, "A monte carlo code to simulate extensive air showers," Report FZKA **6019** (1998).

[5] S. A. Bass *et al.*, "Microscopic models for ultrarelativistic heavy ion collisions," Prog. Part. Nucl. Phys. **41**, 255–369 (1998), arXiv:nucl-th/9803035.

[6] M. Bleicher *et al.*, "Relativistic hadron hadron collisions in the ultrarelativistic quantum molecular dynamics model," J. Phys. G **25**, 1859–1896 (1999), arXiv:hep-ph/9909407.

[7] Sergey Ostapchenko, "Monte Carlo treatment of hadronic interactions in enhanced Pomeron scheme: I. QGSJET-II model," Phys. Rev. D **83**, 014018 (2011), arXiv:1010.1869 [hep-ph].

[8] The considered altitude for this study was chosen for being the reference height for the R&D studies being conducted by the Southern Wide-field Gamma-ray Observatory [16].

[9] P. Assis *et al.*, "The Mercedes water Cherenkov detector," Eur. Phys. J. C **82**, 899 (2022), arXiv:2203.08782 [physics.ins-det].

[10] A. Borione and et. al, "A large air shower array to search for astrophysical sources emitting γ-rays with energies $\geq 10^{14}$ eV," Nuclear Instruments and Methods in Physics Research A **346**, 329–352 (1994).

[11] A. Aab and et. al, "Calibration of the underground muon detector of the Pierre Auger Observatory," Journal of Instrumentation **16**, P04003 (2021).

[12] P. Abreu *et al.*, "MARTA: a high-energy cosmic-ray detector concept for high-accuracy muon measurement," Eur. Phys. J. C **78**, 333 (2018), arXiv:1712.07685 [physics.ins-det].

[13] Antoine Letessier-Selvon, Pierre Billoir, Miguel Blanco, Ioana C. Mariş, and Mariangela Settimo, "Layered water Cherenkov detector for the study of ultra high energy cosmic rays," Nucl. Instrum. Meth. A **767**, 41–49 (2014), arXiv:1405.5699 [astro-ph.IM].

[14] N. Chiba *et al.*, "Akeno giant air shower array (AGASA) covering 100-km**2 area," Nucl. Instrum. Meth. A **311**, 338–349 (1992).

[15] H. Bozdog *et al.*, "The detector system for measurement of multiple cosmic muons in the central detector of KASCADE," Nucl. Instrum. Meth. A **465**, 455–471 (2001).

[16] Harm Schoorlemmer, Ruben Conceição, and Andrew James Smith, "Simulating the performance of the Southern Wide-view Gamma-ray Observatory," PoS

ICRC2021, 903 (2021).