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Optimization Studies of a Water Cherenkov Detector for Gamma-ray Astronomy

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Ground-based, wide field of view instrumentation in gamma-ray astronomy is currently limited to the northern hemisphere and hence, lacks sensitivity to our Galactic Center and the rest of the southern sky. A Southern Gamma Observatory comprising an array of ground-level detector units with a high fill factor (> 70 %) at high altitude (> 4 km) could be used to observe the southern sky. Water Cherenkov Detectors (WCDs) have shown their potential as detector units for such an array. Detailed simulations are needed to understand the response of WCDs to the flux of secondary particles impinging on them. In this contribution, we study the complete simulation chain from the air shower simulation with CORSIKA to the detector level simulation with GEANT4, in an attempt to optimize WCDs.

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1. Introduction

As a result of the declining flux emitted by cosmic sources, at Very High Energies (VHE) of ∼100 GeV – ∼100 TeV, γ-rays can be best observed by ground-based detectors through their induced electromagnetic cascade in the atmosphere. There are two approaches to observe these particle cascades: Recording Cherenkov light emitted by these cascade particles with Imaging Atmospheric Cerenkov Telescopes (IACTs), or observing the cascade particles directly with particle detectors. IACTs need dark and cloud-less conditions resulting in a low duty cycle of ∼1000 hours/year while telescope optics and camera size result in small Field-Of-View (FOV) of <10°. Additionally, increasing the high energy limit requires an increased collection area, which can be prohibitively expensive. Particle detectors, on the other hand, are relatively inexpensive, intrinsically wide FOV and have ∼ 100% duty cycle. High altitude (> 4 km) and a high fill factor (> 70 %) allow such detectors to be complimentary in the same energy range as IACTs.

Currently, there are two ground particle detectors in operation. Both HAWC [1] on the flanks of the Sierra Negra volcano in Mexico and LHAASO [2] in the eastern Tibetan plateau comprise an array of Water Cerenkov Detector (WCD) units with Photo-Multiplier Tubes (PMTs) that are triggered by Cherenkov photons produced by the passage of secondary particles impinging on them. These instruments are providing compelling results in TeV γ-ray astronomy, however their location in the northern hemisphere limits sensitivity to our Galactic Center and the rest of the southern sky. An array in the southern hemisphere aims to provide unprecedented observations of interesting phenomena in the TeV γ-ray sky [3]. An inner array with a high fill factor of $> 70\%$ will enhance sensitivity for sub-TeV γ rays while an outer array with a fill factor of 8% in Fig 1 aims to improve sensitivity at higher energies. Air shower simulations with CORSIKA (COsmic Ray SImulations for KAScade) [4] and detector level simulation with GEANT4 (for GEometry ANd Tracking) [5] have been performed to improve on WCD designs similar to HAWC.

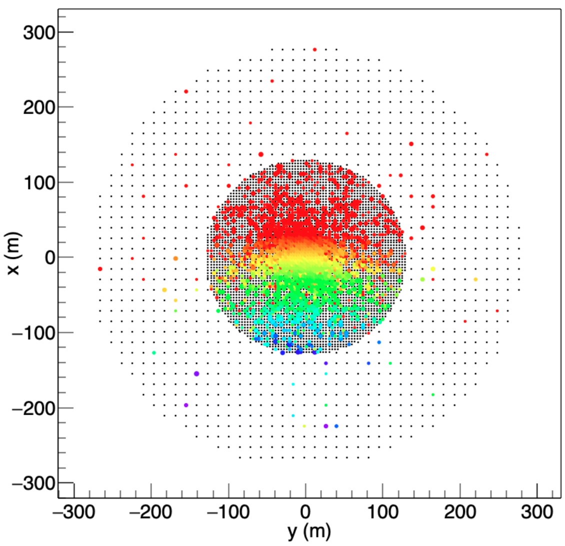

Figure 1: Top view of a γ-ray observatory comprising an inner and outer array of $> 70\%$ and 8% fill factor respectively. This illustration of a 2000 GeV γ-ray air shower at a 0° zenith angle incident on the array shows photo-electrons (p.e) collected at individual WCD units, where the color indicates an arrival time gradient.

2. Design Overview

Here we describe a possible detector concept (Fig. 2) that comprise the following building blocks:

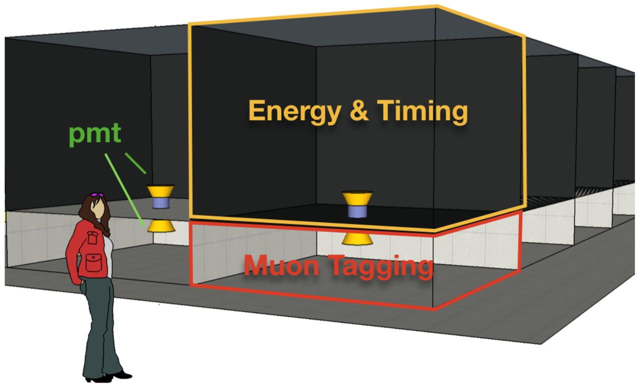

Figure 2: The illustration shows a conceptual design of a detector unit. Each WCD unit comprises an upper and lower chamber with a light sensor in each chamber.

- Upper Chamber. A light-tight chamber with a reflective lining comprising a single light sensor facing upwards. This chamber provides the energy and timing of the impinging particle where the upward facing light sensor ensures that the direct Cherenkov photons are detected first.

- Lower Chamber. A light-tight chamber with a highly reflective lining and comprising a single light sensor facing downwards. This chamber will enable muon tagging as only a small fraction of the higher energy photons and electrons at ground level can punch through into the lower chamber, while most muons will also deposit photons in this chamber.

3. Simulation

At ground level, for γ-ray induced extensive air showers (EAS), the peak of the number density distribution in terms of number per log energy interval (dN/dlog E) is around $\sim$6 MeV for photons, $\sim$20 MeV for electrons and 2$-$3 GeV for muons [6]. GEANT4 within the HAWC-SIM framework used by the HAWC collaboration [1] enables running simulations of such particles striking the WCD units. In this study, we first optimize individual units by varying the dimensions and the reflectivity of the material lining the walls of the two chambers for the different particle species. In Fig. 3, on the left, we illustrate a single muon entering a WCD unit with highly reflective upper and lower chamber wall linings and, on the right, a γ-ray enters an identical unit. The μ and γ-ray energies were chosen to illustrate a similar number of photons deposited in the upper chamber of the WCD unit. Low energy γ-rays do not punch through into the lower chamber.

In simulating air showers, the Monte Carlo uses the CORSIKA 7.4005 simulation package [4]. For the standard simulated event set, we selected QGSJet-II [7] for energies above 80 GeV and FLUKA [8, 9] hadronic models for below 80 GeV energies, respectively. For electromagnetic processes, the EGS4 electromagnetic model [11] was used.

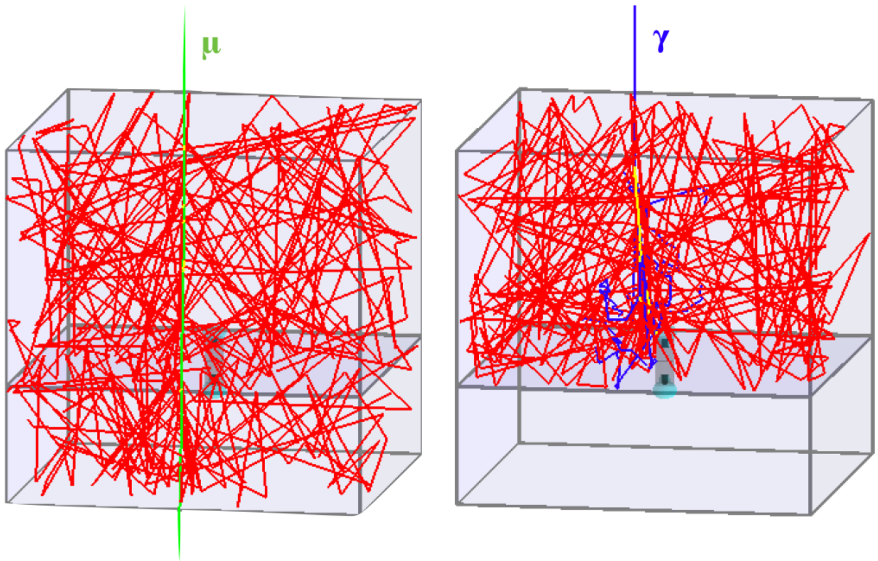

Figure 3: The illustration shows a muon (green track) and a γ-ray (blue track) depositing similar amount of Cherenkov photons (red tracks) after entering WCD units comprising highly reflective wall linings.

66 ## 4. Results

67 ### 4.1 Reflectivity

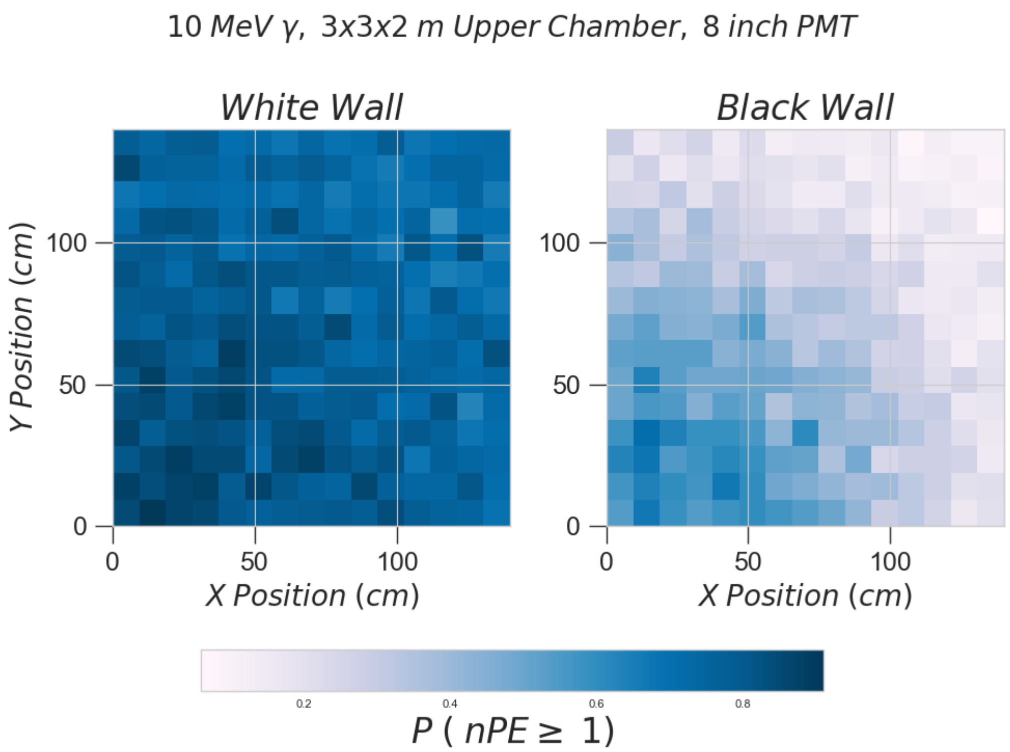

Figure 4: Scan of the upper chamber of a WCD unit with vertical 10 MeV γ-rays with white walls on the left and black walls on the right. The PMT is located at (0, 0).

In order to investigate the effect of wall reflectivity on the probability of the detection of photons at a light sensor, vertical γ-rays at 10 MeV energies were used to scan a quadrant of the surface of the upper chamber of 3x3x2 m dimensions in a WCD unit.

Walls with a rough top layer of either high reflectivity (white) like Tyvek as used by the Pierre Auger Observatory [10] or low reflectivity (black) like Polypropylene as used by HAWC have been selected (see Fig. 4). An 8 inch PMT was the light sensor in this study. Due to the angle of the Cherenkov cone in water, the black walls result in a reduced sensitive area.

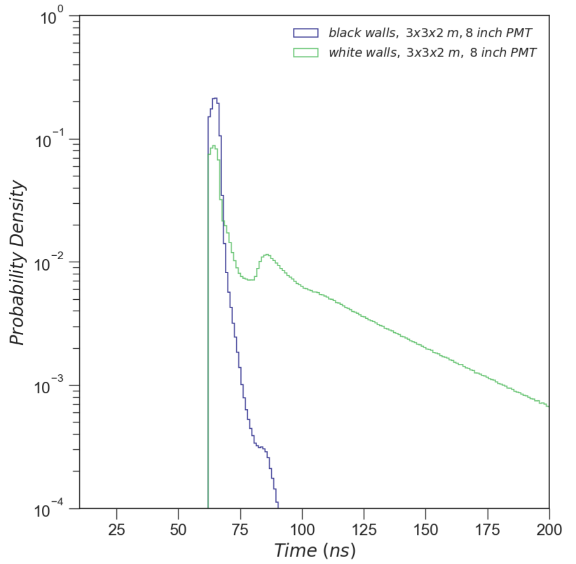

Figure 5: Timing distribution of a 3x3x2 m upper chamber of a WCD unit with γ-ray energy ranging from 1 MeV to 1 GeV. The green and blue lines indicate a white-walled and black-walled chamber, respectively.

4.2 Timing

Time degradation arises from late photons arriving at the light-sensor with a white-walled compared to a black-walled upper chamber. γ-rays with energy ranging from 1 MeV to 1 GeV were used to scan the surface of a WCD unit with an upper chamber of 3x3x2 m dimensions. The first p.e's arriving at the light-sensor will be used for timing; however, further investigation is necessary given the long tail in the white-walled scenario (see Fig 5).

4.3 Upper Chamber Dimension

Vertical γ-rays with energies from 1 MeV to 1 GeV were used to scan the surface of the upper chamber of WCD units of different dimensions and reflectivity, and compared to the HAWC configuration (see Fig. 6). The probability of detection between the white-walled chamber of 3x3x2 m dimensions is almost double that of the HAWC configuration at lower energies ($\leq$ 100 MeV). However, at higher energies with a shallow chamber, there is a probability that the γ-rays do not cascade, and subsequently, no Cherenkov photons arrive at an 8 inch PMT. A deeper chamber of 3x3x3 m solves this problem at the cost of slightly reducing sensitivity below $\sim$25 MeV.

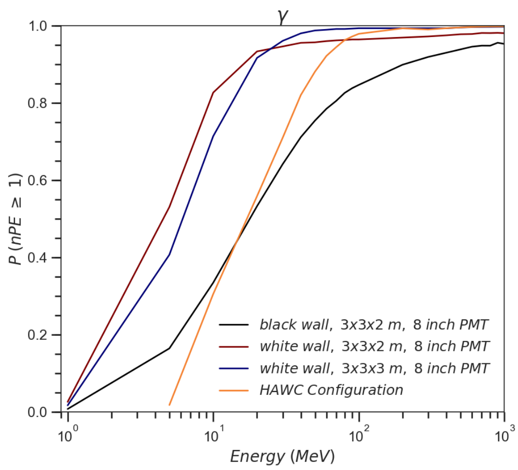

Figure 6: Probability of detection of one or more p.e in the upper chamber of a WCD unit with γ-ray energy ranging from 1 MeV to 1 GeV for various WCD designs.

4.4 Lower Chamber Dimension

As the light ratio between the upper and lower chamber is used to identify muons, the lower chamber needs to be of sufficient depth to distinguish them from electromagnetic particles that can enter this chamber. Vertical μ- with energies from 100 MeV to 4 GeV were used to scan the surface of WCD units with an upper chamber of 3x3x2 m and lower chamber of 3x3 m^2 surface area but with varying depths (see Fig. 7). Above a depth of ∼1.5 m, the number of p.e's in the lower chamber remains roughly the same despite an increase in depth while the fluctuations decrease.

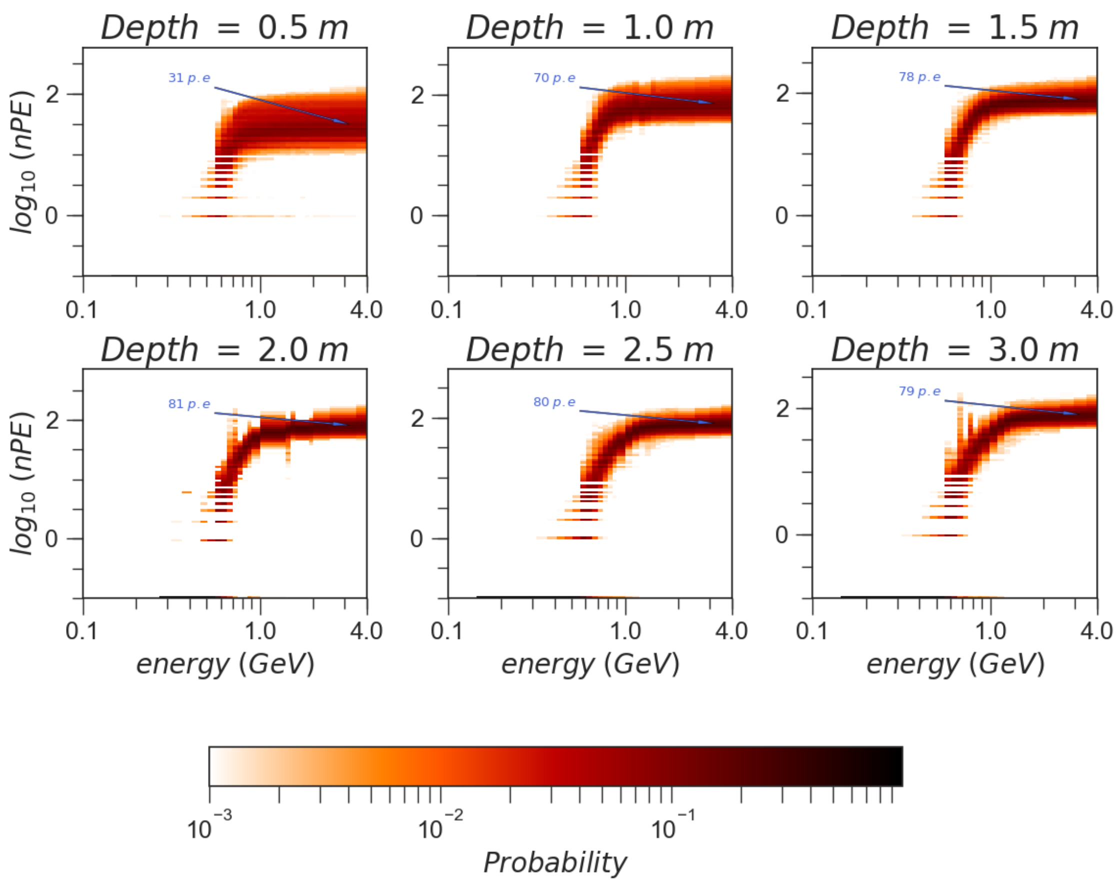

Figure 7: The number of p.e in a WCD unit with a white-walled 3x3 m lower cell of various depths with μ-energy ranging from 100 MeV to 4 GeV.

Additionally, vertical γ-rays with energies from 10 MeV to 2 GeV in a WCD unit with upper chamber dimension of 3x3x2 m and lower chamber dimension of 3x3x1 m is compared with vertical μ- with energies from 100 MeV to 4 GeV in an identical WCD unit (see Fig 8). Muon identification is possible as the number of p.e detected in the two chambers remain constant above some energy threshold.

Furthermore, for very high γ-ray energies, the upper PMT can saturate as the particle density is very high. These γ-rays penetrate the lower chamber and can thus be used to get a reasonable estimate of the particle energy and thereby increase the dynamic range (see Fig 9). A 3 inch PMT in the lower chamber may be sufficient in this scenario.

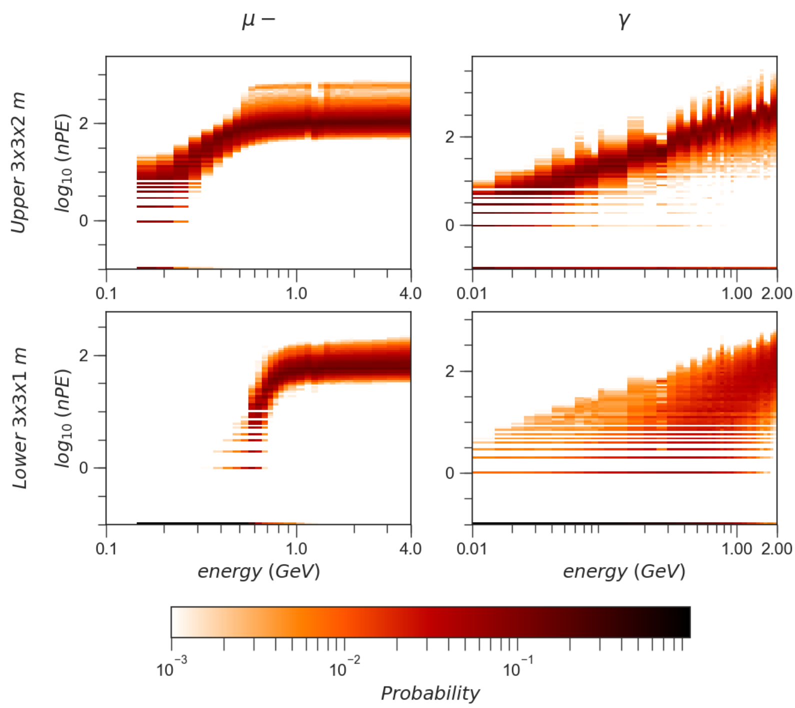

Figure 8: The number of p.e in a WCD unit with a white-walled 3x3x2 m upper and 3x3x1 m lower chamber with μ- energy ranging from 100 MeV to 4 GeV on the left and γ-ray energy ranging from 10 MeV to 2 GeV on the right.

4.5 Gamma-hadron separation

Photons deposited aid in muon identification and subsequent gamma-hadron separation as the muon content is much higher and easily identifiable in hadronic cascades compared to those initiated by γ-rays as shown in Fig 10 for a WCD unit with an upper chamber of 3x3x3 m and lower chamber of 3x3x1.5 m dimensions. Here 10,000 vertical 5000 GeV proton and 2000 GeV γ-ray initiated showers have been simulated.

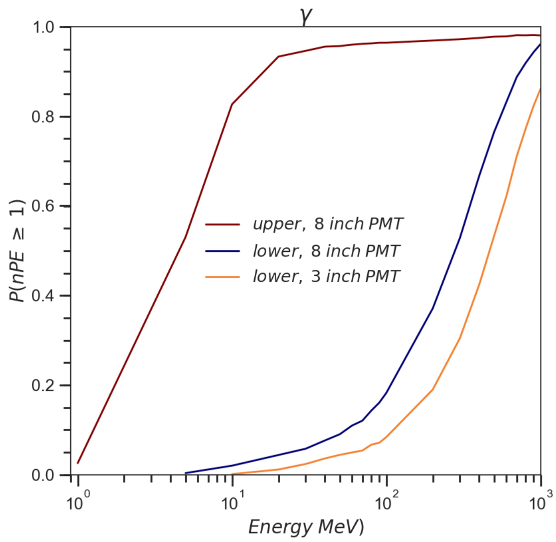

Figure 9: Probability of detection of one or more p.e in a WCD unit with a white 3x3x2 m upper and 3x3x1 m lower chamber with γ-ray energy ranging from 1 MeV to 1 GeV. The dynamic range when the upper chamber is saturated recovers in the lower chamber for sufficiently high γ-ray energies.

5. Summary & Outlook

We have begun the process of optimizing a WCD-based concept detector to improve sensitivity in the sub-TeV γ-ray energy range. Each detector unit comprises two chambers with reflective wall linings and a PMT in each chamber. The upper PMT facing upwards is intended for timing and energy while the lower PMT facing downwards will enable muon tagging and increasing dynamic range.

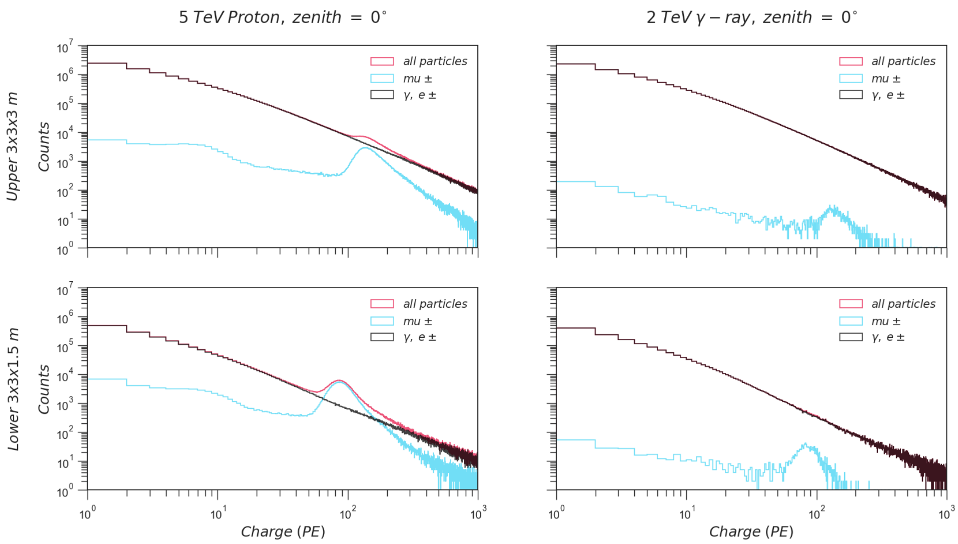

Figure 10: Charge distribution for all particles, electromagnetic particles and muons from vertical 5 TeV protons (left) and 2 TeV γ-rays (right) arriving at the upper (top) and lower chamber (bottom) of WCD units of 3x3x3 m and 3x3x1.5 m dimensions respectively. A clear peak associated with well contained muons is visible.

We are investigating different options for chamber dimensions, reflectivity, and PMT sensitive area in the WCD units. A compact and highly reflective upper chamber should lower the energy threshold for the impinging particles and in conjunction with a lower chamber should improve gamma-hadron separation and air shower reconstruction.

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