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Optimization of water Cherenkov detector for a next-generation gamma-ray observatory

Nuno Costa[1,a]

[1] *Instituto Superior Técnico, Lisboa, Portugal*

Project supervisor: R. Conceição, B. Tomé, P. Costa

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Abstract. In the pursuit of enhancing the capabilities of Water Cherenkov Detectors (WCDs) for next-generation gamma-ray observatories, this paper presents a comprehensive investigation into their optimization. Employing computer-based simulations, our study unveils a significant and intriguing finding: WCDs with dynamically adjusted diameters consistently outperform their counterparts with constant diameters. This novel insight not only challenges conventional wisdom but also offers a transformative perspective on the design and efficacy of WCDs in the context of high-energy astrophysics research. What sets this discovery apart is its far-reaching impact on cost-saving measures for high-altitude wide-field observatories, often located in remote and logistically challenging areas. By optimizing WCDs through dynamic diameter adjustments, observatories can significantly reduce the volume of water required per tank, minimizing logistical complexities and associated expenses. This breakthrough not only advances our understanding of particle detection but also paves the way for more efficient and cost-effective high-energy astrophysics research in the world's most remote regions.

KEYWORDS: SWGO, Cherenkov Radiation, Water Cherenkov Detector

1 Introduction

1.1 Exploring Particle Detectors

In the field of high energy astrophysics the exploration of cosmic rays and gamma rays plays a role in unraveling the most mysterious and energetic phenomena in the universe. These particles and high energy photons provide us with insights into the nature of interactions between particles and the fundamental physical processes that govern our cosmos. To capture and comprehend these entities, a complex network of detectors stationed on the ground has been meticulously developed. Each detector specializes in observing types of particles or radiation. Among them Water Cherenkov Detectors (WCDs) have emerged as versatile tools for detecting gamma rays – which are known to be the most energetic and enigmatic form of electromagnetic radiation.

This paper explores the landscape of ground based cosmic ray detectors with a focus on highlighting the unique characteristics and optimizations employed by Water Cherenkov Detectors. There have been advancements in these detectors making them an essential component of gamma ray observatories. WCDs make use of a phenomenon called Cherenkov radiation – which refers to radiation emitted when charged particles move through a medium at speeds exceeding that of light in that particular medium. This principle enables researchers to accurately identify and estimate the energy of high energy gamma rays, cosmic rays and neutrinos. It provides them with the opportunity to investigate the environments and phenomena in the universe.

An overview of the diverse cosmic-ray detectors, shedding light on how they function, their strengths, and their limitations is offered on the following sections. Subsequently, the paper will delve into the intricate details of design considerations and optimization strategies that shape the development of Water Cherenkov Detectors (WCDs). This ranges from selecting suitable materials to configuring photodetectors and data acquisition systems that play a pivotal role in elevating the sensitivity and performance of WCDs.

Furthermore, the evolving technological landscape and the growing demands of modern astrophysical research have accelerated ongoing research and development efforts in the field of gamma-ray detection. This paper will also explore the cutting-edge innovations and advancements in WCDs, showcasing how they are meant to contribute significantly to the success of the next-generation gamma-ray observatories. The optimization of these detectors not only improves their detection capabilities but also bolsters our ability to decipher the fundamental mysteries of the universe.

Thus, the following sections will highlight Water Cherenkov Detectors and their application on new projects such as the Southern Wide-field Gamma-Ray Observatory (SWGO). The aim of this project is to provide a mechanism for the detection of high-energy particles covering the energy range from thousands of GeV up to the PeV scale. Through an exploration of their operational principles, design considerations, and optimization techniques, we aim to highlight the crucial role of WCDs in the forthcoming era of gamma-ray detection.

1.2 The Many Types of Ground-Based Particle Detectors

Ground-based particle detectors come in a diverse array of types, each uniquely designed to detect and allow the study of various types of high-energy particles originating from the cosmos. These detectors are what allows us to study

[a]e-mail: nuno.r.costa@tecnico.ulisboa.pt

and understand the mysteries of the universe and, in addition, to unveil the fundamental processes that occur within it. Many of these detectors follow the same working theory: the principle of particle interaction with matter. These detectors are designed to exploit the distinct effects that high-energy particles have when they pass through various materials. Some of them include:

Scintillation Detectors These detectors take advantage of the scintillation process (high energy particles pass through a material and ionize atoms by stripping away electrons), wherein high-energy particles interact with a scintillating material, producing flashes of light that are then detected by photodetectors.[1]

Muon Detectors Muons are high-energy charged particles that can penetrate deep underground or through thick layers of shielding material.[2] These detectors are often used in large-scale experiments located in underground facilities to reduce interference from other particles.

Extensive Air Shower Arrays consist of a network of detectors spread over a large area on the ground. They can detect the secondary particles produced when high-energy cosmic rays interact with the Earth's atmosphere. By analysing the distribution and properties of these secondary particles, researchers can infer the properties of the primary cosmic rays.[3]

The main object of study will be an array of Water Cherenkov Detectors, how they work and how their performance can be optimised.

2 Water Cherenkov Detectors (WCD)

The most common type of WCD is the cylindrical or spherical tank design. This design involves a large volume of ultrapure water contained within the tank, typically made of specialized materials to minimize contamination and optimize Cherenkov light detection. Inside the tank, photomultiplier tubes (PMTs) are strategically positioned to detect the Cherenkov radiation emitted by high-energy particles interacting with the water. This type of detector is widely used in neutrino experiments, gamma-ray observatories, and cosmic-ray studies.

Nowadays, there are a multitude of groundbreaking ground-based particle detectors that harness the unique capabilities of WCDs to explore the universe's most elusive and energetic phenomena. One of those projects that is to be born is the Southern Wide-field Gamma-ray Observatory (SWGO).

The plan and main goal for the Southern Wide-field Gamma-ray Observatory is to build a next generation ground-based, wide-field of view, high-energy gamma-ray detector. This concept has been successfully demonstrated by current generation instruments such as the High-Altitude Water Cherenkov Observatory (HAWC) and the ARGO. The latter being a Resistive Plate Chamber array optimized for the detection of small size air showers covering an area $> 5000m^2$ and operating at high elevation [4].

Currently, there is a significant gap in the southern hemisphere regarding projects encompassing this concept of detectors, where the potential for mapping large-scale emissions and observing transient and variable multi-wavelength and multi-messenger phenomena remains untapped. Furthermore, there is a crucial motivation in building an observatory with these specifications in the southern hemisphere (more specifically South America). This is due to the access to the Galactic Centre and its proximity to a major facility like CTA-South [5].

The core conceptualization for this future observatory can be briefly summarized as follows:

- Situated in South America, latitude range between 10 and 30 degrees south and positioned at an altitude of 4.4km or higher;
- Primarily constructed using water Cherenkov detector units as its functional technology;
- Designed to operate across very-high energy range from hundreds of GeV to PeV;
- Comprising a central detector core with a high fill-factor, significantly larger than HAWC, offering enhanced sensitivity. The core array is complemented by a low-density outer array.

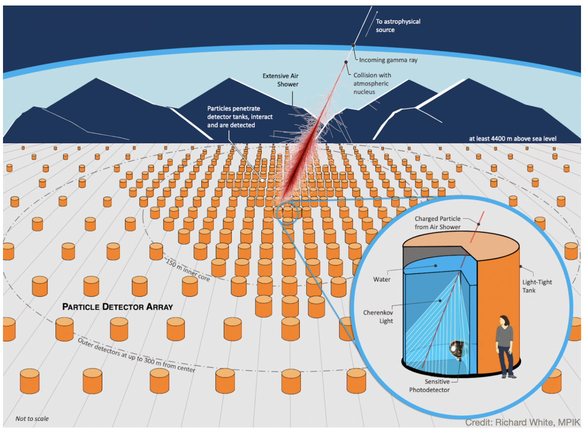

Figure 1. SWGO Layout. Credit: Richard White, MPIK. [5]

2.1 Cherenkov Radiation

At the heart of WCDs lies the Cherenkov effect - a phenomenon where charged particles, moving through a transparent medium faster than the speed of light within that medium, emit a characteristic cone of Cherenkov radiation [6], in the case of WCDs that medium is ultra-pure water.

The Cherenkov radiation is analogous to the sonic boom effect. Akin to driving a speedboat across a calm lake, as it speeds up, it creates a wake of ripples in the water behind it. When charged particles (like an electron or muon) move through a dielectric medium (poor electric conductor but can efficiently support electric fields [7]) at a speed faster than the speed of light in that medium, it creates an electromagnetic wake in the form of Cherenkov radiation.

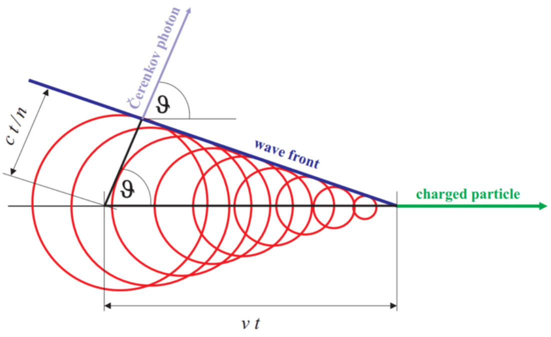

Figure 2. Cherenkov Radiation cone diagram [8]

Cherenkov radiation consists primarily of photons whose wavelengths predominantly fall within the range that is visible to the human eye in the electromagnetic spectrum. As it is possible to infer from 2 the emitted radiation forms a cone, and the trajectory of the particle serves as the central axis of this cone. The angle of the Cherenkov cone, θ, can be calculated through the relation

$$\cos\theta = \frac{c}{vn} = \frac{1}{\beta n}, \qquad (1)$$

where $\beta = \frac{v}{c}$ is the ratio between the particle's velocity and the speed of light in vacuum. The magnitude of the cone's angle increases in direct proportion to the energy of the particle generating the radiation [9]. For a medium like water which has a small refractive index, $n = 1.33$ [10], the minimum velocity a particle has to move in order to generate Cherenkov radiation is: $v = 2.3 \times 10^8$ m s^{-1}.

It is important to note that different types of particles generate Cherenkov radiation with distinct patterns and characteristics. By analyzing the angular distribution and intensity of the emitted Cherenkov light, it is possible to identify the types of particles responsible for the radiation. This allows to differentiate between electrons, muons and gamma rays, among others.

2.2 Optimizing Water Cherenkov Detectors

Optimizing Water Cherenkov Detectors (WCD) involves a combination of design considerations, material analysis and selection, technology advancements, and data analysis techniques. The combination of these techniques aims to enhance their sensitivity, efficiency and performance in detecting high-energy particles, such as astrophysical gamma-rays.

Choosing the right materials for the WCD components, such as the water medium, photomultiplier tubes (PMTs), and reflective surfaces, is crucial. High-purity water minimizes background noise, and high-quality PMTs improve photon detection efficiency. In addition, using PMTs with better quantum efficiency improves temporal resolution, and reduces noise. An ideal photocathode (a negatively charged electrode in a light detection device [11]) has a quantum efficiency of 100%. This means that every photon that interacts with the material triggers the emission of a single photoelectron from the material into the vacuum [12].

One important parameter in the optimization of WCDs is to design the detector to enhance light collection. Great attention is given to the arrangement and positioning of PMTs to maximize the collection of Cherenkov radiation emitted by high-energy particles, increasing the chances of detecting weak signals. Coupling this with the expansion of the detector volume, which provides a larger target for particle interactions, will undoubtedly boost overall particle detection.

However, it is important to bear in mind that, for the case of the SWGO project, one has to be attentive to the logistical constraints of the project site. This means that there is an incentive to find the smallest possible volume whilst keeping the project performance requirements in check. Furthermore, in order to reduce background noise from ambient radiation and enhance the signal-to-noise ratio, shielding and veto systems can be implemented.

Additionally, one area that has been explored by the LIP group tasked with the SWGO project is the refinement of data analysis techniques. It was shown in [13] that advanced data analysis methods, including the implementation of machine learning techniques, can provide excellent results in the tagging of muons, which in turn will help determine the most efficient detector design.

3 The Mercedes WCD Setup

The Mercedes WCD concept is LIP's design proposal for the SWGO WCD stations. It is composed of a single layered water Cherenkov detector with three PMTs placed at the bottom of the tank in a Mercedes logo-like style - 120º star configuration.

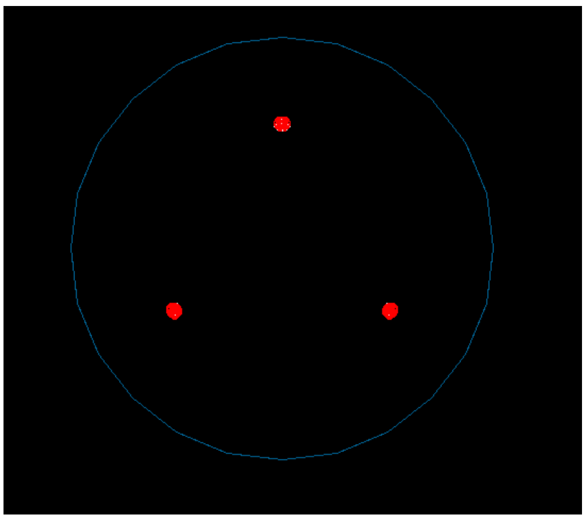

Figure 3. Mercedes WCD in the LATTESsim visualization mode (top view)

The aim of the Mercedes WCD concept is to provide a small, cheap, and highly-efficient alternative to the existing WCD designs that are currently in consideration for the SWGO project. From previous investigative work, this design is expected to be able to efficiently tag vertical and inclined muons [13]. This provides a cost-effective alternative to the existing WCD designs in other projects, such as the LHAASO, located in China, where each tank has a diameter of 6 meters and a height of 1.5 meters, totalling a volume of 42,412 liters of water needed per tank [14]. In addition, the tanks used for the HAWC observatory have a diameter of 7.3 meters and a height of 4.5 meters, requiring a staggering 188,234 liters of water to fill the tank . Comparatively, the default design of the Mercedes WCD (prior to any size optimisation) only takes 21,363 liters, revealing it to be a wiser choice given the logistical difficulties that the remote location of the SWGO project present.

The Mercedes WCD default dimensions are 1.7 meters in height and 4 meters in diameter, being shaped approximately like a cylinder. The inner walls are covered with white diffusing Tyvek material. Tyvek is made from high-density polyethylene (HDPE) fibers that are spun and bonded together to create a strong and versatile material, which has been used in some particle detectors, e.g. Super-Kamiokande neutrino observatory in Japan. Tyvek's light weight and durability coupled with its high reflectivity and light scattering properties make it an excellent option for the interior of the detector.

4 Experimental Procedures

The experimental procedures undertaken in this study revolved around computer-based simulations, harnessing the advanced capabilities of LATTESsim —a simulation framework developed at LIP— coupled with the powerful ROOT framework developed by CERN. Notably, LATTESsim was built upon Geant4, a renowned toolkit widely utilized in high-energy physics, nuclear physics, and medical fields for simulating the passage of particles through matter. Geant4 offers a comprehensive range of functionalities, including accurate modeling of particle interactions, electromagnetic processes, and complex geometries.

In this context, the simulations aimed to replicate particle injection within water Cherenkov tanks of varying heights: 1.2 m, 1.5 m, 1.7 m, and 2.0 m. Initially, the simulations focused solely on adjusting tank height, while maintaining a constant tank diameter of 4.0 m. However, a significant challenge emerged when tank heights exceeded 1.8 m, leading to Photomultiplier Tube (PMT) collisions with the tank walls (due to the automatic positioning of PMTs to account for the dimensions of the Cherenkov cone). This concern prompted a thorough examination of potential solutions. Ultimately, a strategic modification to the underlying source code was implemented. This modification dynamically linked the tank's diameter and PMT positioning to the tank's height. As a result, larger tank heights correspondingly yielded larger tank diameters, effectively circumventing PMT collisions. This innovative approach not only resolved the collision issue but also ensured accurate simulations across the varying tank sizes, enabling more insightful data collection and analysis.

Initially, the simulations incorporated 1000 particle injections, encompassing both muons and gammas, which provided a reasonably robust basis for statistical analysis. The energy selected for these simulations was 20 MeV for gammas. This is due to the fact that it is the median value of the tail of the distribution of low energy gammas generated in an air shower. In addition, in the case of muons the energy level used was 2 GeV because at this energy a muon predominantly produces Cherenkov radiation. At lower energies there's a higher likelihood the muon will decay, and for higher energies additional effects come into play including delta-rays and bremsstrahlung. As the internship progressed, the focus shifted exclusively to muons, allowing for a more specialized investigation. Upon thorough evaluation of simulation results, a strategic decision was made to enhance statistical significance by scaling up the number of particle injections. Consequently, the simulation scale was magnified by a factor of 10, resulting in a total of 10,000 particles being injected. Additionally, a parallel line of simulations was conducted, maintaining a constant tank diameter of 4.0 m while systematically varying the previously established tank heights—1.2 m, 1.5 m, 1.7 m, and 2.0 m. To circumvent the earlier issue of Photomultiplier Tube (PMT) collisions for tank heights exceeding 1.8m, an ingenious modification to the source code was introduced. This alteration ensured fixed PMT positioning, effectively mitigating collision concerns for taller tanks. These refined simulation approaches not only enriched the dataset but also bolstered the accuracy and reliability of the results, facilitating a comprehensive understanding of particle behavior within tanks of diverse dimensions.

Concluding the experimental procedures, the injection parameters underwent a series of alterations. Initially, vertical particle injections from a single point source were employed, providing a foundational understanding of individual particle behavior. This approach was then expanded upon, evolving to injection points uniformly distributed within a circular plane. This modification allowed for the exploration of particle interactions within a confined two-dimensional space, yielding insights into collective behaviors. Building on this, an additional injection configuration was implemented — particles were uniformly injected within a circular plane at a 45-degree angle. This introduced an element of complexity, shedding light on particle trajectories and interactions in a non-standard orientation. By systematically adjusting injection parameters, this study encompassed a comprehensive spectrum of scenarios, offering nuanced perspectives on particle dynamics within the simulated environment.

5 Results

In this section, we will present the primary discoveries and outcomes derived from our research. The central finding of our study revolves around the superior performance of dynamically adjusted Water Cherenkov Detectors (WCDs) when compared to WCDs with constant diameters. Our investigation consistently shows that dynamically adjusted WCDs yield notably higher total signal readings. This observation underscores their effectiveness in capturing and detecting significant events. In our analysis, we have plotted the total signal data for both constant diameter and dynamically adjusted Water Cherenkov Detectors (WCDs). Notably, upon closer inspection of figure 4, the peaks in the signal curves appear to be closer together for the constant diameter WCDs. This observation aligns with theoretical expectations (bigger volume tanks provide the higher total signal) and provides an intuitively understandable result.

However the same cannot be inferred for the dynamically adjusted diameter tanks. As it is possible to conclude from figure 5 the smaller volume tank is the one that is gathering the most total signal. This is a result that does not comply with the previous established fact that as a particle travels through the medium, its production of Cherenkov radiation increases proportionally with distance traveled. These contrasting outcomes invite a deeper exploration of the dynamics at play within dynamically adjusted WCDs and open up exciting avenues for further investigation.

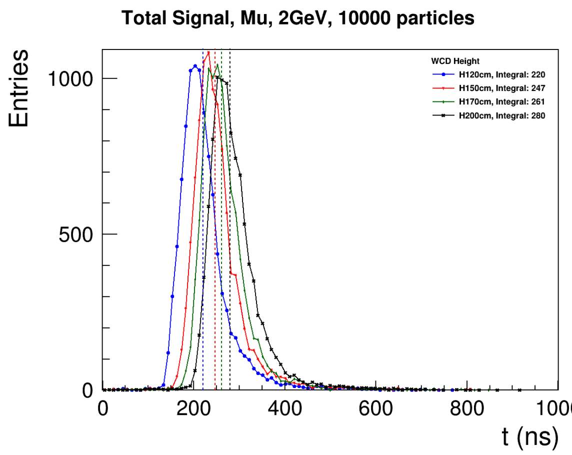

Figure 4. 0 degrees Total Signal plot for constant diameter tanks

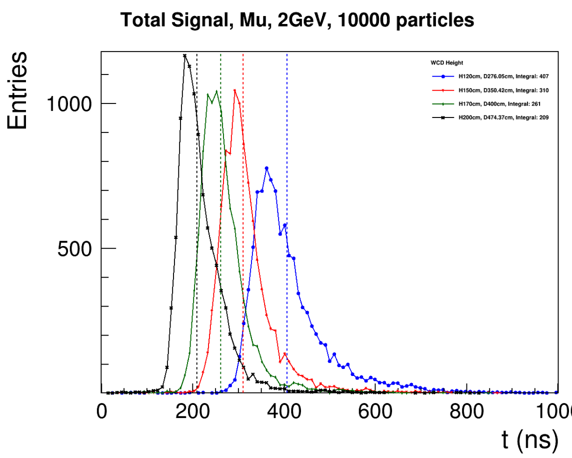

Figure 5. 0 degrees Total Signal plot for dynamically adjusted diameter tanks

In the case of muons injected at a 45-degree angle relative to the top of the tanks, similar data plots were generated for analysis. A consistent trend emerged in this scenario, wherein the smaller volume tanks exhibited notably superior total signal performance when considering the dynamically adjusted diameter case.

To provide a comprehensive overview and quantitative measure of the accumulated signal over time, an integral of the TProfile plots, as shown in figures 8, 9, 10, and 11, was plotted alongside histograms representing the Total Signal. This combined visual representation not only offered a clear summary of the total signal's temporal evolution but also provides a quantitative measure to assess and compare the performance of different tank configurations. This comprehensive approach facilitated a more thorough understanding of how the signal accumulation varied over time across the range of scenarios explored in the study.

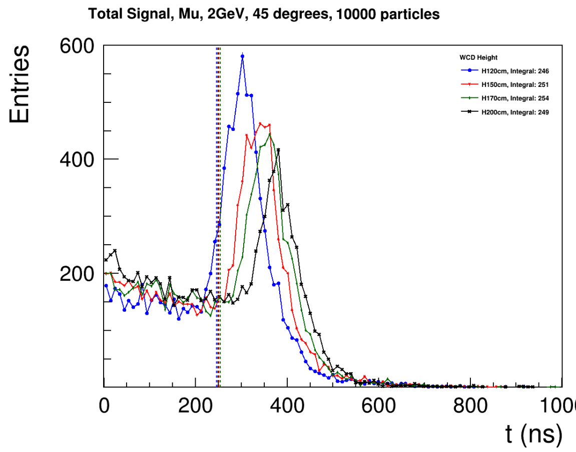

Figure 6. 45 degrees Total Signal plot for constant diameter tanks

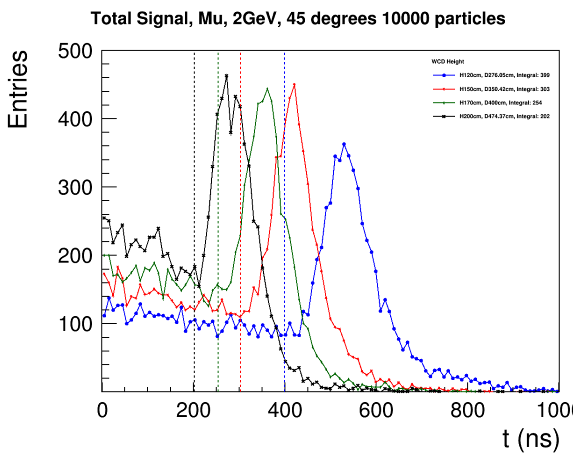

Figure 7. 45 degrees Total Signal plot for dynamically adjusted diameter tanks

TProfile plots were employed as a valuable analytical tool to gain insights into how the signal was recorded across the various tanks in the simulations. TProfile was chosen for its effectiveness in handling binned data and for its ability to represent the mean value of a quantity on the Y-axis. These plots served as a complementary visualization technique alongside the Total Signal plots, enhancing our understanding of the data.

The TProfile plots exhibited a notable consistency with the trends observed in the Total Signal plots. In the case of tanks with a constant diameter, both for particle injections at 0 and 45-degree angles, the plots displayed coherent behavior. Initially, a prominent spike was observed at approximately 10 ns, corresponding to the larger tank (height H=200cm), which dominated the signal. Subsequently, the smaller tank (height H=120cm) exhibited a peak at around 11.5 ns but quickly stabilized, aligning with the anticipated results.

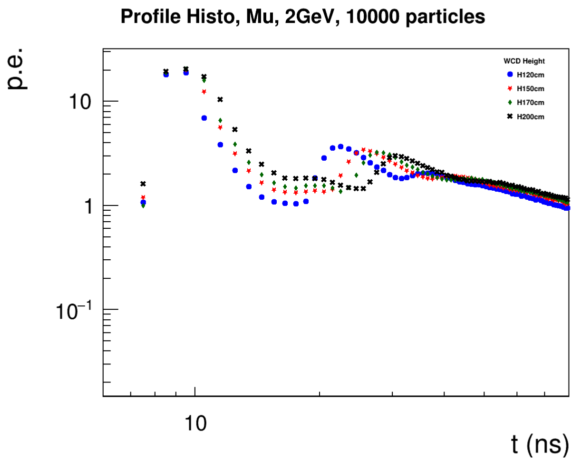

Figure 8. 0 degrees TProfile plot for constant diameter tanks

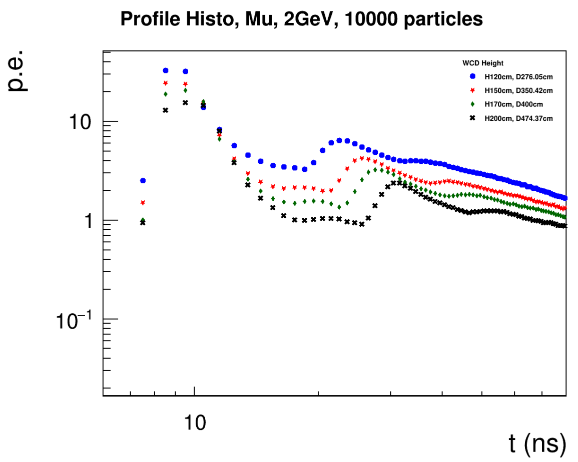

Figure 9. 0 degrees TProfile plot for dynamically adjusted diameter tanks

Intriguingly, the plots for the tanks with dynamically adjusted diameters reveal a distinct behavior among different tank heights. These plots exhibit less entangled lines and align more closely with the trends observed in the Total Signal plots. Notably, a recurring pattern emerges with a peak occurring around the 10 ns mark. However, in contrast to previous scenarios, the smaller tank (H=120cm) consistently registers higher values, while the taller tank (H=200cm) consistently displays smaller values. This trend persists throughout the remainder of the plot.

This shift in behavior suggests that the dynamically adjusted diameter configuration has a significant impact on signal recording, leading to a reversal in signal dominance between tanks of varying heights. These observations further underscore the importance of considering both tank height and diameter when designing and analyzing particle detection systems, as these parameters can have a profound influence on the recorded signals and subsequent data analysis.

These TProfile plots provided a concise and informative representation of signal characteristics, aiding in the identification of critical temporal patterns and facilitating a deeper comprehension of how signal recording varied across different tank configurations

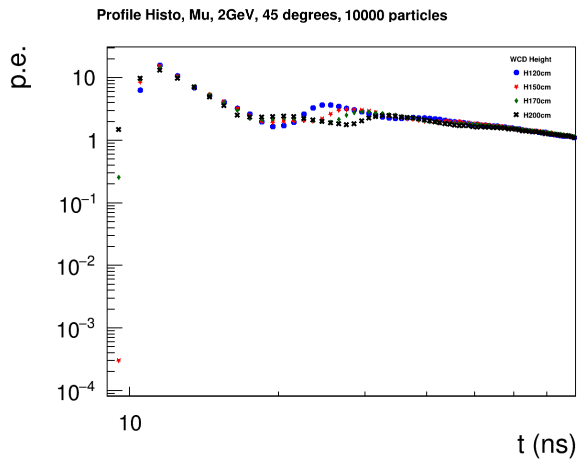

Figure 10. 45 degrees TProfile plot for constant diameter tanks

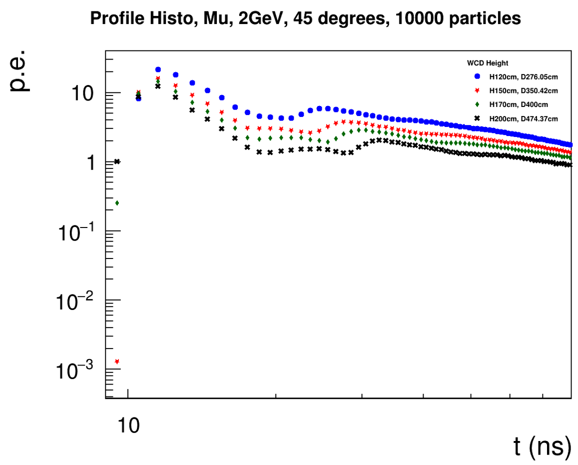

Figure 11. 45 degrees TProfile plot for dynamically adjusted diameter tanks

6 Conclusion

In conclusion, the research on the optimization of Water Cherenkov Detectors (WCDs) for next-generation gamma-ray observatories has provided valuable insights into the complex interplay of design parameters and their impact on signal detection. We have demonstrated that dynamically adjusted WCDs outperform their counterparts with constant diameters, challenging conventional expectations.

The findings reveal that dynamically adjusting the WCD's diameter in relation to its height yields superior total signal performance, particularly in scenarios involving muon injection at a 45-degree angle. This unexpected trend invites further investigation into the underlying physical mechanisms responsible for this phenomenon.

Future work in this field must prioritize elucidating these mechanisms to better comprehend the dynamics of particle detection within WCDs. Only by unraveling the physics behind this phenomenon can we advance our understanding and move forward with other aspects of WCD optimization, such as optimizing the positioning of Photomultiplier Tubes (PMT) angles.

Moreover, the implications of our discovery extend beyond scientific curiosity. They hold the promise of substantial cost savings for the construction and operation of high-altitude wide-field gamma-ray observatories, particularly in remote locations like South America (for the case of the SWGO). By optimizing WCDs through dynamic diameter adjustments, observatories can significantly reduce the volume of water required per tank, alleviating logistical complexities and associated expenses.

This investigation underscores the critical role of WCDs in high-energy astrophysics and their potential to unlock the mysteries of the universe. As we continue to refine and optimize these detectors, we are poised to make significant contributions to the next-generation gamma-ray observatories and the broader field of cosmic ray and gamma-ray research. This discovery not only enriches our scientific understanding but also strengthens the feasibility of groundbreaking research in some of the world's most remote and challenging environments.

7 Acknowledgements

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