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First observational results with the prototype experiment of a stereoscopic water Cherenkov detector array in Tibet

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The SWCDA (Stereoscopic Water Cherenkov Detector Array) is a next-generation ground-based gamma-ray observatory that introduces significant technological innovations to existing Extensive Air Shower (EAS) array detection techniques. This advanced system achieves an order-of-magnitude improvement in sensitivity over conventional ground arrays for gamma-ray observations in the 100 GeV to 100 TeV energy range, while lowering the detection threshold from 500 GeV to 100 GeV. Its unique capabilities - including a wide energy coverage range (100 GeV - 100 TeV), a wide field of view, and high duty cycle - enable complementary observations with future gamma-ray facilities (CTA, SWGO, ALPACA and LHAASO), and contribute to multi-messenger astronomy through coordinated observations with neutrino and gravitational wave detectors. The primary scientific objectives focus on extragalactic sources, particularly transient phenomena such as blazars, active galactic nuclei (AGNs or AGNs flare), gamma-ray bursts (GRBs), and Galactic microquasars to study gamma-ray acceleration mechanisms across the energy spectrum. The detector system consists of two core components: a Liquid Scintillator (LS) array and the SWCDA array. We present detailed performance characteristics from a 100 m^2 SWCDA prototype deployed within the Tibet ASγ air-shower array in late 2024, demonstrating its potential for advancing high-energy astrophysics research.

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1. Introduction

The observational study of high-energy gamma rays represents one of the forefront areas in exploring the origins of cosmic rays and investigating extreme cosmic phenomena. Especially, the flux of gamma rays decreases as a power law with increasing energy. Due to detector size constraints, satellite-based experiments are unable to observe gamma rays with energies above 100 GeV. Thus, the detection of gamma rays beyond this energy relies exclusively on ground-based Extensive Air Shower (EAS) survey array experiments.

For ground-based EAS arrays, which indirectly observe primary particles by detecting secondary particles from air showers, a crucial challenge is the effective separation and identification of high-energy gamma-ray events amidst the overwhelming background of cosmic rays. In 2007, the Tibet ASγ experiment pioneered an innovative underground muon water Cherenkov detector (Tibet-MD), which distinguishes between protons and gamma rays by leveraging differences in the number of muons present in their respective air showers. In 2019, the Tibet ASγ experiment, utilizing a combined surface array (Tibet-III+MD), achieved the first-ever detection of gamma rays with energies up to 450 TeV from the direction of the Crab Nebula [1]. This landmark observation opened a new window for gamma-ray astronomy in the 100 TeV energy range.

However, current ground-based EAS survey array experiments generally have an energy threshold above 500 GeV. Extragalactic high-energy gamma rays often exhibit spectral truncation at the high-energy end due to absorption by the extragalactic background light (EBL), making them difficult to observe effectively with ground-based EAS arrays. As a result, the majority of gamma-ray sources detected so far are of galactic origin. A significant number of potential extragalactic sources—such as blazars, active galactic nuclei (AGNs), and gamma-ray burst, which may dominate at lower energies, remain largely unobserved.

With the completion of the Large High Altitude Air Shower Observatory (LHAASO), currently the most sensitive detector in the Northern Hemisphere, the observation of steady sources in the northern sky has approached saturation. Therefore, the future development of ground-based EAS gamma-ray survey experiments should focus on: 1) surveying the Southern Sky, particularly the Galactic Center region, which remains largely unexplored internationally; 2) extending the observational energy range down to 100 GeV to study extragalactic regions, especially numerous transient extragalactic sources.

A primary research objective of this work is to effectively lower the gamma-ray energy threshold from the TeV level to 100 GeV and significantly enhance the capability to distinguish between protons and gamma rays in the 100 GeV energy region. To address this, we propose a Stereoscopic Water Cherenkov Detector Array (SWCDA) initiative. The scientific goals of this project are to extend observations to the lower energy band of 100 GeV-100 TeV, targeting gamma-ray sources and numerous transient extragalactic phenomena such as blazars, AGNs, and gamma-ray bursts.

2. Development of a wide-field SWCDA for the 100 GeV - 100 TeV at high altitude (5200 m)

In recent years, ground-based Extensive Air Shower (EAS) array experiments, such as the Tibet ASγ, HAWC, and LHAASO have achieved significant results, demonstrating the scientific potential of wide-field-of-view, high-duty-cycle gamma-ray array observations. However, a major limitation of such EAS array detection techniques lies in their reliance on two-dimensional observations, which only provide information on the lateral distribution of cosmic-ray-induced air showers. This constraint severely restricts the ability to discriminate between cosmic rays and gamma rays, resulting in insufficient gamma-ray observation sensitivity to meet scientific requirements in the 100 GeV–TeV energy range. Meanwhile, space-based experiments like Fermi-LAT are limited by their effective detection area, leading to low sensitivity for gamma-ray observations above 100 GeV.

As a result, the 100 GeV–TeV energy band has long remained a sensitivity gap in wide-field, high-throughput gamma-ray astronomy, creating an urgent need for new detection technologies to overcome this bottleneck. To address these challenges, we propose an innovative Stereoscopic Water Cherenkov Detector Array (SWCDA), which upgrades ground-based wide-field observations from one-dimensional (2D plane) to three-dimensional detection.

2.1 Design of the SWCDA

Due to the nearly identical nuclear interaction lengths (83.6 g/cm^2 for water; 90 g/cm^2 for air), radiation lengths (36.08 g/cm^2 for water; 36.66 g/cm^2 for air), and ionization energy losses (1.991 $MeV \cdot g^{-1} \cdot cm^2$ for water; 1.815 $MeV \cdot g^{-1} \cdot cm^2$ for air) between water and air, a multi-layer stereoscopic water Cherenkov detector array (SWCDA) deployed at specific altitudes can achieve three-dimensional observation of extensive air showers (EAS), as illustrated in Fig.1. This SWCDA system simultaneously captures both the longitudinal development and lateral distribution of cosmic-ray-induced air showers.

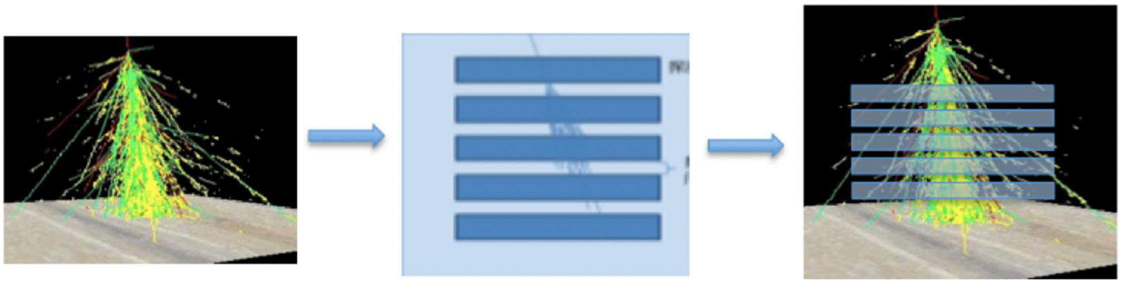

Figure 1: Schematic diagram of the Stereoscopic Water Cherenkov Detector Array (SWCDA).

By observing the same cosmic-ray air shower at different atmospheric depths—such as at altitudes of 5000 m and 2000 m, and underground depths of 1 m, 1.75 m, and 2.5 m, stereoscopic three-dimensional information can be acquired. By leveraging the observed stereoscopic three-dimensional information combined with machine learning methods, we can achieve a significantly improved capability to discriminate between protons and gamma rays compared to existing ground-based array experiments. This advancement will ultimately lead to a qualitative enhancement in cosmic-ray background rejection and an order-of-magnitude increase in gamma-ray observation sensitivity.

2.2 Prototype array of the SWCDA

In late 2024, a 100 m^2 SWCDA prototype detector was constructed at the southeastern corner of the Tibet ASγ surface array (Tibet-III). The SWCDA prototype detector, located in the southeastern part of the Tibet ASγ surface array (Tibet-III), consists of a 10 m × 10 m × 8 m water pool containing an immersed SWCDA water bag, as illustrated in Fig.2.

Figure 2: The prototype experiment of the SWCDA was completed at Yangbajing (4300 m). Left: The orange dots represent the Tibet-III array, the blue squares indicate the Tibet-MD detectors, and the orange square in the southeast corner of the array marks the location of the 100 m^2 SWCDA prototype detector. Center and Right: Physical photographs of the 100 m^2 SWCDA prototype detector.

The SWCDA prototype detector comprises two distinct structural layers. The first layer consists of 16 detector units, each measuring 2.5 m (L) × 2.5 m (W) × 1.6 m (H). Each unit contains an intna water bag lined with black light-absorbing material. The photomultiplier tubes (PMTs) are positioned at the bottom of each unit, facing upward. These detectors are arranged in a tightly packed 4 × 4 grid.

Layers 2 to 5 each contain 16 detector units with dimensions of 5.0 m (L) × 5.0 m (W) × 1.6 m (H). The intna water bags in these units are lined with Tyvek reflective film on the sides and bottom, while the top surface is covered with black light-absorbing material. The PMTs are installed at the top of each unit, facing downward. Each layer is arranged in a 2 × 2 grid and evenly distributed beneath the first-layer water bags across layers 2 to 5.

2.3 Primary energy reconstruction using the SWCDA Prototype Detector

We have incorporated all observational conditions of the experiment and completed the full Monte Carlo simulation [2] using Geant4 [3]. As shown in Fig.3, the number of photoelectrons detected by the first layer of the SWCDA prototype (100 m^2) demonstrates a strong linear correlation with the energy of primary gamma rays (or cosmic rays). The energy of primary gamma rays can be reconstructed based on the number of photoelectrons observed in the first layer of the SWCDA prototype. Based on the above results, it can be found that after future expansion of the SWCDA detector area, its first layer will functionally correspond to the Tibet ASγ surface array (Tibet-III), enabling the reconstruction of both the energy and arrival direction of primary gamma rays.

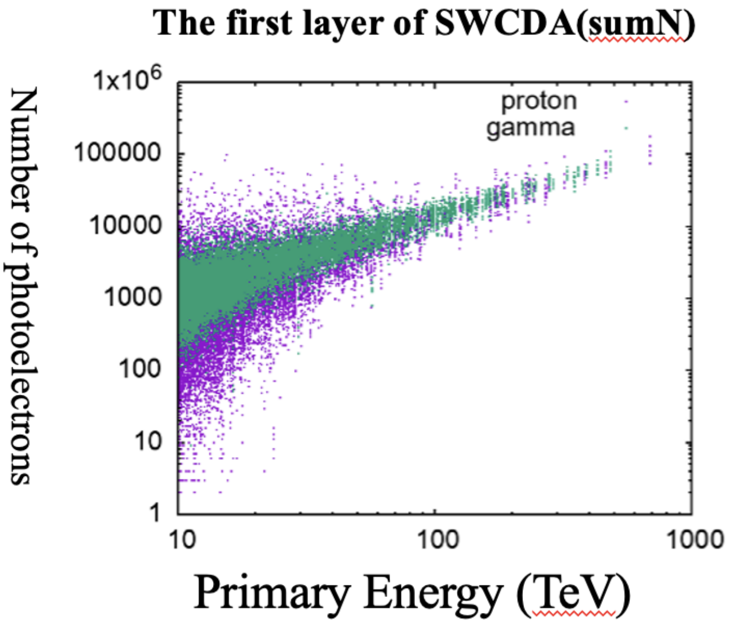

Figure 3: Primary energy reconstruction using total photoelectrons from the first layer of the SWCDA prototype (100 m^2).

2.4 Proton/Gamma Discrimination with the SWCDA Prototype Detector

The lateral and longitudinal distributions of particles within the various layers of the SWCDA differ significantly when particles of different compositions strike the prototype detector. For instance, secondary particles from air showers initiated by gamma rays consist predominantly of electromagnetic components such as photons and electrons. When these particles enter the water medium of the SWCDA, they primarily undergo electromagnetic cascades, which have limited penetration. A key characteristic is that signals are detected only in the upper layers of the detector, with the shower diminishing in the lower layers.

In contrast, secondary particles from air showers initiated by cosmic-ray protons contain hadronic components such as muons. Upon entering the water in the SWCDA, these particles mainly undergo nuclear interactions, which have greater penetration. As a result, signals can be detected across multiple layers of the SWCDA, particularly with stronger signals in the lower layers.

Additionally, at the same energy level, cosmic-ray proton-induced showers contain more muons compared to those initiated by gamma rays. Fig.4(A) shows the sum of all photoelectrons (sumN) in the fourth layer of SWCDA. Almost all the events observed in the fourth or fifth layer of SWCDA are muons. By taking advantage of the characteristic that the number of muons contained in cosmic-ray-origin events is much greater than that in gamma-ray-origin events, a good distinction (gamma/proton) can be made.

Moreover, at the same energy level, the lateral distribution of cosmic-ray proton showers is much broader than that of gamma-ray showers (as shown in Fig.4(B)).

The SWCDA can capture three-dimensional images of showers produced by particles of different compositions entering the detector. From Fig.4, it can be seen that there are significant differ-

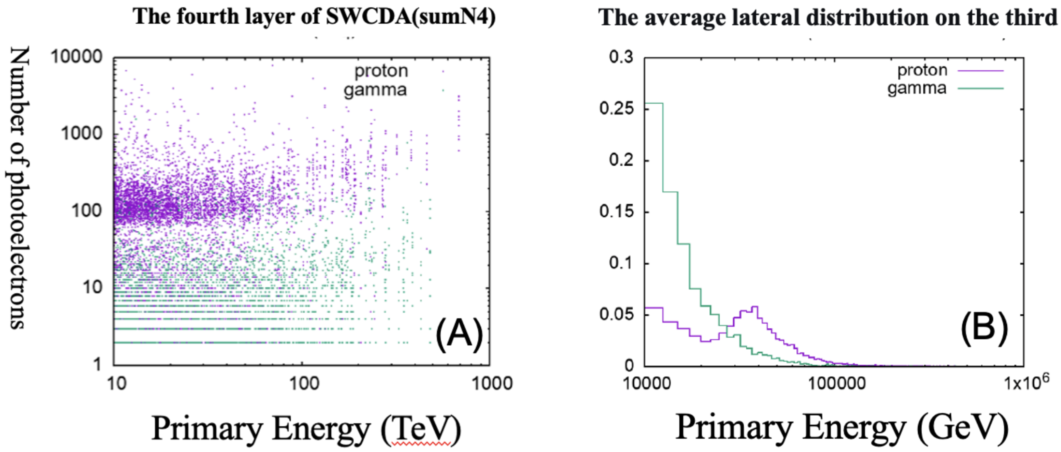

Figure 4: (A) shows the sum of all photoelectrons (sumN4) in the fourth layer of SWCDA. (B)The comparison of the average lateral distributions between proton-initiated events and gamma-ray-initiated events in the third layer, as observed using the SWCDA prototype (100 m^2).

ences in the longitudinal and lateral distribution between proton-origin events and gamma-ray events. Inputting these sensitive parameters into machine learning can well distinguish (gamma/proton) as shown in Fig.5.

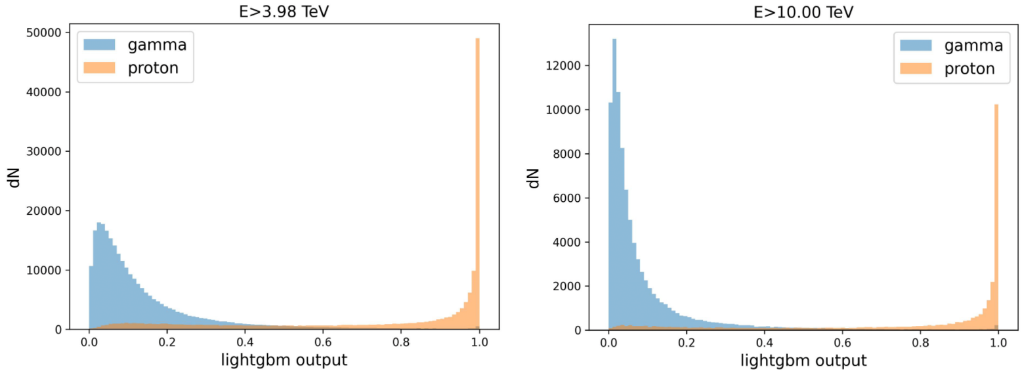

Figure 5: A schematic diagram illustrating the capability of machine learning to distinguish between gamma rays and cosmic rays (protons) at different energy region. The horizontal axis represents the probability output, where values closer to 0 indicate gamma-like events, and values closer to 1 indicate proton-like events. The vertical axis represents the number of events in the test dataset corresponding to each probability output.

This work reveals that for primary energies above 10 TeV, the SWCDA prototype achieves a cosmic-ray background rejection rate of 98.3% while retaining 44% of gamma-ray events, resulting in a Q-factor of 3.36. In comparison, the underground muon detector (MD) of the Tibet MD experiment, with an area of 3,400 m^2. When operating independently under the same energy condition (>10 TeV), retains 87.1% of gamma rays but only achieves a background rejection rate of 89.4% and a Q-factor of 2.67, which is significantly lower than the observational sensitivity of the SWCDA prototype to gamma rays.

Despite the SWCDA prototype much smaller effective area of only 100 m^2 compared to the Tibet MD experiment, the SWCDA prototype demonstrates excellent performance in cosmic-ray background suppression, attributable to its multi-layer stereo structure. It is foreseeable that once the SWCDA array is expanded to cover an area of several tens of thousands of square meters in the future, it will exhibit even more superior performance in observing low-energy gamma rays.

3. Summary and outlook

Traditional ground-based cosmic ray detectors typically employ a single-layer planar structure, which can only provide one-dimensional shower imaging and exhibit very poor discrimination capability between gamma rays and cosmic ray backgrounds in the energy range below a few TeV. Lowering the detection threshold to ∼100 GeV is crucial for observing extragalactic sources like blazars, AGNs, and GRBs, due to strong TeV absorption by extragalactic background light. This work presents the Stereoscopic Water Cherenkov Detector Array (SWCDA) - a multi-layer system constructed with low-cost water-based detectors. By leveraging water's similar interaction properties to air, the SWCDA achieves three-dimensional sampling of air showers, effectively functioning as a large atmospheric calorimeter. This design captures distinct spatial shower morphologies between gamma rays and protons, greatly enhancing particle identification and background rejection in the low-energy regime. Deployed at 5,200 m in Tibet, the SWCDA is projected to lower the energy threshold to ∼100 GeV and improve sensitivity by over tenfold in the 100 GeV–TeV range.

The SWCDA technology establishes a new paradigm in wide-field, low-energy gamma-ray astronomy. Future work will focus on experimental validation through joint observations with existing Tibet ASγ experiment. Scaling the array to cover tens of thousands of square meters will further enhance sensitivity, enabling large-scale surveys and population studies of transients like GRBs and AGNs in the 100 GeV–100 TeV band. The SWCDA promises to serve as a foundational instrument for next-generation ground-based gamma-ray observatories.

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