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Development of a Hybrid Water Cherenkov and Liquid Scintillator Detector for Cosmic Ray Detection

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This study presents a hybrid detector design integrating water Cherenkov and liquid scintillator technologies for future ultra-high-energy cosmic ray (UHECR) and gamma-ray observatories. The detector unit comprises a cylindrical structure (25 cm radius, 115 cm height) with a 7 mm or 10 mm-thick liquid scintillator layer from the JUNO experiment at the top, coupled with a purified water volume. A 3-inch PMT is precisely positioned 40 cm above the tank bottom, encircled by light-blocking material to optically separate water sections, enabling direct Cherenkov light reception. Signal acquisition is performed using a CAEN V1743 digitizer (3.2 GS/s, 12-bit) for high-precision waveform analysis. We systematically evaluated key performance parameters, including light yield, time resolution, and spatial uniformity, comparing liquid scintillator (LS) with plastic scintillator (PS). While PS showed higher light yield, 117.7 p.e. and better time resolution (0.73 ns) than LS (72.49 p.e., 0.93 ns) in individual tests, the basic performance of plastic scintillator was confirmed as stable and viable for energy measurement. Moreover, 7 mm liquid scintillator exhibited more pronounced spatial non-uniformity, that number of photoelectrons (NPE) drops from 89.65 p.e. to 47.45 p.e. compared to PS. Crucially, the hybrid water-based liquid scintillator (WbLS) configurations demonstrated significantly enhanced performance. Specifically, the combination of 2cm LS and 30cm water achieved a high light yield of 199.36 p.e. and an excellent time resolution of 0.91 ns. Optical optimization, such as reflective cones, proved vital in mitigating inherent non-uniformities, ensuring consistent detector response across its volume. This hybrid WbLS design effectively merges the Cherenkov timing precision of water with the high light yield of scintillator, offering superior performance for energy and direction reconstruction. It addresses limitations of traditional detectors like LHAASO-ED and represents a strong, viable, and cost-effective candidate for next-generation observatories like SWGO.

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1. Introduction

Water Cherenkov Detectors (WCDs) and Scintillator Detectors are two widely used technologies in ground-based gamma-ray astronomy. WCDs detect particles through Cherenkov light in water, providing large-area coverage at relatively low cost and showing strong performance in high-energy particle detection, direction reconstruction, and background suppression. Representative examples include HAWC, with 300 WCD units (7.3 m diameter, 4.5 m height, 4 m water depth) [1], and the Pierre Auger Observatory (PAO) surface array [2], consisting of 1600 WCDs (3.6 m diameter, 1.2 m depth). However, WCDs generally suffer from limited energy resolution and low efficiency for detecting low-energy particles. In contrast, Scintillator Detectors measure particle energy via scintillation light, achieving high light yield and precise energy reconstruction, particularly for low-energy electromagnetic particles. Plastic scintillator (PS), as used in the LHAASO electromagnetic detector array (ED) [3], has demonstrated stable performance in large arrays, with each detector unit covering about 1 m^2. Liquid scintillator (LS) offers further advantages: it provides even higher light yield than water, can be cast into flexible shapes without machining, and is generally more cost-effective than solid PS. Nevertheless, the large-scale use of organic LS is limited by issues such as flammability, toxicity, and chemical stability.

To overcome these limitations and meet the requirements of next-generation observatories such as SWGO[4], hybrid detection solutions that combine the strengths of WCDs and EDs represent a promising approach. Water-based Liquid Scintillator Detectors (WbLS) represent such an emerging hybrid solution[5]. They merge the directional properties of Cherenkov light with the high light yield and fast response of scintillators, simultaneously enhancing energy resolution, particle direction reconstruction, and low-energy particle detection[6]. Our current research is in the initial testing phase, focusing on adding liquid scintillator to existing water-based detectors (WCDs) using water tanks as preliminary test units. This small-scale testing aims to evaluate the improvement in WCD performance, specifically in light yield and time resolution, with LS addition. This exploration provides foundational data for future high-performance hybrid detector designs.

2. Comparison of Plastic and Liquid Scintillators

As one of the most precise ground-based observatories to date, LHAASO has achieved significant success in the TeV energy range and made breakthroughs in the PeV range. The Kilometer Square Array (KM2A), as a core component, relies heavily on the performance of the Electromagnetic Detector (ED), which plays a crucial role in high-energy electromagnetic particle detection. To better understand the performance of WbLS detectors, we first compared the performance of LS and PS. The ED, which utilizes PS, serves as a reference due to its excellent light yield and energy resolution. This comparison helps establish a preliminary understanding of the LS performance, providing valuable insights into the potential of WbLS detectors in high-energy electromagnetic particle detection.

2.1 Experimental Setup

To compare performance, we used a light-tight water tank capable of containing the scintillator. The setup of our experiment is shown in Figure 1.

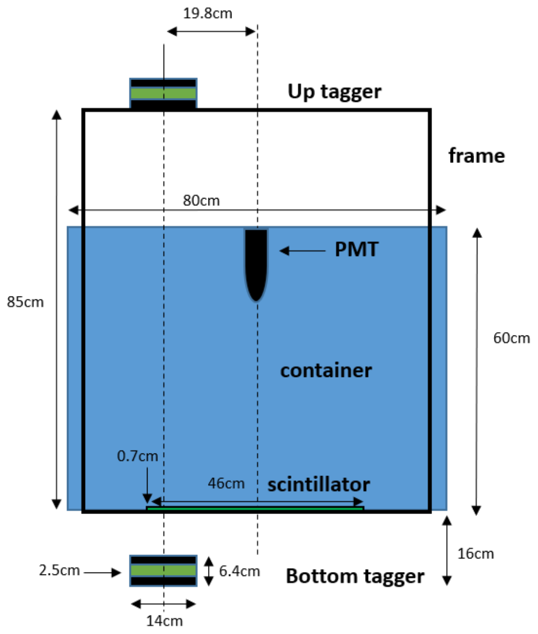


Figure 1: Detector geometry model. The PMT is set at the top

Our experiment used PS identical to LHAASO-ED and LS from the JUNO experiment, known for its high light yield and good time resolution. We employed N2031 model 3-inch PMTs from North Night Vision Company. Calibration at 1200V yielded a gain of 5.6×10^6. The acrylic container for the LS was wrapped in Tyvek to enhance light collection. A Tyvek reflective cone was installed between the PMT photocathode and the acrylic container, improving light collection efficiency. The scintillator was approximately 45 cm from the PMT photocathode.

We evaluated detector performance using cosmic ray muons. Experiments were conducted at Shandong University in Qingdao, where muons near sea level have average energies of a few GeV. As the scintillator is thin, collected energy theoretically follows a Landau distribution, which our results confirmed. Top and bottom taggers triggered coincident events, ensuring vertically passing muons had consistent thickness. Data acquisition used a CAEN V1743 digitizer with a 3.2 GS/s sampling rate.

2.2 Performance Comparison between PS and LS

Accurate reconstruction of extensive air showers in ultra-high-energy cosmic ray experiments requires a quantitative understanding of detector performance. Measurements of light yield, timing resolution, and spatial uniformity provide the basis for evaluating a detector's capability to reconstruct energy, shower front structure, and core position with minimal systematic uncertainty. Higher photon yield directly reduces statistical fluctuations in energy determination, precise timing supports directional reconstruction, and uniform response ensures stability across large detector arrays.

In the experiment, we repositioned the top and bottom taggers to select muons incident at different locations, thereby evaluating the detector's spatial uniformity. The position of tagger is

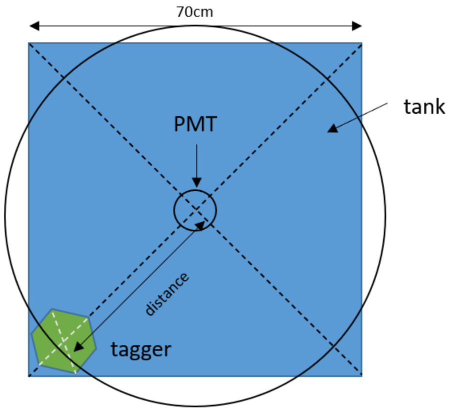
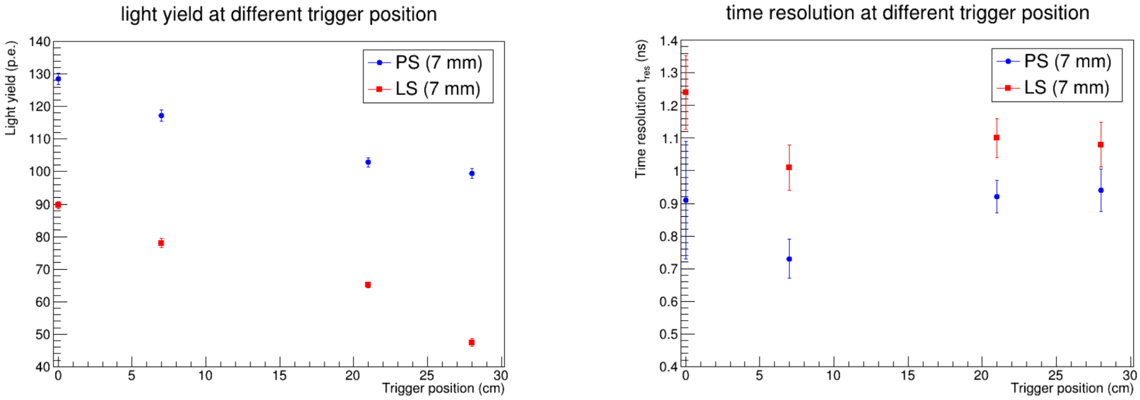


Figure 2: Top view of the tank. The distance denotes the horizontal separation between the tagger and the PMT



(a) Light yield vs. trigger position.

(b) Timing resolution vs. trigger position.

Figure 3: PS (7 mm) vs. LS (7 mm) under the same trigger scheme. PS shows higher central light yield with modest edge fall-off and stable timing, while LS exhibits stronger position dependence and broader timing.

shown in Fig. 2

In our comparison, as is shown in Figure 3, 7-mm PS exhibited approximately 40% higher light yield than 7-mm LS at the detector center and maintained this advantage with only a modest decrease toward the edges. Its timing resolution remained stable at about 0.9 ns across different trigger positions, demonstrating efficient and uniform signal collection. By contrast, LS produced fewer photons and displayed stronger position dependence: the light yield decreased by nearly half from center to edge, and the timing resolution was systematically worse (around 1.1–1.2 ns). These features reflect intrinsic light transport limitations in LS, such as attenuation and boundary effects.

Overall, the results indicate that PS provides higher photon statistics, faster timing, and better spatial uniformity, all of which are directly beneficial for the precise reconstruction of shower energy and arrival direction. LS, although still suitable in certain contexts, would require additional optical optimization to achieve the performance level demanded by large-scale PeV–EeV cosmic ray experiments.

3. Performance of the water-based liquid scintillator

While PS provides higher light yield and more uniform timing than LS at the same thickness, the two media encode complementary information: water enables fast Cherenkov timing with good directional sensitivity, whereas scintillator offers high photon statistics for energy measurements. A WbLS can, in principle, retain both advantages within a single unit. The following tests quantify the performance gain from combining the two media and assess the potential impact on shower energy and front reconstruction in ground arrays.

3.1 Experimental setup

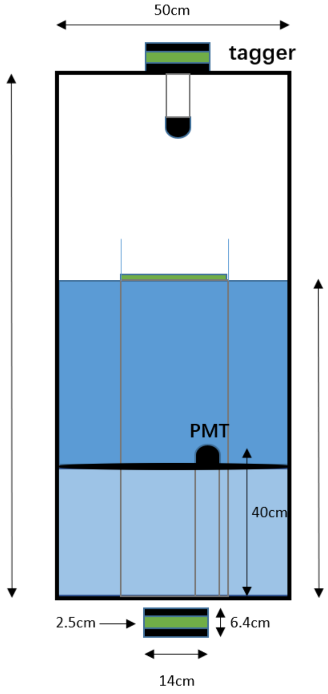


Figure 4: Detector geometry model. The PMT is set at the top, 40 cm above the bottom

The setup of our experiment is shown in Figure 4. This time, the experimental setup for the water-based liquid scintillator (WbLS) hybrid detector introduces several key improvements specifically for its hybrid design, while retaining core elements from previous test schemes. The PMT remains the N2031 model 3-inch PMT, maintaining a gain of 5.6×10^6 at 1200 V. Detector performance evaluation still relies on cosmic muons as a natural particle source, utilizing a top-bottom tagger triggering mechanism. The differences and the focus of this experiment lie in using a distinct cylindrical water tank (25 cm radius, 115 cm height), and a critical upgrade in PMT placement and optical isolation: a PMT is precisely positioned 40 cm above the tank bottom, encircled by light-blocking material to optically separate the water into upper and lower sections, specifically designed to allow it to receive direct Cherenkov light signals from the large water volume above. The media combination also explicitly focuses on introducing a top layer of liquid scintillator (1 cm or 2 cm, from the JUNO experiment) into the pure water Cherenkov medium.

These distinctions represent a shift in this research from component performance testing towards validating the feasibility of an integrated WbLS hybrid detector unit.

3.2 Light Yield and Time Response Uniformity Analysis

We evaluated the spatial uniformity of the detector by testing light yield (NPE) and time resolution under various configurations. The results showed that combining liquid scintillator and water-based detectors provides a significantly greater performance than their individual contributions.

Configuration	**Light Yield (NPE)**	**Time Resolution (ns)**
1 cm LS	31 p.e.	0.92 ns
2 cm LS	83.13 p.e.	0.72 ns
30 cm Water	21.61 p.e.	0.66 ns
2 cm LS + 30 cm Water	67.91 p.e.	0.54 ns
1 cm LS + 30 cm Water	31.12 p.e.	0.86 ns

Table 1: Light Yield and Time Resolution Comparison of Different Configurations

Configuration	**Light Yield (NPE)**	**Time Resolution (ns)**
1 cm LS	25.02 p.e.	2.13 ns
2 cm LS	60.92 p.e.	1.46 ns
30 cm Water	78.55 p.e.	0.82 ns
2 cm LS + 30 cm Water	199.36 p.e.	0.91 ns
1 cm LS + 30 cm Water	118.6 p.e.	1.21 ns

Table 2: Light Yield and Time Resolution Comparison of Different Configurations

In the 1 cm liquid scintillator + 30 cm water configuration, the light yield was 118.6 p.e. with a time resolution of 1.21 ns, showing a noticeable improvement over individual components. The 2 cm liquid scintillator + 30 cm water configuration further increased the light yield to 199.36 p.e. and reduced the time resolution to 0.91 ns, demonstrating that thicker liquid scintillator layers combined with water provide a substantial boost in both light yield and time resolution.

When testing 1 cm and 2 cm liquid scintillator individually, their performances were good, with light yields of 25.02 p.e. and 60.92 p.e. respectively, but they were far less effective compared to the combined configurations.

These results clearly indicate that combining liquid scintillator with water-based detectors yields more than just the sum of their individual performances. The hybrid configurations deliver superior light yield and time resolution, showcasing the potential of such systems to optimize both light collection and time response, improving overall detection efficiency.

4. Conclusion

This study aims to assess the feasibility of the hybrid WbLS detector system for cosmic ray ground array observation through systematic testing and analysis. The feasibility of this approach was initially tested using cosmic ray muons. By comparing the performance of LS and PS, we confirmed the basic viability of using liquid scintillator as the detection medium.

Although in separate tests of light yield and time resolution, LS was slightly lower than PS, LS still provides efficient energy measurement and low-energy particle detection capabilities. Its basic performance is stable and feasible. However, in terms of light yield and time resolution—two core performance indicators—the WbLS hybrid configuration demonstrated exceptional overall advantages. Particularly, the combination of 2 cm liquid scintillator and 30 cm water achieved a light yield of 199.36 p.e. while maintaining an excellent time resolution of 0.91 ns. This indicates that WbLS can effectively combine the Cherenkov timing precision of water and the high light yield characteristics of liquid scintillator, which is crucial for accurate energy reconstruction and event direction reconstruction, addressing the shortcomings of traditional water Cherenkov detectors in energy resolution and conventional scintillator detectors in directionality.

Compared to existing mature solutions such as LHAASO-ED, the WbLS hybrid detector holds promise to not only maintain or even improve energy reconstruction capabilities but also provide superior time and direction reconstruction precision. In summary, the experimental results of this study provide a solid foundation for the feasibility of the water-based liquid scintillator hybrid detector in cosmic ray ground array observation. WbLS has achieved significant improvements in core performance, and it shows great potential in engineering feasibility, safety, and cost-effectiveness, making it a strong candidate technology for future ultra-high energy cosmic ray and gamma-ray observatories, such as SWGO. Future work will focus on further optimizing the formulation of the WbLS medium, its long-term stability, and the development of particle identification algorithms for array detectors.

Acknowledgments

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