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U.S. DEPARTMENT OF ENERGY

Water-based Liquid Scintillator R&D effort at Brookhaven National Laboratory

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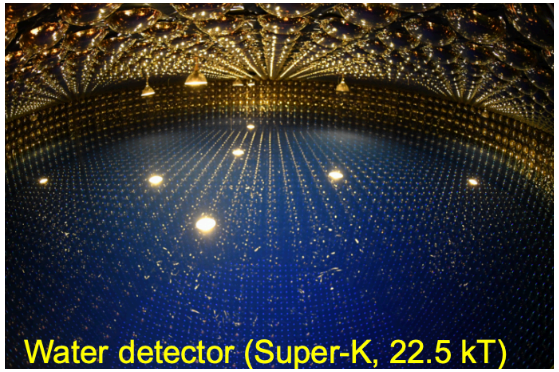
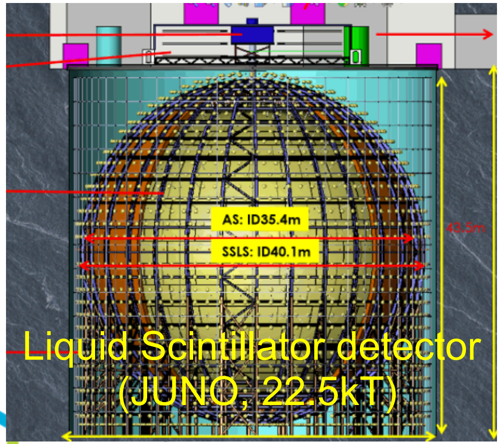
WbLS (Water-based Liquid Scintillator)

WbLS is a hybrid detection material that combines Cherenkov light and scintillation light.

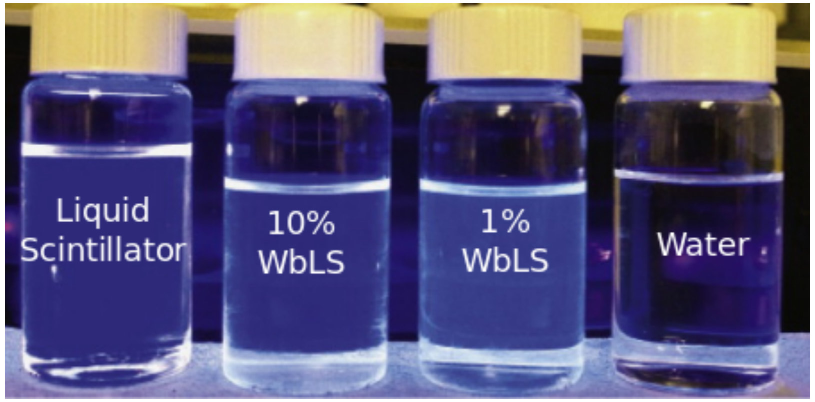

Water detector (Super-K, 22.5 kT)



Liquid Scintillator detector (JUNO, 22.5kT)

Water:
Excellent transparency
Directionality
Particle ID
Cheap

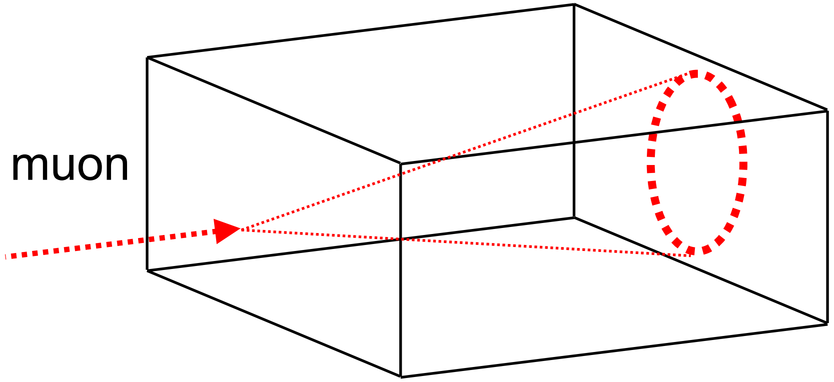
Liquid Scintillator:
High light yield
Low energy threshold
Good energy resolution



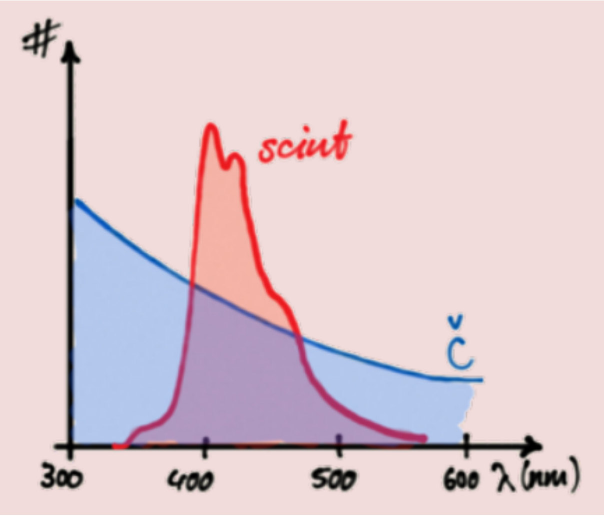
WbLS

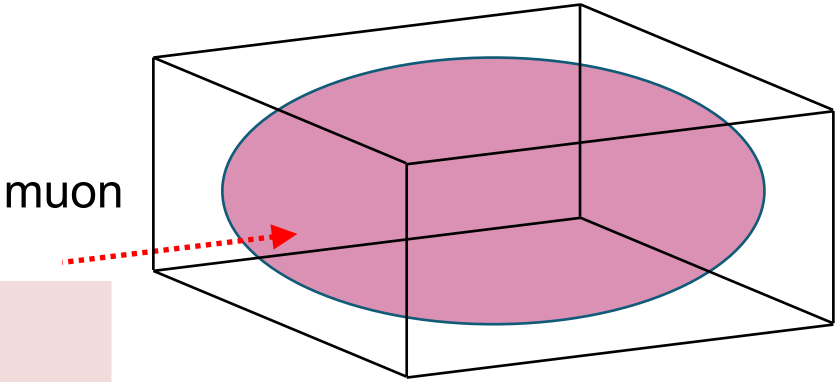
WbLS Basic Performance

Separating Cherenkov and scintillation:
shape, time, wavelength



Cherenkov
unique shape
early





Scintillation
isotropic
late

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WbLS R&D efforts at BNL

Chemical stability:

- Ensure **long-term optical clarity and uniformity** of WbLS mixtures across diverse environmental conditions.
- Validate **scalability** from a 1-ton detector to large-scale systems without compromising performance.

Electronic system:

- Development of **DAQ systems** for large-scale detectors.

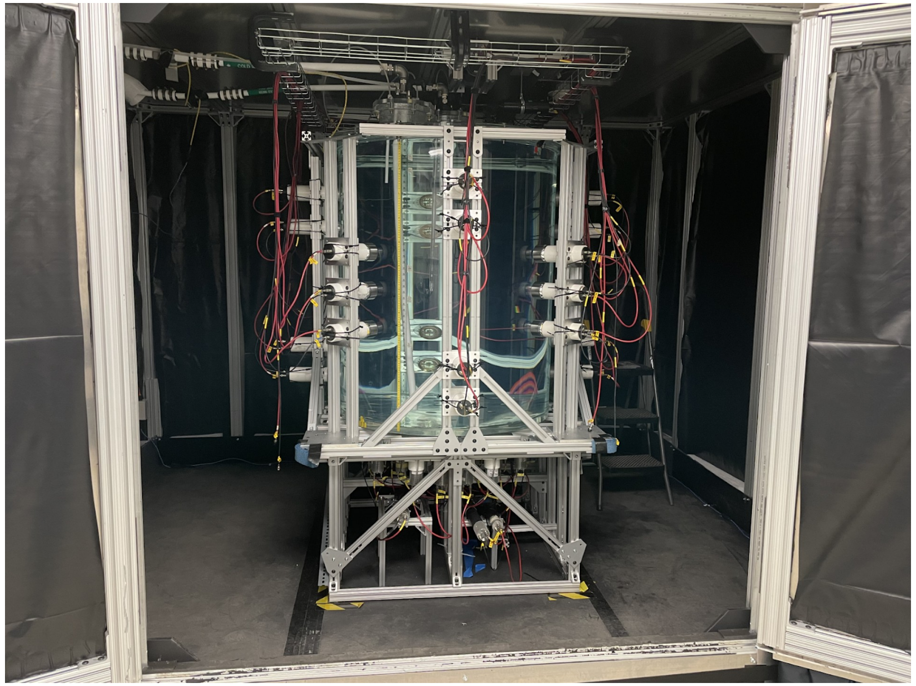
Benchmarking for **Future Experiments such as DUNE** phase2 FD4:

- Benchmark light yield, particle identification capabilities, and stability

Applications in **Nonproliferation**:

- Utilize WbLS for monitoring nuclear reactors

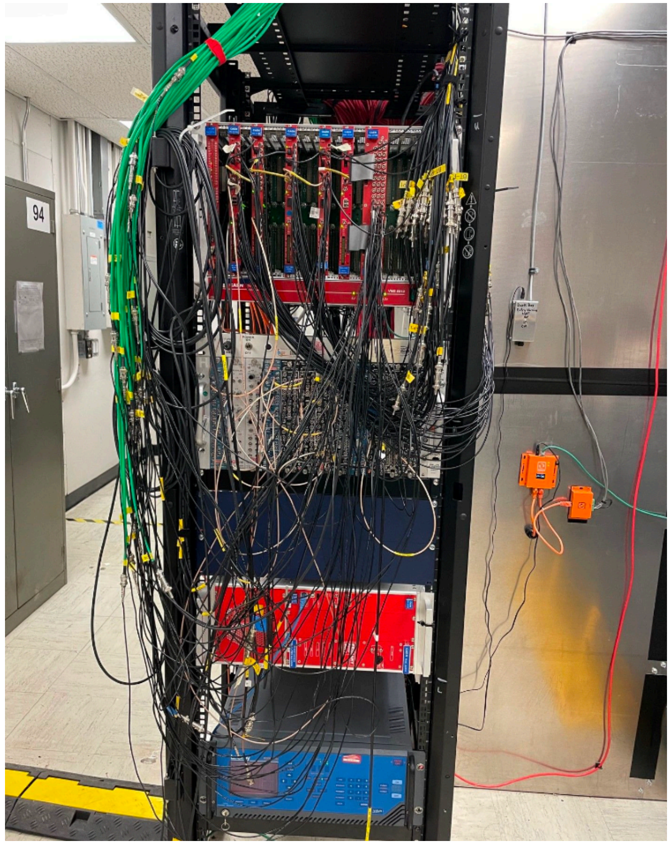
1 Ton Detector Setup



30 2'' PMTs on the bottom

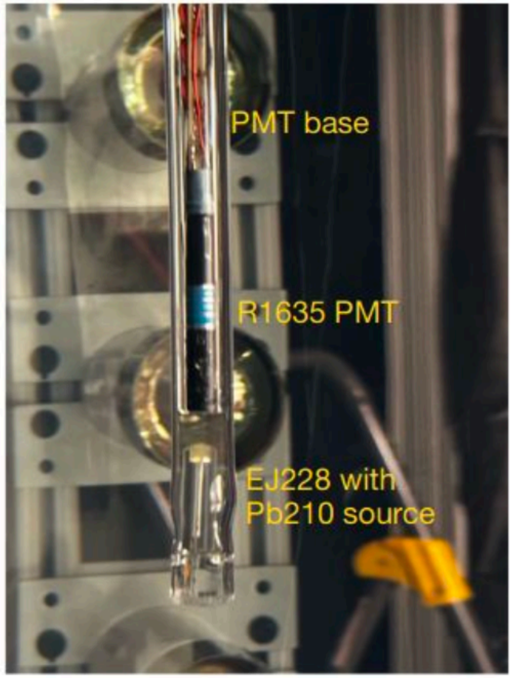
28 3'' PMTs on the side

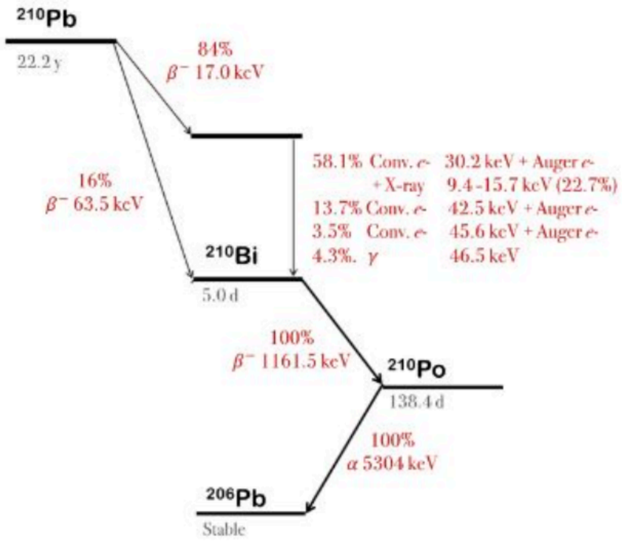
circulation and filteration system

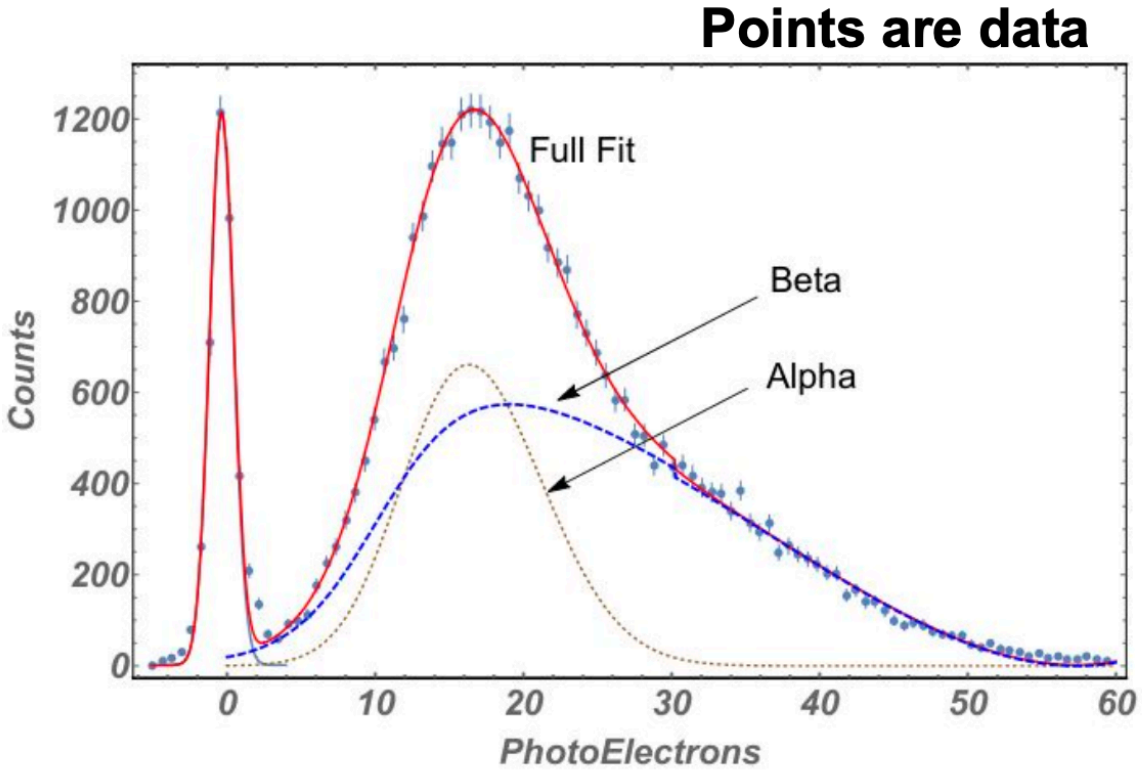


daq system

1 Ton Detector Calibration







^{210}Pb-based source embedded in a plastic scintillator, at the center of the detector.

The source provides continuous light for PMT gain verification.

Trigger Systems for the 1-Ton Detector

Scintillator top paddles:

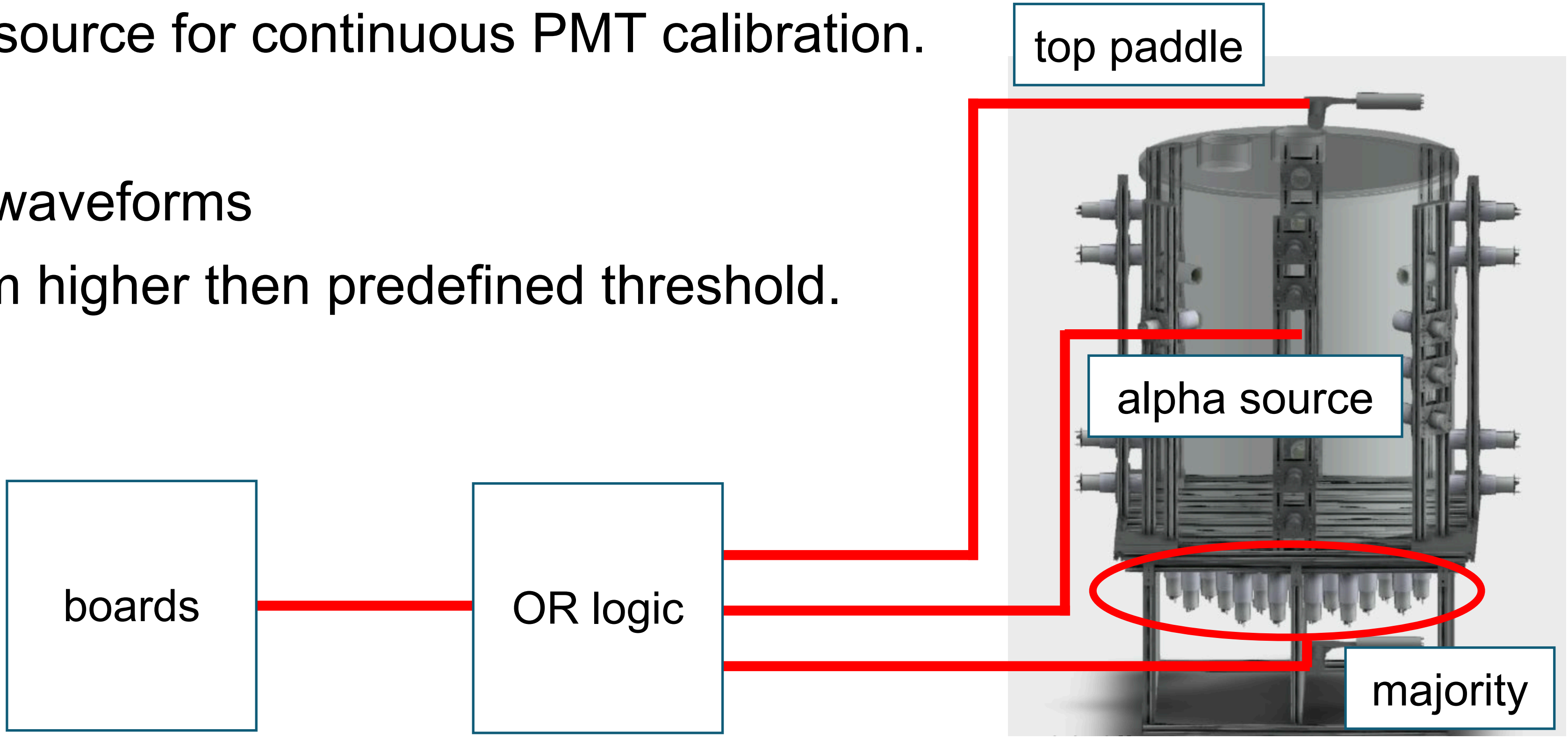
- Two rectangular paddles (10 cm × 12 cm) placed above the tank.

Alpha source trigger:

- Utilize the ^{210}Pb alpha source for continuous PMT calibration.

Majority trigger:

- Sum the bottom PMTs waveforms
- Triggered when the sum higher then predefined threshold.



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1 Ton Detector Analysis

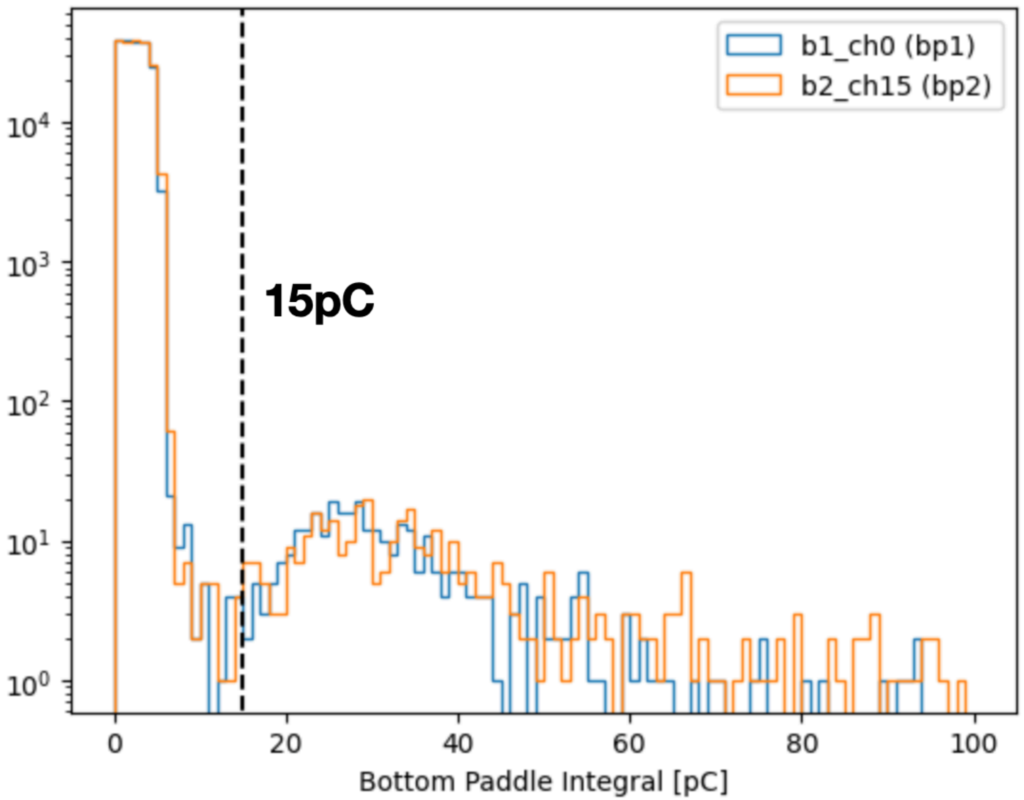
Crossing muon analysis:

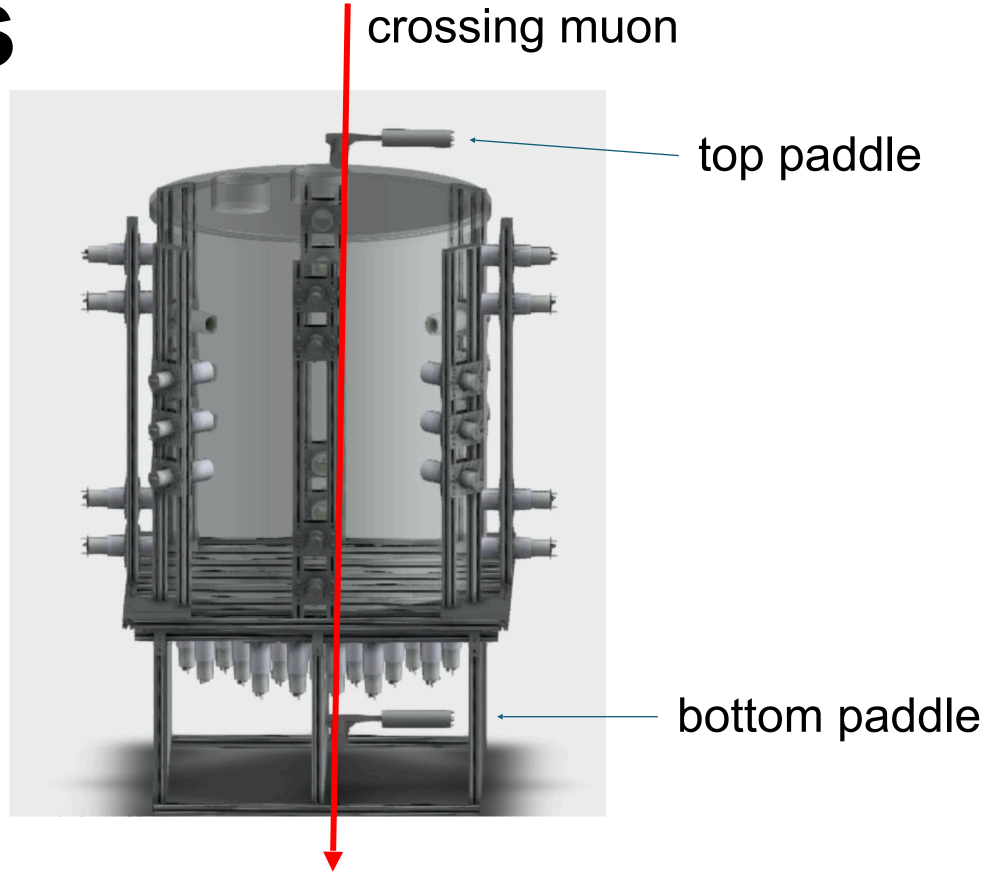
- Selecting vertically through going muon **minimize angular variation and ensure consistent energy deposition**.

Injection analysis:

- Majority triggered events are useful for analyzing the **detector's response during WbLS injection** due to the higher event rate.
- WbLS is injected gradually, starting from pure water, **increasing concentrations in small steps** (0.3%, 0.4%, up to 1%).
- Assess how WbLS concentration impacts light yield.

Crossing muon events

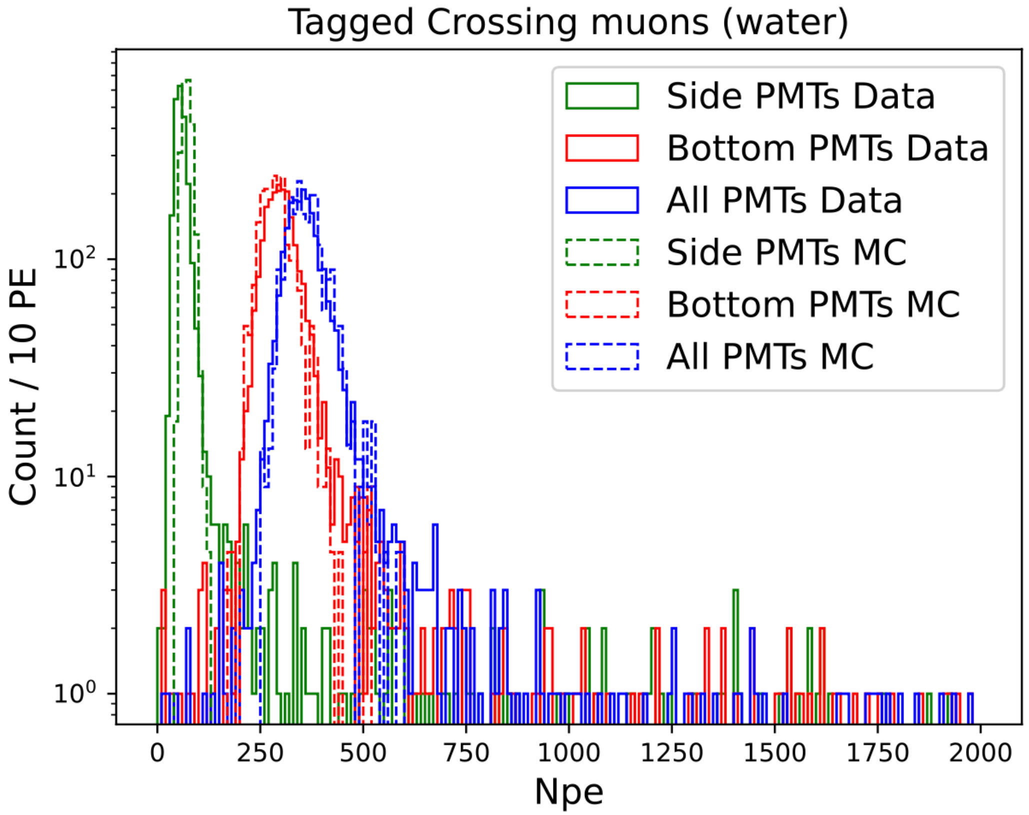


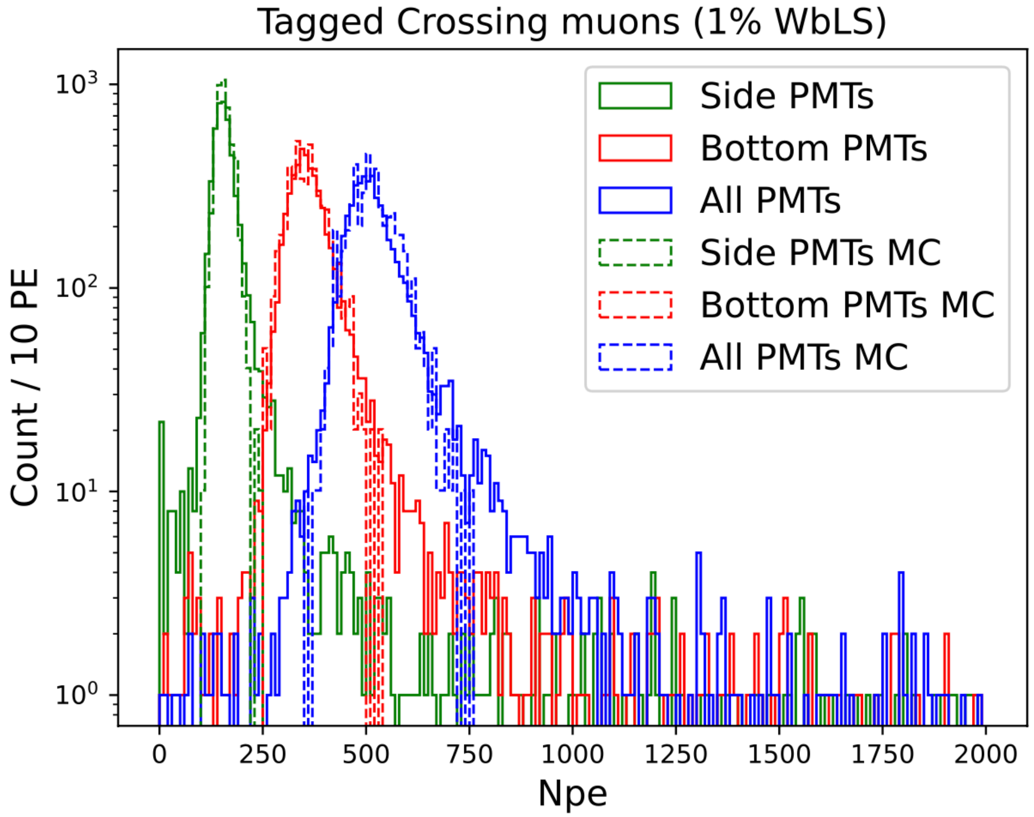


The crossing muon events are tagged by top and bottom scintillator paddles.

Restricts trajectories to vertical paths with minimal angular variation (< 8)

2022 Result





Cherenkov light (pure water): ~297 ± 37 PE (56 ± 13).

Total light yield (1% WbLS): ~350 ± 37 PE (154 ± 22).

Stepwise Injection of WbLS at 1 Ton

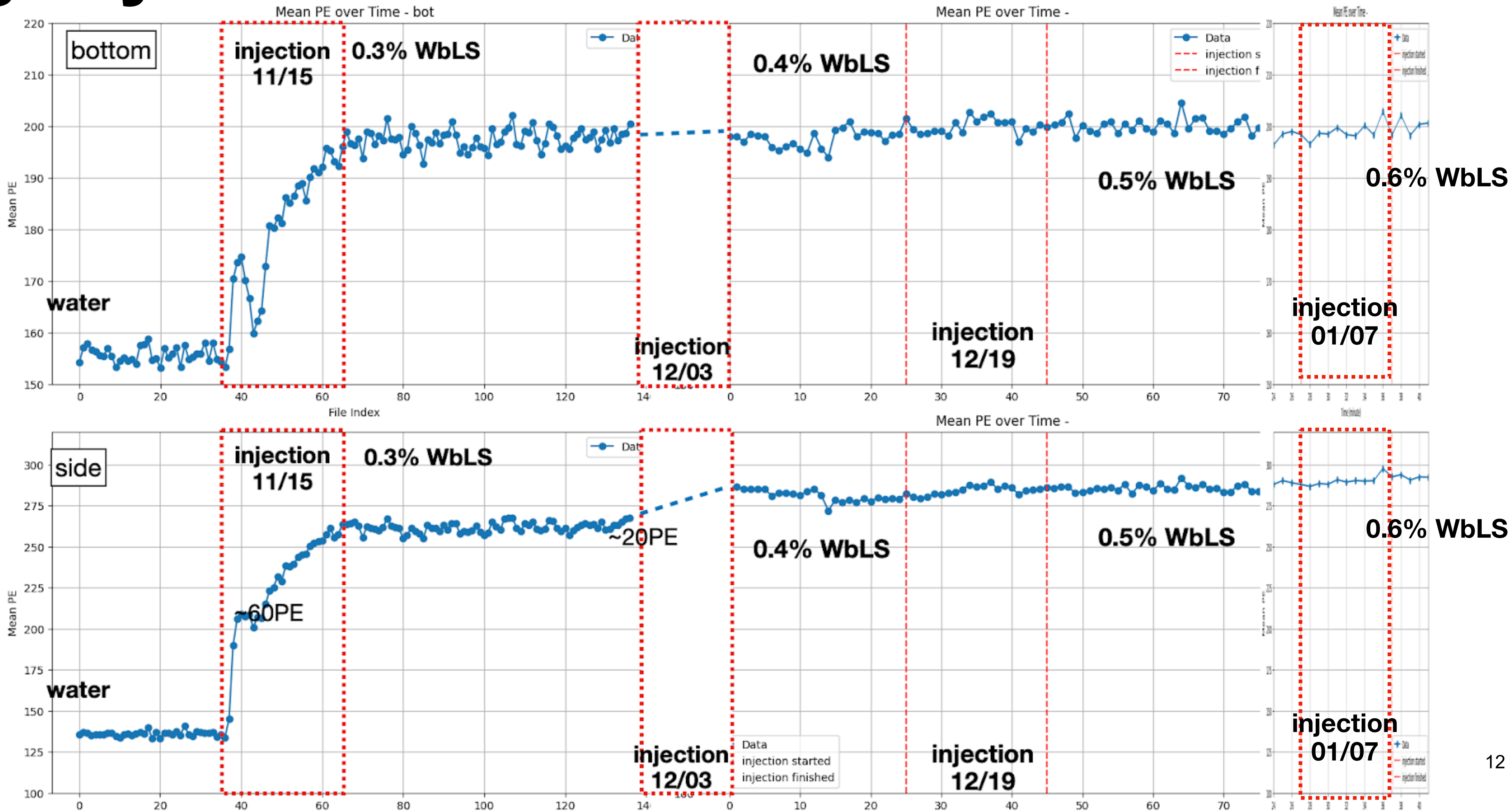
After the initial pure water phase, we began the injection of WbLS in **small, incremental steps**

The injection steps were as follows:

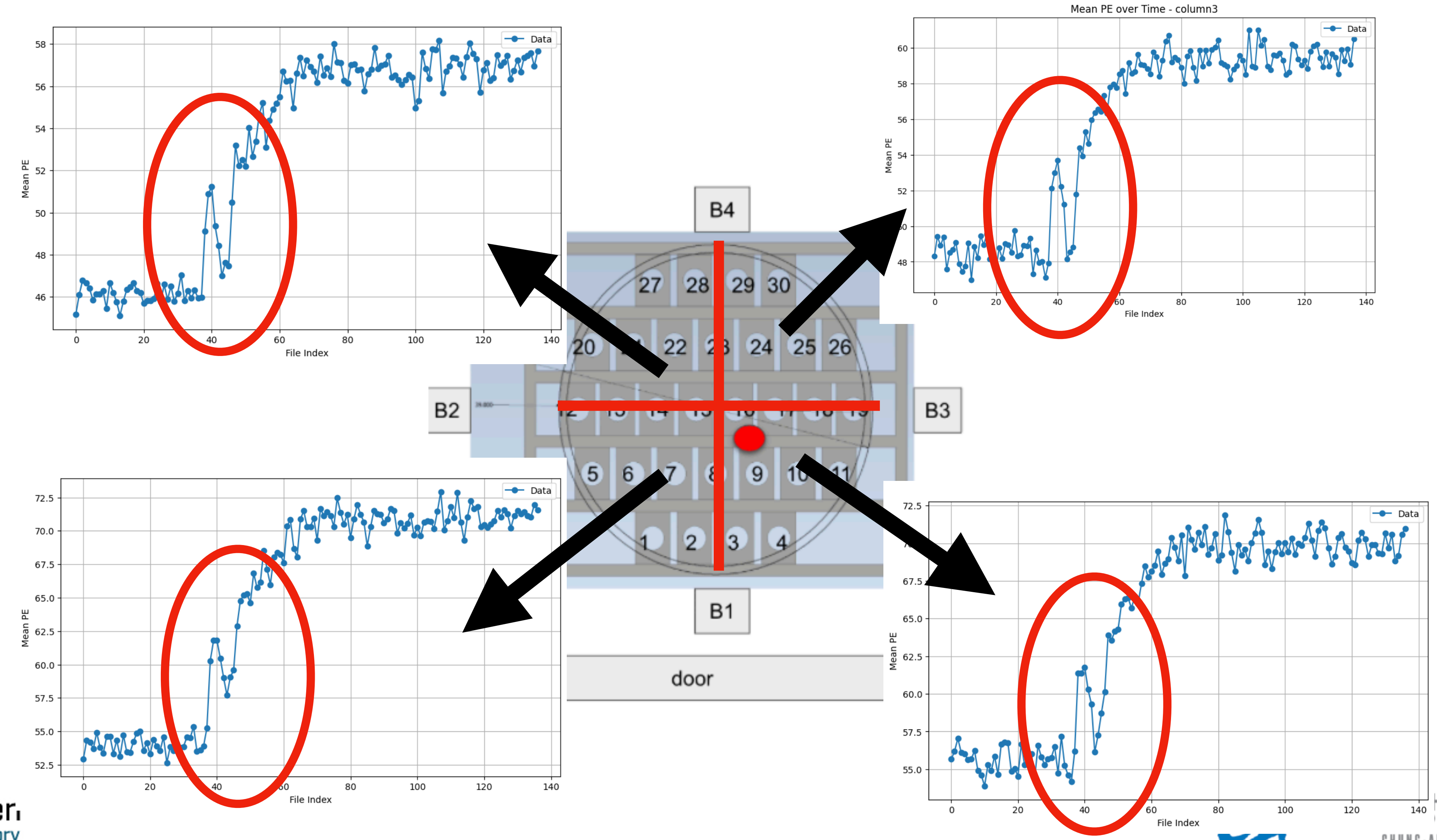
0% (Pure Water) → 0.3% → 0.4% → 0.5% → 0.6% (current phase) → 0.7% (next week) → 1% WbLS concentration.

The increase in **light yield is continuously monitored** during each injection step.

Light yield curve



WbLS Uniformity



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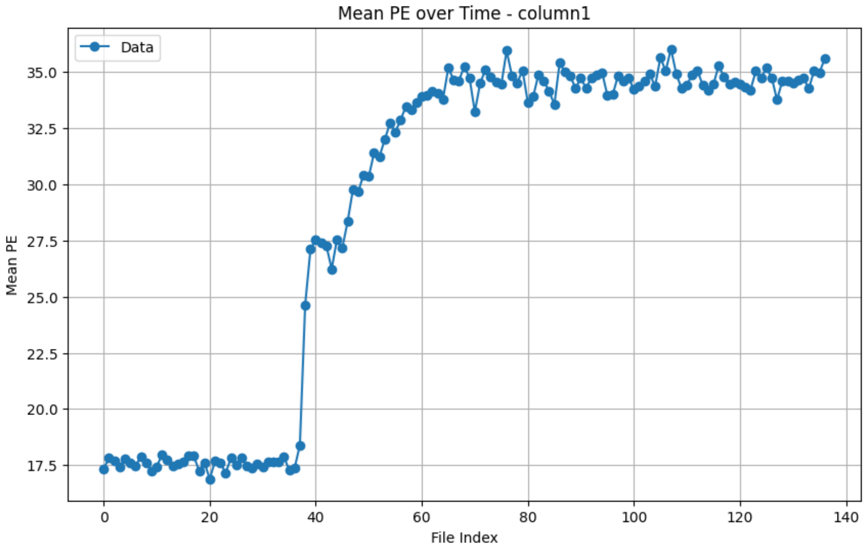
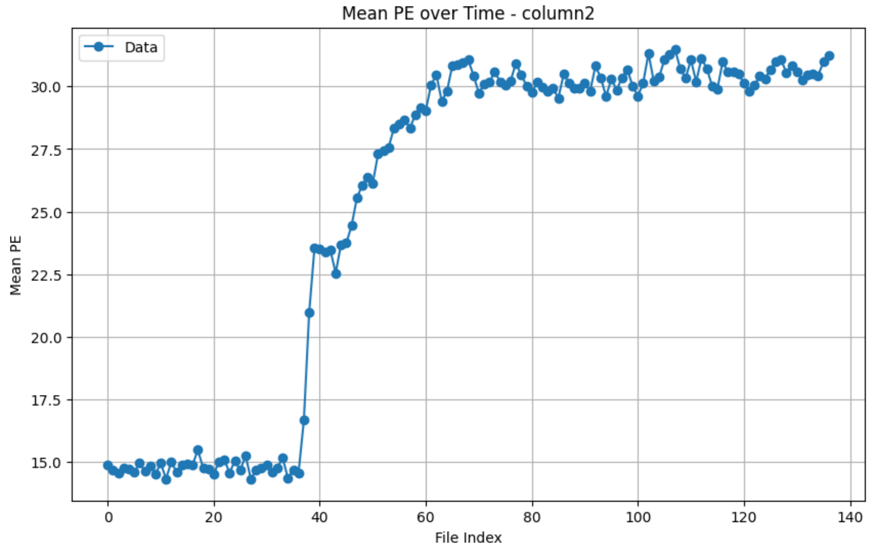
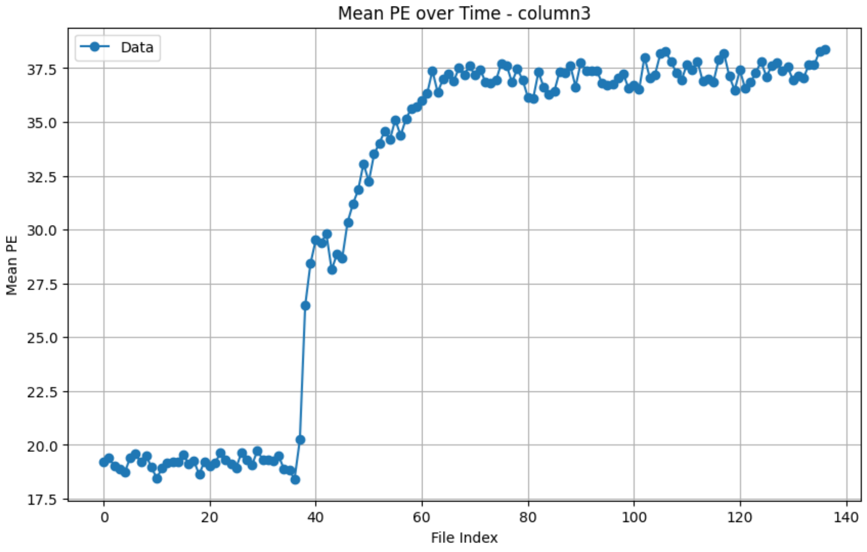
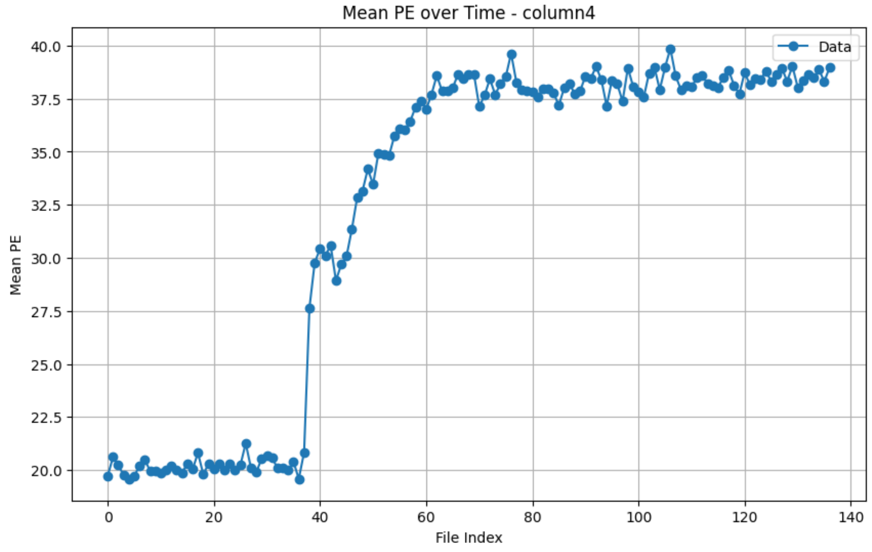
WbLS Uniformity









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Why a 30-Ton Detector is Needed

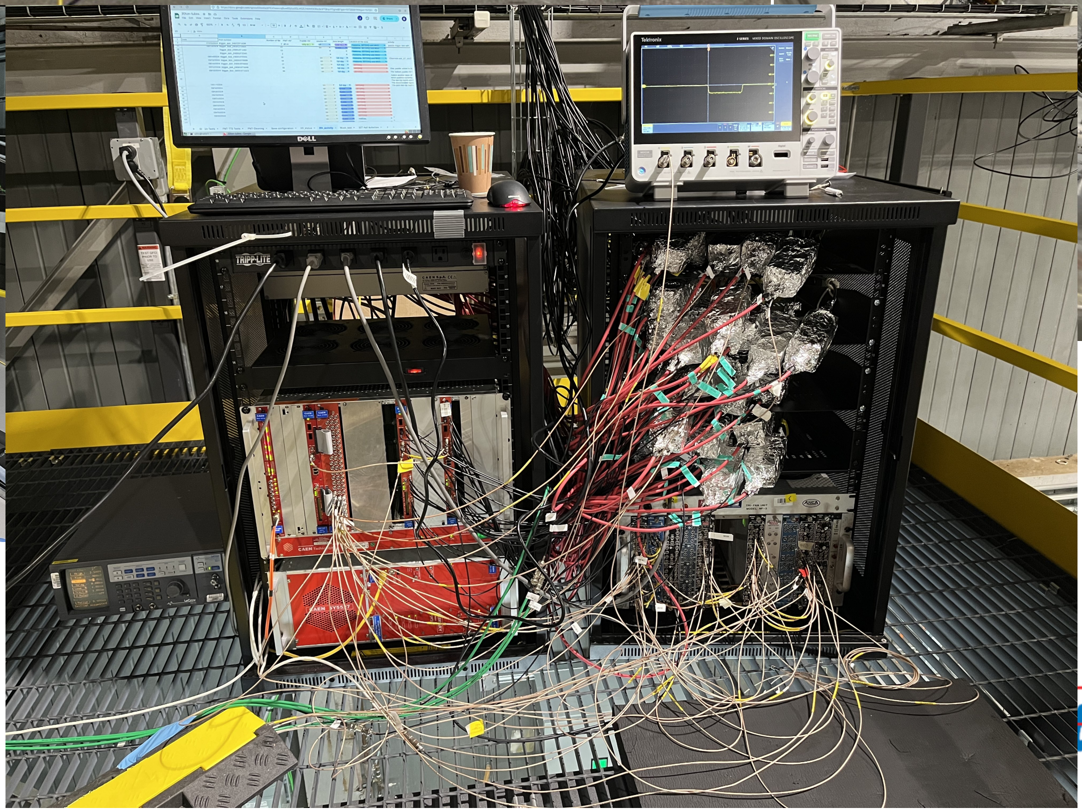
Technology Development for Detector Scaling:

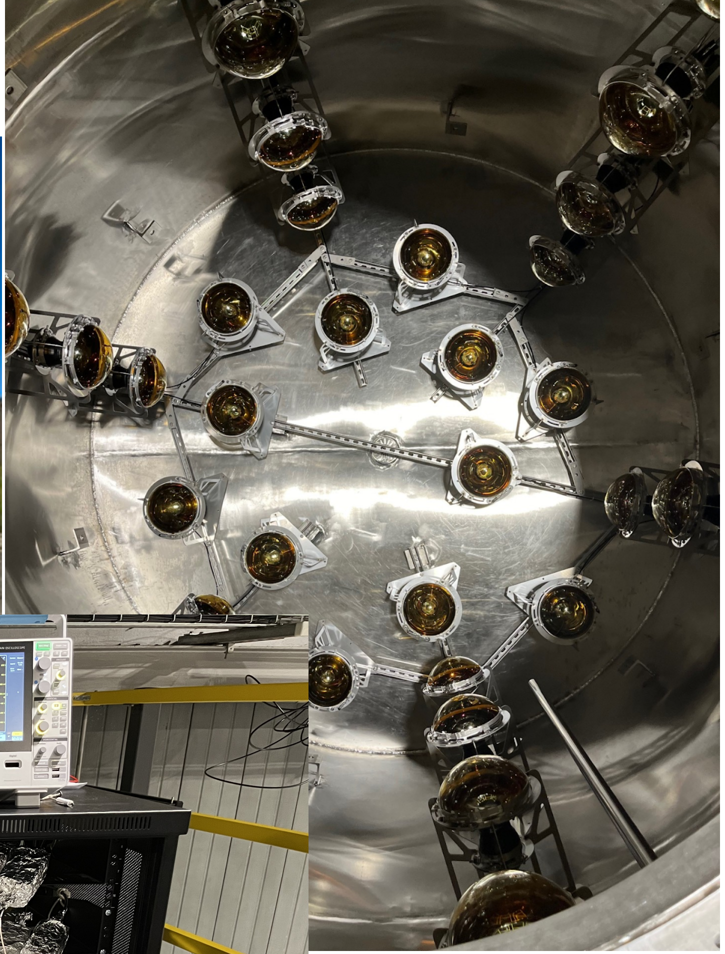
- **The 30-ton detector** provides a step in scaling up from the 1-ton prototype, enabling us **to test and refine systems**.
- **Develop infrastructure** efficient filtration, purification, circulation, and DAQ systems is required to ensure the homogeneity of the WbLS mixture, maintain long-term chemical and optical stability.

Future-Ready for Kiloton-Scale Detectors:

- The 30-ton detector serves as a **benchmark to test the feasibility** of scaling up to even larger detectors.

30 Ton Detector





Summary

WbLS enables **hybrid detection of Cherenkov and scintillation light**, improving sensitivity, directional reconstruction, and energy resolution for next-generation neutrino experiments.

The Previous study at 2022 demonstrated chemical stability and increased light yield.

We are studying light yield in detail along WbLS concentration by injecting small steps

The 30-ton detector serves as a **benchmark to test the feasibility** of scaling up to even larger detectors.

Back up

WbLS Motivation

Advancements in Neutrino Physics:

- Enables simultaneous detection of Cherenkov and scintillation signals.
- Improves directional reconstruction, energy resolution, and sensitivity to low-energy neutrinos.

Feasibility for Large-Scale Detectors:

- Cost-effective and environmentally friendly alternative for kiloton-scale hybrid detectors.

Capability for Metal Loading:

- Supports Gd doping for neutron capture and broader scientific applications.

WbLS Advantages

Signal Quality and Flexibility:

- Tunable scintillation light yield and time profile for specific applications.
- Maintains long-term optical stability for large-scale experiments.

Enhanced Particle Identification:

- Cherenkov/scintillation separation improves background rejection and particle ID.

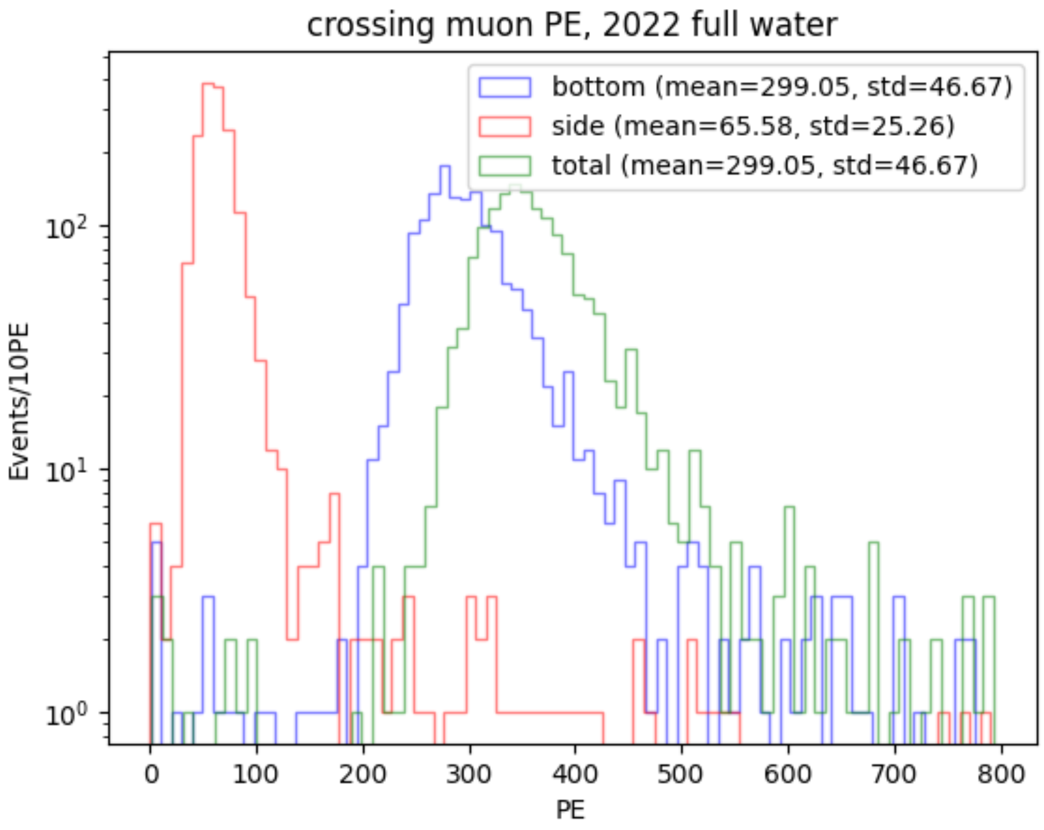
Economic Efficiency:

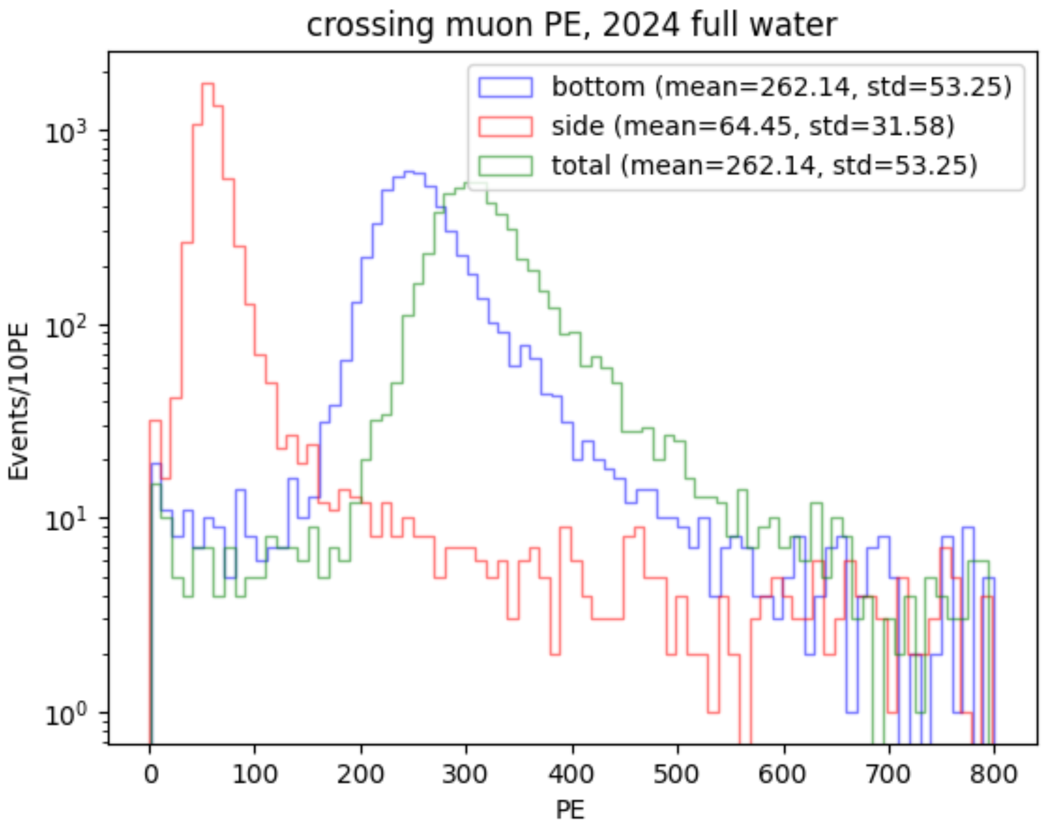
- Water-based composition reduces cost and simplifies production processes.

Optical Transparency and Durability:

- Stable across various temperatures and pH levels, ensuring longevity and reliability.

Water phase


crossing muon PE, 2022 full water
bottom (mean=299.05, std=46.67)
side (mean=65.58, std=25.26)
total (mean=299.05, std=46.67)
Events/10PE
PE
0
100
200
300
400
500
600
700
800
10^0
10^1
10^2


crossing muon PE, 2024 full water
bottom (mean=262.14, std=53.25)
side (mean=64.45, std=31.58)
total (mean=262.14, std=53.25)
Events/10PE
PE
0
100
200
300
400
500
600
700
800
10^0
10^1
10^2
10^3

Simulation setup

RATPAC is used to simulate crossing muon

RATPAC is a simulation package built with GEANT4, ROOT
- physics processes of muon energy deposition
- physics model for Cherenkov light in pure water and acrylic
- optical model for light generation, propagation and light detection

1T detector geometry contains
- acrylic tank
- realistic PMTs

Side PMT PE table

	Water	0.3% WbLS	0.3% WbLS (LY = 0)	0.4% WbLS	0.5% WbLS	0.6% WbLS
data gaussian mean	50.4412 ± 12.5835	123.758 ± 20.8173		130.292 ± 21.739	130.7 ± 21.9	136.951 ± 23.306
data truncated mean	52.07	130.465		134.932	135.768	140.157
MC	64.1155 ± 16.0185	201.311 ± 23.8523	184.274 ± 23.109	207.46 ± 24.0605	213.5 ± 24.9	
data/MC	78%	61%	67%	63%	61%	

bottom PMT PE table

	Water	0.3% WbLS	0.3% WbLS (LY = 0)	0.4% WbLS	0.5% WbLS	0.6% WbLS
data gaussian mean	239.142 ± 36.8306	298.211 ± 44.4736		298.009 ± 38.3124	298.2 ± 40.9	301.912 ± 42.9854
data truncated mean	255.254	299.572		301.963	301.283	304.624
MC	325.79 ± 45.189	426.581 ± 50.8481	409.59 ± 48.8284	429.227 ± 48.0014	435.8 ± 49.1	
data/MC	73%	68%	70%	69%	68%	