Water Based Liquid Scintillator R&D - BNL 30T Demonstrator

Ryan Wang

University of Alabama

Workshop on Hybrid Cherenkov/Scintillation Detection Technique

On behalf of WbLS team

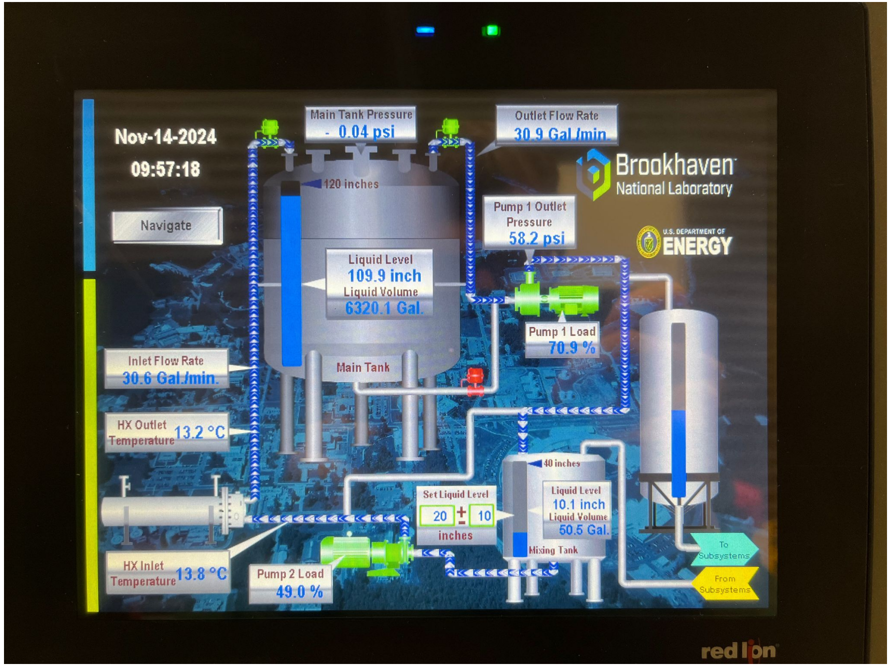
BNL WbLS R&D Program

- **BNL 30T Demonstrator**
  A stainless steel tank holding 30 tons of pure water or water-based liquid scintillator (WbLS), instrumented with thirty-six 10-inch Hamamatsu R16367-100-70 photomultiplier tubes (PMTs) fully submerged in the liquid.
  Commissioning began in summer 2024.

- **Goals:**
  - Assess long-term stability of the system and detector medium
  - Test the full capacity of the circulation and filtration systems
  - Monitoring the optical properties of WbLS
  - Evaluate neutron capture performance in Gd-loaded WbLS

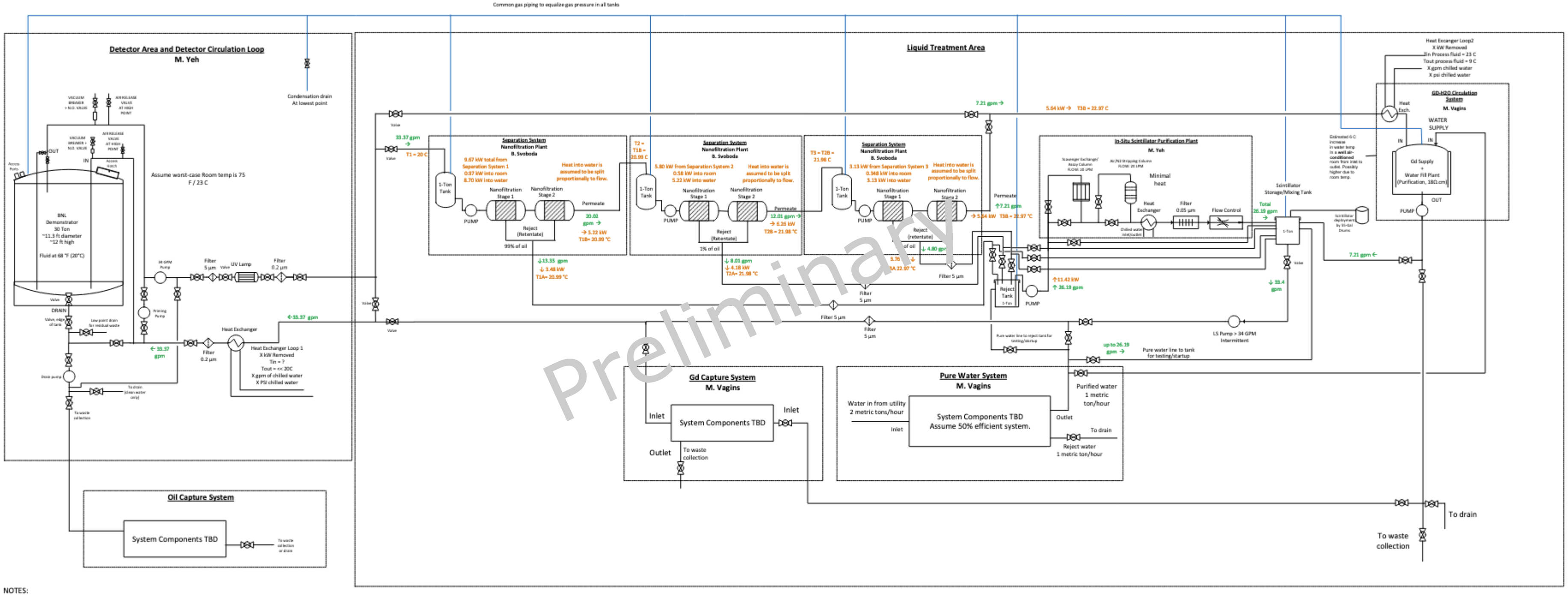
Circulation and online control system

- Ultrapure- water circulation system, nanofiltration and Gd-water treatment tank enable in-situ purification.
- A Programmable Logic Controller (PLC) monitors process variables and provides control outputs to maintain the process parameters
  - The PLC also transmits process variable data for logging, post processing and analysis as well as real time and historical data visualization on a Human Machine Interface (HMI) system for the users/ operators of the detector
- Optimize operational parameters based on physics-driven requirements



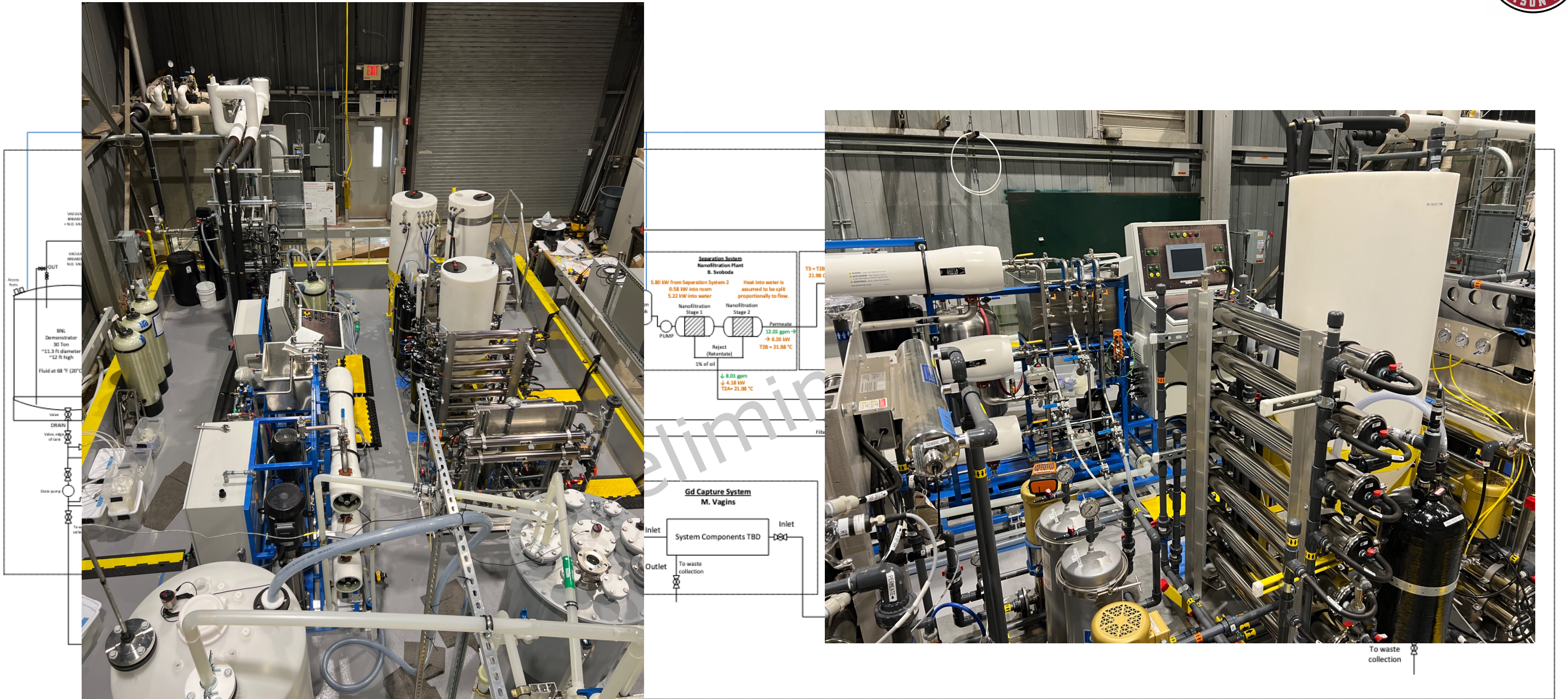
Liquid Purification system parameter will be optimized in 30 T demonstrator!

WbLS Circulation System



NOTES:
1. All tanks must have a vacuum breaker and pressure relief valve.
2. All tanks must have their gas spaces connected so that pressure is equalized among all tanks.

Circulation



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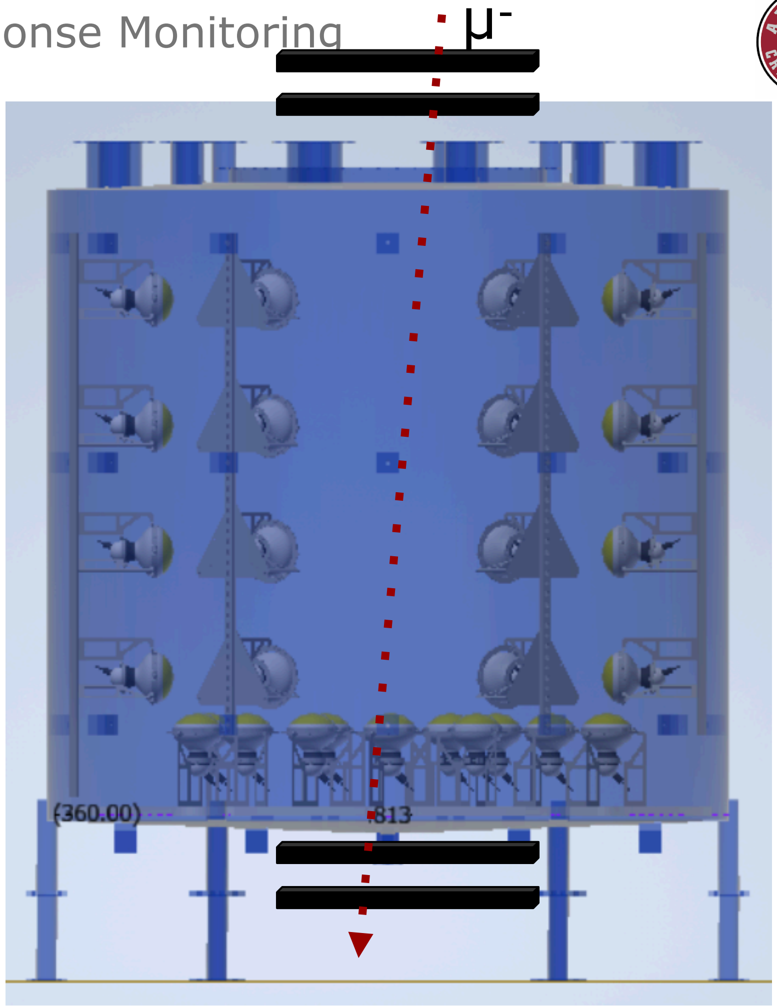
Muon Tagging and Light Response Monitoring

- **Top/Bottom Panels:**
  Used to tag vertically crossing muons for stability monitoring.
- **Vertical Crossing Muons:**
  Enable characterization of light production and propagation through the detector.
- **Side PMTs:**
  - **Rows 1 & 2:** Primarily detect scintillation light with some reflected Cherenkov photons.
  - **Rows 3 & 4:** Detect both Cherenkov and scintillation light.
- **Bottom PMTs:**
  Detect a mix of Cherenkov and scintillation light from through-going muons.
- **Trigger Logic:**
  - **Primary Trigger:** Coincidence between the top two layers of paddle detectors plus a majority logic requirement.
  - **Crossing Muon Tag:** Requires additional coincidence with the bottom two paddle layers.



BNL 30T Demonstrator

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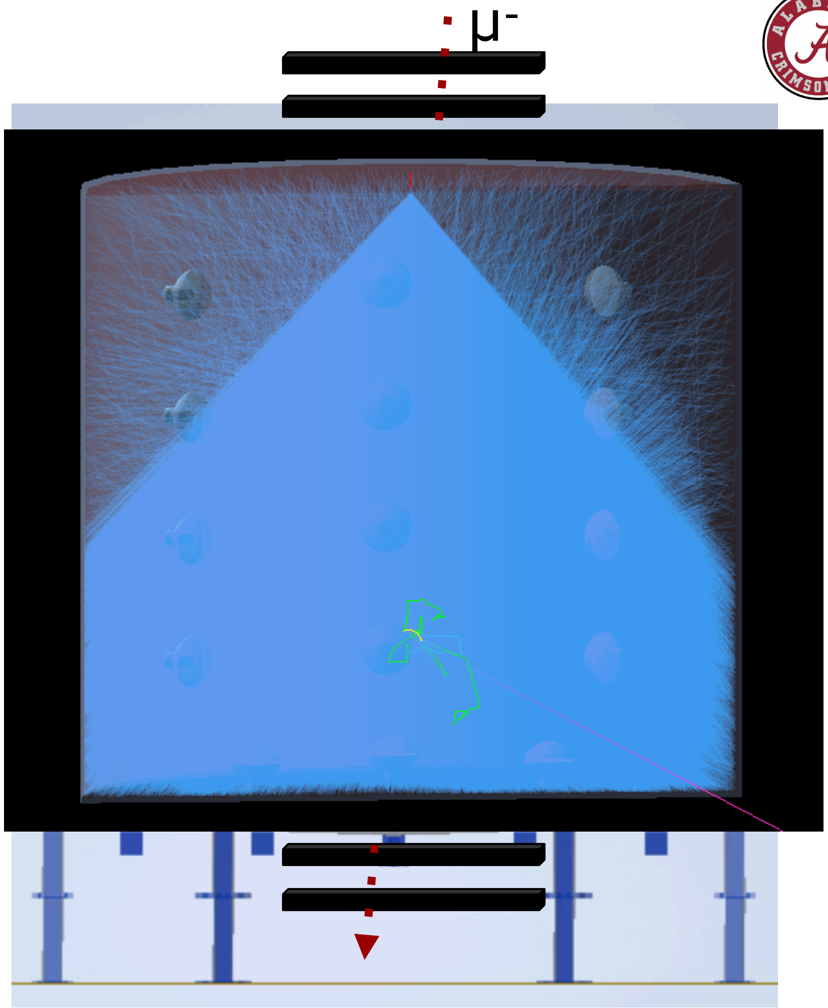
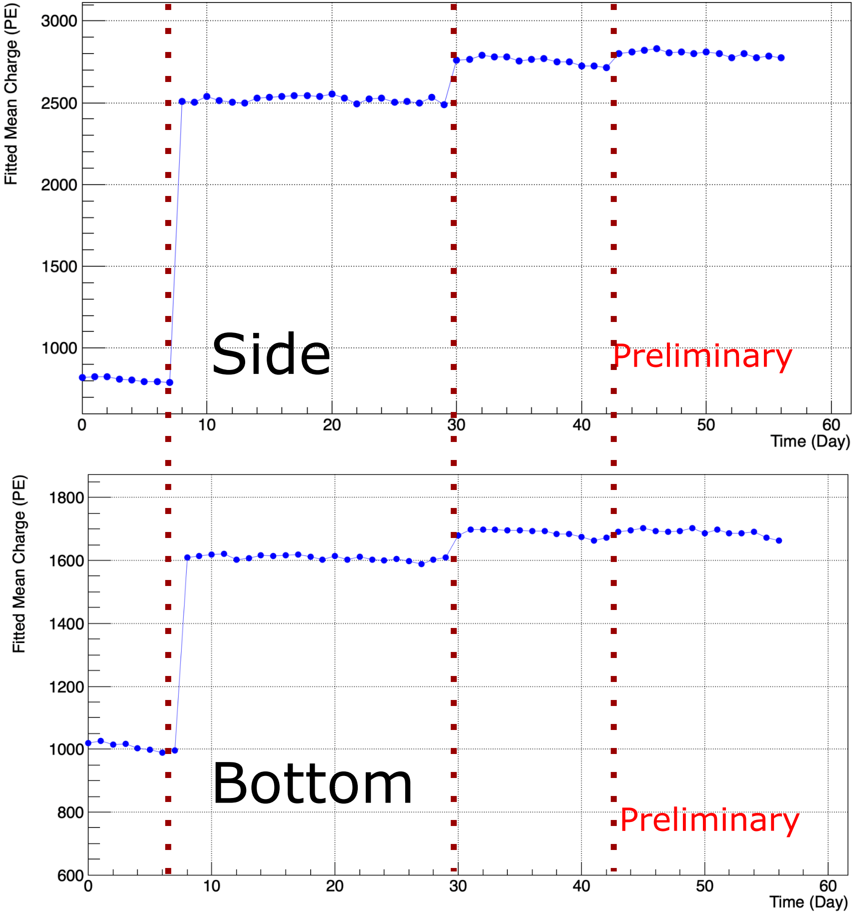
- **Monte Carlo simulation:**
  - Rac-PAC 2 for full detector simulation
    - Work in Progress



Light production from crossing muons

- Three injections
  - Pure water to 0.35% on April 1st
  - 0.35% to 0.7% on April 23rd
  - 0.35% to 1% on May 7th
- Significant gain of light yield in the first injection
- Increased light yield in the subsequent injections, data suggest the saturation of Cherenkov light conversion, further detail study is underway



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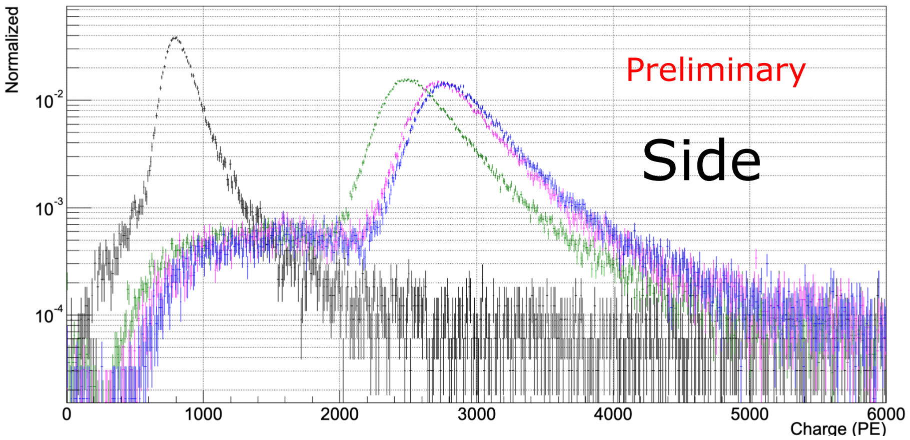

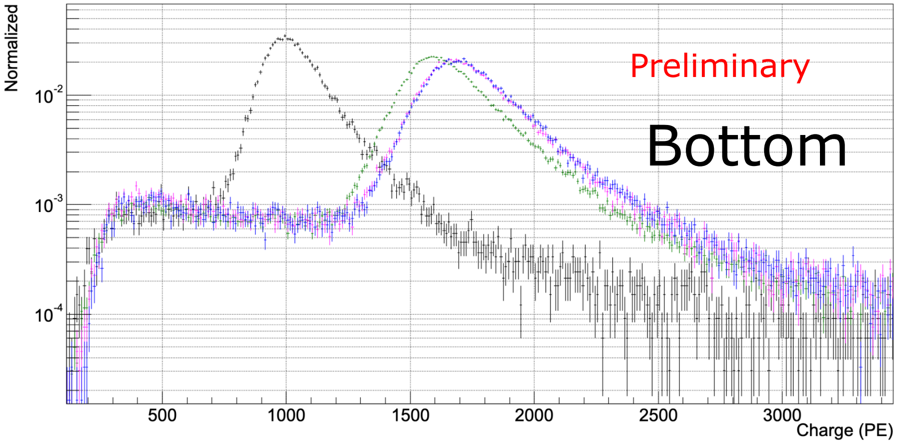

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  - Pure water to 0.35% on April 1st
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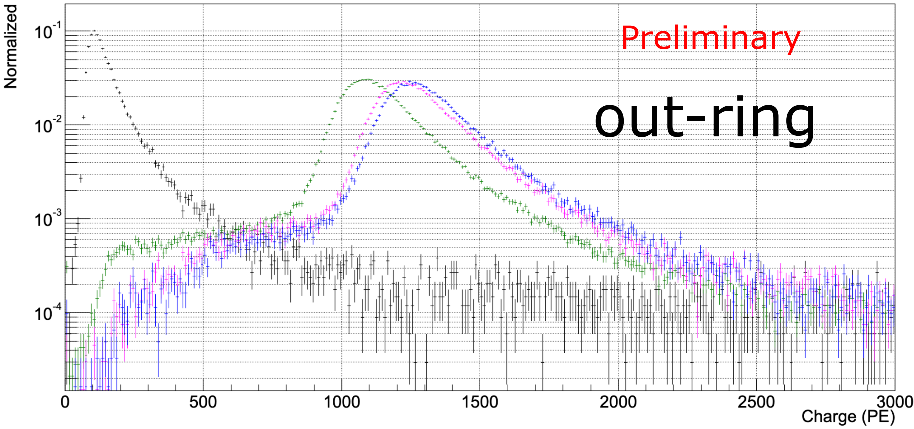
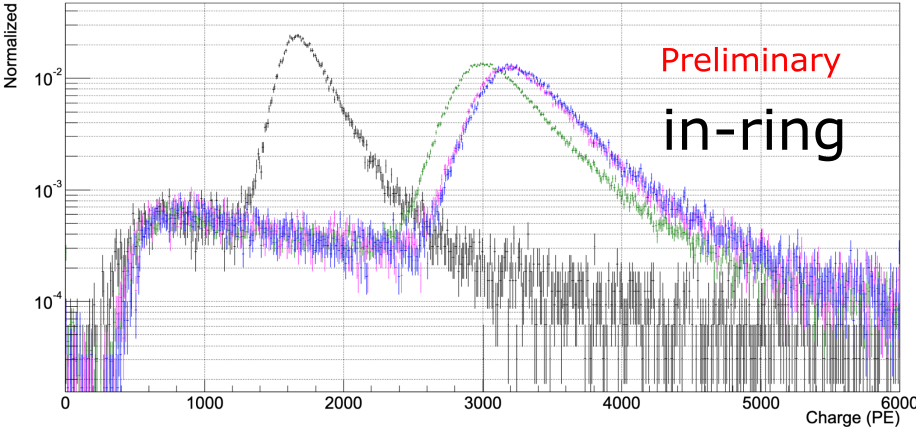
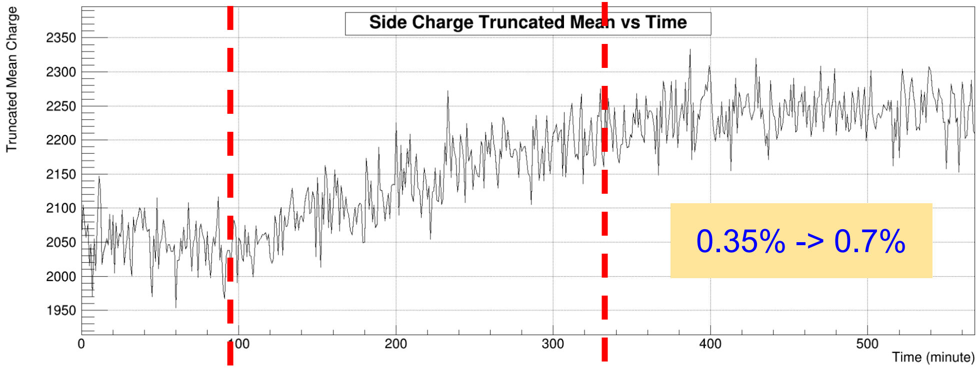
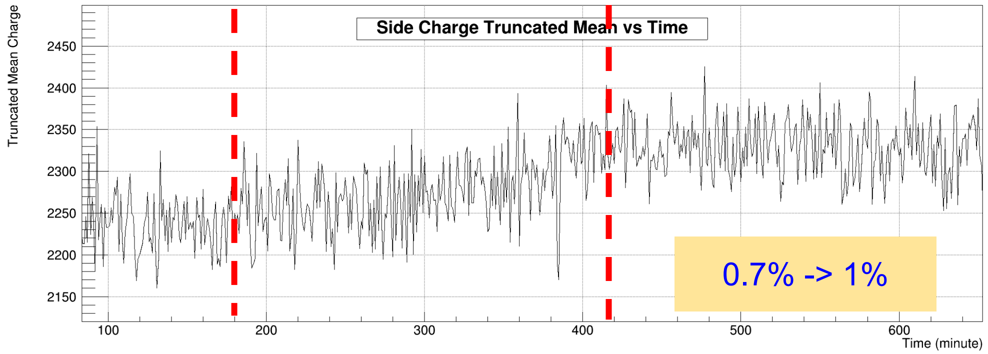
  - 0.35% to 1% on May 7th
- Out-ring: Top two row of side PMTs which are outside the Cherenkov ring
- In-ring: bottom two rows of side PMTs and bottom PMTs





- To observe the transitional behavior every minute, all muons (top paddles + Majority) is used to have enough statistics
- The sequential injection process demonstrated a smooth and consistent increase in light yield (each injection phase lasted 5 hours, marked by two dashed red lines in the time series plot). After the third injection, data suggested a possible saturation in Cherenkov-to-scintillation light conversion.
- Further analysis is ongoing to confirm saturation behavior and assess detector response stability.





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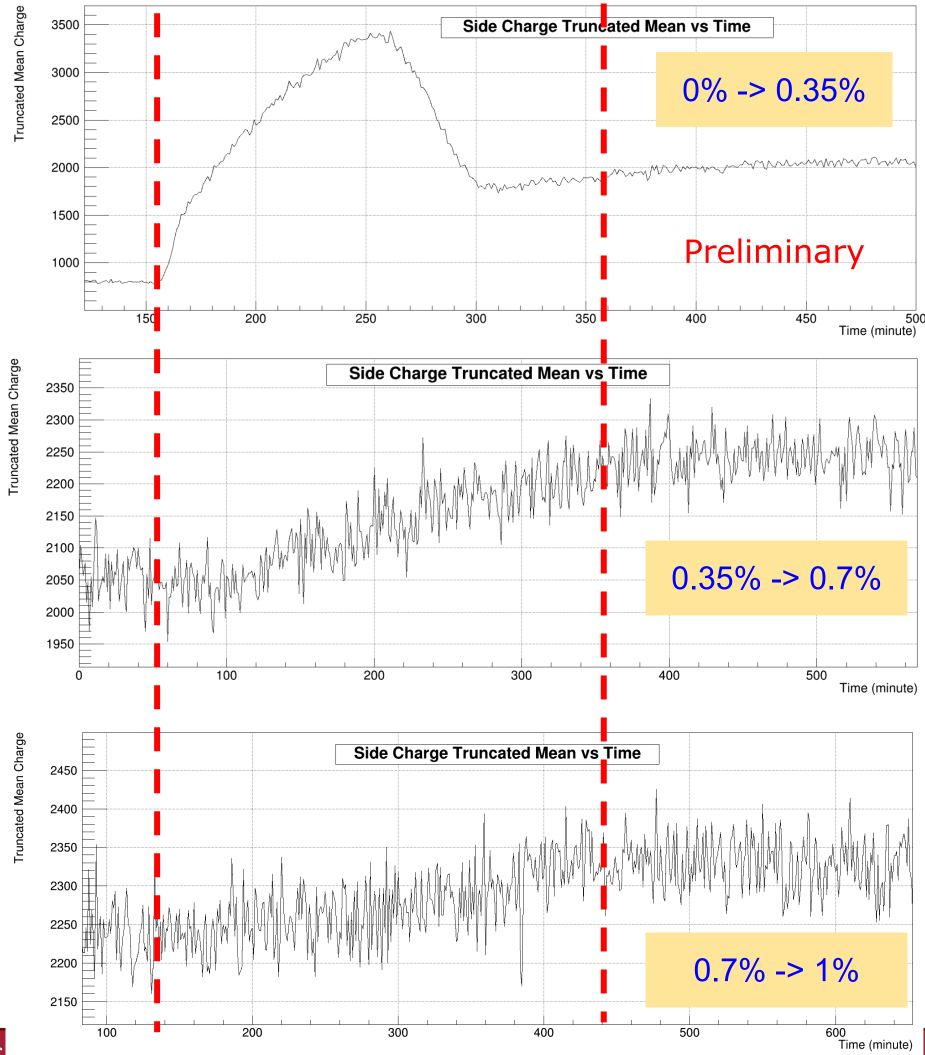
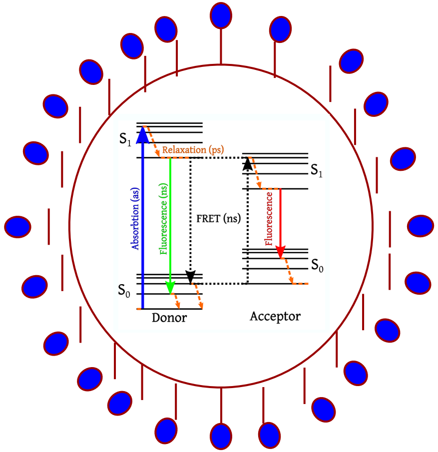
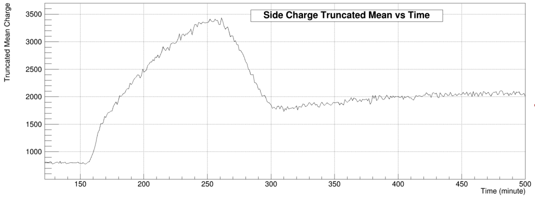
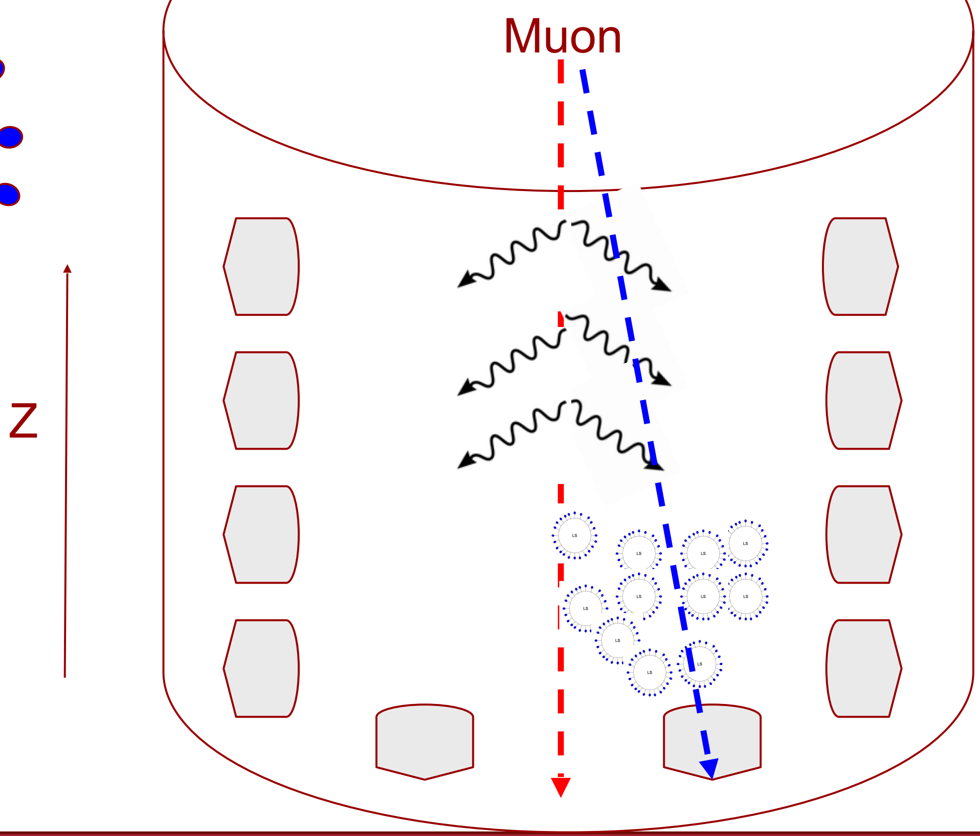




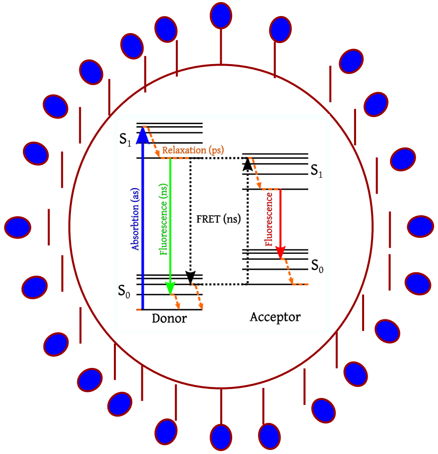


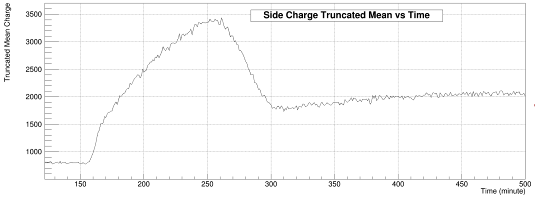


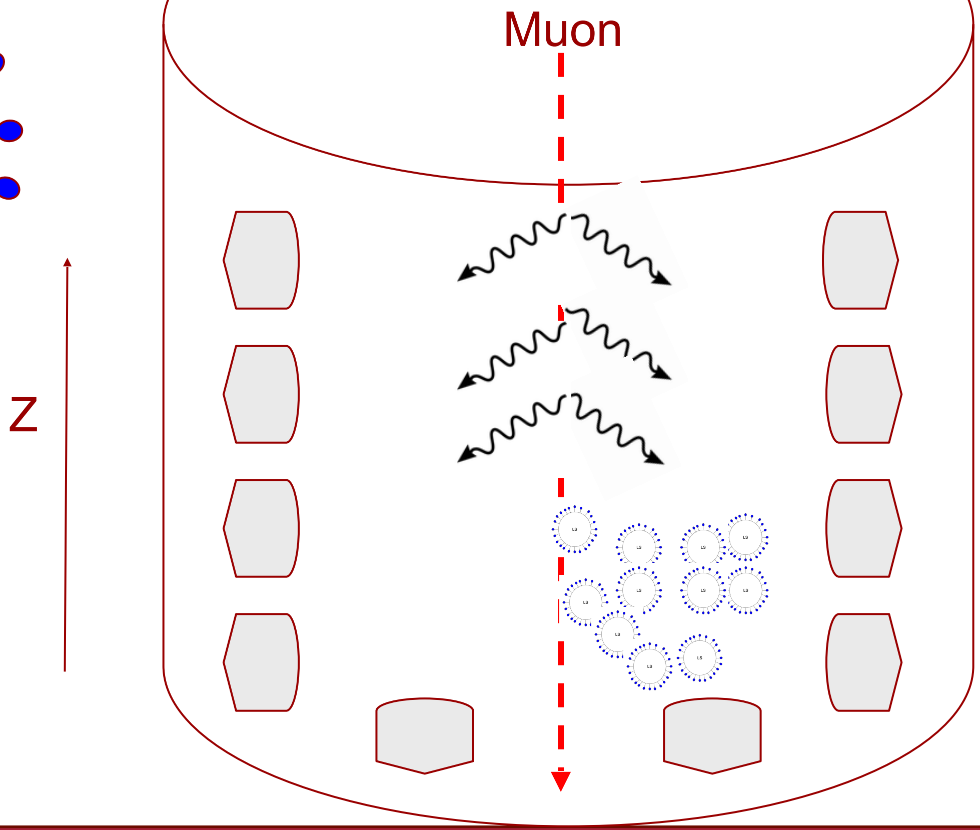
Trigger : Muons pass through two layers of top paddles & Majority trigger of bottom PMT

Which means if we have muons comes in, but without enough number of PMT fired, DAQ won't trigger on this event
This can be seen from the trigger rate per minute on the bottom left, when we start injection, we gain a component to convert cherenkov light into isotropic scintillation lights.

However, after a short period of time, we have enough LS micelle, which groups around a local region, they form somewhat a "optical boundary" with stronger scattering (ref)

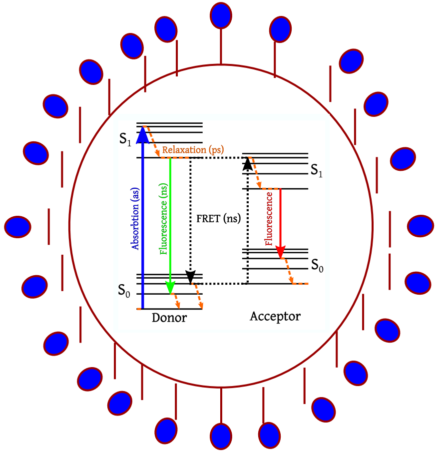


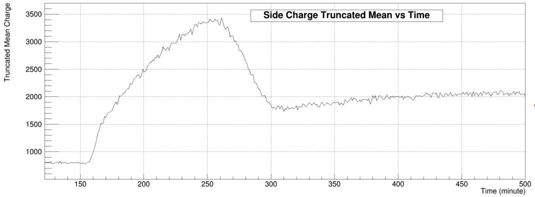


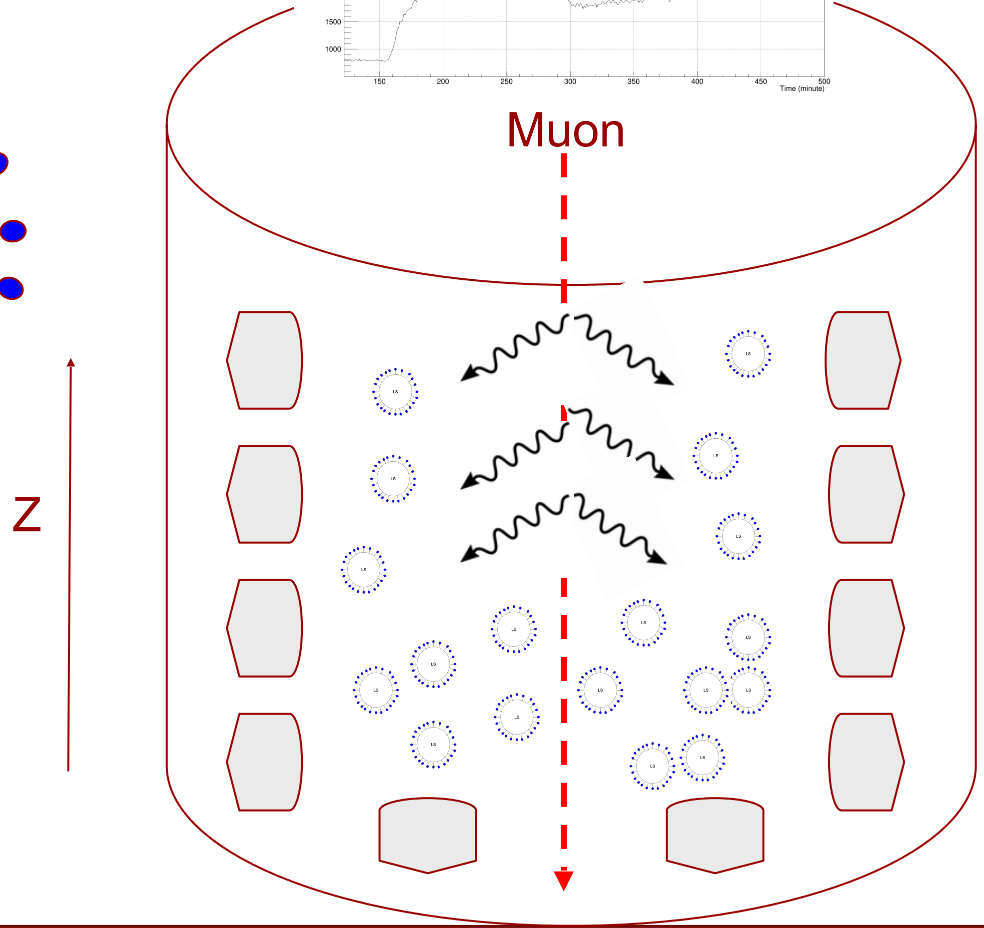


Trigger : Muons pass through two layers of top paddles & Majority trigger of bottom PMT

At that stage, the trigger rate drops because only muons that passing through that "optical boundary" region would produce sufficient light to trigger the system. For other muons, the chekenov light was scattered by "optical boundary" don't have enough bottom PMT fired to trigger the system.

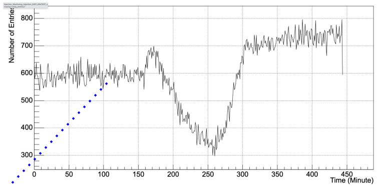


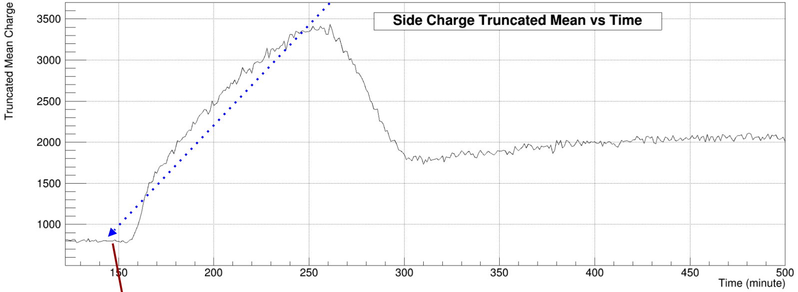




Trigger : Muons pass through two layers of top paddles & Majority trigger of bottom PMT

As these LS micelle diffuse further by circulation system, everything becomes more uniform and the trigger rate was restored to previous level and even higher due to the scintillation component from new LS micelles.


Number of Entries
800
700
600
500
400
300
0
50
100
150
200
250
300
350
400
450
Time (Minute)


Side Charge Truncated Mean vs Time
Truncated Mean Charge
3500
3000
2500
2000
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200
250
300
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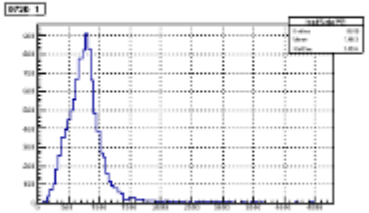
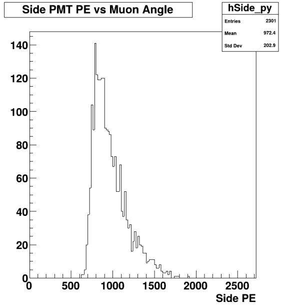
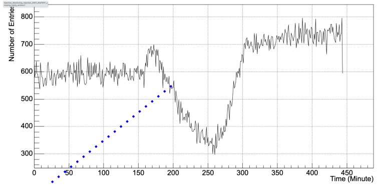
400
450
500
Time (minute)




Side PMT PE vs Muon Angle
hSide_py
Entries 2301
Mean 972.4
Std Dev 202.9
140
120
100
80
60
40
20
0
0
500
1000
1500
2000
2500
Side PE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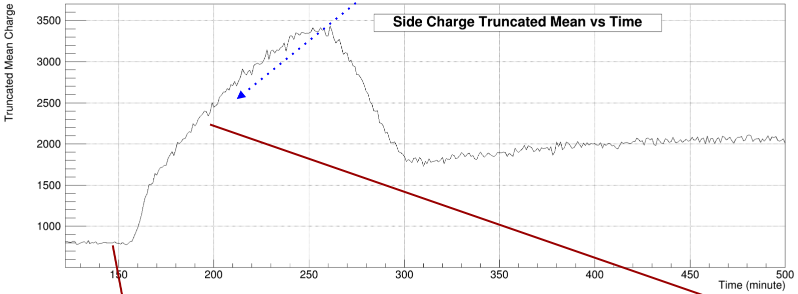
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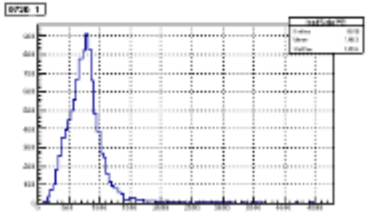

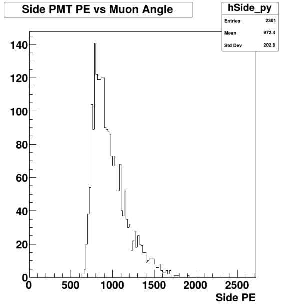
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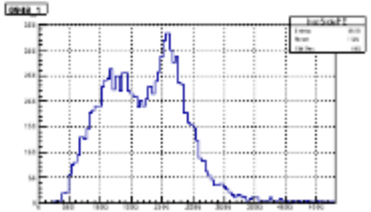
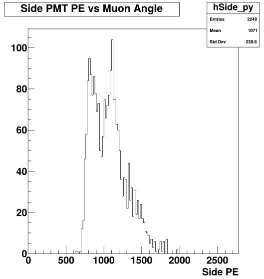
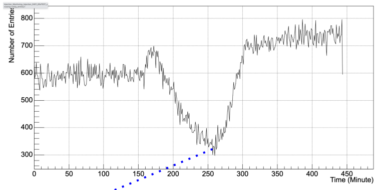



Side PMT PE vs Muon Angle
hSide_py
Entries 2249
Mean 1071
Std Dev 228.6
100
80
60
40
20
0
0
500
1000
1500
2000
2500
Side PE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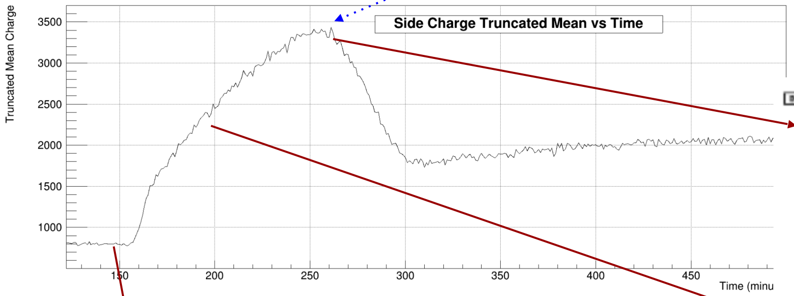
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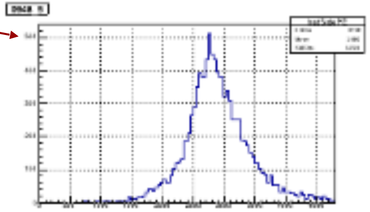

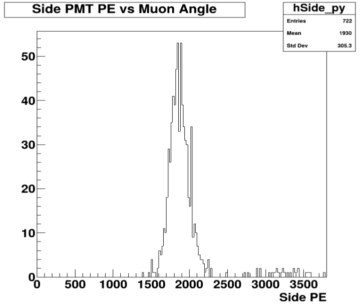
Side PMT PE vs Muon Angle
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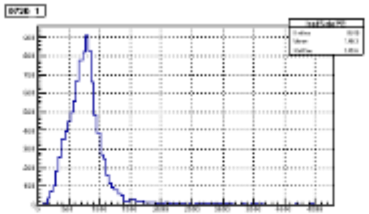
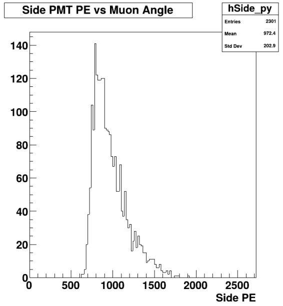
Entries 722
Mean 1930
Std Dev 305.3
50
40
30
20
10
0
0 500 1000 1500 2000 2500 3000 3500
Side PE

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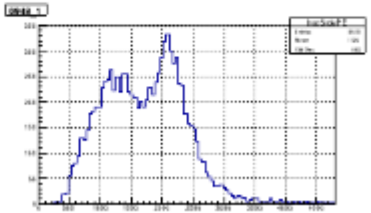

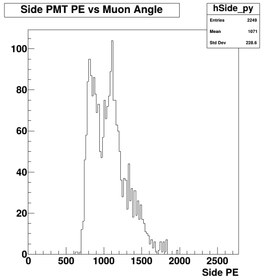
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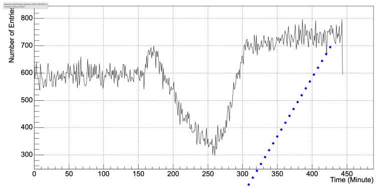
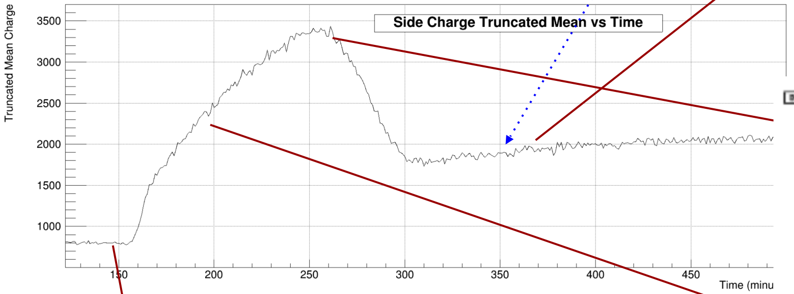
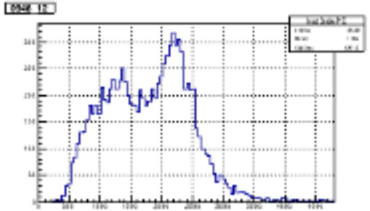
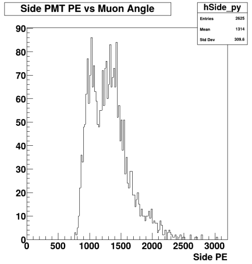
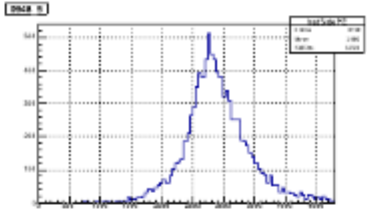
Side PE

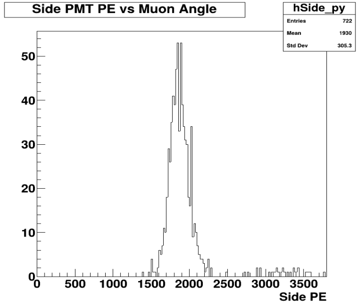

Number of Entries
Time (Minute)

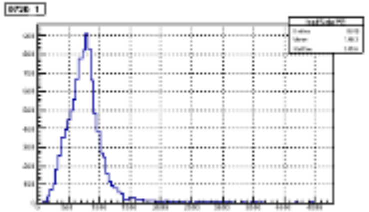

Side Charge Truncated Mean vs Time
Truncated Mean Charge
Time (minu

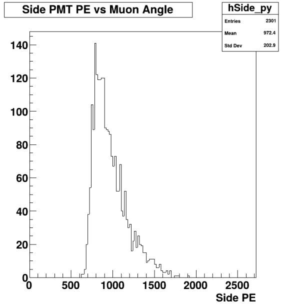



Side PMT PE vs Muon Angle
hSide_py
Entries 2625
Mean 1314
Std Dev 309.6
Side PE




Side PMT PE vs Muon Angle
hSide_py
Entries 722
Mean 1930
Std Dev 305.3
Side PE

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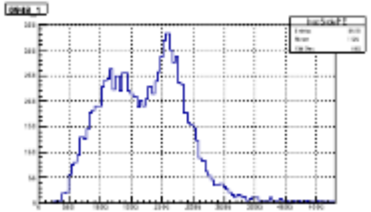

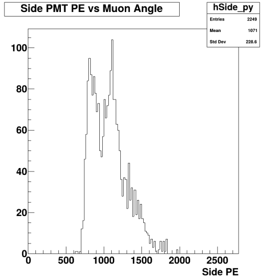
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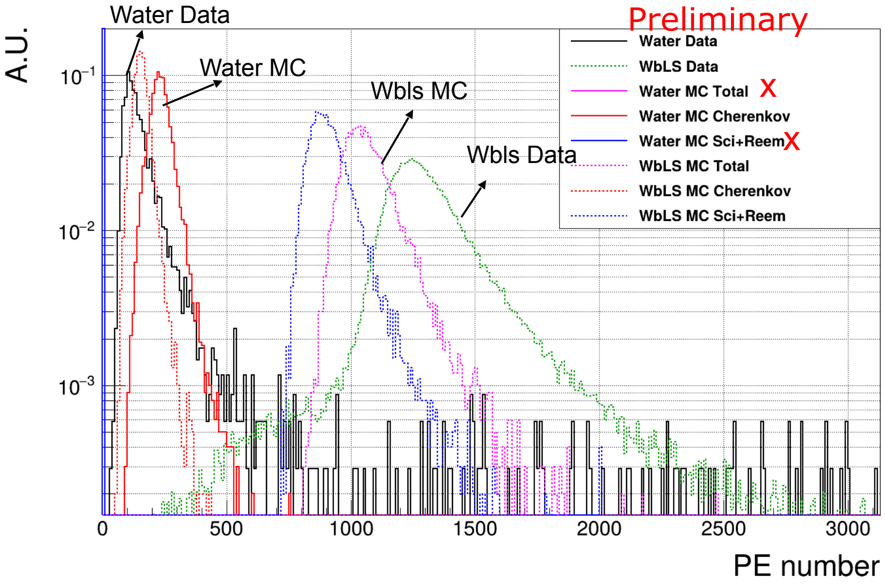
Side PE

30t light yield measurement - 1% WbLS

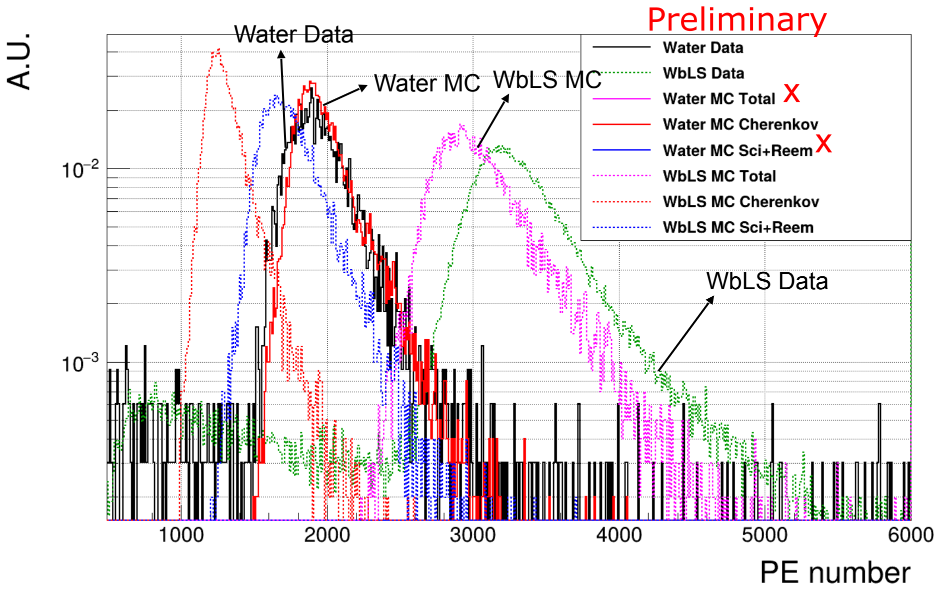
Top two row (out-ring)



Side PMT location corrected

More non-Cherenkov light in data than MC.

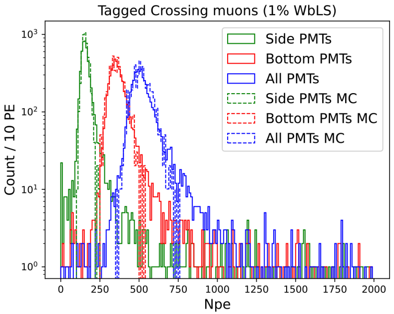
Bottom two row + bottom (in-ring)



Data shows lower light than MC with water.
Data shows higher light than MC with wbls.
More non-Cherenkov light in data than MC.

BNL WbLS Timeline

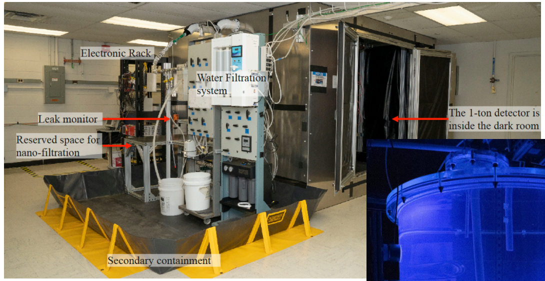
2021 2022 2023 2024 2025



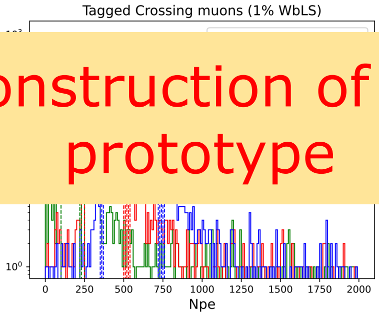
X. Xiang et al.

BNL WbLS Timeline

2021 2022 2023 2024 2025



Construction of 1T prototype



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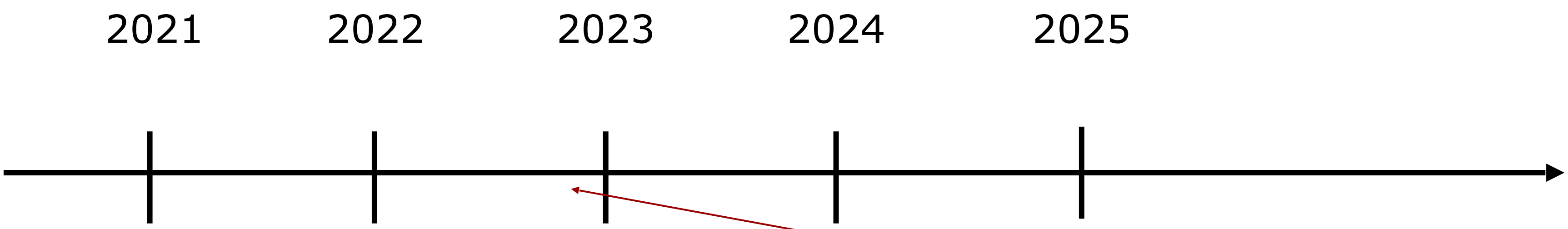
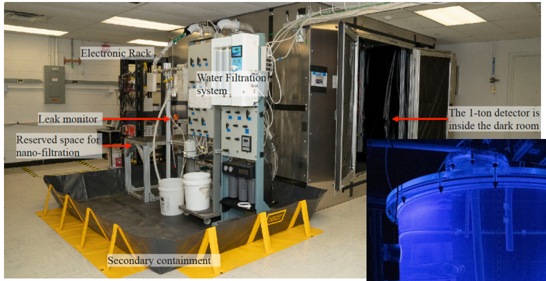
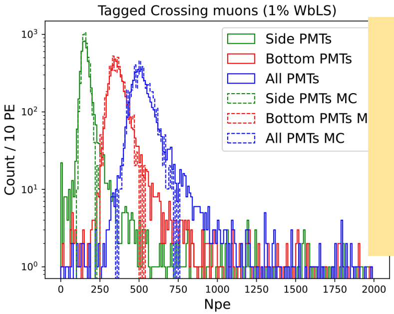
BNL WbLS Timeline



Commissioning and water/WbLS 1% run of 1T prototype





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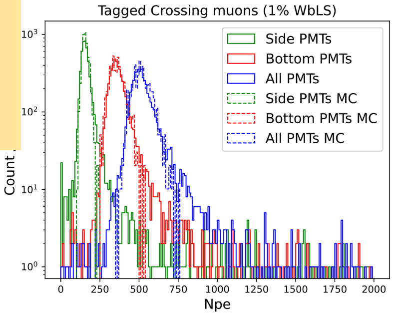
BNL WbLS Timeline

2021 2022 2023 2024 2025

First paper on 1T design and result



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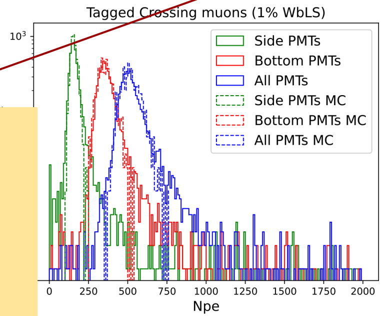
BNL WbLS Timeline

2021 2022 2023 2024 2025

Construction and commissioning of 30T demonstrator



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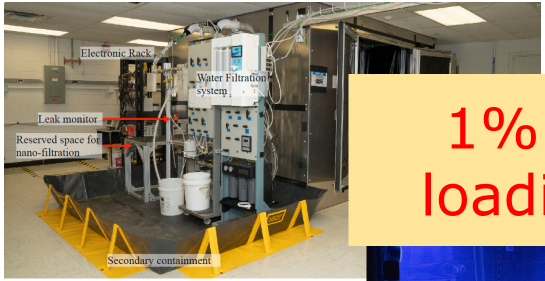
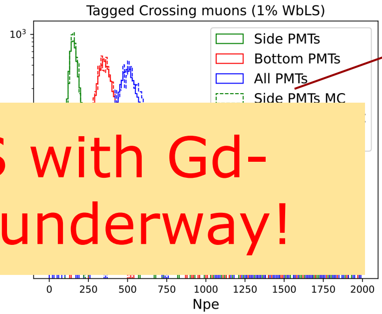
BNL WbLS Timeline

2021 2022 2023 2024 2025





1% WbLS with Gd-loading is underway!

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WbLS Lesson Learned

- Performance proven at multiple ton-scale prototypes; focusing on in-situ circulation system deployment (Sequential Exchange Array, Nanofiltration and Gd-water system). **The 1%WbLS in BNL 30-ton has been stable with SEA only (over a month)**
- Homogeneous mixing can be achieved, with careful engineer control, in a few hours after injection (observed in 1-ton and 30-ton scale).
- Sequential injection is a stepwise introduction of detector media; enabling modular commissioning and early physics data-taking before full detector deployment is completed (incremental validation of system components).
- WbLS is flexible with staged upgrades, such as from Cherenkov to various LS and/or metal loading. This supports a phased scientific program that physics output begins while further capabilities are still being deployed.

Summary

- BNL 30T demonstrator
  - Allows performance assessment, in-situ circulation, and engineering study; feasibility check for a kiloton-scale WbLS detector
  - Designs slow-control system for safety relay integration and remote operation and monitoring
  - Shows no significant obstacles ("show stoppers")
- We are at 1% WbLS, Gd doping is coming soon
  - AmBe neutron calibration for Gd-loaded WbLS stability monitoring
  - Muon/LED-based optical calibration for monitoring the optical properties
- BNL 1T prototype showing promising results, 30T demonstrator results is coming up.

Stable, cost effective and tunable light yield WbLS is suitable for broad physics program!

Collaboration

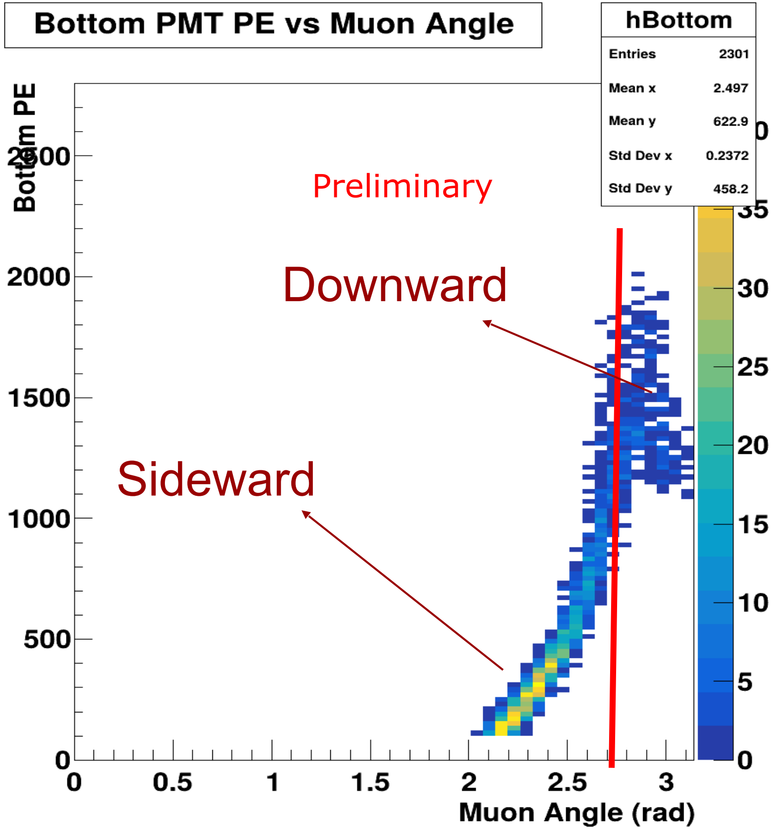
Key Collaboration Institutes (in alphabetical order):

- Brookhaven National Laboratory
- Bronx Community College
- Lawrence Berkeley National Laboratory
- Lawrence Livermore National Laboratory
- Penn State University
- Stony Brook University
- University of Alabama
- University of California, Berkeley
- University of California, Davis
- University of California, Irvine

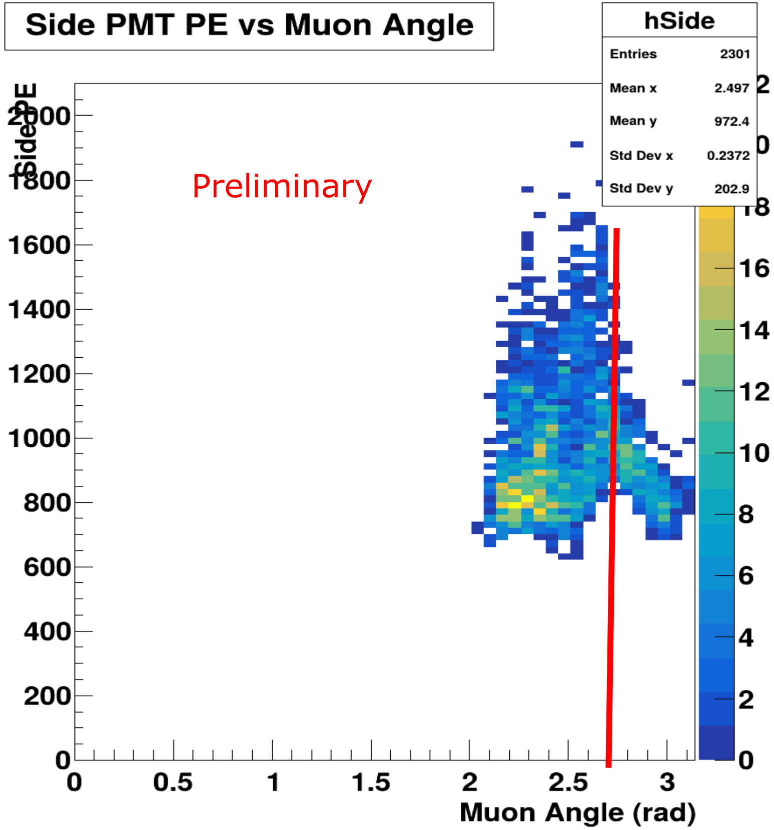
And US/UK BUTTON collaboration

Research supported by NNSA (DNN) and Office of Science (OHEP/ONP).

Backup Slides



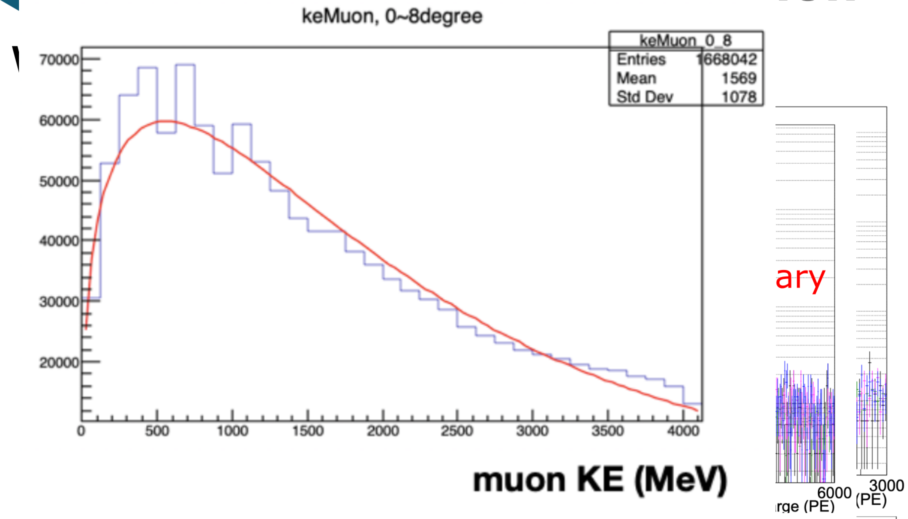
Bottom PMT PE vs Muon Angle
hBottom
Entries 2301
Mean x 2.497
Mean y 622.9
Std Dev x 0.2372
Std Dev y 458.2
Preliminary
Downward
Sideward
Bottom PE
Muon Angle (rad)

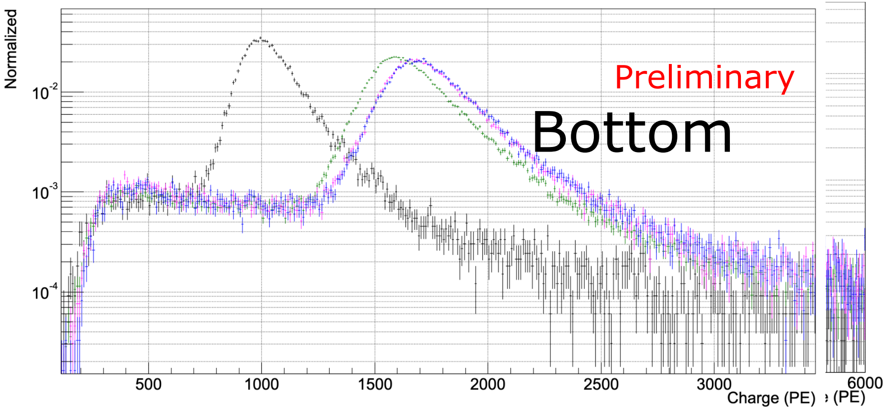


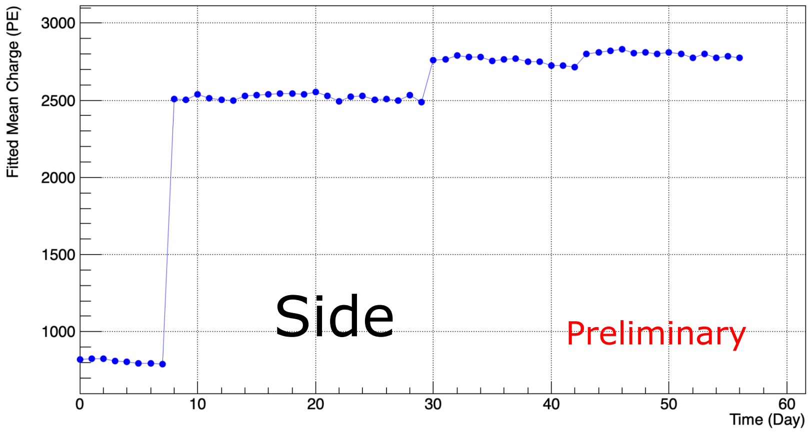
Side PMT PE vs Muon Angle
hSide
Entries 2301
Mean x 2.497
Mean y 972.4
Std Dev x 0.2372
Std Dev y 202.9
Preliminary
Side PE
Muon Angle (rad)

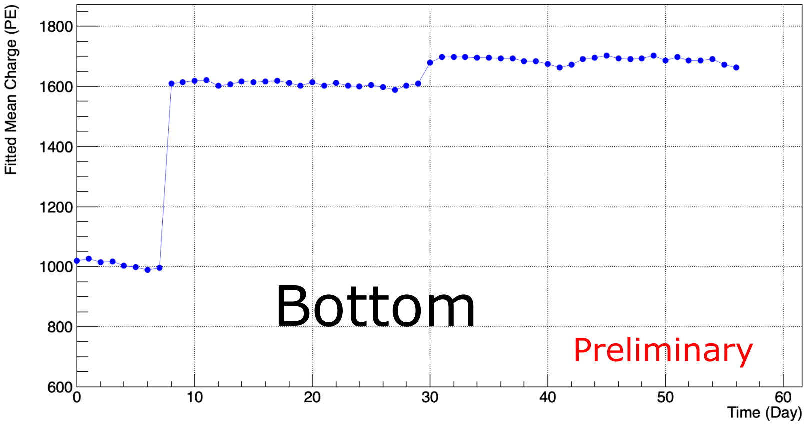
Brookhaven National Laboratory

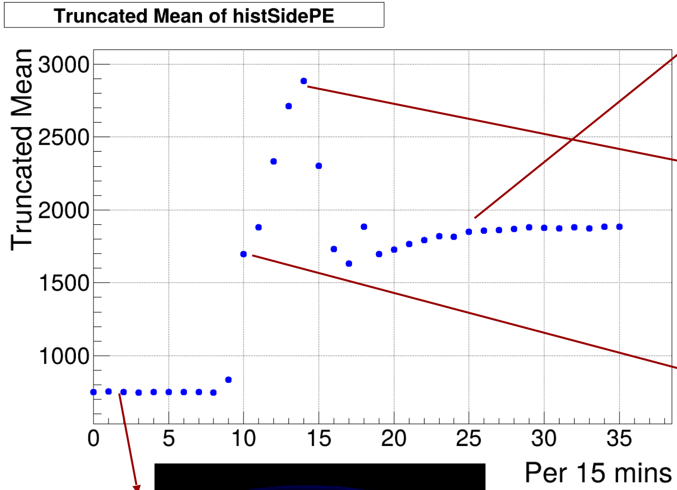
Light production

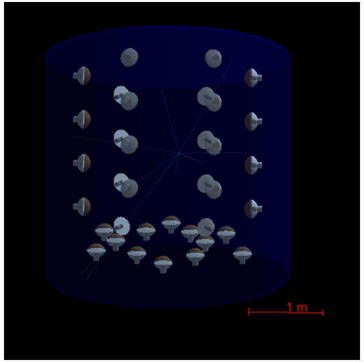


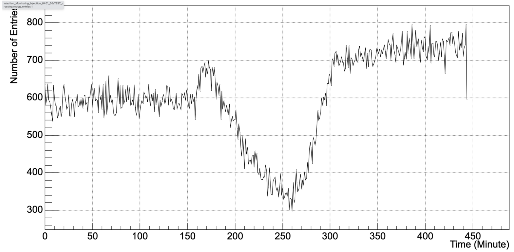


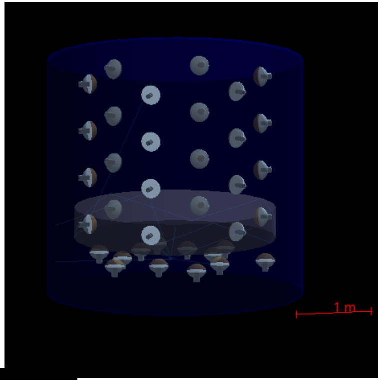


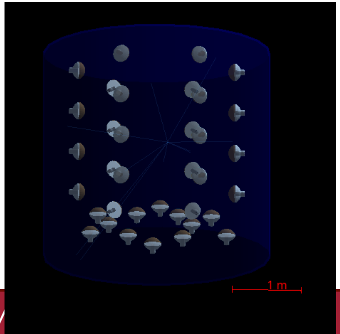


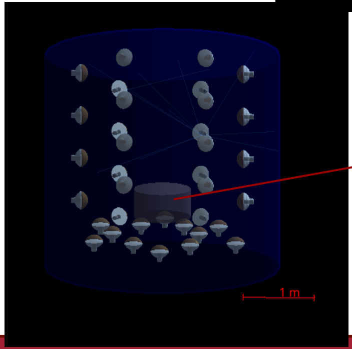












Scintillator without LY with 1 cm scattering

Fitting Result for 1% WbLS

No correction applied to MC in-ring to account for the efficiency difference based on water.

Cherenkov and non-Cherenkov are varied to match the WbLS data in both in-ring and out-ring regions.

Non-Cherenkov contains Cherenkov conversion and direct light yield.

Light yield was assumed to be 100 photons/MeV.