



*Institut
Ruđer
Bošković*



Co-funded by
the European Union



Far detector MC implementation

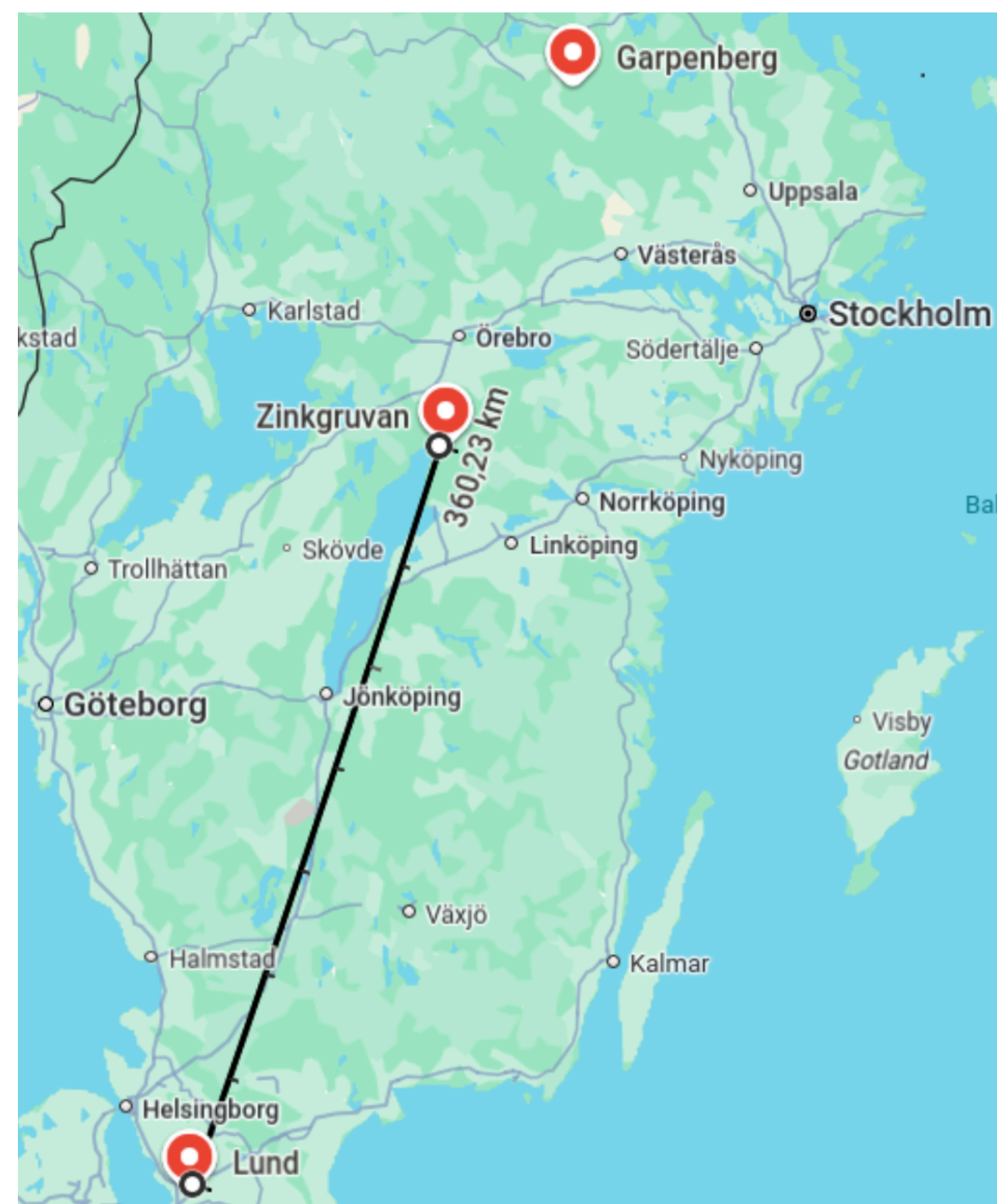
Mahesh Jakkapu

Ruđer Bošković Institute
6/10/2026

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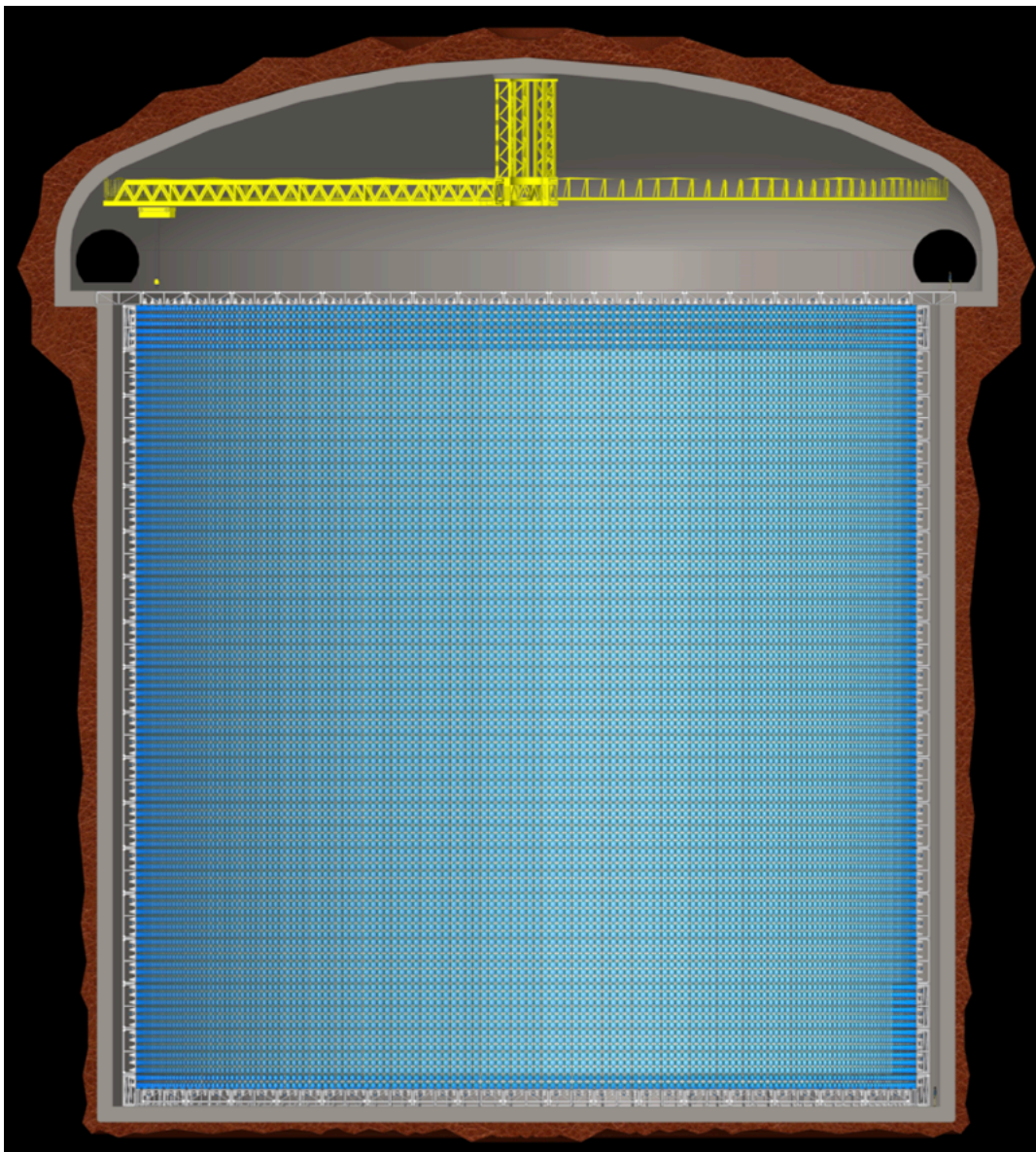
1. Introduction
2. Far detector and physics motivation
3. Detector simulation using GEANT4
4. Gadolinium (Gd) Study
5. Neutrino and anti-neutrino mode separation

ESSvSB far detector



- Located in Zincgruvan mine, approximately 360 km from ESS beam.
- Consists of 2 large water-cherenkov detectors.
- Fiducial mass ~ 540 kt.

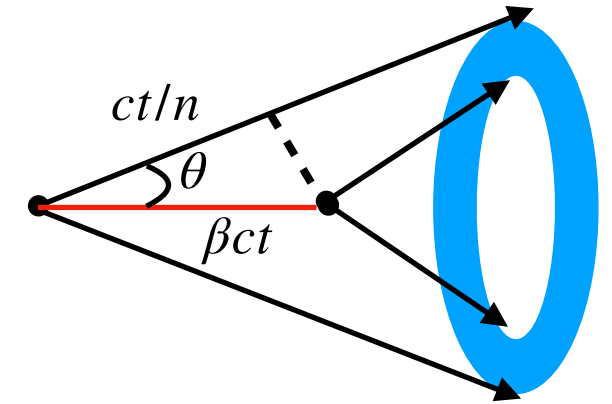
Far detector(Cont..)



- Each tank is 74m height and 74m diameter.
- 38000 20-inch PMTs per detector tank, 30% photo coverage.

Detector principles

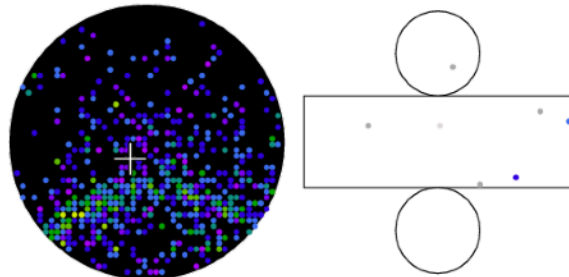
- Charged particles moving faster than the light in the medium emit Cherenkov radiation.
- Muons deposit cleaner rings compared to Electrons



$$\cos \theta = \frac{ct/n}{\beta ct}$$

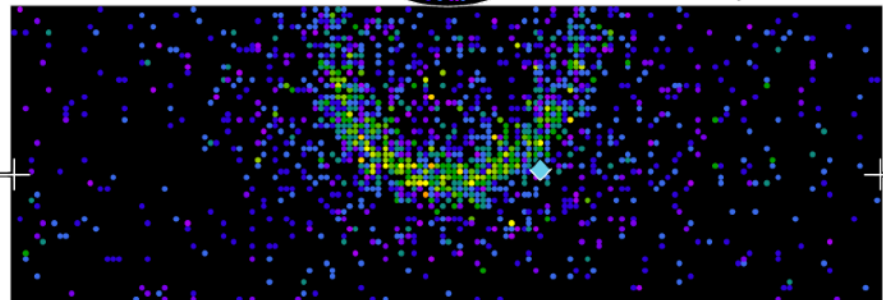
Super-Kamiokande IV

Run 999999 Sub 0 Event 7
11-11-23:19:16:50
Inner: 2011 hits, 3854 pe
Outer: 2 hits, 2 pe
Trigger: 0x07
D_wall: 1405.1 cm
Evis: 419.0 MeV
e-like, p = 419.0 MeV/c

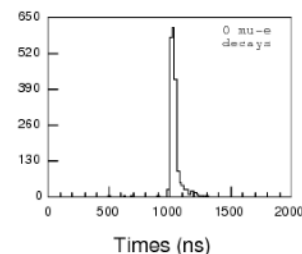
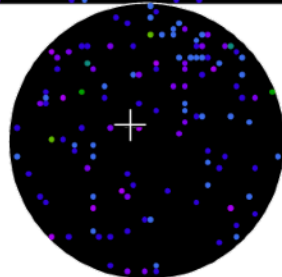


Charge (pe)

• >26.7
• 23.3-26.7
• 20.2-23.3
• 17.3-20.2
• 14.7-17.3
• 12.2-14.7
• 10.0-12.2
• 8.0-10.0
• 6.2- 8.0
• 4.7- 6.2
• 3.3- 4.7
• 2.2- 3.3
• 1.3- 2.2
• 0.7- 1.3
• 0.2- 0.7
• < 0.2

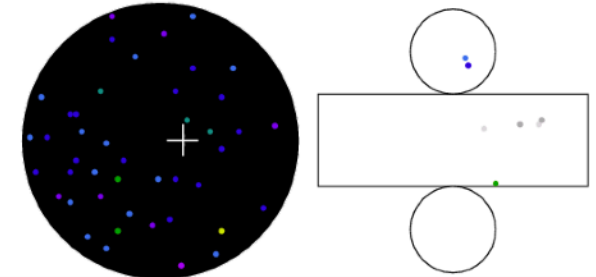


Electron



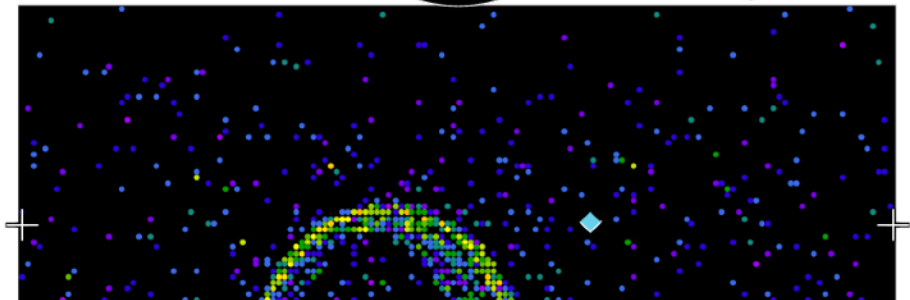
Super-Kamiokande IV

Run 999999 Sub 0 Event 40
11-11-21:09:42:21
Inner: 1049 hits, 3121 pe
Outer: 3 hits, 7 pe
Trigger: 0x07
D_wall: 945.7 cm
Evis: 356.5 MeV
nu-like, p = 320.8 MeV/c

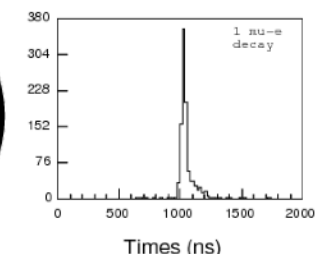
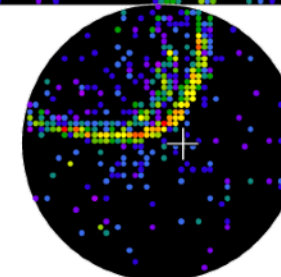


Charge (pe)

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• 3.3- 4.7
• 2.2- 3.3
• 1.3- 2.2
• 0.7- 1.3
• 0.2- 0.7
• < 0.2



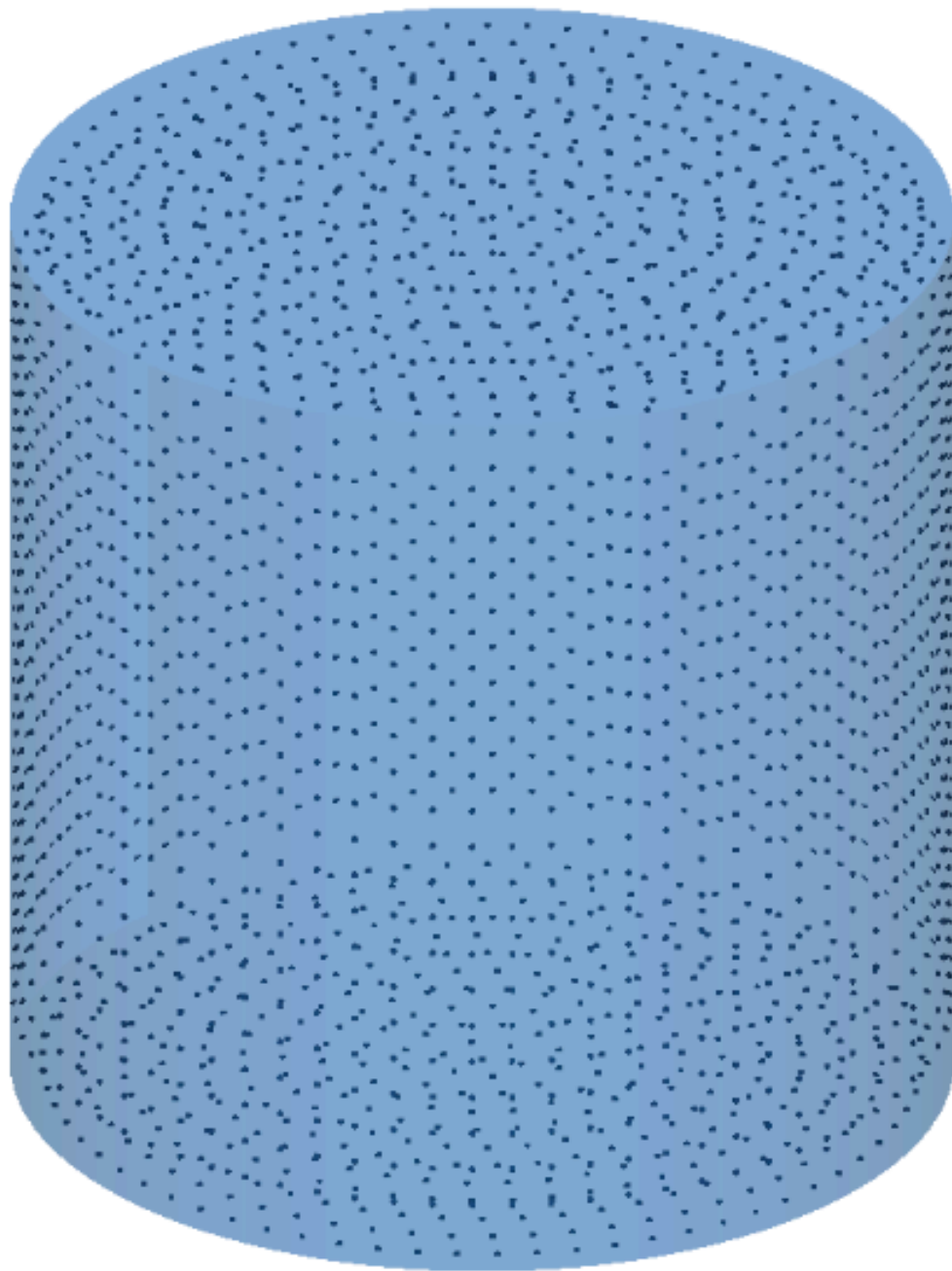
Muon



Goal of detector simulation

- Simulate particle propagation in water.
 - Various interactions (decay, capture etc...)
 - Photons reaching the detector walls.
 - PMT properties (energy and time smearing, detection efficiency)
 - Particle identification.
 - Gd effects.

Detector simulation

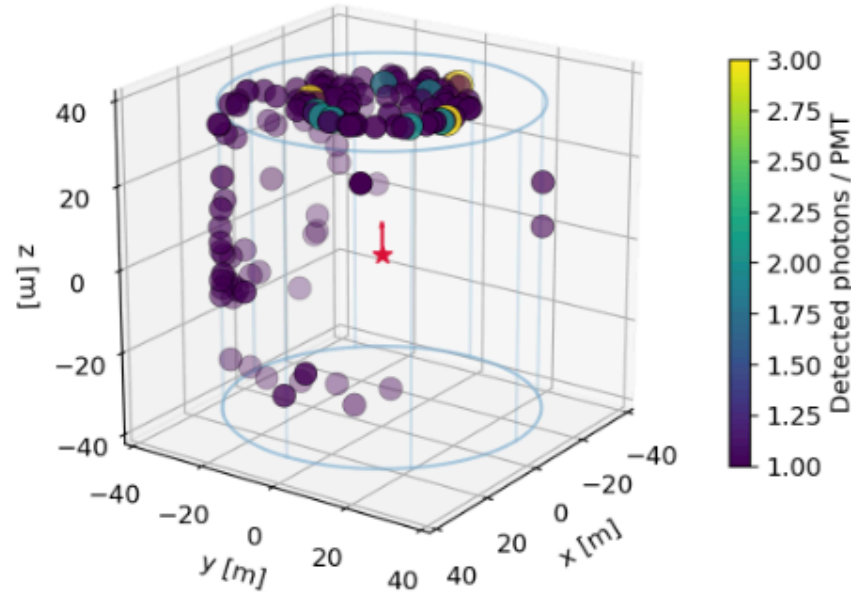


***Smaller coverage due to rendering capabilities**

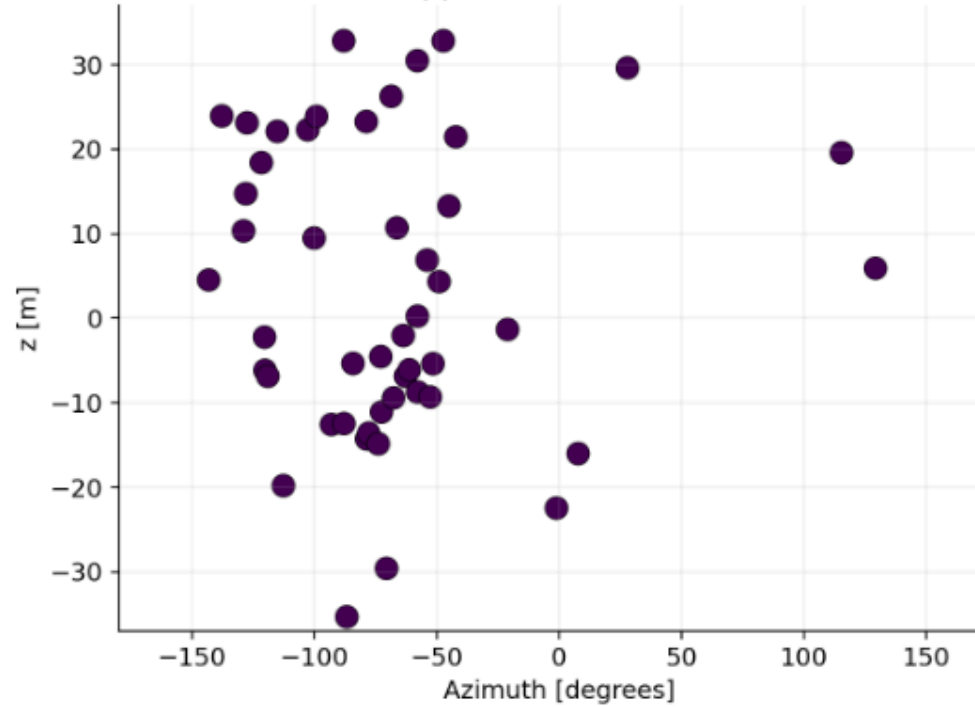
- Software has been built from the scratch for far detector.
- Consists of water(+gd) and PMTs.
 - Gd concentration and PMT distribution can be varied to study the physics.
- Implemented scripts to quickly run test events without having to compile the project repeatedly.

100 MeV mu– event · 30% PMT coverage
153 detected photons across 140 PMTs

Hit PMTs in detector (arrow: muon direction)



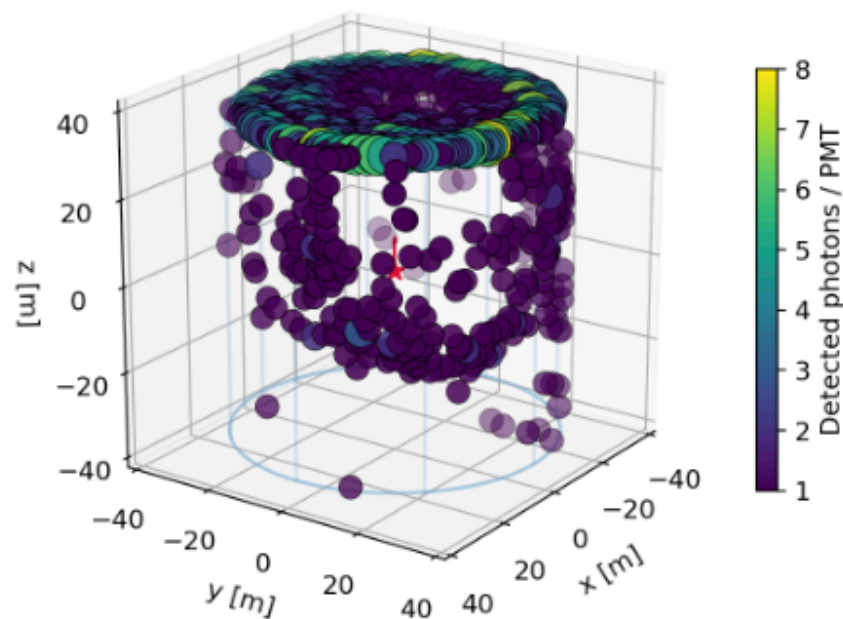
Unwrapped barrel · 48 hit PMTs



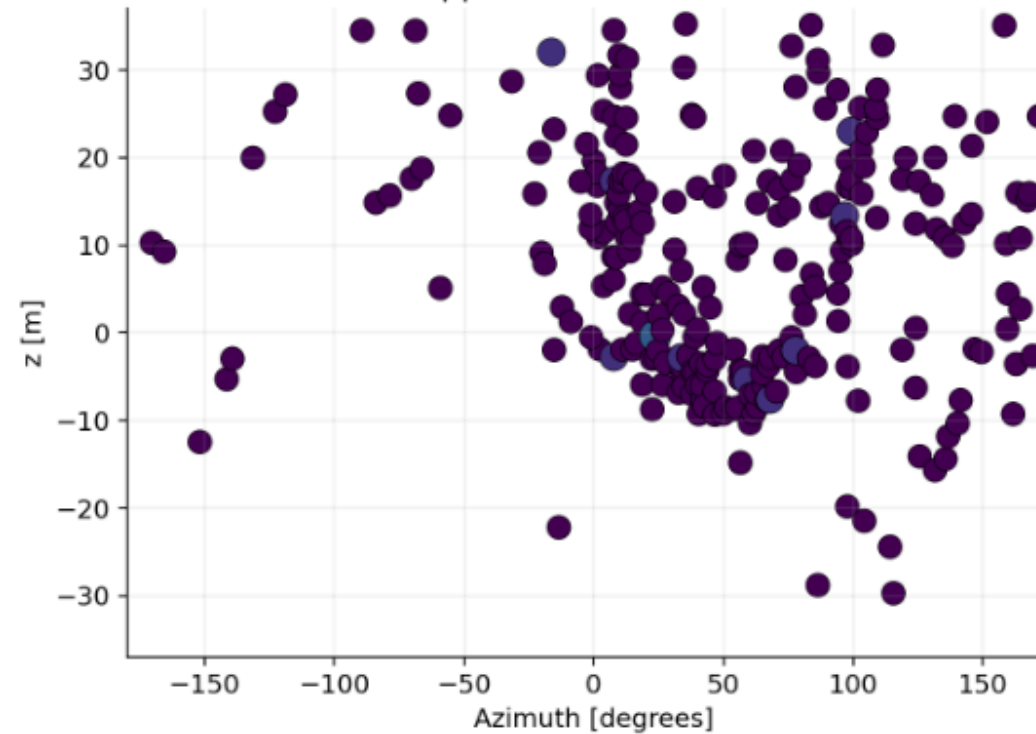
Sample events

500 MeV mu– event · 30% PMT coverage
3306 detected photons across 1959 PMTs

Hit PMTs in detector (arrow: muon direction)



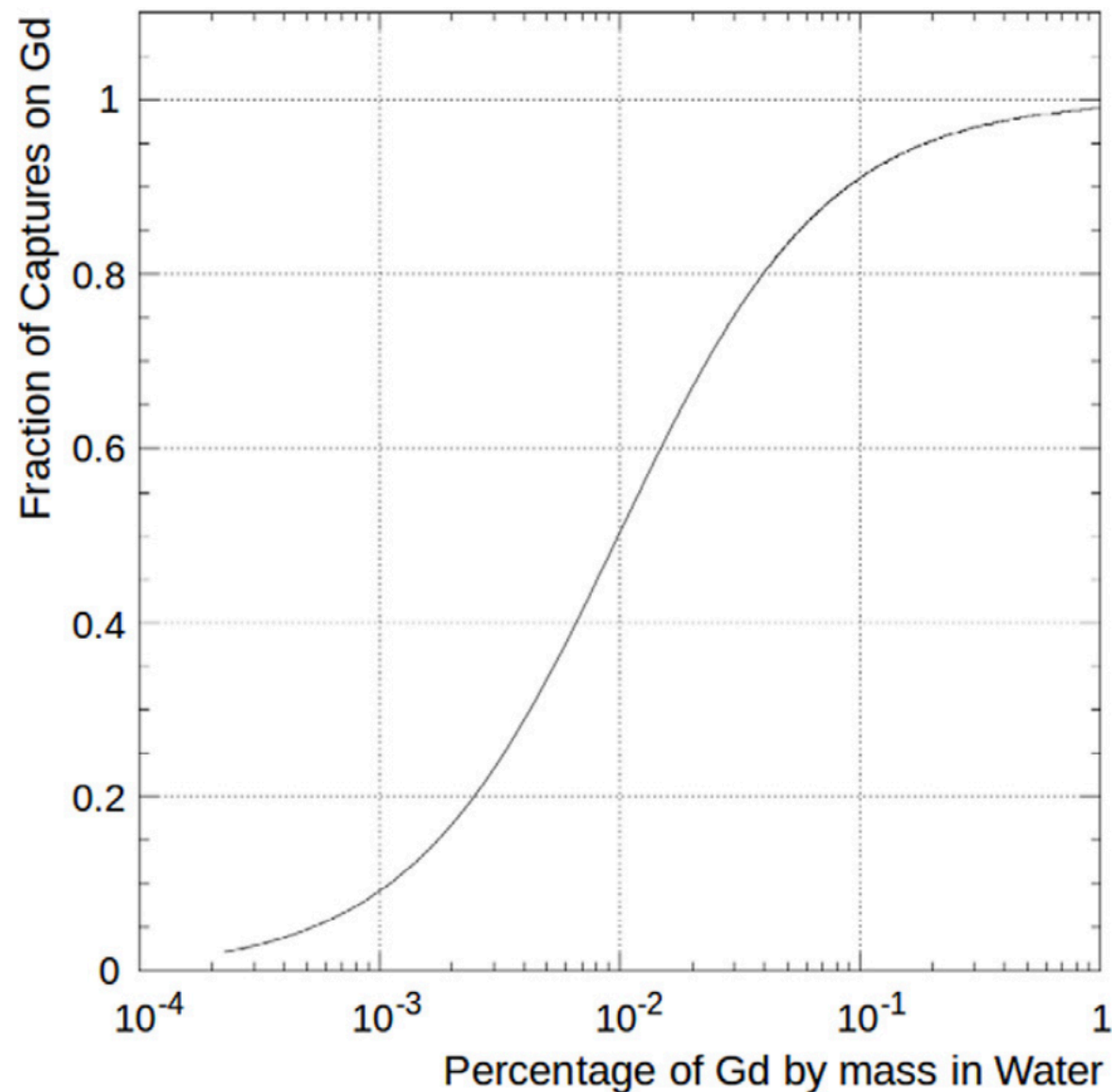
Unwrapped barrel · 256 hit PMTs



Gadolinium doping

- Neutron capture in water produce 2.2 MeV photons, very close to the detection threshold.
- Super Kamiokande doped their detector is a small fraction of Gadolinium Sulphate ($Gd_2(SO_4)_3 \cdot H_2O$)
 - Higher neutron capture cross-section
 - Emits photons with ~ 8 MeV
- Benefits
 - Leads to $\nu - \bar{\nu}$ separation.
 - Better sensitivity to atmospheric, supernova and diffused supernova background
 - Good handle background rejection -> Sterile studies

Cont...



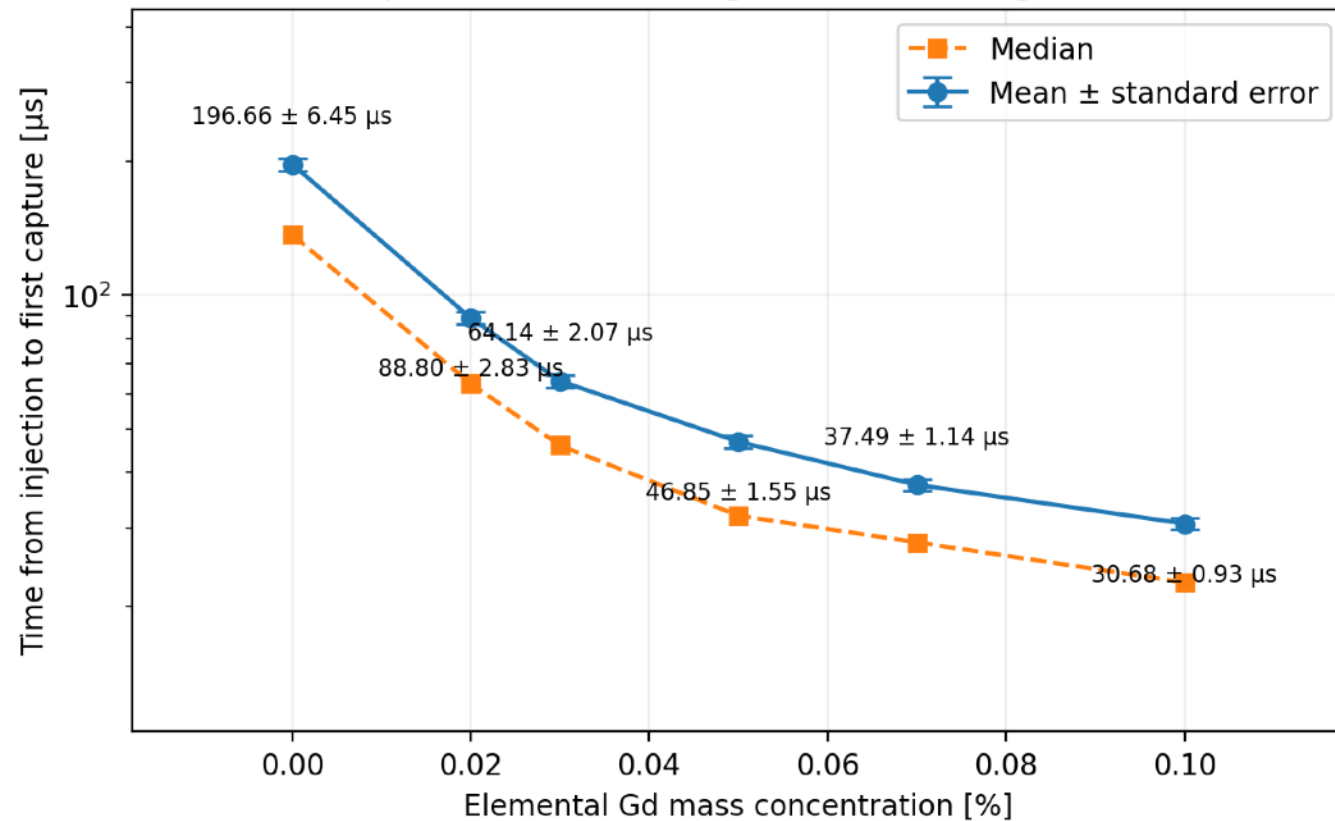
- 0.1% doping of Gd results in 90% of neutron captures on Gd.
- Low concentration means no optical problems.
- Water transparency remains the same.
- No significant radiation backgrounds.

<https://doi.org/10.1016/j.nima.2020.163549>

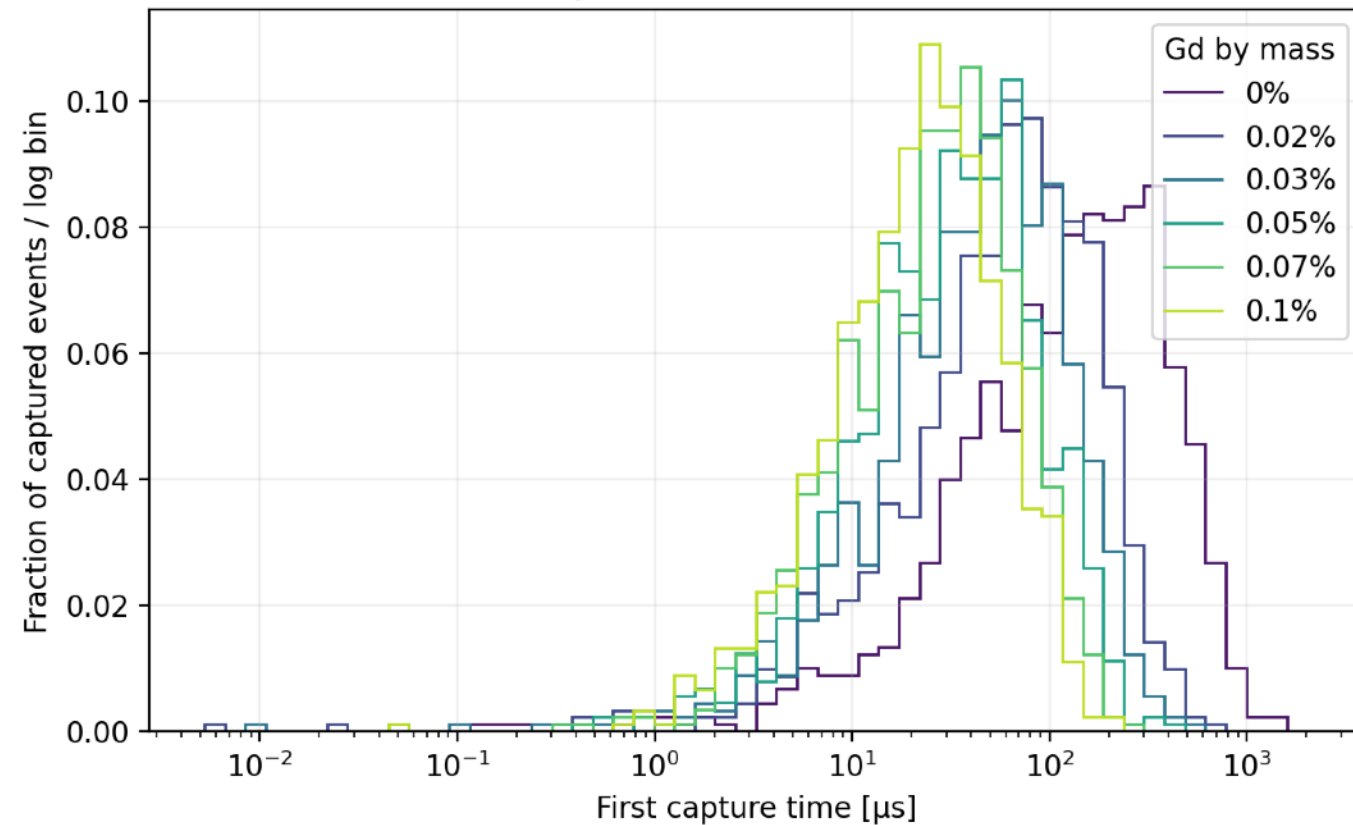
Neutron capture on Gd

20 MeV neutron capture timing vs Gd mass concentration
1,000 neutron-only events per level · first neutron capture per event

Capture time, including neutron slowing down



Capture-time distributions

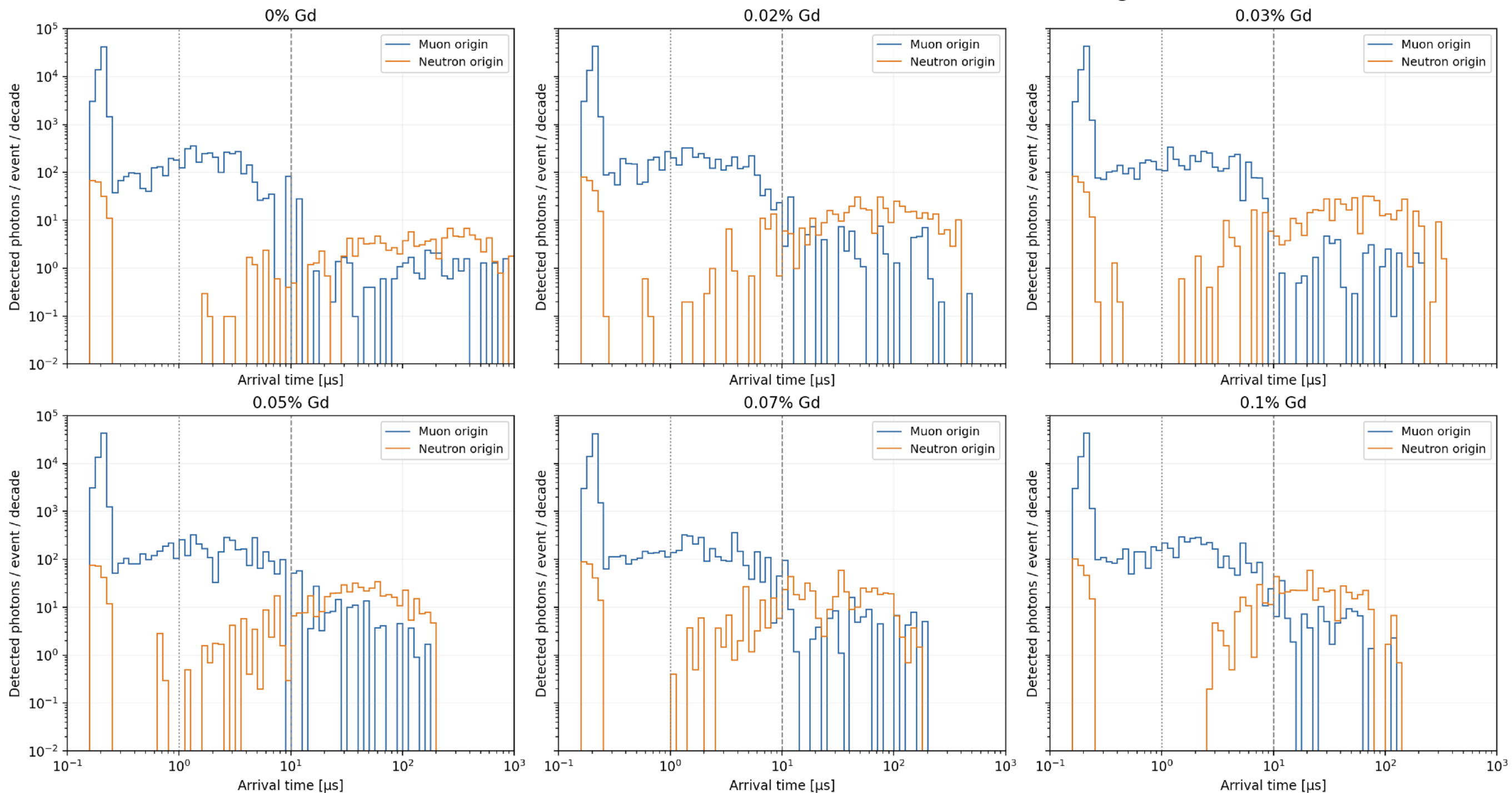


- 20 MeV neutron with varying Gd concentration levels (0, 0.02, 0.03, 0.05, 0.07 and 1%)
- Capture time gets improved and matches with SK observations.

Muon-neutron separation using Gd

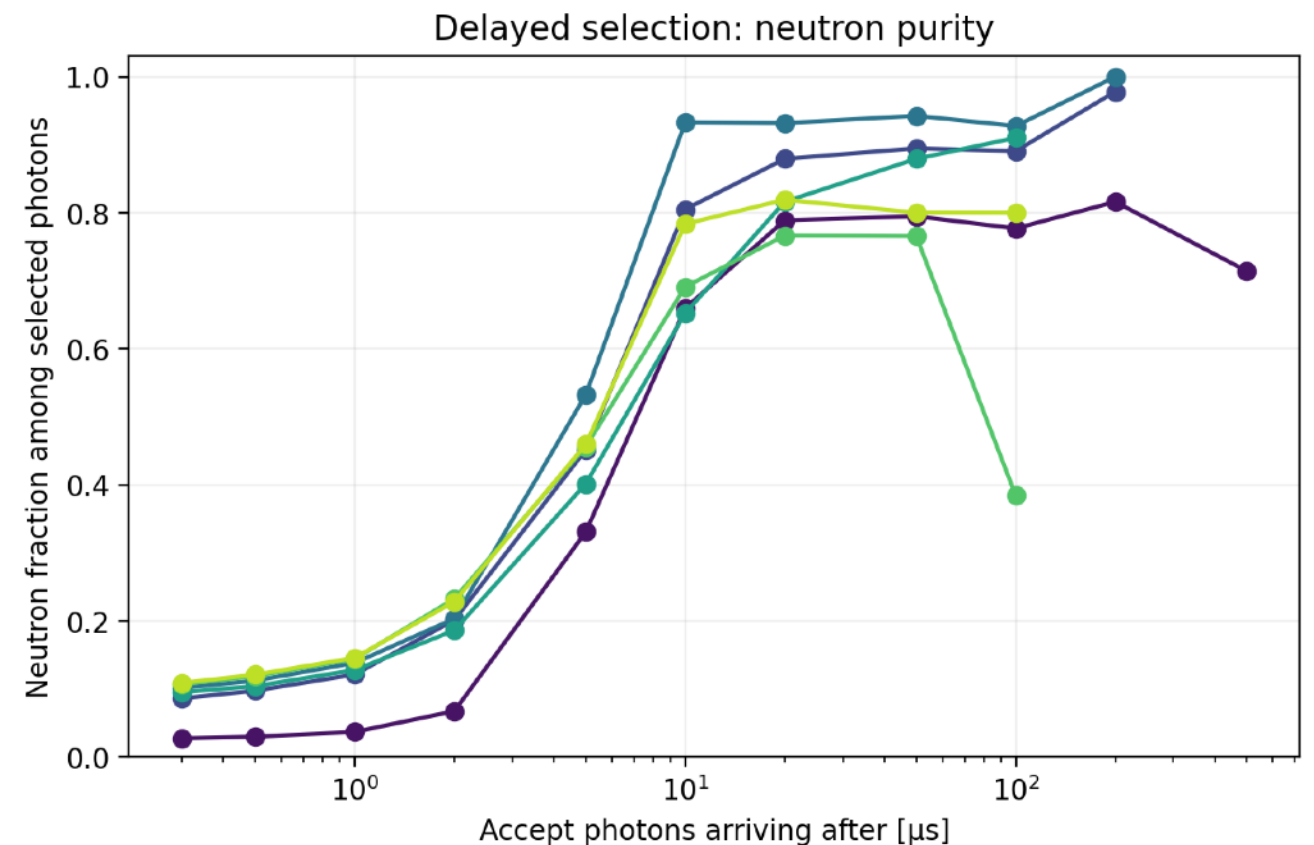
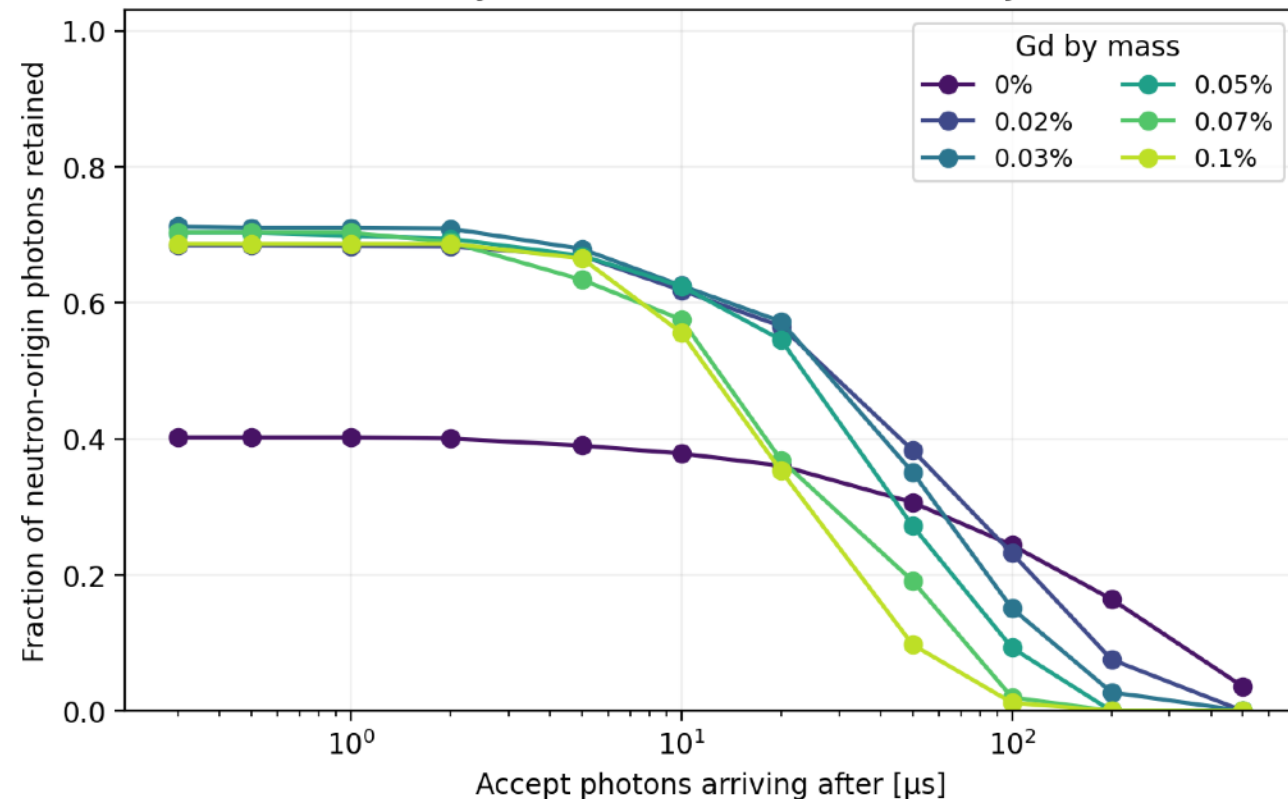
- 500 MeV muon and 20 MeV neutron per event.

Muon + neutron PMT arrival-time separation
200 events / level · 500 MeV mu- + 20 MeV neutron · 30% coverage



- Efficiency and purity of neutron selection from muon background using the arrival time photons at PMTs.
- Increasing the timing cut is not useful for efficiency but improved purity. A simple cut of $3\mu\text{s}$ performs very well.
- All concentration of Gd are far better than no Gd.

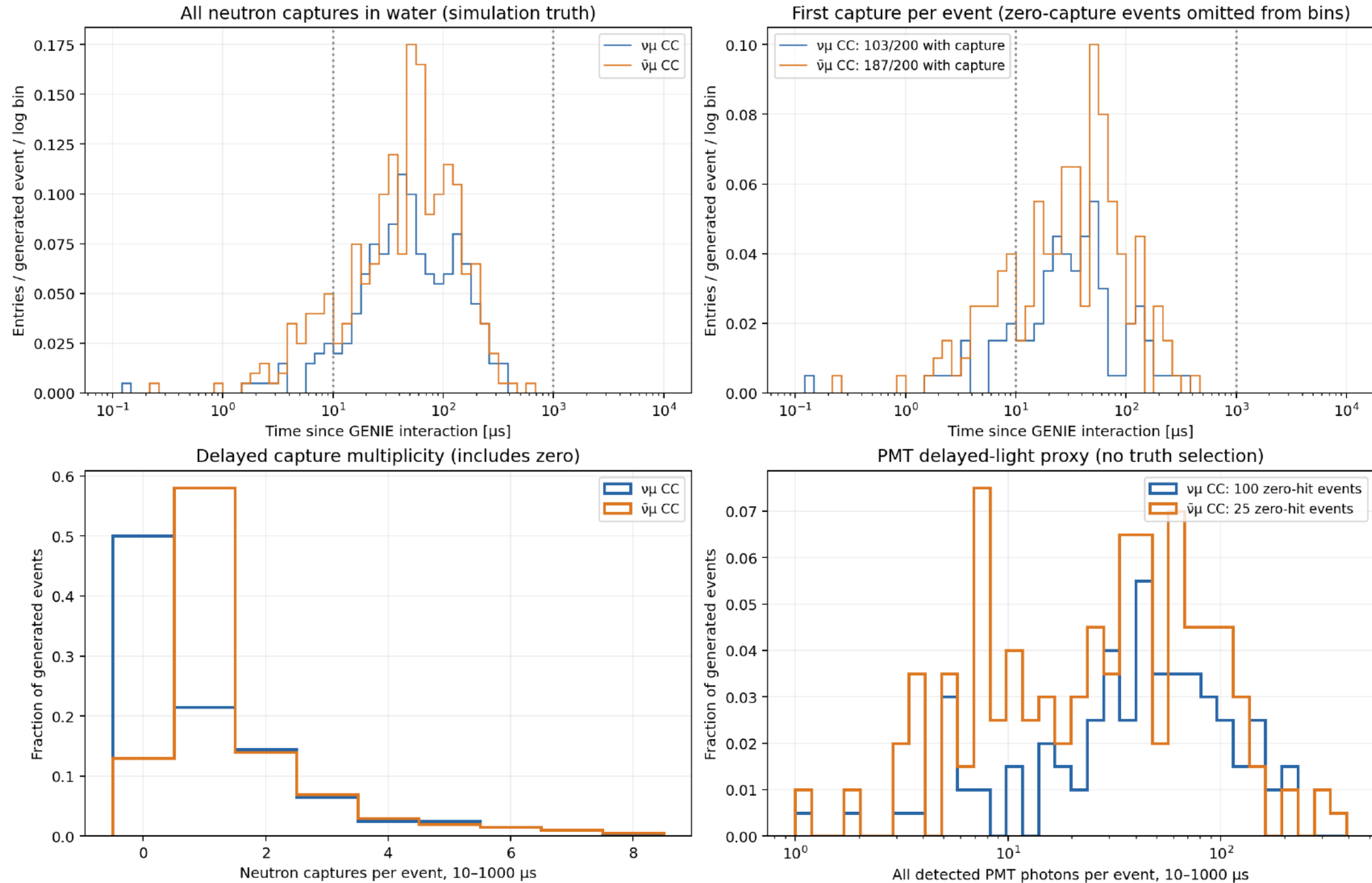
Timing-cut separation of muon- and neutron-origin PMT photons
Photon-level metrics within a common 0–1 ms window; truth ancestry labels
Delayed selection: neutron efficiency



Using neutrino events

- Used events generated using GENIE neutrino event generator and ESSnuSB flux at far detector.

GENIE $\nu\mu$ versus $\bar{\nu}\mu$: neutron-capture signals
200 events each · 0.03% elemental Gd · 30% PMT coverage



Capture times are transport truth. Delayed PMT photons include all sources; no noise, electronics, or neutron-tag reconstruction is modeled.

Using neutrino events

- More events get neutron capture signal in $\bar{\nu}_\mu$ events.
- A good indicator for $\bar{\nu}$ events.
- **Work in progress.**

Paper in preparation

- A tech paper detailing the effects of gadolinium on $\nu - \bar{\nu}$ separation is under preparation.
- Tentative title **“Classification of ν_{μ} and $\bar{\nu}_{\mu}$ events using gadolinium doped water cherenkov detector at ESSnuSB far detector”**
- The same will be cited in the CDR.

Conclusion

- The far detector simulation software is fully functional with Gd doping capabilities.
- Studies show neutron capture times improve with Gd doping.
- Using delayed signal of neutron, $\nu - \bar{\nu}$ identification can be achieved.
- A paper detailing the results is under preparation.