

The Accelerator Neutrino Neutron Interaction Experiment



Andrew Sutton
for the ANNIE Collaboration



Who is ANNIE?

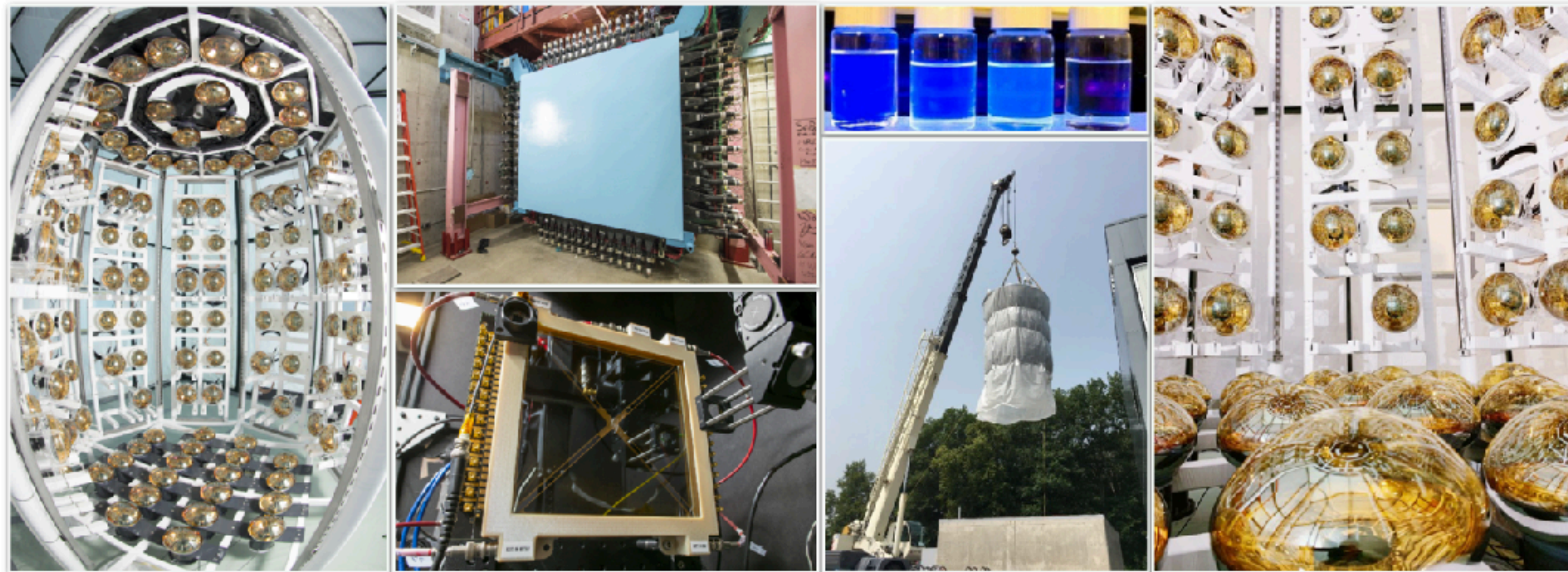


A small collaboration with from 16 institutions
(8 non-US) from 5 countries

What are we looking for?

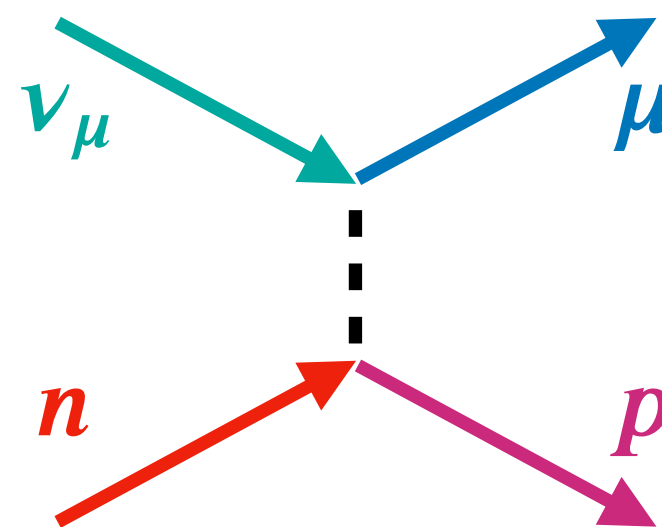
Accelerator Neutrino Neutron Interaction Experiment

- Number of neutrons coming from neutrino interactions (aka neutron multiplicity)
 - Neutron production uncertainties are leading sources of systematic error
- Neutrino-on-water cross section
 - SBN is right next door → Potential joint analysis of water and LAr cross sections



What's up with neutrons?

- In short: they're a bit of a pain
- In long:
 - We really need to know the energies of neutrinos
 - They're invisible until they interact and produce other particles
 - We have to sum up the energy of the outgoing particles
 - Any outgoing neutrons are neutral too!
 - That's fine, just look at quasi elastic (QE) interactions

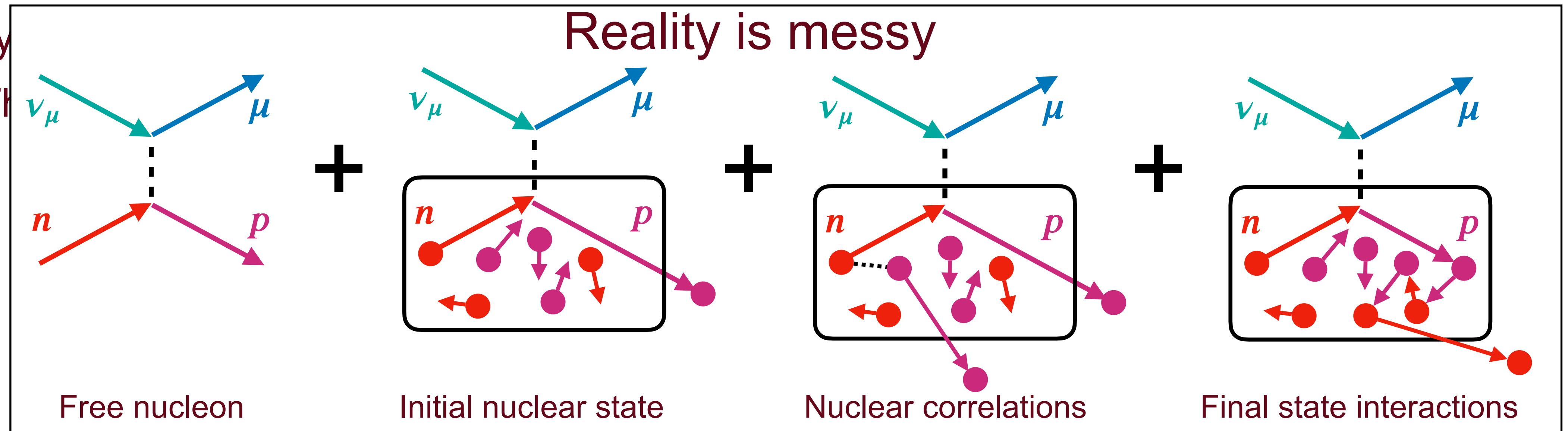


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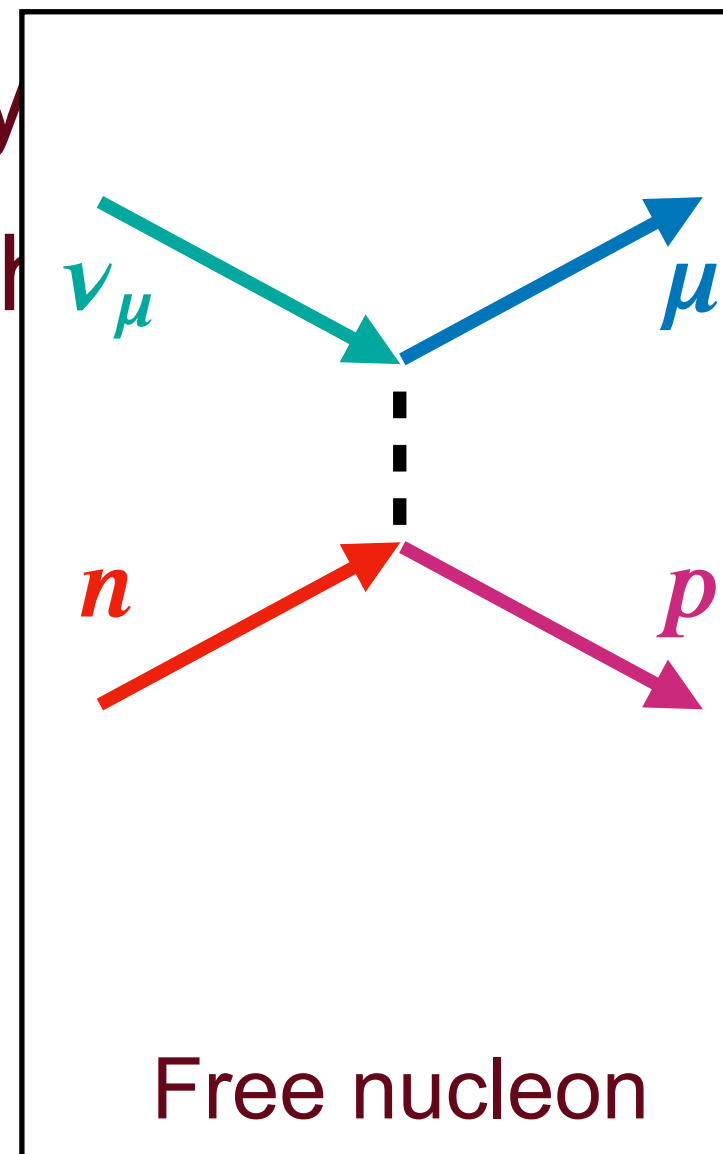
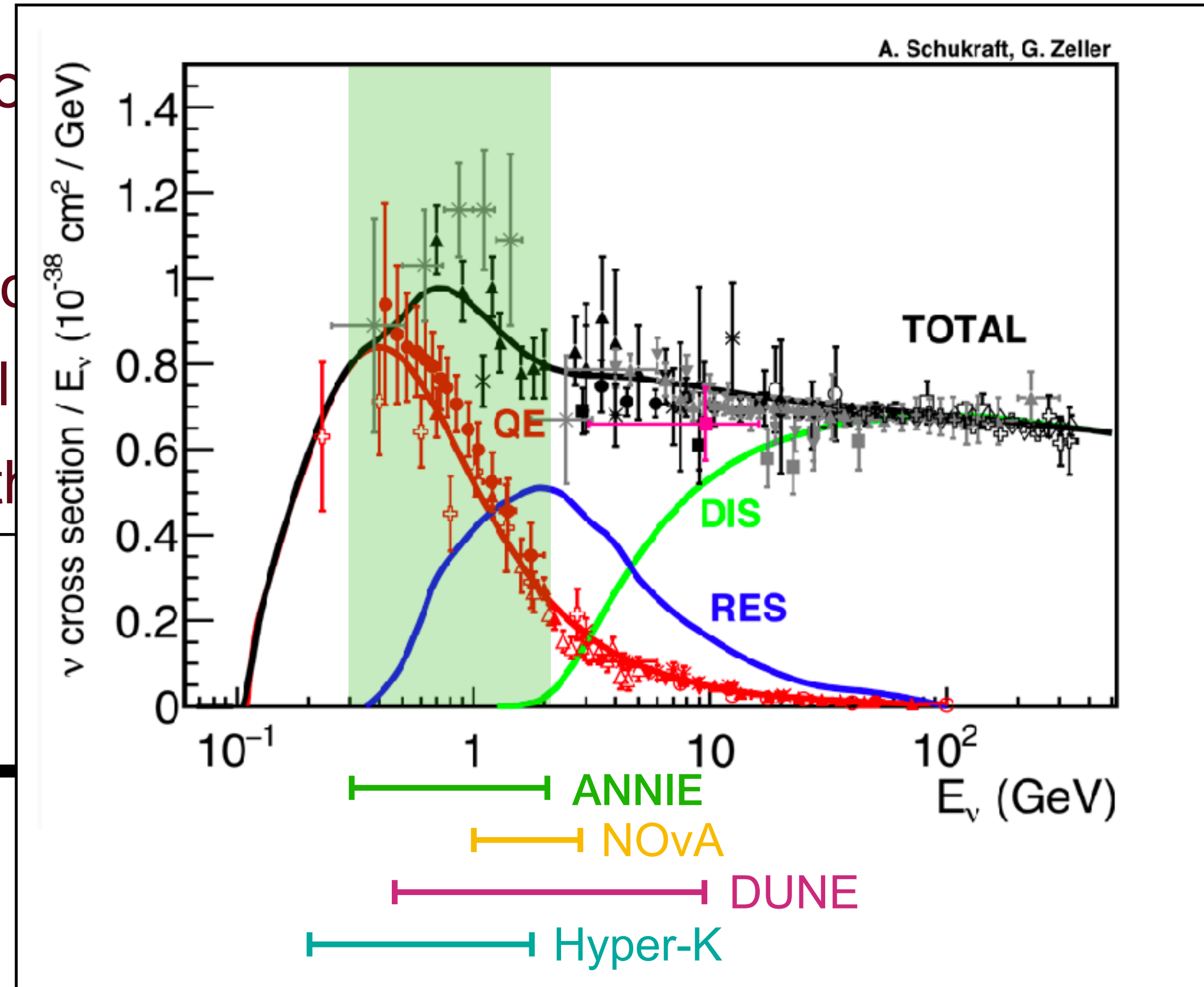
- Any

▶ The



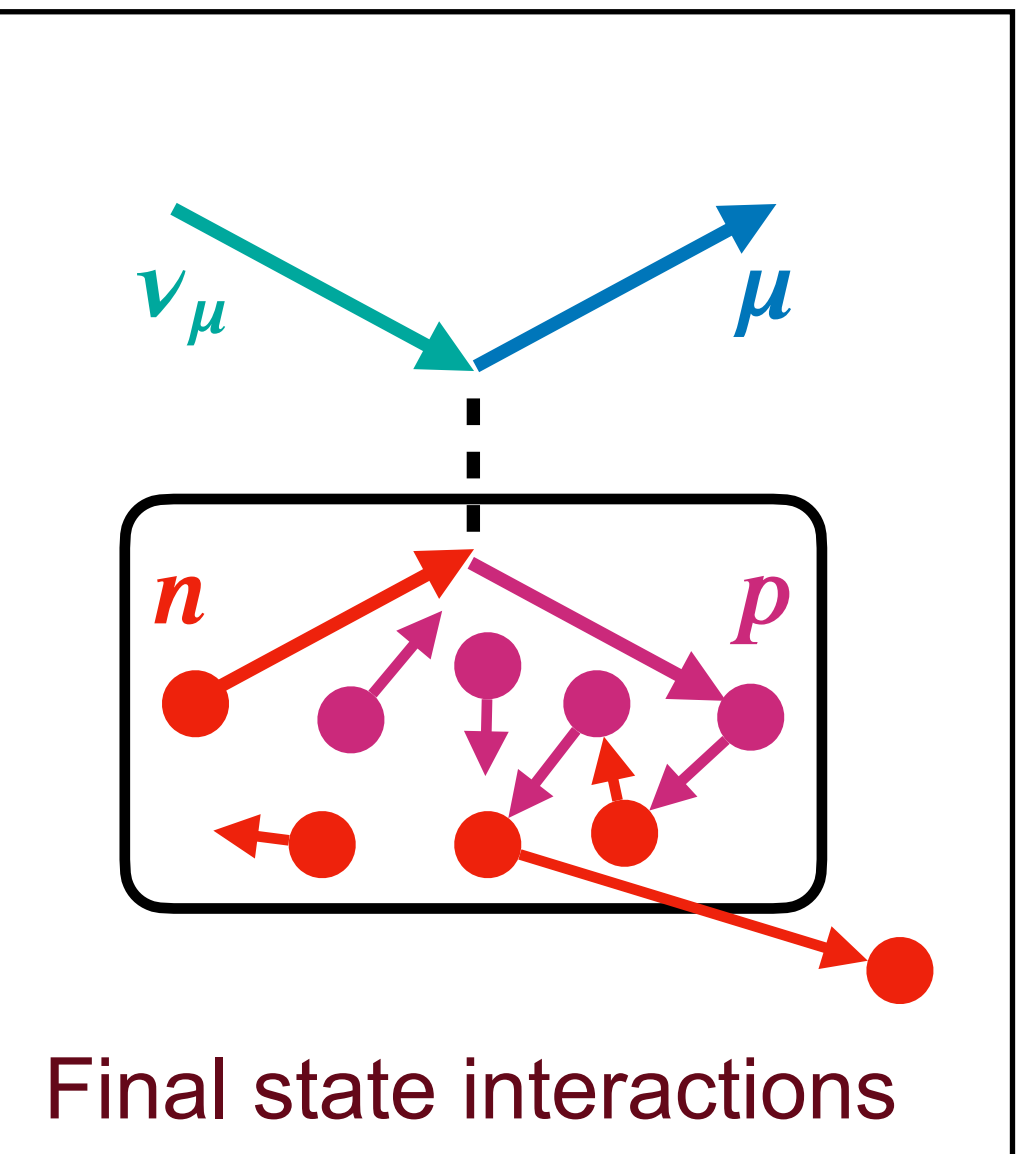
What's up with neutrons?

- In short: they're a bit of a problem
- In long:
 - We really need to know more about them
 - They're invisible until they interact
 - We have to sum up the different ways they can interact
 - Any of these can be important



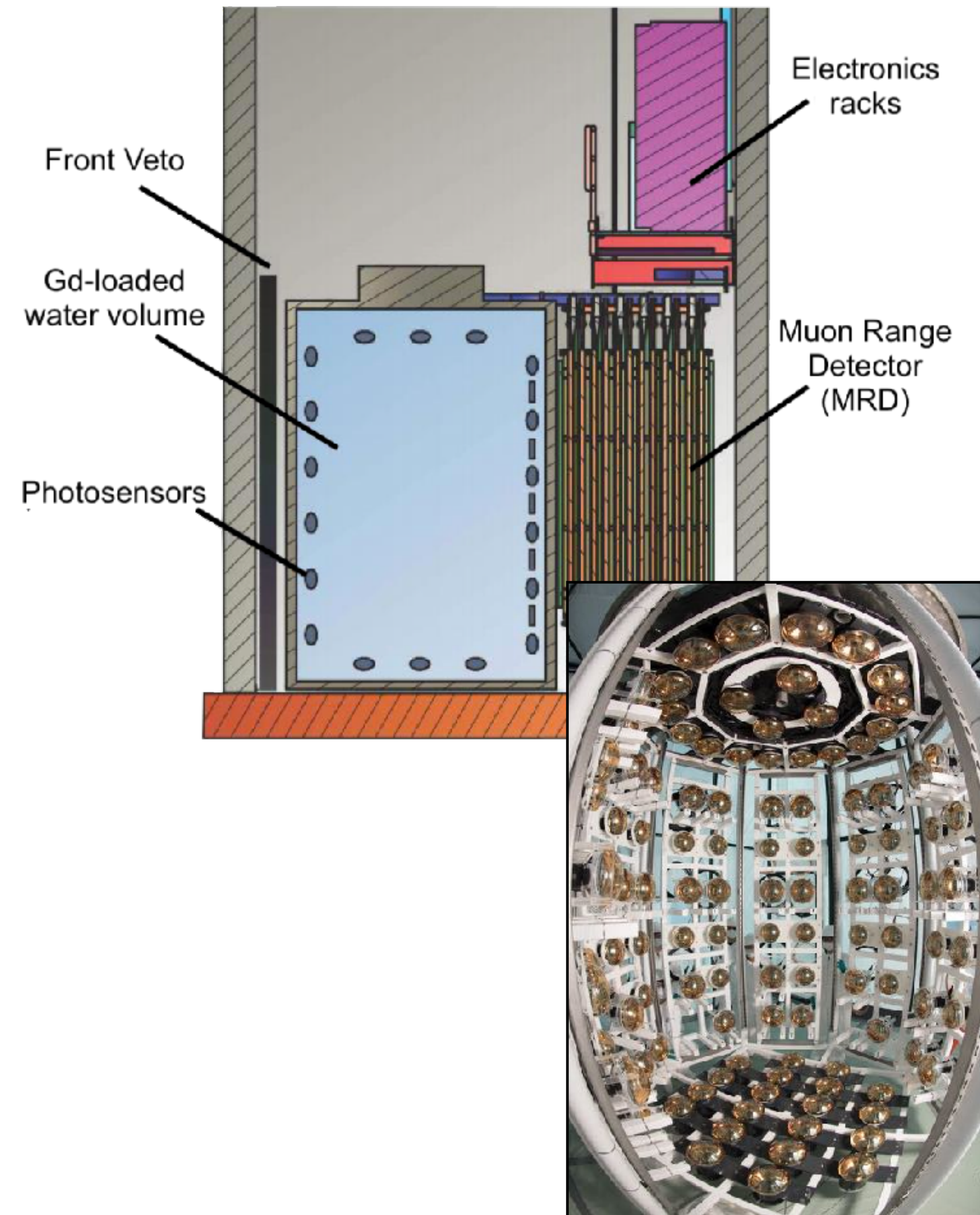
Initial nuclear state

Nuclear correlations



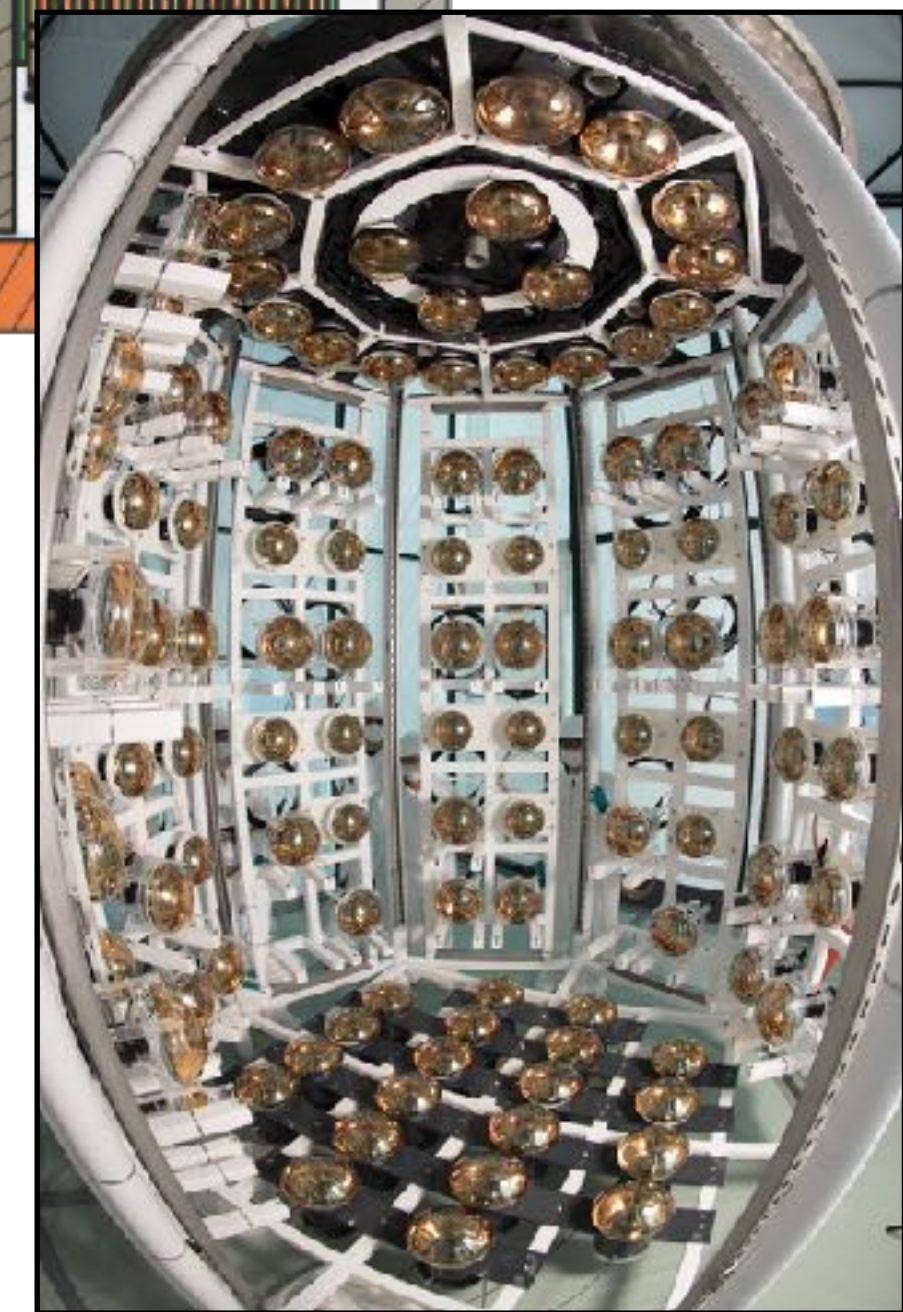
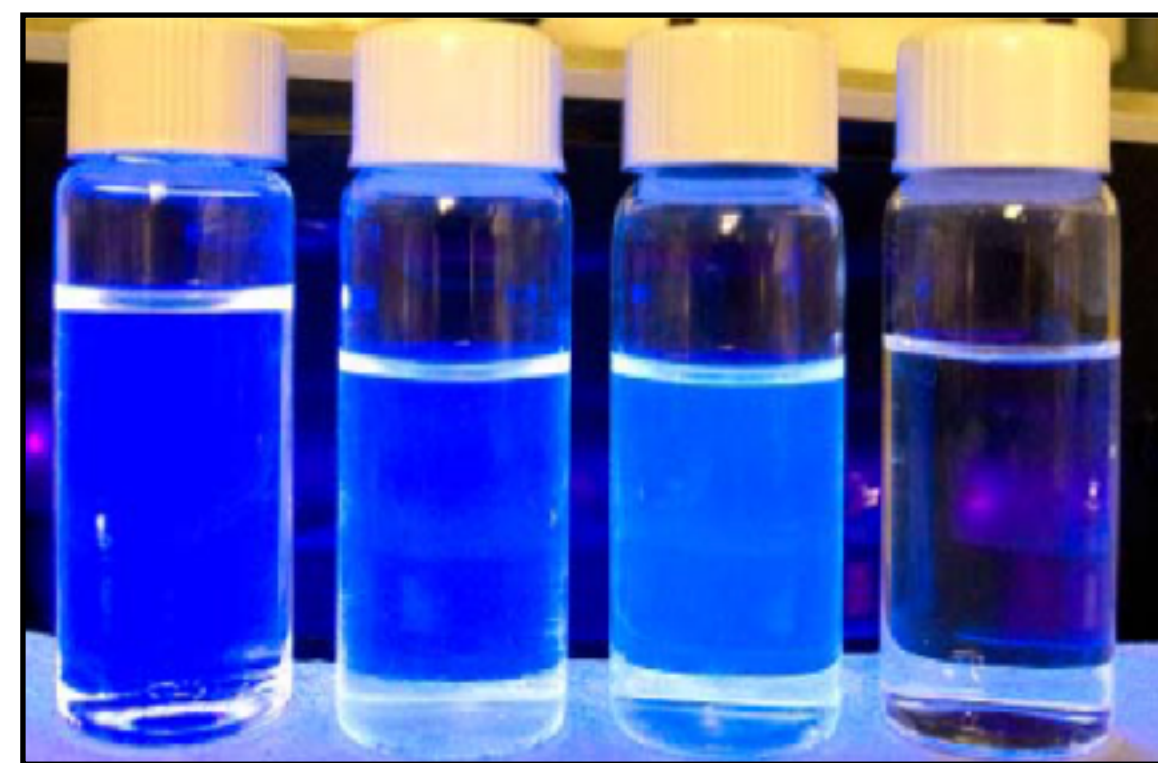
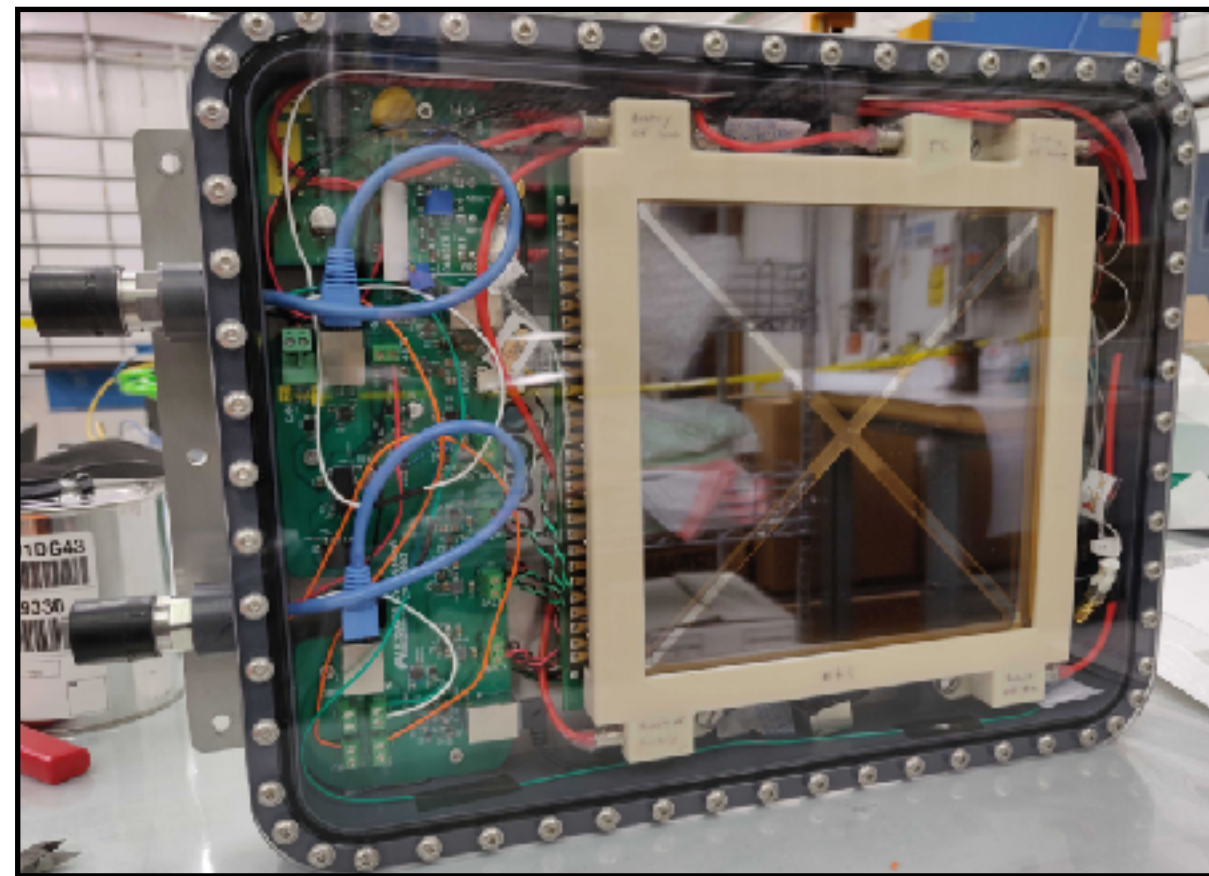
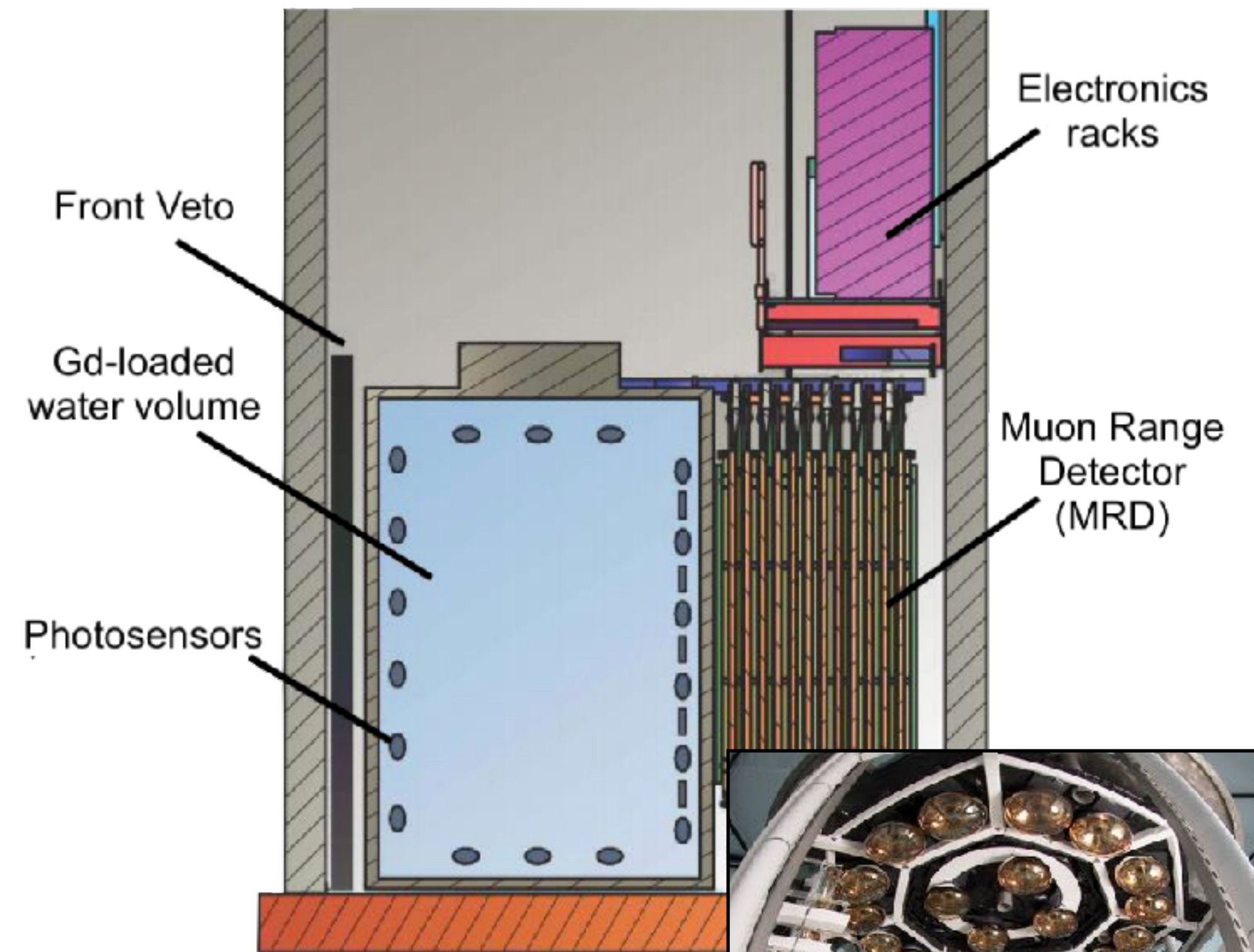
What is ANNIE?

- 26t gadolinium-loaded water Cherenkov detector in the Booster Neutrino Beam (BNB)
 - Gd has a high neutron capture cross section (~150,000X greater than hydrogen)



What is ANNIE?

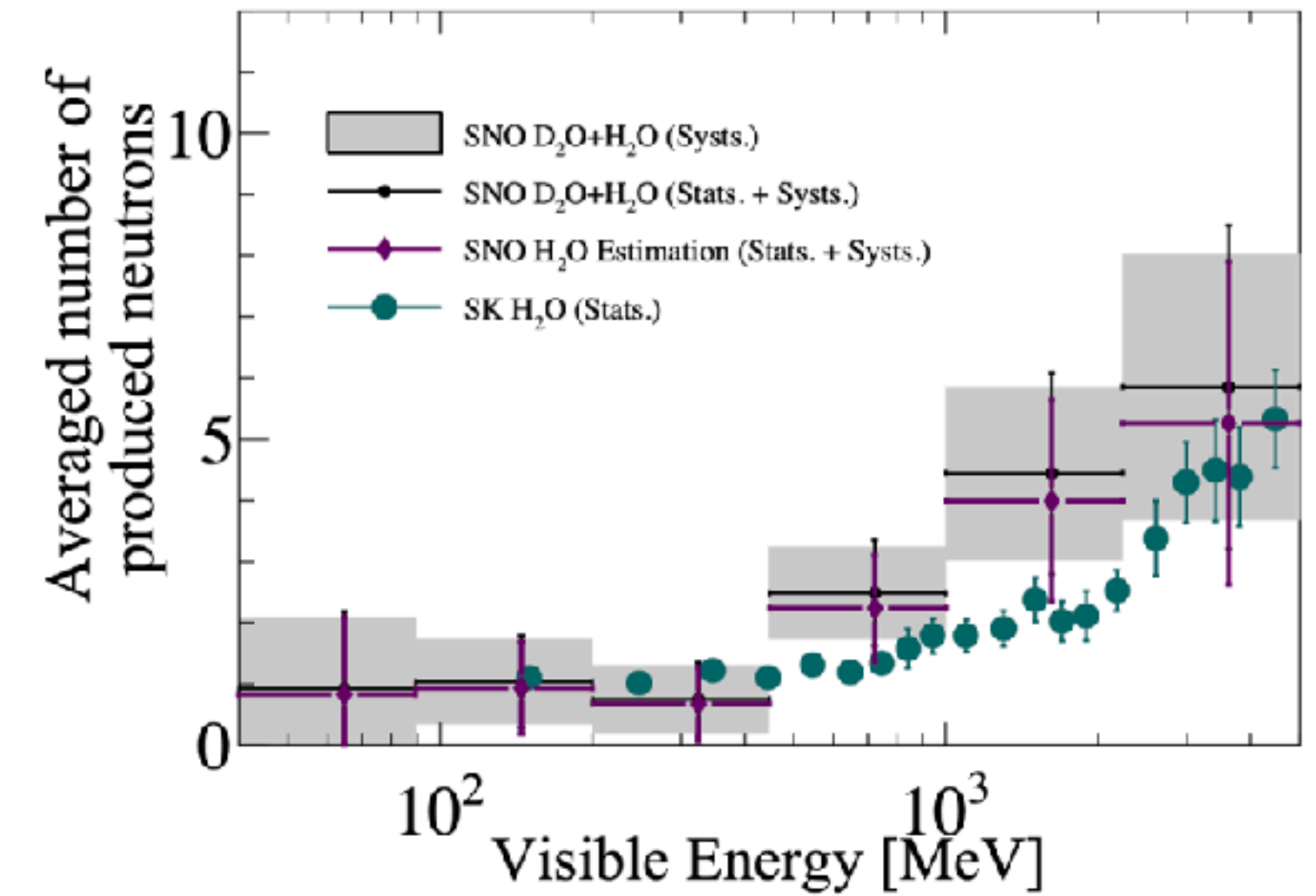
- 26t gadolinium-loaded water Cherenkov detector in the Booster Neutrino Beam (BNB)
 - Gd has a high neutron capture cross section (~150,000X greater than hydrogen)
- Also a testbed for new technologies
 - Large Area Picosecond Photodetectors (LAPPDs)
 - Water-based Liquid Scintillator (WbLS)



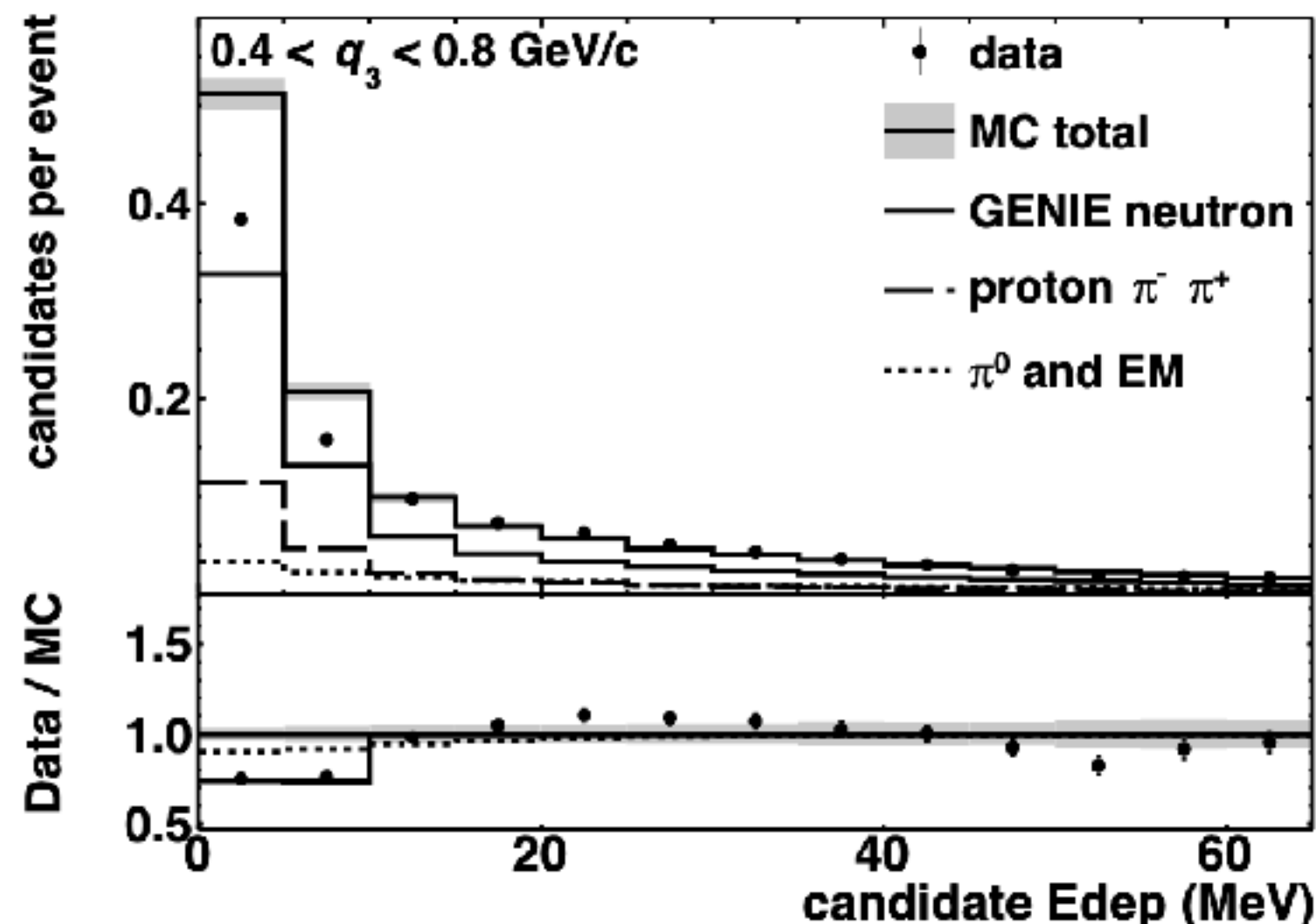
Why ANNIE?

- Significant data/MC discrepancies have been seen
- ANNIE is near the target of a neutrino beam
 - High statistics: $O(10^4)$ neutrino events per year
- Gd loading \rightarrow high detection efficiency ($\sim 65\%$)

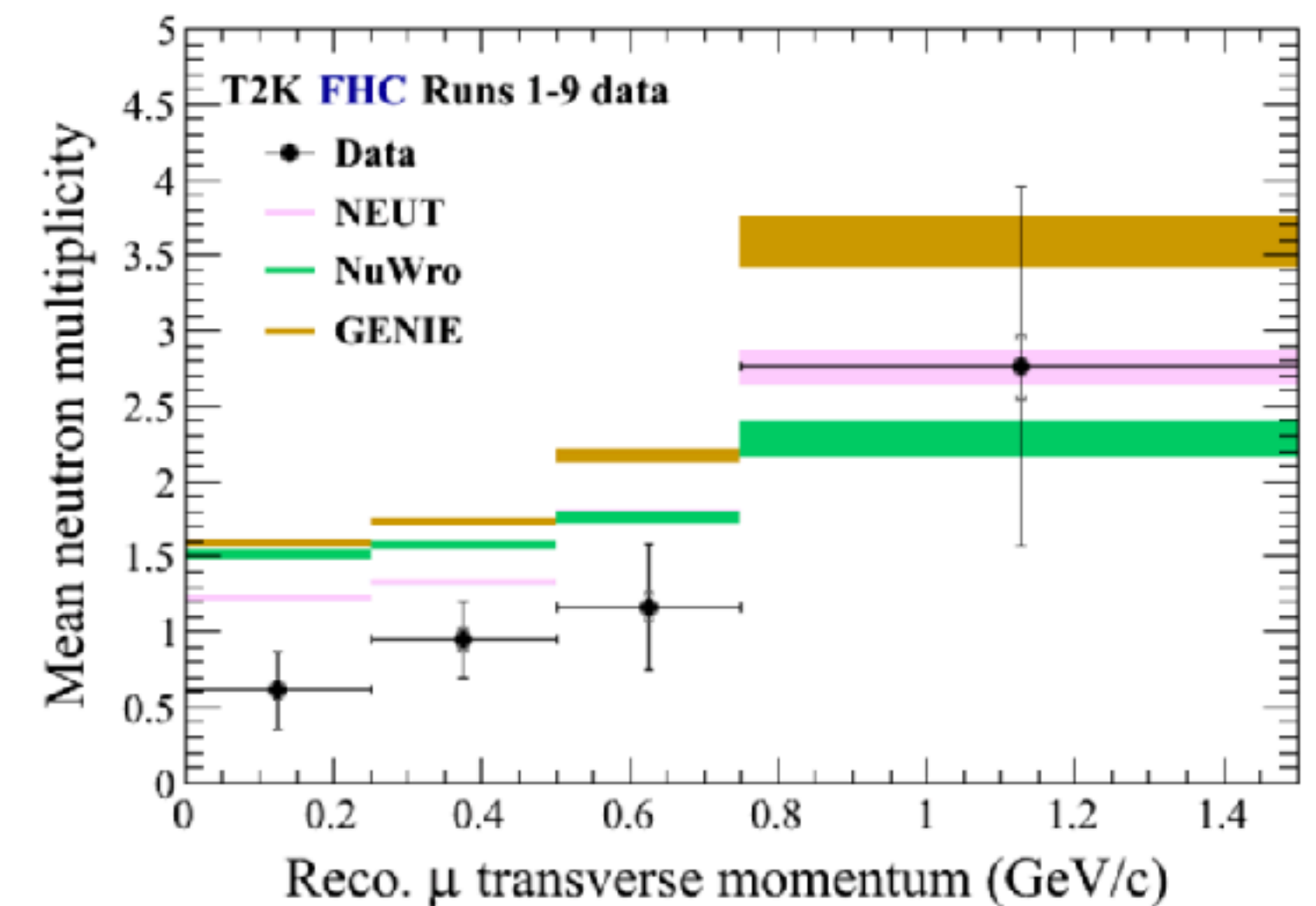
SNO/SK (atm. neutrinos)



MINERvA (beam neutrinos)

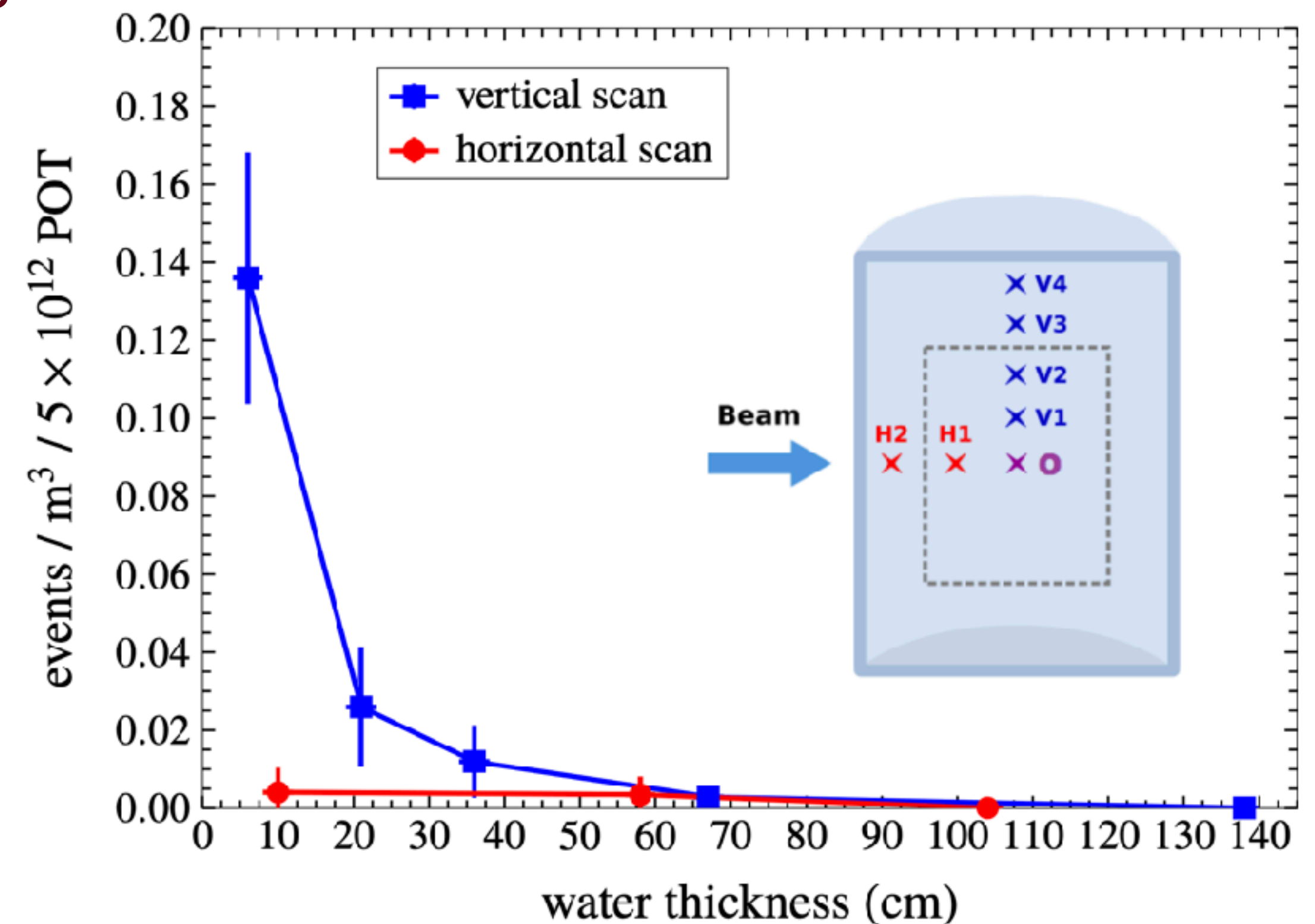


T2K (beam neutrinos)



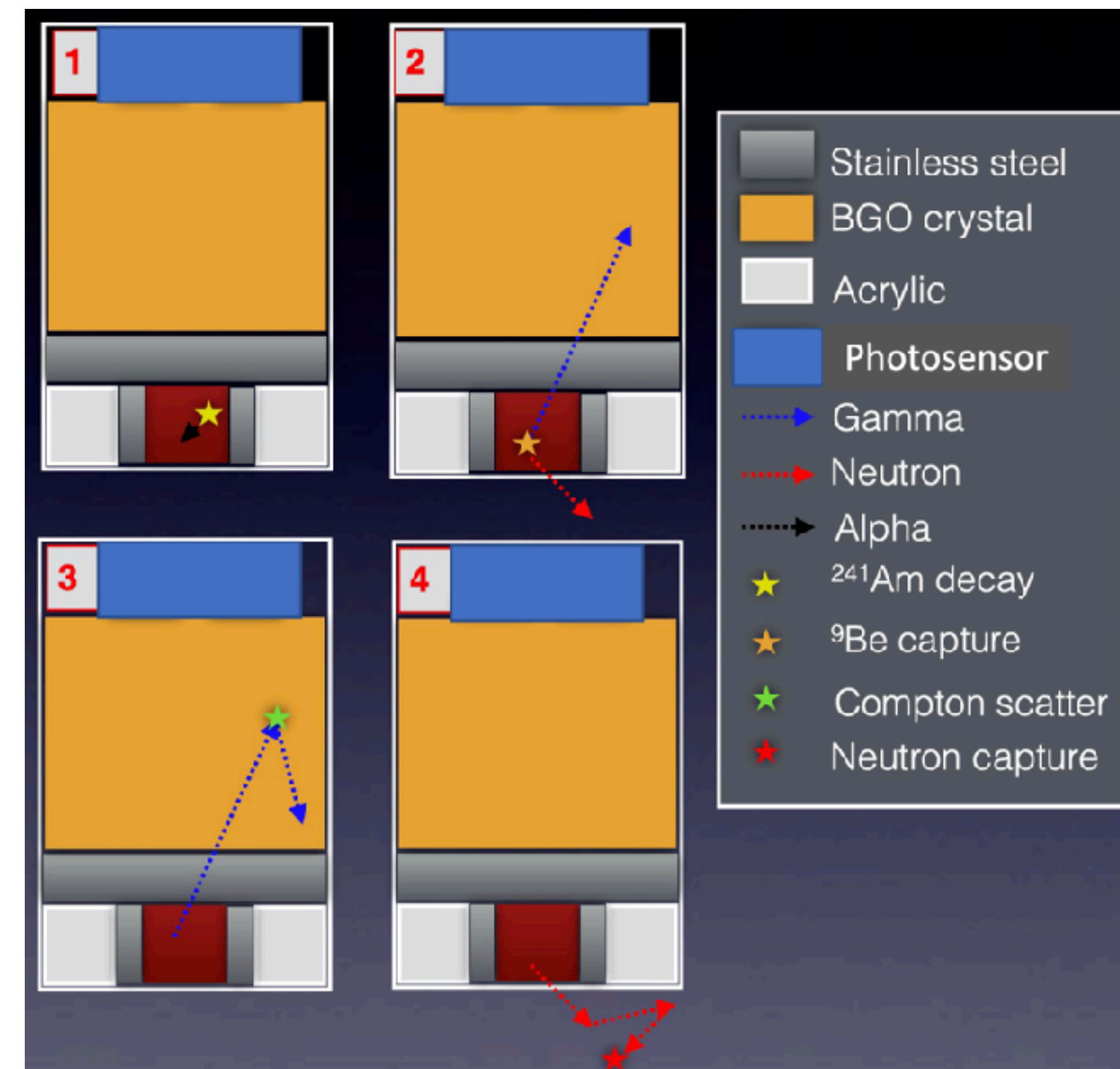
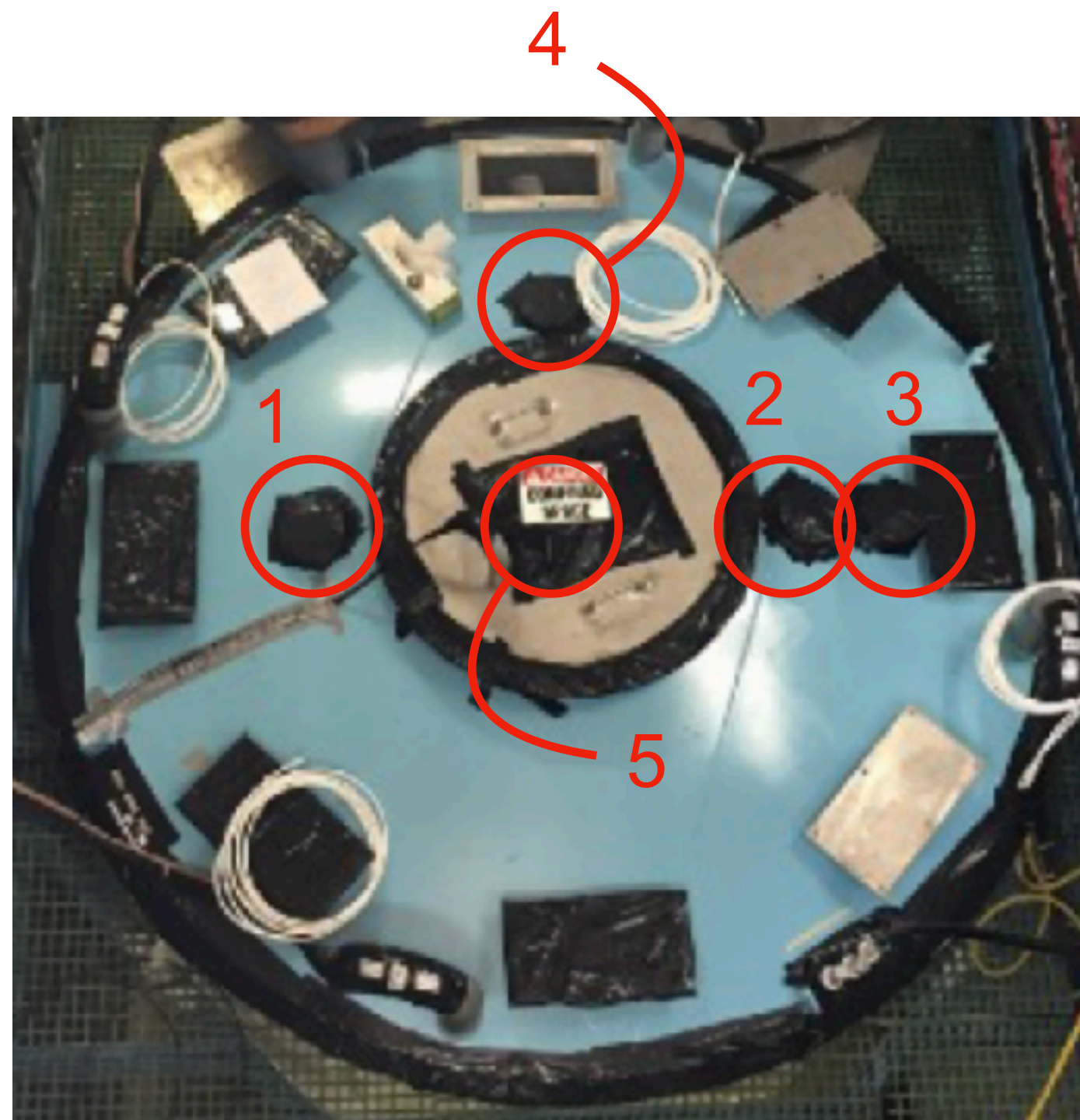
Background measurement (Phase-I)

- Partially instrumented, pure water target without Gd
- Inserted an optically-isolated, Gd-loaded neutron capture volume
- Measure beam-correlated neutron backgrounds
 - Skyshine: neutrons that bounce off the atmosphere
 - Dirt: from neutrino interactions in upstream rock



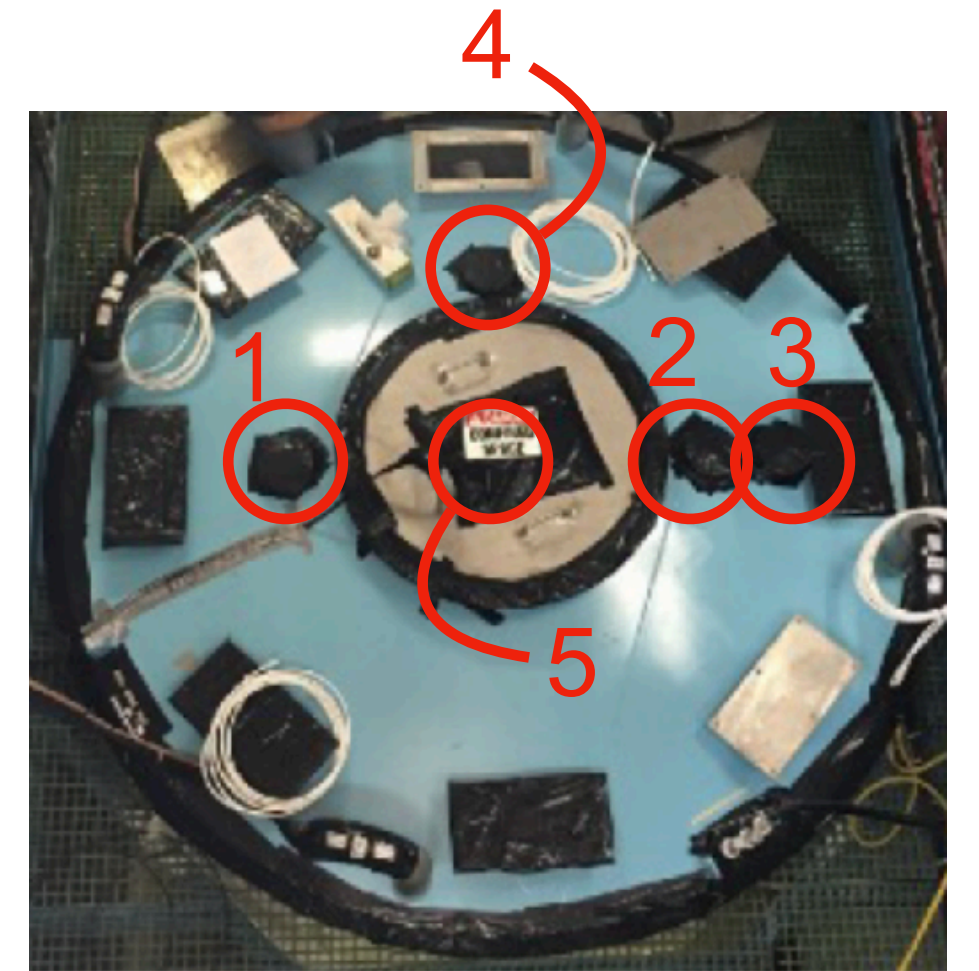
Neutron detection efficiency

- Americium-Beryllium (AmBe) source with a scintillator for triggering
 - Am \rightarrow alpha emitter
 - Be + alpha \rightarrow neutron + gamma (4.4 MeV)

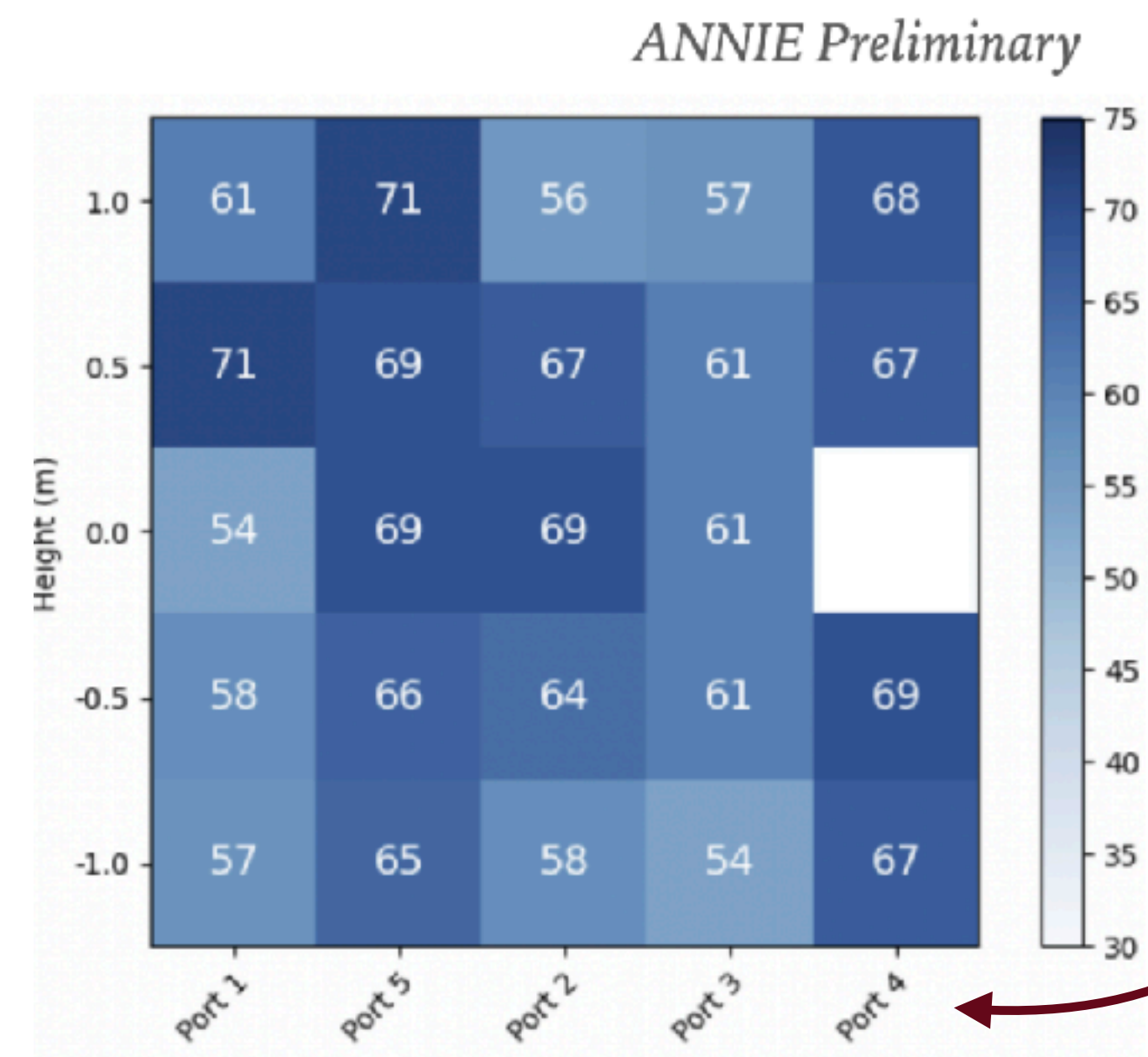
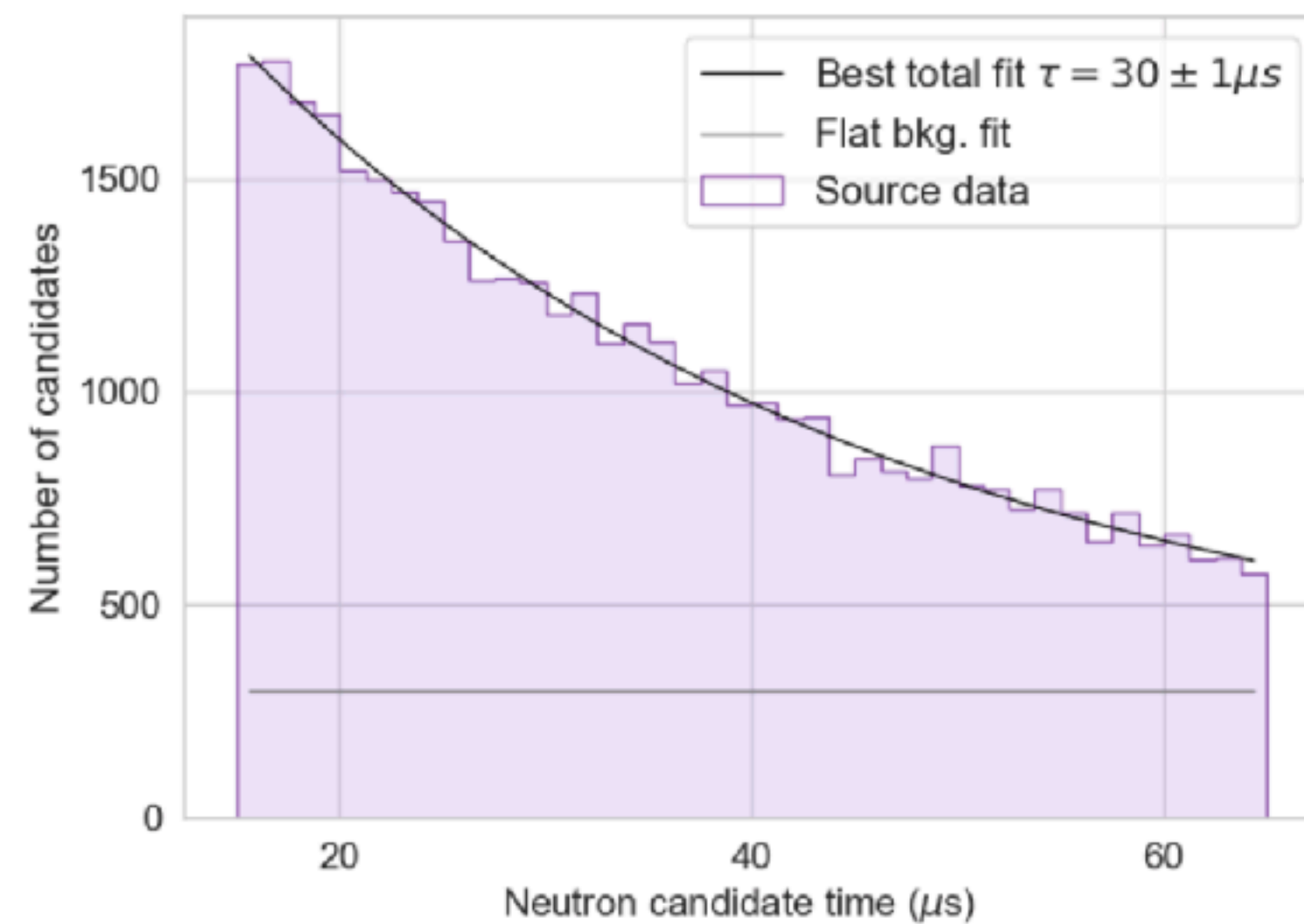


Neutron detection efficiency

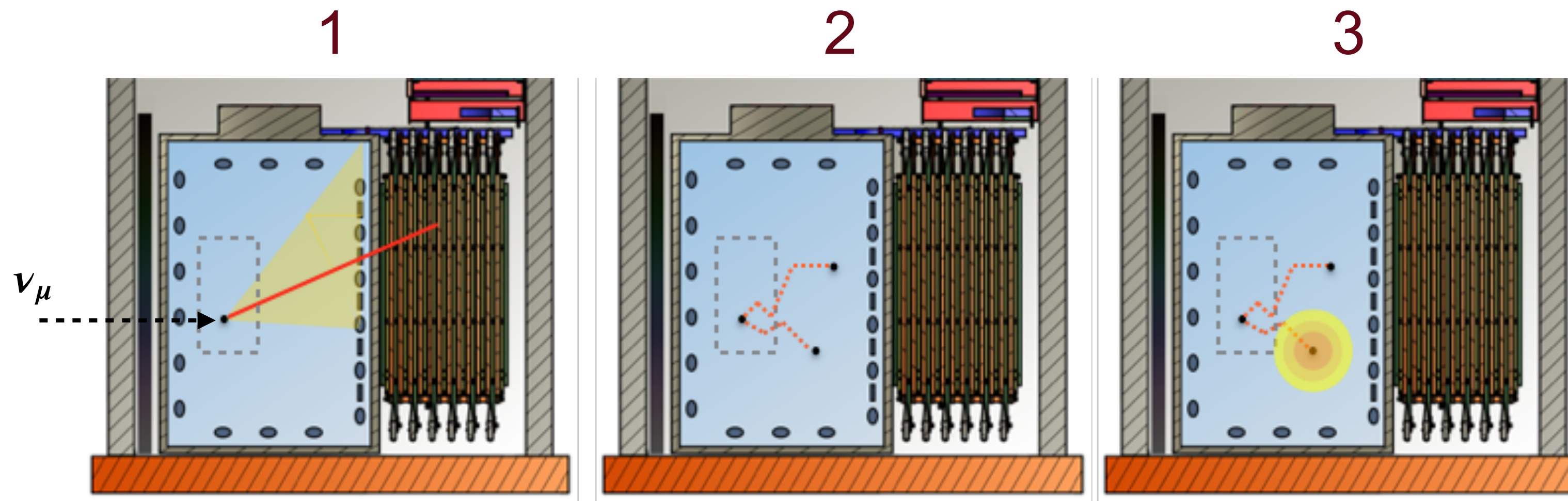
- Americium-Beryllium (AmBe) source with a scintillator for triggering
 - Am \rightarrow alpha emitter
 - Be + alpha \rightarrow neutron + gamma (4.4 MeV)
- Measured capture time of agrees with expectation for 0.2% Gd-loading
- A second deployment campaign is underway



Port numbers



Neutrino interactions in ANNIE



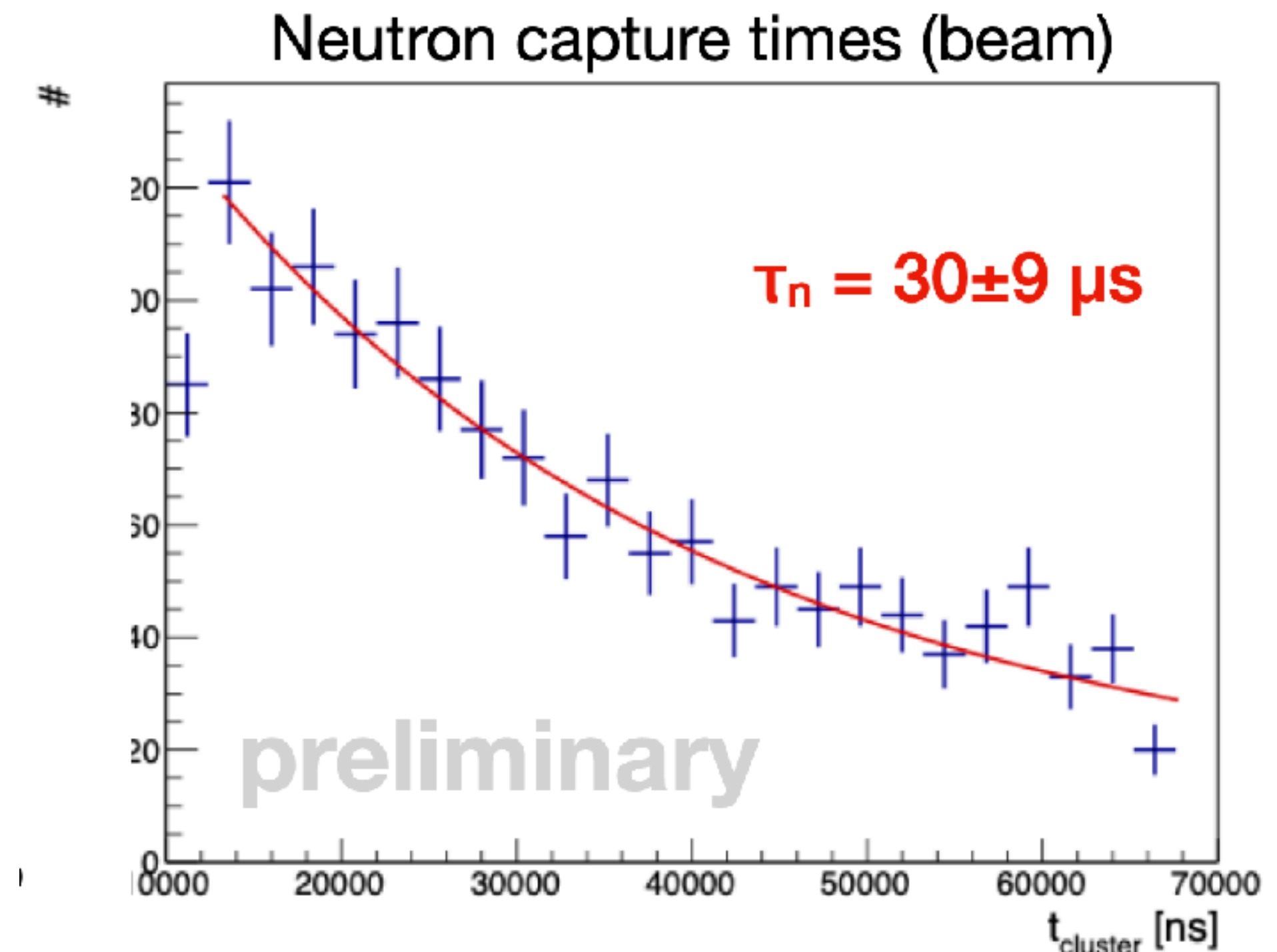
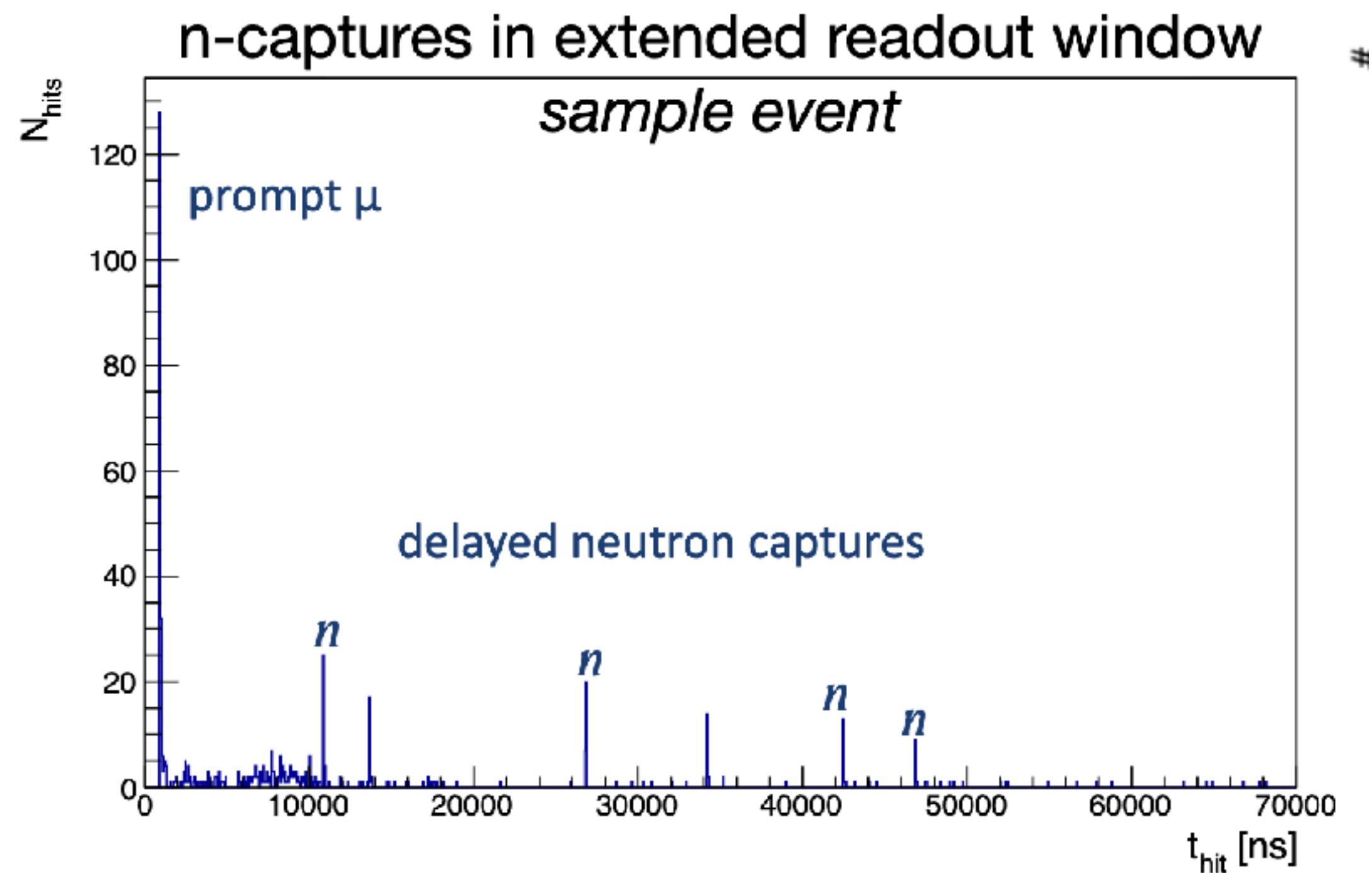
1. ν_μ CC interaction produces an outgoing muon
 - Cherenkov ring (disc) plus MRD track allows for vertex reconstruction

2. Outgoing neutrons bounce around and thermalize

3. Thermal neutrons capture on Gd
 - Produces characteristic 8 MeV photons

First beam neutrinos

- Beam spill + high PMT readings define a 2 μs trigger window
- Additional PMT signals open up an extended 70 μs window to detect delayed neutrons
 - Beam neutron capture time agrees with AmBe calibration

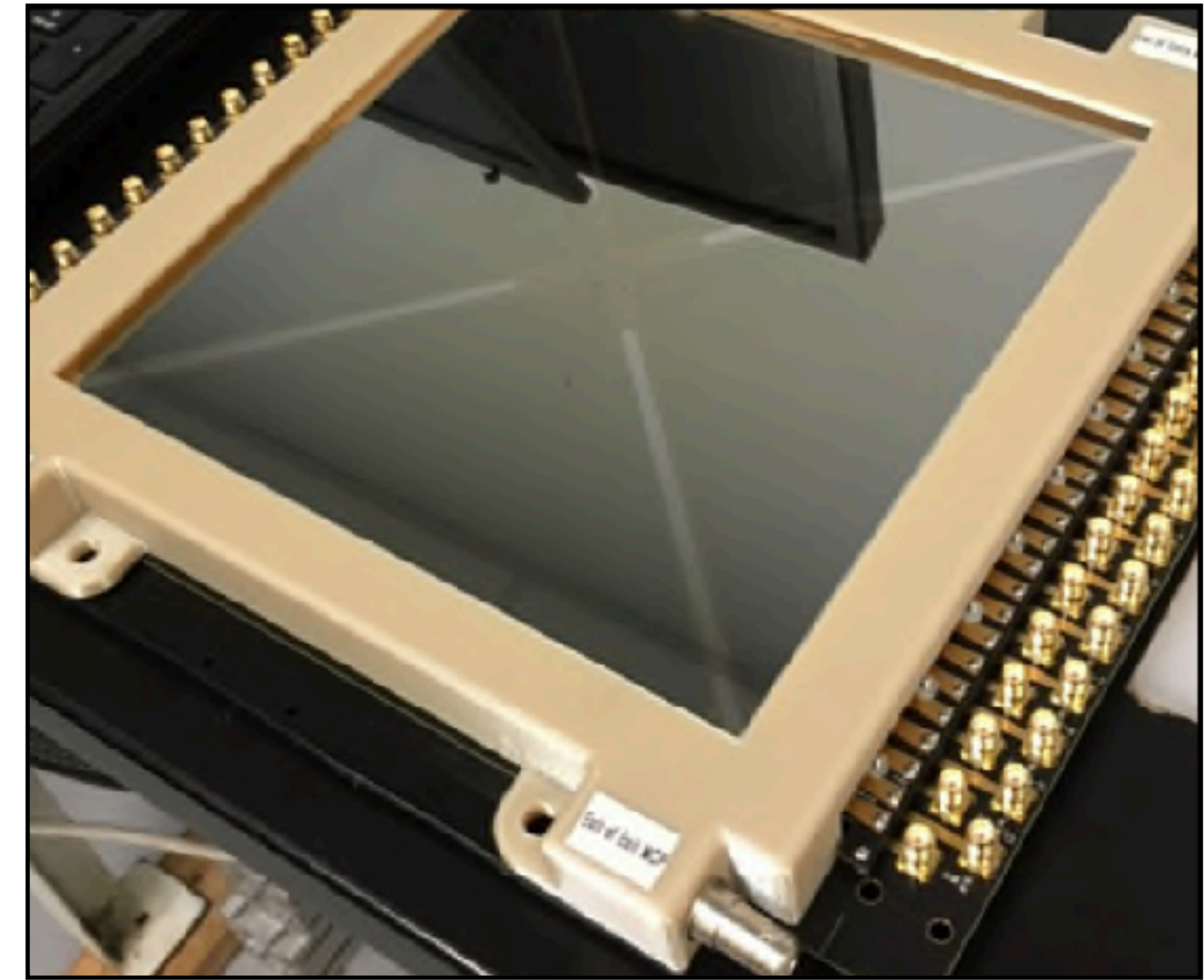


Novel Technologies

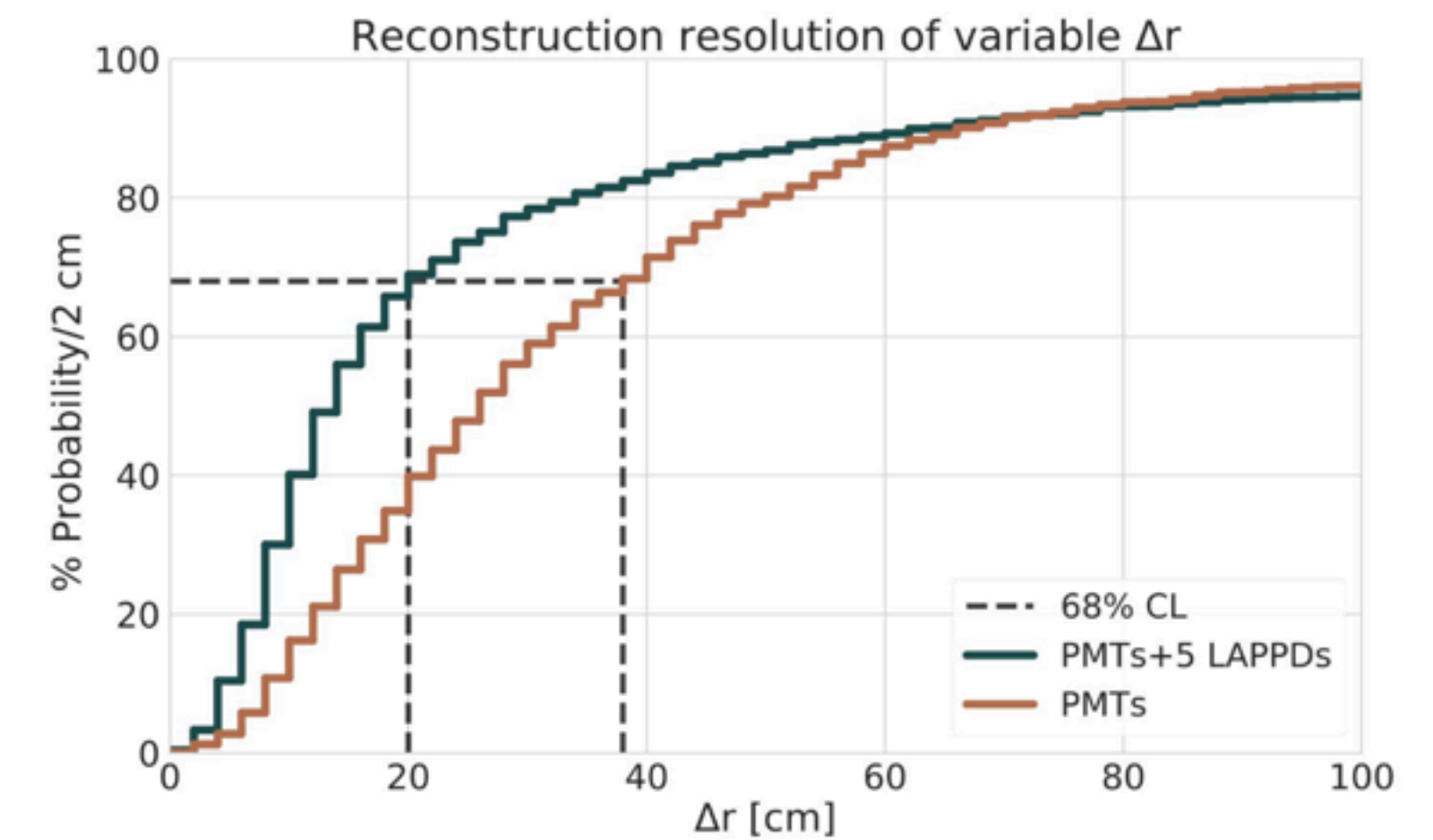
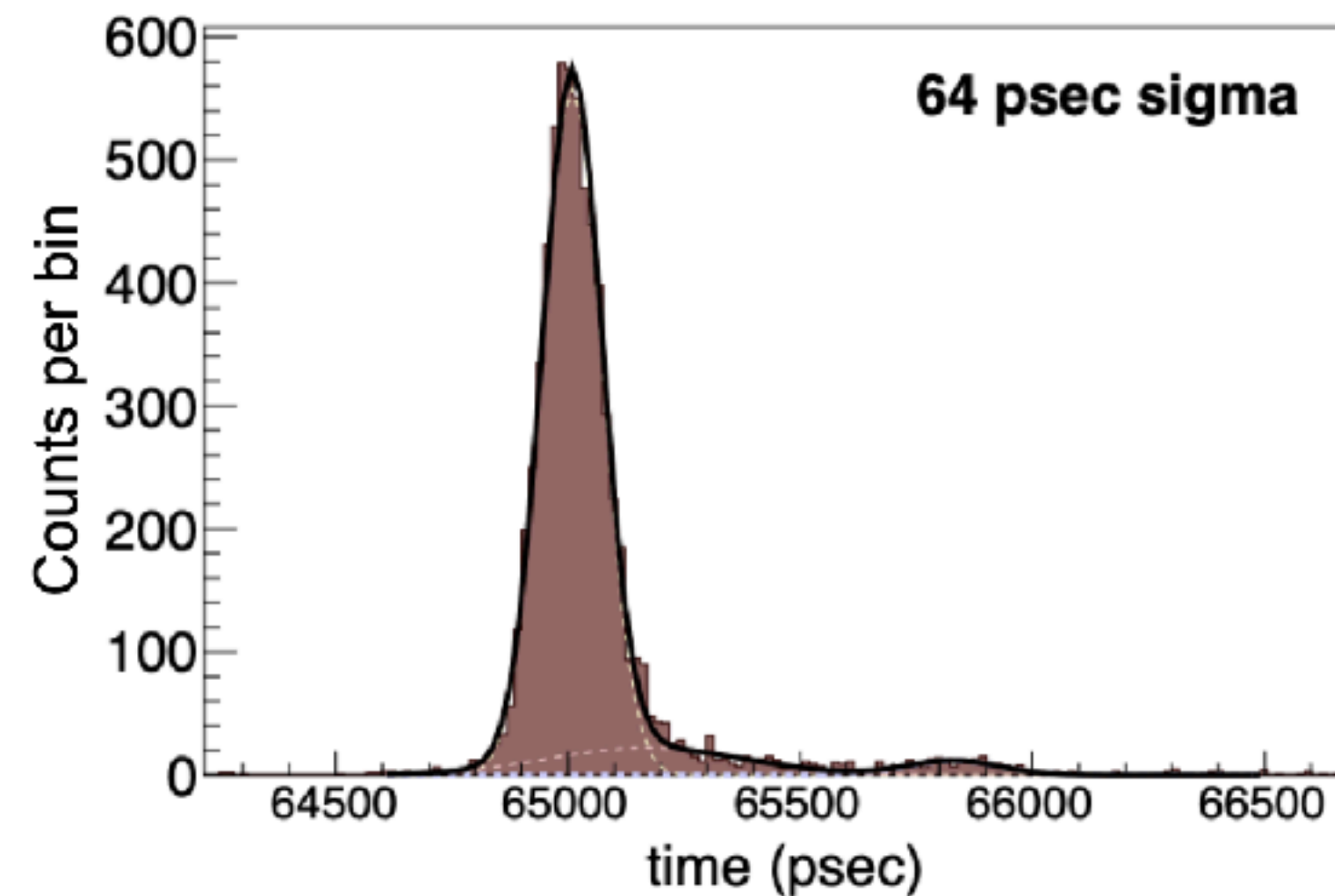
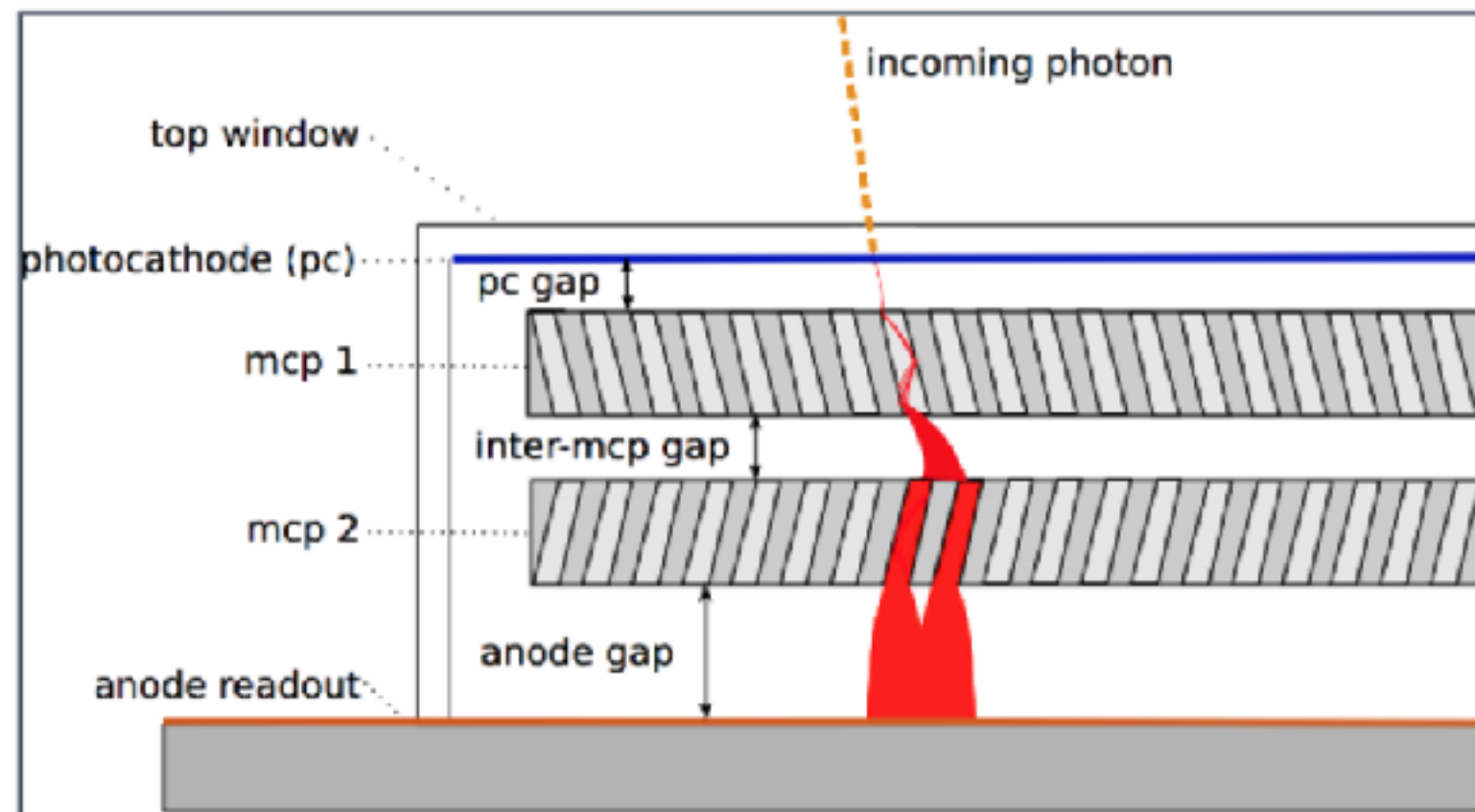
LAPPDs

Large Area Picosecond Photodetectors

- 20 X 20 cm tiles containing two micro-channel plates (MCPs)
- Timing resolution of < 100 psec and sub-cm spatial resolution
- Improves vertex and angular reconstruction by $\sim 2X$



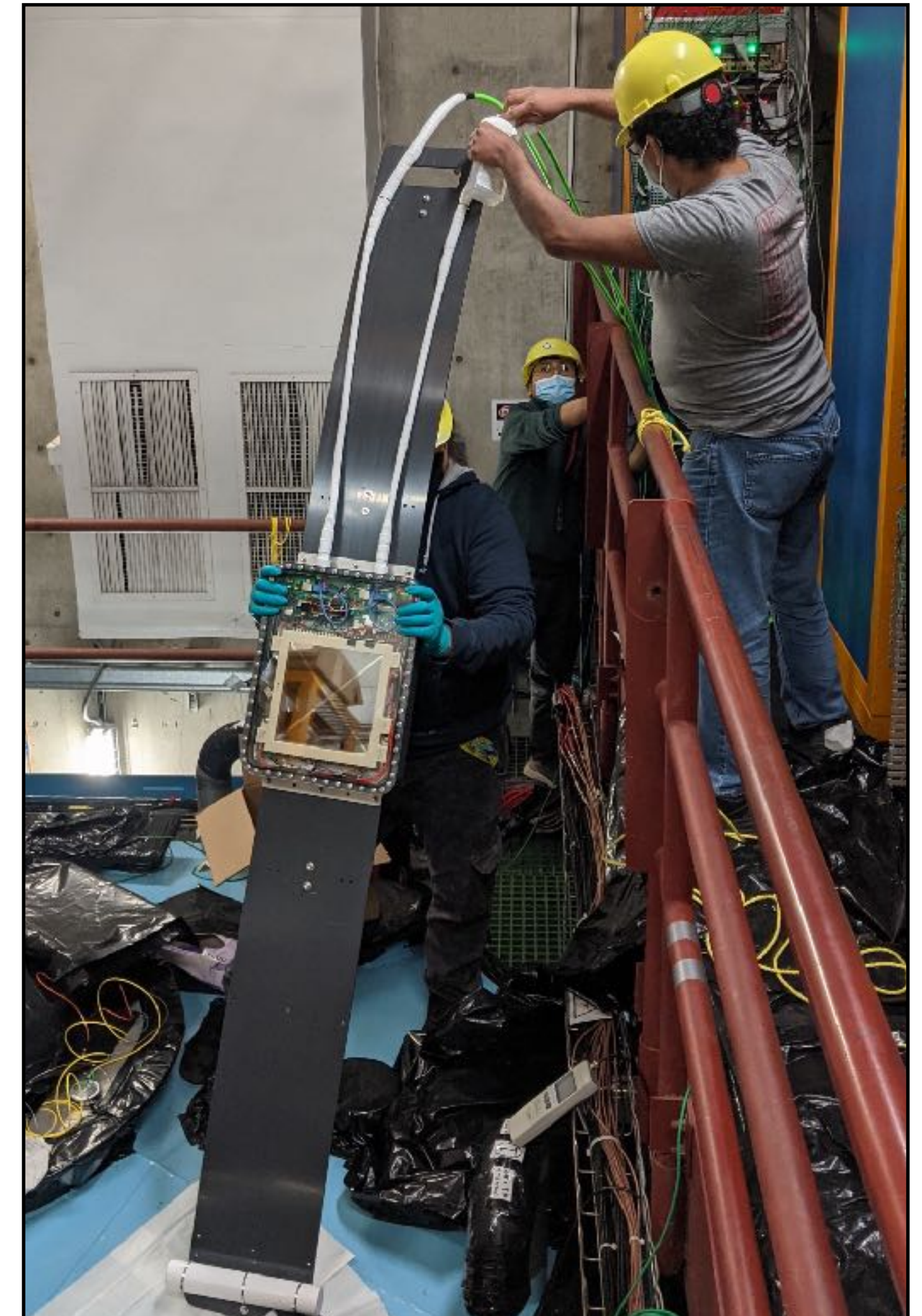
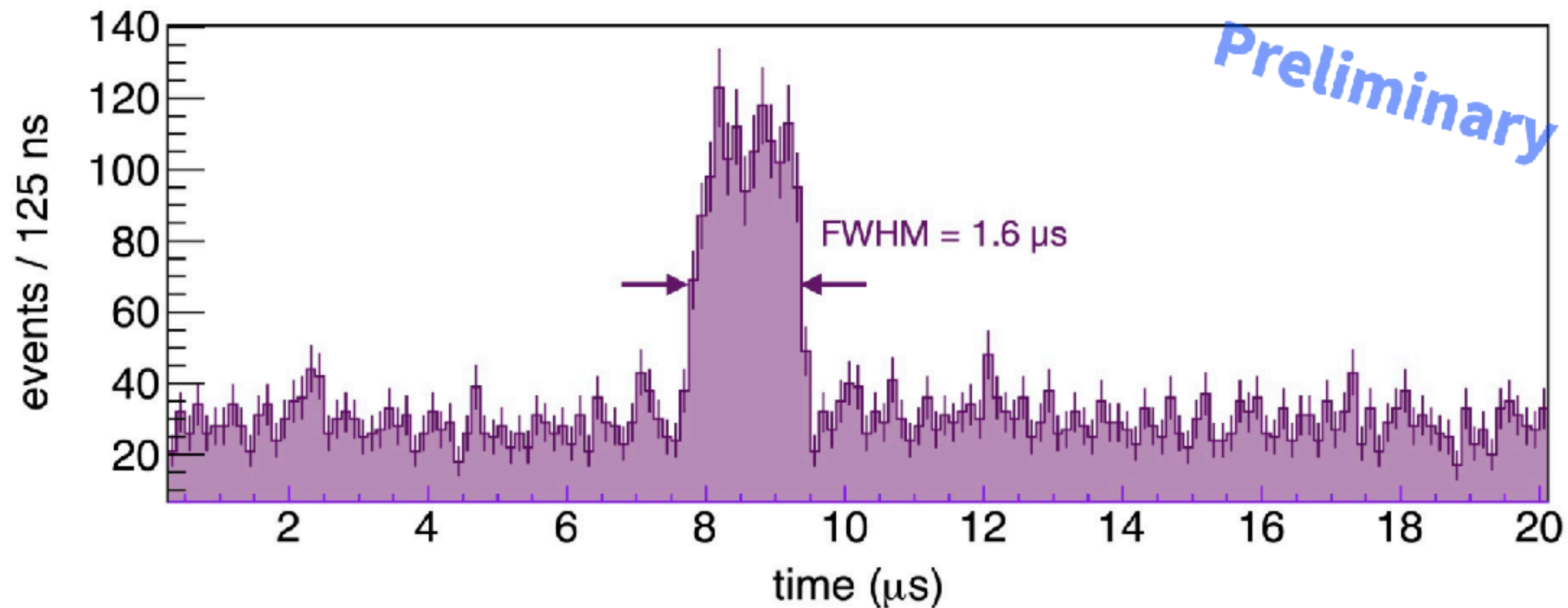
LAPPD cross-section



LAPPD deployment

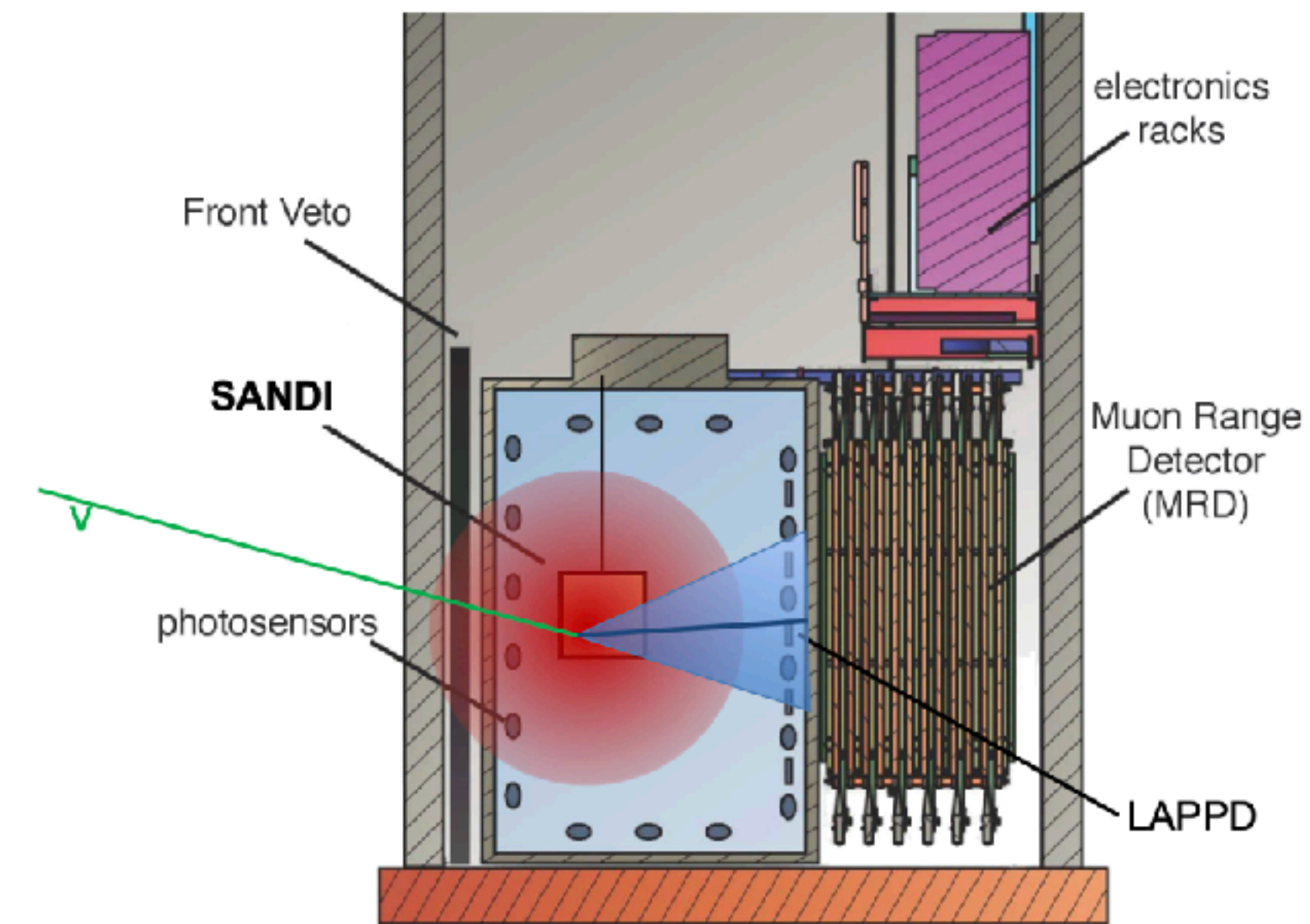
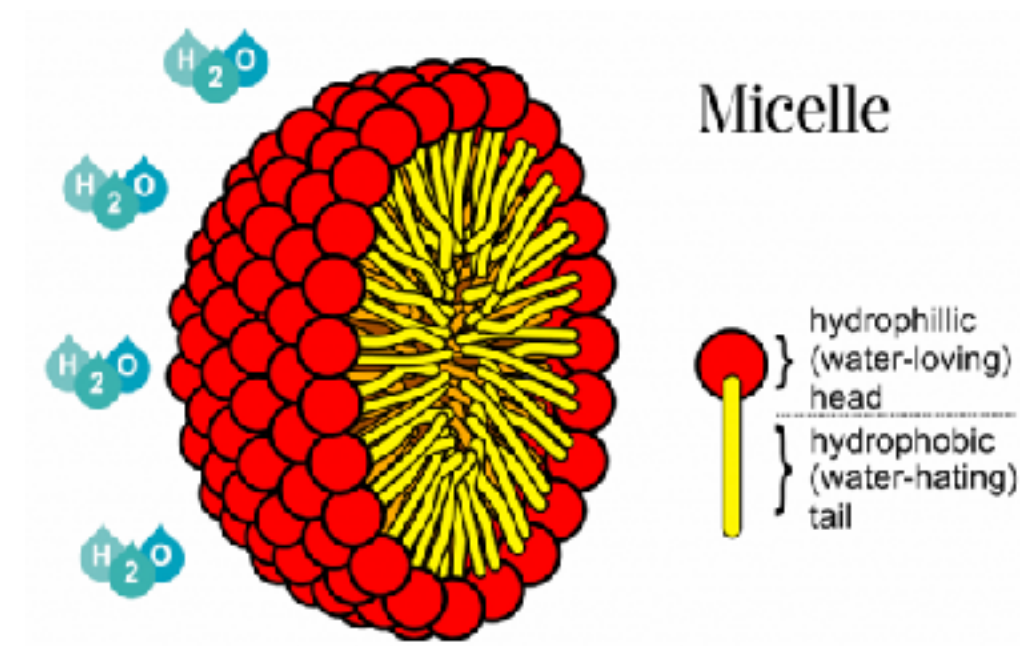
- First LAPPD was deployed in early 2022
- Two additional LAPPDs went in earlier this year
 - Multi-LAPPD readout of a neutrino beam!
- Two more planned in the coming months

First ever neutrino beam events on an LAPPD!



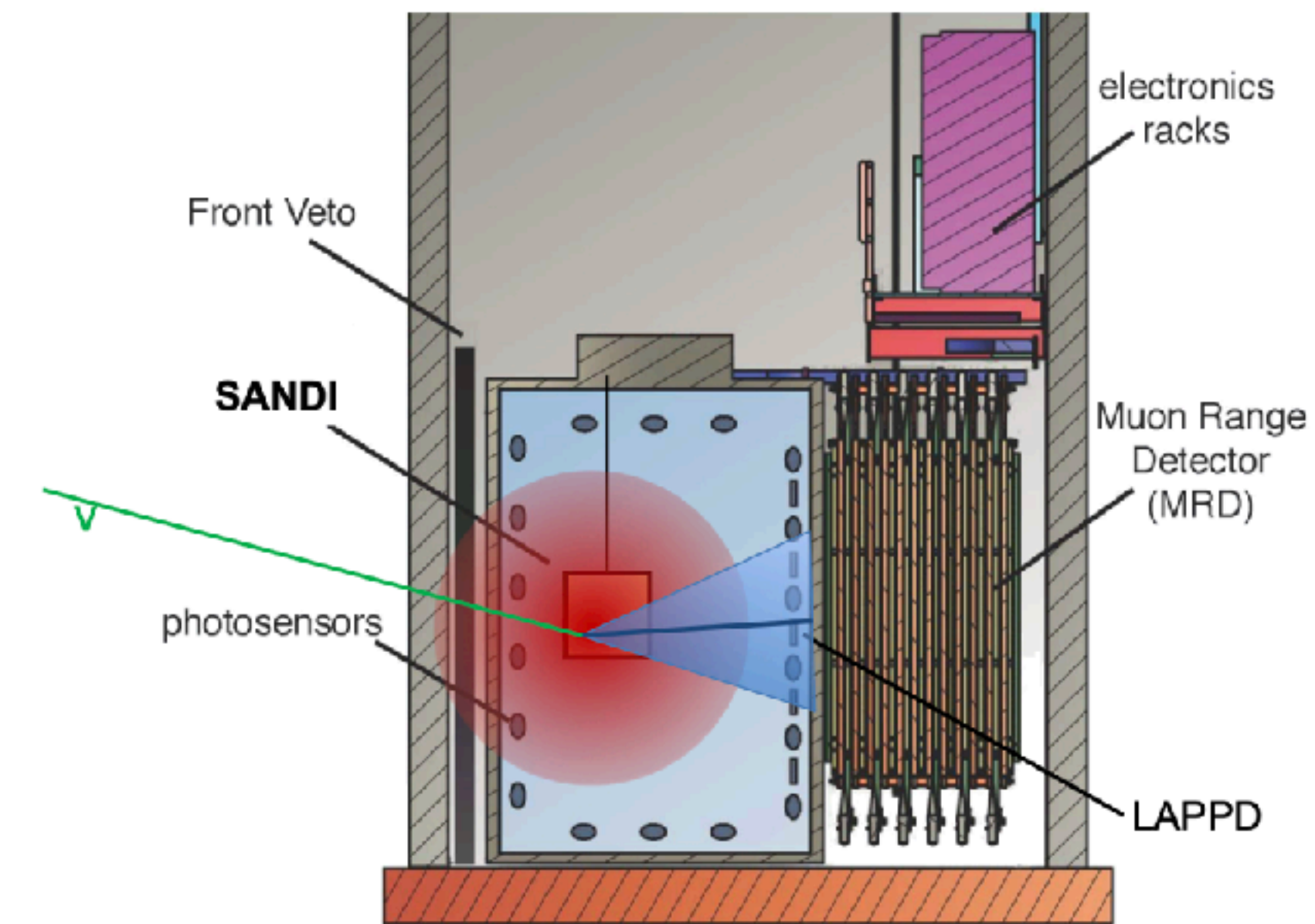
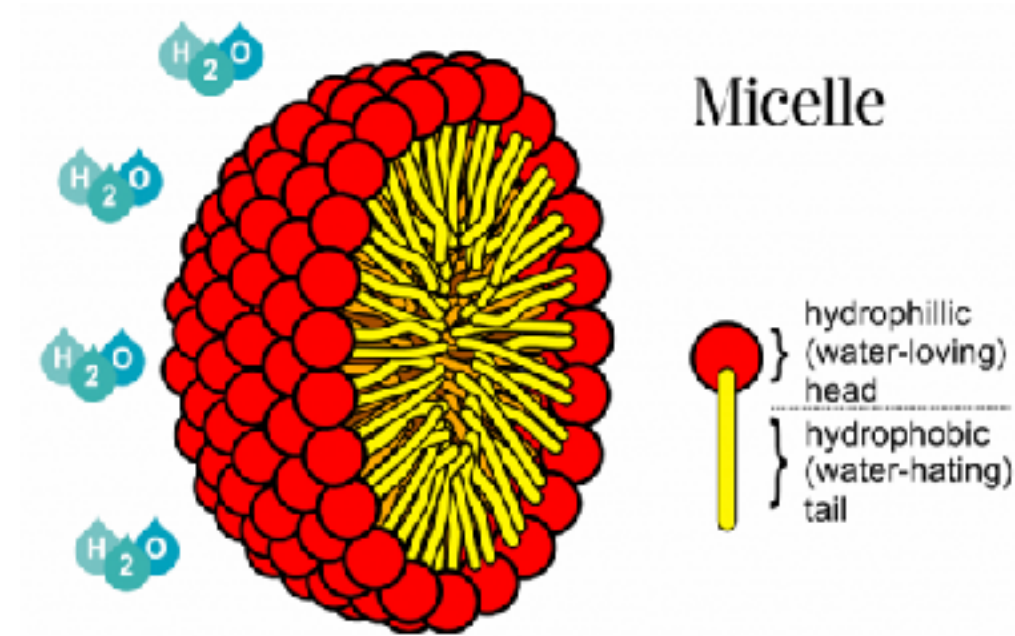
WbLS

- Water-based Liquid Scintillator is a novel detection medium
 - Low attenuation and Cherenkov production of pure water
 - High light yield and low detection threshold of liquid scintillator
 - Tunable and easily loadable

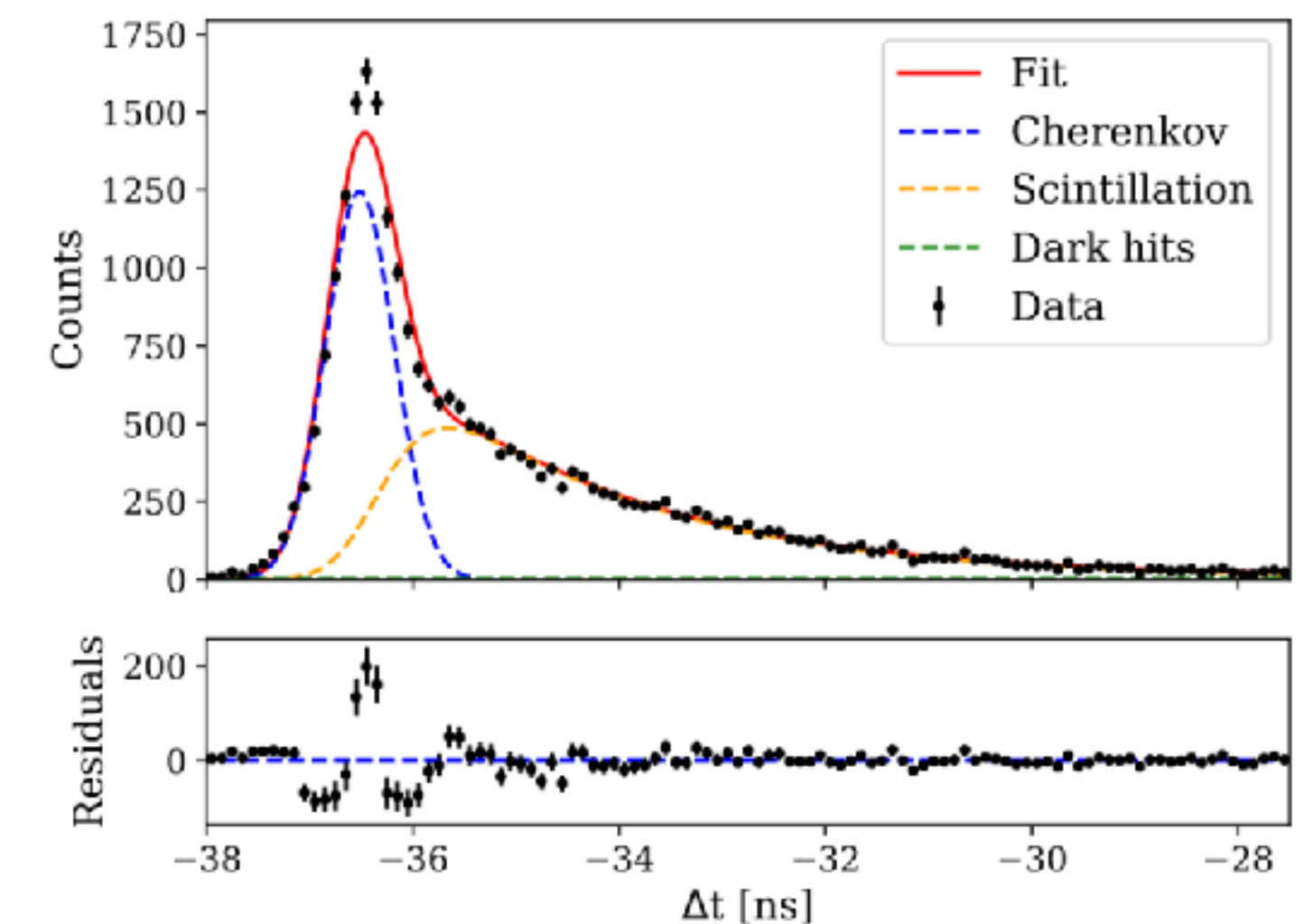


WbLS

- Water-based Liquid Scintillator is a novel detection medium
 - Low attenuation and Cherenkov production of pure water
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 - Tunable and easily loadable
- WbLS + LAPPDs → C/S separation
 - Fast Cherenkov light for good timing and spatial resolution
 - Slower scintillation light gives better energy resolution

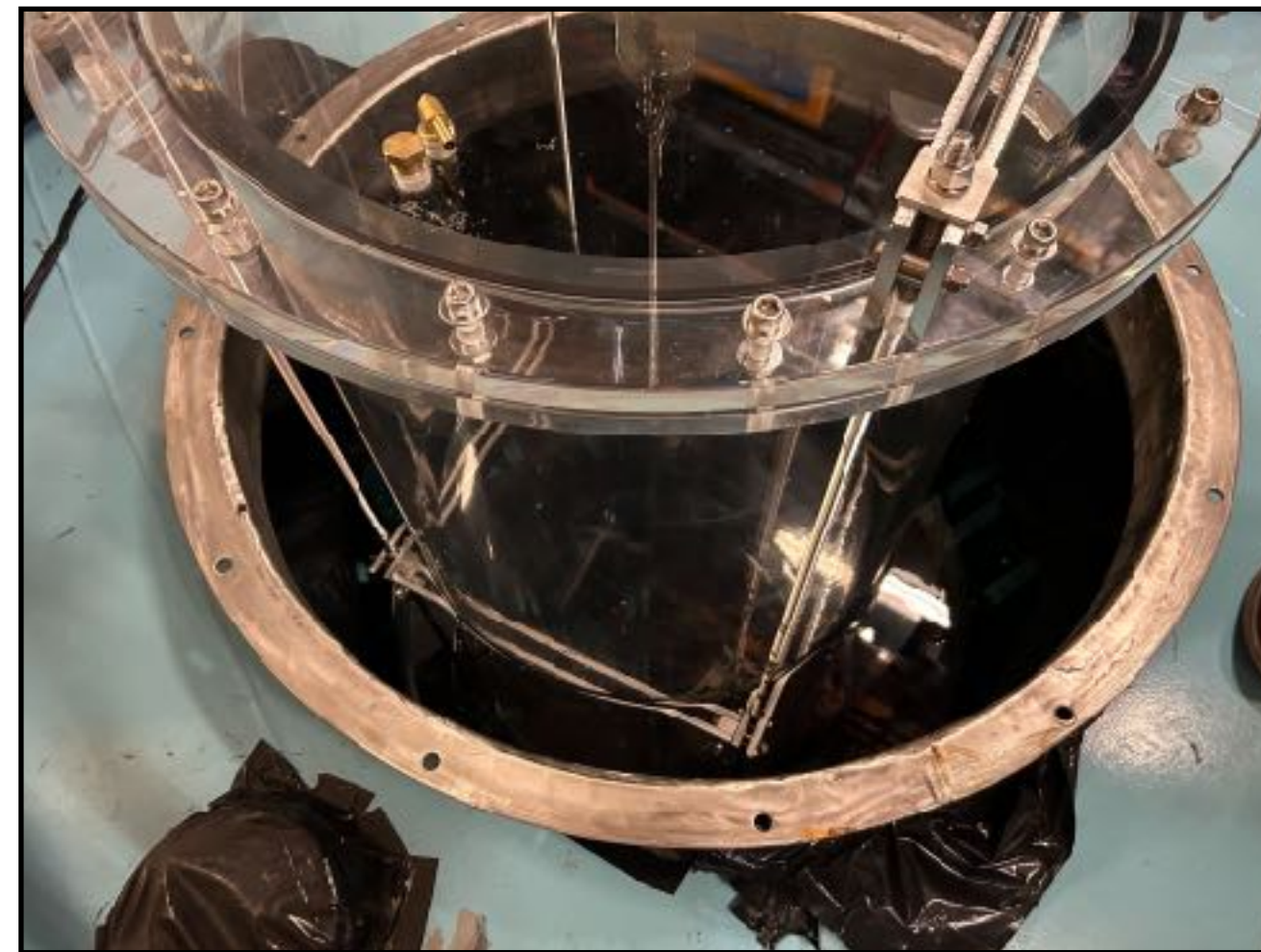
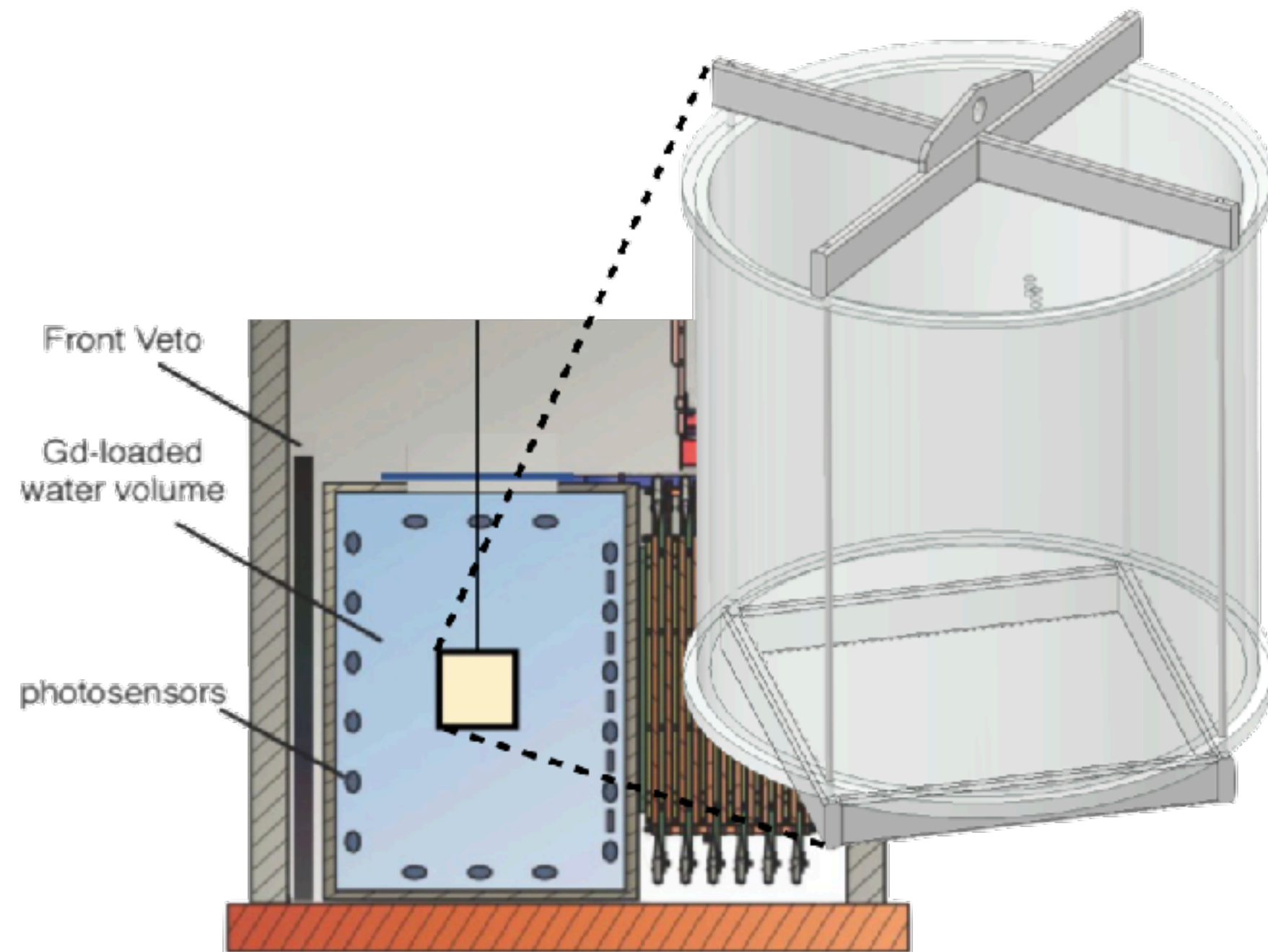


CHESS @ UC Berkeley, [arxiv:2110.13222](https://arxiv.org/abs/2110.13222)

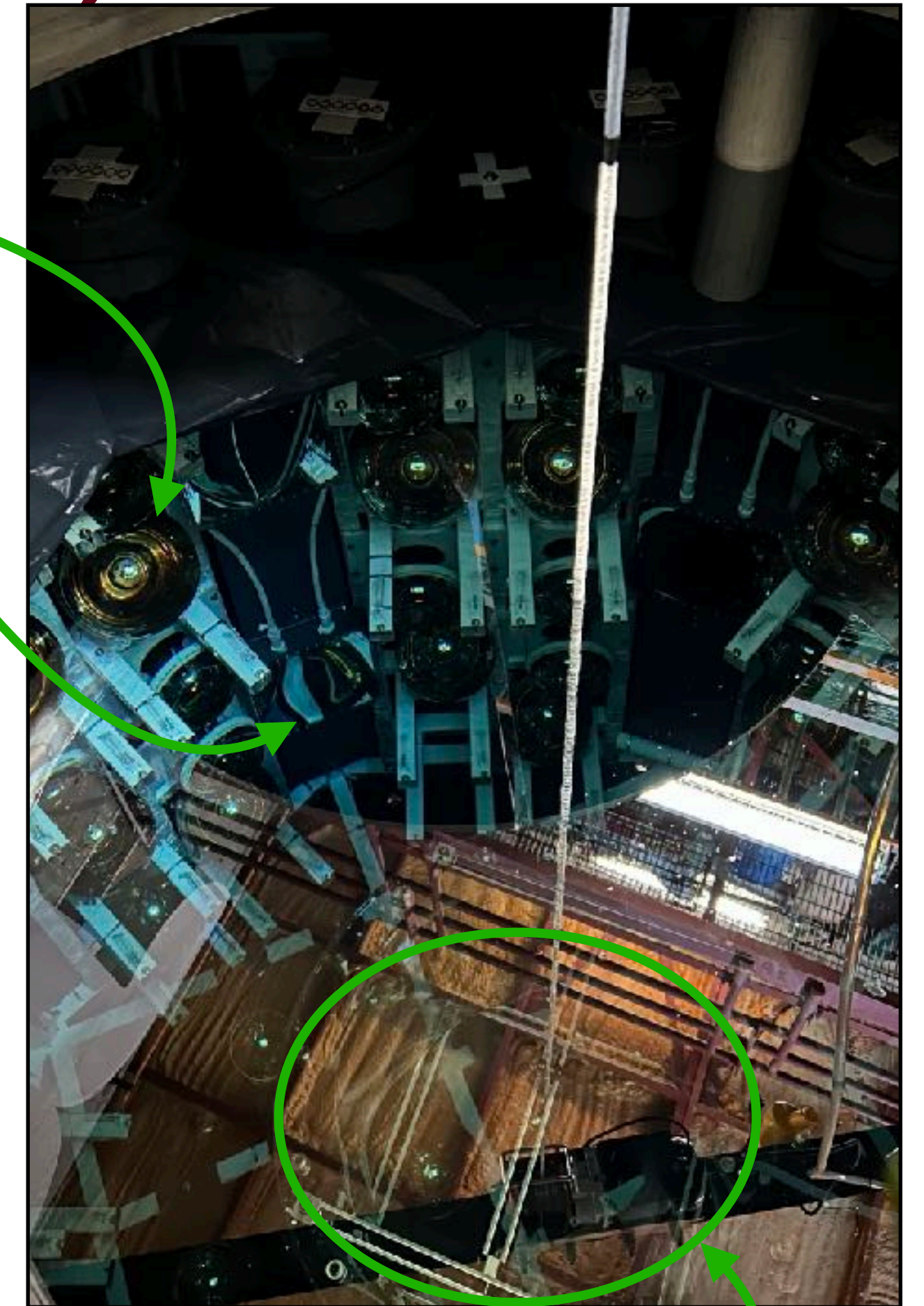


WbLS Deployment (SANDI)

- Scintillator for ANNIE Neutrino Detection Improvement
 - 0.9 X 0.9 m cylindrical vessel → ~360 liters of WbLS
- Deployed in March, took ~2 months of beam data



PMT
LAPPD



SANDI

The future of ANNIE

- Deploy the final two LAPPDs for a total of 5
- Perform the neutron multiplicity analysis
- Work toward a joint ANNIE-SBN water-LAr cross section measurement
- Analyze WbLS data
 - Demonstrate separation of Cherenkov/Scintillation light
 - Redeploy WbLS with Gd-loading



The future of ANNIE

This document was prepared by the ANNIE collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

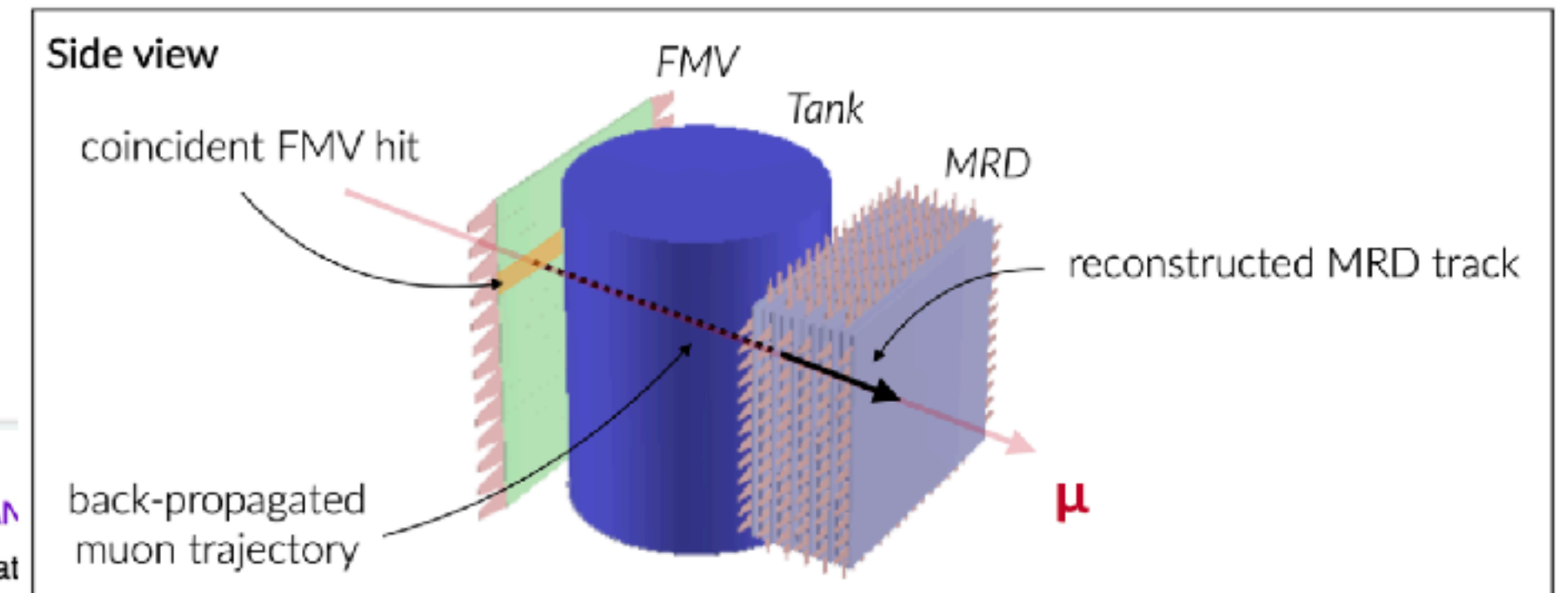
- Deploy the final two LAPPDs for a total of 5
- Perform
- Work to section
- Analyze
 - Demo
 - Rede



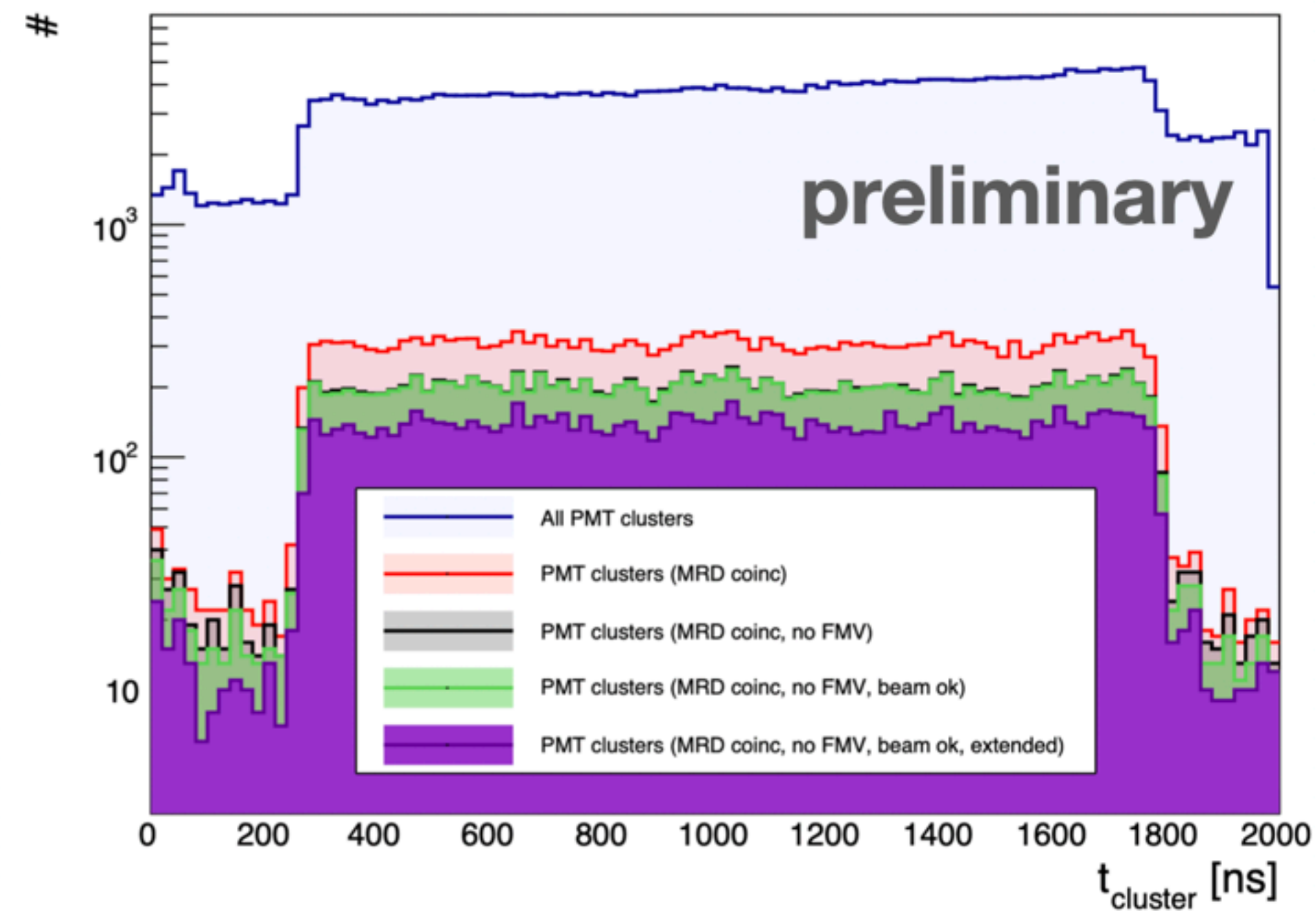
SLIDES-23-147-V

Backups

Neutrino events

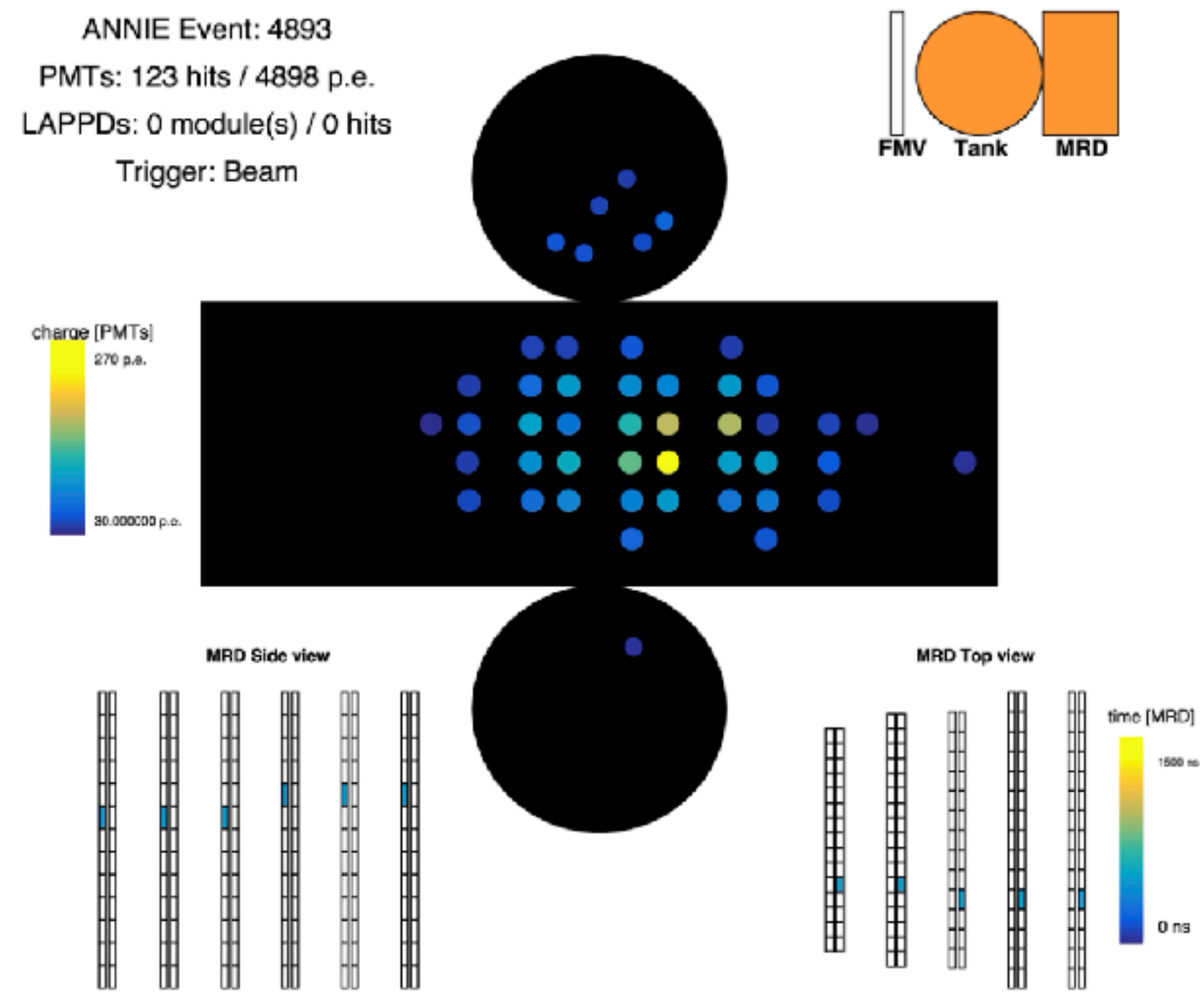


Neutrino candidate time distribution

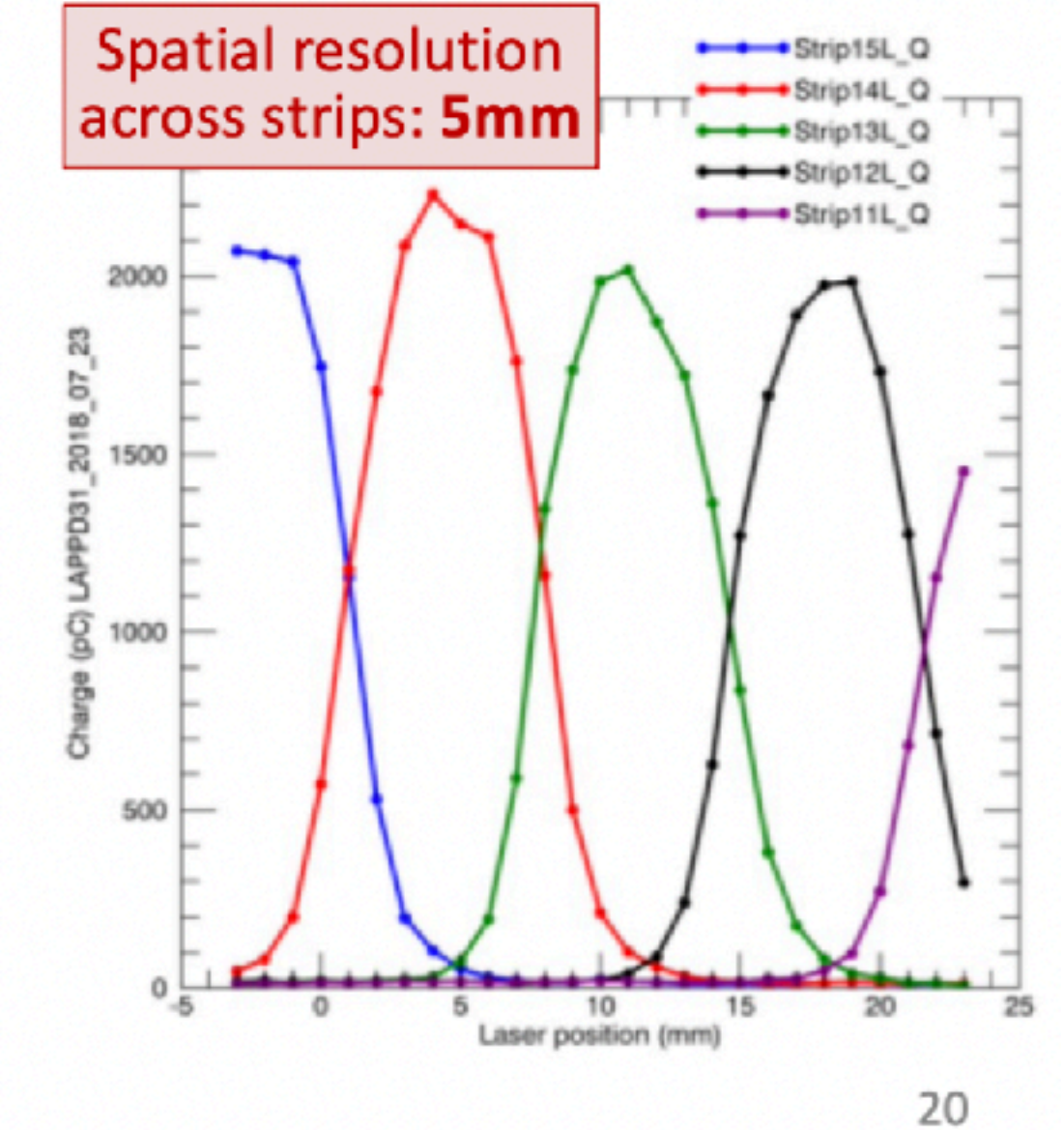
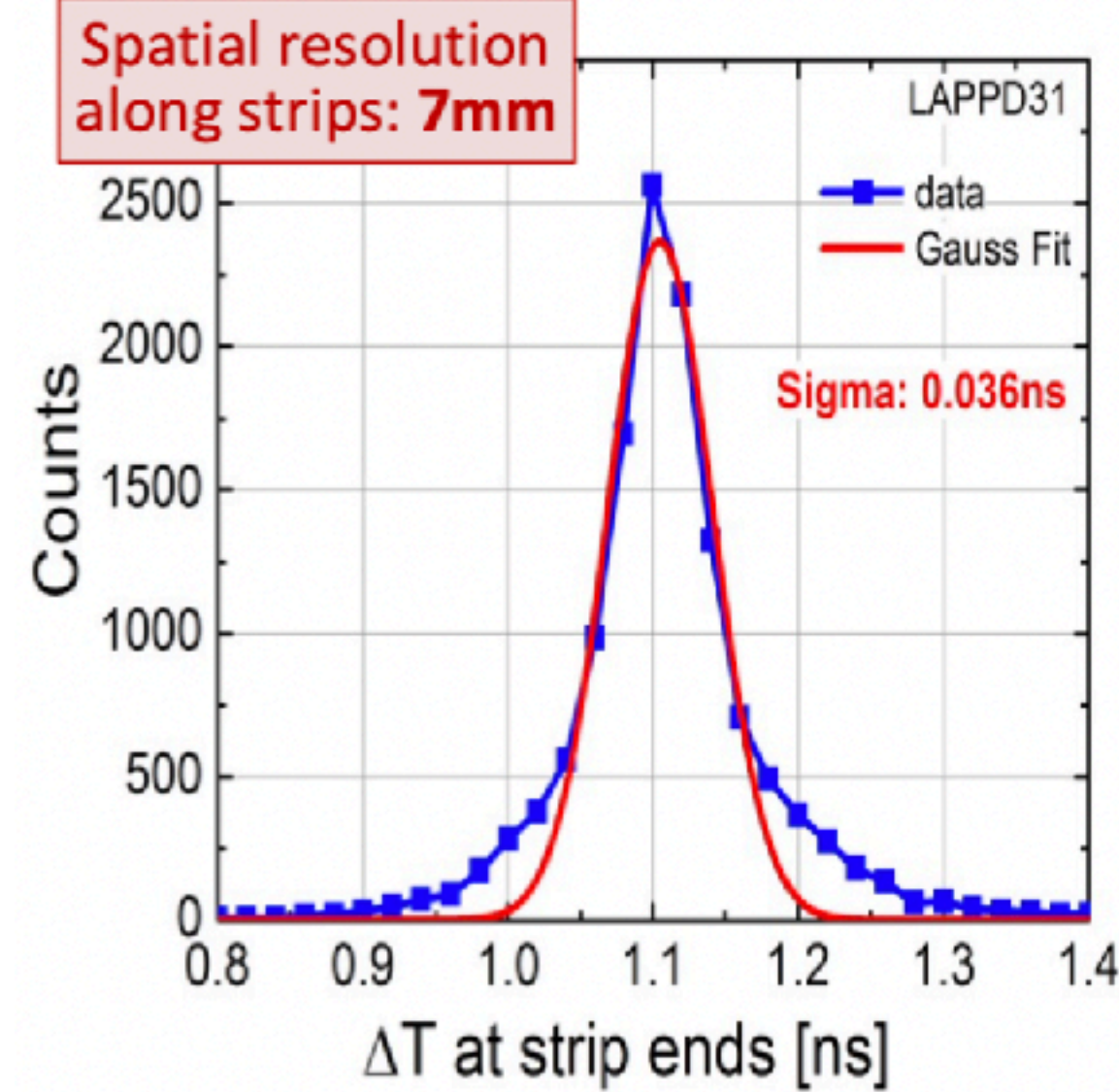
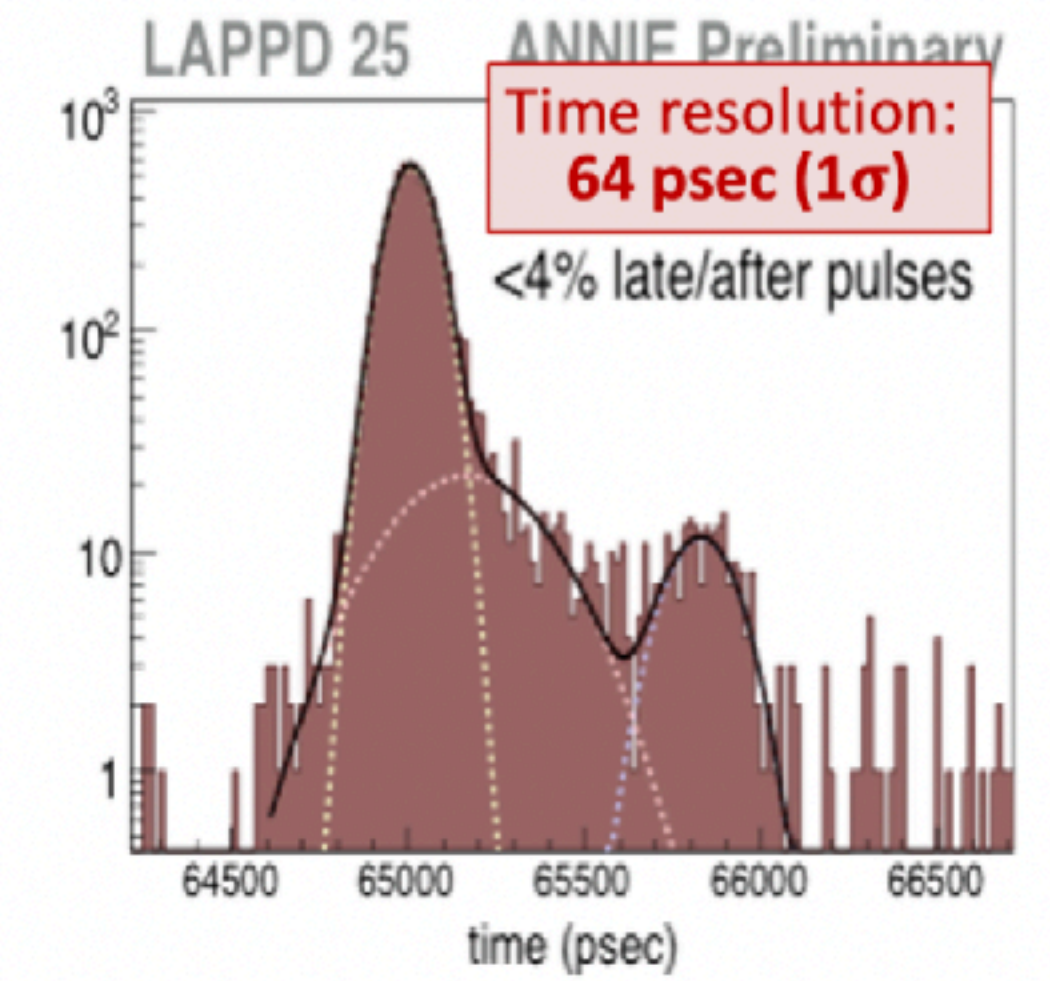
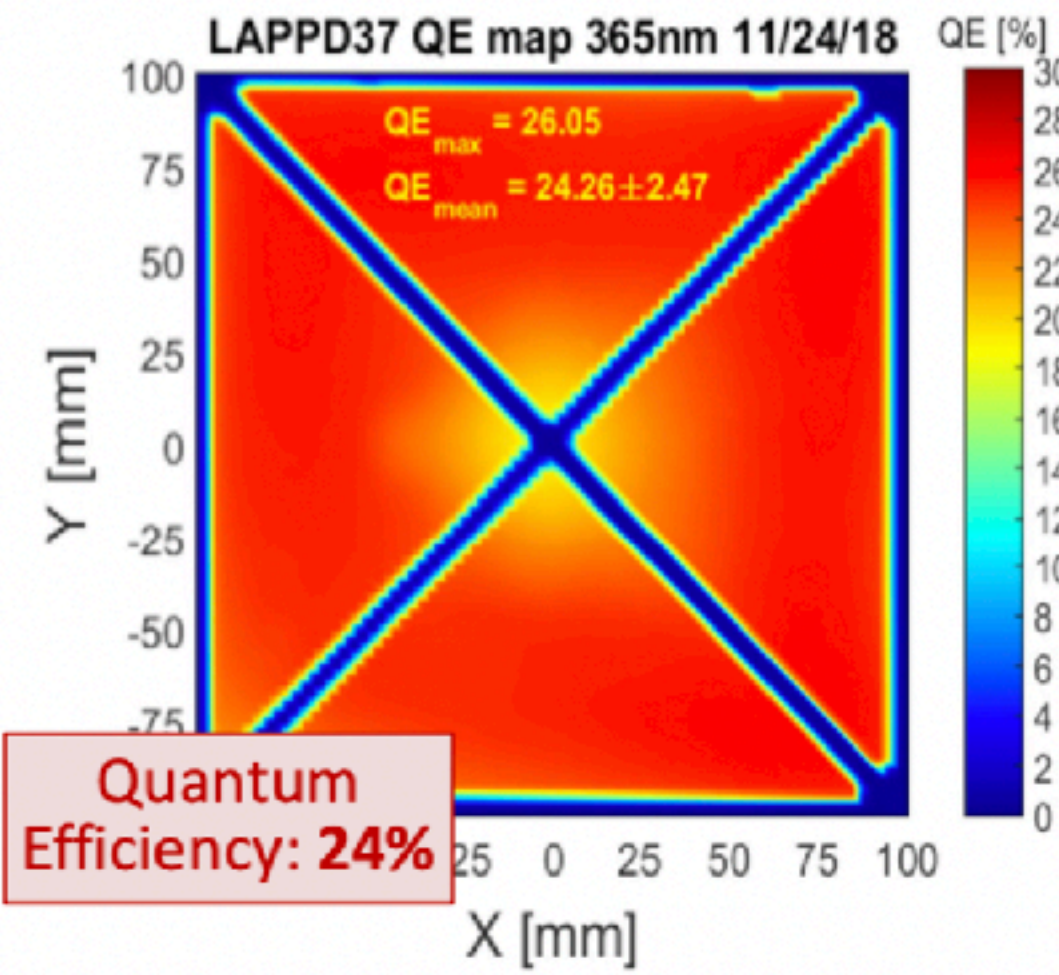
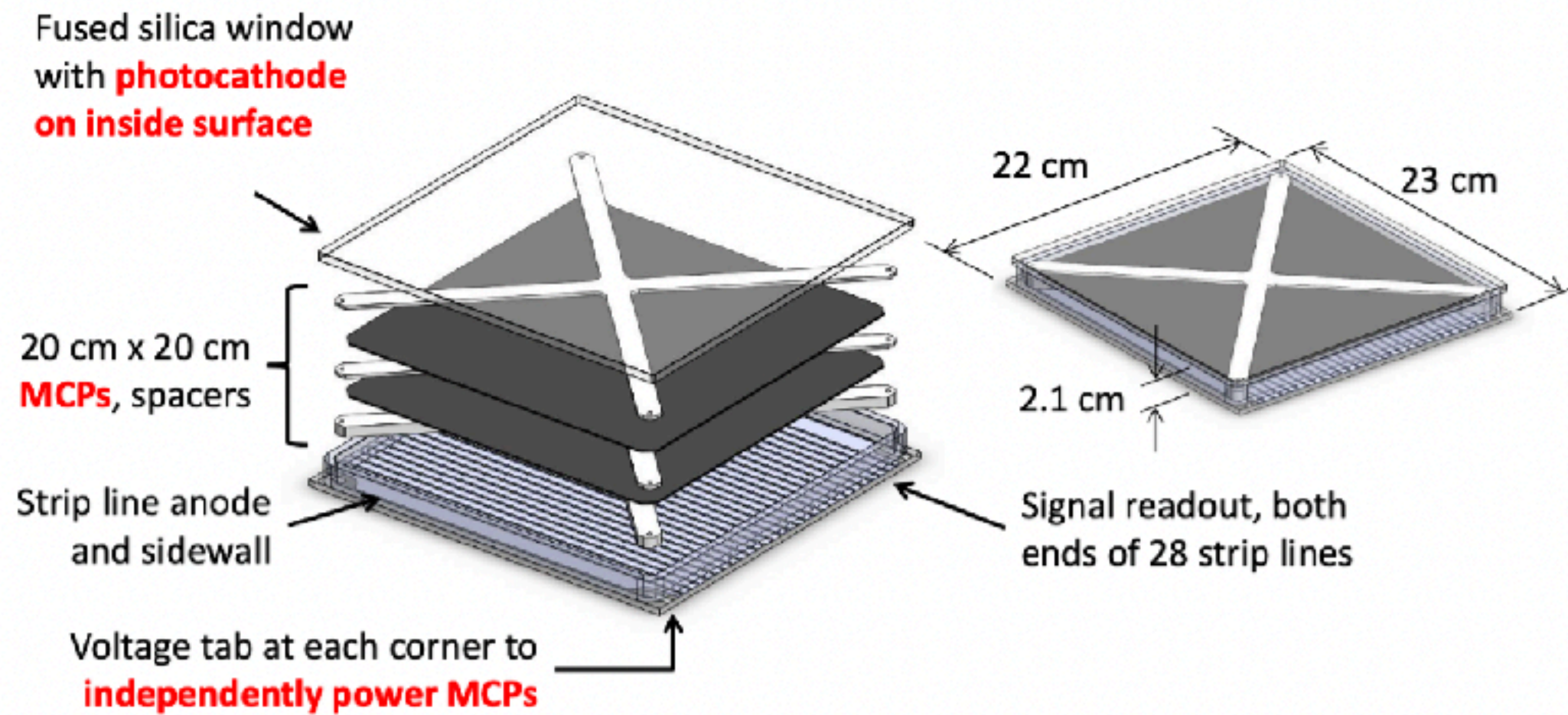


AN
Dat

ANNIE Run: 1415
ANNIE Event: 4893
PMTs: 123 hits / 4898 p.e.
LAPPDs: 0 module(s) / 0 hits
Trigger: Beam

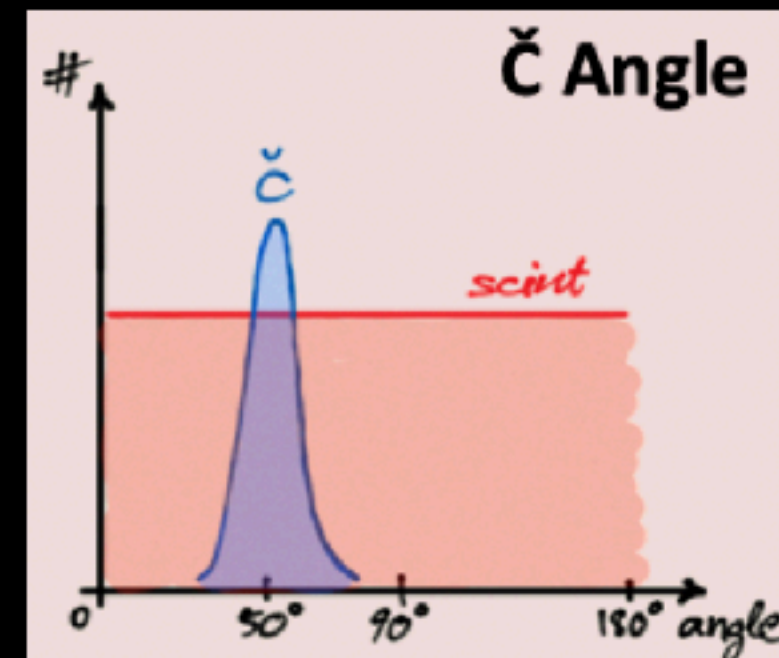
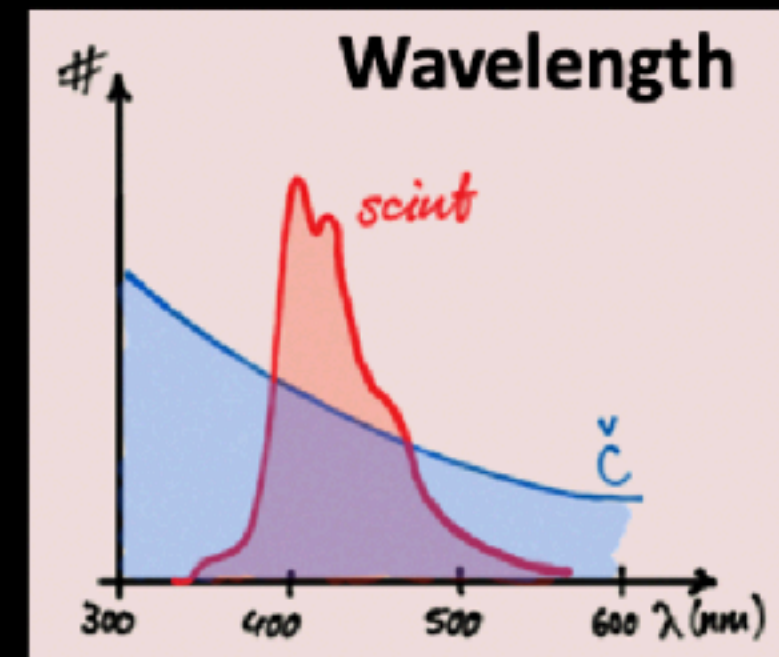
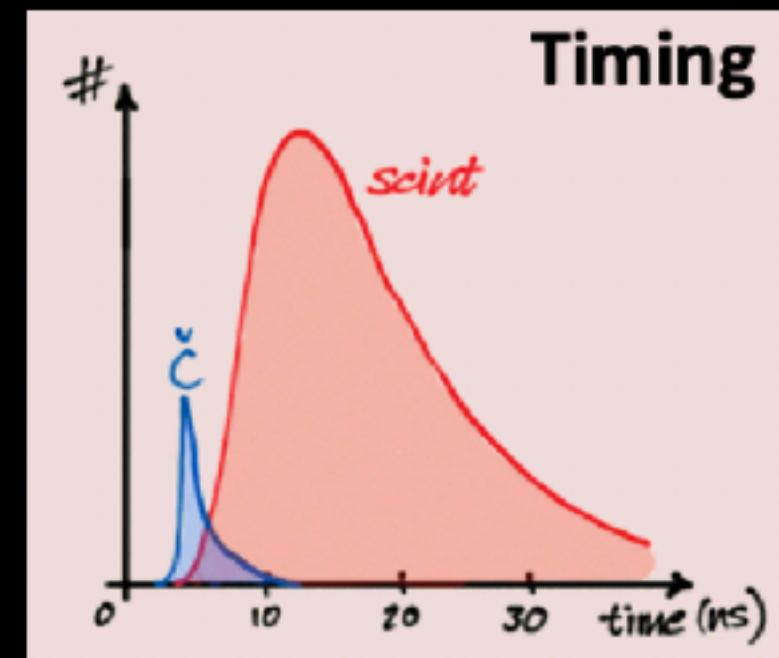
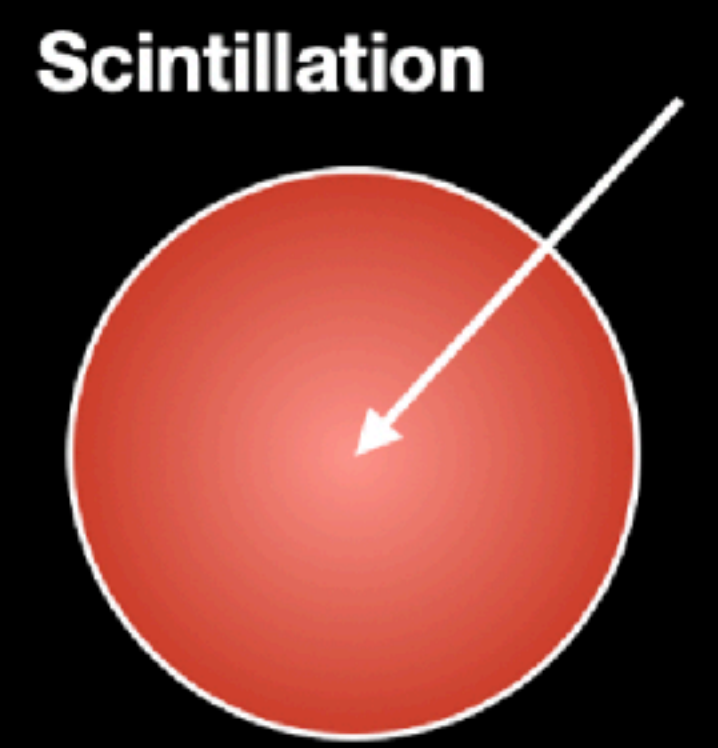


LAPPDs

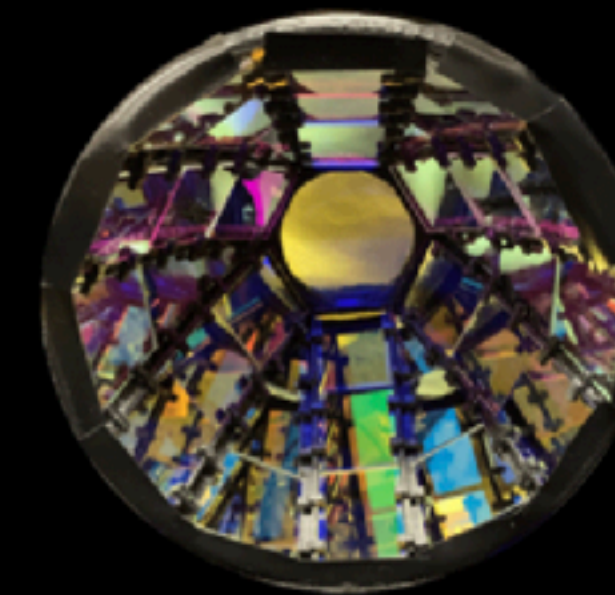
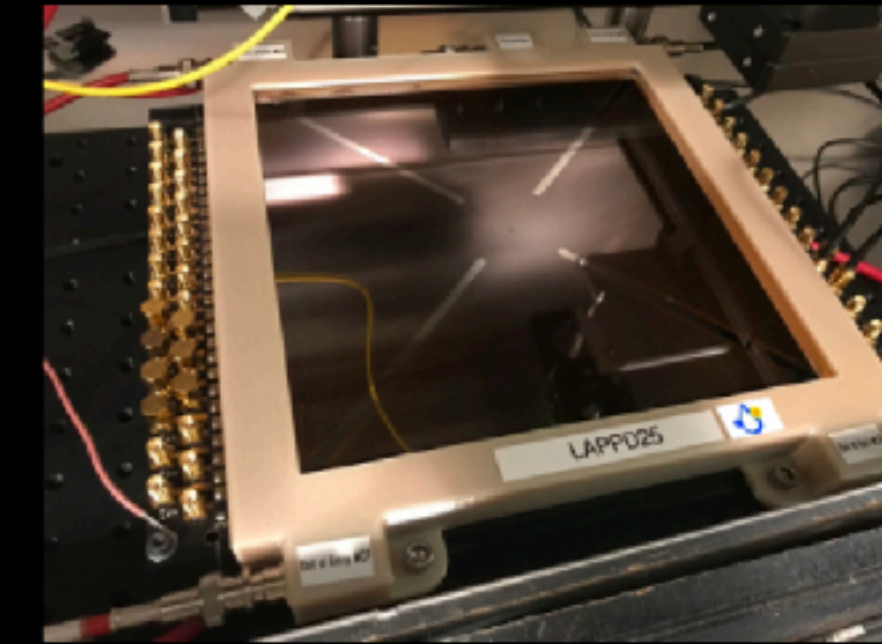


WbLS

Hybrid Detection Cherenkov/Scintillation

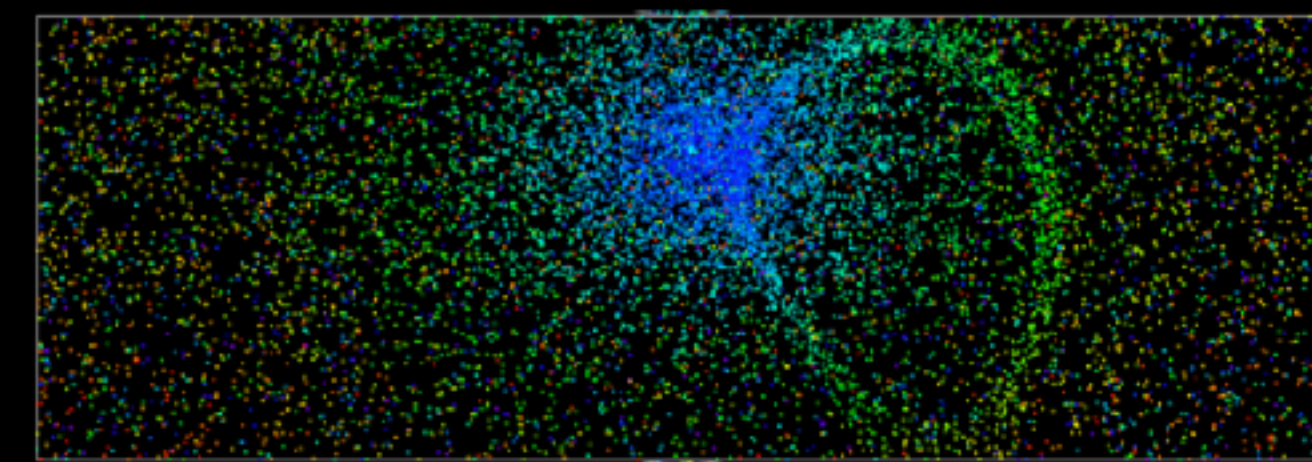


LAPPDs
tts~60ps



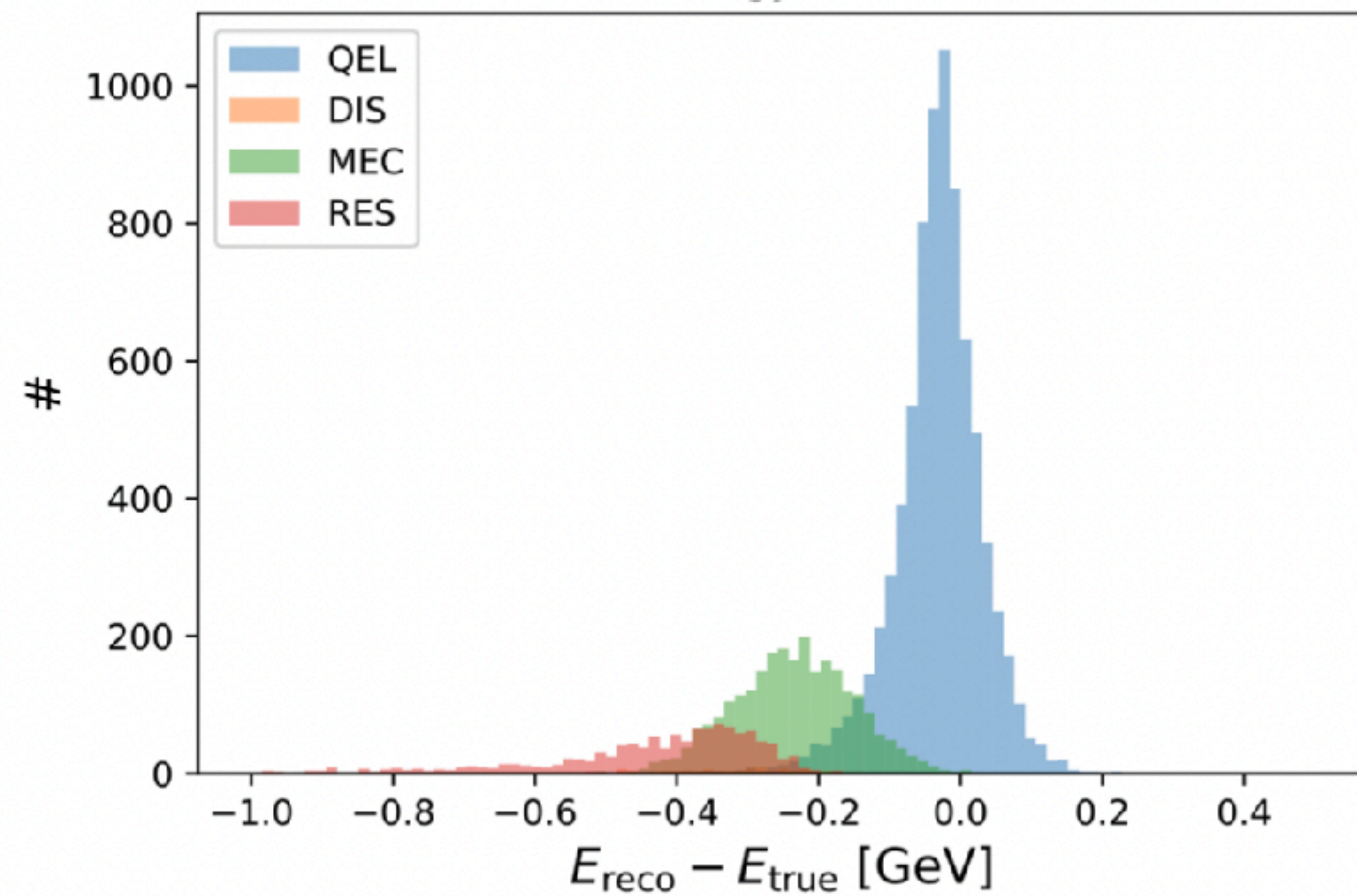
Dichroicons
spectral
sorting

PMT granularity

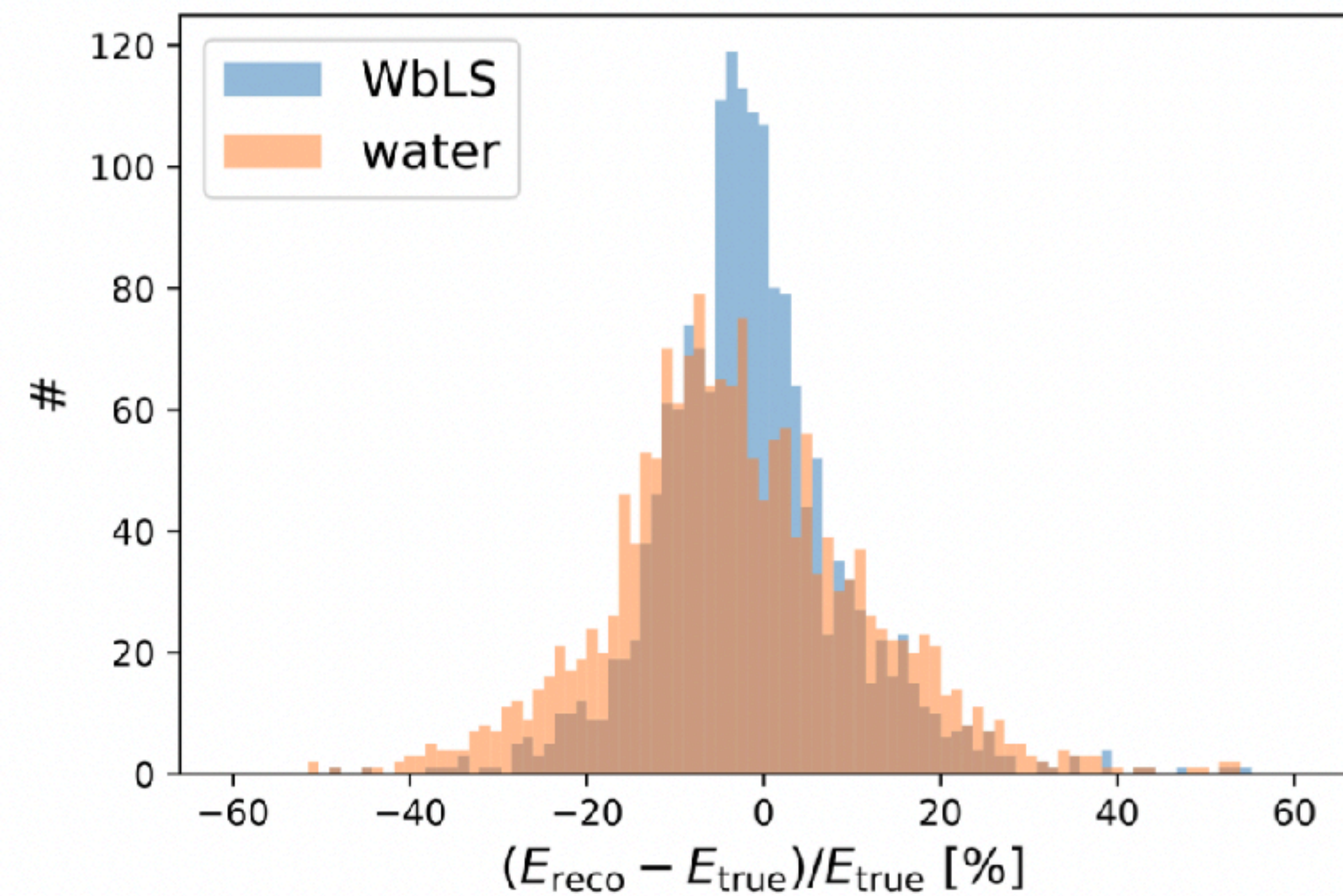


WbLS

energy reconstruction dependent
on interaction type (MC)



impact of WbLS on energy reconstruction
in ANNIE (MC): 15% \rightarrow 11%



BNB

- 8 GeV protons
- 1.6 μs spills
- 3-5 Hz

