Final-state Neutron Identification in ANNIE

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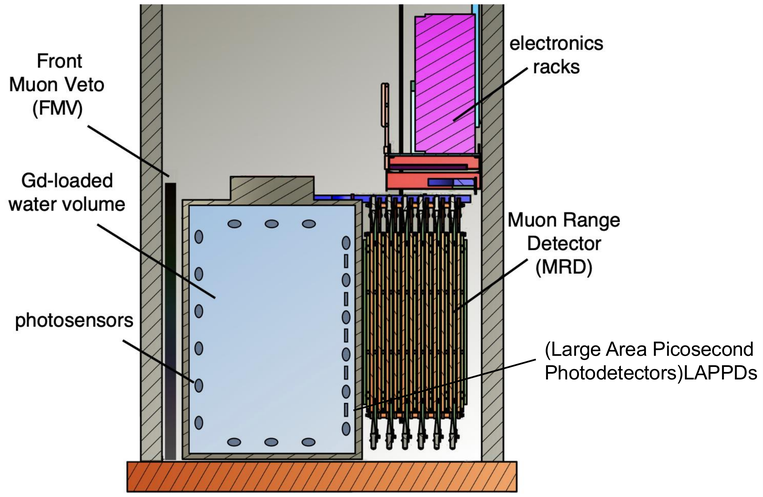
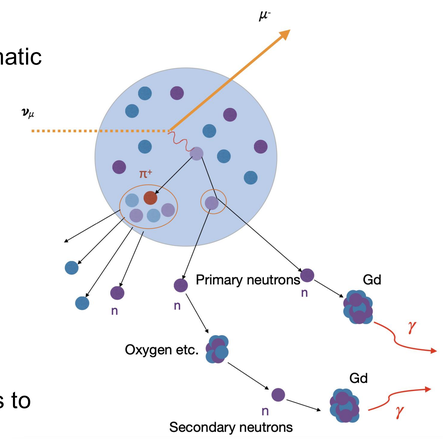
The ANNIE Experiment:

- The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) is a gadolinium-loaded water Cherenkov detector
- Located along the Booster Neutrino Beam (BNB) beamline ($\sim 600\ MeV\ \nu_\mu$ mean energy)
- One of the primary goal is the measurement of neutrino-induced **neutron capture** multiplicity



Why Neutrons?

- They are an important systematic uncertainty in ν oscillation measurements
- Neutron multiplicity helps improve neutrino interaction models and final-state interactions (FSI)
- ANNIE with Gd-loaded water provides excellent capabilities to tag these neutrons

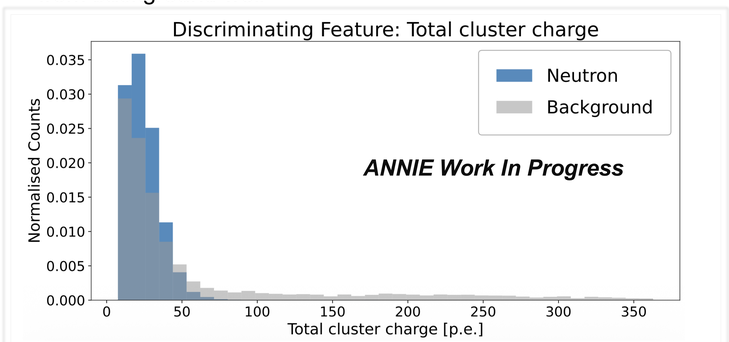


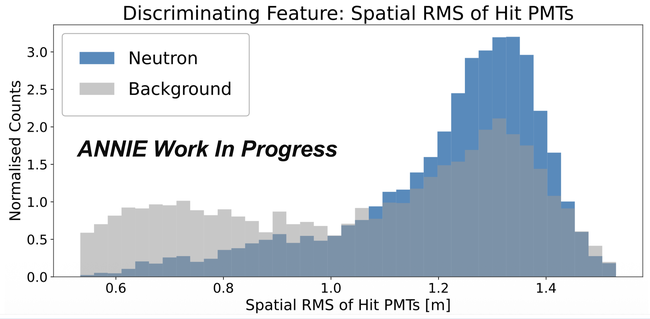
Monte-Carlo (MC) sample:

- GENIE neutrino interaction sample in the ANNIE tank volume: 890,000 events
- ν_μ-CC truth selection: muon final-state lepton, muon momentum 600–1200 MeV/c, forward angle (cos θ > 0.8), contained fiducial vertex
- Keeps **3.3% of events,** the sample used to develop the selection

Neutron Capture Identification on Selected ν_μ-CC events:

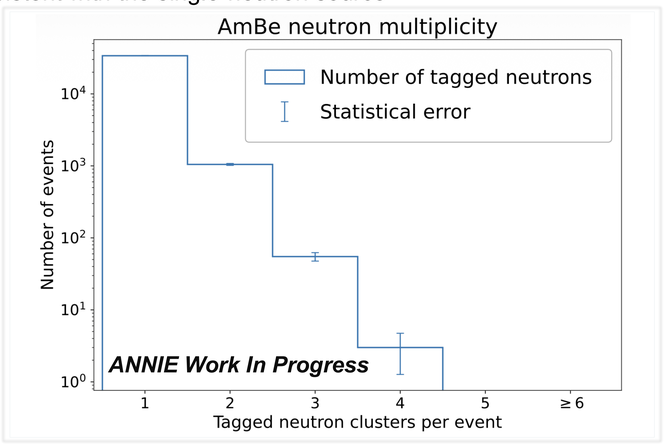
- **Pre-selection:** we explore two clustering methods to identify neutron-related charge hits in the tank
  - ClusterFinder (CF): a 20 ns sliding time window groups hits together
  - OPTICS (Ordering Points To Identify the Clustering Structure): a density-based algorithm that groups together hits that are close in space and time
- **Truth-tagging**: label each cluster as signal (neutron-dominated) or as background, from MC truth
- **Cluster features:** 31 quantities describing each cluster: total charge, spread of hits in space and time, distance to the tank wall, and point-source fit quality
- **Multivariable analysis (MVA) classification:**
  - Train four classifiers: Random Forest (RF), Gradient Boosted Trees (GBT), eXtreme Gradient Boosting (XGBoost), and Neural Network (NN)
  - The classifiers are trained to identify neutron clusters from background clusters
  - We observe that OPTICS + RF yielded optimal results: 0.7545 AUC, 0.882 efficiency, and 0.648 purity
- Here, $eff = \frac{selected\ signal}{all\ true\ signal}, and\ purity = \frac{selected\ signal}{all\ selected\ signal}$
- Here are the two of the main features that separates neutron (signal) from background well





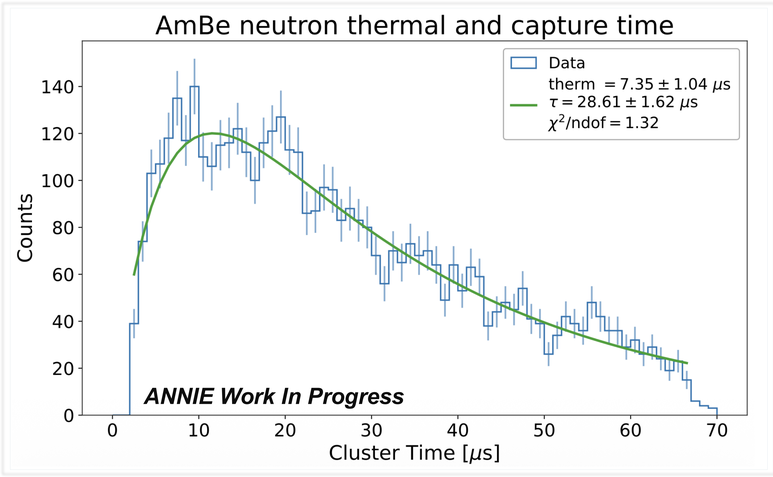
Validation on Americium-Beryllium (AmBe) Data:

- An AmBe source characterizes the detector's response to neutron capture; several campaigns have evaluated it. Here we test the new techniques on the 2023 campaign
- Apply the same OPTICS + RF selection to AmBe calibration data to see how it behaves on real neutrons
- With OPTICS + RF, 96.7% of the events contain exactly one neutron
- Consistent with the single-neutron source



- Neutron capture and thermal time are calculated using

$$A * (1 - e^{\frac{-t}{t_{therm}}}) * e^{\frac{-t}{\tau_{cap}}} + B$$



Conclusion & Takeaways:

- Even with limited MC statistics (890k events), the framework already gives a strong, validated picture for identifying neutrons. Larger samples and a more robust model of the detector response should improve it further
- Further studies on the AmBe backgrounds will be conducted, specially to understand the multi-cluster events

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