ANNIE in 10 minutes: multiplicities, cross sections, and models (oh my!)

Teal Pershing (UC Davis)

For the ANNIE collaboration

Fermilab New Perspectives

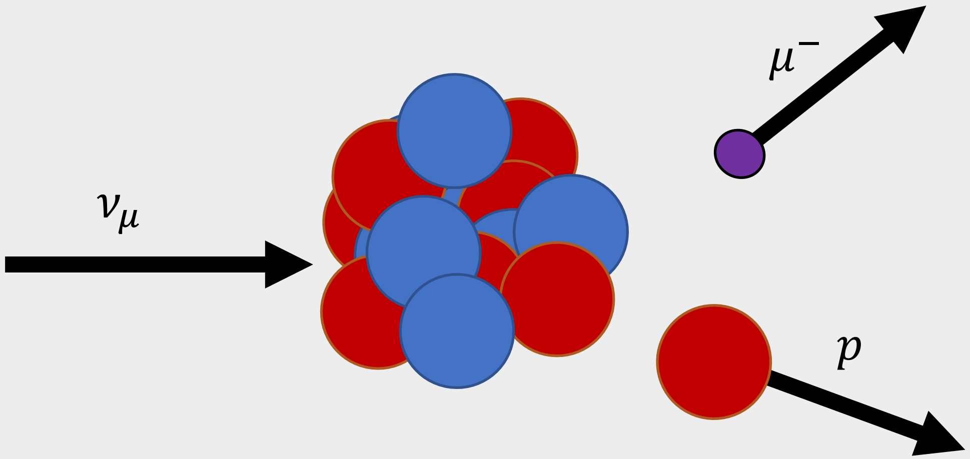
June 10-11th, 2019

Neutrino Event Reconstruction

- Neutrino experiments depend on accurate reconstruction of neutrino interactions (energy, position, direction, time)
- $O(\sim GeV)$ experiments will often focus event selection on charged-current quasi-elastic (CCQE) events
  - Straightforward event topology and kinematics reduce uncertainties in neutrino reconstruction
  - Water-based detectors: only have one Cherenkov cone to reconstruct

Genuine CCQE interaction

$$\nu_\mu + {}^{16}O \rightarrow \mu^- + p + {}^{15}O$$



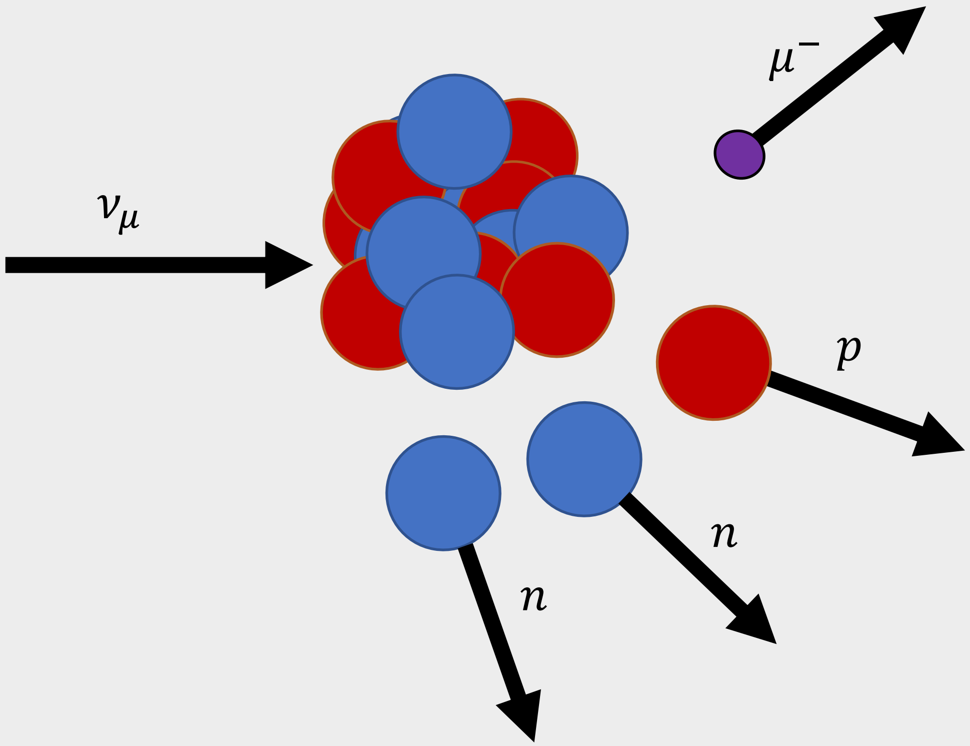
$$E_{\nu,rec} = \frac{M E_\mu - \frac{m_\mu^2}{2}}{M - E_\mu - |\overrightarrow{p_\mu}| \cos\theta_\mu}$$

Reconstructed energy eqn. from: J. Nieves, I. Ruis Simo, et al. "CCQE, 2p2h excitations and nu-energy reconstruction". Arxiv 1304.1032v1 (Apr 2013)

CCQE-like events: a cautionary example

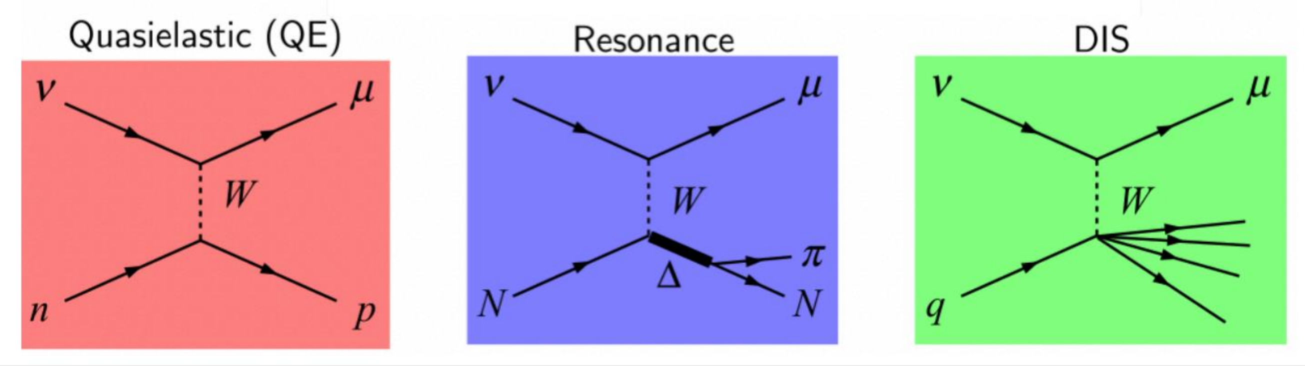
- Need to reliably tag and model CC events that mimic genuine CCQE events ("CCQE-like")
- The presence of neutrons indicate that a neutrino interaction is not a true CCQE event
  - Undetected, can also result in a bias in reconstructed neutrino energy
- More data is needed to refine neutron yield models!

Possible CCQE-like interaction

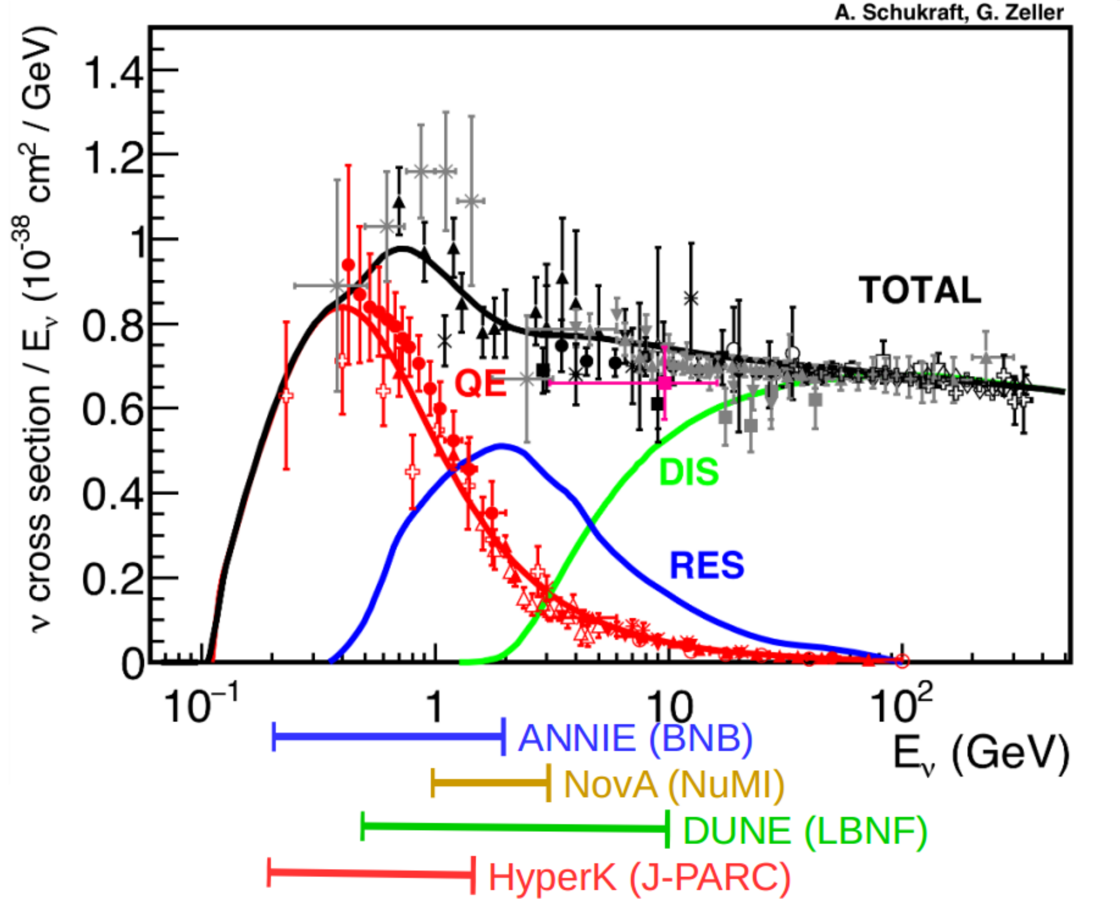


GeV-scale neutrino interactions

- Across the GeV-energy range, there are multiple possible interaction types (and particles produced)
- Additional cross-section measurements can help refine neutrino interaction models
- Neutron multiplicities for different interactions can also be measured
  - Final-state interactions for different events could lead to different neutron multiplicities



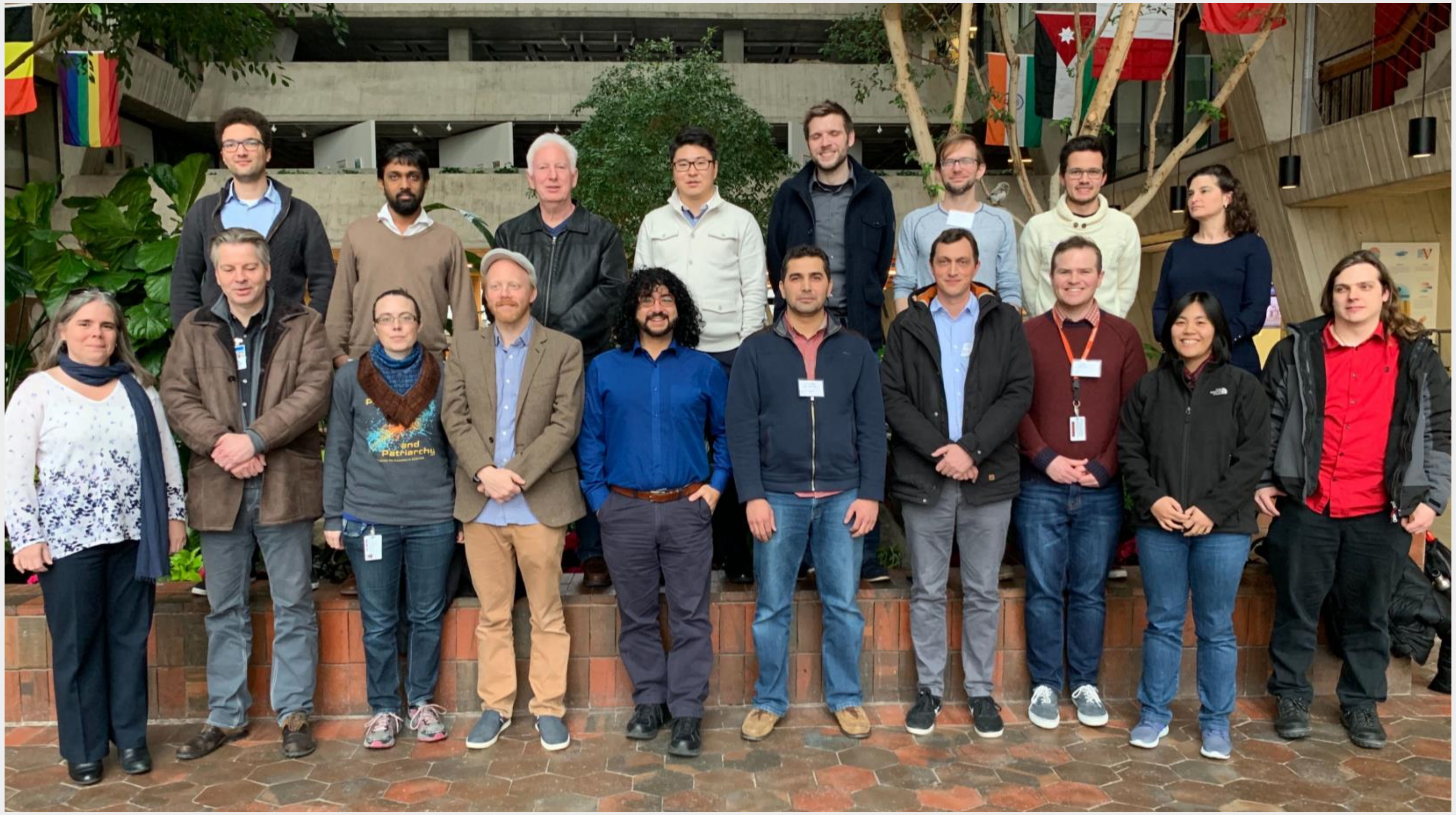
Total neutrino per nucleon charged current cross-sections divided by neutrino energy (arXiv 1305.7513, 2013)



The Accelerator Neutrino-Neutron Interaction Experiment

- 13 institutions, 3 countries, ~30 collaborators
  - Brookhaven National Laboratory
  - Fermi National Accelerator Laboratory
  - Iowa State University
  - Johannes Gutenberg University Mainz
  - Lawrence Livermore National Laboratory
  - Queen Mary University
  - The Ohio State University
  - University of California, Davis
  - University of California, Irvine
  - University of Chicago
  - University of Edinburgh
  - University of Hamburg
  - University of Sheffield

ANNIE Collaboration Meeting, March 2019



The ANNIE detector

- Gadolinium-doped water Cherenkov detector
- ANNIE tank instrumentation: 132 Photomultiplier Tubes (PMTs) and 5 Large Area Picosecond PhotoDetectors (LAPPDs)
- Muon Range Detector (MRD): alternating layers of scintillator paddles and steel
- Front veto used to reject events with muons produced upstream in dirt/rock

Cross-section of ANNIE detector

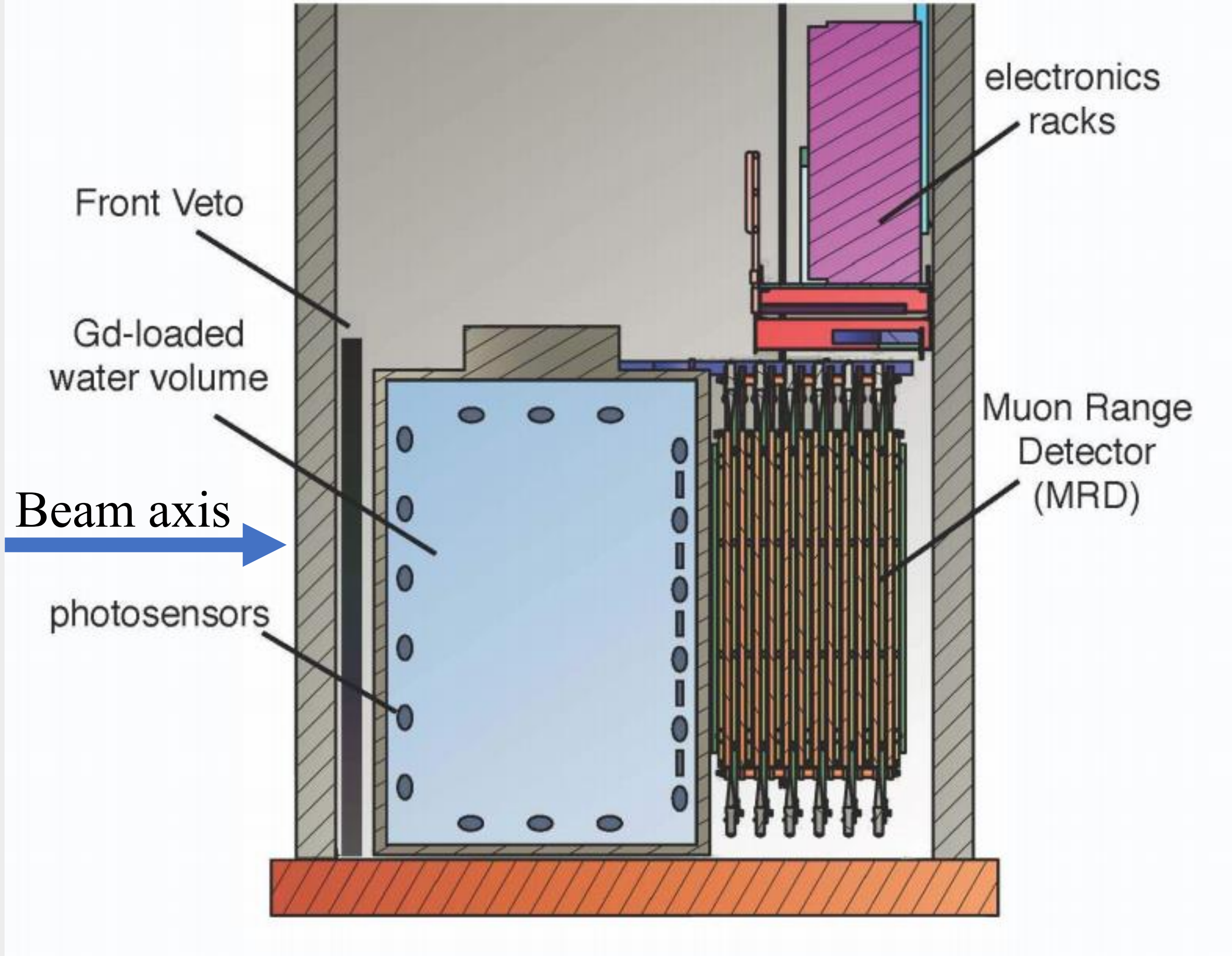
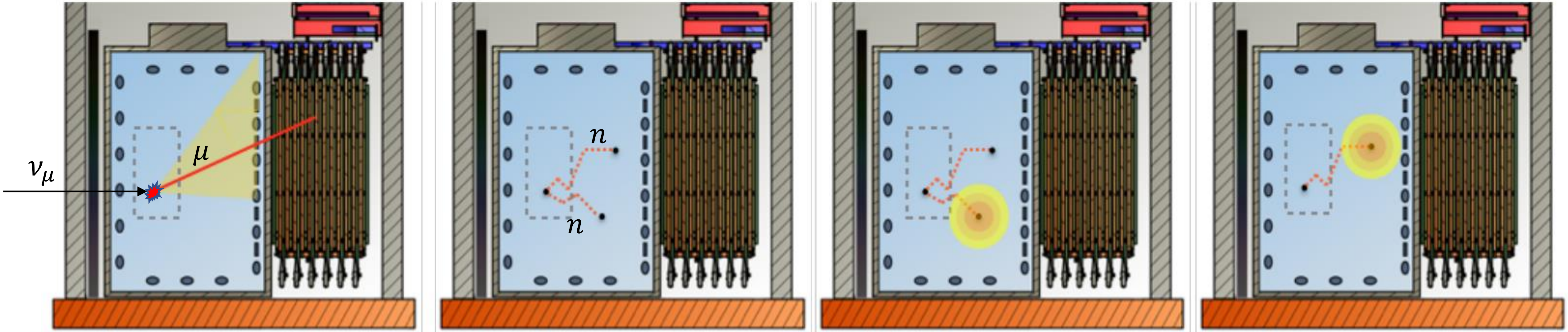


Image reference: "Accelerator Neutrino Neutron Interaction Experiment (ANNIE): Physics phase proposal." arXiv:1707.08222v2

Neutrino & neutron event detection in ANNIE

Example of a charged-current neutrino event in ANNIE

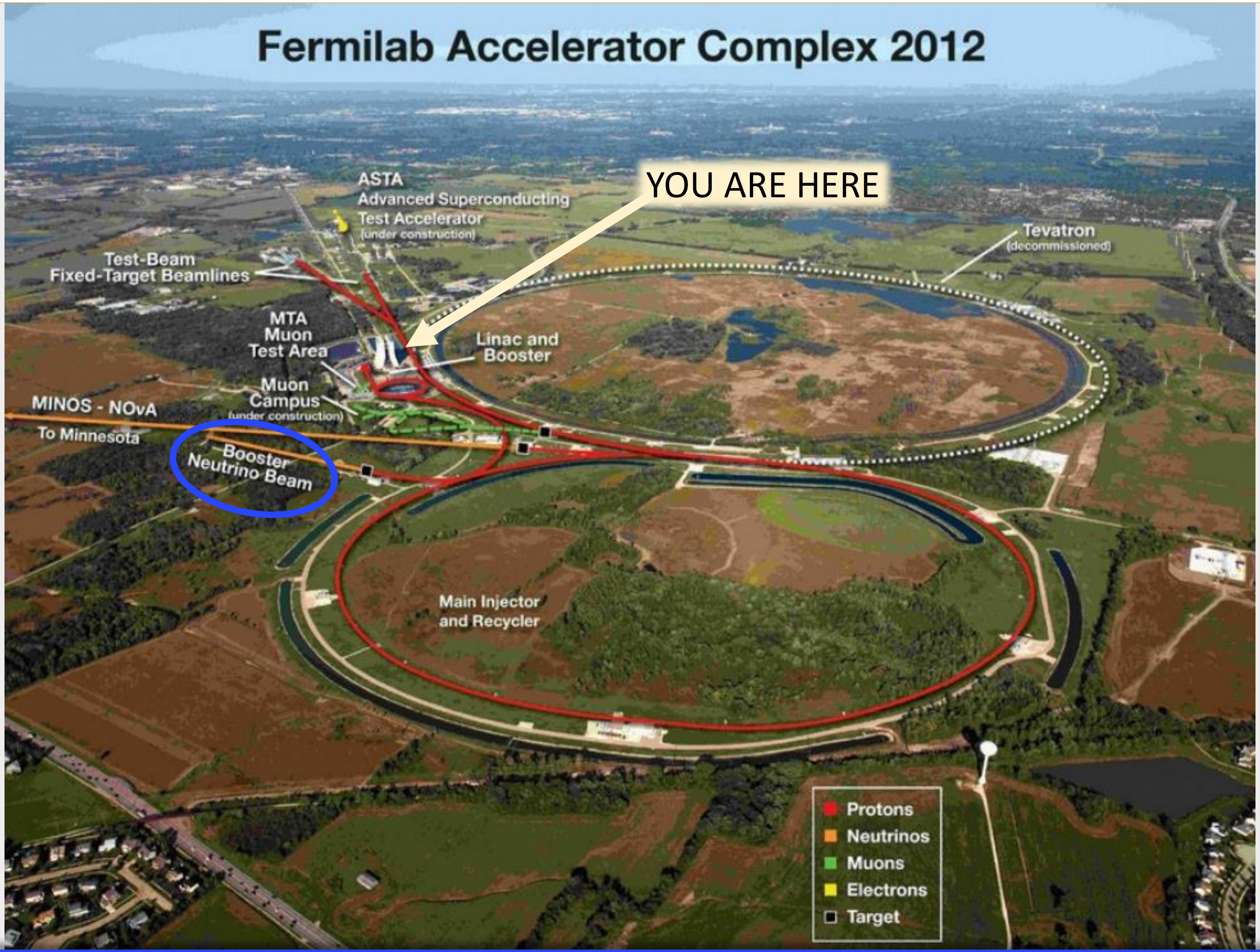


1. Muon neutrino from BNB interacts with nucleus in target volume; muon stops in MRD

2. Neutrons produced (if any) undergo thermalization in target volume

3. Neutrons capture on gadolinium; gadolinium's de-excitation signal (Cherenkov light from ~8 MeV gamma cascade's Compton scatter electrons) is detected

ANNIE Location at FNAL



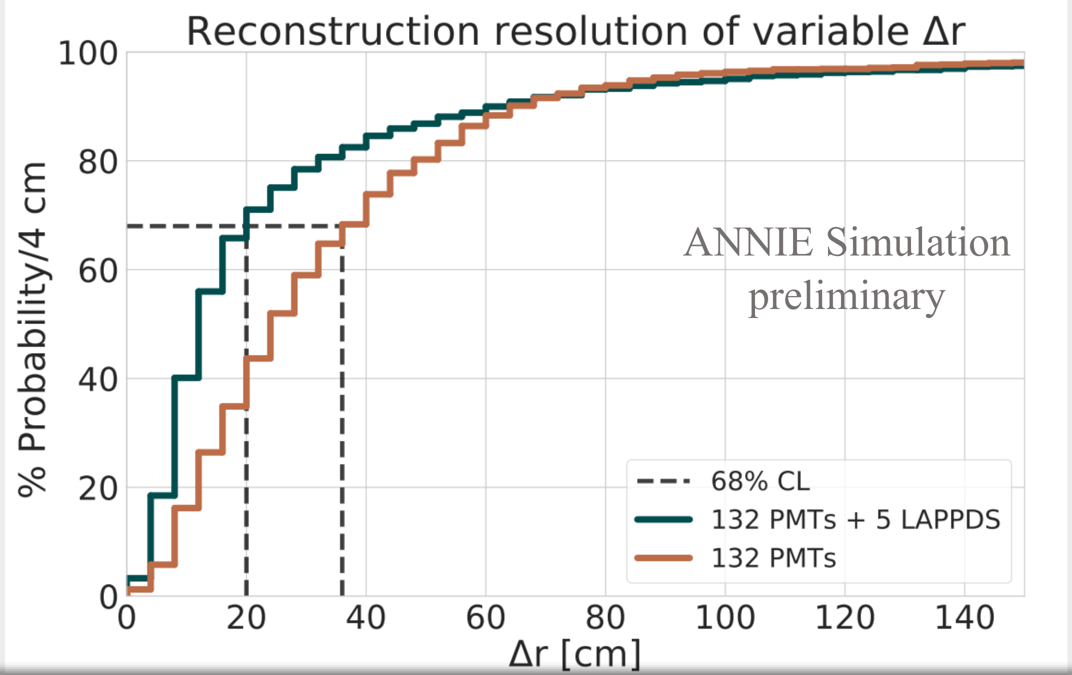
ANNIE Location at FNAL

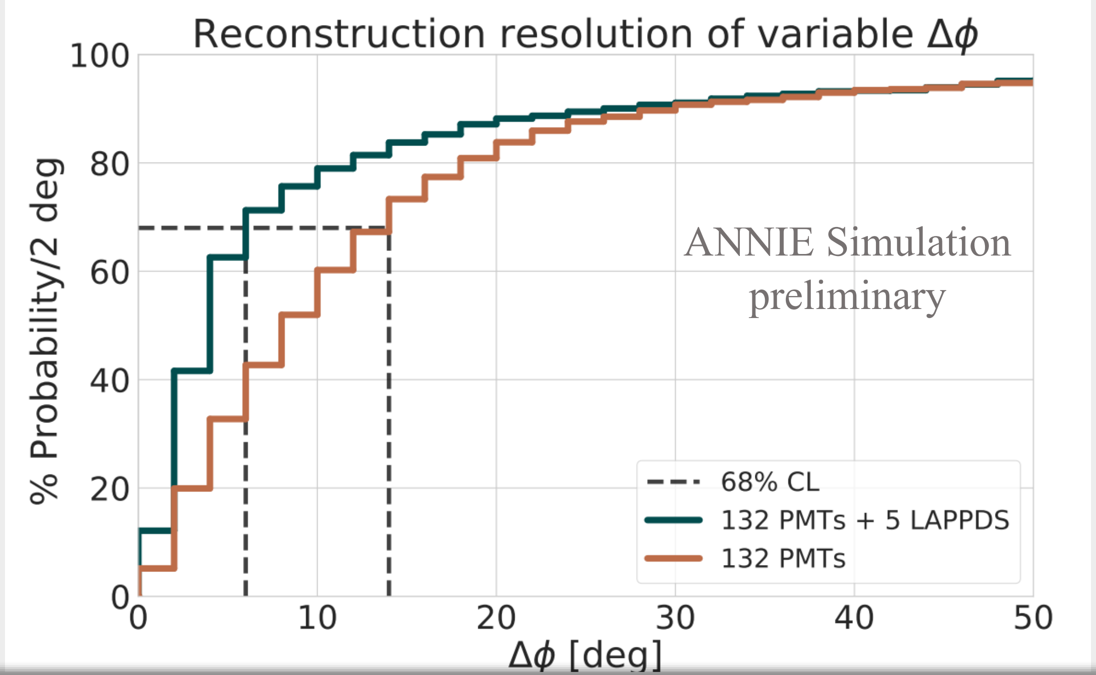
ANNIE Location at FNAL

ANNIE Location at FNAL

ANNIE Detector Simulation

- Full simulation of neutrino interactions in ANNIE using GENIE (neutrino interaction simulation) and WCSim (detector response simulation)
  - Used for detector optimization prior to construction, analysis chain development, systematic uncertainty evaluation, etc.
- An example use case: comparison of vertex reconstruction resolution with/without LAPPDs
  - Reconstruction of simulated data confirms more accurate muon vertex reconstruction achievable with LAPPDs





ANNIE & Beyond

Mass

~40 ktons,

~10,000 sensors

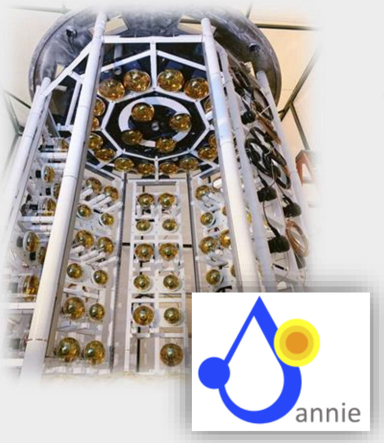
Demonstration/R&D with Gd-doped water, fast sensors, and WbLS

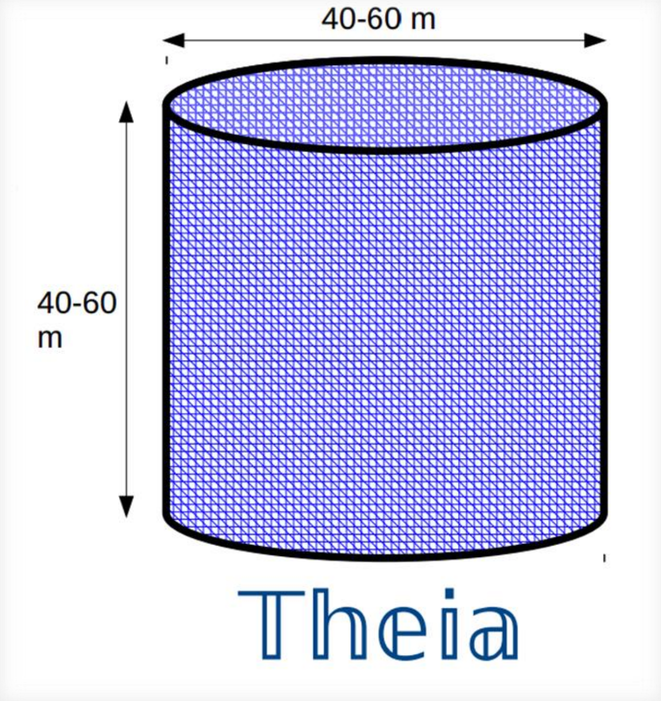
~4 ktons,

~5000 sensors

~30 tons,

~140 sensors





Application of technologies in larger detector settings

Deployment date

2019

2023

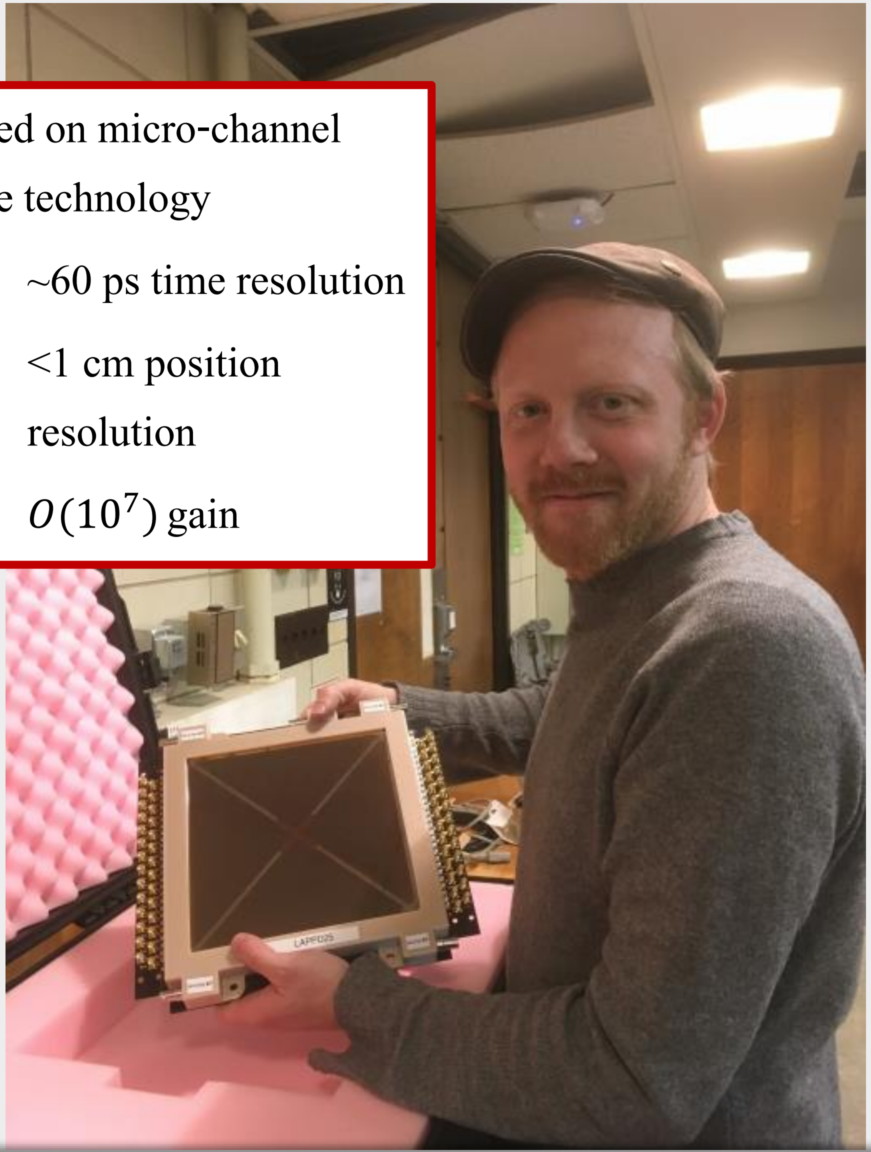
202?

Conclusion

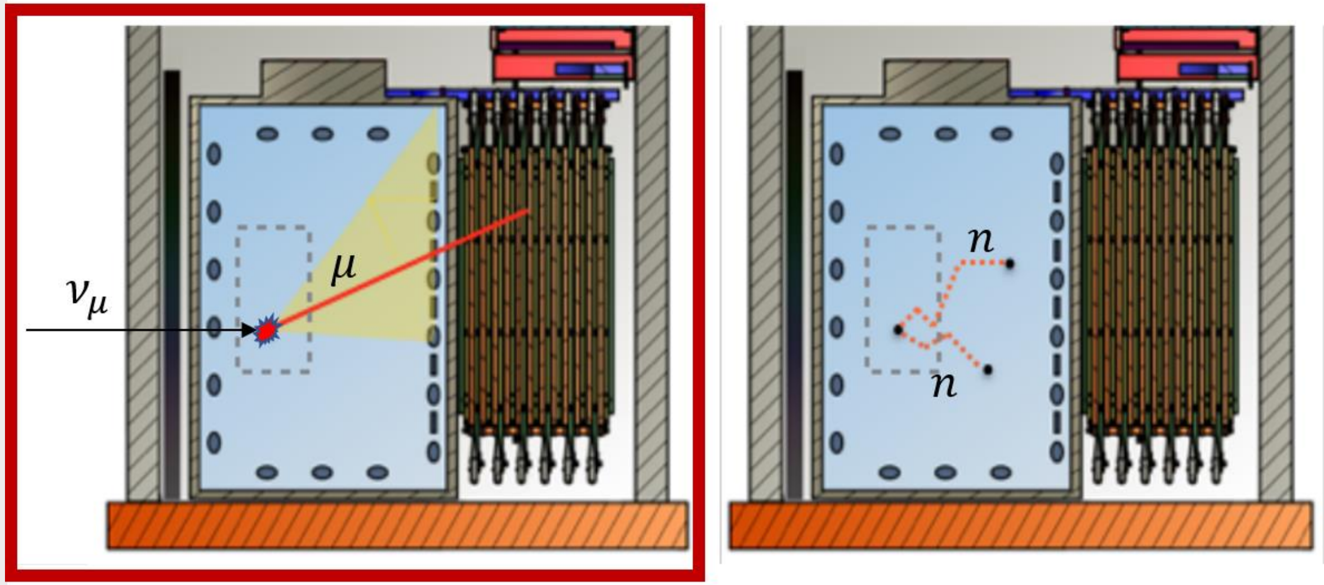
- ANNIE is a gadolinium-doped water Cherenkov detector deployed on the Booster Neutrino Beamline
- ANNIE will measure:
  - The neutron multiplicity from muon neutrino-nucleus interactions
  - Cross sections for muon neutrino interactions on the GeV-energy scale
- Data measured will improve background models and reduce systematics in other neutrino experiments
- Utilizing tools and techniques at the forefront of neutrino physics R&D to reconstruct neutrino interactions
  - Gd-doped water for improved neutron capture sensitivity
  - LAPPDs for improved muon reconstruction
- ANNIE is fully funded and finishing construction now; data taking to begin this month!

Back-up slides

LAPPDs and their place in ANNIE



- Based on micro-channel plate technology
    - ~60 ps time resolution
    - <1 cm position resolution
    - $O(10^7)$ gain

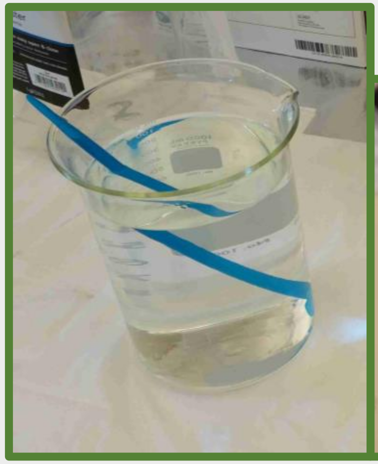


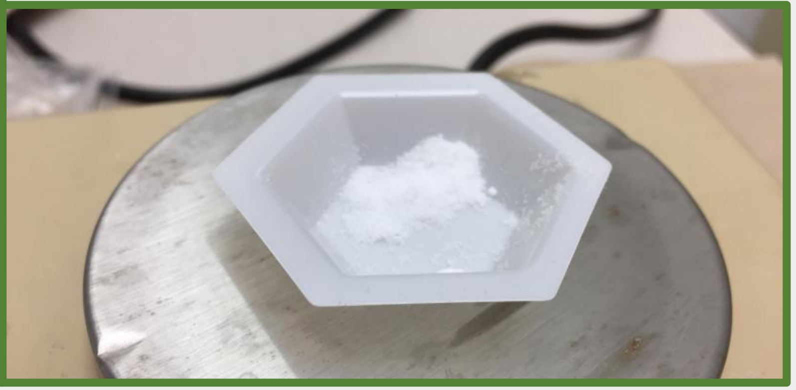
1. Muon neutrino from BNB interacts with nucleus in target volume, then stops in MRD

2. Neutrons produced (if any) undergo thermalization in target volume

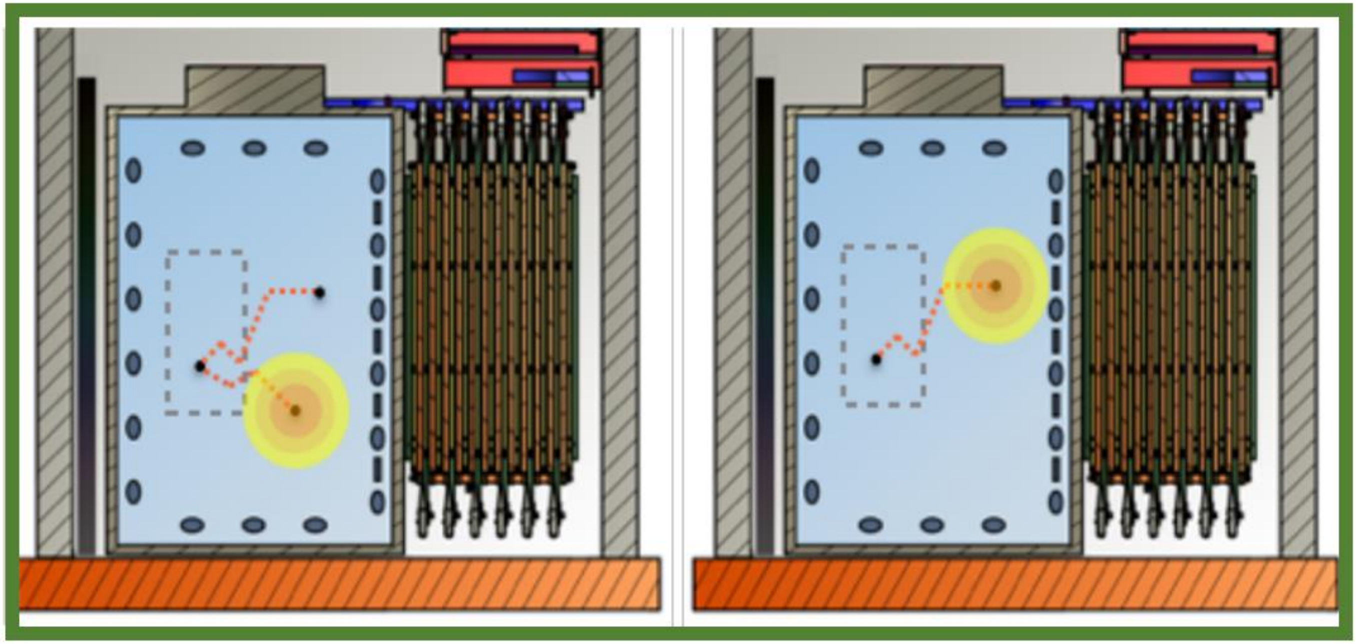
LAPPDs provide improved muon track reconstruction

Gadolinium and it’s place in ANNIE





- Gadolinium doping
  - High thermal neutron capture cross-section (~50,000 b)
  - Low photon scattering/absorption in wavelengths of PMT sensitivity
  - Average of 4.4 MeV observed per neutron capture
    - Above most naturally occurring backgrounds

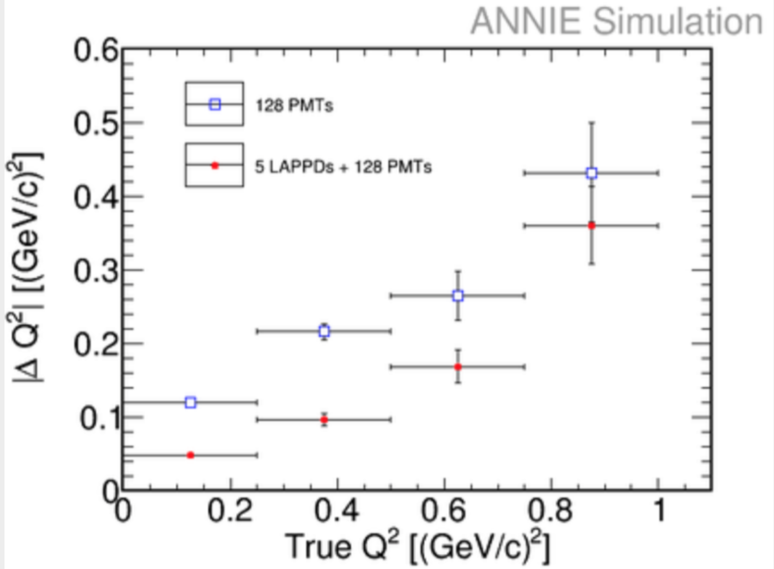


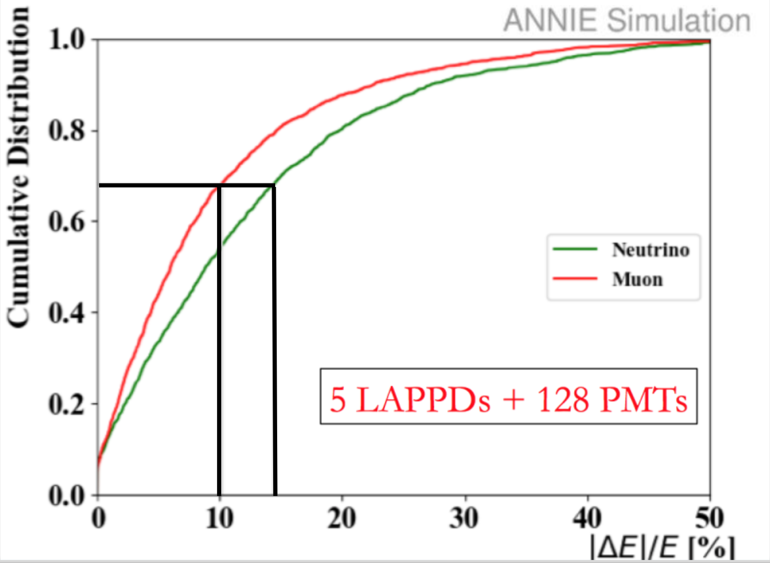
3. Neutrons capture on gadolinium; gadolinium’s de-excitation is detected

Gadolinium-doped water: improved sensitivity to neutron captures in the detection medium (vs. pure water)

Energy Reconstruction in the MRD

- MRD: alternating layers of scintillator paddles and steel
- Hit information in tank PMTs/LAPPDs, MRD paddles, and vertex reconstruction in tank used to reconstruct neutrino energy
- Reconstruction performed using machine learning algorithms trained on simulation data
  - Muon track length in tank and MRD using a Deep Learning Neural Network (DNN) in the Keras API (Tensorflow backend)
  - Muon and neutrino energy using a Boosted Decision Tree (BDT) in Scikit-Learn
- Presence of LAPPDs pivotal to reducing uncertainties in reconstructing total momentum transfer (top)
- With LAPPDs, muon (neutrino) energy resolution is 10% (14%) at the 68% CL



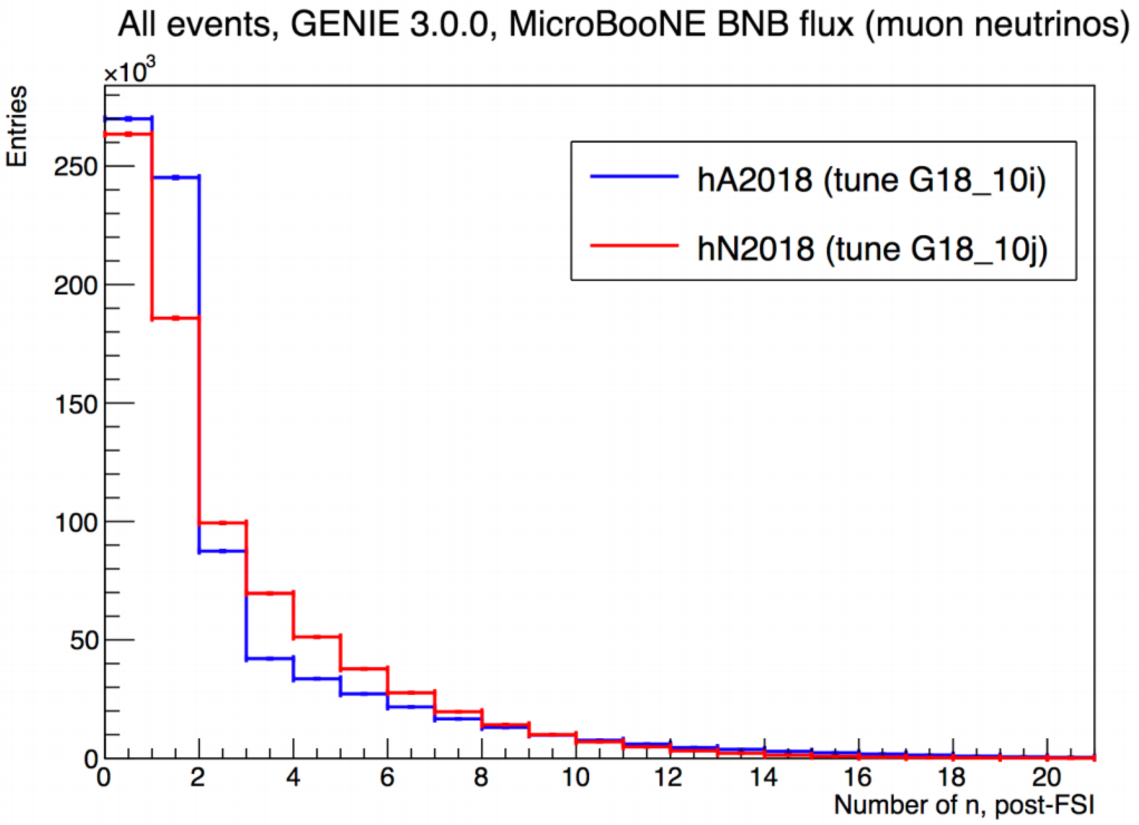


Evangelia Drakopoulou, on behalf of the ANNIE collaboration. "ANNIE Phase II Reconstruction Techniques." NuPhys 2017 proceedings. arXiv:1803.10624v1

Modeling neutron multiplicity

- Properly modeling the particles produced following a neutrino interaction is pivotal to event reconstruction
  - Simulation & modeling used to fill in where data is unavailable
- Current models of neutron multiplicity are in tension
  - Different models of final-state interactions inside the nucleus can result in large differences in neutron production
- **More data is needed to refine neutron yield models!**
- ANNIE will deliver a measurement of neutron multiplicity from neutrino interactions on Oxygen

GENIE v3.0 prediction for neutron yield from neutrino interactions on 40Ar target

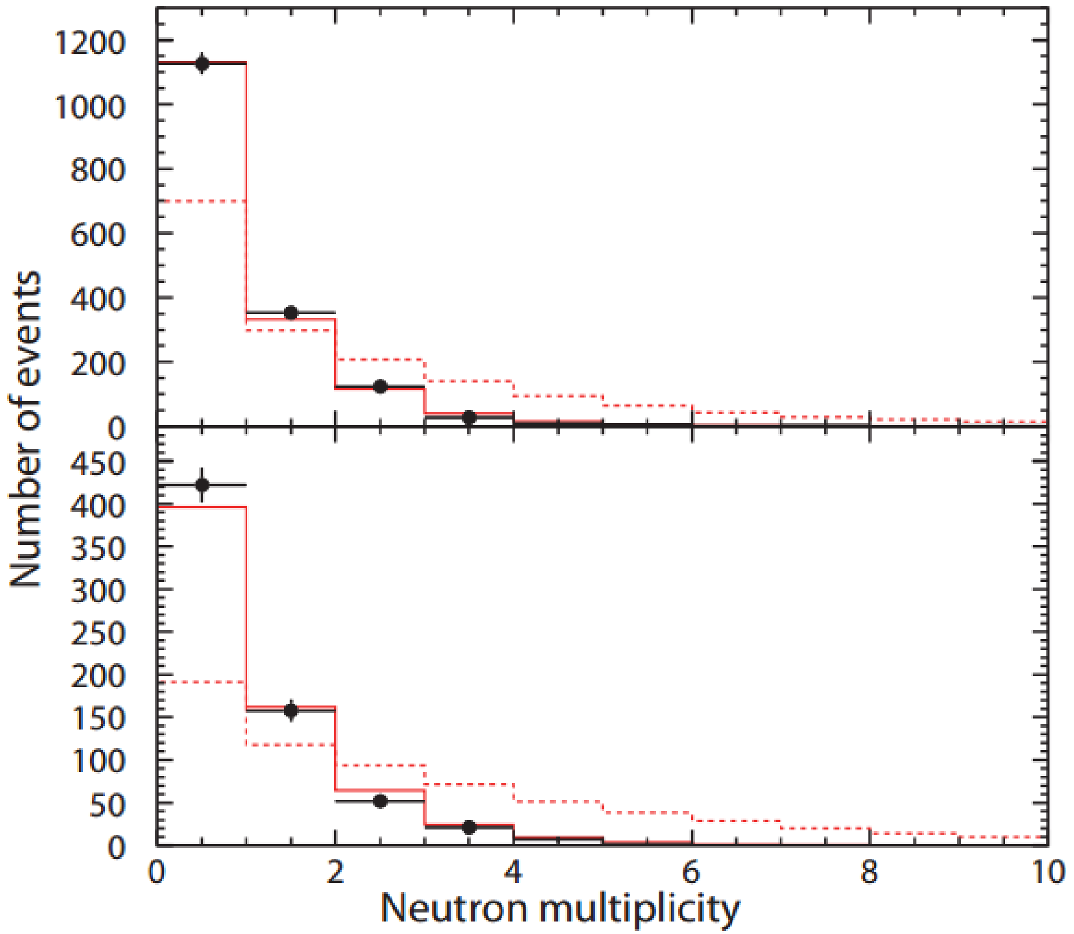


Red and blue show results for different final-state interaction models

S. Gardiner, "Neutrinos knocking out neutrons: The ANNIE Experiment", Fermilab Neutrino Seminar Series, Nov. 15, 2018

Neutron multiplicity measurement in SuperK

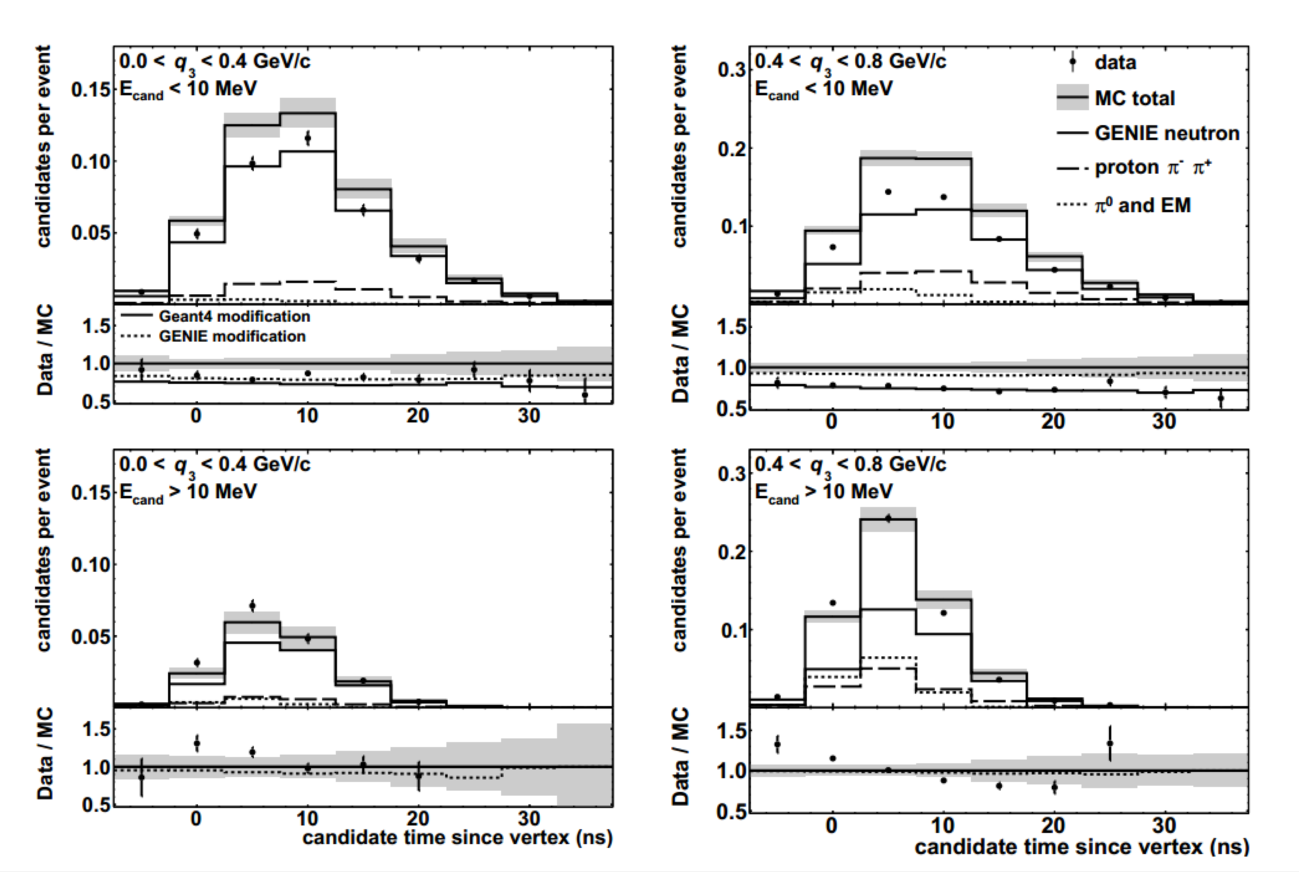
- SuperKamokande proton decay search modes should have no neutrons in the final state ($p \rightarrow e^{+}\pi^{0}, p \rightarrow \mu^{+}\pi^{0}$)
- Plot shown is the neutron multiplicity for proton decay candidates tagged by a neutron follower
  - Solid red line is the MC prediction for neutrons from atmospheric neutrinos
- Some limitations for this measurement to help improve neutron multiplicity models
  - Unknown if incident atmospheric is a neutrino or antineutrino
  - Can only link neutron multiplicity to visible energy (initial atmospheric neutrino direction unknown)



K. Abe et al., The Superkamiokande collaboration. "Search for Proton Decay via $p \rightarrow e^{+}\pi^{0}, p \rightarrow \mu^{+}\pi^{0}$ in 0.31 megaton·years exposure of the Super-Kamiokande Water Cherenkov Detector." arXiv:1610.03597v2 [hep-ex] 21 Dec 2016.

Neutron multiplicity measurement in Minerva

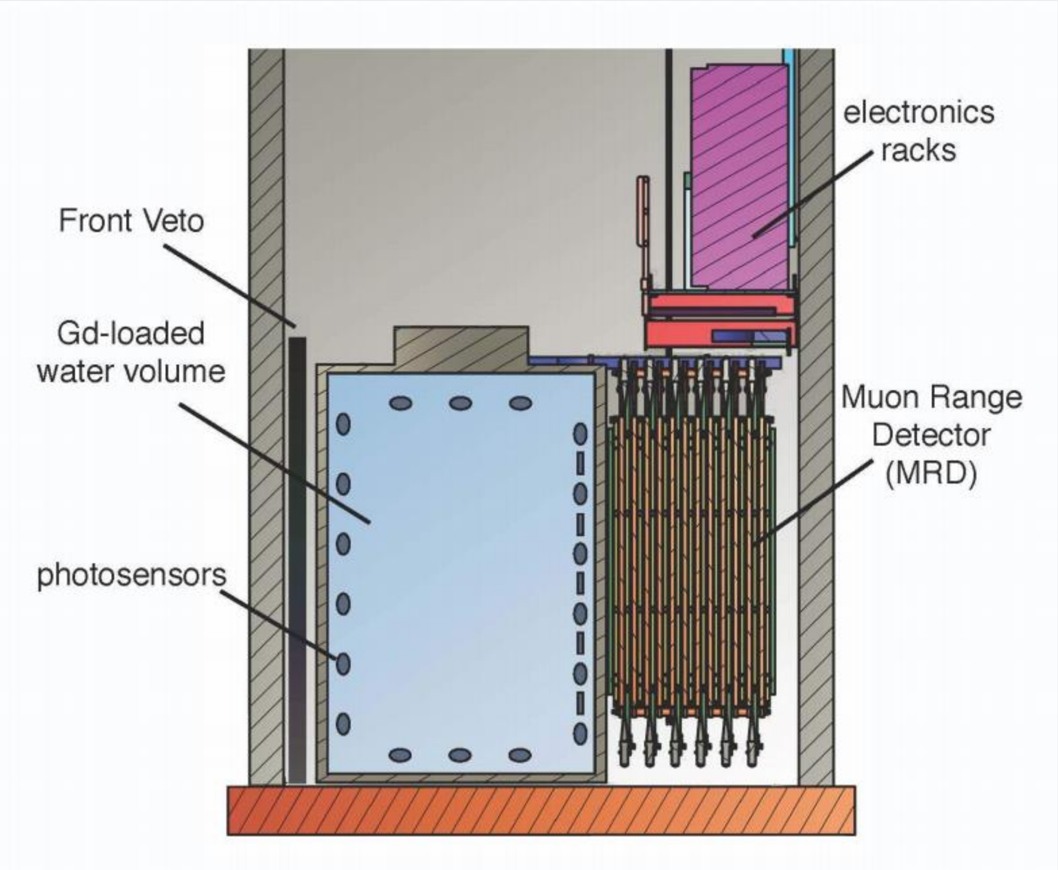
- Minerva has recently posted a measurement of neutron multiplicity to the ArXiv
- ANNIE's measurement is complementary to that made by Minerva
  - Minerva's measurement was made with an antineutrino beam; ANNIE's neutron multiplicity measurement will be made with a neutrino beam
  - Minerva observes interactions on it's hydrocarbon scintillator; ANNIE is a water detector. Different predictions for different target nuclei can be compared
  - Minerva searches for neutrons by observing the first neutron scatter, while ANNIE will detect neutron's through neutron capture
    - ANNIE has no neutron detection threshold



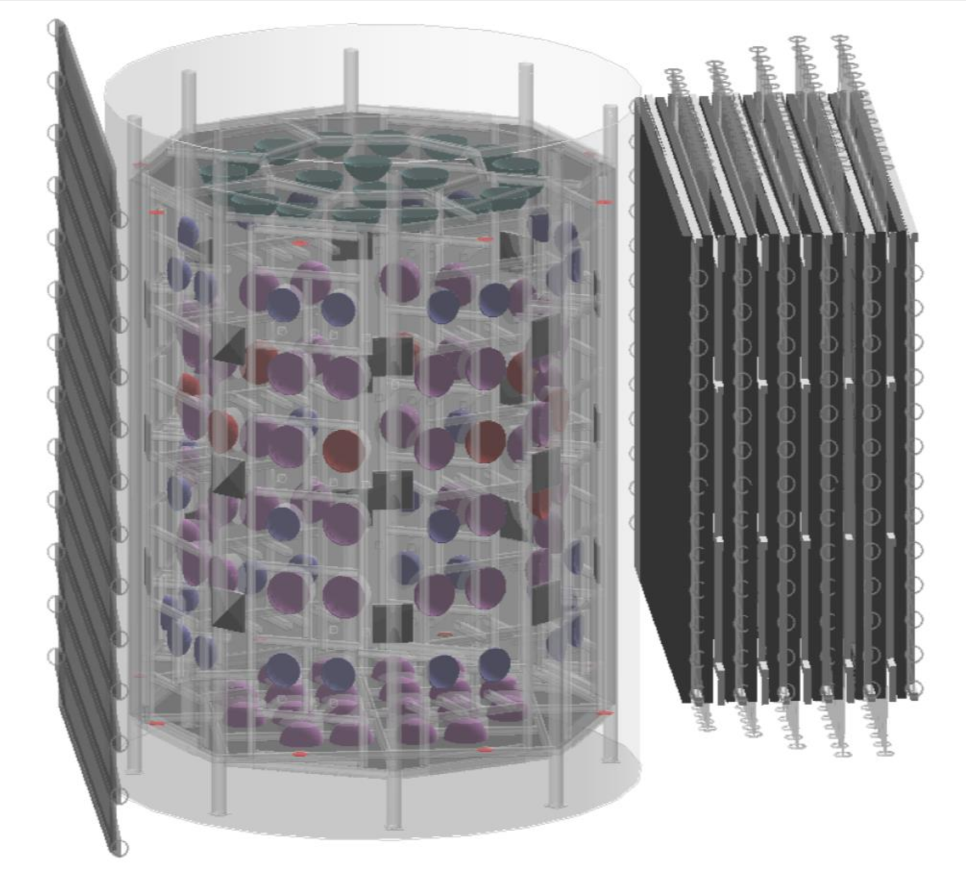
M. Elkins et al., The MINERVA collaboration. "Neutron Measurements from Antineutrino Hydrocarbon Reactions." arXiv:1901.04892v1 [hep-ex] 15 Jan 2019.

Full simulation of ANNIE detector

- While construction has been underway, full simulation of ANNIE detector developed
  - Neutrino interaction simulated using GENIE
  - Tank design converted into geometries for simulating detector response in both WCSim and RAT-PAC

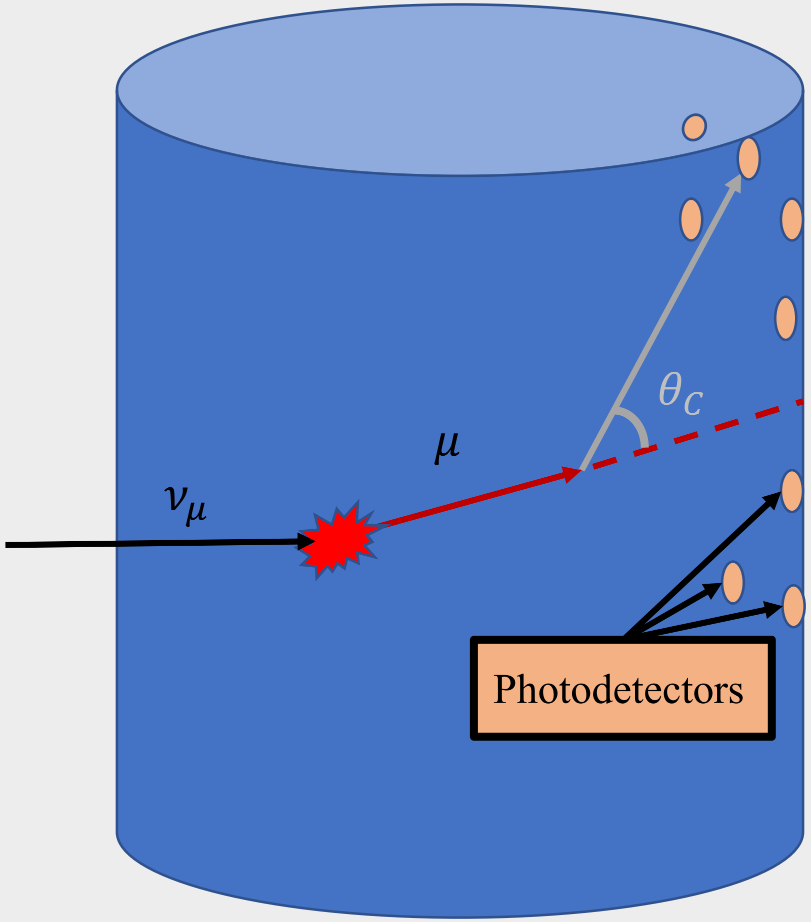


Full realization of detector geometry in simulation



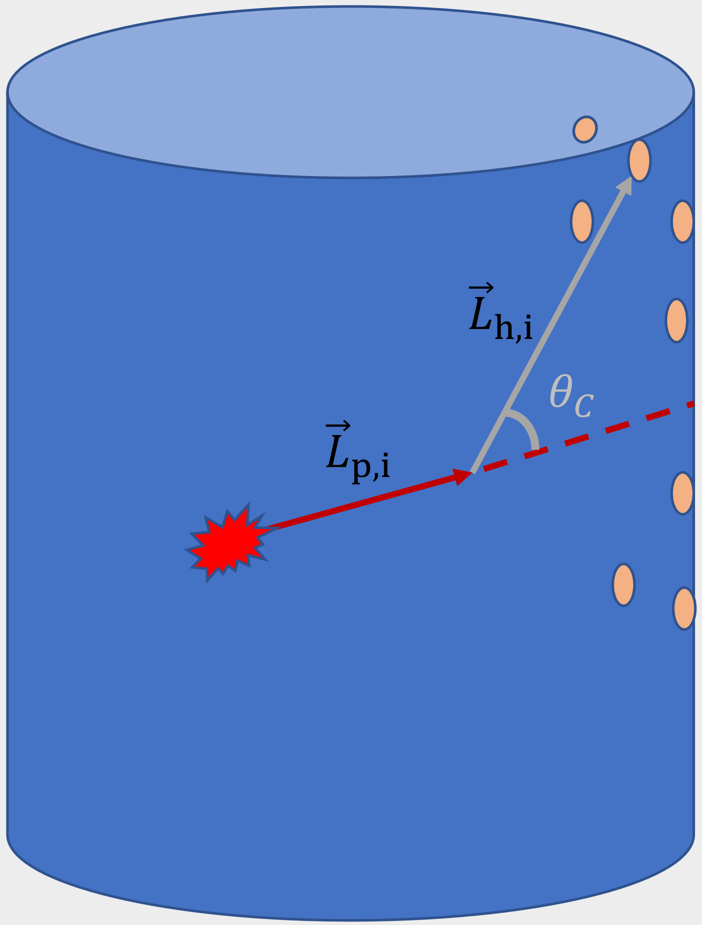
The Extended Vertex Fitter

- The Extended Vertex Fitter simultaneously floats the vertex position $\vec{r}$, direction $\vec{d}$, and $vtxTime$ and calculates two figures-of-merit
  - Extended time residual
  - Cherenkov cone fit
- Then, the negative total FOM is minimized with Minuit
- $FOM_{tot} = \frac{(FOM_{ext}+FOM_{dir})}{2}$



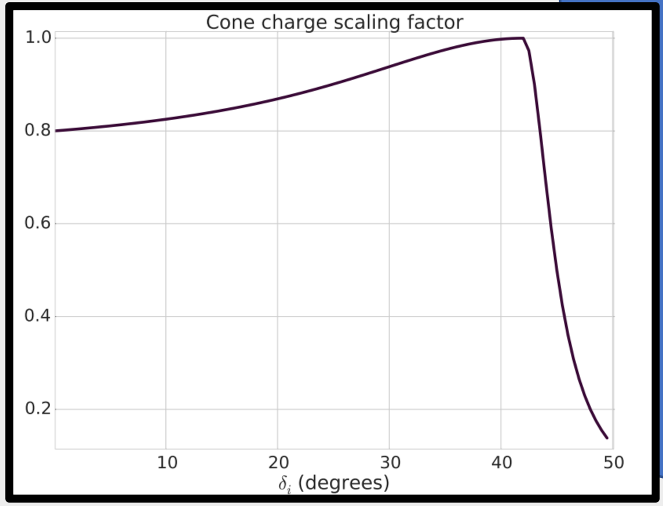
Extended time residual FOM

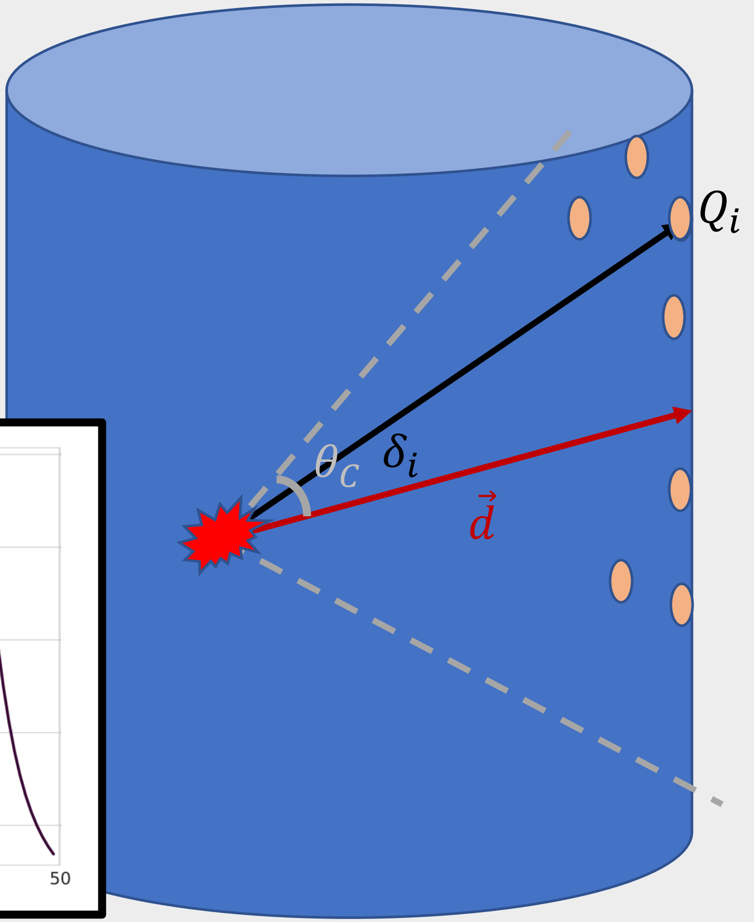
- Consider an event with N detector hits; we want to determine how likely it is the vertex originates from position $\vec{r}$, direction $\vec{d}$, and $vtxTime$
- Model assumes all light is emitted from the muon track at the Cherenkov angle
- The chi-squared value is evaluated using all PMT & LAPPD hits:
  - $\chi^2 = \sum_{i=1}^{N} -2\ln\left[(1 - P_{noise}) * \frac{1}{\sqrt{2\pi}\sigma_i} * e^{\frac{-(\Delta_{ext,\mathrm{i}})^2}{2\sigma_i^2}} - P_{noise}\right]$
  - $\Delta_{ext,\mathrm{i}}$: Hit time residual for i^{th} detector
    - $\Delta_{\mathrm{ext,i}} = \left(\mathrm{hitTime_i} - \frac{|\vec{L}_{p,i}|}{c} - \frac{|\vec{L}_{h,i}|}{\left(\frac{c}{n}\right)}\right) - \mathrm{vtxTime}$
    - $\mathrm{P_{noise}}$: noise model will be implemented for each individual photodetector
- $FOM_{ext} = 100 - 5 * \frac{\chi^2}{ndof}$



The Direction Fitter FOM

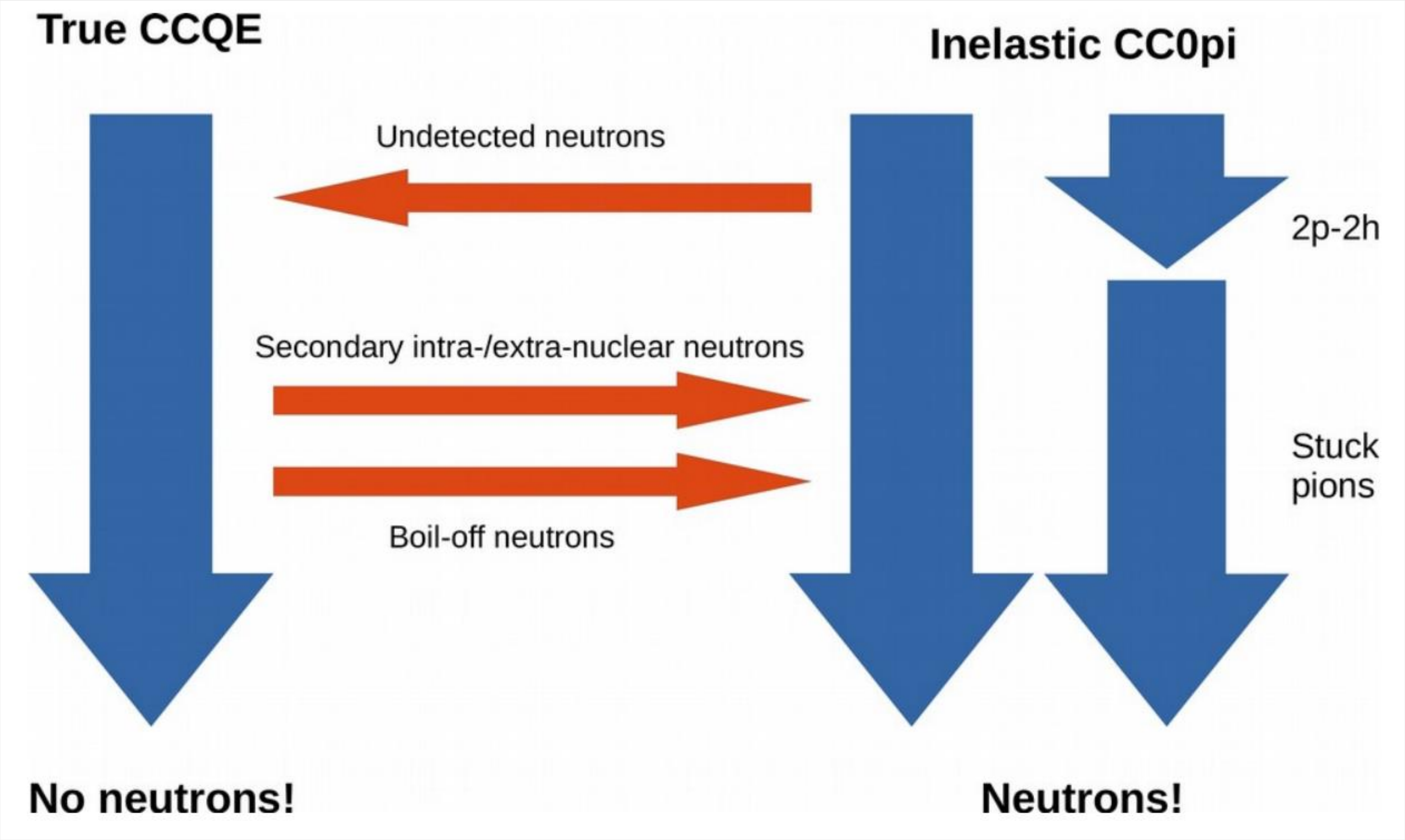
- Consider an event with N detector hits; want to determine how likely it is the muon travels direction $\vec{d}(\theta,\phi)$ from interaction point $\vec{r}$
- The vertex direction is fit by evaluating a "cone charge" parameter
  - Hits inside a Cherenkov cone with high charge dominate the cone charge
- $Q_C = \sum_{i=1}^{N} \begin{cases} Q_i\left(\frac{3}{4} + \frac{0.25}{(1+\delta_i^2/\delta_L^2)}\right), & \delta_i - \theta_C \le 0 \\ Q_i\left(\frac{1}{1+\delta_i^2/\delta_H^2}\right), & \delta_i - \theta_C > 0 \end{cases}$
- $FOM_{dir} = 100 * \left(\frac{Q_C}{Q_{tot}}\right)$





$\theta_C = 42°$ (Cherenkov angle in water)
$\delta_L = \theta_C/2 = 21°$
$\delta_H = 3°$ (Specific to muons)

Neutron multiplicity identification (and confusion)



V. Fischer, "ANNIE: The Accelerator Neutrino-Neutron Interaction Experiment", NNN 2018 Plenary.

DoE Proposal: Tank Vertex Reconstruction

- Simulated muon neutrino interactions in ANNIE using GENIE (neutrino interaction simulation) & WCSim (detector response simulation)
- Initial performance of the Extended Vertex Finder reconstruction on these events is shown
  - MC truth position, direction, and time given as the fitter seed
- Demonstrates the importance of the LAPPDs; the muon vertex can be more accurately reconstructed
- Full chain of tools are now implemented in our new software framework (ToolAnalysis)
- Optimizing performance with no MC Truth information still ongoing