IOWA STATE UNIVERSITY

Ashley Back for the ANNIE Collaboration

Track and vertex reconstruction in ANNIE Phase II

New perspectives
Fermilab, 18th June 2018

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The ANNIE experiment

Primary **physics** goal:

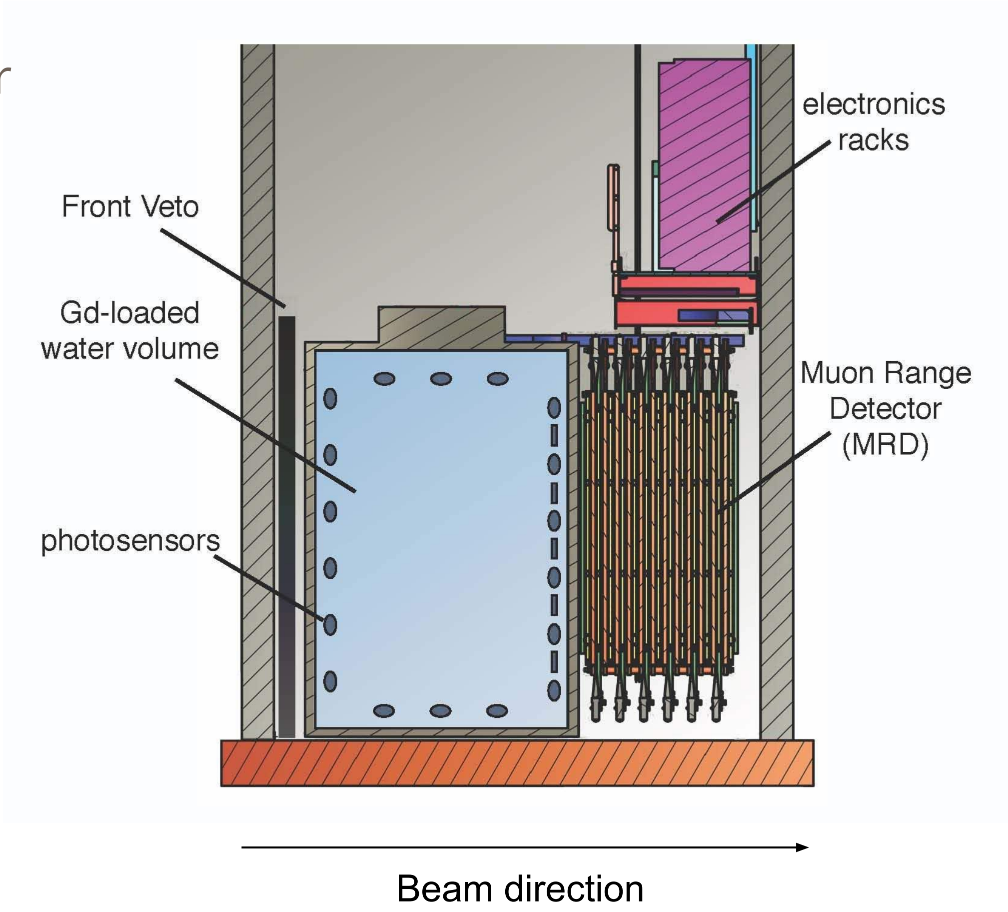
- Measure the abundance of final state neutrons (neutron yield), as a function of momentum transfer, from neutrino-nucleus interactions in water
  - Reduce systematic uncertainties on neutrino energy reconstruction in oscillation searches
  - Constrain backgrounds in proton decay searches

Technological goals:

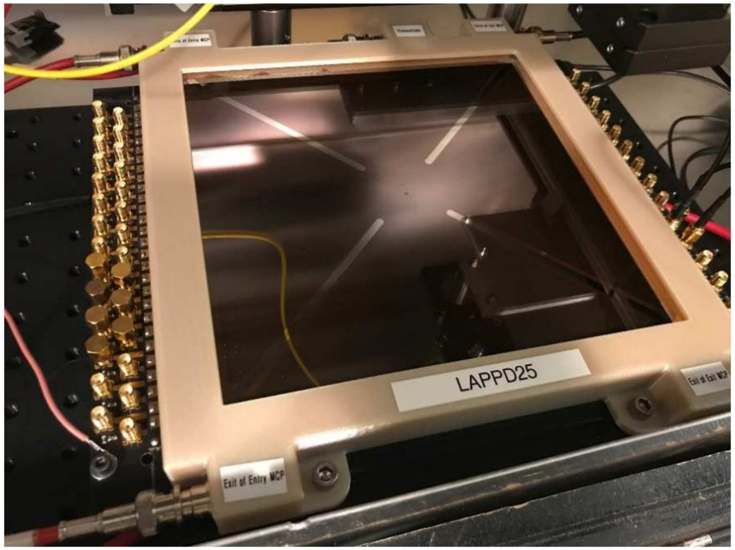
- First application of Gd-loaded water in a neutrino beam
- First demonstration of Large-Area Picosecond Photodetectors (LAPPDs) in a physics measurement

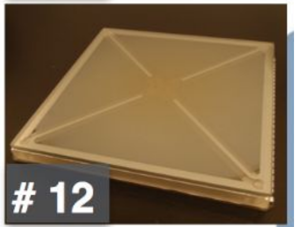
The Phase II detector

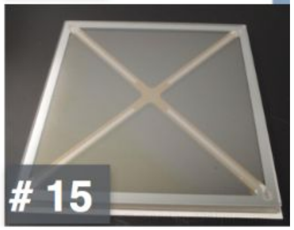
- Gadolinium (0.2%) loaded water
- ~125 PMTs + 5 LAPPDs
    - Coverage on all internal surfaces of tank → LAPPDs focussed downstream
    - Flexibility to add additional LAPPDs
- Fully instrumented MRD
    - 11 layers and 310 channels
- Upgraded electronics and readout
- Commissioning Fall 2018



LAPPDs



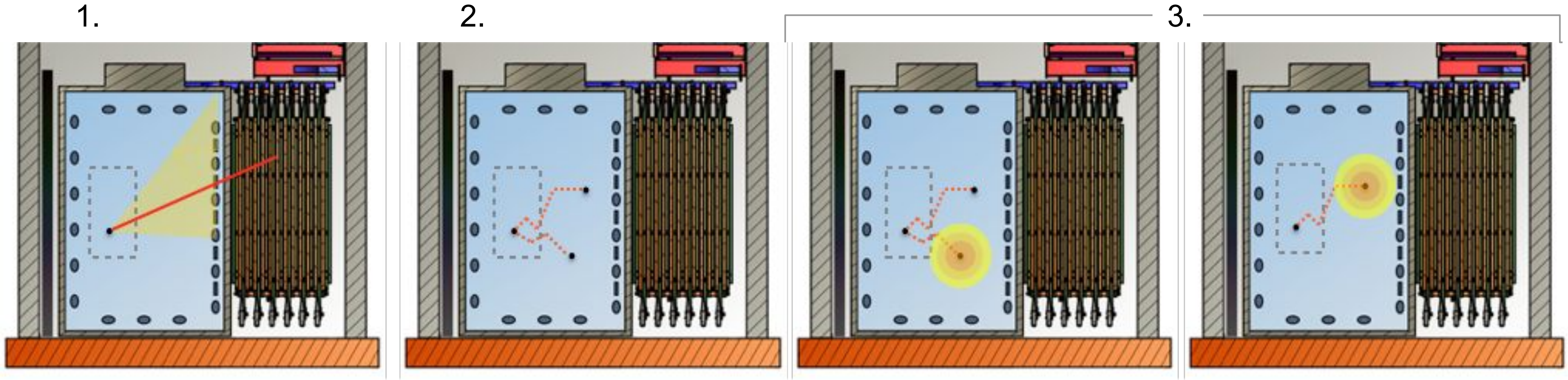




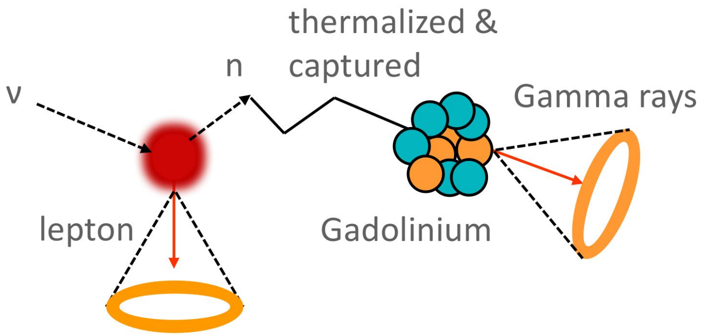
- Micro-channel plate, fast-timing photodetectors
- Large-area: 20 × 20 cm
- Fast timing: <100 ps for a single photoelectron
- High quantum efficiency (QE): >20 %
- Millimetre position resolution

- A number of tiles have been produced and tested → gain, timing and QE
- Purchased tile #25 from INCOM
  - Thorough testing ongoing at ISU
  - Expected to be deployed in ANNIE Phase II

Event signature

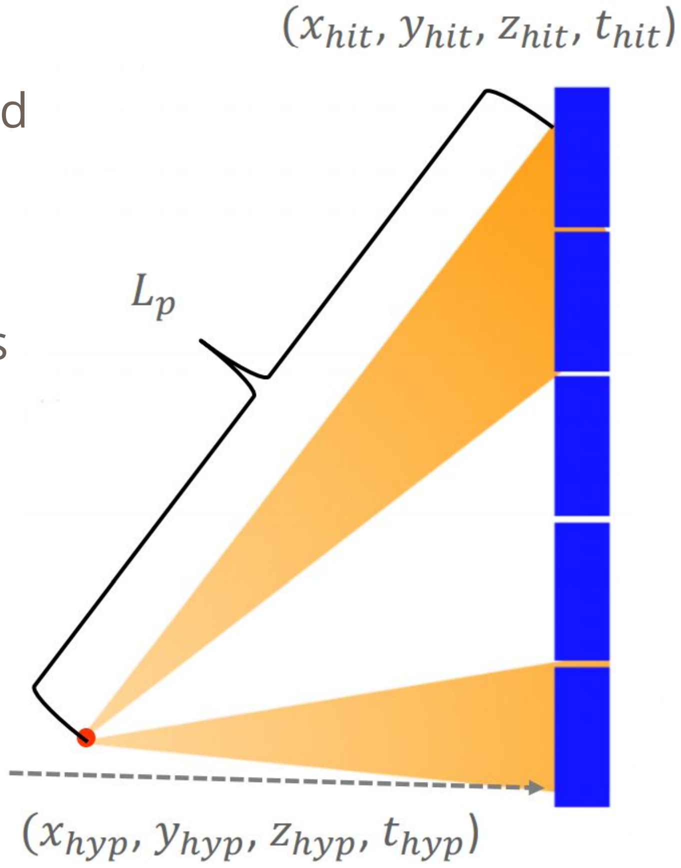


1. Charged-current *ν* interaction in fiducial volume
   a. Cherenkov cone incident on tank PMTs and LAPPDs
   b. Scintillation light from stopping muon in MRD
2. Final state neutrons thermalized and captured on Gd
3. Cascade of 8 MeV detected by tank PMTs



Water Cherenkov reconstruction

1. **"Simple vertex" fit** → (x, y, z, t)
   - Consider a point source at a hypothesised location, emitting Cherenkov light
   - For each hit calculate the timing residual and timing Figure of Merit (FOM)
   - Adjust the four hypothesised parameters to maximise FOM



Credit: Jingbo Wang

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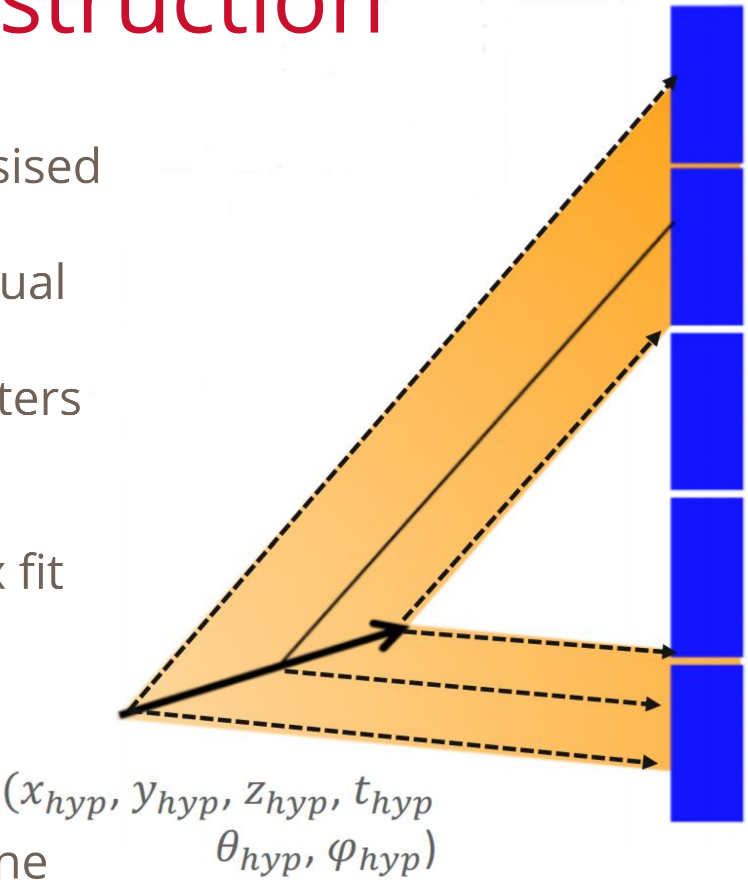
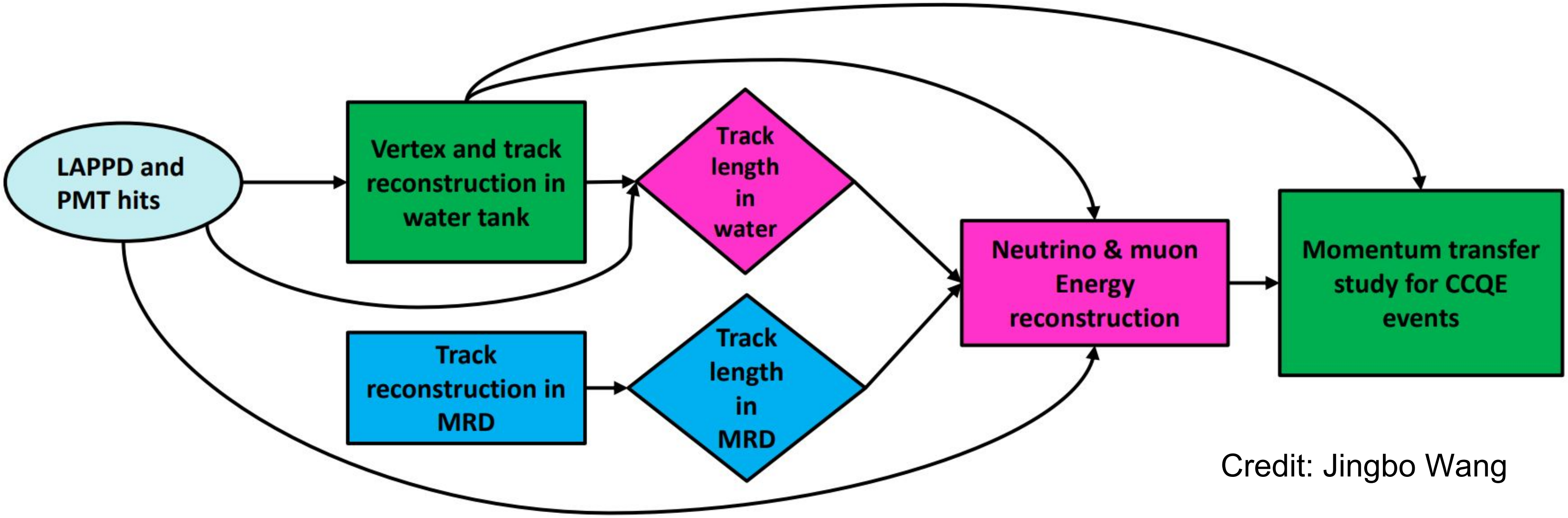
   - Adjust the four hypothesised parameters to maximise FOM
2. **Extended vertex fit** → (x, y, z, t, θ, φ)
   - Start with position from simple vertex fit and add hypothesised track direction
   - For each hit calculate extended time residual including muon travel time
   - Calculate cone FOM by comparing predicted to measured Cherenkov cone
   - Adjust all six parameters to maximise total FOM (time FOM + cone FOM)



Credit: Jingbo Wang

Reconstruction strategy

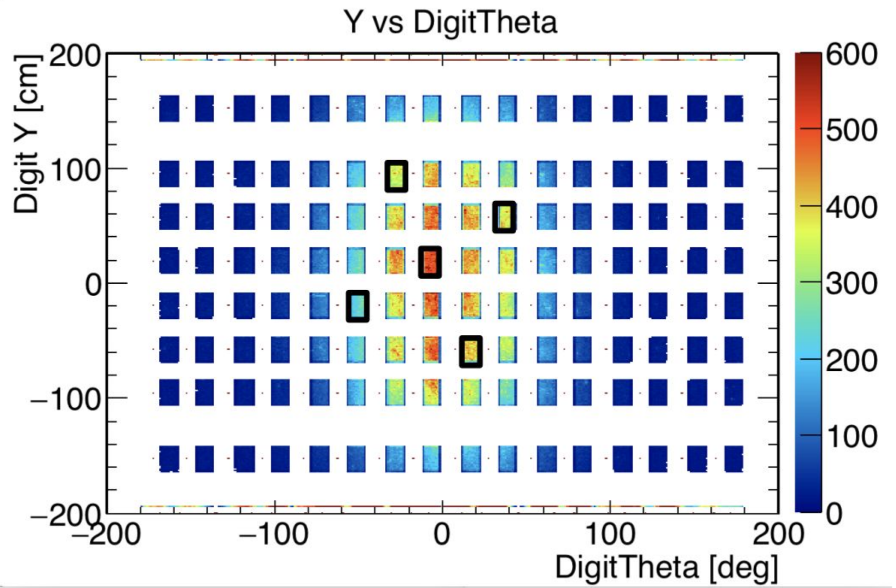


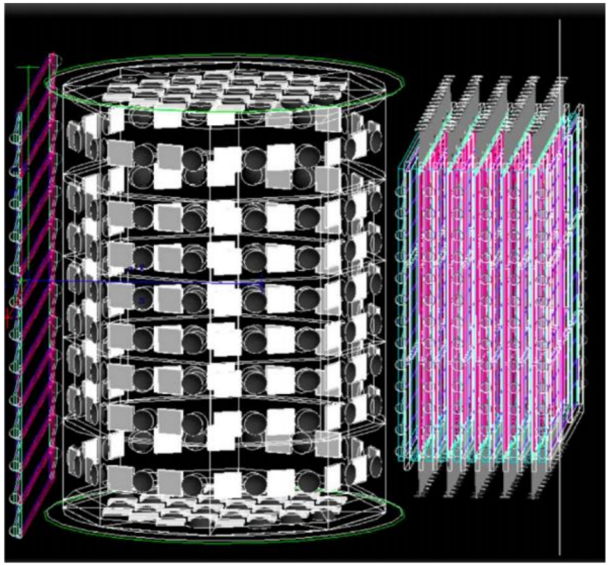
Credit: Jingbo Wang

- Reconstruct vertex and track using extended vertex fit
- Fit track position in all MRD layers → track length in MRD
- Reconstruct track length in water using a deep learning neural network
- Reconstruct muon and neutrino energies using boosted decision tree (BDT)
- Calculate Q^2 assuming CCQE interaction

Phase II simulation

- Full ANNIE Phase II simulation using WCSim
  - Phase II geometry with 128 8-inch PMTs and 128 LAPPDs
- Mask out LAPPDs to test specific configurations
  - **PMT only**: 128 PMTs (~20 % coverage of the inner walls)
  - **LAPPD+PMT**: 128 PMTs + 5 LAPPDs → on downstream wall of the tank
- Use a dataset of ν from GENIE and propagated through WCSim

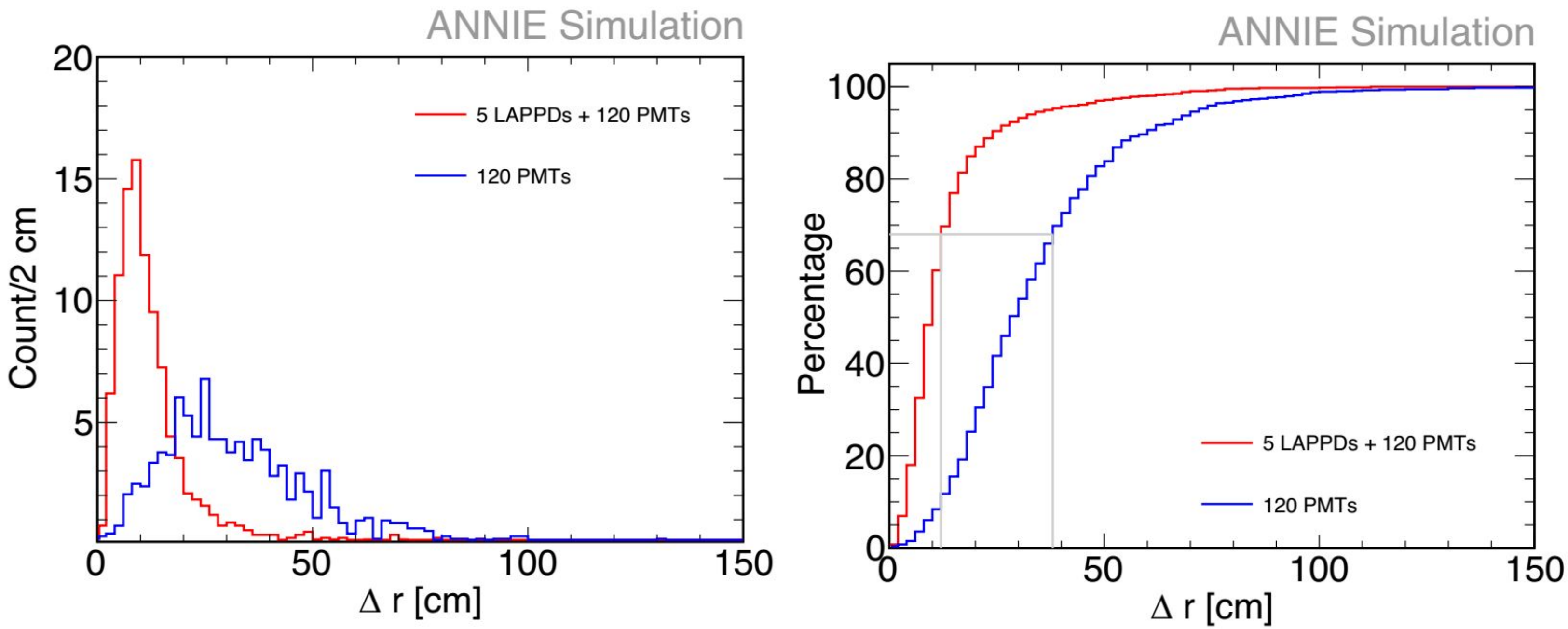




Credit: Marcus O’Flaherty

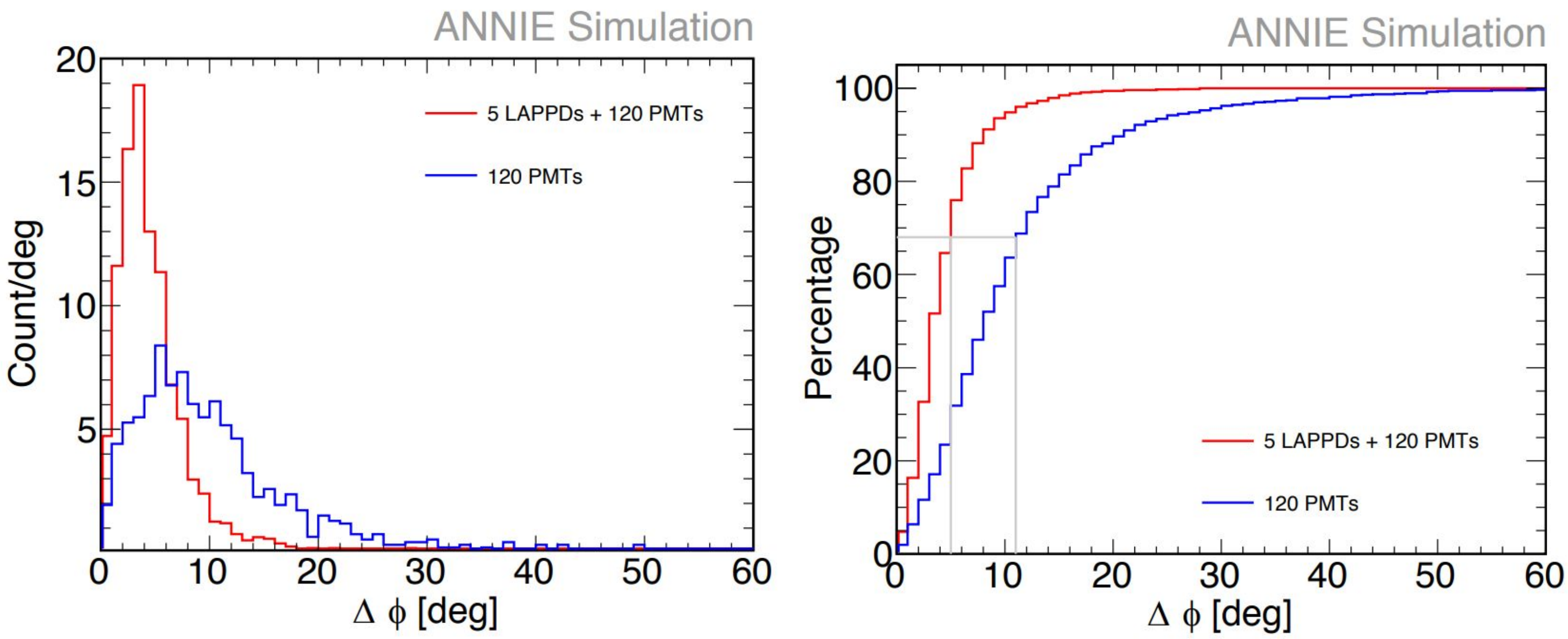
Vertex position resolution

- Select events where the muon is produced within the fiducial volume and stopped within the MRD
- 128 PMT-only (20% coverage): 38 cm
- 5 LAPPDs + 128 PMTs: 12 cm
- Improvement by more than a **factor of three** when we include LAPPD hits in the reconstruction



Muon angle resolution

- Select events where the muon is produced within the fiducial volume and stopped within the MRD
- 128 PMT-only (20% coverage): ~11°
- 5 LAPPDs + 128 PMTs: ~5°
- Improvement by about a **factor of two** when we include LAPPD hits in the reconstruction

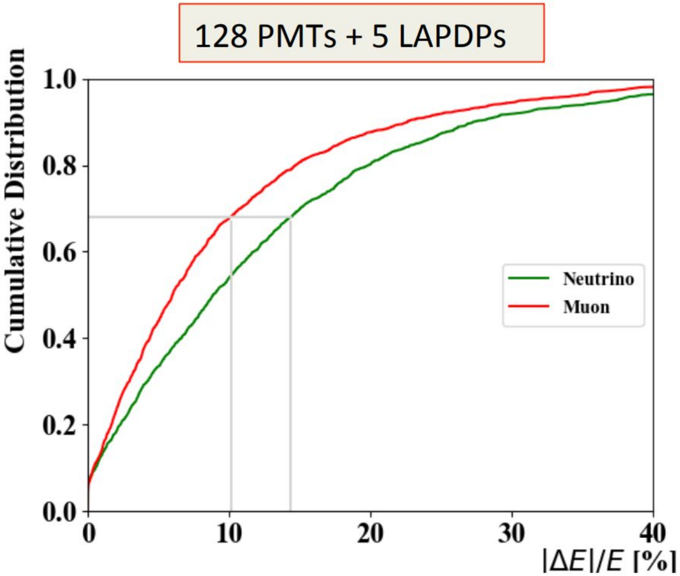


Further reconstruction

Combining the track length in water and the track length in the MRD as inputs to a BDT, we can reconstruct the muon and neutrino energies.

At the 68th percentile of all selected events in the sample, we achieve an energy resolution of:

- 10 %, for the muon
- 14 %, for the neutrino



For more details see: E. Drakopoulou, arXiv:1710.05668v3

Conclusions

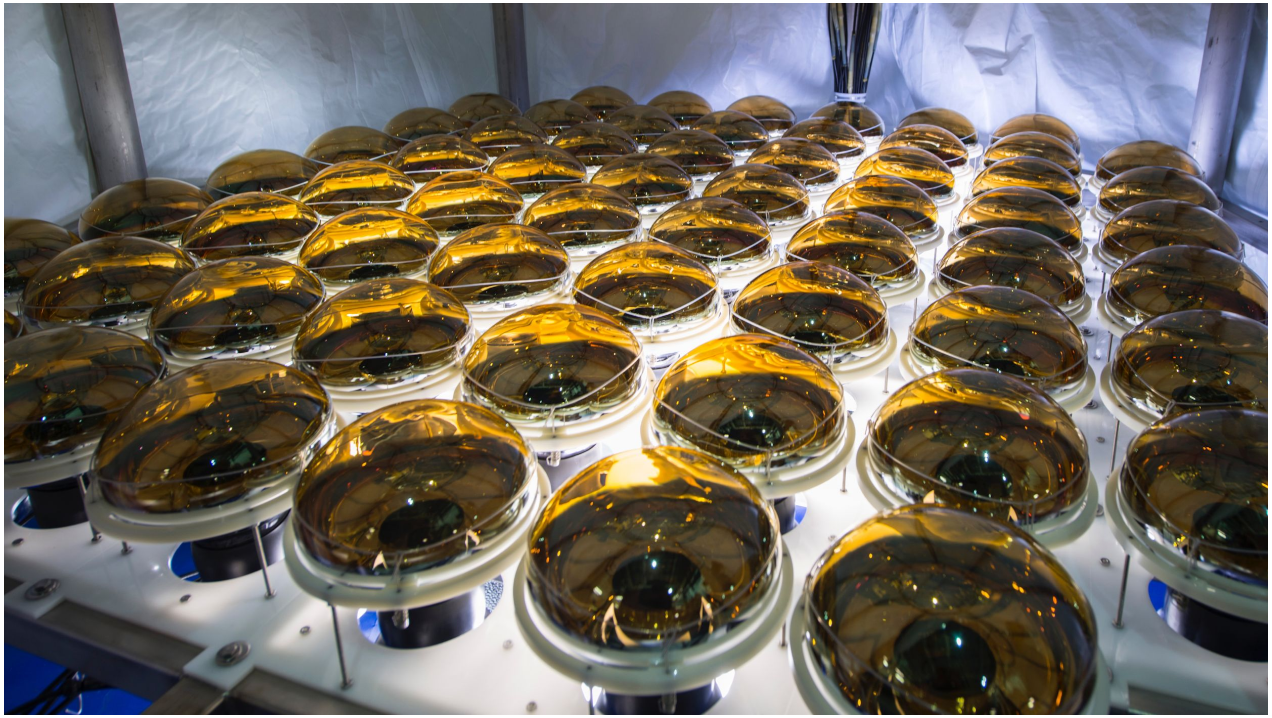
- Deploying LAPPDs and using Gd-loaded water will ensure ANNIE can meet its physics goals for Phase II:
    - Namely measuring the neutron yield, as a function of momentum transfer, from neutrino-nucleus interactions in water

- We have demonstrated reconstruction of the track, vertex and energy using PMT and LAPPD hits

- We see a significant reconstruction improvement over ~20 % coverage by PMTs alone

- Continuing effort to ensure reconstruction is ready for the start of data taking in ANNIE Phase II, later **this year**

Thank you for your attention!



LAPPD commercialized by INCOM.

INCOM. http://www.incomusa.com/

A. Lyashenko, Incom LAPPD, Pico-Second Workshop, Kansas City Sept 15-18 2016

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Vertex and track reconstruction

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Step1: "Simple vertex" fit

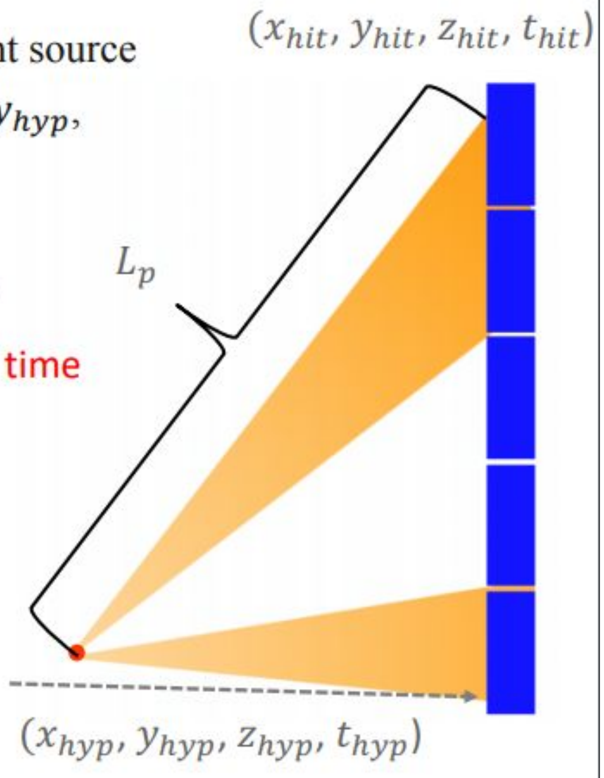
four parameter fit: (x, y, z, t)

- Conceptualize Cherenkov light as coming from a point source
- Assume a hypothesized point-source location (x_{hyp}, y_{hyp}, z_{hyp}, t_{hyp})
- For each photon hit, calculate the point time residual:

$$\Delta t = t_{hit} - \frac{L_p}{c/n}$$

Photon travel time

- **For all the hits, calculate the timing-based Figure-of-Merit (timing likelihood)**
- **Adjust four parameters** to maximize time FOM. FOM takes the maximum value when the width of the time residual distribution is minimized



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Vertex and track reconstruction

Step2: "Extended vertex" fit

six parameter fit: $(x, y, z, t, \theta, \varphi)$

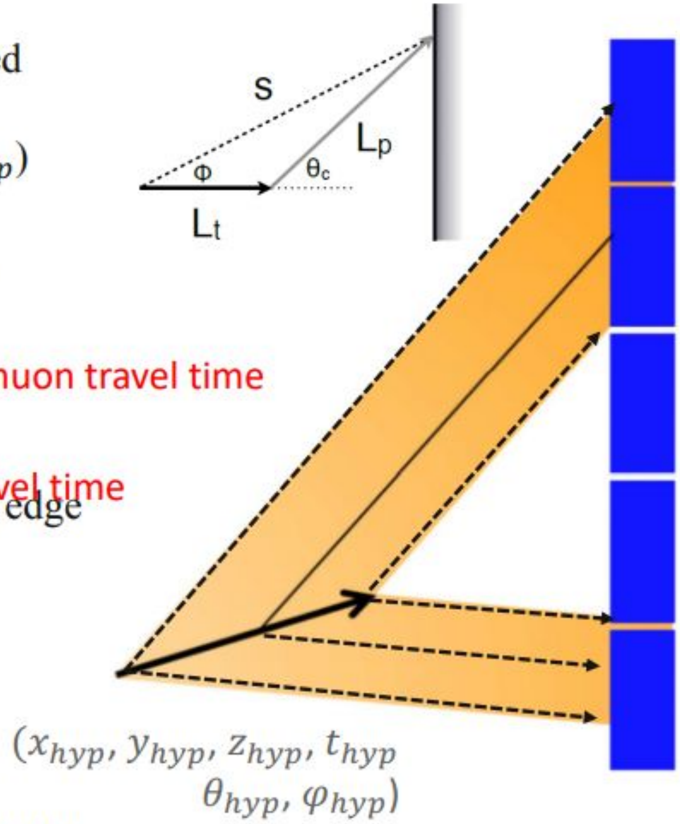
- Starting from the "simple vertex" obtained from step1, assume a hypothesized track $(x_{hyp}, y_{hyp}, z_{hyp}, t_{hyp}, \theta_{hyp}, \varphi_{hyp})$
- For each hit, calculate the extended time residual:

$$\Delta t = t_{hit} - \frac{L_p}{\frac{c}{n}} - \frac{L_t}{c}$$

muon travel time

Photon travel time

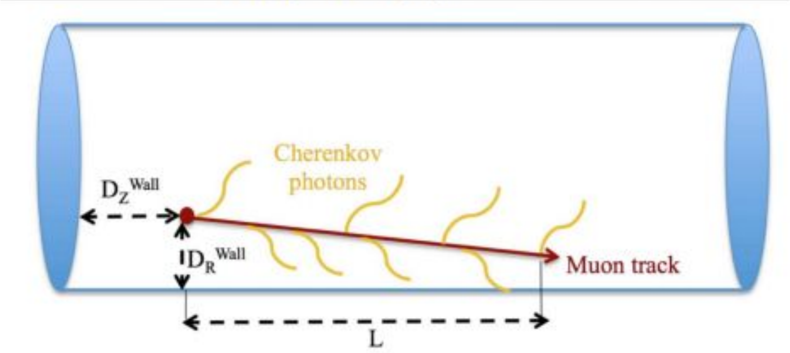
- For each hit, compare the measured cone edge to the simulated one.
- For all hits, calculated the overall FOM **$(\mathrm{FOM}_{time} + \mathrm{FOM}_{cone})$**
- **Adjust six parameters** to maximize the FOM



Track length reconstruction

- Muon energy is measured as the sum of energy deposit in water and MRD
- Track length in the water tank is calculated using a **Deep Learning Neural Network** (from Tensorflow package).
- Tracks in MRD are reconstructed in two 2D views and then matched into a 3D view
- MRD reconstruction is done in a separate framework. For the present studies, the track length is calculated as the distance between the true entry and stop points of the muon (neglect scattering)

Track in water



Track in MRD