

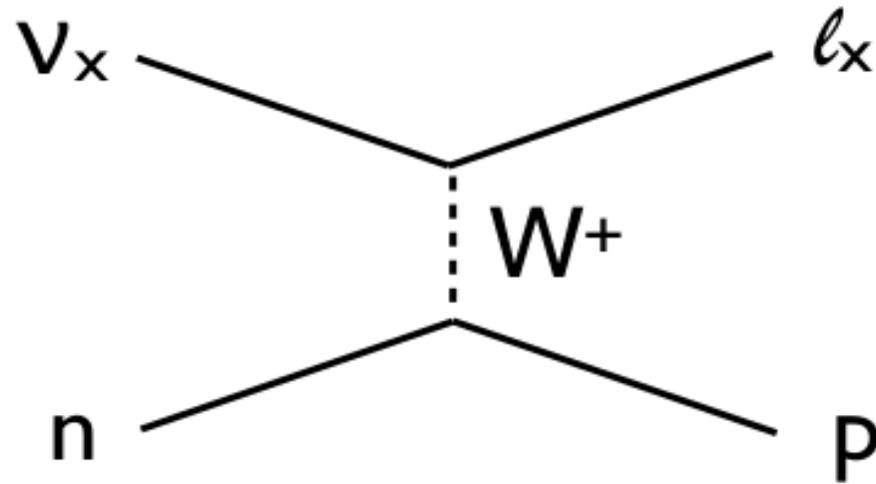
# annie

in 10 minutes



# True CCQE

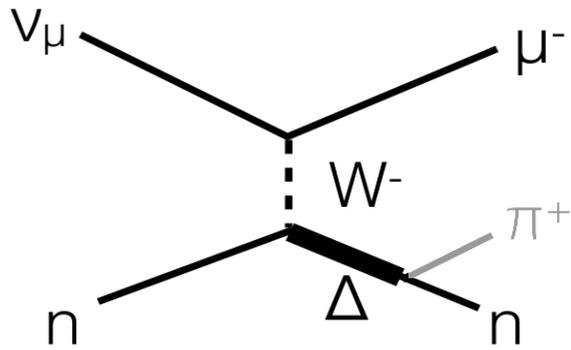
- 2 body scattering
- Target nucleon assumed at rest
- Kinematics from observed lepton



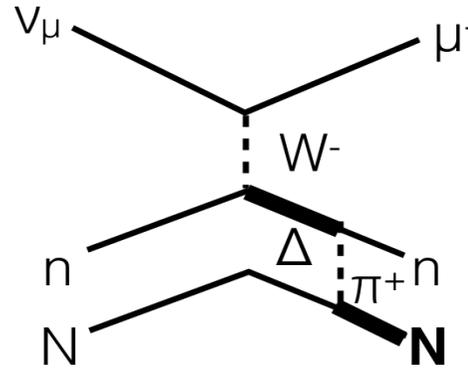
$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)}$$

$$Q_{QE}^2 = 2E_\nu^{QE}(E_\mu - p_\mu \cos \theta_\mu) - m_\mu^2$$

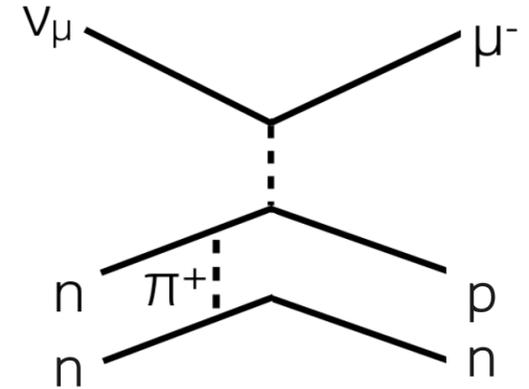
# Fake CCQE



Resonant pion production with undetected pion

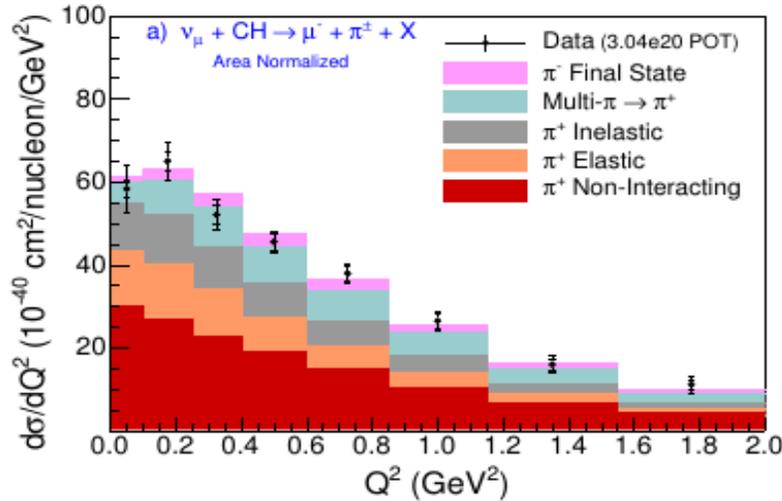


Resonant pion production with 'stuck pion'

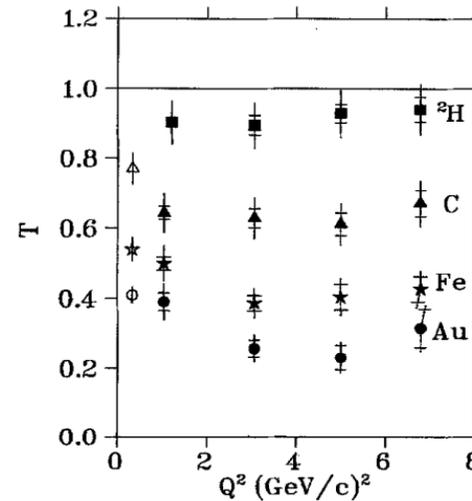


Interaction with correlated pair of nucleons

Minerva CC1π sample



Phys.Rev. D94 (2016) no.5, 052005

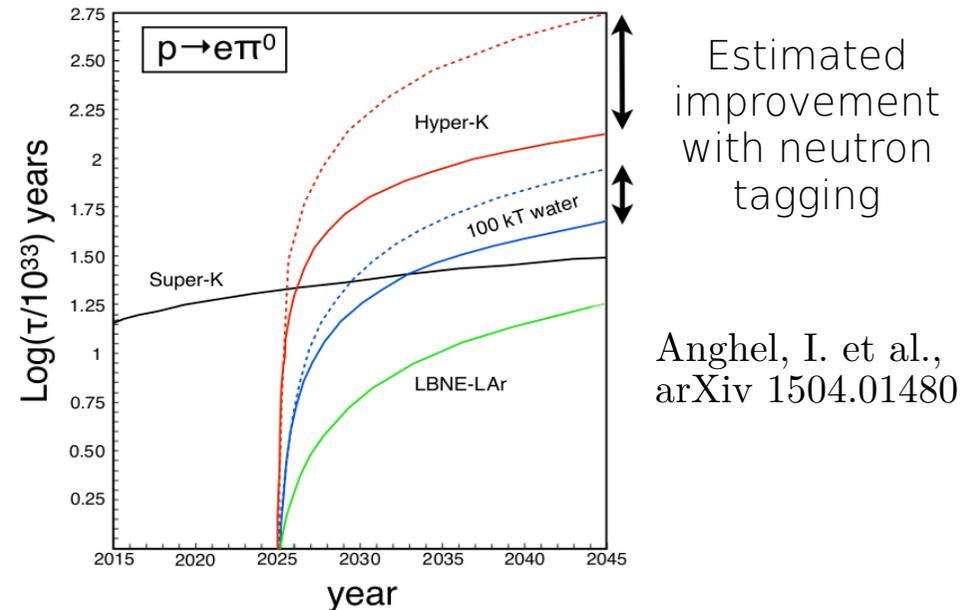
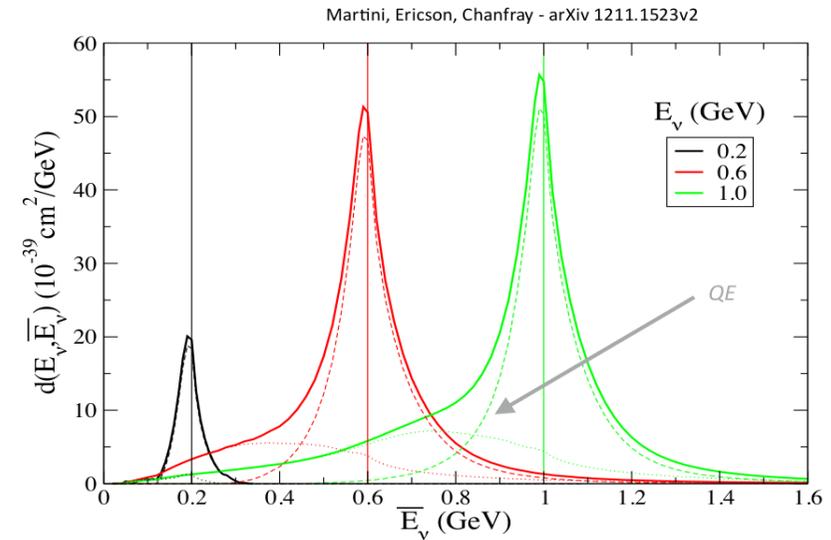


Fraction of protons that escape without re-interaction in e-p elastic scattering

Phys. Lett. B 351 87-92

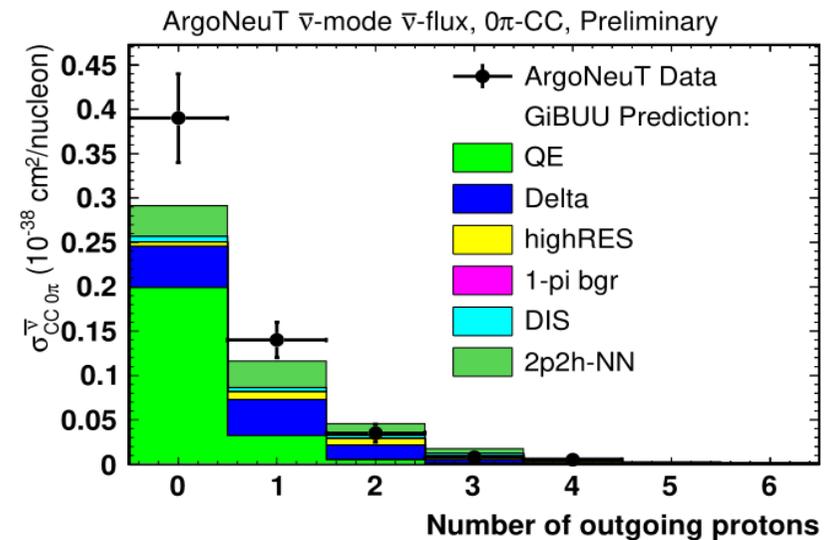
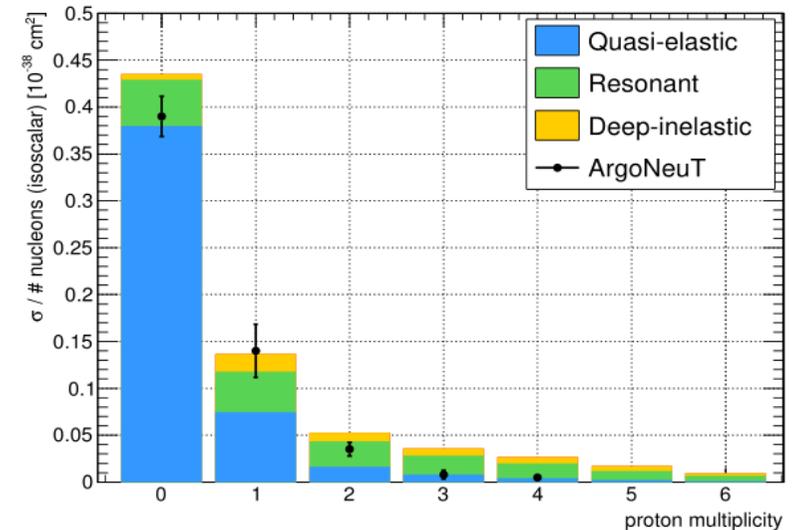
# Physics Impacts

- Downward bias of reconstructed neutrino energy
  - Influences measurement of oscillation parameters
- Source of IBD background
  - Relevant for PDK and DSNB detection
  - Efficiency of neutron tagging in excluding these interactions must be well known
- **Accounting for these affects requires knowledge of multiplicity and kinematic relations**



# Liquid Argon Measurements

- High resolution and low threshold of LAr experiments make protons visible down to 21MeV
- Multiplicity measurements by ArgoNeut demonstrate discrepancies between generators and data
- **Experimental input is crucial to improve generators and theory!**



<https://doi.org/10.7566/JPSCP.12.010017>

" ...As neutrino-antineutrino event-rate comparisons are important for  $\delta$ CP measurements, the relative neutron composition of final hadronic states is significant. It is important to understand the prospects for semi-inclusive theoretical models that can predict this neutron composition.

**Experimentally, programs to detect neutrons are essential."**

NuSTEC white paper Neutrino Scattering Theory and Experiment Collaboration



" ...As neutrino-antineutrino event-rate comparisons are important for  $\delta$ CP measurements, the relative neutron composition of final hadronic states is significant. It is important to understand the prospects for semi-inclusive theoretical models that can predict this neutron composition.

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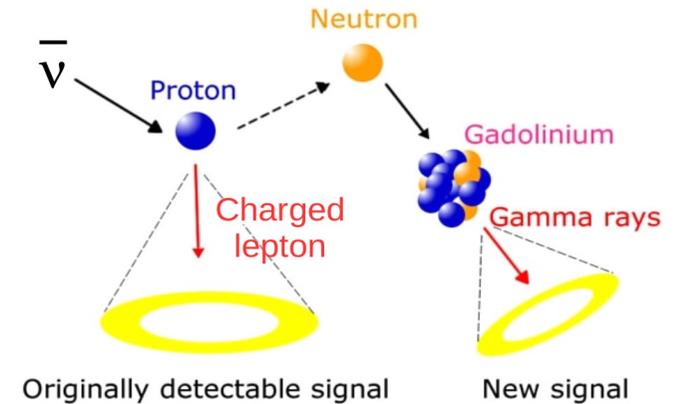
"The main deliverable from this experiment is a measurement of the final-state neutron abundance as a function of momentum transfer from charged current (CC) neutrino interactions."

ANNIE Letter of Intent

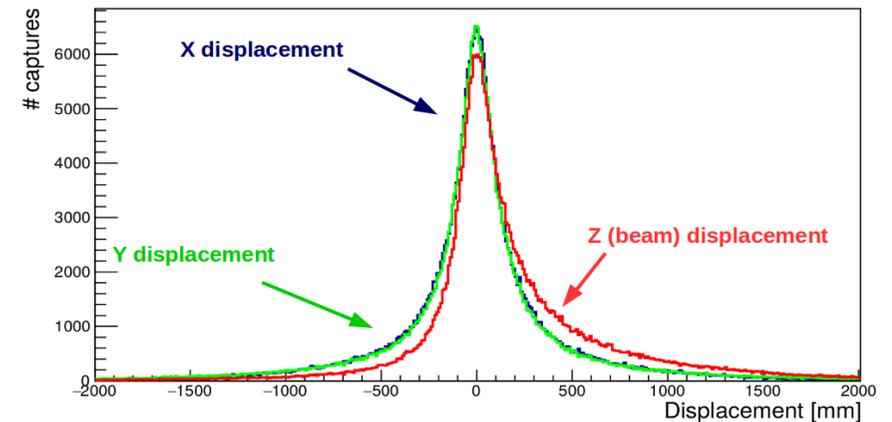


# Making Neutrons Visible

- ANNIE will use Gadolinium doping to achieve neutron visibility
  - 8MeV gamma cascade, ~4-5MeV visible energy
  - 20 $\mu$ s capture time helps minimize backgrounds
  - 20cm capture distance ensure neutrons do not leak out of the tank

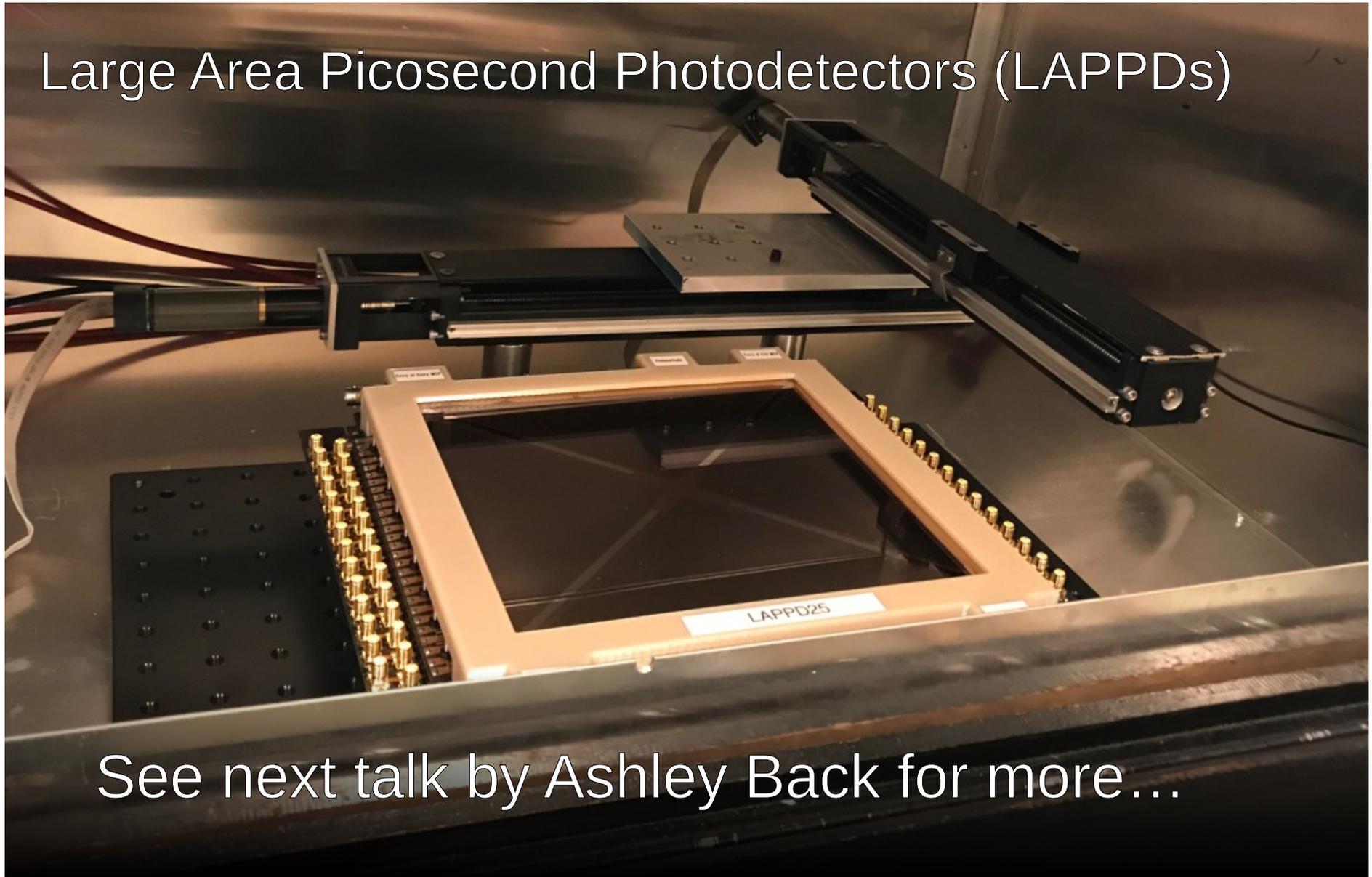


- Nonetheless, given ANNIE's small size it's crucial to maximize fiducial volume  
We need vertex resolution ~10cm, or equivalently, timing resolution ~100ps...



# A New Generation of Photodetector

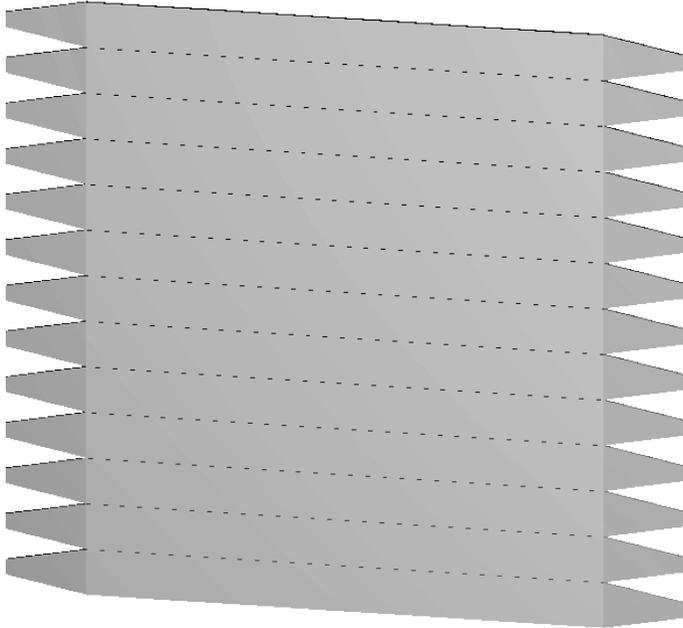
Large Area Picosecond Photodetectors (LAPPDs)



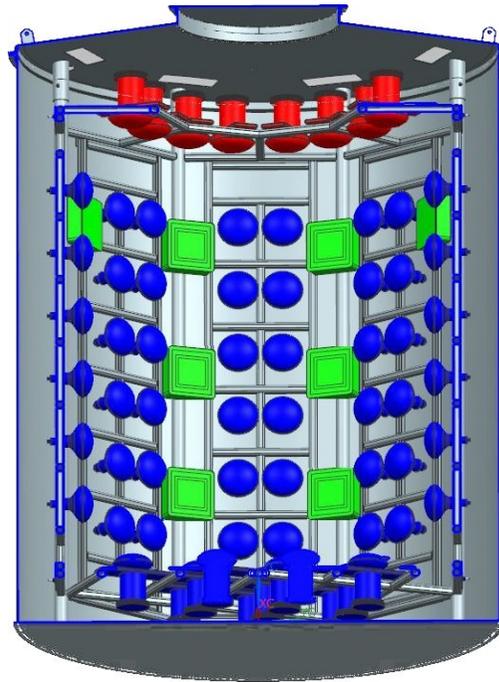
See next talk by Ashley Back for more...

# The ANNIE Detector

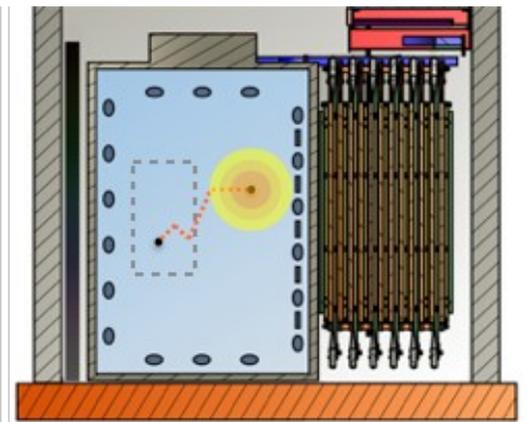
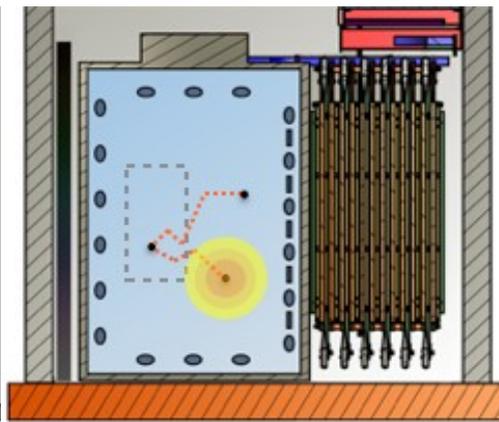
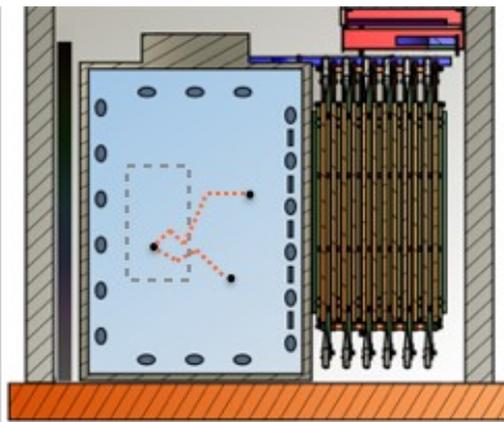
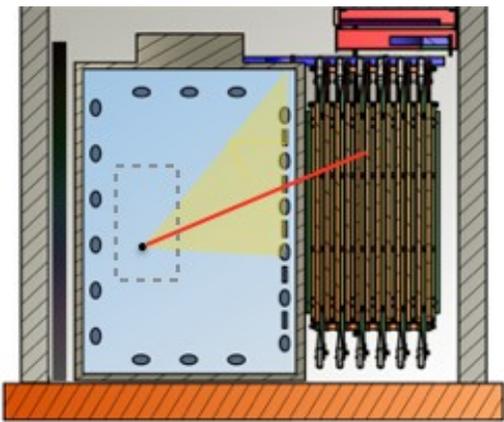
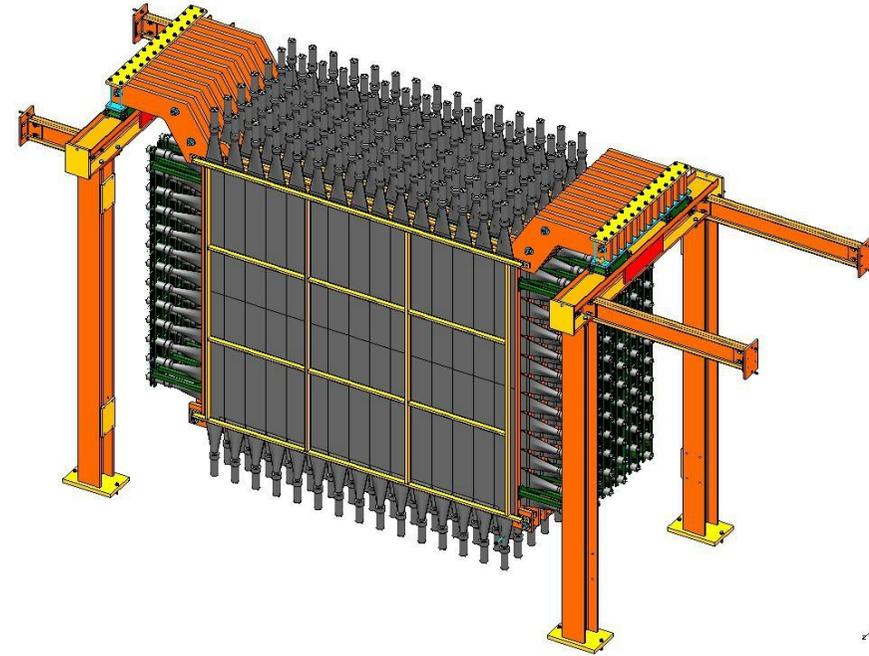
Forward Veto



Gd Doped Water Tank



Muon Range Detector



# ANNIE Phase 1

- Aside from efficiency we also need to know backgrounds
- Primary sources are upstream dirt interactions and 'skyshine' neutrons, scattered from the atmosphere

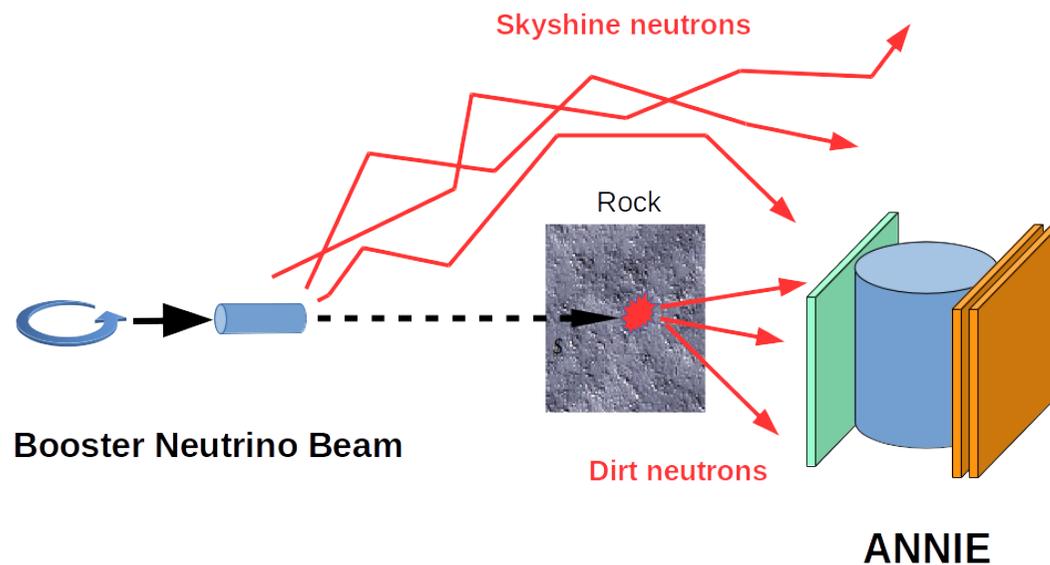
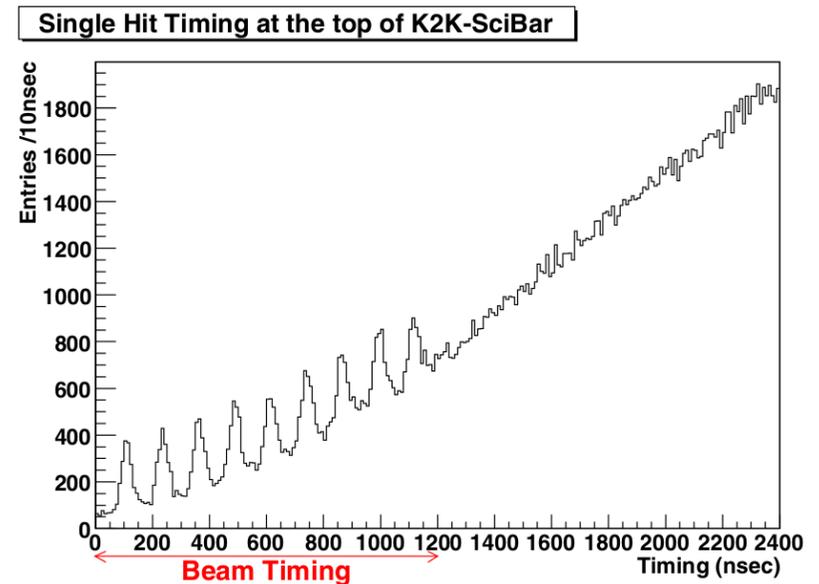


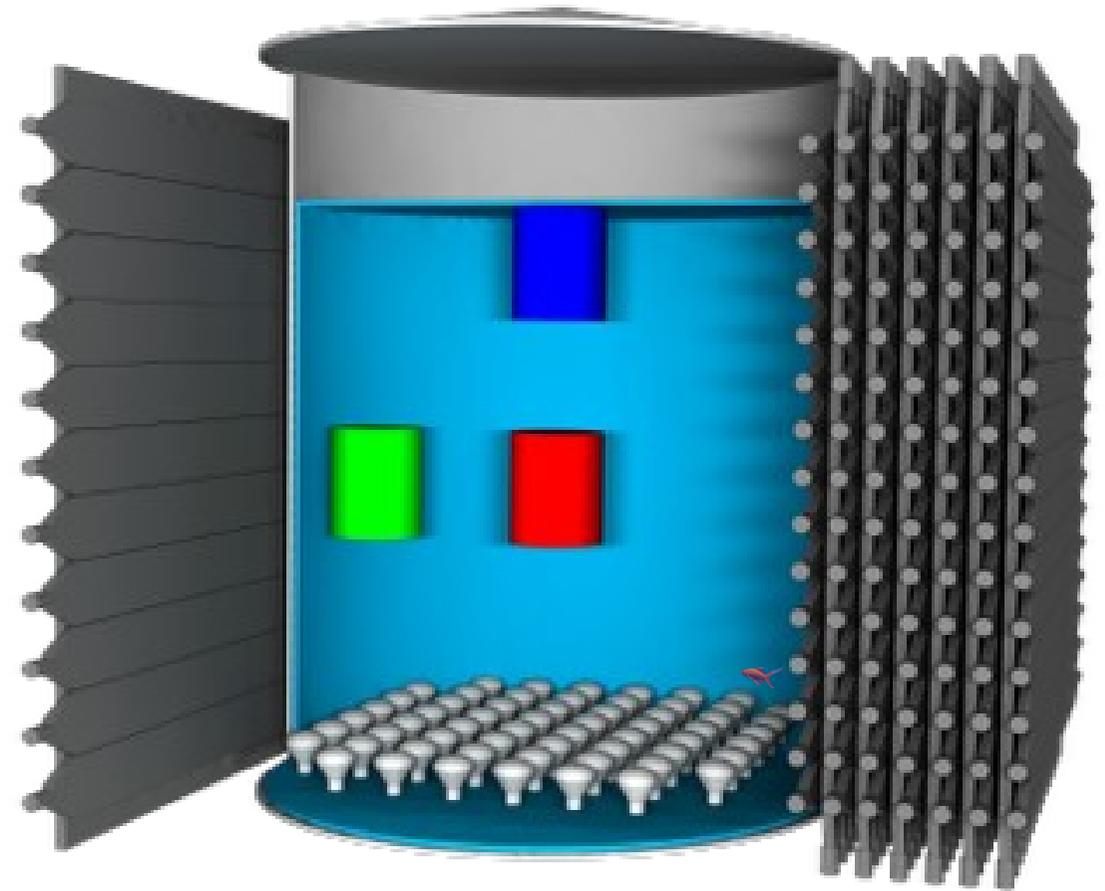
Image: Vincent Fischer



arXiv:hep-ex/0601022

# Phase 1 Detector

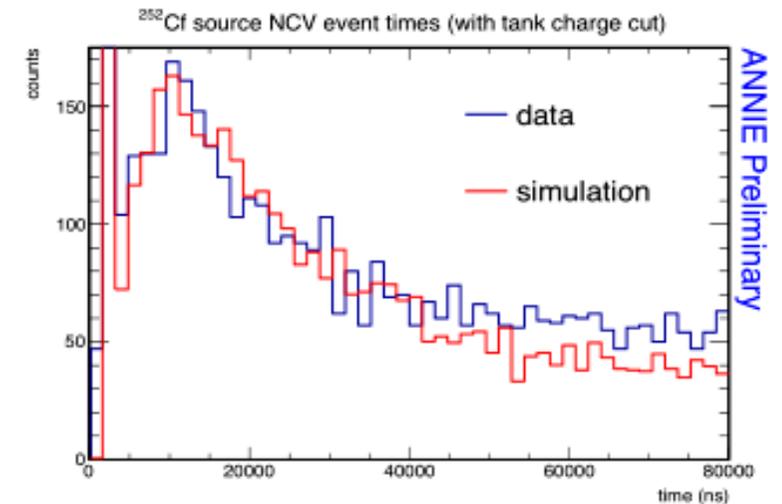
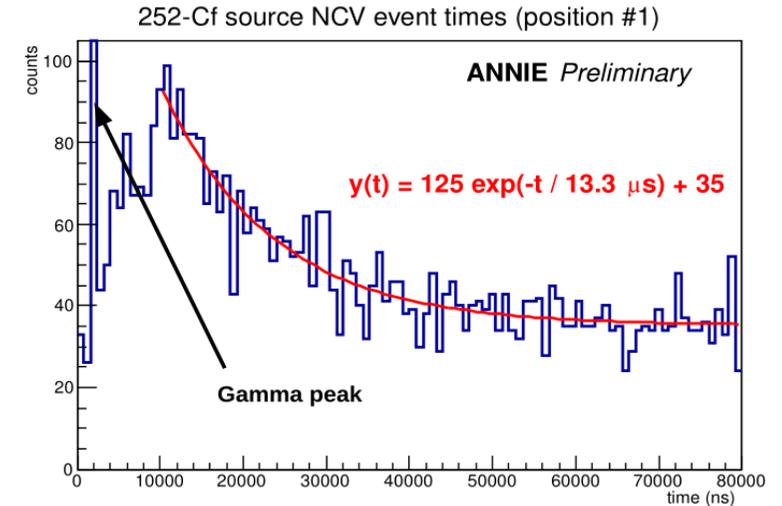
- Moveable sub-volume of liquid scintillator doped with 0.25% Gd
- Optically isolated from tank, with two PMTs watching for events
- White tank liner, 60 PMTs on the bottom to veto muons by cherenkov light
- Positional scan was performed to measure drop-off with overburden and distance from the beam-side wall



Credit: Jonathan Eisch

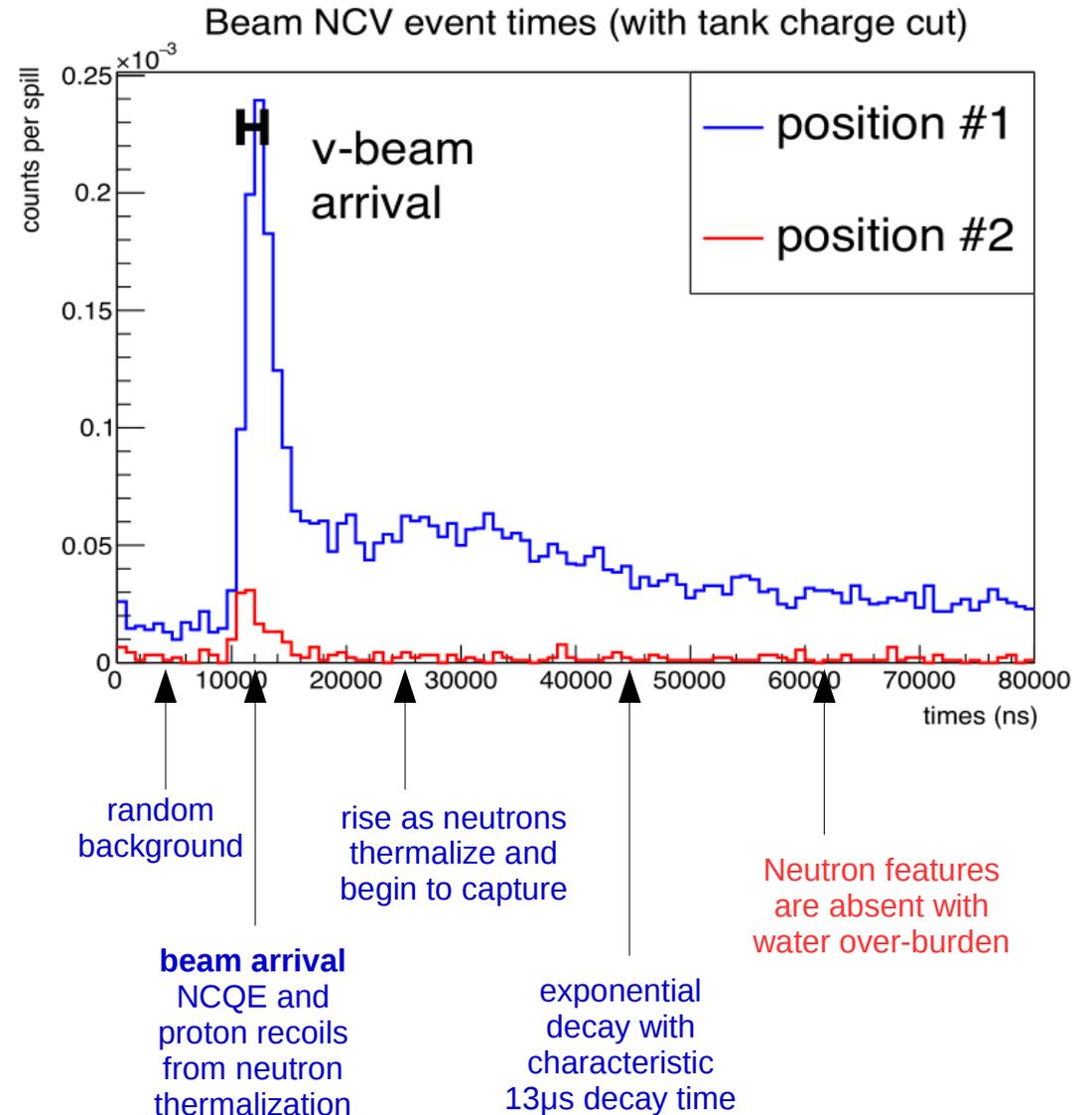
# Detector Calibration

- Neutron response was calibrated with a  $^{252}\text{Cf}$  source, using a scintillator crystal to trigger on gammas emitted during fission
- Source activity was measured using a commercial neutron detector and another source of well-known activity
- Results show the expected  $13\mu\text{s}$  capture time and agree fairly well with Monte Carlo simulations
- Multiple methods of NCV efficiency calculation were used, with good agreement between them



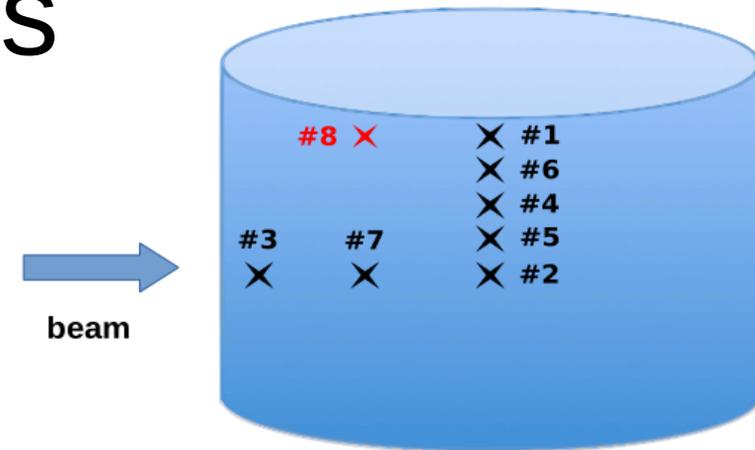
# Results

- Shown is the time profile of events, averaged over many beam spills
- Events are defined as simultaneous hits on both NCV PMTs, with no corresponding tank event
- Position #1 is at the water surface, Position #2 is at the tank centre
- There is a peak of in-time events consistent with neutral current events and proton recoils from thermalizing neutrons
- Following this, there is a rise, then exponential decay of neutron capture events
- There is a stark reduction in neutron events at depths > 2ft

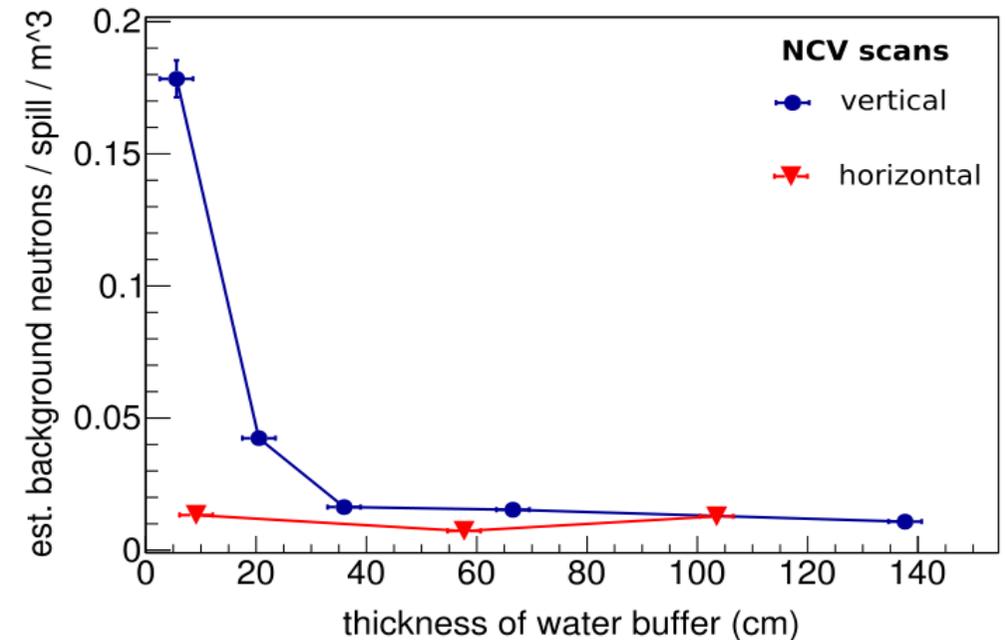


# Results

- The integrated neutron capture counts for seven positions within the tank are shown
- The blue curve traces the drop-off of skyshine with increasing water overburden
- The red curve shows the drop-off of dirt events with increasing distance from the front wall
- Background neutron rates are less than 0.02 per spill per  $m^3$  at all locations with half a meter of water overburden
- Based on this, Phase II will use the full 2.5 ton fiducial volume with good detection efficiency



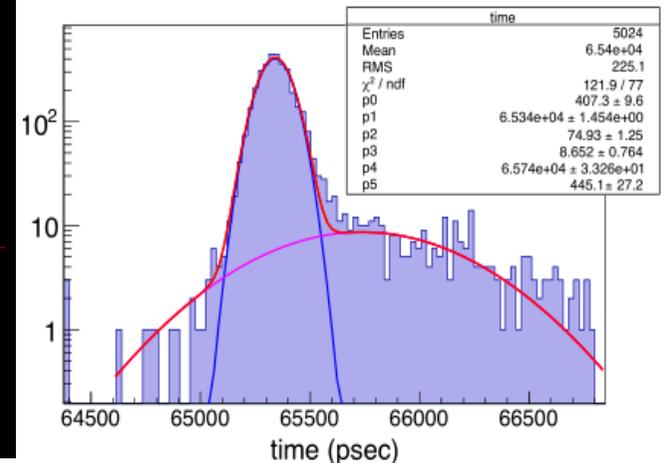
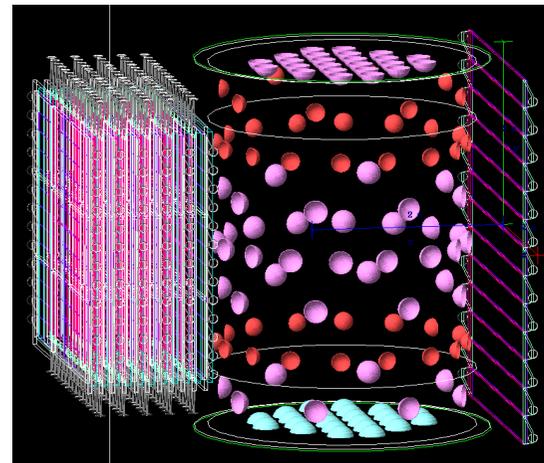
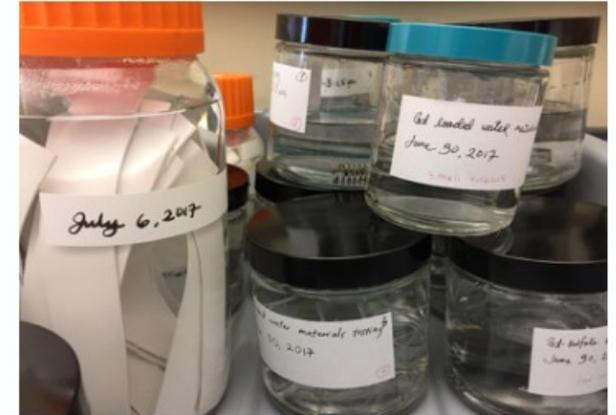
## Neutron capture rate results



plot by Steven Gardiner

# Toward ANNIE Phase II

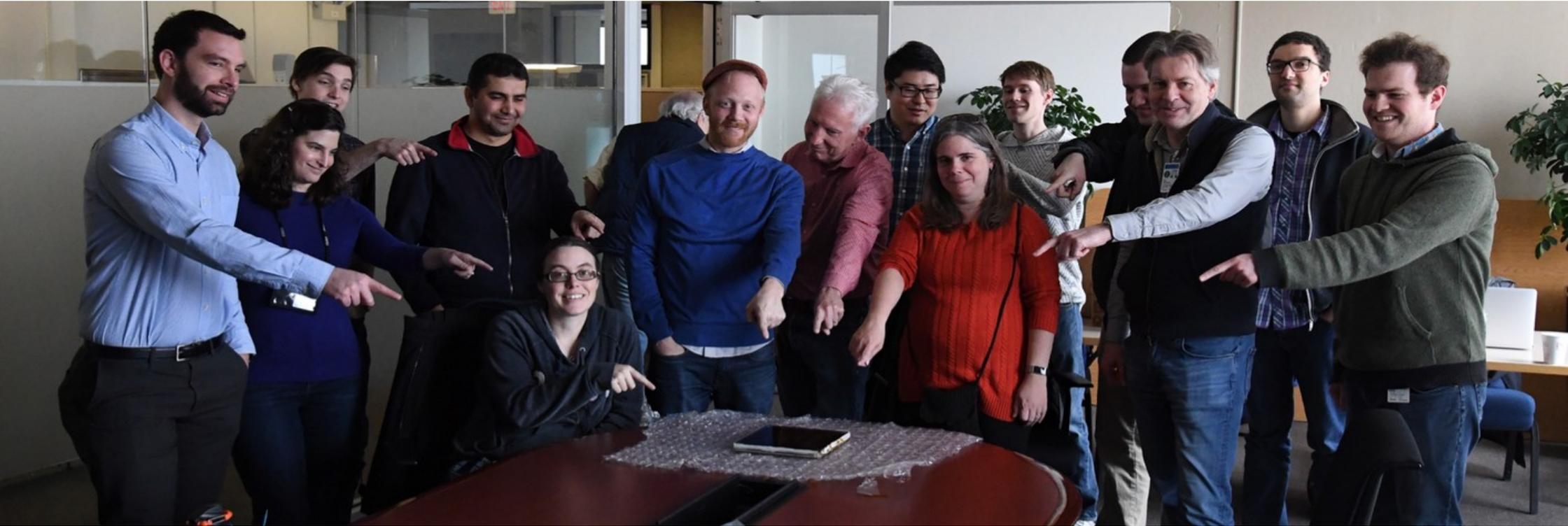
- Detector is being upgraded
- Gd compatibility testing is ongoing
- LAPPDs and electronics are being integrated and characterized
- Simulations and reconstruction are being heavily developed



# Conclusions

- ANNIE will measure **neutron multiplicity**, a key handle for testing interaction models of multi-nucleon final states
- Improve understanding of **neutron tagging**, with applications to background tagging in PDK and DNSB searches, reactor antineutrino detection ...
- Implement **LAPPDs** in a particle detector, gaining experience with a next-generation technology
- **I presented the results from Phase I background measurement**
- Low neutron backgrounds, suitable for physics
- Phase II preparation is progressing
- ANNIE will start taking **physics data in 2018**

# Thank you for listening



ANNIE Collaboration Meeting, January 2017

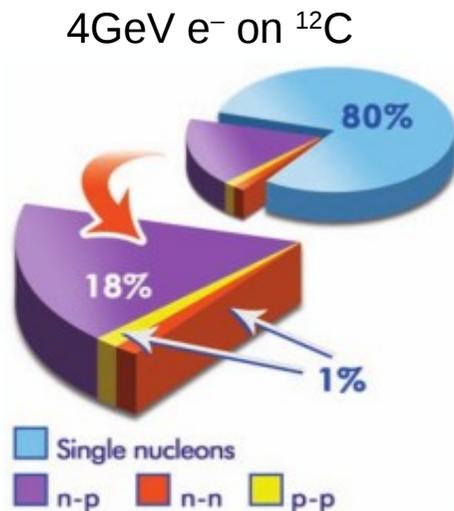
backup slides

# Fake CCQE

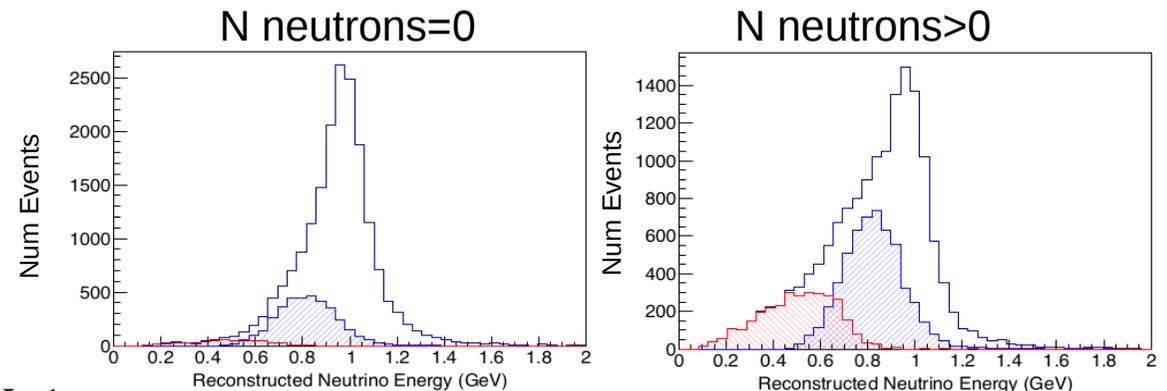
Many different modes, but the majority of them produce 1 or more neutrons

Interaction Fraction	Inclusive	0 Neutron Sample	1 Neutron Sample	More Than 1 Neutron Sample
<b>Truth-level CCQE</b>	67.80%	91.99%	46.65%	37.29%
<b>MEC</b>	20.45%	4.44%	37.37%	37.44%
<b>Single Pion Prod.</b>	10.12%	3.13%	14.15%	21.22%
<b>Deep Inelastic Sc.</b>	1.47%	0.23%	1.74%	3.89%
<b>Misc. Final State Int.</b>	0.16%	0.21%	0.09%	0.16%
<b>Total Breakdown</b>	<b>100%</b>	<b>100%</b>	<b>100%</b>	<b>100%</b>

M. Wetstein, Talk at Fermilab Final State Nucleons Meeting



Reconstructed  $E_\nu$  assuming CCQE kinematics



ANNIE In 10 minutes - new respects 2010

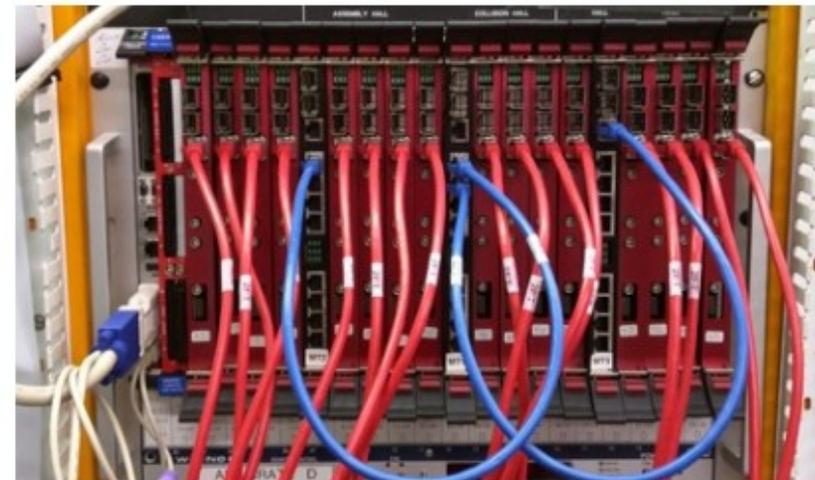
R. Subedi et al, Science 320, 1476 (June 2008)

Events with an absorbed  $\pi$ , 2p-2h Events, All CC0 $\pi$  Events

- 4-channel 500MHz ADC boards developed for KOTO at the University of Chicago, built for ANNIE.
- These cards are used in a several thousand channel DAQ in KOTO.
- Continuous full-waveform digitization:
  - pipeline self-triggering algorithm
  - digital delay-line ring-buffer.
- Custom firmware developed at Iowa State for recording prompt and delayed capture signals
- 16-channel board developed by University of Chicago also available.



4-channel 500MHz ADC card

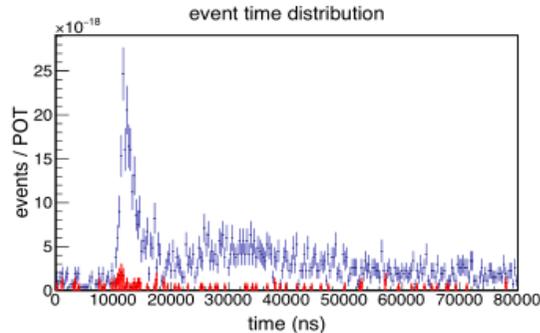


64-channel+trigger cards

# Cross-Section Measurements

- SciBooNE and T2K have made  $\nu_\mu$  charged-current inclusive cross sections on carbon
- No similar measurement on water (oxygen) target exists. T2K recently made such a measurement (not yet published), but the result is flux-integrated
- ANNIE plans to measure differential CC-inclusive cross-section in first Phase II span, others with further running
- Complementary measurement on Ar by SBN-ND could allow  $^{18}\text{Ar} : ^{16}\text{O}$  ratio measurement with systematics cancellation

## Possible Neutral Current Cross-section Measurement



Irreducible excess of non-muon activity in coincidence with the beam seems to be consistent with two detectable neutral current signatures:

- proton recoils in the scintillator
- de-excitation gammas

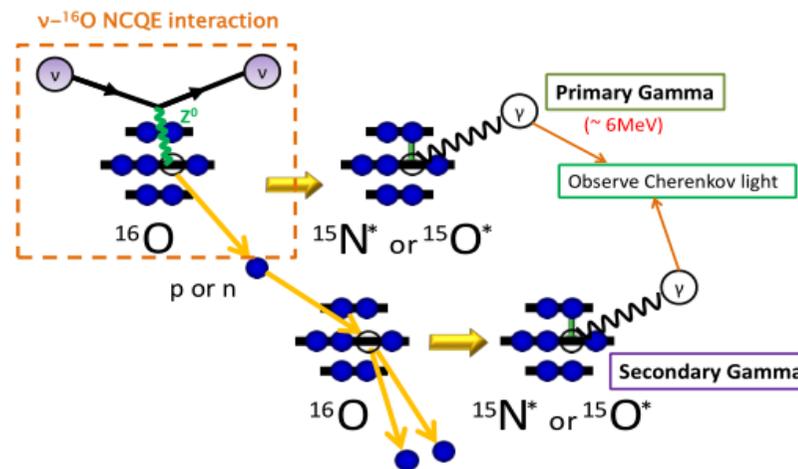
## Tagging Nuclear De-excitation Gammas



- Neutrino interactions typically leave the nucleus in an excited final state
- Many de-excitations involve the emission of MeV gammas with an  $O(1)$  sec time constant
- There is an opportunity to expand on prior work looking at de-excitations from neutral current interactions (T2K/Super-K)
- There is an opportunity to demonstrate a newer capability: tagging de-excitation gammas following a CC-interaction. This would provide a handle to separate between CC interactions on H versus O

Neutral currents with a prompt gamma and subsequent neutron capture are a background for IBD neutrino interactions.

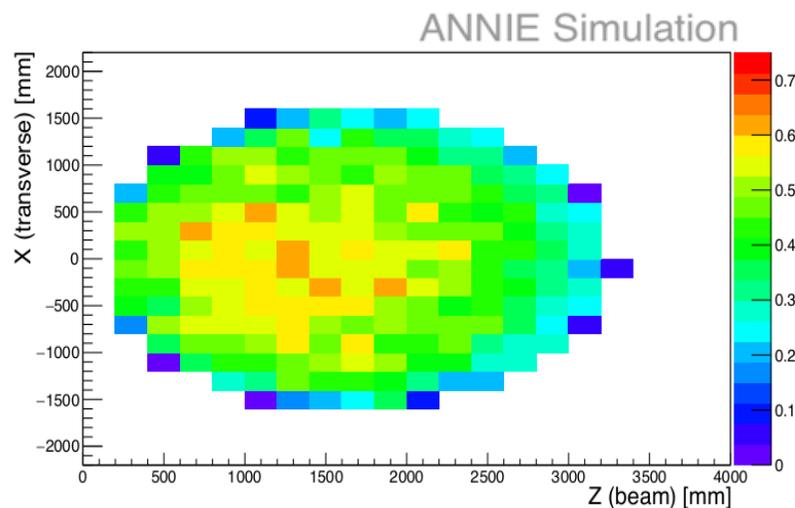
ANNIE can characterize and measure those backgrounds



source: dissertation of Huan Kuxian (T2K)

# Neutron Acceptance and Efficiency

- BNB energy is  $\sim 0.7\text{GeV}$ , maximum neutron energy is  $\sim$ few hundred MeV
- Capture distance is  $<$  tank radius, even for highest energy neutrons
- Effectively no upper bound on energy than the beam energy
  - Although 10% of neutrons  $> 10\text{MeV}$  are expected to capture on Oxygen!
- No lower energy bound as neutrons stop then capture
- Efficiency is therefore just matter of detection, not retention, and is  $\sim 50\text{-}60\%$



Neutron detection efficiency vs neutrino interaction position within 2m fiducial y axis region, 10pe threshold

V. Fischer, U.C. Davis

# NCV Efficiency: Method 1

- Scale MC to data, extract efficiency from best fit
- Had difficulty with RAT-PAC neutron simulations being out by factor 100 – fixed by writing interface to FREYA
- Remaining difficulty that source composition not well known, unknown pile-up contribution from n and gammas
- Low stats, poor signal to noise
- Gives ~9% efficiency – slightly lower than cosmic muon derived detection threshold

# NCV Efficiency: Method 2

- Cosmic trigger structure used to select muons passing through NCV
- Plenty of data
- Steps:
  - Plot distribution of total charge on both NCV PMTs in cosmic muon events in which both NCV PMTs fired (position #2)
  - Plot distribution of energy deposition in NCV for simulated cosmic events
  - Compare peaks → energy to charge scaling factor (assume linear)
  - We trigger on ADC counts, not total NCV charge, so make histogram of total NCV charge for events in which both PMTs fired **at** minimum threshold
  - Find mean. This is the total NCV charge we're effectively triggering on.
  - Convert this charge to energy with above.
  - Simulate thermal neutron captures.
  - Determine fraction of captures with energy deposition above threshold = fraction of detectable neutron captures, or efficiency
- Gives ~12% efficiency

# NCV efficiency: Method 3

- Count integrated neutron candidates in window after gamma peak
- Subtract estimated backgrounds:
  - Constant in time, estimated from before-beam
  - Gamma Pileup = fission rate \* window time \* count in (gamma peak / source triggers)
  - Beam accidentals
- Compare to MC expected signal → Efficiency
  - Expected source events = #triggers \* prob capture in NCV within time window \* NCV efficiency
  - Expected beam accidentals = (fission rate \* window time) \* prob capture in NCV \* NCV efficiency

# NCV Efficiency: Method 3

- Binned likelihood fit to source run time profile
- ~9% efficiency, robust to parameter variation

$$\begin{aligned}
 \langle N_i \rangle &= S_i + B_i \\
 &= N_{\text{trigs}} \epsilon_{\text{NCV}} \left[ P(\text{n capture in } i\text{th bin} | \text{fission}) + \Delta t_i R_{\text{fission}} P(\text{n capture} | \text{fission}) \right] \\
 &\quad + N_{\text{trigs}} \Delta t_i \left[ R_{\text{fission}} P(\gamma \text{ event} | \text{fission}) + R_{\text{other}} \right] + \delta_{i,\text{gamma bin}} N_{\text{trigs}} P(\gamma \text{ event} | \text{fission})
 \end{aligned}$$

fission neutrons from event capturing in bin i
fission neutrons from another event capturing in bin i - neutron pile up (think about gamma pile up first)

gamma pile up = number of fissions \* prob of gamma in fission \* rate of fissions \* time window <<< 'live time'
random other events that trigger NCV = rate of random events \* live time
number of gamma events for prompt gamma bin

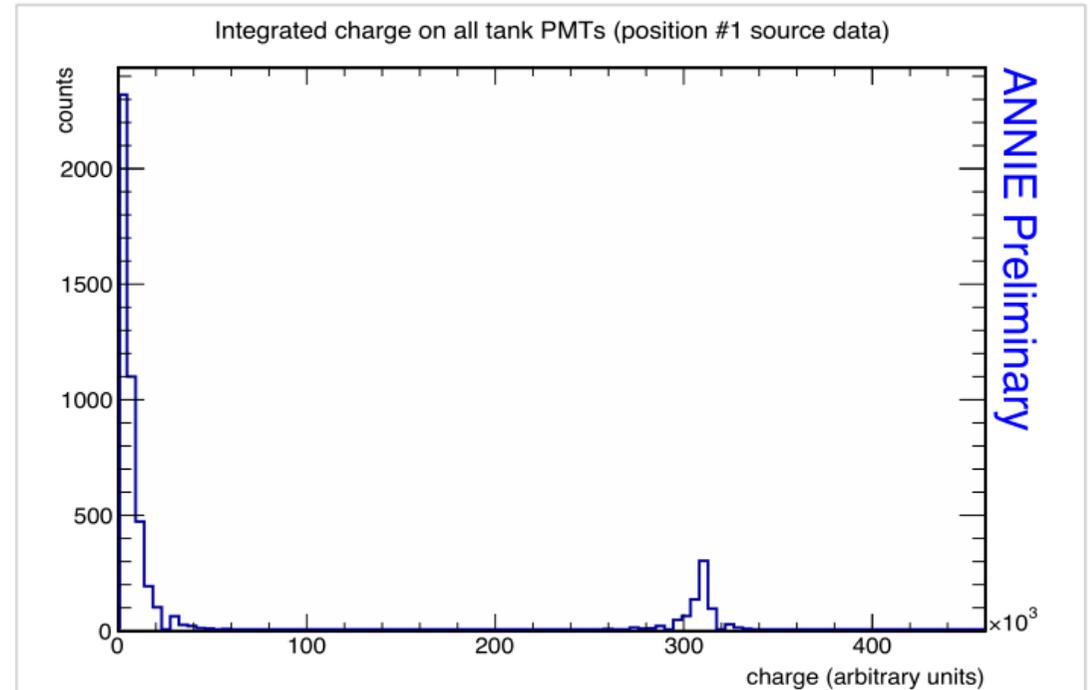
- Expected bin counts are computed using the formula above
- Neutron capture probabilities taken from MC (~10% statistical error on bin-wise values)
- 4 fit parameters:  $R_{\text{fission}}, R_{\text{other}}, \epsilon_{\text{NCV}}, P(\gamma \text{ event} | \text{fission})$ 
  - Vincent's measurement constrains fission rate
- Poisson distribution used to compute likelihood

# Detecting Neutrons

- ANNIE will use Gadolinium doping to achieve neutron visibility
  - 49,700 bn neutron capture cross-section, averaged over natural isotopes
  - 0.2%  $\text{Gd}_2(\text{SO}_4)_3$  doping results in 90% neutron captures on Gd
  - 8MeV total released energy, ~4-5MeV visible energy
- as well reduce time window to reduce backgrounds.
  - Want to be first experiment to do this first time
    - pics of past failures
    - compatibility testing
    - Water filtration system
  - Will be useful for
    - helping tag antineutrino events too, for e.g. reactor /antiproliferation monitoring, contamination removal
    - Identify CCQE vs CCQE-like
    - Identify wrong-sign contamination
    - Identify PDK / DSNB backgrounds

# Data Recording

- High efficiency 'Hefty' mode:  
2 $\mu$ s windows each time there is one of multiple trigger sources
  - RWM
  - Npmts
  - Cosmic ray tagger
  - Either NCV PMT
  - Software: also drives LED
  - Source trigger from LySO crystal
  - Random, zero-bias
- Also read out any TDC hits from MRD within 80 $\mu$ s from trigger



# Event Rates

- BNB delivers  $4 \times 10^{12}$  POT per 1.6  $\mu$ S spill at 5Hz
- Mean energy 0.7GeV
- 93% pure  $\nu_{\mu}$ , 6.4%  $\bar{\nu}_{\mu}$ , 0.6%  $\nu_e$  and  $\bar{\nu}_e$
- Average 1 CC  $\nu_{\mu}$  interaction every 150 spills; no pileup

Event counts in a 2.5-ton fiducial volume over  $2 \times 10^{20}$  POTs, or 1 year of running

	NC	CC	CCQE	CC-Other
All	11323	26239	13674	12565
Entering MRD	2	7466	4279	3187
Stopping in MRD	2	4830	2792	2038

# Source Calibration

- Cf-252 source with a measured activity of  $9927 \pm 1275$  n/s
- LYSO (Lutetium Yttrium Oxyorthosilicate) crystal coupled to a 1-inch PMT used as a fission trigger
- PMT sees scintillation light from gamma-rays emitted during fission; all neutron producing fissions also produce gammas
- Gamma-rays also generate events in the NCV, visible in the first microseconds of the event time distributions
- After  $\sim 10\mu\text{s}$  thermalization time, neutrons capture with a time constant of  $\sim 13\mu\text{s}$
- Efficiency is extracted from event time-profile using a binned likelihood method