FERMILAB-SLIDES-18-078-ND

annie

in 10 minutes

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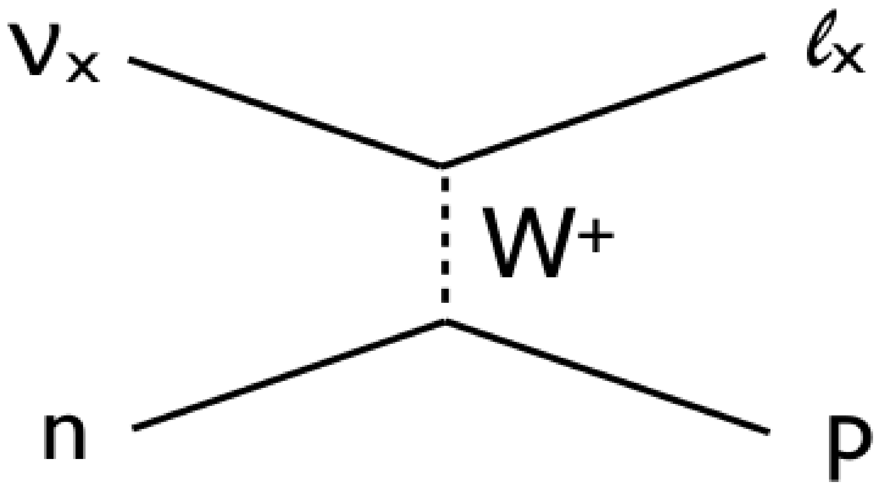
True CCQE

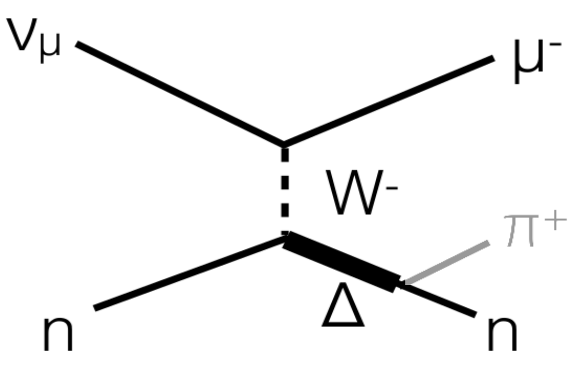
- 2 body scattering
- Target nucleon assumed at rest
- Kinematics from observed lepton



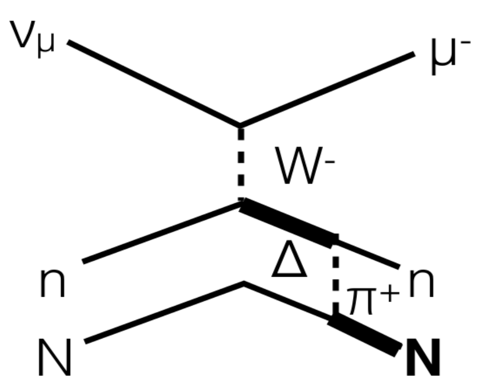
$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

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

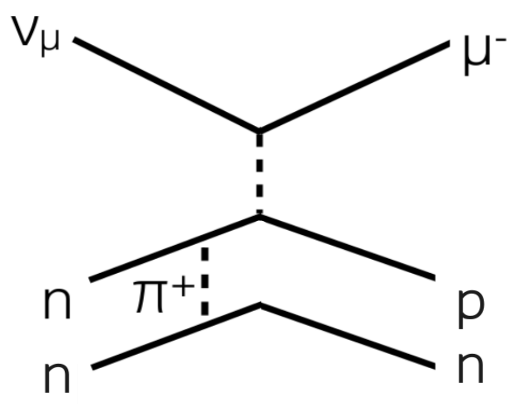
Fake CCQE



Resonant pion production with undetected pion

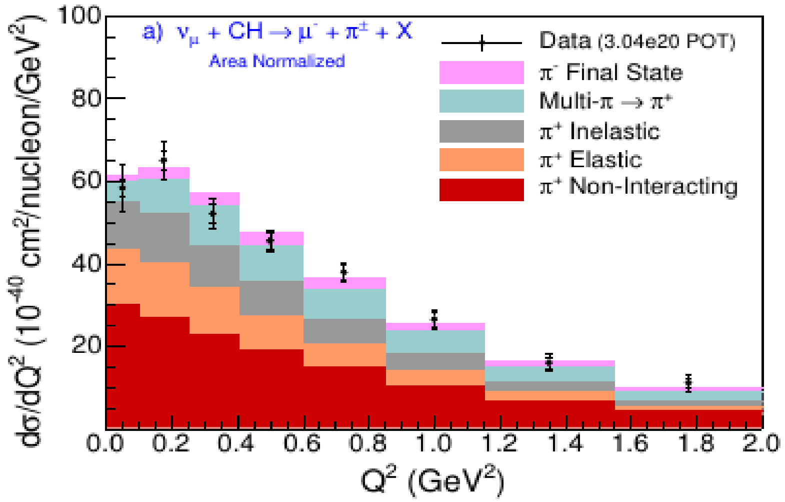


Resonant pion production with 'stuck pion'

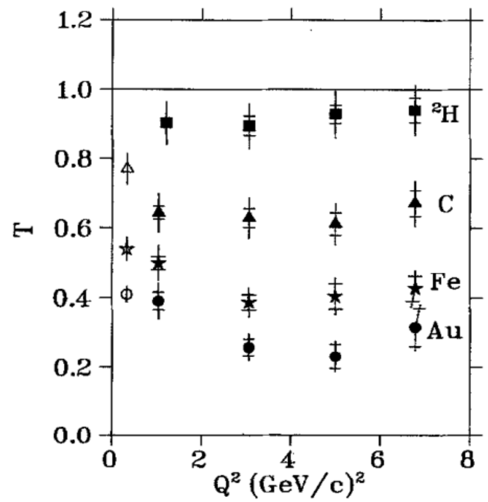


Interaction with correlated pair of nucleons

Minerva CC1π sample



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



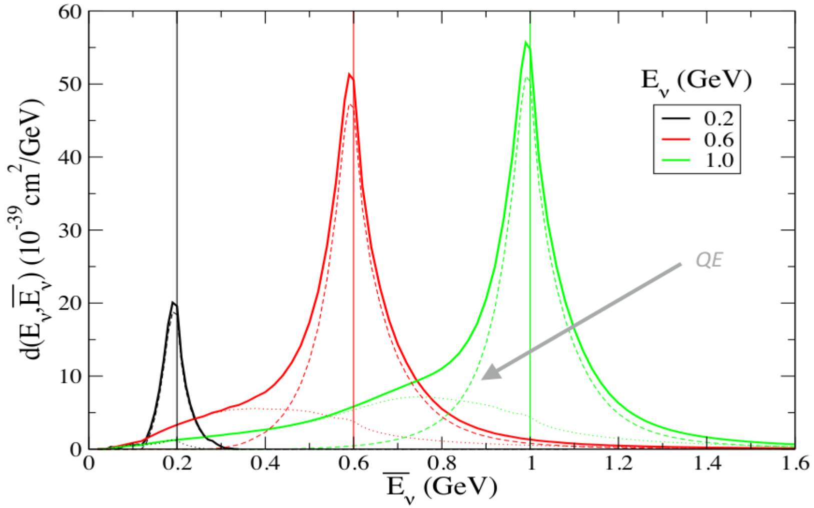
Phys. Lett. B 351 87-92

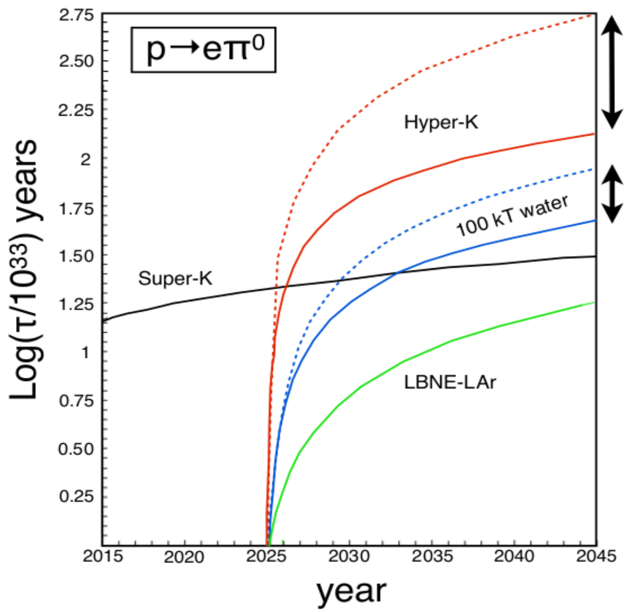
Fraction of protons that escape without re-interaction in e-p elastic scattering

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**

Martini, Ericson, Chanfray - arXiv 1211.1523v2



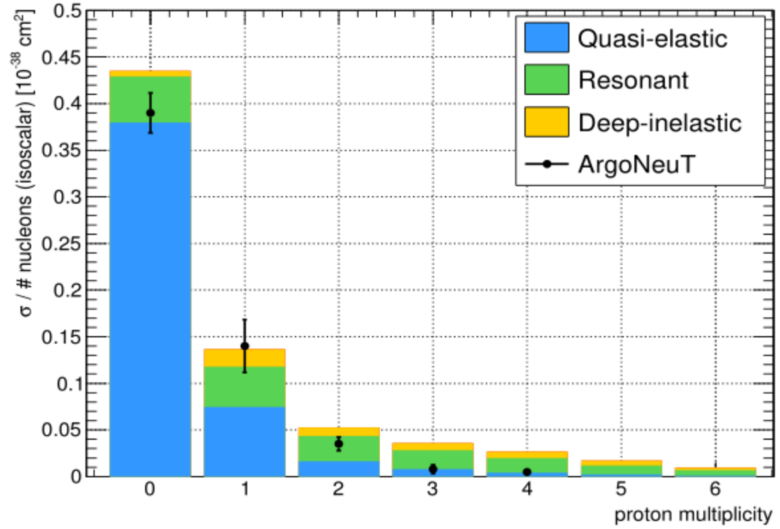


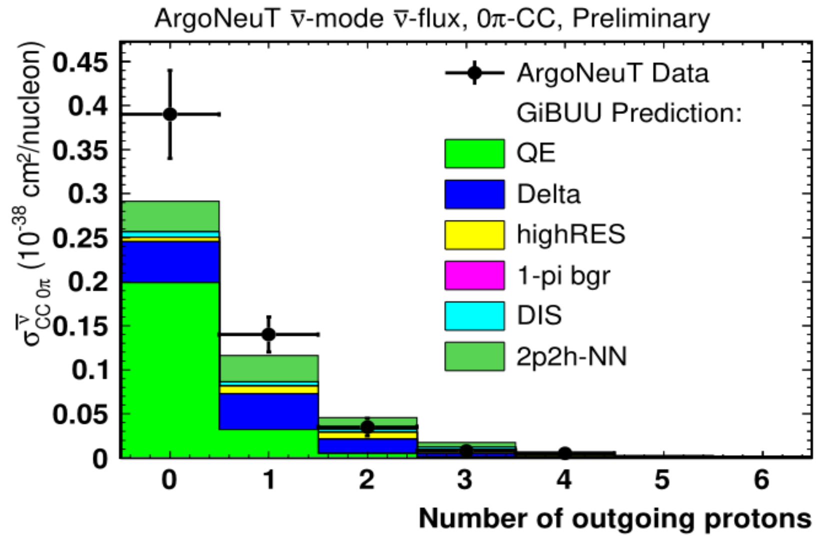
Estimated improvement with neutron tagging

Anghel, I. et al., arXiv 1504.01480

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 δCP 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

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Experimentally, programs to detect neutrons are essential."

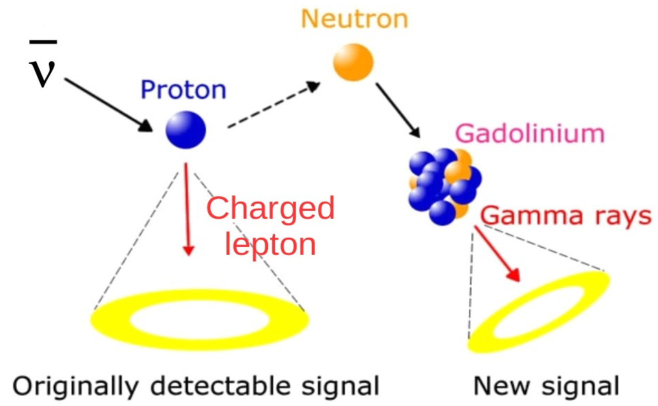
NuSTEC white paper Neutrino Scattering Theory and Experiment Collaboration

“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

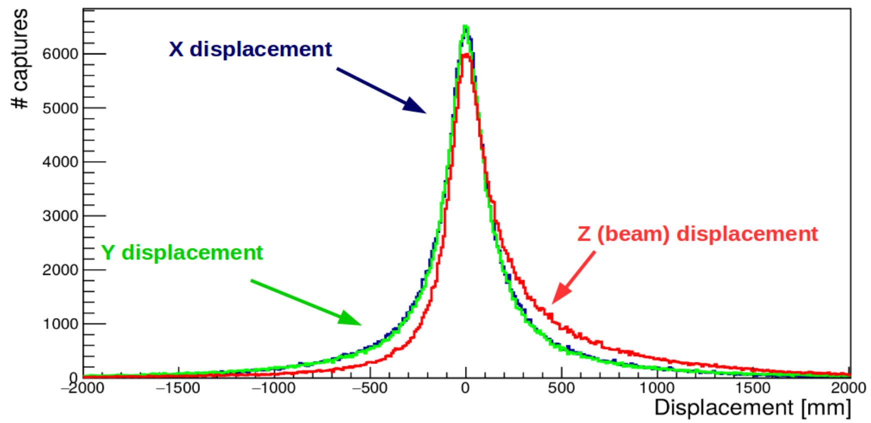
Making Neutrons Visible

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

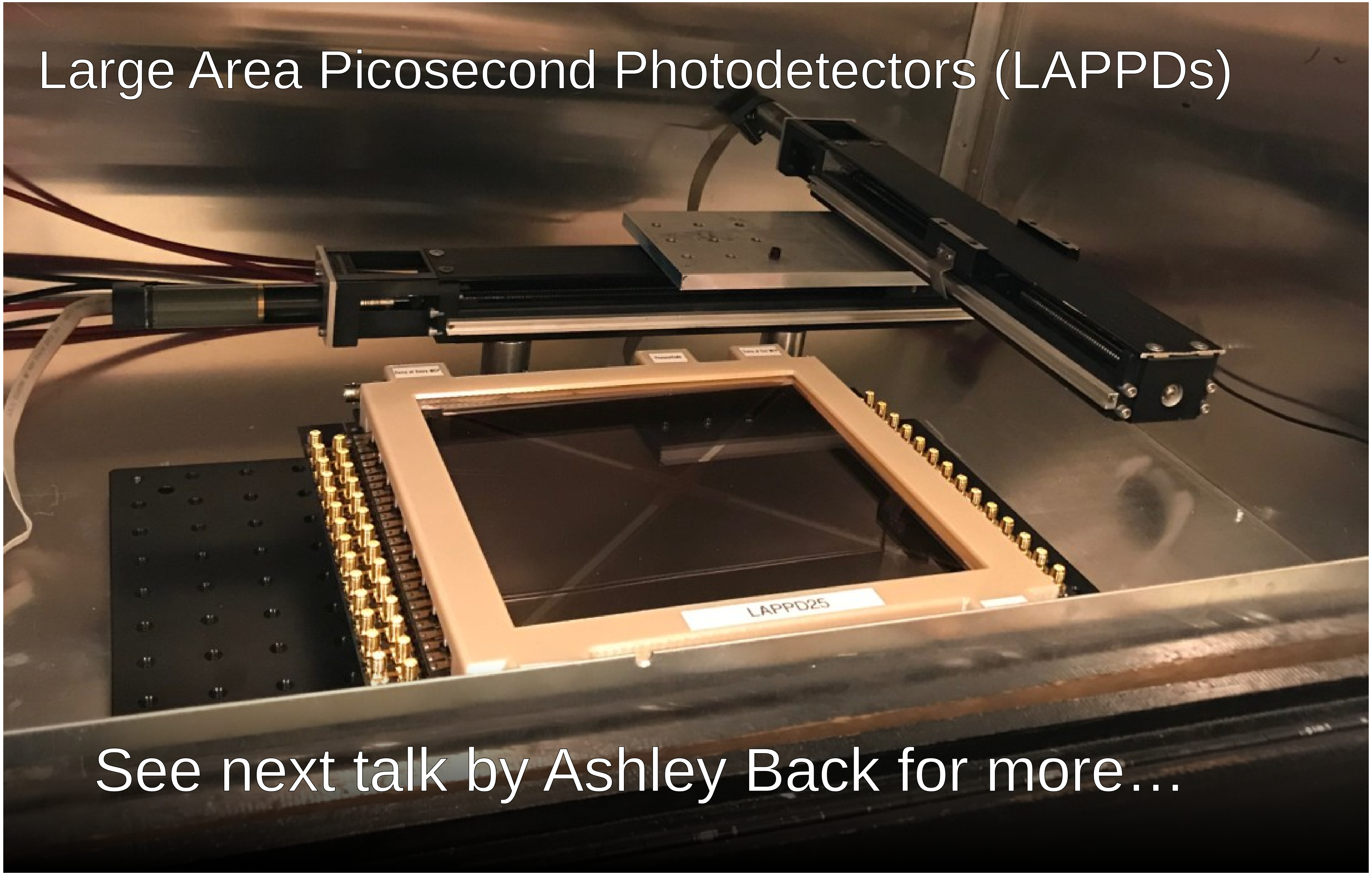


- Nonetheless, given ANNIE’s small size it’s crucial to maximize fiducial volume

  We need vertex resolution ~10cm, or equivalently, timing resolution ~100ps...

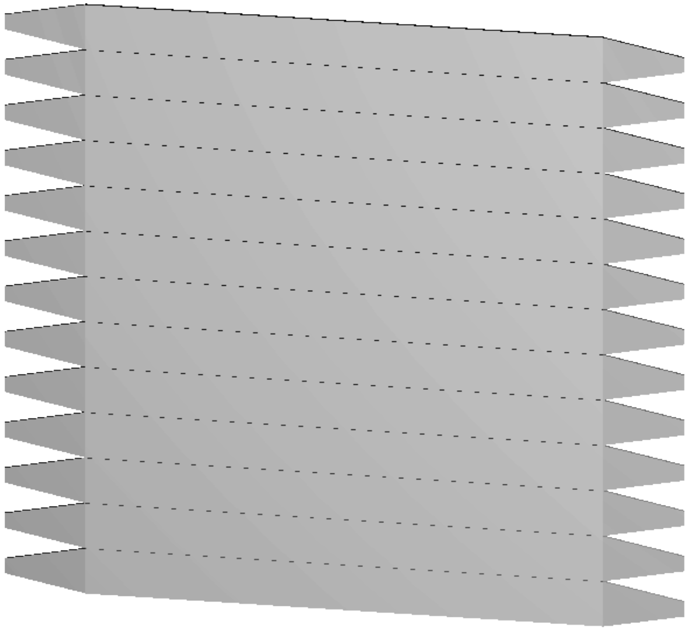


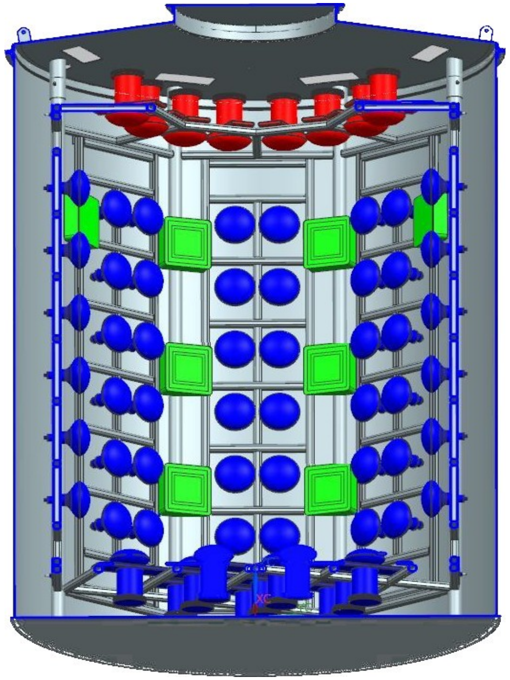
A New Generation of Photodetector

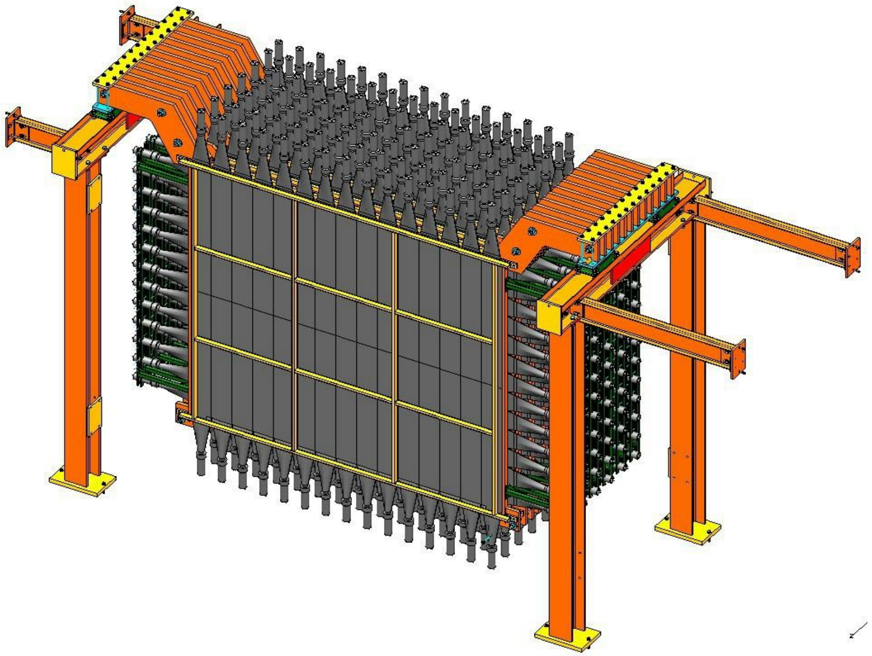


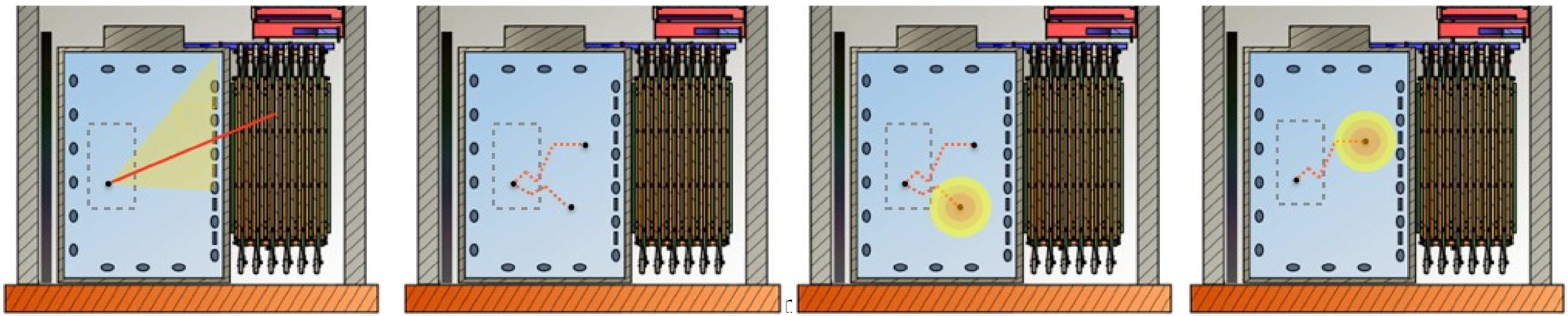
The ANNIE Detector

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

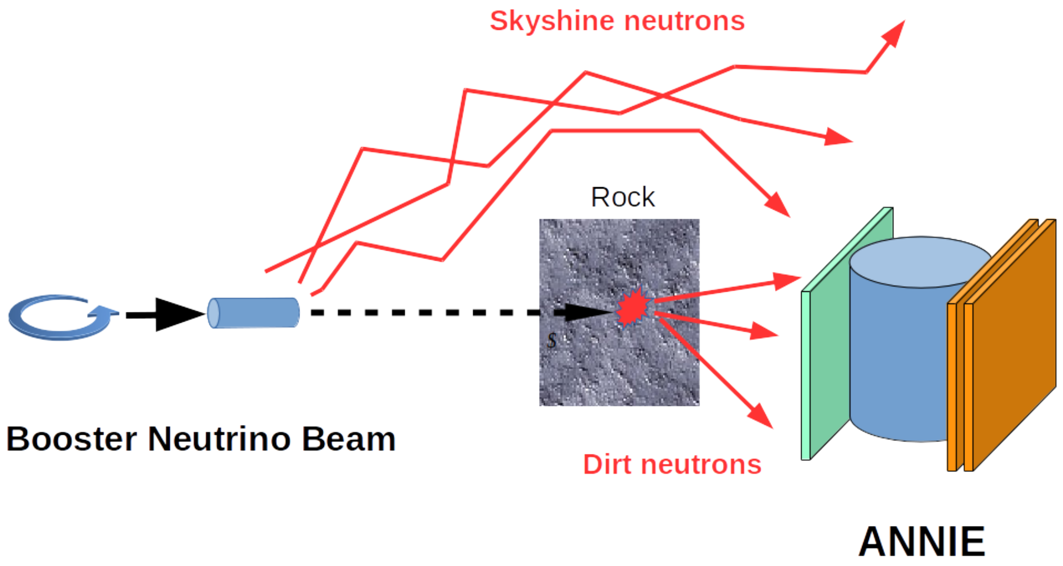
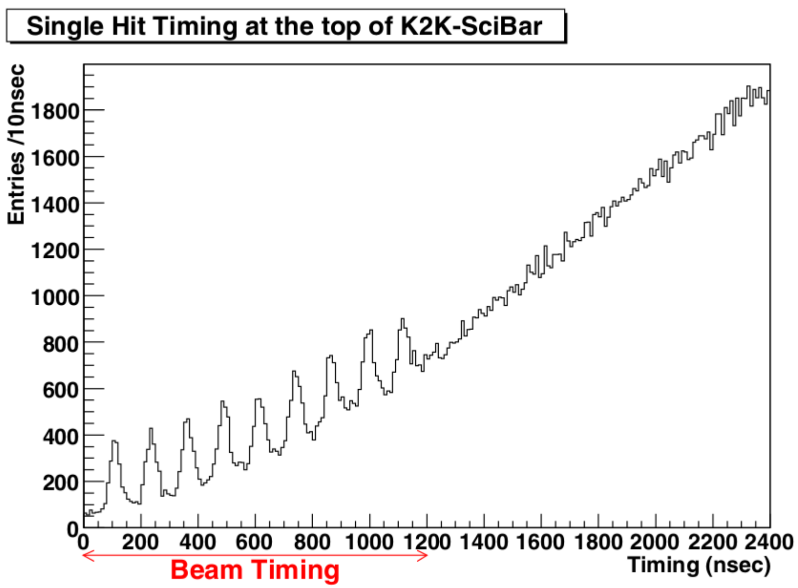


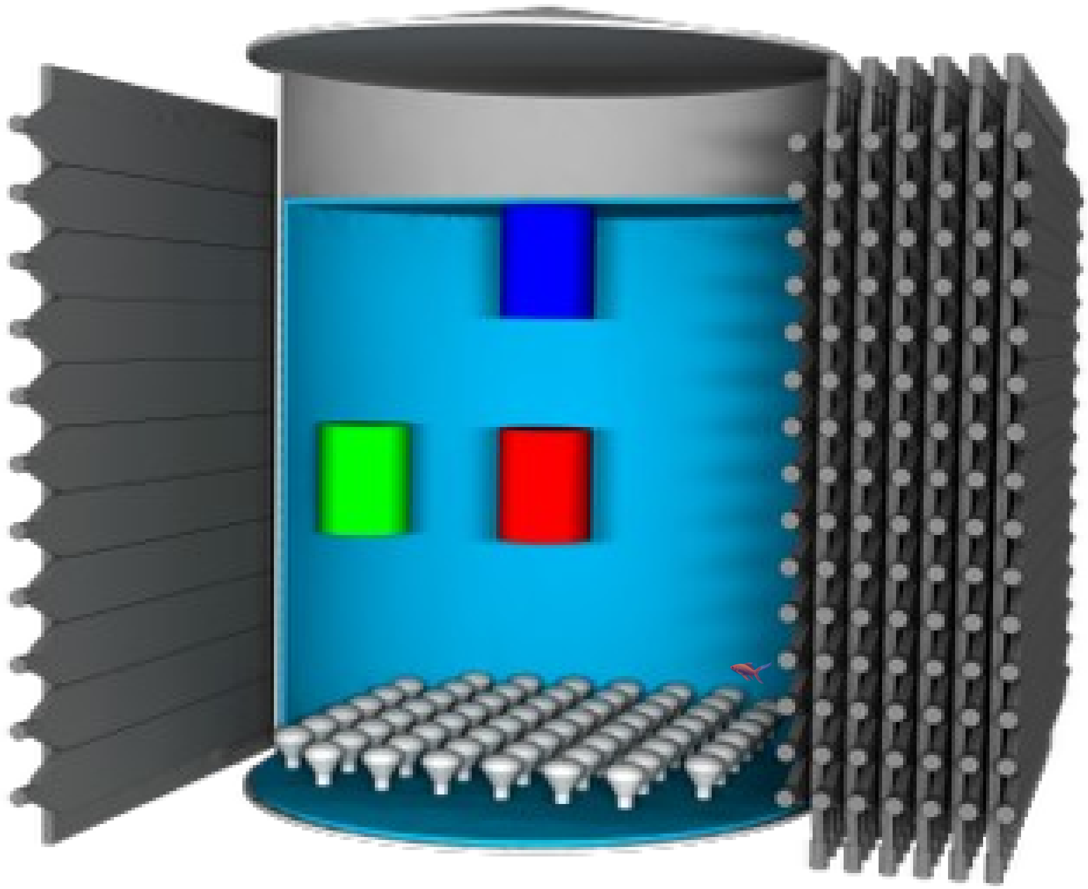
Image: Vincent Fischer



arXiv:hep-ex/0601022

Phase 1 Detector

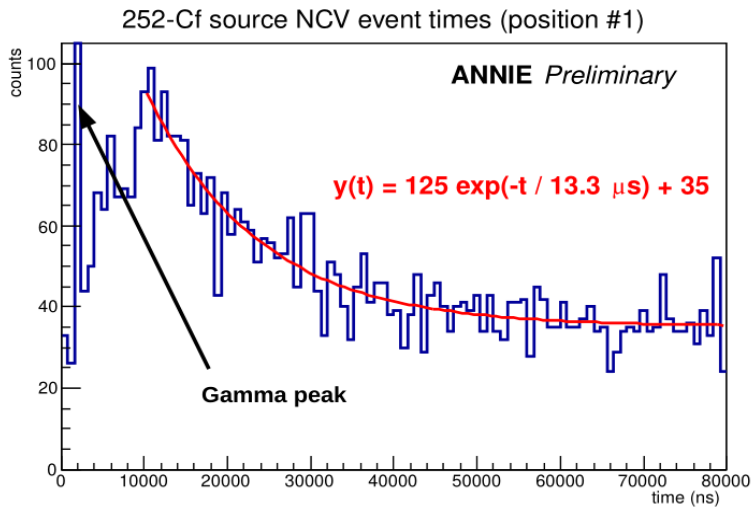
- Moveable sub-volume of liquid scintillator doped with 0.25% Gd
- Optically isolated from tank, with two PMTs watching for events
- White tank liner, 60 PMTs on the bottom to veto muons by cherenkov light
- Positional scan was performed to measure drop-off with overburden and distance from the beam-side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

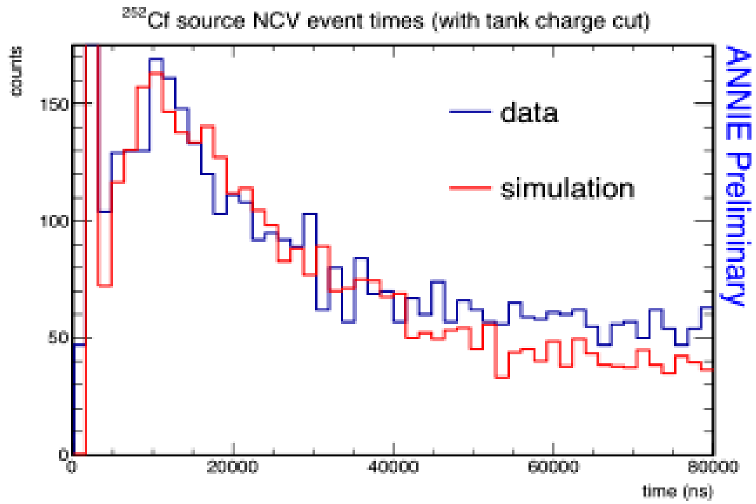


Credit: Jonathan Eisch

Detector Calibration

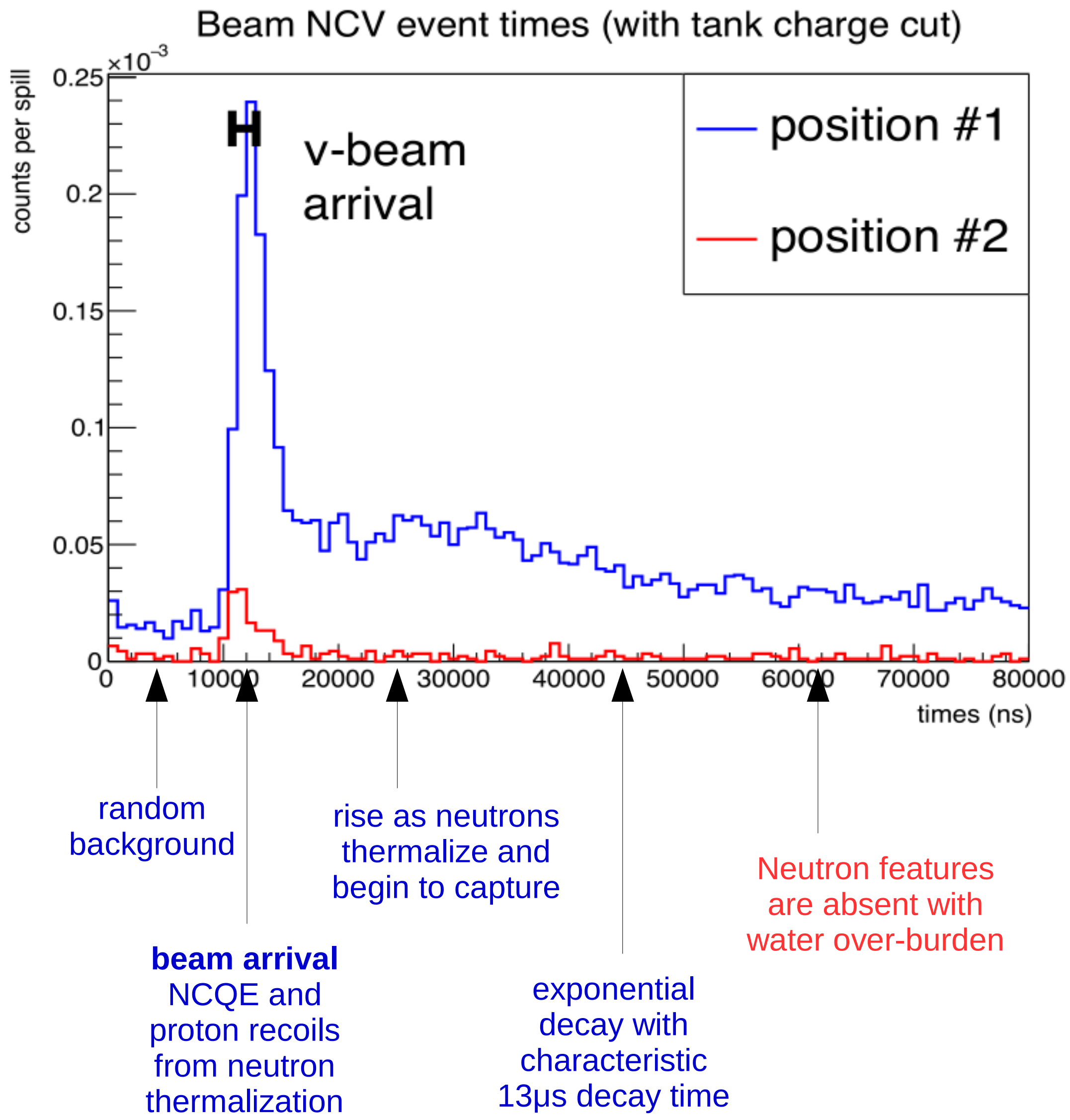
- Neutron response was calibrated with a ^{252}Cf source, using a scintillator crystal to trigger on gammas emitted during fission
- Source activity was measured using a commercial neutron detector and another source of well-known activity
- Results show the expected 13μs capture time and agree fairly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





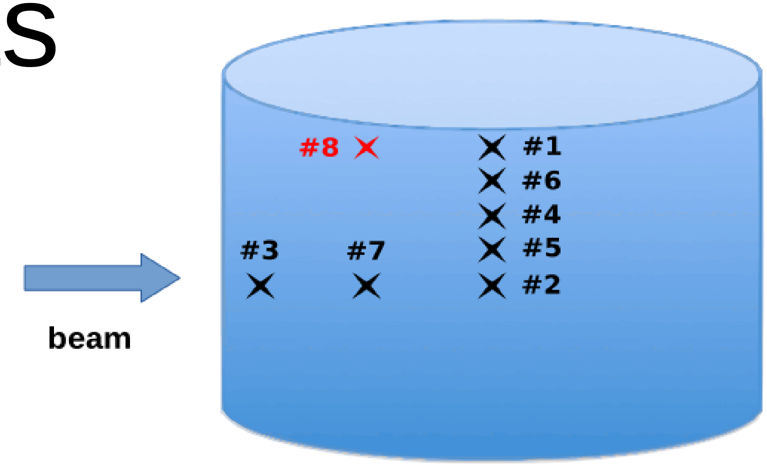
Results

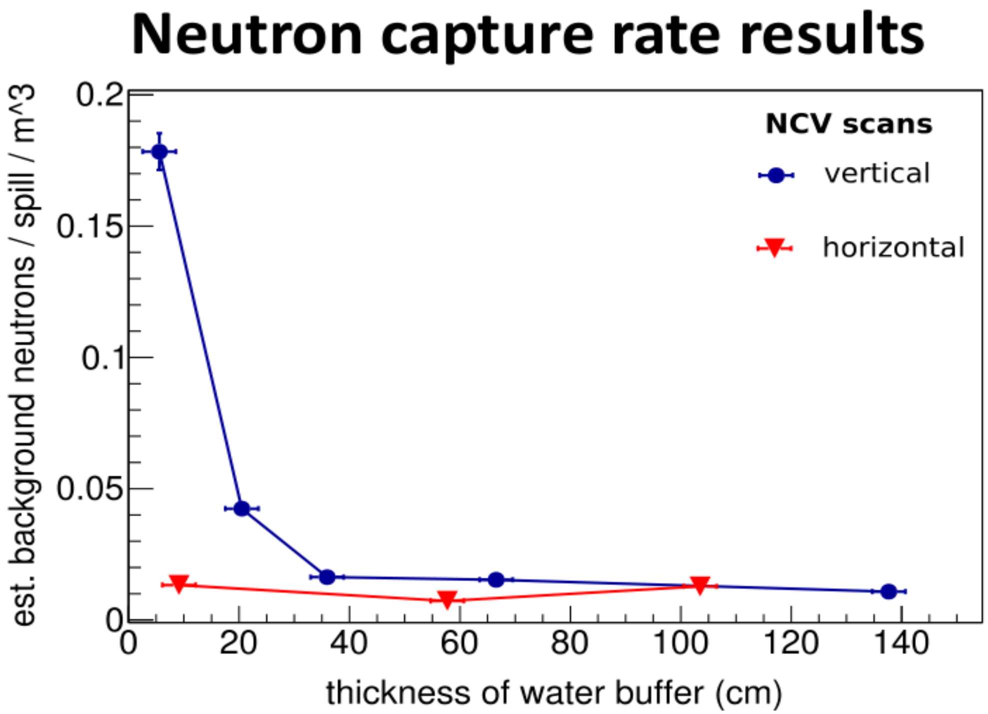
- Shown is the time profile of events, averaged over many beam spills
- Events are defined as simultaneous hits on both NCV PMTs, with no corresponding tank event
- Position #1 is at the water surface, Position #2 is at the tank centre
- There is a peak of in-time events consistent with neutral current 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 over-burden
- 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

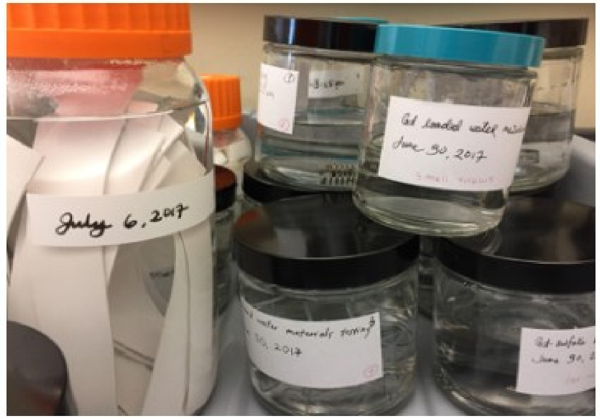


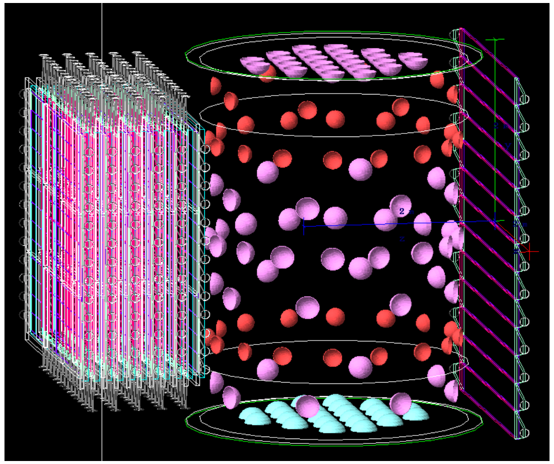


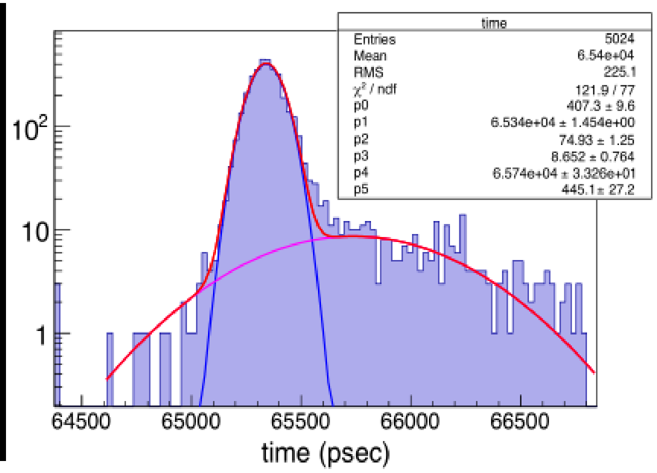
plot by Steven Gardiner

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, reaction 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

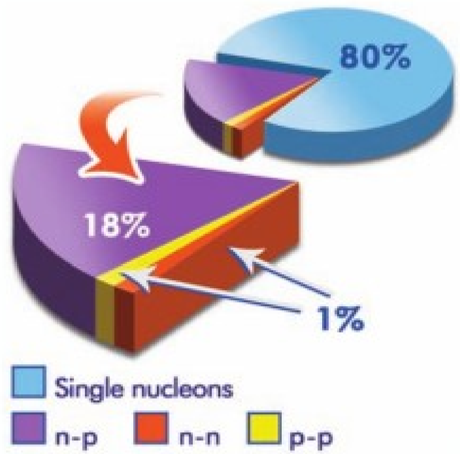
Fake CCQE

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
Truth-level CCQE	67.80%	91.99%	46.65%	37.29%
MEC	20.45%	4.44%	37.37%	37.44%
Single Pion Prod.	10.12%	3.13%	14.15%	21.22%
Deep Inelastic Sc.	1.47%	0.23%	1.74%	3.89%
Misc. Final State Int.	0.16%	0.21%	0.09%	0.16%
Total Breakdown	**100%**	**100%**	**100%**	**100%**

M. Wetstein, Talk at Fermilab Final State Nucleons Meeting

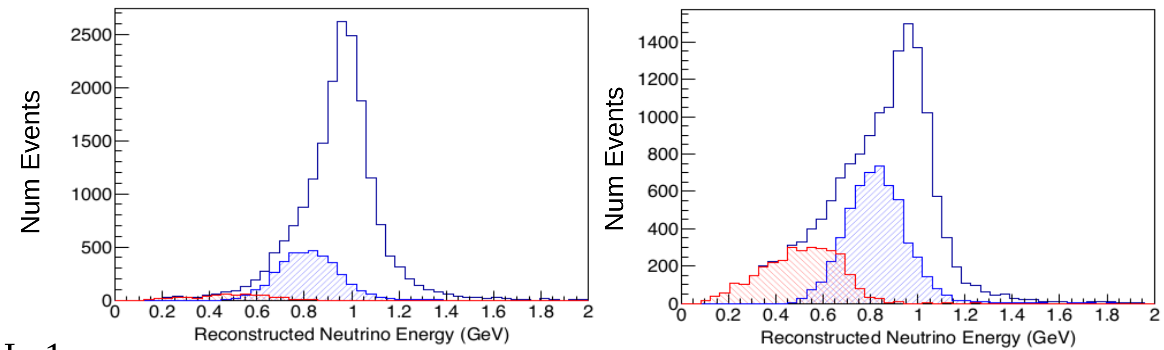
4GeV e^- on ^{12}C



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

Reconstructed E_ν assuming CCQE kinematics

N neutrons=0 N neutrons>0

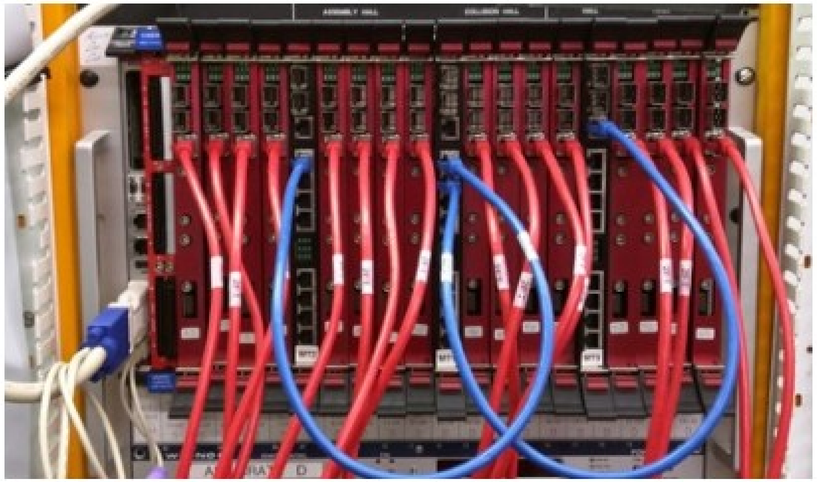


Events with an absorbed π, 2p-2h Events, All CC0π Events

Electronics Development

- 4-channel 500MHz ADC boards developed for K0TO at the University of Chicago, built for ANNIE.
- These cards are used in a several thousand channel DAQ in K0TO.
- 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

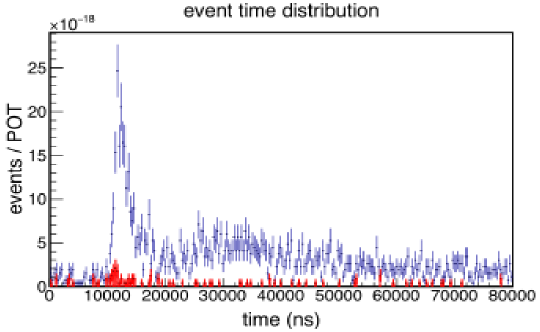


64-channel+trigger cards

Cross-Section Measurements

- SciBooNE and T2K have made ν_μ 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}Ar : ^{16}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:

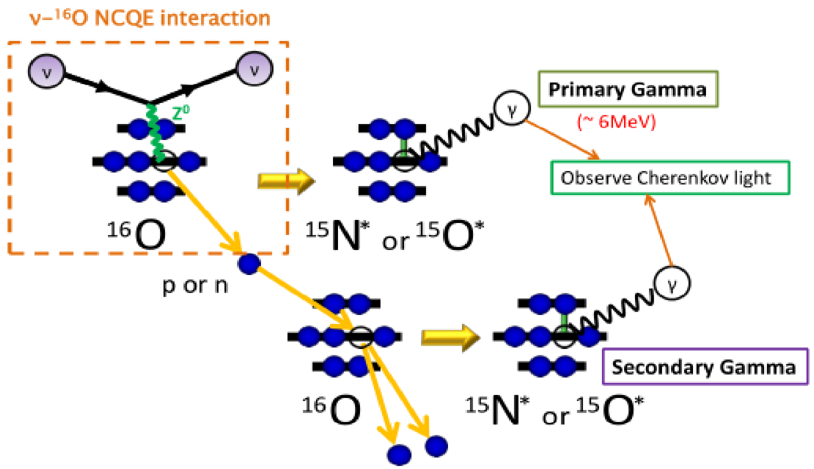
- proton recoils in the scintillator
- de-excitation gammas

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.

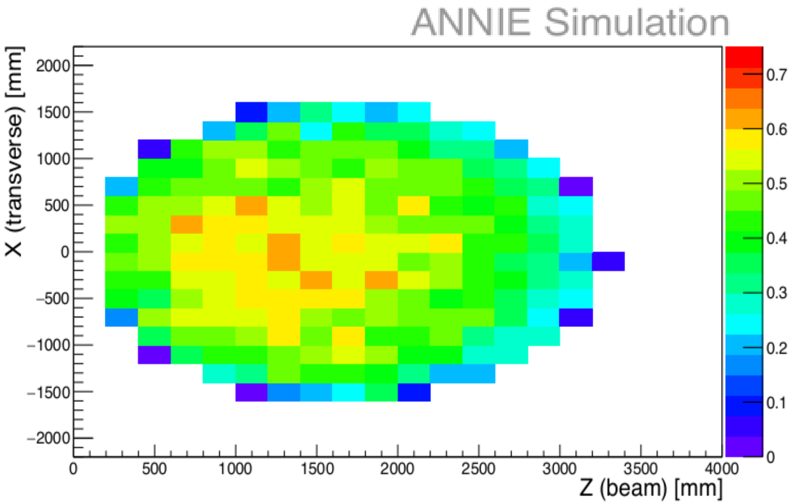
ANNIE can characterize and measure those backgrounds



source: dissertation of Huan Kuxian (T2K)

Neutron Acceptance and Efficiency

- BNB energy is ~0.7GeV, maximum neutron energy is ~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 > 10MeV 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 ~50-60%



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

$$\langle N_i \rangle = S_i + B_i$$

$$= N_{\text{trigs}}\, \epsilon_{\text{NCV}} [P(\text{n capture in } i\text{th bin}|\text{fission}) + \Delta t_{\text{i}}\, R_{\text{fission}}\, P(\text{n capture}|\text{fission})]$$

$$+ N_{\text{trigs}}\, \Delta t_{\text{i}} [R_{\text{fission}} P(\gamma \text{ event}|\text{fission}) + R_{\text{other}}] + \delta_{i,\text{gamma bin}}\, N_{\text{trigs}}\, P(\gamma \text{ event}|\text{fission})$$

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

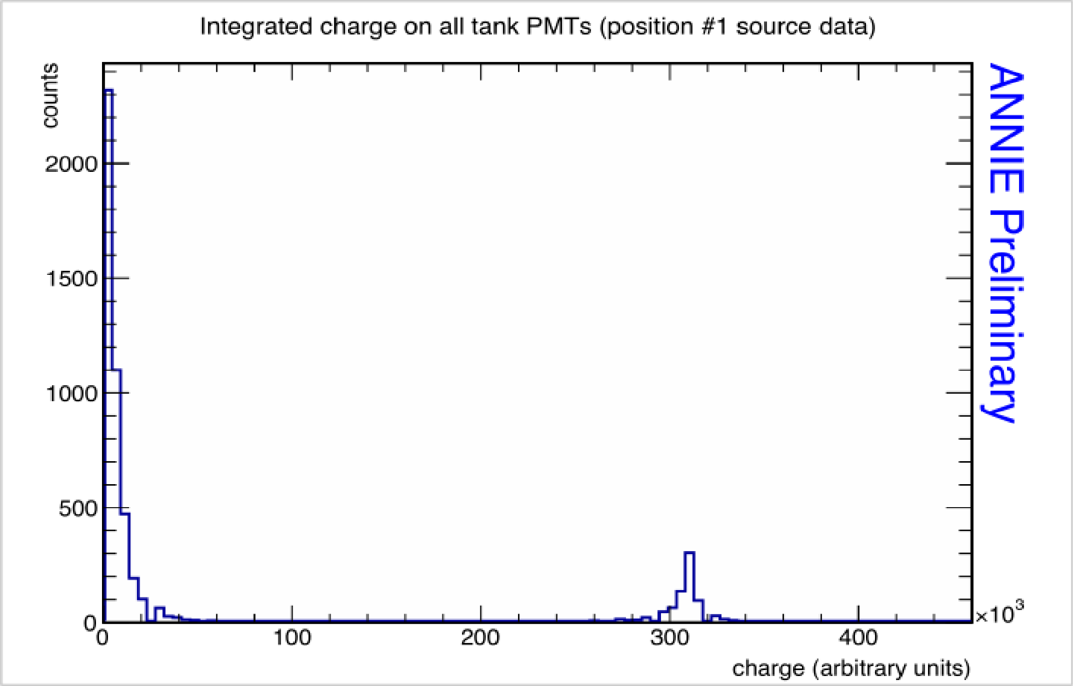
- Expected bin counts are computed using the formula above
- Neutron capture probabilities taken from MC (~10% statistical error on bin-wise values)
- 4 fit parameters: R_{fission}, R_{other}, ϵ_{NCV}, $P(\gamma \text{ event}|\text{fission})$
  - Vincent's measurement constrains fission rate
- Poisson 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% $Gd_2(SO_4)_3$ 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: 2us 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 80us from trigger



Event Rates

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

Event counts in a 2.5-ton fiducial volume over $2\text{x}10^{20}$ 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 ± 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 ~10μs thermalization time, neutrons capture with a time constant of ~13μs
- Efficiency is extracted from event time-profile using a binned likelihood method