annie

ANNIE

The Accelerator Neutrino Neutron Interaction Experiment

Matt Wetstein (ISU) on behalf of the ANNIE collaboration

June 13, 2019

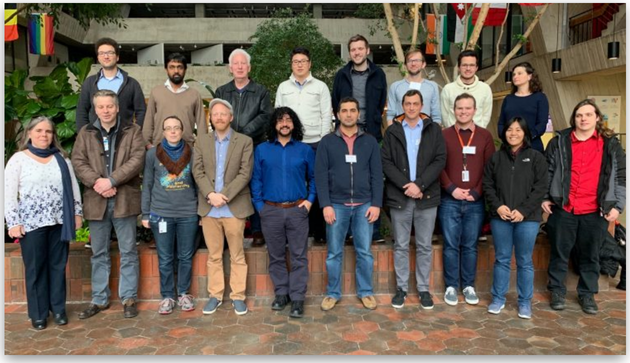
U.S. DEPARTMENT OF ENERGY

The Accelerator Neutrino Neutron Interaction Experiment

ANNIE is a neutrino experiment deployed on the Booster Neutrino Beam

- A physics measurement aimed at better understanding neutrino-nucleus interactions
- An R&D effort to develop and demonstrate new neutrino detection technologies/techniques

We have an international collaboration, consisting of 11 institutions from 3 nations



Detector construction will be completed the next two weeks, with commissioning to begin this summer and beam data taking to begin in fall 2019

The Main Physics Measurement

“Neutrino-nuclear billiards”

The Main Physics Measurement
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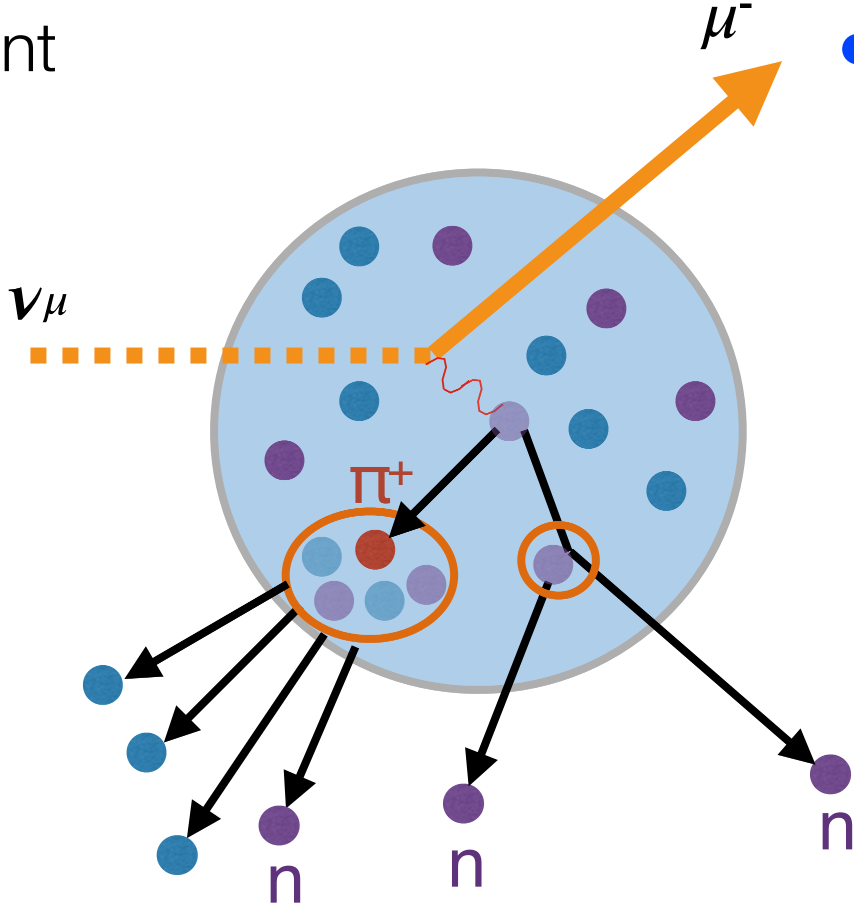
ANNIE measures the multiplicity of final state neutrons as a function of the outgoing lepton momentum and direction

Neutrons are a major component of the nuclear recoil system and a source of missing energy in neutrino reconstruction/detection

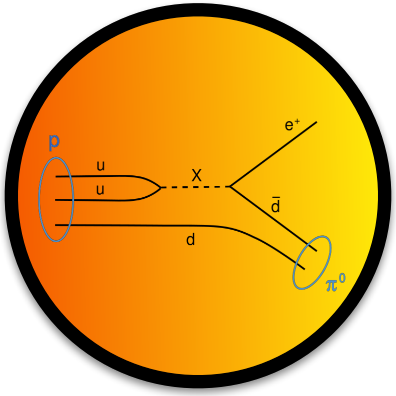


Thus, understanding neutron yields from neutrino interactions is critical to understanding and controlling critical systematics on precision oscillation physics

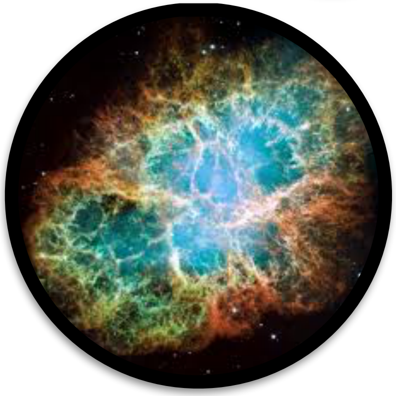
Astronomical Neutrinos/Rare Processes

The presence, multiplicity and absence of neutrons is also a strong handle for signal-background separation in a number of physics analyses

- For proton decay searches, the presence of final state neutrons can be used to efficiently identify backgrounds from atmospheric neutrinos

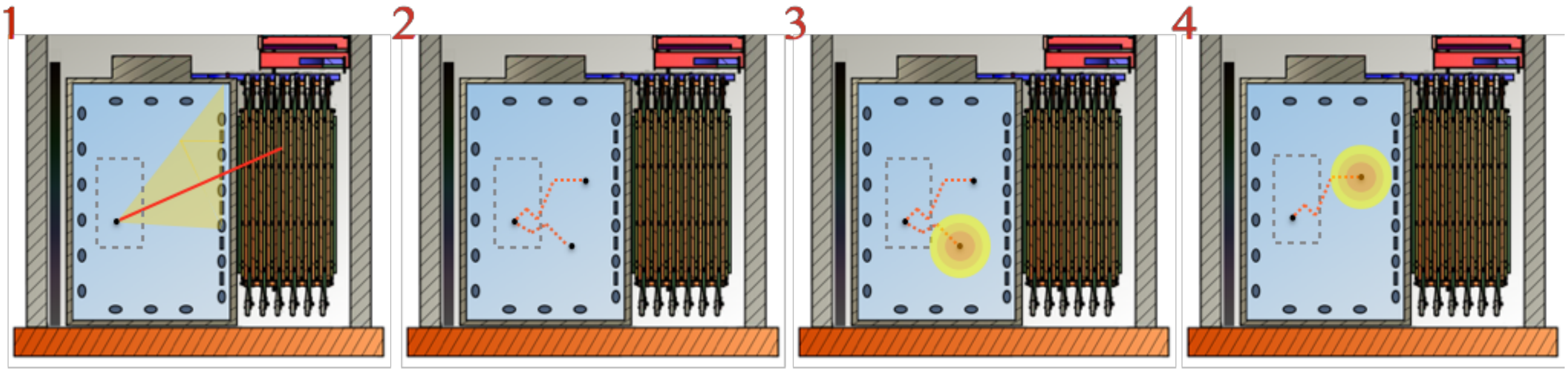


- In searches for the Diffuse Supernova Neutrino Background (DSNB), the presence of any additional neutrons beyond the single IBD neutron can be used to tag and remove higher energy atmospheric neutrino backgrounds



In both cases, estimates of signal purity require an accurate understanding of the neutron multiplicity from the specific class of background events that fake these rare signals.

Schematic of a Typical Event



1. CC interaction in the fiducial volume produces a muon, reconstructed in the water volume and MRD
2. Neutrons scatter and thermalize

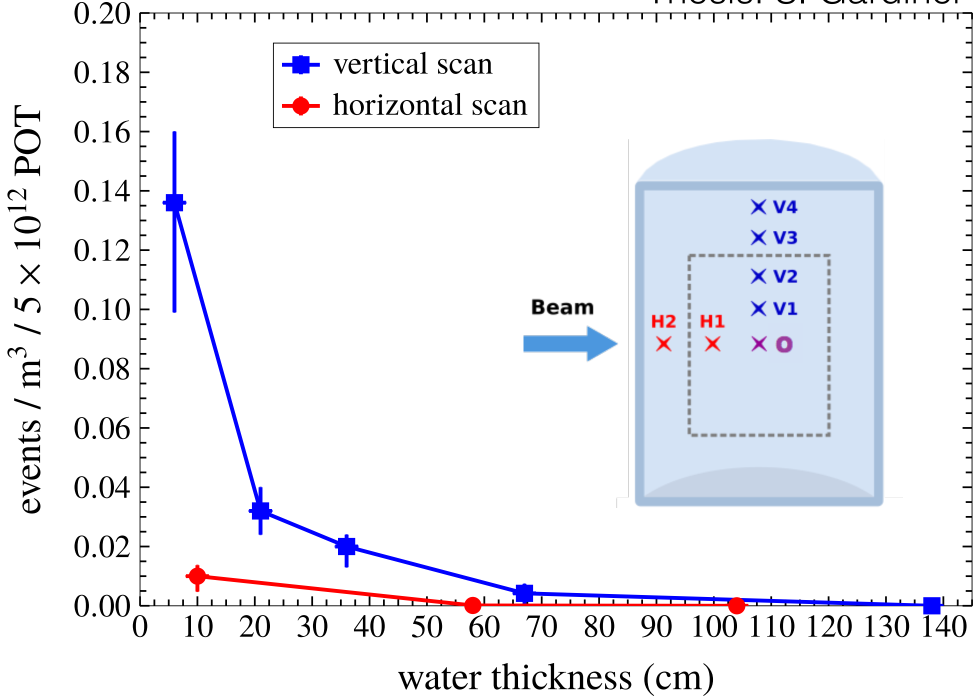
3. - 4. Thermalized neutrons are captured on the Gd producing flashes of light

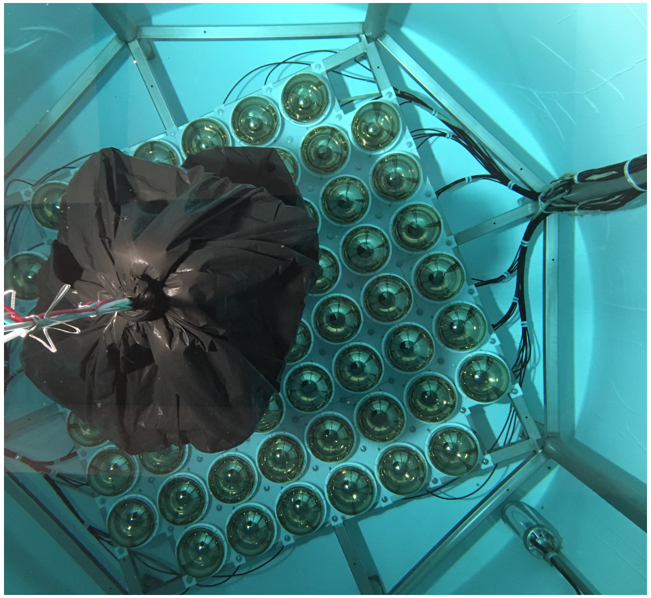
ANNIE Background Neutron Characterization

Data was collected over 2016-2017 in a partially instrumented implementation of the detector. This served as an engineering run and an opportunity to characterize background neutrons on the main ANNIE physics measurements.

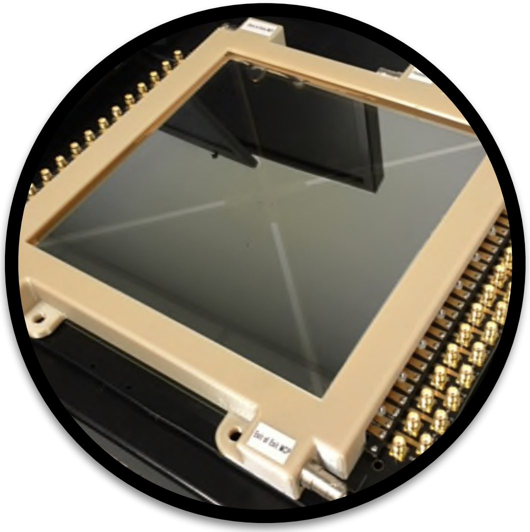
These backgrounds were found to be small and will be mitigated by the buffer layer of water above the detector

Thesis: S. Gardiner





Enabling Technology:
Large Area Picosecond Photodetectors (LAPPDs)



LAPPDs are 8” x 8” MCP-based imaging photodetectors, with tens of picosecond single photon time resolution and mm-scale spatial resolution

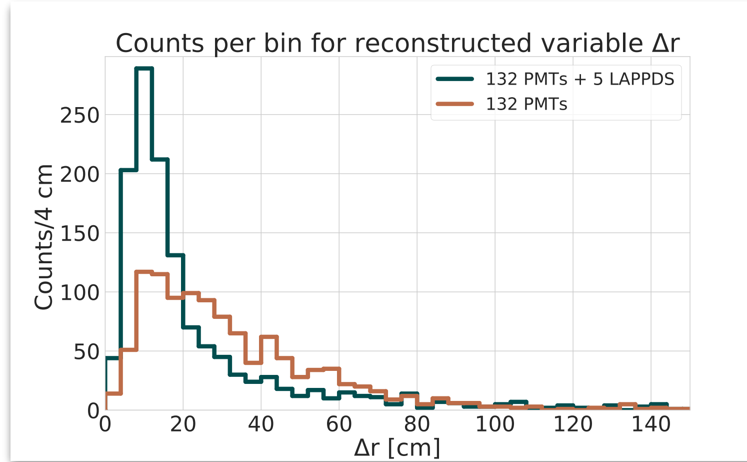
These advanced photosensors are now commercially available (Incom, Inc)

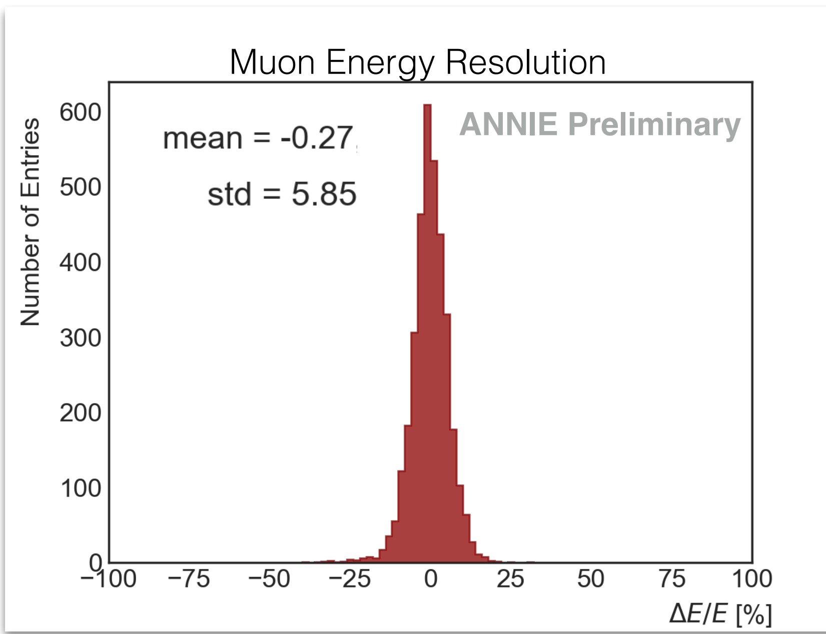
The ANNIE collaboration has purchased and received the initial 5 LAPPDs for our physics measurement

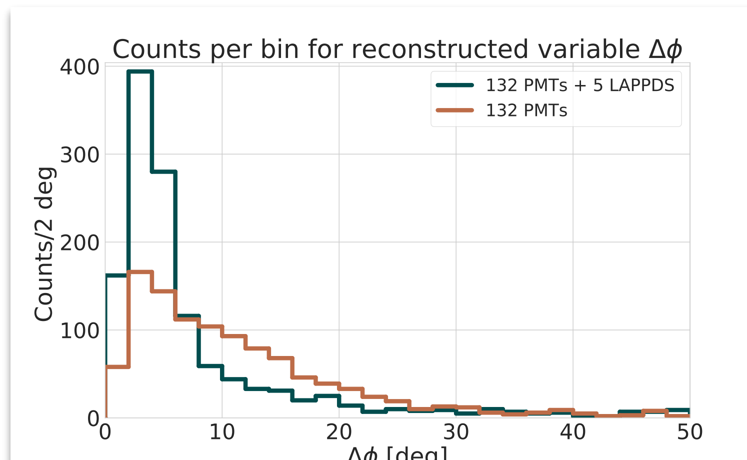
This fall, ANNIE will become the first application of LAPPDs in a neutrino exp.

Enabling Technology: LAPPDs and Fast Timing

- Simulations show that the addition of the 5 initial LAPPDs provides the factor of 2 improvement in vertex resolution needed to achieve target neutron containment and energy resolutions
- Similarly impressive gains in directional resolution will help with reconstruction of more exclusive neutrino final states



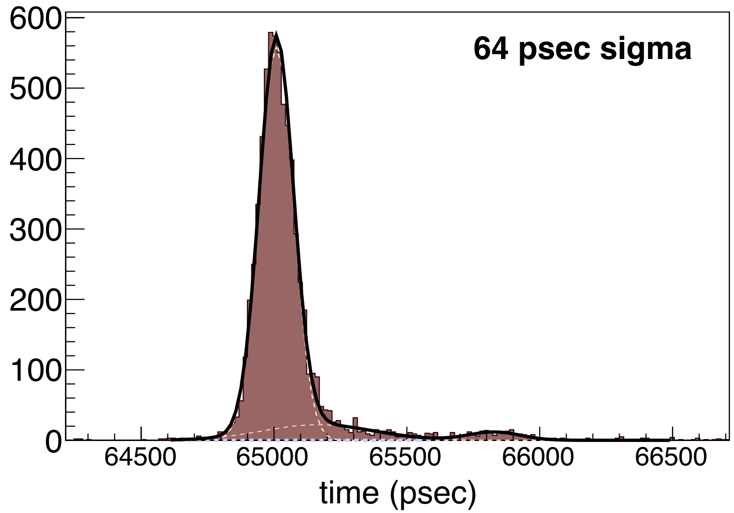


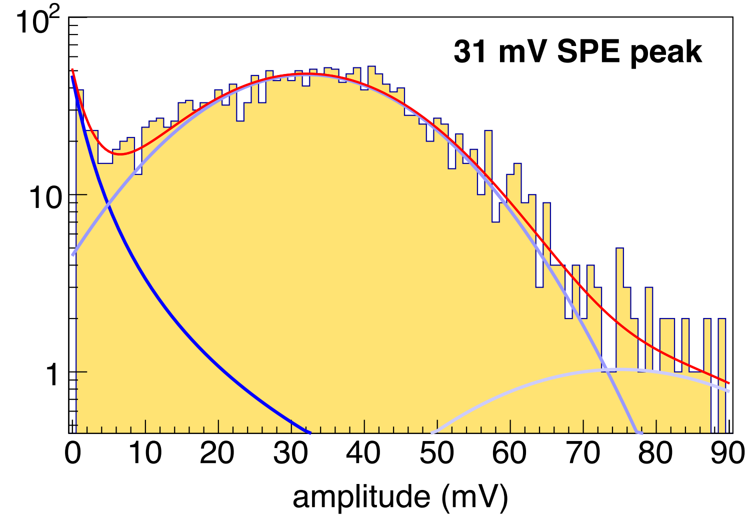


Enabling Technology: LAPPDs and Fast Timing

- Testing of these LAPPDs is nearly complete and preparations for summer deployment are underway

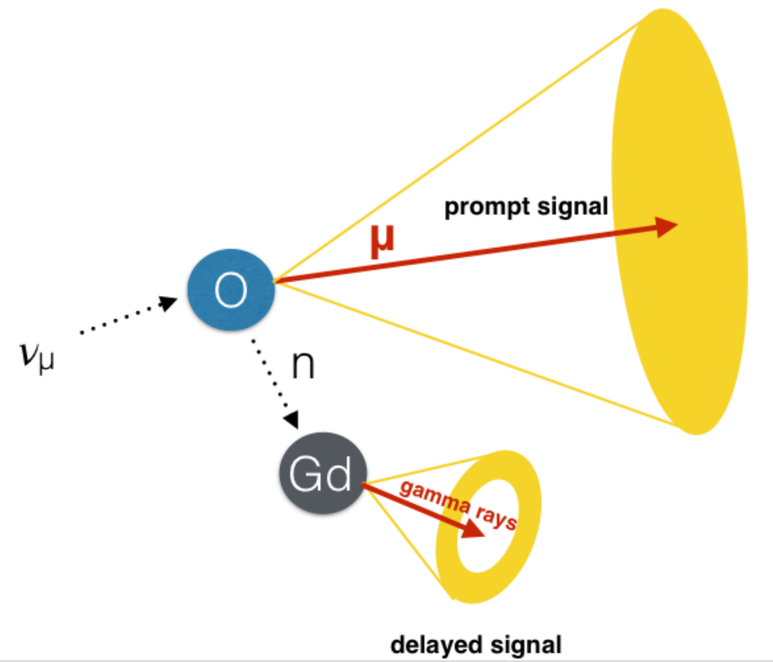
- The LAPPDs perform with resolutions consistent with our requested specifications:
  - <100 ps time resolution
  - gains of 10^7
  - few mm spatial resolutions





Enabling Technology: Gd-loading of water

- Efficient neutron counting is made possible by Gadolinium loading of water
  - Gd has a high neutron capture cross section for thermal neutrons
  - These captures produce a delayed (O(10) microsecond) ~8 MeV gamma cascade, detectable in water from its Cherenkov light

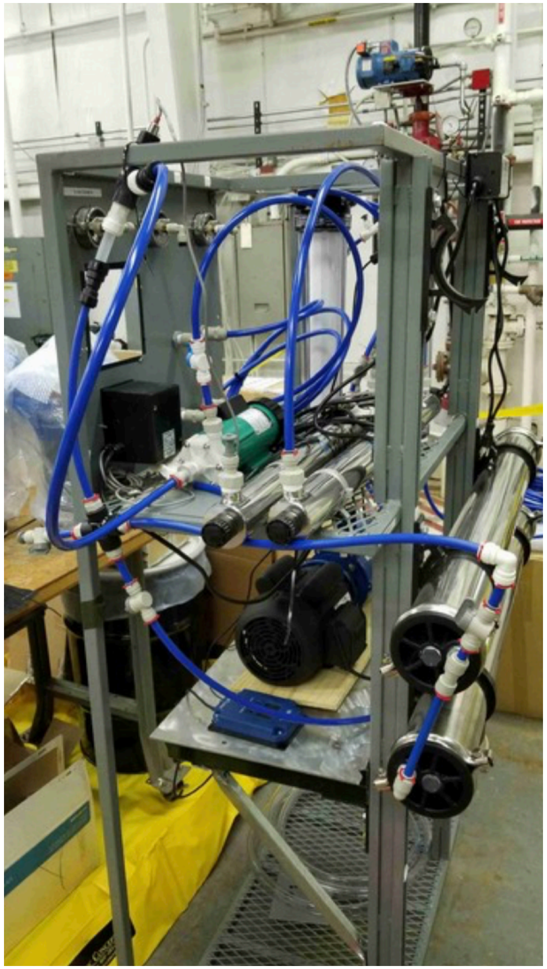


This fall, ANNIE will become the first Gd-loaded near detector on a beam

Enabling Technology: Gd-loading of water

- Development of a low-cost purification system for smaller scale Gd-water deployments
- Additional work on Gd compatibility, teflon wrapping/liner
- Developed a method of making low-cost, sulfate-loaded resin using commercially available materials
    - removes nitrates and free radicals from the water, leaving the Gd-sulfate in solution

ANNIE water skid

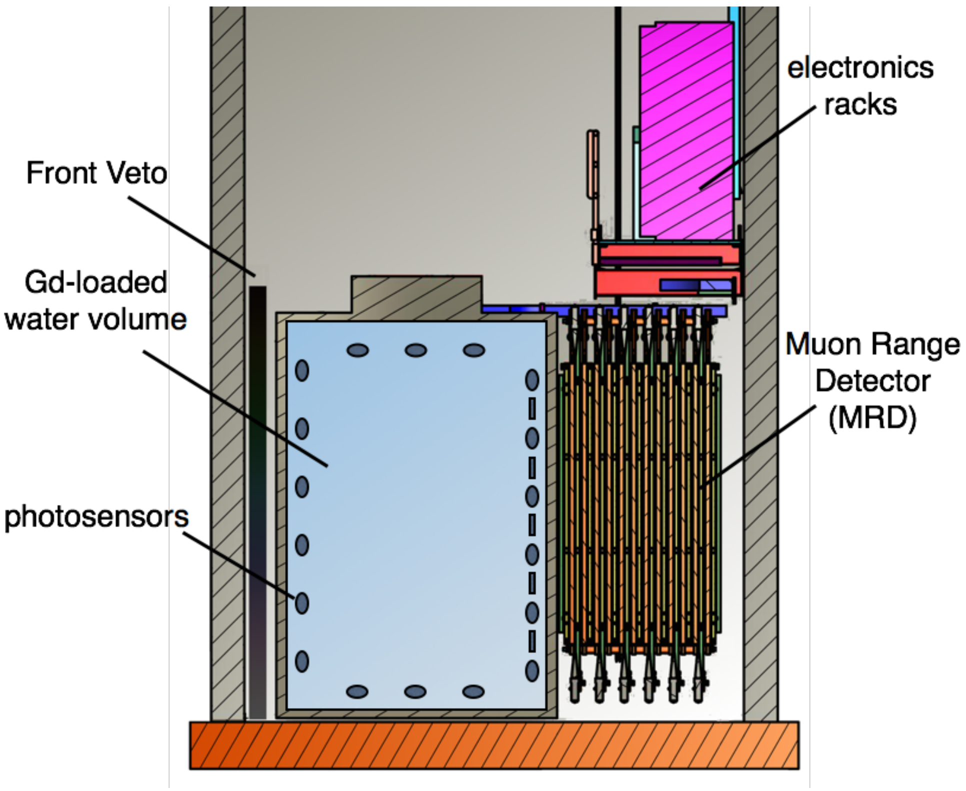


The Experimental Hall

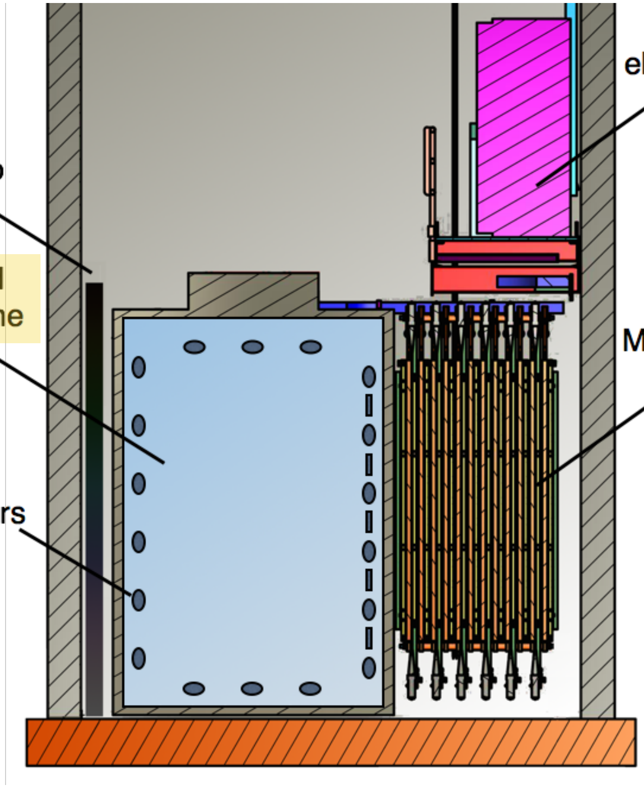
The Experimental Hall

The Experimental Hall

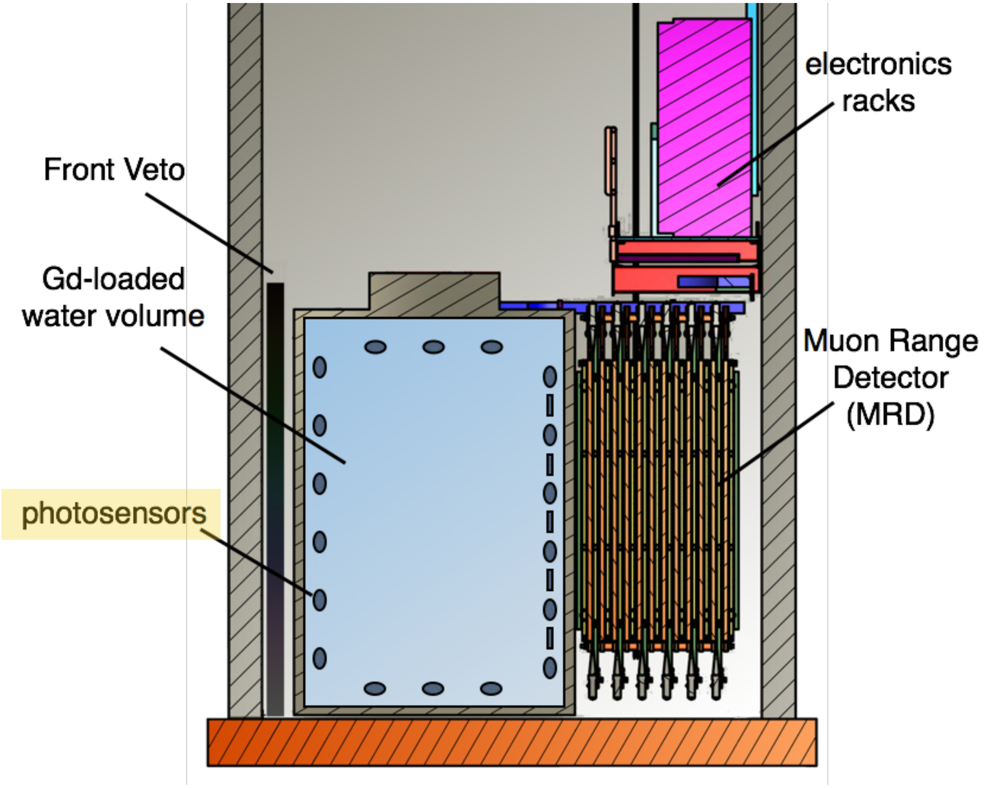
The Detector



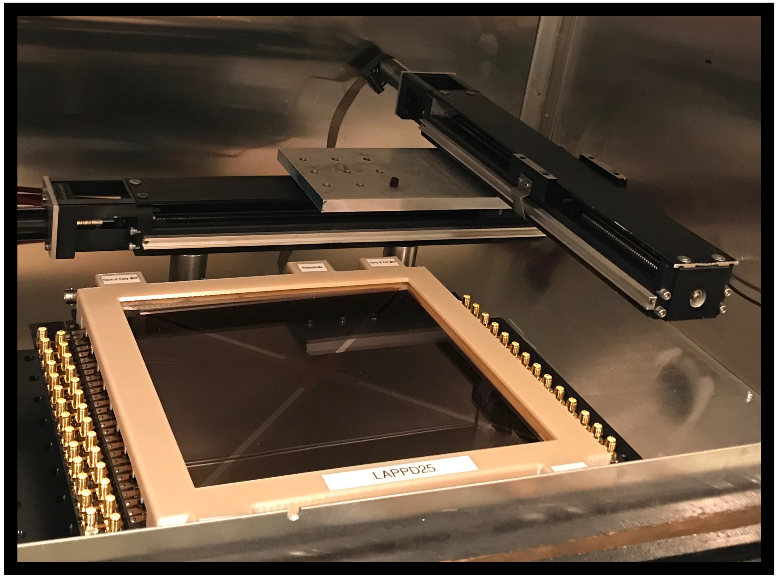
The Detector: Gd-loaded water volume

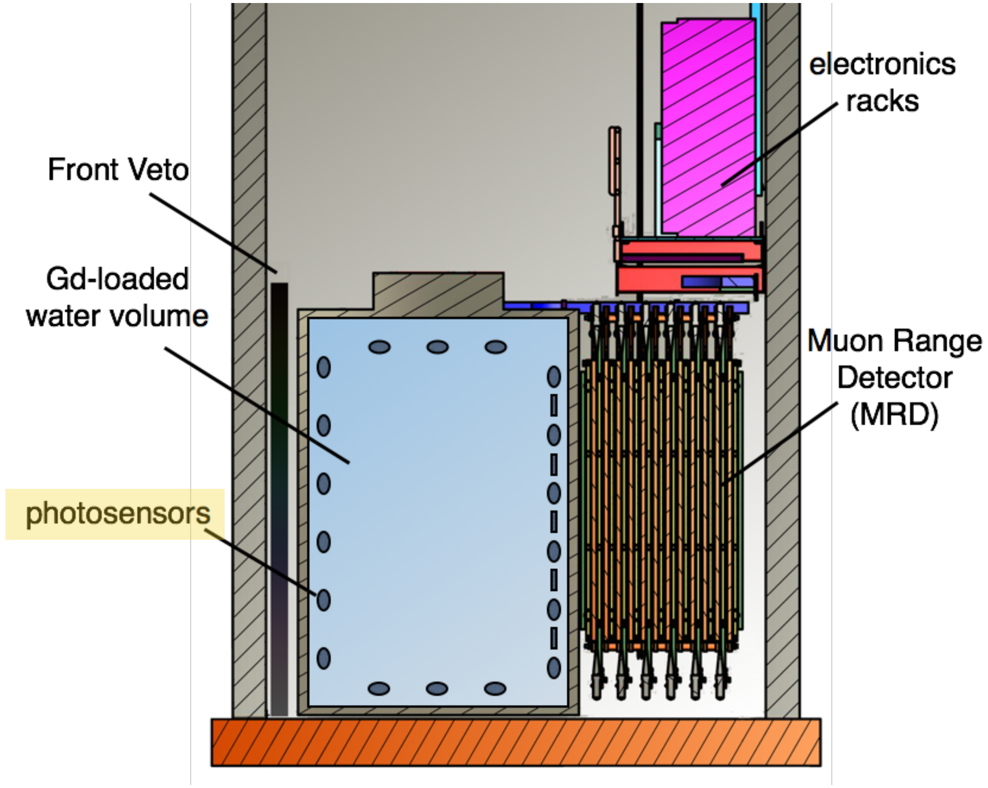


The Detector: PMTs

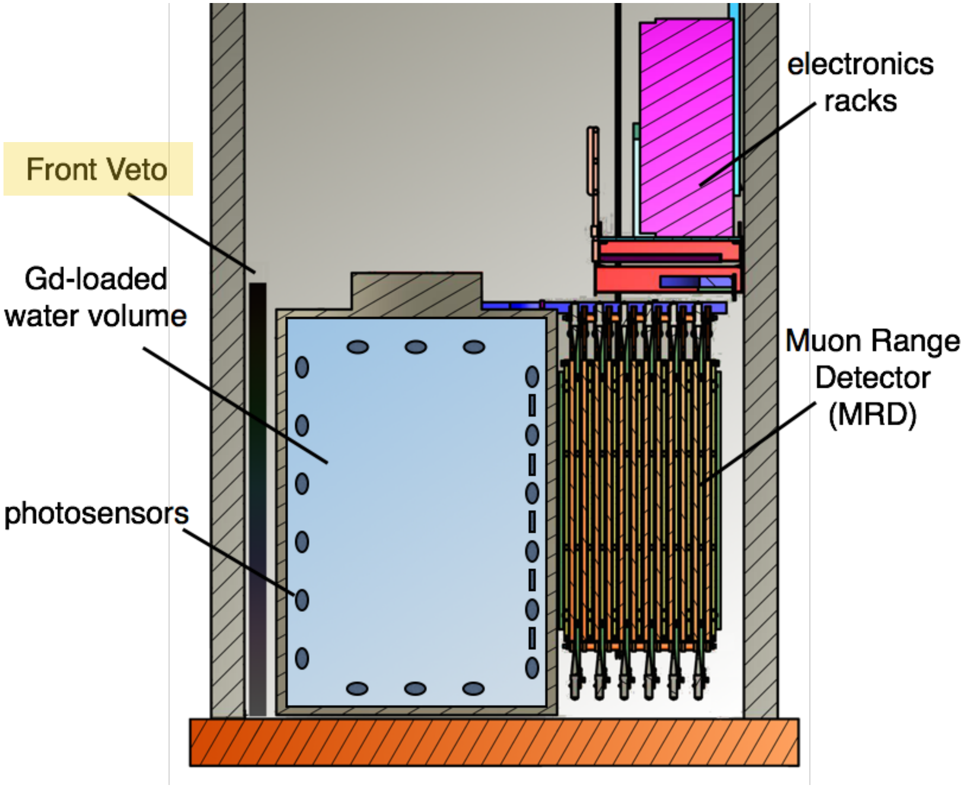


The Detector: LAPPDs

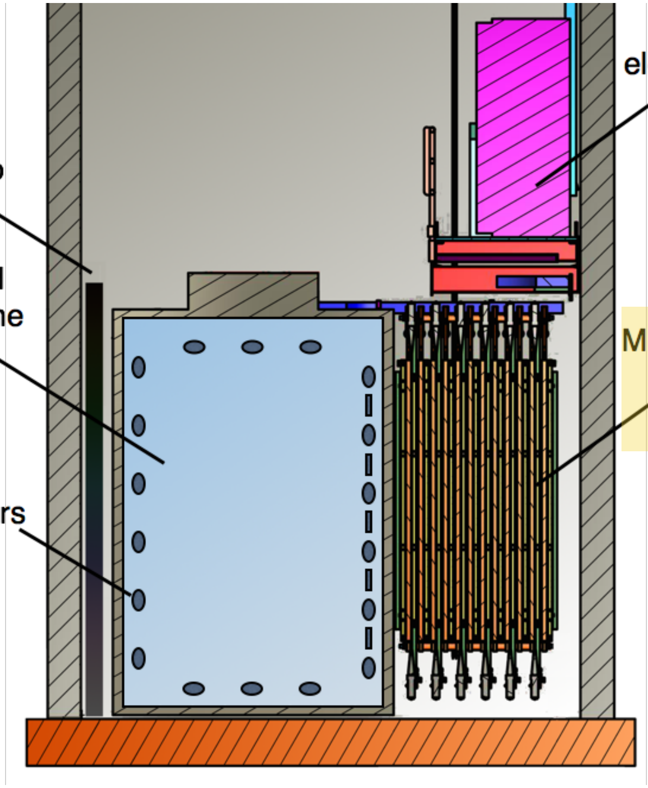




The Detector: Front Muon Veto (FMV)



The Detector: Muon Range Detector (MRD)



Experimental Status

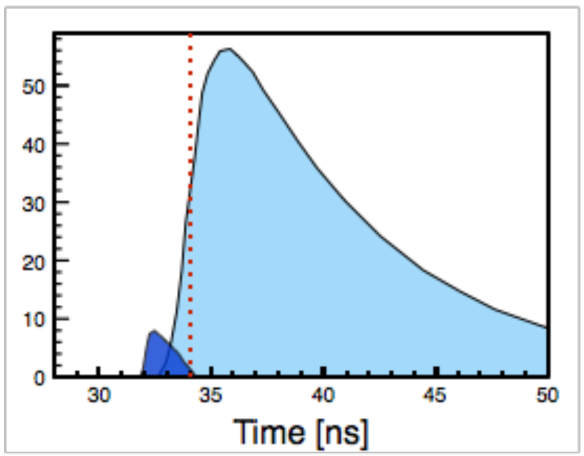
- Detector deployment and water fill to begin over the next two weeks!
- Full commissioning and calibration to start this summer
- The detector is to be fully physics-ready in time for beam data taking in fall

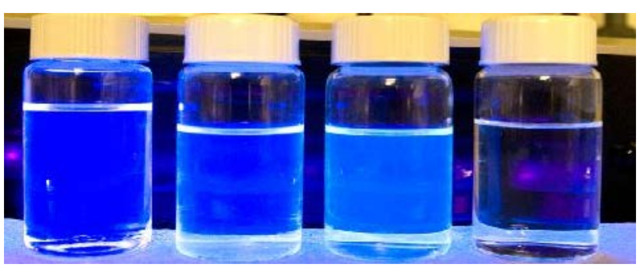
Future ANNIE Physics Opportunities

ANNIE is designed to be flexible. New additions expand the physics reach

Expanded LAPPD coverage

- LAPPDs can be added to the filled tank in situ
- Additional LAPPD coverage, particularly in the backward direction would enable multi-track reconstruction and measurements of more exclusive final states





Adding water-based Liquid Scintillator (wbLS)

The addition of water-based Liquid Scintillator (wbLS) with fast timing would

- combine the tracking capabilities of Cherenkov reconstruction with the energy resolution and expanded sensitivity of scintillation light
- increase sensitivity to low energy and sub-Cherenkov particles (e.g. recoil protons)
- enable more detailed reconstruction of nuclear final states

Conclusion

- ANNIE is the first opportunity to test many of the essential technologies and experimental techniques relevant to next-generation neutrino experiments
- ANNIE will also perform highly efficient and detailed measurements of nuclear final states from neutrino interactions in water relevant to many key analyses
- We have a rich landscape of physics measurements to make and experimental techniques to develop

There are many opportunities to expand the scope of the experiment and opportunities for new groups to have a major impact

A.N.N.I.E.

NEW RELEASE THIS FALL

NEUTRON MULTIPLICITY

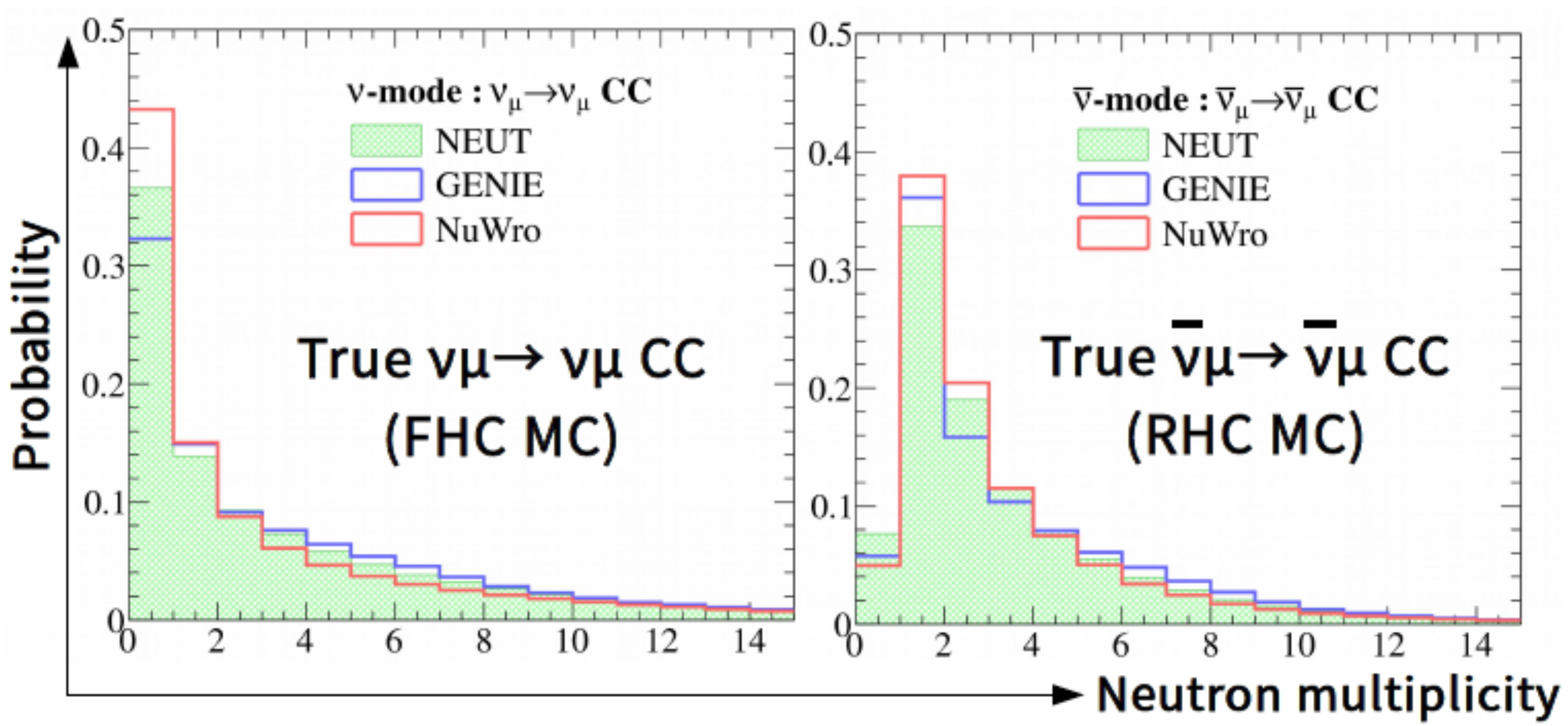
THANK YOU

Additional Slides

Phase II: Neutron Multiplicity Measurements

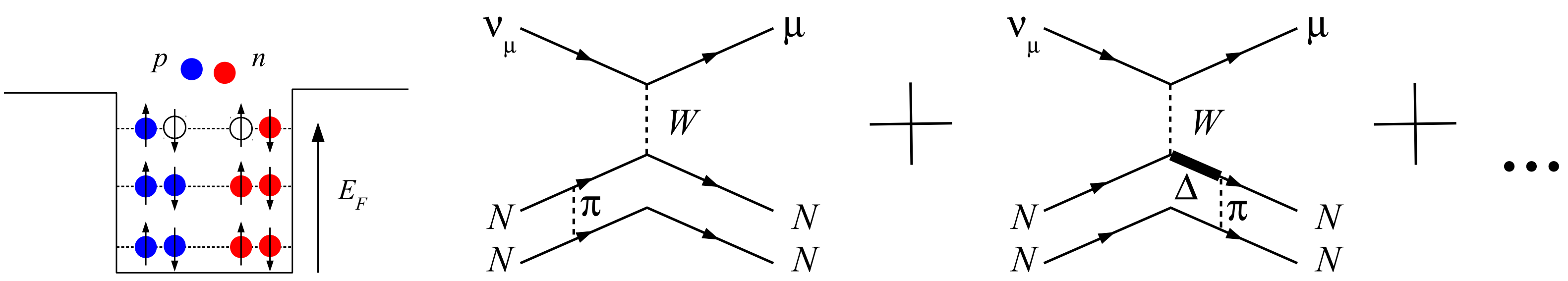
ANNIE is uniquely suited to measure neutron yields a function of muon kinematics (Q^2, p_μ, θ_μ)

- It is on a controlled beam with known direction, flavor, and energy spectrum
- At an energy spectrum close to that of atmospheric neutrinos



Phase II: Neutron Multiplicity Measurements

Neutron tagging provides an important handle for disambiguating otherwise experimentally similar final-states



The presence of neutrons can therefore be used for signal-background separation in a variety of physics analyses

- wrong-sign neutrino separation
- proton decay
- diffuse supernova neutrino background
- tagging inelastic CC0pi events

Phase II: Neutron Multiplicity Measurements

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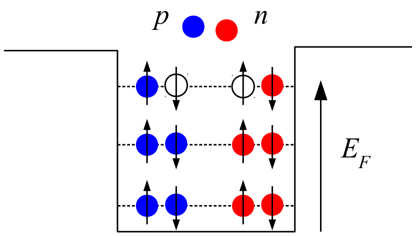
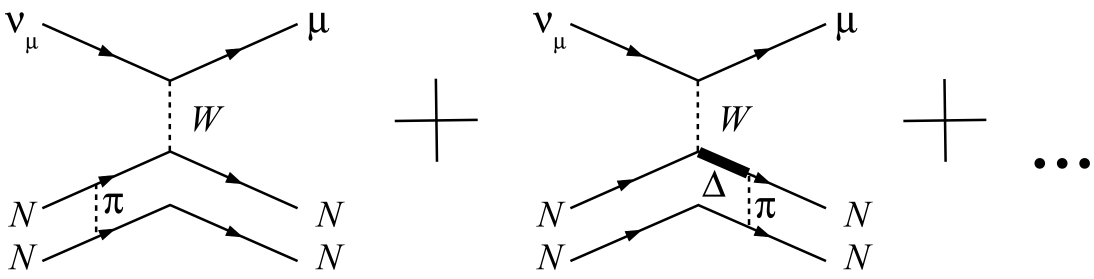




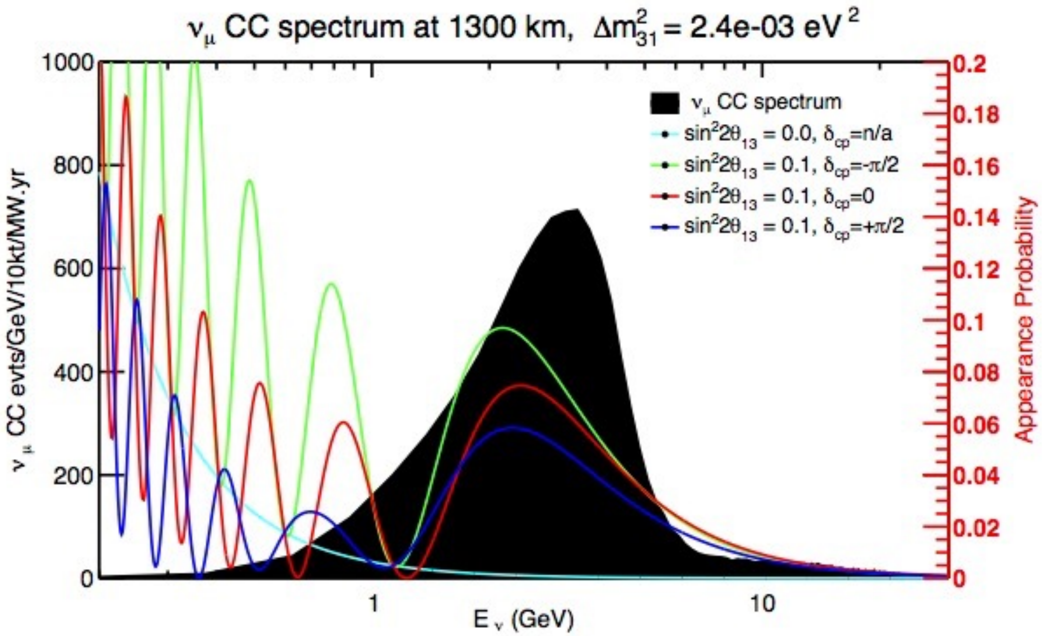
The presence of neutrons can therefore be used for signal-background separation in a variety of physics analyses

• wrong-sign neutrino separation	**0n (FHC)**	**1n (RHC)**
• proton decay	**0n (signal)**	**>0n (bkgd)**
• diffuse supernova neutrino background	**1n (signal)**	**>1n (bkgd)**
• tagging inelastic CC0pi events	**0 or 1n (signal)**	**extra n**

Connections to Theia Physics I

Playing to the strengths of a water-based detector on the LBNF, Theia would most strongly contribute to oscillation at the second maximum:

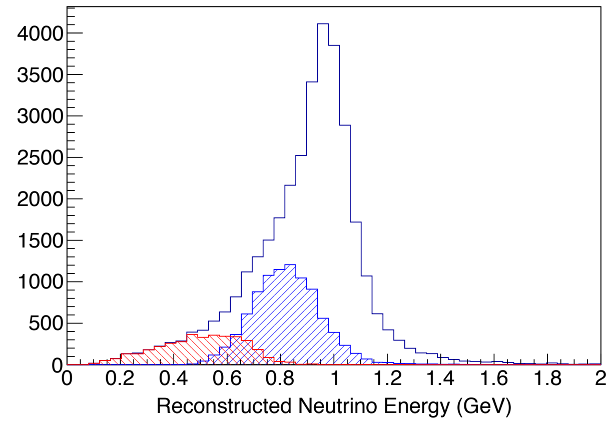
- better low-E reconstruction
- more fiducial mass, ie more stats

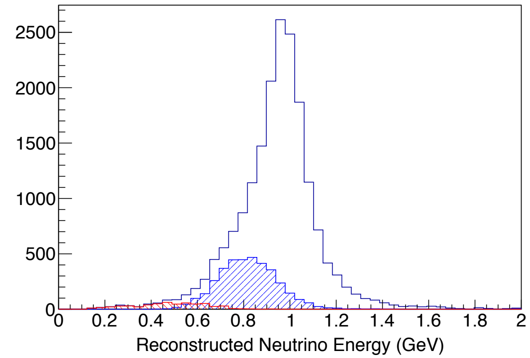


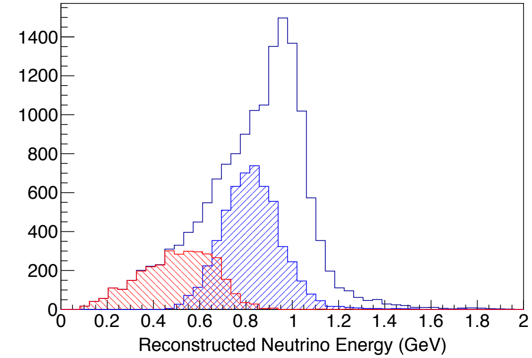
- Succeeding at that measurement will require excellent ~1 GeV neutrino reconstruction, in the context of a wideband, high energy neutrino beam
  - better reconstruction of event topology (track counting and directionality, EM shower structure)
  - more detailed picture of the nuclear system
- ANNIE will characterize these components of neutrino interactions at the relevant energy

Neutrons as an Indicator of Inelasticity

- CCQE interactions on a neutrino beam should, to first order, produce a single recoil proton and no neutrinos
- The presence of neutrons is often an indicator of inelastic processes
- Stuck pions, in particular, very frequently produce neutrons (many-body absorption process)





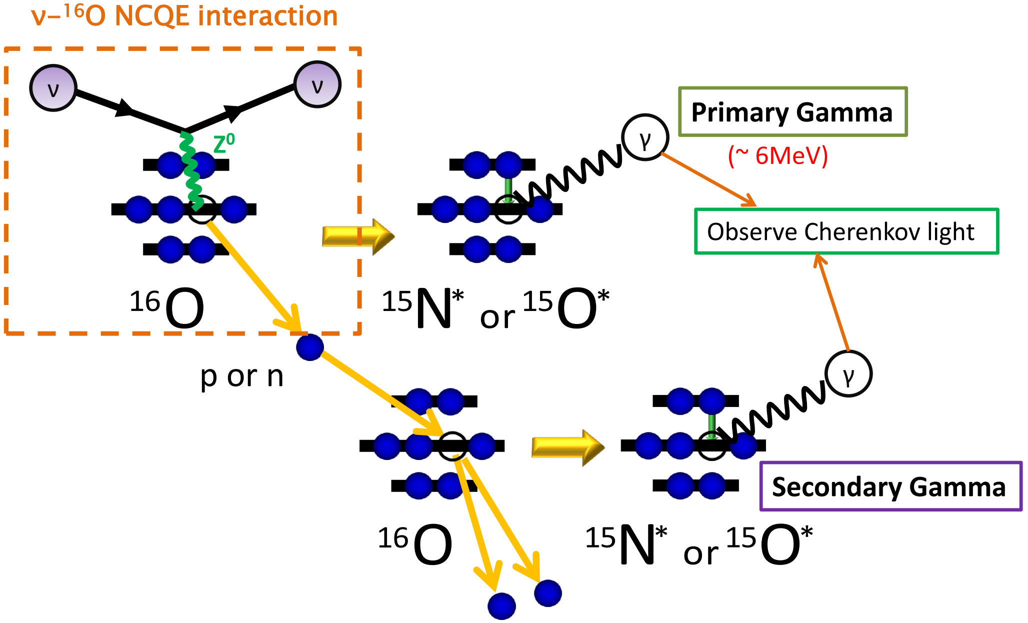


Tagging Nuclear De-excitation Gammas

- 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)

Radiative Fast-Neutron Capture on Oxygen

Roughly 10% of fast (>10 MeV) neutrons will capture on ^{16}O in water targets!!

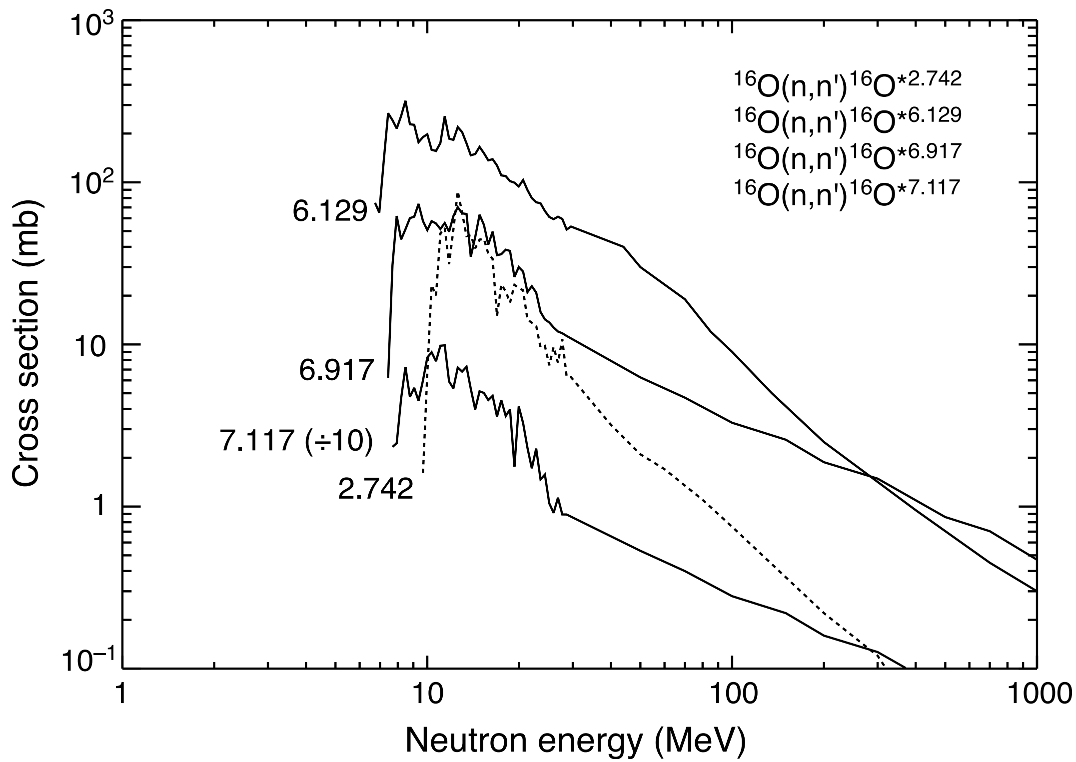
The gamma emission from radiative capture happens on nanosecond timescales

Can we disentangle the 5-10 MeV gammas from the prompt event?

What do we measure that capture rate to be?

Is it more useful or less useful that Gd-captures?

Oxygen captures may provide better constraints on the initial neutron energy.



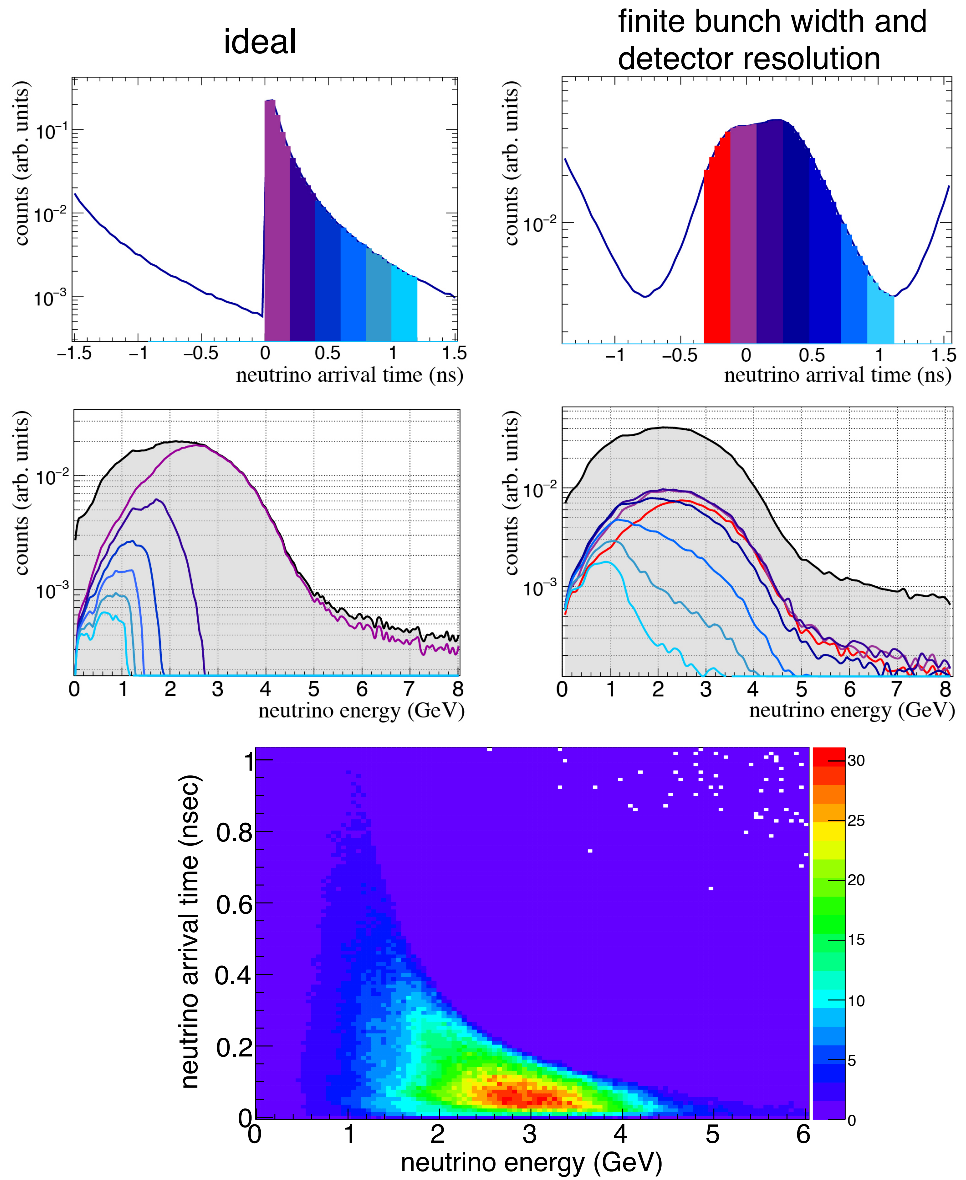
credit: Bei Zhou and John Beacom (OSU)

Fast Timing and Beam Physics

- Timing could potentially be used to select narrower, lower-E neutrino spectra, much like looking off-axis
- Is driven by time-of-flight differences between pion energies
- O(1) nsec time structure of the bunch washes out the effect but the broad tail of late neutrinos remains
- Requires sub-nsec time resolution
- Would enable on-axis experiments to select different fluxes in both near and far detectors
- This is technique is possible for DUNE Theia and testable by ANNIE

https://arxiv.org/abs/1904.01611

LBNF Flux (Simulation)



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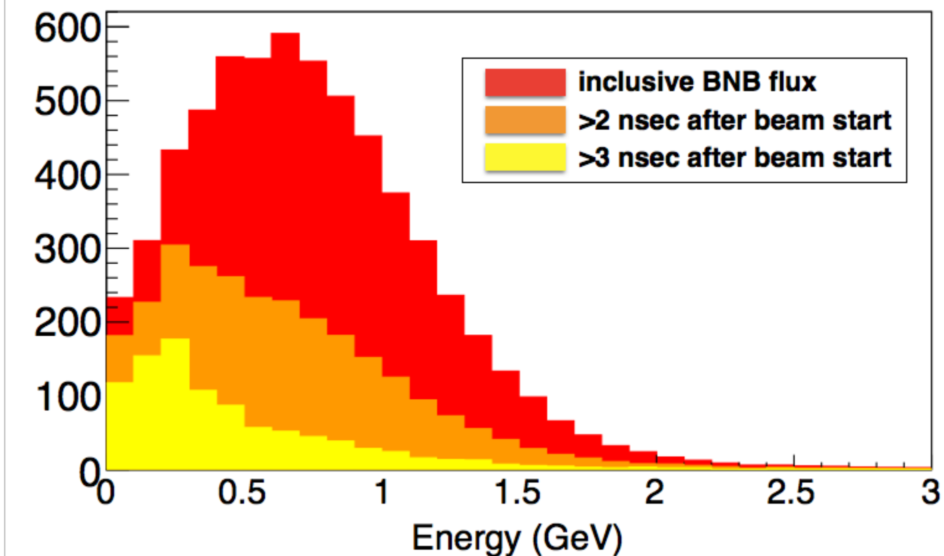
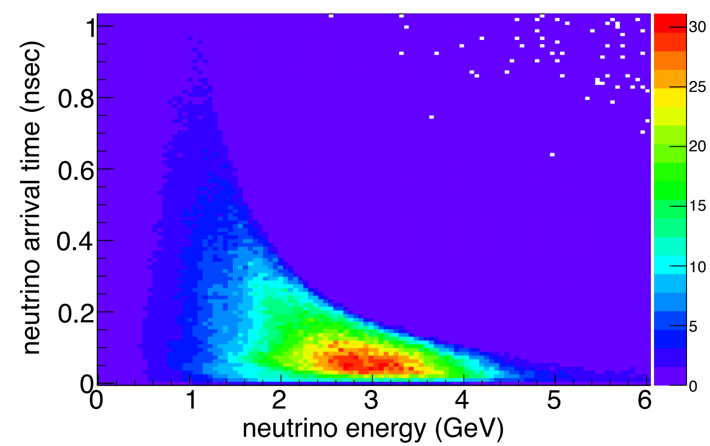
BNB (Simulation)

finite bunch width and detector resolution





(Non-exhaustive) ANNIE Physics List

Baseline ANNIE Year-1 Measurements

- Neutron multiplicity in bins of lepton kinematics
- Relation between neutron multiplicity and CC-elasticity
- CC-incusive cross section

Baseline ANNIE Year-2 Measurements

- More statistics to the IIa analyses
- CCQE cross section

Further possible ANNIE Measurements

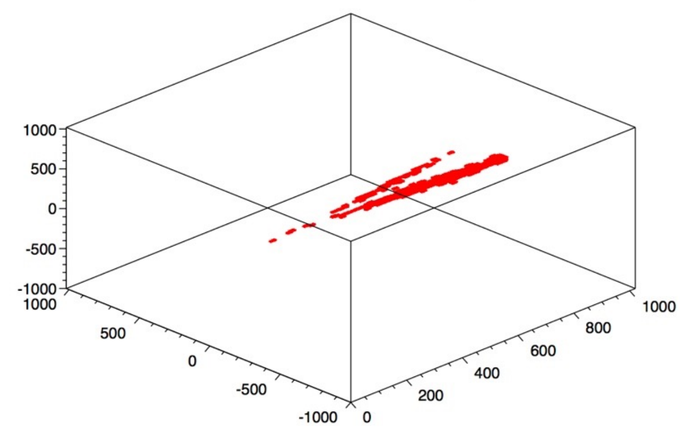
- Pion production cross sections and neutron yields
- Neutral current cross sections and neutron yield

Other directions + wbLS

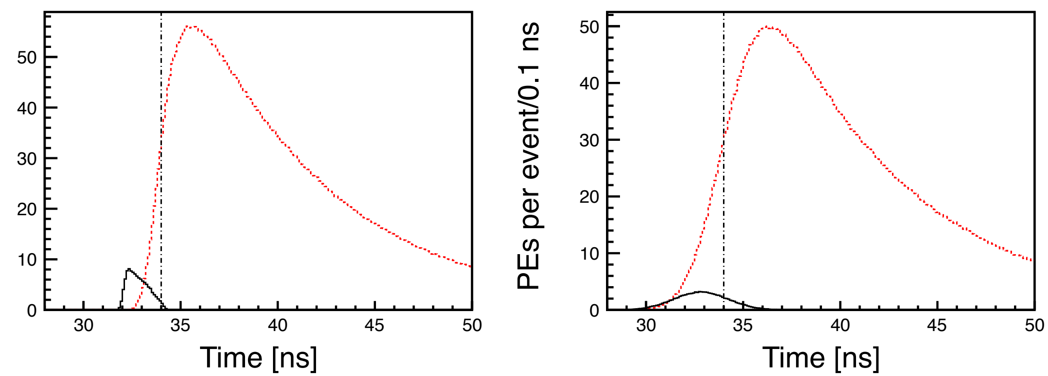
- Calorimetric energy reconstruction
- Beam timing
- De-exitation gammas
- Oxygen capture rates

LAPPD applicability

- Fast timing is interesting in itself
  - better vertex reconstruction
  - ability to reconstruct overlapping events and tracks
  - better able to resolve structure of EM showers



- Timing may be even more interesting in combination with wbLS
  - Cherenkov = tracking
  - Scintillation = calorimetry



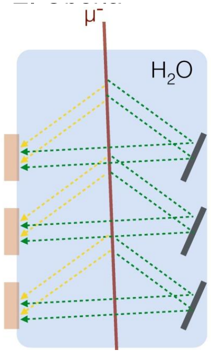
(a) Default simulation. (b) Increased TTS (1.28 ns).

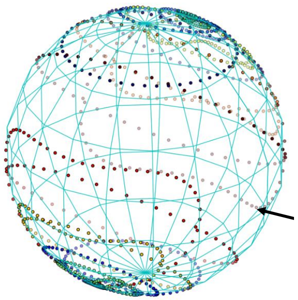
LAPPD applicability

- Imaging is an essential capability
  - Because LAPPDs are imaging photodetectors, their marginal value increases with more dense occupancy. Could we develop interesting schemes to better concentrate the light.
  - Rotation from spatial to time domain (Liouville Theorem)

Multi-bounce optics (U Chicago - Oberla, Frisch, Angelico, Elagin)

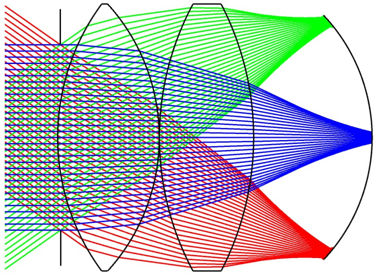
https://arxiv.org/abs/1510.00947





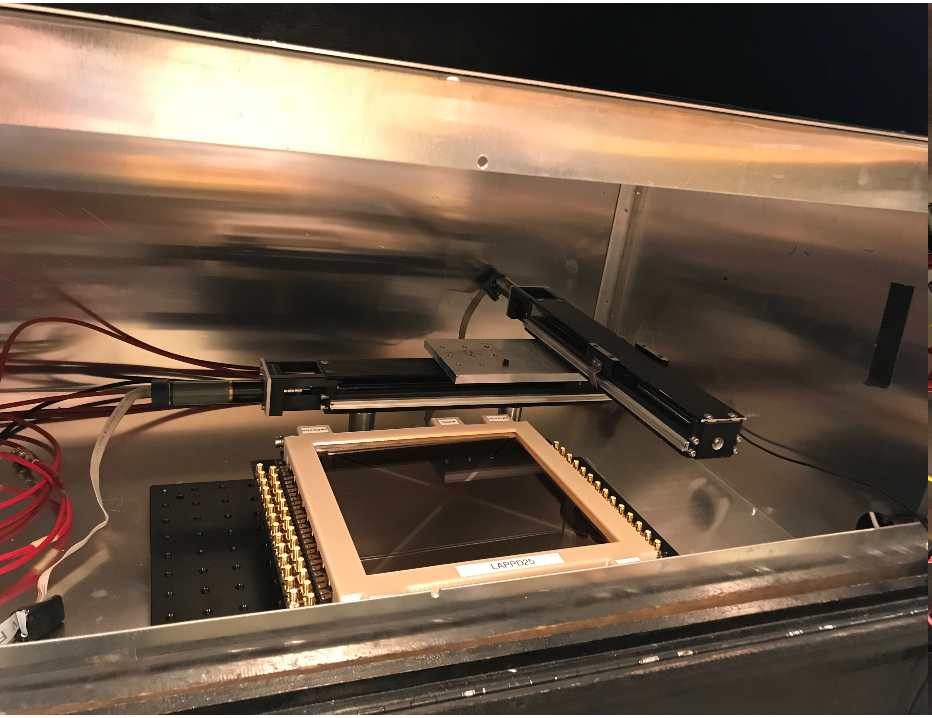
Plenoptic imaging (Dalmasson et al)

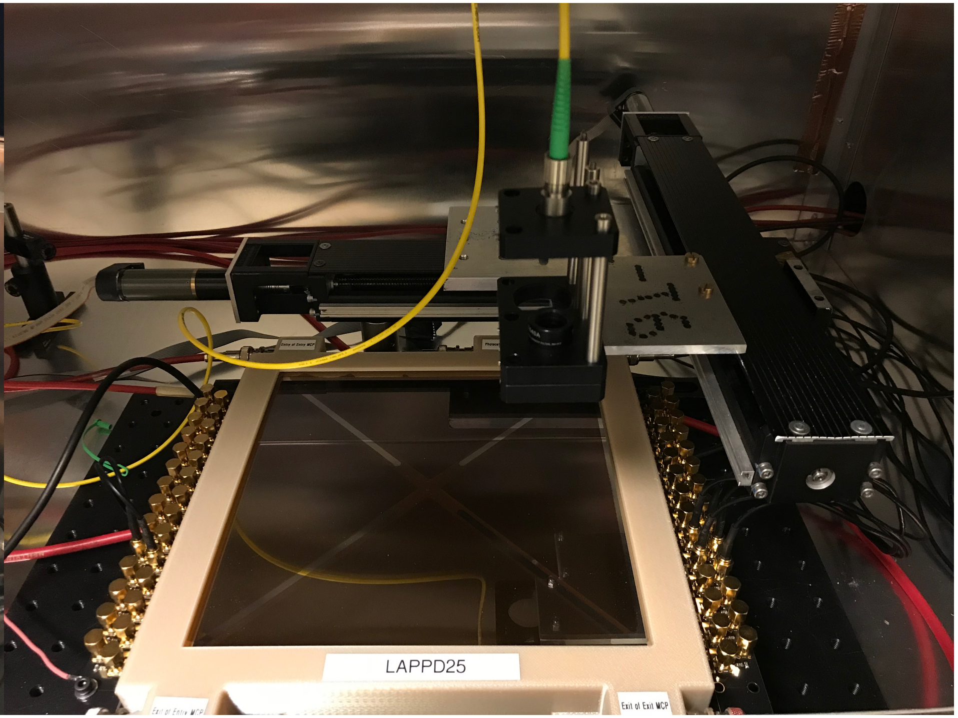
https://arxiv.org/abs/1711.09851



Timing + Imaging photosensors could enable a very different kind of Cherenkov/scintillator detector)

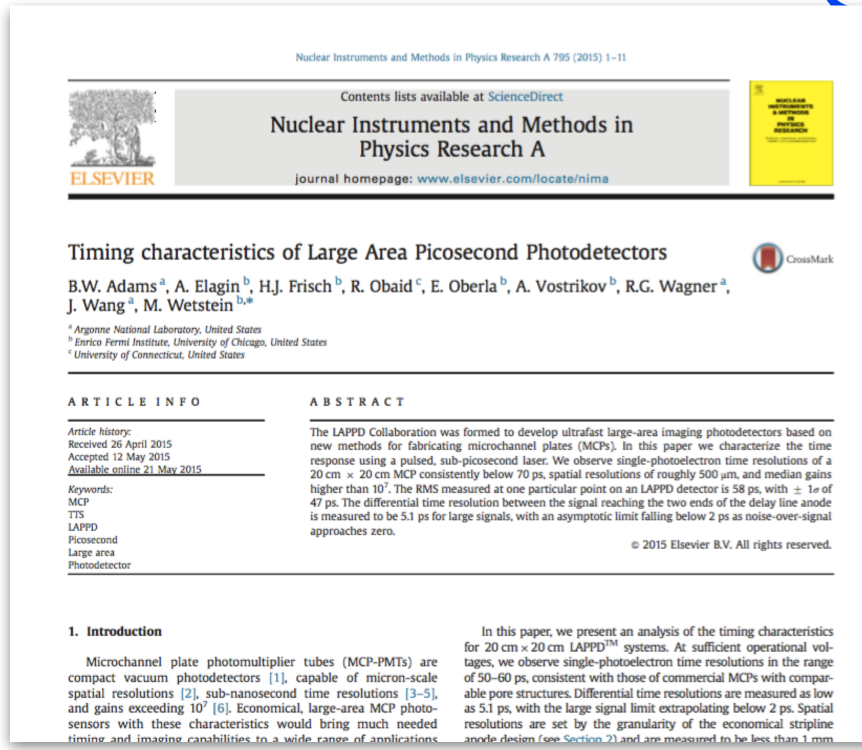
Iowa State - LAPPD Test Stand





- PiLAs laser (up to 30 psec resolution)
- 10 GHz, 20 Gs/sec scope
- PSEC4 electronics
- Dark box
- Motorized optics allow for position scans

Iowa State - LAPPD Test Stand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Timing characteristics of Large Area Picosecond Photodetectors

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ABSTRACT

The LAPPD Collaboration was formed to develop ultrafast large-area imaging photodetectors based on new methods for fabricating microchannel plates (MCPs). In this paper we characterize the time response using a pulsed, sub-picosecond laser. We observe single-photoelectron time resolutions of a 20 cm × 20 cm MCP consistently below 70 ps, spatial resolutions of roughly 500 μm, and median gains higher than 10^7. The RMS measured at one particular point on an LAPPD detector is 58 ps, with ± 1σ of 47 ps. The differential time resolution between the signal reaching the two ends of the delay line anode is measured to be 5.1 ps for large signals, with an asymptotic limit falling below 2 ps as noise-over-signal approaches zero.

1. Introduction

Microchannel plate photomultiplier tubes (MCP-PMTs) are compact vacuum photodetectors [1], capable of micron-scale spatial resolutions [2], sub-nanosecond time resolutions [3–5], and gains exceeding 10^7 [6]. Economical, large-area MCP photo-sensors with these characteristics would bring much needed timing and imaging capabilities to a wide range of applications

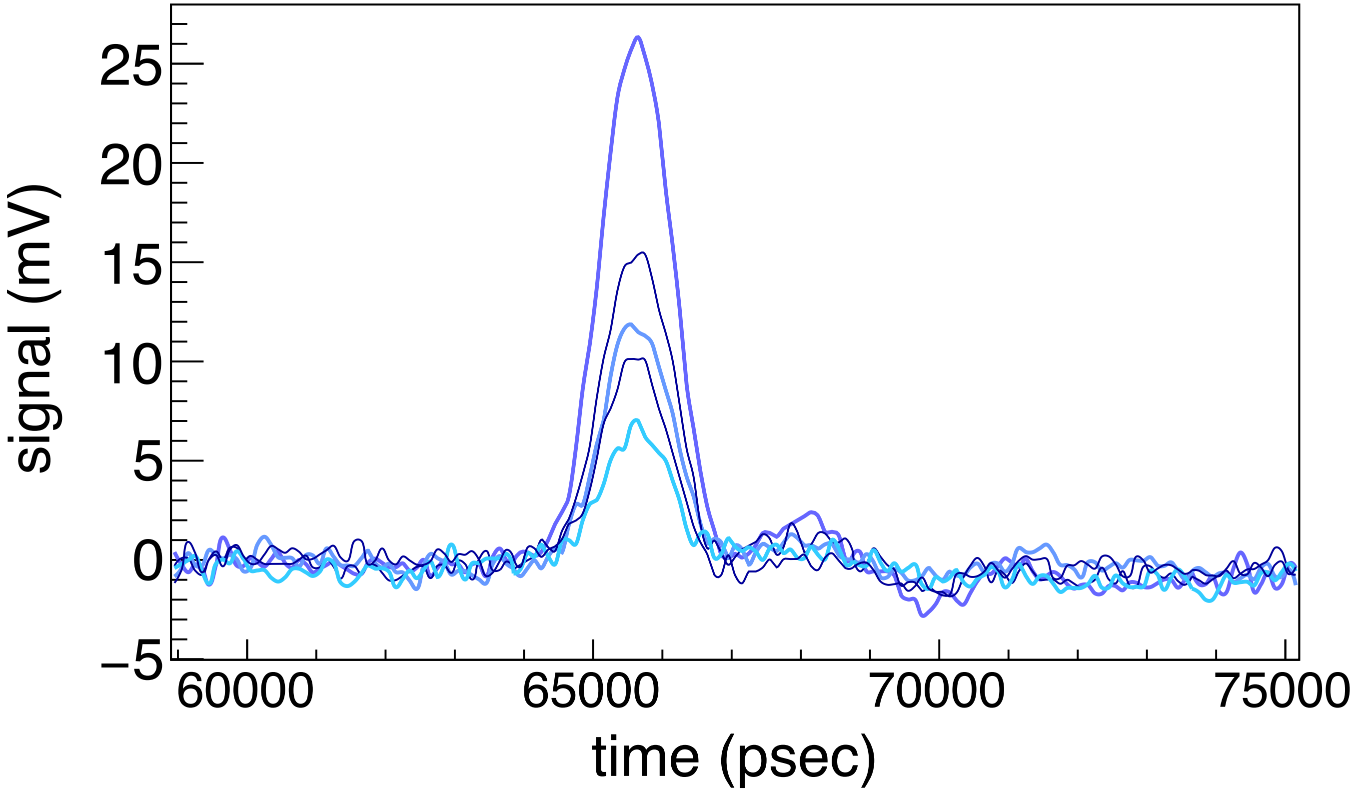
In this paper, we present an analysis of the timing characteristics for 20 cm × 20 cm LAPPD™ systems. At sufficient operational voltages, we observe single-photoelectron time resolutions in the range of 50–60 ps, consistent with those of commercial MCPs with comparable pore structures. Differential time resolutions are measured as low as 5.1 ps, with the large signal limit extrapolating below 2 ps. Spatial resolutions are set by the granularity of the economical stripline anode design (see Section 2) and are measured to be less than 1 mm

The ISU test stand is based on and built by the researchers who wrote *the* canonical papers on LAPPD testing and time resolution.

Results: Typical Single-PE Pulses

FWHM: 1.1 nsec

rise time: 850 psec

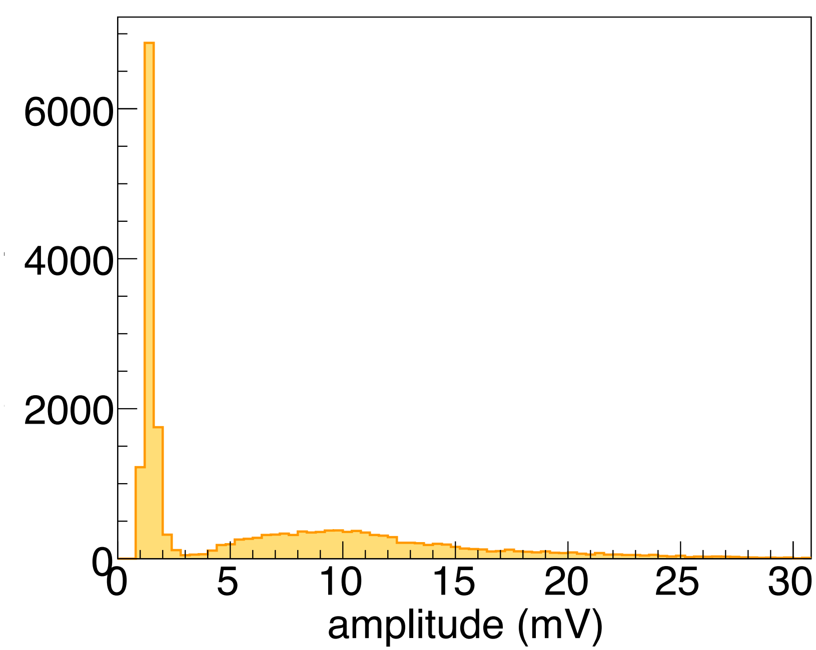


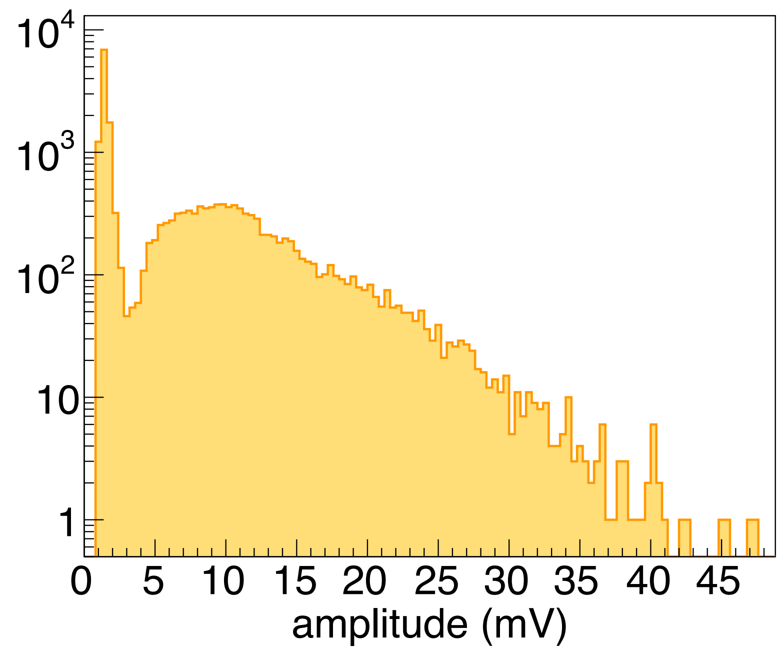
voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

Results: Amplitude

We see very clean separation from pedestal

Pulses are typically above 5mV (single-sided) compared to <1 mV noise

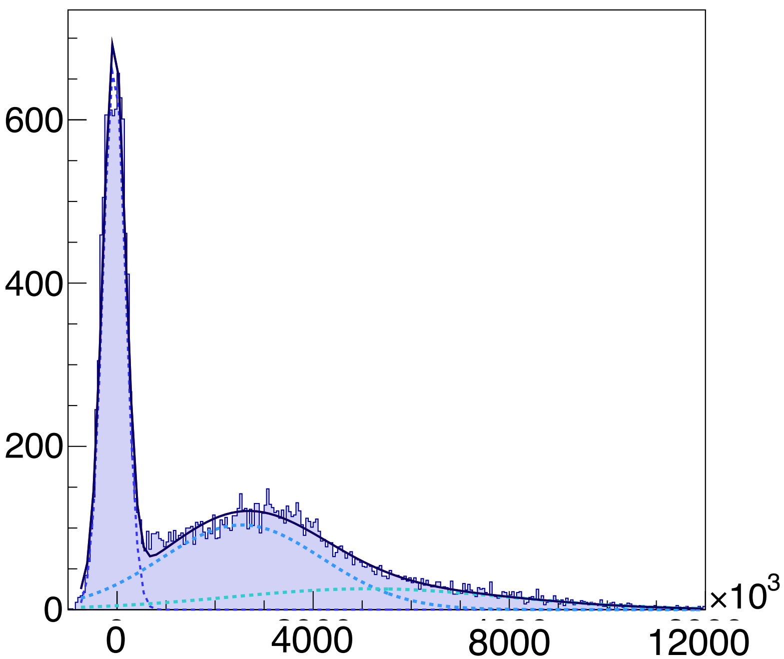


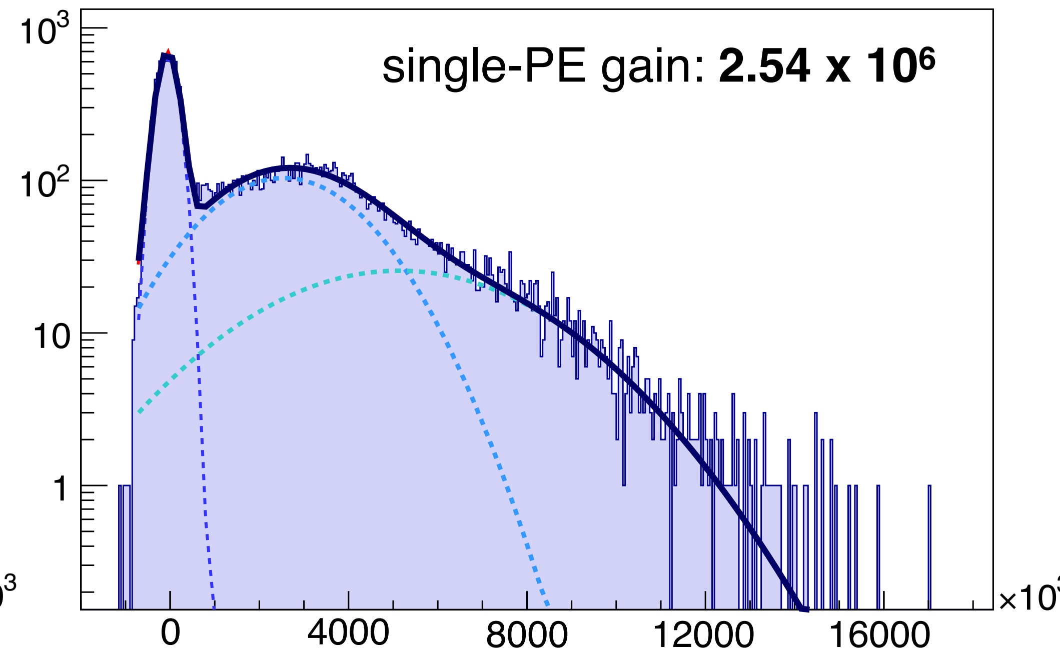


voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

Results: Gain

Even at low operational voltages, we observe peak gains well above 10^6

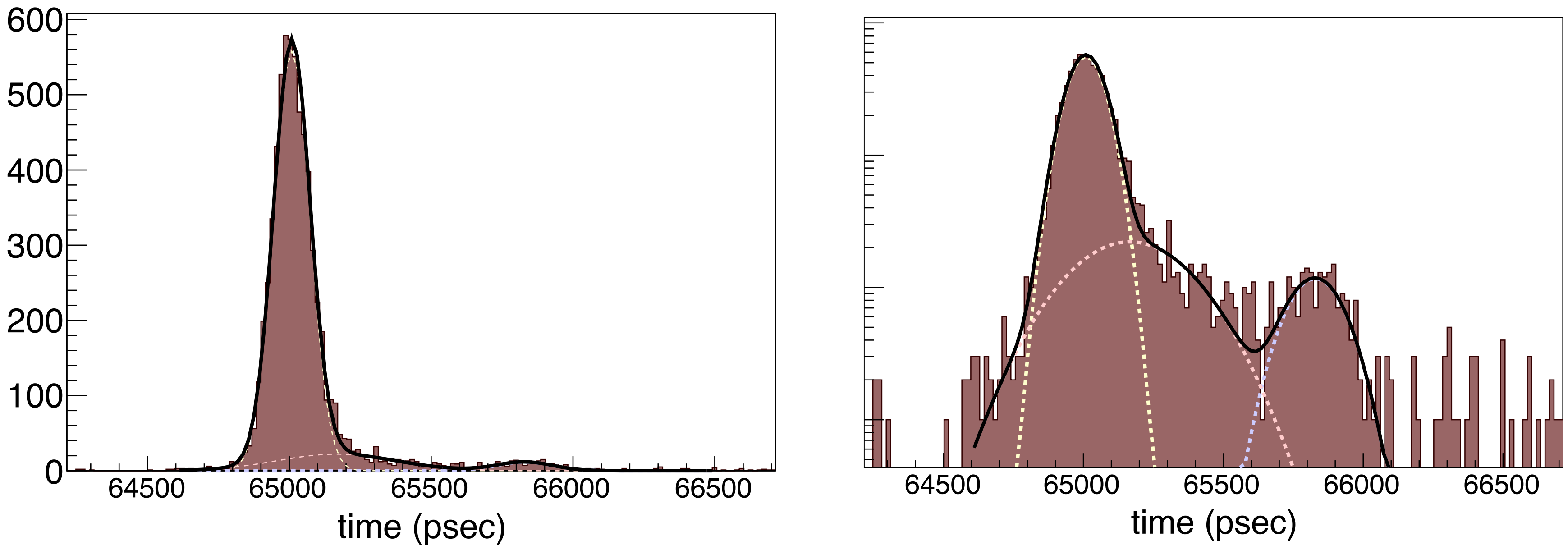




voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

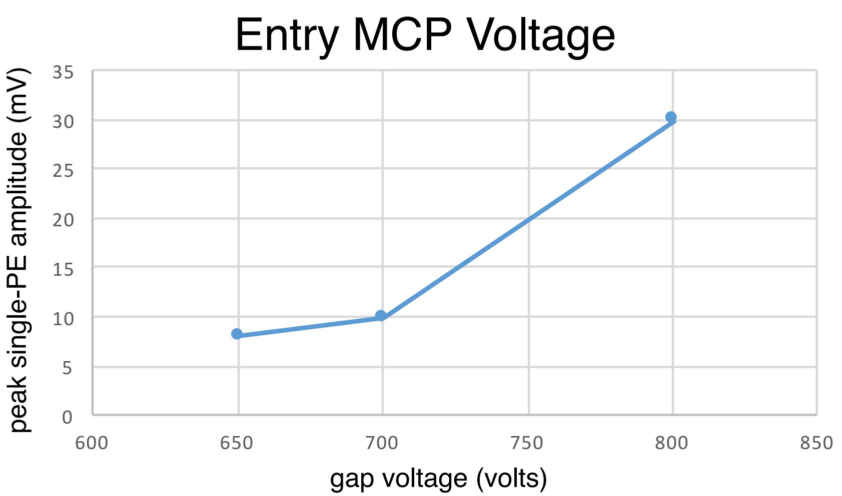
Results: Time Resolution

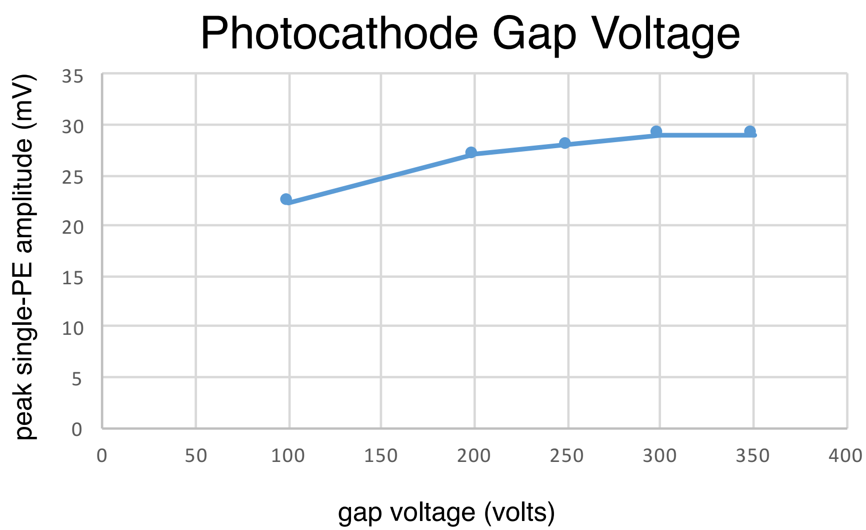
We observe 64 psec time resolution in the main peak of the TTS
with small contribution from after-pulses (~4%), typical of any photodetector



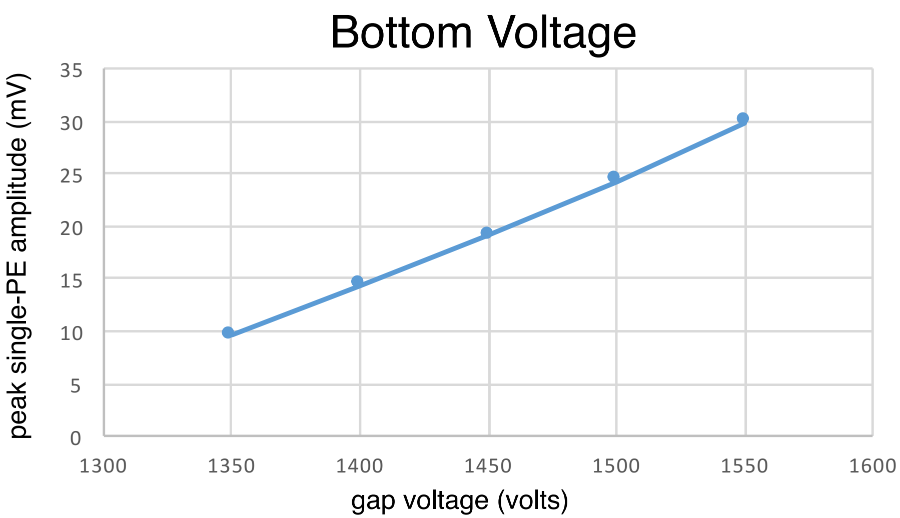
voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

LAPPD 25: Voltage Response



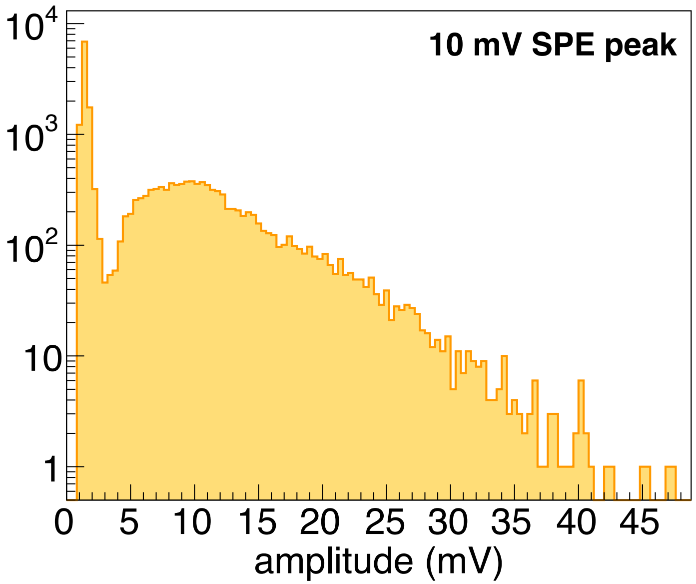


- We varied the voltages to see if we could improve the gain
- At higher voltages, the LAPPD gets noisy, but these gains provide good sPE separation so we're not concerned

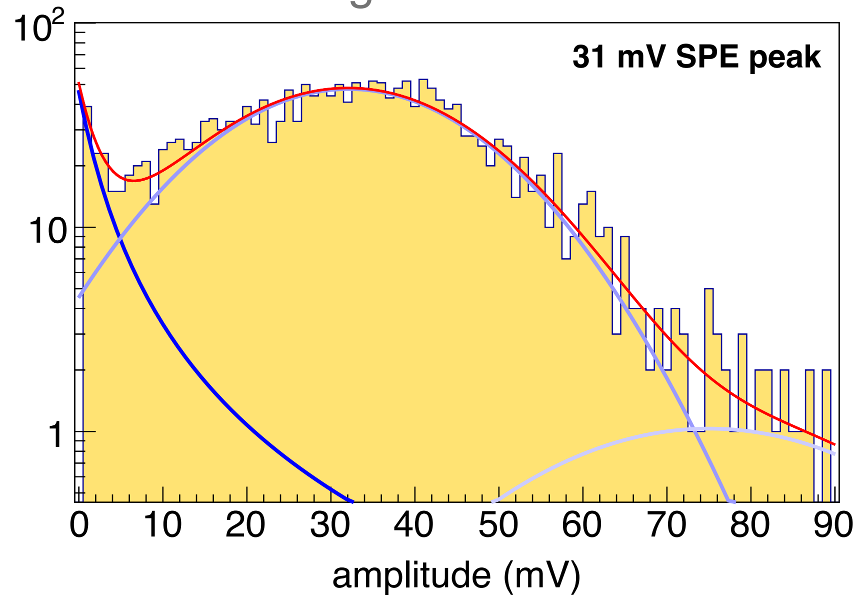


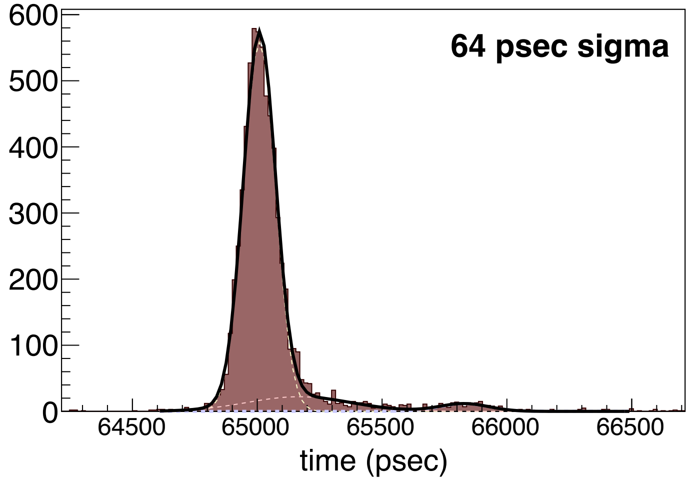
LAPPD 25: Voltage Optimization

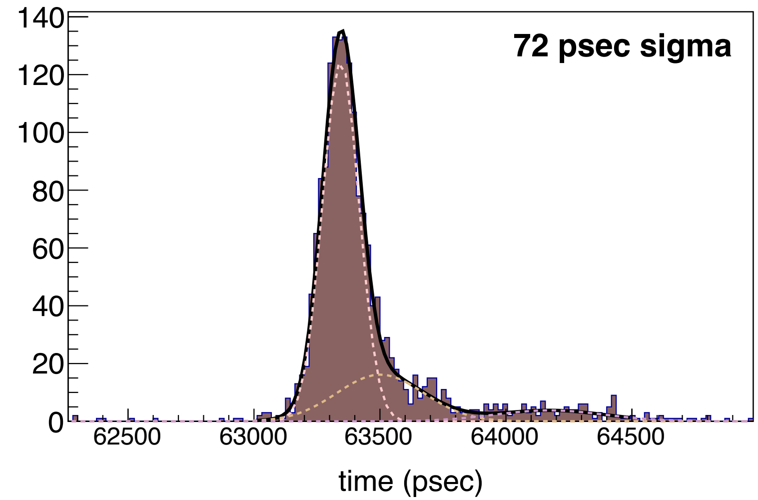
Low Gain



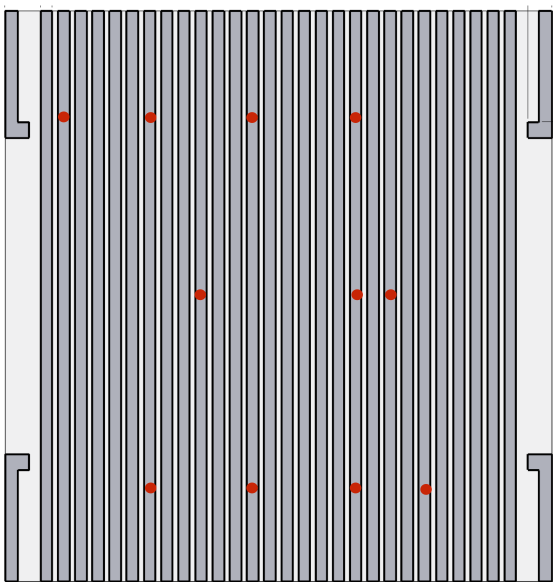
High Gain

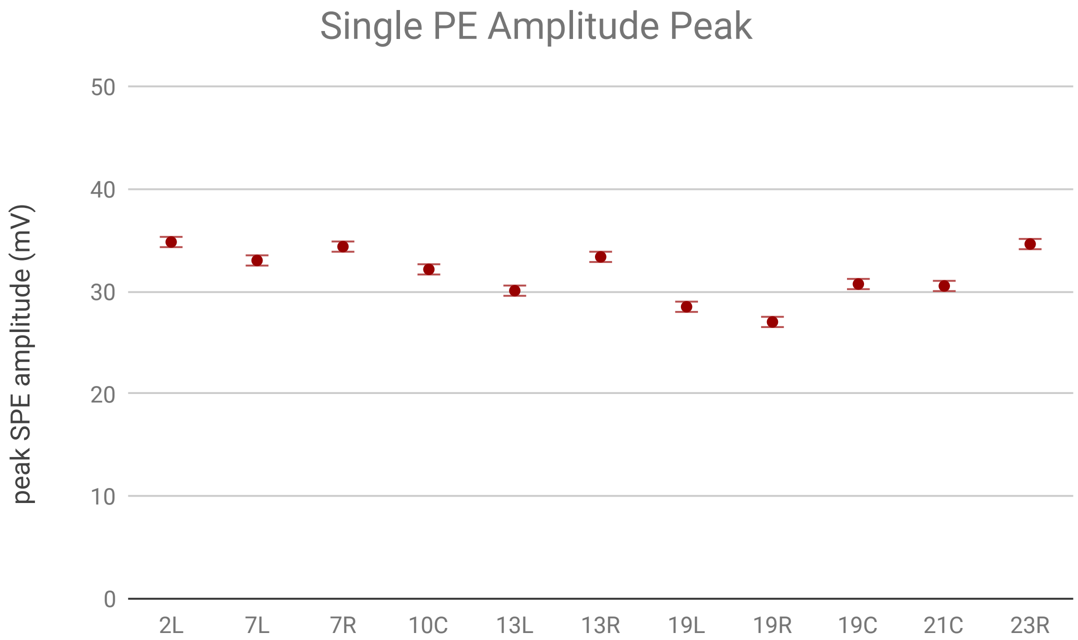






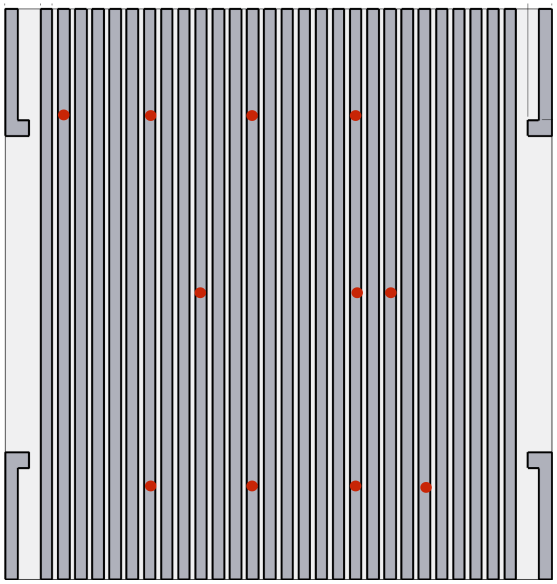
LAPPD 25: Single PE Gain Uniformity

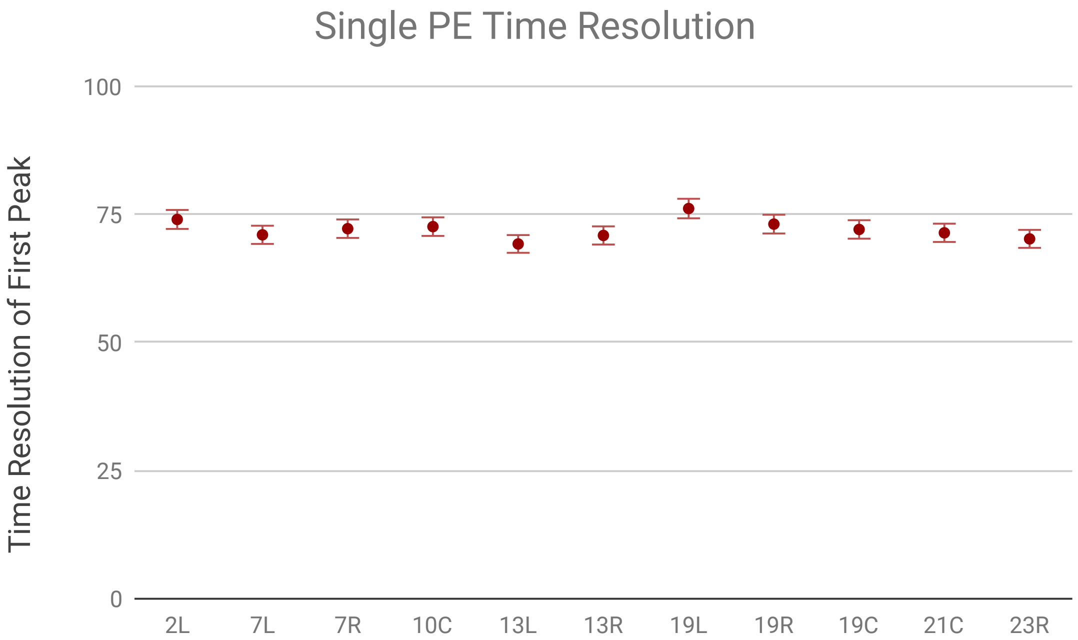




- We recorded 10k triggers as 11 random positions on the tile
- SPE peak amplitude was taken from the mean of the first Gaussian in a 2 PE + pedestal fit
- More systematic scans will become easier with the multichannel PSEC electronics

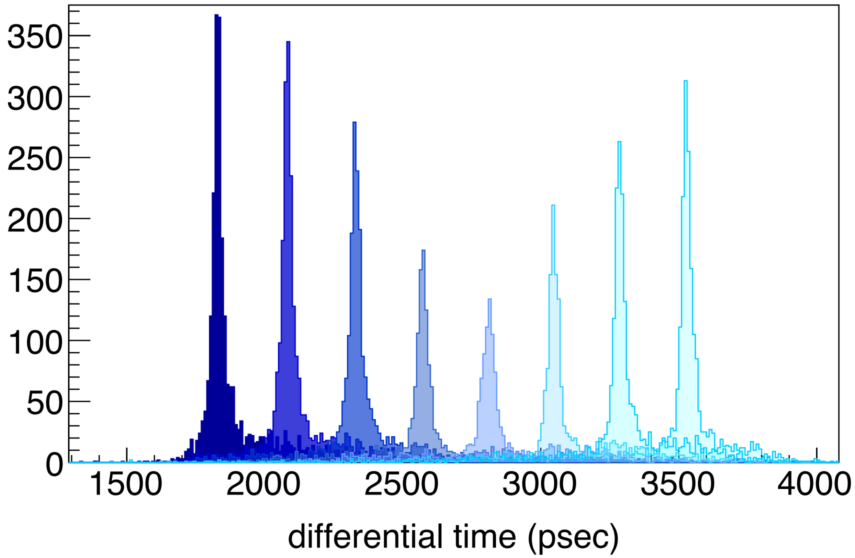
LAPPD 25: Single PE Timing Uniformity

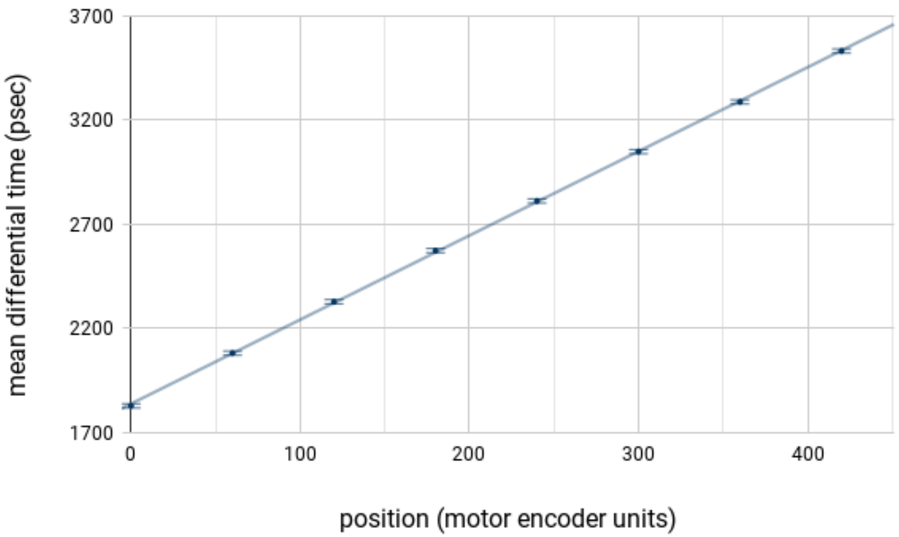


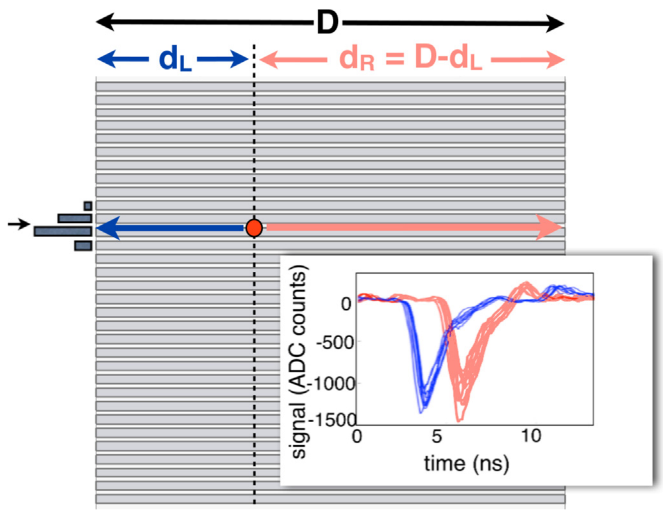


- We recorded 10k triggers as 11 random positions on the tile
- SPE time resolution is taken from the width of the main Gaussian in a 3 gaussian fit for TTS and after pulsing
- After pulsing constitutes a small (<10%) fraction of the pulses

LAPPD 25: Differential Timing / Parallel Position



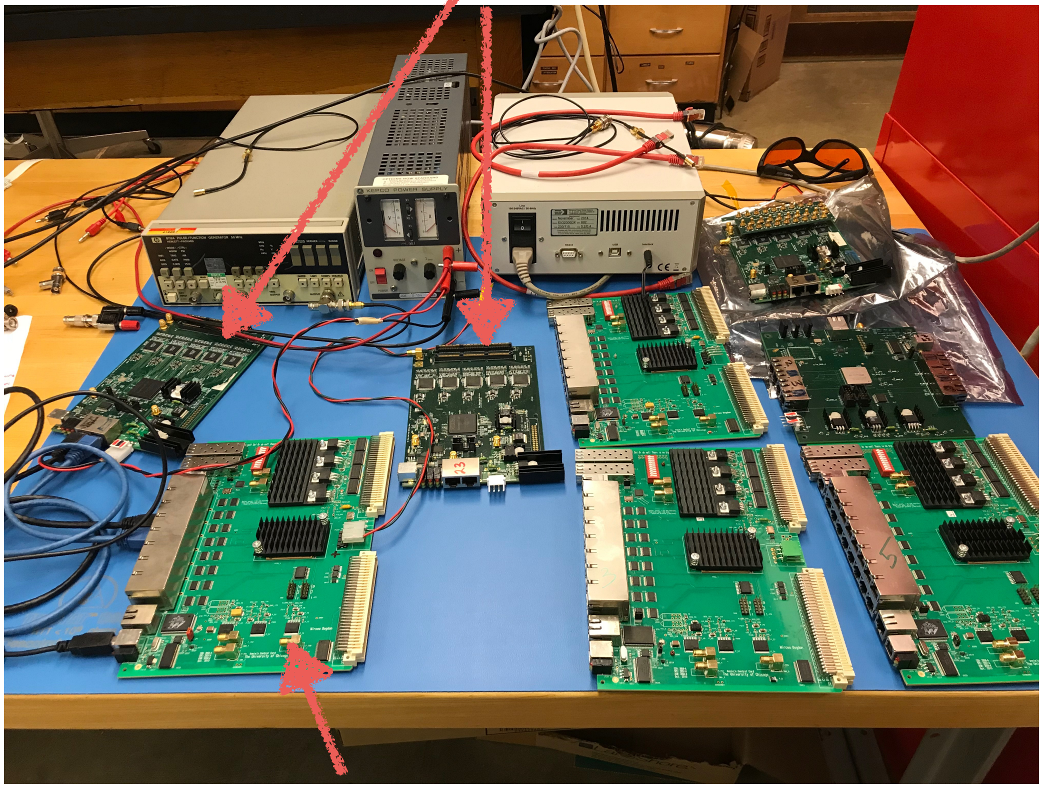




- Position in the direction parallel to the striplines can be determined from the time difference between the two ends
- 25 picosecond single-PE differential time resolution corresponds to 4.35 mm resolution in the parallel direction

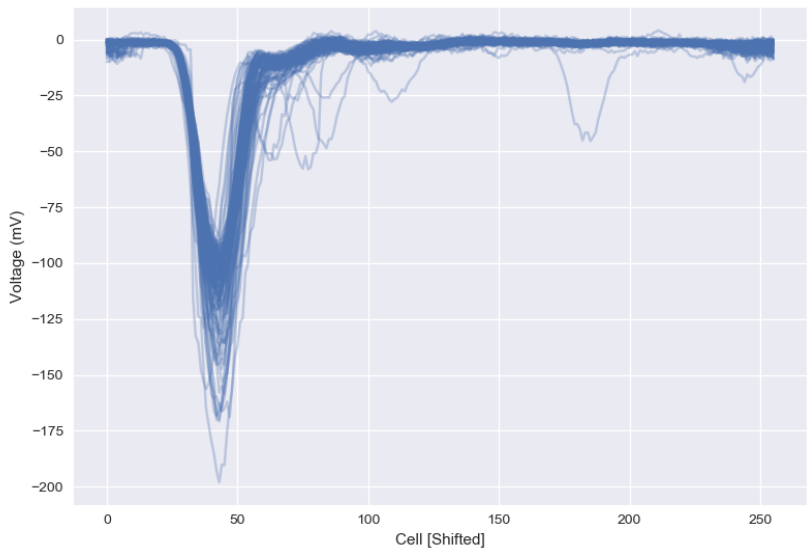
Application Readiness (DAQ)*

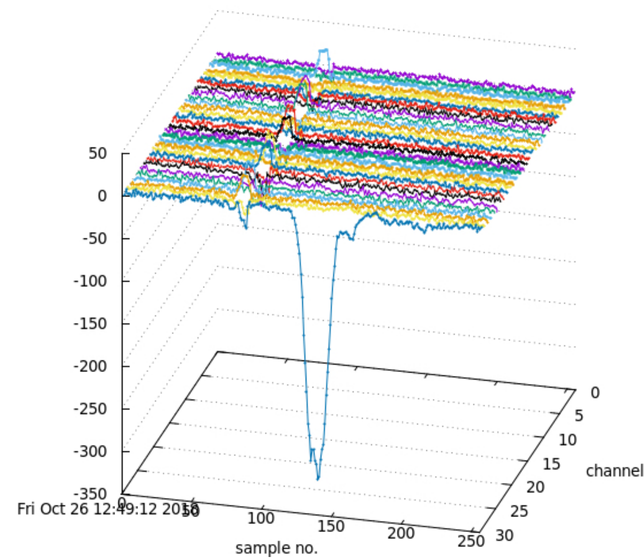
Two 30 channel ACDC cards



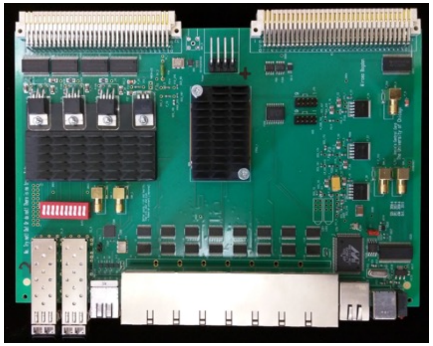
ANNE Central Card (ACC)

Application Readiness (software/integration)



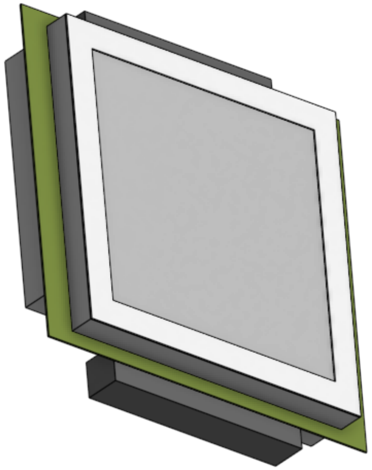


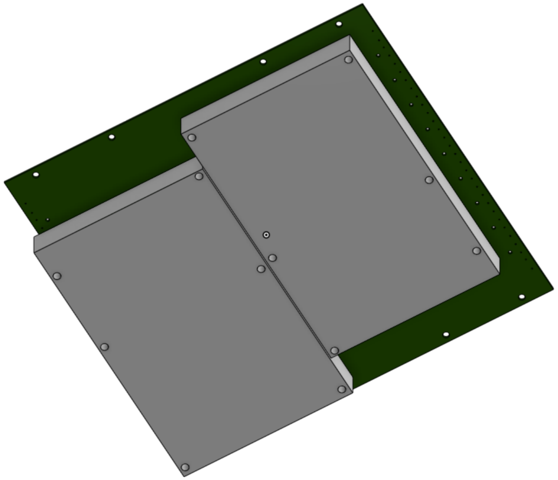
Application Readiness (electronics)

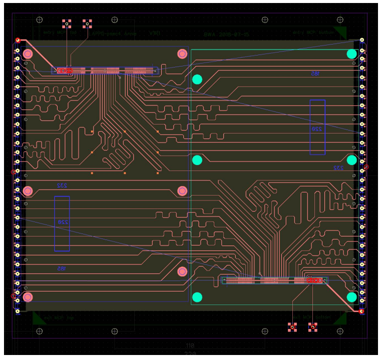


Current Design

- Readout close to the detector
- Two *ACDC* mezzanine waveform digitizers attach to the *pickup board*
- New *ANNIE Central Cards (ACC)*, provide clock and synchronization
- *LV-HV* board provides power and slow controls







Next Evolutionary Step

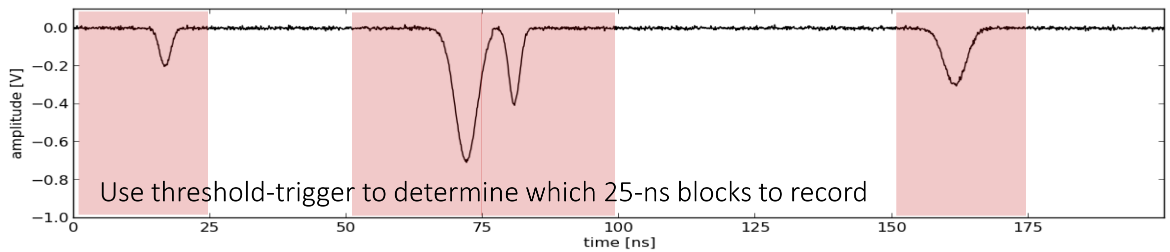
- Digitization of 60 channels on a single integrated ACDC cards
- PSEC-4a with 8x's buffer (200 nsec) in a multi-hit buffering scheme for continuous readout
- Further simplified network topology, possible implementation of white rabbit

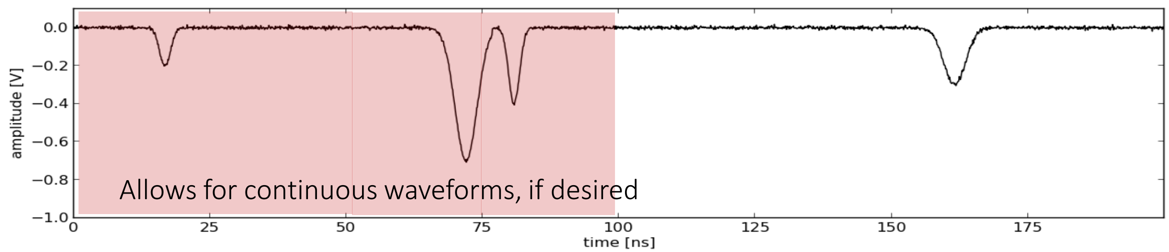
Application Readiness (electronics)

PSEC4a – multi-hit buffering

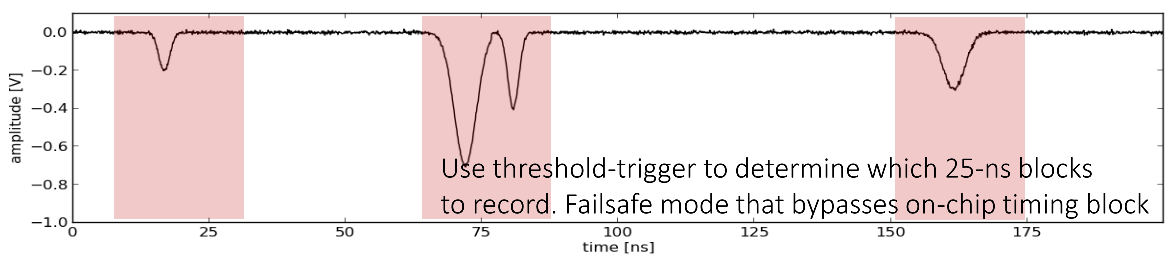
- How many buffers? Considering 2 options: 1024 or 2048 samples per channel
  - Layout space ($) / number of ADC's trade-off vs. typical event occupancy/timing characteristics
- Operation modes:

Clocked addressing: blocks around 40 MHz sample clock. Blocks time-stamped on ASIC





'Trigger-and-transfer': asynchronous blocks, 25 ns wide. (PSEC4-like operation, w/ multi-buffer)

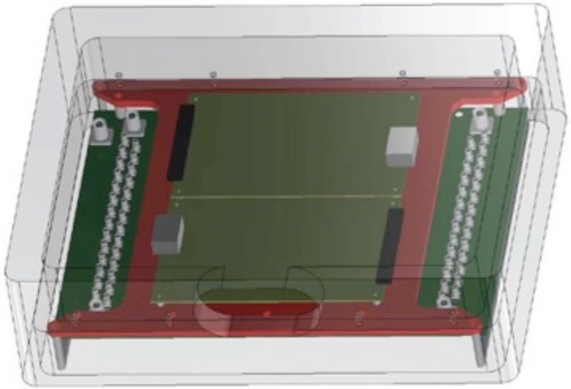


14

Application Readiness (waterproofing)

Near Term

- Water-proof housing to consist of PVC frame mounted on steel backplane
- Window not optically coupled to the LAPPD surface
- High voltage provided externally
- Communication through twisted pair connections

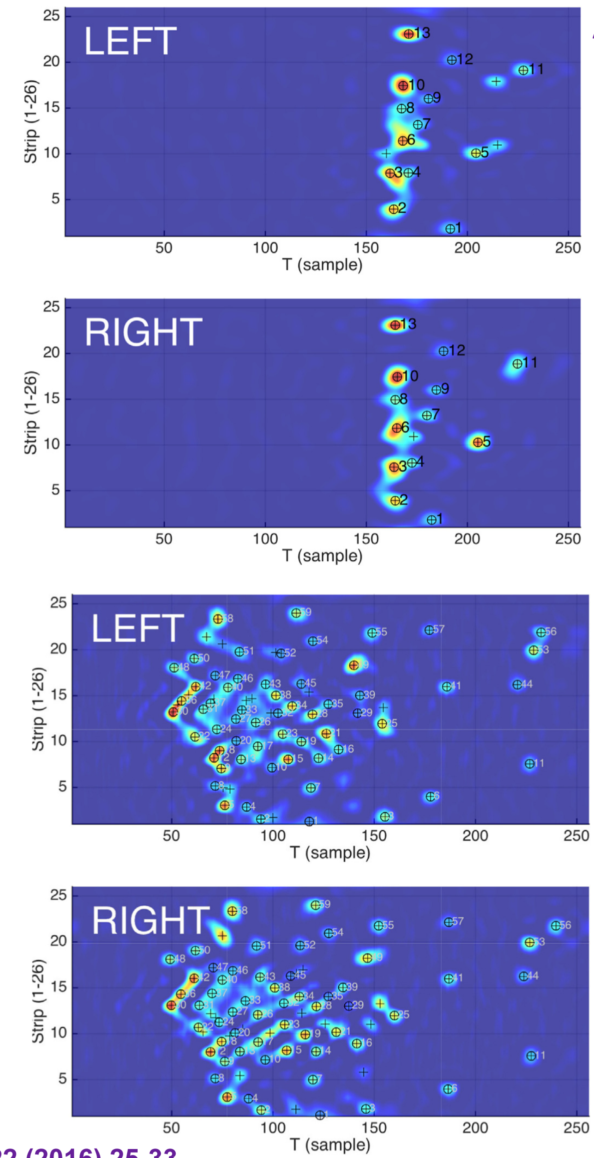


Next Evolutionary Step

- Single fiber for data transfer
- HV made internal to the housing
- Better strategy for optical coupling

Application Readiness (simulations/reconstruction)

- Deconvolving the two-sided readout of the LAPPD is not trivial, especially in high light environments
- It essentially adds an additional step between signals and “hits”
- We are working on a feature extraction approach that simultaneously fits pulses to the 2D time-vs-voltage distribution for both sides of the readout
- D. Grzan (ISU/Davis) wrote the original 1D version
- ANNIE MC in ToolAnalysis now accurately models the LAPPD readout
- Feature extraction will soon be added as a tool in the reconstruction chain



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*Multiple-photon disambiguation on stripline-anode Micro-Channel Plates: Nim A 822 (2016) 25-33**

ANNIE Physics

To turn neutrino physics into a precision science we need to understand the complex multi-scale physics of neutrino-nucleus interactions

- Dom
  long
- Pos
  base
- We
  mea

> " ...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."**
>
> Neutrino Scattering Theory and Experiment Collaboration
> NuSTEC white paper

ANNIE is a final-state X + Nn program to complement X + Np measurements in LAr

The presence, multiplicity and absence of neutrons is **also** a strong handle for signal-background separation in a number of physics analyses!