



ANNIE

Status and R&D Opportunities of Theia

Matt Wetstein (ISU) on behalf of the ANNIE collaboration

November 11, 2019



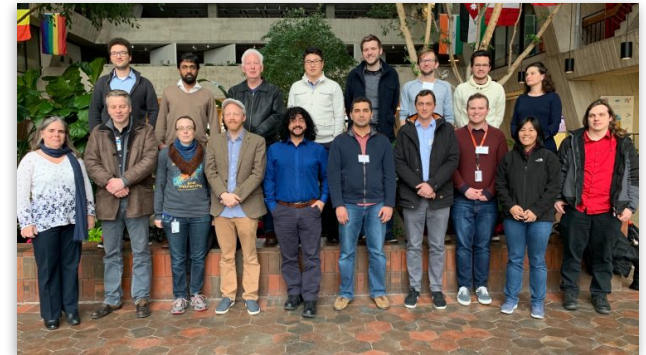
The Accelerator Neutrino Neutron Interaction Experiment



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

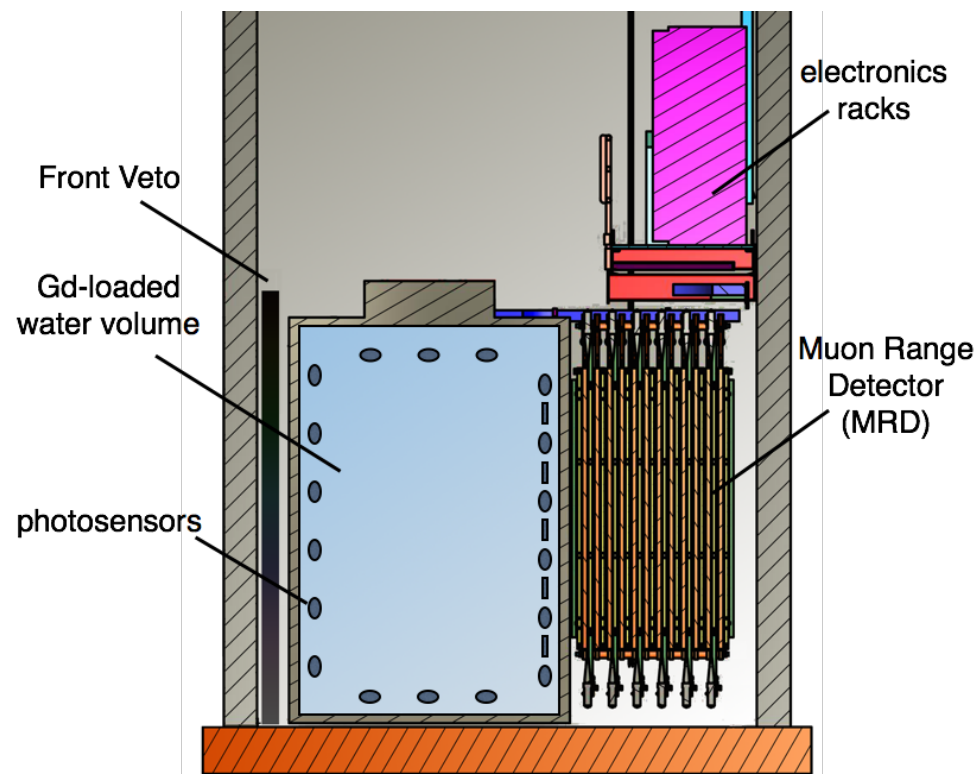


The detector is built! And operational!
Commissioning and calibration is underway.
Current timeline has us taking physics quality data by Dec 8.

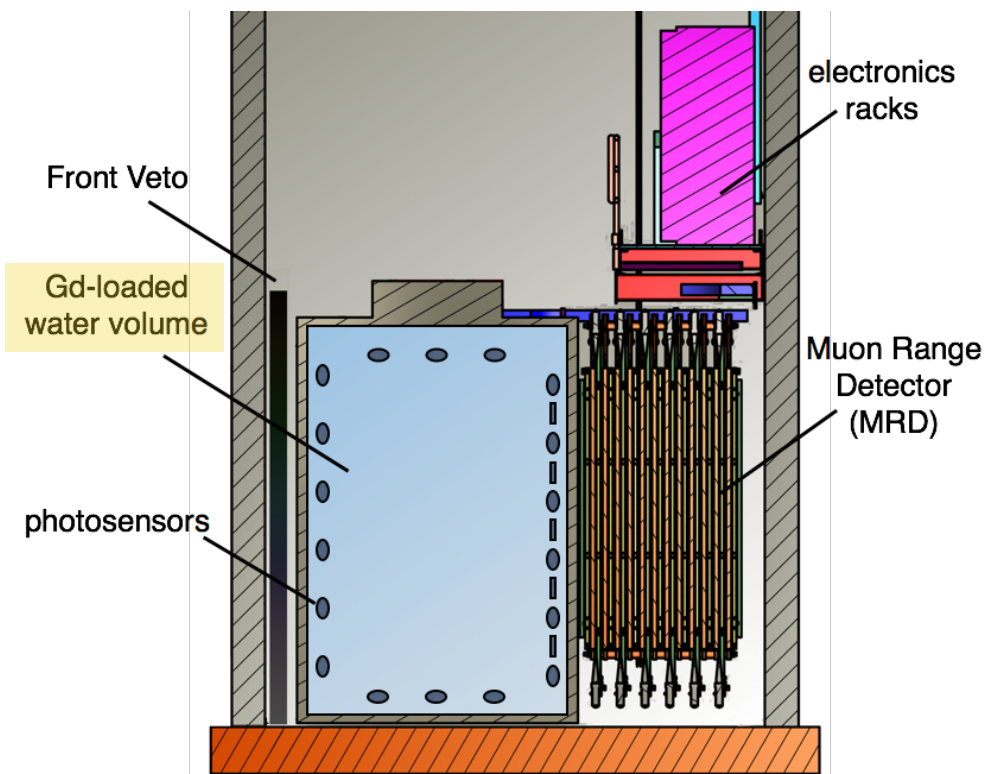
Experiment Status



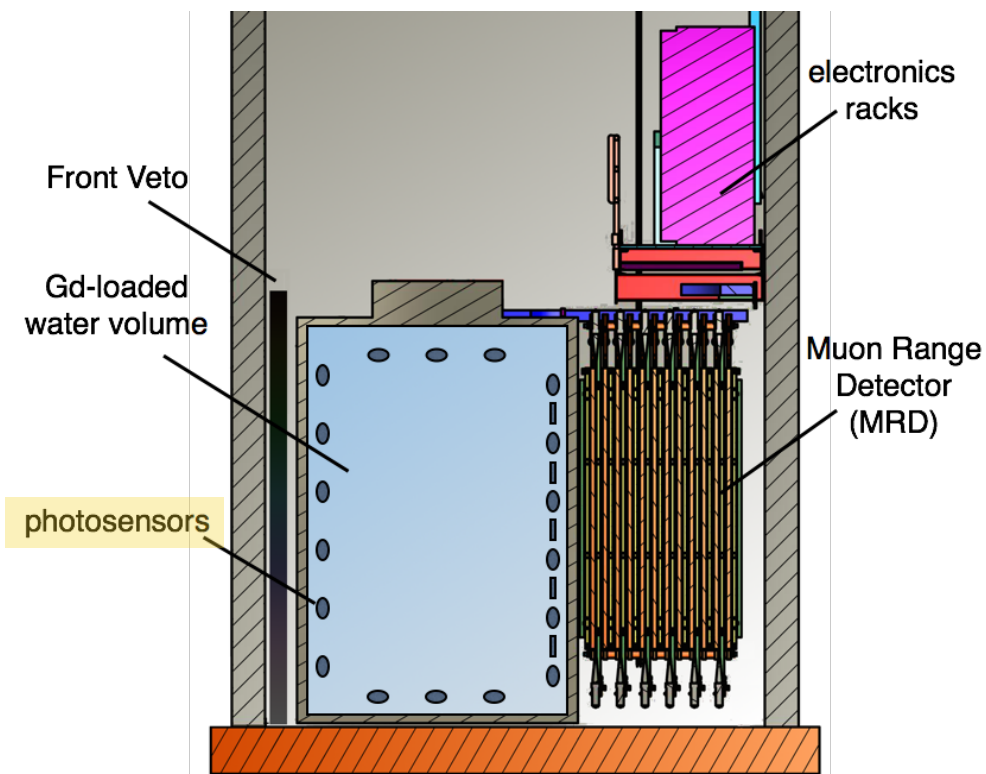
The Detector



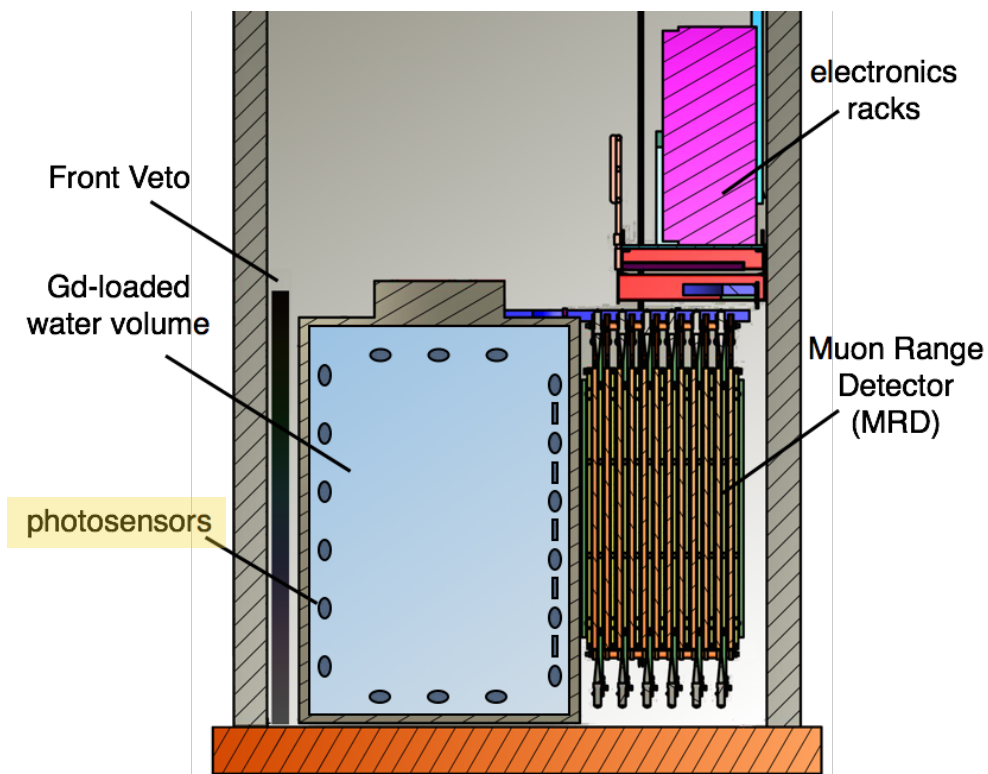
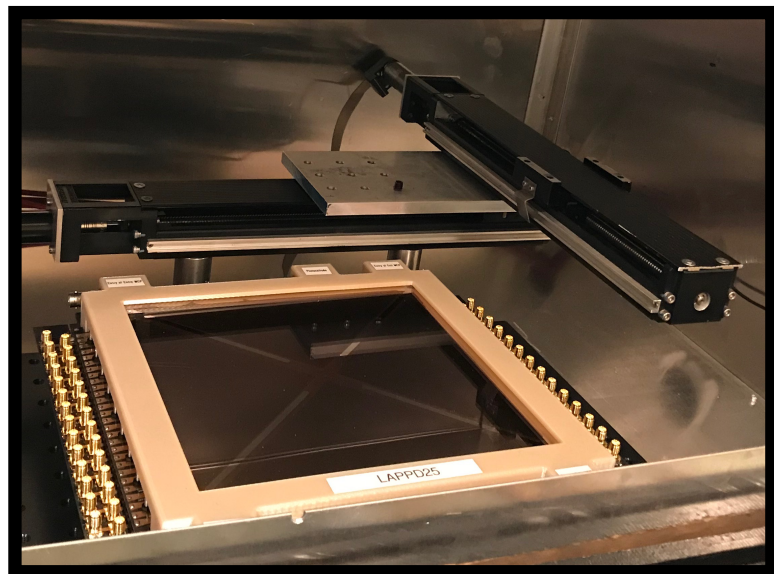
The Detector: Gd-loaded water volume



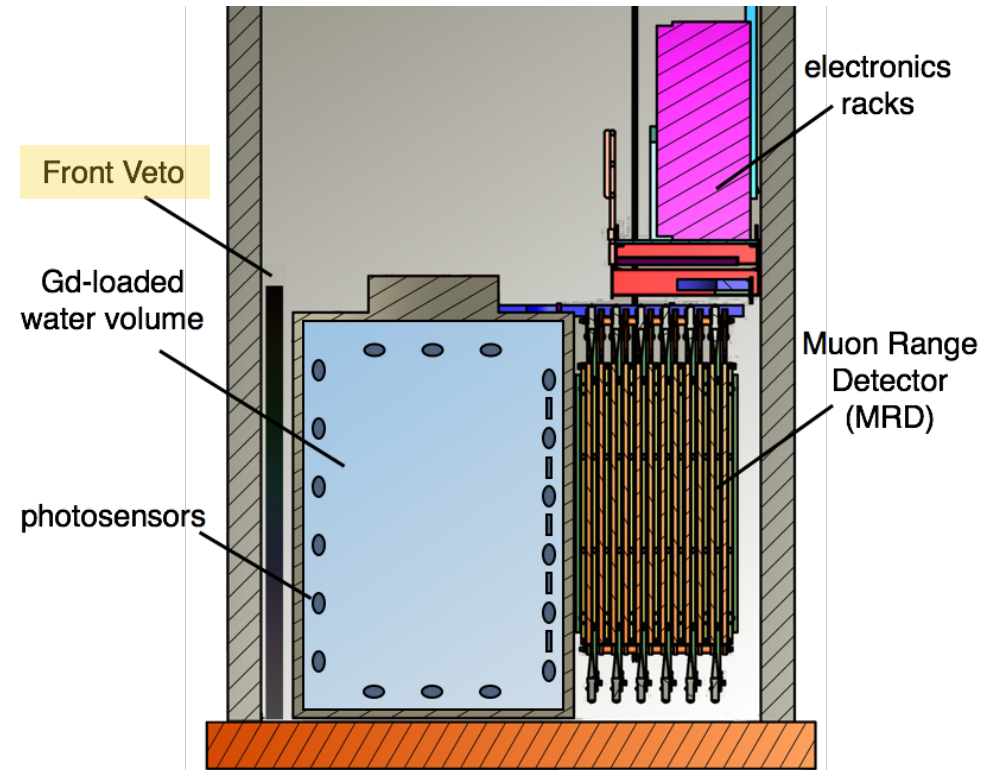
The Detector: PMTs



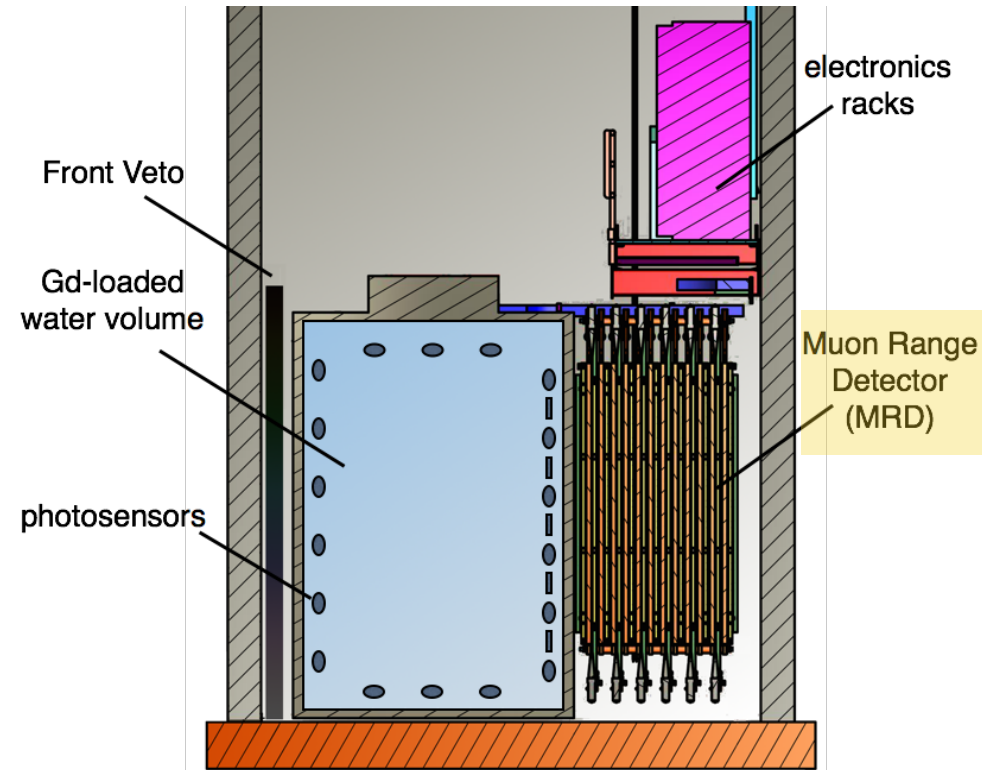
The Detector: LAPPDs



The Detector: Front Muon Veto (FMV)



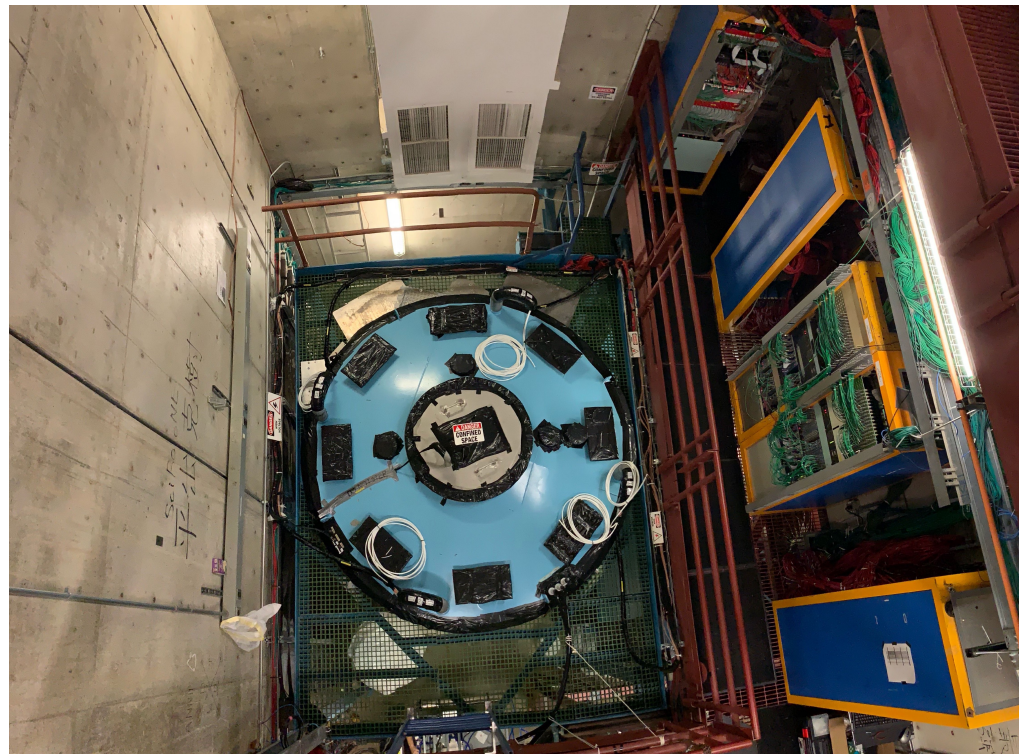
The Detector: Muon Range Detector (MRD)





Experimental Status and Schedule

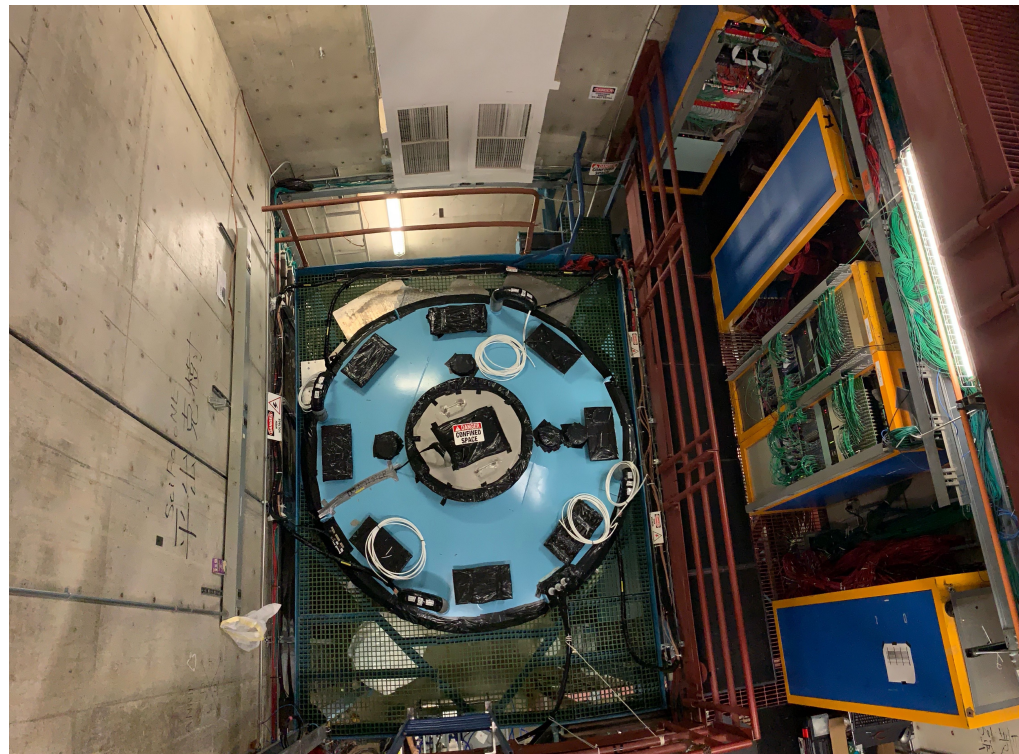
- The ANNIE detector was installed and filled at the end of this summer
- Commissioning and systems integration is wrapping up
- The Booster Neutrino Beam came on ~2 weeks ago
- We're on track for physics quality data by the end of this month
- LAPPDs will going in by the beginning of January
- We will collect data this year until end of beam (~July)
- We also plan on running in water + Gd mode for the next beam year (FY21)
- Phase III, wbLS mode could happen in FY22





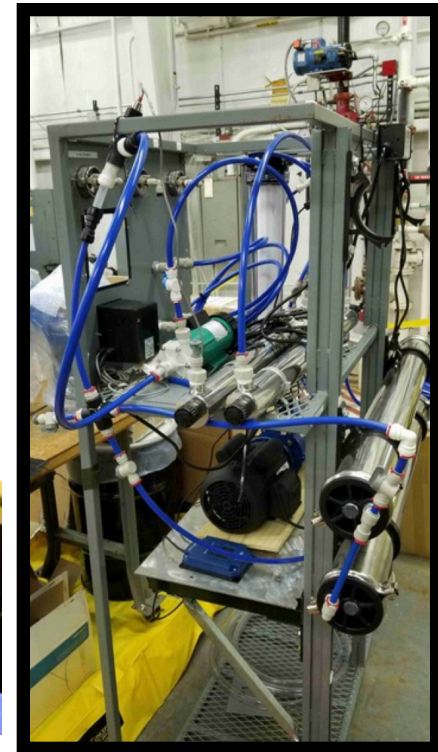
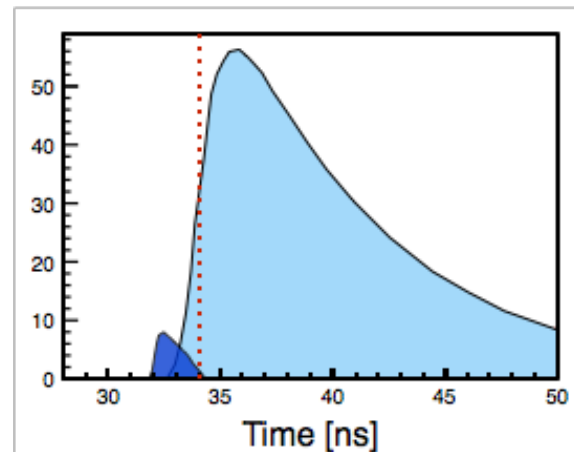
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- LAPPDs will going in by the beginning of January
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- **Deployment of a ton-scale wbLS vessel is possible this summer!**
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- Phase III, wbLS mode could happen in FY22





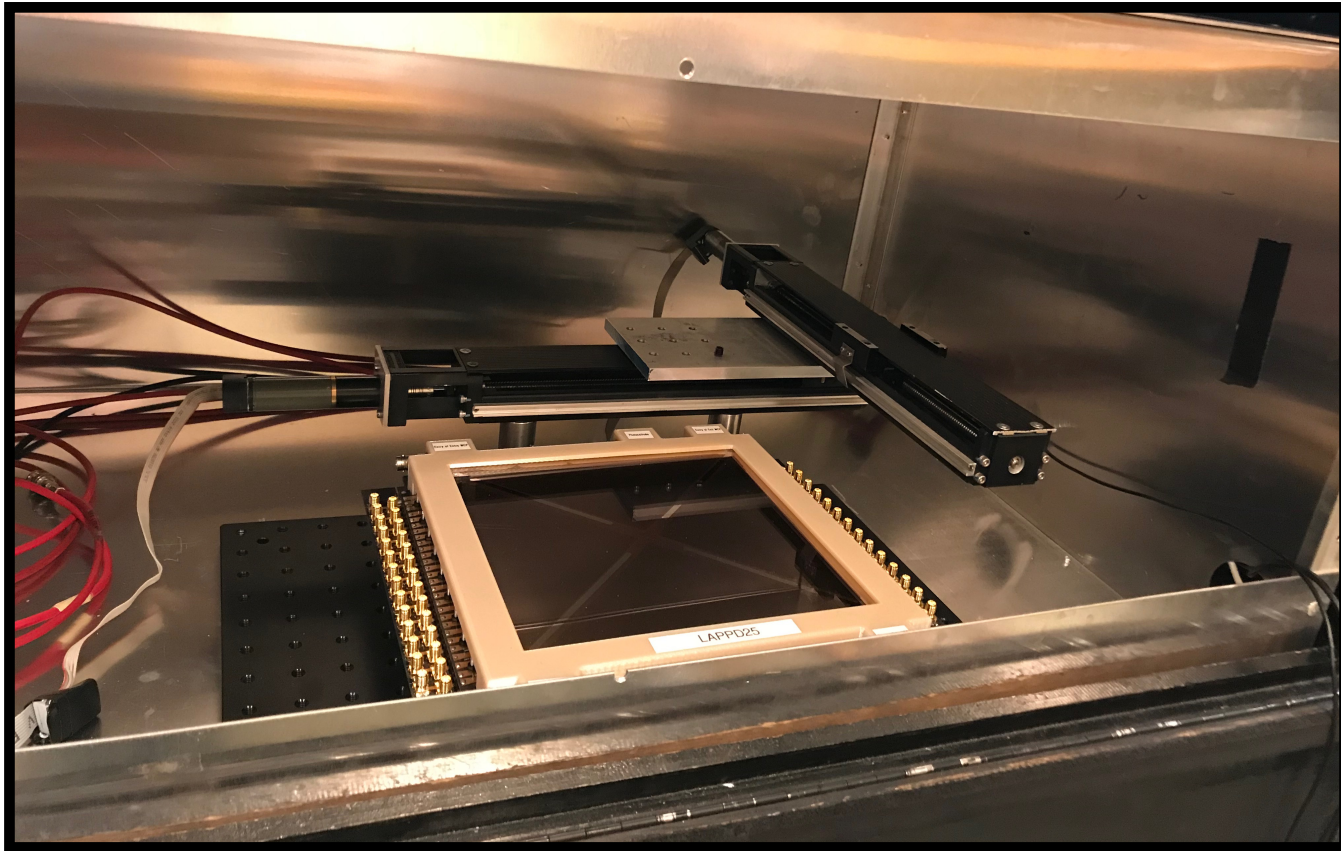
Tech R&D



LAPPD Testing:



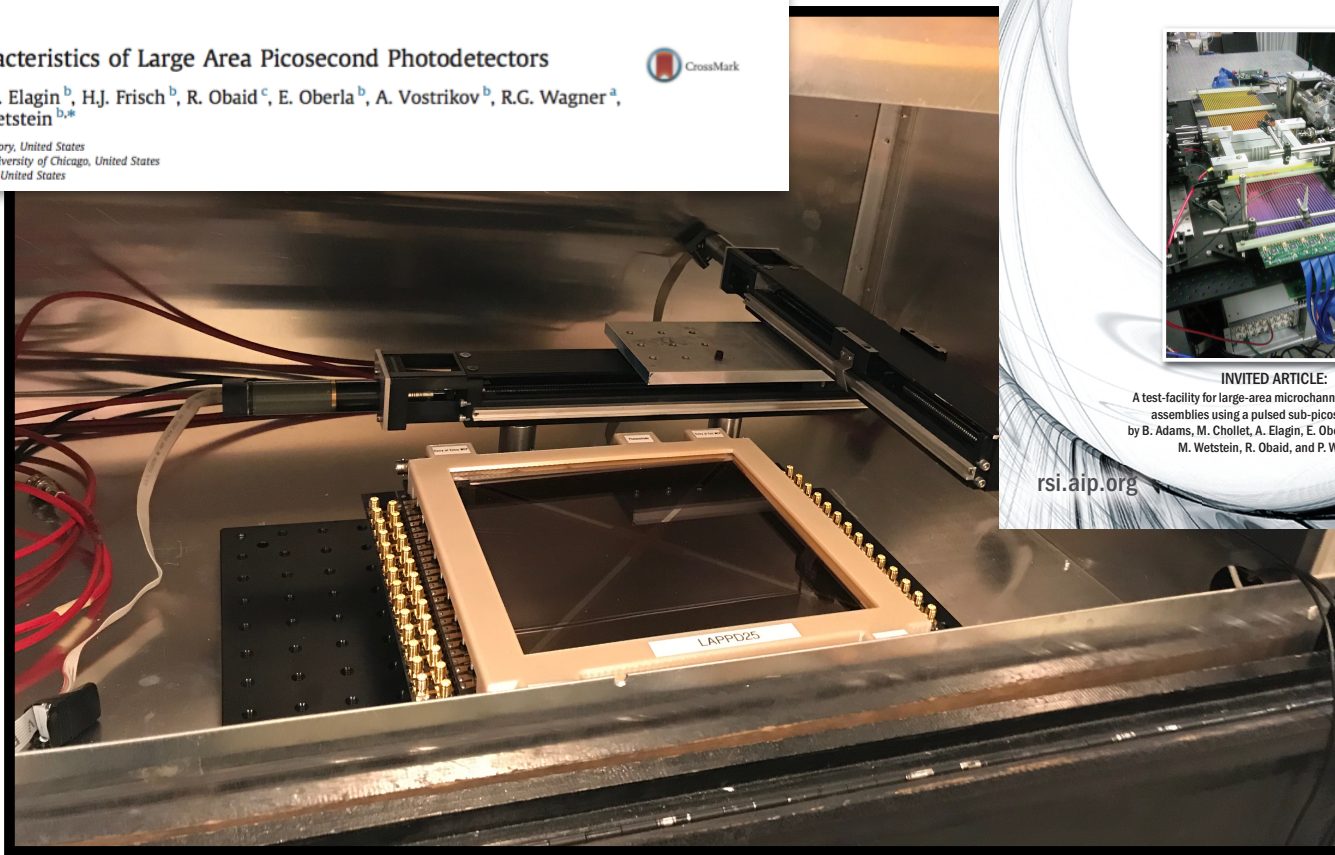
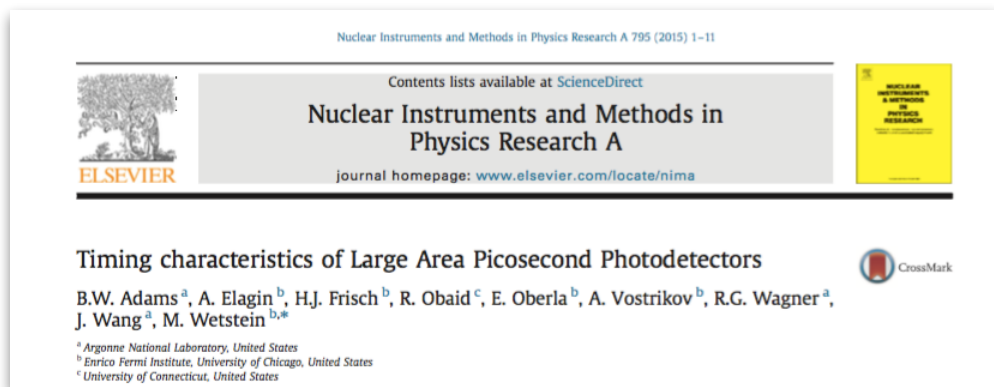
- Original setup used a PiLAs laser and Tektronix scope



LAPPD Testing:



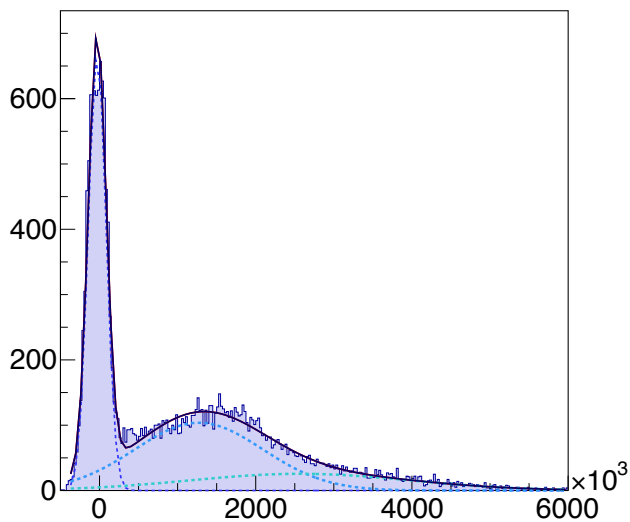
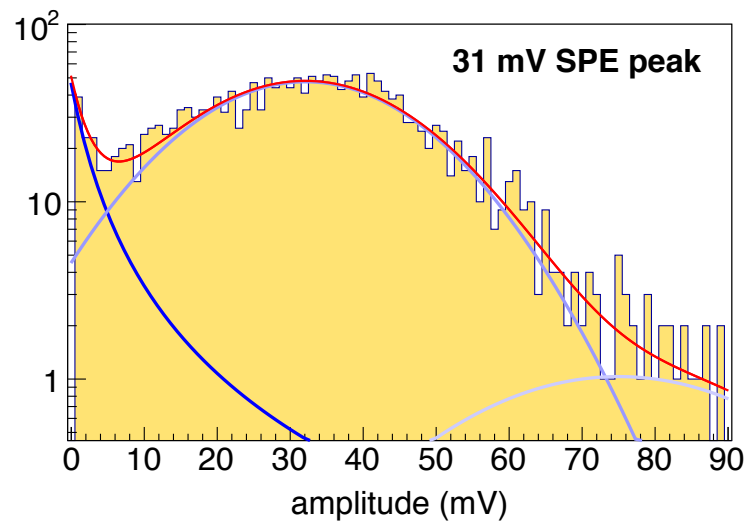
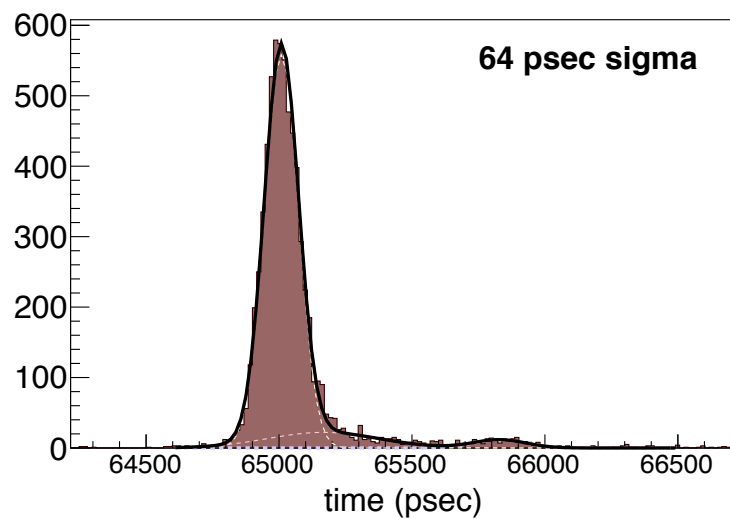
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LAPPD Testing:



LAPPD 25

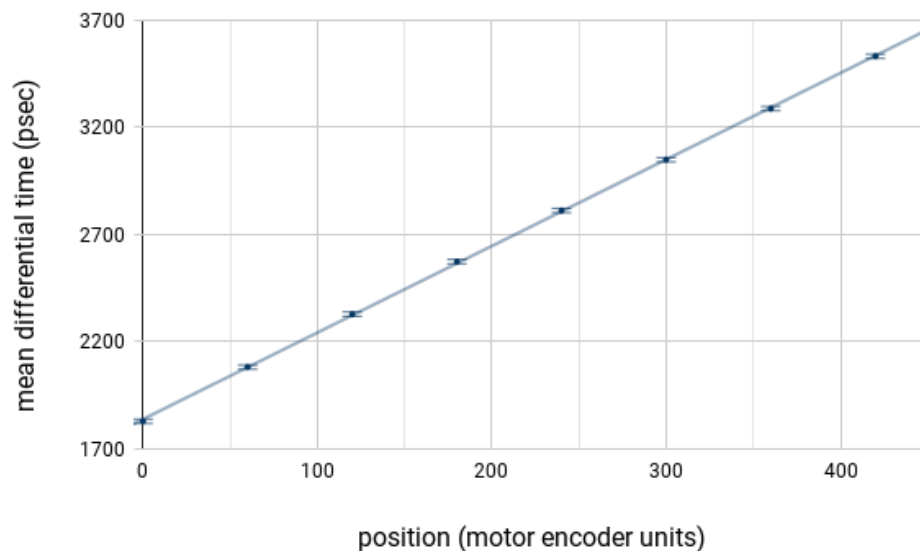
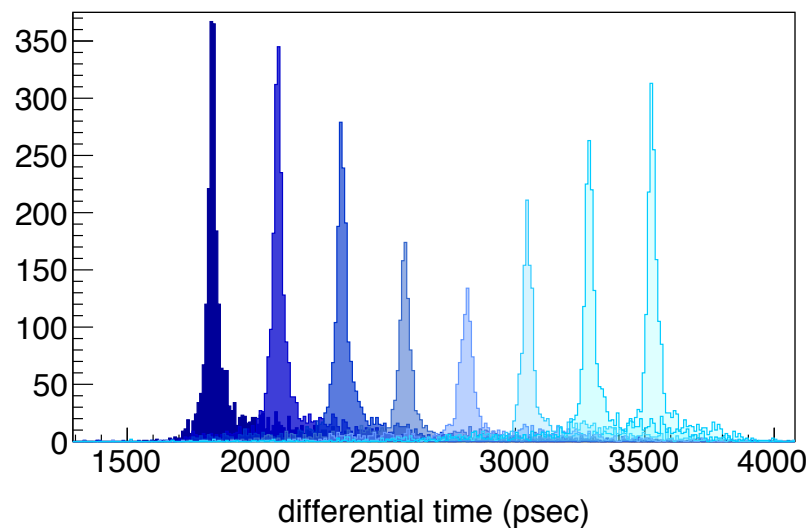


LAPPD Testing:

LAPPD 25



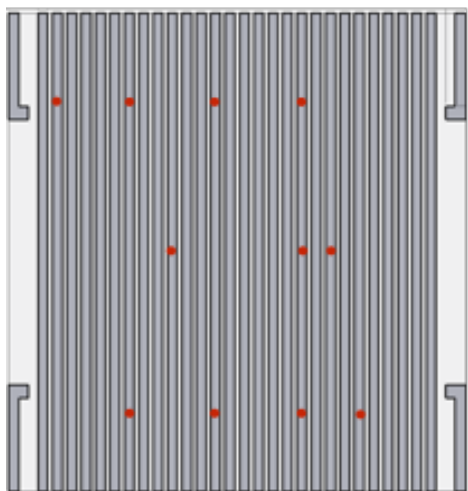
- Position in the parallel direction is set by the difference in arrival time between the two sides of the stripline anodes
- We observe a linear relationship consistent with few mm spatial resolutions



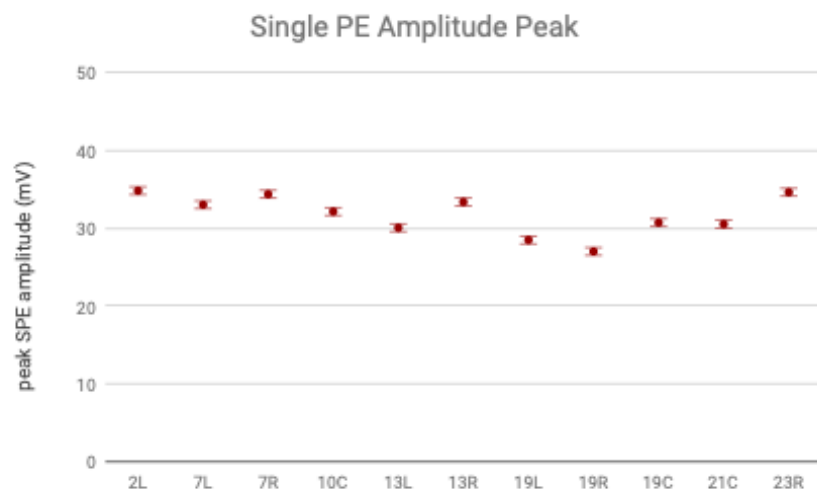
LAPPD Testing:



LAPPD 25



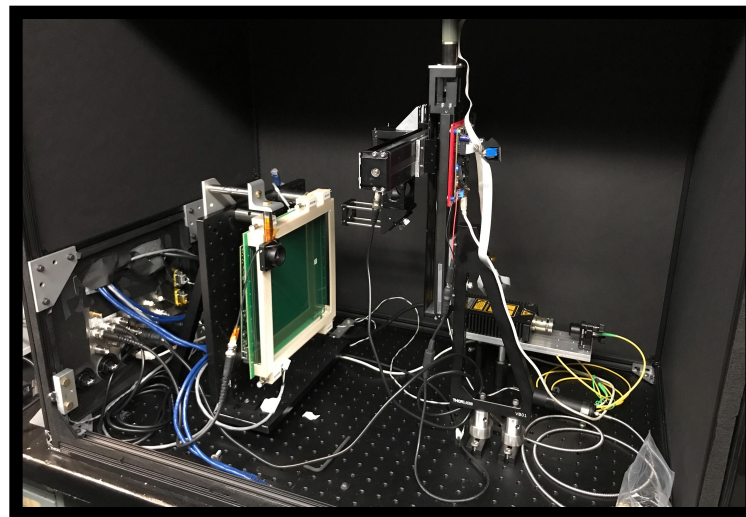
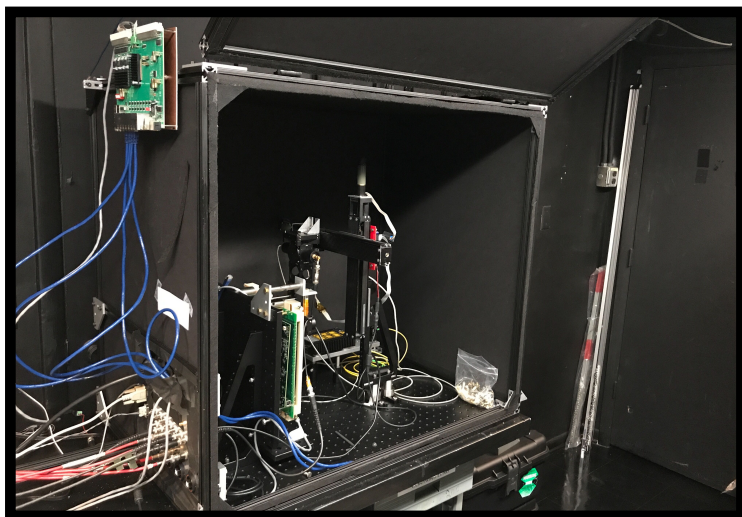
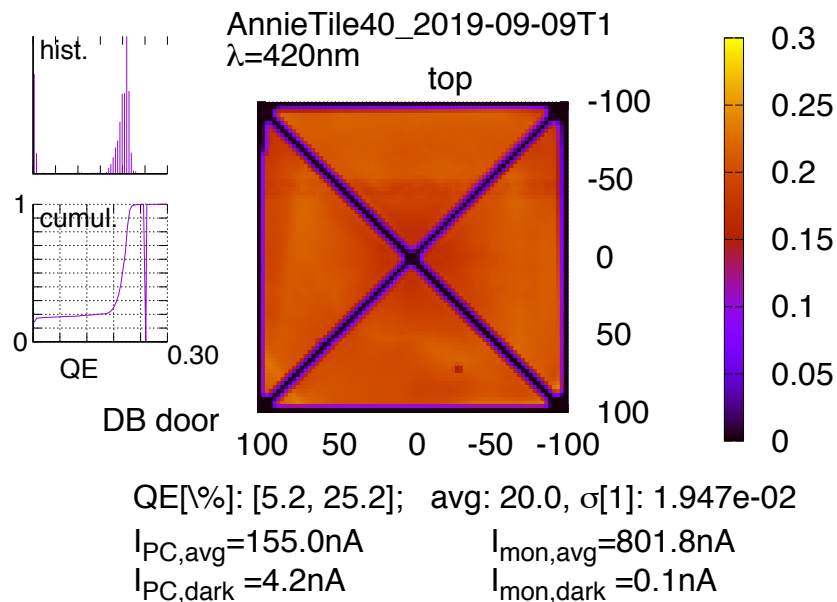
- We explored the spatial and time resolutions of our LAPPDs
- In these plots we show the single PE amplitude and time resolution for different positions with respect to the LAPPD anode



LAPPD Testing:



- The ANNIE/ISU LAPPD characterization facility has been moved to Fermilab and upgraded
- Now capable of QE measurement
- Full readout with PSEC electronics
- Coming soon!

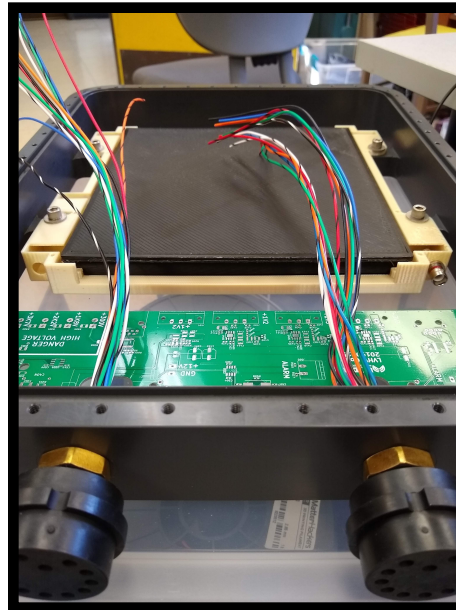
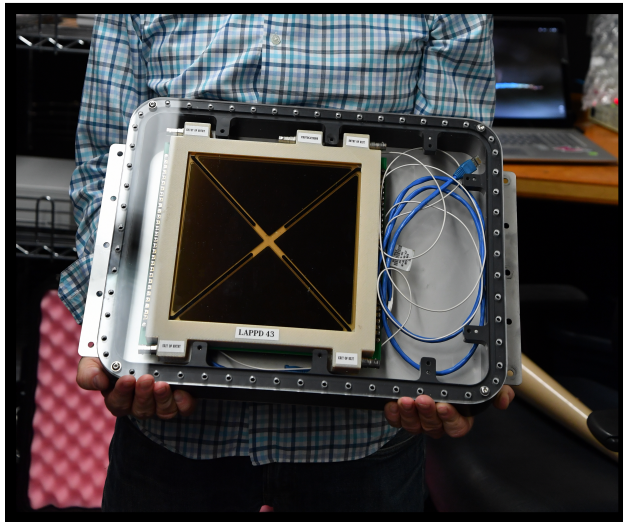




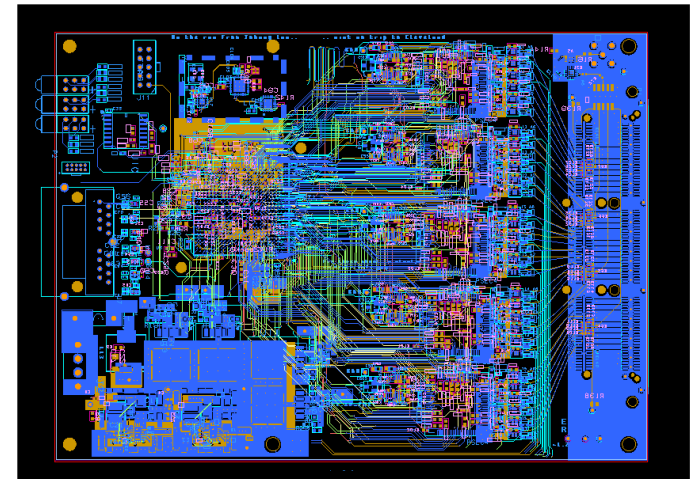
LAPPD Systems Readiness:

- A major component of the ANNIE effort has been directed at making LAPPDs application ready
- Development of the PSEC electronics (firmware improvements)
- Slow control board (LVHV) is built and in testing
- Full integration work is ongoing
- There is a new design for the ACDC card (rev C)
- In FY21 we would like to switch to the revC and improve optical coupling to the window of the waterproof housing

waterproof housing

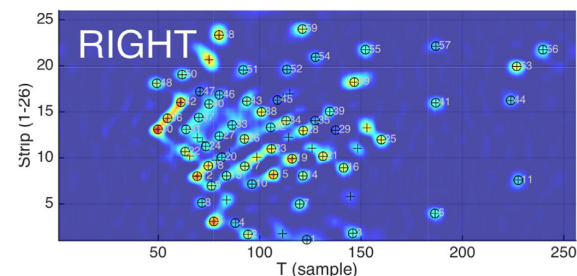
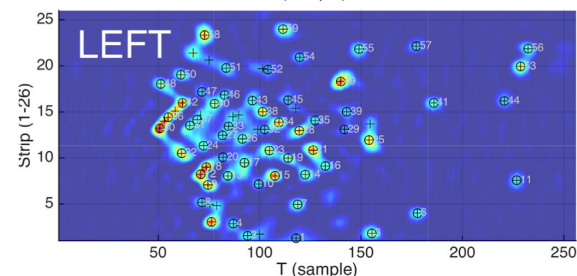
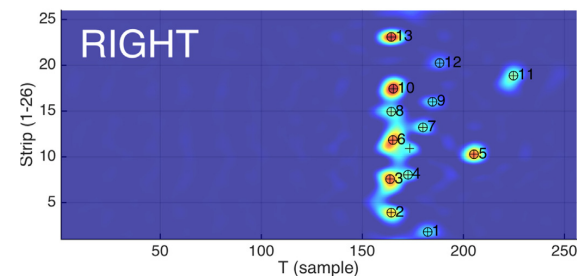
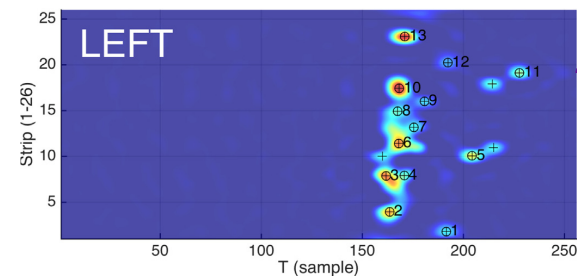


ACDC rev C



LAPPD Data Analysis:

- 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

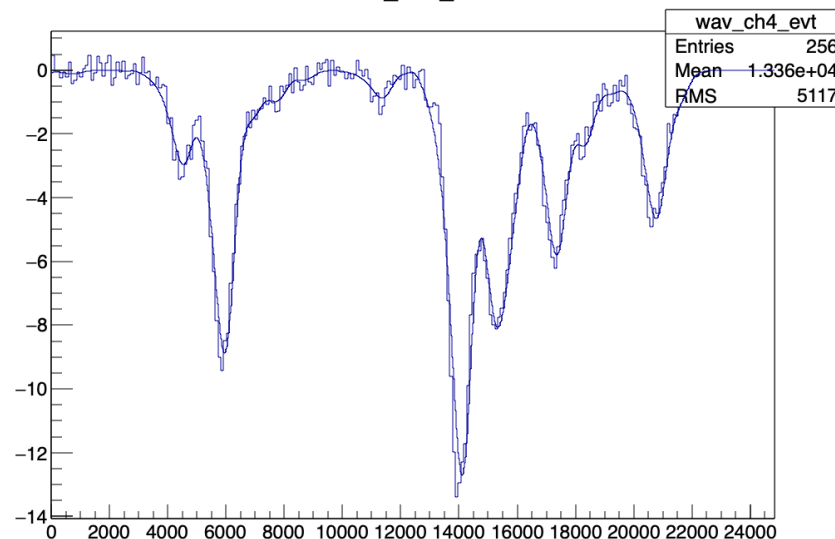


***Multiple-photon disambiguation on stripline-anode Micro-Channel Plates: Nim A 822 (2016) 25-33**

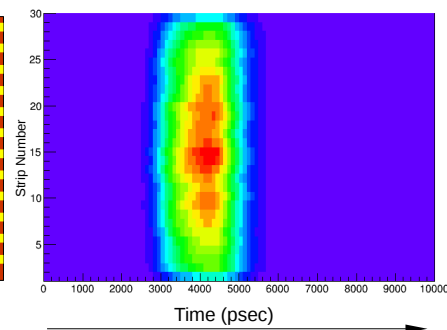
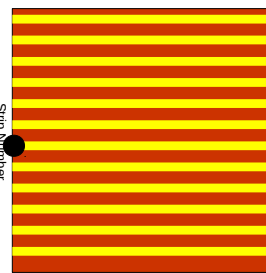
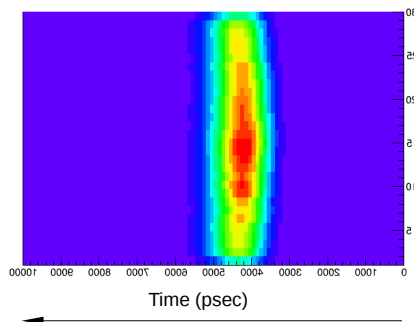
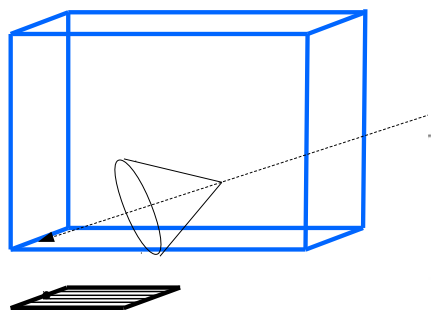
LAPPD Data Analysis:



- Evan Angelico has implemented D Grzan's NNLS algorithm into Tool Analysis
- It currently works for single sided readout
- Next step is to deconvolve both sides of the trace simultaneously
- ...and add in two spatial dimensions



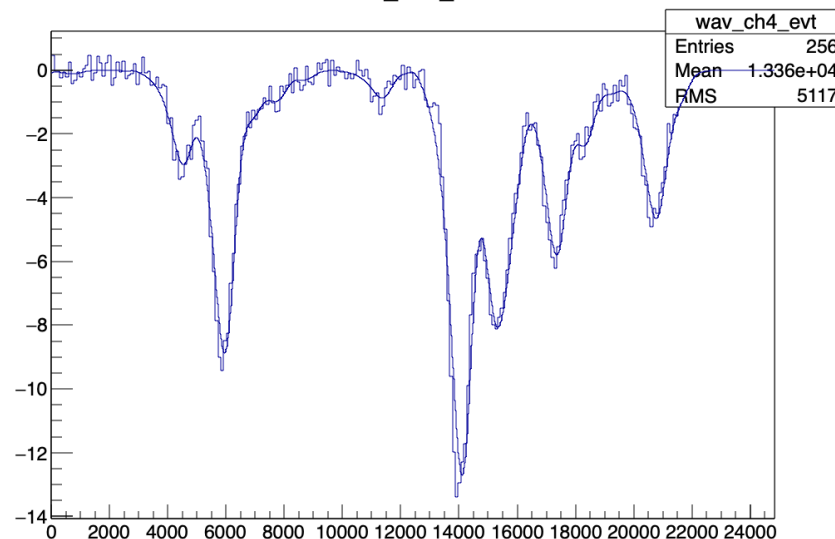
30° - Parallel Orientation



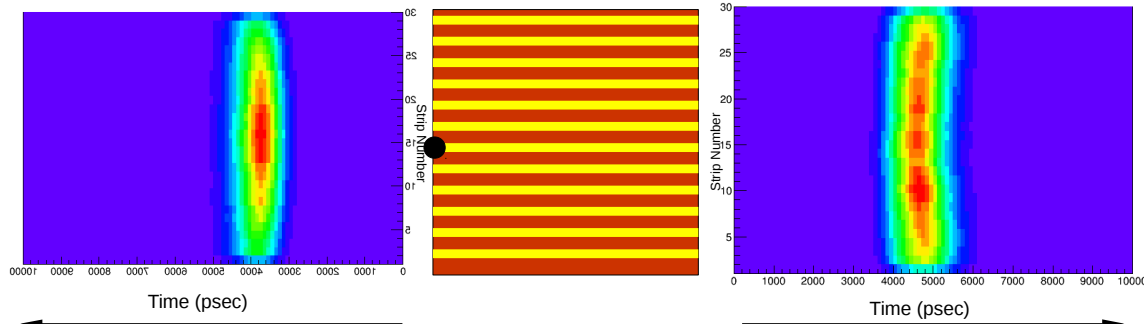
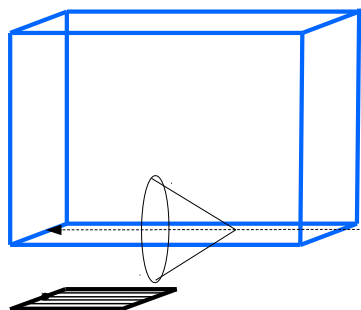
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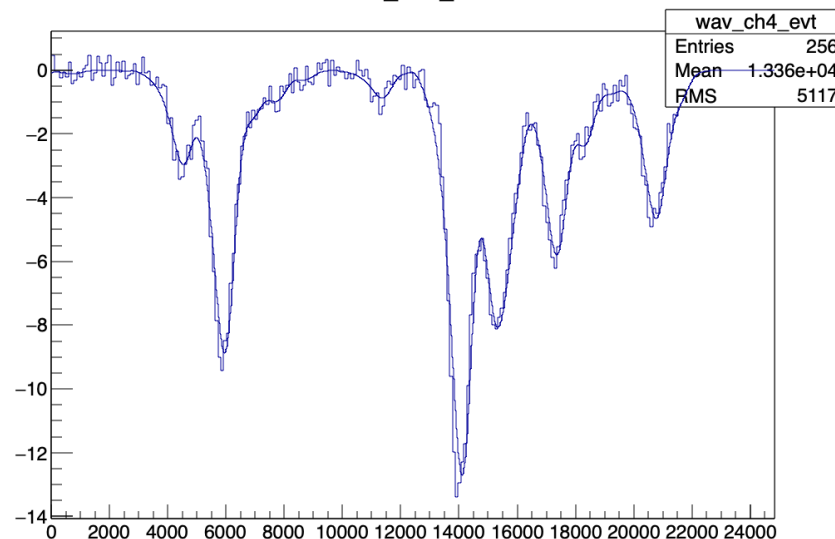
0° - Parallel Orientation



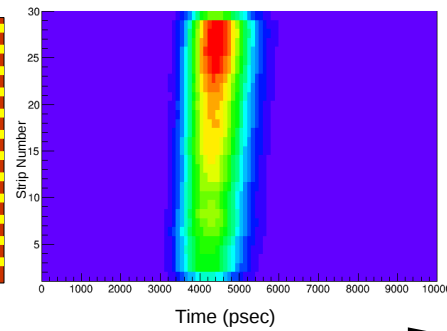
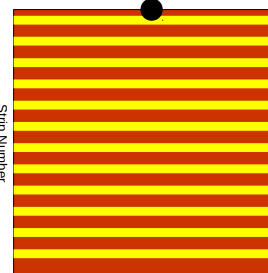
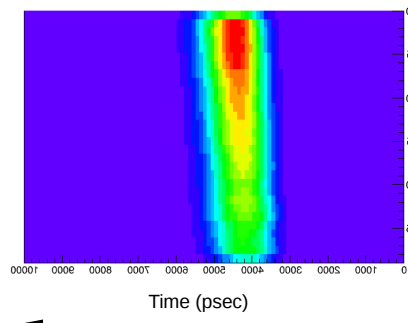
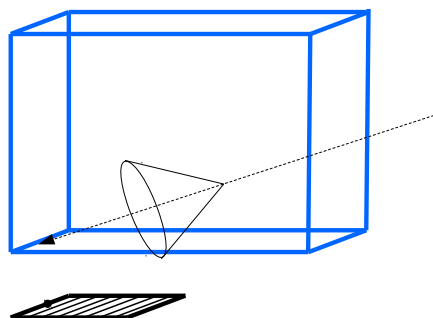
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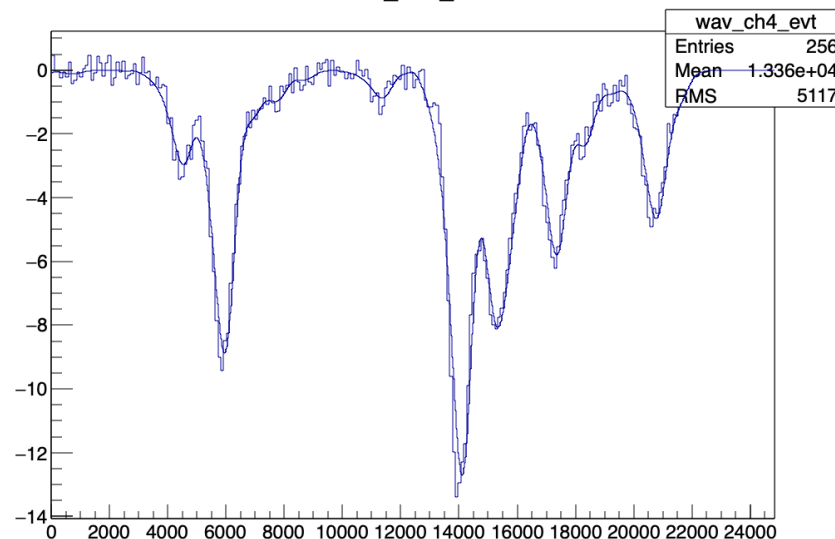
30° - Perpendicular Orientation



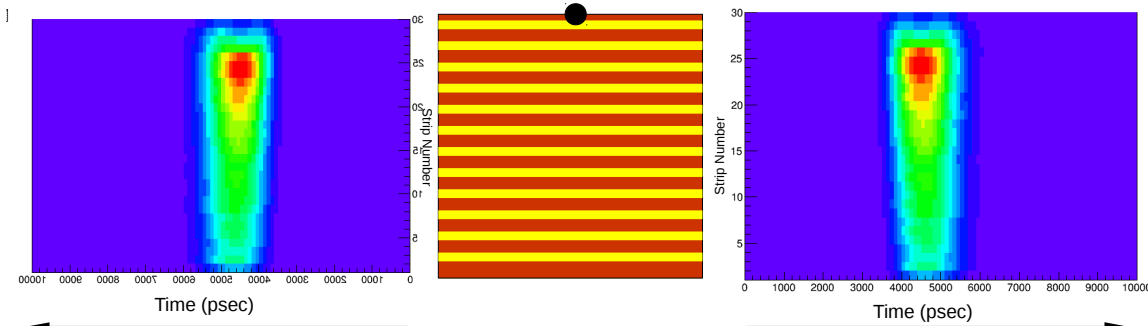
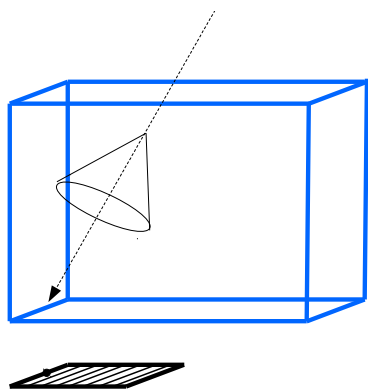
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60° - Perpendicular Orientation



Water System R&D



- 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



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ANNIE water skid



1% loading last month, 10% loading this week!, full loading soon

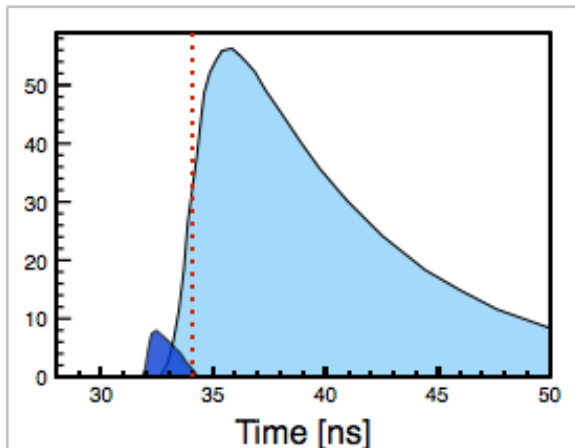


Future ANNIE Physics Opportunities

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

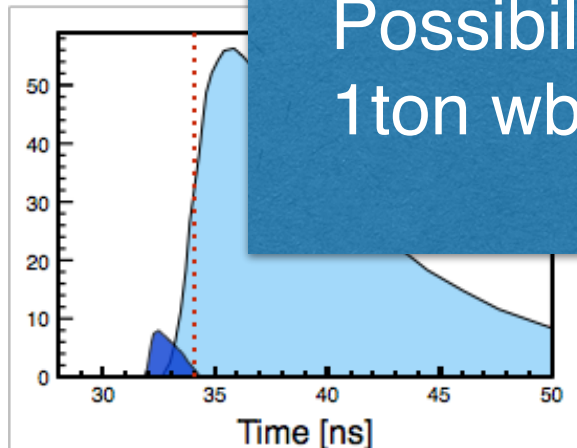


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Possibility of adding a small, 1ton wbLS volume this summer!

Scintillator (wbLS)

Scintillator

- 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



Imaging Optics



- 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)

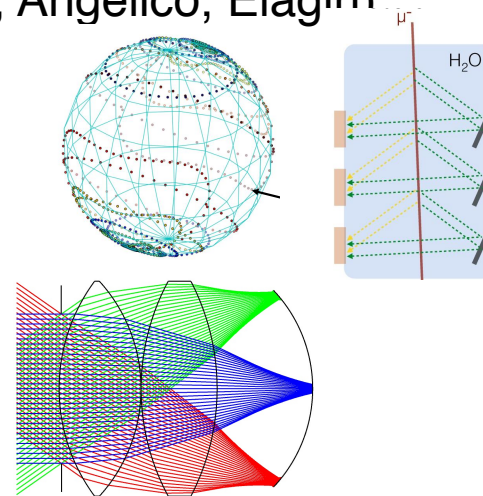
Dichroicons (U Penn)

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

<https://arxiv.org/abs/1510.00947>

Plenoptic imaging (Dalmasson et al)

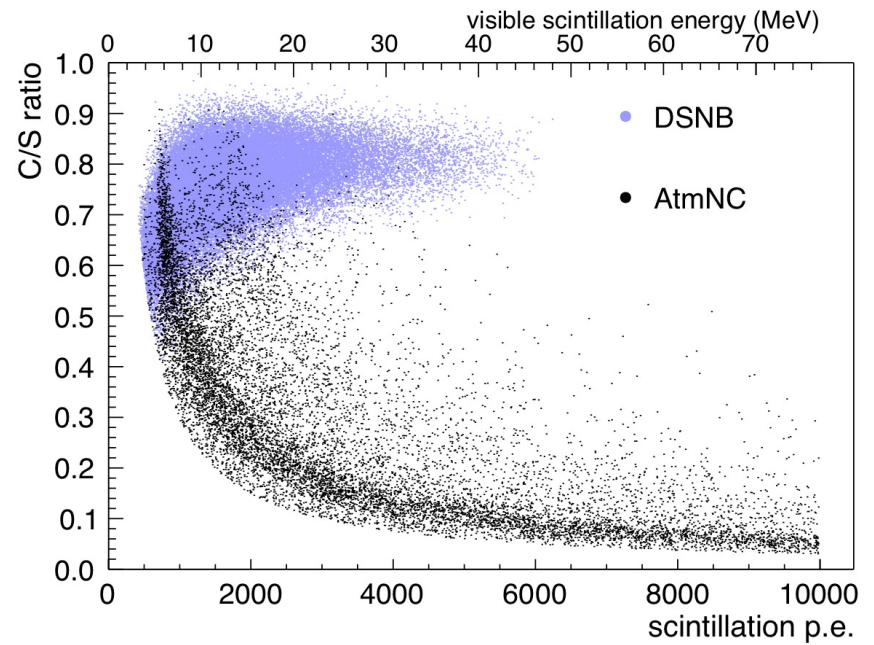
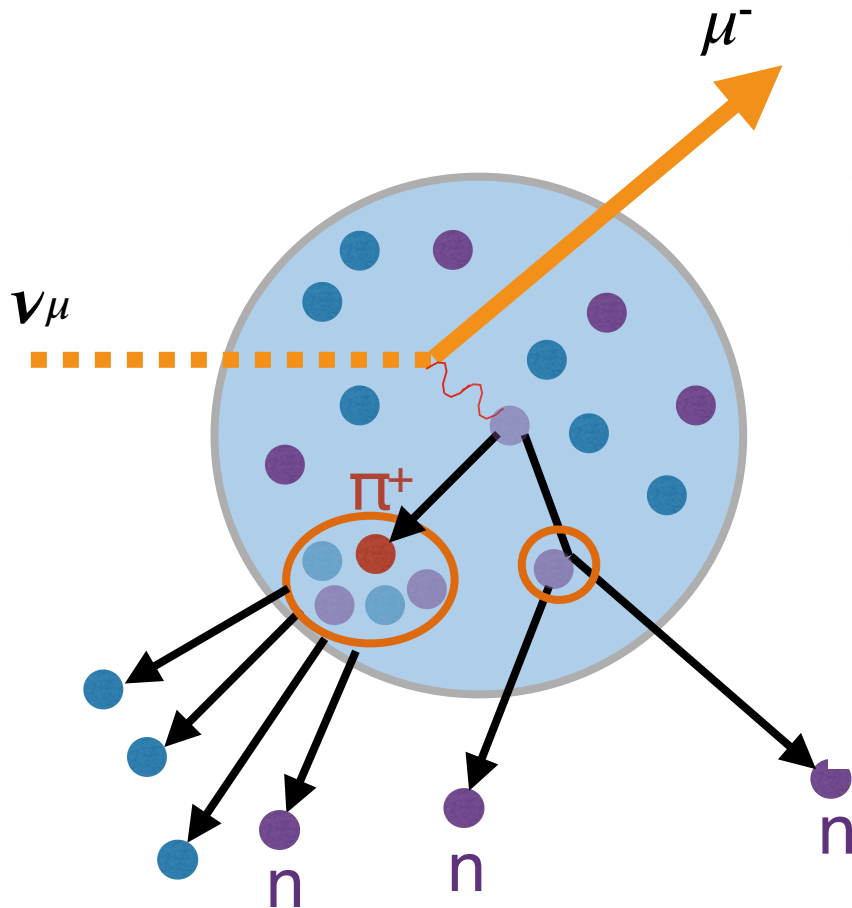
<https://arxiv.org/abs/1711.09851>



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



Physics R&D



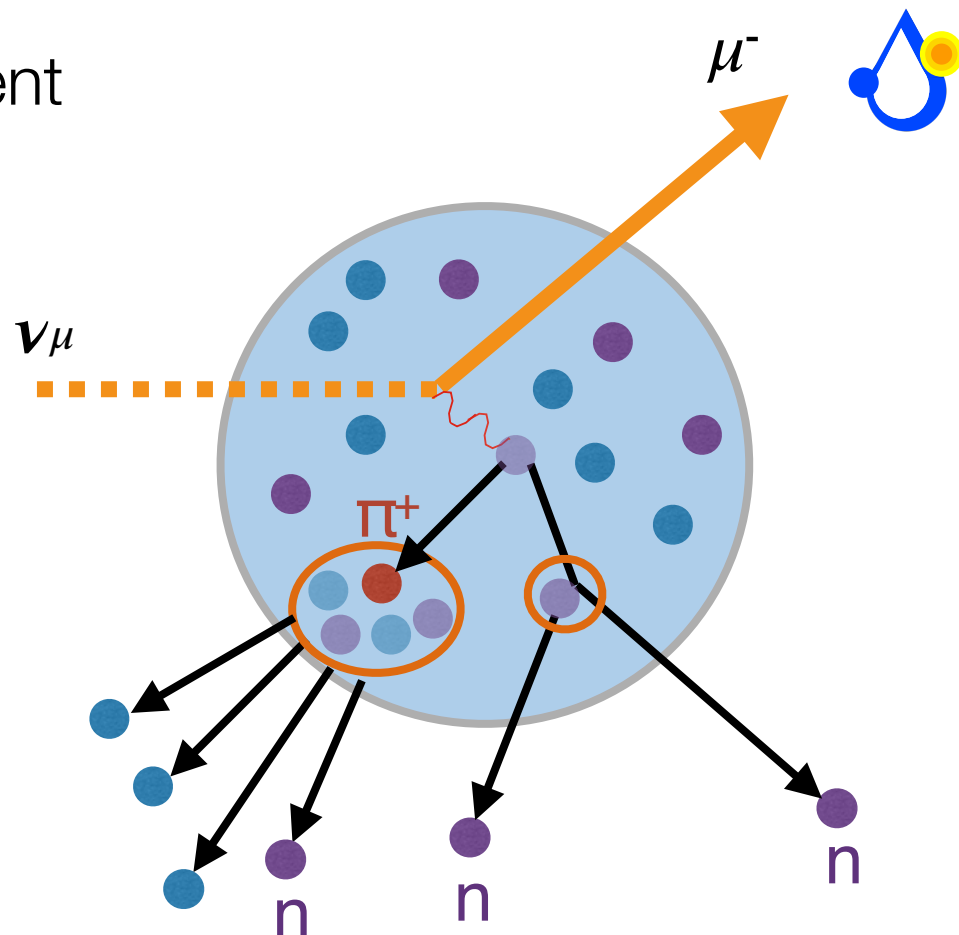
The Main Physics Measurement

“Neutrino-nuclear billiards”

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

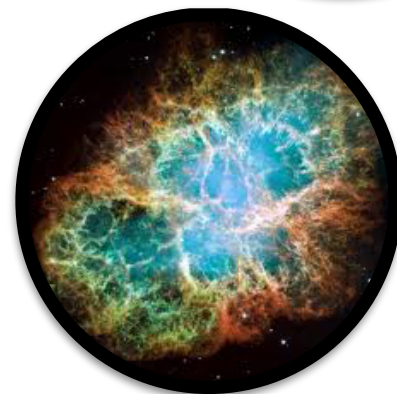
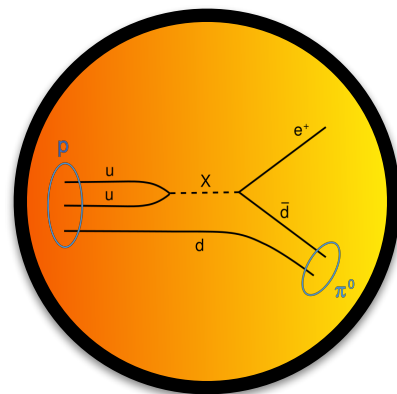


Astronomical Neutrinos/Rare Processes



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.



(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-inclusive cross section
- Beam timing?

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

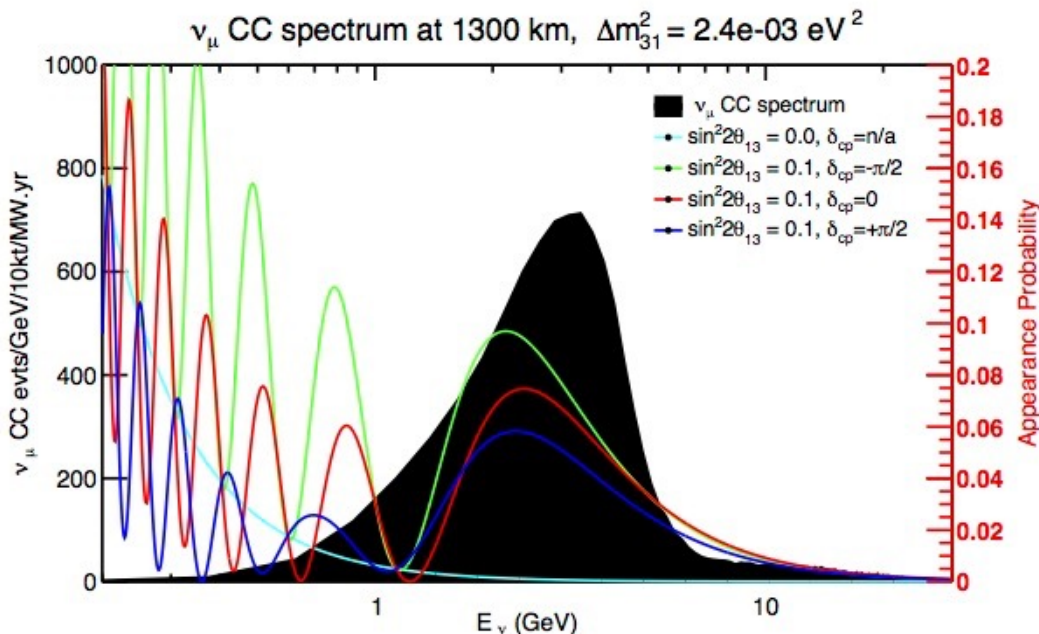
- Calorimetric energy reconstruction
- Beam timing
- De-excitation gammas
- Oxygen capture rates

Connections to Beam 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:

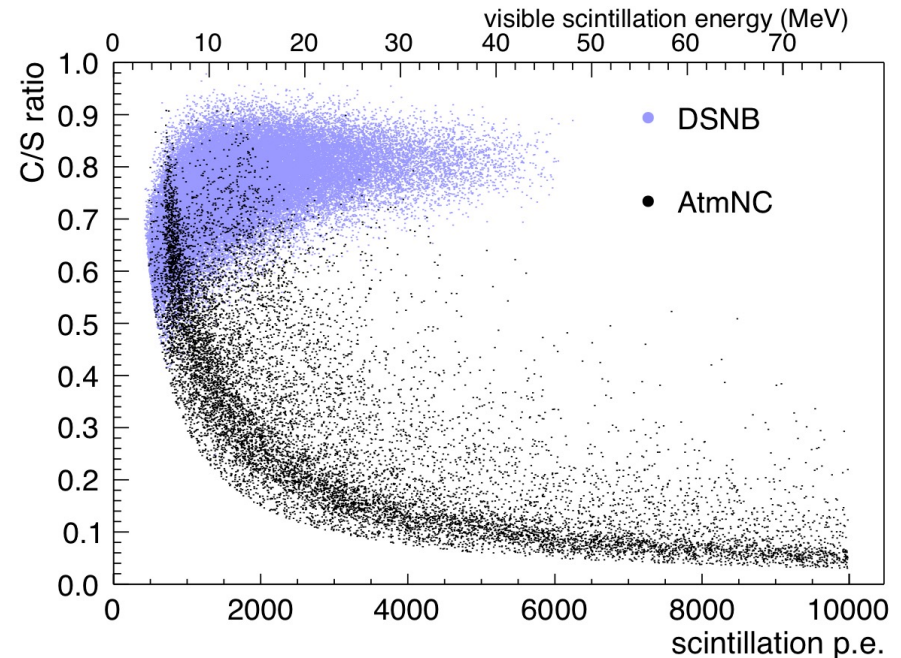
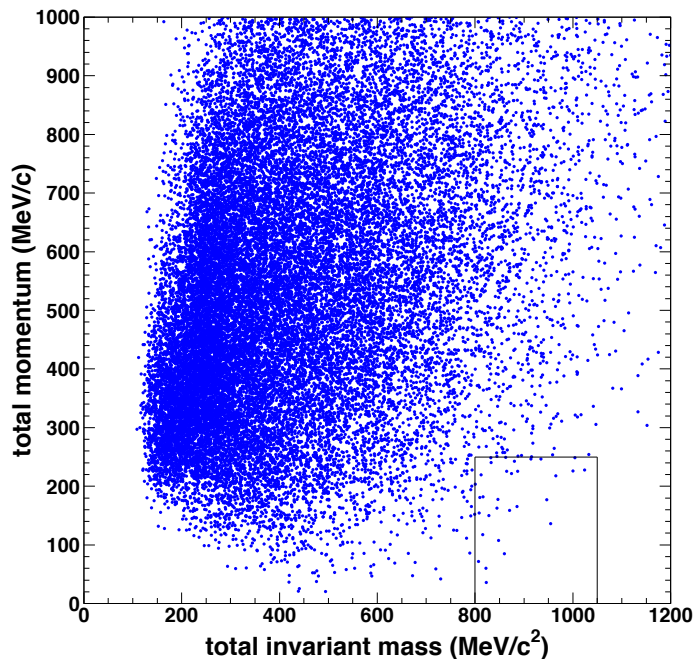
- better low-E reconstruction
- more fiducial mass, ie more stats
- Succeeding at that measurement will require excellent ~ 1 GeV neutrino reconstruction, in the context of a wideband, high energy neutrino beam
 - better reconstruction of event topology (track counting and directionality, EM shower structure)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





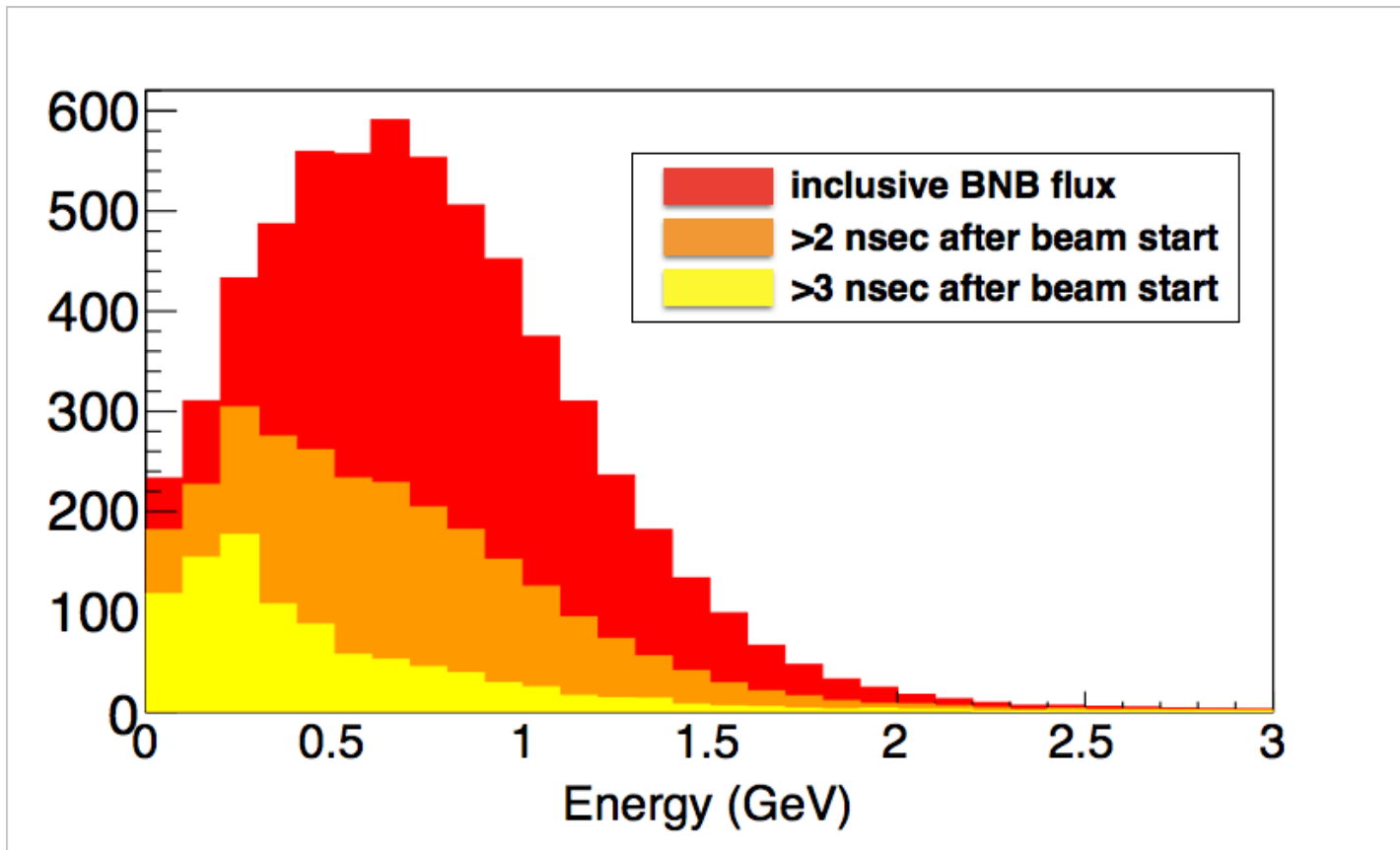
Relevant Cross Sections for SN and PDK

- ANNIE can measure high energy cross sections that feed down and fake lower energy physics (proton decay and DSNB backgrounds)





Timing Dependence of the Neutrino Energy Spectrum is Demonstrable in ANNIE



See my next talk, and

PHYS REV D 100, 032008 (2019)

<https://arxiv.org/abs/1904.01611>

Conclusion

- ANNIE is a Fermilab and DOE approved “Theia demonstrator”
- ANNIE is built and working
- ANNIE is expandable
- As we wrap up commissioning, we will be in a strong position to push for a Phase III

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

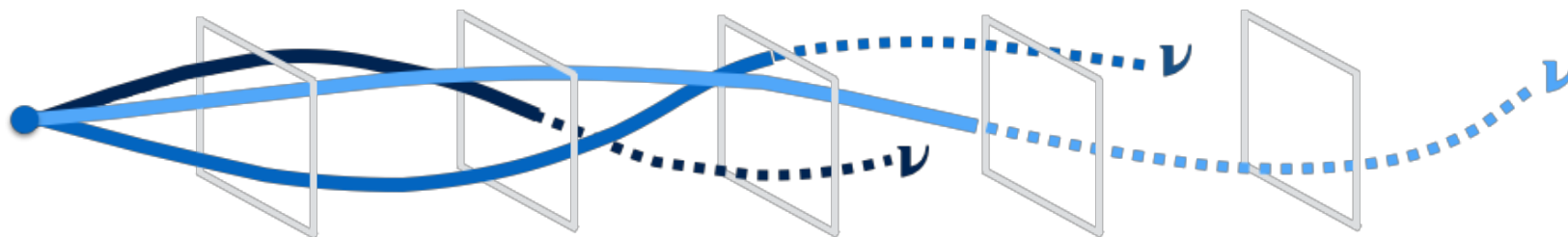


Additional Slides



Workshop on Precision Time Structure in On-Axis Neutrino Beams Fermilab November 2-3

<https://indico.fnal.gov/event/21409/>



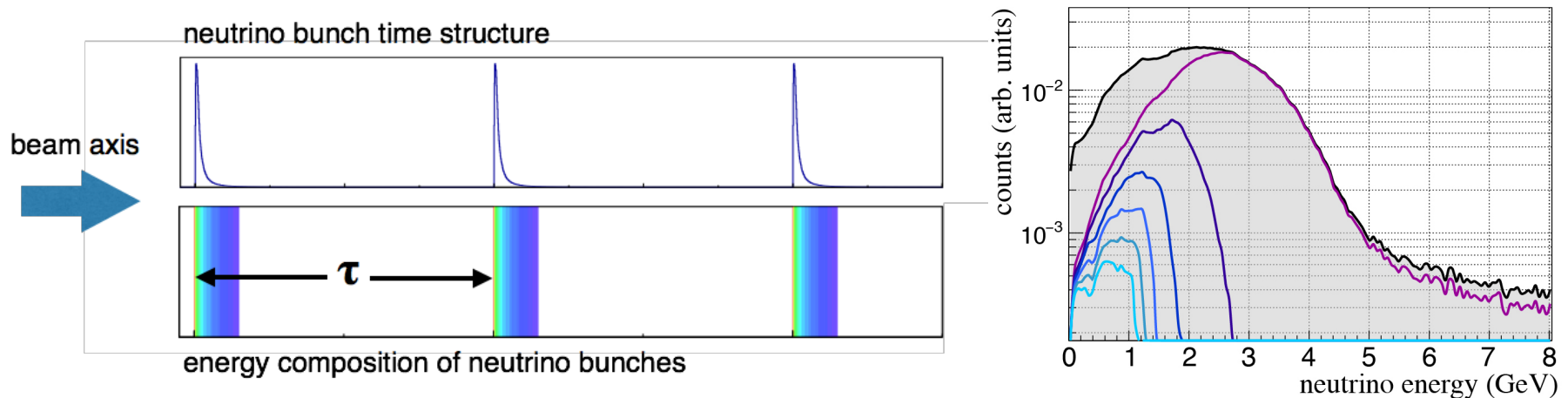
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<https://arxiv.org/abs/1904.01611>



Fast Timing and Beam Physics

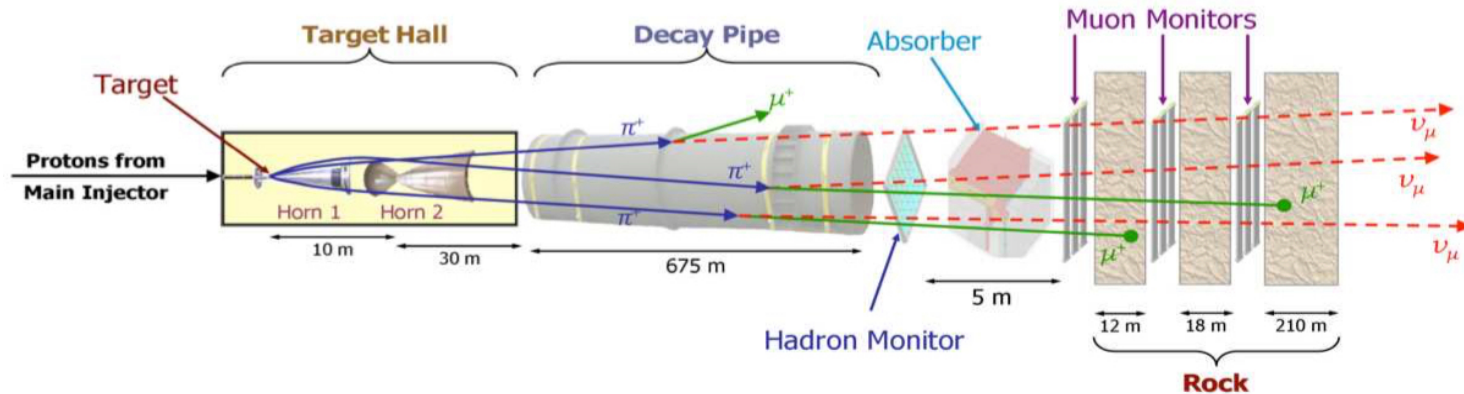
- Neutrino beams have an intrinsic time structure imprinted on them by the accelerators used to produce them
- The relative arrival time of neutrino with respect to the bunch correlates with the neutrino energy, parent hadron, and flavor
- Timing in neutrino beams could therefore provide a strong experimental handle to help understand and reduce beam systematic uncertainties on flux, cross section, and energy reconstruction in DUNE
- It may also provide a new handle in searching for new physics





Kinematics of Beam Timing

The arrival time difference between neutrinos from relativistic hadrons and neutrino from hadron of energy E:

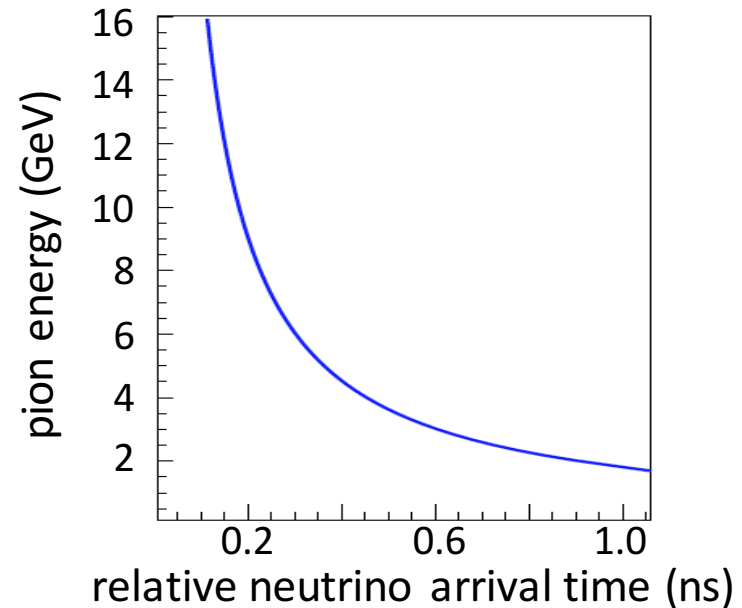


$$\Delta t(E) = \tau(E)[1 - \beta(E)]$$

$$\Delta t(E) = (\gamma\tau_0)[1 - \sqrt{1 - 1/\gamma^2}]$$

$$\Delta t(E) \rightarrow \tau_0 \quad \text{as} \quad \gamma \rightarrow 1$$

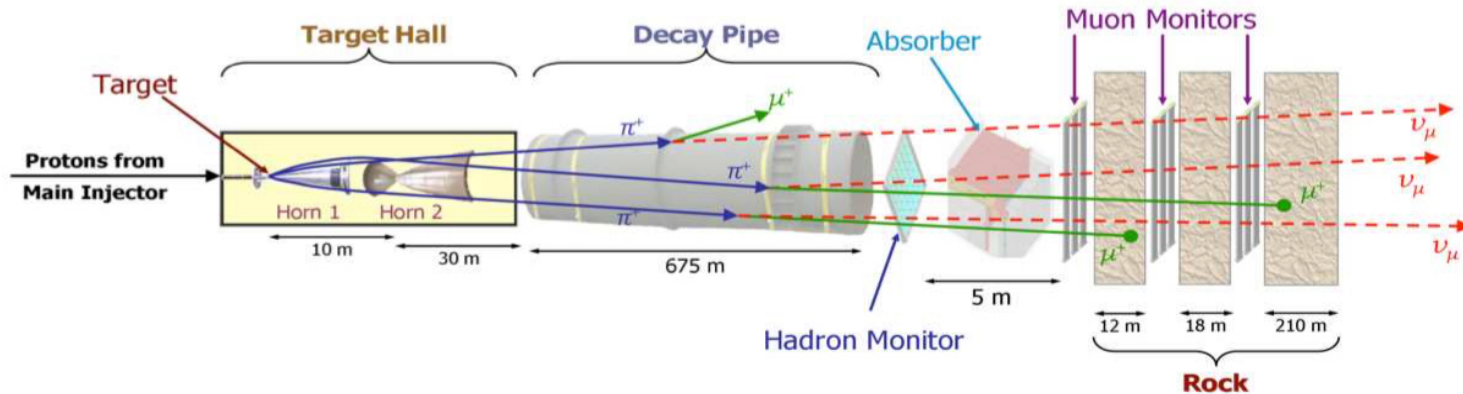
$$\Delta t(E) \rightarrow \tau_0/2\gamma \quad \text{for} \quad \gamma \gg 1$$





Kinematics of Beam Timing

The arrival time difference between neutrinos from relativistic hadrons and neutrino from hadron of energy E:

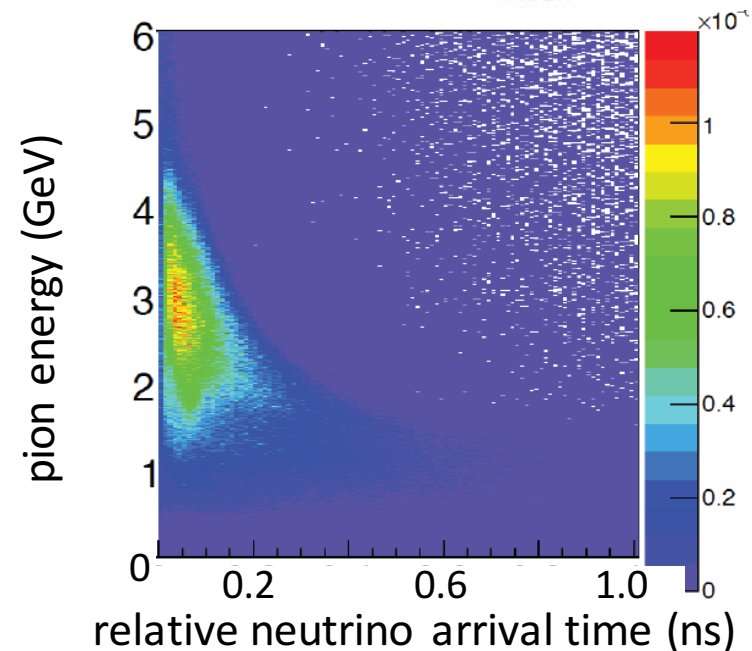


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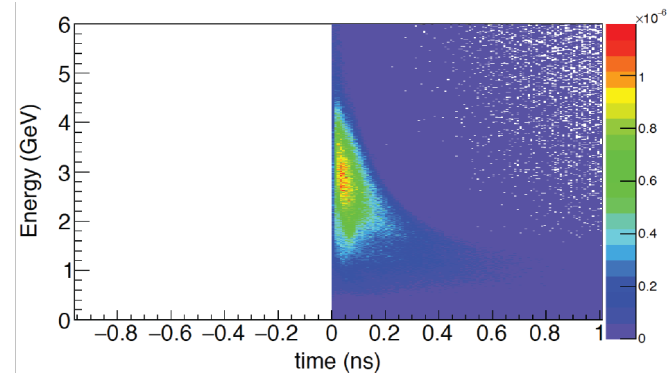


Characteristic Timescales/Limiting Factors

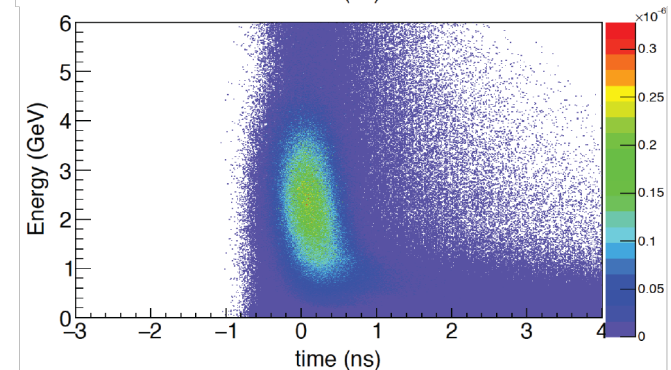
Stroboscopic techniques require sufficiently short bunch sizes

- If all hadrons are produced at the same time, the different neutrino energies will stratify over roughly ~ 1 nsec
- This effect starts to wash out if the proton beam width or detector resolutions exceed a nsec
- The current Fermilab RF structure is not designed to deliver proton bunches much shorter than 1 nsec.

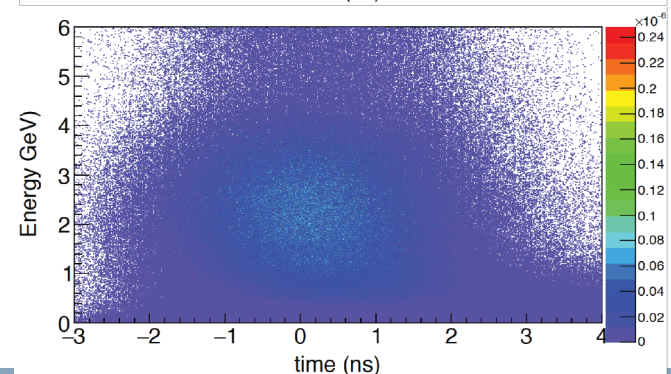
infinitesimal
proton bunch



200 psec
smearing



1 nsec
smearing



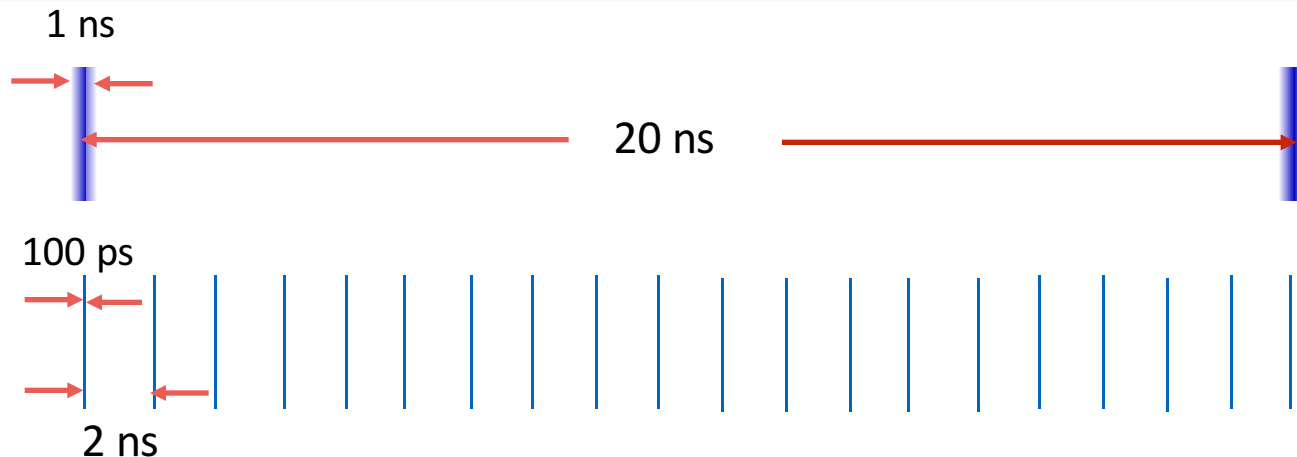


Rebunching the Beam

- Compressing the existing proton bunches in time is not feasible
- However, imposing a higher frequency harmonic on top of the bunch structure would be compatible with FNAL accelerator operation.
- The 10x harmonic, going from 53.1 MHz to 531 MHz, has a particularly advantageous relationship between bunch size and spacing
- The total number of protons is preserved, just “reorganized”

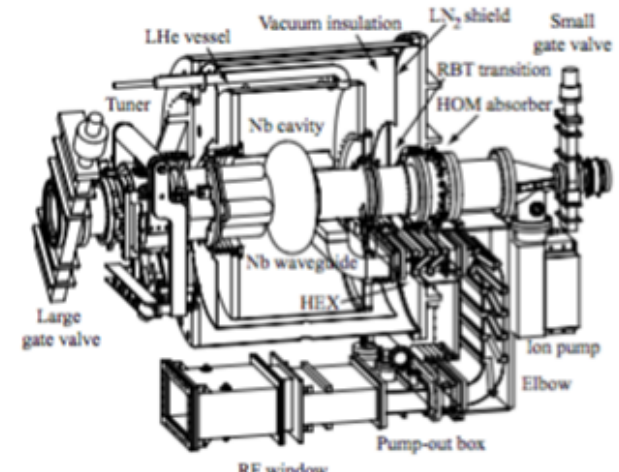
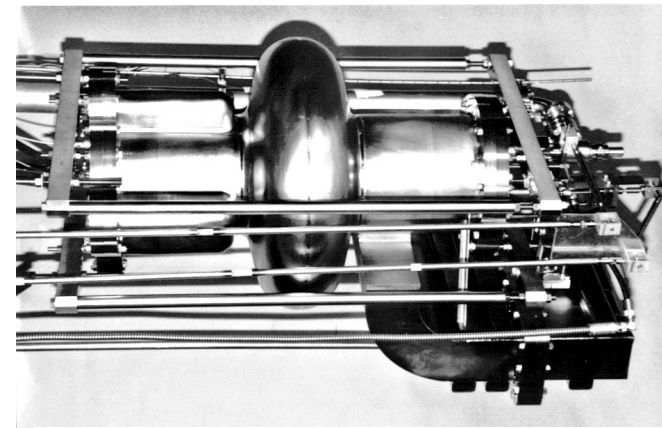
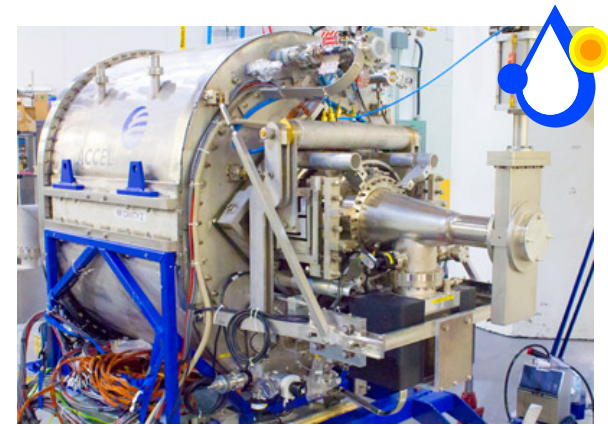
53.1 MHz \rightarrow 531 MHz

O(1) ns bucket every 20 ns \rightarrow O(100) ps bucket every 2 ns



Adding a Superconducting RF Cavity

- Rebunching could be achieved with the addition of just 1 or 2 superconducting RF (SRF) cavities
- There is a commercially available SRF cavity that closely matches our needed expectations: The Cornell B Cavity:
 - 500 MHz (versus 531 MHz)
 - Well tested in the field
 - Large aperture
- Feasible to implement, would be first MI cryomodule

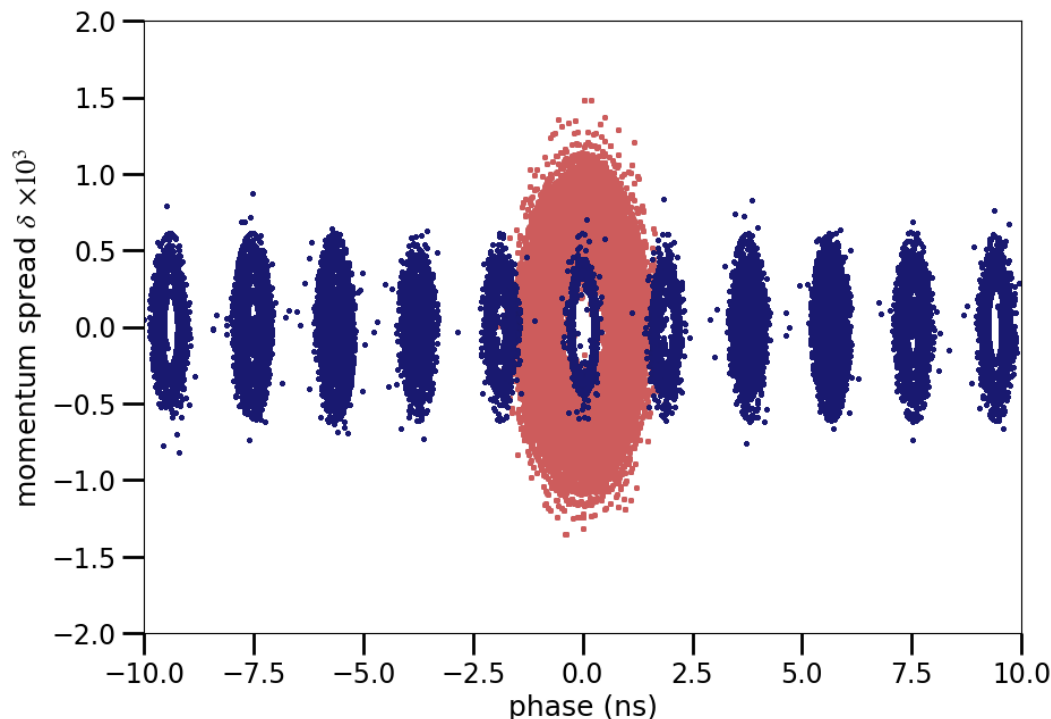




RF Simulation

A realistic, multi-particle simulation was performed to study the following properties of the rebunching procedure:

- ramp-down/ramp-up functions for rebunching at a higher frequency
- the final time structure/RMS time widths of the 531 MHz bunches



- The resulting rebunched structure is promising
- Typical 531 MHz bunches have an RMS of around 200 ps
- These bunches have sharp edges and substructure, which could be measured by RF monitors and exploited for better extracting time information

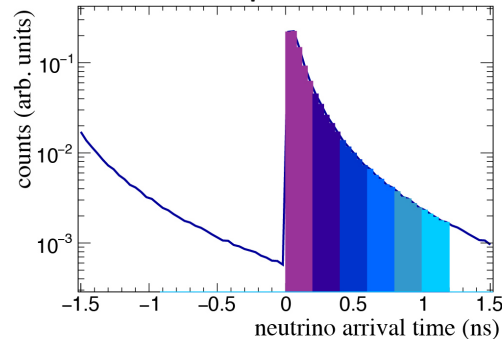
Evan Angelico, Sergei Nagaitsev



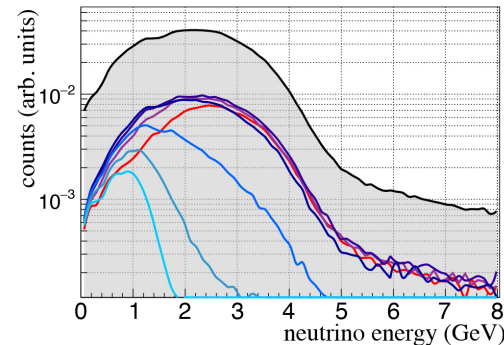
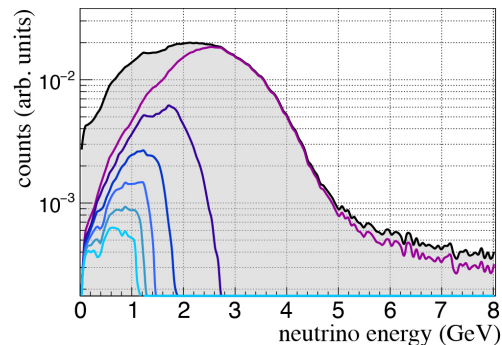
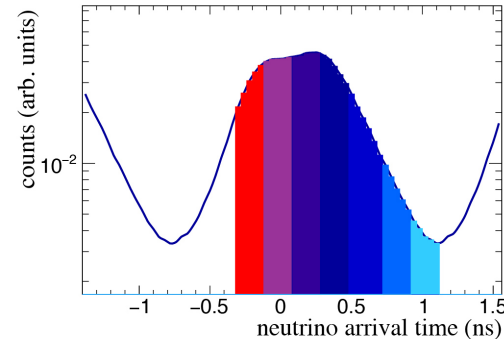
Time slicing in a more realistic scenario

- Even with
- a realistic simulation of the 531 MHz rebunched time structure
 - an additional 100 ps Gaussian to account for detector effects
 - the effects of pileup between the bunches
- it is still possible to select isolated, lower energy flux bins

Inifinitesimal proton bunches



"realistic scenario"



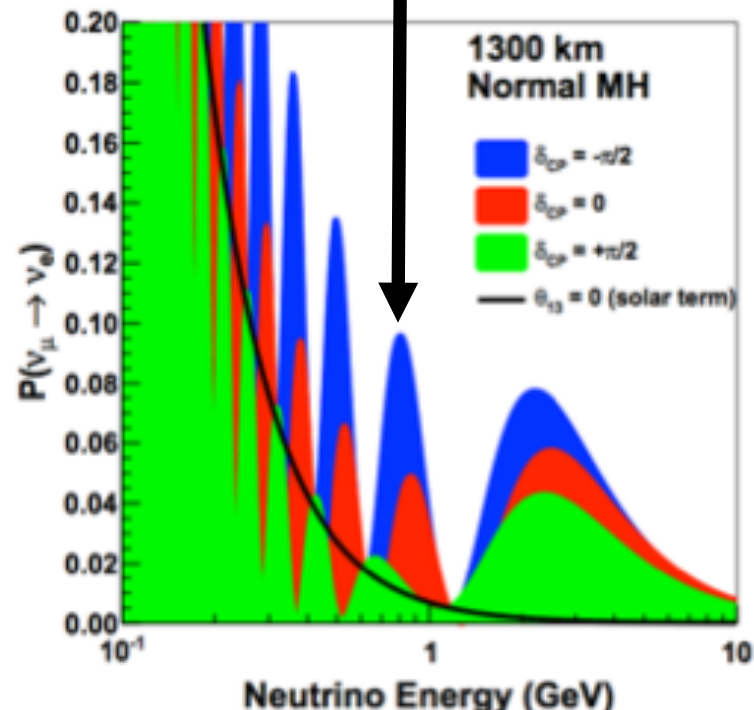
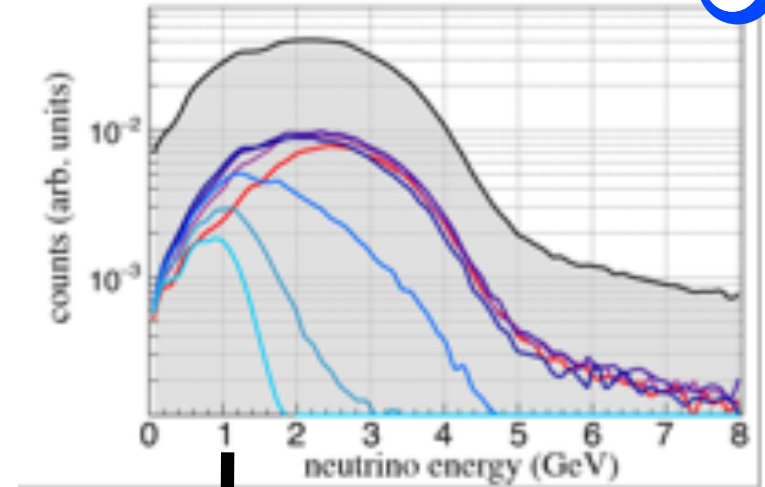


The second maximum

Time slicing in the far detector is particularly advantageous as it can

- select a more pure sample of neutrinos from the second maximum
- suppress “feed down” from higher energy backgrounds
 - Resonant pion production
 - Deep Inelastic Scattering
- Suppress downward migration of reconstructed energy from higher energy interactions

Being able to fit both maxima would place strong constraints on oscillation parameters



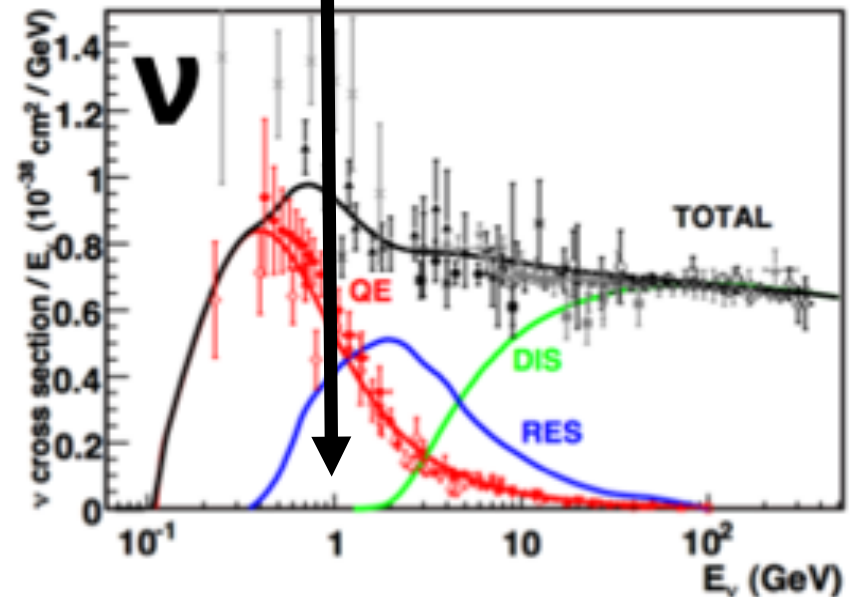
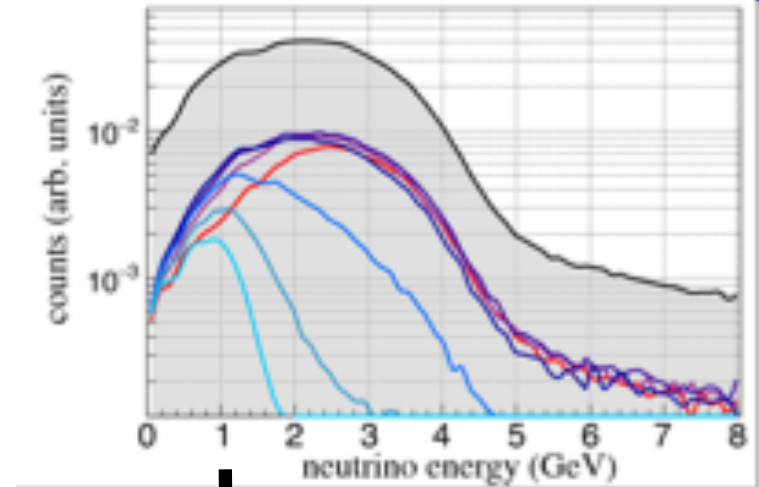


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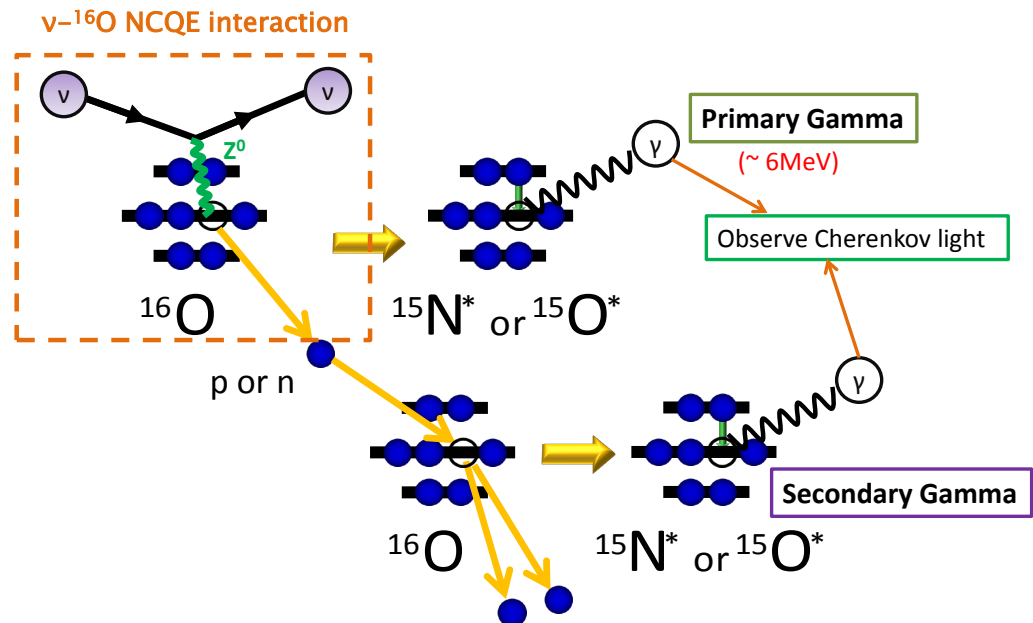


Tagging Nuclear De-excitation Gammas

- 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!!

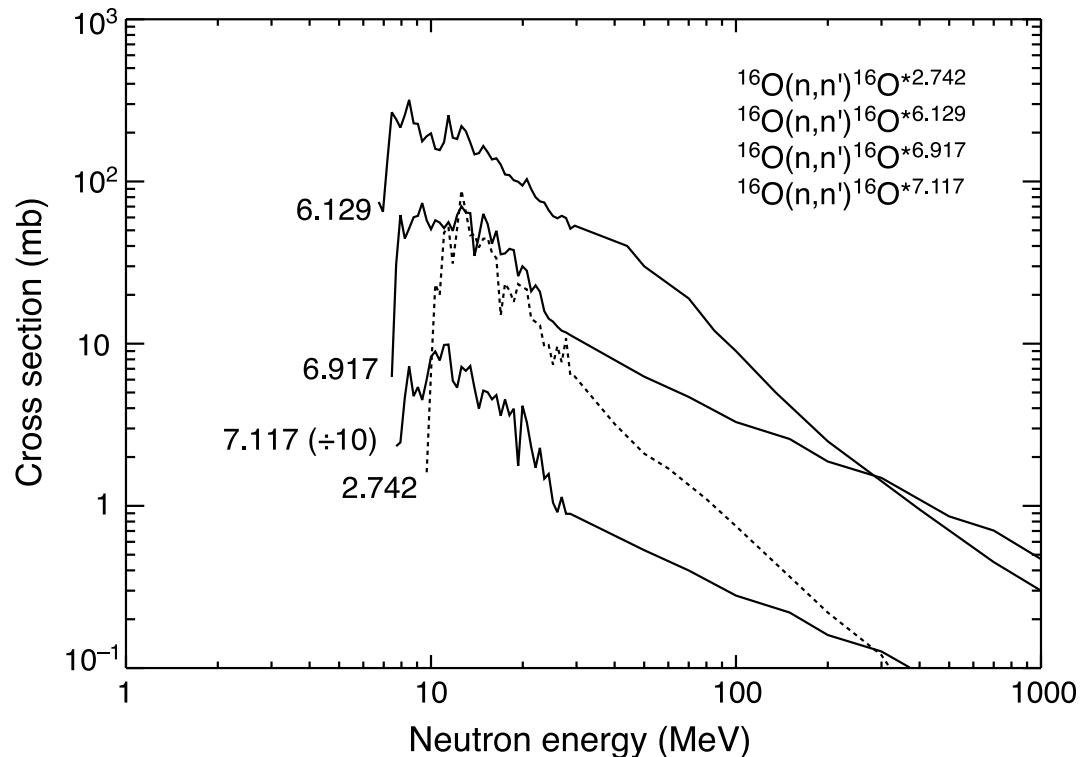
The gamma emission from radiative capture happens on nanosecond timescales

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.

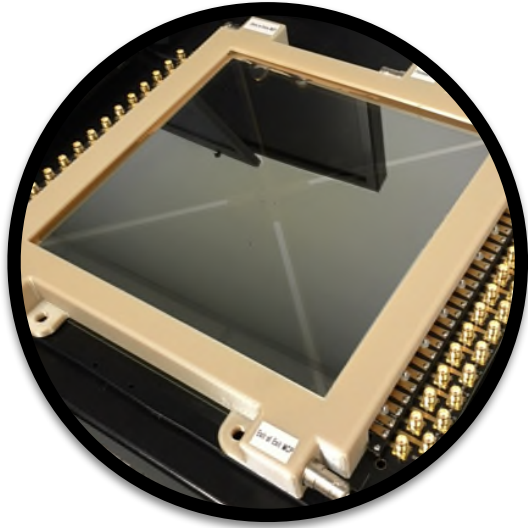


credit: Bei Zhou and John Beacom (OSU)



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)

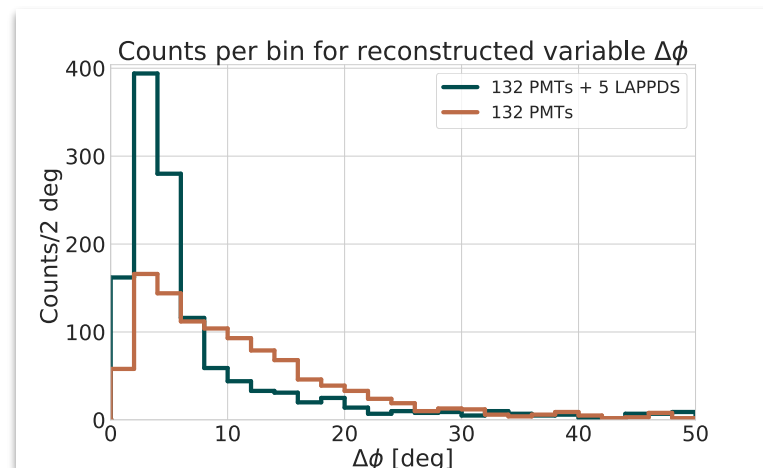
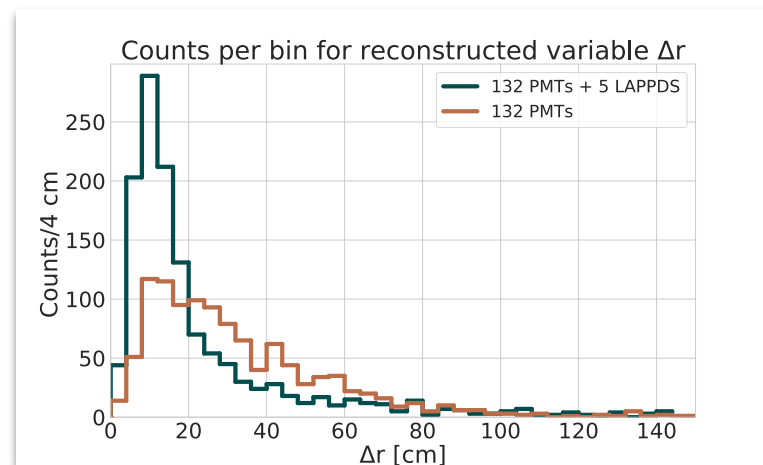
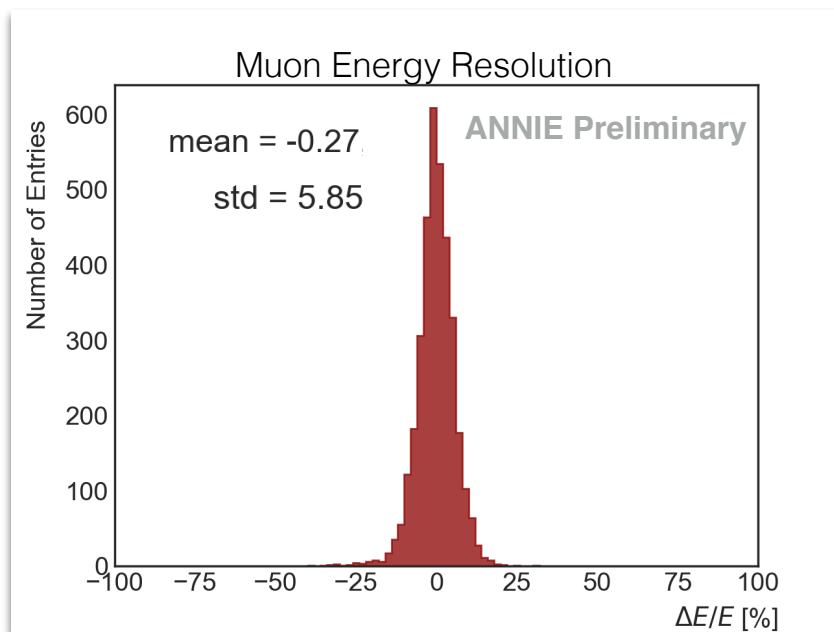
The ANNIE collaboration has purchased and received the initial 5 LAPPDs for our physics measurement

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

Enabling Technology: LAPPDs and Fast Timing



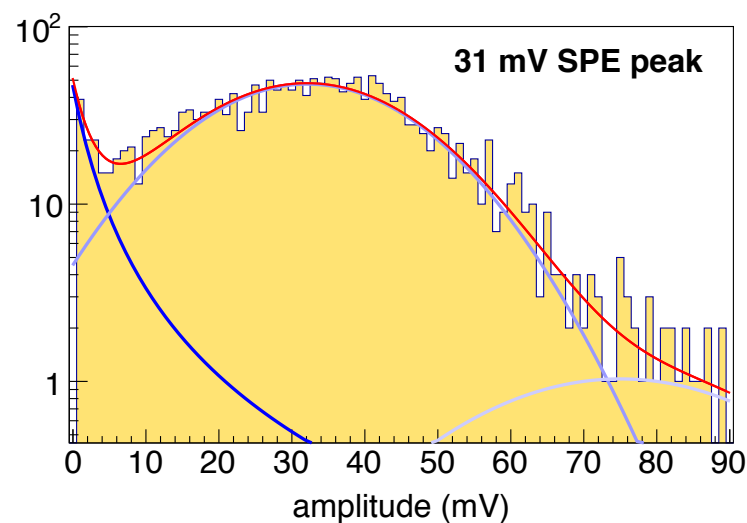
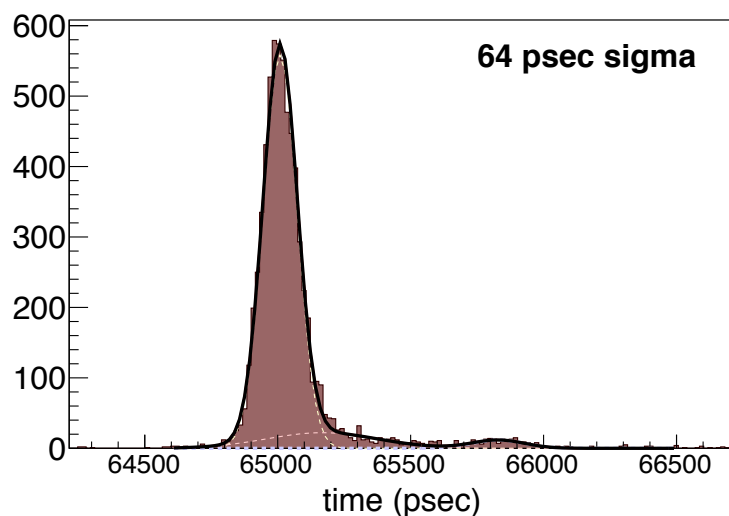
- Simulations show that the addition of the 5 initial LAPPDs provides the factor of 2 improvement in vertex resolution needed to achieve target neutron containment and energy resolutions
- Similarly impressive gains in directional resolution will help with reconstruction of more exclusive neutrino final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



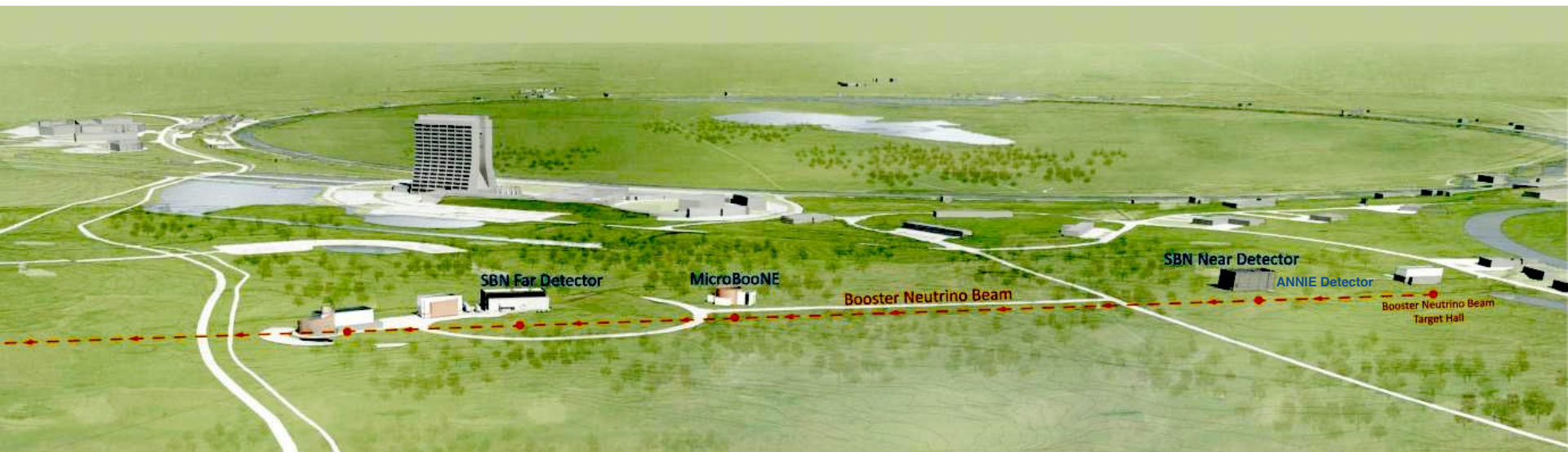
Enabling Technology: LAPPDs and Fast Timing



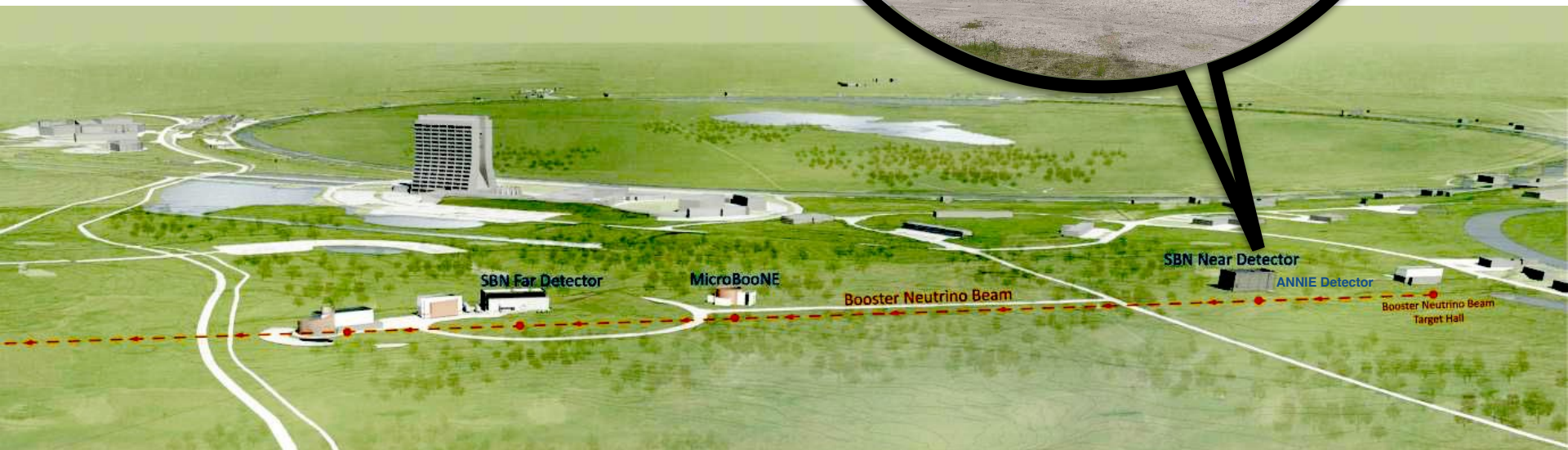
- Testing of these LAPPDs is nearly complete and preparations for summer deployment are underway
- The LAPPDs perform with resolutions consistent with our requested specifications:
 - < 100 ps time resolution
 - gains of 10^7
 - few mm spatial resolutions



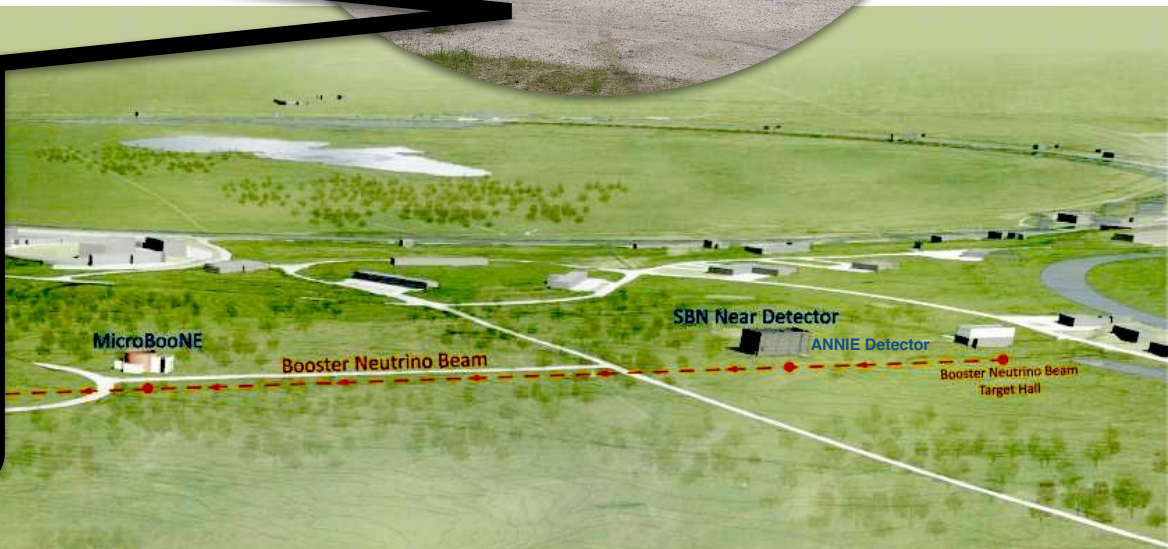
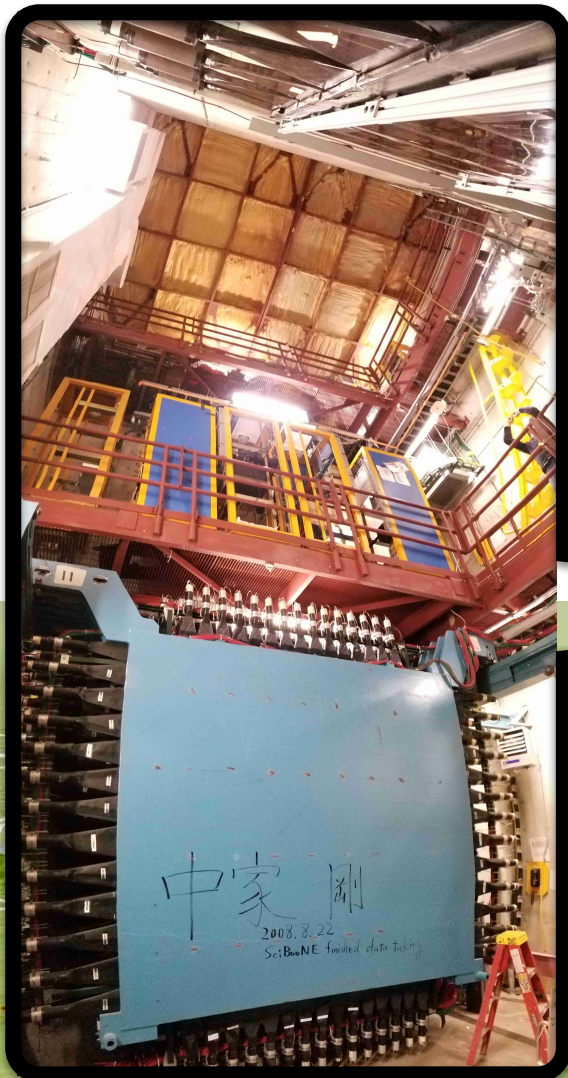
The Experimental Hall



The Experimental Hall



The Experimental Hall

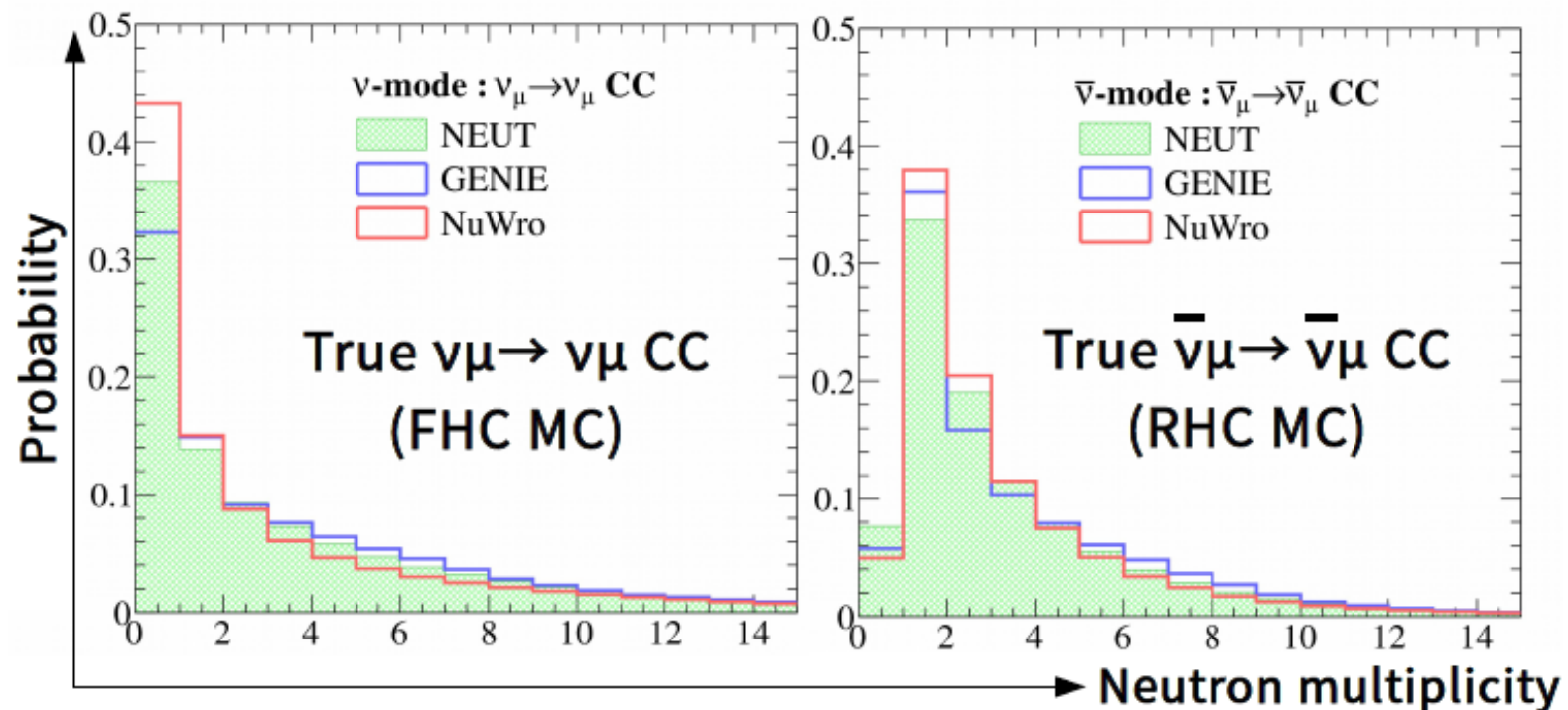




Phase II: Neutron Multiplicity Measurements

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

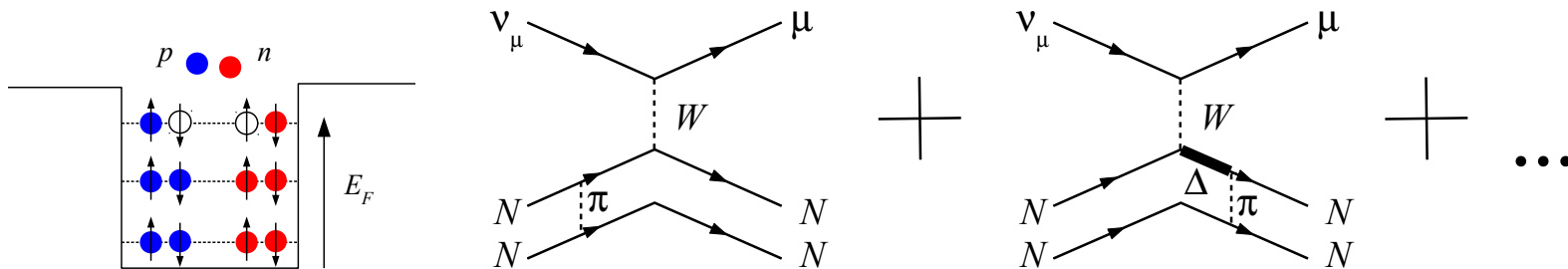
- It is on a controlled beam with known direction, flavor, and energy spectrum
- At an energy spectrum close to that of atmospheric neutrinos





Phase II: Neutron Multiplicity Measurements

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



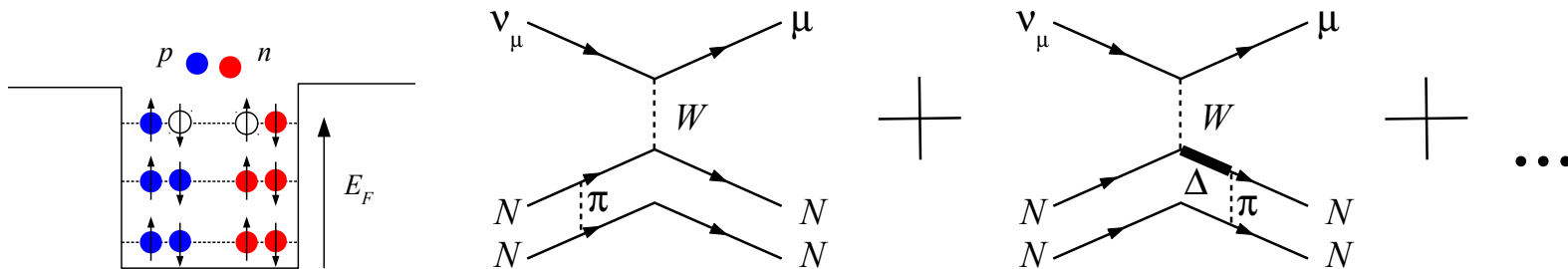
The presence of neutrons can therefore be used for signal-background separation in a variety of physics analyses

- wrong-sign neutrino separation
- proton decay
- diffuse supernova neutrino background
- tagging inelastic CC0 π events



Phase II: Neutron Multiplicity Measurements

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



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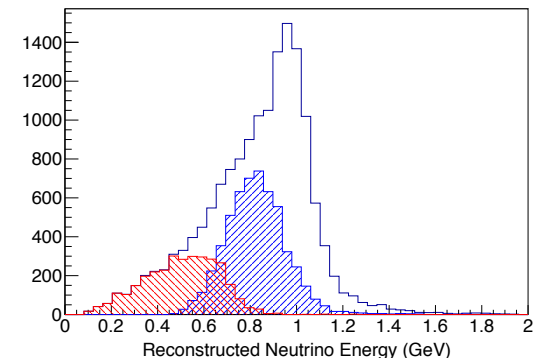
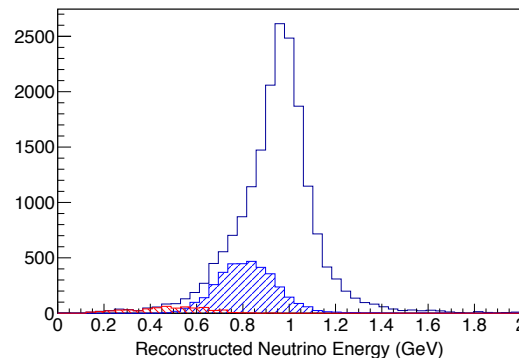
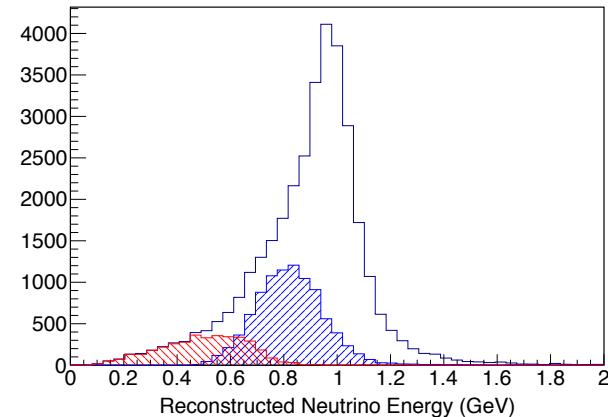
- wrong-sign neutrino separation
- proton decay
- diffuse supernova neutrino background
- tagging inelastic CC0pi events

0n (FHC)	1n (RHC)
0n (signal)	>0n (bkgd)
1n (signal)	>1n (bkgd)
0 or 1n (signal)	extra n



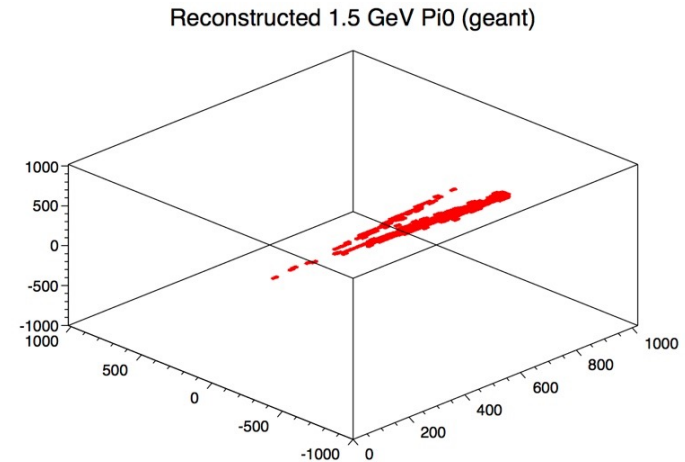
Neutrons as an Indicator of Inelasticity

- 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)

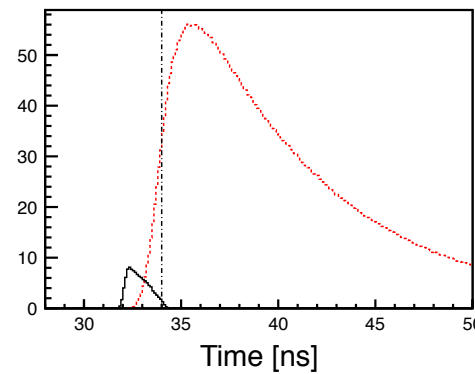




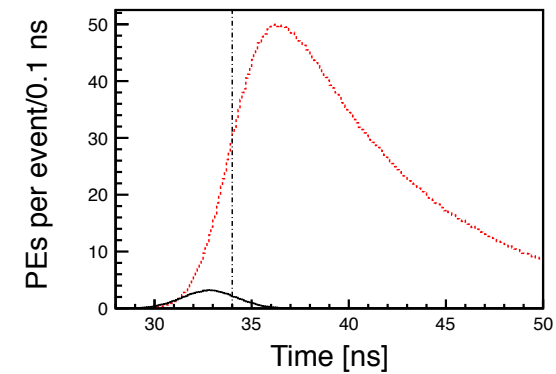
- Fast timing is interesting in itself
 - better vertex reconstruction
 - ability to reconstruct overlapping events and tracks
 - better able to resolve structure of EM showers



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

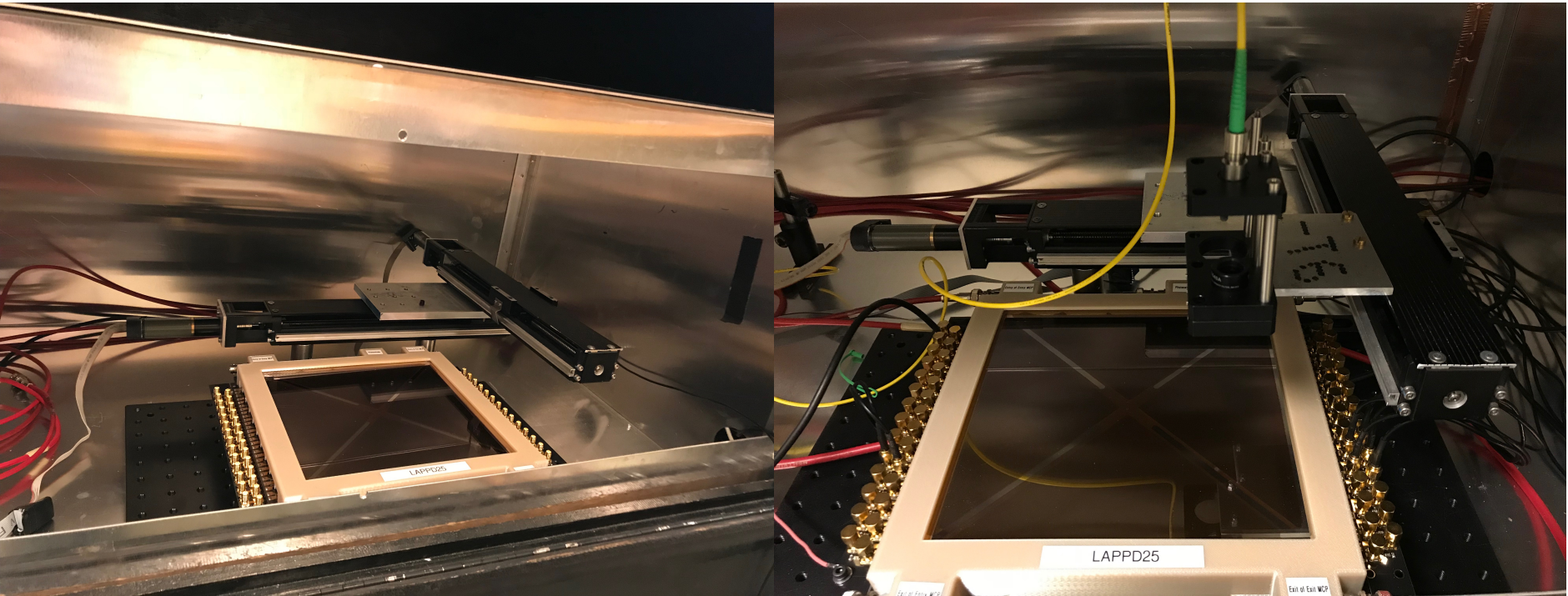


(a) Default simulation.



(b) Increased TTS (1.28 ns).

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



June 2013 Volume 84 Number 6

AIP | Review of Scientific Instruments



INVITED ARTICLE:
A test-facility for large-area microchannel plate detector assemblies using a pulsed sub-picosecond laser
by B. Adams, M. Chollet, A. Elagin, E. Oberla, A. Vostrikov, M. Wetstein, R. Obaid, and P. Webster

rsi.aip.org

Nuclear Instruments and Methods in Physics Research A 795 (2015) 1–11

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Timing characteristics of Large Area Picosecond Photodetectors

B.W. Adams^a, A. Elagin^b, H.J. Frisch^b, R. Obaid^c, E. Oberla^b, A. Vostrikov^b, R.G. Wagner^a, J. Wang^a, M. Wetstein^{b,*}

^a Argonne National Laboratory, United States
^b Enrico Fermi Institute, University of Chicago, United States
^c University of Connecticut, United States

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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 $20 \text{ cm} \times 20 \text{ cm}$ 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 $\pm 1\sigma$ 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.

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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 photosensors 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 $20 \text{ cm} \times 20 \text{ cm}$ LAPPDTM 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.

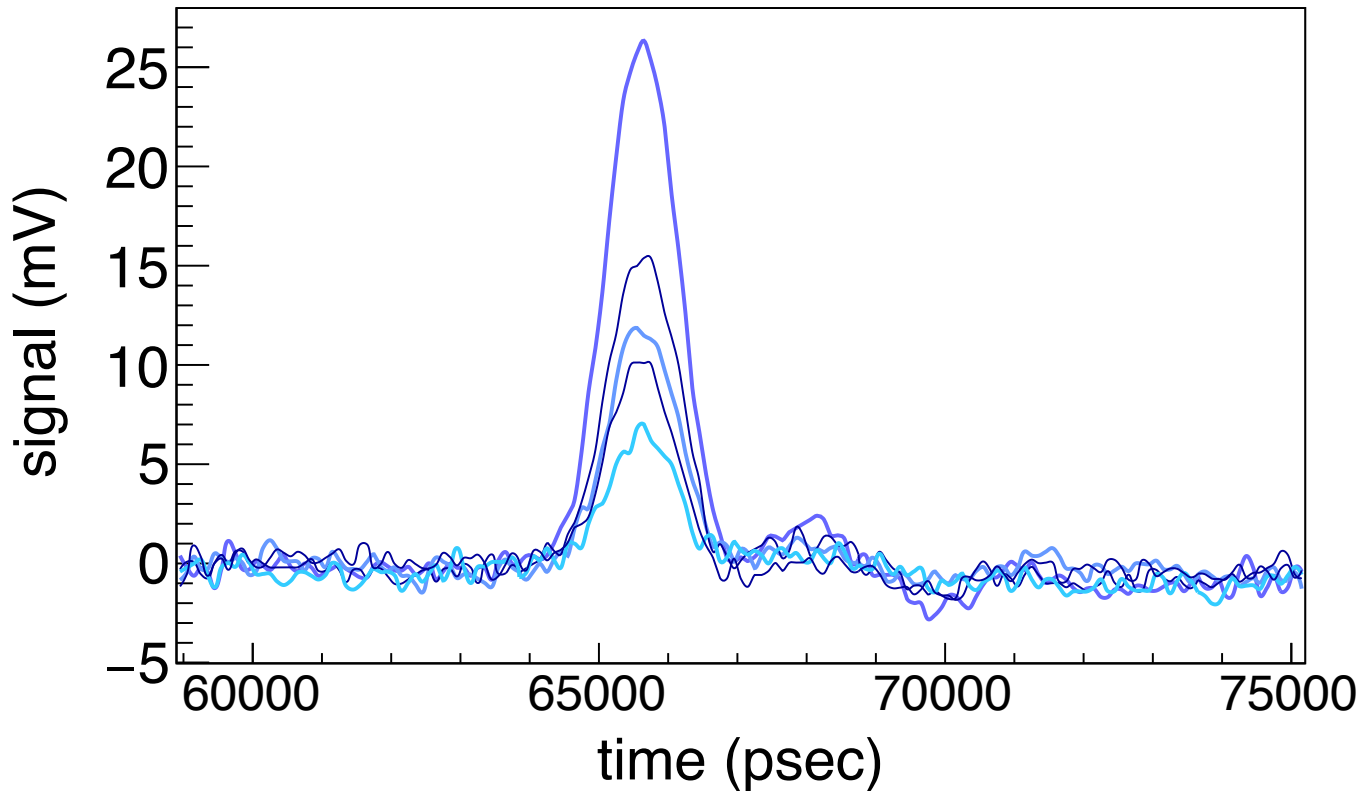
The ISU test stand is based on and built by the researchers who wrote *the canonical papers on LAPPD testing and time resolution.*

Results: Typical Single-PE Pulses



FWHM: 1.1 nsec

rise time: 850 psec



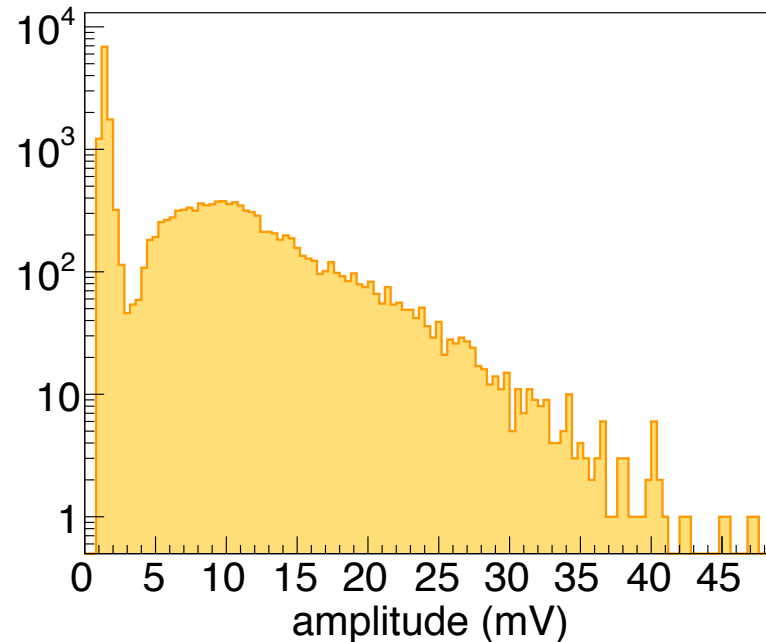
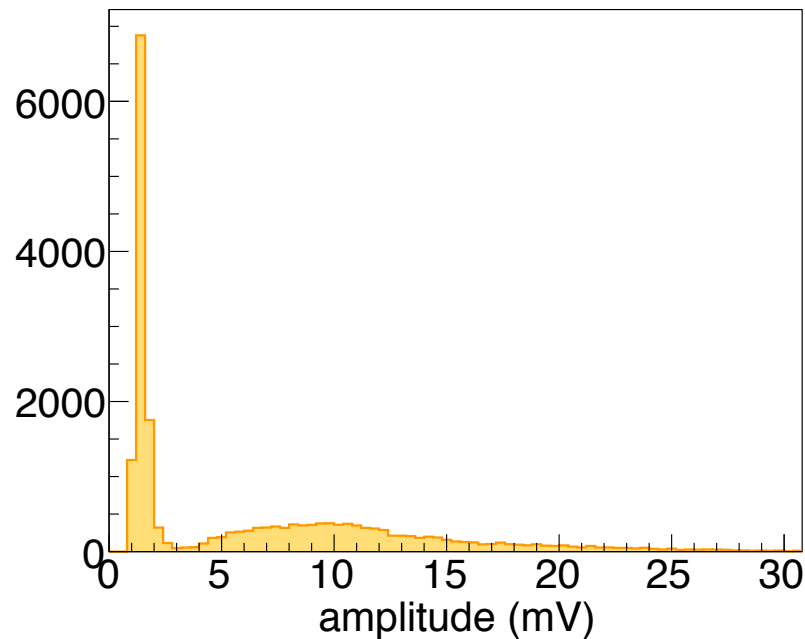
voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

Results: Amplitude



We see very clean separation from pedestal

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

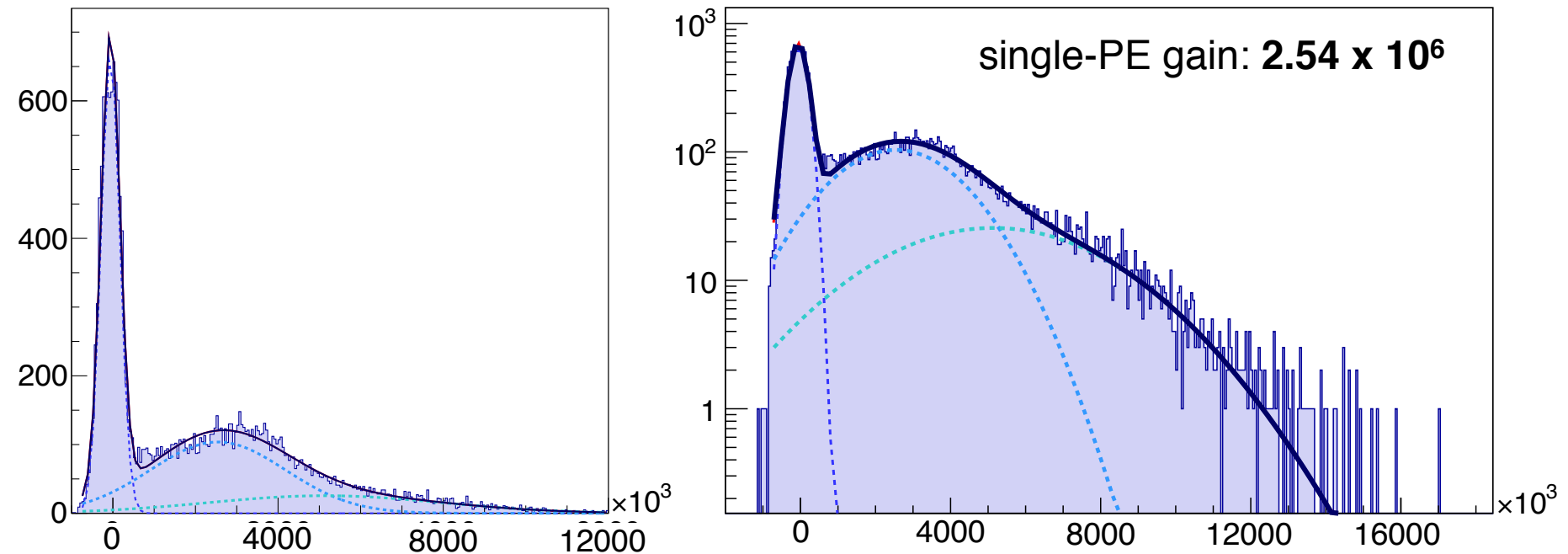


voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

Results: Gain



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

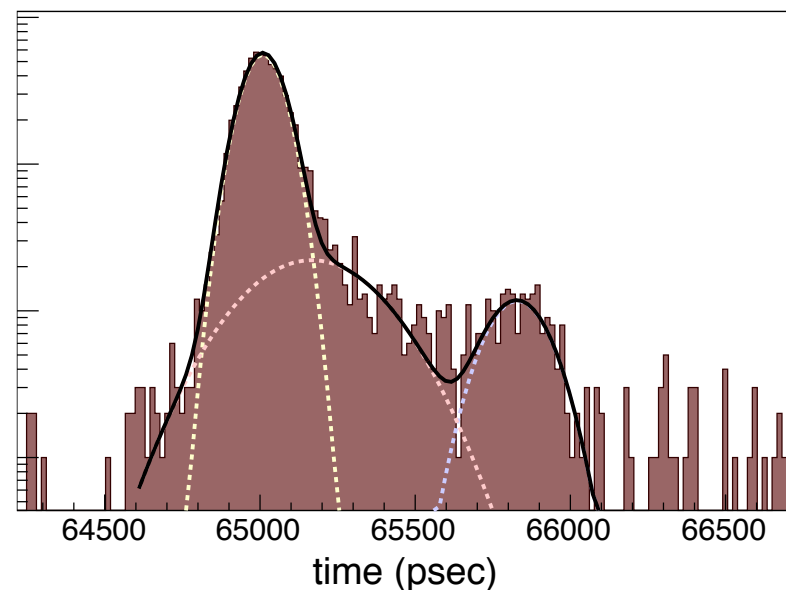
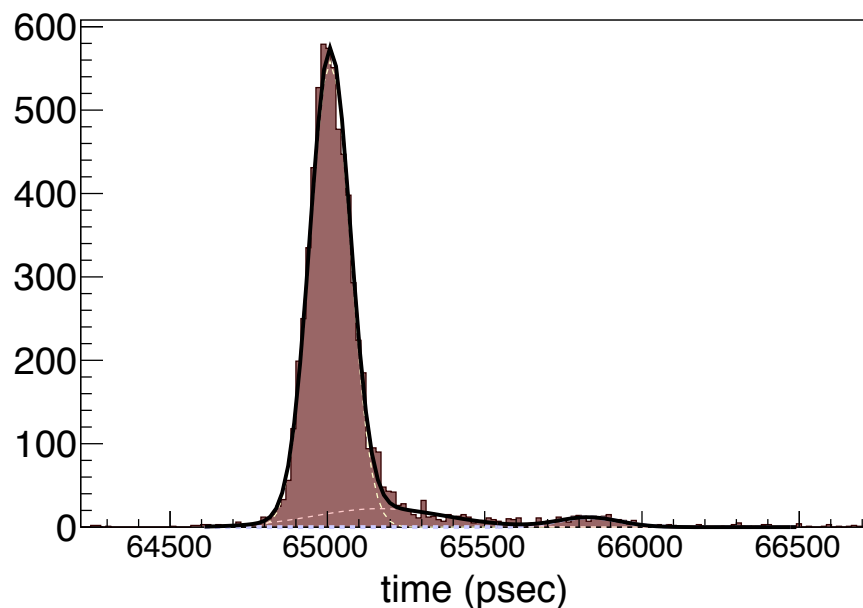


voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

Results: Time Resolution



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

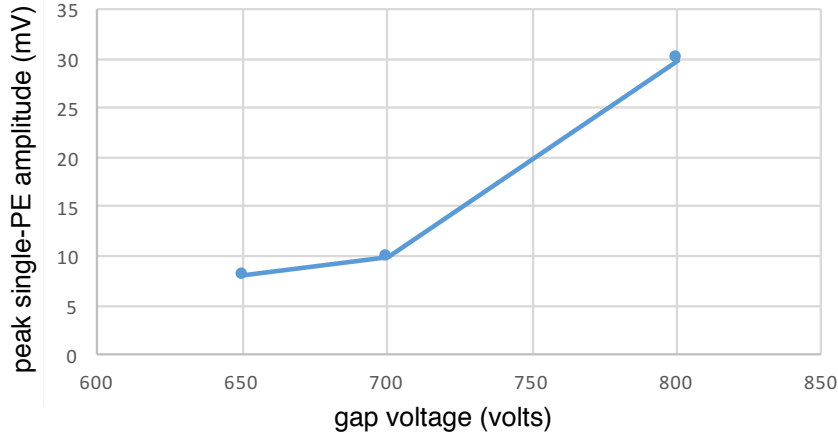


voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

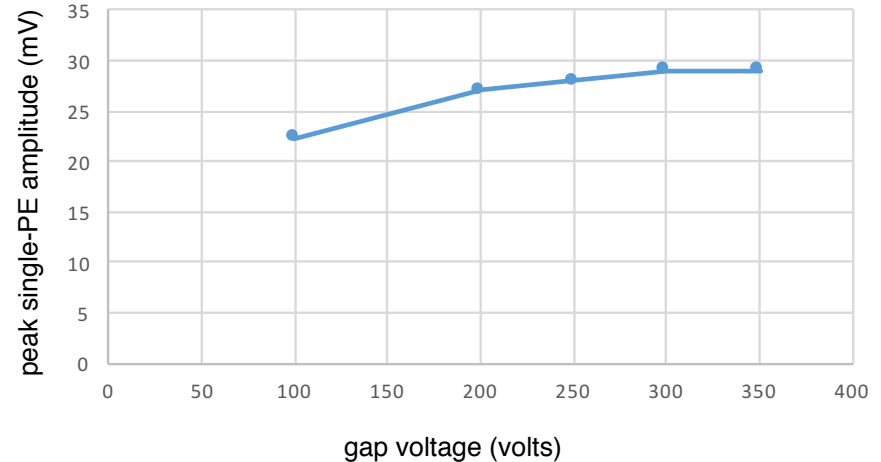
LAPPD 25: Voltage Response



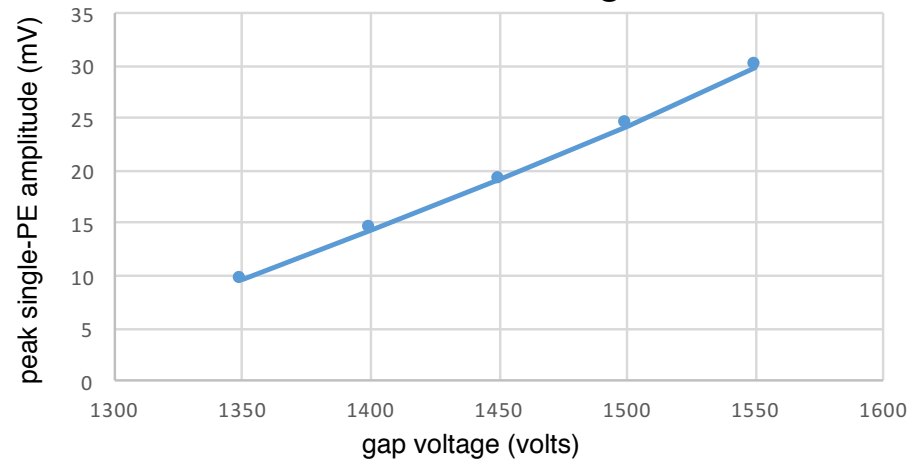
Entry MCP Voltage



Photocathode Gap Voltage



Bottom Voltage

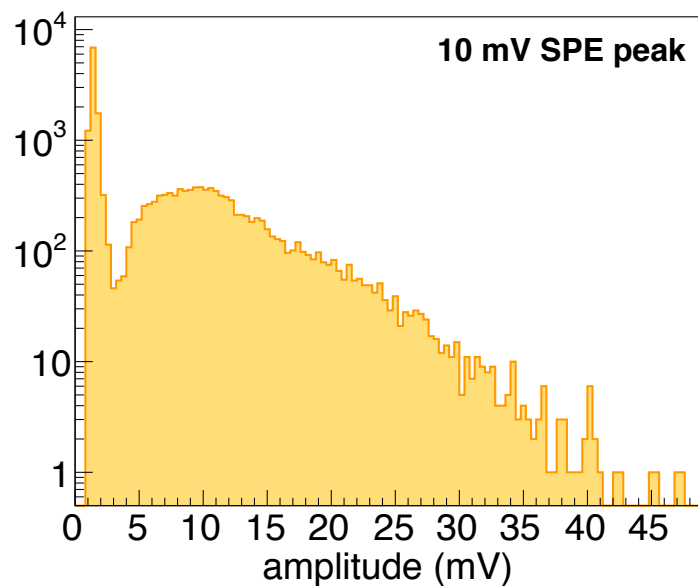


- We varied the voltages to see if we could improve the gain
- At higher voltages, the LAPPD gets noisy, but these gains provide good sPE separation so we're not concerned

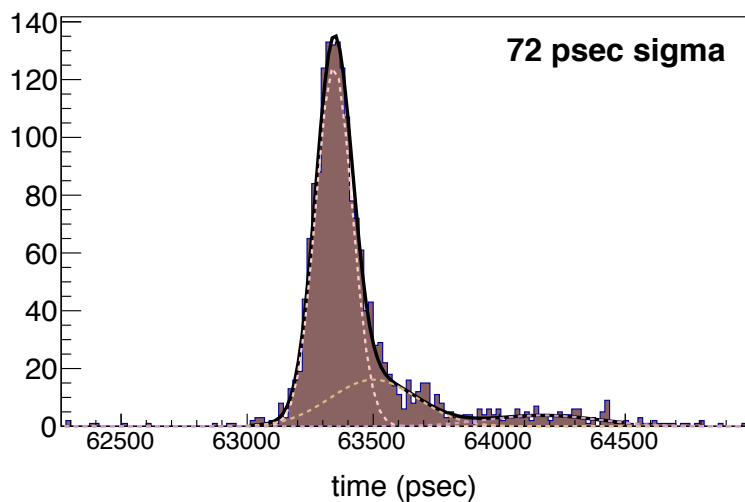
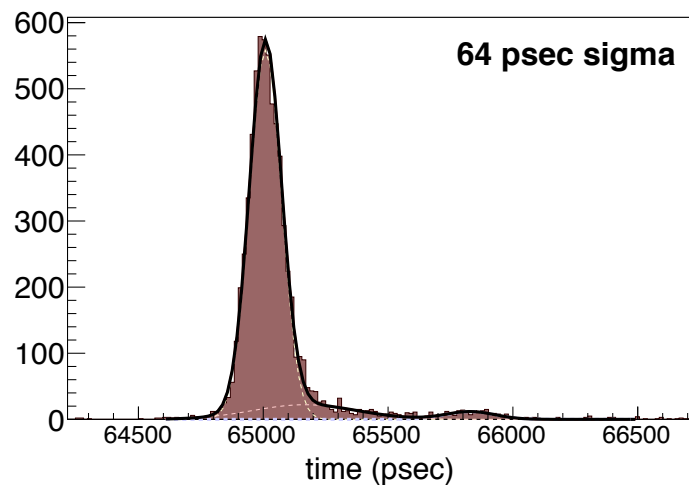
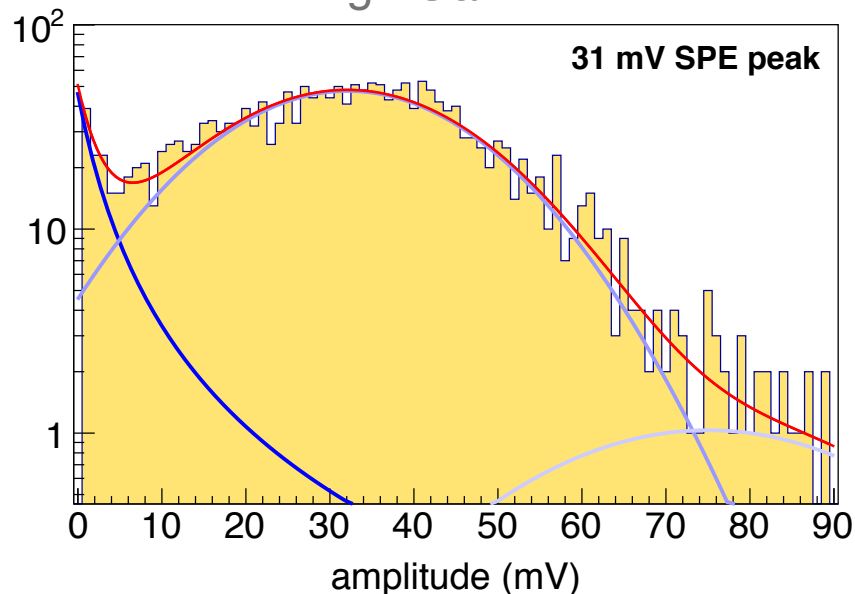
LAPPD 25: Voltage Optimization



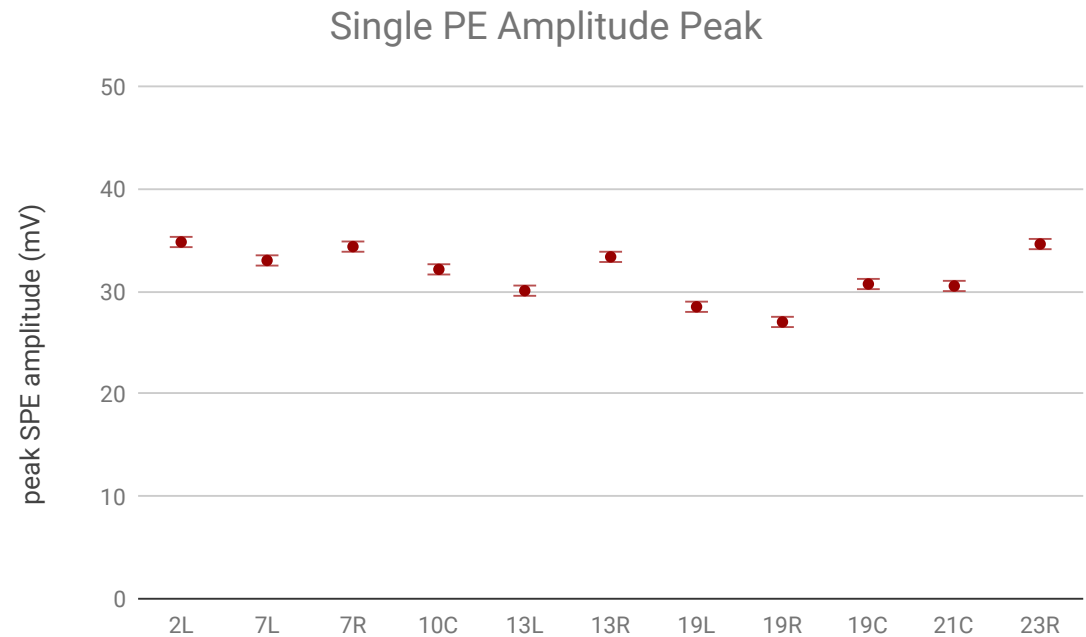
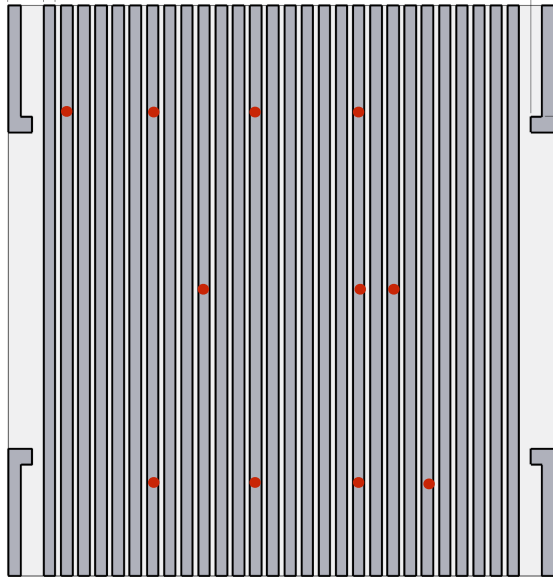
Low Gain



High Gain

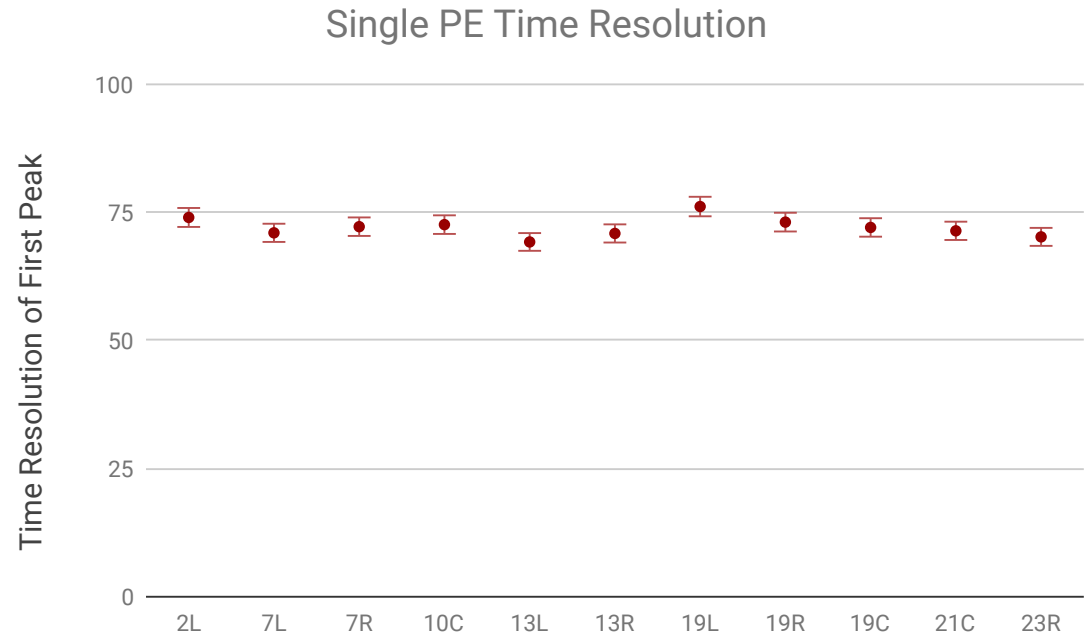
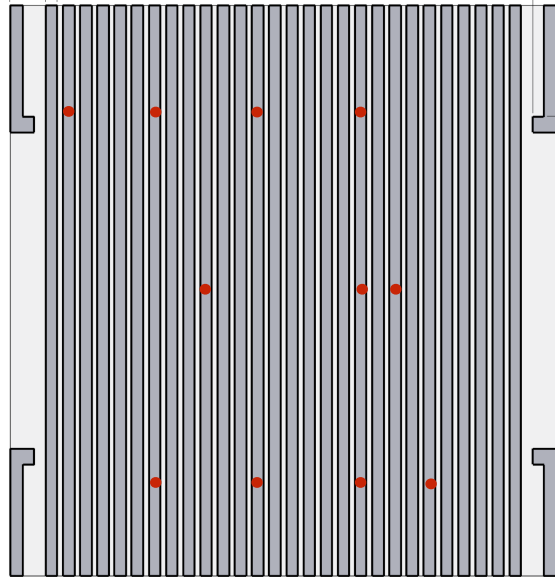


LAPPD 25: Single PE Gain Uniformity



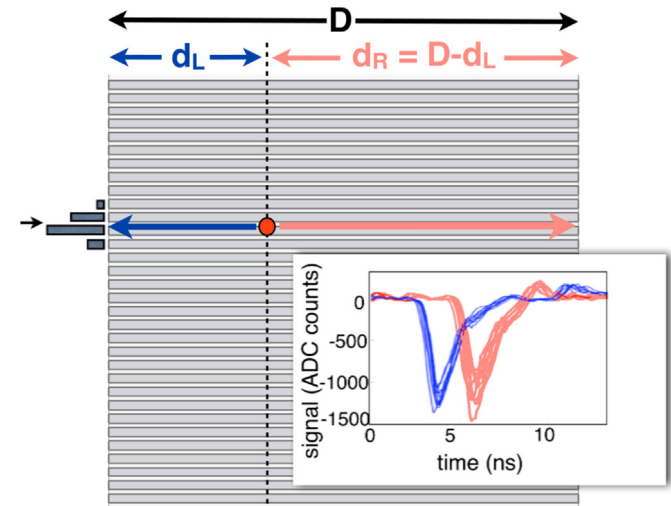
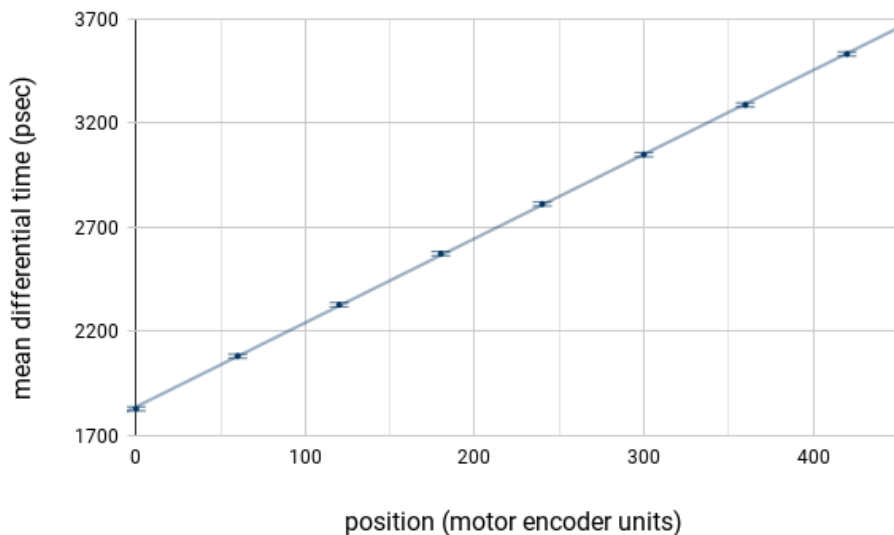
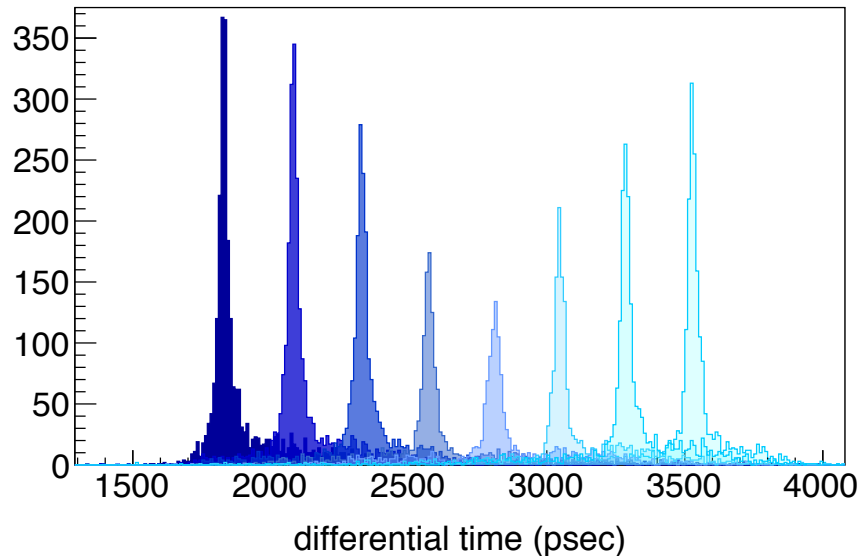
- We recorded 10k triggers as 11 random positions on the tile
- SPE peak amplitude was taken from the mean of the first Gaussian in a 2 PE + pedestal fit
- More systematic scans will become easier with the multichannel PSEC electronics

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

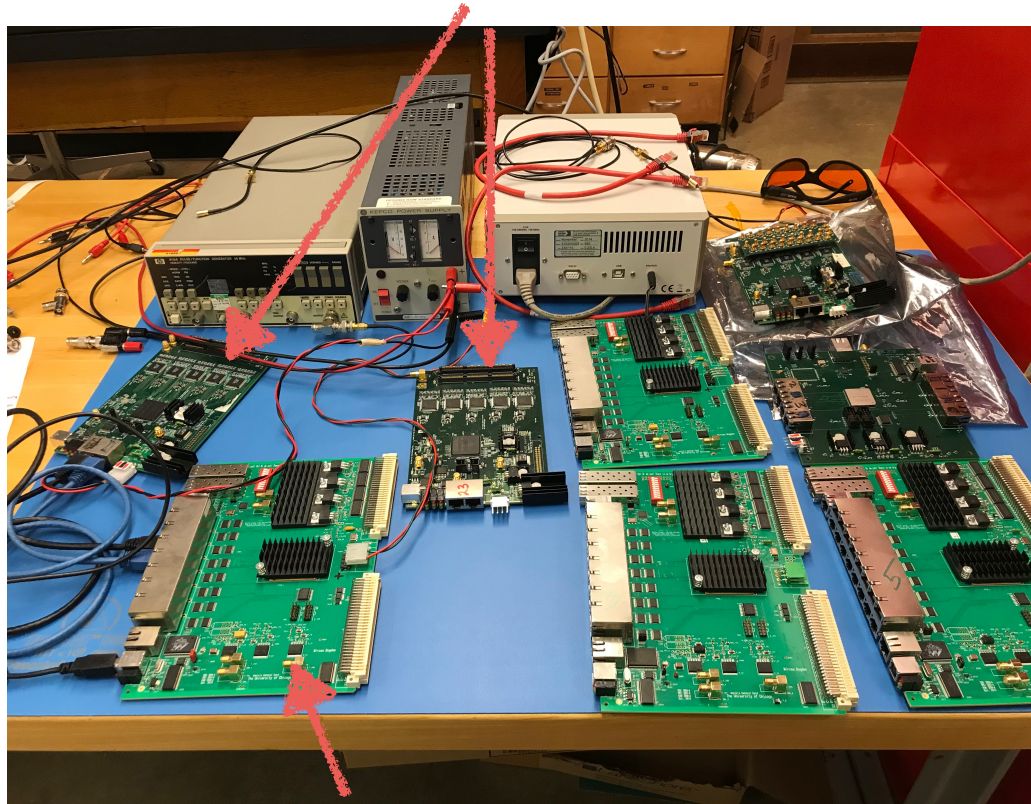


- Position in the direction parallel to the striplines can be determined from the time difference between the two ends
- 25 picosecond single-PE differential time resolution corresponds to 4.35 mm resolution in the parallel direction

Application Readiness (DAQ)*

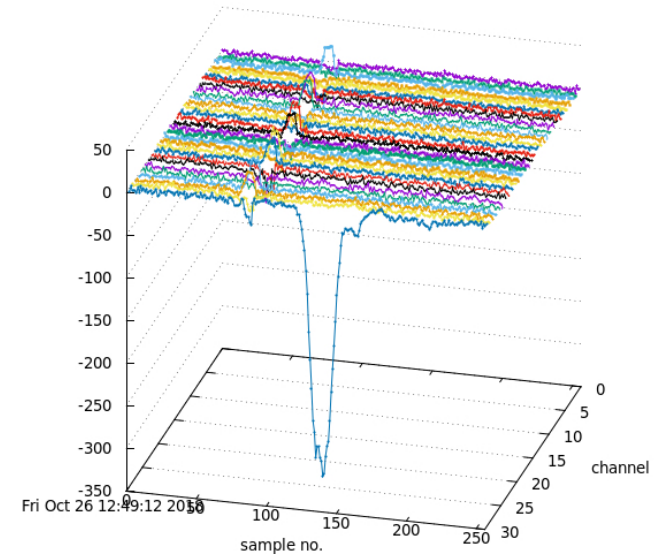
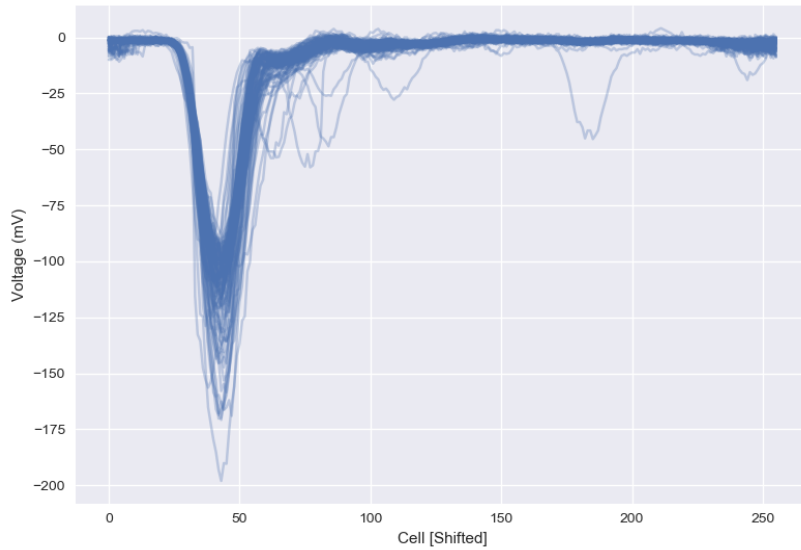


Two 30 channel ACDC cards



ANNE Central Card (ACC)

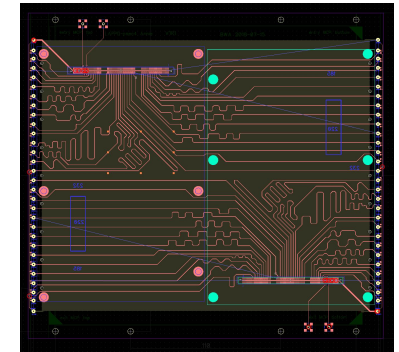
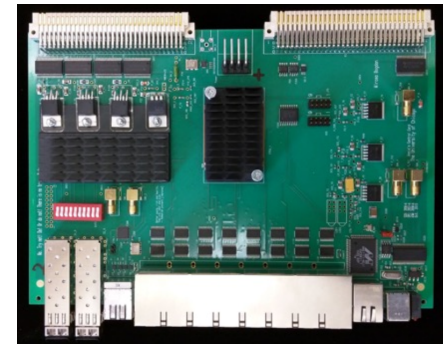
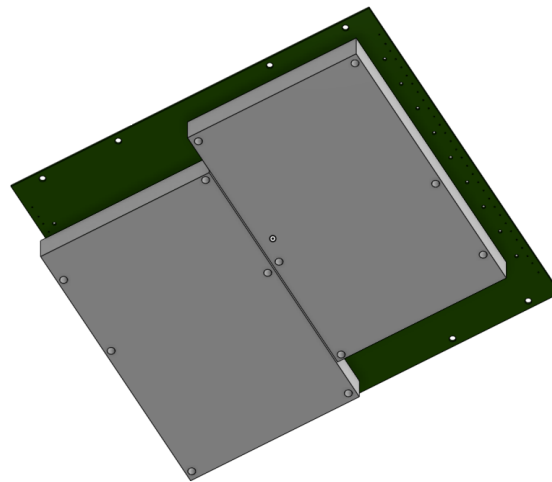
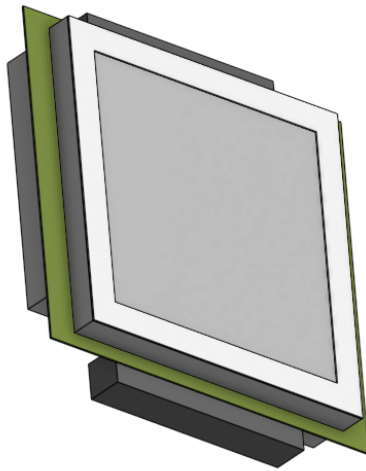
Application Readiness (software/integration)



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

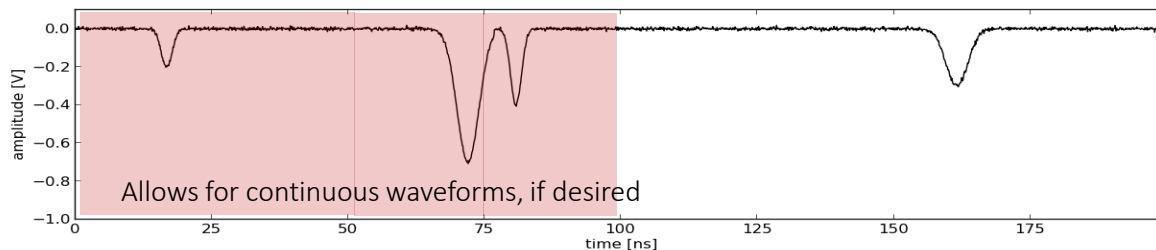
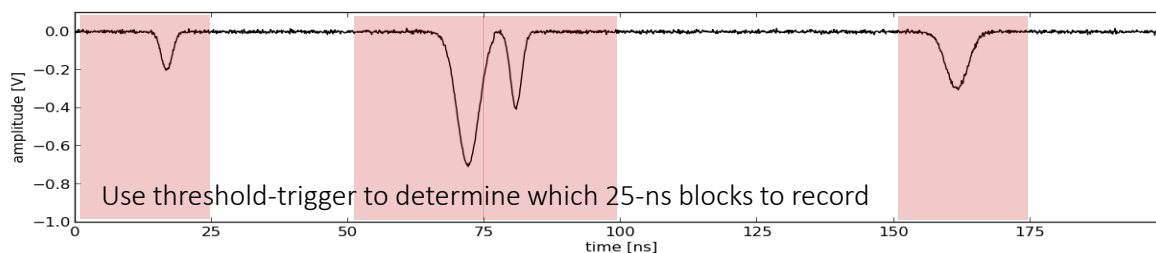
- Digitization of 60 channels on a single integrated ACDC cards
- PSEC-4a with 8x's buffer (200 nsec) in a multi-hit buffering scheme for continuous readout
- Further simplified network topology, possible implementation of white rabbit



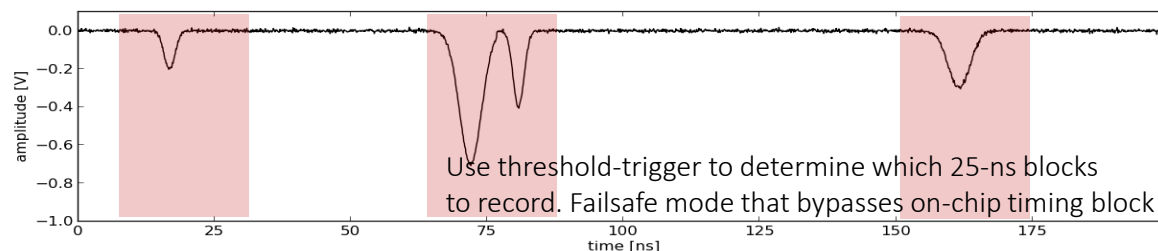
PSEC4a – multi-hit buffering

- 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)



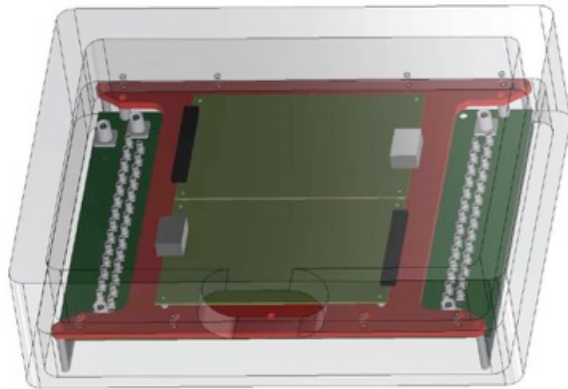
14

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

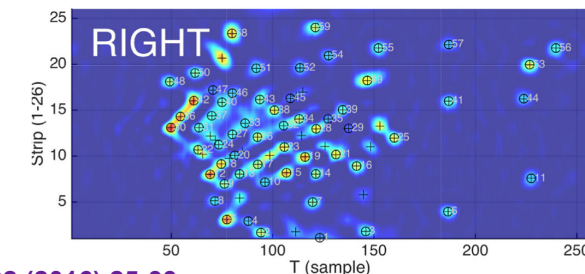
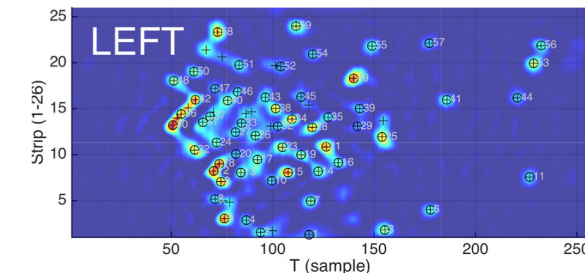
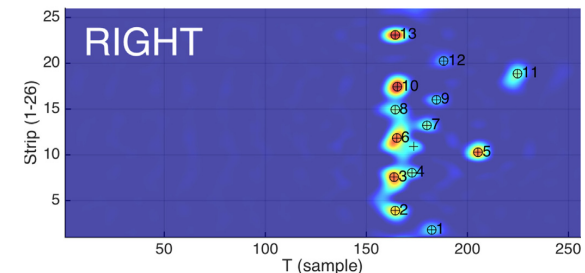
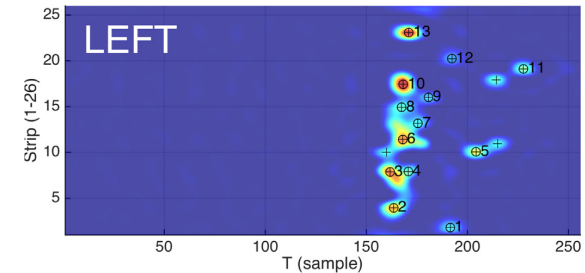
- Single fiber for data transfer
- HV made internal to the housing
- Better strategy for optical coupling



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



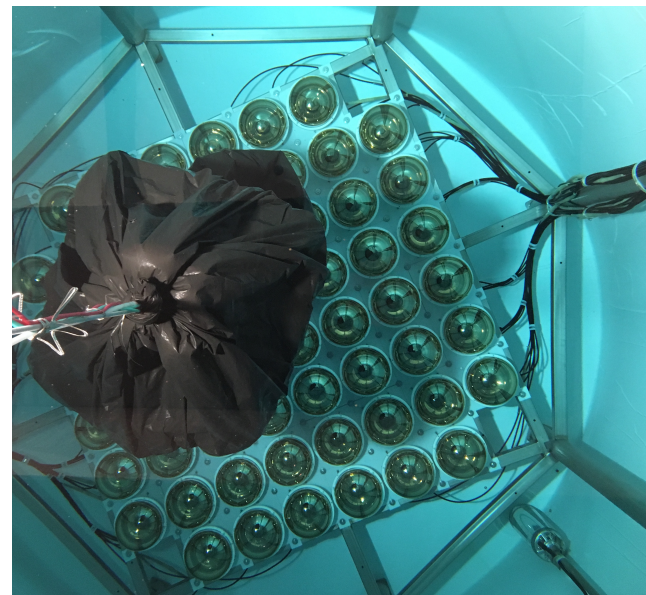
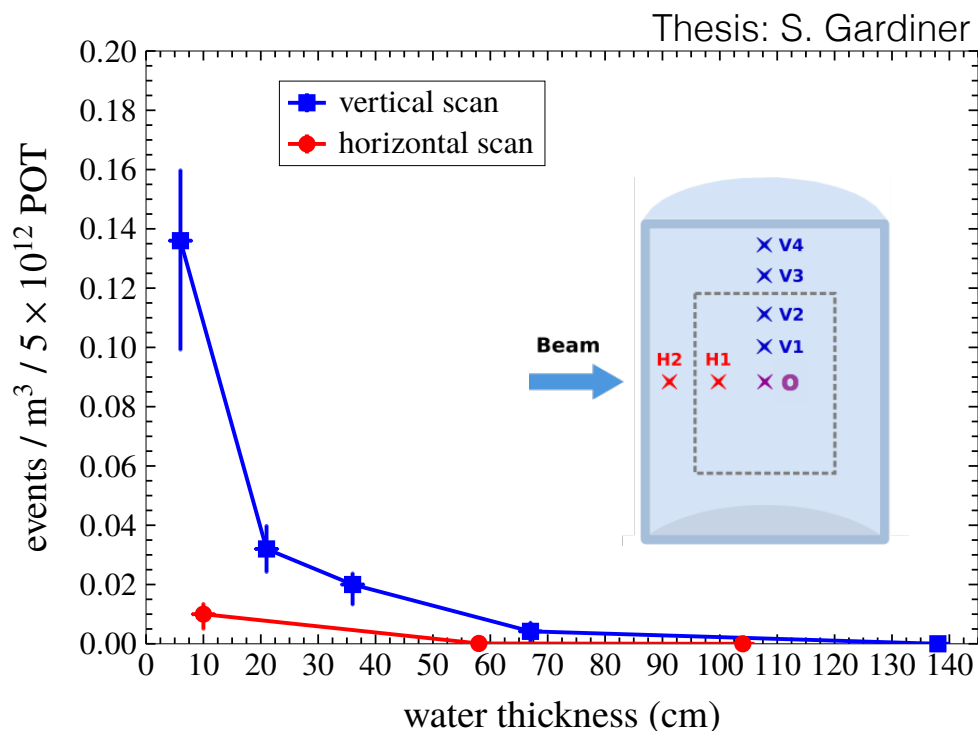
*Multiple-photon disambiguation on stripline-anode Micro-Channel Plates: Nim A 822 (2016) 25-33

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

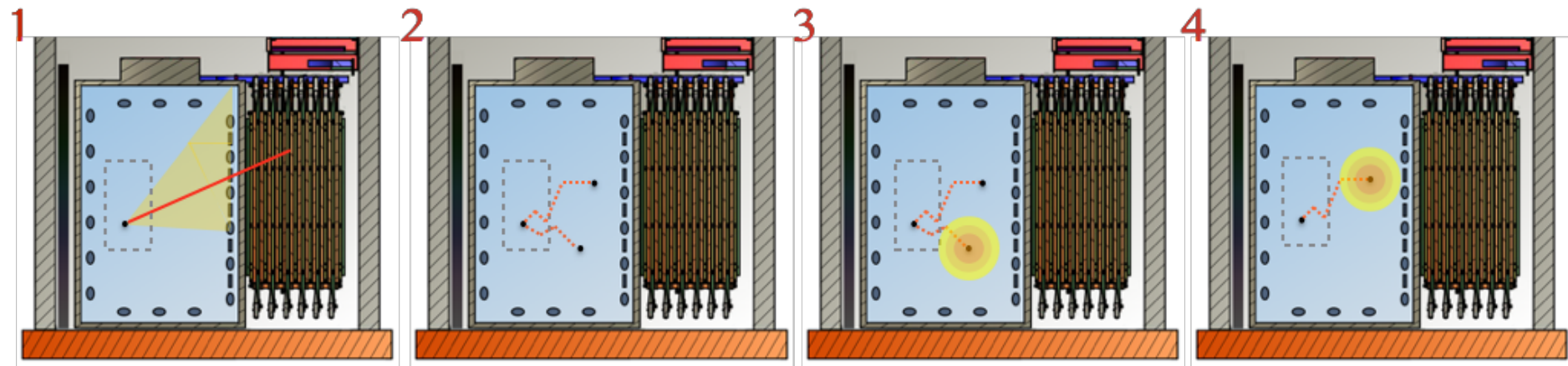


The Main Physics Measurement

“Neutrino-nuclear billiards”



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



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

- Dominant long
- Possible 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 $\chi + \text{NN}$ program to complement $\chi + \text{Np}$ 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!