ANNIE

Status and Plans

Mayly Sanchez on behalf of the ANNIE collaboration

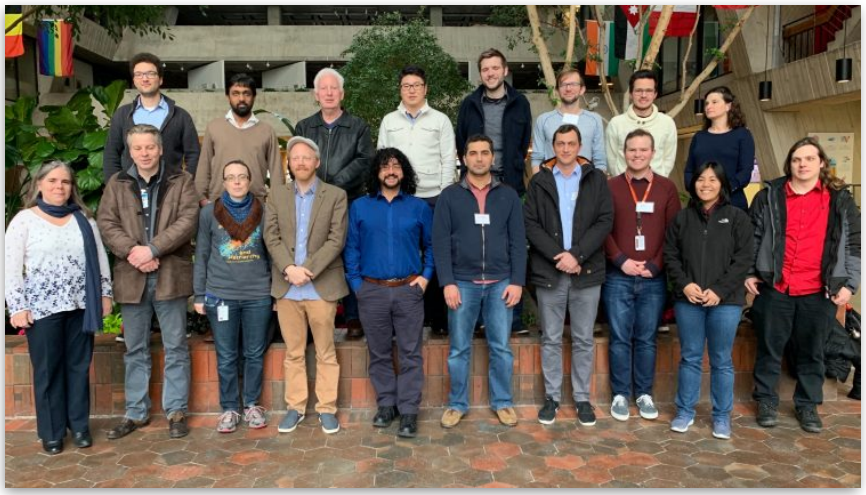
January 15, 2020

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, specifically the neutron yield.
- An R&D effort to develop and demonstrate new neutrino detection technologies/techniques.



ANNIE is an international collaboration:
11 institutions from 3 countries.

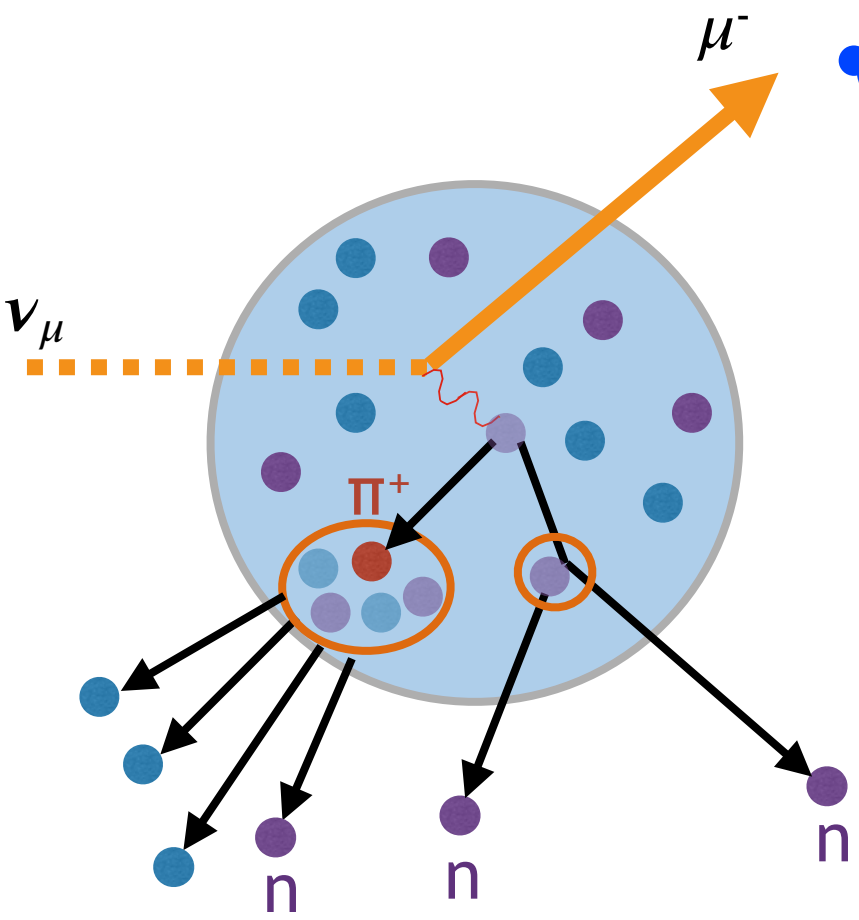
The detector is built, filled and Gadolinium loaded! Most major systems are in operation. LAPPDs are being prepared to be deployed. Commissioning and calibration are close to completion. Physics quality data taking will begin shortly after.

ANNIE 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.



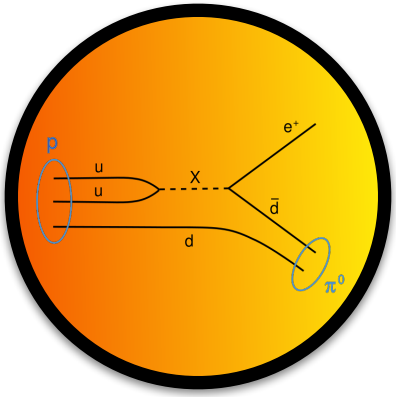
Thus, understanding neutron yields from neutrino interactions is critical to understanding and controlling critical systematics on precision oscillation physics.

Neutrons are a significant systematic uncertainty in experiments like NOvA

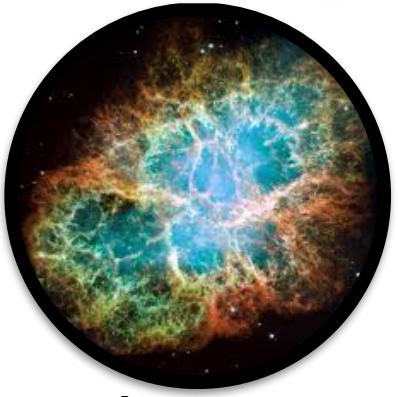
Impact on Astronomical Neutrinos/Rare Processes

The presence, absence and multiplicity 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.



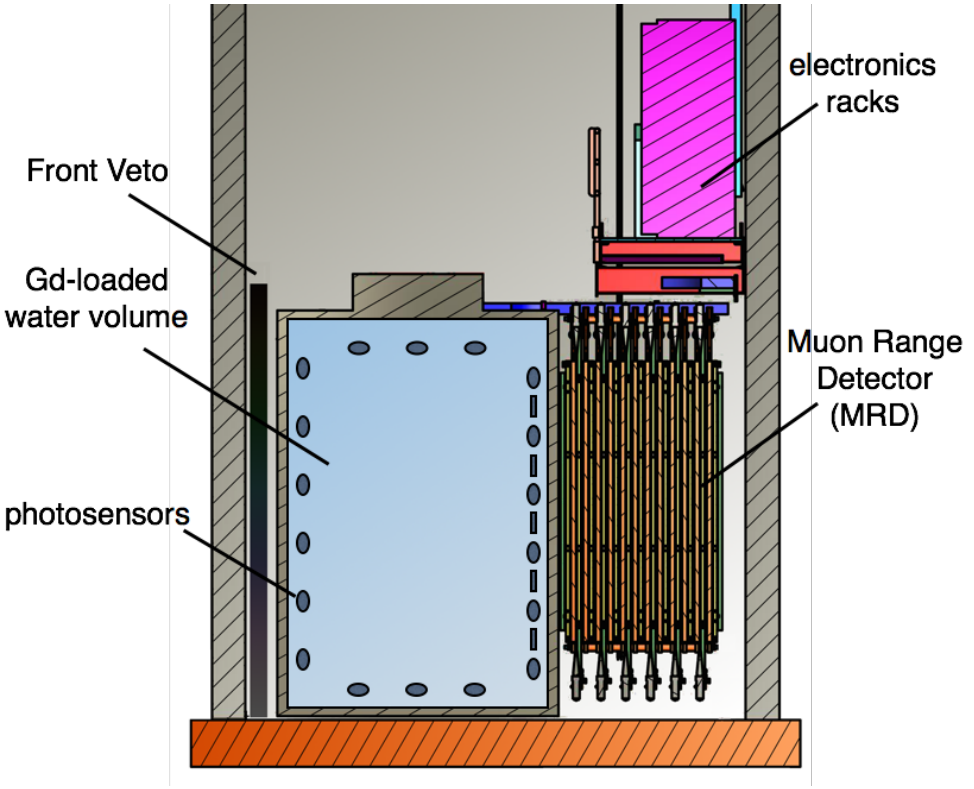
- In searches for the Diffuse Supernova Neutrino Background (DSNB), the presence of any additional neutrons beyond the single inverse beta decay neutron can be used to tag and remove higher energy atmospheric neutrino backgrounds.



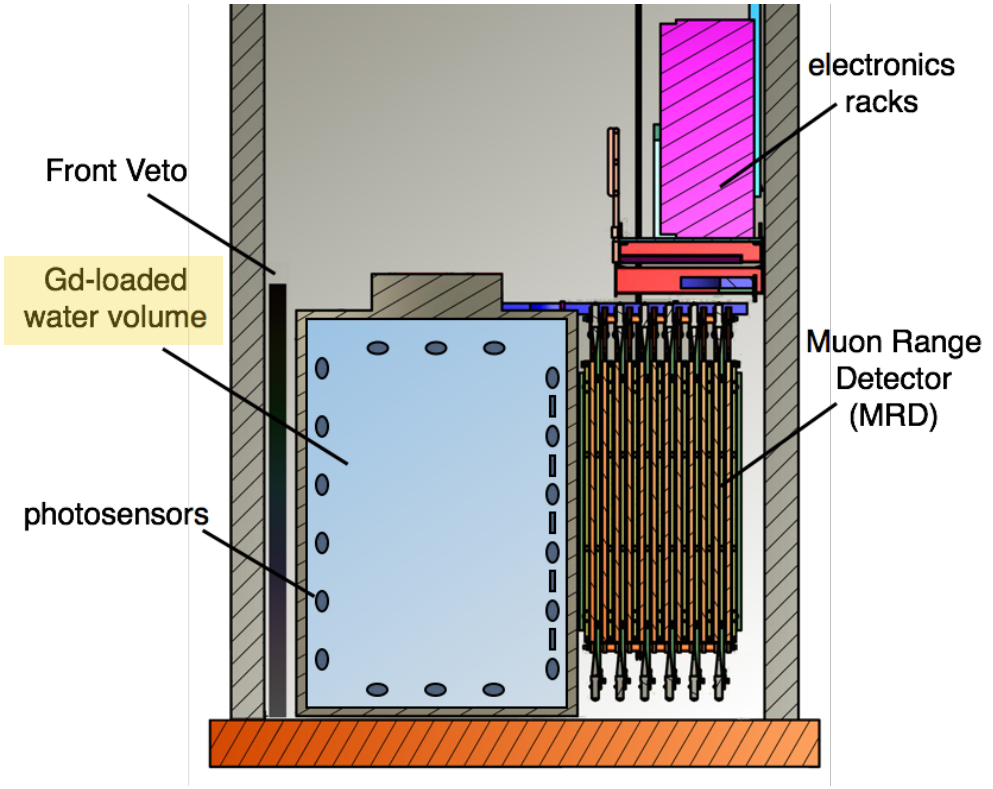
In both cases, estimates of signal purity require an accurate understanding of the neutron multiplicity from the specific class of background events that fake these rare signals.

SuperK is adding Gd to enhance their sensitivity to these physics processes

The ANNIE Detector

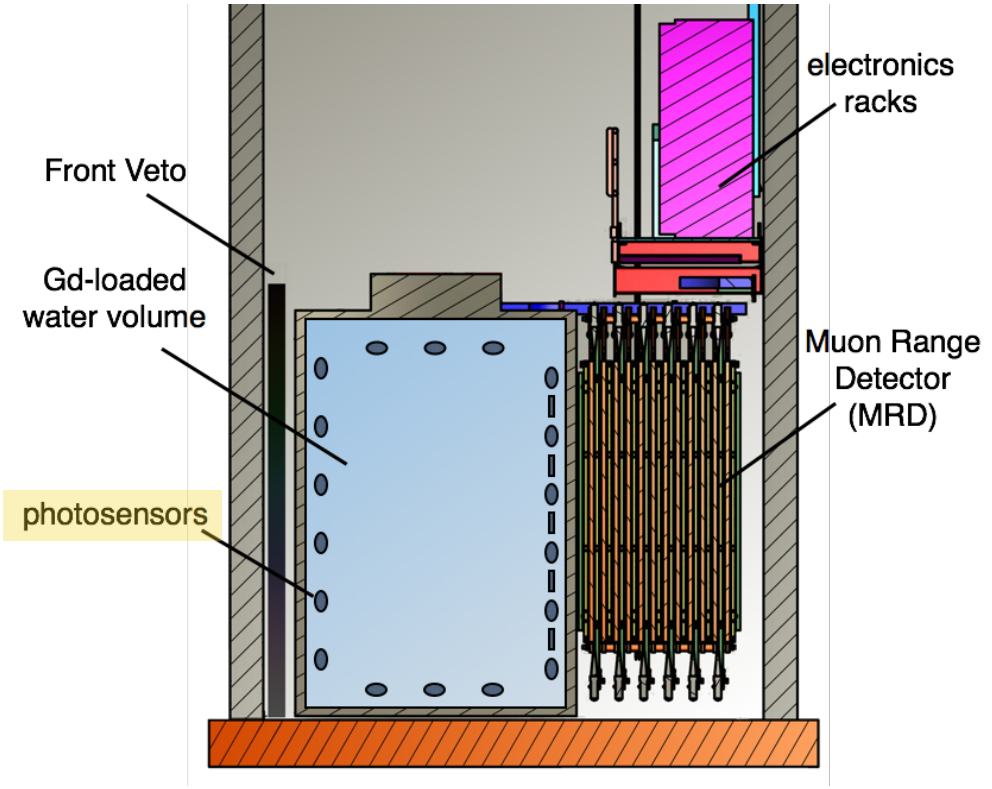


The ANNIE Detector: Gd-loaded water volume



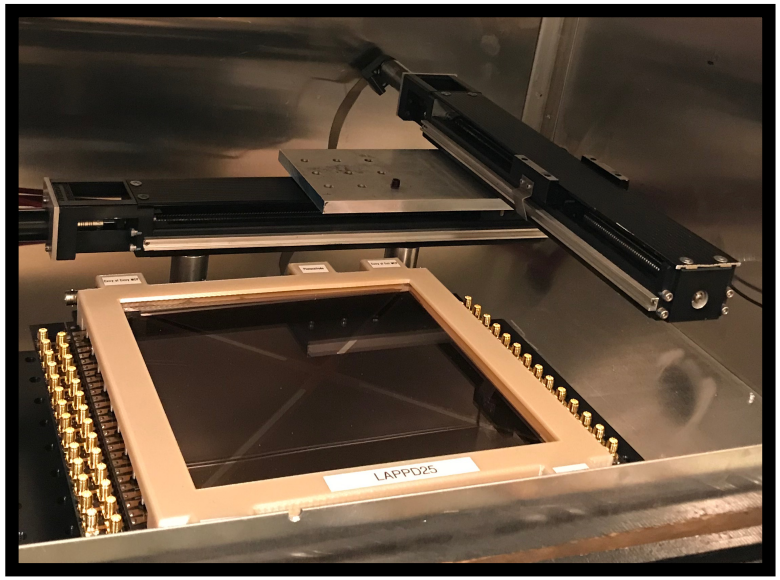
Steel tank holds 26 tons of Gd-loaded water

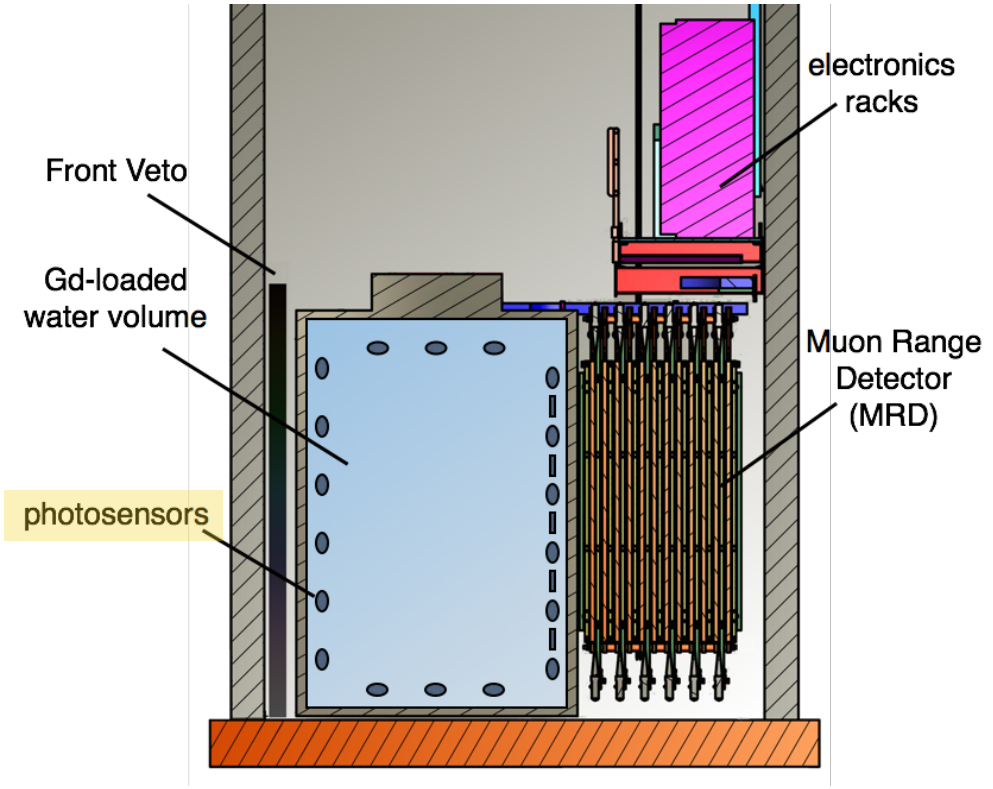
The ANNIE Detector: PMTs



132 8-11” photomultiplier tubes:
20 LUX, 20 ETL, 40 ANNIE, 52 WM

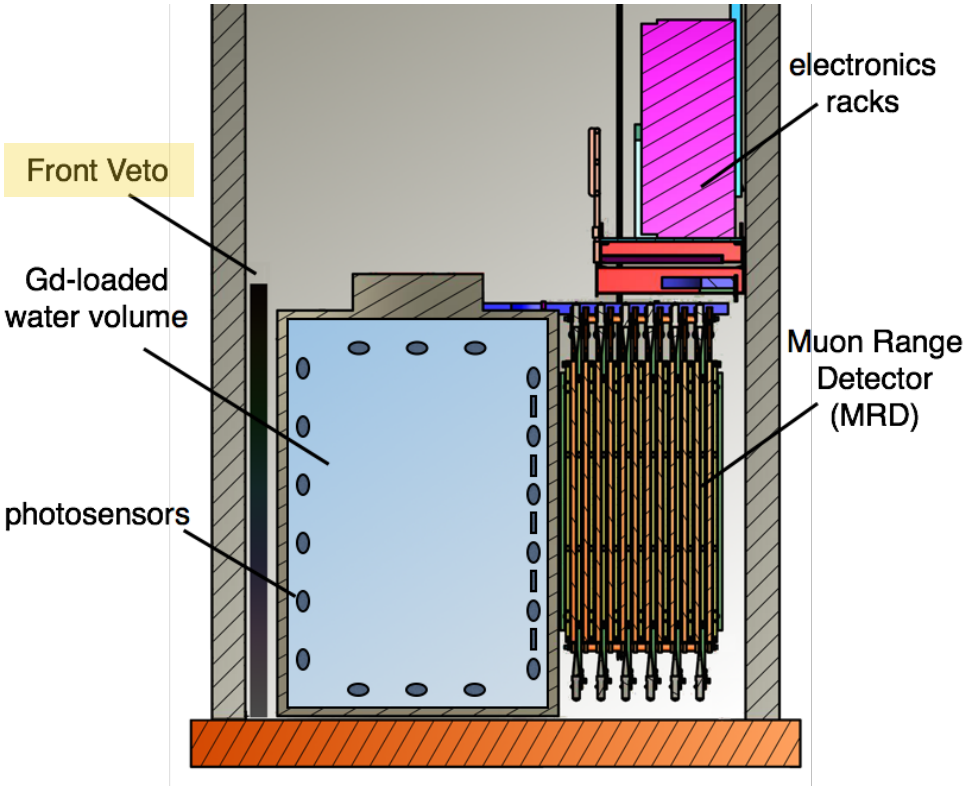
The ANNIE Detector: LAPPDs





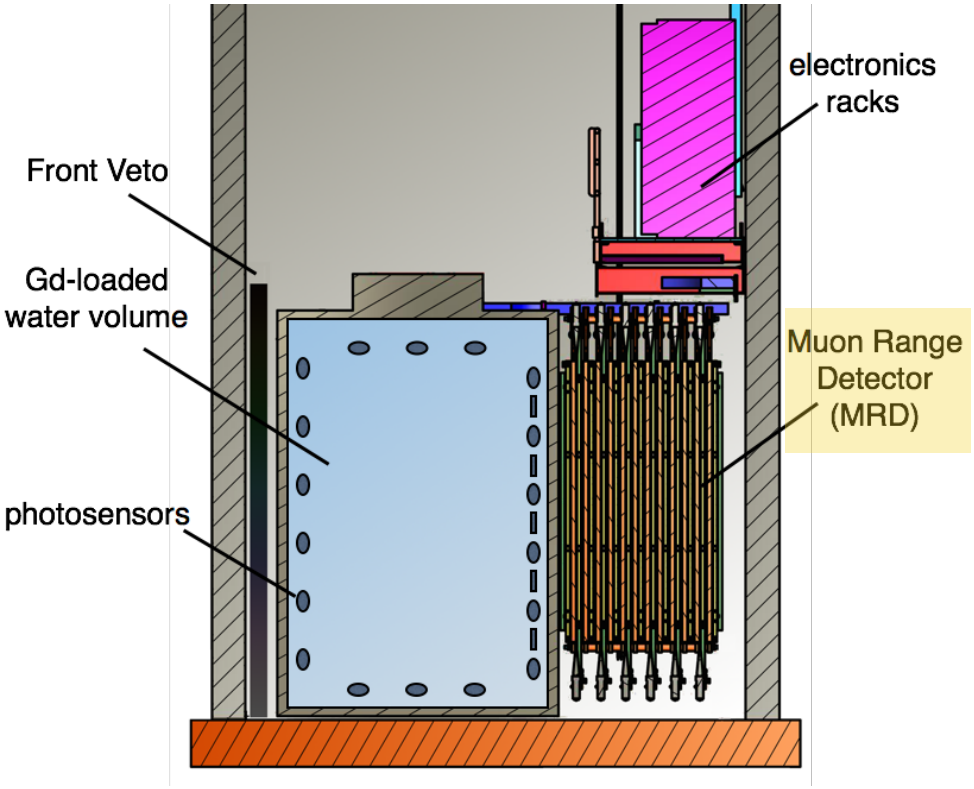
5 LAPPDs, 300 readout channels

The ANNIE Detector: Front Muon Veto (FMV)



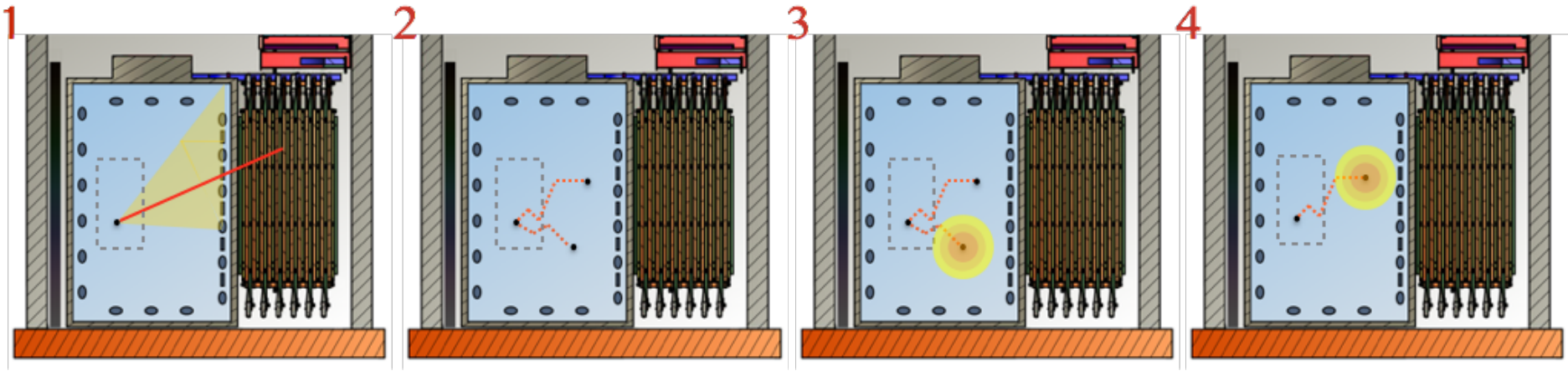
2 overlapping layers of muon paddles:
26 scintillating paddles with 2” PMTs

The ANNIE Detector: Muon Range Detector



11 X-Y alternating scintillator layers with 5cm iron absorber in between; 332 TDC channels

A Neutrino Interaction in ANNIE



1. Neutrino charged current 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 will readout a 70-80 μsec window from the PMT system which results in >90% neutron capture efficiency. Parallel data streams from LAPPDs and the MRD are later combined using GPS tagging.

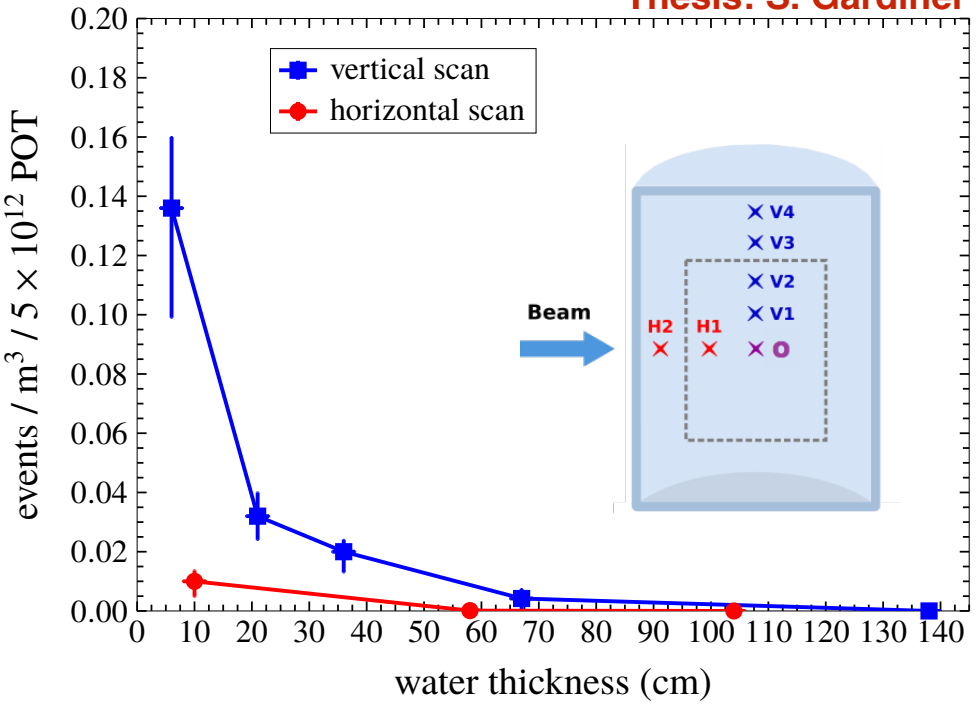
ANNIE Background Neutron Characterization

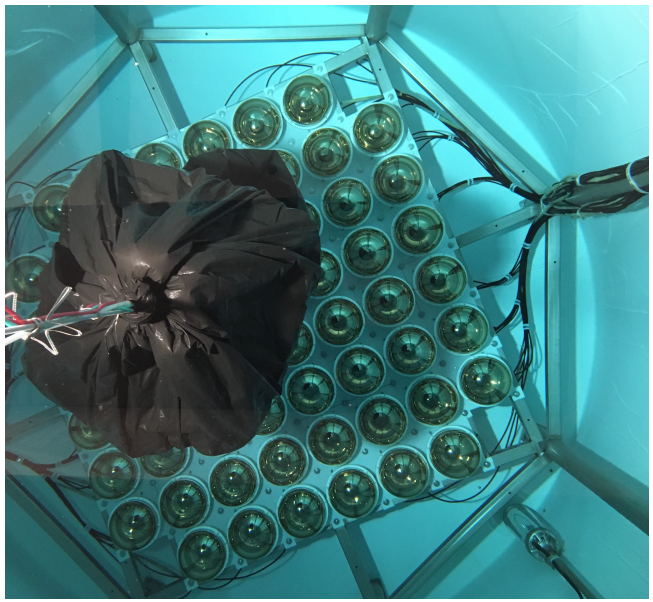
Data was collected over 2016-2017 in a partially instrumented implementation of the detector. This served as an engineering run and an opportunity to characterize background neutrons for ANNIE physics measurement.

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

Results submitted for publication on JINST: arXiv:1912.03186 [physics.ins-det].

Thesis: S. Gardiner



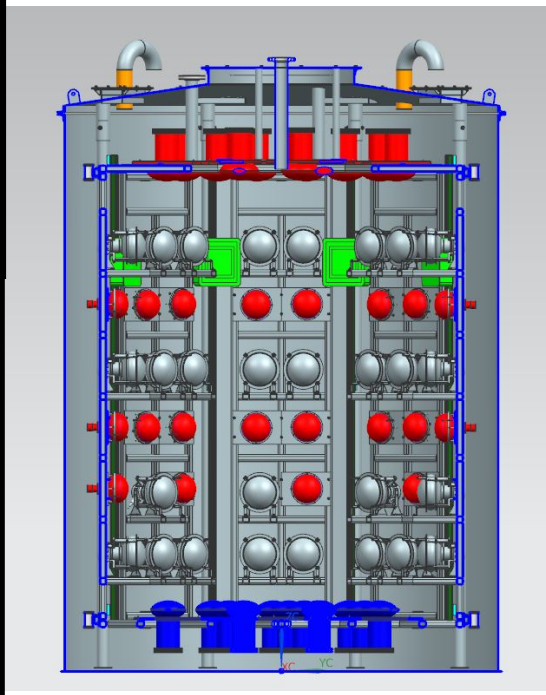


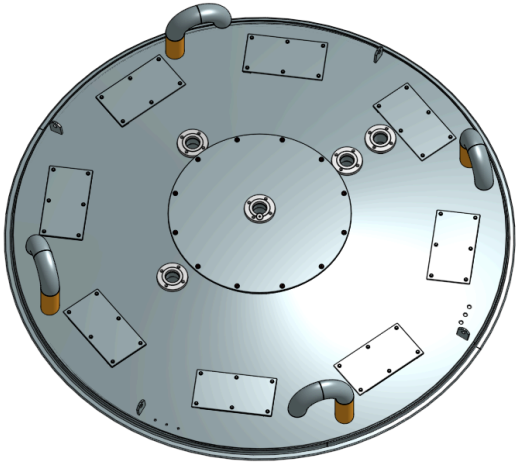
ANNIE Phase I

ANNIE Mechanical Design

- The main ANNIE detector was designed with Fermilab engineering support, based on the successful design employed during Phase I.
- A stainless steel inner structure supporting the PMTs hangs from the lid of the tank.
- This inner-structure and lid are self-standing and can be removed from the tank for ease of PMT installation.
- First the tank is installed in the hall. The inner structure, once instrumented, is then lowered into the tank.
- The tank and liner were purchased by the ANNIE collaboration. The inner structure and feedthroughs on the lid were made by Fermilab.

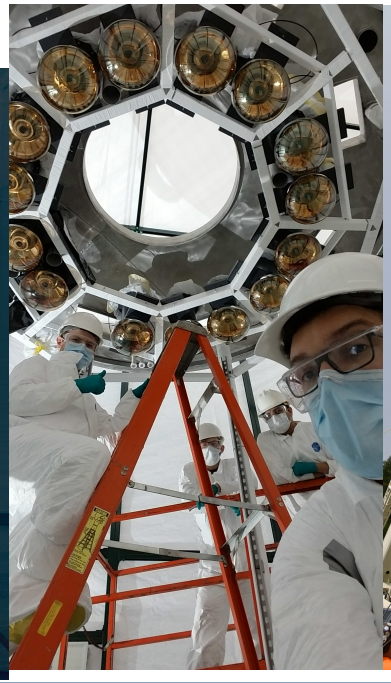
Completed detector is installed in the hall





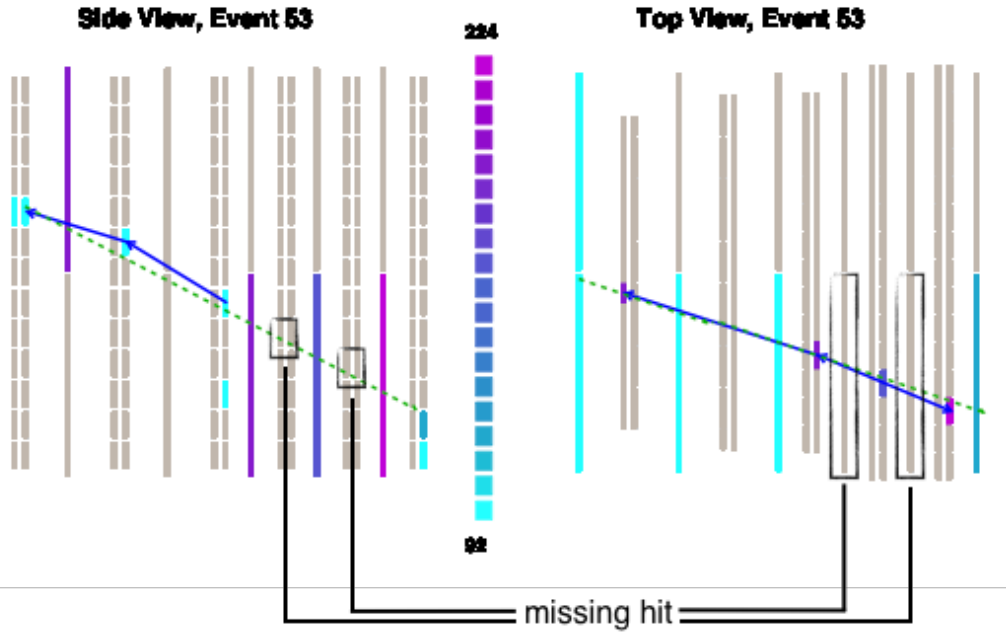
ANNIE Construction

- Schedule was driven by the arrival of funding and the longest lead time items.
- Cleaning and passivation of the inner structure was completed by early May.
- Construction efforts were postdoc and student led:
  - Cleaning and teflon-wrapping of the steel structure.
  - Mounting the PMTs.
  - Application of the black sheet.
- The inner structure was completed and deployed in the hall by mid-August 2019.



Assembling the ANNIE Detector

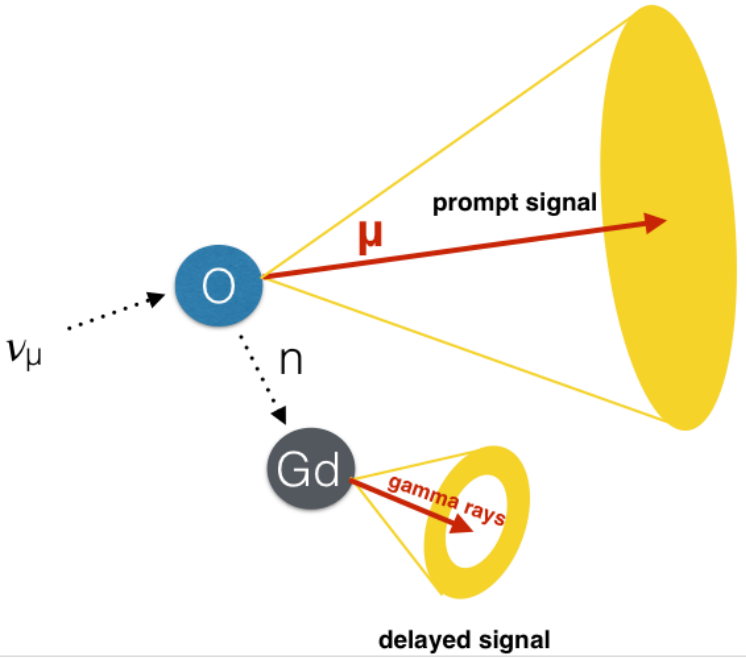
ANNIE Muon Range Detector



- The refurbished ANNIE MRD is now fully operational, along with a working suite of track reconstruction tools.
- Efficiencies are evaluated by looking at how frequently any given paddle misses a through going track.
- The majority of paddles perform at better than 80% efficiency. We are now working on troubleshooting the low efficiency channels and equalizing the gains.

Enabling Technology: Gd-loading of water

- Efficient neutron counting is made possible by Gadolinium loading of water.
  - ANNIE uses 52 kg of gadolinium sulfate for a 0.1% Gd-load.
  - Gd has a high neutron capture cross section for thermal neutrons.
  - These captures produce a delayed (O(10) μsec) ~8 MeV gamma cascade, detectable in water from its Cherenkov light.

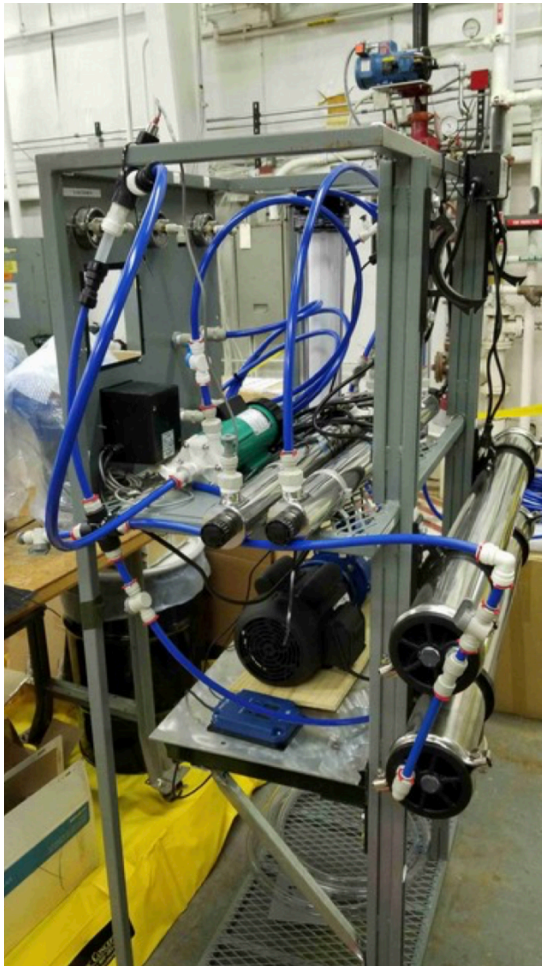


ANNIE is now the first Gd-loaded water Cherenkov detector on a neutrino beam

Enabling Technology: Gd-loading of water

- Significant work on testing Gd material-compatibility for all components of the detector including teflon wrapping/liner.
- Development of a low-cost purification system for smaller scale Gd-water deployments.
- Developed a method for 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



Novel purification method will be written up for publication

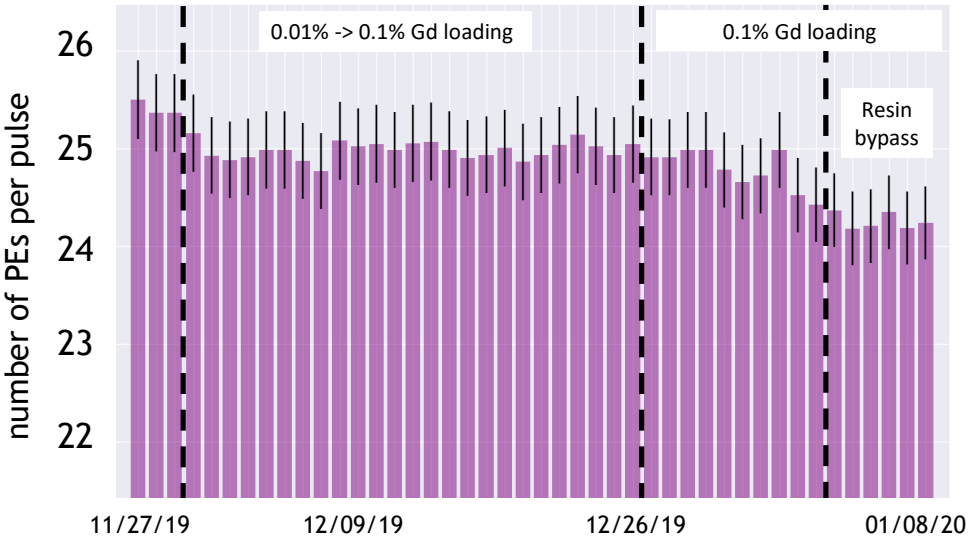
Enabling Technology: Gd-loading of water

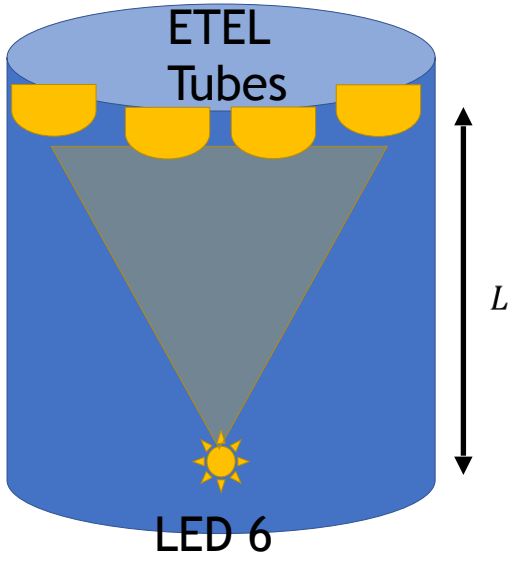
- 1% of nominal loading:
  - From 09/25 to 11/29 → 2 months
- 10% of nominal loading:
  - From 11/29 to 12/17 → 2 weeks
- Full loading:
  - Process took a week (12/17 to 12/24)
- Detector fully loaded since 12/24

Staged loading with in-situ measurements and water sampling monitoring

Enabling Technology: Gd-loading of water

- A LED system has been used to monitor transparency (number of photoelectrons observed by top PMT tubes).
  - Monitored on daily basis through the Gd-loading phases.
  - Water transparency has been been constant within uncertainty.
- Consistent with other measurements:
  - Water skid in-situ instruments:
    - Conductivity meter
    - pH meter
  - Direct measurement of transparency from samples:
    - UV-Vis Spectrometry
  - Standalone tests from samples:
    - Measurement of iron levels



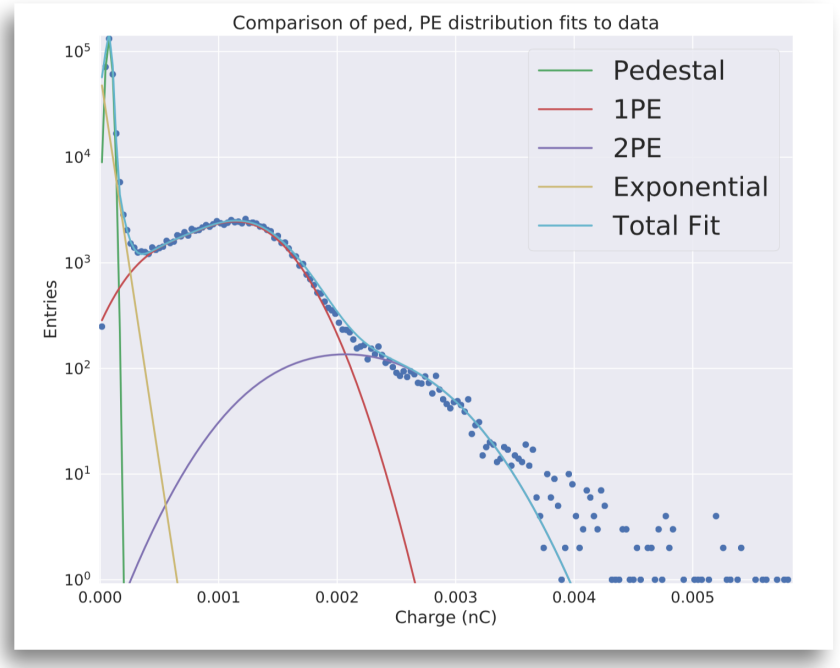


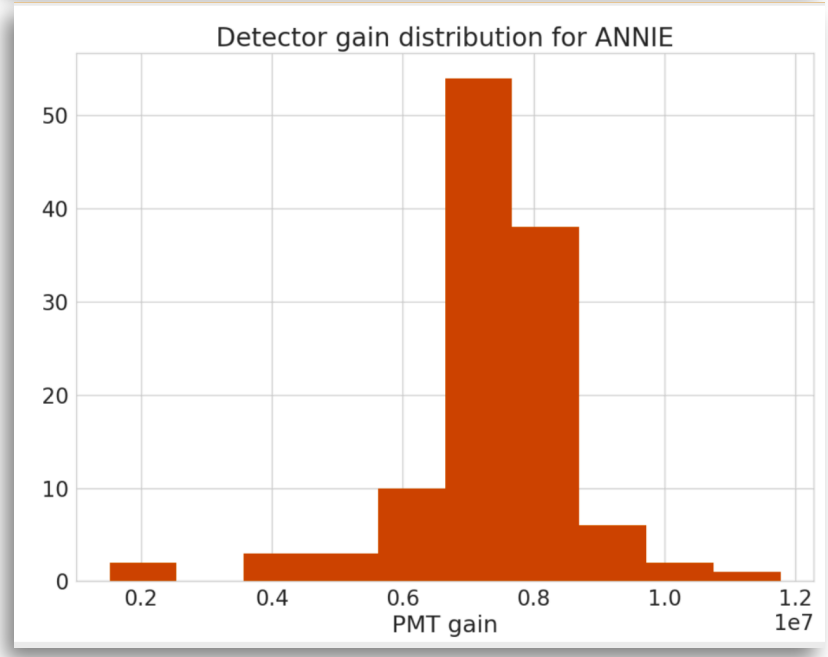
ANNIE Calibration

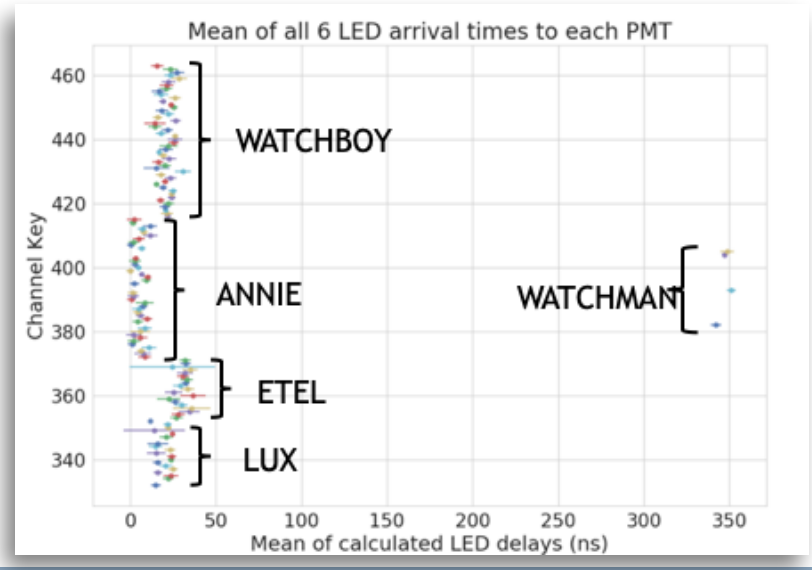
Method	Use	Status
LEDs	Water transparency measurement	**Complete. Daily measurements are taken.**
	PMT Timing (5ns)	**Complete**
	PMT gain matching	**Complete**
AmBe	Neutron capture efficiency	Source is ready. DAQ triggering is finalized. Initial deployment next week.
Laserball	PMT timing (sub-ns)	Pulsed laser and fiber on hand. Ball being designed this week. Deployment ready by end of February.
Standard candle	Detector stability	Design finalized, Cs source at UC Davis. Build complete by end of January.

ANNIE Calibration

- Have extracted single PE gain for each PMT.
- PMT voltages have been set for average gain of 7×10^6.
    - Balance of good peak-to-valley ratios (1.5-2 throughout the detector) with reasonable dark rates (<10 kHz for most PMTs) .
- Cable delays have been determined with an uncertainty of 5 ns.

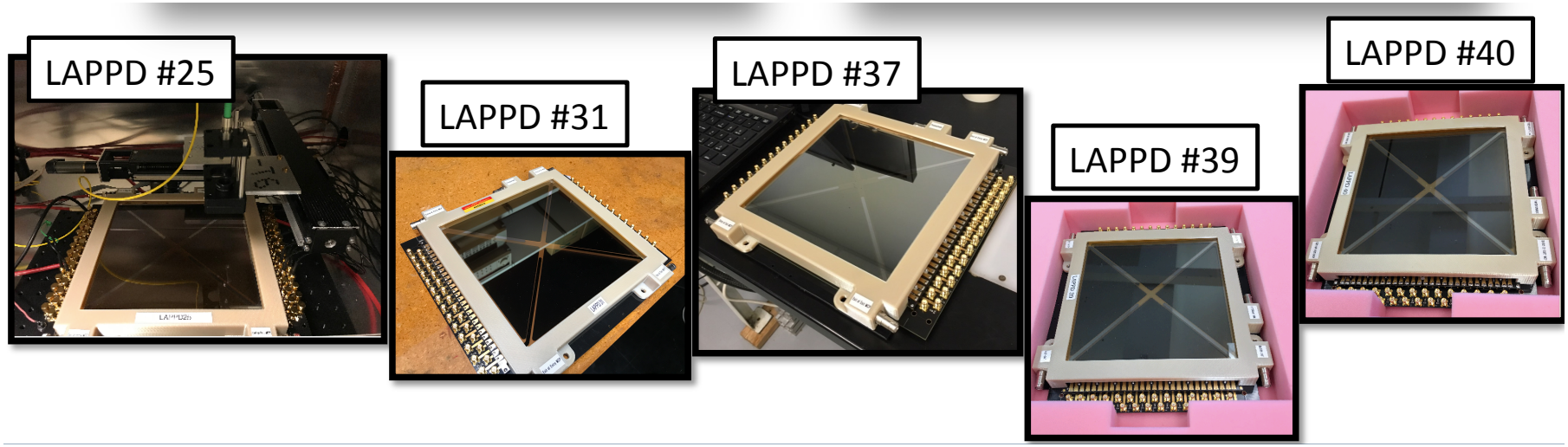




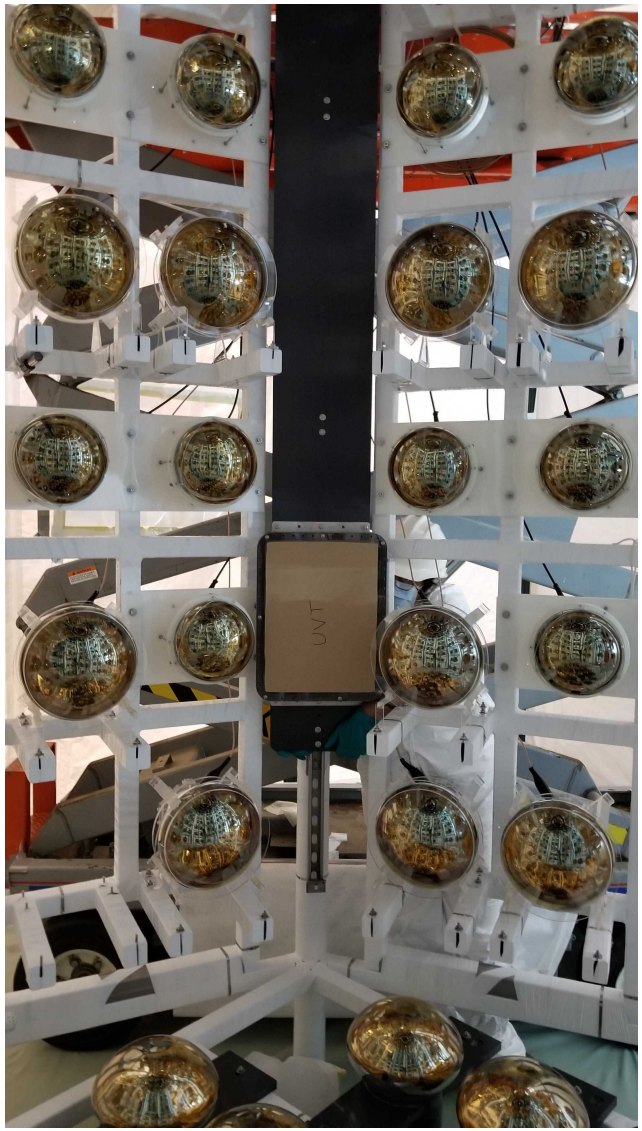


Enabling Technology: LAPPDs

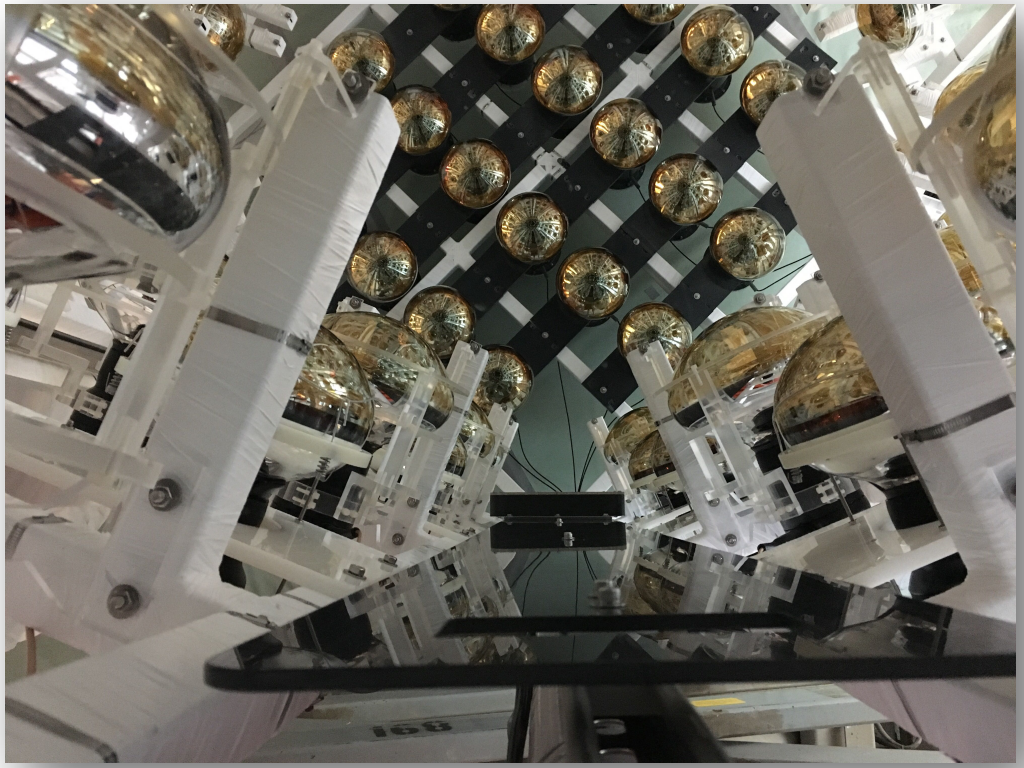
- ANNIE has received all 5 LAPPDs planned for this phase. They are at Fermilab, under systematic testing at our facility in Lab-6.
    - LAPPDs meet the ANNIE specifications: eg. QE more than 20%.
- We have completed the necessary work for their deployment:
    - Design and testing of the waterproof housing.
    - Development of the slow controls system.
    - Modifications to the firmware and software to enable the PSEC readout system.
- All of the pieces are now in place and the schedule is driven by efforts to assemble, integrate, and deploy the LAPPDs.



Enabling Technology: LAPPDs



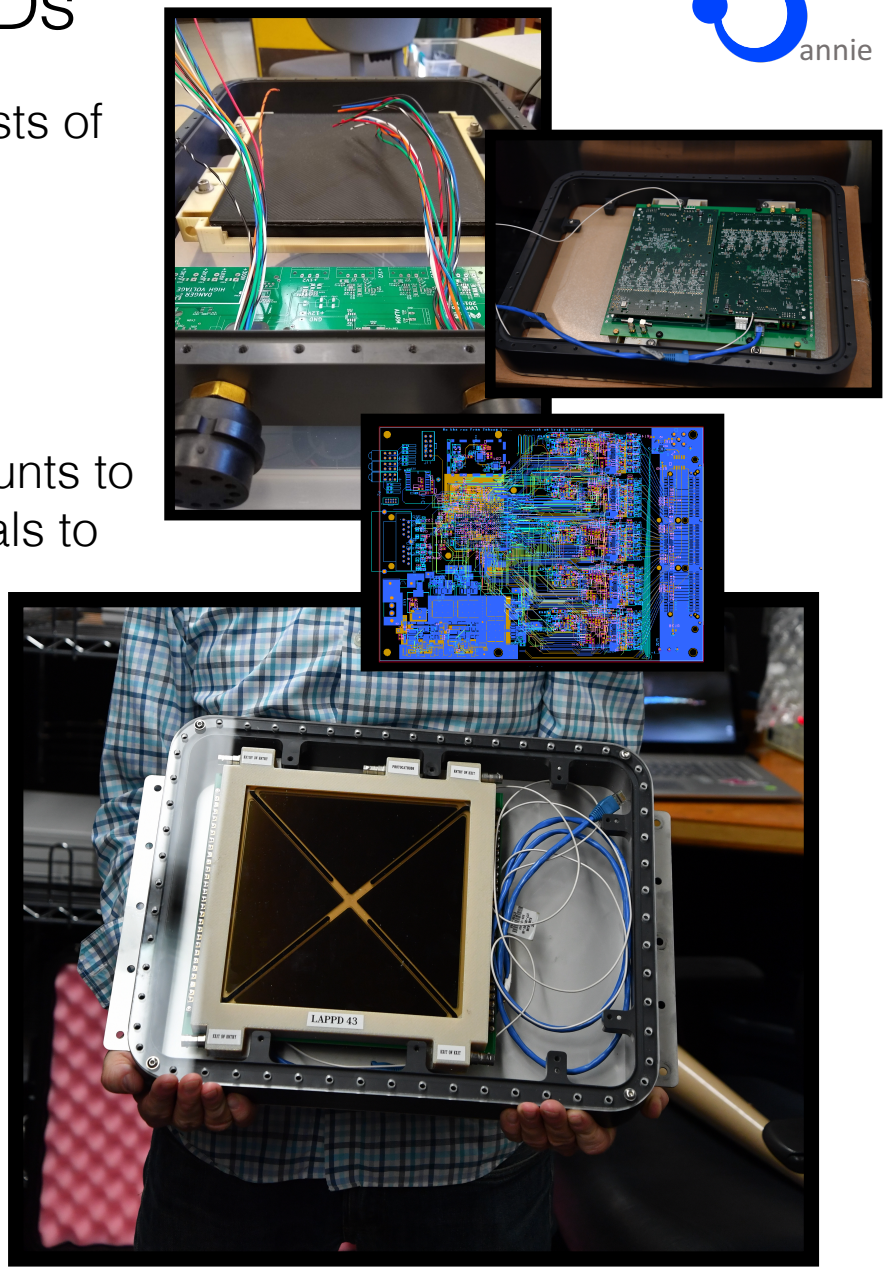
- The LAPPDs deployment is designed for flexibility. The housing is mounted on a PVC panel that slides on tracks attached to the detector's mechanical structure.
- Deployment was tested before the detector was installed in the hall.



Enabling Technology: LAPPDs

- Current design of the LAPPD package consists of
  - a waterproof housing with
    - acrylic window
    - steel backplane
    - PVC sidewalks
  - a board (Analog Pickup Board) that mounts to the back of the LAPPD and brings signals to the two readout mezzanine cards
  - two readout cards (ACDC cards)
  - a trigger logic board
  - a slow controls board (LV-HV card)
- All boards are built and undergoing testing in preparation for deployment.

First experience in deploying a multi-LAPPD system

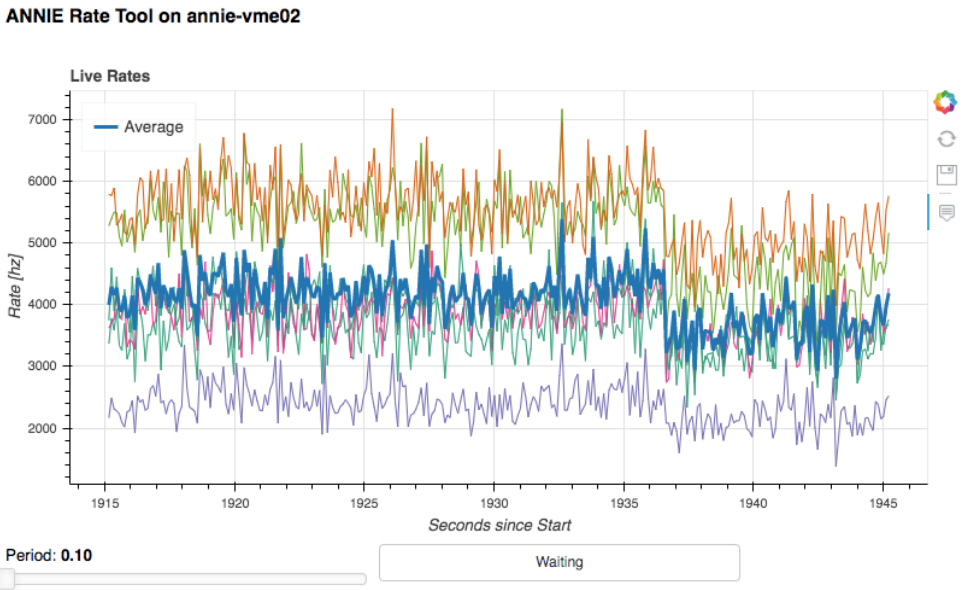


ANNIE Data Acquisition

- The ANNIE DAQ consists of 4 parallel systems:
  - The PMT readout uses flash ADC cards developed by the K0TO collaboration with firmware newly rewritten for ANNIE.
  - The MRD uses the same CAMAC system employed by SciBooNE.
  - The LAPPDs are digitized with custom electronics designed at U Chicago. around the PSEC-4 waveform sampling ASIIC.
  - Timing and trigger logic are handled by a central trigger card.
- The parallel data streams from these systems is managed by the ToolDAQ software framework, designed for Hyper-K and a candidate for use in WATCHMAN and Theia.

Status:

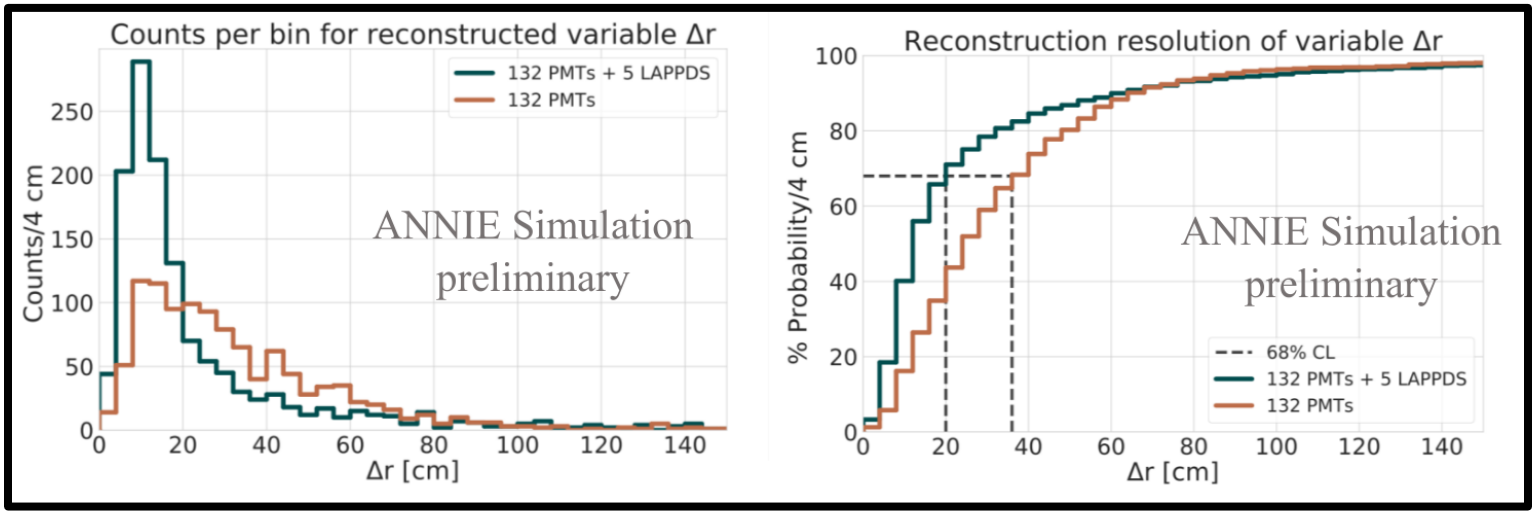
- Firmware needed for FY2020 beam operation is complete.
- Commissioning of the DAQ is complete for calibration triggers.
- First beam trigger runs are being recorded as of this week.
  - Stay tuned for first neutrino events in the next few days.



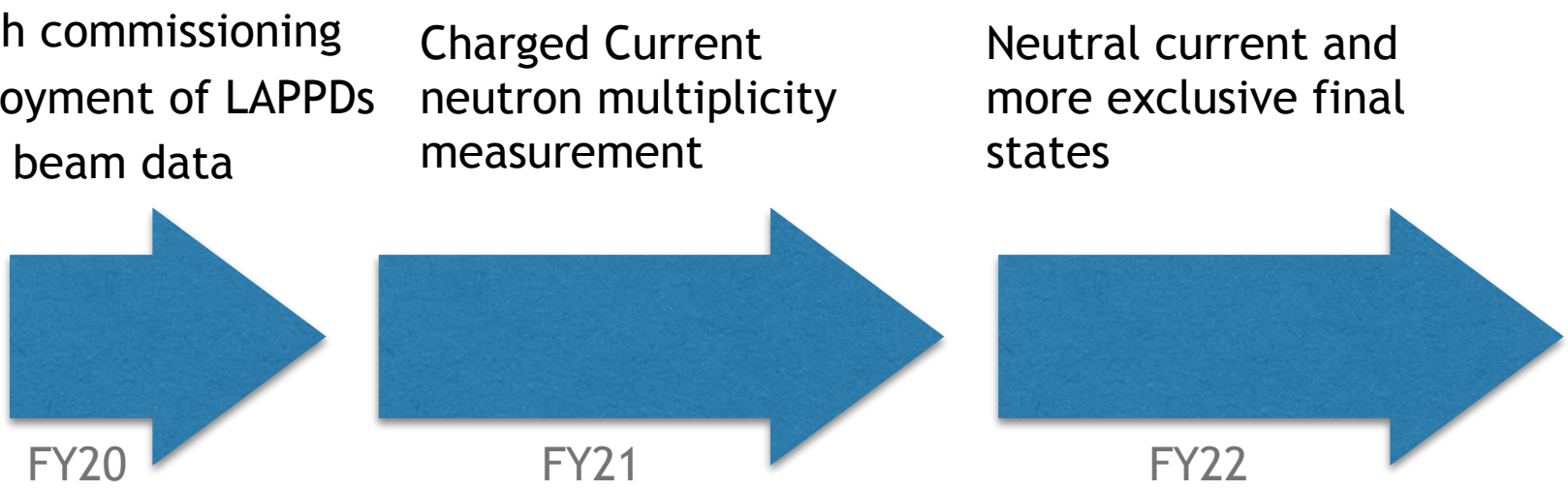
Rates during light tightening

ANNIE Simulation, Reconstruction and Analysis

- A complete detector simulation (based on WCSim) has been developed.
- A modular framework (ToolAnalysis) for data and simulation reconstruction and analysis is being exercised and is fully integrated with ToolDAQ.
- We have shown improved vertex and direction resolution from the addition of 5 LAPPDs compared to using just the PMTs.
- We have also developed machine and deep learning techniques for muon and neutrino energy reconstruction.
- Work on developing single ring selection and neutron tagging is in progress.

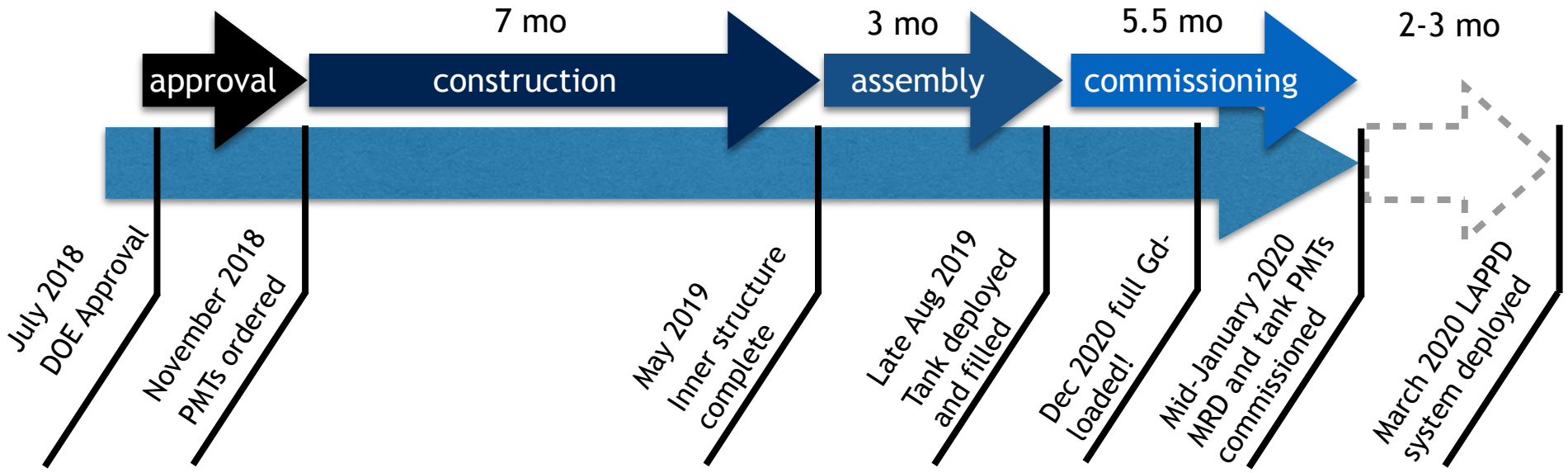


ANNIE Physics Analyses Timeline



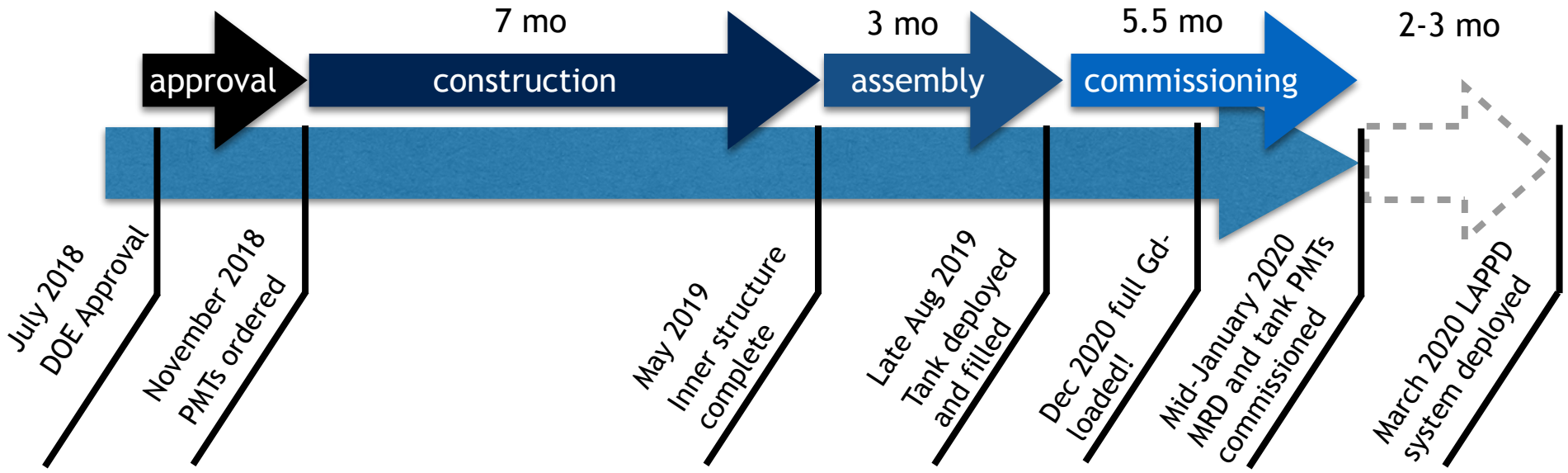
- ANNIE physics measurements require data from 2 years of running:
  - In the first year we will focus on Charged Current interactions with stopped muons in the Muon Range Detector (MRD).
  - Other topologies/kinematics such as Neutral Current events and lower energy CC interactions where the muon stops in the water volume require data beyond the first year.
- Many opportunities for possible additions to expand physics capabilities:
  - More LAPPDs, addition of water-based Liquid Scintillator – seeing sub-Cherenkov particles, detailed reconstruction of multi-track events, improved neutron capture position resolution.

Summary



- The ANNIE collaboration has constructed, assembled and installed the detector which is now under commissioning and calibration.
- Significant care has gone into the successful Gd-loading of the detector. Water transparency is excellent and is being continuously monitored.
- PMT gain (and first order timing) calibration is now complete and neutron source calibration will start shortly.

Summary



- LAPPDs are being characterized before deployment, the hardware and firmware are in a complete state paving the way for work on system integration and deployment.
- Work on reconstruction and analysis has started. With the detector fully operational focus of the collaboration will shift to analyzing the data.
- **First beam data being recorded as we speak, expect physics quality neutrino data soon.**

THANK YOU

(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
- 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

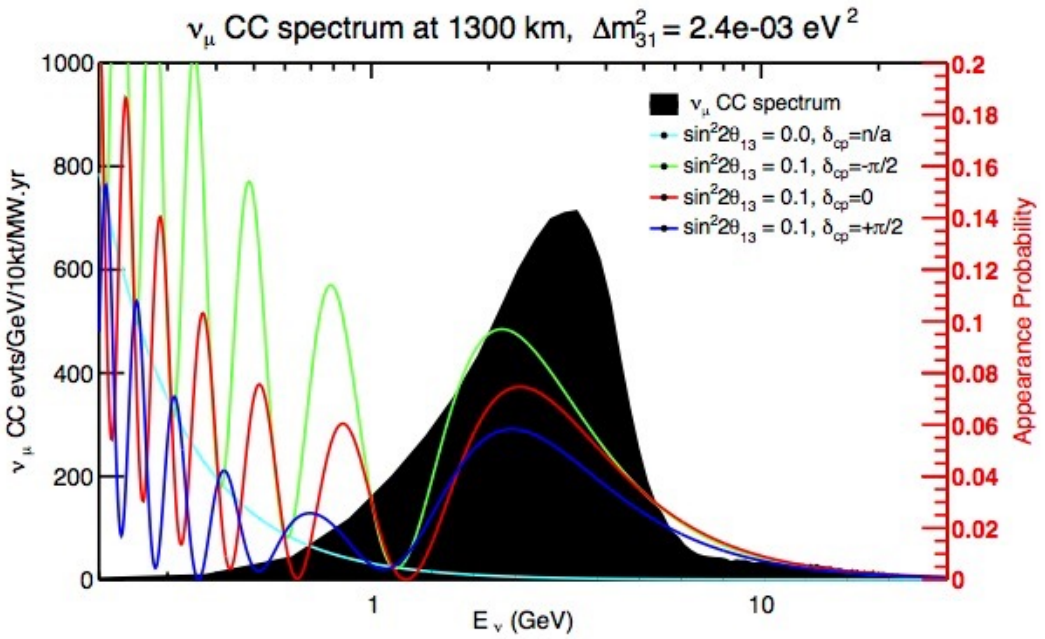
Other directions + wbLS

- Calorimetric energy reconstruction
- Beam timing
- De-exitation 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:

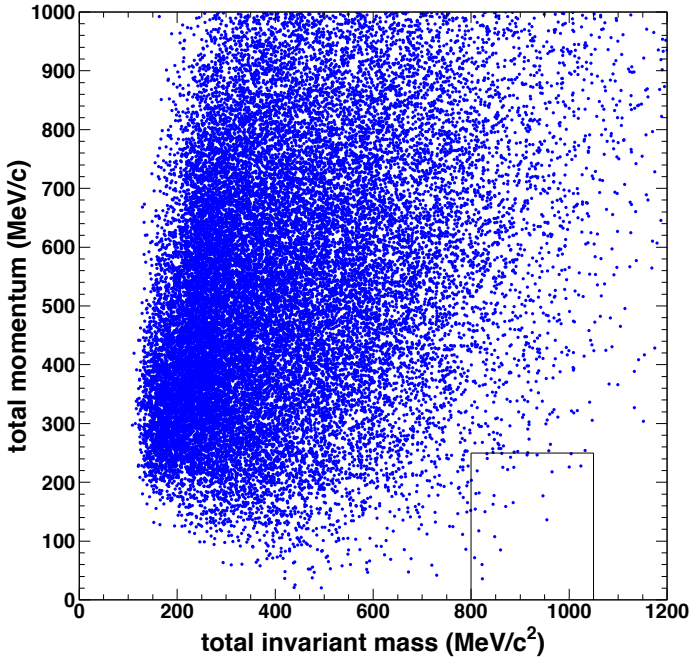
- better low-E reconstruction
- more fiducial mass, ie more stats

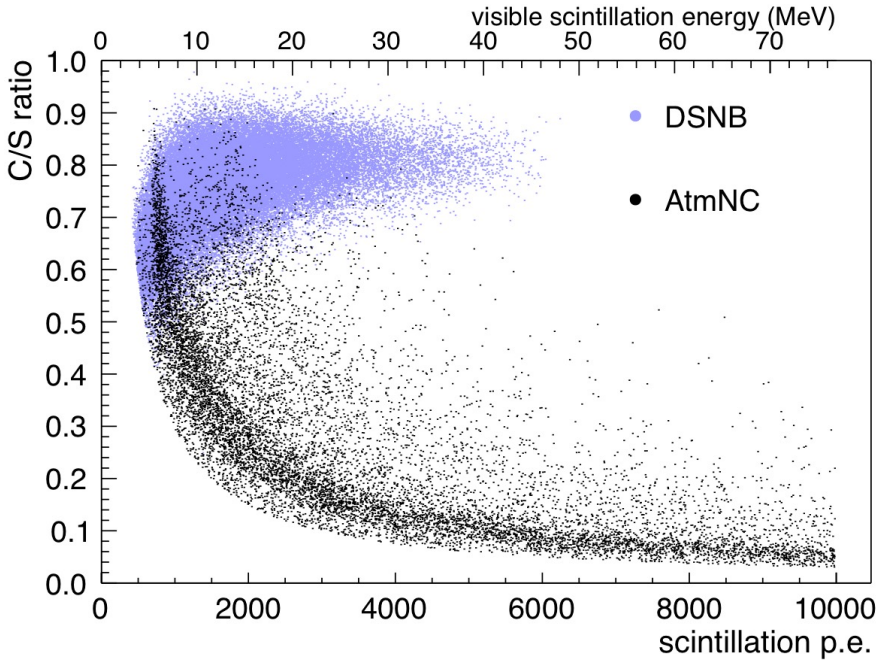


- Succeeding at that measurement will require excellent ~1 GeV neutrino reconstruction, in the context of a wideband, high energy neutrino beam
  - better reconstruction of event topology (track counting and directionality, EM shower structure)
  - more detailed picture of the nuclear system
- ANNIE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



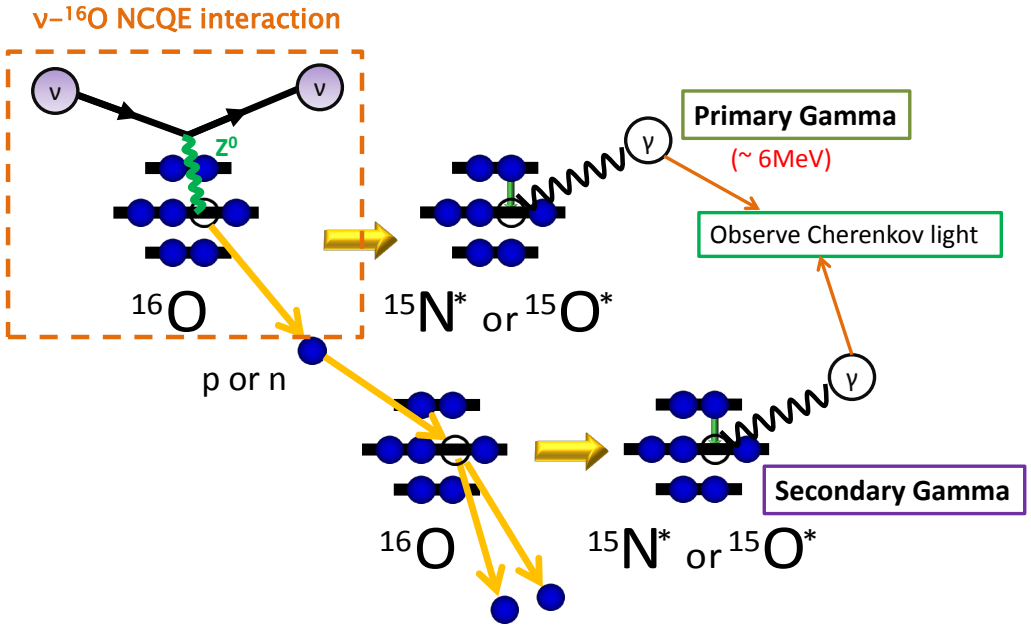


Tagging Nuclear De-excitation Gammas

- 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!!

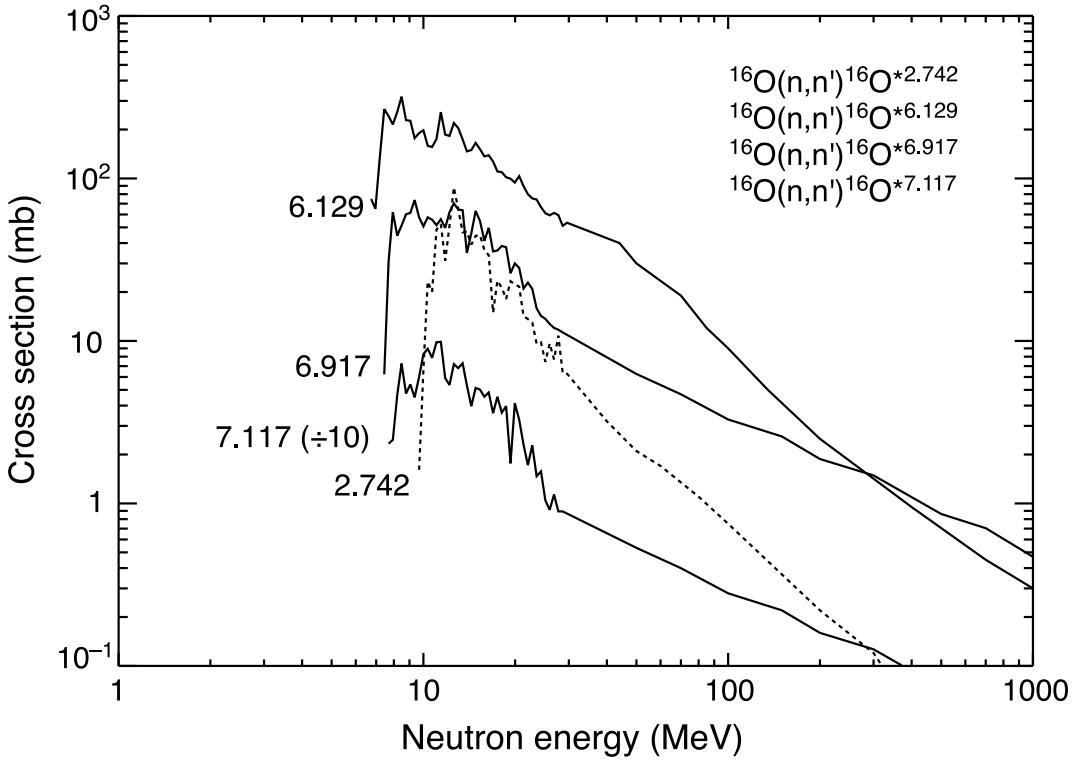
The gamma emission from radiative capture happens on nanosecond timescales

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

What do we measure that capture rate to be?

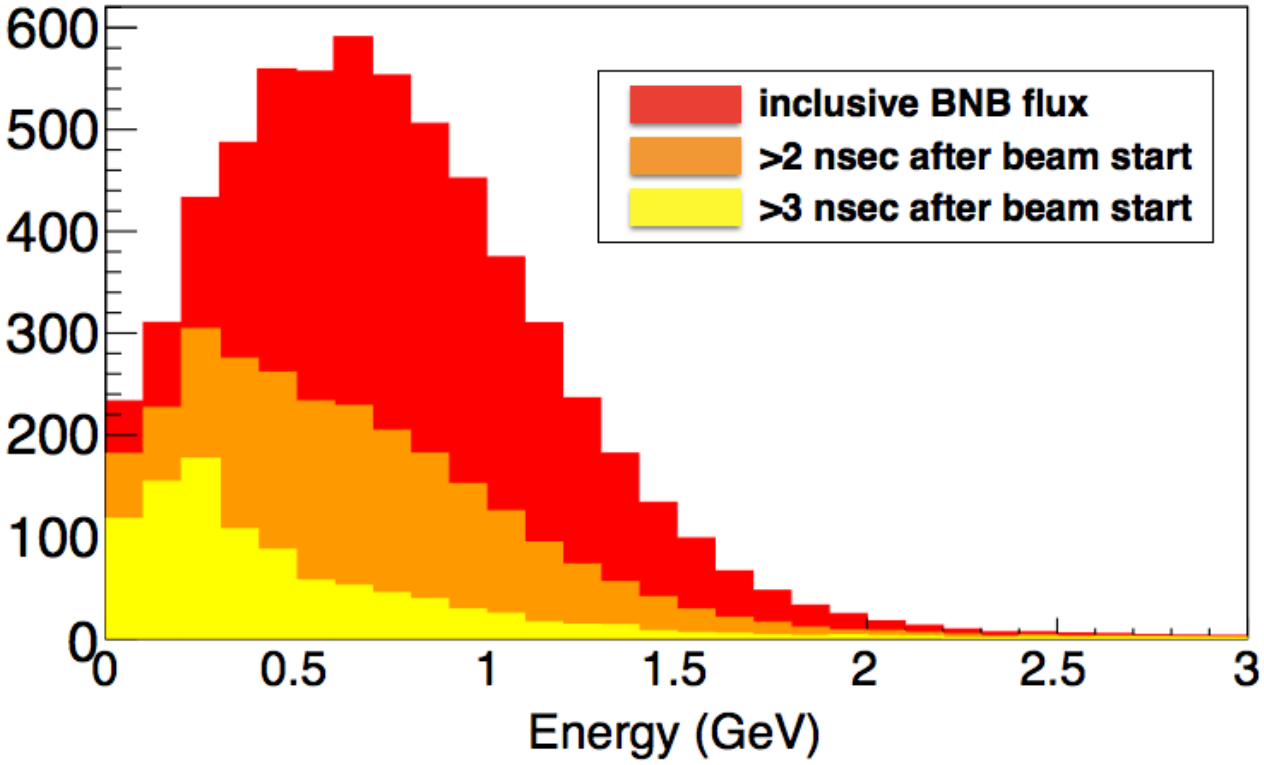
Is it more useful or less useful that Gd-captures?

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



credit: Bei Zhou and John Beacom (OSU)

Timing Dependence of the Neutrino Energy Spectrum is Demonstrable in ANNIE



See my next talk, and

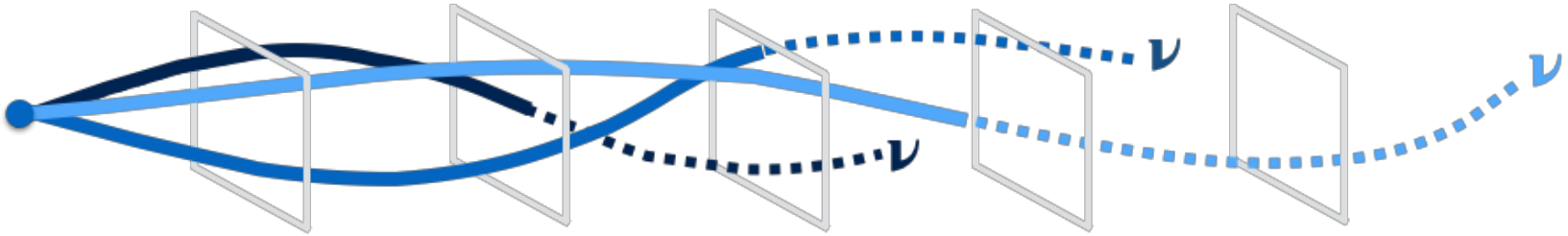
PHYS REV D 100, 032008 (2019) https://arxiv.org/abs/1904.01611

Fast Timing and Beam Physics

Workshop on Precision Time Structure in On-Axis Neutrino Beams

Fermilab November 2-3

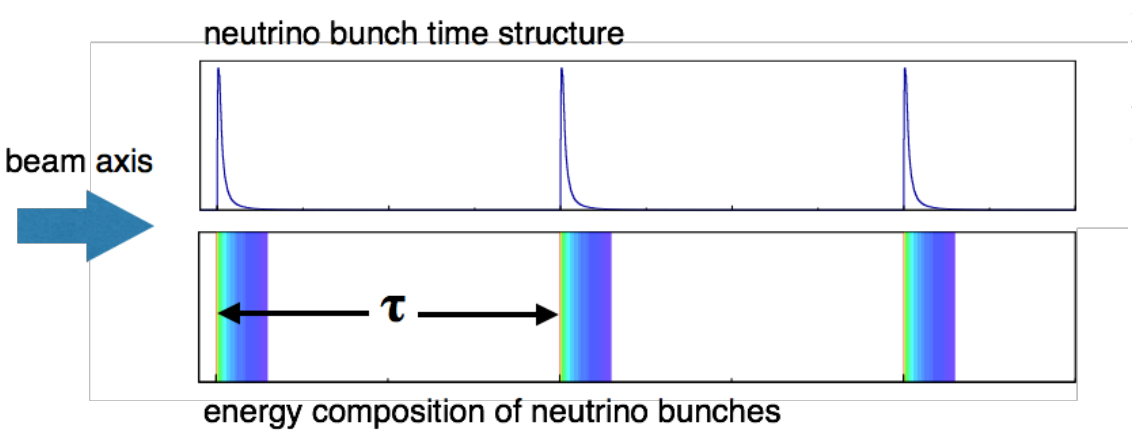
https://indico.fnal.gov/event/21409/

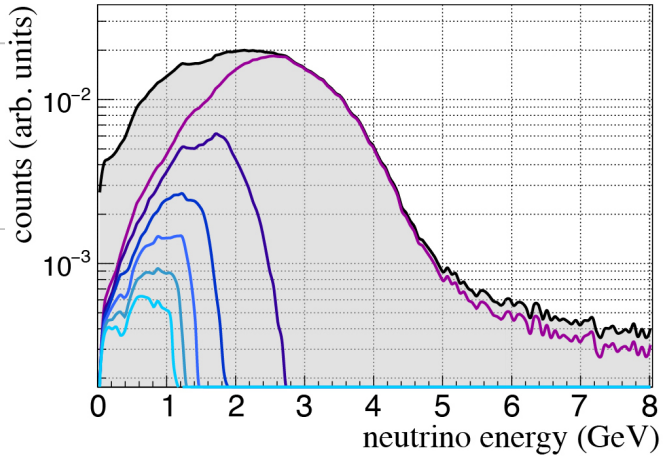


PHYS REV D 100, 032008 (2019) https://arxiv.org/abs/1904.01611

Fast Timing and Beam Physics

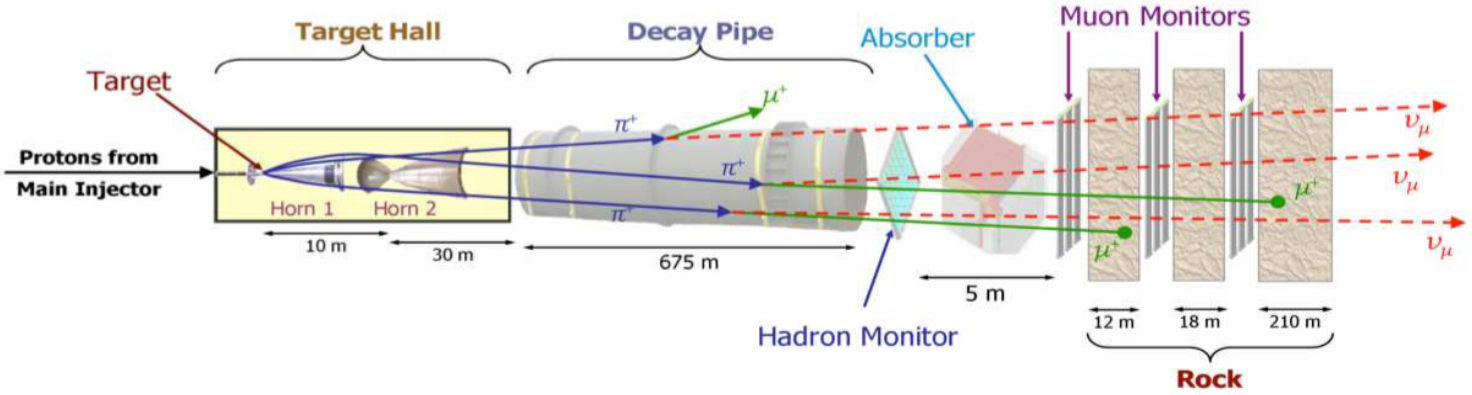
- Neutrinos beams have an intrinsic time structure imprinted on them by the accelerators used to produce them
- The relative arrival time of neutrino with respect to the bunch correlates with the neutrino energy, parent hadron, and flavor
- Timing in neutrino beams could therefore provide a strong experimental 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:

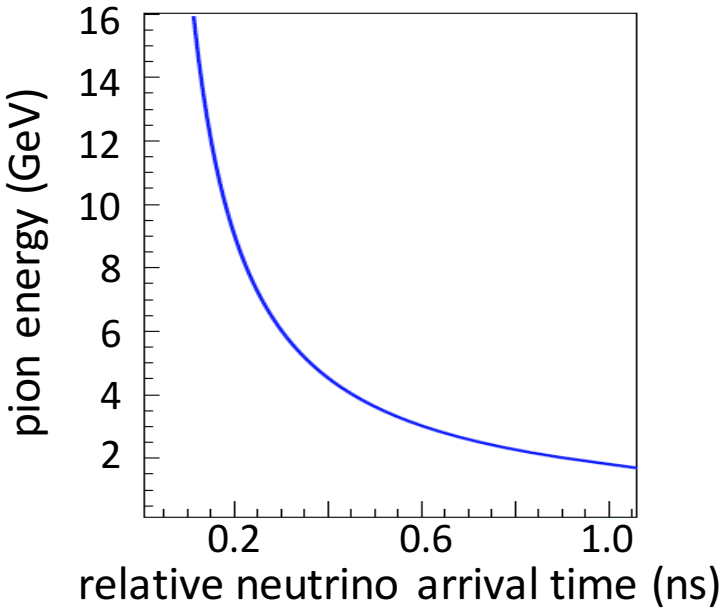


$$\Delta t(E) = \tau(E)[1-\beta(E)]$$

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

$\Delta t(E) \rightarrow \tau_0$ as $\gamma \rightarrow 1$

$\Delta t(E) \rightarrow \tau_0/2\gamma$ for $\gamma >> 1$



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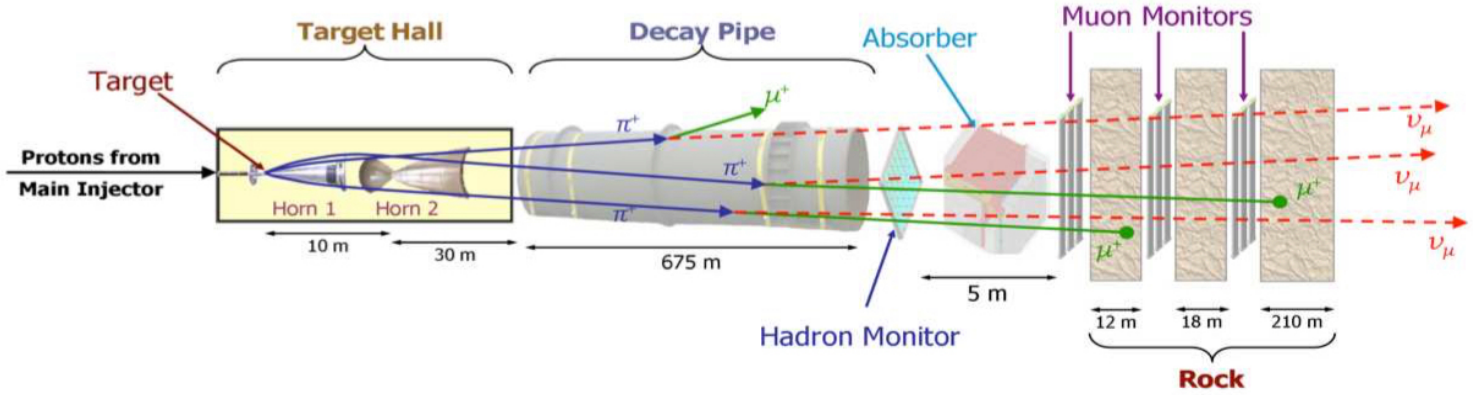

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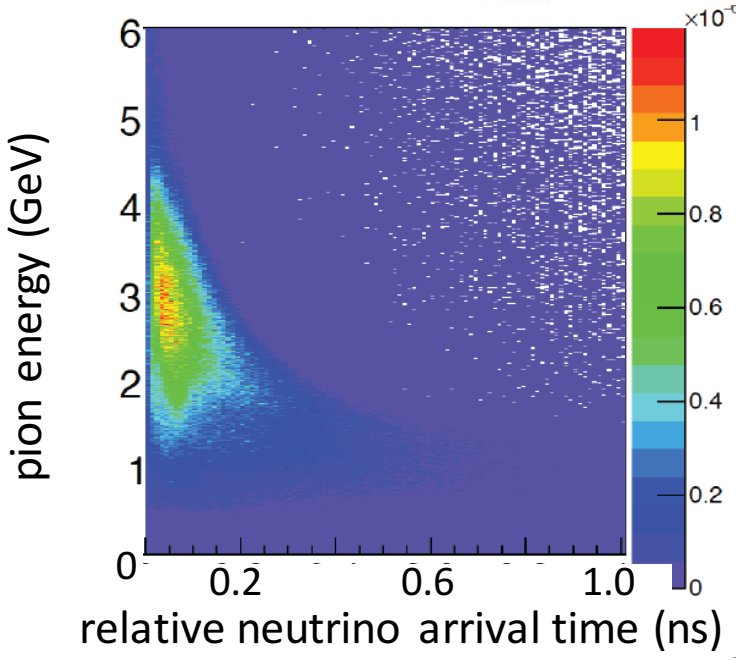
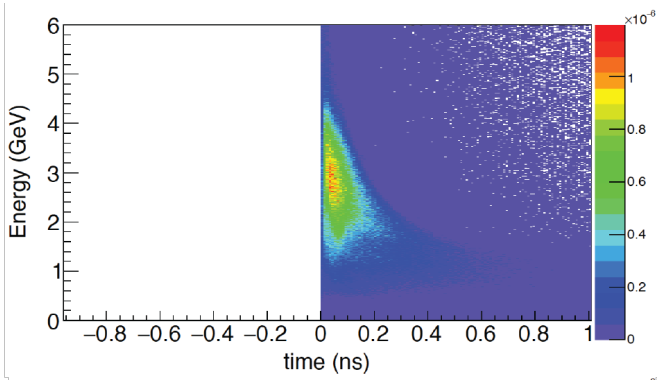


Characteristic Timescales/Limiting Factors

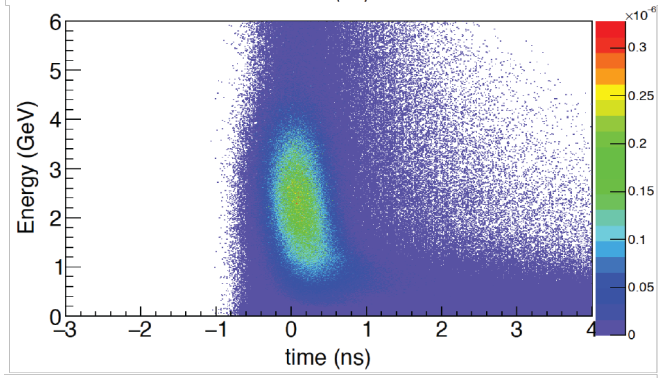
Stroboscopic techniques require sufficiently short bunch sizes

- 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.

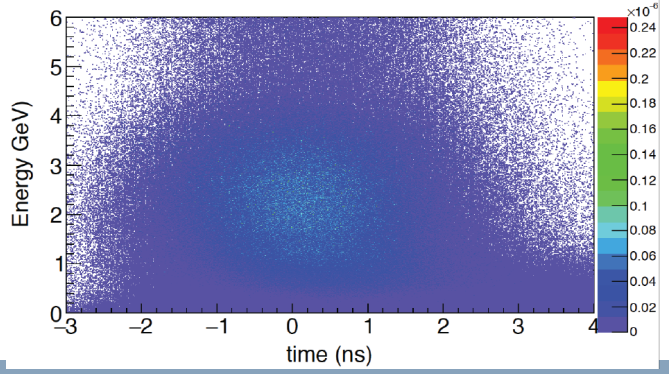
infinitesimal proton bunch



200 psec smearing



1 nsec smearing



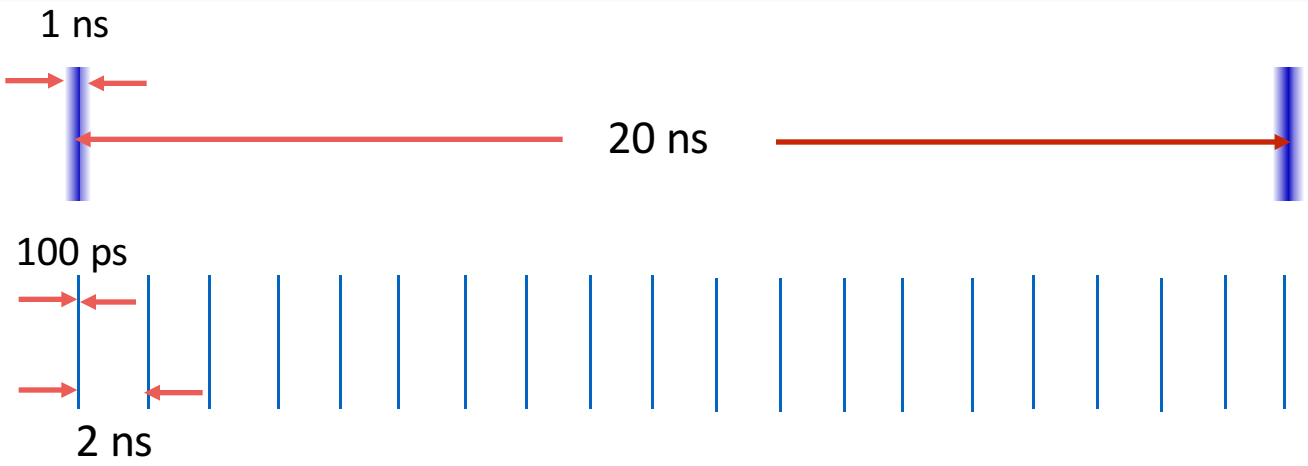
Rebunching the Beam

- Compressing the existing proton bunches in time in 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”

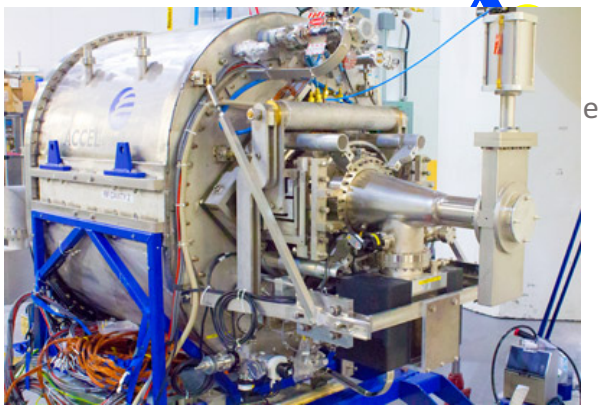
53.1 MHz → 531 MHz

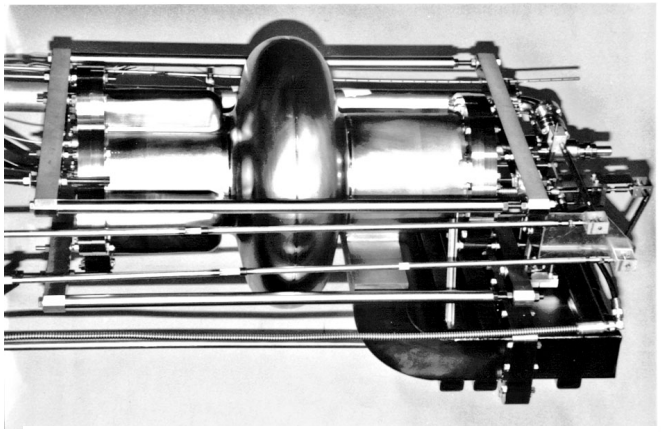
O(1) ns bucket every 20 ns → O(100) ps bucket every 2 ns

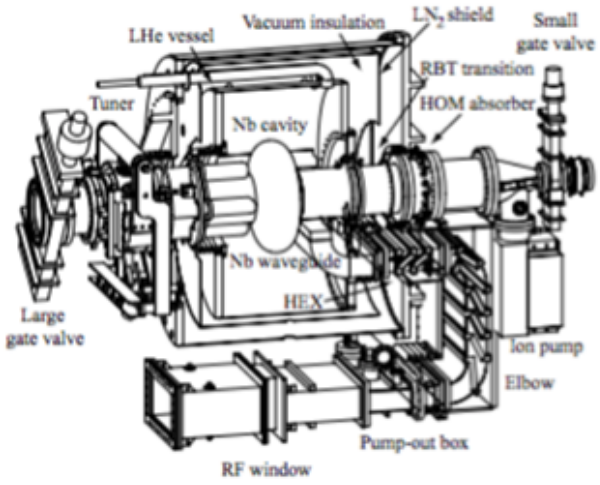


Adding a Superconducting RF Cavity

- 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



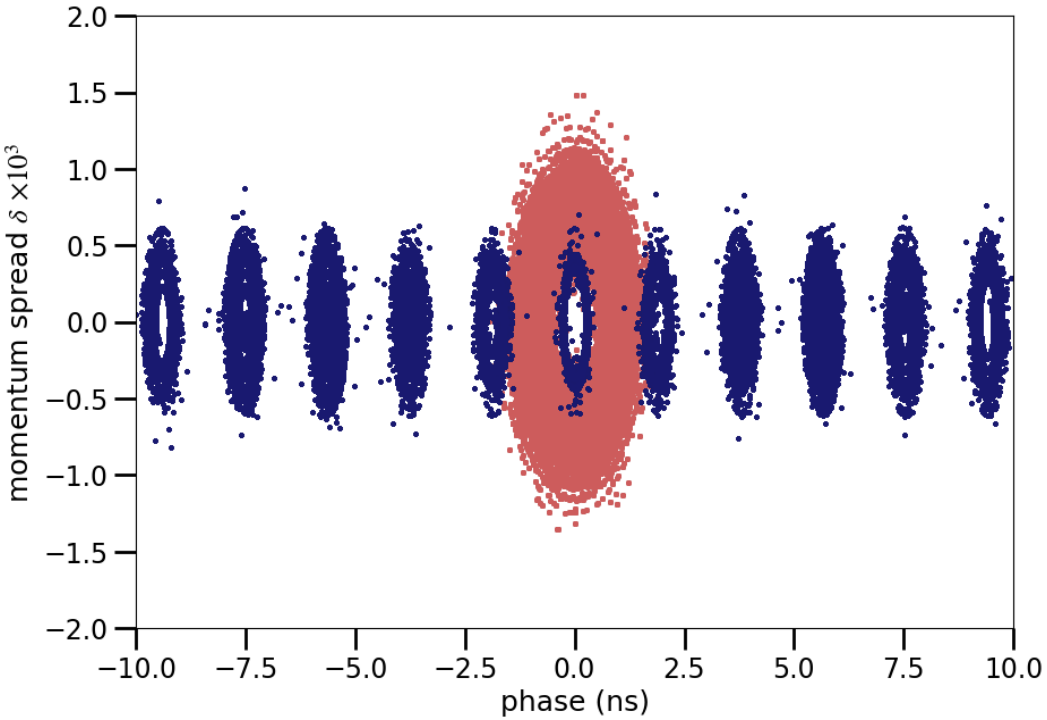




RF Simulation

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



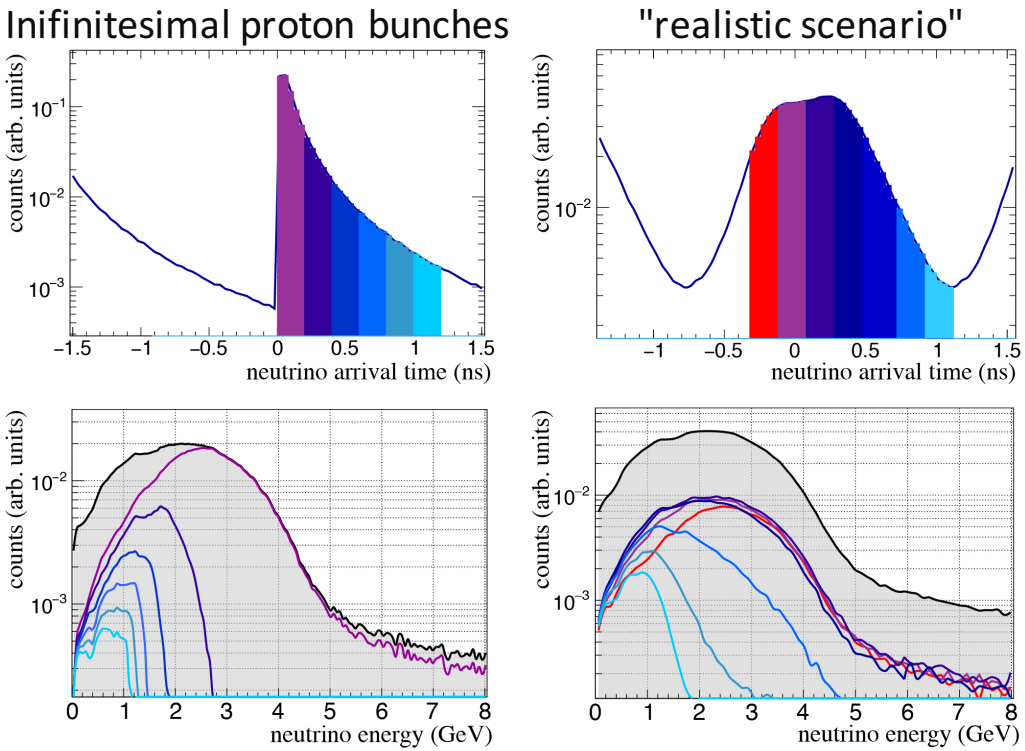
- The resulting rebunched structure is promising
- Typical 531 MHz bunches have an RMS of around 200 ps
- These bunches have sharp edges and substructure, which could be measured by RF monitors and exploited for better extracting time information

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 Gausian to account for detector affects
- the effects of pileup between the bunches

it is still possible to select isolated, lower energy flux bins

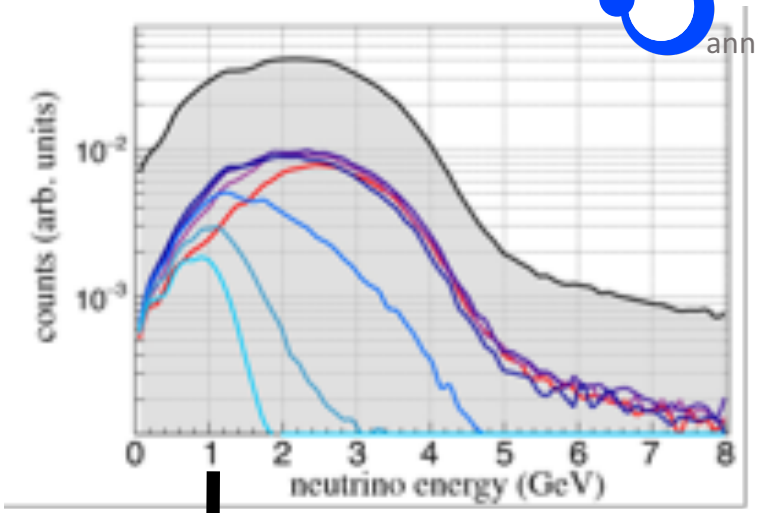


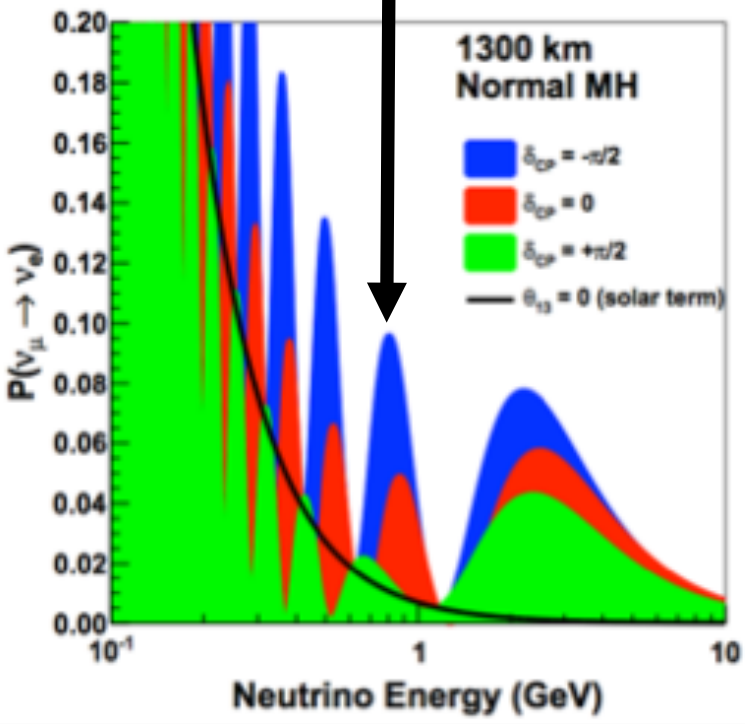
The second maximum

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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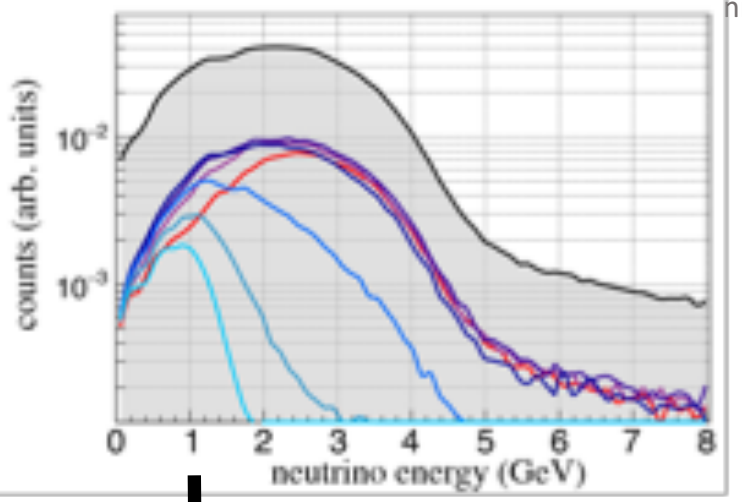
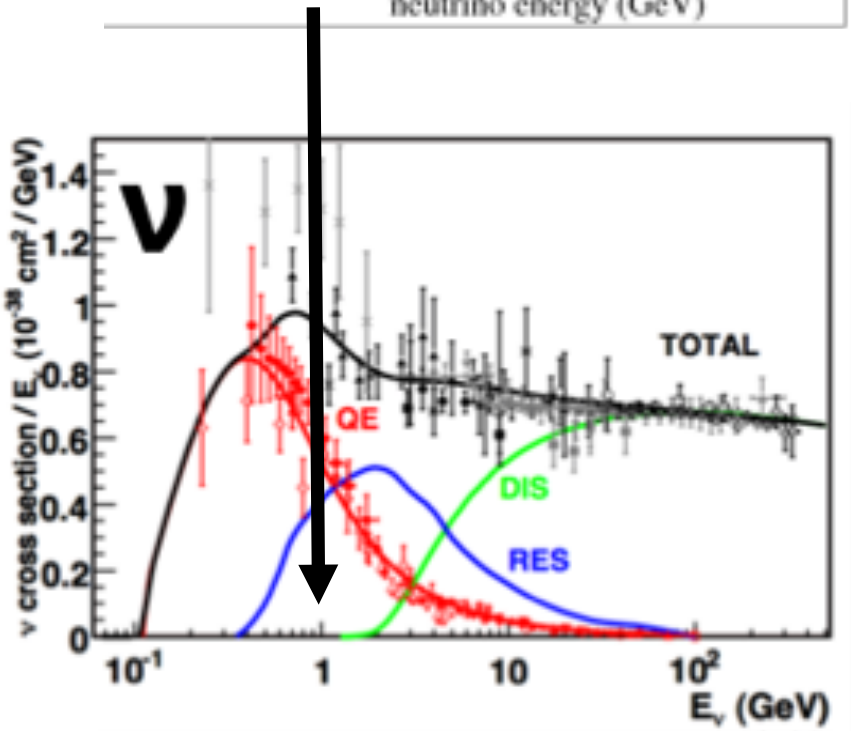
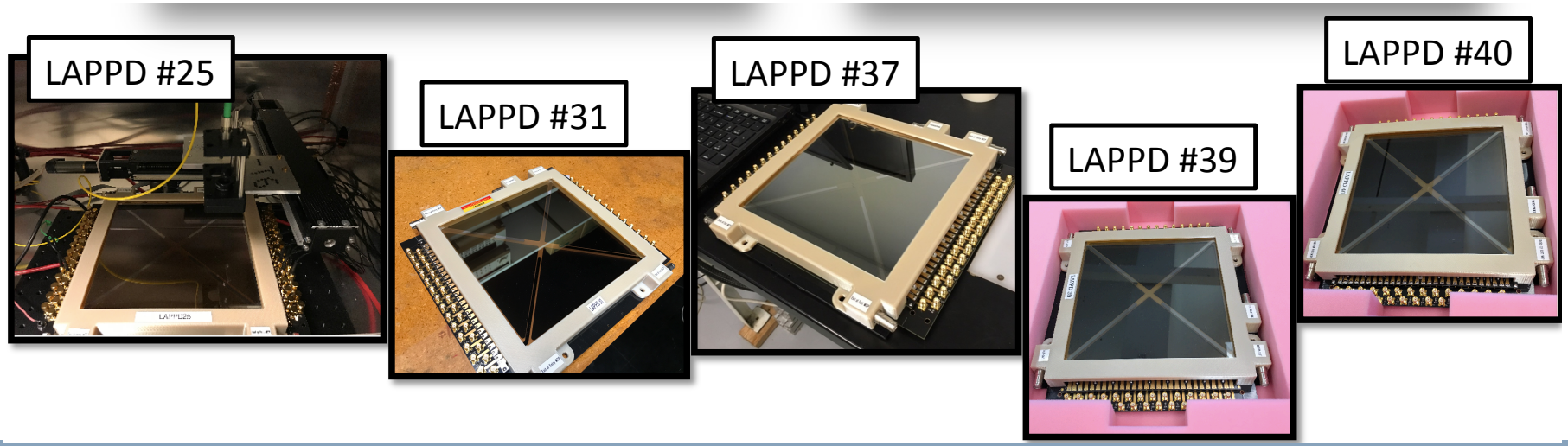




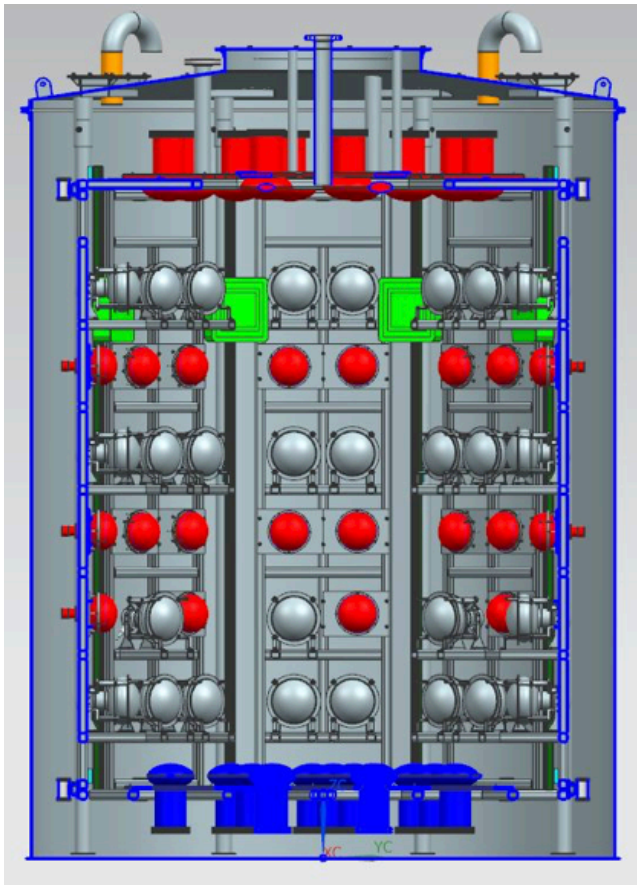
Introduction

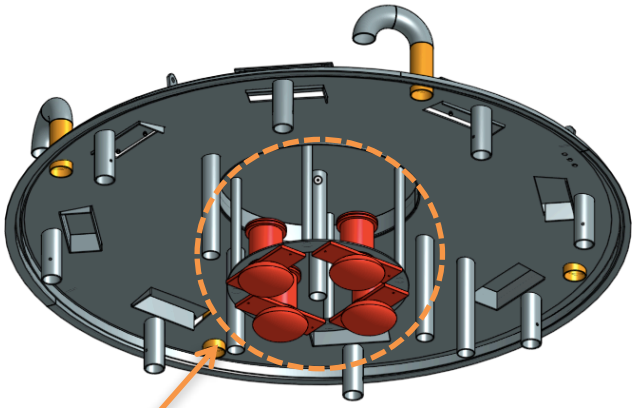
- ANNIE has received all 5 LAPPDs for our first Phase II measurements. They are at Fermilab, under systematic testing at our facility in Lab-6
- Over the last year, we have completed the necessary work for their deployment
    - design and testing of the waterproof housing
    - development of the slow controls system
    - modifications to the firmware and software to enable the PSEC readout system
- All of the pieces are now in place and the schedule is driven by efforts to assemble, integrate, and deploy the LAPPDs



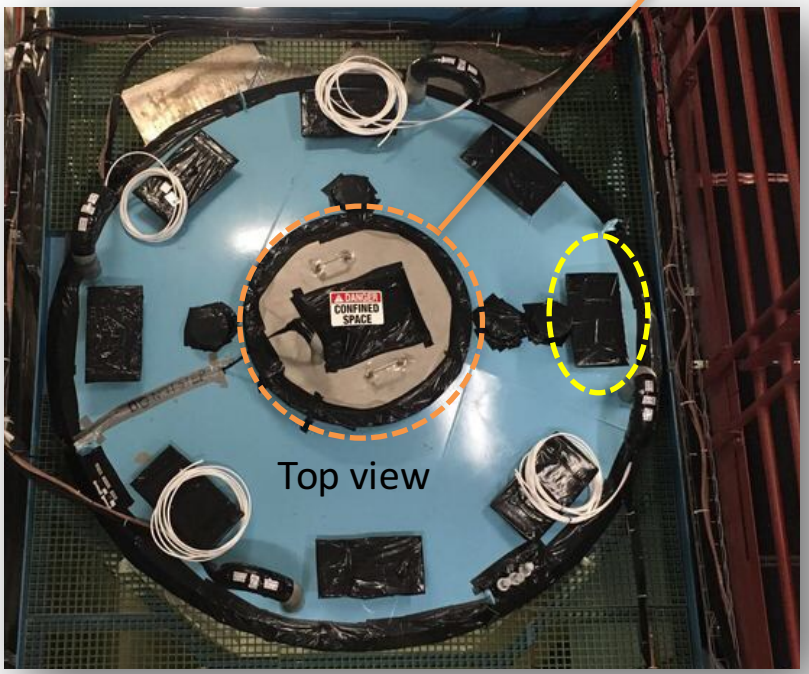
Flexible Tank Design

- The inner frame attached to the tank lid is an octagonal structure.
- It was designed for 132 PMTs and ~40 LAPPDs which are deployable in-situ
- A unistrut as an LAPPD tracker was mounted at each corner (vertex).



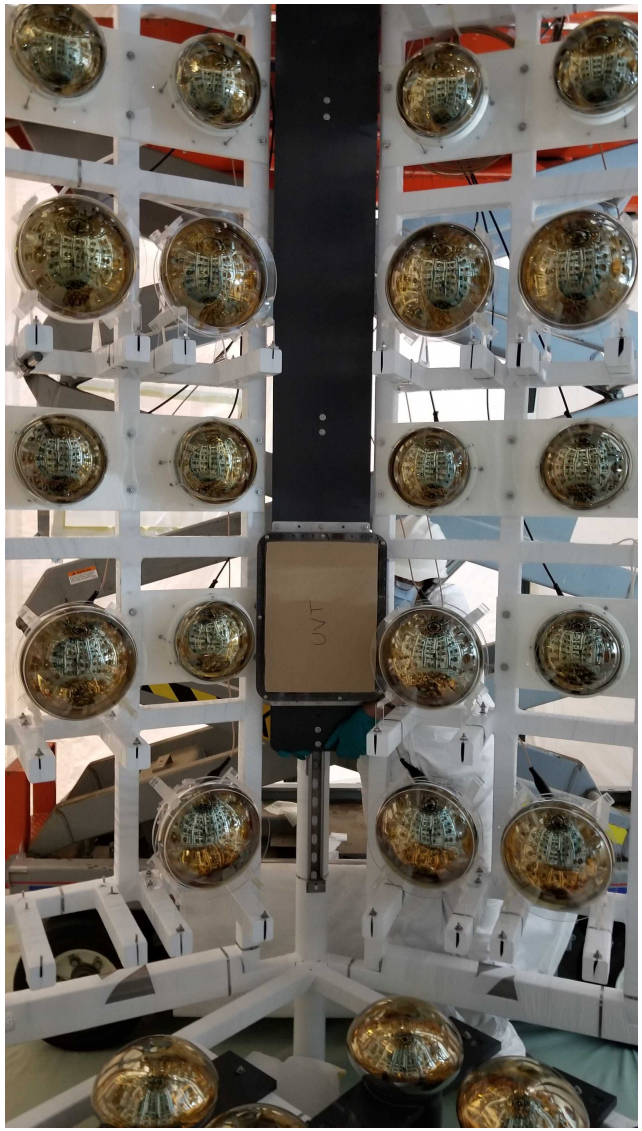


Bottom view

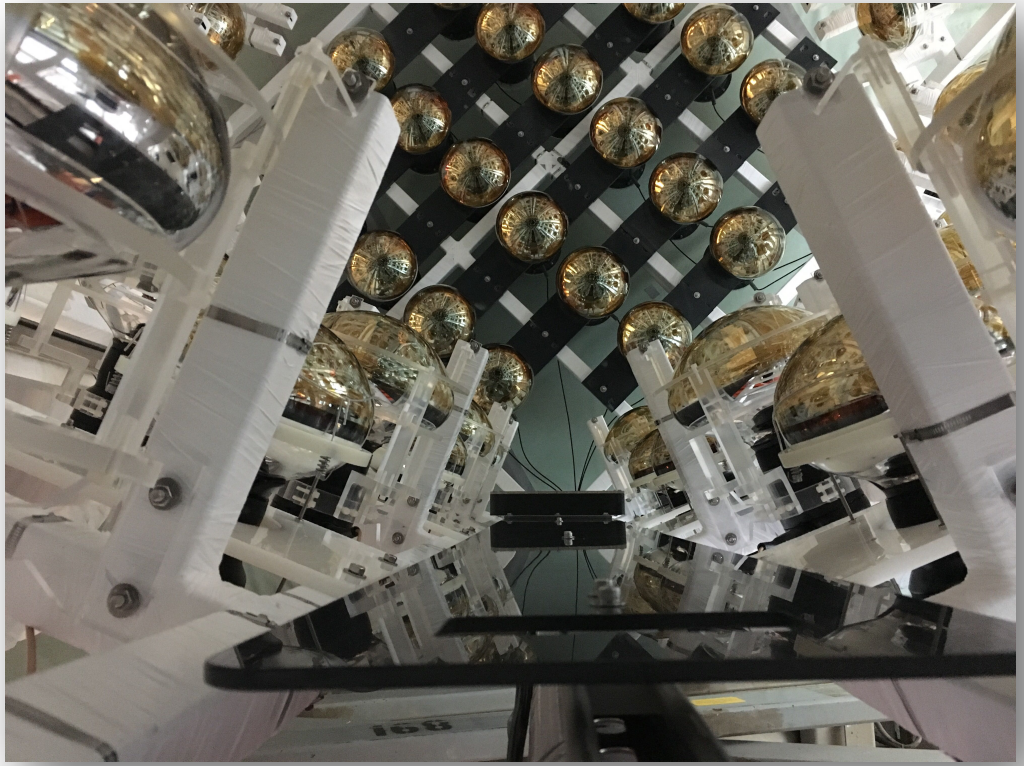


Top view

LAPPD Deployment



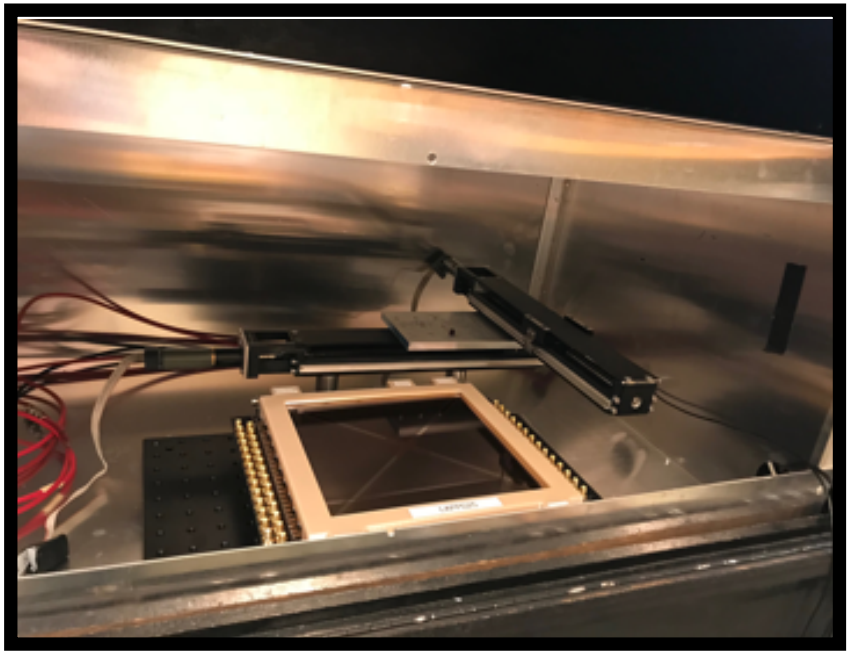
- The LAPPD housing is mounted on ¼ inch PVC panel and it slides on the track with Polypropylene sliders screwed on the back of the panels.
- Deployment was successfully tested before the ANNIE detector was installed.



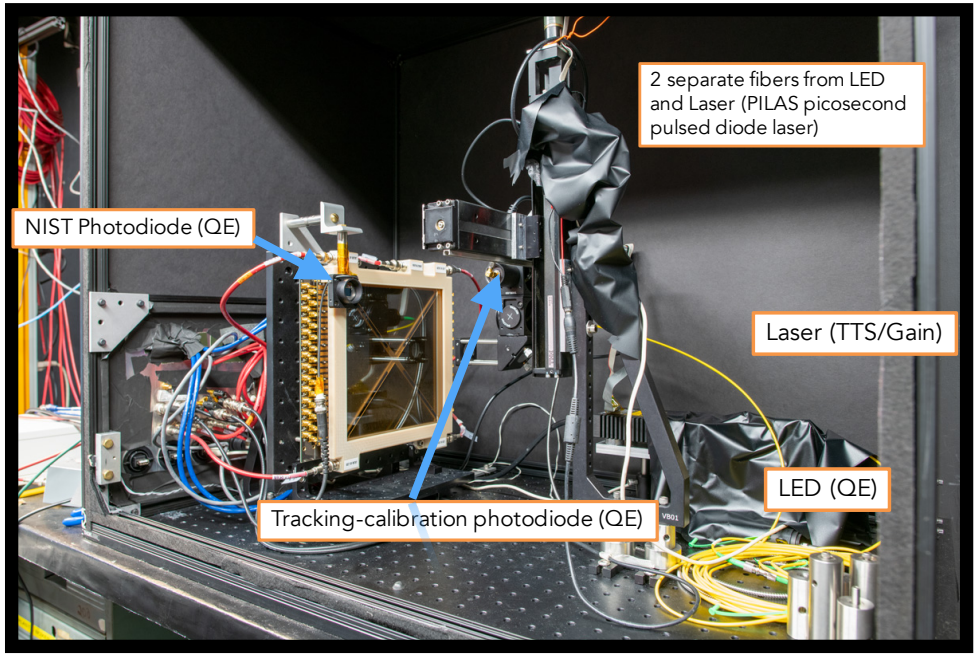
New Test Facility at Fermilab (Lab-6)

- A new test facility was built at Fermilab with full 56-channel readout, based on the ANNIE PSEC4-electronics
- 5 HV modules deliver power and are full computer controlled
- The translation state includes fiber-optic heads that deliver light from two sources: a laser for timing and gain measurements, and an LED for QE measurements
- The setup also includes picoameters and NIST-calibrated photodiode for the QE measurement

Original ISU test stand



New LAPPD Test Stand at Fermilab



LAPPD Testing Status

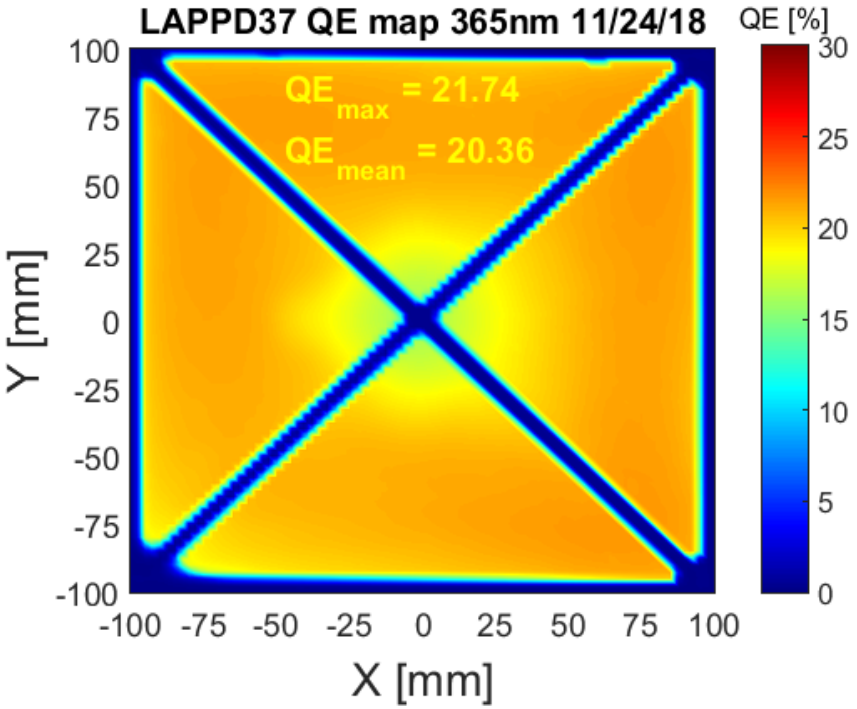
Measurements taken only on one or two LAPPDs:

1. Scan transverse through strips 16mm in 1mm steps, 1-5 PE per trigger, 5k triggers per step.
2. Scan the entire length of a strip in the parallel direction in 5mm steps, 1-5 PE per trigger, 5k triggers per step.

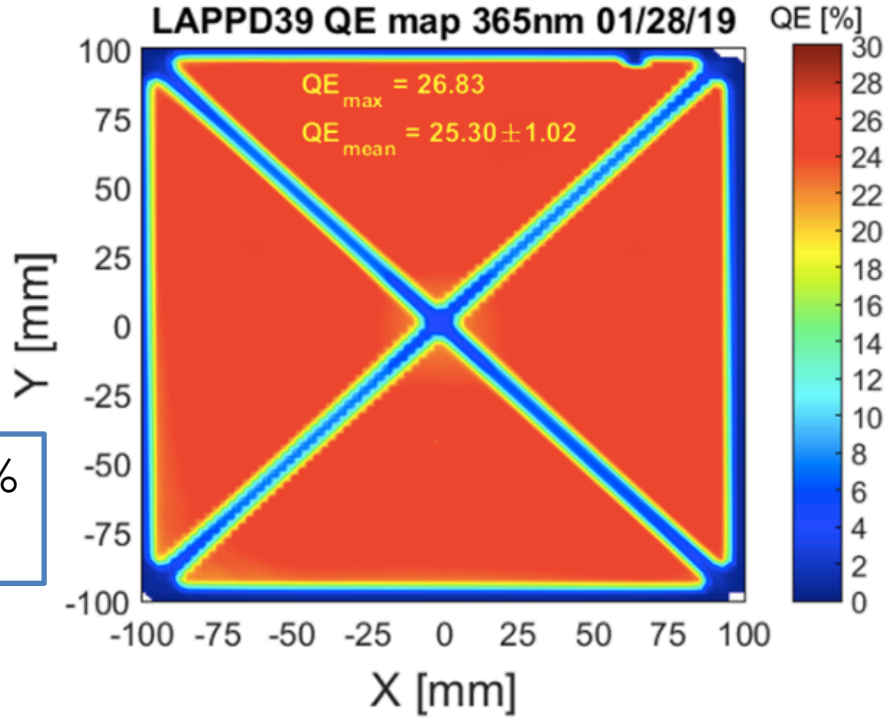
Measurements for each ANNIE LAPPD:

3. Voltage dependence dataset: 4 x 4 x 4 grid of cathode, topmcp, and bottommcp voltages at a single position
4. Position dependence of gain: 8 x 8 grid of positions on LAPPD 1PE gain distribution.
5. Precision gain measurement: at one position, measure 1PE gain with high statistics.
6. Dark rate measurement: 200k random triggered events with no light source. Search for pulses in data and put upper bound / statistical error on dark-rate.
7. QE measurement at t0. QE measurement at t0+1week of LAPPD being powered without interruption.

LAPPDs meet the maximal ANNIE specifications



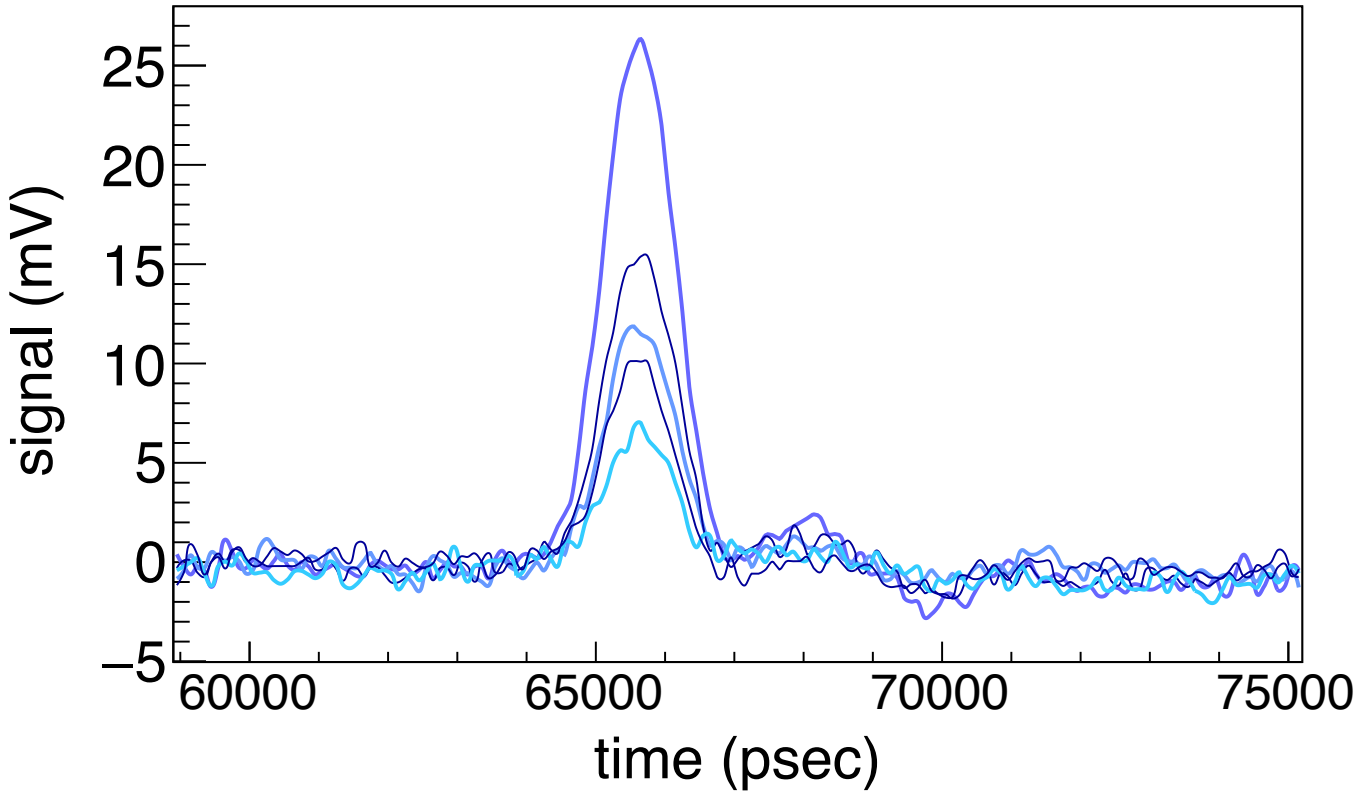
- The QE results of 2 LAPPDs, #37 and #39
- QE characterization of other LAPPDs is in progress at Fermilab.



- Quantum Efficiency (QE) is more than 20%
- Nice uniform response from the LAPPDs

Results: Typical Single-PE Pulses

FWHM: 1.1 nsec
rise time: 850 psec

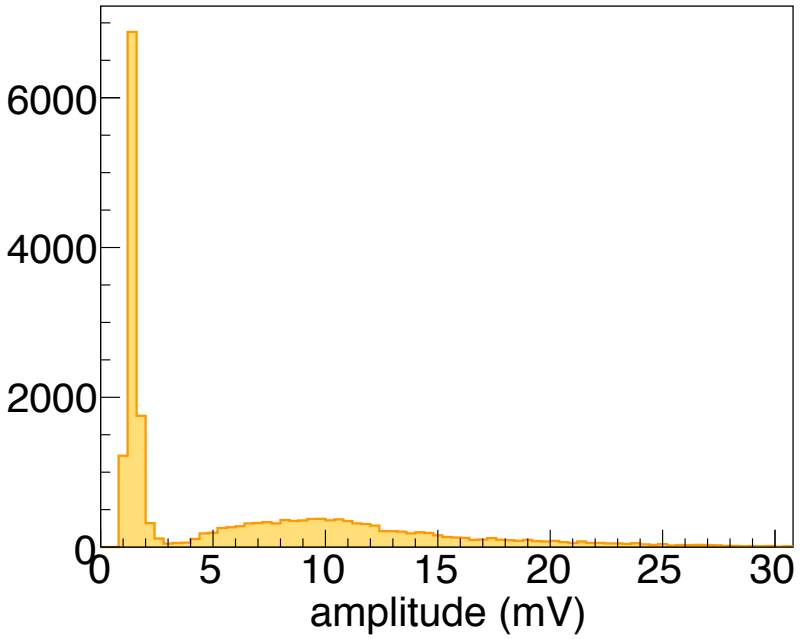


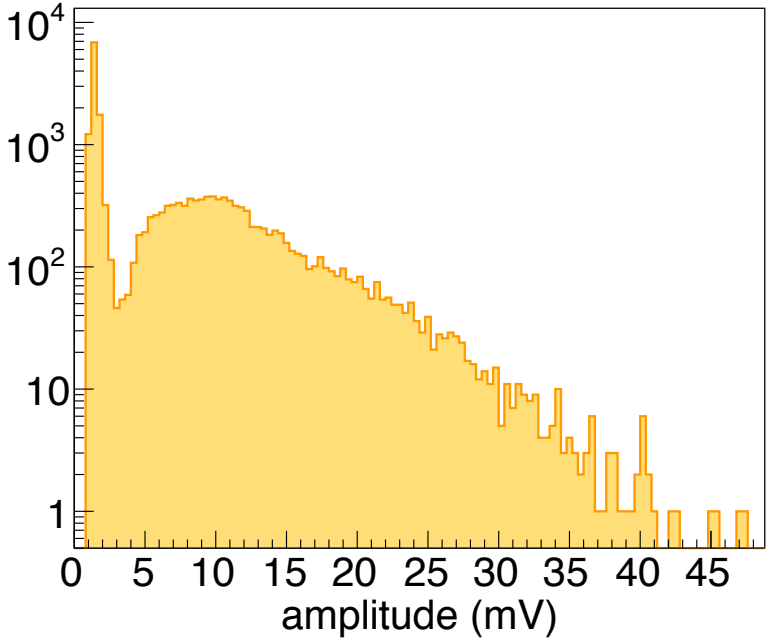
voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

Results: Amplitude

We see very clean separation from pedestal

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

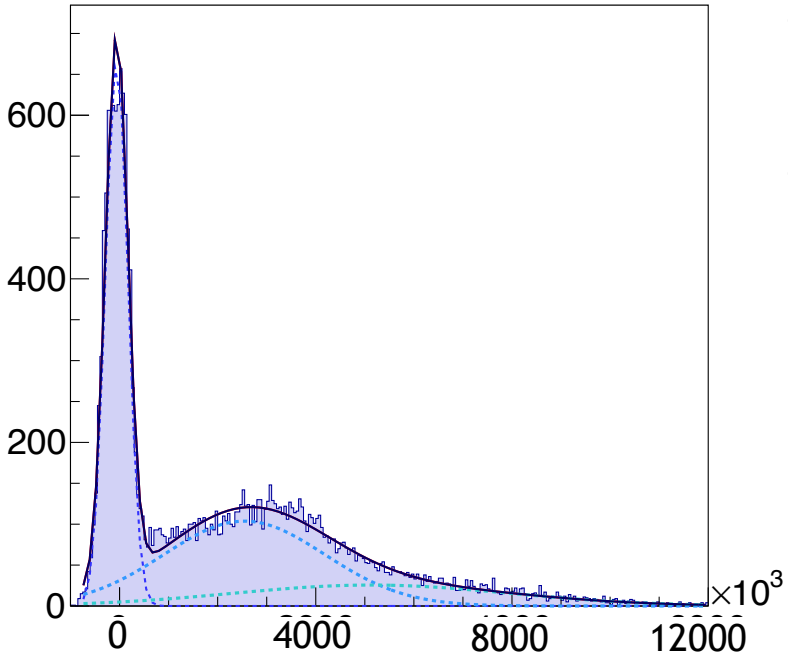


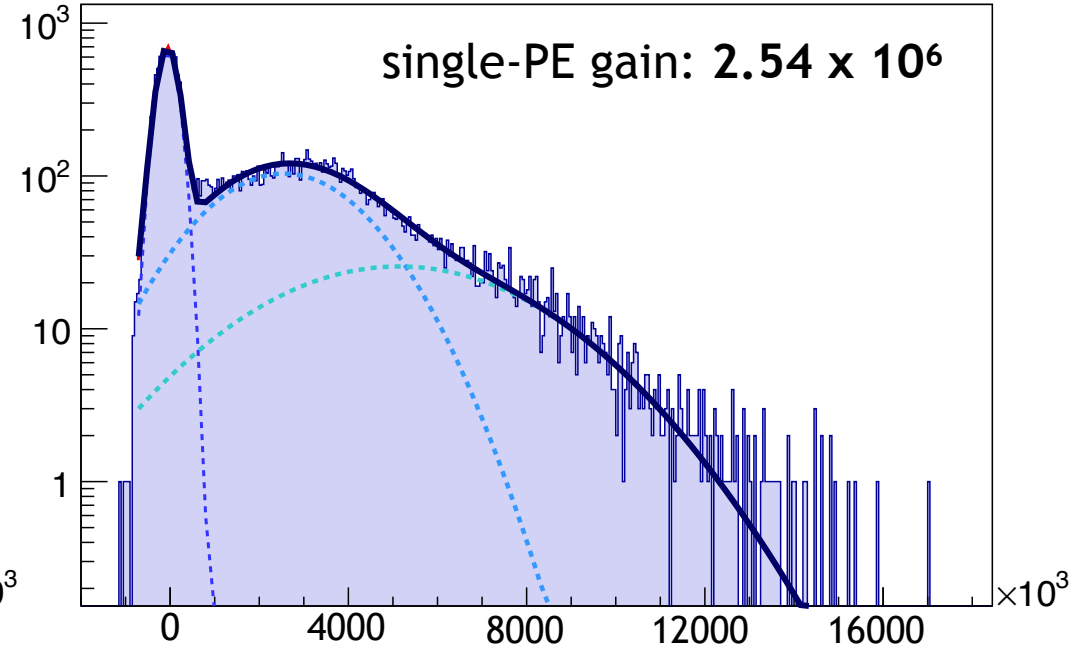


voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

Results: Gain

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

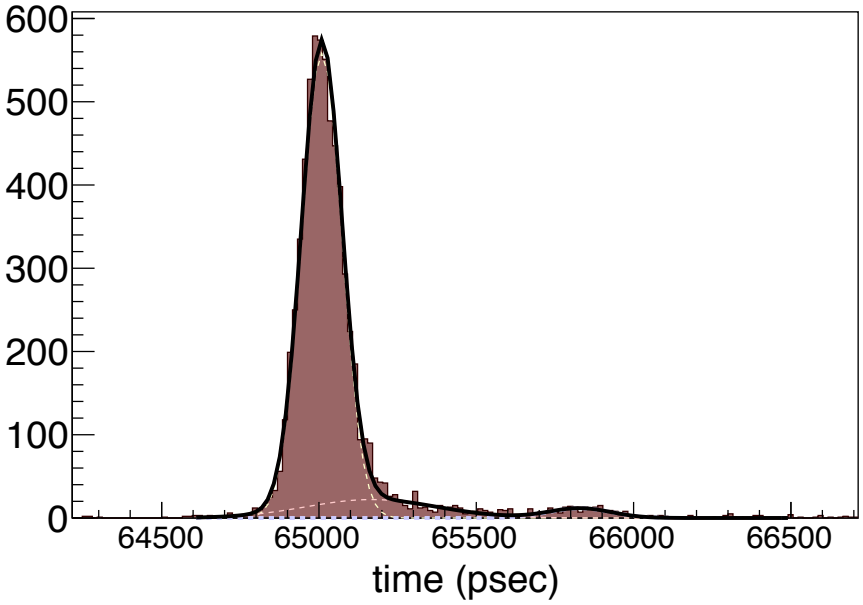


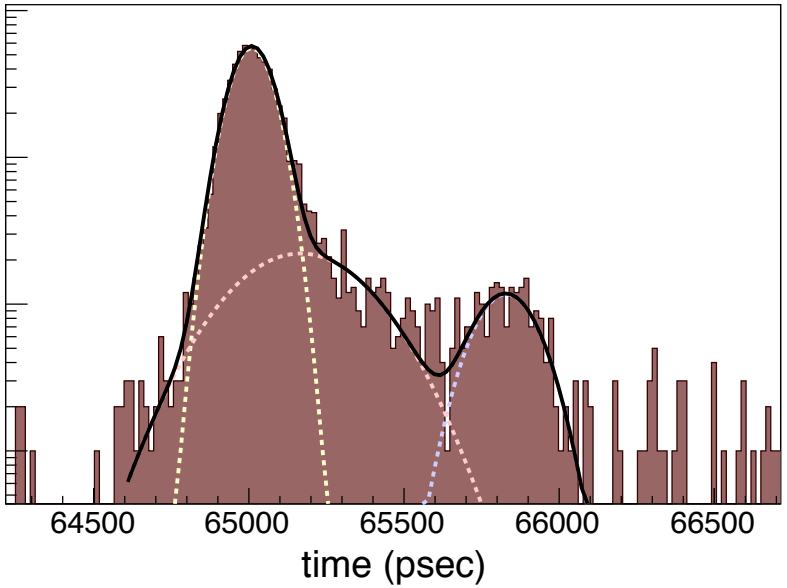


voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

Results: Time Resolution

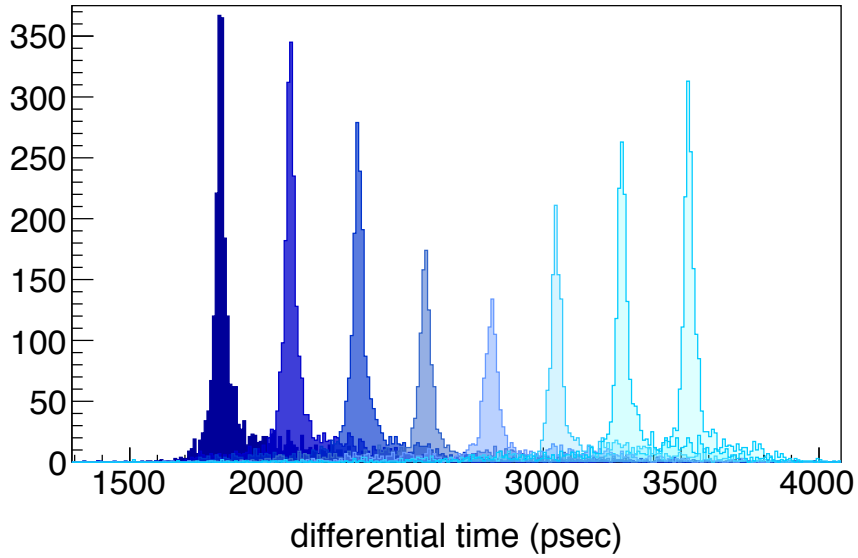
We observe 64 psec time resolution in the main peak of the TTS
with small contribution from after-pulses (~4%), typical of any photodetector

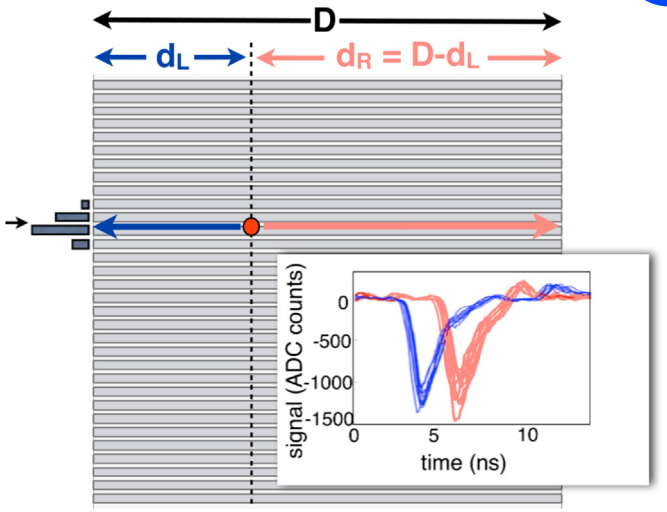


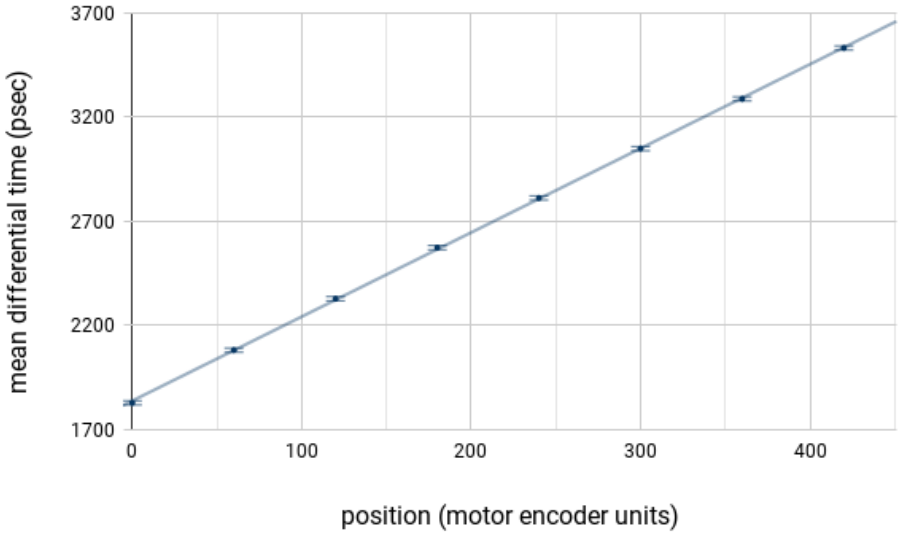


voltages: PC=350V MCP1=800V interMCP=200V MCP2=950V anode=200V

LAPPD 25: Differential Timing / Parallel Position

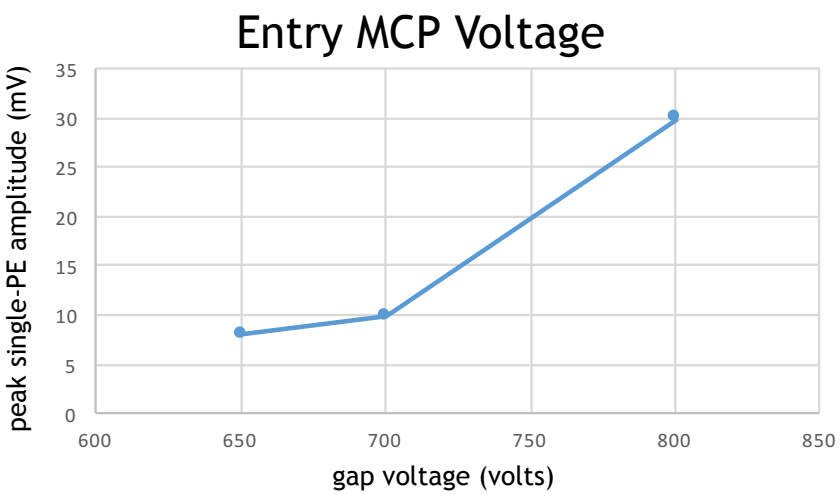


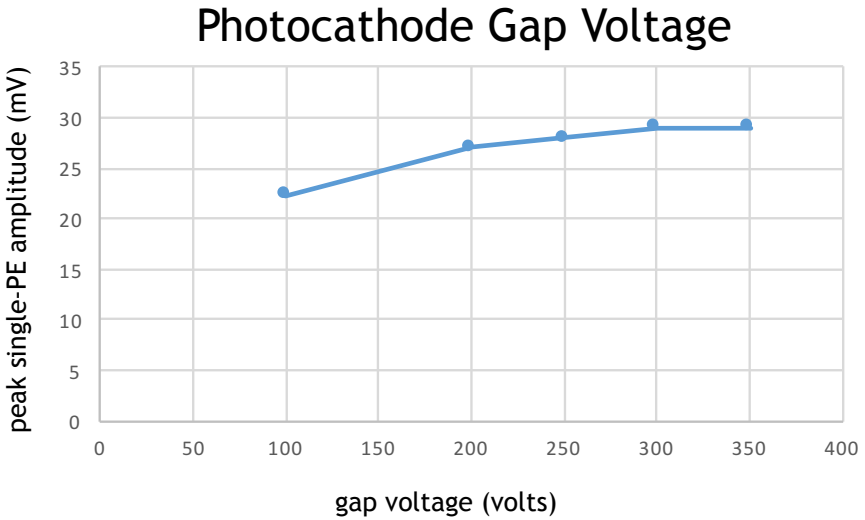




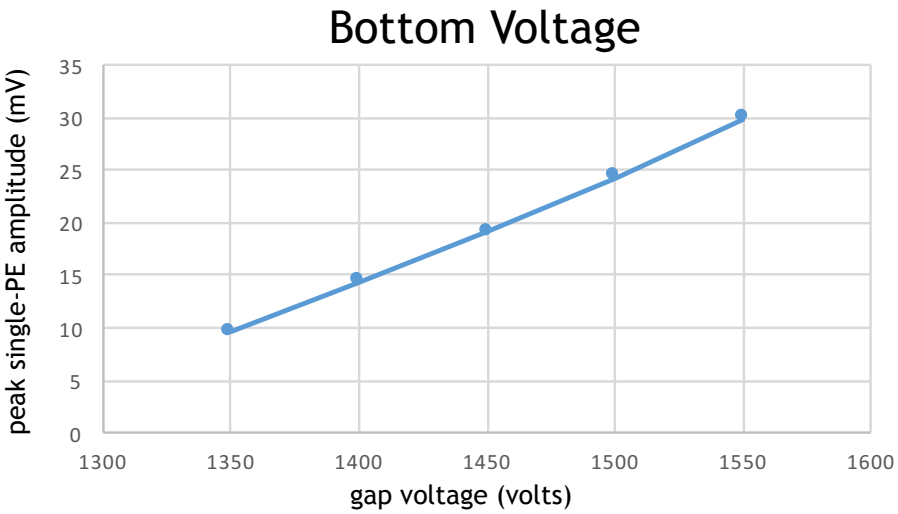
- Position in the direction parallel to the striplines can be determined from the time difference between the two ends
- 25 picosecond single-PE differential time resolution corresponds to 4.35 mm resolution in the parallel direction

LAPPD 25: Voltage Response



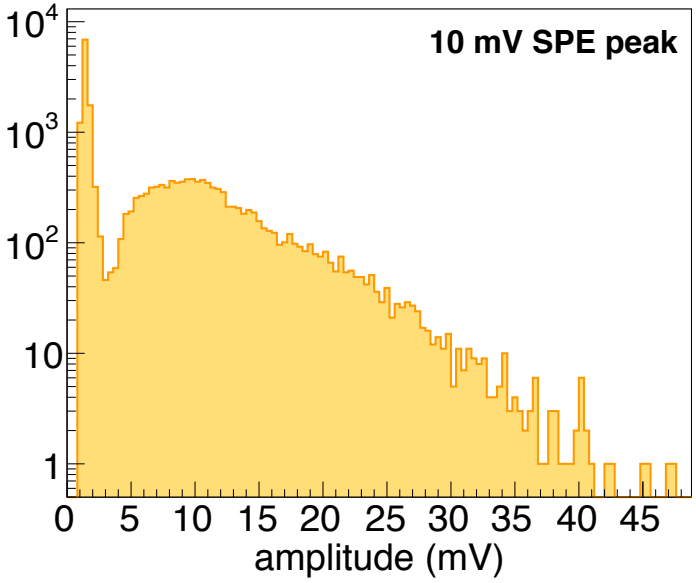


- We varied the voltages to see if we could improve the gain
- At higher voltages, the LAPPD gets noisy, but these gains provide good sPE separation so we're not concerned

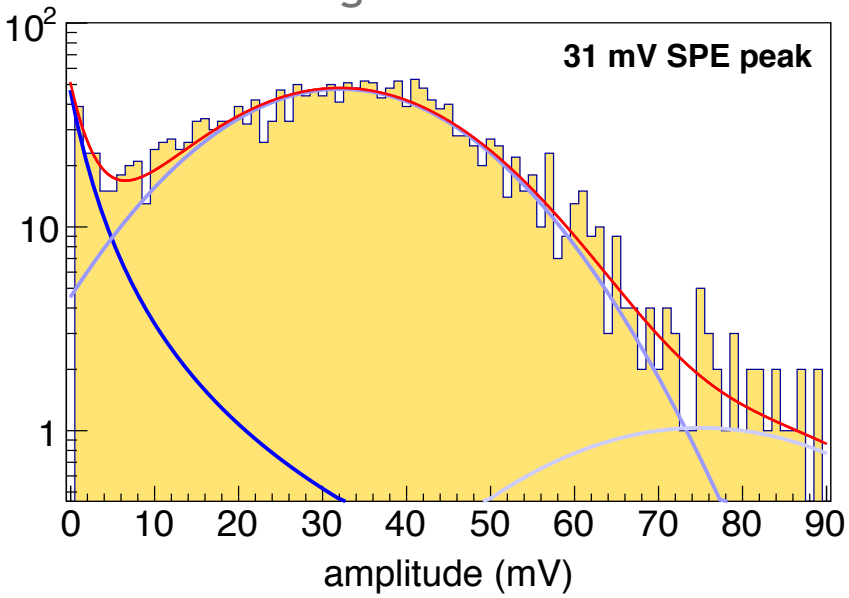


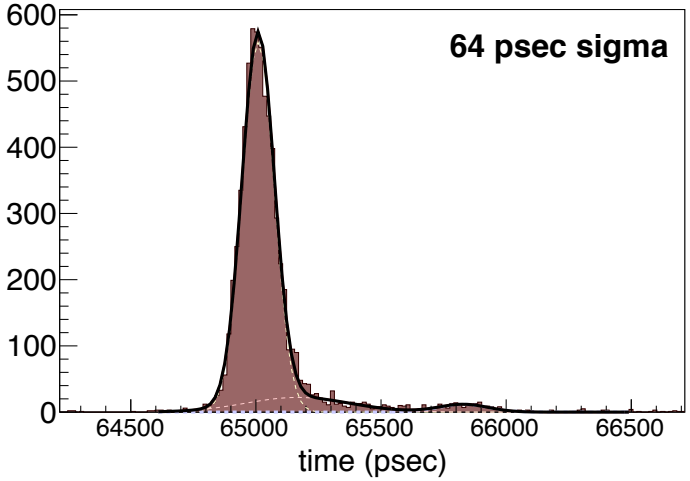
LAPPD 25: Voltage Optimization

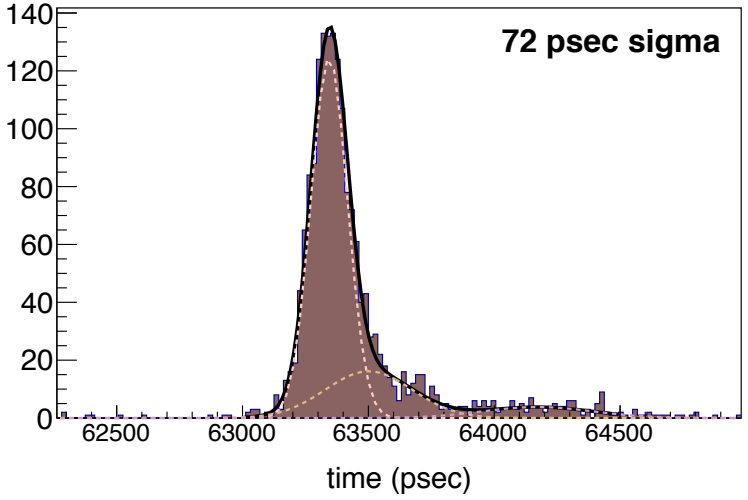
Low Gain



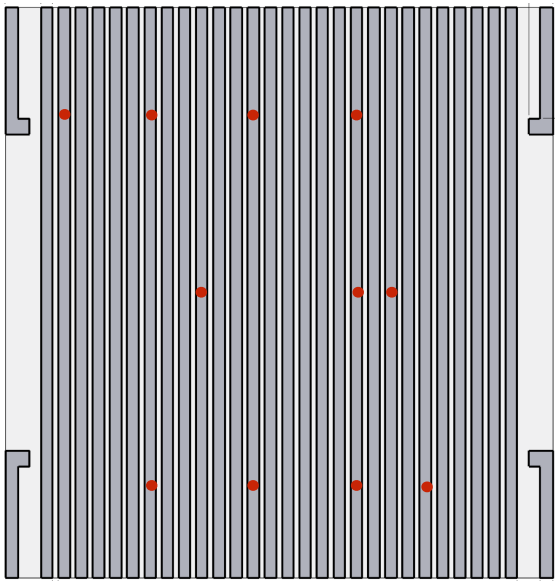
High Gain

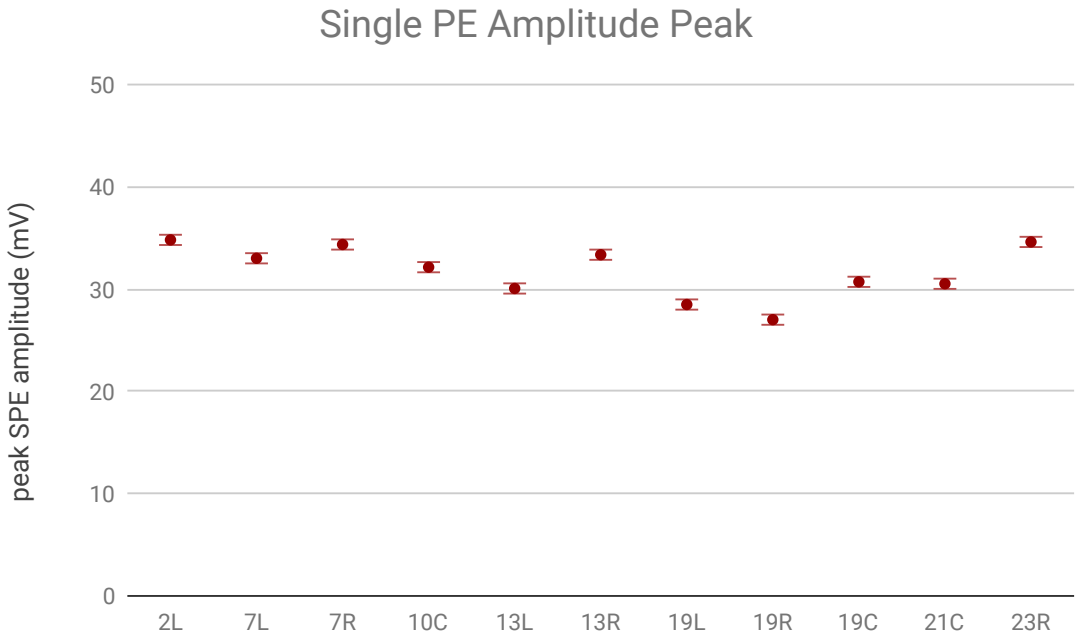






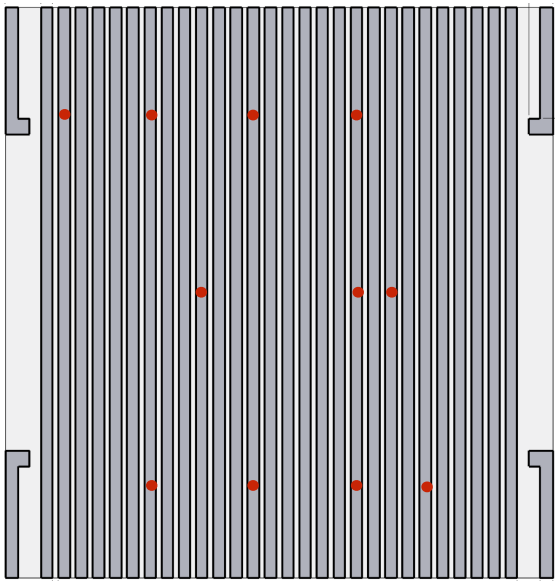
LAPPD 25: Single PE Gain Uniformity

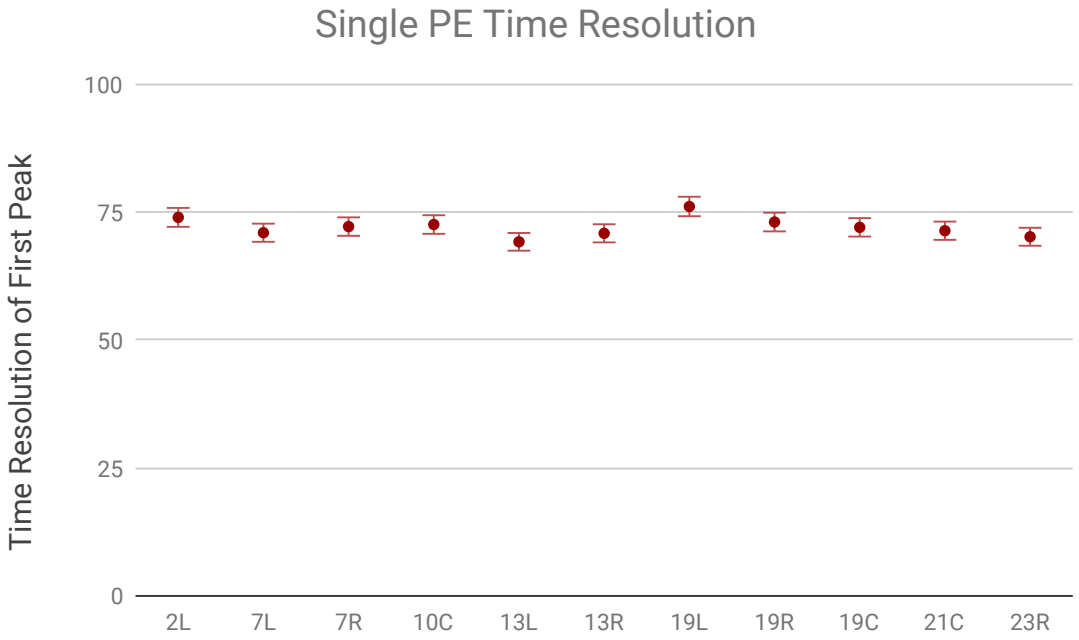




- We recorded 10k triggers as 11 random positions on the tile
- SPE peak amplitude was taken from the mean of the first Gaussian in a 2 PE + pedestal fit
- More systematic scans will become easier with the multichannel PSEC electronics

LAPPD 25: Single PE Timing Uniformity

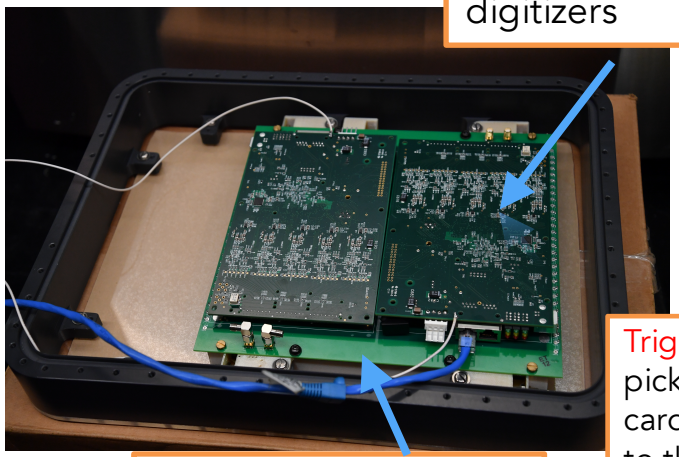




- We recorded 10k triggers as 11 random positions on the tile
- SPE time resolution is taken from the width of the main Gaussian in a 3 gaussian fit for TTS and after pulsing
- After pulsing constitutes a small (<10%) fraction of the pulses

Development of Water-Proof Housings & Mechanical Interfaces

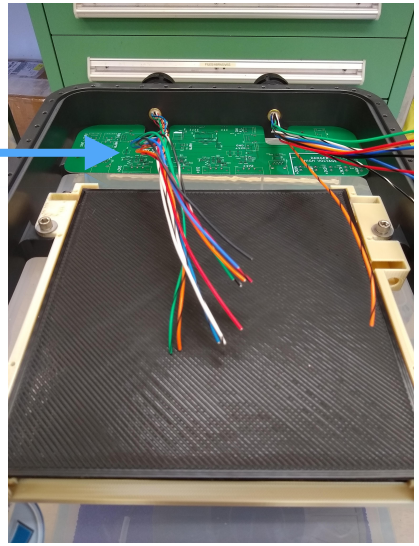
2 ACDC Cards as waveform digitizers

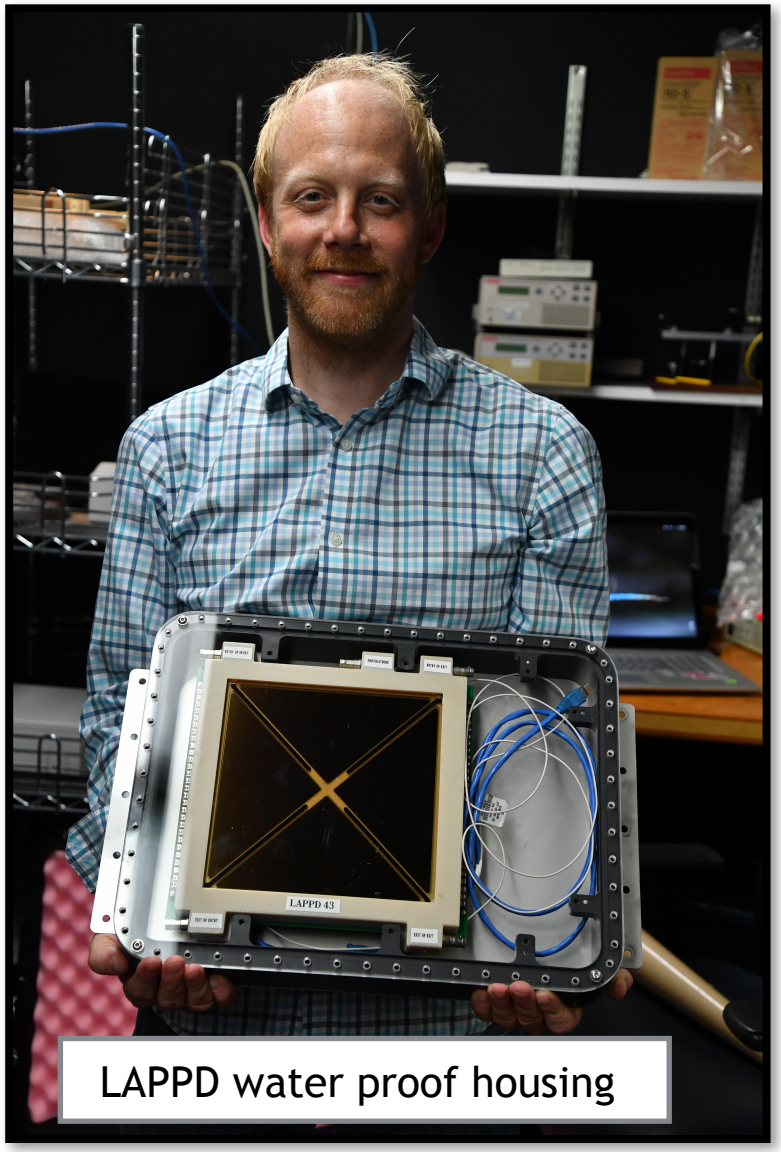


Trigger card in between pickup board and ACDC cards to provide trigger to the ACDCs.

Analog pickup board

LV-HV board to provide power and slow controls

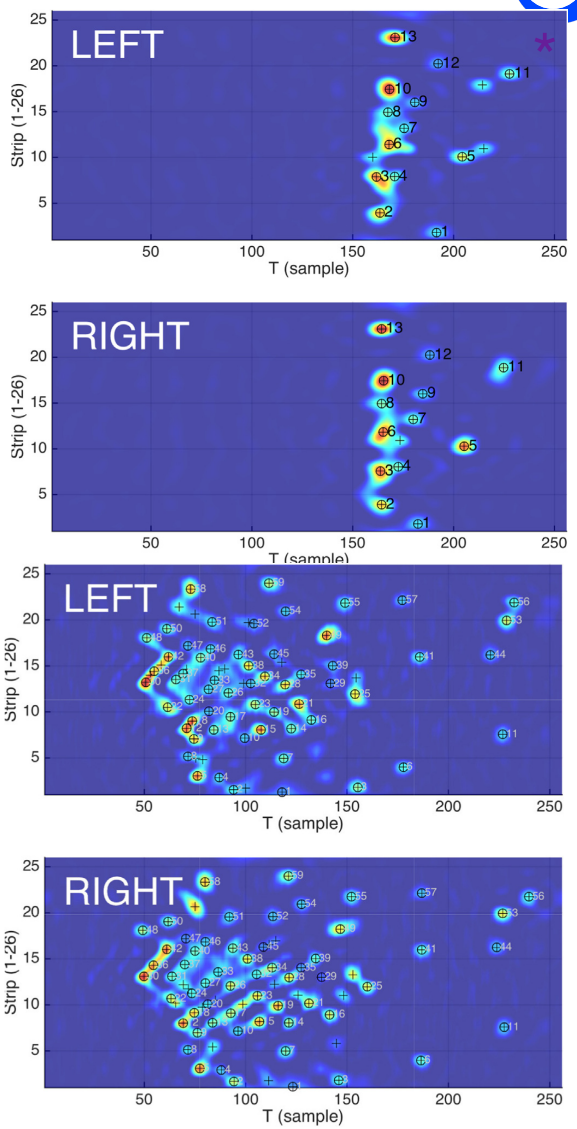




LAPPD water proof housing

LAPPD Simulations and Reconstruction

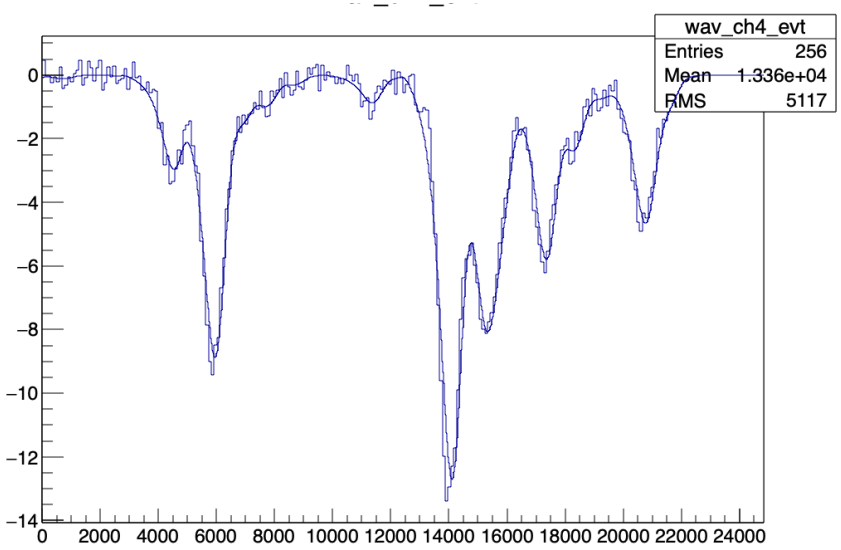
- Deconvolving the two-sided readout of the LAPPD is not trivial, especially in high light environments
- It essentially adds an additional step between signals and “hits”
- We are working on a feature extraction approach that simultaneously fits pulses to the 2D time-vs-voltage distribution for both 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



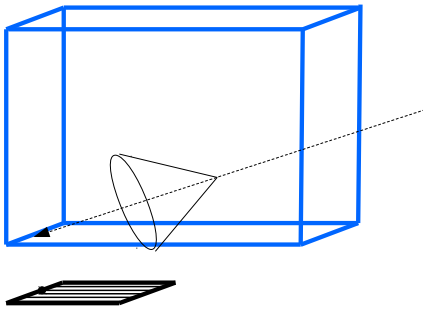
*Multiple-photon disambiguation on stripline-anode Micro-Channel Plates: Nim A 822 (2016) 25-33

Incorporation of LAPPDs into WATCHMAN/AIT Simulations

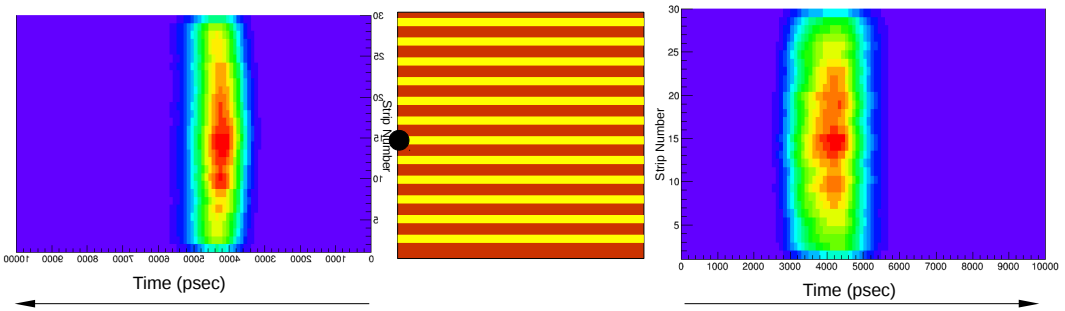
- Working with Evan Angelico at UC, we have implemented David Grzan's NNLS algorithm into Tool Analysis
- It currently works for single sided readout
- Next step is to deconvolve both sides of the trace simultaneously
- …and add in two spatial dimensions



- It is still possible that I will be able to port these tools to RatPac by January

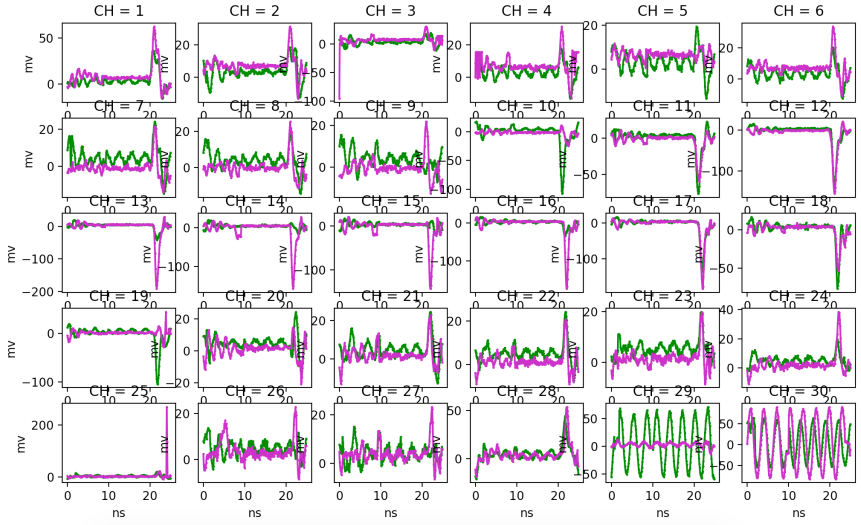


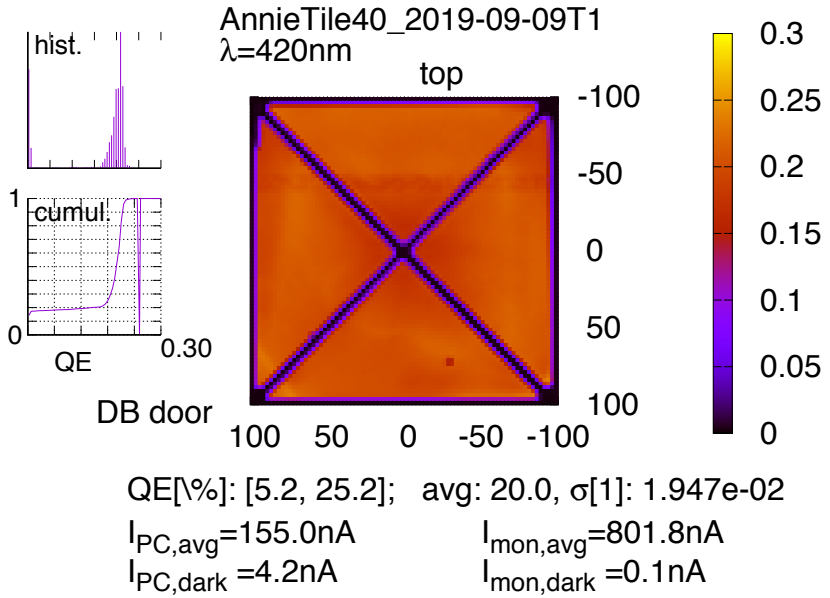
30° - Parallel Orientation



Newly Expanded LAPPD Test Capabilities

- Commissioning of the setup is almost complete
- Both the QE and laser systems have been operated and produced limited data
- QE characterization scans are now being performed on all of the ANNIE LAPPDs
- Full laser scanning is almost ready, pending modifications to the PSEC firmware and will begin fully in December
- This setup is available for long term LAPPD studies, including testing of novel gen-2 LAPPDs, and it can be replicated/expanded for further use by the collaboration





QE[\%]: [5.2, 25.2]; avg: 20.0, σ[1]: 1.947e-02

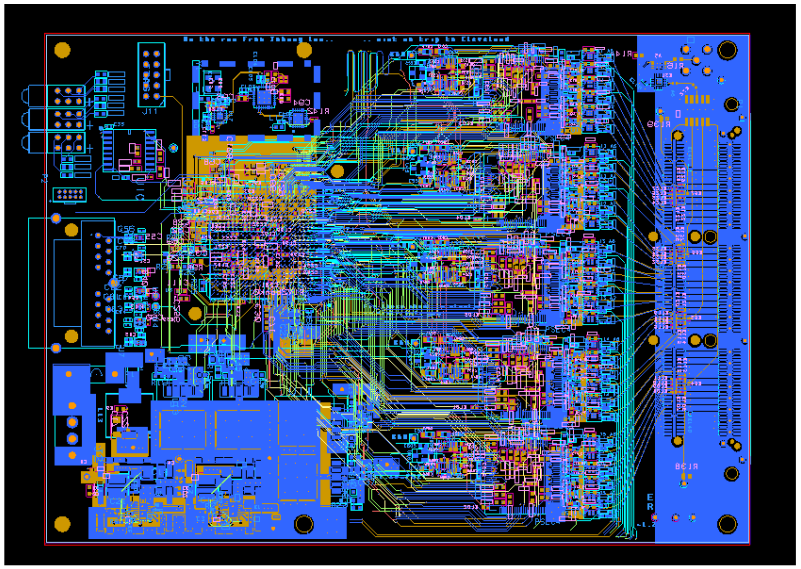
$I_{PC,avg}$=155.0nA $I_{mon,avg}$=801.8nA

$I_{PC,dark}$ =4.2nA $I_{mon,dark}$ =0.1nA

Development of Power and Readout Package for LAPPDs

- There were a number of known problems with the LAPPD readout cards
  - Wonkiness in the clock distribution from the Central Cards
  - Inefficient voltage regulators generating waste heat
  - Inconsistent self-triggering
- So far, ANNIE has dealt with these problems by offloading some of the functionality to additional boards: LV-HV card / trigger logic board

- Eric Oberla (UC) was commissioned to redesign the ACDC card



https://users.rcc.uchicago.edu/~ejo/ACDC_revC_design/

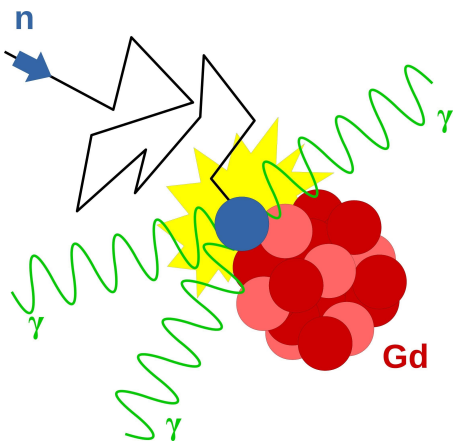
Development of Power and Readout Package for LAPPDs

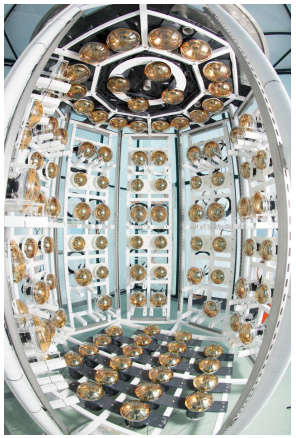
- The design of Rev-C is now complete
- Major upgrades:
  - Fully redesigned clock distribution based on ultra-low jitter LVCMOS fanout buffer
  - New power management
    - linear regulators are replaced with a combination of switching regulators (LT8611) and low-dropout regulators
    - improved noise filtering
    - low-risk, based on a recent design for the Askaryan Radio Array
  - Redesign of the self-triggering mechanism - individual trigger thresholds for each PSEC4 channel descriinator
  - Communications with the Central Card have been improved
- Also a variety of minor improvements: removed unnecessary connectors, better fusing, more debugging hooks, temperature sensor…
- Prototype boards have been ordered and are being populated

https://users.rcc.uchicago.edu/~ejo/ACDC_revC_design/

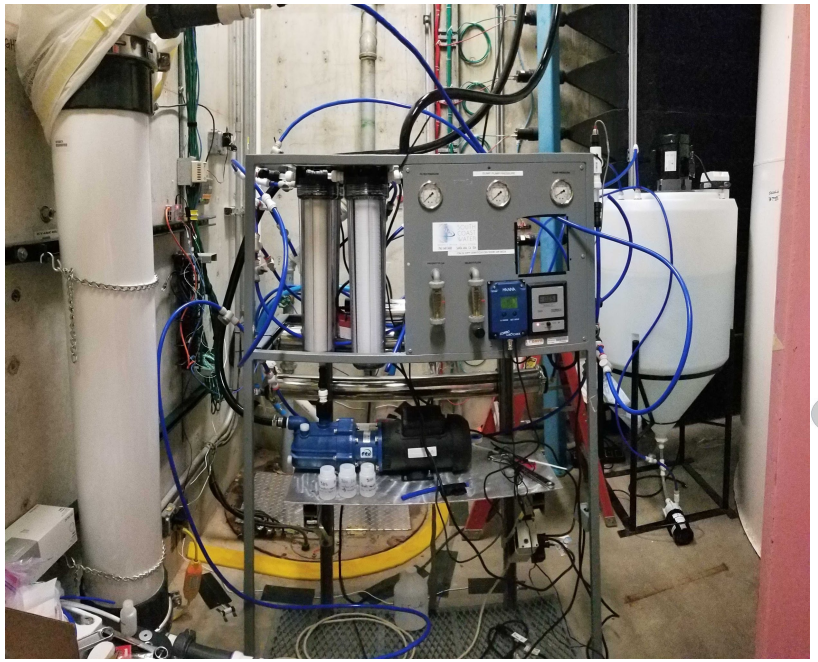
The ANNIE Gd-loaded water

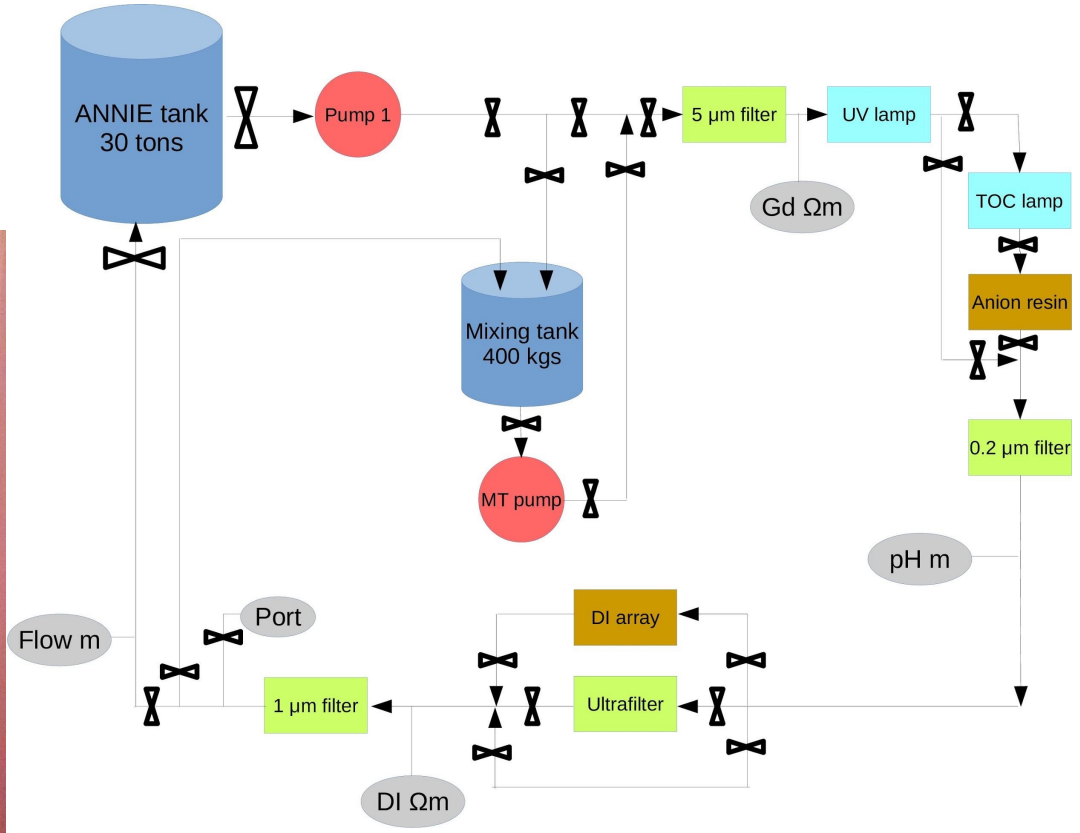
- Neutron capture on Gd:
  - 150,000 times the capture cross section of H
  - Brings down capture time from 200 to 30 μs
  - Emits a 8 MeV gamma cascade instead of a 2 MeV gamma
- The ANNIE water:
  - 26 tons of water loaded with 0.2% gadolinium sulfate
  - ~52 kg of gadolinium sulfate ($Gd_2(SO_4)_3$)
  - High levels of optical transparency for Cherenkov light
  - Homogeneity of Gd within the tank
  - Stable water quality over time





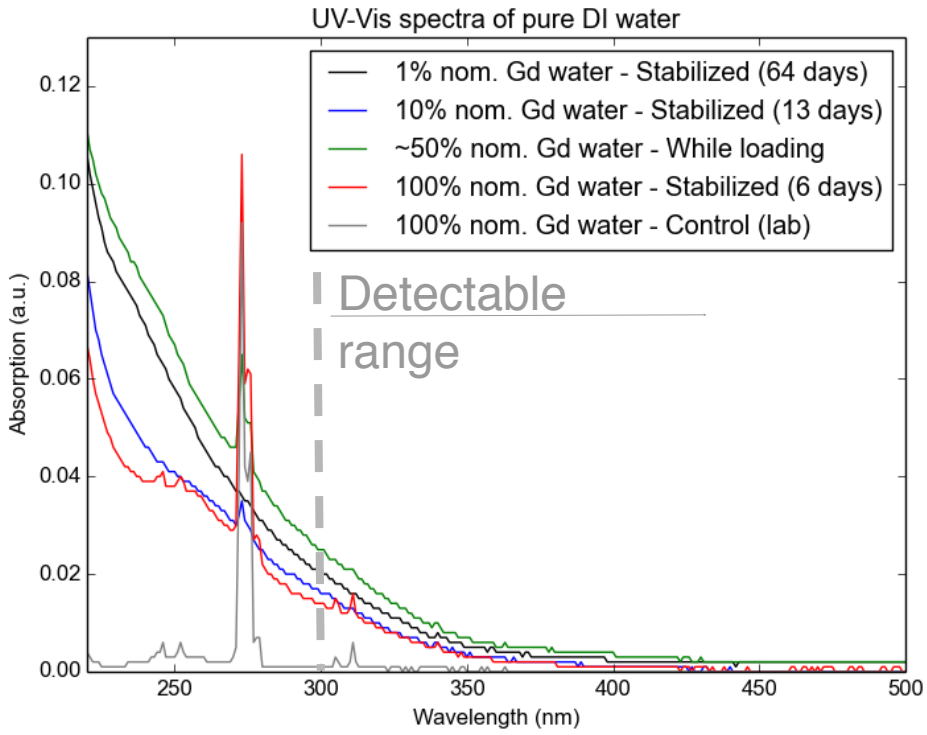
Water system schematic





Gd water quality

Latest water transparency



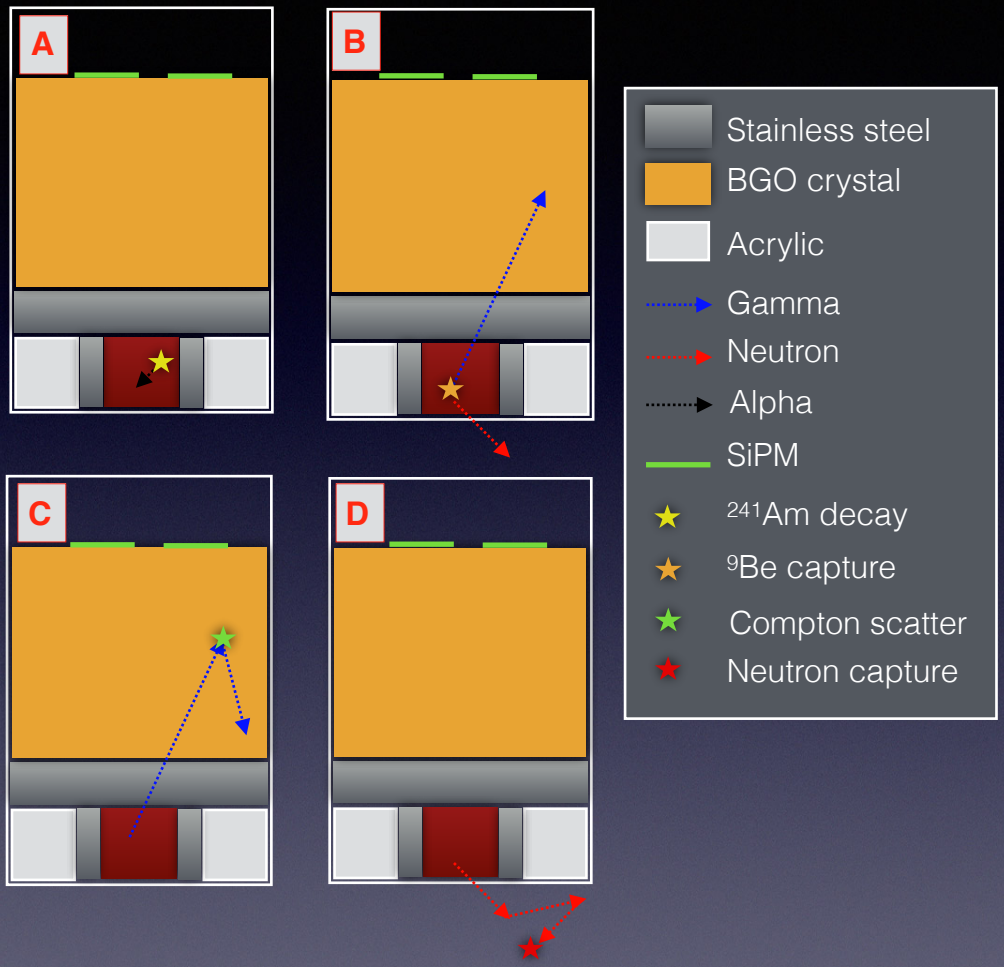
- Light absorption caused by dust, dissolved plastics and gadolinium absorption peaks
- Water quality increases over time as water is purified through water system
- With the latest absorption:

→ 80% of Cherenkov light remaining after 5 m

- Gadolinium concentration is stable

AmBe and BGO Setup

- AmBe source is a mixture of ^{241}Am and ^{9}Be.
- ^{241}Am decays to ^{237}Np via alpha emission (half-life = 432.2 yr).
- ^{9}Be can capture the emitted alpha to produce ^{12}C* and a neutron.
  - Depending on the exact cocktail of ^{241}Am and ^{9}Be, ~1 neutron per 10^{5} - 10^{6} ^{241}Am decays is produced.
  - The exact cocktail also impacts the alpha energy upon capture and the resulting neutron energy spectra.
- ^{12}C* produces a prompt 4.44 MeV gamma.
- When a 4.44 MeV gamma is produced, we know there is a neutron. Thus, we can use the 4.44 MeV gamma as a trigger and wait to see if we see the neutron capture.
- Bismuth germanium oxide (BGO) crystal used to detect the 4.44 MeV gamma.
  - High light yield of ~8500 photons per MeV.
  - Emits in a favorable wavelength regime (480 nm peak emission with a range of 375-650 nm).
  - Not hydroscopic - great as this is going in water.
  - Very dense at 7.13 g/cm^3, meaning Compton scatters are more likely.



A. ^{241}Am decays to ^{237}Np via alpha emission (half-life = 432.2 yr).

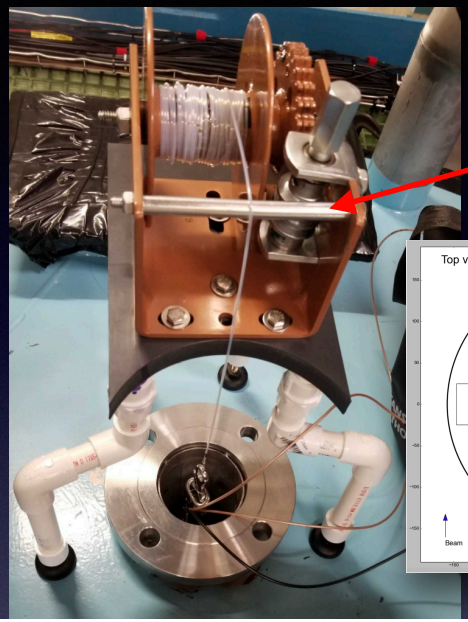
B. ^{9}Be can capture the emitted alpha to produce ^{12}C* and a neutron. ^{12}C* produces a prompt 4.44MeV gamma.

C. 4.44 MeV gamma can Compton scatter in the BGO crystal - this gives us a trigger.

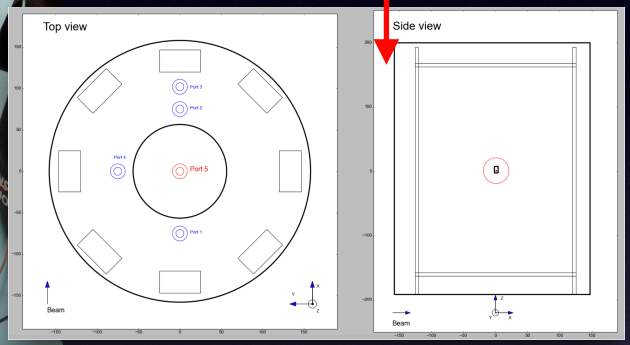
D. Neutron thermalises in ANNIE and is captured on Gd.

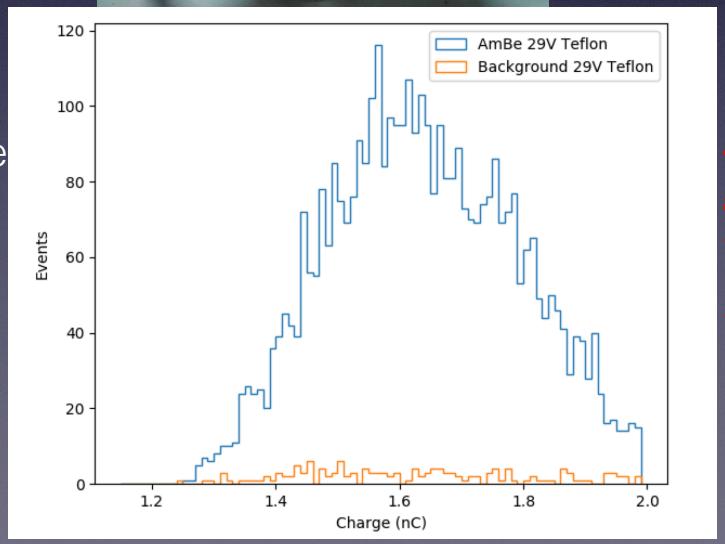
AmBe source ready next week

- Final step is to finalise the DAQ triggering off the SiPMs
- Everything else is ready to go:
  - Triggering on 4.44 MeV gammas was a success (DocDB #3239)
  - Operating voltages have been optimised (DocDB #3239)
  - Deployment mechanism is complete and deployment procedure is available (DocDB #3480)
  - 6 day deployment plan - after one day deployment run - has been agreed upon



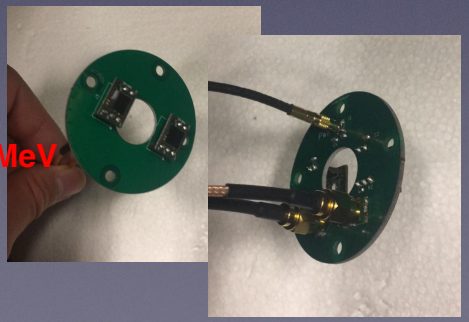
Deployment mechanism has been tested with an estimated position uncertainty of 5cm





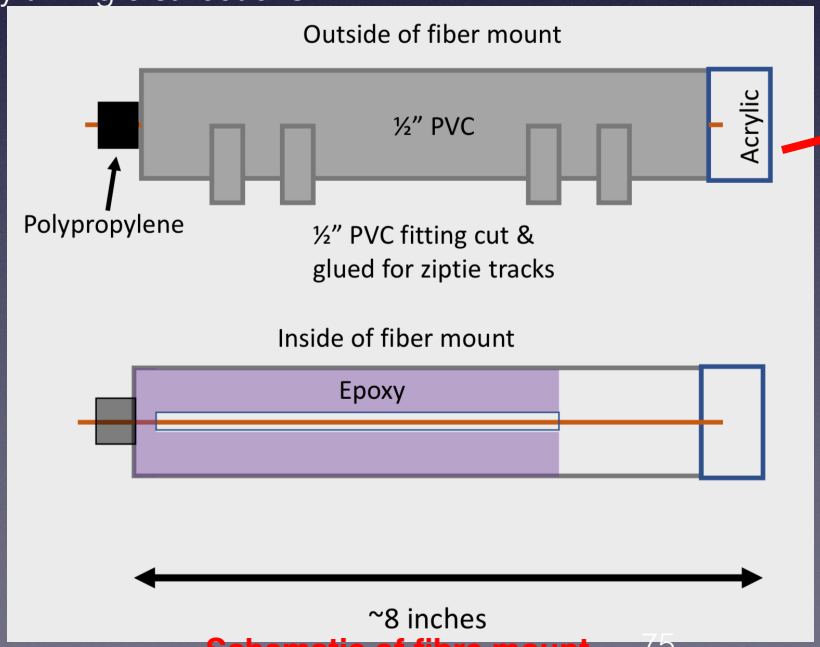
Total charge distribution after selection cuts.
- **Signal to background ratio of 25:1**
- **Will be improved further with muon veto**

SiPM circuit to trigger on 4.44 MeV gamma

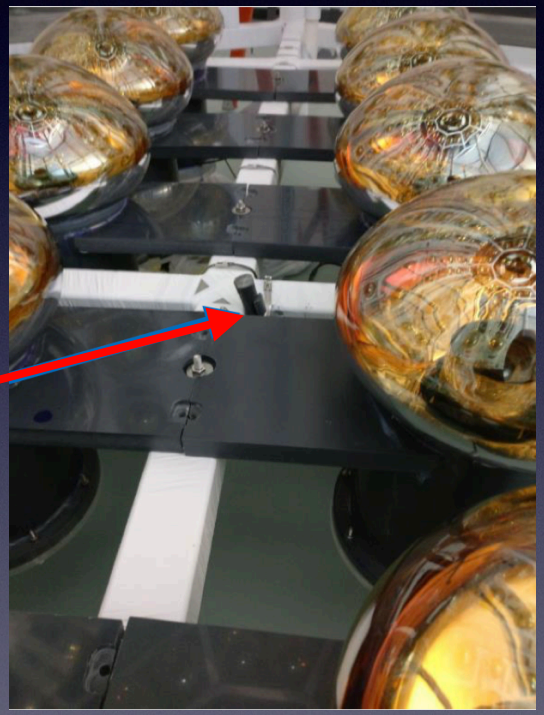


LED system has been running smoothly since November

- The LED system has been operational since November.
- 6 LEDs in total. 4 near the equator, one at the top and one at the bottom.
- LED has been used for:
  - Gain calibration
  - Transparency monitoring
  - Preliminary timing distributions



Schematic of fibre mount

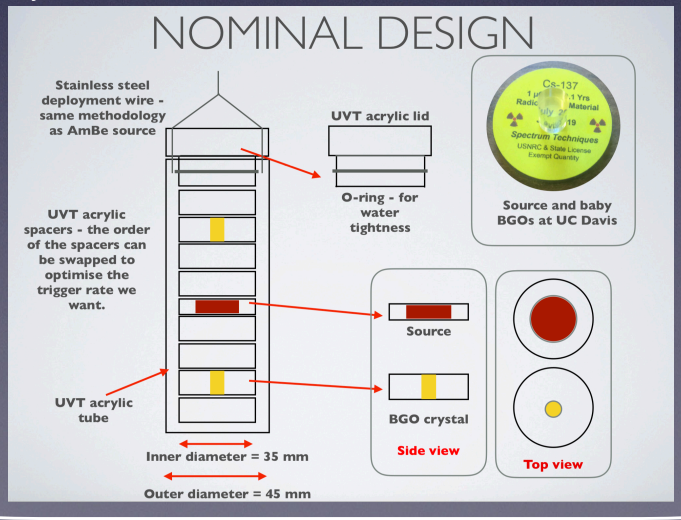


Bottom LED fibre placement

Next steps

Standard Candle (DocDB #3242)

- Idea was to design an easily deployable “standard candle” with no electronics
- Will be placed in strategic locations throughout the detector to build up a detected energy spectrum of each PMT
- This can be used to calibrate the PMT responses over time and also water transparency
    - This will be independent of LED’s serving as great cross-check
- Design is with the machine shop. Expected to be completed by the end of January.
- After testing and shipment, expect to be operational by end of February.

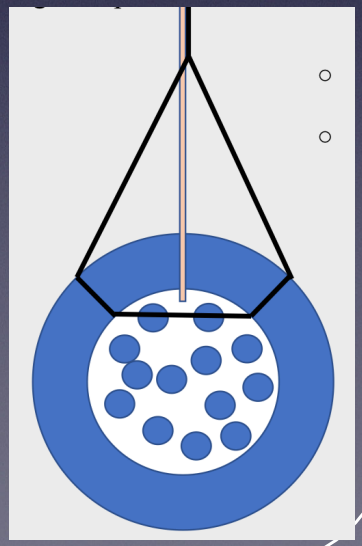


Laserball (DocDB #2978)

- This will serve as the most precise PMT timing calibration method via deployment at the centre of the detector
- Picosecond pulsed diode lasers and Single Mode FC/APC Fiber Optic Patch Cables are on hand.
- Ball needs to be designed. This will begin this week at UC Davis, with the homogeneity of the light to be tested.
- Aim to have the design finalised by the end of January.
- Ready to be installed by the end of February.

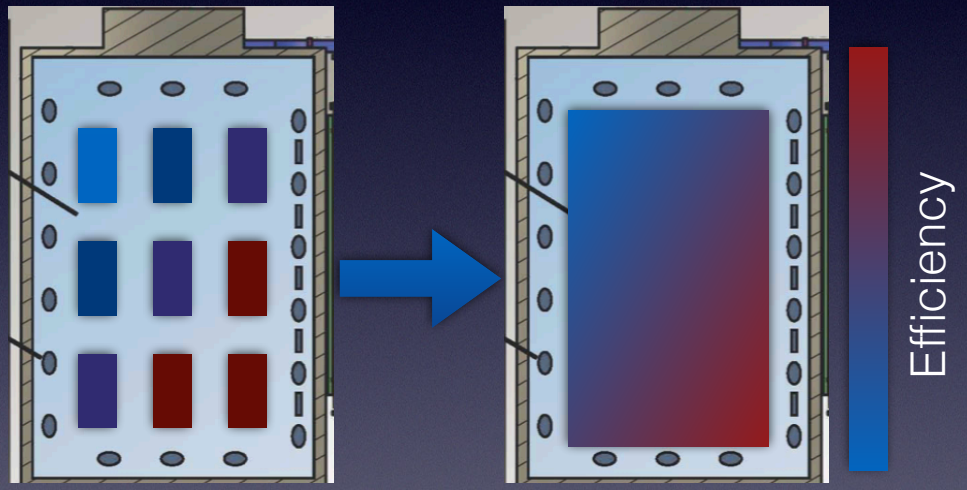
Example proposed laserball design:

- **Outer acrylic sphere**
- **Inner acrylic beads**
- **All designs will undergo homogeneity and buoyancy/ deployment testing**



AmBe calibration methodology

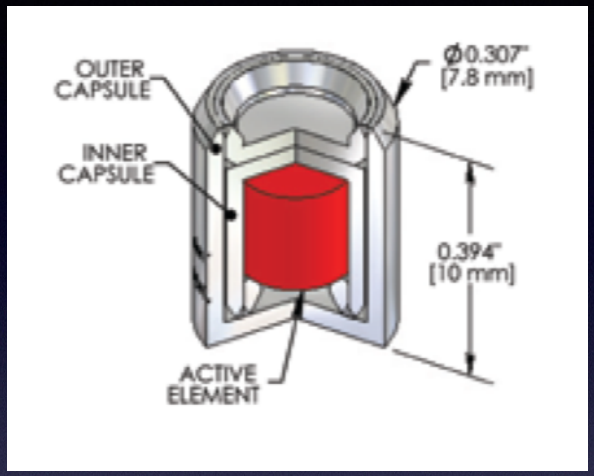
- By deploying the source at specific locations, the efficiency as a function of position, can be mapped.



By placing the AmBe calibration source throughout the detector.…

…the neutron capture detection efficiency will be mapped.

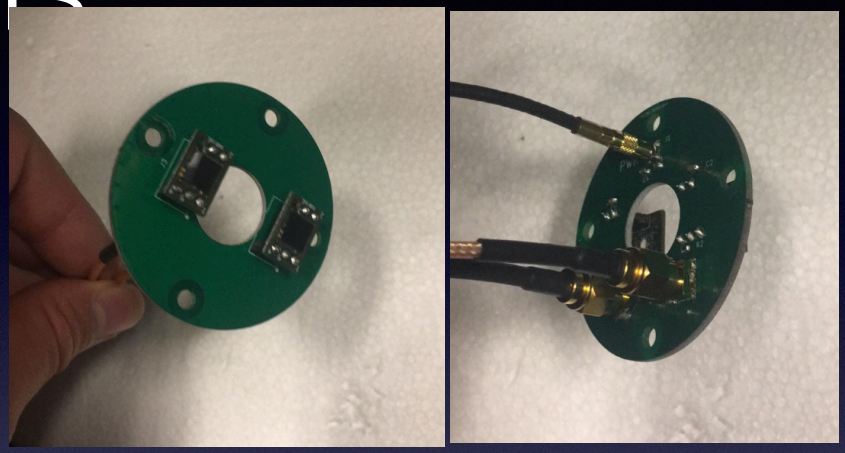
The AmBe source



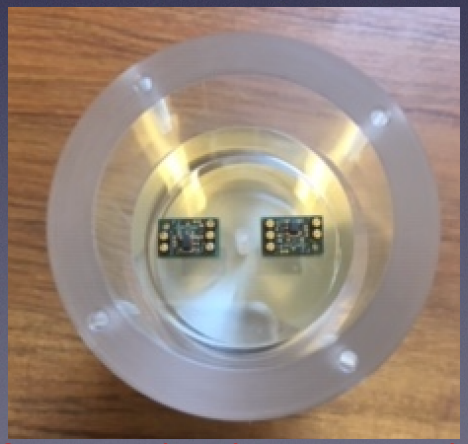
- Source is at Fermilab
- Am activity is 100 μCi:
  - Typical 10^{-4} efficiency gives about 100 tagged neutrons/second
- Source has two, water-tight, stainless steel layers of encapsulation
  - “Inner” and “outer” capsule

The trigger readout uses SiPMs

- SiPM circuit secured above BGO crystal, within the water tight acrylic container.
- 3 cables feed out from the top:
  - 2 signal cables - SMA connectors
  - 1 power cable - MCX connector
- Using 60035 J-series SiPMs
  - Typical operating voltage is 26-30 V.
  - Dark count rate is 50 - 150 kHz/mm^2 = 1.8 - 5.4 MHz. Coincidence trigger and high trigger threshold required.
  - Gain is 2.9 - 6.3 X 10^6
- Cables epoxied through the acrylic lid to maintain water tight seal.



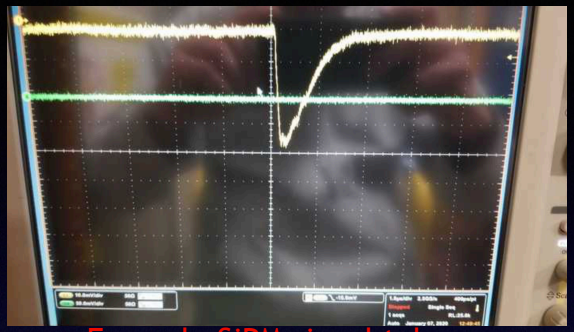
SiPM electronics board



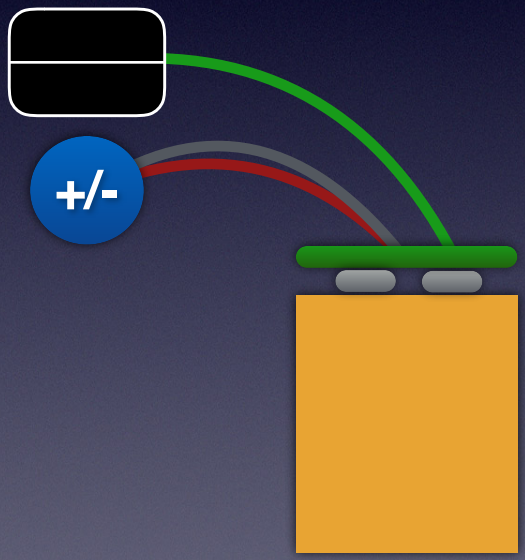
SiPMs are placed in contact with the BGO crystal

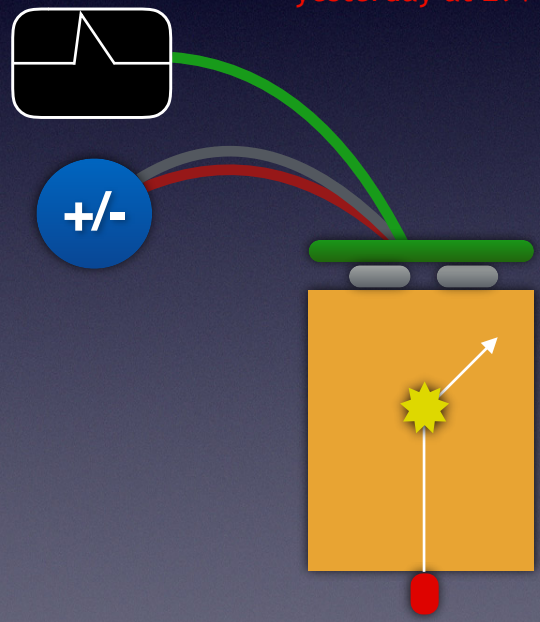
Trigger commissioning setup

- Testing undertaken to optimise setup:
  - Signal background separation (tested with and without the AmBe source)
    - Biasing voltages tested from 28.0V to 30.0V - ~29.0V gives best S/N ratio
    - Tested with and without reflective teflon layer - next slide



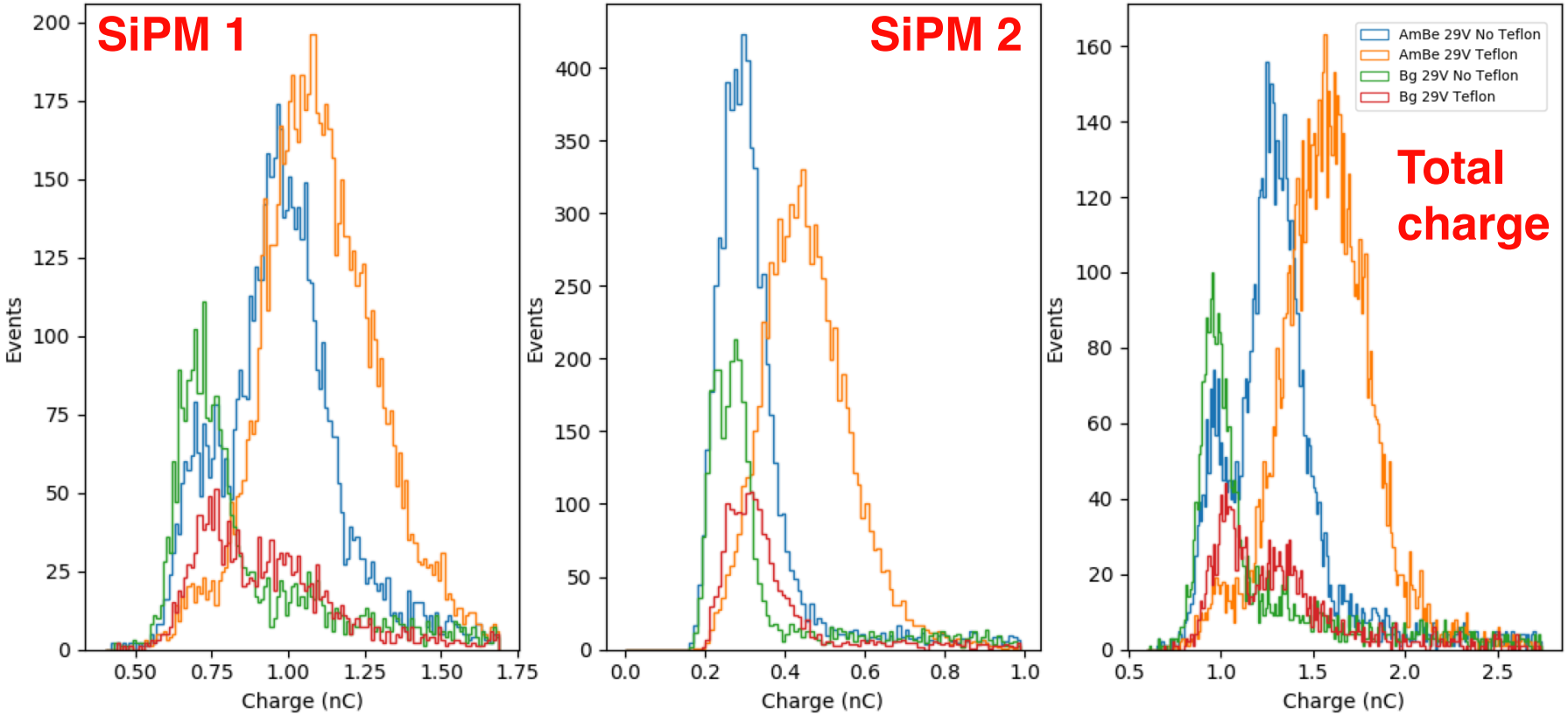
Example SiPM signal taken yesterday at 29V bias





- DAQ setup:
  - Trigger on one SiPM (> 5mV) then acquire both signals.
  - Analysis then conducted to assess the effect of SiPMs using coincidence and different trigger thresholds on S/N ratio.

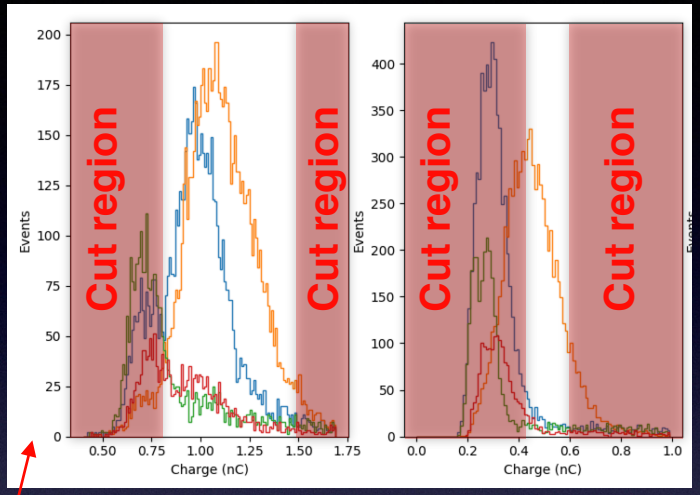
29V bias found to be most effective

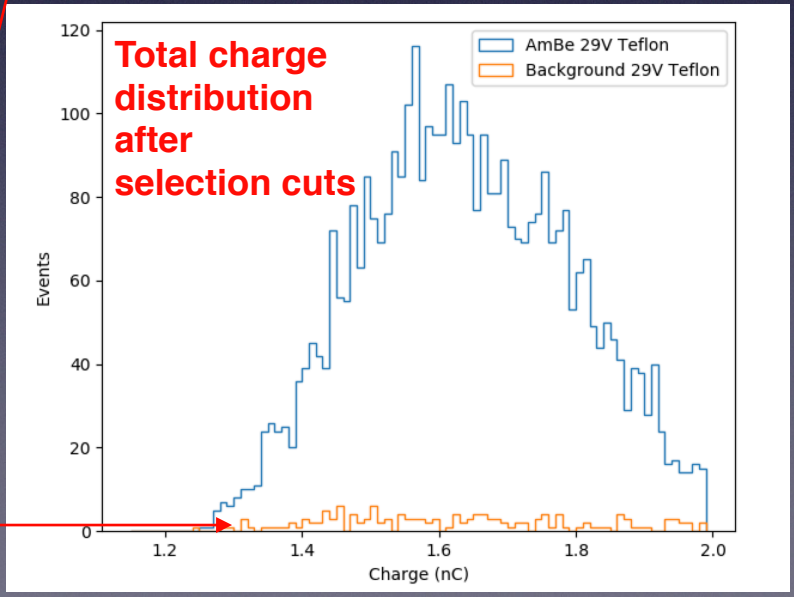


- 29V bias was found to give great signal to background separation
- Use of reflective coating around the BGO has huge impact:
  - Significant improvement in S/N separation (~3.7 times better separation)
  - Trigger rate increases by 63%

Can achieve great signal-to-noise separation

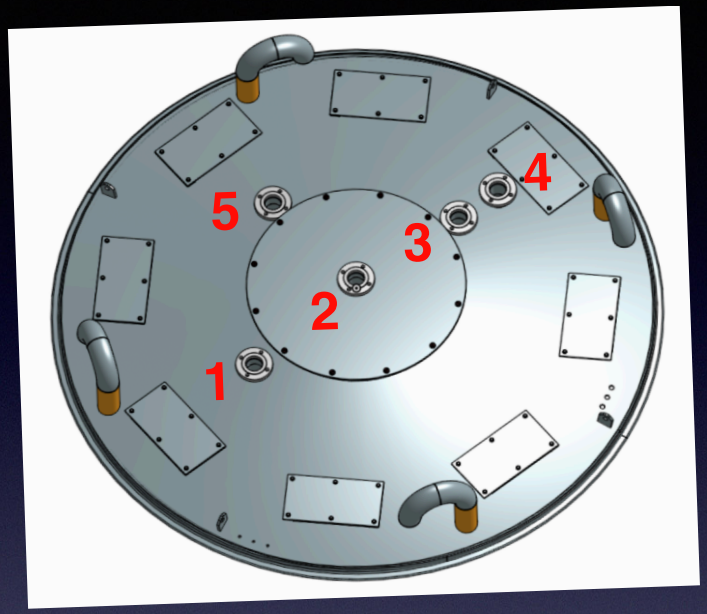
- 30 minute run:
  - Signal-to-noise ratio = 24.96 (4194 signal events, 168 background events passing selection cuts)
  - Cuts will be further optimised with in-situ tests this week
- To attain the best S/N ratio, we will digitize each output separately.
  - Gain and response of each SiPM is not the same.
  - Muon rejection using the detector can increase this further.



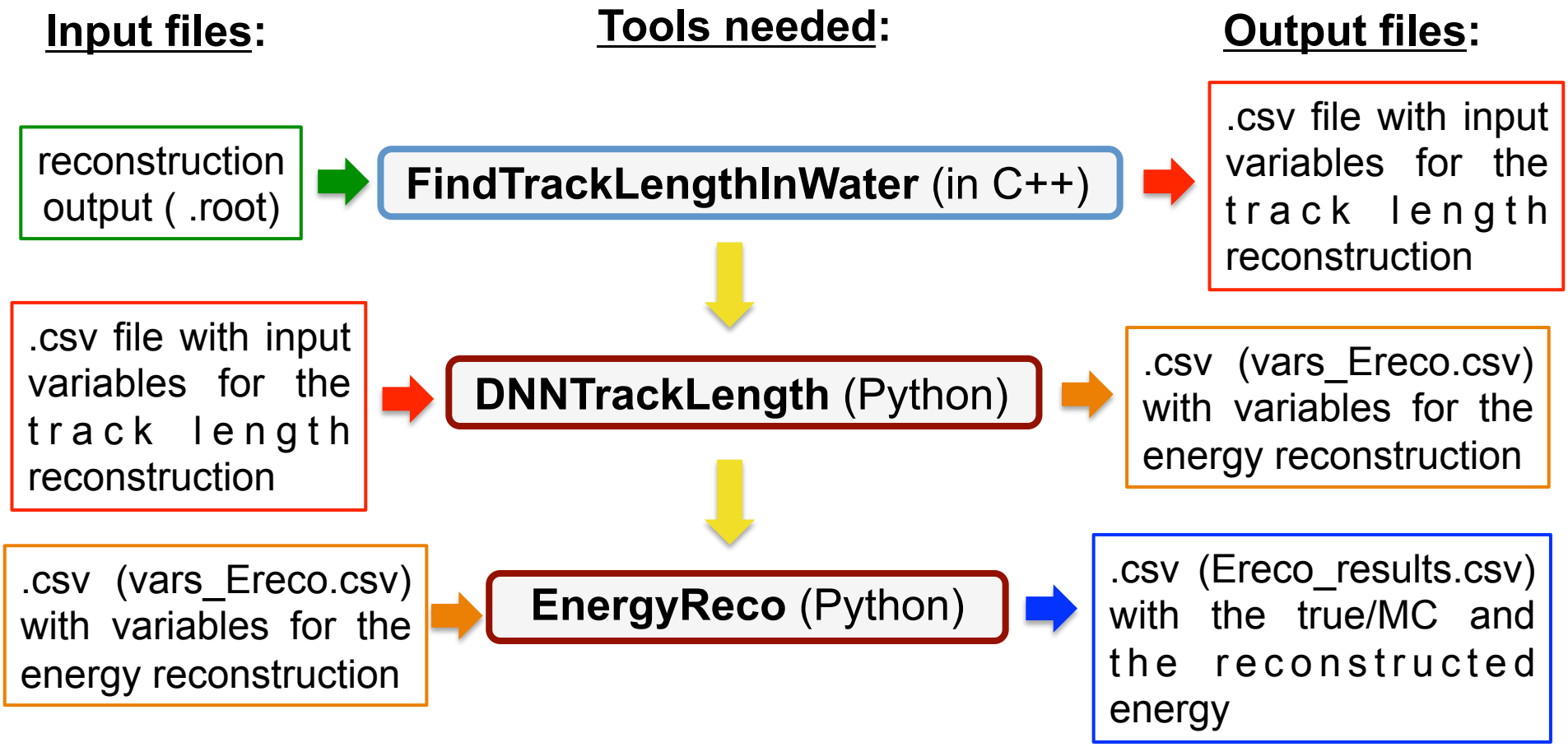


Deployment mechanism

- AmBe source is to be deployed using 1mm stainless steel wire
  - Minimal shadowing
  - Easy to deploy
  - Gd-water compatible
  - Stress-tested
- Nominal calibration campaign will last 1 week
  - All 5 calibration ports to be used
  - 5 heights for each port
  - Inhomogeneities in the neutron capture efficiency will have knock on effects for WATCHMAN
- When deployed three additional “optical layers” will be used:
  - Inner, reflective white, layer to guide as much light to the SiPMs as possible
  - Middle, absorbing black, layer to ensure no light from the BGO escapes from the container
  - Outer, white reflective layer to minimise photon absorption

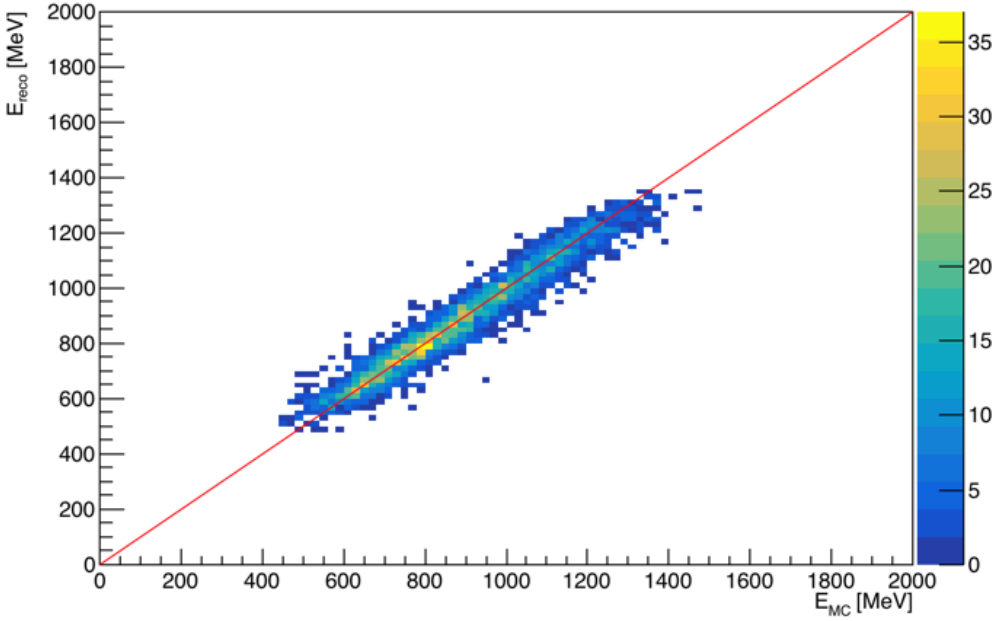


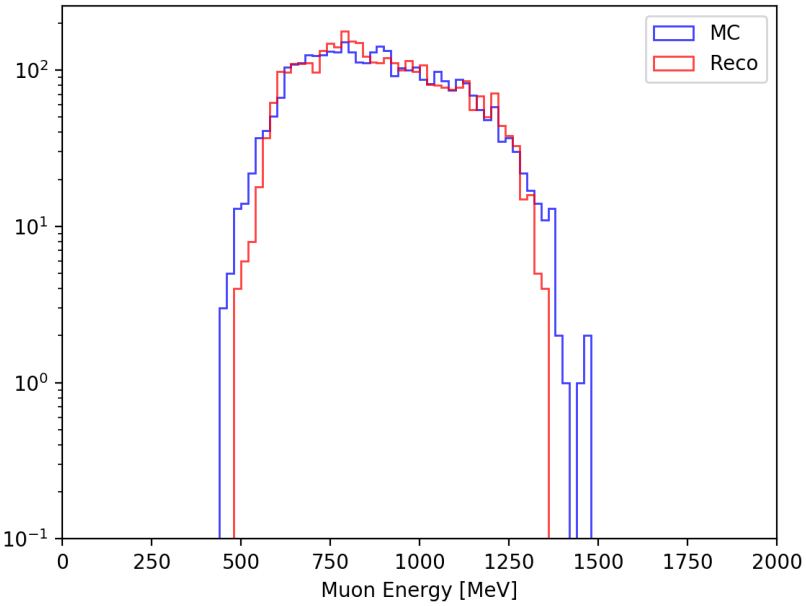
Energy Reconstruction in ToolAnalysis



Results on Muon Energy Reco using the latest production

- The BDTG parameters have been optimised using script: *optimising_parameters_energy.py*

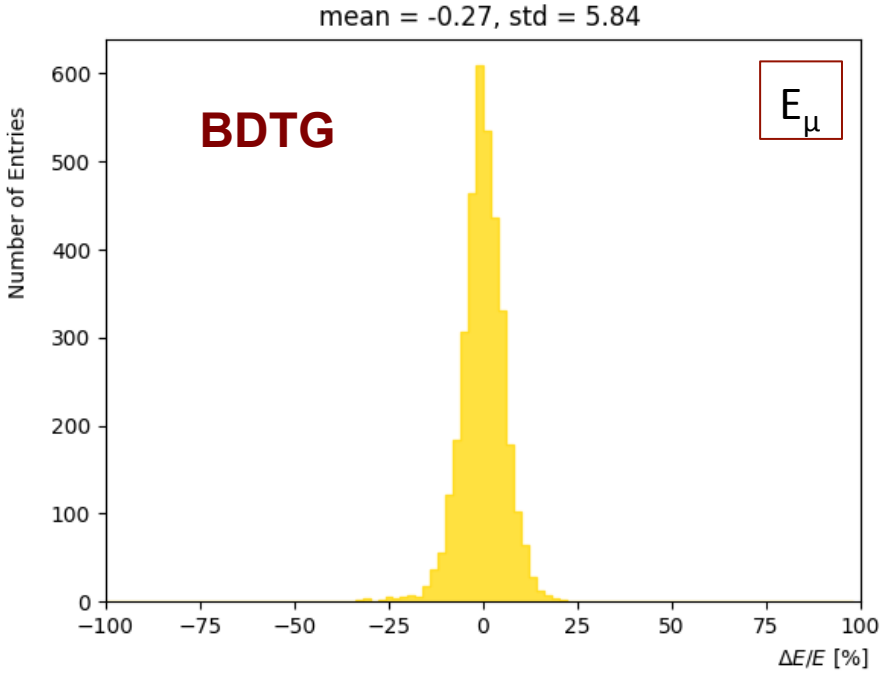


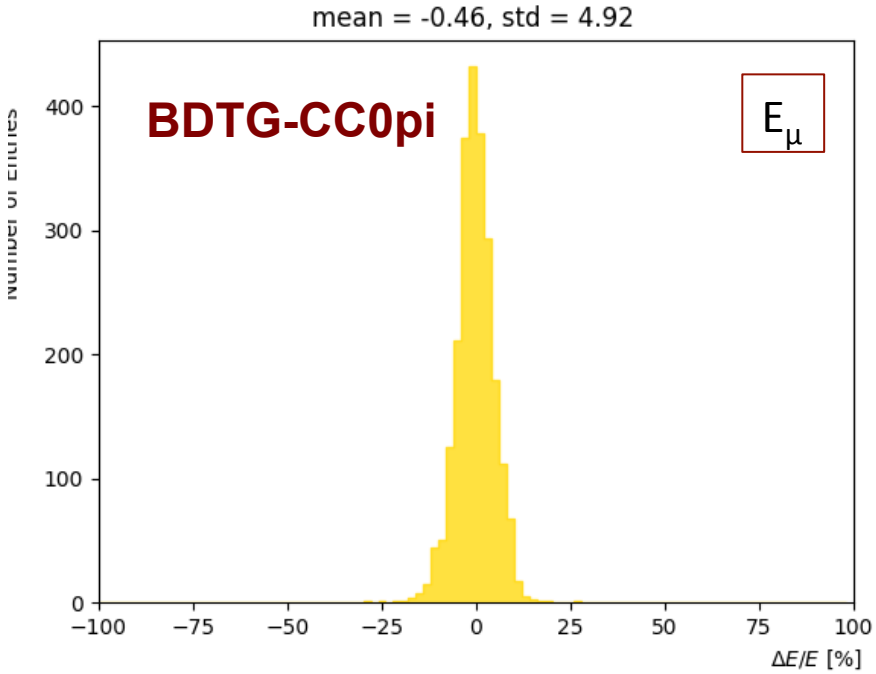


~ 3500 events used for the energy prediction and 1000 events for the BDT training

Results on Energy for CC0pi events

- The events presented so far are not CCQE only.
- If we select CC0pi events we are getting a slightly better energy reconstruction.





Percentage of events in ΔE/E<10%:	92.4%	||	95.4%
Percentage of events in10%<=ΔE/E<20%:	6.8%	||	4.3%
Percentage of events in ΔE/E>=20%:	0.8%	||	0.3%