University of Chicago

Argonne NATIONAL LABORATORY

ANNIE
Atmospheric Neutrino Neutron Interaction Experiment

Letter of Intent: ANNIE

The Accelerator Neutrino Neutron Interaction Experiment

Matt Wetstein and Mayly Sanchez

on behalf of the ANNIE Collaboration:

I. Anghel, J. F. Beacom, M. Bergevin, C. Blanco, E. Catano-Mur, F. Di Lodovico, A. Elagin, H. Frisch, J. Griskevich, R. Hill, G. Jocher, T. Katori, F. Krennrich, J. Learned, M. Malek, R. Northrop, C. Pilcher, E. Ramberg, J. Repond, R. Sacco, M.C. Sanchez, M. Smy, H. Sobel, R. Svoboda, S.M. Usman, M. Vagins, G. Varner, R. Wagner, A. Weinstein, M. Wetstein, L. Winslow, L. Xia, and M. Yeh

...

Fermilab PAC Meeting

January 16, 2015

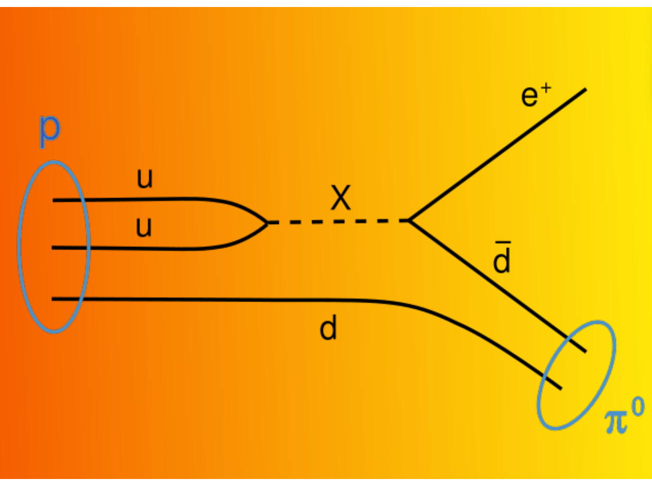
U.S. DEPARTMENT OF ENERGY

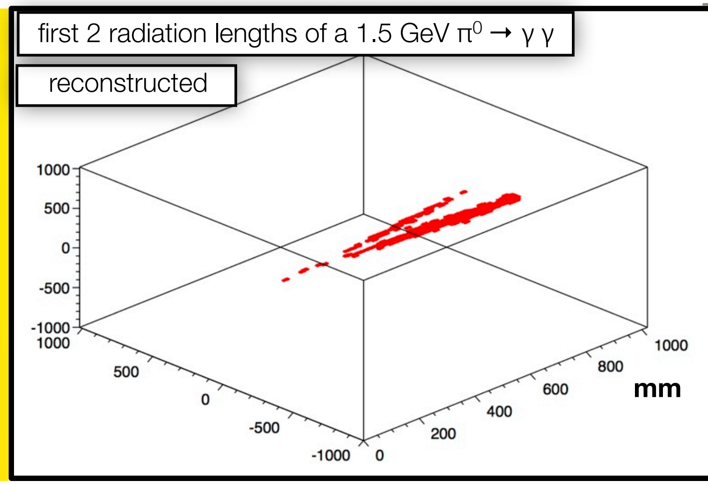
What is ANNIE?

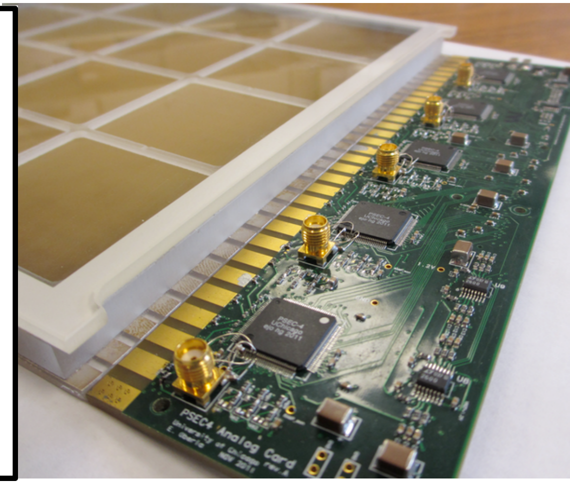
Accelerator Neutrino Neutron Interaction Experiment

- A measurement of the abundance of final state neutrons from neutrino interactions in water, as a function of energy.

for understanding neutrino-nucleus interactions and addressing a limiting factor in proton decay and supernova neutrino physics





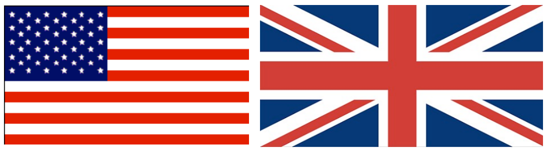


- A new technological path for the long-term Fermilab program
- A community that broadens the Fermilab user base

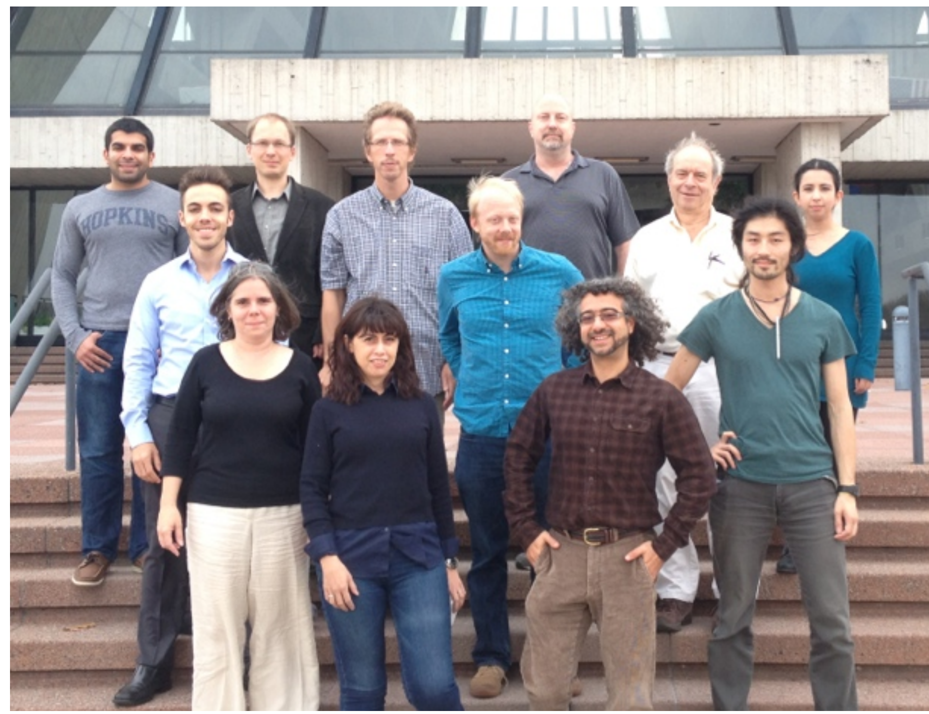
The Collaboration

34 collaborators

15 Institutions



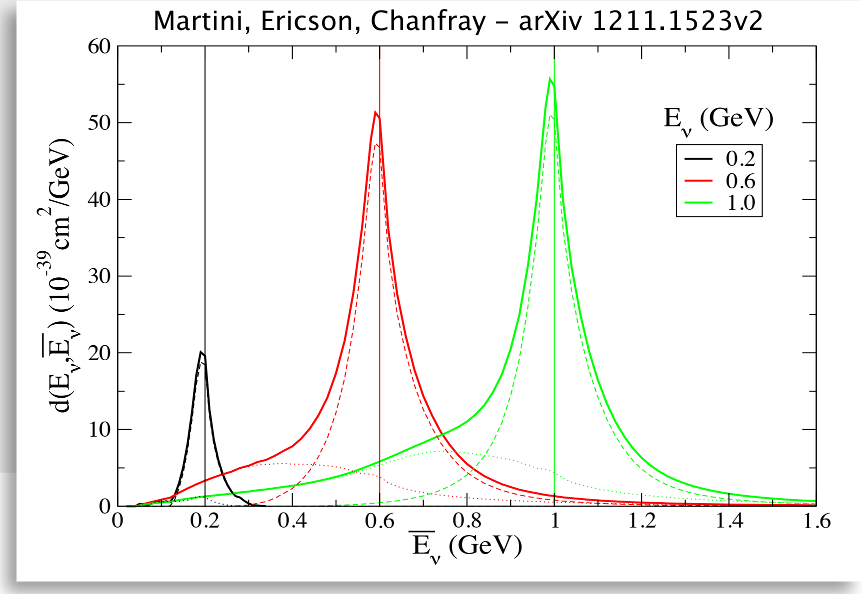
- Argonne National Laboratory
- Brookhaven National Laboratory
- Fermi National Accelerator Laboratory
- Imperial College of London
- Iowa State University
- Johns Hopkins University
- MIT
- Ohio State University
- Ultralytics, LLC
- University of California at Davis
- University of California at Irvine
- University of Chicago, Enrico Fermi Institute
- University of Hawaii
- Queen Mary University of London



How Do Neutrino's Interact With Nucleii?

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

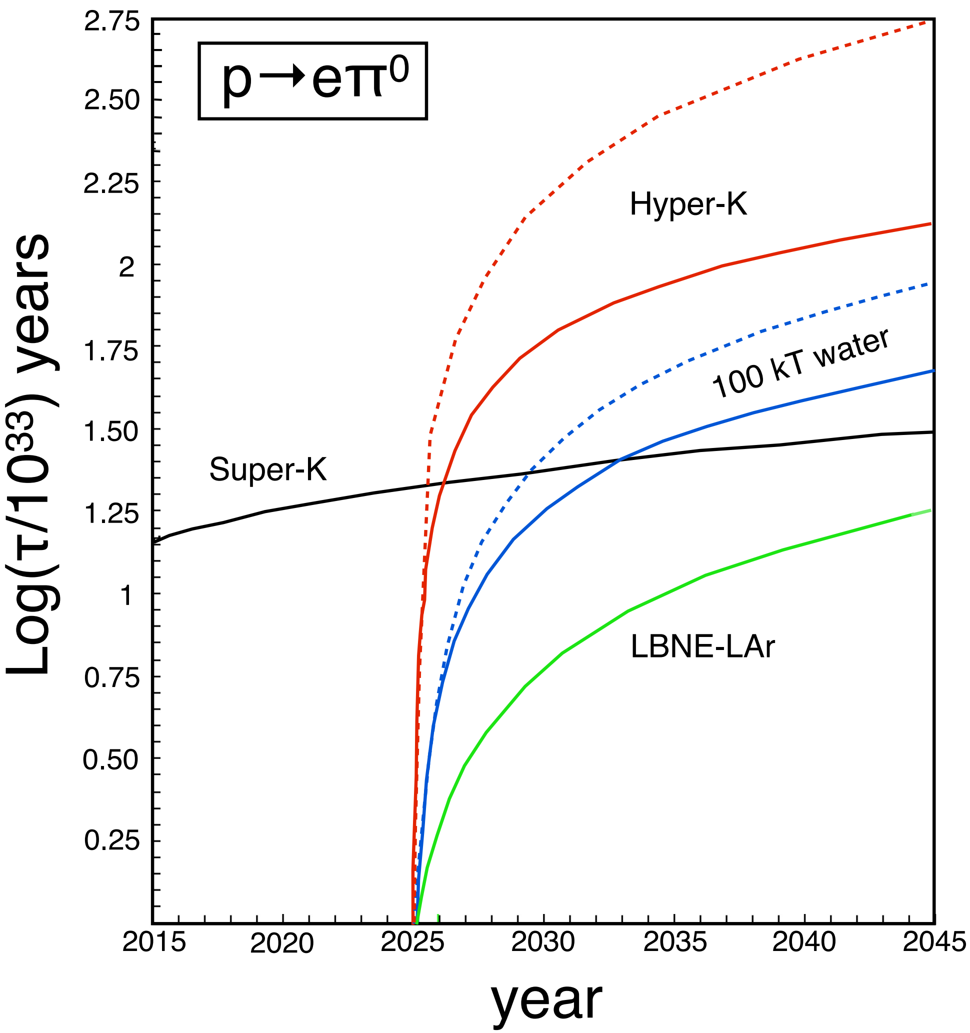
- Dominant source of systematics on future long baseline oscillation physics
- Source of uncertainty and controversy in short baseline anomalies
- We need comprehensive and precise measurement for a variety of targets/E_ν



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

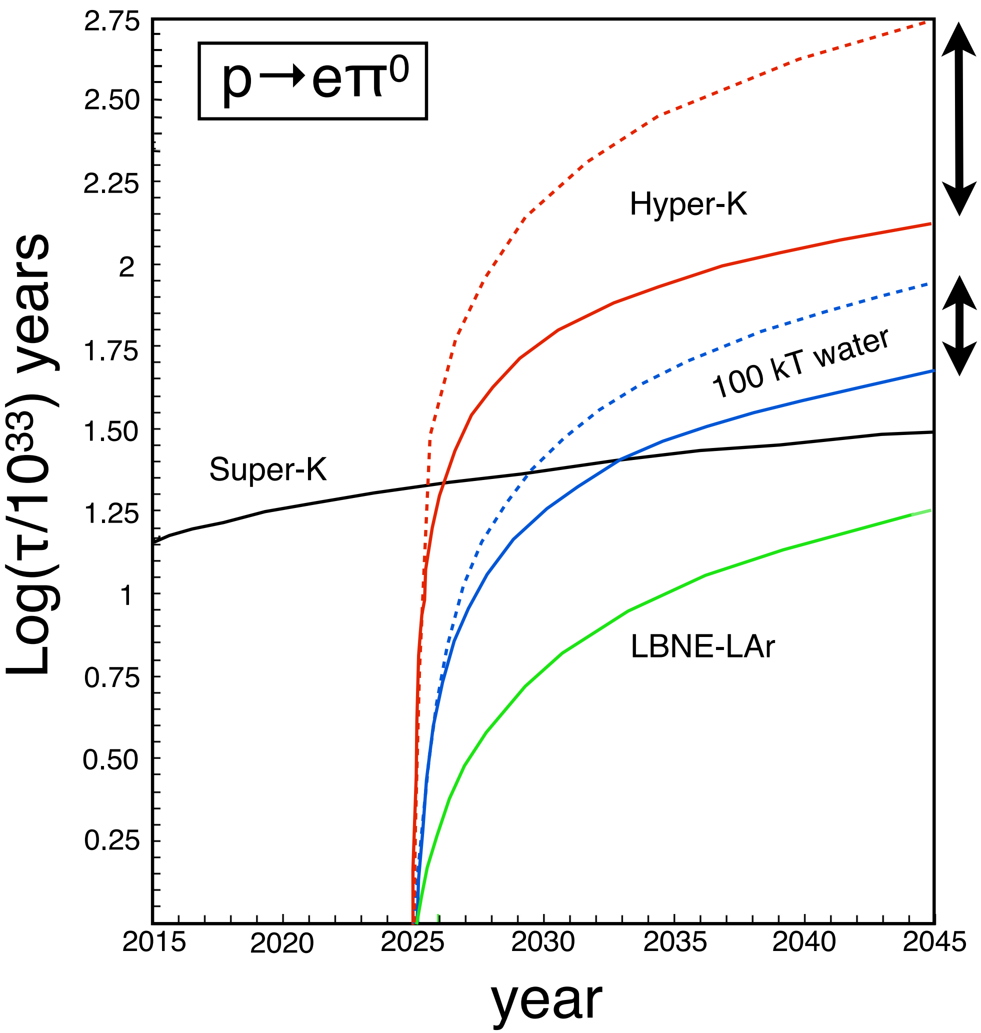
The presence, multiplicity and absence of neutrons is a strong handle for signal-background separation in a number of physics analyses!

Example from Proton Decay



- Next-gen proton decay (PDK) experiments will be background limited (from atmos. neutrinos)
- These backgrounds very often produce final-state neutrons, whereas PDKs rarely do
- The presence of neutrons detected with Gd-loaded water can be used to reject these. (Beacom and Vagins)
- We need data from a controlled beam experiment
- Fermilab can have a large impact on this P5 physics driver ("The Unknown")

Example from Proton Decay



How much background does neutron tagging remove?

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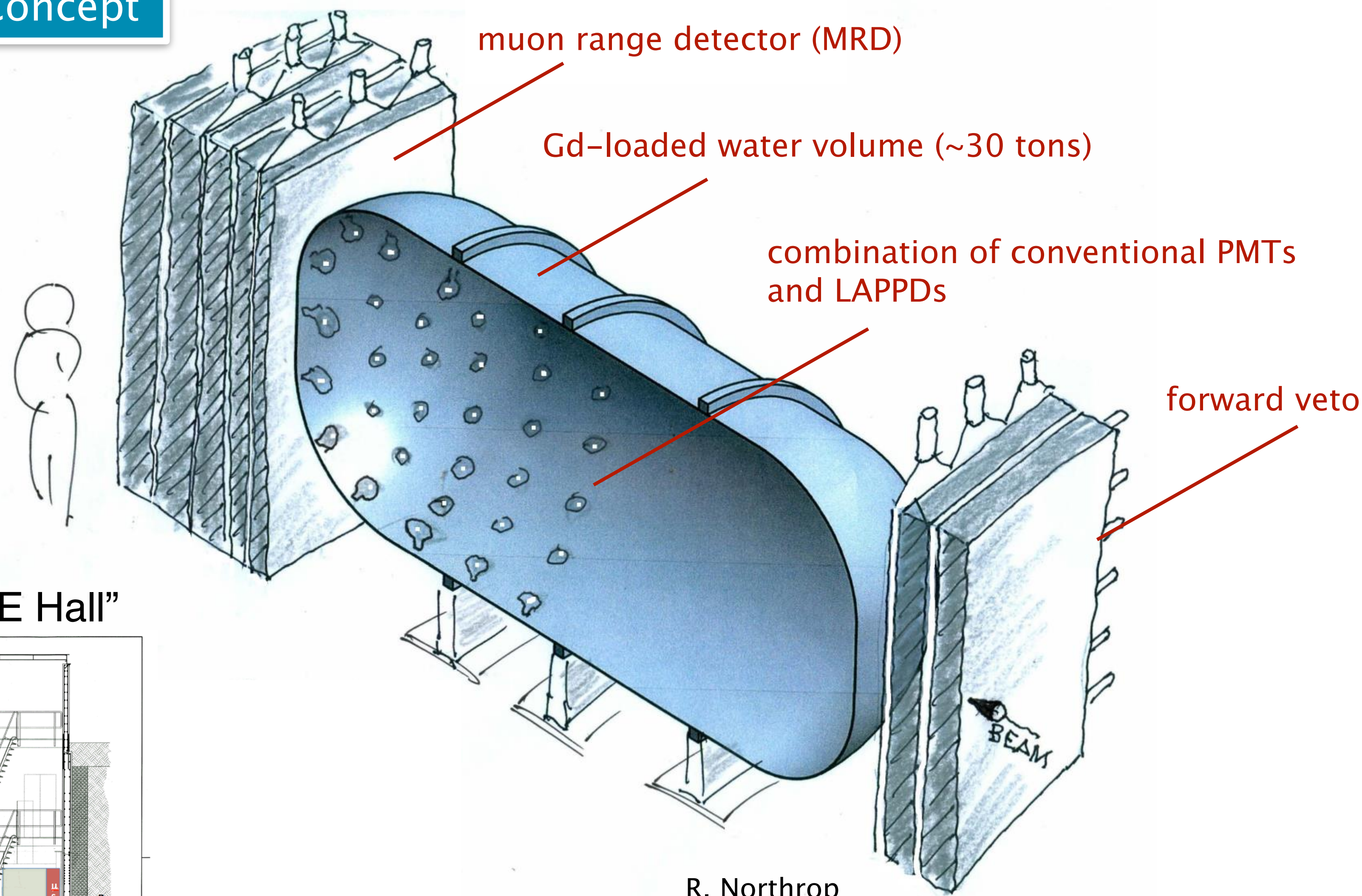
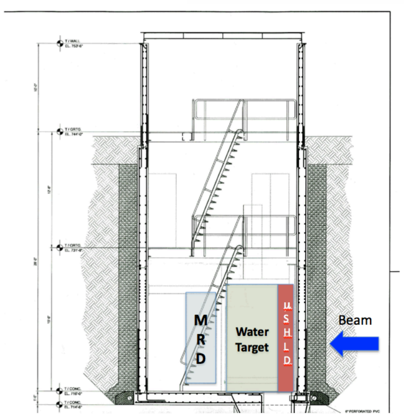
Background uncertainties are an even bigger problem if you have candidate events and want to attribute confidence.

ANNIE Concept

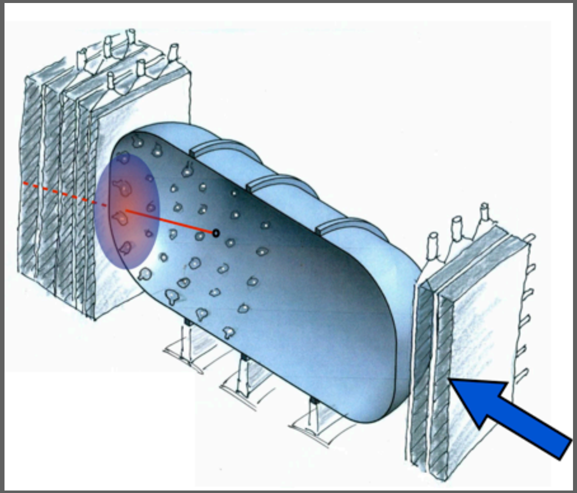


“ANNIE Hall”

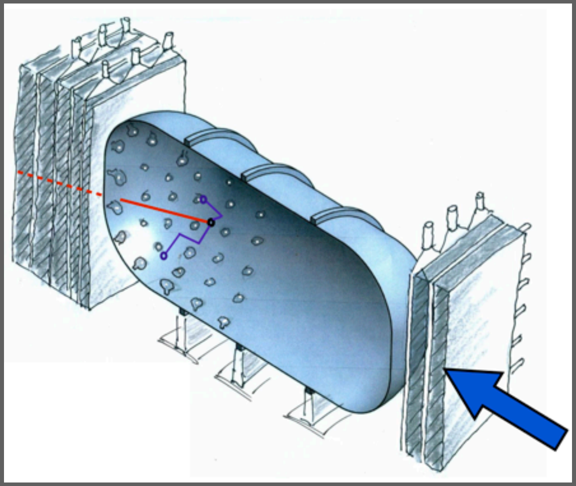


(formerly the SciBooNE pit)

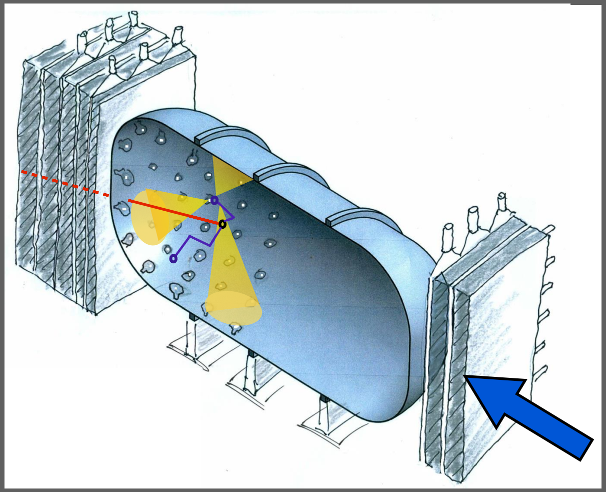
ANNIE Concept



Prompt muon tracks through water volume, ranges in MRD

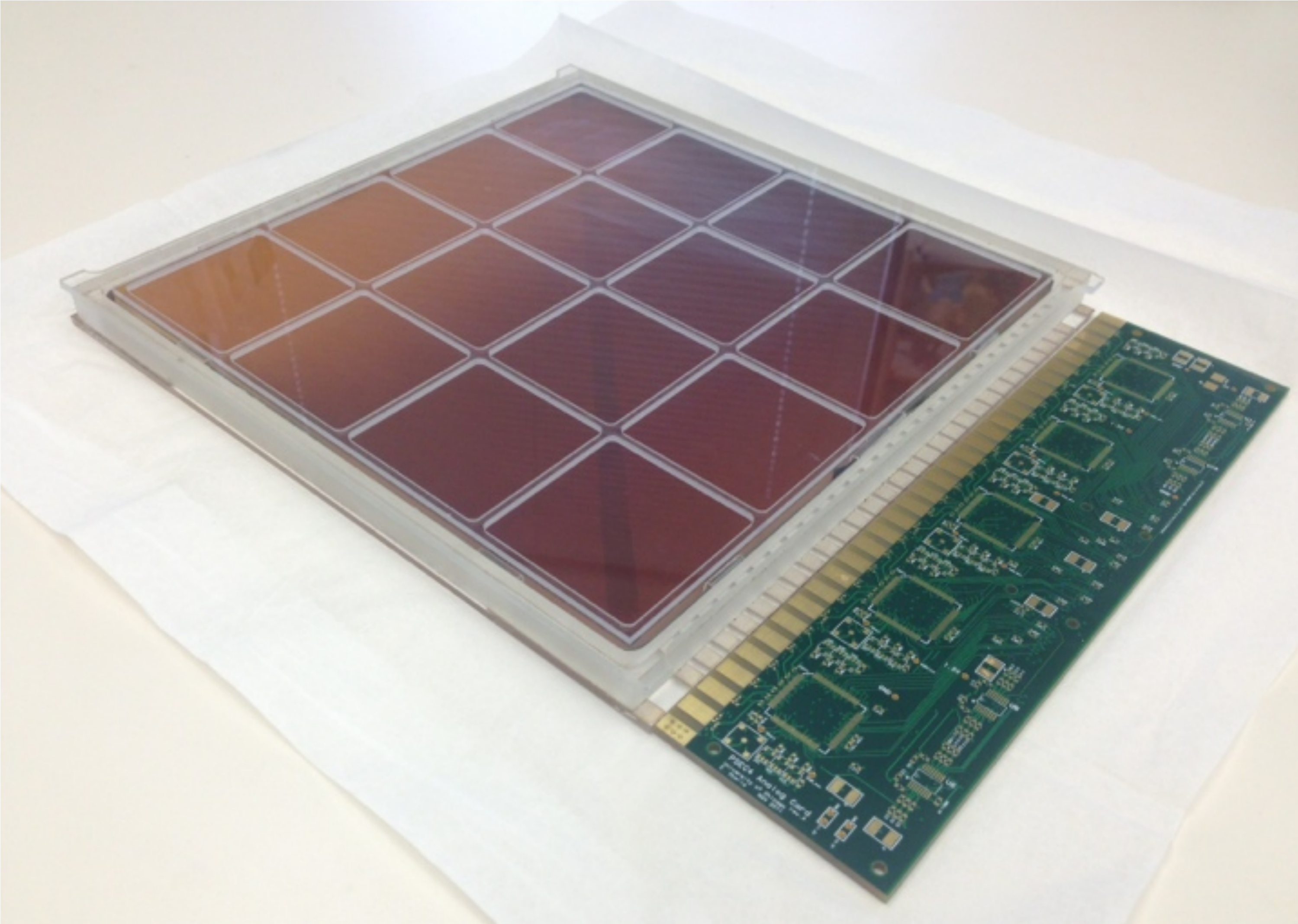


neutrons thermalize and stop in water



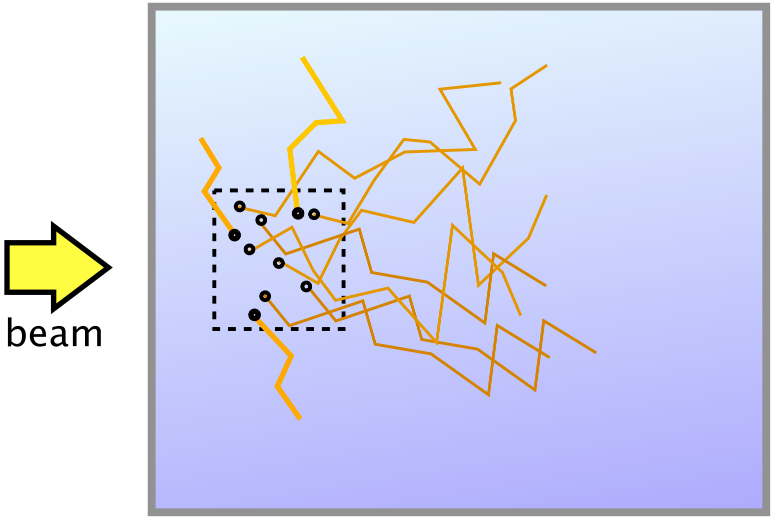
neutrons capture on Gd, flashes of light are detected

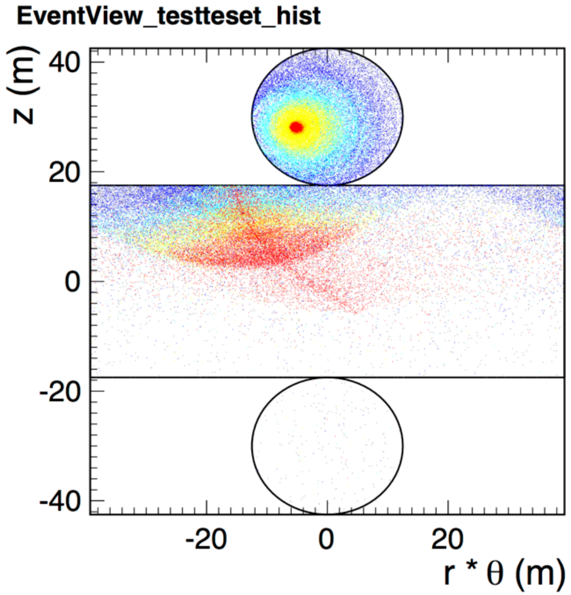
LAPPDs can provide the needed photodetector capabilities

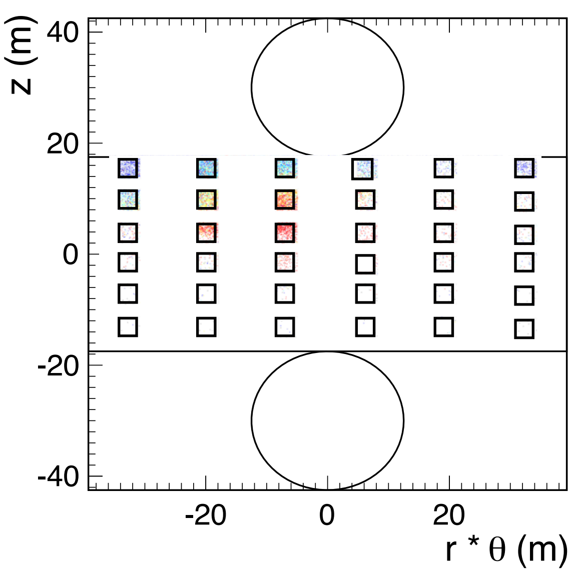


LAPPDs can provide the needed photodetector capabilities

Timing based reconstruction to choose interaction points sufficiently far from the walls of the detector to stop the neutrons







Fine granularity to help resolve Cherenkov cone-edges

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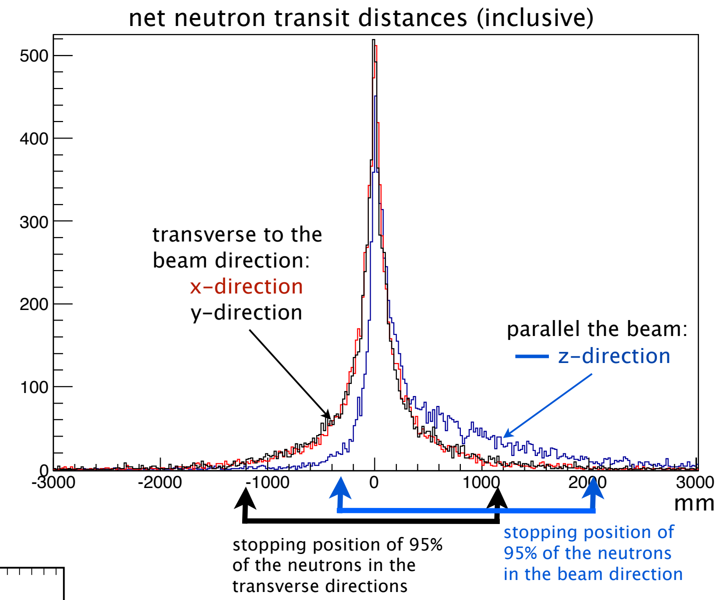

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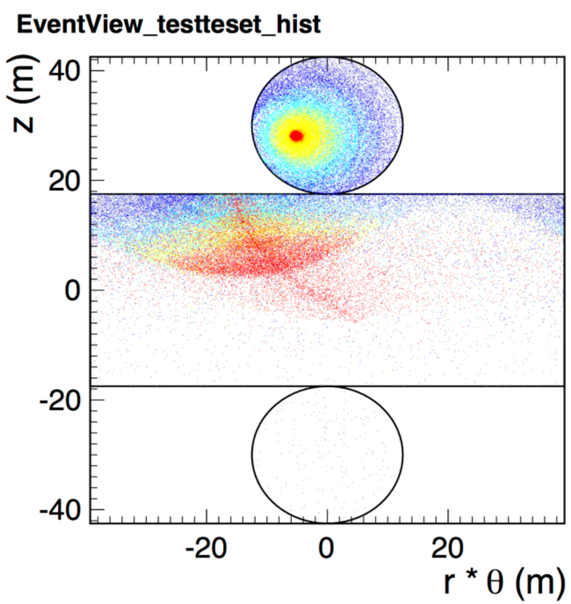
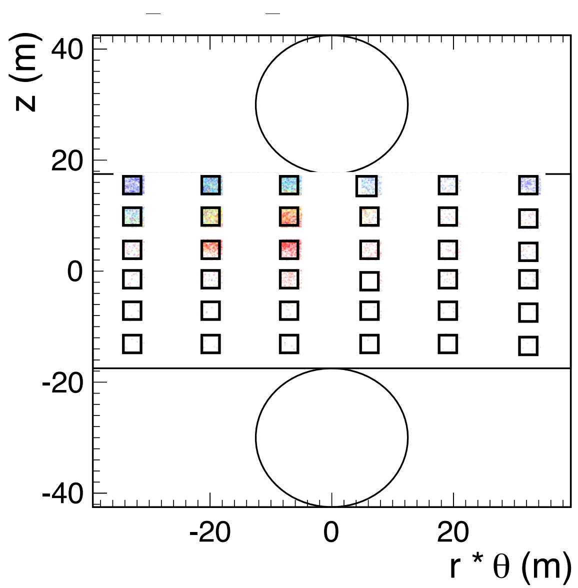


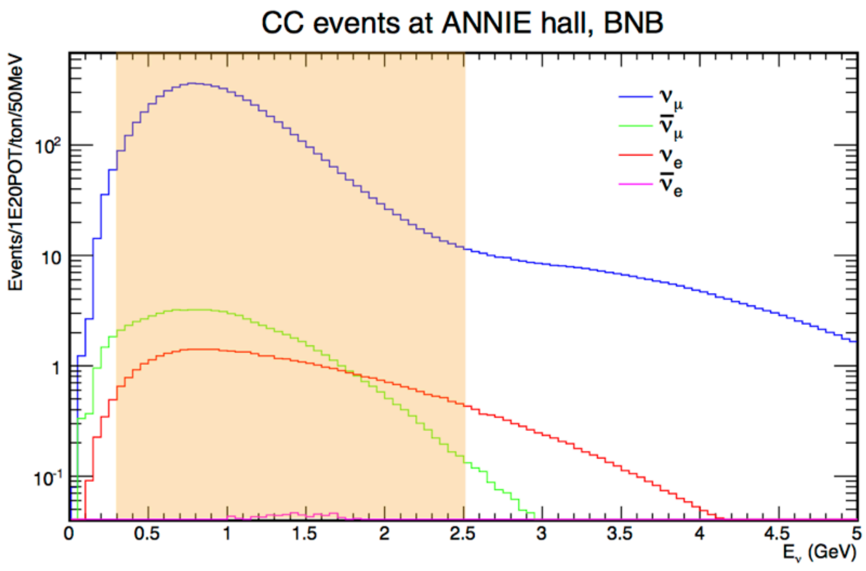


Fine granularity to help resolve Cherenkov cone-edges

Neutrino Beam and Site

We need 3 things in a beam:

- Energy peaked in the range of the proton mass/atmospheric neutrino flux (1-2.5 GeV)
- Statistics
- Low pileup rate



Location	ν_μ CC [0.25-2.5 GeV]	ν_μ CC [0-10 GeV]	Percentage
SciBooNE Hall	6626	6991	95%
SciBooNE surface	708	847	84%
MINOS ND	3362	168078	2%
NOvA ND	8115	12074	67%
NDOS	76	91	84%

events/ton/10^{20} POT

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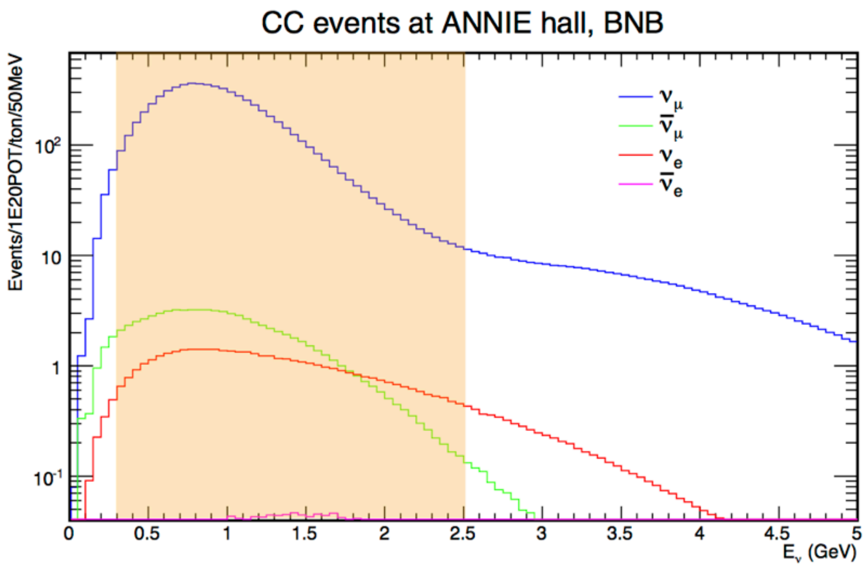

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events/ton/10^{20} POT

Neutrino Beam and Site

Location	ν_μ events/POT/ton	ν_μ events/spill	Avg. pileup/spill
SciBooNE	$2.80 * 10^{-16}$	0.03	5.0×10^{-5}
NOvA ND	$6.04 * 10^{-16}$	0.65	0.0045
MINOS ND	$1.85 * 10^{-14}$	20	3.76

The SciBooNE Hall is unique in meeting these conditions, and it would be a waste not to use it for physics

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events/ton/10^{20} POT

Phased Approach

Sept 2015

- Installation

- Phase I: Test experiment:
  - measurement of neutron backgrounds
  - operate the water volume with PMTs
  - ready for testing of limited number of LAPPDs when available

Dec 2015

- Phase II: First physics run:
  - limited, but sufficient LAPPD coverage
  - focus on CCQE-like events

Dec 2016

- Phase III: Second physics run:
  - full LAPPD coverage (10-20%)
  - more detailed even reconstruction
  - compare neutron yields for CC, NC, and inelastic

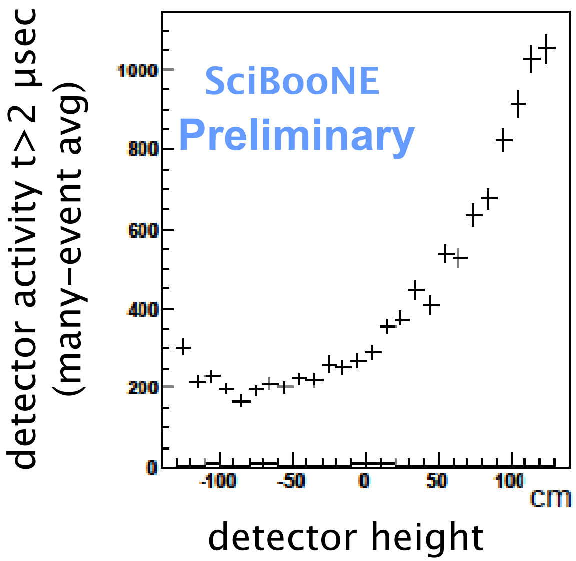
Dec 2017

Phase I: Test Experiment

Relies heavily on reuse of existing components.

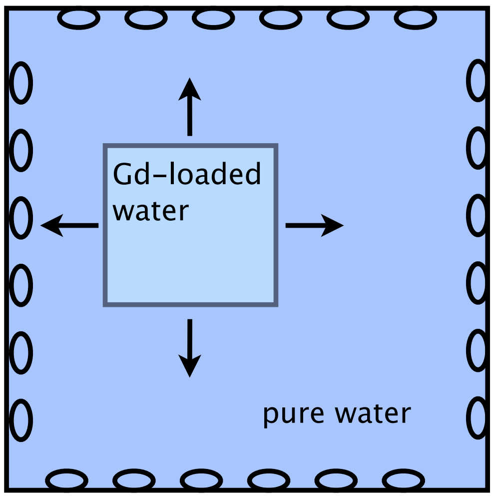
ANNIE will see neutron backgrounds from 2 sources:

- **skyshine:** neutrons from the beam dump migrating into the Hall from above
- **dirt neutrons:** neutrons produced by neutrino interactions in the rock, upstream of the detector



We need to understand these backgrounds before we determine the final configuration of ANNIE.

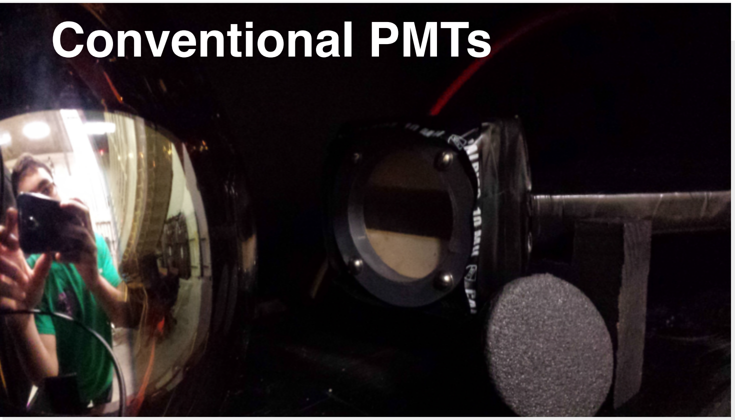
With a Phase I detector, we can test the first LAPPDs submerged in water, as they become available.



Requires input and coordination with Fermilab.

ANNIE: progress on available components

Successful effort made to test and inventory Irvine PMT stock over the summer



Rating	-1	0	1	2	3	Rating≥ 1	#PMTs to be Analyzed
TYPE S (1)	11	4	36	21	6	63	7
TYPE I (2)	76	2	18	16	9	43	67

- UC Irvine has 180 spare 8” Hamamatsu PMT spares from Super-K and IMB.
- The 60 necessary for Run 1 are ready for immediate use.

ANNIE: progress on available components

Target Vessel

- U Chicago has an aluminum pressure tank used in cosmic ray balloon measurements.
- Can be made into a viable water vessel.

(Farming water storage tank)

- Ready made, upright plastic tanks are available for < $5k

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(Farming water storage tank)

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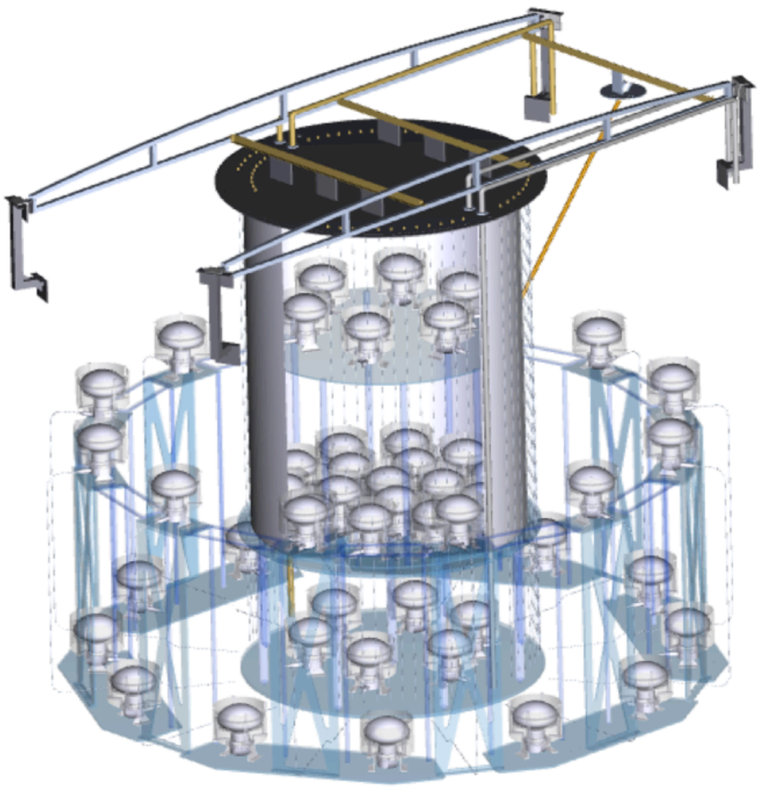
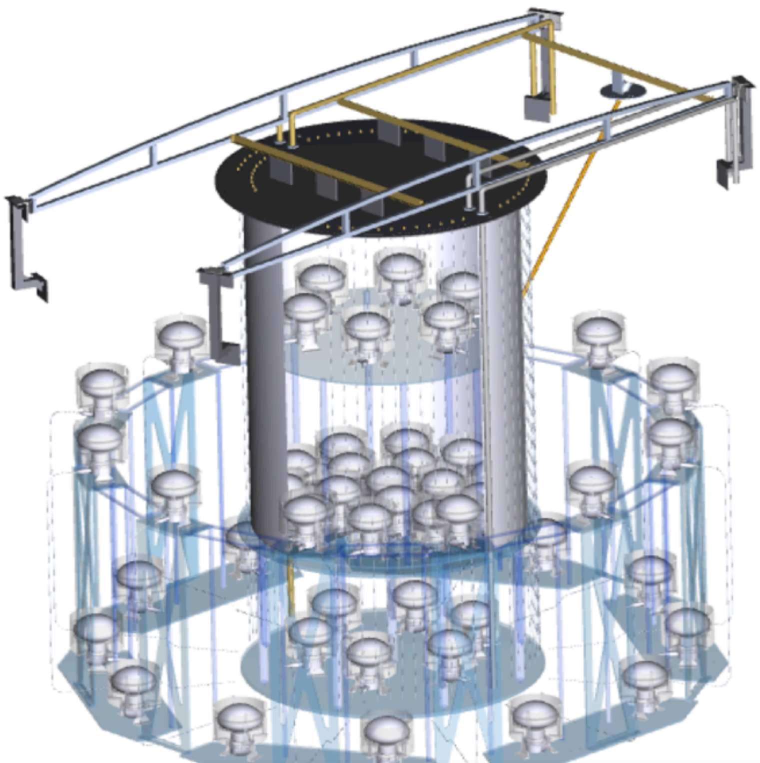
- 50 kg of Gd-sulfate available from M. Vagins.
- UC Davis water purification system available for long term loan.

PMT Readout and HV System



- The WATCHMAN collaboration will be decommissioning its 3m x3m WATCHBOY detector likely by summer or early fall.
- Their Institutional Board has discussed the possibility of lending the complete PMT system from WATCHBOY (HV, readout, and possibly PMTs).
- They are enthusiastic about supporting ANNIE, wherever possible.
- See official letter of support from the spokespersons.

PMT Readout and HV System



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A tank + PMTs + WATCHBOY systems = Phase I

Progress Towards ANNIE Phase II

- Incom Inc confirmed plans to have an LAPPD production line by mid 2016.
- Prototype MCPs and LAPPDs likely available sooner, in small numbers.

- PSEC4 readout with self-triggering and 240 channel systems has been demonstrated. Work is underway to enable larger systems.*
- LAPPD geometry lends itself well to water proofing. Work has begun on that task.*

- IA State group has developed a strategy for a complete LAPPD-PMT Run II DAQ and trigger system.
- Progress has been made towards MC development and reconstruction with heavy UK support (Queen Mary and Imperial).
- Imperial is working on options to refurbish the MRD. ANL digital HCAL group has joined and offered the RPC based calorimeter as an MRD option.

- * funded by WATCHMAN R&D budget

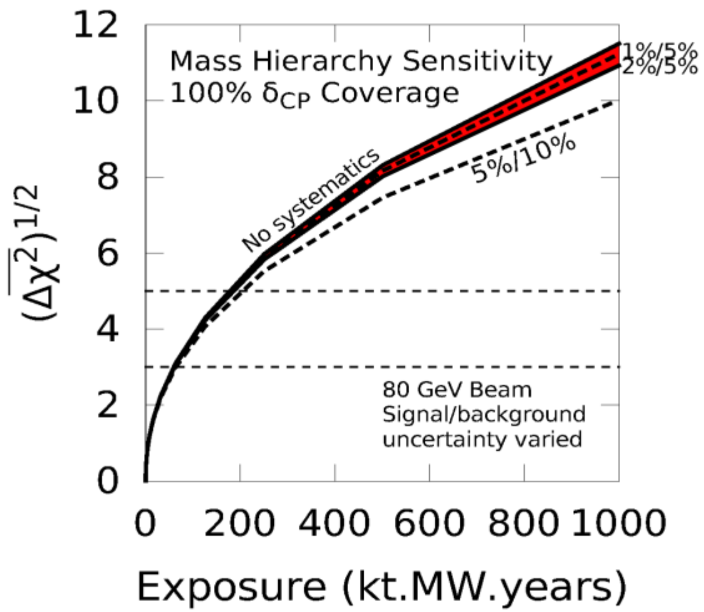
Phase I Budget and Personnel

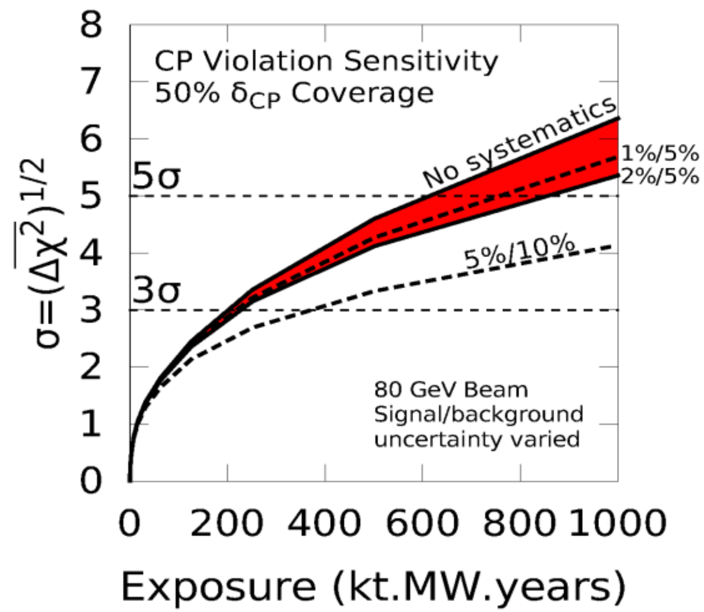
- We have done a preliminary budget exercise for Phase I.
- Estimated materials budget is under $100k (even with a 100% contingency), mostly shipping and installation costs.
- Further detail will require input and coordination with Fermilab.
- Personnel for Phase I to be funded on existing grants: 6 (3 FTE) postdocs, 3 (2 FTE) grad students , 4 (1 FTE) engineer/technician.

detector system	institutional commitment
Photodetection (LAPPD)	Chicago/ANL
Photodetection (conventional)	UC Irvine
Gd loading and water system	UC Davis/UC Irvine
Electronics	Chicago/IA State/Queen Mary
MRD	Imperial/ANL
Front Anti-Coincidence Counter	UC Davis
Simulations	Chicago/IA State/Ultralytics/Queen Mary/Imperial

Conclusion

- A detailed understanding neutrino nucleus interactions is necessary to meet the needs of future precision neutrino measurements.
- Fermilab has detectors to measure final states w/ X + N_p.
- ANNIE provides necessary tech for an X + N_n program.
- ANNIE will also provide the demonstration of techniques that are necessary to future large tonnage precision detectors.





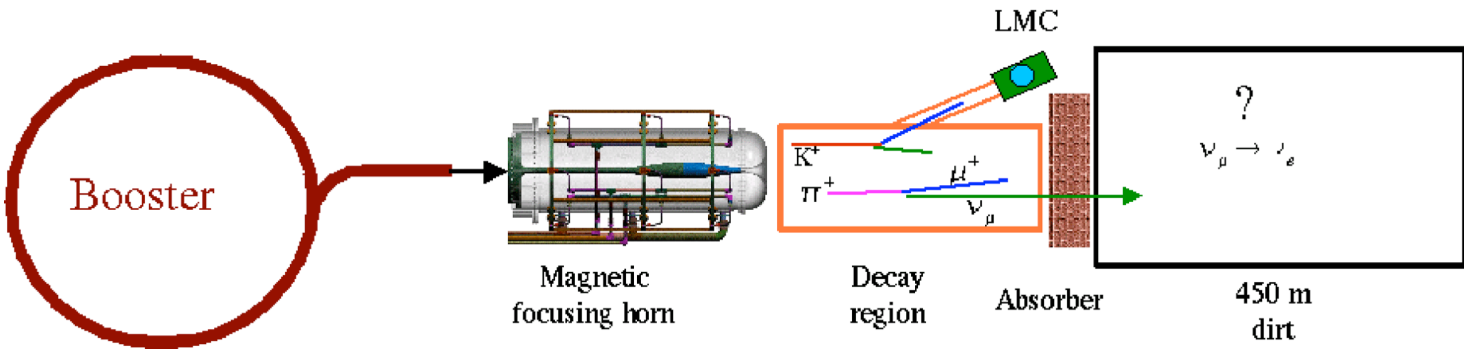
Relevance to a broad community

Letters of Support

Adam Bernstein and Bob Svoboda	WATCHMAN collaboration
Mark Vagins	EGADS/GADZOOKS/Gd-pioneer
John Beacom	SN neutrino theory/Gd-pioneer
Gabriel Orebi Gan	Advanced Scintillator Detector Concept
Akira Kanaka	Triumf
Michael Wurm	LENA
Thomas Patzak	College de France
Bob Wagner/Marcel Demarteau	ANL/Detector Development

Fermilab support required

- Endorsement of the ANNIE physics program and goals.
- Commitment to installation of Phase I in the SciBooNE Hall.
- Support for budget and engineering.



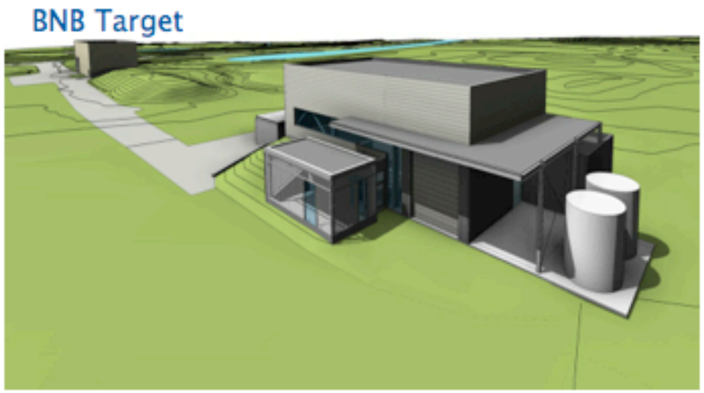
Thank You

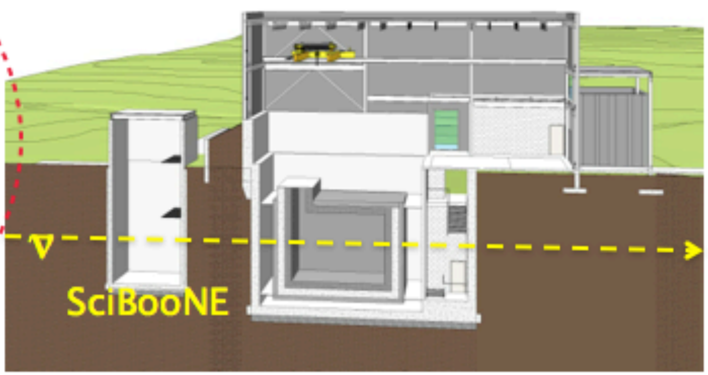
Backup Slides

LAr-ND1 Cryogenics

Near Detector Building

- Structure to support 3m concrete overburden covering detector inside the building
- Design status:
  - Final design started in January
  - Complete in May 2015
- Break ground in late summer 2015 and beneficial occupancy in fall 2016.
- Exploring option of cryogenics in surface extension of near detector building
  - Preserves SciBooNE hall for a detector rather than infrastructure
  - Little or no impact on LAr1-ND cryogenics cost
  - Initial estimate of ~$300k additional construction cost

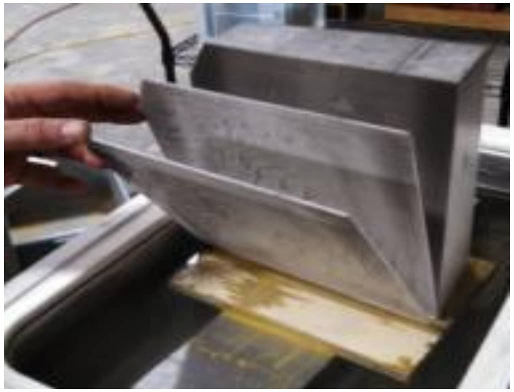


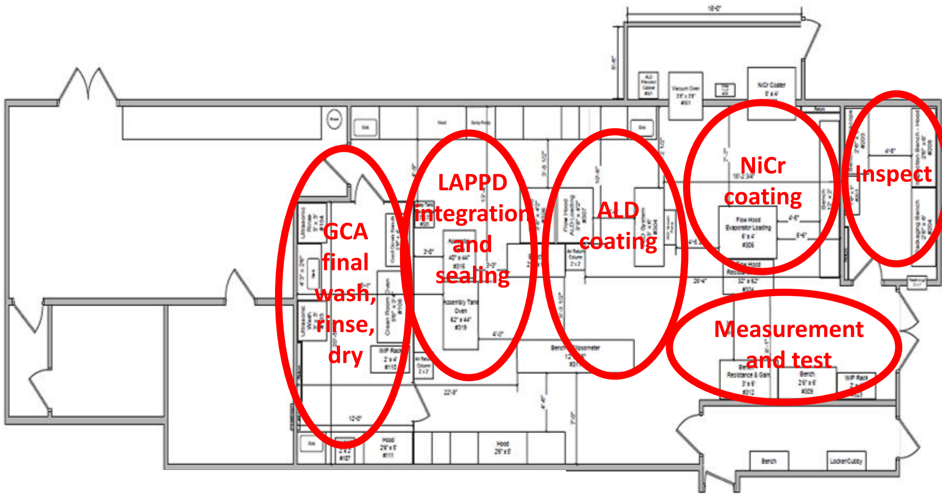


LAPPD Readiness

Incom is 1 year into their planned 3 year, $3M STTR commercialization effort

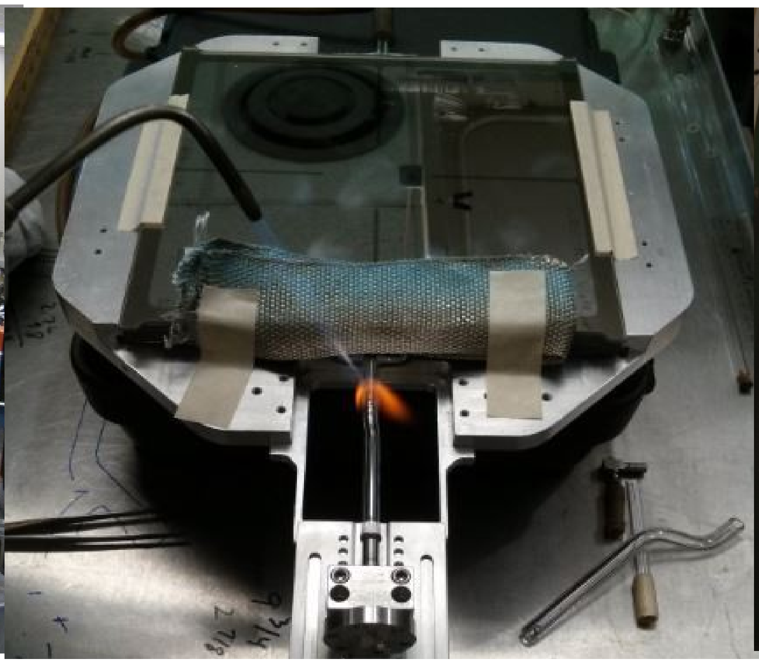
- Clean room is built.
- ALD reactor has been delivered
- Evaporator is delivered.
- Slicing machines are in operation
- Assembly chamber designed and ordered

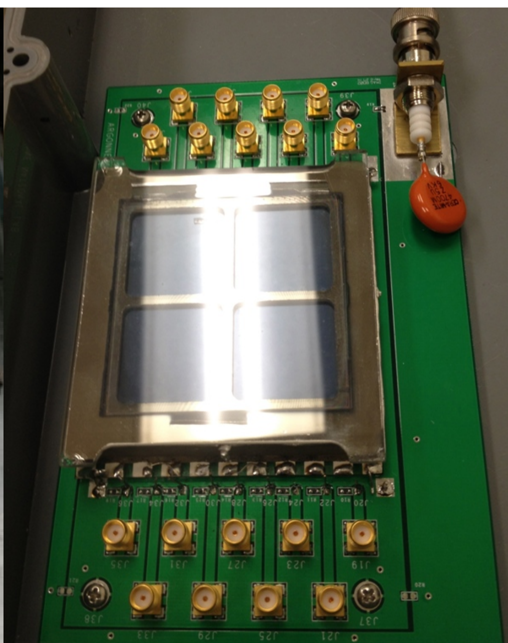




LAPPD Readiness

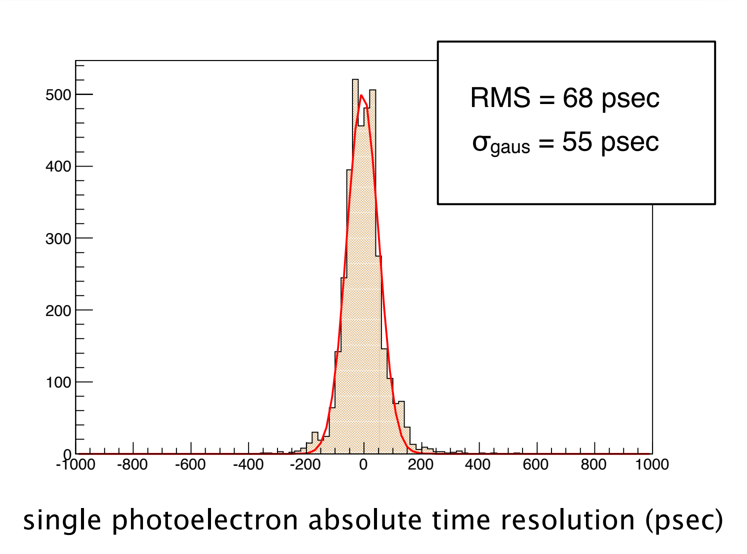
- Berkeley SSL: just funded to make a small number of tiles this year
- Argonne has successfully sealed small-format glass tiles (6 cm x 6 cm) using similar process and design
- U Chicago is commissioning an advanced fabrication facility, developing ways to lower cost and improve yields

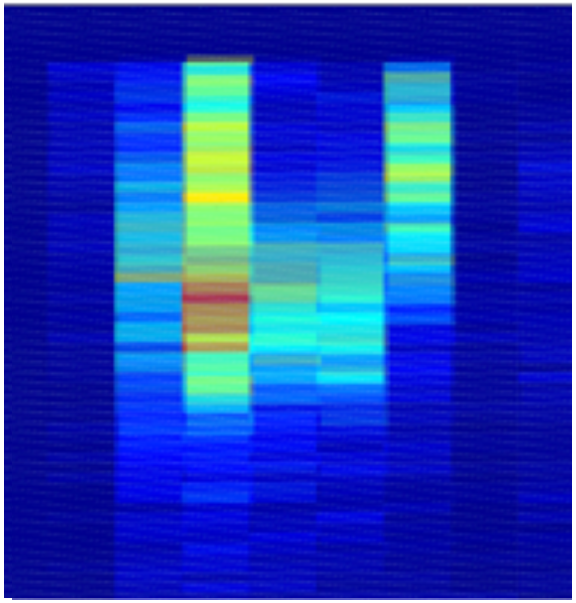




LAPPDs can provide the needed photodetector capabilities

Timing based reconstruction to choose interaction points sufficiently far from the walls of the detector to stop the neutrons





Fine granularity to help resolve Cherenkov cone-edges

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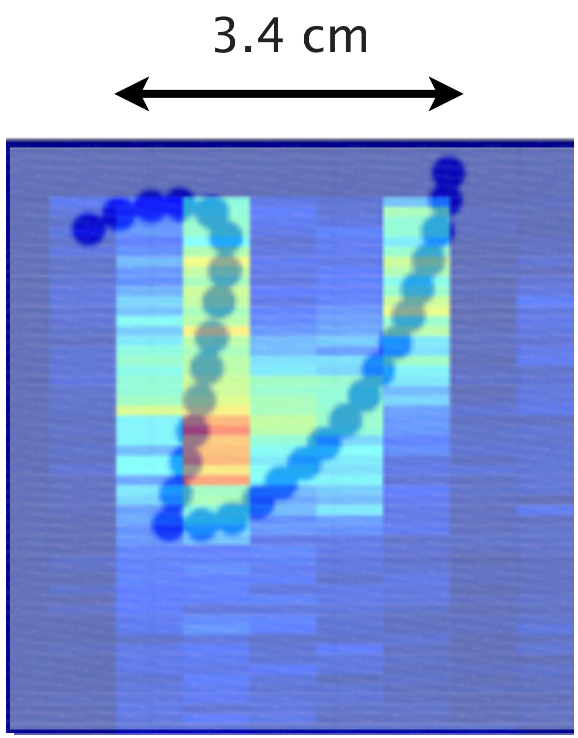

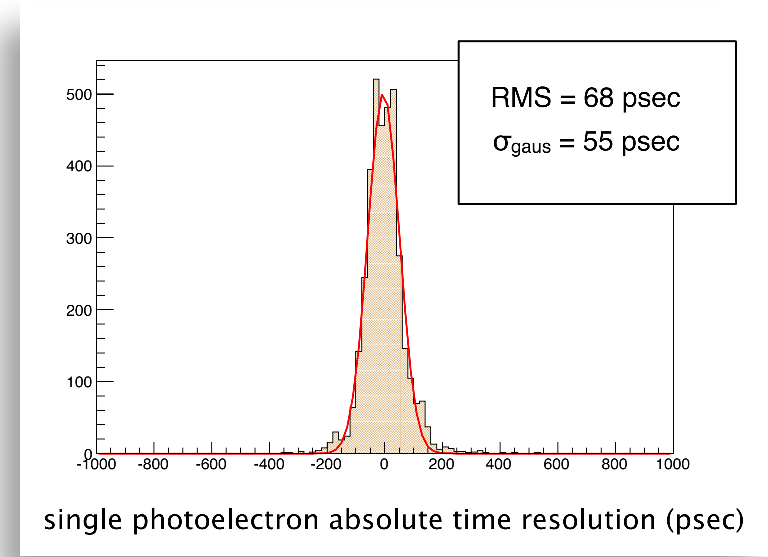

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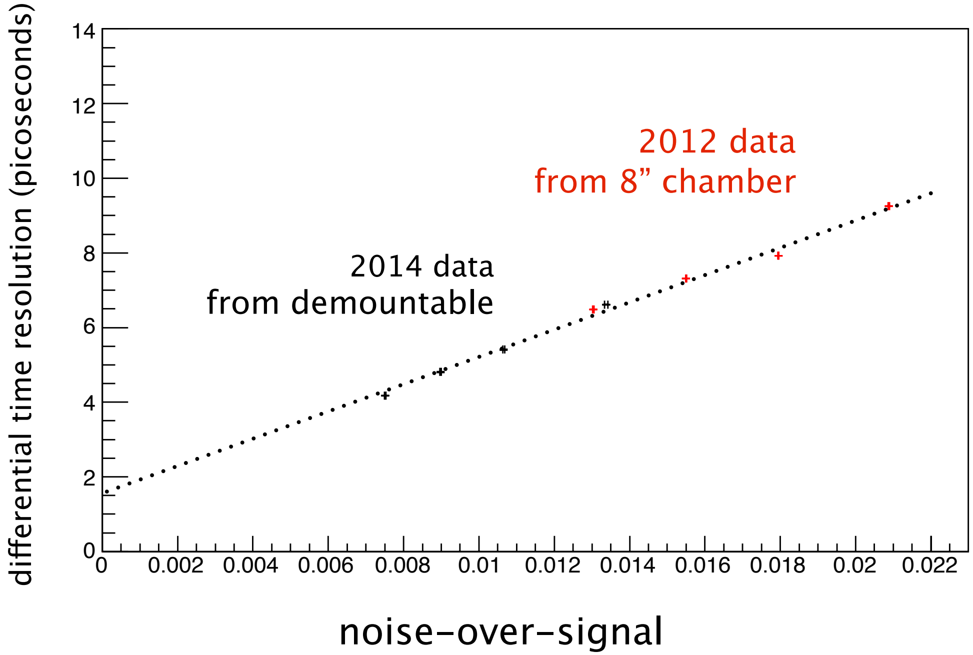
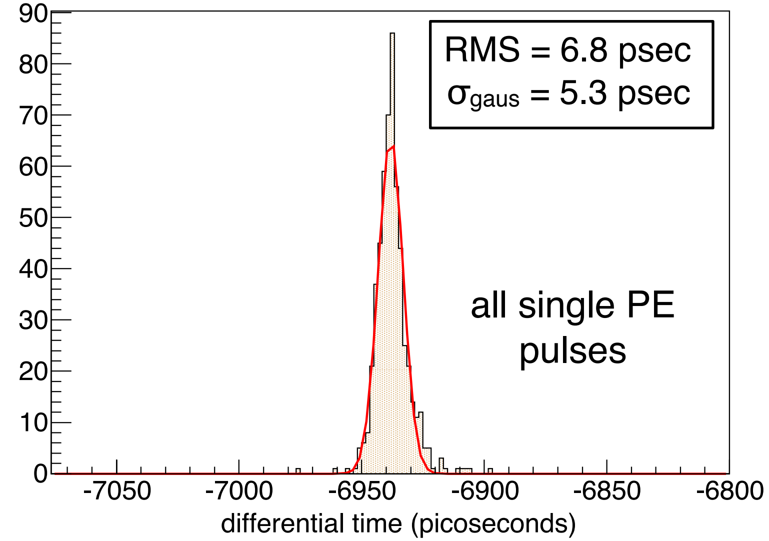
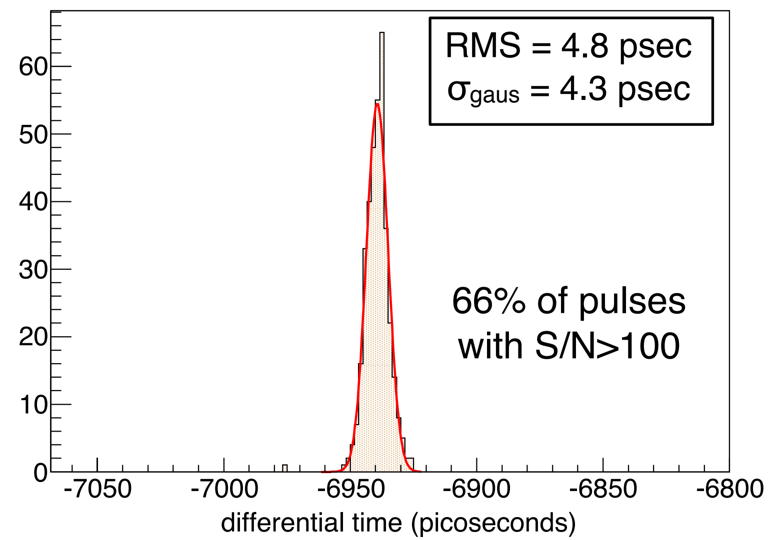


differential time resolution between two ends of stripline



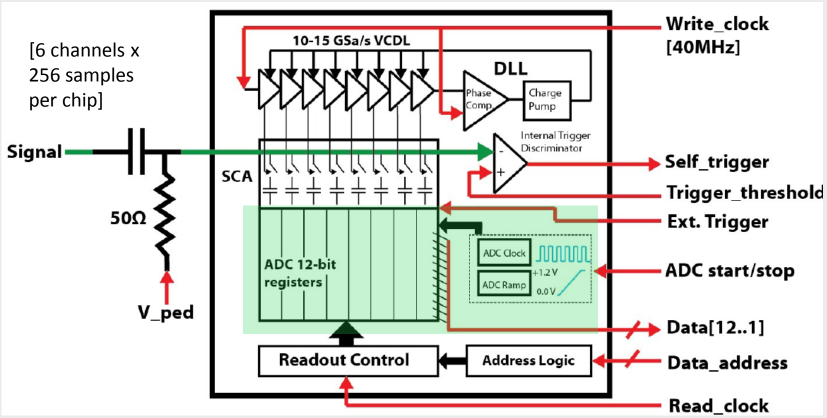


LAPPD Readiness

PAC: ...as well as demonstration the can be used in WCh

Readying LAPPD electronics

- Self triggering and 240 channel systems have already been demonstrated



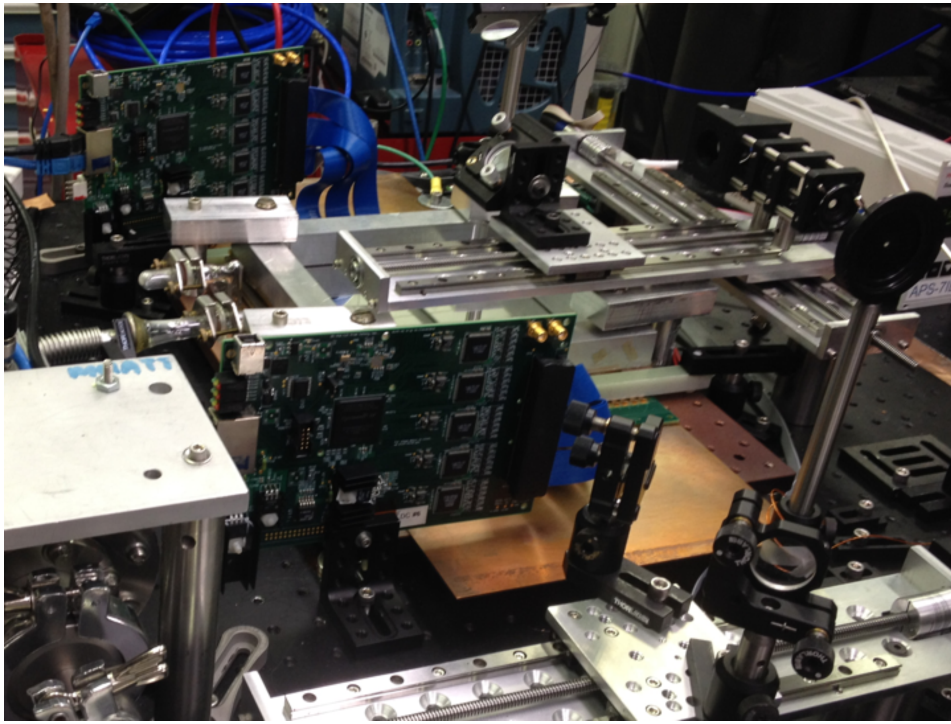
Waterproof operation

- geometry lends itself well to water proofing. we've started work on this.

WATCHMAN collaboration has earmarked LAPPD development funding to address these tasks

ANNIE technical developments – electronics and HV

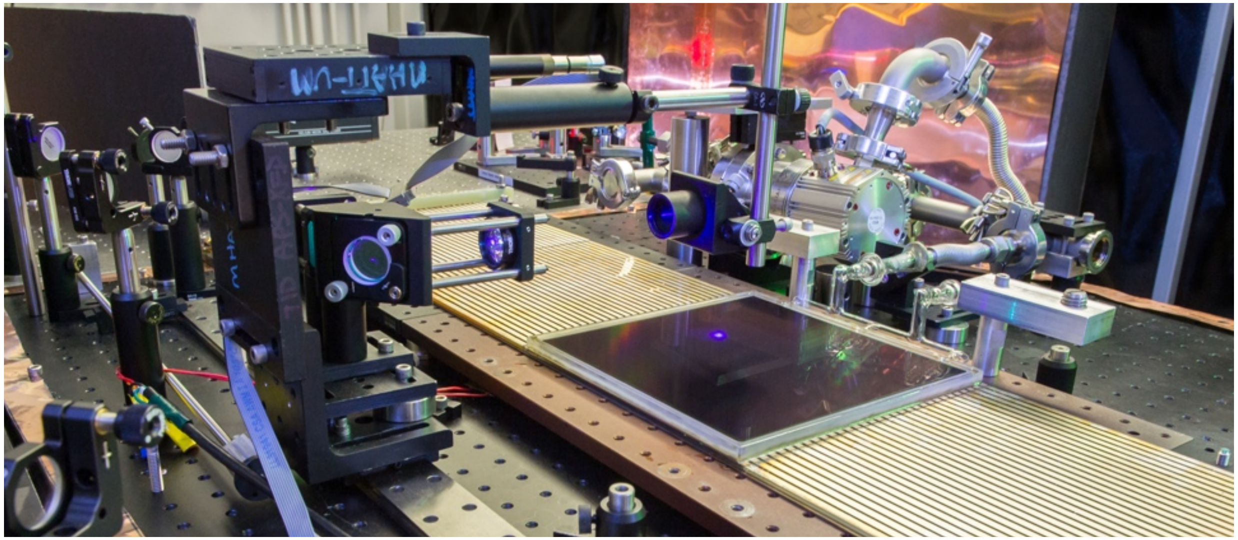
- Systematic studies of LAPPD performance under multi-photon pileup were performed using the PSEC4 electronics this summer. PSEC electronics worked very well. To be published soon.
- Work is ongoing to fund the development of the PSEC5.
- Eric Oberla (UC) is continuing development of the PSEC4 firmware. Some development work on the triggering capabilities may come through work with the WATCHMAN collaboration.
- One technical task is to develop a method for hi-pot'ing in water. An electrical functional, hermetically sealed small tile has been made available to do some demonstration work with HV in water.



What is an LAPPD

The Large Area Picosecond Photodetectors (LAPPD):

- large, flat-panel, MCP-based photosensors
- 50-100 psec time resolutions and <1cm spatial resolutions
- based on new, potentially economical industrial processes.
- LAPPD design includes a working readout system.

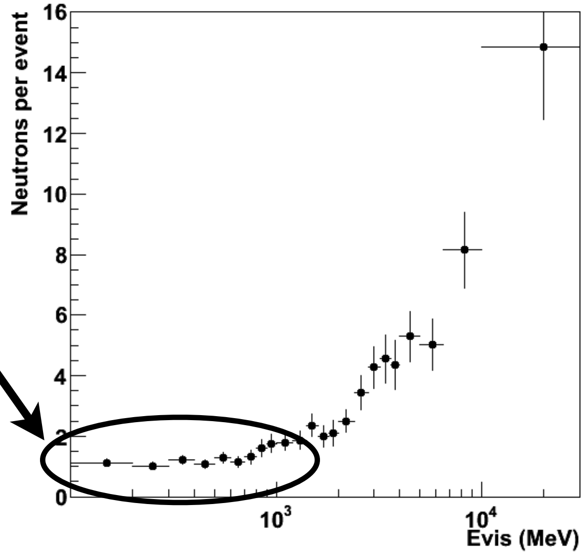


Did Super-K Measure Neutron Yields

Measurement published 2011 conference proceeding:

Neutron yields as a function of E_{vis} from atmospheric neutrino interactions. Neutrons were detected from capture on pure water (efficiency ~19%)

Neutron yields at the energies of interest are just on the edge of being useful.

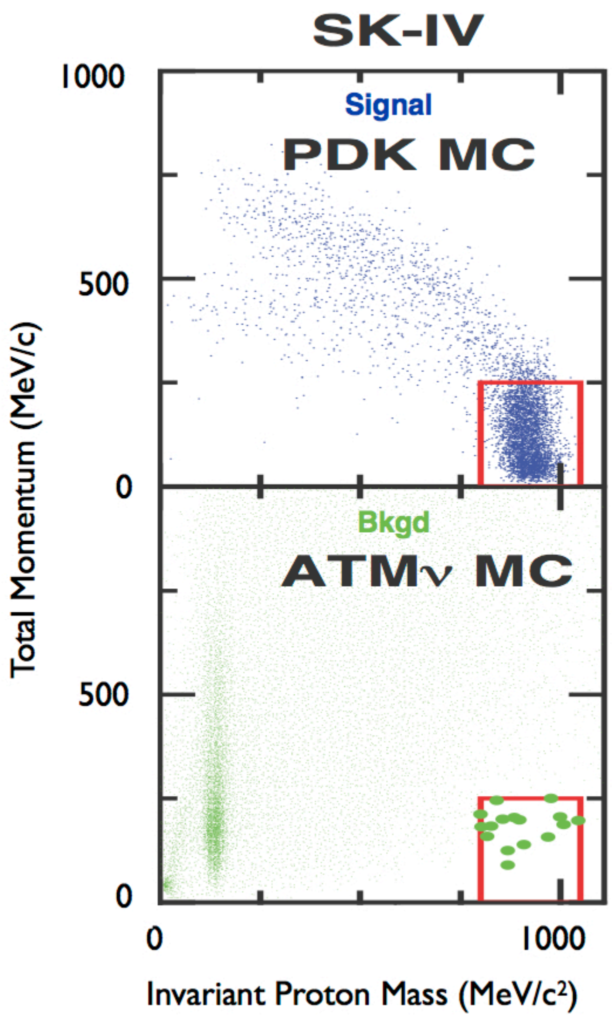


Neutrino energy is approximated from E_{vis} alone, since direction is not known. Moreover, these yields average over neutrino and anti-neutrino interactions, ν_{μ}'s and ν_e's.

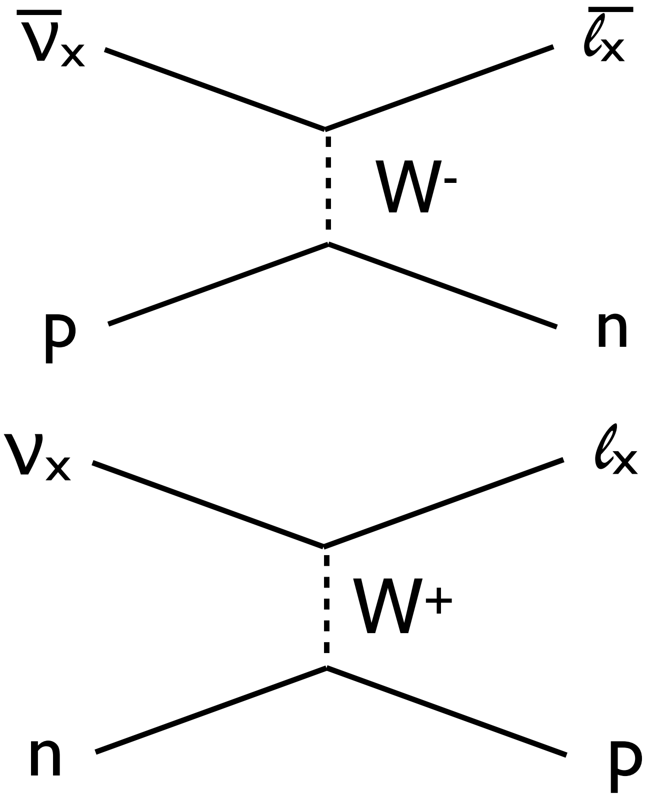
We really need a controlled beam experiment, where we can use more detailed kinematic variables, and where we can identify neutron production for different flavors and interaction types.

Did Super-K Measure Neutron Yields

For modeling neutrons from PDK backgrounds (and other physics), we want to look in a 2D kinematic space



Final State Neutrons



At the tree level, neutrino-nucleon interactions produce either one or zero neutrons

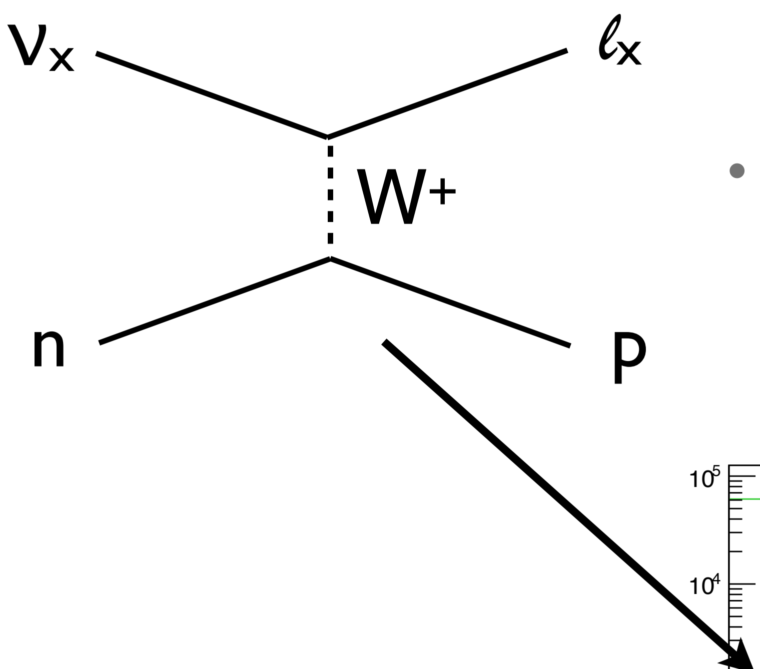
However, a variety of more complicated neutrino-nucleus interactions enhance the likelihood of one or more final-state neutrons

The abundance of final state neutrons is a strong handle on various neutrino nucleus models

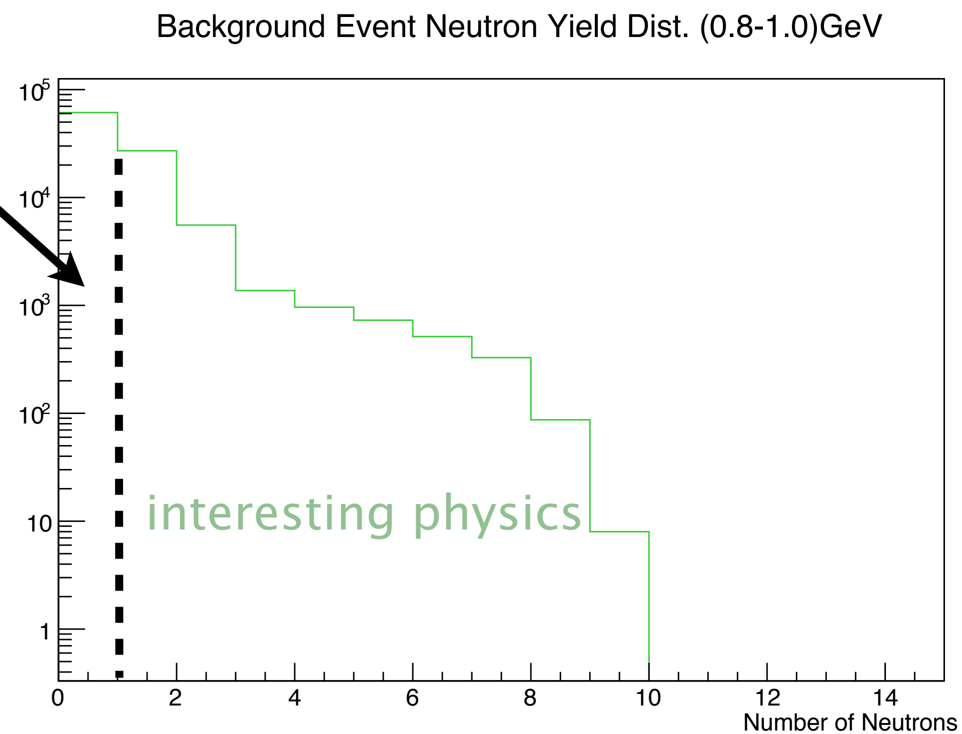
Also a strong handle for discriminating between signals and backgrounds in various neutrino and PDK analyses

The theoretical underpinnings of this observable are not well known
FS neutron abundances have not been well measured

Final State Neutrons



- Studying neutron yields for a pure neutrino beam is particularly interested, because the trivial case produces **NO** neutrons.
- Any final state neutrons will come from the interesting physics we want to study!



Neutron Production Mechanisms

- secondary (p,n) scattering of struck nucleons within the nucleus
- charge exchange reactions of energetic hadrons in the nucleus (e.g., $\pi^- + p \rightarrow n + \pi^0$)
- de-excitation by neutron emission of the excited daughter nucleus
- capture of π^- events by protons in the water, or by oxygen nuclei, followed by nuclear breakup
- Meson Exchange Currents (MEC), where the neutrino interacts with a correlated pair of nucleons, rather than a single proton or neutron.
- secondary neutron production by proton or neutron scattering in water

It is not enough merely to identify the presence or absence of neutrons

To calculate exclusions and to attribute confidence to discovery, you need to know your fake rate.

$$f = P(0) + P(1)(1-\epsilon) + P(2)(1-\epsilon)^2 + P(3)(1-\epsilon)^3 + ...$$

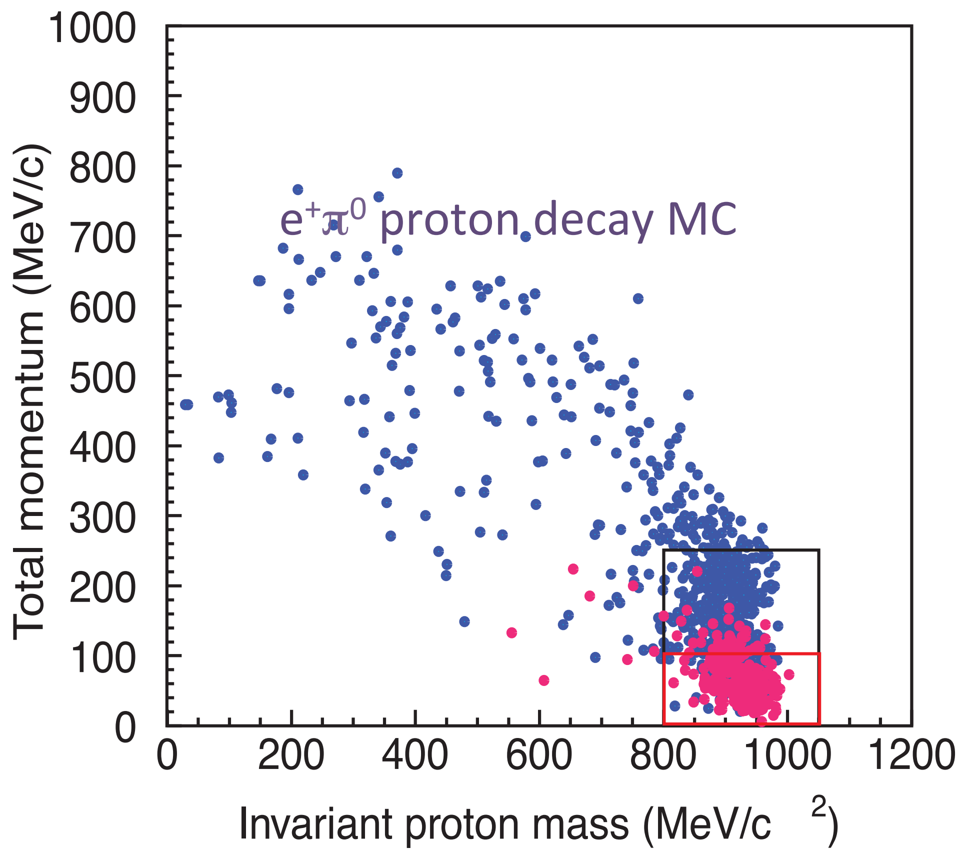
which depends on...

neutron detection efficiency

and the underlying probability distribution of N neutrons P(N)

The smaller ε is, the better you need to understand the shape of P(N)

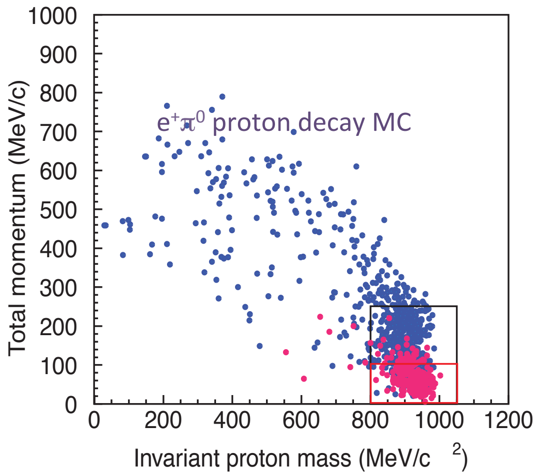
Is neutron tagging necessary for PDK?



Is neutron tagging necessary for PDK?

- You kill a lot of bkgd but you loose efficiency. The optimal balance depends on how well you can reduce backgrounds without the cuts.
- You can't totally get rid of backgrounds. So even if you see event, you would like clarity.
- Even with much reduced background rates, you care about the relative abundance compared to signal...that depends on what the PDK lifetime turns out to be.
- More importantly, the neutron tag for background reduction is to first order across the board - true for ALL proton decay modes, not just epizero. Many of these do not have the simple momentum cuts of epizero.

To first order for epizero mode you lose 2/(0.4*8+2) => 62% of your signal. That's like curling your detector to 1/3. (the 0.4 is the fraction of pi zeros not interacting in the nucleus, which destroys the invariant mass balance). In HK there is a point at which "free proton" becomes better due to increasing background (maybe after 10 years or so, as I recall). If you can remove 80-90% of background, this would never be the case.

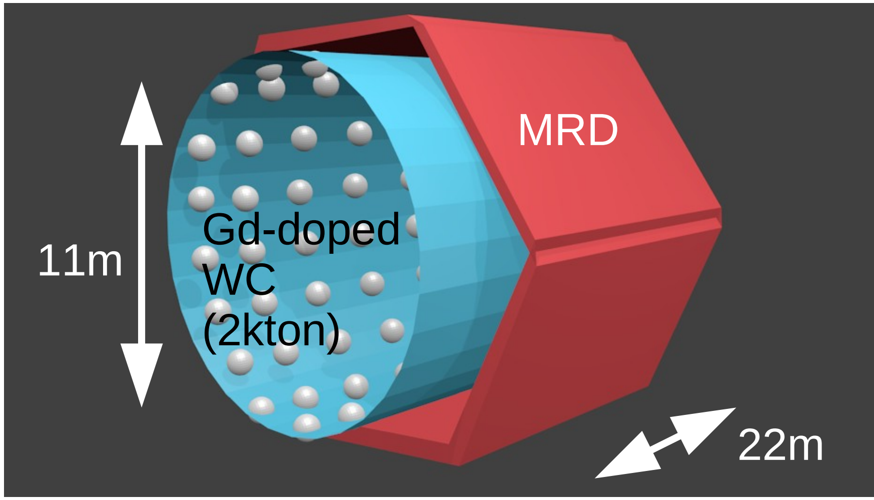


Will Hyper-K Have neutron detection capabilities?

SNOWMASS mini-White paper does mention Gd, and the soon-to-be-published HK white paper features it prominently both for atmospheric neutrino sign selection and supernovae

Sign-discrimination/TITUS

Tokai Intermediate Tank for Unoscilated Spectrum



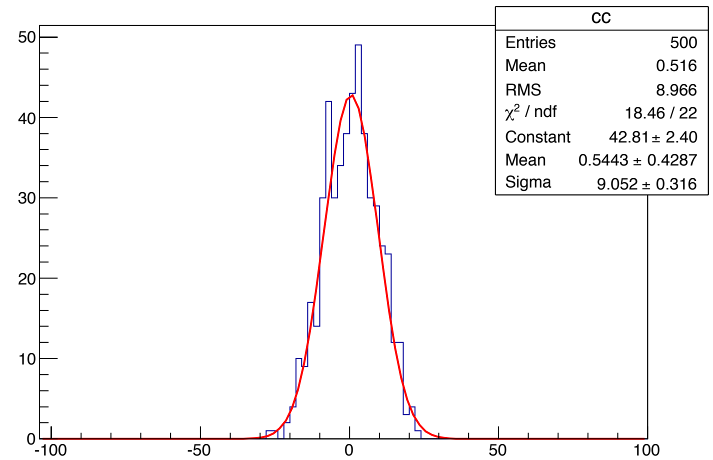
Beam Mode & Selection	CC QE	CC MEC	CC 1π	CC Other	NC	'Wrong-Sign' CC
$\nu\mu$ all (CC-incl)	37%	10%	28%	19%	3%	4%
ν_μ with n = 0 (CCQE-enhanced)	63%	12%	11%	13%	< 1%	< 1%
ν_μ with n > 0 (CCQE-depleted)	20%	7%	38%	25%	5%	5%
$\bar{\nu}_\mu$ all (CC-incl)	55%	7%	5%	2%	4%	27%
$\bar{\nu}_\mu$ with n = 0	30%	< 1%	2%	1%	8%	59%
$\bar{\nu}_\mu$ with n = 1	82%	3%	< 1%	< 1%	1%	13%
$\bar{\nu}_\mu$ with n > 1	41%	13%	11%	3%	4%	28%

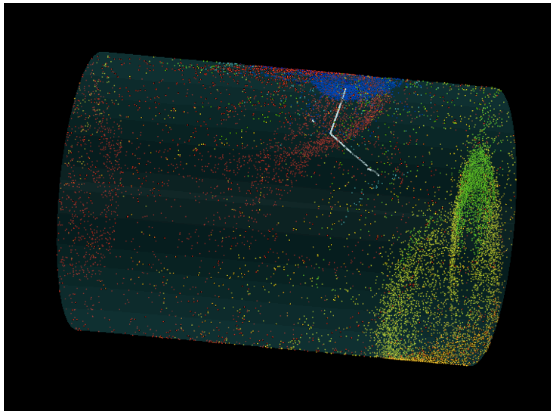
Simulations

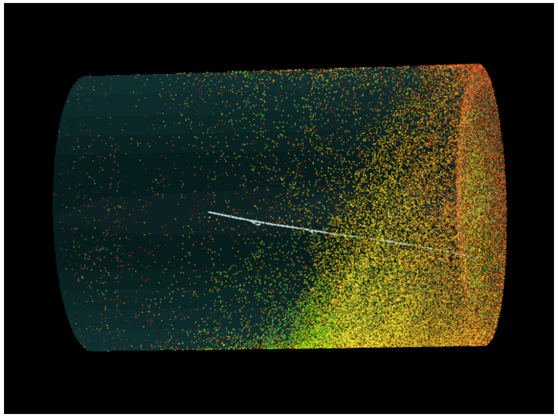
We've developed a fast MC for studying detector optimization - now used by ANNIE and some Hyper-K collaborators

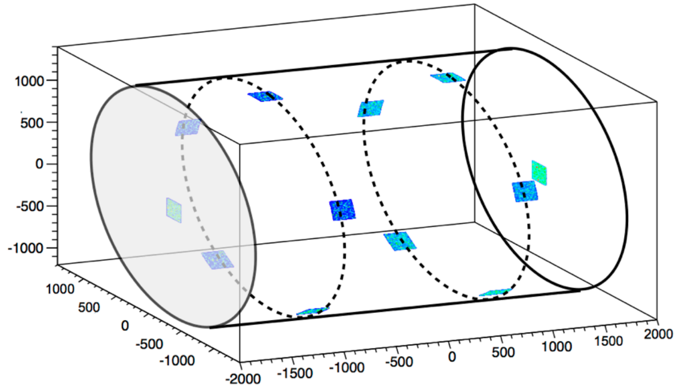
Studies of vertex resolution are underway

We're developing a strategy for managing the basic physics with low (<15) LAPPD coverage





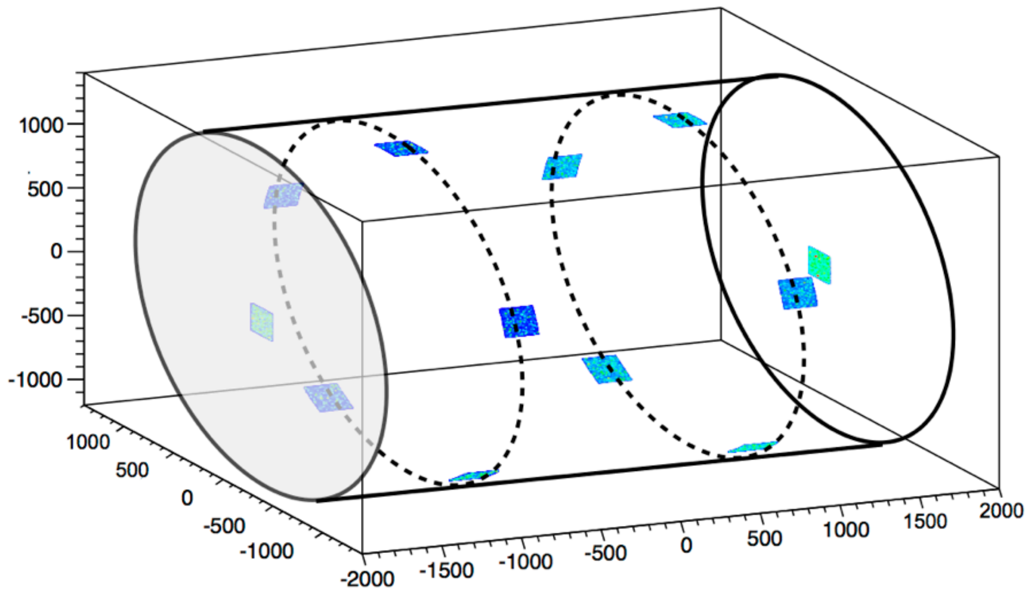




Simulations

Our planned reconstruction strategy is to use:

1. LAPPDs to discriminate between single-track and multi-track events,
2. timing on the LAPPDs to find the vertex in multi-track events, and
3. the combination of PMT hits and MRD track reconstruction (at minimum) to find the cone-edge for single tracks.

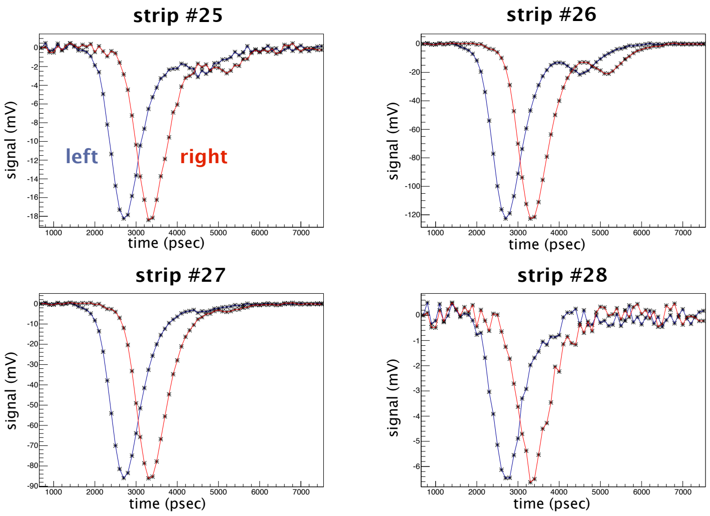


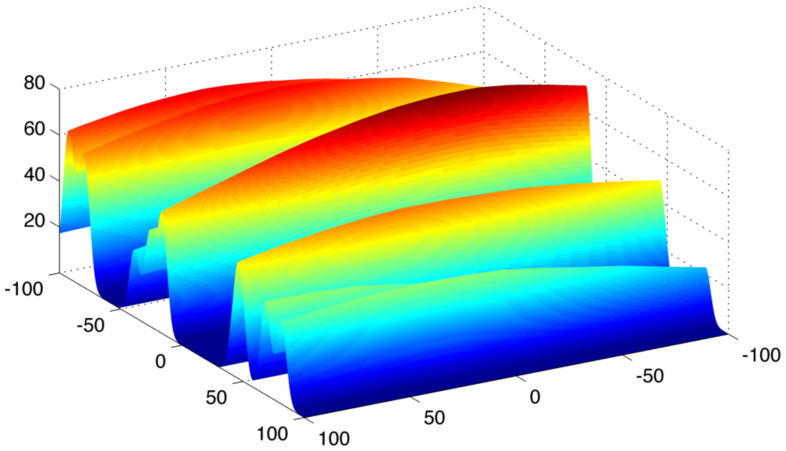
Simulations

We're also working on a more realistic, full Monte Carlo

We've build a model of the digital LAPPD response

We're making progress in understanding photon pileup on LAPPD striplines





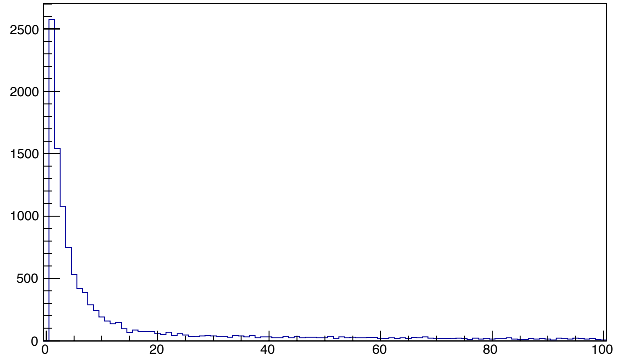
Simulations

We're also working on a more realistic, full Monte Carlo

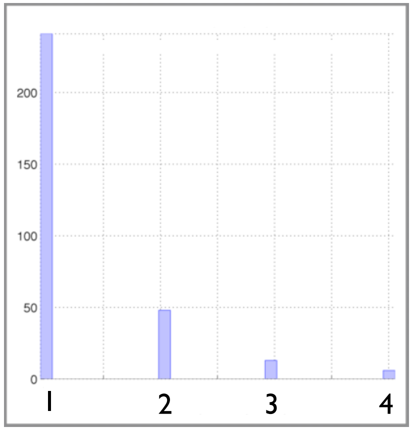
We've build a model of the digital LAPPD response

We're making progress in understanding photon pileup on LAPPD striplines

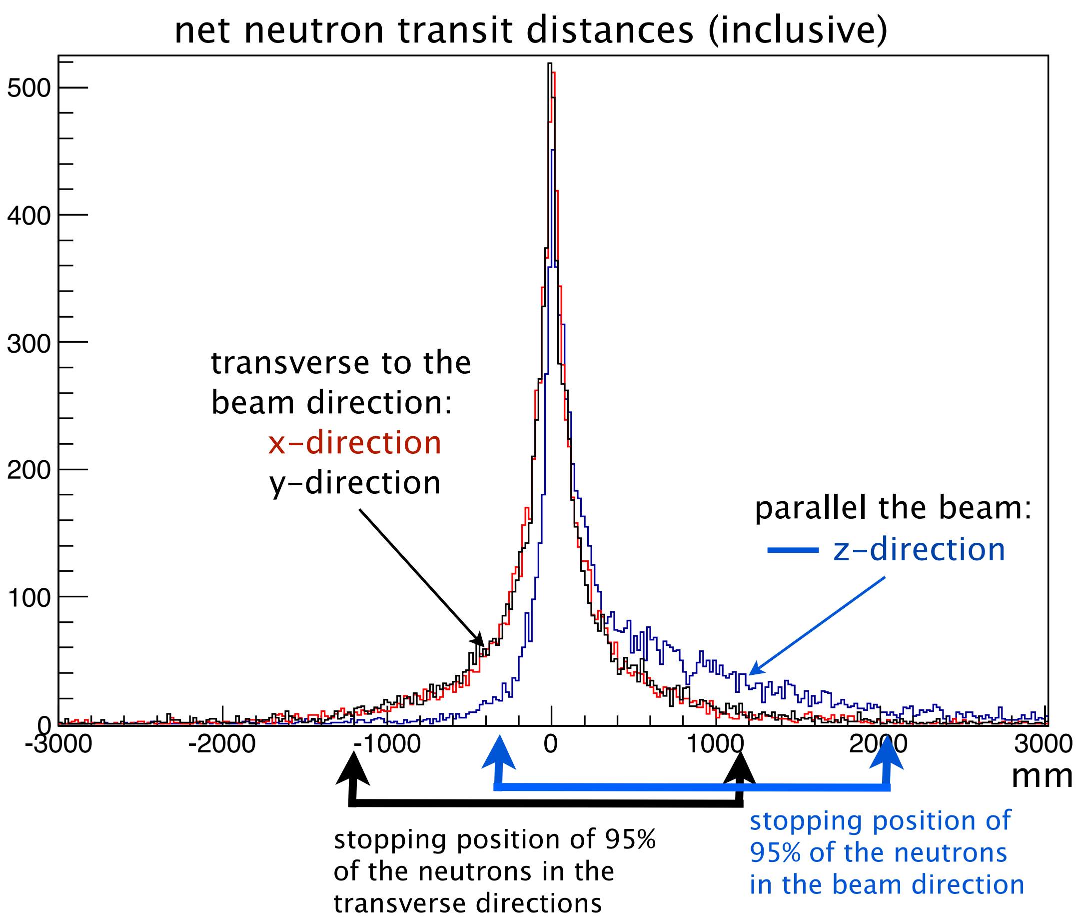
Number of hits per LAPPD (1000 evts)



number of hits per channel (1 event)



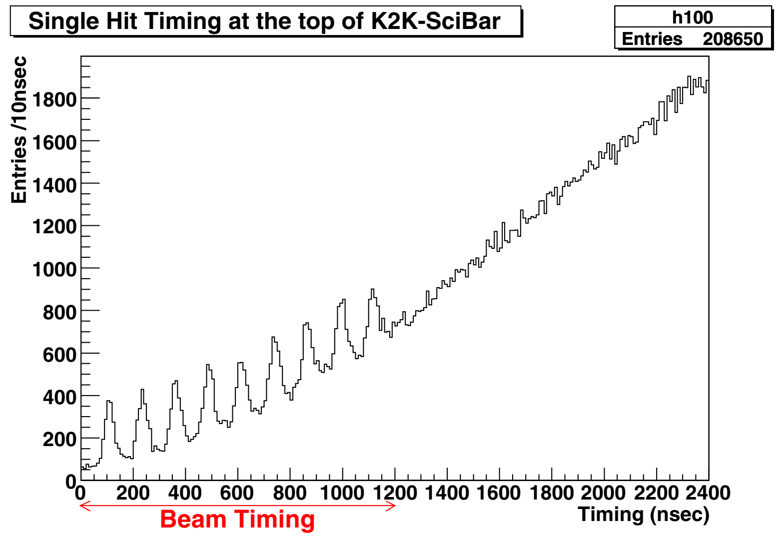
Neutron Simulations



What is skyshine? What are dirt neutrons?

From the SciBooNE proposal

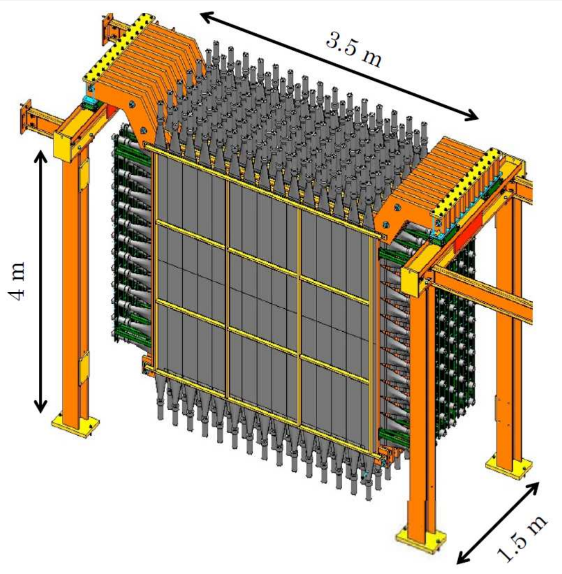
The two most significant beam related backgrounds are dirt neutrinos and neutron skyshine. Dirt neutrinos interact in the earth around the detector hall, sending ener- getic particles into the detector, and skyshine is the flux of neutrons from the decay pipe or beam dump that are initially projected into the air but are scattered back toward the ground and interact in the detector. Experience with MiniBooNE indi- cates that dirt neutrinos form a negligible background for charged current events. The expected effect on neutral current analyses is also small due primarily to the lack of a high energy tail in the BNB flux.



	60 m		90 m	
	beam-on	beam off	beam-on	beam-off
# spills	25,589	10,072	33,441	10,233
singles (1)	16	0	14	0
singles (2)	37	0	20	1
coincidences	5	0	4	0

Table 1.6: *BNB skyshine test results.*

Muon Range Detector



Not needed for year 1. Exploring 2 options:

- Refurbish SciBooNE MRD
  - Structure and steel has been transferred from Morgan Wasco
  - Needs PMTs
- ANL digital HCAL group has joined ANNIE and are offering their RPC based system as an MRD (possibly magnetizable).

PHASE I: Technical Development and Neutron Background Measurements

Available components:

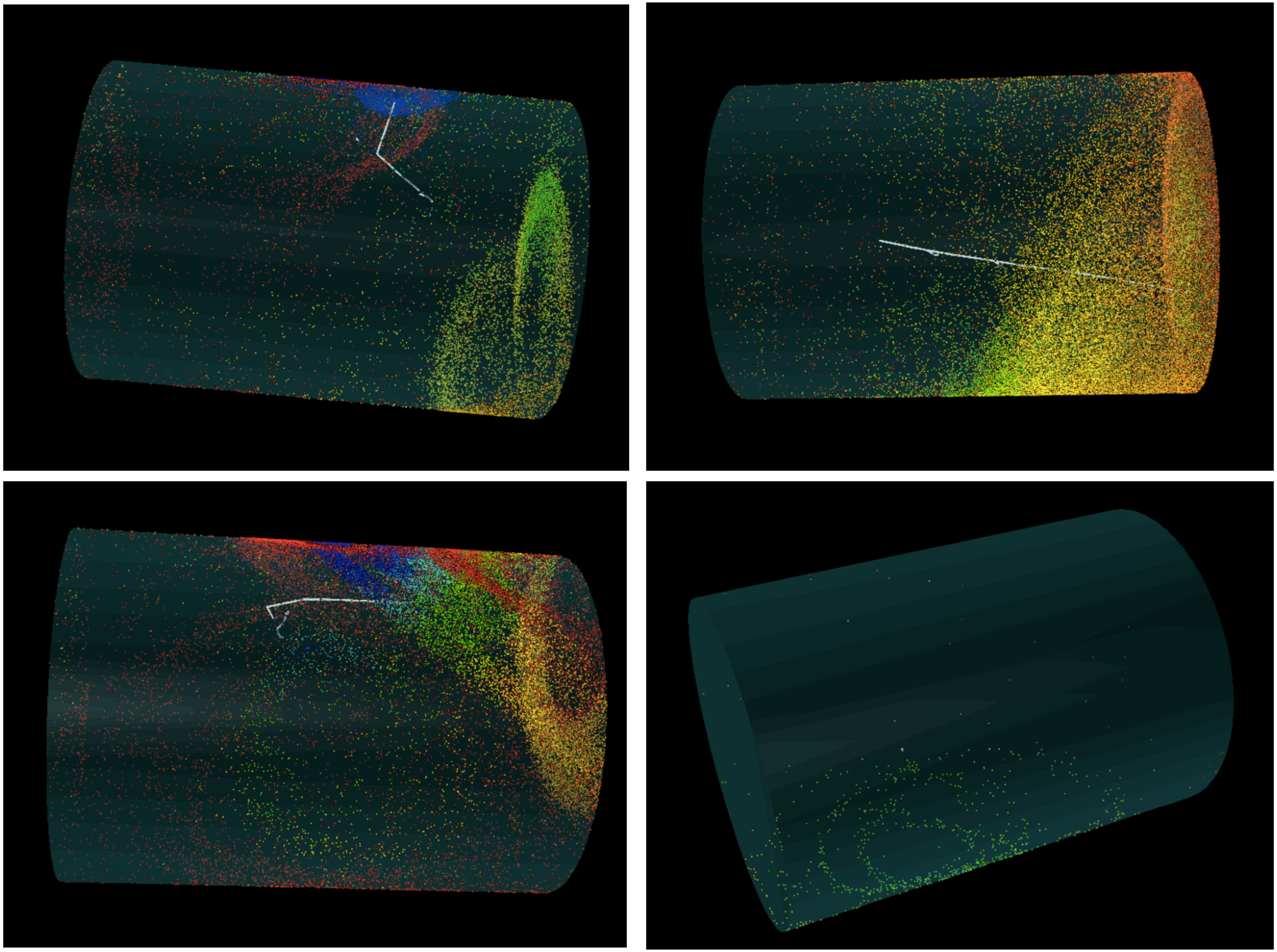
- ANNIE tank with the 58 working Type-S PMTs, an inner volume of Gd-water
- existing WATCHMAN readout
- 1+ LAPPDs

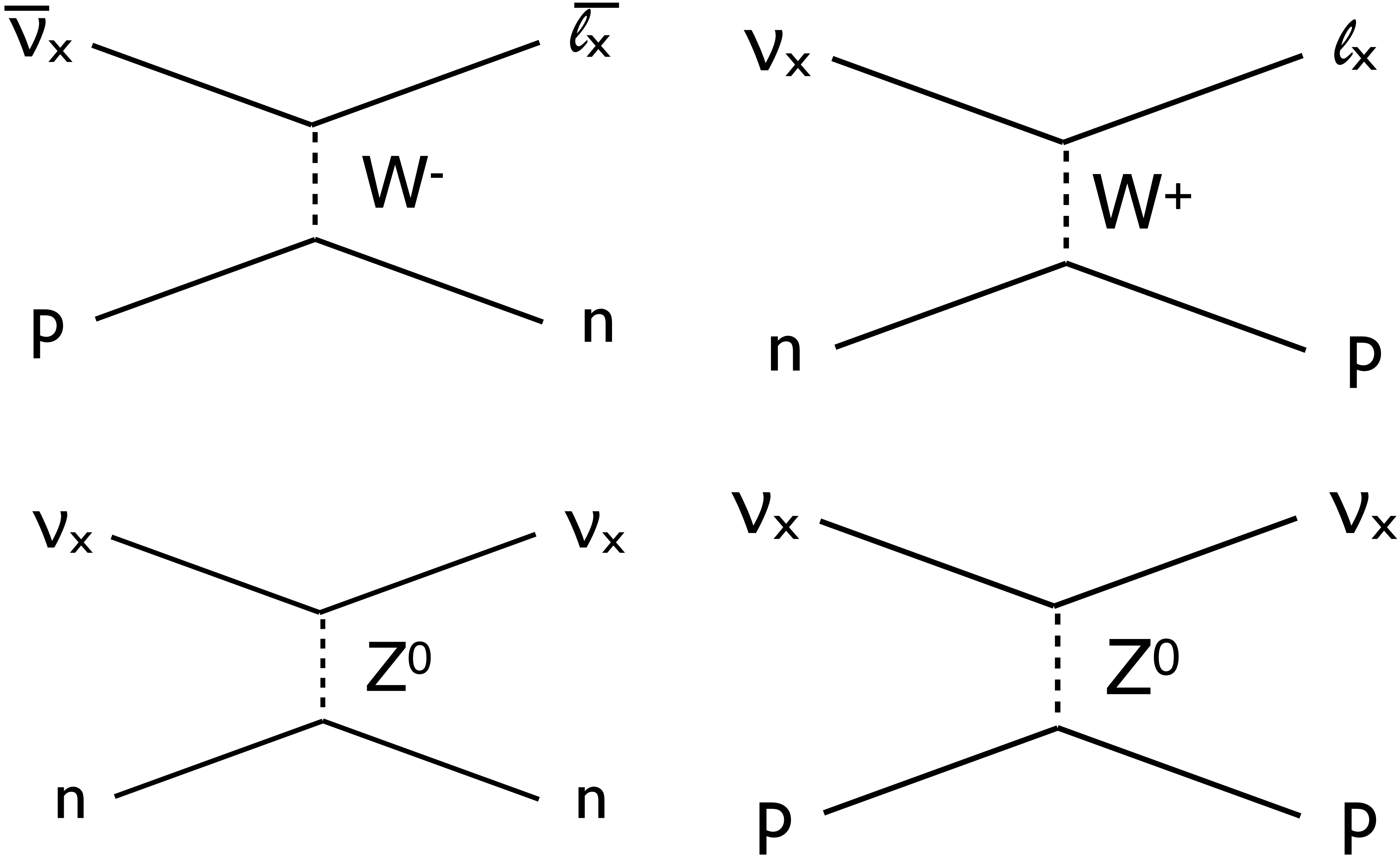
Technical goals:

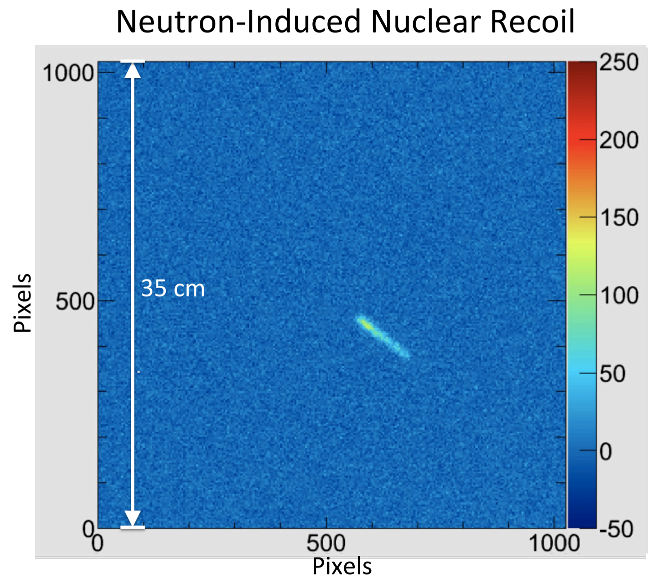
- Operation of the type-S PMTs in water
- Basic electronics - ability to see beam structure, prompt evt, and delayed captures
- In situ optical calibration with pulsed LED or fiber laser
- Neutron calibration with a source?
- Data-MC certification

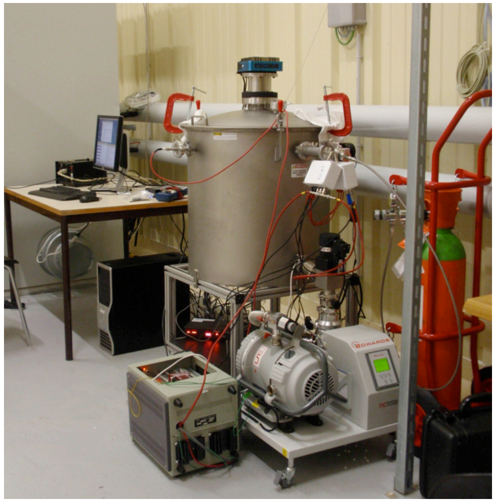
Physics goals:

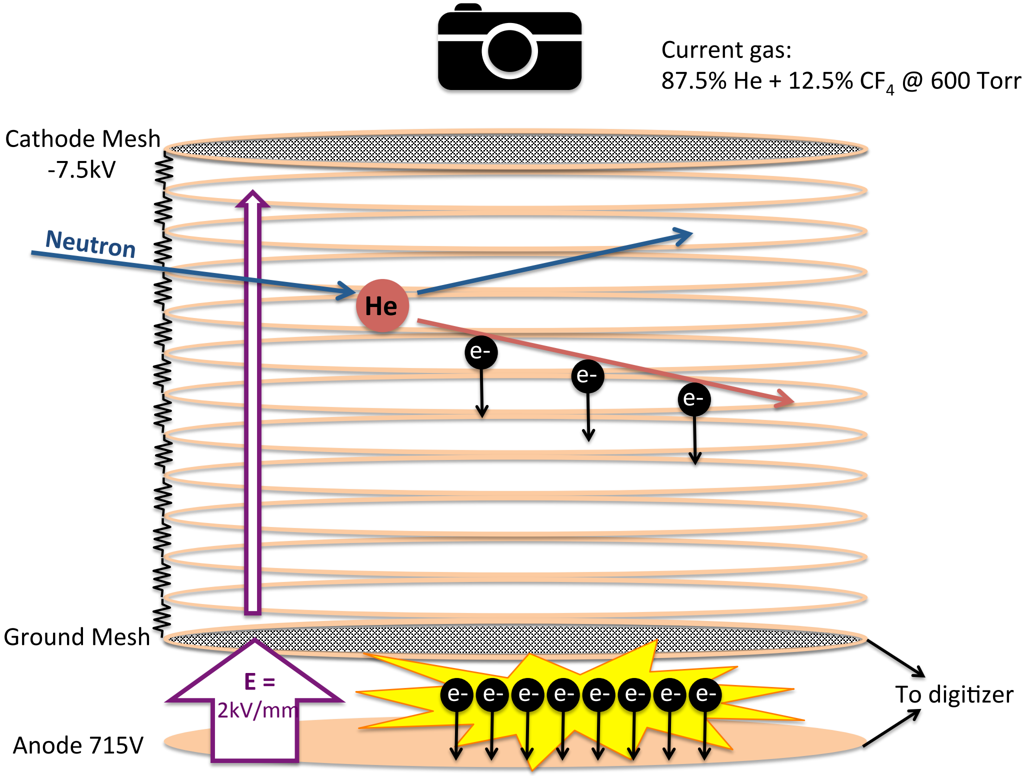
- Comparison of in situ and ex situ measurements of neutron rates
- Understand skyshine and dirt neutrons - rates, position dependence, time structure
- Relevant measurements for LAr-ND1




$\overline{\nu}_x$
$\overline{\ell_x}$
W^-
p
n
ν_x
ℓ_x
W^+
n
p
ν_x
ν_x
Z^0
n
n
ν_x
ν_x
Z^0
p
p


Neutron-Induced Nuclear Recoil
35 cm
Pixels
Pixels
1000
500
0
0
500
1000
250
200
150
100
50
0
-50

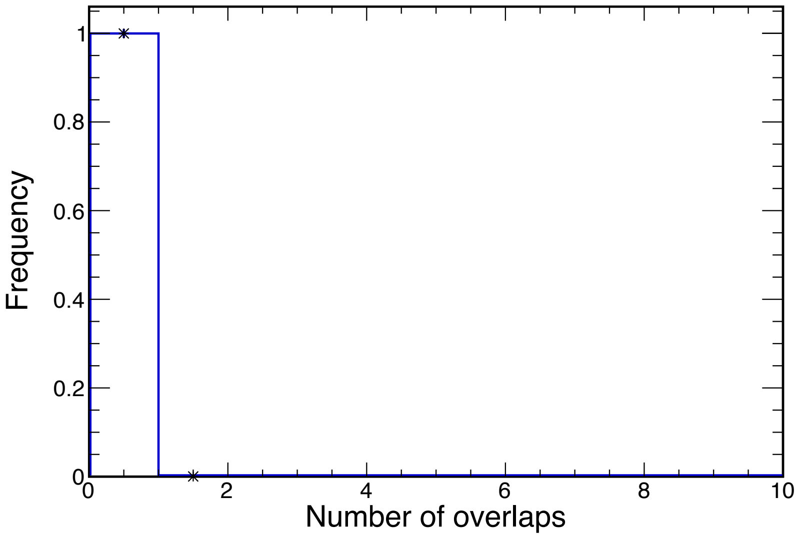



Current gas:
87.5% He + 12.5% CF_4 @ 600 Torr
Cathode Mesh
-7.5kV
Neutron
He
e-
Ground Mesh
E =
2kV/mm
Anode 715V
To digitizer

Why ANNIE is an ideal first implementation of LAPPDs

- Manageable beam structure

30 ton water detector (=100 ns event length);
SciBooNE hall & Booster beam (=0.04 ev per spill)



As expected, with $\ll 1$ event/spill, we get ~ 0 overlaps. Similar result even if factor of 1 order of magnitude in number of events has been made.

credit: E Catano-Mur

Full Track Reconstruction: A TPC Using Optical Light?

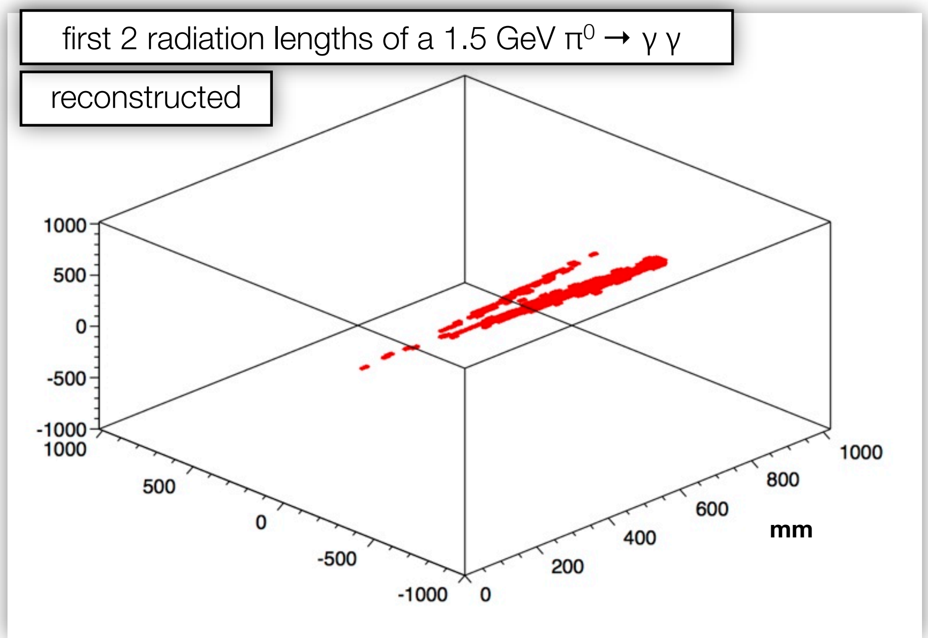
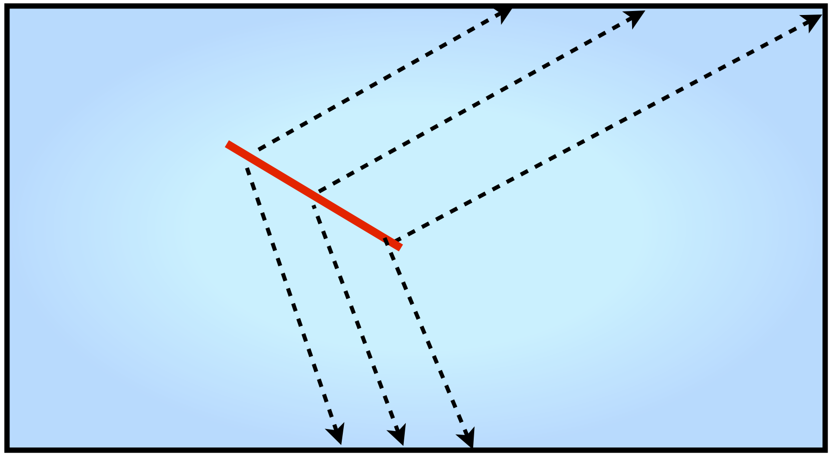


Image reconstruction, using a causal "Hough Transform" (isochron method)

"Drift time" of photons is fast compared to charge in a TPC!

~225,000mm/microsecond

Need fast timing and new algorithms



(see ANT13 LAPPD talk)

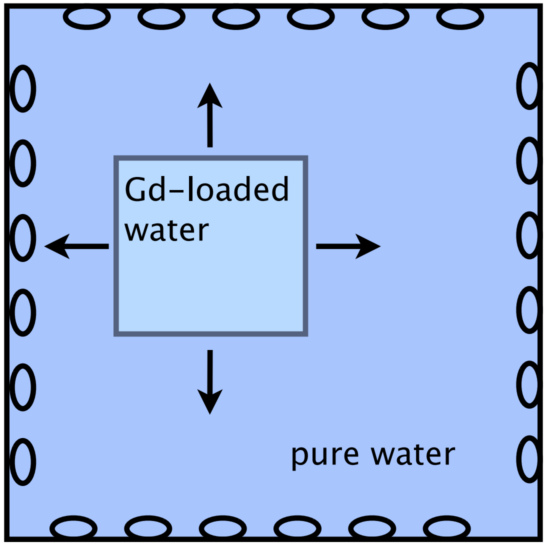
(see ANT13 mTC talk)

PHASE I: Technical Development and Neutron Background Measurements

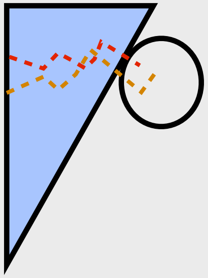
What's needed - next steps:

- work with FNAL engineers for an installation budget estimate
- electronics!!
- finalize neutron measurement strategy
- an LAPPD or 6cm tile
- a case for collaboration with LAr ND-1

Possible concept for the neutron measurement



DCTPC with wedge shaped tank to study the stopping power of water



PHASE II: Physics Run I

Available components:

- ANNIE tank
  - 58 working Type-S PMTs
  - low but “sufficient” coverage of LAPPDs (10-20?)
  - Filled with Gd-loaded water
- MRD
- neutron monitoring (DCTPC or a custom reproduction)

Technical goals:

- full DAQ
- operation and successful tracking with water POT’ed LAPPDs
- working MRD - compare MRD tracking with LAPPDs
- timing calibration

Physics goals:

- measure neutron yield versus reconstructed q^2 and Evis
- separate CC vs NC measurements
- attempt to identify PDK backgrounds

PHASE III: Physics Run II

Available components:

- ANNIE tank
  - full PMT coverage (>100 PMTs)
  - high coverage LAPPD scenario
  - Filled with Gd-loaded water
- MRD
- neutron monitoring (DCTPC or a custom reproduction)

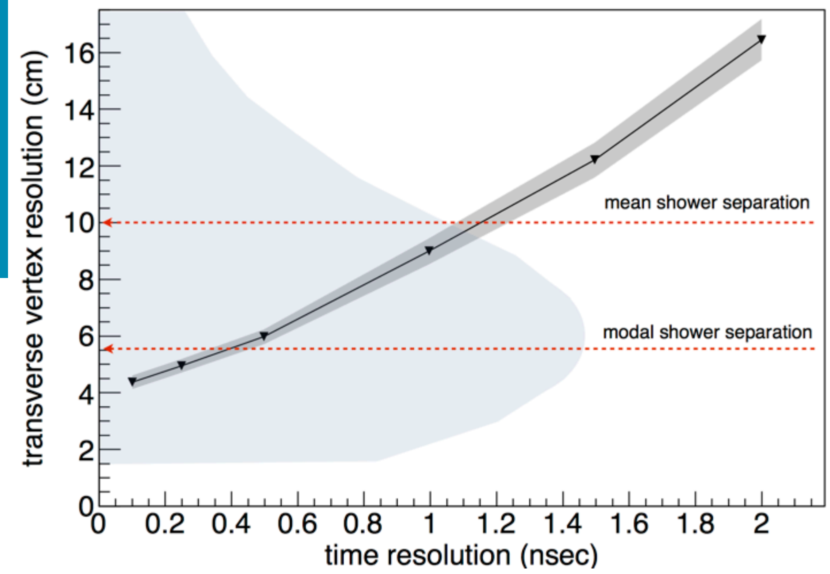
Technical goals:

- Full event reconstruction - analysis using mostly active volume

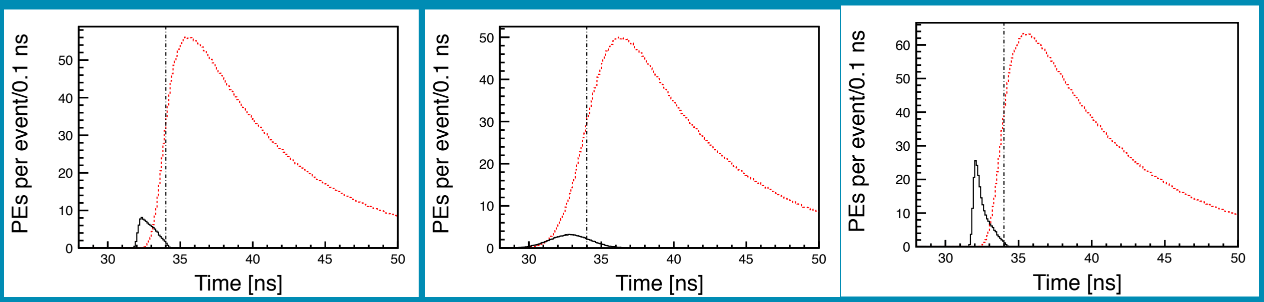
Physics goals:

- neutron yield with precision event reconstruction and identification
- full identification of PDK backgrounds

Timing to reduce Pi0 backgrounds



Timing to separate between Cherenkov and scintillation light



(a) Default simulation.

(b) Increased TTS (1.28 ns).

(c) Red-sensitive photocathode.

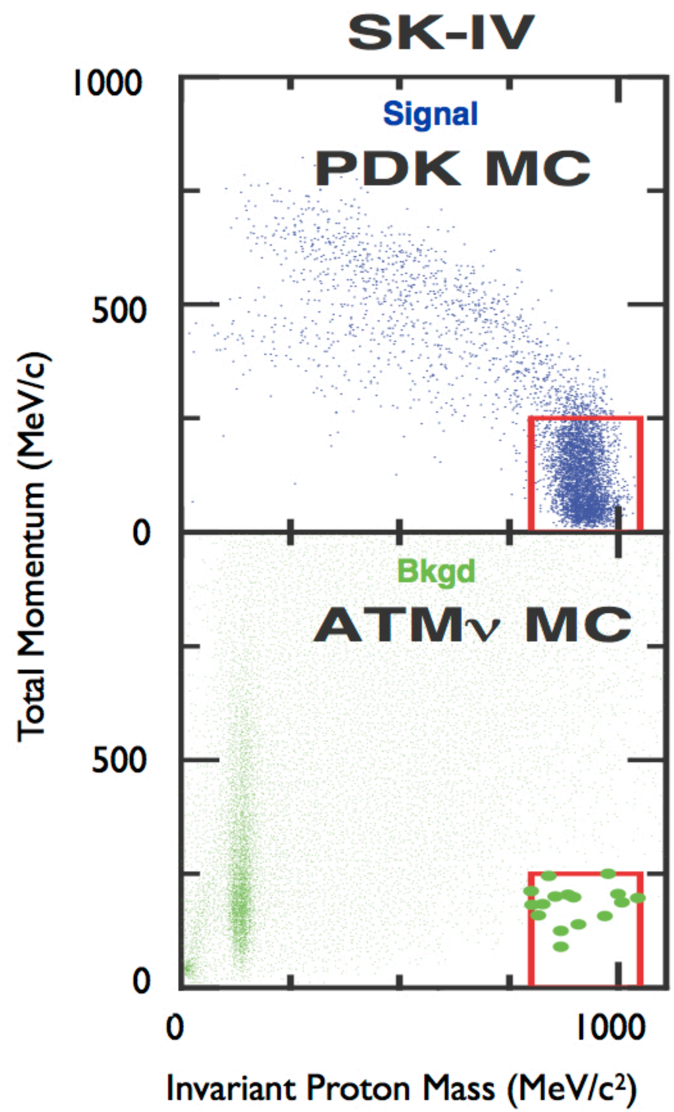
C. Aberle, A. Elagin, H.J. Frisch, M. Wetstein, L. Winslow. Measuring

Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors;

arXiv:1307.5813

Physics: Proton Decay

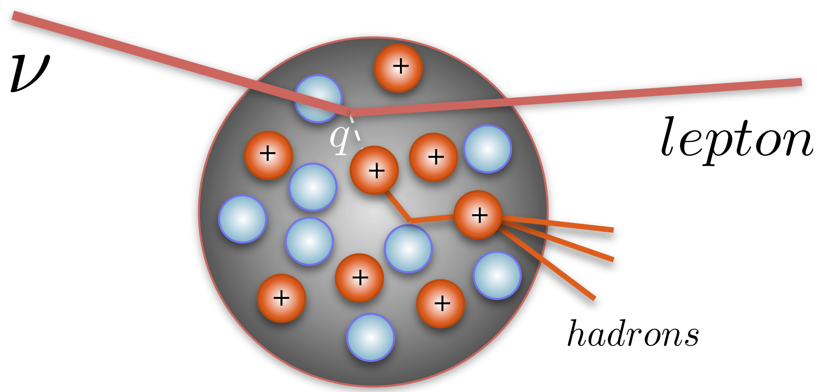
Backgrounds come almost exclusively from atmospheric neutrino interactions.

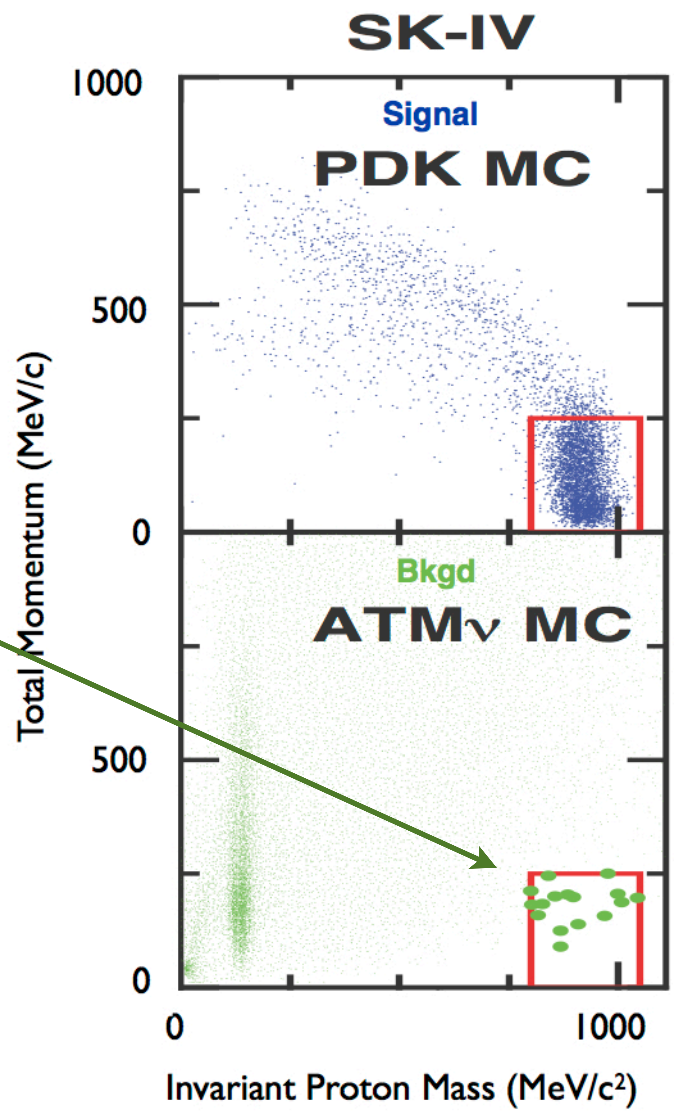


Motivation

Backgrounds come almost exclusively from atmospheric neutrino interactions

High energy neutrino interactions typically produce neutrons in the final state



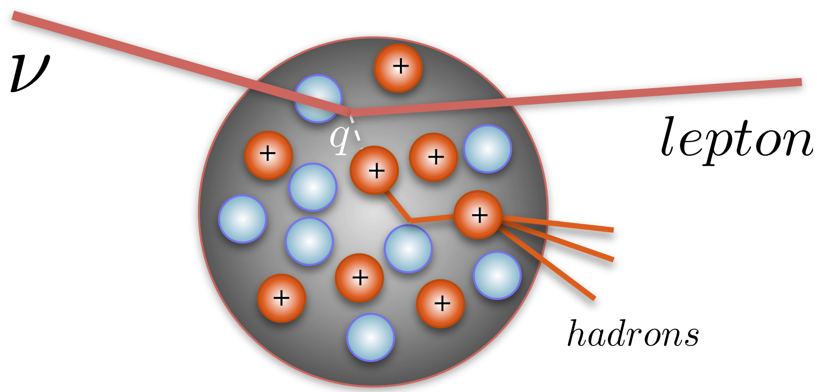


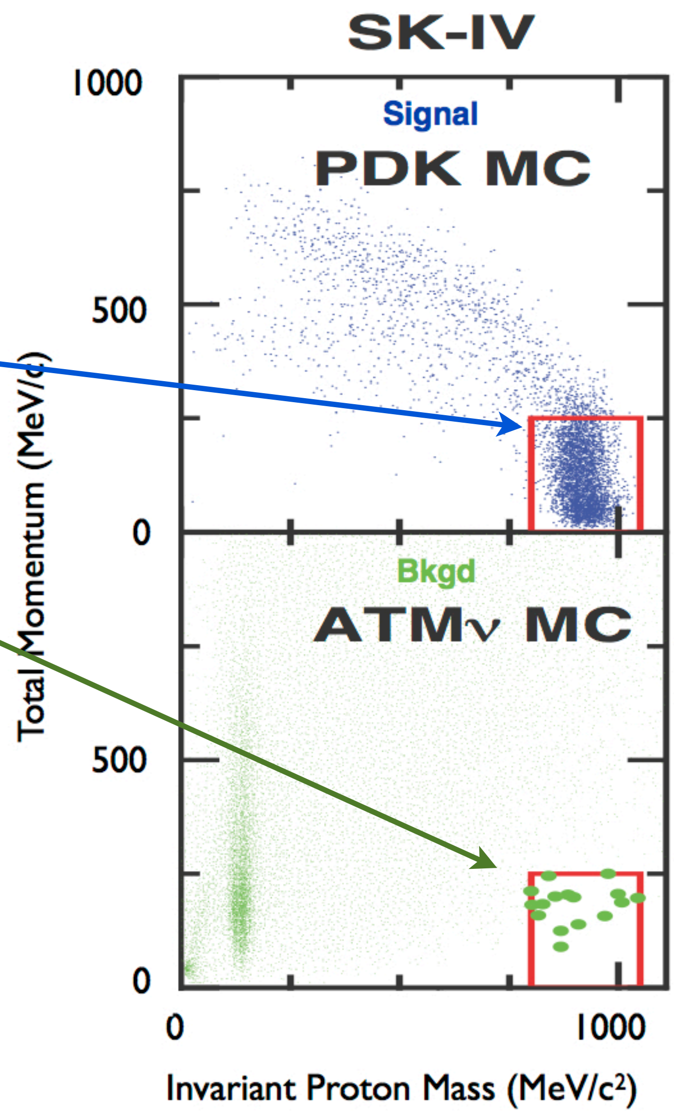
Motivation

Backgrounds come almost exclusively from atmospheric neutrino interactions

Proton decay events are expected to only rarely produce neutrons in the final state.

High energy neutrino interactions typically produce neutrons in the final state





Motivation

Backgrounds come almost exclusively from atmospheric neutrino interactions.

Proton decay events are expected to only rarely produce neutrons in the final state.

High energy neutrino interactions typically produce neutrons in the final state.

neutron-tagging: a strong handle for separating between signal and background.

Efficient neutron-tagging can be achieved by dissolving Gadolinium salts in water. Gd has a high neutron capture cross-section and the captures release 8 MeV in gammas. (Beacom and Vagins)