
UCDAVIS
UNIVERSITY OF CALIFORNIA
R.Svoboda, DPF, August 4, 2017

There's plenty of room *in between* at the Timing Frontier!

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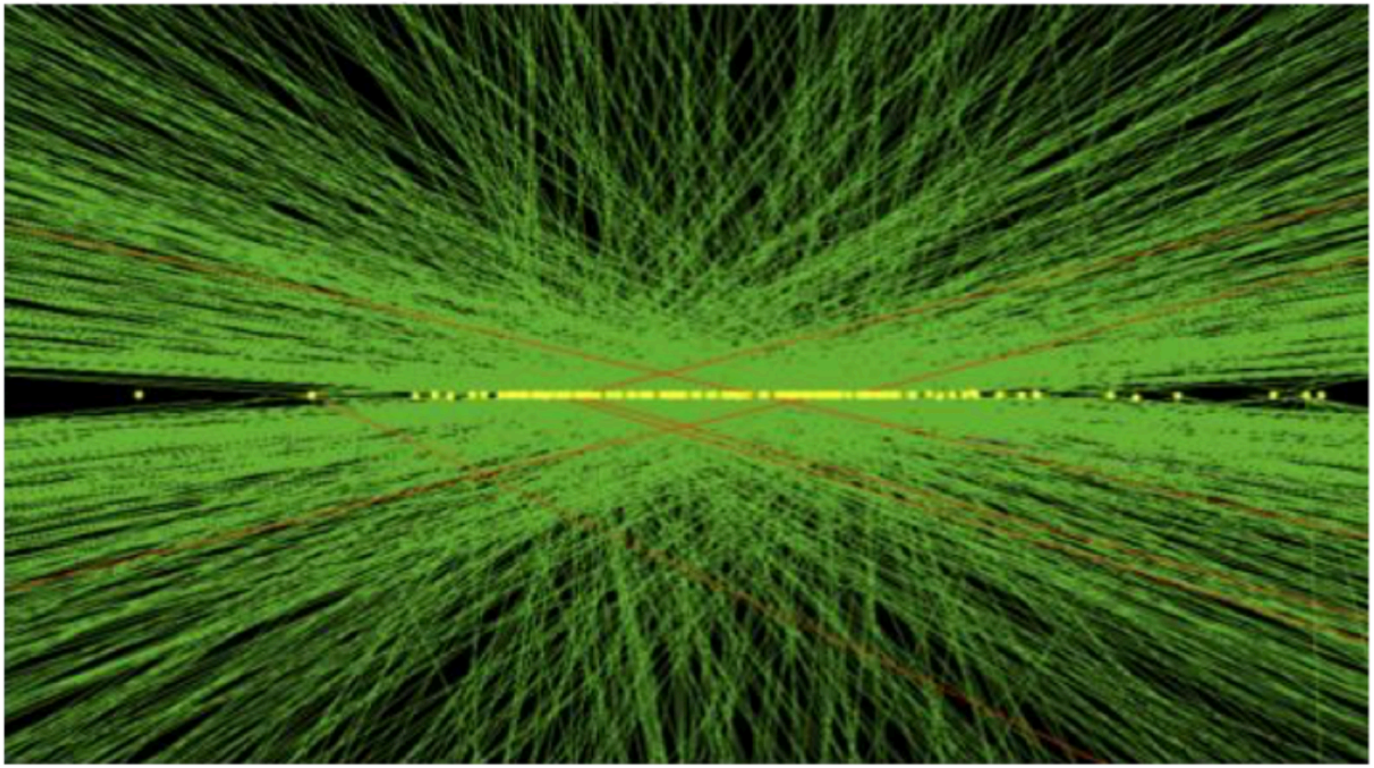
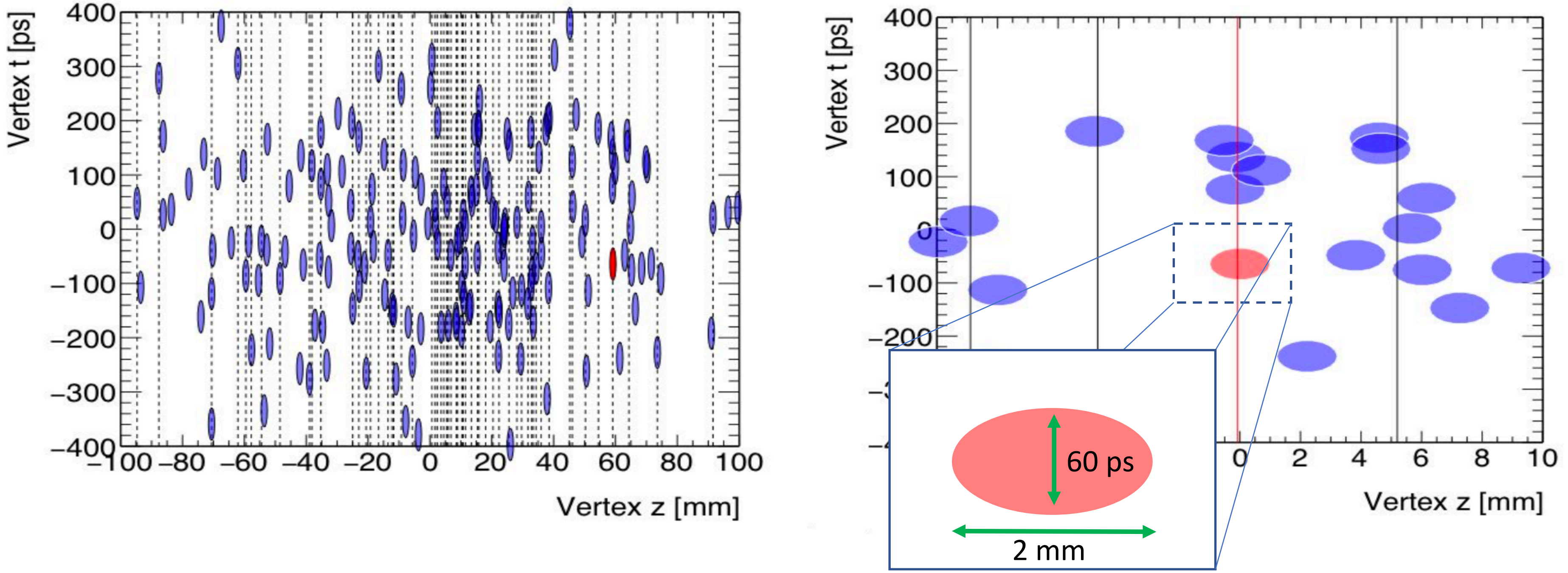
The HL-LHC Environment

The HL-LHC will have on average 200 overlapping events every beam crossing. Very difficult environment for finding tracks and associating to vertices. Probably even worse for future higher energy hadron collider. Especially difficult in the forward region, where track density is very compressed spatially, but where we have to find the forward scattered jets for VBF studies.



(A.Seiden, UCSC)

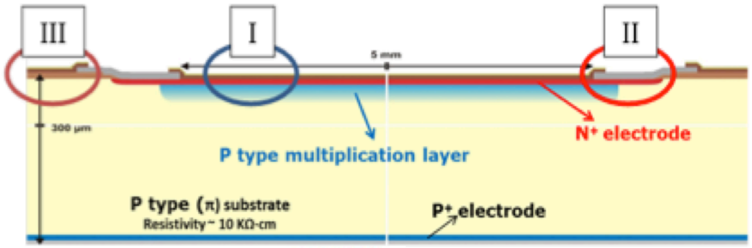


Event display showing the time and z position of all vertices in an event with 200 additional interactions. Blue ellipses correspond to truth vertices. The size of the ellipses are 30ps and 1mm. The red ellipse indicates the truth hard-scatter vertex. The dotted lines indicate the position of the reconstructed primary vertices in the event. The right plot is a zoom around the hard-scatter vertex.

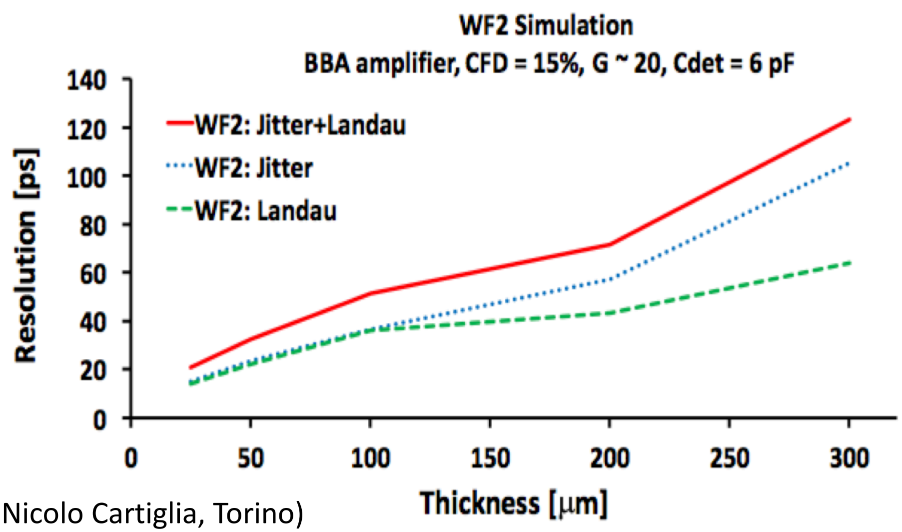
Pile up of event vertices in space can be separated if we can get timing resolutions of ~30-60 ps in a high rate, radiation hard detectors with spatial resolutions ~1 mm

(A.Seiden, UCSC)

Ultra-Fast Silicon Detectors: LGAD (Low Gain Avalanche Detectors) Detectors with Gain and Large Electron Drift Velocity



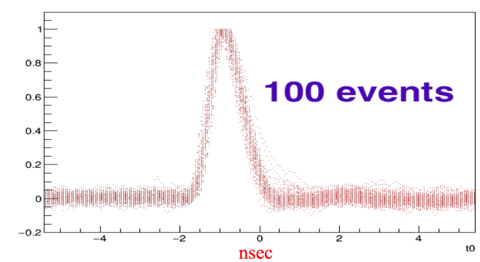
Goal: Gain field ~ 300 kV/cm over a few μm near junction. Bulk field ~ 20 kV/cm, gives a saturated electron drift velocity ~ 10^7cm/sec. Want to have gain for electrons but not holes, leads to gain ~ 20.



(Nicolo Cartiglia, Torino)

Jitter is the electronics contribution, which is noise/slew rate.
Landau is contribution of variations in charge deposition.

Scaled Pulses: Beam Test Last August. 50 micron thick sensor



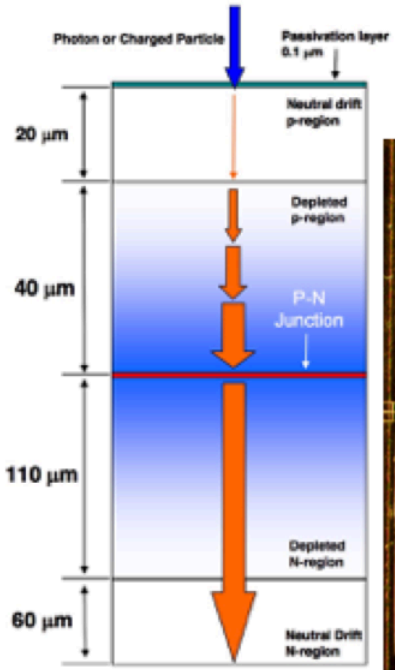
Pulse height divided by maximum value. Gives a standard pulse shape, which is very stable. This is why constant fraction discriminator works so well.

(A.Seiden, 2017 Americas Workshop on Linear Colliders)

Timing Optimized Deep Depleted APDs

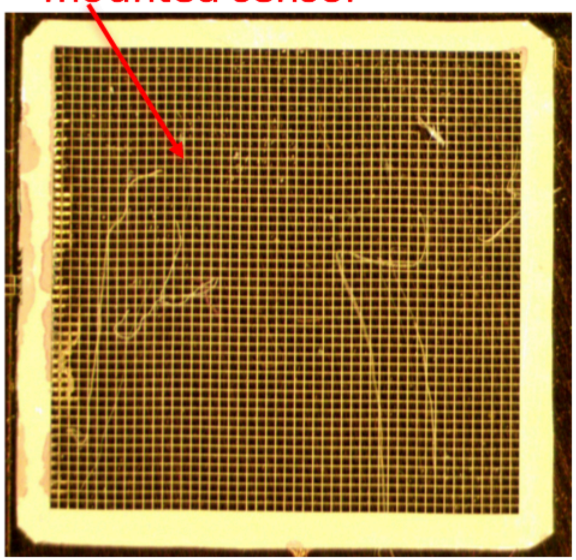
- Medium-gain (300x) APD read out with capacitatively coupled mesh
- Gain and drift regions overlap, mesh helps stabilize E-field over device

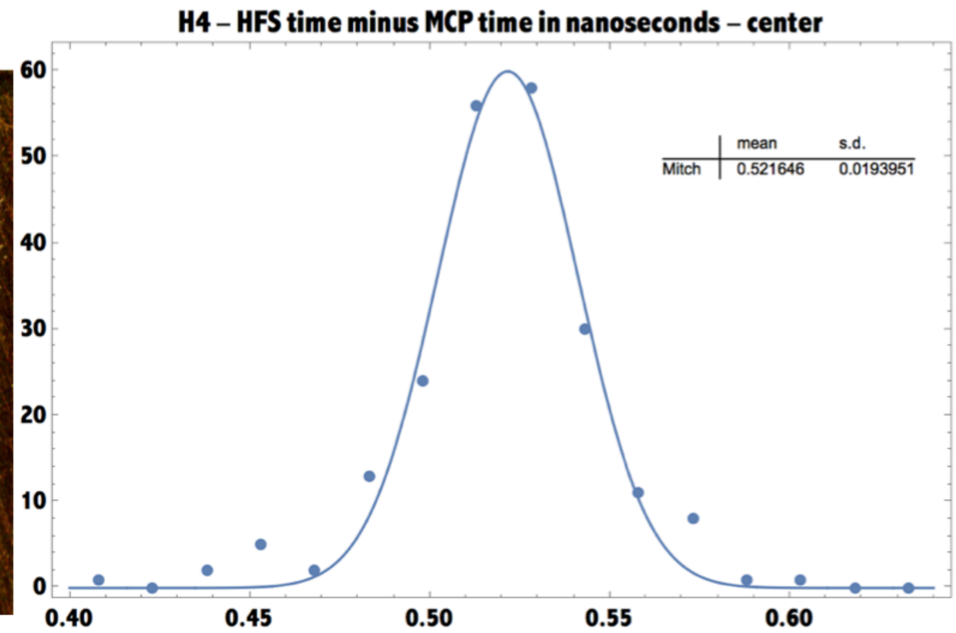
- 20ps resolution achieved for large sensors (8x8mm2), high capacitance
- No conclusive studies of irradiation at the moment



(L. Gray, FNAL)

Mesh visible atop mounted sensor

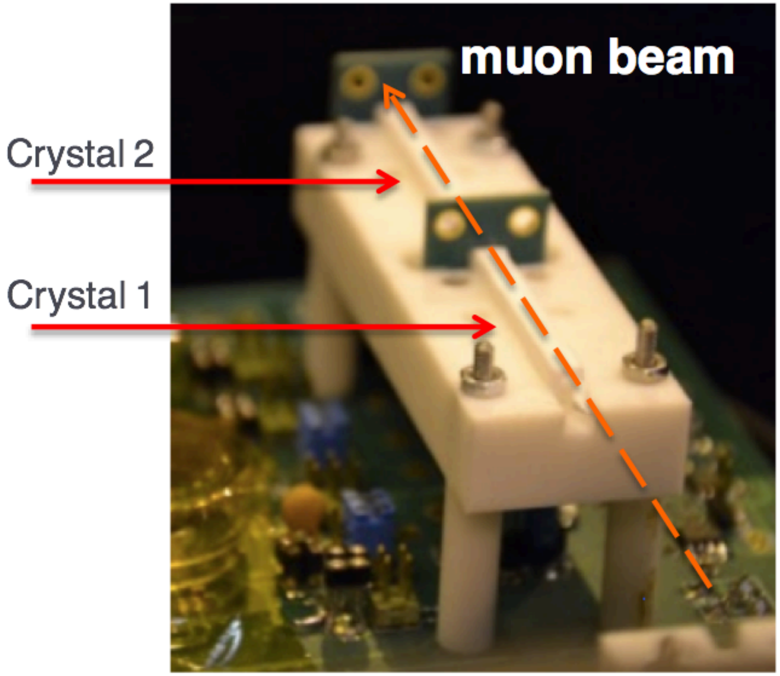




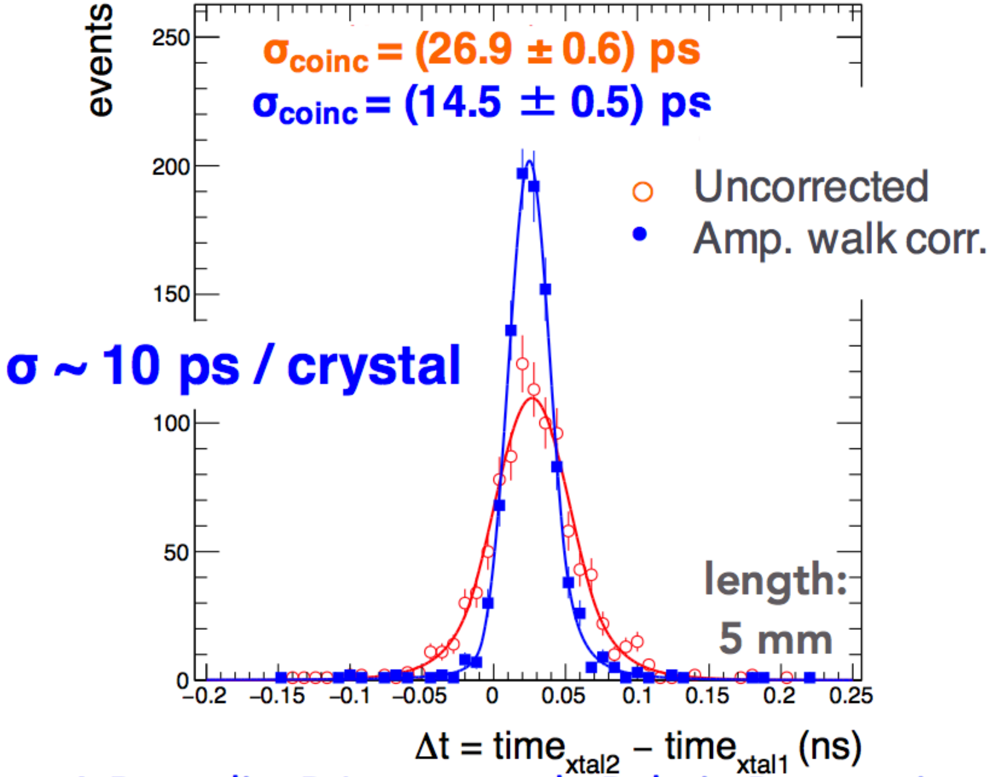
(S. White, et al.)

Fast Scintillating Crystals for Precision Timing

- Thin crystals with SiPM affixed to back, photostatistics drive time resolution
- Depending on light collection, and dark count rate, time resolution can be as good as 10 ps
- Reducing SiPM coverage of crystal reduces light collection efficiency and timing resolution



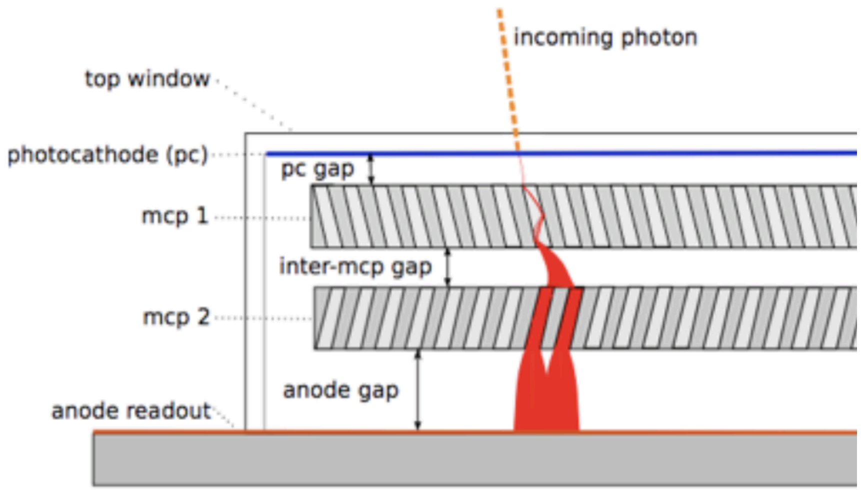
However, crystal too heavy to use within a tracker

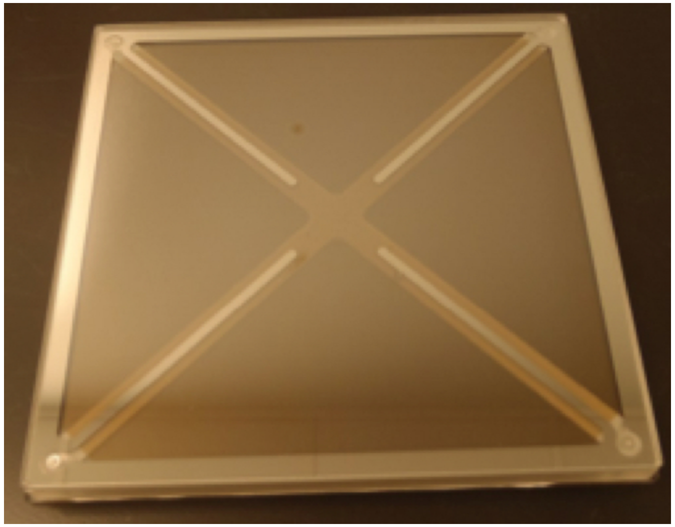


A.Benaglia, P. Lecoq, et al., Pub. in Preparation
On the Properties of Crystal Timing in LYSO

(L. Gray, FNAL)

Large Area Picosecond PhotoDetectors (LAPPDs)





- LAPPDs are 8” x 8” MCP-based imaging photodetectors, with target specifications of:
  - ~50 picosecond single-PE time resolution
  - < 1 cm spatial resolution
  - > 20% QE
  - > 10^6 gain
  - low dark noise (<100 Hz/ch)
  - Strip line readout

- Ring Imaging Detectors
- TOF systems
- Optical tracking detectors (JUNO, TITUS, NUPRISM, CHIPS, HYPER-K, THEIA,…)
- PET scanners
- …

higher, more uniform Q.E. has been achieved with good stability

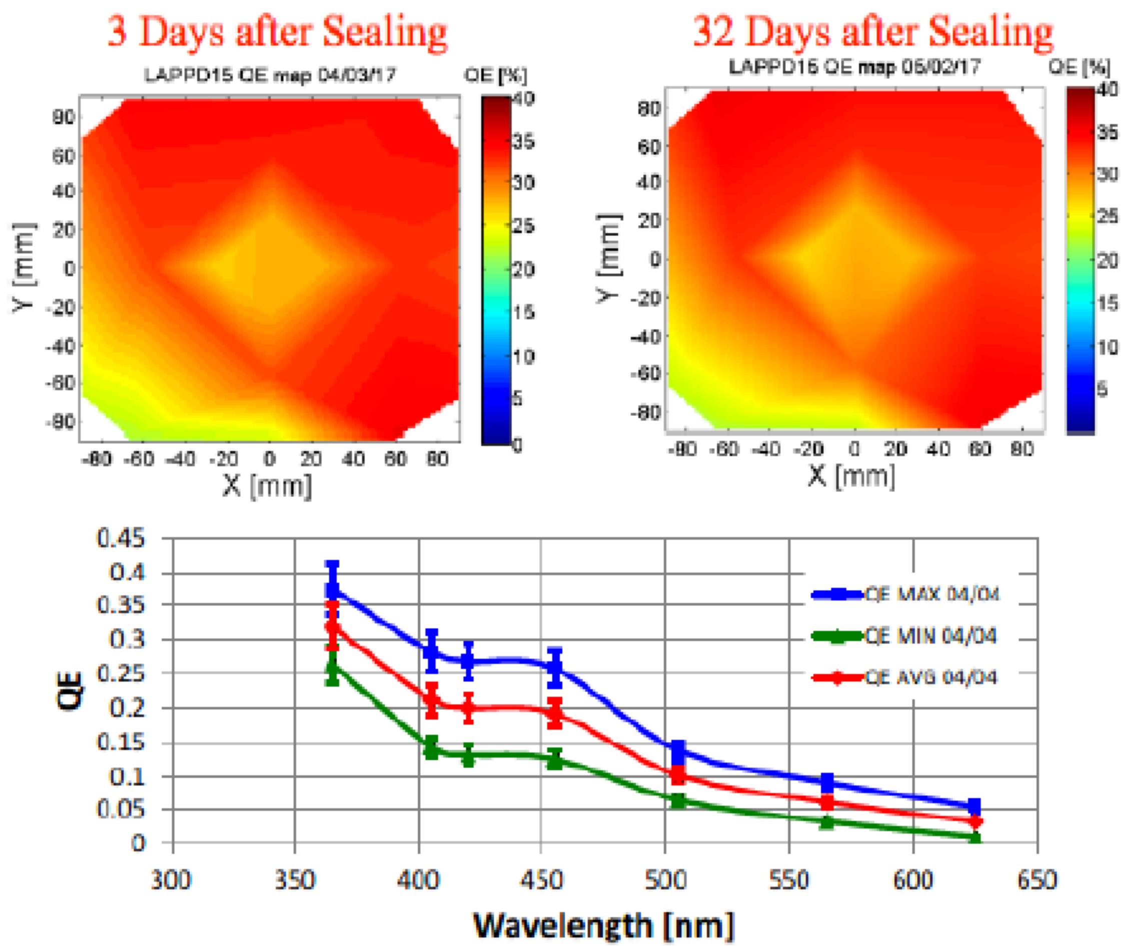
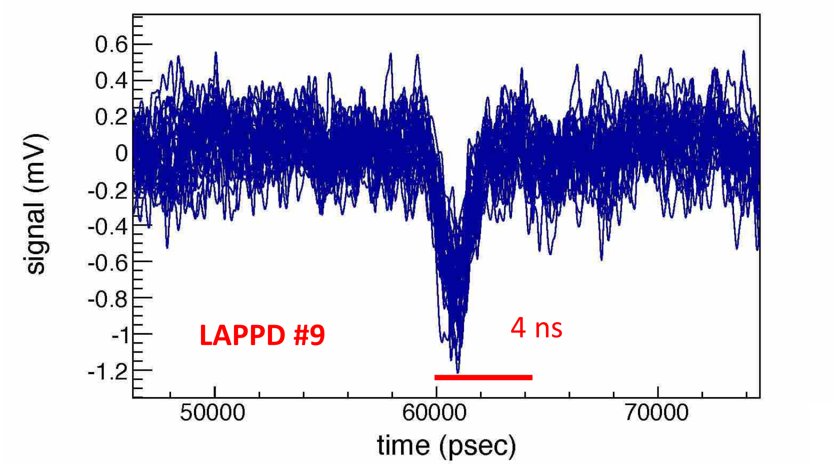


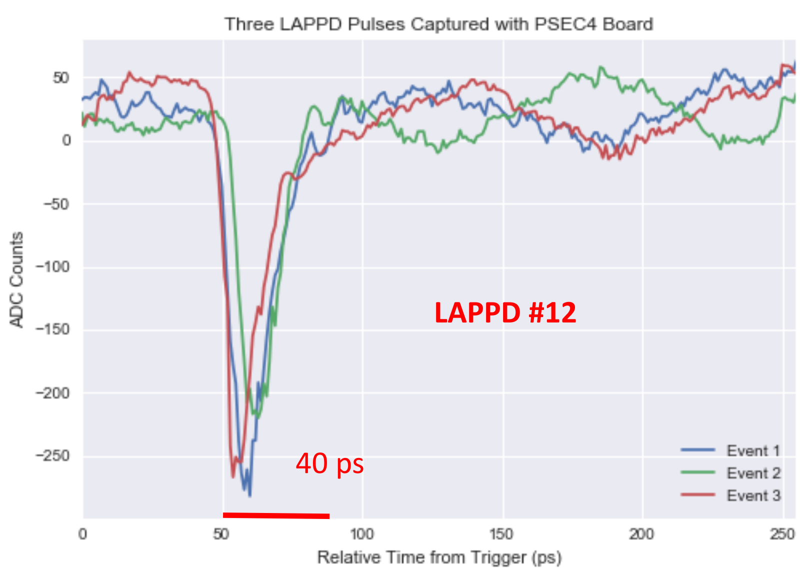
Figure 15: TOP: LAPPD-15 QE map at 3 days (LEFT) and 32 days (RIGHT) after sealing. BOTTOM: The average QE at 375 nm remains at 30%, with a maximum 35% and minimum of 22%.

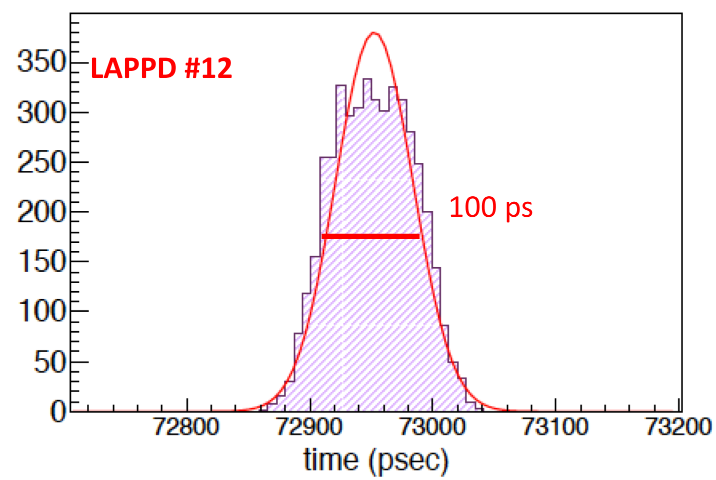
(Incom)

Timing pulses and gain distributions



Single photoelectron
40 Gs/s scope



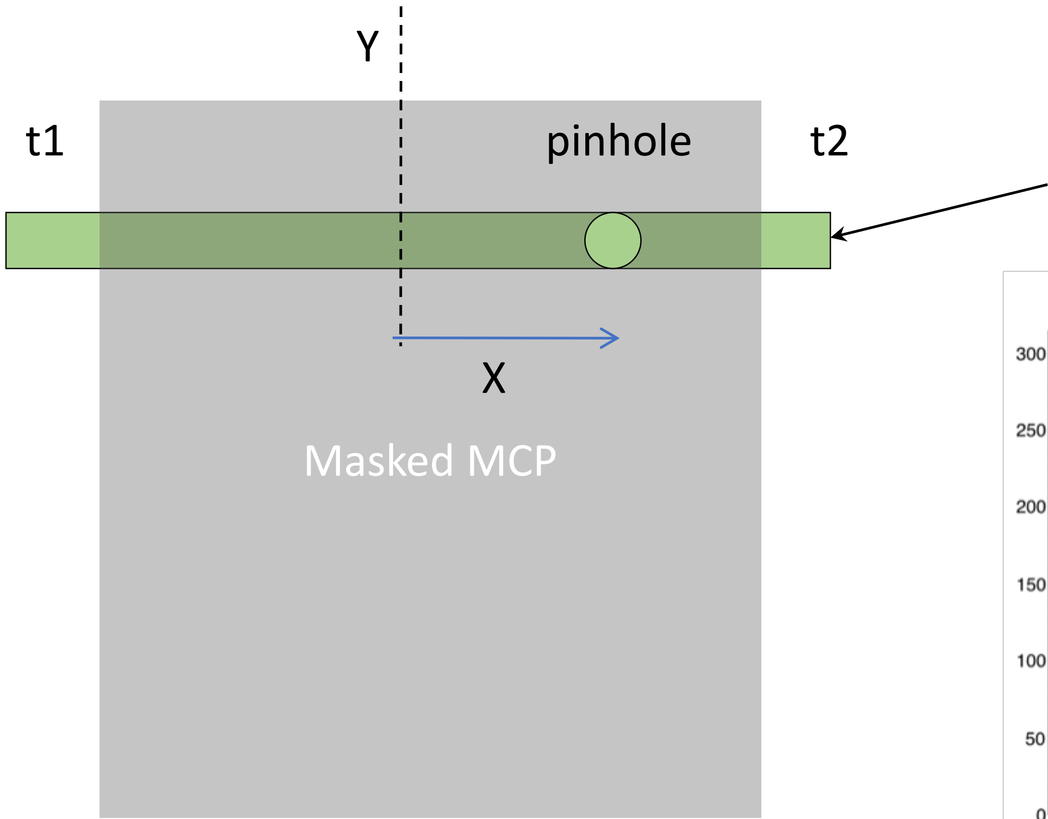


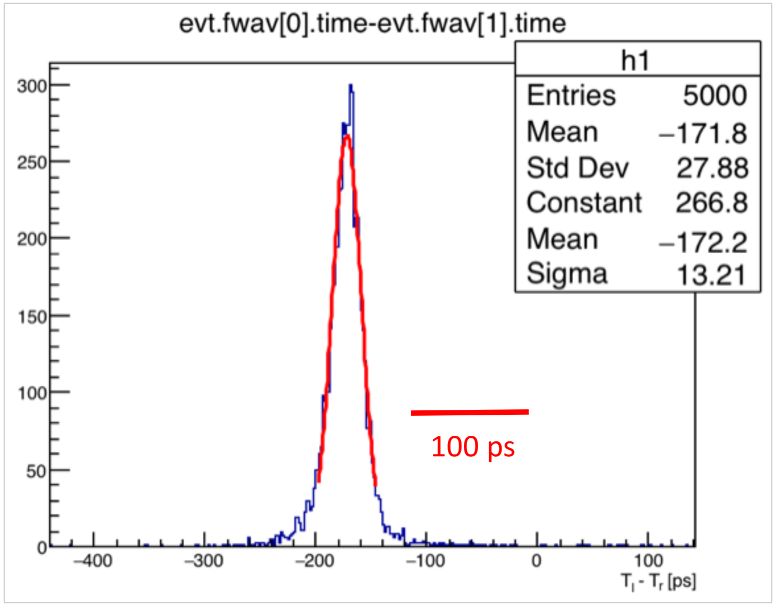
Multi-photoelectron TTS
PSEC custom electronics

Multi-photoelectron
PSEC custom electronics

(M. Wetstein, ISU)

Measure Δt across strip for position in X, charge sharing between strips for position in Y





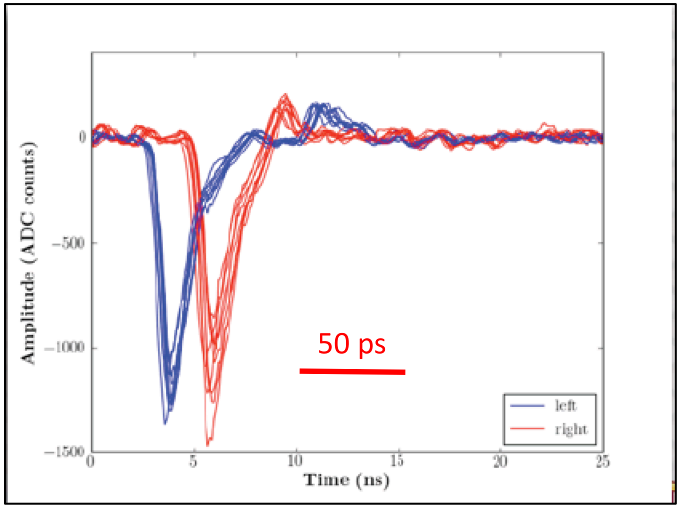
t2 – t1

X=(172 ps)(0.18 mm/ps)/2 = 15.5 mm offset

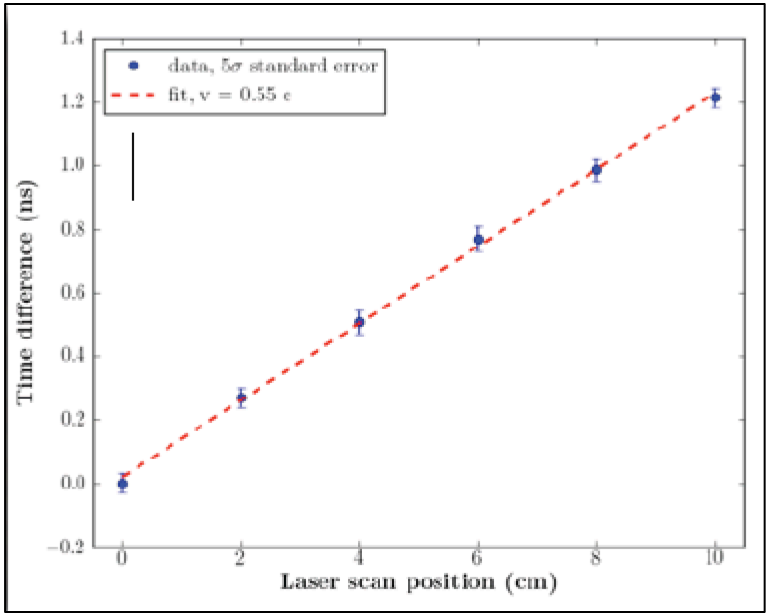
σ_X = (13)(0.60 c) = 1.2 mm

(R. Svoboda, UCD)

LAPPD has similar performance



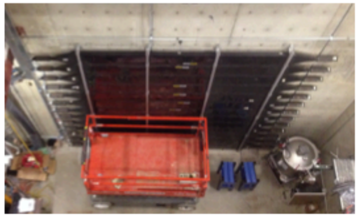
Pulses from opposite sides of a readout strip

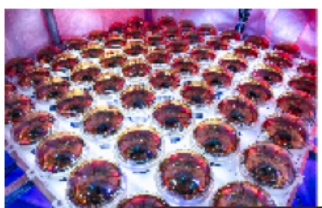


Time difference as a function of laser illumination gives v=0.55 c

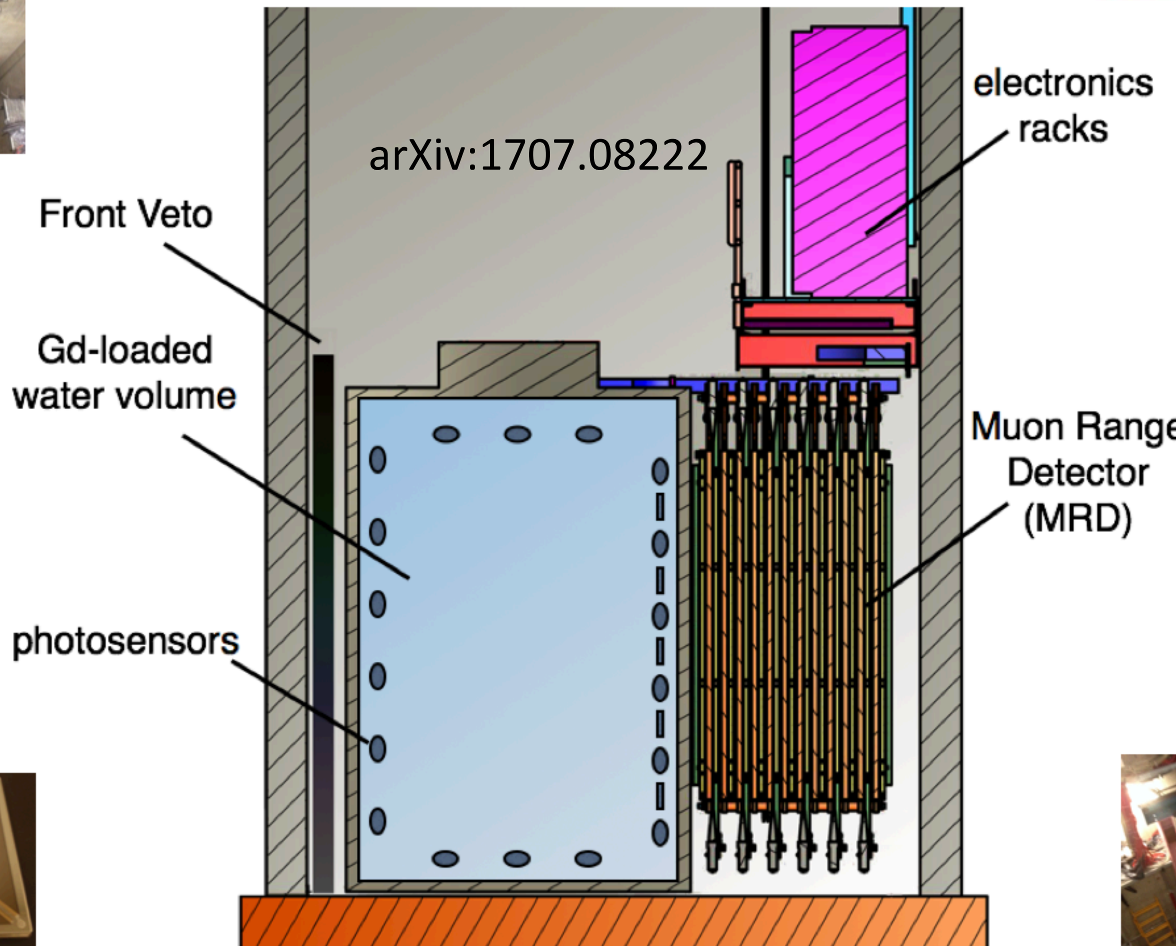
millimeter-scale photon position with 30 ps time resolution and large area (400 cm^2)

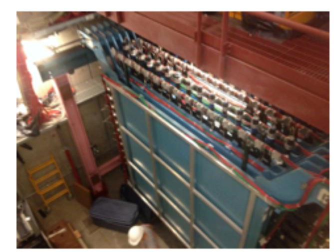
ANNIE Experimental Design





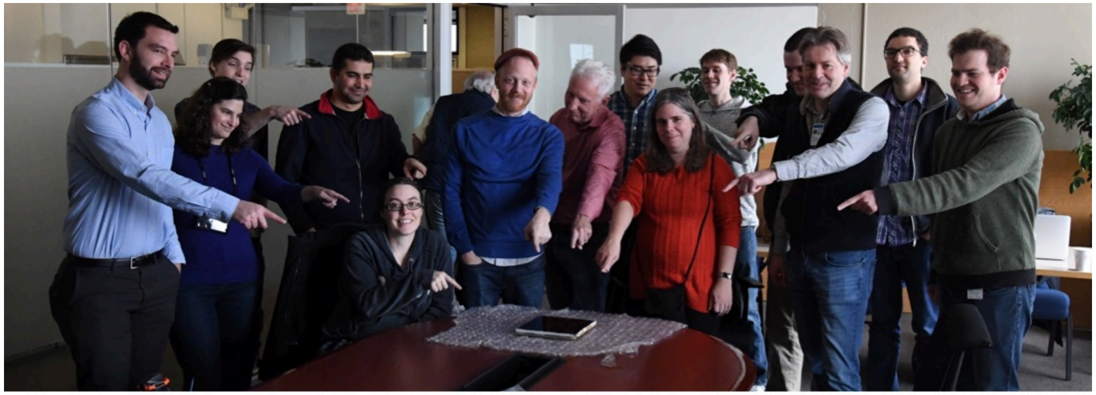
LAPPD Early Adopter - 2018





ANNIE completed Phase I background measurements July 2017 – ready for Phase II

LAPPDs are ready for use in ANNIE



ANNIE Collaborators expressing themselves on the importance of LAPPDs

<u>QE</u>

<1%

5%

15%

25%

Incom has now produced multiple LAPPD prototypes, quickly approaching the specifications needed by ANNIE.

ANNIE will need **at least five** LAPPDs by Fall, 2018 and could use as many as **twenty** in the current ANNIE target tank

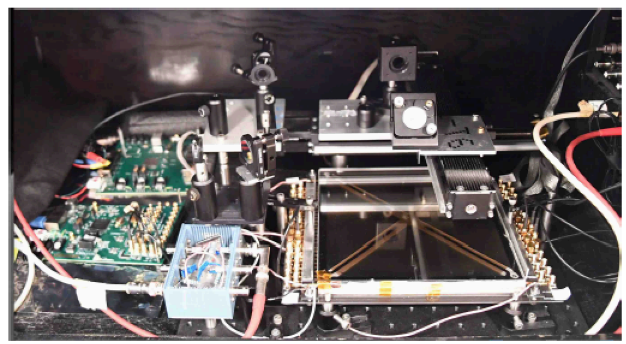
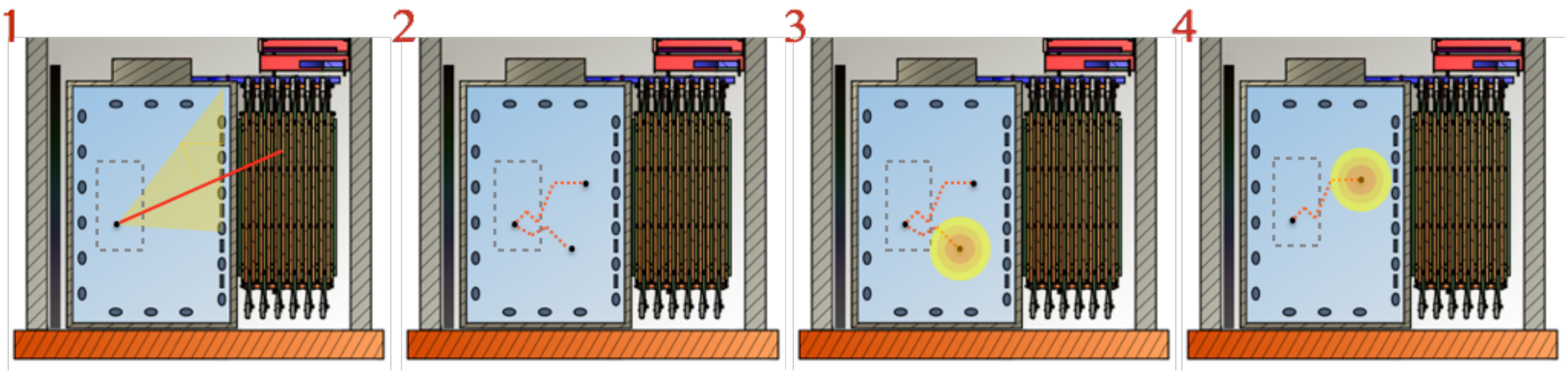


Figure 16: LAPPD-12 installed in the ISU test stand.

ANNIE Collaboration LAPPD Test Stand at ISU

ANNIE Experimental Concept



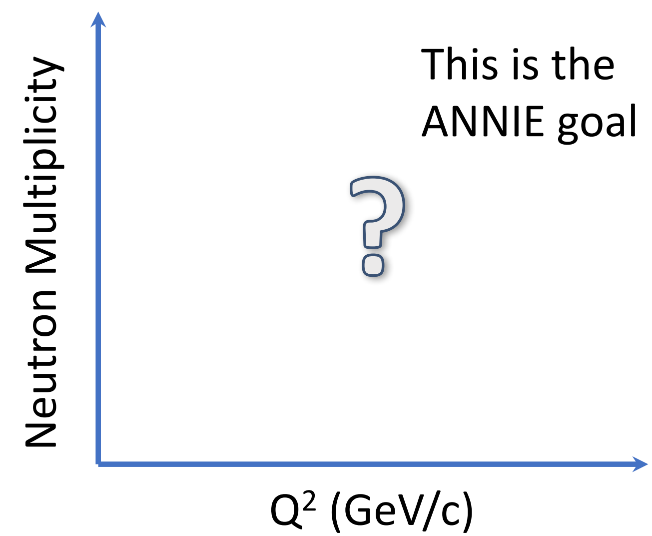
1. CC interaction in the fiducial volume produces a muon, reconstructed in the water volume and MRD
2. Neutrons scatter and thermalize
3. - 4. Thermalized neutrons are captured on the Gd producing flashes of light

CCQE events allow extraction of Q^2 from lepton reconstruction: vertex, direction, energy (from MRD)

significant event rate in 2.5 ton FV

Table 3: Fiducial Event Counts for 1 Year of Running

	NC	CC	CCQE	CC-Other
All	11323	26239	13674	12565
Entering MRD	2	7466	4279	3187
Stopping in MRD	2	4830	2792	2038
Fully Penetrating MRD	0	1454	761	693
Exiting Side of MRD	0	1181	726	455

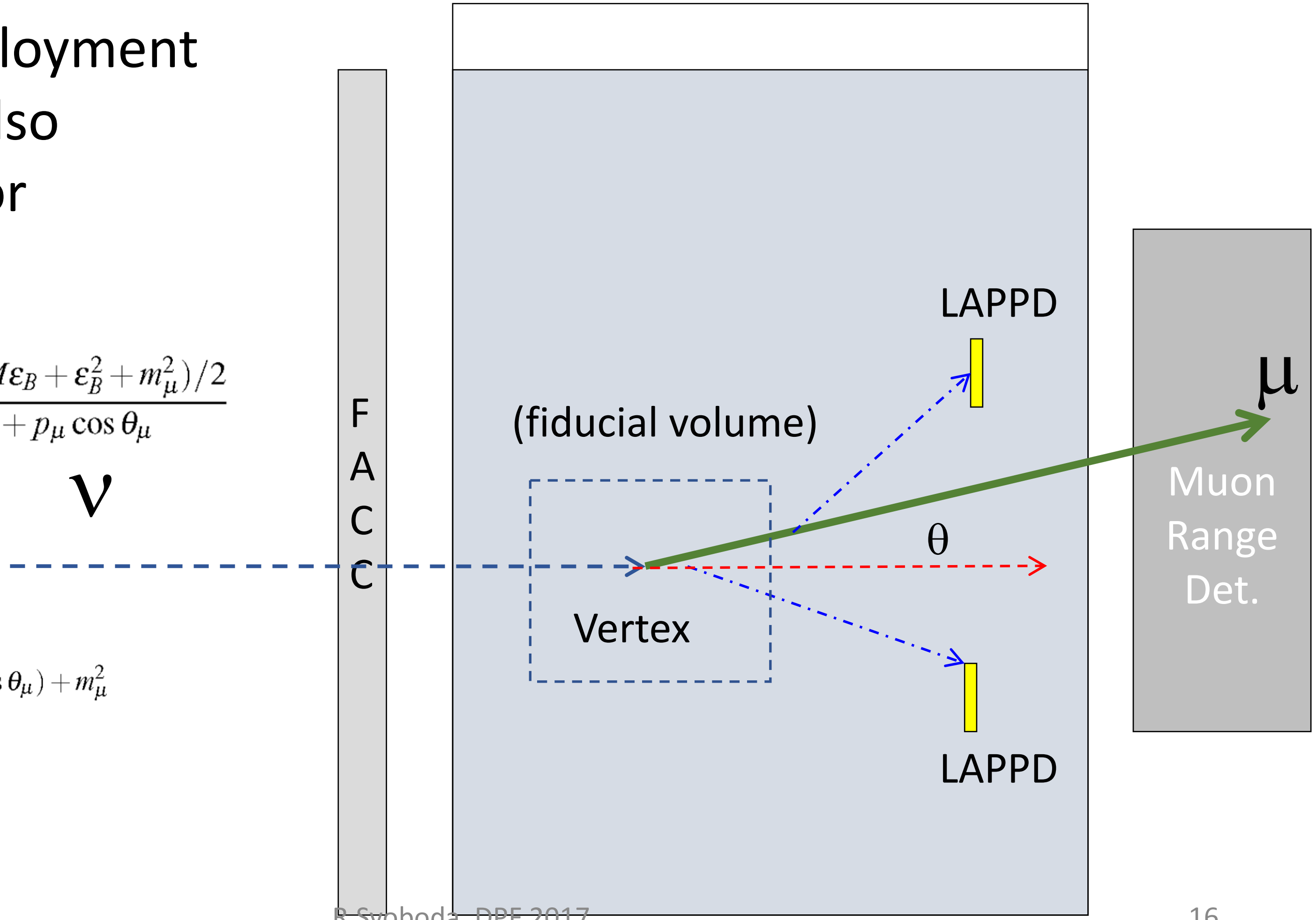


Fast Timing and Vertex/Direction Reconstruction

Phase II deployment of LAPPDs also necessary for kinematics

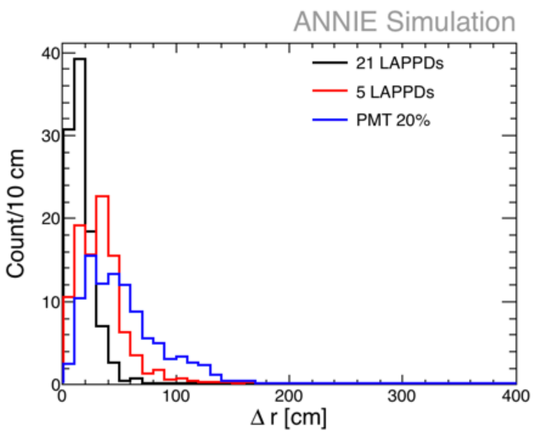
$$E_{\nu}^{QE} = \frac{(M+\varepsilon_B)E_{\mu} - (2M\varepsilon_B + \varepsilon_B^2 + m_{\mu}^2)/2}{M + \varepsilon_B - E_{\mu} + p_{\mu}\cos\theta_{\mu}}$$

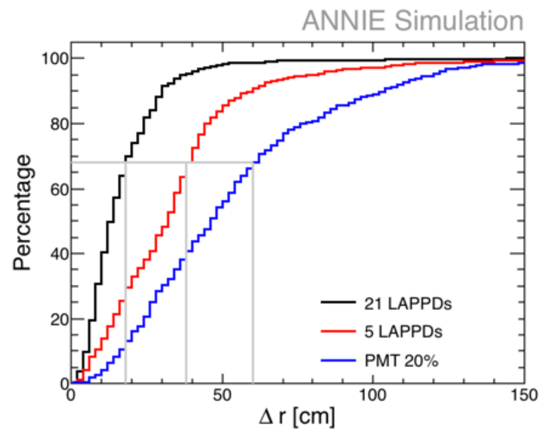
$$Q_{QE}^2 = -2E_{\nu}^{QE}(E_{\mu} - p_{\mu}\cos\theta_{\mu}) + m_{\mu}^2$$



Why does ANNIE need LAPPDs?

LAPPDs provide needed vertex resolution to select fiducial events and precise direction to reconstruct CCQE kinematics



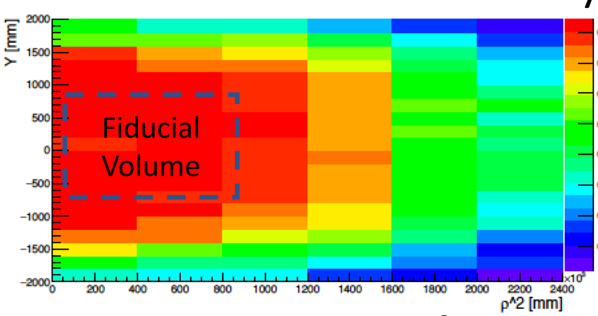


(J.Wang, UCD and A.Back, ISU)

20% conventional PMTs: 60 cm resolution
5 LAPPDs (only): 38 cm resolution
21 LAPPDs (only): 16 cm resolution

neutron capture detection efficiency

tank height

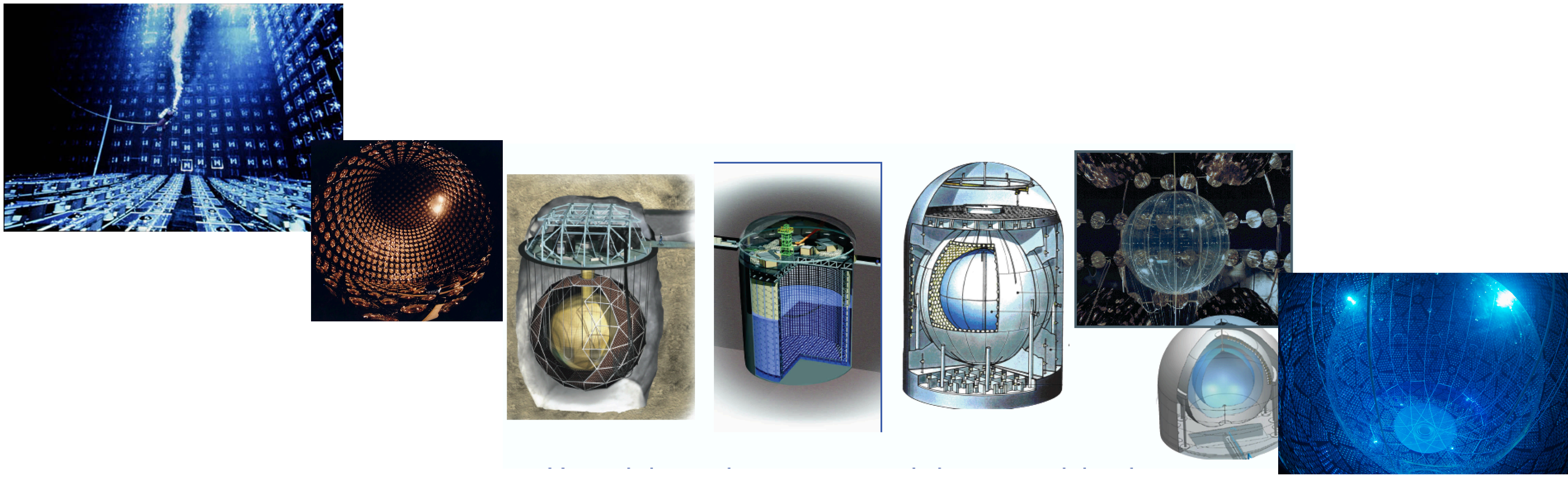


(tank radius)^2

(V.Fischer, UCD)

Recommended to proceed to Phase II by FNAL PAC – endorsed by FNAL Director. Planned start Fall 2018.

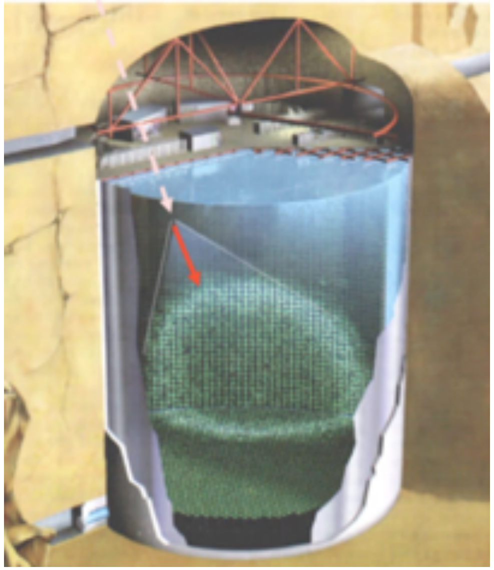
Breakthroughs in Neutrino Physics were enabled by the invention of large optical detectors using scintillator or water



Large size for cost, fast timing for background reduction, low threshold, **reconfigurable** **as the field progressed**

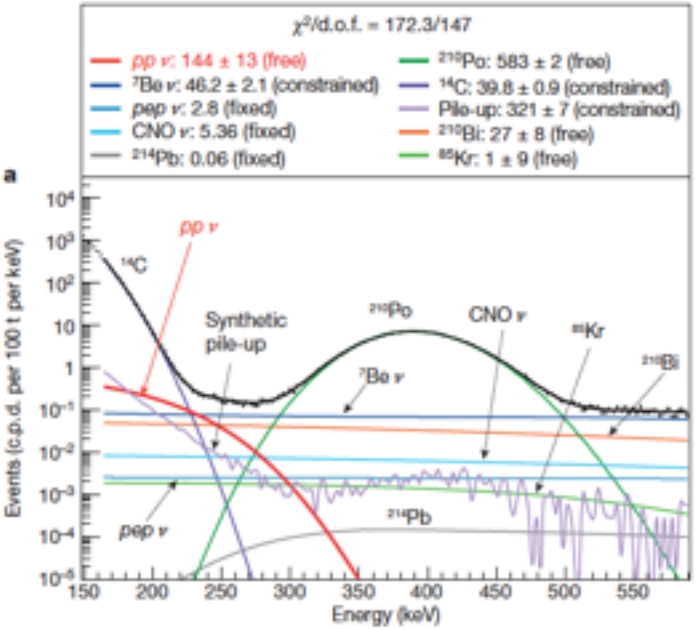
Water Cherenkov

- Excellent Transparency
  - large size
- Directionality
- Particle ID
- Potential for large Isotopic Loading



Liquid Scintillator

- High Light Yield
  - low threshold
  - good energy resolution
- Can be radiologically very clean



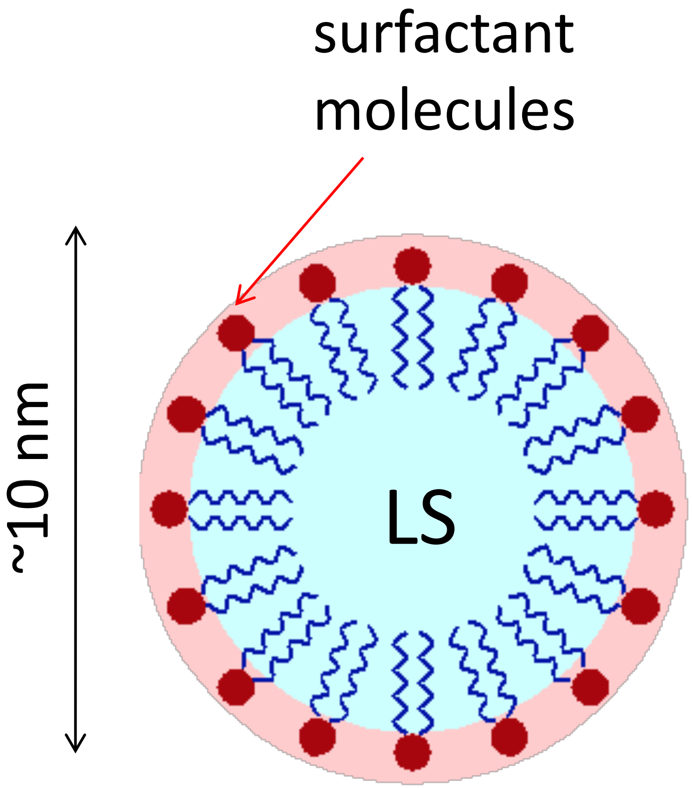
Could we make a Hybrid Detector?

- Use LS mixed with oil or Water-based Liquid Scintillator (WbLS) to adjust light yield and transparency
- Directionality via fast timing to separate Cherenkov and Scintillation light
- Deep location to enable a broad program
- Reconfigurable design: "**follow the physics**"

…to follow the physics?

- Zero neutrino double beta decay in a neutrino mass Normal Ordering world (where ν_e is light)
- Detection of the Diffuse SN Neutrino Background
- High precision measurement of δ_{CP} – could it be maximal?
- Measurement of the CNO contribution to solar fusion
- Investigate the “New Solar Neutrino Problem”
- Observe a black hole formation in real time
- Investigate potential unexplored proton decay modes
- Investigate the Earth’s geothermal energy budget
- Dark matter in the Sun
- ...and so it goes

Intriguing Idea: Micelle sequestering of LS in water

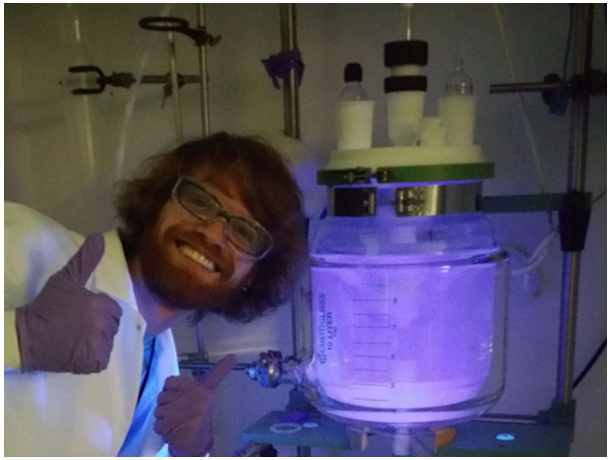


Liquid Scintillator (LS) forms small (~10 nm scale) droplets called *micelles* in water that are stabilized by surfactant molecules with a hydrophilic head and hydrophobic tail. Micelles form under controlled chemical conditions and are shown to be stable over year time scales.

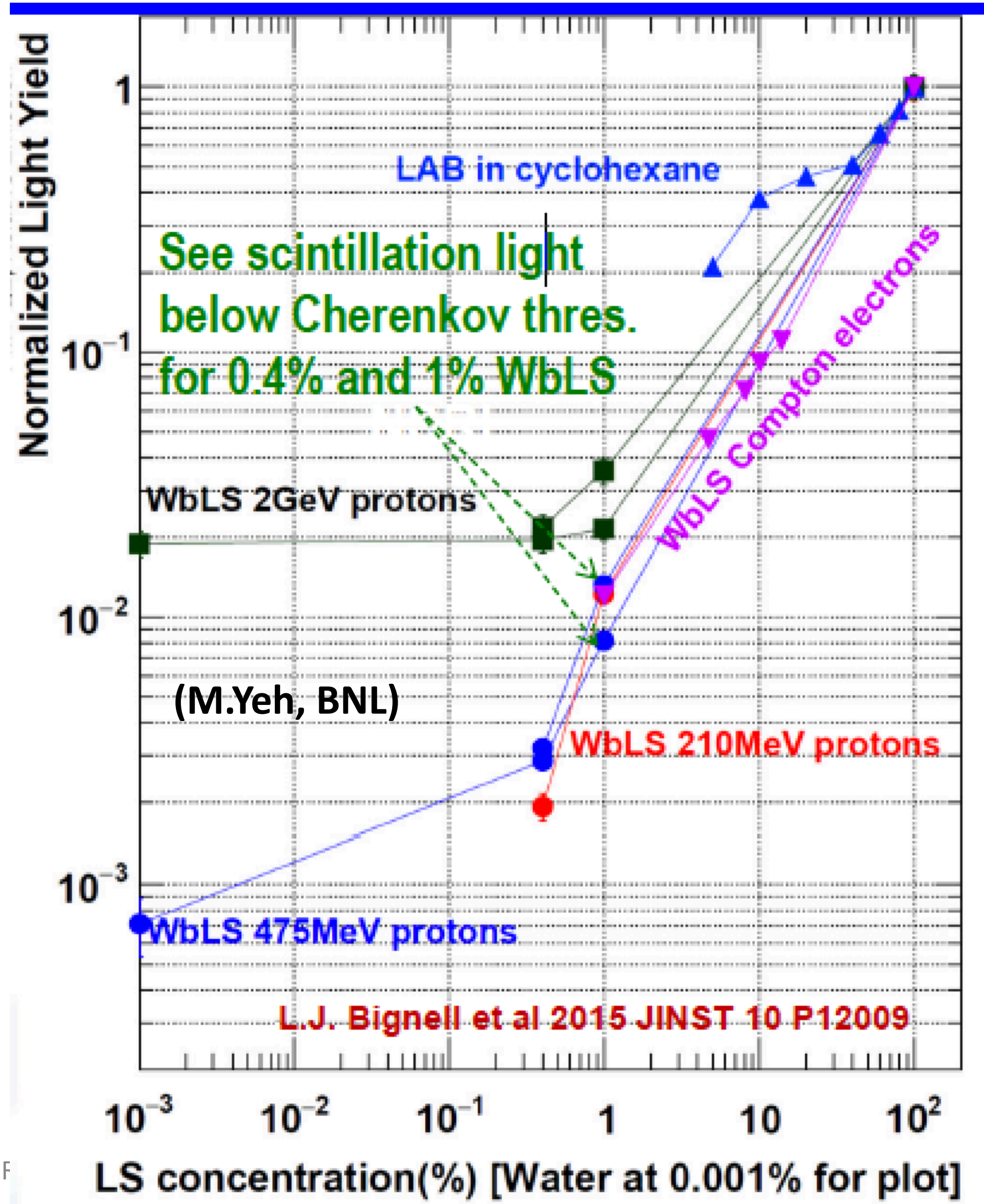
Can adjust scintillation yield by changing micelle concentration.

Dilution of LS in water allows for **tuning** light yield to match the physics.

WbLS cocktail in water (violet) and cyclohexane (blue)



(M. Askins, UCD)



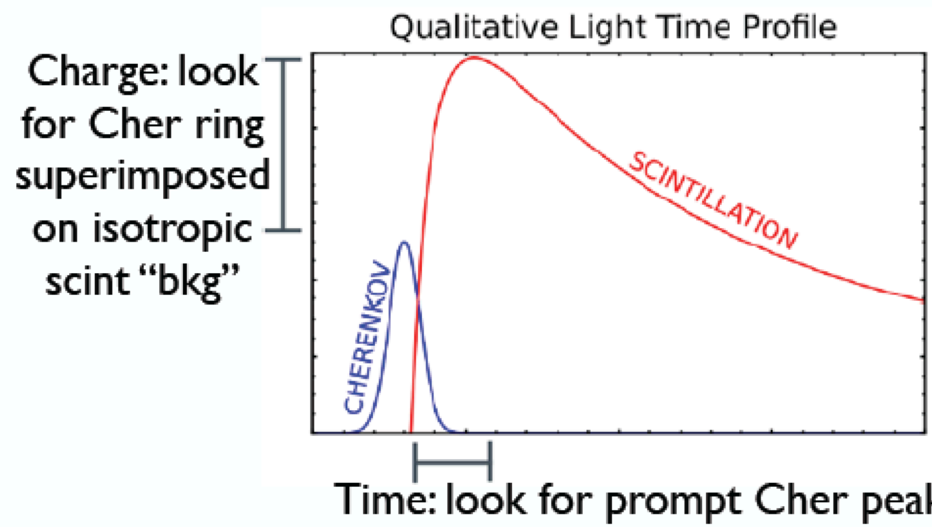
Cherenkov/scintillation separation

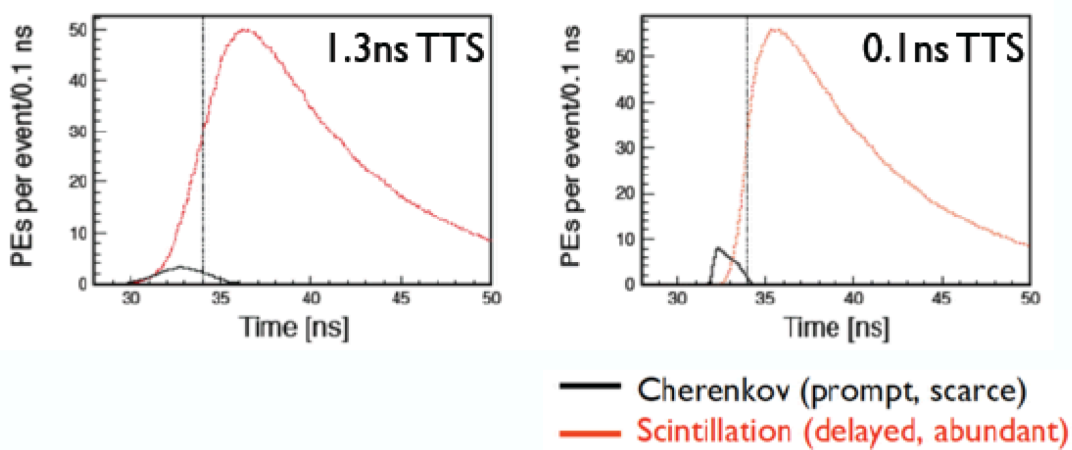
Separate signals in:

CHESS

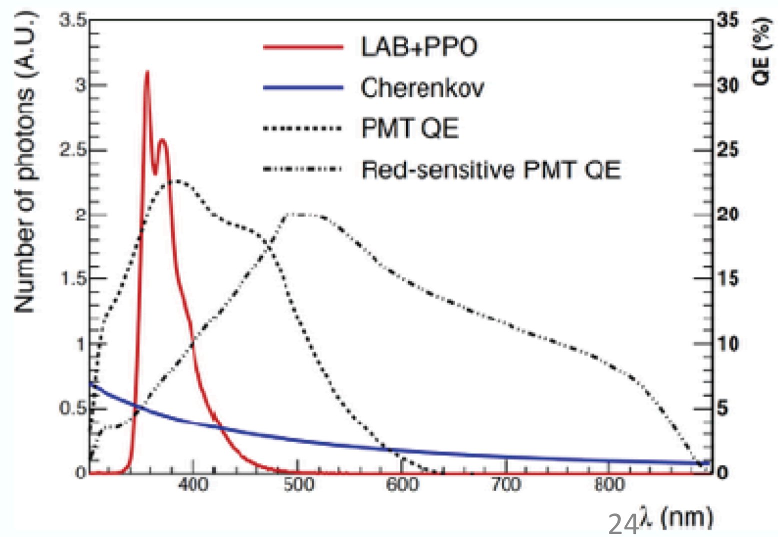
- Time
  - Ultra-fast detection (LAPPD?)
  - Delay scint light
- Charge
  - Tune relative light yields
  - Readout sensitivity
- Wavelength
  - LS spectrum (fluor) / readout

(G. Orebi Gann, LBL)





C. Aberle et al, JINST 9 P06012 (2014)



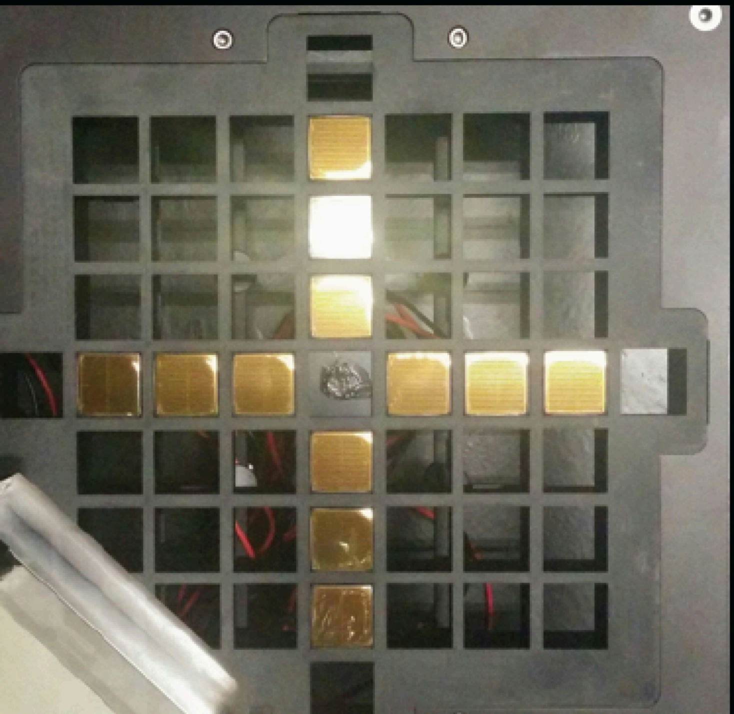
CHESS: CHErenkov-Scintillation Separation

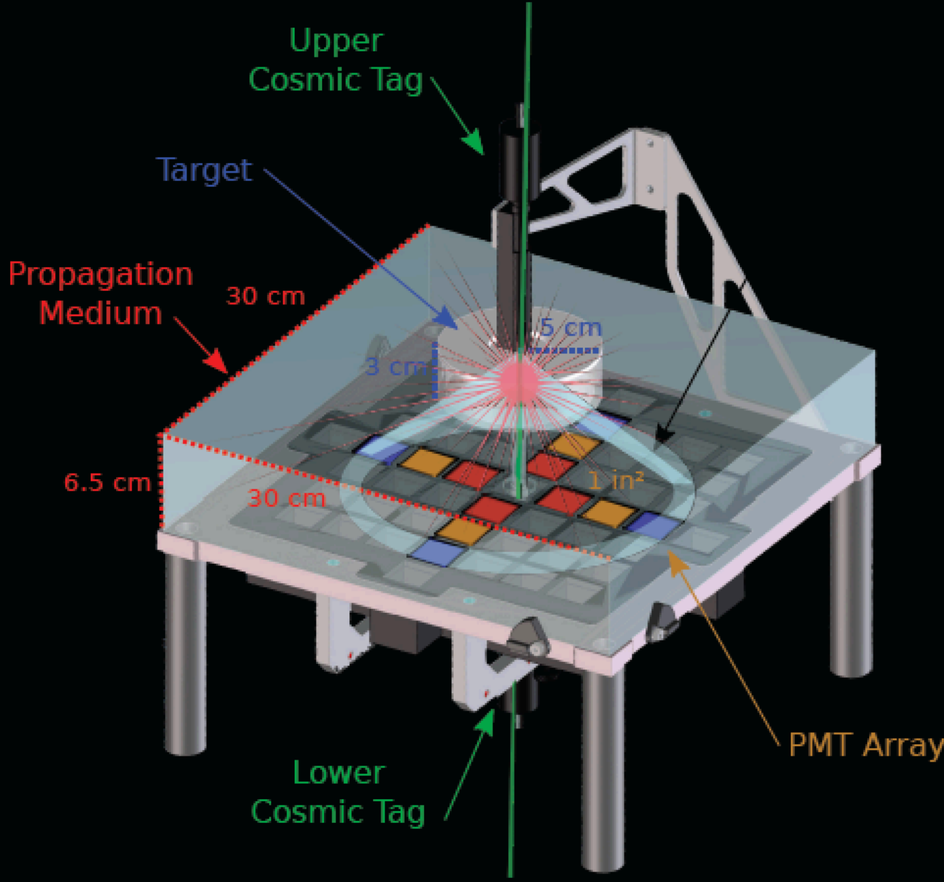
Supported by LBNL LDRD (FY '15-16)
arXiv: 1610.02029

Select vertical cosmic muon events

Image Cherenkov ring in Q and T on fast-PMT array

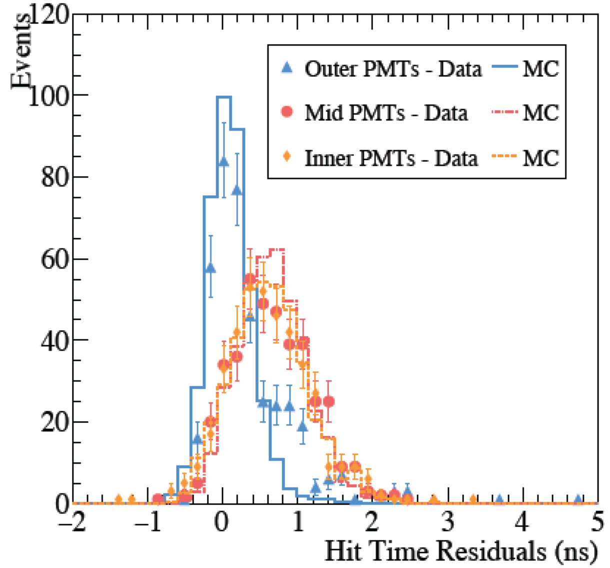
Allows charge- and time-based separation





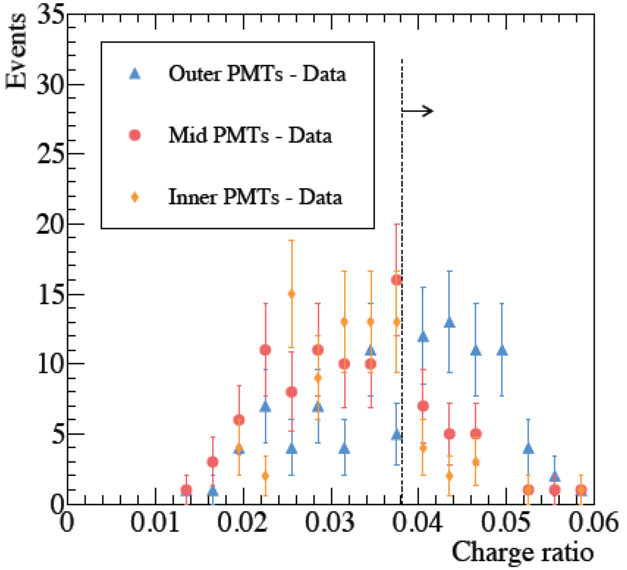
12 1-inch H11934 PMTs (300ps FWHM, 42% QE)
CAEN V1742 (5GHz)
675 samples (135ns window)
CAEN V1730 (500MHz)

Successful C/LS separation!



Time at fixed threshold
Corrected by ToF, channel delays

NOTE: Rise time = 0.75 ± 0.25 ns



Ratio of charge in prompt, 5ns window
to charge in total (135ns) window

(G. Orebi Gann, LBL)

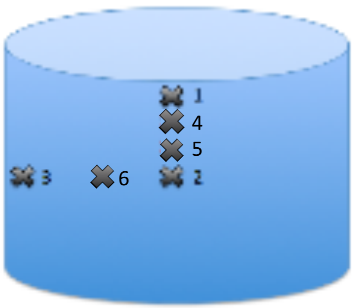
arXiv:1610.02011

Conclusions

- ***There is plenty of room in between!***
- No time to cover necessary fast electronics – important!
- Detectors with picosecond timing are starting to be developed that will have wide use in almost every sub-field of particle physics and have many commerical uses.
- **Important** for future of high rate colliders that need mm scale vertex resolution, low power, and radiation hardness
- **Important** for large neutrino detectors requiring high mass, low cost, wide dynamic range (sub-MeV to 10 GeV), plus the ability to load isotopes and operate with very high radiopurity for long periods of time and use doped water.
- ***There is plenty of rom in between!***


BACKUP

Phase I: background measurement

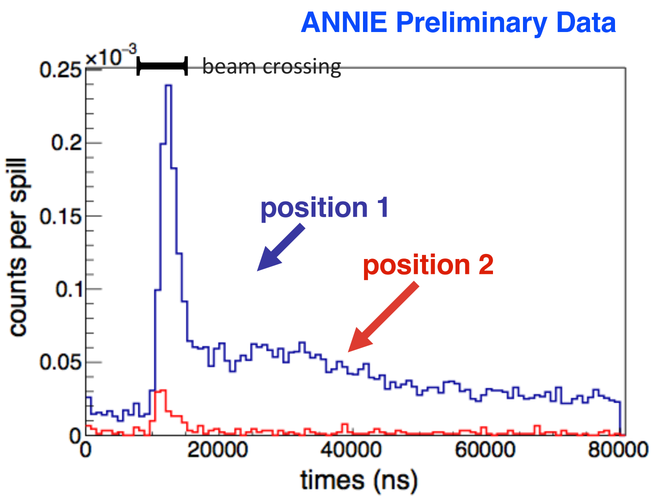


- the NCV was moved to 6 positions, scanning the neutron rates as a function of depth and distance from the beam

- strong suppression of skyshine neutrons was observed with increasing depth

- preliminary estimates based on measurements below the surface indicate neutron backgrounds in less than 2% of spills

Backgrounds are suppressed at depths > 50 cm and sufficiently low for Phase II



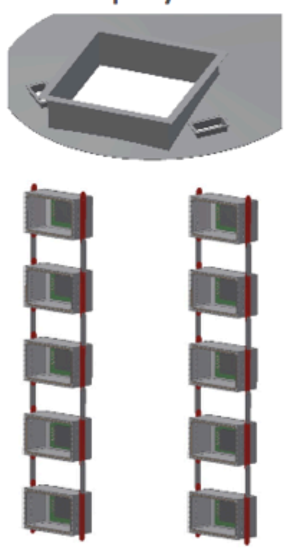
Progress Towards Phase II

19 LUX PMTs

45 WATCHMAN PMTs

22 LBNE PMTs

LAPPD deployment



LAPPD housing

- We have in hand free large area PMTs to use for Phase II. Need only ~40 8in new ones
- New design for the LAPPD housing assemblies allows for LAPPDs to be installed into the already assembled detector
- PMT and MRD readout systems and DAQ are already working and expandable.
- The LAPPD, PSEC-4 readout system is largely complete

ANNIE Timeline

Summer 2017

Completion of Phase II inner structure and tank lid

Removal of the tank from the Hall
Finish MRD refurbishment

Fall/Winter 2017

PMT refurbishment and acquisition

Electronics acquisitions

Spring 2018

PMT installation

Reinstallation of inner structure and water fill

Summer 2018

Phase II commissioning

Introduction of Gd

LAPPD installation

Fall 2018

Phase II data taking

ANNIE Q^2 Acceptance

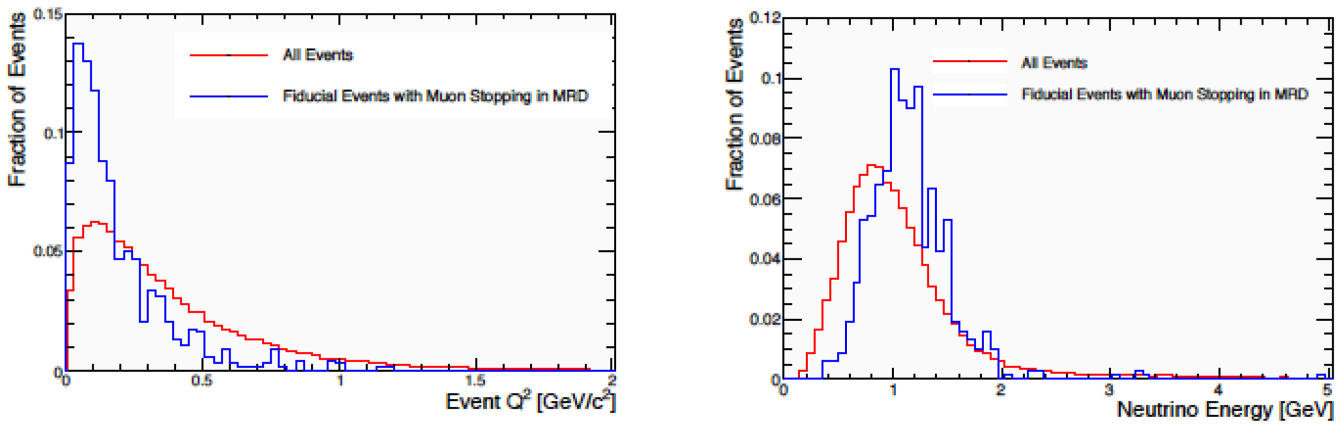


Figure 18: LEFT: The normalized Q^2 distribution for all events (red line) and for 2.5-ton fiducial events with muons ranging out in the MRD (blue line). RIGHT: The normalized E_ν distribution for all events (red line) and for 2.5-ton fiducial events with muons ranging out in the MRD (blue line).

It is important to measure neutron multiplicity as a function of these parameters and therefore we want a wide spread in neutrino energy and Q^2

ANNIE Phase I:

- A measurement of potential background neutrons in ANNIE Phase II
    - rock neutrons
    - “skyshine”
- A Neutron Capture Volume (NCV) measures position dependent neutron rates
- Phase I enabled ANNIE to build and operate all the main components of the detector
- It also provided an opportunity to anticipate, understand, and mitigate major risks for Phase II