ANNIE

The Accelerator Neutrino Neutron Interaction Experiment

Matt Wetstein (ISU) on behalf of the ANNIE Collaboration

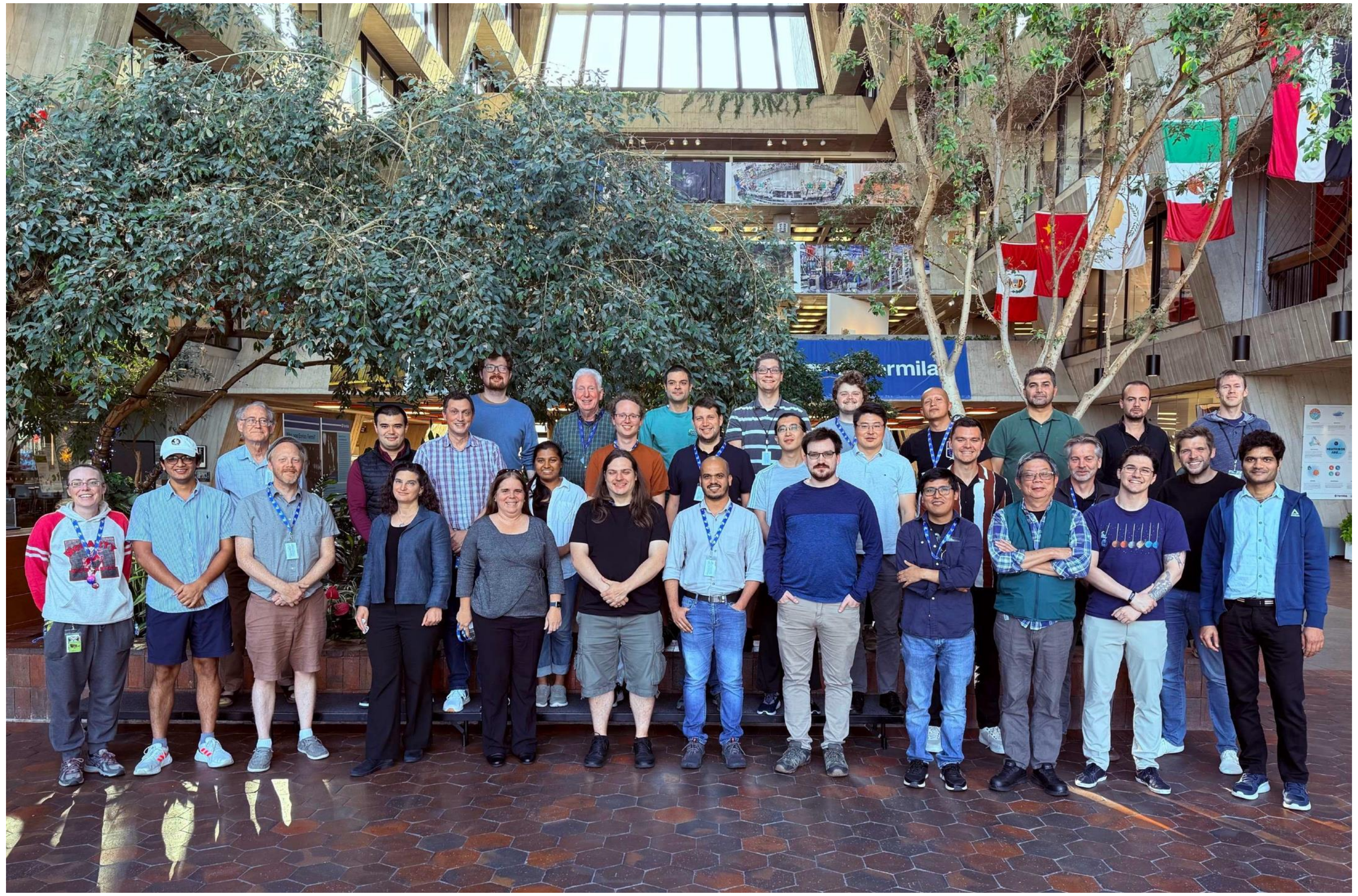
September 2024

U.S. DEPARTMENT OF ENERGY

The Accelerator Neutrino Neutron Interaction Experiment

ANNIE is a neutrino experiment deployed on the Fermilab Booster Neutrino Beam

- **Physics:** measurement aimed at better understanding neutrino-nucleus interactions
- **Technology**: An R&D platform to develop and demonstrate new neutrino detection technologies/techniques
- **Training:** 10+ Annie postdocs and students now have faculty or permanent lab positions



We have an international collaboration, consisting of 45 collaborators from 17 institutions in 6 countries

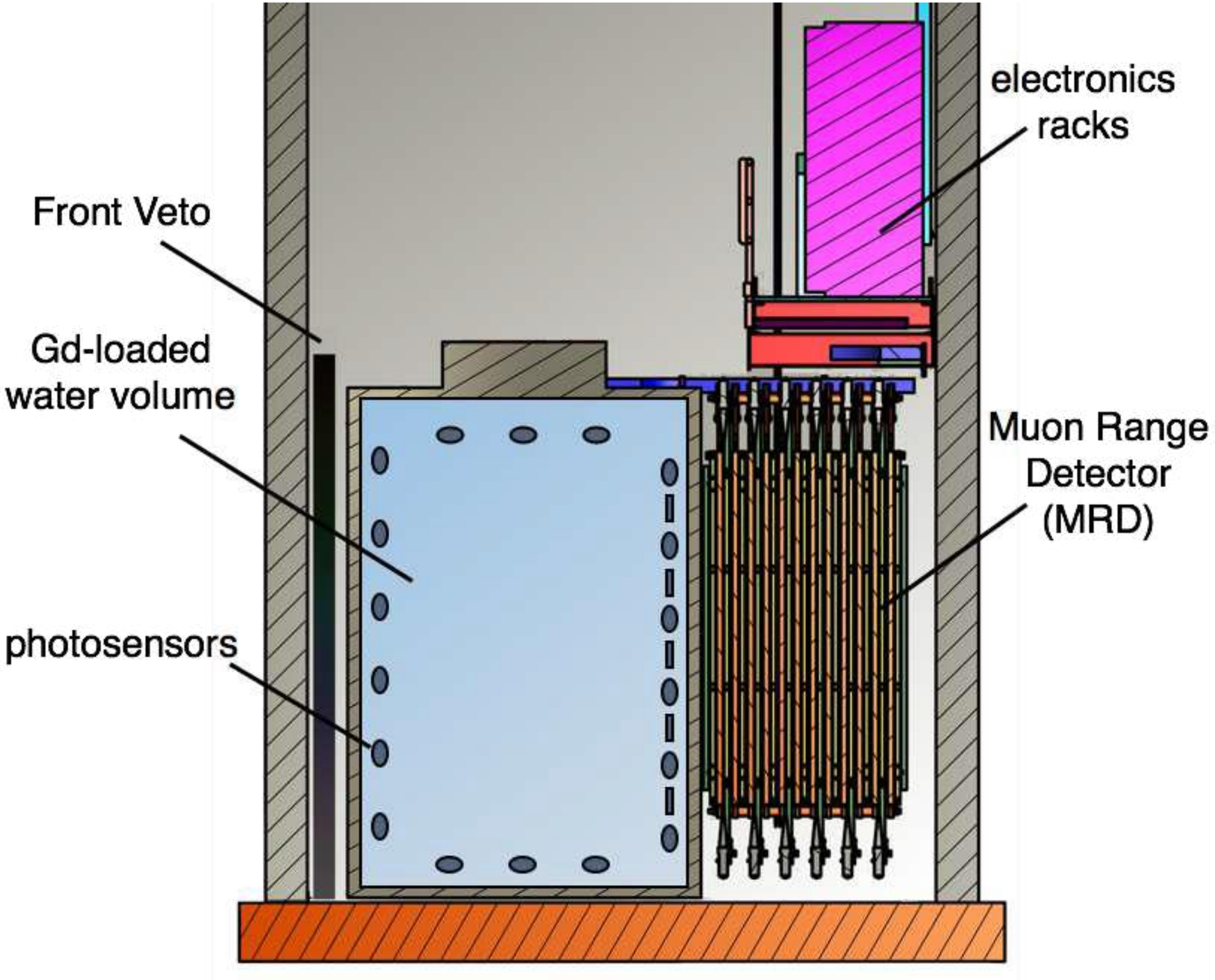
Experimental Hall

Experimental Hall

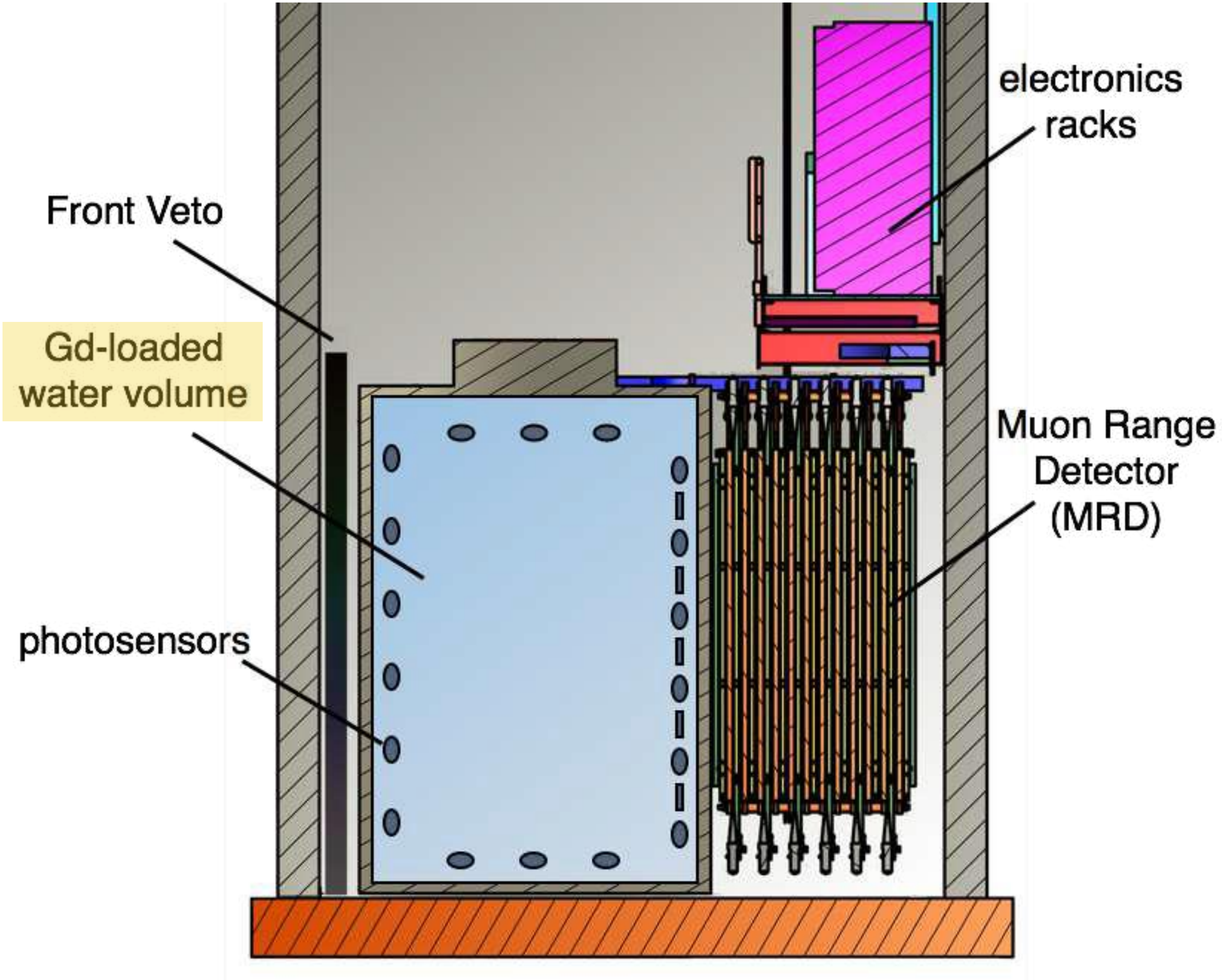
Experimental Hall

Experimental Hall

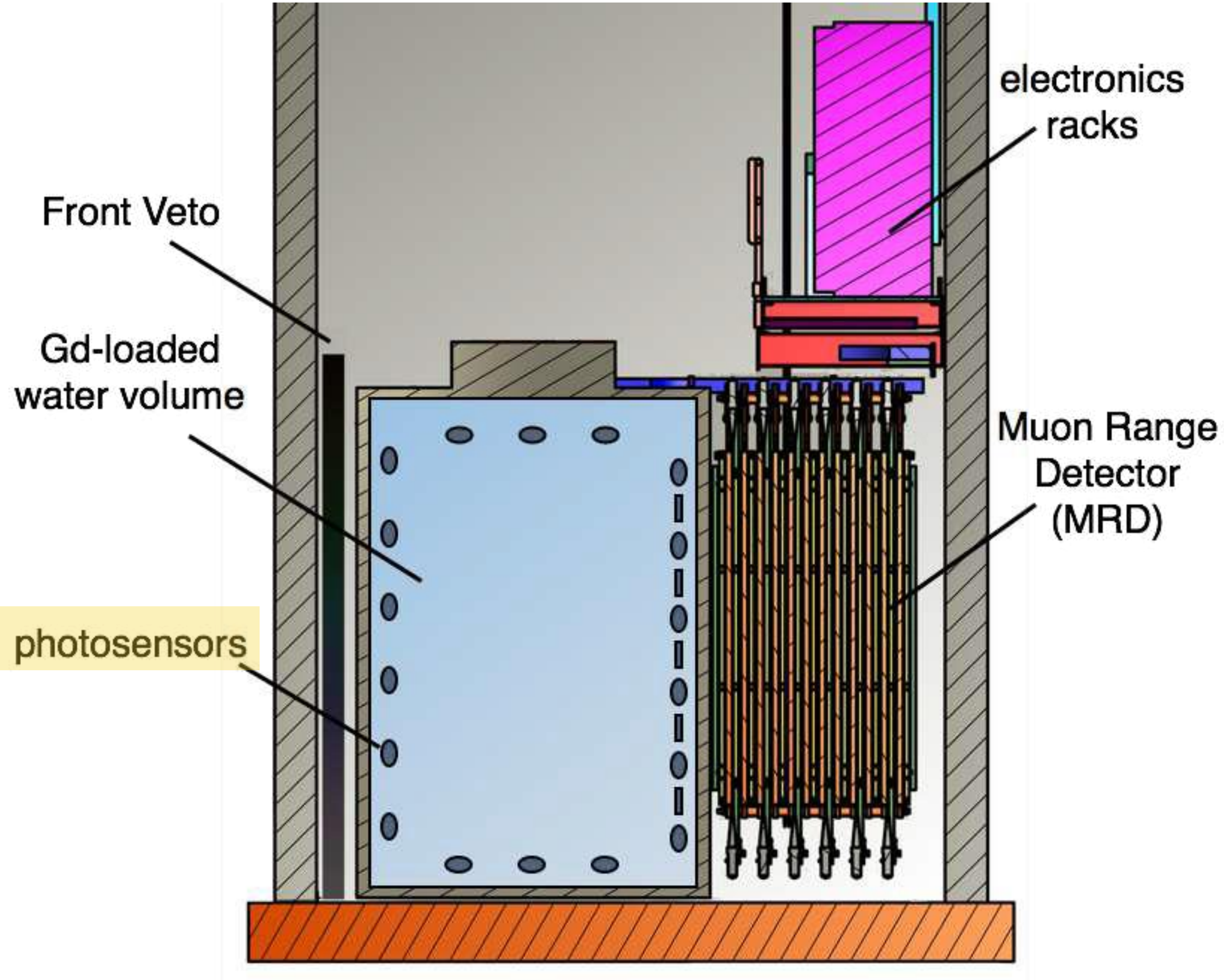
ANNIE Detector



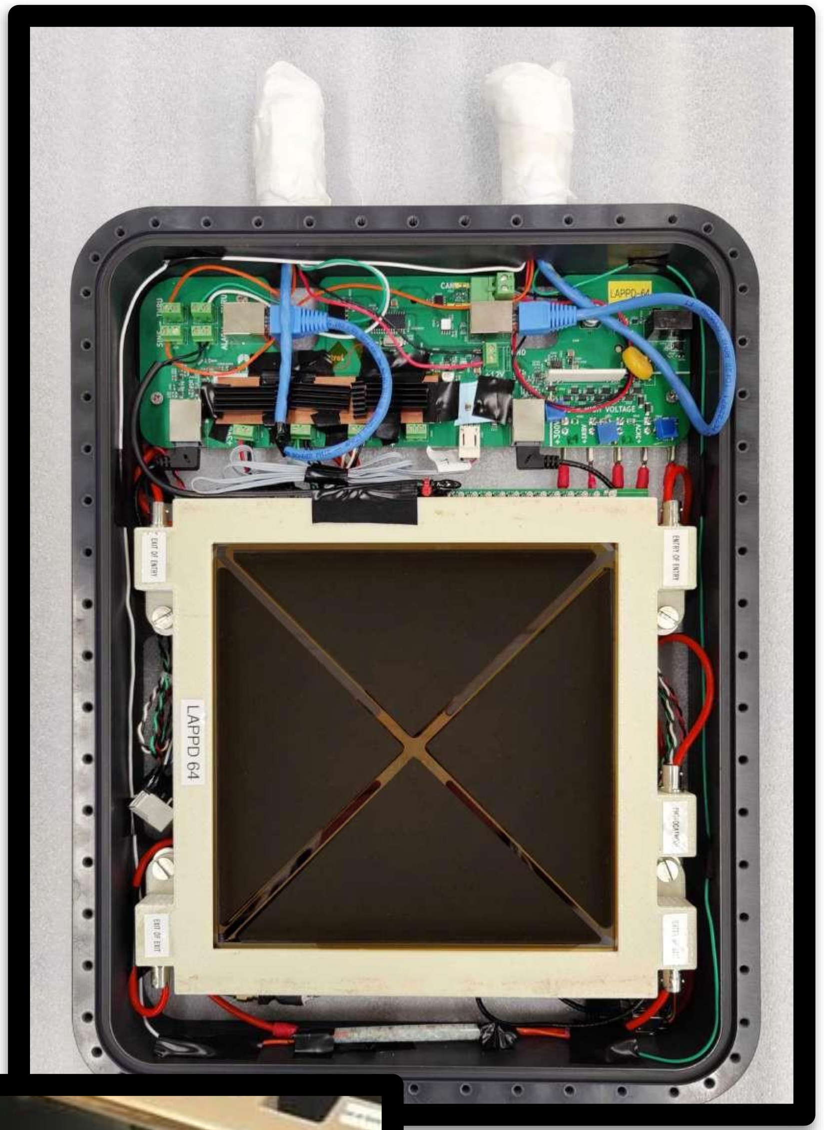
ANNIE Detector: Gd-Loaded Water Target



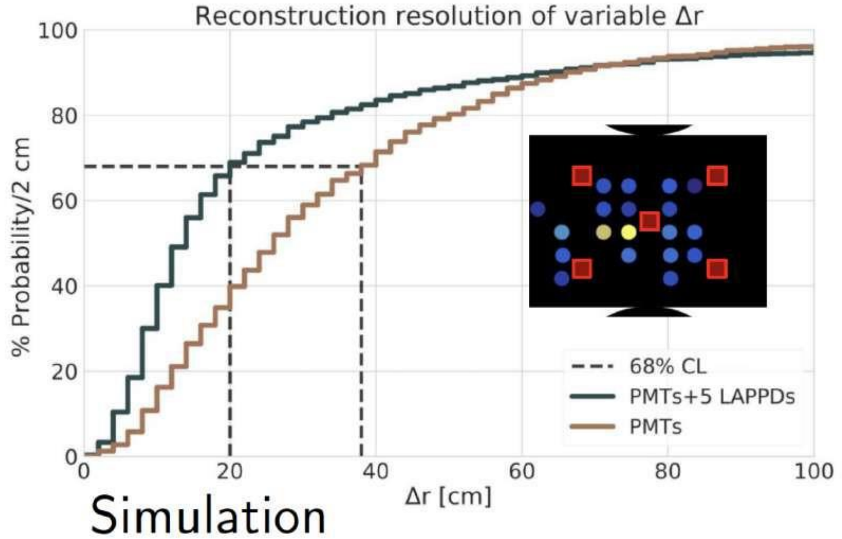
ANNIE Detector: Conventional PMTs

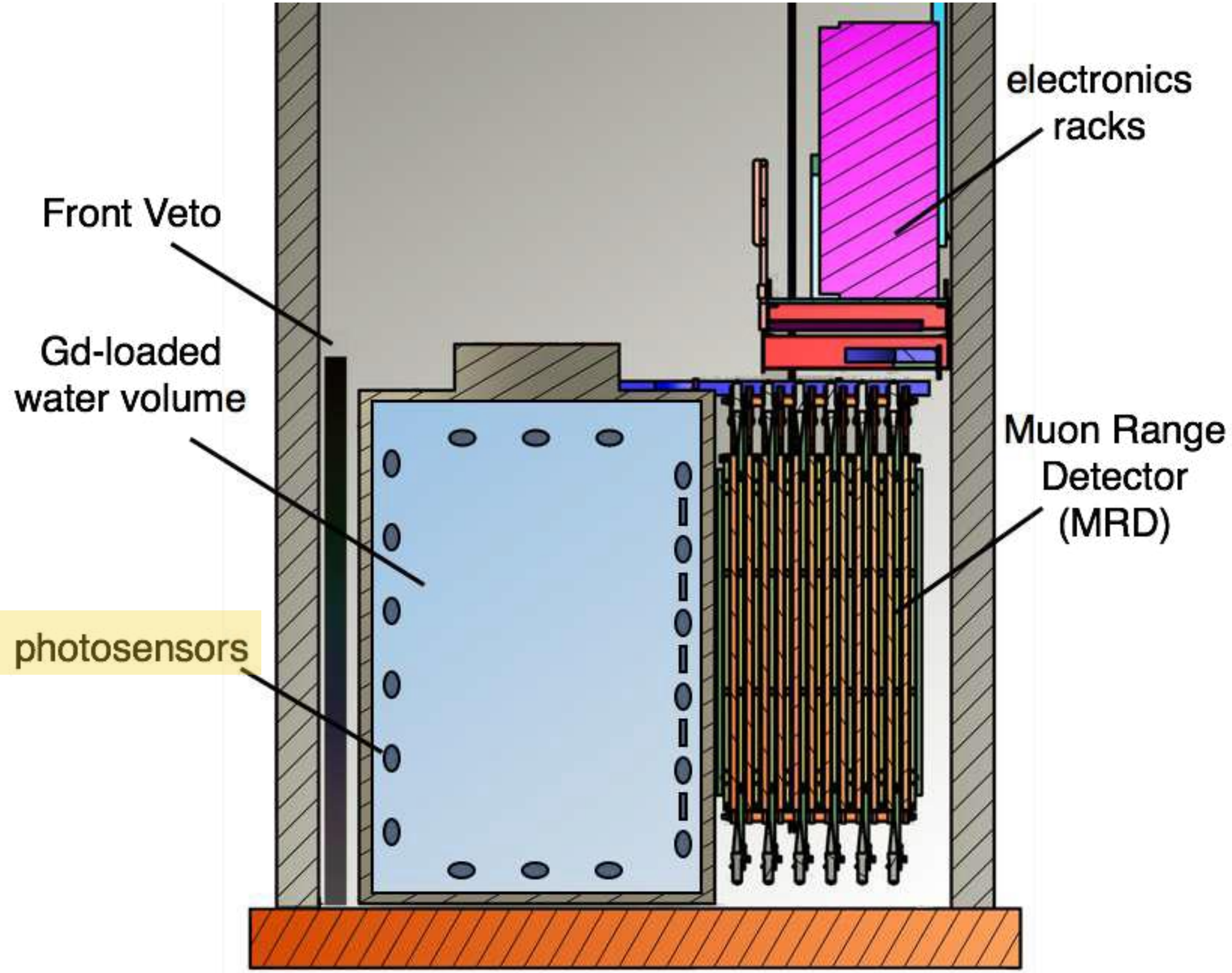


ANNIE Detector: LAPPDs

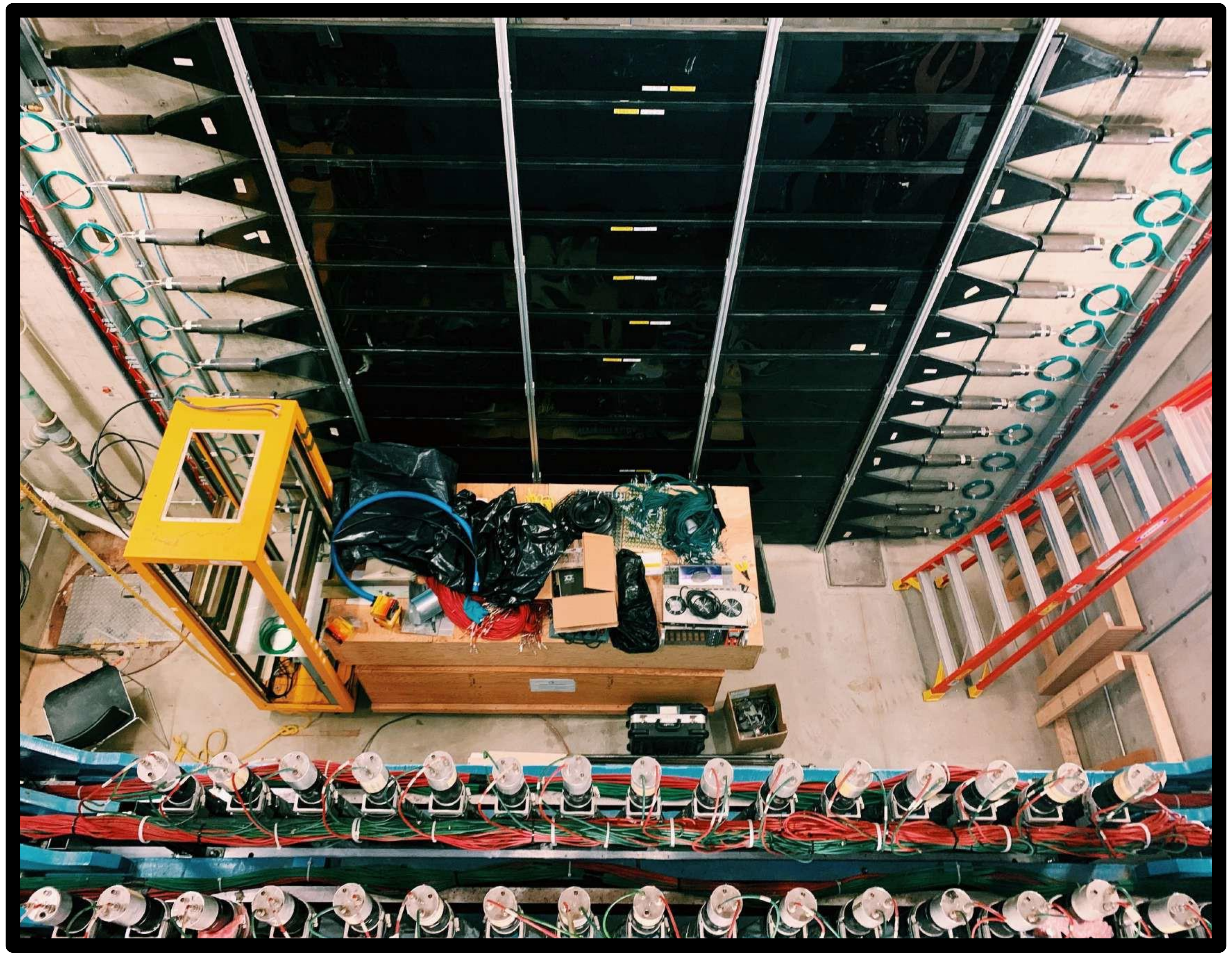


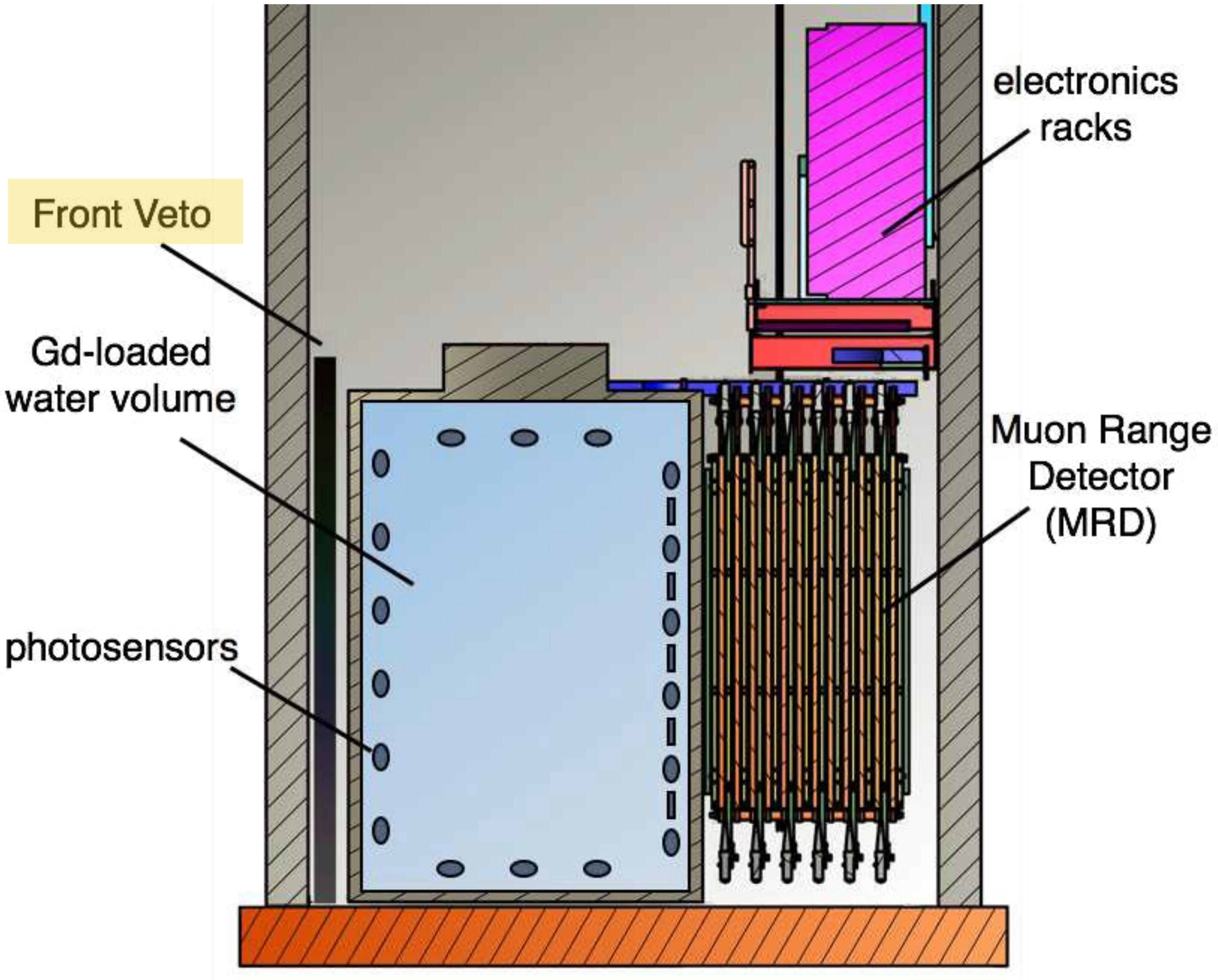
Enhanced reconstruction and vertexing



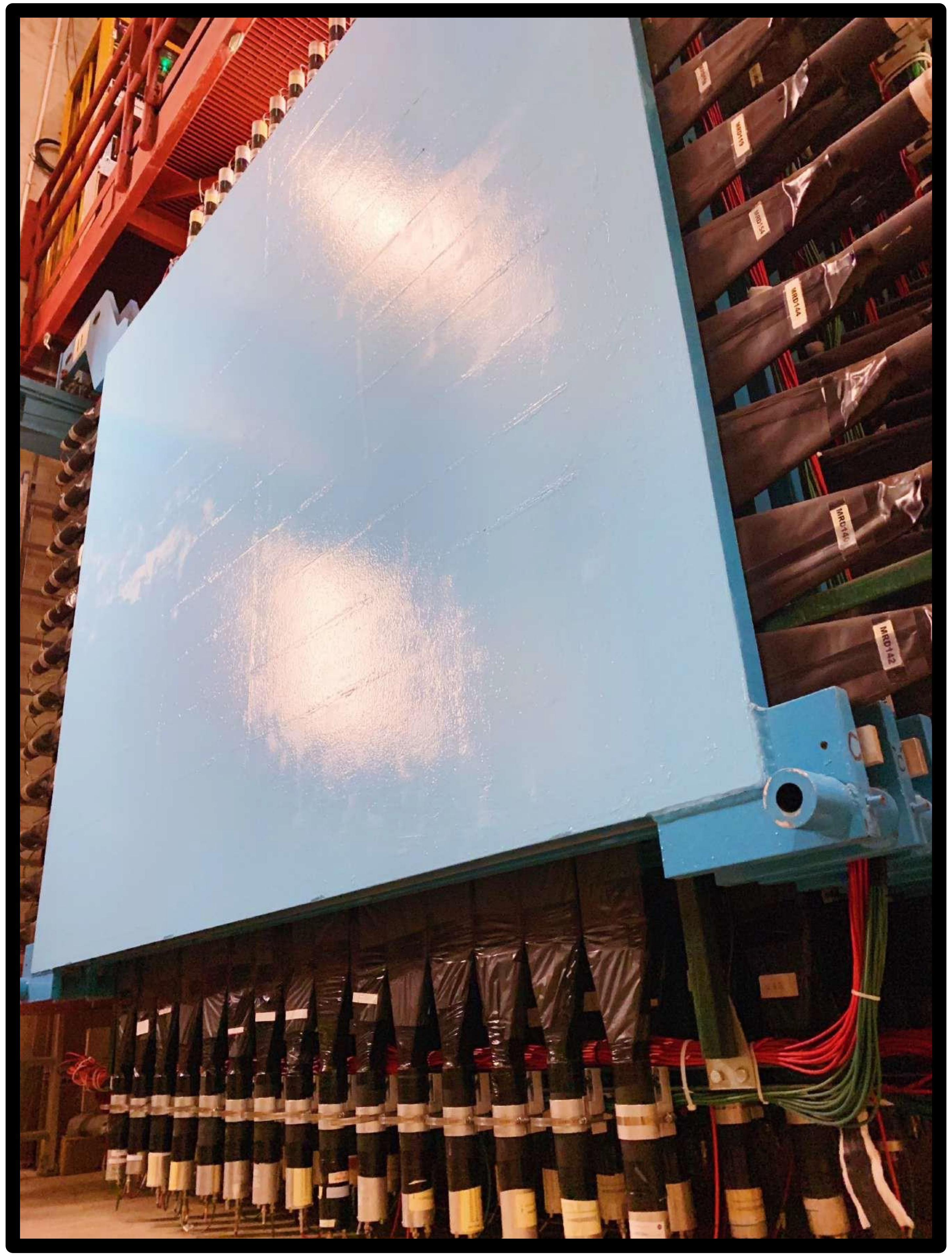


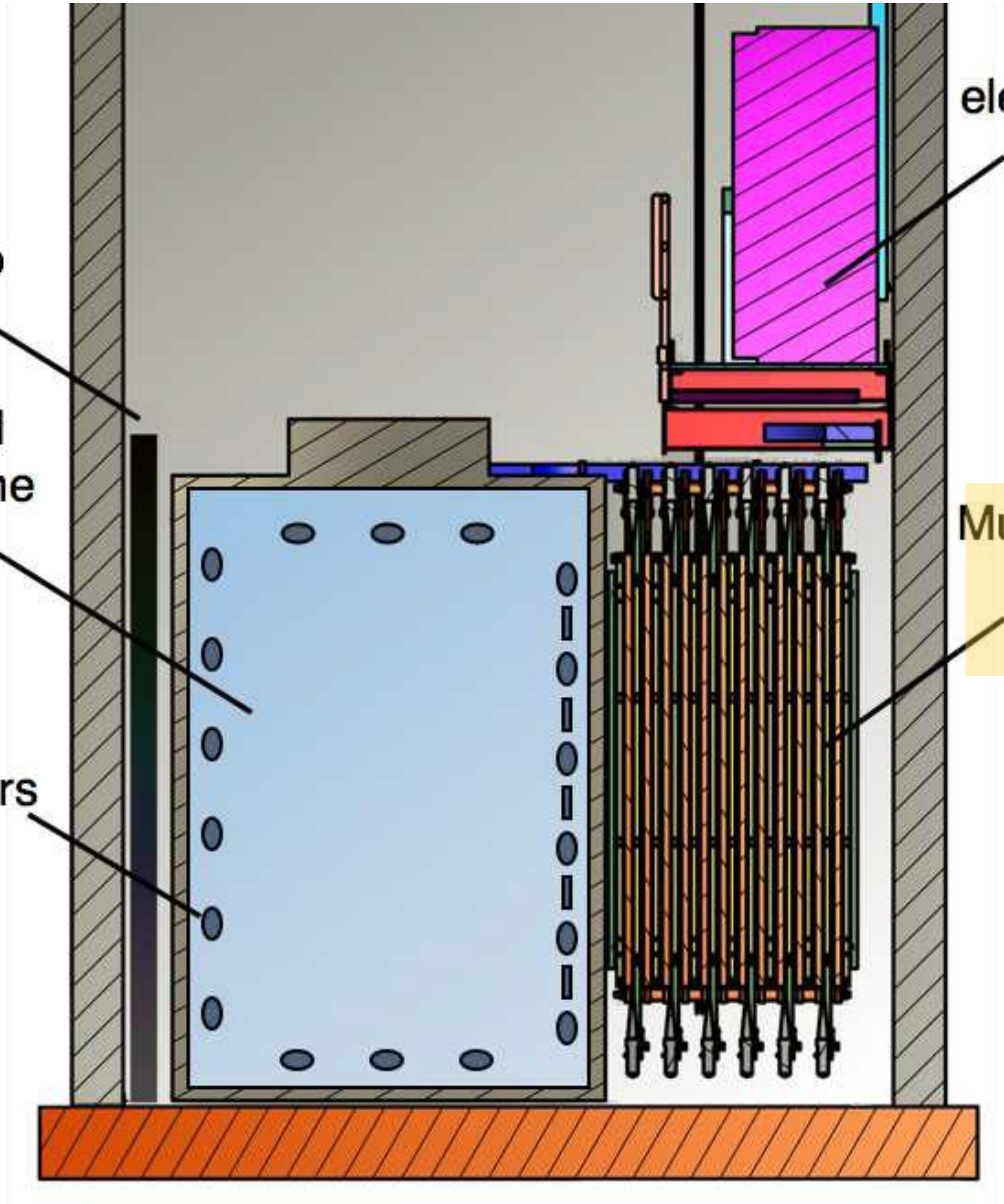
ANNIE Detector: Front Muon Veto



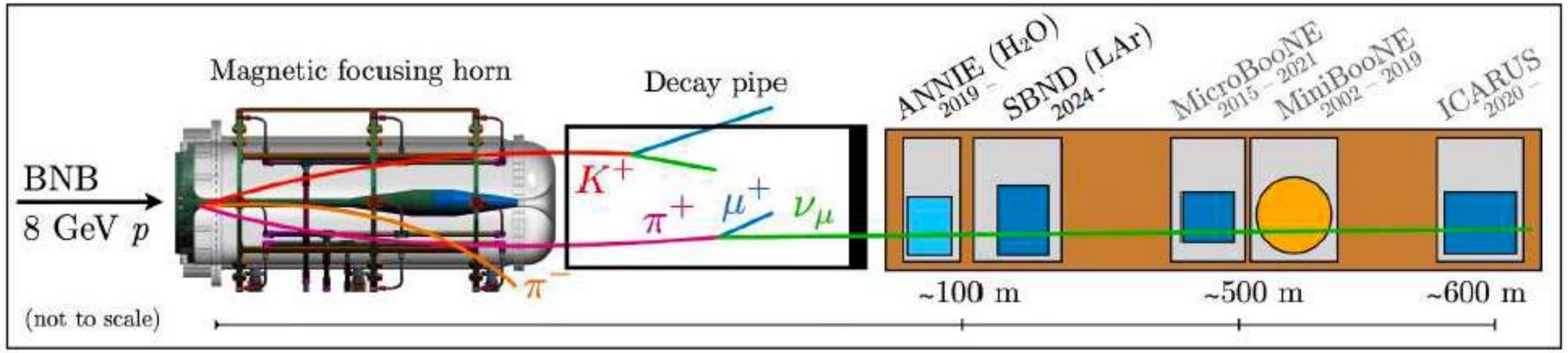


ANNIE Detector: Muon Range Detector





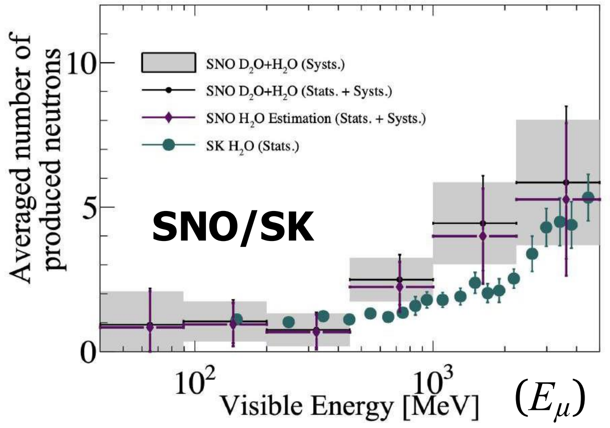
ANNIE Physics

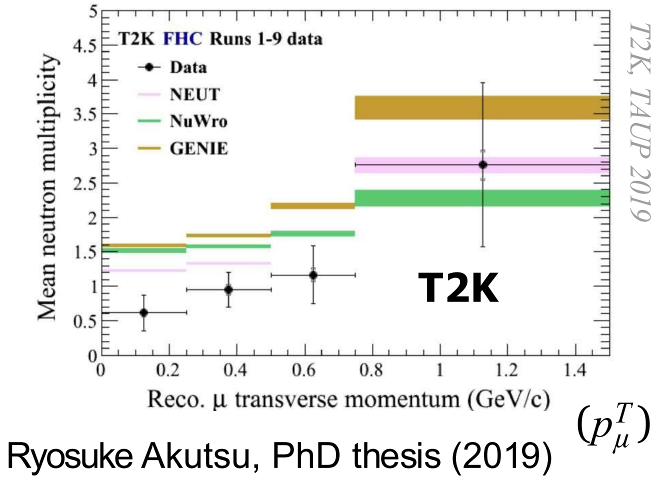


Close proximity to a high intensity GeV-scale neutrino beam makes ANNIE well-suited for high statistics cross-section program, primarily on O and H.

Primary physics goal: Neutron multiplicity and CC cross sections as a function of kinematic variables such as lepton momentum and direction

SNO, PRD 99 (2019) 11, 112007





Ryosuke Akutsu, PhD thesis (2019)

But ANNIE is capable of more:

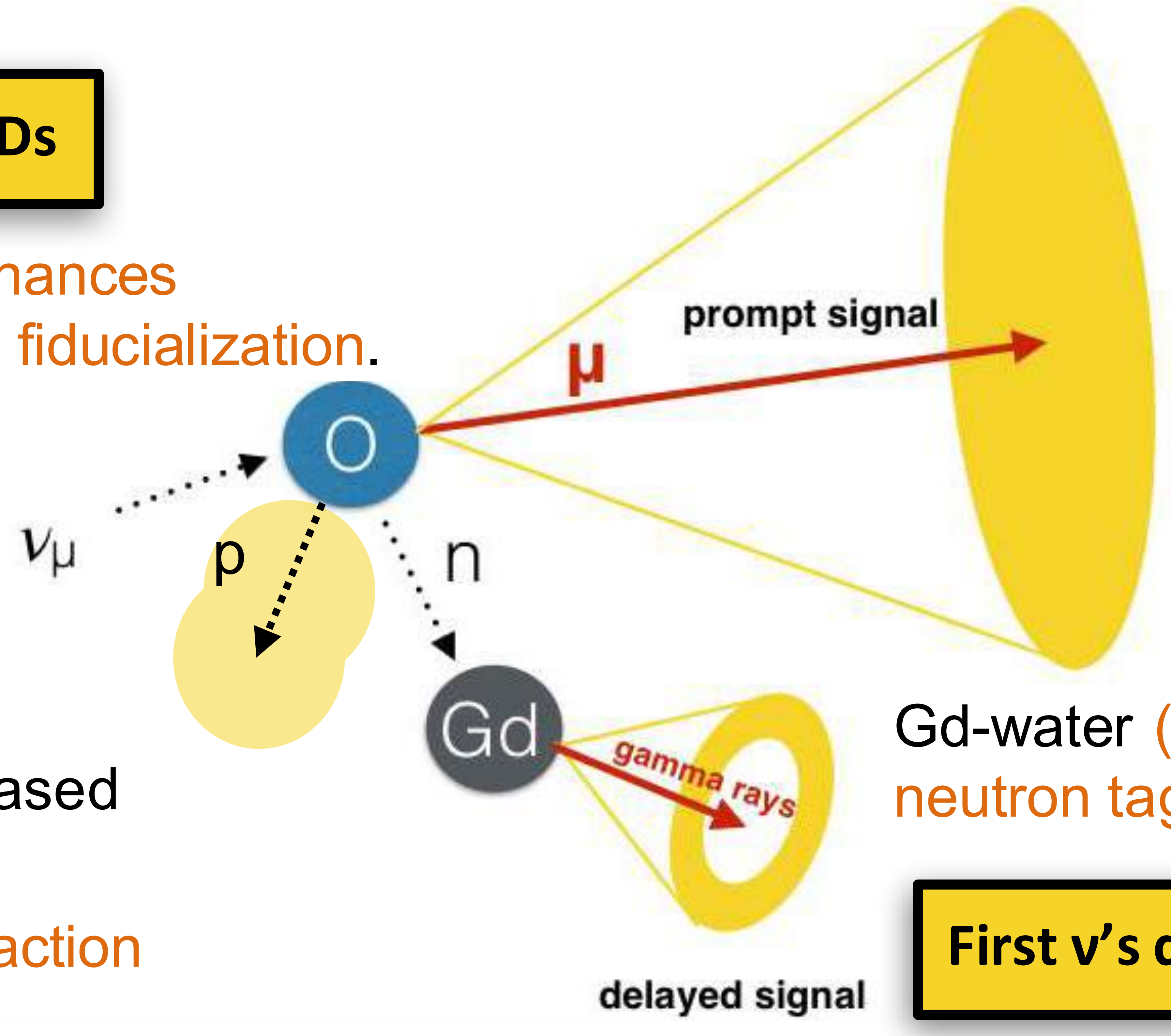
- Measuring correlated cross sections **on the same beam as LAr**
- **Sub-nanosecond timing** with respect to beam RF (new techniques/BSM)
- Neutral current measurements with gamma cascades and neutrons

Emerging Technologies

ANNIE is a flexible test-bed for next generation detector technologies (novel photosensors/fast-timing and novel detection media)

First ν's detected with LAPPDs

Adding LAPPDs to PMTs enhances interaction vertex resolution, fiducialization.



First ν's detected in WbLS

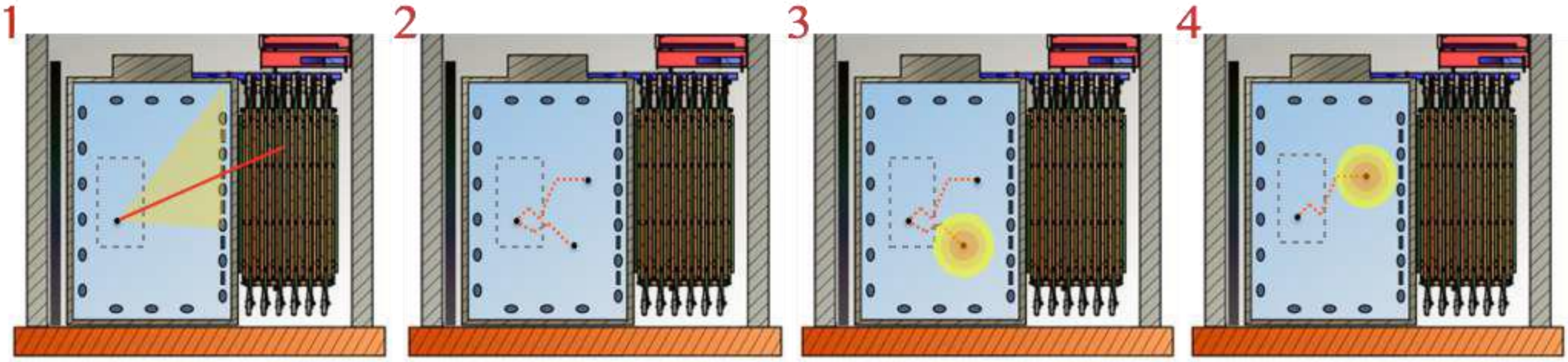
Deployable volume of water-based liquid scintillator (WbLS)

(Calorimetry, elements of interaction below Cherenkov threshold)

Gd-water (High efficiency neutron tagging)

First ν's detected in Gd-water

A Schematic of a Typical Event



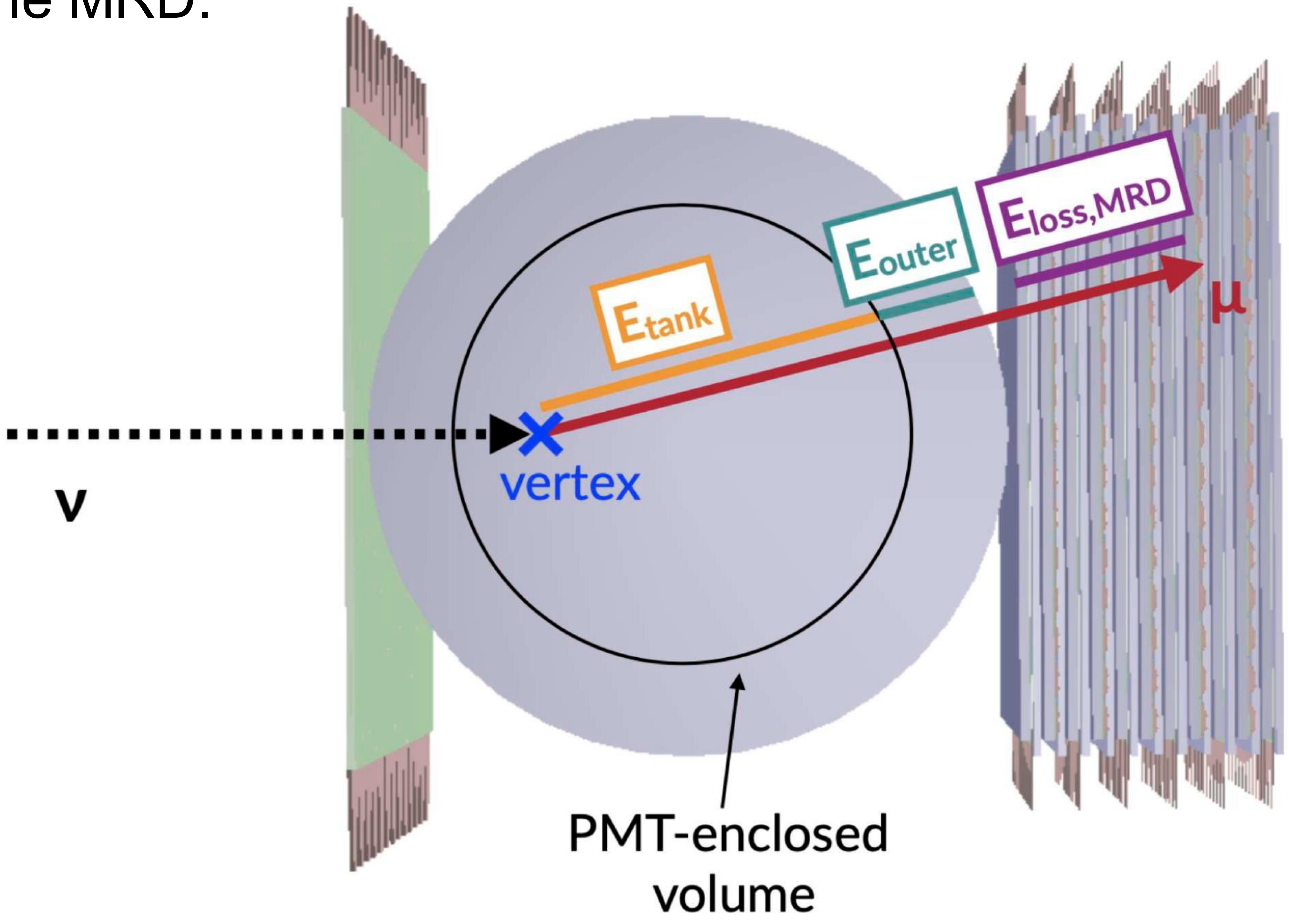
1. CC interaction in the fiducial volume produces a muon, reconstructed in the water volume and MRD
2. Neutrons scatter and thermalize

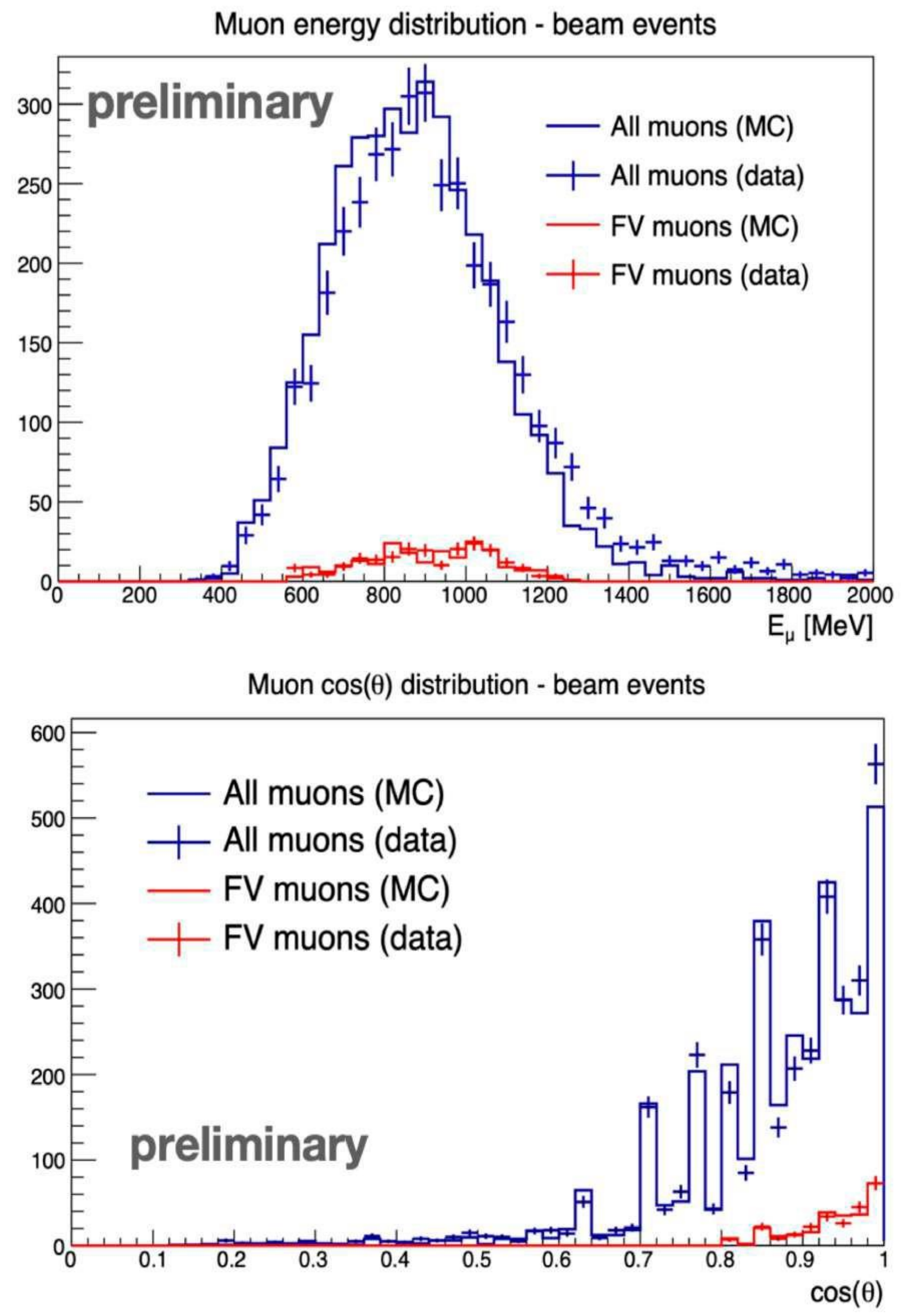
3.- 4. Thermalized neutrons are captured on the Gd producing flashes of light

Reconstruction in ANNIE

ANNIE leverages multiple detector subsystems to reconstruct muon angle and energy, using both Cherenkov (scintillation) light in the water volume and the MRD.

- MRD requirement restricts μ momentum and angular coverage
- $0.4 \lesssim E_\mu \lesssim 1.2$ GeV, $\theta_\mu \gtrsim 60$
- Tank-only ring reconstruction (under development) enables wide coverage for CC kinematics



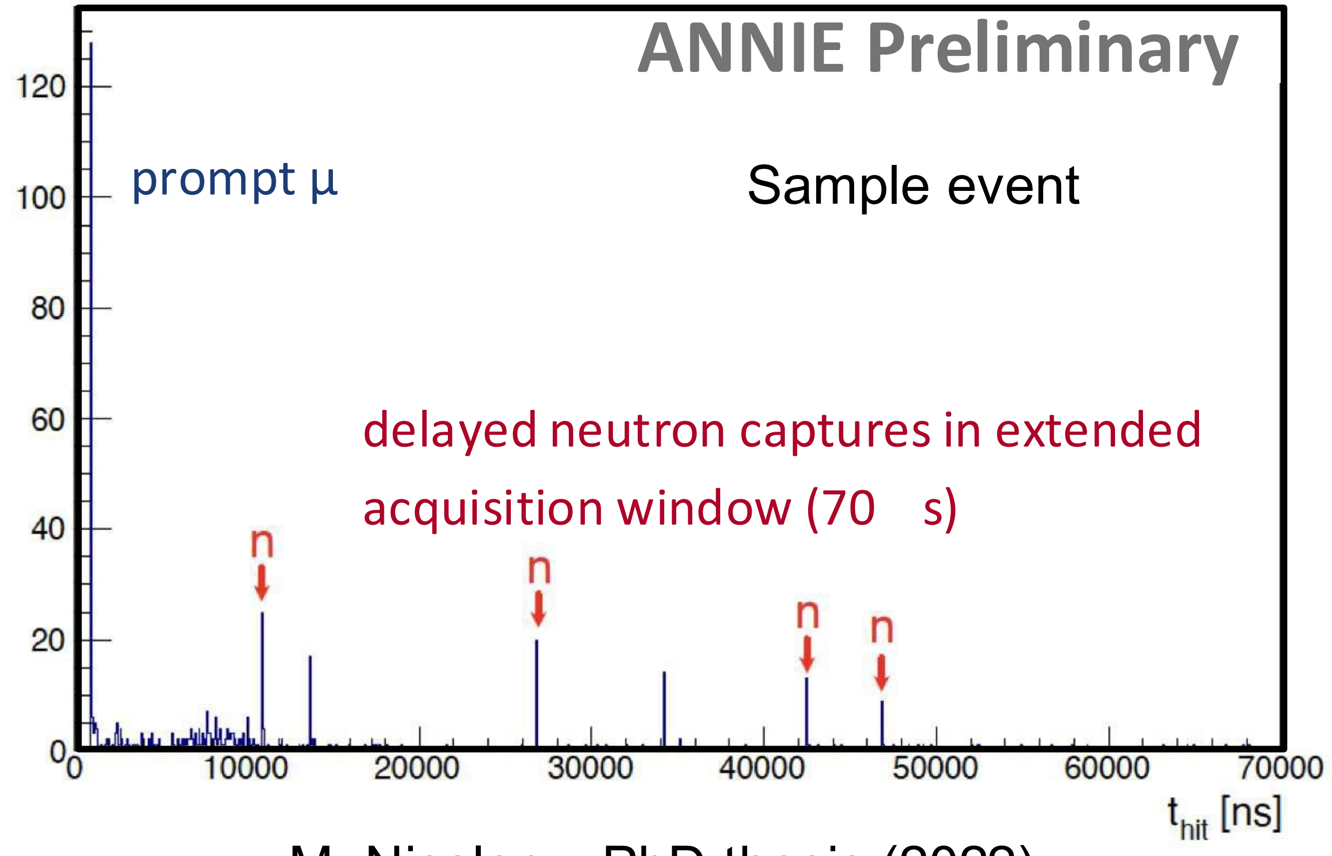


Significant progress in achieving MC-data agreement

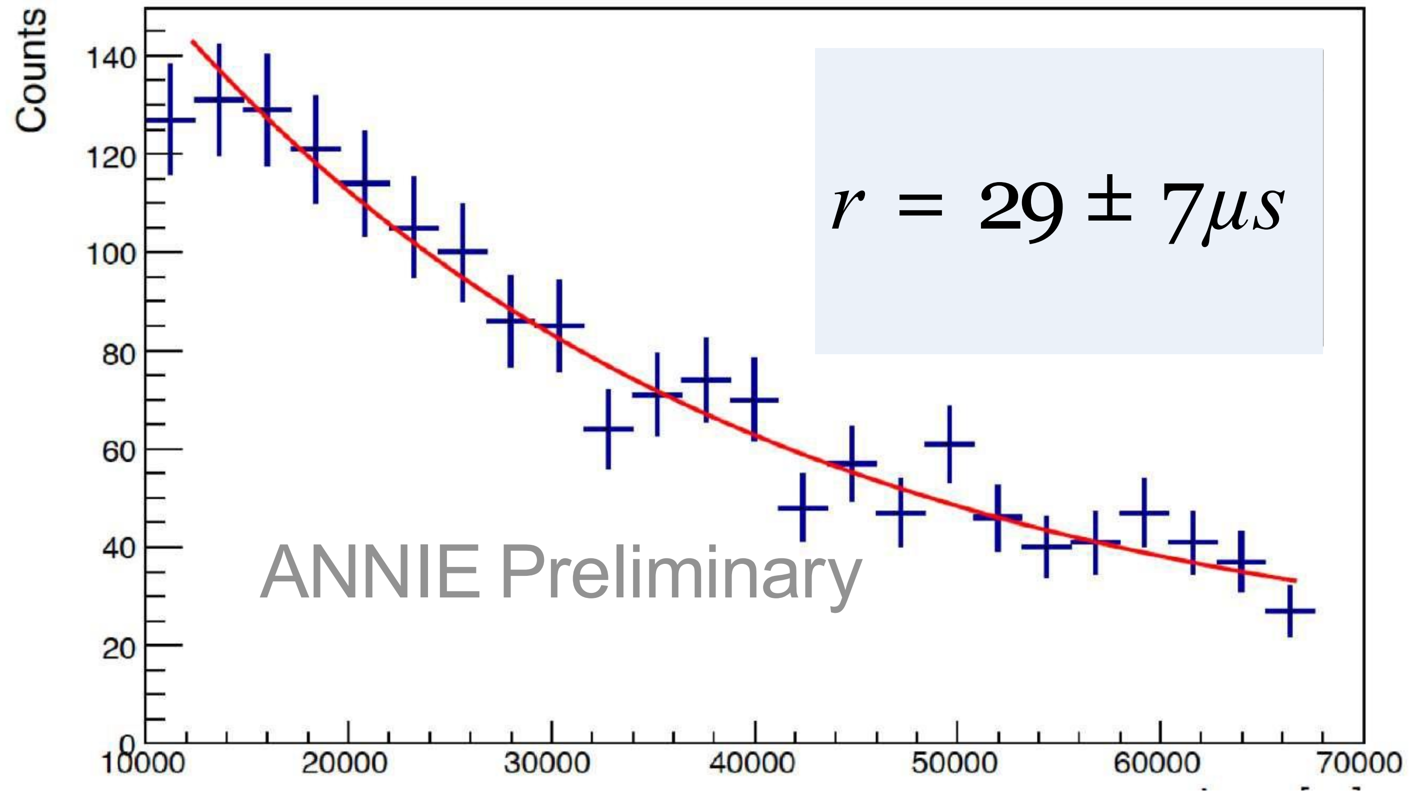
Thesis: M. Nieslony

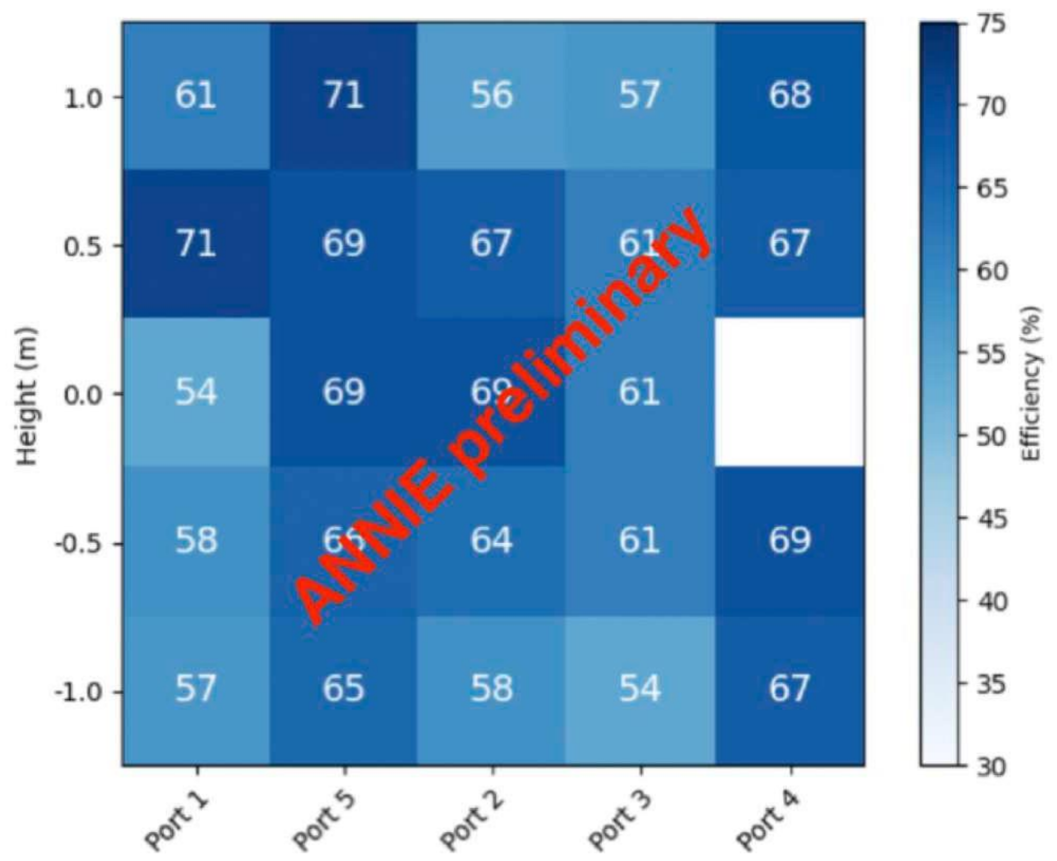
Neutron Detection

- Tank PMTs used to detect neutrons
- Neutron capture time profile from beam data agrees well with prediction for nominal 0.1% Gd concentration.
- Position dependent neutron capture efficiency has been measured to be consistent with expectations: ~55-70%.



M. Nieslony, PhD thesis (2022)





5 calibration ports

First ν-induced neutrons detected in Gd-water

LAPPDs Then and Now

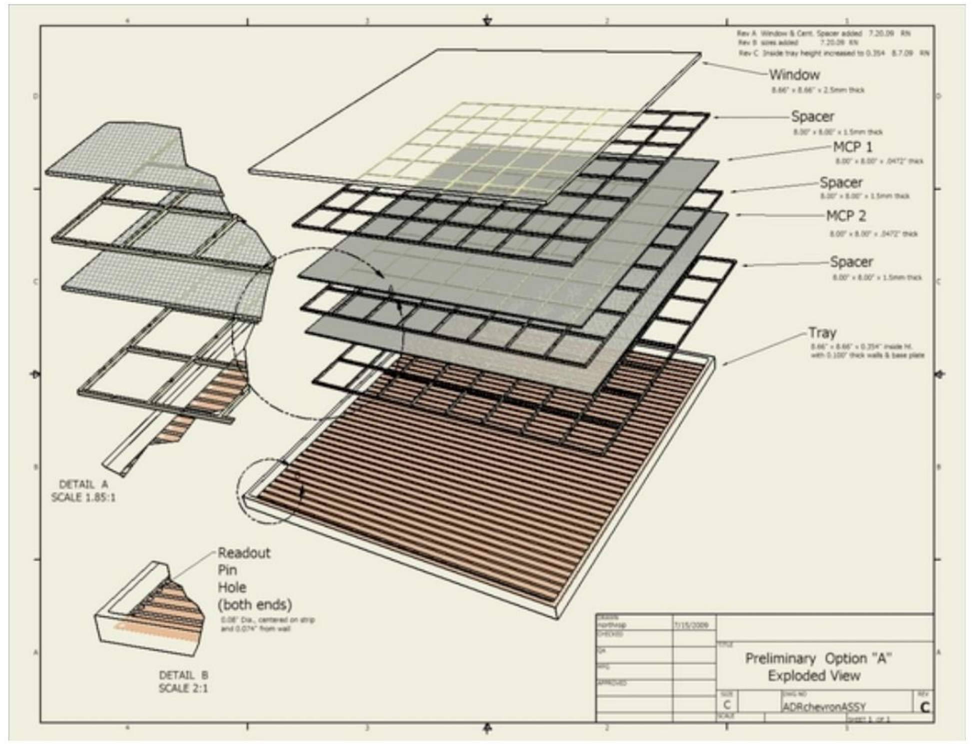
RICH2010

LAPPD Collaboration: Large Area Picosecond Photodetectors

LAPPD Collaboration:
Pushing the Limits of the Timing Frontier

Microchannel Plates are an existing photo-multiplier technology known for:

- Picosecond-level time resolution
- Micron-level spatial resolution
- Excellent photon-counting capabilities
- Being expensive



What if we could exploit advances in material science and electronics to develop new methods for fabricating:

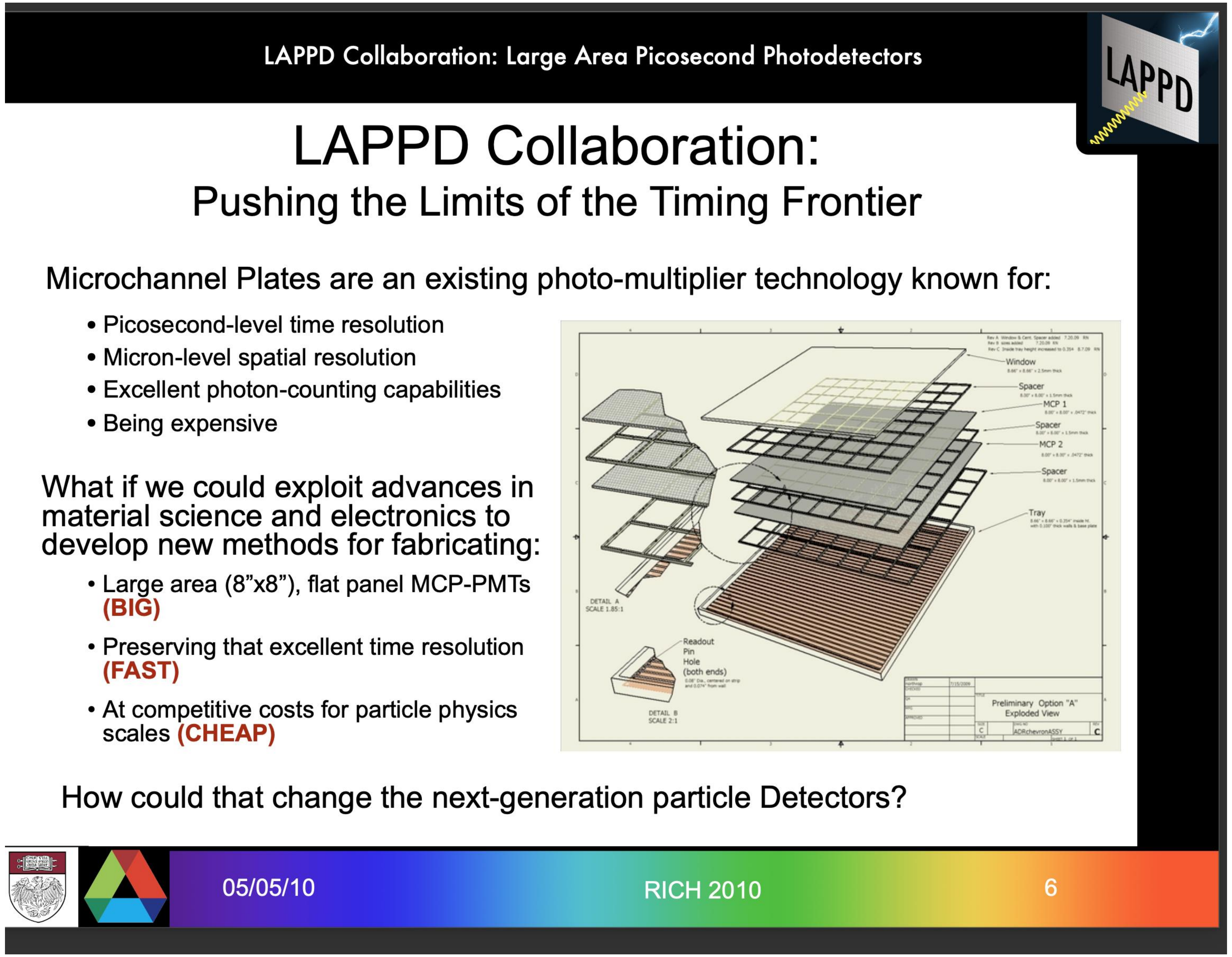
- Large area (8”x8”), flat panel MCP-PMTs **(BIG)**
- Preserving that excellent time resolution **(FAST)**
- At competitive costs for particle physics scales **(CHEAP)**

How could that change the next-generation particle Detectors?

05/05/10 RICH 2010 6

LAPPDs Then and Now

RICH2010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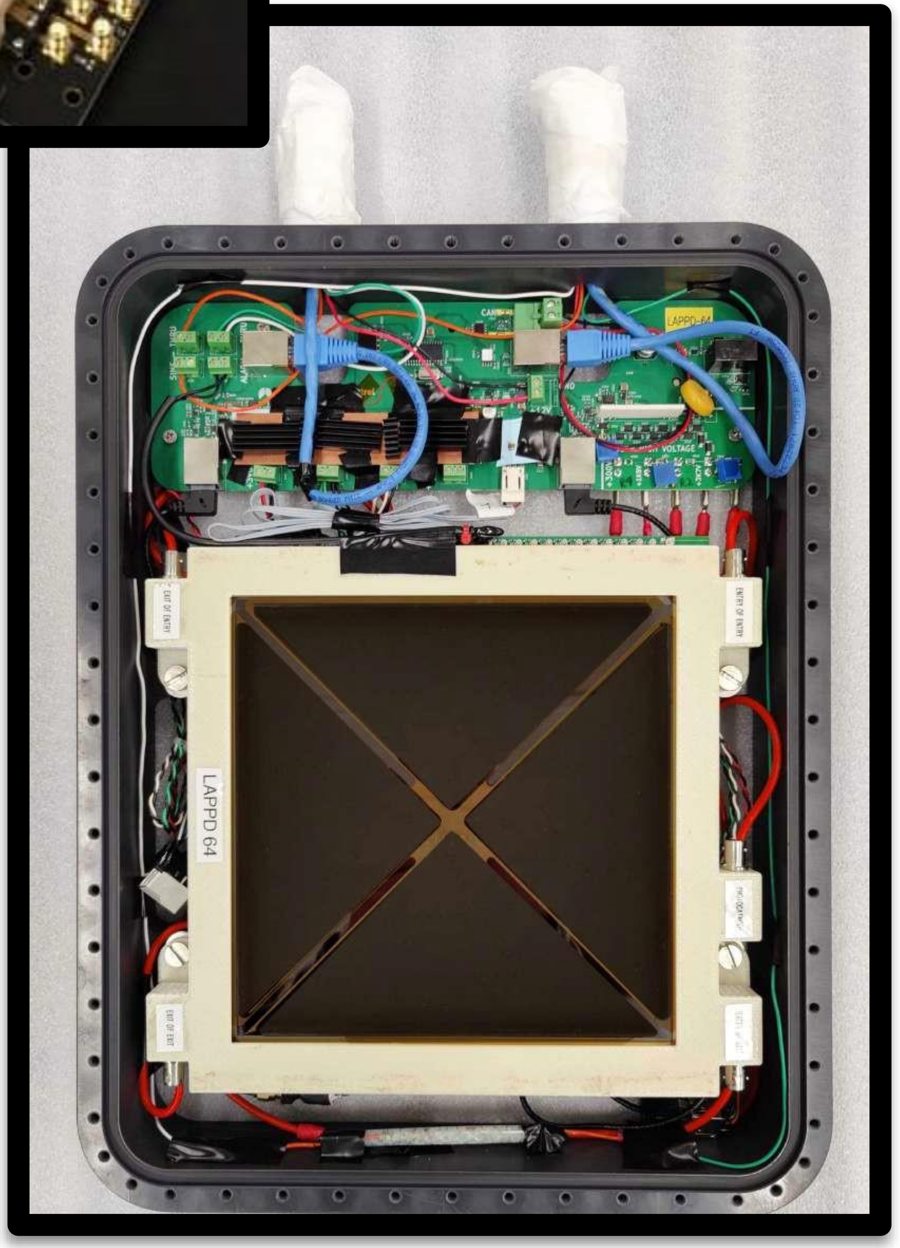
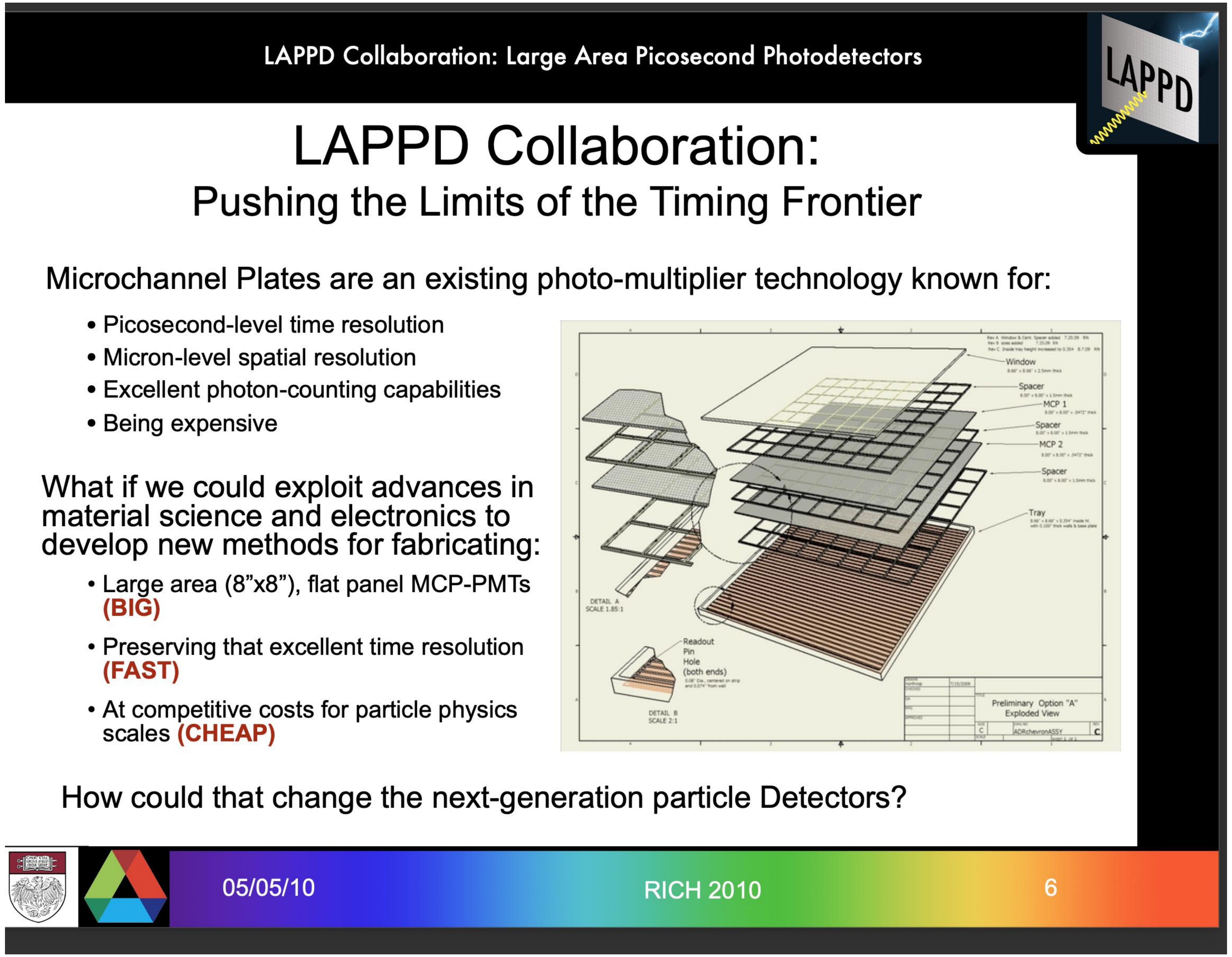
RICH2025 (ANNIE)



LAPPDs Then and Now

RICH2010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LAPPD

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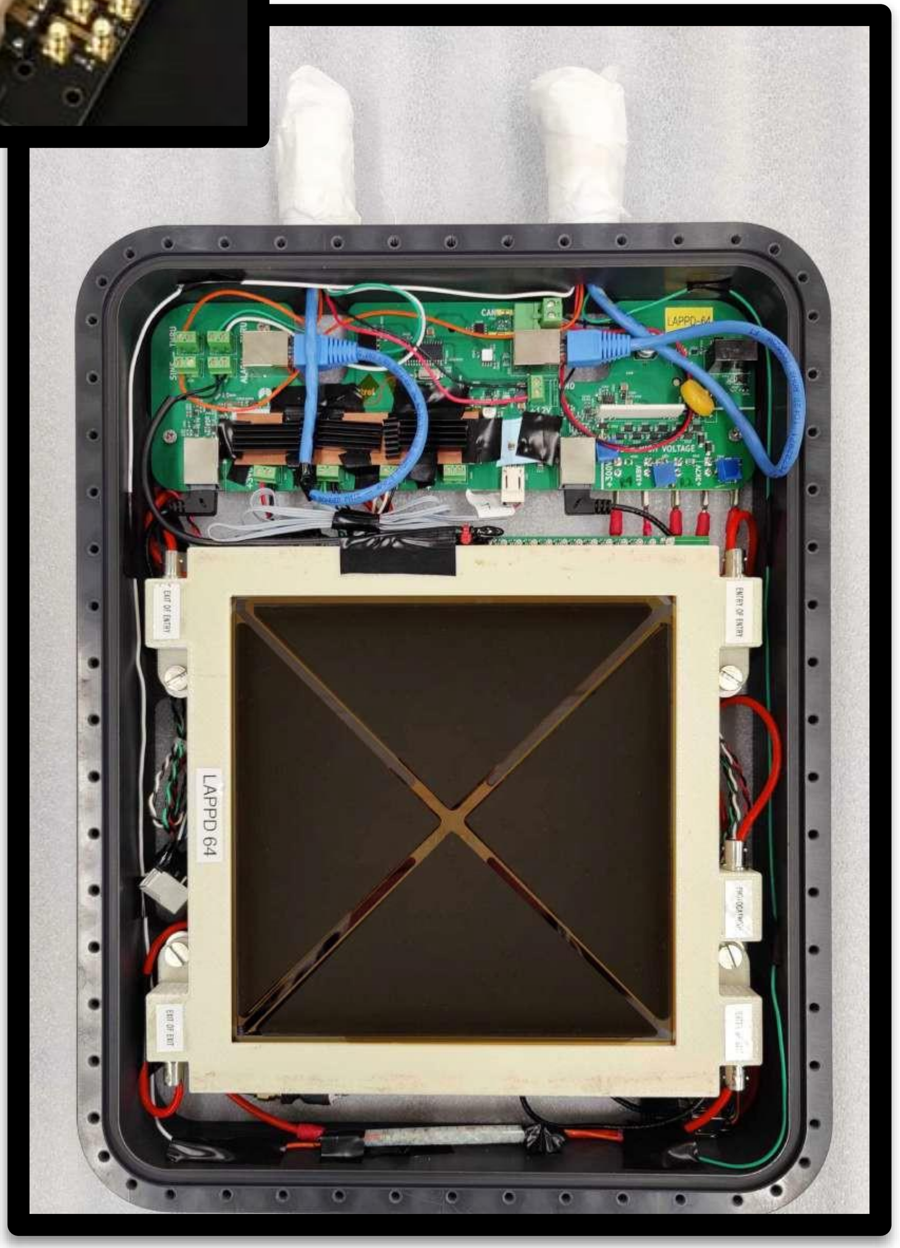
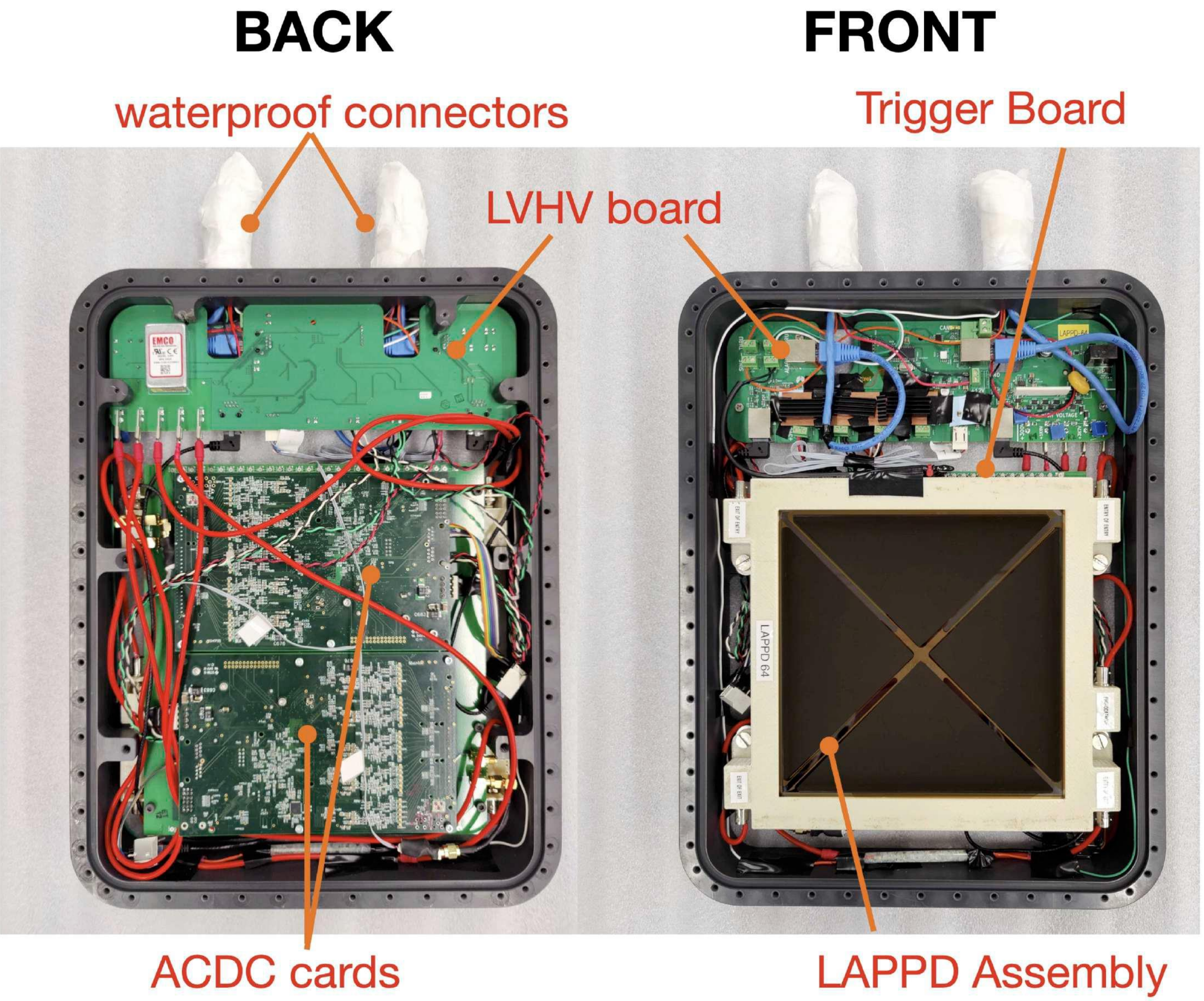
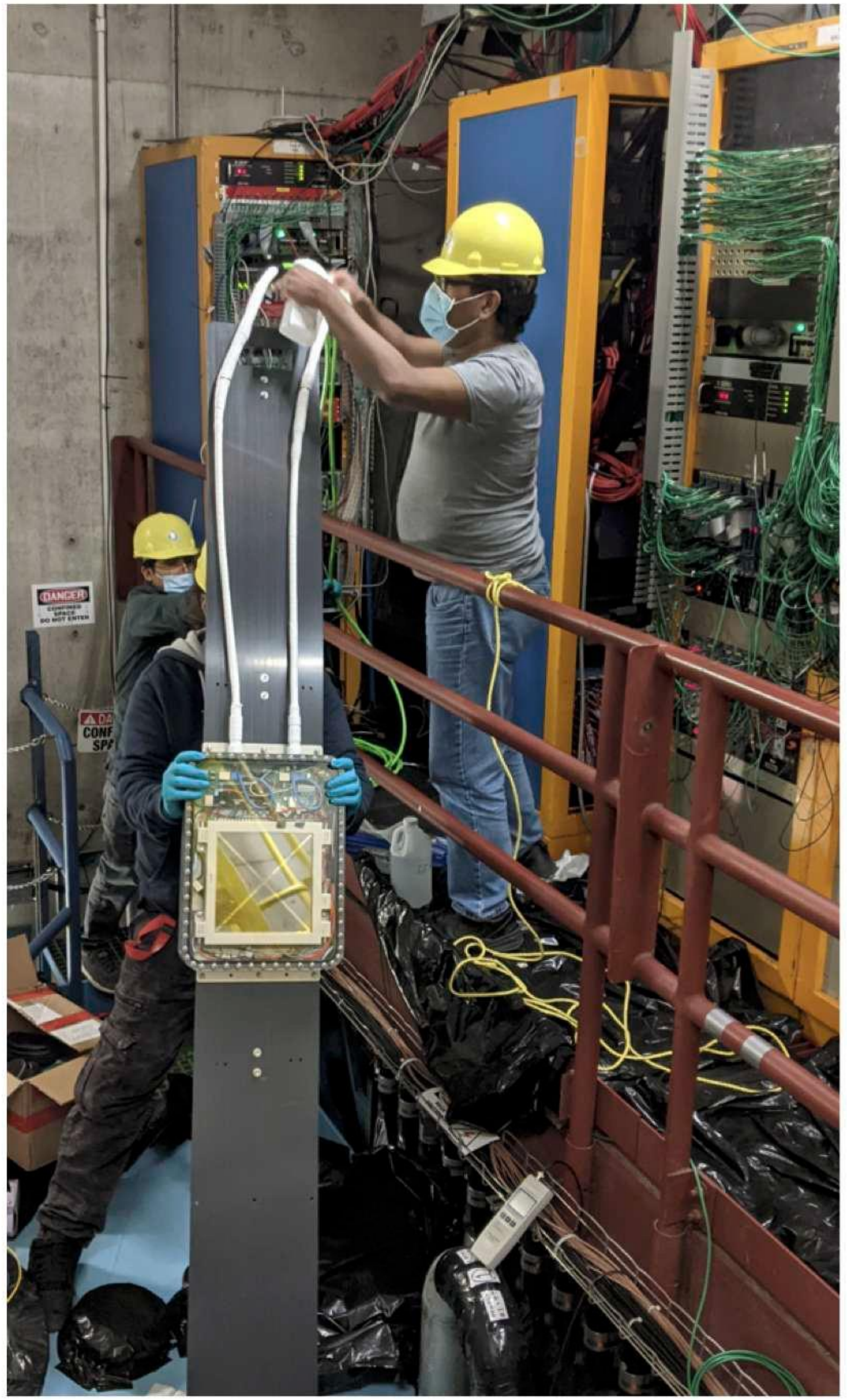


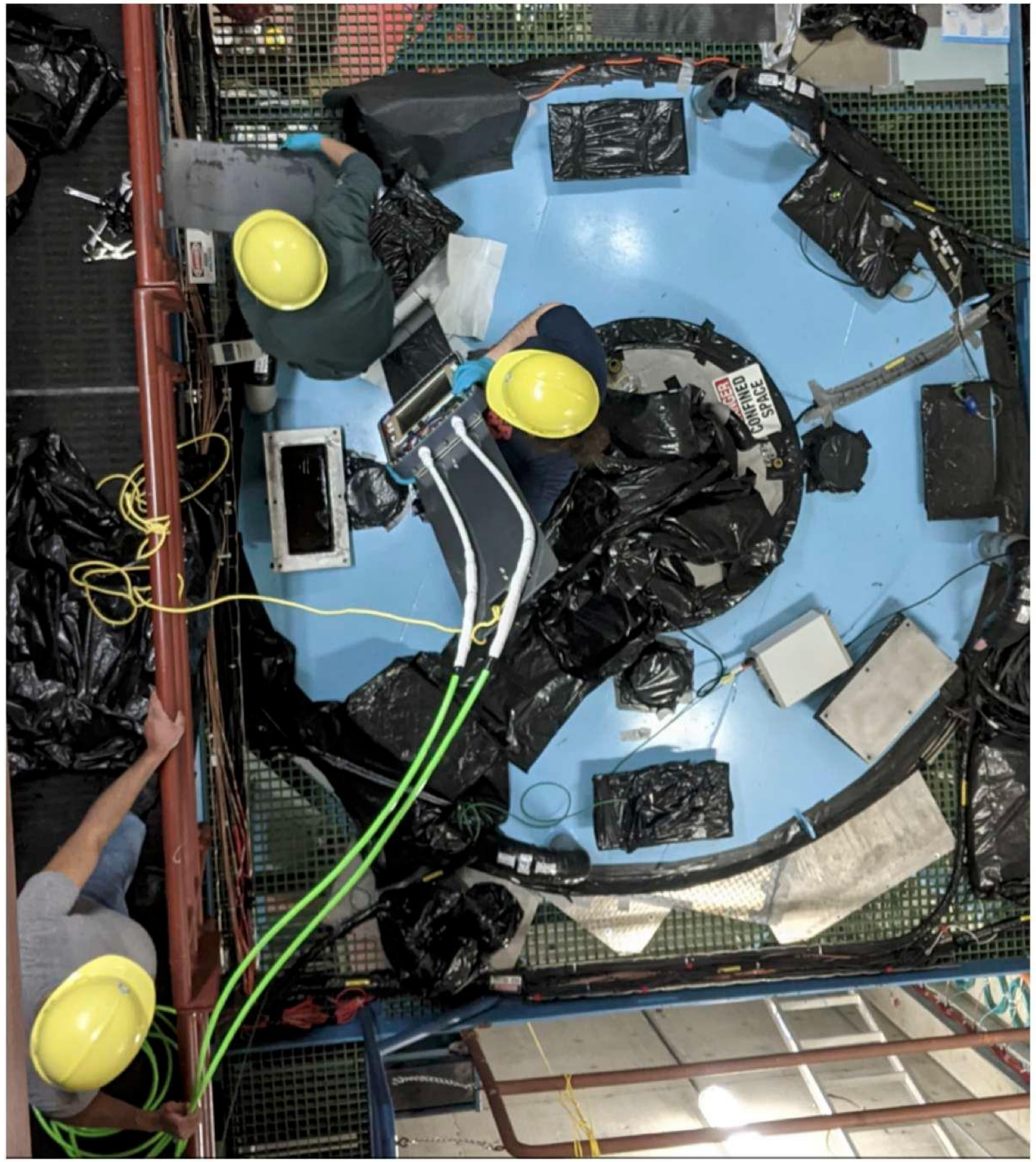
Brief technical history of the LAPPD project: https://arxiv.org/abs/1603.01843

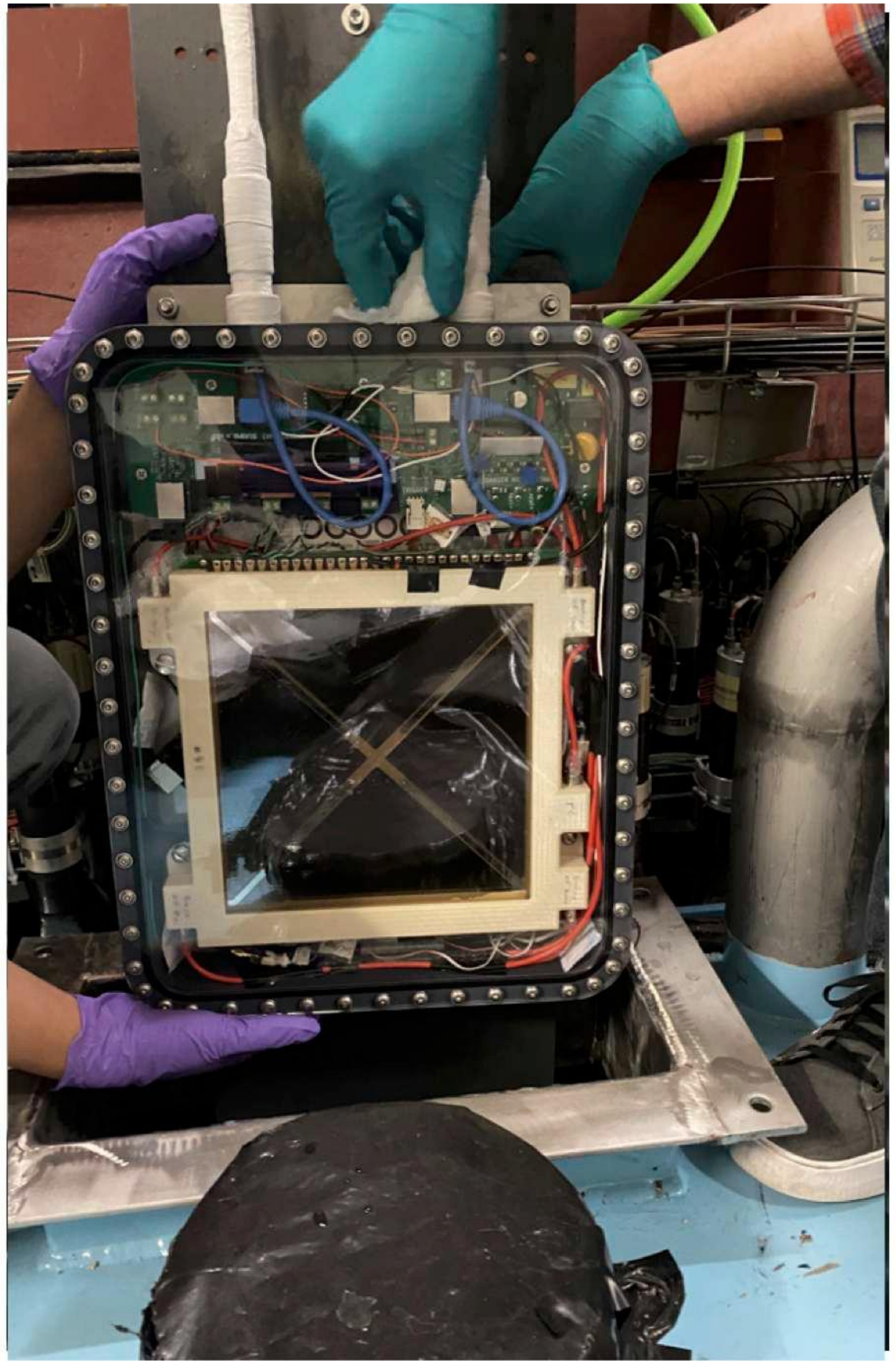
Be a PAL (Packaged ANNIE LAPPD)



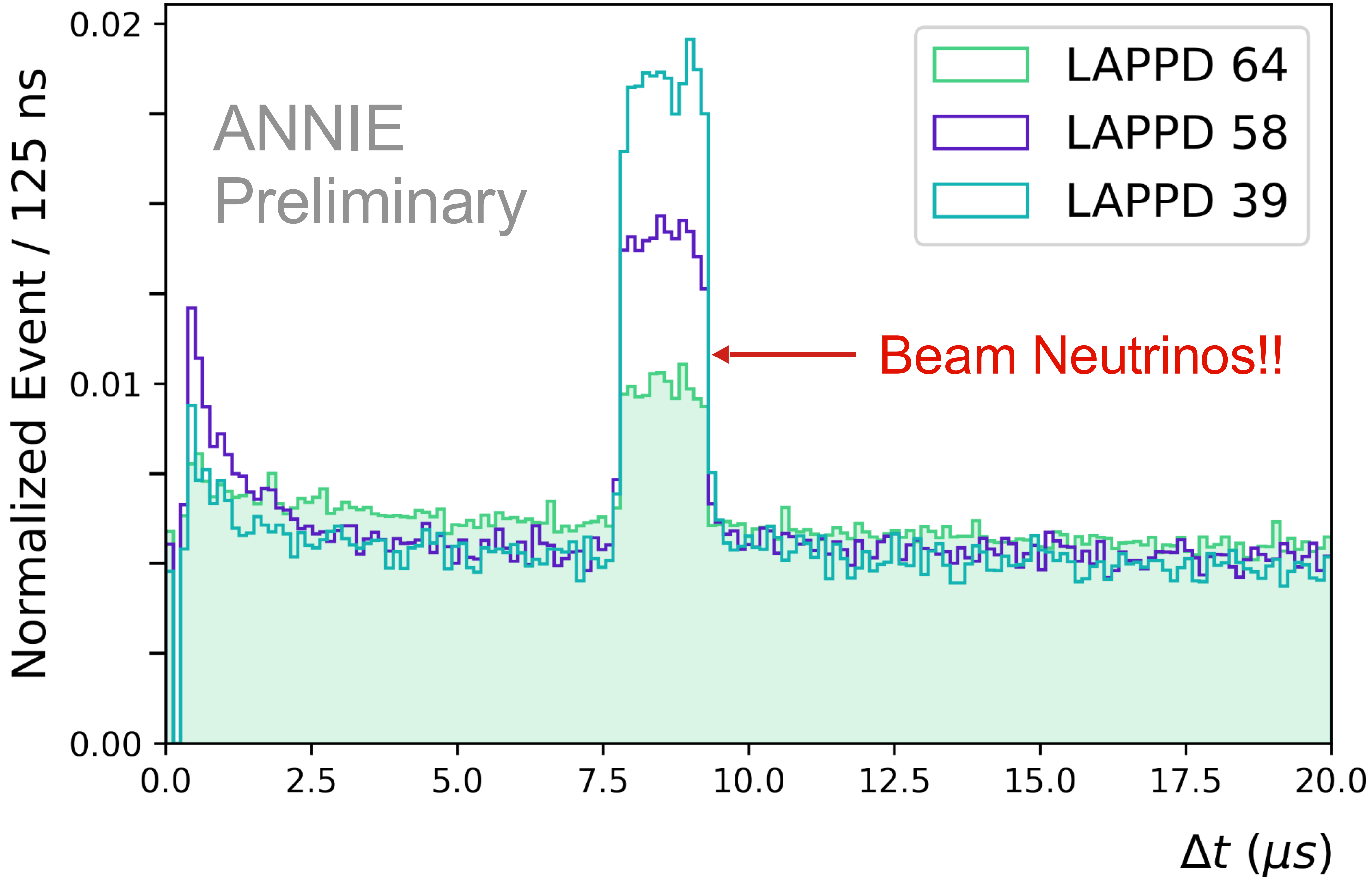
- Waterproof housing
- Digitization and high voltage produced close to the detector
- Triggering and communications
- Environmental monitoring and slow controls

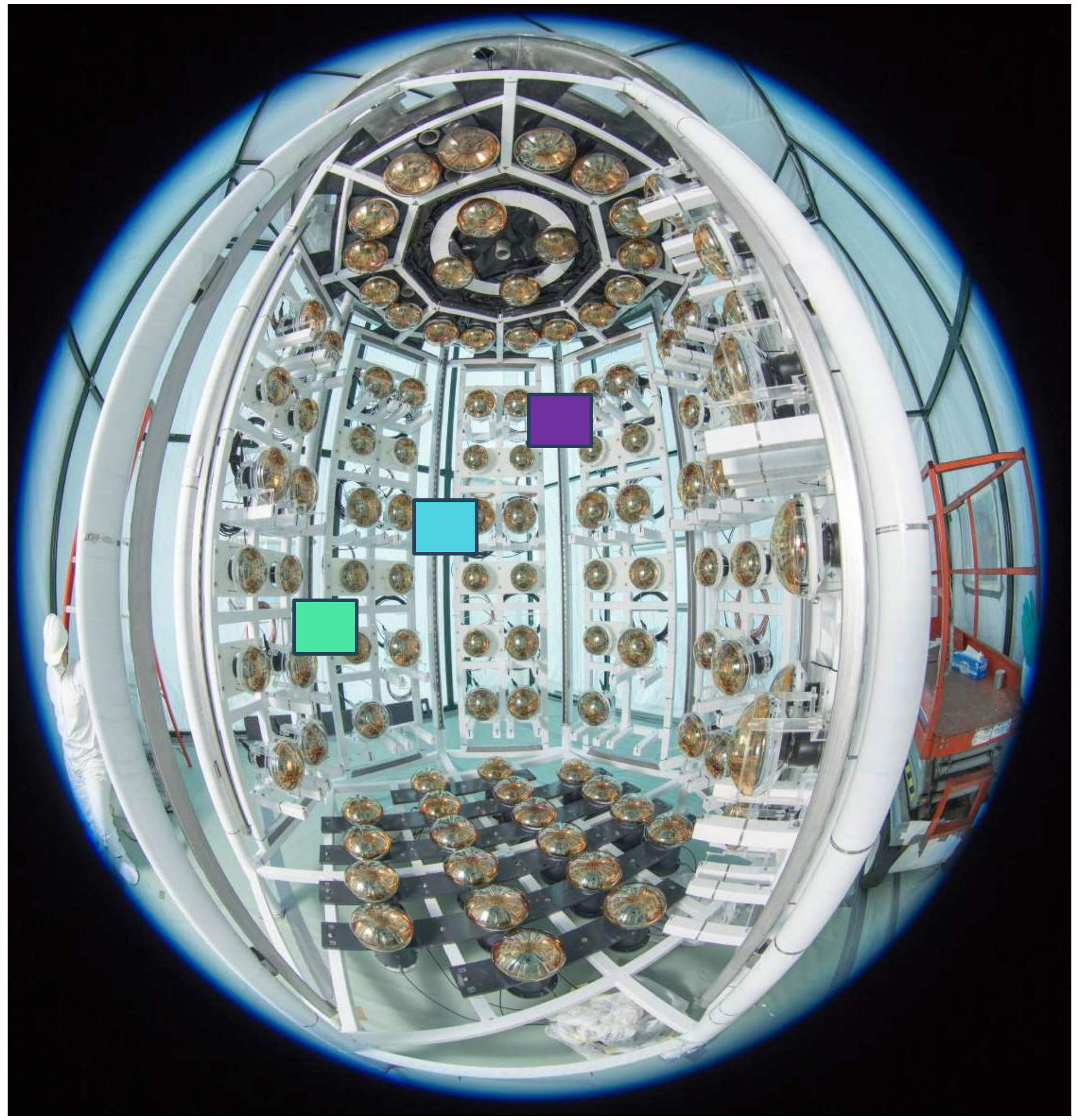



CONFINED SPACE



First Neutrinos on (multiple) LAPPDs

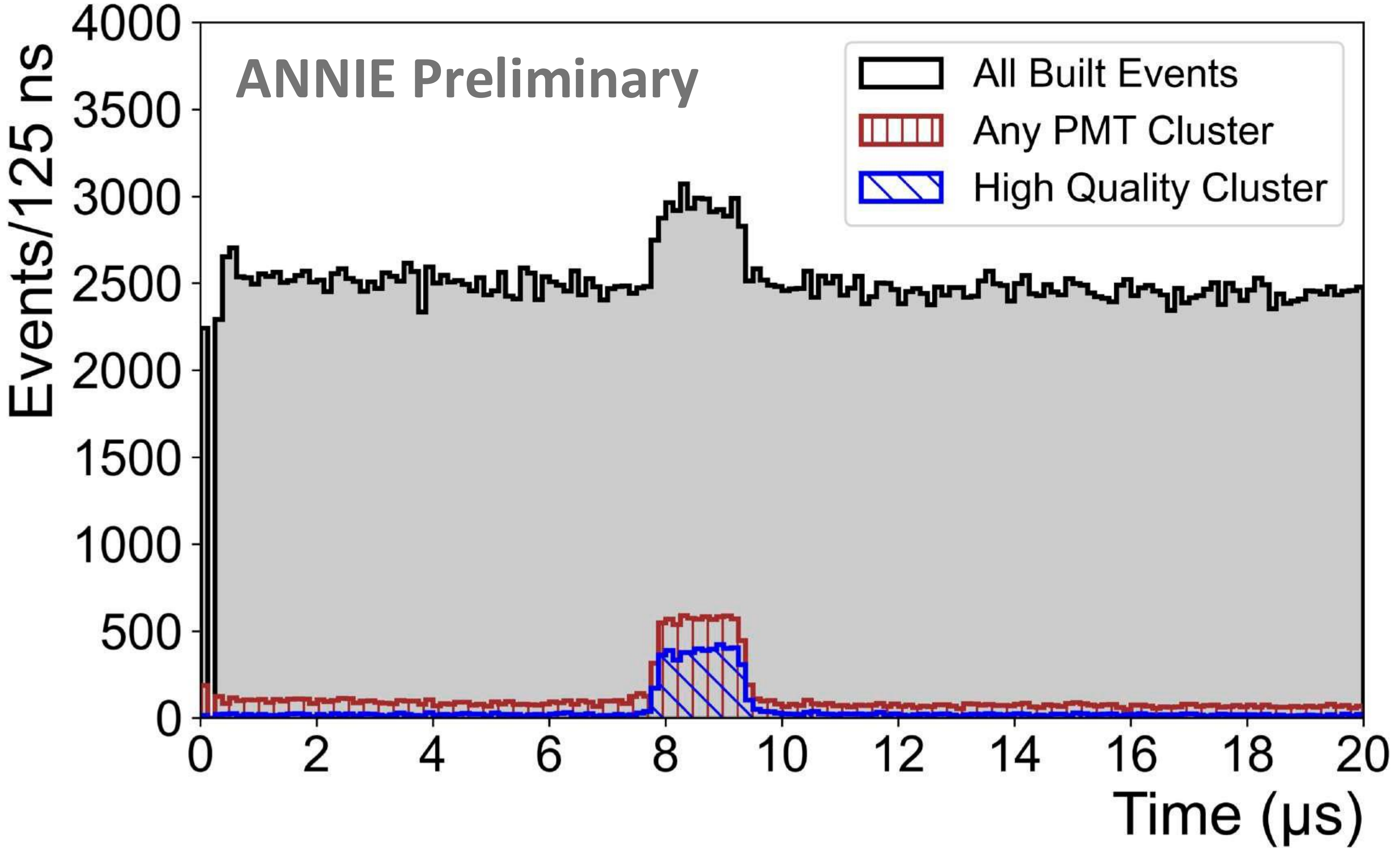




Neutrinos seen concurrently by three LAPPDs operating in ANNIE

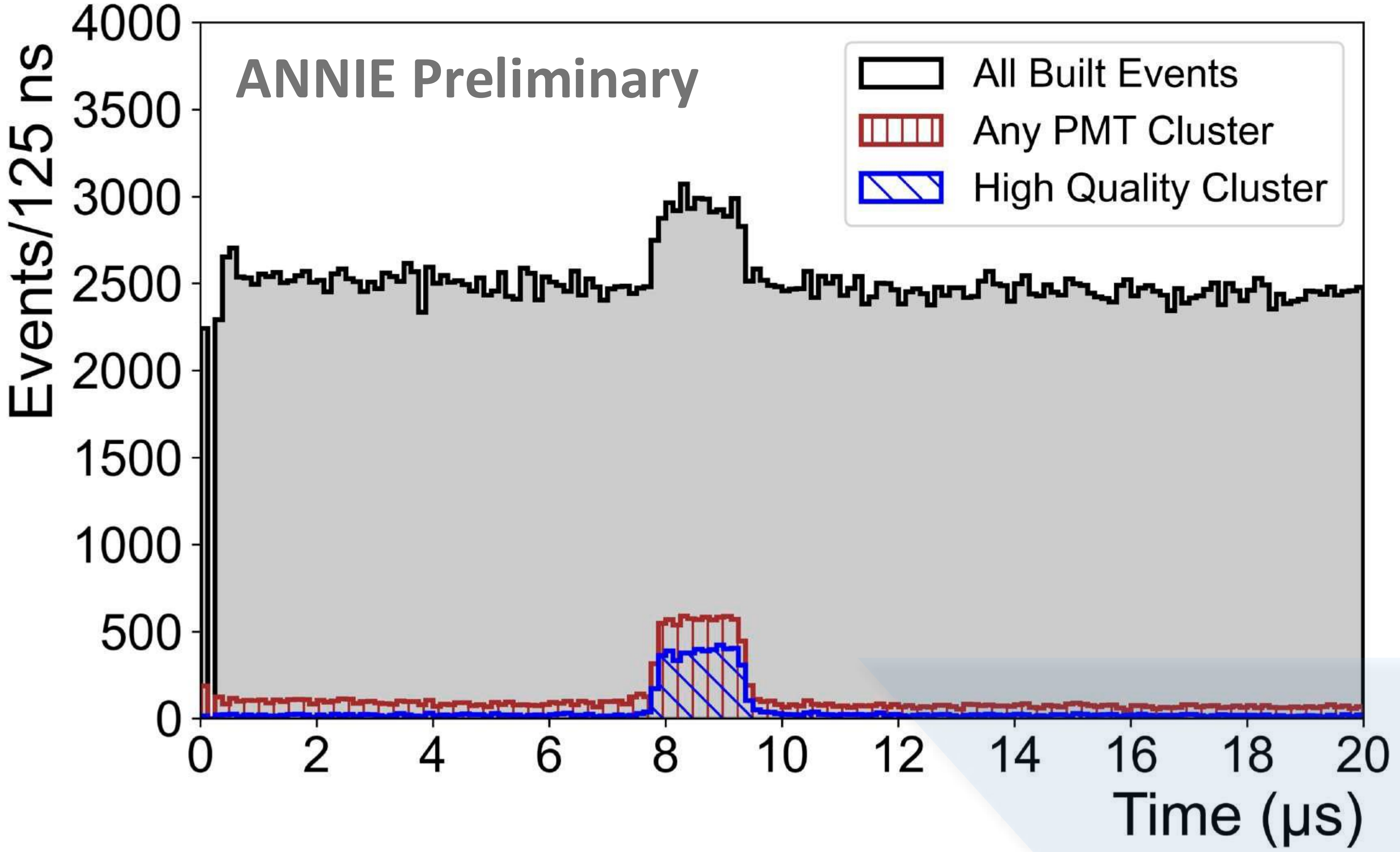
World's first: Neutrinos observed with LAPPDs!

First Neutrinos on (multiple) LAPPDs



We are able to leverage multiple detector subsystems to eliminate nearly all dark noise accidentals with near 100% efficiency.

First Neutrinos on (multiple) LAPPDs



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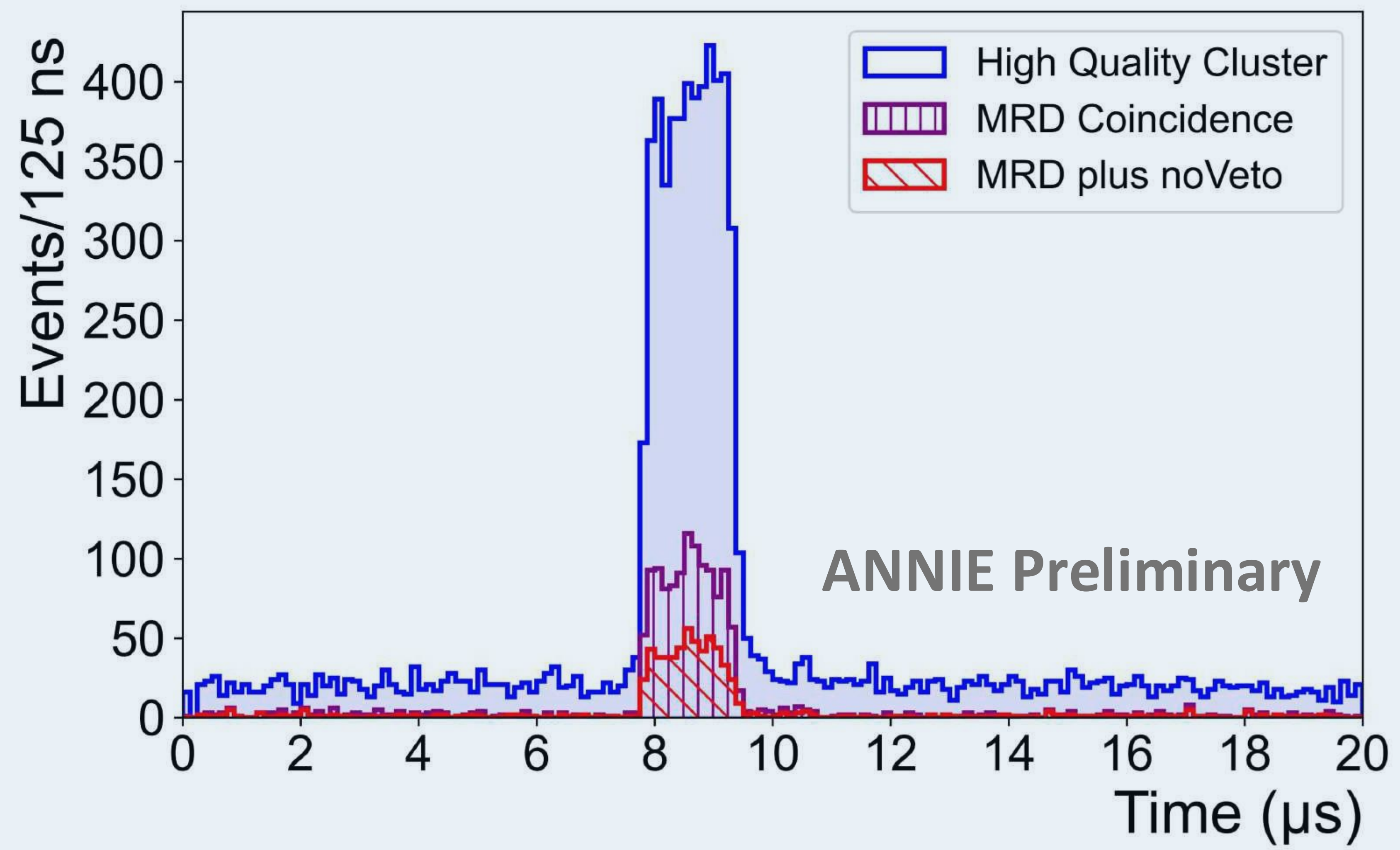
CC neutrino interactions in the tank selected by requiring an MRD coincidence and no signal in the forward veto.



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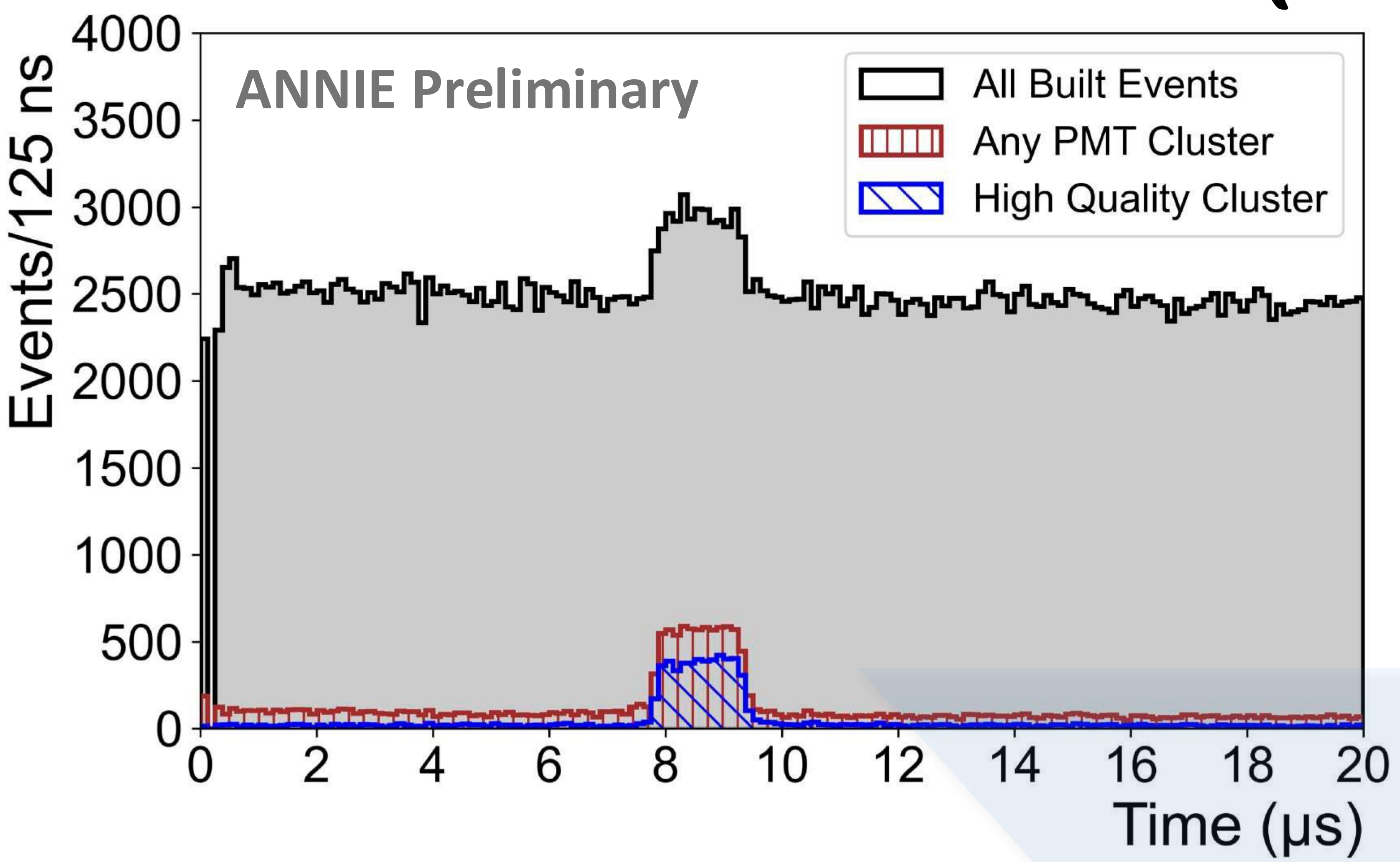

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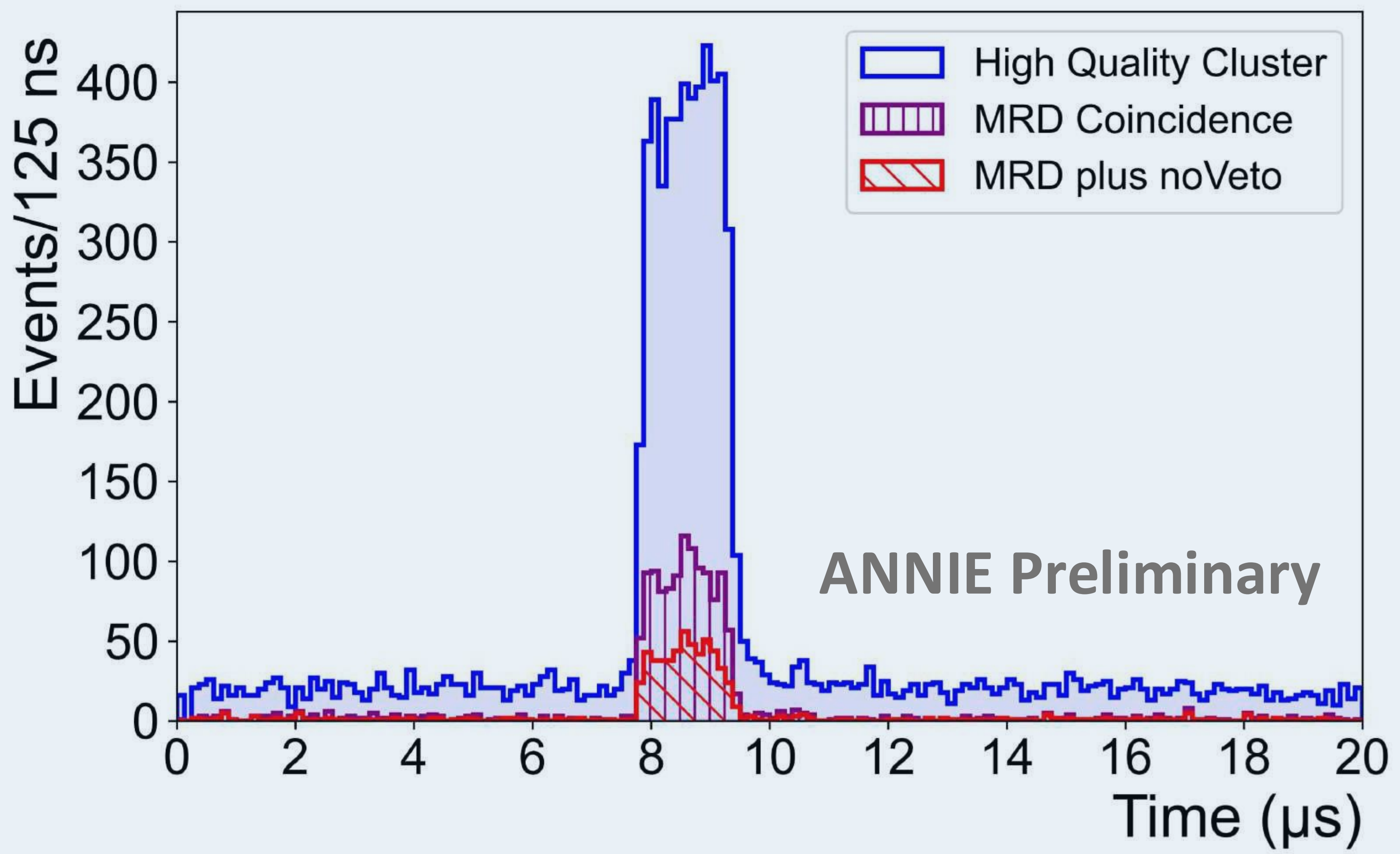


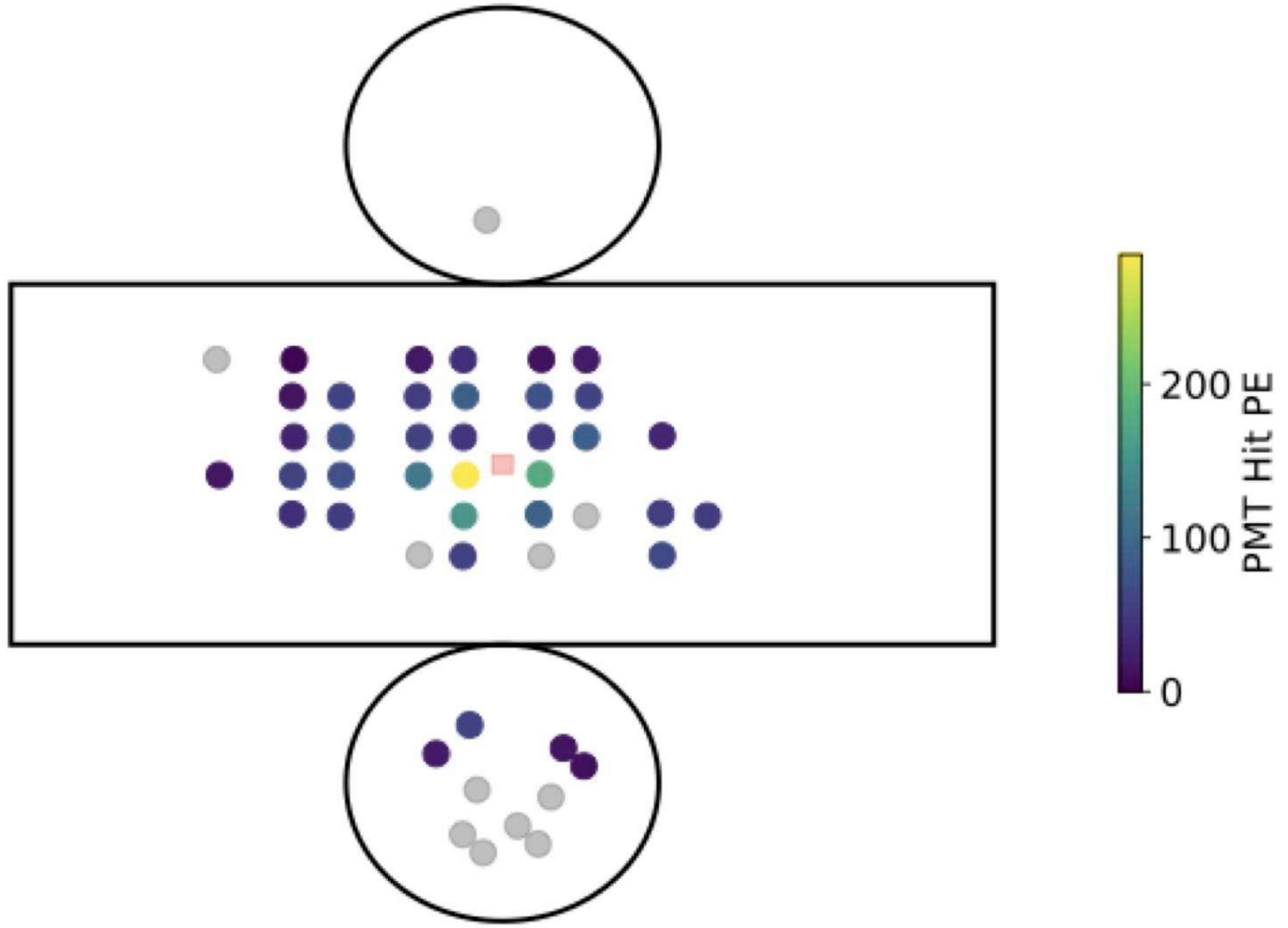
CC neutrino interactions in the tank selected by requiring an MRD coincidence and no signal in the forward veto.

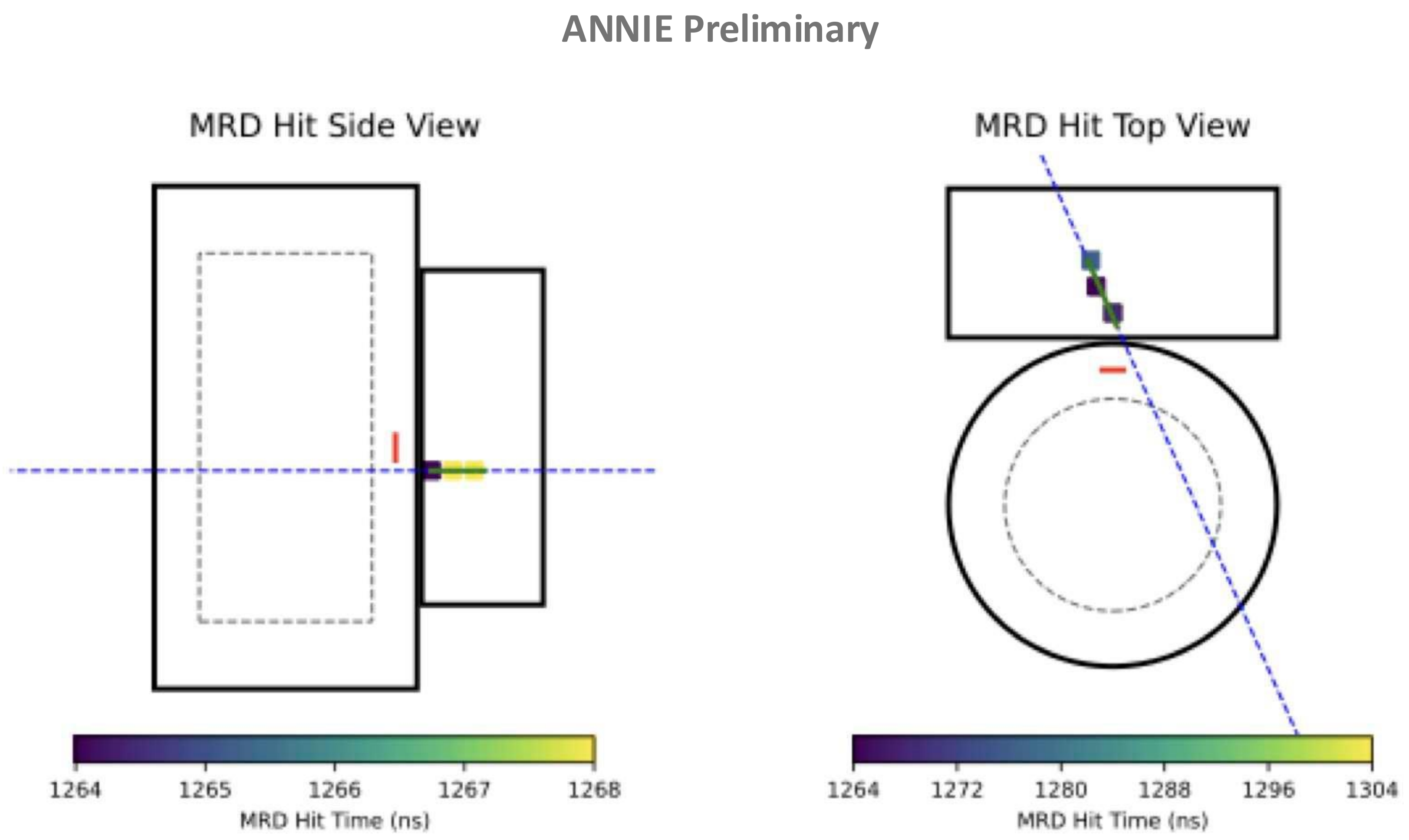
Submitted to JINST, now on arXiv! https://arxiv.org/abs/2508.11111

Building a Bank of LAPPD Events

These selections provide a “golden sample” of neutrino interactions we can use to study LAPPD performance in relation to independent event information.

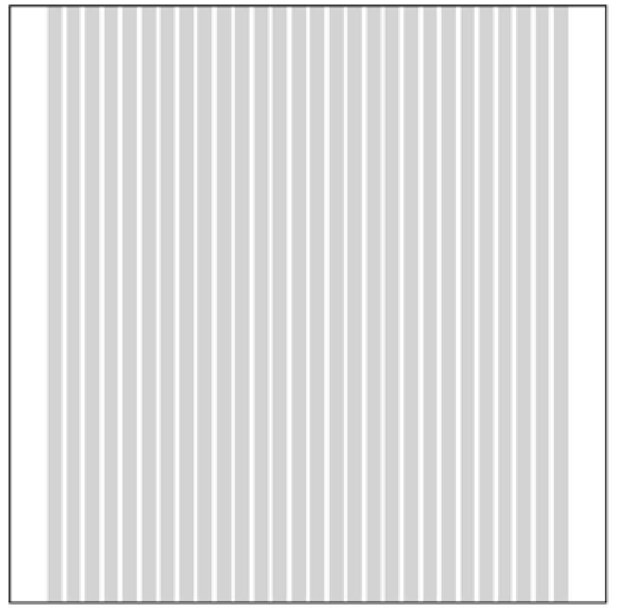
- The new paper features a sample of 500 physics-quality events with a single LAPPD
- We have since collected roughly 14,000 physics quality events with 2 and 3 LAPPDs.

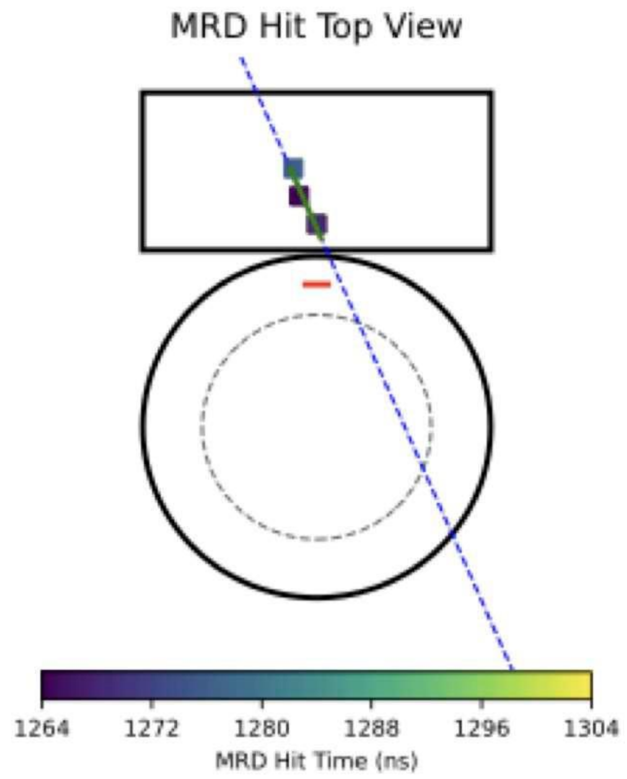


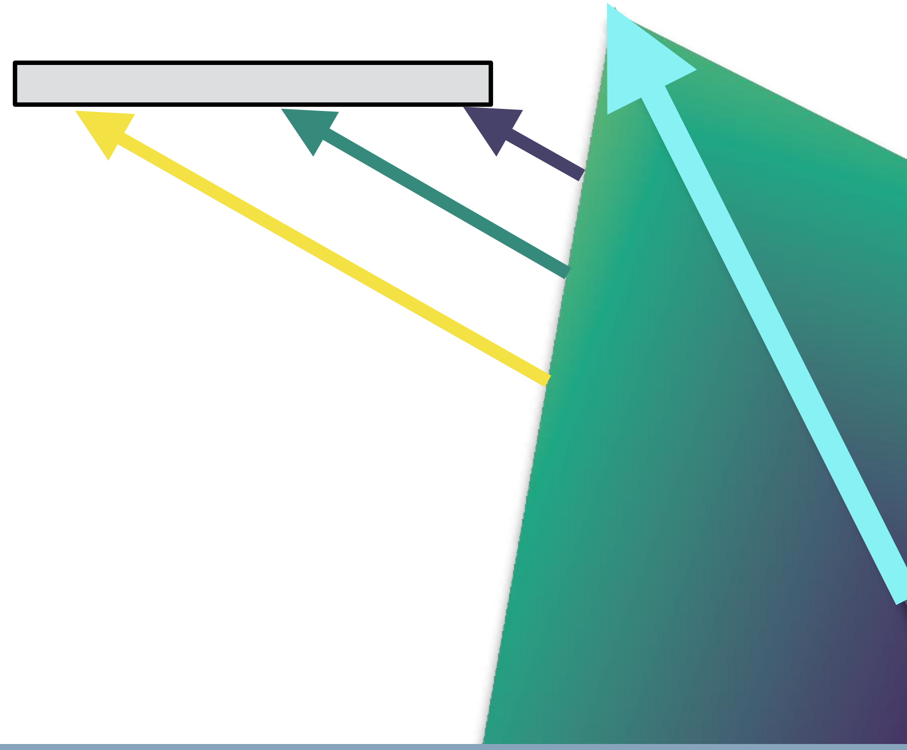


LAPPDs Are IMAGING Photosensors

Time evolution of a Cherenkov ring across the surface of a single LAPPD depends on track direction







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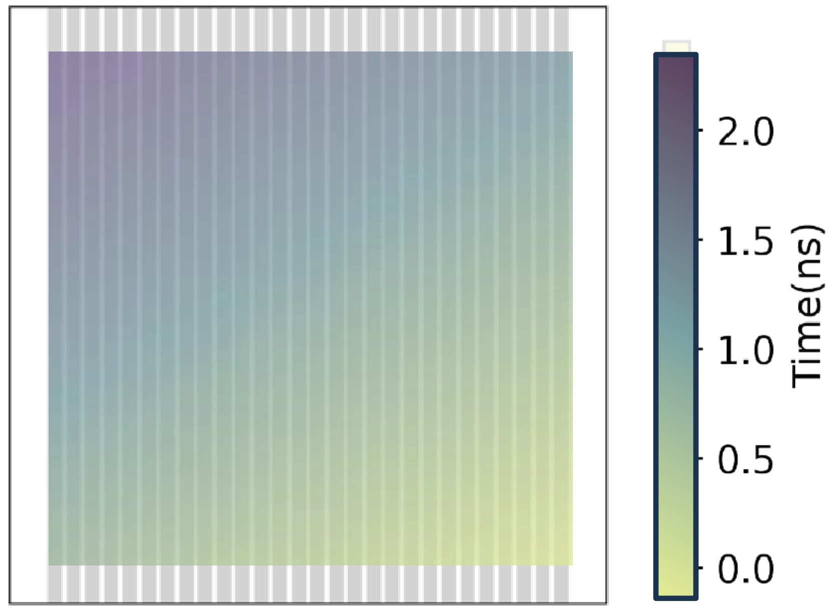

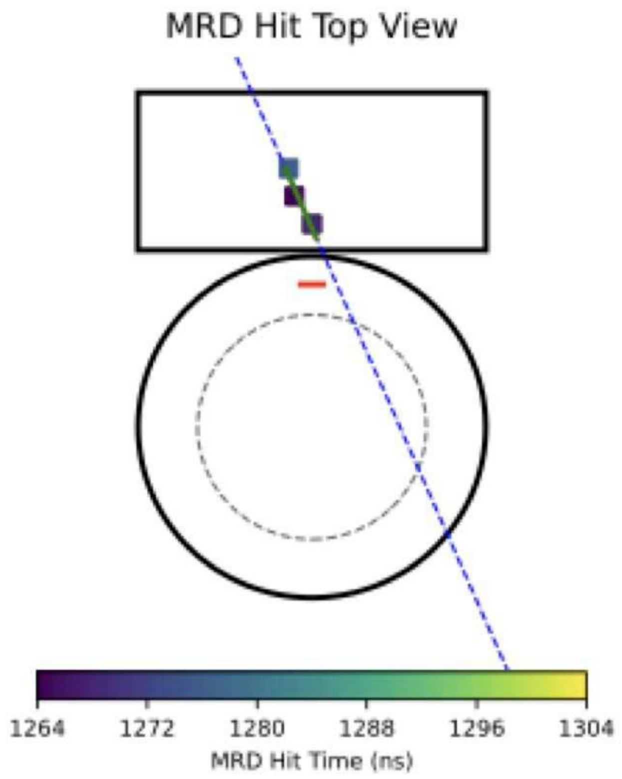

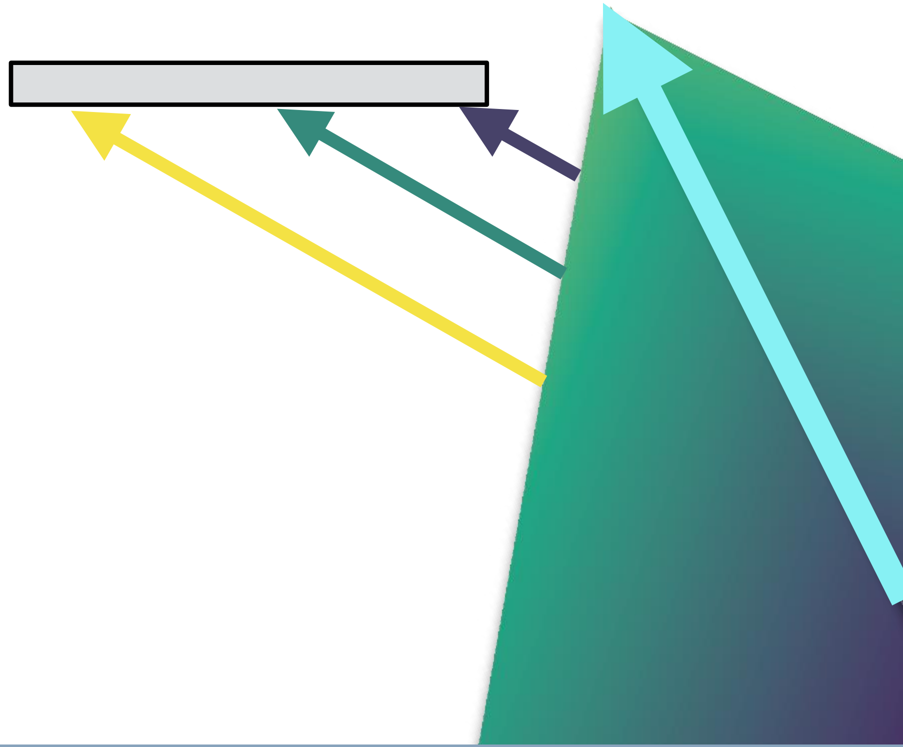

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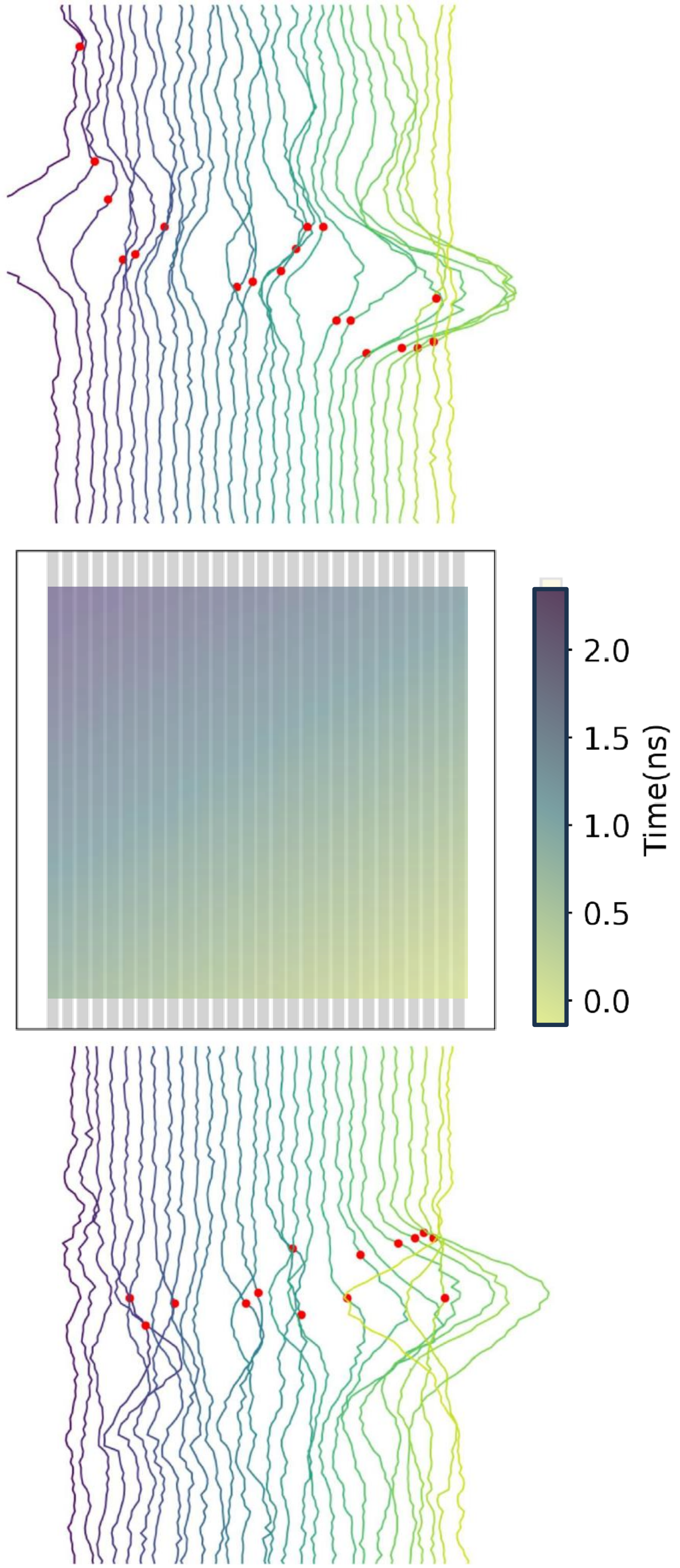

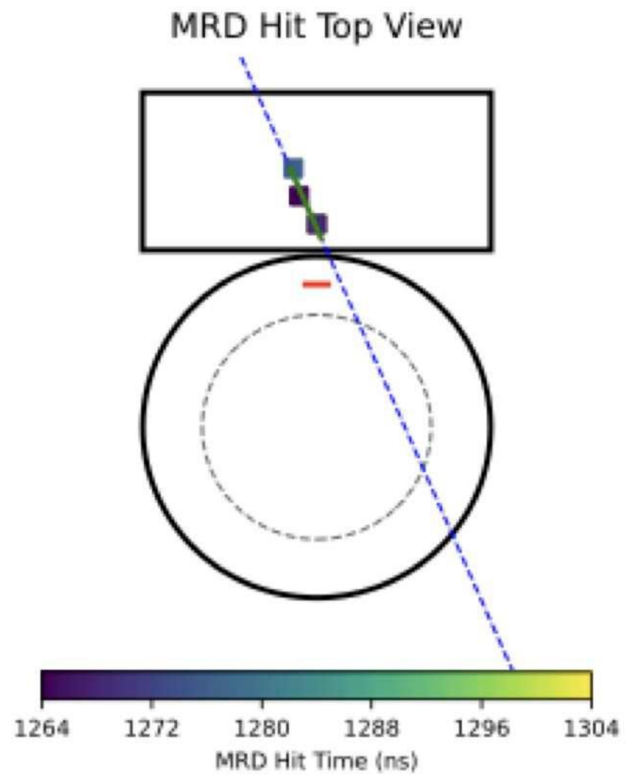

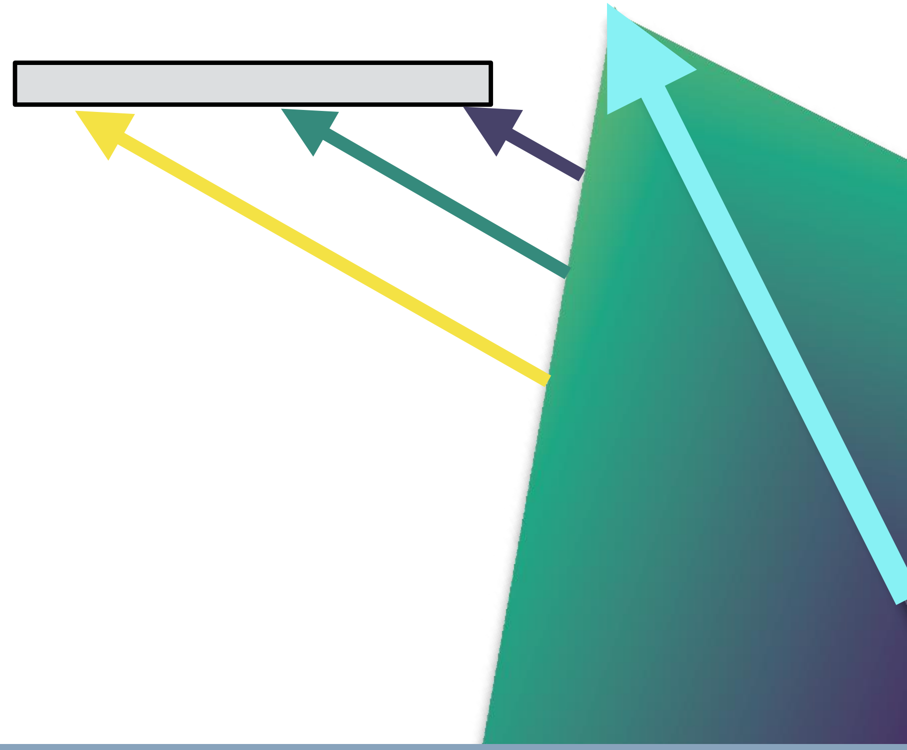

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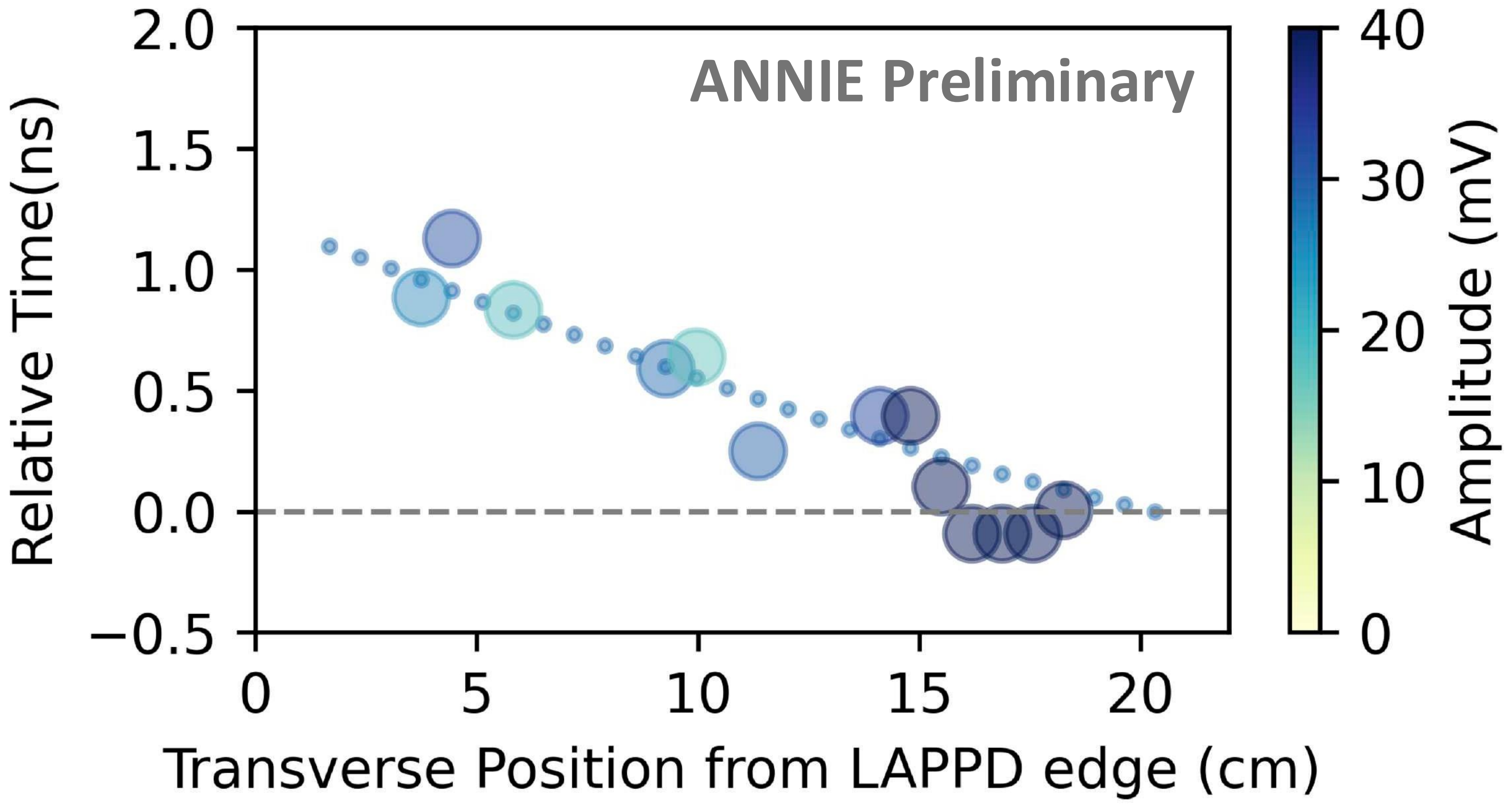
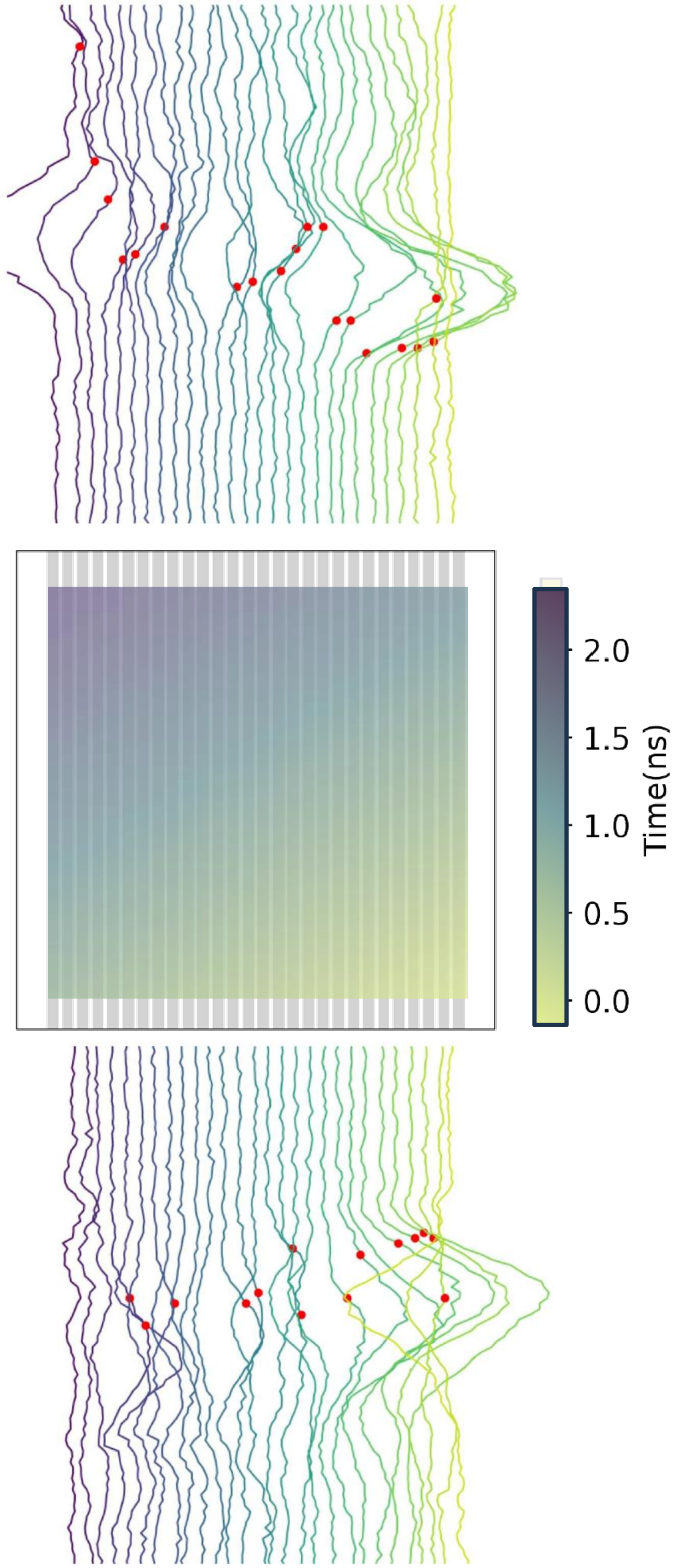
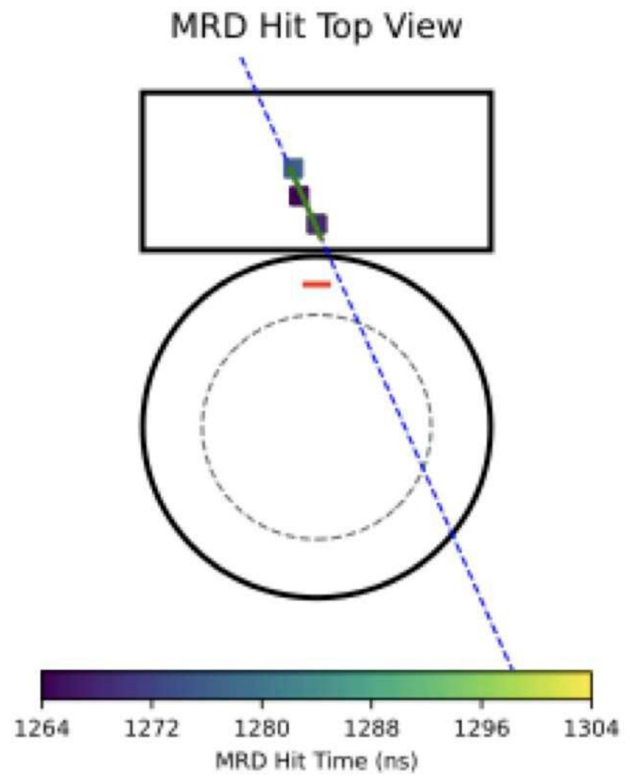
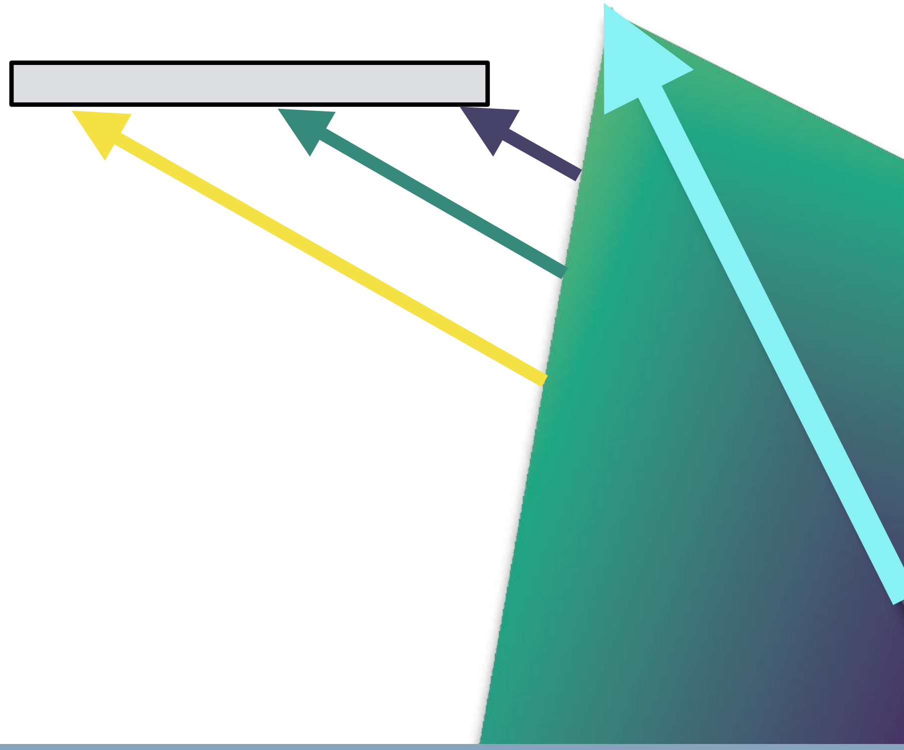






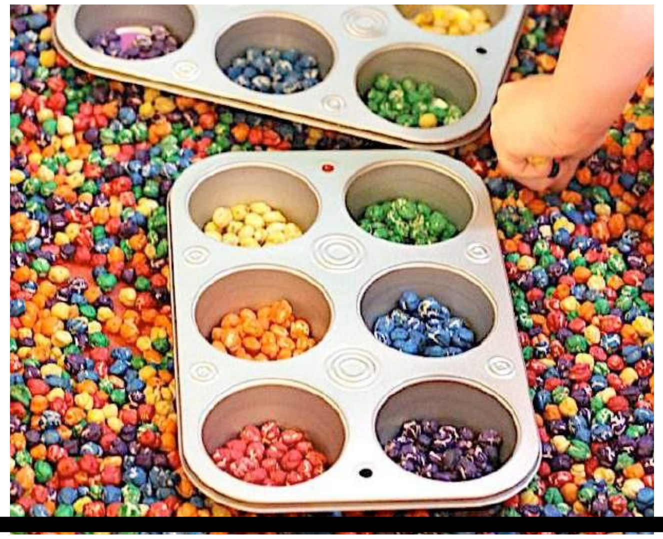


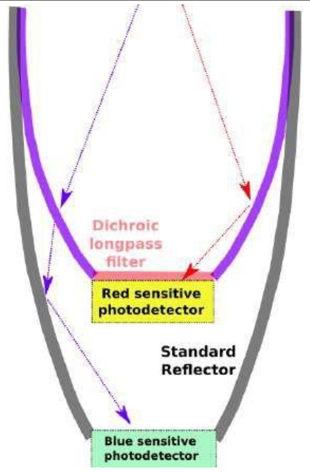
Predicted gradient base on independent MRD track reconstruction!

LAPPDs Are IMAGING Photosensors

Because LAPPDs are imaging photodetectors, they are MORE than faster swap-in replacements for PMTs

Spectral Soring

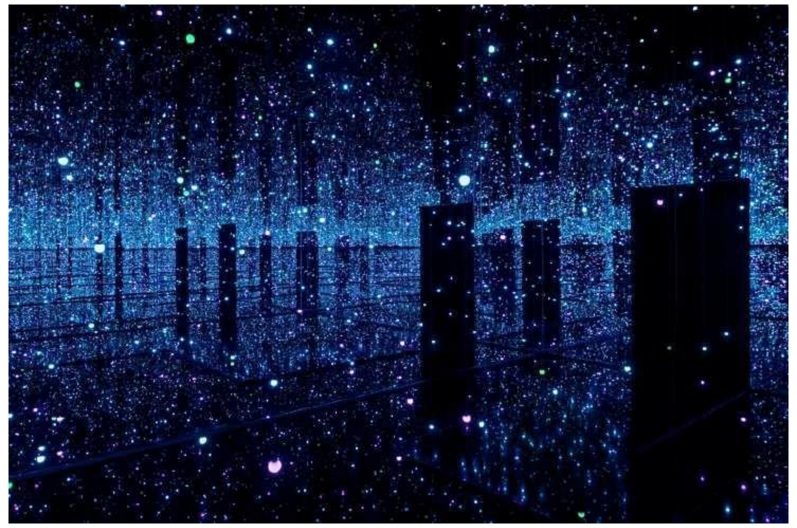




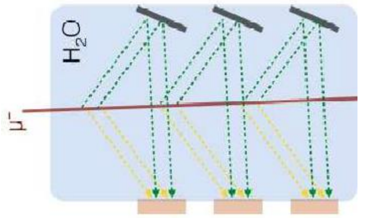
h;ps://arxiv.org/abs/1912.10333

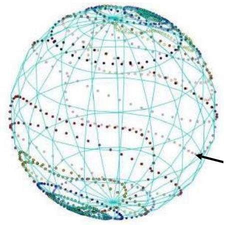
Dichroicons (Kaptonoglu, Kein - U Penn)

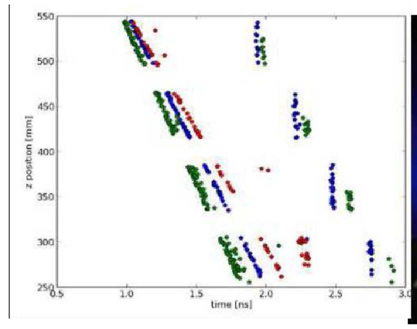
Reflective opics



Ar$st: Yayoi Kusama



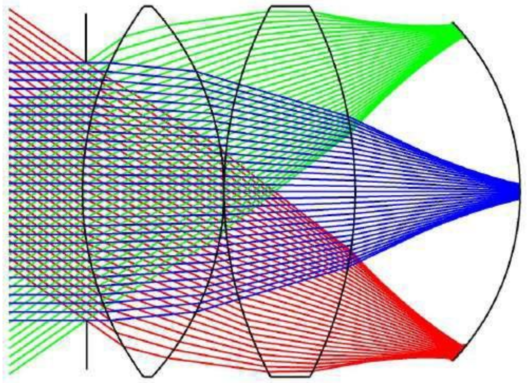




Multi-bounce optics (U Chicago - Oberla, Frisch, Angelico, Elagin)

h<ps://arxiv.org/abs/1711.09851

Plenoptic Imaging



Plenoptic imaging (Dalmasson et al)

h<ps://arxiv.org/abs/1510.00947

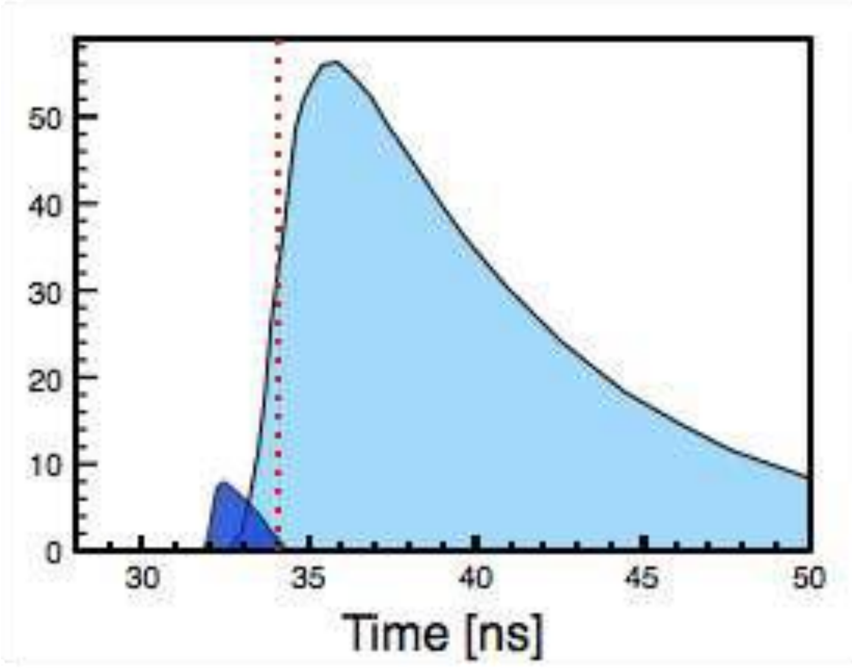
Timing+imaging could enable novel approaches to light concentration and sorting, interesting games in optical phase space.

Can we move beyond bounding volumes with phototubes on the surface?

First Water-based LS in a ν-Beam

Addition of WbLS enables hybrid detection of both Cherenkov and scintillation light, providing both prompt tracking information (Cherenkov) and calorimetry (scintillation)

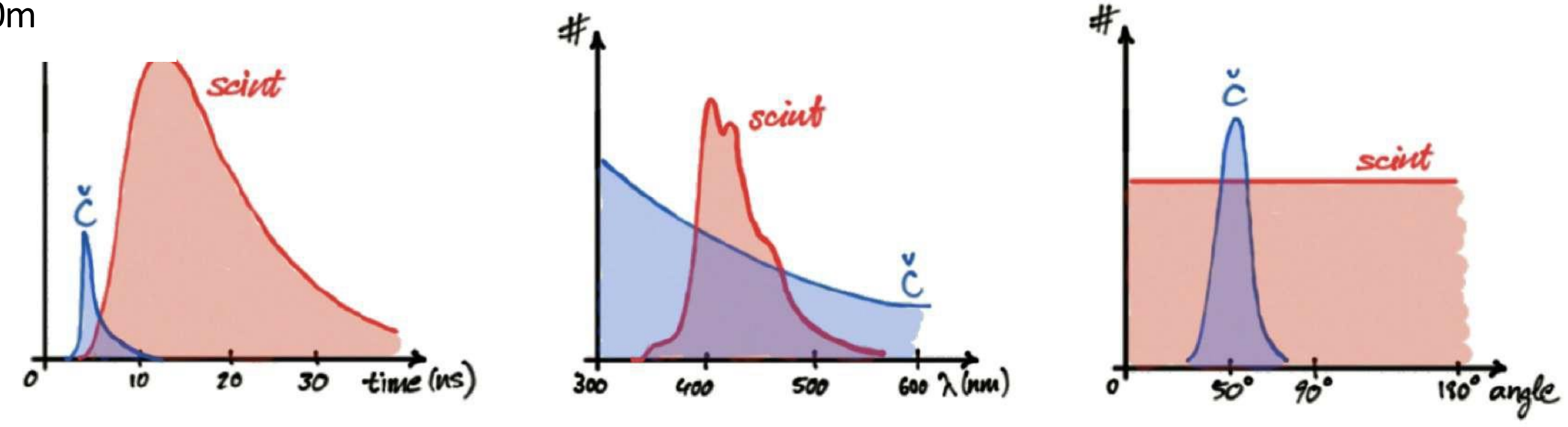
- Enhanced Energy Reconstruction
- Detection of particles below Cherenkov threshold
- Better particle ID/background rejection
- Enhanced neutron signals



C. Aberle, A. Elagin, H.J. Frisch, M. Wetstein, L. Winslow. (2013)

h;ps://arxiv.org/abs/1307.5813

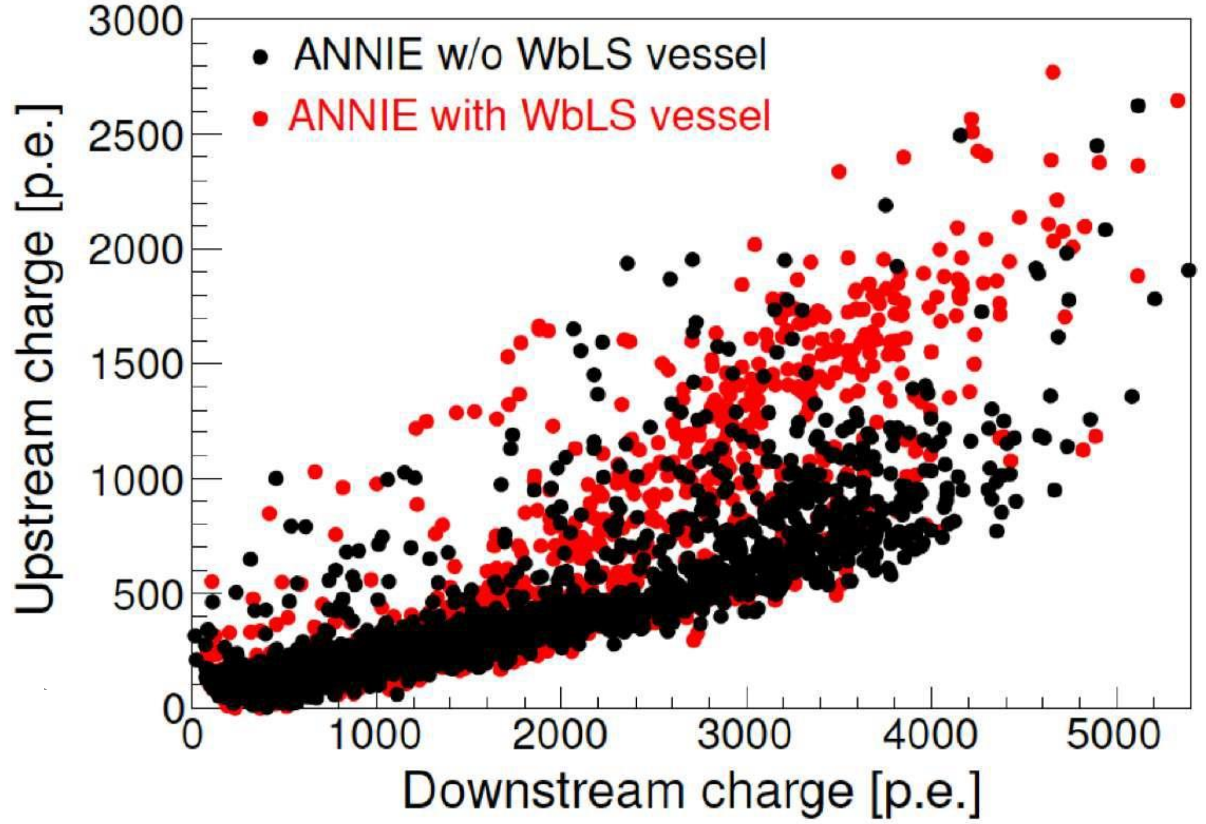
Scalable to large detectors



Candidate technology for DUNE FD4

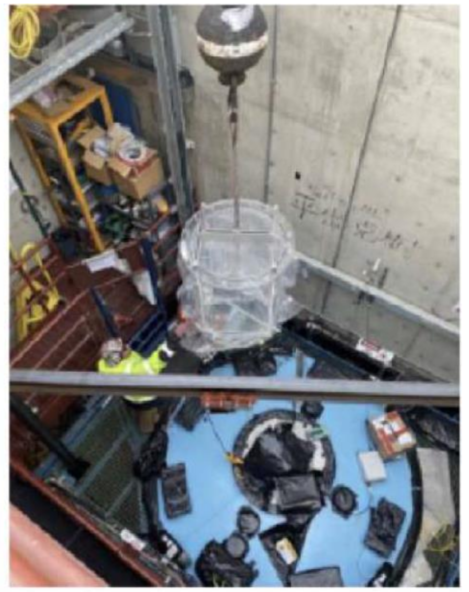
First Water-based LS in a ν-Beam

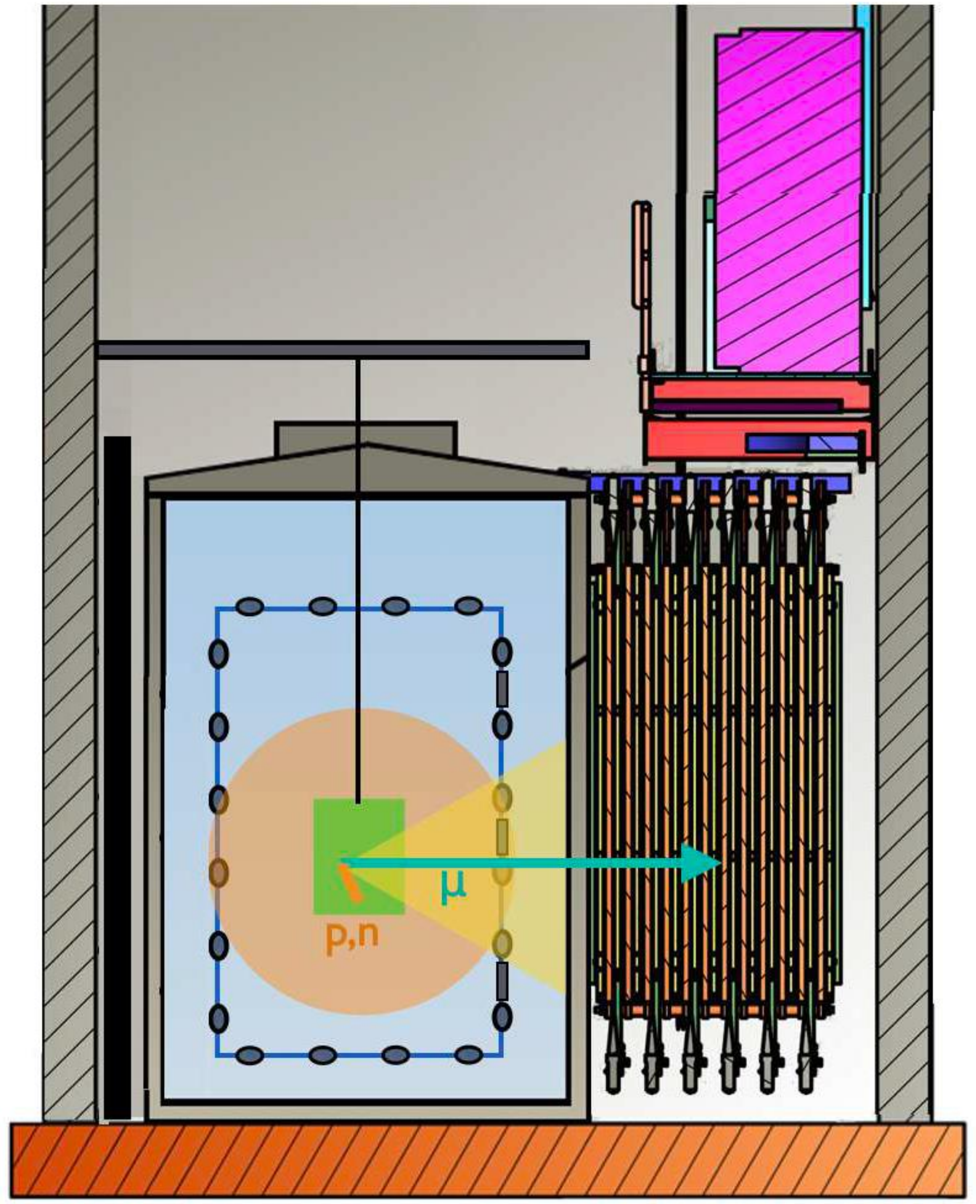
- SANDI - a ~3’x 3’ acrylic vessel containing 356 kg of 0.5% LS water-based liquid scintillator (WbLS)
- March -May 2023 (2 months) = few thousand events
- Candidate events with WbLS show substantially more light in the upstream TPCs
- Now published in JINST!
- SANDI is back in ANNIE for the beginning of the FY24 beam year (w/ LAPPDs!)



M. Ascencio-Sosa *et al* 2024 *JINST* **19** P05070

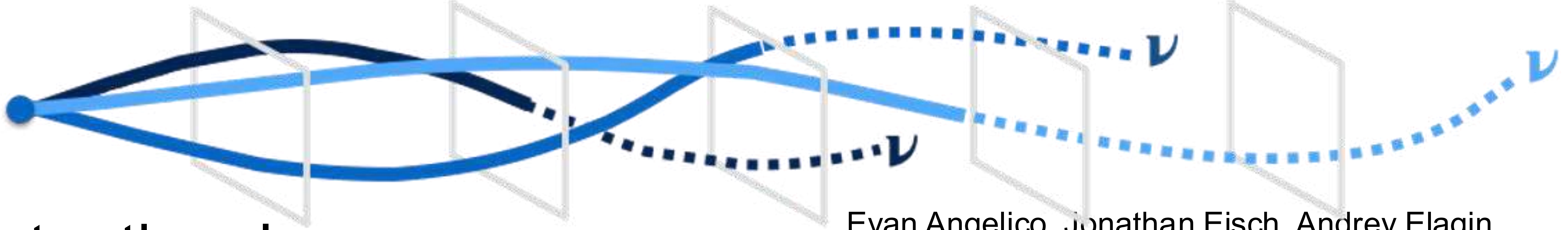
https://arxiv.org/abs/2312.09335





World’s first: Neutrinos observed with WbLS!

Beam Timing



Higher energy pions travel faster than low energy pions with respect to the timing of the proton bunch.

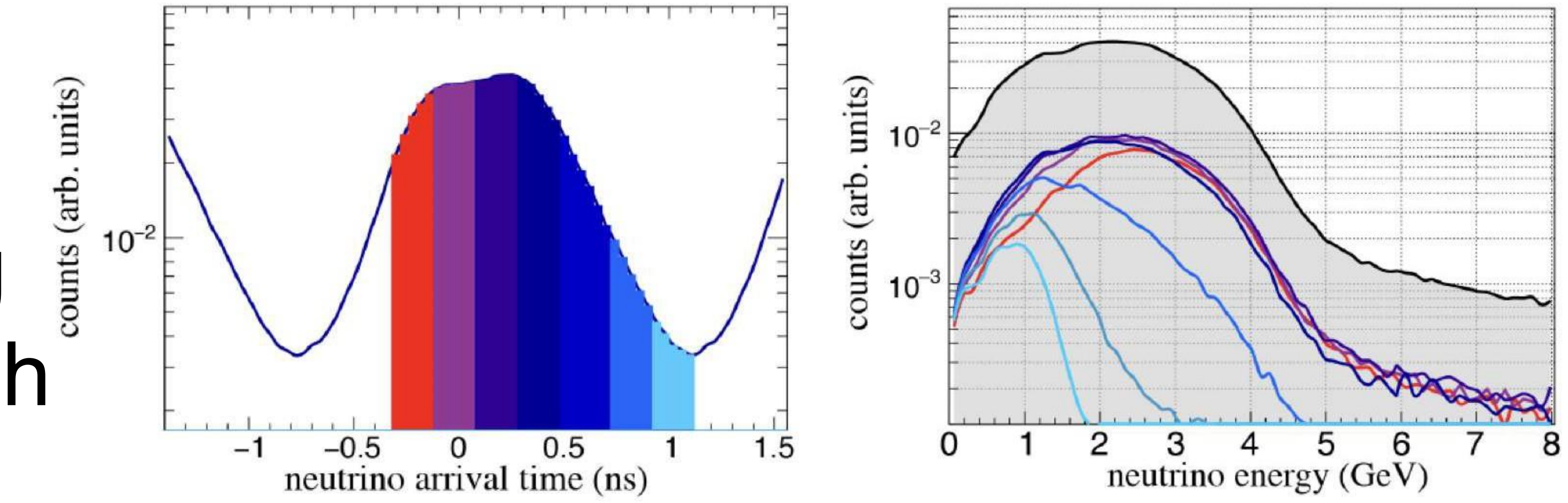
This means it is possible to theoretically select different neutrino energy spectra based on the timing of the interaction with respect to the beam RF - though it does necessitate shorter bunch sizes.

In future long baseline experiments, this could enable techniques similar to approaches sampling off-axis angles (“Prism” concept). Only it could be applied to far, as well as near detectors.

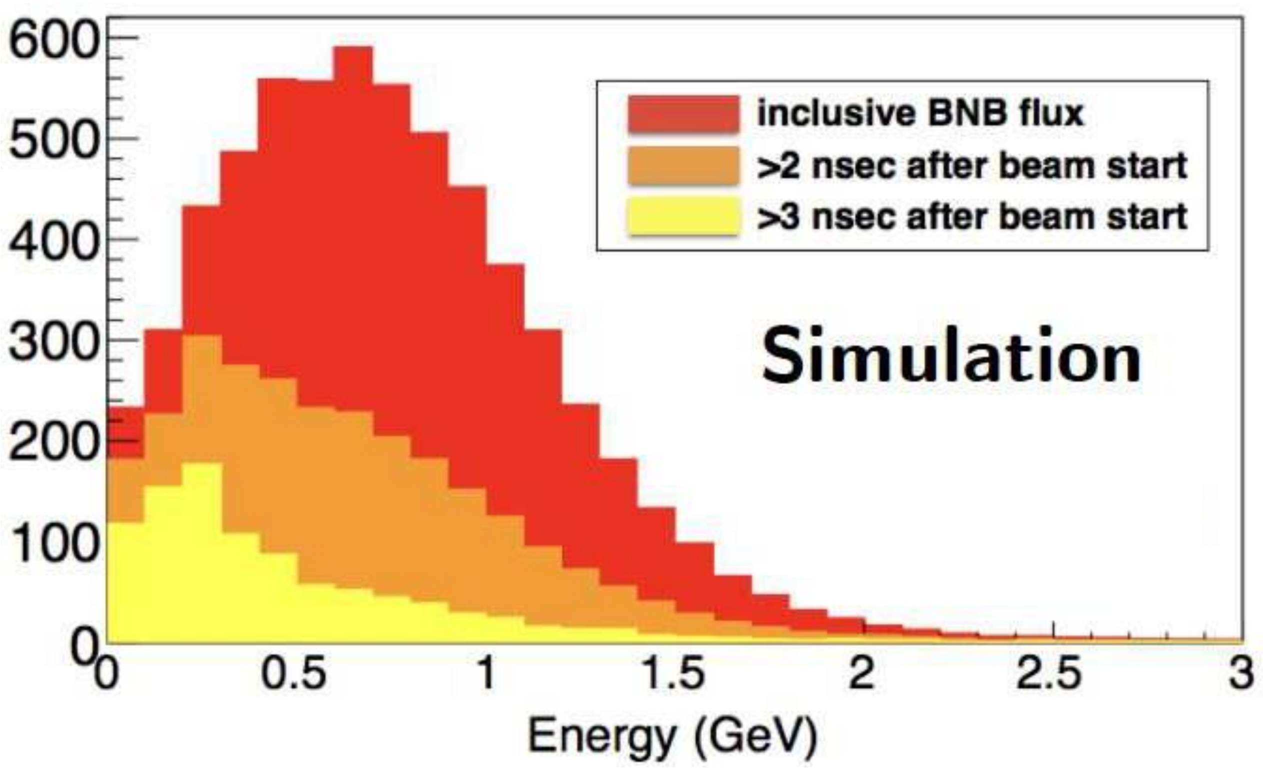
ANNIE is capable of measuring this effect on the BNB

Evan Angelico, Jonathan Eisch, Andrey Elagin, Henry Frisch, Sergei Nagaitsev, Matthew Wetstein

https://arxiv.org/abs/1904.01611



250 ps bunches, 100 ps detector (“LBNF” with rebunching)

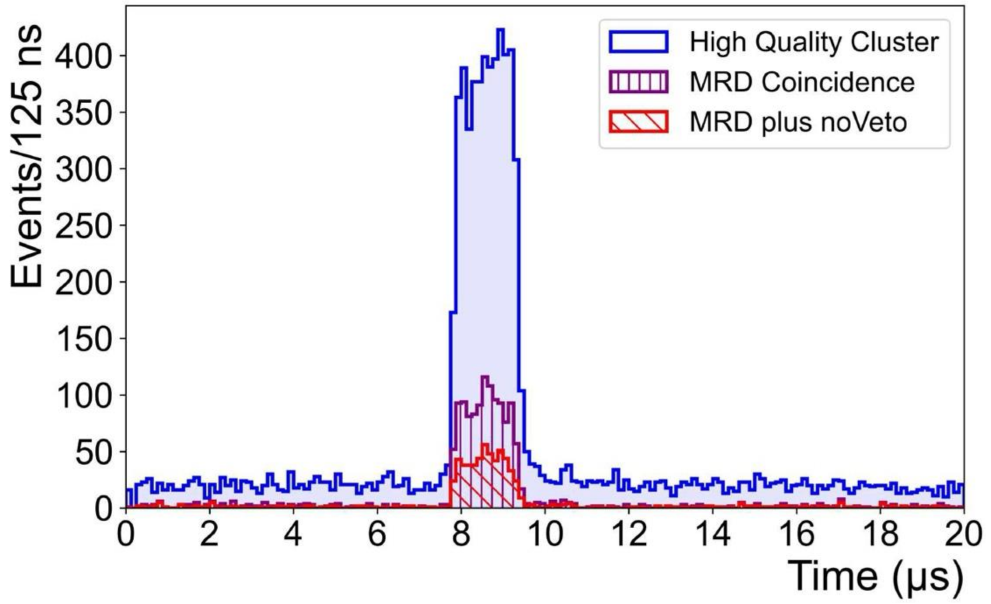


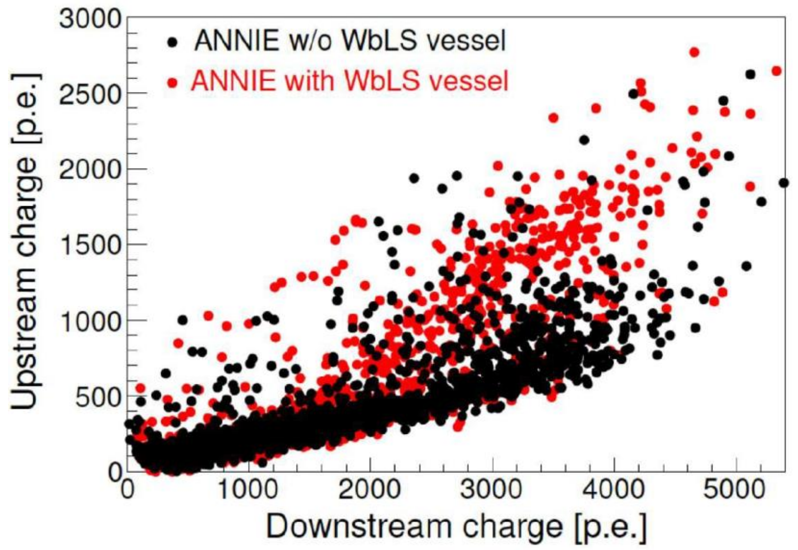
Also see: Workshop on Precision Time Structure in On-Axis Neutrino Beams

Summary

ANNIE has achieved many important technical firsts

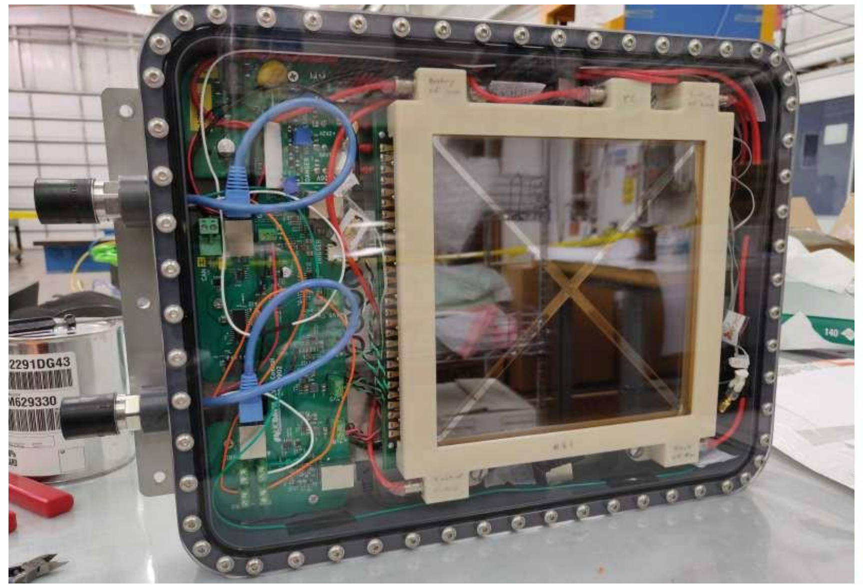
- **First detection of neutrinos with Gd-water**
- **First detection of neutrinos with an LAPPD**
- **First detection of neutrinos with WbLS**

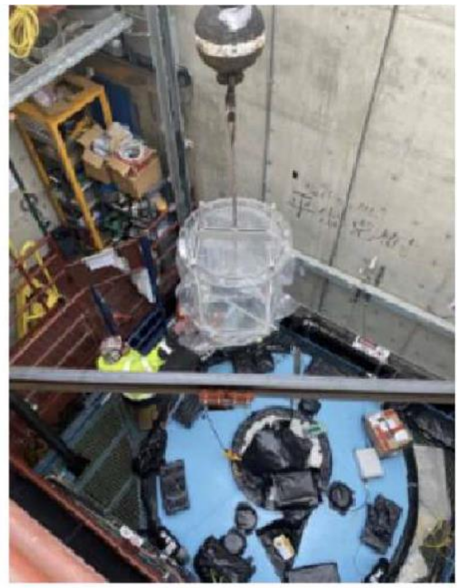




- Gained considerable operational experience w/ these technologies
- Made significant progress on the reconstruction tools
- First data with LAPPDs shows powerful imaging capabilities

ANNIE is now in a unique position to measure neutrino-nuclear cross sections in water - complementary and synergistic the the LAr short baseline program at FNAL



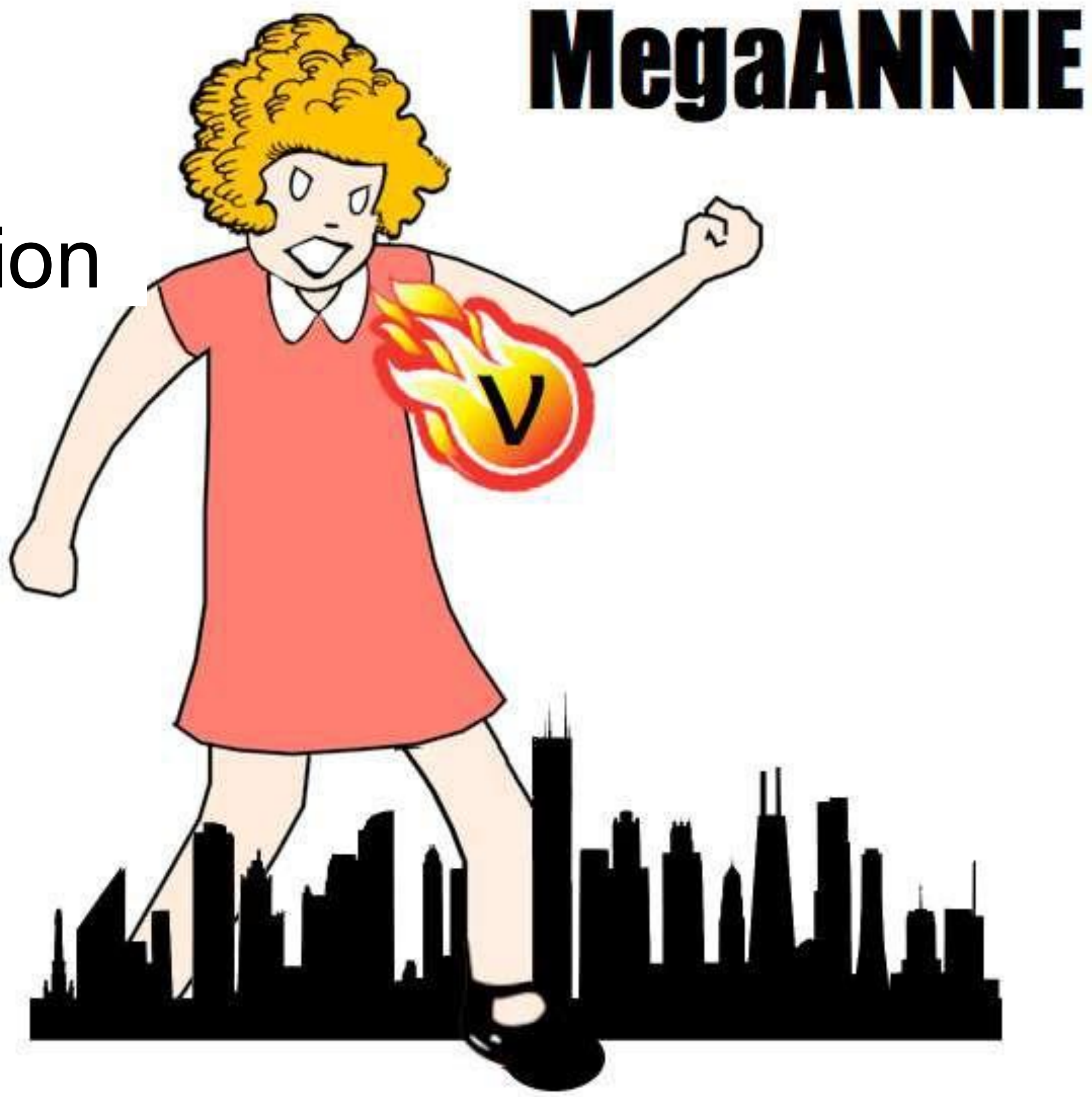


With 3+ LAPPD modules installed & commissioned, ANNIE is set for 2 years of high quality data taking to leverage the excellent event reconstruction enabled by multiple LAPPDs.

Looking Ahead

ANNIE is an ideal testing ground for WbLS for hybrid Cherenkov/ scintillation reconstruction of neutrino events in future long-baseline experiments.

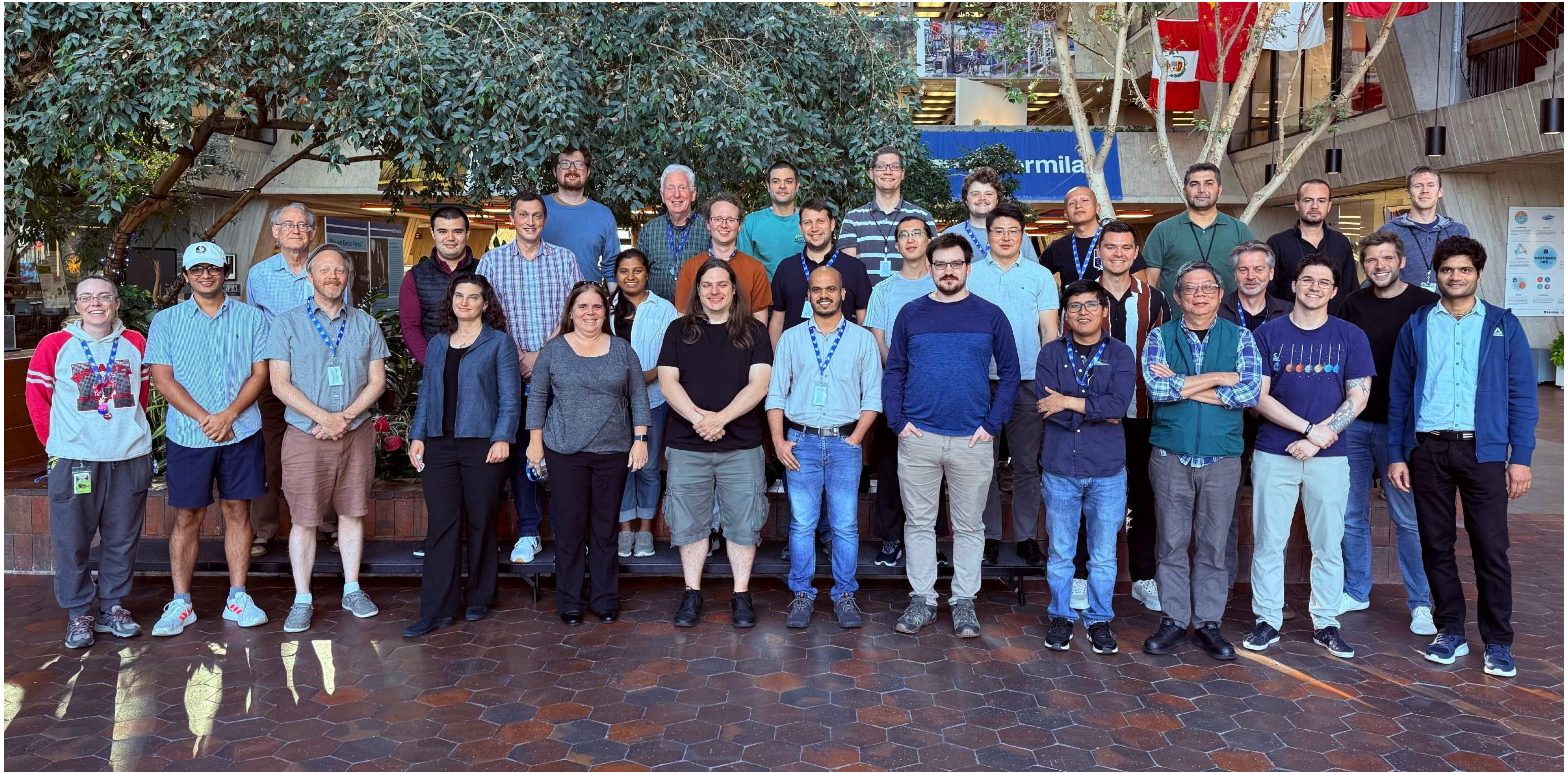
- Larger data sample with multi-LAPPD read-out
- Demonstrate C/S separation based on LAPPD data
- Look for scintillation-only hadronic neutral current events
- Plans for Gadolinium-loaded WbLS → enhanced neutron detection



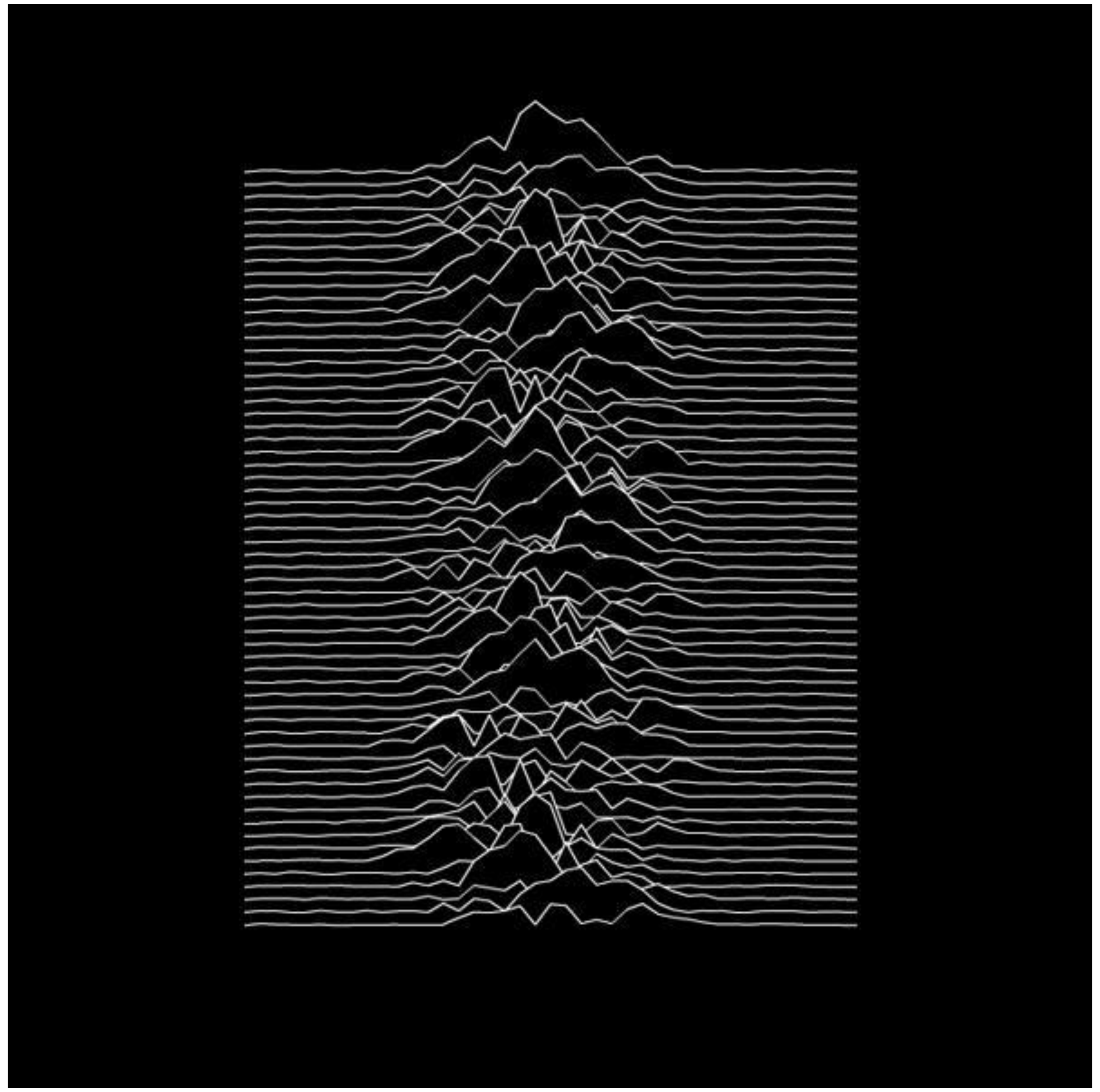
Planning for R&D program with an enlarged WbLS volume and new upstream LAPPDs with updated electronics.

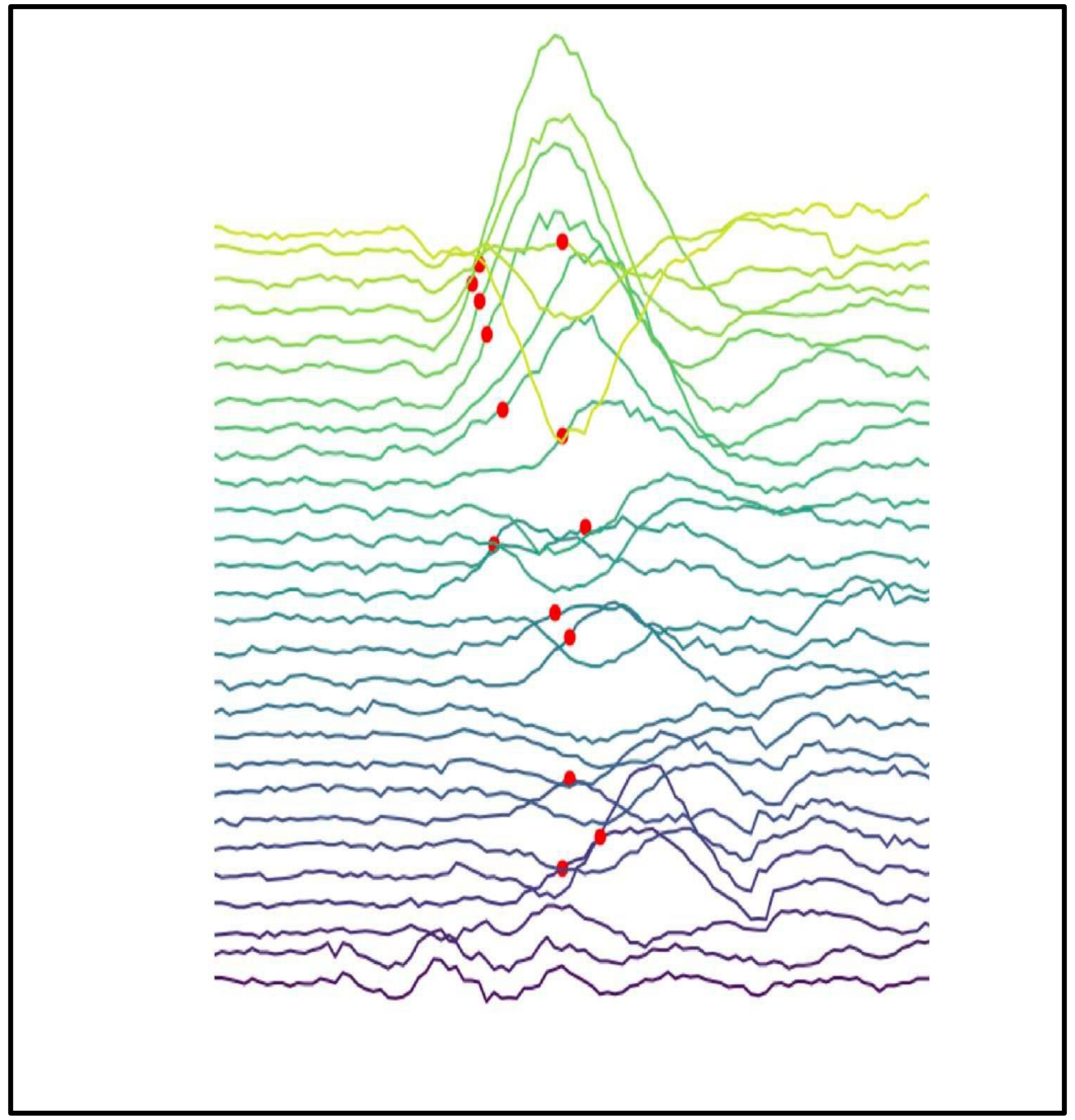
- Received positive feedback from the Fermilab PAC.
- A high-statistics measurement is a key step in demonstrating these technologies for long-baseline neutrino experiments.

Thanks!



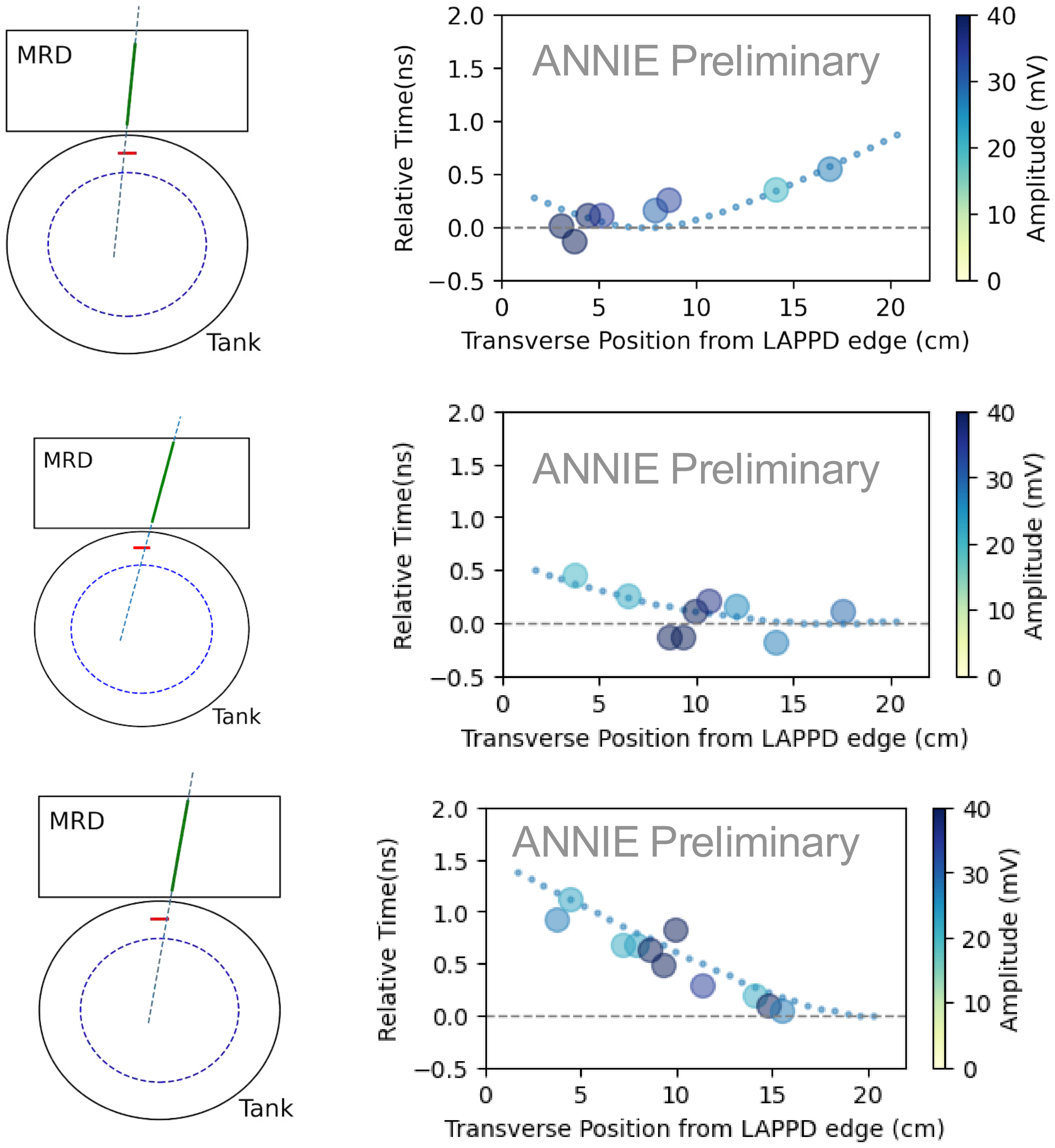
Backups





LAPPDs are Imaging Photosensors

- Qualitative difference between
  - Tracks to left and right of LAPPD
  - Tracks intersecting LAPPD



Amanda Weinstein- Iowa State University

Fermilab Users Meeting—July 11, 2024

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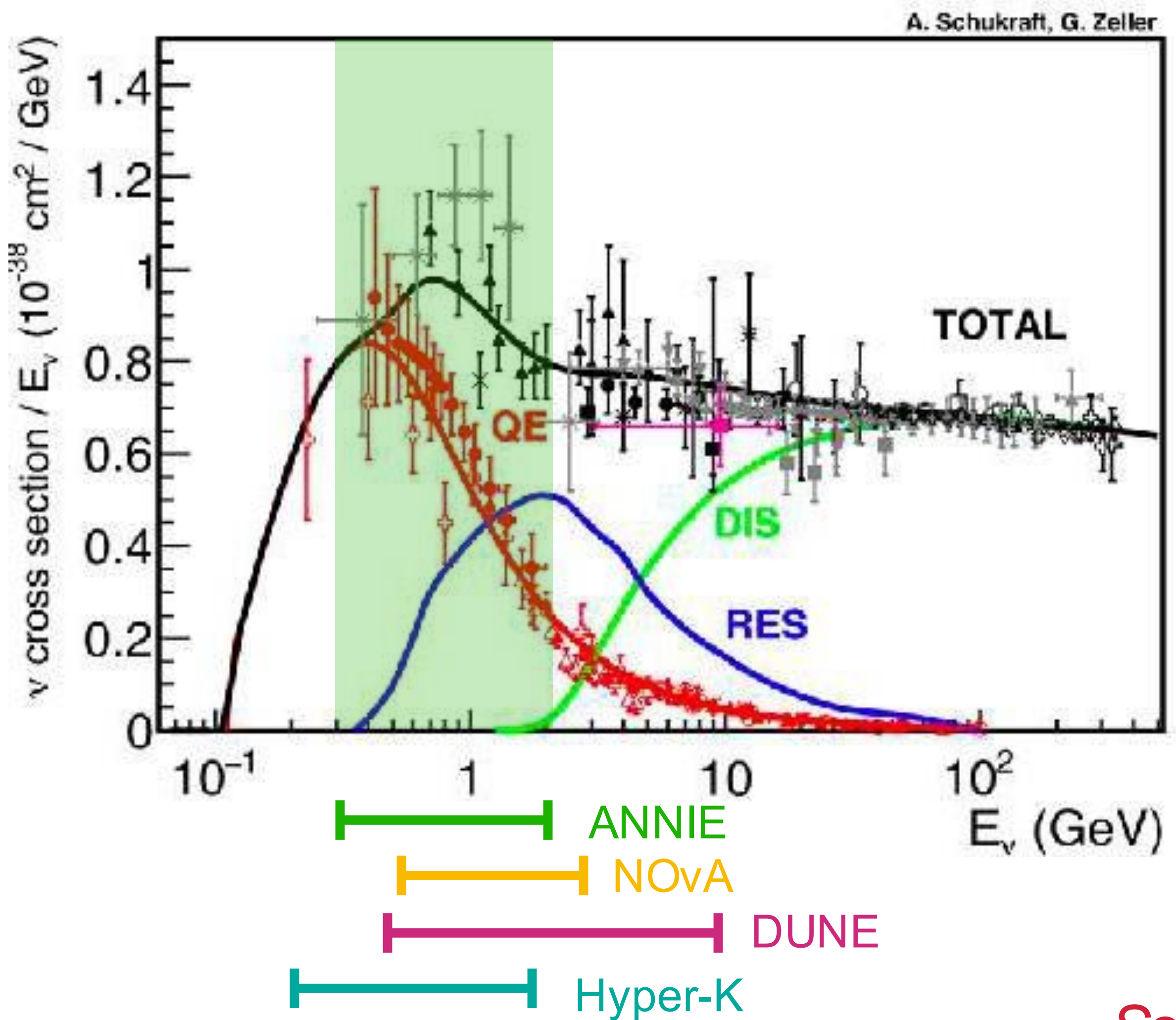
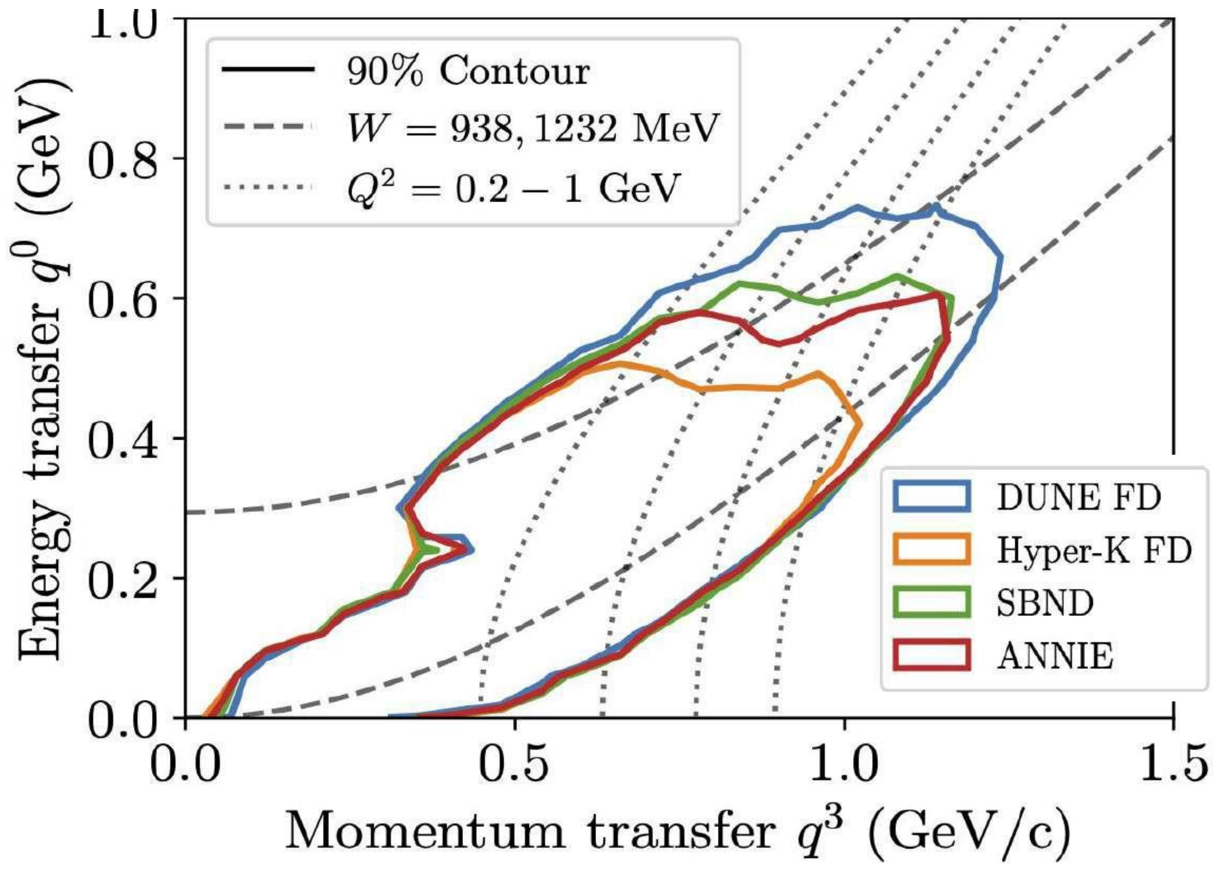
ANNIE Physics Program

Measurements relevant to the neutrino oscillation program:

- Proximity to BNB target → high flux, overlap with T2K/LBNF
  - Spans the neutrino energy range where DUNE & HK overlap
  - Currently taking data, analyzing existing ~2 year dataset





See also: Mun Jung Jung's SBND talk (April 17)

Credit: Andy Mastbaum (NUINT 24)

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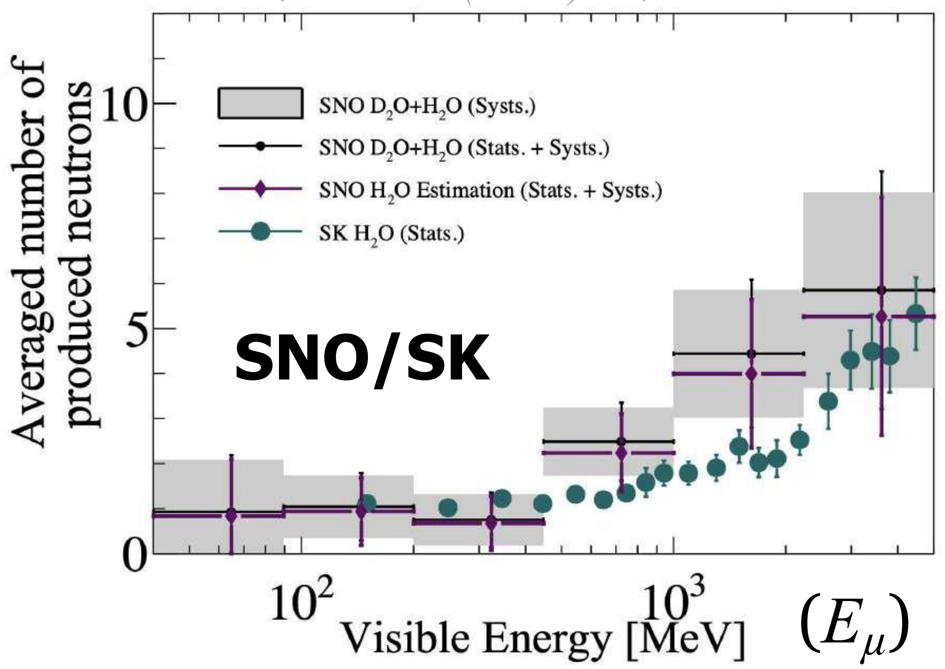
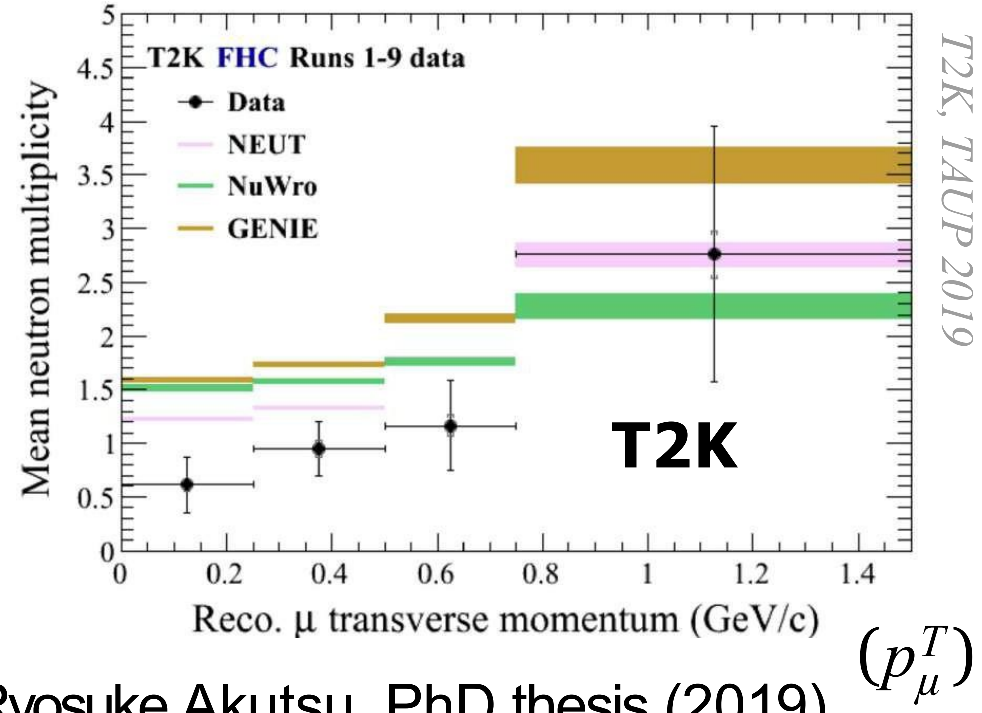
ANNIE Physics Program

Measurements relevant to the neutrino oscillation program:

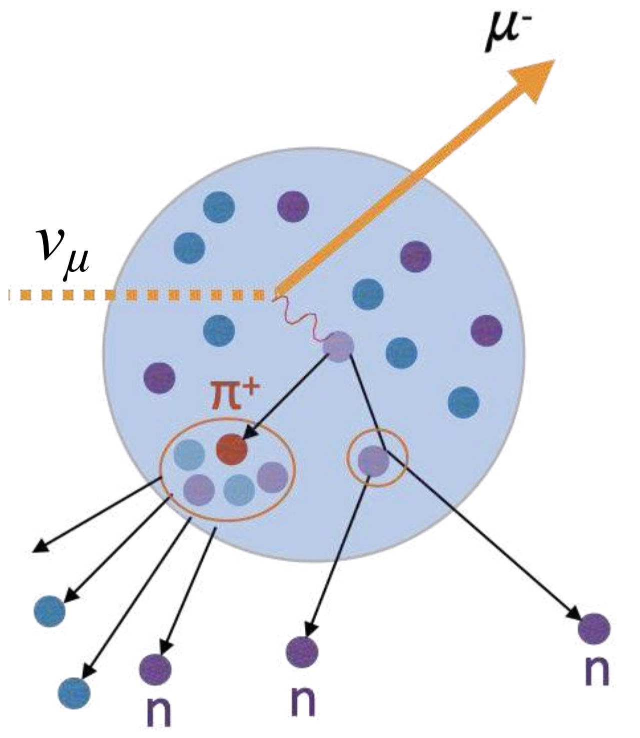
- Proximity to BNB target → high flux, overlap with T2K/LBNF
- ν_μCC interactions with oxygen, final state neutrons
    - Differential cross sections, *high-statistics* multiplicity vs. Q^2
    - Improved modeling of FS neutral production, input to generators
    - Constrain systematics for E_ν reconstruction in oscillation experiments

SNO, PRD 99 (2019) 11, 112007





Ryosuke Akutsu, PhD thesis (2019)



Credit: Andy Mastbaum (NUINT 24)

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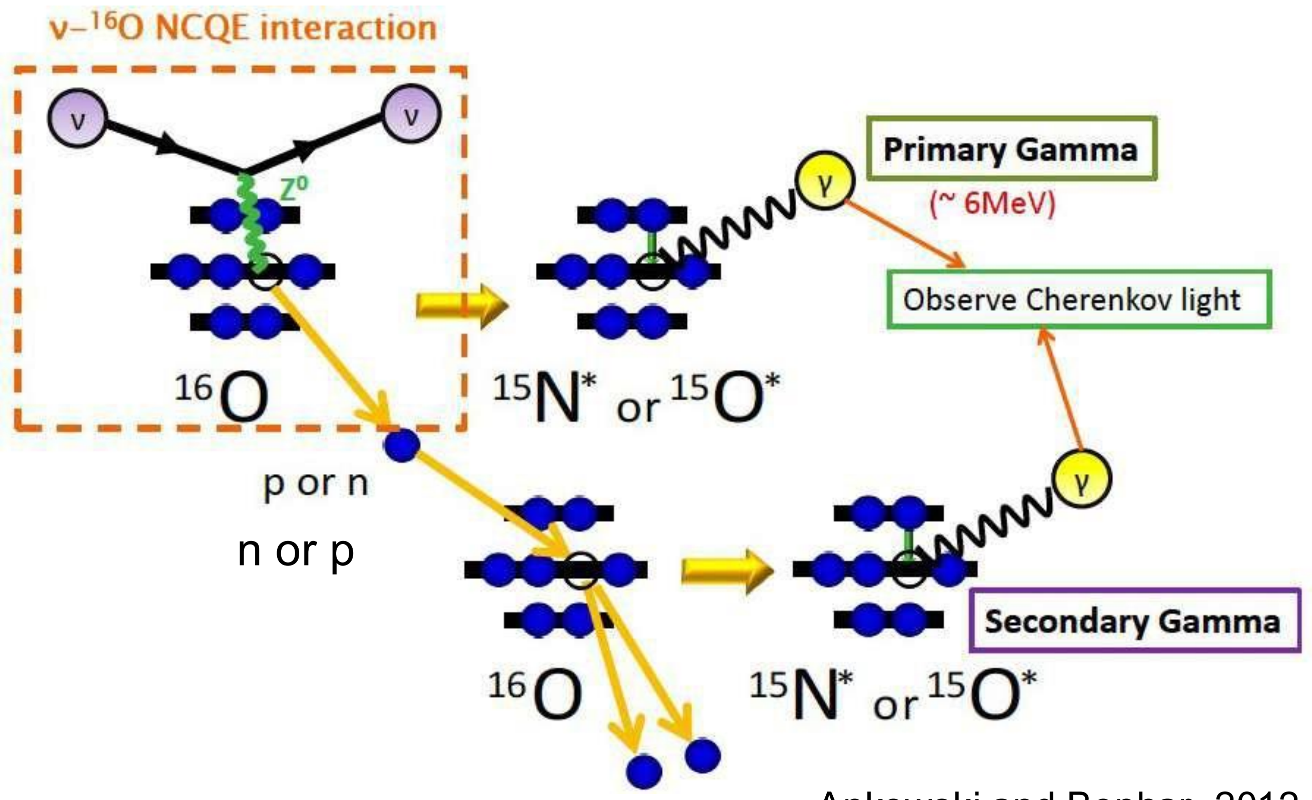
ANNIE Physics Program

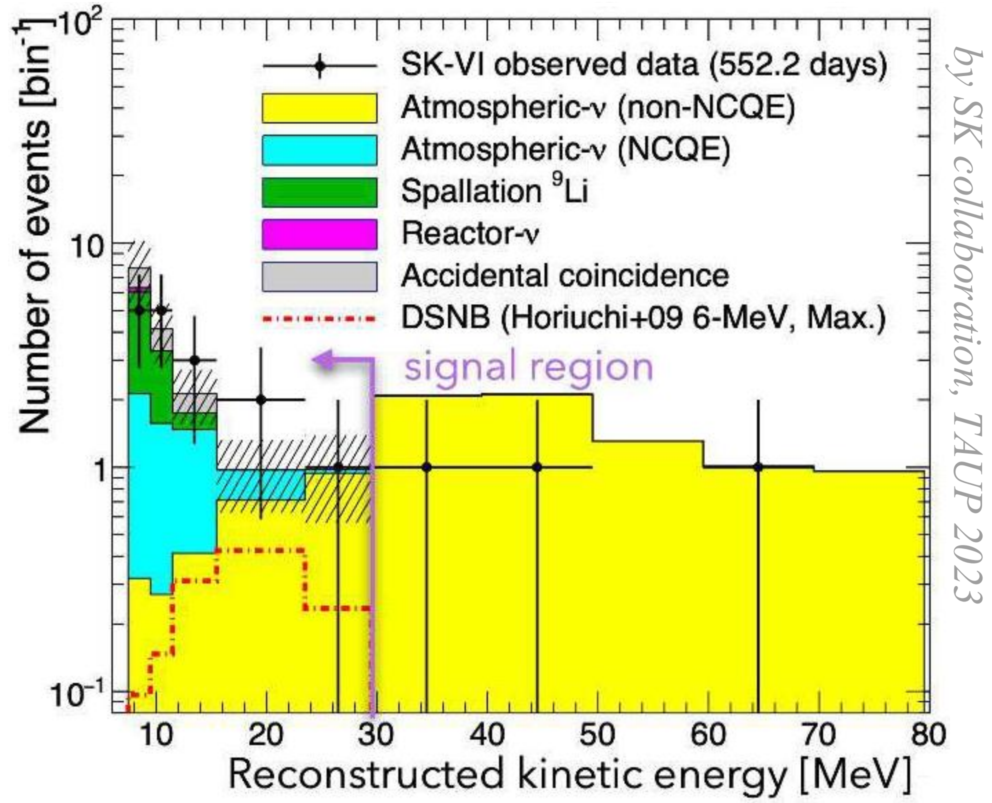
Measurements relevant to the neutrino oscillation program:

- Proximity to BNB target → high flux, overlap with T2K/LBNF
- ν_μCC interactions with oxygen, final state neutrons
- νNC interactions (cascade and neutrons)
  - Constrain backgrounds for LBL & *p* decay, DSNB searches
  - ~10k fiducial NC events/beam year, ~50% of which are NCQE



Ankowski and Benhar, 2012

SK DSNB



See also: Jie Cheng, Atm. NC (April 15); Anna Ershova, de-ex in p FSI (April 15)

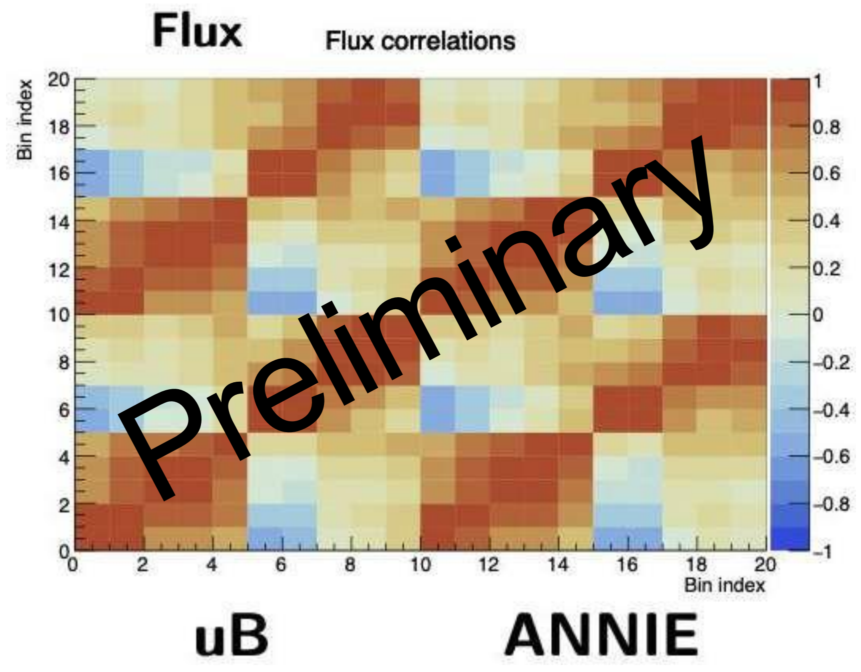
11

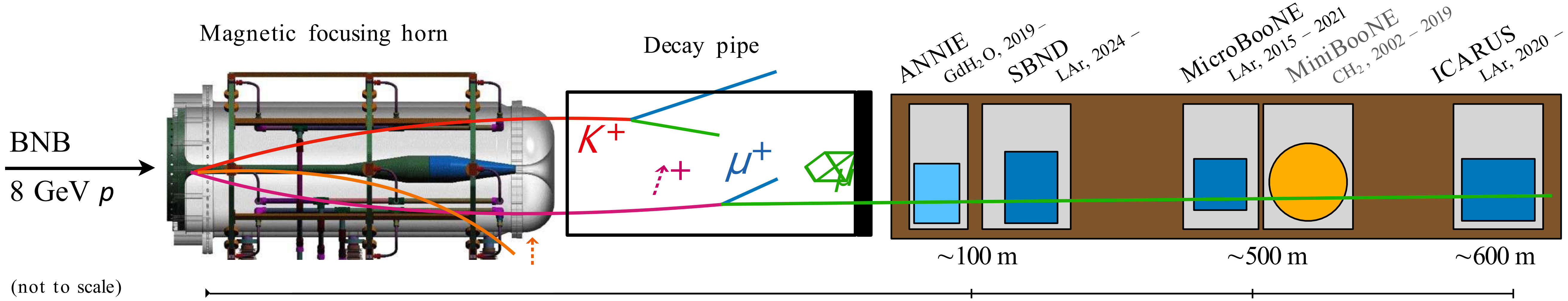
Credit: Andy Mastbaum (NUINT 24)

ANNIE Physics Program

Measurements relevant to the neutrino oscillation program:

- Proximity to BNB target → high flux, overlap with T2K/LBNF
- ν_μCC interactions with oxygen, final state neutrons
- νNC interactions (cascade and neutrons)
- Same neutrino beam as SBN LArTPCs
  - Precision $^{40}Ar/H_2O$ comparisons
  - Probe   scaling, simultaneous tuning
  - Correlations in hadron production (n/p)





See also: Steven Gardiner, Andy Furmanski, μBooNE CC0πNp (April 17)

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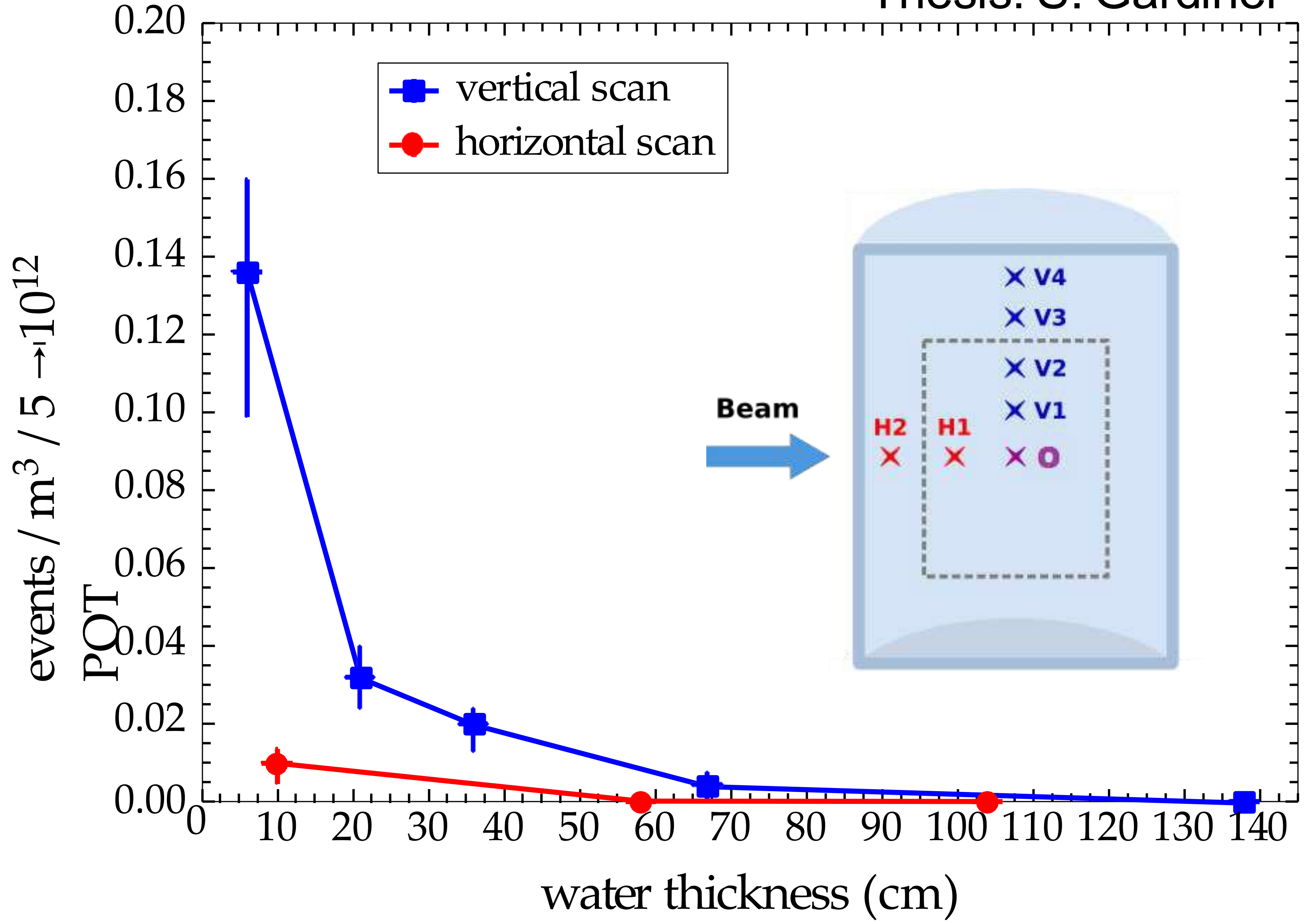
Credit: Andy Mastbaum (NUINT 24)

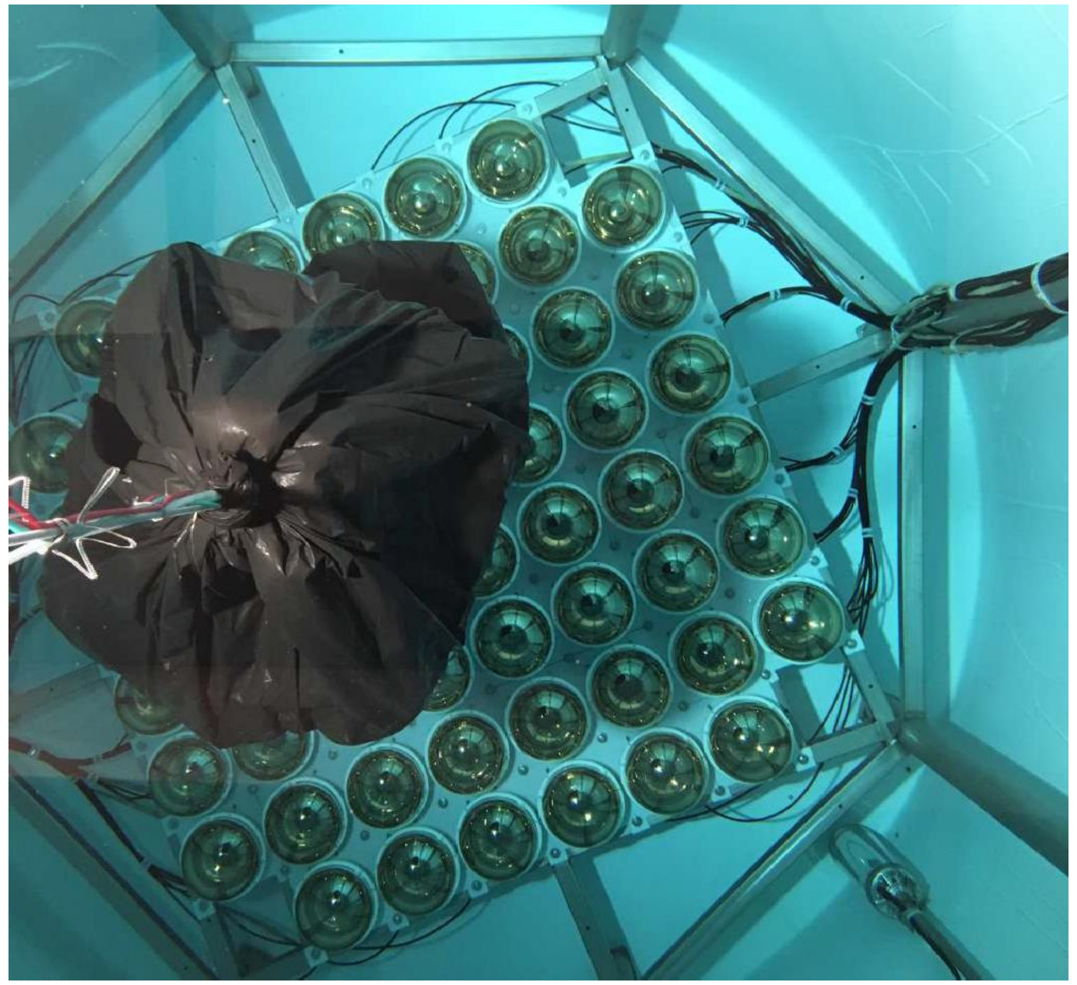
ANNIE Background Neutron Characterization

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

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

Thesis: S. Gardiner





Enabling Technology:
Large Area Picosecond Photodetectors (LAPPDs)

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

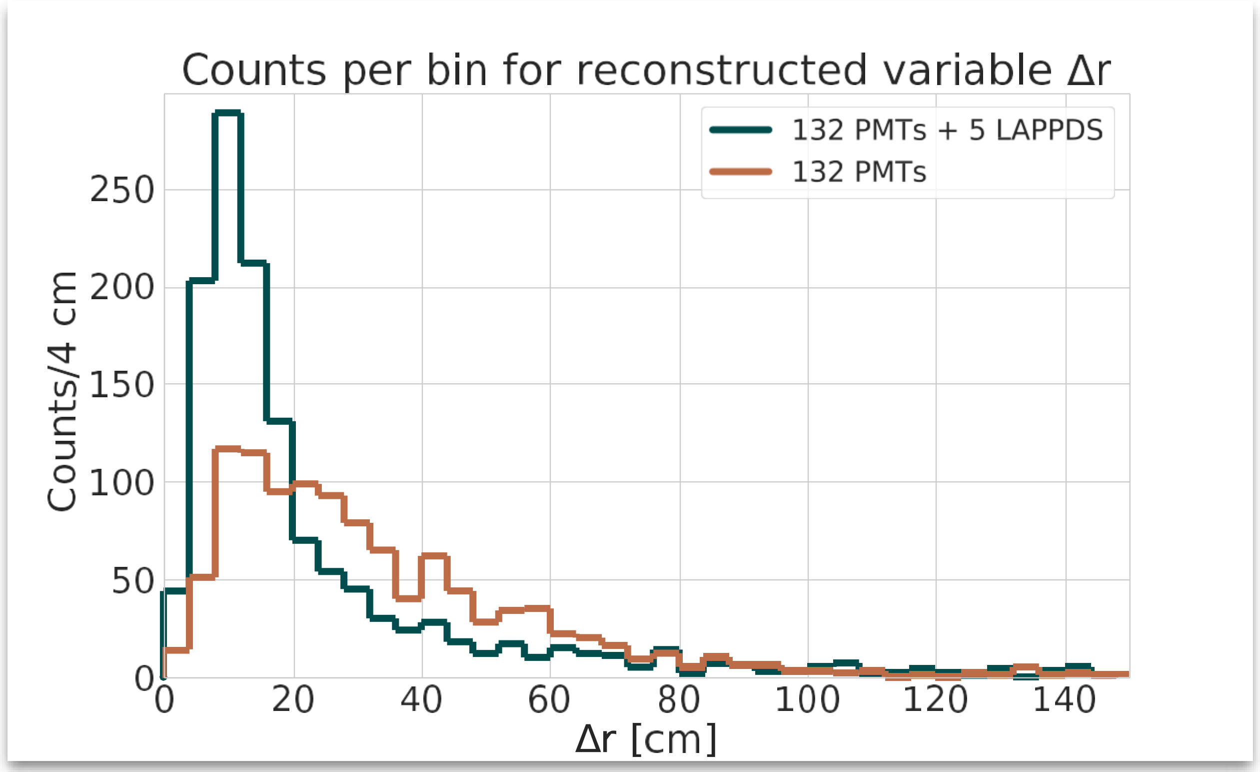
These advanced photosensors are now commercially available (Incom, Inc)

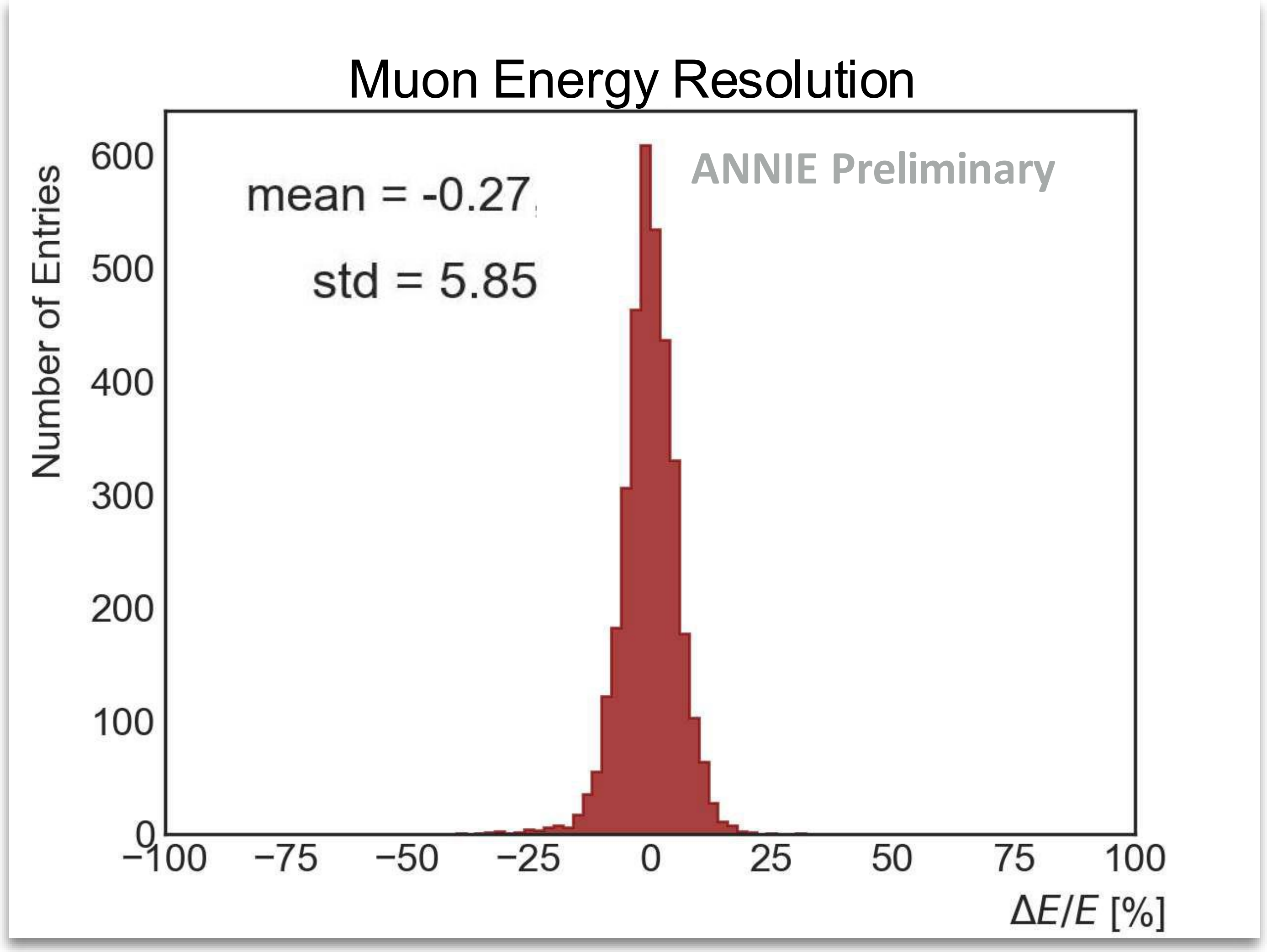
The ANNIE collaboration has purchased and received the initial 5 LAPPDs for our physics measurement

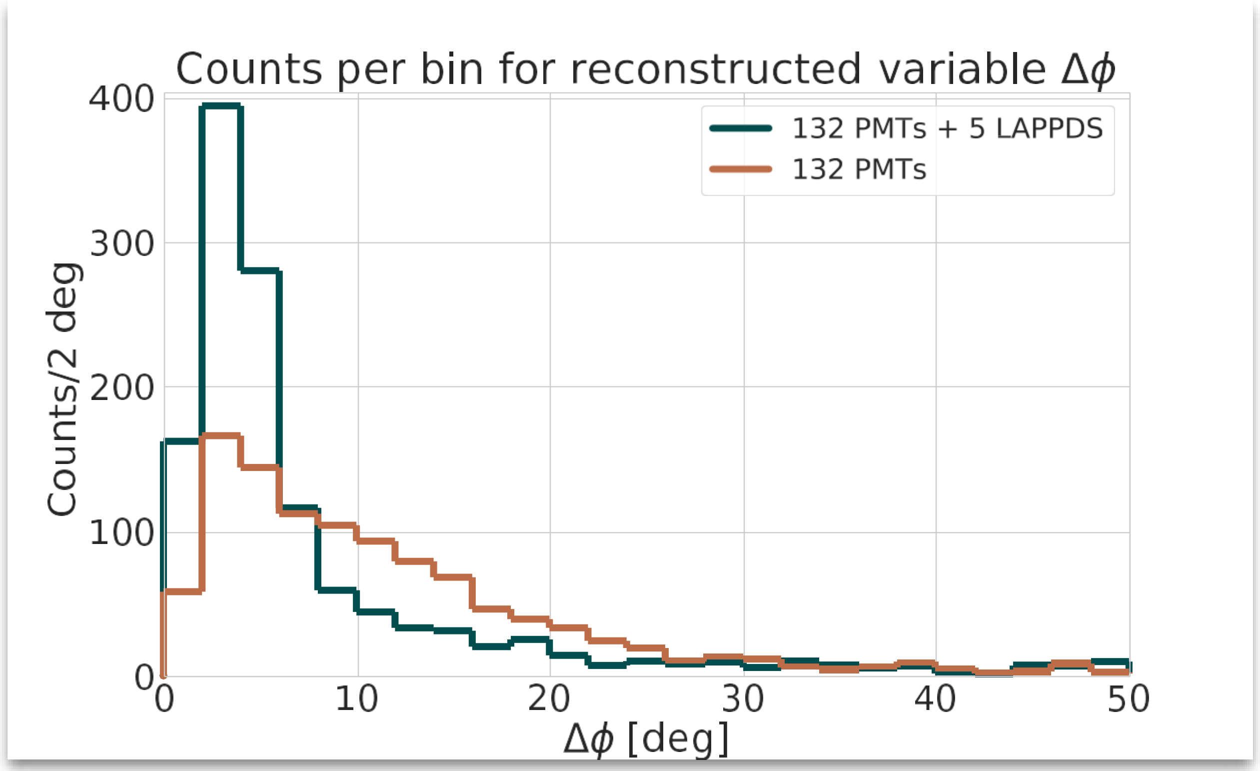
This fall, ANNIE will become the first applica8on of LAPPDs in a neutrino exp.

Enabling Technology: LAPPDs and Fast Timing

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



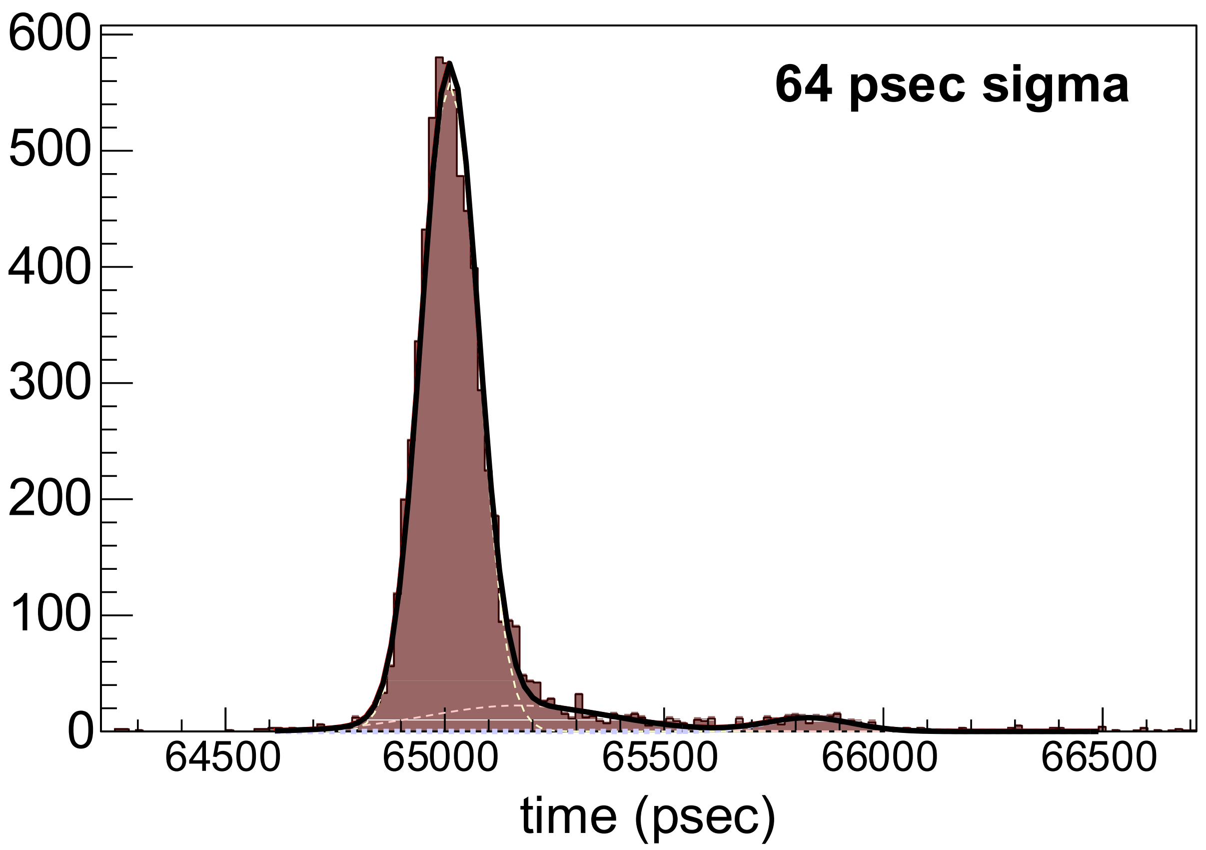


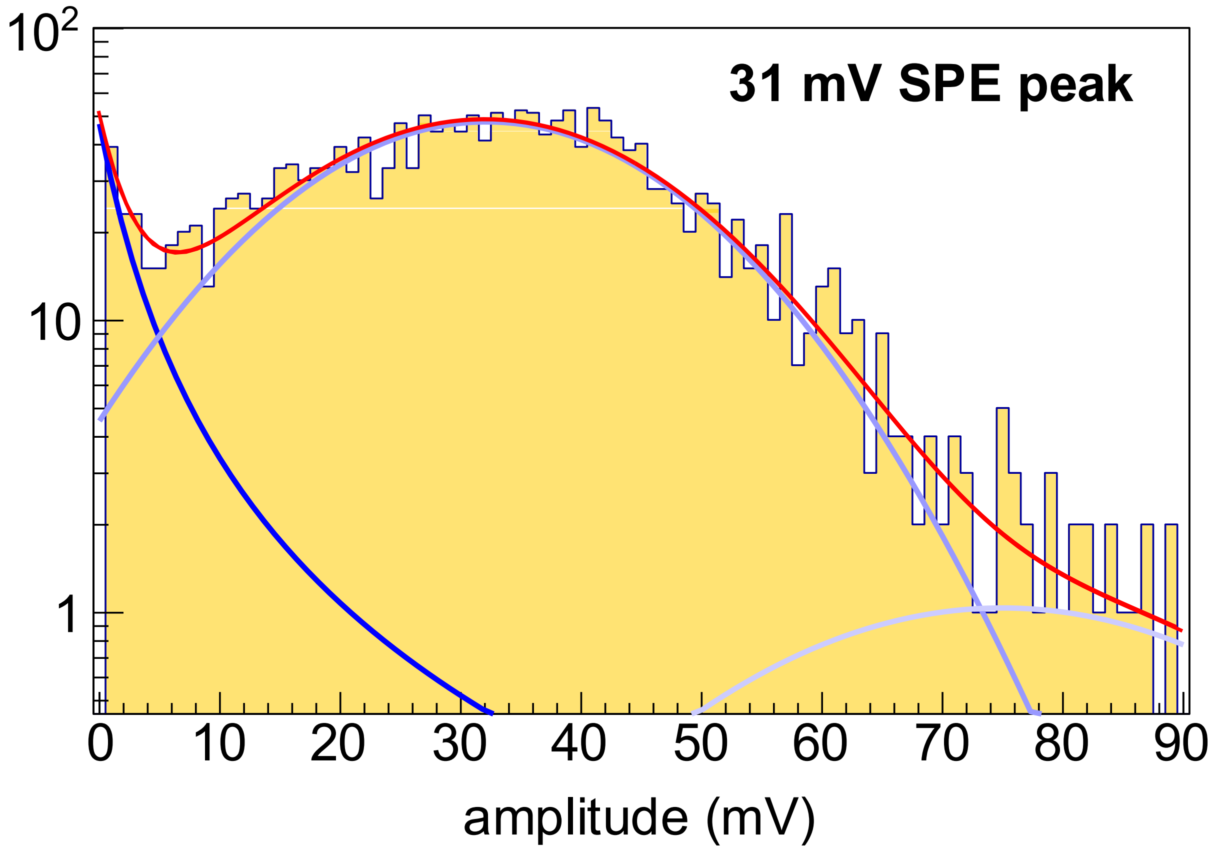


Enabling Technology: LAPPDs and Fast Timing

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

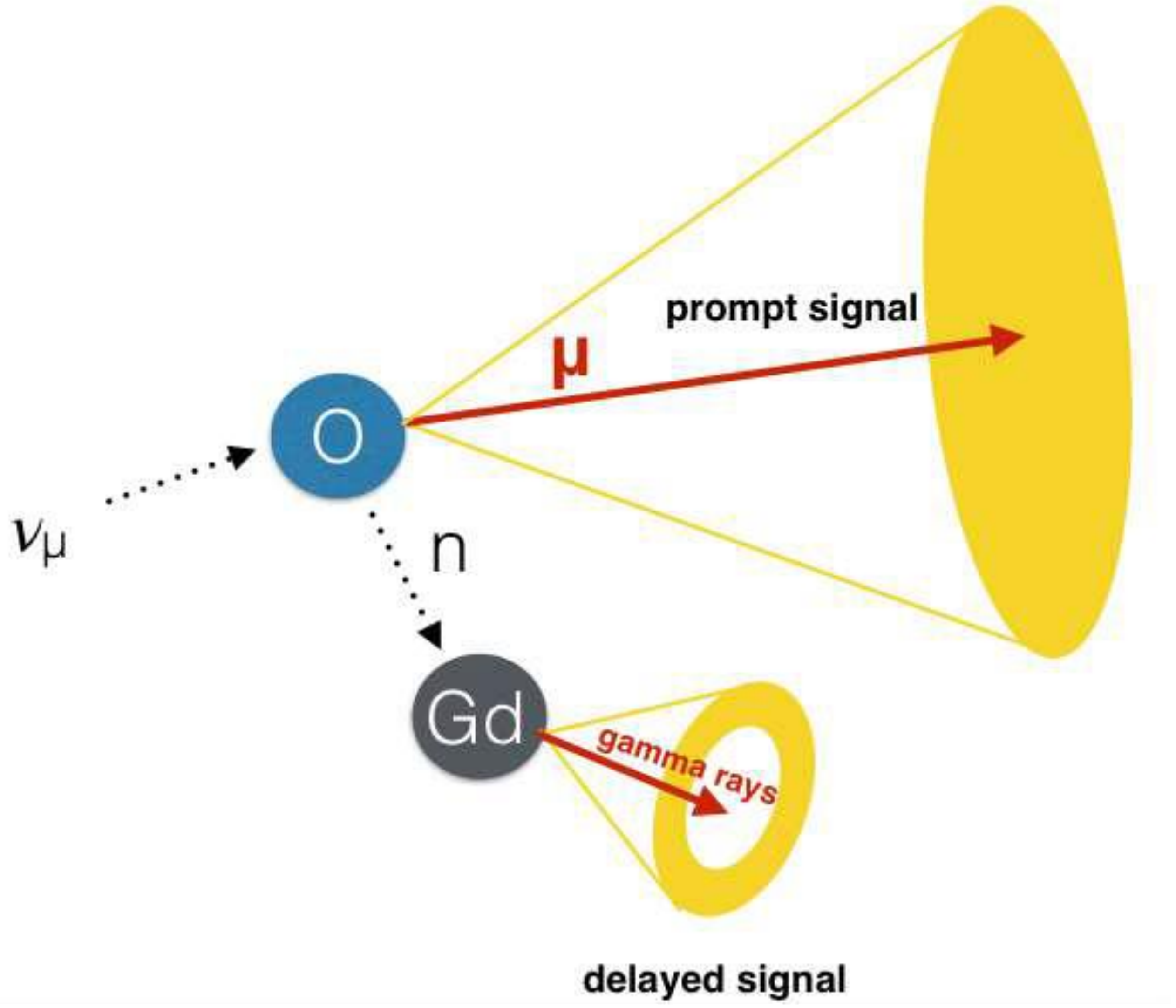
- The LAPPDs perform with resolutions consistent with our requested specifications:
  - <100 ps time resolution
  - gains of 10^7
  - few mm spatial resolutions





Enabling Technology: Gd-loading of water

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

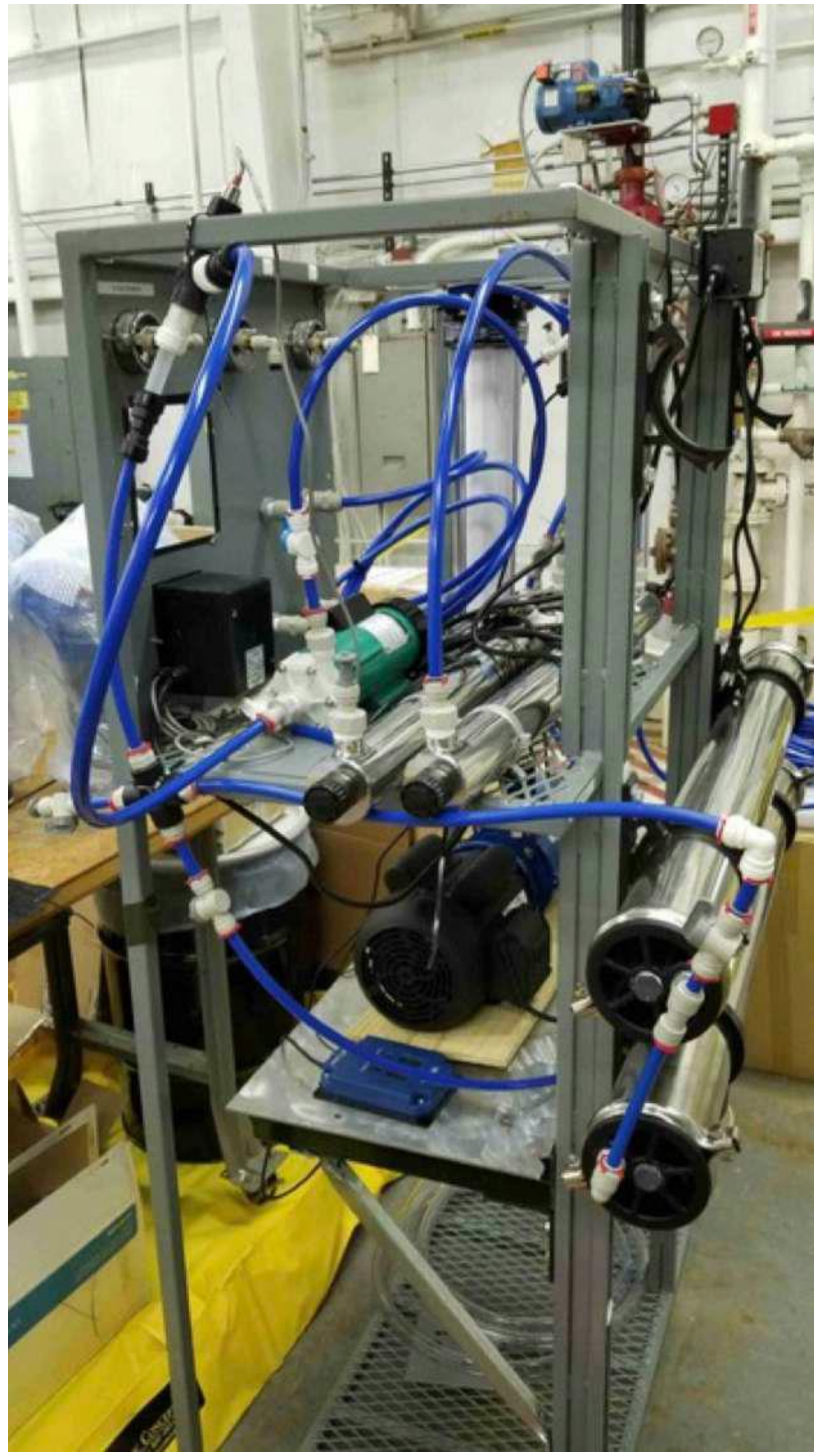


This fall, ANNIE will become the first Gd-loaded near detector on a beam

Enabling Technology: Gd-loading of water

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

ANNIE water skid

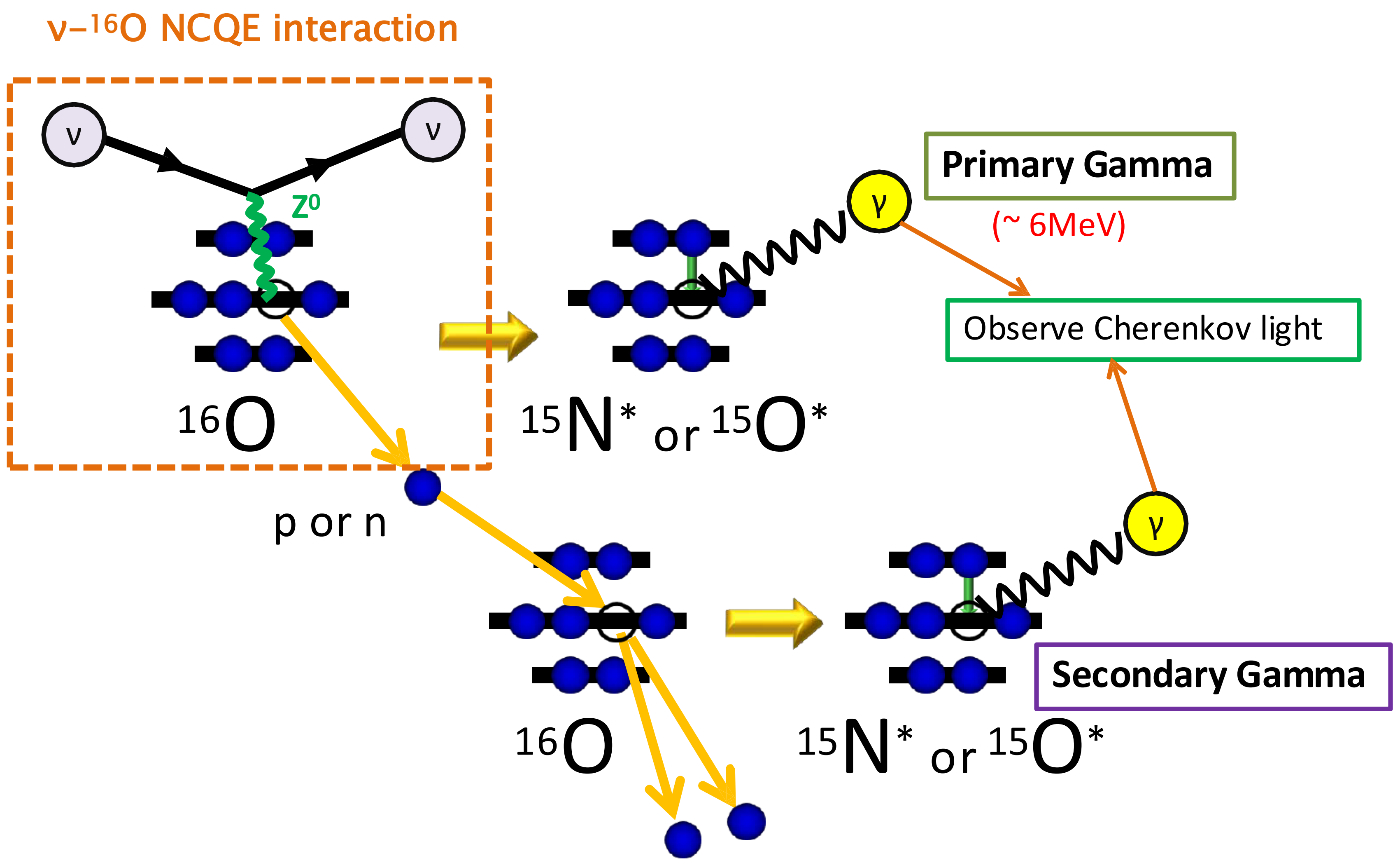


Tagging Nuclear De-excitation Gammas

- 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 interac2ons.

ANNIE can characterize and measure those backgrounds



source: disserta2on 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!!

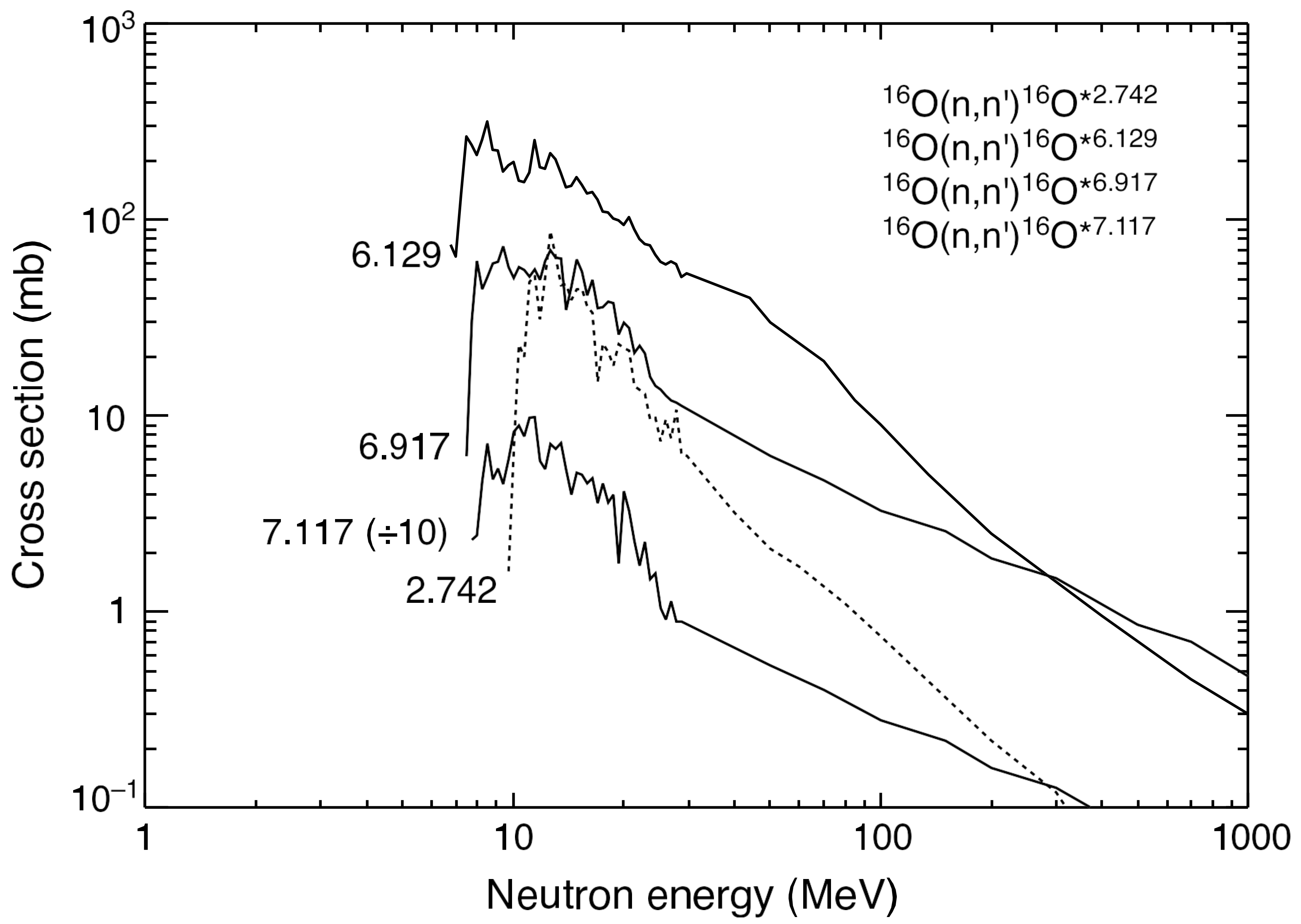
The gamma emission from radia2ve capture happens on nanosecond 2mescales

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?

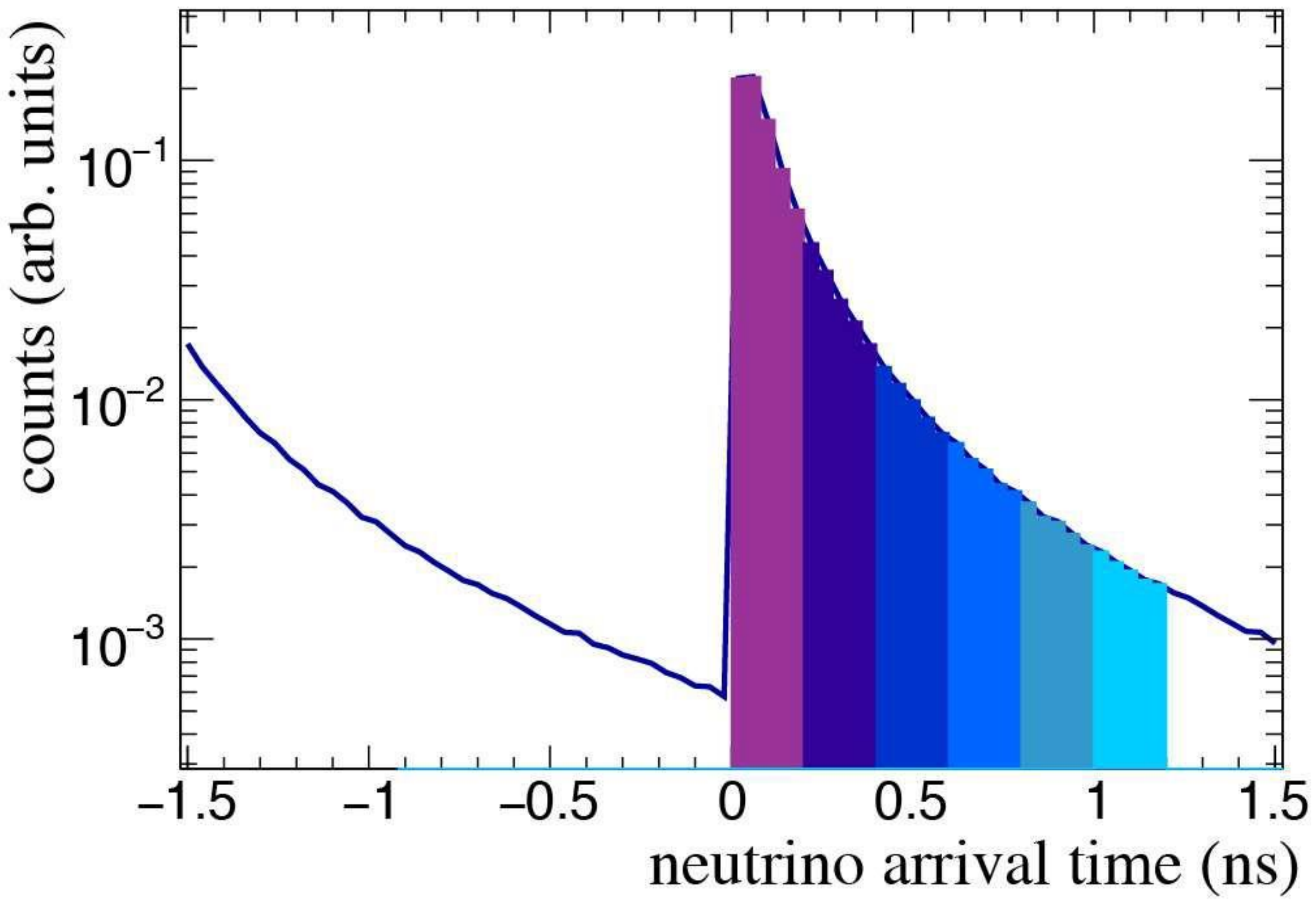
Oxygen captures may provide be;er constraints on the ini2al neutron energy.

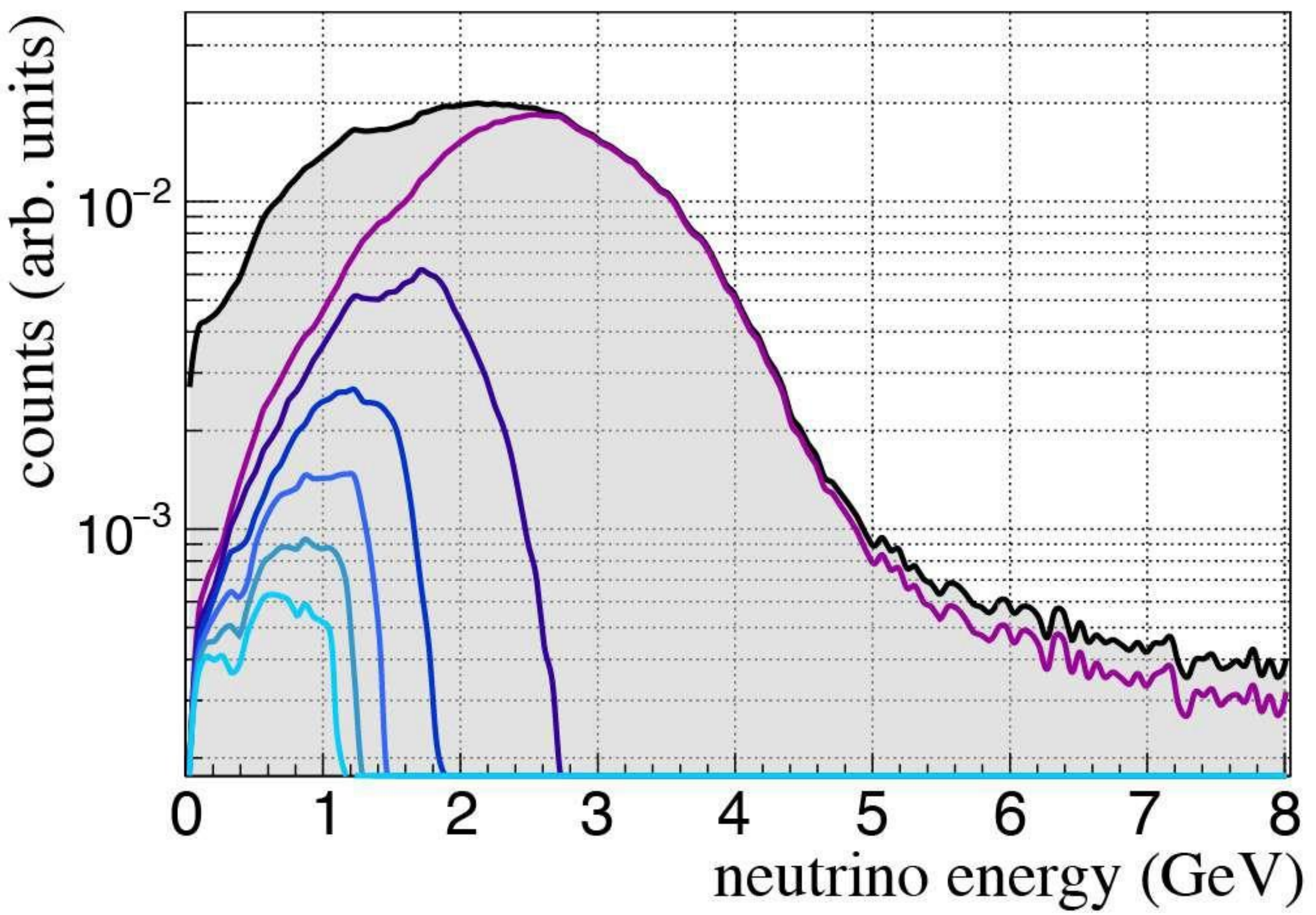


credit: Bei Zhou and John Beacom (OSU)

Basic Timing Concept

- Precision timing can be used to measure the arrival time of neutrinos with respect to the rest of the bunch
- Later neutrinos tend to have lower energies due to the correlation between neutrino energy and the velocity of the parent hadron
- This allows one to select different flux spectra based on timing
- All of these fluxes co-exist within a single on-axis detector



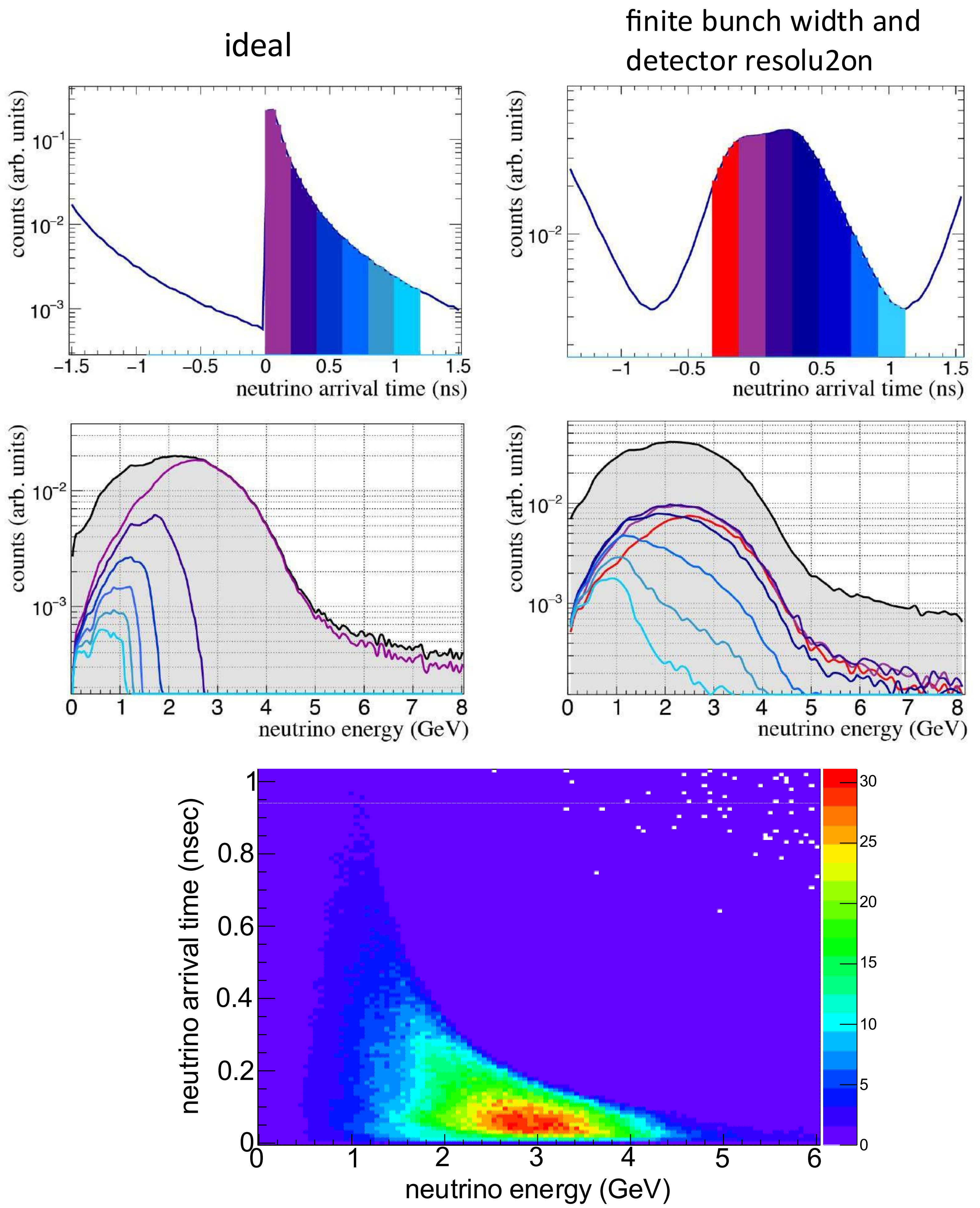


Fast Timing and Beam Physics

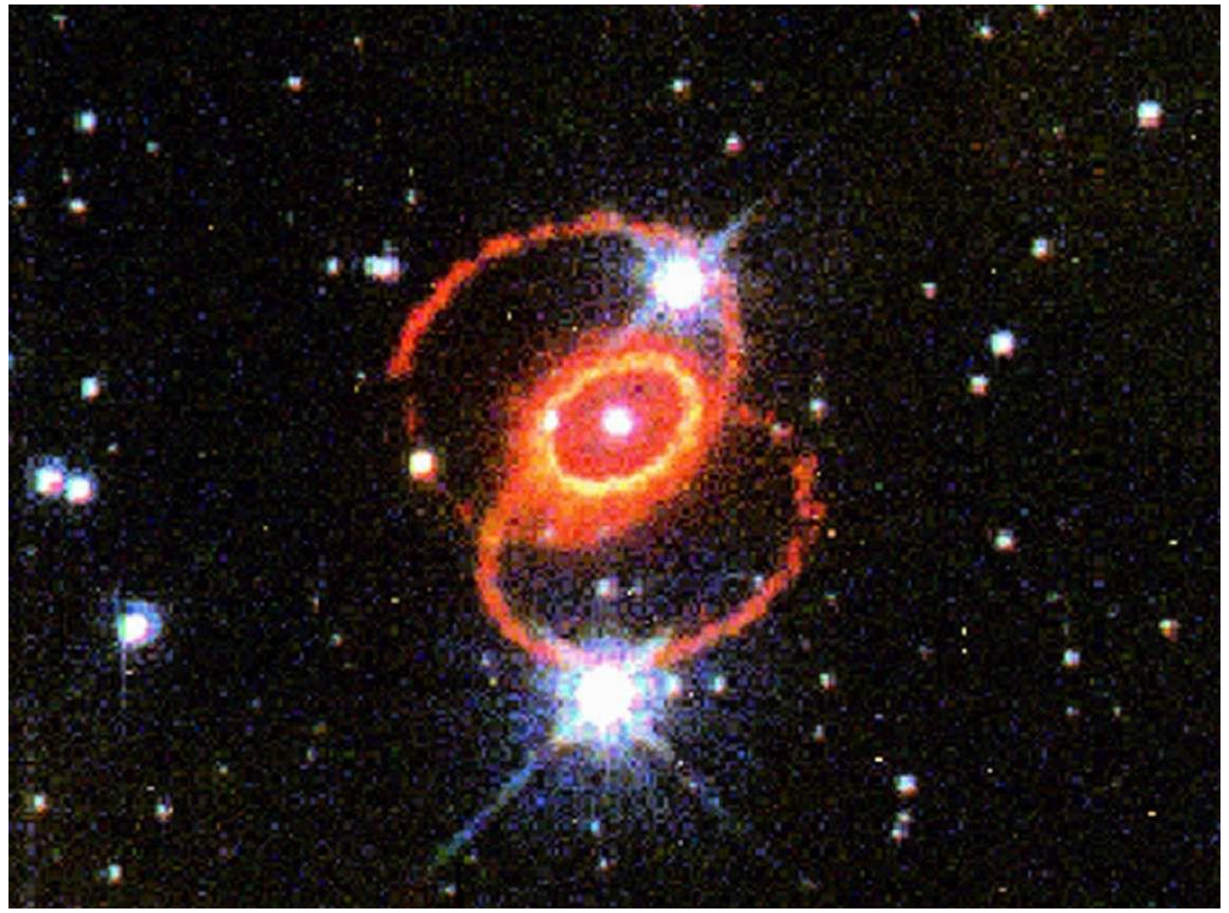
- Timing could potentially be used to select narrower, lower-E neutrino spectra, much like looking off-axis
- Is driven by time-of-flight differences between pion energies
- O(1) nsec time structure of the bunch washes out the effect but the broad tail of late neutrinos remains
- Requires sub-nsec time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

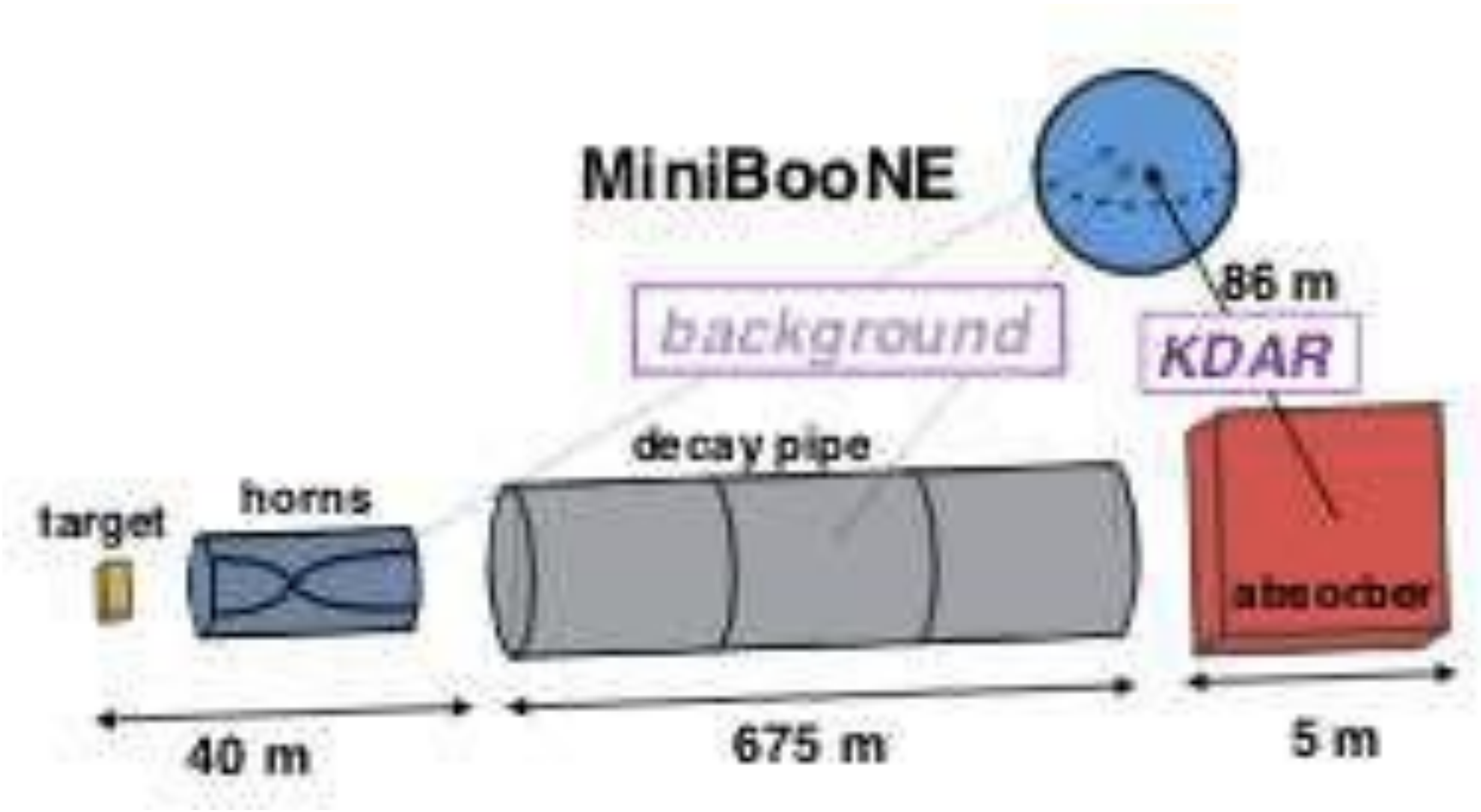
h"ps://arxiv.org/abs/1904.01611

LBNF Flux (Simula8on)



Prior Efforts on Timing





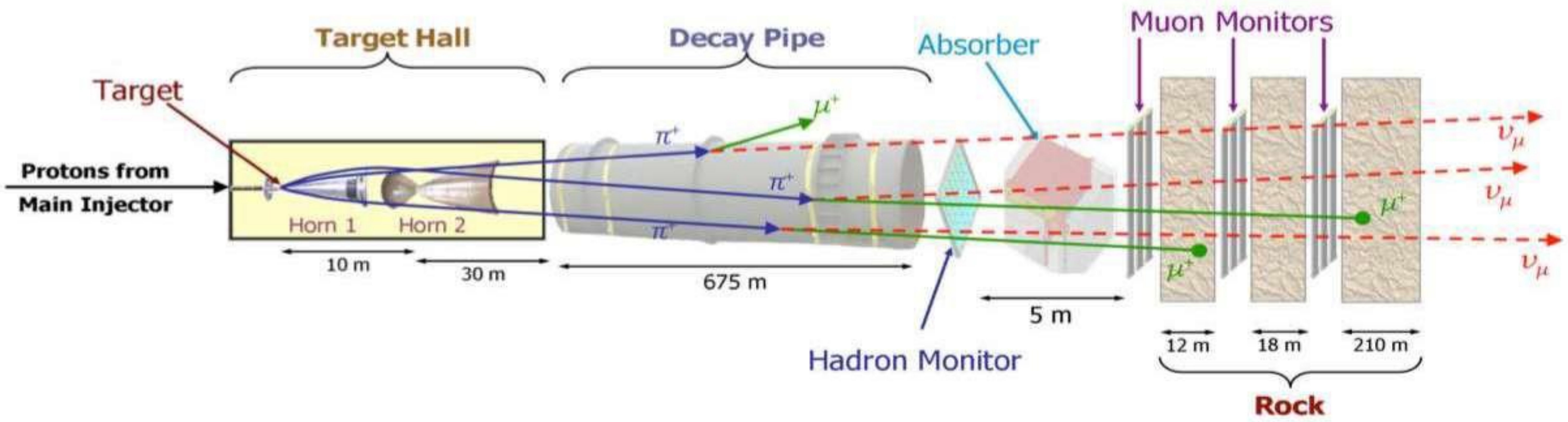
- M Goldhaber suggested that neutrino arrival times could be used in the analysis of SN1987a 10.1142/S0217751X03017154
- MINOS demonstrated precision timing with the sub-structure of NUMI in their neutrino time-of-flight paper https://arxiv.org/abs/1408.6267
- MiniBooNE recently published a stopped Kaon analysis based on arrival time with respect to the bunch. https://arxiv.org/abs/1801.03848
- MiniBooNE also explored the idea of selecting different energy spectra

Melanie L Novak, Bucknell (2002)

- Proton beams collide with a target, producing pions and kaons
- These hadrons are selected by sign and momentum and focused by a series of magnetic horns

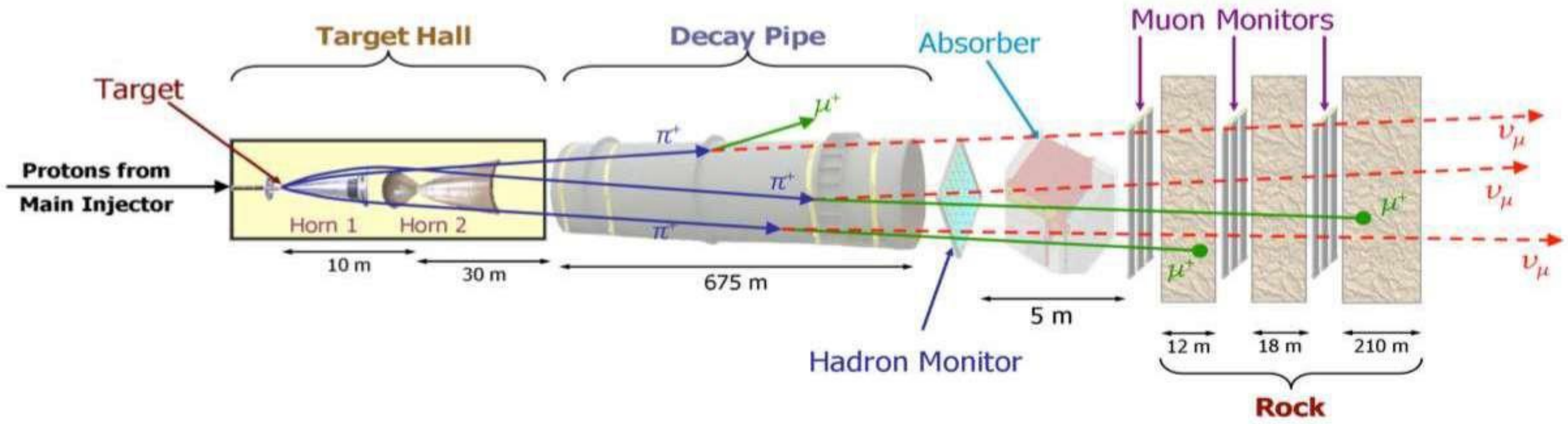
- The hadrons decay into muons and ν_μ's with a strongly forward directionality.
- An intrinsic background or ν_e's originates from early-decay of the muons. An additional wrong-sign component originates from hadrons not rejected by the magnetic horns.

The final kinematics of the neutrinos are driven by hadron kinematics & decay time



Kinematics of the Neutrino Timing

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

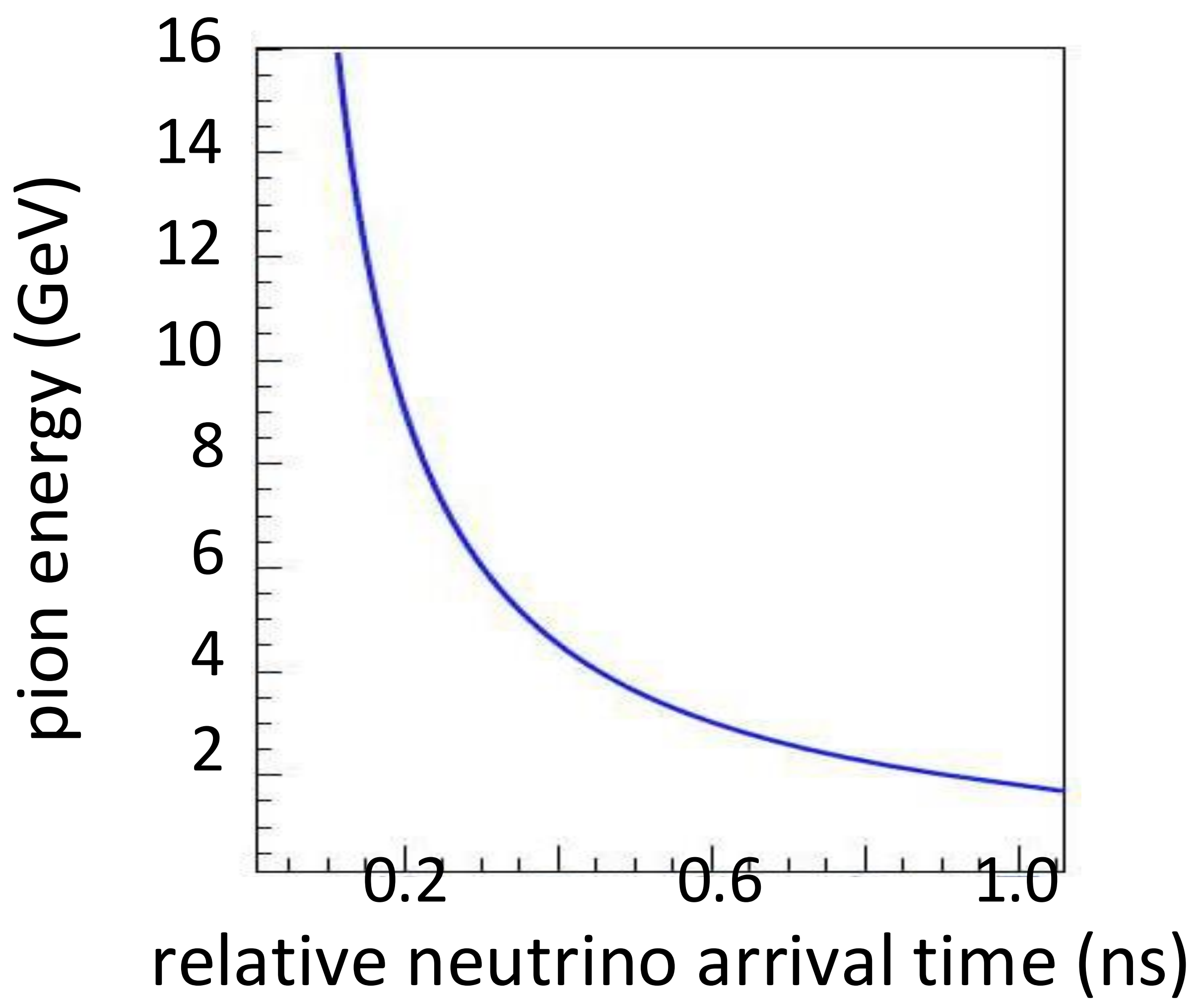


$$\Delta t(E) = \tau(E)[1-\beta(E)]$$

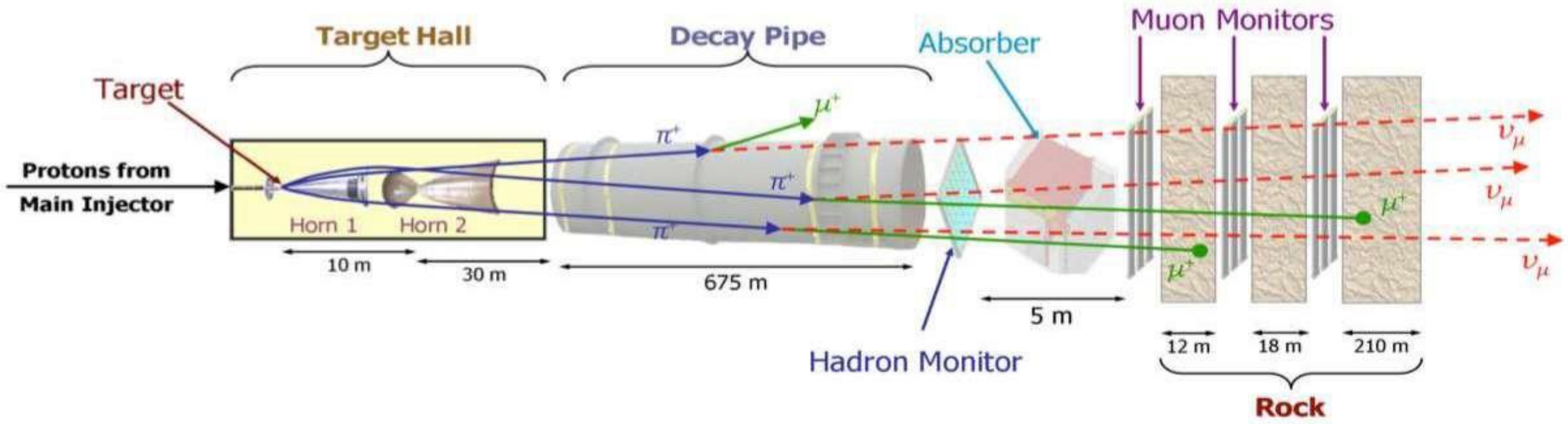
$$\Delta t(E) = (\gamma\tau_0)[1-\sqrt{(1-1/\gamma^2)}]$$

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

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



Kinematics of the Neutrino Timing



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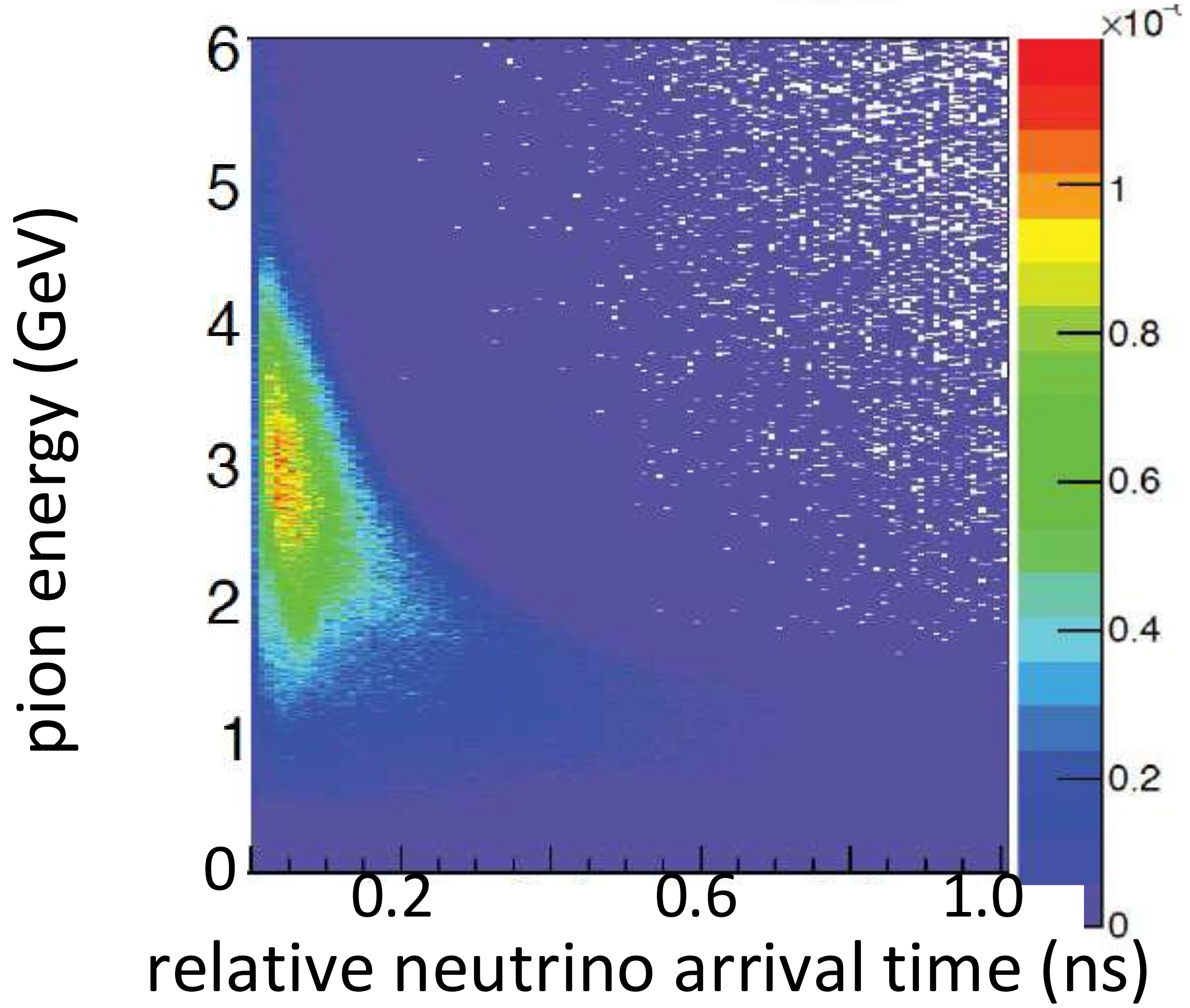
$$\Delta t(E) \rightarrow \tau_0 \quad \text{as} \quad \gamma \rightarrow 1$$

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



Characteristic Timescales/Limiting Factors

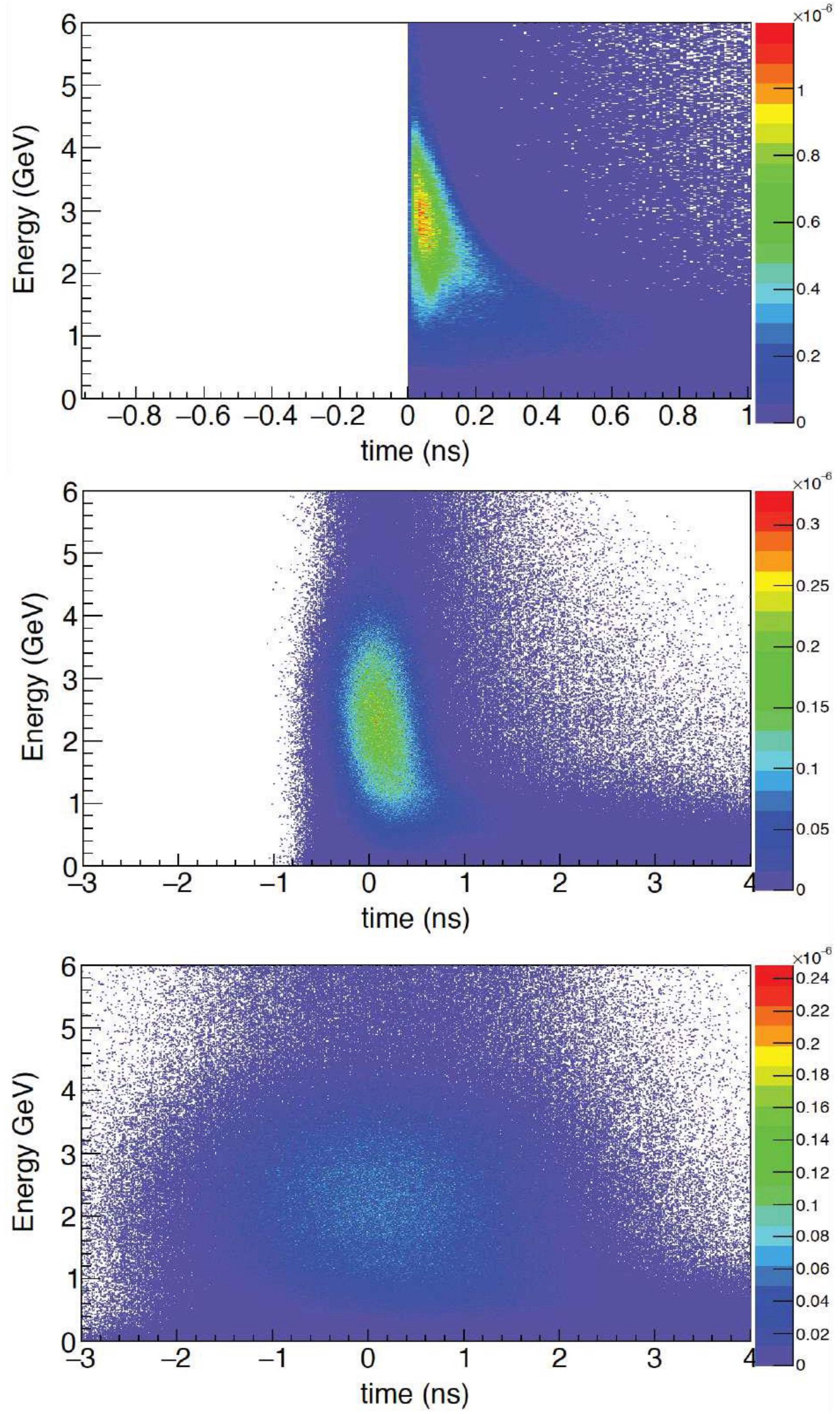
Stroboscopic techniques require sufficiently short bunch sizes

- 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

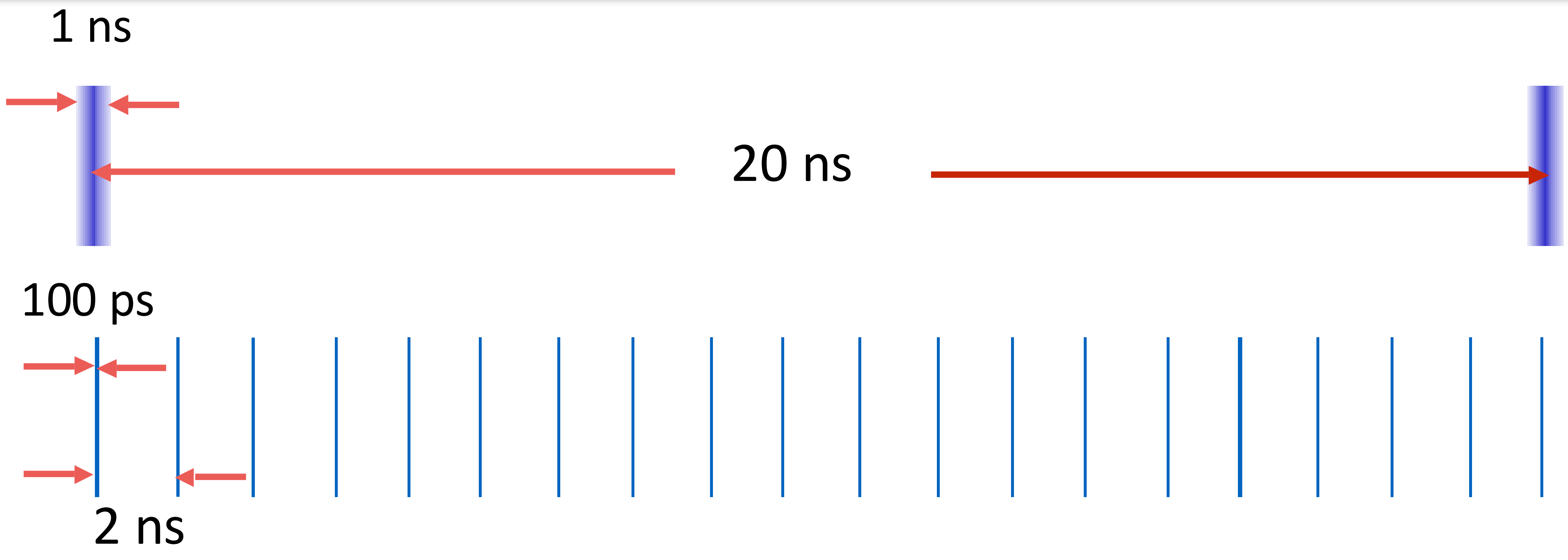


Rebunching the Beam

- 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



Bunch Rotation

Some techniques within the current capability of the Fermilab accelerator complex could shorten bunch Wmes.

Credit: Ganguly et al

h;ps://arxiv.org/abs/2410.18256

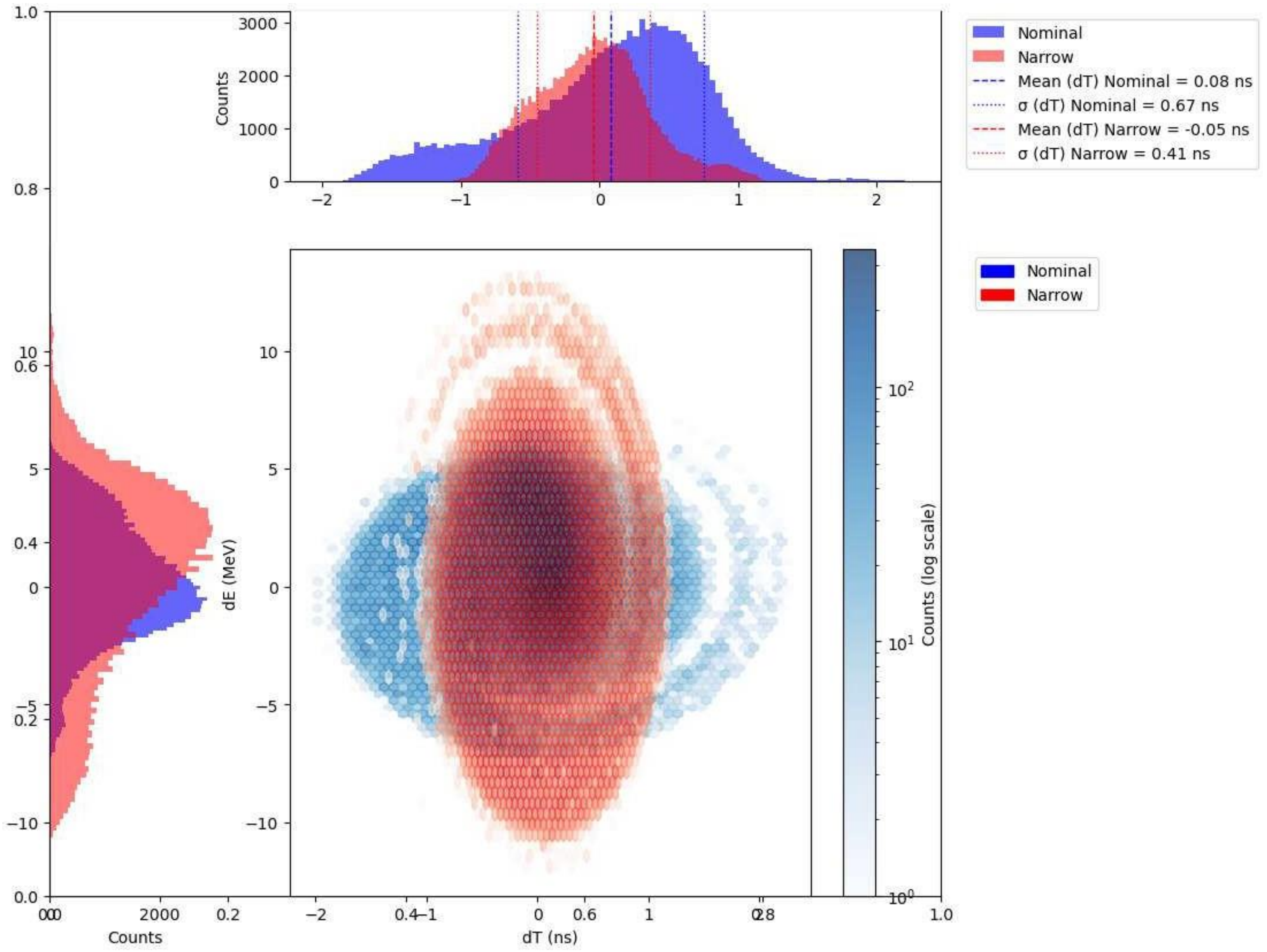
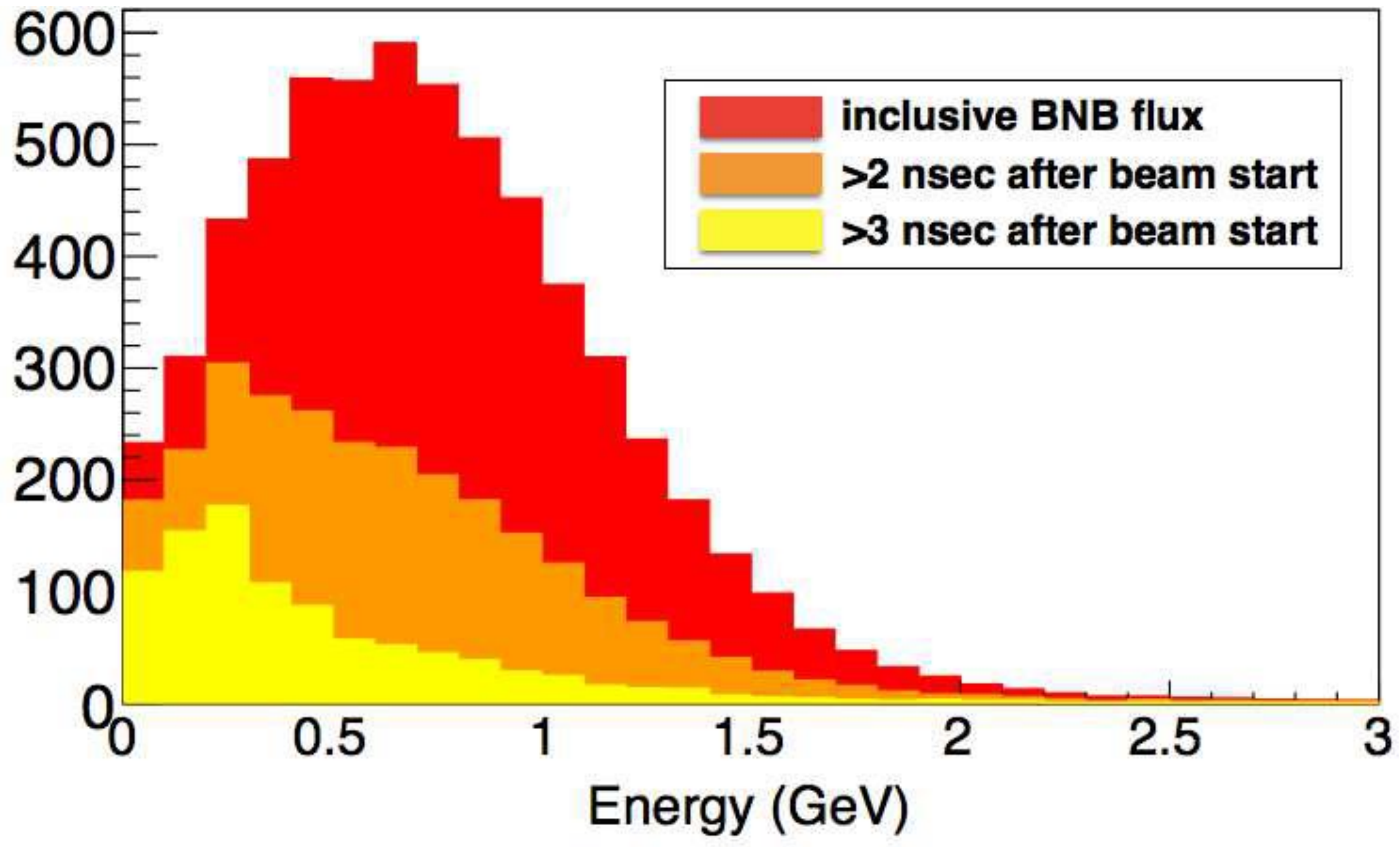


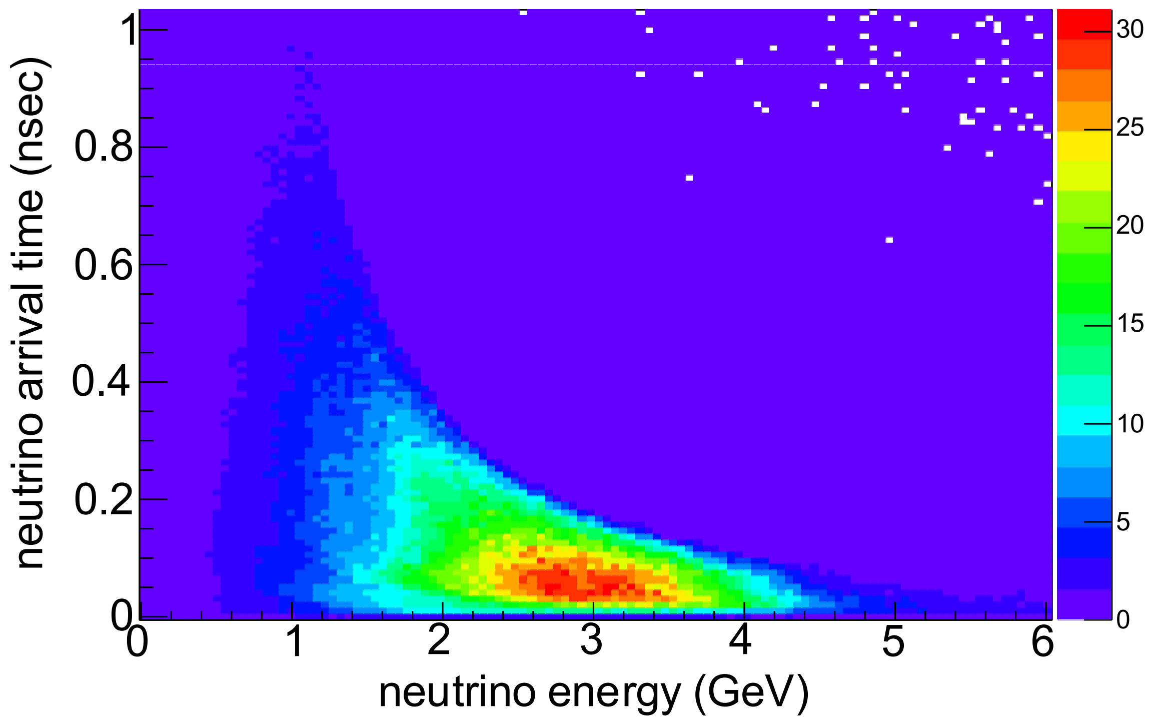
Fig. 11: Simulation of phase space with nominal (blue) and minimized (red) bunch lengths. The plot shows the exchange of time (dT) and energy (dE) with varying bunch lengths in the Booster at Fermilab.

Fast Timing and Beam Physics

BNB (Simula8on)

finite bunch width and
detector resolu2on





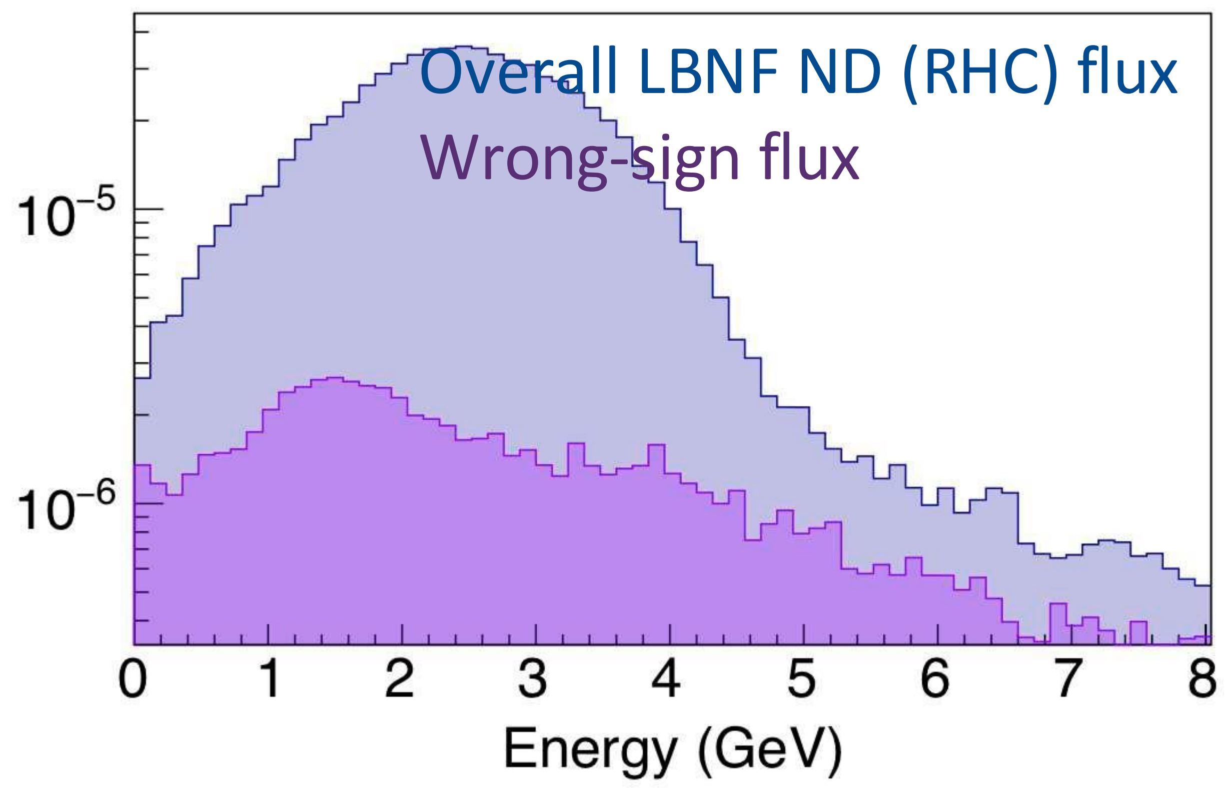
- Timing could potentially be used to select narrower, lower-E neutrino spectra, much like looking off-axis
- Is driven by time-of-flight differences between pion energies
- O(1) nsec time structure of the bunch washes out the effect but the broad tail of late neutrinos remains
- Requires sub-nsec time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

h"ps://arxiv.org/abs/1904.01611

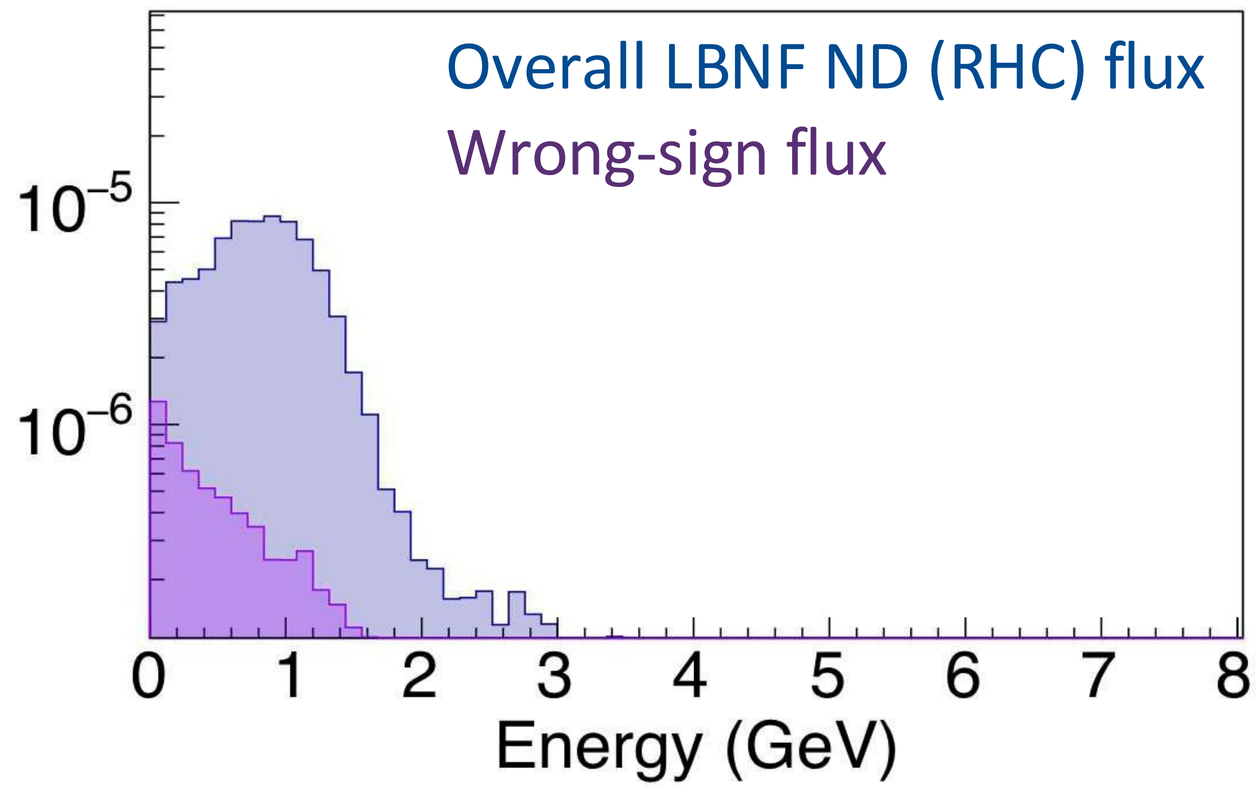
Separating different components of the beam

- The relative normalization and ***shape*** of the different components of the neutrino flux (wrong-sign, intrinsic ν_e , K/π) evolve differently and in deterministic ways with respect to the timing cuts
- Fitting in multiple time slices greatly constrains the fit to the overall flux

time slice from -0.3 to –0.1 ns



time slice from 0.9 to 1.1 ns



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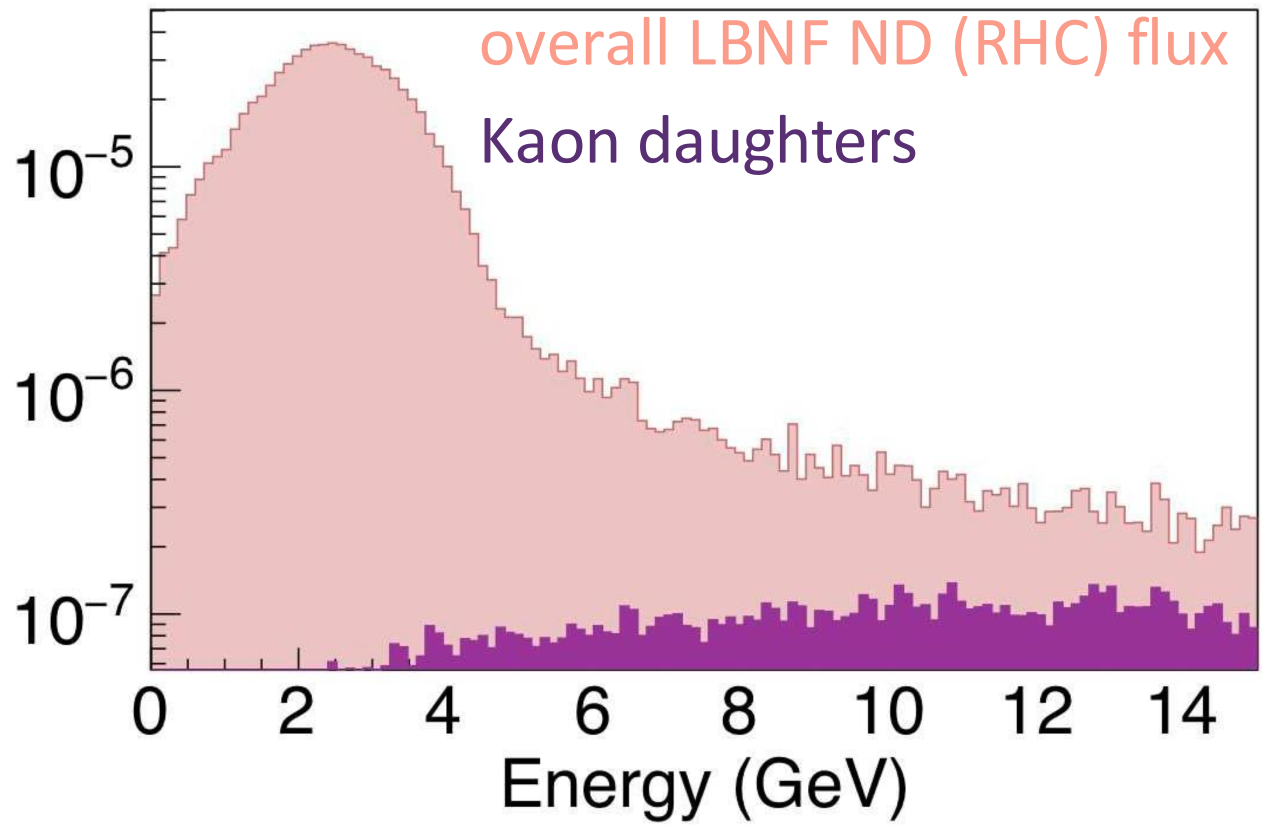

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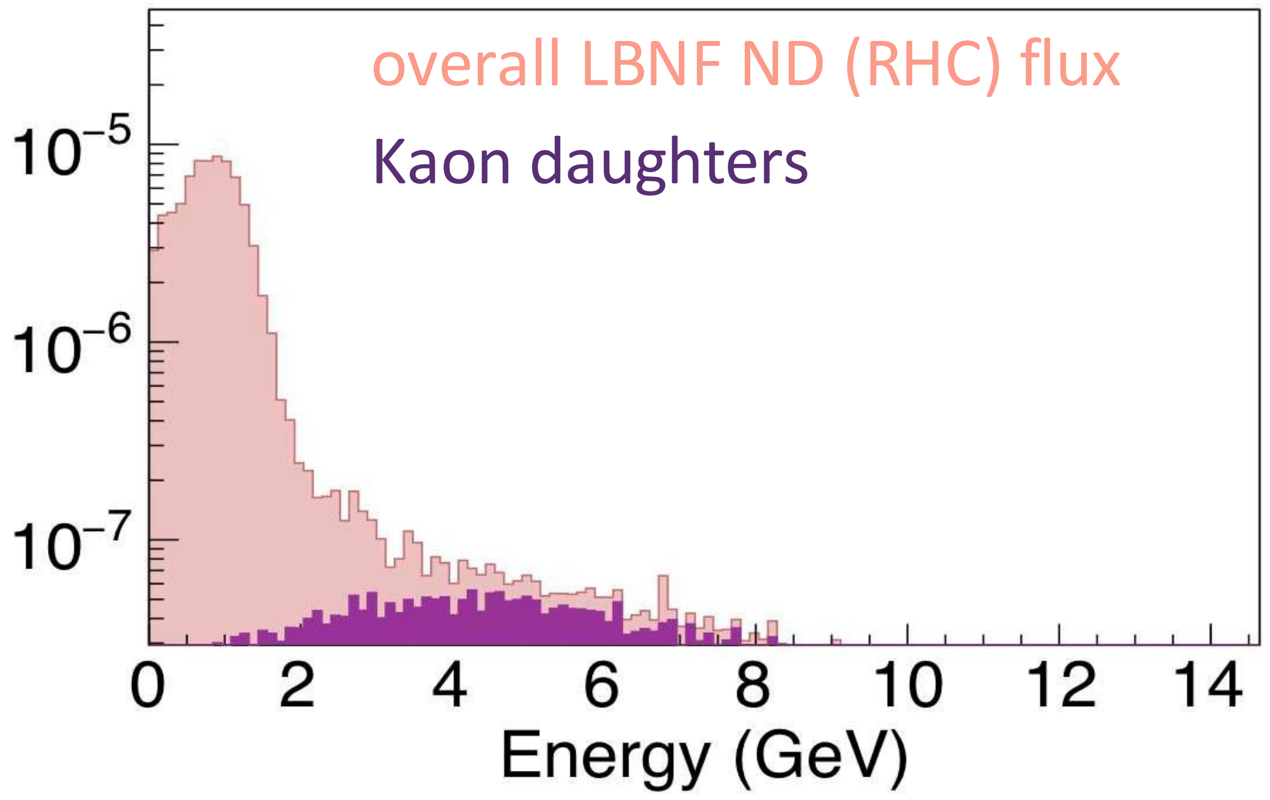

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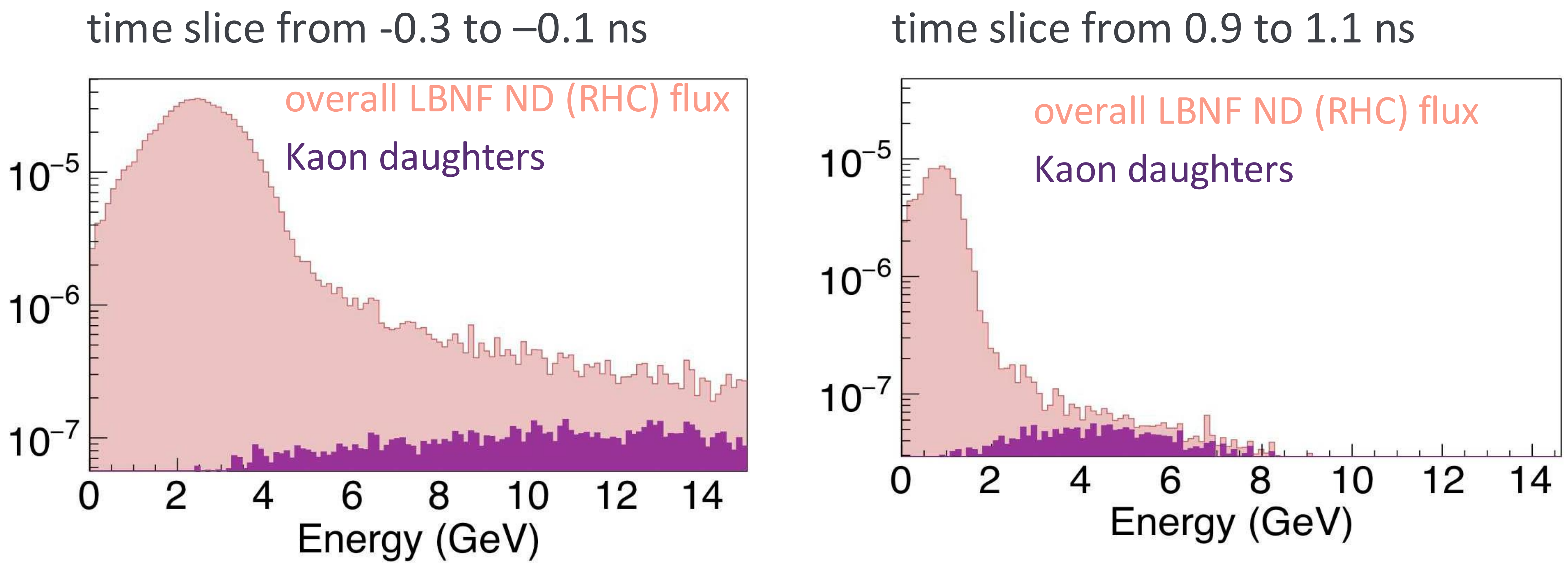

- Imagine having to fit the flux model to a 2-d grid of spectra binned in off-axis angle *and* time slice!