Photon Detector Designs for the Deep Underground Neutrino Experiment

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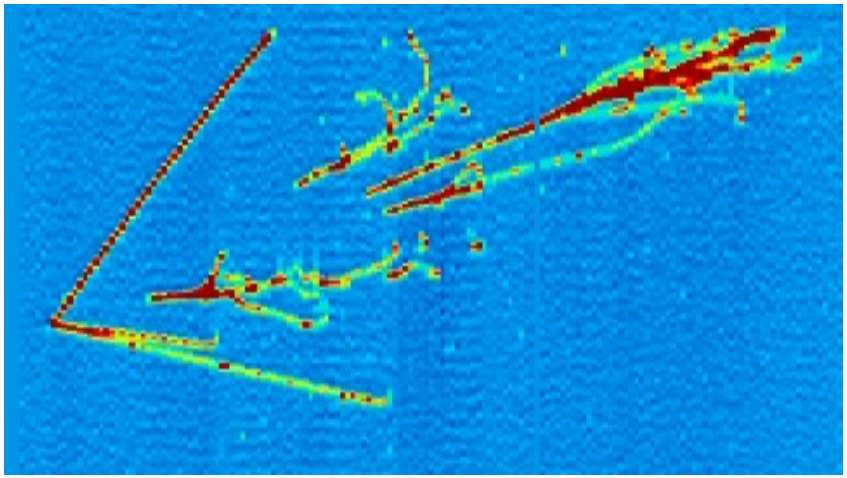
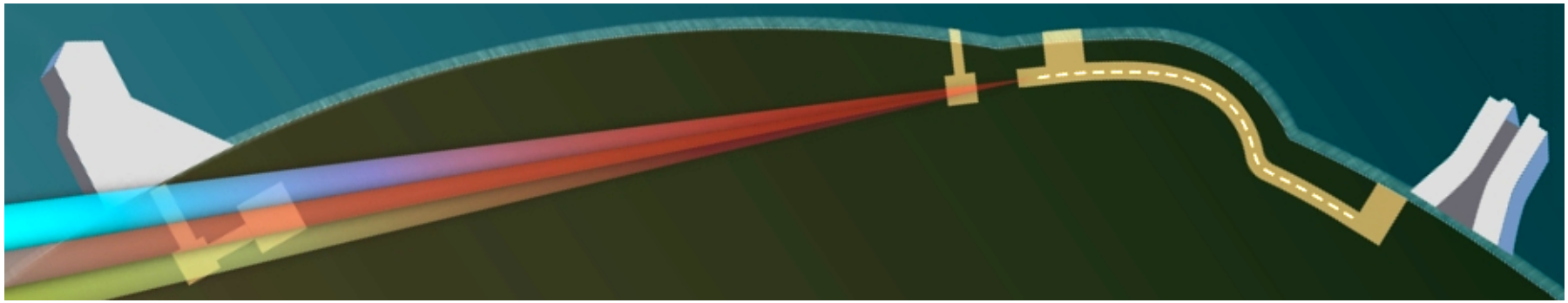
On behalf of the DUNE Collaboration

Outline

- Principles of photon detection in DUNE
- Light guides for a single-phase TPC
  - Baseline design
  - Alternatives
- Silicon photomultipliers
- Design testing in LAr at FNAL
  - Data-simulation comparisons
- Scintillation structure analysis
- Continuing hardware R&D

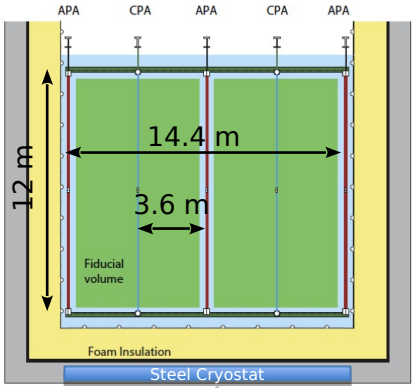


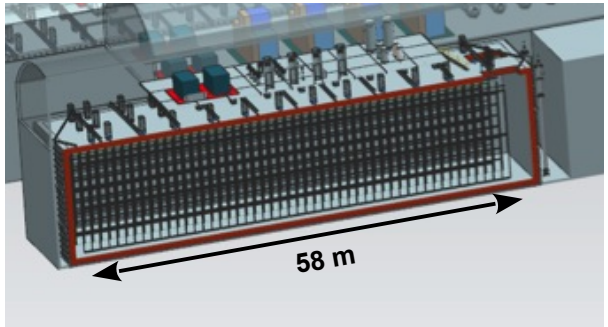


- Scintillation from de-excitation of argon molecular state
  - 128 nm UV, two components
    - Prompt (singlet state) signal (τ ~ 6 ns)
    - Slow (triplet state) signal (τ ~ 1.5 μs)

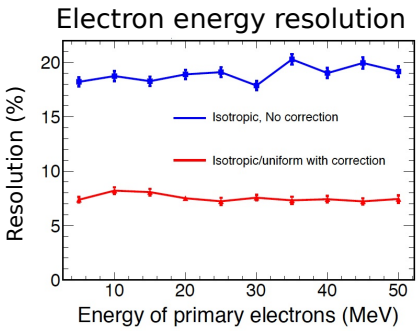
$$\mathrm{Ar}^* + \mathrm{Ar} \rightarrow \mathrm{Ar}_2^* \rightarrow 2\mathrm{Ar} + \gamma$$

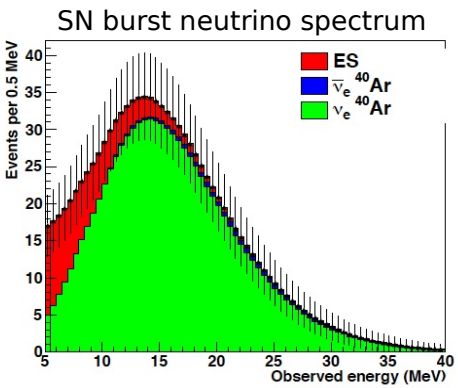
- Photon signal gives t_0 for transverse position determination
  - Calculate drift distance from time of arrival and known drift velocity in TPC E-field
  - Resolution of < 100 ns easily attainable





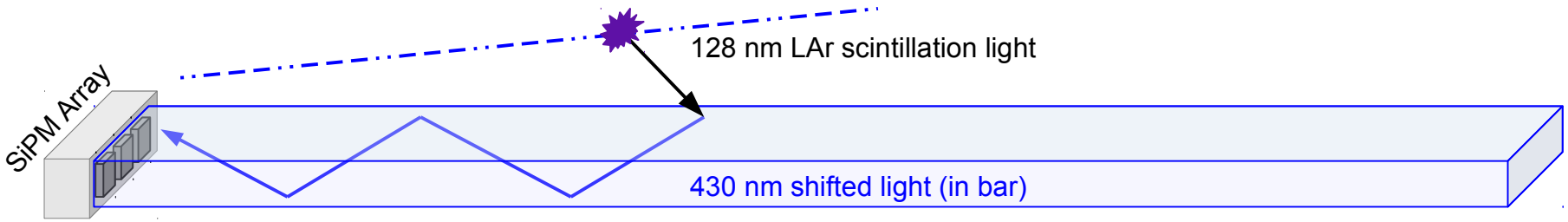
- Important for non-beam events
  - Proton decay events
  - Atmospheric neutrinos
  - Supernova burst neutrinos
  - Cosmic ray rejection



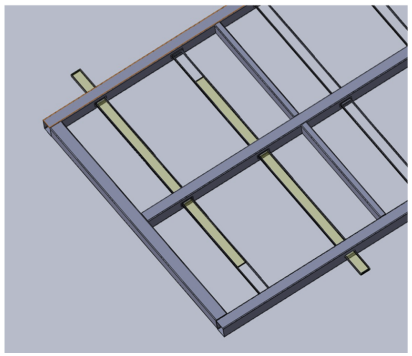


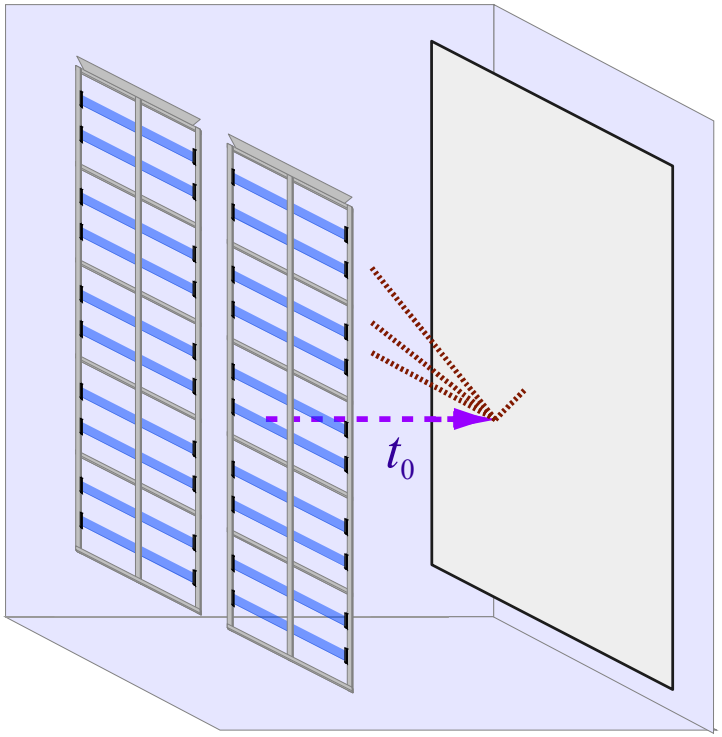
- Particle identification/discrimination
  - Ratio of prompt to total light depends on ionization density of track

- Large active-area UV-collecting light guides
  - Acrylic or polystyrene imbued with wavelength-shifting compound
    - Based on design pioneered by MIT
    - Dip-coating w/ TPB in solvent (after studying many different methods)
  - 430 nm light propagated by total internal reflection to end

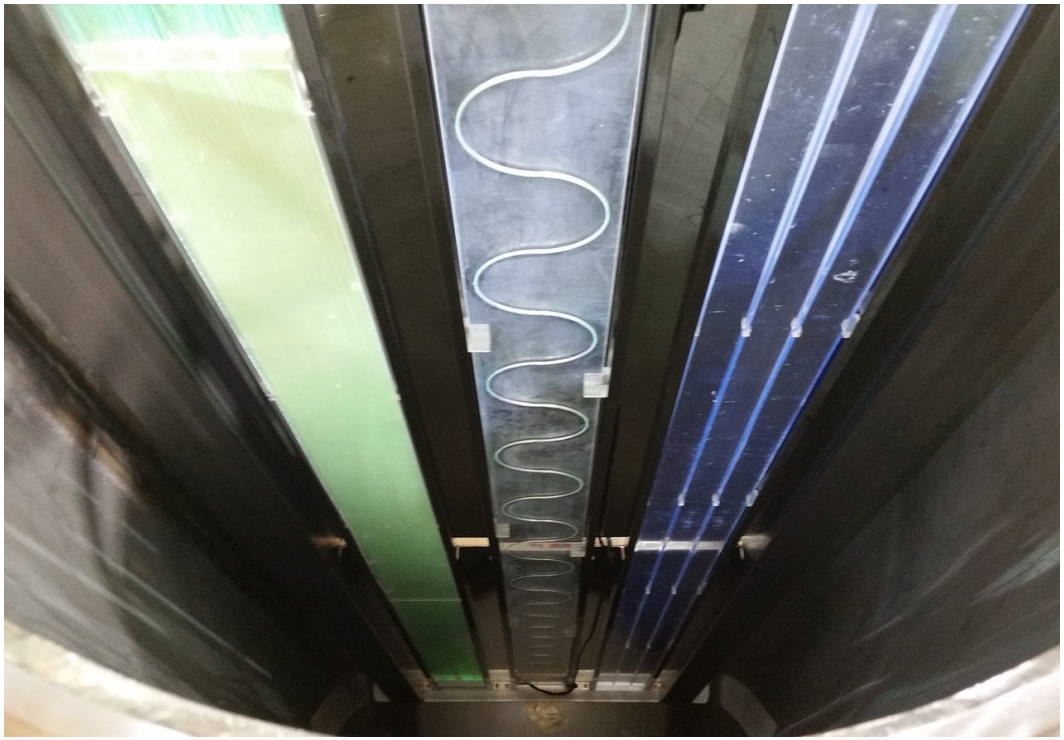


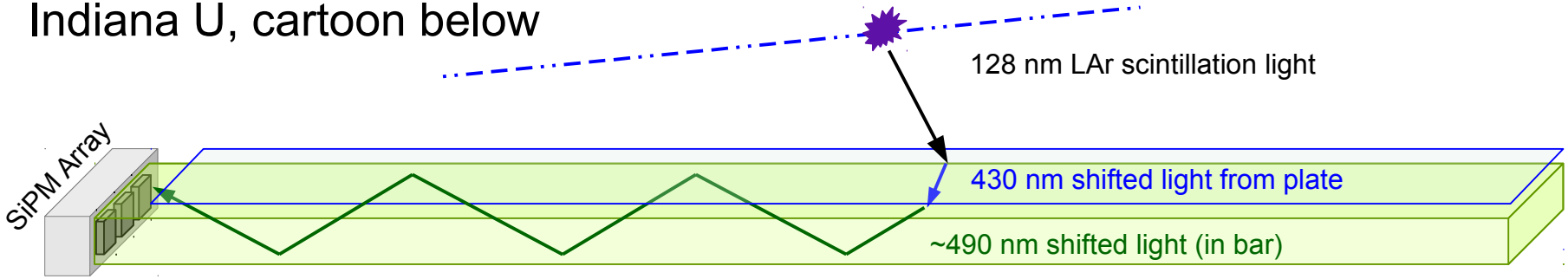
- Imbed PD paddles inside anode plane assembly behind collection wires
  - Large photosensitive area with small photocathode area
  - Low-voltage SiPM bias
  - Easily scalable



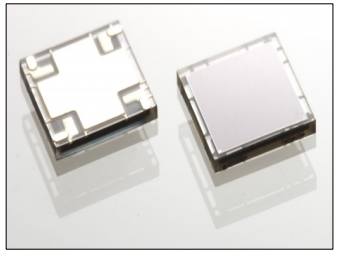


- Multiple alternative designs under investigation
  - Decouple UV wavelength shifter (WLS) from transport for improved attenuation length
  - Dip-coated acrylic bars
    - Baseline design
    - Indiana U, right-most paddle
  - WLS panel (VUV → blue) + imbedded WLS fibers
    - Louisiana State U, center
  - WLS radiator (VUV → blue) + WLS fibers (blue → green)
    - Colorado State U, left-most
  - WLS Radiator (VUV → Blue) + WLS bar (blue → green)
    - Indiana U, cartoon below





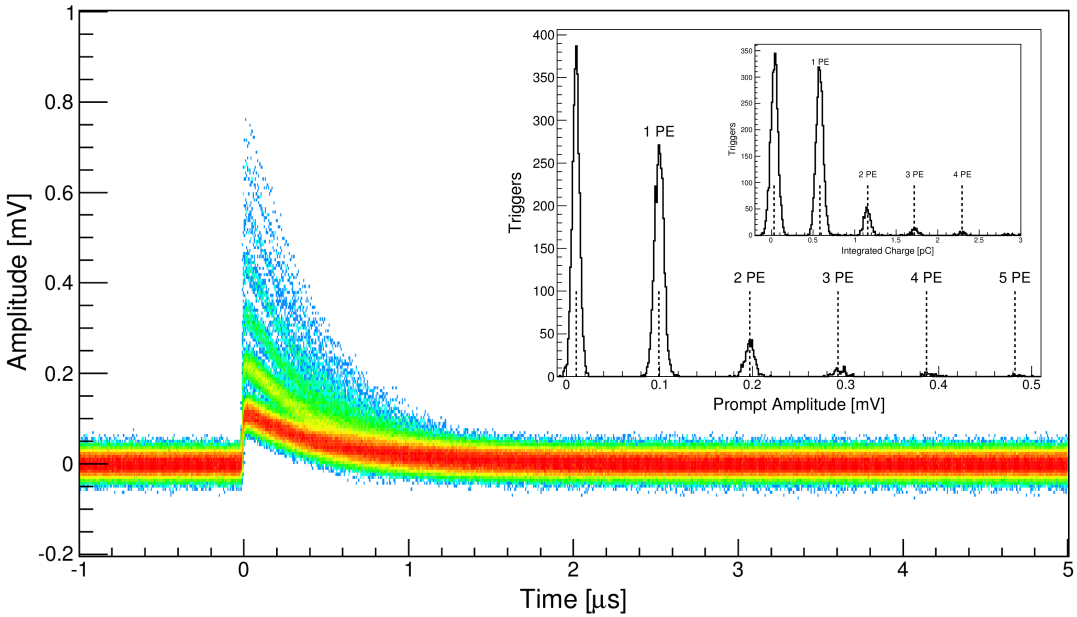
- Strongly reverse-biased array of photodiodes
  - Low noise (few Hz in cryo)
  - Excellent charge resolution



SensL MicroFC-60035-SMT
6 × 6 mm package
>19,000 microcells

Dark noise characteristics in LN2 at V_{bias} = 24.5 V

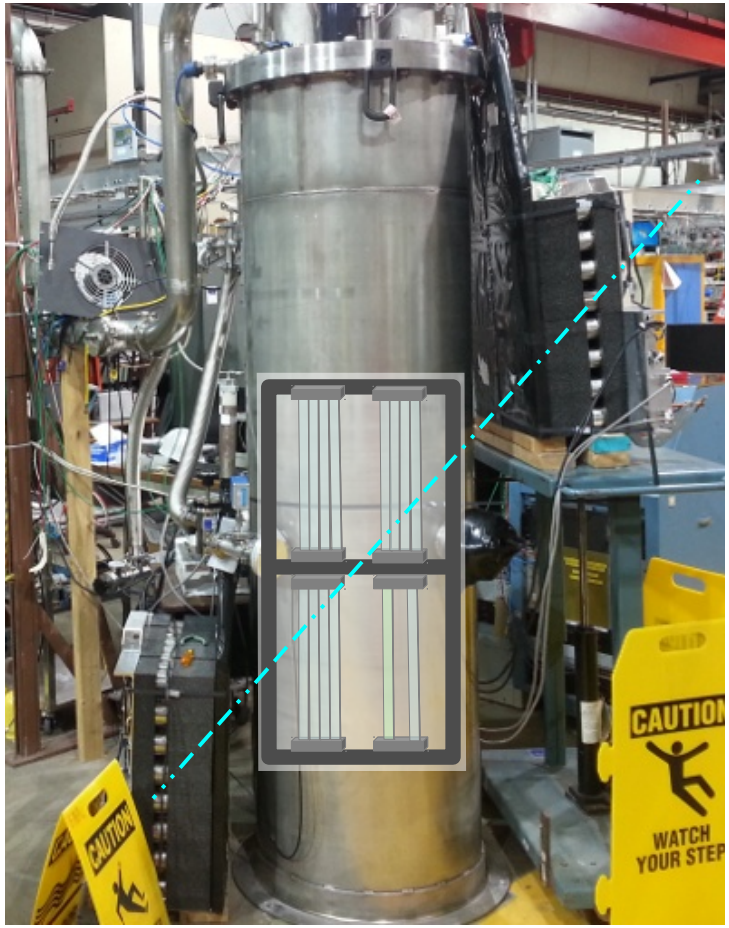
SiPM	Gain	Noise [Hz]	Cross-Talk Probability	Rise Time [ns]	Recovery Time [ns]
A-0	3.5×10^6	11	0.17	13	484
A-1	3.6×10^6	9	0.21	12	483
A-2	3.6×10^6	9	0.18	13	494
B-0	3.5×10^6	9	0.22	11	460
B-1	3.6×10^6	8	0.19	14	491
B-2	3.5×10^6	10	0.19	14	502
C-0	3.4×10^6	8	0.22	13	492
C-1	3.6×10^6	10	0.20	12	473
C-2	3.5×10^6	8	0.18	11	449
D-0	3.6×10^6	8	0.19	13	468
D-1	3.5×10^6	9	0.22	13	479
D-2	3.5×10^6	8	0.22	13	491
mean	3.5×10^6	9	0.20	13	481
st.dev.	6.5×10^4	1	0.02	1	16

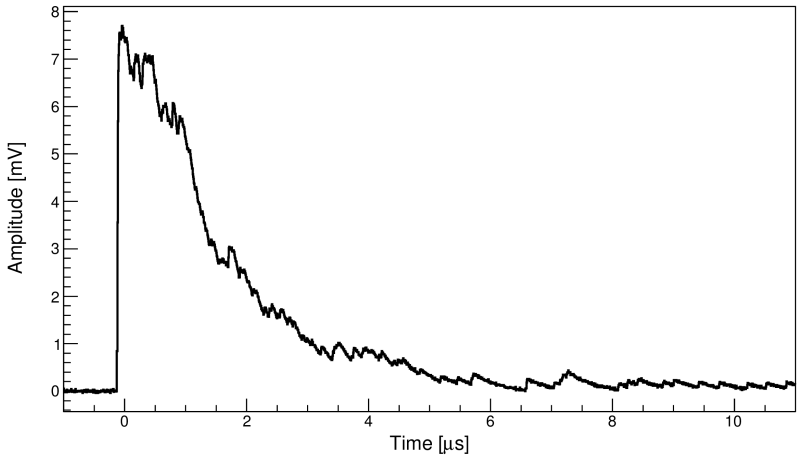


- SiPM Signal Processor (SSP)
  - 150 MHz waveform digitizer
    - Argonne Natl. Lab HEP Elec. Group
  - Resolve fine waveform details
    - ~3 ns timing resolution
    - 13 µs waveform buffer

Design Tests in LAr at Fermilab

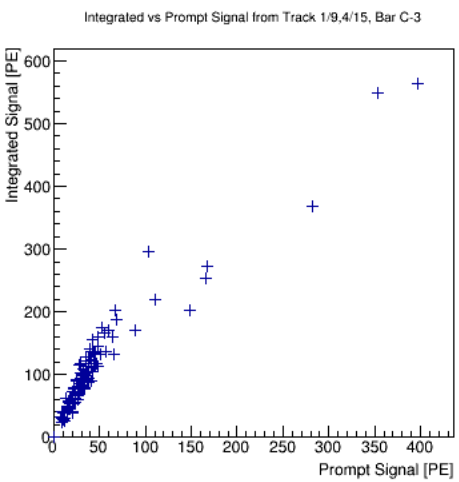
- "TallBo" facility at FNAL
  - 84" LAr dewar
- Ultra-high purity liquid argon
  - Vacuum to remove residual atmosphere
  - Condenser to maintain closed system
- Multiple lightguide designs (fall 2014)
  - Dip-coated acrylic bars
  - Cast acrylic and polystyrene bars
  - Flash-heated spray-coated acrylic bars
  - Y11 fibers w/ TPB-coated acrylic radiator
- Hodoscope (cosmic ray) trigger
  - 2 8x8 Arrays of PMTs + BaF crystals
    - CREST cosmic-ray balloon exp't.
  - 2 scintillator paddle planes
    - Allows shower rejection, reconstruction of single tracks

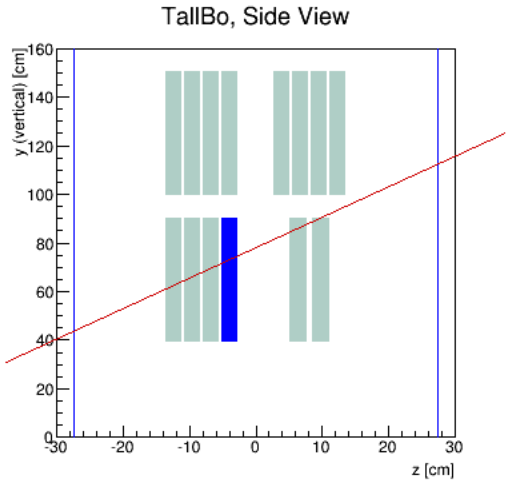


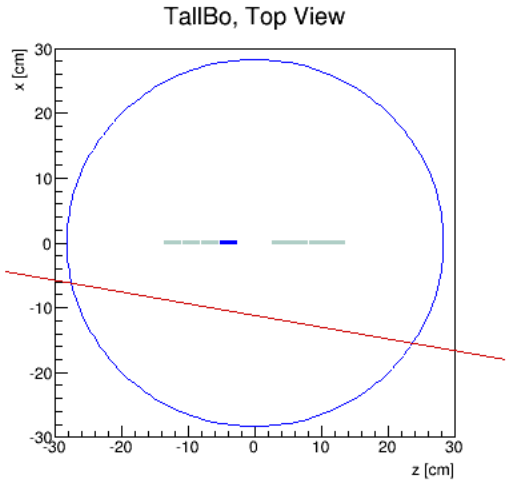


Preliminary Performance Results

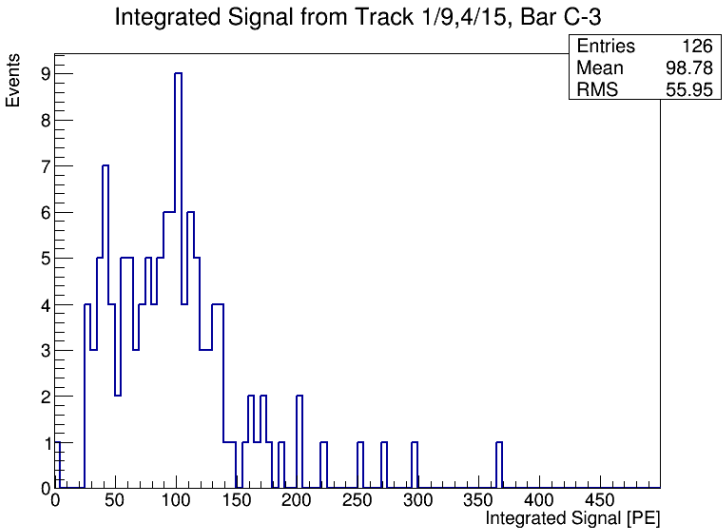
- Signals from example hodoscope trajectory



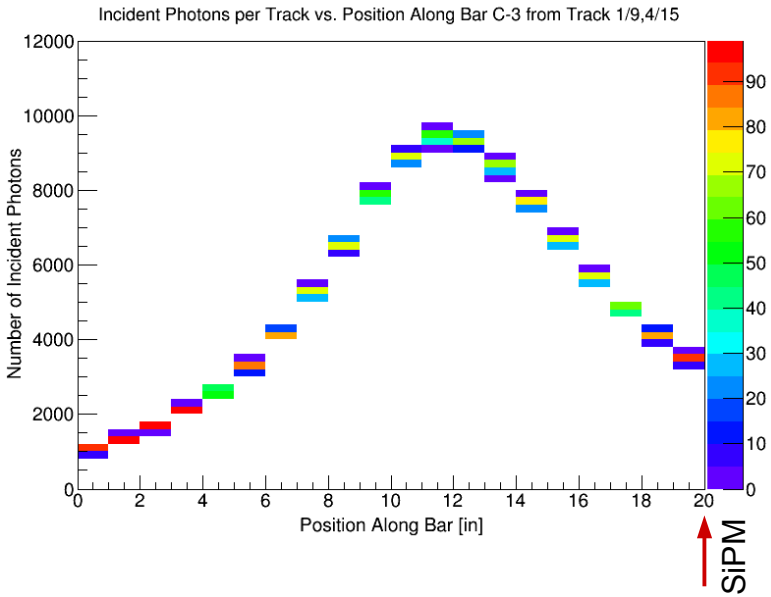




- Data: integrated charge in 10 us waveform [PE]



- Sim: number of incident photons from the line source (toy MC)



Preliminary Performance Results (Baseline Designs)

- Estimated detector efficiency
  - Ratio = [Mean #γ Detected (data)] / [Mean #γ Incident (sim)]

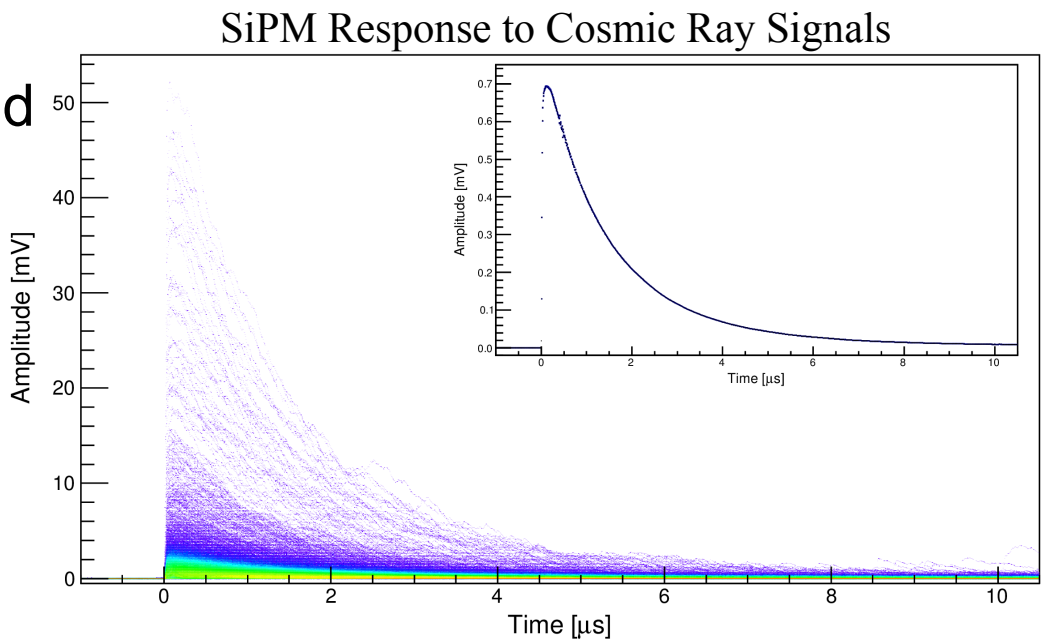
Technology	UV Wavelength Shifter	Detector Efficiency
acrylic (uncoated)	none	0.01%
acrylic, doped	bis-MSB	0.05%
WLS Fibers w/ Radiator	TPB	0.05%
acrylic, dip-coated	TPB	0.08%
polystyrene, doped	bis-MSB	0.08%
acrylic, doped	TPB	0.08%
acrylic, dip-coated	TPB	0.10%
polystyrene, doped	TPB	0.11%
acrylic, dip-coated	bis-MSB	0.13%
acrylic, dip-coated	bis-MSB (+50%)	0.15%
acrylic, dip-coated	TPB (+50%)	0.16%

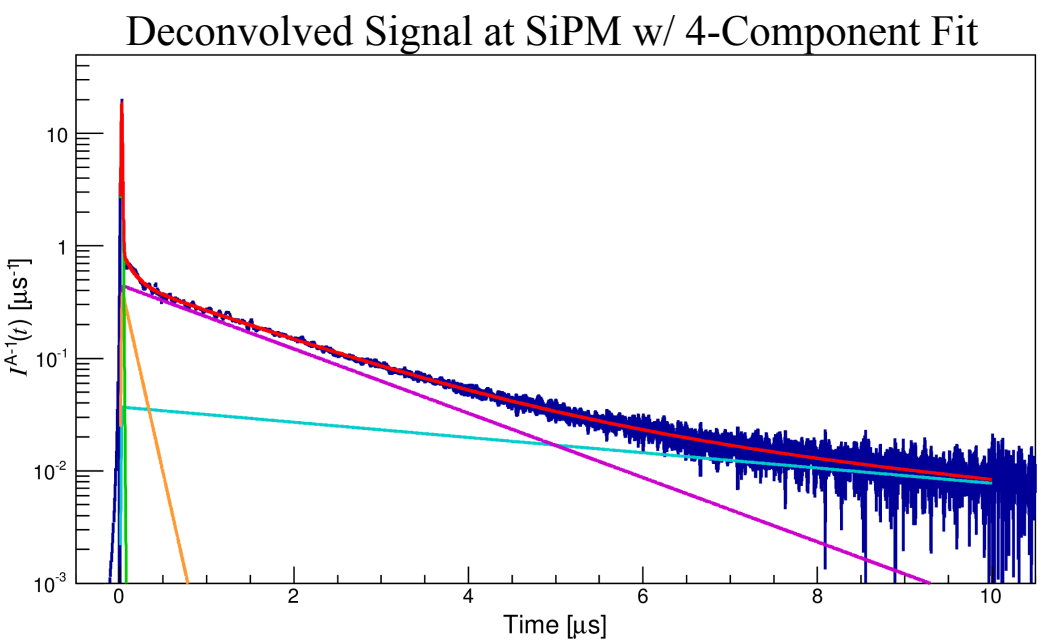
Goal: > 0.3%

- Alternative designs will likely show an improvement by a factor of 2-3
  - *Strongly* driven by improvements to attenuation
  - Design comparisons at TallBo currently underway
  - Can also explore double-ended readout, more paddles per APA
- Caveats
  - Reflections estimated using WARP measurements
  - Rayleigh scattering not yet modeled (efficiencies underestimated → good!)

Scintillation Structure Analysis

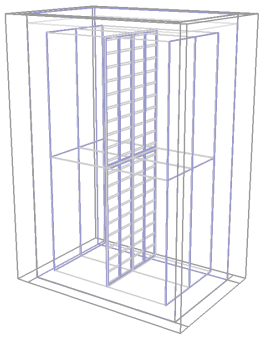
- Time structure of signal at SiPM
  - Deconvolve average waveform from cosmic rays using measured single-PE response (dark noise)
- Three- or four-component models capture all features, including prompt singlet signal (~25%) and 1.5 μs "late light"
  - Evidence for long (~7 μs) component in acrylic light guides (not present in polystyrene)
- Important to understand for timing resolution and pulse-shape discrimination
- Publication in preparation

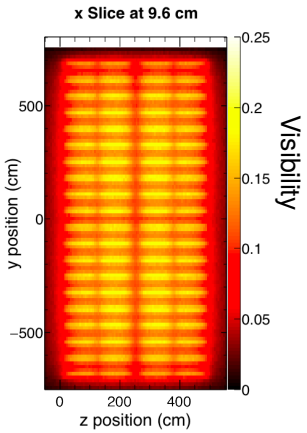




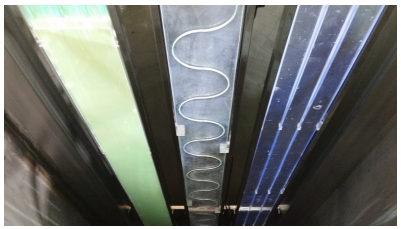
Continuing Photon Detector R&D

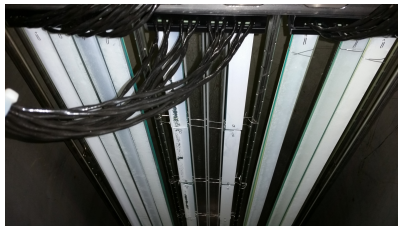
- DUNE Far Detector simulation development (ongoing)
  - Estimate sensitivity of various photon detector system configurations to physics events (proton decay, SN, etc.)



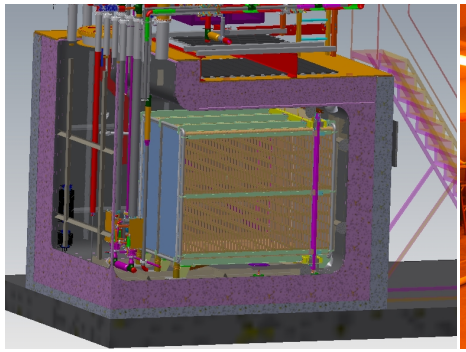


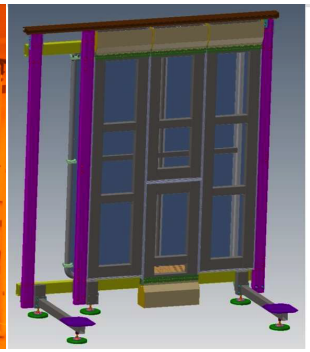
- Current TallBo testing (summer 2015)
  - Direct comparisons of baseline design with all four alternatives





- 35-ton Phase 2 (winter 2015)
  - First test of light guide photon detectors in APA coupled with single-phase TPC

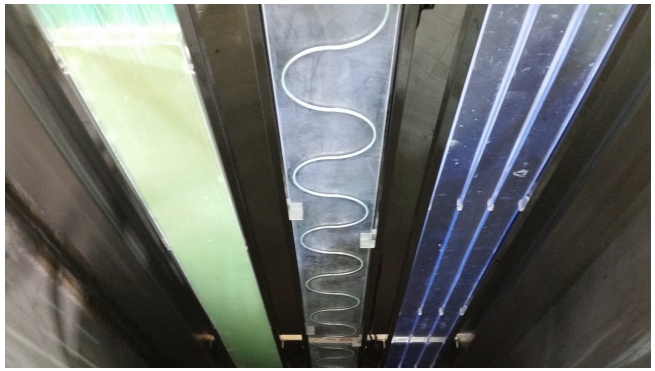


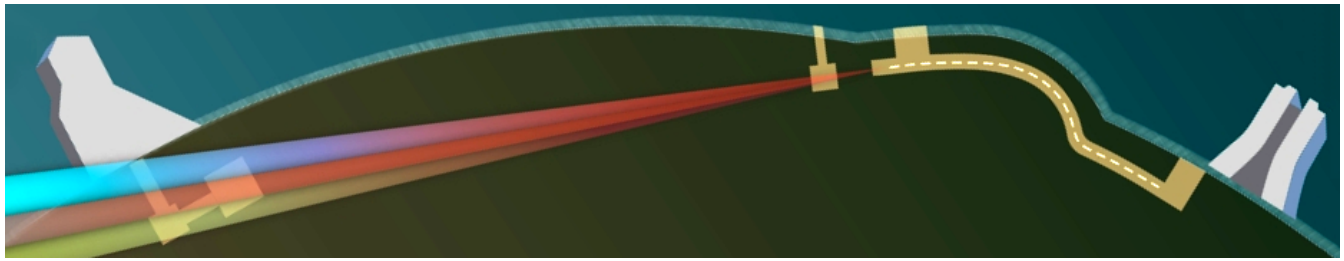


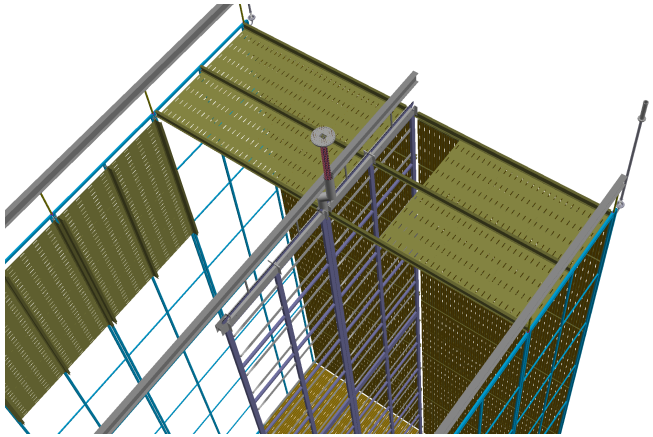
- CERN single-phase TPC prototype (2018)
  - Down-selected photon detector design deployed in single-phase TPC
  - New charged particle beam in CERN north area
  - Comparisons to WA105 dual-phase TPC performance

Conclusions

- Lots of progress developing a light guide photon detector for the DUNE LAr TPC
  - Variety of designs have been explored
  - Successful performance comparison tests
  - SiPM readout quite promising for LAr operation
  - Several TPC+PD tests on the horizon







- Big effort with thanks to many folks
  - Indiana U.
    - Stuart Mufson, Jim Musser, Jon Urheim, Mark Gebhard, Brice Adams, Mike Lang, Brian Baugh, Paul Smith, Bryan Martin, Bruce Howard, Jonathon Lowery
  - MIT
    - Janet Conrad, Matt Toups, Ben Jones, Len Bugel
  - Colorado State U.
    - Norm Buchanan, Dave Warner, Ryan Wasserman, Dylan Adams, Jay Jablonski, Tom Cummings, Forrest Craft, Andrea Shacklock
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  - Louisiana State U. – Thomas Kutter
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  - (And many others!)