A Lightguide-Based Photon Detection System for a Large-Volume LAr TPC

Denver Whittington, et. al.

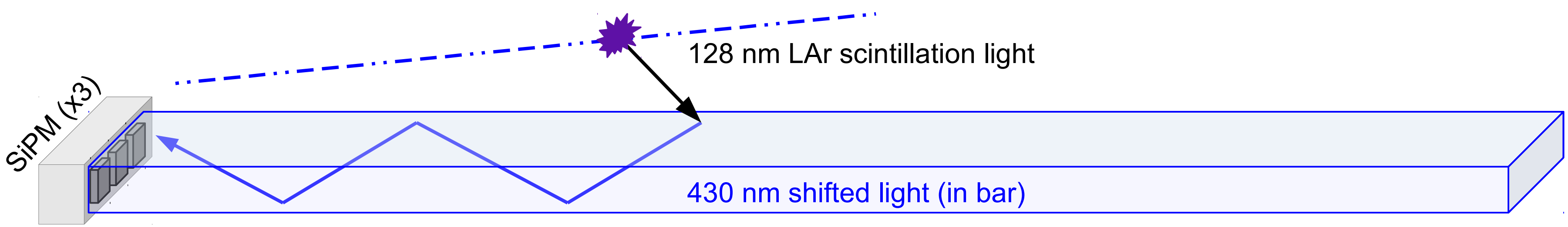
January 22, 2015
ELBNF Collaboration Meeting

Light Collector Design

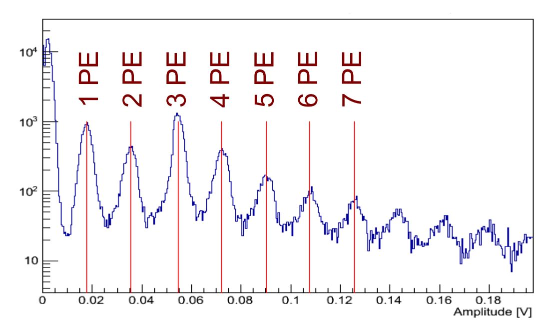
- Scintillation from de-excitation of argon molecular state
  - 128 nm UV, two components
    - Prompt (singlet state) signal (τ ~ 6 ns)
    - Slow (triplet state) signal (τ ~ 1.5 μs)

$$Ar^* + Ar \rightarrow Ar_2^* \rightarrow 2Ar + \gamma$$

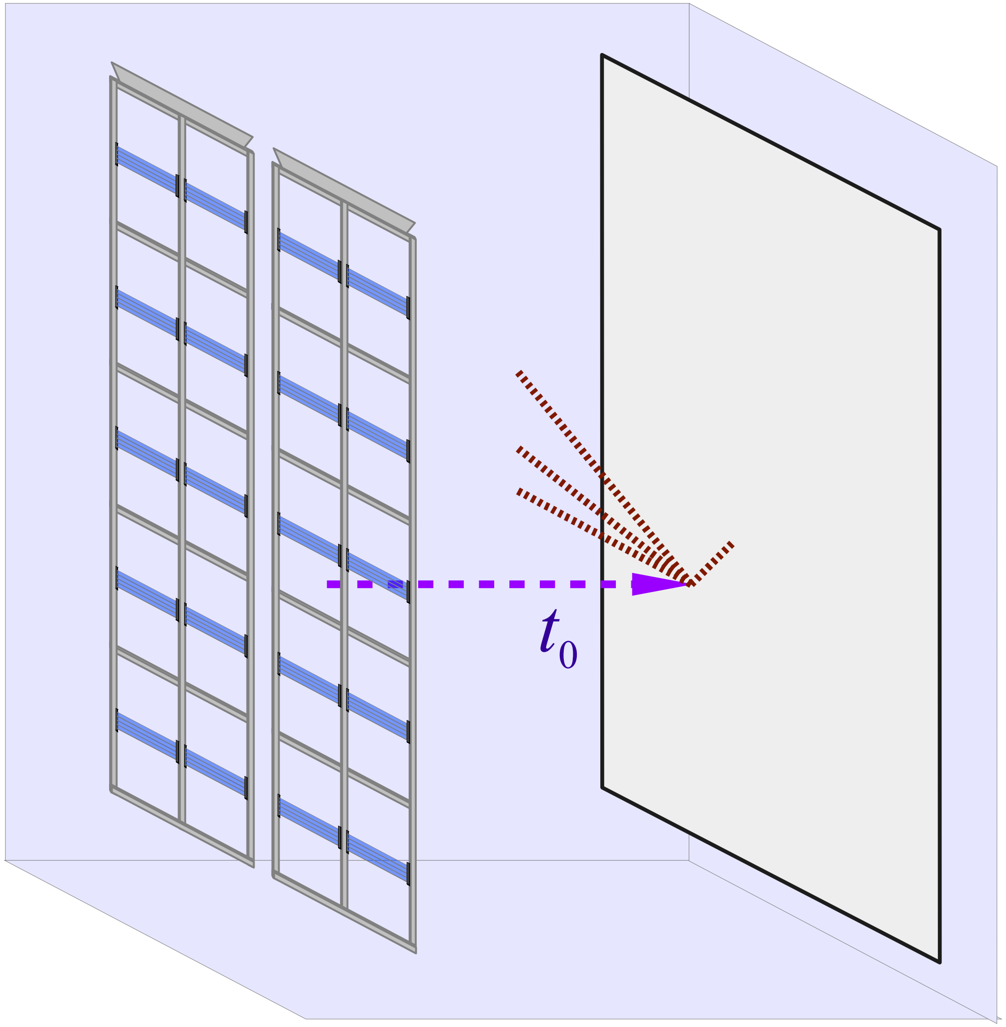
- Large active-area UV-collecting lightguides
  - Acrylic or polystyrene imbued with wavelength-shifting compound
  - 430 nm light propagated by total internal reflection to end



- 3 Silicon Photomultipliers (SiPM) read-out end of lightguide
  - Strongly reverse-biased array of photodiodes
  - 6 mm x 6 mm active area,
  - ~25 V bias (gain of a few x10^6)
  - Quantized, discrete single-pixel signals
    - At cryogenic temperature

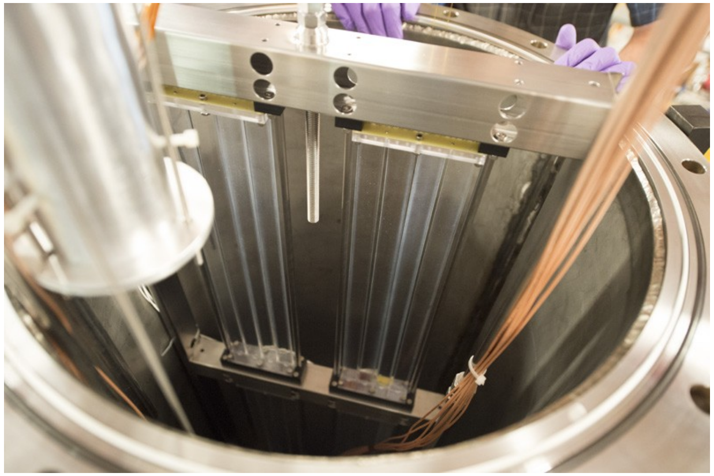


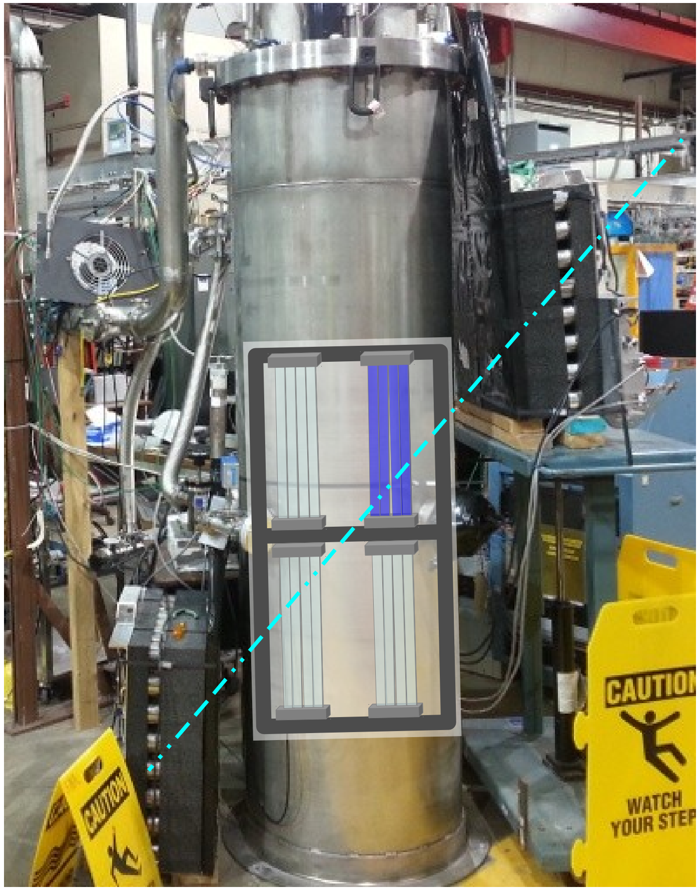
- Imbed PD paddles inside anode plane behind collection wires
  - Large photosensitive area with small photocathode area
  - Easily scalable
  - Low-voltage SiPM bias
- Prompt signal from charged track gives t_0 for transverse position determination
  - Calculate drift time from time of arrival and known drift velocity in TPC E-field
  - Resolution of < 100 ns easily attainable
- Non-beam event triggering
  - Supernova burst neutrinos
  - Proton decay events
  - Cosmic ray rejection



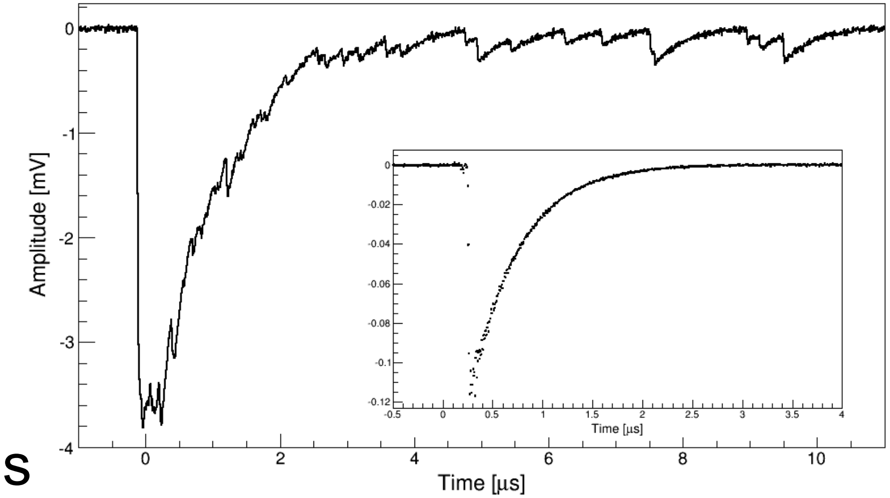
- Particle identification/discrimination
  - Ratio of prompt to total light depends on ionization density of track

- TallBo
  - Ultra-high purity liquid argon
  - Condenser to maintain closed system
  - Third run Oct./Nov. 2014
- Multiple lightguide designs
  - Dip-coated acrylic bars
  - Cast acrylic and polystyrene bars
  - Flash-heated spray-coated acrylic bars
  - Y11 fibers w/ TPB-coated acrylic
- Hodoscope (cosmic ray) trigger
  - 2 8x8 Arrays of PMTs + BaF crystals
    - CREST cosmic-ray balloon exp't.
  - 2 scintillator paddle planes
  - Allows shower rejection (single tracks)
- 150 MHz waveform digitizer
  - "SiPM Signal Processor"
    - Argonne Natl. Lab HEP Elec. Group
  - Resolve fine waveform details

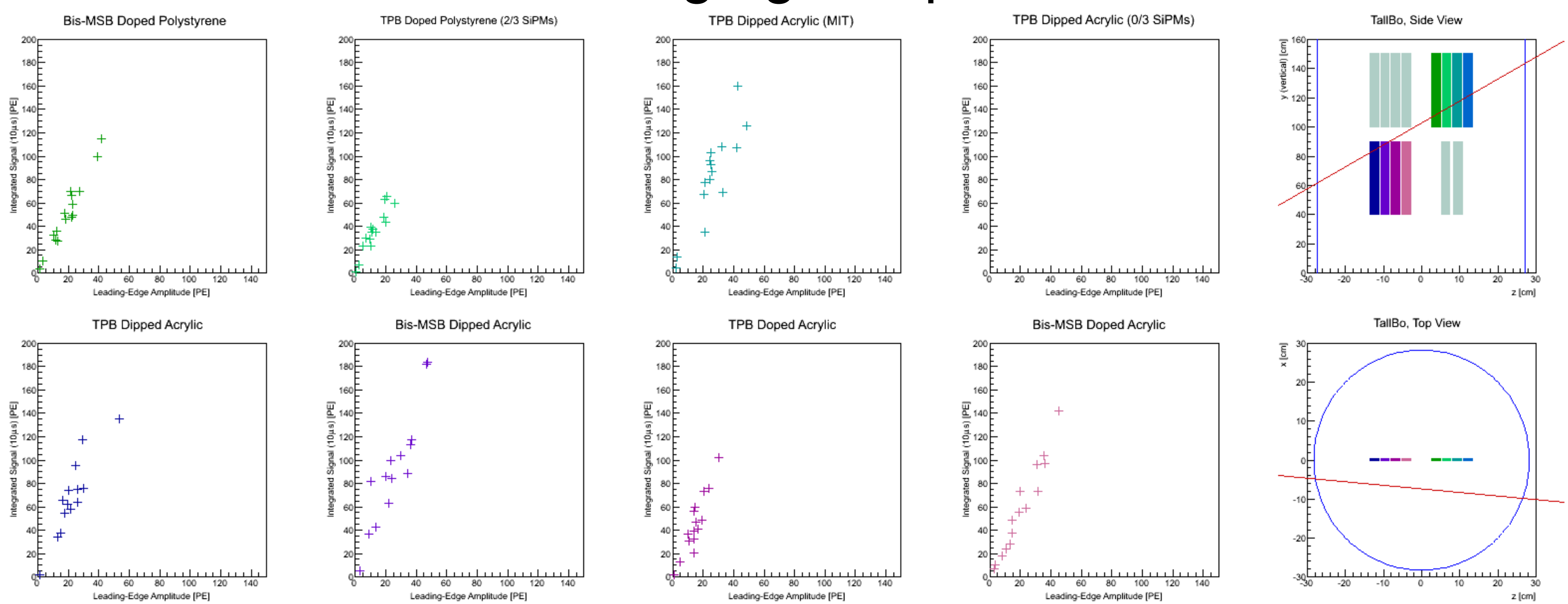




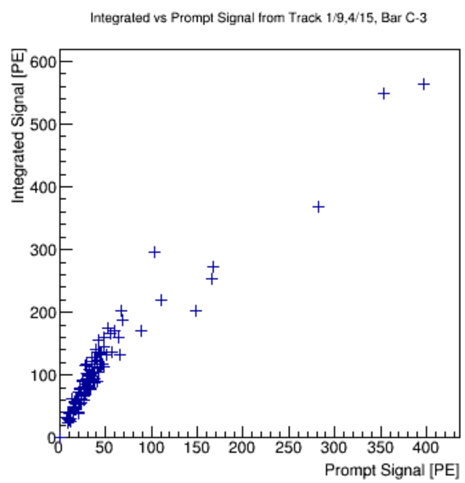
- Hodoscope trigger
  - Four-fold coincidence (low bkg)
  - Track position reconstruction
- Waveform analysis
  - Amplitude of prompt signal
  - Integrated signal in 10-μs waveform
  - Both easily calibrated to photoelectrons

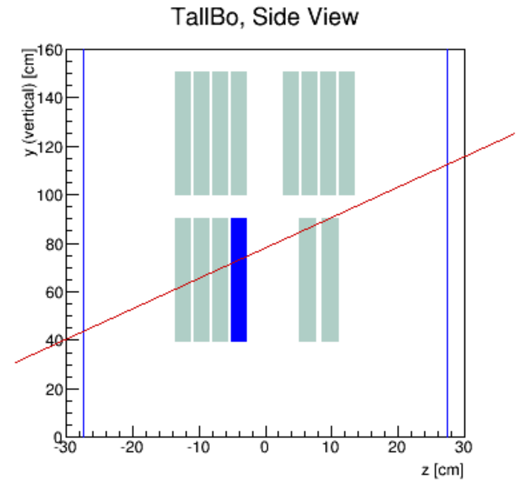


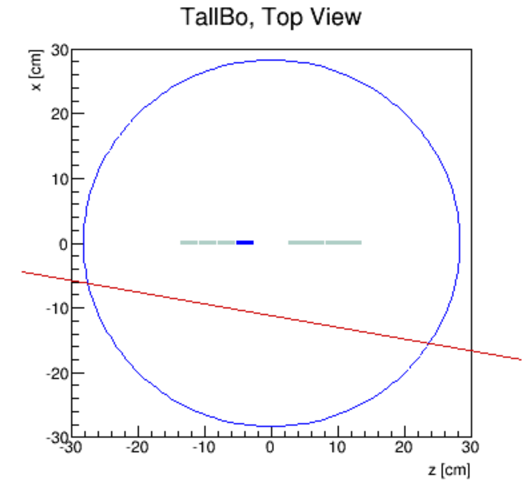
- Good estimate of relative lightguide performance



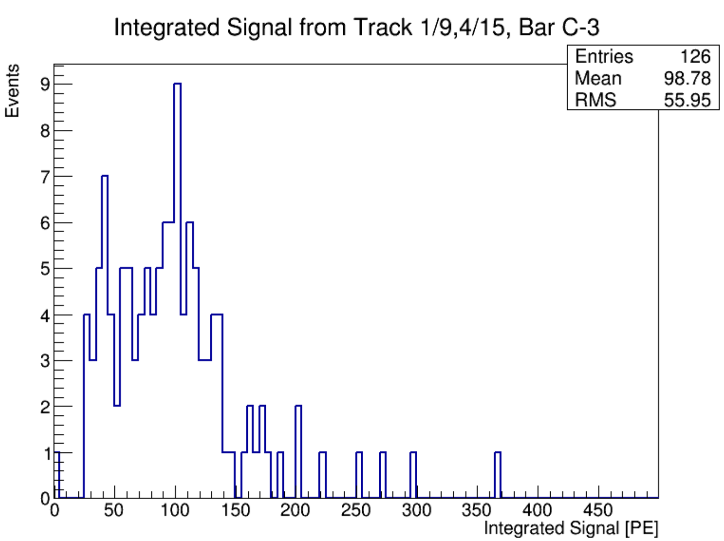
- Example hodoscope trajectory

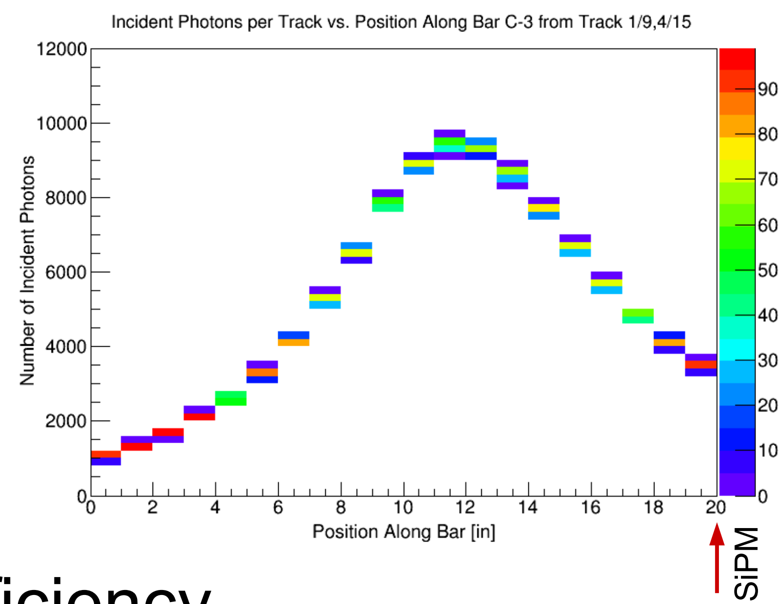


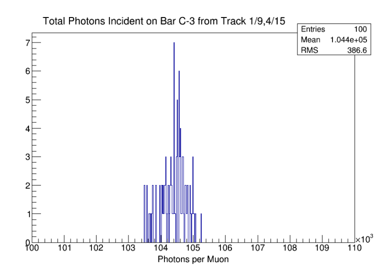




- Data: integrated charge in 10 us waveform [PE]
- Sim: number of incident photons from the line source (toy MC)







- Global photon detection efficiency
  - Ratio = [Mean #γ Detected (data)] / [Mean #γ Incident (sim)]

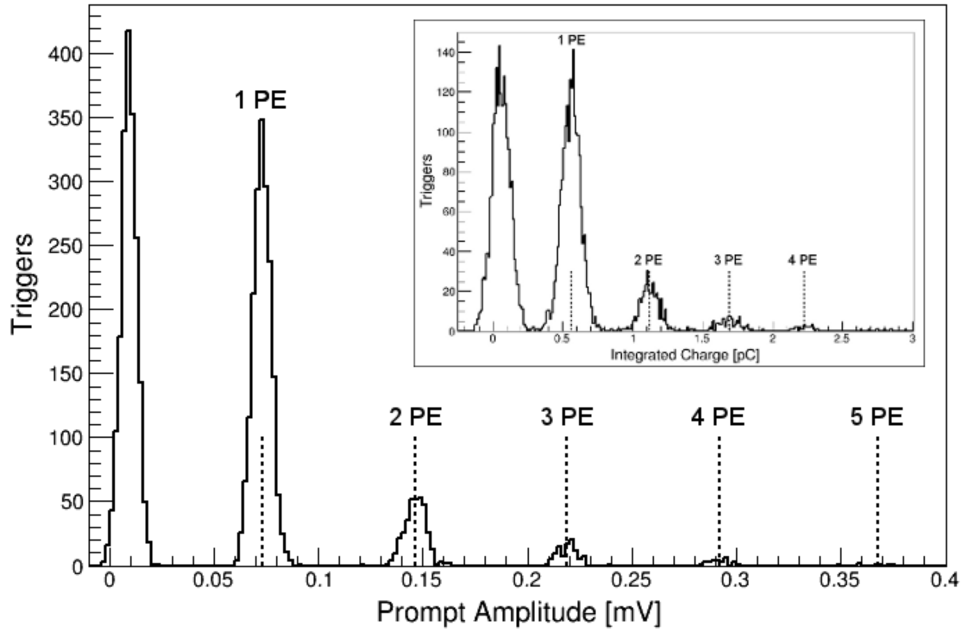
- Cannot yet disentangle attenuation from surface efficiency
  - Direct measurements (alpha source) to be made soon

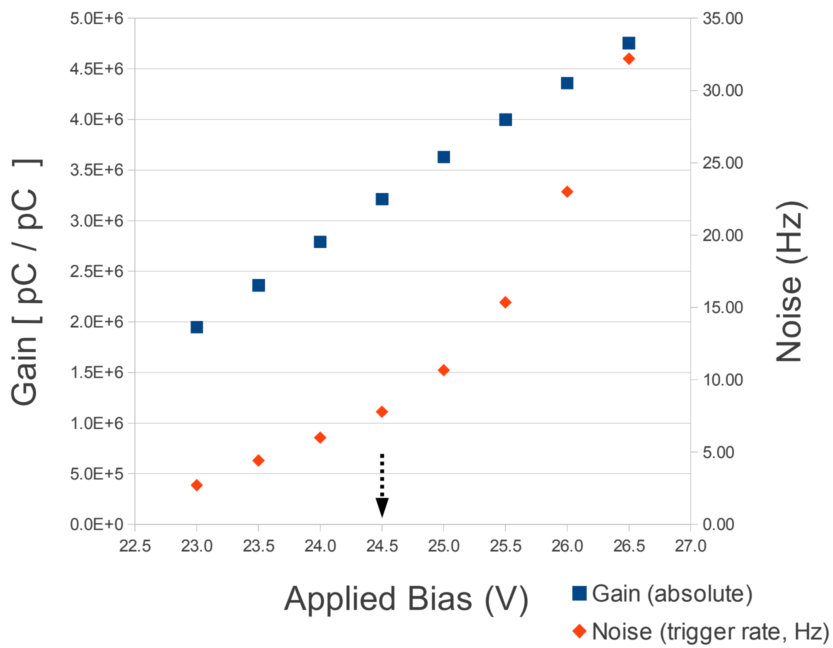
Estimate of VUV Photon Conversion & Collection Efficiency

Technology	SiPMs in Readout	Incident Fraction Detected	Full-Readout Detection Efficiency	SiPM Efficiency × Coverage	Conversion & Collection Efficiency
A-0 (bis-MSB Dipped +50%)	1 / 3	0.00049	0.146%	0.084	0.58 %
A-3 (Uncoated Acrylic)	3 / 3	0.00014	0.014%	0.249	0.06 %
B-0 (bis-MSB Doped Polystyrene)	1 / 3	0.00027	0.080%	0.084	0.32 %
B-1 (TPB Doped Acrylic)	1 / 3	0.00027	0.082%	0.084	0.32 %
B-2 (TPB Dipped (MIT))	1 / 3	0.00035	0.104%	0.084	0.41 %
C-0 (TPB Dipped)	3 / 3	0.00076	0.076%	0.249	0.31 %
C-1 (bis-MSB Dipped)	3 / 3	0.00132	0.132%	0.249	0.53 %
C-2 (bis-MSB Doped Acrylic)	3 / 3	0.00048	0.048%	0.249	0.19 %
C-3 (TPB Doped Polystyrene)	3 / 3	0.00109	0.109%	0.249	0.44 %
D-0 (TPB Dipped +50%)	3 / 3	0.00162	0.162%	0.249	0.65 %
D-1 (Y11 Fibers w/ TPB Plate)	2 / 2	0.00051	0.051%	0.350	0.15 %

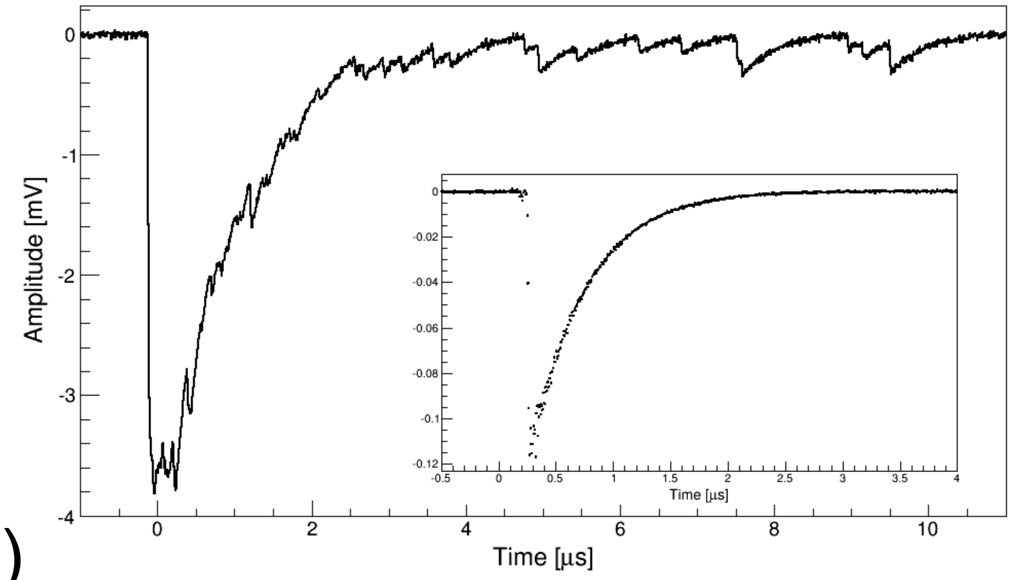
- Looks like a good first estimate of efficiencies.
  - “Full-Readout Detection Efficiency” is expectation from full SiPM readout
    - Some excluded due to limited number of available digitizer channels during run
    - Goal estimated to be 0.3% (B. Baller)
  - Relative performance agrees with other observations in data.

- Noise is easy to measure
  - Count number of events with integrated amplitude ≥ 0.5 pe, divide by acquisition time (300 s)
- Single µcell events easy to tag
  - Require both integrated and prompt amplitude to be ≥ 0.5 and ≤ 1.5 pe
- Gain is easy to calculate
  - Sum ADC counts, convert to charge
- 24.5 V seems optimum bias voltage
  - Highest gain before rapid noise increase
- Extra µcells
  - Cross talk = simultaneous extra µcell
  - After-pulsing = delayed extra µcell
  - Analysis of time structure
    - Cross talk probability ~ 18%
    - After-pulse probability ~ 2.2%
    - After-pulse lifetime ~ 23 ns





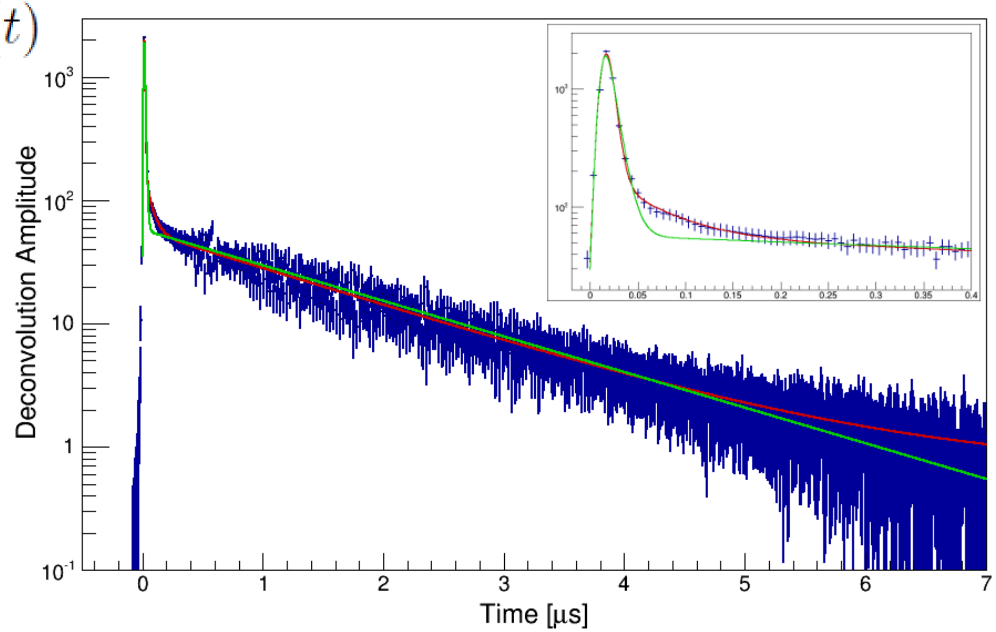
- Example waveform from cosmic-ray muon
  - Bright prompt signal
  - Single-PE pulses from long-lifetime component



- Average single-PE response of SiPM measured (dark noise)
  - Combination of single-µcell response (inset) with cross talk and after pulsing

$$F_{pe}(t) = (1 + p_{ct})\mathcal{R}_{\mu c}(t) + \mathcal{P}_{ap}(t) * \mathcal{R}_{\mu c}(t)$$

- Deconvolve average waveform from cosmic rays using single-µcell response
  - Time structure of signal at SiPM
  - Two-component model (green) fails to capture all features

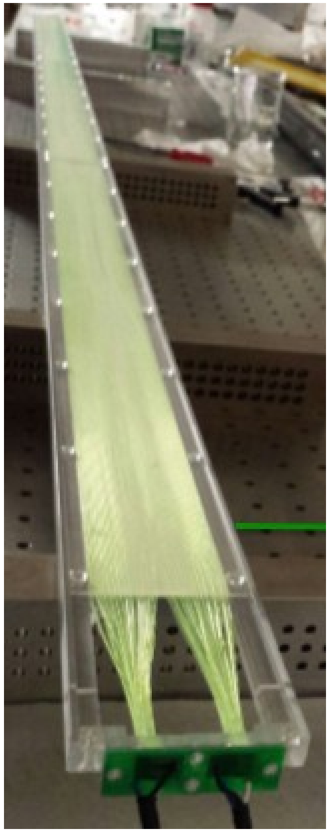


- Return to TallBo at FNAL May-June 2015
  - Test long versions of three technologies side-by-side
    - First test of 1.5 m bar design
  - Hodoscope trigger w/ more flexible location

- Plastic bar w/ WLS (dipped or doped)

- Simple to manufacture
- Variety of design options
- Indiana U., MIT

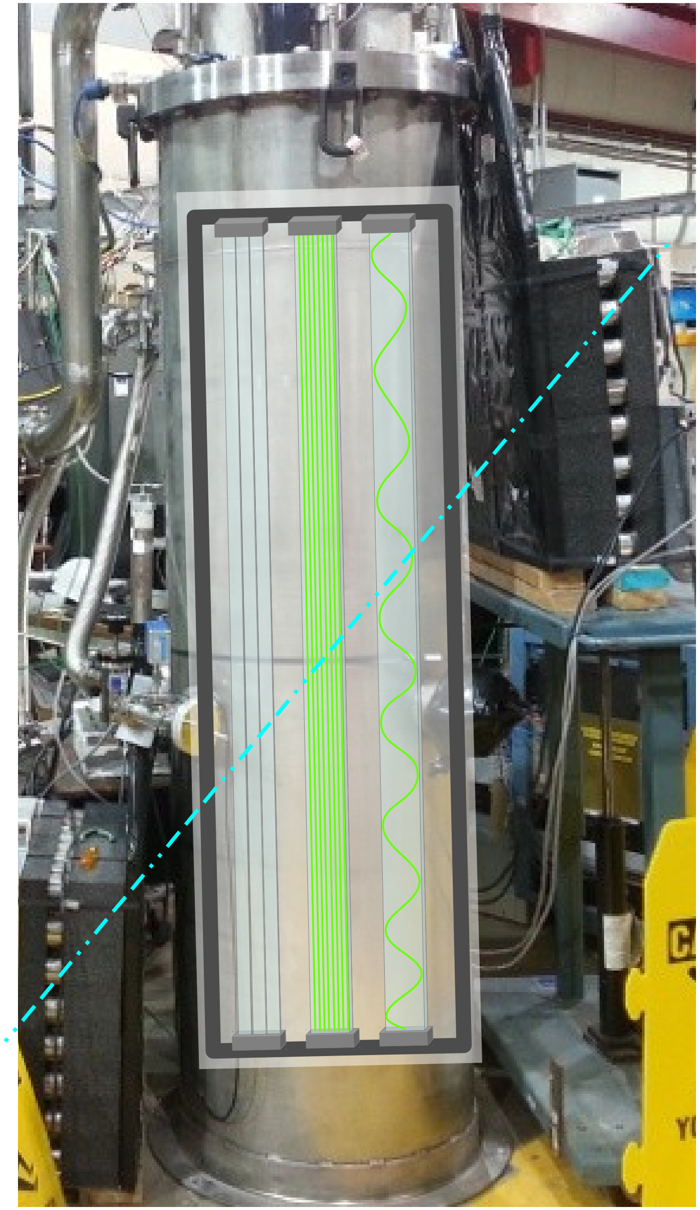
- Y-11 fibers behind TPB-coated plate



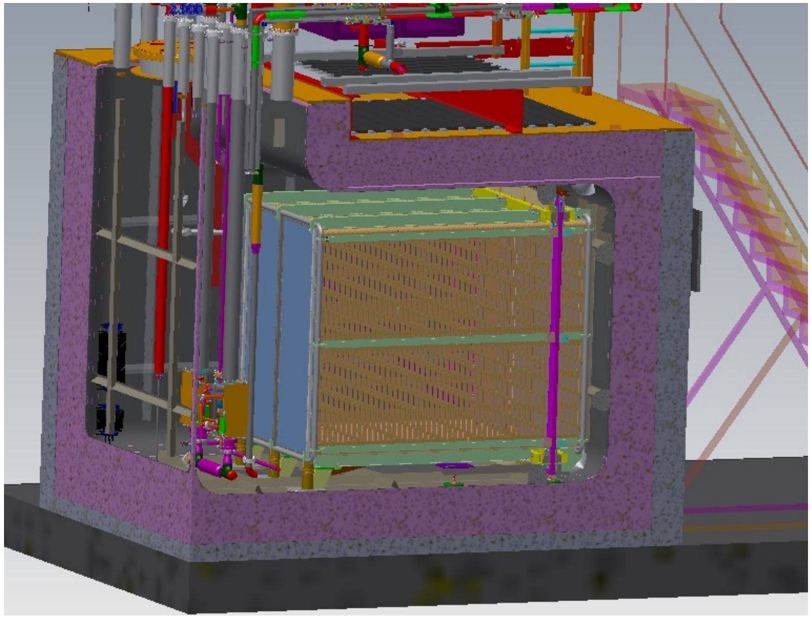
- Long fiber atten. length
- Fewer SiPM channels
- Colorado State U.

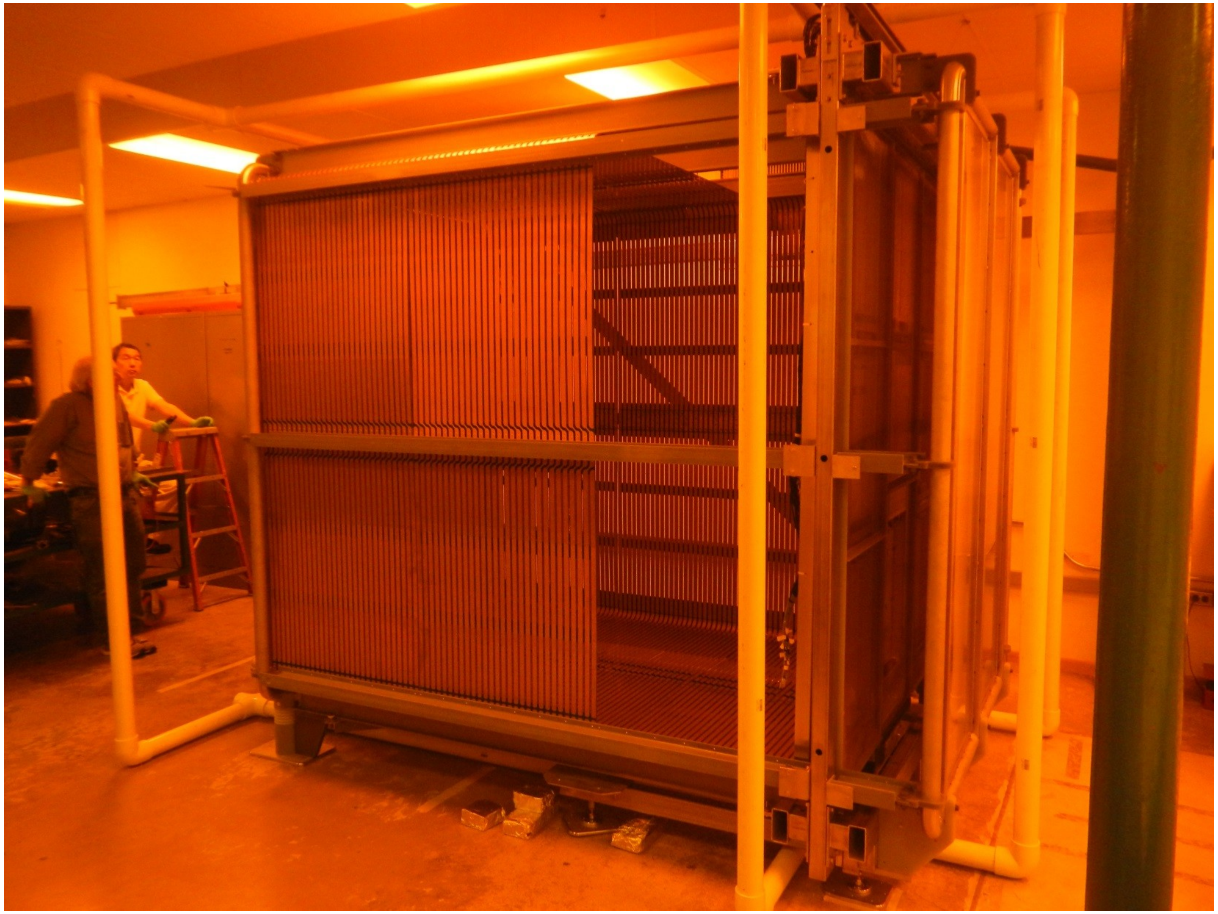
- Plastic plate w/ TPB and Y-11 fiber inside

- Double-ended readout
- Fewer SiPM channels
- Louisiana State U.

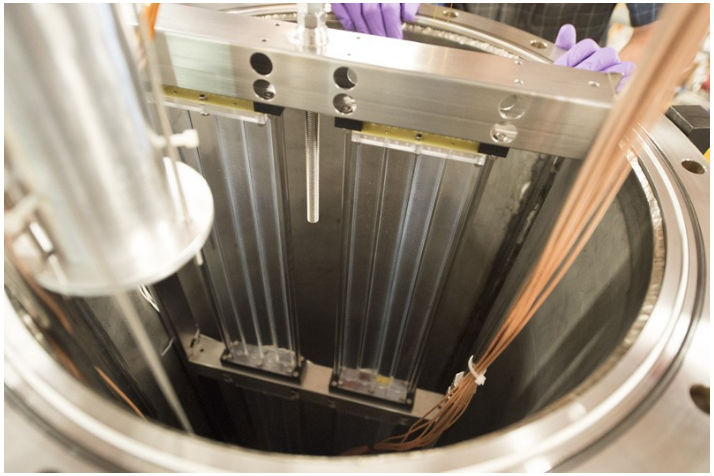


- Phase 1 – LAr membrane cryostat technology demonstration
- Phase 2 – Single-phase TPC with lightguide-based PD system
  - First simultaneous operation
  - Valuable opportunity to test integration, trigger, reconstruction, etc.
    - Cosmic-ray data
  - Side-by-side test of various lightguide designs
  - Installation underway, operations this spring





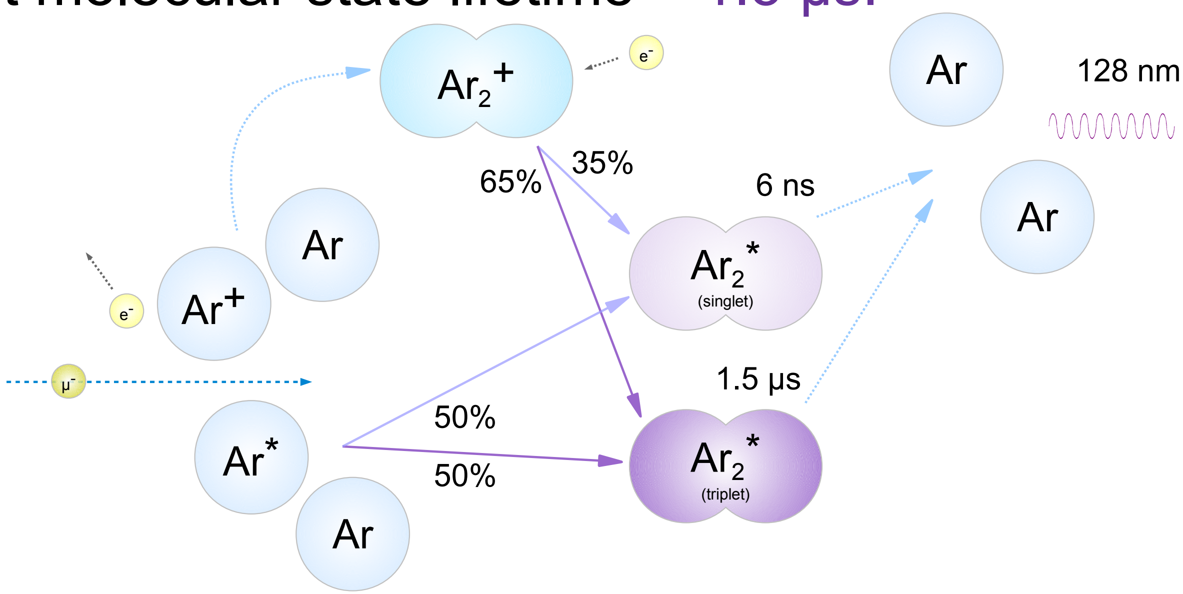
- Lots of progress developing a lightguide-based LAr scintillation photon detector system
  - Variety of designs have been explored
  - Comparison tests successful with more coming up
  - SiPM readout shows much promise for operation in LAr

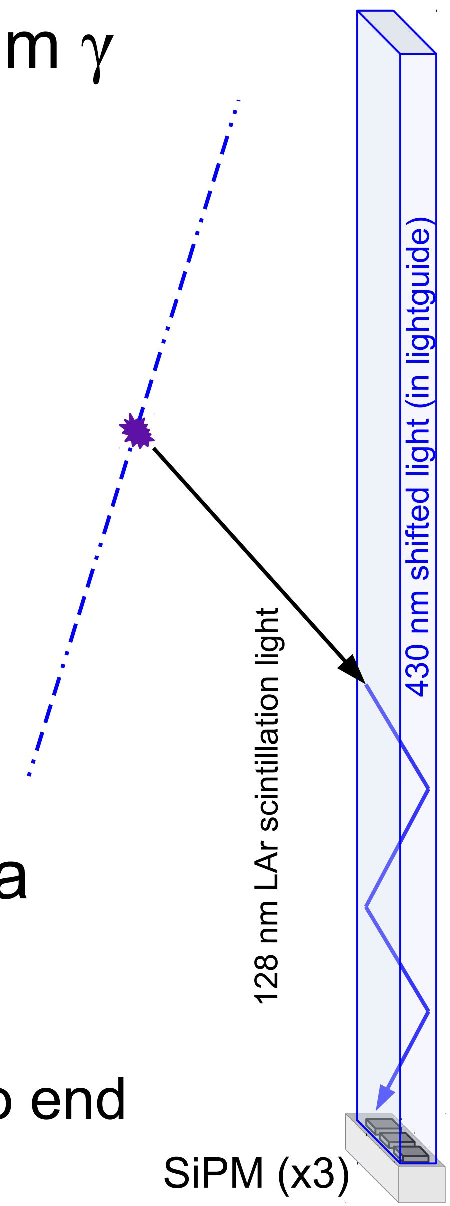


- Big effort with thanks to many folks
  - Indiana U.
    - Stuart Mufson, Jim Musser, Jon Urheim, Mark Gebhard, Brice Adams, Mike Lang, Brian Baugh, Paul Smith, Bryan Martin, Bruce Howard, Jonathon Lowery
  - MIT
    - Janet Conrad, Matt Toups, Ben Jones, Len Bugel
  - Colorado State U.
    - Norm Buchanan, Dave Warner, Ryan Wasserman, Dylan Adams, Jay Jablonski, Tom Cummings, Forrest Craft, Andrea Shacklock
  - LBNL – Victor Gehman, Richard Kadel
  - Louisiana State U. – Thomas Kutter
  - Argonne Natl. Lab
    - Gary Drake, Patrick De Lurgio, Andrew Kreps, Michael Oberling, John T. Anderson, Zelimir Djurcic, Himansu Sahoo, Victor Guarino
  - Fermilab
    - Brian Rebel, Stephen Pordes, Marvin Johnson, Ron Davis, Bill Miner

Backup Slides

- Charged particles excite and ionize argon atoms.
- Recombination / self-trapped excitation → excited Ar_2 molecule
- Excited Ar_2^* disassociates and emits one 128 nm γ
  - Singlet molecular state lifeimte ≈ 6 ns
  - Triplet molecular state lifetime ≈ 1.5 μs.





- Scintillation signal collected by large active-area UV-sensitive lightguides
  - Acrylic or polystyrene imbued with WLS compound
  - 430 nm light propagated by total internal reflection to end
  - Signal detected by silicon photomultipliers (SiPMs)

- SensL-MicroFB-60035-SMT
  - From SpecSheet – PDE at Peak Wavelength (420 nm)
    - 31% at V_{br} + 2.5 V
    - 41% at V_{br} + 5.0 V
    - *Includes* microcell fill factor (64%)
  - Which to use?
    - Gain at 24.5 V in LAr = ~3.5×10^6
    - Gain at V_{br} + 2.5 V at room temperature = ~3×10^6
    - Seems likely PDE in LAr at V_{bias} = 24.5 V is a little over 31%
  - *Conservative estimate PDE for this SiPM in LAr at 420 nm is ~35%*

- Geometric Factors
  - SiPM Coverage on Bar = (6mm × 6mm × 3) / (6mm × 25.4mm) = 71%
  - SiPM Coverage on Fiber System = 100%

- Fraction of Incident Photons Measured
  - [Surface Conversion] ⊗ [Internal Reflection & Attenuation] ← goal
    × [Geometric Coverage] × [SiPM Photon Detection Efficiency] } ~ 25 %

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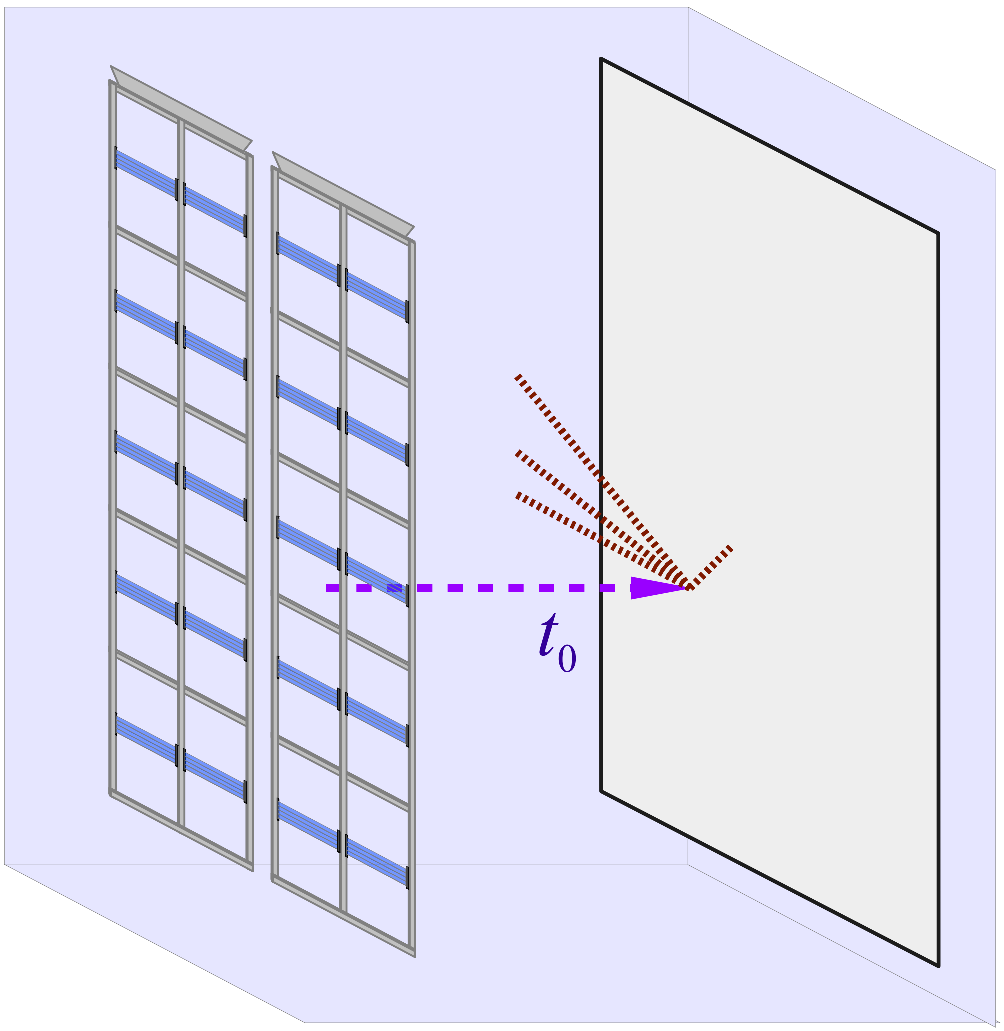
  - Large photosensitive area with small photocathode area
  - Easily scalable
  - Low-voltage SiPM bias



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- Y-11 fibers behind TPB-coated plate
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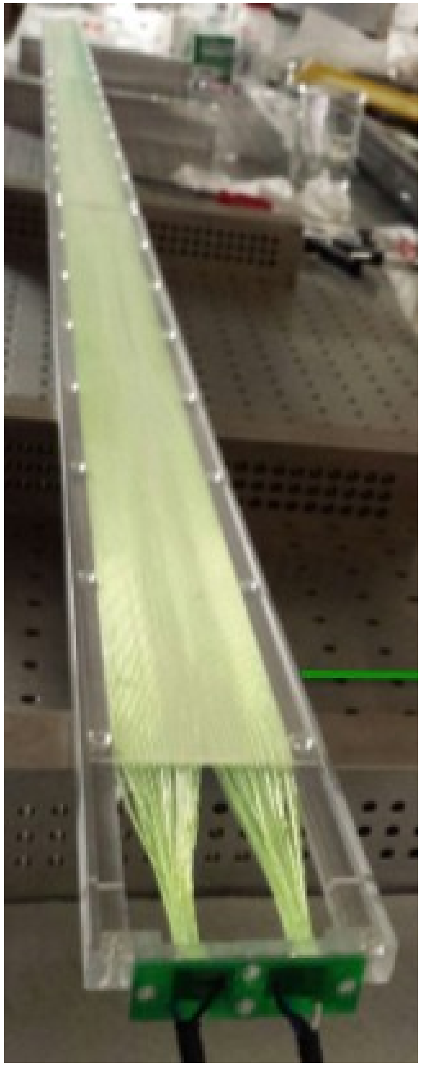

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