# Photon Detector System Performance Testing

*Denver Whittington*,
Stuart Mufson,
Bruce Howard

Indiana University

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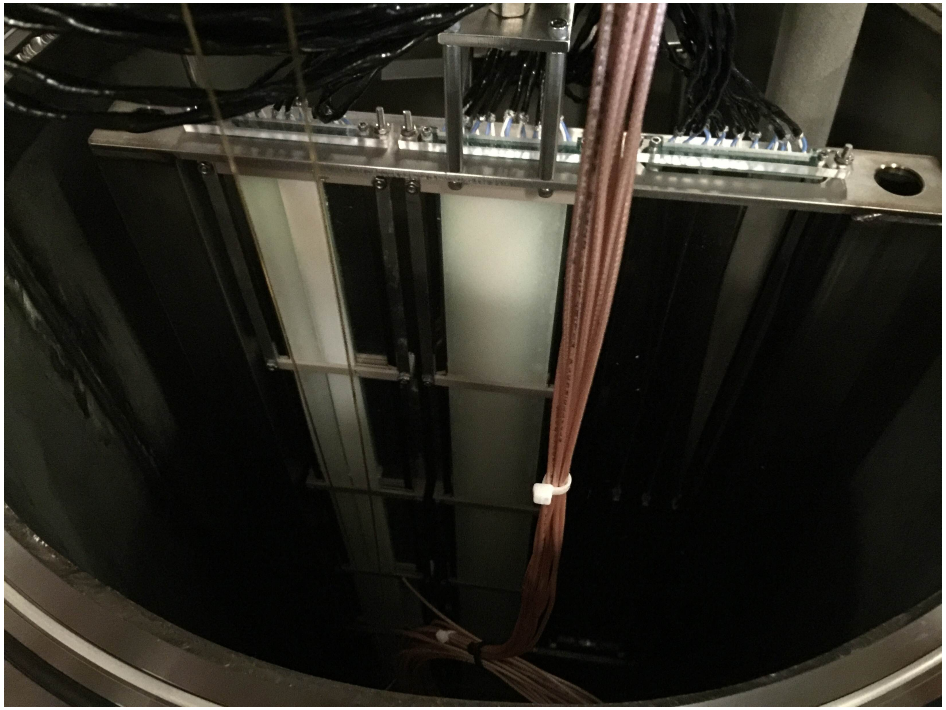
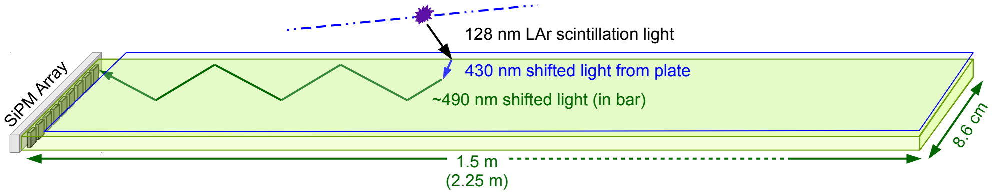
## Charges addressed

1. *Does the Photon Detector System design enable validation and refinement of the DUNE photon detector requirements?*
4. *Does the documentation of the Photon Detector System technical design provide sufficiently comprehensive analysis and justification for the Photon Detector System design adopted?*

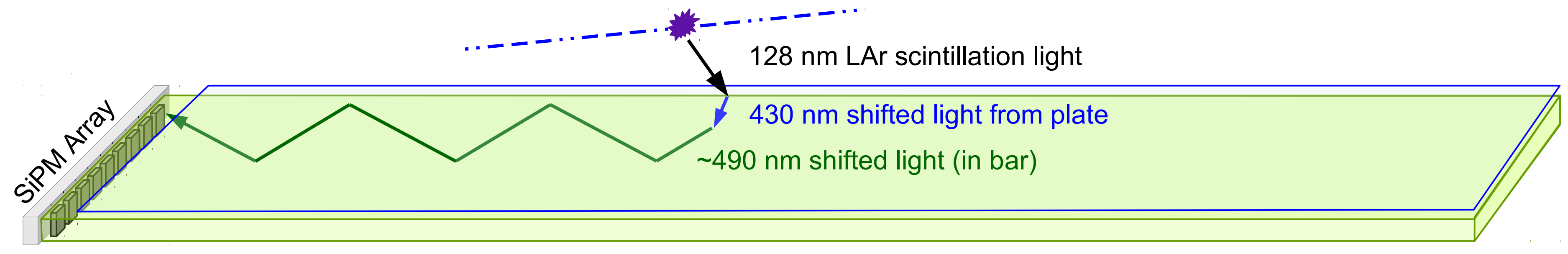


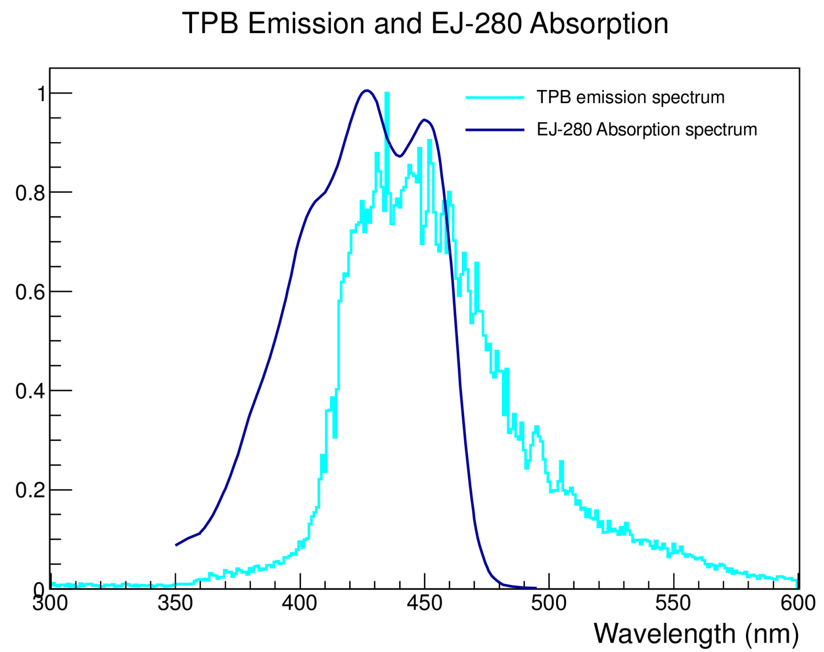
## Outline

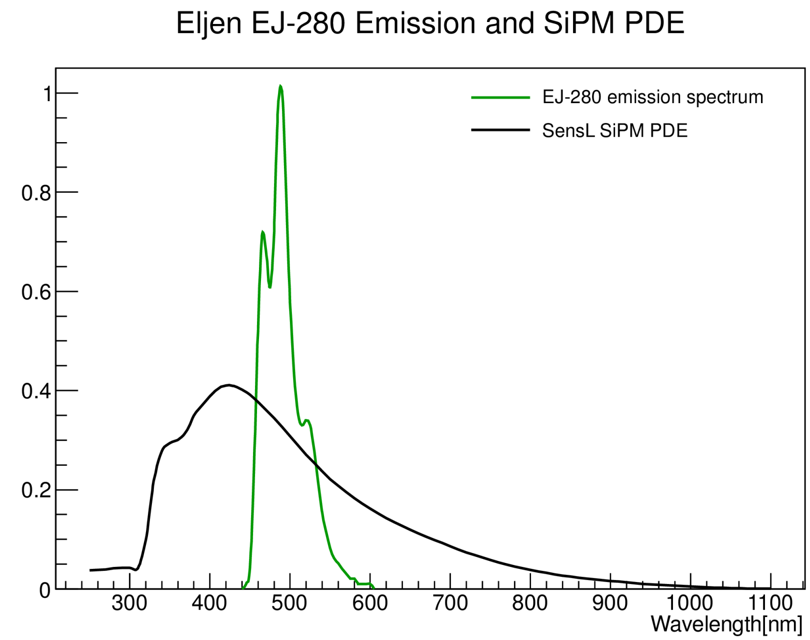
- Light guide designs
- TallBo facility
- Light guide attenuation
- Relative light guide performance
  - Summer 2015, Winter 2016
- Light guide efficiency
  - Data-simulation comparisons
  - Light guide component analysis
- Conclusions and Recommendations



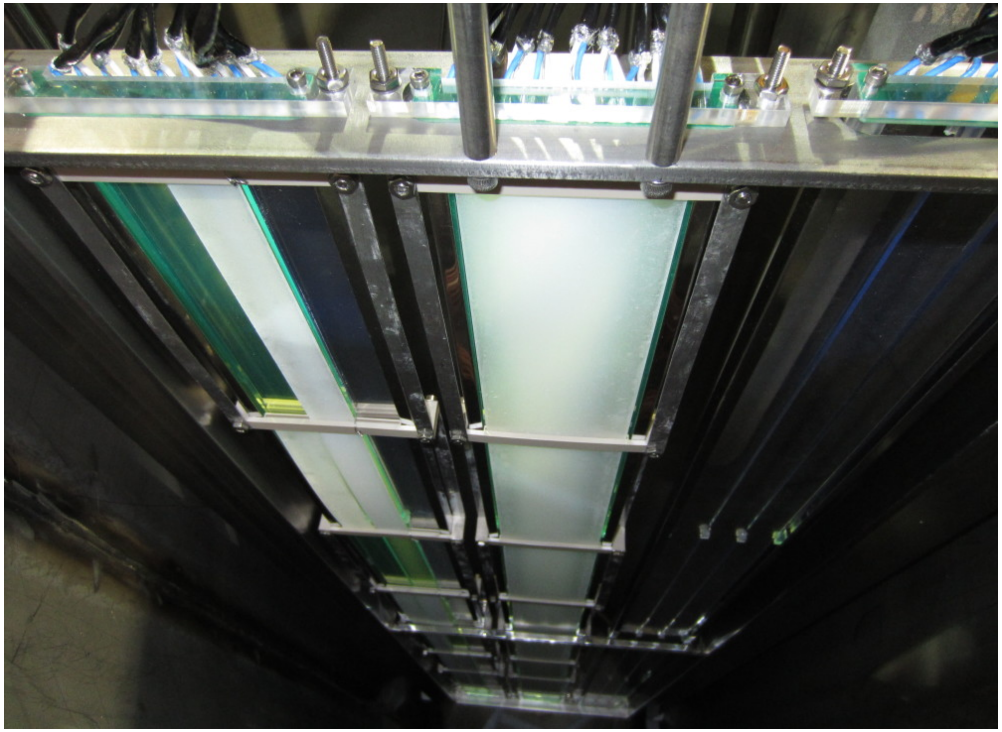
- Shift 128-nm VUV photons into visible wavelengths
- Channel visible signal to readout via total internal reflection

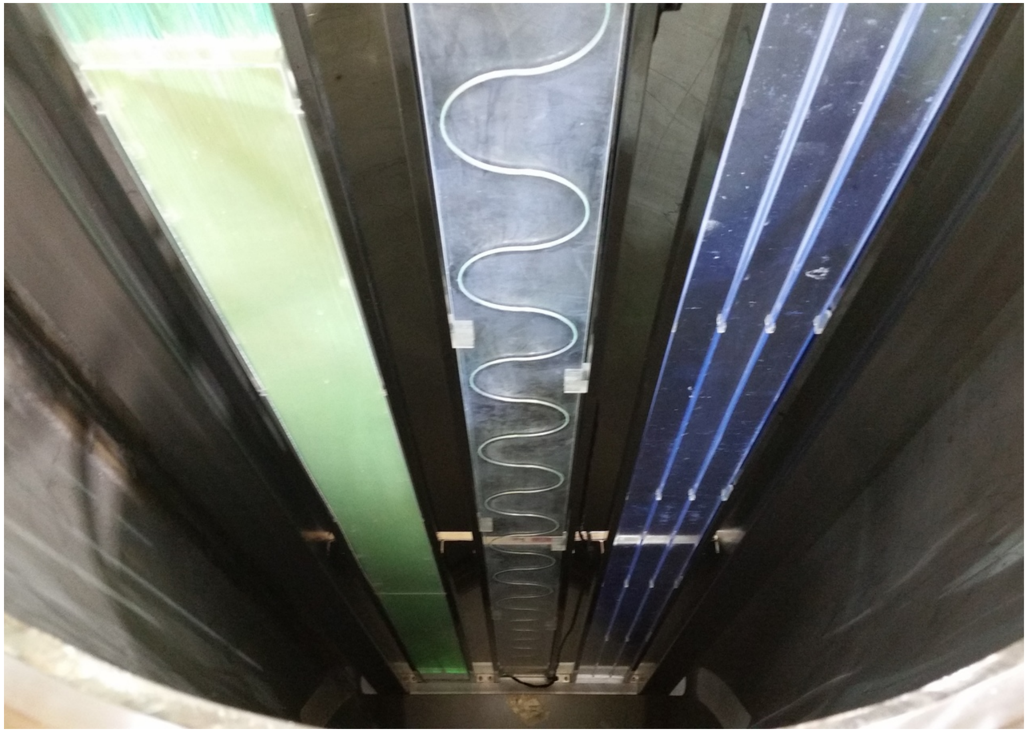


- Shift 128-nm VUV photons into visible wavelengths
- Channel visible signal to readout via total internal reflection
- Maintain good *conversion efficiency* and *attenuation length*
- A variety of designs have been explored.
  - WLS plate + WLS light guide (IU)
  - Dip-coated acrylic light guide (IU/MIT)
  - WLS plate + WLS fibers (CSU)
  - WLS fibers inside coated acrylic panel (LSU)

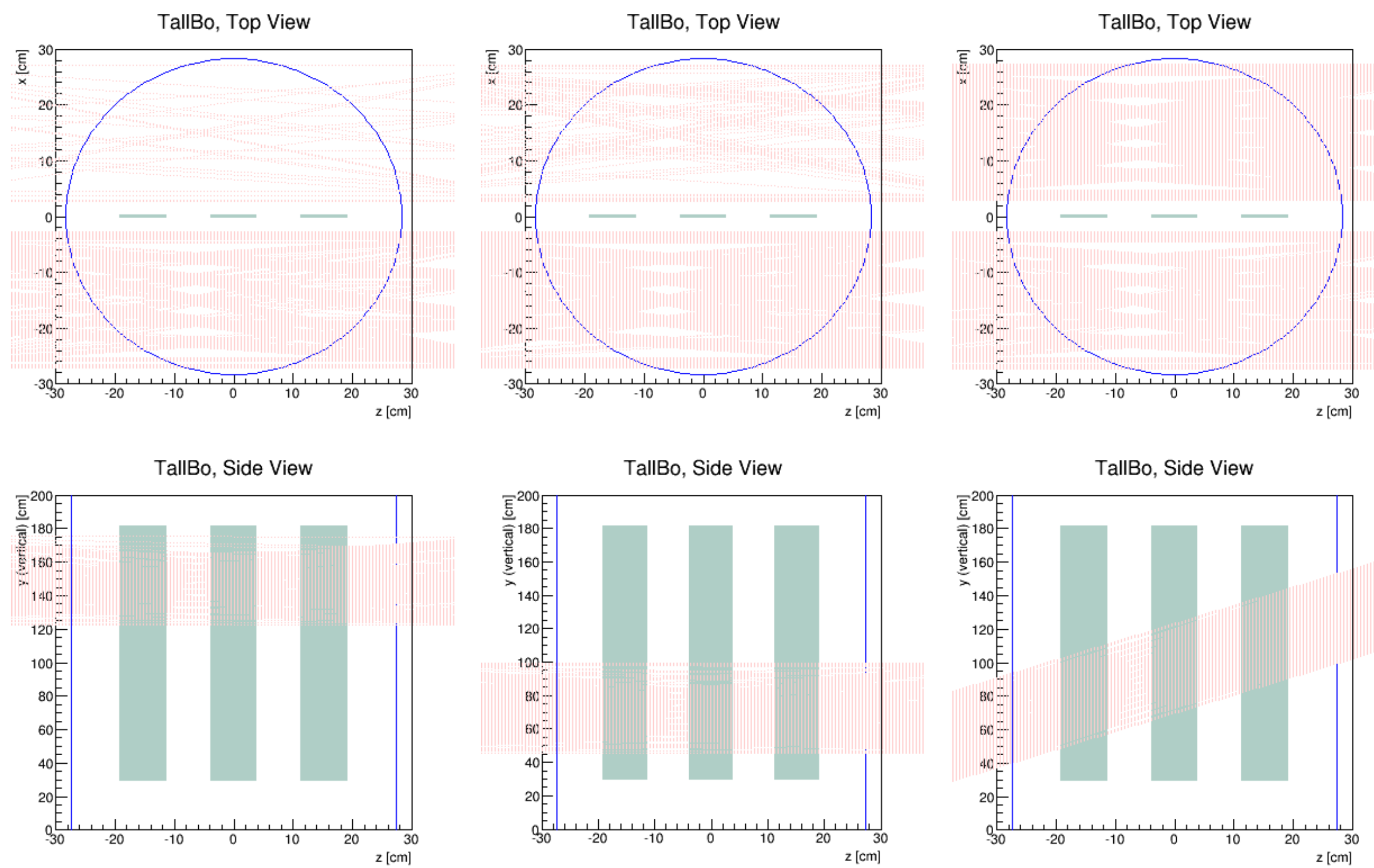




- "TallBo" facility at FNAL
  - 84" LAr dewar
- Ultra-high purity liquid argon
  - Vacuum to remove residual atmosphere
  - Condenser to maintain closed system
  - N2, O2, and H2O monitors
- Space for multiple designs
  - 3 full-width paddles or 12 one-inch light guides
  - Each ~150 cm length
- Hodoscope (cosmic ray) trigger
  - 2 8x8 Arrays of PMTs + $BaF_2$ crystals
    - CREST cosmic-ray balloon exp't.
  - 2 scintillator paddle planes
  - Allows shower rejection, reconstruction of single tracks

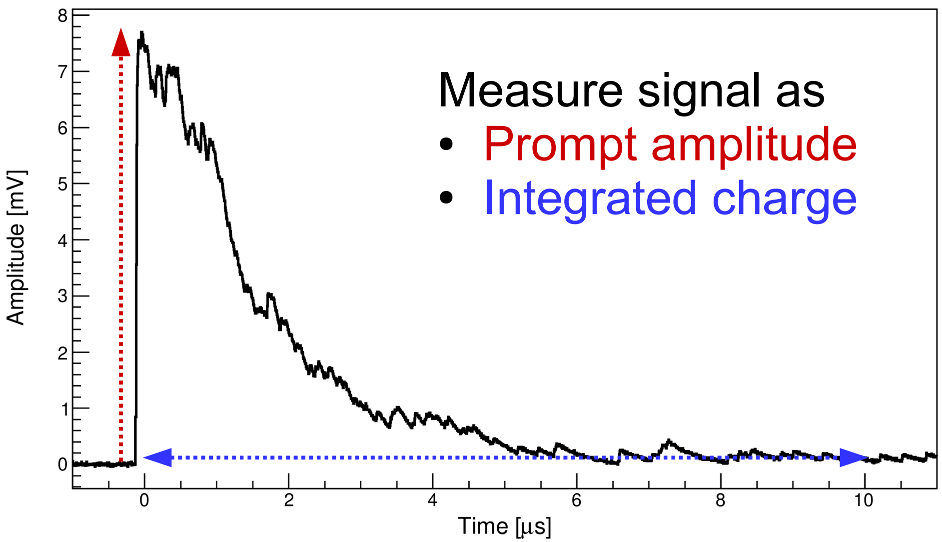
- Three possible hodoscope positions
  - high-high, low-low, high-low
- Require exactly one PMT hit on each hodoscope module
- Exclude tracks crossing from one side of paddles to the other


High-High | Low-Low | High-Low

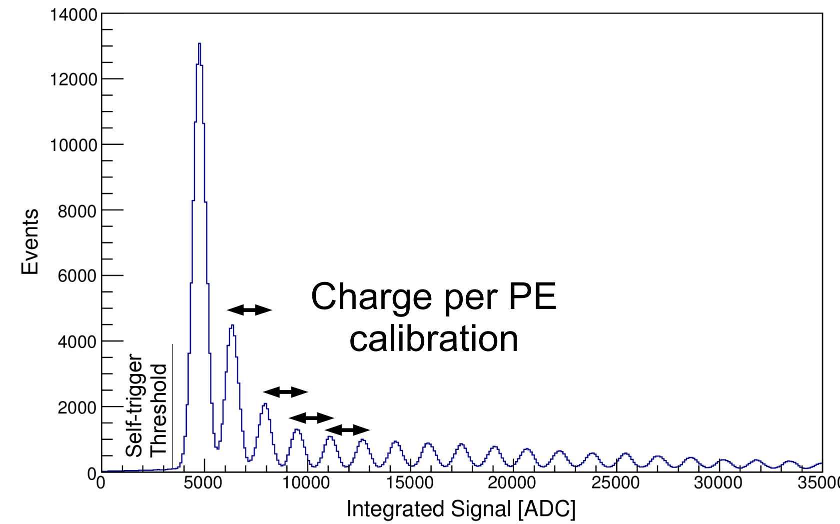


# Cosmic-ray Signals

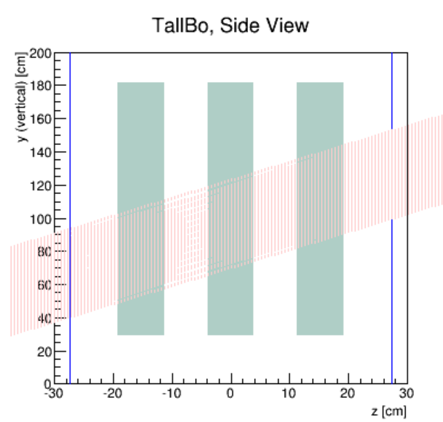
## Example cosmic-ray waveform

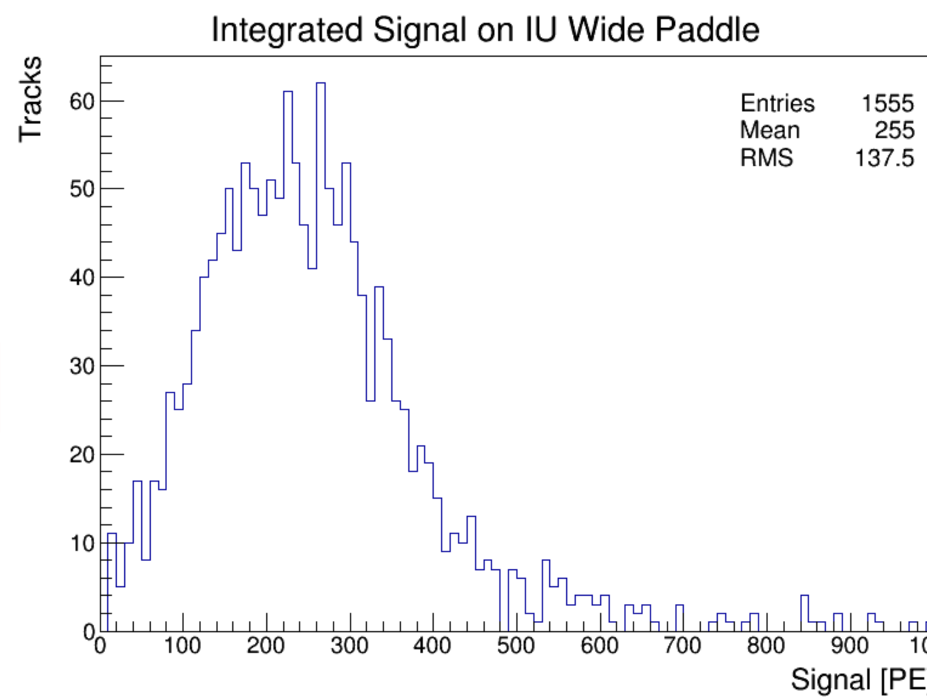



## Discrete SiPM signals

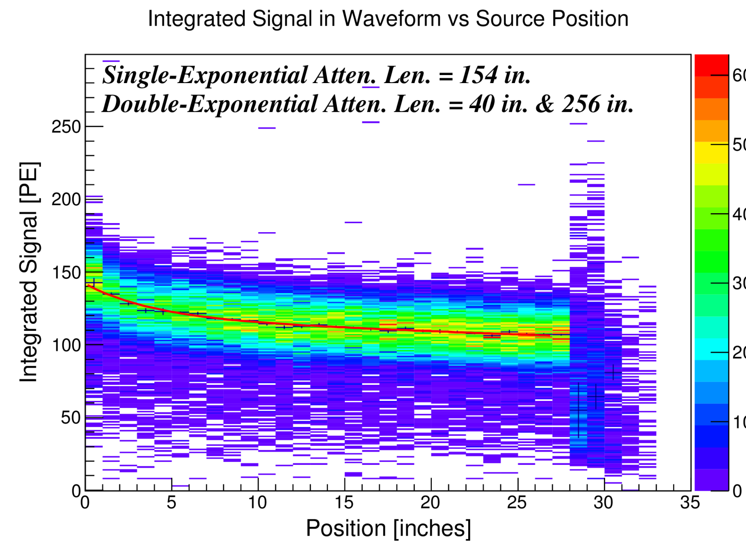


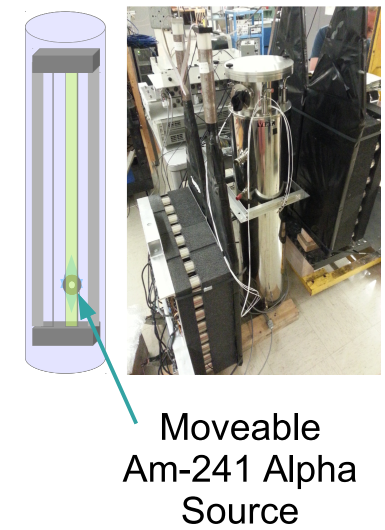

- Example signal distribution
  - Wide WLS light guide + WLS plate
  - High-Low track selection
  - Integrated charge calibrated to PE



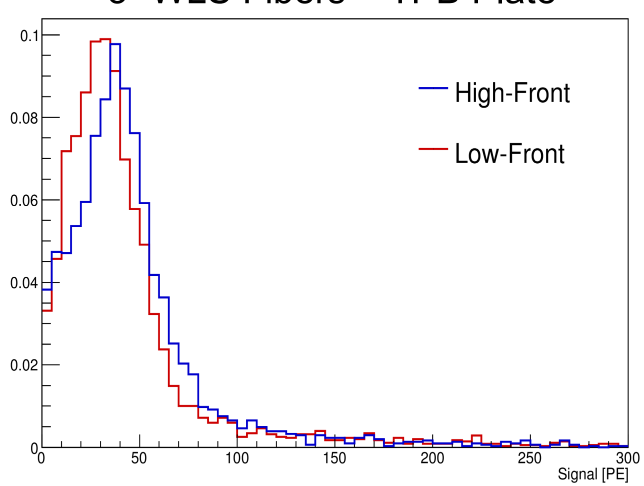
- Direct measurement
  - LAr dewar at IU
  - Movable alpha source and plate to illuminate light guide
  - Consistently long attenuation length measurements



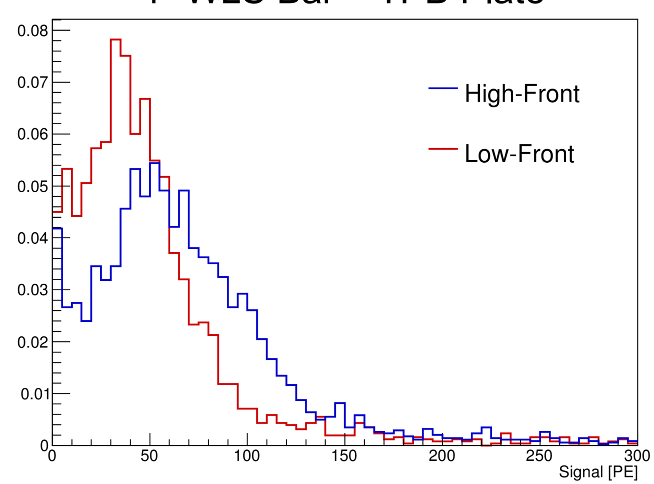




- Indirect measurement
  - Comparison of “high-high” and “low-low” tracks at TallBo
  - Reasonable indication of attenuation

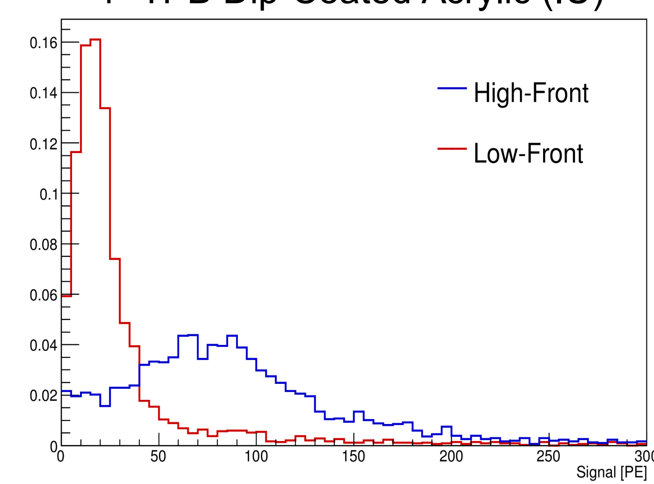
3” WLS Fibers + TPB Plate




1” WLS Bar + TPB Plate

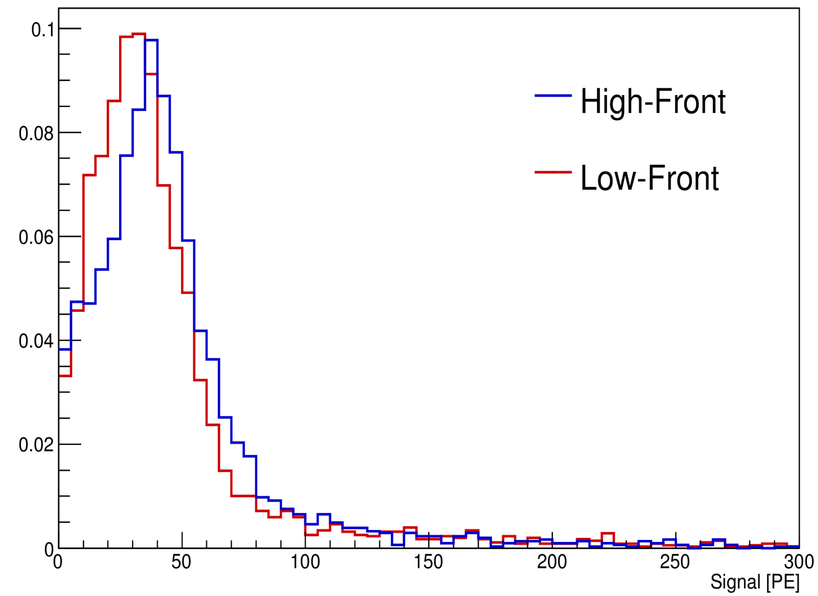


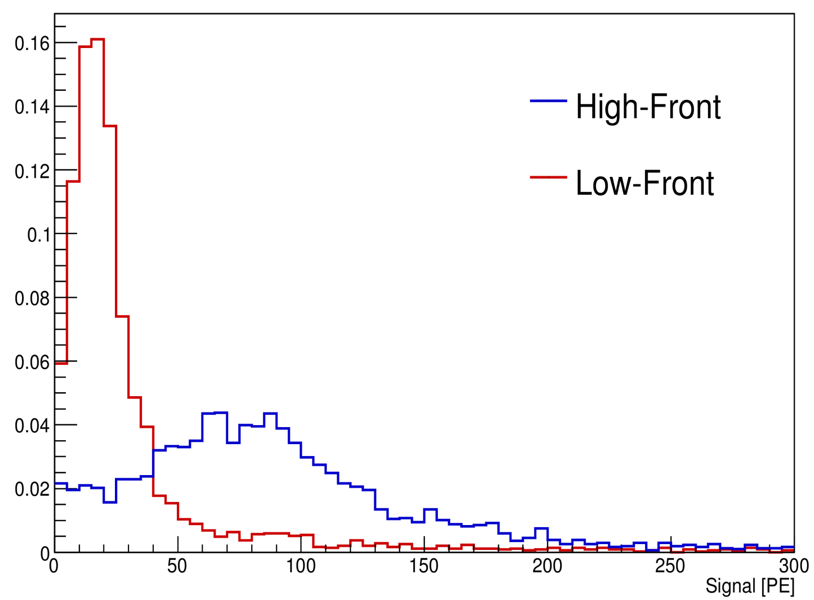

1” TPB Dip-Coated Acrylic (IU)

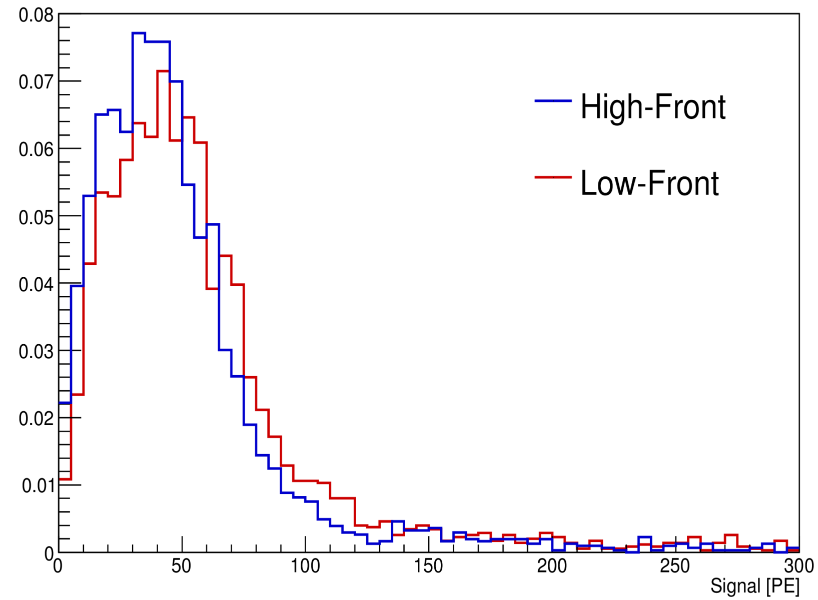


# Relative Performance

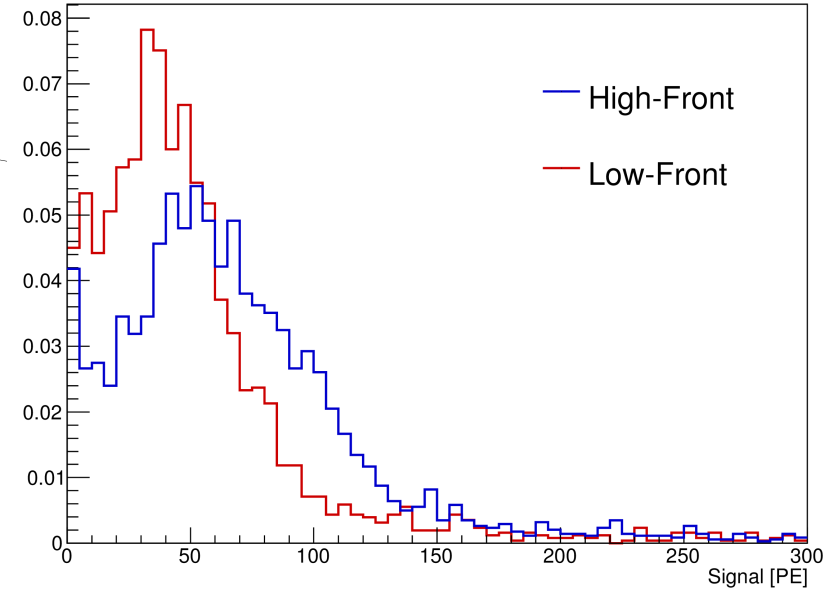
- Summer 2015 (TallBo4 Phase 1) – full-width modules
  - Y11 fibers + TPB-coated acrylic plate
  - Y11 fibers in TPB-coated acrylic pane
  - TPB dip-coated acrylic bars x3 (IU recipe)

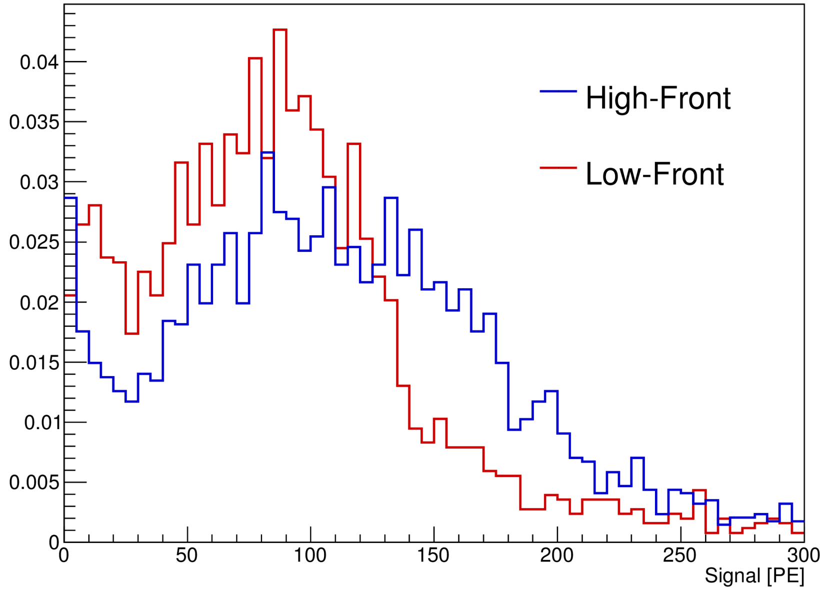


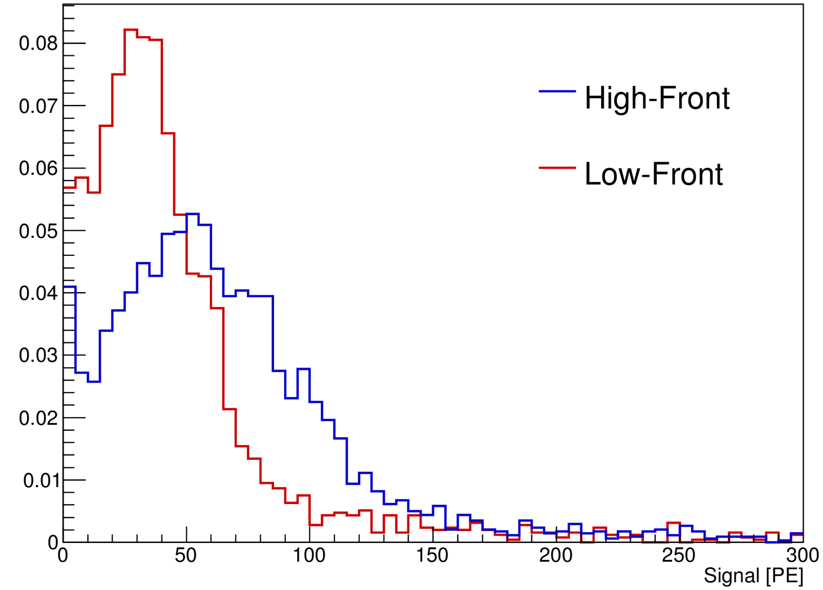



- Summer 2015 (TallBo4 Phase 2) – brightest 3 examples (1" wide)
  - EJ-280 polyvinyltoluene + TPB-coated acrylic plates
  - EJ-280 polystyrene + TPB-coated acrylic plates
  - TPB dip-coated acrylic bar (MIT recipe)

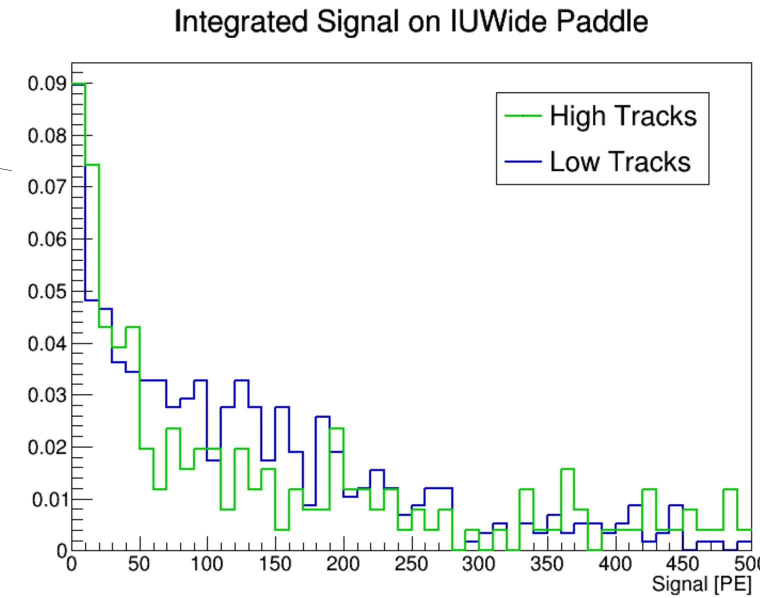


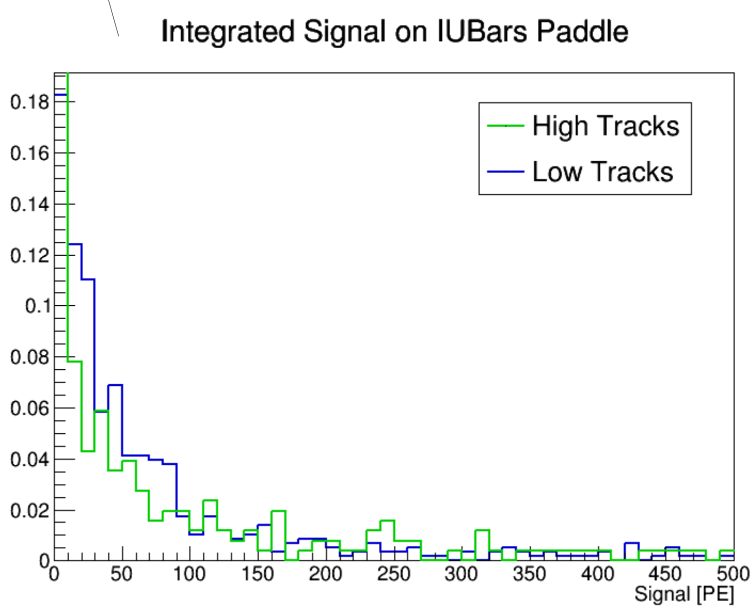



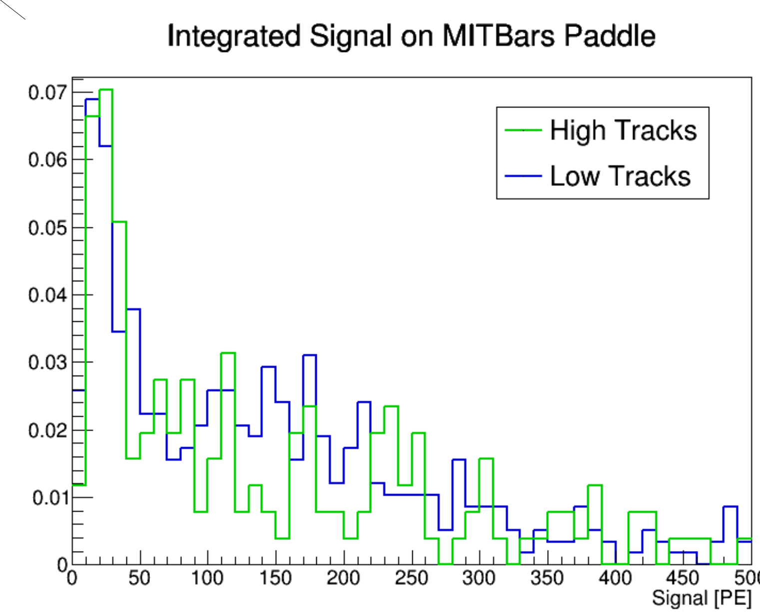



# Winter 2016 (TallBo5)

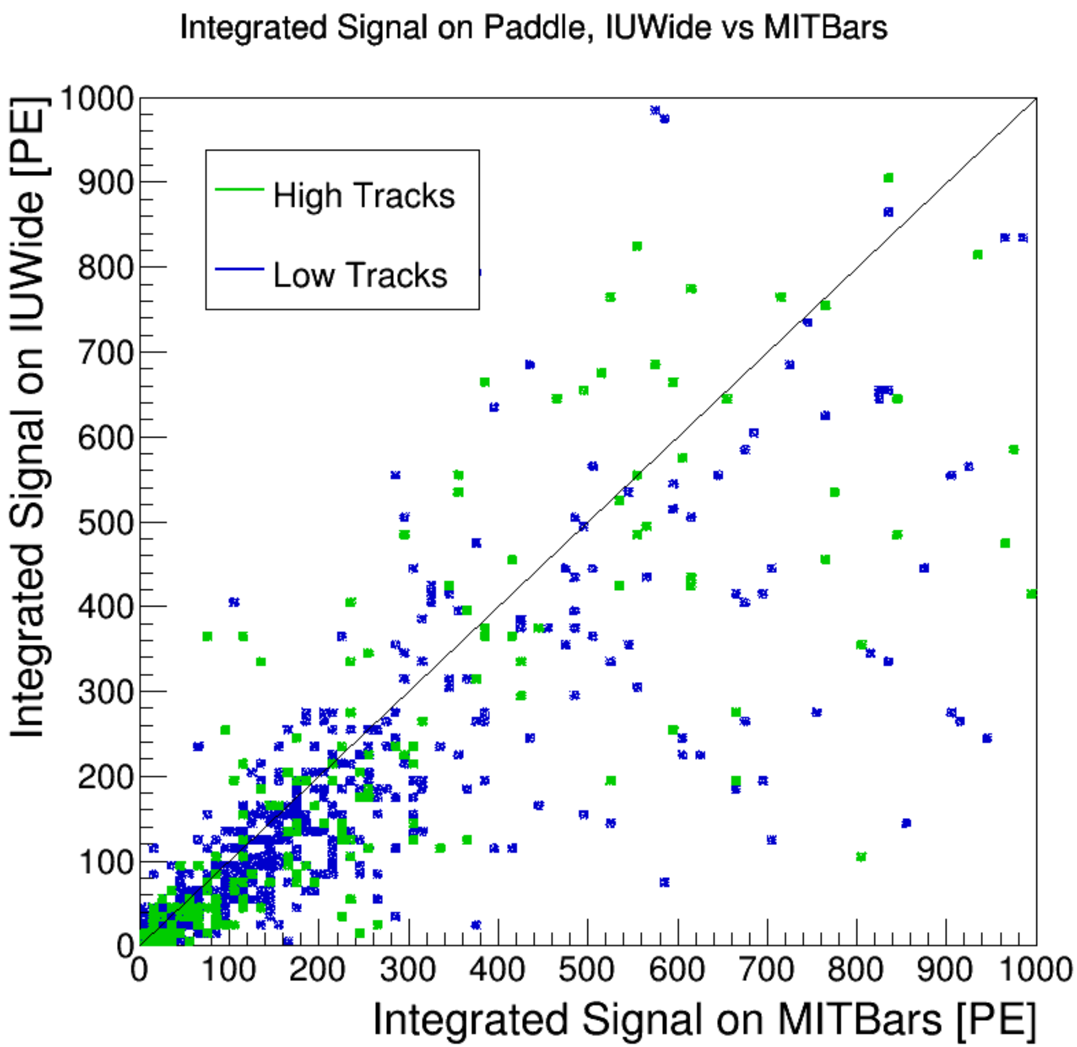
- EJ-280 polystyrene + TPB -coated acrylic plates (wide)
- TPB dip-coated acrylic bar x3 (MIT recipe)
- Combination of 3 1”-wide light guide designs



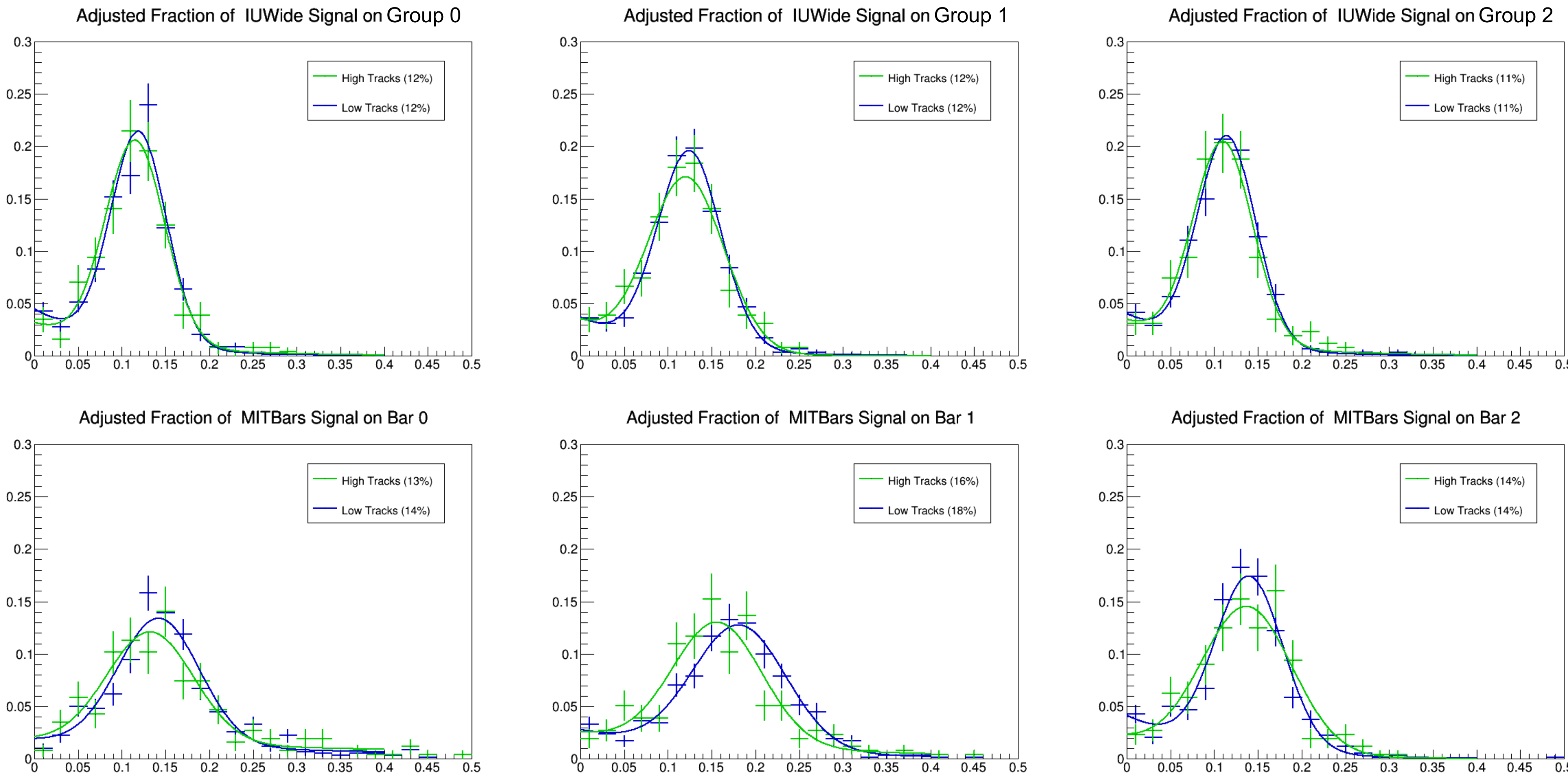



- Winter 2016 (TallBo5)
  - Persistent trigger issues made it difficult to distinguish signal
  - Alternative comparison metrics
    - Correlation between signals on full paddles



- Winter 2016 (TallBo5)
  - Persistent trigger issues made it difficult to distinguish signal
  - Alternative comparison metrics
    - Signal detected on bar (or group of 3 SiPMs) / Total across all SiPMs



- Ray-tracing ToyMC simulation
  - Developed by J. Lowery (IU undergrad)
  - Light guides modeled as 2D planes at positions in center of dewar
  - Calculates number of photons incident along light guide from each hodoscope track trajectory
    - Includes reflection off of stainless steel dewar walls (25% – Icarus)
    - Assumes MIP value of 40k photons/MeV (84k photons/cm in LAr)

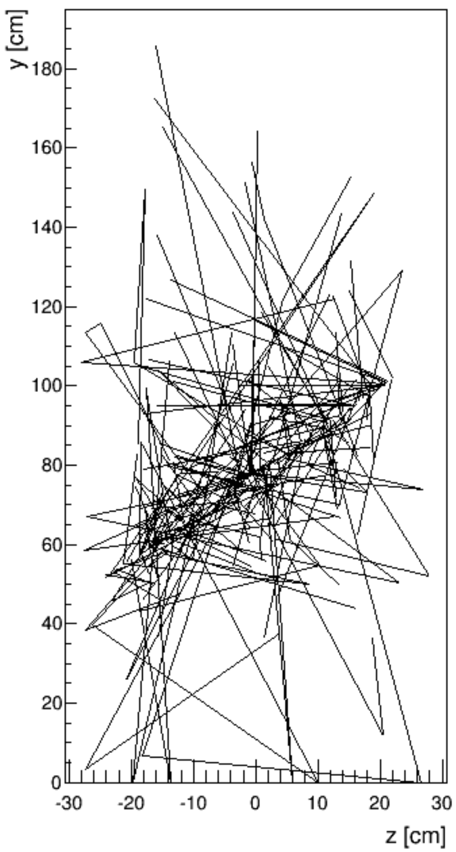
Table 1
*Liquid Argon properties.*

| | | | |
|---|---|---|---|
| Liquid phase: | 1.00 bar | 87.2 K | $1.396\ g/cm^3$ |

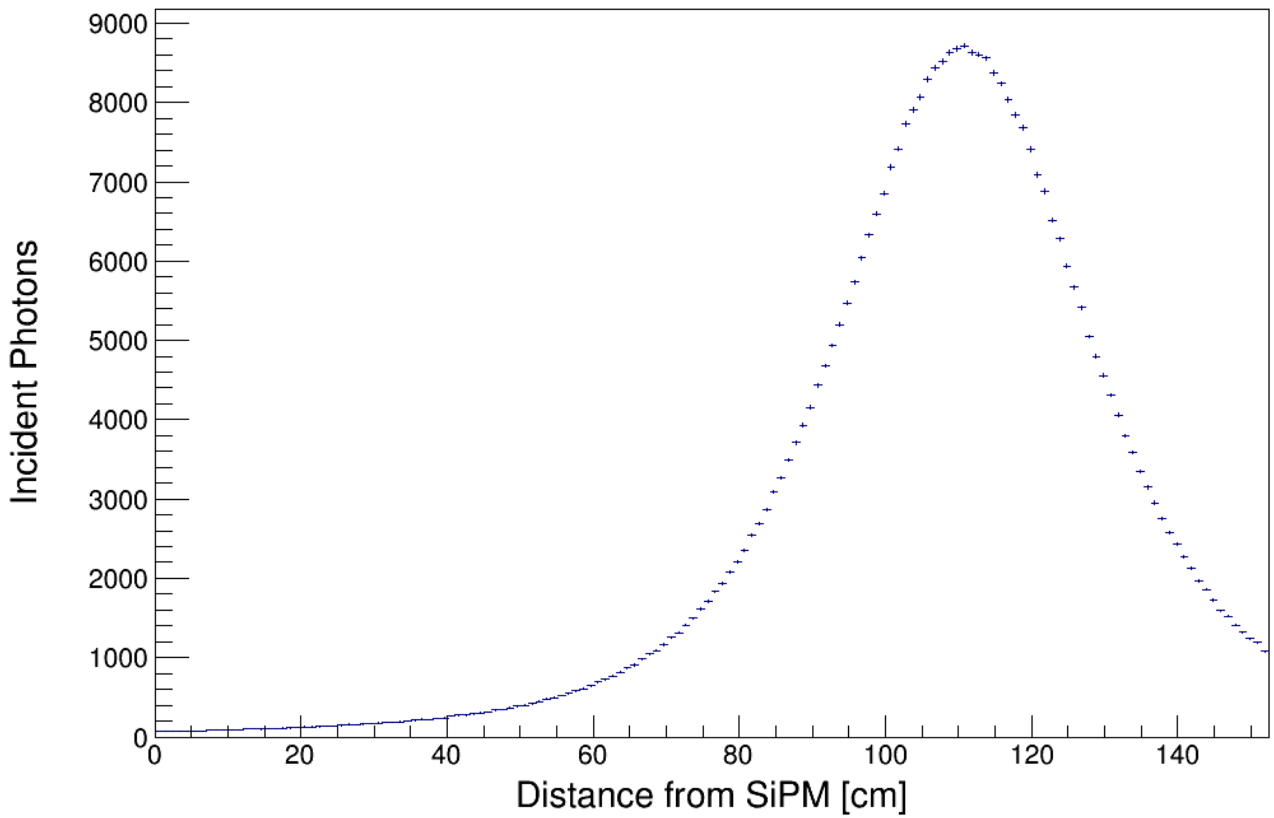
Table 2
*Liquid Argon Ionization and Scintillation properties.*

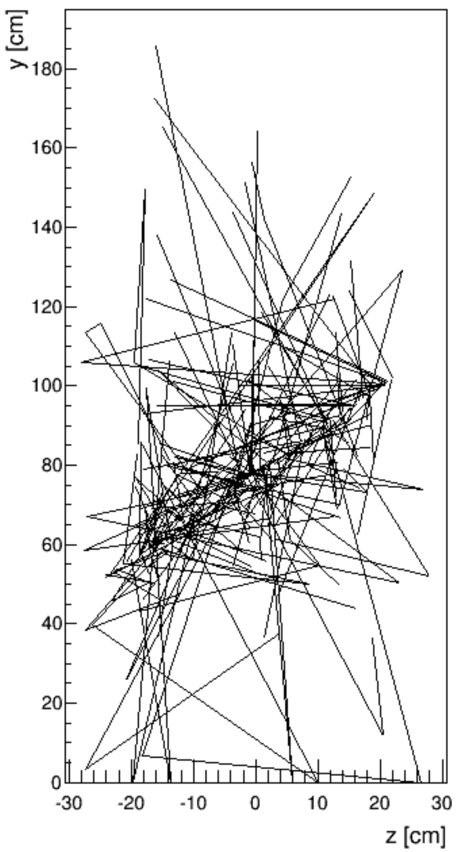
| | | |
|---|---|---|
| Mean energy loss (*mip*) | | $\langle dE_{mip}/dx \rangle = 1.519$ MeV cm$^2$/g |
| Photon yield | [@ 0-Field] (ideal) | $Y_{ph} = 5.1\times 10^4\ \gamma/\mathrm{MeV}$ |
| | [@ 0-Field] (*mip*) | $Y_{ph} =\sim 4.0\times 10^4\ \gamma/\mathrm{MeV}$ |
| | [@ 500 V/cm] (*mip*) | $Y_{ph} =\sim 2.4\times 10^4\ \gamma/\mathrm{MeV}$ |
| | [@ > 15 kV/cm] (*mip*) | $Y_{ph} =\sim 1.3\times 10^4\ \gamma/\mathrm{MeV}$ |

$$N_{photons} = \rho_{LAr} \cdot \left\langle \frac{dE_{mip}}{dx} \right\rangle \cdot Y_{ph} \approx 84821\ photons/cm$$

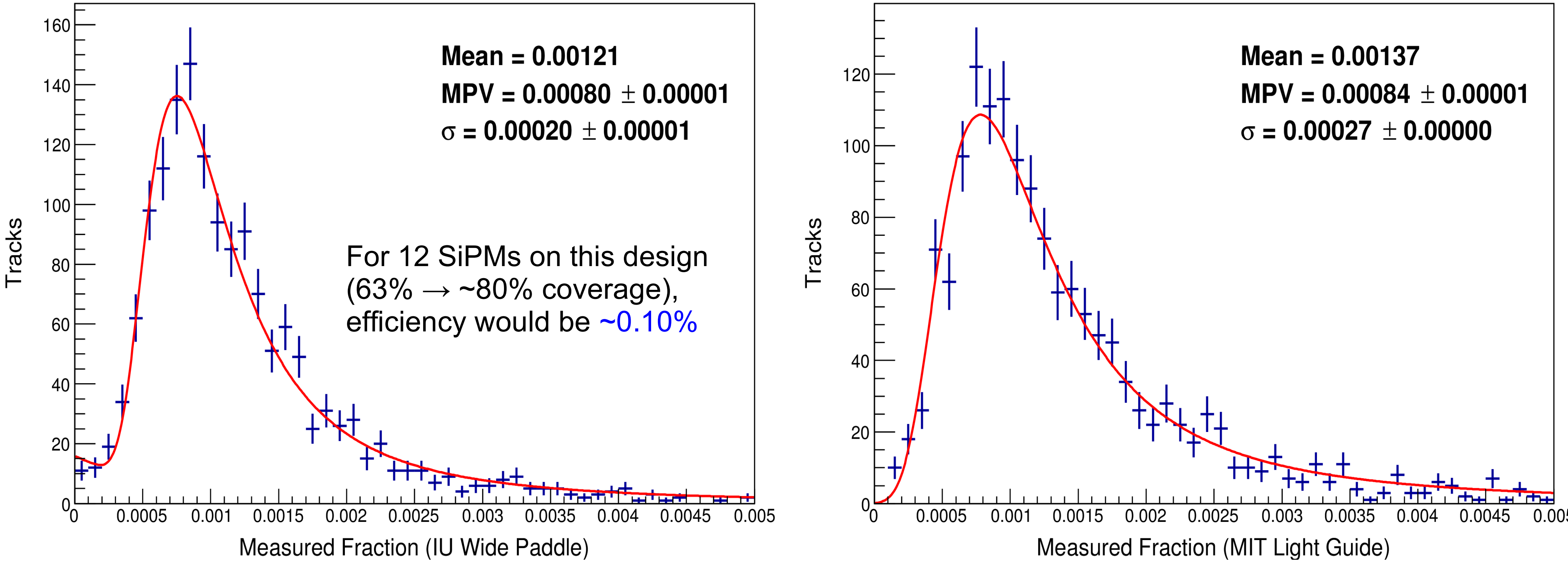


- Ray-tracing ToyMC simulation
  - Data
    - Find integrated signal (PE) in 10 μs measured from data to matching simulated track trajectory
  - Simulation
    - Sum total number of incident photons across bar ⊗ 2 m attenuation
    - *To add:* gaps in plate coverage



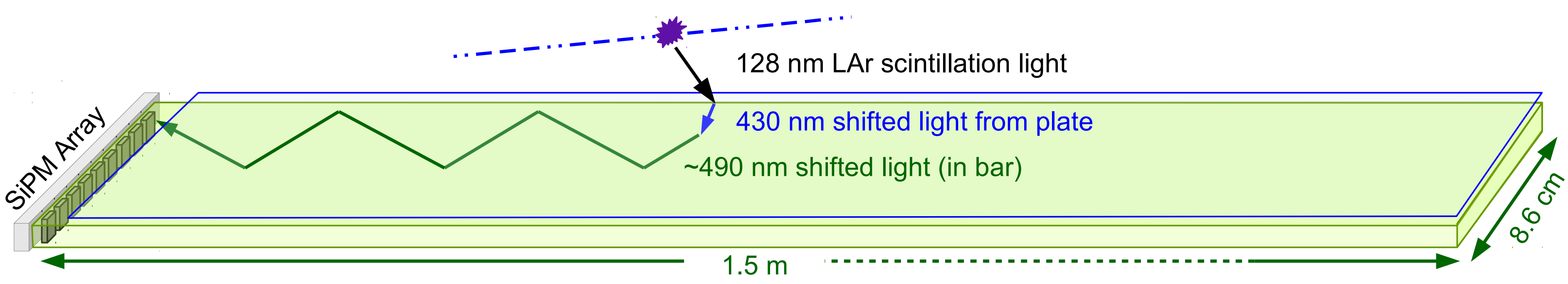



- Calculate fraction of incident photons detected per track event

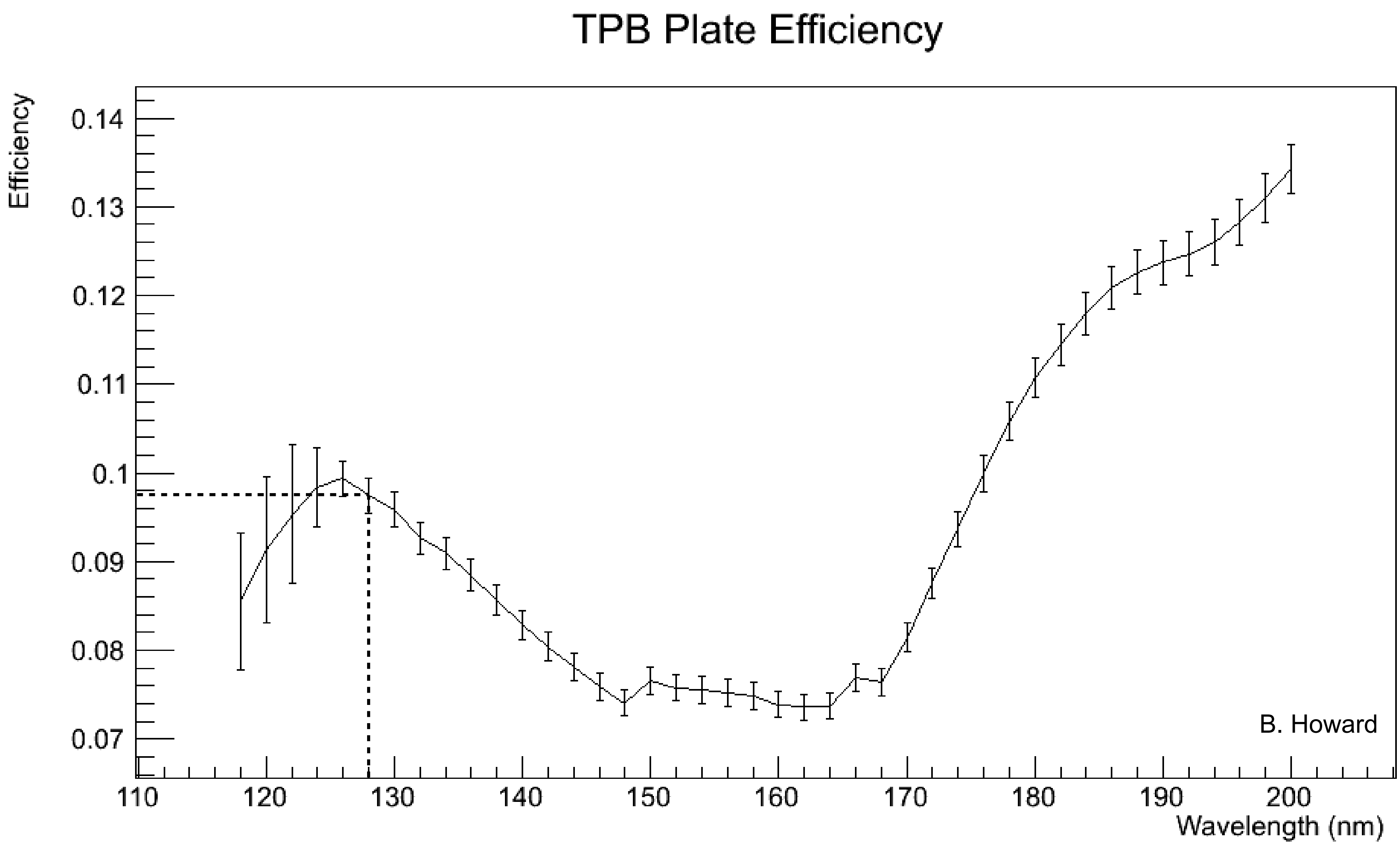



- Landau + exponential fit
  - Most probable value measures efficiency to detect MIP scintillation photons
  - Denominator simulated with a 2 m attenuation length
  - Does not include correction for cross-talk probability (~30%)

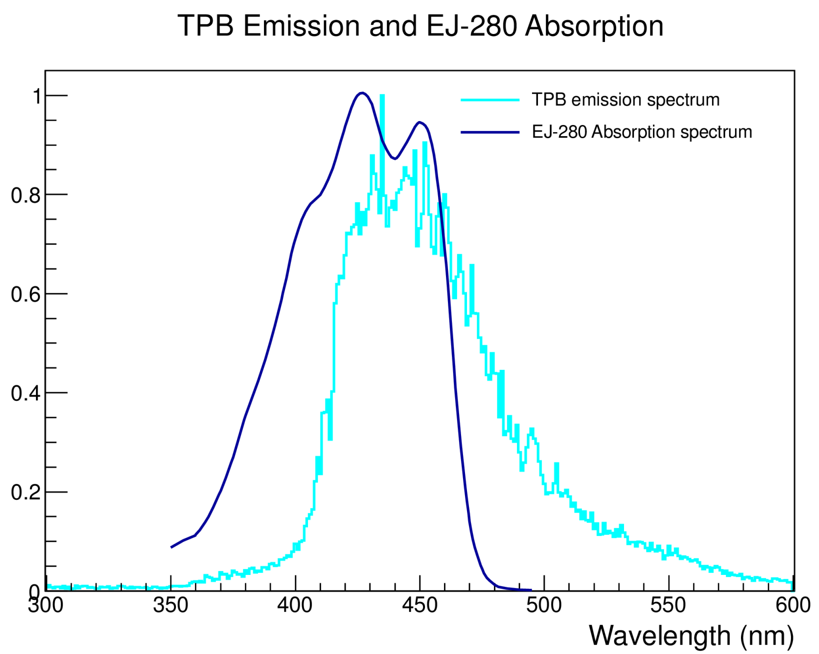
- VUV Conversion at TPB Plate
  - VUV photons strike TPB
  - TPB emits VIS (blue) photons
  - VIS (blue) photons strike WLS bar
  - *Measure with VUV Monochrometer*
- VIS Transport and Detection
  - WLS emits VIS (green) photons
  - VIS (green) photons propagate via total internal reflection
  - Some photons reach SiPMs and generate signal
  - *Manufacturer Specifications + Simulation*



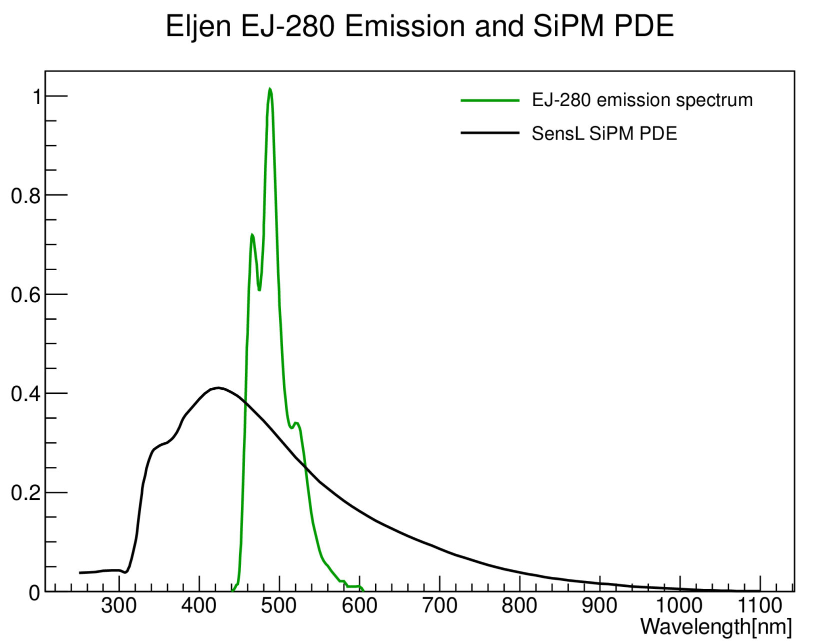
- Example VUV forward conversion efficiency
  - VIS photons at SiPM / VUV photons incident on TPB sample
    - Not corrected for SiPM solid angle (but SiPM is close to VUV spot)



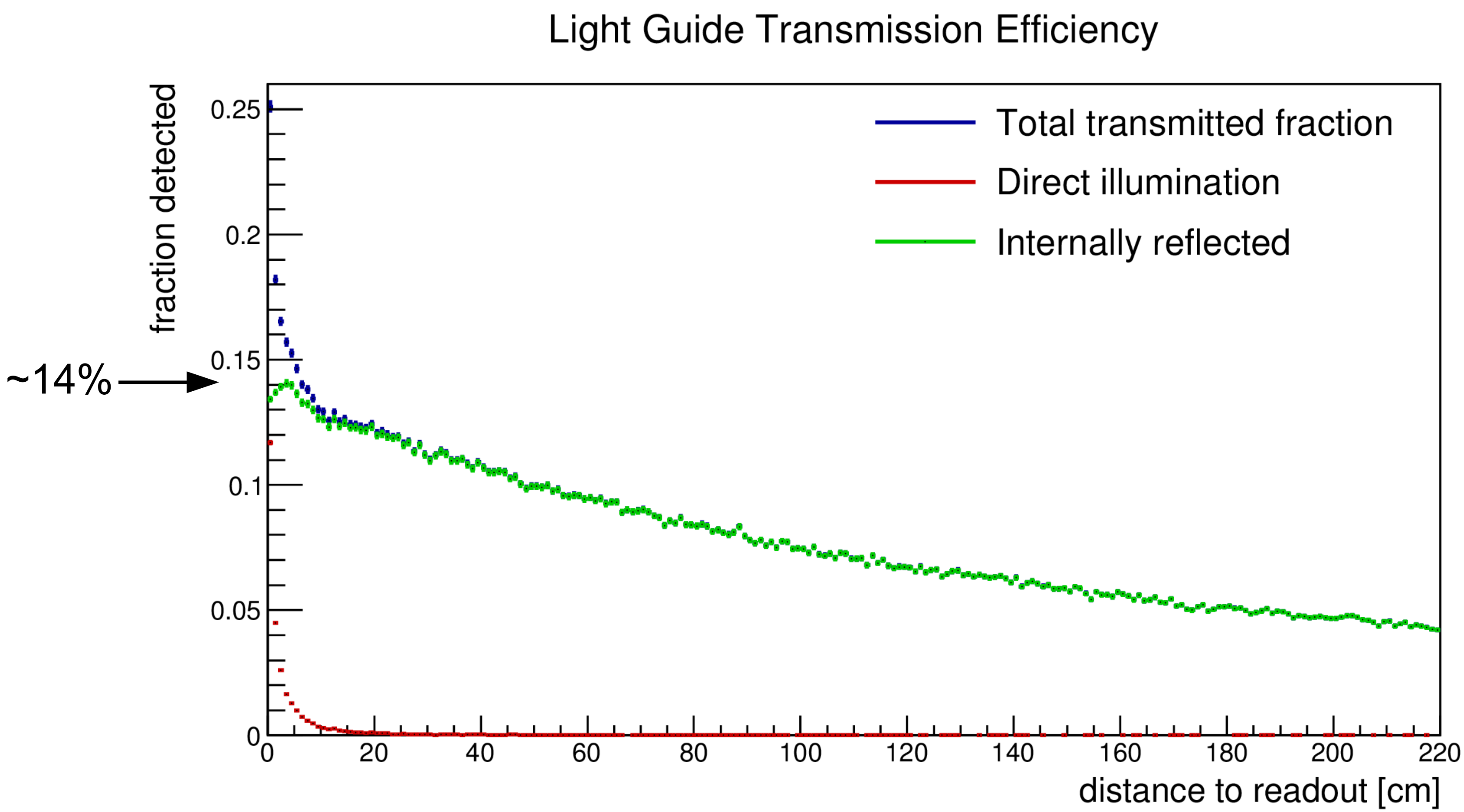
- TPB Emission vs EJ-280 Absorption
  - ~ 44% of TPB emission incident on light guide is wavelength-shifted to green




- EJ-280 Emission vs sensL 60035-SMT PDE
  - EJ-280 output is close to maximum SiPM eff.
  - ~ 32% of light from the EJ-280 reaching the SiPM is registered as signal

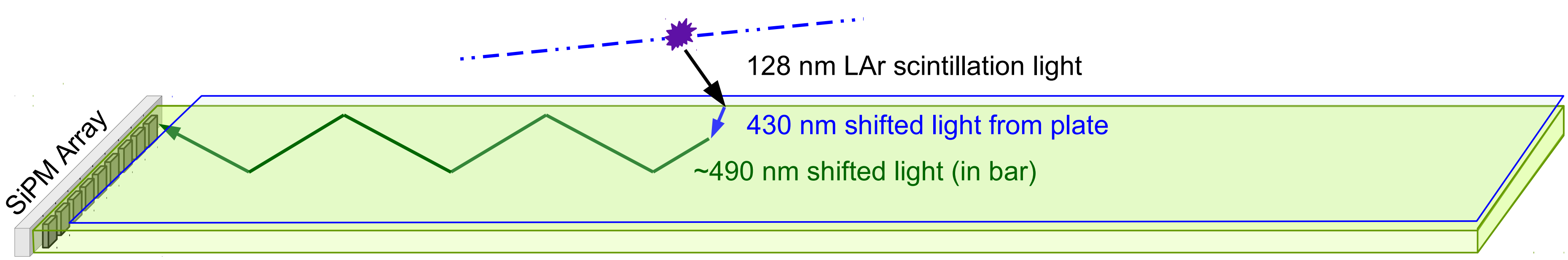


- Ray-tracing simulation of light guide
  - WLS photon emitted inside EJ-280 light guide
  - Propagate (via internal reflection) until lost or arrives at readout end
  - Assume 1% loss probability at light guide surfaces
    - "attenuation" length of ~2 m



- VUV light converted by TPB
  - Forward conversion efficiency from VUV monochrometer – ~10%
- VIS light converted within light guide
  - Conversion efficiency – ~44%
- Green light transported within light guide
  - Transport efficiency from simulation – ~14% × exp( -x / 2m )
- Detected by SiPMs
  - Geometric coverage of SiPMs (area) – 63% *9 SiPMs* (80% *12 SiPMs*)
  - SiPM photon detection efficiency – ~32%

- Total expected efficiency (above calculation) **~0.12%** (0.16%)
- Measured efficiency (data from cosmic rays) **~0.08%** (0.10%)




- Target (LArSoft studies) of ~0.3% total efficiency for SNν

- Final light guide test at Blanche test facility (PAB)
  - Deploy full-width half-length EJ-280 light guides with optimized plates
  - Exercise QA/QC procedures (see S. Mufson's talk)
    - Light guides
    - TPB-coated plates
  - Validate expected efficiency
    - Resolve tension between data/sim comparison and component analysis
    - Incorporate correction for SiPM cross talk
  - Measure absolute photon yield from MIP cosmic rays
    - Combine light guide component analysis with cosmic ray simulation

- ProtoDUNE-SP
  - Investigate performance of full-scale light guides in-situ
    - Beam events & cosmic rays
  - Quantify variation in light guide performance in TPC
  - Employ full larsoft simulation → more robust efficiency estimates

- *Results*
  - EJ-280 bar +TPB plate (IU) and dip-coated acrylic (MIT) light guide designs quite comparable
    - Relative brightness similar, attenuation length appears long
  - Absolute efficiency estimated from data/simulation comparison (TallBo5)
    - Expect 0.10% efficiency (photons detected / incident) with 12 SiPMs on TPB Plate + WLS Bar design from data-simulation comparison
    - Expect 0.16% efficiency from light guide component analysis

    } Probably somewhere in between
- *Recommendations*
  - Continued work to improve TPB (or bis-MSB) plate design
    - Expect improvement by factor of 2 with QC (see talk by S. Mufson for current work)
  - Consider painting inactive sides of light guides w/ reflector
    - Could increase internal reflection trapping by ~45%
  - Double-ended light guide readout
  - Increase number of light guides per APA
    - Likely not necessary for ProtoDUNE, potentially vital for FarDet
- *More details*
  - TallBo4, Summer 2015 (DUNE DocDB 138)
  - TallBo5, Winter 2016 (Presentation from May CSU Workshop)