Photon Detector System Performance Testing

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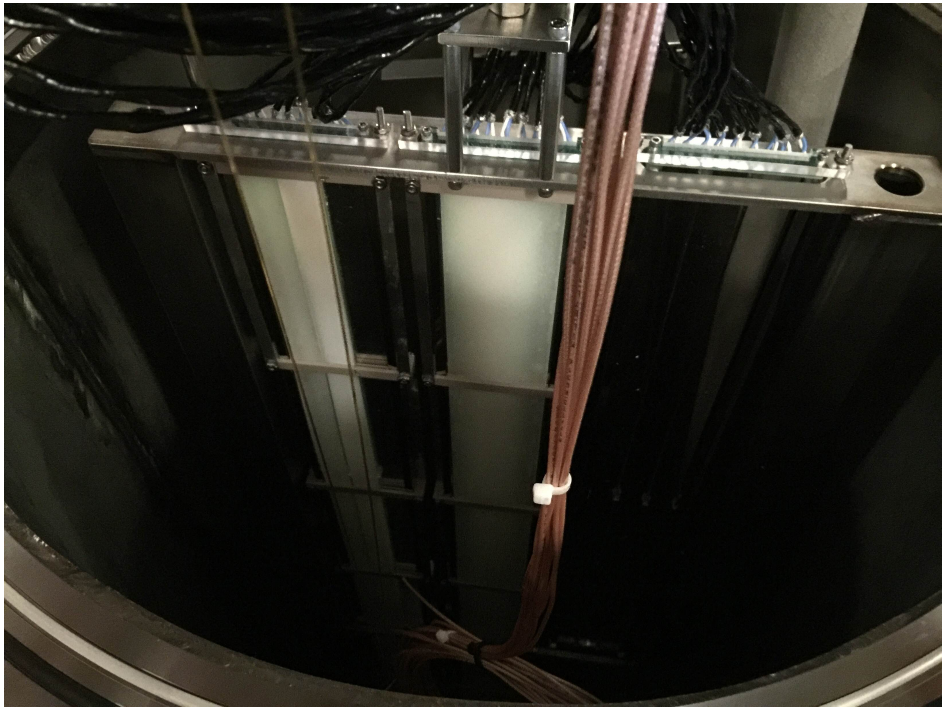
August 2, 2016

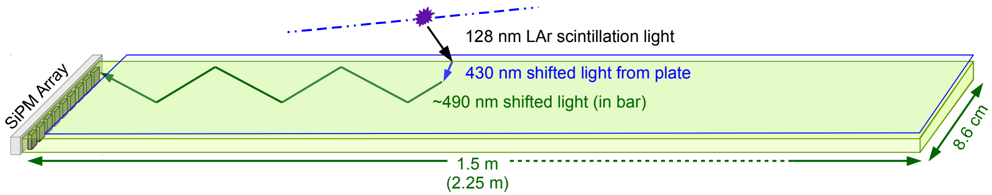
Charges addressed

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

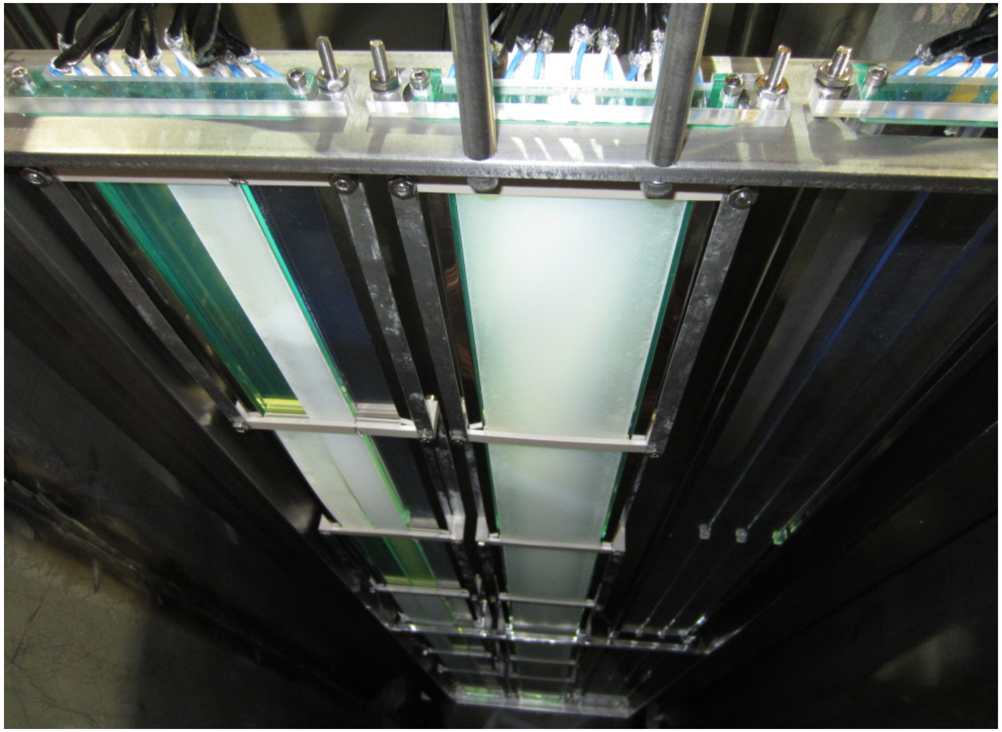
- Light guide designs
- TallBo facility
- Light guide attenuation
- Relative light guide performance
  - Summer 2015, Winter 2016
- Light guide efficiency
  - Data-simulation comparisons
  - Light guide component analysis
- Conclusions and Recommendations

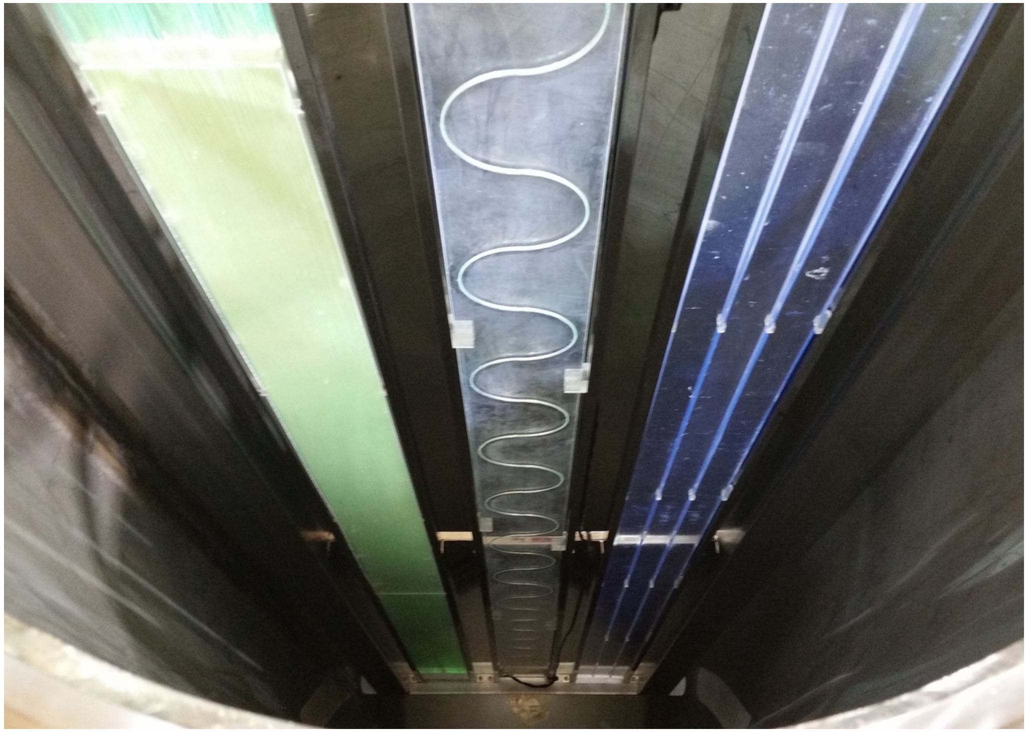




Light Guide Designs

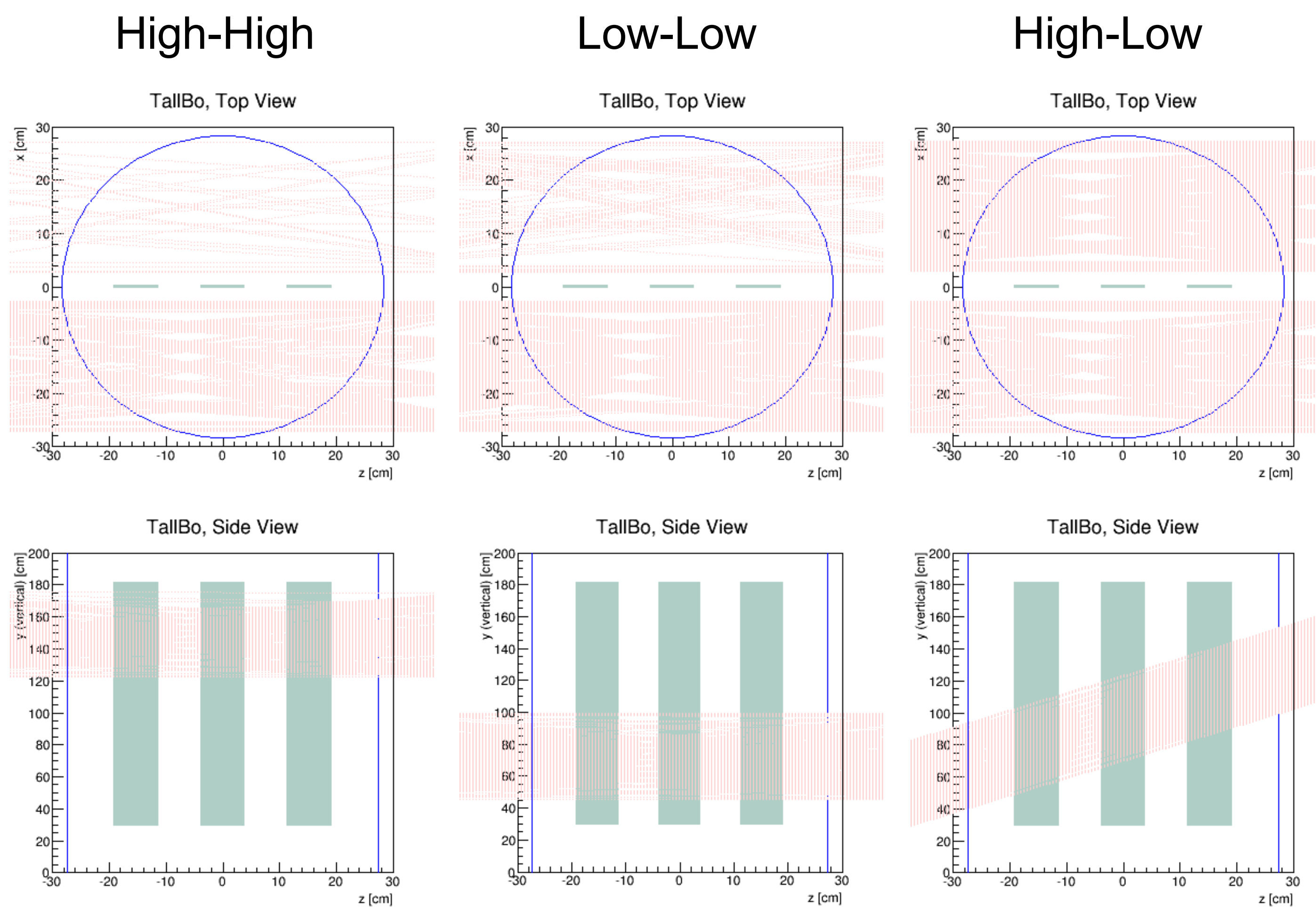
- Shift 128-nm VUV photons into visible wavelengths
- Channel visible signal to readout via total internal reflection
- Maintain good *conversion efficiency* and *attenuation length*
- A variety of designs have been explored.
  - WLS plate + WLS light guide (IU)
  - Dip-coated acrylic light guide (IU/MIT)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



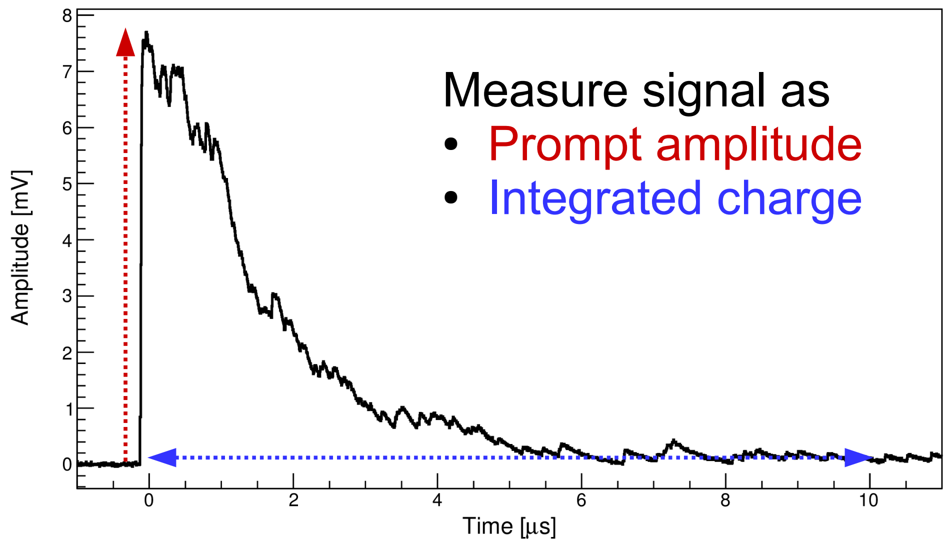


- “TallBo” facility at FNAL
  - 84” LAr dewar
- Ultra-high purity liquid argon
  - Vacuum to remove residual atmosphere
  - Condenser to maintain closed system
  - N2, O2, and H2O monitors
- Space for multiple designs
  - 3 full-width paddles or 12 one-inch light guides
  - Each ~150 cm length
- Hodoscope (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

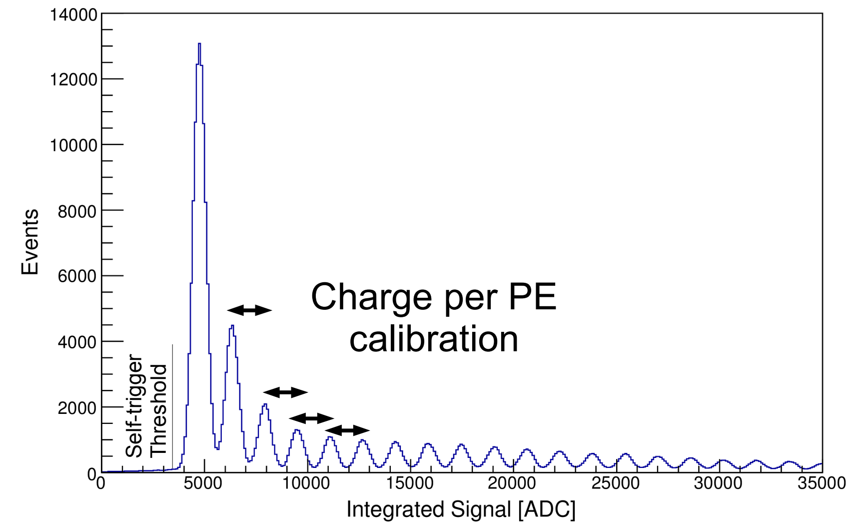
- Three possible hodoscope positions
  - high-high, low-low, high-low
- Require exactly one PMT hit on each hodoscope module
- Exclude tracks crossing from one side of paddles to the other



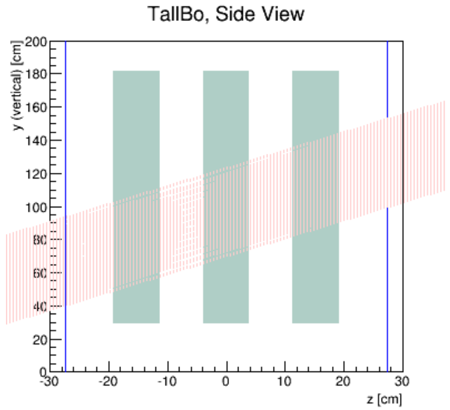
Example cosmic-ray waveform

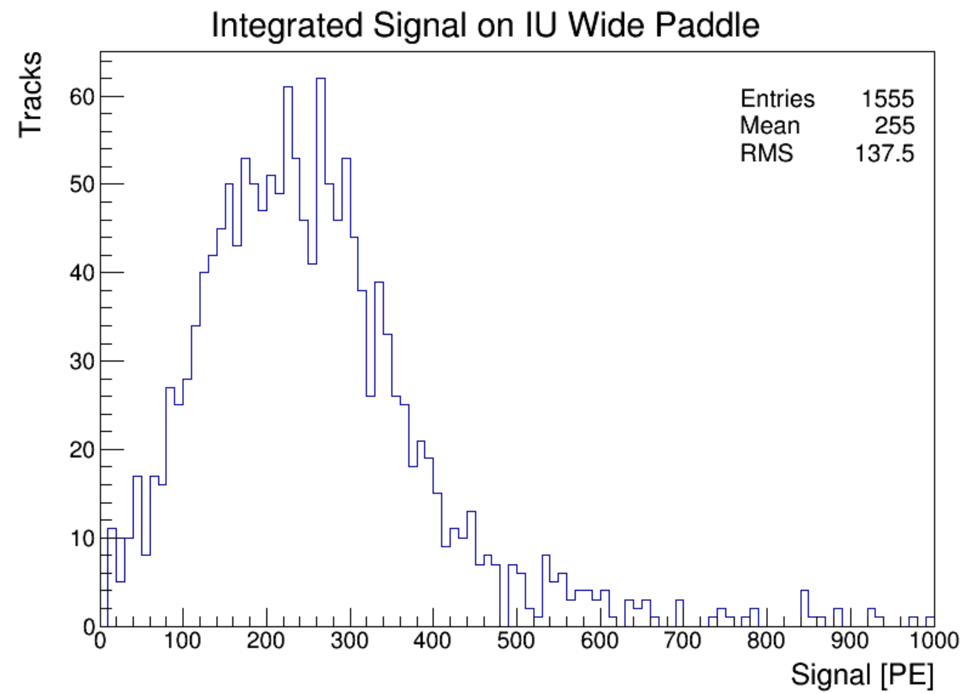


Discrete SiPM signals

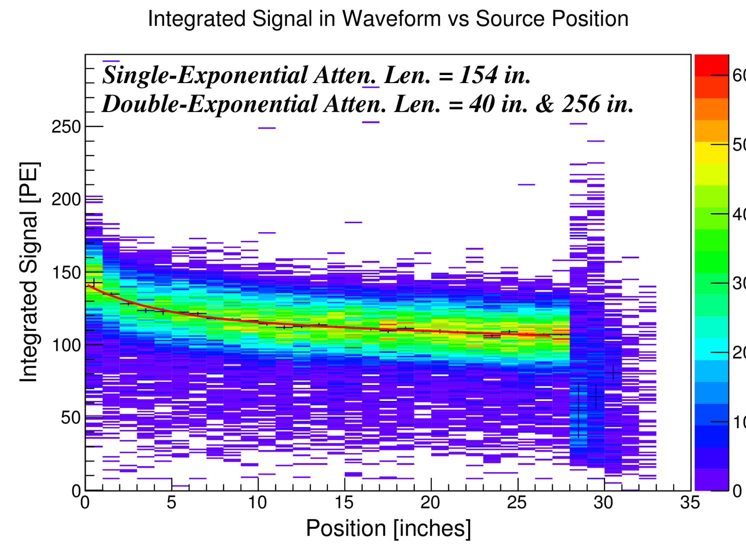


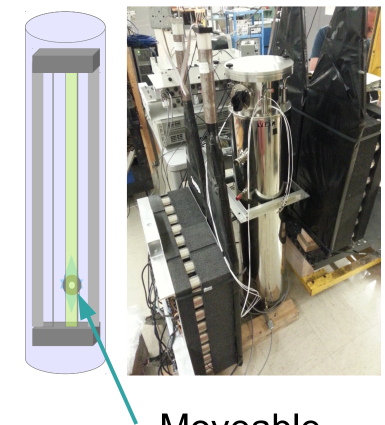
- Example signal distribution
  - Wide WLS light guide + WLS plate
  - High-Low track selection
  - Integrated charge calibrated to PE





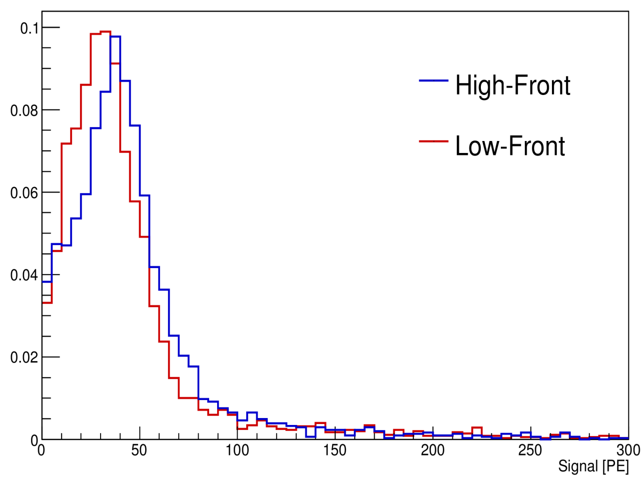
- Direct measurement
  - LAr dewar at IU
  - Movable alpha source and plate to illuminate light guide
  - Consistently long attenuation length measurements



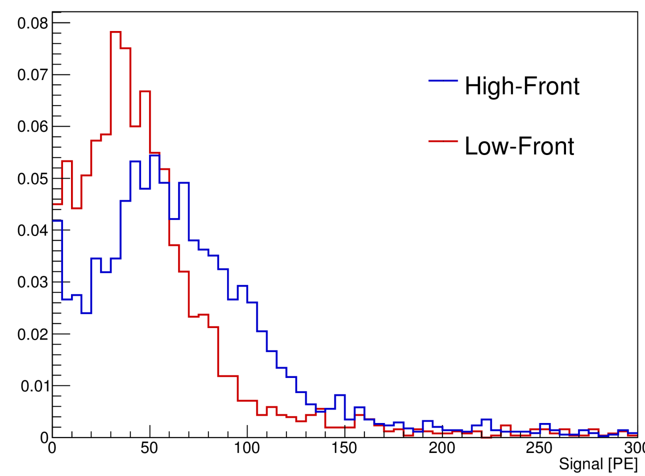


- Indirect measurement
  - Comparison of “high-high” and “low-low” tracks at TallBo
  - Reasonable indication of attenuation

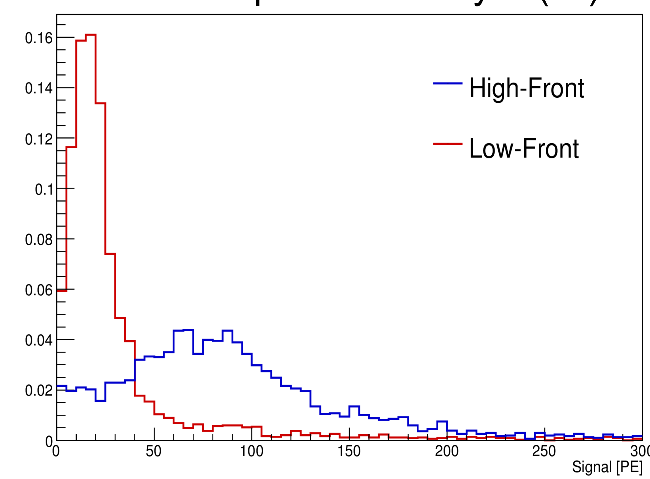
3” WLS Fibers + TPB Plate



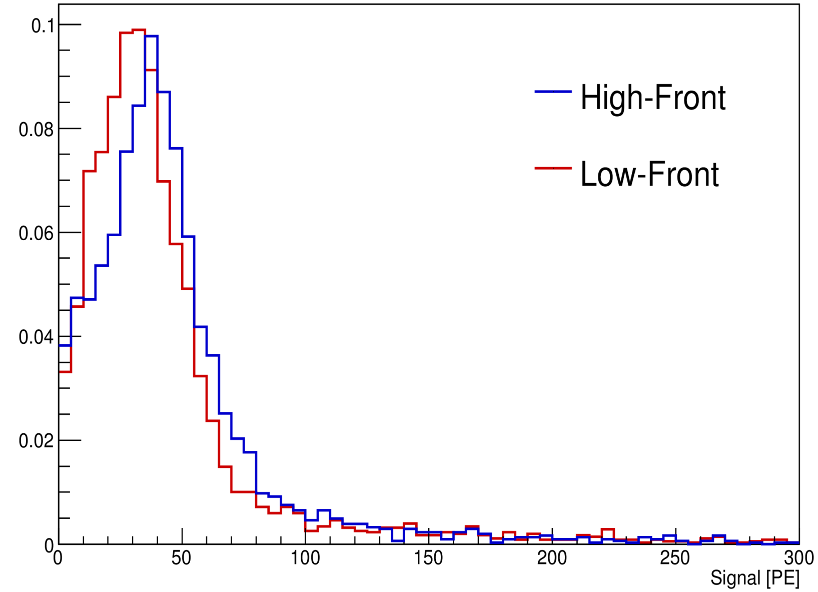
1” WLS Bar + TPB Plate

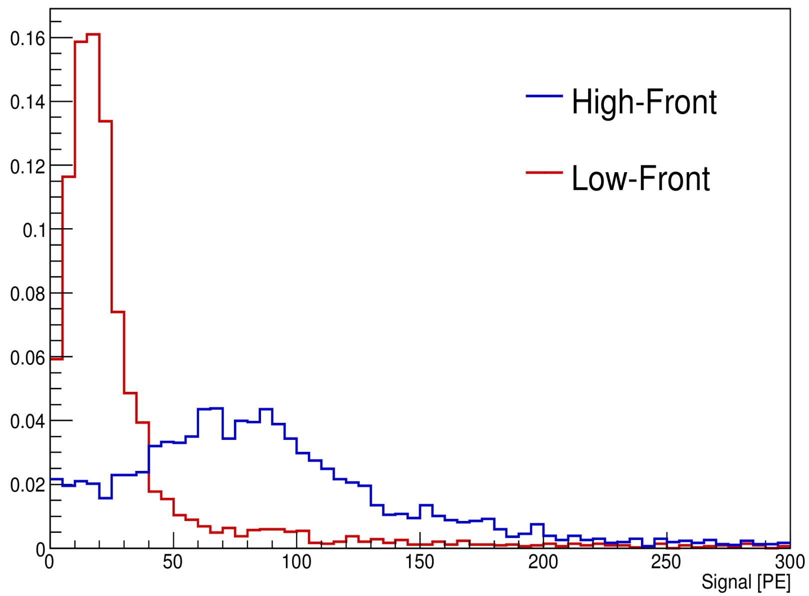


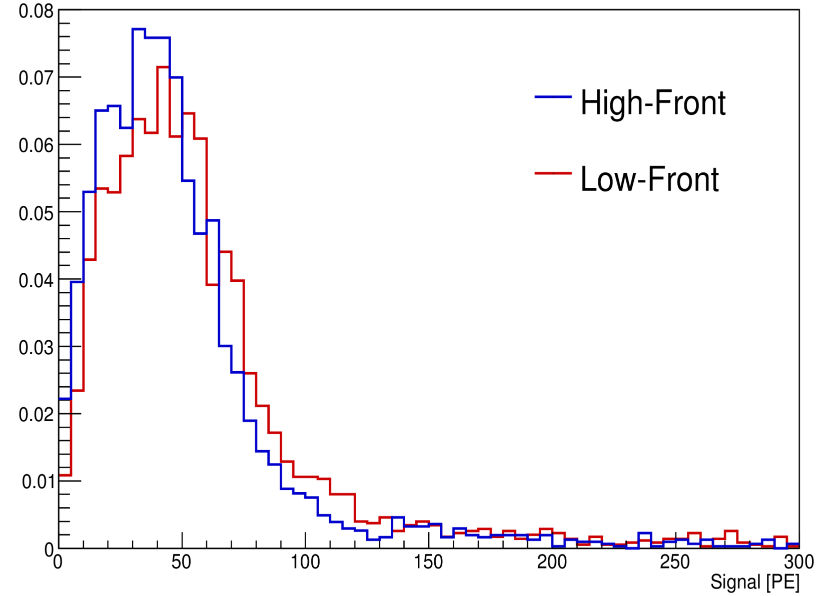
1” TPB Dip-Coated Acrylic (IU)



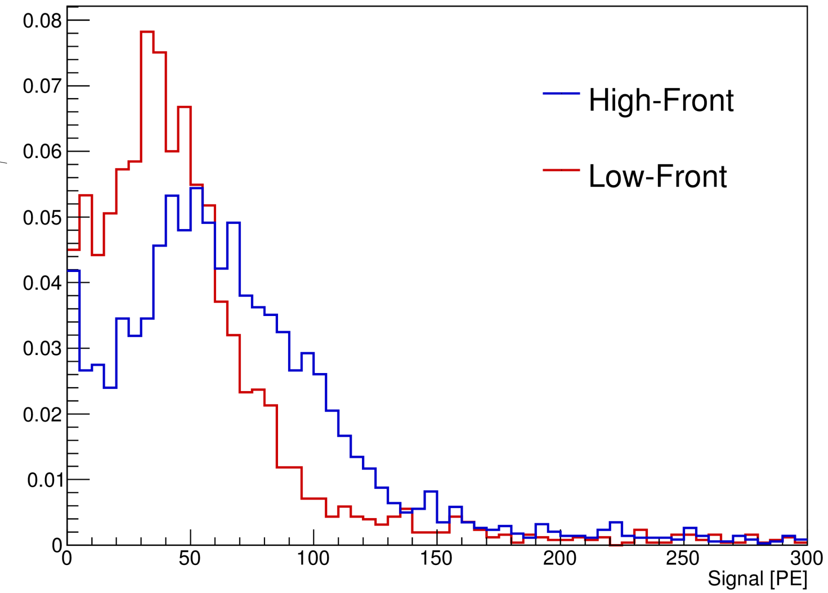
- Summer 2015 (TallBo4 Phase 1) – full-width modules
  - Y11 fibers + TPB-coated acrylic plate
  - Y11 fibers in TPB-coated acrylic pane
  - TPB dip-coated acrylic bars x3 (IU recipe)

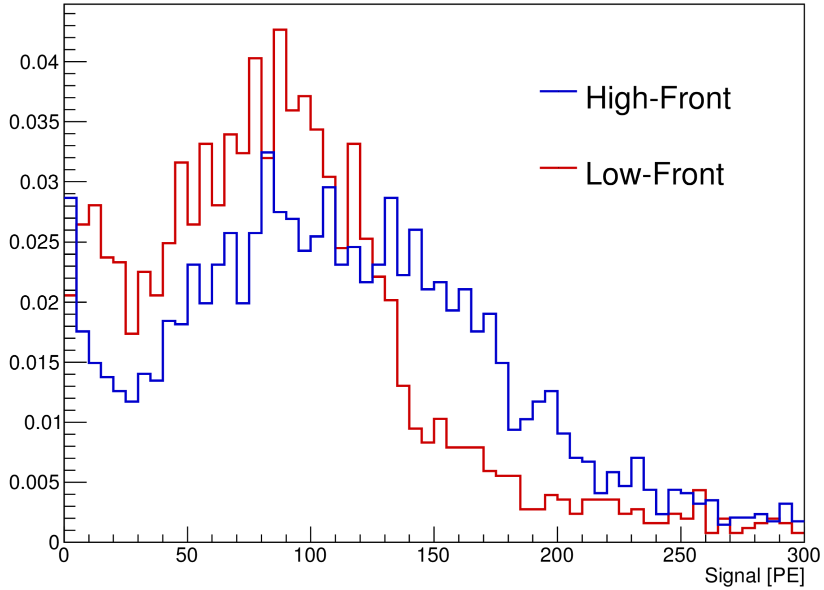


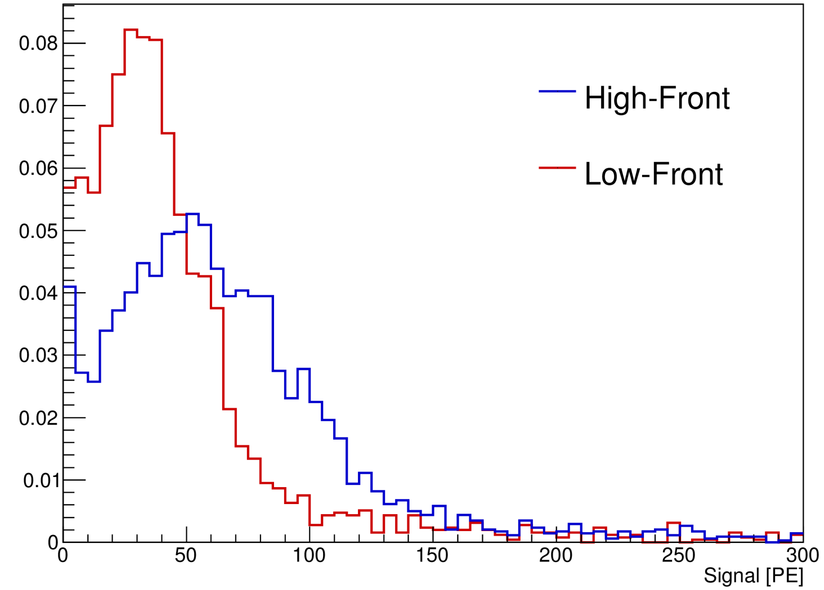




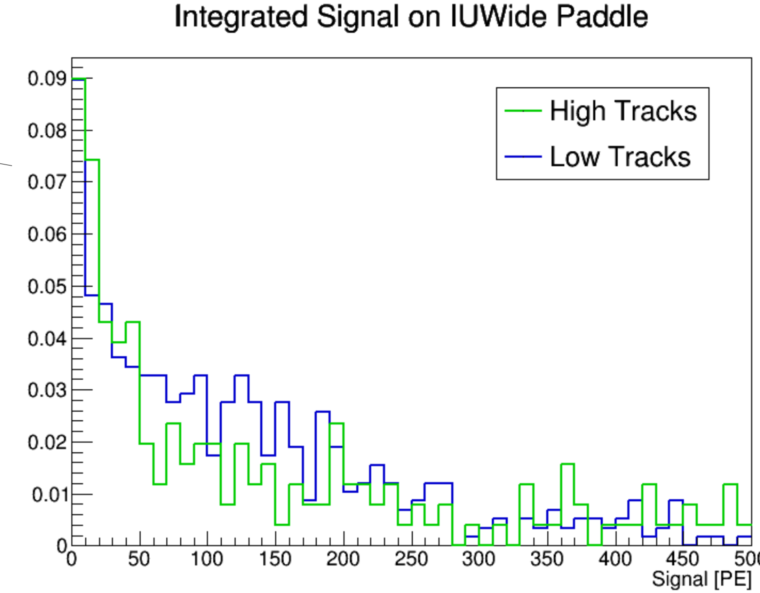
- Summer 2015 (TallBo4 Phase 2) – brightest 3 examples (1” wide)
  - EJ-280 polyvinyltoluene + TPB-coated acrylic plates
  - EJ-280 polystyrene + TPB-coated acrylic plates
  - TPB dip-coated acrylic bar (MIT recipe)

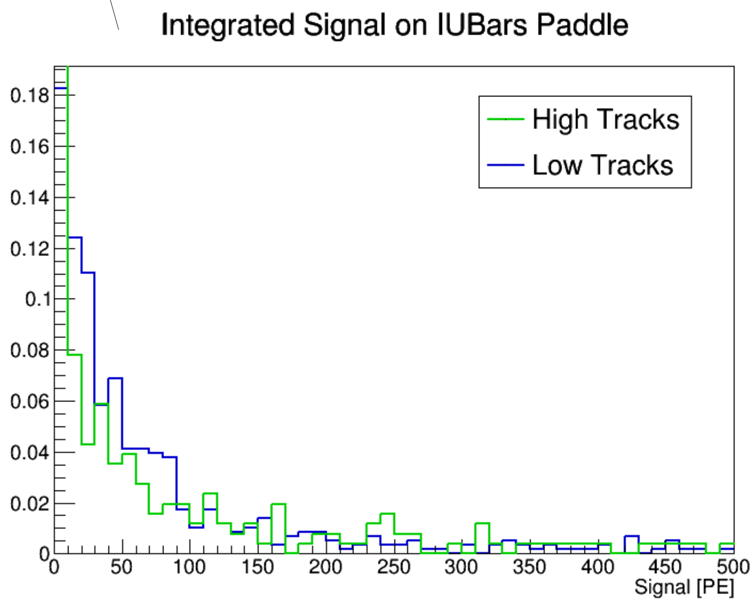


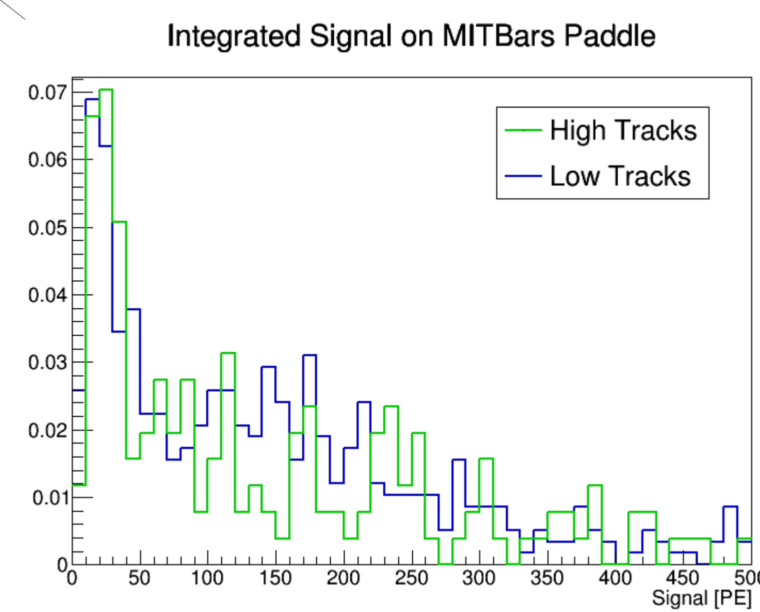




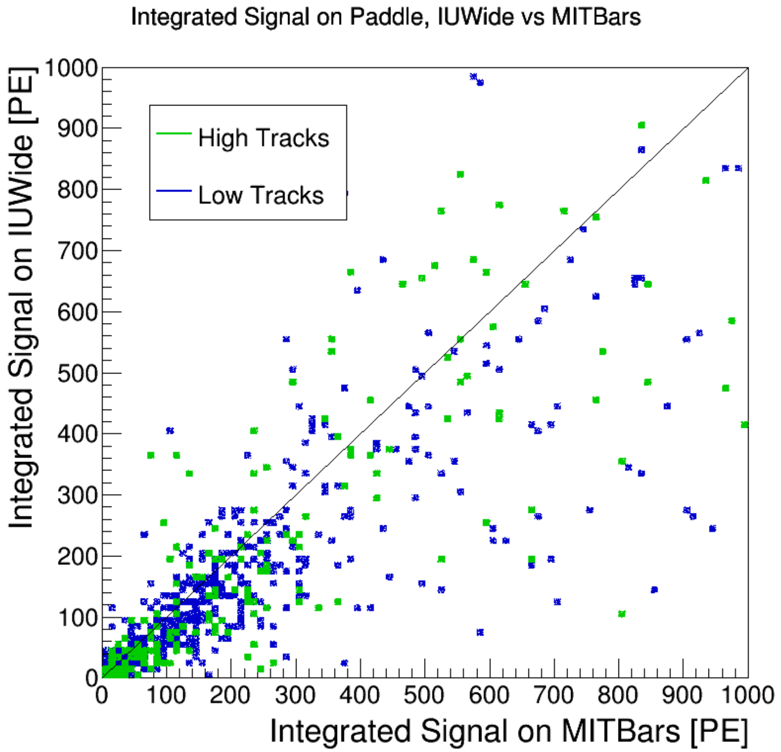
- Winter 2016 (TallBo5)
  - EJ-280 polystyrene + TPB -coated acrylic plates (wide)
  - TPB dip-coated acrylic bar x3 (MIT recipe)
  - Combination of 3 1”-wide light guide designs



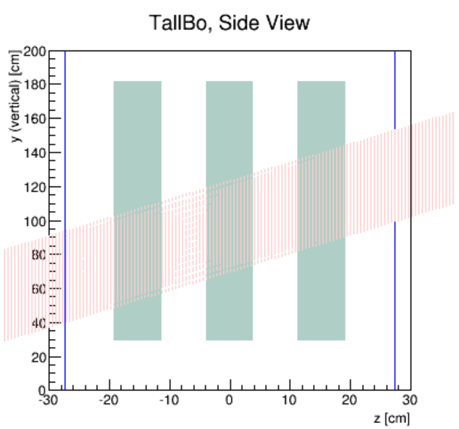




- Winter 2016 (TallBo5)
  - Persistent trigger issues made it difficult to distinguish signal
- Alternative comparison metrics, e.g. correlation between signals on full paddles
  - IU Wide paddle vs All 3 MIT 1” bars
  - Nearly equivalent in relative performance



- Collected more data in “high-low” configuration
  - Steep angle
    - Longer tracks, higher rate
  - Use comparison to simulated tracks to correct for varying track proximity and detector dimensions
    - Focused on IU Wide paddle and best of 3 MIT 1” bars



- 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)

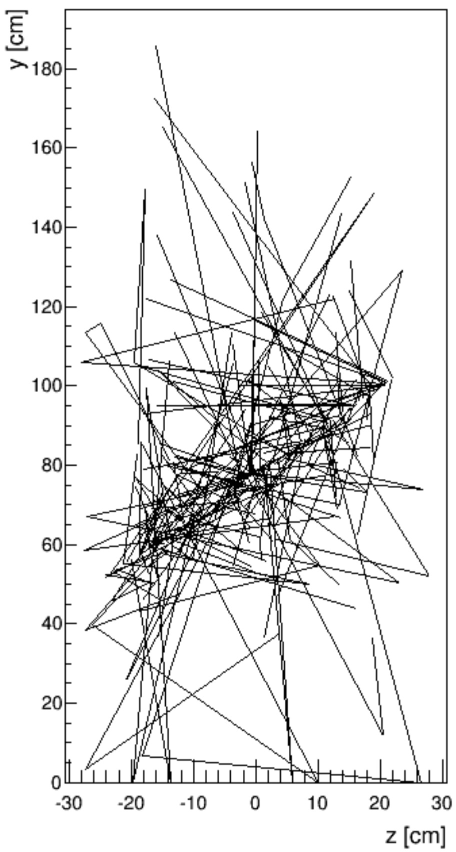
Table 1
Liquid Argon properties.

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

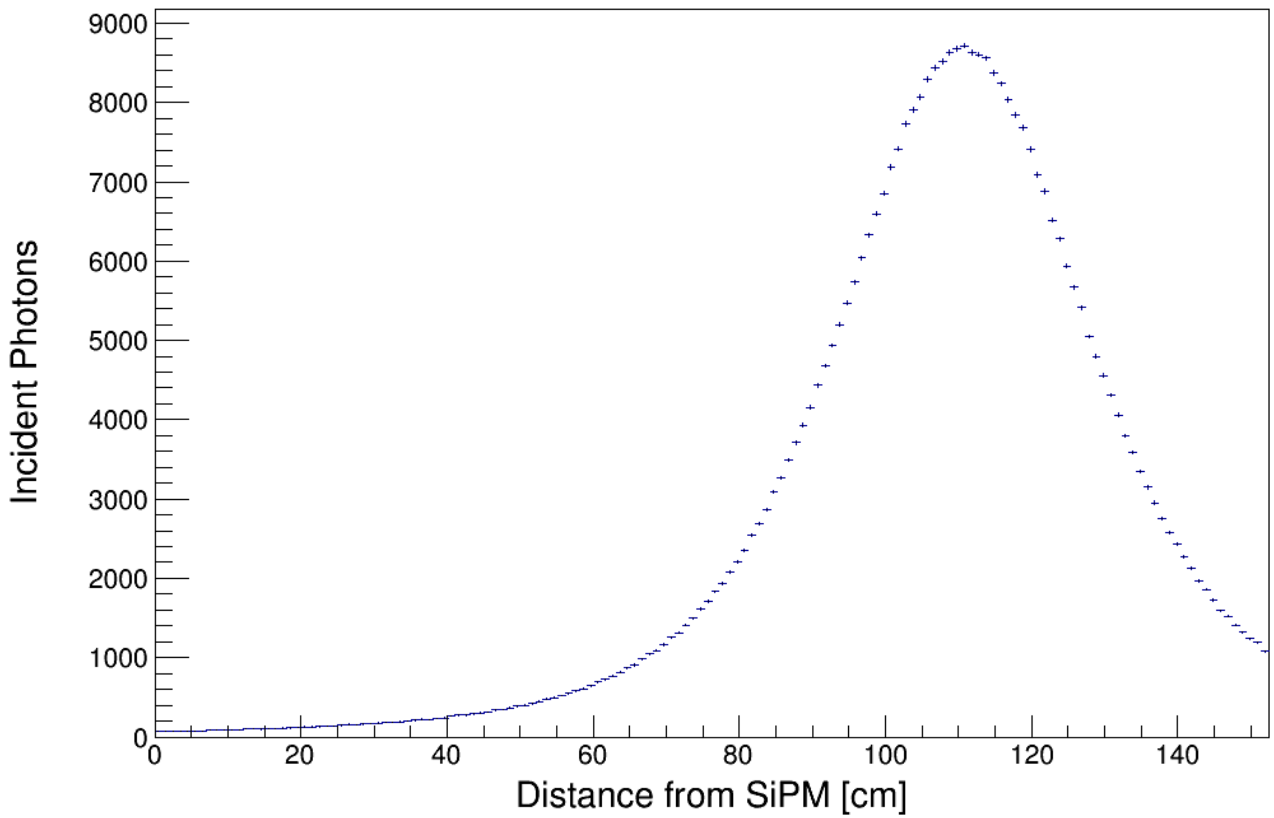
Table 2
Liquid Argon Ionization and Scintillation properties.

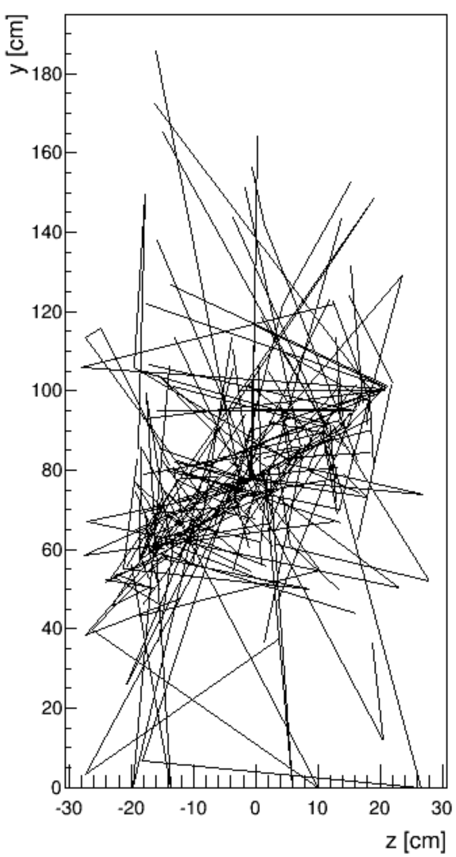
Mean energy loss (*mip*)		$\langle dE_{mip}/dx \rangle = 1.519\ MeV\ cm^2/g$
Photon yield	[@ 0-Field] (ideal)	$Y_{ph} = 5.1\times 10^4\ \gamma/MeV$
	[@ 0-Field] (*mip*)	$Y_{ph} =\sim 4.0\times 10^4\ \gamma/MeV$
	[@ 500 V/cm] (*mip*)	$Y_{ph} =\sim 2.4\times 10^4\ \gamma/MeV$
	[@ > 15 kV/cm] (*mip*)	$Y_{ph}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

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

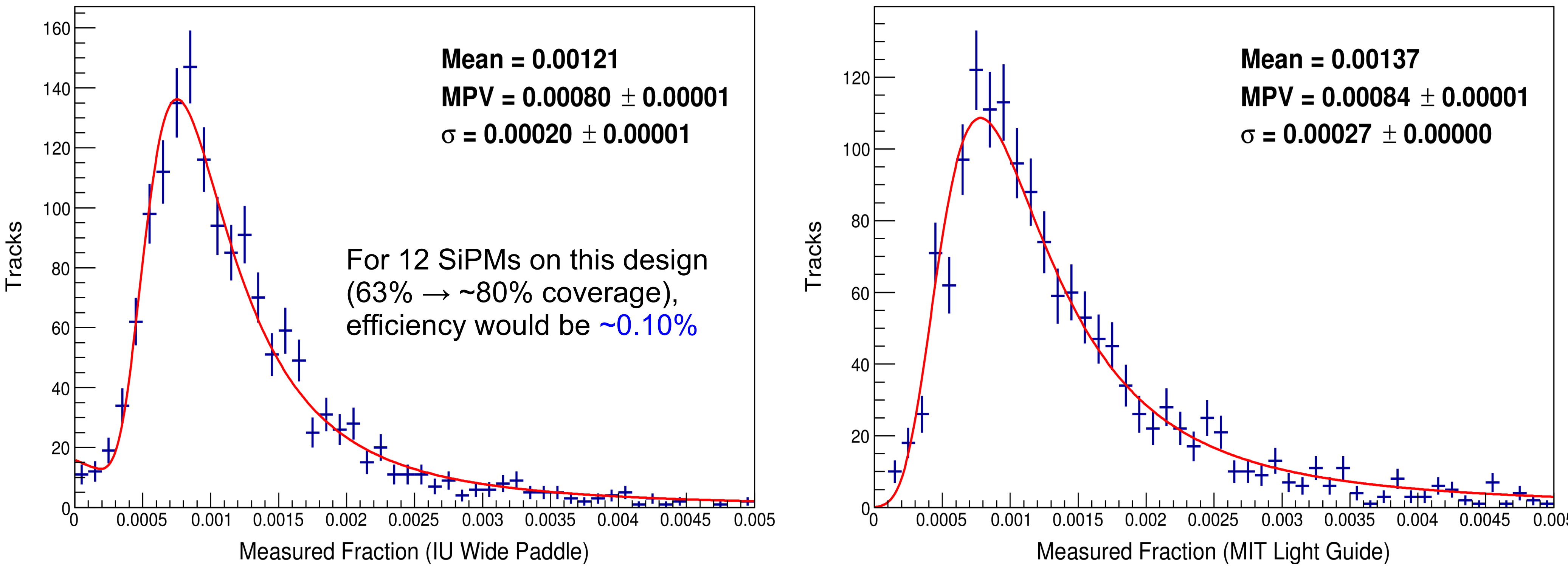


- Ray-tracing ToyMC simulation
  - Data
    - Find integrated signal (PE) in 10 μs measured from data to matching simulated track trajectory
  - Simulation
    - Sum total number of incident photons across bar ⊗ 2 m attenuation
    - *To add:* gaps in plate coverage





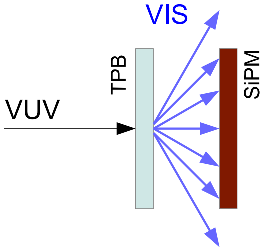
- Calculate fraction of incident photons detected per track event

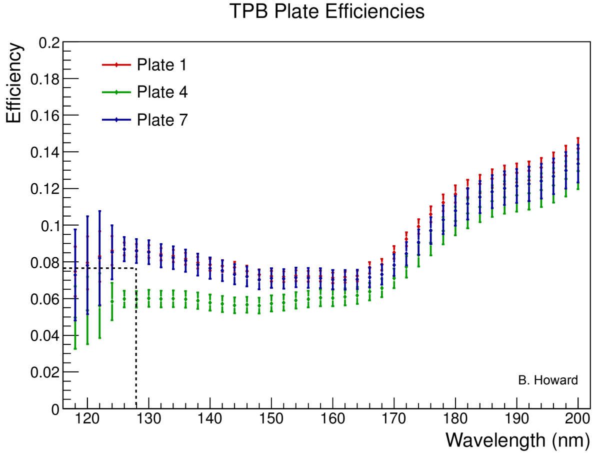


- $$\text{Efficiency} = \frac{\text{\# Photoelectrons output by SiPM to DAQ}}{\text{\# VUV photons incident on light guide}} \times \exp(-x / 2m)$$

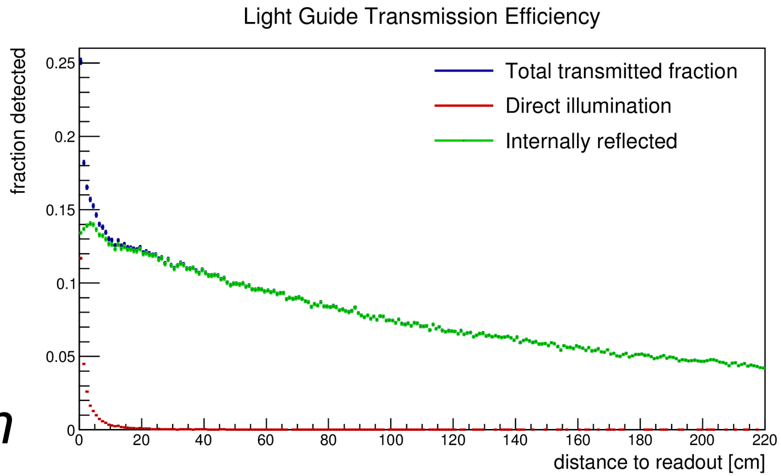
- Landau + exponential fit
  - Most probable value measures efficiency to detect MIP scintillation photons
  - Denominator simulated with a 2 m attenuation length
  - Does not include correction for cross-talk probability (~30%)

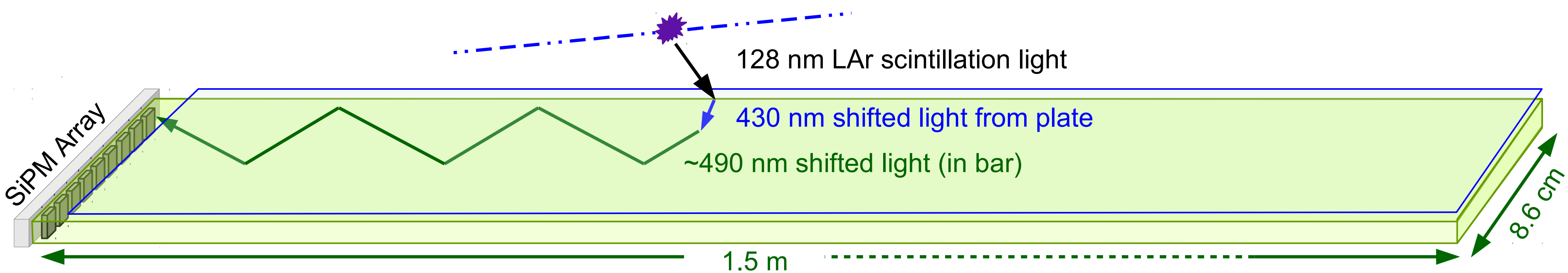
- VUV Conversion at TPB Plate
  - VUV photons strike TPB
  - TPB emits VIS (blue) photons
  - VIS (blue) photons strike WLS bar
  - *Measure with VUV Monochrometer*





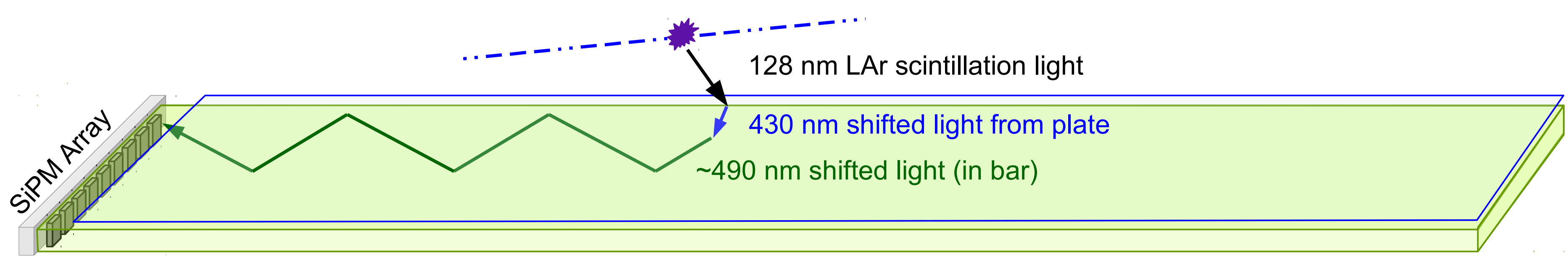
- VIS Transport and Detection
  - WLS emits VIS (green) photons
  - VIS (green) photons propagate via total internal reflection
  - Some photons reach SiPMs and generate signal
  - *Manufacturer Specifications* + *Simulation*





- VUV light converted by TPB
  - Forward conversion efficiency from VUV monochrometer – ~8%
- 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%

- Expected efficiency coefficient (above calc.) **~0.10%** (0.13%)
- Measured efficiency coefficient (cosmic rays) **~0.08%** (0.10%)

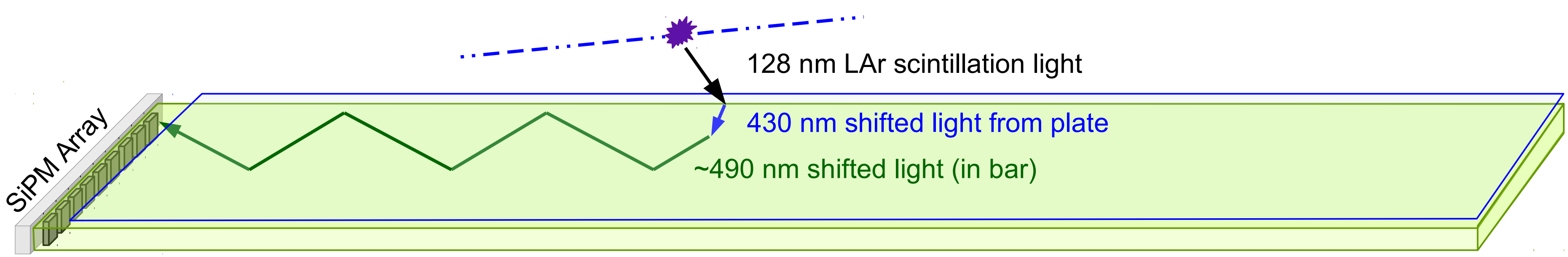


- Target (LArSoft studies) of ~0.5% efficiency coefficient (for SNν)

- *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
      - Vary reflections in simulation, consider Rayleigh scattering
      - Improve 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

- *Value Engineering*
  - Continued work to improve TPB (or bis-MSB) plate design
    - Expect improvement by factor of ≥ 2 with QC (see talk by S. Mufson)
  - Continued work to improve dipping methods (see talk by M. Toups)
  - Explore alternative wavelength shifters
    - There may be a better doped light guide match to TPB and/or SiPM
      - Current EJ-280 design is best match for a catalog product to the TPB emission, reasonably well matched emission to SiPM, available on schedule
  - Consider painting inactive sides of light guides w/ reflector
    - Could increase internal reflection trapping by ~45%
  - Explore double-ended light guide readout
  - Increase number of light guides per APA (FarDet)



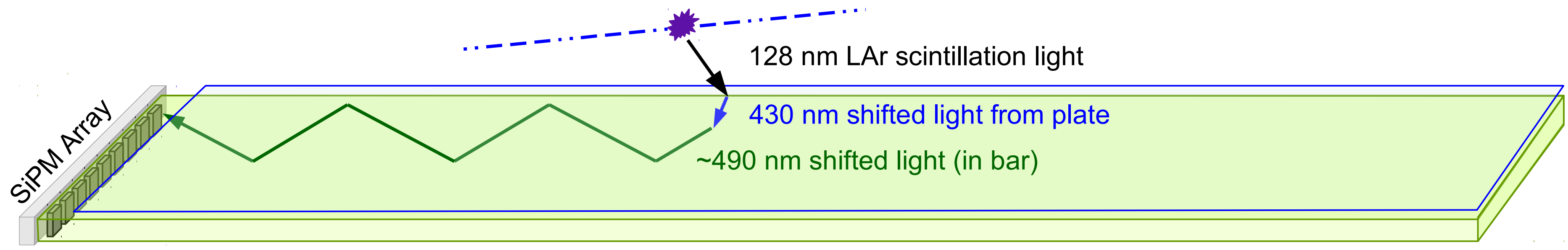
1. *Does the PDS design enable validation and refinement of the DUNE PD requirements?*
   YES – The current PD designs will provide ample sensitivity for the ProtoDUNE measurement program.
4. *Does the documentation of the PDS technical design provide sufficiently comprehensive analysis and justification for the Photon Detector System design adopted?*
   YES – The PD design testing program has enabled measurement and optimization of PD performance.

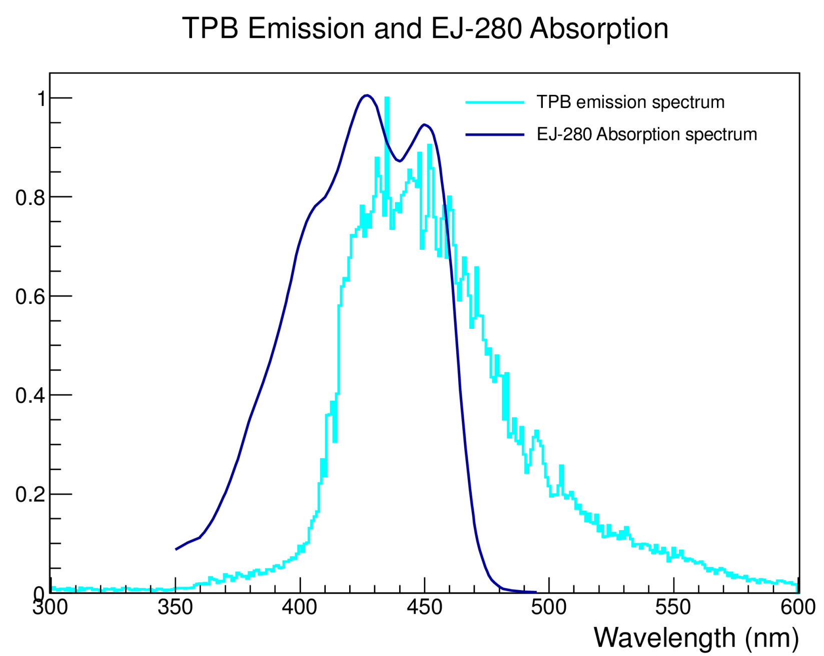
- Tests at TallBo have refined PD options to the current designs
  - Iteration and improvement on designs, comparison tests of novel ideas
  - WLS bar +TPB plate (IU) and dip-coated acrylic (MIT) designs *quite comparable*
    - Relative brightness similar, attenuation length appears long
  - *Absolute efficiency* coefficient estimated from data/sim comparison (TallBo5)
    - Expect 0.10% efficiency (photons detected / incident) with 12 SiPMs on TPB Plate + WLS Bar design from data-simulation comparison
    - Expect 0.13% efficiency from light guide component analysis
- Current designs *meet requirements for ProtoDUNE*
  - Will robustly inform further refinement needs toward preliminary final design for DUNE single-phase far detector
  - Project that *improved radiators* should approach DUNE LE/SNν requirements
- *More details*
  - TallBo4, Summer 2015 (DUNE DocDB 138, JINST 11 C05019)
  - TallBo5, Winter 2016 (Presentation from May CSU Workshop)

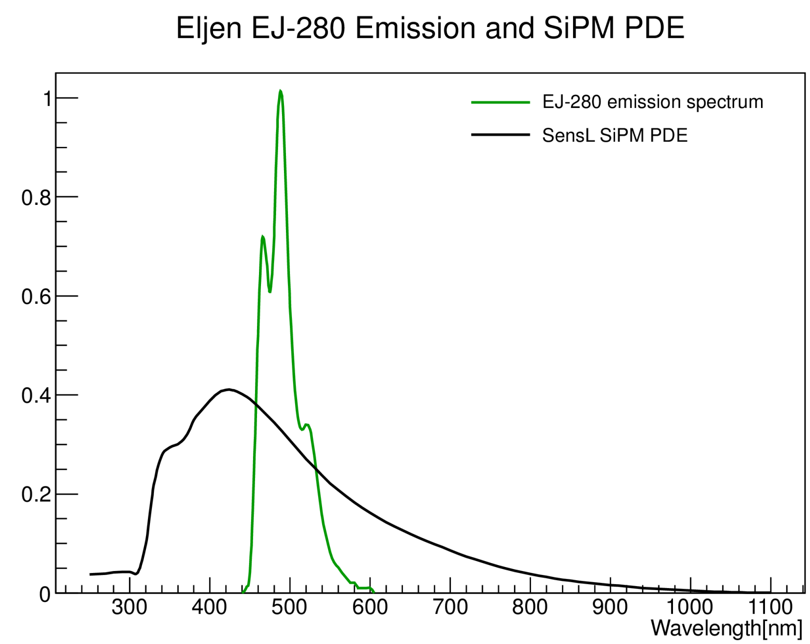
Backup

Light Guide Principles

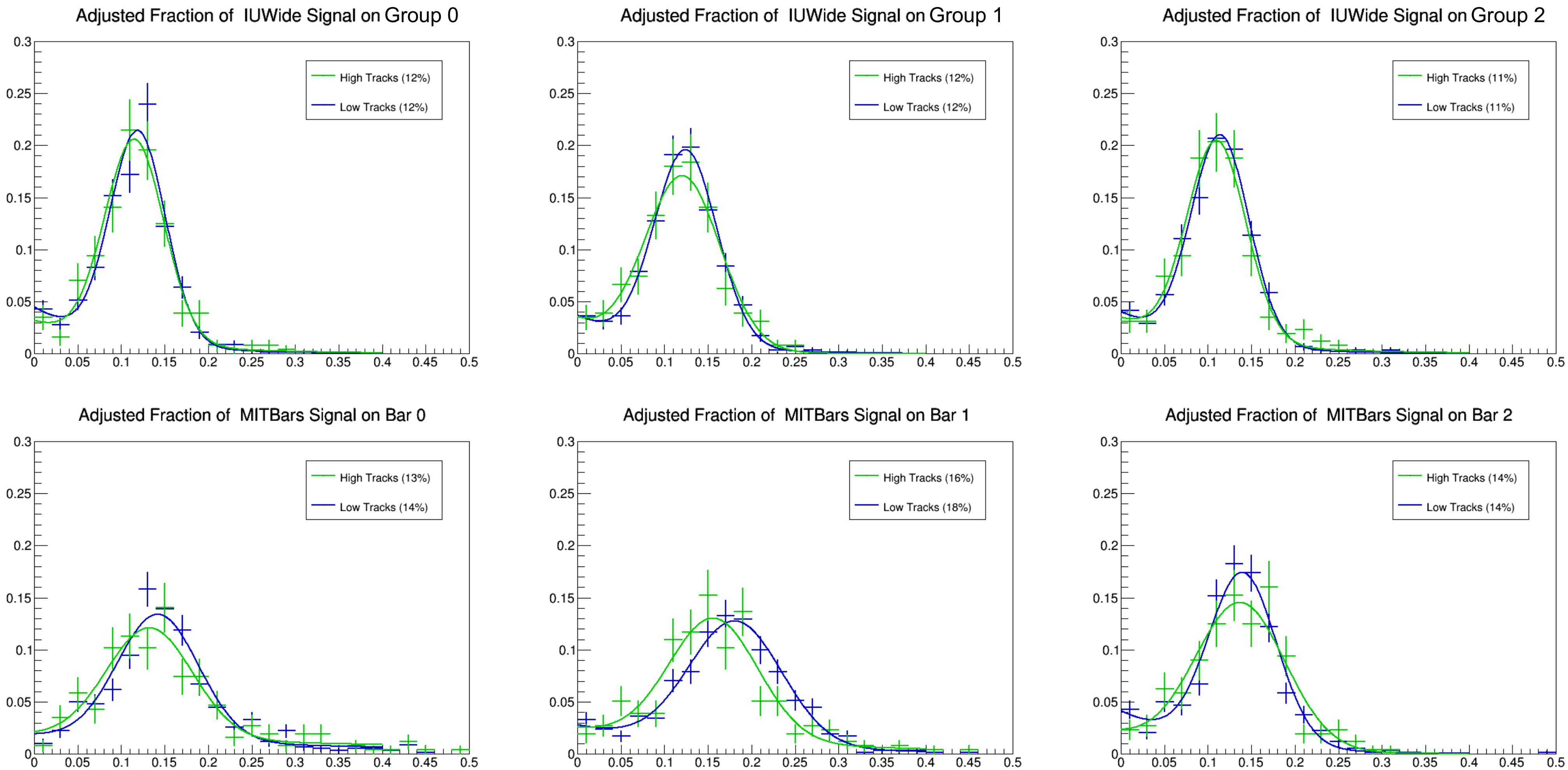
- Shift 128-nm VUV photons into visible wavelengths
- Channel visible signal to readout via total internal reflection



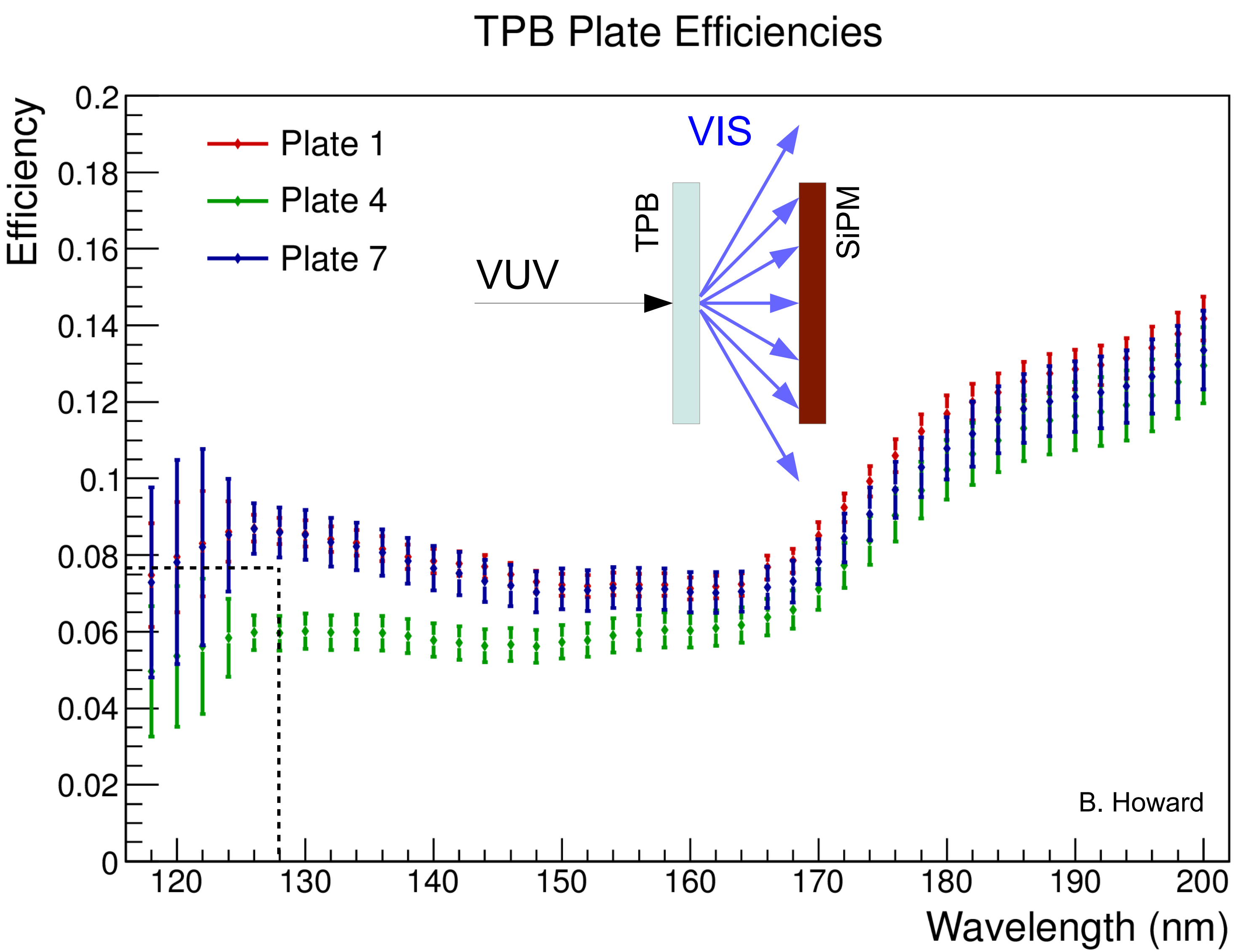




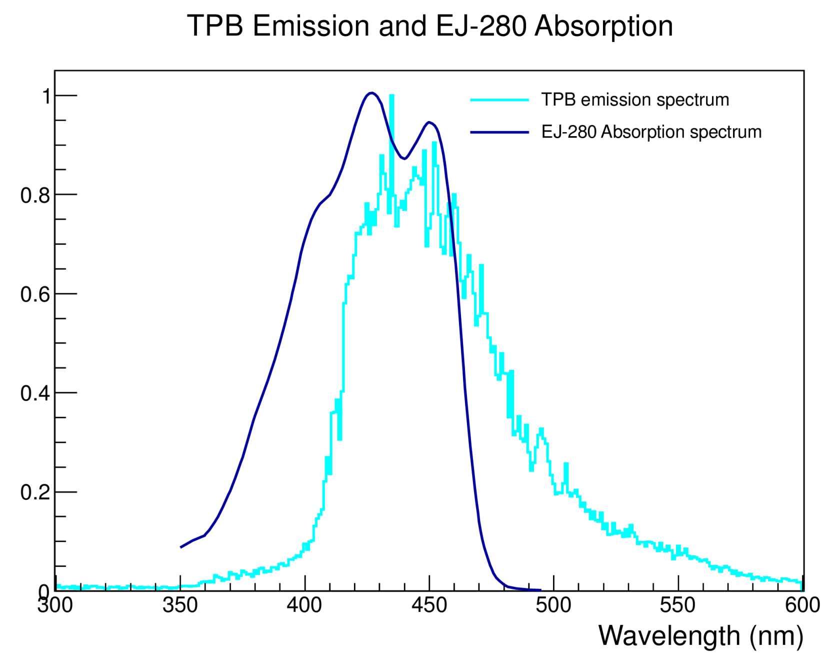
- Winter 2016 (TallBo5)
  - Persistent trigger issues made it difficult to distinguish signal
  - Alternative comparison metrics
    - Signal detected on bar (or group of 3 SiPMs) / Total across all SiPMs



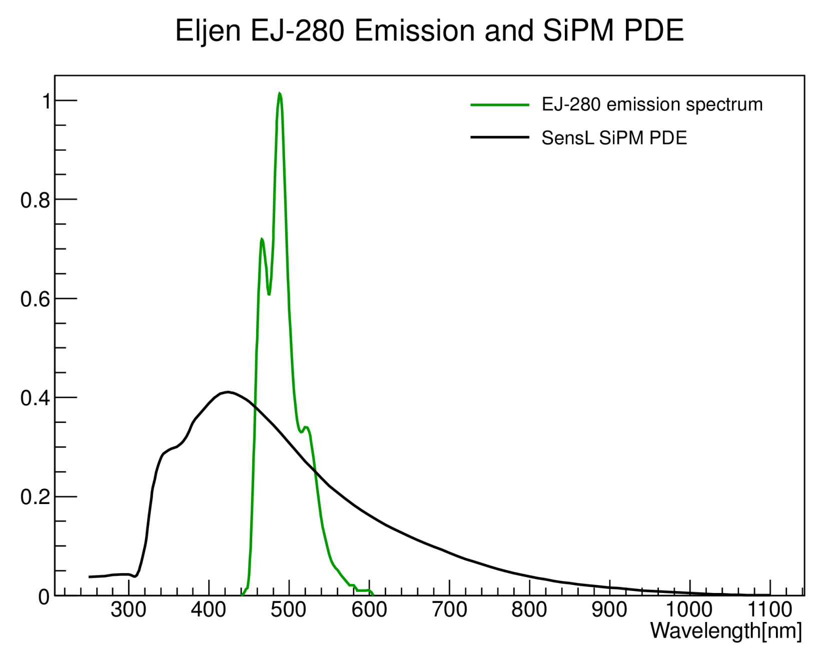
- Example VUV forward conversion efficiency
  - VIS photons at SiPM / VUV photons incident on TPB sample
    - Not corrected for SiPM solid angle (but SiPM is close to VUV spot)



- 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