Liquid argon scintillation detection utilizing wavelength-shifting plates and light guides

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For the DUNE Collaboration
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DEEP UNDERGROUND NEUTRINO EXPERIMENT

INDIANA UNIVERSITY

Context

- This talk reports on a prototype photon detection technology designed for large liquid argon time projection chambers, specifically for DUNE
  - Description of technology
  - Characterization techniques
    - Laboratory testing
    - Component simulation
    - Prototype testing
  - Results from testing
  - The path forward

- An advanced version of a paper has been drafted detailing the testing described here. Intend to submit to NIM:

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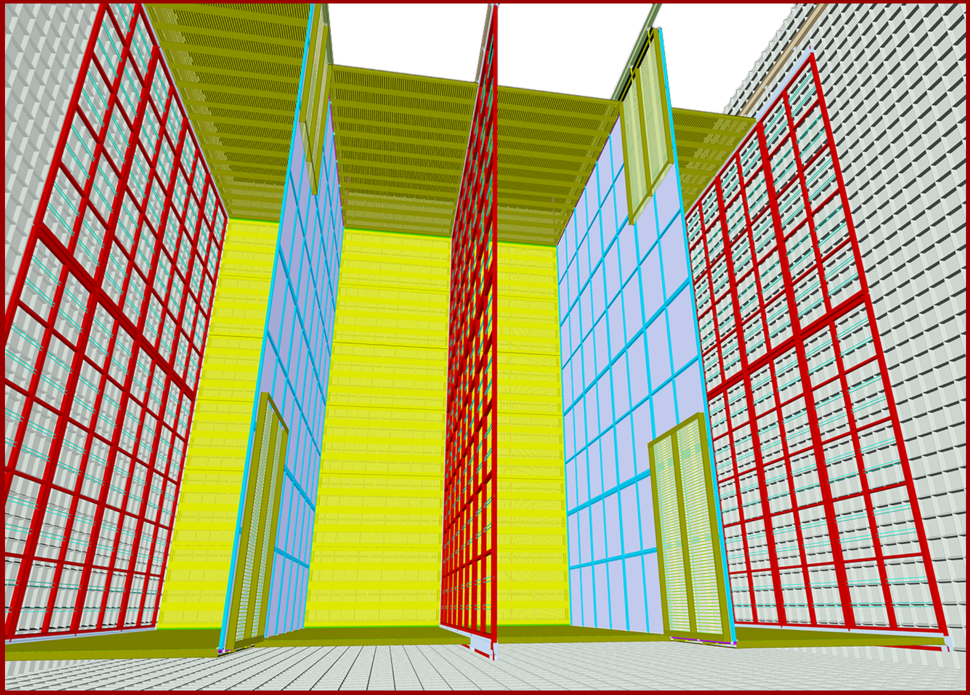
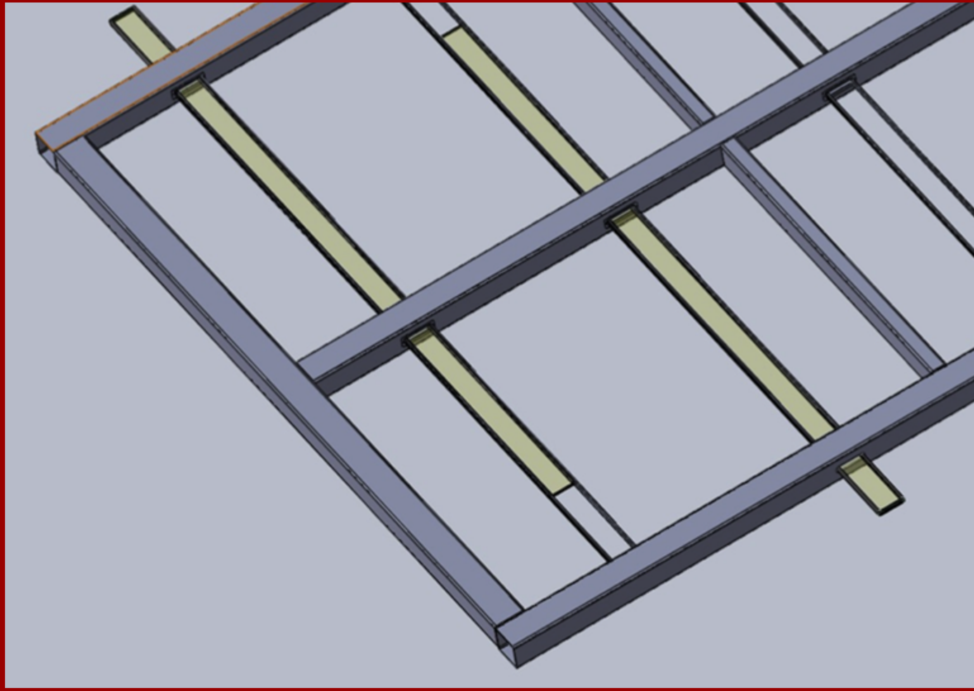
Introduction

- Deep Underground Neutrino Experiment (DUNE)
  - large fiducial volume liquid argon [LAr] time projection chamber [TPC]
  - ***Modules have 10kt active volume***, ~mile underground in S. Dakota
- While main detector system is the TPC, employing photon detector [PD] system for VUV scintillation adds valuable input
  - Precise timing from PD system can give ~mm resolution in drift direction [arXiv: 1601.02984]
  - Especially useful for non-beam physics events (e.g. supernova/nucleon decay)
- PD system for the single-phase TPC design fits *within* anode plane, between sets of wires for adjacent TPC volumes
  - Will discuss a prototype PD system utilizing wavelength-shifting plates and light guides





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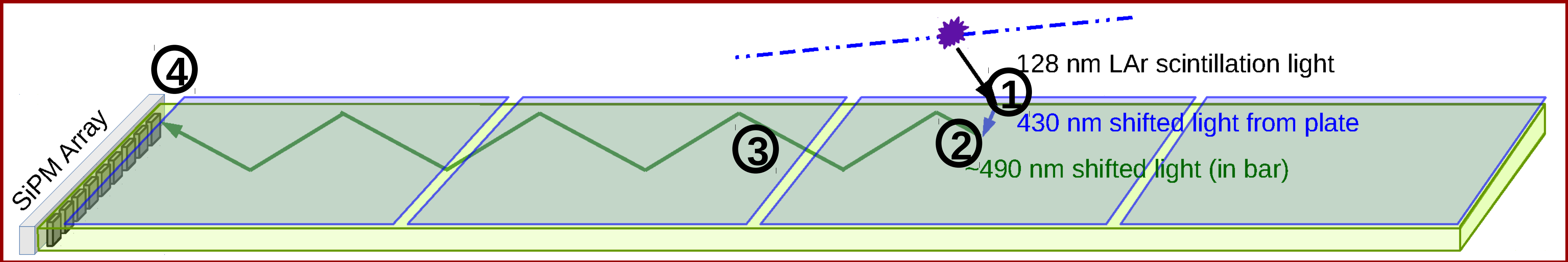
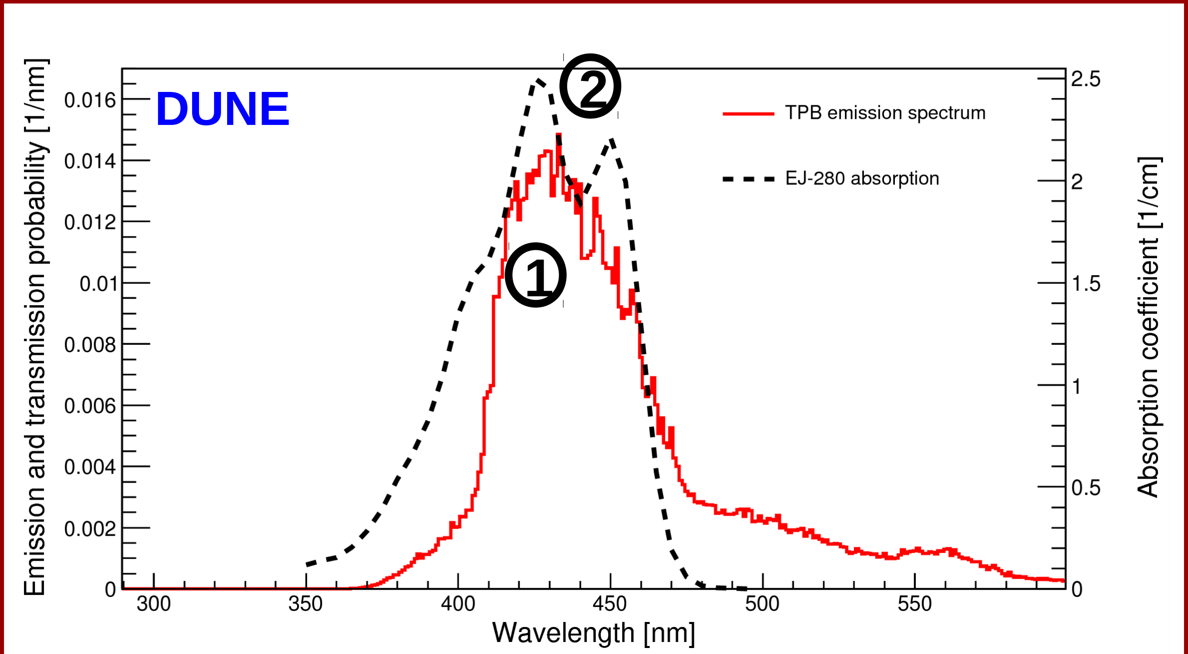
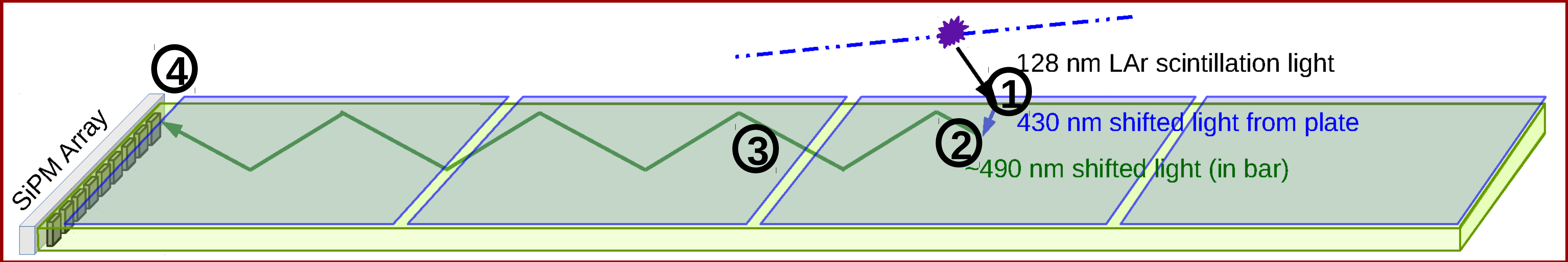
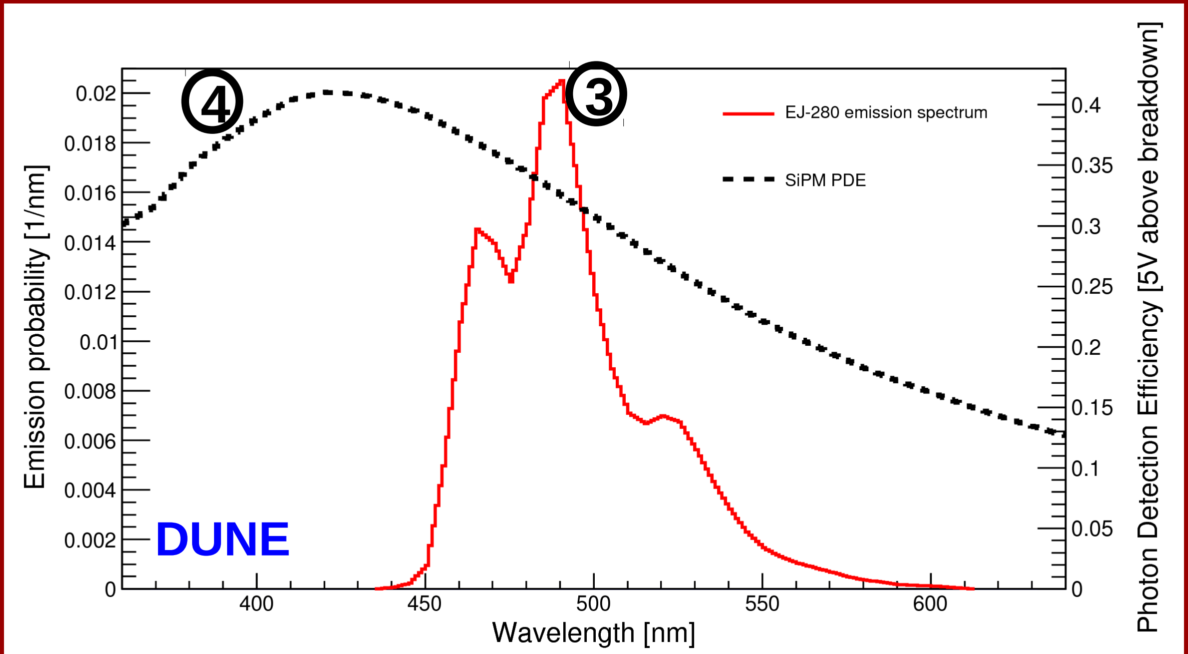




Measured emission spectrum for TPB-coated plates used in characterization studies, with transmission factored in, and EJ-280 absorption spectrum provided by Eljen.





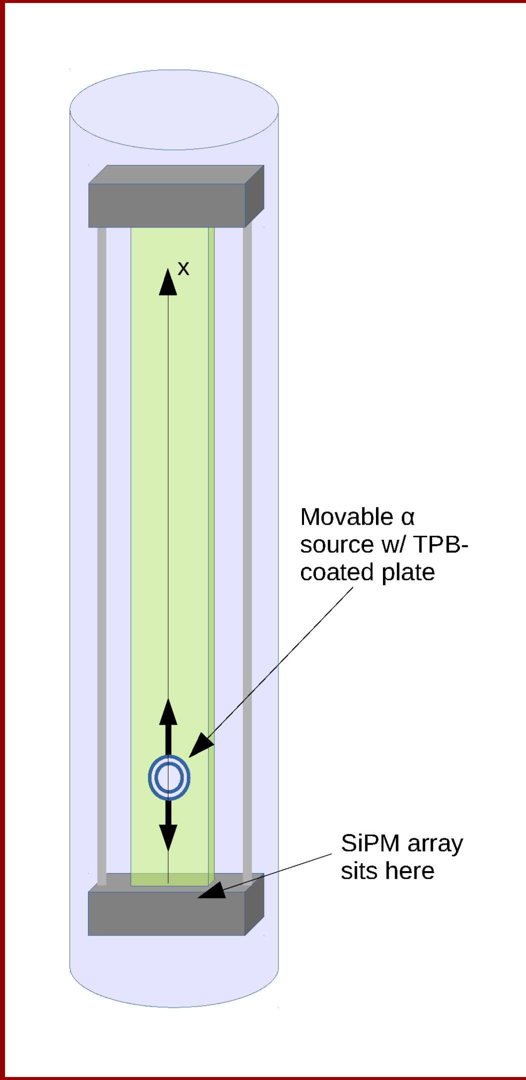
EJ-280 emission spectrum and SiPM PDE

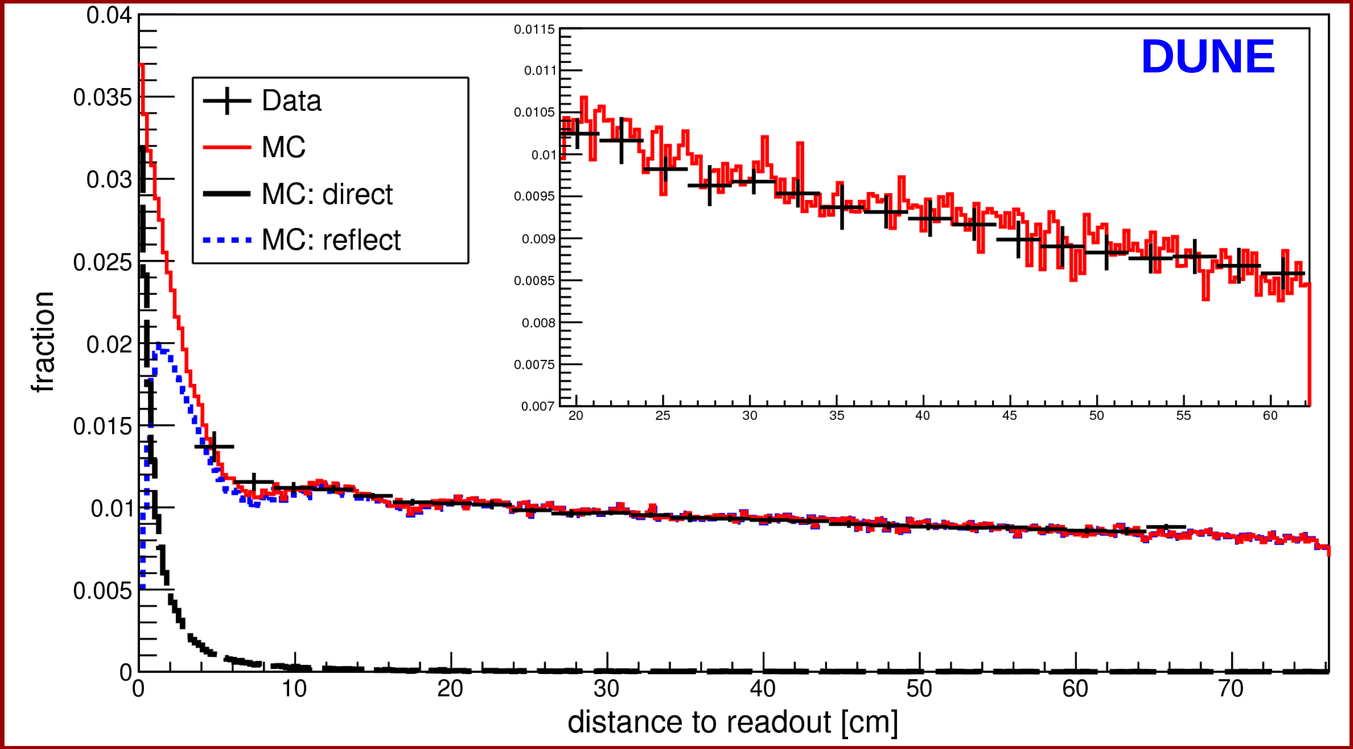
Characterization of technology

- To characterize performance of this PD technology, tests were performed in our local laboratory and in the LAr test facilities available at Fermilab
- Local lab tests characterize individual pieces of technology
  - Attenuation effects of light guide
  - Wavelength-shifting efficiency of plates
  - SiPM characterization
  - A simulation tying together the various components provides determination of efficiency
- Testing at Fermilab conducted w/ integrated prototype in Blanche dewar facility to study response to scintillation
  - Provides another determination of efficiency and insight on LAr scintillation response

Attenuation in light guide

- For 30” prototype light guide used in test at Fermilab, could directly study the attenuation properties in LAr





Long tail > 2m attenuation

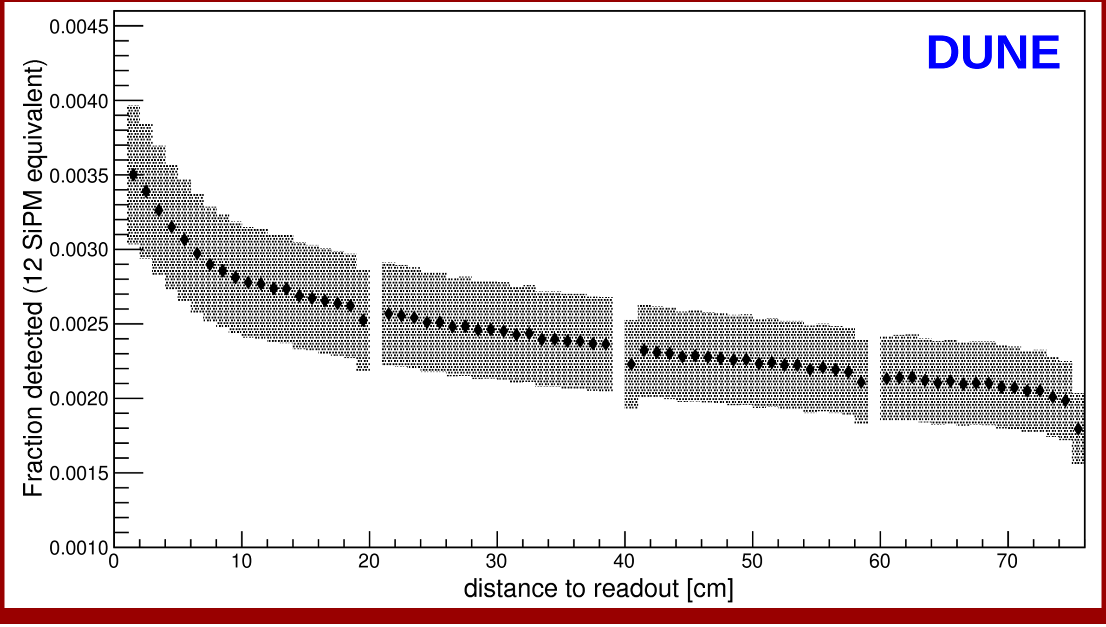
Plate and total efficiencies

- Determine plate efficiencies in VUV monochromator with ^{2}H lamp: measure converted light relative to incident light at given wavelength

Prototype plate efficiencies

1. 0.53 +/- 0.10	**3. 0.58 +/- 0.07**
2. 0.55 +/- 0.06	**4. 0.42 +/- 0.06**

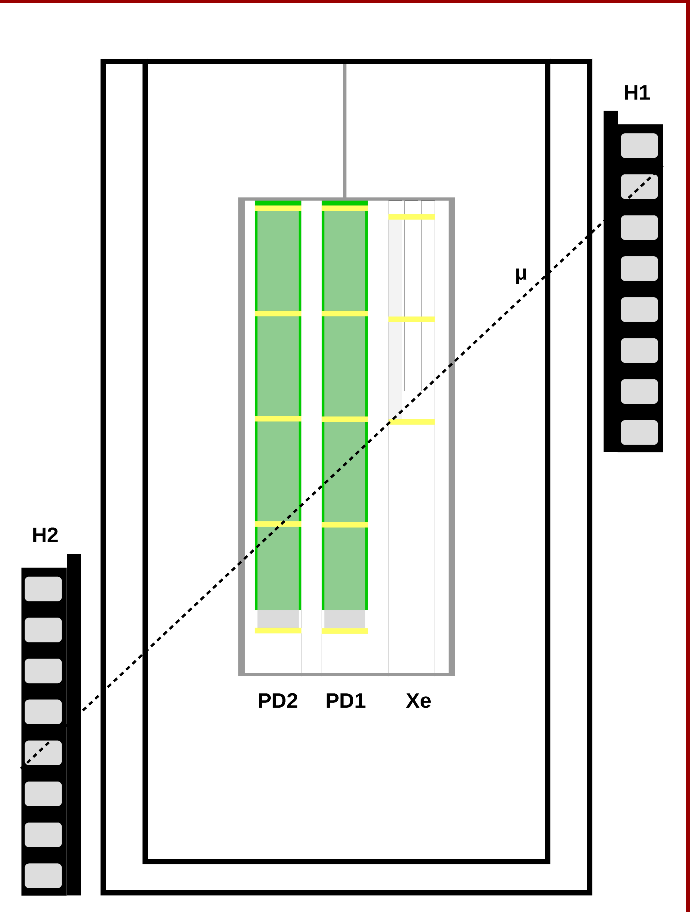
- Monte Carlo simulation with photons originating on plate and traversing through system, factoring in the efficiencies for the processes. Plate efficiency is an averaging (exposure-weighted) of individual efficiencies above:

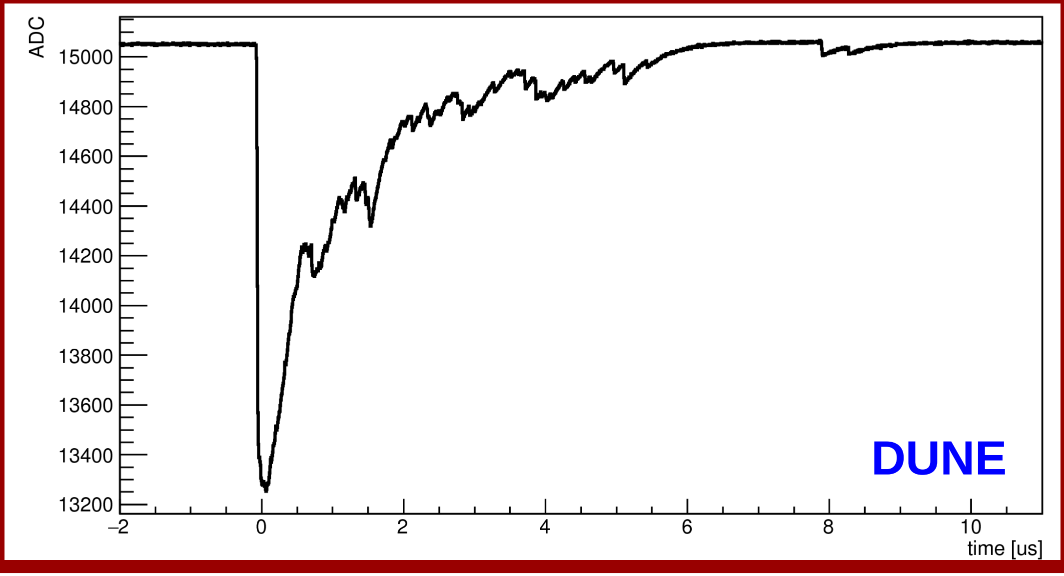


"Transport function" characterizes the attenuation of signal along light guide: 0.29 exp(-x/4.3cm) + 0.71 exp(-x/225cm)

Integrated prototype test

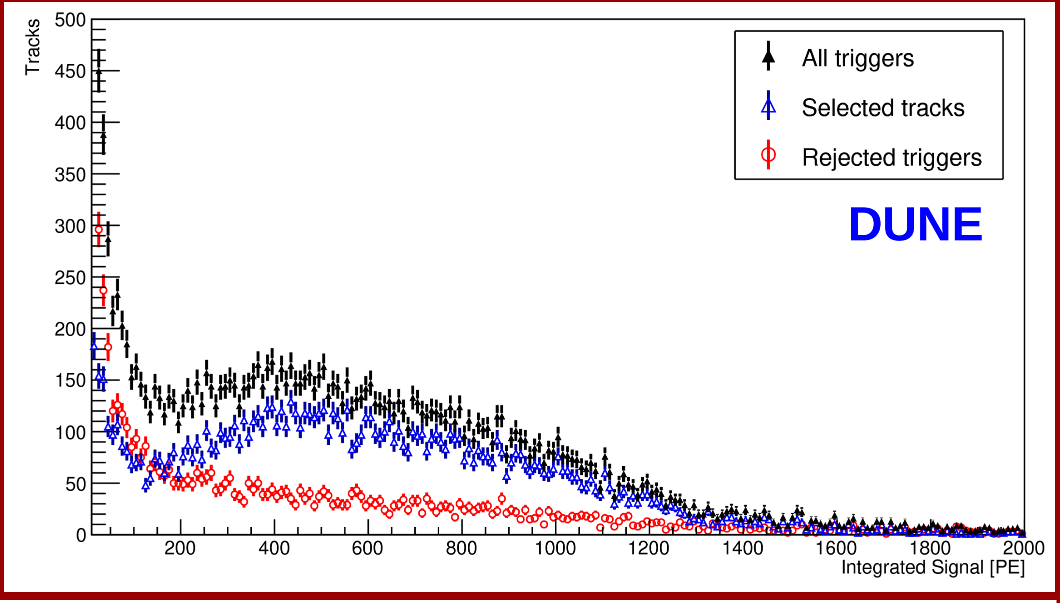
- In addition to component tests, test the pieces together in integrated prototype at Fermilab's LAr test facilities
  - Large volume dewars: O(100s) liters LAr
  - Delivered LAr typically low in N_2
  - Filtered input to reduce O_2 and H_2O impurity
  - Cryogenic system to condense Ar to help maintain levels before needing a top-off
  - Contamination monitors read the levels of N_2, O_2, H_2O in the LAr
- Test 30" light guide with the 4 wavelength-shifting plates in dewar w/ ~570 liters LAr
- Use hodoscopes to trigger on through-going cosmic-ray muons
  - Provides trajectory of cosmic-ray track in dewar
  - Rejects cosmic showers
- Calibration set taken with self-triggering gives conversion ADC → PE

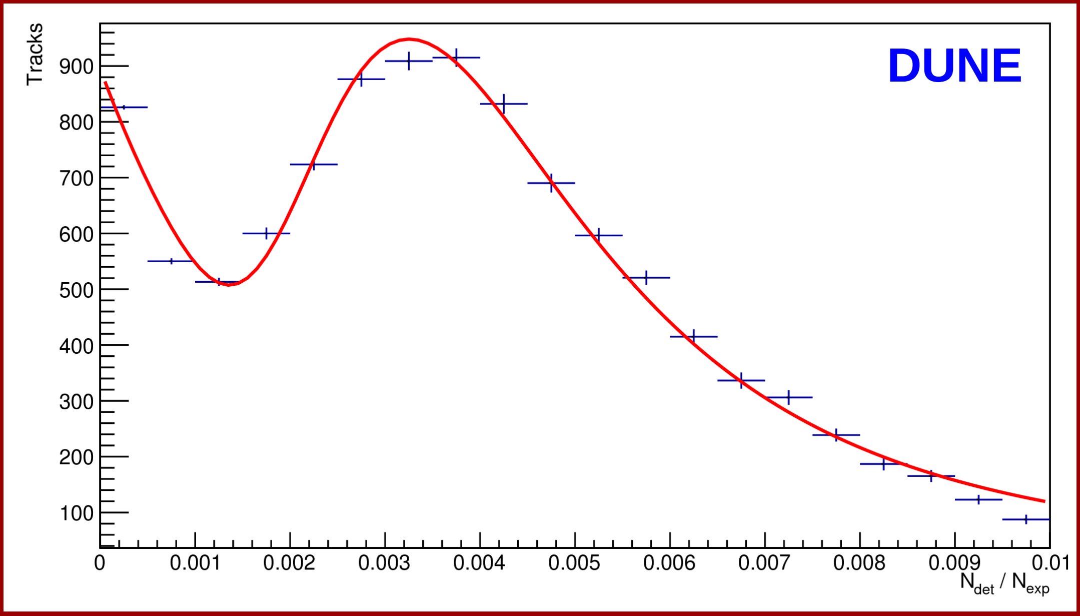




Integrated prototype test

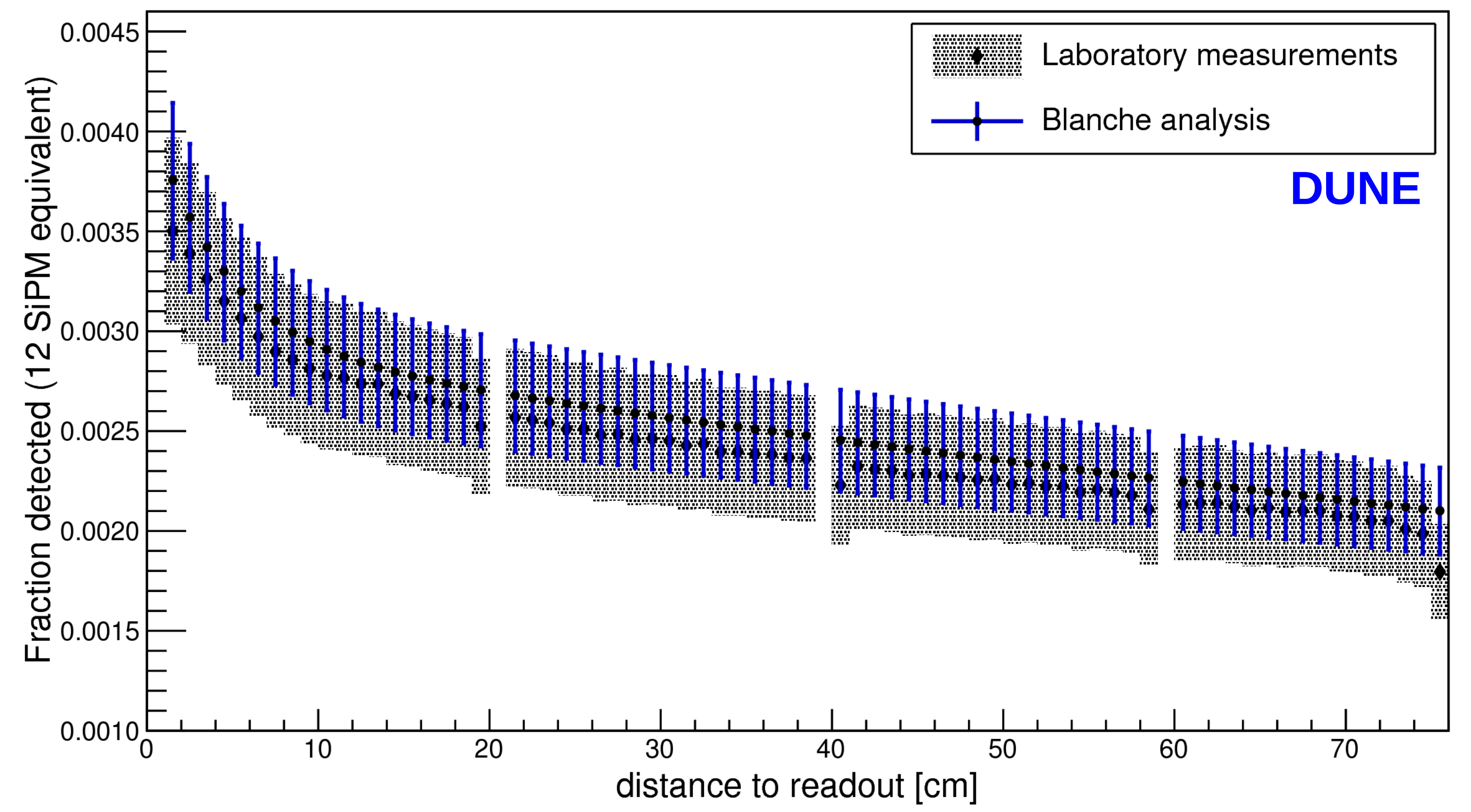
- Integration of digitized waveforms from given event yields the number of PE read out (N_{det})
- Monte Carlo sim throws photons from given trajectory (using 40,000 ph/MeV from Doke et al [1990, 2002] and MIP energy loss in LAr) and tracks photons in dewar to determine expected number of photons hitting module
- Using transport function for light guide, figure out expected number of photons reaching readout end given perfect efficiency (N_{exp}).
- Ndet/Nexp characterizes efficiency of module at readout end
  - Since expect through-going cosmic-ray muons to be roughly MIPs, average MPV of many Landau fits used to characterize efficiency in Blanche setup (PE/photon)
  - Correct this ratio for 12 SiPMs possible on modules, and for cross-talk
  - Efficiency .0042, factor back in transport to get efficiency as function of distance from readout





Comparison of methods

- Analysis of data from Blanche is dependent on the simulation using 40,000 photons/MeV, and the component-based analysis is not
  - Comparison of the results then yields information on this scintillation yield value from the literature.



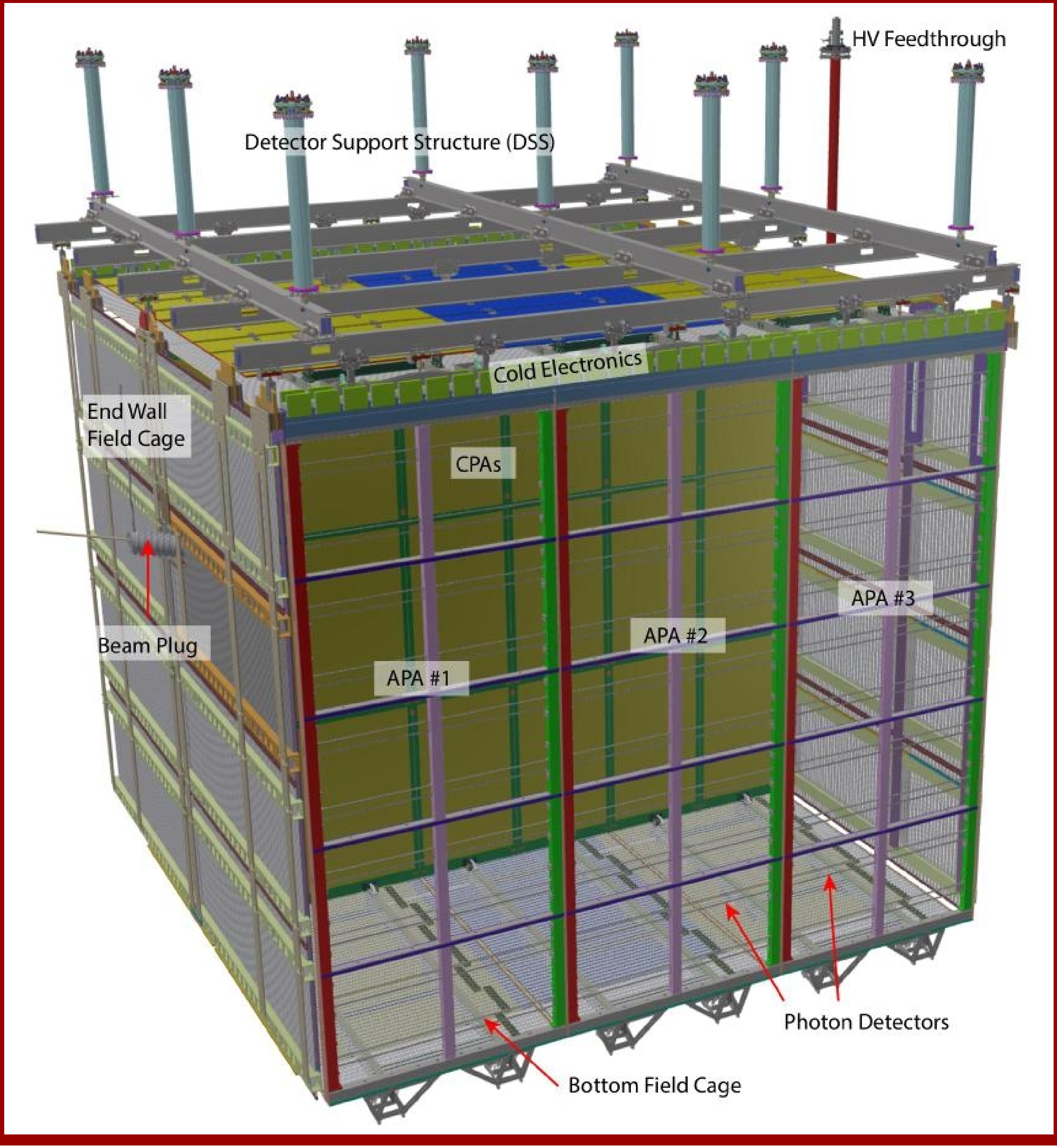
The path forward

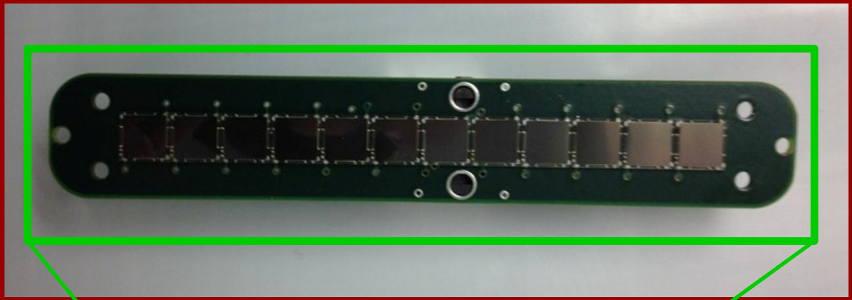
- This photon detection system decouples the conversion and photon transportation processes and fits inside anode plane
- Characterization studies have been performed for both the individual components and for an integrated prototype
- Full-scale prototypes will be tested in the upcoming protoDUNE-SP experiment at CERN
- The component matching is decent but leaves room for potential improvement to the efficiency of the design
  - Example: Could try to find SiPMs with better match to light guide or light guide with better match to SiPMs
- Doubled-ended readout will increase efficiency
  - Various ganging schemes can reduce the required number of readout channels per SiPM array, making this a more feasible option
- With commercialization of the plate production, could achieve more uniform and consistent plates

BACKUP

protoDUNE

arXiv: 1706.07081





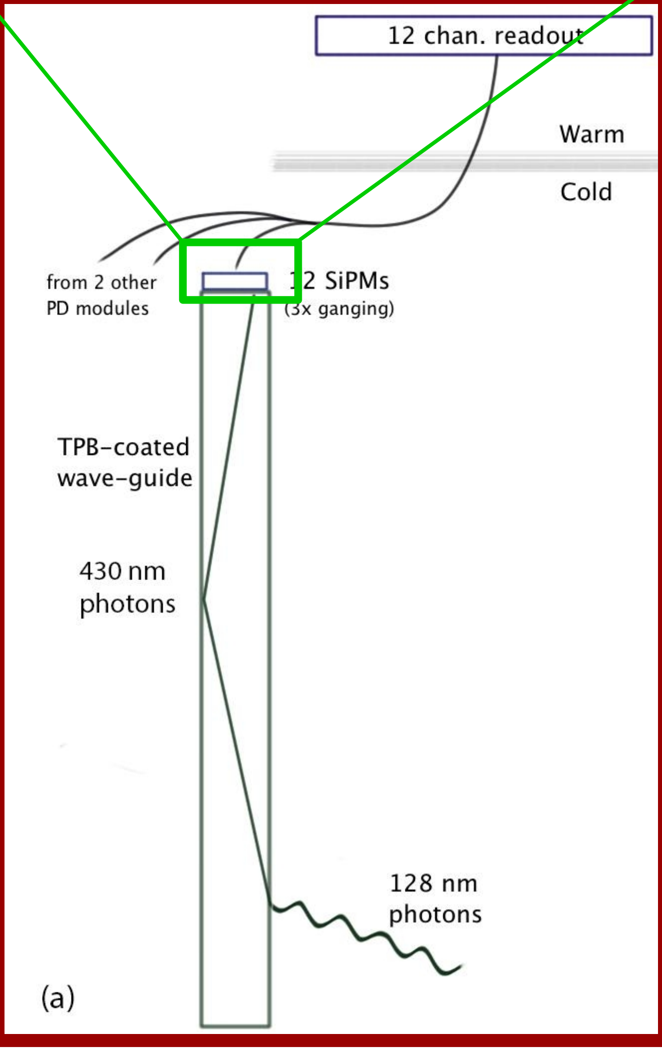


Plate efficiencies

- Determine plate efficiencies in VUV monochromator
  - Allows us to select wavelengths to irradiate samples
  - Measure H2 lamp output with VUV photodiode
  - Measure conversion of VUV photons on samples from TPB plates placed in front of SiPM
  - Efficiency:

$$\epsilon_{\mathrm{TPB}} = \boxed{(I^{\mathrm{SiPM}}/I^{\mathrm{VUV}})} \times (\boxed{\mathcal{R}^{\mathrm{VUV}}}/\boxed{\mathcal{R}^{\mathrm{SiPM}}}) \times \boxed{\frac{1}{f_{\mathrm{geo}}}}$$

Measured quantity

Estimated using transmission through aperture

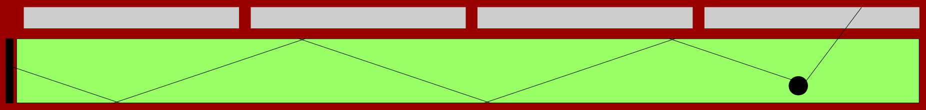
$$\mathcal{R}^{\mathrm{VUV}} = R^{\mathrm{VUV}}(128\ \mathrm{nm}) \times hc/\lambda(128\ \mathrm{nm})$$

$$\mathcal{R}^{\mathrm{SiPM}} = \int d\lambda_{\mathrm{vis}} \mathcal{P}_{\mathrm{TPB}}(\lambda_{\mathrm{vis}}) R^{\mathrm{SiPM}}(\lambda_{\mathrm{vis}}) \frac{hc}{\lambda_{\mathrm{vis}}}$$

Component simulation of PD system

- Originates photons on the plates
  - Assumes Lambertian (cosine) emission
- Tracks them through plates, to light guide
- Allows for absorption, emission in EJ-280
- Photons reflect off faces if within critical angle
- Photons trapped in light guide can be lost
  - re-absorption/emission process
    - Due to inefficiency of the EJ-280 in light guide
    - Due to re-emission in wrong direction
  - hitting a further face outside of the critical angle
  - a further free parameter for some unspecified, random loss process at reflection. This is used to match the simulation to attenuation data in laboratory
- Photons escaping readout end are then checked against SiPM PDE
- Weights for plate efficiency & SiPM coverage

The idea



<u>The simulation returns:</u>

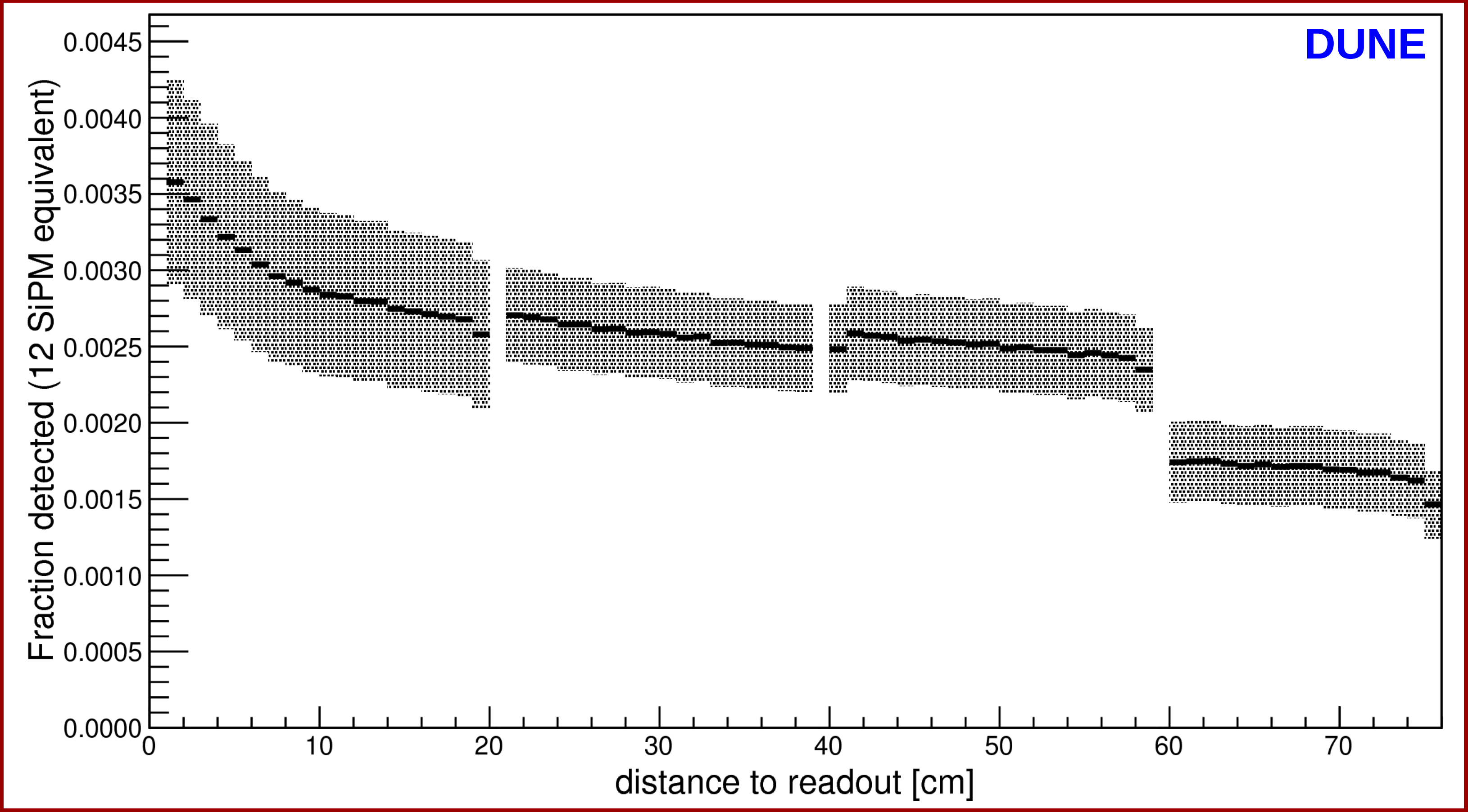
1) Ratio of photons detected per photons absorbed at a given location in light guide (A)

Describes transport function: details the attenuation of light as a function of distance from readout end

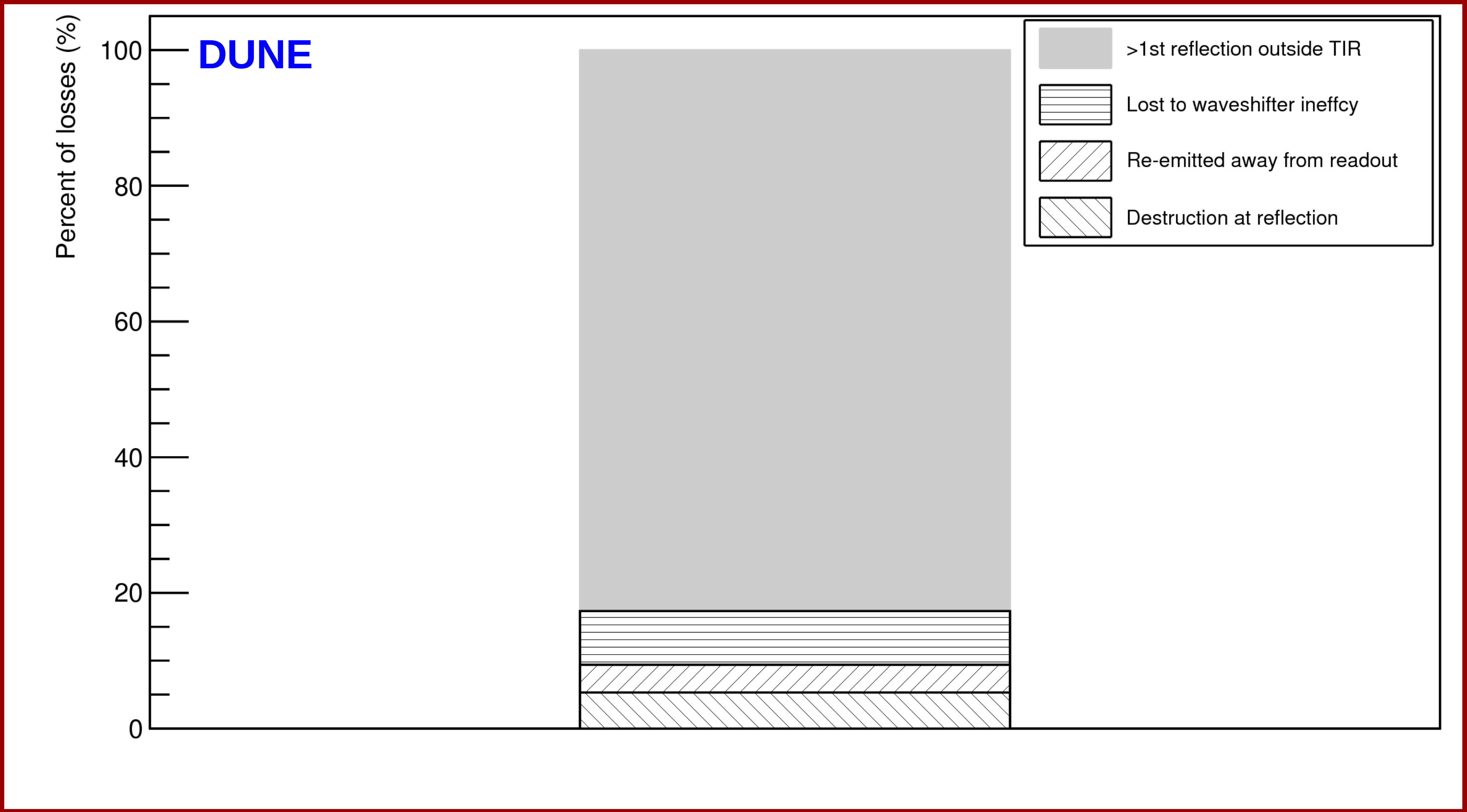
2) Ratio of photons detected to photons per photons initially hitting plates at distance B

Describes PD efficiency as function of distance from readout

Component simulation of PD system



Component simulation of PD system

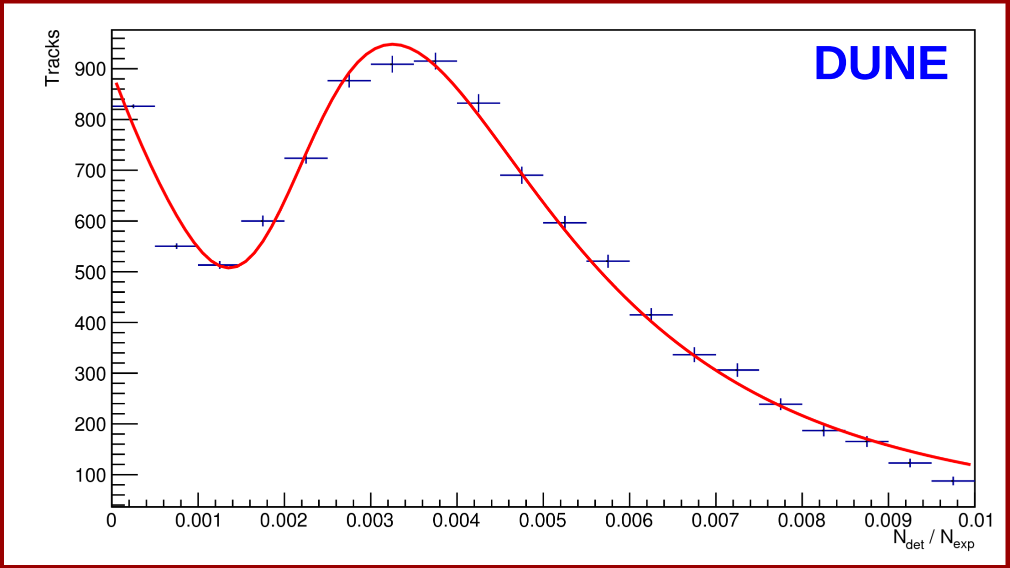


Simulation for prototype test

- Track trajectory given from hodoscope
- Generate 40,000 photons/MeV along the track (see Doke et al 1990 and 2002)
  - Given density and MIP energy loss, this is ~84,000 photons/cm of track
- Track photons around the dewar until lose photon to some process or it hits active area of PD system
  - Allow for reflections off wall
  - Rayleigh scattering: a length is chosen at random from exponential with characteristic length. If path length exceeds this, scattering occurs. Procedure follows that in a version of Geant4 (G4OpRayleigh) but uses ROOT functions instead of G4, to work in this standalone C++ code
    - Nominal length taken to be 110cm (Neumeier et al 2015)
    - Lower and higher values in literature taken as systematic band (66cm from Ishida et al 1997 and 163 cm from Neumeier et al 2012)
  - Absorption length: a length is chosen at random from exponential with characteristic length. If path length is greater than this, photon considered lost
    - Have measurements of contaminants from the LAr in Blanche. At levels of contamination, H_2O is the dominant contaminant, even though it is least abundant
    - For H_2O, estimate absorption length of 11.9m (using Watanabe and Zelikoff 1953)
  - Photons hitting top of liquid level are considered lost

Integrated prototype test

- Given no background/no fluctuations, ratio N_{det}/N_{exp} would characterize PD efficiency
  - Since expect the muons to be roughly MIPs, use the most probable value of Landau to characterize the efficiency and we include an exponential to characterize background, analyze with MC method and many trials to account for errors in the ratio
  - Average of the MPVs of the Landau fits characterize PE/photon for the 8 SiPMs used



MPV: 0.0035

- Correct result to efficiency (photons out/photon in) for 12 SiPMs
  - Correct for cross-talk in SiPM
  - Factor 12/8 since able to fit 12 SiPMs across light guide
- Determined efficiency at readout end is then 0.0042
- Factoring back in the transport function converts efficiency to a function of distance

Exposure-weighted average

- The simulation for prototype test gives expected photons hitting along the module
  - N(n) = number of photons incident in position bin n
- The component analysis gives efficiency of each plate
  - ε(n) = efficiency of the plate located at bin n. There are 4 along the light guide

Prototype plate efficiencies

1. 0.53 +/- 0.10	**3. 0.58 +/- 0.07**
2. 0.55 +/- 0.06	**4. 0.42 +/- 0.06**

- Calculate the average efficiency <ε> of the plates, going bin-by-bin along the length of the light guide, using photons hitting the plate there as its weight to average
  - <ε> = 0.52