Response of the 20” Super-K PMT in Magnetic fields of up to 250mG

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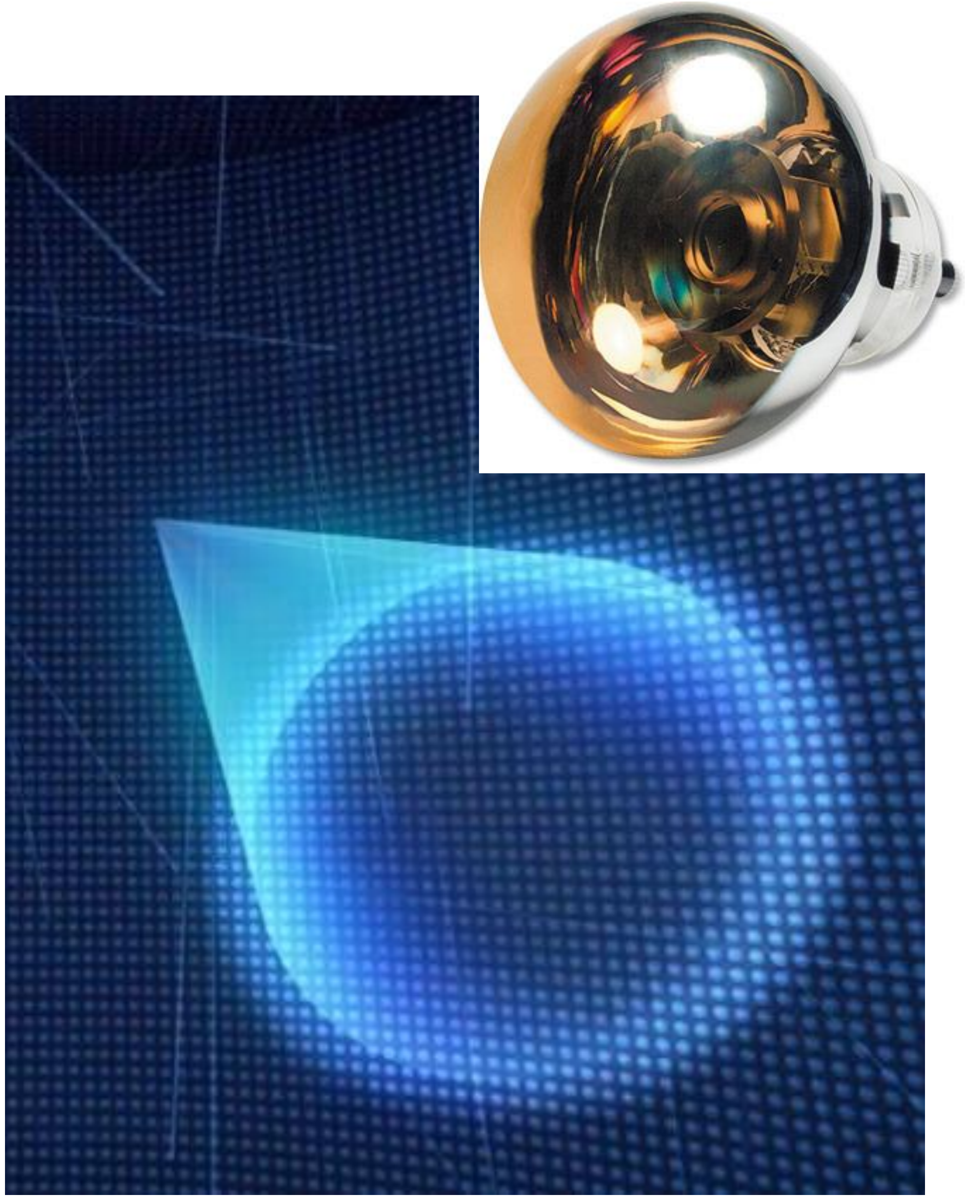
10th of June 2025, CAP @ Saskatoon SK

Making Sense of Light in Water

- Super Kamiokande is a water Cherenkov neutrino detector – large volume of water with Photo-multiplier Tubes (PMTs) used to detect Cherenkov light from charged daughter particles of neutrino interactions
  - 11k 50cm PMTs are used. Huge!

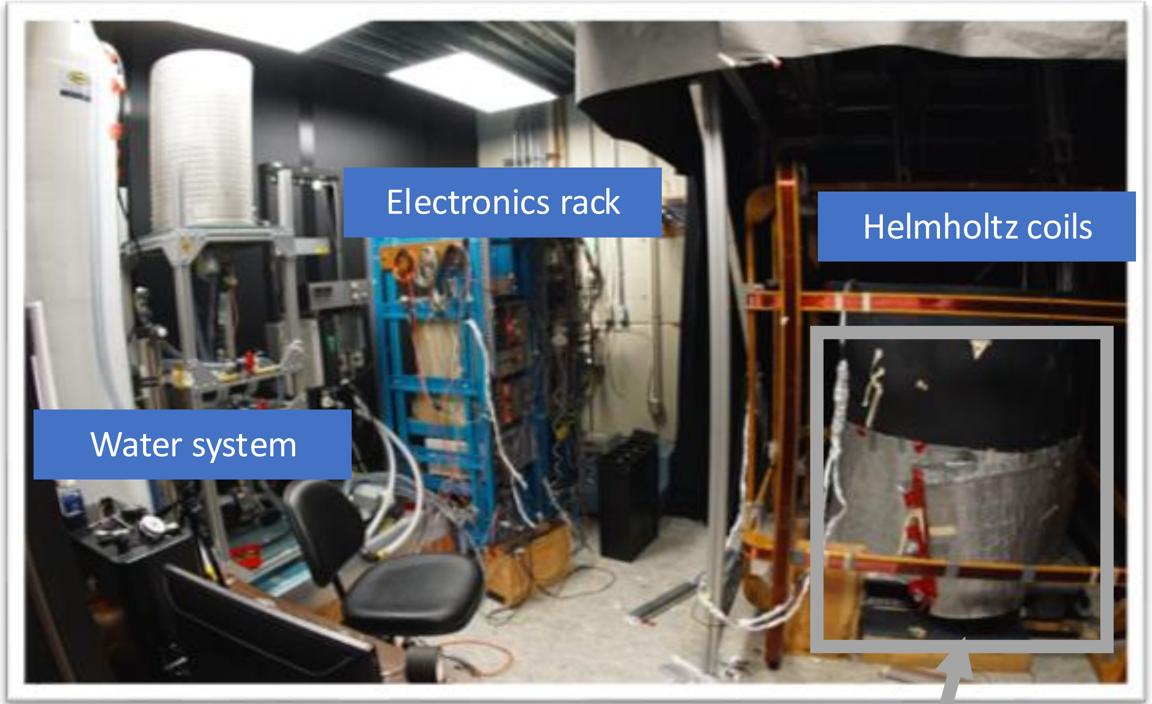
- Amount of light and layout of detected light tell us about the physics involved and the particles that produced the light

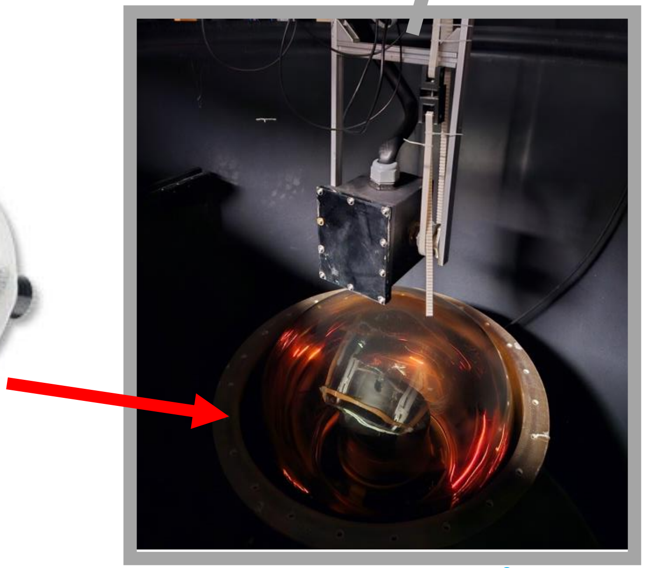
- **Challenge: PMT response has angular dependence in addition to a magnetic field dependence!**
  - recent challenges in SK have made understanding field effects >100mG a high priority



The Photosensor Test Facility at TRIUMF

- Pulsed picosecond-width laser light source @ 405 nm, attenuated to single photon level
- Emit light from mobile gantry with five degrees of freedom (x/y/z/tilt/pan), can change light polarization using Gian-Taylor polarizer
- kHz frequency pulse generator fires laser, digitizer readout
- Hamamatsu R9880U monitor PMT used to track laser stability
- Measurements typically done in water to mimic SK operating conditions

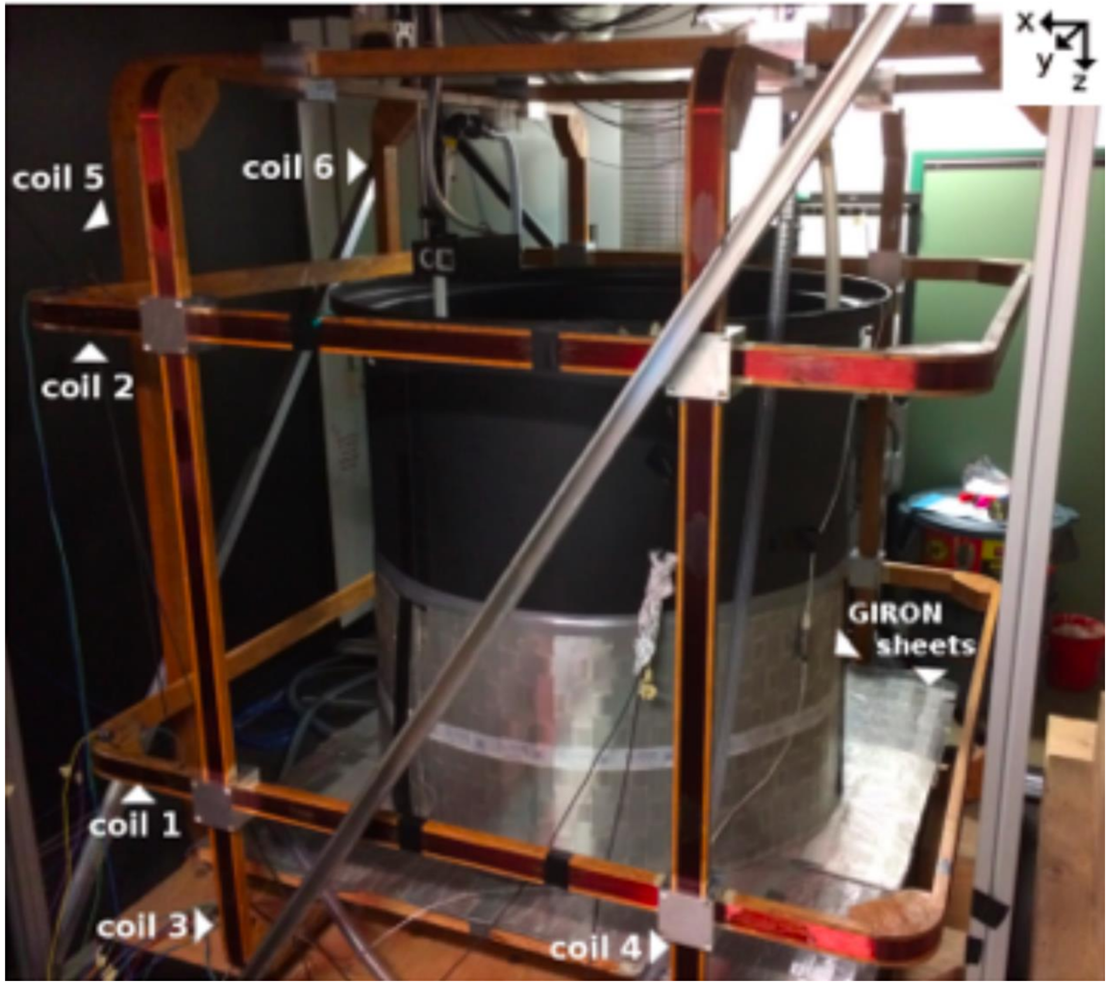


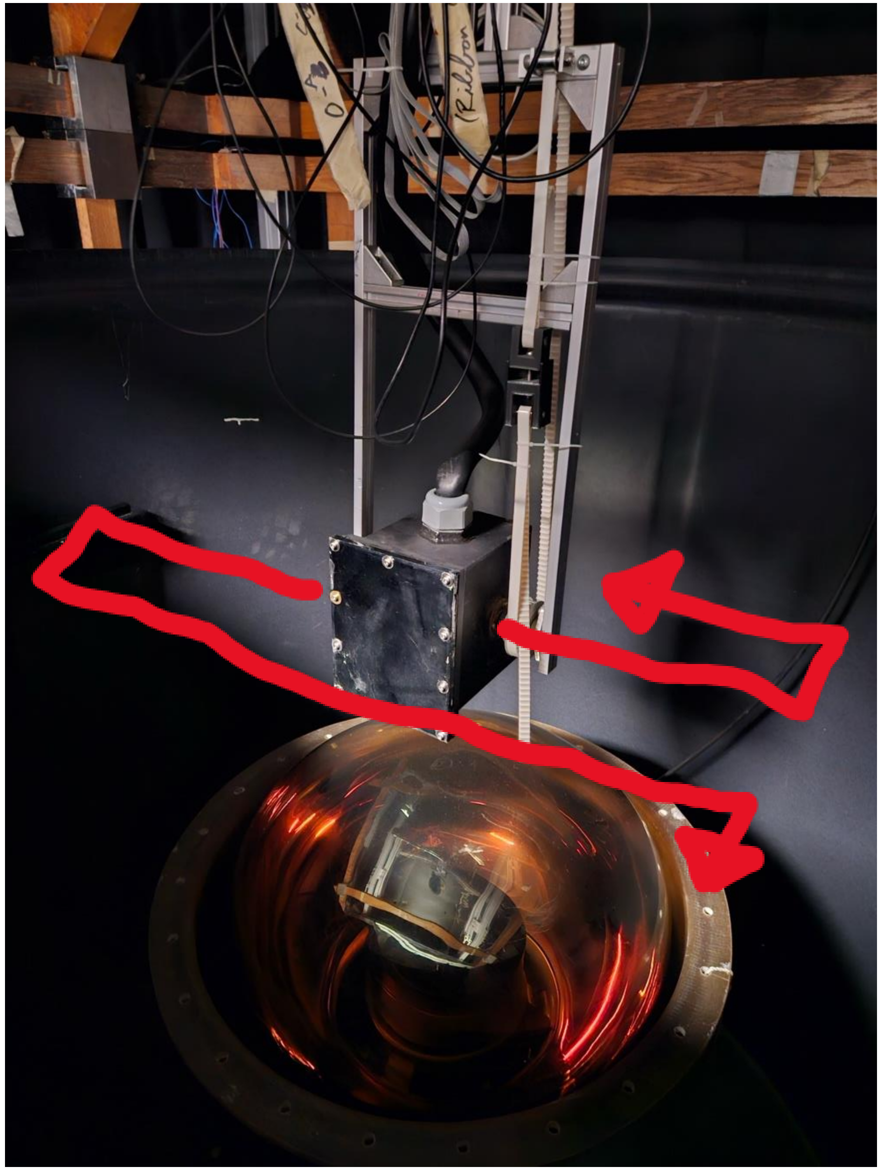


Configuring Magnetic Field

- Six Helmholtz coils arranged around the PMT tank
- Different coil voltages will allow us to
  - Compensate for the Earth's magnetic field
  - Explore magnetic fields of up to 500mG in an arbitrary direction

- Effects from the surrounding metallic structure require us to carefully calibrate the coil voltages to achieve desired field inside
- Account for observed hysteresis by following a degaussing procedure on changing configured field

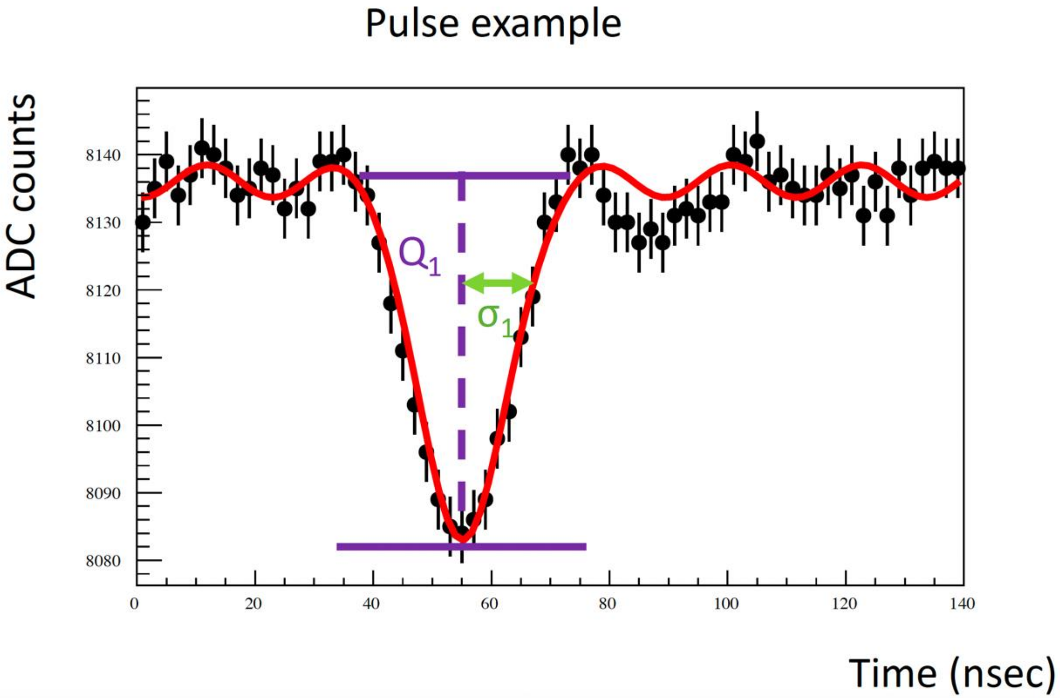




Triggering our laser source and digitizer simultaneously. OB visits scan points sequentially, takes data for ~12 seconds, moves to the next point.

We digitize the trigger signal, the 50cm PMT signal, and a monitor PMT signal.

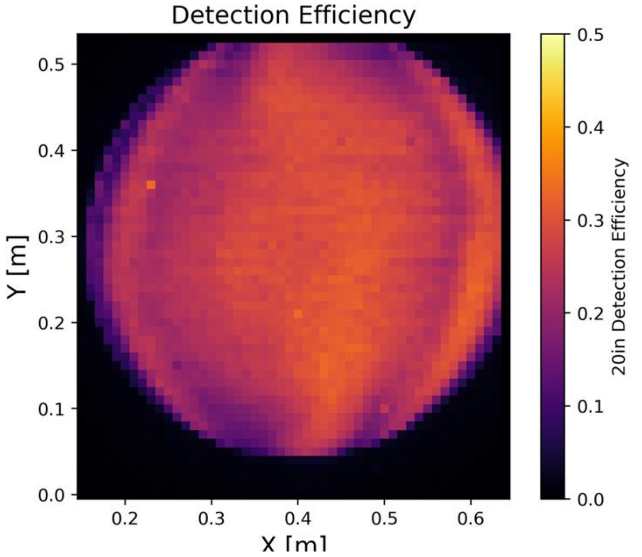
Can determine timing and charge information for each PMT from waveform fits.

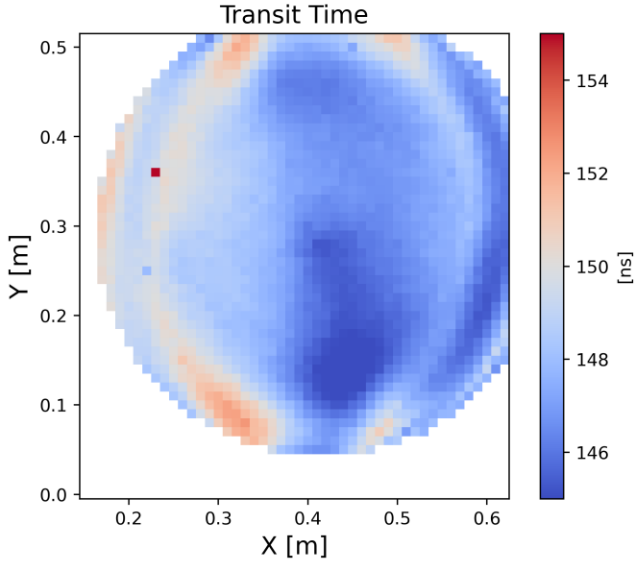


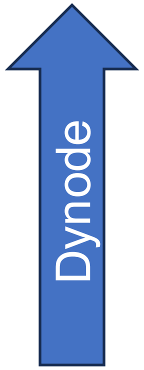
Vertical Injection Examples – taken at 0mG

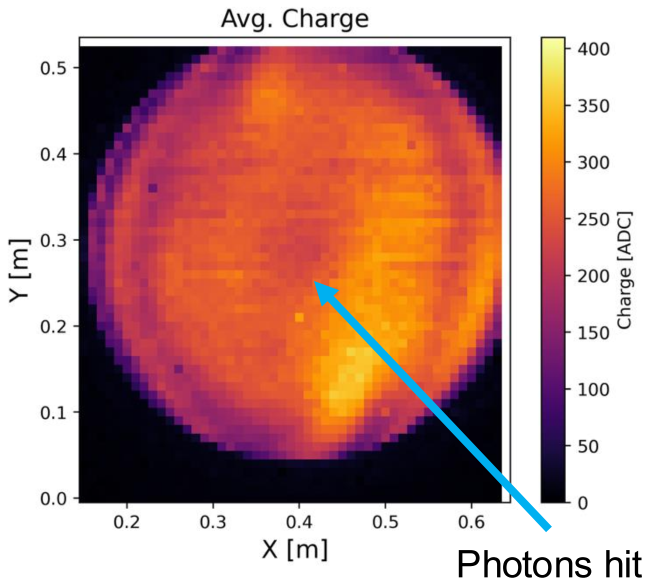
Each pixel shows the quantity measured for light injected downwards at that (x,y) position.

Heatmap shows measured quantity (gain, charge, etc.)

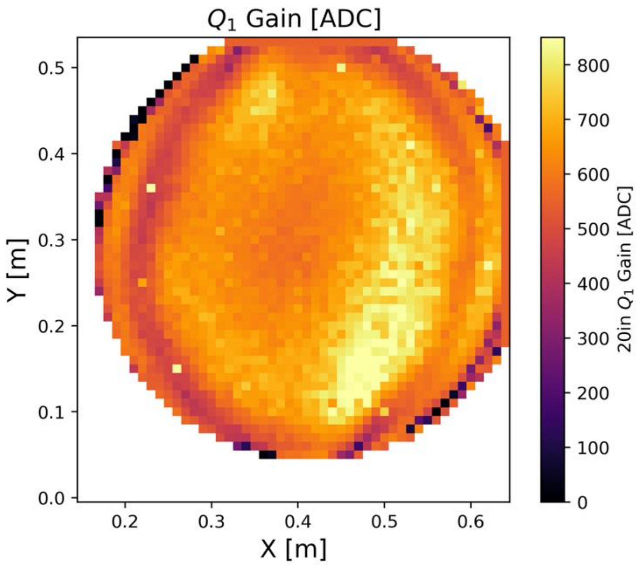


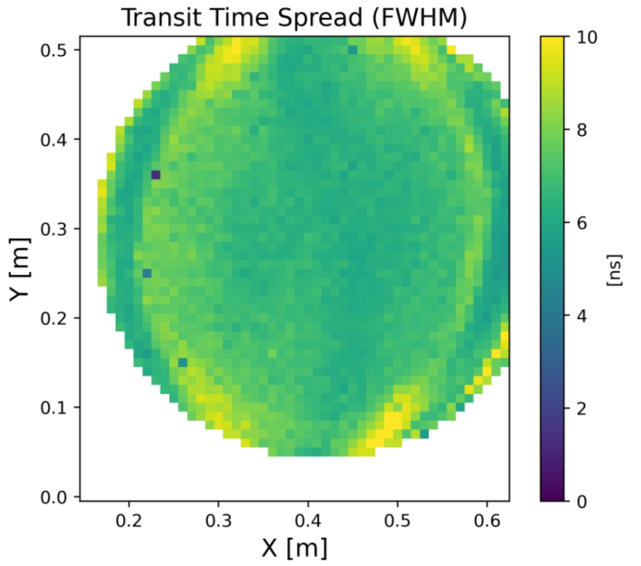






Photons hit dynode – fewer reflections



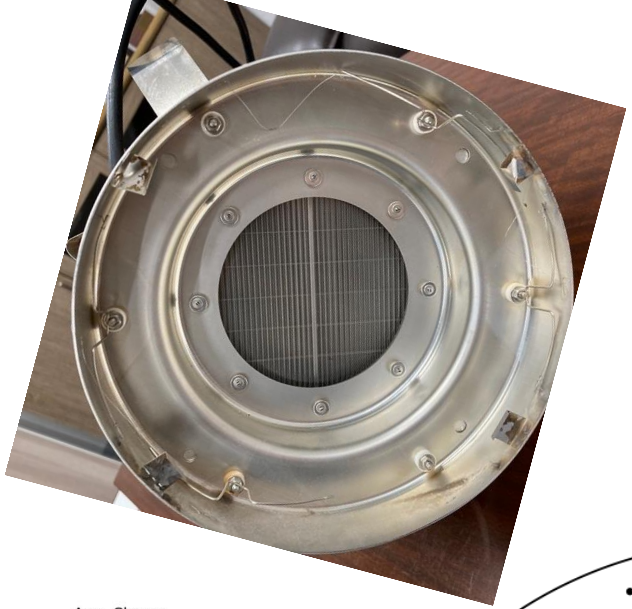


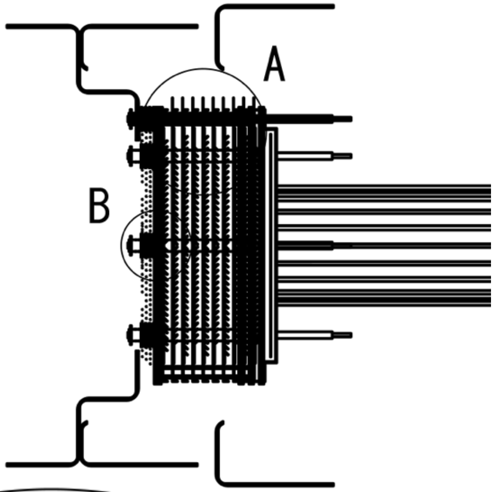
PMT Dynode Detail

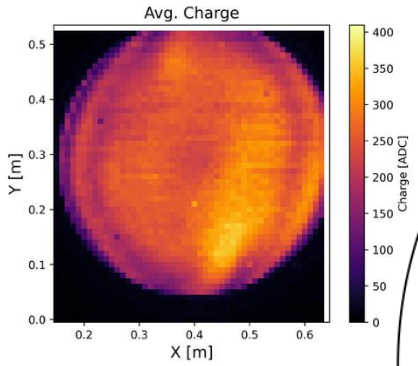
1. Photoelectron (PE) produced on PMT bulb (photocathode)
2. PEs pulled by electric fields towards dynode
3. PE kicks off more electrons at first dynode, electrons pulled towards second dynode
4. Repeat until the anode is reached – signal read out

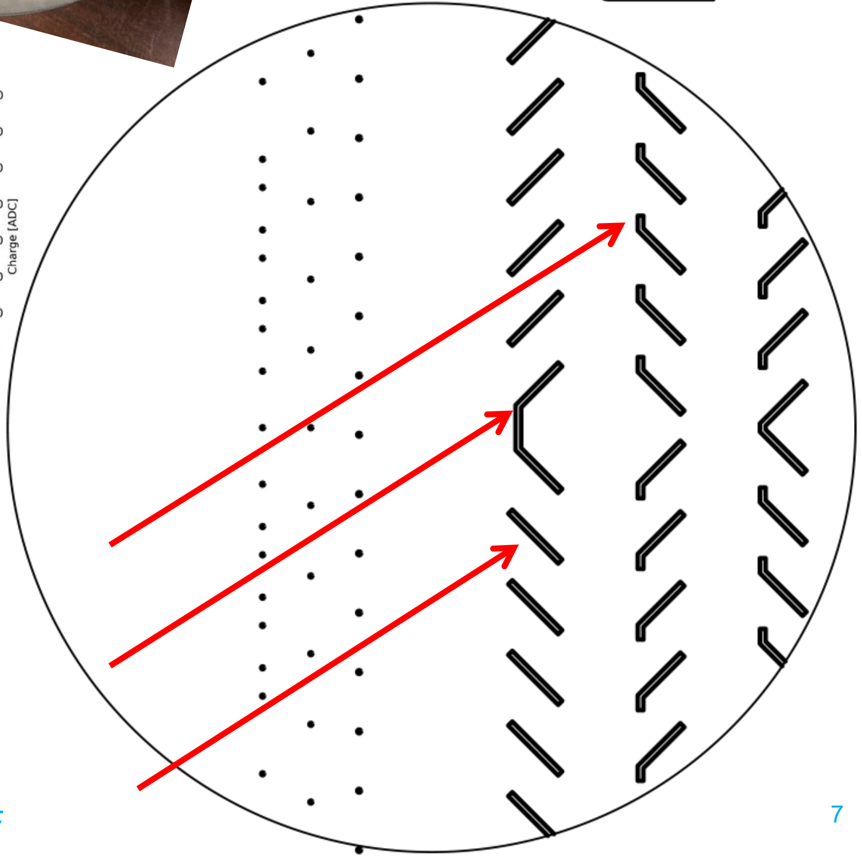
SK PMT uses a “venetian blind” style dynode. Series of angled dynodes mirrored across a central spine down the center.

Complicated interplay between PE release location and magnetic fields change the way.





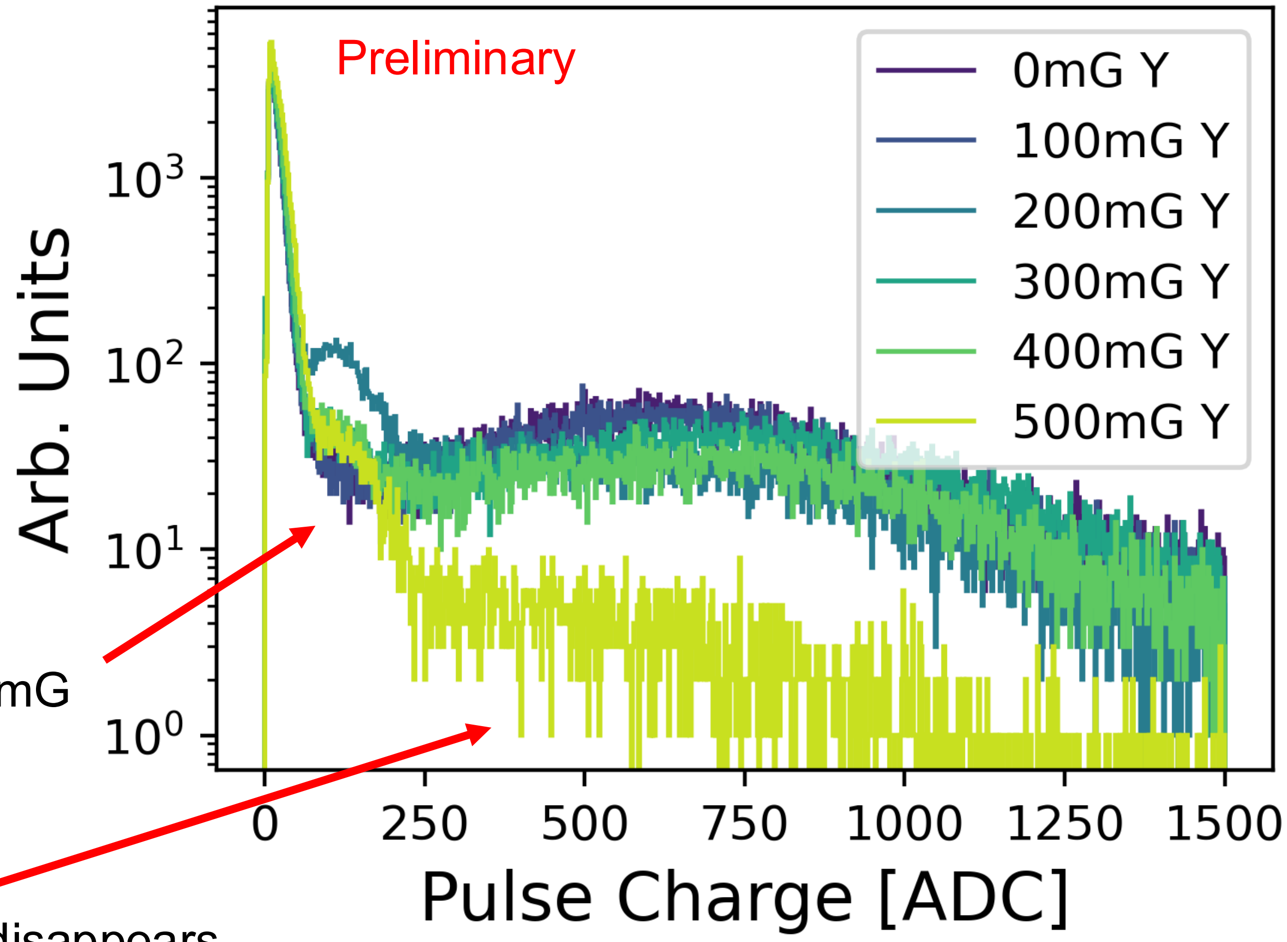




Charge Distributions – Fixed Point

PTF collected waveforms for ~2 minutes offset from the center of the PMT at several field strengths.

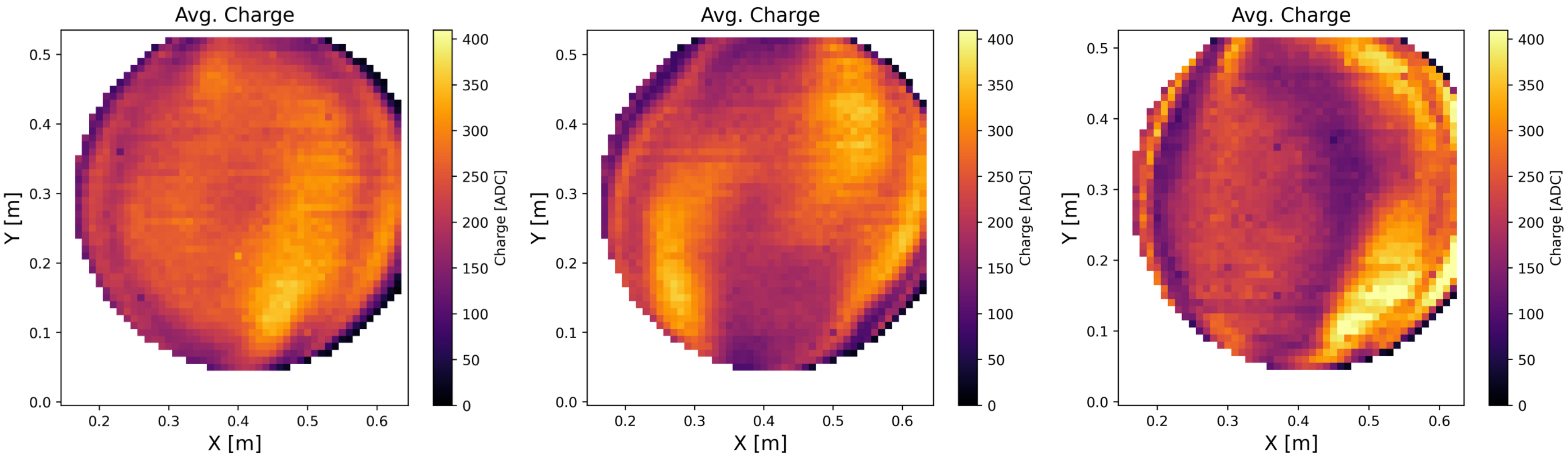
Consistent with PE dynode-skipping- field may determine the where exactly the skip-probability is at its maximum?



Under-amplification seen for all cases with magnetic field >100mG

1pe peak nearly disappears for 500mG +

Field Effects on Charge Collection



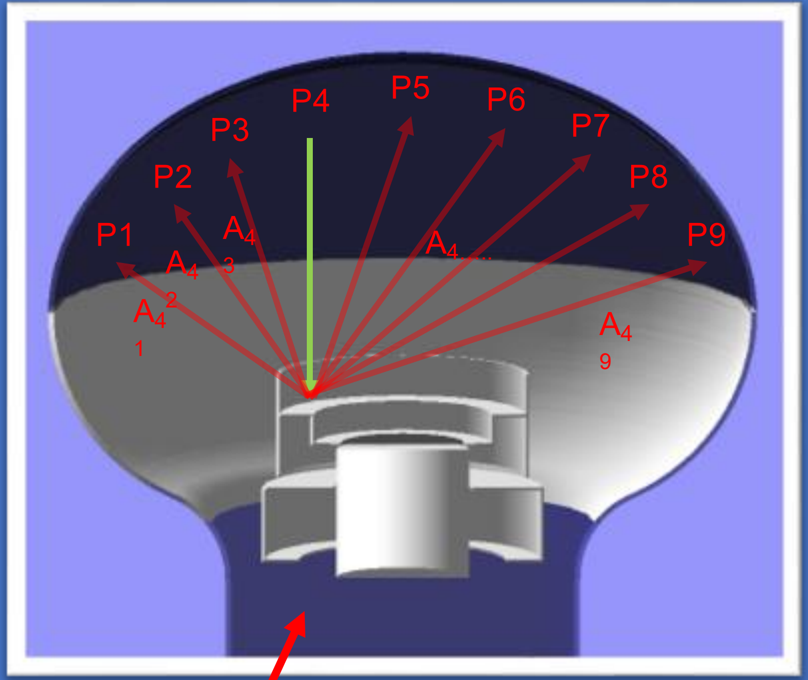
Average charge per waveform as a function of the (x) and (y) position of light injected vertically for three magnetic field strengths; the dynode runs along the y-axis. From left to right: 0mG, 250mG in +z, and 250mG in +y.

PMT Simulation

Generalizing vertical injection data for approximating other light injection angles

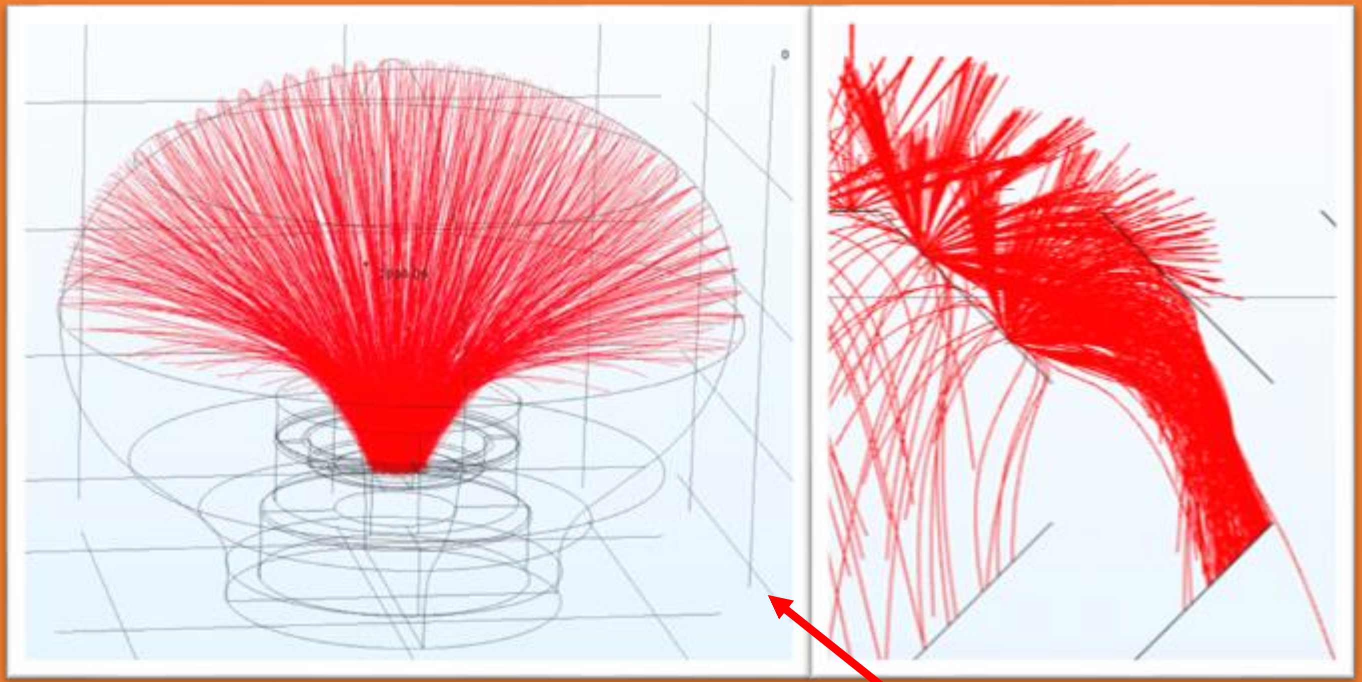
Photon simulation, PE Production

Optical Effects, Angular dependency



PE Propagation and Dynode Simulation

Magnetic Field Effects

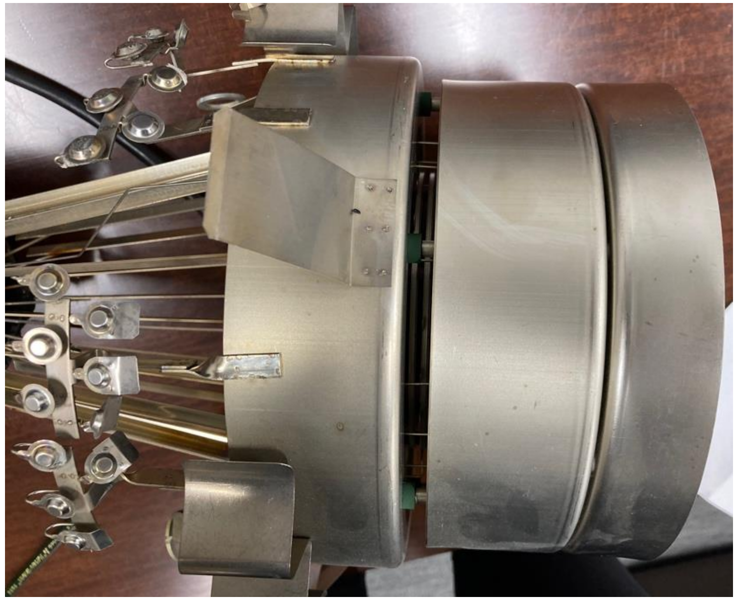


Geant

PTF

Addressing both simultaneously means too many degrees of freedom – want to decouple these effects

Modeling Optical Effects

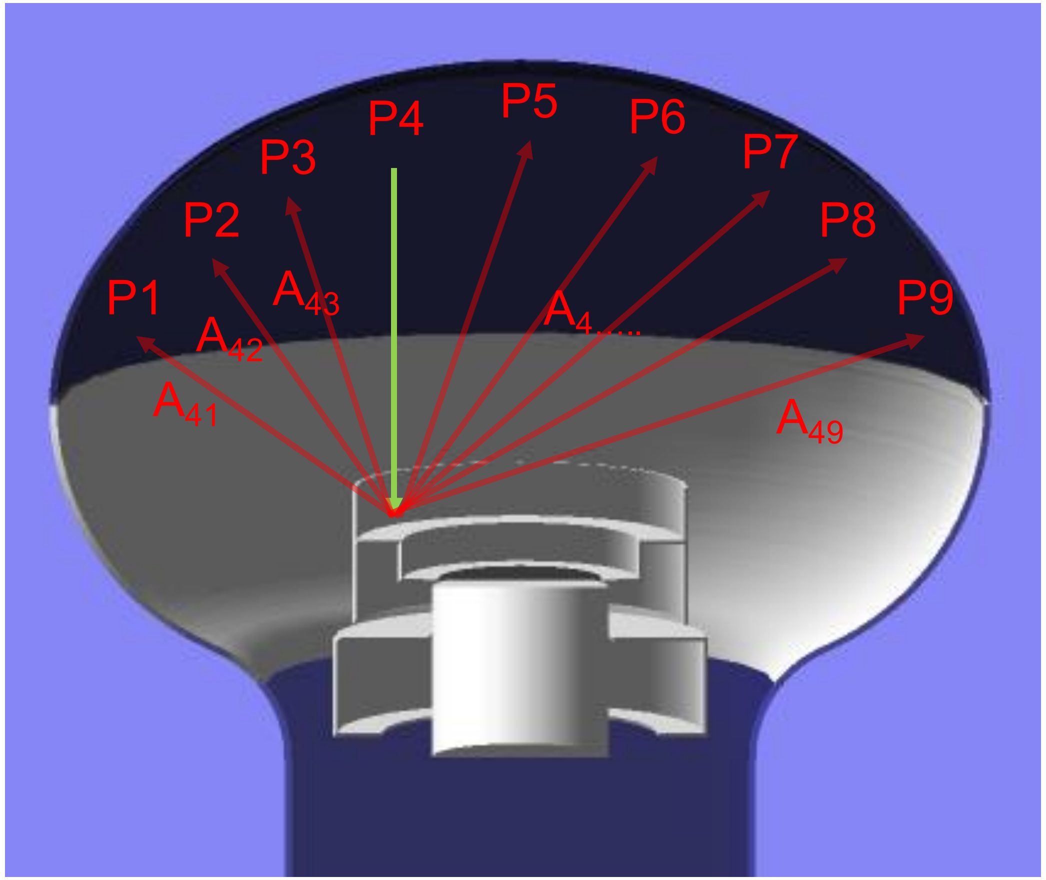


There is a non-negligible amount of internal reflection! Optical properties affect where photons are absorbed based on injection location.

We use a Geant4 model with an optical simulation built in WCSim and a geometry based on measurements of an imploded SK-PMT’s dynode.

Optical Simulation – Extracting PDE

Use vertical-injection PTF data + optical simulation to solve for the collection efficiency.



PTF Measurement (detection efficiency) at i'th position.

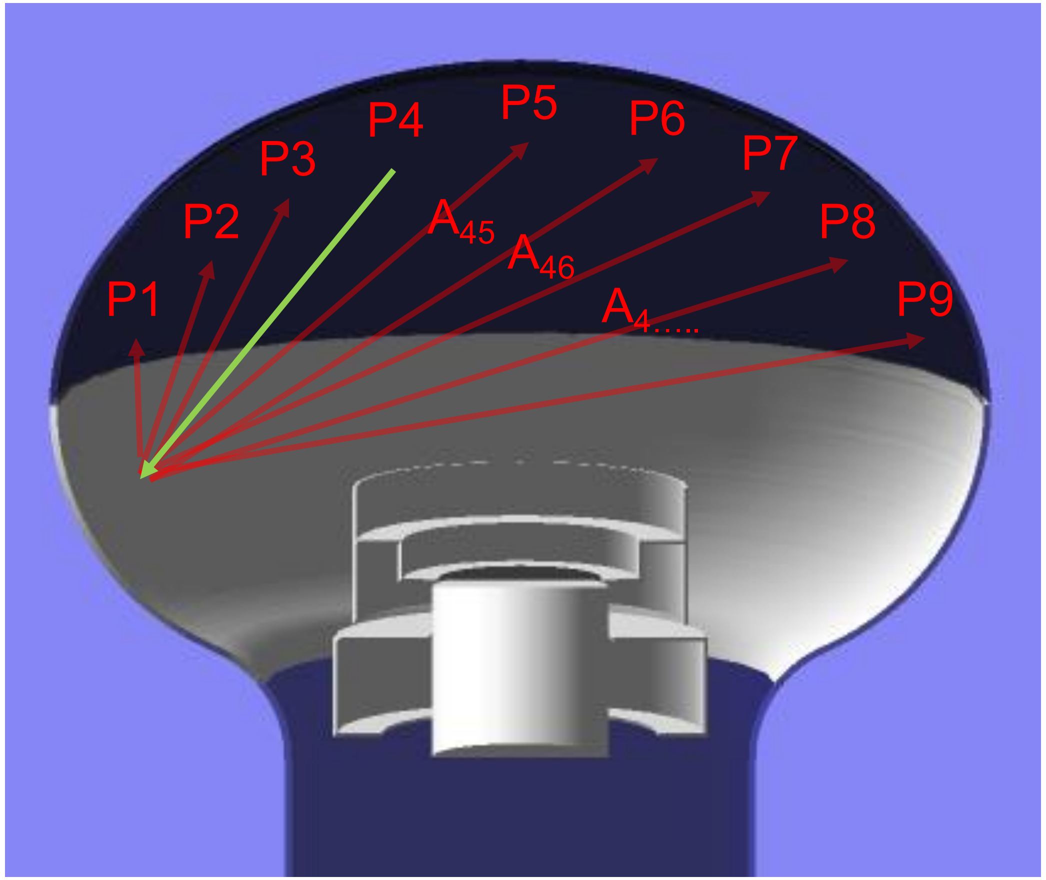
To solve: Collection eff. of PE produced at j'th position. Depends on B-field!

$$\begin{pmatrix} \mathrm{PDE}_1 \\ \mathrm{PDE}_2 \\ \vdots \\ \mathrm{PDE}_n \end{pmatrix} = \begin{pmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{pmatrix} \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{pmatrix}$$

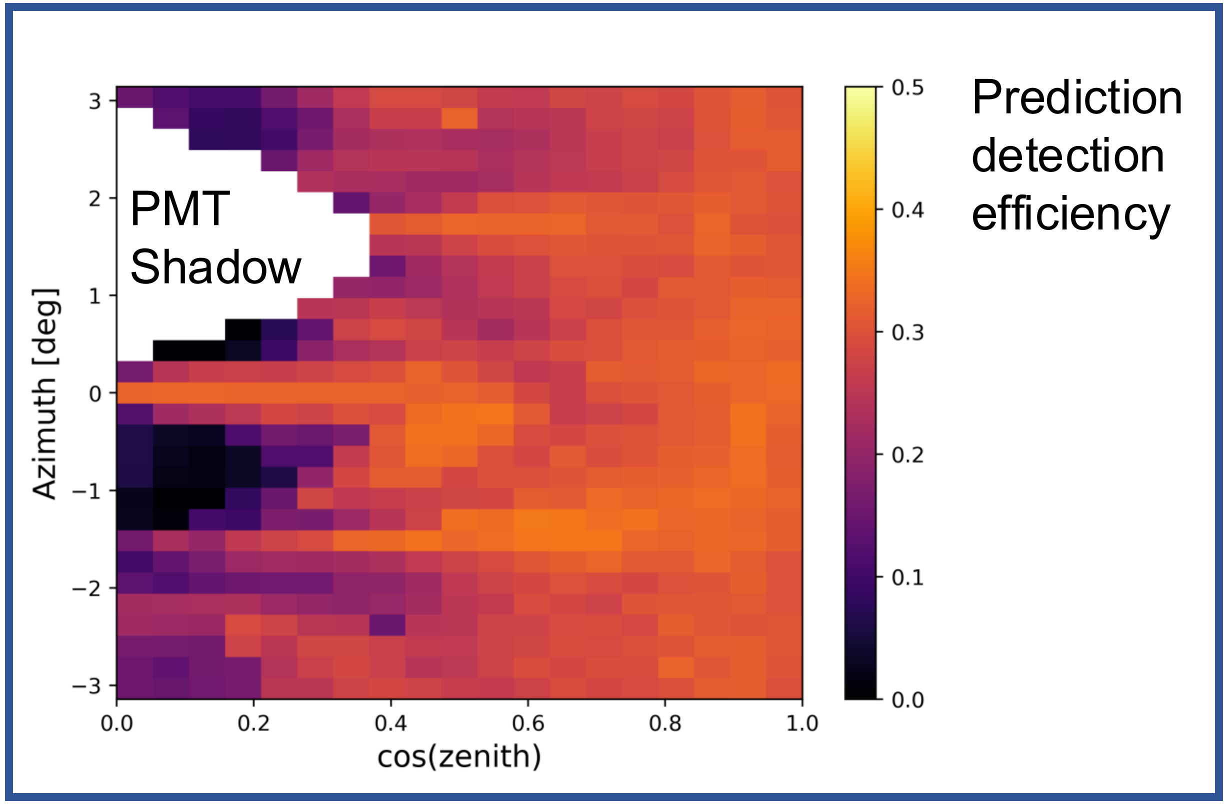
Determined from optical simulation. Depends on injection angle, geometry.

Method used for JUNO collaboration in arxiv:2204.02703

Predicting Photon Detection Efficiences for Tilted Light



The previous collection efficiency is unchanged

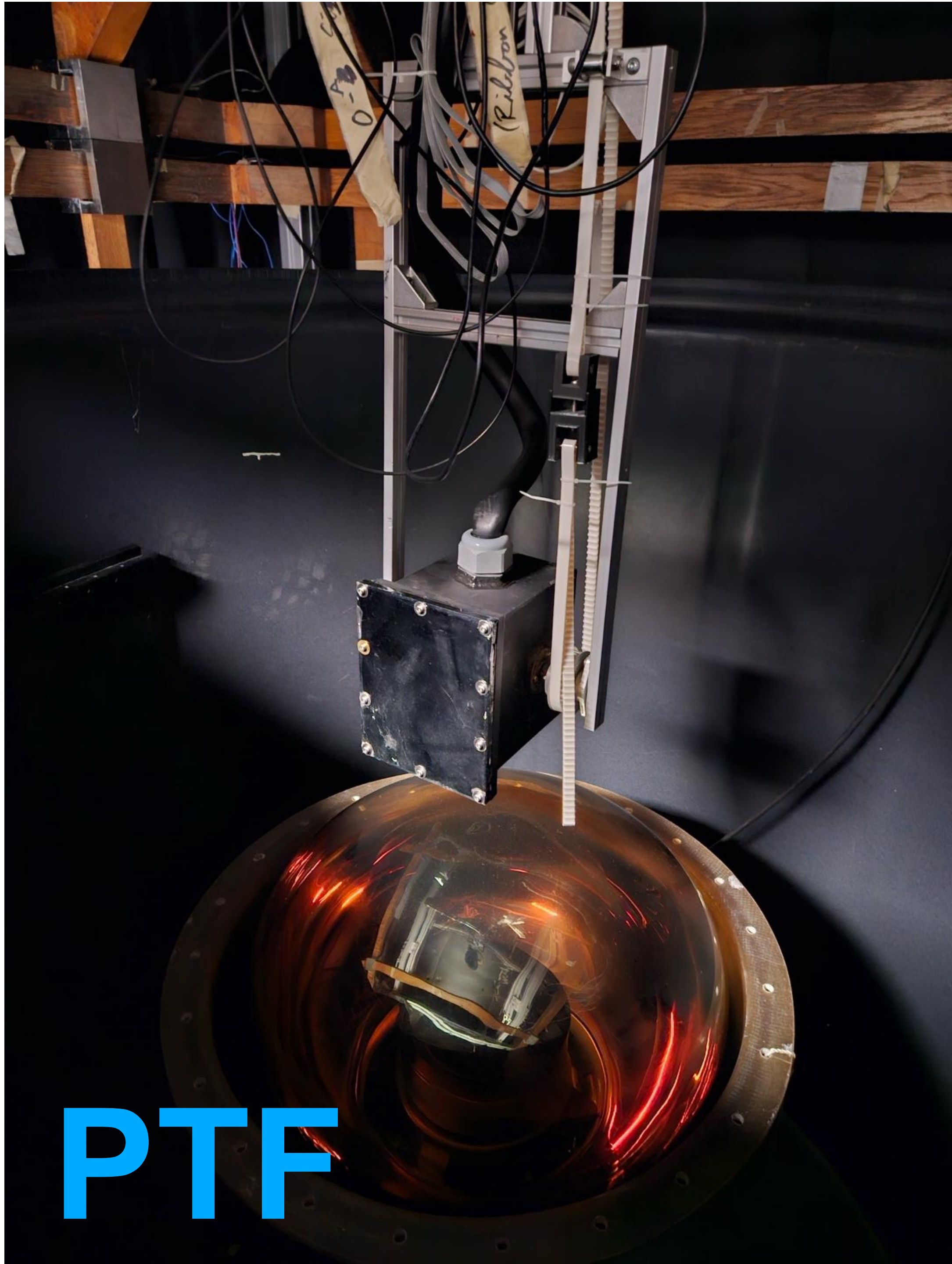


Simulate a *new* **tilted-injection transmission matrix**, and use determined efficiency to predict a new PTF measurement for light injected at a given point.

Summary

- Measurement campaign of SK PMTs under large magnetic fields underway
- Working to develop a model of PMT angular and magnetic field response
- Trying to separate out optical effects from PE detection efficiency

- PTF itself is up and running – future getting started soon on new applications!
  - Working with a team from SFU who will use PTF to study response and light emission profile for P-ONE P-CALs and POMs
  - May be performing similar measurements with the HK PMTs



Thank you for your time

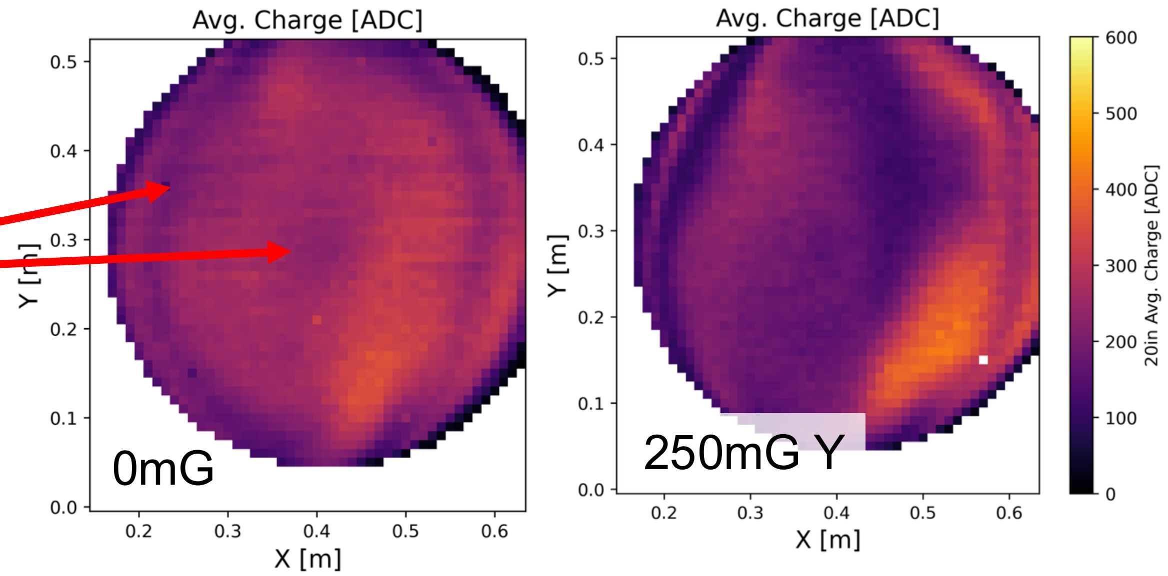
Backup

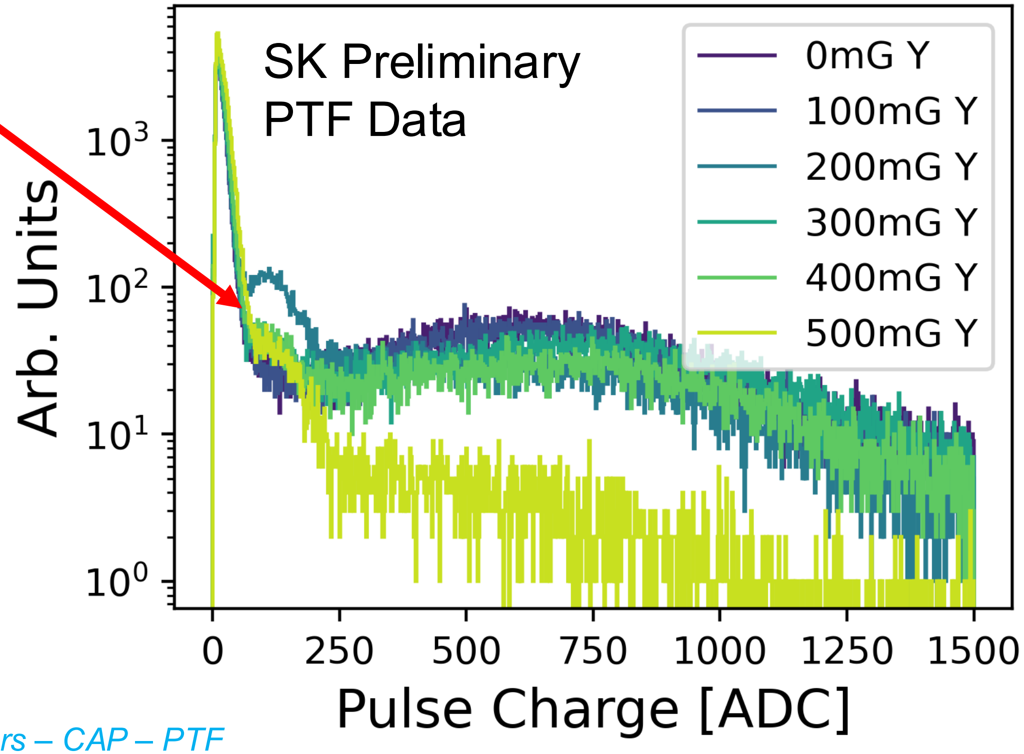
PTF Measurements

Have observed spatial effects from reflections and the dynode structure in the SK PMT

Under-amplification observed as a consequence of magnetic field effects on PE trajectories through the PMT bulb

This system can measure PMT gain, transit time, transit time spread, detection efficiency, and more!

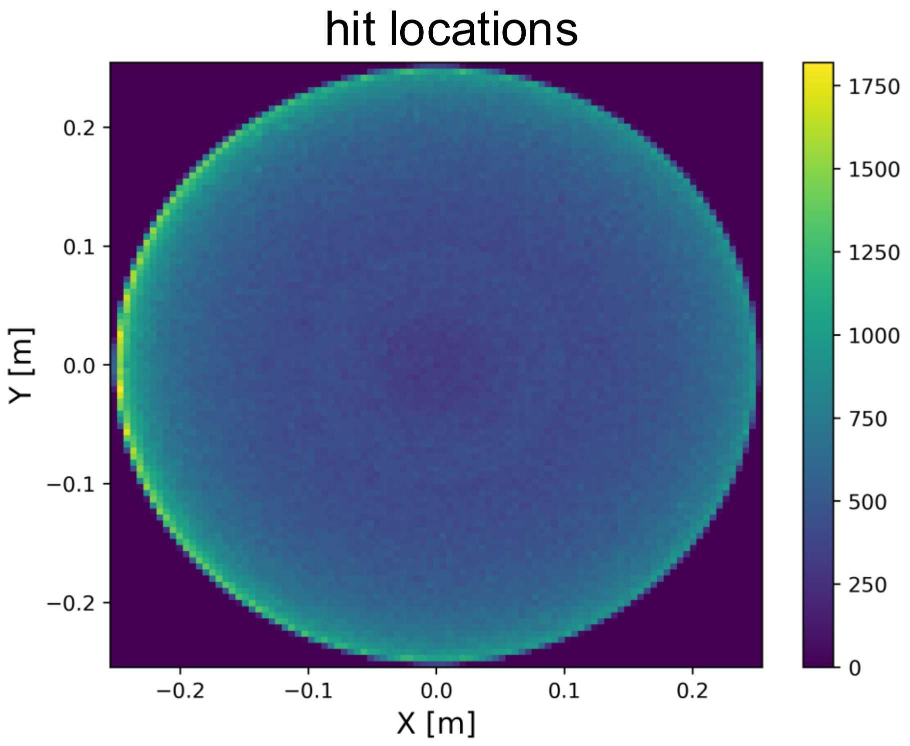


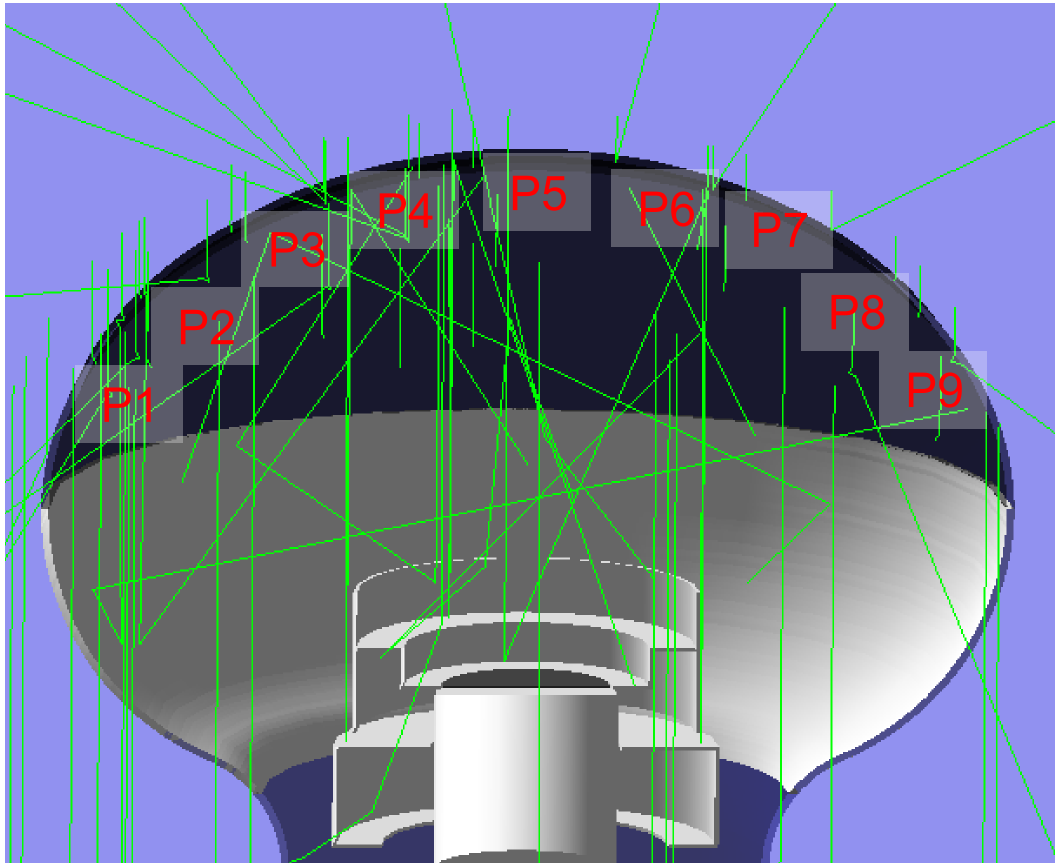


Building the Transmission Matrix

1. Photons are injected by sampling uniformly along azimuth and cos(zenith), like a unit sphere. Coordinates are scaled by A/B/C

2. Photons are binned in a 4D histogram based on cathode hit location and injected location





Track where photons are absorbed given an injection location

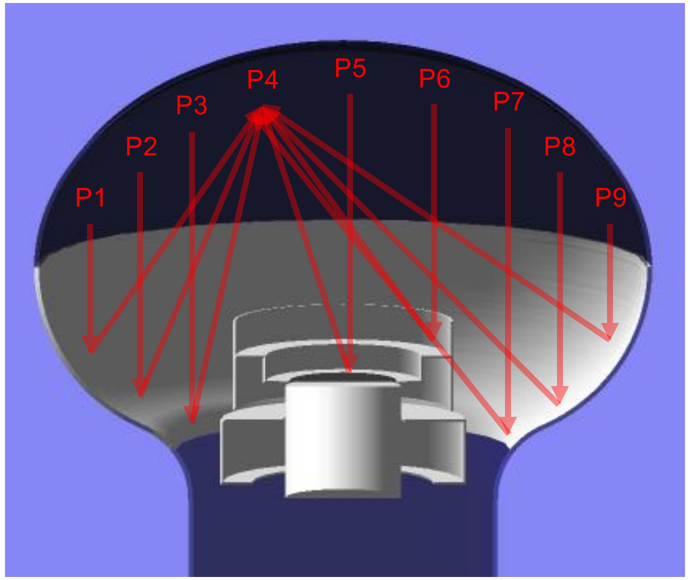
Inverting the Transmission Matrix

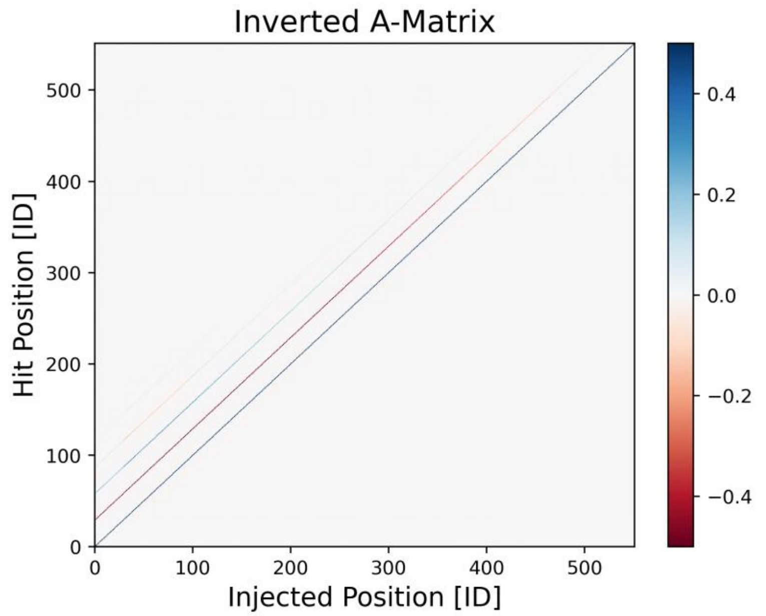
4. The 4D tensor is down-cast into 2D; axes are (hit location) and (injected location)
   a) Diagonal is absorption at injection loc

5. This transmission matrix then needs to be inverted to determine the collection efficiency
   4. A given collection efficiency depends on all other detection efficiencies plus the inverted transmission matrix

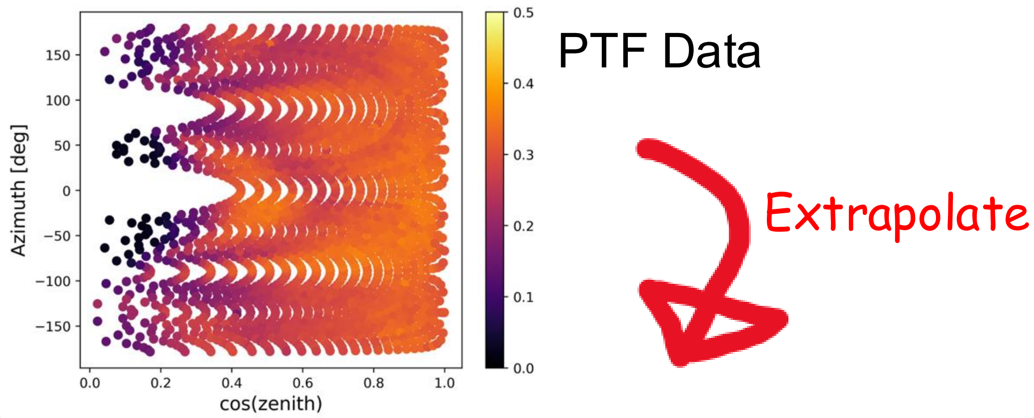
$$\begin{pmatrix} \mathrm{PDE}_1 \\ \mathrm{PDE}_2 \\ \vdots \\ \mathrm{PDE}_n \end{pmatrix} = \begin{pmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{pmatrix} \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{pmatrix}$$

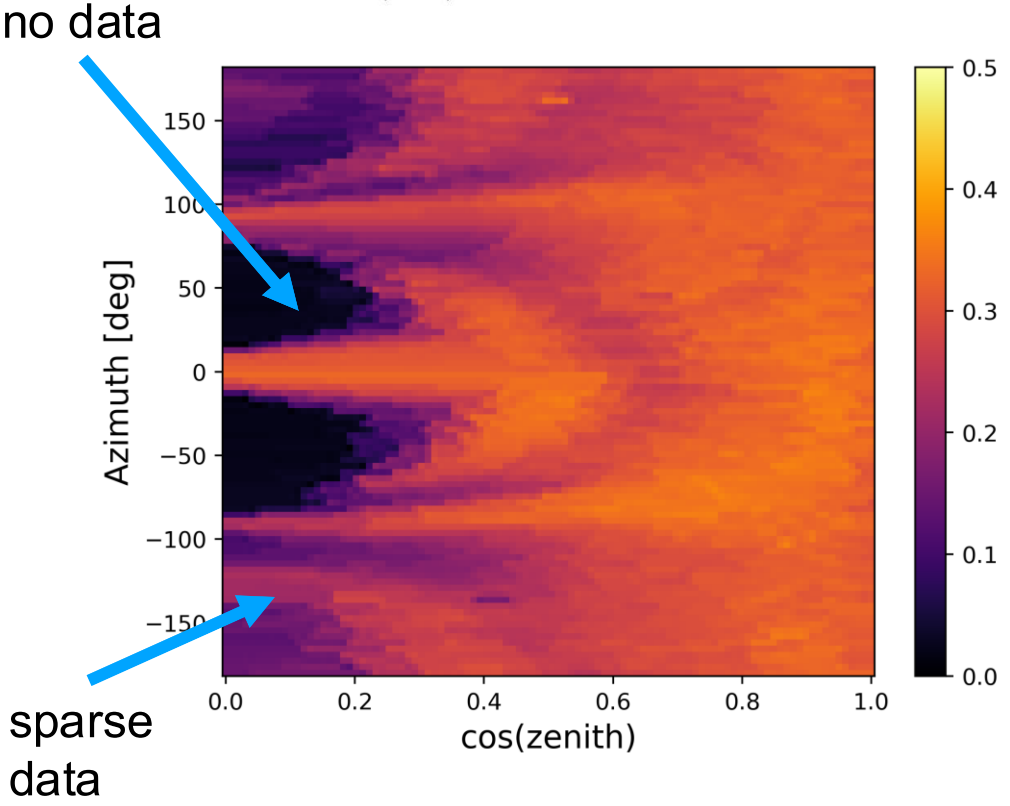
$$A^{-1} \begin{pmatrix} \mathrm{PDE}_1 \\ \mathrm{PDE}_2 \\ \vdots \\ \mathrm{PDE}_3 \end{pmatrix} = \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{pmatrix}$$





Extracting PTF Detection Efficiency



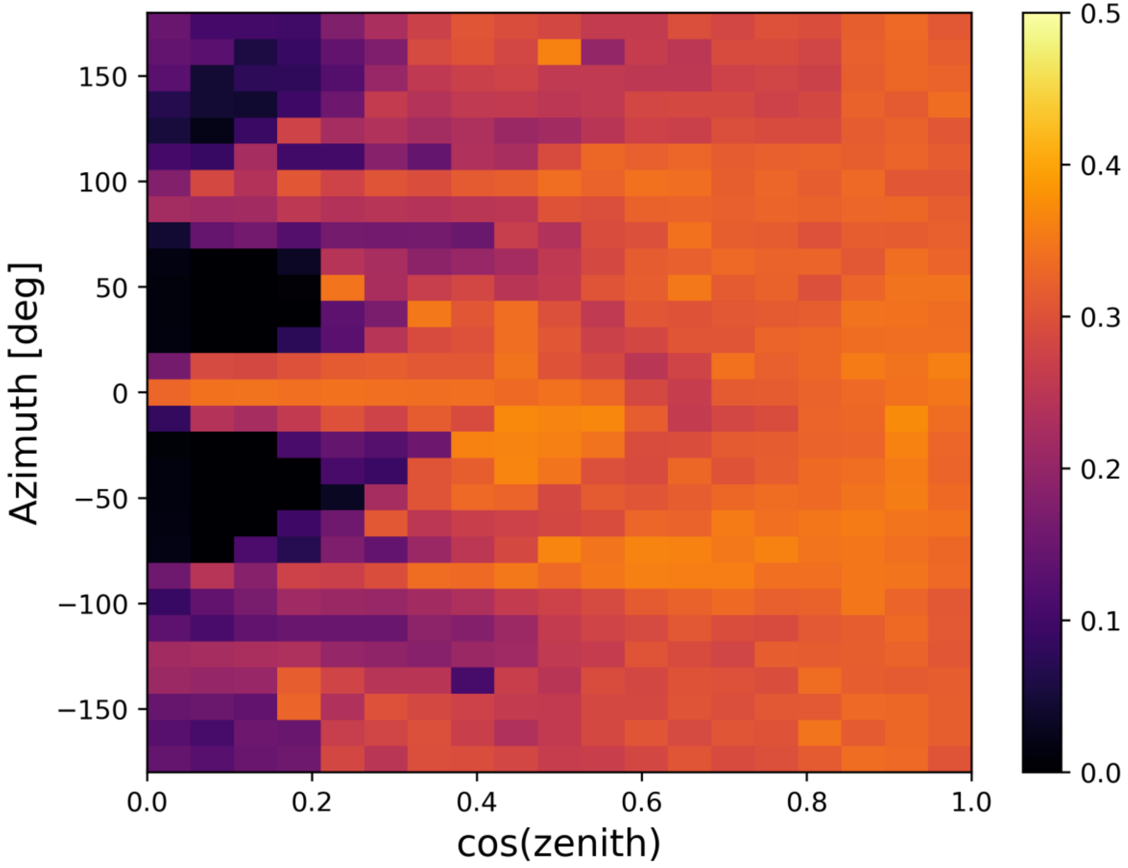


$$\begin{pmatrix} PDE_1 \\ PDE_2 \\ \vdots \\ PDE_n \end{pmatrix} = \begin{pmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{pmatrix} \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{pmatrix}$$

1. PTF Detection Efficiency data are determined
2. X/Y injection points are projected on to PMT, Z coordinate calculated
3. From coordinates, theta/phi are calculated
4. Interpolate detection efficiencies out from known points to full theta/phi grid
   a) nearest point value to full grid
   b) interpolation between those grid points
5. Flatten data along with meshed theta/phi points

Calculating F-Factor (collection efficiency)

Binning determined by
binning used in A-matrix



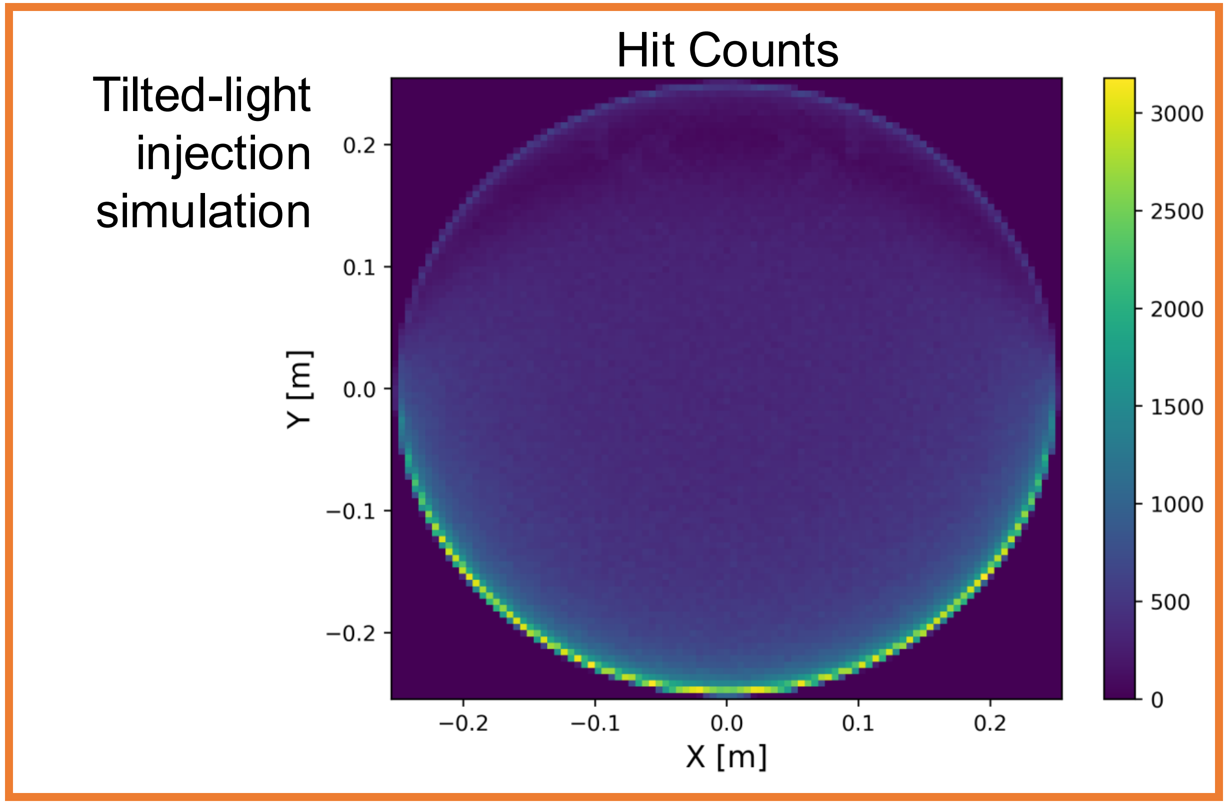
Collection Efficiency

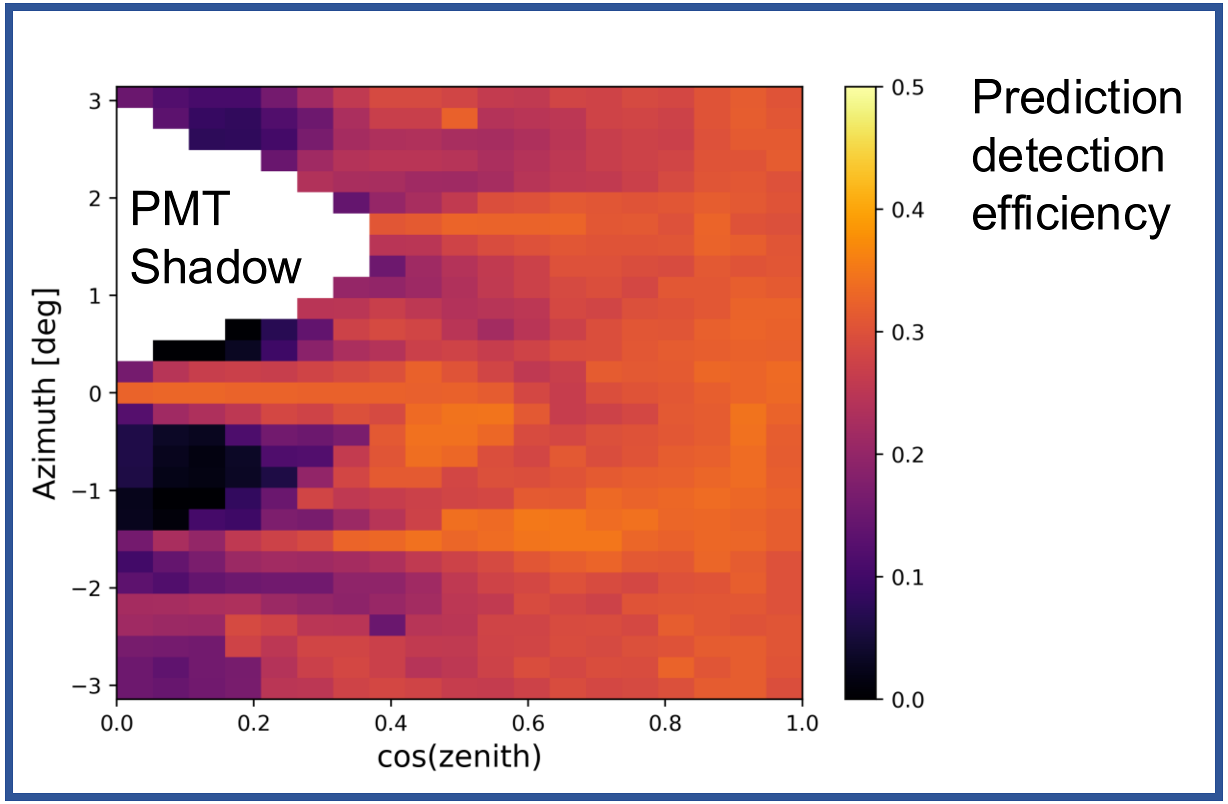
$$\begin{pmatrix} \mathrm{PDE_1} \\ \mathrm{PDE_2} \\ \vdots \\ \mathrm{PDE_n} \end{pmatrix} = \begin{pmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nn} \end{pmatrix} \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{pmatrix}$$

$$A^{-1} \begin{pmatrix} \mathrm{PDE}_1 \\ \mathrm{PDE}_2 \\ \vdots \\ \mathrm{PDE}_3 \end{pmatrix} = \begin{pmatrix} F_1 \\ F_2 \\ \vdots \\ F_n \end{pmatrix}$$

Extract collection efficiency from inverted transmission matrix and PTF measurement (detection efficiency).

Predicting Photon Detection Efficiencies for Tilted Light

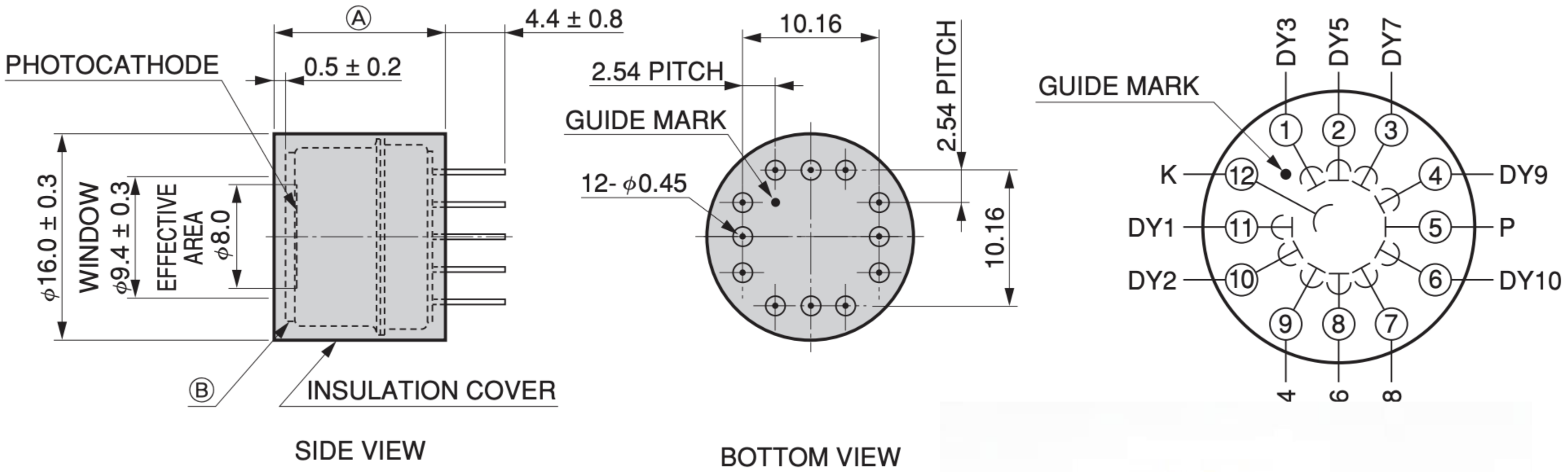




Use *new* **tilted-injection transmission matrix**, and the collection efficiency, to predict a photon detection efficiency for light injected at a given point.

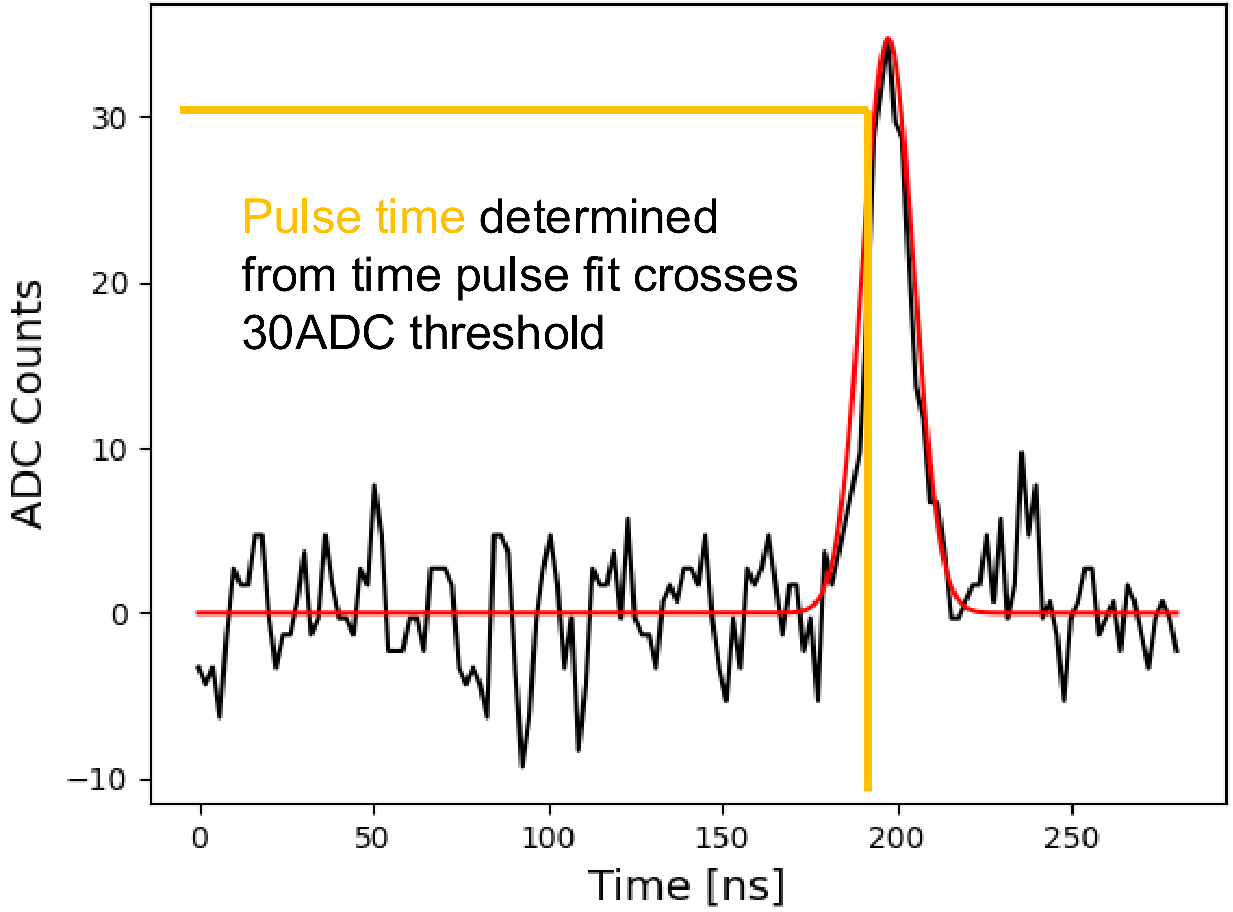
The Monitor PMT – Hamamatsu R9880U @ 1100V

Figure 4: Dimensional outline and basing diagram (Unit: mm)

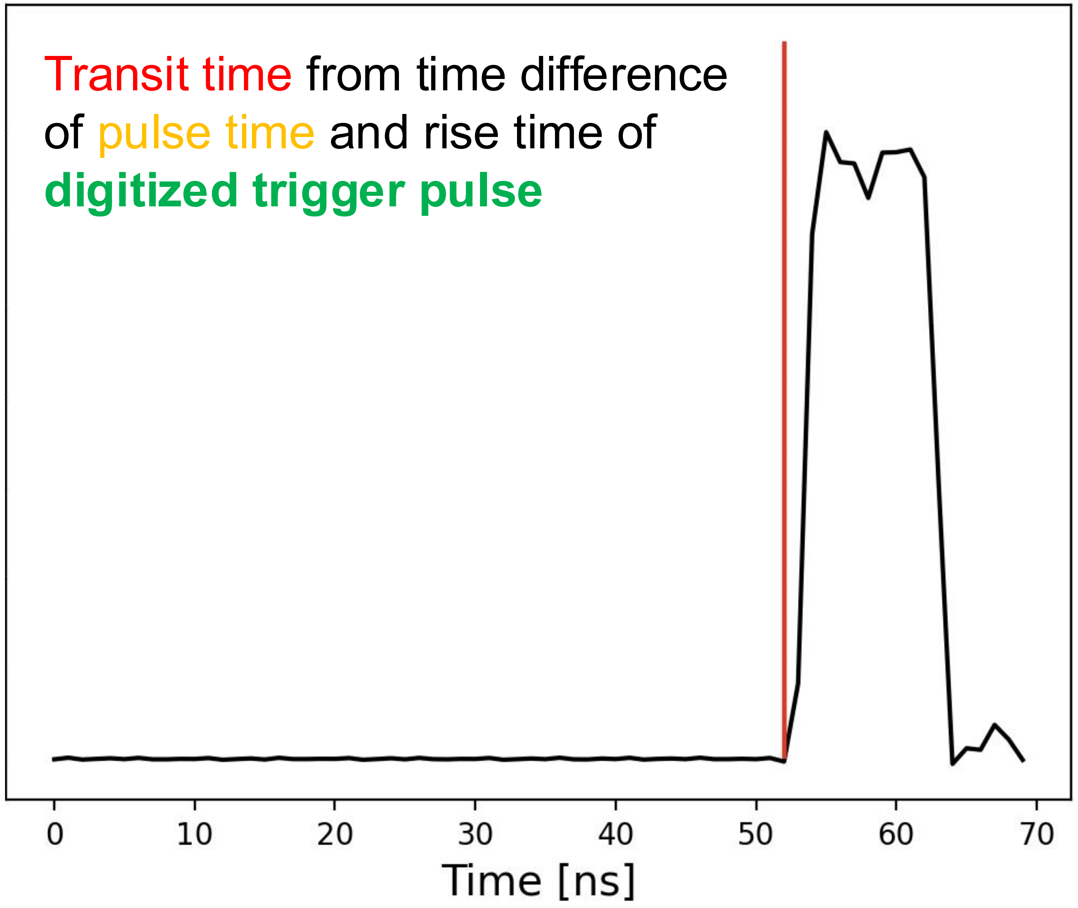


Suffix	Ⓐ	Ⓑ (Window thickness)
-01/-04/-20/-110/-113/-210	12.4 ±0.4	0.8
-09/-116	13.1 ±0.4	1.2

Mean Transit Time and TTS



20” PMT waveform



Timing Signal

Mean Transit Time and TTS

20” PMT waveform