A complete PMT optical model for JUNO

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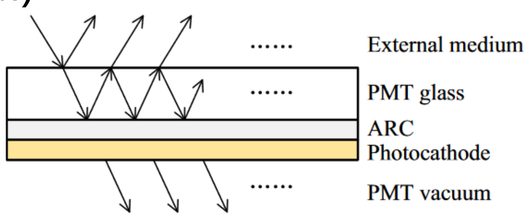
Introduction

- The main goal of JUNO is to determine the neutrino mass ordering.
  - desired energy resolution: 3%@1 MeV
- 17,612 20” photomultiplier tubes (PMTs) in central detector
  - 4,997 HPK dynode PMTs and 12,615 NNVT MCP PMTs
  - high photon detection efficiency (PDE) (~29%) [1]
  - large photocathode coverage (~75%)
- An accurate PMT optical model is critical for building a precise simulation and understanding the energy response.
  - PDE angular and spectral responses in water
  - PDE non-uniformity in a single PMT or among PMTs

PMT optical model

a. Fit R(θ) and PDE(θ) to obtain thickness (d) of anti-reflective coating (ARC) and photocathode (PC)
   - assume d(θ) is a quadratic function θ: zenith angle

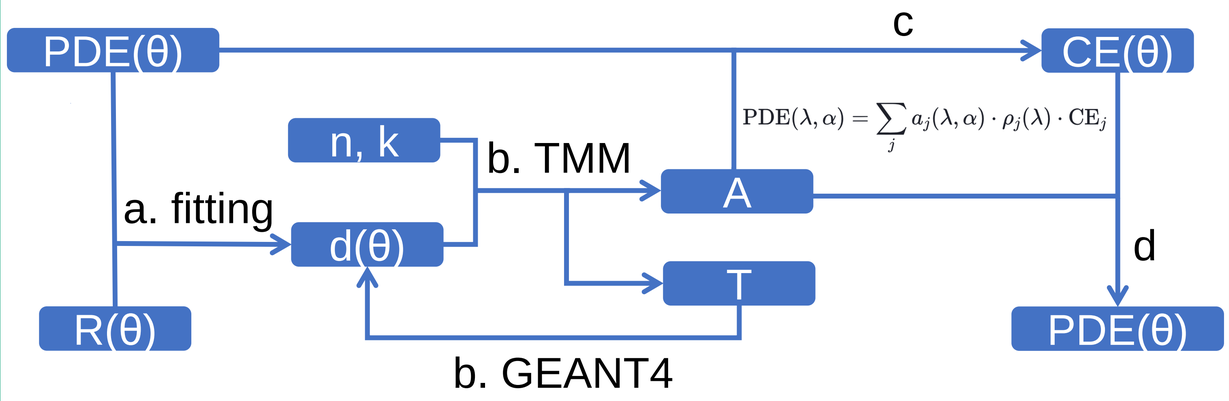
b. Simulate photon absorption and distinguish contributions from incident and transmitted photons [2]
   - transfer matrix method (TMM)
     - reflectance (R)
     - transmittance (T)
     - absorbance (A)
   - GEANT4
     - track the transmitted photons inside PMTs



c. Obtain collection efficiency (CE) [2]
   - interpolation based on reference points
   - solve the equations

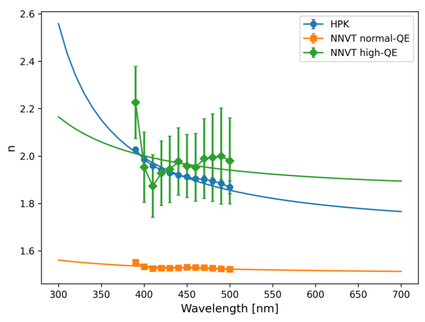
$$\mathrm{PDE}(\lambda,\alpha)=\sum_j a_j(\lambda,\alpha)\cdot\rho_j(\lambda)\cdot\mathrm{CE}_j \iff \begin{pmatrix}\mathrm{PDE}_1\\ \vdots\\ \mathrm{PDE}_n\end{pmatrix}=\begin{pmatrix}\beta_{1,1} & \cdots & \beta_{1,n}\\ \vdots & \ddots & \vdots\\ \beta_{n,1} & \cdots & \beta_{n,n}\end{pmatrix}\begin{pmatrix}\mathrm{CE}_1\\ \vdots\\ \mathrm{CE}_n\end{pmatrix}$$

d. Simulate non-uniform PMT PDE with angular and spectral dependence using the above equation

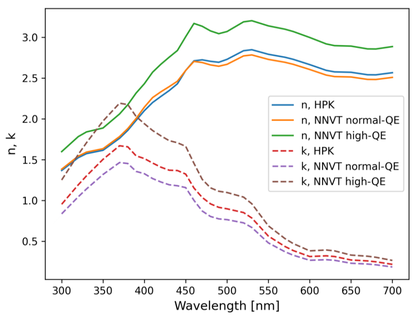


Input data for model

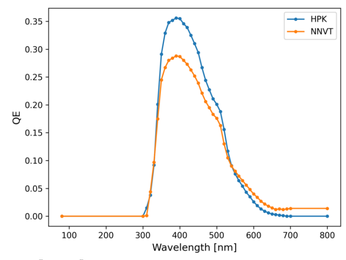
- Refractive index (n) of ARC
  - data from [2]
  - dispersion relation



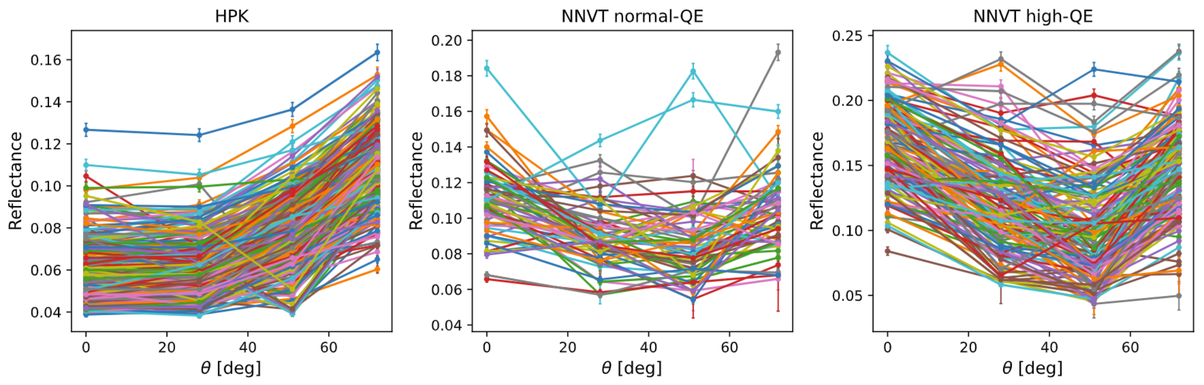
- Refractive index (n,k) of PC
  - data from [2, 3]



- Quantum efficiency (QE)
  - calculate escape factor = QE/A
  - constrain PDE spectral dependance



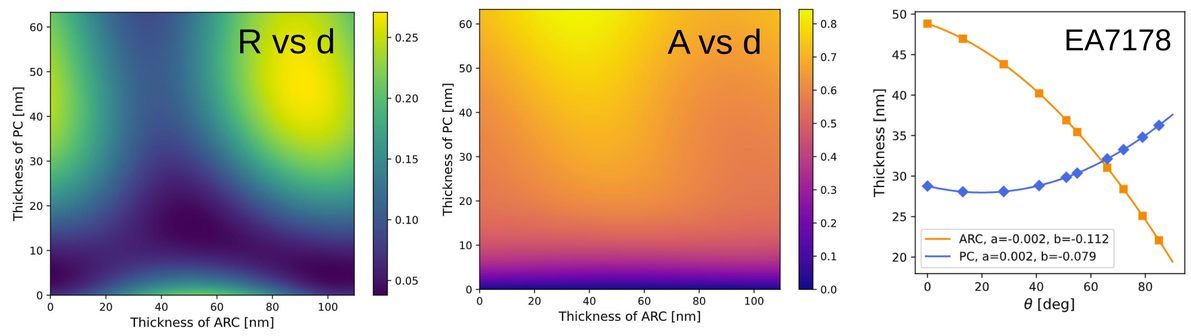
- Averaged PDE and PDE(θ) (PDE uniformity)
  - tested in container system and scanning station respectively [1]
- R(θ)
  - tested at 4 zenith angles
  - 8 degree incident angle at 415 nm



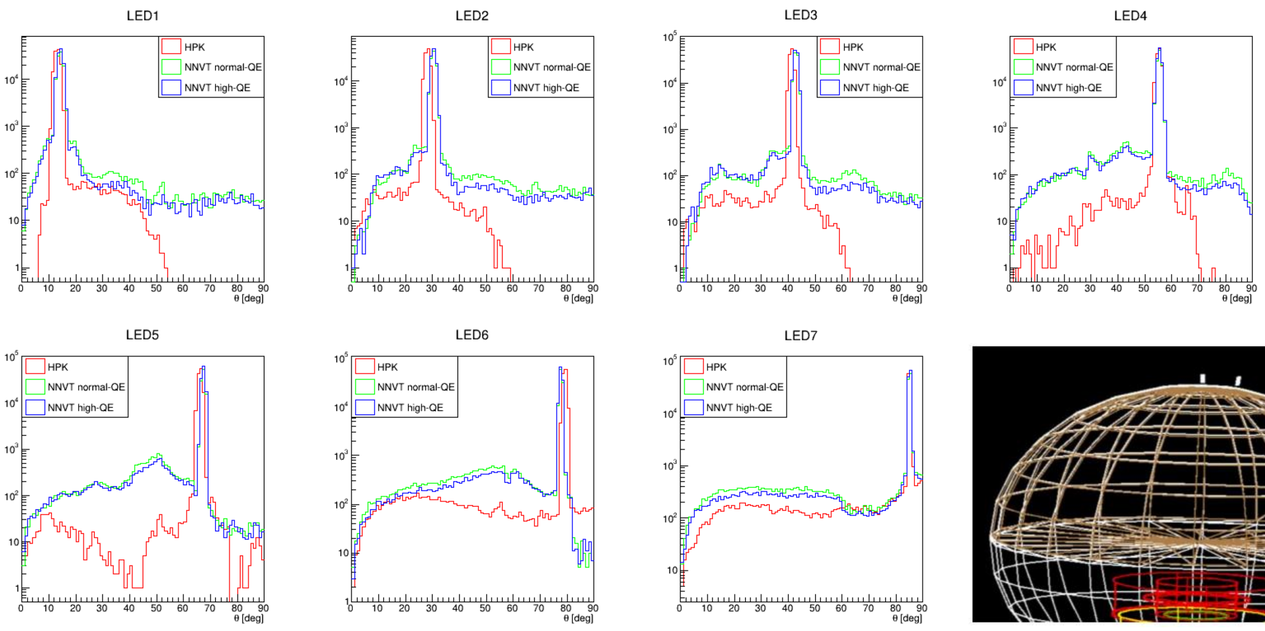
- Generate a random R(θ) or PDE(θ) curve sample from data distribution under averaged PDE constraint for PMTs without R or PDE uniformity test

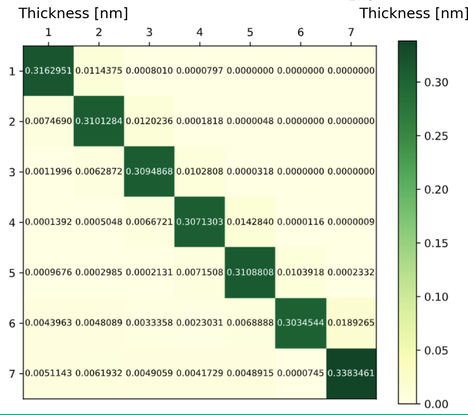
Results

- Thickness of ARC and PC

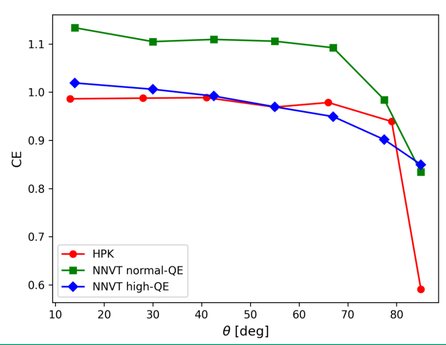


- Simulate photon absorption position of PDE(θ)





- CE



Summary

- A complete PMT optical model for JUNO is established.
- Non-uniform PMT PDE can be simulated with angular and spectral responses.
- The impact of PMT PDE non-uniformity on JUNO energy resolution will be evaluated.

References

[1] A. Abusleme et al., Mass testing and characterization of 20-inch PMTs for JUNO. Eur. Phys. J. C 82, 1168 (2022).
[2] Y. Wang et al., A new optical model for photomultiplier tubes, Eur. Phys. J. C 82, 329 (2022).
[3] S.W. Harmer et al., Variation in optical constants between photocathodes. Nucl. Instrum. Methods A 564(1), 439–450 (2006).