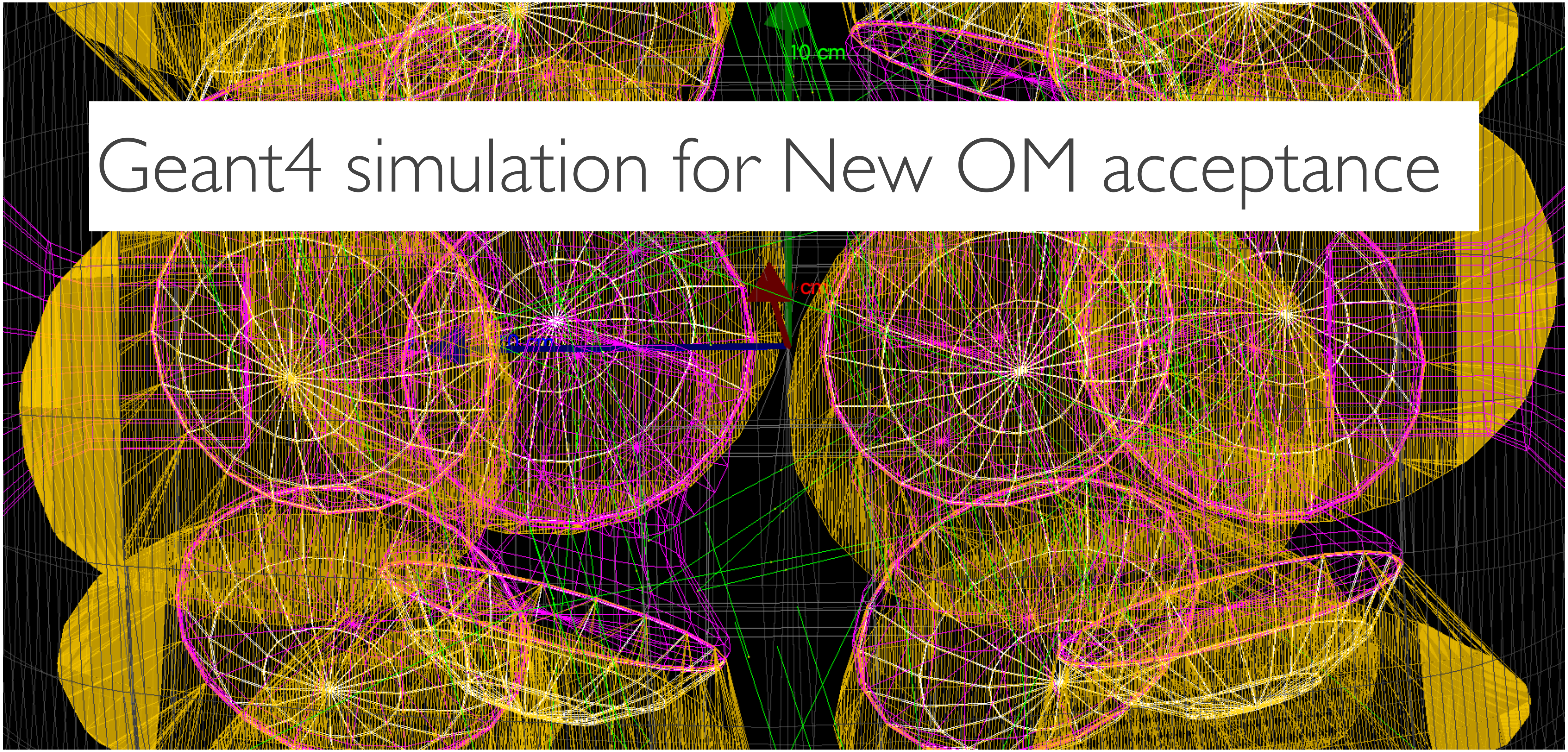
Geant4 simulation for New OM acceptance



Kotoyo Hoshina, Nobuhiro Shimizu, Delaney Butterfield, Vedant Basu

Oct 19 2021

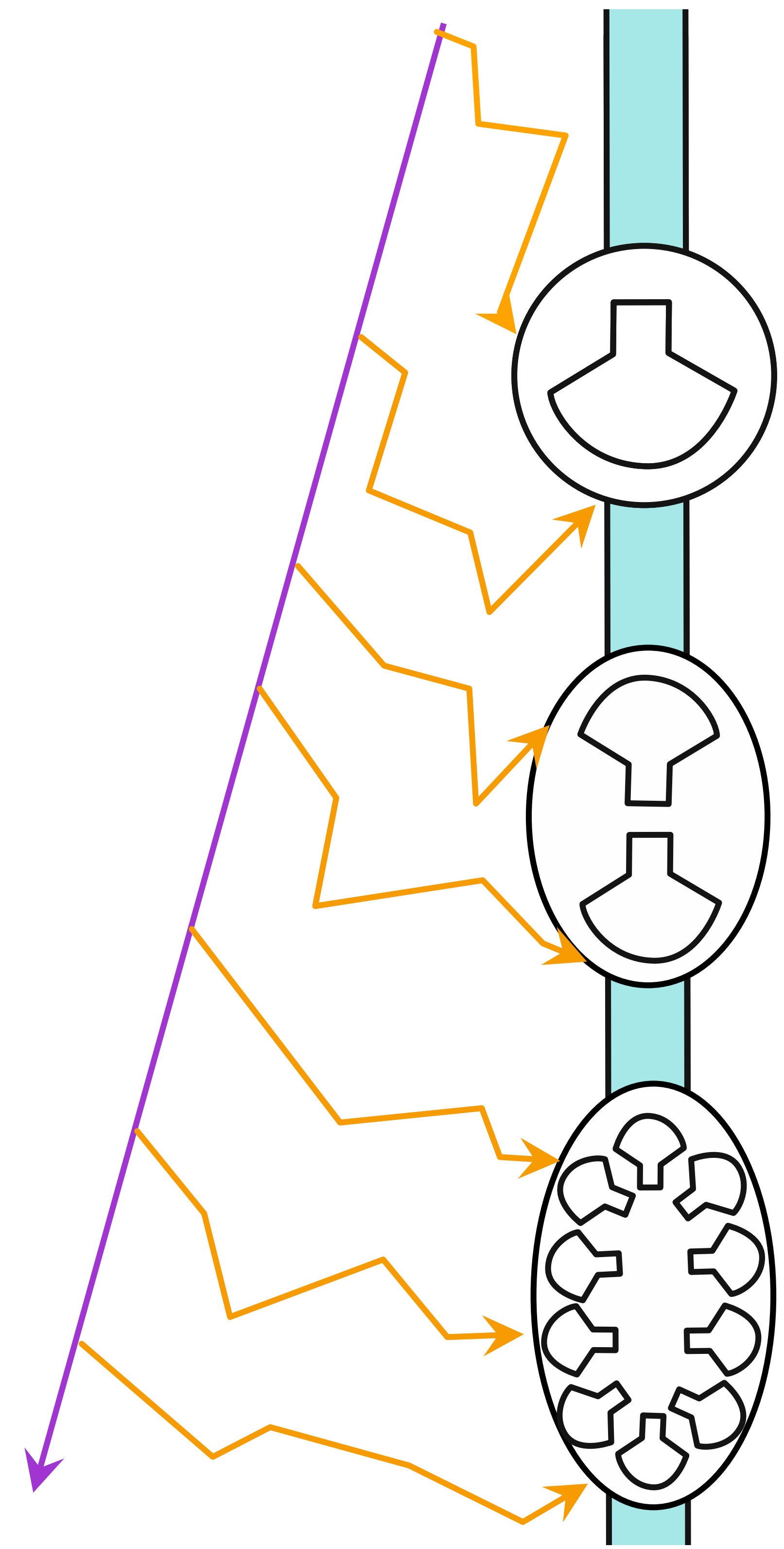
2021 Photon Propagator Workshop

Photon propagation in the Upgrade and beyond

How do we track photons at the last feet

- Gen2 will have several types of OM
- New OM designs are not finalized yet, and using full-simulation for conceptual design and performance research will be too heavy.
- Required features for simulation
    - Simple structure which even beginners of Geant4 can be easily implement
    - Allow simultaneous development : different OMs can be implemented in parallel

I upgraded DOMINANT for this study
https://github.com/icecube/doumeki

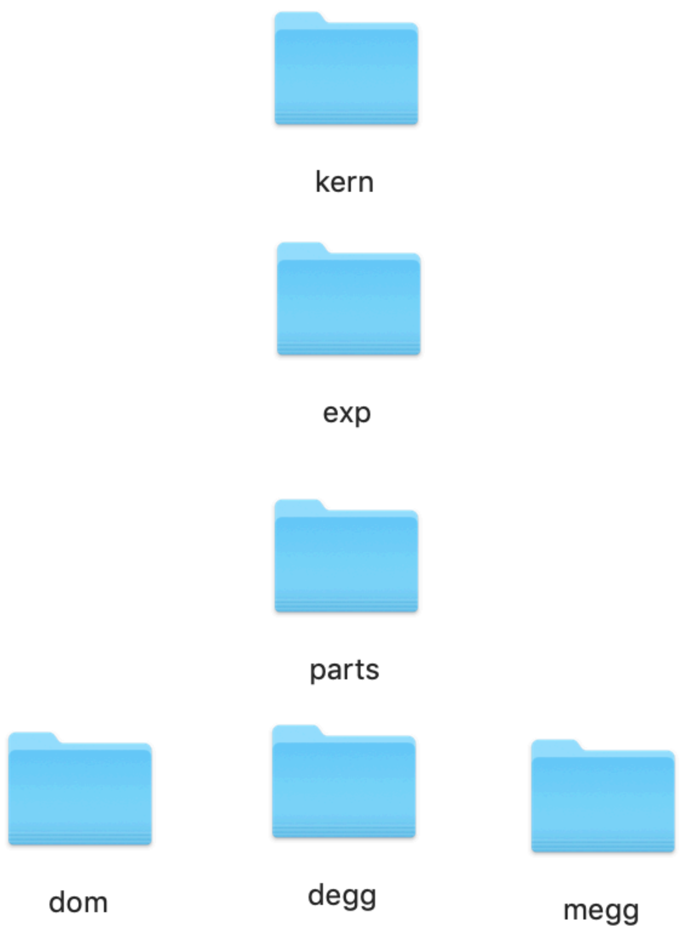


Doumeki vs Full ray-trace

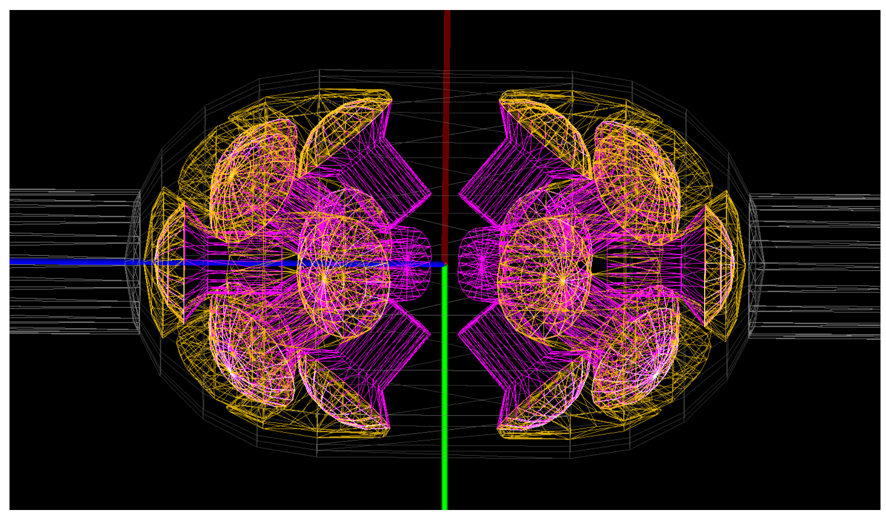
Doumeki v1	⟷	Full ray-trace with IceTray
averaged	accuracy	photon-by-photon
quick	speed	not bad with ppc?
easy	Coding for new geom	?
flexible	flexibility	?
May not be used for near light source? (assuming parallel beam) may be improved with v2	Limitation	Earning statistics could be difficult?

Dominant is upgraded to DOUMEKI

- Digitized Optical Unit Module Emulation KIt
  (Doumeki is a Japanese traditional monster that has 100 eyes)



All reusable parts are now in "parts" dir

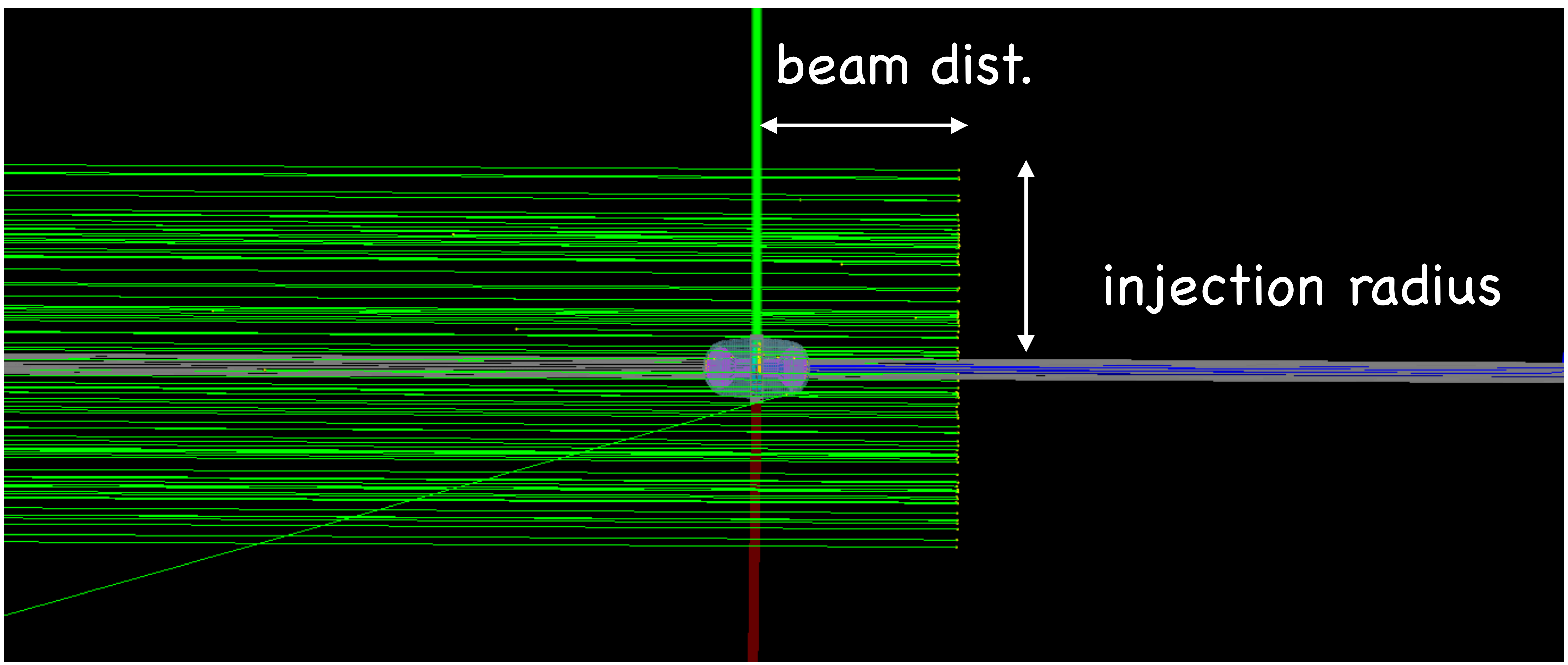


J4LOM18.cc
J4LOM18Gel.cc
J4LOM18GelHit.cc
J4LOM18GelSD.cc
J4LOM18Inside.cc
J4LOM18ParameterList.cc

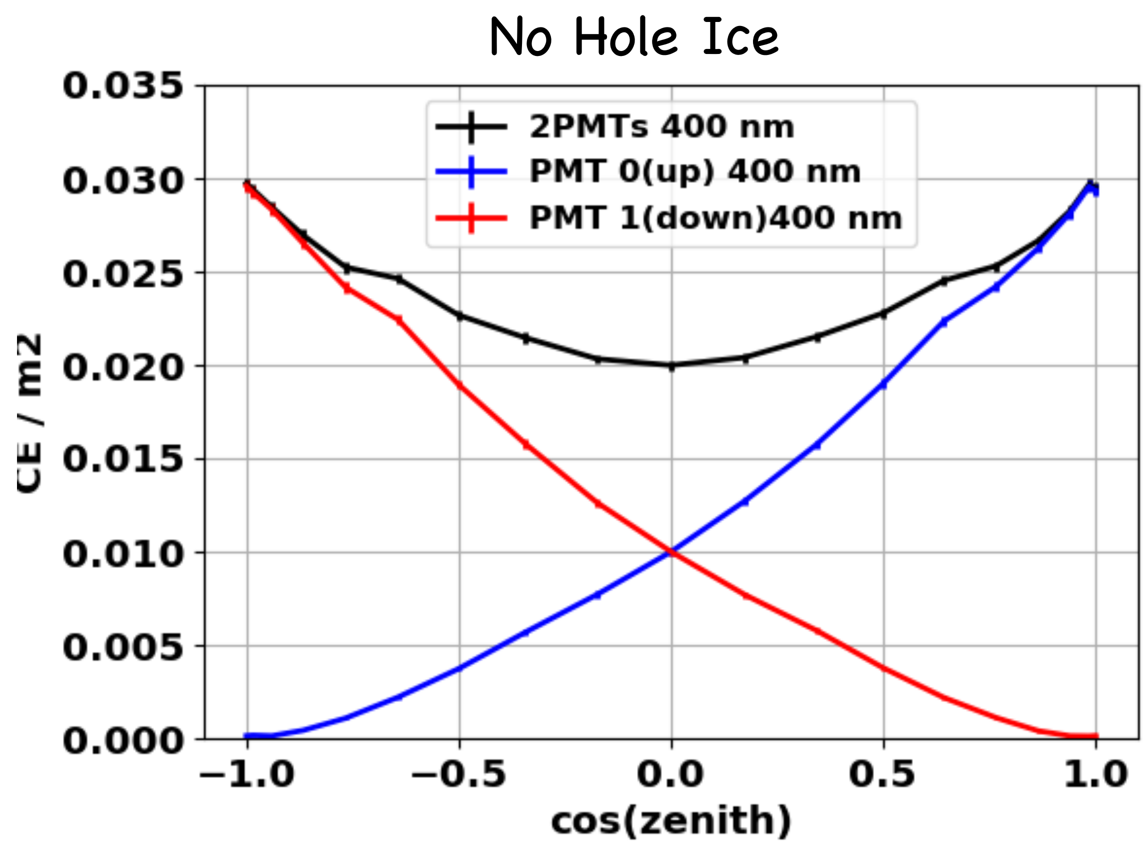
Only 6 files are needed to compose LOM18

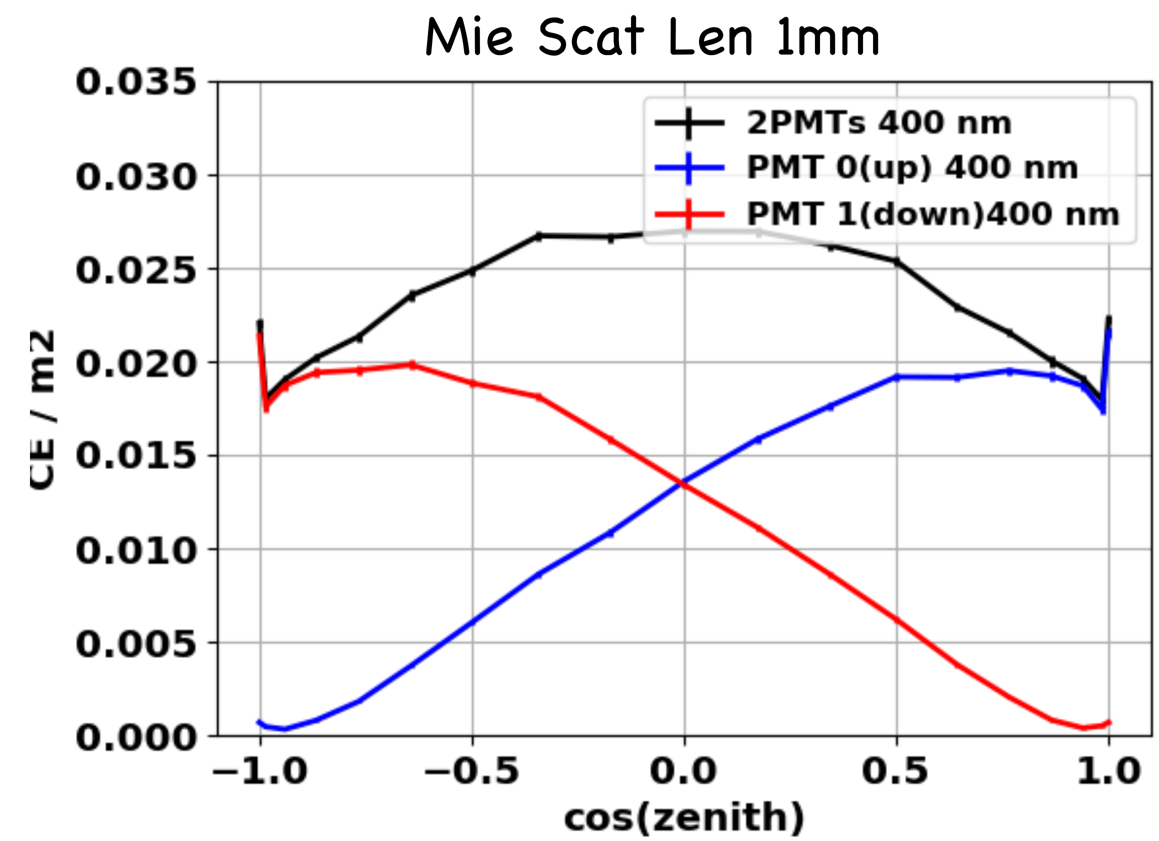
What we can do with Dominant / Doumeki

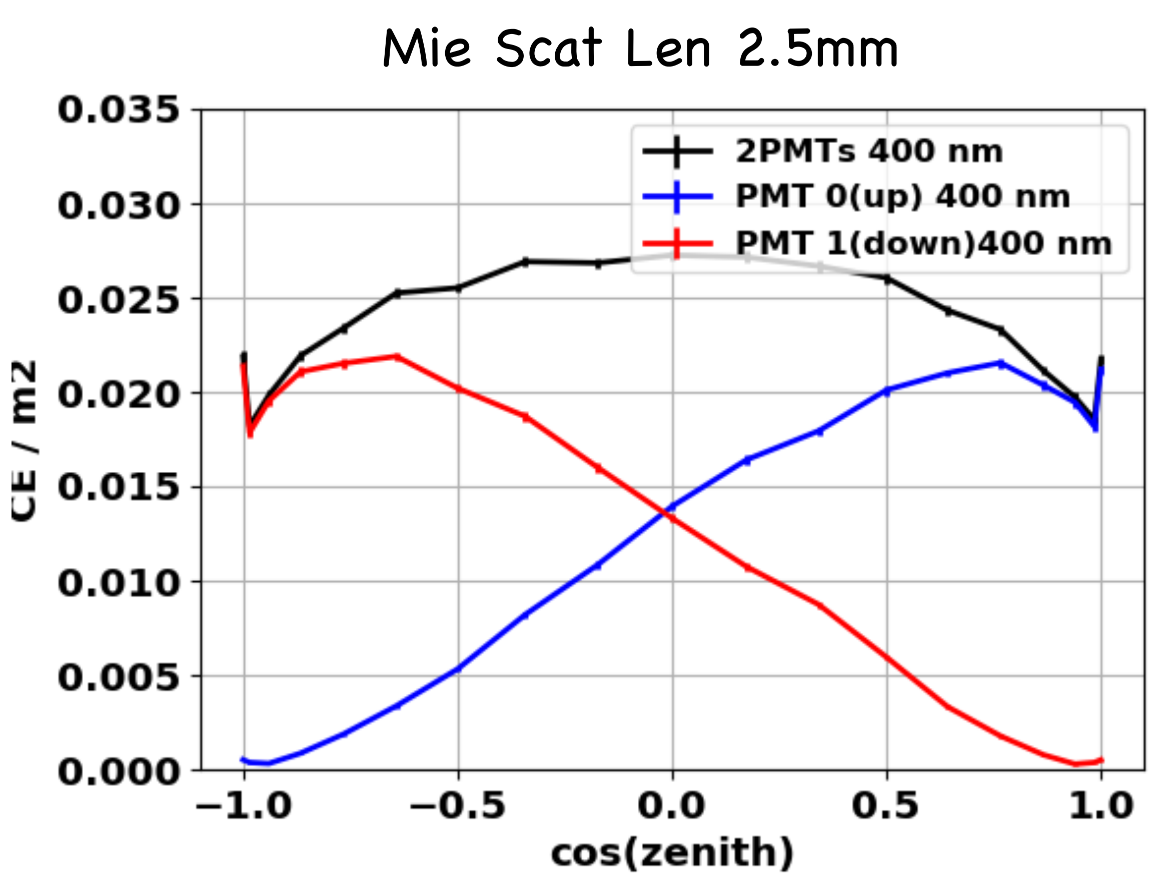
- Changing HoleIce scattering (geometrical scattering length) :
- Changing beam distance and beam shape (spherical beam will be installed soon at the request from Lu)
- acceptance [m^{-2}] = n_survived / (n_injected_per_1m^2)
  = n_survived / (n_injected / injection_section)

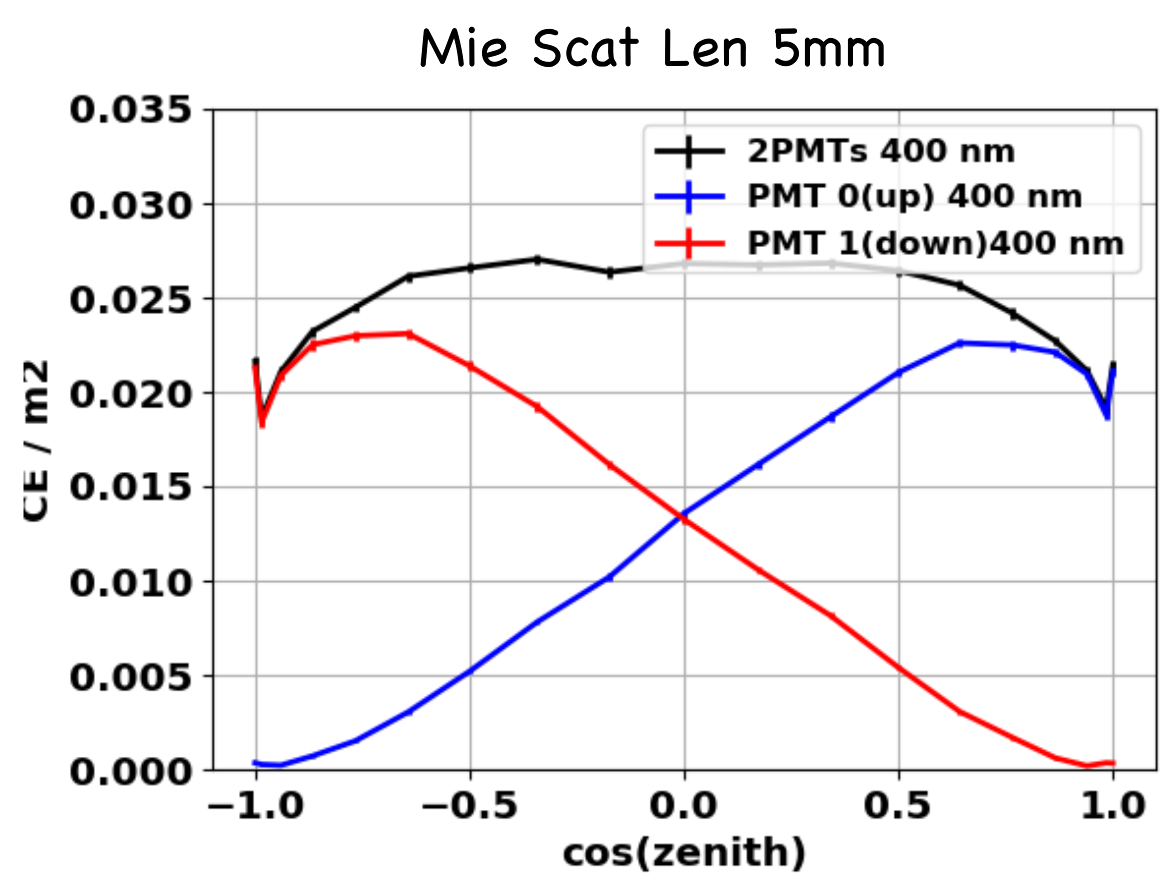


Scattering Length HoleIce radius 6cm, injection radius 1m, beam dist. 1m

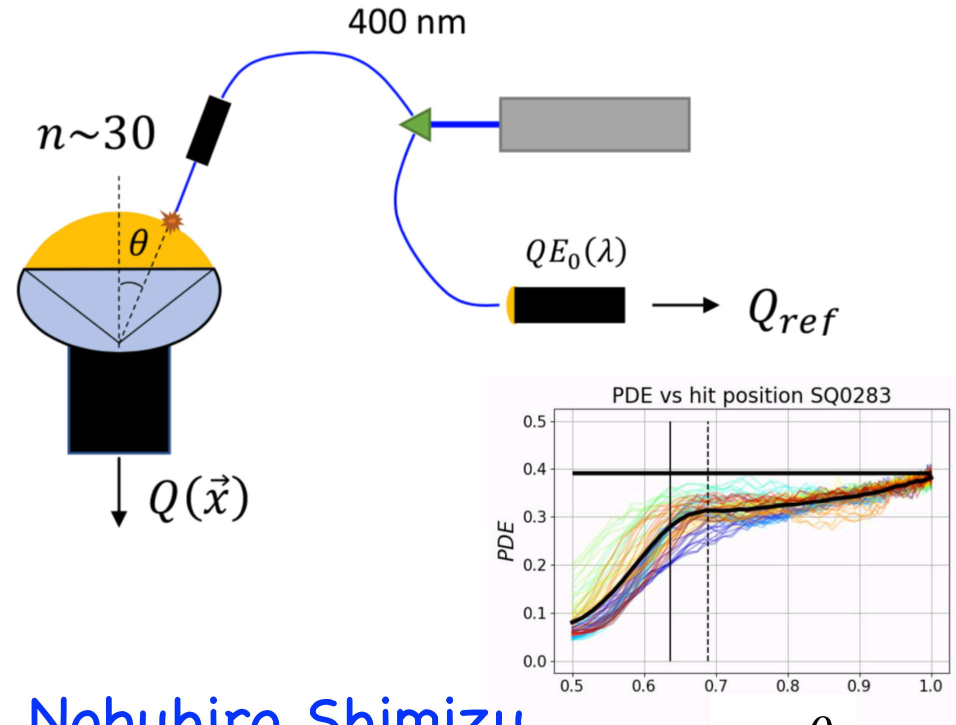




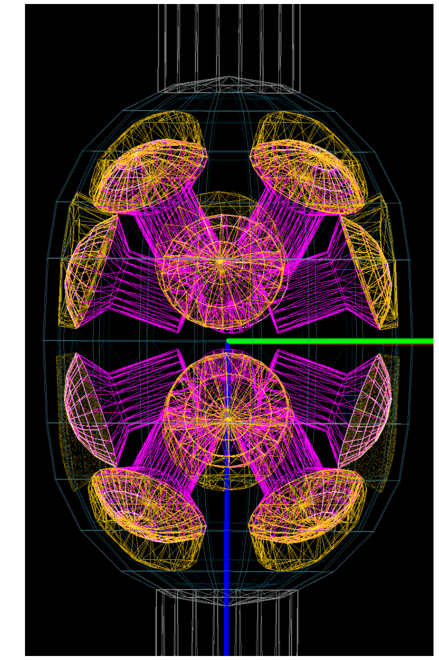




Activities around Dominant/ Doumeki



Nobuhiro Shimizu and Martin Unland works for PMT performance measurement and establishing acceptance curve for bare PMT



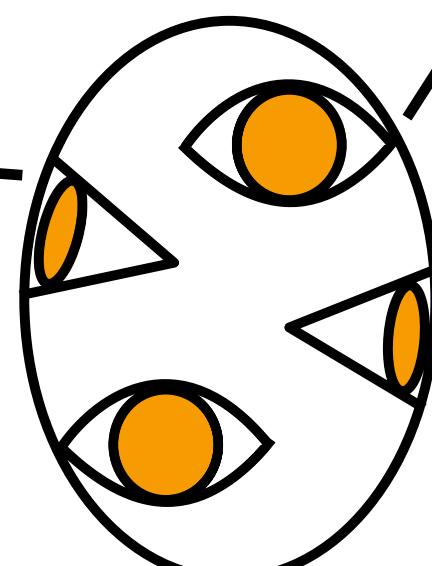
Delaney Butterfield Implemented LOM16 basic structure

Samuel Benda will use it to optimize PMT alignment

(c) D-Egg

(e) LOM−18

Chiba group and Nobuhiro Shimizu implemented basic structure of LOM18

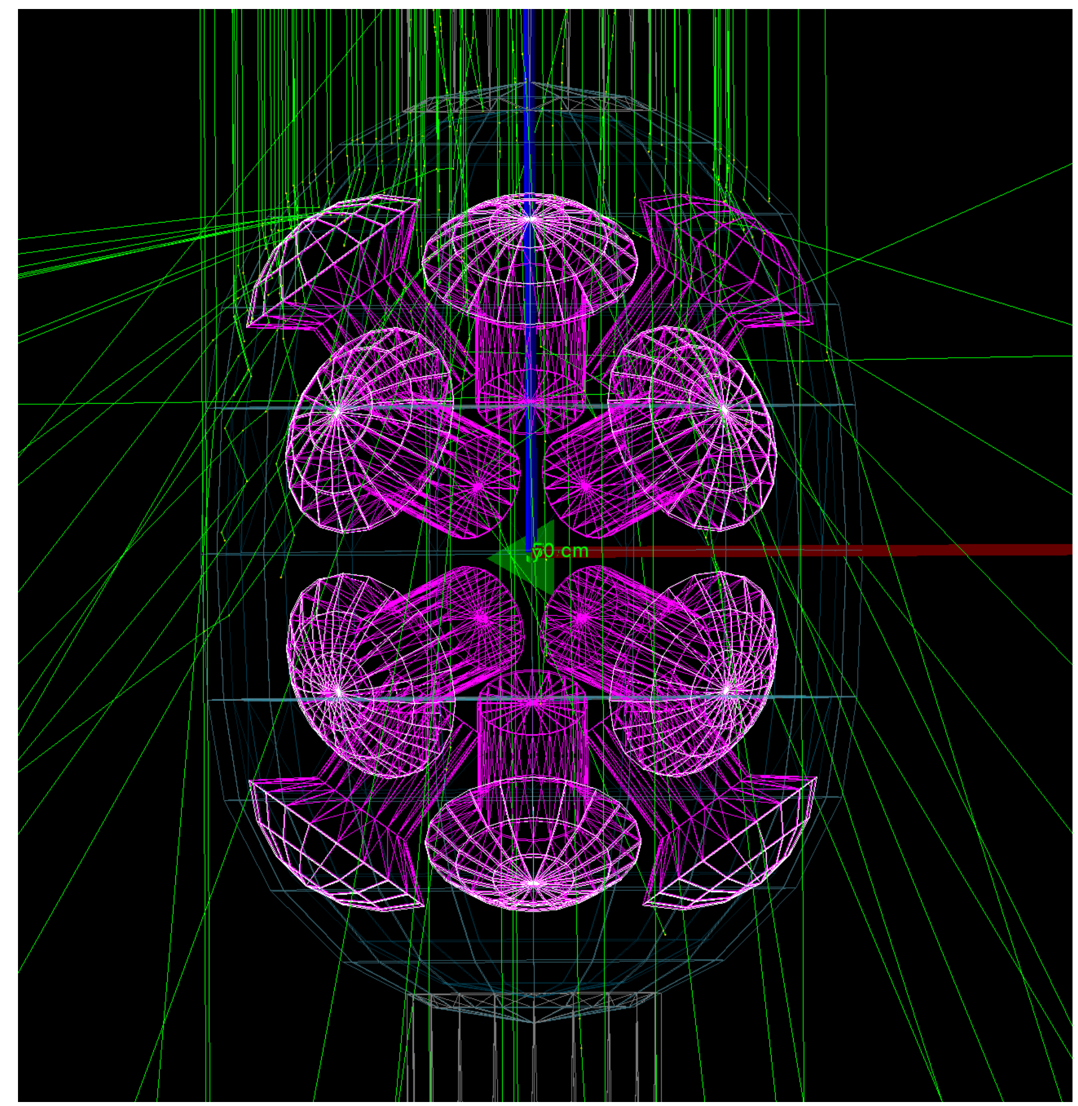


DOUMEKI

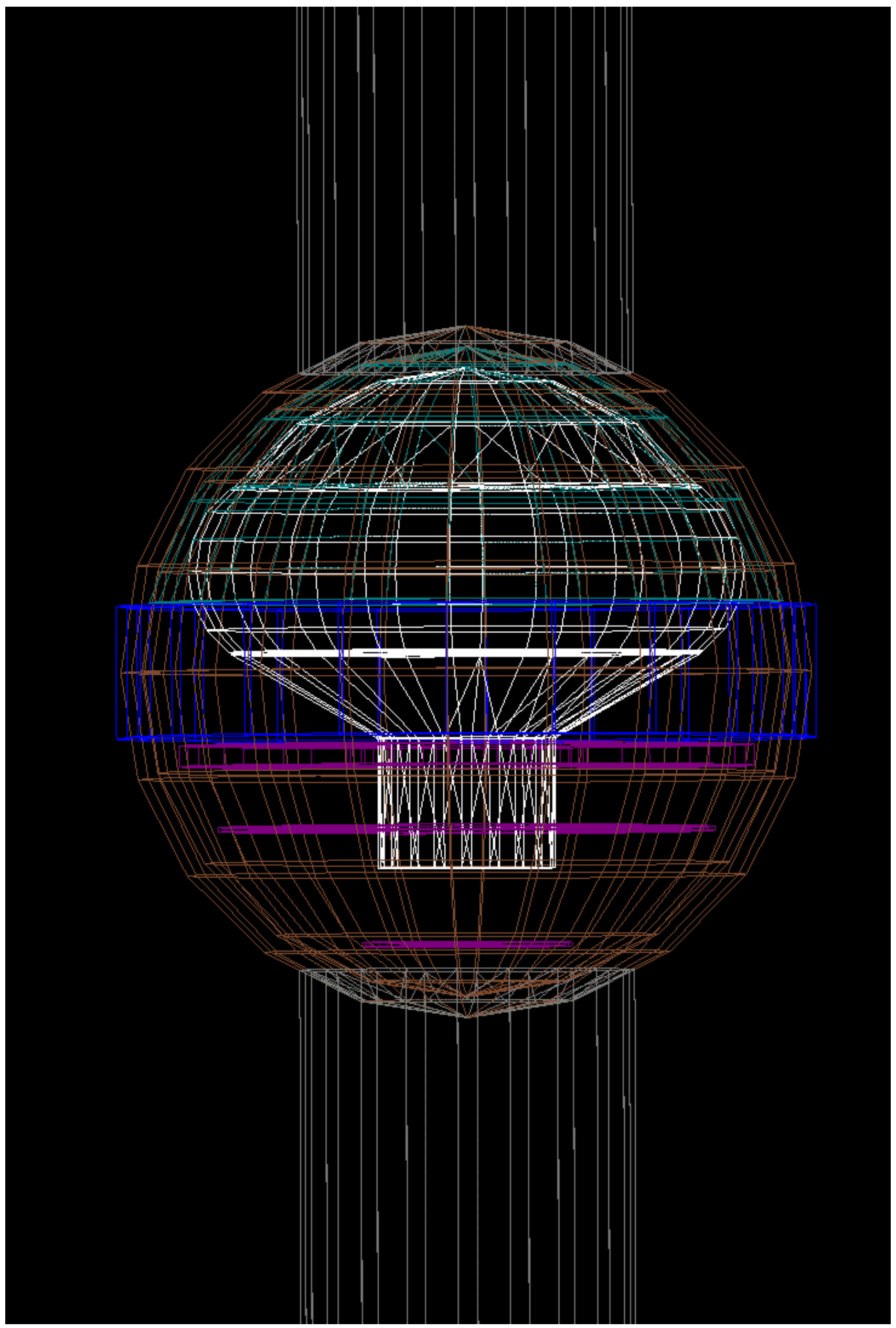
Martin Unland provided M-DOM implementation of Geant4, Kotoyo will try to port the geometry to DOUMEKI

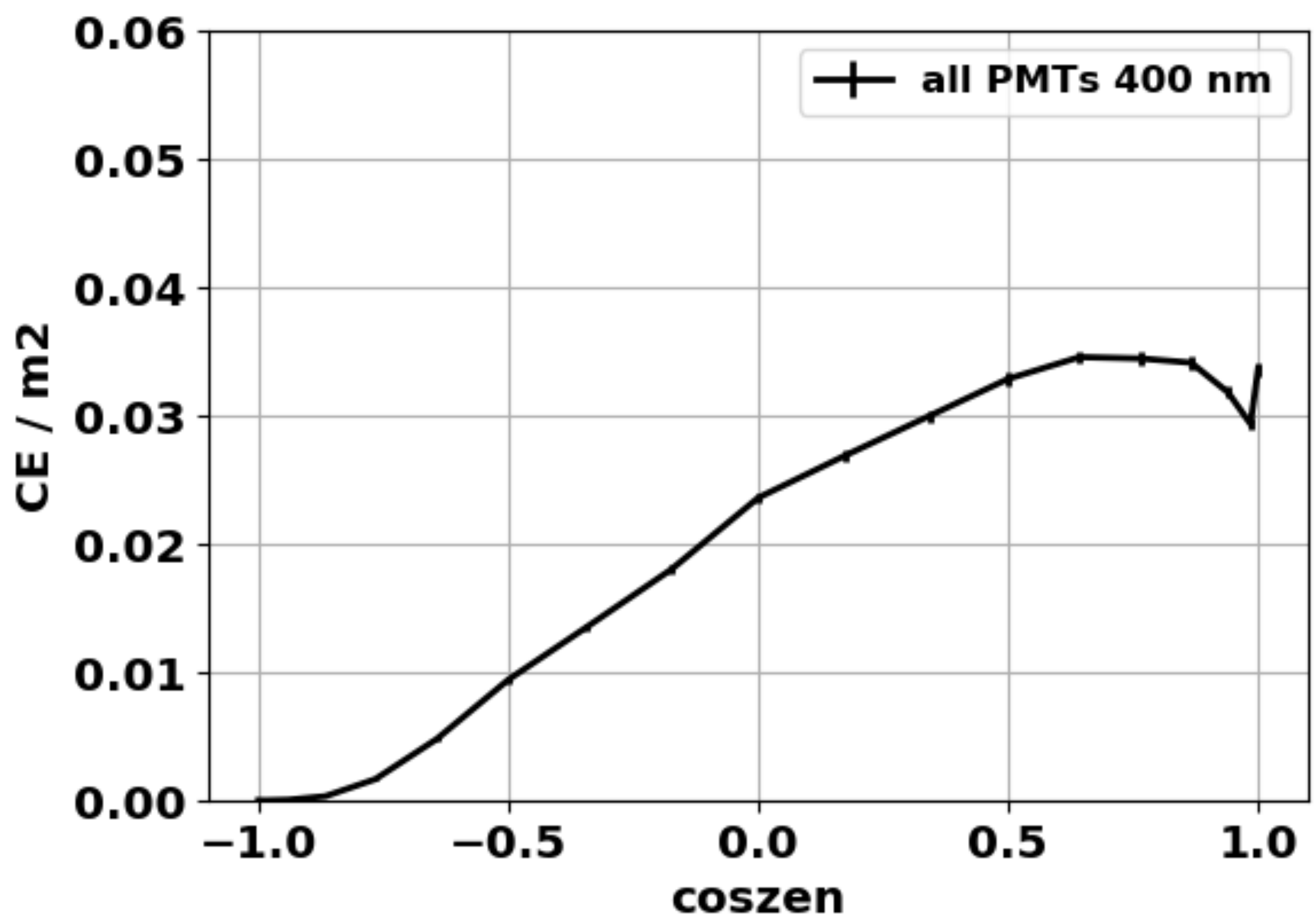
Getting OM Acceptance Table

- Parallel photon beam is assumed
  - Injected every 10 degrees in zeniths and azimuths
- In total 361 angles (19x19) are tested
  - Today I show "azimuth averaged" plots for comparison
  - A brute force solution is just use the 361 tables for production
  - each table contains photon acceptance info for each PMT

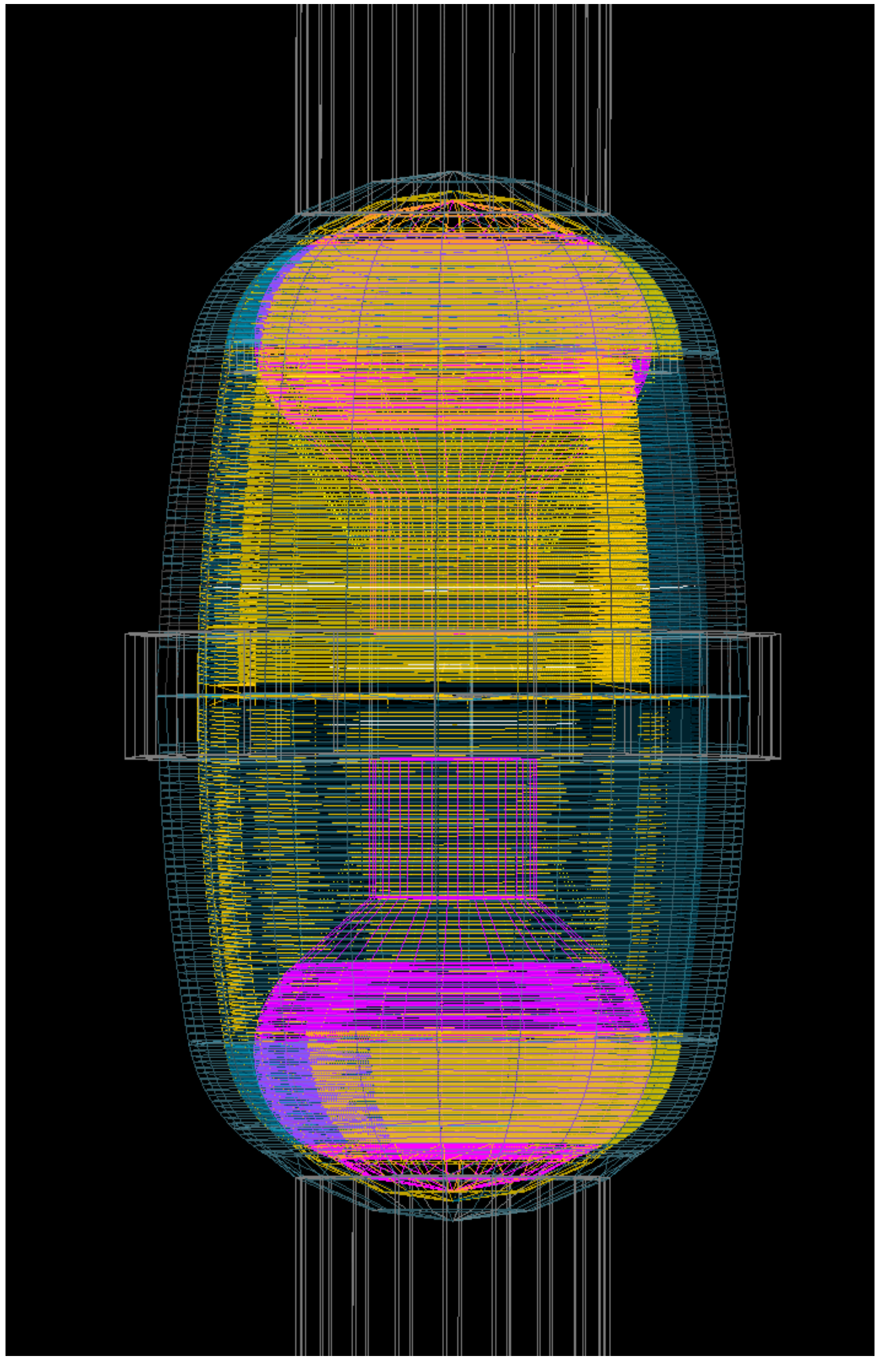


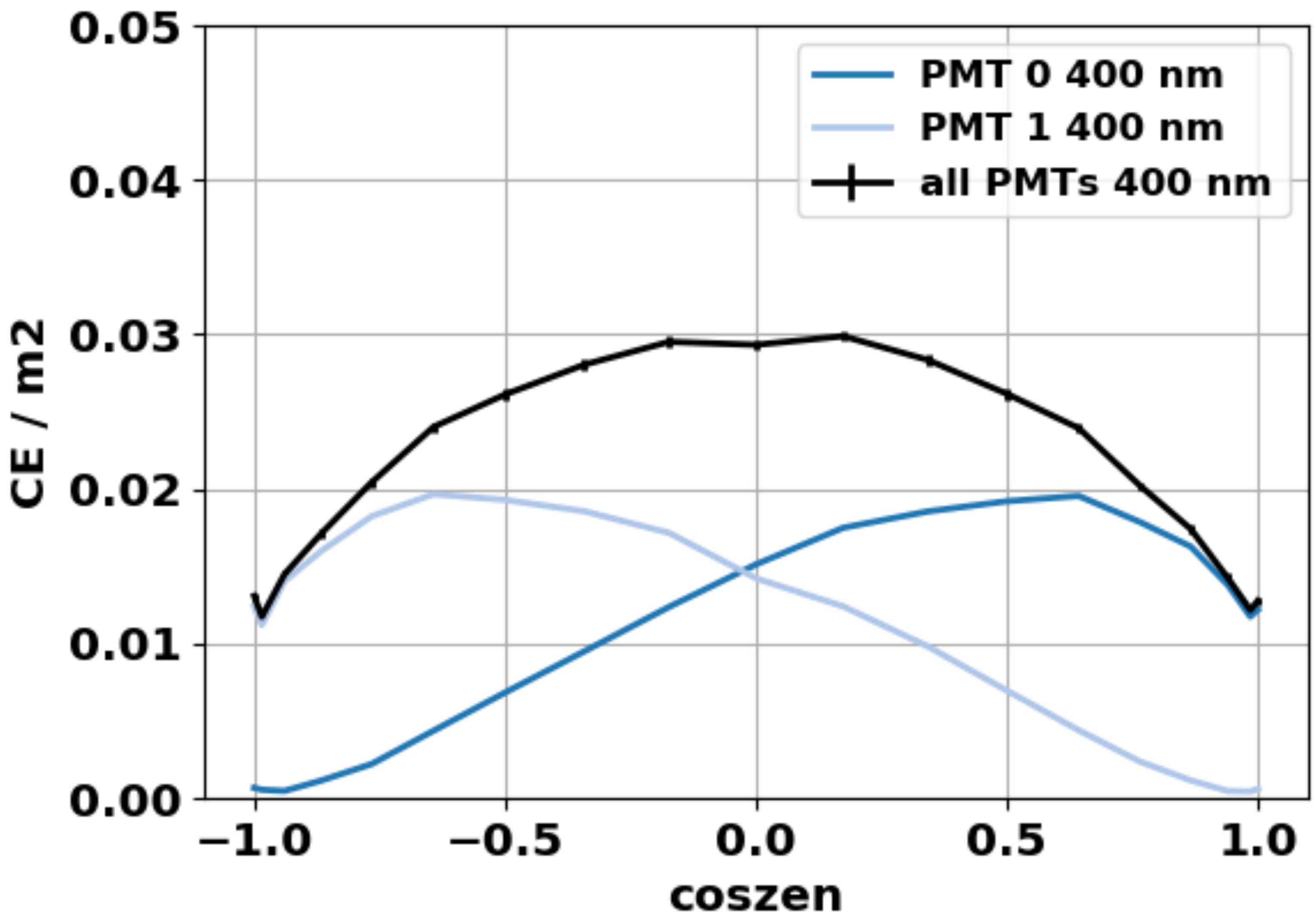
DOM Photon Acceptance Table (azimuth averaged) HoleIce geometrical scattering. length 3mm, HoleIce diameter 16cm



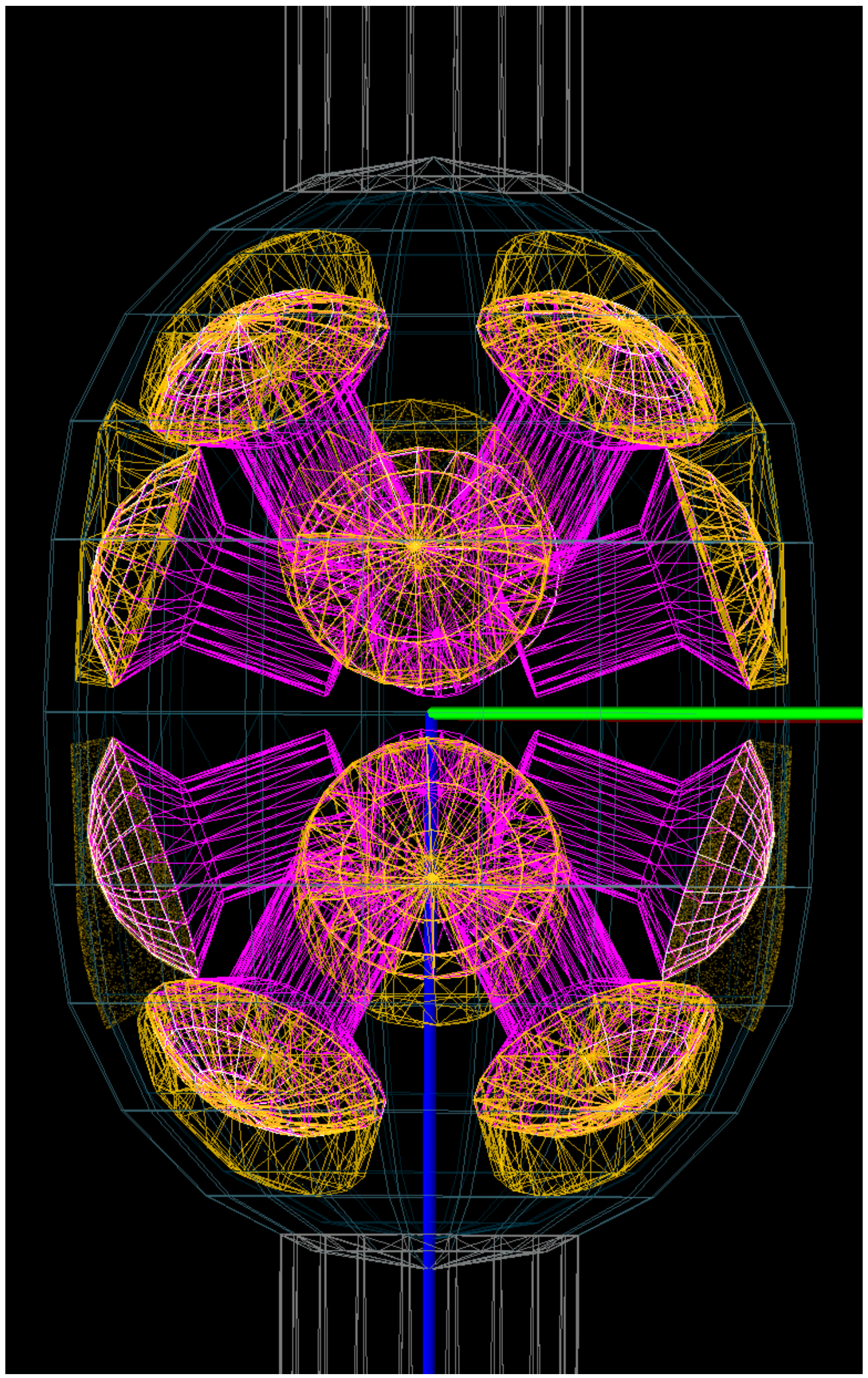


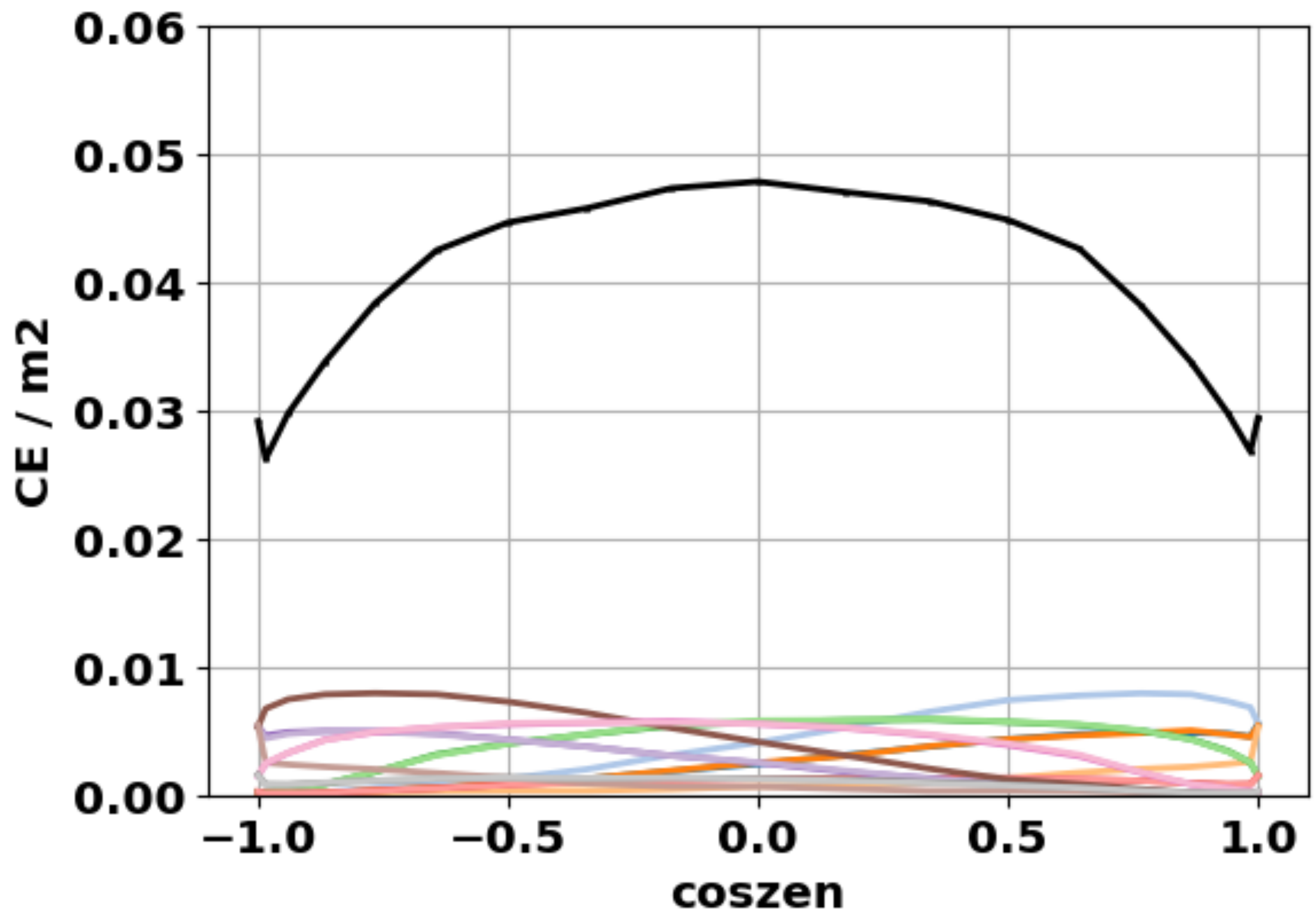
DEgg Photon Acceptance Table (azimuth averaged) HoleIce geometrical scattering. length 3mm, HoleIce diameter 16cm



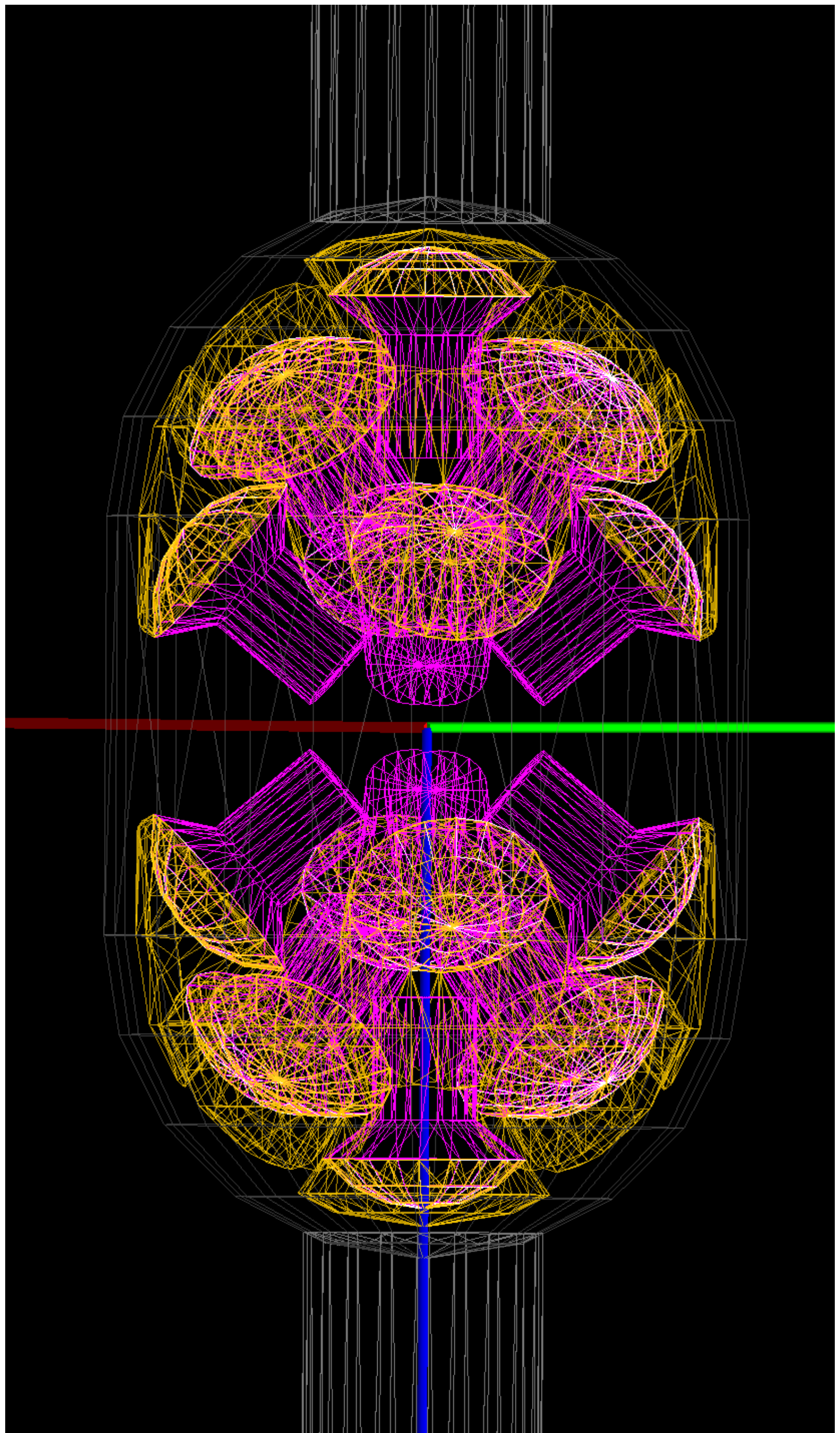


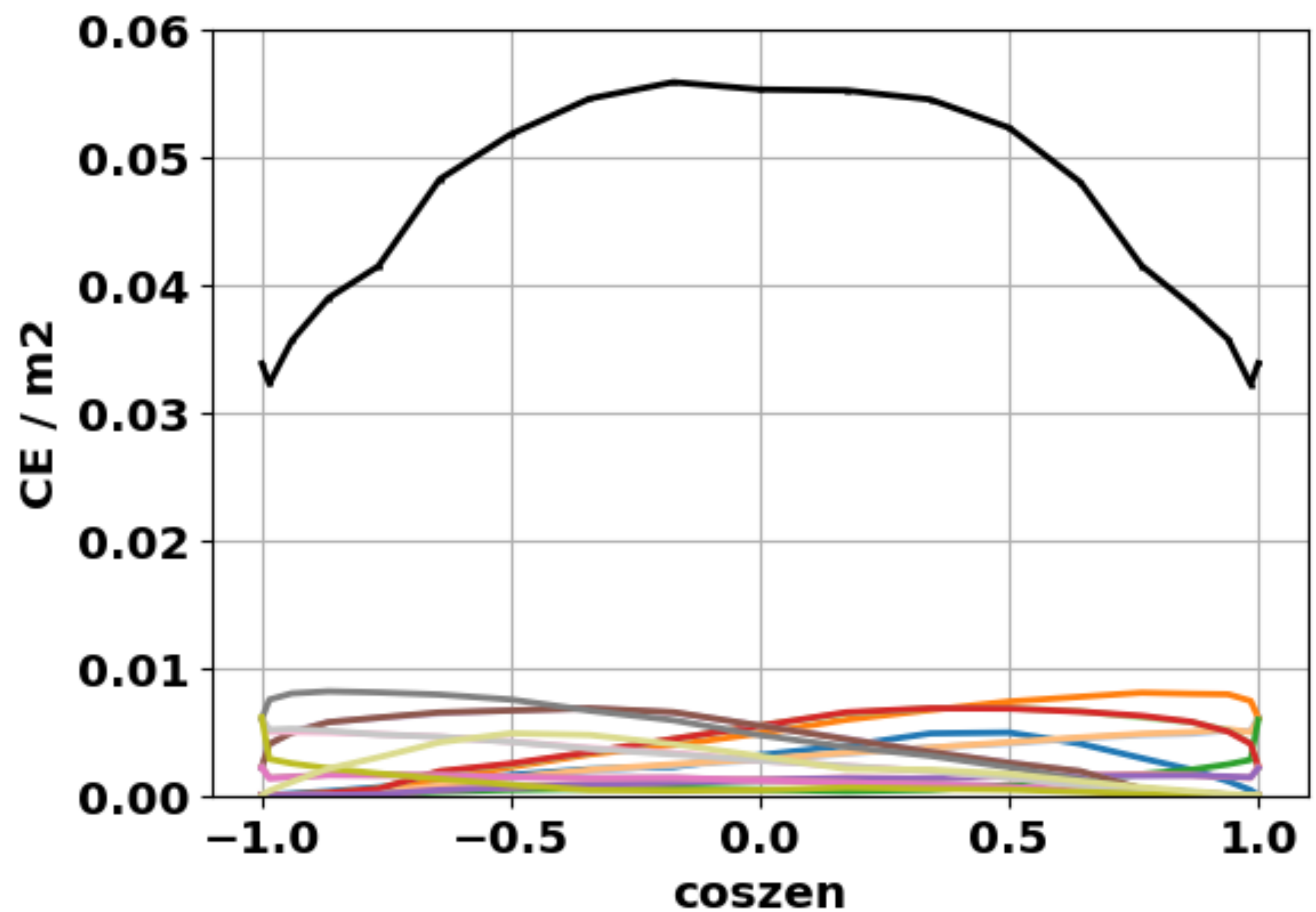
LOM16 Photon Acceptance Table (azimuth averaged) HoleIce geometrical scattering. length 3mm, HoleIce diameter 16cm



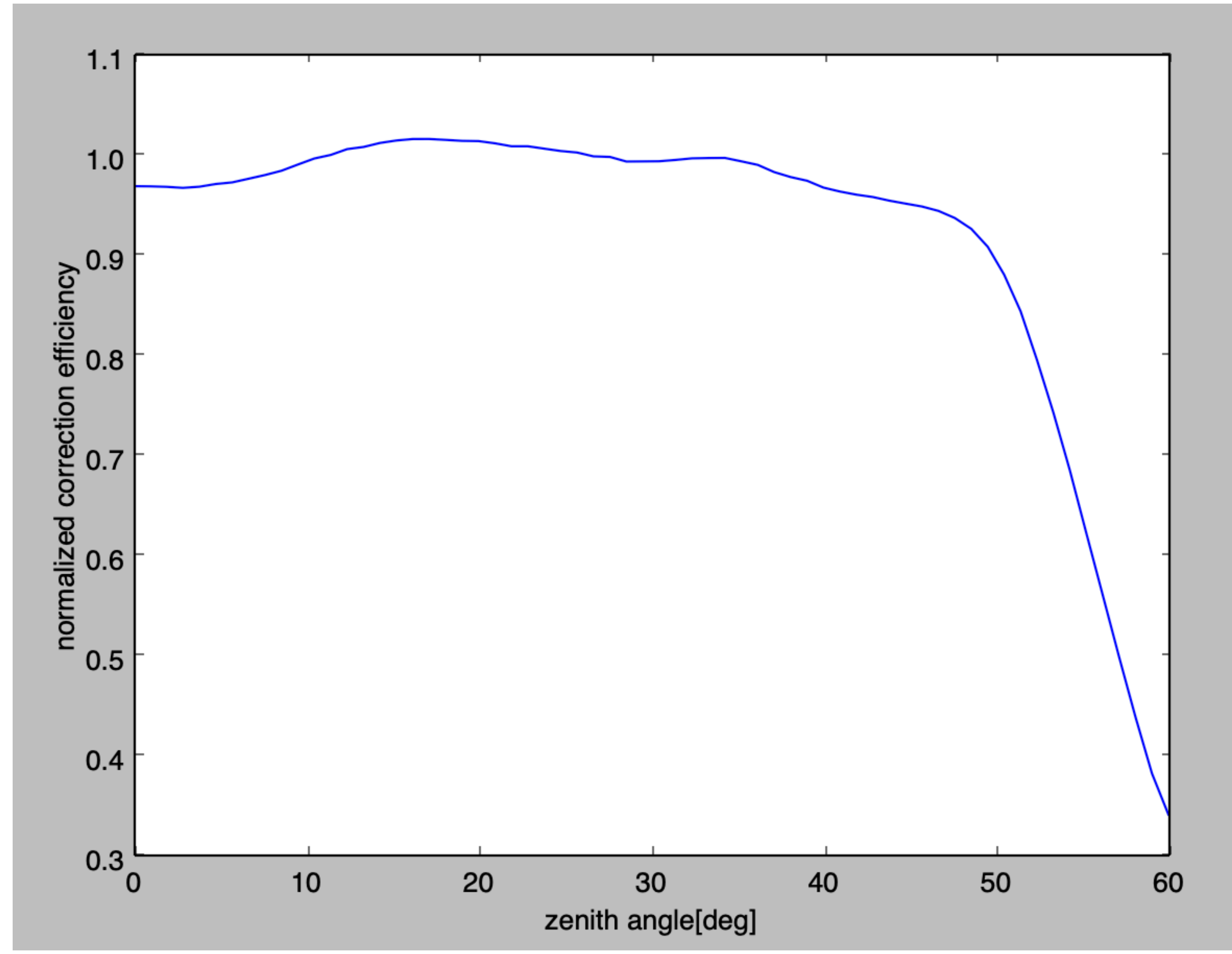


LOM18 Photon Acceptance Table (azimuth averaged) Holelce geometrical scattering. length 3mm, Holelce diameter 16cm

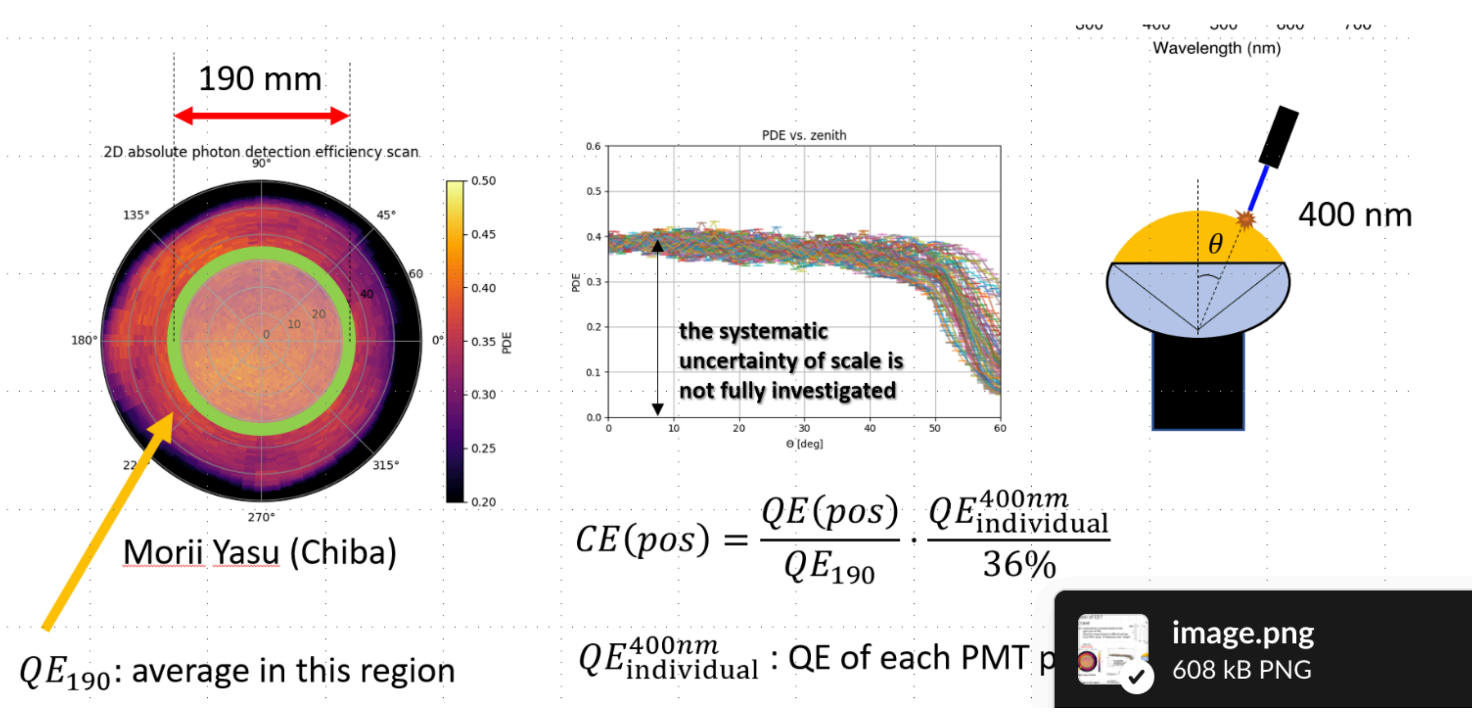




Looks fantastic, but don’t forget to take into account of CE!



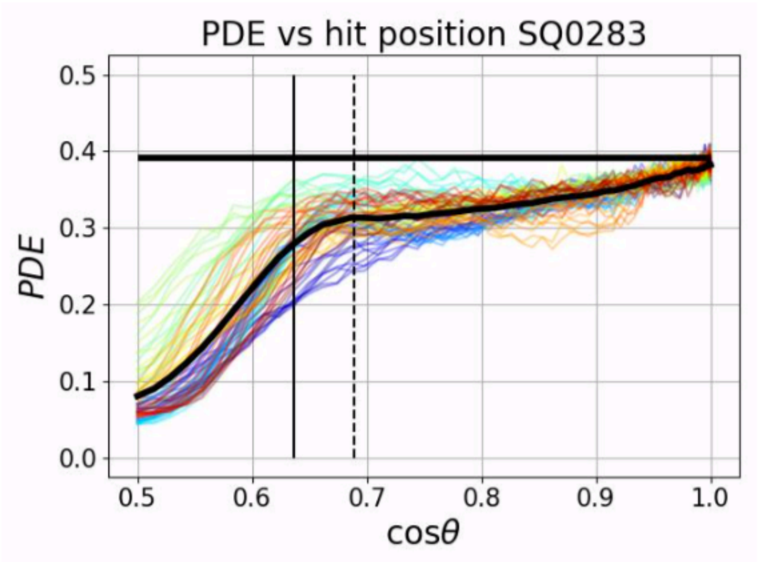
- 2D Collection Efficiency Map is measured by Nobuhiro S. and Martin U.
- At the edge of PMT Cathode collection efficiency drops significantly
- Adding more PMTs result in increase of the inefficient area.
- Gain, Charge resolution may drop at the edge of PMTs

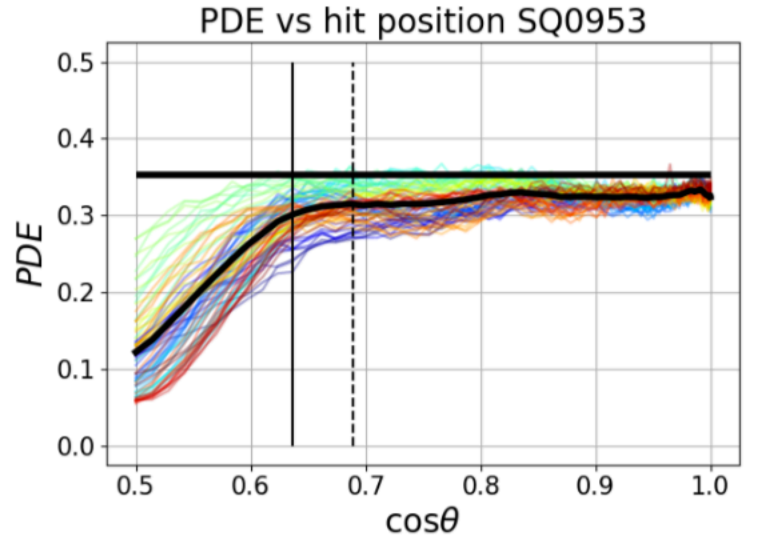


Motivation to extract $DE(\lambda, \vec{x}; q_{th})$ from experiment

DE: Detection Efficiency
λ: wavelength
x: photon's hit position on cathode
q_{th} : threshold of charge response

Chiba has a θ-ϕ scan setup and measured "photo detection efficiency"





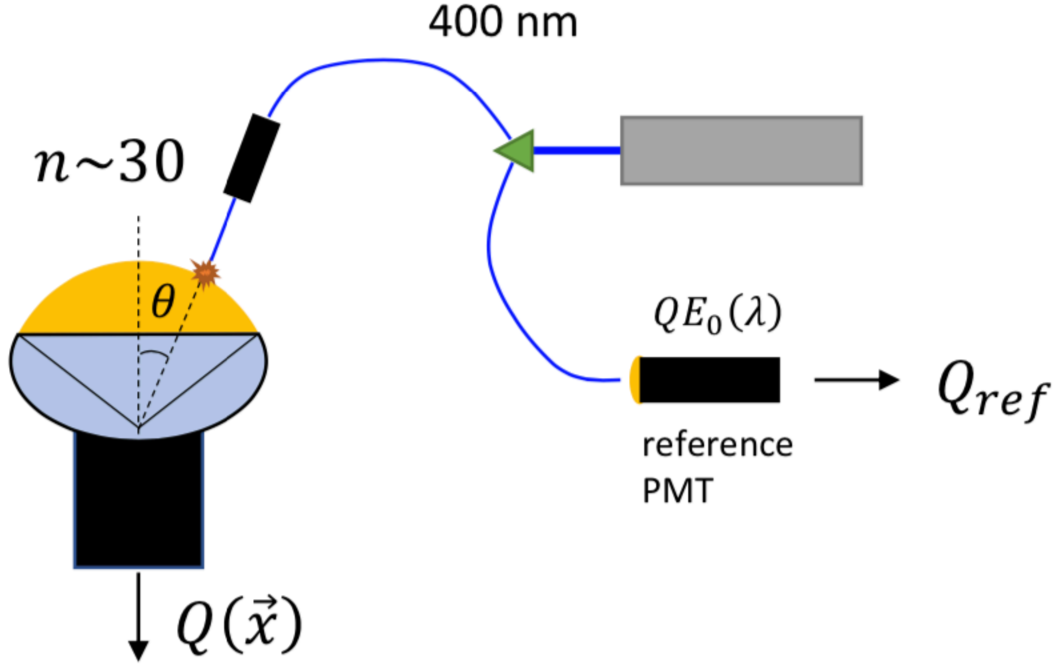


Photo detection efficiency is experimentally obtained as

$$\text{"}PDE\text{"}(\vec{x}) = \frac{Q(\vec{x})/G(\vec{0})}{Q_{ref}/G_{ref}} \cdot QE_0(\lambda)$$

○ given by Hamamatsu data sheet

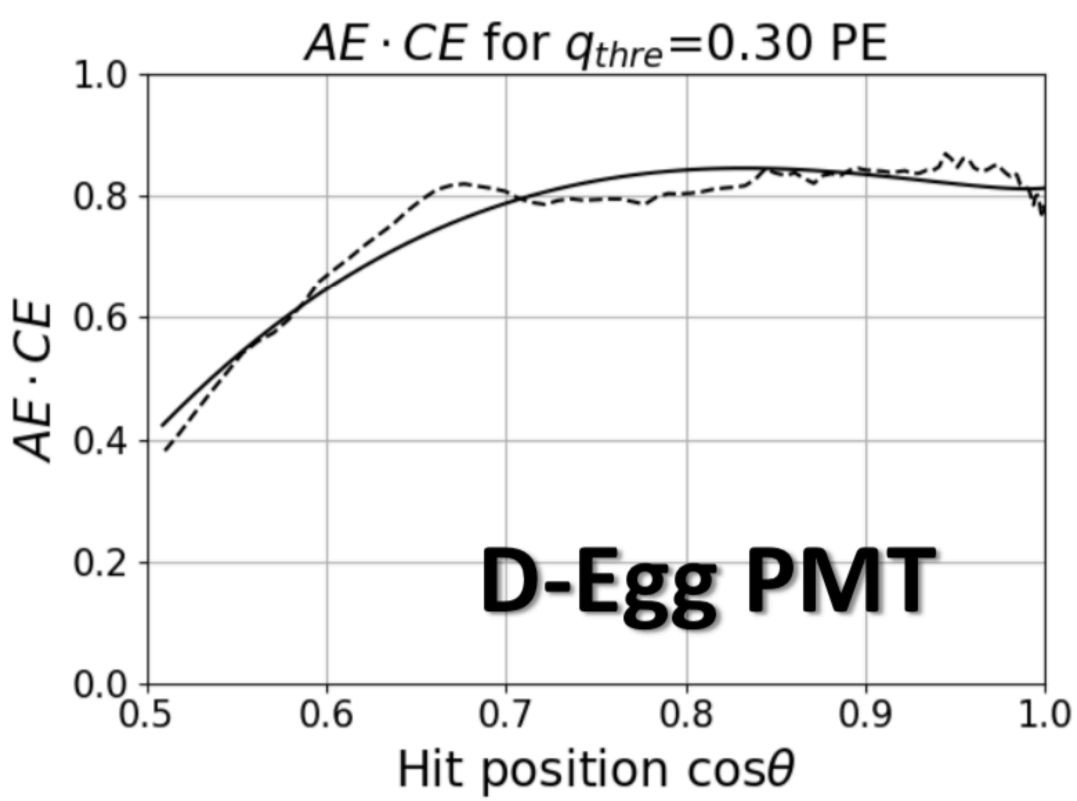
G is a gain of PMT and $\vec{0}$ means its center.

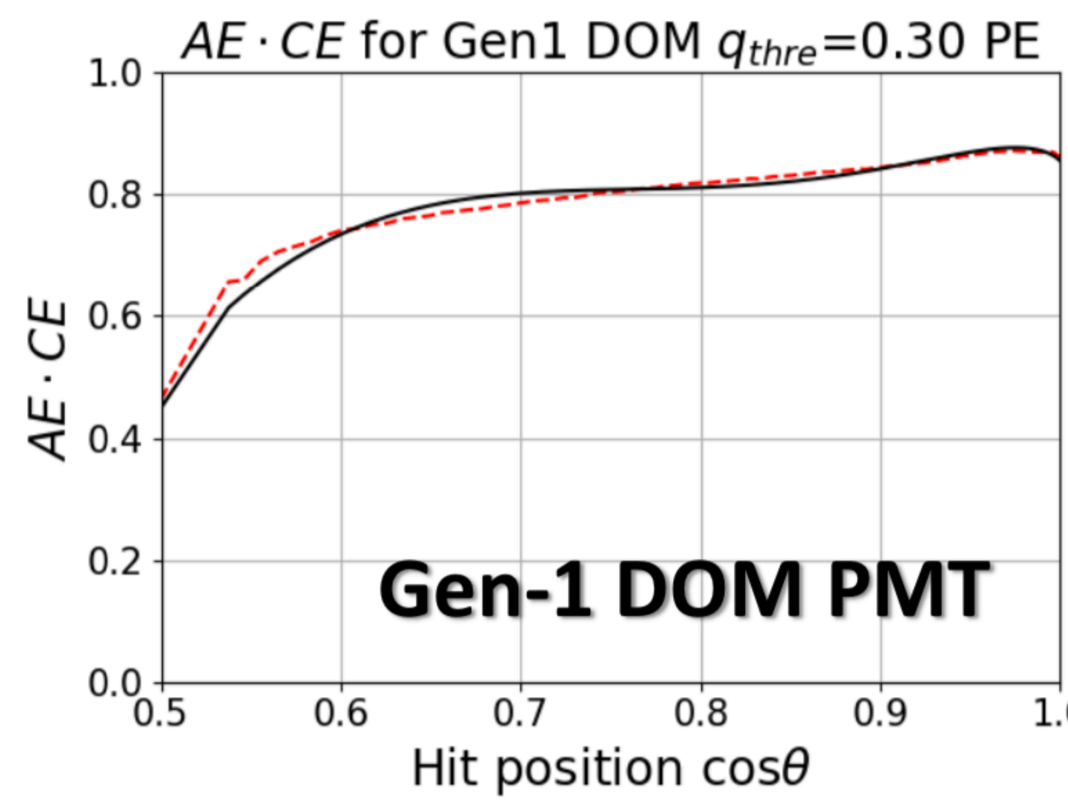
The position dependence changes depending on the PMT.

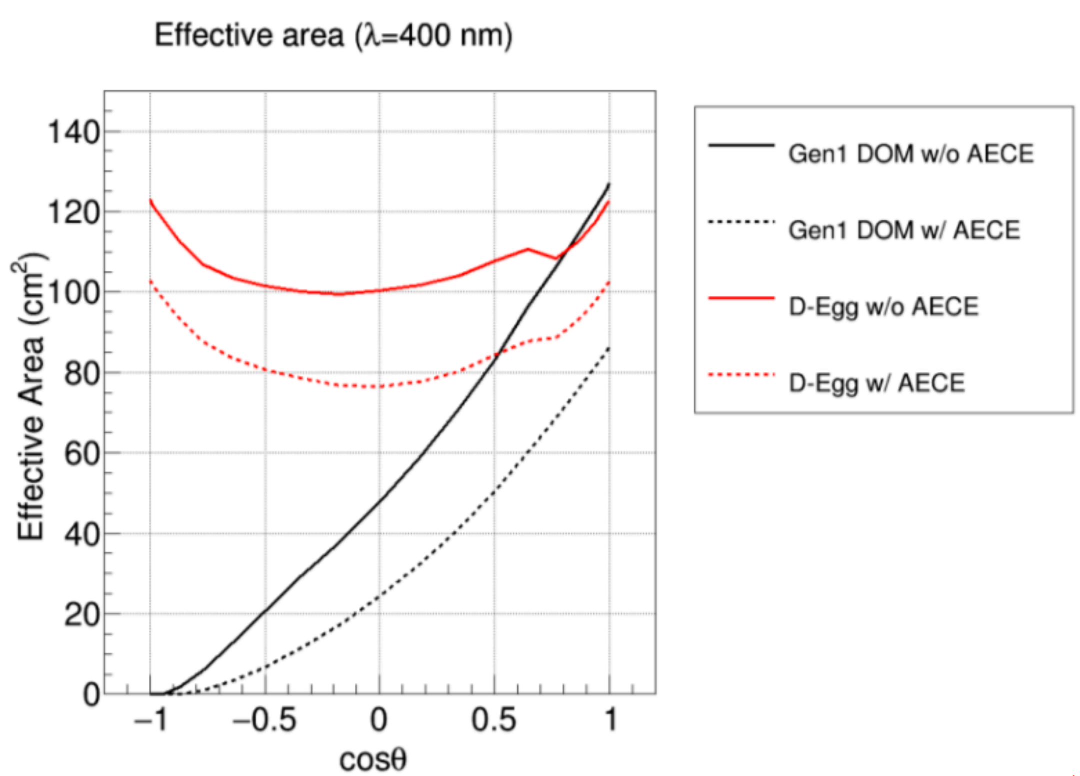
This PDE will be reinvestigated.

Nobuhiro Shimizu, calibration call 9/10/2021

Comparison of OMs







OM	Effective area average (cm2)
Gen1 DOM w/o AE·CE	52.8
Gen1 DOM w/ AE·CE	30.3
D-Egg w/o AE·CE	105.8
D-Egg w/ AE·CE	84.2

x 2.8

Nobuhiro Shimizu, calibration call 9/10/2021

Summary

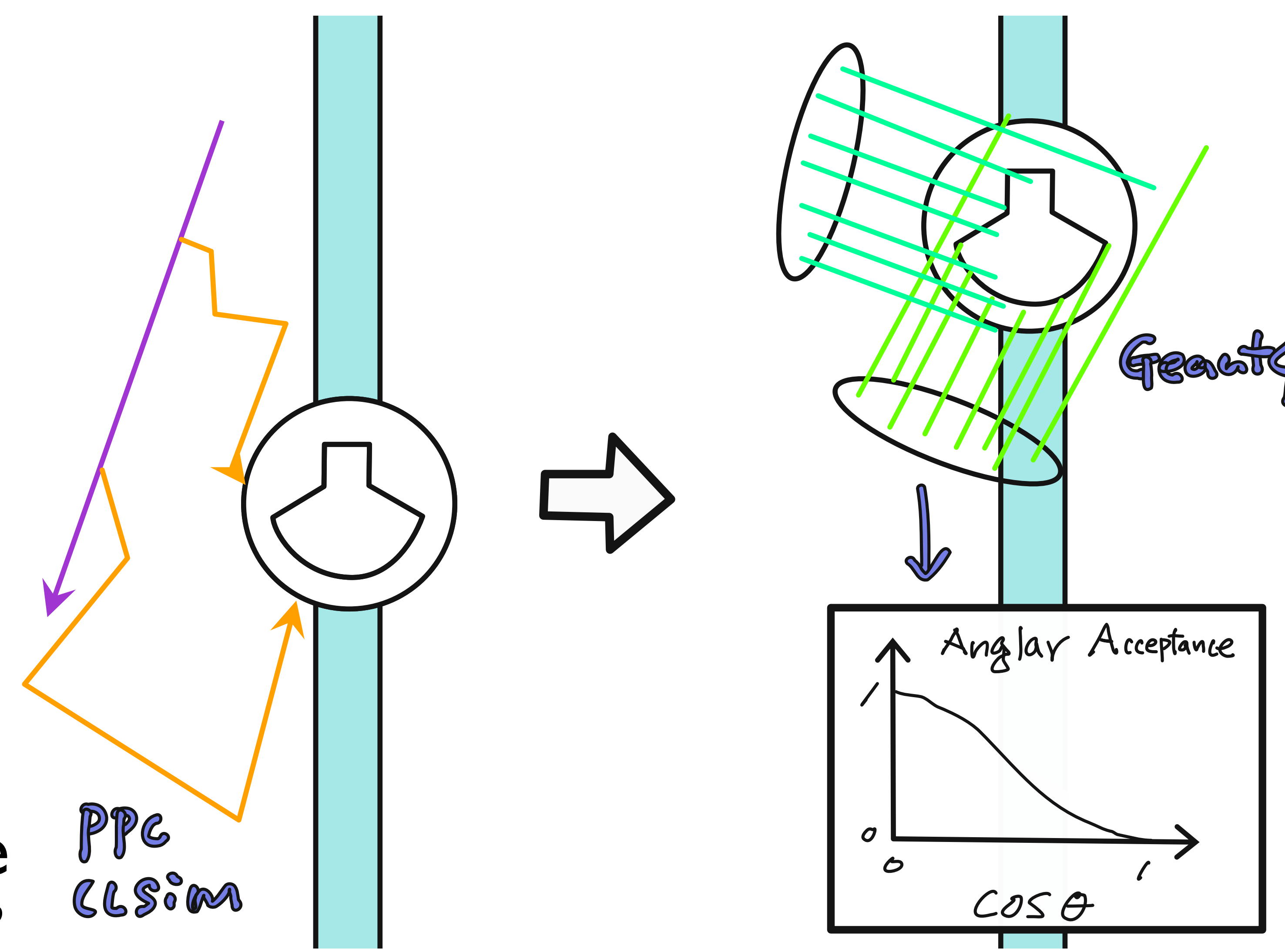
- Dominant is upgraded to DOUMEKI to implement new optical sensors
    - Old DOMINANT is frozen
    - https://github.com/icecube/doumeki.git
    - DOM, D-Egg, LOM16, LOM18 basic designs are implemented, mDOM will be added soon
    - Primary usage of DOUMEKI is optimizing new OM design
    - Zenith-azimuth dependent acceptance tables can be generated, but assumes parallel photon beam
- Detection efficiency need to be convoluted for a fair comparison. Nobuhiro S. is working for detailed PMT performance measurement and established new PMT acceptance curve.
  See his wiki page
  https://wiki.icecube.wisc.edu/index.php/Modeling_of_Optical_Modules

backup

How did we track photons at the last feet

- Trace photons from track or cascade to near by DOM surface using PPC or CLsim
- How photons are propagated inside DOM and how many photons are actually arrived at PMT's photo-cathode is separately simulated using Geant4 and summarized as an "Angular Acceptance Curve"
- At the IceTray simulation, PPC or CLsim just refers the "Angular Acceptance Curve"

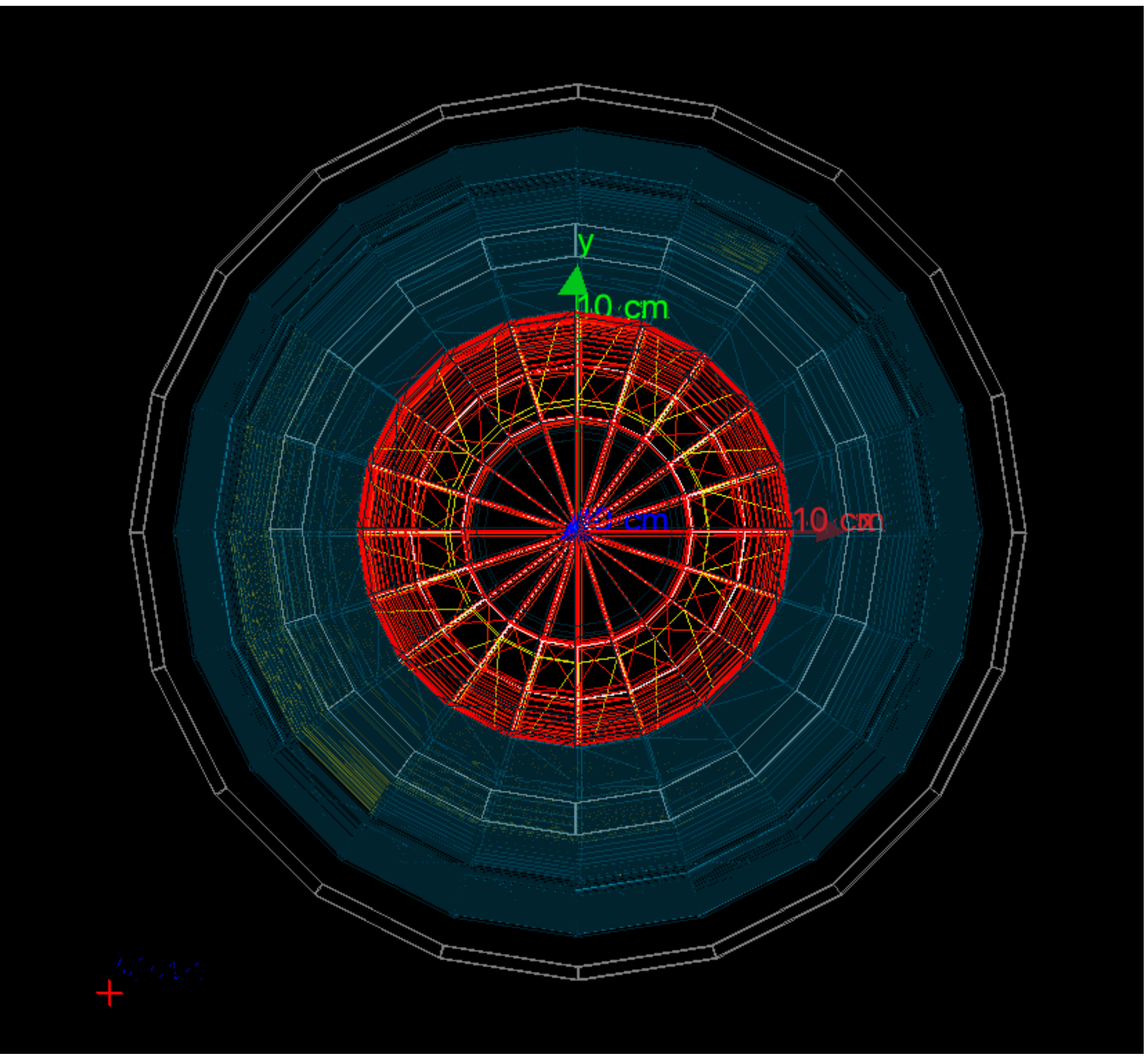
Case : IceCube

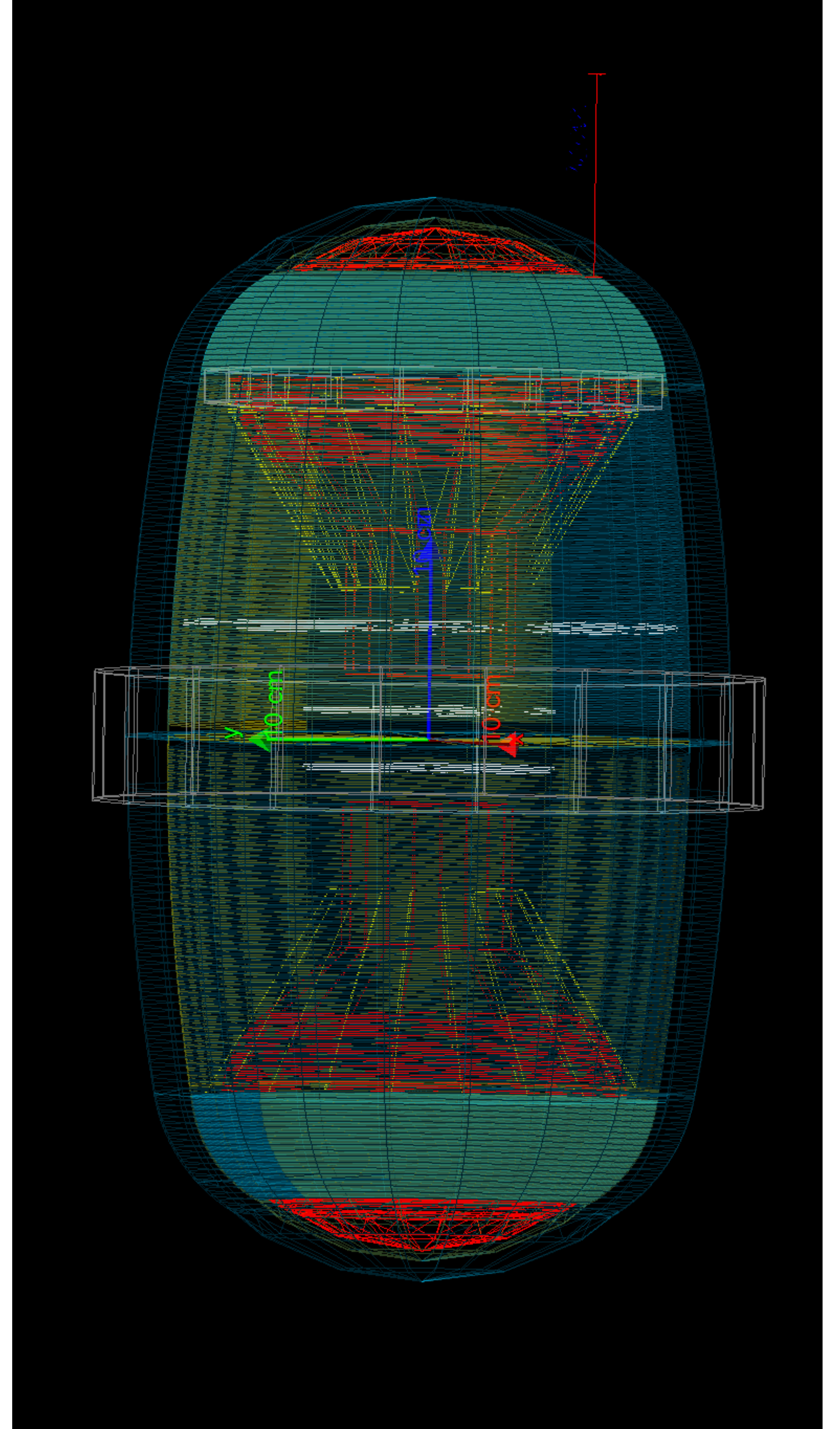


Purposes of the study

- Making angular acceptance table for D-Egg, M-Egg and LOM
  - LOM is not implemented yet
- Studying how systematics parameters affect to angular acceptance
  - PMT
    - Uniformity of collection efficiency
    - Uniformity of gain
    - Charge response
  - Hole ice property (Mie scattering length)
  - Beam injection distance

DEgg

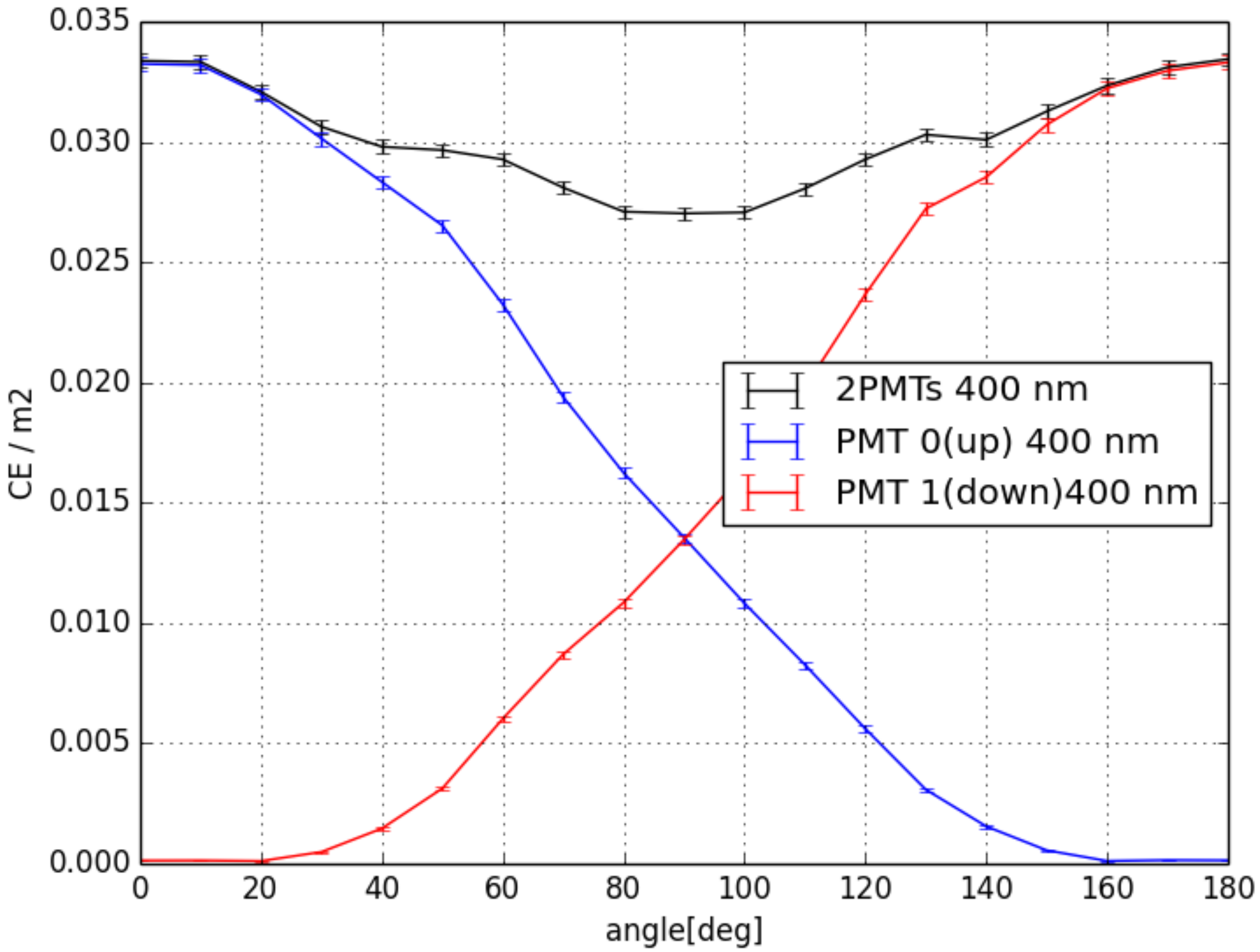




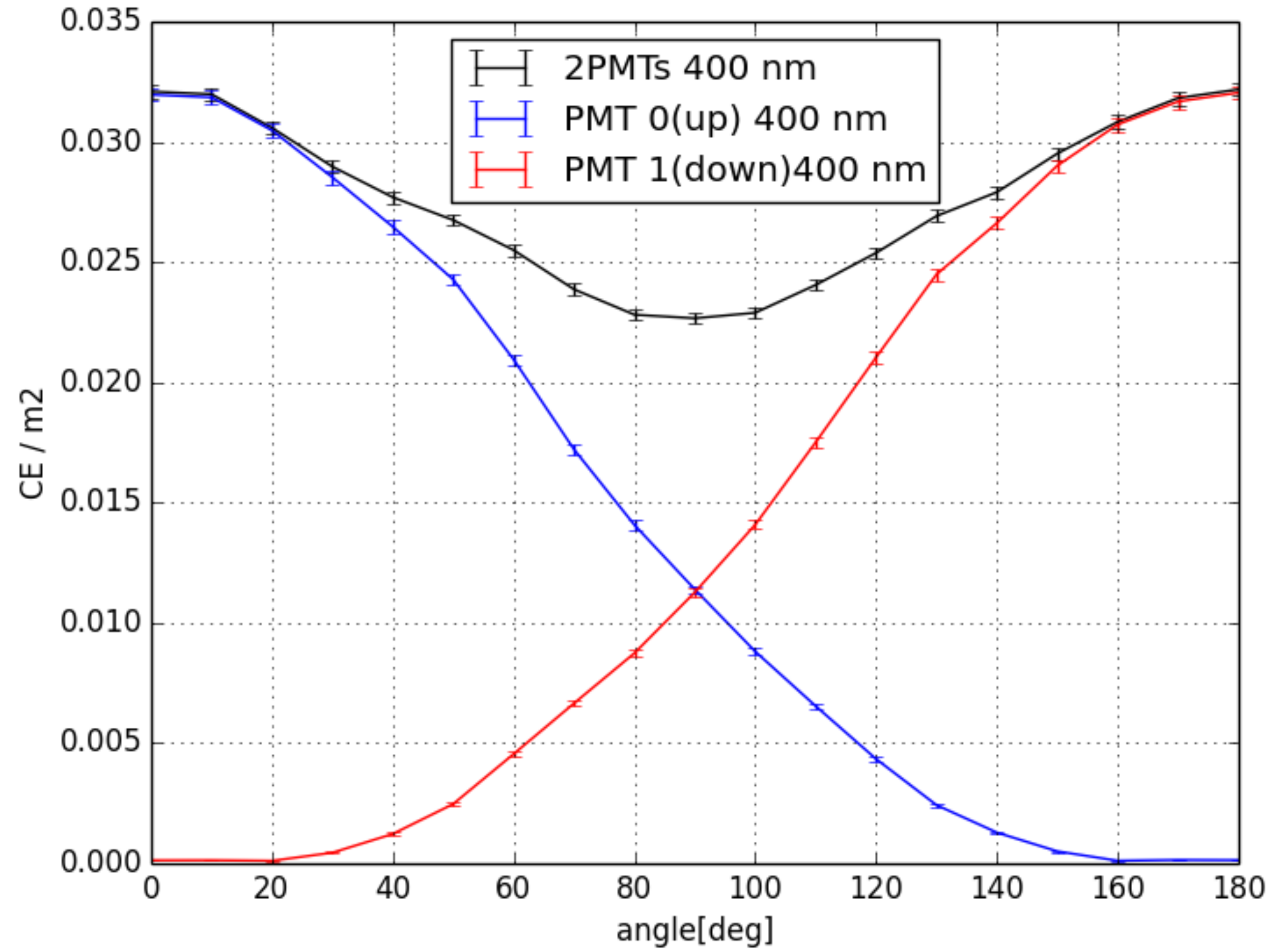
CE acceptance

100evts, 1000run average, no hole ice

CE = 1

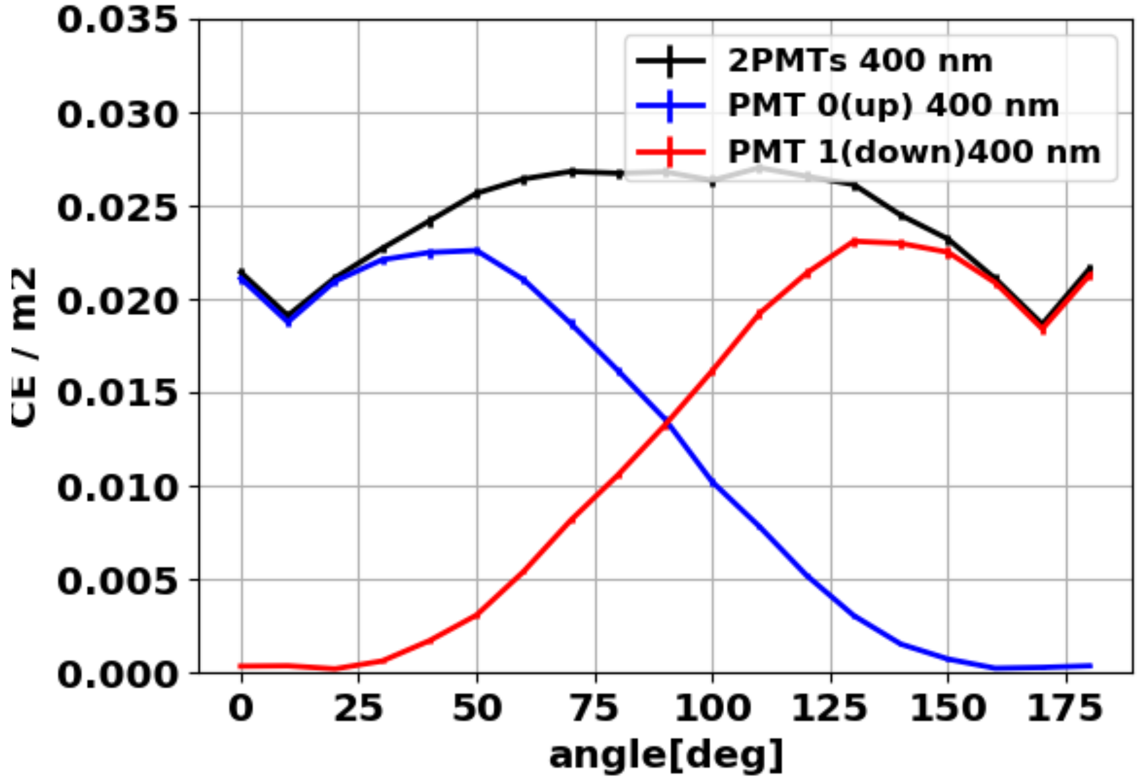


with CE

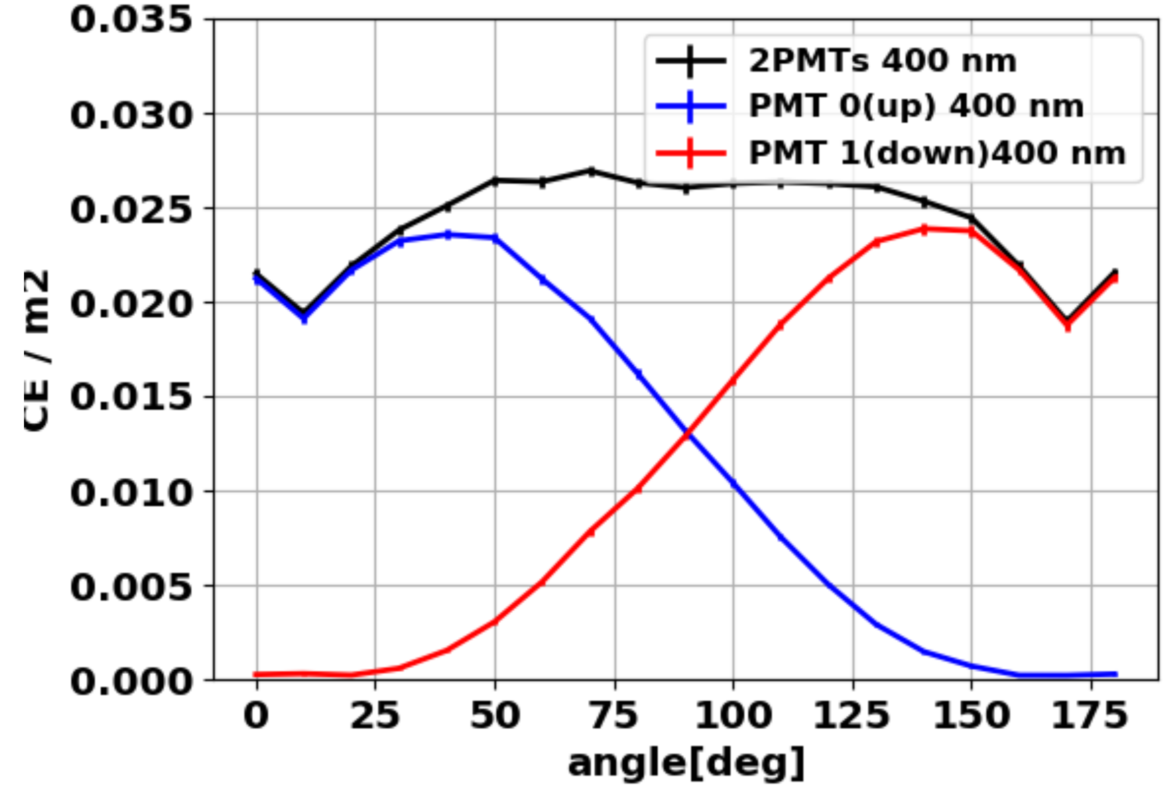


Scattering Length Holelce radius 6cm, injection radius 1m, beam dist. 1m

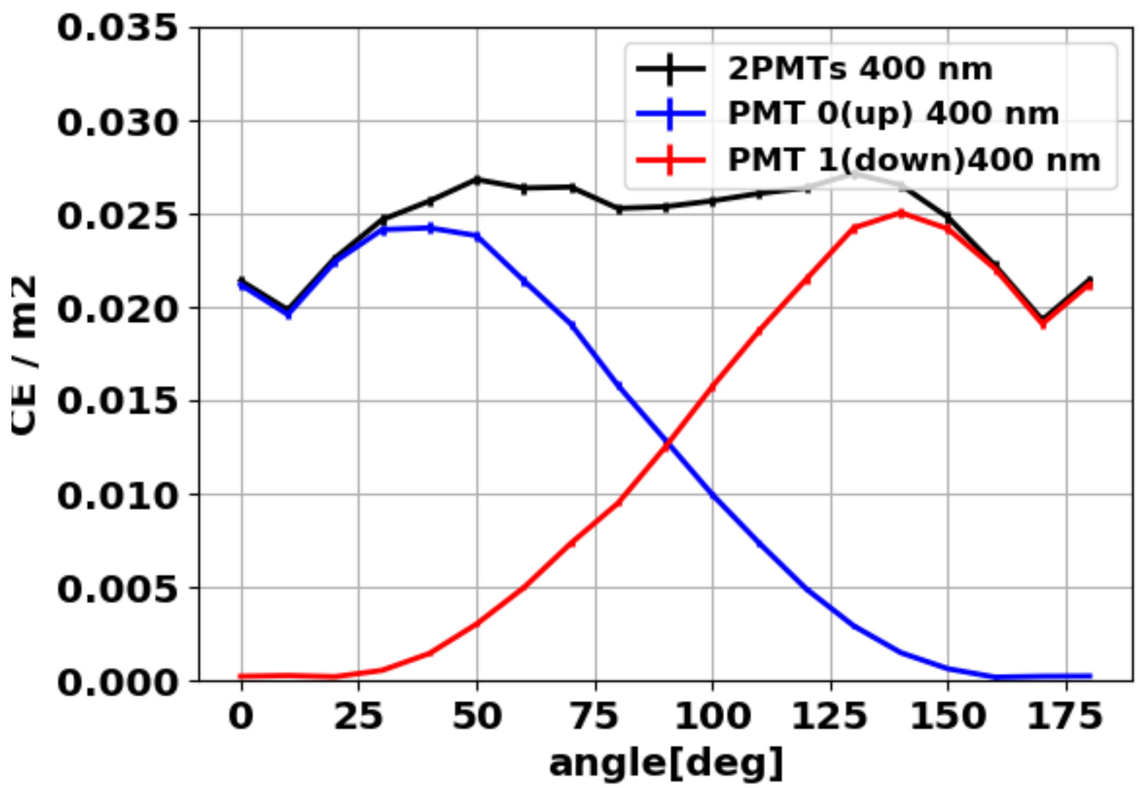
Mie Scat Len 5mm



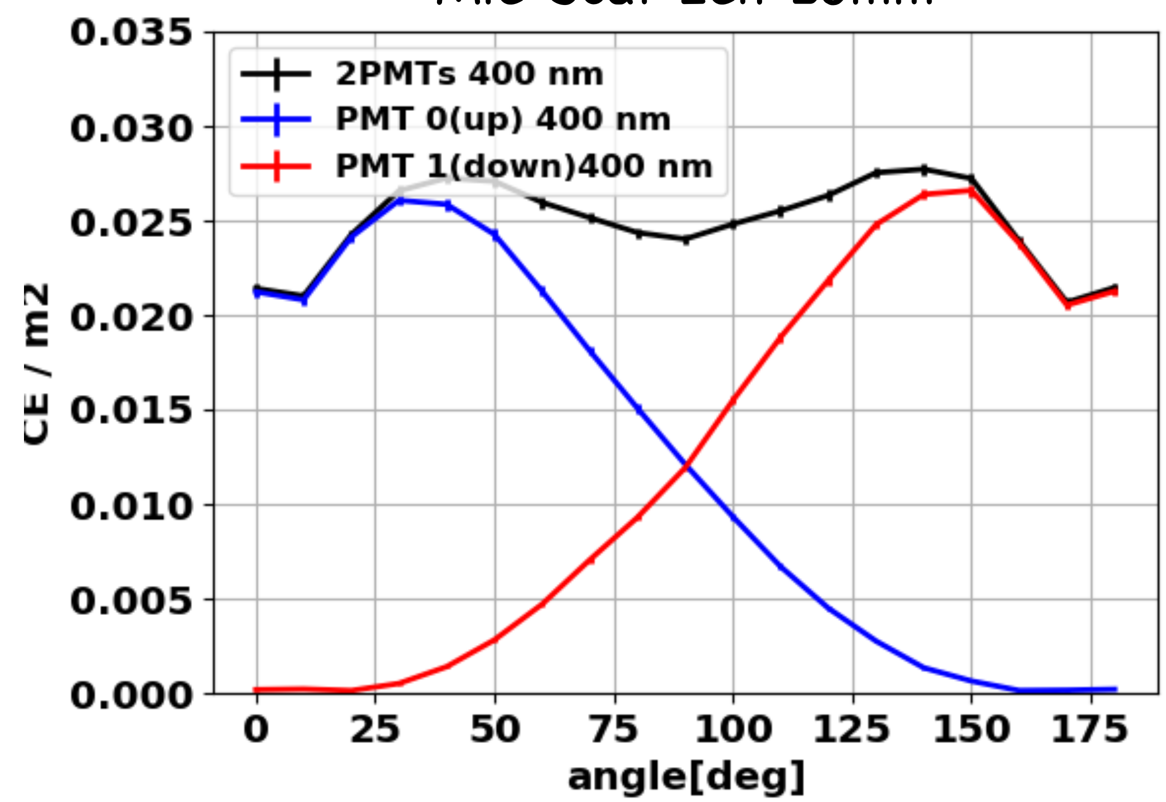
Mie Scat Len 7.5mm



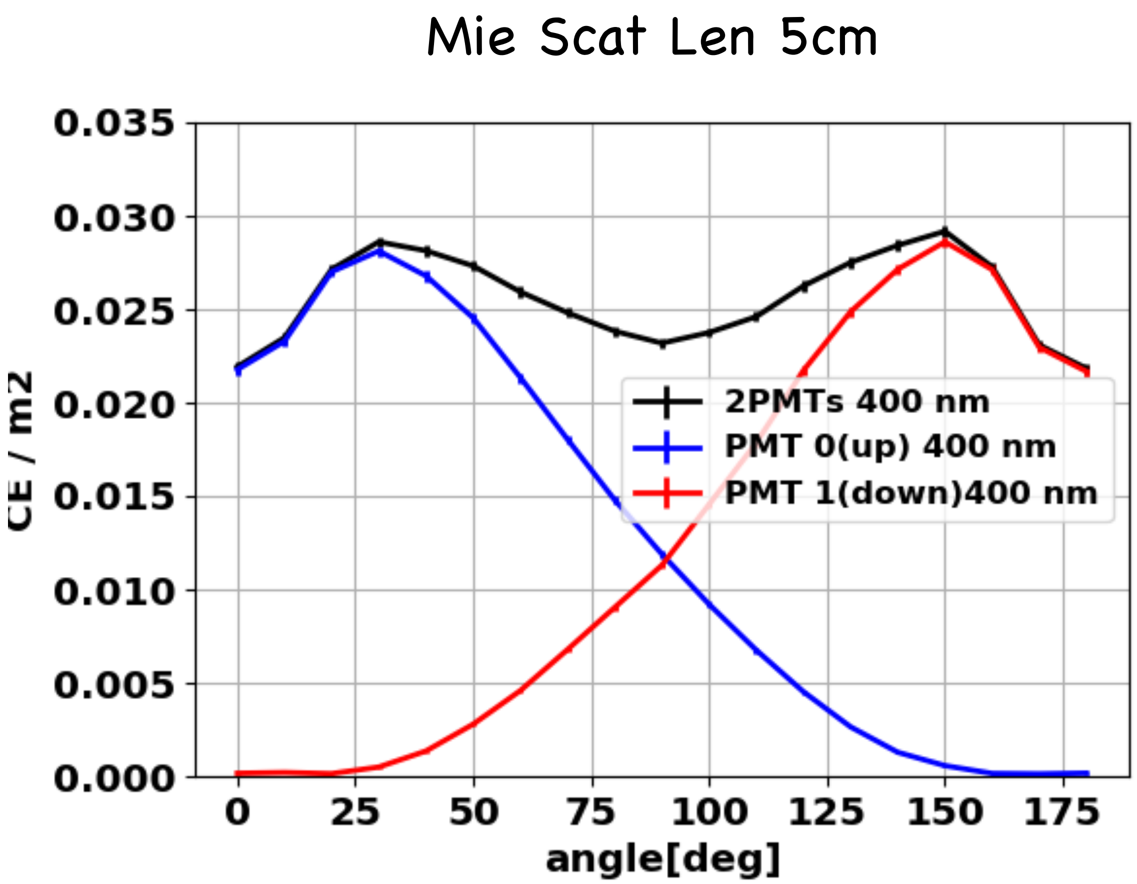
Mie Scat Len 10mm

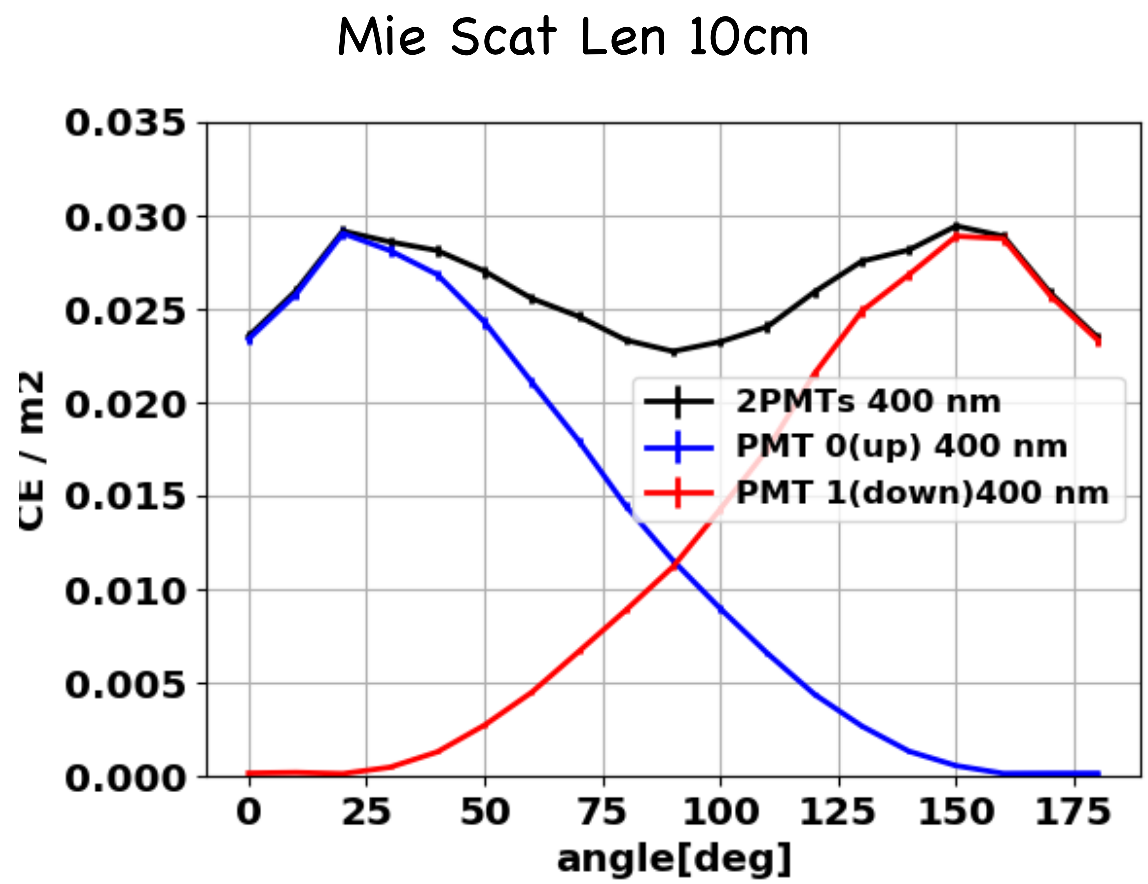


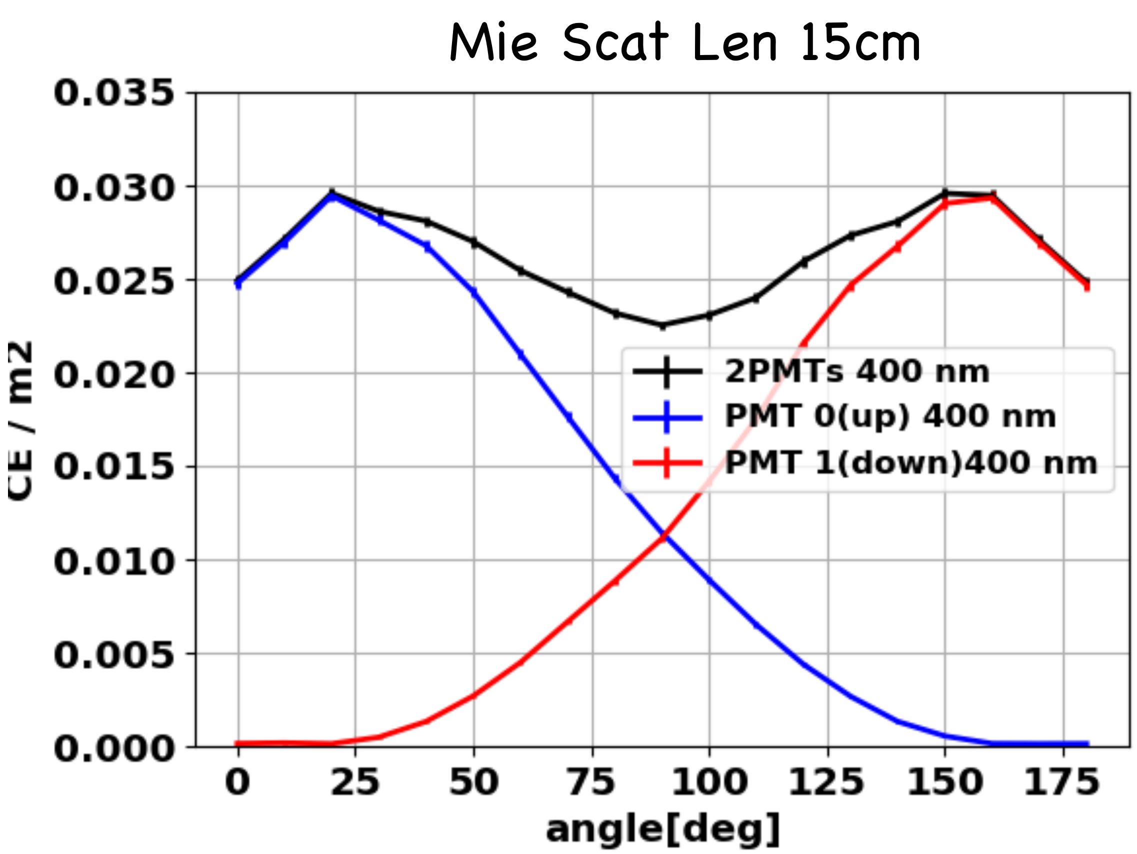
Mie Scat Len 20mm

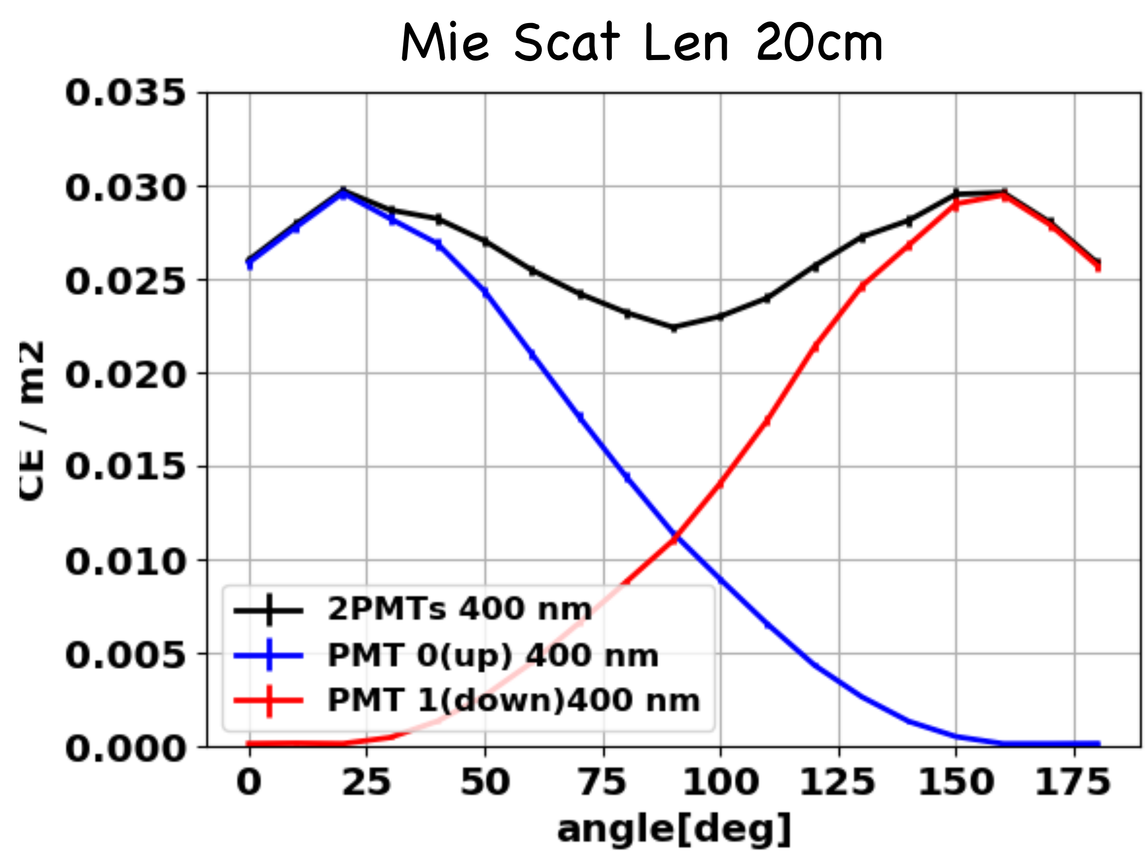


Scattering Length Holelce radius 6cm, injection radius 1m, beam dist. 1m

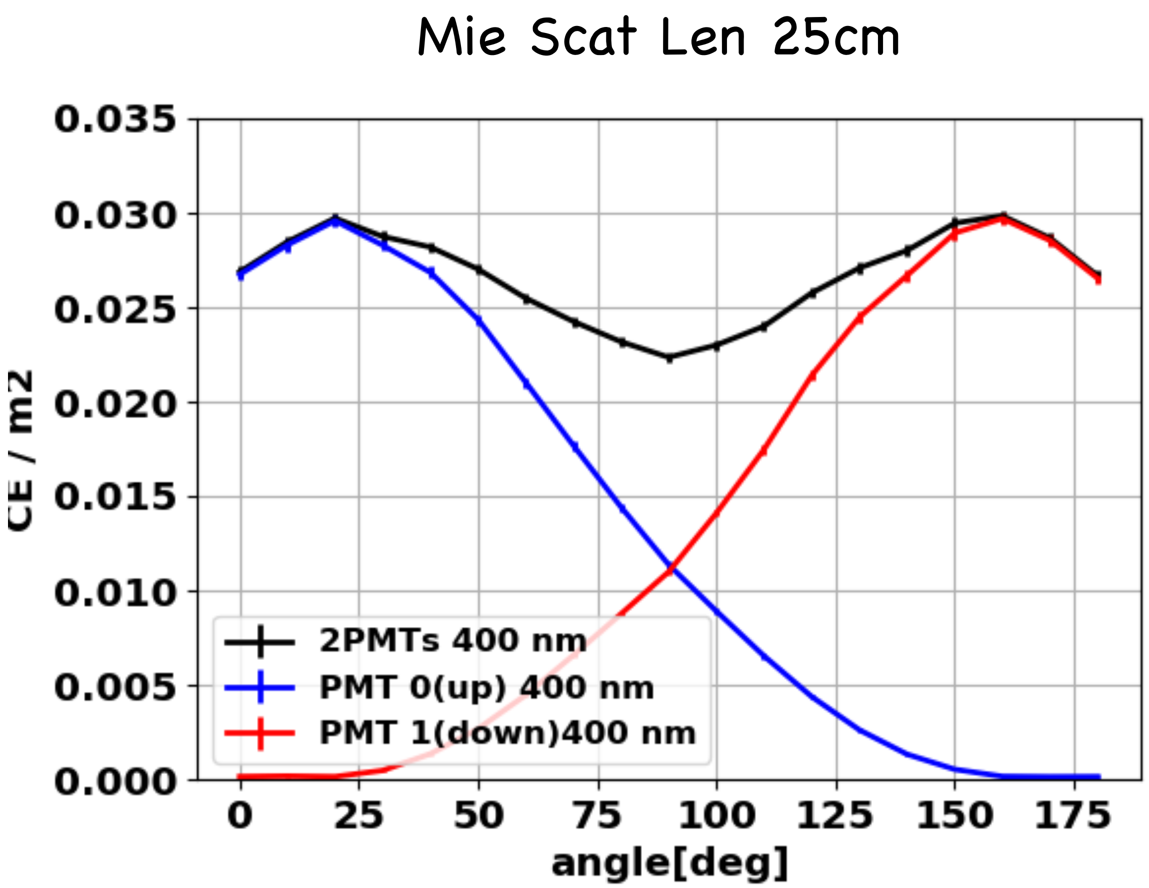


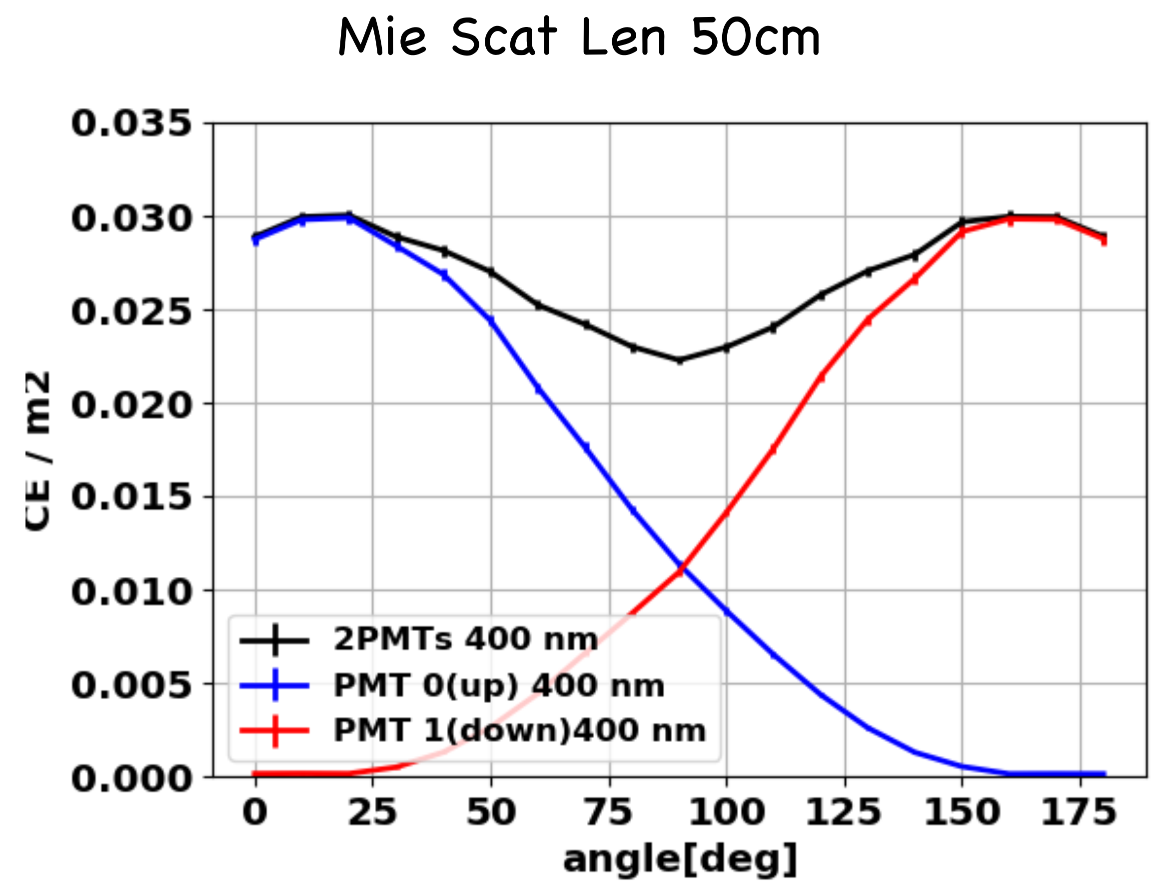


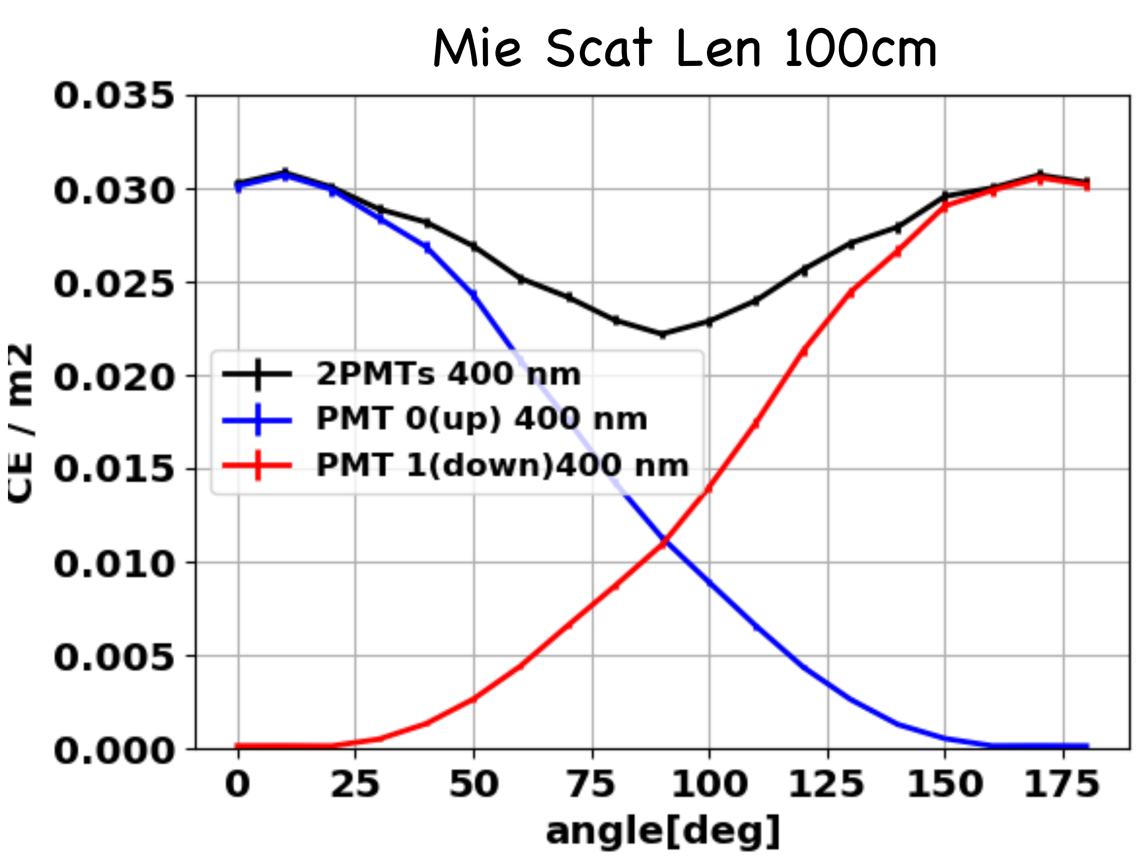


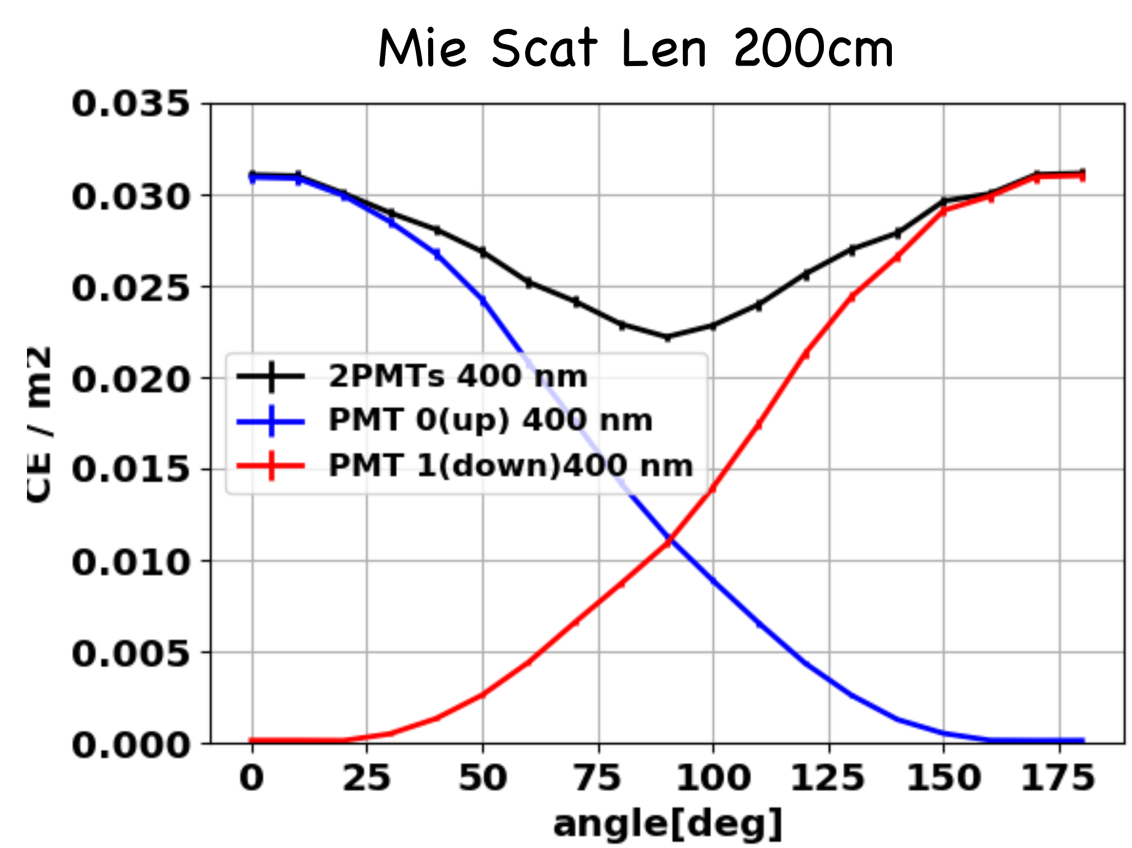


Scattering Length Holelce radius 6cm, injection radius 1m, beam dist. 1m



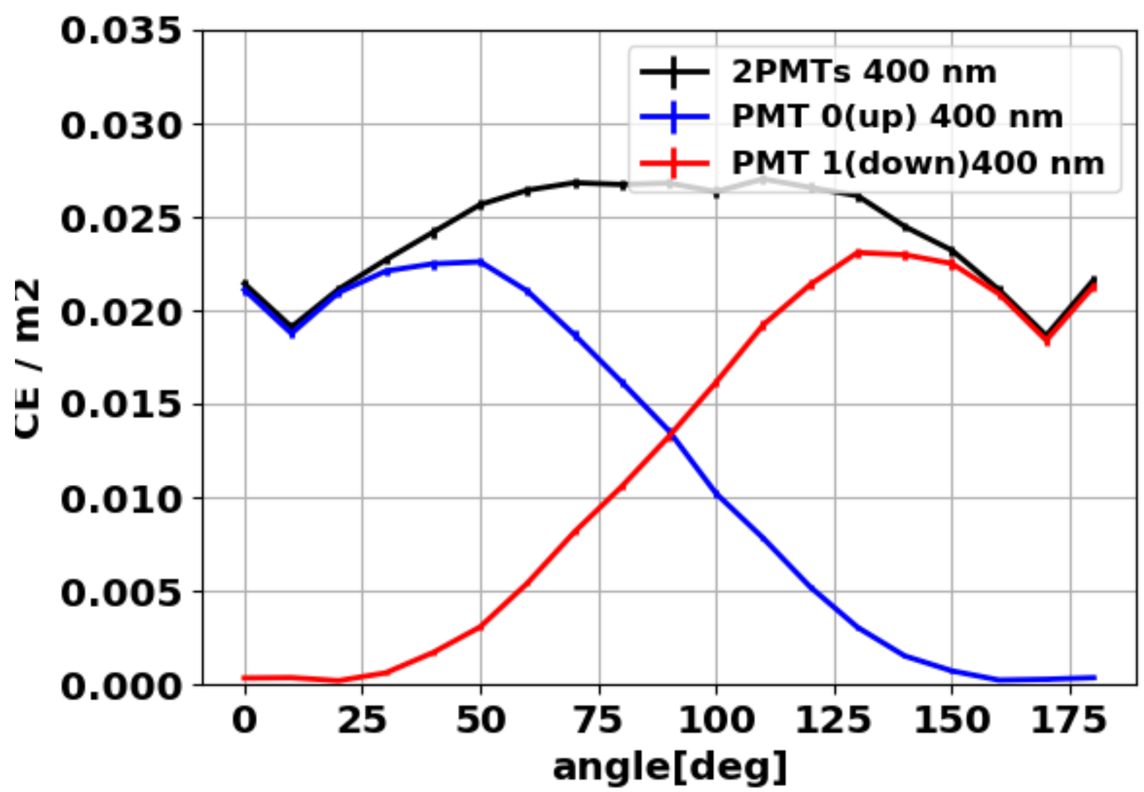




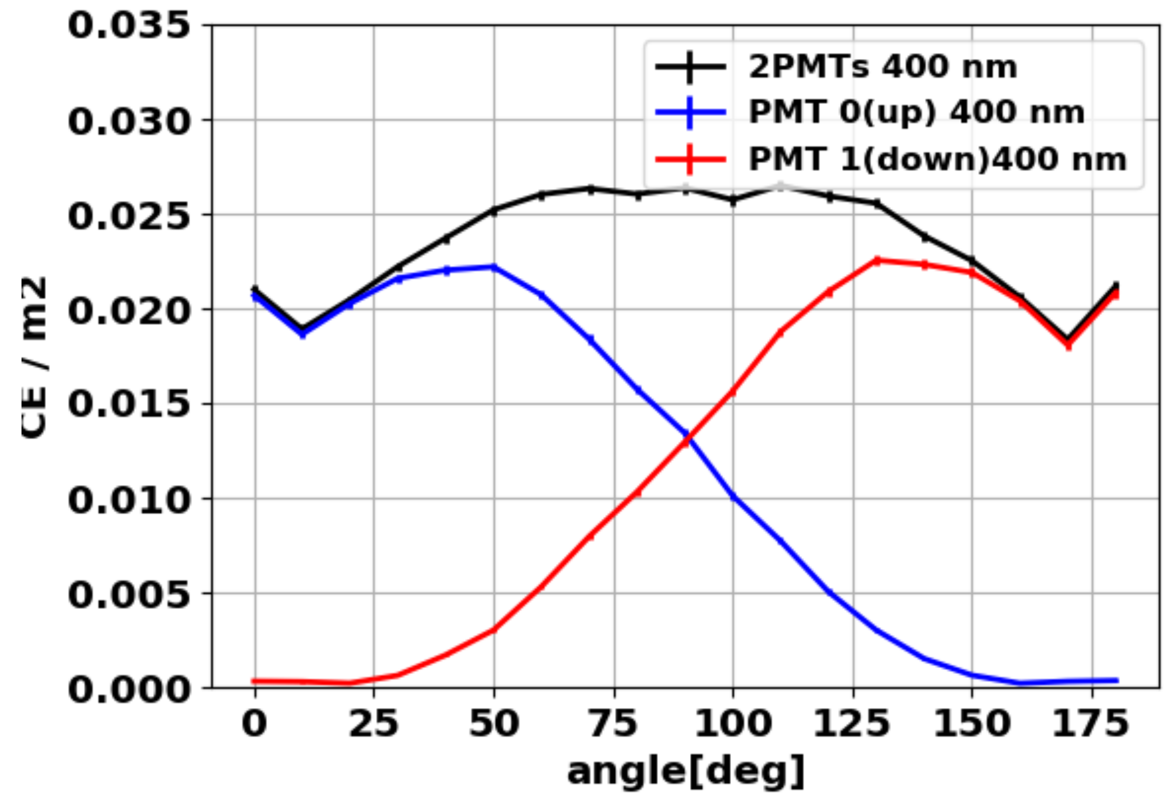


Beam Distance Holelce scattering length 5mm, injection radius 1m

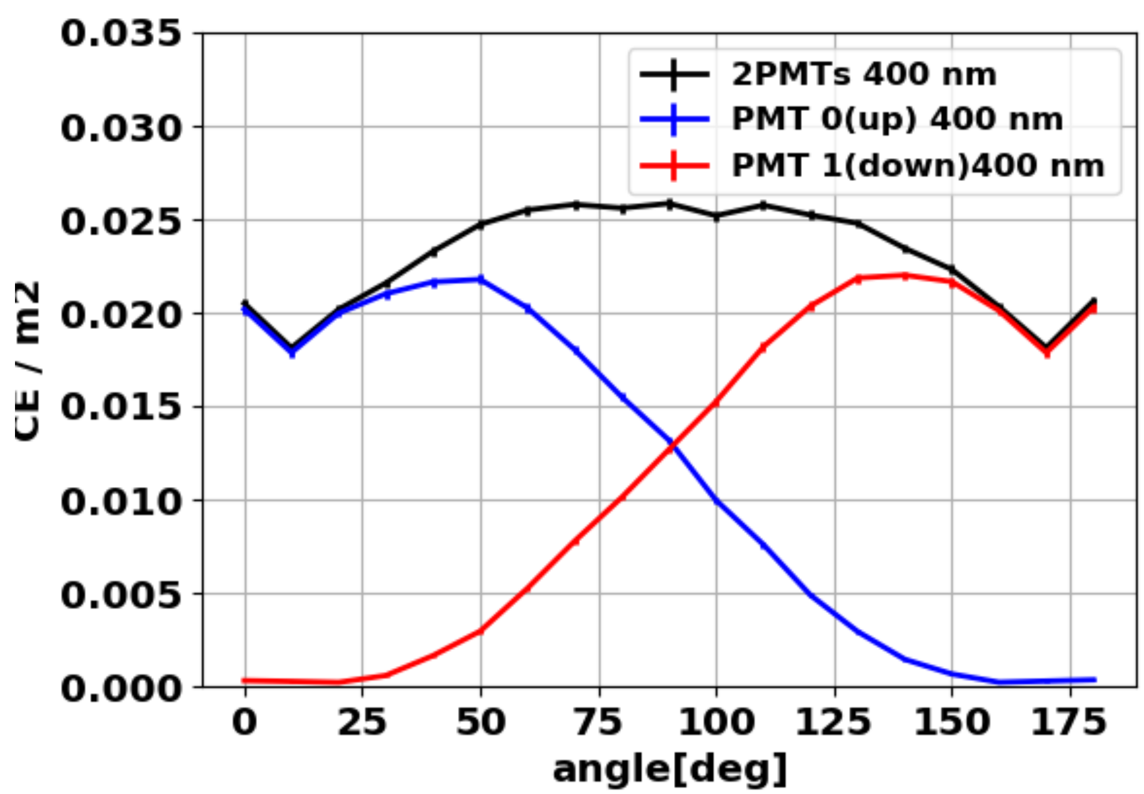
beam dist. 1m



beam dist. 3m



beam dist. 5m

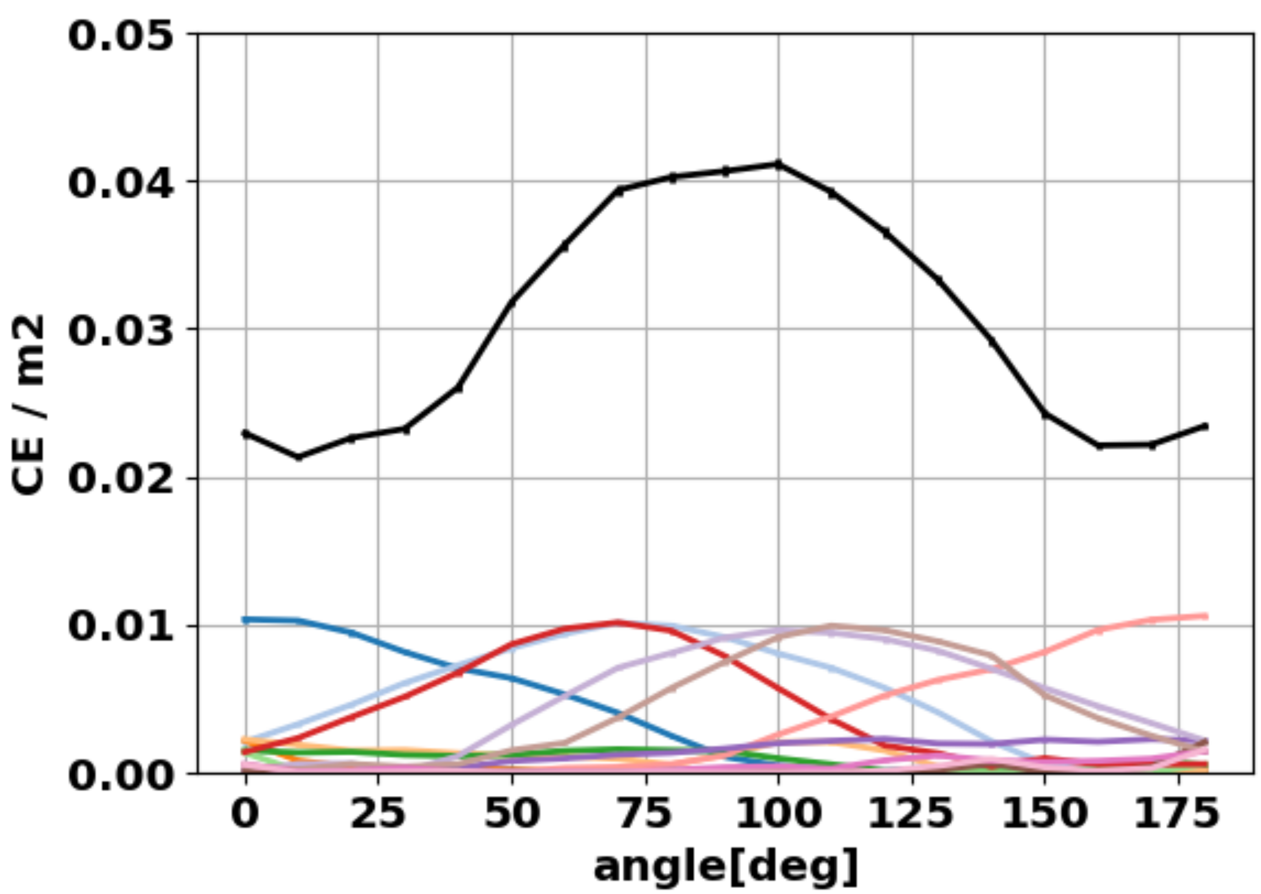


Variation of beam injection distance is not sensitive to angular acceptance !

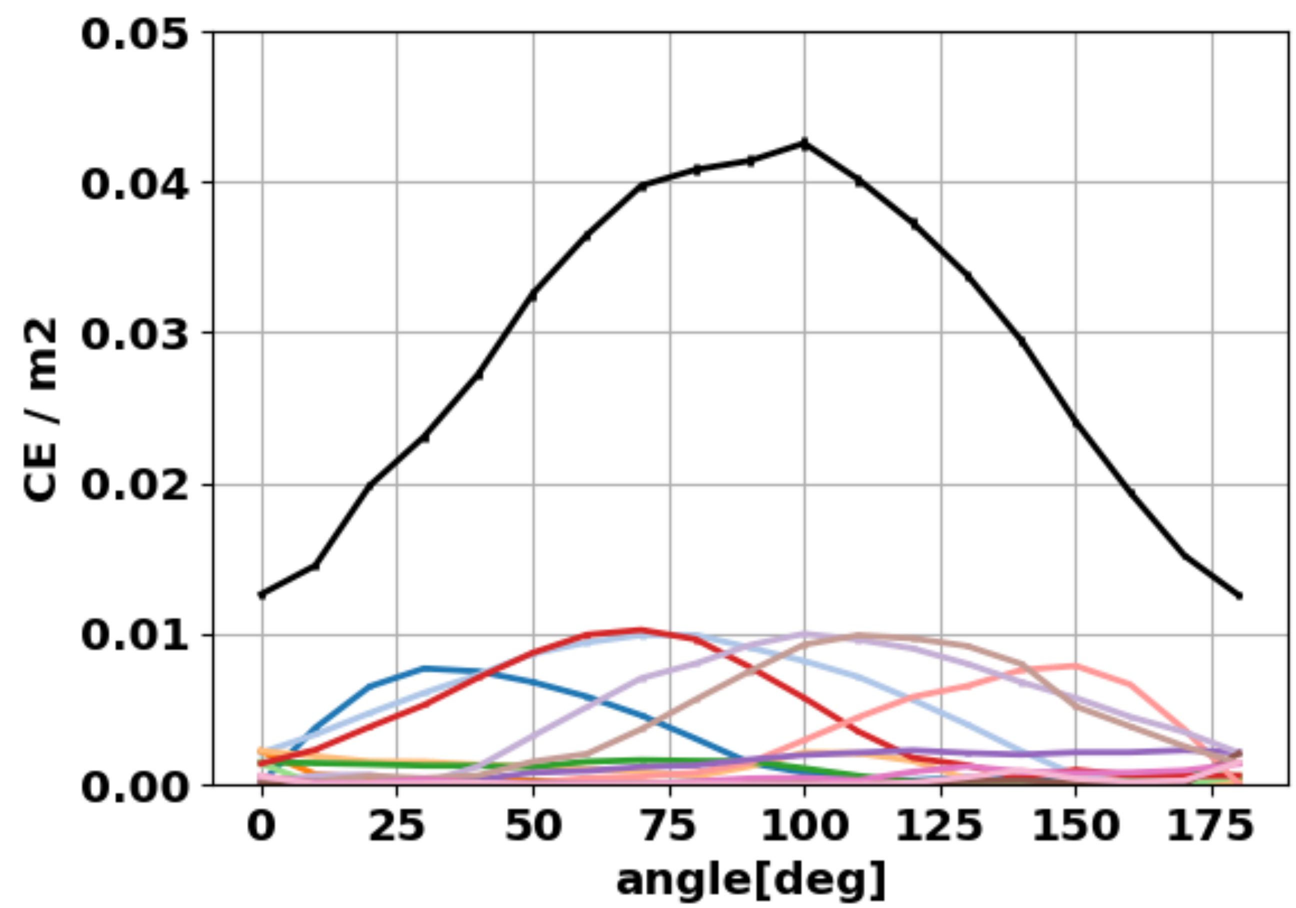
M-Egg Hole ice effect (injection radius 1m, beam dist.1m)

black : total
colors : each PMT

no holeice



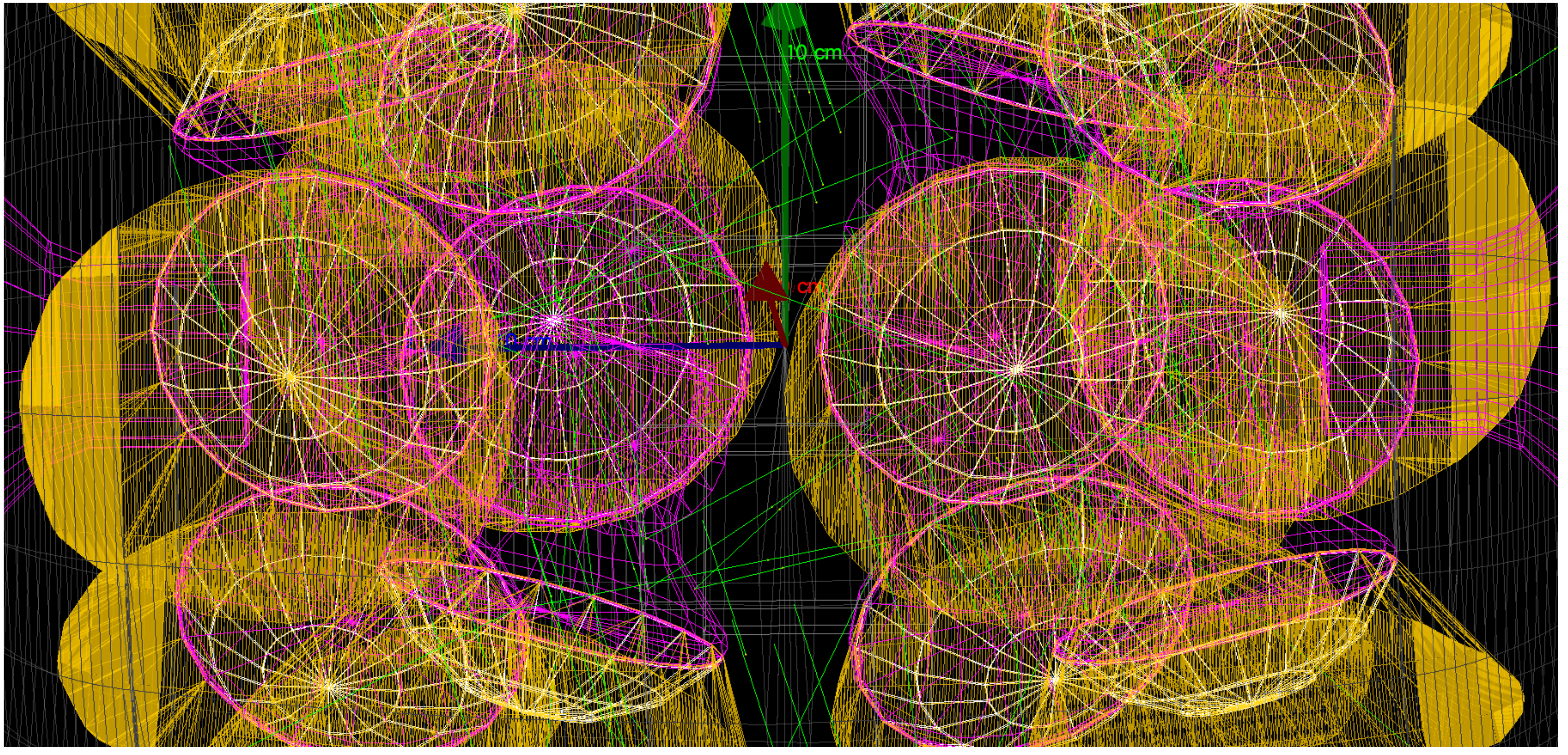
holeice 6cm, scat 3cm



Dima said geometrical scattering length in bubble column is approximately 3cm.

How much accuracy is needed for installation?

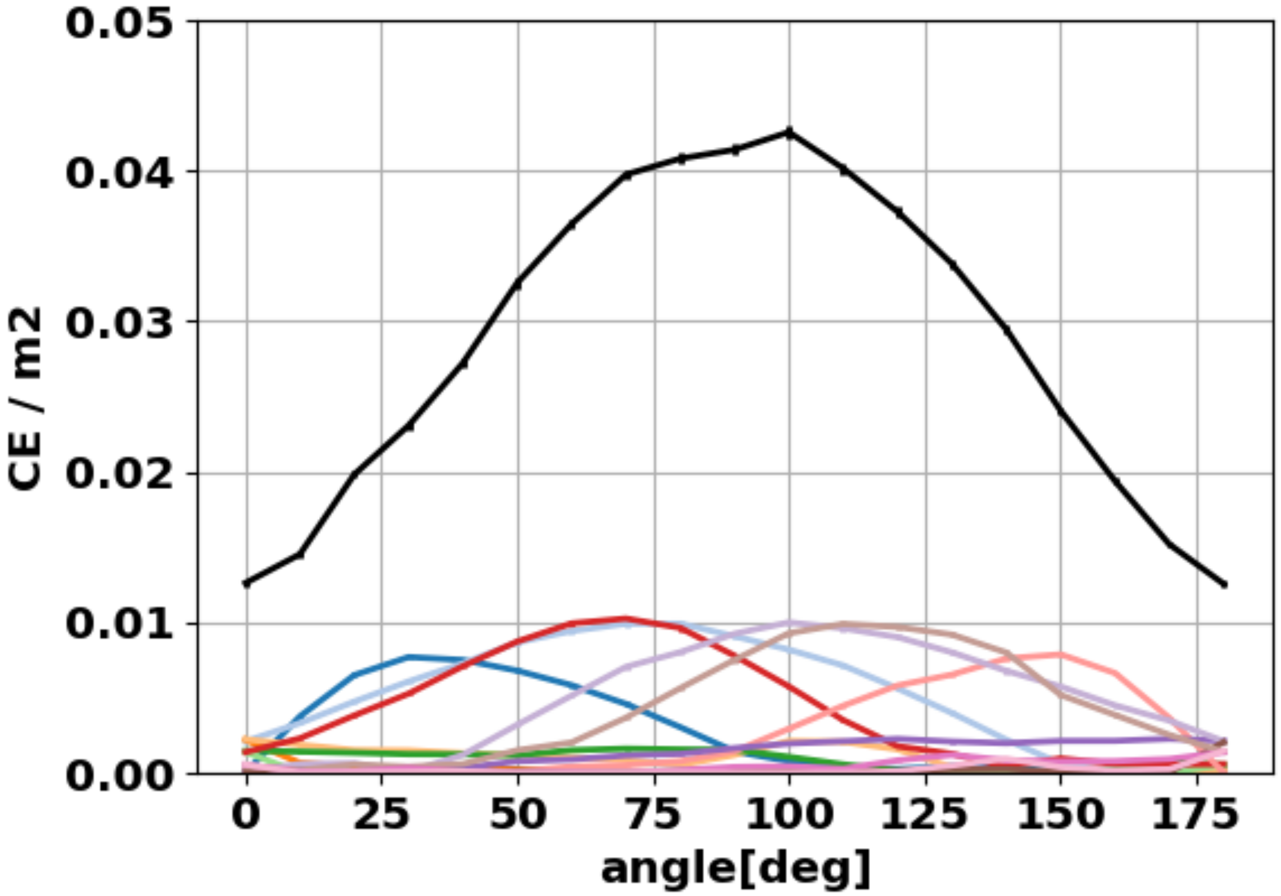
- Standard version : PMTs are just a chunk of glass (and stop simulation when a photon hits any part of PMT
- New version :
  - Installed PMT Cathode and photons are killed at cathode
  - Install PMT base (aluminum) with dielectric_metal surface (mirror refraction)



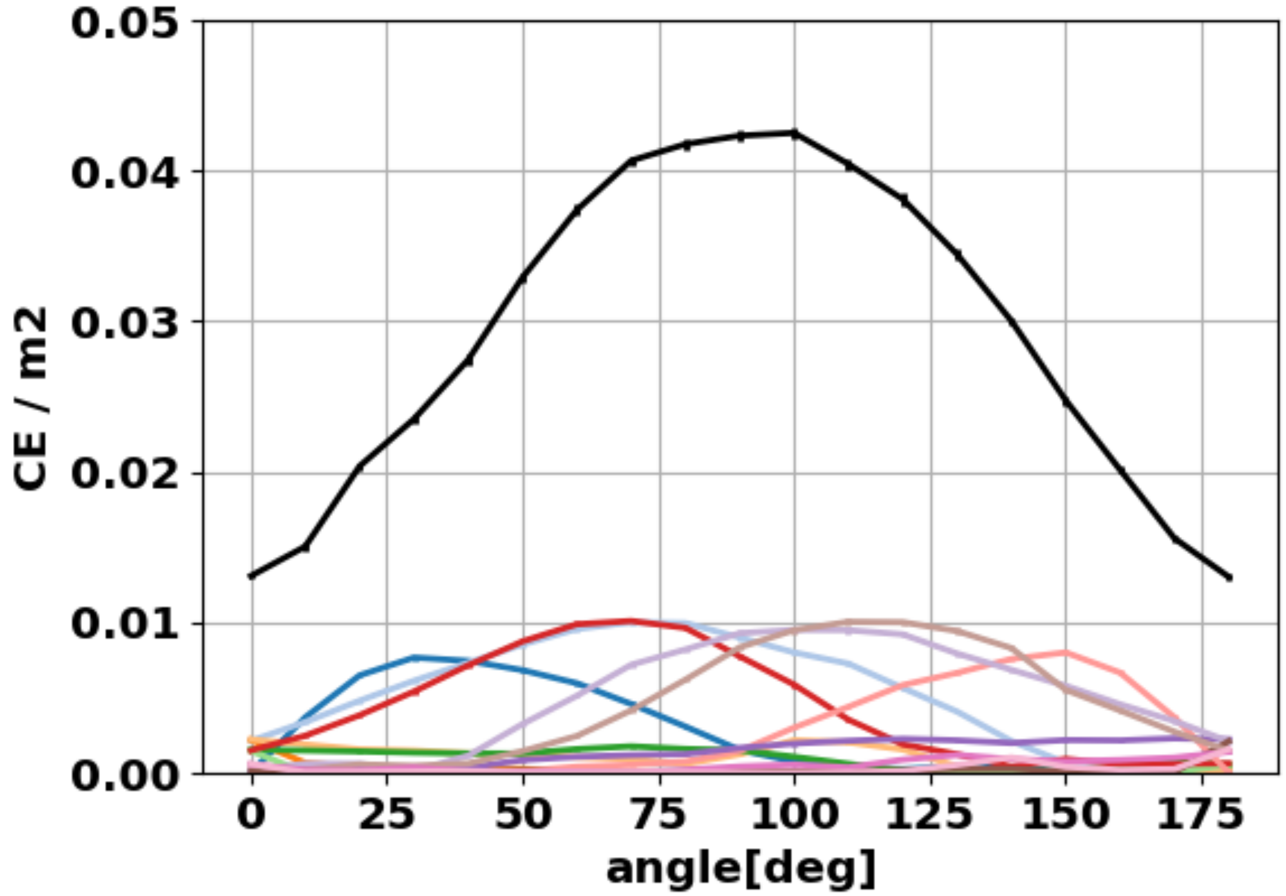
How much accuracy is needed for installation?

holeice 6cm, scat 3cm

glass PMT



photocathode + aluminum PMT



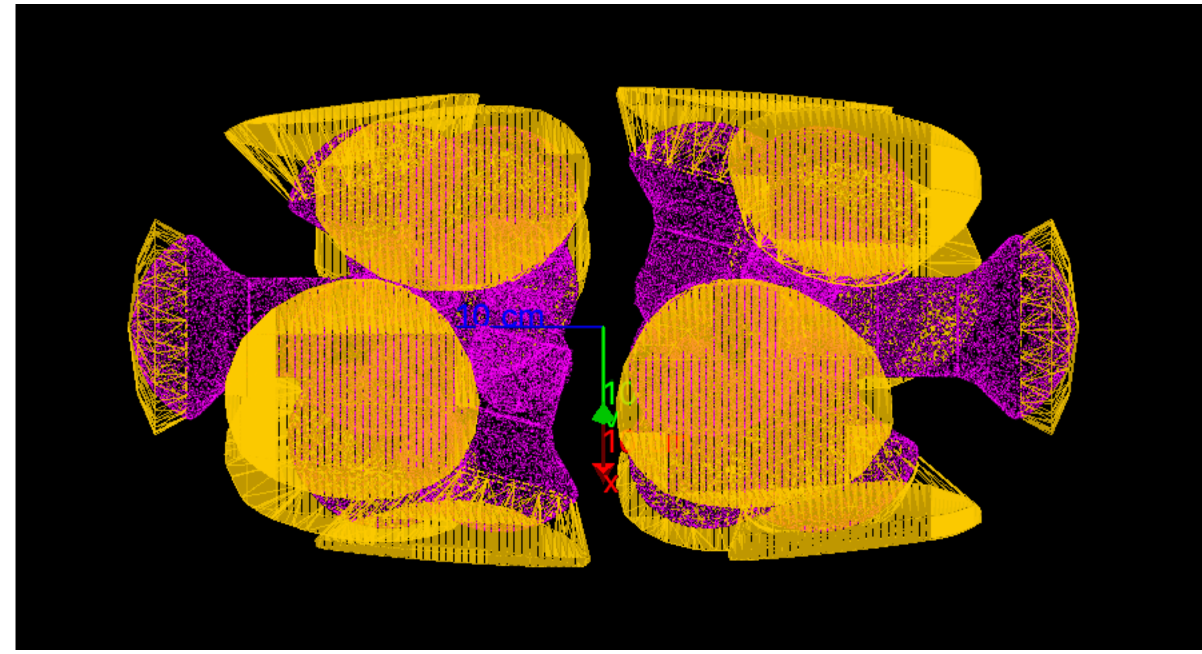
Minimum effect, may be negligible?

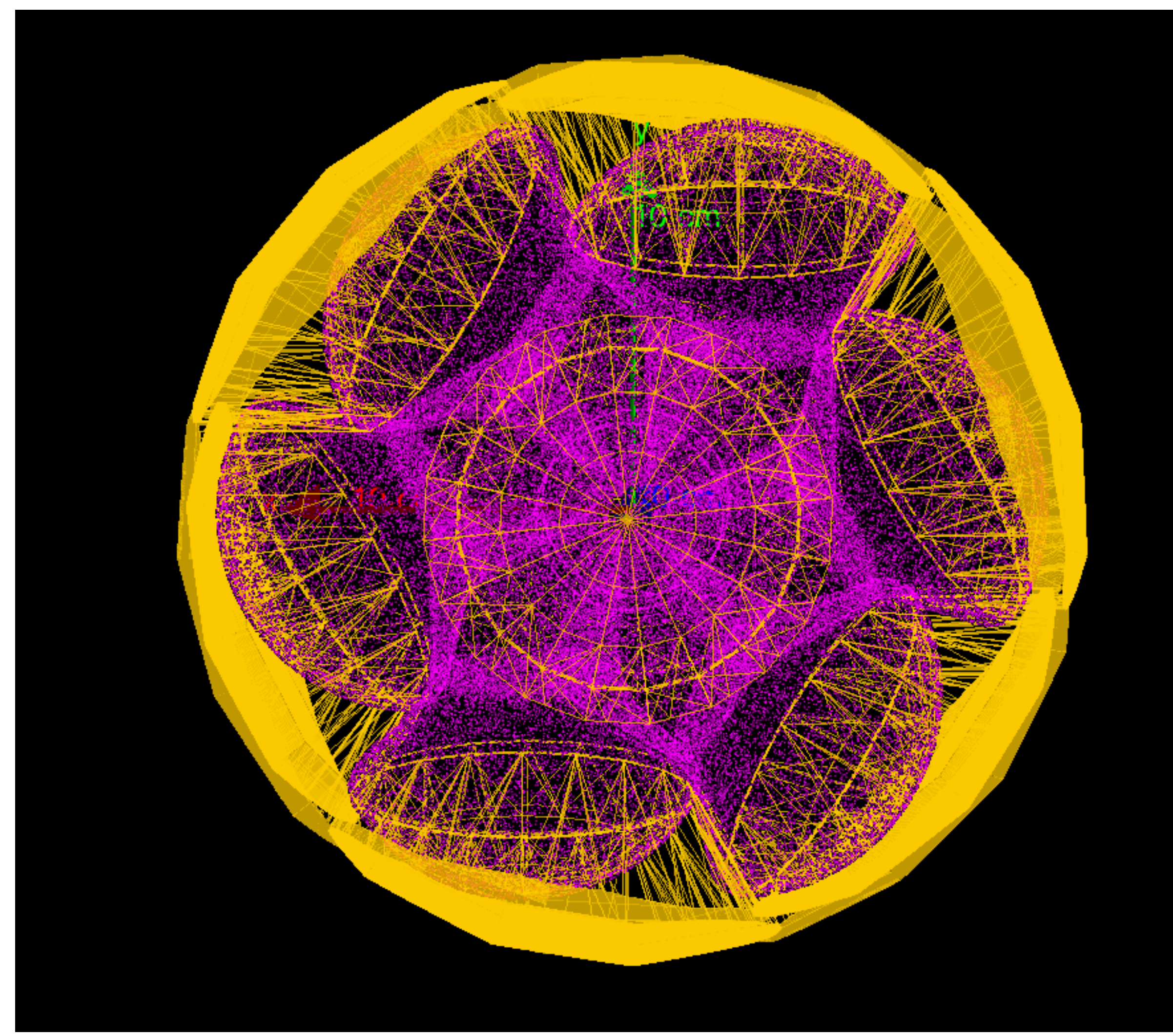
Other geometries?

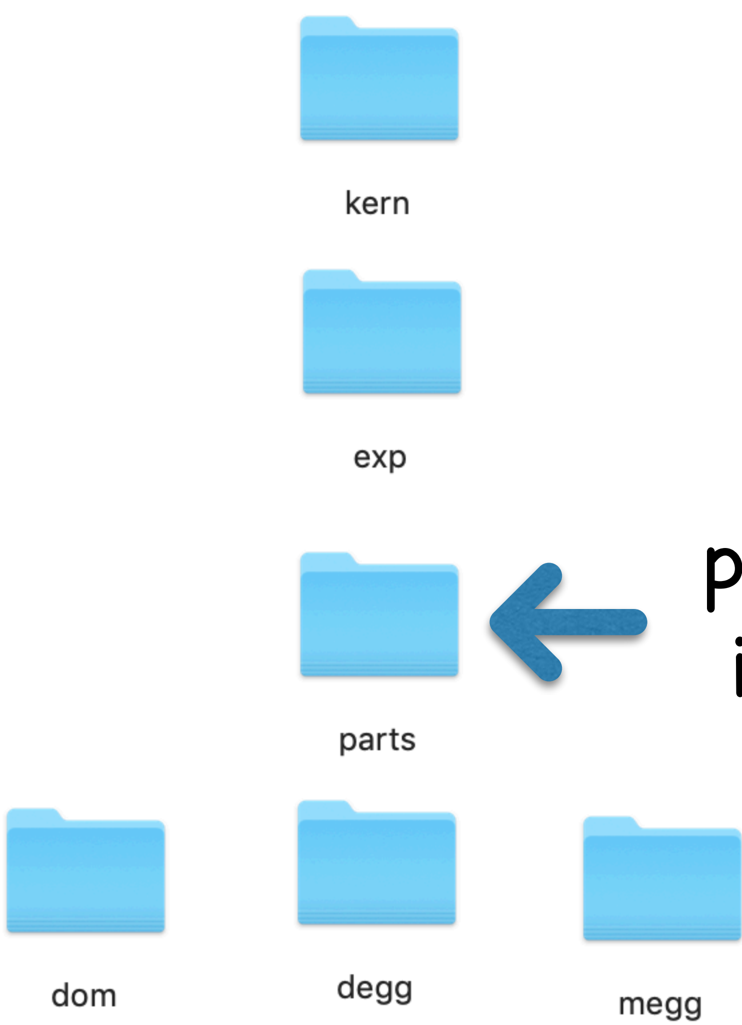
- I’ve been waiting for LOM geometry (glass, gel, pmt positions, etc.) for several months.
    - If someone want to do it yourself, I’m happy to have a short boot camp for Geant4 & Dominant/Doumeki beginners.
- Scintillation process can be simulated (Geant4 should be able to do it!).
- Any other idea?

M-Egg

- Number of classes under MEgg directory : 6.
  - Most of parts can be reused from D-Egg



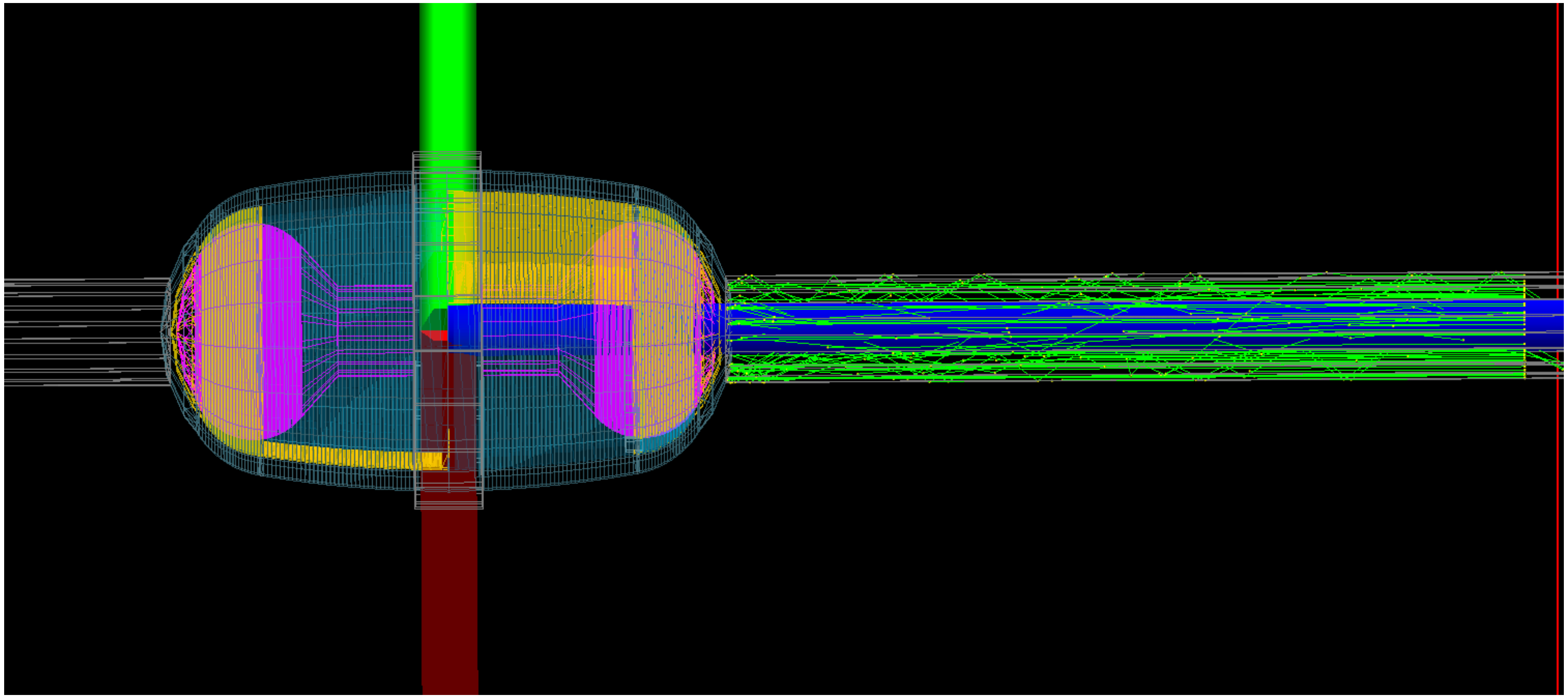




All reusable parts are now in "parts" dir

Issue of G4OpBoundaryProcess

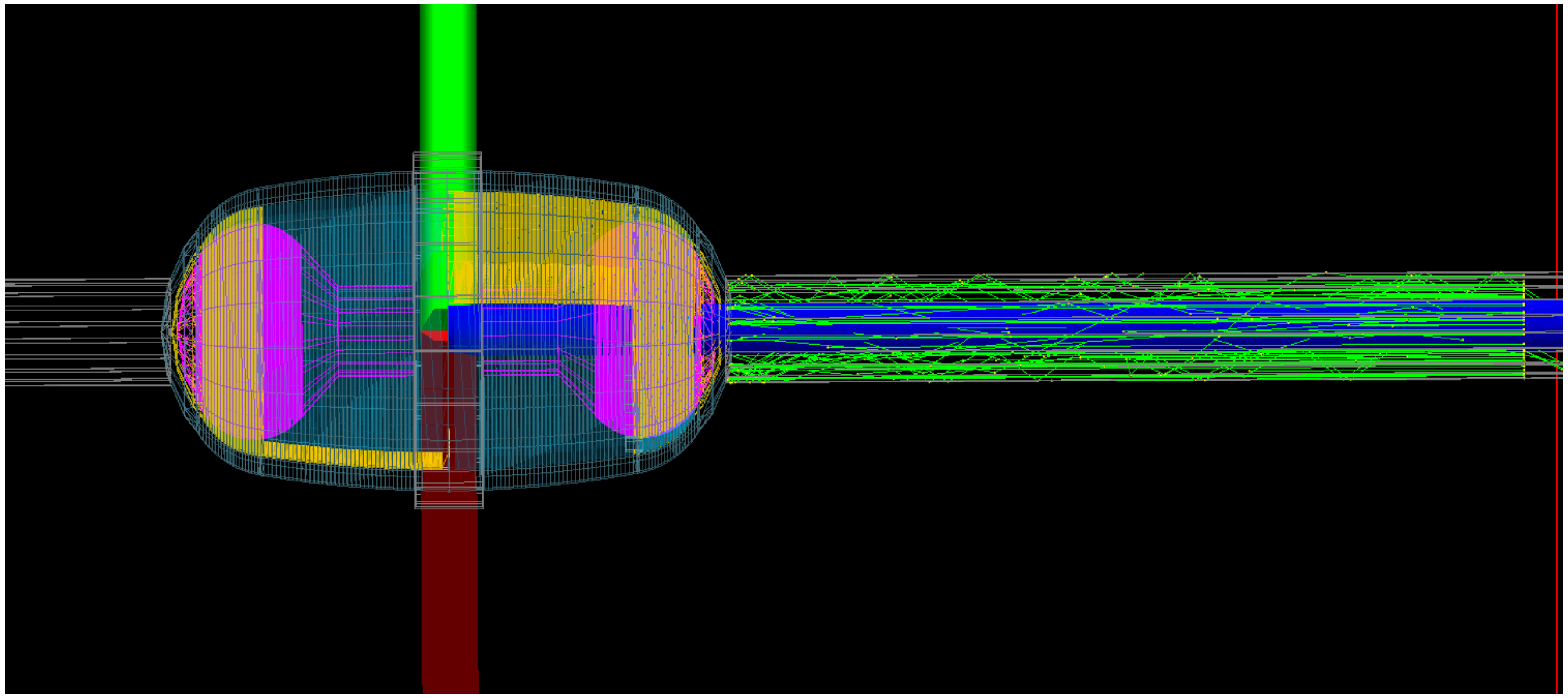
- I prepared two types of ice for bulk ice and hole ice
  - hole ice has a property table Mie scattering
  - other properties are identical
- Then I found photons are reflected at the boundary of hole ice and bulk ice!
- It is by design of G4OpBoundaryProcess… 😓



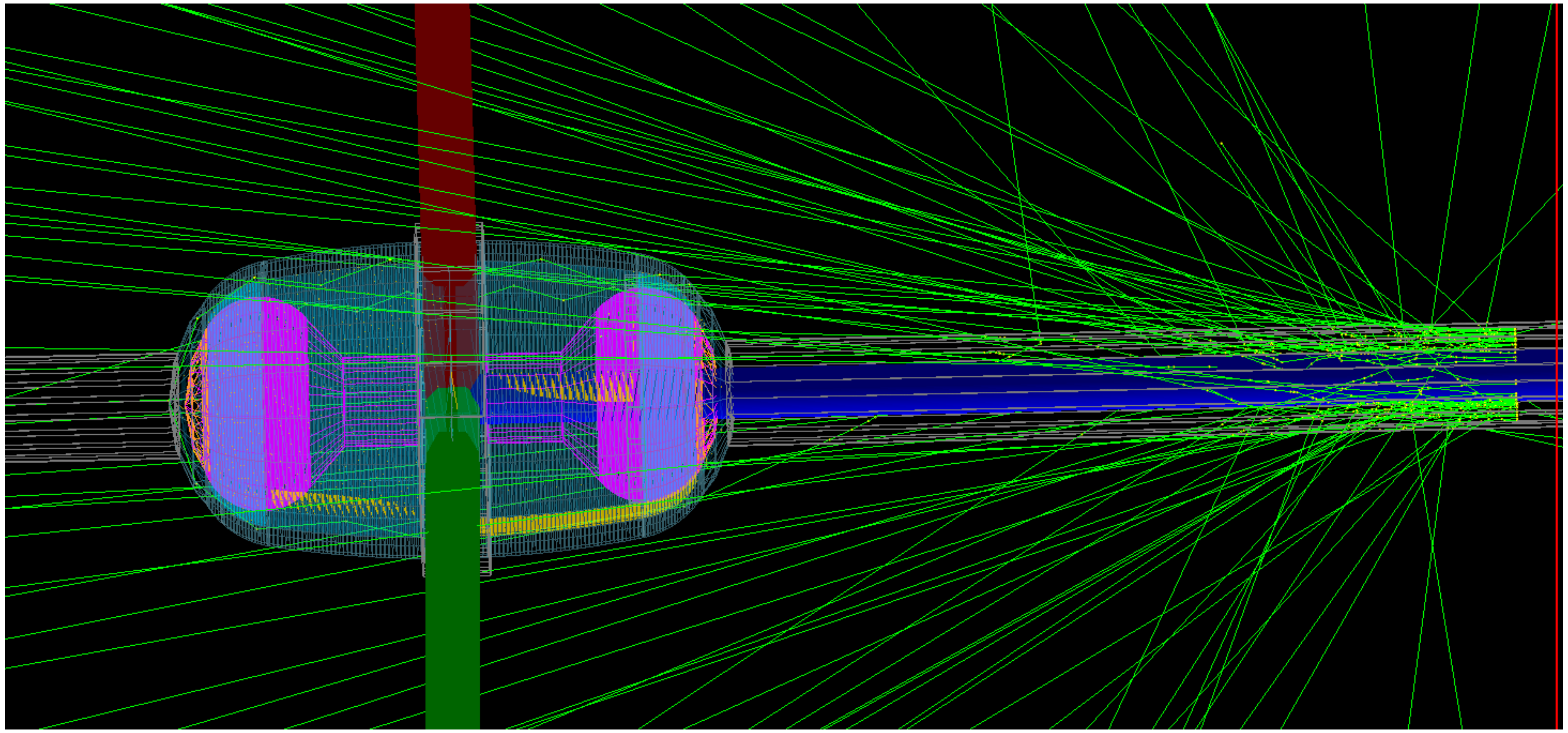
G4Material and G4OpBoundaryProcess

- G4Material = Set of component & userlimits(=refraction index, mie scattering, etc.)
  - but we have two ices that have different Mie scattering length (bulk ice and hole ice)
- G4OpBoundaryProcess skips Fresnel refraction only when pointers to G4Material of two neighboring physical volumes are identical.
  - If we use two G4Material for ices, Fresnel refraction is called without exception! (refraction index is not checked)
- I will contact Geant4 group how should we treat this problem, but for now, I use my modified G4OpBoundaryProcess that skips Fresnel refraction when refraction index is same…

Modified G4OpBoundaryProcess



Original



Modified

G4OpMieHG

- Using Henyey-Greenstein phese function
- Parameters:
  - Mean scattering length (geometrical, not effective)
  - Forward vs Backword scattering ratio
  - g-parameter for forward and backword

1. THE HENYEY-GREENSTEIN PHASE FUNCTION.

Henyey and Greenstein (1941) introduced a function which, by the variation of one parameter, $-1 \leq g \leq 1$, ranges from backscattering through isotropic scattering to forward scattering. The function is

$$p(\theta) \;=\; \frac{1}{4\pi}\;\frac{1\;-\;g^2}{[1+g^2-2g\;\cos(\theta)\;]^{3/2}}\;\;, \qquad (1)$$

This function is normalized such that the integral over 4π steradians is unity:

$$\int_0^{2\pi}\left\{\int_0^{\pi} p(\theta)\;\sin(\theta)\;d\theta\right\}\;d\phi\;=\;1 \qquad (2)$$

We can write it as a function of $\mu = \cos(\theta)$:

$$p(\mu)\;=\;\frac{1}{2}\;\frac{1\;-\;g^2}{[1+g^2-2g\;\mu\;]^{3/2}}\;\;,\quad \text{and then}\quad \int_{-1}^{1} p(\mu)\;d\mu\;=\;1\;\;. \qquad (3)$$

Forward scattering is $\theta = 0, \mu = 1$, and in that case $p(1) = (1-g^2)/2(1-g)^3$, while for back-scattering, $\theta = \pi, \mu = -1$, and $p(-1) = (1-g^2)/2(1+g)^3$. We see that the ratio of forward to back scattering is $[(1+g)/(1-g)]^3$. For $g > 0$, forward scattering is dominant, while for $g < 0$, backscattering predominates.

https://www.astro.umd.edu/~jph/HG_note.pdf

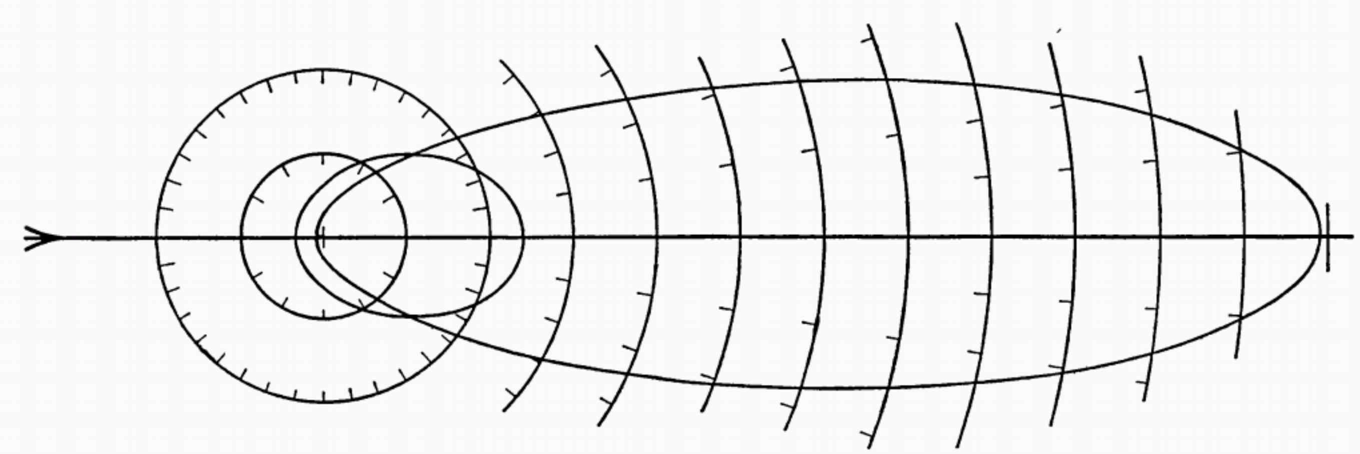


FIG. 3.—Polar diagram of the phase function of equation (2), for $\gamma = 1$. The more elongated curve is for $g = +\frac{2}{3}$; the other, for $g = +\frac{1}{3}$. The radiation is incident on the particle from the left, as shown by the arrow.

Henyey, L.G. and Greenstein, J.L. (1941) Diffuse Radiation in the Galaxy. Astrophysical Journal, 93, 70-83.