# Progress on Single Crystal Simulations at UMD

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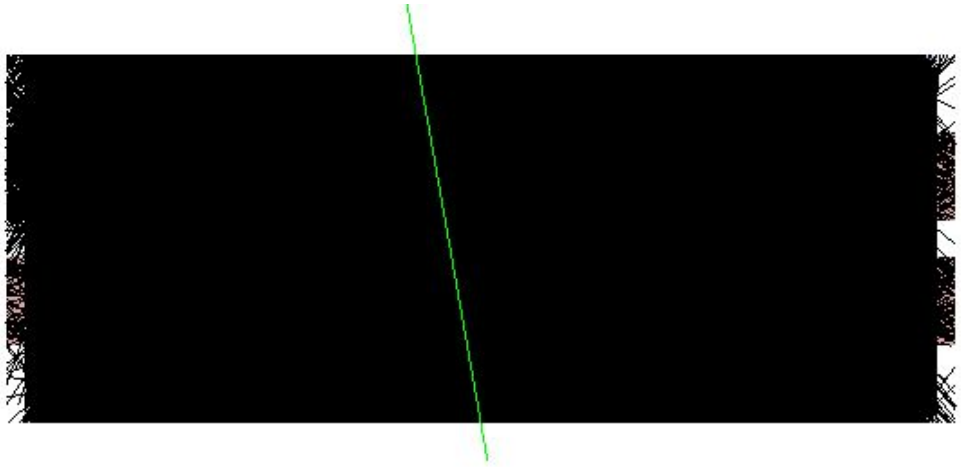
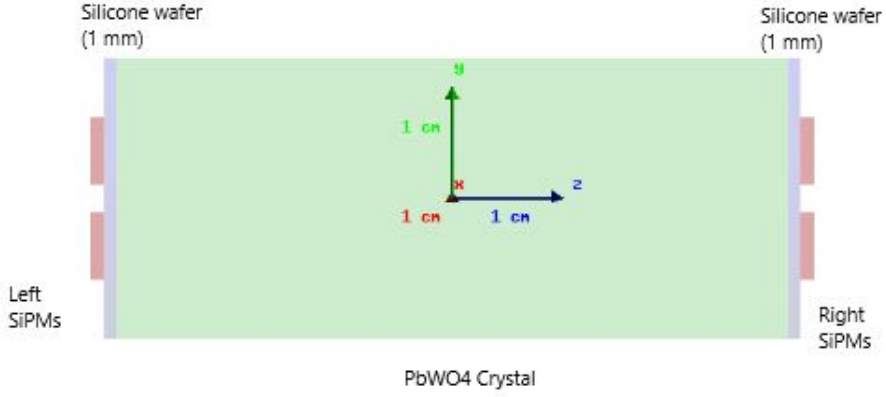
# Recap

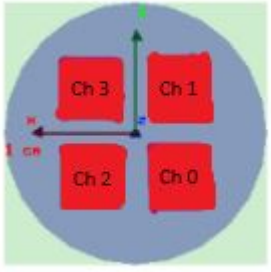
- Currently simulating a dual-readout crystal detector with GEANT4 + DD4hep for 120 GeV protons with FNAL Test Beam setup (June)
  - Comparing MC plots of PbF2 and PbWO4 with the data
  - Agreement seen for PbF2 is not bad but for PbWO4, both ends with and without wavelength filter seem to be scintillation dominated
  - Investigating the reasons for mismatch in MC and data (MC much less than data at ~20 deg and much greater than data at ~70 deg) for PbF2

# Recap - FNAL Test Beam (120 GeV protons) - setup

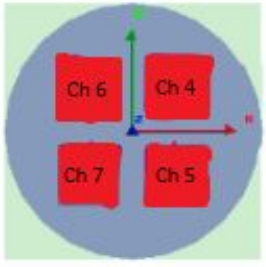
- Crystal dimensions are 2.5 cm × 2.5 cm × 6 cm for all the materials
- Four SiPM channels arranged in a 2 × 2 array on each square face
- Median of the whole distribution of events is taken for comparison with data
- Proton passes through the center of the crystal
- Channels 1,3 and 4,6 (in the graphs) are the ones farther from the face on which the beam is incident, and channels 0,2 and 5,7 are the ones that are closer





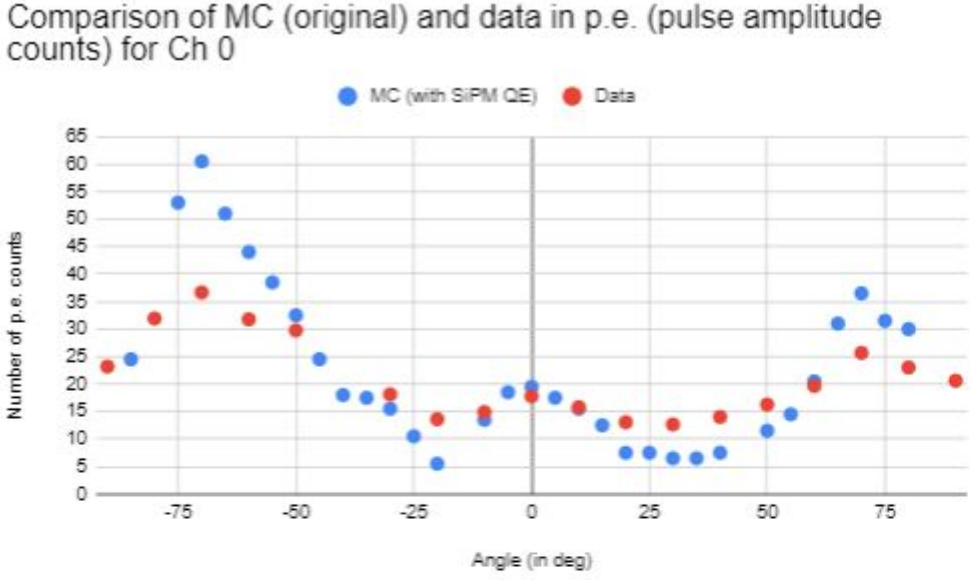



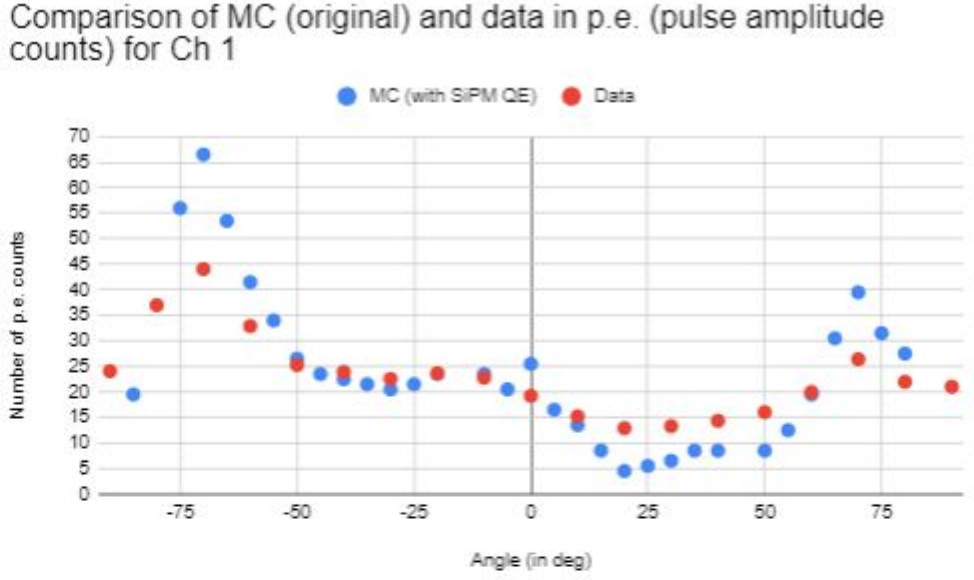

Viewed from the left side

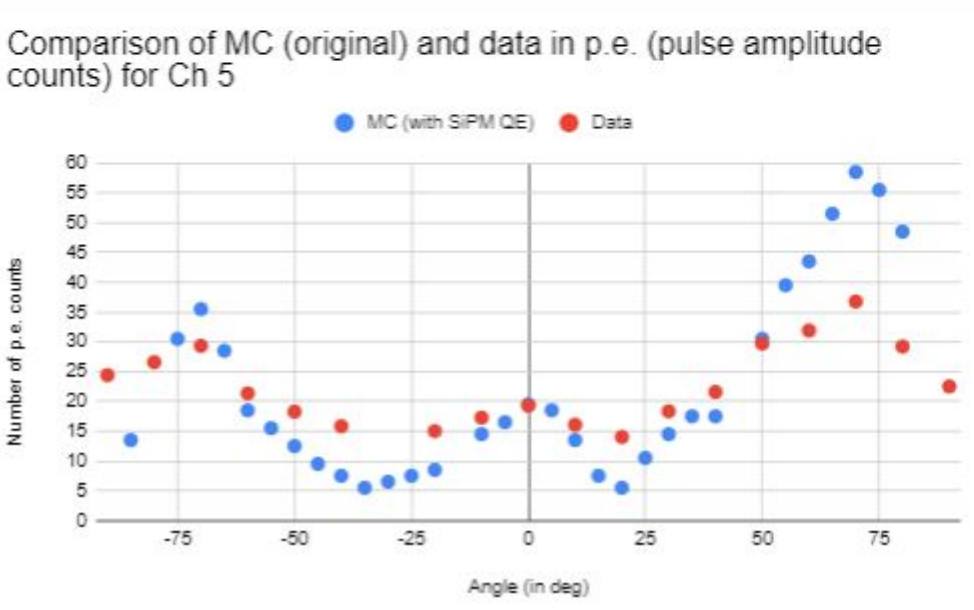


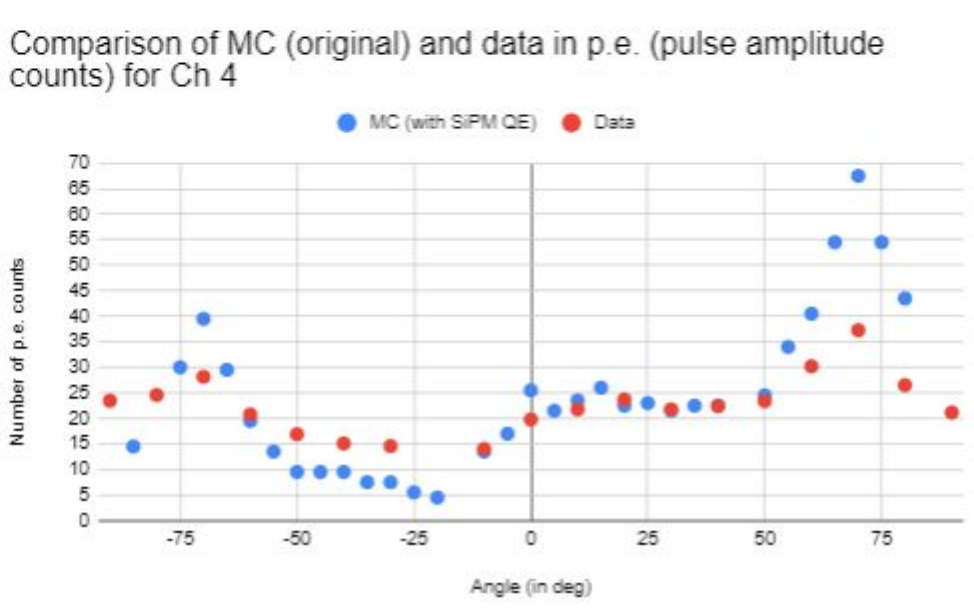

Viewed from the right side

Old result - Channelwise Comparison of original simulation with median from MC and median of pulse amplitude counts from data (with a conversion factor of 3 ADC counts / p.e.)
Even though there are 8 channels only 4 will be compared to avoid redundancy between correlated pairs of channels

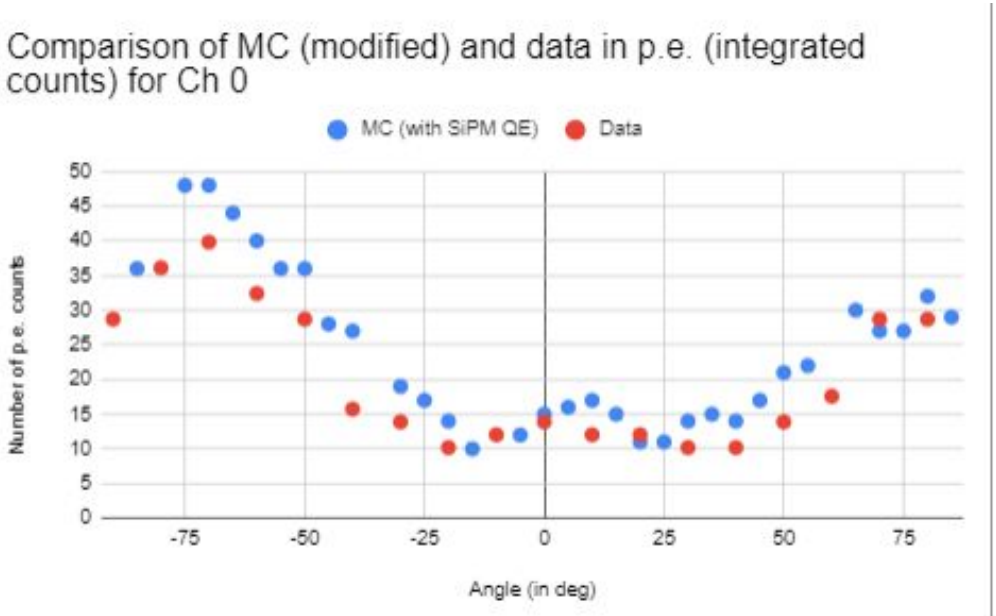


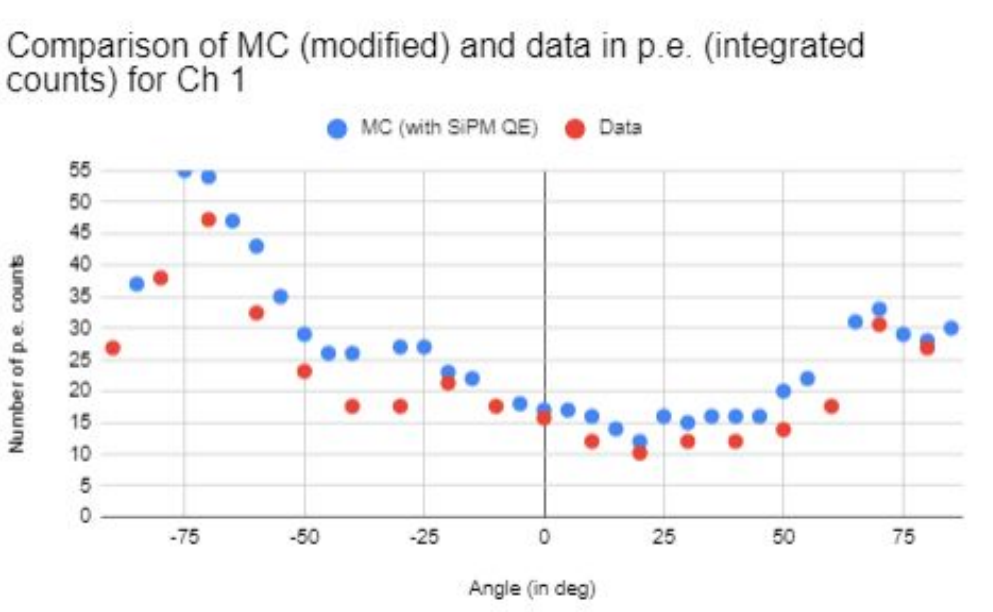



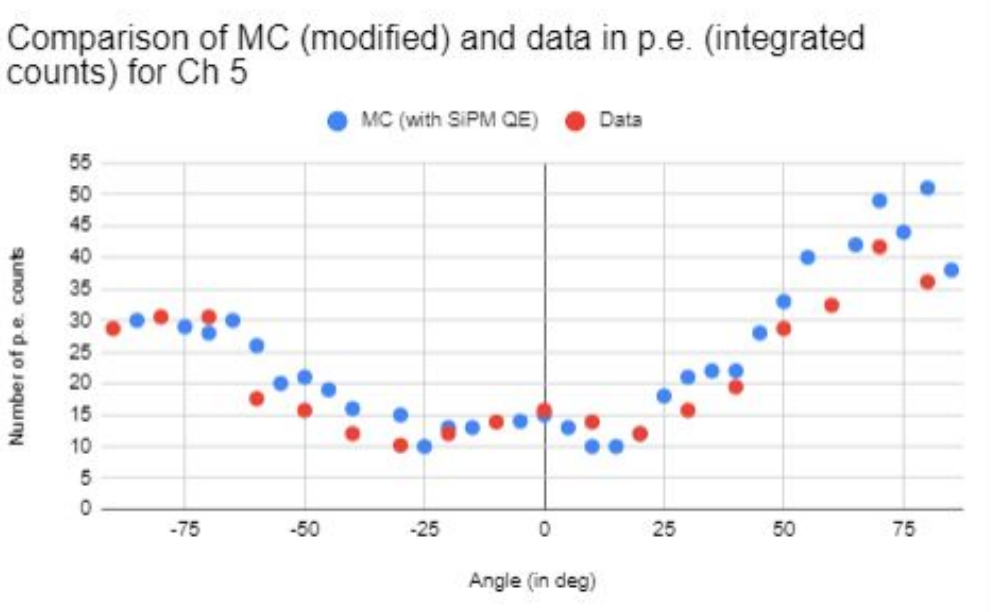



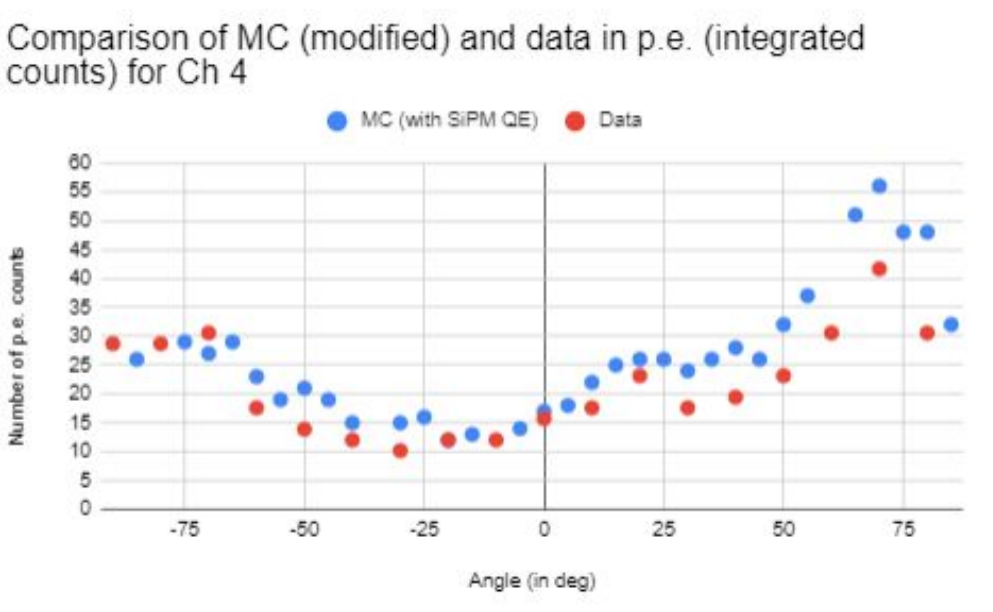



Current best result - Comparison of MPVs of MC and integrated counts from data with some cuts applied (pulse amplitude>5*noise) and a conversion factor of 67.5 integrated ADC counts/p.e.



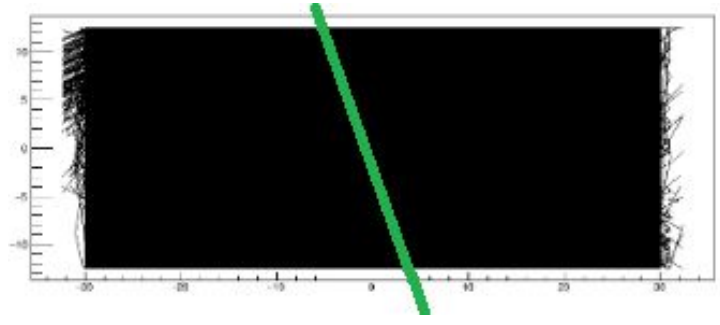



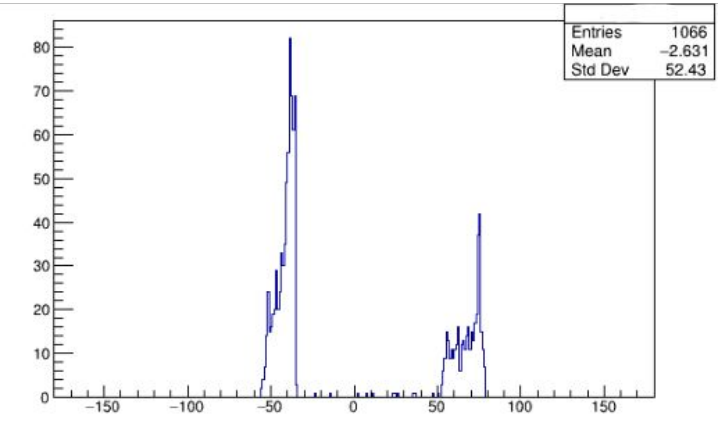
# Modifications made to the geometry for simulation

- Checked geometrically and with event displays why the counts were so low in the 20 deg region (slide 7-13)
- Introduced roughness at the long faces to increase counts in the 20 deg region (slide 14-15)
- Explored the effects of changing proportions of types of reflection (slide 18-23)
    - Did not bring about the desired difference in the regions of the higher angles
- Changed different parameters to try to decrease the counts in the ±70 deg region (slide 24-38)
- Changed the degree of roughness to check the extent of changes in counts (slide 39)

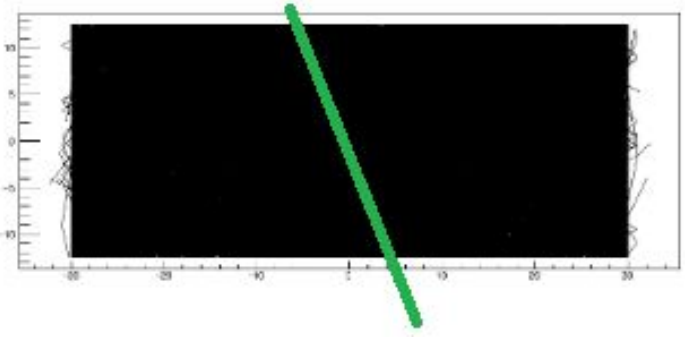
## Recap - Geometrical check

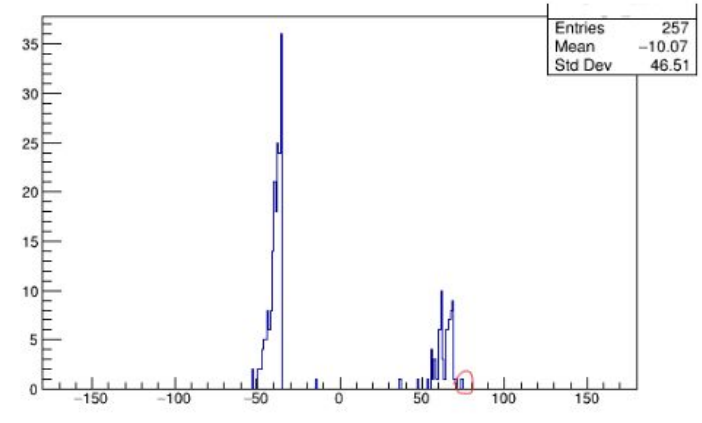
- 1 event for -20 deg and 1 event for -10 deg for comparison (the generated photon counts are such that they are slightly less than the median value, and do not belong to the Landau tail)
- The cuts on the tracks are:
  1) Photons hitting the top surface at their first reflection (these are the ones that are included in the emission cone and in the display profile)
  2) Cut 1) and hitting the left face of the crystal (z = -30 mm) in the region containing the near side SiPMs (y=-1.25 mm to y=-7.25 mm) at some stage in their trajectory
  3) Cut 1) and hitting the grease (z = -31 mm) and y=-1.25 mm to y=-7.25 mm) at some stage in their trajectory
- Also the distributions of the angles of the first steps of the tracks wrt the normal to the top face (+y direction) - the ones going to the right side have a -ve value, and a +ve value assigned for the ones going to the left side





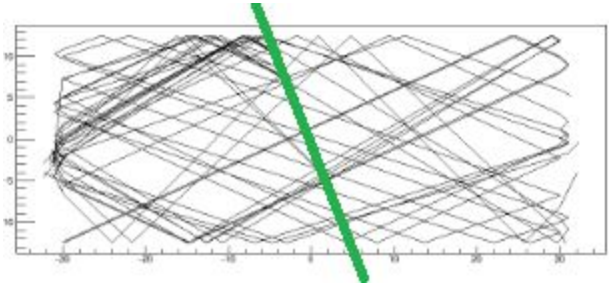

(1)

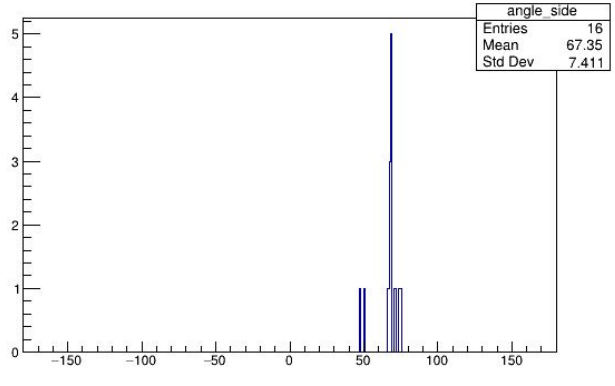





(2)

Most of the ~76 deg peak reduced, which is expected if we consider direct y reflections

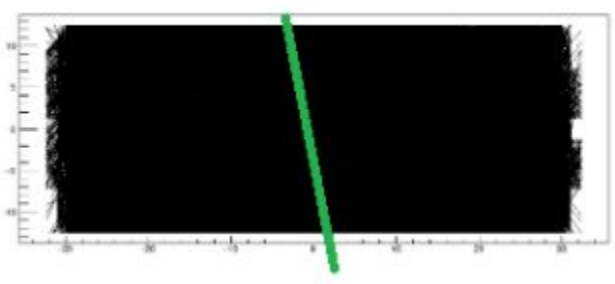


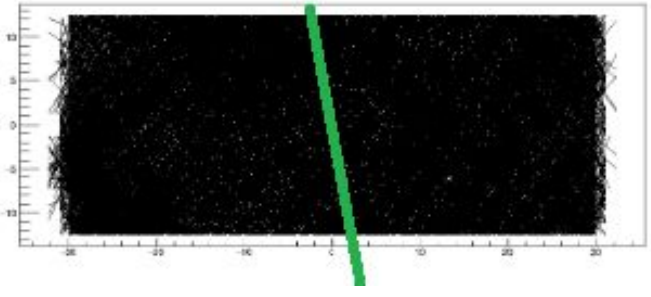


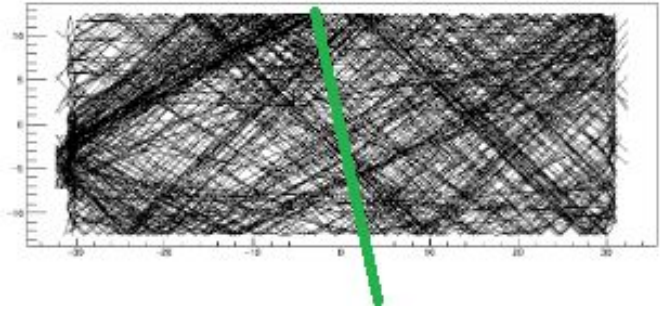

(3)

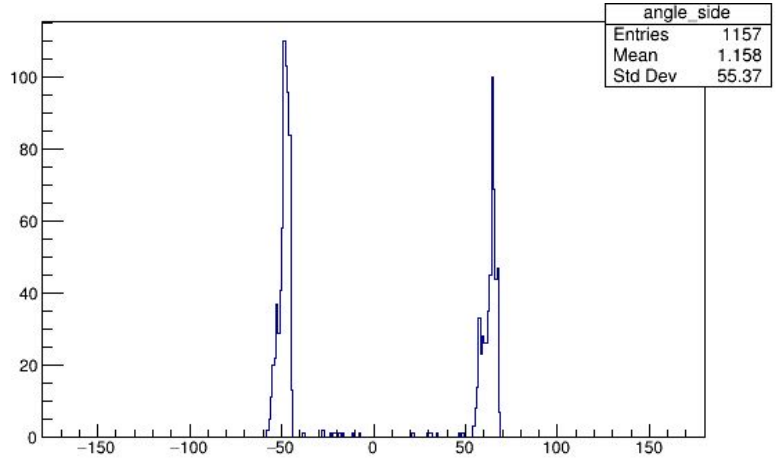
The right side (-ve angles) peak filtered, due to the TIR at the grease - crystal interface (~36 and ~54 deg is the critical angle)

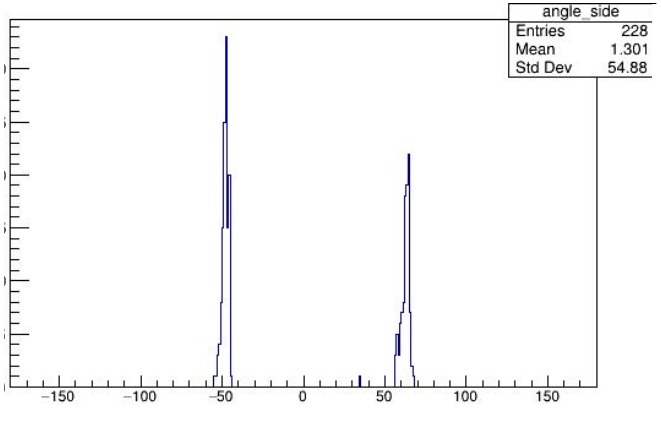
- -10 deg case - 66 deg with mainly y reflections should also not reach the bottom left region (y=-1.25 mm to y=-7.25 mm) so probably more contribution from the x reflections
- But even with a simple geometrical calculation (first order reflections from the top surface) we do have counts from 63 deg reaching there so it is possible

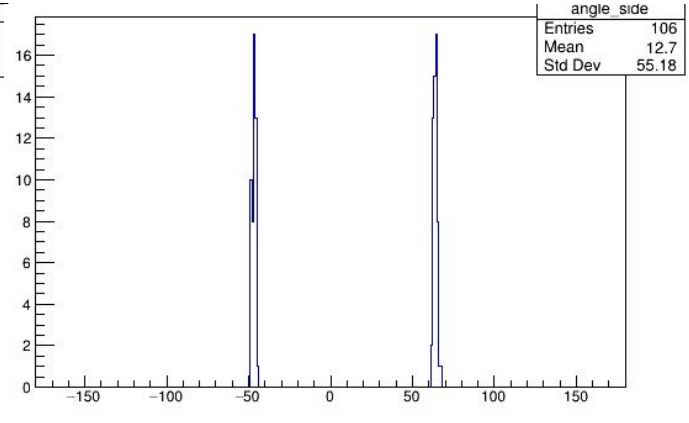








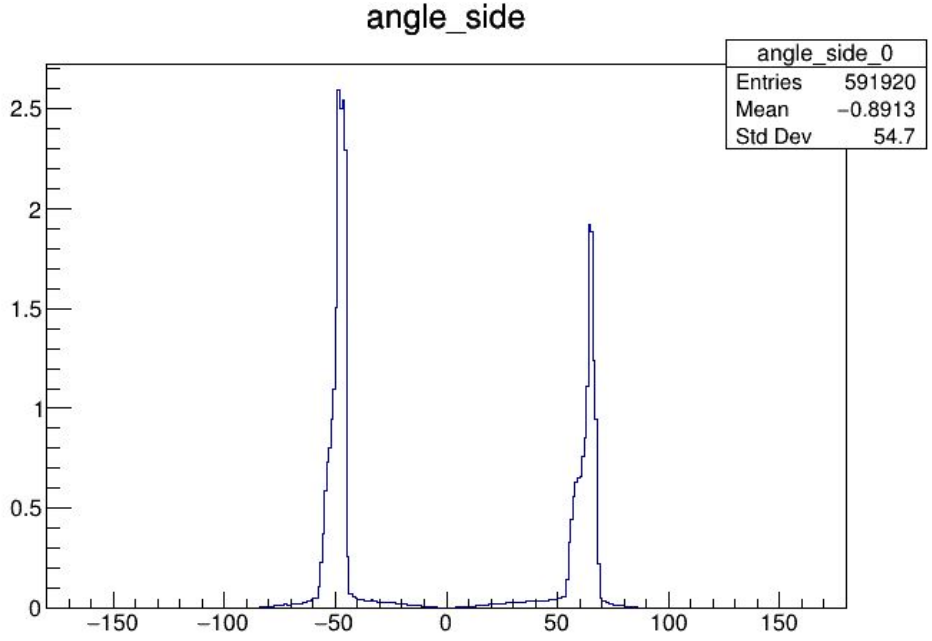



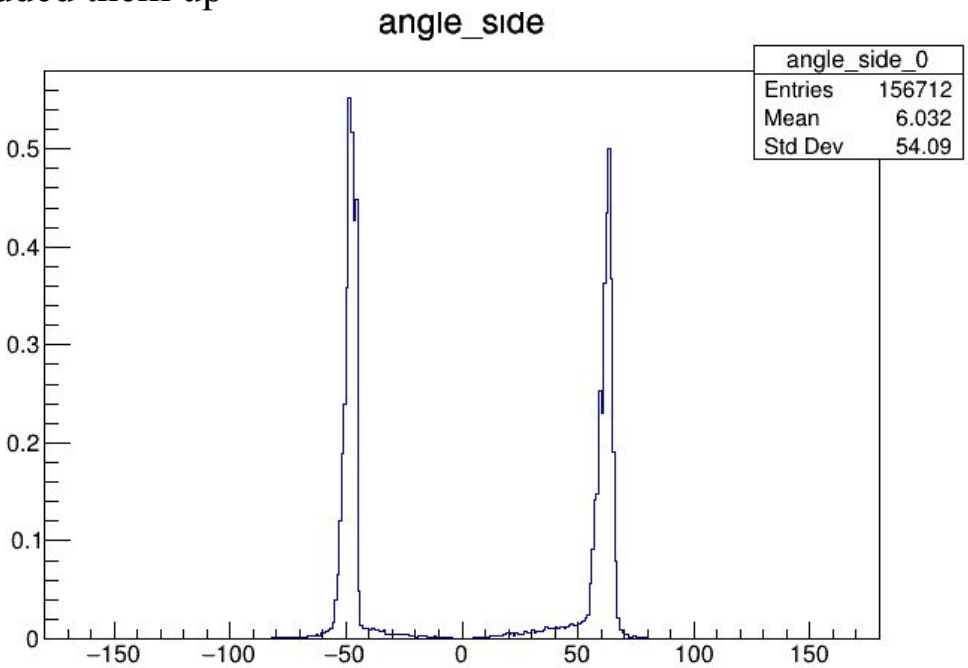

(1) (2) (3)

- Going to check whether this distribution remains similar by averaging over several events

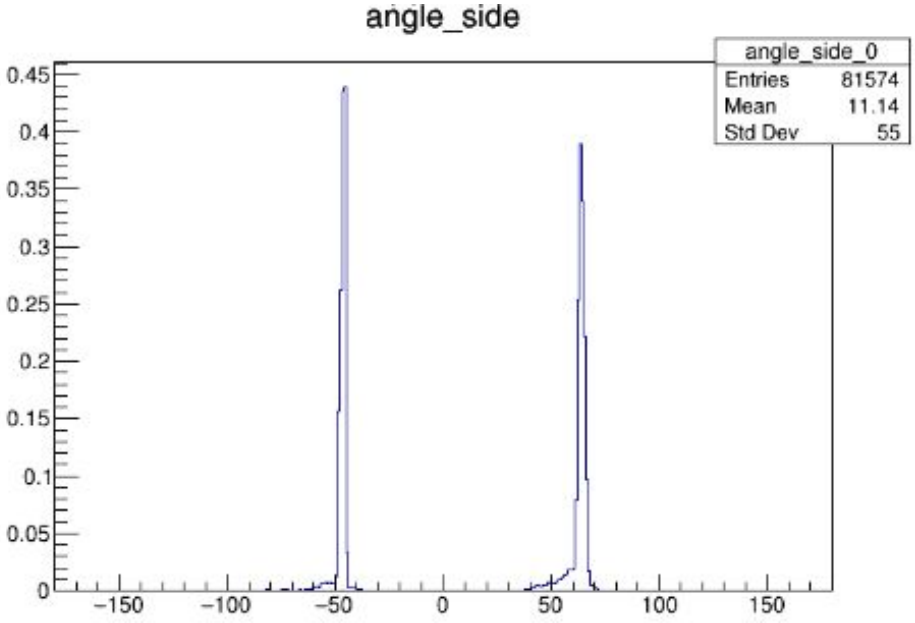
- Angular distribution by combining several events (10, 20 and 30 deg) - Normalized the distribution for each event (of 100 events) wrt the corresponding gen photons and added them up




(1)

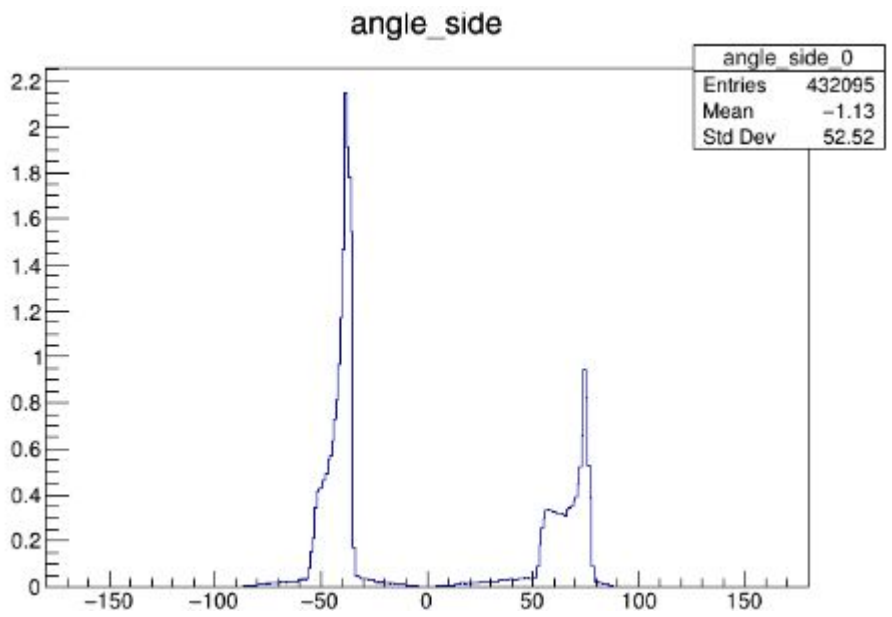



(2)

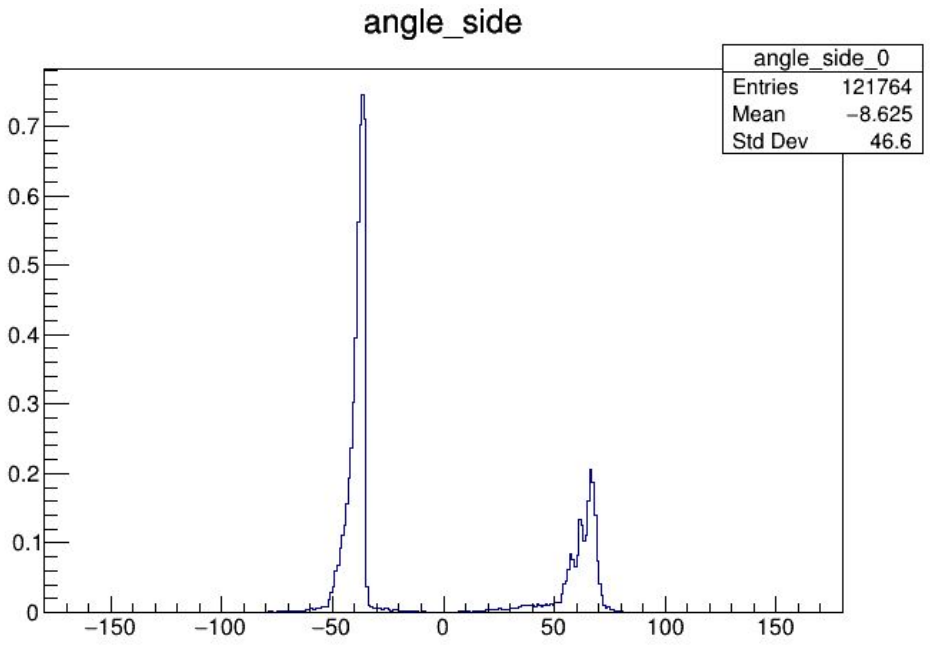



(3)

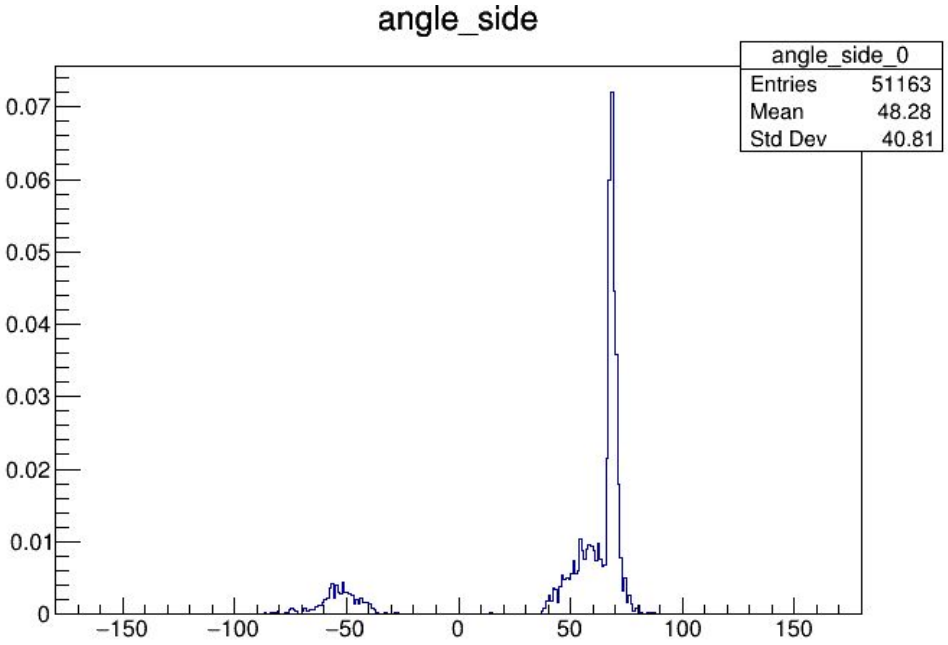
10 deg incidence




(1)

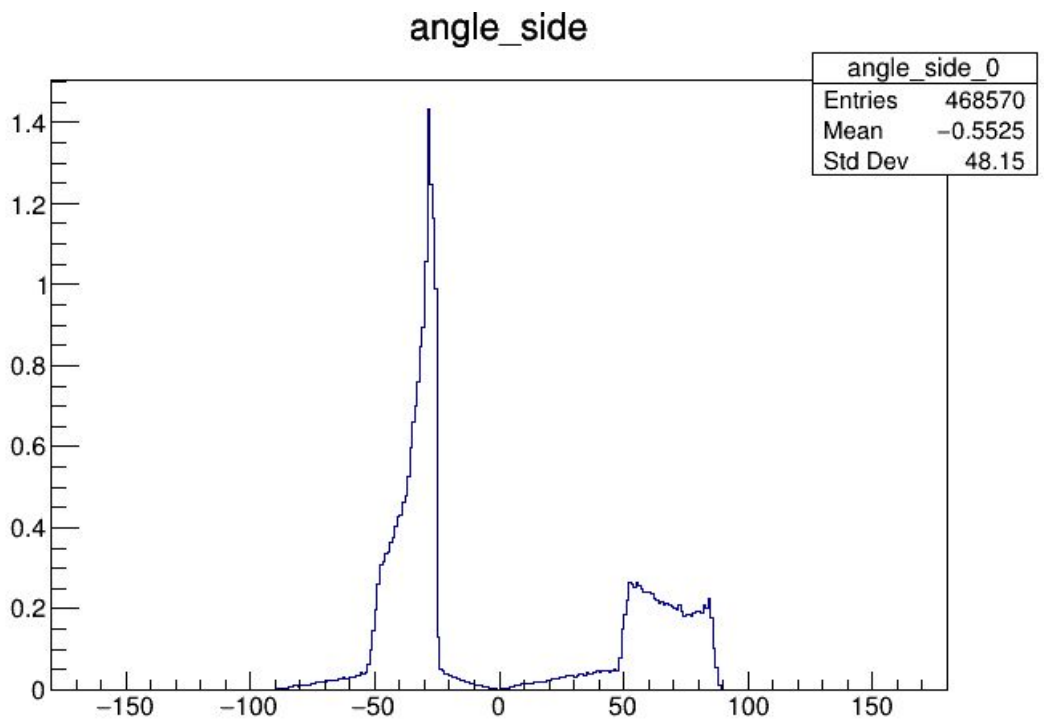



(2)

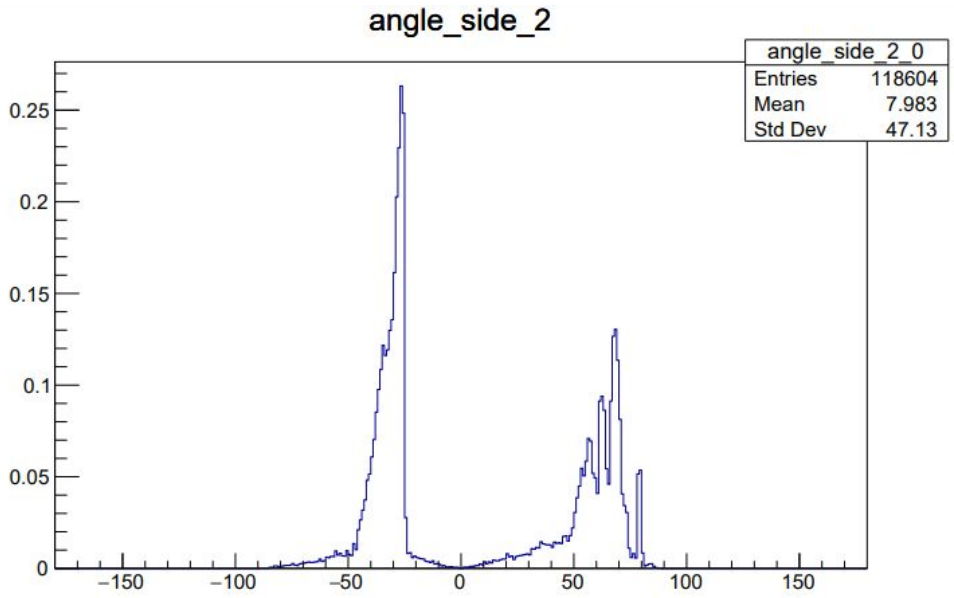



(3)

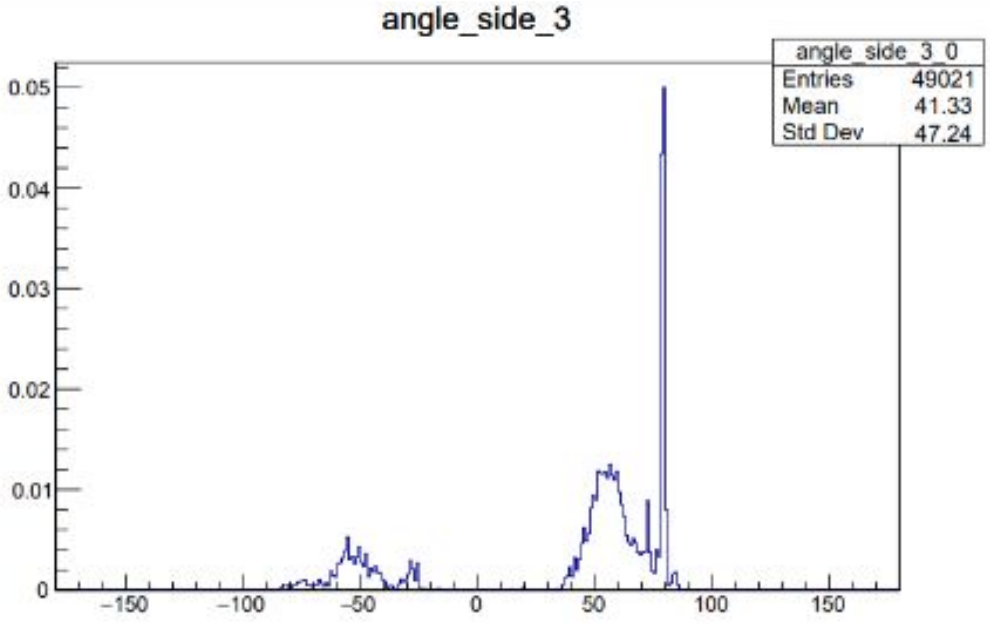
20 deg incidence (Confirms the absence of the ~76 deg peak as observed for the 1 event case, in going from cut 1) to cut 2))




(1)



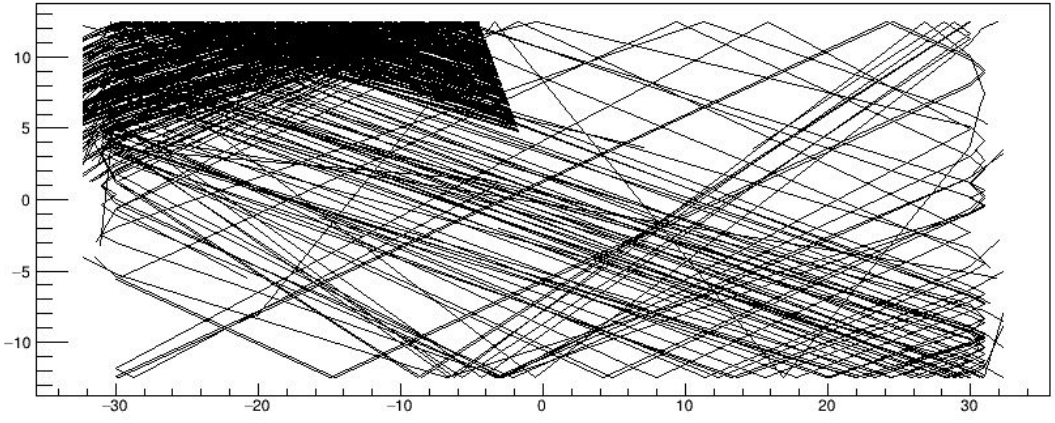

(2)



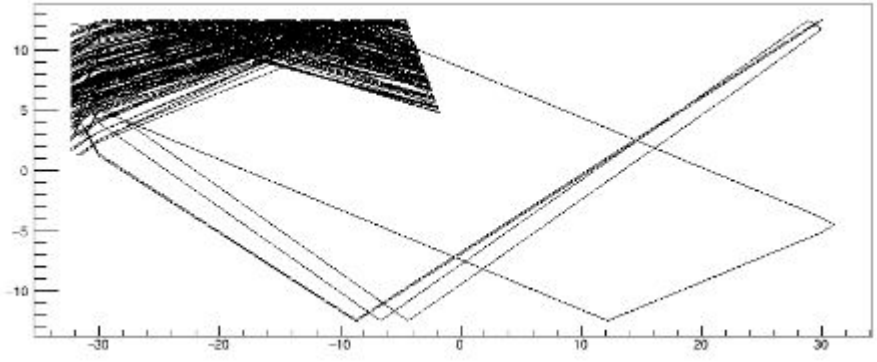

(3)

30 deg incidence (The 76 deg peak persists in the 3rd cut, could be reaching the face of the crystal in cut 2 due to subsequent reflections at the perpendicular long faces)

- Even then the counts from the disappearing peak (~70-80 deg for the 20 deg incidence case) could increase if the absorption lengths were increased because all the counts reaching the top region might eventually reach the bottom SiPMs if they were reflected enough
- To verify whether this is true, tracked the photons starting at an angle ~70-80 deg wrt the normal to the top face and ~70% reach the top region and escape into the SiPMs or into the air
- Only ~15-max 25% of the counts actually get absorbed in the crystal

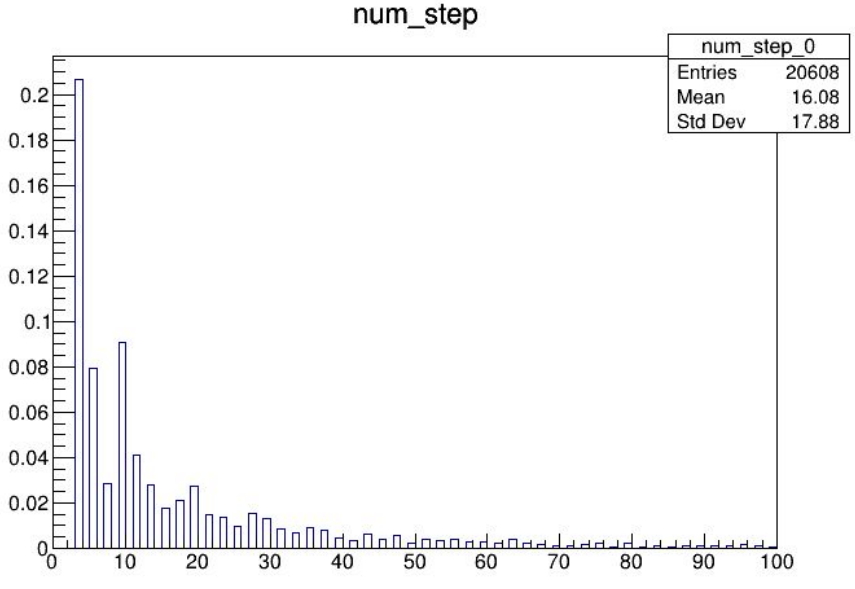


Number of tracks starting at 70-80 deg (176)

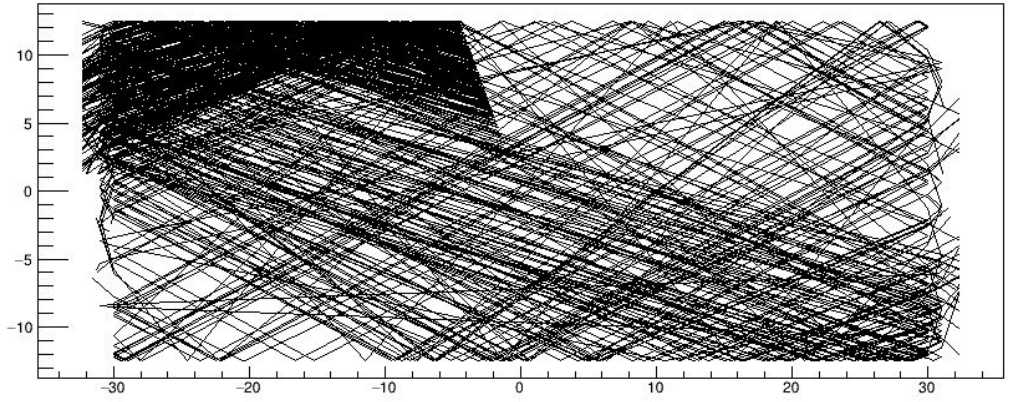


Number of tracks ending at the top left region (122)

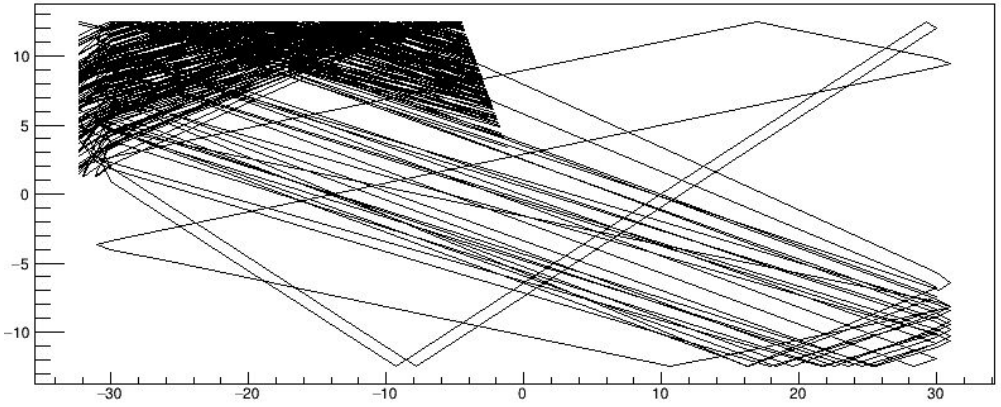
Histogram of number of steps for photons ending inside the crystal for 100 events (Normalized wrt number of gen photons for each event and added up) - Contrary to my expectation the MPV is at a quite low step number - 3



- On increasing the absorption lengths to 10 times the original ones, the proportion of photons reaching the top region is the same but that of the ones getting absorbed and terminating inside the crystal has reduced

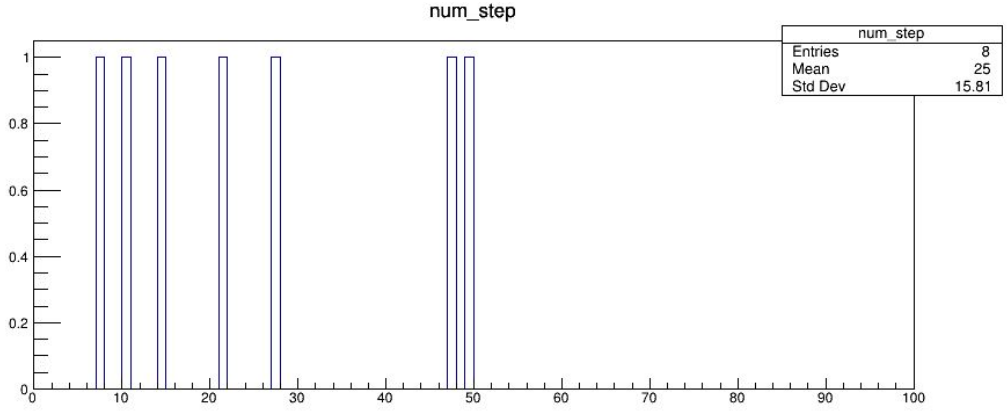



Number of tracks starting at 70-80 deg (212)



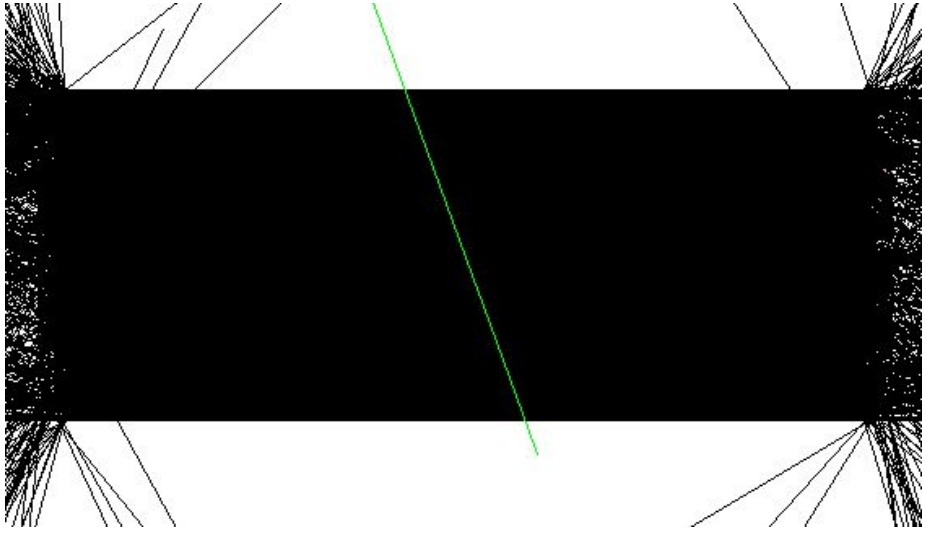

Number of tracks ending at the top left region (149)

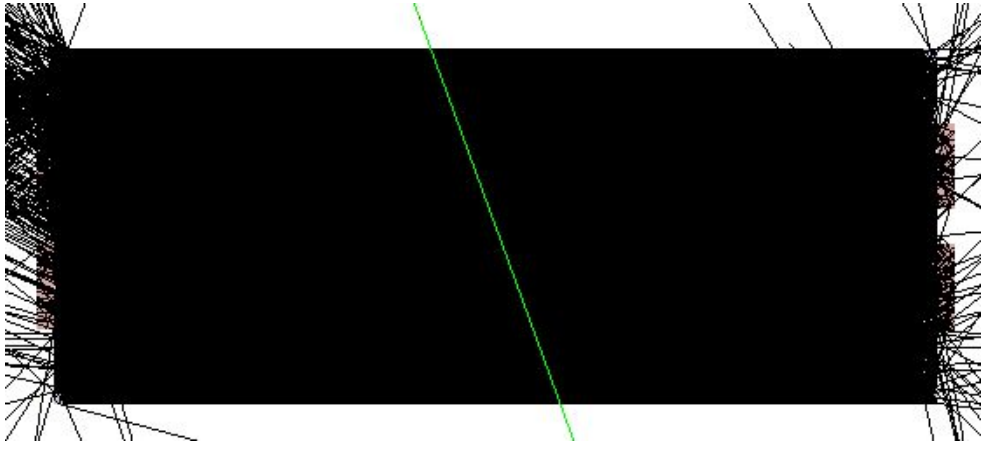
Histogram of number of steps for photons ending inside the crystal for 1 event
Count has reduced from 29 to 8 and the MPV for number of steps has also increased



Changing parameters of the model in the simulation to bring it closer to data

- Adding a rough surface to increase the minimum counts in the near side channels
- Currently using unified ground dielectric-metal at the 4 long faces of the crystal [This includes the model, type and finish of the optical surface]
- Since the variation of surface roughness is applied when the reflection type is specular lobe, put specularlobeconstant to 1.0 and reflectivity to 1 (100% specular lobe reflection) and also compared to 100% specular spike reflection (no widening of angular distribution after reflection)
- Example of event display for specular lobe case (sigma alpha - roughness parameter set to 1 rad) vs specular spike case for -20 deg proton incidence



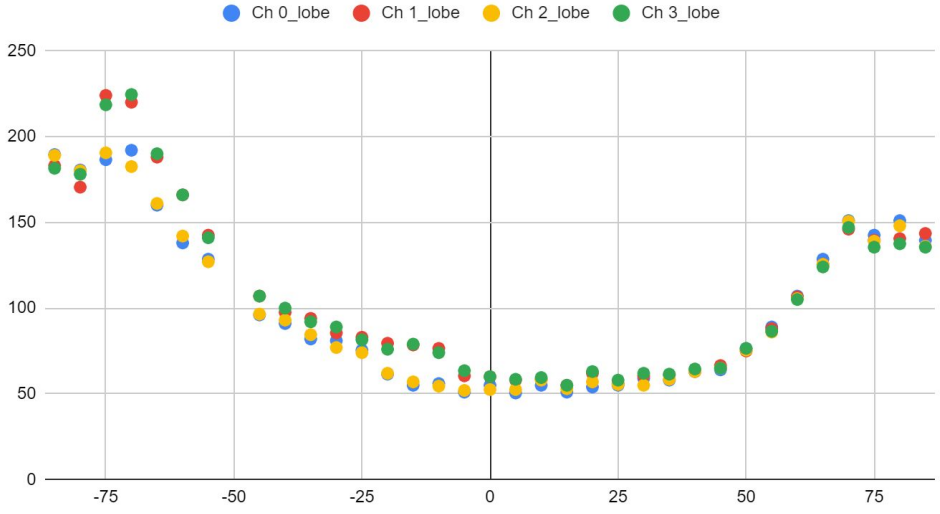


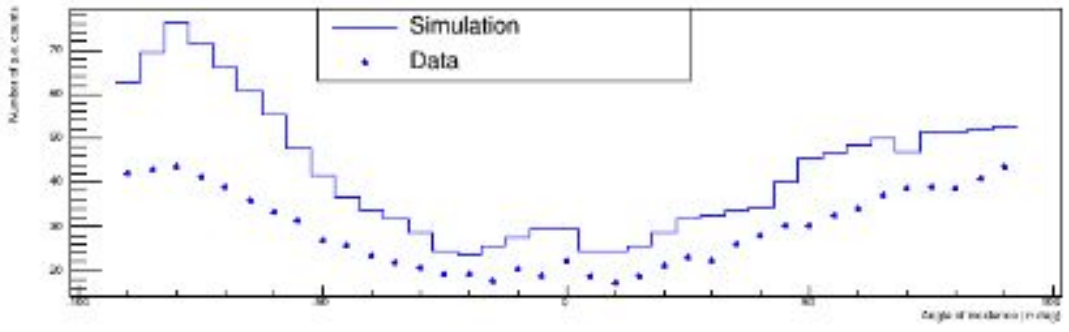
[Ch 0 counts]=**61 -** bottom left
[Ch 1 counts]=67
[Ch 2 counts]=**50 -** bottom left
[Ch 3 counts]=77
Much less difference in counts between bottom and top channels

[Ch 0 counts]=**31 -** bottom left
[Ch 1 counts]=71
[Ch 2 counts]=**23 -** bottom left
[Ch 3 counts]=74

- Comparison of plots before and after introducing roughness in surface - this almost looks a little bit like the scintillation curve (for PbWO4) because with the widening of the angular distribution we would be expected to lose the directionality associated with Cerenkov photons
- This succeeded in increasing the counts in the region from -30 deg to 30 deg but there is still a big discrepancy (MC ~1.5 to 2 times the data in the -70 deg and 70 deg region)

Left side Channels (rough surface - specular lobe)

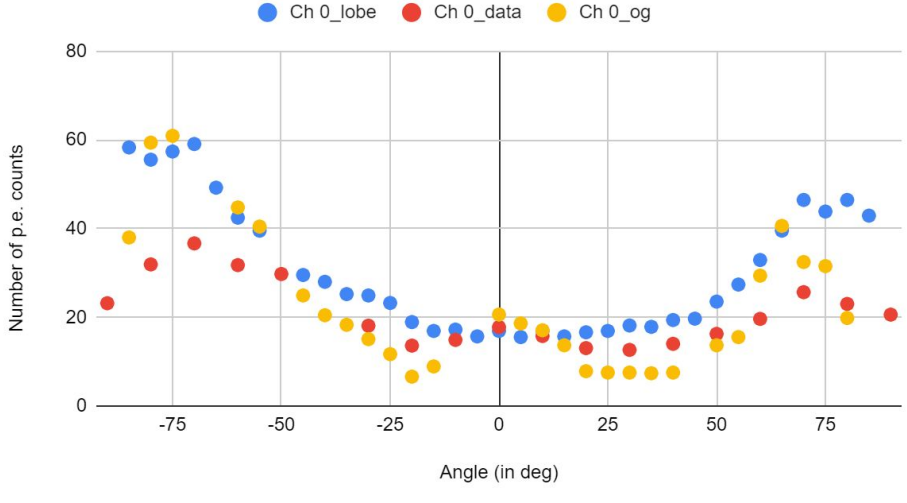


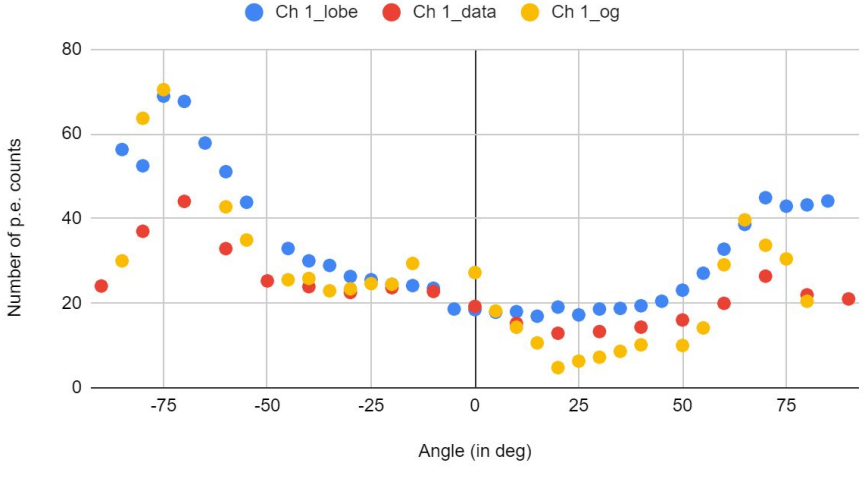

PbWO4 scintillation dominated curve

Comparison with data (scaling down of MC by common factor of 3.25 to mimic SiPM QE)

Comparison for Ch 0 - lobe and spike (og) vs data




Comparison for Ch 1 - lobe and spike (og) vs data

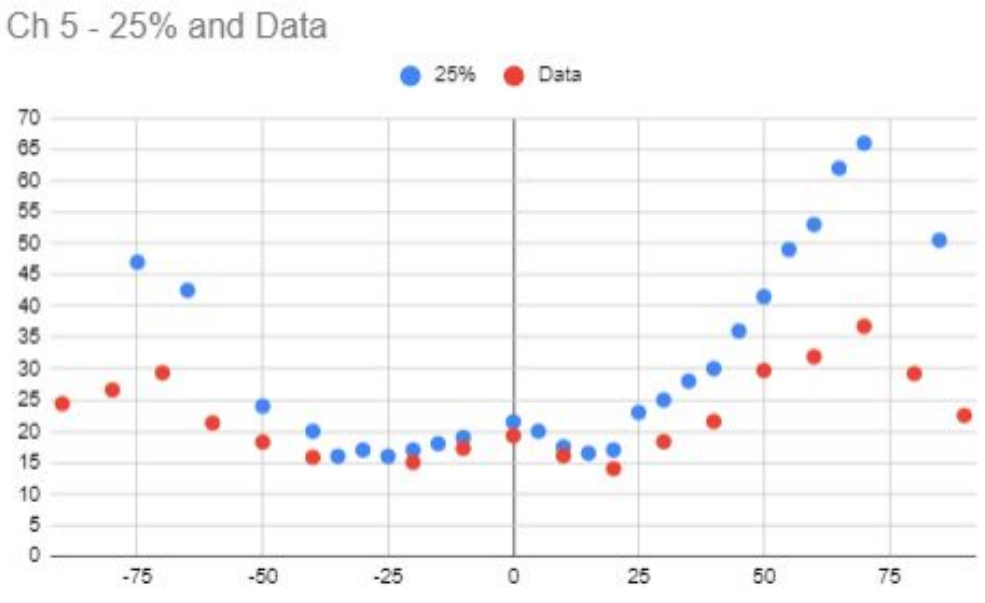


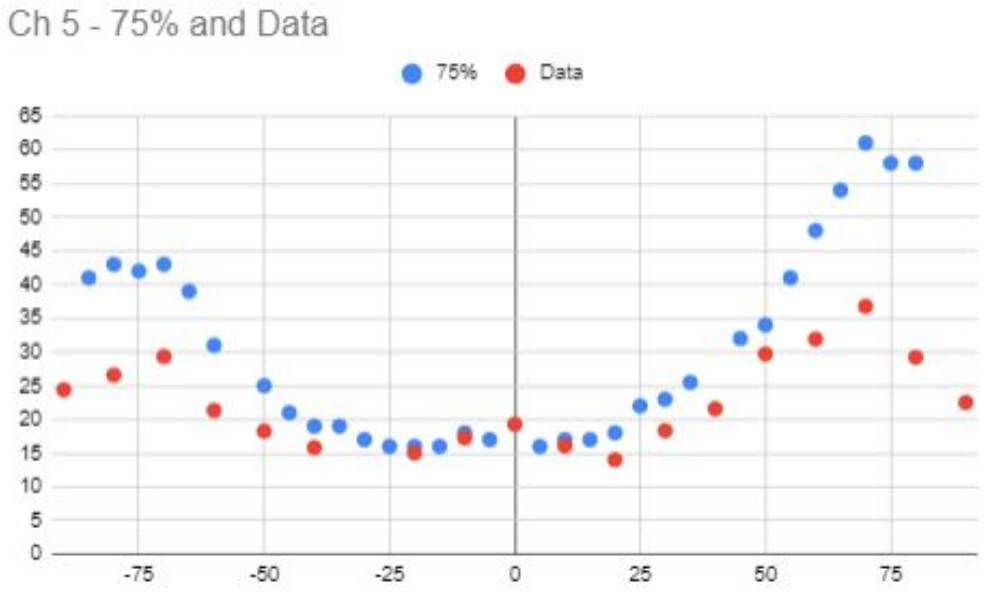
- Also made comparisons with data for different % values of specular lobe and specular spike reflections [Plots in backup slides *18-23*]
- This was done to introduce some variation since at the time it was not clear how to change the roughness with DD4hep
- However (as expected) the 70 deg MC counts will not reduce below the limiting (100% specular spike) case no matter how much the % proportion is changed

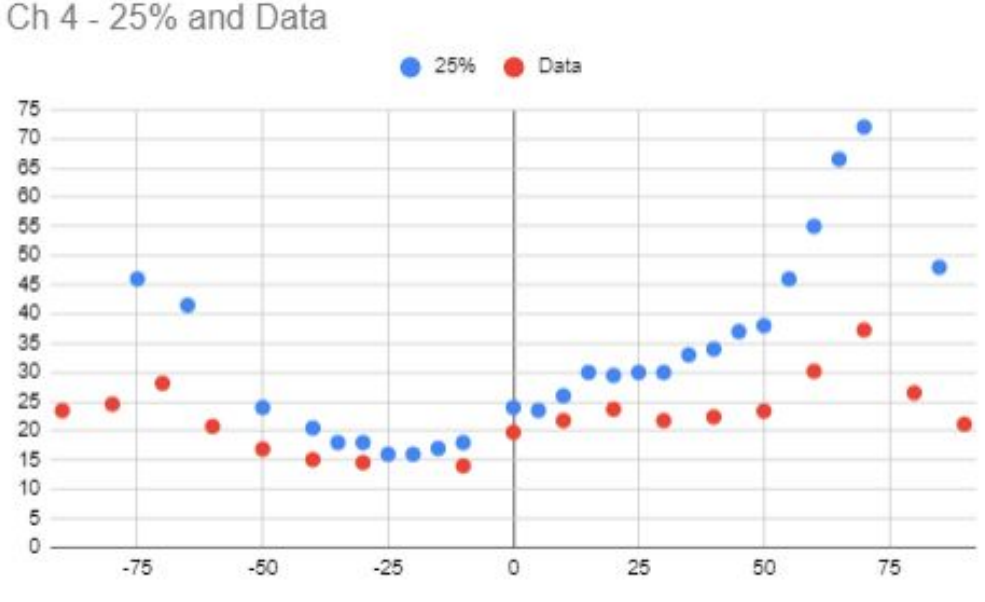
- Other possible ways to reduce counts
- At the **silicone cookie - Air interface** (Explanation for this in backup slides *24-28*)
  - 1) Putting a rough surface so that some of the photons hit the face at less than the critical angle and escape into the Air, so that they do not reflect and go to the SiPMs
  - 2) Reducing the reflectivity at that face (although it seems most of the reflection happening there are through total internal reflection, so not sure whether this can be applied for that process)
  - 3) Adding some material with refractive index higher than Air to decrease TIR (not really representative of the physical situation?)
- At the long faces (**crystal - Air interface**)
  - 4) Again reducing the reflectivity at the 4 faces (this will probably decrease counts for the lower angles of incidence too)
- First implemented 4) and fixed the parameters at the long faces to 25% specular lobe and 75% specular spike reflection to get better match for smaller values of angles
- The current best match between the MC and the data MPV is obtained for **25% specular lobe, 75% specular spike, 95% reflectivity at long face, and smooth surface with 100% reflectivity at the silicone cookie-Air interface**
  - To - do
    - To check how close these parameters are to the physical case
    - Running more events for better MPV and for comparing event wise distribution from MC with data

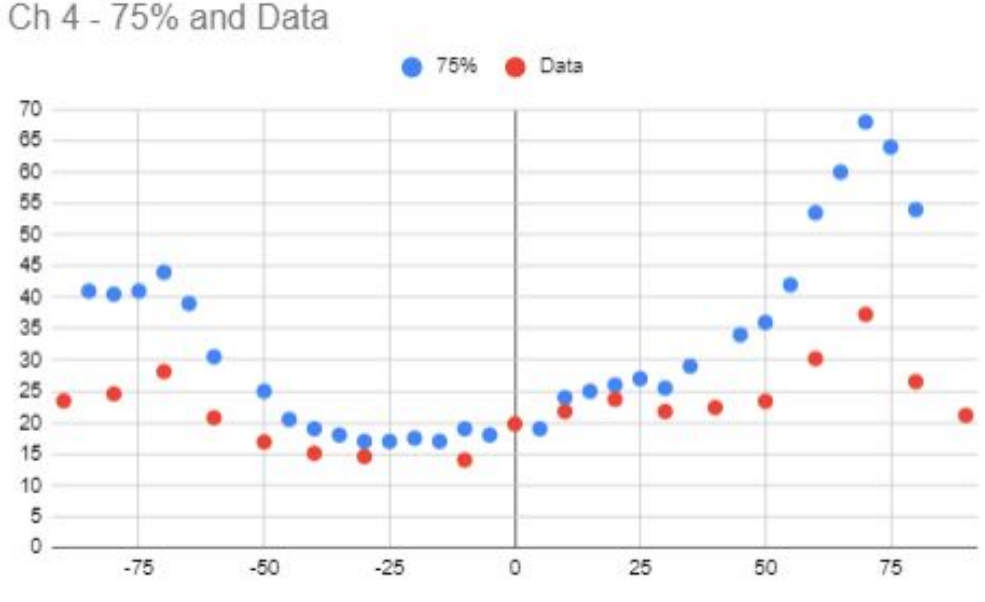
# Backup

Individual channelwise comparison with data - Right side



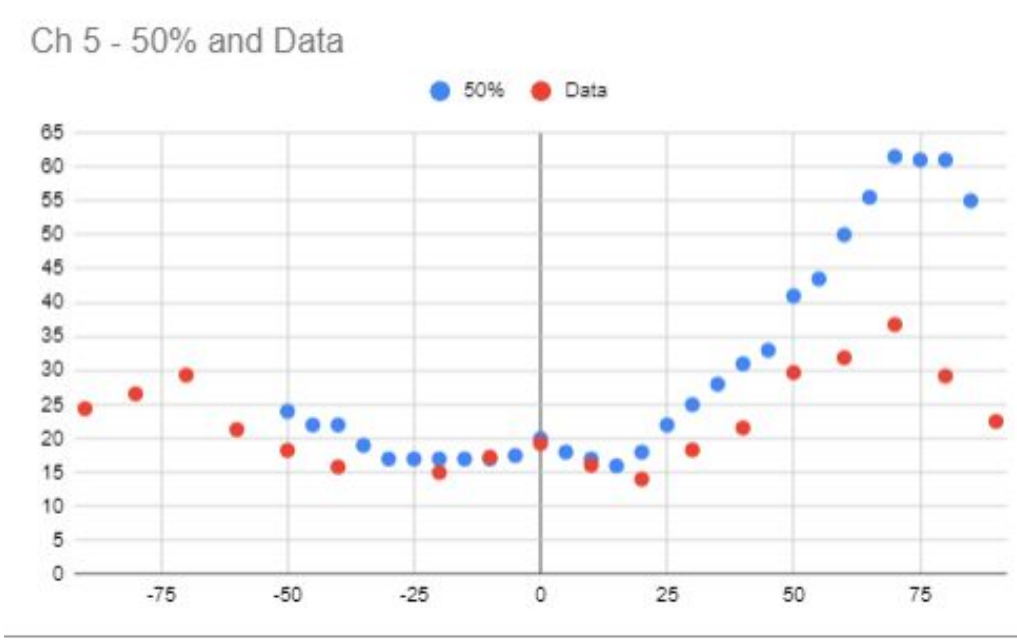



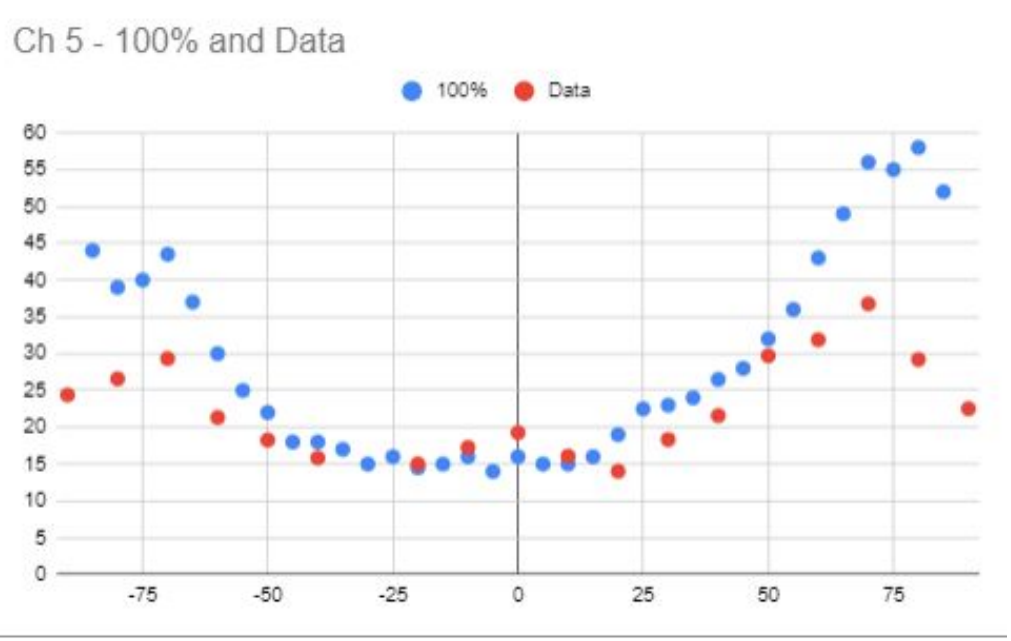



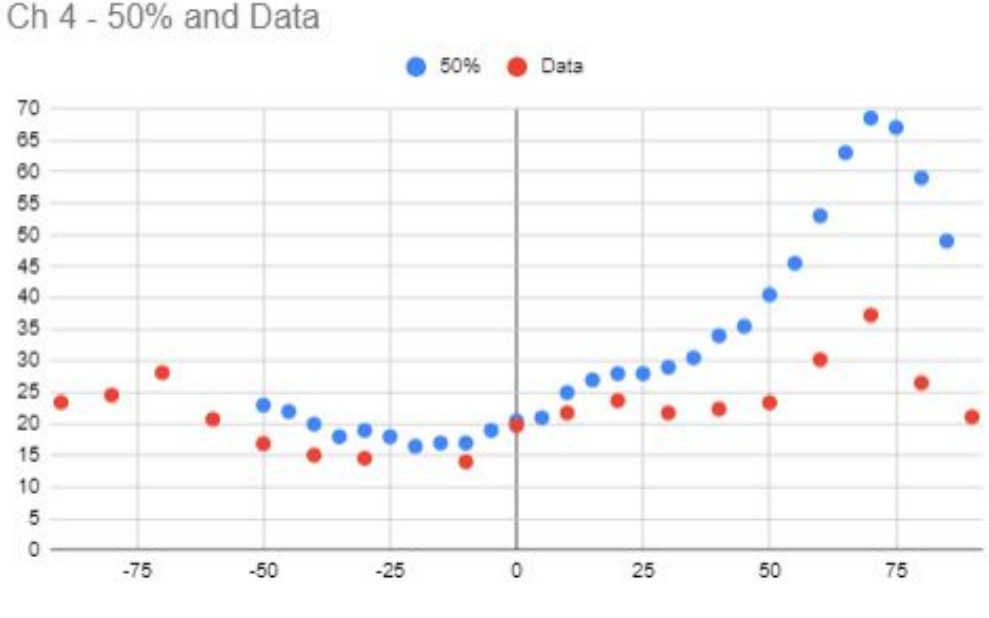



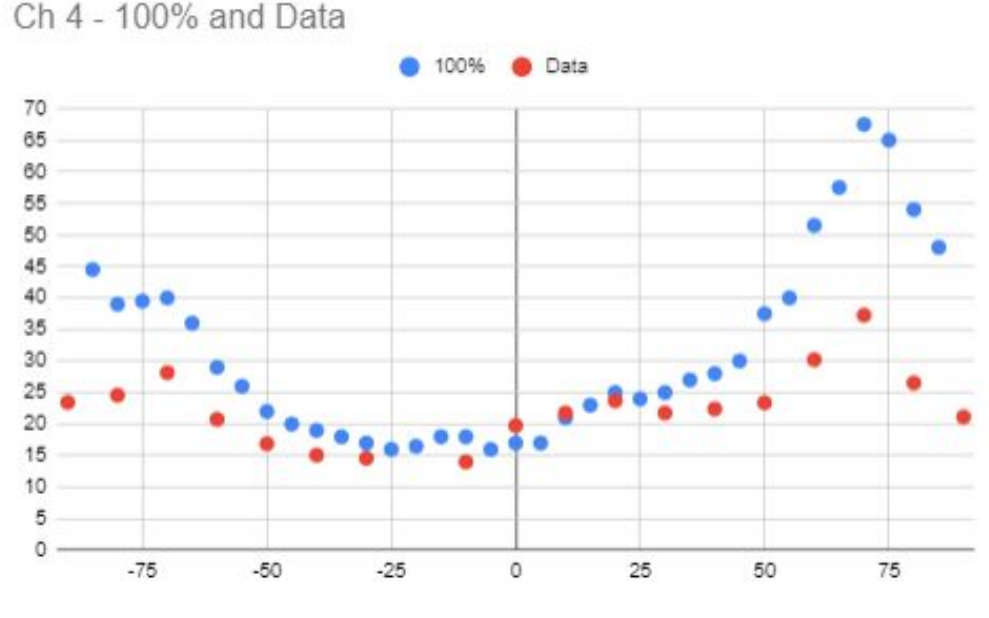

Good agreement seen only in the -30 deg to 30 deg region

- Individual channelwise comparison with data - Right side

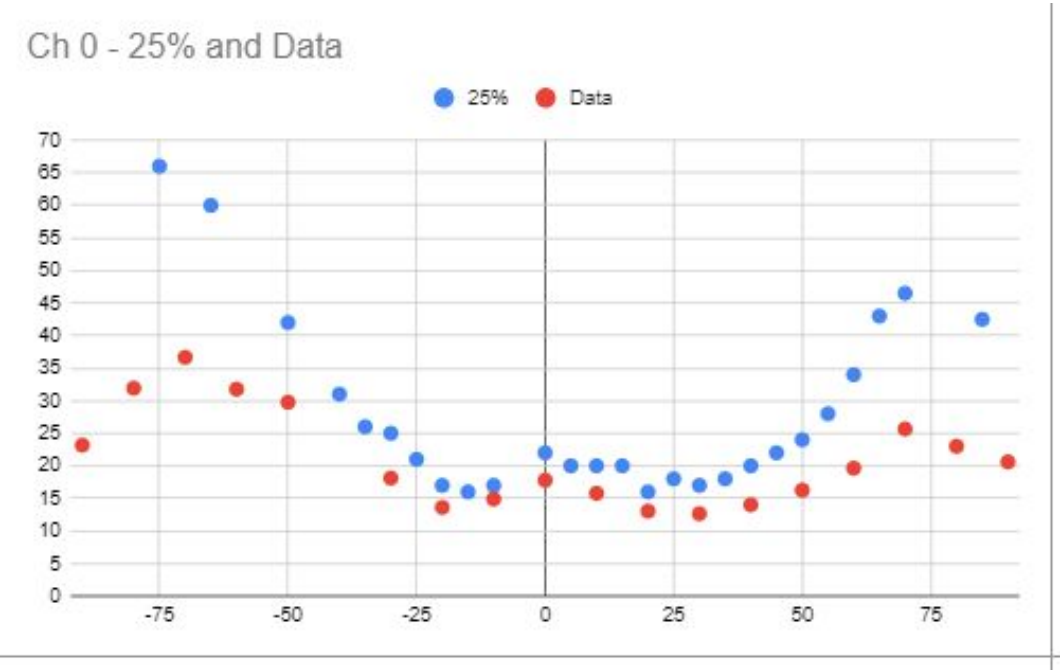


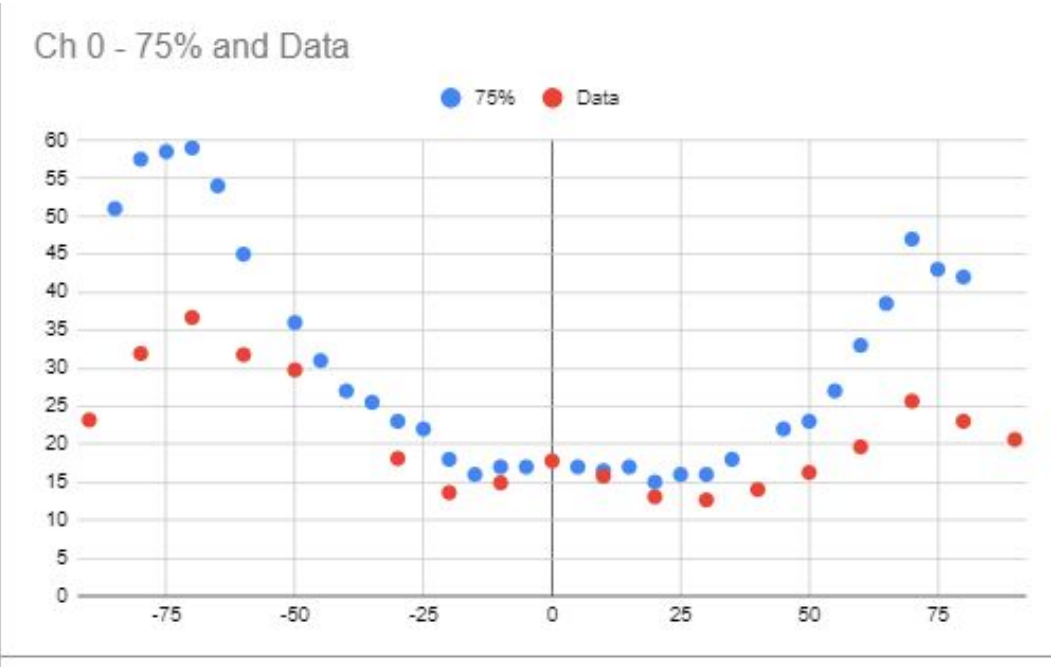



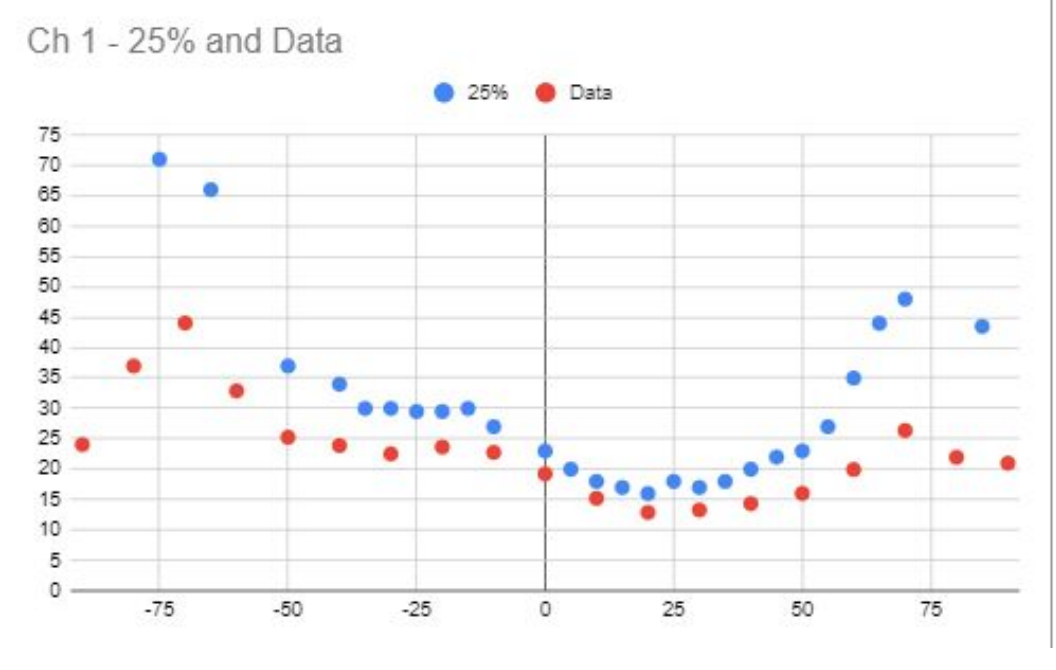



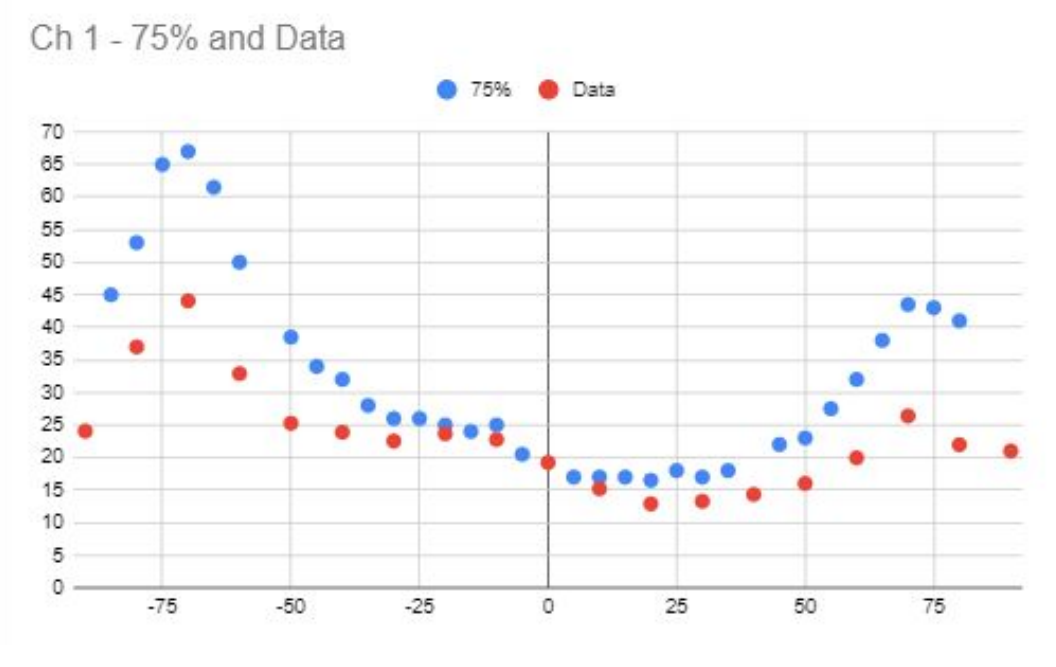



- Individual channelwise comparison with data - Left side

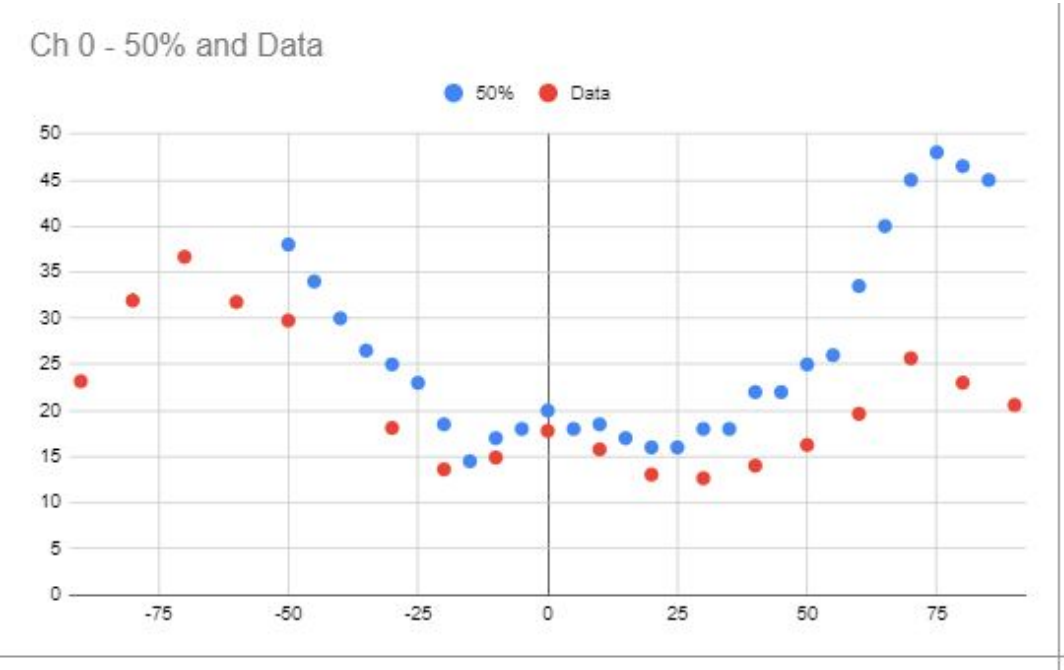


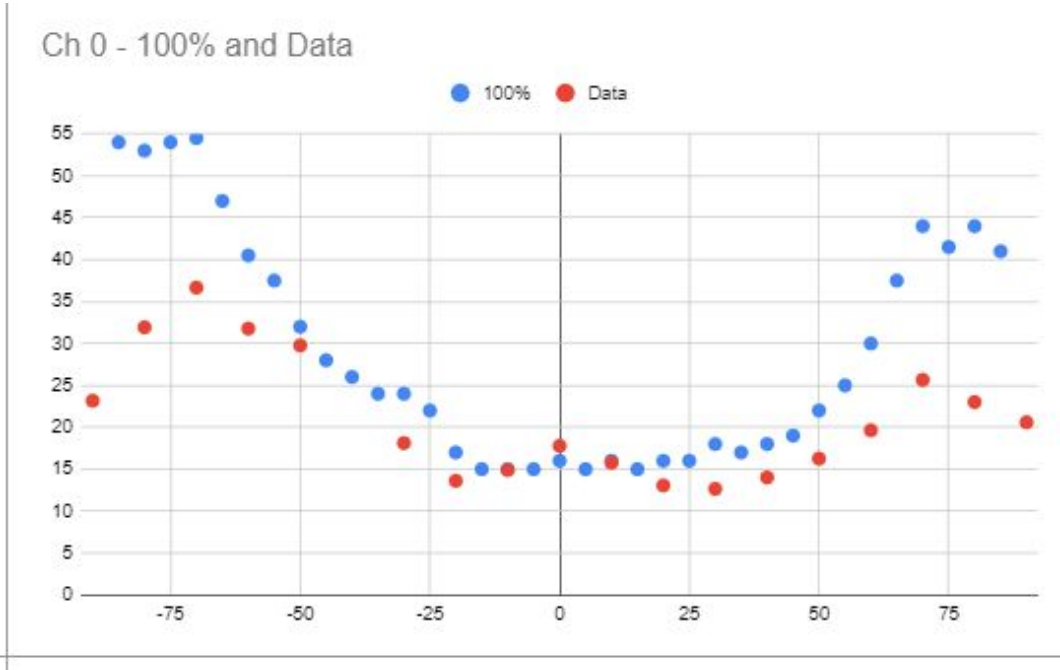



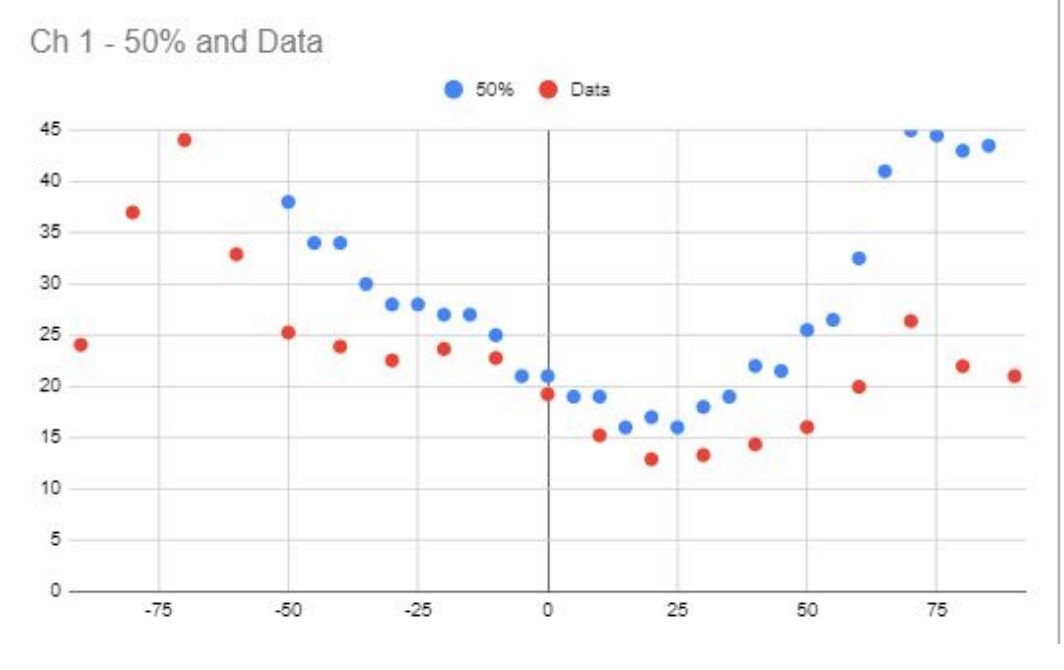



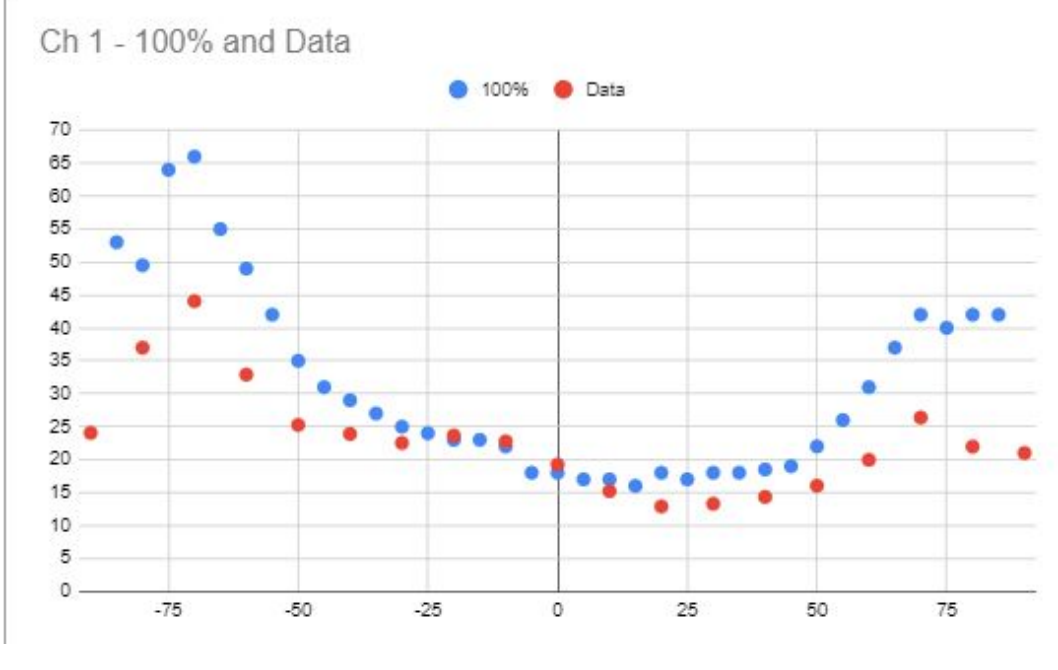



- Individual channelwise comparison with data - Left side

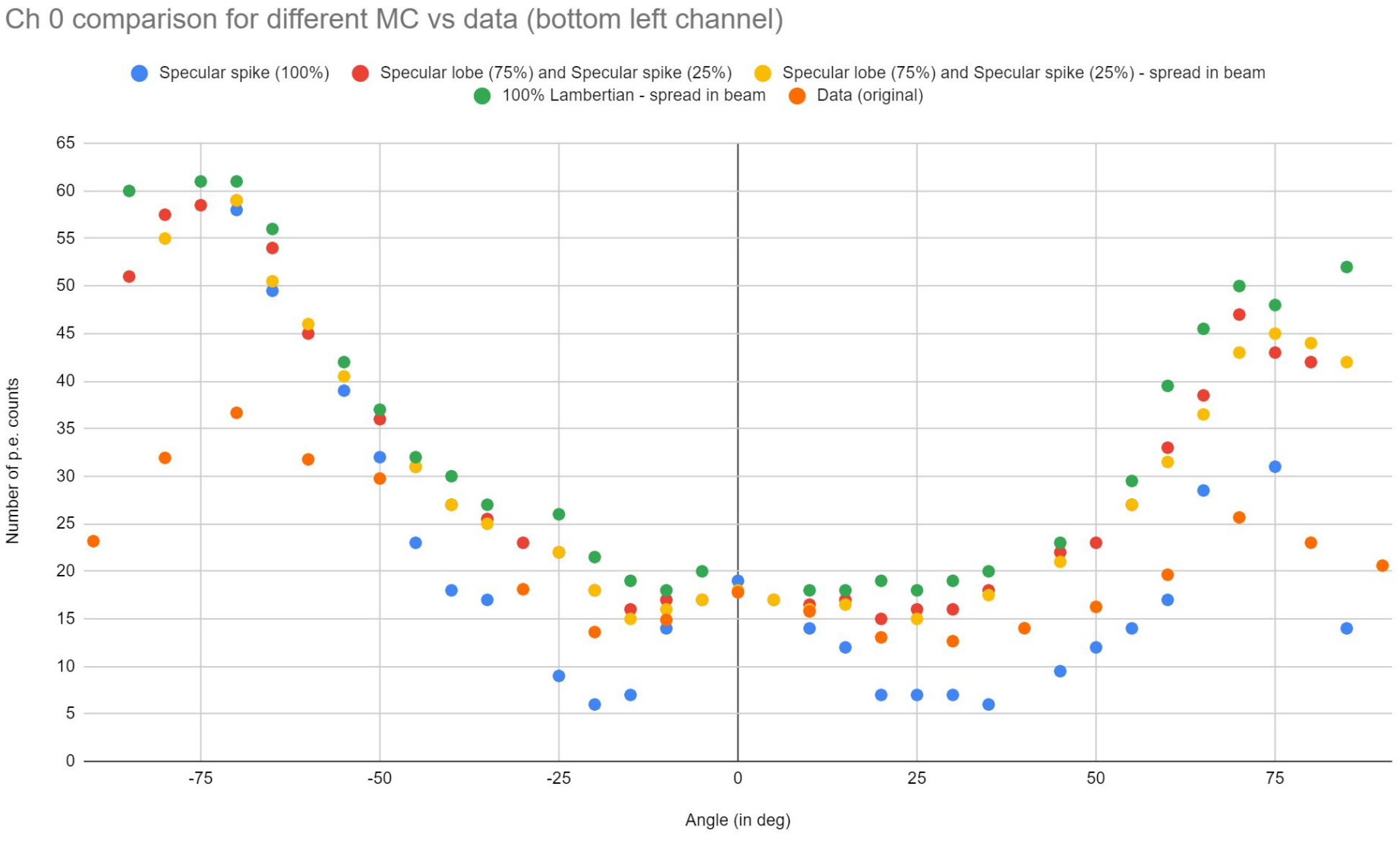


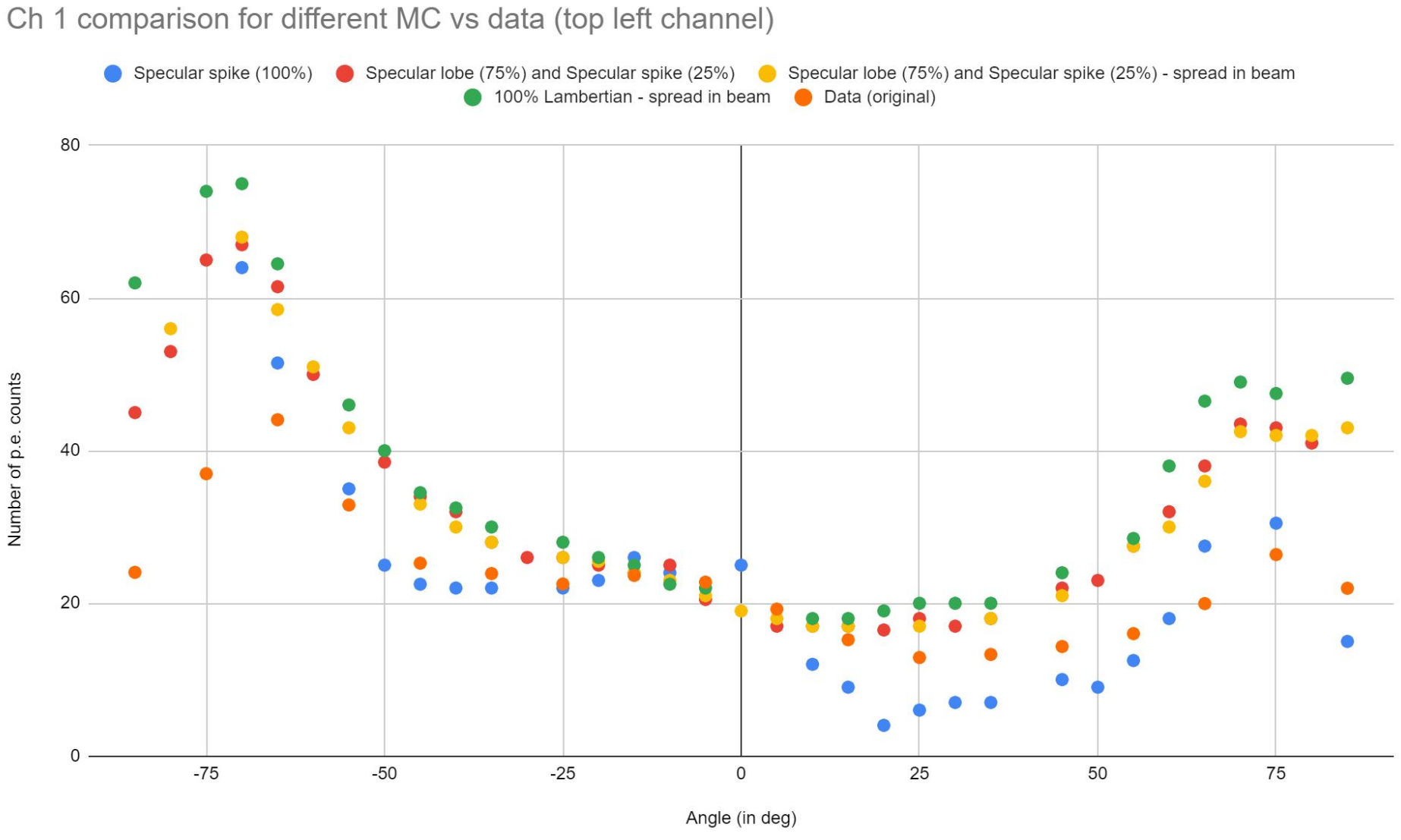



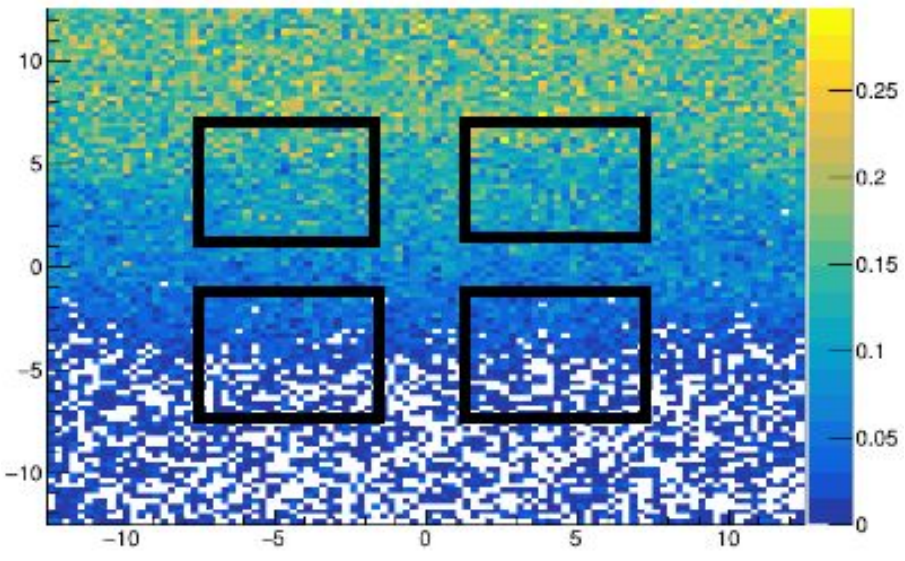
- Channelwise comparison of the different cases with data
- Simulated for some more cases including beam spread and Lambertian reflection



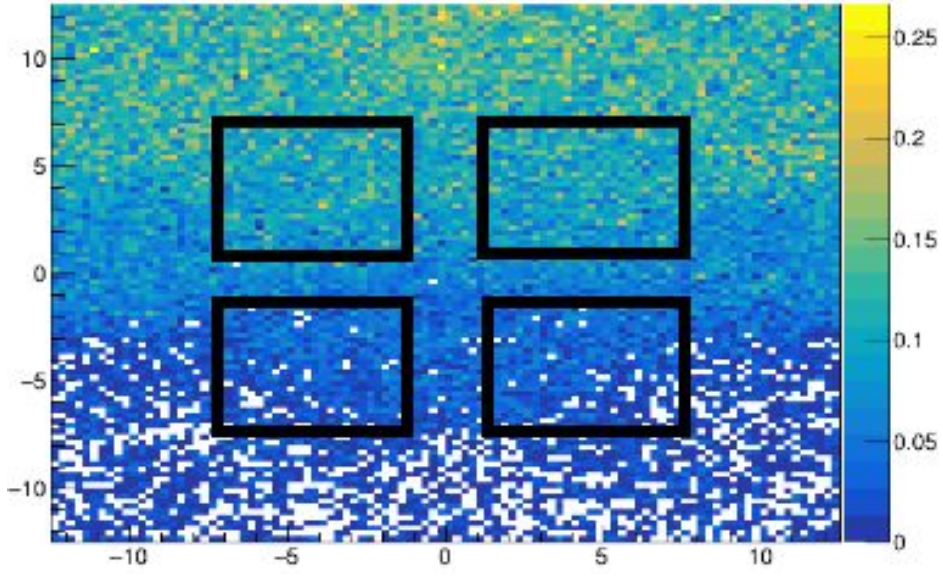
- Channelwise comparison of the different cases with data



- Also ran events with the entirety of the square faces covered with SiPMs and calculating the counts in the relevant regions in the x-y where the original channels are

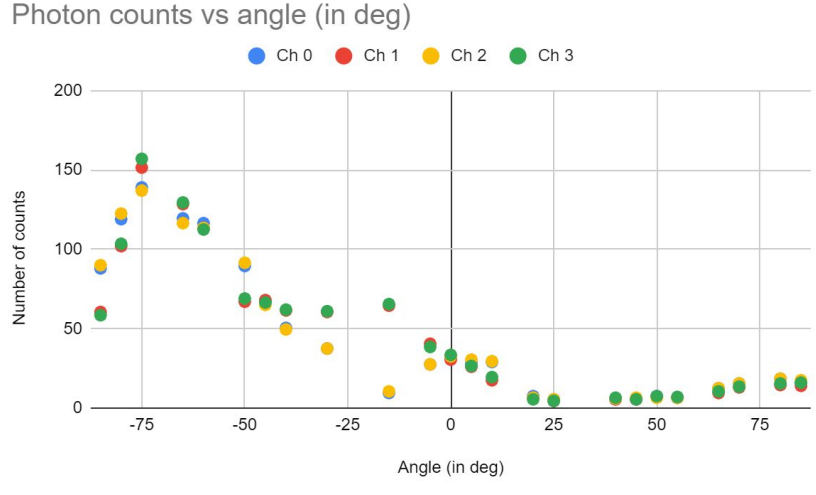


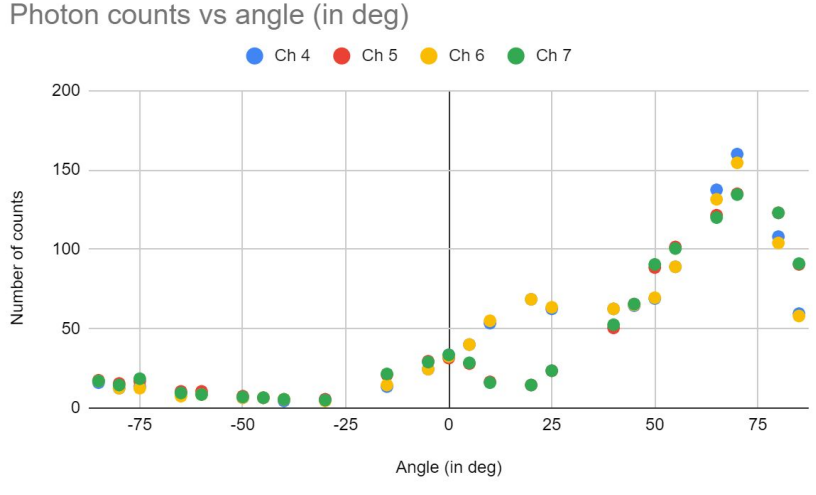

- -20 deg (Left side channels 0 to 3)



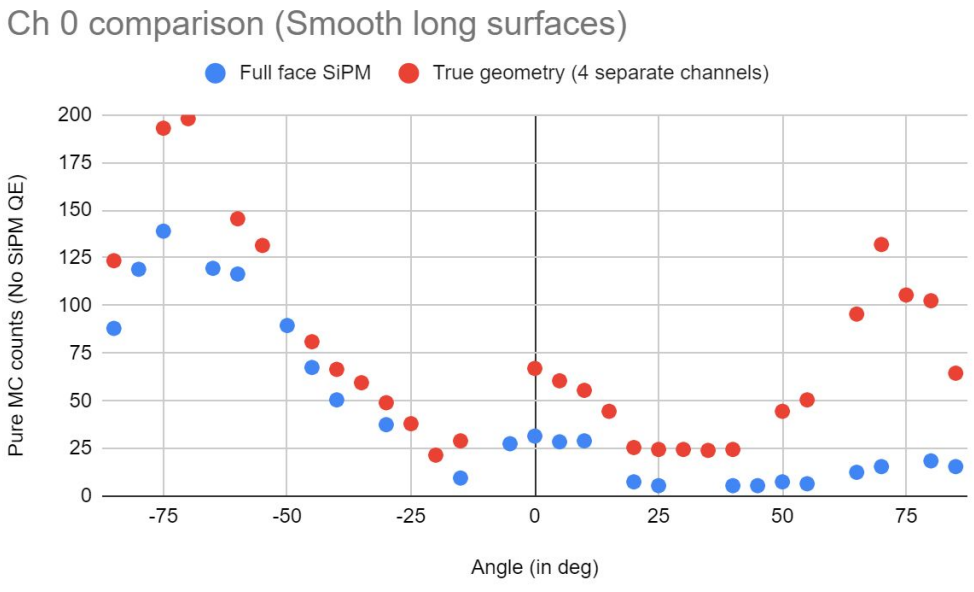

- -10 deg (Left side channels 0 to 3) for comparison - a little more occupancy towards the bottom of the face

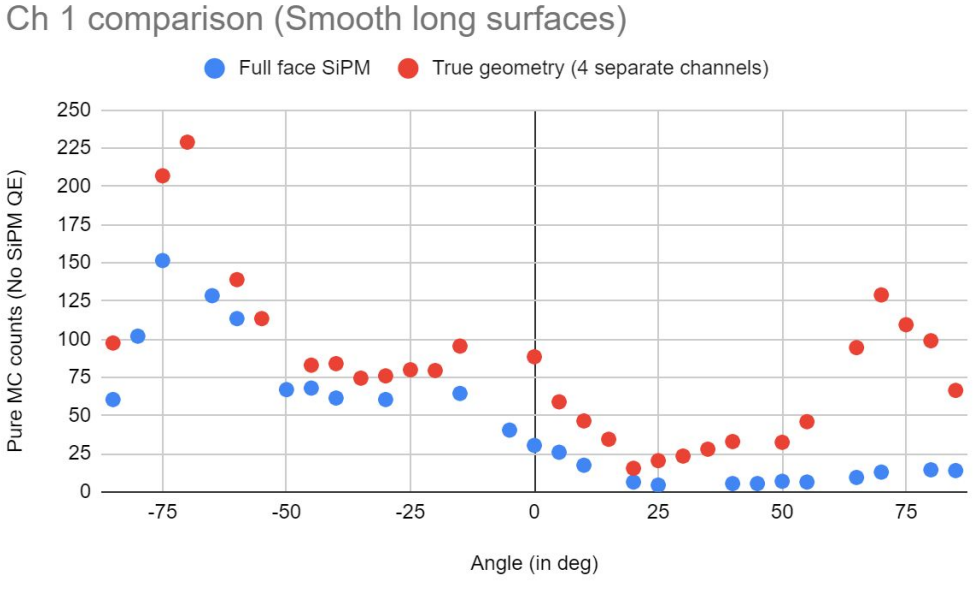
- Angular dependence plots - the peaks and the minima are much less extreme wrt the true geometry- could be because the photons that initially hit the SiPM area outside the original channels are automatically not available for this setup, but in the previous geometry those could hit the original channels after TIR from the grease Air interface

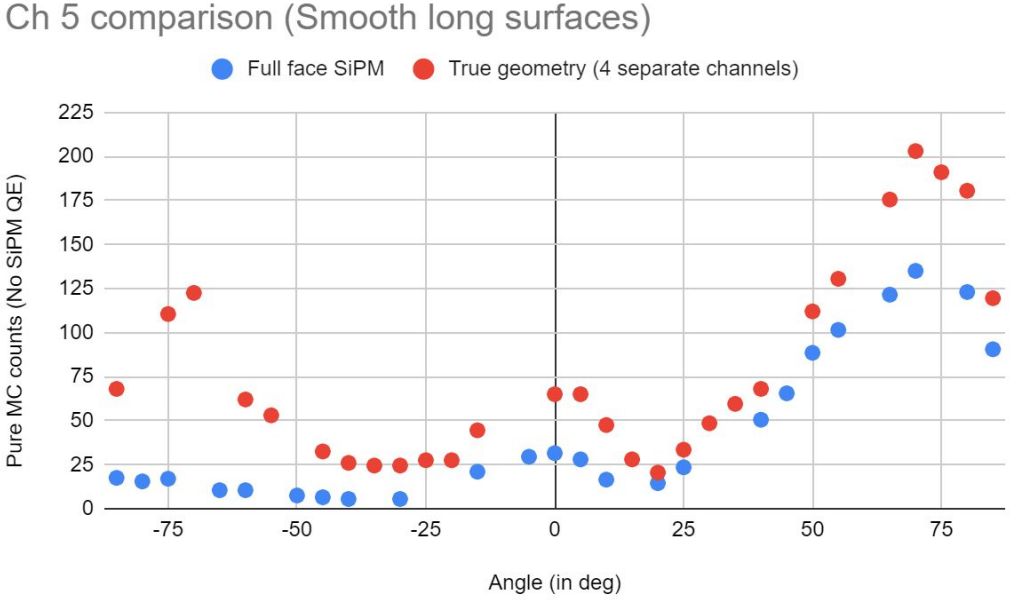


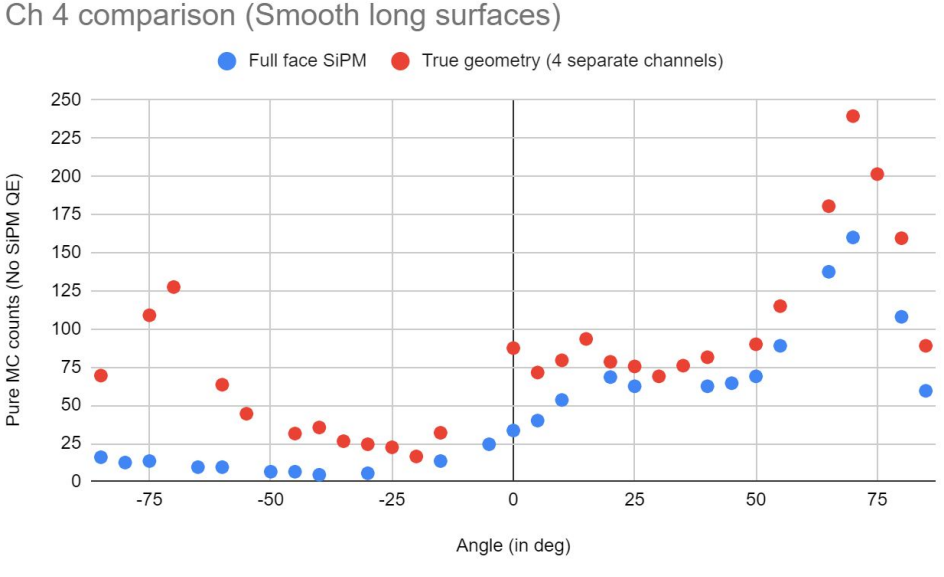



Comparison of full face geometry with true geometry i.e. 4 separate SiPM channels

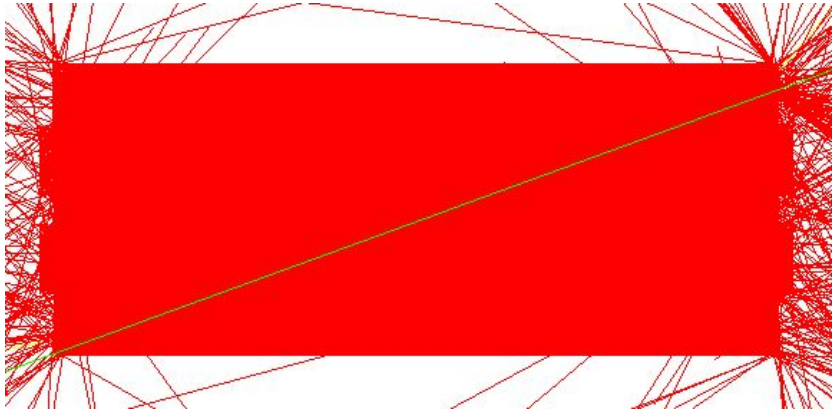


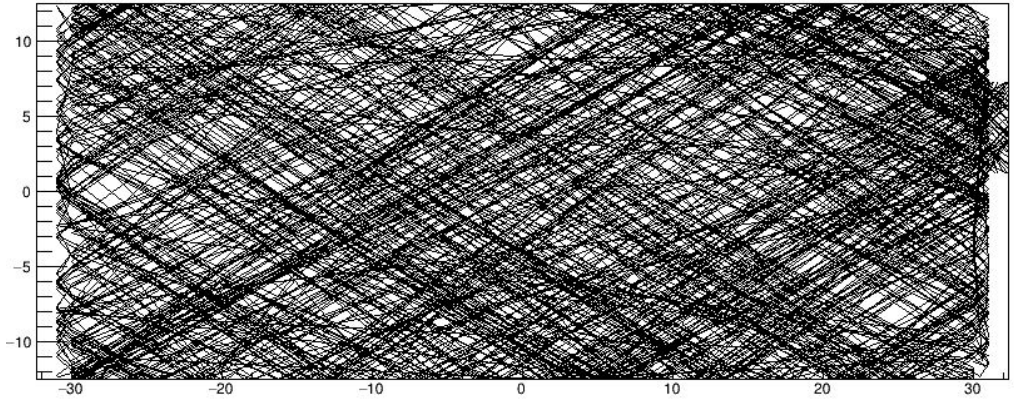



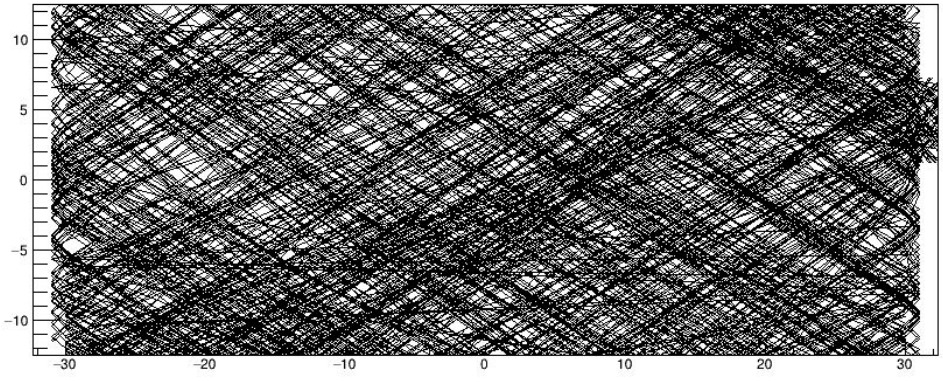
- Investigation of low counts for geometry with full face SiPMs - checked how many photons were reflecting from the silicone cookie - Air interface and hitting each SiPM (smooth long faces)
- 1 event display shown below



Total = **190**, TIR at Silicone-Air - **76**

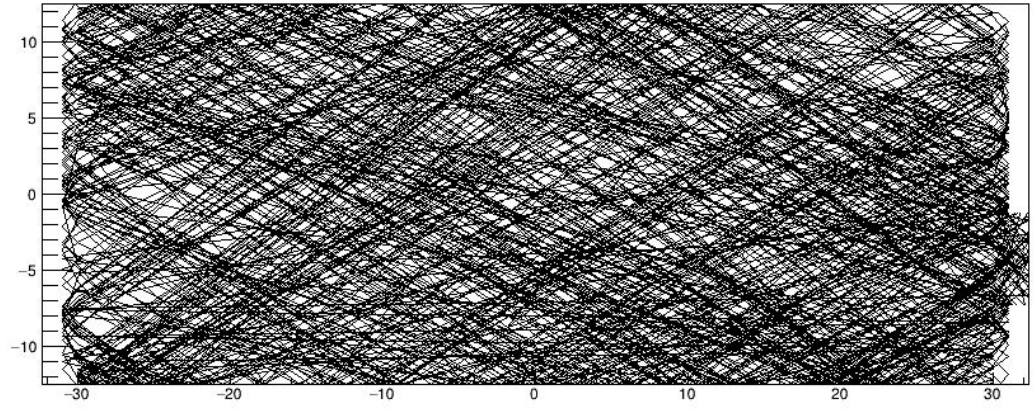



Total = **272**, TIR at Silicone-Air - **78**

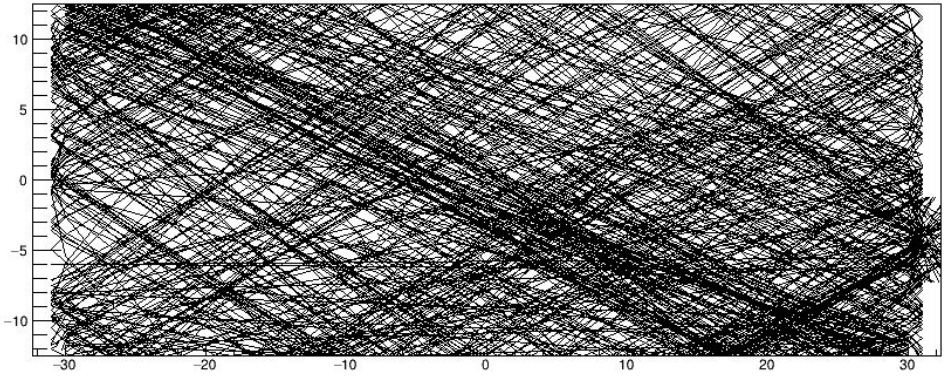



Ch 4 and Ch 6 (Top channels)

Total = **172**, TIR at Silicone-Air - **69**

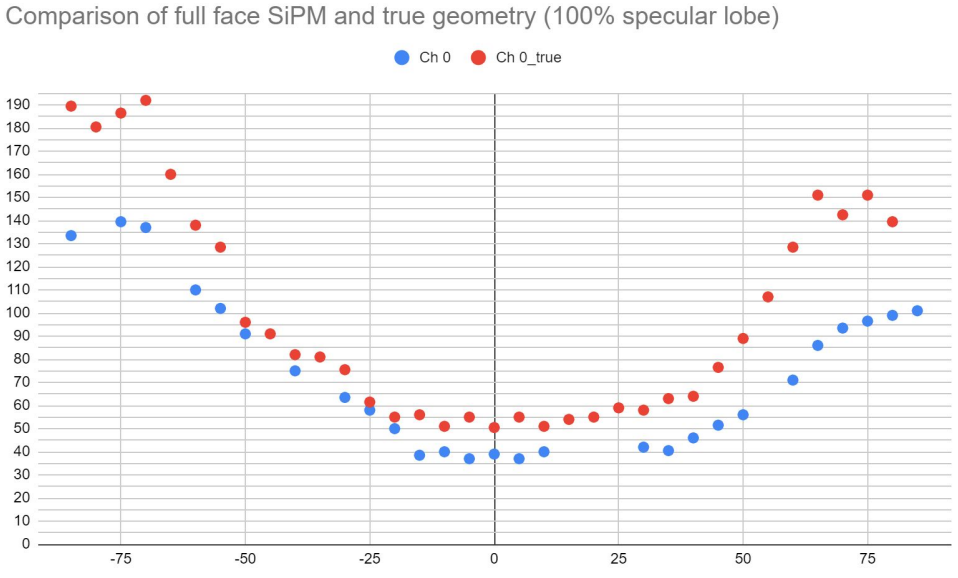


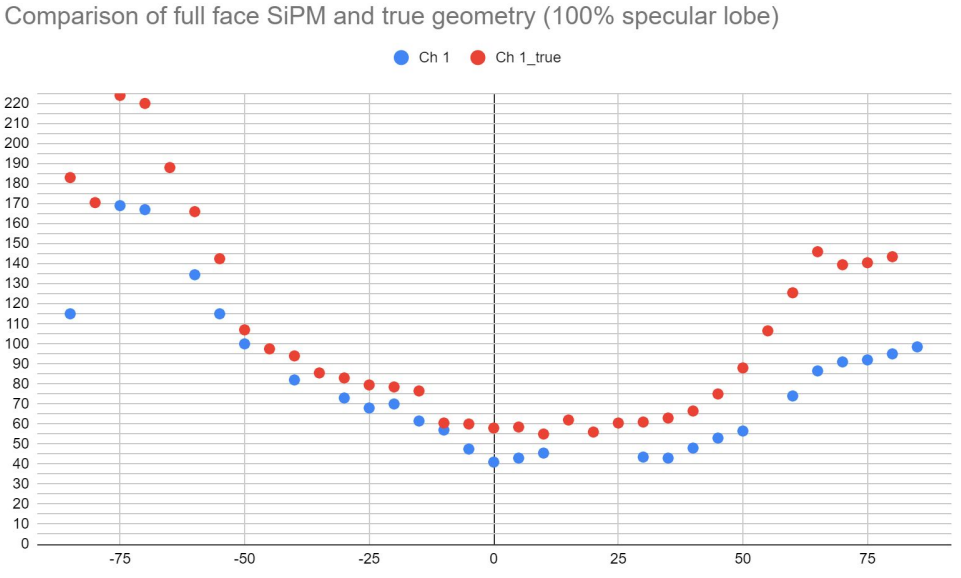

Total = **193**, TIR at Silicone-Air - **73**

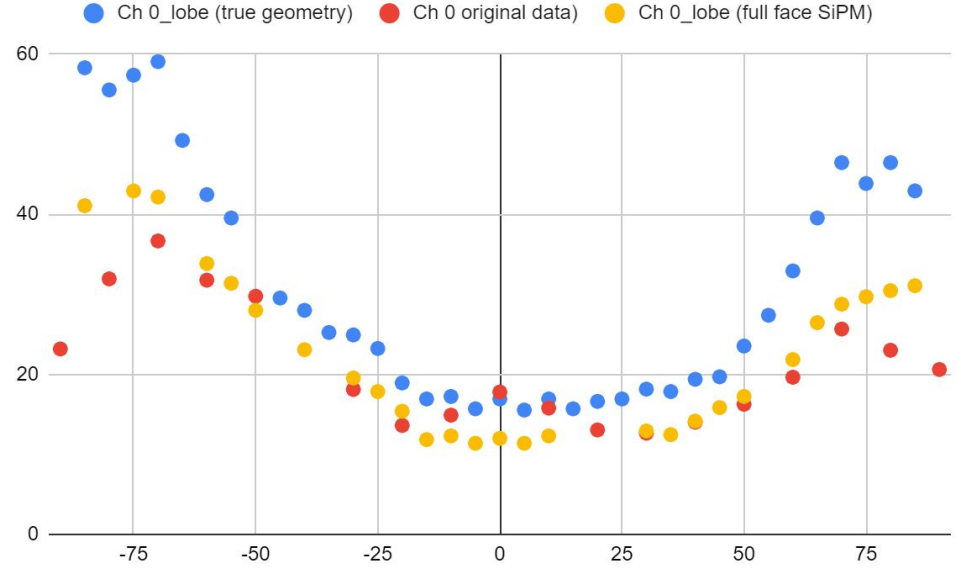


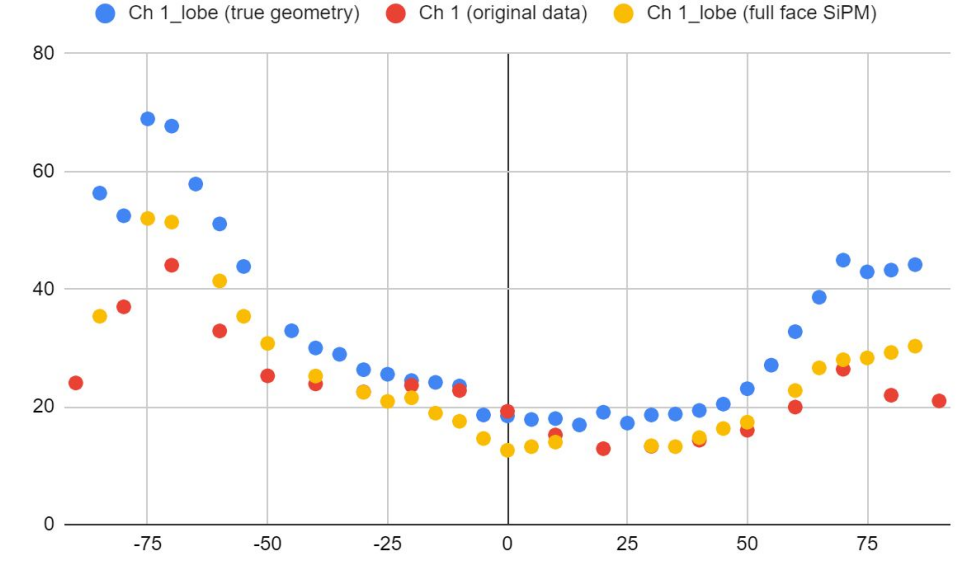

Ch 5 and Ch 7 (Bottom channels)

- Also ran with rough surface (100% specular lobe) for the full face covered with SiPM



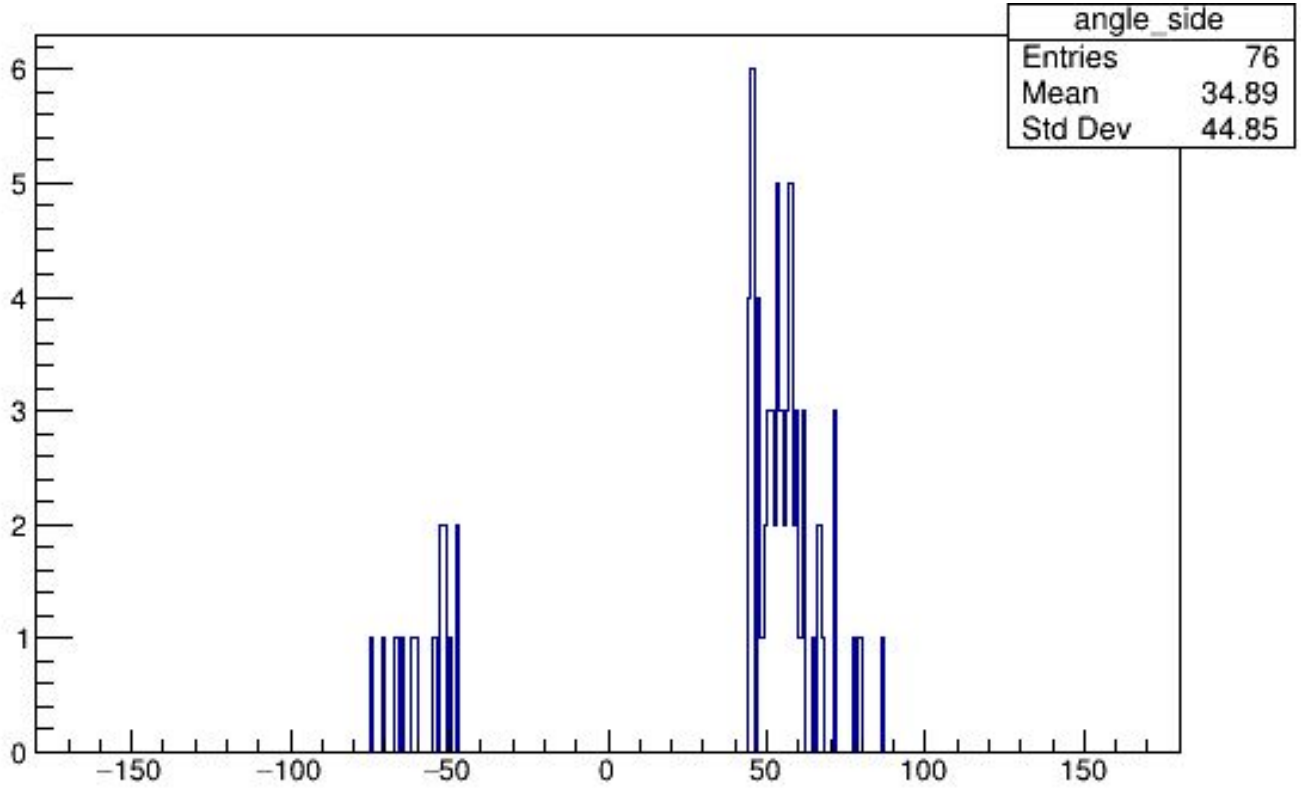



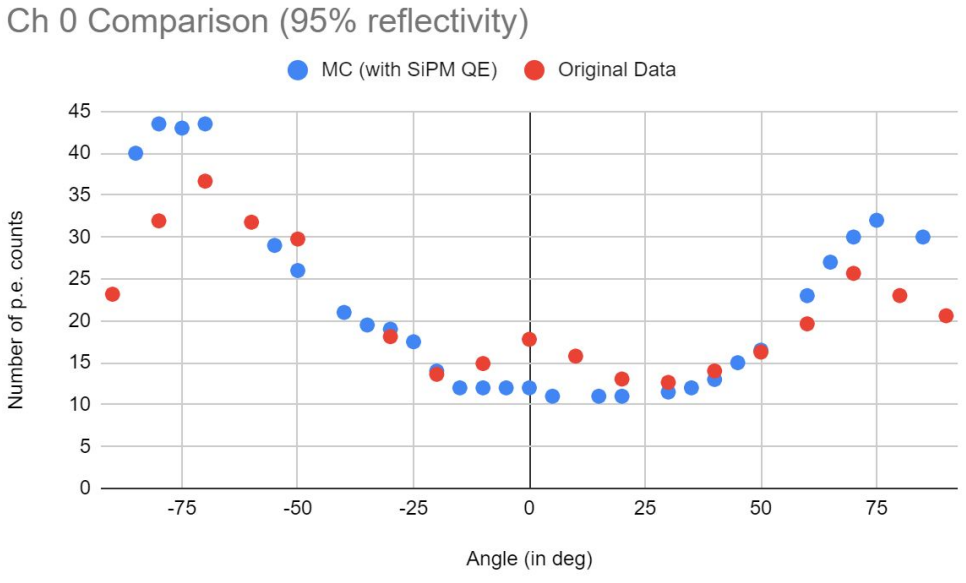



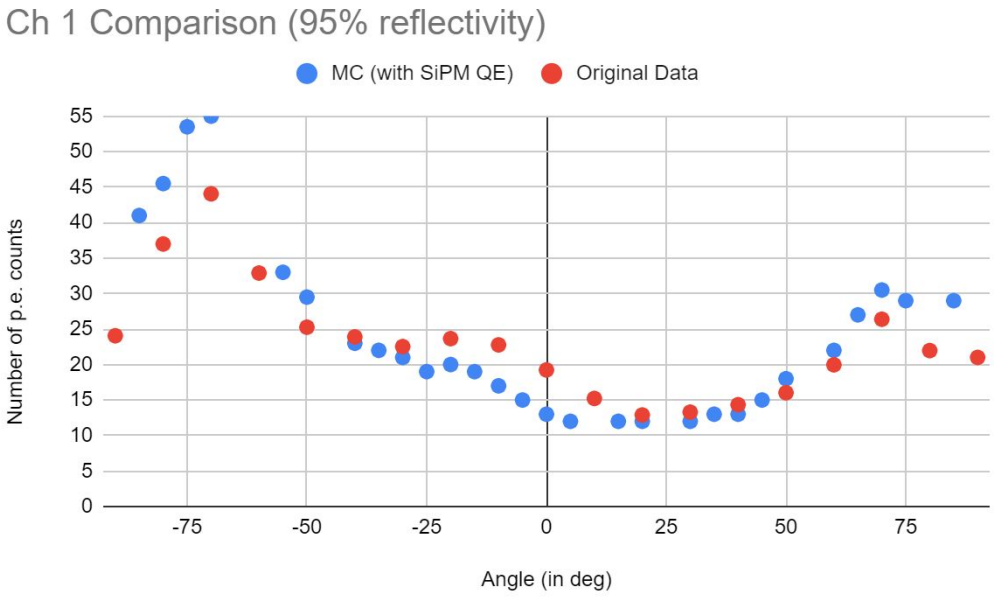

Scaled down counts (by 3.25) to mimic SiPM QE

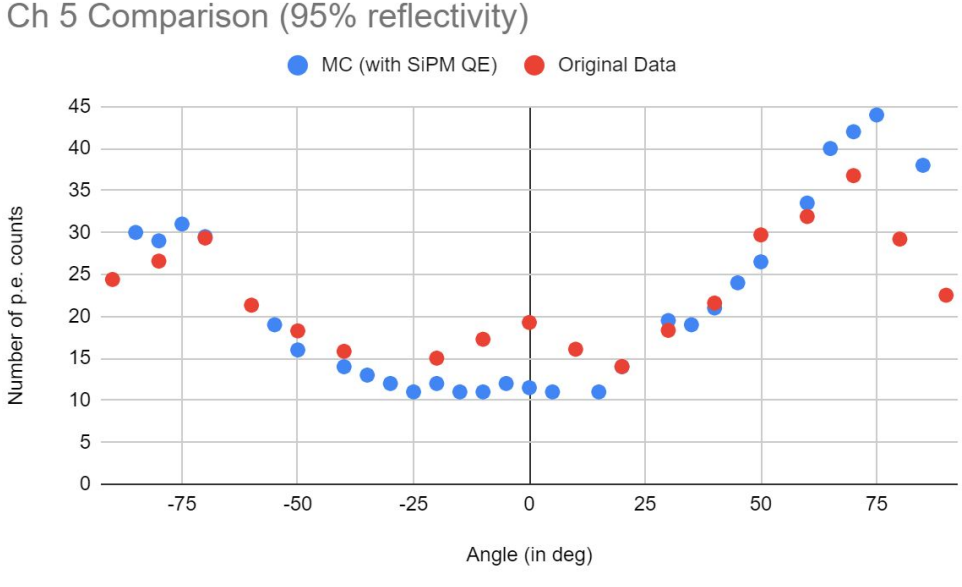
- Angle at reflection at the silicone cookie - Air interface for the photons that further reach one of the SiPMs - All the angles are greater than the critical angle for the interface (~44 deg)
- This was done to check whether there is any type of reflection other than TIR happening (likely not)

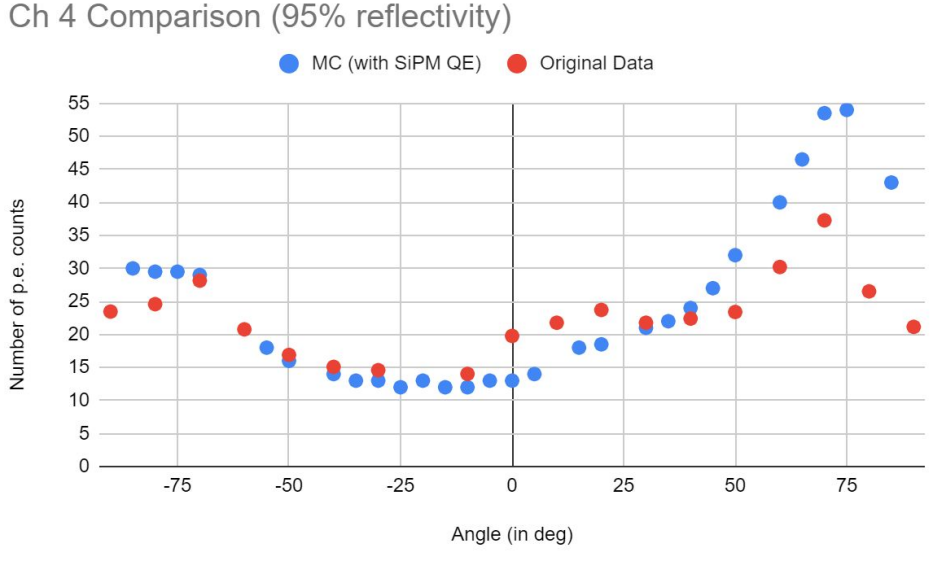


- 95% reflectivity at long face (with 100% specular lobe reflection) - comparison with original data
- Counts have lowered near the 0 deg region as well, so likely will have to decrease reflections at the cookie - Air interface as well

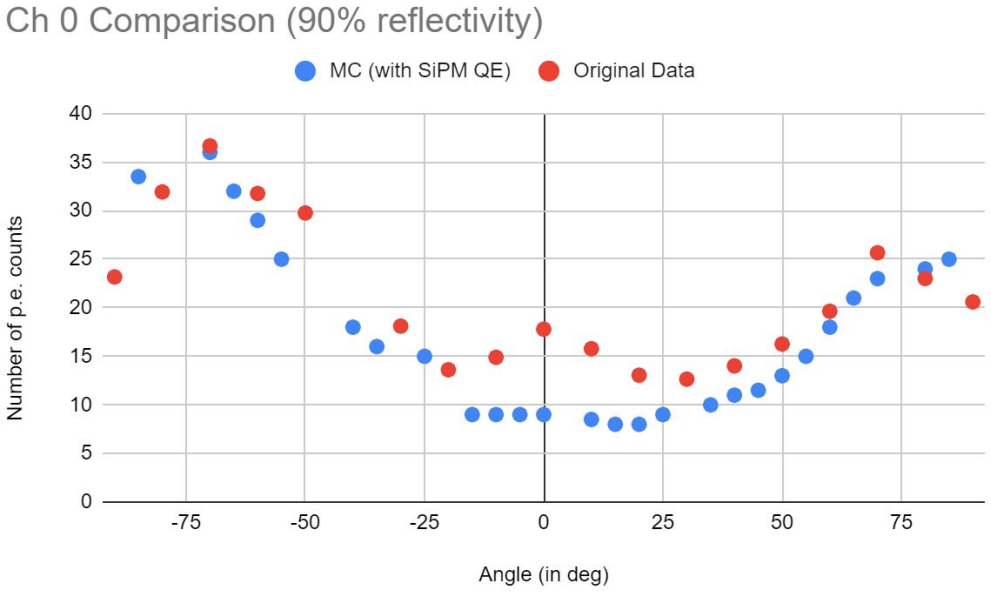


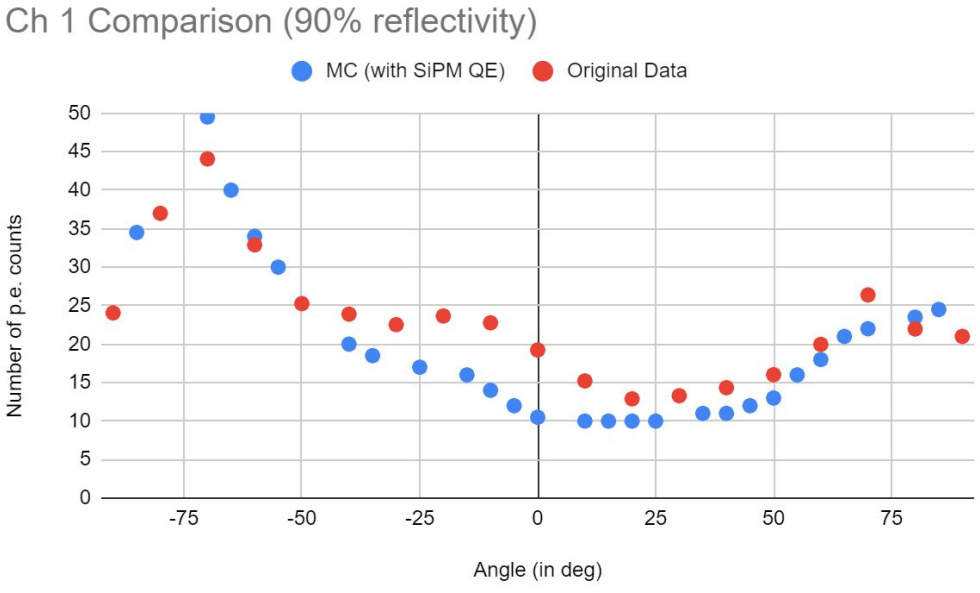



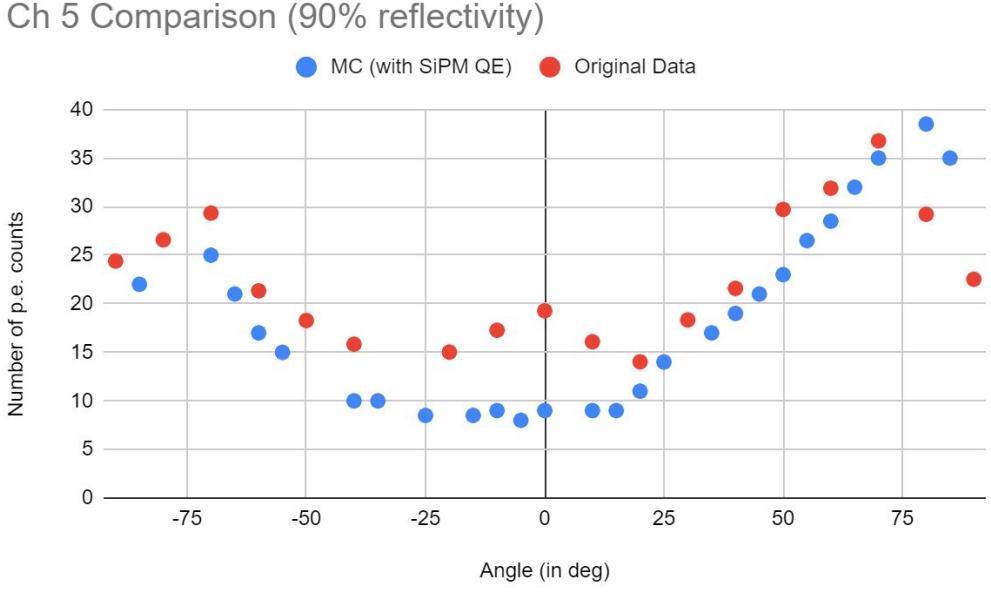



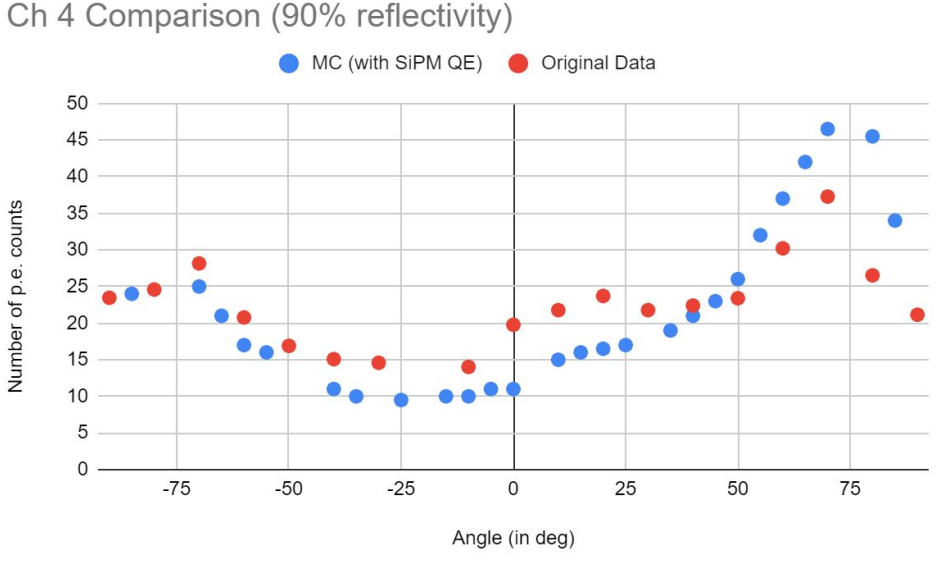



- 90% reflectivity at long face (with 100% specular lobe reflection) - comparison with original data

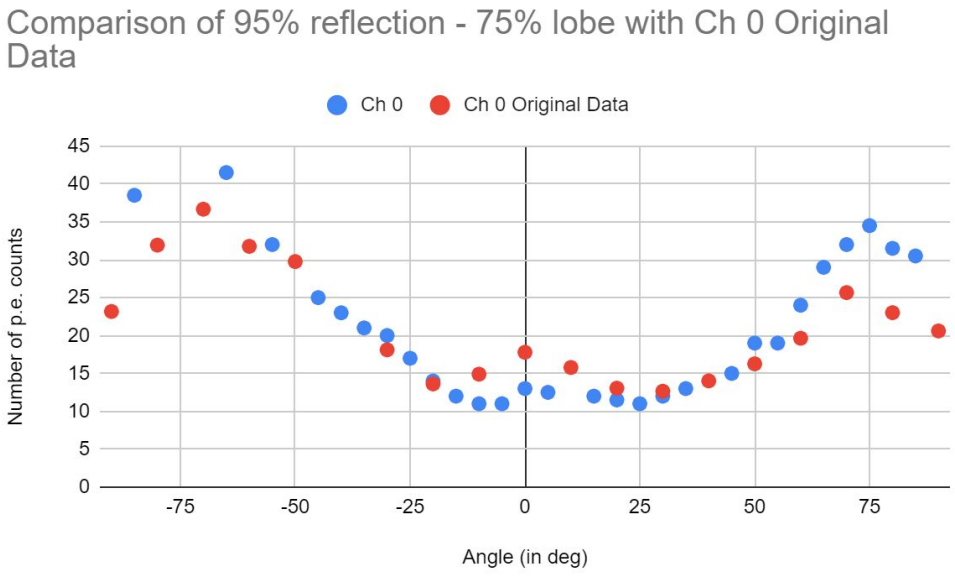


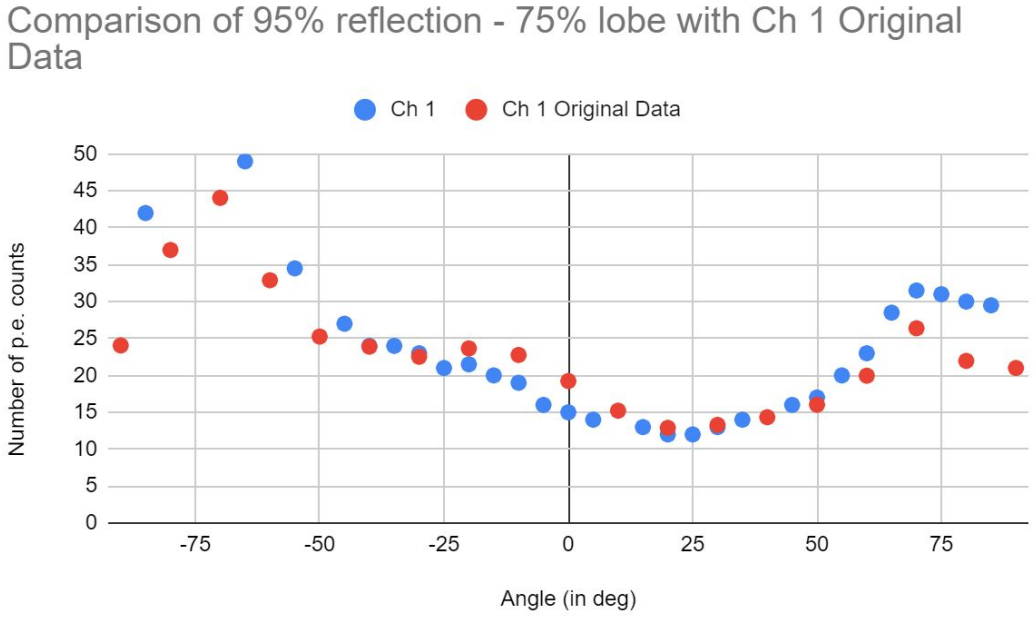



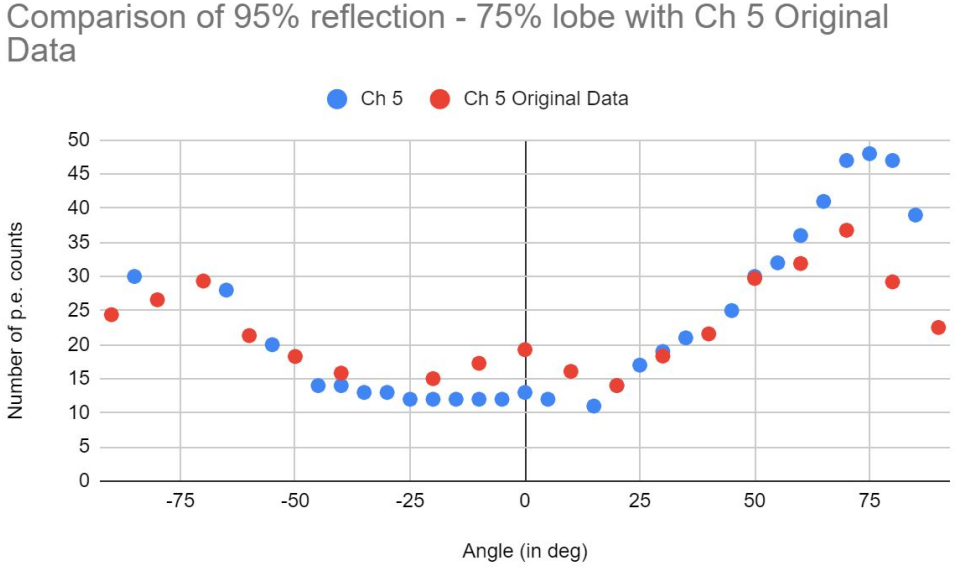



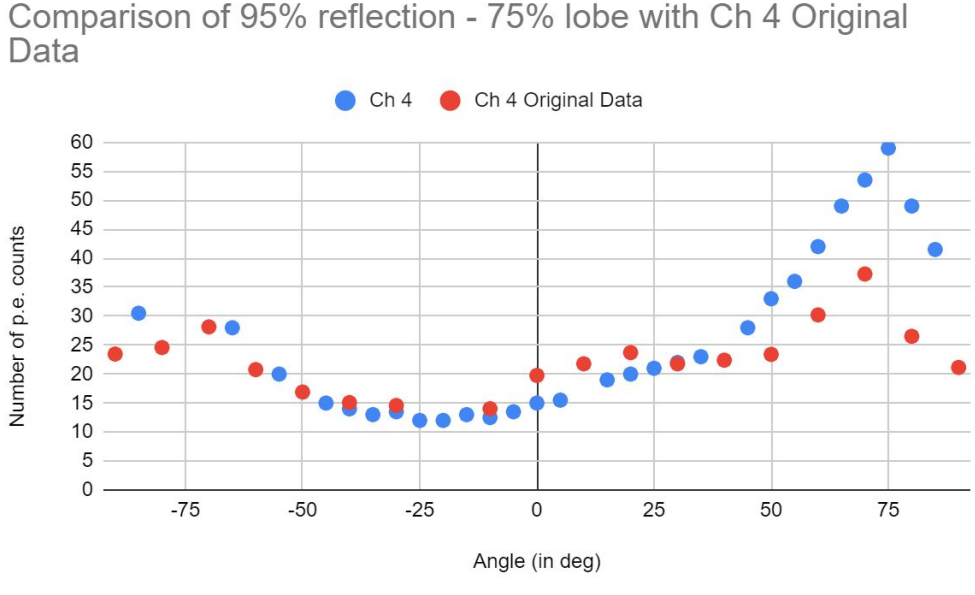



- 95% reflectivity at long face (with 75% specular lobe and 25% specular spike reflection) - comparison with original data

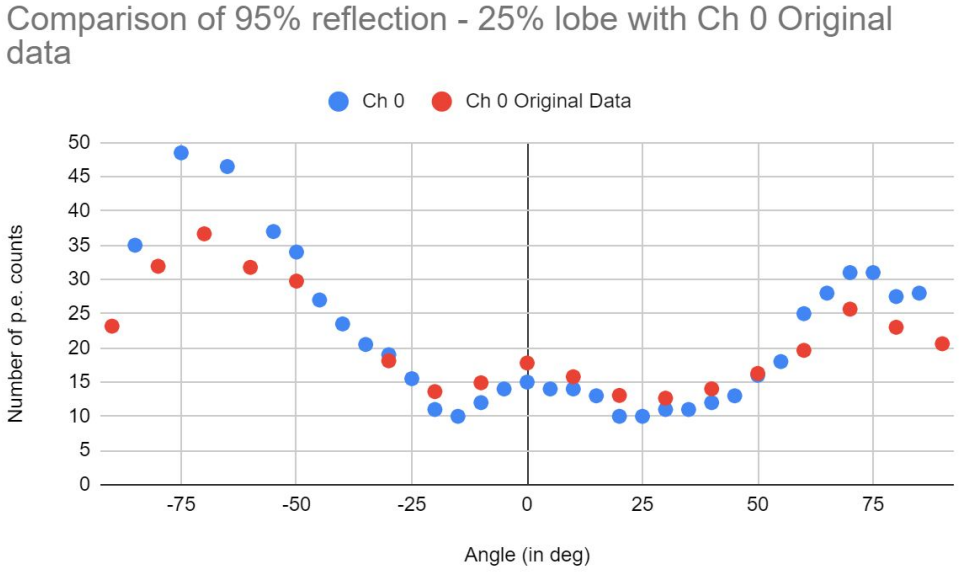


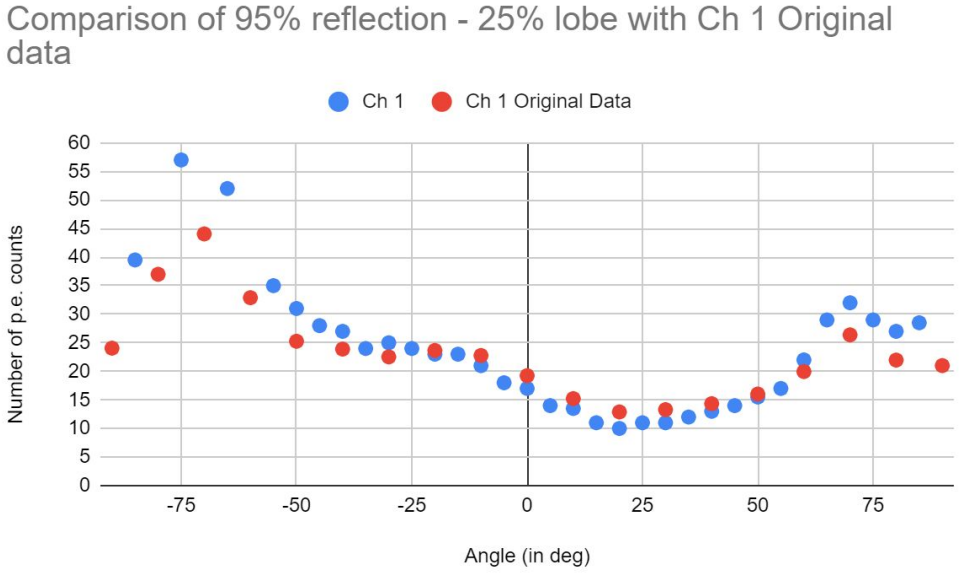



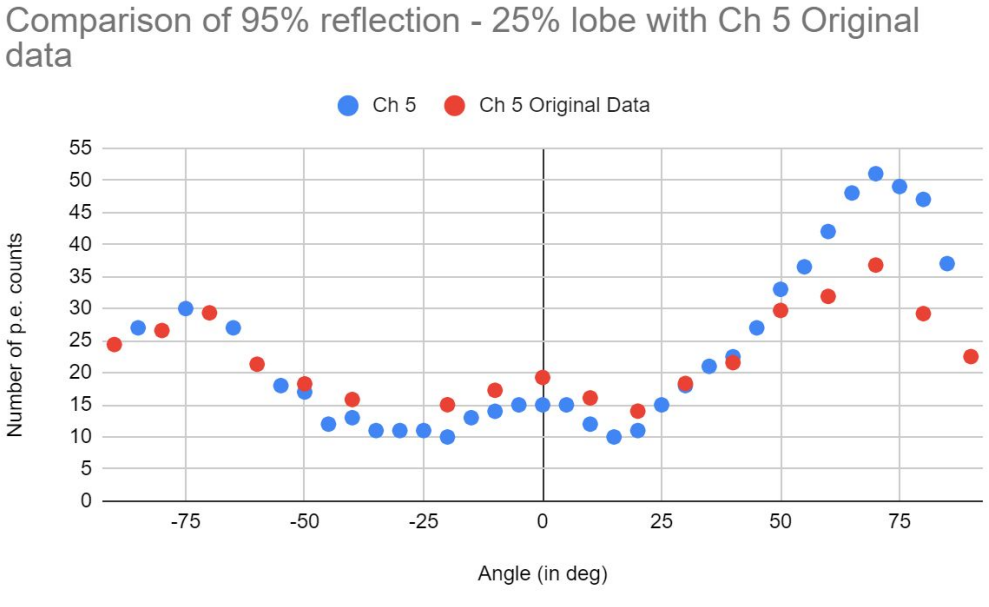



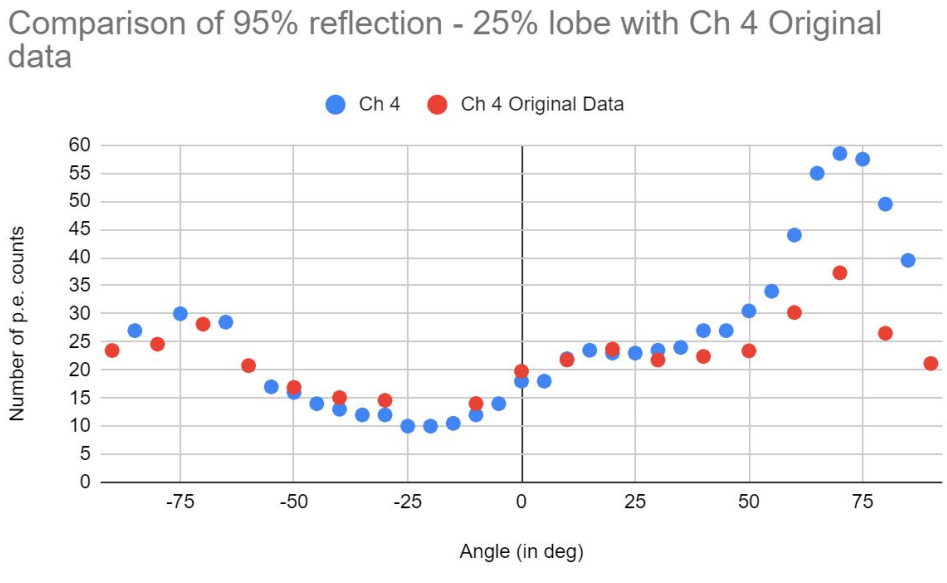



- 95% reflectivity at long face (with 25% specular lobe and 75% specular spike reflection) - comparison with original data (more structure and hence better match near the 0 deg region)

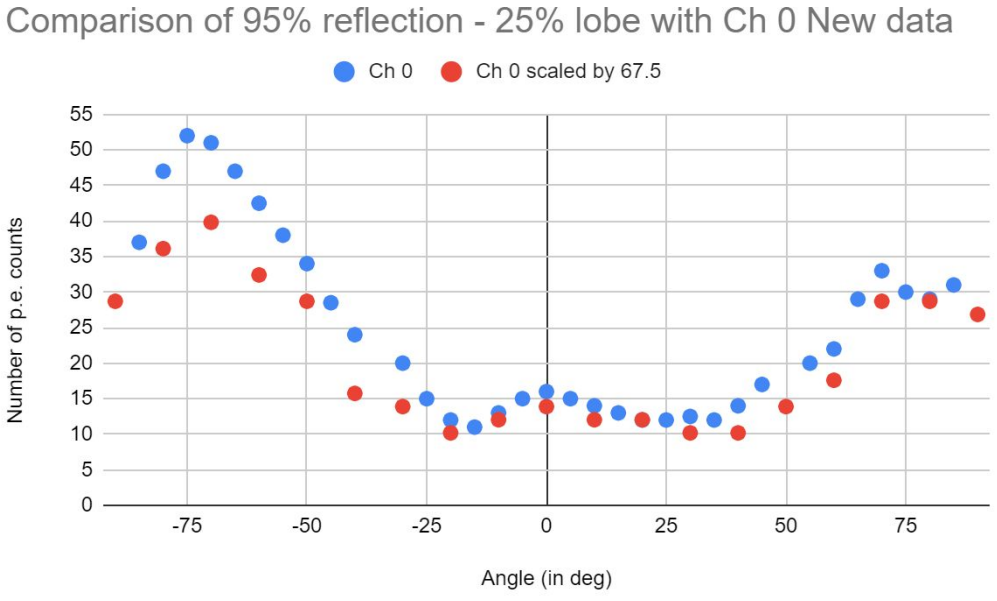


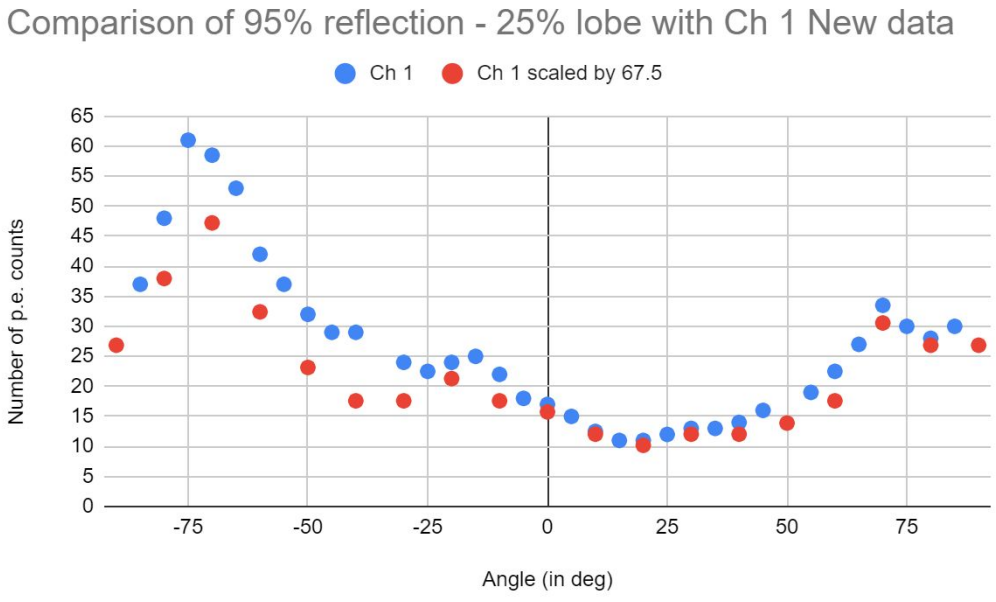



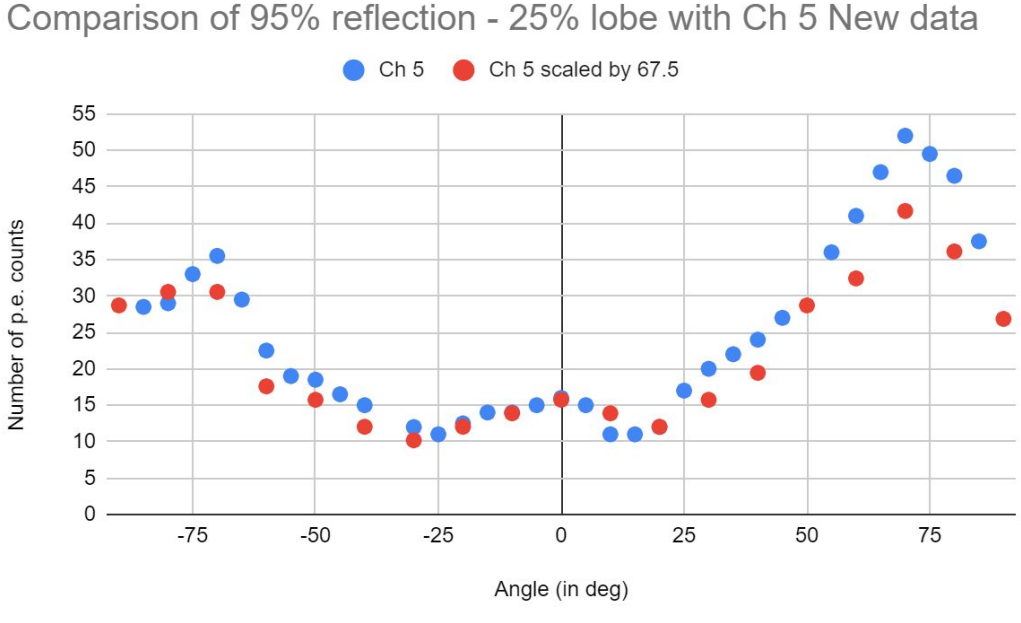



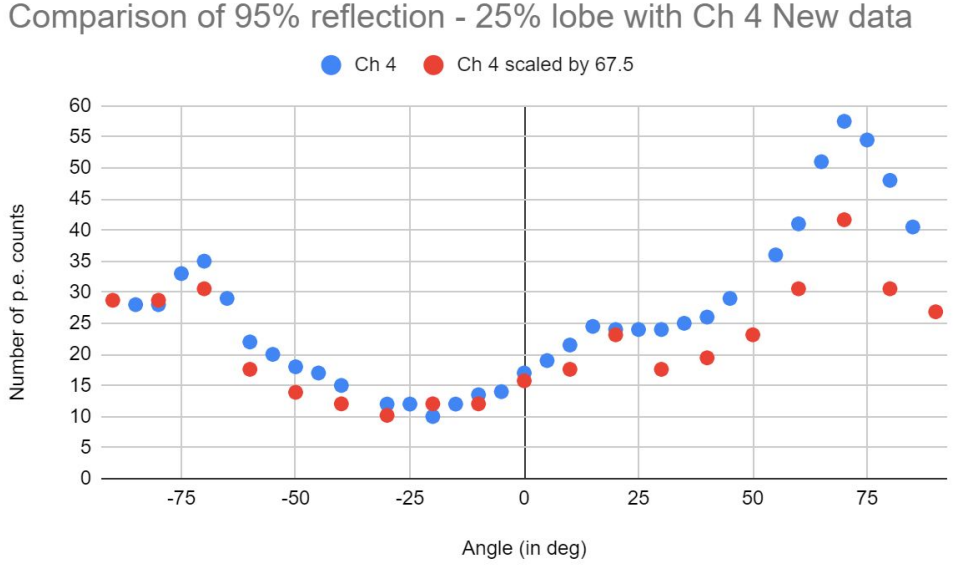



- 95% reflectivity at long face (with **25% specular lobe** and **75% specular spike** reflection) - comparison with *new* data scaled down by 67.5 [conversion factor provided by Hui-Chi]
- In case of PbF2, the new imposed cut (amplitude>5*noise) does not change the position of the MPV and the MIP peak is still retained

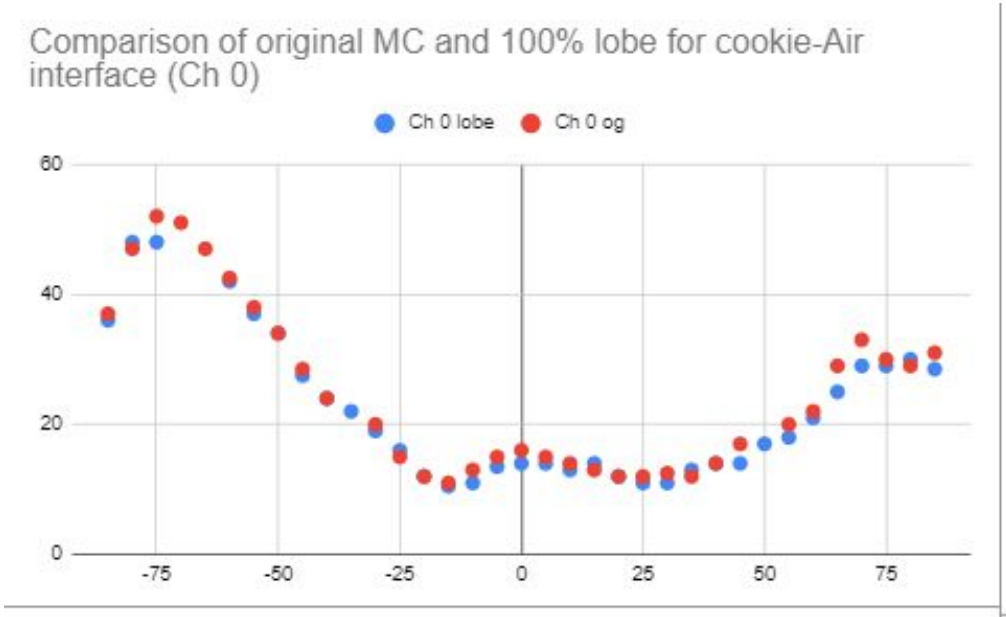


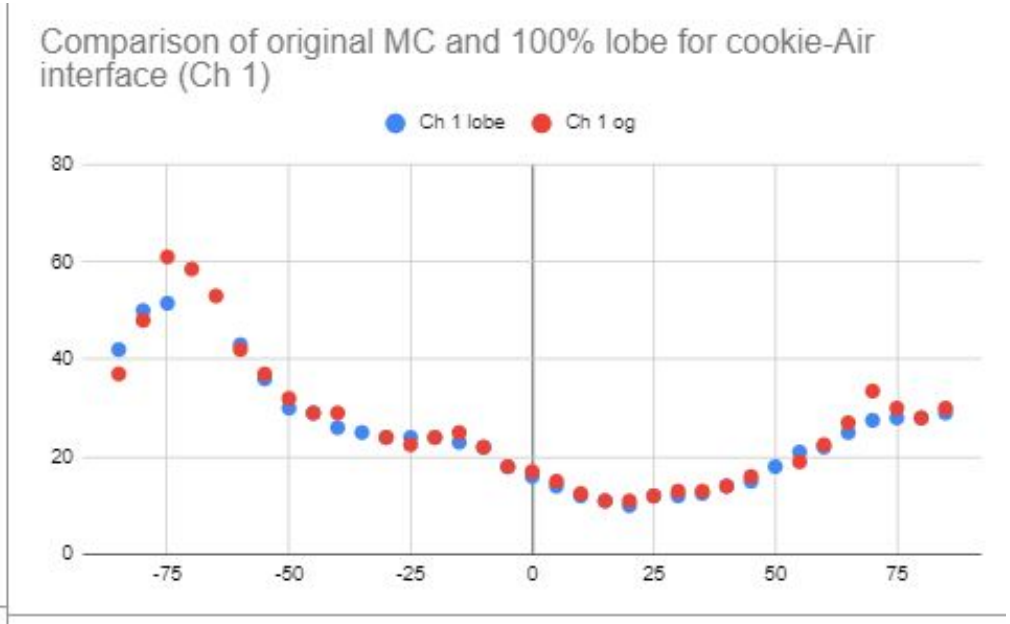



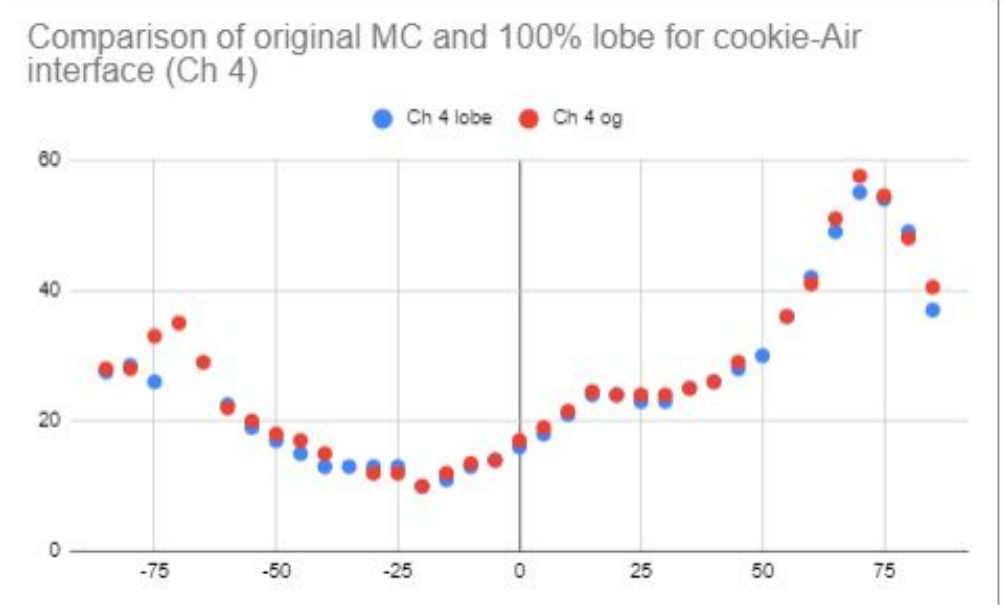



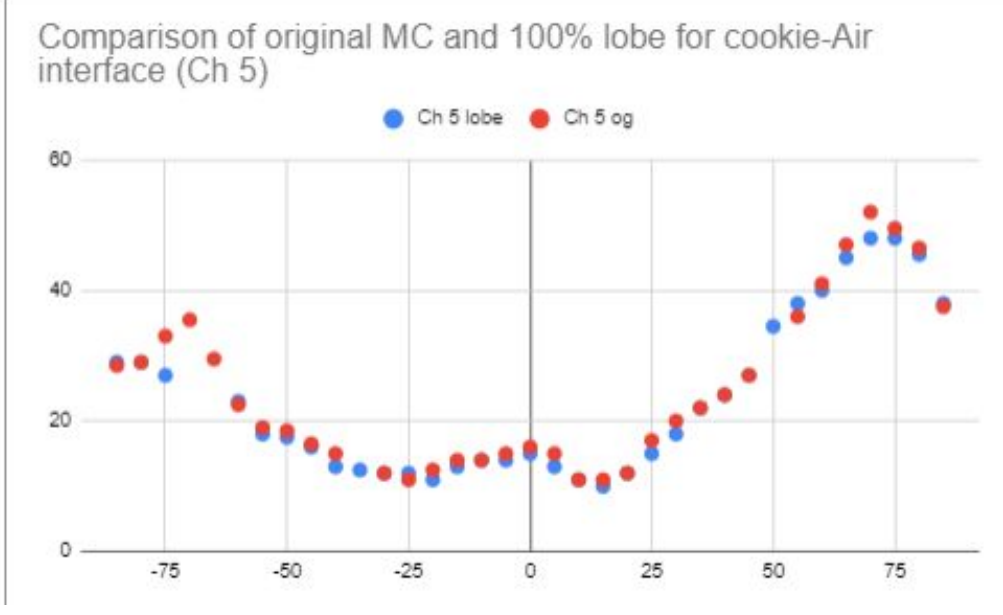



- Attempting to reduce the counts in the dominant peak by putting a **rough surface** and/or **<100% reflectivity** at the silicone cookie - Air interface
- No significant reduction in counts for the dominant peak (~70 deg) even with rough surface applied

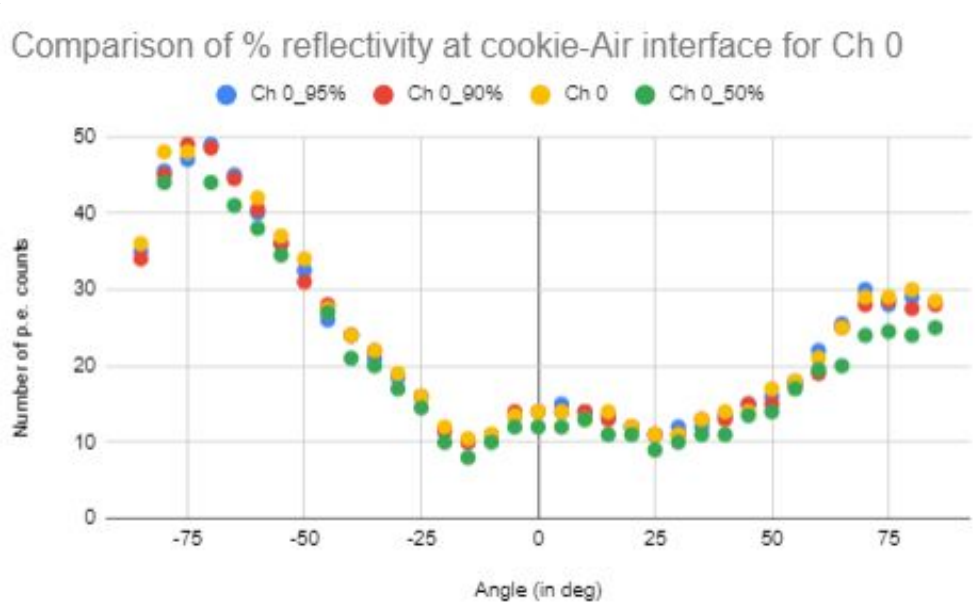


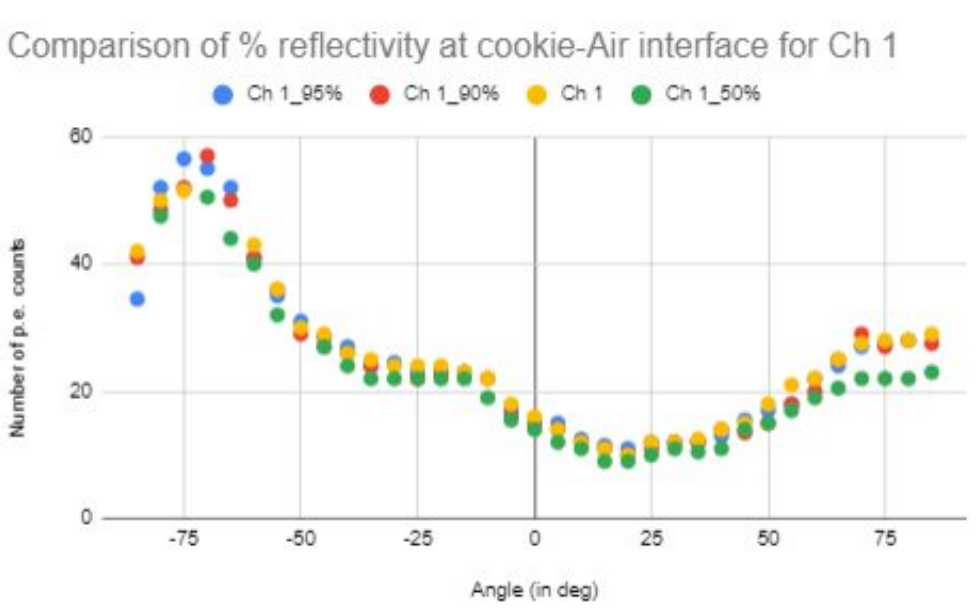



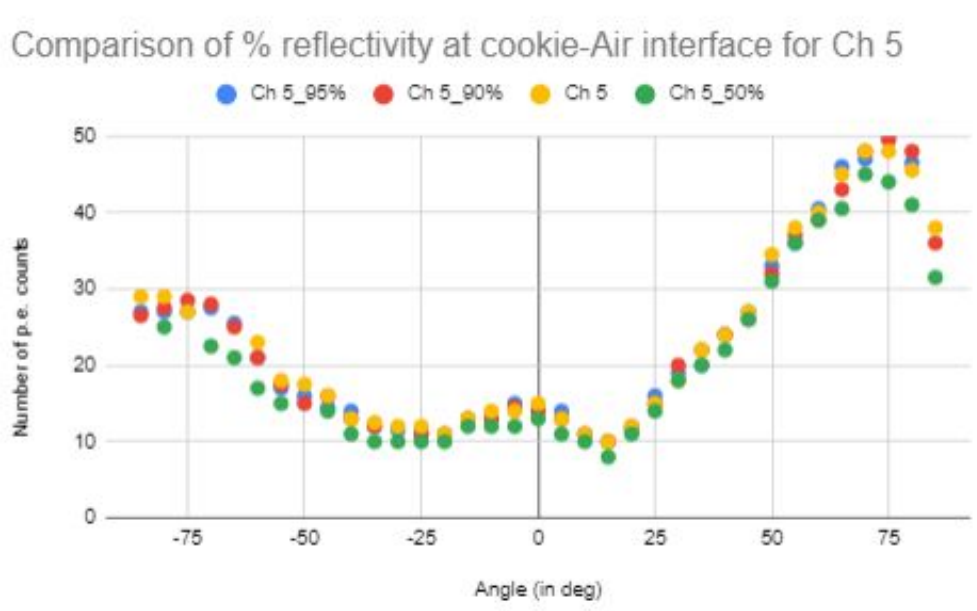



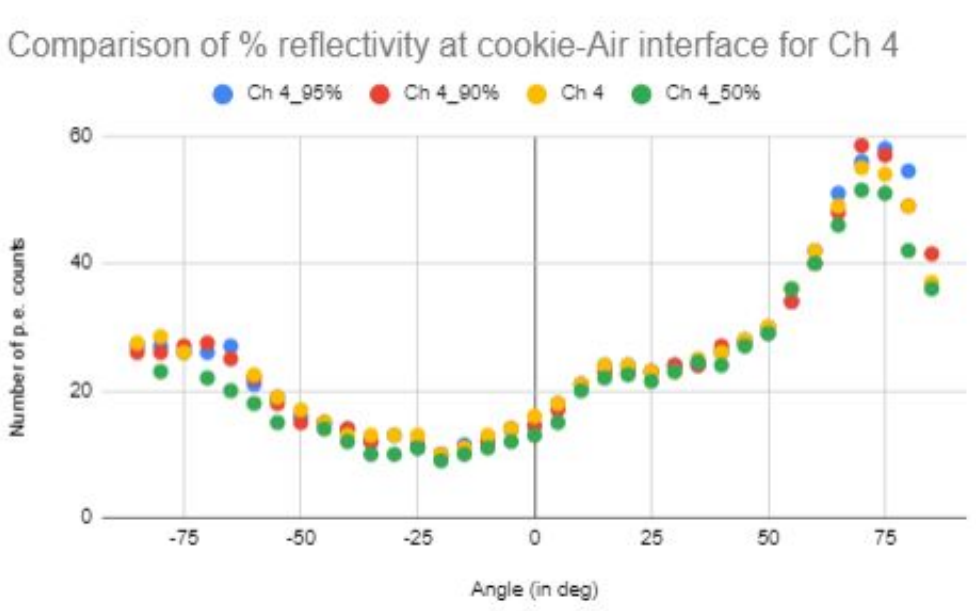



- Applying <100% reflectivity at the silicone cookie-Air interface - counts not as sensitive to % change as with reduction of the %reflectivity at the long face
- Below curves are all MC (100%, 95%, 90% and 50% reflectivity)

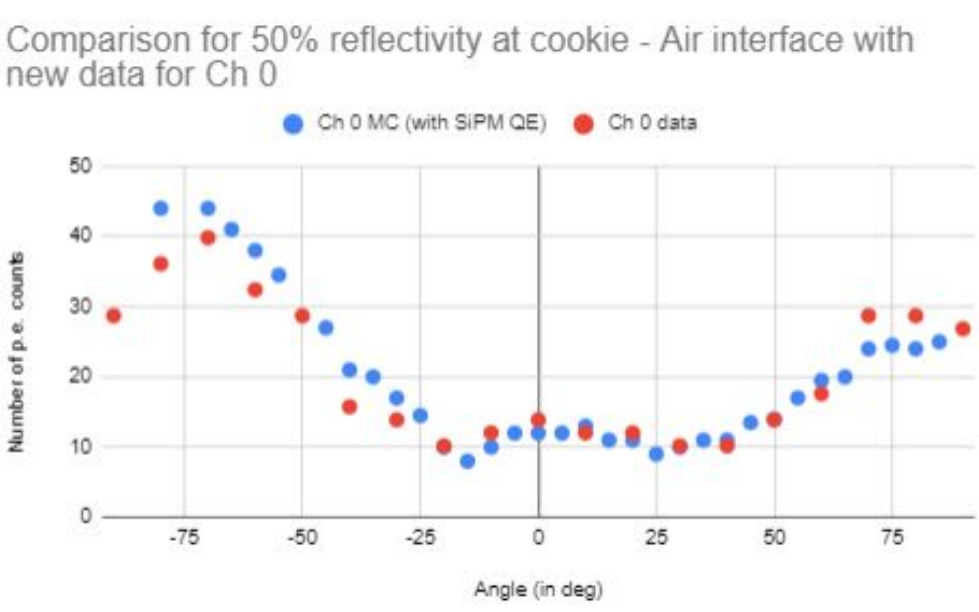


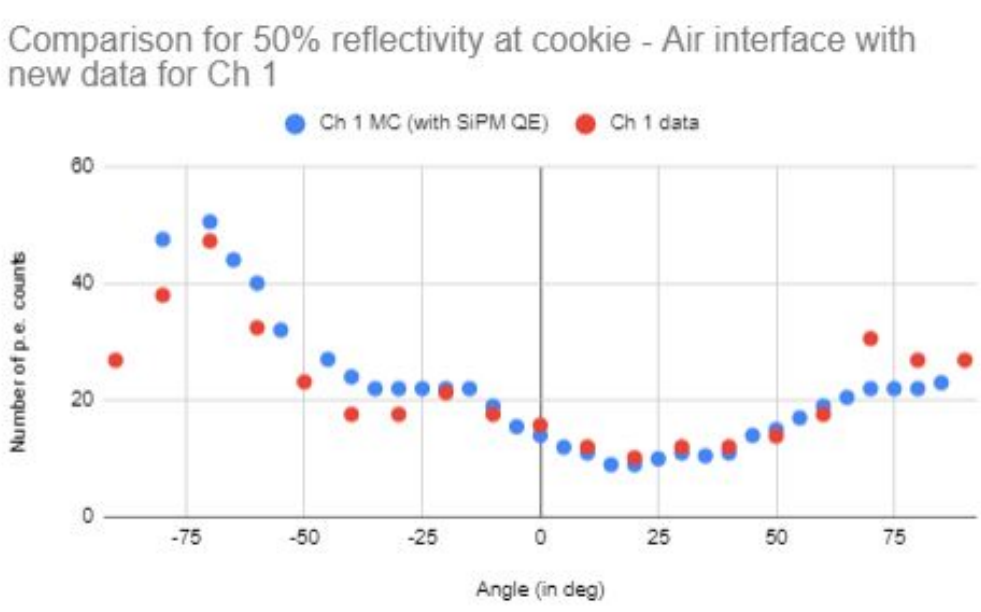



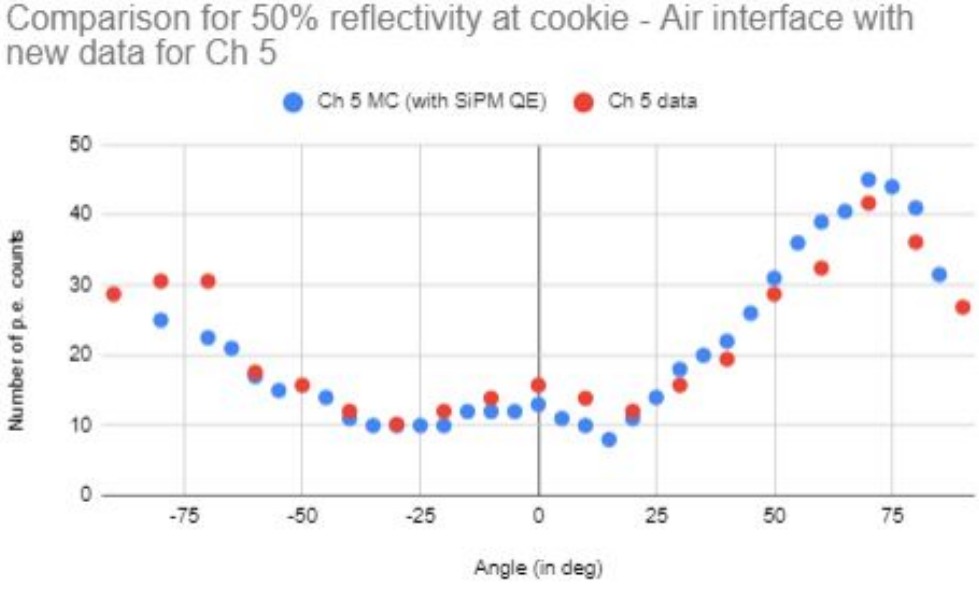



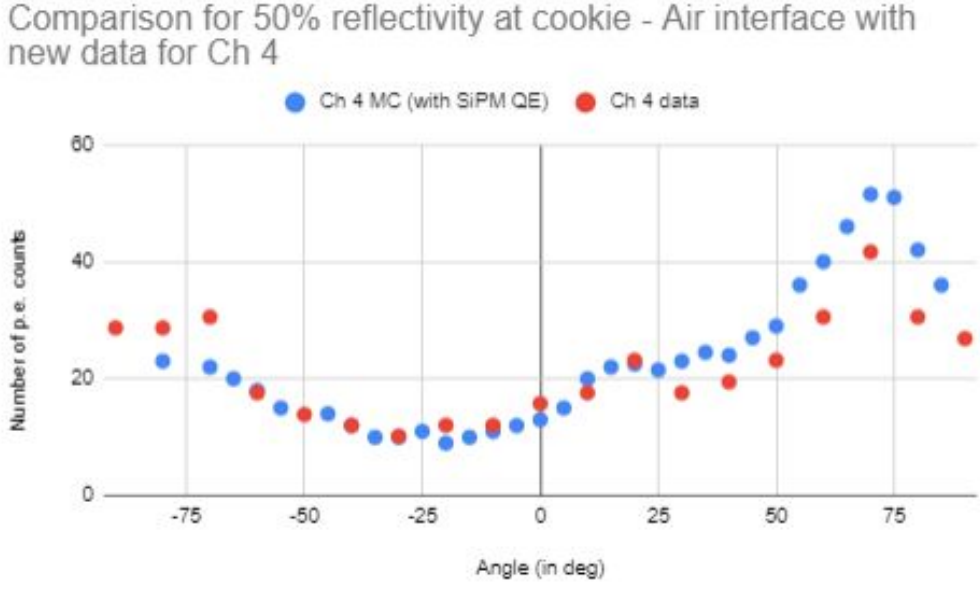



- Comparison of MC (**100% specular lobe**, **50% reflectivity** at cookie - Air interface and **95% reflectivity** with **25% specular lobe** and **75% specular spike** at long face) with new data



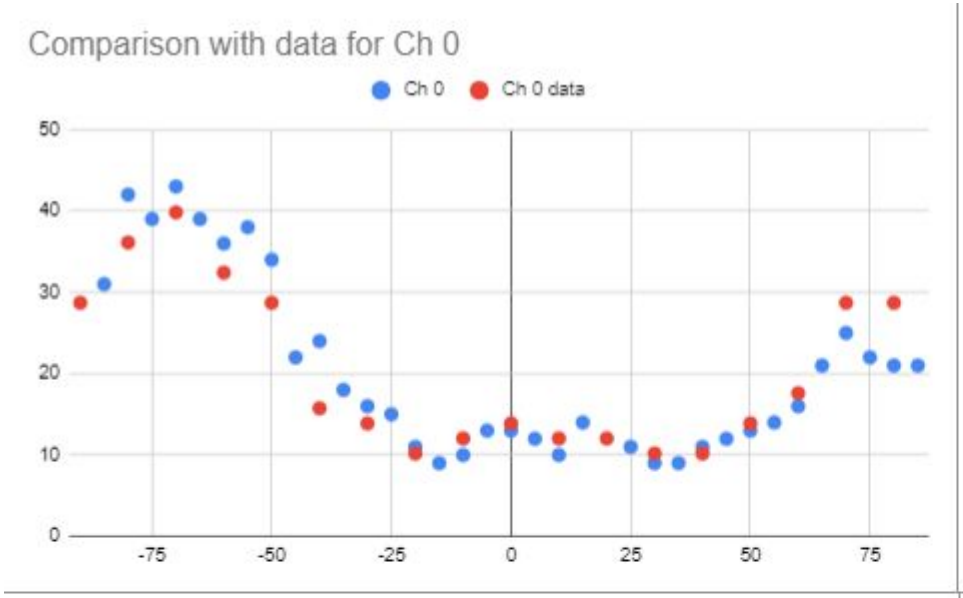



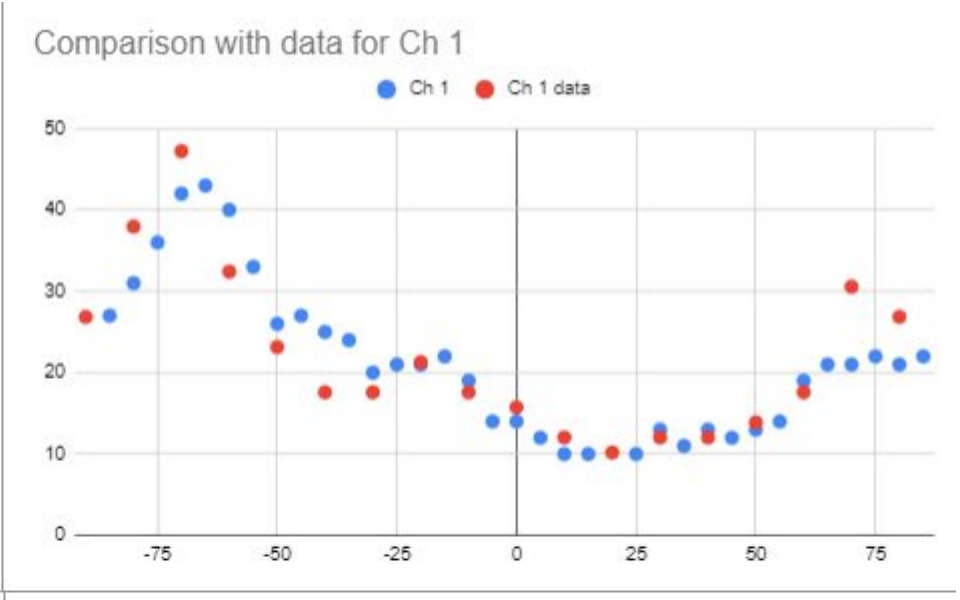



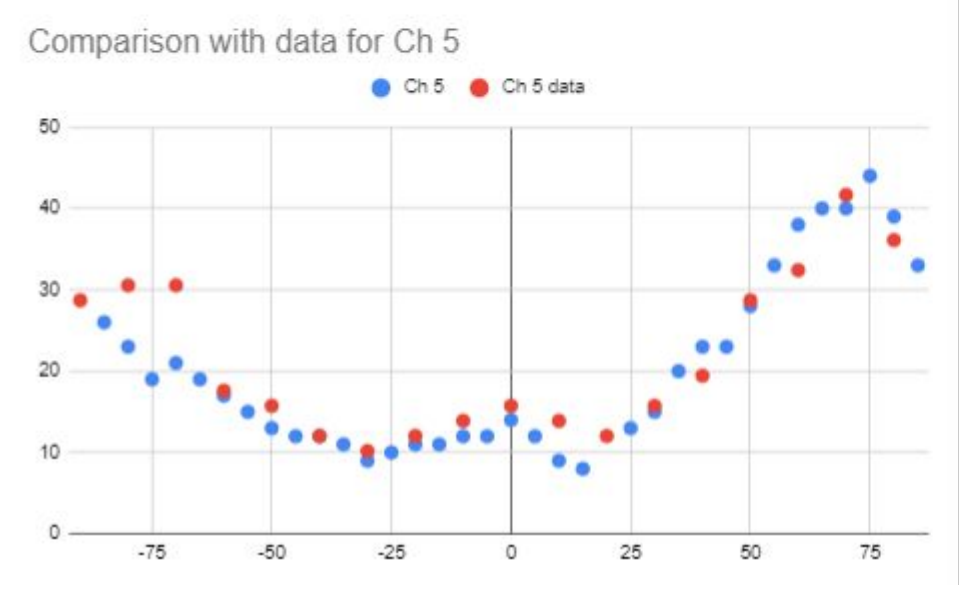



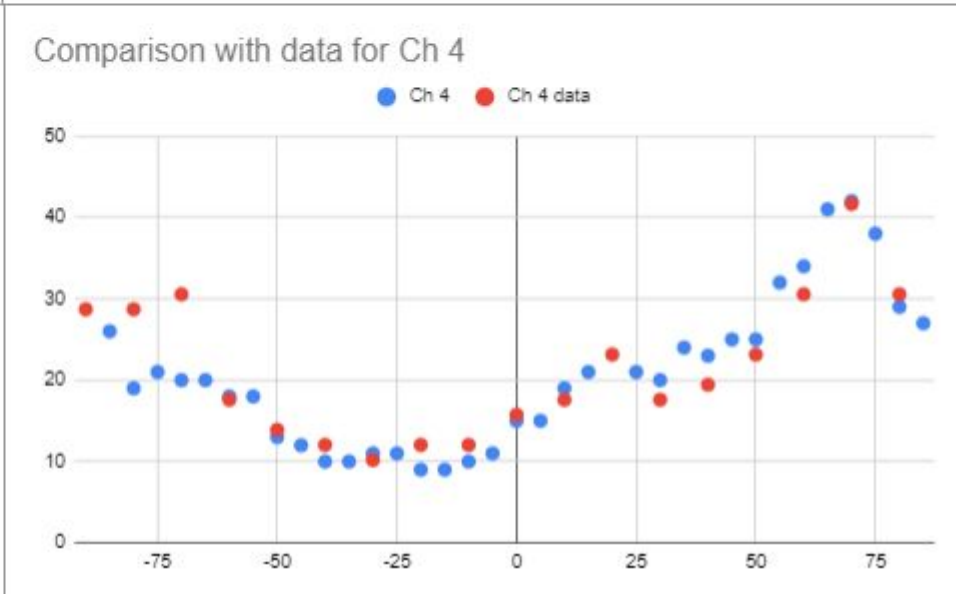
- But all these comparisons were with the median of event wise distribution of counts for every incidence angle in MC, while it is with MPV of the distribution of counts in the new data

- Comparison of MC (**100% specular spike**, **50% reflectivity** at cookie - Air interface and **95% reflectivity** with **25% specular lobe** and **75% specular spike** at long face) with new data

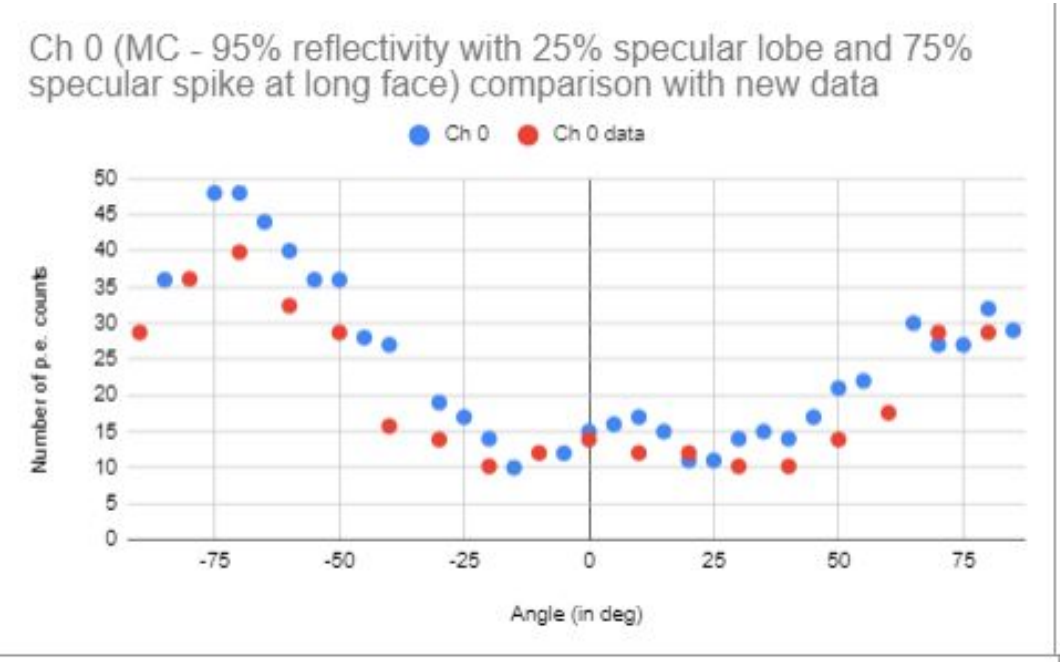


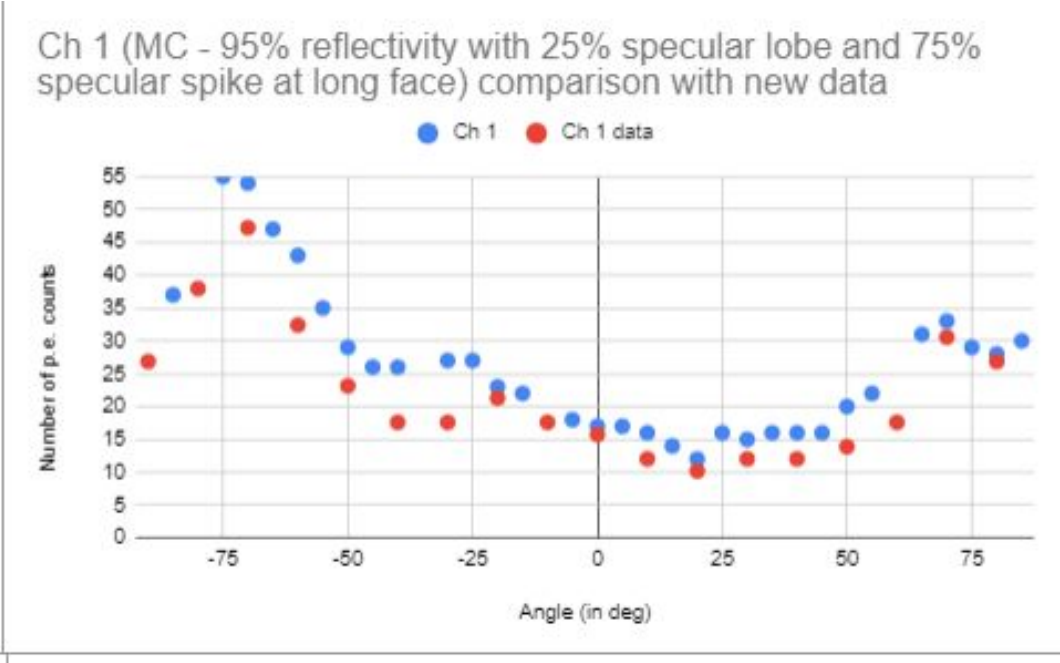



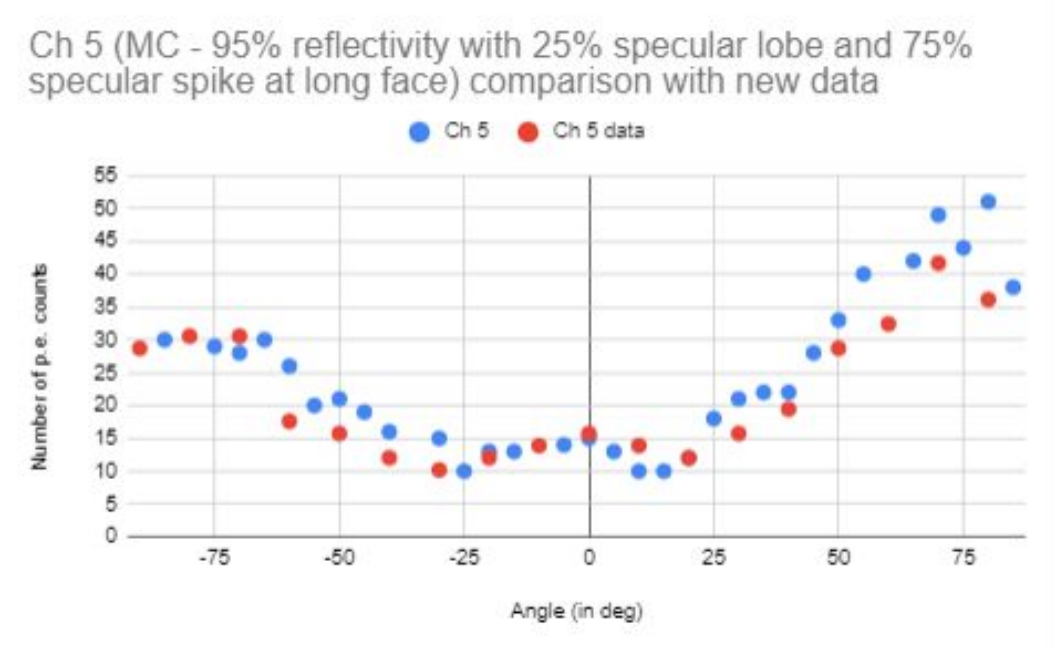



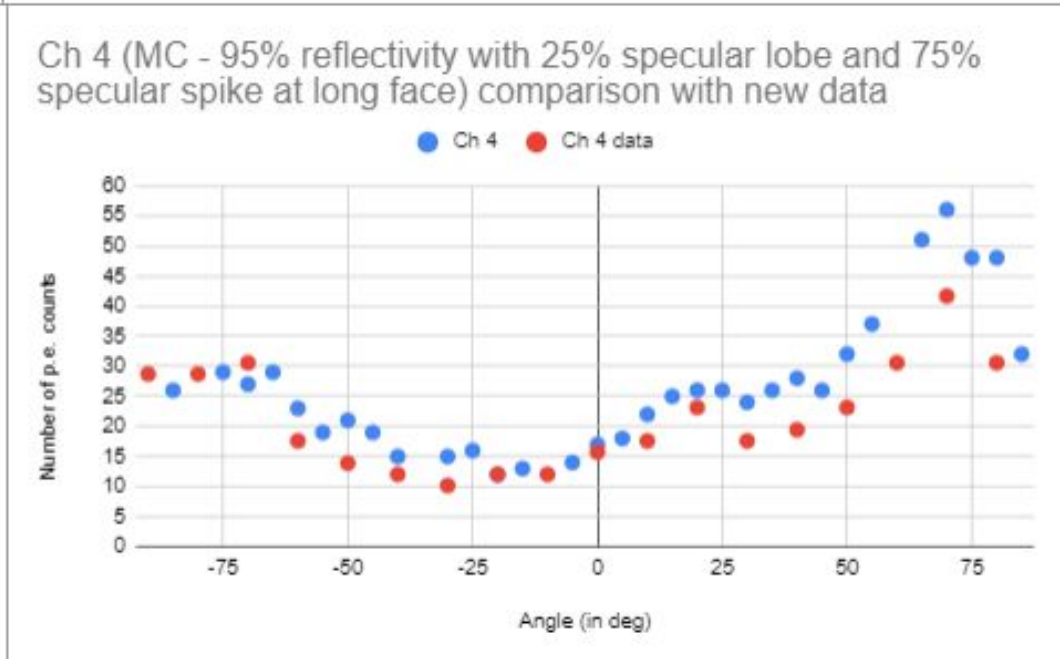



- This 50% reflectivity at the cookie - Air interface had a problem with the MC counts being less than data for the far side peak however, so comparing MPV without any special boundary at the cookie - Air interface with data as well



- Change in roughness - was set by default to 1 rad (~60 deg) so checked for 0 (~specular spike condition), 30, 60 and 90 deg for 25% specular lobe, 75% specular spike, 95% reflectivity at long face
- Again not much difference between the curves for all the non zero values