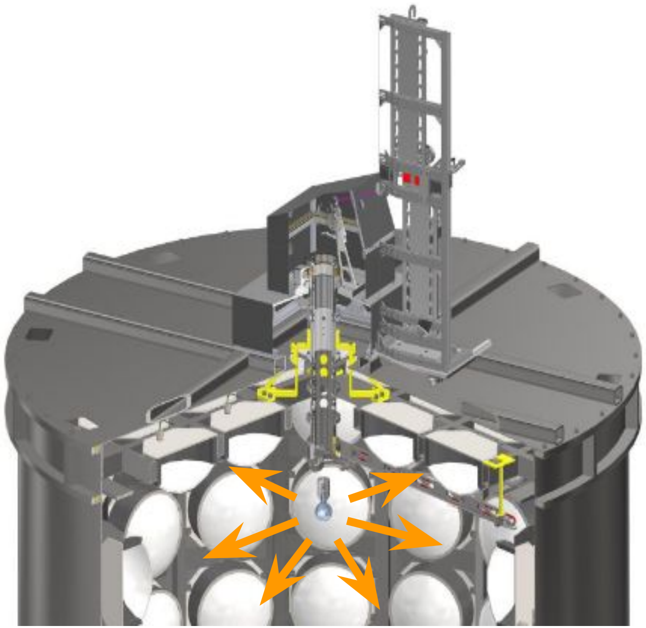
Imperial College London

PMT in-situ calibration with the laser diffuser for WCTE

Alie Craplet (alie.craplet17@imperial.ac.uk)

The calibration process

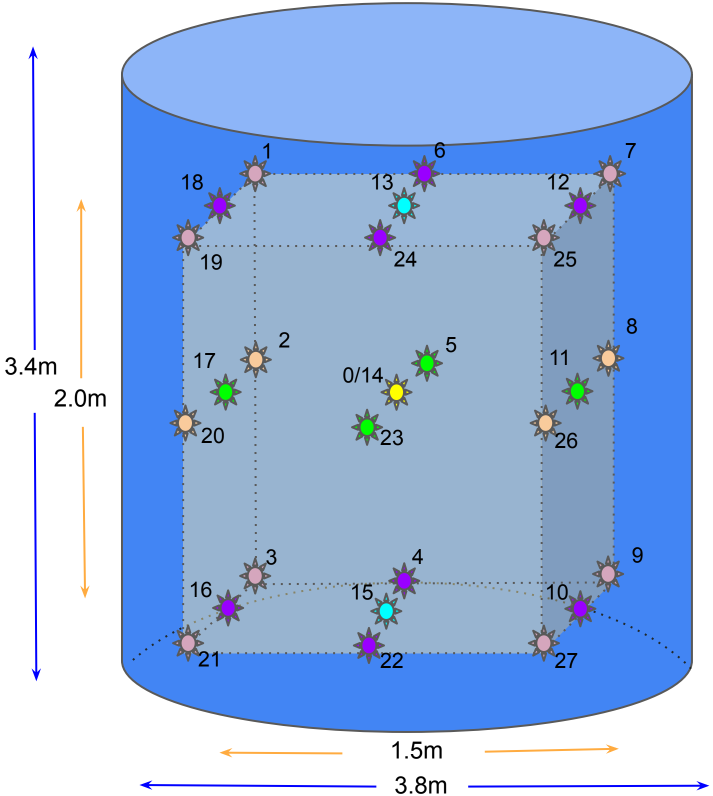


- Laser diffuser and calibration deployment system (CDS) build and tested at Imperial
- Source displaced at key positions within the tank, short light bursts shot.
- Hit times used for **timing** calibration.
- Number of photo-electron recorded used for PMT **angular response** calibration and **water attenuation length** estimation

Simulated datasets

- Datasets simulated with WCSim and the WCTE 16cShort (16c4r) geometry (without CDS arm)
- Source simulated as a /**gps/particle opticalphoton** at different positions
- 3k events (10k photons per event) simulated.
- Uniform light emission in phi 0-360° and theta 20-180°.
- Photon energy: 3.505eV (353.7 nm) or 3.089eV(401.9nm)
- Studies done with either the 4 mPMT masked or not.

Source positions simulated in WCSim



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Timing calibration

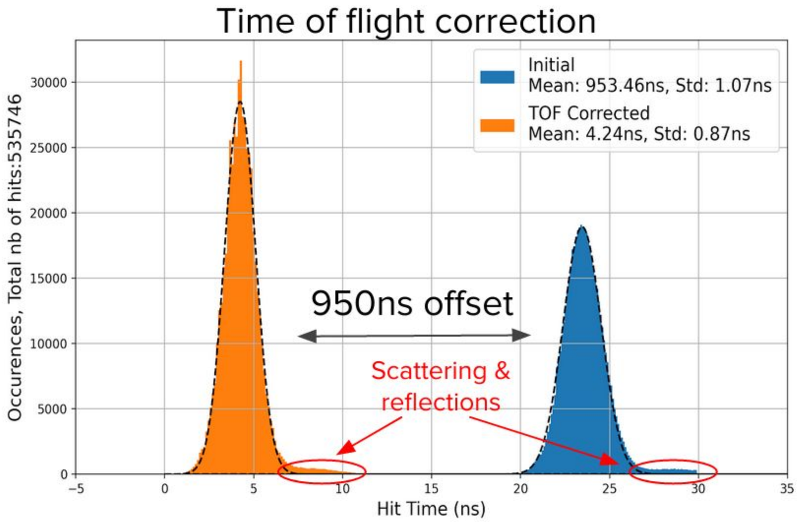
Use the hit times of each PMT to figure out the required timing offset

Timing calibration - method

1. Time of flight correction of the digitised hit times

$$t_c = t_{\mathrm{raw}} - t_{\mathrm{trig}} - R/c_w$$

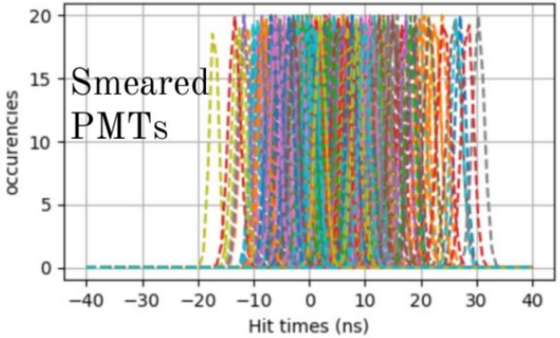
- t_c: TOF-corrected hit time
- t_{raw}: Digitised hit time
- t_{trig}: DAQ triggering time
- R: Source - PMT distance
- c_w: Light velocity in water



2. Add to TOF-corrected hit time a PMT-dependent smearing drawn from a Gaussian $t_s \sim \mathrm{G}(\mu_s,\ \sigma_s)$

$$t_D = t_c + t_s$$

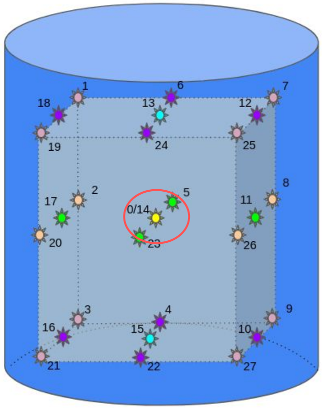
t_D: Smeared and TOF-corrected hit time



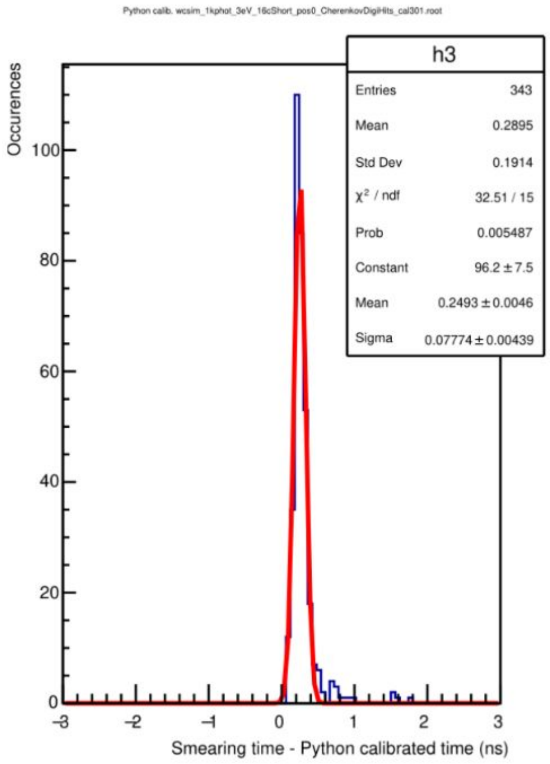
3. Gaussian fit to t_D giving best fit parameters $t_D \sim \mathrm{G}(\mu_D,\ \sigma_D)$

   Comparison of μ_D to t_s to check accuracy of the calibration

Timing calibration - Results for source at centre



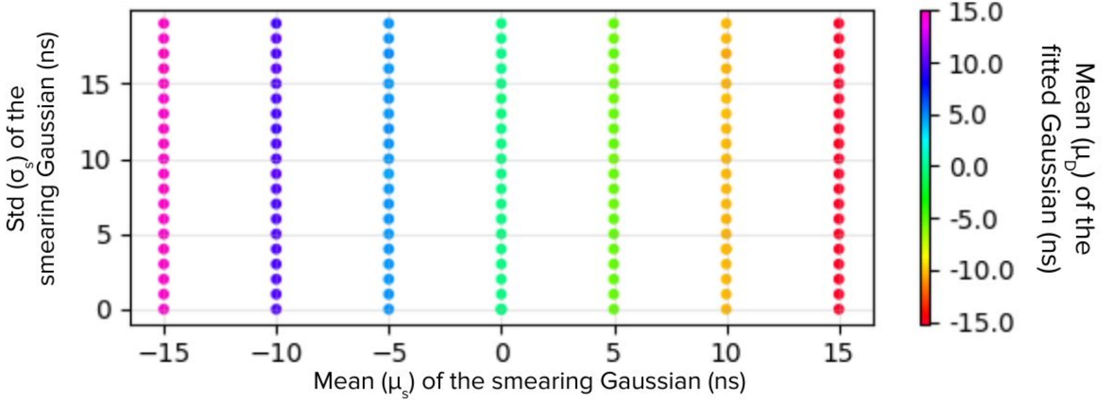
Source at [0, 0, 0]



$t_s - \mu_D$

The t_s - μ_D distribution is centered at +0.29ns with a standard deviation of ~0.2ns.

The accuracy of the calibration doesn't depend on the value of the smearing parameters.



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Angular response and attenuation length

Fit the number of photoelectron to extract $A(\cos(\theta))$ and α

The wcsim_hybrid_attenuation_fit code

Imperial College London

Written and adapted to run with WCTE-geometry wcsim-made files by Ka Ming Tsui (Liverpool):
https://github.com/kmtsui/wcsim_hybrid_attenuation_fit/tree/feature_wcte

This method uses a set of multiplicative factors and a Minuit minimisation to fit the number of P.E. in the data using:

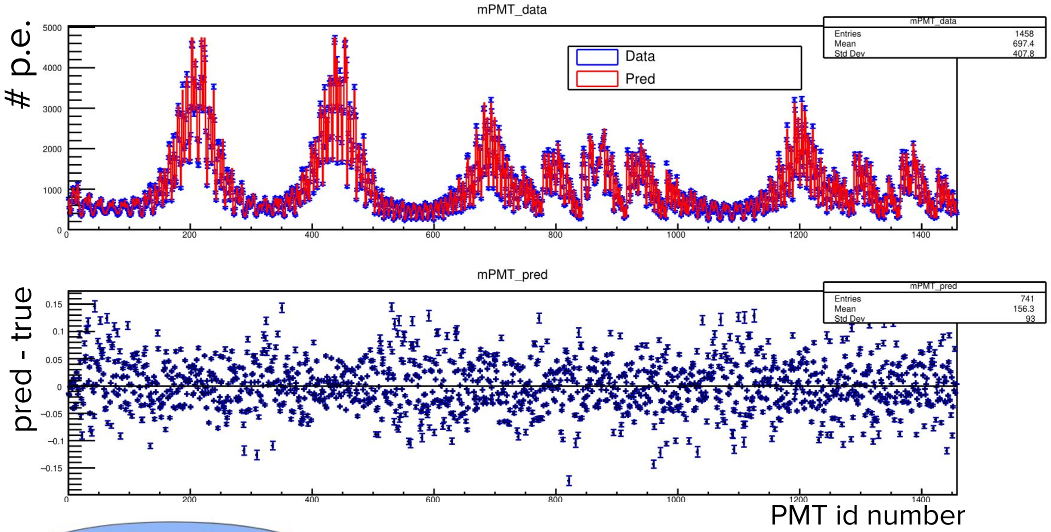
Fixed — Fitted factors

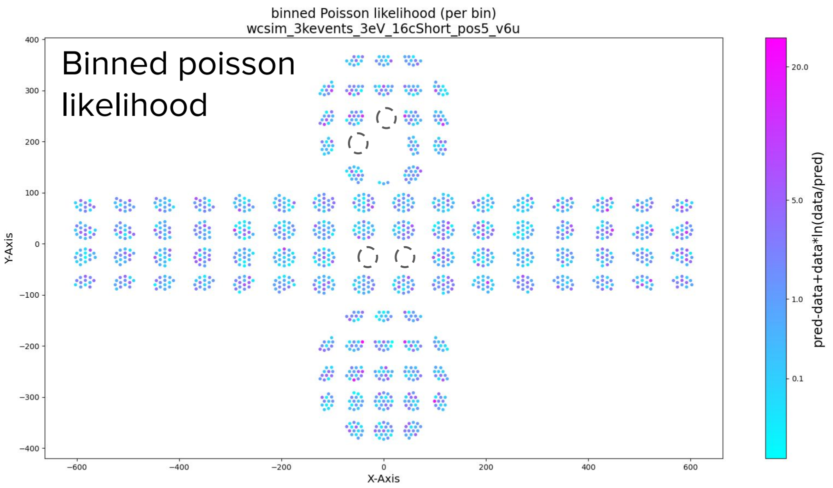
$$\text{PE\_predicted} = \text{Norm} \times \underbrace{\exp\{-\text{R}/\alpha\}}_{\text{Attenuation factor}} \times \underbrace{\omega}_{\text{Solid angle subtended by the PMT}} \times \underbrace{\text{Angular Response}}_{\text{Fitted in bins of cos(θ) or as a polynomial function of θ}}(\cos(\theta))$$

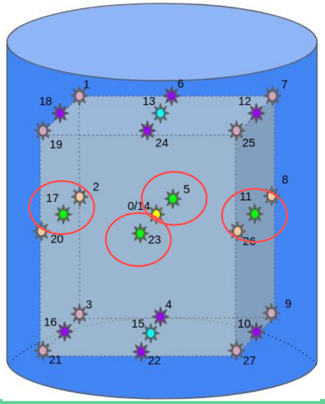
Before the fit, the PMTs can either distributed in bins of cos(θ) and distance R from the light source (100 bins total) or, if the fit is unbinned, each bin holds the data from one PMT.

The code extracts the attenuation length in the water α and the angular response of the PMTs.

P.E. fit for attenuation length and pmt angular response extraction





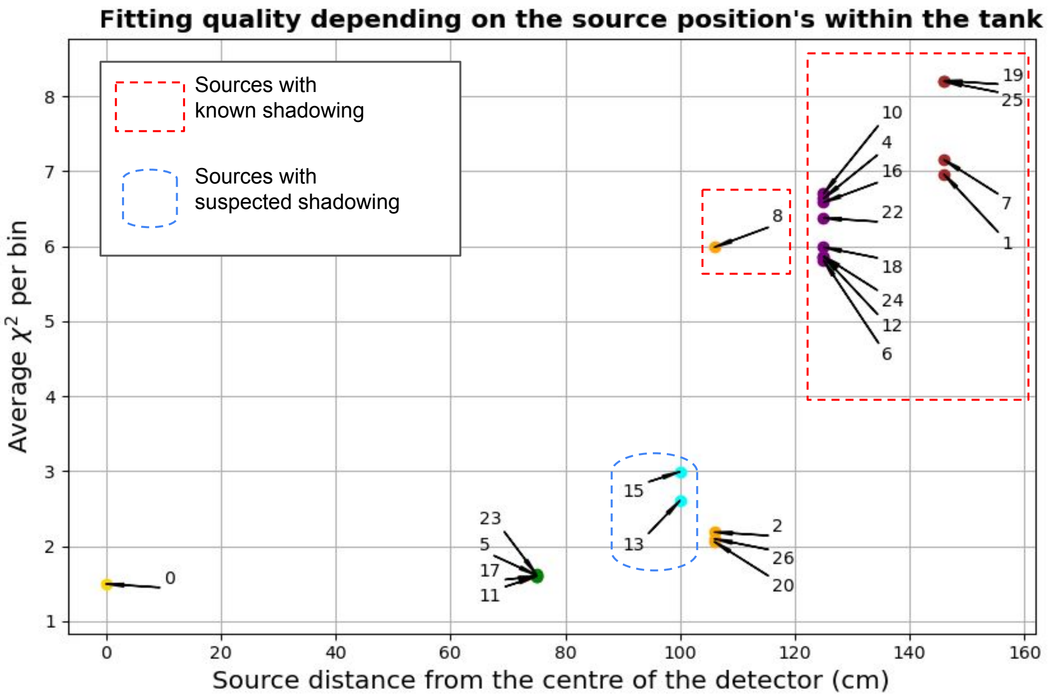


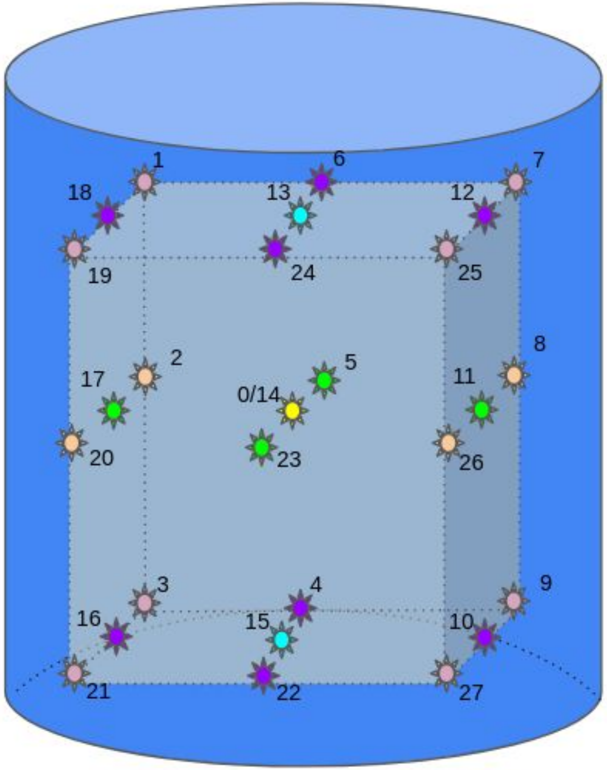
Source dist from 0	75cm
Source positions	5, 17, 11, 23
Chi2/non empty bin (approximately)	~1.5

The number of photo-electron is in general very accurately fitted by the program with a χ^2 value between 1 and 2.

The fit quality seems to be uniform across the tank - no significant reflections/shadowing.

Effect of shadowing on fitting quality





Source positions further away from the centre of the detector are worsley fitted, shadowing plays a very important role on the fitting quality.

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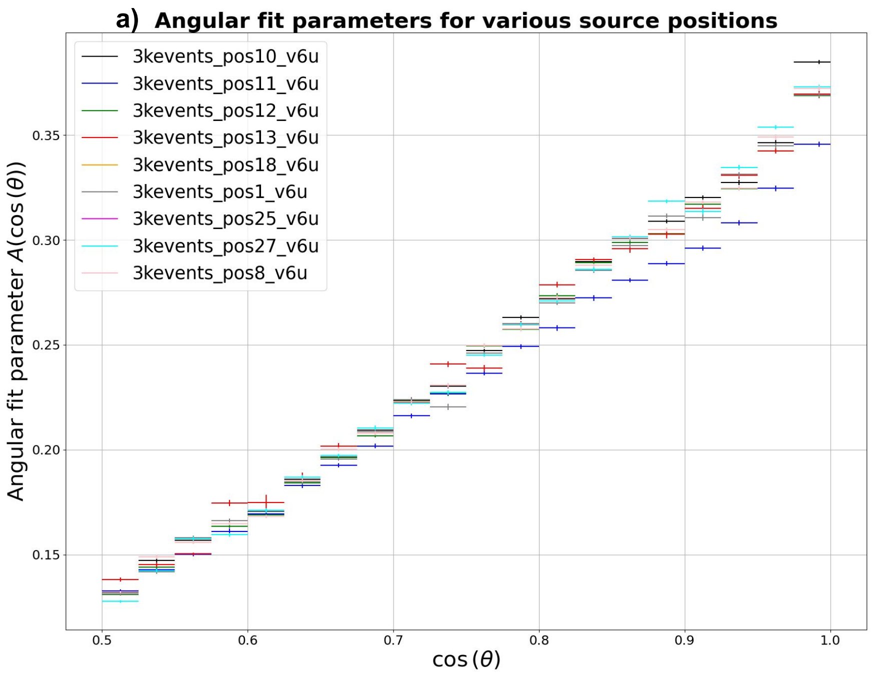
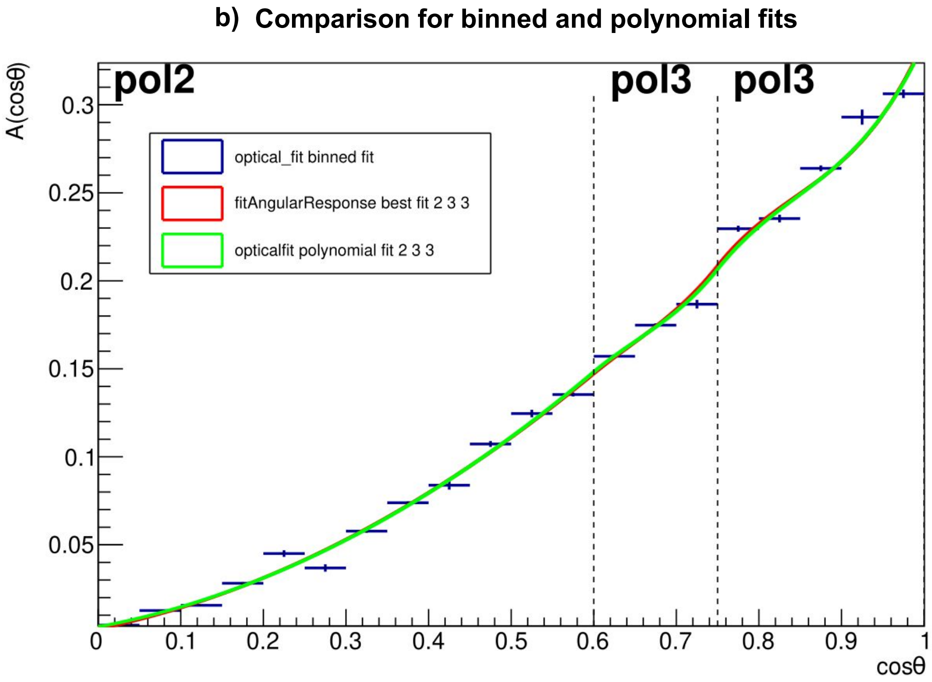
Angular response

$$\mathrm{PE\_predicted} = \mathrm{Norm} \times \exp\{-\mathrm{R}/\alpha\} \times \omega \times \mathrm{Angular\ Response}(\cos(\theta))$$

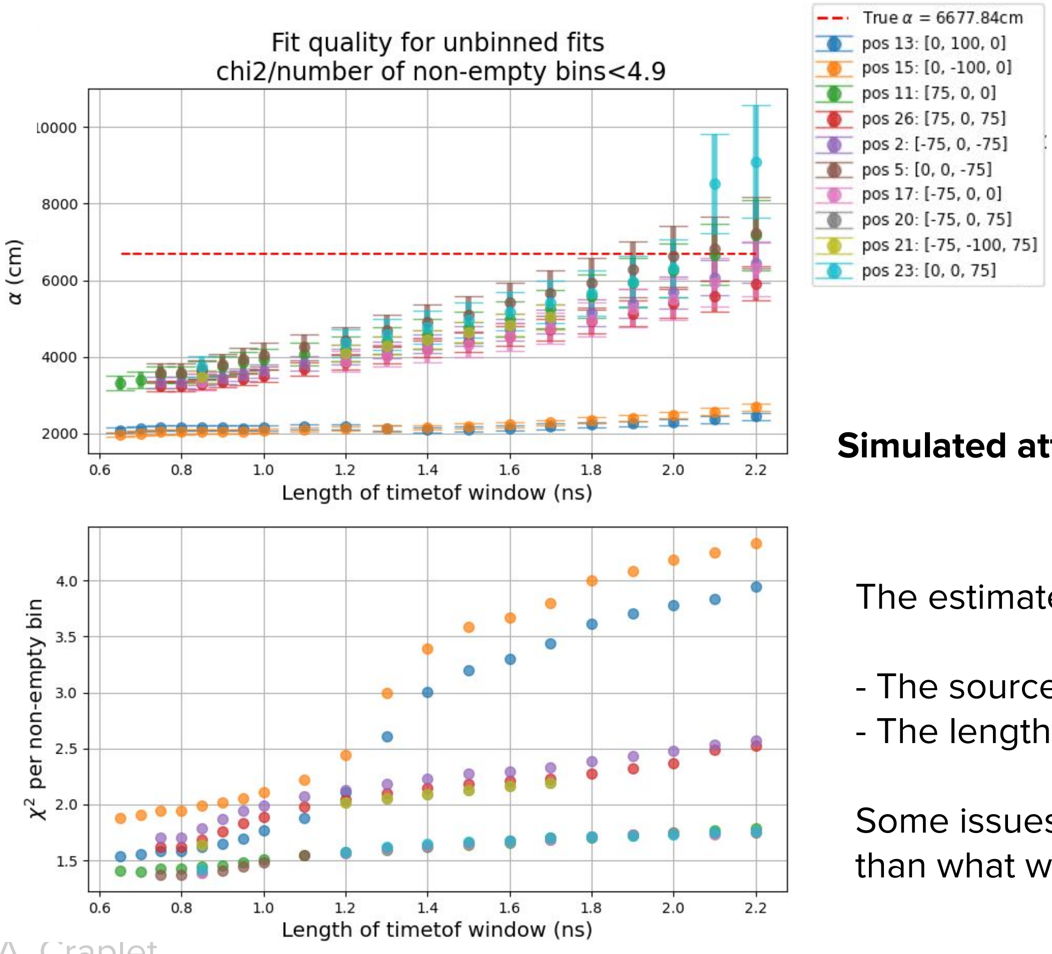




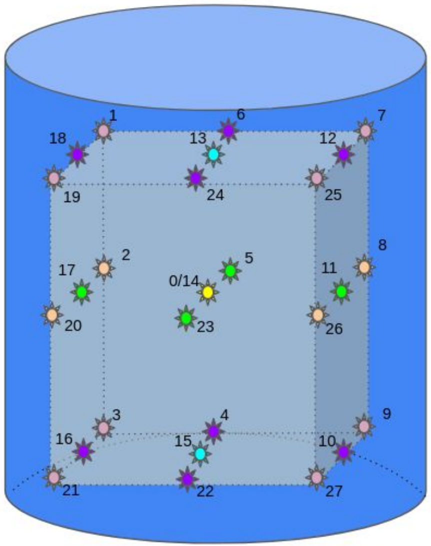
Consistent angular response across source positions, both the binned and polynomial response agree.

Attenuation length

$$\text{PE\_predicted} = \text{Norm} \times \exp\{-\text{R}/\alpha\} \times \omega \times \text{Angular Response}(\cos(\theta))$$



Simulated attenuation length: 66m



The estimate of the attenuation length depends mainly on:

- The source position
- The length of the the TOF-corrected window

Some issues probably remain - we expect a smaller error than what we see.

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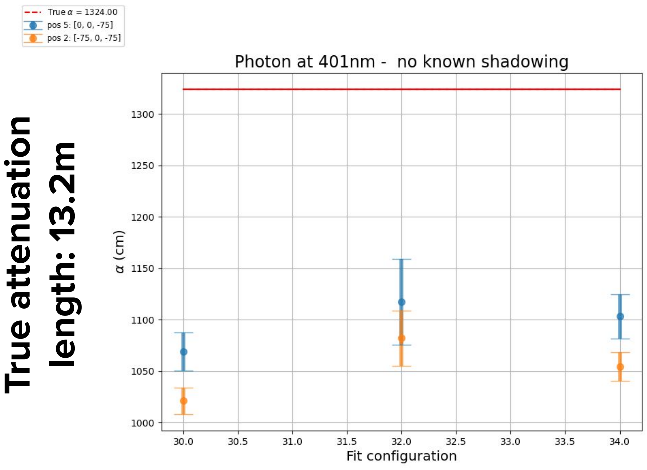
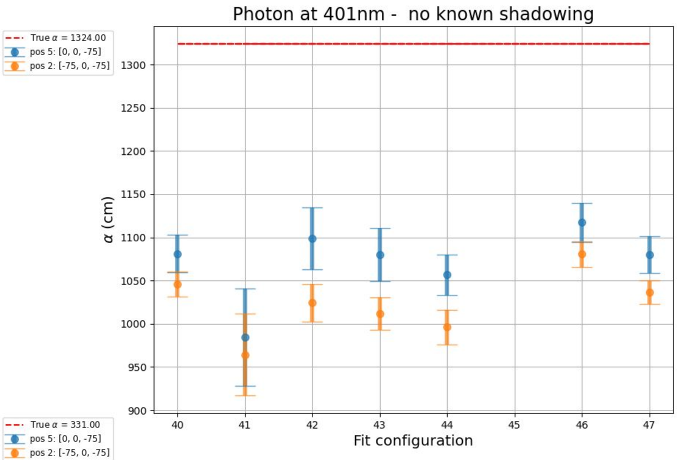
Attenuation length without shadowing

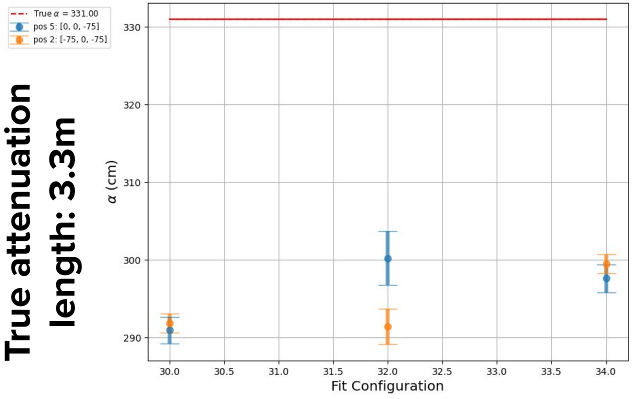
$$\text{PE\_predicted} = \text{Norm} \times \exp\{-R/\alpha\} \times \omega \times \text{Angular Response}(\cos(\theta))$$

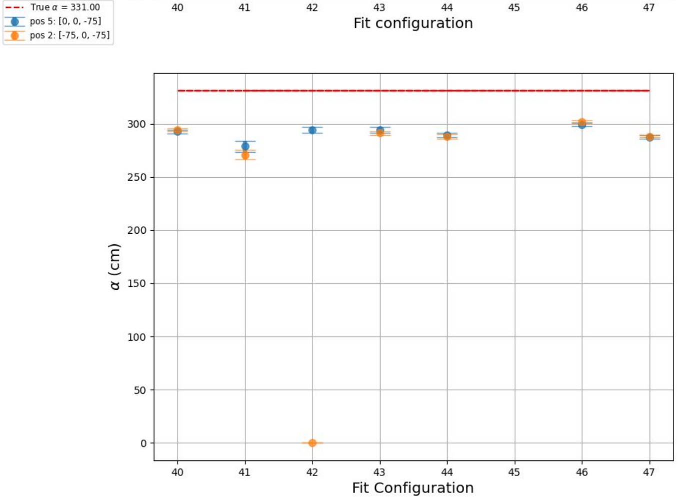
True attenuation length: 13.2m

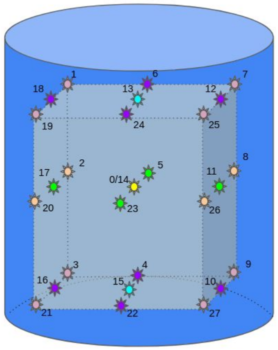




True attenuation length: 3.3m







Configurations:

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46: 40 (timetof < 0.25ns)
47: 40 (timetof < 0.05ns)

Conclusion

- The possibility of using the laser diffuser and the CDS for in-situ PMT timing and angular response calibration is demonstrated

- Any (simple) time smearing can be calibrated to within about 0.2ns, well below the PMT transient time spread

- The angular response of the PMT is found to be consistent and can be used as a benchmark for the calibration

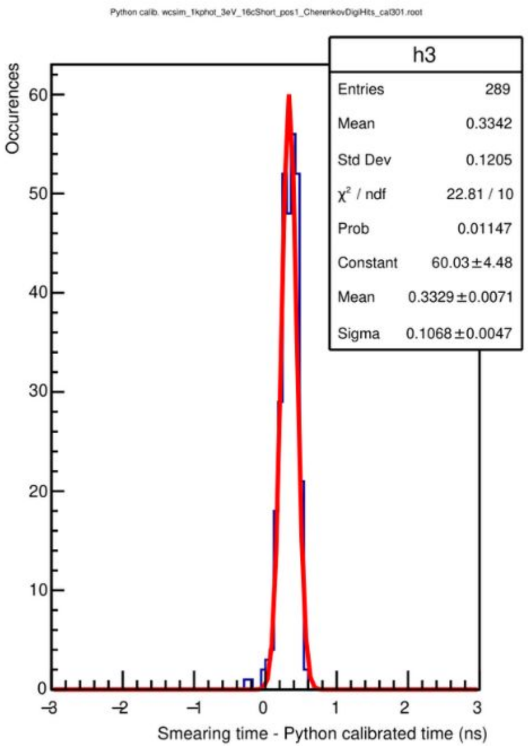
- Some work is required to make sure the attenuation length estimate is optimal

- The CAD model of the CDS will next be added to the simulation to verify the impact of shadowing and light reflection

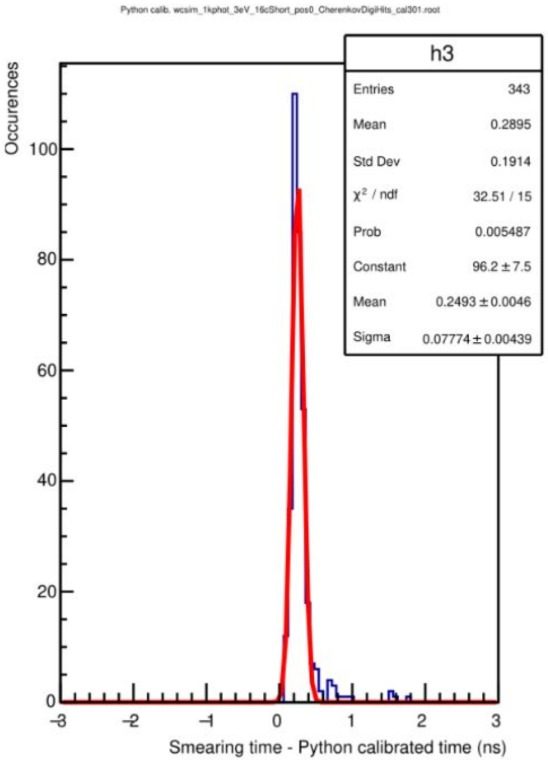
Back-up slides

Timing calibration - Results

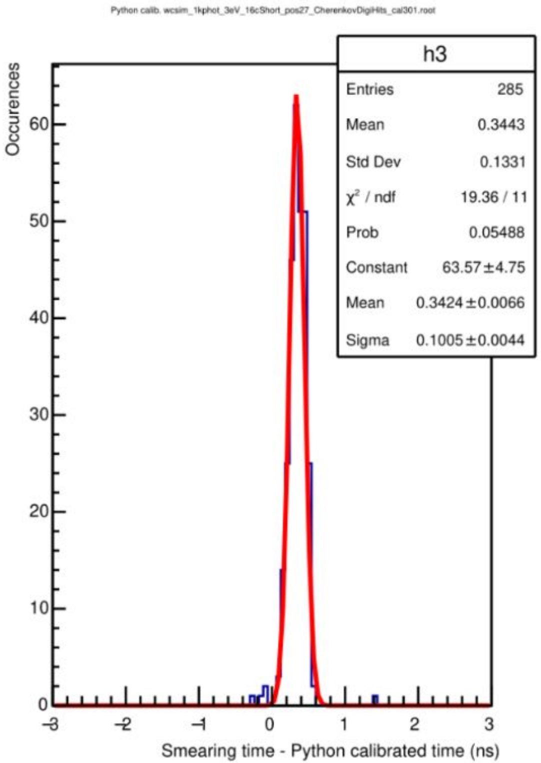
Source at [-75, -75, 100]



Source at [0, 0, 0]

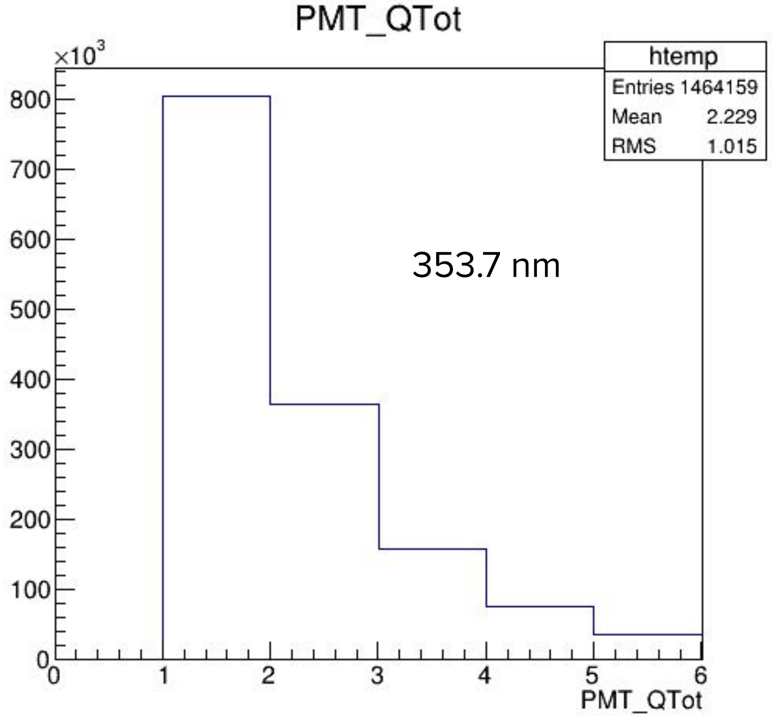


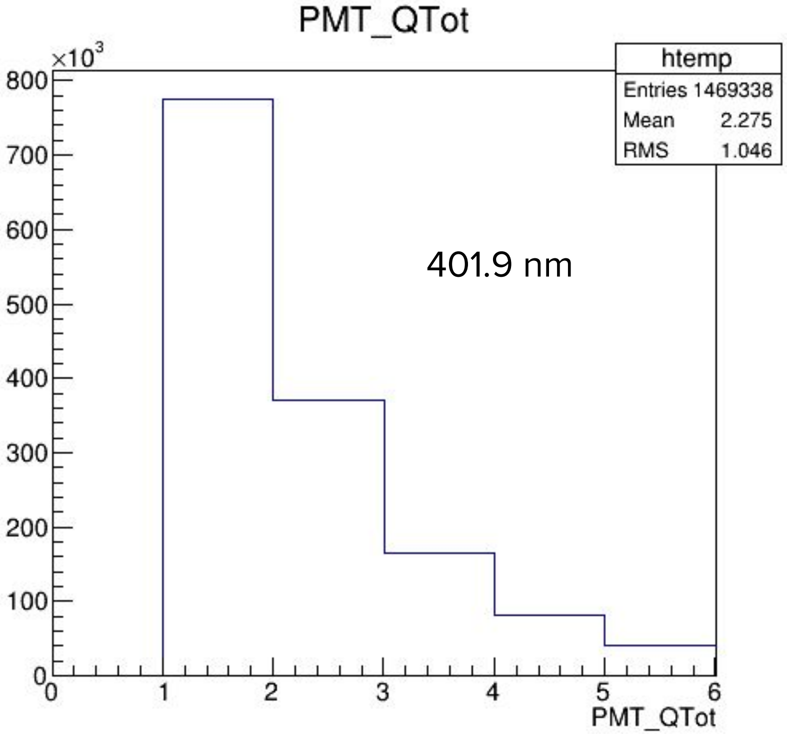
Source at [75, 75, -100]



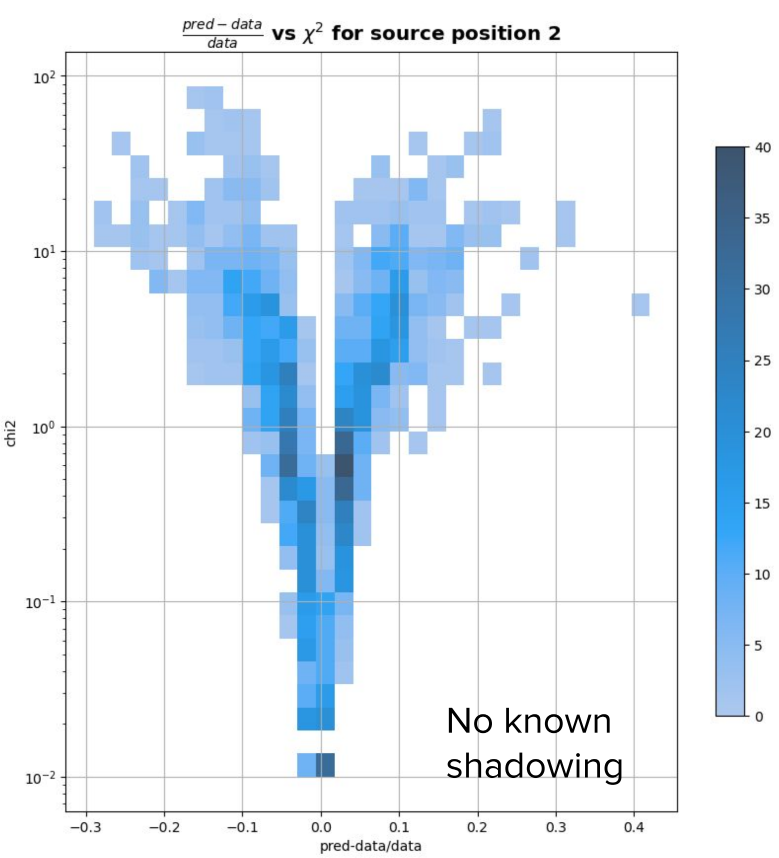
p.e. per PMT

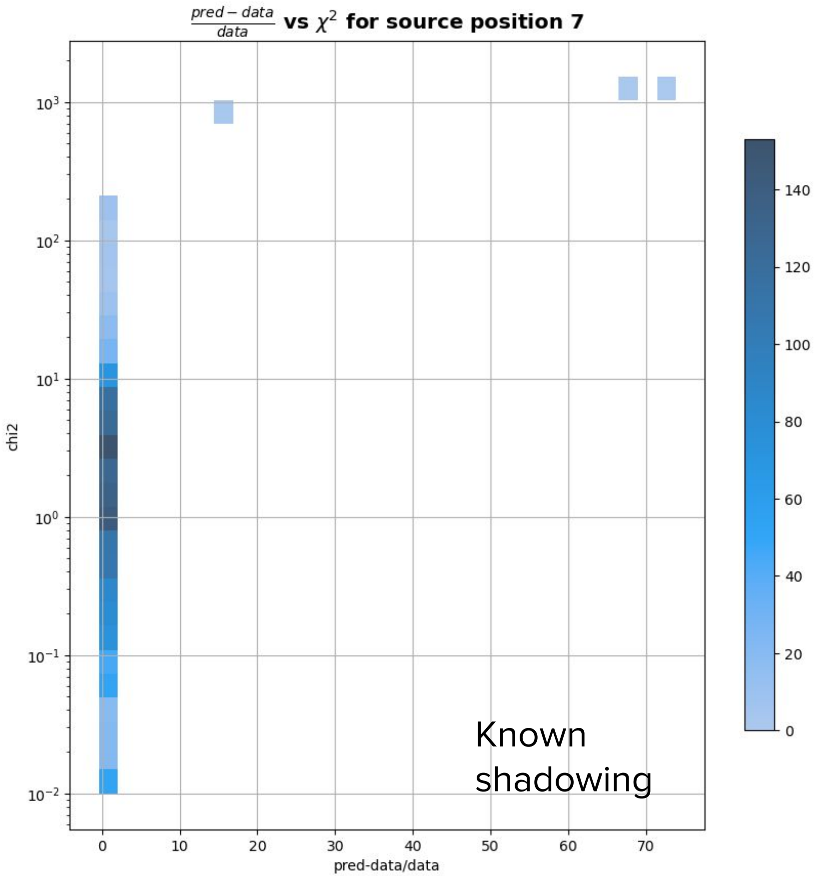
Checks by A. Bercebal-Ruiz





Scattering or absorption?





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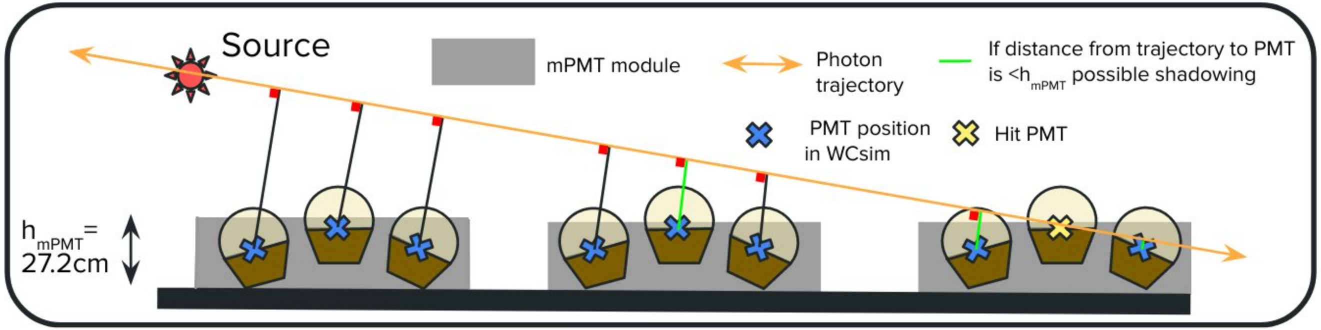
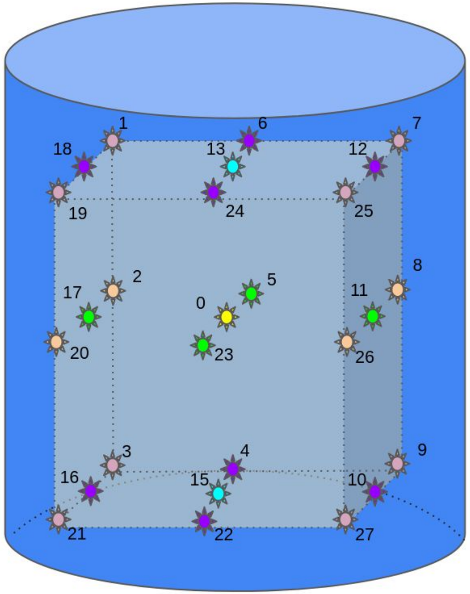
Geometrical checks

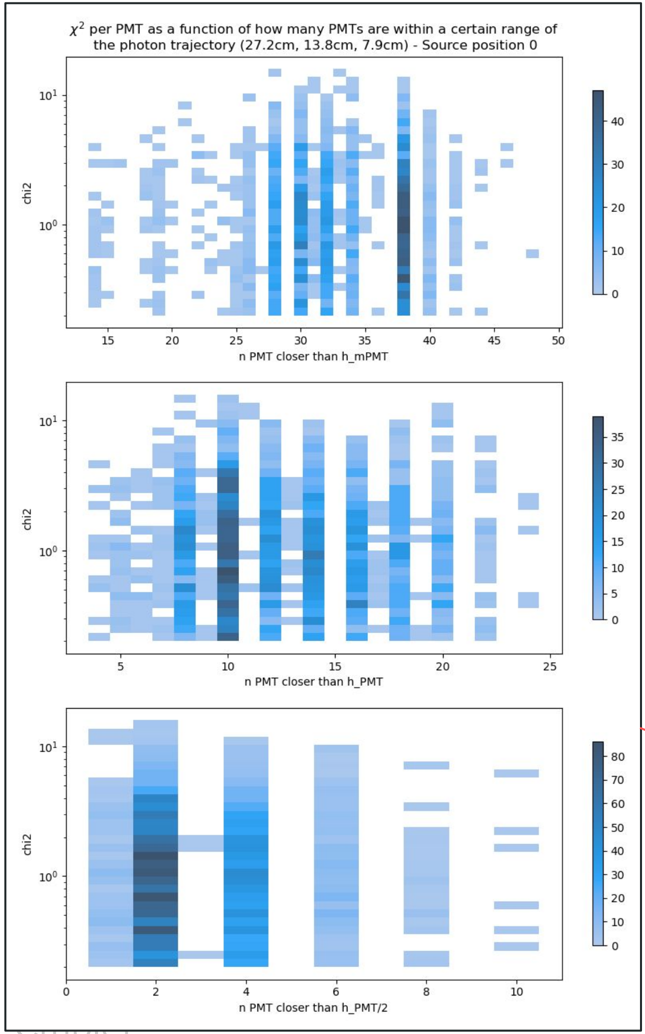




Check the distance of closest approach between a given photon trajectory (associated with a hit PMT) and the other PMT as a function of the χ^2 of the hit PMT.

Hope that if there is PMT-induced shadowing we will see that a lot of mPMT and/or PMT will cross the line of sight.

All geometrical checks were made with a cut on the timetof (raw) at 0.25ns

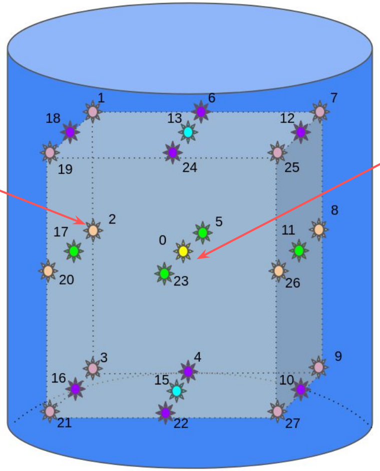


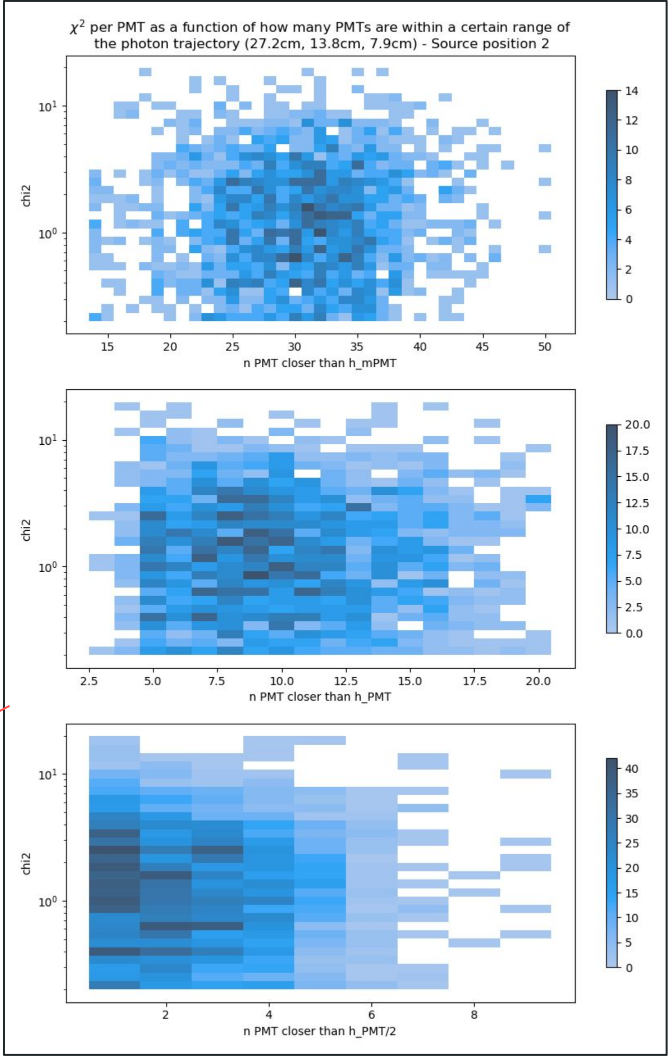
Geometrical checks

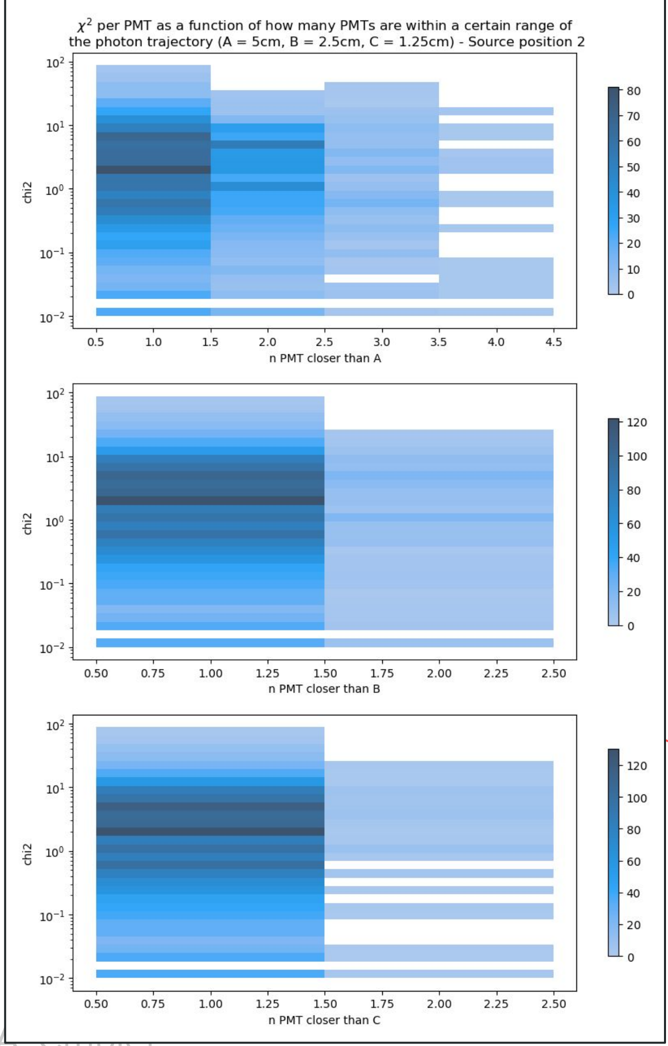
Top: total number of PMTs closer to the line of sight than h_{mPMT}(27.2cm)

Middle: total number of PMTs closer to the line of sight than h_{PMT}(13.8cm)

Bottom: total number of PMTs closer to the line of sight than $h_{PMT}/2$ (7.9cm)







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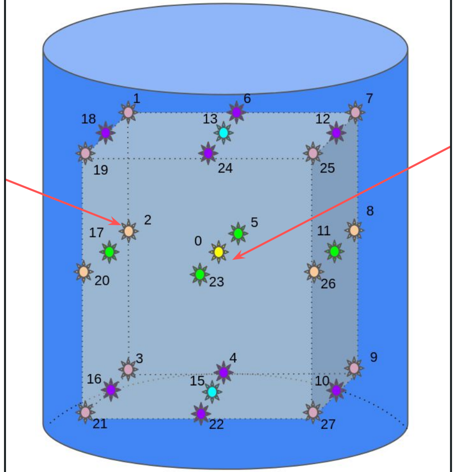
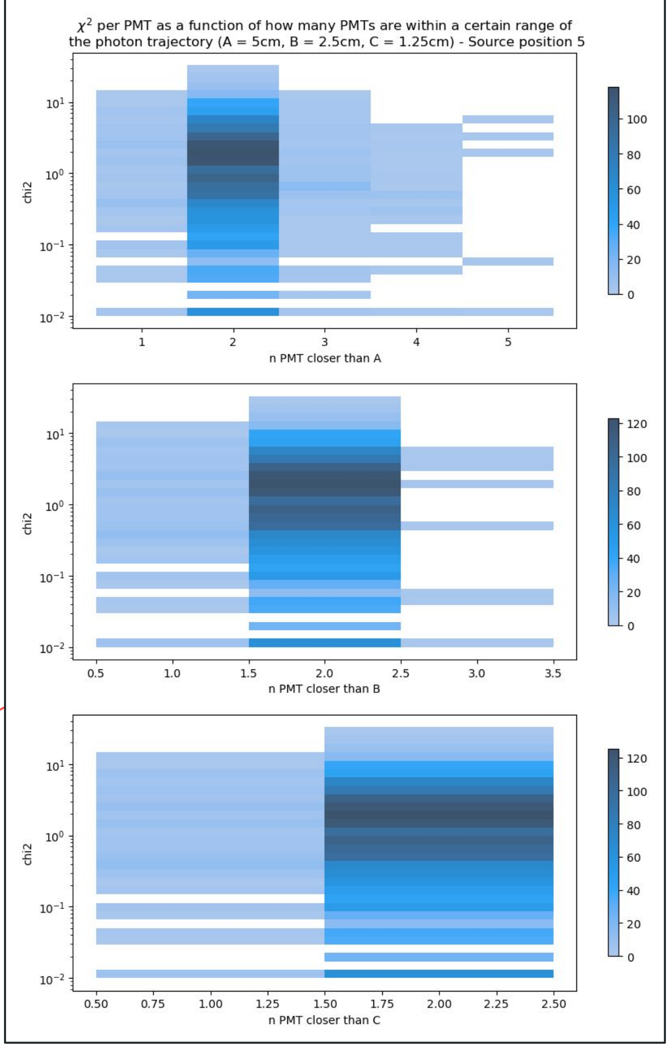
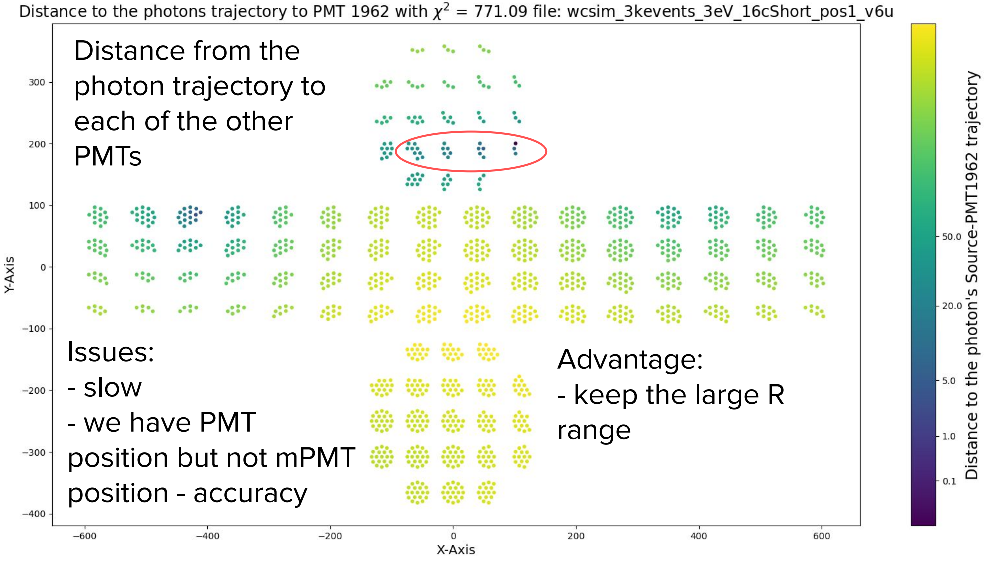
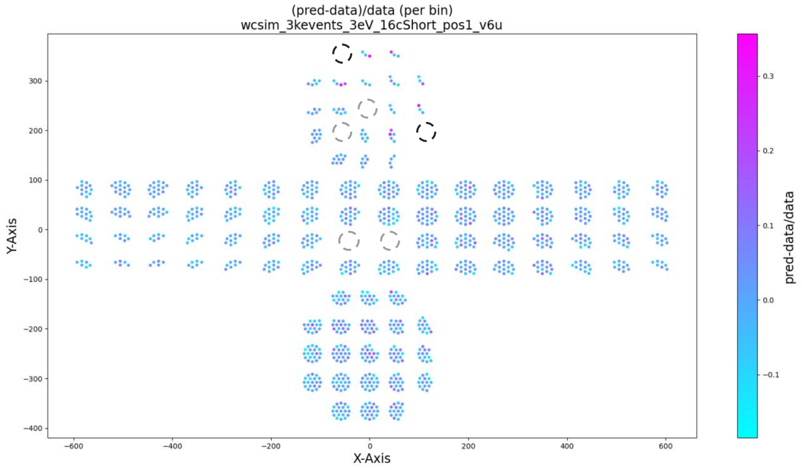


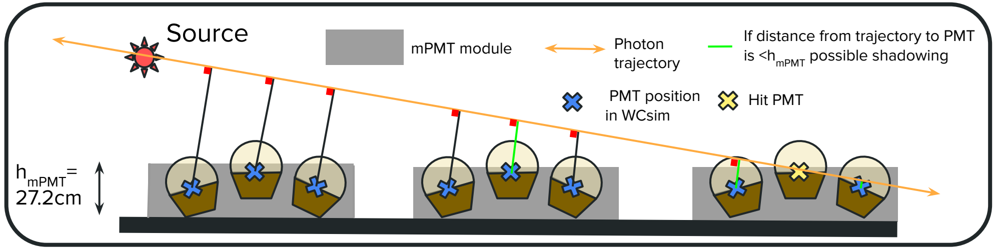


Possible other fixes: **Option 2**: mask (m)PMT as required

For each source-PMT trajectory -> check the distance between the trajectory and each PMT -> if dist to any PMT is < thresh: mask







Above: simply removed the two most problematic mPMTs.
Less accurate than simply displacing the source

Attenuation length with shadowing 2mPMT removed

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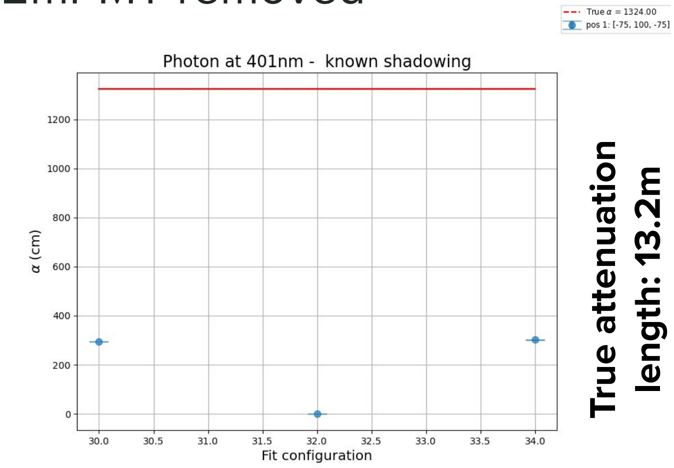
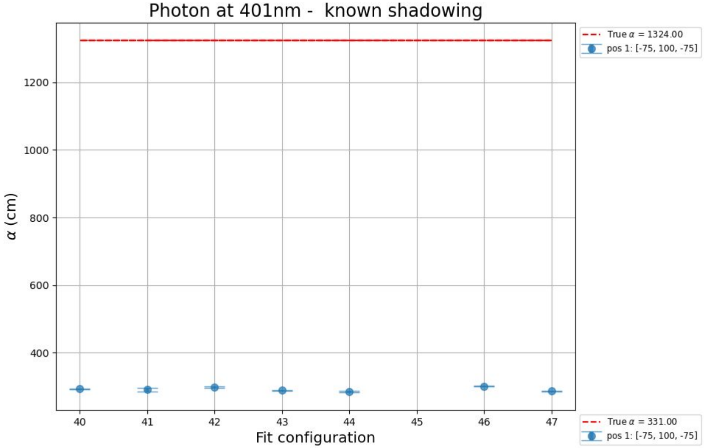
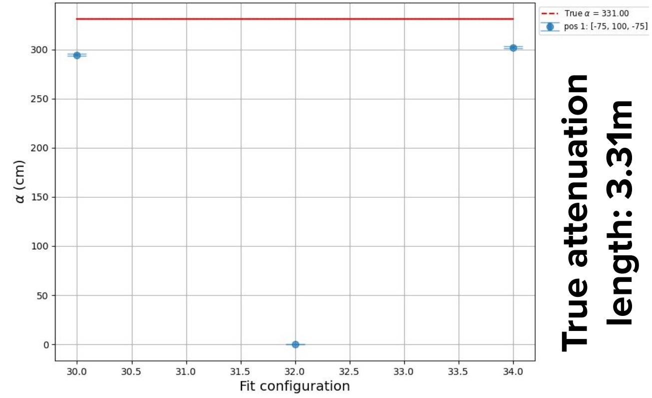
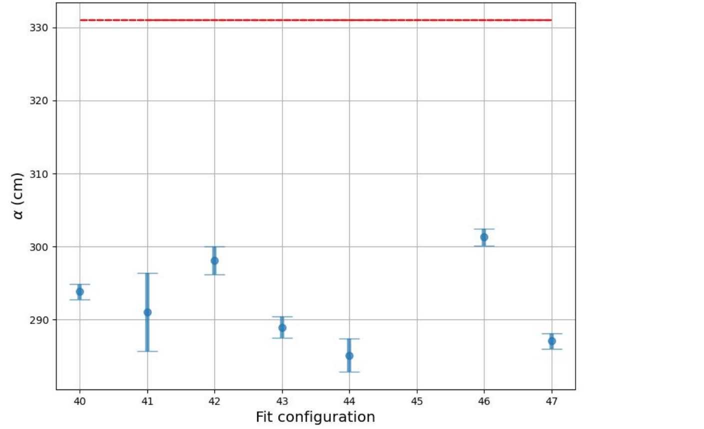


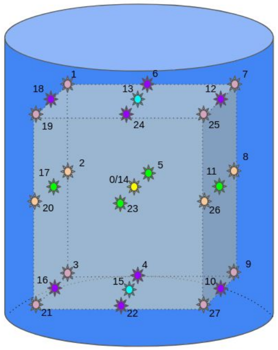
True attenuation length: 13.2m





True attenuation length: 3.31m





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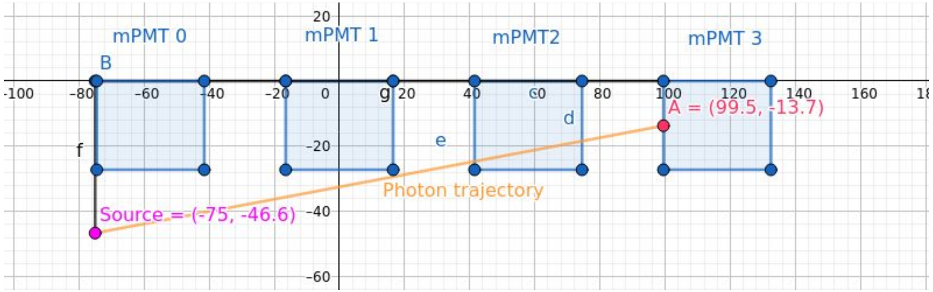
Geometrical check where there is known shadowing



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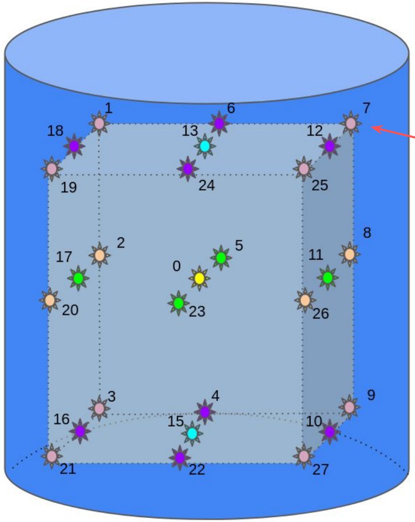

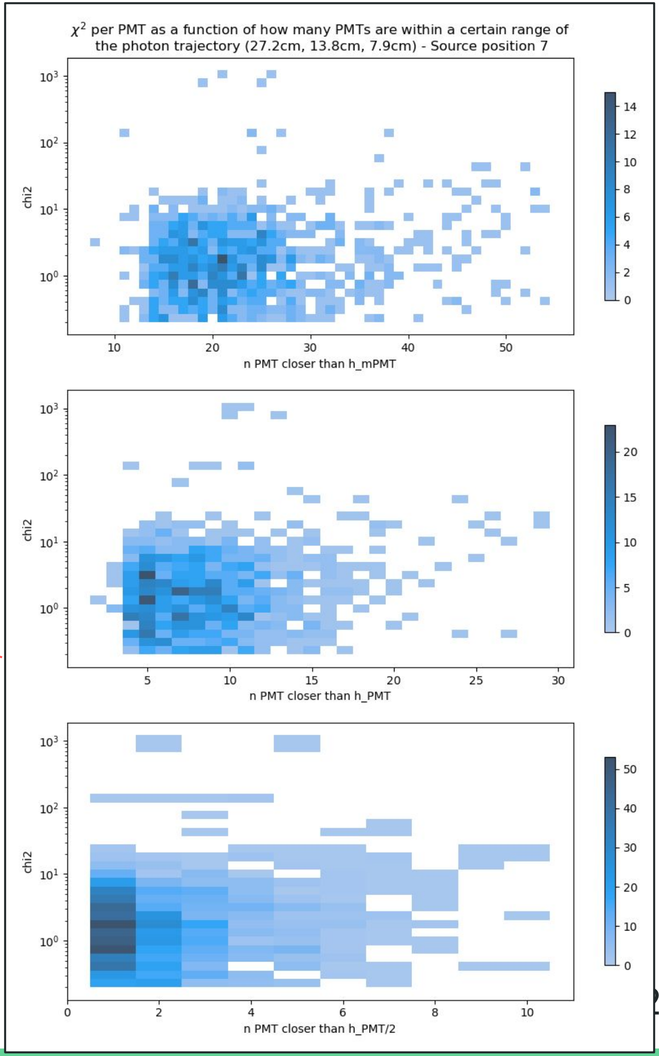

Nothing very obvious is coming out of this...

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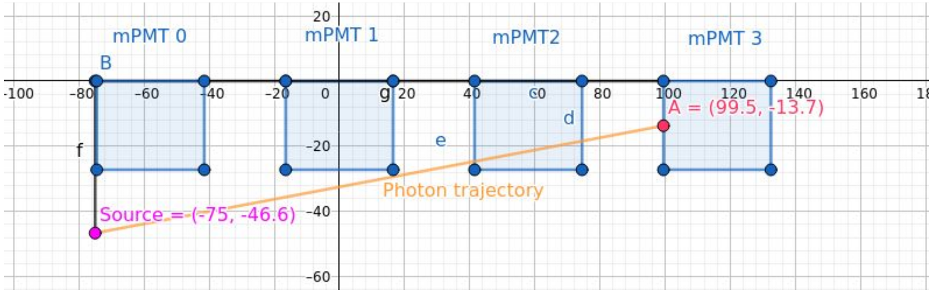
Geometrical check where there is known shadowing



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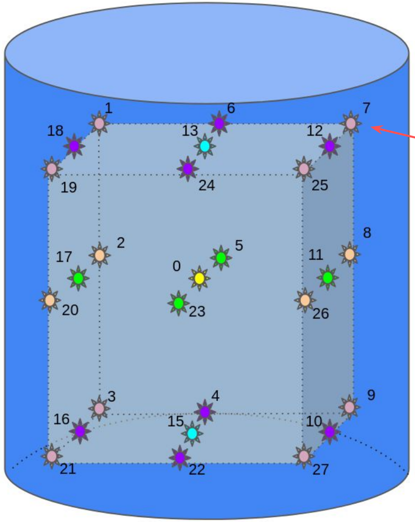
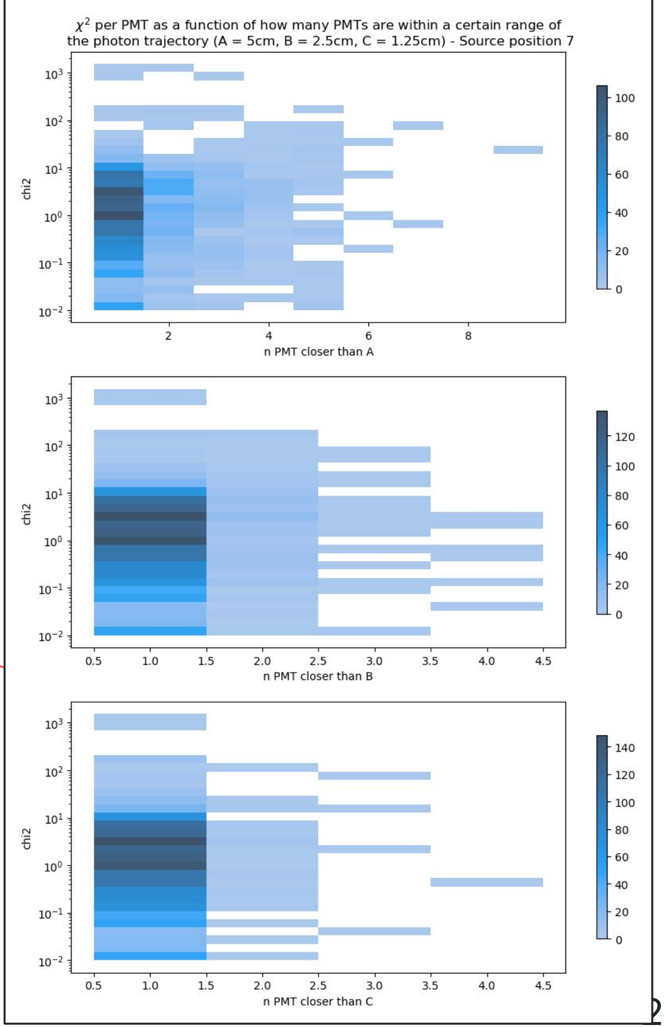




Nothing very obvious is coming out of this...

Investigation of alpha estimate

Timetof(raw)<0.15ns

$\Delta\alpha = \alpha_{\text{alpha fixed at true value, norm fitted}} - \alpha_{\text{alpha fitted, norm fixed @ best fit value obtained from previous fit where } \alpha \text{ was fixed @ its true value}}$

$\Delta\chi^2 = \chi^2_{\text{alpha fixed at true value, norm fitted}} - \chi^2_{\text{alpha fitted, norm fixed @ best fit value obtained from previous fit where } \alpha \text{ was fixed @ its true value}}$

Unibinned fit (1333 bins) Source in pos 2	$\Delta\alpha$	$\Delta\chi^2$
10 bins in costh [0.5, 1.01]	6677.84 - 4103.64 = 2574.20 cm	3369- 3266 = 103
20 bins in costh [0.5, 1.01]	6677.84 - 3758.36 = 2919.48 cm	2224- 2101 = 123

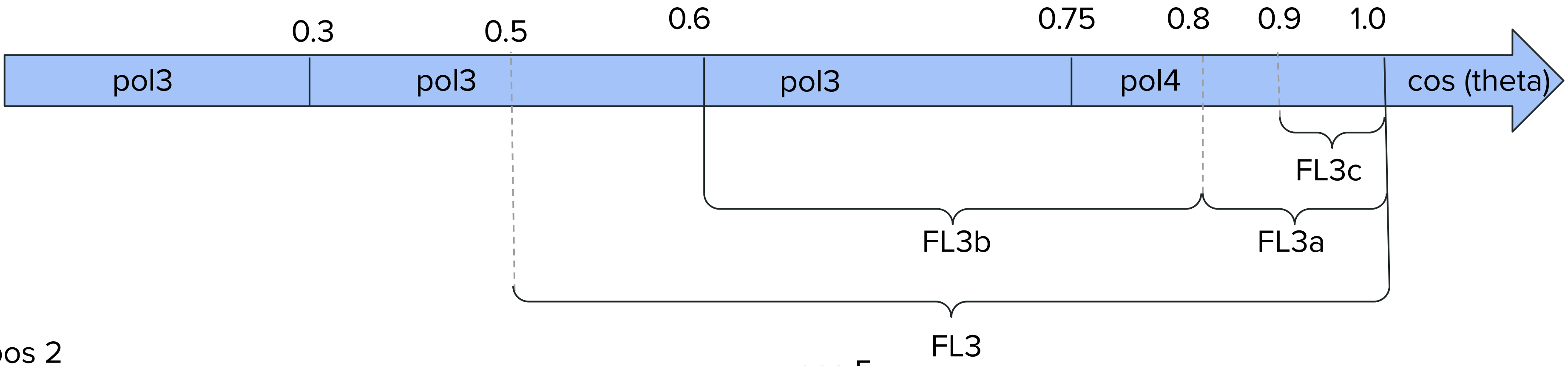
It looks like more freedom in the angular response fits the distribution better but biases against α which is then fitted further away from its true value. Too many Θ-dependant fit parameters?

In this case the three rings parameterization was used.

Best fit norm (alpha fixed) is quite far from the calculated value (~70% smaller -> did I forget Q.E.?)

Other investigations - cos(theta) portions @ 401.9nm

Fit PMTs: unbinned, Angular response: polynomial



pos 2

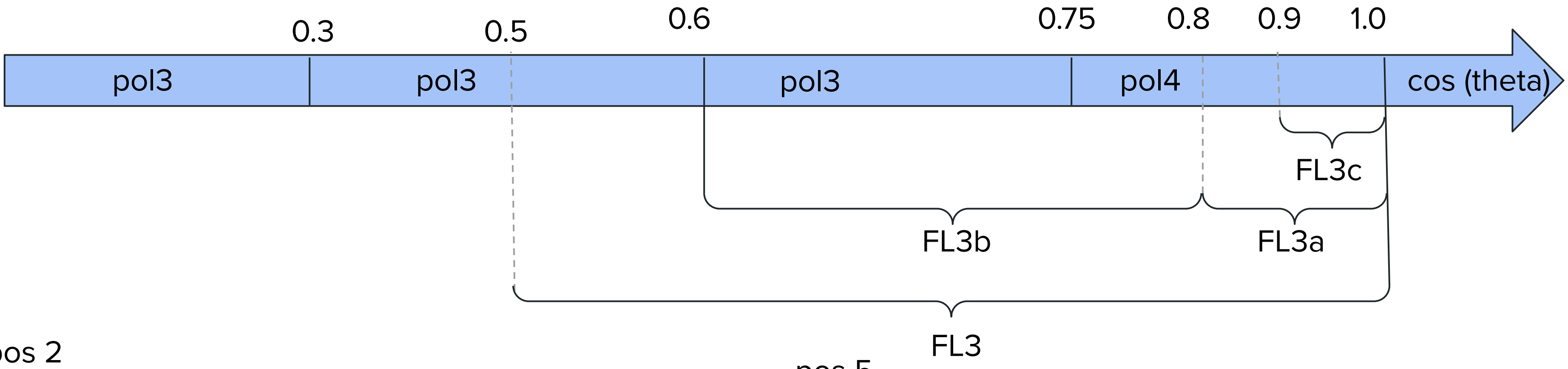
No DN		FL3	FL3a	FL3b	FL3c
401nm-pos2 alpha = 107m	chi2 alpha	Inf 0.02 +/- 0	1.53 37.9 +/- 2.2	1.40 44.5 +/- 4.3	1.43 35.4 +/- 2.5
401nm-pos2 alpha = 3.31m	chi2 alpha	1.43 2.9+/- 0.01	Inf 0.02 +/- 0	1.28 2.9 +/- 0.02	10.8 9.8 +/- 0.2
401nm-pos2 alpha = 13.24m	chi2 alpha	1.53 10.2 +/- 0.1	1.62 9.8 +/- 0.2	1.31 10.8 +/- 0.3	1.48 9.5 +/- 0.2

pos 5

No DN		FL3	FL3a	FL3b	FL3c
401nm-pos5 alpha = 107m	chi2 alpha	1.20 51.3 +/- 4.5	1.16 41.0 +/- 3.6	1.23 74.3 +/- 17	1.21 40.4 +/- 4.8
401nm-pos5 alpha = 3.31m	chi2 alpha	1.39 3.1 +/- 0.01	40.6 100+/- inf	1.44 3.1 +/- 0.03	1.44 3.1 +/- 0.03
401nm-pos5 alpha = 13.24m	chi2 alpha	1.36 13.9 +/- 0.3	1.40 13.7+/- 0.4	1.25 14.3 +/- 0.6	

Other investigations - cos(theta) portions @ 353.7nm

Fit PMTs: unbinned, Angular response: polynomial



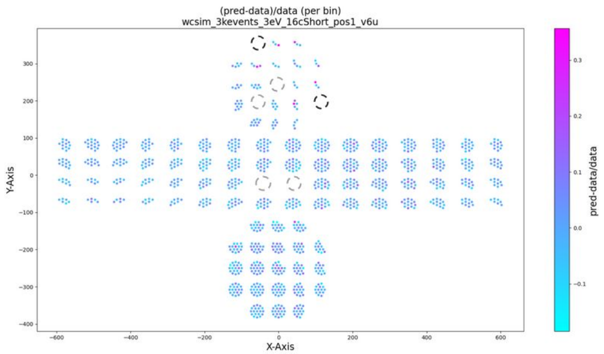
pos 2

No DN		FL3	FL3a	FL3b	FL3c
353nm-pos2 alpha = 66.8m	chi2 alpha				
353nm-pos2 alpha = 2.5m	chi2 alpha				
353nm-pos2 alpha = 10.0m	chi2 alpha				

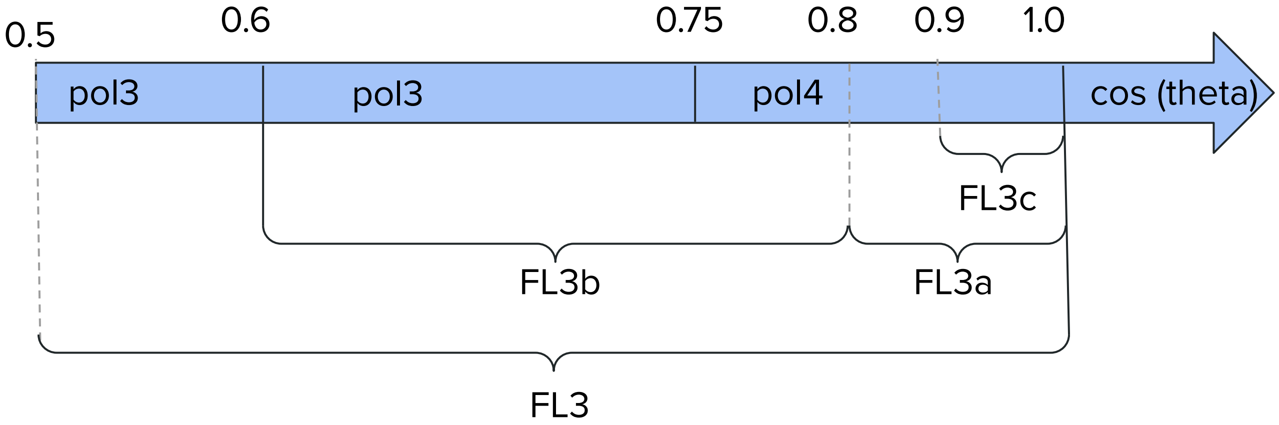
pos 5

No DN		FL3	FL3a	FL3b	FL3c
353nm-pos5 alpha = 66.8m	chi2 alpha				
353nm-pos5 alpha = 2.5m	chi2 alpha				
353nm-pos5 alpha = 10.0m	chi2 alpha				

Other investigations - cos(theta) portions pos 1 with 2 mPMTs removed



Fit PMTs: unbinned, Angular response: polynomial



pos 1 - 353.7nm

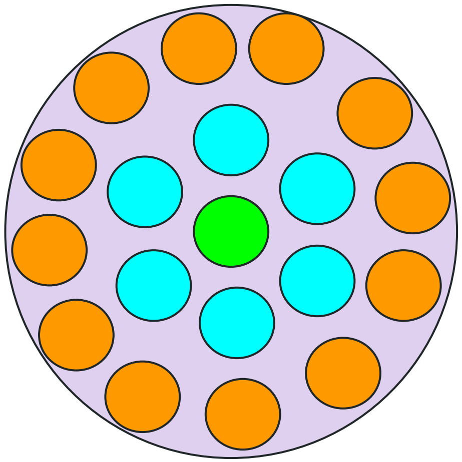
No DN		FL3	FL3a	FL3b	FL3c
353nm-pos2 alpha = 66.8m	chi2 alpha				
353nm-pos2 alpha = 2.5m	chi2 alpha				
353nm-pos2 alpha = 10.0m	chi2 alpha				

pos 1 - 401.9nm

No DN		FL3	FL3a	FL3b	FL3c
401nm-pos5 alpha = 66.8m	chi2 alpha				
401nm-pos5 alpha = 2.5m	chi2 alpha				
401nm-pos5 alpha = 10.0m	chi2 alpha				

Other investigations - ring selection @ 401.9nm

mPMT module



Fit:

Unbinned PMTs
Binned angular response (20 bins)
0.5<costh<1.01

pos 2

No DN		FL4	FL4a	FL4b	FL4c
401nm-pos2 alpha = 66.8m	chi2 alpha				
401nm-pos2 alpha = 2.5m	chi2 alpha				
401nm-pos2 alpha = 10.0m	chi2 alpha				

pos 5

No DN		FL4	FL4a	FL4b	FL4c
401nm-pos2 alpha = 66.8m	chi2 alpha				
401nm-pos2 alpha = 2.5m	chi2 alpha				
401nm-pos2 alpha = 10.0m	chi2 alpha				

pos 1 - 2mPMT masked

No DN		FL4	FL4a	FL4b	FL4c
401nm-pos2 alpha = 66.8m	chi2 alpha				
401nm-pos2 alpha = 2.5m	chi2 alpha				
401nm-pos2 alpha = 10.0m	chi2 alpha				

Other Investigations - Timetof cuts @ 401.9nm

PMT: unbined	0.05ns	0.15ns	0.25ns
Angular response polynomial	FL3e	FL3	FL3d
Angular response binned	FL4g	FL4	FL4f

pos 5

No DN		FL3	FL3d	FL3e	FL4	FL4f	FL4g
401nm-pos5 alpha = 66.8m	chi2 alpha						
401nm-pos5 alpha = 2.5m	chi2 alpha						
401nm-pos5 alpha = 10.0m	chi2 alpha						

pos 2

No DN		FL3	FL3d	FL3e	FL4	FL4f	FL4g
401nm-pos2 alpha = 66.8m	chi2 alpha						
401nm-pos2 alpha = 2.5m	chi2 alpha						
401nm-pos2 alpha = 10.0m	chi2 alpha						

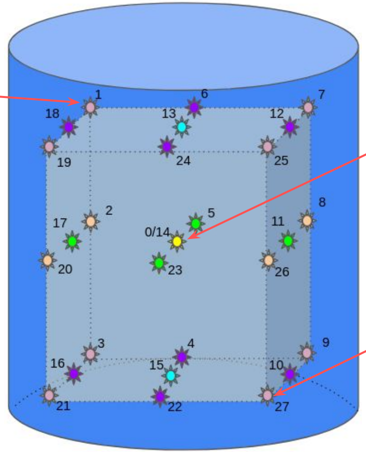
pos 1 - 401.9nm

No DN		FL3	FL3d	FL3e	FL4	FL4f	FL4g
401nm-pos5 alpha = 66.8m	chi2 alpha						
401nm-pos5 alpha = 2.5m	chi2 alpha						
401nm-pos5 alpha = 10.0m	chi2 alpha						

Timing calibration - Results

The source at centre of the detector provides better calibration than when on more extreme positions.

$t_D \sim G(0.33, 0.11)$

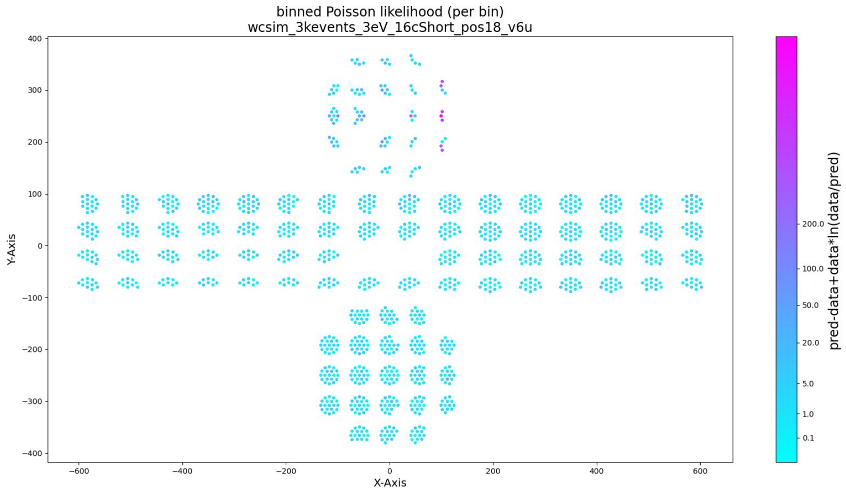


$t_D \sim G(0.25, 0.08)$

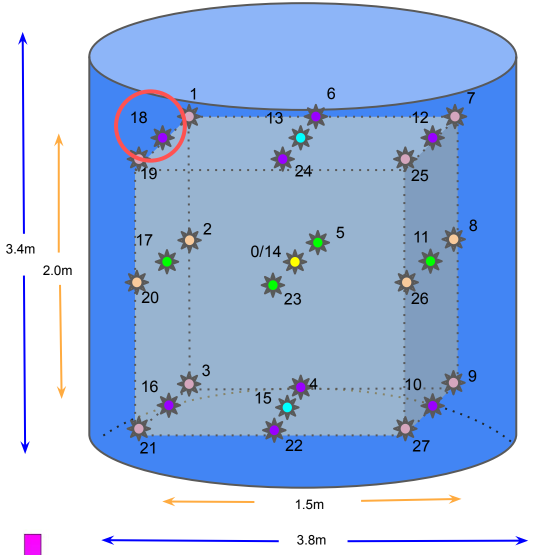
$t_D \sim G(0.34, 0.10)$

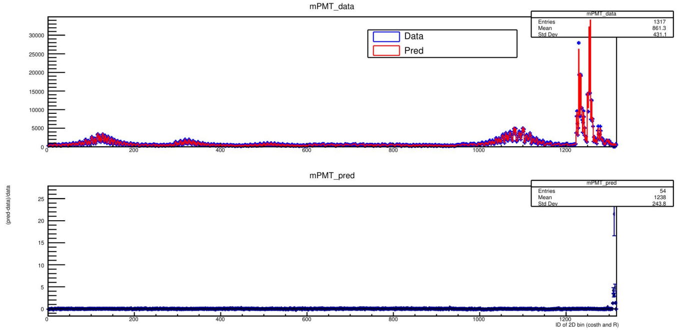
Geometry comparison - 16c4r $t_D^{16c4r} \sim G(0.25, 0.08)$ similar to 16c5r $t_D^{16c5r} \sim G(0.25, 0.06)$ for source at the centre of the tank.

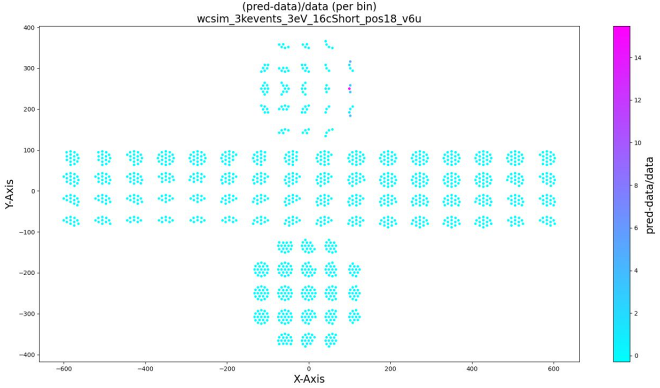
Fit failures - 125 cm away from centre of the tank



~10 times more hits predicted compared to observed.







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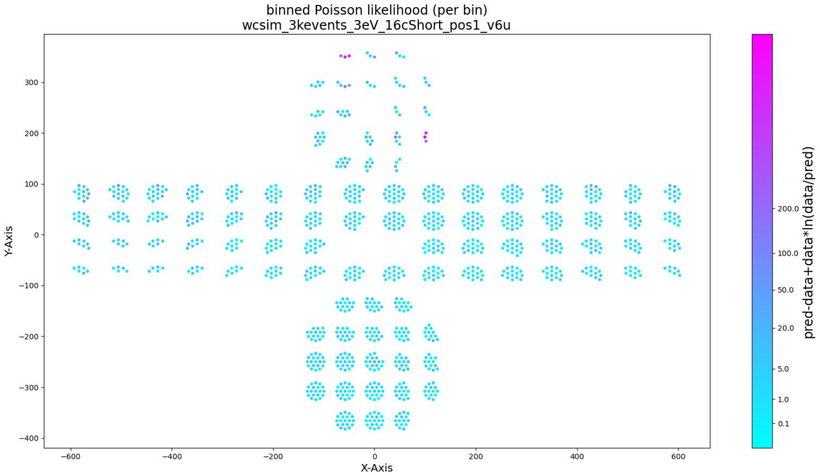
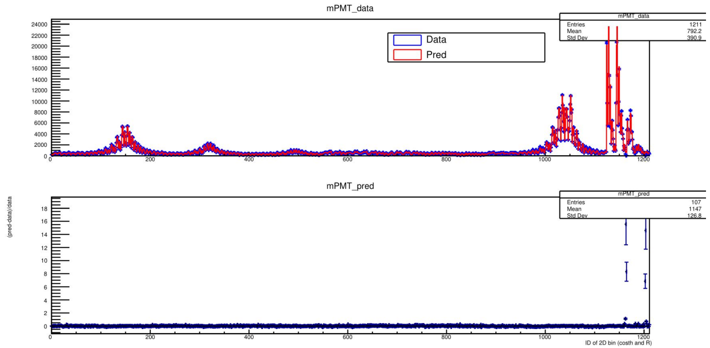
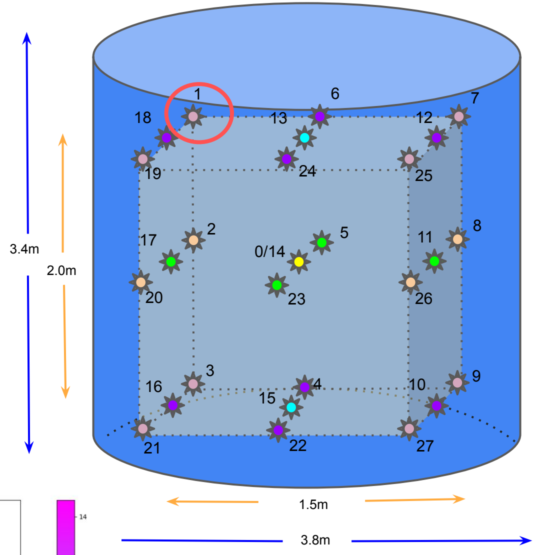
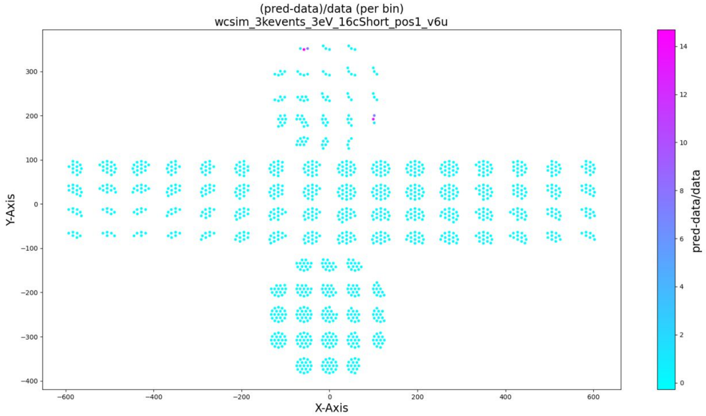
Fit failures - 146 cm away from centre of the tank





~10 times more hits predicted compared to observed.





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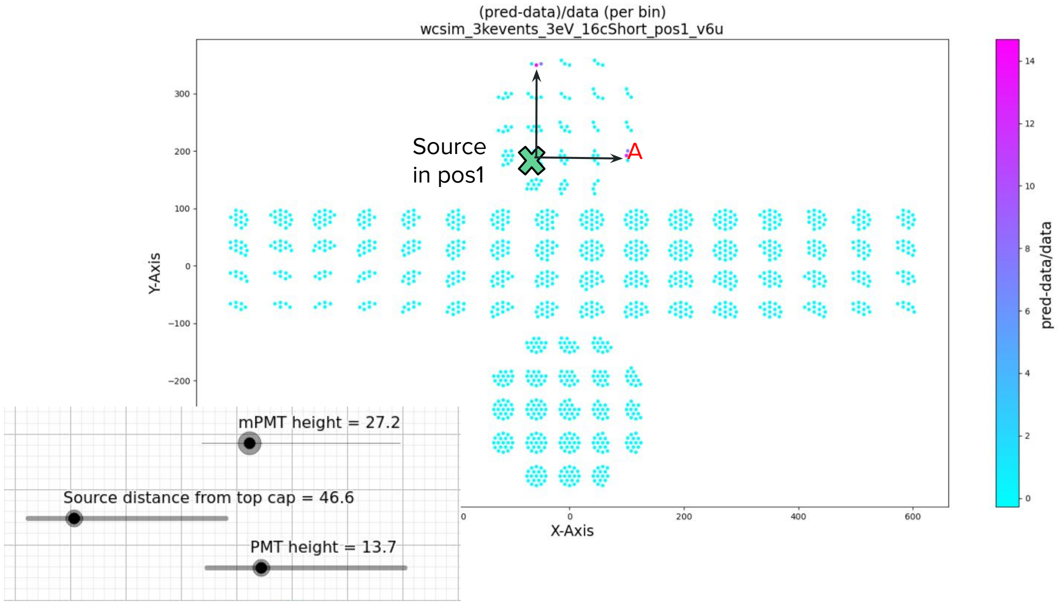
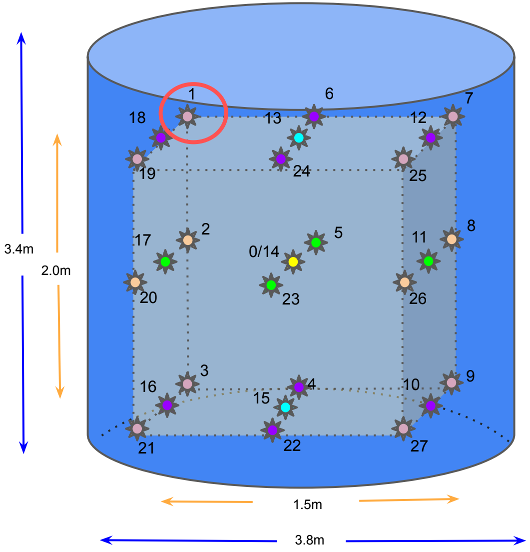
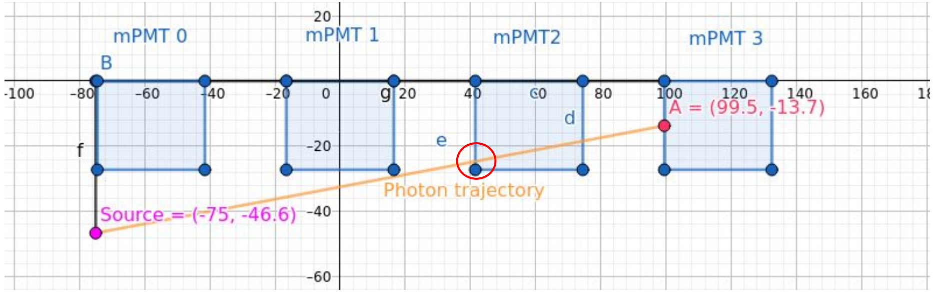
Explanation: shadowing by the mPMT surface







- **Assumed** that the PMT point in WCSim is at the centre of the height of the mPMT module
- Light absorption by outside mPMT surface
- No excess p.e. recorded at mPMT2 - expect that the light is absorbed by outer cover and not detected by the mPMT2 module's PMTs

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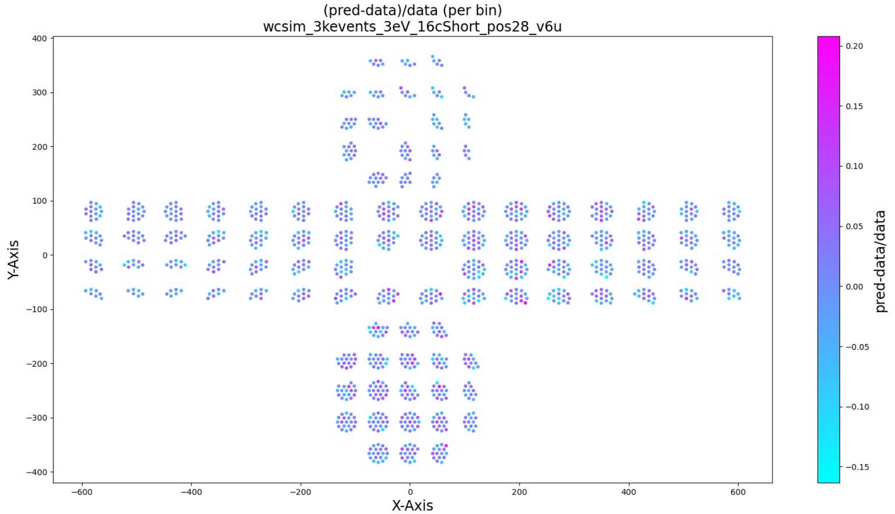
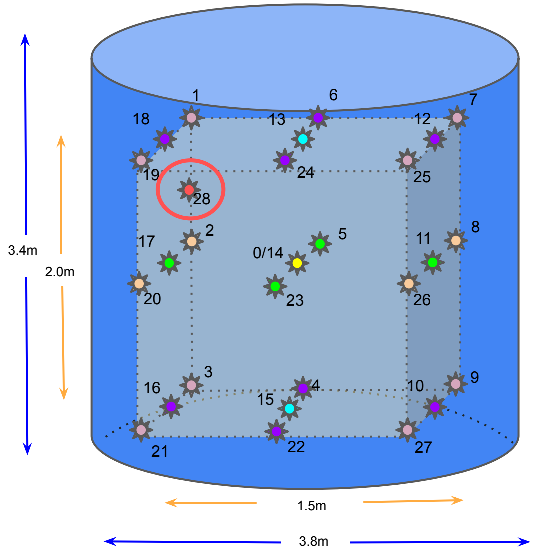
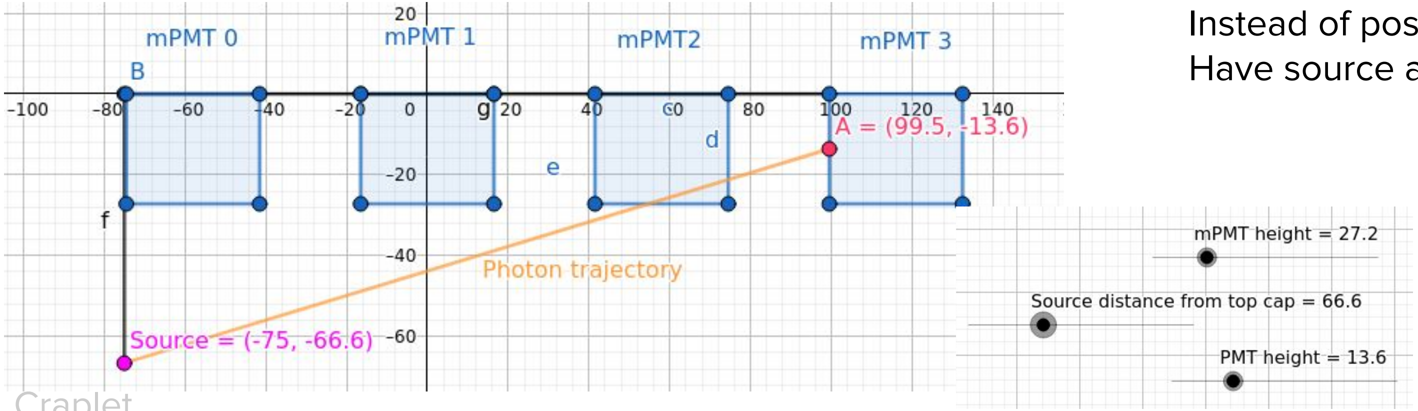
Fix1: lowering the source



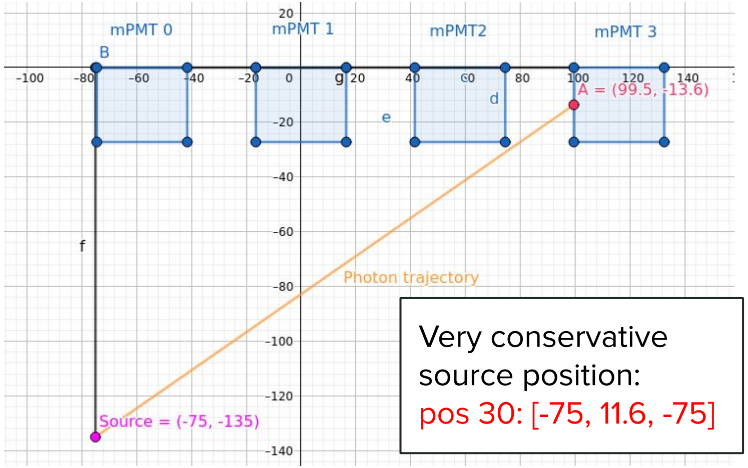


Instead of pos1: [-75, 100, -75]
Have source at pos 28: [-75, 80, -75]

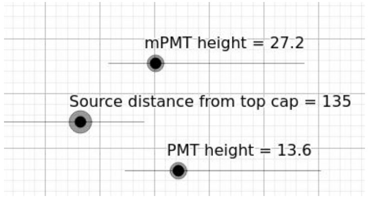


Also improves the PMT coverage!

Long term fix: **Option 1:** very conservative source position

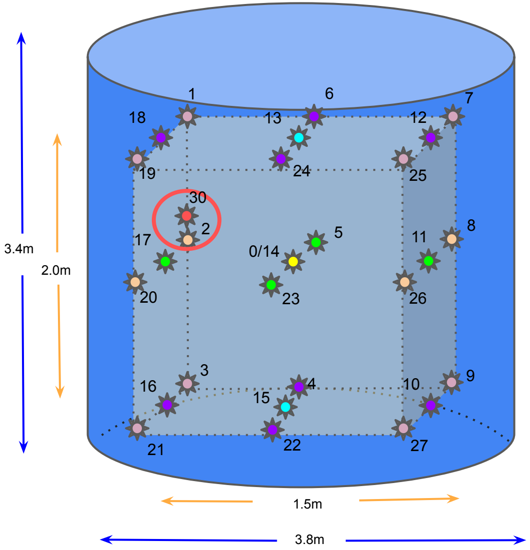


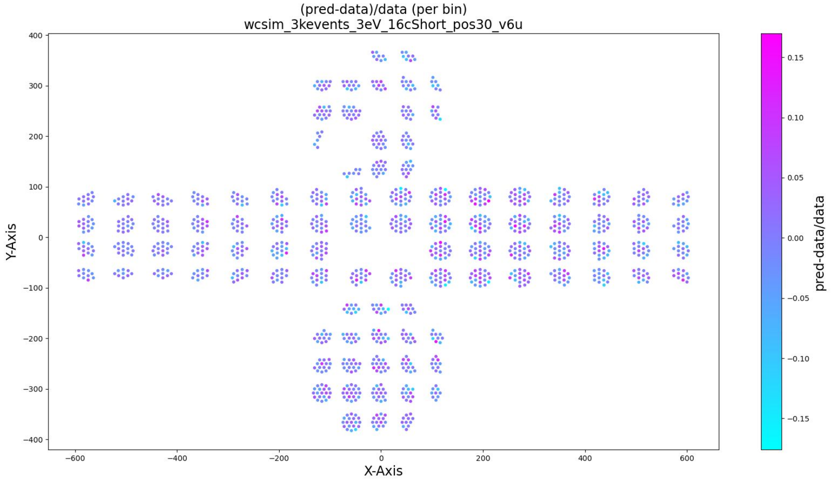
Very conservative source position:
pos 30: [-75, 11.6, -75]



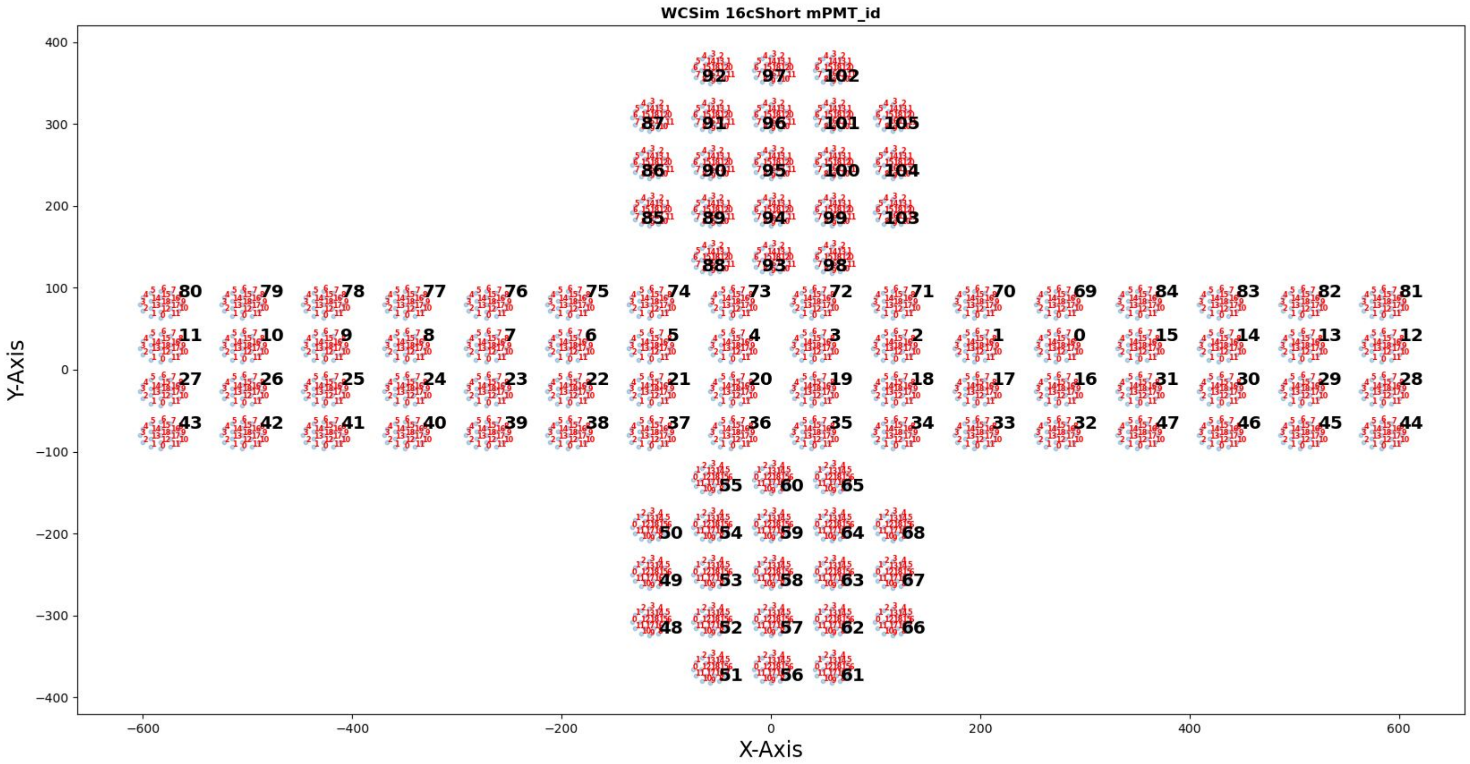
Issues:
- reduces our R range

Advantage:
- faster calibration procedure



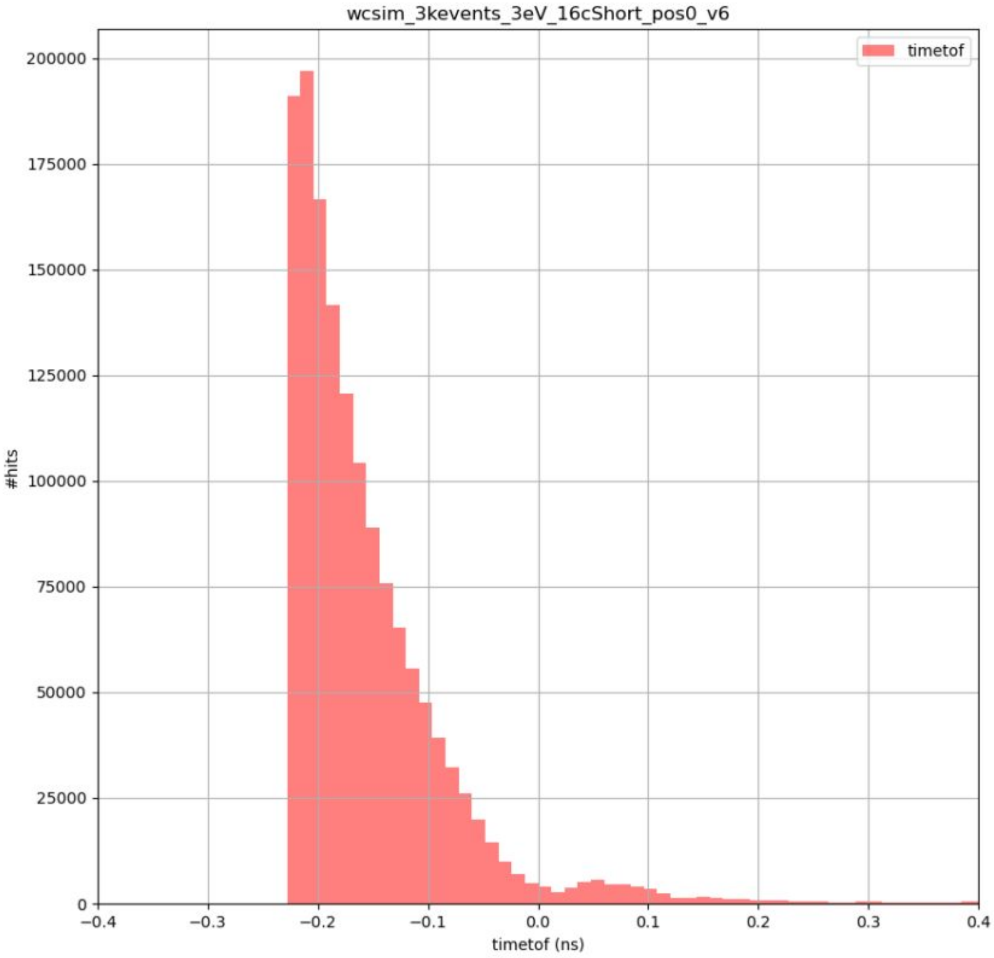


Geometry



WCSim 16cShort mPMT_id
Y-Axis
X-Axis
400
300
200
100
0
−100
−200
−300
−400
−600
−400
−200
0
200
400
600
92 97 102
87 91 96 101 105
86 90 95 100 104
85 89 94 99 103
88 93 98
80 79 78 77 76 75 74 73 72 71 70 69 84 83 82 81
11 10 9 8 7 6 5 4 3 2 1 0 15 14 13 12
27 26 25 24 23 22 21 20 19 18 17 16 31 30 29 28
43 42 41 40 39 38 37 36 35 34 33 32 47 46 45 44
55 60 65
50 54 59 64 68
49 53 58 63 67
48 52 57 62 66
51 56 61

Time tof



A. Craplet