Casual Write Up for Simulating PVT Block in a Cosmic Environment Using CRY and Geant4

Author: Ronald Collins
Date : 26/07/2021

Section 1 – An overview of the Simulation-Analysis chain:

This casual report follows a 6-month placement (February 2021 – July 2021) that I spent working under Stephen Quillin and Michael Collett. The project focussed on simulating a polyvinyl toluene (PVT) block in the simulation environment GEANT4 [1]. The GEANT4 [1] simulation program does not have a built-in cosmic ray shower library, so the Cosmic-ray Shower Library (CRY) [2] was also used. An overview of the simulation and analysis seen in figure 1 the majority of the programs are small programs that rely on information from CRY [2] and GEANT4 [1].

This PVT block is a radiation portal monitor, designed to analyse radiation that passes next to the detector. But false positives must be accounted for. One of the biggest potential sources for false positives is the background caused by atmospheric interactions with cosmic particles such as protons. As such the Cosmic-ray Shower Library (CRY) [2] is required to accurately quantify the effect of the cosmic particles will have on the detector. CRY [2] produces particles as they would pass a section of 2d area either 1, 3, 10, 30, 100, and 300 m squared [3]. At three different possible elevations (sea level, 2100 m, and 11300 m). From this the following information is extracted and put into a .csv file which is in turn put into GEANT4 [1]:
EventNo,SecondaryNo,ke[MeV],x[m],y[m],z[m],direction cosine u,direction cosine v,direction cosine w,charge[eV],time[s],pdgid.

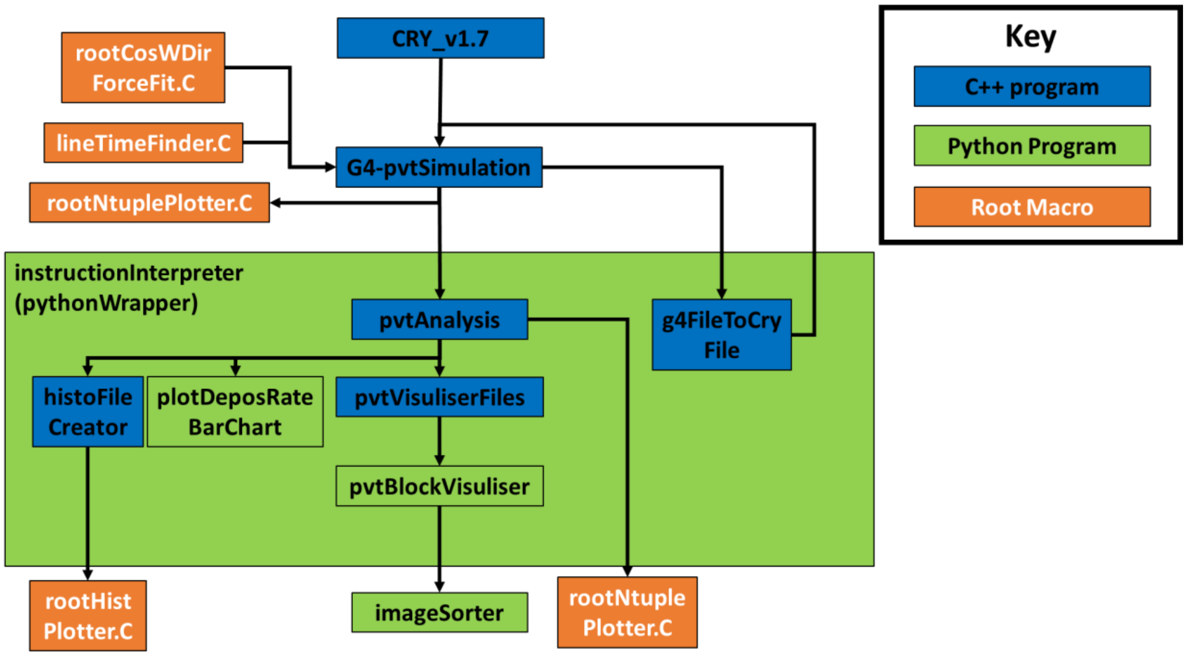


Figure 1: An overview of the simulation and analysis chain used in the project. The simulation section is covered by CRY [2] and GEANT4 the rest of the chain is analysis. CRY [2], GEANT4 [1] and the instructionInterpreter all use macros to select options and run.

Section 2 – Tweaked version of CRY:

As figure 1 shows CRY [2] is the start of the chain. The most recent version of the CRY [2] available is 1.7 assumed to be released in 2012 as that is the most recent date for the documentation [3][4]. Due to the old web page, lack of updated documentation and outdated GEANT4 implementation it is assumed that CRY [2] is no longer in active development [3][4][5]. This is a problem for using GEANT4 [1] and CRY [2] together as the examples that use CRY [2] and GEANT4 [1] that CRY [2] comes with are obsolete. This is especially frustrating as the multi-threaded version of GEANT4 [1] (version 10.0) was released on December 6th 2013 [6][7] as a result the latest version of CRY [2] is incompatible with a multi-threaded build of GEANT4 without a significant amount of alteration. It is possible to build a version of modern GEANT4 [1] without using multi-threading, but many of the libraries inside the GEANT4 [1] example CRY [2] comes with are discontinued and depreciated. This results in CRY [2] being incompatible with modern builds of GEANT4 [1] without extensive re-writes and updates to the CRY[2] library or updating the GEANT4 [1] examples CRY [2] comes with.

As a result, there are three options:

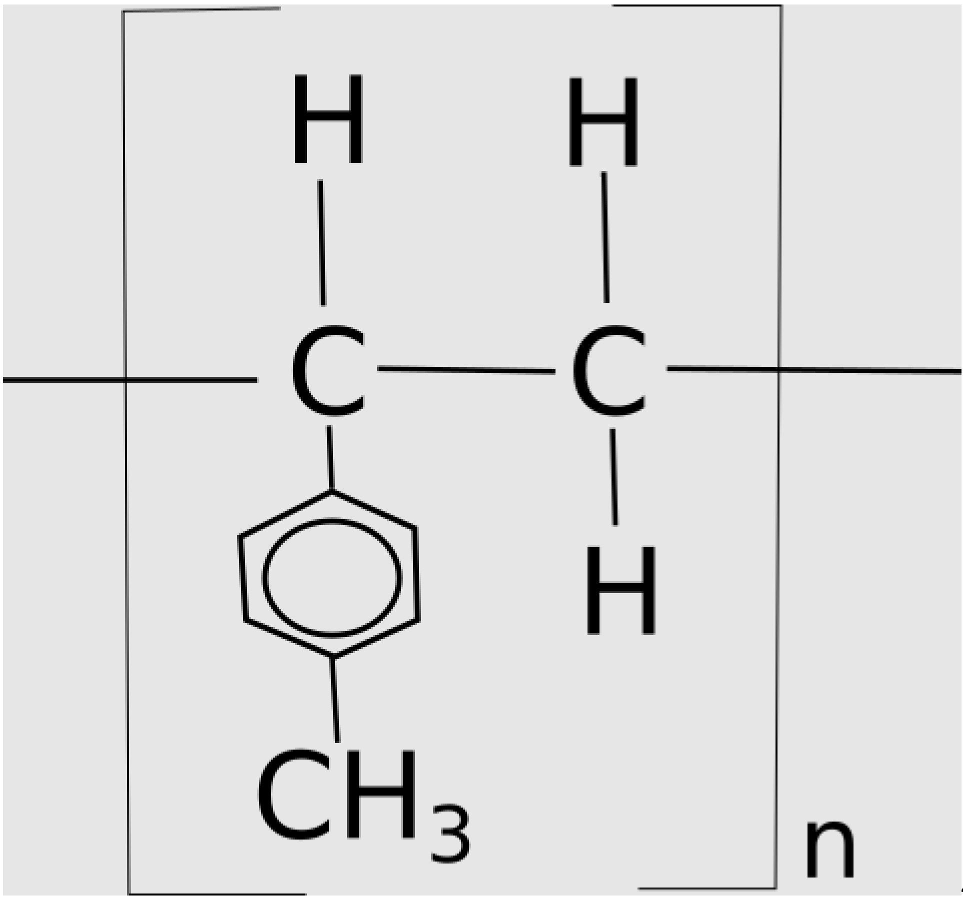
1. Use an old build of GEANT4 [1] (oldest available on Geant4 website 9.6 released November 30th 2012 [8], presumed to work but not tested)
2. Find a way to integrate CRY [2] and GEANT4[1] that does not rely on the existing examples inside the CRY [2] library
3. Rework CRY [2] or the GEANT4 [1] examples in CRY [2] until they work with a modern build of GEANT4 [1] (not enough time during 6-month project)

Of these two options 2 is the most preferable option. It is unknown if older versions of GEANT4 are supported at all past their most recent patch. For example, the oldest version of GEANT4 shown on the website is 9.6 which had its last patch in January 2015 [9] and has received no additional support that is visible on the website. As Linux kernels and compliers (such as gcc and g++) update and change using older versions of GEANT4 [1] becomes more and more difficult to justify. Unsupported versions of Linux without outdated kernels pose a security risk and as such are not a suitable solution to the problem. Whilst currently GEANT4 [1] 9.6 does build properly on modern Linux systems eventually this will not be the case and as such a way to avoid using the older version is strongly preferred for the sake of longevity. This also applies to CRY [2] itself however as the library is significantly simpler than GEANT4 [1] with fewer dependencies it will likely run fine in containers such as singularity for many years to come. Also, the performance penalty for using such a system is minimal with CRY [2] due to the library's relative simplicity.

Though it is important to note that the size of the text files is significant. For most of the testing a very large 11Gb file was required to simulate100 million events. This is due to the fact that text files are an inefficient way of storing data and ideally in future CRY [2] should be more properly integrated into GEANT4 [1] to prevent large amounts of disk space from being used.

Section 3 – G4-pvtSimulation:

The simulation creates a PVT block with a density of 0.7 g/cm^3, which is a density approximate to polystyrene. The number of carbon and hydrogen atoms was determined from the isomer seen in figure 2 from this the number of carbon atoms was determined to be 9 and the number of hydrogen atoms was determined to be 10. These values were then put into the DetectorConstruction.cc in the G4-pvtSimuation. The values for steel and aluminium which form the shielding around the detector were determined from Wikipedia and are rough approximations. It was assumed that the steel surrounding the detector is low-carbon steel with a carbon percentage of 0.15%. The thickness of steel shielding was assumed to be 1 cm and the aluminium thickness was assumed to be 0.5 cm. The geometry of the detector will automatically rearrange to account for larger shielding. The world material is determined through the inbuilt material strings in GEANT4 [1] either “G4_Galactic” or “G4_AIR.” And the concrete material is determined by the material string “G4_CONCRETE.”



4.

Figure 2: Isomer of Polyvinyl toluene from: https://en.wikipedia.org/wiki/Polyvinyl_toluene

The overview of the simulation can be seen in figure 3 there is a large concrete floor which extends 3m by 3m by 1.5m below the detector. The gap between the between the shielding and the detector is 1cm and can be seen more clearly in figure 4. In many instances the and concrete shielding is often excluded to check that the simulation is running as expected. In reality the shielding and concrete are only added in at the very end of the project once everything else has been finalised and checked.

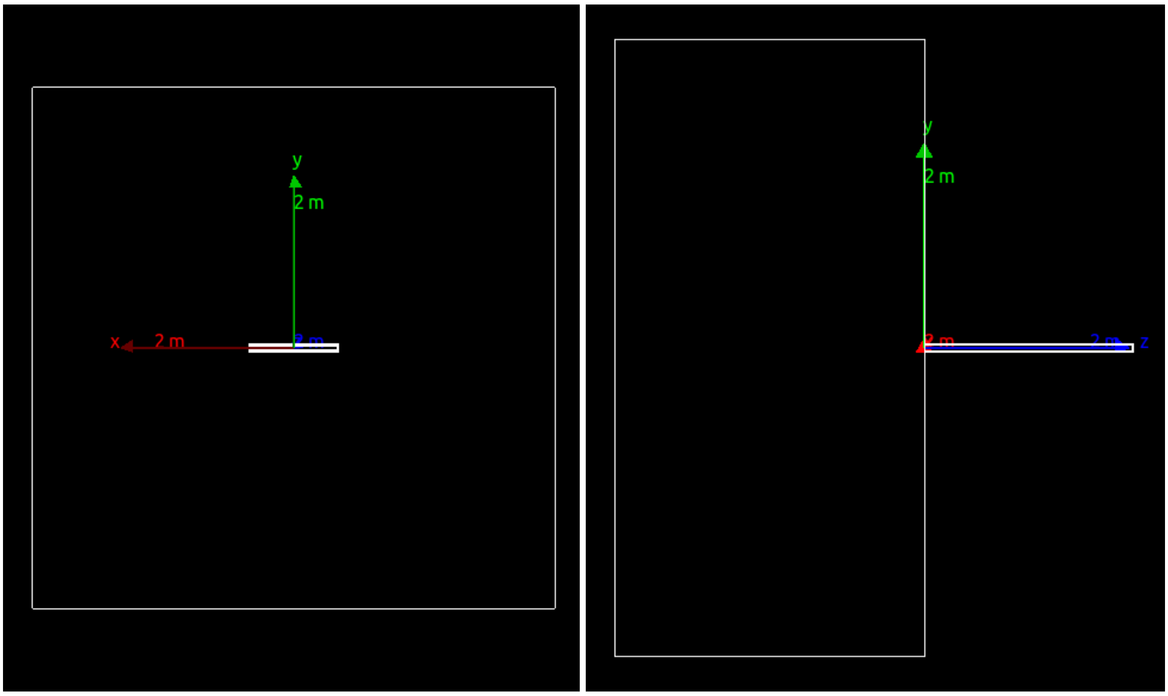


Figure 3 An overview of the PVT block with shielding and concrete floor with a top down view on the left and a side on view on the right

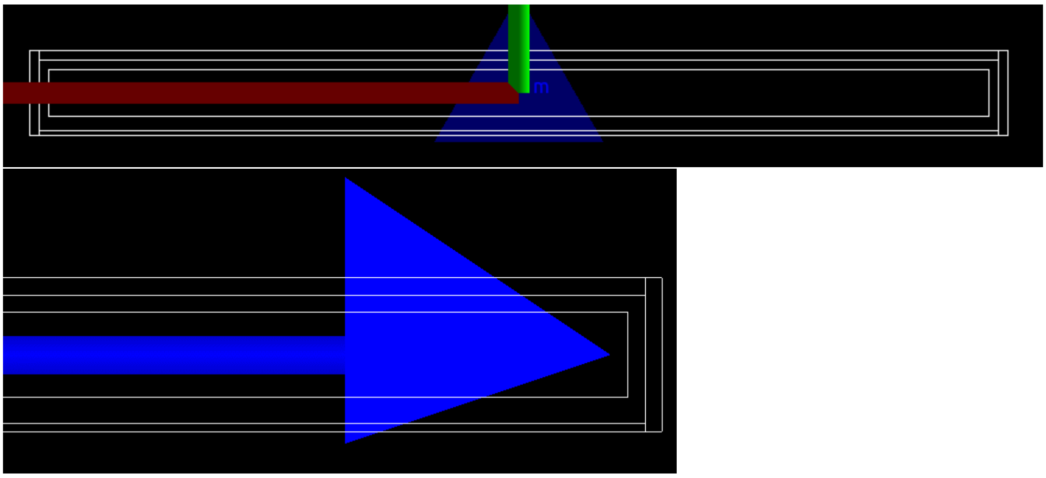


Figure 4 A zoomed in view of the PVT block and shielding showing the top down view on the upper plot and the side on view on the bottom plot

Section 4 smoothing Cosine W values from CRY

In the CRY [2] library the direction of the particles is determined by direction cosines (https://en.wikipedia.org/wiki/Direction_cosine) u, v and w were $u^2 + v^2 + w^2 = 1$. The simulation converts the information that CRY [2] produces into spherical polar coordinates (φ and θ) seen in figure 5. The phi information is a random distribution that crosses the plane at $z = 0$. However there are issues with cosine w information as the binning is very course. The values for the cosine W binning can be seen in figure 6 which vary from -1 to 0 with binning 0.05. This binning can be improved upon and will need to be improved to prevent large depositions from unusual angles. An 8-dimensional polynomial was fitted to the generated cosine direction in W shown in figure 6.

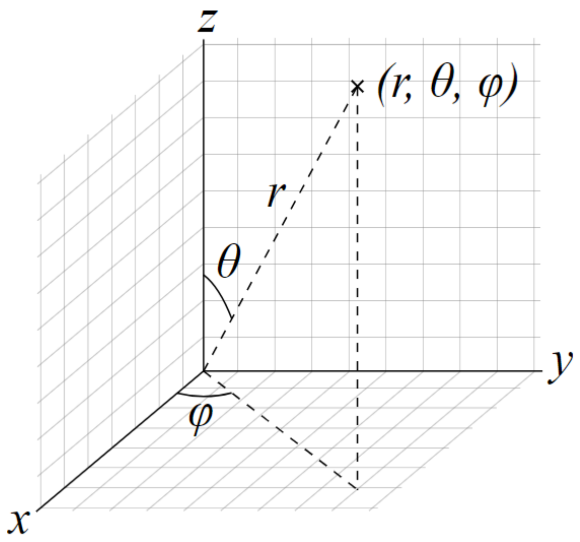


Figure 5: A spherical polar coordinate system typically defined in physics from https://en.wikipedia.org/wiki/Spherical_coordinate_system

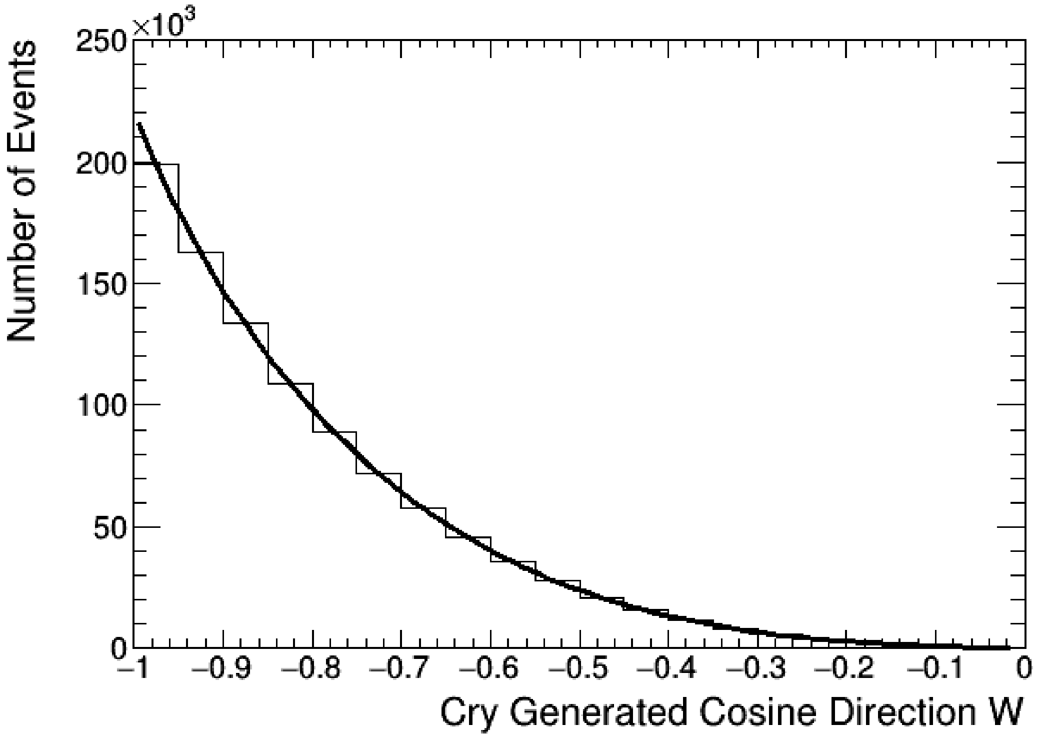


Figure 6: An 8-dimensional polynomial fitted to the generated cosine direction that the CRY [2] library produced

The generated cosine direction is then smoothed on a bin by bin basis seen in figure 7 is the smoothing for the very first bin ranging from -1 to -0.95 in generated Cosine direction W. The smoothing is done on a bin by bin basis to prevent the loss of information, CRY [2] generates each particle with energy and direction being related to each other. However this direction is uniformly produced in 0.05 bins which is too course if the simulation becomes large. Which is necessary when trying to accurately quantify the rate of cosmic noise. The generated cosine direction is then converted to a cumulative probability distribution an example for this can be seen in figure 8. The cumulative probability for each bin is then fed into the GEANT4 [1] simulation when the cosmic smoothing option is enabled. These cumulative probability distributions are read in via .csv files.

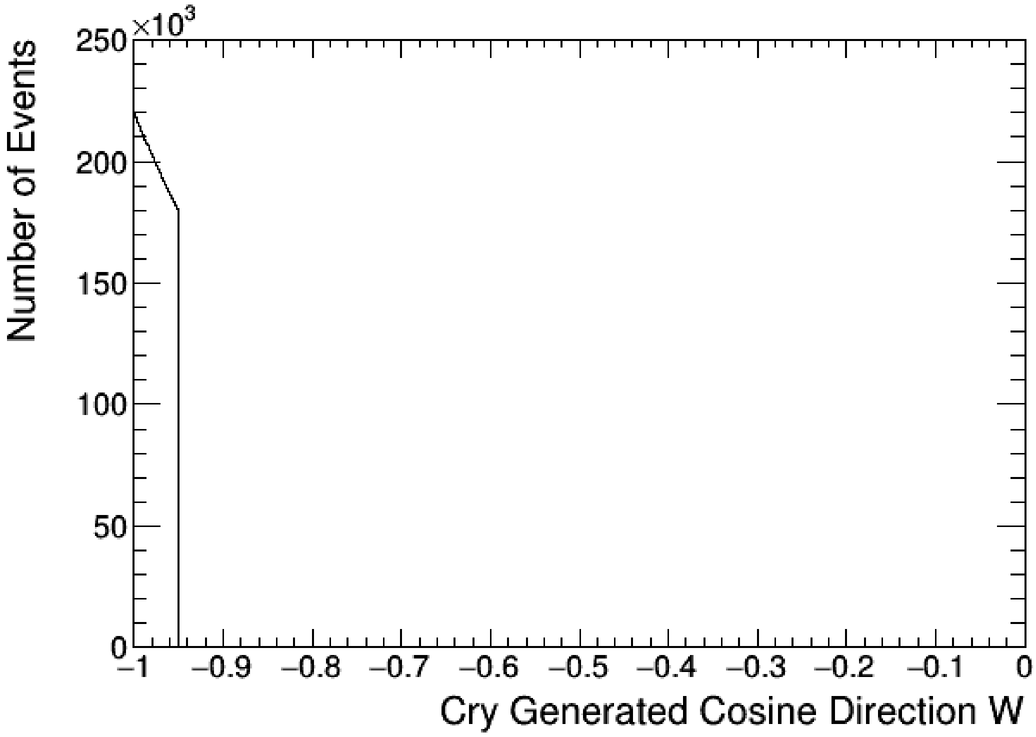


Figure 7: The smoothing of cosine direction W for the first bin of the CRY [2] generated cosmic background.

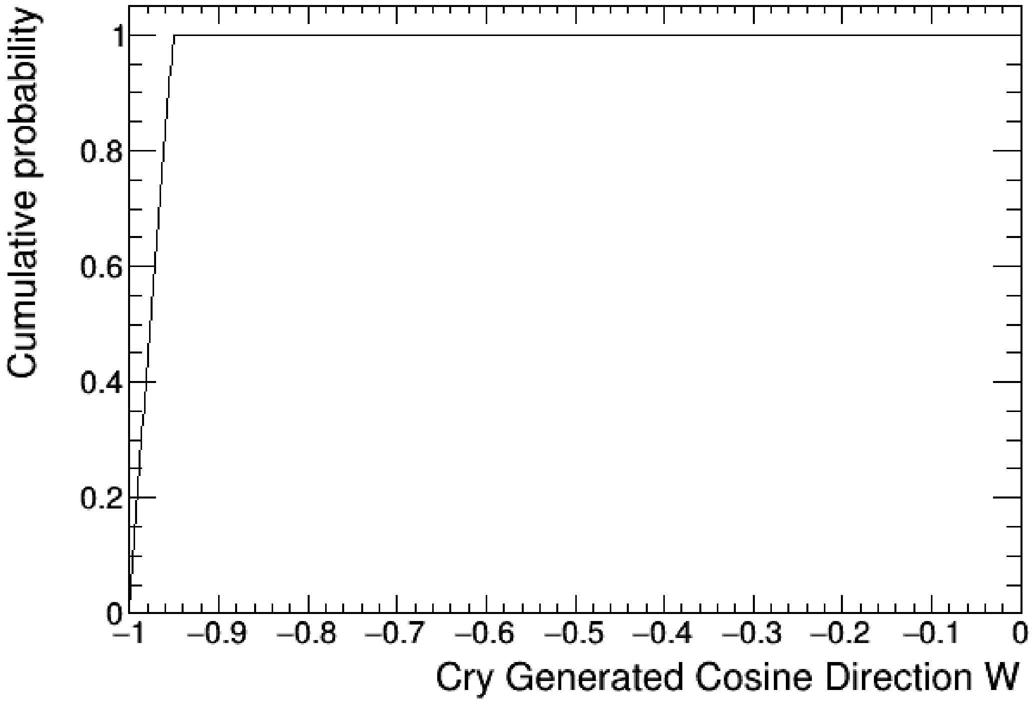


Figure 8 The cumulative probability distribution for figure 7.

The effect of the smoothing can be seen in in figures 9 and 10. Figure 9 shows how the smoothing compares to the original distribution produced by CRY [2]. Figure 10 shows how this impacts the production of θ in the simulation, the smoothing gets rid of the unnatural peaks in the distribution which are artefacts of the course binning found directly in the CRY [2] library. This effect is important to remove so that the simulation is as close to reality as possible. For this reason, going forward in the report, all the plots will use the smoothed distribution.

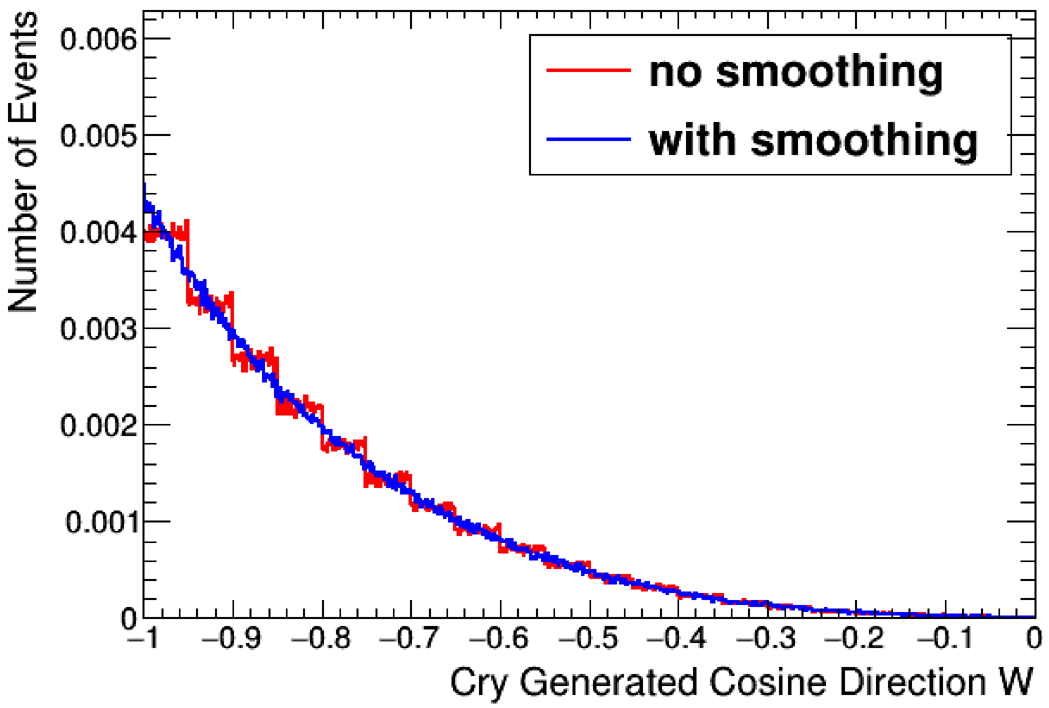


Figure 9: How the smoothed cosmic distribution for cosine direction w looks (with smoothing) in comparison to the original CRY [2] distribution (no smoothing).

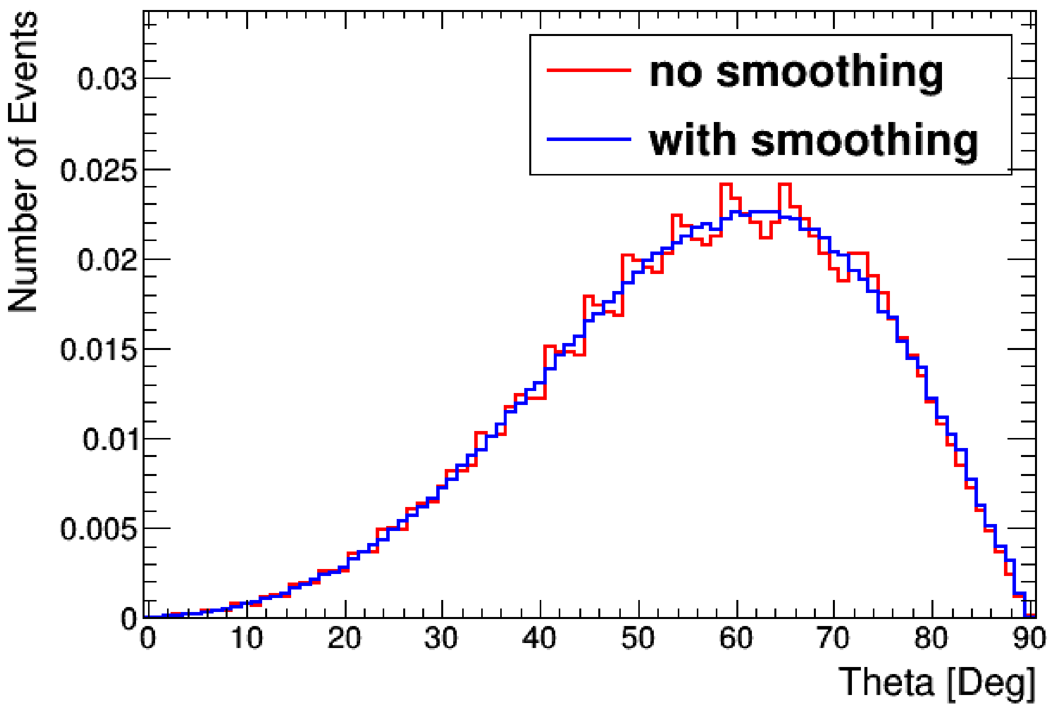


Figure 10: How the smoothing for the cosmic distribution cosine W affects the theta distribution. The generated CRY [2] distribution is represented by "no smoothing" the smoothed distribution is represented by "with smoothing"

Section 5 Scoring Particles in the PVT Block

In this analysis a "primary" event is considered to be primary if the CRY [2] library were to simulate the deposition. For example, a particle that crosses the detector that CRY [2] generated the information for would be considered a primary such as in figure 11. However, these are not the only events that are sorted into the "primary" category. The other events considered primary were also those shown by figure 12, events where the particle that CRY [2] generated would cross the detector at all. Even if the primary itself wouldn't deposit any energy in the detector such as with figure 12 which shows a gamma particle interaction. Gamma rays don't directly interact with the scintillator they Compton scatter the electrons inside the scintillator.

Events are only considered "secondary" if the particle that CRY [2] produced never enters the detector that is being simulated in GEANT4 [1]. This type of event can be seen in figure 13 the primary particle produced by CRY [2] never comes close to the PVT block but a secondary particle is produced by GEANT4 [1]. This secondary particle produced by GEANT4 [1] is what interacts with the detector as such this event is considered a secondary event. The reason to split the events between "primary" and "secondary" in this way is to split the events caused directly by the CRY [2] distribution has (primary events) and the events caused directly by GEANT4 [1] (secondary events).

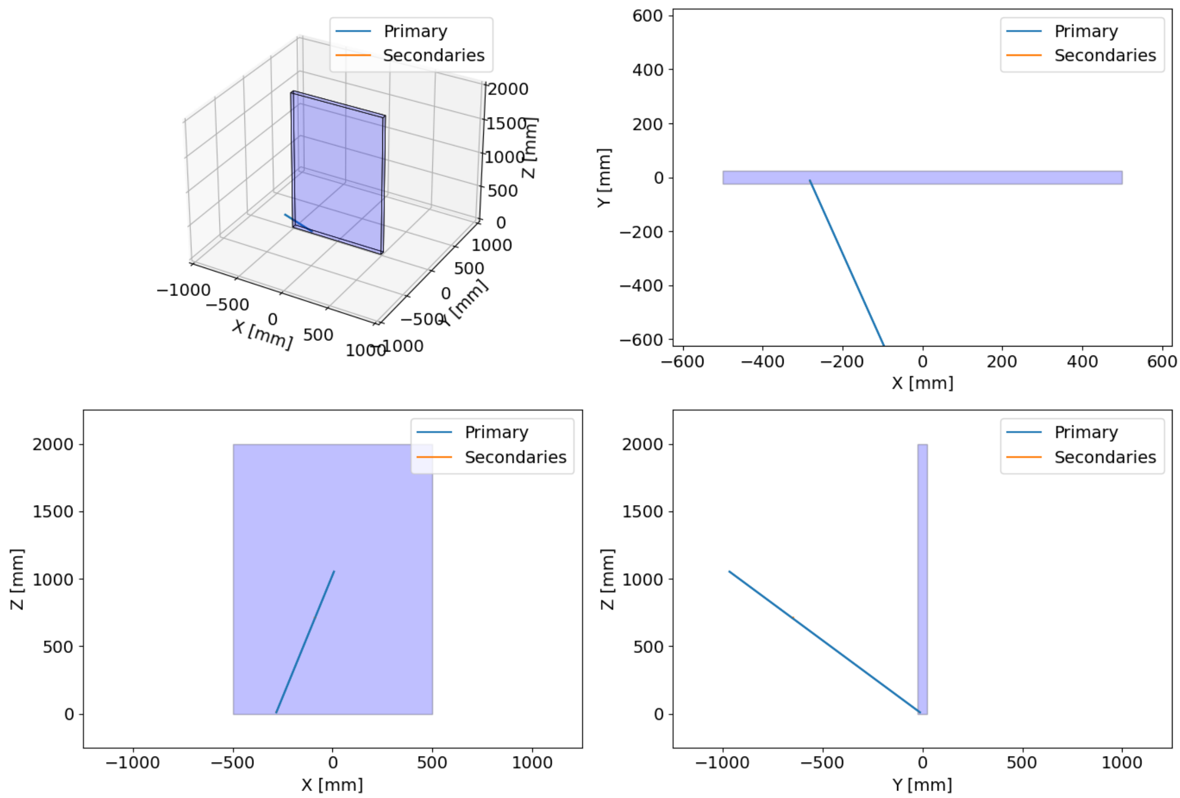


Figure 11: Deposition in the PVT block which has been caused directly from a muon produced by the CRY [2] distribution. Considered a "primary" event.

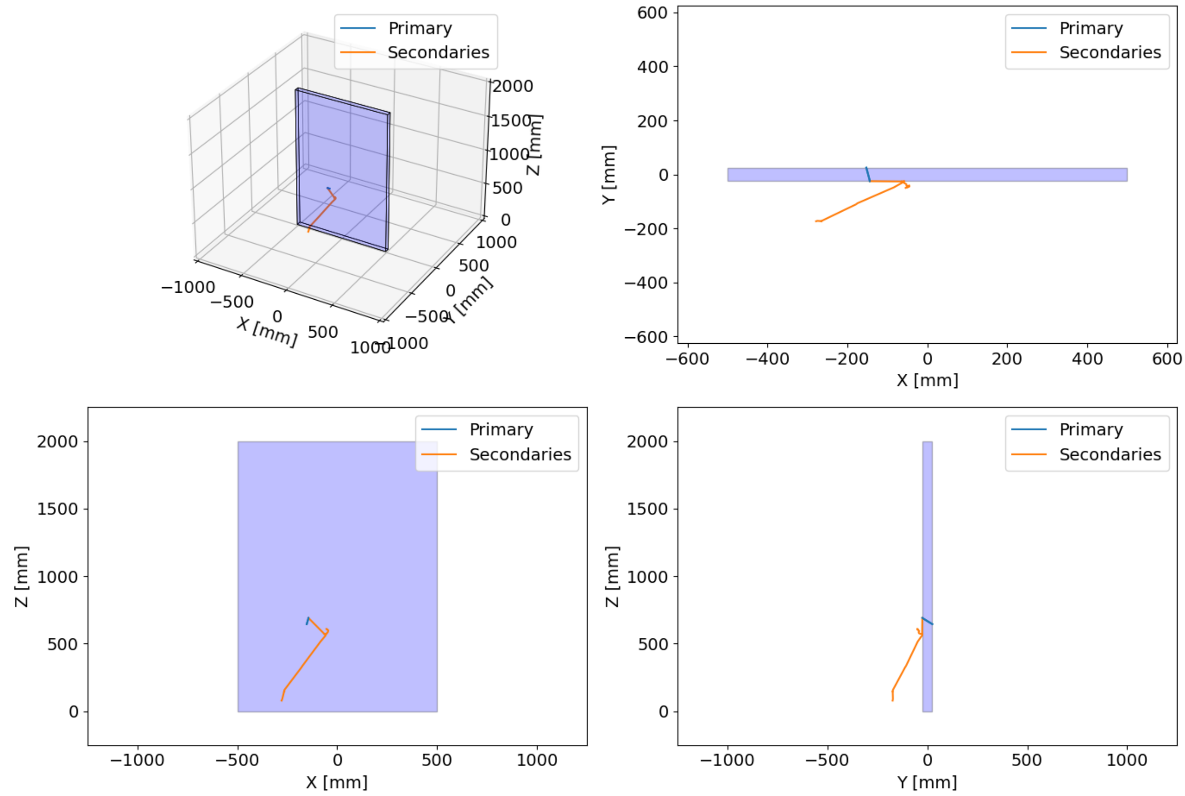


Figure 12: Deposition in the PVT block which has been caused by a gamma ray from the CRY [2] distribution interacting with electrons in the detector via Compton scatter which in turn produces a deposition. As this deposition is has been caused by CRY [2] it is considered a “primary.”

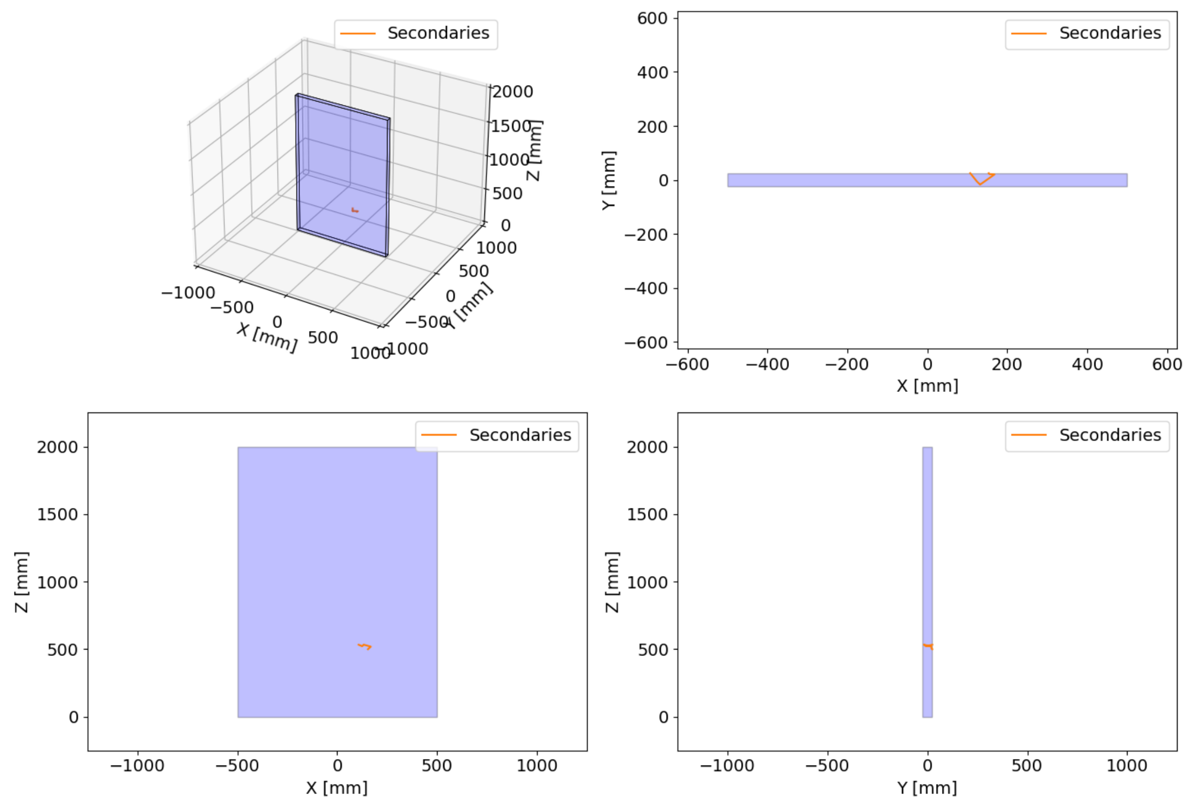


Figure 13 A deposition produced exclusively by GEANT4 [1] the primary event is far away and this secondary event has come from outside the bounds of this plot to the deposit inside the PVT block. Only these types of events are considered secondaries

Section 6 Disc vs Dome Approach

Once all of the above has been set up there now needs to be an approach which can correctly integrate all of the information into a distribution which correctly models reality. There are two possible options.

1. Creating a “Disc” of events directly above the PVT block which then fires downwards using the CRY [2] generated distribution as starting points.
2. Creating a “Dome” of material which targets the original CRY [2] distribution points as the ending points and back projects to form a hemisphere around the detector which should approximate the real-world hemisphere. Providing the simulated hemisphere is large enough.

Advantages of Disc approach:

- Limited air to travel through
- Simple model to implement
- The disc doesn’t need to be significantly larger than the PVT block greatly reducing simulation time

Advantages of Dome approach:

- More accurate to real-world data a hemisphere is being modelled to a hemisphere
- Providing the dome is large enough side on cosmic events and top down cosmic events will be very accurately modelled

The advantages of these two approaches can therefore be seen as opposite to one another with the Disc approach giving better performance and the Dome approach giving more accurate results. Therefore, if the disc approach results approximate the dome approach it can be used instead to greatly increase performance.

The distribution for the disc approach can be seen below in figure 14,15 and 16. The starting positions are determined by CRY [2] and the detector which is 2 meters tall is placed below the distribution. The distribution is a disc with a diameter of 100m which is suspended 10m off of the ground to ensure that all of the side on cosmic depositions will be accounted for. Un fortunately it would appear that this approach isn’t suitable for this simulation setup.

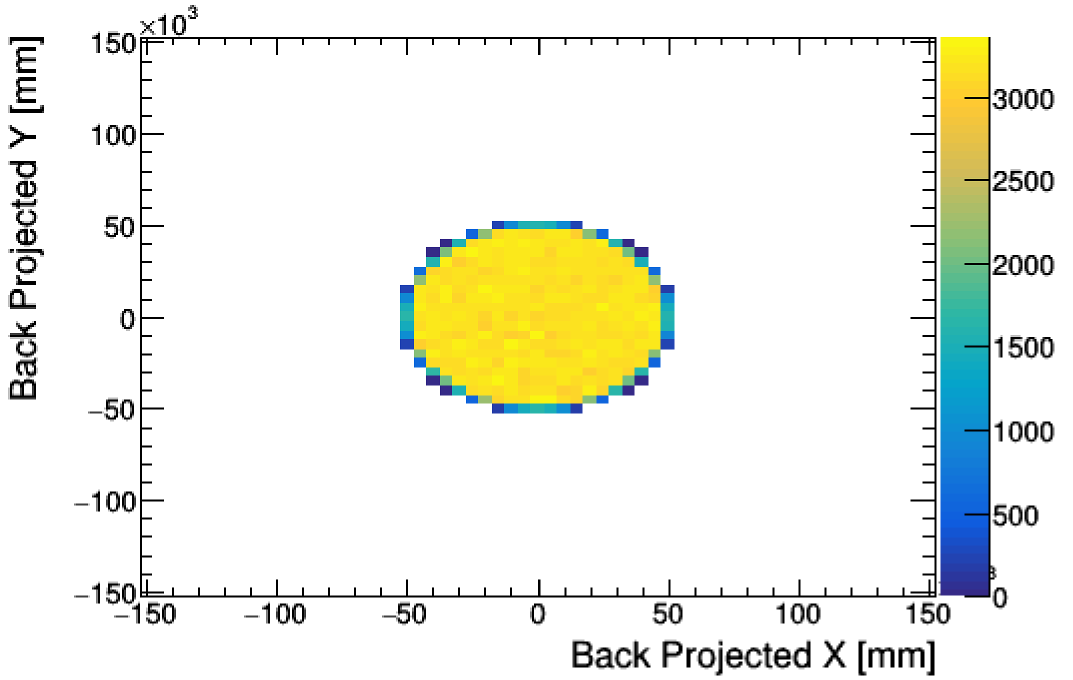


Figure 14: Top down view of the starting distribution for the disc distribution the diameter of the disc is 100m

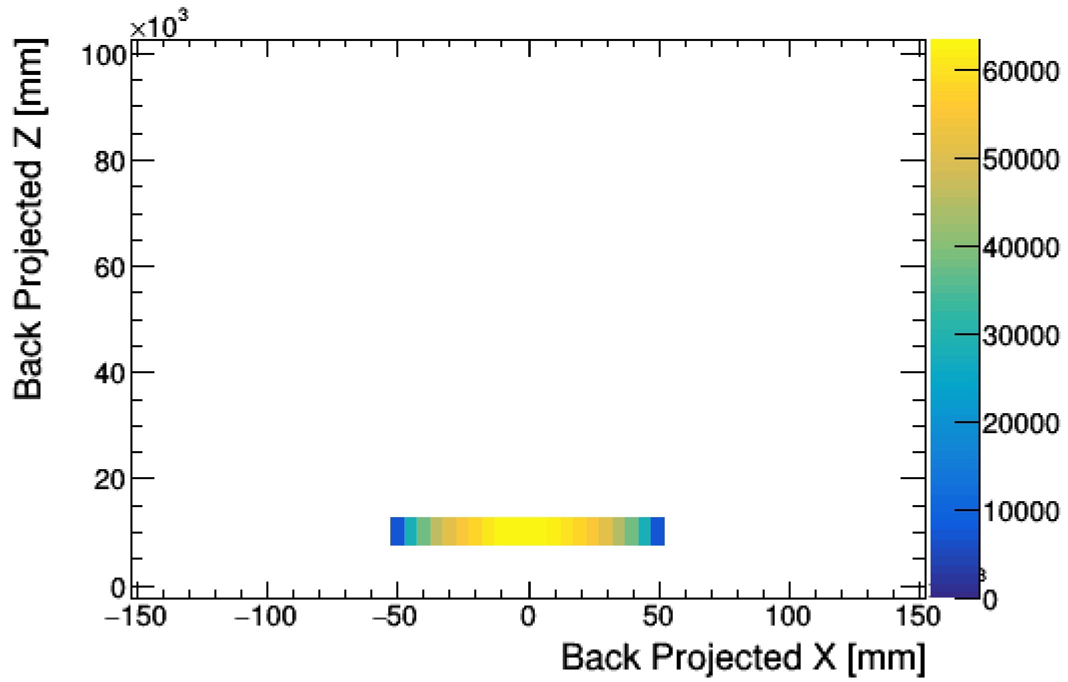


Figure 15: Side on view xz of the starting distribution for the disc distribution with a z offset of 10m

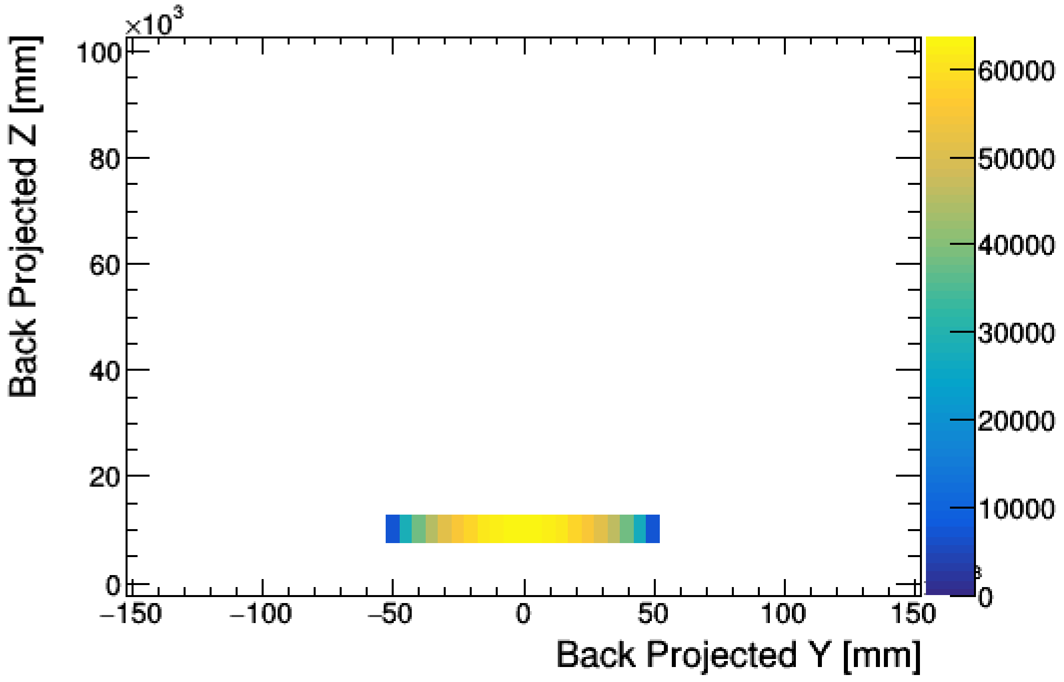


Figure 16: Side on view yz of the starting distribution for the disc distribution with a z offset of 10m

If the distribution is suitable then we would expect the crossed z axis to be roughly the same as the generated distribution in x and y seen in figure 14. However as seen in figure 17 the crossed z axis values look completely different to figure 14. The issue can be seen in figure 18. The centre of the simulation is being saturated, the centre bin of figure 17 has ~ ten times more events than expected. The edges of the circle from 5m to 45m radius in x and y hold fewer events than expected. This is an issue as the detector is located at the coordinates (0,0,0) at the centre of the simulation. Therefore, a disc distribution would result in a much higher cosmic noise rate than would be expected from real-world data.

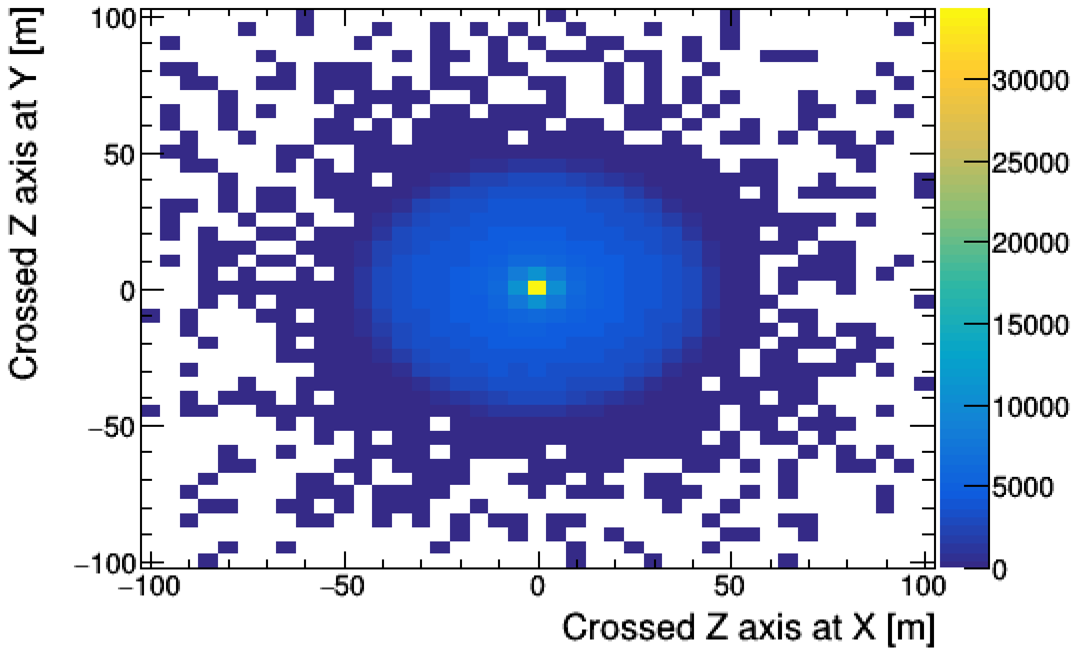


Figure 17: Where the events cross the z axis in the XY distribution in G4_galactic for the disc distribution. The centre is highly saturated by a factor of ~ ten.

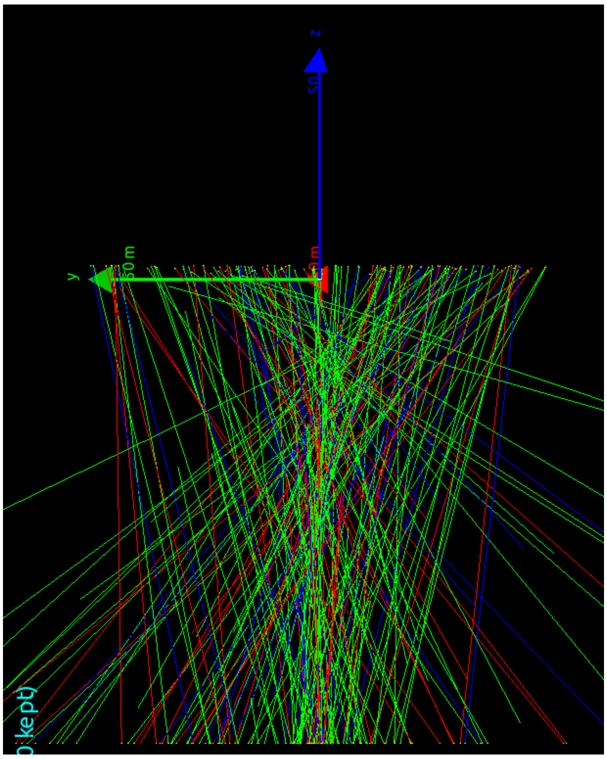


Figure 18: How 100 events look when the disc distribution is used to simulate the cosmic distribution. The events tend towards the centre which causes over saturation.

The disc distribution can be altered to prevent the saturation of the centre this is done by changing the theta distribution so instead of it being realistic (figure 19) it fires exclusively downwards (figure20). As can be seen in figure 21 the centre is no longer saturated and matches the expected distribution shown in figure 14. As a result, the only way this approach can approximate reality is if it fires directly downwards. Under some circumstances this is a suitable approximation for finding the cosmic background rate:

- A very short squat detector
- A detector that can only observe directly upwards
- A detector that has significant shielding at the sides but minimal shielding at the top

None of these apply to the PVT block in question. As such this approximation is not suitable for this simulation

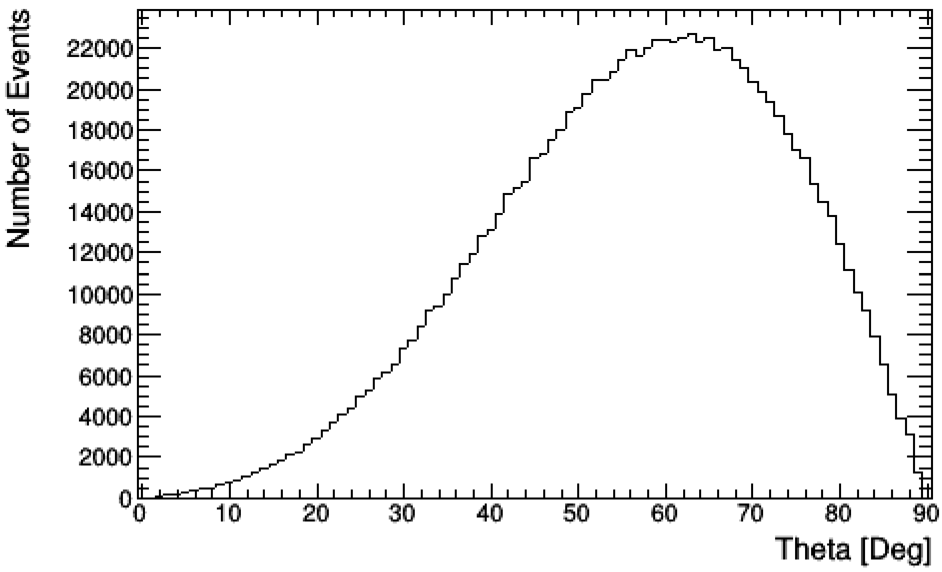


Figure 19: A realistic distribution of θ with smoothing applied (see figures 9 and 10). The distribution peaks at ~ 60^{o}. Most cosmic events have a slight angle to them.

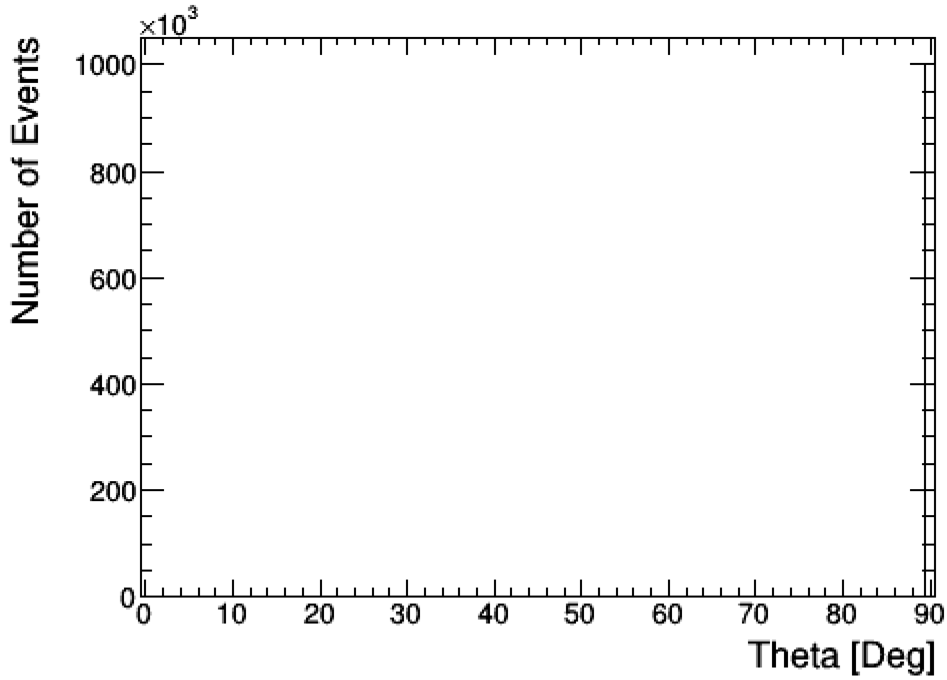


Figure 20: θ distribution which only fires downwards. As if all cosmic events come from directly upwards as seen by the detector.

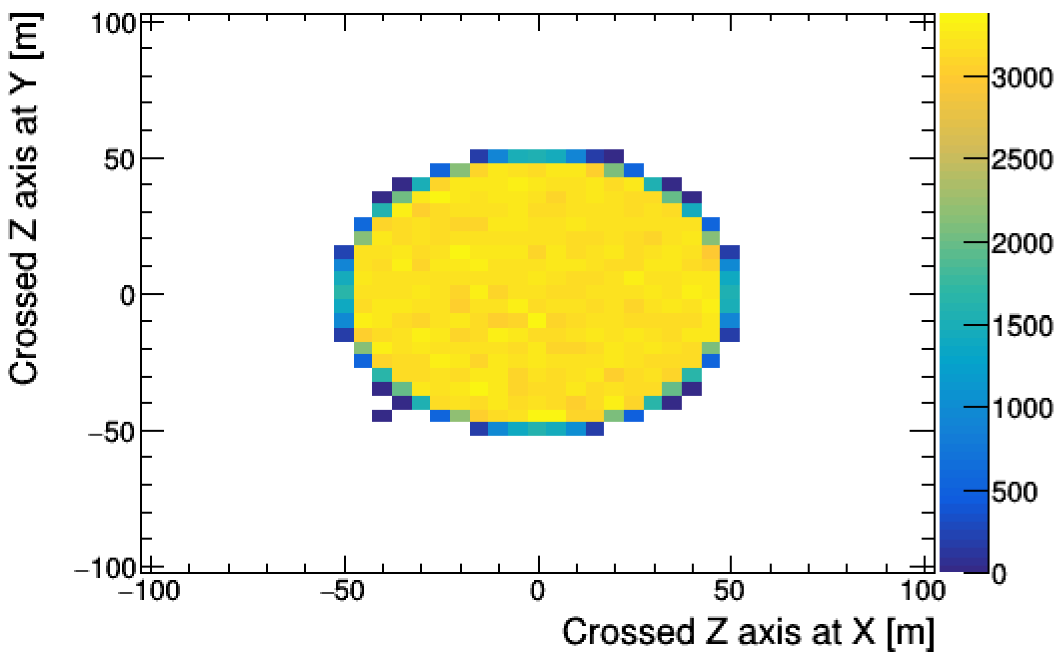


Figure 21: Crossed z axis for the disc distribution that only fires downwards in G4_Galactic. The centre is no longer saturated as it was in figure 17.

The Dome approach therefore is needed due to the large number of events that will cause deposition from the sides of the detector. Only ~ 1% of the exposed service area is on the top of a PVT block of 1m by 5cm by 2m, so the full simulation of the cosmic hemisphere via the dome approach as its necessary to consider incoming side on cosmic events. The dome approach takes the generated x and y position that the CRY [2] library produces as a final target and back projects using the θ and φ information that CRY [2] produces. This gives distributions shown by figures 22, 23 and 24 which show the XY, XZ and YZ starting distributions respectively.

The dome approach tries to approximate the real-world cosmic hemisphere, but as its only simulating a small area compared to the Earth's cosmic hemisphere an unusual pattern can be seen in the dome distribution. The halo visible in figures 22, 23 and 24 is a result of this approximation. The dome must be significantly larger than the detector to avoid the central saturation, this is the opposite to the disc approach. The disc approach becomes less accurate to real-world data the further away from z = 0 the disc is offset by whereas the dome approach becomes more realistic the larger the simulated dome.

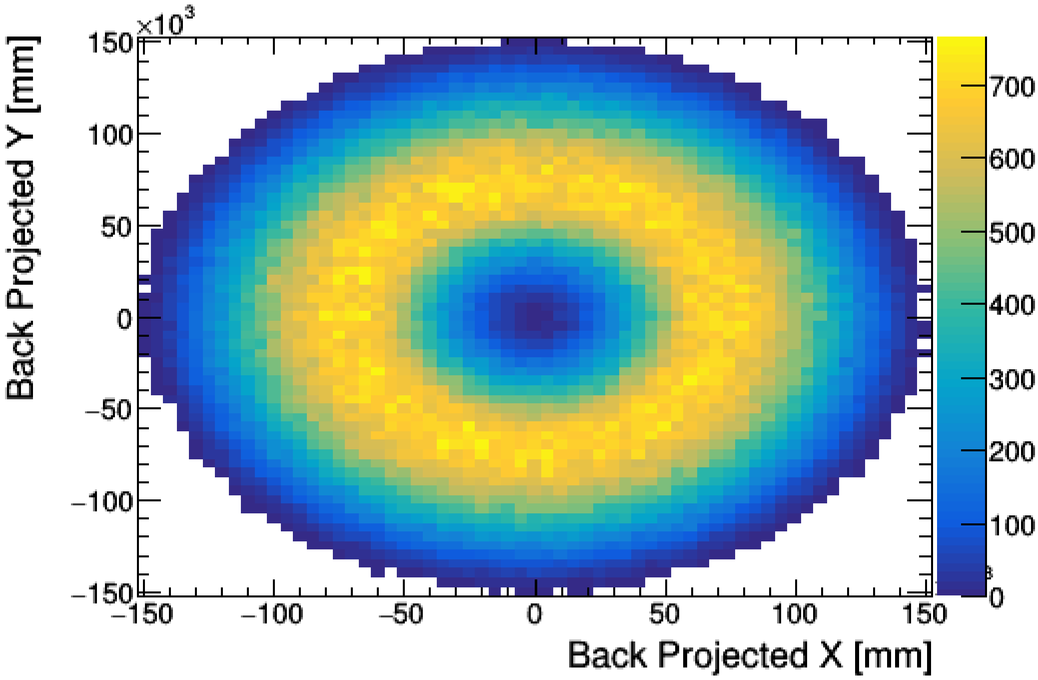


Figure 22: The back projected X and Y position for the dome approach when the back-projection radius is set to 100 m. The ring is due to the peak seen in the θ distribution in figure 19.

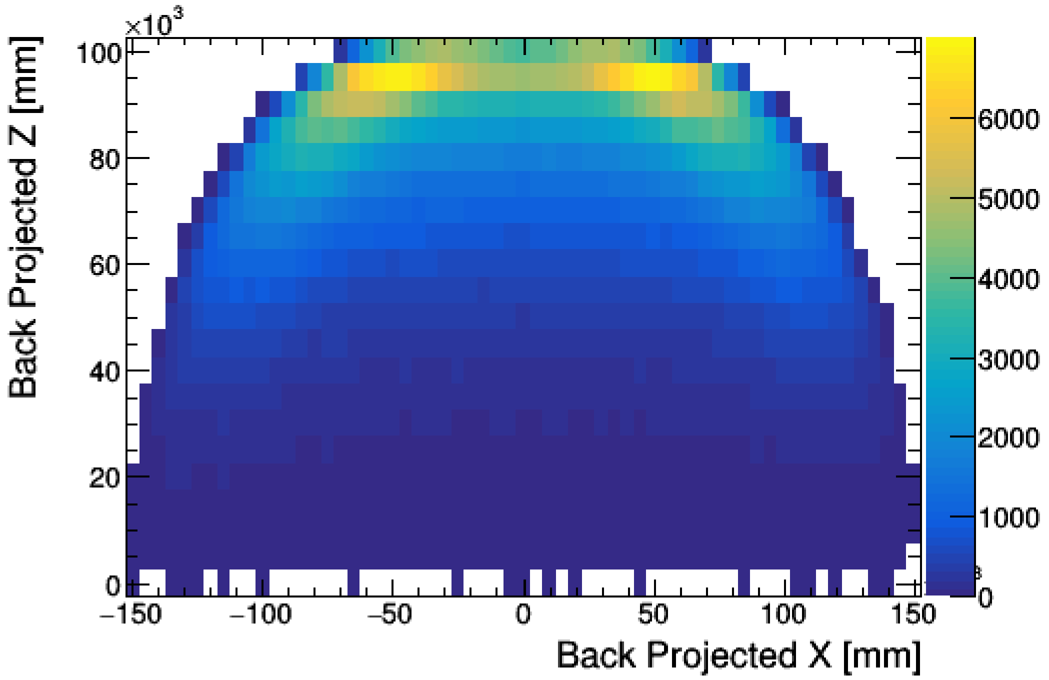


Figure 23: The back projected X and Z position for the dome approach when the back-projection radius is set to 100m. The halo at ~ 95 m is due to the peak seen in the θ distribution in figure 19.

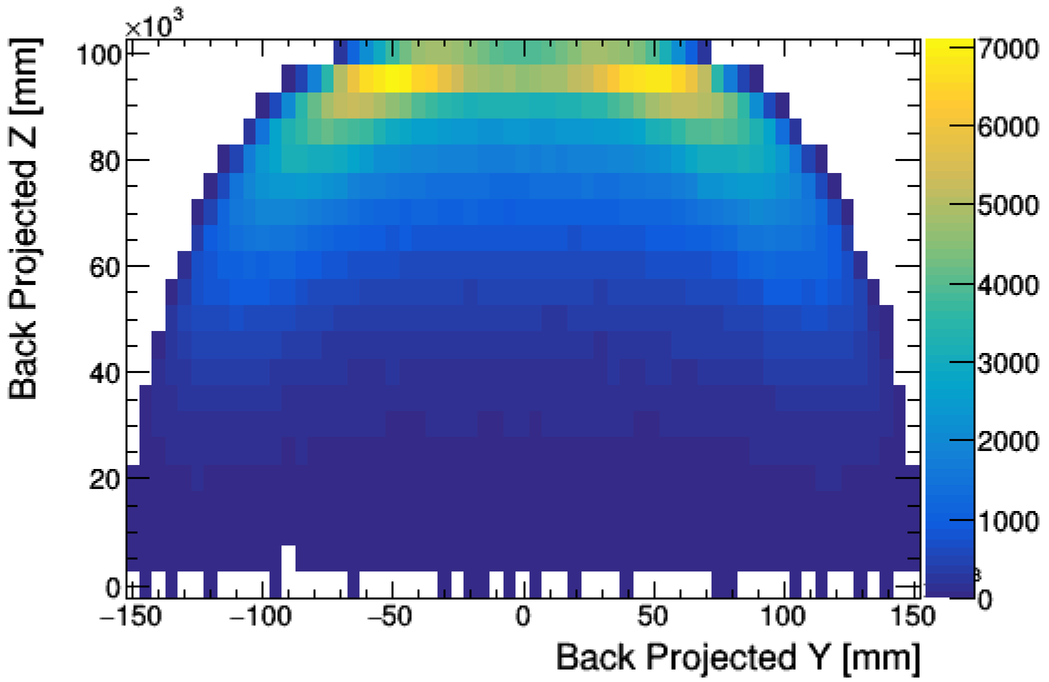


Figure 24: The back projected Y and Z position for the dome approach when the back-projection radius is set to 100m. The halo at ~ 95 m is due to the peak seen in the θ distribution in figure 19.

The success of this approach can be seen in figure 25 the circle of the generated CRY [2] X and Y values has been largely persevered with only minimal scattering. But unlike the disc approach the dome approach has achieved this whilst accurately simulating the side on events. As a result, this approach is preferred over the disc approach for the tall narrow geometry of the PVT block (1m by 1cm by 2m). However, if the geometry of any given detector is closer to that of a thin square block of material the more accurate the disc model would become.

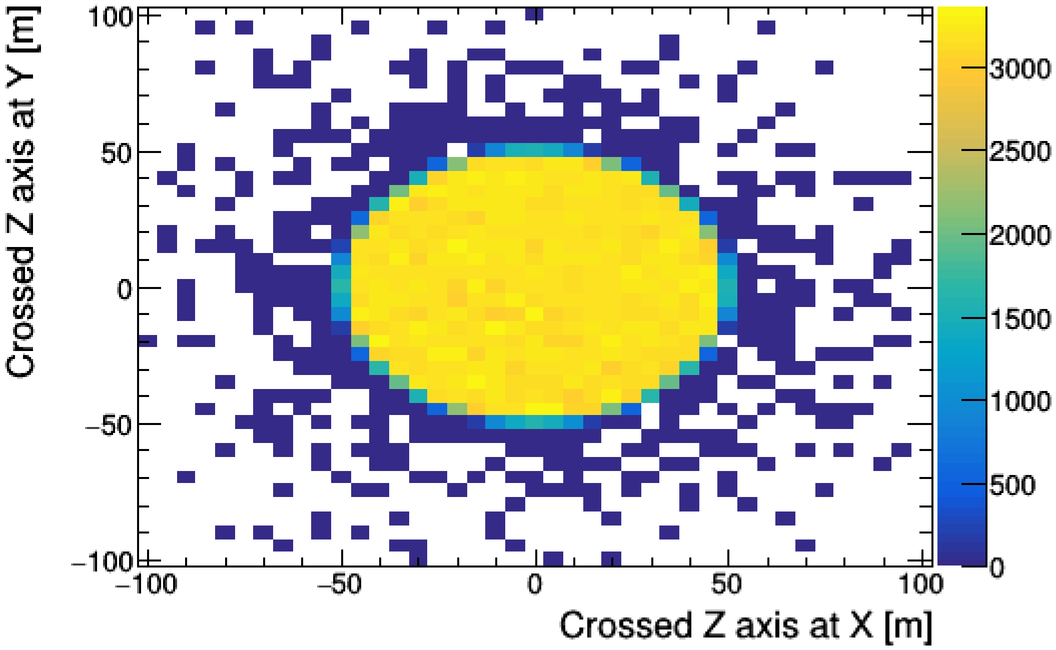


Figure 25: Where the dome distribution events cross the z axis in G4_Galactic. It closely matches the figures 14 and 21. There is some minor scattering but overall matches the CRY [2] distribution for what crosses the z axis

The rates for each model can be compared against the CRY [2] library directly. 161867 μ^- and 174291 μ^+ are produced in 2824.79s for 1 m^2 which gives a cosmic muon rate of 119.00 particles s^{-1} m^{-2}. How the two models compare can be seen in figures 26 and 27. Figure 26 shows how the disc approach compares if a realistic θ distribution is used when compared to the dome approach. Due to the centre saturation shown in figure 17 the cosmic rate is perceived by the 1m by 1m by 1cm PVT block at the centre of the simulation to extremely high. But as seen in figure 27 when the disc distribution fires directly downwards the rates for cosmic muons seen in the column "all muons" are almost identical to what is expected from the CRY [2] library (119.00 particles s^{-1} m^{-2}). However, this will not consider the incoming side events which will account for ~ 99% of the events when the geometry is the standard 1m by 1cm by 2m.

Finally, the effect of the atmosphere needs to be considered as well. The effect on a block of PVT 1m by 1m by 1cm is relatively insignificant for the primary rate as seen in figure 28. However, the effect of the atmosphere is significant for production of secondaries also seen in figure 28. This is because GEANT4 [1] and CRY [2] try to simulate some of the same particles. Any particle that crosses the Z axis in GEANT4 [1] will also have been considered by the CRY [2] library. Therefore, the secondary production in air for GEANT4 [1] should be considered an over approximation due to this "double simulation" of some particles.

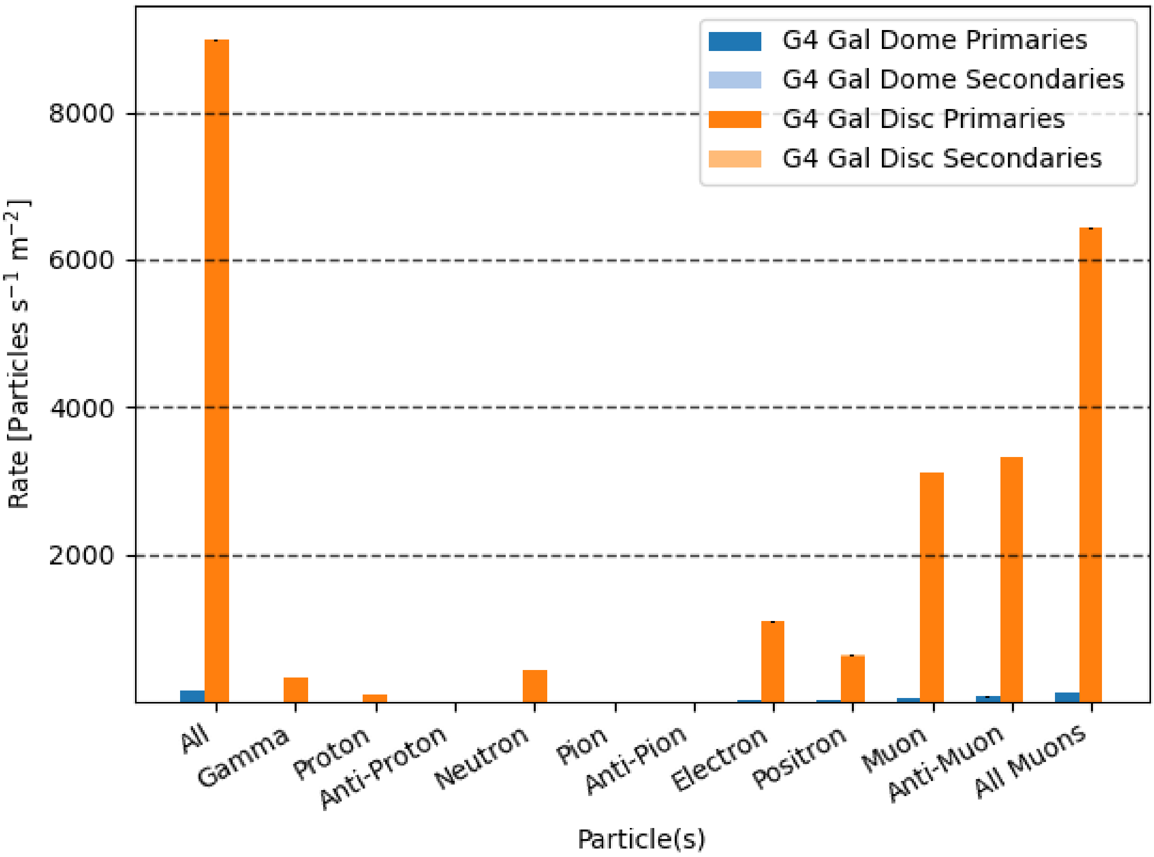


Figure 26: Disc (z offset 10m disc diameter 100m) vs dome (disc radius 100m back projection 100m) approach when both use a realistic θ distribution when firing into a 1m by 1m by 1cm PVT block in G4_Galactic. The Disc approach causes massive saturation in the centre of the simulation thus causing a very high particle rate which is unjustifiable.

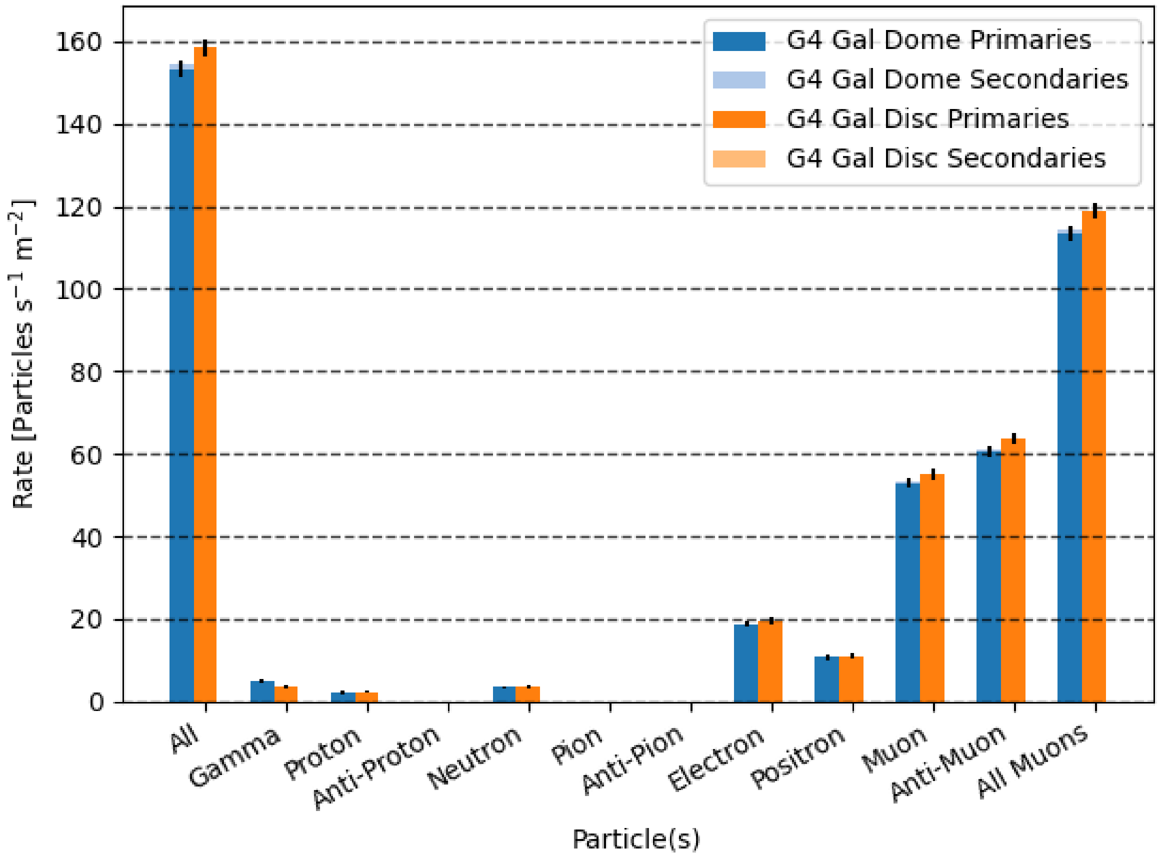


Figure 27: Disc (z offset 10m disc diameter 100m) vs dome (disc diameter 100m back projection 100m) approach when the Dome approach uses realistic θ and the disc approach fires directly downwards into a 1m by 1m by 1cm PVT block in G4_Galactic. The results for both are consistent with each other and match expected rates given by CRY [2].

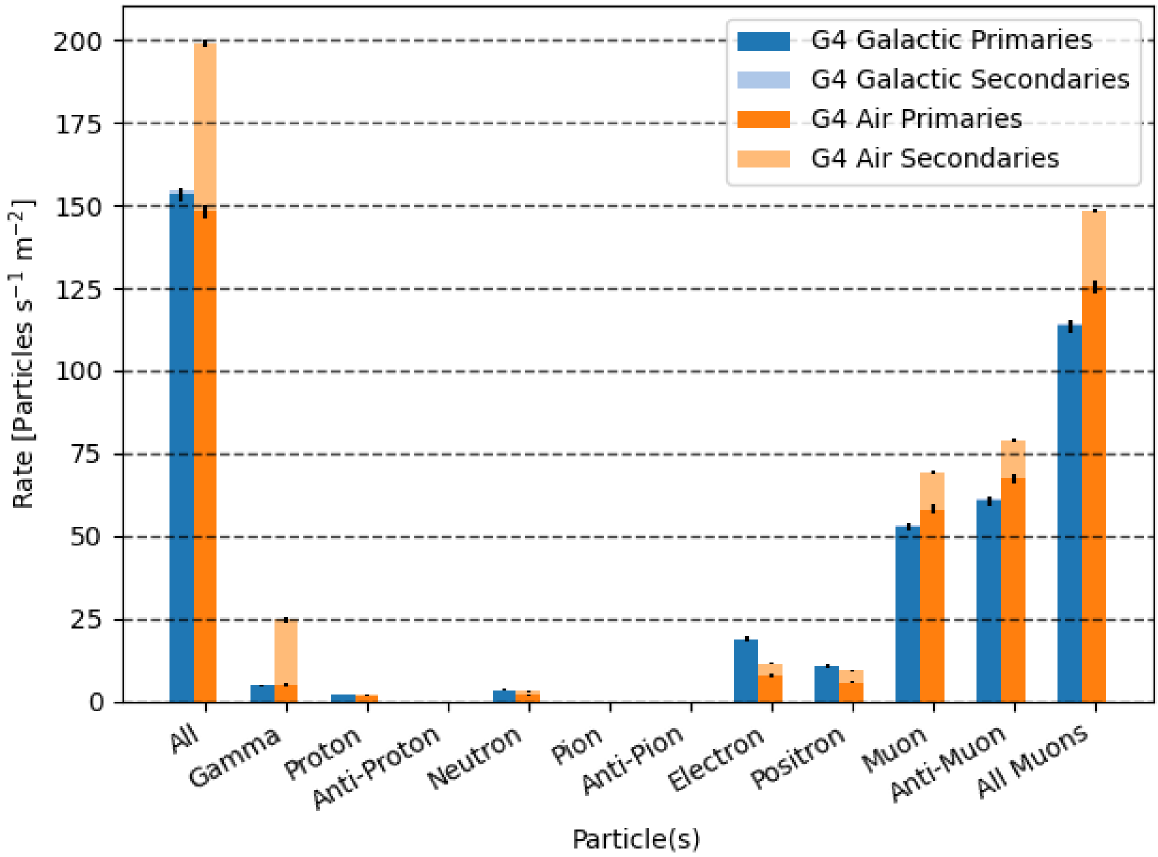


Figure 28: How the atmosphere effects the event rates for a PVT block of 1m by 1m by 1cm. The expected rate is most closely modelled by the G4_Galactic world environment using the dome approach (disc diameter 100m back projection 100m). This is because GEANT4 [1] and the CRY [2] library are trying to simulate secondaries at the same time. Therefore, the number of secondaries being produced is too high.

Section 7 Simulated Rates and Scattering

The effect of the atmosphere is much more significant when the geometry is the standard dimensions for the PVT block (1m by 5cm by 2m). As figure 29 shows the atmosphere causes many more particles to interact with the PVT block both with primaries and secondaries. The secondary production is partially due to “double simulation” where GEANT4 [1] and CRY [2] produce some secondary events which are actually the same particles. More interesting is the increase in primary particle rate which is significantly higher in G4_Air than in G4_ Galactic. This is due to the increase in scattering that the Air provides as can be seen in figures 30 and 31.

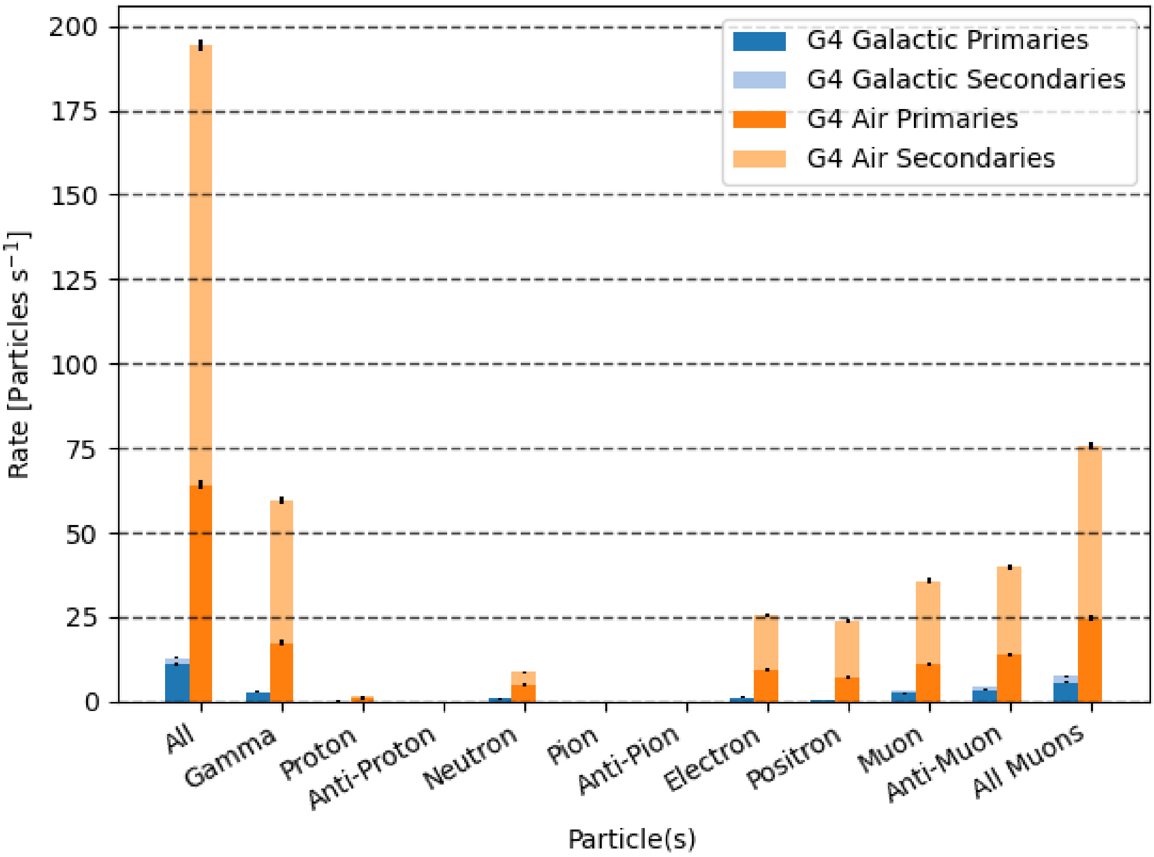


Figure 29: How the atmosphere effects the event rates for a PVT block of 1m by 5cm by 2m using the dome approach (disc diameter 100m back projection 100m). Secondary production is too high in Air as GEANT4 [1] and CRY [2] double simulate some secondary events. The G4_Air also has higher primary depositions due to the scattering caused by the air.

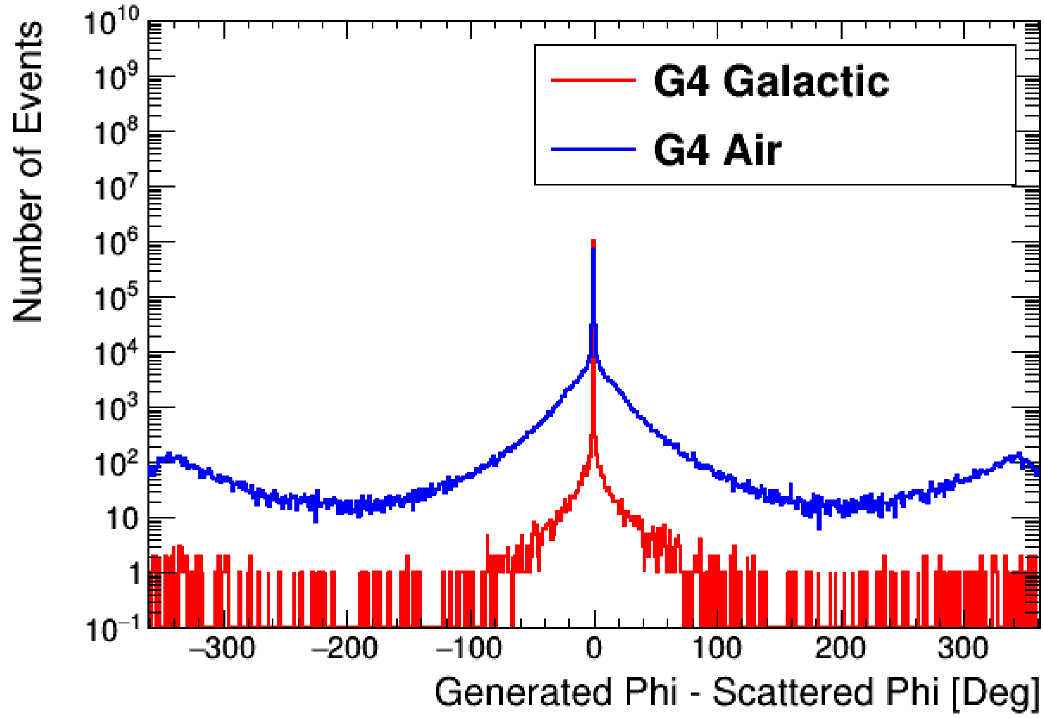


Figure 30: Difference between generated φ and scattered φ (φ where event crosses z axis). 0 represents no scattering. ~ 1% of the G4_Galactic events scatter significantly where as ~ 30% of the G4 Air events scatter significantly.

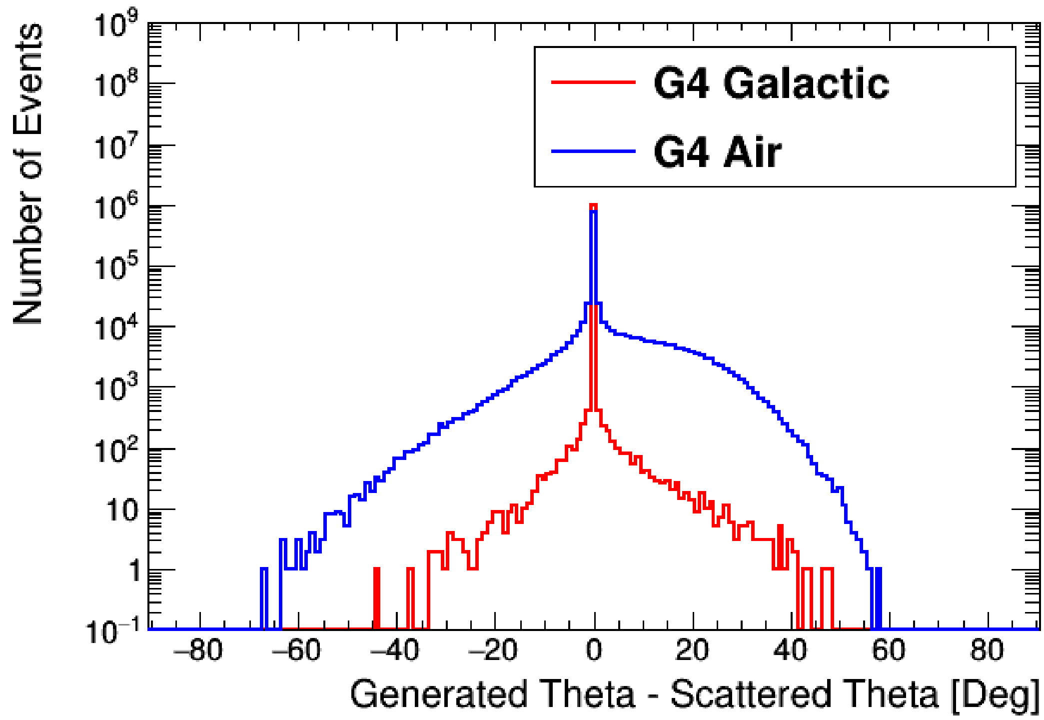


Figure 31: Difference between generated θ and scattered θ (θ where event crosses z axis). 0 represents no scattering. The significant amount of scattering in θ indicates that a large number of events being deposited in the PVT block are probably side on events.

As a result of this scattering the primary rate of particles is significantly higher than might be expected. There is also a significant amount of scattering caused by the shielding and the concrete as can be seen in figure 32 when compared to figure 29. In figure 32 the scattering of the G4_Galactic primaries has been significantly increased where it is much closer to the G4_Air rate than in figure 29. This is due to the shielding and concrete that has been added to the simulation that was not present in the previous figure 29. From this it can be extrapolated that the primary rate appears to be tending towards the G4_Air rate rather. It is probable that this primary rate is closer to reality.

Then a threshold of 10 keV can be added to the analysis so only particles which cause light in the scintillator will be considered. The result in figure 33 (and tables 1 and 2) shows the rate with concrete shielding and a threshold of 10 keV, which gives two possible ways to interpret results. Either the primary and secondary rate of the G4_Air are accurate to real-world rates or the primary rate of the G4_Air is accurate and the secondary rate of the G4_Galactic is correct. Due to the double simulation in G4_Air it is more probable that the primary G4_Air rate in figure 33 of ~ 65 particles s^{-1} and the secondary rate in figure 33 of ~ 85 particles s^{-1} is most probable to be accurate. Overall this gives a rate of 151 $\pm$ 2 particles s^{-1} due to the cosmic muon background for a PVT block of size 1m by 1cm by 2m the complete list of results can be seen in Table3.

Finally, the energy deposition above a threshold of 10 keV can be seen in figure 34. Most of the energy depositions occur below 0.5 MeV. The number of energy depositions between 10 keV and 3 MeV for G4_Galactic is 3883 where as the number of depositions with more than 3MeV for G4_Galactic is 613. For G4_Air The number of energy depositions between 10 keV and 3 MeV is 6087 where as the number of depositions with more than 3 MeV is 1974. In both cases most of the events occur below 3 MeV.

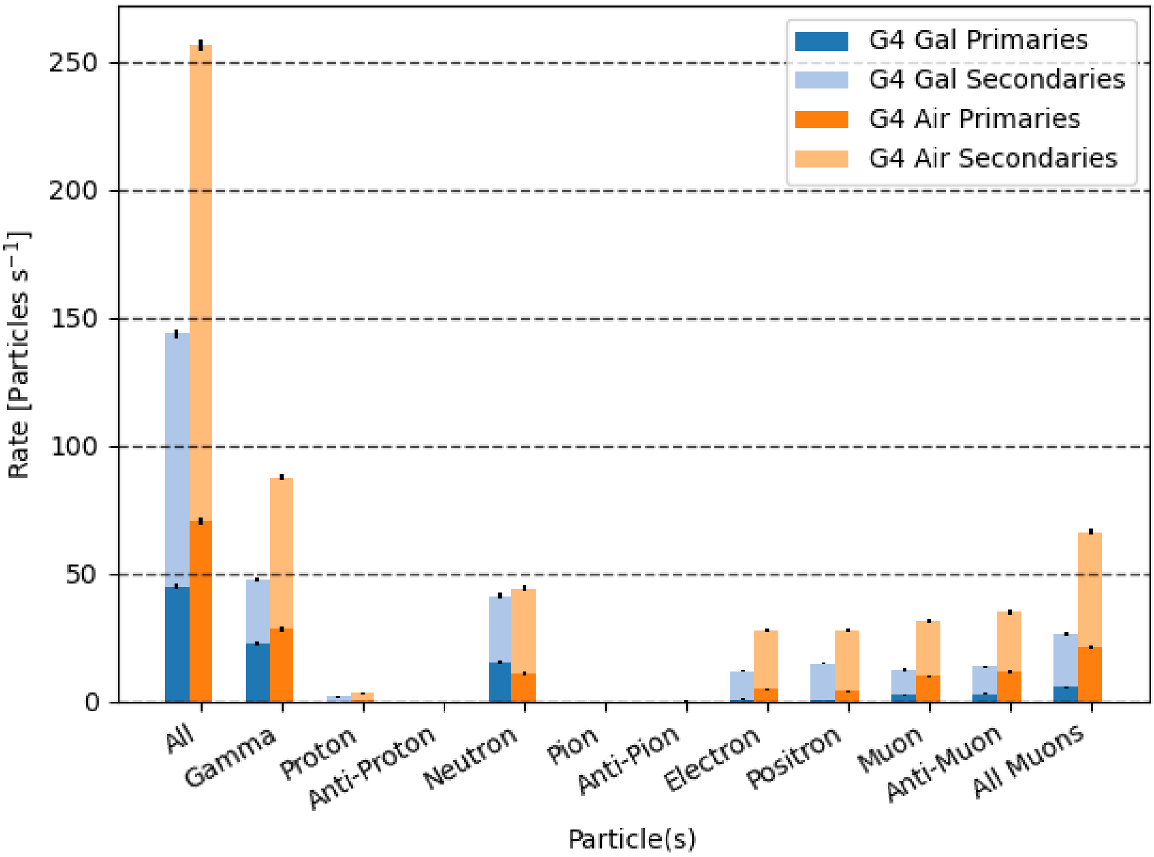


Figure 32: Particle rate for Dome approach (disc diameter 100m back projection 100m) on a PVT of 1m by 5cm by 2m with shielding and concrete but threshold. The Primary particle rate for both Air and Galactic are similar but the secondary rate for Air is still very high.

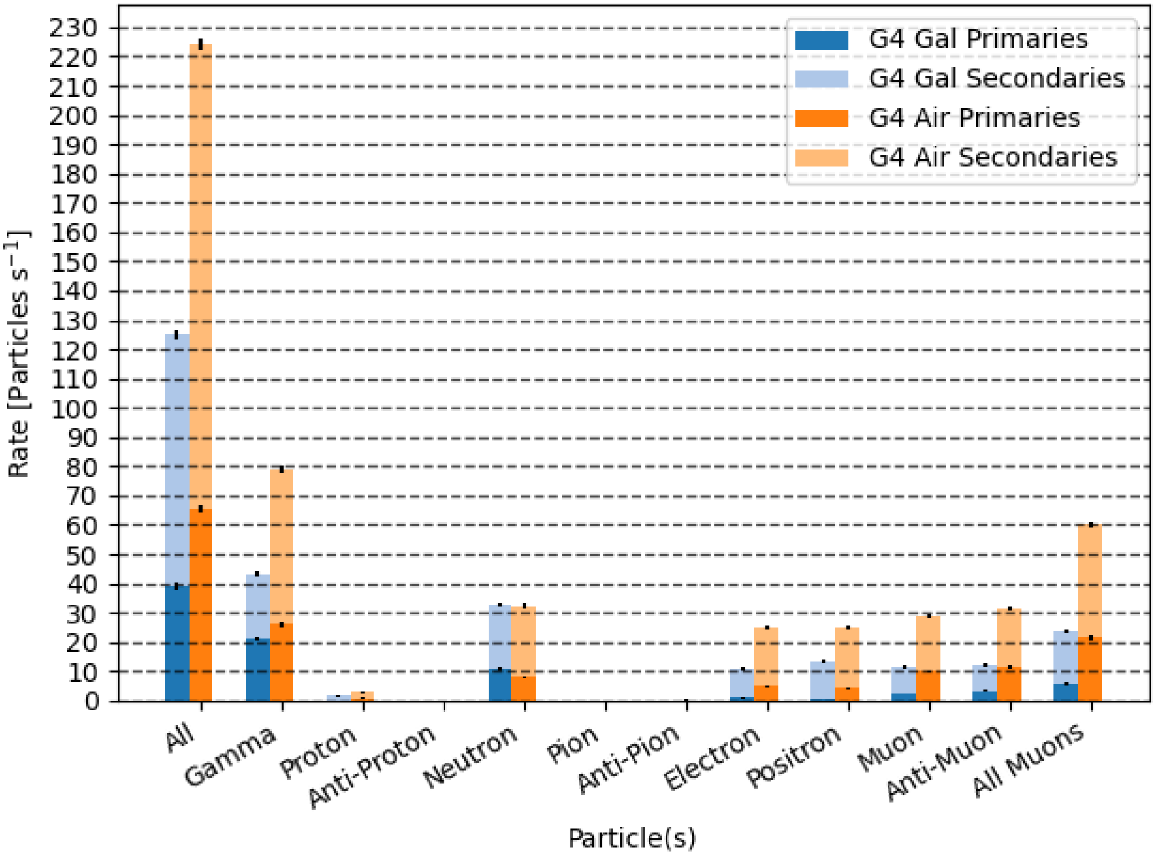


Figure 33: Particle rate for Dome approach (disc diameter 100m back projection 100m) on a PVT of 1m by 5cm by 2m with shielding and concrete but with a threshold of 10 keV. The most accurate primary rate is likely to be the air as the scattering is being correctly modelled. The most accurate rate for the secondaries is likely to be the Galactic secondary rate. Numbers seen in tables 1 and 2.

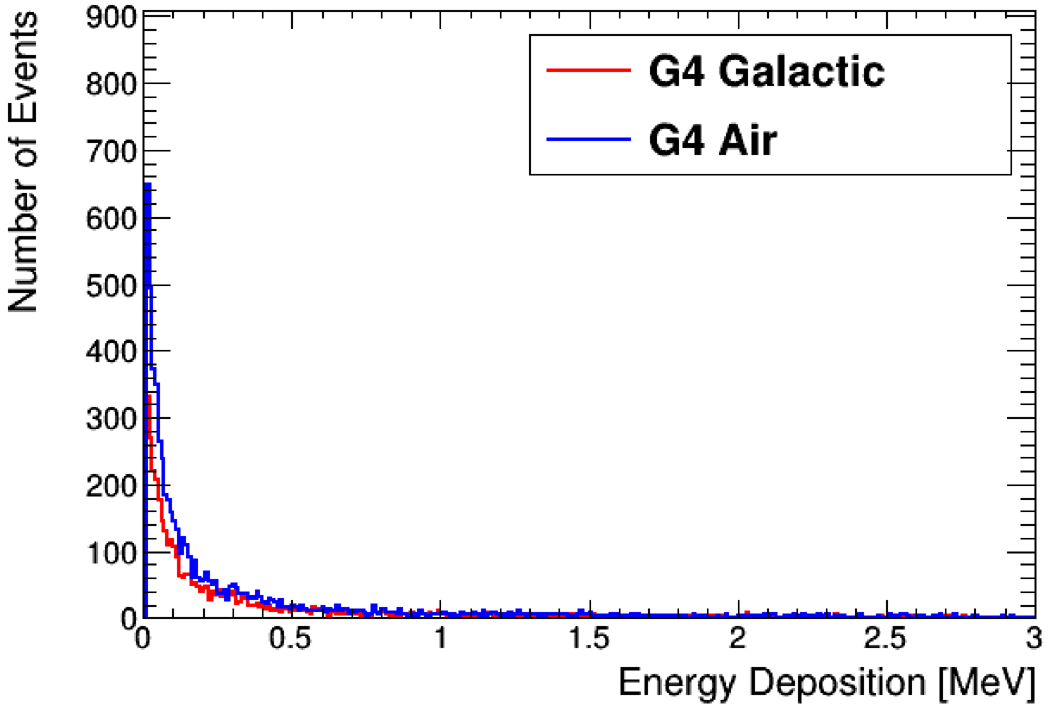


Figure 34: Energy deposition of in the PVT block with dimensions 1m by 5cm by 2m with steel shielding and concrete floor using a dome approach with disc diameter of 100m and back projection of 100m. The energy range is between 10 keV and 3 MeV with 10 keV binning.

<u>Section 8 Conclusion and Further work</u>

In conclusion, the rate of particles for a PVT block of size 1m by 5cm by 2m is 151 $\pm$ 2 particles s^{-1} for all particles. This was done using a dome approach which allows for the simulation of side on particles whilst also simulating the vertical cosmic events using a realistic θ distribution seen in figure 19. This was done whilst smoothing out the z information seen in figure 10. In order to come to this rate, it had to be assumed that the primary rate in G4_Air was the most accurate as G4_Galactic doesn't consider scattering. But the secondary production is over approximated by G4_Air as a result it is more likely that the secondary production is correct in G4_Galactic.

The best approach to use is a dome approach with a disc diameter of 100m and a back projection of 100m. Due to the peak in the realistic θ distribution in figure 19 there is a halo visible in the distribution when using this approximation seen most clearly in figure 22. This halo is not of concern and the rates from the generated Dome approach roughly match the rate of 119.00 cosmic muons that would be expected from the CRY [2] library alone seen in figures 27 and 28. Whilst the disc approach can also be used under some circumstances it is not suitable for the standard geometry (1m by 1cm by 2m). This is due to the centre saturation seen in figure 17 which in turn leads to figure 26 where the detector reads a very high cosmic rate which is unjustifiable.

The most important work going forwards is measuring real world data to ascertain weather or not the models from GEANT4 [1] and CRY [2] are justifiable. In particular if the muon rate can be measured than this would greatly assist as cosmic rays are the only major source of muons and so the measuring of their rate would be the most useful in testing this model. In addition, the uranium and thorium decay chains also need to be modelled as they can add a significant amount of background. Also adding Radon gas would make it more realistic as well.

In terms of optimisation, reading in a large text file for CRY [2] is very inefficient and if possible, a rework which allows for a multi-threaded approach whilst not reading in a text file would be preferable. The only possible point of concern would be the double simulation of secondary events in air. Currently it is very easy to tell if GEANT4 [1] and CRY [2] are double simulating events, it is not known if the CRY [2] library takes this into account when it is integrated more completely. If not, determining which secondaries are due to the simulation in CRY [2] and which are due to GEANT4 [1] would be necessary as with the text file approach.

Particle(s)	Primary Rate [Particles/s]	Error on Primary Rate [Particles/s]	Secondary Rate [Particles/s]	Error Secondary on Rate [Particles/s]
All	65.3391	1.34813	158.883	2.10225
Gamma	26.078	0.851933	52.824	1.21251
Proton	0.753726	0.145055	2.14951	0.24496
Anti-Proton	0	0	0	0
Neutron	8.01093	0.472048	24.3387	0.8228
Pion	0	0	0.0675565	0.0477696
Anti-Pion	0	0	0.134871	0.134871
Electron	4.98499	0.372596	20.1349	0.748825
Positron	4.10675	0.338719	20.841	0.763045
Muon	9.96899	0.526878	18.7684	0.722933
Anti-Muon	11.5047	0.566111	19.9453	0.745389

Table 1: The primary and secondary rates for G4_Air with a concrete floor and steel shielding around the PVT block with dimensions 1m by 5cm by 2m

Particle(s)	Primary Rate [Particles/s]	Error on Primary Rate [Particles/s]	Secondary Rate [Particles/s]	Error Secondary on Rate [Particles/s]
All	39.0786	1.04256	85.9728	1.54636
Gamma	21.2498	0.768792	21.9452	0.781269
Proton	0.0566989	0.0400922	1.64427	0.215903
Anti-Proton	0	0	0	0
Neutron	10.8837	0.550412	21.6282	0.775907
Pion	0	0	0.0596851	0.0422037
Anti-Pion	0	0	0.0720448	0.0720448
Electron	0.891655	0.157624	9.8918	0.525002
Positron	0.390624	0.104399	13.058	0.603606
Muon	2.48133	0.26302	8.9495	0.499513
Anti-Muon	3.14494	0.295851	8.90601	0.497861

Table 2: The primary and secondary rates for G4_Galactic with a concrete floor and steel shielding around the PVT block with dimensions 1m by 5cm by 2m

Particle(s)	Prim Air + Sec Gal Rate [Particles/s]	Error Prim Air + Sec Gal Rate [Particles/s]
All	151.3119	2.051507676
Gamma	48.0232	1.155928669
Proton	2.397996	0.26010586
Anti-Proton	0	0
Neutron	29.63913	0.908218579
Pion	0.0596851	0.0422037
Anti-Pion	0.0720448	0.0720448
Electron	14.87679	0.643781702
Positron	17.16475	0.69214938
Muon	18.91849	0.726025939
Anti-Muon	20.41071	0.753888082

Table 3: The primary rate from G4_Air added with secondary rate from the G4_Galactic simulation with a concrete floor and steel shielding around the PVT block with dimensions 1m by 5cm by 2m. These numbers are the most likely to be accurate given the scattering caused by the G4_Air and the secondary production from G4_Galactic.

References

[1] S. Agostinelli et al. “GEANT4–a simulation toolkit”. In:Nucl. Instrum. Meth. A506 (2003), pp. 250–303.doi:10.1016/S0168-9002(03)01368-8.

[2] Chris Hagmann, David Lange, and Douglas Wright. “Cosmic-ray shower generator(CRY) for Monte Carlo transport codes”. In:2007 IEEE Nuclear Science Sympo-sium Conference Record. Vol. 2. 2007, pp. 1143–1146.doi:10.1109/NSSMIC.2007.4437209

[3] https://nuclear.llnl.gov/simulation/doc_cry_v1.7/cry.pdf

[5] https://nuclear.llnl.gov/simulation/

[4] https://nuclear.llnl.gov/simulation/doc_cry_v1.7/cry_physics.pdf

[6]https://indico.cern.ch/event/279530/contributions/634985/attachments/511913/706522/MultithreadingInGeant410.pdf

[7] https://geant4-data.web.cern.ch/ReleaseNotes/ReleaseNotes4.10.0.html

[8] https://geant4-data.web.cern.ch/ReleaseNotes/ReleaseNotes4.9.6.html

[9] https://geant4.web.cern.ch/support/download_archive?page=7