MOLLER Beam Dump Simuations

A thesis submitted in partial fulfillment of the
requirement for the degree of Bachelor of Science in
Physics from the College of William and Mary in Virginia,

by

Jarod Worden

Advisor: Prof. David S. Armstrong

Prof. Wouter Deconinck

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Abstract

The purpose of the MOLLER experiment is to discover physics beyond the Standard Model of Particle Physics by analyzing the weak neutral current between electrons to help expand on the theory of the Standard Model or show that we need another theory to better explain our experiments. The goal for my physics project is to use GEANT4 simulations of the MOLLER experiment and analyze the dynamics of the particles in the simulation to identify possible areas of the experiment that need to be updated. One such area of focus is the beam dump of the MOLLER experiment where it is expected that backward scattered particles produced from the beam dump will be detected in particle detectors. Analyzing the GEANT4 simulations of the experiment have shown that there are a large number of backward scattered particles from a lead ring inside the apparatus compared to the beam dump. The back-splash from this lead ring may interfere with the particle detectors that are supposed to register forward moving particles when the MOLLER experiment begins collecting data.

Chapter 1

Introduction

The Standard Model of Particle Physics (SM) is used to explain how the electric force, the weak force, and the strong force interact with elementary particles. The MOLLER Experiment aims to examine the weak charge of the electron and explore physics outside of the SM. The experiment uses Parity Violating Asymmetry of polarized electron-electron scattering to more accurately determine the value of the weak charge of the electron. Other significant discoveries that the MOLLER experiment may contribute towards is the further understanding of hidden weak scale scenarios such as compressed supersymmetry, lepton number violating amplitudes, and light MeV-scale dark matter mediators[1].

The MOLLER experiment will take place at Jefferson Lab in Newport News, Virginia; at present, it is in its design stage. While the apparatus for the experiment is being constructed, analysis of simulated data is needed to improve the design and efficiency of the apparatus that will be used. The objective of my research project is to study data that is produced by GEANT4 Monte Carlo track simulations of the experiment. I focus on the beam dump area of the apparatus where I analyze backward scattered particles that are produced in the beam dump during the experiment that could interfere with particle detectors upstream.

Chapter 2

Theory

The MOLLER experiment generates an electron beam and polarizes these electrons in the direction parallel to their propagation. These electrons collide with nonpolarized electrons and scatter producing quantifiable physics (such as the scattering angle of the electrons) that will be used to measure the weak charge of the electron. The apparatus that the MOLLER experiment will use is pictured in Figure 2.1. The beam dump is where the generated beam's energy will be absorbed, and is located downstream of the detector systems. Figure 2.2 represents a sketch of the beam dump area that is implemented in the GEANT4 simulation software. GEANT4 is used to simulate the passage of particles through matter. It utilizes Monte Carlo methods which allow for random sampling of initial conditions [2]. In the context of my research project, it involves coding the geometry and material of the MOLLER apparatus used and simulating polarized electrons propagating through the structure.

The relevant theories that will be discussed in this section that pertain to my research project are parity symmetry and asymmetry, the extraction of the weak charge of the electron and how that value compares to the theoretical value of the weak charge as proposed by the Standard Model of particle Physics (SM), and the process of Bremsstrahlung.

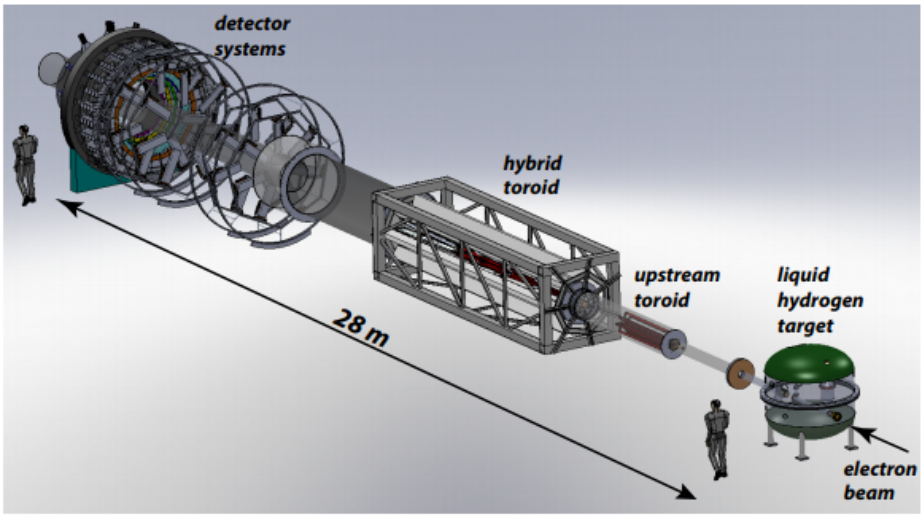

Figure 2.1: Proposed apparatus for the MOLLER experiment. The generated electron beam will propagate through the apparatus towards the detector systems that will lead to the beam dump [1].

2.1 Weak Charge of the Electron

The weak force is one of the four fundamental forces in nature that controls how particles interact with each other. The four fundamental forces are gravity, electromagnetism, the strong force, and the weak force. The weak force is unique in that it is the only known force that does not conserve parity symmetry.

2.1.1 Parity Symmetry and Asymmetry

Parity symmetry occurs when a change in the algebraic sign of a coordinate system does not change the spatial state of a particle in that system [3]. It was believed that parity is conserved for all fundamental forces until the Wu experiment [3] demonstrated that parity is not conserved in all instances. The experiment involved the beta decay of Cobalt 60 nuclei and found that the decay direction depended on the orientation of the nuclear spin. Figure 2.3 demonstrates beta decay in Cobalt nuclei and shows that the weak force interactions do not conserve parity [3].

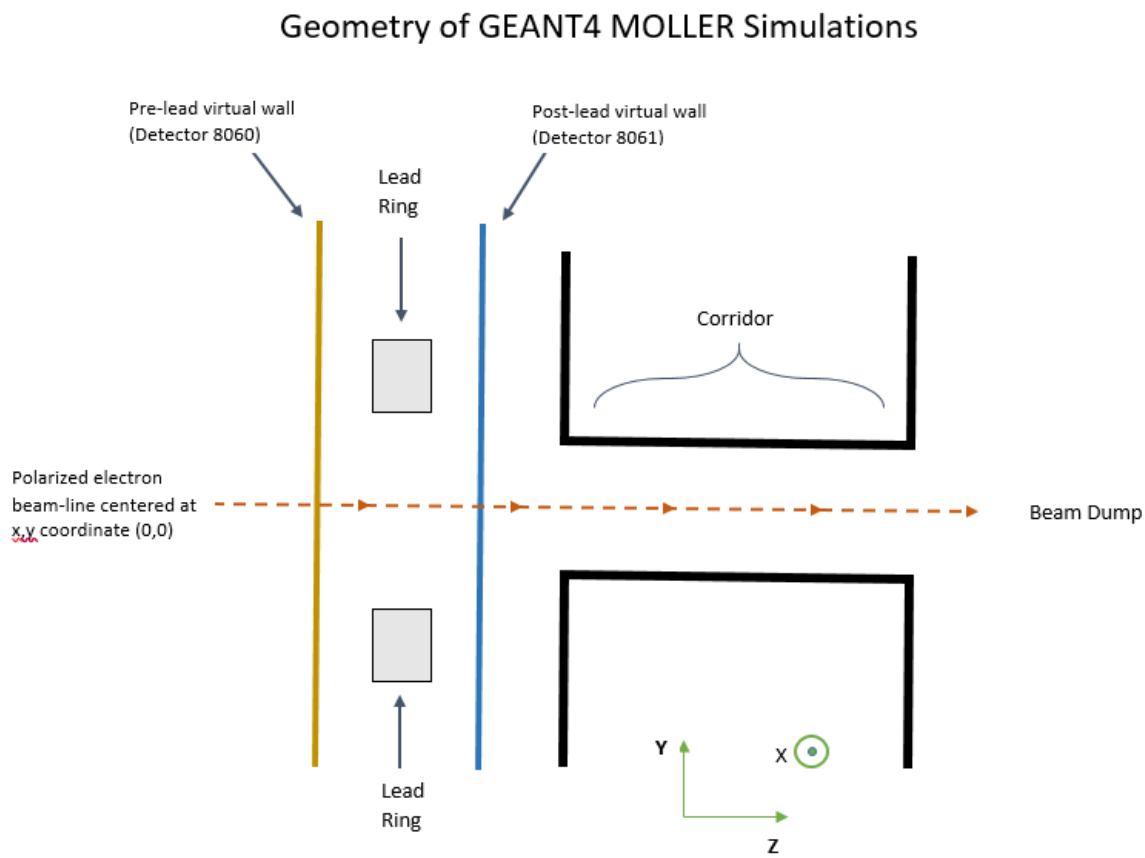

Figure 2.2: Sketch of the geometry of the beam dump for the MOLLER experiment used in the GEANT4 simulations. The generated electron beam will travel along the dashed line to the beam dump. Two virtual detectors of interest are the pre-lead detector, which is located slightly upstream from a lead ring, and a post-lead detector, which is slightly downstream from the lead ring. The Cartesian coordinates for the system have the positive z axis going towards the beam dump with the positive x axis pointing into the page and the y axis pointing up.

2.1.2 Measuring the Weak Charge

The MOLLER experiment will be comparing the weak charge of the electron to the weak charge predicted by the SM by measuring the Parity Violating asymmetry to determine the weak charge of the electron. The Parity Violating asymmetry can give us the weak charge of the electron through equation (2.1):

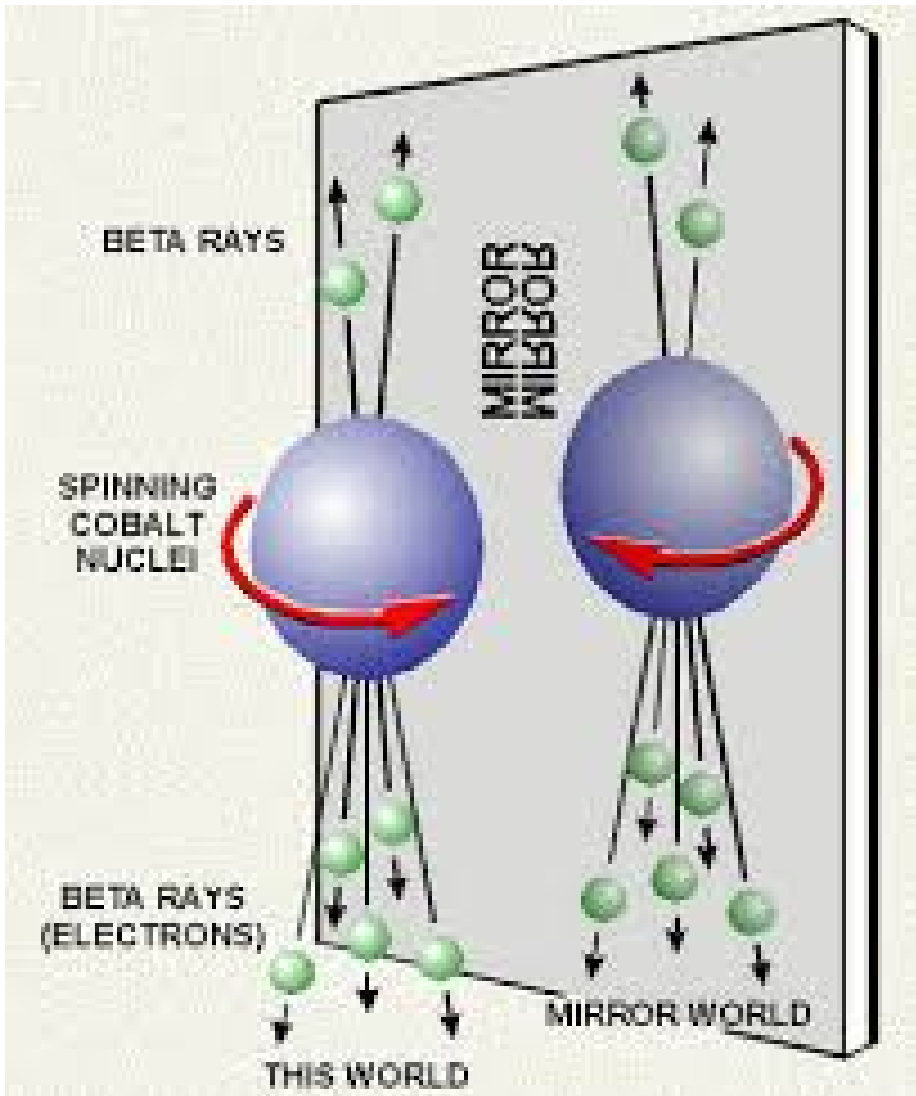

Figure 2.3: Beta decay of Cobalt atoms [4]. This diagram demonstrates how parity is not conserved in weak force interactions. The spin of the Cobalt nuclei determines how the beta rays will be ejected. If the Cobalt nuclei in the mirror world was to be flipped to have its spin oriented in the same direction as the spin of the Cobalt nuclei in the real world, the beta rays in the mirror world would be ejected in the opposite direction compared to the beta rays in the real world[4].

$$A_{pv} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{2y(1-y)}{1+y^4+(1-y)^4}Q_W^e \tag{2.1}$$

In equation (2.1), A_{pv} represents the measured Parity Violating Asymmetry of

the electron, σ_R and σ_L are the scattering cross sections for spin aligned and spin anti-aligned electrons with their momentum vectors, m is the electron mass, E is the beam energy, G_F is the Fermi coupling constant, α is the fine structure constant, $y \equiv 1 - \frac{E'}{E}$ where E' is the energy of the scattered electron, and Q_W^e is the weak charge of the electron [3].

The values of m, α, G_F are already known. The apparatus of the MOLLER experiment will be able to quantify the remaining variables for equation (2.1) except for Q_W^e, which can then be derived. Once Q_W^e is extracted, this value will be compared to the SM interpretation of the weak charge.

Another process that pertains to my research project is Bremsstrahlung.

2.2 The process of Bremsstrahlung

There is a lead 'donut' in the detector system of the apparatus which used to reduce the energy of scattered electrons so Pion detectors downstream do not register them. The electrons that go through the lead have their kinetic energy reduced by interacting with the electric fields of the lead atoms. This process can then lead to photons being created with energy equal to the lost energy of the electrons [5]. This process is Bremsstrahlung and the scattered particles from this process might interfere with the detectors. This interaction occurs many times within the lead wall and makes it possible for electrons with relatively high energy to be emitted in the backwards direction and interfere with the detectors upstream.

Chapter 3

Experimental Technique

For my research project, I need to examine simulated particles that are produced from the beam dump of the experiment and see if the particles coming backward interfere with detectors upstream that are needed to take data for forward moving particles. The beam dump is located at the back of the apparatus where the electrons will end up and have their energy absorbed. In order to do this, I used GEANT4 simulations of the MOLLER experiment to analyze the data that is produced by the simulations and see what possible areas of the beam dump produce backward scattered particles that will interfere with the detectors. The simulated apparatus has a majority of the geometry and materials coded into the structure, but some of the components, like the detectors, are modelled as being 'virtual'. These virtual detectors do not have any contributing geometry or material in the apparatus, but act as a wall normal to the beam pipe, to examine the properties of the particles passing through that plane.

Utilizing GEANT4 and the nature of how Monte Carlo methods operate, the data collected will be different depending on the randomized initial conditions set on the electrons in the beam. Some of the variables that are changed due to these varying initial conditions are the spatial coordinates, the momentum of the particle, the type of particle, etc.

An incident electron with specific initial conditions can produce many other differ-

ent kinds of particles when it interacts with the apparatus. These produced particles then have there own specific variables and then could produce other particles in a chain reaction during the simulation. Due to this process, the data sent to me by Professor Deconinck contained $10,000,000$ particles with their own variable quantities. In order to hold all the different variables that are needed to analyze the interaction, a jagged array data structure was used. This structure breaks up each variable into an array type of a length that is the amount of particles that are registered in the simulation. This allows me to find the specific particles that I want by ignoring the particles that do not meet the requirements.

Once I obtain the data I need for the specific particles, I interpret the data through graphing certain variables needed to see the process of the MOLLER experiment through the simulations. For example, I produced a graph (figure 2) of electrons, positrons, and photons with a negative z momentum and plotted where they originated from in terms of their x and y coordinates (vx and vy).

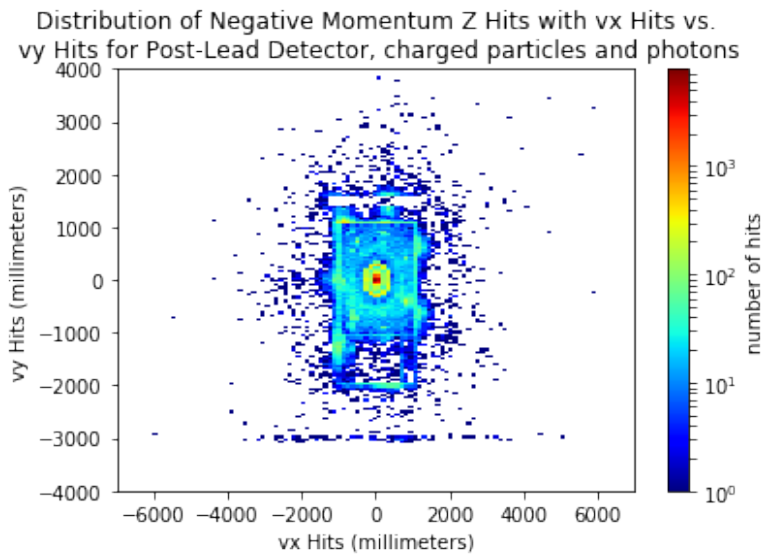

Figure 3.1: Graph of the negative momentum charged particles (electrons and positrons) and photons coming from beyond detector 8061, which is a detector before the beam dump. The hits on this figure show where the particles that are coming backwards originated in the x and y coordinate. It is also binned such that the density of particles in a single space is color coded with a log scale of the number of hits.

Chapter 4

Results

My main task for this research project was to see how much back-splash from the beam dump of the apparatus affects the data collection of the virtual detectors. The beam dump is used to absorb the energy of the electrons, but it may also reflect a percentage of the charged particles coming towards it. The two virtual detectors at risk for back splash are detectors 8060 and 8061 (which are the pre-lead and post-lead detectors respectively). The spatial coordinates for this simulation are x,y, and z. z is parallel to the apparatus while x and y are normal to the apparatus with the positive x axis pointing to the left and the positive y axis pointing up. The detectors are normal to the z axis of the apparatus. Detector 8060 is located $0.2m$ upstream from detector 8061, and the beam dump is located approximately $3m$ downstream from detector 8061. There is also a lead ring of a thickness of about $0.3m$ separating them. The lead ring also has a radius of $1m$ in relation to the x and y axes. This lead ring will be implemented as electron absorption for downstream Pion detectors.

An important part of my research project is identifying what types of particles are coming backwards from the beam dump through the virtual detectors and with what energy. The energy is important because the detectors will not account for the energies of low energy particles. The types of particles and the amount registered are given in Tables 4.1 and 4.2.

Table 4.1: Number of particles for pre-lead detector

Particle type of pre-lead detector	Count
electron	9946
positron	657
photon	109356
muon neutrino	481
muon antineutrino	444
neutron	3467

Table 4.2: Number of particles for post-lead detector

Particle type of post-lead detector	Count
electron	2416
positron	160
photon	68729
muon neutrino	445
muon antineutrino	478
neutron	703

From the table of particle types, it can be seen that the largest contributor to the backwards moving particles are the photons. There are also electrons along with a few other particles. The focus for my research project mainly concerns these particles since the real detectors of the MOLLER experiment won't register the remaining particles. The muon neutrinos, muon antineutrinos, and neutrons can be ignored.

For comparing these particles, it is better to compare their momentum than their energies since the energies would take into consideration their rest energy. Since the detectors will register particles with a certain kinetic energy, momentum is a more useful quantity to use. The momentum graphs (figure 4.1 and figure 4.2) show the momenta of the backwards scattered electrons, positrons, and photons. There are a high number of low momentum particles, which is good, since real detectors will not register low momentum particles. The data analysis going forward will concern

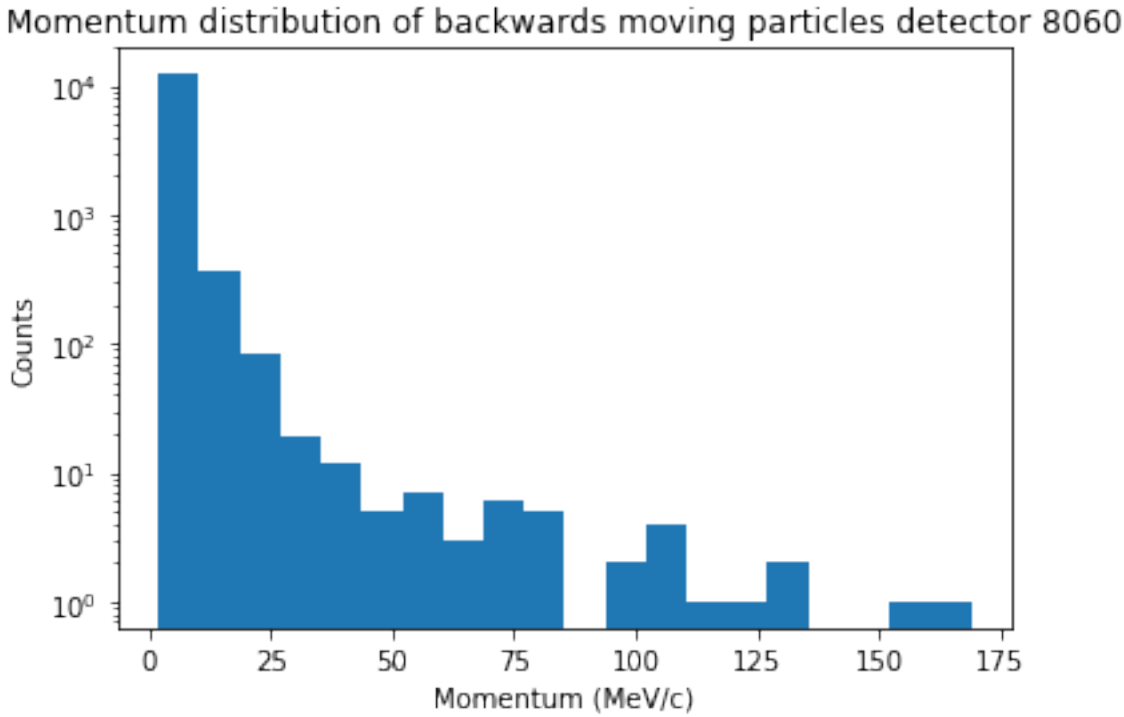

Figure 4.1: Momentum distribution for detector 8060 for backwards moving photons, electrons, and positrons

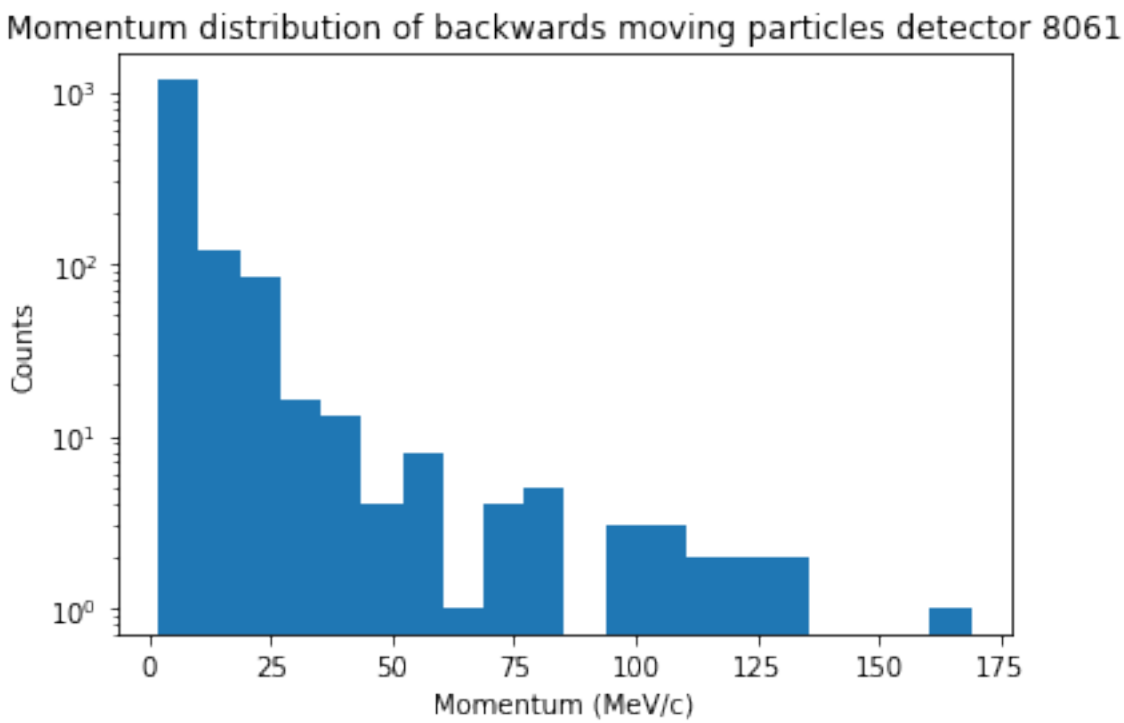

Figure 4.2: Momentum distribution for detector 8061 for backwards moving photons, electrons, and positrons

particles with total momentum of 2 MeV/c or greater.

Now the issue would be to find the backward moving particles' original x and y coordinates with the requirements that they are charged particles with a minimum total momentum of 2 MeV/c. To make the graphs easier to interpret, since the particles are produced in a beam pipe, I made a value of the radial distance from the primary electron beam that is represented as $\sqrt{vx^2 + vy^2}$. The graph also includes the vz value which is where the particles are generated in the z axis. I made these plots for both detector 8060 (figure 4.3) and 8061 (figure 4.4).

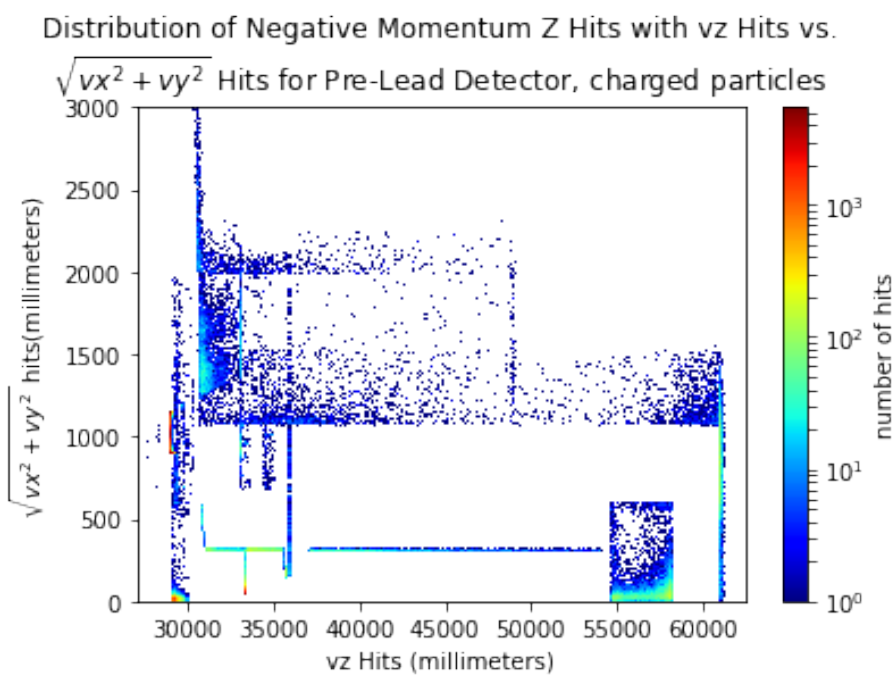

Figure 4.3: Negative momentum charged particles (electrons and positrons) and photons coming from beyond detector 8060, which is a detector before the beam dump. Detector 8060's z location is 28910 mm. The hits on this figure show where the particles that are coming backwards originated in the x and y coordinate. It is also binned such that the high density of particles in a single space is color coded with a log scale of the number of hits.

Analyzing these plots, there are a low number of particles coming back from detector 8061 since there are few hits compared to the large amount of particles

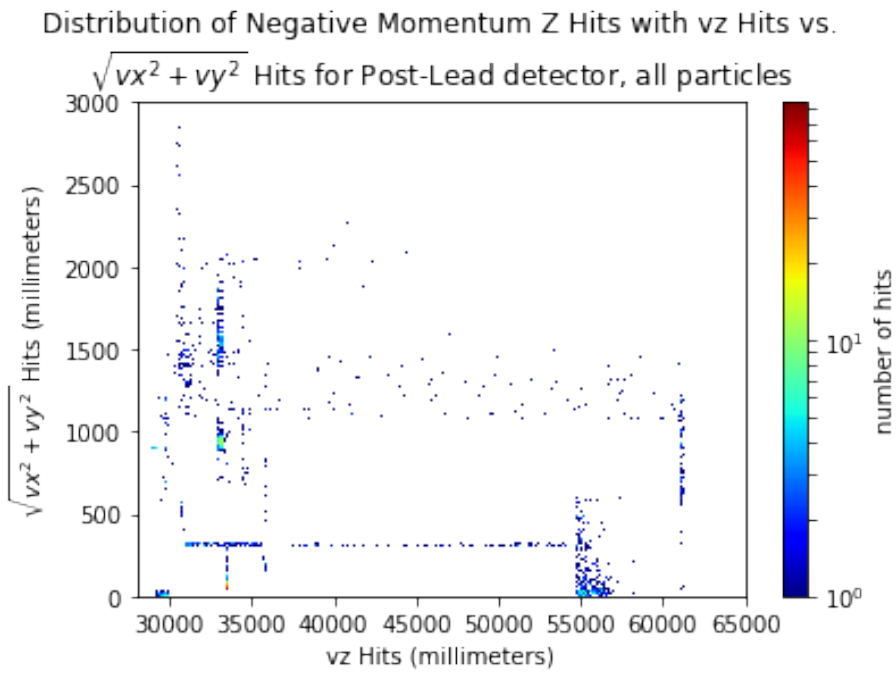

Figure 4.4: Negative momentum charged particles (electrons and positrons) and photons coming from beyond detector 8061. Detector 8061's z location is 29170 mm. This has similar characteristics as figure 5, but with less hits than detector 8060.

already coming through from the positive direction that is generated by the primary beam. The main issue is with detector 8060. Looking into the high density hits that are marked by a deep red color, the large amount of negative moving particles are coming from the area in front of the 30000 millimeter mark. Analyzing this further, the area in deep red, around radius 1000 mm, is between the detectors which is where the lead ring is located. Figure 4.5 focuses in on the area between detectors 8060 and 8061.

This shows that there is a high density of particles produced from the lead ring that are being reflected back into detector 8060. This result was not expected, since it was previously believed that many of the backward scattered particles would be produced from the beam dump that is located at position 54000 millimeters to 57500

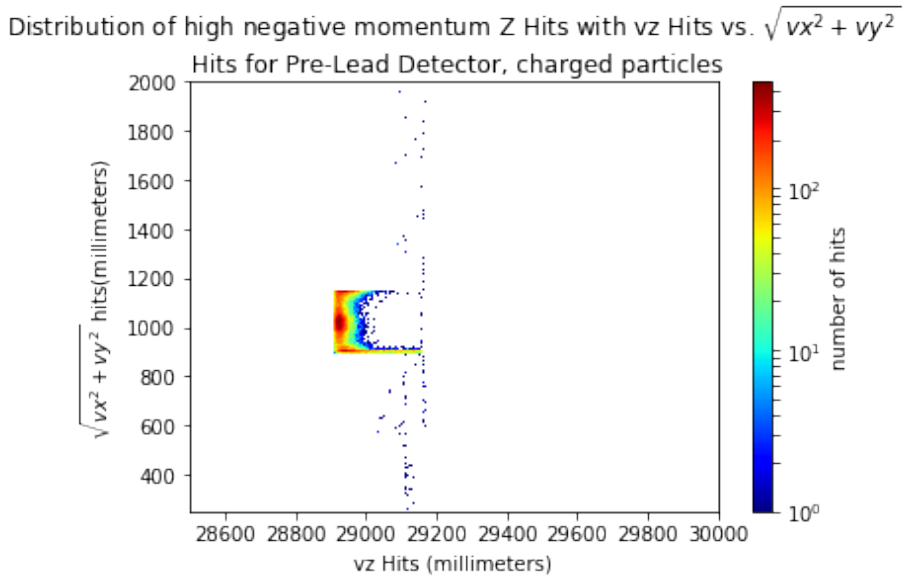

Figure 4.5: Negative momentum charged particles (electrons and positrons) and photons coming from the lead ring and scattering backwards into detector 8060.

millimeters. This process may be caused by a generation of an electromagnetic shower, which may be caused by the process of Bremsstrahlung. This may be an issue to the experiment caused by the materials used in the apparatus.

The information from the backward scattered pre/post-lead detectors can be compared to the amount of Moller particles that are analyzed at detector 28. Detector 28 is one of the main detectors that is located upstream from the pre-lead detector. The Moller electrons from detector 28 are located 93.5 cm to 110 cm out radially from the center beam. Figure 4.6 represents forward moving electrons and shows the Moller electron ring that is produced from the polarized electrons scattering off the target upstream.

From Figure 4.6, the Moller electrons can be compared to the backward scattered particles from detectors 8060 (Figure 4.7) and 8061 (Figure 4.8) that also located 93.5 cm to 110 cm radially from the center beam. The remaining graphs will have

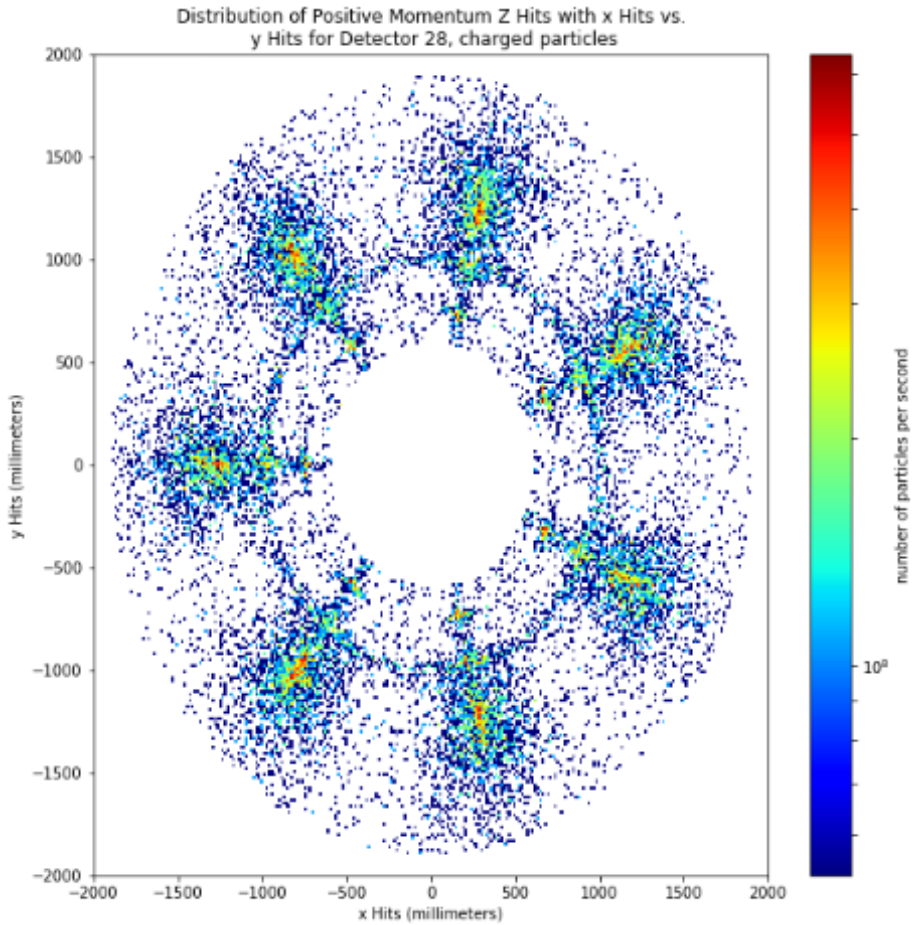

Figure 4.6: The forward moving electrons from Detector 28 that are located 60 cm to 180 cm radially from the center beam. The Moller electron ring is located 93.5 cm to 100 cm radially from the center.

counts representing counts per second since the experiment will be analyzing the rate of particles propagating through a detector.

From Figure 4.7, the number of backward scattered particles from detector 8060 compared to the Moller electrons is 3.997 percent. From Figure 4.8, the number of backward scattered particles from detector 8061 compared to the Moller electrons is .882 percent. There are less backward scattered particles coming from detector 8061 than 8060, but this is because some of the backward momentum particles from detector 8060 also come from detector 8061 that originated back in the beam dump.

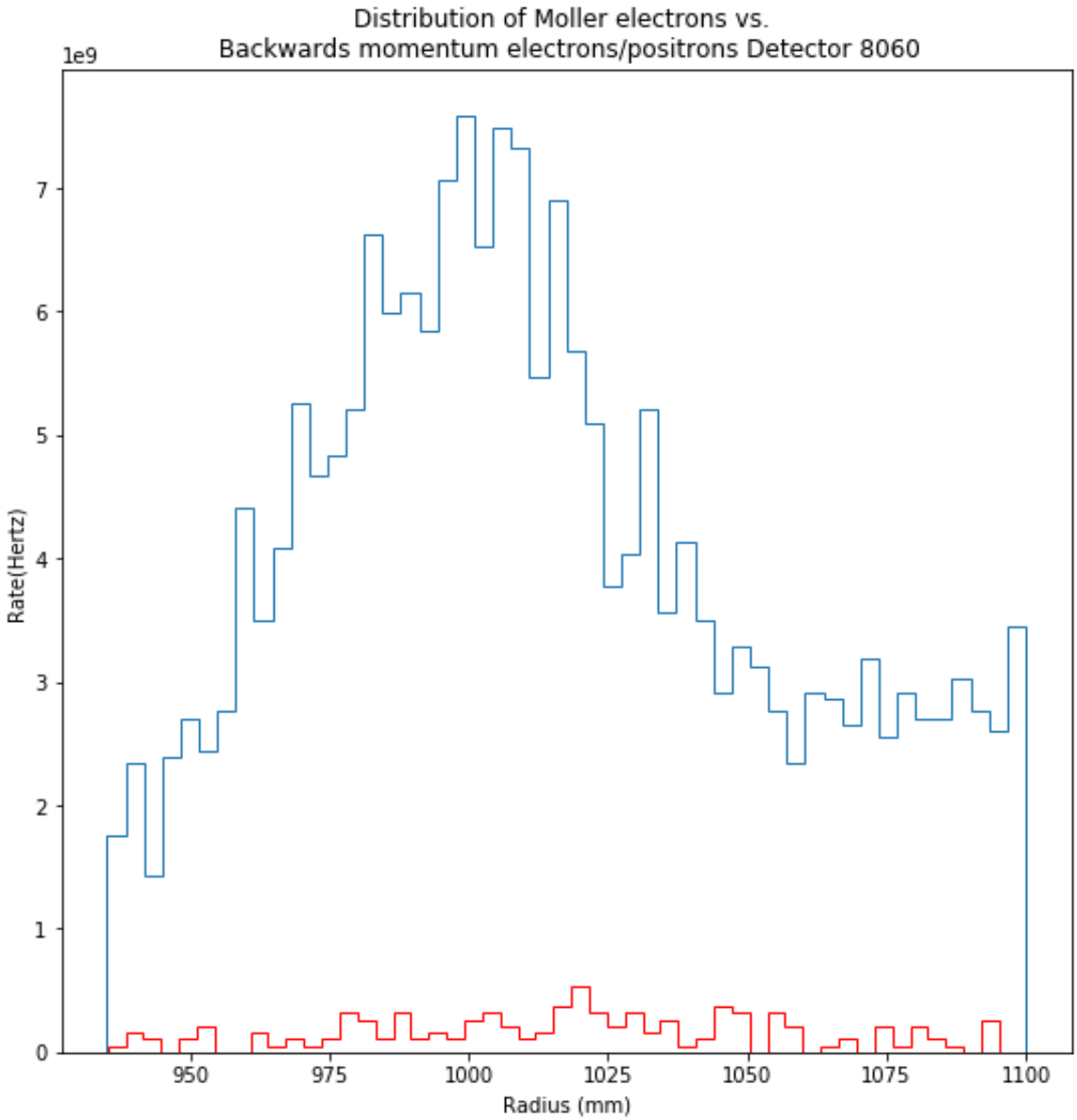

Figure 4.7: Number of electrons and positrons of the pre-lead detector and the number of electrons/positrons of the Moller electrons with respect to their radial distance from the beam center. The blue line represents the forward going Moller particles while the red line represents the particles from the pre-lead detector. The y axis is in rate since the detectors will be registering rates of particles. The rate is the count of the data multiplied by a constant.

In order to find the number of backward scattered particles from the lead ring, the number of particles from detector 8061 needs to be subtracted from the number of

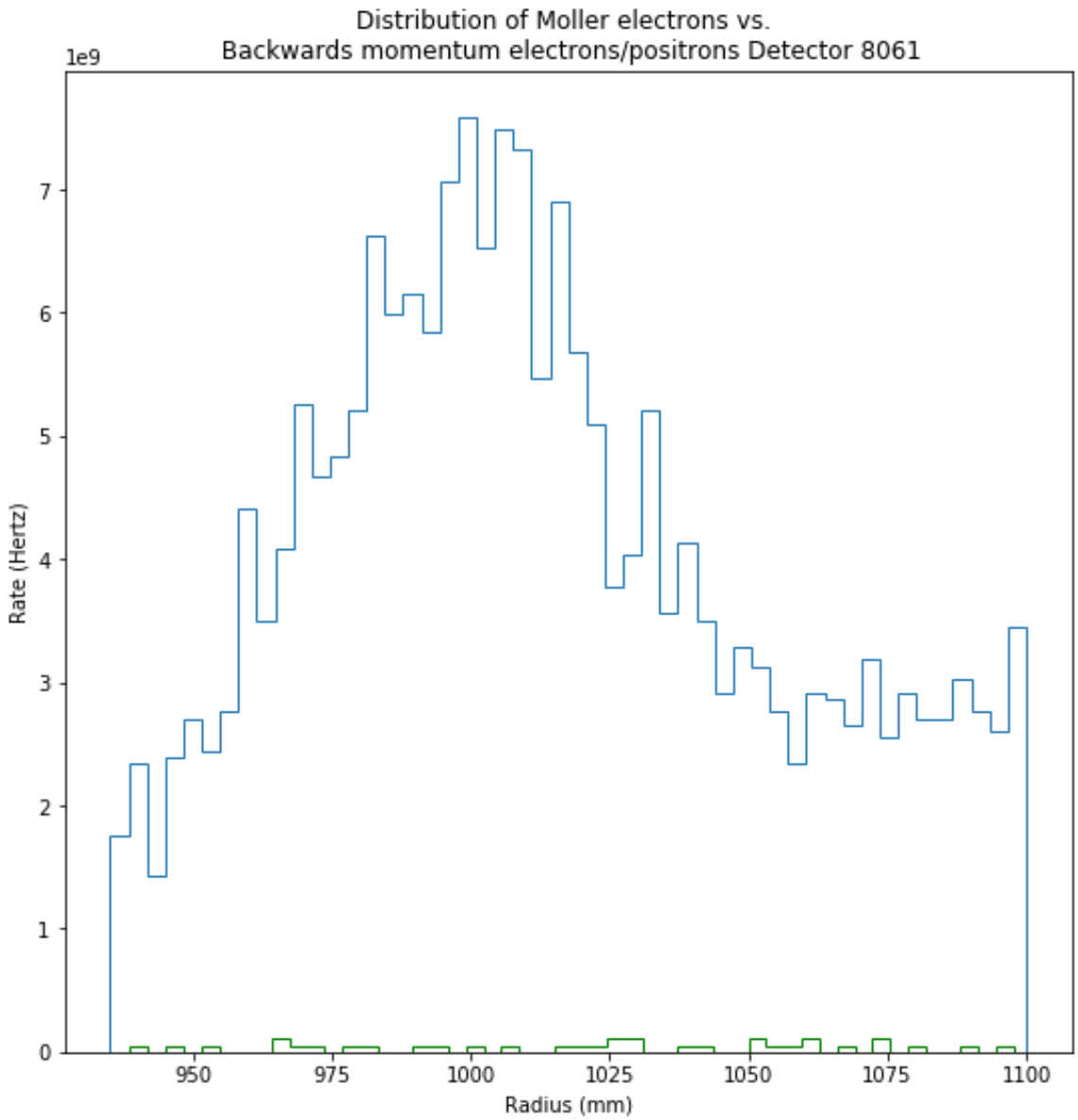

Figure 4.8: Number of electrons and positrons of the post-lead detector and the number of electrons/positrons of the Moller electrons with respect to their radial distance from the beam center. The blue line represents the forward going Moller particles while the green line represents the particles from the post-lead detector. The y axis is in rate since the detectors will be registering rates of particles. The rate is the count of the data multiplied by a constant.

particles from 8060. Figure 4.9 shows the distribution of the detectors compared to each other with the number of backwards momentum particles.

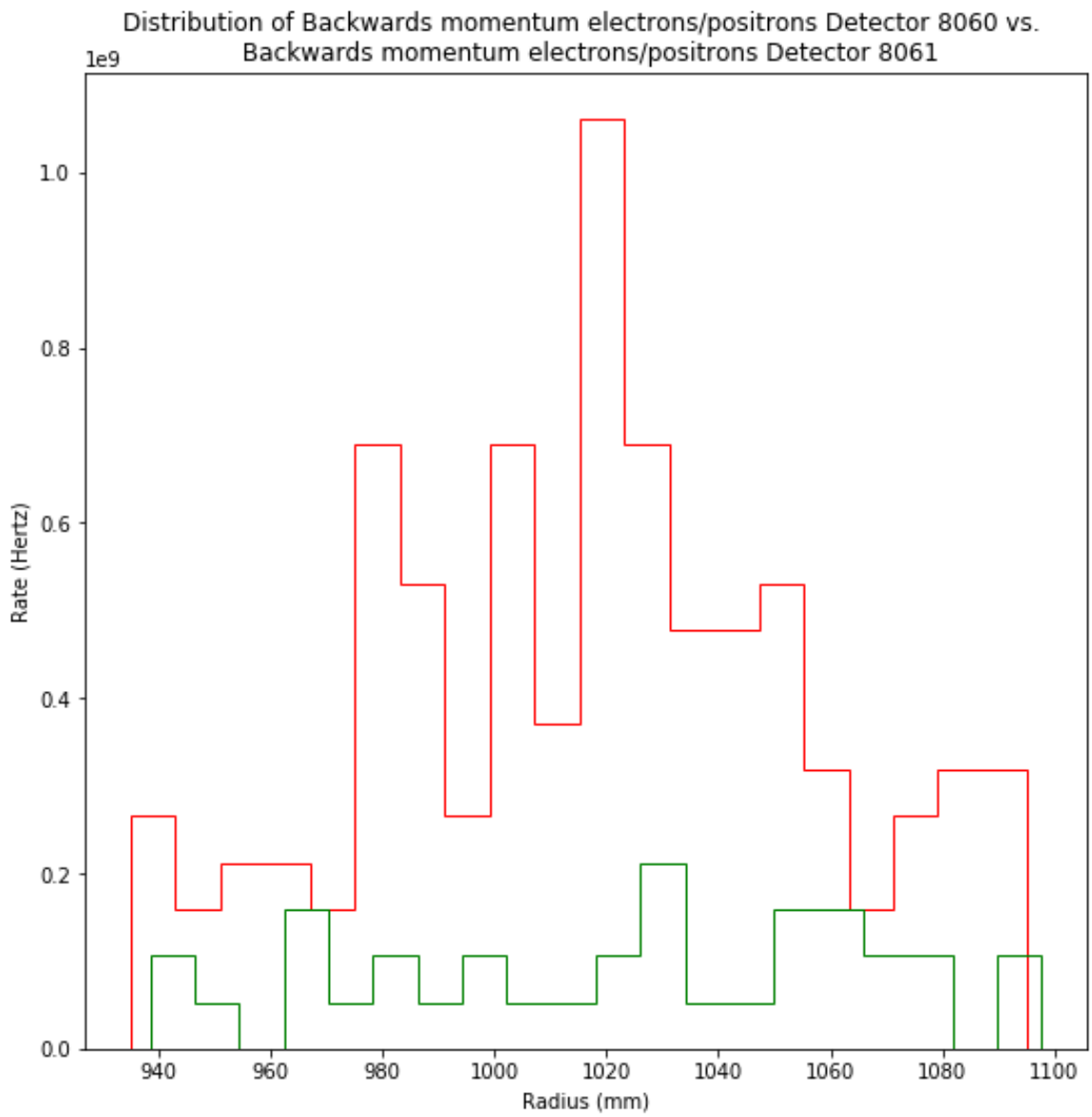

Figure 4.9: Distribution comparing the number of backward scattered electrons from detector 8060 and detector 8061. The red line represents the particles from detector 8060 and the green line are particles from detector 8061. The y axis is in rate since the detectors will be registering rates of particles. The rate is the count of the data multiplied by a constant.

Figure 4.9 shows the distribution of backwards scattered particles of detectors 8060 and 8061. The number of particles from detector 8061 compared to 8060 is

22.08 percent. This gives the appropriate number of particles coming back from the lead ring by subtracting the total number of backward momentum particles of detector 8061 from detector 8060. Then the ratio of backward scattered particles from the lead ring compared to the Moller electrons is 3.114 percent.

Chapter 5

Conclusion/Outlook

After analyzing the data of the MOLLER experiment produced by GEANT4 simulations, another concern about the back splash of particles going through the virtual detectors has been shown to be produced by the lead ring. It was previously thought that the majority of backward scattered particles that would affect the detectors would come from the beam dump. Detector 8061 appears to be minimally affected by backward scattered particles, but Detector 8060 appears to have a large amount of backward scattered particles with high momentum coming backwards caused by the lead ring. Analyzing the number of Moller electrons to the number of backward scattered particles for detectors 8060 and 8061 that are 93.5cm to 110cm radially out gives a ratio of 3.997 percent when comparing detector 8060 particles with the Moller electrons and a ratio of .882 percent when comparing detector 8061 particles with the Moller electrons. From this, it is possible to get the ratio of particles coming back from the lead ring compared to the number of Moller electrons, which has a ratio of 3.114 percent.

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