Background Asymmetry Simulation for the MOLLER Experiment

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Introduction:

The MOLLER experiment at Jefferson Laboratory aims at the measurement of the parity-violating asymmetry in the scattering of longitudinally polarized electrons. The high-precision goals necessitate estimation of background asymmetry resulting from electrons scattering from various materials into the detector. Since this asymmetry is impossible to calculate with sufficient precision, a computer simulation needed to be developed. Geant4, the toolkit for the simulation of passage of particles through matter, was chosen as a simulation platform [1]. Its suitability was confirmed by simulating Moller scattering as well as bremsstrahlung in a thin iron foil and comparing results to the literature on the subject. Having gained confidence in the ability of Geant4 to simulate these fundamental processes in isolation, we created a simulation with the targets of thicknesses comparable to or larger than the radiation length of iron. Results from both simulations will be presented and compared to the available data. The copy of the C++ simulation code, as well as data analysis and visualization ROOT scripts, can be found in the author's GitHub repository at https://github.com/mklobukov/moller

Simulation Setup 1: Confirmation of Moller Scattering in an Iron Foil

To verify that Geant4 is able to handle polarized scattering processes, a simulation was developed in which an 11 GeV beam of longitudinally polarized electrons was aimed at a polarized 10-micron iron foil, as shown in Figure 1. The first task for this simulation geometry was to check Moller scattering in Geant4, so the simulation was configured to identify all events in which electron scattering occurs and both electrons leave the target material with the energy of at least 1 GeV. Results of this simulation will be shown in the next section.

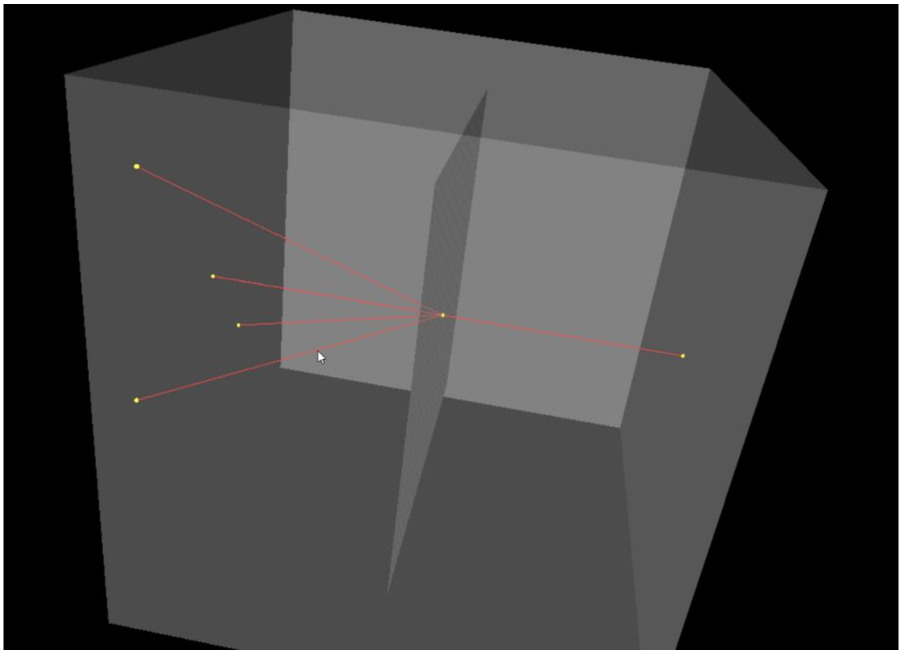

Figure 1: Simulation setup for a polarized 10-micron iron foil being bombarded by a beam of polarized electrons. The red lines represent electron trajectories after the target is hit with several electrons. Note the relatively small scattering angle and the small number of scattering events due to the thinness of the target.

Simulation Setup 2: Bremsstrahlung in Iron Foil

Next, bremsstrahlung in Geant4 needed to be verified. Keeping the simulation geometry described in the section above, the event filtering criteria were changed to focus on photons and their polarizations. The selected events now involved one electron and one photon leaving the target with the energies above 100 MeV.

Simulation Setup 3: Asymmetry Calculations in a Thick Iron Slab

Having ascertained that the polarized Moller and bremsstrahlung processes in Geant4 agree with publications on the subject, we modified the simulation to model more closely a physical part in the MOLLER experiment. Now the electrons were shot at a thicker, 2cm target, which is slightly larger than the radiation length of iron (~1.76cm). A multitude of physical processes were now at work in the material, and the simulation produced the so-called electromagnetic shower, as shown in Figure 2 and Figure 3. The calculations were now performed for all particles leaving the target with the energies above 100 MeV.

For a given width, the simulation had two variable parameters: polarization of the target and polarization of the incident beam. The former was set at 8%, 50%, and 100%; while the latter was fully polarized either in the same or the opposite direction to target polarization. Asymmetry was calculated by fixing the target width and target polarization while flipping the direction of the beam polarization.

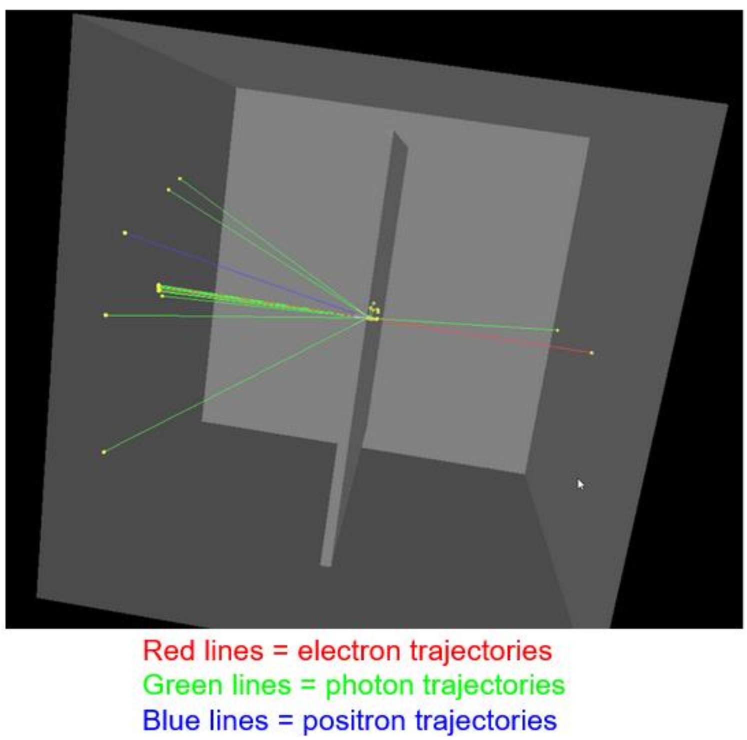

Figure 2: Simulation visualization for a single incident electron with the target width of 2cm. Note a larger number of scattered particles compared to a thin foil

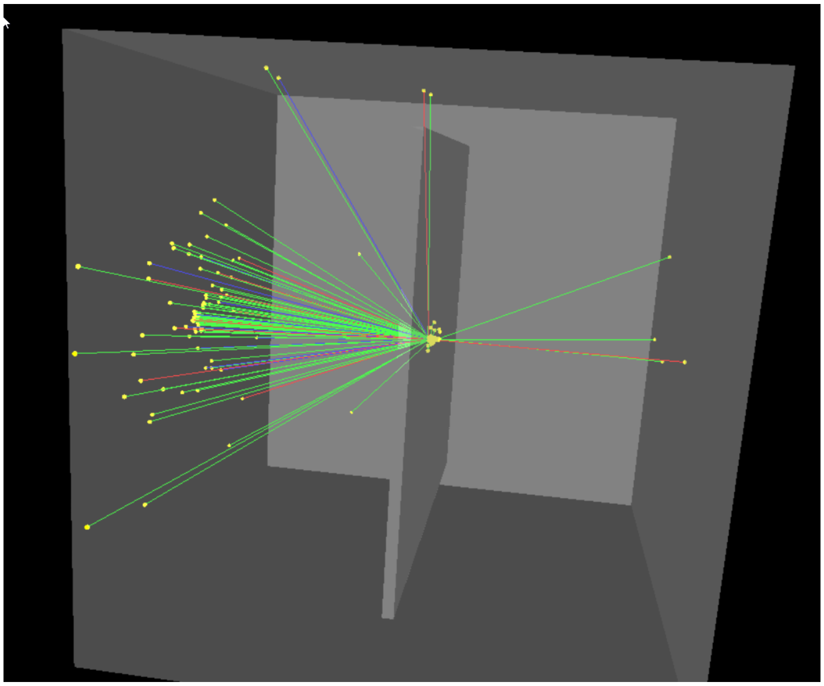

Figure 3: Simulation visualization for 5 incident electrons with the target width of 2cm. The electromagnetic shower is clearly visible with even such small number of events.

The results of this simulation setup were compared qualitatively with the experiments by Barday [4] and Zwart [5]. Despite beam energy and geometry differences, the simulation output was consistent with these publications. Eventually, it will be necessary to adjust simulation geometry and beam energies and conduct a proper quantitative comparison with the benchmarks from these papers.

Simulation Results:

Results of the simulations with a thin iron foil will be presented first. Figure 4 shows a plot of the cross section against cosine of the center-of-mass angle of the scattered electrons. Figure 5 is a plot of asymmetry vs cosine of the center-of-mass angle. Asymmetry was calculated as

$$A = \frac{P - N}{P + N}$$

where P is the number of scattered particles for a positively polarized electron beam, and N is the number of scattered particles for a negatively polarized beam. Calculation of the cross section and asymmetries reveals that the simulation data is in accordance with theory, and that we can be confident about the simulation of scattering events inside the thicker targets where multiple physical processes occur.

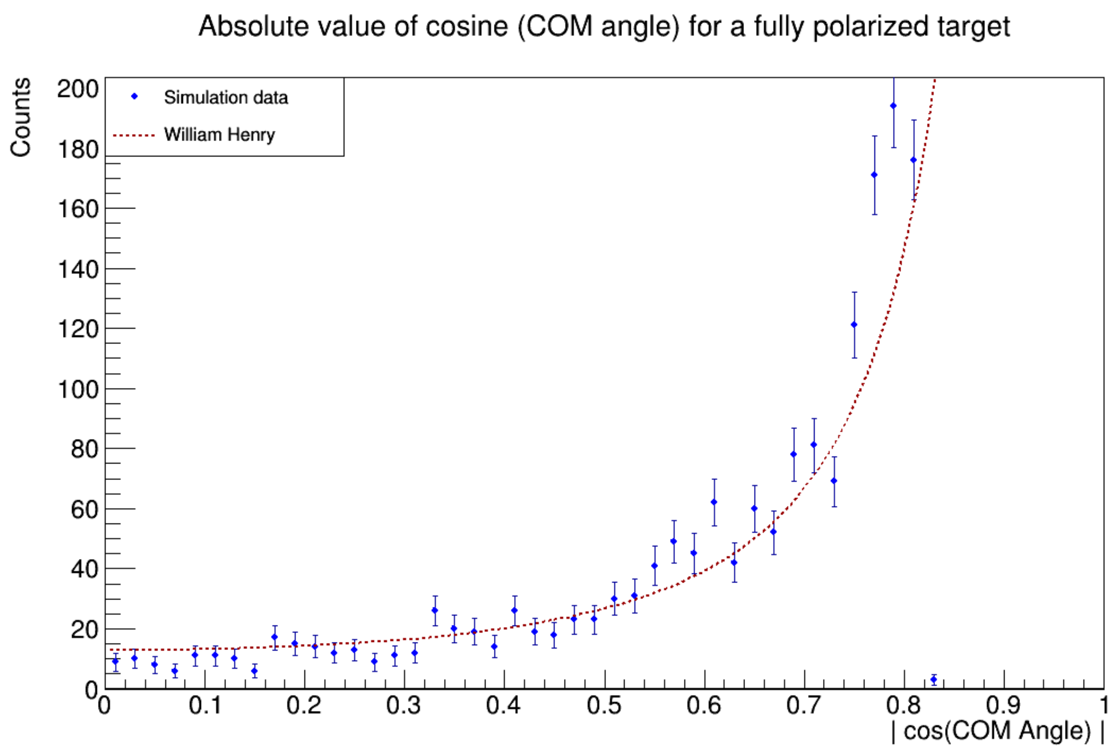

Figure 4: Comparison of cross section from simulation with the formula from William Henry's thesis for a fully polarized target [2].

Confirmation of bremsstrahlung in Geant4 was performed by comparing simulation data for photon polarizations with the findings of Olsen and Maximon [3]. The histogram in Figure 6 shows the average photon polarization binned by photon's energy. The close correspondence between the two curves indicates that Geant4 can reliably model bremsstrahlung.

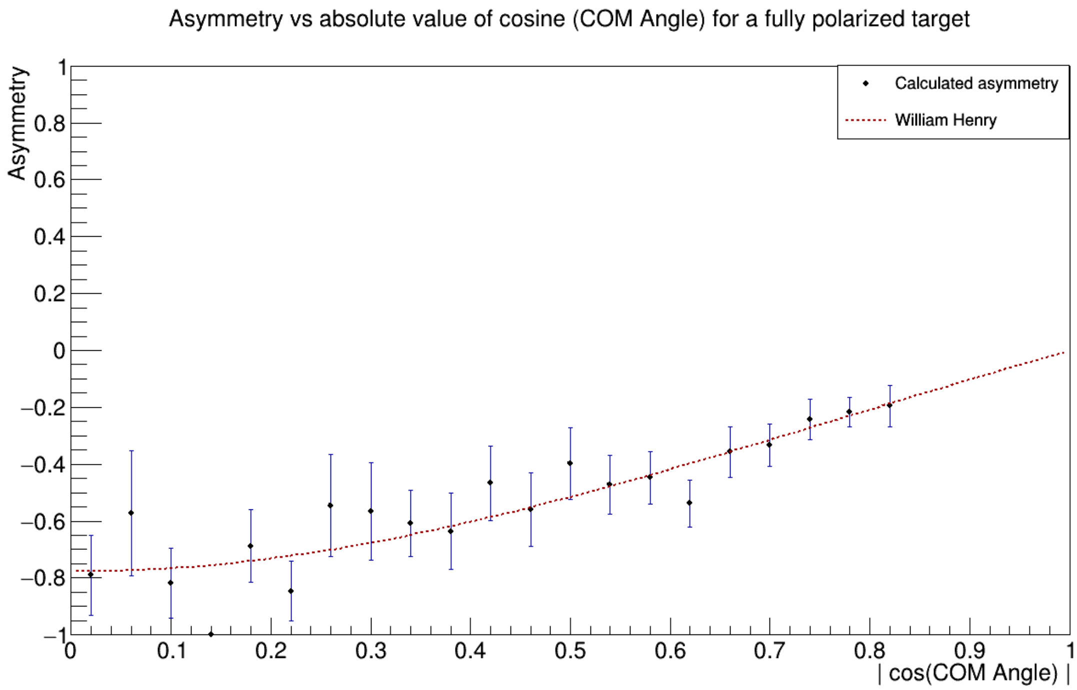

Figure 5: Comparison between asymmetry calculated from the simulation data and the formula from William Henry's dissertation [2].

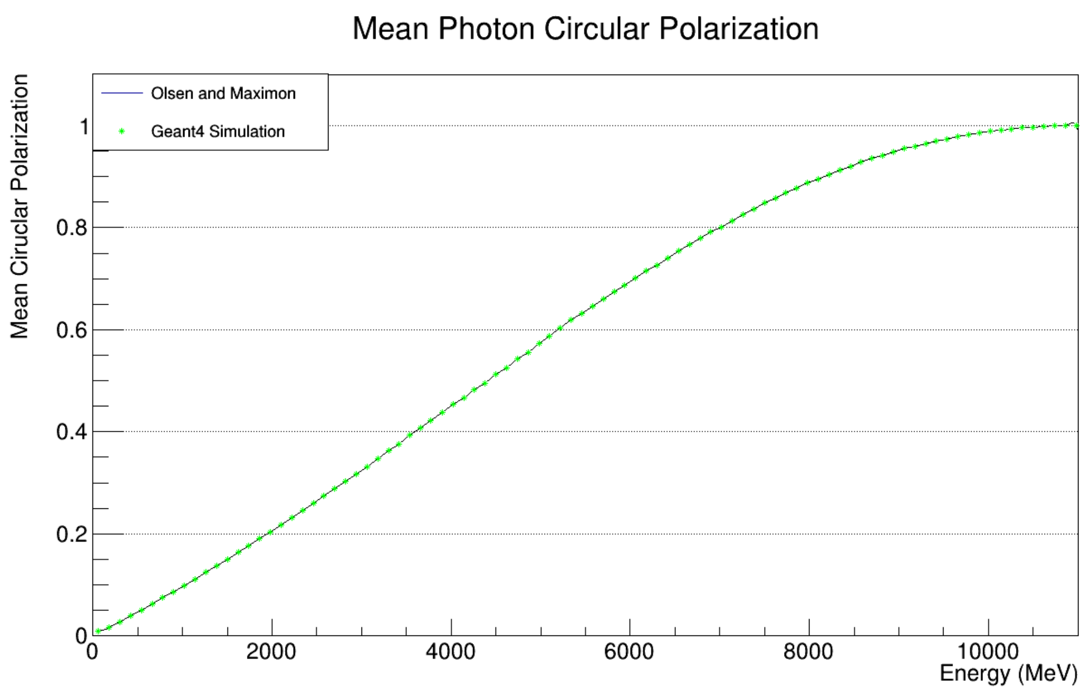

Figure 6: Comparison between simulation data for mean photon polarization and the paper by Olsen and Maximon [3].

Asymmetries for the thicker target were then calculated and plotted separately for electrons and photons in a simulation with 1.6 million incident electrons (see Figure 6 and Figure 7). To reduce the value of asymmetry uncertainty, another simulation was run with 10 million incident electrons. Because of limited computational resources, only the 100% target polarization was explored in this larger simulation to establish an upper limit on the value of asymmetry, since asymmetry is expected to get smaller in proportion to the decrease in target polarization.

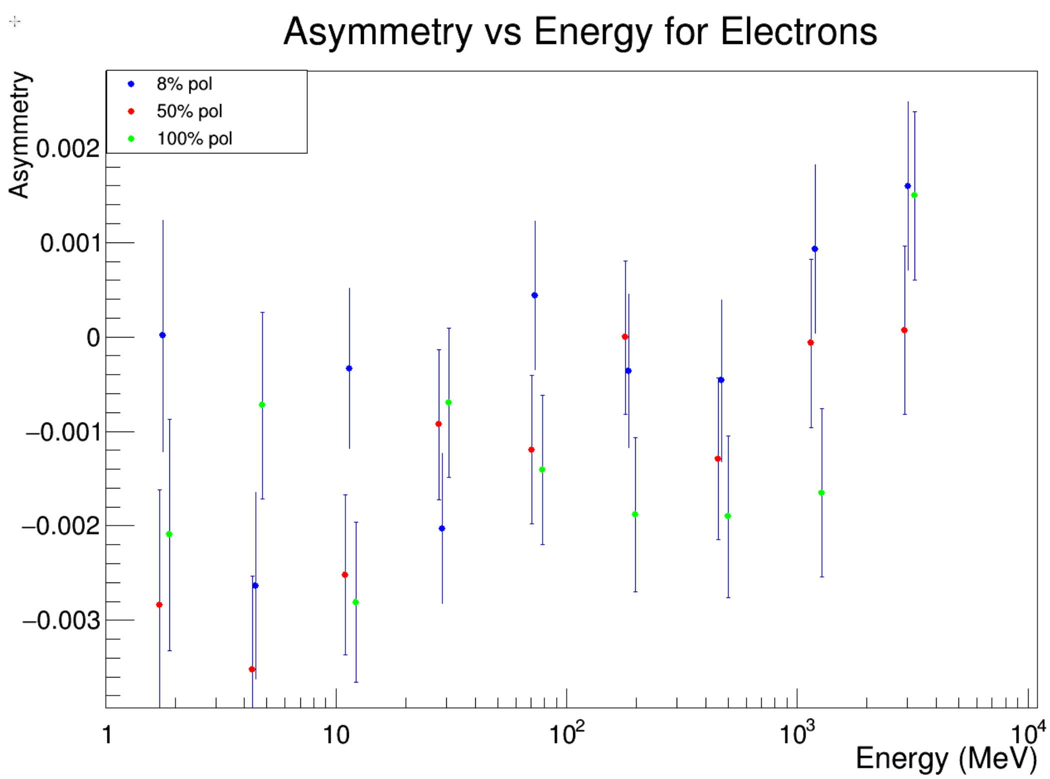

Figure 6: Asymmetry vs energy for electrons, three different target polarizations

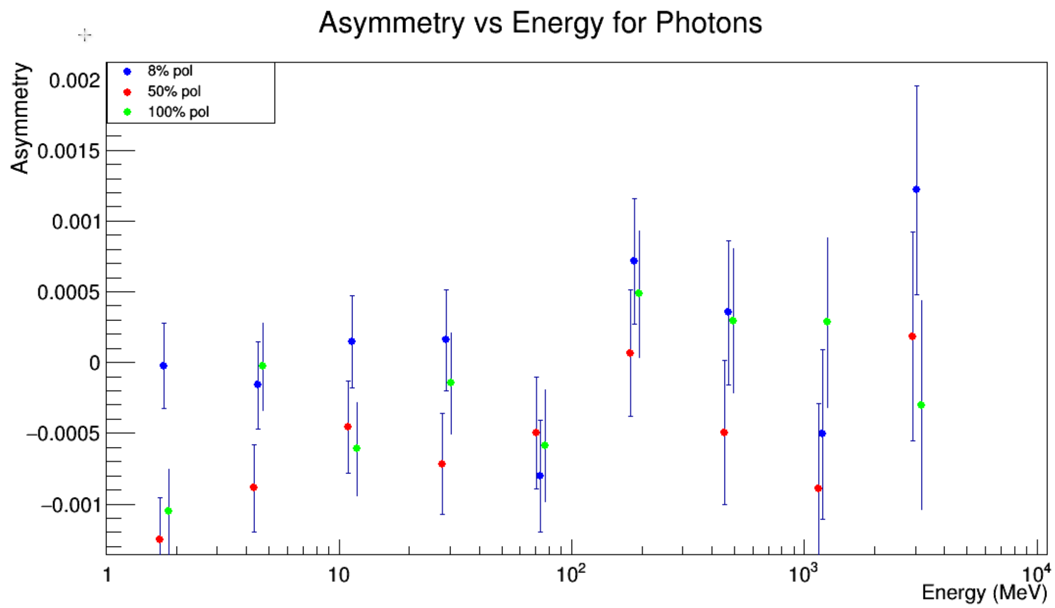

Figure 7: Asymmetry vs energy for photons, three different target polarizations

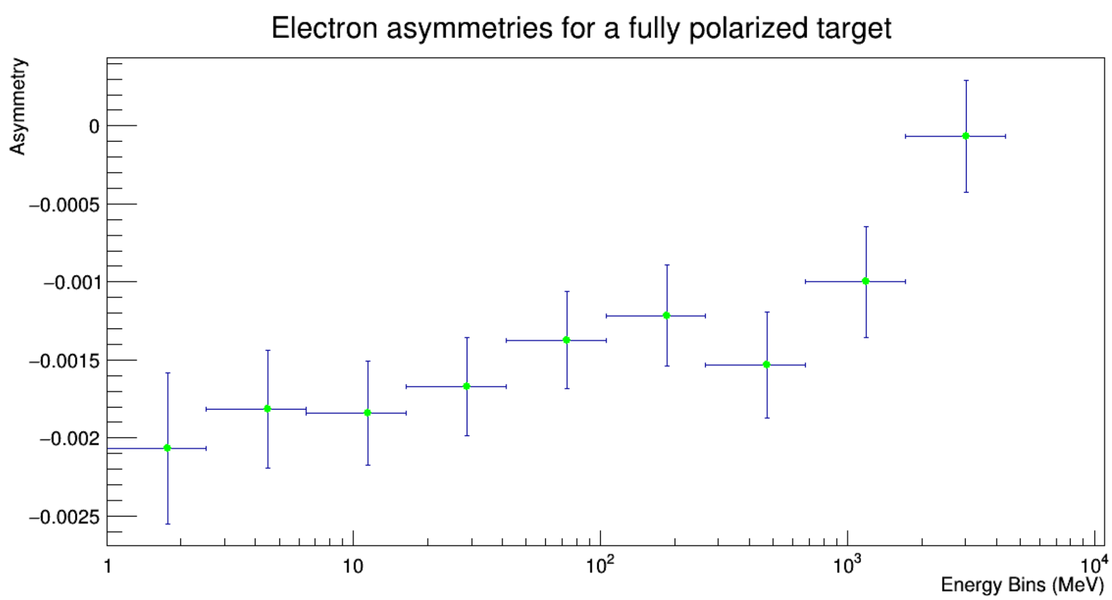

Figure 8: Asymmetry results for electrons from a larger simulation with 10 million incident electrons, fully polarized target

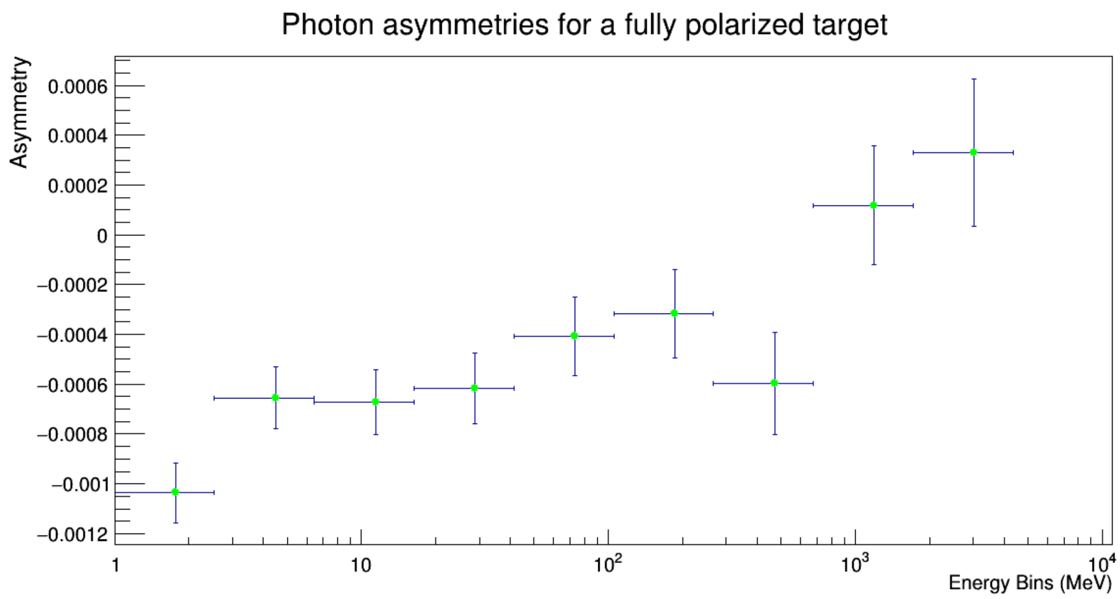

Figure 9: Asymmetry results for photons from a larger simulation with 10 million incident electrons, fully polarized target

Summary of Results

The first two simulation setups successfully demonstrated that Geant4 is able to simulate Moller scattering and bremsstrahlung when both the target and incident electrons are polarized. The simulation results follow the patterns of equations by William Henry [2] as well as Olsen and Maximon [3].

The third simulation setup involving a thicker target was observed to produce electromagnetic shower. As asymmetry plots indicate, the magnitude of asymmetry for a fully polarized target is capped at approximately 0.003. Since the decrease in target polarization is expected to cause a proportional decrease in the asymmetries, we have gained assurance that the asymmetry in materials with a more realistic polarization of about 8% is significantly lower. The MOLLER experiment requires that the background asymmetry contribution be at most 0.1. While proving this limit would require simulation of the entire apparatus, arriving at the asymmetries in the 0.001 range is a reassuring sign that the background symmetries will not be excessive and helps justify further efforts at more precise simulations of asymmetry contributions.

References

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[2] Henry, W. Precision Moller polarimetry and applications at Jefferson Laboratory. United States. https://doi.org/10.2172/1574104

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[4] Barday, R. *et al.* Compton transmission polarimeter for a very precise polarization measurement within a wide range of electron currents. *Journal of Physics: Conference Series* **298,** (2011).

[5] Zwart, T. *et al.* Transmission Polarimetry at MIT Bates. *AIP Conference Proceedings* **675,** (2003).