

# PHYSICS VALIDATION OF MONTE CARLO SIMULATIONS FOR DETECTOR BACKGROUNDS AT A MUON COLLIDER\*

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## Abstract

Muon colliders are considered to be an important future energy-frontier accelerator. A muon collider could be built as a circular accelerator into the TeV energy range as a result of the reduced synchrotron radiation expected from the larger rest mass of muons. For a muon collider with 750 GeV  $\mu^+$  and  $\mu^-$  with  $10^{12}$   $\mu$  per bunch, it can be expected that there would be  $4.3 \times 10^5$  muon decays per meter per beam. These decays will produce very energetic off-momentum electrons that can generate detector backgrounds that can affect the physics. The main backgrounds include electrons from muon decays, synchrotron radiation from the decay electrons, hadrons produced by photonuclear interactions, coherent and incoherent beam-beam pair-production, and Bethe-Heitler muon production. In this paper we will discuss simulation results in terms of observed physics processes in G4beamline.

## INTRODUCTION

This study is part of a continuing R&D effort to simulate beam-induced backgrounds at a muon collider. A muon collider, potentially located at Fermilab, would complement the LHC for particle physics research at the energy frontier. However, a number of technical challenges must be overcome before such a facility could be built. Unlike current (or past) colliders where stable particles are collided, muons decay with a mean rest-frame lifetime of 2.2  $\mu$ s. The resultant electrons (positrons) can hit the beampipe, collimating masks, or other components and electromagnetically shower.

These beam-induced backgrounds will be the main source of detector backgrounds at a muon collider. In order to maximize the veracity of our simulations, validation studies of the main physics processes contributing to the background including photonuclear interactions and showers and Bethe-Heitler muon production, were conducted in order to confirm that these processes are correctly implemented in the GEANT4 [1] overlay, G4beamline.

## G4beamline

G4beamline [2], specifically designed for simulating beamlines, is a single particle tracking and simulation program built on GEANT4. The main advantage of

G4beamline is that the simulation description is of the same order of complexity as the system that is itself being simulated. Thus, users without C++ coding experience can rapidly begin constructing simulations that meet their needs with built-in beamline elements.

G4beamline is available as a single executable for most modern computing platforms so that users do not need to build G4beamline, GEANT4, nor their associated libraries. Of course, users can always install secondary GEANT4 data files such as thermal neutron cross sections. Source files for G4beamline are also available for users who wish to add their own customized beamline elements, though this does require some C++ coding.

A G4beamline input file is a single ASCII file containing the geometric, material, and field parameters for the beamline elements. These inputs can also include variations to global simulation parameters if required.

## SIMULATION STUDIES

Beamline muon decays will produce electrons and those electrons will produce high-energy photons through bremsstrahlung. These particles will proceed to interact with collimating masks, magnet elements, and detector shielding to produce secondary electromagnetic showers. Studies of these electromagnetic showers will be discussed first.

Photonuclear neutron production will also be carefully examined as these neutrons will survive multiple beam crossings and will contribute heavily to the background in hadronic calorimeters. The simulation of neutron-absorbing materials, such as borated polyethylene will be considered. Finally, photonuclear pair production of muons (Bethe-Heitler production) is discussed.

For these physics validation studies, single particle beams at a single energy with no transverse momentum are generated incident on solid cylinders of material (e.g. tungsten and iron) with no magnetic or electric fields present. The G4beamline simulation results are compared with calculated theoretical results [3, 4] as a check of basic physics processes. This work therefore contributes to G4beamline validation documentation.

## Electromagnetic Showers

In the current design for a muon collider, a series of tungsten collimating masks are placed between magnet elements to strip off the beam halo. Tungsten has a radiation length of 3.5 mm. Initial simulations were for electron beams incident on a tungsten cylinder with 150

\*Work supported by DOE STTR Grant DE-SC00005447.

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mm radius and 351 mm thickness to determine the shower profile. While such thicknesses are not to be expected in collimating masks, it is possible to encounter comparable depths within the tungsten cone near the interaction region in the detector.

The vast majority of secondary particles can be grouped into four classes: gamma rays, electrons, positrons, and neutrons. Electron and positron fluence peaks near 10 radiation lengths while the gamma fluence peaks near 11 radiation lengths as expected due to bremsstrahlung. As shown in Figure 1, the neutron fluence peak occurs around 12 radiation lengths for 25 GeV incident electrons and increases to 17 radiation lengths for 750 GeV incident electrons.

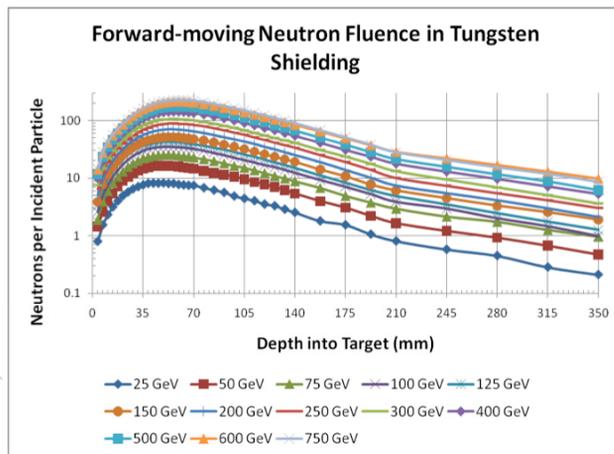


Figure 1: Normalized forward-moving neutron fluences for electron beam energies following the boosted Michel distribution from [5].

### Neutron Absorption

The standard method to absorb neutrons is to use borated polyethylene (BPE). The polyethylene  $((C_2H_2)_n)$  slows high-energy neutrons into the thermal region so that the boron can capture them. Boron has two stable isotopes,  $^{10}B$  and  $^{11}B$ , whose abundances are 19.9% and 80.1%, respectively, but only  $^{10}B$  is an efficient neutron absorber. To test neutron absorption, a series of simulations were done. The first set of simulations were electron beams incident on a 36-mm thick tungsten disc used as a spallation source with a cylinder of borated polyethylene (either 5% or 30% boron) immediately behind it. The BPE was created in G4beamline as a mixture of polyethylene and naturally-occurring boron rather than  $^{10}B$ -enriched boron. These simulation runs showed that the boron concentration in the mixture made no difference.

This led to an examination of the boron isotopic cross sections within the GEANT4 data files themselves. GEANT4 isotopic data nominally comes from the National Nuclear Data Center (NNDC), but a comparison of the GEANT4 data files with NNDC plots showed a number of major differences. For elastic scattering cross sections at

low energies ( $<0.1$  eV), GEANT4 assumes a flat cross section for both  $^{10}B$  and  $^{11}B$ ; whereas the cross sections exponentially increase at lower energies for both. For inelastic scattering, GEANT4 shows  $^{11}B$  to have a higher cross section than  $^{10}B$  above 10 MeV, as seen in Figure 2. This directly contradicts NNDC data which shows the cross section of  $^{10}B$  to be always above that of  $^{11}B$  and that the difference between cross sections should be increasing above 10 MeV, as seen in Figure 3.

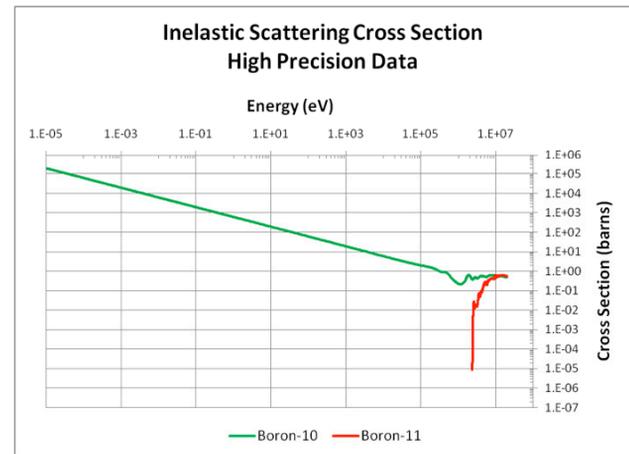


Figure 2: Inelastic neutron scattering cross sections for  $^{10}B$  and  $^{11}B$  from G4NDL (version 3.14) [1].

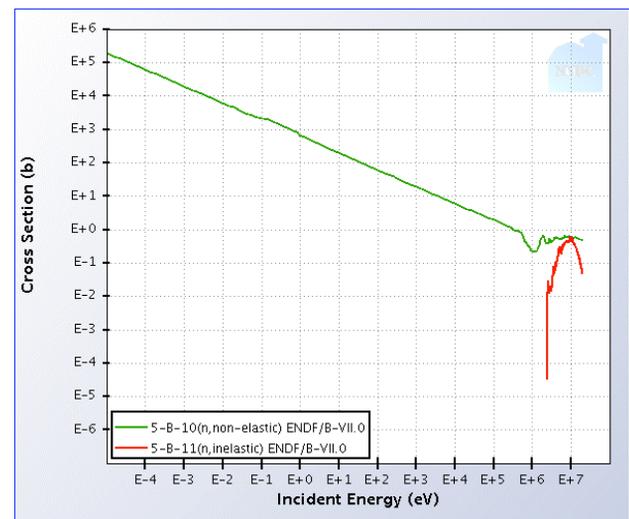


Figure 3: Inelastic neutron scattering cross sections for  $^{10}B$  and  $^{11}B$  [6].

There also appears to be a systematic issue in GEANT4 where  $^{10}B$  neutron capture,



is not properly implemented. Studies of this process in G4beamline are ongoing.

### Bethe-Heitler Muon Production

Following [3, 4], the cross section for Bethe-Heitler muon pair production on thin targets as a result of incident photons can be calculated by

$$\sigma = \frac{28}{9} Z^2 \alpha r_\mu^2 \left( \ln \left( \frac{2\hbar\omega}{m_\mu c^2} \right) - \frac{109}{42} \right) \quad (2)$$

where  $Z$  is the atomic number,  $\alpha$  is the fine structure constant,  $r_\mu$  is the classical muon radius,  $m_\mu$  is the mass of the muon, and  $\hbar\omega$  is the energy of the photon.

As a consistency check, we used this calculation for photons incident on a thin iron target. Since there will be a significant amount of iron in the beamline, Bethe-Heitler muons may contribute to detector backgrounds; however these muon pairs would not originate from the interaction region.

G4beamline 2.08 (the current version) can handle Bethe-Heitler muon production by activating the “gammaToMuPair” physics process. Older versions of G4beamline do not have this capability.

G4beamline shows a consistent deficit in Bethe-Heitler muon pairs produced when compared to theoretical calculations as shown in Figure 4.

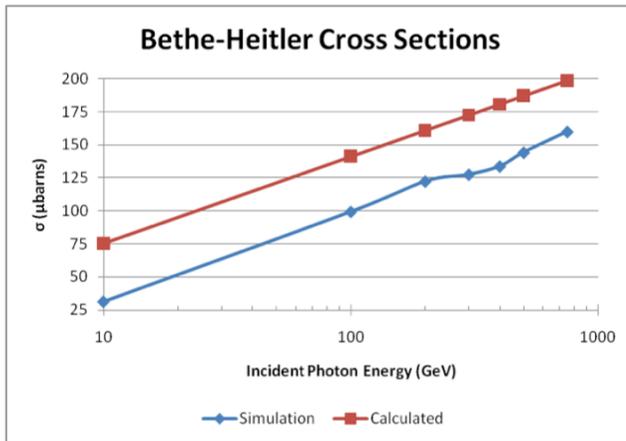


Figure 4: Bethe-Heitler cross sections for various photon energies incident on a thin iron target.

### CONCLUSION

Initial validation studies of a few muon collider physics background processes using G4beamline have been undertaken and results presented. Further studies are needed to correctly implement neutron capture by  $^{10}\text{B}$  and to understand the deficiency of Bethe-Heitler muon pairs produced in the G4beamline simulation. These studies are ongoing and future results will be reflected in updated releases of G4beamline.

### ACKNOWLEDGMENTS

This work is supported in part by DOE STTR Grant DE-SC00005447.

The authors would like to thank Dr. Sergey Uzunyan for his invaluable assistance (and patience) while working with the Northern Illinois Center for Accelerator and Detector Development (NICADD) computing cluster located at Northern Illinois University.

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