Understanding the Higgs boson with the Large Hadron Electron Collider

Jonathan Esteves

School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa.

E-mail: `jonathan.esteves@students.wits.ac.za`

Abstract. The Large Hadron Electron Collider (LHeC) at the European Laboratory, CERN, is expected to collide electrons and protons at high energy. Studies pertaining to the feasibility of observing the Higgs boson in this environment were reported in the Conceptual Design Report. Here the effect of decreasing the electron energy in an ep collision to find the optimal, economic electron energy for the study of the Higgs boson in the future LHeC is studied. Two production mechanisms are addressed: a Higgs boson production process in an ep collision, and a background process. The electron energy was varied between 10 GeV and 100 GeV in increments of 10 GeV. The results obtained in this study have shown that using an electron energies between 40 GeV and 60 GeV would be sufficient to measure the properties of the Higgs boson without compromising on the validity of obtained results.

1. Introduction and Theory

Peter Higgs proposed a mechanism that allowed for the existence of a fundamental particle, the higgs boson, almost half a century (48 years) before its discovery at CERN's LHC (Large Hadron Collider), in Switzerland on July 4th 2012 [1][2].

On October 8th 2013, the higgs boson discovery won Francois Englert and Peter Higgs the Nobel prize in physics, and resulted in: better understanding the origin of mass, confirmation of theoretical assumptions made with respect to the Standard Model, validation of theory related to electroweak forces and supersymmetry, and lastly it opens a new sector to study. The higgs production process has not yet been studied to its potential, and fortunately requires a relatively cost-effective, accelerator complex.

The current electron energy estimatation of 60 GeV is challeneged by observing the effect a decrease of electron energy has on the production of the higgs boson, in an electron-proton collision. CERN, a European Laboratory, are planning on constructing the LHeC (Large Hadron Electron Collider) such that accelerated electrons from the LHeC can collide with accelerated protons from the LHC [3]. Studies pertaining to the feasibility of observing the higgs boson in this environment, has been conducted by generating Monte Carlo events (50 000 events were generated) for two processes at different electron energies, differing by 10 GeV in a [10, 100] GeV interval.

Signal, the first process studied, is described by an electron-proton collision resulting in an electron neutrino, a higgs boson, and a jet. Figure 1 depicts the most probable, lowest-order

Feynman diagrams for single higgs production in an electron -proton collision [4]. The background process is described by an electron-proton collision resulting in an electron neutrino, bottom quark, bottom anti-quark and a jet. Figure 2 depict four of the lowest-order Feynman diagrams for the background collisions considered [4].
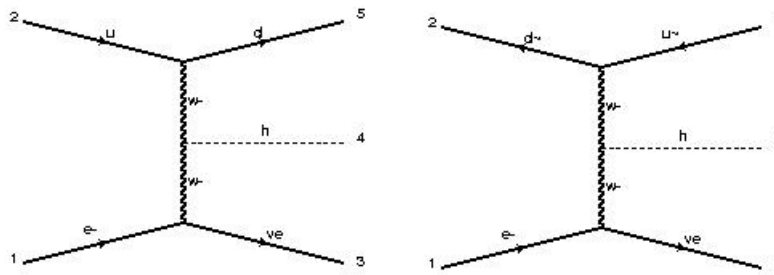

Figure 1. Two lowest-order Feynman diagrams for single higgs production in an electron - proton collision
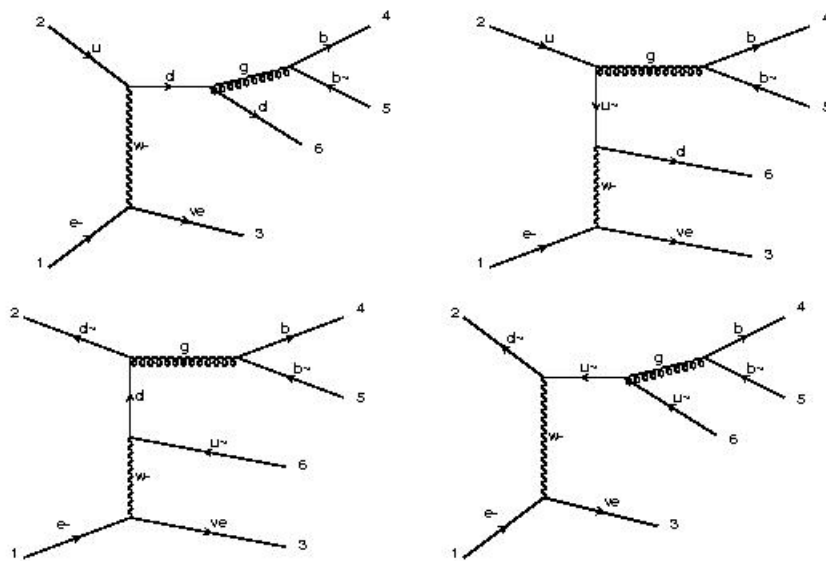

Figure 2. Four lowest-order Feynman diagrams of background collisions considered

In the standard model, gauge bosons mediate the forces and are associated with the $SU(3)_{colour}$ x $SU(2)_L$ x $SU(1)_Y$ group symmetries. The gluonic force of the strong interactions is described by the $SU(3)_{colour}$ factor whilst the unified electroweak interactions are described by the $SU(2)_L$ x $SU(1)_Y$ factors [5].

The invariance of the $SU(2)_L$ x $SU(1)_Y$ factors are broken down to the subgroup denoted by $U(1)_{EM}$ (the unbroken gauge invariance of electromagnetism subgroup). This results in four gauge bosons namely W^-, W^+, Z and the γ (photon) [5][6].

This symmetry is not necessarily broken by explicit interaction of the subatomic particles, but rather they are broken by the asymmetry of the state of lowest energy. In quantum field theory, the framework of spontaneous symmetry breaking and the symmetry of the state of lowest energy is known as a vacuum [6].

Each time a spontaneously broken direction (which gives rise to the Goldstone boson) corresponds to a gauge symmetry, the associated Goldstone boson and a massless gauge boson combine to form a massive gauge boson. This is known as the higgs mechanism [6]. This is the same mechanism that was proposed by Peter Higgs in the 1960's, which hypothesizes that there must exist some sort of 'lattice' that fills the universe. This lattice is formally known as the Higgs field [7].

The Higgs field is defined as; "hypothetical physical field that endows elementary particles with mass and that is mediated by the Higgs boson". There are many analogies for the Higgs field but the most popular is of a famous person walking into a room that is relatively densely occupied with people. As the famous person enters the room, the people closest to the entrance are drawn to him/her. The famous person attracts people that are close by as he/she moves through the room. The clustering at each of the famous person's steps can be seen as an increase in resistance to movement, i.e. the famous person has gained mass. If a normal (non-famous) person was to enter the room, no one would be drawn to him/her and they would not have gained any mass. In this same respect, not all particles affect the field (they are massless). A particle with mass would experience greater 'resistance' to change in the presence of the Higgs field and would require energy to commence movement once it has been stopped [7].

One of the optimal conditions for the study of the Higgs boson is the minimisation of background detected in the same region of the detector as signal detection. This conceptual report studies the effect on the following predicted properties pertaining to the processes under consideration: cross section (measure of area in collision process), rapidity (measure of rate of motion in the induced electromagnetic field), transverse momentum (momentum measurement along beam axis), distance in the rapidity-phi plane (distance between particles of interest) and invariant mass (mass measurement in an invariant basis). Studying these predicted properties will allow for further insight into the processes system behaviour, as function of electron energy.

2. Results

When generating data for two electron - proton collision processes (constant proton energy of 7000 GeV and varied electron energy), a total of 300 kinematic distributions were obtained. This data was processed and the electron dependence of the average; cross section, rapidity, transverse momentum, distance in the (rapidity, phi) plane and invariant mass, is illustrated in figures 3 to 11.
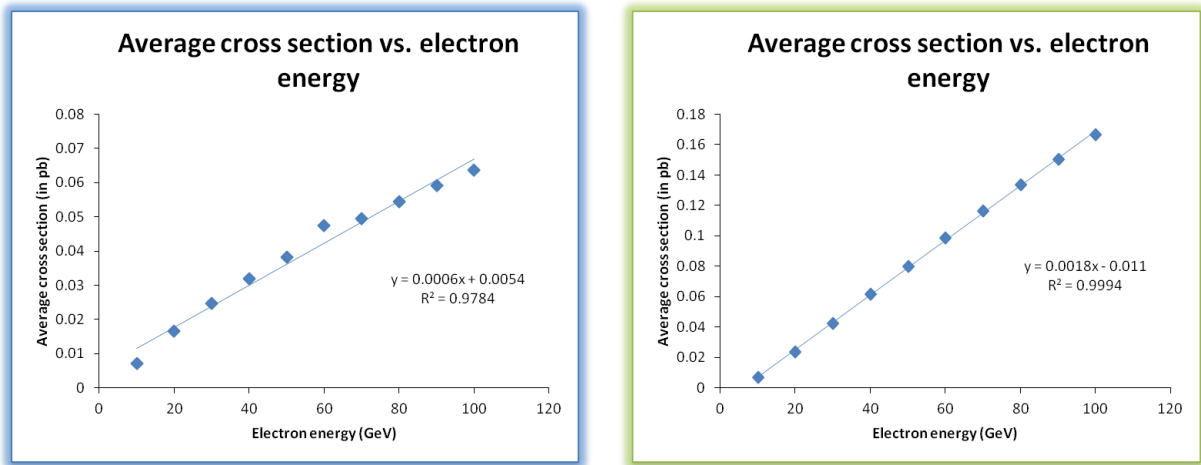
Figure 3. The average cross section as a function of electron energy for the Higgs boson production process and the background process, left and right respectively.
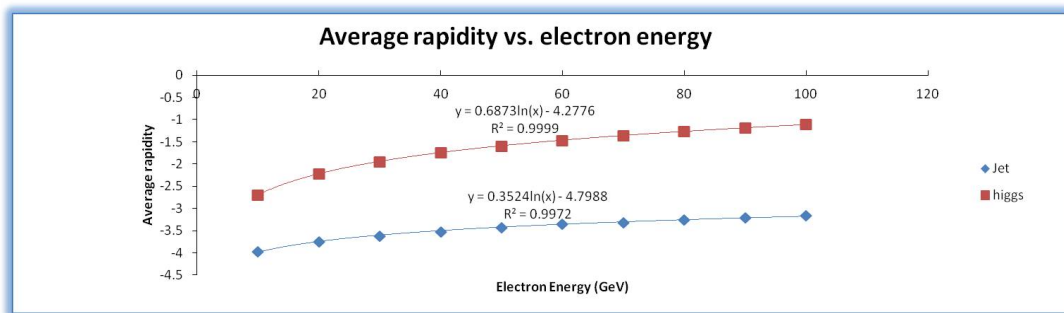

Figure 4. The average rapidity as a function of electron energy for the Higgs boson production process.
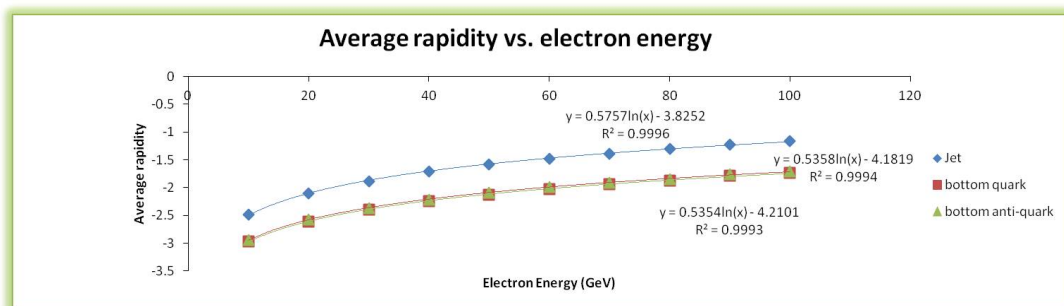

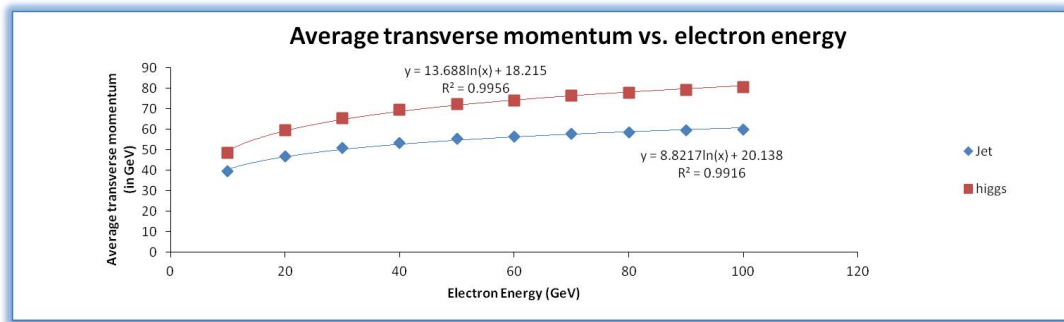**Figure 5.** The average rapidity as a function of electron energy for the background process.

Figure 6. The average transverse momentum as a function of electron energy for the Higgs boson production process.
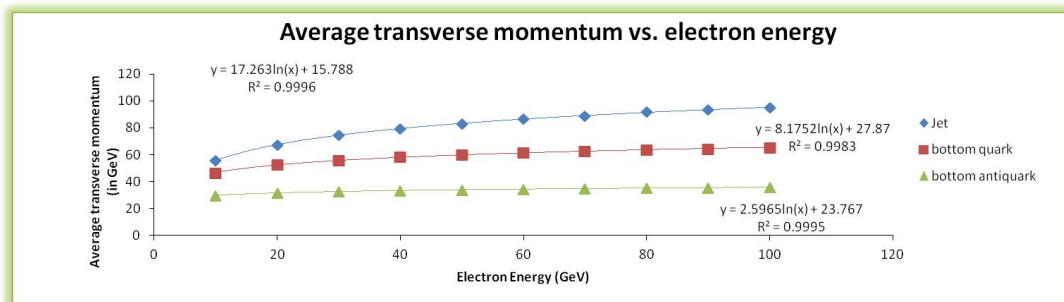

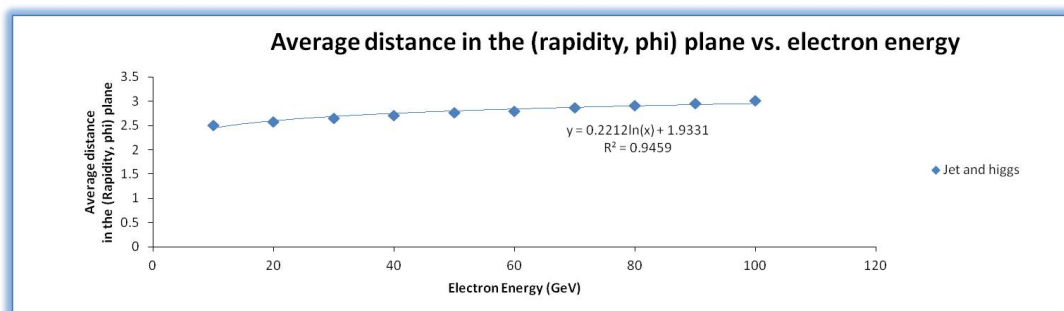**Figure 7.** The average transverse momentum as a function of electron energy for the background process.

Figure 8. The average distance in the (rapidity, phi) plane as a function of electron energy for the Higgs boson production process.
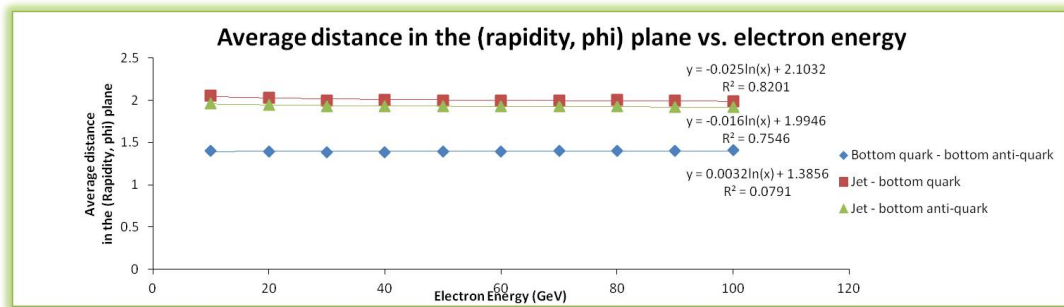
Figure 9. The average distance in the (rapidity, phi) plane as a function of electron energy for the background process.
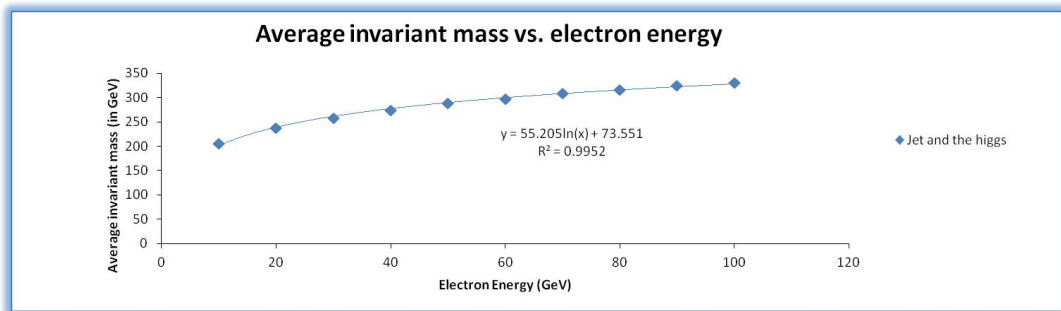

Figure 10. The average invariant mass as a function of electron energy for the Higgs boson production process.
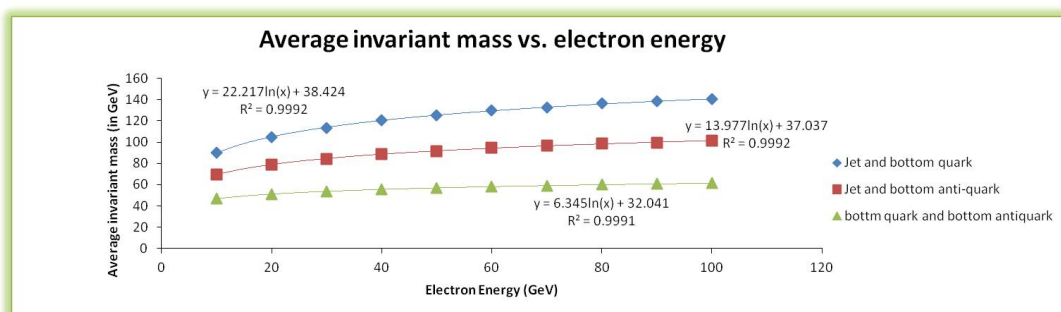

Figure 11. The average invariant mass as a function of electron energy for the background process.

3. Discussion and Conclusion

The relationship between cross section and electron energy, in both signal and background, is best described by linear growth [refer to figure 3]. The physical interpretation of this is; there is more energy and therefore more particle taking place in the collision, i.e. a larger cross section

is obtained with an increase in electron energy. A difference in gradient is noted between signal and background, depicting characteristic behaviour of the two systems. Studying the rapidity to electron dependence reveals that as one decreases the electron energy, the Higgs rapidity decreases (becoming more comparable to the rapidity of the jet in background) [refer to figures 4 and 5]. The Higgs rapidity is expected to be indistinguishable from the background rapidity for electron beam energies lower than 40 GeV. This is physically justified by the characteristic rapidity properties of the Higgs boson production process; the jet in the Higgs process has lower rapidity than that of the higgs boson whilst in background; the scattered quarks have a lower rapidity than the jet. The Higgs rapidity is greater than that of the jet in background, however the Higgs system is camouflaged by background as a lower electron beam energy limit is taken. Rapidity considerations has resulted in the placement of a lower bound on electron beam energy, 40 GeV. Considerations of transverse momentum, distance in the (rapidity, phi) plane and invariant mass revealed weak electron beam energy dependence [refer to figures 6, 7, 8, 9, 10 and 11].

Results have shown that using an electron energy between 40 GeV and 60 GeV would be sufficient to measure properties of the Higgs boson, without compromising on the validity of obtained results. This conclusion is founded mainly on rapidity to electron dependence of the two considered processes in an electron-proton collision.

References
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