Searching for BSM physics in Higgs to WW coupling with e^+e^- collisions

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Abstract. The study of Higgs production in e^+e^- collisions presents us with an avenue for studying Higgs to WW coupling in the t-channel. Our understanding of the tensor structure of the Higgs boson is furthered by learning the phenomenology of how it couples to the WW pair in these reactions. This can be done by applying effective coupling strength constants to an effective Lagrangian as beyond standard model (BSM) terms and performing Monte Carlo studies with these terms present. The investigation includes a two dimensional analysis of the polar angle and the Higgs boson momentum, such that the correlation between these variables can lead to enhanced sensitivity to new dynamics. We also present an energy scan of cross sections for the processes. A likelihood analysis is performed to show that an electron positron collider operating with an integrated luminosity of 5fb^{-1} would be enough to fully realise an admixture of BSM effects.

1. Introduction
With the July 2012 discovery of what appears to be the Higgs boson [1, 2], we now have a great opportunity to further our knowledge of the particle. We do know that the particle which was discovered resembles the Higgs boson described by the standard model (SM), but a large amount of research is being conducted with the goal of searching for signatures associated with it which can only be described by physics beyond the standard model (BSM).

The Large Hadron Collider (LHC) is the only active provider of data and information pertaining to Higgs production, but we cannot expect it to provide an answer to all of the questions which the scientific community can pose about the Higgs boson. This is why a thorough study of e^+e^- collisions is vital if we wish to find BSM physics intrinsic to Higgs production.

Since e^+e^- collisions are seldom used to study Higgs production in general, it is necessary to first try and evaluate what BSM effects such a collider can produce. In this study, we do this by computationally modelling the channels in e^+e^- which are involved in Higgs production, namely the t-channel and s-channel, incorporated with BSM parameters. Once the hypotheses are created, a likelihood analysis is used to determine the luminosity which an e^+e^- collider should have in order to comfortably detect BSM effects experimentally.

2. Problem Formulation
Electroweak symmetry breaking (EWSB) in the SM is transmitted from the scalar sector to the gauge sector by the use of gauge boson-scalar couplings. The precise couplings of the SM Higgs

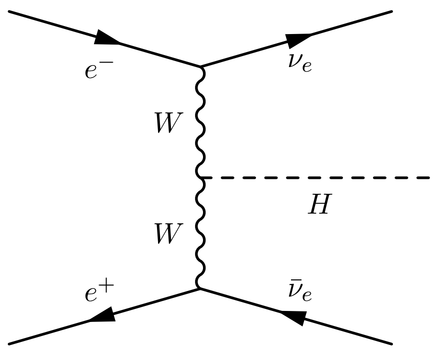

Figure 1. The t-channel process of interest. This is one of three Feynman diagrams (not including diagrams with a Z boson decay in the final state) associated with the t-channel. The vertex in the center of the diagram is where the Higgs to WW coupling is evident. Precise measurements of this vertex are imperative in this study.

to the massive electroweak gauge bosons, $W^\pm$ and Z, come from

$$\mathcal{L}_{int} = -gM_W \left(W_\mu W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu \right) H. \tag{1}$$

The constants g, M_W and θ_W are all accurately measured, implying that this vertex is fully determined in the SM. In order to fully understand EWSB, independent measurements of these vertices are required.

The virtue of e^+e^- collisions is that they provide a channel of Higgs production which allows for the study of Higgs to WW coupling, namely the t-channel, of which a Feynman diagram associated with the process is shown in figure 1. A good understanding of this coupling will indicate whether or not there is any BSM signature associated with the Higgs boson.

2.1. Background Theory

The $H(k) - W^+_\mu(p) - W^-_\nu(q)$ vertex can be parametrised as [3]:

$$i\Gamma^{\mu\nu}(p,q)\epsilon_\mu(p)\epsilon^*_\nu(q), \tag{2}$$

where deviations from the SM form of $\Gamma^{\rm SM}_{\mu\nu}(p,q) = -gM_W g_{\mu\nu}$ would indicate the presence of BSM physics. These BSM deviations can be specified in terms of two effective strength constants, λ and λ', by the equation [3]

$$\Gamma^{\rm BSM}_{\mu\nu}(p,q) = \frac{g}{M_W}[\lambda(p.qg_{\mu\nu} - p_\nu q_\mu) + \lambda'\epsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma]. \tag{3}$$

The constants λ and λ' are the effective strengths for the anomalous CP-conserving and CP-violating operators respectively. The full vertex is then determined by the sum of these two operators,

$$\Gamma_{\mu\nu} = \Gamma^{\rm SM}_{\mu\nu} + \Gamma^{\rm BSM}_{\mu\nu}. \tag{4}$$

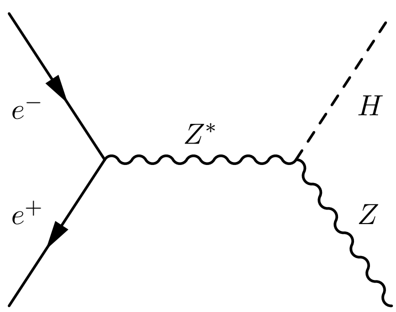

Figure 2. One of the Feynman diagrams associated with the s-channel. This process is also known as *Higgs-strahlung* since it can be likened to the electronic process of bremsstrahlung. Although we are not directly studying this process, its effects must still be accounted for.

A precise identification of the non-vanishing nature of λ and λ' can tell us whether the modification in HWW-couplings are CP-conserving or CP-violating in nature and, if both are present, what their relative proportion is.

2.2. Computational Methodology

`MadGraph` [4] was used to do the Monte Carlo simulations, where the necessary rules were generated by a Mathematica package called `FeynRules`.

In performing the simulations, the expressions for the BSM parameters λ and λ' are determined from

$$\lambda = -(a+ic)\frac{4M_W^2}{\Lambda_1^2} \quad \text{and} \quad \lambda' = -i(b+id)\frac{8M_W^2}{\Lambda_2^2}, \tag{5}$$

respectively. The parameters a, b, c, d, Λ_1, and Λ_2 are real values specified in generating the Monte Carlo data. Values of λ and λ' were arbitrarily chosen to be either 1 or -1 in this study, allowing for four different hypotheses to be studied. This required that Λ_1 and Λ_2 be approximately 160 GeV and 226 GeV respectively, while the different hypotheses were built by varying the values of the parameters a, b, c, and d.

The process $e^+e^- \to H\nu\bar{\nu}$ occurs through two channels. The s-channel features the production of the neutrinos through the decay of a Z boson, given by

$$e^+ + e^- \to H + Z \to H + \nu + \bar{\nu}. \tag{6}$$

The t-channel features the production of the Higgs and neutrino pair through vector boson fusion given as

$$e^+ + e^- \to H + \nu_e + \bar{\nu}_e \setminus Z. \tag{7}$$

Note that the '$\setminus Z$' symbol means that processes contributing to the final state resulting from the decay of the Z boson are excluded.

The t-channel is of primary concern here. It contains information pertaining to the Higgs W^+W^- coupling and has not, in general, been studied as extensively as the s-channel. Even though we focus primarily on the t-channel, the s-channel effects must still be incorporated. To achieve this, the Monte Carlo simulations were run with both the t-channel and s-channel active. The major s-channel contributions were then cut from the distributions.

2.3. Likelihood Formalism

The test statistic used to distinguish hypotheses is incorporated as the logarithm of a profile likelihood ratio.

A profile likelihood ratio is defined as the ratio of two likelihood functions regarding two differing hypotheses. Due to the discrete nature of the probabilities in this analysis, the likelihood functions are created as the product of binned Poisson probabilities over all channels and bins [1]. For Monte Carlo simulation studies, the likelihoods can be parametrised by the probability density function, P_i, of hypothesis i and a set of pseudo-data points, D_j, according to the hypothesis j. The likelihood function is then expressed as $L(P_i|D_j)$.

The profile likelihood ratio, λ_{ij}, is then constructed for two different hypotheses i and j as

$$\lambda_{ij} = \frac{L(P_i|D_i)}{L(P_j|D_i)}, \tag{8}$$

or alternatively as its reciprocal, depending on the analysis required.

As stated earlier, the test statistic used is actually the logarithm of the profile likelihood ratio. This quantity for the test statistic, q_{ij}, is then expressed as

$$q_{ij} = \log\lambda_{ij} = \log\frac{L(P_i|D_i)}{L(P_j|D_i)}. \tag{9}$$

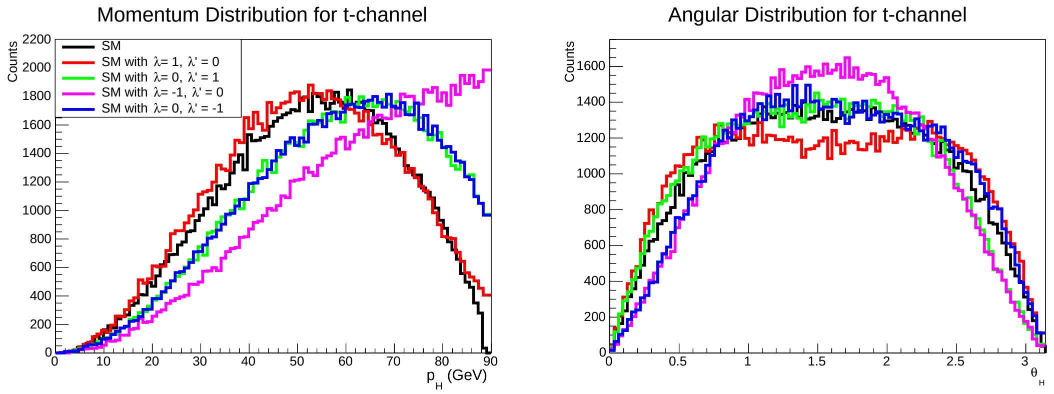

Figure 3. Plots of the Higgs particle properties at $\sqrt{s} = 250\text{GeV}$ for different BSM models and the SM. Left: Higgs momentum (p_H) distribution from the t-channel which features a wide range of momentum values indicating that exclusions near the s-channel peak allow for exploration of the t-channel and variations from the SM. Right: The θ_H distribution from the t-channel. The distribution is indeed affected by all of the BSM parameters.

In Monte Carlo studies, these test statistics emerge as binned peaks. These peaks are built by running pseudo-experiments, each of which compute a value for the test statistic based on a randomly generated set of pseudo-data. The number of pseudo-data points generated is fixed by the cross section of the event being studied.

The test statistics concerned in this analysis are always produced in pairs, in order to discriminate between the SM hypotheses and a BSM hypothesis. This pair of test statistics is represented as

$$q_1 = \log \frac{L(P_{SM}|D_{SM})}{L(P_{BSM}|D_{SM})} \quad \text{and} \quad q_2 = \log \frac{L(P_{SM}|D_{BSM})}{L(P_{BSM}|D_{BSM})}. \tag{10}$$

In this study the test statistic q_1 in equation 10 tends to have a more positive value due to its ordering, and we refer to it as the *upper* test statistic strictly for our purposes; while the opposite is true for q_2, which we will refer to as the *lower* test statistic.

After test statistics are created, an hypothesis can then be tested for rejection by finding the associated p-value which can be calculated from:

$$p = \int_m^\infty q_2 dq, \tag{11}$$

where the value m is the median of the upper test statistic q_1.

Knowing the p-value is of utmost importance, since its value is regarded as the percentage of confidence by which one can reject a certain hypothesis. This confidence can further be quantified by knowing the *significance* of the separation between the two test statistics. The median significance, Z_{med}, is defined as the number of standard deviations between the median of the lower test statistic and the left edge of the p-value area, that is, the median of the upper test statistic.

3. Results

The distributions shown in figures 3 and 4 are examples of the results of Monte Carlo simulations performed for determining the emerging Higgs particle momentum, p_H, and scattering angle,

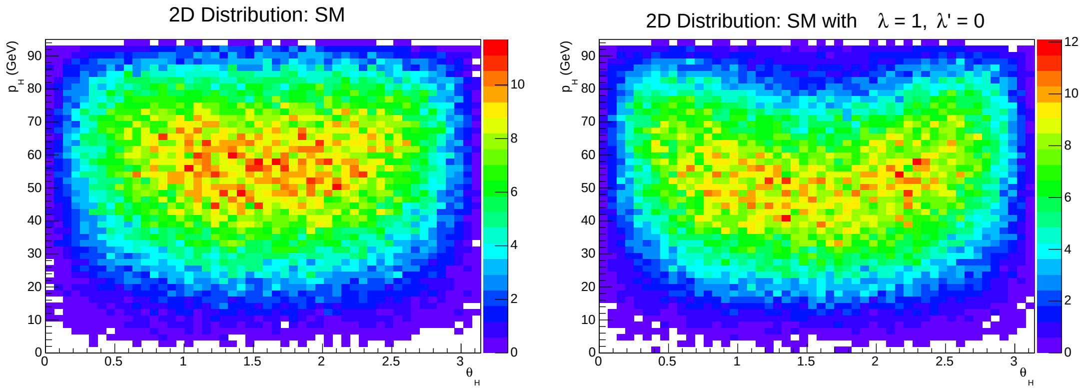

Figure 4. Two dimensional histograms showing the correlation of the t-channel Higgs momentum and θ_H at $\sqrt{s} = 250$GeV. The z-axis is an indication of the frequency of events and is in arbitrary units.

θ_H, respectively for the t-channel. These were taken from simulations with a specified centre of mass energy (CME) of $\sqrt{s} = 250$GeV, although various energies were analysed.

As stated earlier, both the s-channel and the t-channel must be considered, but we are only interested in studying the HWW coupling inherent in the t-channel. This was done by excluding a two sigma window on either side of the s-channel momentum peak in the t-channel. Doing this ensures that 95% of the events within the range are cut out, however there will be a 5% migration of some events that were within the window, being detected as having been from without.

The cross sections were scanned as functions of CME, as shown in figure 5, such that we could decouple the kinematics and CME from the total cross section of the processes. Such outputs would have to be modified by the cuts we imposed and other considerations. The cuts on the allowed momentum too will affect the cross section. The fraction of events that survive the cut, multiplied with the cross section signifies the cross section for the process. Finally, the Higgs to $b\bar{b}$ branching ratio of 57.7% must also be considered.

A likelihood analysis for each BSM hypothesis was performed for integrated luminosity values of 1fb^{-1}, 5fb^{-1}, and 10fb^{-1}. The number of pesudo-data points in each analysis was determined from the effective cross section of the SM. The likelihood analysis was performed using a total number of 100,000 pseudo-experiments for each test statistic. The two dimensional distributions, examples of which are shown in figure 4, were also included in the likelihood analysis to demonstrate the effect of the correlation between the two variables, p_H and θ_H. The median significance values were plotted as a function of the CME and are shown in figure 6 for the variation of λ'. A more detailed study and clearer results have been omitted but can be found in reference [5].

4. Conclusions

The results which were obtained from the likelihood analysis provide a good motivation for the role of an electron positron collider in understanding the BSM variations in the HWW coupling which was analysed. The median significance values of the two dimensional analyses were, in general, greater than those done for one dimensional analyses, implying a far greater confidence in rejecting certain hypotheses. An electron positron collider which produces collisions at an integrated luminosity of 5fb^{-1} would be an effective tool in studying e^+e^- collisions with regards to identifying BSM physics.

The correlation of the two dimensional distributions thus carries vital information about the dynamics of the processes which are studied in e^+e^- collisions. In addition to this, an energy scan of the cross sections is an effective tool in decoupling the kinematics from the total cross sections, as described above. It is also evident from the results tables that an increased integrated luminosity of the particle beams in e^+e^- colliders will, of course, have the effect of providing a better chance of rejecting BSM hypotheses and, therefore, furthering our understanding of the Higgs boson.

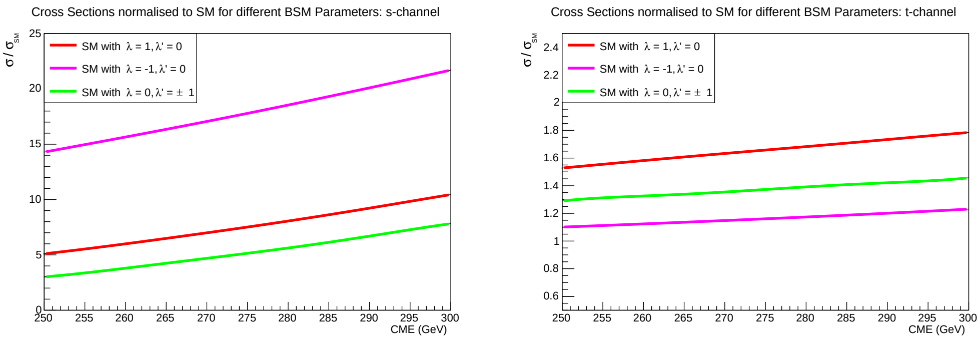

Figure 5. The cross sections for both the s-channel and t-channel produced by `MadGraph`, normalised to the SM cross section. These cross sections were further altered by the cuts made to the distributions. Note that the λ' parameter produced the result of identical cross sections for both $\lambda' = -1$ and $\lambda' = 1$.

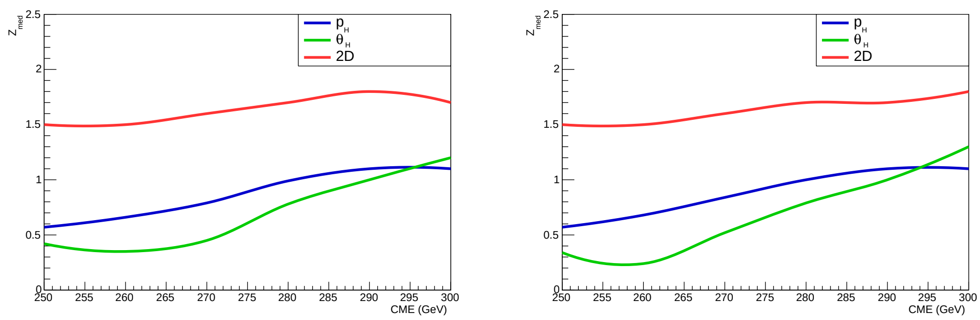

Figure 6. The median significance results from performing likelihood studies at 1fb^{-1} of pseudo data. This not only highlights the power of using two dimensional distributions, but also shows how the correlation of p_H and θ_H is useful in identifying or rejecting BSM hypotheses. These plots pertain to the $\lambda' = 1$ (left) and $\lambda' = -1$ (right) hypotheses.

Acknowledgments

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