Probing the Tri-Linear Higgs Self-Coupling

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Abstract

This paper explores my activities during the 2019 CCI program at Fermi National Accelerator Laboratory (Fermilab) and how they relate to one of the ongoing projects being worked on by many employees and physicists at the LPC (LHC Physics Center). This project uses CMS (Compact Muon Solenoid) simulation samples to study the feasibility of probing tri-linear Higgs-self coupling in a process where a single Higgs is produced in vector boson scattering associated with two additional protons, i.e. , where the W bosons decay leptonically and the Higgs decays to $b\bar{b}$. The leptons are required to have the same charge in order to suppress other standard model backgrounds. Any deviations of the Higgs-self coupling from the value predicted by the Standard Model (SM) could be indications of Beyond the Standard Model (BSM) physics. Given that I do not have a strong background in physics, Significant contributions by me are not to be expected in this study, especially in such a short amount of time (as these studies could take years). In this project, I have acquired knowledge of basic particle physics interactions, detector functionality, and how the research process is conducted here at Fermilab and at CERN. I have also gained technical expertise in using ROOT to perform data analysis using the LHC data collected by the CMS detector. This paper will show multiple distribution plots that I have created in ROOT to aid in the study of the tri-linear Higgs-self coupling $pp \rightarrow WWjjH$ process. These plots are all preliminary as the signal sample was only very recently produced (July 30th).

Introduction

Numerous studies and research are being conducted at the LPC at Fermilab and at CERN. Physicists are always trying to more precisely measure Standard Model (SM) particles and their interactions with other various SM particles. One such particle that is of priority is the Higgs boson, and the measuring of the tri-linear Higgs-self coupling which directly probes the Higgs potential. Precisely measuring the Higgs-self couplings will advance our understanding of Electro-Weak Symmetry Breaking (EWSB), therefore leading to a more complete picture in understanding our universe. We study the Higgs-self coupling via a process of $pp \to WWjjH$ where $WW \to l^{\pm}l^{\pm}\nu\nu$ and $H \to b\bar{b}$. As an intern entering this study with minimal background, I quickly acquired the necessary background knowledge of physics concepts of this study, as well as the techniques and methodologies for analyzing the LHC data collected by the CMS detector.

Progress

Approach

Relating to the broader study of the Higgs boson, the paper “Higgs Couplings without the Higgs” explains the general goal well, stating that the precise measurement of the Higgs boson couplings to other Standard Model (SM) particles is an unquestionable priority in the future of particle physics. These measurements are important probes for our understanding of a relatively poorly measured sector of the SM; at the same time, they offer a window into heavy dynamics Beyond the Standard Model (BSM). Indeed, it is well-known that the exchange of heavy states (with masses beyond the direct collider reach) leaves imprints in low-energy experiments, in a way that is systematically captured by an Effective Field Theory (EFT) [1]. The goals of the project for the summer have been to generate a set of CMS simulation samples of this signal process, and to start study on the distributions, to test the feasibility of the HwH sensitivities as suggested in the paper above. Below is the diagram for the specific process that is being used in this study, $pp \rightarrow WWjjH,\ \ WW \rightarrow\ \ l^{\pm}l^{\pm}vv,\ \ H \rightarrow b\bar{b}$.

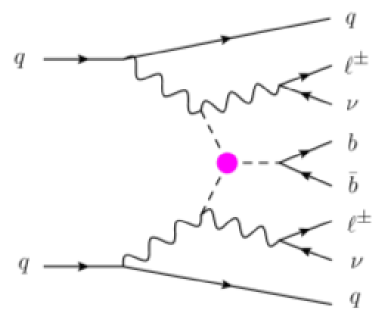

Figure 1: Feynman diagram of the desired signal process

This is a model of the process chosen for study due to it being a very clean channel, making it the obvious choice. The selection of same sign leptons also eliminates much of the backgrounds. Currently this process cannot be measured. To measure it, certain experimental modifications and parametrizations are being made. First, we must start with the following equation for the Higgs potential in the standard model.

$$V(H) = \frac{1}{2} m_H H^2 +\ \lambda_3 v H^3 +\ \frac{1}{4}\lambda_4 H^4 + O(H^5), \tag{1}$$

$$V^{SM}(\Phi) = -\mu^2(\Phi^{\dagger}\Phi) + \lambda(\Phi^{\dagger}\Phi)^2, \tag{2}$$

$$where\ \mu^2 = \frac{m_H^2}{2}\ and\ \lambda = \frac{m_H^2}{2v^2},\ \ m_H = 125\ GeV,\ v \simeq 246\ GeV.\ [2]$$

Through Electro-Weak Symmetry Breaking (EWSB) in equation (2), the mass of the Higgs is determined, and thus the standard model completely determines the Higgs self-coupling constant to be

$$\lambda_3^{SM} = \lambda_4^{SM} \simeq 0.13. [2]$$

In the case of the trilinear coupling and at the order we are considering, one-loop corrections for single Higgs processes, adding higher dimensional operators that only affect the Higgs self-couplings can directly be introduced via an anomalous coupling

$$\lambda_3 = \kappa_3 \lambda_3^{SM}. [2] \qquad (3)$$

From this modified coupling, the formula for the λ_3 dependence of a generic NLO observable $\Sigma_{\lambda_3}^{BSM}$can be written as

$$\Sigma_{\lambda_3}^{BSM} = Z_H^{BSM} \Sigma_{LO}(1 + \kappa_3 C_1 + \delta Z_H), \qquad (4)$$

$$Z_H^{BSM} = \frac{1}{1-(\kappa_3^2 - 1)\delta Z_H}\ ,\ \ \delta Z_H = -1.536\ \times\ 10^{-3}\ . [2]$$

In equation 4, C_1 is the process and kinematic dependent component, and Σ_{LO} is the leading order prediction value for the observable (in our case cross-section). Significant deviations in λ_3 due to the value (currently unknown) of anomalous coupling κ_3 can be an indication of a new discovery of BSM physics, traditionally deviations must be at or exceed $\pm 5\sigma$. The value of κ_3 will be found through observing its effects on the cross-section of the signal and finding which is the best fit with the data. The most optimistic experimental studies for HL-LHC suggest that it could be possible to exclude values in the range $\lambda_3 < -1.3\lambda_3^{SM}$ and $\lambda_3 > 8.7\lambda_3^{SM}$ via the $b\underline{b}\gamma\gamma$ signatures. Additional and complementary strategies for the determination of λ_3 are thus desirable at the moment [2]. This signal also has a very small cross section (50 for 3000 fb^{-1}) so signal over background optimization is crucial. Due to this, finding this signal will require High-Luminosity Large Hadron Collider (HL-LHC) Dataset.

Activities

After spending a large portion of the summer mastering the basics of data analysis using the ROOT framework and C++ programming language in anticipation for the generation of the signal samples as mentioned earlier in this report, I am now fully qualified to contribute to the first step of analysis after samples such as these are produced. This first step is to create preliminary plots in order to study the accuracy of the generated samples (i.e. make sure that they were generated properly with the correct signal and modifications). Below are some of the more important plots that I have created in order to verify the integrity of the sample.

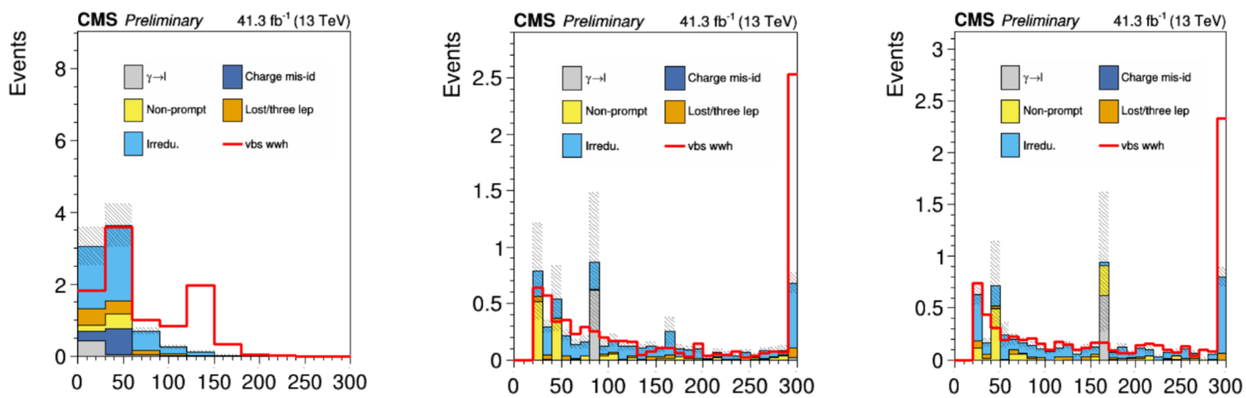

Figure 2: LEFT: Mass of $b\bar{b}$, CENTER: Pt of leading b jet, RIGHT: Pt of second position b jet.

Signal is represented by the legend label “vbs wwh”. The purpose of preliminary plots is to study the distributions in order to verify that the signal sample was simulated properly. The most notable observation that was made from this set of plots was about the mass of $b\bar{b}$, which seems to agree with the Feynman diagram of the signal process as there is a spike at the mass of the Higgs boson (125 GeV). The other two plots were created in order to explain why there are some events where $b\bar{b}$ does not equal the mass of the Higgs.

Future Work and Impact

After verifying the sample, the next step is to start analysis in preparation for the next dataset coming from the future HL-LHC. Given that the sample created was a private sample (not the official sample from the CMS collaboration), the project will likely be delayed again until an official sample for the signal is released, hence why a lot of the work done on this project is only preliminary. The ambitions of this project are that it will lead to a publication of new physics BSM, and thus a better understanding of our universe, such is the goal of all Physics Research. This new physics will be centered around the most unknown part of the SM, the Higgs boson.

Conclusions

In conclusion, progress has been made on this study, however it is still a very long way from reaching any sort of definite conclusion and possible publication. Even though we are still at the beginning stages, now that we have the signal sample generated, further progress is no longer halted. In addition, obtaining the skills necessary (plotting and physics) is crucial in order to further analyze and create distributions for this signal. If I were to be paired on this project in the future, I am confident I will be of much use and make an even bigger contribution.

References

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[3] Shah A. (2019), Status of Signal Sample Generation. Retrieved from https://docs.google.com/presentation/d/199hi9V7ibuSzYqfhaWqwf9Dete-PMKpKCWnZORGL_p8/edit#slide=id.g5d3b264d59_2_12.

Appendix

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