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Constraints on the Higgs boson decay width from off-shell production decay into Z-boson Pair in simulated data

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by

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Abstract

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The discovery of the Standard Model (SM) Higgs boson at the Large Hadron Collider (LHC) was a major achievement of the experimental particle physics community in the 21st century. Though a fair portion of the physics analysis focus has shifted to Supersymmetry (SUSY) physics, the direct search of SUSY models has yield null result so far. Meanwhile, the many properties of Higgs are still to be measured.

In this analysis, we present constraints on the decay width of Higgs boson, Γ_{H}, by using the on-shell and off-shell decay rates of Higgs to a pair of Z bosons and both Z's decay to a pair of electrons or muons. The result represent the expected constraints using the physics events and CMS experiment detector response simulated data via Monte Carlo methods (MC). The data and expected results correspond to run 2018 which has an integrated luminosity of $59.7\,\mathrm{fb}^{-1}$ at center-of-mass energy of 13 TeV.

Contents

Chapter 1

Introduction

In this chapter I present a brief introduction of the LHC physics and the physics behind the off-shell methods for constraining Higgs decay width.

1.1 Physics at LHC

After the discovery of Standard Model (SM) Higgs boson in 2012, the Large Hadron Collider (LHC) went through a series of upgrades during Long Shutdown 1 (2013-2015) and finally restarted with center-of-mass energy reaching 13 TeV. Though the last particle promised by the SM has been discovered, no Supersymmetry (SUSY) particle has been spotted so far.

The null results has not discouraged physicists from other attempts of probing the beyond the Standard Model (BSM) physics in other ways. Higgs boson has a special role in the process mainly due to the Higgs field which it originates from couples to massive particles and could be a window to probe BSM the physics, as discussed in Section 1.3.

The LHC has been operating at the same energy for the past 3 years (2016-2018) and each year the delivered luminosity as been ramping up.[**?**] In this analysis, we will be using simulation that corresponds to Run period 2018, which in turn corresponds to a $59.74\,\mathrm{fb}^{-1}$ luminosity for the Compact Muon Solenoid (CMS) detector.[**?**]

1.2 The CMS Detector

The CMS is one of the two general purpose detectors built around LHC (the other one is ATLAS). It is 'compact' only when comparing to the ATLAS detector and is in fact heavier than the latter. Though we are not using the data accumulated by the CMS detector, the simulated events are reconstructed based on the material and electronics responses of the real detector using the Geant4 package.[**?**]

The defining feature of the CMS detector is the solenoid (as in its name) around the beam line. This superconducting solenoid produces a 4 T magnetic field and is 12.5 m long free bore.[?] This feature allows the track of any charged particle (given the momentum is not ridiculously high) to be bent when penetrating the detector layers and leave behind a track which provides information regarding the particle's electric charge.

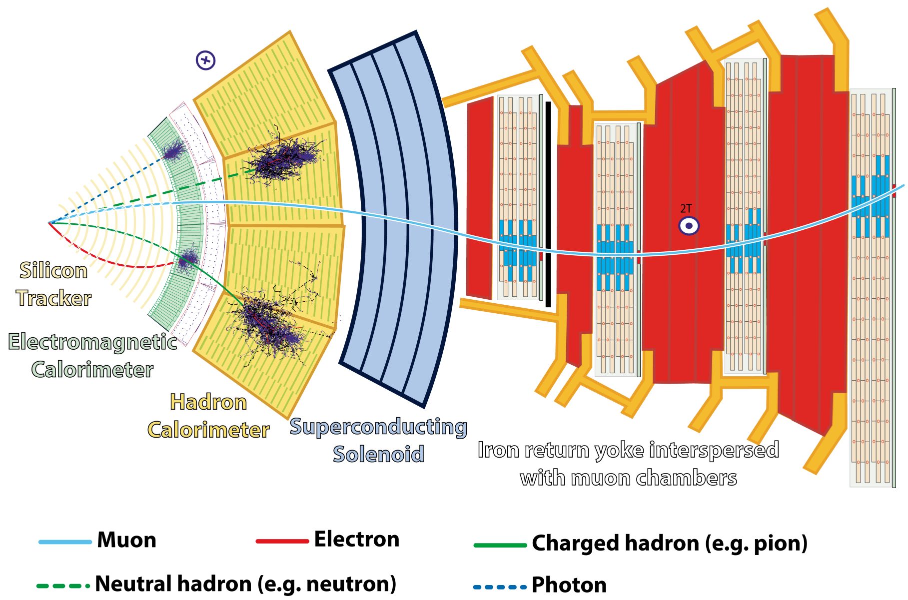

Figure 1.1: A section slice of the CMS detector where we can see how particles with different physical properties interact differently with the detector.

One important kind 'final-state' particles used in this thesis this charged lepton, which includes electrons and muons (half-life of tauon is too short); 'final-state' here means they are the end products of decay chain and interact with detector components directly. If we concentrate on the red and blue lines in 1.1, we can see that for the electrons (blue), they leave a few hits (4) that resemble a curved track within the Silicon Tracker layer and are stopped at the Electromagnetic Calorimeter (ECAL).

For the muons, they largely go through all the interior layers unhinged due to their high mass; pay close attention to the 'S'-shaped curve, this is due to the opposite magnetic field outside of the superconducting solenoid. Information regarding muons are largely and most reliably extracted from the muon chambers withing the iron return yoke. Notice how the muon chambers occupy more than half of the detector by size, such design allows the CMS detector to exceeds in muon measurements and is the primary reason for the overall design.

TODO: PF and anti-k algorithm in the context of this thesis

1.3 The Higgs boson and off-shell methods

[1]Caola F, Melnikov K. Constraining the Higgs boson width with ZZ production at the LHC. Phys Rev D 2013;88:054024. https://doi.org/10.1103/PhysRevD.88.054024.

The importance of a Beyond the Standard Model (BSM) physics is self-evident, though the SM is one of the most precise theory in physics we ever had, the model requires many 'inputs' from experiment for parametrization, and, it cannot account for phenomena such as neutrino oscillation with its original form. While the direct searches in the past few years have all yield null results, many indirect probing have been going as well.

As mentioned above, the Higgs boson has a special place as it can be seen as a 'bridge' between the SM and the BSM (in some models) as some SUSY particles can decay into it or it can decay into SUSY particles, or simply have a BSM production Feynman diagram that leads to more Higgs bosons than the SM would expect. In any of these cases, the basic properties of the SM Higgs boson remain important.

Many properties are well measured, such as it's mass and spin [**?**], others, however, have not entered the relm of 'precision' physics so far. One of them is the decay width of the Higgs boson, which is of course associated to the particle's half-life. The SM predicts that the Higgs boson to have a decay width of 4.1 MeV. The problem is that the energy resolution of the CMS detector, which is around $\mathcal{O}(1)$GeV for the di-photon or 4-leptons final states, is not even remotely small enough to check this prediction directly.

I will give a very brief account[?] for the proposed (and been completed in previous years' run) method that can constrain the Higgs decay width using events that fall into the off-shell tail.

When the Higgs boston decays to two vector bosons (VV), in the scope of this thesis, two Z bosons, either one of the vector bosons is off-shell, or the Higgs boson is off-shell, this is because $m_{\mathrm{H}} \approx 125\,\mathrm{GeV}$ is smaller than the mass of two W's($\approx 160\,\mathrm{GeV}$) or two Z's($\approx 182\,\mathrm{GeV}$). The Higgs boson decay branching ratio is coupled to the dauther particles' mass thus this cross section $\sigma_{\mathrm{H}\to\mathrm{VV}}$ is enhanced as the mass of Higgs boson gets closer to the on-shell VV mass.

In fact, the production of Higgs boson from a pair of vector boson is also related to the decay width of Higgs boson Γ_{H} via the propagator term. In terms of the differential corss section:

$$\frac{\mathrm{d}\sigma_{\mathrm{vv}\to\mathrm{H}\to\mathrm{VV}}}{\mathrm{d}q_{\mathrm{H}}^2} \sim \frac{g_{\mathrm{vvH}}^2 g_{\mathrm{HVV}}^2}{\left(q_{\mathrm{H}}^2 - m_{\mathrm{H}}^2\right)^2 + m_{\mathrm{H}}^2 \Gamma_{\mathrm{H}}^2} \tag{1.1}$$

where the two g on the right-hand side are the couplings for production from VV and decay to VV respectively. Integrating this equation near the on-shell mass of the SM Higgs boson or in the tail region (above the mass of VV), one can translate the differential cross section into event rate that can be (in theory) measured in experiments:

$$\begin{aligned} N^{\text{on-shell}}_{\mathrm{vv}\to\mathrm{H}\to\mathrm{VV}^*} &\sim \frac{g_{\mathrm{vvH}}^2 g_{\mathrm{HVV}}^2}{m_{\mathrm{H}}\Gamma_{\mathrm{H}}} \sim \mu_{\mathrm{vvH}} \\ N^{\text{off-shell}}_{\mathrm{vv}\to\mathrm{H}^*\to\mathrm{VV}} &\sim \frac{g_{\mathrm{vvH}}^2 g_{\mathrm{HVV}}^2}{\left(2m_{\mathrm{V}}\right)^2} \sim \mu_{\mathrm{vvH}} \cdot \Gamma_{\mathrm{H}} \end{aligned} \tag{1.2}$$

The key takeaway is that, up to some correction factors, the event rates of off-shell scales linearly respect to the Higgs decay width Γ_{H} which allows us to indirectly measure the width itself.

maybe elaborate a bit more?

1.4 Background and signal simulation

[1]Agostinelli S, Allison J, Amako K, Apostolakis J, Araujo H, Arce P, et al. Geant4—a simulation toolkit. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 2003;506:250–303. https://doi.org/10.1016/S0168-9002(03)01368-8.

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1.5 The CMS detector and event reconstruction

[1]CMS Collaboration. Performance of CMS muon reconstruction in pp collision events at sqrt(s) = 7 TeV. J Inst 2012;7:P10002–P10002. https://doi.org/10.1088/1748-0221/7/10/P10002.

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[3]Cacciari M, Salam GP, Soyez G. FastJet user manual. Eur Phys J C 2012;72:1896. https://doi.org/10.1140/epjc/s10052-012-1896-2.

[4][0802.1189] The anti-k_t jet clustering algorithm n.d. https://arxiv.org/abs/0802.1189 (accessed May 25, 2020).

Chapter 2

Methods

2.1 Event selection and physical variables

- Description of homebrew event variables and their physical significance
- DJJ_VBF prescription

2.2 Backgrounds

- Remarks on a few ‘fakeable’ physical objects
- a interference background in Higgs sample
- Base plots of variables, justify some cuts

2.3 Signal simulation reweighting

- Physics of Higgs signal sample (the weight, ME)
- the need for pieceing together samples with different LHE Mass
- procedures
- plots
- results (also see appendix A)

2.4 Strategy in variable selection and binning

1

Chapter 3

Results and interpretation

Appendix A

Weights Table for Higgs Sample

Appendix B

Additional Figures

Bibliography