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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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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, the CMS detector, and the physics behind the off-shell methods for constraining Higgs decay width. Finally, a very brief technical account for the Monte Carlo (MC) events production.

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.

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 (red), 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 (blue line in 1.1), 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. Although information such as momentum relies on hits on the silicon tracker, the hits in the muon

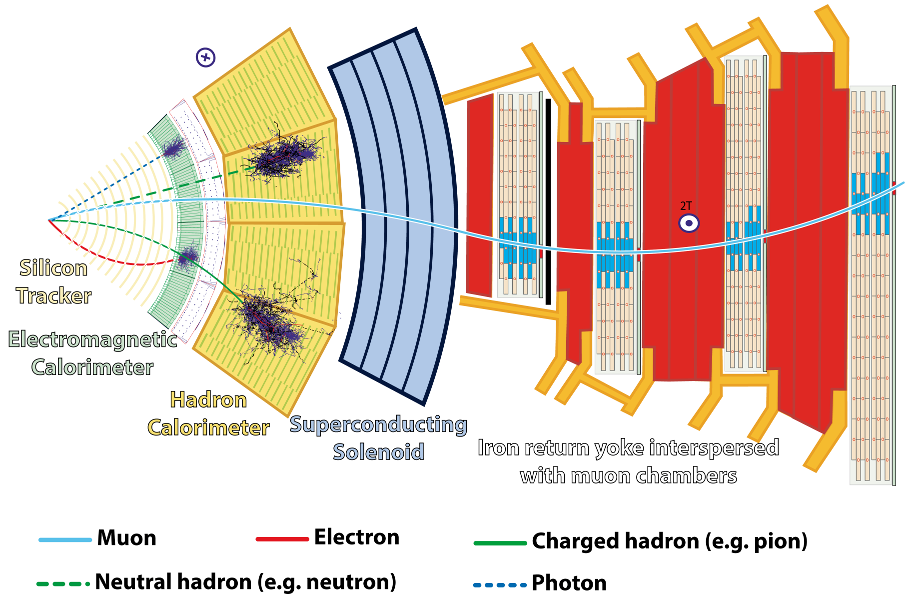

Figure 1.1: A section slice of the CMS detector where we can see how particles with different physical properties interact differently with the detector.

chambers and a matching trajectory is needed for the object to be reconstructed as a muon. Notice how the muon chambers occupy more than half of the detector by size, such design allows the CMS detector to excel in muon measurements and is the primary reason for the overall design.

Zooming out from the individual component of the CMS detector, the complete reconstruction process is complex and sometimes requires information from multiple parts of the detector, this algorithm is called the Particle Flow (PF) [**?**]. While simple and neutral object like photon whose energy is directly measure by the ECAL (with correction for zero-suppression), electron measurements need the information from the inner tracker (one way to determine momentum), energy at the ECAL, and also sum of the energy of photons produced by bremsstrahlung compatible with the electron's track.

For gluons and quarks that come out of the interaction vertex, due to quark confinement, the detector is only be able to 'see' a narrow 'spray' of final state (stable) particles whose collection is called 'jet'. There are different ways and criteria to combine a collection of measurements into a single physical object, and in CMS, the anti-k_t clustering algorithm is used. In short, the algorithm would cluster objects in a cone (meaning it has a fixed $\eta - \phi$ space) originated from the vertex according to some parameter. But it also needs to be resilient to QCD effects that would cause jet to split, such as shown in Fig. 1.2, where previous generation of algorithm may misidentify them.

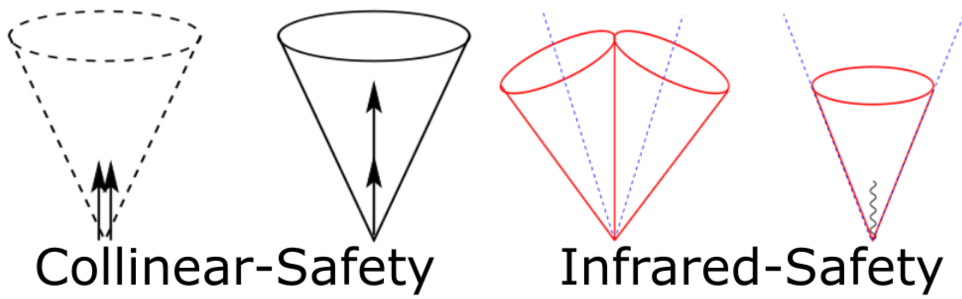

Figure 1.2: A illustration of two kinds of QCD effects in jets[1]

In this analysis, we use the AK4 jets which means that the algorithm is given a $R = 0.4$ parameter, another common choice is $R = 0.8$ which is preferred in some cases for boosted topologies due to a larger 'opening angle'.

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

[1] `https://twiki.cern.ch/twiki/bin/viewfile/Sandbox/Lecture?rev=1;filename=Philipp_Schieferdeckers_Lecture.pdf#page=3`

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 realm 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 boson 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 daughter 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 cross 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:

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

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.

In this thesis, we will focus on the $\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2\nu$ channel at the CMS detector using simulated (MC) events. This work done here is part of the ongoing work within a group formed by UCSB HEP group, Université Libre de Bruxelles, and Beihang University under the CMS Collaboration[2]. The analysis items and methods included in this thesis is a subset of what will be in the official analysis and is a part of the final measurement. More detail on what approximation has been taken in order to obtain a preliminary expected result is discussed in the next few sections.

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

[2]Internally, CMS AN-20-081

A: Accelerators, Spectrometers, Detectors and Associated Equipment 2003;506:250–303. https://doi.org/10.1016/S0168-9002(03)01368-8.

[2]Gritsan AV, Roskes J, Sarica U, Schulze M, Xiao M, Zhou Y. New features in the JHU generator framework. ArXiv:200209888 [Hep-Ex, Physics:Hep-Ph] 2020.

[3]The NNPDF Collaboration, Ball RD, Bertone V, Carrazza S, Deans CS, Del Debbio L, et al. Parton distributions for the LHC Run II. J High Energ Phys 2015;2015:40. https://doi.org/10.1007/JHEP04(2015)040.

[4]Melia T, Nason P, Röntsch R, Zanderighi G. W+W-, WZ and ZZ production in the POWHEG BOX. J High Energ Phys 2011;2011:78. https://doi.org/10.1007/JHEP11(2011)078.

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Various programs are used in the long chain of simulated events production. POWHEG BOX [**?**] is used for the signal simulation.

A description of LO / NLO and various program and NNPDF version etc. involved

Chapter 2

Methods

In this chapter, a description of event selection is given, as well as definitions of key physical variables and how they are used to select events. Then, a procedure regarding how the signal sample is manipulated to produce a high statistics off-shell tail is described. Finally, the binning of variables used to obtain the results is determined and defined.

2.1 Event selection and physical variables

Proton bunches cross each at a rate of about 400 MHz in the beam line of the LHC, naturally, not all of these crossings are recorded due to both technical limitation of the electronics as well as the fact that the vast majority of these crossings don't produce inelastic collision that is energetic enough to be interesting to us.

After the selection of Level 1 (L1) trigger and the higher level trigger (HLT), less than 1000 events per second are permanently recorded and would go to off-line, full reconstruction. Among these, we only select the ones that passes certain triggers.

give a correct account for what trigger is used for 2018 TriggerHelpers::kDoubleMu, TriggerHelpers::kDoubleEle, Trigger Help.cc TriggerHelpers::kSingleMu, TriggerHelpers::kSingleEle range pt

The jets are all AK4 jets unless mentioned otherwise. We shall also define a few of the uncommon variables in the list, and will give a few physical motivation in the next few paragraphs.

After selecting mandating passing certain triggers, we make a base line cut in the variables based on more delicate physics reason, the list of base line cuts is as below:

- No ak4-jet b-tagged jet
- Both leptons have $p_{\mathrm{T}} > 25\,\mathrm{GeV}$
- $\left|\Delta\phi_{\ell\ell\_E_{\mathrm{T}}^{\mathrm{miss}}}\right| > 1.0$
- $\left|\Delta\phi_{\ell\ell\mathrm{Jets}\_E_{\mathrm{T}}^{\mathrm{miss}}}\right| > 2.5$
- $|m_{\ell\ell} - 91.2\mathrm{GeV}| < 15\mathrm{GeV}$: the signal process consists of $\mathrm{Z} \to \ell\ell$, we require the di-lepton system has a mass that is consistent within the Z mass peak.
- $p_{\mathrm{T}}^{\ell\ell} > 55\mathrm{GeV}$: the Drell–Yan (DY) process creates a lot of backgrounds events, but their di-leptons go back-to-back with expected value of this variable close to 0.
- $E_{\mathrm{T}}^{\mathrm{miss}} > 125\mathrm{GeV}$: the signal process creates true $E_{\mathrm{T}}^{\mathrm{miss}}$ with neutrinos, this cut also reduce bkg such as DY.
- $\min\left|\Delta\phi_{\mathrm{j}\_E_{\mathrm{T}}^{\mathrm{miss}}}\right| > 0.25$

A lot of the cuts are related to angles between various physical objects presented in the reconstruction. The reason is simple: the signal events, where Higgs goes to ZZ and one Z goes to 2 charged lepton the other goes to 2 neutrinos, ideally would have the two

Z's 'back-to-back' in Higgs' rest frame leading to a large angel in the transverse plane. (assuming the $E_{\mathrm{T}}^{\mathrm{miss}}$ mainly comes from the two neutrinos, of course)

Furthermore, in background events which do not mandate this kinematic feature, the correlation in the directions of $E_{\mathrm{T}}^{\mathrm{miss}}$ and of observable physical objects is weaker.

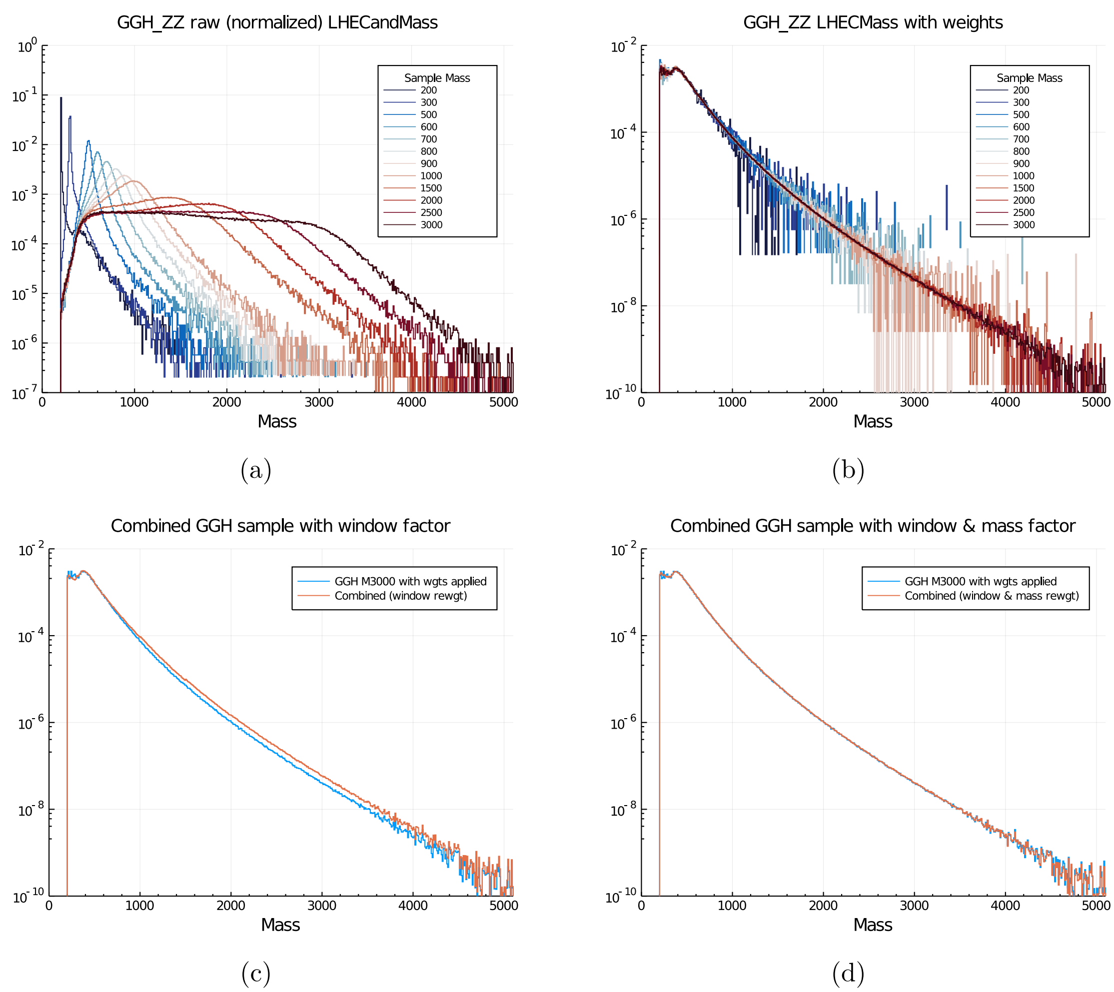
To use this kinematic feature to increase signal to background ratio, we define $\left|\Delta\phi_{\ell\ell\_E_{\mathrm{T}}^{\mathrm{miss}}}\right|$ as the azimuthal angel (perpendicular to the beam line) between the di-lepton system and the transverse missing energy. In the signal events that produce 0 jet, this variable should be π. The cut is lowered to 1.0 due to the finding that in the (not so rare) case where there are jet(s) recoiling against the ZZ system, the variable dips quite low.

This leads to the next variable on the list $\left|\Delta\phi_{\ell\ell\mathrm{Jets}\_E_{\mathrm{T}}^{\mathrm{miss}}}\right|$, which is almost the same except that we add all jets' momentum into the di-lepton system to account for the events that have produced jets, which in turn would cause the angel be lower in such a multi-body final states.

Finally, min $\left|\Delta\phi_{\mathrm{j}\_E_{\mathrm{T}}^{\mathrm{miss}}}\right|$ is the minimum azimuthal angel difference between any of the jet (that passes cuts) and the $E_{\mathrm{T}}^{\mathrm{miss}}$, it exist because jets are as mentioned, one of the most difficult physical objects measure, they often create so-called instrumental $E_{\mathrm{T}}^{\mathrm{miss}}$ due to jet mismeasurements and it can be quite large in magnitude. However, such mismeasurements often yields large $E_{\mathrm{T}}^{\mathrm{miss}}$ in the direction of the original jet. This cuts requires angular separation since in signal process, the jet recoils against ZZ system.

2.2 Signal simulation reweighting

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



(a) (b) (c) (d)

Figure 2.1: TO BE ADDED

describe these steps

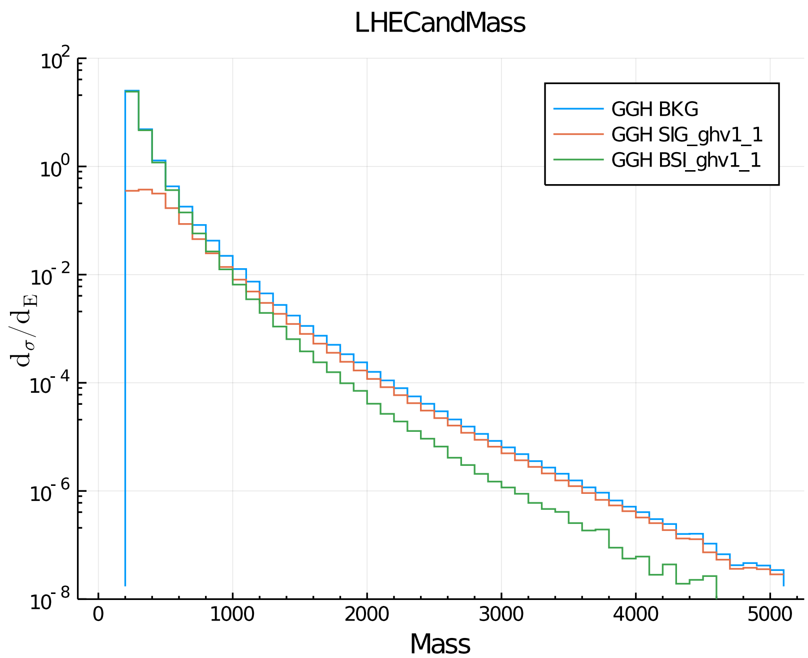
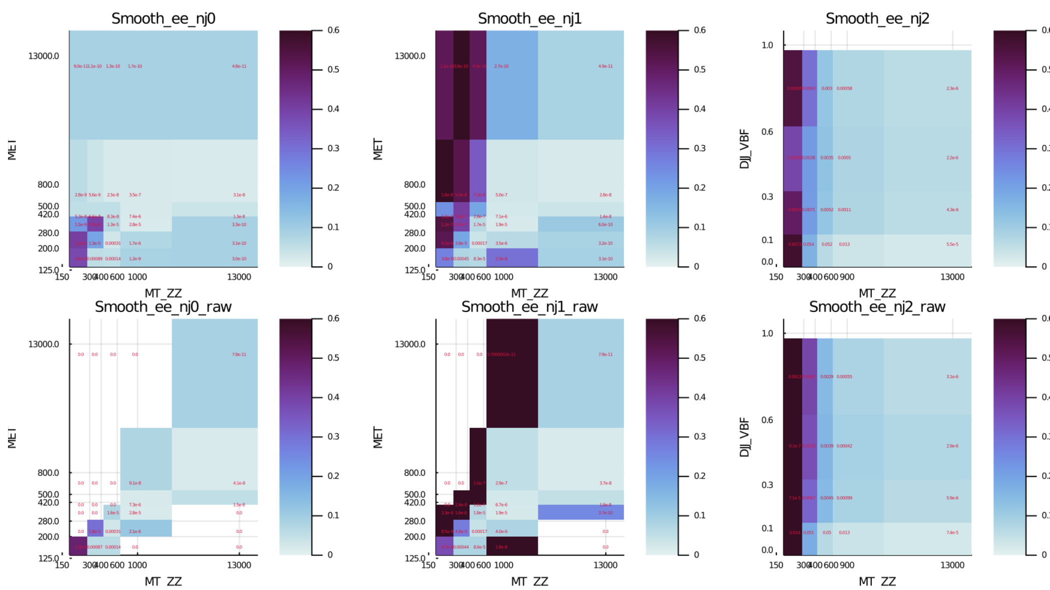


Figure 2.2: TO BE ADDED

2.3 Strategy in variable selection and binning



make plots publication quality and give quantitative justification for choice

Chapter 3

Results and interpretation

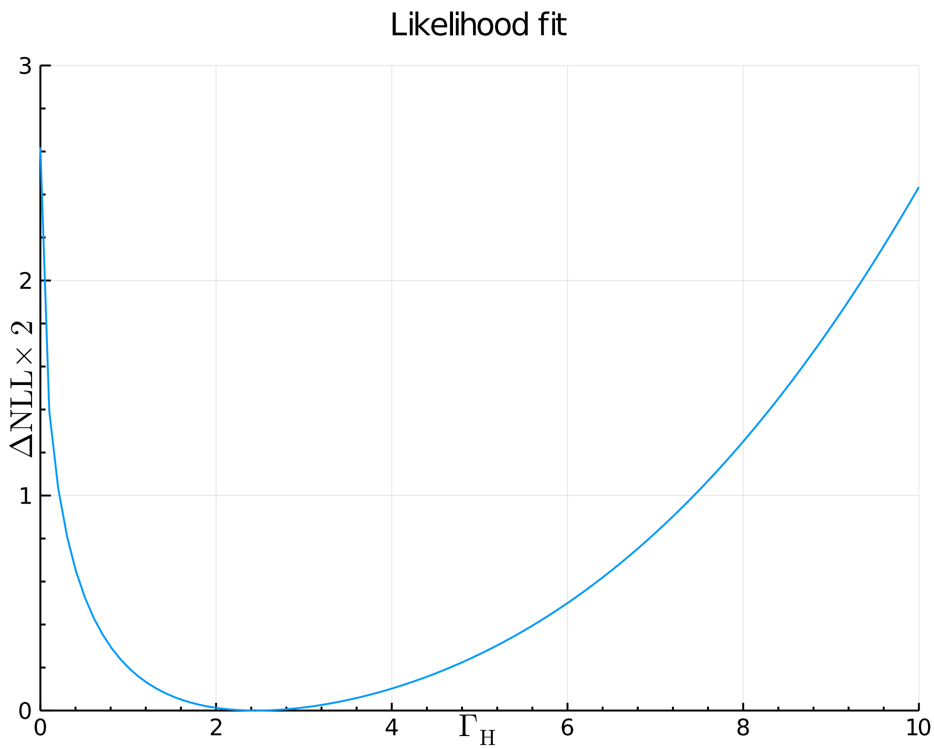


Figure 3.1: TO BE ADDED

interpret intersection with -2*deltaNLL = 3.84, y-axis intersection, rejection of null hypo.

Appendix A

Weights Table for Higgs Sample

Appendix B

Additional Figures

Bibliography