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The Search for the Higgs Boson Decaying into a Z Boson and a Photon

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ABSTRACT

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Since its discovery in 2012 at the Large Hadron Collider (LHC), efforts have been made to measure and characterize the properies of the Higgs boson. Among these efforts have been searches for rare decays of the Higgs predicted by the Standard Model (SM) of particle physics. One such decay is the process $H \to Z\gamma$, which is predicted by the SM to have a branching fraction of XX. An observation of this decay mode at a rate deviating from the SM prediction would provide indirect evidence of new physics beyond the SM. Previous searches for $H \to Z\gamma$ were carried out using proton-proton collision data from Run 1 of the LHC. Run 1 exclusion limits on the process were placed at roughly ten times the SM expectation by the Compact Muon Solenoid (CMS) experiment.

This thesis describes the search for $H \to Z\gamma$ in the $\ell\ell\gamma$ final state with the CMS detector using LHC Run 2 proton-proton collision data. The process is not observed, and exclusion limits are placed on the production cross section times branching fraction at XX times the SM expectation.

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CHAPTER 1

Introduction

introductory text

CHAPTER 2

Theory

2.1. The Standard Model

The Standard Model (SM) is currently our best theoretical framework for understanding the nature of fundamental particles. It is rooted in the idea that particles exist as excitations of quantum fields. These fields are constructed so as to obey fundamental symmetries of nature, and they yield the particles of our universe, as well as their interactions. The SM is not only elegant and extensive, but provides a wide variety of measurable observables for the experimentalist to probe. So far, many measurements have been made of the currently known elementary particles, and the predictions of the SM have held up in each case. In this respect, it is a wildly successful theory. In other respects, it is obviously incomplete.

2.2. Electroweak Theory

2.3. Spontaneous Symmetry Breaking (Higgs Mechanism)

The electroweak Lagrangian lacking the Higgs term CITE EQUATION is insufficient. In particular, it does not provide an explanation for massive gauge bosons. Experimental evidence for massive gauge bosons dates back to the early? twentieth century. Beta decay experiments indicated charged current interactions mediated by a massive W boson, and later experiments indicated additional neutral current interactions mediated by a massive Z boson (CHECK THIS). Later in the twentieth century (GIVE SPECIFIC DATES/REFS) the W and Z bosons were discovered. Indeed, the W and Z masses have been found to be roughly 80 GeV and 91 GeV respectively. An explanation came in the form of the Higgs mechanism (CITE), which spontaneously breaks the SU(2)xU(1) gauge symmetry of the elecroweak Lagrangian. In addition, there arises a real Higgs field accompanied by a massive Higgs boson, and fermion masses are explained via their Yukawa couplings to the Higgs boson. The discovery of the Higgs boson and the subsequent measurements of its properties have provided proof that the Higgs mechanism is indeed a central piece of the Standard Model.

To understand how the Higgs mechanism works, consider the introduction of a complex scalar field Φ, which transforms as a doublet under SU(2).

$$\Phi = \begin{bmatrix} \phi^+ \\ \phi^0 \end{bmatrix} \tag{2.1}$$

Its contribution to the Lagrangian is given by:

$$\mathcal{L}_{\mathcal{H}} = (D^\mu\Phi)^\dagger(D_\mu\Phi) - V(\Phi) \tag{2.2}$$

where the Higgs potential takes the form

$$V(\Phi) = \mu^2|\Phi^\dagger\Phi| + \lambda\Big(|\Phi^\dagger\Phi|\Big)^2. \tag{2.3}$$

D_μ is the covariant derivative

$$D_\mu = \partial_\mu - \frac{ig}{2}\tau \cdot A_\mu - \frac{ig'}{2}B_\mu Y. \tag{2.4}$$

Consider the case that the parameters of the Higgs potential λ and μ satisfy the conditions $\lambda > 0$ and $\mu^2 < 0$. Then the shape of the potential is shown in **??**. Clearly, there is no minimum of the potential at $\Phi = 0$. Rather, an infinite set of minima lie around a circle in the complex plane. Hence, it is said that Φ has a nonzero vacuum expectation value (VEV). The value of the VEV in terms of μ and λ can be determined by explicitly minimizing the potential:

$$\begin{aligned} \frac{\partial}{\partial(\Phi^\dagger\Phi)} V(\Phi) &= 0 \\ \mu^2 + 2\lambda\Big(|\Phi^\dagger\Phi|\Big) &= 0 \\ \mu^2 + 2\lambda\Big[(\phi^+)^2 + (\phi^0)^2\Big] &= 0 \end{aligned} \tag{2.5}$$

Clearly, this can be minimized in many ways depending on individual values of ϕ^+ and ϕ^0 in the vacuum. By convention, and without loss of generality, we choose the case in which $\phi^+ = 0$. In this case we obtain the equation

$$\phi^0 = \sqrt{\frac{-\mu^2}{2\lambda}} = \frac{1}{\sqrt{2}} v \tag{2.6}$$

where we have defined $v \equiv \sqrt{-\mu^2/\lambda}$.

The existence of the Higgs VEV has profound implications. To see this, it is helpful to reparameterize the scalar doublet field Φ as follows:

$$\Phi = \frac{1}{\sqrt{2}} e^{i\frac{\tau^a}{2}\theta_a(x)} \begin{bmatrix} 0 \\ v + h(x) \end{bmatrix} \tag{2.7}$$

As Φ is invariant under local SU(2) gauge transformations, the prefactor may be rotated away. This is equivalent to setting $\theta(x) = 0$ in equation 2.7. This choice of gauge is known as the unitary gauge, and leads to

$$\Phi = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v + h(x) \end{bmatrix} \tag{2.8}$$

Given the above form of Φ, we can now evaluate the Higgs Lagrangian (equation 2.2), starting with the kinetic term $(D^\mu \Phi)^\dagger (D_\mu \Phi)$.

$$\begin{aligned}
(D^\mu \Phi)^\dagger (D_\mu \Phi) &= \left|(\partial_\mu - \frac{ig}{2}\tau \cdot A_\mu - \frac{ig'}{2} B_\mu Y)\Phi\right|^2 \\
&= \frac{1}{2}\left| \begin{bmatrix} \partial_\mu - \frac{i}{2}(gA^3_\mu + g'B_\mu) & -\frac{ig}{2}(A^1_\mu - iA^2_\mu) \\ -\frac{ig}{2}(A^1_\mu + iA^2_\mu) & \partial_\mu + \frac{i}{2}(gA^3_\mu - g'B_\mu) \end{bmatrix} \begin{bmatrix} 0 \\ v + h(x) \end{bmatrix} \right|^2 \\
&= \frac{1}{2}\left| \begin{bmatrix} -\frac{ig}{2}(A^1_\mu - iA^2_\mu)(v + h(x)) \\ \partial_\mu h(x) + \frac{i}{2}(gA^3_\mu - g'B_\mu)(v + h(x)) \end{bmatrix} \right|^2 \\
&= \frac{1}{2}\partial_\mu h(x) \partial^\mu h(x) + \frac{1}{8}(gA^3_\mu - g'B_\mu)(gA^\mu_3 - g'B^\mu)(v + h(x))^2 \\
&+ \frac{g^2}{8}(A^1_\mu - iA^2_\mu)(A^1_\mu + iA^2_\mu)(v + h(x))^2
\end{aligned} \tag{2.9}$$

With some foreknowledge of the result, let us define the physical gauge fields and their masses as follows:

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(A_\mu^1 \mp iA_\mu^2) \qquad m_W = \frac{gv}{2} \tag{2.10}$$

$$Z_\mu = \frac{1}{\sqrt{g^2+g'^2}}(gA_\mu^3 - g'B_\mu) \qquad m_Z = \sqrt{g^2+g'^2}\frac{v}{2} \tag{2.11}$$

$$A_\mu = \frac{1}{\sqrt{g^2+g'^2}}(g'A_\mu^3 + gB_\mu) \qquad m_A = 0 \tag{2.12}$$

Then the kinetic term of the Higgs Lagrangian can be recast as

$$\begin{aligned}(D^\mu\Phi)^\dagger(D_\mu\Phi) = & \frac{1}{2}\partial_\mu h(x)\partial^\mu h(x) \\ & + \frac{1}{2}m_Z^2 Z_\mu Z^\mu + m_W^2 W_\mu^+ W^{-\mu} \\ & + \frac{v}{4}(g^2+g'^2)Z_\mu Z^\mu h + \frac{1}{8}(g^2+g'^2)Z_\mu Z^\mu h^2 \\ & + \frac{v}{4}g^2 W_\mu^+ W^{-\mu} h + \frac{1}{8}g^2 W_\mu^+ W^{-\mu} h^2\end{aligned} \tag{2.13}$$

Equation 2.13 provides a great deal of information on the physical ramifications of the Higgs mechanism. The first term is the kinetic term of the physical Higgs boson field. The second and third terms are the mass terms of the Z and W bosons respectively. The fourth and fifth terms show the linear and quadratic couplings of the Z boson to the Higgs boson respectively. Finally, the sixth and seventh terms show the linear and quadratic couplings of the W boson to the Higgs boson respectively. Given the form of equation 2.8, a similar expansion can be carried out on the Higgs potential (equation 2.3). Here, the terms involving the physical Higgs boson are most interesting, so constant terms are dropped.

$$V(\Phi) = \frac{\mu^2}{2}(v+h)^2 + \frac{\lambda}{4}((v+h)^2)^2$$
$$\rightarrow \lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4}h^4 \tag{2.14}$$

The first term is a Higgs mass term, with $m_H = \sqrt{2\lambda v^2}$. The second and third terms describe the Higgs trilinear and quartic self-coupling respectively.

The Lagrangian including the Higgs doublet Φ can be further extended to incorporate interactions between the Higgs and fermion fields. These interactions, along with the nonzero Higgs VEV, provide a mechanism to generate the fermion masses. The interactions take the form of Yukawa couplings:

$$\mathcal{L}_{Yukawa} = Y^d_{ij}\bar{Q}^i_L \Phi d^j_R + Y^u_{ij}\bar{Q}^i_L \tilde{\Phi} u^j_R + Y^e_{ij}\bar{L}^i_L \Phi e^j_R + h.c. \tag{2.15}$$

where

$$\tilde{\Phi} \equiv i\tau_2 \Phi^* \tag{2.16}$$

Plugging in the unitary gauge Φ parameterization of equation 2.8, this evaluates to

$$\mathcal{L}_{Yukawa} = \frac{Y^d_{ij}}{\sqrt{2}}\bar{d}^i_L(v+h)d^j_R + \frac{Y^u_{ij}}{\sqrt{2}}\bar{u}^i_L(v+h)u^j_R + \frac{Y^e_{ij}}{\sqrt{2}}\bar{e}^i_L(v+h)e^j_R \tag{2.17}$$

It is worth looking closely at the terms in equation 2.17. For a given fermion type, the first term in the parentheses is a fermion mass term. The second term in the parentheses gives the coupling of the fermion to the Higgs boson. With this in mind, we observe that the fermion mass is given in terms of the couplings and the Higgs vev by

$$m_f = \frac{y_f v}{\sqrt{2}} \tag{2.18}$$

where y_f is the relevant value taken from the Yukawa coupling matrix. In addition, we see that the strength of the fermion coupling to the Higgs boson is given by $\frac{m_f}{v}$. Thus, fermions couple to the Higgs boson with strength directly proportional to their masses. This result has important consequences in the context of collider experiments, as it regulates the rates of Higgs production and decay related to each fermion-Higgs vertex.

2.4. Higgs Production

2.5. Higgs Decay

2.6. Physics Beyond the Standard Model

CHAPTER 3

Experimental Apparatus

apparatus text

CHAPTER 4

Overview of Analysis Strategy

Before discussing the full details of the analysis procedure and results, it is worth summarizing the broader strategy taken in our search for $H \to Z\gamma$. As two prior CMS results have been published with Run 1 data and 2016 data, we will emphasize the ways in which our analysis overlaps and differs from these previous approaches. Very broadly, the current search is similar to the previous analyses in trigger, object, and basic event selection. However, it is significantly more advanced in three body mass reconstruction, event categorization, and background modeling. We will show that the innovations in these areas have significantly improved the expected sensitivity and statistical robustness of the search with respect to the past CMS analyses.

Chapter 5 provides a detailed description of the data and Monte Carlo simulation used in our analysis. Standard dimuon and dielectron trigger streams are used for 2016, 2017, and 2018 LHC data. The full dataset corresponds to an integrated luminosity of 137 fb^{-1}. In other words, we use the full CMS Run 2 dataset at 13 TeV center of mass energy. Simulated signal samples are used to determine the expected signal yields and three body mass shape. Simulated background samples are used for MVA training and category optimization. However, the background shape and normalization in the final result is determined by fitting the data and does not rely on any simulation.

Chapter 6 describes the basic object and event selection used in the analysis, and Chapter 7 describes further selection and categorization using MVAs. As mentioned, the basic selection requirements are fairly similar to previous CMS analyses. Muons are selected with a loose cut-based ID, while electrons and photons are selected with loose MVA IDs. Loose ID requirements are chosen in order to maximize signal efficiency. Background is then suppressed through a combination of basic cuts and MVA methods. Basic kinematic cuts on isolation, mass, and photon energy variables are able to significantly reduce backgrounds from initial and final state radiation, while the MVA methods are able to strongly disciminate against backgrounds from jets misreconstructed as photons. Finally, a kinematic fit procedure in the dilepton mass is able to significantly improve the signal mass resolution. The kinematic fit is an innovation of the current analysis and contributes to its improved sensitivity.

Chapter 8 details the approach to signal and background modeling of the three body mass spectrum. As in previous CMS $H \to Z\gamma$ searches, the signal shape is determined via an analytic fit to simulation. A resonant background contribution from $H \to \mu^+\mu^-$ is modeled similarly. The nonresonant background contribution is taken from a fit to data in the range of 105 to 170 GeV. This background model includes both the turn-on arising from the real Z boson peak as well as the falling spectrum at higher mass. We note that the turn-on was fit in the Run 1 analysis as well, but was dropped in the 2016 analysis. A more thorough discussion of the merits of fitting the turn-on will be described in chapter 8.

Chapter 9 describes the systematic uncertainties relevant for the analysis, and Chapter 10 gives a basic overview of the statistics used to arrive at the final results. It is worth noting that given the current integrated luminosity, the analysis is dominated by statistical uncertainty. Chapter 11 gives the full set of results, including best fit signal strength, limits, and comparisons with $H \to \gamma\gamma$.

CHAPTER 5

Data and Simulation

CHAPTER 6

Object and Event Selection

6.1. Triggers

The topology and basic kinematics of the $H \rightarrow Z\gamma$ process guide the choice of triggers used in this analysis. As this is a three body decay, the p_T of the photon tends to be less than in other channels like $H \rightarrow \gamma\gamma$. Consequently, the CMS photon trigger p_T thresholds are too great to make them viable options. Instead, we trigger on the leptons arising from the decay of the Z boson, which tend to have larger p_T . The best approach to maximize signal efficiency is to use the double lepton triggers. The double muon trigger has p_T thresholds of 17 and 8 GeV, and the double electron trigger has thresholds of 23 and 12 GeV. These are the lowest unprescaled double lepton triggers generally available for CMS Run 2 analysis. Events passing both the double muon and double electron triggers are treated as double muon events.

The triggers are applied to both data and simulation. Trigger efficiencies and scale factors are measured using the simulation samples corresponding to each data-taking year. These measurements use a tag and probe method [CITE]. The tag and probe method takes advantage of the high purity of $Z \rightarrow \ell^+\ell-$ events near the Z mass peak. One lepton functions as the tag, and satisfies a set of tight trigger, identification, isolation, p_T requirements. The second lepton, the probe, must pass a looser selection and is used to measure the efficiency in question. Using this approach, trigger efficiencies for each leg of a given double lepton trigger are measured in both data and simulation. Then a corrective scale factor, defined as the ratio of data efficiency to simulation efficiency, is applied to the simulation. Scale factors are measured and applied in bins of p_T and $|\eta|$.

For the double electron trigger efficiency measurements, the tag electron must satisfy the following requirements. It must pass the single electron trigger, pass a tight cut-based identification, have $p_T > 30\,(35)$ in 2016 (2017/2018), and have $|\eta| < 2.5$. The probe electron must pass the loose electron MVA identification (with isolation) requirement. The efficiencies for each leg of the trigger are measured separately, so in each case, the probe electron must match the trigger leg being measured. The efficiencies and scale factors of each double electron trigger leg for 2016, 2017, and 2018 are shown in Figures [FIGS].

For the double muon trigger efficiency measurements, the tag muon must satisfy the following requirements. It must pass the single muon trigger, pass a tight cut-based identification, have $p_T > 26\,(29)$ GeV for 2016 (2017/2018) and satisfy $|\eta| < 2.4$. The probe muon must pass the $H \to ZZ$ identification and isolation cuts. The details of the $H \to ZZ$ muon identification will be described later. The efficiencies for each leg of the trigger are measured separately, so in each case, the probe muon must match the trigger leg being measured. The efficiencies and scale factors of each double muon trigger leg for 2016, 2017, and 2018 are shown in Figures [FIGS].

6.2. Muon Selection

A loose cut-based muon identification is used in the analysis. This identification was originally developed by the $H \to ZZ$ analysis [REF] and is well-suited for $H \to Z\gamma$ due to the similarity of the multiple, potentially soft, muons in the final state. All muons are first required to pass a set of common cuts, followed by a separate set of cuts for high p_T (greater than 200 GeV) and low p_T muons. All muons must satisfy $p_T > 5$ GeV, $|\eta| < 2.4$, $|d_{xy}| < 0.5$ cm, and $|d_z| < 1$ cm, where d_{xy} and d_z are impact parameters defined with respect to the primary vertex of the interaction using the best muon track. Additionally, the three dimensional impact parameter (analogously defined) must have a magnitude less than four times its uncertainty. Muons must either be reconstructed as global muons or tracker muons. Muons with standalone tracks (tracks only in the muon system) are rejected. Muons must pass a particle flow-based isolation requirement, where the relative particle flow isolation within a $\Delta R = 0.3$ cone is defined as

$$\mathcal{I} \equiv \Big(\sum p_T^{\text{charged}} + \max \big[0, \sum p_T^{\text{neutral}} + \sum p_T^{\gamma} - p_T^{\text{PU}}(\ell) \big] \Big) / p_T^{\ell}. \tag{6.1}$$

Muons must satisfy $\mathcal{I} < 0.35$.

For muons with $p_T < 200$ GeV, muons satisfying the common requirements and identified by the particle flow identification algorithm are selected. For muons with $p_T > 200$ GeV, muons are selected if they pass the particle flow identification or if they pass a set of high-p_T requirements. These requirements are the following: the muon must be matched to segments in at least two muon stations; satisfy $\frac{p_T}{\sigma_{p_T}} < 0.3$, $|d_{xy}| < 0.2$ cm, $|d_z| < 0.5$ cm, have at least one pixel hit, and have tracker hits in at least six tracker layers.

In 2016, data-taking was affected by a problem in which the level one trigger sent only one candidate per 60° sector instead of up to three [REF?]. As a result, when two muons in the same endcap had a low $\Delta\phi$ separation, only one would fire the trigger. To account for this, 2016 data events containing identified muons with $\Delta\phi < 70°$ in the same endcap region are rejected.

Identification efficiencies and scale factors corresponding to the muon identification above are measured and provided by the $H \to ZZ$ analysis working group, and are shown in Figure [FIG].

6.3. Electron Selection

Electrons are identified using a boosted decision tree multivariate (MVA) discriminator trained on Drell-Yan plus jets simulation with prompt electrons matched to generator-level objects as signal and unmatched and non-prompt electrons as background. The features used in the training include p_T , supercluster η, shower shape variables, ratio of hadronic to electromagnetic energy, track and pixel hit variables, and isolation variables [REF]. These features are sensitive to bremsstrahlung along the electron trajectory, momentum-energy matching between electron trajectory and ECAL cluster, shower shape, and electrons from photon conversions. Since isolation features are included in the training of the discriminator, there is no need for separate isolation cuts. Electrons pass the identification requirement of the $H \to Z\gamma$ analysis if their discriminator score is higher than a loose working point value, corresponding to 98% signal efficiency. In addition to the MVA cut, electrons must have $|d_{xy}| < 0.5$ cm and $|d_z| < 1$ cm with respect to the primary vertex. Electrons with $p_T \leq 7$ GeV are rejected.

Electron identification efficiencies and scale factors are measured using a tag and probe method on dielectron events near the Z boson peak. These electrons must pass the single electron trigger with a p_T threshold of 27 (32) GeV for 2016 (2017/2018) data. The dielectron mass must be between 60 and 120 GeV. The tag electron must pass a tight cut-based electron identification and have $p_T > 30$ (35) GeV for 2016 (2017) and $|\eta|$ ¡ 2.5. The probe electron must pass the loose MVA identification cut and associated impact parameter and p_T cuts described above. Identification efficiencies and scale factors are measured and applied in bins of p_T and supercluster η. The scale factors for each data-taking year are shown in Figures [FIGS].

6.4. Photon Selection

Photons are identified using a boosted decision tree MVA discriminator trained on photon plus jets simulation. The features used in the training include supercluster kinematics, isolation variables, and shower shape variables [REF]. To reject electrons faking photons, a conversion-safe electron veto is applied. In order to improve agreement between simulation and data in the $H \to Z\gamma$ analysis, shower shape corrections are taken from the Higgs to diphoton analysis [REF] and applied to simulated events. The original MVA provided by the EGamma POG is then reevaluated after these corrections. The following features are corrected: R_9, defined as the ratio of energy in the 5x5 array of ECAL crystals to the supercluster energy; S_4, defined as the ratio of the maximum energy 2x2 array to the energy of the 5x5 array; the energy weighted shower widths σ_η and σ_ϕ; the energy weighted widths by crystal index $\sigma_{i\eta i\eta}$ and $\sigma_{i\eta i\phi}$; photon isolation, charged isolation with respect to the primary vertex, and charged isolation with respect to the worst vertex choice. The validity of the shower shape corrections is checked using tag and probe procedures for $Z \to e^+e^-$ events where the probe electron mimics a photon and $Z \to \mu^+\mu^-$ events with an FSR photon. A comparison of the agreement between uncorrected and corrected simulation with data is shown in Figures [FIGS]. Simulation comparisons with data for individual shower shape features before and after correction can be found in Appendix [APPENDIX], Figures [FIGS].

After deriving the corrected photon MVA discriminator, 90% signal efficiency working point cuts for barrel and endcap photons are determined for the $H \rightarrow Z\gamma$ analysis. The working points are defined based on real photons from SM $Z\gamma$ simulation, and correspond to discriminator scores greater than -0.4 (-0.59) for barrel (endcap) photons. A comparison of these working points with the standard EGamma POG 90% efficiency working points, plotted on the receiver operator characteristic (ROC) curve for SM $Z\gamma$ and Z plus jets simulation, is shown in Figure [FIG]. The efficiency of the photon identification is measured with $Z \rightarrow e^+e^-$ data using a tag and probe technique. The tag electron must pass the single electron trigger with p_T threshold 27 (32) GeV in 2016 (2017/2018), tight cut-based identification, have $p_T > 30$ (35) GeV for 2016 (2017/2018), and have $|\eta| < 2.5$. The probe electron must pass the photon MVA identification with shower shape corrections described above. The scale factors, measured and applied in bins of p_T and supercluster η, are shown in Figure [FIG]. The efficiencies and scale factors for the conversion-safe electron veto are measured by the EGamma POG using $Z\mu^+\mu^-$ events with an FSR photon and applied in the $H \rightarrow Z\gamma$ analysis. The scale factors are cataloged in Table [TAB].

6.5. Jet Selection

Jets are selected in order to categorize events coming from potential VBF Higgs production, but no jet multiplicity requirement is present for the $H \rightarrow Z\gamma$ selection. In fact, the majority of simulation and data events selected in the analysis have no jets. However, identifying and selecting jets to categorize VBF events can still significantly improve the sensitivity of the search. Jets are required to pass a loose cut-based identification in 2016 and a tight cut-based identification in 2017 and 2018. These sets of identification cuts are determined and provided by the JetMET POG. Additionally, jets must satisfy $p_T > 30$ GeV, $|\eta| < 4.7$, and $\Delta R > 0.4$ with respect to each lepton and the photon selected in the analysis. An issue with noise in the ECAL endcap in 2017 caused an artificial increase in jet multiplicity in data within a specific kinematic phase space [REF]. To mitigate this, jets are rejected if they have raw $p_T < 50$ GeV and $2.65 < |\eta| < 3.139$. This cut reduces the efficiency to reconstruct dijet pairs by 12% in the specified region. To tag VBF events, we are interested in dijet pairs. To this end, if there are more than two jets satisfying the above criteria, only the two jets with highest p_T are selected.

6.6. Object Corrections

CHAPTER 7

Event Categorization

CHAPTER 8

Signal and Background Modeling

CHAPTER 9

Systematic Uncertainties

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Statistical Analysis

CHAPTER 11

Results and Interpretation

CHAPTER 12

Conclusion

References

[1] A bibliographic item. A bibliographic item. A bibliographic item. A bibliographic item.

[2] Another bibliographic item.

[3] Yet another bibliographic item.