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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 $\mathsf{H} \rightarrow \mathsf{Z}\gamma$, 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 $\mathsf{H} \rightarrow \mathsf{Z}\gamma$ 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 $\mathsf{H} \rightarrow \mathsf{Z}\gamma$ 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.

Acknowledgements

Text for acknowledgments.

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introductory text

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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:

$$\frac{\partial}{\partial(\Phi^\dagger\Phi)}V(\Phi) = 0 \tag{2.5}$$

$$\mu^2 + 2\lambda\Big(|\Phi^\dagger\Phi|\Big) = 0 \tag{2.6}$$

$$\mu^2 + 2\lambda\Big[(\phi^+)^2 + (\phi^0)^2\Big] = 0 \tag{2.7}$$

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

$$\phi^0 = \sqrt{\frac{-\mu^2}{2\lambda}} = \frac{1}{\sqrt{2}}v \tag{2.8}$$

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

The existence of the Higgs VEV leads naturally to the masses of the W and Z bosons. This can be shown by squaring the covariant derivative acting on the scalar doublet Φ and evaluating the result in the vacuum. Note that in the vacuum, all terms involving the partial derivative ∂_μ will yield zero contribution. Therefore, keeping only the relevant terms, the squared covariant derivative reduces to

$$|D_\mu|^2 \to (\frac{g}{2}A^a_\mu\tau^a + \frac{g'}{2}B_\mu)(\frac{g}{2}A^{b\mu}\tau^b + \frac{g'}{2}B^\mu) \tag{2.9}$$

Evaluating this in the vacuum yields

$$\Delta\mathcal{L} = \frac{1}{2}\begin{bmatrix}0 & v\end{bmatrix}(\frac{g}{2}A^a_\mu\tau^a + \frac{g'}{2}B_\mu)(\frac{g}{2}A^{b\mu}\tau^b + \frac{g'}{2}B^\mu)\begin{bmatrix}0\\ v\end{bmatrix} \tag{2.10}$$

$$\Delta\mathcal{L} = \frac{1}{2}\frac{v^2}{4}[g^2(A^1_\mu)^2 g^2(A^2_\mu)^2 + (g'B_\mu - gA^3_\mu)^2] \tag{2.11}$$

From this, we can identify the fields and masses for the positively and negatively charged W bosons and the neutral Z boson and photon. These are as follows:

$$W^\pm_\mu = \frac{1}{\sqrt{2}}(A^1_\mu \mp iA^2_\mu) \qquad m_W = \frac{gv}{2} \tag{2.12}$$

$$Z^0_\mu = \frac{1}{\sqrt{g^2 + g'^2}}(gA^3_\mu - g'B_\mu) \qquad m_Z = \sqrt{g^2 + g'^2}\frac{v}{2} \tag{2.13}$$

$$A_\mu = \frac{1}{\sqrt{g^2 + g'^2}}(g'A^3_\mu + gB_\mu) \qquad m_A = 0 \tag{2.14}$$

2.4. Higgs Production

2.5. Higgs Decay

2.6. Physics Beyond the Standard Model

CHAPTER 3

Results and Interpretation

results text

References

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

[2] Another bibliographic item.

[3] Yet another bibliographic item.