Unlocking the Universe: Rediscovering the Higgs Boson

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Abstract

The discovery of the Higgs Boson was revolutionary within the realm of particle physics. The discovery led to several breakthroughs in our understanding of the Standard Model, and of the fundamental forces which govern the laws of our universe. The purpose of our research is to reconstruct this remarkable discovery through the Higgs Boson's decay into two electrons and two muons via a pair of Z gauge bosons. The stability of the end products make this channel of decay quite notable in that it is simpler to trace back to the Higgs Boson. Utilizing simulation data taken from CERN, we have employed several cuts through which we have reconstructed the decay channel and formed plots to determine the presence of the Higgs Boson. The results of our research characterize the importance of one of the most groundbreaking discoveries of the last century, whilst also providing insight into the challenges faced in pursuit of said discovery.

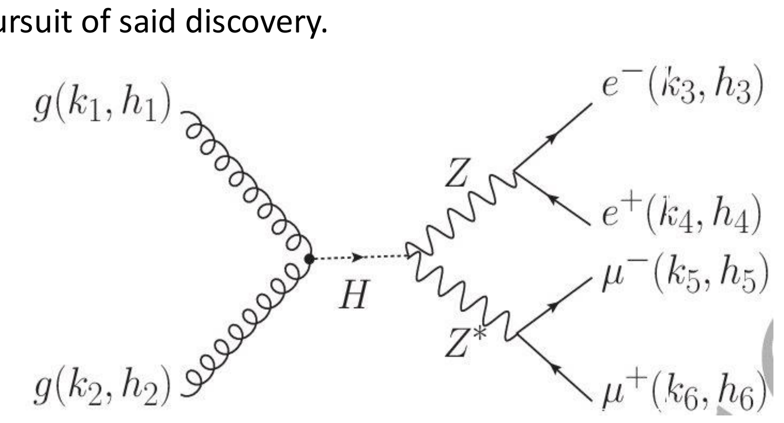

Figure. Feynman Diagram of $H \to ZZ \to 4\ell$ decay by He, R. et al. in [5]

Introduction

The Standard Model

The Standard Model (SM) of particle physics has been experimentally verified numerous times to be the most accurate model of the interactions between elementary particles.

- Formulated in successive decades of the mid 20th century, the SM mathematically combines the description of the three known fundamental forces and classifies all known elementary particles.
- The theory of ***electroweak symmetry breaking (Higgs Mechanism)*** [6] described by Peter Higgs in 1964 gives **all massive particles their mass** is a central part of the model.
- Experimental confirmations of many aspects of the SM in the 1990s and early 2000s lent it credence but made the **absence** of experimental confirmations of the **Higgs Mechanism** confounding. [1]

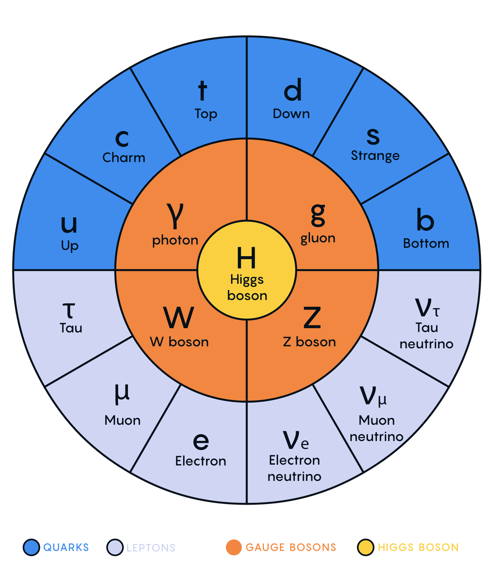

Figure. The Standard Model of Particle Physics by Wolchover N., et al. in [7]

Discovery of the Higgs Boson

- It was not until 2011-2012 when the ATLAS and CMS collaboration teams at CERN reported an excess of proton-proton collision events at center of mass energy $\sqrt{s}$ = 7 TeV at the LHC.
- The perfect condition for the SM-predicted Higgs production and decay in the **124 - 126 GeV mass region**.
- It was found that there was "clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 GeV." [1]

Process

- Use of **CMS simulation data** meant to replicate what is found in a high energy collision at CERN.
- Application of **masks** to isolate events consistent with the presence of a Higgs Boson.
- Calculation of **Z boson masses** from constituent leptons.
- **Reconstruction of the Higgs mass** via the summation of Lorentz Vectors.
- Application of **weights** when plotting final graphs.

CMS open dataset

The CMS experiment at CERN has periodically released the data and relevant simulations to the public domain regularly since 2014. [3]

- The dataset from the 2010 – 2012 run (Run 1) of the LHC is almost entirely in the public domain.
- The dataset from the 2015 – 2018 run (Run 2) of the LHC has been partially released starting in 2021.
- The data and their associated simulations have been instrumental in independent verification and study of the discovery of the Higgs Boson.

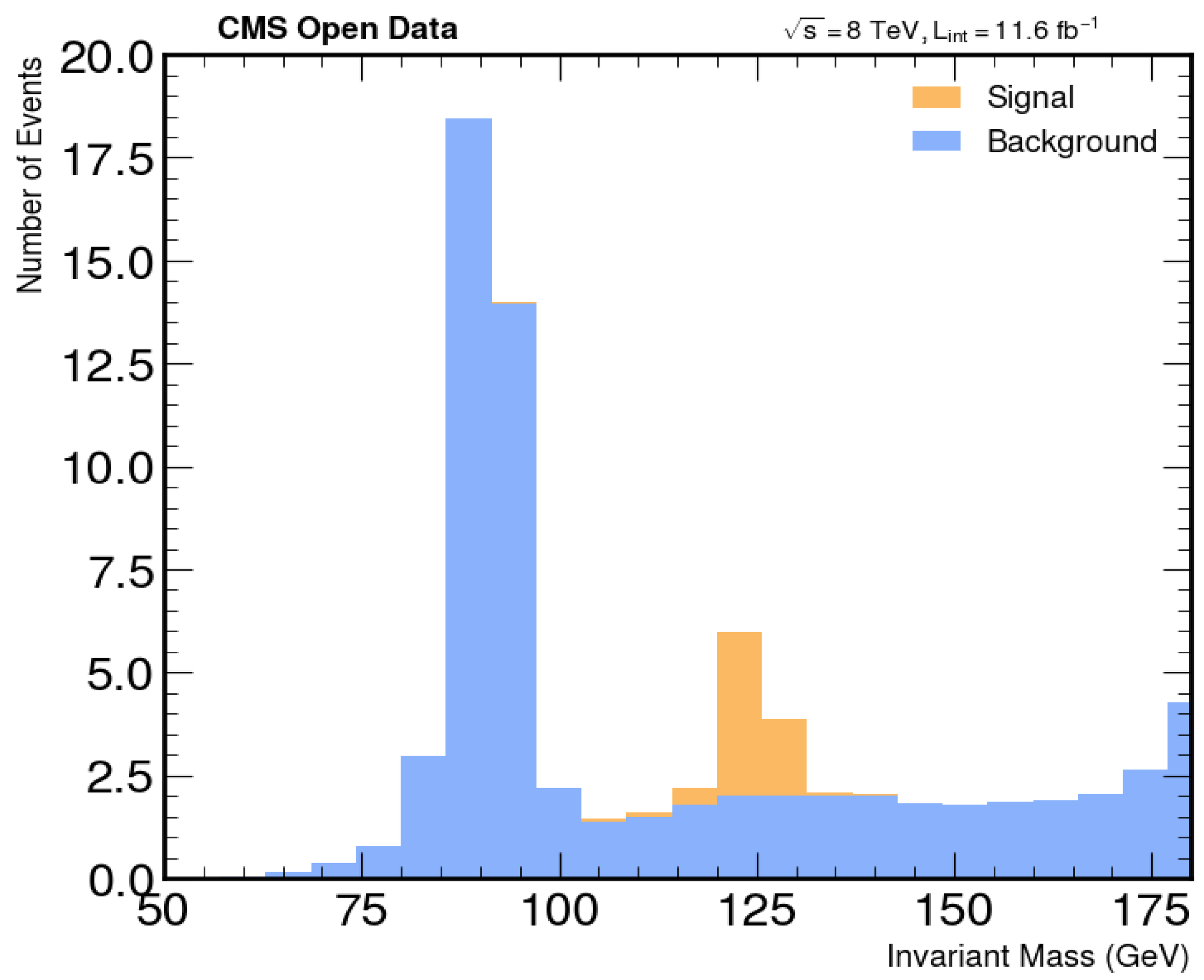

Figure A. Invariant Mass from $H \to ZZ \to 4\ell$ channel

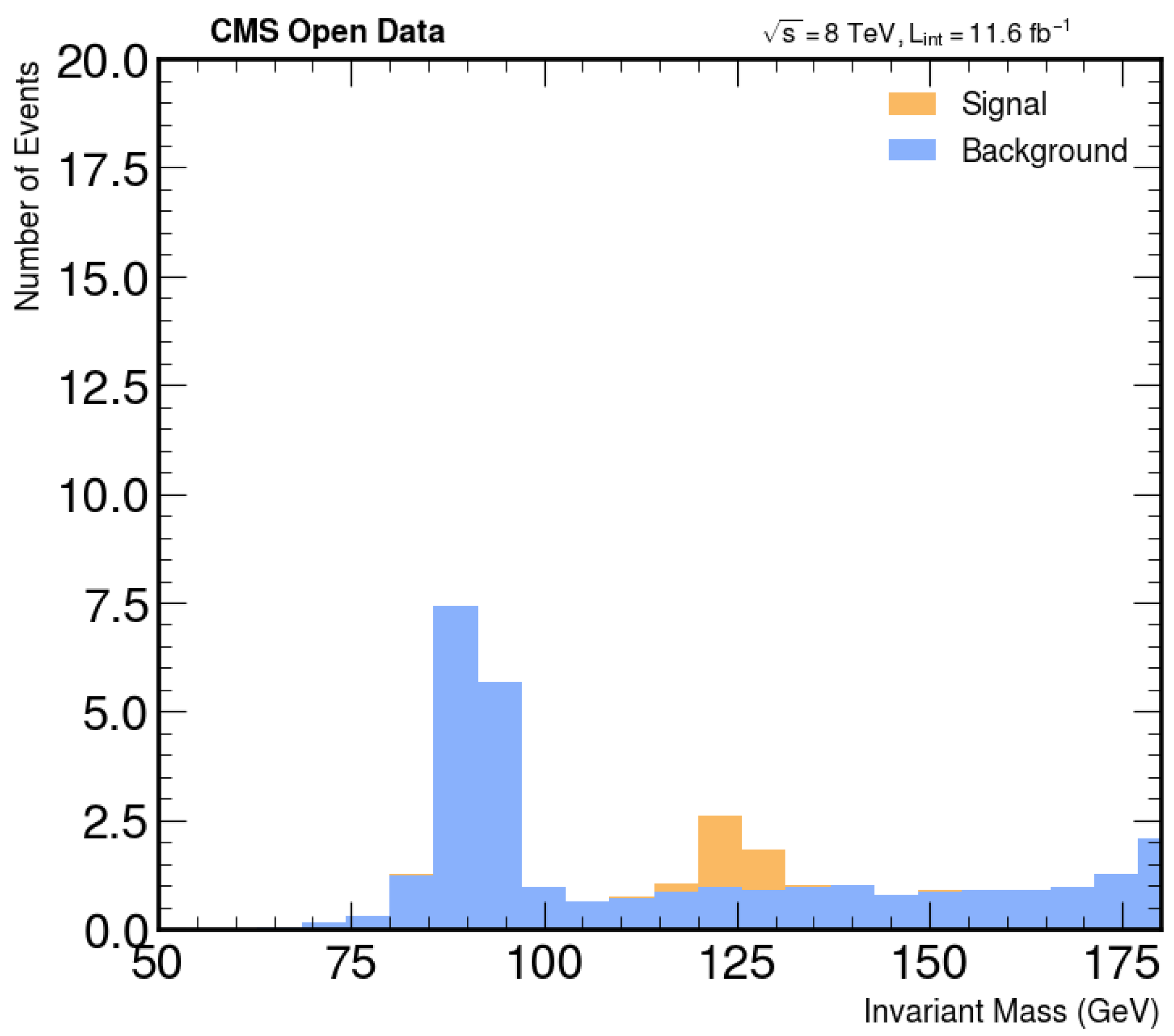

Figure B. Invariant Mass from $H \to ZZ \to 2\mu 2e$ channel

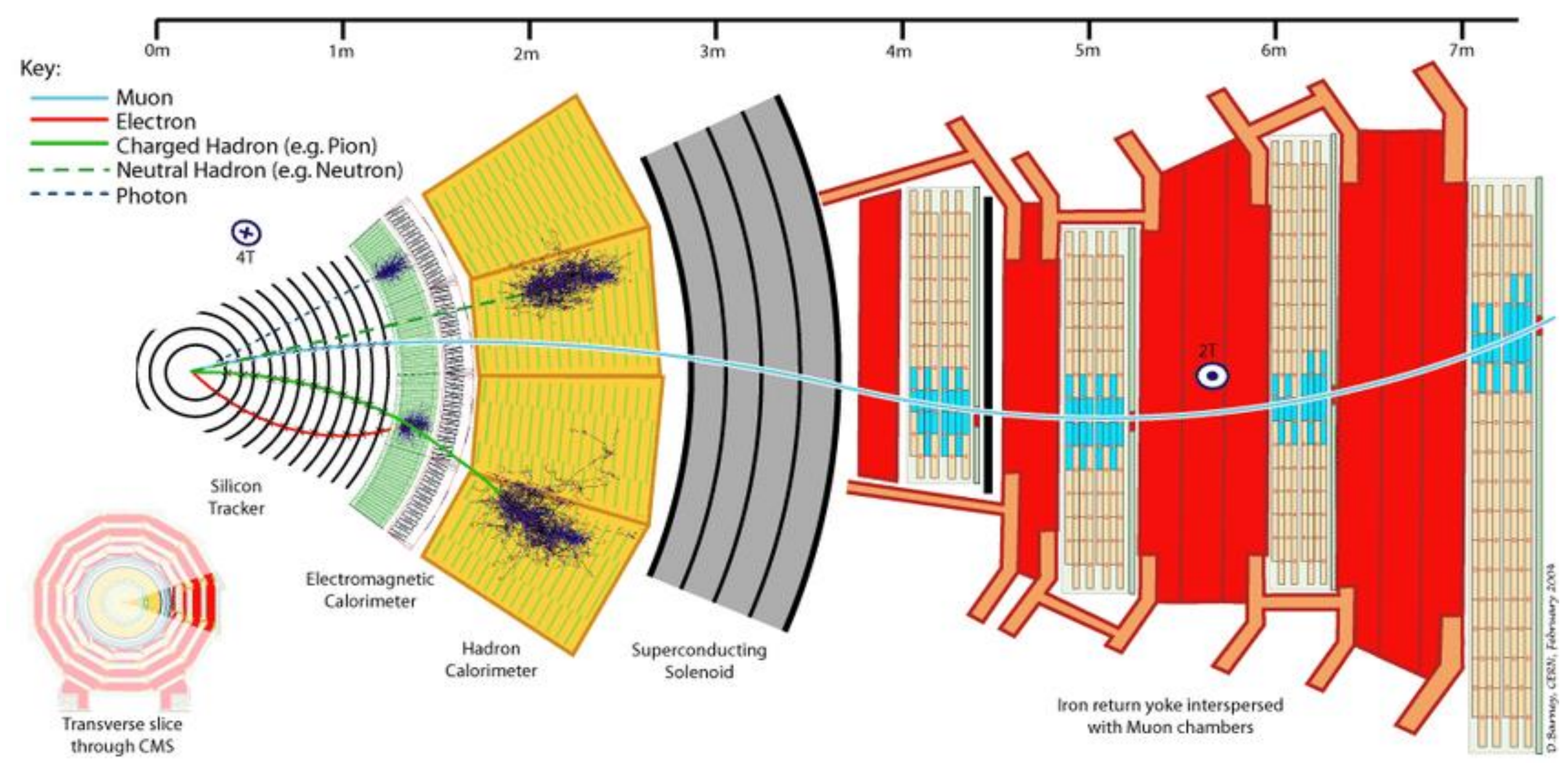

Figure. Cross-sectional view of the CMS detector by Dris, S. in [4]

Results

- A spike in the signal of the two muon, two electron channel was observed around **125 GeV.** This corresponds to the predicted mass of the Higgs Boson.
- The spike serves as strong evidence for the existence of the Higgs Boson. This discovery validates the theoretical predictions of British physicist Peter Higgs and his colleagues.
- Similar spikes were found when employing a similar process for the four muon and four electron channels.
- The spikes at 125 GeV in all three Higgs to four lepton channels serve to corroborate the detection of the Higgs Boson.
- A spike in the background was observed at around **90 GeV**. This is the mass of a Z boson.
- These spikes were found in all three channels and suggest the presence of Z gauge bosons.

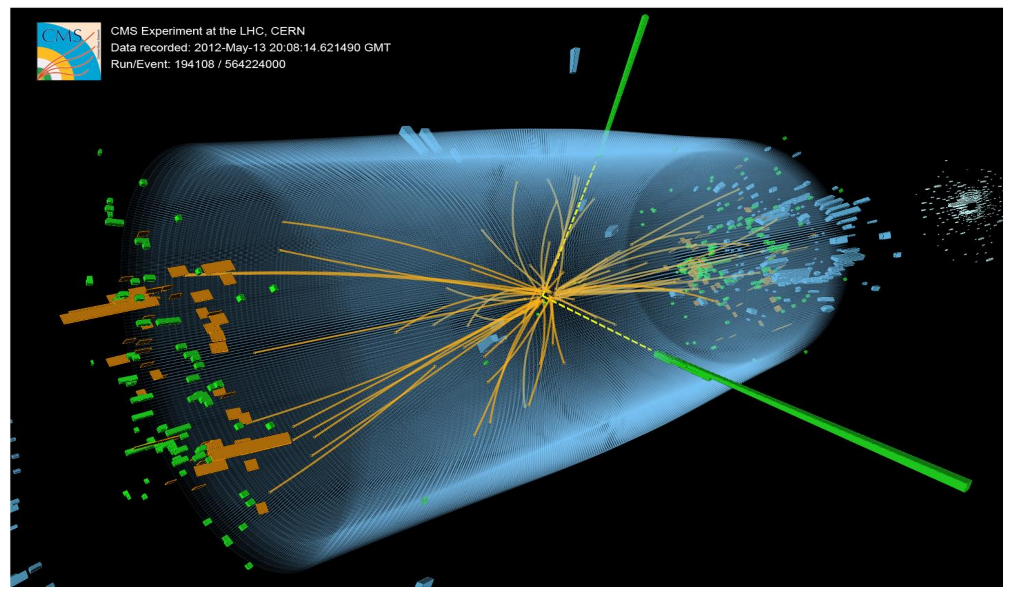

Figure. candidate photon-photon event (8 TeV) by ATLAS in [2]

Selection Criteria

- Initial Event Count
  - Number of Muons = 2
  - Number of Electrons = 2
- Eta Cuts
  - Electron/Muon Eta ≤ 2.5
- Momentum Cuts (for each lepton pair)
  - First Lepton Momentum > 20
  - Second Lepton Momentum > 10
- Isolation Criteria
  - Electron/Muon < .4
- Primary Vertex
  - Electron/Muon 3D Impact Parameter Unit Vector < 4
  - Magnitude of Change in Electron/Muon XY < .5
  - Magnitude of Change in Electron/Muon Z < 1.0
- Charge Balance
  - 1 positive and 1 negative Electron/Muon

References

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[2] CMS Collaboration (2013). CMS Higgs Search in 2011 and 2012 data: candidate photon-photon event (8 TeV): 3D, r-phi and r-z transverse views. https://cds.cern.ch/images/CMS-PHO-EVENTS-2013-003-1

[3] CMS Collaboration, (2012). CMS Open Data. CERN Open Data Portal, root://eospublic.cern.ch//eos/root-eos/cms_opendata_2012_nanoaod/

[4] Dris, S (2010). *Cross-sectional view of the CMS detector* [Figure 1]. In *Performance of the CMS Tracker Optical Links and Future Upgrade Using Bandwidth Efficient Digital Modulation*. https://www.researchgate.net/figure/Cross-sectional-view-of-the-CMS-detector-11-The-HCAL-contains-and-measures-the-energy_fig3_41217449

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[7] Wolchover, N., Velasco, S., Reading-Ikkanda, L. (2020). *A new map of the Standard Model of particle physics* [Figure 2]. Quanta Magazine. https://www.quantamagazine.org/a-new-map-of-the-standard-model-of-particle-physics-20201022/