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Searching for the Higgs Boson Through its Decay into a Muon-Antimuon Pair

"THE HIGGS BOSON WOULD BECOME THE MOST SOUGHT-AFTER PARTICLE IN ALL OF PARTICLE PHYSICS."

OUTLINE

Our project seeks to find the Higgs Boson, the particle dubbed the "God Particle" in mainstream media, a near mythical particle that has eluded physicists for decades. After a 40 year search, a subatomic particle was observed in 2012 by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) in CERN [1]. It had the expected properties of the Higgs Boson. One of the predicted decays (hypothesised but yet to be observed) of the Higgs is into a muon-antimuon pair ($H \rightarrow \mu\mu$), which is what our project focuses on. We used Open Data from ATLAS in looking for this rare decay.

THE HIGGS BOSON

All particles are excitations of fields - the Higgs Boson is an elementary particle in the Standard Model and an excitation of the Higgs Field, giving mass to elementary particles. The Higgs Field is a scalar, therefore its associated boson is scalar and has a spin of 0 (as opposed to vector bosons which have a spin of 1). Through simultaneous symmetry breaking, the field breaks the weak isospin of the electroweak interaction and gives mass to many particles via the Higgs Mechanism.

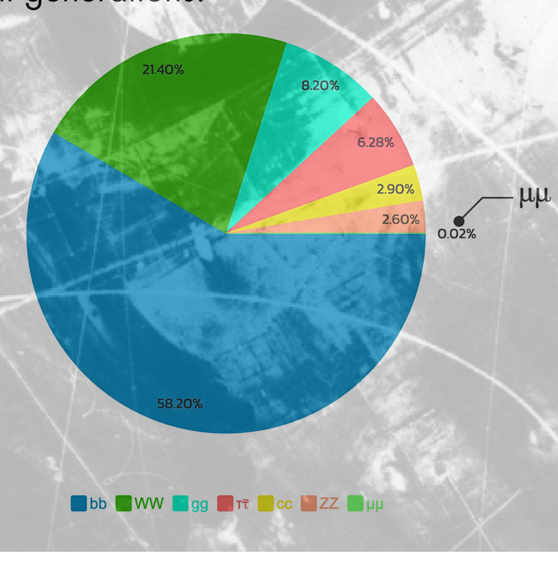
Discovery: The Higgs Boson was officially discovered in 2012 by the ATLAS and CMS experiments at the Large Hadron Collider at 4.9 sigma Significance, shocking the world of modern physics [1]. It is measured to have an invariant mass of 125.38±0.15 GeV, which is equivalent to 133x the mass of a proton. It was consistent with the predicted properties by Peter Higgs in 1964 [2]: even (positive parity), no electric charge, no colour charge, zero spin and zero strong force interaction. Even the proportions of the decay paths have agreed with those predicted. The first direct probe of fermionic interactions was the decay to tau particles, which was observed in the combination of ATLAS and CMS results performed at the end of Run 1.

THE DECAY

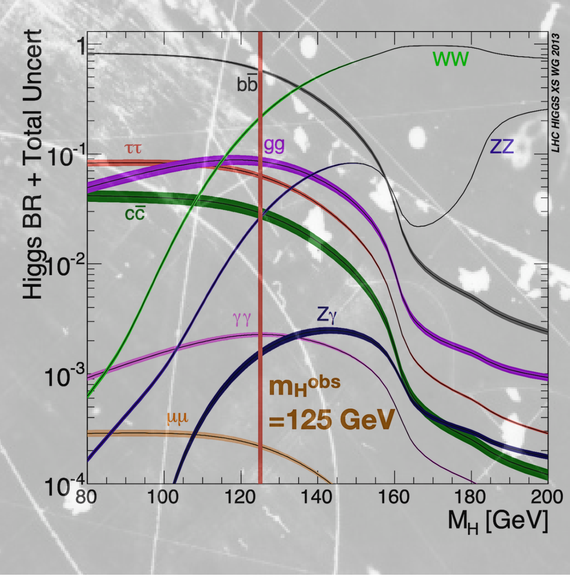
Decays: The Higgs is very unstable with a lifetime of 1.6×10^{-22} seconds decaying into other particles almost immediately which makes it difficult to find. By measuring decay rates to different particles, the predicted mechanism by which they acquire mass can be tested directly. Measurements performed so far have focused on the Higgs boson interactions with the most massive particles, such as the W and Z bosons, and only with particles from the most massive generation, the top and bottom quarks and the tau lepton. The interaction of the Higgs boson with lighter particles, such as muons, has so far not been discovered. Measuring the full spread of Higgs Boson interactions is critical to test if the Higgs field can explain the full range of particle masses.

Rare Decays: The SM predicts several rare Higgs Boson decay channels, which have not yet been observed. Among these are decays to second-generation leptons and quarks, eg. $H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$ and $H \rightarrow cc$. The focus of this project is on one of the rarest decays, into a dimuon($\mu\mu$). The expected branching fraction for the decay of the Higgs boson (invariant mass=125.38GeV) to a pair of muons is $B(H \rightarrow \mu^+ + \mu^-) = 2.18 \times 10^{-4}$ while previously found more common decays have much higher branching fractions, making them easier to detect.

$H \rightarrow \mu\mu$: Only about one in five thousand Higgs bosons are predicted to decay to muons. And similarly, like a needle in a mountain of needles, for every predicted Higgs boson decay to muons at the LHC, there are about one thousand muon pairs that mimic every single Higgs boson. This background from other particles (e.g. Z bosons) makes isolating the Higgs boson decay to muons extremely difficult Therefore the efficacy of event selection and simulation are paramount. The $H \rightarrow \mu\mu$ decay offers the best opportunity to measure the Higgs interaction with second-generation fermions at the LHC, providing new insights into the origin of mass for different generations.



These two graphs show the probabilities of the Higgs Boson decaying into various particles. ***Left (Figure 1)****:This shows the likelihood of the Higgs decaying into a dimuon pair as a percentage: 0.02%.* ***Right (Figure 2)****:This percentage translates to a branching fraction of 2.18×10^{-4} as seen in Figure 2.*



EVENT SELECTION

To find this extremely rare decay we used selection criteria: a set of filters applied to the data to distinguish the relevant signal from background data. After extensive research [2][3], these selection criteria allow us to identify and isolate the specific events where this dimuon decay has occurred:

- **Two muons with opposite charge** → These criteria are used to select events that contain a muon-antimuon pair.
- **Transverse momentum of lead muon > 27 GeV** → Used to select high-energy muons, which are more likely to be produced in the decay of heavy particles like the Higgs boson.
- **Transverse momentum of sublead muon > 15 GeV** → This ensures that both muons in the event are detected with a reasonable efficiency. If the second muon has too low of a transverse momentum, it may be missed or misidentified, leading to an incomplete or biased analysis.
- **-2.7 < Pseudorapidity of muons < 2.7** → Used to select muons that are produced in the central region of the detector. Muons that are produced at larger angles from the beamline are excluded from the analysis because these muons are less likely to be related to the Higgs boson decay and are more likely to be background noise from other sources.
- **No b-tagged jets** → Bottom quarks, or b-quarks, make up a large amount of background data. B-tagging is a technique used to identify jets that contain b-quarks, so they can be removed from the data, therefore increasing the signal-to-background ratio.
- **Transverse momentum of jets > 25 GeV** → This criterion is used to select only those jets that are produced with high energy while minimising the contribution from low-energy background events.
- **4.5 > Pseudorapidity of jets > 2.5** → This criteria is used to select jets that are produced in the central region of the detector to restrict the range of angles for the jet. By removing jets that are produced at larger angles, called forward jets, or smaller angles from the beamline, we are able to reduce the background noise from interfering jets and improve the signal-to-background ratio, increasing the chances of detecting this rare Higgs boson decay in the data.

With these selection criteria we found events most likely to exhibit the characteristics of the $H \rightarrow \mu\mu$ decay. Using the Python module provided by IRIS, we used the transverse momentum, pseudorapidity, azimuthal angle and energy of the selected events to reconstruct our desired decay, creating our dimuon mass: $M_{\mu\mu}$.

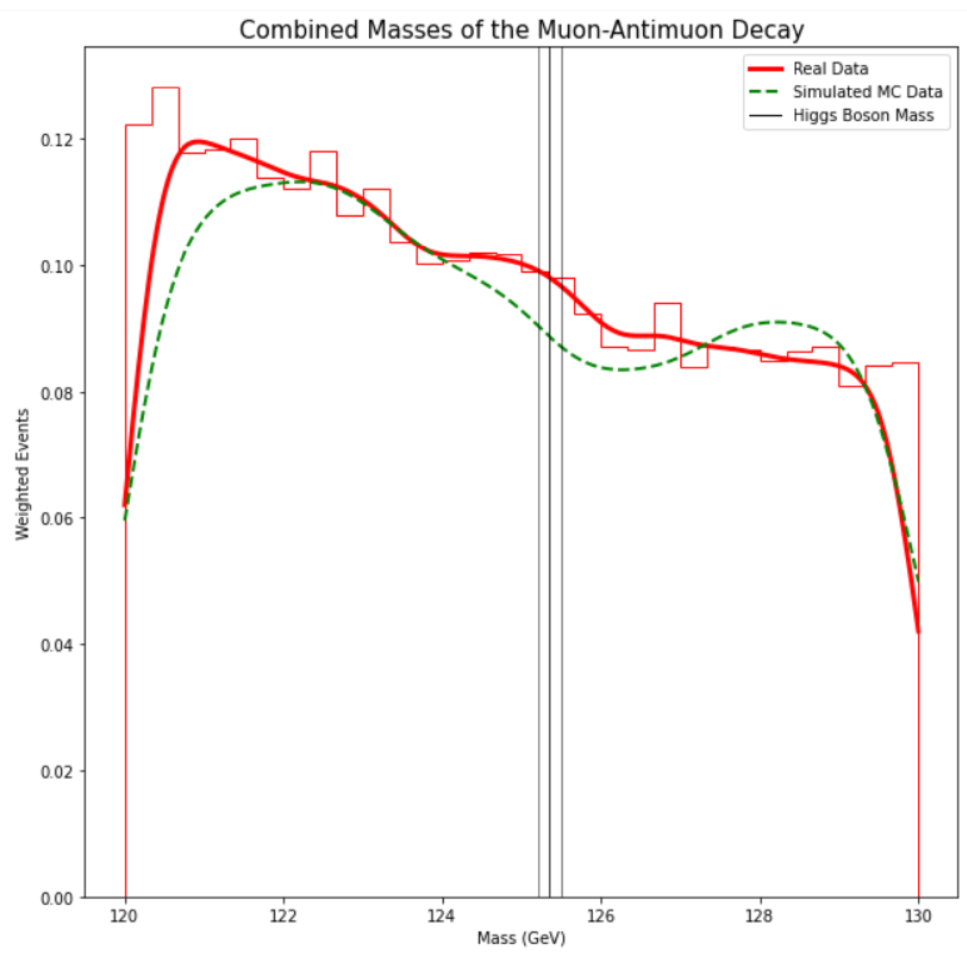


Figure 3: *This graph shows the probability density function (PDF) overlayed on the histogram of the dimuon masses, in red, after selection criteria were applied. The green line is the PDF line of the simulated (background) events.*

EVENT SIMULATION

We simulated the collisions of particles in the LHC using files from the 13TeV ATLAS Open Data. Monte Carlo (MC) simulation files were used to simulate the behaviour of subatomic particles produced by the LHC. We used diboson and Higgs MC files from the open data, which we believed would mimic the expected behaviour of the $H \rightarrow \mu\mu$ decay. The simulated events were weighted to have the same proportions, then compared to real data that had met the selection criteria, allowing us to identify events that were consistent with the expected behaviour of $H \rightarrow \mu\mu$ decay. Importantly, this distinguishes real data from events that are the result of other background processes, increasing the signal-to-background ratio. Any difference in the 2 lines on Figure 3 suggests a deviation from the expected behaviour, providing evidence for the $H \rightarrow \mu\mu$ decay.

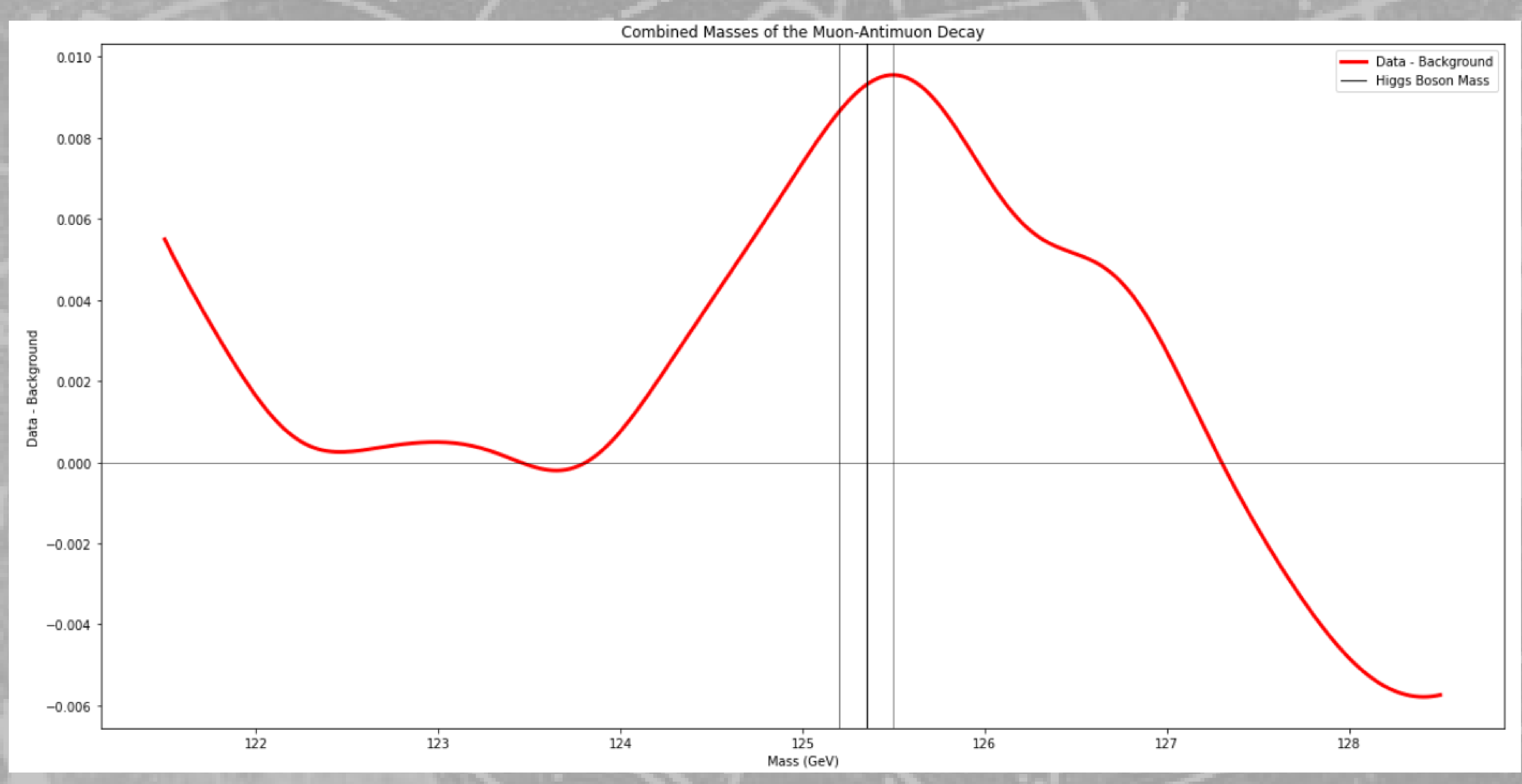


Figure 4: *Graph of Weighted Events - Background Data*

RESULTS & ANALYSIS

After applying event selection, reconstruction, and simulation, we were able to create Figure 4. In total, 12.2 million real events and 9.4 million MC events were processed, then given equal weightings. The selection criteria was able to filter these events to approximately 35% of their size. Figure 4 displays the weighted events minus any background data, therefore giving the best, most isolated result. There is a significant spike at 125.5 GeV, which lies in the interval for the Higgs mass (125.38±0.15 GeV). Due to the rarity of this decay, we were unable to isolate all of the signal data from the background, which left us with variance at m ≈ 121 GeV and 128 GeV. Evidently from Figure 3, there is an increased area of frequency between 128 and 129 GeV, showing the presence of another decay which passed through our rigorous selection criteria. This highlights the ongoing challenges in isolating rare events from background noise. Ideally we would investigate this decay in order to possibly isolate the signal data further which would produce a more defined spike.

We were able to calculate the p-value from the Z score, $p(H \rightarrow \mu\mu)=0.138$. This means that there is a 1 in 7.25 chance that this result was a coincidence. Further data could be processed to give a bigger spike and lower p-value, as well as completing the tasks outlined in 'next steps'.

CONCLUSION

From the results of our research, we have found further evidence for the Higgs boson decay into two muons. Our graph shows that there was a significant excess of events around 125GeV, which is consistent with the expected signal from the Higgs Boson decay. Our discovery, therefore, provides acute evidence of the existence of the Higgs decay into a muon-antimuon pair, but more accurate results would be needed to confirm this as a discovery. As the possible decays are numerous, the results from different decay modes can be combined to improve the precision of the measurements and provide a more complete understanding of the Higgs boson's properties.

NEXT STEPS

There are 4 exclusive categories of Higgs Boson production: Gluon Fusion (ggh), Vector Boson Fusion (VBF), Association with Vector Boson (VH), and Association with Top Quark and Antiquark Pair (ttH).
VBF has shown to be the most successful out of the four; its events could be investigated to obtain better results. Our next steps would be to apply specific selection criteria to each of these to refine our search for the dimuon pair - likely resulting in a bigger spike. The ATLAS Open Data provided extensive MC data, but ideally the event simulation could be improved using MadGraph software to create unique background data for this decay. Finally, using Machine Learning algorithms to identify b-tagged jets more accurately could further isolate the signal data.

REFERENCES

[1] ATLAS Collaboration (2012) *'Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC'* Available at: https://arxiv.org/abs/1207.7214 (Accessed: 16 March 2023) **| [2] CMS Collaboration (2020)** *'Evidence for Higgs boson decay to a pair of muons'* Available at: https://arxiv.org/abs/2009.04363 (Accessed: 12 April 2023) **| [3] ATLAS Collaboration (2017)** *'Search for the Dimuon Decay of the Higgs Boson in pp Collisions at $\sqrt{s}$ = 13 TeV with the ATLAS Detector'* Available at: https://arxiv.org/abs/1705.04582 (Accessed: 8 April 2023) **| [4] Higgs, P.W (1964)** *'Broken Symmetries and the Masses of Gauge Bosons'* Available at: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.13.508 (Accessed: 6 May 2023) **| Fig.1:** We created this using data from: 'https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR' **| Fig.2: Marchiori, G. (2019)** *'Rare and lepton-flavour-violating Higgs boson decays in ATLAS'* (Accessed: 16 March 2023)

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