# The search for Higgs Bosons produced through Vector Boson Fusion (VBF) and decaying into four muons

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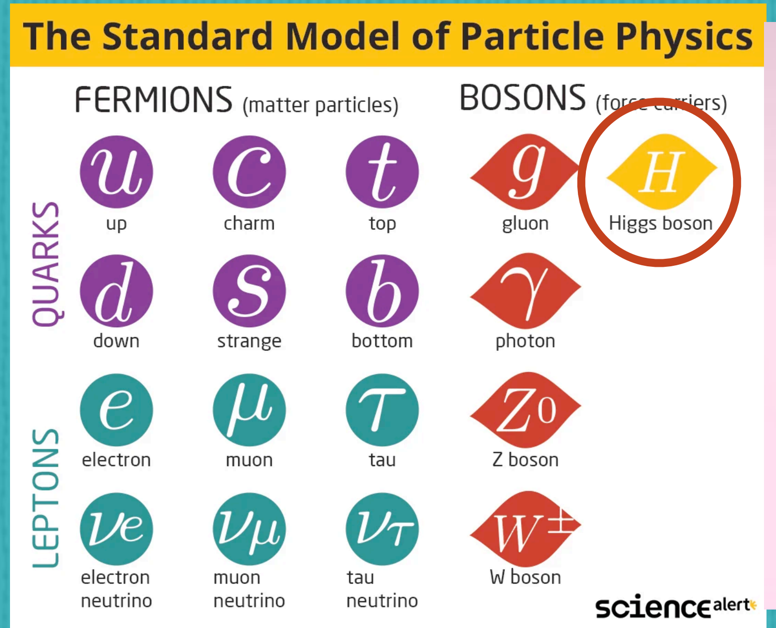
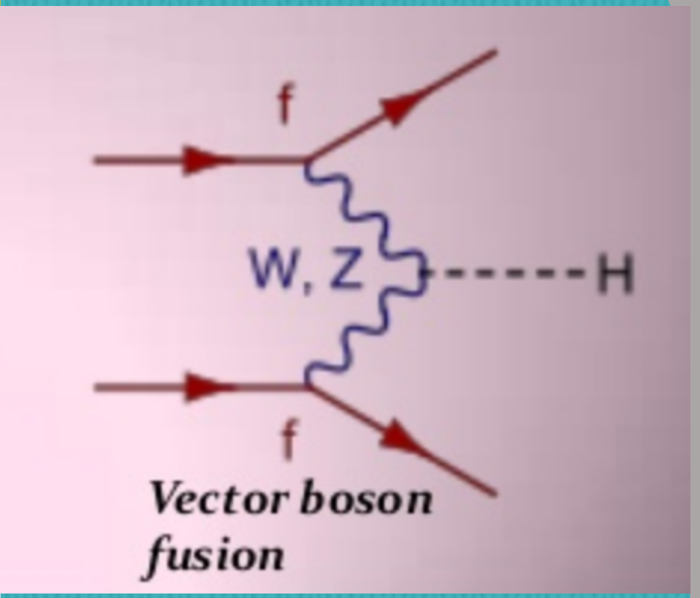
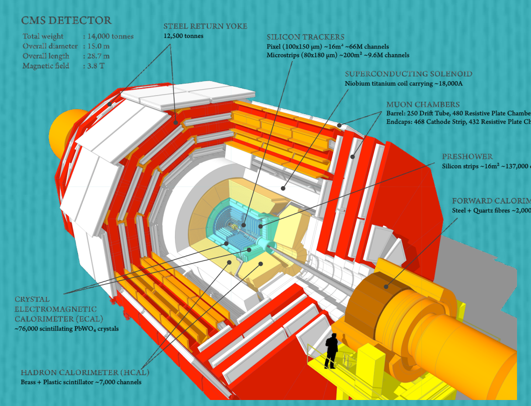
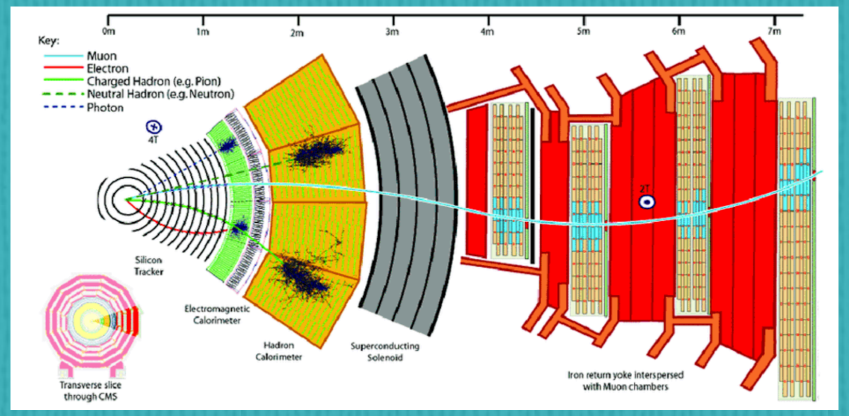
## What are we searching for?




The Standard Model is a collection of all of the known fundamental particles in our universe and their interactions. In the 1970's an addition to the Standard Model was theorized (the Higgs Boson), and it was first measured experimentally in 2012. **There are four main processes that produce the Higgs Boson through a proton collision, and we are searching for the only one of those four that hasn't been measured yet, namely, the Vector Boson Fusion (VBF) process (top right picture is its Feynman Diagram), focusing specifically on ZZ to 4 muon decay.** This process is expected to play a role as a source of background noise in the search for SuperSymmetric (SUSY) particles, which is one of the central quests of particle physics, given that it is a central component of most Grand Unification Theories (GUT's) which seek to unify in a single theory the description of all four known forces of nature.

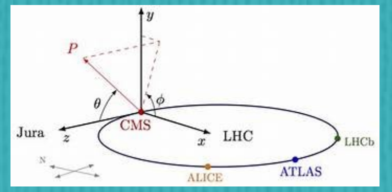





The data that we are using in this research project is from the The Large Hadron Collider (LHC), which is the largest particle accelerator in the world, located at CERN in Switzerland (not pictured). It is an underground structure about 17 miles in circumference where protons are accelerated and made to collide at 4 spots, and the particles that result from that collision are measured. **We took our research data more specifically from one of those 4 detectors, called the CMS, or Compact Muon Solenoid (pictured above).** As can be seen, these detectors are multi-layered with different fundamental particles producing differing experimental traces in its subcomponents.

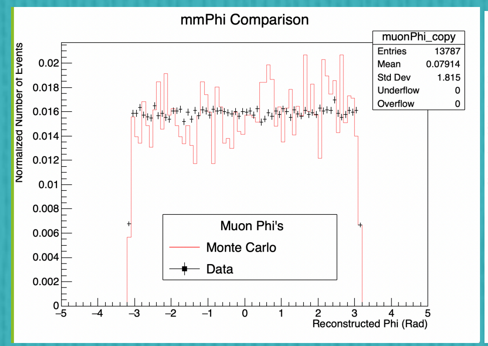
## Characterizing the Higgs Signal and Drell Yan Background Kinematics

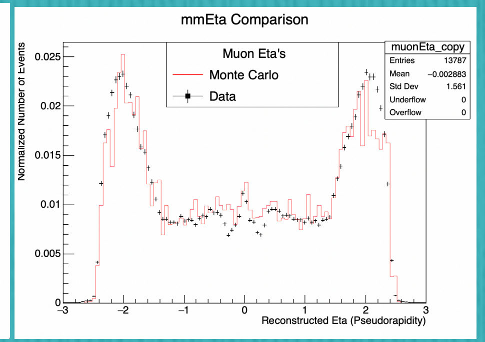
Phi: $\Phi$




Eta: $\eta \equiv -ln\left[tan\left(\frac{\theta}{2}\right)\right]$

- **We started by developing our algorithms on a background process that behaves very similarly to the VBF Higgs process, namely, Z Boson production and decay into leptons (AKA Drell-Yan).**
- The reason is because the Drell-Yan process is about 9 Million times more likely to occur than the VBF Higgs (these processes are probabilistic), resulting in more data events for us to work with.
- We analyzed a Monte Carlo (MC) theoretical simulation of the Drell-Yan process, as it interacts with a simulated CMS detector, starting with comparing kinematical variables between different decay products like Muons, Taus, Electrons, and particle streams called "Jets", and finishing between comparing the MC with real-world data.

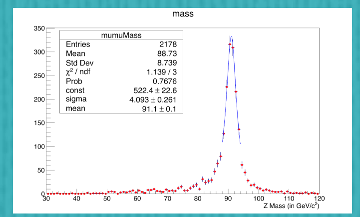


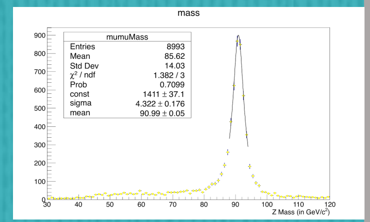




Drell Yan Z event crude selection criteria:

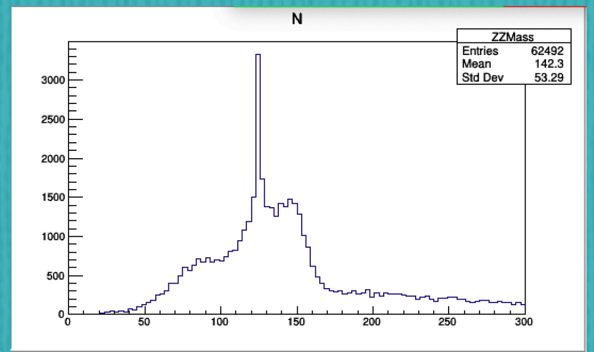
- 2 Opposite charge leptons, or quark Jets, of Pt>20GeV and $\eta$<2.1 (means hard scattered jets are selected if Z decays into quarks)
- $\Delta R > 2$ between leptons or "hard" jets
- Secondary Vertex displacement X & Y >0.07
- Isolation < 0.1 for Electrons and Muons
- MET< 2 GeV

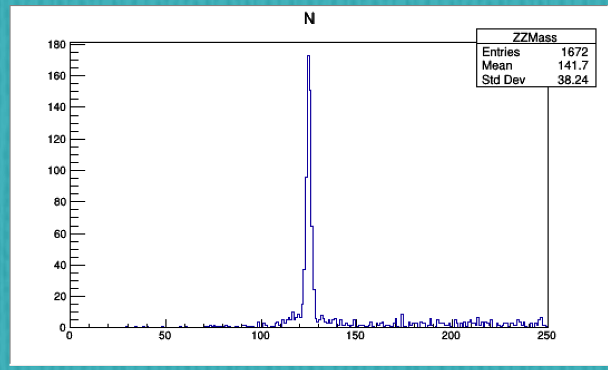
- We then compared our MC plots and real-world data plots with a Breit-Wigner fit, and saw that they agreed well (of the graphs to the right: the red is MC, yellow is data).
- Simulation Validation studies were made with Background (Drell-Yan) decaying into 2 muons.
- The VBF Higgs selection criteria is 4 final state muons
- We generated filtered data samples with both Drell-Yan background and Higgs signal samples that survived our event selection cuts



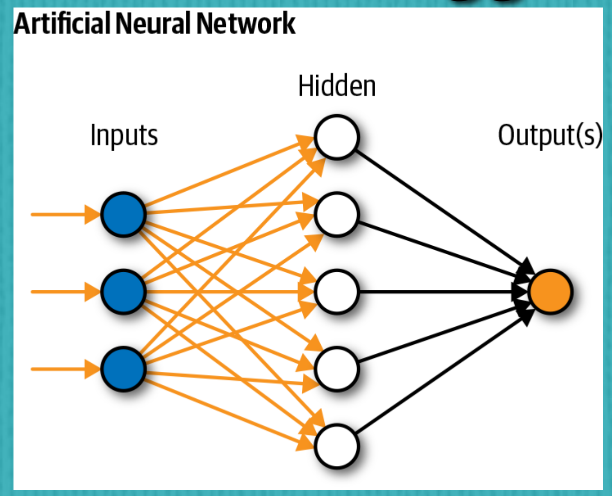



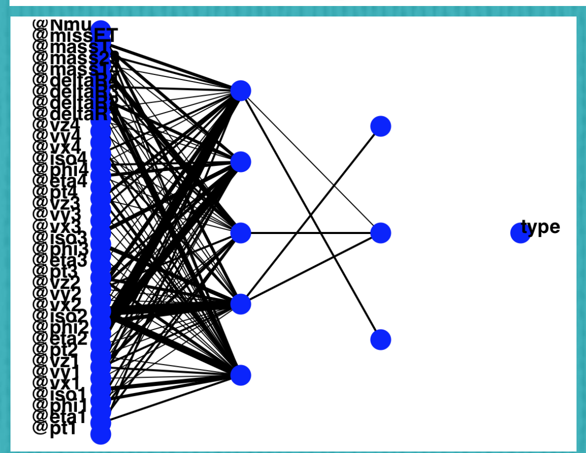

- Our first attempts to reconstruct the Higgs mass from our simulated Monte Carlo sample resulted in a main peak at 125 GeV, which is the expected mass of the Higgs
- We eventually found a flaw in our our mass reconstruction algorithm. After correcting this algorithm's issues, Higgs' mass peak is very nicely reconstructed at 125 GeV with little noise (bottom right).



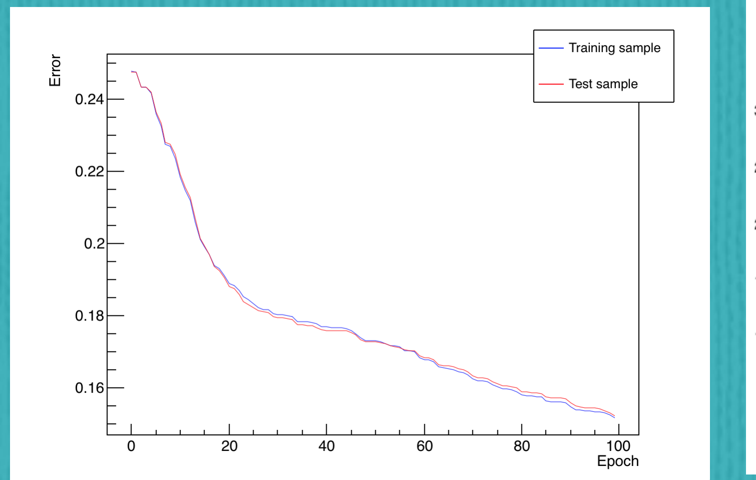

## Neural Network Separation of Higgs and Background

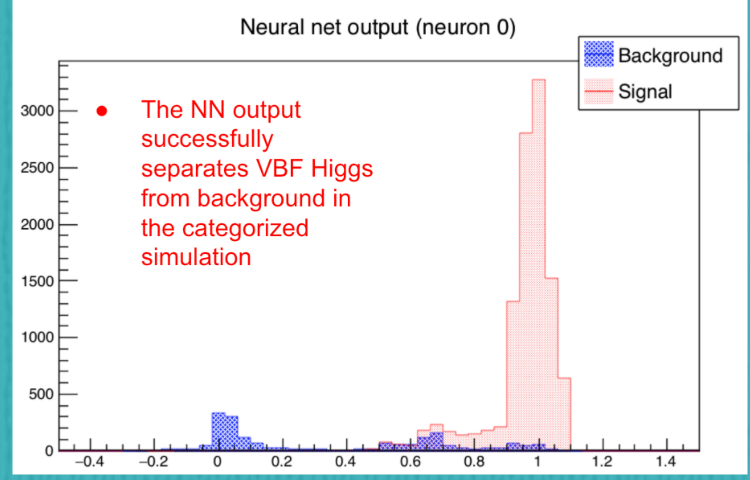


- My colleague, Julian, then took these events and created a special type of file called an Ntuple, with the purpose of using those Ntuple files as inputs to train a neural network (NN) to distinguish between the Higgs events that we want to study from background events that we do not want to study. The end goal is training the neural network with our simulated Higgs and Background events to increase the efficiency of selecting the right events ("Higgs acceptance") and then applying it to filtered Ntuples extracted from experimental data.
- The illustrations to the left are a visual representation of the Neural Network's training algorithm, with the leftmost circles being all of the input variables of our data (measurements of: phi, eta, pt., etc.), the inner circles being the hidden layers of "neurons", and the rightmost circle being the output.
- The output of our Neural network is just one neuron with a value of 1 for signal (Higgs) and 0 for background processes.
- The arrows between circles of varying thickness are the neural network weights after we had trained our algorithm. Signifying the impact that each particle kinematical variable on the final output..

- We had a great amount of success with the training of the NN using Ntuples from the MC simulation. These figure below left represents the error associated with the training by "epoch", which is one iterative round of adjustments to the NN weights. As expected the error decreases and begins to stabilize as the iterative epochs progress.
- The bottom right figure represents the output of our NN algorithm. **If it is working efficiently we expect signal categorized events grouped near a value of 1 and background events near 0. And it indeed behaves this way.** The network is not fully optimized, however, as evidenced by some of the background samples peaking away from the main peak at 0




- **Our ultimate goal is to further optimize this NN and then apply it to experimental CMS data, on order to hopefully observe VBF Higgs events for the first time**
- My main task over the coming summer will be to optimize this NN in order to increase as much as possible the sensibility of this search methodology for VBF Higgs bosons at CMS

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