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OPTIMIZATION OF THE SEARCH CRITERIA FOR DETECTING THE STANDARD MODEL HIGGS BOSON DECAYING TO WW^* BOSONS

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OPTIMIZATION OF THE SEARCH CRITERIA FOR DETECTING THE STANDARD MODEL HIGGS BOSON DECAYING TO WW^* BOSONS

A THESIS APPROVED FOR THE HOMER L. DODGE DEPARTMENT OF PHYSICS AND ASTRONOMY

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Abstract

It is important to measure the properties of the Higgs boson that has been detected at the LHC to determine if it exactly matches the predictions of the Standard Model (SM) Higgs or if it deviates from those predictions. For example, it may also be a superposition of Higgs-like particles. Improving the signal of the Higgs boson will help experimentalist determine the properties of the particle and discern whether it is the actually the SM Higgs. Cuts are made on kinematic variables to maximize the signal and minimize the background. Gridscanner was used to determine whether the default cuts used to process data have been optimized such that the signal to background ratio for the 0-jet signal region of the SM Higgs is a maximum. The Higgs data used for this analysis is from the production of the Higgs via gluon-gluon fusion (ggF). These Higgs particles are then measured in the H $\rightarrow WW^{*} \rightarrow e\nu\mu\nu$ decay channel. The analysis began by making gridscanner plots of the various parameters of interest. It was found that the default cuts were in agreement with the gridscanner plots up to a certain degree of uncertainty. New cuts were then tested in the analysis. Examination of the cutflows revealed that the new cuts yielded a lower signal to background ratio then the default. Further analysis showed that each individual default cut is superior to each corresponding new cut. This process was then repeated for a restricted M_T region 60 < M_T<140 GeV. It was decided to investigate this restricted region because this mass range contains the majority of the Higgs signal.

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Theoretical Background

The Standard Model contains all theories describing the behavior and interaction of known subatomic particles. The Standard Model (SM) contains two main classifications of particles. The first being Fermions, which have half integer intrinsic spin (e.g. $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \ldots,$) (Weiner). Fermions constitute the fundamental building blocks of matter ("The Standard Model"). Then there are Bosons, which have integer intrinsic spin (e.g. 1, 2, 3,…,). The fundamental Bosons of the SM are mediators of the fundamental forces ("The Standard Model").

Fermions are divided into three generations, with each generation containing more massive particles (Thomson, 2). Further sub-divisions are then made based on their different interactions with the fundamental forces. There are two fundamental fermions types, quarks and leptons, from which all matter can be constructed (Thomson, 4). Quarks are fermions with $\frac{1}{2}$ spin. Each generation of quark contains two quarks that differ by charge. There are the up-type quarks with an electric charge of $+\frac{2}{3}$ and the down-type with electric charge $-\frac{1}{3}$. The three up-type quarks in order of ascending mass are known as the up, charm and top quarks. Similarly, the three down-type quarks in order of ascending mass are: the down, strange and bottom quarks (Braibant et al. 10).

Leptons, like quarks are fermions. However they differ in that they do not possess color charge and therefore do not interact with the strong force (Thomson, 4). There are also three generations of lepton that differ by mass and are separated within the generations by charge. The electron, muon and tau-lepton have a charge of -1. While, the electron neutrino, muon neutrino and tau neutrino have zero charge (Thomson, 3). Furthermore each fermion has its own antiparticle that is opposite in charge and chirality.

Generation	1^{st}	2^{nd}	3^{rd}	Charge (Q)
Quarks	Up	Charm	Top	$+\frac{2}{3}$
	Down	Strange	Bottom	$-\frac{1}{3}$
Leptons	Neutrino Electron	Neutrino Muon	Neutrino Tau	0
	Electron	Muon	Tau	-1

Table 1: SM Fermions grouped by their generation and charge.

Bosons in the SM, as stated previously are force mediators. When specific bosons are exchanged between particles a discrete amount of energy is transferred. Each fundamental force is mediated by the exchange of particular bosons. Strong interactions are mediated by gluons, while the electroweak interactions are mediated by massive $W^{\pm}$ bosons and Z bosons along with massless photons ("The Standard Model"). Gravity is currently not included in the Standard model; however, the proposed, but undiscovered graviton, should be the corresponding force-carrying particle of gravity. The Higgs is the most recent boson to be discovered and was confirmed in 2012 by ATLAS and CMS. It was a monumental discovery because the Higgs field gives mass to all massive elementary particles. The Higgs Mechanism was introduced to explain why the $W^{\pm}$ and Z bosons have mass. The Higgs mechanism works by breaking electroweak symmetry. The Higgs Boson itself is produced by a quantum excitation of the Higgs field (Thomson 460, 470).

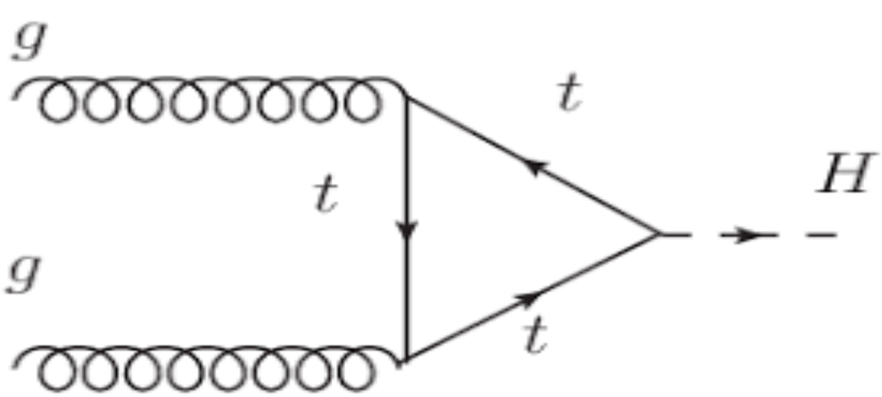
Mediator	Charge	Mass	Description
8 gluons	0	0	Strong mediator
Photon (γ)	0	0	Electromagnetic mediator
$W^{\pm}$	± 1	~80.4 GeV	Weak mediator
Z^0	0	~91.2 GeV	Weak Mediator
Higgs Boson	0	125.2 GeV	Couples with massive particles

Table 2: SM bosons grouped by their charge, mass and force mediation.

Higgs Production

The Higgs Boson was discovered in 2012 at the Large Hadron Collider (LHC). The Higgs boson is different from other gauge bosons in that it is a spin 0 scalar particle (Thomson 6). The Higgs had proven to be elusive due to its small production cross-section and high mass of 125 GeV ("The Higgs Boson"). However, after the construction of the LHC the Higgs was finally detected by the ATLAS and CMS detectors.

The Higgs can be produced through a variety of methods. The four main production mechanisms of the Higgs Boson at the LHC are gluon-gluon fusion (ggF), vector-boson fusion (VBF), associated production with a gauge boson and associated production with a pair top or antitop quarks (Grojean). Of these different production methods ggF has the greatest production cross-section by an order of magnitude. This is the Higgs production mechanism used for this thesis. Gluon-gluon fusion occurs by colliding two protons. Protons are comprised of two up quarks and one down quark held together by the strong force mediated by gluons. If the gluons inside these two protons have sufficient energy upon collision, they may generate a virtual top quark and virtual anti top quark, which can then annihilate to produce the Higgs (Figure 1) (Charley, How to Make a Higgs Boson).

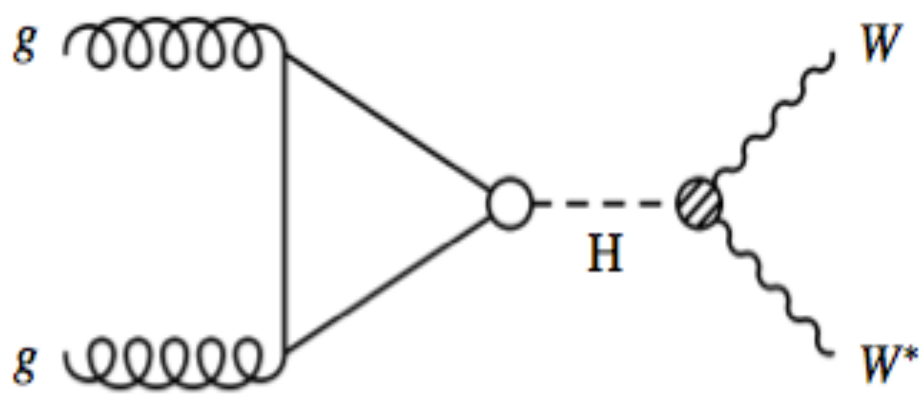


Adelman, Jahred et al. "Representative Feyman diagram of Higgs boson production via gluon fusion." Inspire-HEP, http://inspirehep.net/record/1256937/plots

Figure 1: Higgs produced through a top quark loop.

Higgs Decay

The Higgs decays extremely rapidly and as a result of this what is detected is not the actual Higgs but the remnants of its decay. For this reason understanding the decay modes of the Higgs is crucial. In 2018 it was discovered that the Higgs has a decay mode to bottom quarks ($b\bar{b}$). Theoretical predictions indicate that this is the most common decay mode and occurs 60% of the time. This decay mode is extremely challenging to detect since it is a hadronic decay and hard to distinguish from the other activity present in a hadronic collision (Charley, LHC Scientists Detect Most Favored Higgs Decay). The decay mode that is studied in this thesis is the decay mode H → WW^*, where one W boson decays leptonically to an electron and an electron neutrino and one W boson decays leptonically to a muon and muon neutrino. Since the W bosons decay leptonically events of interest are easier to distinguish.

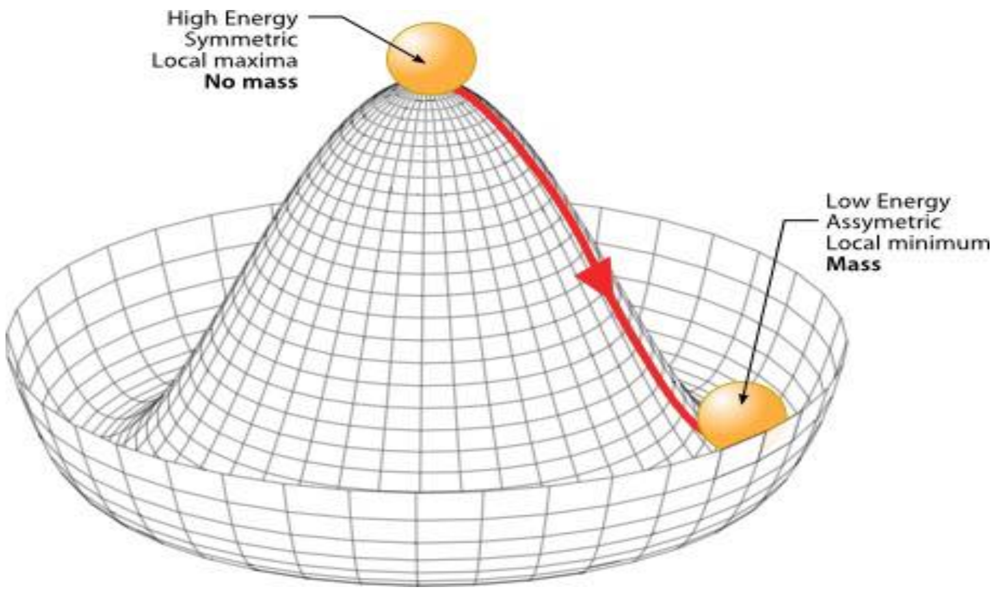


Aaboud, M et al. "ggF production." Physics Letters B, 29th August 2018 https://arxiv.org/abs/1808.09054.

Figure 2: Higgs production via ggF that results in the Higgs decaying to WW^*

Higgs Physics

The Higgs field gives intrinsic mass to fundamental particles through the process of spontaneous symmetry breaking. Spontaneous symmetry breaking is a mode of symmetry breaking, where the underlying laws are invariant under a symmetry transformation, however the system as a whole changes. The Higgs field potential energy can be visualized as a "Mexican hat" (Bellaiche).



Bellaiche, Fred. 2nd September 2012, http://www.quantum-bits.org/?p=233.

Figure 3: Demonstrates spontaneous symmetry breaking.

The vacuum expectation value is therefore non-zero. The Higgs mechanism works by adding spontaneous symmetry breaking to the SU(2)×U(1) gauge theory. This allows the photon to remain massless, while giving mass to the Z and $W^{\pm}$ boson. Fermions also acquire mass from the Higgs field by Yukawa coupling between the fermion field and the Higgs field (Bellaiche).

The simplest Higgs model is the single Higgs doublet, which has four degrees of freedom and two complex scalar fields. Since the Higgs Mechanism is responsible for generating the mass of the electro-weak bosons one of the scalar fields must be neutral (ϕ^0), because Z boson are neutral. The other field must be charged ($\phi^+ = (\phi^-)^*$) to account for the $W^{\pm}$ bosons (Thomson, 479).

$$\phi = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

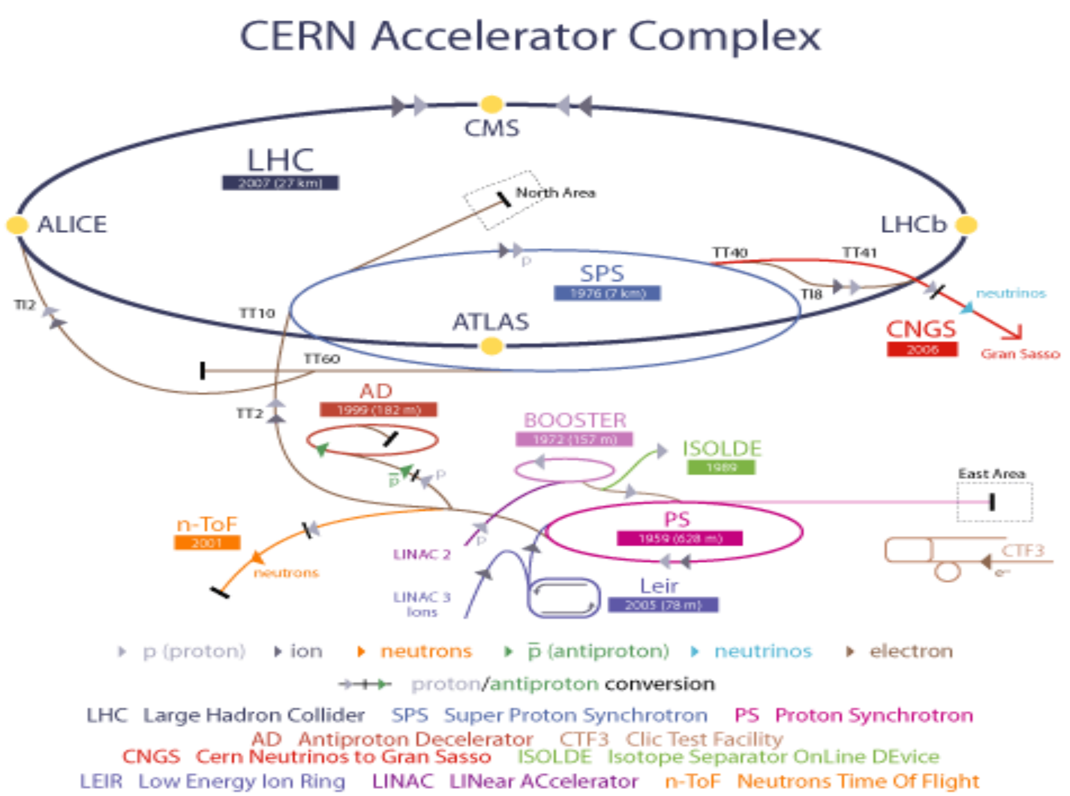
Since the Higgs is a quantum particle it possible that the discovered Higgs could be a superposition of states. Therefore what we are currently calling the Higgs may actually be a superposition of the SM Higgs and a heavier resonance Higgs.

$$\phi = \alpha\phi' + \beta\phi'' + \ldots +$$

In the above equation ϕ is the particle that has been detected. ϕ' is the standard model Higgs and ϕ'' is a higher mass Higgs. α and β are coefficients that dictate probabilities for ϕ' and ϕ'' such that $|\alpha|^2 + |\beta|^2 + \ldots + = 1$. Studying the Higgs is important to determine if the particle detected at the LHC exactly matches the SM Higgs. Other possible models include two and even three Higgs doublet models. These models may be verified through experimental test and analysis.

Large Hadron Collider

The Large Hadron Collider is the world's most powerful particle accelerator. Inside the LHC high-energy particle beams travel at near the speed of light inside until collisions take place. Particles travel in separate beam pipes maintained at ultrahigh vacuum and are guided by a powerful magnetic field generated by superconducting electromagnets. Once the particles obtain their peak energy inside the LHC they are guided into one of the four detectors where the actual collisions takes place ("The Large Hadron Collider").



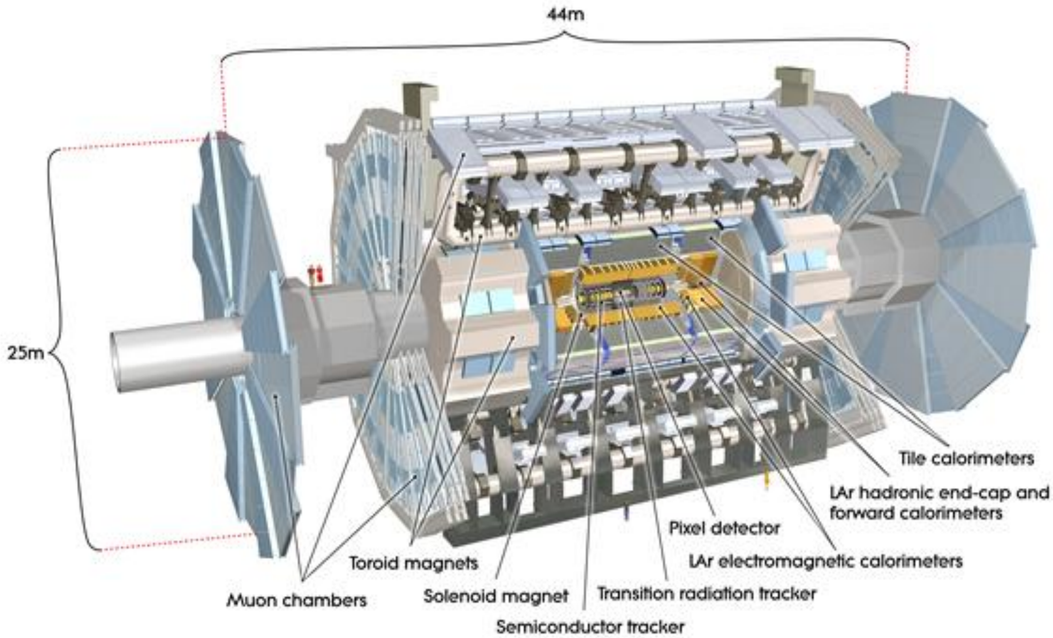
Mobs, Esma. "The LHC is the last ring (dark blue line) in a complex chain of particle accelerators. The smaller machines are used in a chain to help boost the particles to their final energies and provide beams to a whole set of smaller experiments, which also aim to uncover the mysteries of the Universe." 08-07-2018, https://cds.cern.ch/record/2197559

Figure 4: Layout of CERN.

ATLAS Detector

The ATLAS detector is one of the general-purpose detectors used to make measurements of the Higgs, precision tests of the Standard Model, and investigate beyond the Standard model phenomena (“ATLAS”). It is located at CERN, 100 m underground, and is the largest volume particle detector ever built. Particles accelerated at the LHC collide at the center of the ATLAS detector (“ATLAS”). The impact results in the formation of new particles that can then be detected inside of ATLAS. ATLAS achieves nearly full solid angle coverage and uses six different detecting subsystems arranged in layers around the collision point. The detector records the paths, momentum and energy of the particles. This information can then be used to identify new particles. The collision of particles produces an enormous amount of data. In order to process this data ATLAS uses a trigger system. Trigger systems determine which events will be recorded for future analysis by making a fast decision on whether the event is potentially unusual or interesting, or whether it can be ignored. The remaining data is then analyzed using complex data-acquisition and computing systems (“ATLAS”).

ATLAS consists of various components including an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic calorimeters, hadronic calorimeters and a muon spectrometer. The inner tacking detector is situated in a 2 T magnetic field and measures the trajectory of particles up to a pseudorapidity of $|\eta|$ = 2.5. In particle physics pseudorapidity ($\eta = -\ln\left[\tan\frac{\Theta}{2}\right]$) is a spatial coordinate that describes the angle of a particle relative to the beam axis. Here Θ is the angle between the positive direction of the beam axis and the particles three momentum (Wong 24). Pseudorapidity is a useful spatial coordinate since it is Lorentz invariant. Outside the inner detector are the calorimeters, which measure the energy of particles. The muon spectrometer consists of two separate trigger chambers for event selection and measures the momentum of muons by their deflection in a magnetic field (Aaboud et al, Measurements of Gluon–Gluon Fusion 3).



Pequenao, Joao. "Computer generated image of the whole ATLAS detector." 27th March 2008, http://atlas.cern/discover/detector

Figure 5: ATLAS Detector

Purpose of Cuts

Cuts are made on kinematic variables that have different shapes for signal and background. Effective cuts maximize the signal and minimize the background. The signal is the particular particle physics phenomenon that we are interested in studying. The background constitutes all events that look very similar to our signal, but are not of interest. In the case of Higgs detection there are many other decay channels produced from the proton collision besides the ones stemming from the Higgs that have final state particles very similar to, or even exactly identical to, those of the Higgs signal. These similar decay channels makeup the background.

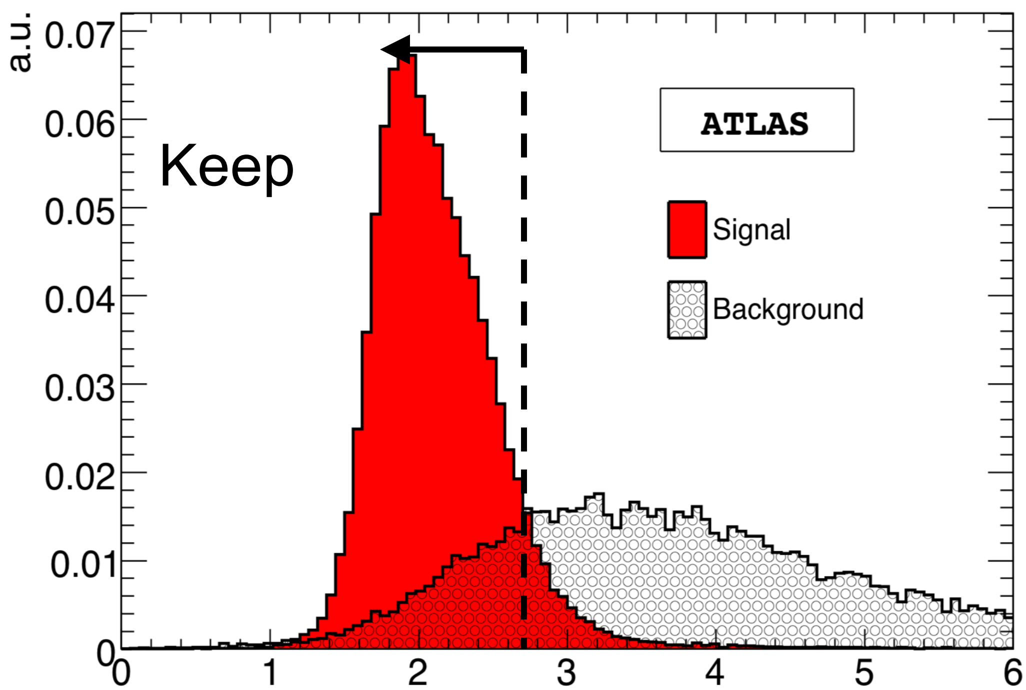
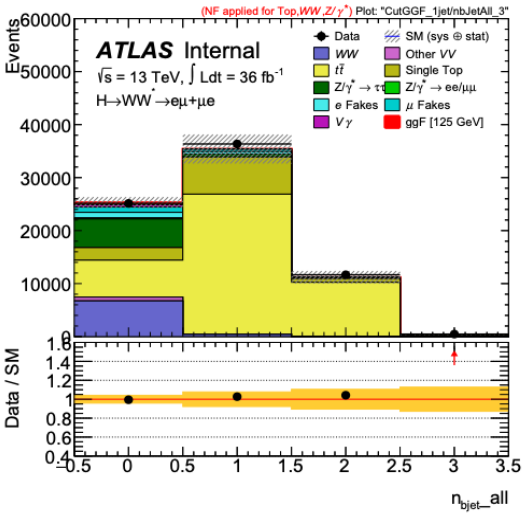
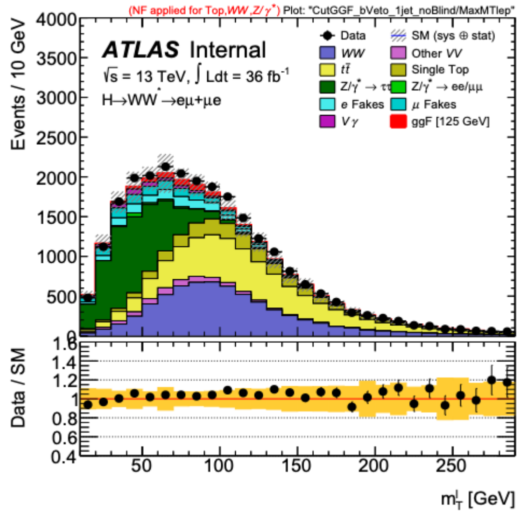


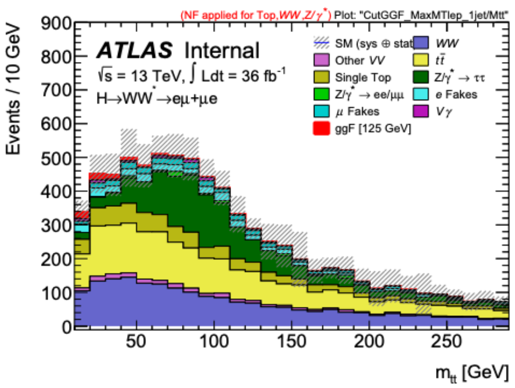
Figure 6: This graph demonstrates how an effective cut is made. The dotted line represents where a cut would be made. Placing a cut in this region will keep the majority of the signal (red), while eliminating most of the background (grey).



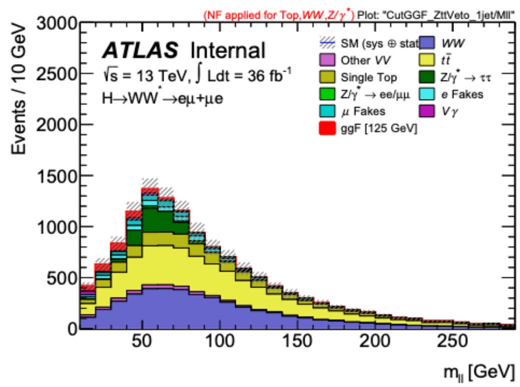
(a) $N_{b\text{-jet}}$ after the cut on $N_{\text{jet}} = 1$



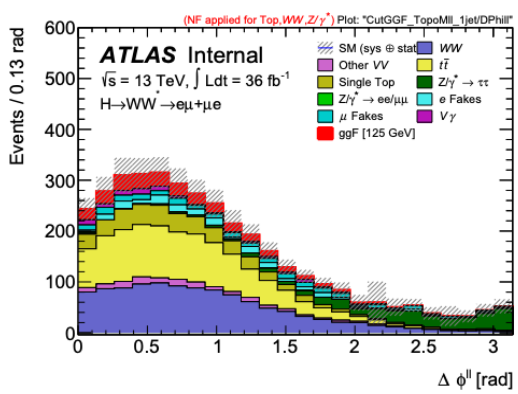
(b) m_{T}^{ℓ} after the cut on $N_{b\text{-jet}} = 0$



(c) $m_{\tau\tau}$ after the cut on $\max(m_{\text{T}}^{\ell}) > 50\,\text{GeV}$

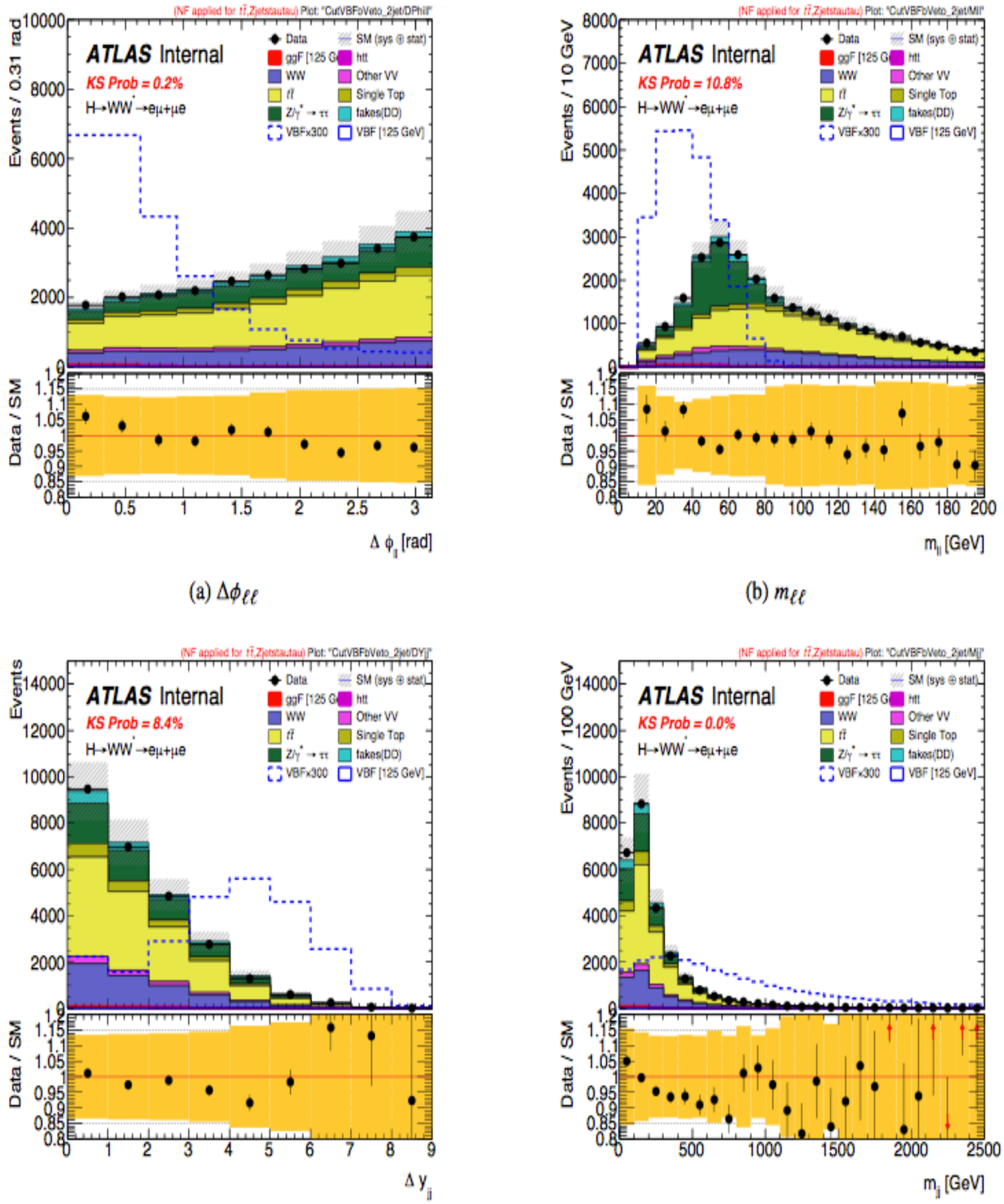


(d) $m_{\ell\ell}$ after the cut $m_{\tau\tau} < m_Z - 25\,\text{GeV}$



(e) $\Delta\phi_{\ell\ell}$ after the cut $m_{\ell\ell} < 55\,\text{GeV}$

Figure 7: These ggF plots demonstrate how the signal to background ratio is gradually increased as cuts are made over the various parameters.



(a) $\Delta\phi_{\ell\ell}$ (b) $m_{\ell\ell}$

(c) Δy_{jj} (d) m_{jj}

Figure 8: These are VBF plots that indicate how the signal region can be separated from the background. The blue dotted line represents 300 × the signal, the rest of the stack plots is background. Using this visualization it is clear how cuts can be made over the various parameter to keep the signal (dotted line), while removing the background.

Gridscanner

Given that cuts affect the signal to background ratio, it is important that the correct cuts are being used to optimize this value. In the context of this thesis the signal to background ratio means $\frac{S}{\sqrt{S+B}}$, where S is the signal and B is the background. For this thesis Gridscanner was used to check whether the default cuts given had been optimized. Gridscanner is a program used by ATLAS to generate plots of the expected significance vs. the parameters over which the cuts are made. The expected significance in this case was defined as $\frac{S}{\sqrt{S+B}}$. The plots generated using Gridscanner showed what regions of each specific parameter contained the largest expected significance. The direction of the arrows indicates what side of the maximum value should be kept when making a cut.

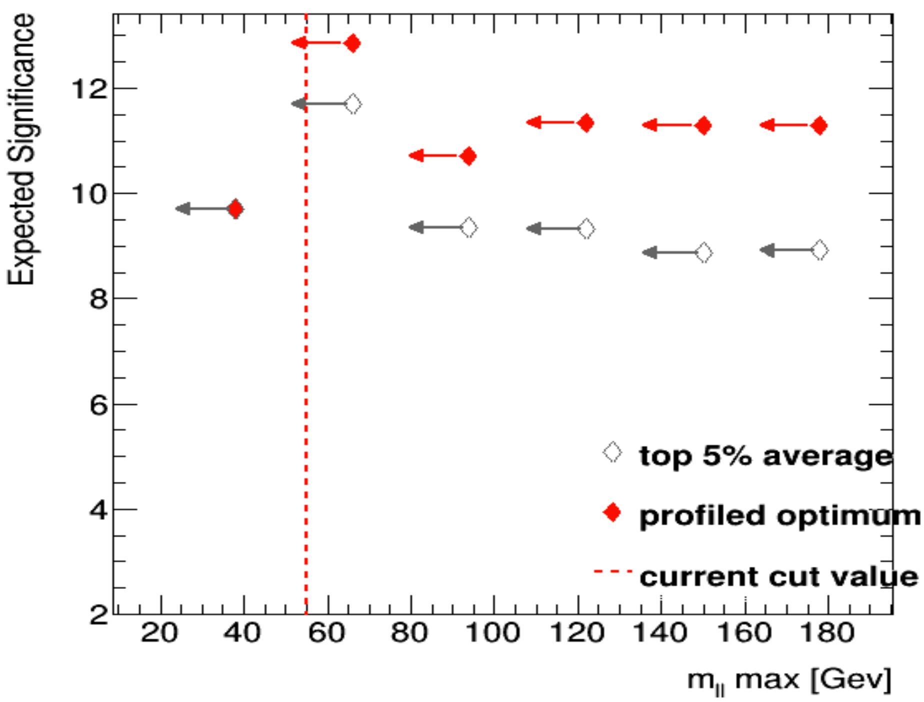


Figure 9: Gridscanner plot of the mass of the leading lepton (M_{ll}). From this plot it is clear that the cut should be made keeping the region less than 55 GeV. This plot was made over the entire M_T region. The profiled optimum (red arrows) represent the best value obtained when using a fixed M_{ll} value and selecting the best value of the other parameters in the parameter space. The top 5% average (grey arrows), represent the top 5% of values from the parameter space with M_{ll} fixed.

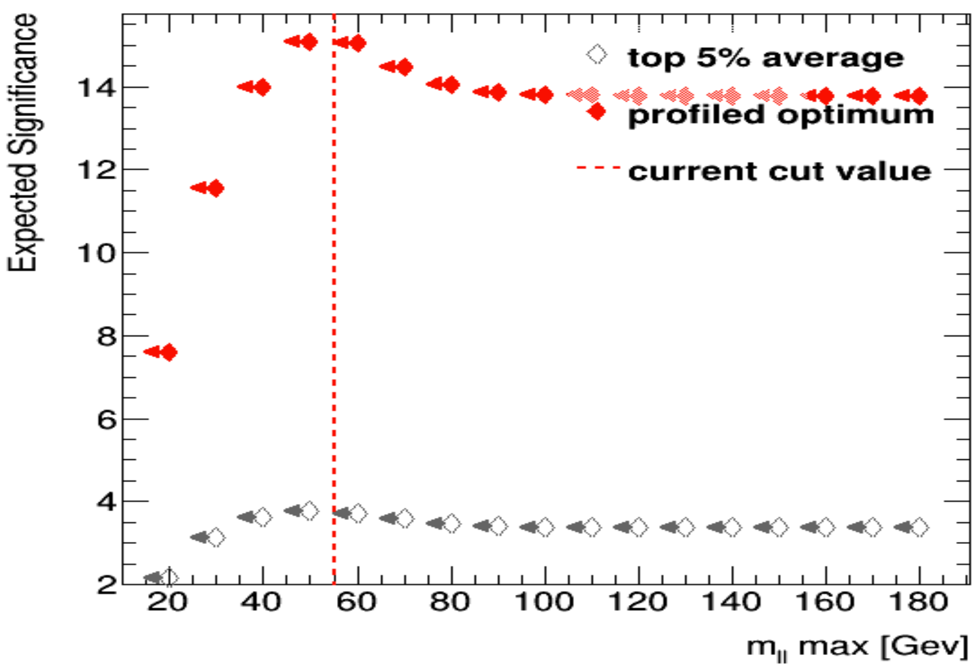


Figure 10: Gridscanner plot of M_{ll} over a restricted M_T region from 60 to 140 GeV. This plot also indicates that a cut should be made keeping the region less than 55 GeV.

Gridscanner Results

Gridscanner plots were made using two separate selection criteria. The first run was made over the entire transverse mass (M_T) region. The transverse mass is defined as being invariant under a Lorentz boost along the *z* direction (which is parallel to the proton beam direction). In natural units the general equation can be written as $M_T = \sqrt{m^2 + p_x^2 + p_y^2}$ (Beringer et al). For this thesis the specific form of M_T that must be used is $M_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - \left|p_T^{ll} - E_T^{miss}\right|^2}$ (Aaboud et al, Search for Heavy Resonances 5). The gridscanner plots were created for the parameters listed in the table below. The gridscanner plots indicated that the default cuts were close to the maximum optimization. This is because the cuts inferred from gridscanner were in agreement with the default plots up to a certain degree of uncertainty. This was confirmed when stack plots produced from slightly different cuts yielded a lower signal to background ratio than the default. The next set of gridscanner plots were made over a restricted M_T region from 60 to 140 GeV. It was decided to investigate this restricted region because this is the mass range over which most of the Higgs signal is found. The default cuts for the restricted M_T region were also in agreement with the gridscanner plots up to a certain degree of uncertainty.

Default Cuts	New Cuts (unrestricted M_T region)	New Cuts (60 GeV < M_T < 140 GeV)
$M_{ll} < 55\ GeV$	$M_{ll} < 55\ GeV$	$M_{ll} < 55\ GeV$
$\Delta\varphi\ (ll, E_T^{miss}) > 1.57$ rad	$\Delta\varphi\ (ll, E_T^{miss}) > 1.75$ rad	$\Delta\varphi\ (ll, E_T^{miss}) > 1.57$ rad
$P_T^{\ell\ell} > 30$	$P_T^{\ell\ell} > 22$	$P_T^{\ell\ell} > 35$
$\Delta\varphi_{ll} < 1.8$ rad	$\Delta\varphi_{ll} < 1.4$ rad	$\Delta\varphi_{ll} < 2.1$ rad
$p_T^{lead} > 22$ GeV	$p_T^{lead} > 35$ GeV	$p_T^{lead} > 27$ GeV
$p_T^{sublead} > 15$ GeV	$p_T^{sublead} > 18$ GeV	$p_T^{sublead} > 18$ GeV
$E_T^{miss} > 45$ GeV	$E_T^{miss} > 45$ GeV	$E_T^{miss} > 45$ GeV

Table 3: List of default cuts and new cuts made.

Stack Plots Signal to Background Ratios

The ultimate goal of this research was to investigate whether the signal to background ratio for the Higgs boson had been optimized. If not new cuts would then be made to optimize it. Four different sets of cuts were used to create stack plots. The first stack plots made were for the default cuts. The signal to background ratio of the 0-jet signal region was then determined from the cutflows. The signal to background ratio ($\frac{S}{\sqrt{S+B}}$) for the default cuts was determined to be 13.94. Then using the gridscanner plots a new set of cuts was decided upon and another set of stack plots were produced using these new cuts. These new cuts generated a signal to background ratio of 6.79. This value was less than the default. However, the cuts used were close in value since the gridscanner plots agreed with the default values up to a certain degree of uncertainty. Next the M_T region was restricted from 60 to 140 GeV and the default cuts were used. The signal to background ratio was found to be 15.40. It was expected that this restricted region would yield a higher signal to background ratio, since very little Higgs signal exists outside this region. Finally stackplots were generated for new cuts made in the restricted M_T region. The cuts produced a signal to background ratio of 13.08.

	Default cuts	New cuts	Restricted M_T region with default cuts	Restricted M_T region with new cuts
Signal to Background ratio	13.94	6.79	15.40	13.08

Table 4: Final signal to background ratio's that resulted from the various cuts made. These were obtained for the 0-jet signal region. The first two columns are for the entire M_T and therefore can be compared. The last two columns are for the restricted M_T and can be compared.

The effectiveness of each cut made was then determined by calculating its associated signal to background ratio. The percent difference between cuts was then obtained to compare the individual cuts. This was done because even if the total signal to background ratio of the default cuts is higher this does not guarantee that each individual cut in the cutflow is superior. Each default cut for the unrestricted M_T region was found to be superior. In the restricted M_T region two new cuts produced a better percent difference than the corresponding default cuts. These cuts were $p_T^{lead} > 27$ GeV and $\Delta\varphi_{ll} < 2.1$ rad. The first term is the transverse momentum of the leading lepton and the second is the azimuthal angle between the two leptons (Aaboud et al, Measurements of Gluon–Gluon Fusion 5). These cuts were then used to produce stackplots with all the other cuts set to the default to confirm whether they can actually improve the signal the background ratio. The $p_T^{lead} > 27$ GeV cut produced a signal to background ratio of 14.75, which is slightly lower than the default. The $\Delta\varphi_{ll} < 2.1$ rad cut produced a signal to background ratio of 15.63, the highest achieved thus far. Therefore, the $\Delta\varphi_{ll} < 2.1$ rad cut is superior to the default in the restricted M_T region. This new cut was then used in the unrestricted region with the other cuts set to the default and it improved the signal to background ratio to 14.27.

Defaults cuts	Signal to background ratio	Percent difference	New cuts	Signal to background ratio	Percent difference
$p_T^{lead} > 22$ GeV	4.33	5.7%	$p_T^{lead} > 35$ GeV	3.66	18.51%
$p_T^{sublead} > 15$ GeV	4.09		$p_T^{sublead} > 18$ GeV	3.04	
$E_T^{miss} > 45$ GeV	4.53	10.21%	$E_T^{miss} > 45$ GeV	2.81	7.86%
$\Delta\varphi\ (ll, E_T^{miss}) > 1.57$ rad	7.02	43.12%	$\Delta\varphi\ (ll, E_T^{miss}) > 1.75$ rad	3.75	28.66%
$P_T^{\ell\ell} > 30$	7.71	9.37%	$P_T^{\ell\ell} > 22$	3.91	4.81%
$M_{ll} < 55\ GeV$	13.82	56.76%	$M_{ll} < 55\ GeV$	7.76	65.98%
$\Delta\varphi_{ll} < 1.8$ rad	13.49	2.42%	$\Delta\varphi_{ll} < 1.4$ rad	6.51	17.52%

Table 5: Table of the default and new cuts made for the unrestricted M_T region. The table includes the signal to background ratio and percent difference for each of the cuts.

Restricted M_T region default cuts	Signal to background ratio	Percent difference	Restricted M_T region new cuts	Signal to background ratio	Percent difference
p_T^{lead} > 22 GeV	5.16	3.35%	p_T^{lead} > 27 GeV	5.18	8.87%
$p_T^{sublead}$ > 15 GeV	4.99		$p_T^{sublead}$ > 18 GeV	4.74	
E_T^{miss} > 45 GeV	7.20	36.26%	E_T^{miss} > 45 GeV	6.10	25.09%
Δφ (ll, E_T^{miss}) > 1.57 rad	9.25	24.92%	Δφ (ll, E_T^{miss}) > 1.57 rad	7.92	25.96%
$P_T^{\ell\ell}$ > 30	12.23	27.75%	$P_T^{\ell\ell}$ > 35	10.50	28.01%
$M_{ll} < 55\ GeV$	15.20	21.65%	$M_{ll} < 55\ GeV$	12.775	19.55%
$\Delta\varphi_{ll}$ < 1.8 rad	15.06	0.925%	$\Delta\varphi_{ll}$ < 2.1 rad	12.769	0.047%

Table 5: Table of the default and new cuts made for the restricted M_T region. The table includes the signal to background ratio and percent difference for each of the cuts.

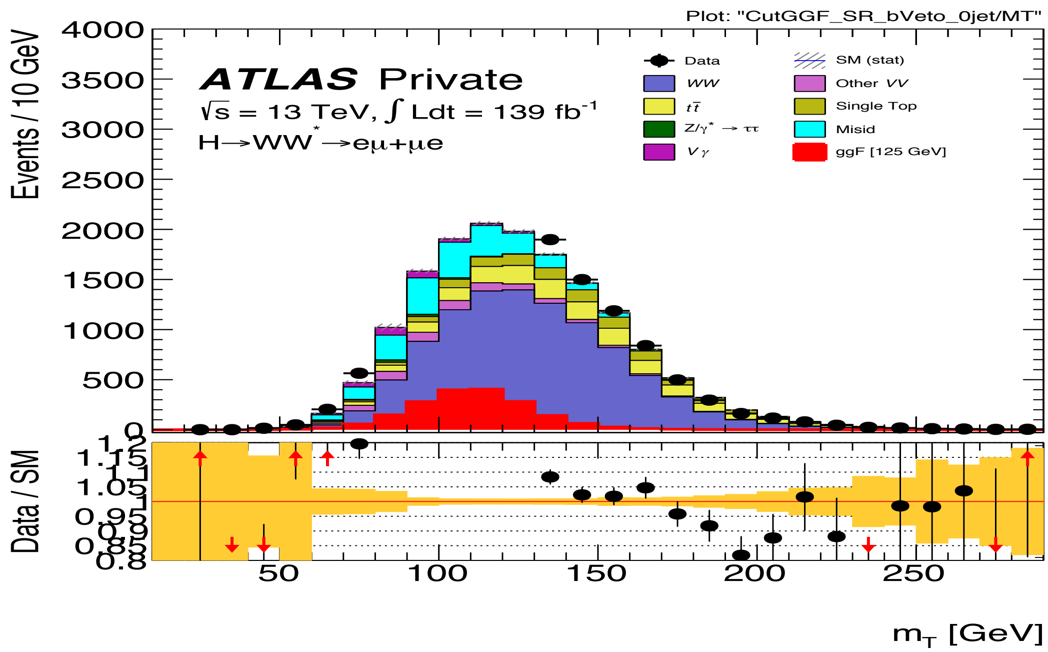


Figure 11: Stack Plots of $e\nu\mu\nu$ final state. The entire M_T region is used with the default cuts.

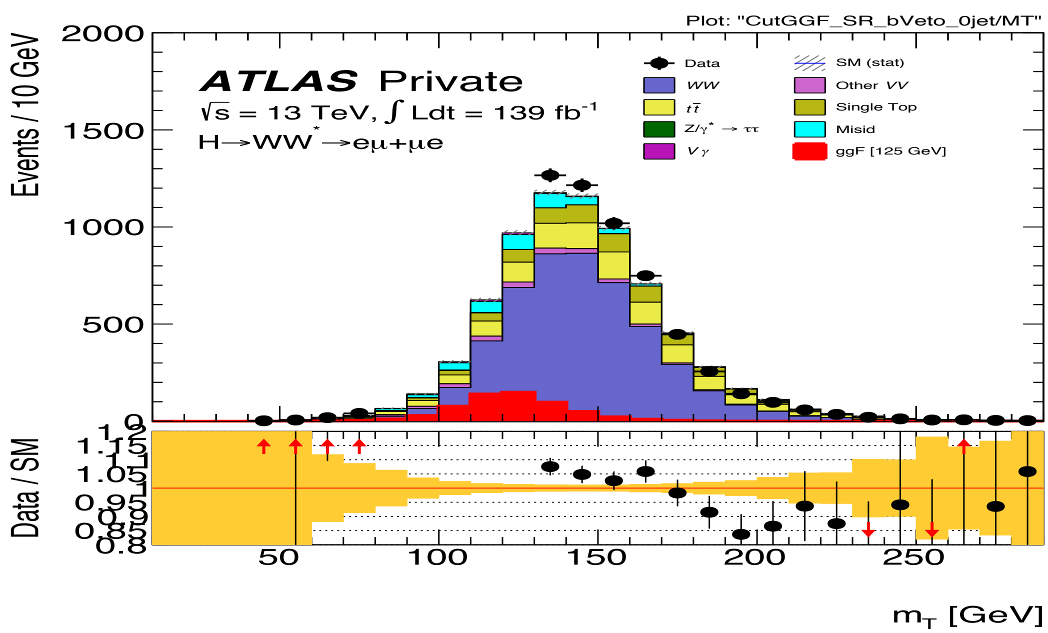


Figure 12: Stack Plots of $e\nu\mu\nu$ final state. The entire M_T region is used with the new cuts made from examining gridscanner plots.

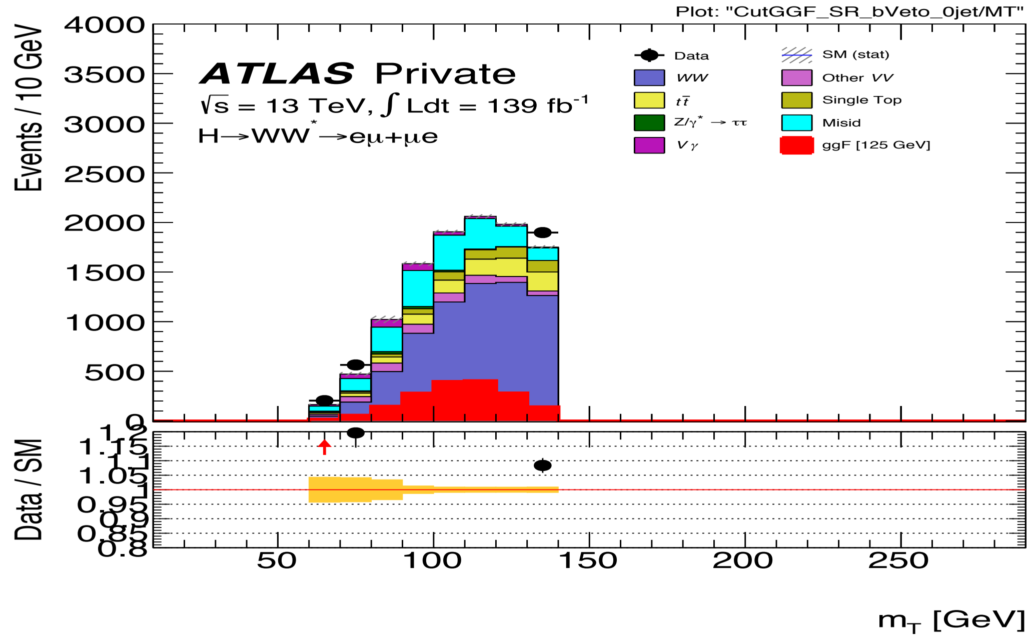


Figure 13: Stack Plots of $e\nu\mu\nu$ final state. The M_T region from 60 to 140 GeV is used with the default cuts.

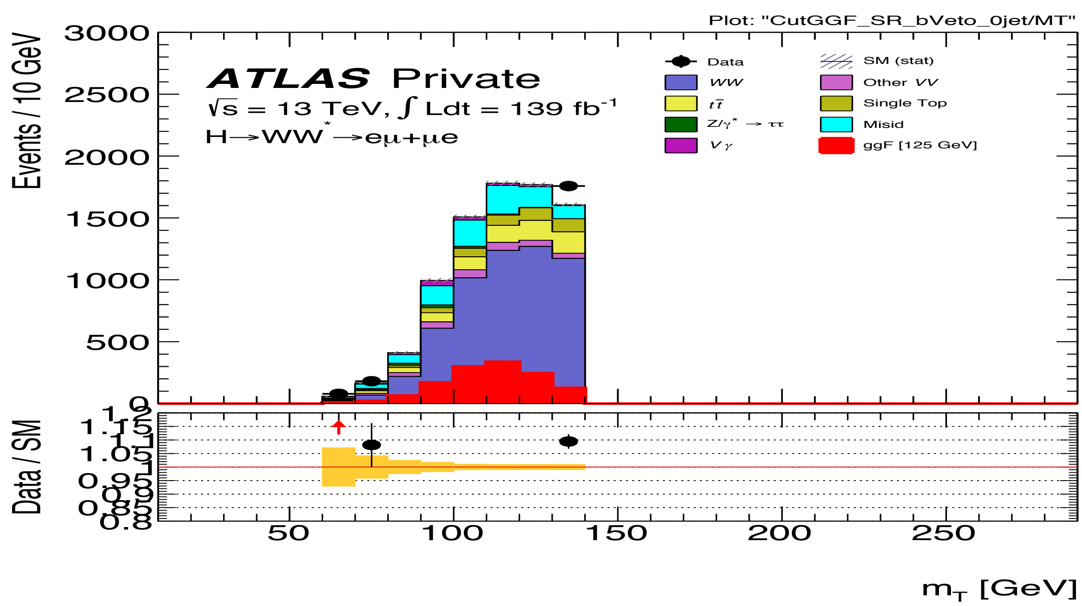


Figure 14: Stack Plots of $e\nu\mu\nu$ final state. The M_T region from 60 to 140 GeV is used with new cuts.

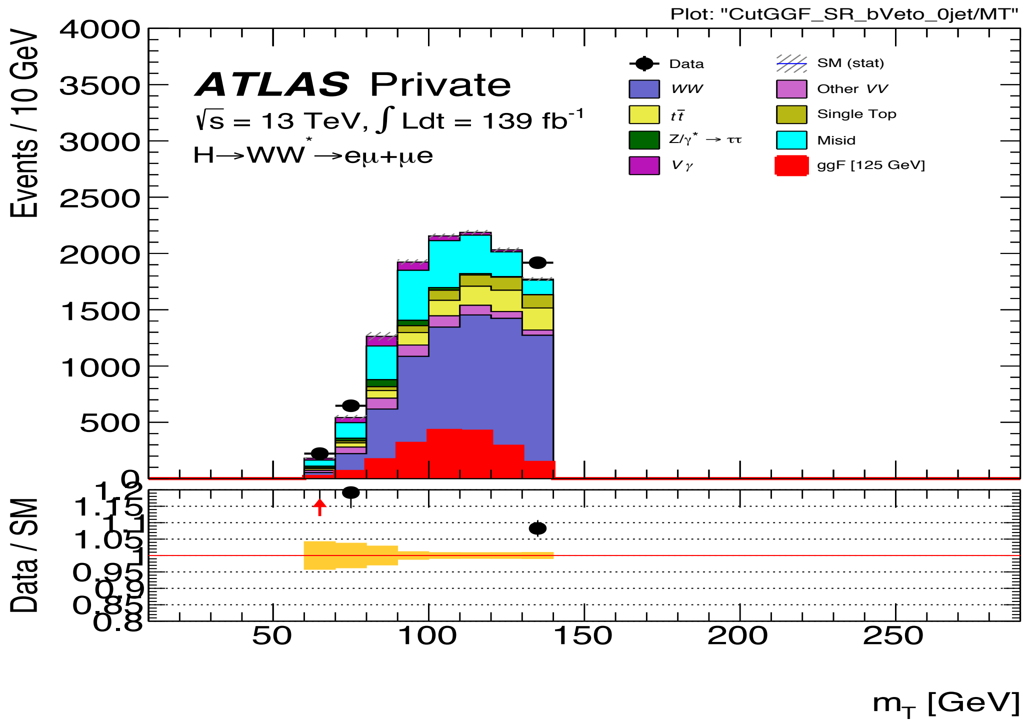


Figure 14: Stack Plots of $e\nu\mu\nu$ final state. The M_T region from 60 to 140 GeV is used with the new $\Delta\varphi_{ll} < 2.1$ rad cut and the default cuts.

Conclusion

The gridscanner plots produced for the parameters of interest were in agreement with the default cuts indicating that these cuts had already been optimized. This was further confirmed when new cuts were used to generate stackplots. The cutflows of these stackplots yielded a significantly lower signal to background ratio than the original cuts. It was then investigated whether any new cut was superior to the corresponding default cut. The signal to background ratio of each cut was calculated as well as the percent difference between these values. This analysis showed that each default cut was better. Therefore, it was concluded that the default cuts had been optimized.

The default cuts were then analyzed over a restricted M_T region from 60 to 140 GeV. This restricted M_T region produced the largest signal to background ratio. This was expected since the majority of the Higgs signal is located in this mass range and when the cut is made mostly background is lost. Gridscanner plots were then produced and again were in agreement with the default cuts up to certain degree of uncertainty. New cuts were used to generate stackplots and the cutflows once more yielded a lower signal to background ratio than the default. Each individual cut was analyzed in the same manner as the unrestricted region. Two cuts were found that yielded a better percent difference and were used alone with the default cuts to investigate whether they would improve the signal to background ratio with all the other parameters held constant. These were $p_T^{lead} > 27$ GeV and $\Delta\varphi_{ll} < 2.1$ rad. The $p_T^{lead} > 27$ GeV yielded a signal to background ratio of 14.75 which is less than the default. The $\Delta\varphi_{ll} < 2.1$ rad cut on the other hand produced a signal to background ratio of 15.63. Therefore, this cut is superior to the default in the restricted M_T region. This indicates that the default cuts are not completely optimized when examining the restricted M_T region. This cut was then tried in the unrestricted M_T region and it resulted in a signal to background ratio of 14.27.

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Appendix

Any commands to be run inside the terminal will be preceded by >>>

First step: install HWWAnalysisCode, which contains gridscanner

>>> git clone --recursive https://gitlab.cern.ch/YOUR-CERN-USER-NAME/HWWAnalysisCode.git

Second step: Make a multidimensional histogram

The location to make it is as follows:

>>> cd /AnalysisExample/HWWAnalysisCode/share/config/histograms/ggF

To make it use >>>mkdir SRScan_1jet

Inside this multidimensional histogram you will put all the kinematic variables you wish to make gridscanner plots of. Below is an example of one I used.

```
THnSparseF('SRScan_1jet', '', 9, {28, 24, 60, 38, 50, 50, 34, 25, 10}, {10., 0.,
 10., 10., 0., 0., 0., 0., 10.}, {290., 3.14, 310., 200., 250., 250., 170., 3.27
, 290.}) << ( Mll: ($(Mll)/1000.) : 'm_{ll} [Gev]', DPhill: $(DPhill) : '\#Delta
 \#phi^{ll} [rad]', leadLepPt: $(lep0).pt()/1000 : 'p_{t}^{l0} [GeV]', subleadLe
pPt: $(lep1).pt()/1000 : 'p_{t}^{l1} [GeV]', MET: ($(MET)/1000.) : 'E_{T}^{miss}
 [Gev]', TrackMET: $(TrackMET)/1000. : 'E_{T,track}^{miss} [Gev]', Ptll: $(Ptll)
/1000. : 'P_{t}^{ll} [GeV]', DPhillMET: $(DPhillMET) : '\#Delta \#phi^{ll,MET} [
rad]', MT: $(MT)/1000. : 'm_{T} [Gev]');

@CutGGF_0jet: SRScan_1jet;
```

You must format this correctly depending on what kinematic variable you wish to use and how many of them you are putting in the histogram. You get the information on the kinematic variables from the file **histograms-ggf.txt**. This file contains the entire list of kinematic variables that can be used to make gridscanner plots. It is located in the same directory where you will make your multidimensional histogram.
/AnalysisExample/HWWAnalysisCode/share/config/histograms/ggF

The first number in the multidimensional histogram is 9. This number represents how many kinematic variables you have booked. The next group of numbers in the curly brackets represents the number of intervals that will be examined. The following group of number in the curly brackets represents the starting value or minimum value and the last group in curly brackets represents the largest value or end value. Now the first number in every curly bracket correspond to the first kinematic variable listed and the second number in every curly bracket corresponds to the second variable and so forth. For example M_{ll} has 28 bins, a minimum value of 10 and a maximum value of 290. M_T must always be booked, because this is the variable that we scan over.

Third step: Book the multidimensional histogram in analyze

The path to analyze is as follows
/AnalysisExample/HWWAnalysisCode/share/config/master/ggF

I used analyze-ggF-default.cfg, but you may have to use a different version depending on what you are doing.

This is what booking the histogram looks like inside of analyze-ggF-default.cfg

```
# book histograms
histograms: config/histograms/ggF/histograms-ggf.txt
multidimHistograms: config/histograms/ggF/SRScan_3jet.txt
```

Fourth Step: Book the kinematic variable in the scan-boundaries file

The scan-boundaries.txt file can be located as follows:
>>> cd `/AnalysisExample/HWWAnalysisCode/share/config/gridscanner`

In this file you will book every kinematic variable that you have in your multidimensional histogram. This file determines what region of the variable will be examined with the gridscanner plots. What is booked in the multidimensional histogram is the entire range of the variable, but when making gridscanner plots you may only be interested in a fraction of that region. So using this file any region can be examined as long as it exists within the range of what is booked in the multidimensional histogram.

Here is an example of what the file looks like

```
# Syntax:
# For variablesLowerScan: [lowerBin, upperBin, nSteps] < <variable name>
# For variablesUpperScan: <variable name> < [lowerBin, upperBin, nSteps]

#Mll < [20, 180, 16]
#DPhill < [0, 3.14, 5]

[1.0, 3.14, 8] < DPhillMET
[10, 100, 9] < Ptll
[10, 35, 5] < TrackMET
#[60, 150, 10] < MT
#[10, 150, 14] < TrackMET
#[10, 50, 7] < leadLepPt
#[10, 30, 10] < subleadLepPt
#[0, 100, 10] < MET
```

Notice how it contains the same kinematic variable as the multidimensional histogram even though some are commented out at the moment.

Fifth step: run analyze.py

Now that you have you multidimensional histogram made and booked you can run analyze.py. Make you sure that you name the output file carefully so you know exactly what gridscanner plots you are making.

Sixth step: Book your scan-boundaries.txt, analyze output file and multidimensional histogram in GridScanner-ggf-nom.cfg

This file is located in the same place as the scan-boundaries file
`/AnalysisExample/HWWAnalysisCode/share/config/gridscanner`
In this file you can set your cut region where the optimization is done. You can define what to consider signal and background and you choose your figure of merit. This file is very important and should be completely understood when using gridscanner.

```
# -*- mode: conf -*-
# input file, colon separates sample folder name

# General Options
# ==========================================

runGridScanner.inputFile: sampleFolders/analyzed/samples-analyzed-ggf-default-al
lplots-MTcuts-SRScan_3jet.root:samples
runGridScanner.outputFile:  results/GridScanner-ggf-nom/gridscanner-results.root

# plot directory
runGridScanner.plotDirectory:   results/GridScanner-ggf-nom

# name of the booked multidimensional histogram
# as specified in your multidimensional histogram definition file
runGridScanner.nDimHistName:  SRScan_3jet

# set region (cut) where optimization is done
runGridScanner.simple.regions: CutGGF_0jet

# PrepareGrid Options
# ==========================================


# what channels to scan? (done in separate scans)
runGridScanner.scanChannels:  [em+me]

# define what to consider as signal and background for grid scan
#runGridScanner.simple.signal: /sig/$(LEPCH)/mh125/ggf
runGridScanner.simple.signal: /sig/$(LEPCH)/[c16a+c16d+c16e]/mh125/ggf
runGridScanner.simple.background: /bkg/$(LEPCH)

# the following text file specifies the variables
# and their ranges to scan. for further
# information see file
runGridScanner.boundaryList: config/gridscanner/scan-boundaries.txt

# choosing the figure of merit(s).
# multiple figure of merits can be specified.
# curent available options:
# poisson, s/sqrt(b), s/sqrt(s+b), s/b, s*s/(b*b)
# runGridScanner.evaluator: poisson
runGridScanner.figureOfMerits: s/sqrt(s+b)
```

Everything shown in the above photos is important so before making your run ensure that you are using the correct signal, background, figure of merit and optimization region.

Seventh step: Run gridscanner

To run gridscanner use the following commands:

Start in the share directory and use:

>>> ../tools/runGridscanner.py config/gridscanner/ GridScanner-ggf-nom.cfg

Then run

>>> ../tools/runGridScanner.py config/gridscanner/GridScanner-ggf-nom.cfg --plotResults --plotInputs

Now you should have produced your gridscanner plots, which will be located in the results directory.