Determining The CP Properties of a Light Neutral Higgs Boson

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Abstract

The study presented here performs an investigation of CP nature for a low mass, neutral Higgs boson, utilizing variables which display sensitivity to the CP-even and CP-odd coefficients of the $t\bar{t}h$ interaction Lagrangian upon computation of weighted moments of the corresponding production cross-section[1]. In this investigation, the distributions of the six variables, as defined by Gunion, are analyzed for Monte-Carlo data representing a semileptonic, complex final state $t\bar{t}h$ process, corresponding to a purely scalar Higgs. A background analysis of the QCD $t\bar{t}b\bar{b}$ source was also conducted.

1 Background

1.1 Characterization of *CP* Nature via Gunion Variables

For a low mass Higgs boson ($m_h \lesssim 130GeV$), a significant mode of observation for production is represented in the channel $gg \rightarrow t\bar{t}h$ with the subsequent Higgs decay, $h \rightarrow b\bar{b}$ or $h \rightarrow \gamma\gamma$. It has been shown that certain weighted moments of the production cross-section for such an interaction can be used to characterize the CP nature of the Higgs [1]. Let us consider the Lagrangian for the Higgs-top coupling,

$$\mathcal{L} = \bar{t}(c + id\gamma_5)th, \tag{1}$$

where the coefficients c and d represent the CP-even and CP-odd components respectively. Upon calculation of the spin-averaged cross-section for this associated top Higgs production, one obtains terms which are proportional to $c^2 - d^2$; computation of certain weighted moments allows for isolation of such terms, by use of operators which maximize sensitivity of the cross-section to said terms. The variables shown in equation 2, defined by Gunion and He, display such sensitivity to the $c^2 - d^2$ component of the cross-section and are investigated in this analysis of Higgs CP nature.

$$\begin{aligned}
a_1 &= \tfrac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})}{|\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})|}, \quad & a_2 &= \tfrac{p_t^x p_{\bar{t}}^x}{|p_t^x p_{\bar{t}}^x|}, \\
b_1 &= \tfrac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})}{p_t^T p_{\bar{t}}^T}, \quad & b_2 &= \tfrac{(\vec{p}_t \times \hat{n}) \cdot (\vec{p}_{\bar{t}} \times \hat{n})}{|\vec{p}_t||\vec{p}_{\bar{t}}|}, \\
b_3 &= \tfrac{p_t^x p_{\bar{t}}^x}{p_t^T p_{\bar{t}}^T}, \quad & b_4 &= \tfrac{p_t^z p_{\bar{t}}^z}{|\vec{p}_t||\vec{p}_{\bar{t}}|}
\end{aligned} \tag{2}$$

Referring to the definitions of these Gunion variables as shown in equation 2, $\vec{p}_t$ and $\vec{p}_{\bar{t}}$ denote the three-momenta of the top and anti-top quarks, respectively, p_t^T and $p_{\bar{t}}^T$ refer to the respective magnitudes of the transverse momenta of the top and anti-top quarks and $\hat{n}$ denotes the unit vector in the direction of the beam, hence representing the unit vector in the z direction, in accordance with the usual convention.

1.2 Signal and Background Channels

This study presents an investigation of Higgs CP nature by analyzing the distributions corresponding to the six Gunion variables obtained by analysis of Monte Carlo data corresponding to a semileptonic, complex final state $t\bar{t}h$ process; specifically the analyzed MC events represent the process $gg \to t\bar{t}h$ with $h \to b\bar{b}$ as well as one hadronic top decay and one leptonic top decay. The Feynman diagram depicting the process is shown in figure 1.

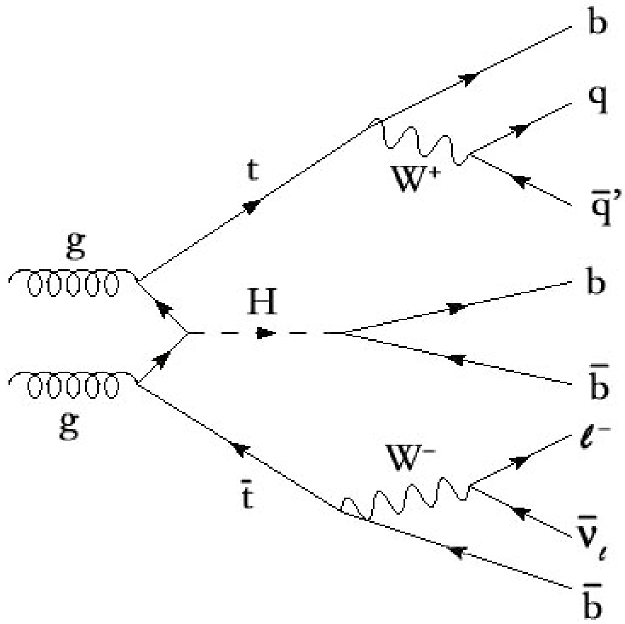


Figure 1: Feynman diagram showing the specific complex final state Higgs process used for analysis.

The semileptonic process was chosen for analysis in this study, rather than the fully hadronic or fully leptonic process in which both top quarks decay either hadronically or leptonically, so as to allow for distinction between the momenta of the top and anti-top quarks; in calculation of the Gunion variables, the values p_t and $p_{\bar{t}}$ may be distinguished by associating the reconstructed momenta of the hadronically and leptonically decaying quarks with each.

It should also be noted that this analysis focused specifically on the Higgs decay channel $h \to b\bar{b}$ rather than the $h \to \gamma\gamma$. Although the $b\bar{b}$ channel does have an advantage in that the production cross-section is much larger, a significant disadvantage is presented by the fact that this channel also has a much larger background than the corresponding $\gamma\gamma$ process. The most significant source of background for the channel examined in this analysis is the QCD process $gg \to t\bar{t}b\bar{b}$. Table 1 gives the cross-sections for the signal and background processes and the corresponding contributing factors for each[2].

Component	Multiplicative Factor	
-	Signal	Background
Initial production cross-section	519 fb	8.2 pb
Branching ratio, $h \to b\bar{b}$	0.6841	-
Branching ratio, $W \to jj$	0.685	0.685
Branching ratio, $W \to \ell\nu_\ell : \ell \in \{e, \mu\}$	0.21	0.21
Lepton charge symmetry	2	2
Filter efficiency	0.96	0.95
Total cross-section	98 fb	2.24 pb

Table 1: Detailed derivation of total cross-sections for the signal and background processes

2 Analysis

The analysis was conducted by reconstruction of events corresponding to the process described in the latter section, in particular, reconstruction of the $t\bar{t}h$ system and extraction of the top momenta so as to calculate and plot the distributions of the six Gunion variables. The same analysis procedure was executed for AODs containing events for both the $t\bar{t}h, h \to b\bar{b}$ signal process and the $t\bar{t}b\bar{b}$ background process. The signal events analyzed in this study correspond to a purely scalar Higgs of mass 120 GeV. The number of events analyzed for each process was chosen in accordance with the corresponding ratio of cross-sections.

More specifically, the analysis code[2] consisted of several algorithms which achieved selection and reconstruction of the entire semileptonic, complex final state Higgs process. Events were first passed through a lepton preselection, requiring exactly one lepton possessing the desired criteria (the numbers used for the various selection cuts can be found in table 2). Those events passing lepton preselection were then passed through a jet preselection, which required at least six jets passing the selection cuts, at least four of which were tagged as b jets. The next step in the analysis procedure was reconstruction of the leptonically decaying W boson from the preselected lepton. One should note that a collinear approximation was used for the neutrino momentum, ie. the neutrino momentum was assumed to be collinear with the lepton momentum. Following reconstruction of the leptonic W boson, the hadronically decaying W boson was reconstructed by pairing of jets. Moreover, acceptance of events for this stage limited the reconstructed W mass to fall within a specified interval centered around the nominal W mass of 80.4 GeV. Reconstruction of the $t\bar{t}h$ system was then achieved by Chi-squared minimization, looping over candidate hadronic and leptonic W bosons and b jets. As in the case of the hadronic W reconstruction, a window on the nominal top mass of 175.0 GeV was implemented for event acceptance. The final step of the reconstruction procedure involved reconstruction of the Higgs using the remaining b jets.

The reconstruction efficiency of the analysis is outlined in table 3, in particular, the selection efficiency at each stage of reconstruction for both signal and background events. For comparison purposes, the efficiencies are given for analysis conducted on 15250 events for

Procedure	Selection Cut
Lepton Preselection	Minimum electron transverse energy: $E_T^e \geq 25\,GeV$ Maximum electron pseudorapidity: $\eta^e \leq 2.5$ Minimum muon transverse energy: $E_T^\mu \geq 20\,GeV$ Maximum muon pseudorapidity: $\eta^\mu \leq 2.5$
Jet Preselection	b tagging: $bWeight \geq 5.5$ Minimum jet transverse energy: $E_T^{jet} \geq 20\,GeV$ Maximum b jet pseudorapidity: $\eta^b \leq 2.5$ Maximum light jet pseudorapidity: $\eta^{light} \leq 5.0$
Hadronic W Reconstruction	$W\,mass\,window = 25\,GeV$
$t\bar{t}hReconstruction$	$top\,mass\,window = 20\,GeV$

Table 2: Table showing the selection cut values used for the various reconstruction procedures of the analysis

both signal and background; results however were obtained conducting analysis over signal and background event numbers which maintained the approximate corresponding ratio of cross-sections, specifically 15 250 signal events and 350 750 background.

Selection Cut	Signal		Background	
	Events Accepted	Overall Efficiency	Events Accepted	Overall Efficiency
-	15 250	-	15 250	-
Lepton Selection	10657	69.88%	10531	69.06%
Jet Selection	365	2.39%	252	1.65%
Hadronic W	250	1.64%	168	1.10%
$t\bar{t}$ Reconstruction	170	1.11%	97	0.64%
Higgs Reconstruction	96	0.63%	34	0.22%

Table 3: Selection efficiencies of the reconstruction process for both $t\bar{t}h, h \rightarrow b\bar{b}$ signal and $t\bar{t}b\bar{b}$ background events

3 Results

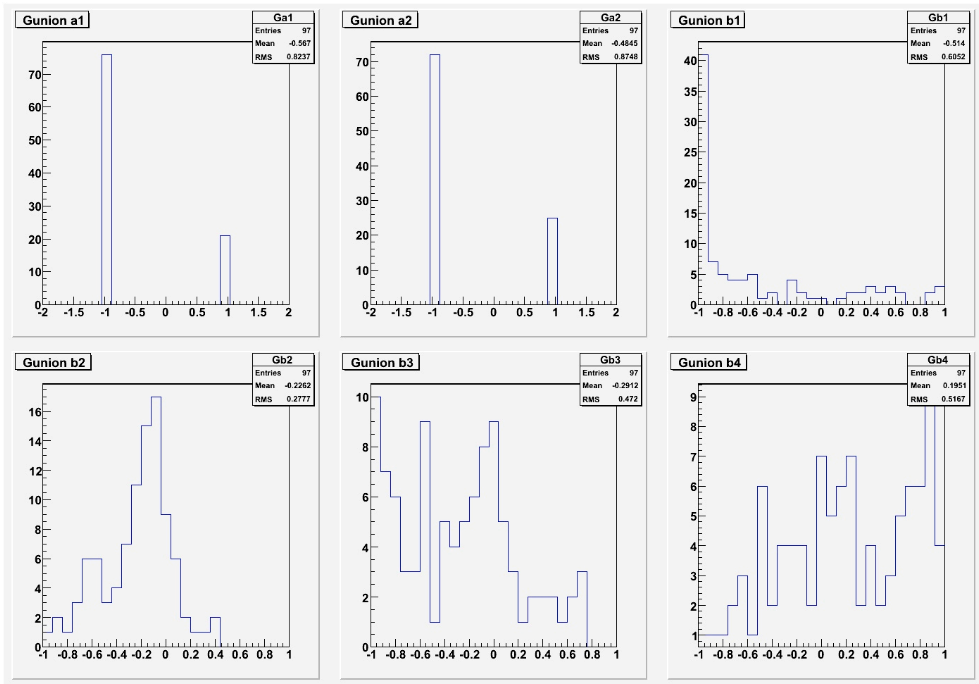
The resulting distributions of the analysis are given here, showing the distributions of the six Gunion variables and the corresponding fits. The distributions of the six Gunion variables for analysis of both signal and background events are shown in figure 2. Figure 3 shows the template fits obtained from these distributions. It may be noted that the corresponding Gunion variable distributions for signal and background appear to be very similar in form at this stage of the analysis, particularly due to the large degree of statistical fluctuation in the data resulting from the limited number of available events upon which to conduct the analysis. However, as shown in figure 4, the reconstructed Higgs mass provides a means by which to distinguish the signal and background events; one should note that in the distribution of reconstructed signal events a distinct peak is observed at the expected position of approximately $120 GeV$ whereas the corresponding background plot displays no such peak but rather a more or less uniform distribution over a large range of masses.

4 Conclusion

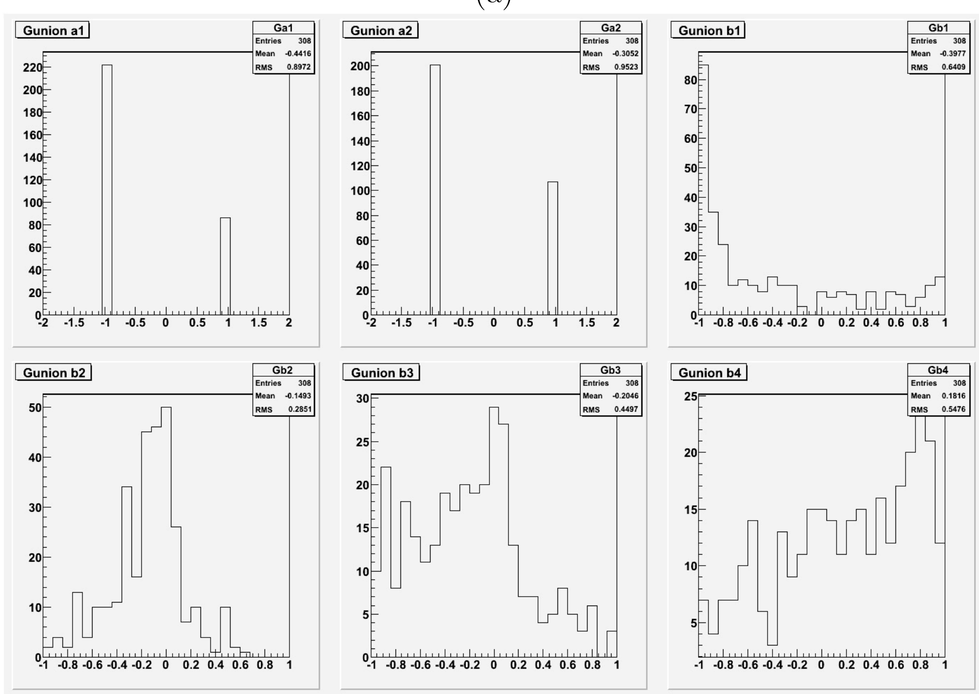
This investigation has presented an analysis of Higgs CP properties, determining the signal and background distributions of the six Gunion variables and thereby establishing a foundation upon which to conduct future analysis of real data with the purpose of characterizing the CP nature of an observed low mass Higgs via calculation of the weighted moments possessing the desired sensitivity to the CP-even and CP-odd coefficients of the Lagrangian representing the Higgs-top coupling.

Nevertheless, a significant portion of work still remains for future investigation in order to thoroughly characterize the Gunion distributions. The first area of which is of course to conduct the analysis for the signal corresponding to a purely pseudoscalar Higgs boson, so as to characterize and contrast the distributions corresponding to both possibilities of CP-even and CP-odd Higgs. In addition to the remaining aspect of the signal analysis, there still remain additional sources of background to be studied. This study focused on the QCD $gg \rightarrow t\bar{t}b\bar{b}$ channel as it is the most significant source of background, however a significant source of background is also provided by the corresponding electroweak process as well as the more generalized channel including final state light jets, rather than specifically b jets. Although these channels both have a much lower cross-section than the background channel analyzed here, the contribution must still be investigated.

In addition to these uninvestigated aspects of the analysis, it should be noted that several steps should be taken to further develop the method of the analysis performed here, mainly to improve the quality of the obtained fits. The first step to be taken in future study will be to further minimize the statistical fluctuations so as to smooth out the Gunion distributions. This may be achieved simply by conducting the analysis over a larger number of events, as the number of events available for this study was limited, particularly when preserving the signal to background cross-section ratio. Moreover, the low number of entries in the distributions and resulting degree of statistical fluctuation may also be minimized by improvements to the efficiency of the reconstruction process possibly by investigating adjustments to the selection criteria. Having implemented these improvements to the analysis procedure and obtained the separate distributions for signal and background datasets, an analysis will be conducted obtaining a composite fit of Monte-Carlo containing both signal and background events.



(a)



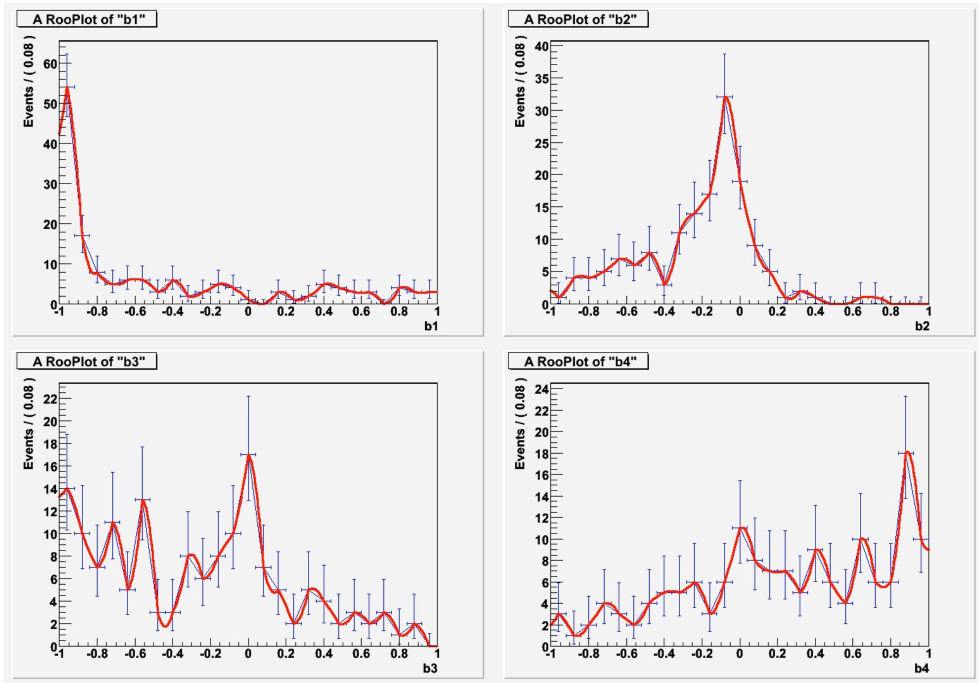
(b)

Figure 2: The unfitted distributions of the six Gunion variables are shown above, obtained by analysis on both signal and background events. Figure (a) shows the resulting distributions for reconstruction of 15 250 signal events representing $gg \to t\bar{t}h, h \to b\bar{b}$ while figure (b) shows the corresponding distributions obtained by analysis on 350 750 $t\bar{t}b\bar{b}$ background events.

5 References

1. Gunion, John F. and He, Xiao-Gang. "Determining the CP Nature of a Neutral Higgs Boson at the CERN Large Hadron Collider." Physical Review Letters 76.24 (1996). 4468-4471.

2. ATLAS CSC $t\bar{t}h$ Working Group. Tth hbb Analysis page. https://twiki.cern.ch/twiki/bin/view/AtlasProtected/TthhbbAnalysis



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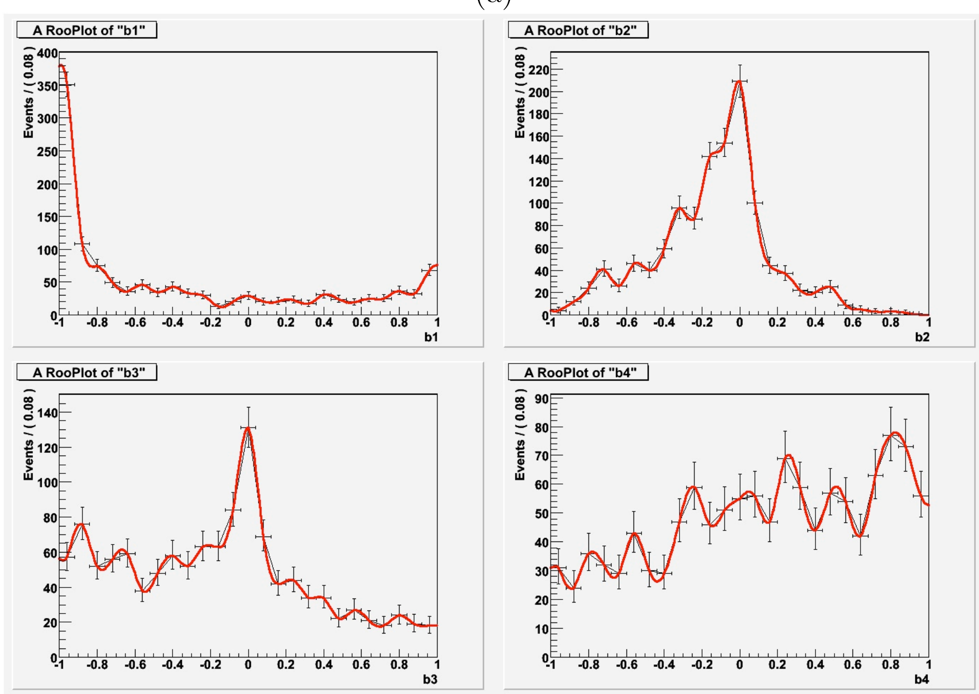
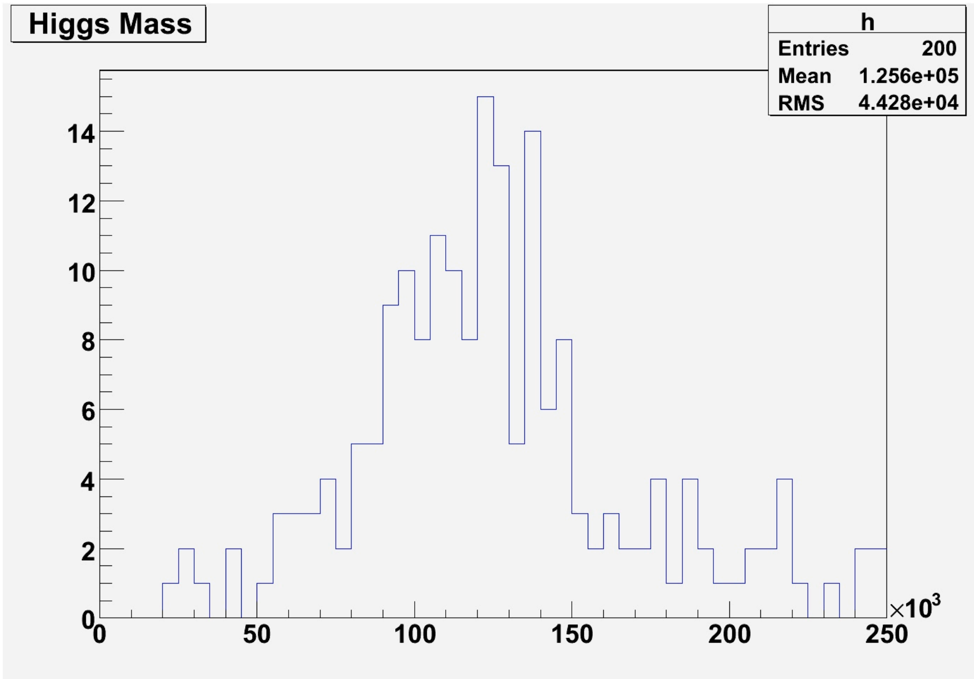


(b)

Figure 3: The fitted forms of the Gunion distributions are shown here with figure (a) displaying the signal distributions and figure (b) showing the corresponding background plots. As Gunion variables a_1 and a_2 are discrete variables, having value ± 1 by definition, these distributions are not included in these fits. Later treatment of these variables when fitting to real data will require manual Chi-squared fitting.



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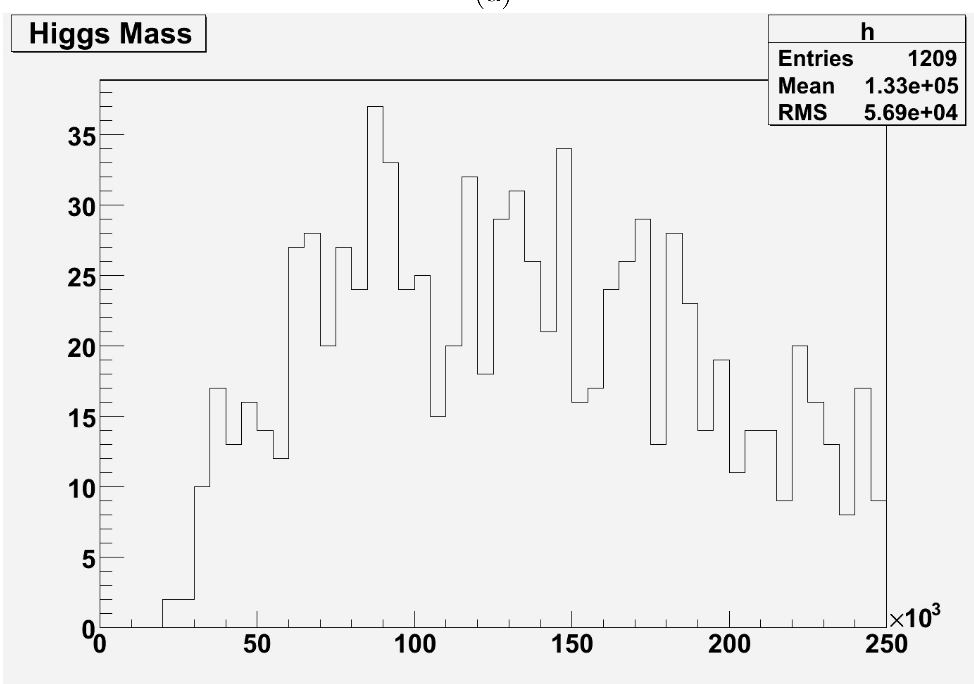

(b)

Figure 4: The above plots show the reconstructed Higgs mass distributions. Figures (a) and (b) represent the signal and background datasets respectively.