Single top quark production in association with the Higgs: a feasibility study

Claire Antel[1]

Department of Physics, University of Cape Town, Cape Town, 7701, South Africa

E-mail: claire.antel@cern.ch

Abstract. Due to the interference between top and W loops in the $H \to \gamma\gamma$ decay, there is a degeneracy in the minima of the Higgs coupling fits to fermions and bosons reported by ATLAS and CMS. Although one minimum is consistent with the Standard Model, the second minimum lies in a tantilizing region that is open to new physics.

This anamolous case is studied further by making use of a fermionic-bosonic interference that takes place in the single top production in association with a Higgs, in which the cross-section is significantly enhanced for anomolous coupling values. A truth level feasibility study of the tH process with $H \to b\bar{b}$ is conducted at 8 TeV and 21 fb^{-1} of data. A sensitivity of 1.6 is found for the enhanced non-SM case which is insufficient for a detection. A 3σ value is reached at 100 fb^{-1}. However, this value falls to below 1σ when including a 10% uncertainty in background. This indicates that due to the worsening systematic effects at increased luminosities, the signal will likely remain undetectable for the upcoming 14 TeV run at the LHC.

1. Introduction

The year 2012 marks the discovery of the final particle predicted by the Standard Model. The CMS and ATLAS experiments at CERN concurrently announced the observation of the Higss Boson at 125 GeV [1, 2]. Having found the Higgs, focus is now shifted to measuring its properties in order to determine if the new particle behaves like the SM Higgs or if properties are revealed to be anomalous, leading us into physics Beyond the Standard Model (BSM).

One of the properties of the Higgs is the strength of its coupling to other particles. Its coupling to fermions are known as Yukawa interactions. In this paper, the strength of the top Yukawa coupling is investigated by looking at the single top channel in association with Higgs production. This specific channel is of interest as it is sensitive to the sign of the top Yukawa coupling scale factor. Furthermore, there exist certain constructive interferences that lead to an enhanced signal production rate for an anomalous coupling value [3]. Despite the boost in signal, there is considerable background for this channel. This paper explores a truth-level feasibility study assuming a dataset of 21.3 fb^{-1} and a centre of mass energy of 8 TeV using the ATLAS detector at the LHC.

2. Theory Background

Both CMS and ATLAS have published their best fits to the coupling strength of the Higgs to other SM particles. Figure 1 displays the coupling fits done by ATLAS. The vector boson and

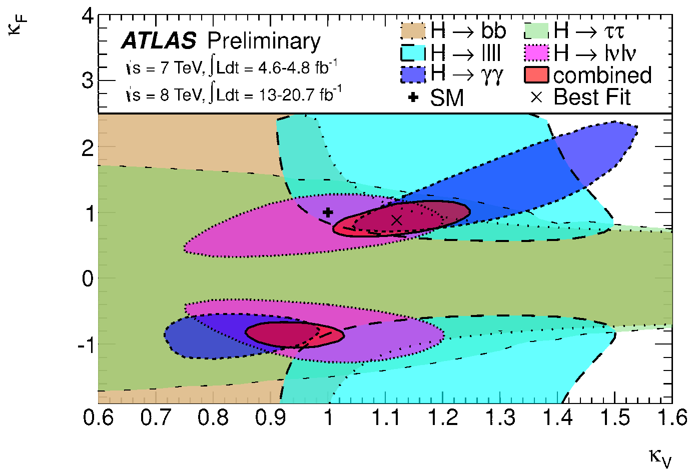


Figure 1. κ_V vs κ_F coupling fits for every Higgs decay channel and their combination. The dashed lines mark the 68% CL contours. The best fit and the SM prediction (1:1) are marked by crosses. Although the best fit agrees within 68% with SM, there remains an area of positive correlation at negative κ_F values which is significant at a $\sim 1\sigma$ level [4].

fermion coupling strengths are given in terms of κ_V and κ_F respectively. These are defined using a simplified parametrisation as

$$\kappa_V \equiv g_{hWW}/g_{hWW}^{SM} \qquad \text{and} \qquad \kappa_F \equiv g_{ht\bar{t}}/g_{ht\bar{t}}^{SM} \tag{1}$$

They essentially quantify the deviation from the SM prediction, g^{SM}.

In this fit, κ_V is constrained to > 0; nothing is lost by setting a positive constraint on one of the two factors because only the *relative* signs between the two coupling scale factors are physical. The 68% CL contour lines are traced out for each fit for a decay channel of the Higgs, as well as the combined fit. It is found that two minima result - one at (1:1), and the other at (1:-1). An important feature of the plot is the symmetry of the areas for every decay channel except for the $H \to \gamma\gamma$ decay. The symmetry in $\pm\kappa_F$ values is due to these channels being *insensitive* to the sign of the fermion coupling value. The $\gamma\gamma$ channel in contrast is dependant on the relative sign between κ_F and κ_V. This results from the dependence of the event yield on the coupling scale factors which goes like

$$\mathcal{N} \propto \frac{\kappa_x^2 \kappa_y^2}{\kappa_H} \tag{2}$$

where index x is from the production process and index y the decay channel. Because only the square of the κ values appear, it is only the absolute values of these that can be determined. However, the decay of Higgs to two photons is loop induced - the decay happens through a loop of heavy virtual particles. The major loop contributions are from the top, bottom and W boson. It is thus that κ_γ is a function of the more fundamental coupling scale factors, κ_F and κ_V, scaling as $|\alpha\kappa_V + \beta\kappa_F|^2$. This channel is therefore the only channel that can discriminate between signs. It however has the lowest branching ratio ($\sim 0.2\%$) and so statistics are not high enough to lift the degeneracy in minima evident in figure 1. For this reason, other channels that are also sensitive to the relative sign are needed. Several works (e.g. [3], [5]) have suggested the single top channel. Similar to the $H \to \gamma\gamma$, it too contains an interference term. The two main processes are presented in figure 2, where the Higgs is either radiated from a top or a W. The interference between the fermionic and bosonic process leads to an enhancement of the number of signal events if the coupling factors are opposite in sign. It in fact leads to a boost a magnitude higher for a k_F value of -1. Different Higgs decay channels can subsequently be considered. Here we focus on the $H \to b\bar{b}$ decay which has the largest branching ratio ($\sim 58\%$), and so the highest statistics, but it however also suffers from significant background. It is investigated if optimised cuts may exclude enough background to be able to make a detection feasible.

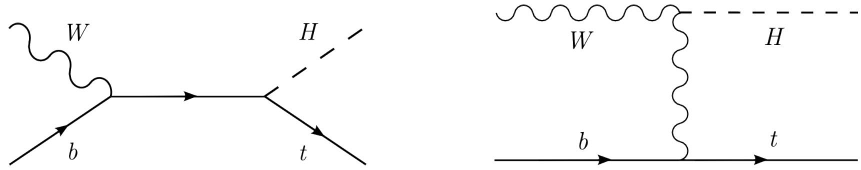


Figure 2. Feynman diagrams of the two major contributions (s channel, left, and t channel, right) to the core process $Wb \to tH$.

3. Monte Carlo Samples

The top is required to decay leptonically, i.e. $t \to W + b \to \ell + \nu + b$. The final signal is then $p + p \to t + H + j \to \ell + 3$ b-jets$+j + MET$. The extra jet (j) is a by-product of the initial collision and a characteristic feature of tH production. It is generally produced at large rapidities and thus referred to as a forward jet. MET is missing transverse energy which originates from the neutrino that will shoot through the detector undetected.

Samples were generated at a centre-of-mass energy of 8 TeV. Two samples were generated for the signal: an SM-case, $\kappa_F = 1$ and a non-SM case, $\kappa_F = -1$.

The following backgrounds are considered:

- $tb\bar{b}$j: an irreducible background
- tZj, where $Z \to b\bar{b}$: an irreducible background
- $t\bar{t}$, where $t \to bc\bar{s}$: a reducible background, where the c or $\bar{s}$ are mistagged as a b-jet
- $t\bar{t}j$, where $t \to bc\bar{s}$: a reducible background, where the c or $\bar{s}$ are mistagged as a b-jet and the third jet is missed.

The charge conjugate processes of the last two backgrounds are also included.

Only samples with at least one top decaying leptonically are used. The cross sections of the signal samples are 1.66 (SM) and 27.81 fb^{-1} (non-SM). The cross sections for the background samples are 11.28, 6.27 and 210.85×10^3 fb^{-1} for $tb\bar{b}j$, tZj and $t\bar{t}$ (includes $t\bar{t}j$), respectively. The $t\bar{t}$ sample is significantly larger than the rest (by 4 to 5 magnitudes), but it is also reducible.

4. Event Selection

Although a lot of cuts were considered only cuts that improved the sensitivity are included in this paper.

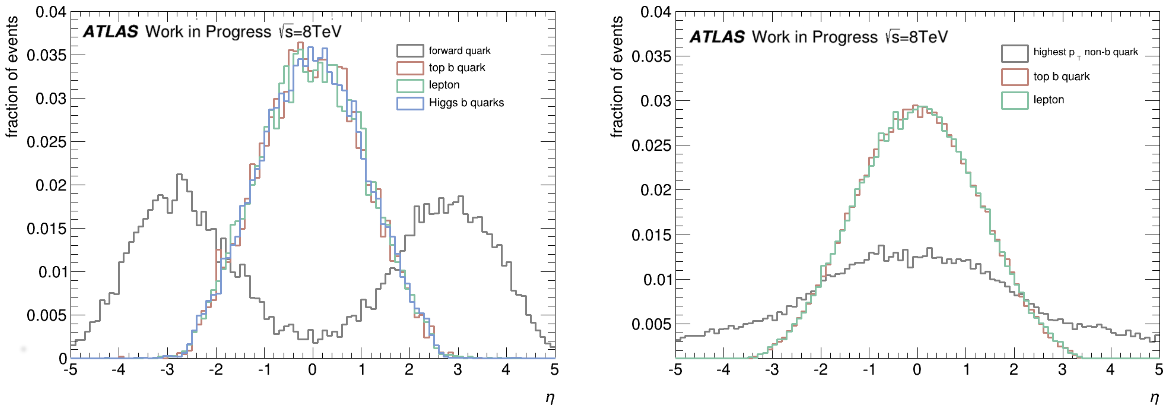
Basic acceptance cuts are made from the outset, motivated by suppression of low-momentum pileup and underlying event particles and keeping the acceptance area to regions where the detector is of optimum efficiency. These cuts are a $p_T > 25$ GeV and $|\eta| < 2.5$ cut on all jets (save for the forward jet) and leptons.

4.1. lepton cut

Events containing exactly one electron or one muon are selected (τ leptons are ignored in this truth study due to a low efficiency rate). This cut serves as a *1 lepton* trigger. The lepton number distribution (τs excluded) for each sample will result in the one lepton requirement cutting out $\sim$ 33% of events in the signal and tZj cases (due to the elimination of τ lepton events), $\sim$ 40% of events in the $t\bar{t}$ case and leaves the $tb\bar{b}j$ events untouched (due to the τ filter already been applied during sample file generation).

4.2. η distributions

An important distinction between the signal and $t\bar{t}$ samples lies in the η distributions. The distributions for the signal and $t\bar{t}$ samples are displayed in figure 3 (the distributions for the $k_F = 1$, $tb\bar{b}j$ and tZj samples look similar to the $k_F = -1$ distribution).



(a) signal $\kappa_F = -1$ **(b)** $t\bar{t}$

Figure 3. η comparisons: the distributions of MC truth η of light non-b quarks (grey) - in the case of signal events this is the forward quark, Higgs candidate b quarks (blue), the top b quark (red) and leptons (green) are shown for each sample.

For the signal events, two peaks flank the central region at high $|\eta|$ resulting from the forward jet. This feature is absent for $t\bar{t}$. Events are thus selected by requiring a high-p_T jet at $|\eta| > 2.5$.

4.3. b-jet number

The b-jet cut is the most effective cut that can be used. This is clear when looking at the b-jet number distribution for each sample. The $t\bar{t}$ background can be reduced by as much as 99% as the majority of events only include two b-tagged jets. Subsequently, keeping all events with 3 b-jets or more leads to a $\sim$ 34% cut in signal events, $\sim$ 45% in tZj events, $\sim$ 59% cut in $tb\bar{b}j$ events and a fine $\sim$ 99% cut in $t\bar{t}$ events. The 25 GeV cut is evidently more effective in the $tb\bar{b}j$ and tZj events, as a smaller fraction of 3 b-jet events remains.

4.4. Higgs mass reconstruction

The salient difference between the signal and the backgrounds is the presence of the Higgs boson. This means that the invariant mass of two of the b-jets in a signal event combined should reconstruct to a value that is close to the Higgs mass.

All samples include a W boson and a top. Thus, after having found the b-tagged jet that most likely originates from the top, one can expect the remaining 2 b-tagged jets (in 3 b-tagged jets events) to reconstruct well to a Higgs mass for the signal samples and poorly for the background samples where no Higgs exists. A difficulty arises when reconstructing the W boson however, as neutrinos cannot be detected. Instead, the observable is the missing transverse energy assumed to be the neutrino. Only the transverse component of MET is reconstructed directly, the z-component needs to be estimated using additional information.

After permuting through all 3 or 4 b-tagged jets in the event, the b-tagged jet that together with the reconstructed W boson vector adds up to the invariant top mass closest, is selected. Finally, the invariant mass of the remaining b-tagged jets is computed. Normalized histograms of the $m_{b\bar{b}}$ distributions are shown in figure 4. In the case of 4 b-tagged jets events, the pair closest to the Higgs mass is chosen. The tZj sample especially shows a deviation from a Higgs-like peak: it leans more to the left, with a mean at 17 GeV above the Z boson mass. The RMS values of the distributions for $tb\bar{b}j$ and $t\bar{t}$ are $10 - 17$ GeV wider than the RMS values for the signal samples. Following this, the constraint 90 GeV $< m_{b\bar{b}} <$ 140 GeV is applied to events. In reality, these distributions will be widened by experimental effects.

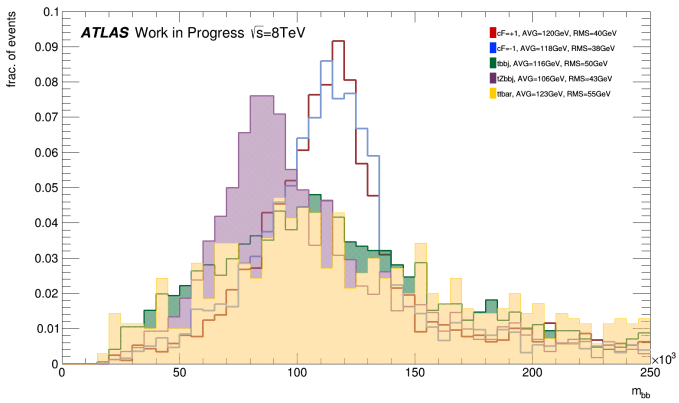


Figure 4. The mass distribution of the Higgs candidate for signal and background (normalised to 1): The b-tagged jet that is used for the top reconstruction is eliminated and the remaining pair of jets (or the pair that reconstructs closest to the Higgs mass in the case of a 4 b-tagged jets event) are used. Basic cuts, 3/4 b-jets, 1 lepton and 1 fwd jet cuts have been applied.

5. Discussion on Sensitivity

The cut flow for an integrated luminosity of 21 fb^{-1} is laid out in table 1. The significance is estimated as $S/\sqrt{B}$, which is valid for a large background and assuming poisson fluctuations. No systematic errors are included. The greatest boost to the significance is the 3 b-jet cut. The requirement of a forward jet is also useful and the constraints on $m_{b\bar{b}}$ marginally so.

The final significance, $S/\sqrt{B}$, is $\sim$ 0.1 in the $\kappa_F = +1$ case and $\sim$ 1.7 in the $\kappa_F = -1$ case. It is clear that for the Standard Model scenario the signal is basically indistinguishable from background noise. For the non-SM scenario the situation is improved due to its enhanced cross-section, however a significance value of at least 3 is needed to resolve the ambiguity in sign. Adding to that, the systematic uncertainties involved in measuring real data will obscure this value further. Data at 8 TeV and with 21 fb^{-1} integrated luminosity is likely to be insufficient to determine the sign of the top Yukawa coupling scale factor. In table 2, the significance estimates are summarized. Included are also the significance values assuming higher integrated luminosities

Table 1. Cut flow

cuts	$\kappa_F = +1$	$\kappa_F = -1$	$tb\bar{b}j$	tZj	$t\bar{t}$	Σ(bg)	$\frac{S}{\sqrt{B}}$ (SM)	$\frac{S}{\sqrt{B}}$ (non-SM)
initial	35	592	240	134	4491105	4492071	0.02	0.28
1 lepton	18	325	94	66	2218853	2219013	0.01	0.22
b jet no.	11	204	70	35	22984	23089	0.07	1.34
1 fwd jet	4	86	24	12	2813	2849	0.08	1.61
$m_{b\bar{b}}$	2	48	8	4	737	749	0.07	1.75

of 50 and 100 fb^{-1}, and an estimation of the significance if a 10% statistical uncertainty were assumed.

Table 2. Summary of significance calculations in the SM and non-SM case. Included are calculations for different integrated luminosities and assuming a systematic uncertainty of 10%.

	L (fb^{-1})	$S/\sqrt{B}$	$S/\sqrt{B+(0.1B)^2}$
$\kappa_F = +1:$	21	0.07	0.03
	50	0.11	0.03
	100	0.16	0.03
$\kappa_F = -1:$	21	1.75	0.60
	50	2.71	0.62
	100	3.83	0.63

For the next run of the LHC protons will be collided at 14 TeV and an integrated luminosity of 75-100 fb^{-1} is aimed for. With higher energies the cross-sections are increased which will boost the significance. However, the effects of the systematic uncertainties also increase with rising luminosity. The numbers at higher luminosities and 8 TeV cross-sections in table 2 fall well below 3σ if one includes a reasonable systematic uncertainty of 10%, indicating that even with the increased amount of data the signal events will remain undetectable for the upcoming run.

6. Conclusion

Degeneracies remain in the measurement of the fermionic and bosonic Yukawa couplings. It was studied whether the single top channel, being sensitive to the relative signs of these couplings, may be able to resolve these. A look at Monte Carlo events at truth level already suggests that a detection will not be possible. Projecting the sensitivity to higher integrated luminosities and assuming a 10% systematic uncertainty suggests that the signal yield for the upcoming run at the LHC, at higher centre-of-mass and an integrated luminosity 3-4 times greater, will be insufficient to lift the ambiguity in the sign of the couplings.

References

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