Study of $H \rightarrow b\bar{b}$ in association with a single top quark

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Abstract

The production of the Higgs boson in association with a single top quark, $tH$, is a very important process for testing the Standard Model theory. There are three production channels: associated production with $W$, $t$-channel and $s$-channel. In this study only $tHq$ production with $H \rightarrow b\bar{b}$ decay and top leptonic decay has been generated and analyzed. The $tH$ production is important for probing the sign of the Higgs-top Yukawa coupling, $y_t$. Namely, there is an interference between diagrams which depends on the relative sign of $y_t$. LO Madgraph is used as a tool for generating events, calculating the cross-sections and Feynmann diagrams. The cross-section is parameterized as a continuous function of $y_t$. The kinematics of the process appears to be dependent on the $y_t$ used. In addition, the dominant background from $tt$ production with heavy flavor jets has been generated and potential discriminating variables to separate $tH$ from this background have been analyzed and discussed.

1 Introduction and motivation

Nowadays, we know about Higgs-top Yukawa coupling ($y_T$) from ATLAS and CMS measurements (figure 1) [1].

[1]
Parameter $\kappa_T$ is a multiplicative modifier to the $y_T$ that we use in general in measurements to probe any deviation from the Standard Model (SM) prediction of the $y_T$. The precision on $\kappa_T$ measurement mainly comes from measurements of the $ggF$ (gluon-gluon fusion) production and $H \rightarrow \gamma\gamma$ decay, but there we assume that only Standard Model particles contribute to the loops (figure 2).

To measure $y_T$ directly (at tree level) we can do only through $ttH$ production. The Feynmann diagram from the figure 3 offers us sensitivity to $y_T^2$, while if we look at $tH$ production we can also get a sensitivity of the sign of the coupling. This is the main theoretical motivation for $tH$ production search. There are three production channels: associated production with $W$, t-channel and s-channel. S-channel gives small contributions to the value of cross-sections, so it is negligible.
W- and t-channel have two diagrams that interfere and give sensitivity to sign of the Higgs-top Yukawa coupling. Leading Order (LO) Madgraph is used to generate cross-sections, diagrams and events. Feynmann diagrams for $tHq$ and $tHW$ production are showed in figures 4 and 5.
The focus of the report is on the $tHq$ production, but conclusions can be extrapolated later to the $tHW$ production as well.

2 ATLAS detector

The ATLAS experiment is one of the main experiments in the LHC. The position of charged particles, (with transverse momentum above 500 MeV) as they traverse the detector, is measured in the Inner Detector [4]. The energy of hadrons, electrons and photons are measured by the calorimeter system. Using several different technologies, the calorimeter system provides coverage up-to $|\eta|=4.9$ [4]. The Inner Detector provides coverage up-to $|\eta| \approx 2.5$ [5]. The variables which would be used below: $\eta$ (pseudorapidity), $\phi$ (azimuthal angle) and $\Delta R$ (the distance) are a part of the coordinate system used in the ATLAS. $\Delta R$ is defined as:

$$\Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2}.$$ (1)
3 Calculation of the cross-sections for $tHq$ production

The calculation of the cross-sections is done using Madgraph leading order Monte Carlo generator. $999999$ events are generated at $\sqrt{s}=13$ TeV.

Figure 6: Cross-section $\sigma$ and $\sigma/\sigma_{SM}$ as a function of $\kappa_t$

The figure 6 shows the histogram with cross-sections as a function of $\kappa_T$. One can observe that it behaves as an asymmetric parabolic function. It is expected, because without interference of diagrams, it would be a symmetric parabolic function. In order to define the function that can be used to parameterize the cross-section in any point of the $\kappa_T$, measured values of the cross-sections are taken for three values of $\kappa_T$ ($\kappa_T=-1,0,1$), parameters $P_0, P_1$ and $P_2$ (figure 7) are calculated.
Figure 7: Cross-section $\sigma$ as a function of $\kappa_t$ - asymmetric parabolic function

The results obtained in this way are identical to the result that are obtained by direct fit in ROOT. These results and the function parameters from ROOT fit are showed in the figure 8.

Figure 8: The function fitted by ROOTfit

As conclusion, in general we can continuously parameterize $\sigma$ as a function of $\kappa_t$. 
4 Kinematics of the $tHq$

In order to discover if we can generate only a Standard Model template and test all other scenarios by parameterizing cross sections, but assuming the same kinematics, 999999 events for five values of the $\kappa_T$ are generated and the main kinematic features of the generated leptons and quarks are analyzed. Also, the kinematics of the dominant background $tt+HF$ (production of $tt$ with additional heavy flavor jets\(^1\)) would be under consideration in order to distinguish between signal and background. I made analysis in ROOT for this task.

4.1 Lepton kinematics

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{PT_lepton.png}
\caption{Transverse momentum of leptons.}
\end{figure}

\(^1\)Jets originating from $b$- and $c$- quarks
One conclusion so far is that the Standard Model looks slightly different from Beyond Standard Model (BSM), so maybe indeed using SM template for lepton $p_T$ might not be sufficient. Any selections that should have to be done at the detector level are not done, but it can been immediately seen that if single lepton triggers that require offline cut of $p_{T,\text{lepton}} > 27 \text{ GeV}$ are used, as the most suitable for this production, a big fraction of the events would be lost.

Figure 10: Pseudorapidity of lepton.
4.2 Kinematics of the $b$-quarks

Figure 11: Transverse momentum of the leading $b$-quark.

Figure 12: Transverse momentum of the first subleading $b$-quark.
Plots with the transverse momentum of the leading $b$-quark and transverse momentum of the first subleading $b$-quark shows a significant difference in $p_T$ of the leading $b$-quark between signal and background, while for signal different values of the $\kappa_T$ give similar distributions. Of course, it still need to be seen on the detector level and if reconstructed jets gives any separation.

4.3 Invariant mass of 2 $b$-quarks closest in $\Delta R$

![Invariant mass of the two nearest $b$ quarks](image)

Figure 13: Invariant mass of 2 $b$-quarks closest in $\Delta R$.

This is a very promising variable for separation of a signal from the background, because invariant mass for all signal hypothesis peaks at mass of the Higgs boson, while it is not the case for background.
4.4 Non-\(b\)-quark from the matrix element

Figure 14: Transverse momentum of the non-\(b\)-quark from the matrix element.

Figure 15: Pseudorapidity of the non-\(b\)-quark from the matrix element.
For $p_T$ the background is quite different from signal and Standard Model is quite different from BSM. From the plot of $\eta$ of non-$b$-quark is concluded that most of the signal shape is outside ATLAS Inner detector coverage and inclusion of the forward jets are needed for this analysis. This is also very important signature in the detector to tag them.

5 Conclusions

Events for $tHq$ process for various $\kappa_t$ values and dominant background are generated.

Cross-sections can be parameterized as a function of the $\kappa_t$.

If we want to use kinematics to study sensitivity to various $\kappa_t$, we probably need to generate templates as many distributions differ depending on the $\kappa_t$.

Good discrimination of the signal is given by non-$b$-quark in the forward region and invariant mass mass of the two $b$-quarks closest in $\Delta R$, but also another kinematics can be used as a good potential discrimination.

6 Outlook

Next steps which should be done:
Looking this kinematics at the detector level using reconstructed events in the ATLAS detector.
Trying to put various discriminating kinematic distributions into some MVA discriminant for the highest separation of signal and background, or try to develop in Madgraph Matrix Element discriminant.

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