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BOOSTED HIGGS CHANNELS

MATTHIAS SCHLAFFER
DESY, Notkestrasse 85, D-22607 Hamburg, Germany

In gluon fusion both a modified top Yukawa and new colored particles can alter the cross section. However in a large set of composite Higgs models and in realistic areas of the MSSM parameter space, these two effects can conspire and hide new physics in a Standard Model-like inclusive cross section.
We first show that it is possible to break this degeneracy in the couplings by demanding a boosted Higgs recoiling against a high-p_T jet. Subsequently we propose an analysis based on this idea in the $H \to 2\ell + \not{E}_T$ channels. This measurement allows an alternative determination of the important top Yukawa besides the $t\bar{t}H$ channel.

1 Introduction

The top quark and its coupling to the Higgs play a central role in the hierarchy problem. Many models for physics beyond the Standard Model (BSM) addressing this issue predict a modified top Yukawa coupling and its precise measurement can thus give crucial input to the search for BSM dynamics.

Two important processes for this measurement are $t\bar{t}h$ and gluon fusion. The former is difficult to measure due to the high multiplicity final state while the latter has a sizable cross section despite being loop suppressed. However gluon fusion is not only altered by a modified top Yukawa coupling but also by new colored particles, e.g. scalar tops or composite top partners, that can run in the loop besides the ordinary top quark.

If the new loop particles are heavier than the Higgs, $m_h^2/4\,m_{loop}^2 \ll 1$, their contribution to the gluon fusion process can be described by an effective gluon-gluon-Higgs interaction[1]

$$\mathcal{L}_{eff} = \kappa_g \frac{\alpha_S}{12\pi v} G^a_{\mu\nu} G^{a\,\mu\nu} h\,, \tag{1}$$

where κ_g is a coefficient quantifying the size of the interaction with $\kappa_g = 0$ corresponding to the Standard Model (SM), α_S is the strong coupling constant, $v \approx 246\,\mathrm{GeV}$ the Higgs vacuum expectation value, and $G^a_{\mu\nu}$ the gluon field strength tensor. The modified top Yukawa can be easily accounted for by multiplying the top Yukawa term by a new coefficient κ_t, where $\kappa_t = 1$ corresponds to the SM. Yet the mass relation $m_h^2/4\,m_t^2 \ll 1$ is fulfilled for the top quark and thus the top induced gluon fusion process can be described alternatively by Eq. (1) with κ_g replaced by κ_t. Consequently the inclusive gluon fusion cross section is given by $\sigma_{\rm incl}(\kappa_t, \kappa_g)/\sigma_{\rm incl}^{\rm SM} \approx (\kappa_t + \kappa_g)^2$ with corrections to this formula being beyond the reach of the LHC[2].

Therefore the inclusive gluon fusion process at the LHC cannot be used to disentangle the two coefficients. An independent measurement of κ_t and κ_g is however important as new physics could alter them such that their deviations from the SM value cancel mutually and yield a SM-like inclusive cross section.

This cancellation of BSM effects in gluon fusion is not merely of academic interest but actually happens in realistic scenarios. The prime example for this are composite Higgs models.

It was shown in Refs.[4] that the effects of a modified Yukawa coupling cancel the contributions from the top partner loops in a large range of realistic models and make the inclusive cross section completely insensitive to the top partner mass spectrum. Only a small rescaling of the cross section is obtained.

In the MSSM the cancellation is not as generic as in the composite Higgs models but can happen as well for large values of the trilinear coupling A_t when it is comparable to the mass of the second stop. Breaking the degeneracy could even be used to access stealth stops.

The main idea of the analysis proposed in the next two sections is to obtain a different relation between κ_t and κ_g by making the inclusion of top mass effects necessary. This is achieved by introducing a new scale to the process that lies above the top mass but below the potential mass of the top partners. To introduce this scale we demand that the Higgs is produced in association with a hard jet against which it recoils[a].

2 Analysis of Higgs + jet

The amplitude for $pp \to h + \text{jet}$ is given by $\mathcal{M}(\kappa_t, \kappa_g) = \kappa_t \mathcal{M}_{IR} + \kappa_g \mathcal{M}_{UV}$, where $\mathcal{M}_{IR}$ is the amplitude for the top loop contribution given in Refs.[5], and $\mathcal{M}_{UV}$ is the amplitude stemming from the effective gluon-Higgs interaction. In analogy to the expression for the inclusive cross section we write

$$\frac{\sigma_{p_T^{\min}}(\kappa_t, \kappa_g)}{\sigma^{SM}_{p_T^{\min}}} = (\kappa_t + \kappa_g)^2 + \delta \kappa_t \kappa_g + \epsilon \kappa_g^2 \,, \tag{2}$$

where $\sigma_{p_T^{\min}}$ stands for the cross section for $pp \to h + \text{jet}$ with a minimal transverse momentum of the Higgs of $p_T^{\min}$. The newly introduced coefficients δ and ϵ quantify the deviation from the inclusive cross section and are calculated using the MSTW 2008 LO PDFs[6] and the transverse mass $m_T = \sqrt{m_h^2 + p_T^2}$ as factorization and renormalization scale. For $p_T^{\min} \to 0$ the process approaches the inclusive production and the coefficients vanish. However for $p_T^{\min} = 800\,\text{GeV}$ they become $\delta(\epsilon) \approx 4(8)$. Of course these large coefficients come with the price of a small cross section due to the much smaller phase space. As a good compromise between large enough coefficients δ and ϵ and a not too small cross section we found $p_T^{\min} = 650\,\text{GeV}$ by a rough optimization procedure. In order to cancel systematic uncertainties we divide the boosted cross section by the almost unboosted cross section with $p_T^{\min} = 150\,\text{GeV}$ and take as observable

$$\mathcal{R}^0 = \frac{\sigma_{650\,\text{GeV}}(\kappa_t, \kappa_g)\, K_{650\,\text{GeV}}}{\sigma_{150\,\text{GeV}}(\kappa_t, \kappa_g)\, K_{150\,\text{GeV}}} \,, \tag{3}$$

where the cross sections are multiplied with the corresponding NLO K-factor obtained from MCFM-6.6[7] to take higher order effects into account.

The allowed region in the κ_t-κ_g-parameter plane is constrained by performing a simple χ^2-fit using the inclusive and the boosted cross section as input. For the 95% CL contours in Fig. 1 we assumed the center of mass energy $\sqrt{s} = 14\,\text{TeV}$, integrated luminosity $\mathcal{L} = 3\,\text{ab}^{-1}$, and a systematic uncertainty of 20% on both cross sections as well as a statistic error on the boosted cross section. As Higgs decay channel we chose the decay into $\tau^+\tau^-$ with a SM branching ratio and the reconstruction efficiencies reported in Ref.[8]. For more details and references see Ref.[9].

3 Collider study

In order to confirm the promising results from the previous section we performed a realistic collider study. As final state for the signal process we consider $h \to 2\ell + \not{E}_T$ with its most dominant contribution coming from $h \to W_\ell W_\ell^*$ and $h \to \tau_\ell^+ \tau_\ell^-$. As background processes we

[a] See Refs.[3] for other studies considering the boosted Higgs production in association with a jet to access the Higgs couplings

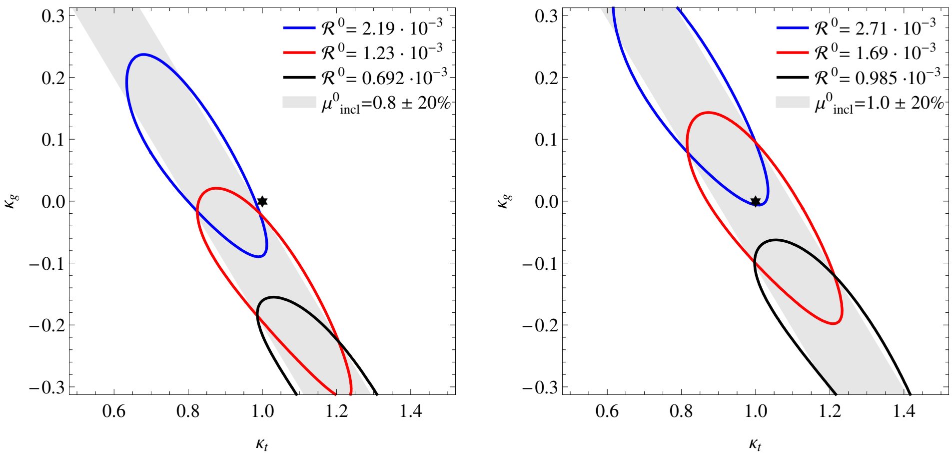

Figure 1 – 95% CL contours in the κ_t-κ_g plane assuming an inclusive signal strength μ^0_{incl} of 0.8 (left) and 1.0 (right). The gray band shows the constraint from considering only the inclusive cross section and the ellipses the constraint from the χ^2 fit. The blue, red, and black contour correspond to $\kappa_t = 0.8$, 1.0, and 1.2, respectively. The corresponding values for $\mathcal{R}^0$ are displayed and the star indicates the SM value.

consider W, Z, and $t\bar{t}$ + jets production, where the W bosons (including those of the t decay) are decaying leptonically and the Z bosons may decay only into $\tau^+\tau^-$ since a Z decaying into e or μ can be reconstructed and easily rejected.

First the basic event structure—boosted Higgs and recoiling jet—is demanded by reconstructing the Higgs transverse momentum $p_T^h = p_T^{\ell_1} + p_T^{\ell_2} + \not{E}_T$ and rejecting events with $p_T^h < 200\,\text{GeV}$. Moreover a fat jet with $p_T > 200\,\text{GeV}$ is required. Next we observe that a spin correlation in the $h \to W_\ell W_\ell^*$ channel leads to $\not{E}_T$ lying outside the cone defined by the two leptons. In the $h \to \tau^+\tau^-$ channel no such correlation exists and $\not{E}_T$ lies mostly inside this cone. This criterium allows us to distinguish the channels and tailor the analysis accordingly.

In the $h \to W_\ell W_\ell^*$ channel we calculate $m^2_{T,\ell\ell} = m^2_{\ell\ell} + 2(E_{T,\ell\ell}\not{E}_T - \boldsymbol{p}_{T,\ell\ell} \cdot \not{\boldsymbol{p}}_T)$ which gives a lower bound on the Higgs mass and reject all events with $m_{T,\ell\ell} > m_h$. In addition we demand that the two leptons are close by: $\Delta R_{\ell\ell} \leq 0.4$. In the end we achieve $S/B \sim 0.4$ and $S/\sqrt{B} > 6$ for $\mathcal{L} = 300\,\text{fb}^{-1}$ in this channel.

In the $h \to \tau^+\tau^-$ channel a large fraction of the $t\bar{t}$ and W background can be rejected by vetoing events with a dilepton mass $m_{\ell\ell} > 70\,\text{GeV}$. Eventually the Higgs mass can be reconstructed by the collinear approximation which assumes that the neutrino momenta are parallel to the reconstructed leptons and make up all missing energy. Requiring the reconstructed mass to lie within 10 GeV of the actual Higgs mass yields $S/B \sim 0.4$ and $S/\sqrt{B} > 9$ for $\mathcal{L} = 300\,\text{fb}^{-1}$.

For the $h \to \tau^+\tau^-$ channel we performed a binned likelihood ratio fit using the CL_s method[10] under the assumption of the worst-case scenario without deviations in the inclusive cross section measurement. The results are shown in Fig. 2. In this scenario the boosted Higgs can be seen against the background at 95% CL with an integrated luminosity of less than $100\,\text{fb}^{-1}$. A more detailed description of the analysis and further references can be found in Ref.[11].

4 Conclusion

We used boosted Higgs production in gluon fusion to disentangle the contributions of a modified top Yukawa coupling and of new top partners quantified by κ_t and κ_g, respectively. By combining the inclusive and the boosted cross section which have a different dependence on κ_t and κ_g the allowed region in the κ_t-κ_g-plane can be constrained. Assuming the worst case scenario with a SM inclusive cross section and a systematic uncertainty of 10%, κ_g can be constrained at 95% CL to $-0.4 \leq \kappa_g \leq 0.3$ by considering only the decay $h \to \tau_\ell^+\tau_\ell^-$ with an integrated luminosity

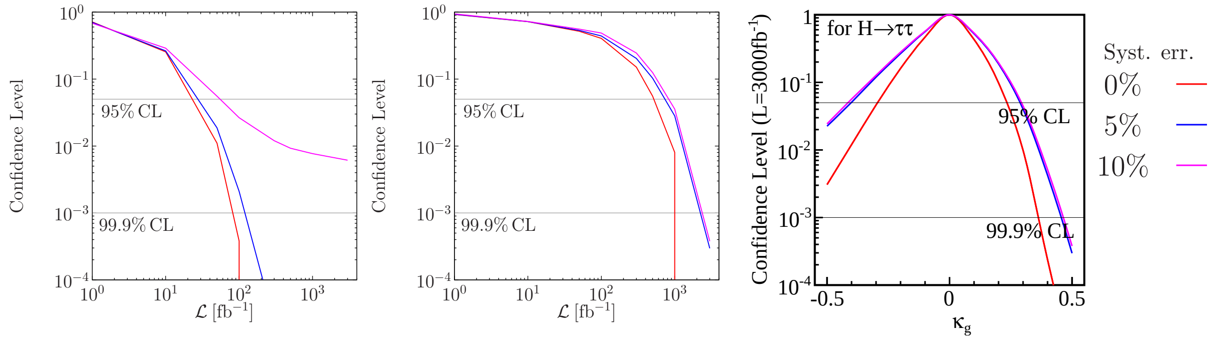

Figure 2 – p-values for boosted Higgs with $\kappa_t = 1.0$ against background processes (left) and BSM signal with $\kappa_t = 0.5$ against SM signal (center) as function of luminosity. The right panel shows the p-values as function of κ_t for an integrated luminosity of $3\,\mathrm{ab}^{-1}$. For these plots only the $h \to \tau_\ell \tau_\ell$ channel was considered.

of $3\,\mathrm{ab}^{-1}$. Therefore the boosted Higgs channel is an interesting alternative to determine the top Yukawa coupling independently of the $t\bar{t}h$ channel.

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