A calculation for $Br(Z' \to tth)$ in a B-L model

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Abstract. Models with extra gauge bosons often requires an extended Higgs sector, with properties that deviate from the Standard Model (SM) case. These modifications would affect the strength of the signals that are used to search for the Higgs spectrum at present and future colliders. However, it is also possible that new signals could arise in these models. In particular, the existence of such new gauge bosons could also be used to provide new production mechanisms. In this paper we will study a useful decay for a new gauge boson, Z', with SM-like couplings, namely $Z' \to f\bar{f}h$, through its branching ratio. We conceive this process as a higgsses possible source, steaming from the fact that the LHC is going to be a natural source of new gauge neutral bosons, in the case nature agrees with us about its existence. We found a corresponding branching ratio of order 10^{-3}, under certain scenaries. In particular we have used $m_h = 125\,\text{GeV}$ as the last results.

1. Introduction

After so many years of preparation, the LHC started to test in very significant ways the Higgs sector of the SM. We know now that the SM Higgs boson has $m_h = 125$ GeV, which agrees quite well with the range preferred by the analysis of electroweak precision tests [1, 2]. The LHC has also provided important bounds on the scale of new physics beyond the SM.

One of the simplest extensions of the SM, with broad motivations, is the presence of new gauge bosons, which could arise within a variety of contexts, ranging from simple extra U(1) gauge symmetries [3], left-right models [3–6], GUTs, [7], and even string theory [8–10]. In particular, the extension of the SM with an extra $\mathrm{U}(1)'$ has been studied extensively. Predictions for detection at LHC as well as other phenomenological studies have been presented [3–6, 8–10].

Here, we would like to know what would be the consequences for the Higgs sector once such extra neutral gauge boson would be detected. In the first place, we know that such models with extra gauge bosons, often require an extended Higgs sector, with properties that desviate from the Standard Model case. These modifications will change the strength of Higgs interactions with SM particles, which in turn would induce modifications of the standard signals that are used to search for the Higgs spectrum at present and future colliders. However, the new gauge boson could also induce new signals for the Higgs bosons.

In this work, we calculate the branching ratio for the 3-body decay of the Z' into a Higgs boson and a top anti-top pair, i.e. $Z' \to t\bar{t}h$. We find that it is possible to get $\mathbf{Br}'s$ (Branching Ratios) as high as 10^{-3}, which could be feasible to be studied at LHC.

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2. A simple model with an extra Z'

In this section we sumarize the main features of the model [11–16].

$$\mathcal{L} = (D^\mu \Phi)^\dagger (D_\mu \Phi) + (D^\mu \chi)^\dagger (D_\mu \chi) - V(H, \chi)$$

the covariant derivate is [12],

$$D_\mu = \partial_\mu + i \left[g \frac{\sigma^a}{2} W^a_\mu + Q^Y_i B_\mu + g_P Y^P_i B'_\mu \right]$$

for the singlet under SU(2), we obtain:$(D^\mu \chi)^\dagger (D_\mu \chi) = \frac{1}{2}\partial^\mu h' \partial_\mu h' + \frac{1}{2}(h' + x)^2 (2 g'_1 B' \mu)^2$ and the potential is [12]: $V(H, \chi) = m^2 H^\dagger H + \mu^2 |\chi|^2 + \lambda_1 (H^\dagger H)^2 + \lambda_2 |\chi|^4 + \lambda_3 H^\dagger H |\chi|^2$

There are several bounds for the Z' mass and its couplings, as the mixing angle, for different scenarious and processes [13, 17]. Some **Br** for different channels have been studied in [18], they use $M_{Z'} = 1\,\mathrm{TeV}$. By the other side, Ref. [19] exclude $M_{Z'} < 1140\,\mathrm{GeV}$ with standard-model-like couplings and $M_{Z'} < 887\,\mathrm{GeV}$ in superstring-inspired models. Hencefor if a new gauge boson exists, its mass would have $M_{Z'} \sim \mathcal{O}\,(\mathrm{TeV})$ because it is necessary to avoid fine-tunnings.

The mixing angle (θ'), between Z and Z' states, has a definite bound from precision measurement observables, namely, $|\theta| \lesssim 10^{-3}$ [20]. The coupling ${g'}_1$ has values model-dependent but it is bounded by $\mathcal{O}\left(10^{-1}, 10^{-2}, 10^{-3}\right)$; for instance, see [20]. In [11], they found a dinamical way to constrain ${g'}_1$ for the $B - L$ model. The general relation for the coupling and the mass is given by, $M_{Z'} > {g'}_1 6\,\mathrm{TeV}$ It is possible to find a light new gauge boson if its couplings to the SM field are small [14]. We refer to the reader to [15] for a deeper insight.

3. $Z' \to f\bar{f}h$ Branching ratio

We calculate the $\mathbf{Br}(Z' \to f\bar{f}h)$ with the following Feynman diagrams,

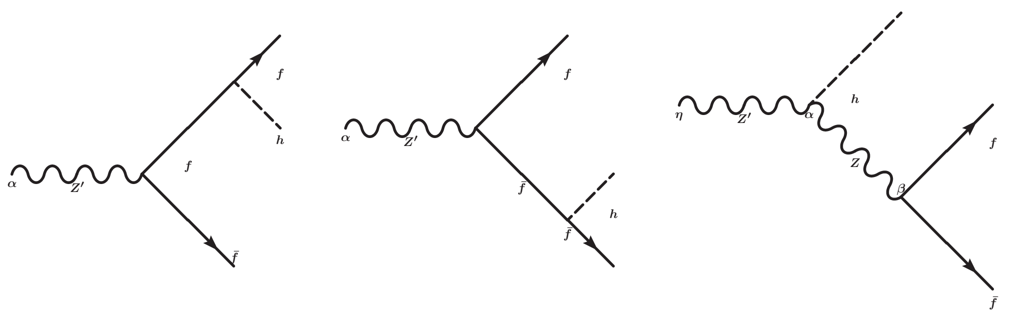

Figure 1. Feynman diagram for the process

taking into account all the interference terms in the calculations, we get,

$$\begin{aligned} \frac{d\Gamma(Z' \to f\bar{f}h)}{dx_f dx_{\bar{f}}} = {} & \frac{M_{Z'}}{256\pi^3} \left[\frac{g^4 M^2_{Z'}}{2\cos^4\theta' \Gamma^2_f} \left[\left(\mu_f + 2\mu_h + x_{\bar{f}} - 1\right) \left(\frac{1}{2} \left({g^f_A}^2 + {g^f_V}^2 \right) \left(-2\mu_f + \mu_h + x_f + x_{\bar{f}} - 1 \right) - 4\mu_f {g^f_V}^2 \right) + \right.\right. \\ & \left. \frac{\mu_f}{2} \left(5{g^f_V}^2 - 3{g^f_A}^2 \right) \left(-2\mu_f + \mu_h + x_f + x_{\bar{f}} - 1 \right) + 2\mu_f^2 \left({g^f_A}^2 - {g^f_V}^2 \right) \right] + \\ & \frac{g^4 M^2_{Z'}}{2\cos^4\theta' \Gamma^2_{\bar{f}}} \left[\frac{1}{2} \left({g^f_A}^2 + {g^f_V}^2 \right) \left(-2\mu_f + \mu_h + x_f + x_{\bar{f}} - 1 \right) \left(4\mu_f + 2\mu_h + x_f - 1 \right) - \right. \\ & \left. 2\mu_f \left({g^f_A}^2 - {g^f_V}^2 \right) \left(4\mu_f + 3\left(2\mu_h + x_f - 1 \right) \right) \right] + \end{aligned}$$

$$\frac{8g^2v^2A_1^2M_{Z'}^2}{\cos^2\theta M_Z^2\Gamma_Z^2}\left[2\mu_f\left({g_V^f}^2-{g_A^f}^2\right)+\frac{1}{2}\left({g_A^f}^2+{g_V^f}^2\right)(-2\mu_f+\mu_h+x_f+x_{\bar{f}}-1)\right]+$$
$$\left(\frac{8g^2M_{Z'}}{\cos^2\theta'}\right)^2\left(\frac{1}{\Gamma_f\Gamma_{\bar{f}}}\right)\times$$
$$\Bigg[2\mu_f\left(\frac{1}{2}\left({g_V^f}^2-3{g_A^f}^2\right)\left(-2\mu_f+\mu_h+x_f+x_{\bar{f}}-1\right)+\left({g_A^f}^2-{g_V^f}^2\right)(2\mu_f+2\mu_h+x_f-1)\right)+$$
$$\left({g_A^f}^2+{g_V^f}^2\right)(2\mu_f+2\mu_h+x_f-1)\left(\mu_f+2\mu_h+x_{\bar{f}}-1\right)\Bigg]+$$
$$\left(\frac{g^3vm_fA_1M_{Z'}}{\cos^3\theta'}\right)\left(\frac{1}{\Gamma_fM_Z\Gamma_Z}\right)\left[-\left({g_A^f}^2+{g_V^f}^2\right)\left(\mu_f+2\mu_h+x_{\bar{f}}-1\right)-\frac{1}{2}\left({g_V^f}^2-3{g_A^f}^2\right)\times\right.$$
$$\left.(-2\mu_f+\mu_h+x_f+x_{\bar{f}}-1)-2\mu_f\left({g_A^f}^2-{g_V^f}^2\right)\right]+\left(\frac{4g^3m_fvA_1M_{Z'}}{\cos^3\theta'}\right)\times$$
$$\left(\frac{-\left({g_A^f}^2+{g_V^f}^2\right)\left(\mu_f+2\mu_h+x_{\bar{f}}-1\right)-\frac{1}{2}\left({g_V^f}^2-3{g_A^f}^2\right)(-2\mu_f+\mu_h+x_f+x_{\bar{f}}-1)-2\mu_f\left({g_A^f}^2-{g_V^f}^2\right)}{M_Z\Gamma_Z\Gamma_f}\right)\Bigg] \quad (1)$$

where the integration limits, for the scaled energy variables, $x_i = 2E_i/M_{Z'}$, are:

$$2\sqrt{\mu_f} \leq x_{\bar{f}} \leq 1-\mu_h-2\mu_f$$
$$\frac{1}{2}\frac{A-B}{1-x_{\bar{f}}+\mu_f} \leq x_f \leq \frac{1}{2}\frac{A+B}{1-x_{\bar{f}}+\mu_f}$$

and, $A=(2-x_{\bar{f}})(1+2\mu_f-\mu_h-x_{\bar{f}})$, $B^2=(x_{\bar{f}}^2-4\mu_f)\left((1-x_{\bar{f}}-\mu_h)^2-4\mu_f^2\right)$, $\mu_i=\frac{m_i^2}{M_{Z'}^2}$, $(i=f,\bar{f})$ and $\sum_{i=1}^3 x_i = 2$.

A_1 is a coefficient comes from the vertex hZZ'; where $A_1 = 2\left(\frac{\cos\alpha}{4}\Theta_{hZZ'} - r\sin\alpha{\Theta'}_{hZZ'}\right)$, $\Theta_{hZZ'} = -\sin 2\theta'(g^2+g'^2)$, ${\Theta'}_{hZZ'} = 4{g'}_1\sin 2\theta'$ and $r=\frac{v}{v'}$ for a pure $B-L$ model.

We must stress that even when the $Z-Z'$ mixing angle it is often set to zero, there are plausible models that allow a 10^{-3} level, value which we use (see [8–10]). In order to be confident about the certainty of a zero mixing, we studied the cases for $10^{-4,-5}$ for the mixing angle. We used the neutrino's masses from [16].

Recent results have set a strict bound for the Higgs boson mass, at 125 GeV [1, 2, 21]. This is the nominal value we use.

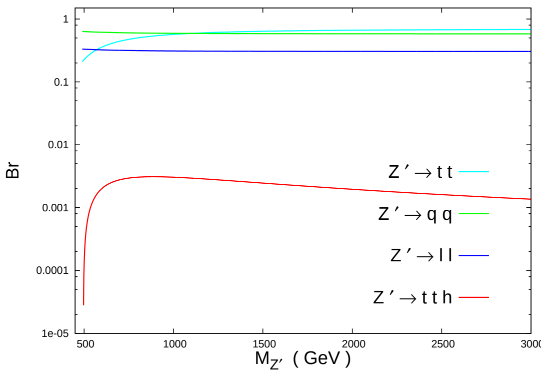

Figure 2. We have set $v' = 1$ TeV and $\theta' = 1\times10^{-4}, \alpha = \frac{\pi}{2}$

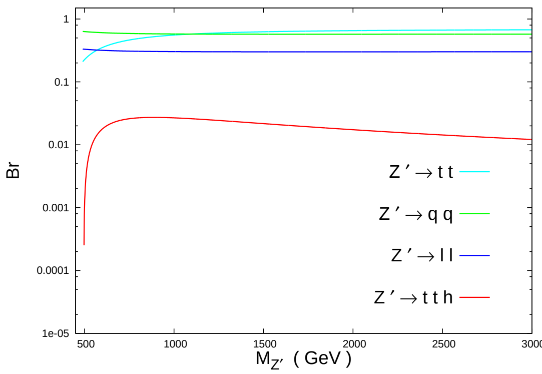

Figure 3. We have set $v' = 3$ TeV and $\theta' = 1\times10^{-5}$. $\alpha = \frac{\pi}{2}$.

In figs. (2) and (3), we show the Branching ratio (**Br**) for different channels as a function of the new gauge boson mass. We have considered $q = u, c, d, s, b.$ and $l = e, \mu, \kappa, \nu_e, \nu_\mu, \nu_\kappa$. We use for definitiveness SM-like couplings for Z'-SM fermions (a $B-L$ like scenarious). We explored

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the **Br** for $\theta' = 1 \times 10^{-4}, 1 \times 10^{-5}$ and 1×10^{-6} with $v' = 1\,\text{TeV}, 2\,\text{TeV}$ and $3\,\text{TeV}$; however there were no significant differences.

4. Conclusions

A **Br** of 10^{-3} is well within the reach of the LHC studies. So, in the case of a Z' discovery, this process would be a good candidate to search and study a new gauge boson, of course in the case the nature choices as the next step a sequential model. Otherwise, in other kind of models, it could be a good source of Higgses, in order to clarify if the boson just announced it is effectively the SM boson or not.

CMS or ATLAS [1, 2] could be able to detect a new gauge boson in the TeV range. As well as to measure and reconstruct both a pair of top and a pair of photons, as could be the Z' signature in our case. The QCD background for the final states $\bar{t}t\gamma\gamma$ has a continuum spectrum for the photons, while the Higgs signal we are looking for has been refined meanwhile. In this way, the possibility of the Z' reconstructing is a reachable level from the invariant mass of the final states. A more detailed and exhaustive work is in order, and it will be published elsewhere.

Acknowledgments

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