Search for HZZ' couplings at the LHC

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Abstract – New physics models predict the possibility of extra neutral gauge bosons (Z') associated with an extra U(1)' gauge symmetry. We study the couplings of the Higgs boson to the Z boson and Z' boson predicted by the new physics models. Since there is stringent limit on the Z' boson mass from the Z' \to t\bar{t}l\bar{l}' channel at the LHC experiments, we use two benchmark models: the leptophobic Z'_{LP} which has no couplings with leptons and the eta Z'_{\eta} which has small couplings with fermions. The couplings of the Z' boson to quarks can also be investigated through the Z'q\bar{q} interactions. The accessible ranges of the parameter space have been searched for processes pp \to HZ\bar{X} and pp \to HHZ\bar{X} at the LHC with \sqrt{s} = 14\, \text{TeV}.

Introduction. – Experimental opportunities can be exploited to search for hints beyond the standard model (BSM) physics after the recent discovery of the Higgs boson with a mass of 125 GeV by the ATLAS and CMS experiments [1,2] at the LHC. Due to its gauge charges the Higgs boson may interact with the BSM fields. This new interaction can also modify the couplings between the Higgs and SM fields at tree level or loop level. Within some extensions of the standard model (SM) a new neutral gauge boson Z' can be included [3–6].

The phenomenological studies on the Z' boson signatures can be found in [7–14]. The present constraints on the Z' mass and couplings from both electron-positron and hadron-hadron colliders have been presented in [15]. Since the existing constraints on the Z' boson mass are stringent we take into account two benchmark Z' models, such as the leptophobic Z'_{LP} which has no lepton couplings and the eta Z'_{\eta} which has small lepton couplings [16]. The precision measurements at the Z boson resonance lead to the limit on Z-Z' mixing [17–20]. The ATLAS and CMS experiments at the LHC, running at higher center-of-mass energy and luminosity, have updated the Tevatron limits on the Z' boson mass [21,22]. The ATLAS Collaboration searches for a massive resonance decaying to top quark pairs in the hadronic channels, and excludes the leptophobic Z' boson with mass smaller than 1.32\, \text{TeV} [23]. The CMS Collaboration excludes leptophobic Z' boson resonance with a mass of m_{Z'} < 1.3\, \text{TeV} for its width \Gamma_{Z'} = 0.012 m_{Z'} in the search of heavy resonance decaying into $t\bar{t}$ pair with subsequent lepton decays [24].

In this work, we investigate the HZZ' couplings via the processes pp \to HZ\bar{X} and pp \to HHZ\bar{X} at the LHC with \sqrt{s} = 14\, \text{TeV}. The couplings of the Z' boson to quarks can also be investigated via Z'q\bar{q} interactions. For the signal process pp \to HZ\bar{X}, the Z' boson contributes in the s-channel resonance diagrams through family diagonal neutral current couplings. However, the signal process pp \to HHZ\bar{X} has contributions from both the Z'-boson resonance and the Z-exchange diagrams. We calculate the signal and background cross-sections and obtain the accessible ranges of the mass for two different Z' models (such as Z'_{LP} and Z'_{\eta}) at the four-fermion and six-fermion final states resulting from $H \to bb$ and $Z \to l^+l^−$ decays. These modes exist even if the Z' boson decouples from the leptons. The ratio of the cross-sections for the $HZ$ and $HZZ$ production can help to understand the HZZ' interaction and distinguish between different Z' models.

The production cross-section. – The interaction of the Higgs boson ($H$) with the Z boson ($Z$) and the new Z' boson can be written through the kinetic term of the scalar field. The relevant interaction term can be written as $L_{HZZ'} = -g_{ZZ}g_{Z'}z[H]vH_{\mu}Z^{\mu}$. The new boson Z' couples to the fermion field ($f$) with the interaction term $L_{f(Z')} = (g_{Z'}/2)\bar{f}\gamma^\mu(C_{Z'}^f - C_{A}^f)\gamma_\mu f$. Here, the vector ($C_{Z'}^f$) and axial-vector ($C_{A}^f$) couplings are model dependent. We use a linear change of variable $g_{Z'} = \gamma_{Z'}g_{e}/\cos\theta_W \sin\theta_W$ for the coupling constant. The triple...
Table 1: Vector and axial-vector couplings of $Z'$ boson predicted by the leptophobic (LP) model and the $\eta$ (ETA) one.

| $Z'$ (LP) | $C_{uV}$ | $C_{uA}$ | $C_{dV}$ | $C_{dA}$ | $C_{lV}$ | $C_{lA}$ | $C_{\nu V}$ | $C_{\nu A}$ |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| $Z'$ (ETA) | 0 | 4/6 | 1/2 | 1/6 | −1/2 | 1/6 | −1/6 | −1/6 |

Fig. 1: (Colour on-line) Decay width of the $Z'$ boson depending on its mass for two different models.

Fig. 2: (Colour on-line) Branching ratios of the $Z'$ boson as predicted by the leptophobic model (LP) depending on its mass.

Fig. 3: (Colour on-line) Branching ratios of the $Z'$ boson as predicted by the $\eta$ (ETA) model of $E_6$ depending on its mass.

Fig. 4: (Colour on-line) The cross-section for the process $pp \rightarrow HZX$ depending on the mass of the $Z'$ boson for the LP model.

Fig. 5: (Colour on-line) The cross-section for the process $pp \rightarrow HZX$ depending on the mass of the $Z'$ boson for the ETA model.

The production processes have contribution from the resonance production of the $Z'$ boson. Therefore, we have included the decay width ($\Gamma$) of the $Z'$ boson in the calculation for different $Z'$ models, as shown in fig. 1 for leptophobic (LP) and $\eta$ (ETA) models. The branching ratios (BR) vs. $Z'$ mass are given in fig. 2 and fig. 3 for the LP and ETA models, respectively.

The $HZZ'$ coupling depends on the $U(1)'$ charge. In the model the triple coupling parameter $z[H] = −1$. The $U(1)'$ couplings to the fermions for two different $Z'$ models are given in table 1. Since the extensively studied Drell-Yan process even constrained the possible $Z'\ell^+\ell^-$ couplings, we consider two candidate models in which the $Z'$ bosons have small or no couplings to leptons. We implement tree-level interaction vertices of $HZZ'$ and $Z'f\bar{f}$ into CalcHEP [25] and we use the proton parton distribution function CTEQ6L [26].

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At the LHC with $\sqrt{s} = 14$ TeV, the cross-section of the $HZ$ production through the signal process is about 0.20 pb and 0.15 pb with $Z'$ boson mass $m_{Z'} = 1.5$ TeV for the LP and the ETA models, respectively. The cross-section of the $HHZ$ production is around 3.85 fb and
2.78 fb with $Z'$ boson mass $m_{Z'} = 1.5$ TeV for the LP and the ETA model, respectively. As shown in figs. 4, 5 and 6, 7, the background cross-sections result in 0.7 pb and 0.29 fb for the $HZ$ and the $HHZ$ production at $\sqrt{s} = 14$ TeV, respectively. The ratios of the cross-sections for $pp \to HZX$ and $pp \to HHZX$ processes depending on the mass of the $Z'$ boson for the two different $Z'$ models ETA and LP are presented in fig. 8. This figure also includes the ratio of the SM cross-sections for the given processes. The curves shown in fig. 8 represent large deviations from the SM line depending on the $Z'$ boson mass. While the mass of the $Z'$ boson is increasing, the model difference becomes more apparent. The final states of $2l + 2b_{\text{jet}}$ and $2l + 4b_{\text{jet}}$ are the main backgrounds for the $HZ$ and the $HHZ$ productions. In order to suppress the relevant background, we can apply the invariant mass cuts, on dileptons to be around the $Z$ boson mass, on dijets with each jet as $b$-tagged to be around the Higgs mass.

**Parameter space analysis.** – In the analysis, we use the cross-section of the signal and background for the final states explained in the previous section. A pair of $b$-jets gives an invariant mass distributions peak around the Higgs mass and the dilepton invariant mass distribution give peak around the $Z$ mass. It is also helpful to use angular separations of the leptons, $b$-jets and between leptons and jets. The massive $Z'$ boson can be reconstructed from the resonance peak in the invariant mass spectrum of the final states $2l + 2b_{\text{jet}}$ and $2l + 4b_{\text{jet}}$ originating from the $HZ$ and the $HHZ$ productions, respectively. The luminosity needs for $3\sigma$ signal observability for the final state $2l + 2b_{\text{jet}}$ depending on the mass of $Z'$ boson for the two different $Z'$ models ETA and LP are given in fig. 9. Having an integrated luminosity of $L_{\text{int}} = 100$ fb$^{-1}$ at the LHC with $\sqrt{s} = 14$ TeV, it is possible to search for the $Z'$ boson up to a mass value of $M_{Z'} = 1.50$ TeV and 1.80 TeV for the ETA and the LP models as seen from fig. 9. The search range for the $Z'$ boson mass can be found as $M_{Z'} = 1.80$ TeV and 1.95 TeV for the ETA and the LP models for $2l + 4b_{\text{jet}}$ as given in fig. 10.

**Conclusions.** – We present the attainable parameter space for two different $U(1)'$ models by studying the processes $pp \to HZX$ and $pp \to HHZX$ at the LHC with $\sqrt{s} = 14$ TeV. The $HZ$ production has large cross-section and it has the advantage of two $b$-jets and two charged leptons in the final state. The background for the $HHZ$ production has lower cross-section than the $HZ$ produc-
tion, however it has the advantage of four $b$-jets and two charged leptons in the final state. The Higgs boson mostly decays into two $b$-jet channel and we use the advantage of efficient identification of dileptons from the $Z$ boson. The couplings of the $Z'$ boson to the SM quarks play a role in the production, and the $U^1$ charge of the Higgs boson scales the $HZZ'$ coupling. The searches for $HVV$ couplings will also extend our perspectives for new physics at the LHC with $\sqrt{s} = 14$ TeV and $L_{int} = 100\text{fb}^{-1}$.

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