Chapter 6

Summary and conclusions

This thesis deals with the LHC phenomenology of vectorlike quarks that arise in various warped extra dimensional theories and the color octet electrons which appear in some quark-lepton compositeness models. Chapter 1 is an introductory chapter where we briefly discuss some theoretical shortcomings of the SM and motivate the need for BSM physics that explains some of the unanswered questions of the SM. Many BSM extensions predict the existence of new heavy fermions with masses near the TeV scale. In this thesis we study the LHC phenomenology of two types of such new heavy fermions, namely the vectorlike quarks (VLQ) that arise for instance in various warped extra-dimensional theories, and the color octet electrons ($e_s$) that appear in some quark-lepton compositeness models. We briefly survey some theoretical as well as recent experimental references that are relevant to our study.

In Chapter 2 we review the construction of the RS model, including the derivation of the warped metric as a solution to the Einstein’s equations [93]. We show how this model solves the gauge hierarchy problem of the SM and present a short discussion on models with bulk gauge and fermion fields coupled with a Higgs peaked at the IR brane. We give the details of some warped models both without [106] and with [107] custodial protection of the $Zb_Lb_L$ coupling [112] that have been proposed earlier in the literature. Our work has been presented in Refs. [112, 114] where we discuss the gauge sector and different
quark representations of these models. For each of these models we carefully work out various Lagrangian terms in the mass basis relevant to the phenomenology we discuss in the thesis. In Chapter 3 we present the parameter choices, which we use for our numerical results, for the different warped-space models discussed in Chapter 2. We consider three different cases of warped models differing in the fermion representations under $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$ gauge group. We label them by the representation $t_R$ appears in, namely, Doublet Top (DT), Singlet Top (ST) and Triplet Top (TT) models. More than one $b'$ (charge -1/3), $t'$ (charge 2/3) and $\chi$ (charge 5/3), can be present depending on the model, and they can mix among themselves and the SM quarks. We plot mass eigenvalues and various important couplings for the LHC phenomenology as functions of bulk mass parameter $c_{qL}$ for different warped models. We identify all kinematically allowed two-body decay modes of $b'$, $t'$ and $\chi$, and compute total decay widths and branching ratios of them in the warped models we discussed earlier.

In Chapter 4 we study the LHC signatures of vectorlike $b'$, $t'$ and $\chi$ quarks. We implement different warped models in matrix element and event generators MadGraph 5 [134] and CalcHEP [118] to compute signal and main irreducible SM backgrounds. We explore the pair production channel for discovery of the new VLQs. However, in addition to pair production, we also look into some of their important single production channels since single production processes can give useful information about the electroweak nature of the underlying models. There are some distinct signatures of vectorlike nature of the $b'$, $t'$ and $\chi$. For example, a unique signature of a vectorlike $b'$ is that it decays to $bZ$ and $bh$ modes in addition to the $tW$ mode which is also present for a chiral (4th generation) $b'$. We study the LHC signatures of the $b'$ particularly focusing on $bZ$ and $bh$ channels to expose its vectorlike nature [114]. We explore the $pp \to b'b'$ pair production and, $b'Z$, $b'h$ and $b'Zb'$ single production processes at the 14 TeV LHC followed by their decays to different final states [114]. Using the $b'b' \to bZbZ \to bjjbll$ channel we find that the LHC reach to be about $M_{b'} \approx 1250$ GeV with about 1300 fb$^{-1}$ integrated luminosity. For $pp \to b'Z$ channel we also present model independent contour plots for c.s. and luminos-
ity varying $\kappa_{b'bZ}$ and $M_{b'}$. We consider $pp \rightarrow b'bZ \rightarrow bZ bZ$ channel which includes the double resonant (DR) pair production ($b'b'$) and also the single resonant (SR) production of $b'$ including the contribution from $b'b'^*$ where one of the $b'$ is offshell. We expect that SR contribution scales as $\kappa^2_{b'bZ}$ while DR contribution depends on the $g_s$. We show that $\kappa_{b'bZ}$ can be extracted by using an invariant mass cut [112]. Isolating SR contribution from $pp \rightarrow b'bZ$ events by using the invariant mass cut, we explicitly demonstrate that SR c.s. indeed scales as $\kappa_{b'bZ}^2$. In general it is straightforward to measure couplings from single production channels but these typically have smaller cross-sections. In this thesis we outline a possible method to extract couplings by observing that decay of an off-shell particle is sensitive to the coupling of the decay vertex. A more detailed analysis is done in Ref. [122].

For the $t'$ phenomenology we explore the $pp \rightarrow t'th \rightarrow thth$ channel which includes the (DR+SR) production of $t'$ and compute the signal c.s. for different $t'$ masses in the warped models and main irreducible SM backgrounds at the 8 and 14 TeV LHC. We find that the 14 TeV LHC can probe the $t'$ mass of the order of 1 TeV with 100 fb$^{-1}$ of integrated luminosity in the warped space models.

For the $\chi$ we consider $pp \rightarrow \chi tW \rightarrow tWtW$ channel which includes the (DR+SR) production of $\chi$. We find that using this channel the 14 TeV LHC can probe $M_{\chi} \approx 1.5$ TeV (1.75 TeV) with 100 fb$^{-1}$ (300 fb$^{-1}$) of integrated luminosity. Similar to the $b'$, we show that the SR production of the $t'$ and $\chi$ can be used to extract the new physics couplings related to those processes.

For $b'$, $t'$ and $\chi$ we present model independent discovery luminosity plots as functions of couplings for different masses using SR production which has the potential of giving information on the underlying electroweak nature of these states. Although our study is motivated by warped space models, we present our results in a model independent fashion wherever possible.

Chapter 5 deals with color octet electrons arising in some composite models. These models assume that SM particles may not be fundamental and they are actually bound
states of substructural constituents called preons [70]. These constituents are visible only beyond the compositeness scale $\Lambda$. Some composite models naturally predict the existence of color octet fermions with nonzero lepton numbers.

We discuss the LHC phenomenology of $e_8$ in an effective theory framework. To generate signal and background events, we have implemented the Lagrangian in FeynRules [132] to generate Universal FeynRules Output (UFO) [133] format model files suitable for MadGraph5 [134] to generate events. Although, here we consider only the $e_8$, our results are applicable for the color octet partner of muon, i.e., $\mu_8$ also. We briefly discuss various preonic models of quark-lepton compositeness in which $e_8$ are present. We display the interaction Lagrangian of a generic $e_8$ and decay width of $e_8$ for different choice of $\Lambda$. Our work has been presented in Ref. [136] where we explore various resonant productions (pair and various single production channels) of $e_8$'s in the context of the LHC. We have identified a new set of single production diagrams whose contribution is comparable to other dominant production channels of the $e_8$. In a realistic computation, after parton showering and hadronization, it is very difficult to separate different production processes from each other. A common feature in all the resonant production channels of the $e_8$ is the presence of two high $p_T$ electrons and at least one high $p_T$ jet in the final state. Using this feature, in our work [136], we implement a search method where the signal is a combination of pair and single production events. This method has potential to increase the LHC reach significantly. To generate the combined events we use MLM shower-$k_T$ matching algorithm [135] to match the matrix element partons with the parton showers. The main SM background comes from the inclusive $Z$ production and we compute the $Z + n$ jets ($n = 0, 1, 2, 3$) background using the shower-$k_T$ scheme.

Assuming 100% branching ratio for the decay, $e_8 \rightarrow eg$, we estimate the LHC discovery potential for the $e_8$'s. We show that using only the pair production channel the 14 TeV LHC can probe $e_8$ with mass up to 2.5 TeV (2.8 TeV) with 100 fb$^{-1}$ (300 fb$^{-1}$) of integrated luminosity. We demonstrate that this reach can be increased further by combining signal events from different production processes. However, this increment is $\Lambda$ dependent as
the single production c.s. scales as $1/\Lambda^2$. For $\Lambda = 5$ TeV (10 TeV) the increment is about 0.9 TeV (0.4 TeV) with 100 fb$^{-1}$ of integrated luminosity at the 14 TeV LHC and with 300 fb$^{-1}$ of integrated luminosity it is about 1.2 TeV (0.5 TeV). We point out that our analysis can also be used to probe $\Lambda$, the compositeness scale, for any fixed $M_{e_8}$. This is possible because of the scaling of the single production c.s. with $\Lambda$. We show that for $M_{e_8} = 2$ TeV the 14 TeV LHC with 100 fb$^{-1}$ (300 fb$^{-1}$) of integrated luminosity can probe $\Lambda \sim 35$ TeV (55 TeV). We note that the data from the current leptoquark searches at the LHC can be used to search for $e_8$'s also. We point out that the current data for first generation charged leptoquark in the pair production channel clearly rules out a $e_8$ of mass less than 900 GeV [77, 78].