Like-sign Di-lepton Signals in Higgsless Models at the LHC

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Abstract

We study the potential LHC discovery of the $Z_1$ KK gauge boson unitarizing $W^+_LW^-_L$ scattering amplitude. In particular, we explore the decay mode $Z_1 \rightarrow t\bar{t}$ along with $Z_1 \rightarrow W^+W^-$ without specifying the branching fractions. We propose to exploit the associated production $pp \rightarrow WZ_1$, and select the final state of like-sign dileptons plus multijets and large missing energy. We conclude that it is possible to observe the $Z_1$ resonance at a $5\sigma$ level with an integrated luminosity of 100 fb$^{-1}$ at the LHC upto 650 GeV for a dominant $WW$ channel, and 560 GeV for a dominant $t\bar{t}$ channel.
I. INTRODUCTION

Weak gauge boson masses are electroweak symmetry breaking (EWSB) effects and how they arise still remains an open question in particle physics. The minimal Higgs boson model provides a simple solution to the electroweak symmetry breaking as well as fermion masses. Without a scalar Higgs boson, the scattering amplitudes for the longitudinally polarized gauge bosons ($W_L$ and $Z_L$) grow with energy as $E^2$ and they violate the (perturbative) partial wave unitarity at the energy scale $4\pi M_W/g \sim 1.5$ TeV \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$ \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$, where $\xi = 1$ for leptons and $\xi = \sqrt{3}$ for quarks. Due to the large top quark mass, the scale of mass generation for the top quark yields the strongest bound, to be about 3.5 TeV \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$.}}. Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$ \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$.}.

Recently there have been attempts to generate EWSB without Higgs bosons in the framework of extra dimension models \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$.}. In the so-called “Higgsless” models, unitarity is restored by contributions from a tower of Kaluza-Klein (KK) gauge bosons. The $E^2$ dependence in the scattering amplitude of $W_L$ and $Z_L$ is cancelled by the Kaluza-Klein (KK) modes $Z_n$, $W_n$. The unitarity in massive fermion scattering will also be protected by allowing $Z_n t \bar{t}$.

There have been several studies regarding the LHC search of the first KK $W_n$ boson ($W_1$) via weak boson fusion (WBF) \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$.} and associated production \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$.}. These studies all focused on the decay channel $W_1 \rightarrow WZ$ and chose multilepton final states. Despite the small $Z$ leptonic decaying branching fraction (BR), the SM backgrounds are always under control. In WBF $jjW_1 \rightarrow jjW^{\pm}Z$ through the $3\ell + jj + E_T$ final state, the claimed reach is 1 TeV for $5\sigma$ discovery at 100 fb$^{-1}$ integrated luminosity \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$.}. For the associated production $ZW_1 \rightarrow W^{\pm}ZZ \rightarrow 4\ell + jj$ final state had been proposed and the claimed reach is about 620 GeV at $5\sigma$ for 100 fb$^{-1}$ integrated luminosity \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$.}.

In this paper, we will explore another aspect of this class of model. Given the large top quark mass, we argue that $Z_1$ should couple to $t \bar{t}$ significantly \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$.} if $Z_1$ is the dominant contribution of unitarizing the scattering amplitudes involving top pairs. We take a phenomenological approach to the $Z_1$ boson, and allow it to decay to both $W^+W^-$ and $t \bar{t}$ channels without specifying the decaying BRs. Focusing on the $W^+W^-Z_1$ coupling, the $Z_1$ can be produced through WBF channel $jjZ_1$ and associated production $WZ_1$\footnote{Associated production of a strongly interacting vector (V) with heavy quarks has been considered in Ref. \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$.}. The perspectives for its observation at the LHC look promising.}. Al-

1 Associated production of a strongly interacting vector (V) with heavy quarks has been considered in Ref. \footnote{Unitarity bounds are also reached at $16\pi/\sqrt{2} G_F M_f \xi$ for massive fermion scattering amplitudes $f\bar{f} \rightarrow W_L^+ W_L^-$.}. The perspectives for its observation at the LHC look promising.
ollowing $Z_1 \rightarrow W^+W^-/Z_1 \rightarrow t\bar{t}$ decays, the final states will contain $jjt\bar{t}/jjW^+W^-$ and $W^±t\bar{t}/W^±W^+W^-$. Unlike the $W_1$ case in [3, 4], the WBF channel $jjZ_1$ suffers from huge irreducible Standard Model (SM) background of $t\bar{t}$ plus jets. Our studies focus on the leptonic decays of like-sign $W$s via associated production. Consequently, the final states to be studied consist of multijet $+\ell^±\ell^± + E_T$. In comparison with previous studies, we can reach a mass of 550 GeV−650 GeV for $t\bar{t}$ and $WW$ modes, at a 5$\sigma$ level with 100 fb$^{-1}$ of the integrated luminosity.

This paper is organized as follows. In Sec.II, we discuss the parameters in the model, bounds on KK gauge boson masses and their couplings to SM particles due to unitarity requirement in scattering amplitudes and precision electroweak tests. In Sec.III, we discuss the search of $Z_1$ gauge boson at the LHC allowing both $Z_1 \rightarrow W^+W^-$ and $Z_1 \rightarrow t\bar{t}$ decays and focus on the multijet $+\ell^±\ell^± + E_T$ final states. We will conclude in Sec. IV.

II. MODEL PARAMETERS

In Higgsless models, it is shown [4] that the scattering amplitude of the longitudinal components of massive $W$ and $Z$ bosons can be unitarized by the KK excitations of the gauge bosons $Z_n$ and $W_n$. The cancellation of $E^2$ and $E^4$ terms lead to the following sum rules of $Z_n$ as [4]

$$g^2_{WWW} = g^2_{WWZ} + g^2_{WW\gamma} + \sum_n (g_{WWZ_n})^2,$$

$$4g^2_{WWW}M_W^2 = 3 \left[ g^2_{WWZ}M_Z^2 + \sum_n (g_{WWZ_n})^2M_{Z_n}^2 \right],$$

where $g_{WWW} = g^2 = e^2/\sin \theta_W$ is the SM four $W$ contact interaction coupling, $g_{WWZ}/g_{WW\gamma}$ are the SM coupling between $WW$ and $Z/\gamma$ respectively.

We focus on the first KK excitation $Z_1$ boson and assume other higher KK excitations to be less relevant to the collider search. However, such a truncation will lead to a violation of partial wave unitarity at a scale $\Lambda \simeq 4\pi M_{Z_1}/g$ [4]. For instance, if $M_{Z_1} = 500$ GeV, then $\Lambda$ is of $\mathcal{O}(10 \text{ TeV})$, which should not affect our phenomenological considerations.

In principle, the introduction of new gauge boson will also modify the SM couplings. We keep $g_{WW\gamma}$ and $g_{WWW}$ to their SM value and $g_{WWZ_1}$ and $g_{WWZ}$ can be computed through
Eq. 1 and Eq. 2. We obtain the couplings as
\[
g^2_{WWZ_1} = \frac{(4M_W^2 - 3M_Z^2)g^2_{WWWW} + 3M_Z^2g^2_{WWY}}{3(M_{Z_1}^2 - M_Z^2)},
\]
\[
g^2_{WWWZ} = \frac{3M_Z^2(g^2_{WWWW} - g^2_{WWY}) - 4M_W^2g^2_{WWWW}}{3(M_{Z_1}^2 - M_Z^2)}.
\]
The $Z_1$ mass $M_{Z_1}$ will then be the only input parameter in the analysis. If $M_{Z_1} = 500$ GeV, the deviation of $g^2_{WWWZ}$ from its SM value is smaller than 1%, which is consistent with the current experimental bound.

Previous studies have shown that it is hard to accommodate precision electroweak data if $Z_1$ couples to the SM fermions. Even if $Z_1$ only couples to the third family, it is disfavored by the strong constraints on the $Zb\bar{b}$ coupling. A fermiophobic $Z_1/W_1$ have been studied in Refs. [10, 11]. A few viable models have been suggested to incorporate this Ref. [7, 12]. In this paper, we will take $Z_1$ to couple mainly to $t\bar{t}$ and $W^+W^-$ but without specifying the values of the branching fractions $BR(Z_1 \rightarrow t\bar{t})$ and $BR(Z_1 \rightarrow W^+W^-)$ a priori.

III. $Z_1$ AT THE LHC

For a vector state, the dominant production mechanism is the Drell-Yan process, $q\bar{q} \rightarrow Z_1$, if there are sizable couplings to light quarks [13]. With highly suppressed couplings to light fermions as preferred in Higgsless models, the dominant production channel for $Z_1$ is commonly considered as the weak boson fusion (WBF) mechanism $pp \rightarrow Z_1jj$. We extend the calculation by including the the associated production $pp \rightarrow WZ_1$. Fig. 1 shows the total cross sections of $Z_1$ from associated production and WBF production at the LHC for 10 (dotted curves) and 14 TeV (solid curves). We have chosen the PDF CTEQ6L and the factorization scale $\mu_F = \sqrt{s}/2$. As expected, we see that the associated production is larger at smaller value of $M_{Z_1}$ and the WBF mechanism takes over at higher values. The two curves cross near $M_{Z_1} \sim 400 - 600$ GeV, where the cross sections are quite sizable, about 100−200 fb.

The WBF processes for $W_LW_L$ scattering have unique kinematic features: two forward/backward energetic jets with large dijet invariant mass and lack of central jet activities. However, the $Z_1 \rightarrow t\bar{t}$ and $Z_1 \rightarrow W^+W^-$ channels via WBF suffer from huge backgrounds, mainly from $t\bar{t}$ plus jets of order several hundreds pb, while the $Z_1$ WBF production rate is only of a few hundreds fb which is $O(10^3)$ smaller. The $WZ_1$ associated production,
FIG. 1: $Z_1$ Production rates at the LHC for 10 (dotted curves) and 14 TeV (solid curves).

however, benefits from the additional handle of $W^\pm$. We therefore focus on this associated production channel. The processes under consideration are

$$pp \to W^\pm Z_1 \to W^\pm t \bar{t} \text{ and } W^\pm W^+W^-.$$  \hfill (5)

As for the final state reconstructions, although the hadronic decay of $t$ or $W$ will help to fully reconstruct the $Z_1$ resonance, these channels suffer from huge standard model background from $t\bar{t}$ plus jets. To effectively suppress the backgrounds, we look for the signal of like-sign di-leptons. We choose the $W^\pm$ associated with the $Z_1$ production always decaying into leptons ($\ell = e, \mu$) and take the $W^\pm$ from $Z_1$ decay of the like-sign as the previous $W^\pm$, which also decays leptonically. The third $W^\mp$ decays hadronically. The final states that we are looking for are

$$pp \to W^\pm Z_1 \to \begin{cases} W^\pm W^+W^- \to \ell^\pm\ell^\pm + jj + E_T, \\ W^\pm t\bar{t} \to \ell^\pm\ell^\pm + b\bar{b} jj + E_T, \end{cases}$$  \hfill (6)

with $jj$ always reconstruct on-shell $W$. The BR then carries a factor of

$$\left(\frac{2}{9}\right)^2 \times \frac{2}{3} = 3.29\%,$$  \hfill (7)

to be multiplied by BR($Z_1 \to t\bar{t}$) or BR($Z_1 \to W^+W^-$) in addition.
To simulate detector effects on energy-momentum measurements, we smear the electromagnetic energy and lepton momenta by a Gaussian distribution whose width is parameterized as [15]

$$\frac{\Delta E}{E} = \frac{a_{cal}}{\sqrt{E/\text{GeV}}} \oplus b_{cal}, \quad a_{cal} = 5\%, \quad b_{cal} = 0.55\%. \quad (8)$$

We did not separately smear the muon $p_T$ by tracking resolution, since separate smearing do not affected the results practically. The jet energies are also smeared using the same Gaussian formula as in Eq. (8), but with [15]

$$a_{cal} = 100\%, \quad b_{cal} = 5\%. \quad (9)$$

A. $Z_1 \rightarrow WW$

We first consider the $Z_1 \rightarrow W^+W^-$ channel for the like-sign dilepton plus dijet $\ell^\pm\ell^\pm + jj + E_T$ final state. We propose the basic cuts for the event selection as:

$$p_T^j > 25 \text{ GeV} ; \quad |\eta_j| < 3.0$$
$$p_T^\ell > 15 \text{ GeV} ; \quad |\eta_\ell| < 2.5$$
$$\Delta R(j,j) > 0.4 ; \quad \Delta R(j,\ell) > 0.4. \quad (10)$$

We further demand that the dijet in our signal reconstruct an on-shell $W$ boson

$$|M_{jj} - M_W| < 15 \text{ GeV}. \quad (11)$$

After these selection cuts, the leading QCD background ($uu, \bar{d}d \rightarrow W^\pm W^\pm jj$) is reduced to a negligible level. The remaining background is mostly the electroweak $WWW$ production with two like-sign $W$ decaying leptonically and the third $W$ decaying hadronically. At this stage, this $WWW$ background rate is already smaller than that of the signal if BR($Z_1 \rightarrow W^+W^-$) $\sim 100\%$. We note that the decay products from a heavy resonance $Z_1$ will be fairly energetic, with a typical transverse momentum $p_T^j \sim 0.5M_{Z_1}\sqrt{1 - 4M_W^2/M_{Z_1}^2}$. This is shown in Fig. 2 where we plot the hardest jet $p_T$. We can further improve the signal purity by imposing a cut, for instance,

$$\max(p_T^j) > 150 \text{ GeV}. \quad (12)$$
FIG. 2: Normalized max($p_T^j$) distribution for $2j + \ell^+\ell^- + \not{E}_T$ final states of $W^\pm Z_1 \rightarrow W^\pm W^+ W^-$ and the SM $W^\pm W^+ W^-$ at $M_{Z_1} = 500$ GeV after $M_{jj}$ cut.

We show the results for the signal with $M_{Z_1} = 500$ GeV and $\text{BR}(Z_1 \rightarrow W^+ W^-) = 100\%$ and backgrounds in Table II. With a given number of events for the signal ($S$) and background ($B$), we conservatively estimate the statistical significance by

$$S/\sqrt{S + B}. \quad (13)$$

We see that the signal observability is quite convincing with $10-30$ fb$^{-1}$ even before the final cut of Eq. (12). However, with this additional cut, the $S/B$ is significantly improved from 2 to 8, making the systematics of the measurement much less a concern. If we take the $\text{BR}(Z_1)$ as a free parameter, we can see that requiring a $5\sigma$ signal sensitivity, one is able to probe the $\text{BR}(Z_1 \rightarrow WW)$ to a level of 54% with 30 fb$^{-1}$.

There are two missing neutrinos in the final states that we propose and only one of them is from the resonance. Consequently, the reconstruction of the resonance $Z_1$ is very challenging. The like-sign dilepton final states will also cause combinatorial problem as it is difficult to distinguish a lepton from the $W^\pm$ in $W^\pm Z_1$ or from the $Z_1$. Between the two reconstructed invariant masses $M_{jj}$, we propose to use the smaller one since this will be bounded by the resonance mass $M_{Z_1}$. Figure 3 shows the distribution of the smaller $M_{jj}$ for $M_{Z_1} = 500$ GeV after $M_W$ reconstruction and max($p_T^j$) cut. We see a clear endpoint near $M_{Z_1}$. Because of the limited statistics, we would not impose further cut on this variable,
TABLE I: Signal/Background Comparison in \( pp \to \ell^\pm \ell^\pm + 2j + \not{E}_T \) final states \( M_{Z_1} = 500 \) GeV and \( \text{BR}(Z_1 \to W^+W^-) = 100\% \).

|                      | No Cut | Basic Cut Eq. (10) | \(+ M_{jj} \) Eq. (11) | \(+ \text{max}(p_T^j) \) Eq. (12) |
|----------------------|--------|--------------------|---------------------|----------------------------------|
| Signal (fb)          | 6      | 2.8                | 2.7                 | 1.7                              |
| \( W^\pm W^\pm jj \) BG (fb) | 41     | 17                 | 0.33                | 0.03                             |
| \( W^\pm W^\mp W^\mp \) BG (fb) | 4.1    | 1.1                | 1.1                 | 0.18                             |
| Total BG (fb)        | 45     | 18                 | 1.5                 | 0.21                             |

FIG. 3: \( M_{\ell jj} \) distribution for signal at \( M_{Z_1} = 500 \) GeV and background after \( M_{jj} \) and \( \text{max}(p_T^j) \) cuts.

although it could help to determine the mass of \( Z_1 \).

B. \( Z_1 \to t\bar{t} \)

In the case where \( Z_1 \to t\bar{t} \) has significant decay branching fraction, we will look for \( \ell^\pm \ell^\pm + bbjj + \not{E}_T \) final states. We adopt the same event selection as in Eq. (10). The
FIG. 4: Normalized $\max(p_T^j)$ distribution of $pp \rightarrow W^\pm Z_1 \rightarrow t\bar{t}W^\pm \rightarrow 4j + \ell^\pm \ell^\pm + E_T$ at $M_{Z_1} = 500$ GeV and SM $t\bar{t}W^\pm$ background.

|                | No Cut | Basic Cuts | $\max(p_T^j) > 150$ GeV | $+M_{\ell\ell j}$ cut |
|----------------|--------|------------|--------------------------|----------------------|
| Signal(fb)     | 6      | 1.4        | 0.91                     | 0.64                 |
| SM BG(fb)      | 14     | 3.6        | 1.1                      | 0.25                 |
| S/B            | 0.40   | 0.84       | 2.5                      |                      |
| $S/\sqrt{S+B}$ at 30 fb$^{-1}$ | 3.4 | 3.5 | 3.7 | |
| $S/\sqrt{S+B}$ at 100 fb$^{-1}$ | 6.2 | 6.4 | 6.8 | |

TABLE II: Summary Table of $pp \rightarrow W^\pm Z_1 \rightarrow W^\pm t\bar{t} \rightarrow 4j + \ell^\pm \ell^\pm + E_T$ for $M_{Z_1} = 500$ GeV and its leading SM background $t\bar{t}W^\pm$.

leading irreducible SM background comes from the process $t\bar{t}W^\pm$ which also contains two $b$-jets. Therefore, a requirement of $b$-tagging in our study would not help to reduce this background. The first handle we exploit is again the boost effects from heavy resonance $Z_1$. Fig. 4 shows the $\max(p_T^j)$ distributions for SM $t\bar{t}W^\pm$ and $W^\pm Z_1 \rightarrow t\bar{t}W^\pm$. We thus impose the same cut as in Eq. (12) on $\max(p_T^j)$.

As for the $Z_1$ mass reconstruction from $t\bar{t}$, we encounter the same problem of the combinatorics as before. The two on-shell top quarks provide extra handle in reconstruction. One can first try to reconstruct the hadronic top quark then the $Z_1$ resonance. We first
require one of the reconstructed $M_{jjj}$’s to be close to top quark mass to reconstruct the hadronic decaying top. The other jet will be combined with the two leptons to make $M_{\ell j}$ invariant mass. Similar to the $Z_1 \rightarrow WW$ search, we propose to explore the invariant mass distribution for one of the leptons plus the fourth jet, and choose the smaller invariant mass between the two $M_{\ell j}$ to reconstruct the leptonic decaying top quark. We wish to consider the reconstructed top pair invariant mass $M_{tt}$ with the endpoint related to $M_{Z_1}$. We plot the smaller $M_{\ell 4j}$ distribution in Fig. 5 after the $\max(p_T^j)$ cut. This motivates us to select the mass window to estimate the accessible sensitivity to the signal, and we choose

$$0.8M_{Z_1} < M_{\ell 4j} < M_{Z_1}.$$  \hfill (14)

The results are summarized in Table II with variety of cuts. We see that the statistical significance is also convincing with 50–100 fb$^{-1}$.

To summarize this section, in Fig. 6(a) we plot the integrated luminosity needed to reach a $3\sigma$ (solid lines) and $5\sigma$ (dashed lines) statistical significance versus $M_{Z_1}$, with a reconstruction window $0.6M_{Z_1} < M_{\ell 2j} < M_{Z_1}$, which helps more for a heavier $Z_1$. To claim a $3\sigma$ discovery of the $Z_1 \rightarrow W^+W^-$ for $M_{Z_1} = 1$ TeV, it would require 500 fb$^{-1}$ integrated luminosity. We also plot the BR parameter reached at $3\sigma$ (solid lines) and $5\sigma$ (dashed lines) level with a 100 fb$^{-1}$ integrated luminosity in Fig. 6(b), again versus $M_{Z_1}$. One can reach
FIG. 6: (a) Integrated luminosities required for 3σ and 5σ significance of detection after $Z_1$ reconstruction; (b) Accessibility to BR($Z_1 \to WW$) and BR($Z_1 \to t\bar{t}$) at the 5σ level with 100 fb$^{-1}$.

60% BR with 3σ significance for 700 GeV and 580 GeV of $Z_1$ decay to $WW$ and $t\bar{t}$ channels, respectively. We adopt the criterion of Eq. (13) for estimations.

If the $Z_1$ is heavier, for the $Z_1 \to W^+W^-$ channel, the hadronic decaying $W$ from $Z_1$ will be highly boosted and one may define one fat $W$-jet, of which the jet mass is within $M_W$ window. The signature will then become $\ell^\pm \ell^\pm + J_W + E_T$. Although it would be challenging to quantify this background without detailed simulation of the detector effects, one may expect that the background should be smaller as studied in [16], and in particular there will be no leading process $W^\pm W^\pm j$ in the SM. If $Z_1 \to t\bar{t}$ is dominant, the coverage is only up to 650 GeV or so for 100 fb$^{-1}$ integrated luminosity. The top quarks decaying from the $Z_1$ are not boosted into one top-jet cone. For larger $Z_1$ mass, if top decay becomes highly boosted, the discovery will become more challenging as we won’t have the isolated like-sign dilepton any more.

IV. CONCLUSION

We have studied the LHC phenomenology of $Z_1$ that unitarize the $WW$ scattering amplitude. $Z_1$ does not couple to light fermions but we allow it to couple to the top quark.
We choose the associated production $W^\pm Z_1$ and study both $Z_1 \to W^+W^-$ and $Z_1 \to t\bar{t}$ without specifying the decaying BRs. By choosing the multijet $+ \ell^\pm \ell^\pm + E_T$ final state, we find that it is quite feasible for the signal to be larger than the SM irreducible background. Even though it is hard to fully reconstruct the resonance $Z_1$, we propose to use the edge of jets plus lepton invariant mass $M_{\ell nj}$ to get some information of the resonance $Z_1$ mass. For 100 fb$^{-1}$ integrated luminosity, assuming 100% decay BR, for 5$\sigma$ discovery significance, the $Z_1 \to t\bar{t}$ can be searched upto 560 GeV and $Z_1 \to W^+W^-$ search can reach 650 GeV respectively.

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[1] C. H. Llewellyn Smith, Phys. Lett. B 46, 233 (1973).
D. A. Dicus and V. S. Mathur, Phys. Rev. D 7, 3111 (1973). J. M. Cornwall, D. N. Levin and G. Tiktopoulos, Phys. Rev. Lett. 30, 1268 (1973) [Erratum-ibid. 31, 572 (1973)].
Phys. Rev. D 10, 1145 (1974) [Erratum-ibid. D 11, 972 (1975)].
B. W. Lee, C. Quigg and H. B. Thacker, Phys. Rev. Lett. 38, 883 (1977).
Phys. Rev. D 16, 1519 (1977).
M. S. Chanowitz and M. K. Gaillard, Nucl. Phys. B 261, 379 (1985).
[2] T. Appelquist and M. S. Chanowitz, Phys. Rev. Lett. 59, 2405 (1987) [Erratum-ibid. 60, 1589 (1988)].
[3] F. Maltoni, J. M. Niczyporuk and S. Willenbrock, Phys. Rev. D 65, 033004 (2002) [arXiv:hep-ph/0106281]. D. A. Dicus and H. J. He, Phys. Rev. D 71, 093009 (2005) [arXiv:hep-ph/0409131].
[4] C. Csaki, C. Grojean, H. Murayama, L. Pilo and J. Terning, Phys. Rev. D 69, 055006 (2004) [arXiv:hep-ph/0305237].

[5] A. Birkedal, K. Matchev and M. Perelstein, Phys. Rev. Lett. 94, 191803 (2005) [arXiv:hep-ph/0412278].

[6] H. J. He et al., Phys. Rev. D 78, 031701 (2008) [arXiv:0708.2588 [hep-ph]].

[7] C. Schwinn, Phys. Rev. D 71, 113005 (2005) [arXiv:hep-ph/0504240].

[8] T. Han, G. Valencia and Y. Wang, Phys. Rev. D 70, 034002 (2004) [arXiv:hep-ph/0405055].

[9] R. S. Chivukula, D. A. Dicus and H. J. He, Phys. Lett. B 525, 175 (2002) [arXiv:hep-ph/0111016].

[10] R. Sekhar Chivukula, B. Coleppa, S. Di Chiara, E. H. Simmons, H. J. He, M. Kurachi and M. Tanabashi, Phys. Rev. D 74, 075011 (2006) [arXiv:hep-ph/0607124].

[11] R. S. Chivukula, E. H. Simmons, H. J. He, M. Kurachi and M. Tanabashi, Phys. Rev. D 72, 015008 (2005) [arXiv:hep-ph/0504114].

[12] G. Cacciapaglia, C. Csaki, G. Marandella and J. Terning, Phys. Rev. D 75, 015003 (2007) [arXiv:hep-ph/0607146].

[13] For a Higgsless model with 4-sites, see, e.g., E. Accomando, S. De Curtis, D. Dominici and L. Fedeli, arXiv:0807.5051 [hep-ph]; For a study in a generic dynamical electroweak symmetry breaking model, see, e.g., A. Belyaev, R. Foadi, M. T. Frandsen, M. Jarvinen, F. Sannino and A. Pukhov, Phys. Rev. D 79, 035006 (2009) [arXiv:0809.0793 [hep-ph]].

R. S. Chivukula, D. A. Dicus, H. J. He and S. Nandi, Phys. Lett. B 562, 109 (2003) [arXiv:hep-ph/0302263].

Y. Nomura, JHEP 0311, 050 (2003) [arXiv:hep-ph/0309189].

[14] A. S. Belyaev, R. S. Chivukula, N. D. Christensen, E. H. Simmons, H. J. He, M. Kurachi and M. Tanabashi, arXiv:0907.2662 [hep-ph].

[15] CMS TDR: CMS Physics: Technical Design Report V.2: Physics Performance, CERN-LHC C-2006-021. ATLAS TDR: ATLAS detector and physics performance. Technical design report. Vol. 2, CERN-LHCC-99-15

[16] T. Han, B. Mukhopadhyaya, Z. Si and K. Wang, Phys. Rev. D 76, 075013 (2007) [arXiv:0706.0441 [hep-ph]].