Drell-Yan Production of $Z'$ in the Three-Site Higgsless Model at the LHC

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In the Higgsless models, there are extra gauge bosons which keep the perturbative unitarity of a longitudinally polarized gauge boson. The three-site Higgsless model is a minimal Higgsless model and contains three extra gauge bosons, $W^{±}$ and $Z'$. In this paper, we report the discovery potential of the $Z'$ gauge boson via Drell-Yan production with $Z'(mass=380, 500, 600 \, \text{GeV}) \to WW \to \ell\nu qq$ ($\ell = e, \mu$) at the LHC ($\sqrt{s}=14 \, \text{TeV}$).

I. INTRODUCTION

The standard model (SM) describes the phenomenology of elementary particles very well. Its predictions are consistent with many experimental results. Spontaneous symmetry breaking (SSB) is an important concept in the SM, and the electroweak symmetry breaking (EWSB) is known to be spontaneously broken. In the SM, the EWSB is triggered by a Higgs boson. However, the Higgs boson has not been discovered yet in any experiment. This fact means the origin of EWSB still remains a mystery. A Large Hadron Collider experiment at CERN (LHC) \cite{1} has started with a center-of-mass energy of $\sqrt{s} = 7 \, \text{TeV}$ and the LHC is expected to reveal the origin of the EWSB. There are two possibilities, that is, scenarios with and without the Higgs boson to describe the EWSB. We focus on the latter scenario in this paper. In case the Higgs boson does not exist, there is no longer so-called naturalness problem. However, in this case there are problems in the unitarity of the longitudinal gauge boson scattering \cite{2, 3, 4} and in the consistency with electroweak precision tests.

During the past decade, models with extra dimensions have been studied as a new paradigm. It has brought a solution of the gauge hierarchy, a solution of the Yukawa hierarchy, many new particles called Kaluza-Klein (KK) particles and dark-matter candidates (with the symmetry called KK parity). The Higgsless model \cite{5, 21} is one of the extra-dimensional models. It does not contain any physical scalar field. The EWSB is triggered by boundary conditions for an extra-dimensional direction.

The Higgsless model can keep a perturbativity, and can be translated into a model in four dimensions by the discretization of the extra-dimensional direction. This translation is known as the deconstruction \cite{22, 23}. The deconstruction allows us to interpret a gauge symmetry in extra dimension as a direct product of infinite number of gauge symmetries. Hence a model with a direct product of finite number of gauge symmetries can be regarded as a low energy effective theory, where one of the ultraviolet (UV) completions is described with an extra-dimensional model. Such models can be constructed by a bottom-up approach using non-linear sigma models. The structure of their gauge sector is based on a generalized hidden local symmetry \cite{24, 30}.

The three-site Higgsless model \cite{31} is a minimal deconstructed Higgsless model and contains three extra relatively heavy gauge bosons, $W^{±}$ and $Z'$ as explained later. The electroweak gauge symmetry of this model is $SU(2) \times SU(2) \times U(1)$, which is broken down to $U(1)_{QED}$. Hence this model is a low energy effective theory of the Higgsless model in extra dimension and other UV complete models. Through studies of this model, we can find validity of other similar models at a time. This is an advantage of this model, and it is important to find phenomenological constraints on this model.

Phenomenological constraints on this model are compatible with current experiments \cite{31, 33}. Hence the LHC should be the most powerful experiment to test this model. Because we have already know the precise bounds on parameters in this model, we can accurately predict physics and signals at the LHC. There are papers on the three-site Higgsless model for the LHC \cite{34, 35, 36}, and many of them are based on the so-called parton level analysis. The parton level analysis ignores the effects of hadronizations and detector responses, which are needed to get more realistic prospects. Results, for example, the requirement of integrated luminosity needed for new particle discovery, without considering such effects might be optimistic. Therefore hadronizations and detector simulations are performed for the results shown in this paper.

According to the parton level analysis, Drell-Yan (DY) production process of the $W^{±}$ and $Z'$ bosons is the most promising channel for their discovery. Less integrated luminosity is required for the discovery of heavy gauge bosons through the DY process than others. As explained later, the coupling among the $Z'$ and fermions, $g_{Z'ff}$, is stronger than the coupling among the $W'$ and fermions, $g_{W'ff}$ and a parameter dependence of $g_{Z'ff}$ is more moderate compared with $g_{W'ff}$. Therefore we focus on the DY production of $Z'$ in this paper, and study it with a way beyond the parton level analysis.

This paper is organized as follows. In section II, we review the three-site Higgsless model briefly. In section III, we perform feasibility studies with the experimental condition of the ATLAS experiment \cite{42} for some signal points. Section IV is devoted for summary and discussion.
II. THE THREE-SITE HIGGSLESS MODEL

In this section we review the three-site Higgsless model briefly. This is a minimal Higgsless model, and its electroweak gauge symmetry is \( SU(2)_0 \times SU(2)_1 \times U(1)_2 \). The electroweak symmetry breaking is described using the Hidden local symmetry language, or non-linear sigma fields. We explain gauge and fermion sectors with its Lagrangian and physical features for each sector.

A. Gauge sector

The gauge sector of this model is written as

\[
\mathcal{L}_{\text{gauge}} = -\frac{1}{4} G_{\mu
u}^a G^{a\mu\nu} - \frac{1}{4} \sum_{i=1}^2 W^a_{i\mu\nu} W_{i\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{f^2}{4} \text{tr} \left[ \left( D_\mu U_i \right)^\dagger (D^\mu U_i) \right].
\]

Eq. (1) is a gluon sector, and Eq. (2) are a electroweak sector. \( W^a_{\mu\nu} \) and \( B_{\mu\nu} \) are gauge fields of \( SU(2)_0 \), \( SU(2)_1 \) and \( U(1)_2 \), respectively. Their gauge couplings are \( g_0 \), \( g_1 \) and \( g_2 \), respectively. \( U_i \) are would-be Nambu-Goldstone bosons in non-linear sigma representation\(^1\),

\[
U_i = \exp \left( i \frac{\tau^a_{i}}{f_i} \right),
\]

and their covariant derivatives are following:

\[
D_\mu U_1 = \partial_\mu U_1 + i g_0 \frac{\tau^a_{0}}{2} W^a_{0\mu} U_1 - i g_1 \frac{\tau^a_{1}}{2} W^a_{1\mu} U_1 - i g_2 \frac{\tau^a_{2}}{2} B_{\mu} U_1,
\]

\[
D_\mu U_2 = \partial_\mu U_2 + i g_1 \frac{\tau^a_{1}}{2} W^a_{1\mu} U_2 - i g_2 \frac{\tau^a_{2}}{2} B_{\mu} U_2.
\]

Notice that \( U(1)_2 \) gauge symmetry acts on \( U_2 \) as a “partially gauged \( SU(2)_2 \)”. All fields in the above Lagrangian are not mass eigenstate but gauge eigenstate except gluon field. Mass matrices for gauge bosons can be derived from Eq. (2). By taking a mass eigenstate basis, we can obtain physical particles, that is, charged gauge bosons \( W^\pm_\mu \) and neutral gauge bosons \( Z_\mu \) and \( A_\mu \) as linear combinations of \( W^0_\mu \), \( W^1_\mu \) and \( B_\mu \). There are three extra heavy gauge bosons \( W^{\pm}_\mu \) and \( Z^\prime \), which have almost the same mass. From experimental constraints on the \( WWZ \) coupling \[3, 14\], we get a lower bound on them, \( M_{Z^\prime} \sim M_{W'} \geq 380 \text{ GeV} \). Using constraints from \( S \) and \( T \) parameters, we can find a upper bound on them, \( M_{Z^\prime} \sim M_{W'} \leq 610 \text{ GeV} \).

B. Fermion sector

This model has following fermions: \( \Psi_{L0} \sim (2, 1)_Y \), \( \Psi_{L1} \sim (1, 2)_Y \), \( \Psi_{R1} \sim (1, 2)_Y \) and \( \Psi_{R2} \sim (1, 1)_Q \), where \( Y = 1/6 \) for quarks and \( Y = -1/2 \) for leptons. We can write down kinetic terms of fermion by using them. The representation of fermions in this model is summarized in Table I.

| \( \Psi_{L0} \) | \( SU(2)_0 \) | \( SU(2)_1 \) | \( U(1)_2 \) | \( SU(3)_c \) |
|----------------|----------------|----------------|----------------|----------------|
| \( \Psi_{L1} \) | 1 | 2 | \( \frac{1}{3} \) | \( \frac{1}{3} \) |
| \( \Psi_{R1} \) | 1 | 2 | \( \frac{1}{3} \) | \( \frac{1}{3} \) |
| \( \Psi_{R2} = (u_{R2} \ d_{R2}) \) | 1 | 1 | \( \frac{1}{3} \) | \( \frac{1}{3} \) |

TABLE I: The representation of fermions in this model. 2 and 3 mean fundamental representations for \( SU(2) \) and \( SU(3) \) respectively, and 1 means singlet. Other numbers are values of hypercharge. The numbers in parenthesis in columns of \( U(1)_2 \) and \( SU(3)_c \) are for leptons.

Mass and Yukawa interaction terms in this model are as follows:

\[
\mathcal{L}_{\text{fermion}} = - \sum_{i,j} \left[ (\bar{\Psi}_{L0})^i U_{1i} m_{1ij} (\Psi_{R1})^j + (\bar{\Psi}_{L1})^i U_{2ij} m_{2ij} (\Psi_{R2})^j \right] + (h.c.),
\]

where \( M \) is Dirac mass, \( i \) and \( j \) are indices of generation or flavor, and

\[
m_{2ij} = \begin{pmatrix} m_{2u} & 0 \\ 0 & m_{2d} \end{pmatrix}_{ij}.
\]

In general, \( m_{1ij} \) and \( M_{ij} \) are not flavor blind. However, to avoid a large FCNC, \( m_{1ij} \) and \( M_{ij} \) are assumed to be flavor blind, namely, \( m_{1ij} = m_{\delta ij} \) and \( M_{ij} = M_{\delta ij} \). Under this assumption, the structure of all flavors in this model is embedded in \( m_{2u} \) and \( m_{2d} \). Again, \( \Psi's \) are not mass eigenstates but gauge eigenstates. By diagonalizing mass matrices, we find that masses of heavy fermions can be described to be approximately \( M \). Using constraints from \( S \) and \( T \) parameters, we can find a lower bound on \( M \), \( M \geq 1800 \text{ GeV} \), which is much heavier than bounds for heavy gauge bosons. Therefore the study of production processes of heavy gauge bosons, is more promising than heavy fermions at the LHC.

\(^1\) \( \tau^a \) is Pauli matrices.
C. Couplings among the heavy gauge boson and light fermions

Coupling among $W'$ and light fermions, namely $g_{W'ff}$, is strongly constrained from electroweak precision measurements [22]. Its order of magnitude is $g_{W'ff}/g_W \sim O(10^{-2})$, where $g_W = e/s_Z$ and $s_Z^2 \equiv 1 - c_Z^2$, $c_Z \equiv M_W/M_{Z'}$. Coupling among $Z'$ and light fermions are as follows.

$$g_{Z'ff,L} \simeq g_W \left( \frac{\tau_3}{2} G_3 - t_Z^2 \frac{M_W}{M_{Z'}} \right),$$

$$g_{Z'ff,R} \simeq g_W \left( -t_Z^2 \frac{M_W}{M_{Z'}} \right),$$

where

$$G_3 \equiv \sqrt{2} g_{W'ff}/g_W + t_Z^2 \frac{M_W}{M_{Z'}},$$

$$t_Z \equiv \frac{s_Z}{c_Z}.$$

We can see that $g_{Z'ff}$ is larger than $g_{W'ff}$, and its parameter dependence is moderate compared with $g_{W'ff}$. Therefore $Z'$ is more suitable than $W'$ as a discovery channel via DY production process.

III. DISCOVERY POTENTIAL AT THE LHC

In this section, we perform feasibility studies of the Higgsless model at the LHC. To investigate the $Z'$ discovery potential, we apply a simple detector simulation with smearing methods, which approximately reproduce the ATLAS experimental condition at proton-proton collision of a center-of-mass energy of $\sqrt{s} = 14$ TeV [45].

The discovery potential is studied with $Z' \to WW \to ℓνqq$ ($ℓ = e, \mu$) decay process, where one of $W$ bosons decays leptonically and the other hadronically. This channel is capable of reconstructing $Z'$ resonance by solving analytically longitudinal component of a neutrino as described in the following section.

Finally, the discovery potential estimated from invariant mass of two $W$ bosons, $M_{WW}$, as a function of integrated luminosity is shown.

A. MC sample and cross section

Signal and dominant background processes are generated with various Monte Carlo (MC) generators as follows. This study uses three preferable $Z'$ signal mass points whose parameters are summarized in Table III The $Z'$ signal and $WW$ background processes are generated with CalcHEP [46] and the parton shower and hadronization are simulated with PYTHIA [47]. The $tt$ process is generated with MC@NLO [48], $W$+jets with ALPGEN [49, 50] and the parton shower and hadronization are simulated with HERWIG [51].

The discovery potential is studied with a simplified ATLAS detector [52].

| $M_{Z'}$ (GeV) | $M_W$ (GeV) | $\frac{g_{W'ff}}{g_W}$ | $Br(Z' \to WW)$ |
|--------------|----------|-----------------|----------------|
| 380          | 3500     | 0.023           | 0.971          |
| 500          | 3500     | 0.023           | 0.987          |
| 600          | 4300     | 0.022           | 0.991          |

TABLE III: Cross section of $Z'$ signal and background processes. The number of $W$+jets is for single lepton flavor.

B. Event selection

The final state of $Z'$ considered in this paper is $ℓνqq$. Experimentally, the neutrino can be observed as a missing transverse energy ($E_{T}^{miss}$) and the quark is observed as a jet which is a cluster of hadron. While the lepton ($e$ and $μ$) can be measured precisely and used for an event trigger.

First, exactly one high-$p_T$ lepton into the detector coverage of a tracking detector ($p_T > 50$ GeV, $|η| < 2.5$)$^2$ is required. The inefficiency of lepton identification and trigger is taken into account and 80% of efficiency from combined identification and trigger, which is based on MC studies for the ATLAS detector [45], is applied.

Next, a large missing transverse energy ($E_{T}^{miss} > 50$ GeV) is required. In addition, exactly two jets with $p_T > 50$ GeV and $|η| < 3.2$ which is corresponding to the coverage of the calorimeter are required. If there are jets with $p_T > 25$ GeV, $|η| < 2.5$ and matched to $b$-quark, the $b$-tagging which has 50% efficiency and 2.5×10$^{-3}$ false tag rate are applied. Here we assume that there is no

$^2$ A pseudo-rapidity $η$ is defined by $-2\ln(\tan\frac{θ}{2})$, where $θ$ is the angle with respect to the beam line.
dependence of $p_T$ and $\eta$ on the $b$-tagging efficiency and false tag rate. Events are rejected to reduce enormous $t\bar{t}$ background if at least one $b$-tagged jet exists in the event. The reconstructed dijet invariant mass, $M_{jj}$, is required to be close to the nominal $W$ mass;

$$|M_{jj} - M_W| < 15 \text{ GeV}.$$ 

This selection is very effective to suppress $W(\to \ell\nu) + $ jets background which does not have hadronic decay of $W$ boson.

Two $W$ bosons decayed from heavy $Z'$ boson are highly boosted. Hence the events with high $p_T^{\ell}$ (from $p_T^W$ and $E_T^{\text{miss}}$) and $p_T^{\nu}$ are selected. The selection criteria depending on $Z'$ mass ($M_{Z'}$) are applied to maximize the discovery potential: $p_T^{\ell} > 150, 200$ and $250$ GeV and $p_T^{\nu} > 150, 200$ and $250$ GeV are required for $M_{Z'} = 380, 500$ and $600$ GeV, respectively.

$Z'$ invariant mass cannot be reconstructed from observables due to the missing information of longitudinal neutrino momentum ($p_z^\nu$). However we can calculate the longitudinal neutrino momentum by assuming the on-shell $W$ mass constraint [41]:

$$M_W^2 = (E^\ell + E^\nu)^2 - (p_T^\ell + p_T^{\nu})^2,$$

where $E^\ell$ and $p_T^\ell$ are energy and momentum of the charged lepton and neutrino, respectively. The longitudinal component of neutrino momentum is solved analytically from Eq. (3) as:

$$p_z^\nu = \frac{(M_W^2 - M_z^2 + 2p_T^\ell \cdot p_T^{\text{miss}})p_z^\nu \pm \sqrt{D}}{2(E_T^{\text{miss}} - p_z^\nu)}$$

(4)

where $p_T^\ell$ and $p_T^{\text{miss}}$ are transverse momentum of charged lepton and neutrino and $D$ is a discriminant represented as

$$D = E_T^{\text{miss}} \left\{ (M_W^2 - M_z^2 + 2p_T^\ell \cdot p_T^{\text{miss}})^2 - 4(E_T^{\text{miss}})^2(E_T^{\text{miss}} - p_z^\nu)^2 \right\}.$$ 

Two solutions of $p_z^\nu$ can be obtained from Eq. (4). It is found that a lower $|p_z^\nu|$ solution have slightly higher probability to match to the true $p_z^\nu$ value and gets better $M_{Z'}$ resolution as shown in Table [41]. However a higher $|p_z^\nu|$ solution also has sufficiently high probability to match to the true $p_z^\nu$. In addition, 25% of events have no solution due to a negative discriminant due to the resolution effect of the smearing. In this case $D$ is likely close to zero. It is found that $p_z^\nu$ value corresponding to true value can be obtained even if the imaginary part is neglected in the $p_z^\nu$ calculation ($D = 0$).

Figure [41] left) shows the $\Delta M_{W'W}$ distribution for each neutrino solution type in $M_{Z'} = 500$ GeV, where $\Delta M_{W'W}$ is a difference between a reconstructed $M_{W'W}$ and its true value. Since we adopt all the solutions in any case, the correctly reconstructed one has a peak around zero in the $\Delta M_{W'W}$ distribution but the wrongly one makes a tail in the high $\Delta M_{W'W}$ region. This behavior is observed in the reconstructed $M_{Z'}$ distribution as shown in Figure [41] (right). We see not only a clear peak but also a long tail in the high mass region. Table [41] shows mean and $\sigma$ values for each solution type. The $M_{W'W}$ distribution of a lower $|p_z|$ gives the best resolution and $M_{W'W}$ distribution of other solution types can be reconstructed with slightly higher mean value.

In this study, all three solutions are used to maximize a signal acceptance.

| Solution Type | Fraction | Mean (GeV) | $\sigma$ (GeV) |
|---------------|----------|------------|----------------|
| Two solutions | 75%      | 500.0      | 18.1           |
| No solution   | 25%      | 507.2      | 19.6           |

TABLE IV: The fraction of each solution type to events after event selection and mean and $\sigma$ values extracted from a single Gaussian fit for each solution type.

C. Discovery potential

The discovery potential of $Z'$ signal in the three-site Higgsless model is evaluated for three representative mass points.

The number of signal events are defined as

$$N_{\text{signal}} = N_{\text{2sol}}^{\text{low}} | \text{low} | + N_{\text{2sol}}^{\text{high}} | \text{high} | + N_{\text{no sol}}^{\text{real part}},$$

where $N_{\text{2sol}}^{\text{low}} | \text{low} |$ is for a lower $|p_z|$ solution, $N_{\text{2sol}}^{\text{high}} | \text{high} |$ for a higher $|p_z|$ and $N_{\text{no sol}}^{\text{real part}}$ for the no-solution case. Similarly, the number of background events ($N_{\text{bkg}}$) are defined as the sum of three solutions. Figure 2 shows the reconstructed $M_{W'W}$ distribution before $p_T^\ell$ and $p_T^{\nu}$ selection. All neutrino solutions are filled in this plot. Figure 3 shows the reconstructed $M_{W'W}$ distribution after $p_T^\ell$ and $p_T^{\nu}$ selection in $M_{Z'} = 500$ GeV.
The discovery potential is evaluated from the number of expected signal and background in a $M_{Z'}$ mass window, which is determined to get the maximum significance. This significance is defined as follows:

$$\text{Significance} = \frac{N_{\text{signal}}}{\sqrt{N_{\text{bkg}}}}.$$ 

Table V shows the number of expected signal and background into the signal mass window for each signal mass point. The bottom line shows significance. The number of events are normalized to 1 fb$^{-1}$.

Figure 4 shows the expected significance as a function of integrated luminosity. Two vertical lines correspond to the $3\sigma$ evidence and $5\sigma$ discovery thresholds, respectively.

IV. SUMMARY AND DISCUSSION

We have studied the discovery potential of the three-site Higgsless model with the $Z'$ gauge boson via Drell-Yan production at proton-proton collision of a center-of-mass energy of $\sqrt{s} = 14$ TeV. The discovery potential of $Z' \rightarrow WW \rightarrow \ell\nu qq$ is evaluated with the simplified detector simulation of ATLAS experiment condition which takes into account the effect of hadronization and experimental efficiency and resolution. The significance is obtained with the event counting in the signal mass window. We show that the significance reaches $3\sigma$ threshold in the integrated luminosity 1-6 fb$^{-1}$ and $5\sigma$ threshold in the 3-20 fb$^{-1}$ for theoretically preferable $Z'$ mass region, 380-610 GeV. The required integrated luminosity for the observation corresponds to a few years’ running of the LHC at $\sqrt{s} = 14$ TeV.

Depending on the model parameters, we have found less integrated luminosity is required for the discovery of

| $M_{Z'}$ (GeV) | 380 | 500 | 600 |
|---------------|-----|-----|-----|
| $W+\text{jets}$ | 53.7 | 45.9 | 9.25 |
| $t\bar{t}$ | 19.8 | 19.9 | 4.75 |
| $WW$ | 5.73 | 5.91 | 1.48 |
| Total background | 79.2 | 71.7 | 15.5 |
| Signal | 25.5 | 15.3 | 4.6 |
| Significance | 2.86 | 1.81 | 1.17 |

TABLE V: The number of signal and background in the signal mass window region for each mass point and obtained significance at 1 fb$^{-1}$. These numbers include all three solutions.
the \(Z'\) boson through the Drell-Yan process than other production processes. On the other hand, for the discovery of the \(W^{\pm}\) boson, other production processes have an advantage over the Drell-Yan process because of the fermiophobia of the \(W^{\pm}\) boson. It is important to discover the \(W^{\pm}\) boson because we have to check the origin of the \(Z'\) boson is the \(SU(2)\) gauge symmetry for a verification of Higgsless models. There are many models which predict the \(Z'\) boson which is not associated with \(SU(2)\) gauge symmetry\(^{[50]}\). Precision predictions in such \(Z'\) production are studied in\(^{[57, 60]}\), for example. Hence we need to discover \(W^{\pm}\) for a verification of Higgsless models. There is a mutually complementary relationship between the Drell-Yan process and other production processes in order to verify Higgsless models at the LHC.

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