Collider Phenomenology of Higgsless models

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Abstract. We study the LHC signatures of new gauge bosons in the minimal deconstruction Higgsless model (MHLM). We analyze the $W'$ signals of $pp \rightarrow W' \rightarrow WZ$ and $pp \rightarrow W'jj \rightarrow WZjj$ processes at the LHC, including the complete signal and background calculation in the gauge invariant model and have demonstrated the LHC potential to cover the whole parameter space of the MHLM model.

PACS. 12.60.Cn Extensions of electroweak gauge sector – 12.15.Ji Applications of electroweak models to specific processes

1 Introduction

Disentangling the nature of electroweak symmetry breaking (EWSB) is one of the important challenges of particle physics today and upcoming CERN Large Hadron Collider (LHC), in particular. Among several appealing theories of EWSB, Higgsless models are especially promising. In particular, those models predict new heavy gauge bosons serving as a key for EWSB and delaying unitarity violation of longitudinal weak boson scattering without invoking a fundamental Higgs scalar. Dimensional deconstruction formulation of the Higgsless theories is shown to provide their most general gauge-invariant formulation under arbitrary geometry of the continuum fifth dimension (5d) or its 4d discretization with only a few lattice sites.

The Minimal Higgsless Model (MHLM) consists of just 3 lattice sites (“The Three Site Model”) and predicts just two extra $W'$ and $Z'$ bosons which mass is 4400 GeV is consistent with all the precision data. MHLM is gauge invariant via spontaneous symmetry breaking and predicts just one pair of nearly degenerate $(W', Z')$ bosons, unlike any 5d Higgsless models with a tower of Kaluza-Klein gauge-states. This model contains all the essential ingredients of Higgsless theories being the simplest realistic Higgsless model with distinct collider signatures. In this study we investigate phenomenology of MHLM signals at the LHC including the complete signal and background calculation demonstrate the LHC potential to cover the whole parameter space of the MHLM model.

2 MHLM model

The MHLM is defined as a chain moose with 3 lattice sites, under the 5-dimensional $SU(2) \times SU(2) \times U(1)$ gauge theory with electroweak symmetry breaking encoded in the boundary conditions of the gauge fields. Gauge and Goldstone sectors of MHLM have 5 parameters in total – 3 gauge couplings $(g_0, g_1, g_2)$ and 2 Goldstone decay constants $(f_1, f_2)$, satisfying two conditions due to its symmetry breaking structure,

\[
\frac{1}{g_0^2} + \frac{1}{g_1^2} + \frac{1}{g_2^2} = \frac{1}{c^2}, \quad \frac{1}{f_1^2} + \frac{1}{f_2^2} = \frac{1}{v^2}. \tag{1}
\]

For the optimal delay of unitarity violation we choose equal decay constants $f_1 = f_2 = \sqrt{2}v$ as fixed by the Fermi constant. Choice of $M_W$ and $M_W'$ as inputs allows to determine $(g_0, g_1, g_2)$ gauge couplings. The MHLM exhibits a delay of unitarity violation for weak boson scattering $V_L^a V_L^b \rightarrow V_L^c V_L^d$ $(V = W, Z)$ and for $M_W' \lesssim 1$ TeV, each elastic $V_L^a V_L^b$ scattering remains unitary over the main energy range of the LHC.

The fermion sector contains SM-like chiral fermions: left-handed doublets $\psi_{0L}$ under $SU(2)_0$ and right-handed weak singlets $\psi_{2R}$. For each flavor of $\psi_{0L}$, there is a heavy vector-fermion doublet $\Psi_1$ under $SU(2)_1$. The mass matrix for $\{\psi, \Psi\}$ is

\[
M_F = \begin{pmatrix} m & 0 \\ M m' \end{pmatrix} \equiv M \begin{pmatrix} \epsilon_L & 0 \\ 0 & \epsilon_R \end{pmatrix}. \tag{2}
\]

The mass-diagonalization of $M_F$ yields a nearly massless light fermion $F_0$ and a heavy new fermion $F_1$ of mass $M_F = M \sqrt{1 + \epsilon_L^2}$. The light SM fermions acquire small masses proportional to $\epsilon_R$. For the present high energy scattering analysis we only need to consider light SM fermions relevant to the proton structure functions at the LHC, which can be treated as

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massless to good accuracy. So we will set $\epsilon_R \simeq 0$, implying that $\psi_{2R}$ and $\Phi_{1R}$ do not mix.

One should stress that fermion sector plays a crucial role in the MHLM. First of all, fermion gauge couplings in the MHLM [3] are the key to ensure an exact gauge-invariance in our collider study contrary to previous studies [6]. Secondly, the fermion sector is the key which provide consistency of MHLM with precision electroweak data. The proper adjustment of amount of delocalization of fermions to amount of delocalization of gauge bosons fixes $\epsilon_L$ via the ideal fermion delocalization [3] (IDDL) condition and leads to vanishing $W'$-SM fermion couplings and thus zero electroweak precision corrections at tree-level [6, 8].

One should notice that the mass of the heavy fermions is strongly bounded from below to $M_{F_i} > 1.8$ TeV [6]. Therefore the essential phenomenology of MHLM at the LHC is related to signals form new gauge bosons $W'$ and $Z'$ which can be as light as $\sim 400$ GeV. To simplify the analysis we consistently decouple the heavy fermion by taking the limit ($M, m \to \infty$) while keeping the ratio $\epsilon_L \equiv m/M$ finite. This finite ratio $\epsilon_L$ will be fixed via IDDL [3].

We have implemented MHLM model into CalcHEP package [10] using LanHEP program [11] for automatic Feynman rules generation. This implementation has been consistently cross-checked in t’Hooft Feynman and Unitary gauges and publicly available at http://hep.pa.msu.edu/belyaev/public/3-site/.

3 Phenomenology of MHLM

As discussed above, in MHLM the couplings of new heavy bosons to SM fermions are highly suppressed to satisfy precision EW data while the couplings of new heavy bosons to SM gauge bosons are non-vanishing to provide the delay of unitarity for $V^{(a\,b)}_{L\,L} \to V^{(c\,d)}_{L\,L}$ amplitudes.

These two essential features define the phenomenology of not only MHLM but the whole class of the Higgsless extradimensional models (HLEDM) whose phenomenology will be dominated by the first KK-mode.

In MHLM, the decay width of $W'$ or $Z'$ are defined by their decays to $WZ$ or $WW$ pairs, respectively

$$\Gamma_{W'\to WW(WZ)} = \frac{\alpha M_{W'}}{48 s^2 W'} [1 + O(x^2)]$$  \hspace{1cm} (3)

where $\alpha = e^2/4\pi$ and $x = 2M_{W}/M_{W'}$. For $M_{W'} = (0.5 - 1)$ TeV one has $\Gamma_{W'} \simeq (5 - 31)$ GeV. On the other hand, under the IDDL $W'$ does not decay to light SM fermions while $Z'$ decay to SM-fermions is highly suppressed

$$\Gamma_{Z'\to e^{+}e^{-}} = \frac{5\alpha M_{W'} x^2 W'}{96 c_w^2} [1 + O(x^2)].$$  \hspace{1cm} (4)

Therefore, one can expect, that the most promising discovery channels would be $Z'(W')$ production via gauge couplings with SM gauge bosons. Moreover, $W'$ production looks more favourable since the minimal number of neutrinos after $W'$ leptonic decay is one ($W' \to WZ \to 3\nu$), while $Z' \to WW \to 21\nu$ decay channel ends with two neutrinos disabling the reconstruction of the $Z'$ peak.

We found that the most favorable signal processes for discovery of the MHLM at the LHC are the associated $W'Z$ ($pp \to W'Z \to WZZ \to 4\ell 2q$) production as well as $W'W'$ production in $WZ \to W$ fusion process ($pp \to W'qq \to WZqq \to 3\ell 2q$) representative Feynman diagrams for which are shown in Fig. (a) and Fig. (b), respectively. The cross sections versus $M_{W'}$ for $pp \to W'Z$ and $pp \to W'qq^{(j)}$ processes including $4\ell 2q$ and $3\ell 2q$ respective branching ratios are presented in Fig. [2]. For $pp \to W'qq^{(j)}$ process the quark energy ($E_q > 300$ GeV), $P_{T\ell q}(P_{T\ell q} > 30$ GeV) and rapidity gap cuts were applied $|\Delta y_{\ell q}| > 4$. These cuts are essential for the background suppression as we discuss below. Hereafter we use CTEQ6L [11] parton density function and QCD scale $Q = \sqrt{s}$ and $Q = M_Z$ for $pp \to W'qq^{(j)}$ and $pp \to W'qq^{(j)}$ processes, respectively.

As we have mentioned above, we propose to analyze the $pp \to W'Z \to WZZ$ process via leptonic decays of the two $Z$ bosons and hadronic decays of $W$ providing a clean signature of 4-leptons plus 2-jets, $jj4\ell$ ($\ell = e, \mu$). The backgrounds include: (a)
the irreducible SM production of \( pp \rightarrow WZZ \rightarrow jj4\ell \), (b) the reducible background of the SM production, \( pp \rightarrow ZZZ \rightarrow jj4\ell \), with one \( Z \) to \( jj \) (mis-identified as \( W \) due to finite experimental di-jet mass resolution) and (c) the SM process \( pp \rightarrow jj4\ell \) other than (a) and (b), which also includes the \( jj4\ell \) backgrounds with \( jj = gg, gg \).

To suppress backgrounds we impose the cuts,

\[
M_{jj} = 80 \pm 15 \text{ GeV}, \quad \Delta R(jj) < 1.5, \\
\sum_{Z} p_{T}(Z) + \sum_{j} p_{T}(j) = \pm 15 \text{ GeV}.
\]  (5)

The first cut selects di-jets arising from on-shell \( W \) decay to be within the experimental resolution \([12]\); the second cut requires the dijet separation of the signal; and the third cut uses the conservation of transverse momentum in the signal to suppress the background. Furthermore, we impose the following electron and jet ID/acceptance cuts

\[
p_{T}\ell > 10 \text{ GeV}, \quad |\eta_{\ell}| < 2.5, \\
p_{T}j > 15 \text{ GeV}, \quad |\eta_{j}| < 4.5.
\]  (6)

In Fig. 3 we present the \( M_{Zjj} \) event distributions for the signal and background under these cuts for an integrated luminosity of 100 fb\(^{-1}\). We depict the signal by a dashed curve, the backgrounds (c) with \( jj = gg, gg \) by dashed and dashed-double-dotted curves, respectively, and the total background (a)+(b)+(c) by a solid curve. The backgrounds (a) and (b) are so small that they are not visible in Fig. 3. Finally we have chosen \( M_{W} = 115 \) GeV to estimate signal significance and LHC reach. In this mass window we have summed contributions from two \( Z \) bosons for signal and background. The gauge-invariance of this calculation is verified by comparing the signal distributions in unitary and 't Hooft-Feynman gauges; as shown in Fig. 3 by red-dashed and blue-dotted curves, they perfectly coincide. From the calculated number of signal and background events, we derive the statistical significance from the Poisson probability in the conventional way. The integrated luminosity required for detecting the \( W' \) in this channel will be summarized in Fig. 5.

Next, we analyze the LHC potential to discover \( W' \)-boson in the \( pp \rightarrow WZqq' \) process, where the signal is given by the \( W' \) contribution to \( WZ \rightarrow WZ \) scattering subprocess. We perform a complete analysis of \( pp \rightarrow WZjj \), and choose the pure leptonic decay modes of \( WZ \) with 3 leptons plus missing-\( E_{T} \) \([13,14]\). We carry out a full tree-level calculation including both signal and background together.

To effectively suppress \( qq \rightarrow WZ \) and \( pp \rightarrow WZjj \) \( (jj = gg, gg) \) QCD backgrounds we apply the following cuts on jet energy cut

\[
|\Delta \eta_{jj}| > 4, \quad E_{j} > 300 \text{ GeV}
\]  (7)
in addition to acceptance cuts given by

\[
p_{T}\ell > 10 \text{ GeV}, \quad |\eta_{\ell}| < 4.5
\]

where \( E_{j} \) and \( p_{T}\ell(i) \) are transverse energy and momentum of final-state jet(lepton), \( \eta_{j(i)} \) is the jet(lepton) rapidity, and \( |\Delta \eta_{jj}| \) is the difference between the rapidities of the two forward jets. For computing the SM EW backgrounds, we need to specify the reference value of the SM Higgs mass \( M_{H} \). Because the SM Higgs scalar only contributes to the \( t \)-channel in \( pp \rightarrow qq'WZ \), we find that varying the Higgs mass in its full range \( M_{H} = 115 \) GeV – 1 TeV has little effect on the SM background curve. Hence we can simply set \( M_{H} = 115 \) GeV in our plots without losing generality.

Using cuts \([7,8]\) we have computed the \( WZ \) invariant mass \( (M_{WZ}) \) distribution in both unitary gauge and 't Hooft-Feynman gauge and have revealed an extremely precise and large cancellation between the fusion and non-fusion contributions for \( pp \rightarrow WZqq' \) process, as required by the exact gauge-invariance. These cancellations cannot be inferred without a truly gauge-invariant model, contrary to the approach of imposing only a naive 5d sum rule \([7]\). Traditional analyses \([13]\) of gauge-boson fusion in a strongly-interacting symmetry breaking sector have relied on using separate calculations of the signal and background while in our case in the correct gauge-invariant implementation of MHLM we can perform direct calculation of \( qq \rightarrow WZqq' \) process for signal and background together.

Since there is just one neutrino in 3\( \ell \nu \) signature, we can use transverse mass variable, \( M_{T}^{2}(WZ) = \sqrt{M^{2}(\ell\ell) + p_{T}(\ell\ell) + p_{T}\text{miss}^{2}} - |p_{T}(\ell\ell) + p_{T}\text{miss}|^{2} \) \([13]\) for the effective signal over the background rejection. In Fig. 4 we present \( M_{T}^{2}(WZ) \) distributions for \( M_{Z'} = 500, 700, 900 \) GeV exhibiting clear Jacobian peaks. We compute signal significance for the 0.85\( M_{W} < M_{T} < 1.05M_{W} \) window and obtain the required integrated luminosities for \( 3\sigma \) and \( 5\sigma \) detections of the \( W' \) boson presented in Fig. 5.

4 Summary

We present the first study on LHC potential to observe signatures predicted by Minimal Higgsless Model
vital for analyzing the invariant Higgsless model (such as the MHLM \cite{6}), is that the calculation in the context of an exactly gauge
suppress all SM backgrounds. W e would like to stress WZZ
that the absence of a Higgs-like signal in $pp \rightarrow ZZ \ell \ell$ will be strong evidence for Higgsless electroweak symmetry breaking.

To conclude, for the first time we have consistently studied MHLM model which is very well motivated and has several appealing features: it is simple but generic, since the phenomenology of any Higgsless extradimensional model is dominated by the first KK-mode; the perturbatively calculable MHLM could shed a light on its conjectured strongly interacting theory; MHLM consistently implements the first KK-mode in a gauge-invariant way; MHLM satisfies precision EW measurements, suggests a very distinctive phenomenology while its parameter space, as we have shown, is fully testable at the LHC.

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