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Vector Bosons Signals of
Electroweak Symmetry Breaking*

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We study the physics potential of the 8 TeV LHC (LHC-8) to discover signals of extended gauge models or extra dimensional models whose low energy behavior is well represented by an $SU(2)^2 \otimes U(1)$ electroweak gauge structure. We find that with a combined integrated luminosity of $40\,\mathrm{fb}^{-1}$, the first new Kaluza-Klein mode of the W gauge boson can be discovered up to a mass of about $400\,\mathrm{GeV}$, when produced in association with a Z boson.

1. Introduction

The ATLAS and CMS experiments at the LHC have now each collected over $20\,\mathrm{fb}^{-1}$ of data at an 8 TeV collision energy. These data will enable the LHC to make incisive tests of the predictions of many competing models of the origin of electroweak symmetry breaking (EWSB), from the Standard Model (SM) with a single Higgs boson, to models with multiple Higgs bosons, and to so-called Higgsless models of the EWSB. The Higgsless models[2] contain new spin-1 gauge bosons which play a key role in EWSB by delaying unitarity violation of longitudinal weak boson scattering up to a higher ultraviolet (UV) scale.[3] Very recently, the effective UV completion of the minimal three-site Higgsless model[4] was presented and studied in[5] which showed that the latest LHC signals of a Higgs-like state with mass around $125 - 126\,\mathrm{GeV}$[6] can be readily explained, in addition to the signals of new spin-1 gauge bosons studied in the present paper.

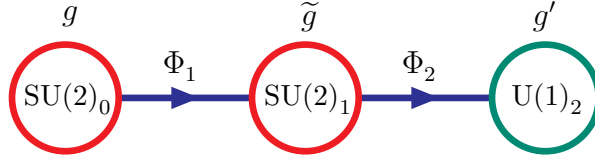*This contribution is an abbrievated version of ref.[1]

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Fig. 1.   Moose diagram of the minimal linear moose model (MLMM) with the gauge structure $SU(2)_0 \times SU(2)_1 \times U(1)_2$ as well as two independent link fields Φ_1 and Φ_2 for spontaneous symmetry breaking. The relevant parameter space of phenomenological interest is where the gauge couplings obey $g, g' \ll \tilde{g}$.

In this talk, we explore the physics potential of the LHC-8 to discover a relatively light fermiophobic electroweak gauge boson W_1 with mass $250 - 400\,\text{GeV}$, as predicted by the minimal three-site moose model[4] and its UV completion.[5] Being fermiophobic or nearly so, the W_1 state is allowed to be fairly light. More specifically, the 5d models that incorporate ideally[7] delocalized fermions,[8,9] in which the ordinary fermions propagate appropriately in the compactified extra dimension (or in deconstructed language, derive their weak properties from more than one $SU(2)$ group in the extended electroweak sector[10,11]), yield phenomenologically acceptable values for all Z-pole observables.[4] In this case, the leading deviations from the SM appear in multi-gauge-boson couplings, rather than the oblique parameters S and T. Ref.[12] demonstrates that the LEP-II constraints on the strength of the coupling of the Z_0-W_0-W_0 vertex allow a W_1 mass as light as $250\,\text{GeV}$, where W_0 and Z_0 refer to the usual electroweak gauge bosons.

2. The Model

We study the minimal deconstructed moose model at LHC-8 in a limit where its gauge sector is equivalent to the "three site model"[4] or its UV completed "minimal linear moose model" (MLMM).[5] Both the three site model and the MLMM are based on the gauge group $SU(2)_0 \otimes SU(2)_1 \otimes U(1)_2$, as depicted by Fig. 1 and its gauge sector is the same as that of the BESS models[14,15] or the hidden local symmetry model.[16–20] The extended electroweak symmetry spontaneously breaks to electromagnetism when the distinct Higgs link-fields Φ_1 connecting $SU(2)_0$ to $SU(2)_1$ and Φ_2 connecting $SU(2)_1$ to $U(1)_2$ acquire vacuum expectation values (VEVs) f_1 and f_2. The weak scale $v \simeq 246\,\text{GeV}$ is related to those VEVs via $v^{-2} = f_1^{-2} + f_2^{-2}$ and, for illustration, we take $f_1 = f_2 = \sqrt{2}v$. Below the symmetry breaking scale, the gauge boson spectrum includes an extra set of weak bosons (W_1, Z_1), in addition to the standard-model-like weak bosons (W_0, Z_0) and the photon. Furthermore, the scalar sector of the MLMM[5] contains two neutral physical Higgs bosons (h^0, H^0), as well as the six would-be Goldstones eaten by the corresponding gauge bosons (W_0, Z_0) and (W_1, Z_1).

One distinctive feature of the MLMM is that the unitarity of high-energy longitudinal weak boson scattering is maintained jointly by the exchange of both the new spin-1 weak bosons and the spin-0 Higgs bosons.[5] This differs from either the

SM (in which unitarity of longitudinal weak boson scattering is ensured by the exchange of the Higgs boson alone)[21] or the conventional Higgsless models (in which unitarity of longitudinal weak boson scattering is ensured by the exchange of spin-1 new gauge bosons alone).[3] It has been shown[12] that the scattering amplitudes in such highly deconstructed models with only three sites can accurately reproduce many aspects of the low-energy behavior of 5d continuum theories.

The unitarity of the generic longitudinal scattering amplitude of $W_0^L W_0^L \rightarrow W_0^L W_0^L$, in the presence of any numbers of spin-1 new gauge bosons $V_k \, (= W_k, Z_k)$ and spin-0 Higgs bosons h_k, was recently studied in Ref.[5] For the MLMM, tree-level unitarity implies sum rule,[5]

$$G_{4W_0} - \frac{3M_{Z_0}^2}{4M_{W_0}^2}G_{W_0 W_0 Z_0}^2 \;=\; \frac{3M_{Z_1}^2}{4M_{W_0}^2}G_{W_0 W_0 Z_1}^2 + \frac{G_{W_0 W_0 h}^2 + G_{W_0 W_0 H}^2}{4M_{W_0}^2}\,, \qquad (1)$$

where the symbols (h, H) denote the two mass-eigenstate Higgs bosons. The sum rule illustrates how exchanging both the new spin-1 weak bosons W_1/Z_1 and the spin-0 Higgs bosons h/H is required to ensure the unitarity of longitudinal weak boson scattering in the MLMM.[5a]

3. Analysis of $W_1^\pm$ Detection at the LHC-8

Extrapolating from our previous work[13] at a 14 TeV LHC, we have found that the best process for detecting W_1 at LHC-8 is associated production, $pp \rightarrow W_1 Z_0 \rightarrow W_0 Z_0 Z_0 \rightarrow jj\ell^+\ell^-\ell^+\ell^-$, where we select the W_0 decays into dijets and the Z_0 decays into electron or muon pairs.

We have systematically computed all the major SM backgrounds for the $jj4\ell$ final state, including the irreducible backgrounds $pp \rightarrow W_0 Z_0 Z_0 \rightarrow jj4\ell$ $(jj = qq')$ without the contribution of W_1, as well as the reducible backgrounds $pp \rightarrow gg Z_0 Z_0 \rightarrow jj4\ell$, $pp \rightarrow Z_0 Z_0 Z_0 \rightarrow jj4\ell$, and the SM $pp \rightarrow jj4\ell$ other than the above reducible backgrounds.

We performed parton level calculations at tree-level using two different methods and two different gauges to check the consistency. In one calculation, we used the helicity amplitude approach[24] to generate the signal and backgrounds. We also calculated both the signal and background using CalcHEP.[27,28] For the signal calculation in CalcHEP, we used FeynRules[22] to implement the minimal Higgsless model.[23] We found satisfactory agreement between these two approaches and between both unitary and 't Hooft-Feynman gauge. We used a scale of $\sqrt{\hat{s}}$ for the strong coupling in the backgrounds and $\sqrt{\hat{s}}/2$ for the CTEQ6L[25] parton distribution functions. We included both the first and second generation quarks in the protons and jets, and both electrons and muons in the final-state leptons.

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[a]We also note that the hWW and hZZ couplings are generally suppressed[5] relative to the SM values because of the VEV ratio $f_2/f_1 = O(1)$ and the $h - H$ mixing.
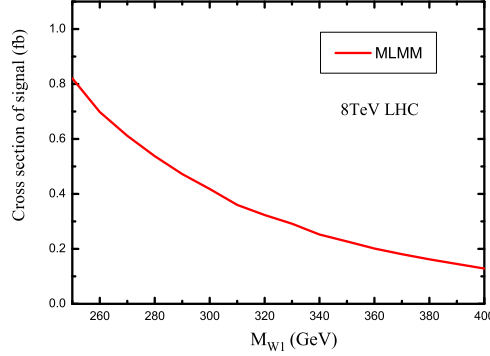
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Fig. 2. Predicted signal cross section for $pp \to W_1 Z_0 \to W_0 Z_0 Z_0 \to jj4\ell$ as a function of the W_1 mass in the MLMM after all cuts at the LHC-8.

In our calculations, we impose basic acceptance cuts,

$$p_{T\ell} > 10\,\mathrm{GeV}, \qquad |\eta_\ell| < 2.5\,,$$
$$p_{Tj} > 15\,\mathrm{GeV}, \qquad |\eta_j| < 4.5\,, \tag{2}$$

and also a reconstruction cut for identifying W_0 bosons that decay to dijets,

$$M_{jj} = 80 \pm 15\,\mathrm{GeV}\,. \tag{3}$$

We further analyzed the distributions of the dijet opening-angle $\Delta R(jj)$ in the decays of $W_0 \to jj$ for both the signal and SM background events. We find that the signal events are peaked in the small opening-angle region around $\Delta R(jj) \sim 0.6$, while the SM backgrounds tend to populate the range of larger opening angles, with a broad bump around $\Delta R(jj) = 1.5 - 3.3$. In order to sufficiently suppress the SM backgrounds, we find the following opening-angle cut[b] to be very effective,[26]

$$\Delta R(jj) \;<\; 1.6\,. \tag{4}$$

At the LHC-8, we note that the above cut reduces the signal events by only $10-15\%$, but removes about $72-80\%$ of the SM backgrounds.

In Fig. 2, we display the predicted total signal cross section for the process $pp \to W_0 Z_0 Z_0 \to jj4\ell$ after all cuts at the LHC-8 have been imposed; this is shown as a function of the W_1 mass for the range $250 - 400\,\mathrm{GeV}$.[c]

In Fig. 3, we display the required integrated luminosities for detecting the $W_1^\pm$ signal at the 3σ and 5σ levels as a function of the $W_1^\pm$ mass M_{W_1}. We see the LHC-8 should be able to observe the $W_1^\pm$ gauge bosons of the minimal linear moose model studied up to masses of order 400 GeV. We look forward to seeing the results.

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[b]These are somewhat weaker than the cut of $\Delta R(jj) < 1.5$ imposed in.[13]
[c]Here, we define the signal region to include all events satisfying the condition, $M(Z_0 jj) = M_{W_1} \pm 20\,\mathrm{GeV}$.
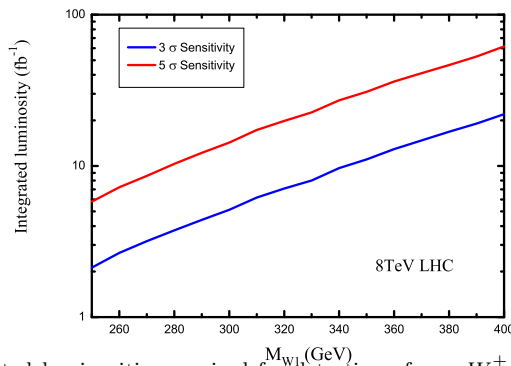
Fig. 3.   Integrated luminosities required for detection of new $W_1^{\pm}$ gauge bosons at the 3σ level in the MLMM (lower blue curve), and at the 5σ level (upper red curve) as a function of the W_1 mass, at the LHC-8.

Acknowledgments

References

1. C. Du, H. -J. He, Y. -P. Kuang, B. Zhang, N. D. Christensen, R. S. Chivukula, E. H. Simmons and , Phys. Rev. D **86**, 095011 (2012) [arXiv:1206.6022 [hep-ph]].

2. C. Csaki, C. Grojean, H. Murayama, L. Pilo and J. Terning, Phys. Rev. D **69**, 055006 (2004) [hep-ph/0305237]; C. Csaki, C. Grojean, L. Pilo and J. Terning, Phys. Rev. Lett. **92**, 101802 (2004) [hep-ph/0308038].

3. R. S. Chivukula, D. A. Dicus, H. J. He, Phys. Lett. B **525**, 175 (2002) [hep-ph/0111016]; R. S. Chivukula and H. J. He, Phys. Lett. B **532**, 121 (2002) [hep-ph/0201164]; R. S. Chivukula, D. A. Dicus, H. J. He, S. Nandi, Phys. Lett. B **562**, 109 (2003) [hep-ph/0302263]; H. J. He, Int. J. Mod. Phys. A **20**, 3362 (2005) [hep-ph/0412113] R. S. Chivukula, H. J. He, M. Kurachi, E. H. Simmons, M. Tanabashi, Phys. Rev. D **78**, 095003 (2008) [arXiv:0808.1682]

4. R. S. Chivukula, B. Coleppa, S. Di Chiara, E. H. Simmons, H. J. He, M. Kurachi, M.

6

Tanabashi, Phys. Rev. D **74**, 075011 (2006) [arXiv:hep-ph/0607124].

5. T. Abe, N. Chen, H. J. He, JHEP (2012), [arXiv:1207.4103 [hep-ph]].

6. G. Aad *et al.,* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]];
   S. Chatrchyan *et al.,* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]].

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

8. G. Cacciapaglia, C. Csaki, C. Grojean and J. Terning, Phys. Rev. D **71**, 035015 (2005) [arXiv:hep-ph/0409126].

9. R. Foadi, S. Gopalakrishna and C. Schmidt, Phys. Lett. B **606**, 157 (2005) [arXiv:hep-ph/0409266].

10. R. S. Chivukula, E. H. Simmons, H. J. He, M. Kurachi and M. Tanabashi, Phys. Rev. D **71**, 115001 (2005) [arXiv:hep-ph/0502162].

11. R. Casalbuoni, S. De Curtis, D. Dolce and D. Dominici, Phys. Rev. D **71**, 075015 (2005) [arXiv:hep-ph/0502209].

12. A. Belyaev, R. S. Chivukula, N. D. Christensen, H. J. He, M. Kurachi, E. H. Simmons, M. Tanabashi, Phys. Rev. D **80**, 055022 (2009) [arXiv:0907.2662]; and presentation in the Proceedings of International Workshop on "Strong Coupling Gauge Theories in LHC Era" (SCGT-2009), arXiv:1003.1786 [hep-ph].

13. H. J. He, Y. P. Kuang, Y. Qi, B. Zhang, A. Belyaev, R. S. Chivukula, N. D. Christensen, A. Pukhov, E. H. Simmons, Phys. Rev. D **78**, 031701 (2008) [arXiv:0708.2588].

14. R. Casalbuoni, S. De Curtis, D. Dominici and R. Gatto, Phys. Lett. B **155**, 95 (1985).

15. R. Casalbuoni *et al.*, Phys. Rev. **D53**, 5201 (1996) [hep-ph/9510431].

16. M. Bando, T. Kugo, S. Uehara, K. Yamawaki and T. Yanagida, Phys. Rev. Lett. **54**, 1215 (1985).

17. M. Bando, T. Kugo and K. Yamawaki, Nucl. Phys. B **259**, 493 (1985).

18. M. Bando, T. Fujiwara, and K. Yamawaki, Prog. Theor. Phys. **79**, 1140 (1988).

19. M. Bando, T. Kugo, and K. Yamawaki, Phys. Rept. **164**, 217 (1988).

20. M. Harada and K. Yamawaki, Phys. Rept. **381**, 1 (2003) [hep-ph/0302103].

21. J. M. Cornwall, D. N. Levin, and G. Tiktopoulos, Phys. Rev. Lett. **30** (1973) 1268;

Phys. Rev. D **10** (1974) 1145; C. H. Llewellyn Smith, Phys. Lett. **46**B (1973) 233. D. A. Dicus and V. S. Mathur, Phys. Rev. D **7** (1973) 3111; B. W. Lee, C. Quigg, and H. B. Thacker, Phys. Rev. Lett. **38** (1977) 883; Phys. Rev. D **16** (1977) 1519; M. S. Chanowitz and M. K. Gaillard, Nucl. Phys. B **261** (1985) 379.

22. N. D. Christensen and C. Duhr, Comput. Phys. Commun. **180**, 1614 (2009) [arXiv:0806.4194 [hep-ph]].

23. N. D. Christensen, P. de Aquino, C. Degrande, C. Duhr, B. Fuks, M. Herquet, F. Maltoni and S. Schumann, Eur. Phys. J. C **71**, 1541 (2011) [arXiv:0906.2474 [hep-ph]].

24. K. Hagiwara and D. Zeppenfeld, DESY-85-133; K. Hagiwara, R. D. Peccei, D. Zeppenfeld and K. Hikasa, DESY-86-058 (1986); K. Hagiwara and D. Zeppenfeld, KEK Preprint 87-158 (1988).

25. J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky and W. K. Tung, JHEP **07**, 012 (2002).

26. This kind of cut should be applied to separated jets. Experimentally, two jets are separable if $\Delta R_{jj} > 0.5$ [see for instance, S. Ask (ATLAS Collaboration), arXiv:1106.2061], and two jet-cones do not overlap at all if $\Delta R_{jj} > 1$. Hence the cut (4) can be realized.

27. A. Pukhov, E. Boos, M. Dubinin, V. Edneral, V. Ilyin, D. Kovalenko, A. Kryukov and V. Savrin, *et al.*, arXiv:hep-ph/9908288.

28. A. Pukhov, arXiv:hep-ph/0412191.