W^{′} Boson near 2 TeV: Predictions for Run 2 of the LHC

Bogdan A. Dobrescu and Zhen Liu

Phys. Rev. Lett. **115**, 211802 — Published 20 November 2015

DOI: 10.1103/PhysRevLett.115.211802

A W' boson near 2 TeV: predictions for Run 2 of the LHC

Bogdan A. Dobrescu[⋆] **and Zhen Liu**[⋆⋄]
⋆ *Theoretical Physics Department, Fermilab, Batavia, IL 60510, USA*
⋄ *PITT PACC, Department of Physics and Astronomy, University of Pittsburgh, PA 15260, USA*

We present a renormalizable theory that includes a W' boson of mass in the 1.8–2 TeV range, which may explain the excess events reported by the ATLAS Collaboration in a WZ final state, and by the CMS Collaboration in e^+e^-jj, Wh^0 and jj final states. The W' boson couples to right-handed quarks and leptons, including Dirac neutrinos with TeV-scale masses. This theory predicts a Z' boson of mass in the 3.4–4.5 TeV range. The cross section times branching fractions for the narrow Z' dijet and dilepton peaks at the 13 TeV LHC are 10 fb and 0.6 fb, respectively, for $M_{Z'} = 3.4$ TeV, and an order of magnitude smaller for $M_{Z'} = 4.5$ TeV.

Introduction.—The LHC, the highest energy collider built so far, has directly probed the laws of physics at distance scales as small as $\sim 5\times10^{-20}$ m, and over the next few years will extend the exploration by another factor of two. The Standard Model (SM) of particle physics has been spectacularly confirmed through various analyses based on data obtained during Run 1 of the LHC.

Recently, though, a few deviations from the SM predictions have been reported by the ATLAS and CMS Collaborations in invariant mass distributions near 2 TeV:
1) a 3.4σ excess at $\sim$2 TeV in the ATLAS search [1] for a W' boson decaying into $WZ \to JJ$, where J stands for a wide jet formed by the two nearly colinear jets produced in the decays of a boosted W or Z boson. The mass range with significance above 2σ is $\sim$ 1.9–2.1 TeV; the global significance is 2.5σ. A CMS search [2] for JJ resonances, without distinguishing between the W- and Z-tagged jets, has a 1.4σ excess at $\sim$1.9 TeV.
2) a 2.8σ excess in the 1.8 – 2.2 TeV bin in the CMS search [3] for a W' and a heavy "right-handed" neutrino, N_R, through the $W' \to N_R\, e \to eejj$ process.
3) a 2.2σ excess in the 1.8 – 1.9 TeV bin in the CMS search [4] for $W' \to Wh^0$, where the SM Higgs boson, h^0, is highly boosted and decays into $b\bar{b}$, while $W \to \ell\nu$.
4) a $\sim 2\sigma$ excess at $\sim$1.8 TeV in the CMS dijet resonance search [5]. The ATLAS search [6] in the same channel has yielded only a 1σ excess at 1.8 TeV.

Although none of these deviations is significant enough to indicate a new phenomenon, it behooves us to inquire whether a self-consistent theory may explain all of them. Here we construct a renormalizable theory that explains quantitatively these deviations, and derive its predictions for signals that can be probed in Run 2 of the LHC.

The deviations showed up in searches for a W' boson but several theoretical and experimental hurdles need to be overcome before a particle of mass near 2 TeV can be inferred. The $eejj$ excess suggests that the W' boson couples to right-handed fermions, as in left-right symmetric models [7]. However, those models predict a Majorana mass for N_R, so the number of events with same-sign lepton pairs should be approximately equal to that for opposite-sign lepton pairs [8] (except for the case where two N_R's with CP violating mixing are degenerate [9]). As the CMS excess consists almost entirely of e^+e^- pairs, we will extend the left-right symmetric models in order to allow a TeV-scale Dirac mass for N_R.

Another issue is that all gauge extensions of the SM that include a W' also include a Z' boson. If that Z' couples to the SM leptons, as in left-right symmetric models, then the dilepton resonance searches force the Z' to be significantly heavier than the W'. This constrains the extended Higgs sector responsible for their masses.

***W′* interactions with quarks.**—A W' boson produced in the s channel with a large cross section must couple to first generation quarks. In order to avoid large flavor-changing neutral currents, it is natural to assume that the couplings are approximately flavor diagonal:

$$\frac{g_{\rm R}}{\sqrt{2}} W'^{+}_{\mu} \left(\bar{u}_R\gamma^\mu d_R + \bar{c}_R\gamma^\mu s_R + \bar{t}_R\gamma^\mu b_R\right) + {\rm H.c.} \qquad (1)$$

The $g_{\rm R}$ parameter can be extracted from cross section measurements for the dominant decay modes. The widths for the W' decays into jj and $t\bar{b}$ are given by

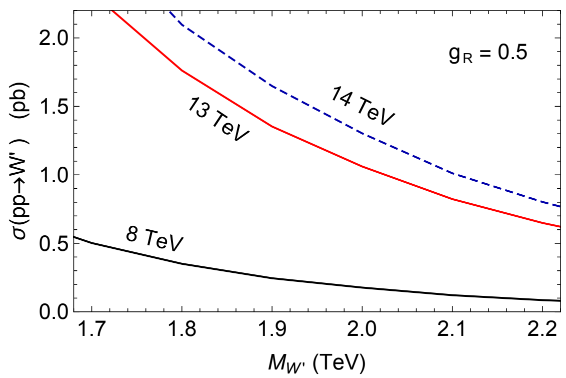
$$\Gamma(W' \to jj) \simeq 2\Gamma(W' \to t\bar{b}) \simeq \frac{g_{\rm R}^2}{8\pi} M_{W'} \quad . \qquad (2)$$

The W' production cross section $\sigma(W')$ is $(g_{\rm R}/g)^2$ times the SM rate for a heavier W, where $g \simeq 0.65$ (at 2 TeV) is the SM $SU(2)_W$ gauge coupling. Fig. 1 shows the next-to-leading order (NLO) cross sections at the LHC for $g_{\rm R} = 0.5$. We obtained these by multiplying the leading-order cross sections computed with MadGraph [10] (using model files generated with FeynRules [11] and CTEQ6L parton distributions [12] with factorization and renormalization scales set at $M_{W'}$) by scale-dependent K-factors. These are computed in [13], and are in the 1.32–1.37 range for $\sqrt{s} = 8$ TeV (1.25–1.28 range for $\sqrt{s} = 13$ TeV) when $M_{W'}$ varies from 1.7 to 2.2 TeV. At 8 TeV, $\sigma(W') \approx 350$ fb (175 fb) for $M_{W'} = 1.8$ TeV (2 TeV).

The CMS dijet excess requires a cross section times geometric acceptance (A_{jj}) roughly in the 50–100 fb range (the 95% CL upper limit is 150 fb [5, 6]). Our simulation gives $A_{jj} \approx 47\%$, so that

$$\sigma_{jj}(W') \equiv \sigma(pp \to W' \to jj) \sim 100\text{–}200\,{\rm fb} \quad . \qquad (3)$$

FIG. 1. NLO cross sections for W' production at $\sqrt{s} = 8$, 13 and 14 TeV, for $g_R = 0.5$. The cross sections scale as g_R^2.



It follows that $g_R \gtrsim 0.4$ for $M_{W'} = 1.8$ TeV ($g_R \gtrsim 0.5$ for $M_{W'} = 2$ TeV); this lower limit corresponds to the case where the jj and $t\bar{b}$ channels saturate the total width.

The fitted dijet rate implies that the predicted rate for $pp \to W' \to tb$ is $\sigma_{jj}/2 \sim 50-100$ fb at $\sqrt{s} = 8$ TeV, which is below the sensitivity achieved by ATLAS searches in this channel [14], but in tension with the CMS limits [15]. This rate increases by a factor of 5 at $\sqrt{s} = 13$ TeV, allowing a definitive test for the presence of a tb peak near 2 TeV.

$W' \to WZ$ signals.—The W' coupling to WZ arises from the kinetic terms of an extended gauge sector, such as $SU(2) \times SU(2) \times U(1)$, and takes the form

$$\frac{g_R}{c_W} \xi_Z \frac{M_W^2}{M_{W'}^2} i \left[W_\mu'^+ \left(W_\nu^- \partial^{[\nu} Z^{\mu]} + Z_\nu \partial^{[\mu} W^{-\nu]} \right) + Z_\nu W_\mu^- \partial^{[\nu} W'^{+\mu]} \right] + \text{H.c.} \quad , \tag{4}$$

where $c_W \equiv \cos\theta_W \approx 0.88$, and $[\mu,\ \nu]$ represents commutation of indices ($\mu\nu - \nu\mu$). The factor of $(M_W/M_{W'})^2$ is due to $W - W'$ mass mixing, and the ξ_Z coefficient is of order one. The $W' \to WZ$ width is given by

$$\Gamma(W' \to WZ) = \frac{g_R^2\, \xi_Z^2}{192\pi} M_{W'} \quad . \tag{5}$$

The $pp \to W' \to WZ$ cross section, $\sigma_{WZ}(W')$, is predicted in terms of the jj one based on Eqs. (2) and (5):

$$\frac{\sigma_{WZ}(W')}{\sigma_{jj}(W')} = \frac{\Gamma(W' \to WZ)}{\Gamma(W' \to jj)} = \frac{\xi_Z^2}{24} \quad . \tag{6}$$

Using Eq. (3), we find $\sigma_{WZ}(W') \approx (4\text{–}8)\,\text{fb} \times \xi_Z^2$.

The ATLAS search for $pp \to W' \to WZ \to JJ$ has identified 13 events with JJ mass in the 1.85–2.05 TeV range, where the background is 5 events (Fig. 5a of [1]). The event selection efficiency is between 0.10 and 0.16 (Fig. 2b of [1]), implying $\sigma_{WZ}(W') \approx 3-10$ fb. Comparing this measured range with the predicted $\sigma_{WZ}(W')$ we find $0.6 \lesssim \xi_Z \lesssim 1.6$. Values of ξ_Z in the 0.6–1 range are natural in simple Higgs sectors, and are allowed by the electroweak observables due to the $(M_W/M_{W'})^2$ suppression [16]. Other explanations for the JJ peak are discussed in [17].

It is imperative to check that the ATLAS $WZ \to JJ$ peak is consistent with results obtained in other WZ final states searched at the LHC. Semileptonic final states of $W' \to WZ$ are particularly sensitive. The case where $W \to \ell\nu$ and $Z \to q\bar{q}$ is constrained by a CMS search [18] optimized for a bulk graviton that decays to WW. At first sight there appears to be some conflict [19] with the ATLAS $WZ \to JJ$ signal. However, a 1σ upward fluctuation in the cross section limit (Fig. 9 of [18]) for a mass of 1.8 TeV relaxes that conflict. In addition, the upper limit of 6 fb on the cross section for bulk graviton production translates into an upper limit on W' production that is higher by a factor of 2.2; this is due to the lack of a combinatorial factor of 2 in the WZ final state compared to the WW one, and also due to the b veto imposed on the WW search. As a result, $\sigma_{WZ}(W') < 13$ fb at the 95% CL. The ATLAS search [20] for $W' \to WZ \to \ell\nu J$ also imposes $\sigma_{WZ}(W') < 13$ fb. Thus, values of $\sigma_{WZ}(W')$ in the 3–10 fb range remain viable.

The case where $Z \to \ell^+\ell^-$ and W decays to quarks is constrained by the CMS search [18] for a bulk graviton that decays to ZZ. The expected limit on the rate shown in Fig. 9 of [18] is 7 fb for a mass in the 1.8–1.9 TeV range. Interestingly, the observed limit is 2σ weaker (around 15 fb), adding one more channel to the list of excesses near 2 TeV. The $W' \to WZ$ semileptonic signal that would account for this $\sim 2\sigma$ excess is compatible with the JJ excess (notice a combinatorial factor of 2).

$W' \to Wh^0$ signals.—The kinetic terms of the extended Higgs sector responsible for breaking the $SU(2) \times SU(2) \times U(1)$ gauge symmetry include a $W'Wh^0$ interaction term given by

$$-g_R\, \xi_h\, M_W\, W_\mu'^{\pm} W^{\mu\mp} h^0 \quad , \tag{7}$$

where ξ_h is a parameter of order one that depends on the details of the Higgs sector. The width for $W' \to Wh^0$ is

$$\Gamma(W' \to Wh^0) = \frac{g_R^2\, \xi_h^2}{192\pi} M_{W'} \quad . \tag{8}$$

If the SM Higgs doublet does not mix with other fields, then $\xi_h = \xi_Z$ and $\Gamma(W' \to Wh^0) \simeq \Gamma(W' \to WZ)$, as required by the equivalence theorem. The agreement between the SM and the measured h^0 properties indicates that the deviations from $\xi_h = \xi_Z$ are small.

In this case the $pp \to W' \to Wh^0$ cross section satisfies $\sigma_{Wh}(W') \approx \sigma_{WZ}(W')$. Searches for $W' \to Wh^0 \to \ell\nu b\bar{b}$ should yield a signal comparable to that for $W' \to WZ \to JJ$ times $B(Wh^0 \to \ell\nu b\bar{b})/B(WZ \to 4j) \approx 0.27$. The 8 excess JJ events reported by ATLAS imply that there should be a few excess $\ell\nu b\bar{b}$ events (the $\ell\nu b\bar{b}$ selection efficiency depends on the efficiency for h^0 tagging, which we estimate to be similar to the one for WZ tagging).

The CMS $W' \to Wh^0$ search has reported 3 $\ell\nu b\bar{b}$ events in the 1.8–1.9 TeV mass bin for a background of 0.3. This supports the assumption that the $\ell\nu b\bar{b}$ and JJ excess events originate from a W' boson.

The small number of events observed in these channels implies large uncertainties. These can be reduced by searches in similar channels. We note here only the CMS search [21] for $W' \to Wh^0$ in hadronic final states ($6j$ and $bbjj$), which exhibits a small (1σ) excess at $M_{W'} \approx 1.8$ TeV, setting a $\sigma_{Wh}(W') < 18$ fb limit at 95% CL.

Leptonic W' decays.—The W' considered here does not directly couple to left-handed leptons, implying highly suppressed W' decays into SM $\ell\nu$ pairs (due to the small $W - W'$ mixing). In order to fit the CMS $eejj$ excess, and to avoid large flavor-changing effects, we assume W' coupling to leptons approximately given by

$$\frac{g_{\rm R}}{\sqrt{2}} W'^{+}_{\nu} \left(\overline{N}^e_R \gamma^\nu e_R + \overline{N}^\mu_R \gamma^\nu \mu_R + \overline{N}^\tau_R \gamma^\nu \tau_R \right) + \text{H.c.} \; , \quad (9)$$

with the heavy right-handed neutrinos (N^e_R, N^μ_R, N^τ_R) being part of three vectorlike fermions with Dirac masses. Since the CMS $\mu\mu jj$ search [3] has not yielded deviations from the SM, the N^μ mass must satisfy $m_{N^\mu} > M_{W'}$.

The N^τ fermion can be light because no dedicated $W' \to \tau N^\tau \to \tau\tau jj$ search has been performed. N^τ may even couple to the electron or muon [22]:

$$\frac{g_{\rm R}}{\sqrt{2}} W'^{+}_{\nu} \, \overline{N}^\tau_R \gamma^\nu \left(s_{\theta_e} e_R + s_{\theta_\mu} \mu_R \right) + \text{H.c.} \qquad (10)$$

with $s_{\theta_\mu} < s_{\theta_e} \lesssim 0.5$ leads to $W' \to e\tau jj$ or $\mu\tau jj$ signals that have escaped detection, and slightly decreases the diagonal couplings (9). In that case an e^+e^-jj signal is produced by $W' \to eN^\tau$, so N^e may also be heavier than W'. The W'^+ decay into e^+N^τ has a width

$$\Gamma(W' \to eN^\tau) = \frac{g_{\rm R}^2 s_{\theta_e}^2}{48\pi} M_{W'} \left(1 + \frac{m_{N^\tau}^2}{2M_{W'}^2} \right) \left(1 - \frac{m_{N^\tau}^2}{M_{W'}^2} \right)^2 . \quad (11)$$

The $B(N^\tau \to ejj)$ branching fraction is naively about $0.6\, s_{\theta_e}^2$. However, N^τ decays into $et\bar{b}$ with hadronic top decays, or into eWZ/h^0 with hadronic decays of SM bosons also appear as ejj, especially for boosted topologies; effectively, $B(N^\tau \to ejj) \sim 0.9 s_{\theta_e}^2$. The $pp \to W' \to eN^\tau \to e^+e^-jj$ rate, $\sigma_{eejj}(W')$, is smaller than the jj signal by a $B(N^\tau \to ejj)\Gamma(W' \to eN^\tau)/\Gamma(W' \to jj)$ factor.

The $eejj$ excess requires $\sigma_{eejj}(W')$ roughly in the 1–2 fb range (see Fig. 4 of [3]), so that it is 0.5–2% of the dijet signal. For $m_{N^\tau} \sim 1$ TeV and $s_{\theta_e} \approx 0.5$, we find a predicted ratio $\sigma_{eejj}(W')/\sigma_{jj}(W') \approx 0.6\%$, consistent with the signal rates indicated by the data.

The $e\tau jj$ final state produced by $W' \to eN^\tau, \tau N^\tau$ is also interesting. The hadronic τ decay leads to an $e + \not{E}_T$ + jets signal that may explain the 2.6σ CMS excess reported in [23]. The leptonic τ decays modify the "flavor-symmetric" background, which distorts the kinematics of the $eejj$ signal, potentially in agreement with observations made in [3]. An alternative is $m_{N^\tau} < m_{N^e} < M_{W'}$. The N^e-N^τ mixing then leads to two e^+e^-jj contributions, with ejj distributions peaked at different masses.

A baseline W' model.—Let us summarize the W' model introduced so far. The primary parameters are $M_{W'}$, $g_{\rm R}$, $\xi_Z \approx \xi_h$, m_{N^τ}, s_{θ_e}. The masses of N^e and N^μ are above $M_{W'}$ and are not relevant here; the coupling of W' to μN^τ, s_{θ_μ}, is a parameter that could become relevant if W' processes with muons are observed.

The mass peaks for jj, Wh^0, and $WZ \to J\ell\ell$ indicate $M_{W'} \approx 1.8$–1.9 TeV, while the $WZ \to JJ$ peak is around 1.9–2.0 TeV. The relatively low resolution and the small number of events makes it likely that the JJ peak would migrate towards 1.85 TeV with more data, if a W' boson exists. The cross sections consistent with the $WZ \to JJ$ and Wh^0 peaks require $\xi_Z \approx \xi_h \approx 0.6$–$1$ for simple Higgs sectors. The $W'eN^\tau$ coupling is $s_{\theta_e} \approx 0.4$–0.5 in order to explain the $eejj$ signal. The N^τ mass is loosely constrained, $m_{N^\tau} \sim 0.4$–1.2 TeV.

Some W' decays could involve scalars from the extended Higgs sector [24], or other new particles. Let B_X be their combined branching fraction. For $B_X = 0$, the W' branching fractions are $B(jj) = 2B(t\bar{b}) \approx 60\%$, $B(WZ) \approx B(Wh^0) \approx 2\%$, $B(eN_\tau) \approx 1.5\%$, $B(\tau N_\tau) \approx 4.5\%$. The cross section that can account for the jj peak then implies $g_{\rm R} \approx 0.45 - 0.6$. For $B_X > 0$, $g_{\rm R}$ scales as $(1 - B_X)^{-1/2}$, so that the left-right symmetric relation $g_{\rm R} = g$ is recovered for $B_X \sim 20\%$–50%.

An $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ theory.—We now present a renormalizable theory that embeds our baseline model. Any gauge symmetry associated with a W' also involves a Z' with correlated properties. The limits on dilepton resonances require a Higgs sector that allows $M_{Z'} \gtrsim 1.5 M_{W'}$. In the original $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ theory [7, 25] the right-handed neutrinos may be very heavy only if they have Majorana masses, which (barring tiny mass splittings [9]) leads to same-sign $\ell^\pm\ell^\pm jj$ events, in contradiction to the CMS result.

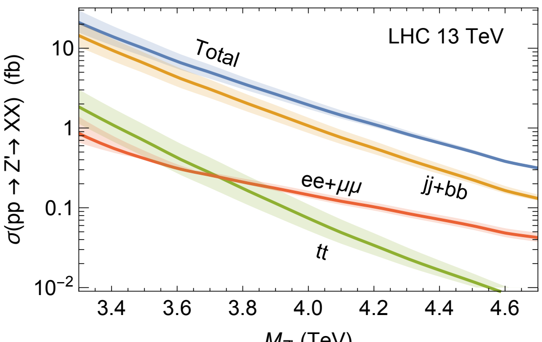
In order for N^τ_R to acquire a Dirac mass we introduce a vectorlike fermion $\psi = (\psi^N, \psi^\tau)^\top$ transforming as $(2, +1)$ under $SU(2)_R \times U(1)_{B-L}$. Its ψ^N_L component can become the Dirac partner of N^τ_R. To see that, let us first describe a simple Higgs sector: an $SU(2)_R$ triplet scalar T breaks $SU(2)_R \times U(1)_{B-L}$ to $U(1)_Y$ giving the bulk of $M_{W'}$ and $M_{Z'}$, and a bidoublet scalar Σ breaks $SU(2)_L \times U(1)_Y \to U(1)_Q$ inducing a small mixing between the charged gauge bosons. For $M_{W'} \gg M_W$, Σ consists of two $SU(2)_W$ Higgs doublets, which break the electroweak symmetry. The SM Higgs does not mix with other scalars in the alignment limit, and the other charged and neutral scalars could be at the TeV scale.

A large Majorana mass for ψ^N_R arises from the $\bar{\psi}^c_R T^\dagger \psi_R$ coupling. Below the ψ^N_R mass, a Dirac mass for N^τ_R and ψ^N_L is generated by the $\bar{\psi}_L T (N^\tau_R, \tau_R)^\top$ coupling. Finally, ψ^τ gets a mass from a $\bar{\psi}_L \psi_R$ term. The latter also induces a contribution to the mass of ψ^N, which cannot be much larger than m_{N^τ}. Thus, the charged fermion ψ^τ is expected to have an $O(M_{W'})$ mass. The same mechanism may involve Dirac partners for N^e_R and N^μ_R.

TABLE I. $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge charges. The SM fermions have generation-independent charges.

Fields	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
$(u_L,\ d_L)$	2	1	+1/3
$(u_R,\ d_R)$	1	2	+1/3
$(\nu_L,\ \ell_L)$	2	1	−1
$(N_R,\ \ell_R)$	1	2	−1
$\psi_L\ ,\ \psi_R$	1	2	+1
Σ	2	2	0
T	1	3	+2

FIG. 2. Z' production cross section times branching fractions as a function of $M_{Z'}$, for $M_{W'} = 1.9$ TeV at the 13 TeV LHC. Shaded bands correspond to $M_{W'}$ in the 1.8–2.0 TeV range.



With the field content of this theory shown in Table I, the fermion kinetic terms induce the W' couplings to quarks and leptons discussed earlier, and $g_{\rm R}$ from Eq. (1) is the $SU(2)_R$ gauge coupling up to corrections of order $M_W^2/M_{W'}^2$. Comparing the bosonic kinetic terms with the $W'WZ$ and $W'Wh^0$ couplings of Eqs. (4) and (7), we find $\xi_h = \xi_Z = \sin 2\beta$ in the Higgs alignment limit [16], where $\tan\beta$ is the ratio of the two Σ VEVs.

Predictions for the Z' boson.—The Z' boson is an $SU(2)_R \times U(1)_{B-L}$ gauge boson, with a small $SU(2)_L$ admixture governed by $M_Z^2/M_{Z'}^2$. The Z' mass is

$$M_{Z'} = \sqrt{2}\, g_{\rm R} \left(g_{\rm R}^2 - g'^2\right)^{-1/2} M_{W'} \ \ , \qquad (12)$$

where $g' \approx 0.36$ is the hypercharge gauge coupling. This implies $M_{Z'} > 1.5 M_{W'}$ as a consequence of the large $SU(2)_R$-breaking VEV of the T scalar. The value of $g_{\rm R}$ indicated by the excess events attributed to W' further constrains $M_{Z'}/M_{W'}$. For $M_{W'} = 1.9$ TeV, the preferred range of $0.45 < g_R < 0.6$ implies 3.4 TeV $< M_{Z'} <$ 4.5 TeV. A larger $g_{\rm R}$ due to $B_X > 0$ would slightly reduce the lower limit on $M_{Z'}$.

The fermion couplings to Z' are given by

$$\left(g_{\rm R}^2 T_R^3 - g_{B-L}^2 \frac{B-L}{2}\right) \left(g_{\rm R}^2 + g_{B-L}^2\right)^{-1/2} \quad . \qquad (13)$$

The $U(1)_{B-L}$ gauge coupling is also determined by $g_{\rm R}$: $g_{B-L} = (1/g'^2 - 1/g_{\rm R}^2)^{-1/2}$. Thus, the theory is highly predictive, *e.g.*, $M_{W'}$ and $M_{Z'}$ measurements would fix the Z' couplings. Fig. 2 shows Z' production cross section times branching fractions at the 13 TeV LHC for $M_{W'} = 1.8$–2 TeV, $m_{N^\tau} = 1$ TeV and $m_{N^e}, m_{N^\mu} > M_{Z'}/2$. The Z' production rate computed using MadGraph 5 is multiplied in Fig. 2 by a constant K factor of 1.2. Besides the decay modes shown there (dijet, $\ell^+\ell^-$, $t\bar{t}$), several others are phenomenologically important, including W^+W^-, Zh^0, $N^\tau \bar{N}^\tau$.

Conclusions.—The W' model presented here appears to be a viable description of the small mass peaks near 2 TeV observed in at least five channels at the LHC. Definitive tests of this model will be performed in several W' decay channels in Run 2 of the LHC. Assuming an $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge origin of the W', we predict the existence of a Z' boson of mass below 4.5 TeV with production rates shown in Fig. 2. Our renormalizable theory includes Dirac masses for right-handed neutrinos.

Acknowledgments: We thank P. Fox, R. Harris, I. Lewis, M. Pierini and N. Tran for constructive comments. ZL was supported by the Fermilab Graduate Student Research Program in Theoretical Physics.

[1] G. Aad *et al.* [ATLAS Collaboration], arXiv:1506.00962.
[2] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1408**, 173 (2014).
[3] V. Khachatryan *et al.* [CMS Collaboration], Eur. Phys. J. C **74**, no. 11, 3149 (2014).
[4] CMS Collaboration, note PAS-EXO-14-010, March 2015.
[5] V. Khachatryan *et al.* [CMS Collaboration], Phys. Rev. D **91**, no. 5, 052009 (2015).
[6] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **91**, no. 5, 052007 (2015).
[7] See *e.g*, R. N. Mohapatra, "Unification and supersymmetry. The frontiers of quark - lepton physics," New York, USA: Springer (2003) 421 p; Ch. 6.
[8] W. Y. Keung and G. Senjanovic, Phys. Rev. Lett. **50**, 1427 (1983).
[9] J. Gluza and T. Jelinski, arXiv:1504.05568.
[10] J. Alwall *et al.*, JHEP **1407**, 079 (2014).
[11] A. Alloul *et al*, Comput. Phys. Comm. **185**, 2250 (2014).
[12] J. Pumplin *et al.*, JHEP **0207**, 012 (2002).
[13] Q. H. Cao *et al.*, Phys. Rev. D **86**, 095010 (2012).
[14] G. Aad *et al* [ATLAS Collaboration], Eur. Phys. J. C **75**, no. 4, 165 (2015); Phys. Lett. B **743**, 235 (2015).
[15] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1405**, 108 (2014). V. Khachatryan *et al.* [CMS Collaboration], arXiv:1509.06051.
[16] B. A. Dobrescu and Z. Liu, arXiv:1507.01923.
[17] H. S. Fukano *et al.*, arXiv:1506.03751. J. Hisano, N. Nagata and Y. Omura, arXiv:1506.03931. D. B. Franzosi, M. T. Frandsen and F. Sannino, arXiv:1506.04392. K. Cheung *et al.*, arXiv:1506.06064.
[18] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1408**, 174 (2014).
[19] M. Pierini, talk at Fermilab Users Meeting, June 2015.
[20] G. Aad *et al.* [ATLAS Collaboration], Eur. Phys. J. C **75**, no. 5, 209 (2015).
[21] V. Khachatryan *et al.* [CMS Collaboration], arXiv: 1506.01443.
[22] J. A. Aguilar-Saavedra and F. R. Joaquim, Phys. Rev. D **90**, no. 11, 115010 (2014).
[23] CMS Collaboration, note PAS-EXO-12-041, July 2014.

[24] B. A. Dobrescu and A. D. Peterson, JHEP **1408**, 078 (2014). A. Jinaru *et al.*, J. Phys. G **41**, 075001 (2014).
[25] J. C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974). R. N. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 566 (1975); 2558 (1975). G. Senjanovic and R. N. Mohapatra, Phys. Rev. D **12**, 1502 (1975); Phys. Rev. Lett. **44**, 912 (1980). P. Minkowski, Phys. Lett. B **67**, 421 (1977).