

Local baryon number at the LHC

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(Received 21 May 2025; accepted 25 June 2025; published 15 July 2025)

The minimal theory in which the baryon number is spontaneously broken at the low scale predicts new fermions, one of which is a dark matter candidate, from gauge anomaly cancellation. We discuss the production mechanisms and decays of these new fermions, which include channels with multileptons and channels with long-lived charged fermions that can give rise to exotic signatures with “kinked” tracks at the Large Hadron Collider. We evaluate the constraints on the theory from current LHC searches and measurements and briefly comment on the excess in top pair production at threshold recently reported by CMS. We also discuss predictions for the $h \rightarrow \gamma Z_B$ decay, where h is the SM-like Higgs and Z_B is the new gauge boson associated with the baryon number.

DOI: [10.1103/2wbm-g6yv](https://doi.org/10.1103/2wbm-g6yv)

I. INTRODUCTION

After the discovery of the Brout-Englert-Higgs boson at the Large Hadron Collider (LHC) [1–3], the Standard Model (SM) of particle physics stands as one of the most successful ever theories in describing nature. The SM precisely explains how quarks and leptons interact via the electromagnetic, weak, and strong gauge forces. In this framework, massive fields acquire mass through the Higgs mechanism, with Higgs boson decays aligning with SM predictions, consistent with increasingly precise data from the LHC [4,5]. As a gauge theory, the SM is built upon the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge group, where lepton and baryon numbers emerge as accidental global symmetries at the classical level. These global symmetries play a crucial role in neutrino physics and cosmology.

Extensions to the SM in which the global symmetry associated with baryon number is promoted to a local gauge symmetry are well motivated for several reasons [6–10], one of which is that they predict a candidate for dark matter (DM), as studied in detail in Ref. [11]. This DM candidate is one of several new fermions required to cancel the triangle

gauge anomalies that would otherwise be introduced along with the new $U(1)_B$ gauge group. In Ref. [11] some phenomenological aspects of these theories were studied, under the assumptions that the additional fermions have masses high enough that they play no direct phenomenological role. All new fermions in this theory acquire mass from the $U(1)_B$ breaking scale and in the majority of cosmologically viable scenarios their masses should be below a few TeV, potentially within reach of colliders. In this article, we investigate in detail the phenomenological aspects of these fermions needed for anomaly cancellation in the minimal theory based on local baryon number [10].

In the theory proposed in Ref. [10], the baryonic anomalies are canceled with only four new fermionic representations. These new fermions acquire mass once the local baryon number is spontaneously broken. This theory predicts two neutral Majorana fermions, χ^0 and ρ^0 , the lightest of which can be a DM candidate, and two charged fermions, Ψ^- and ρ^- . One of the charged fermionic fields, ρ^- , is long-lived and can give rise to striking signatures at colliders. The other decays to a SM fermion and missing energy. In this article, we study in detail all the collider signatures of the theory and point out the regions of parameter space that are already ruled out by LHC searches and measurements. We find the following distinctive signatures, shown schematically in Fig. 1:

- (i) Two charged tracks, Fig. 1(a): The $pp \rightarrow \rho^+ \rho^- \rightarrow \rho^0 \rho^0 \pi^+ \pi^-$ channel gives rise to two kinked charged tracks because the $\rho^\pm$ are long-lived with a decay length of order 5 cm. Here, the ρ^0 field is long-lived and neutral, giving rise to missing energy signatures.

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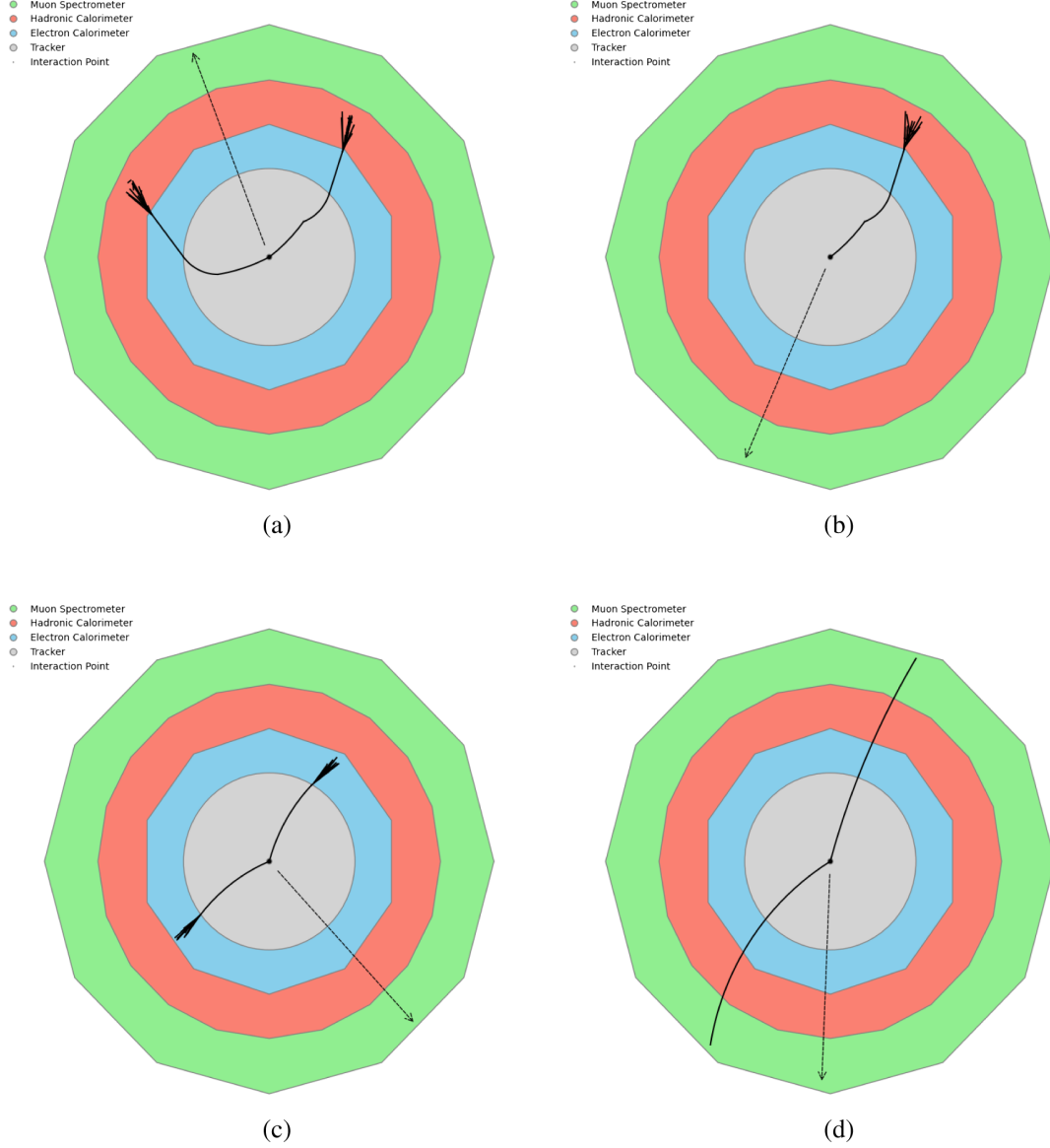


FIG. 1. Schematics of signatures from the production and decays of (a) $\rho^+\rho^-$, (b) $\rho^0\rho^\pm$, (c) $\Psi^+\Psi^- \rightarrow e^+e^-\phi\phi^*$, and (d) $\Psi^+\Psi^- \rightarrow \mu^+\mu^-\phi\phi^*$ at the LHC. $\Psi^+\Psi^- \rightarrow \tau^+\tau^-\phi\phi^*$ is also possible (not shown). The dashed line indicates the summed missing transverse momentum arising from one or more DM candidates exiting the detector undetected. The soft charged pion is shown being produced at the $\rho^\pm$ decay point and stopping in the hadronic calorimeter, the $e^\pm$ are shown stopping in the electromagnetic calorimeter, and the muons are detected in the muon chamber.

- (ii) Single charged track and missing energy, Fig. 1(b): One can have the associated production $pp \rightarrow \rho^0\rho^- \rightarrow \rho^0\rho^0\pi^-$, and since the ρ^- field is long-lived one has a charged track until this field decays into ρ^0 and a pion. The ρ^0 field is neutral and long-lived.
- (iii) Multilepton channels, Figs. 1(c) and 1(d): The pair production, $pp \rightarrow \Psi^+\Psi^- \rightarrow \ell_i^+\ell_j^-\phi\phi^*$, gives rise to two charged leptons and missing energy. The ϕ field is neutral and long-lived in this context.

Note that the new fields predicted can be light, with masses close to the electroweak scale. We study these signatures in detail to understand the possibility of testing

this theory at the LHC. In Ref. [111], we studied the experimental bounds on the leptophobic gauge boson Z_B , associated with the new local baryonic gauge symmetry, the missing energy signatures related to our dark matter candidate, and the signatures from the new Higgs decays. In this paper, we revisit Z_B production and discuss a new decay of the SM Higgs, $h \rightarrow Z_B\gamma$. Our main findings tell us that a well-motivated theory for physics beyond the SM could be discovered in the near future at the LHC.

The article is organized as follows: In Sec. II, we discuss the minimal theory for spontaneous baryon number and outline its main features. In Sec. III, we revisit the

phenomenology and limits on the Z_B , with a note on the recently observed $t\bar{t}$ excess. We examine the fermion decays, including some novel signatures, in Sec. IV. In Sec. V, we return to the Higgs sector of the model, highlighting a new decay for the SM-like Higgs. We summarize our main findings in Sec. VI. In Appendix A, we provide the relevant Feynman rules; in Appendix B, we show the explicit expression for the effective $hZ_B\gamma$ couplings.

II. MINIMAL THEORY FOR BARYON NUMBER

In this theory, the Abelian global symmetry associated with baryon number in the SM is promoted to a local gauge symmetry and the theory is based on the gauge group [6–10]

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_B.$$

This implies an additional gauge boson Z_B associated with the $U(1)_B$ symmetry. This boson must be given mass by spontaneously breaking the new symmetry, leading to an additional CP -even Higgs boson, h_B . In Ref. [10], it was pointed out that all the baryonic anomalies can be canceled with only four extra fermions, with the following quantum numbers:

$$\begin{aligned} \Psi_L &\sim (\mathbf{1}, \mathbf{1}, -1, 3/4), & \Psi_R &\sim (\mathbf{1}, \mathbf{1}, -1, -3/4), \\ \chi_L &\sim (\mathbf{1}, \mathbf{1}, 0, 3/4), & \text{and } \rho_L &\sim (\mathbf{1}, \mathbf{3}, 0, -3/4). \end{aligned}$$

The ρ_L field can be written as

$$\rho_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_L^0 & \sqrt{2}\rho_L^+ \\ \sqrt{2}\rho_L^- & -\rho_L^0 \end{pmatrix}. \quad (1)$$

Mass can be generated for the new fermions by the same Higgs field that gives mass to the new gauge boson, $S \sim (\mathbf{1}, \mathbf{1}, 0, 3/2)$, with the following Yukawa interactions:

$$\begin{aligned} -\mathcal{L} \supset & \lambda_\rho \text{Tr}(\rho_L^T C \rho_L) S + \lambda_\Psi \bar{\Psi}_L \Psi_R S + \lambda_\chi \chi_L^T C \chi_L S^* \\ & + \lambda_e \bar{\Psi}_L e_R \phi + \text{H.c.} \end{aligned} \quad (2)$$

The new scalar field, $\phi \sim (\mathbf{1}, \mathbf{1}, 0, 3/4)$, is introduced to allow the new electrically charged fields, Ψ_L and Ψ_R , to decay into a SM charged lepton and the neutral scalar field, through the last interaction term in the above equation. There are thus three neutral fields, ϕ , χ_L , and ρ_L^0 , present in the theory; however, the heavier two of these can always decay to the lighter via higher-dimensional operators, meaning that there is only one dark matter candidate in this context.¹

¹Notice that the dimension-five operators

$$\begin{aligned} -\mathcal{L} \supset & \frac{y_1}{\Lambda} \ell_L^T i\sigma_2 C \rho_L H \phi + \frac{y_2}{\Lambda} \ell_L^T i\sigma_2 C H \chi_L \phi^* \\ & + \frac{y_3}{\Lambda} H^\dagger \chi_L^T C \rho_L H + \text{H.c.} \end{aligned} \quad (3)$$

are allowed by the gauge symmetry.

The scalar potential in this theory is given by

$$\begin{aligned} V(H, S, \phi) = & -m_H^2 H^\dagger H + \lambda(H^\dagger H)^2 - m_S^2 S^\dagger S + \lambda_s(S^\dagger S)^2 \\ & - m_\phi^2 \phi^\dagger \phi + \lambda_\phi(\phi^\dagger \phi)^2 + \lambda_1(H^\dagger H)S^\dagger S \\ & + \lambda_2(H^\dagger H)\phi^\dagger \phi + \lambda_3(S^\dagger S)\phi^\dagger \phi \\ & + (\mu S^* \phi \phi + \text{H.c.}), \end{aligned} \quad (4)$$

and the scalar fields can be written as

$$\begin{aligned} H &= \begin{pmatrix} h^+ \\ \frac{1}{\sqrt{2}}(v_0 + h_0)e^{i\sigma_0/v_0} \end{pmatrix}, \\ S &= \frac{1}{\sqrt{2}}(v_s + h_s)e^{i\sigma_s/v_s}, \\ \text{and } \phi &= \frac{1}{\sqrt{2}}(h_\phi + v_\phi)e^{i\sigma_\phi/v_\phi}. \end{aligned} \quad (5)$$

Here h_i are the different CP -even Higgs fields and v_i are the vacuum expectation values.

In general, there are two main scenarios, with very different predictions:

- (i) $v_\phi = 0$: In this case, if kinematically allowed, the new charged fermions can decay to the SM charged leptons and the field ϕ . In this scenario, the lightest field among ϕ , ρ_L^0 , and χ_L can be a DM candidate because of the accidental discrete symmetry,

$$\begin{aligned} \mathbb{Z}_2: & \phi \rightarrow -\phi, \rho_L \rightarrow -\rho_L, \chi_L \rightarrow -\chi_L, \\ & \Psi_L \rightarrow -\Psi_L, \Psi_R \rightarrow -\Psi_R. \end{aligned} \quad (6)$$

Notice that this symmetry arises as a natural consequence of the spontaneous breaking of the gauge symmetry.

- (ii) $v_\phi \neq 0$: In this case, all the new fields introduced to cancel the anomaly can decay to the SM fields. The field Ψ_L can mix with the e_R , while the neutral fields ρ_L^0 and χ_L decay via the higher-dimensional operators mentioned above.

In the following, we focus on the first case, since in the second case, there is no DM candidate. This theory predicts the following physical states:

- (i) Z_B is the gauge boson associated with the local baryon number. The Z_B mass is given by $M_{Z_B} = 3g_B v_S/2$ when $v_\phi = 0$.
- (ii) h is the SM-like Higgs boson defined as $h = h_0 \cos \theta_B - h_S \sin \theta_B$.
- (iii) h_B is the new CP -even Higgs defined as $h_B = h_0 \sin \theta_B + h_S \cos \theta_B$. In Ref. [11], the production cross section of the new Higgs, and the experimental bounds on its mass, are discussed.
- (iv) ϕ is a complex scalar field and it can be written as $\phi = (\phi_R + i\phi_I)/\sqrt{2}$. The masses for ϕ_R and ϕ_I read as

$$M_{\phi_R}^2 = -m_\phi^2 + \frac{\lambda_2}{2} v_0^2 + \frac{\lambda_3}{2} v_S^2 + \sqrt{2}\mu v_S, \quad (7)$$

$$M_{\phi_I}^2 = M_{\phi_R}^2 - 2\sqrt{2}\mu v_S, \quad (8)$$

when $v_\phi = 0$.

(v) Two Majorana fermionic fields,

$$\chi = \chi_L + (\chi_L)^C \quad \text{and} \quad \rho^0 = \rho_L^0 + (\rho_L^0)^C, \quad (9)$$

with masses given by

$$M_\chi = \sqrt{2}\lambda_\chi v_S \quad \text{and} \quad M_{\rho^0} = \sqrt{2}\lambda_\rho v_S. \quad (10)$$

(vi) Two charged fermionic fields Ψ^- and ρ^- defined as

$$\Psi^- = \Psi_L^- + \Psi_R^- \quad \text{and} \quad \rho^- = \rho_L^- + (\rho_L^+)^C. \quad (11)$$

For a detailed discussion of the dark matter candidates in this context, see the study in Ref. [12].

III. THE LEPTOPHOBIC GAUGE BOSON

A leptophobic gauge boson is predicted in the theory discussed in the previous section. The phenomenology and experimental bounds for the specific Z_B gauge boson associated with this theory were discussed in detail in Ref. [11]. This study showed that the mass of the Z_B can be close to the electroweak scale and satisfy all collider bounds, without assuming a very small gauge coupling g_B . We revisit this discussion briefly in light of new data, including new LHC measurements of $t\bar{t}$ cross sections and a reported excess close to threshold [13]. Following the method described in Ref. [11], we study Z_B production and decay using Contur [14,15] 3.1 to compare predictions to SM measurements from ATLAS and CMS. To do this, we have implemented our model in FeynRules [16] and exported a universal FeynRules output [17]² directory which allows events to be generated by Herwig 7.3 [18,19] and passed through Rivet 4.0.3 [20,21].

In Fig. 2, we show the branching ratios of the leptophobic gauge boson decays as a function of M_{Z_B} , assuming $M_{\rho^-} = 700$, and $M_{\Psi^-} = 500$ GeV. Notice that Z_B decays mainly to light quarks, but when the decays to new fermions are kinematically allowed, they can have a large branching ratio. We repeat the study of Fig. 5 from Ref. [11], which investigated the sensitivity of the LHC data present in Contur to the Z_B as function of its mass M_{Z_B} in the presence of a DM candidate χ with a mass of 100 GeV. We also present the case in which the χ decay is

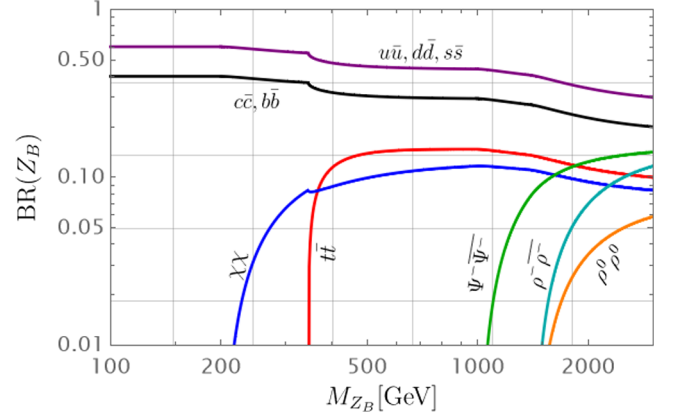


FIG. 2. Branching ratios of the leptophobic gauge boson (Z_B) decays as a function of M_{Z_B} , assuming $M_{\rho^-} = 700$ and $M_{\Psi^-} = 500$ GeV. These results are independent of the g_B value.

not kinematically accessible. We show the results in Fig. 3. There are several changes with respect to [11]: Further measurements have been added to Contur, notably of leptonically decaying top cross sections; the SM uncertainties for the hadronic $t\bar{t}$ and Z + jets are now included; and the model studied here differs in the $Z_B \rightarrow \chi\chi$ branching ratio by a factor of 4 because the χ_L field has a smaller baryon number in the minimal model we discuss in this article. However, the results are qualitatively very similar, with $g_B < 0.25$ allowed for $M_{Z_B} \approx 600$ GeV, with higher values allowed at higher and lower M_{Z_B} values. Close to the $t\bar{t}$ threshold, the upper limit on g_B is around 0.25. It is important to mention that the most sensitive channels are the hadronic $t\bar{t}$ and the $\ell + p_T^{\text{miss}} + \text{jet}$, when the Z_B does not decay to the dark matter candidate; see details in the right panels in Fig. 3.

The enhancement to the $t\bar{t}$ cross section due to the Z_B , as a function of M_{Z_B} , is shown in Fig. 4. Near the $t\bar{t}$ threshold, a cross section of several femtobarn can be accommodated: This is confirmed by a fit using Herwig with Contur,³ which gives a maximum cross section for $pp \rightarrow Z_B \rightarrow t\bar{t}$ of 9.2 pb at 95% confidence level (CL), for $M_{Z_B} = 360$ GeV. The CMS Collaboration has recently reported an excess in this region consistent with the production of a pseudoscalar $t\bar{t}$ bound state with a production cross section of $8.8^{+1.2}_{-1.4}$ pb, while stating that other explanations cannot be ruled out [13]. We note that one such explanation might be a Z_B with mass around 360 GeV, although without a detailed study including the experimental acceptance for a vector state, nothing more definite can be said at this stage.

²Available from the Contur model library <https://gitlab.com/hepcedar/contur/-/tree/main/data/Models>.

³Making use of the Spey [35] functionality introduced in version 3.1.

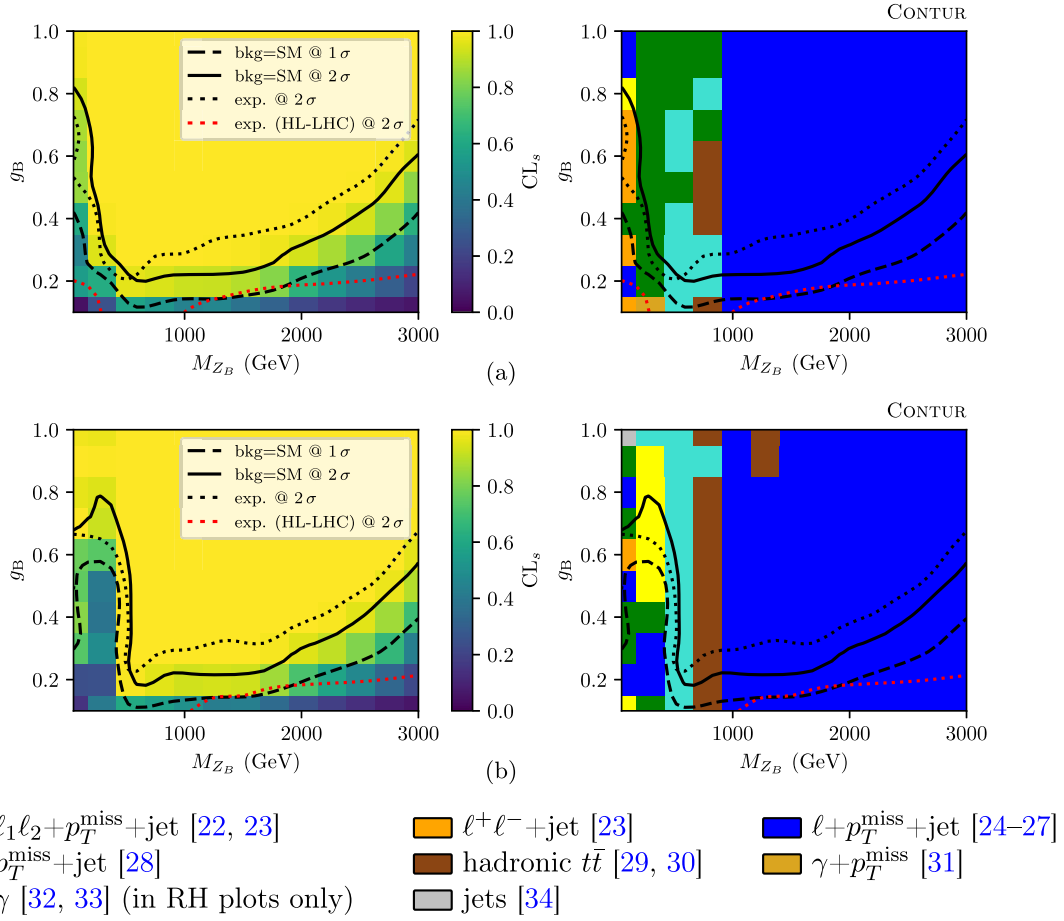


FIG. 3. Exclusion limits in g_B as functions of M_{Z_B} , (a) $M_\chi = 100$ GeV, (b) $M_\chi = 3$ TeV. The solid black line indicates the 95% exclusion and the dashed black line the 68% exclusion. The dotted black line is the expected exclusion, and the dotted red line is a naive estimate of the eventual High-Luminosity LHC (HL-LHC) sensitivity. (see Refs. [22–34]).

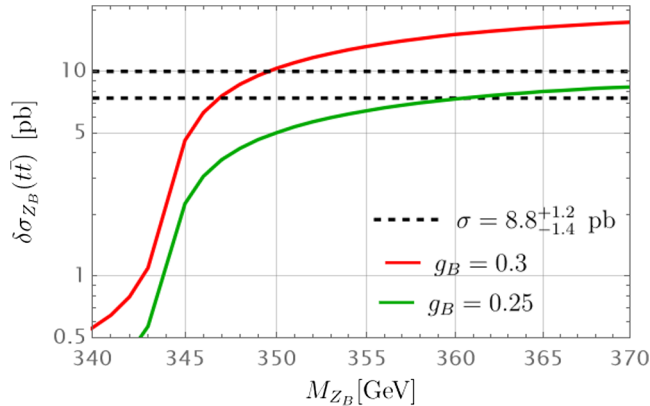


FIG. 4. Extra contribution to the production cross section of $t\bar{t}$ due to Z_B at $\sqrt{s} = 13$ TeV, as a function of M_{Z_B} , for two different g_B values, calculated using MadGraph5 [36]. The cross section excess reported by CMS is also indicated by the dashed black lines.

IV. FERMION DECAYS

The theory predicts two charged fermionic fields Ψ^- and ρ^- with masses given by

$$M_{\Psi^-} = \frac{1}{\sqrt{2}}\lambda_\Psi v_S \quad \text{and} \quad M_{\rho^-} = M_{\rho^0} + \Delta M, \quad (12)$$

where $M_{\rho^0} = \sqrt{2}\lambda_\rho v_S$ and the mass splitting $\Delta M \approx 166$ MeV is generated at one-loop level [37,38]. Since this mass splitting is very small, the dominant allowed decays are $\rho^- \rightarrow \rho^0\pi^-$, $\rho^0 e^- \bar{\nu}$ and $\rho^0 \mu^- \bar{\nu}$, with widths given by

$$\Gamma(\rho^- \rightarrow \rho^0\pi^-) = \frac{2G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{\pi} \sqrt{1 - M_\pi^2/\Delta M^2}, \quad (13)$$

$$\Gamma(\rho^- \rightarrow \rho^0 e^- \bar{\nu}) = \frac{2G_F^2 \Delta M^5}{15\pi^3}, \quad (14)$$

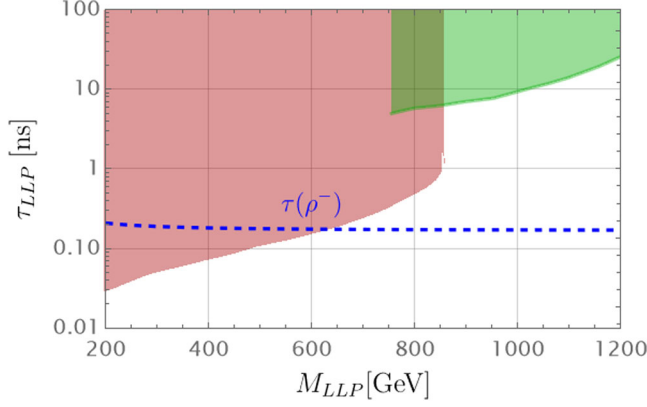


FIG. 5. Allowed parameter space for a charged long-lived particle (LLP). The red shaded region is excluded by the ATLAS measurements [39], and the green shaded region is excluded by the studies in Ref. [43]. The dashed line shows the prediction of this model.

$$\Gamma(\rho^- \rightarrow \rho^0 \mu^- \bar{\nu}) = 0.12 \Gamma(\rho^- \rightarrow \rho^0 e^- \bar{\nu}). \quad (15)$$

Here, $f_\pi = 131$ MeV is the decay constant of the pion. The ρ^- decays mainly into a pion and ρ^0 with a branching ratio $\text{BR}(\rho^- \rightarrow \rho^0 \pi^-) \sim 97\%$. The decay length is given by

$$c\tau_{\rho^-} \approx 5.6 \text{ cm}. \quad (16)$$

Therefore, the charged ρ^- is a long-lived charged particle, which will give rise to tracks in a charged-particle detector which terminate in a “kink” at the decay point, from where a soft pion track will emerge. The general topology is illustrated in Figs. 1(a) and 1(b). Notice that this prediction could change if the higher-dimensional operators in Eq. (3) are allowed. In this case, ρ^- can decay into a charged lepton and the scalar field ϕ .

From the ATLAS and CMS searches looking for a long-lived charged pure wino field produced through the weak

interactions, one can conclude that the mass of the ρ^- field has to be above 650 GeV, see Refs. [39,40] for details. The experimental bounds estimated from reinterpreting these searches are shown in Fig. 5. For our theory, masses above 650 GeV are still allowed. These channels with charged tracks are quite distinctive and can be used to test this theory in the near future. See also Ref. [41] for a recent discussion about charged tracks in new physics models and Ref. [42] for recent experimental bounds.

Figure 6(a) shows the $\rho^0 \rho^-$ production cross section at $\sqrt{s} = 13$ TeV as a function of the charged fermion mass, calculated using MadGraph5 [36]. In Fig. 6(b), we show the predicted cross section for $\Psi^- \Psi^-$ production via the SM γ , Z and the Z_B , for three different Z_B masses, as well as for the case in which Z_B plays no role. As can be seen, the Z_B contribution can significantly change the cross section around the $2M_\Psi \sim M_{Z_B}$ threshold.

The Ψ^- can decay into a charged lepton and the scalar field ϕ if this channel is kinematically allowed. In the opposite case, $M_{\Psi^-} < M_\phi$, the Ψ^- field decays via higher-dimensional operators and it is generically long-lived, giving rise to a charged track. The Ψ^- decays are represented schematically in Figs. 1(c) and 1(d).

Since the production and decay of Ψ^- leads to SM-like signatures involving charged leptons and missing transverse momentum, we may also study these using Contur. As an illustrative example, we assume $M_\Psi = 300$ GeV, $M_\phi = 100$ GeV, $M_{Z_B} = 1$ TeV, and $g_B = 0.25$. The branching ratio of Ψ to each of e , μ , and τ varies over the full range between zero and unity. The results are shown in Fig. 7. Points above the grid diagonal are unphysical, since the sum of the branching fractions exceeds unity.

In the top left and bottom right regions, the Ψ decays with a high branching fraction to electrons or muons, respectively. This results in a same-flavor lepton pair in the final state, which is constrained primarily by the CMS Run 2 high-mass Drell-Yan measurement [44], as can be seen in the right-hand panel of the figure, which indicates the

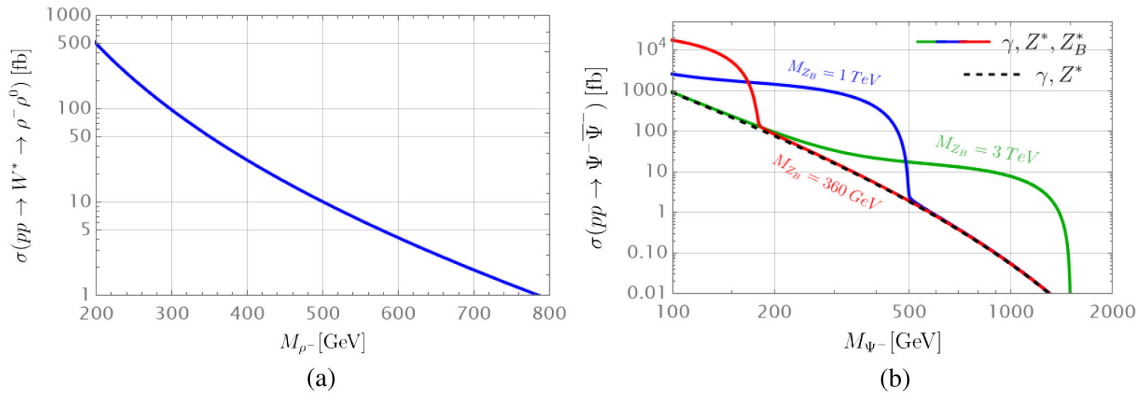


FIG. 6. Leading order Drell-Yan production cross sections of the new fermions at $\sqrt{s} = 13$ TeV, as a function of the charged fermion mass, calculated using MadGraph5 [36]. (a) $\rho^0 \rho^-$, (b) $\Psi^- \Psi^-$ production at the LHC with $g_B = 0.25$ and three different Z_B masses, as well as the prediction when the Z_B plays no role.

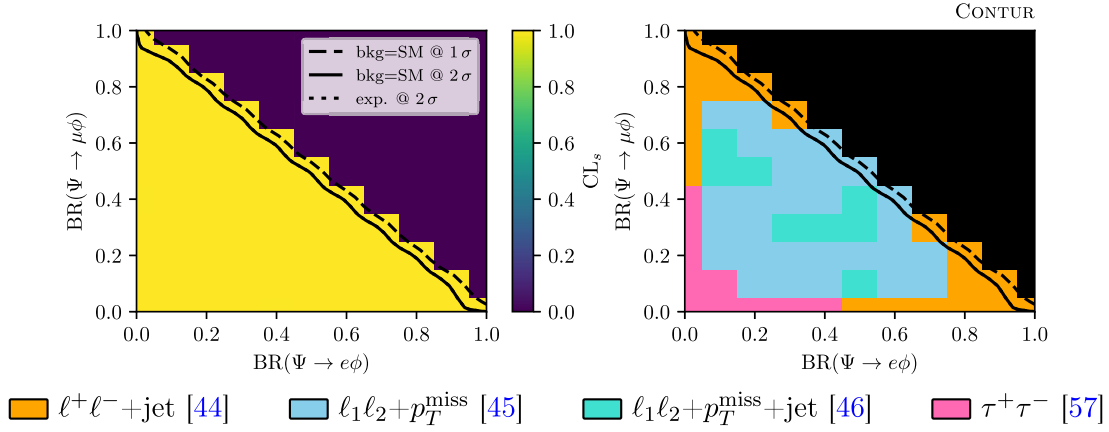


FIG. 7. Left: exclusion for each point in the grid of branching ratios, with interpolated excluded contours overlaid. Right: the measurement with the highest exclusion power at each point. In this scenario, $M_\Psi = 300$ GeV, $M_\phi = 100$ GeV, $M_{Z_B} = 1$ TeV, and $g_B = 0.25$.

measurements providing the strongest sensitivity at each parameter point. An example differential distribution with high exclusion power is shown in Fig. 8(a). In the central region of the grid in Fig. 7, the branching fraction to electrons and muons is approximately equal, leading to more final states with electrons and/or muons and missing energy. This scenario is constrained by measurements of WW production in the unlike dilepton final state [45,46], as shown by the right panel. Example differential distributions in this region are shown in Figs. 8(b) and 8(c).

In the bottom left region of Fig. 7, the branching ratio is primarily to τ leptons, which is more challenging experimentally. Nevertheless, the right panel of Fig. 7 shows that this region of parameter space is excluded by the recent ATLAS di- τ measurement [57]. The distribution driving this exclusion is shown in Fig. 8(d).

As expected, the sensitivity drops as the mass of the Ψ increases. Figure 9 shows the same scenario as Fig. 7, but with the Ψ mass increased to 400 GeV. In this case, the scenarios involving decays to muons and/or electrons are still excluded, but the more challenging di- τ final states are less constrained. Since the muon and electron sensitivities are quite similar, we set them equal to each other, which allows us to perform a scan over the mass of the Ψ and the branching ratio to τ leptons, with the remainder of the decays being equal to electrons or muons. This is shown in Fig. 10 for various Z_B mass scenarios, since, as illustrated in Fig. 6, the size of the contribution will depend upon M_{Z_B} and g_B . We consider four scenarios; one with the Z_B decoupled, one motivated by the possibility of a resonant contribution at top threshold ($M_{Z_B} = 360$ GeV, $g_B = 0.25$) as discussed in Sec. III, one where the Z_B is more massive but within reach ($M_{Z_B} = 1$ TeV, $g_B = 0.25$), and one where it is more massive still, and thus contributes primarily as an off-shell propagator ($M_{Z_B} = 3$ TeV, $g_B = 0.25$).

When the Z_B plays no role [Fig. 10(a)], the model is ruled out for $M_\Psi < 350$ GeV when the Ψ decays mostly to

μ or e , but there is currently no significant exclusion when τ decays dominate. However, a naive⁴ estimate of HL-LHC sensitivity, based upon scaling the experimental uncertainties with the square root of the ratio of the current integrated luminosity to 3 ab^{-1} , shows that a Ψ decaying predominantly to τ leptons could be within reach for M_Ψ up to at least 200 GeV. For a Z_B coupled with $g_B = 0.25$, and $M_{Z_B} = 360$ GeV [Fig. 10(b)], the situation is similar except that there is some current exclusion up to $M_\Psi \approx 140$ GeV. For a Z_B coupled with $g_B = 0.25$, and $M_{Z_B} = 1$ TeV [Fig. 10(c)], the model is excluded for $M_\Psi < 400$ GeV when $\Psi \rightarrow \tau\tau$ dominates and for $M_\Psi < 480$ GeV otherwise. Finally, for a Z_B coupled with $g_B = 0.25$ but $M_{Z_B} = 3$ TeV [Fig. 10(d)], the situation is similar to Fig. 10(a) with the Z_B decoupled, except that the expectation is that deviations in the tails of the lepton distribution are expected to be sensitive for HL-LHC data, regardless of whether the Ψ decays to e , μ , or τ . Note that, in these results, only the sensitivity from $\Psi^+\Psi^-$ production is evaluated; the production of Z_B itself would provide additional sensitivity in other final states, as already discussed in Sec. III.

The main conclusion is that, while some of the parameter space is already ruled out by LHC measurements, a large and well-motivated region remains, much of which is nevertheless in reach of HL-LHC data. Therefore, one can hope to test these predictions in the near future.

V. HIGGS DECAYS

Finally, we return to the Higgs sector and consider the decays of the h_B and the SM-like Higgs in this theory.

⁴This is likely to underestimate the eventual HL-LHC reach, as discussed, for example, in Ref. [59].

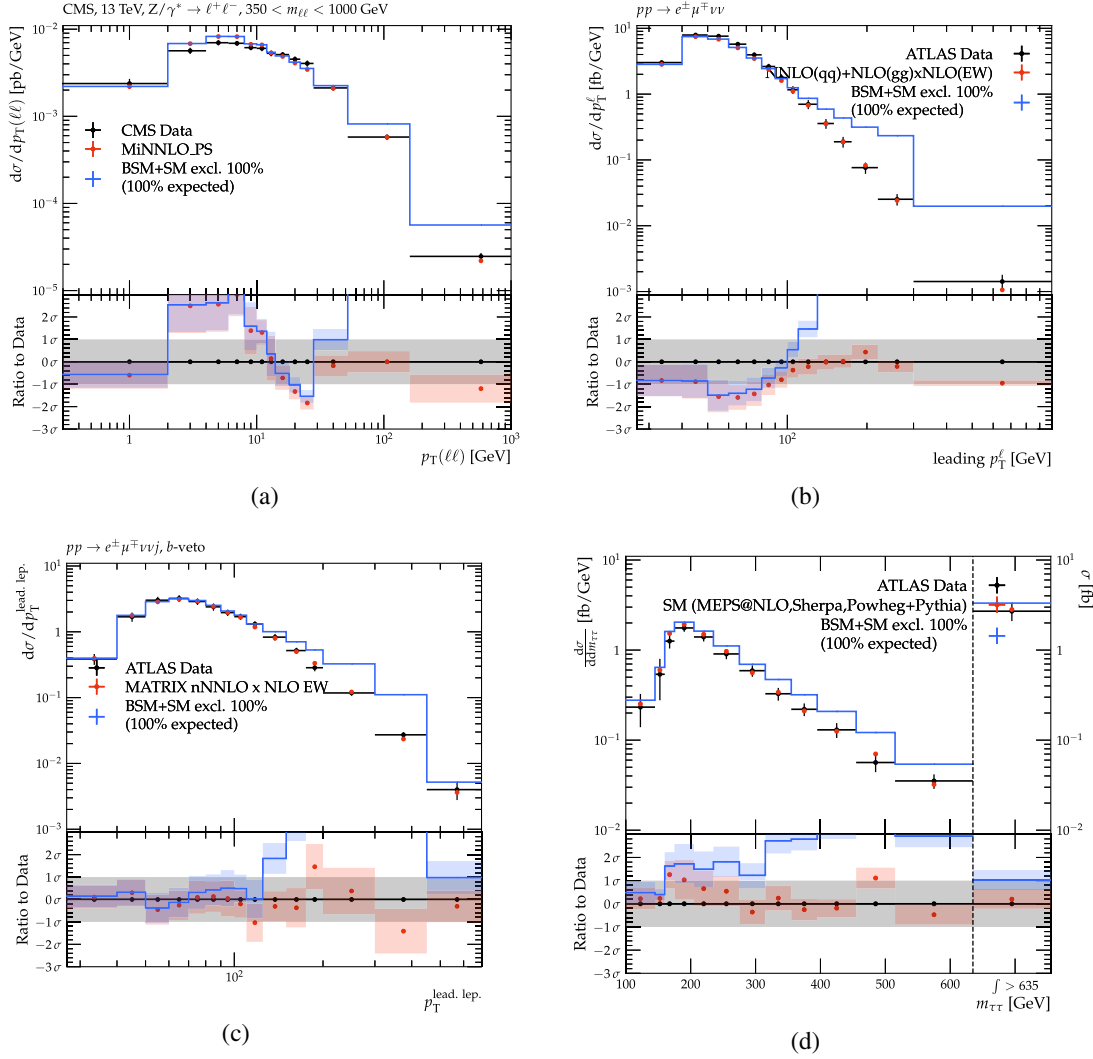


FIG. 8. Beyond the Standard Model (BSM) + SM vs SM only hypotheses for various distributions providing exclusion at parameter points from Fig. 7. (a) Dilepton transverse momentum distribution from [44,47,48]. The signal hypothesis is excluded by an excess of events in the high momentum tail. At this point in the grid, $\text{BR}(\Psi \rightarrow e\phi) = 1$. (b) Leading lepton transverse momentum distributions from Refs. [45,49–53] and (c) Refs. [46,49,50,54–56]. At this point in the grid, $\text{BR}(\Psi \rightarrow e\phi) = \text{BR}(\Psi \rightarrow \mu\phi) = 0.5$. (d) Visible $\tau^+\tau^-$ invariant mass distribution [57,58]. At this point in the grid, $\text{BR}(\Psi \rightarrow \tau\phi) = 1$.

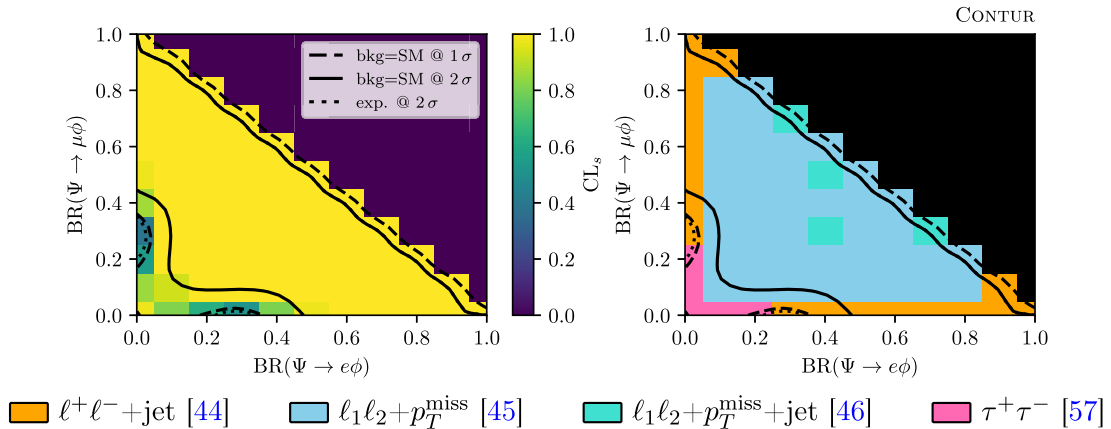


FIG. 9. Same as Fig. 7, but with $M_\Psi = 400$ GeV.

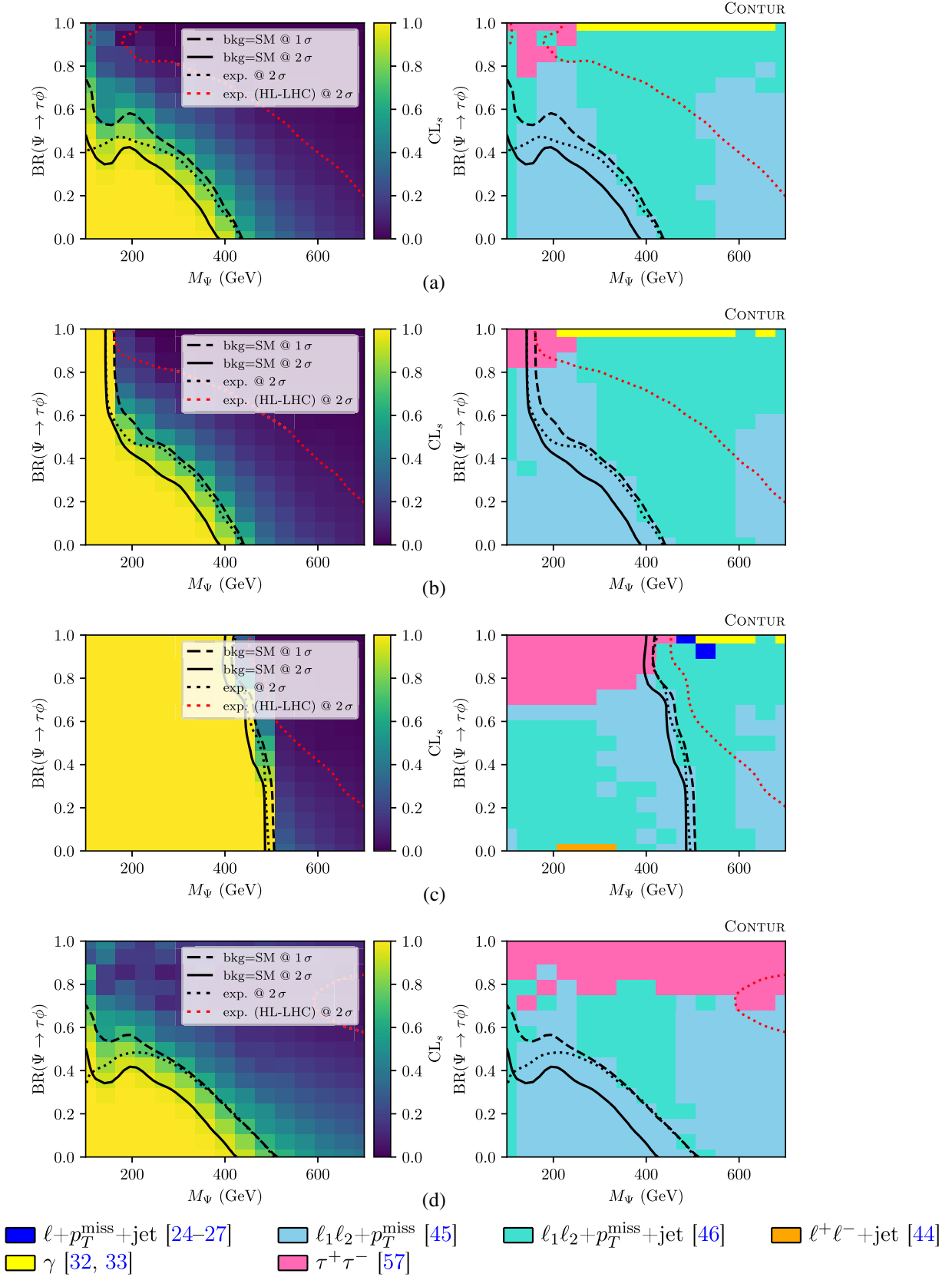


FIG. 10. Exclusion contour in the plane of the Ψ mass and its branching ratio to third generation leptons, assuming branching to the first and second generations are equal. The mass of ϕ was taken to be 50 and $M_\chi = 500$ GeV. (a) $g_B = 10^{-6}$, removing the Z_B contribution to $\Psi^+ \Psi^-$ production. In the other plots, $g_B = 0.25$ and M_{Z_B} is (b) 360 GeV, (c) 1 TeV, and (d) 3 TeV.

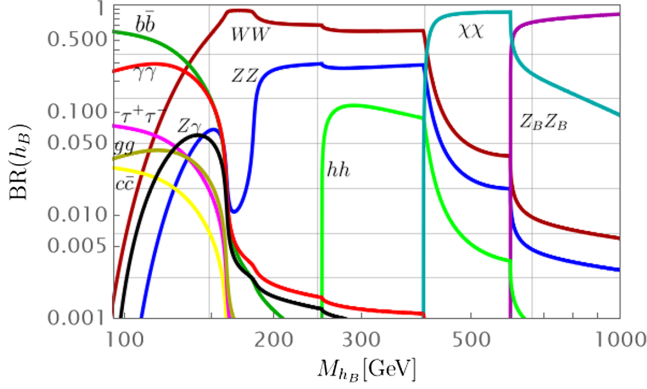


FIG. 11. Branching ratios for h_B decays. Here we use $g_B = 0.25$, $\sin\theta_B = 0.01$, $M_\chi = 200$ GeV, $M_{Z_B} = 300$ GeV, $M_{\Psi^-} = 1$ TeV, and $M_{\rho^-} = 800$ GeV.

A. Cucuyo Higgs decays

The new physical Higgs boson in the theory, H_B , can decay into the SM fields and the new fields. The main decays are

$$h_B \rightarrow \bar{b}b, \gamma\gamma, WW, ZZ, \chi\chi, Z_B Z_B. \quad (17)$$

We refer to this new Higgs as ‘‘Cucuyo Higgs’’ following the discussion in Ref. [11]. In Fig. 11, we show the branching ratios for h_B decays. Here we use $g_B = 0.25$, $\sin\theta_B = 0.01$, $M_\chi = 200$ GeV, $M_{Z_B} = 300$ GeV, $M_{\Psi^-} = 1$ TeV, and $M_{\rho^-} = 800$ GeV. Similar results were presented in Ref. [11], but in the current case the fields needed for anomaly cancellations are different, which has implications for the predicted decays. Figure 11 shows that, as in Ref. [11], the h_B can have a large branching ratio into two photons when its mass is below the WW threshold. It can decay mainly into the dark matter candidate if the relevant masses allow, and it decays mainly into the new gauge boson when this decay is kinematically allowed. The production cross section and the experimental bounds on the Cucuyo Higgs mass were discussed in detail in Ref. [11] and will still apply here with modifications given by the new branching ratios.

B. Decay of the SM-like Higgs

In this theory, the SM-like Higgs can have a new decay at one-loop level due to the fact that the new gauge boson Z_B can have $M_{Z_B} < 125$ GeV. The effective $hZ_B\gamma$ coupling is generated at one-loop level, where inside the loop one has the top quark. The decay width for this process is given by

$$\Gamma(h \rightarrow \gamma Z_B) = \frac{\alpha \alpha_B M_t^2 Q_t^2 |A|^2 (M_h^2 - M_{Z_B}^2)}{128\pi^3 v_0^2 M_h^3}. \quad (18)$$

Here $\alpha = e^2/4\pi$, $Q_t = 2/3$, and $\alpha_B = g_B^2/4\pi$. The explicit form of the A coefficient is given in Appendix B. In Fig. 12, we show the branching ratio for $h \rightarrow \gamma Z_B$ for different

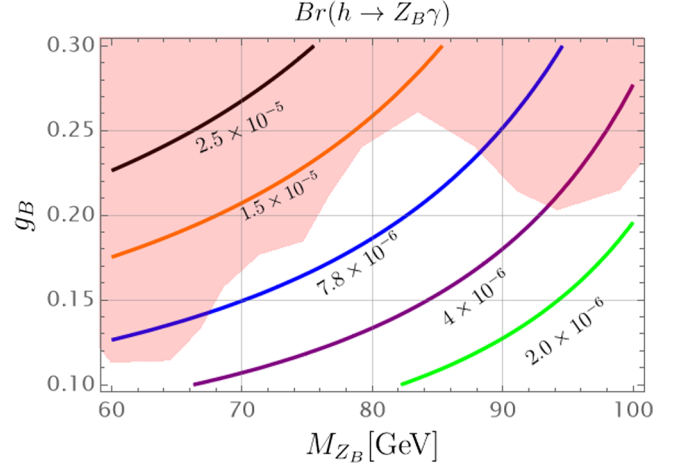


FIG. 12. Branching ratio for $h \rightarrow Z_B \gamma$. The red region is excluded by LHC searches [60].

values of the gauge coupling g_B and new gauge boson mass M_{Z_B} , including the recent LHC bounds taken from [60]. Unfortunately, the branching ratio for this decay is very small. Using the gluon fusion production cross section for the SM Higgs at $\sqrt{s} = 13$ TeV, $\sigma(pp \rightarrow h) = 48.6$ pb [61], we make a naive estimate of the number of events for the $Z_B \gamma$ channel,

$$\sigma(pp \rightarrow h) \times \text{BR}(h \rightarrow Z_B \gamma) \times 3000 \text{ fb}^{-1} \sim 146, \quad (19)$$

using $\text{BR}(h \rightarrow Z_B \gamma) \sim 10^{-6}$ as an example. At the LHC, large QCD backgrounds make this decay very challenging to identify, although given the significant improvements being delivered, for example, in jet tagging using new QCD insights coupled with machine learning (see, for example, Refs. [59,62,63]), we hesitate to completely dismiss the possibility of observation. At future colliders, a dedicated measurement of this channel becomes more feasible.

VI. SUMMARY

The distinctive predictions of the minimal theory for local baryon number, in which the global symmetry associated with baryon number in the SM is promoted to a local gauge symmetry, have been explored. The consequences of the spontaneous breaking of this symmetry were studied, identifying several novel phenomena. The minimal framework requires only four additional fermionic representations to ensure anomaly cancellation, plus an additional scalar field. Notably, it predicts the existence of a leptophobic gauge boson, Z_B , a new ‘‘Cucuyo’’ Higgs boson h_B with a potentially large branching ratio into photons, and new fermionic states with intriguing decay patterns. In this theory, the SM Higgs can decay into a photon and Z_B when kinematically allowed, although the branching ratio is small, making this decay very difficult to observe at the LHC. The h_B

decays were revisited, showing the branching ratios and computing the decay into two photons due to the presence of the new charged fermions needed for anomaly cancellation.

The long-lived fermion field ρ^- can be produced either in pairs or alongside its neutral partner, leading to distinct signatures featuring kinked tracks and missing momentum. Additionally, multilepton events and missing energy signatures offer intriguing prospects. We established a lower bound on the ρ^- mass by analyzing searches for charged tracks at the LHC, while for Ψ^- , we identified the allowed parameter space based on various leptonic decay channels. Dilepton measurements, including those of τ leptons, play an important role in constraining the parameter space. Within the allowed parameter space, it is possible that $Z_B \rightarrow t\bar{t}$ decays could play a role in explaining the excess reported recently by CMS in the $t\bar{t}$ cross section near threshold.

These findings suggest that a well-motivated and unique gauge theory beyond the Standard Model could describe physics below the TeV scale while remaining consistent with all experimental constraints. The predictions of the theory could be observed in data to be collected over the next years at the HL-LHC.

ACKNOWLEDGMENTS

P. F. P. thanks the SIMONS Foundation for financial support during his stay at the Galileo Galilei Institute for Theoretical Physics in Florence, Italy. J. E. is supported by the STFC UCL Centre for Doctoral Training in Data Intensive Science (Grant No. ST/W00674X/1) including departmental and industry contributions. This work made use of the High Performance Computing Resource in the Core Facility for Advanced Research Computing at Case Western Reserve University.

DATA AVAILABILITY

No data were created or analyzed in this study.

APPENDIX A: FEYNMAN RULES

$$q\bar{q}Z_B : i\frac{g_B}{3}\gamma^\mu, \quad (A1)$$

$$\chi\chi Z_B : -i\frac{3}{4}g_B\gamma^\mu\gamma^5, \quad (A2)$$

$$\overline{\rho^-}\rho^- Z_B : i\frac{3}{4}g_B\gamma^\mu\gamma^5, \quad (A3)$$

$$\overline{\Psi^-}\Psi^- Z_B : -i\frac{3}{4}g_B\gamma^\mu\gamma^5, \quad (A4)$$

$$\chi\chi h_B : i\frac{3}{2}\frac{g_B M_\chi}{M_{Z_B}}\cos\theta_B, \quad (A5)$$

$$Z_B Z_B h_B : -i3g_B M_{Z_B}\cos\theta_B g^{\mu\nu}, \quad (A6)$$

$$ZZ h_B : 2i\frac{M_Z^2}{v_0}\sin\theta_B g^{\mu\nu}, \quad (A7)$$

$$WW h_B : 2i\frac{M_W^2}{v_0}\sin\theta_B g^{\mu\nu}, \quad (A8)$$

$$\overline{\rho^-}\rho^- h_B : i\frac{3}{2}\frac{g_B M_{\rho^-}}{M_{Z_B}}\cos\theta_B, \quad (A9)$$

$$\overline{\Psi^-}\Psi^- h_B : i\frac{3}{2}\frac{g_B M_{\Psi^-}}{M_{Z_B}}\cos\theta_B, \quad (A10)$$

$$\overline{\Psi^-}\Psi^- h : -i\frac{3}{2}\frac{g_B M_{\Psi^-}}{M_{Z_B}}\sin\theta_B, \quad (A11)$$

$$\overline{\Psi^-}\Psi^- Z : -i\frac{e\sin\theta_W}{\cos\theta_W}\gamma^\mu, \quad (A12)$$

$$\overline{\rho^-}\rho^- Z : i\frac{e\cos\theta_W}{\sin\theta_W}\gamma^\mu, \quad (A13)$$

$$\overline{\rho^-}\rho^0 W^- : ig_2\gamma^\mu, \quad (A14)$$

$$\overline{\Psi^-}e_i\phi_R : \frac{i}{\sqrt{2}}\lambda_e^i P_R, \quad (A15)$$

$$\overline{\Psi^-}e_i\phi_L : \frac{-i}{\sqrt{2}}\lambda_e^i P_R. \quad (A16)$$

APPENDIX B: $h(p)Z_B(p_1)\gamma(p_2)$ EFFECTIVE INTERACTION

The effective coupling between h , Z_B , and the photon is generated at one-loop level, where inside the loop one has the top quark, computed using `Package-X` [64,65]. This coupling can be written as

$$\delta\Gamma_{hZ_B\gamma}^{\mu\nu} = g_B \frac{M_t}{v_0} \frac{eQ_t}{16\pi^2} (Ag^{\mu\nu} + Bp_1^\mu p_2^\nu + Cp_2^\mu p_1^\nu + Dp_1^\mu p_1^\nu + Ep_2^\mu p_2^\nu). \quad (B1)$$

Here, $p_1^2 = M_{Z_B}^2$ and $p_2^2 = 0$, being p_1 and p_2 the four momentum vectors associated with the Z_B and the photon, respectively. The coefficients in the above equations are given by

$$\begin{aligned}
A &= 4M_t \left(-2 + \frac{2M_{Z_B}^2}{M_{Z_B}^2 - M_h^2} (\Lambda(M_h^2, M_t, M_t) - \Lambda(M_{Z_B}^2, M_t, M_t)) \right. \\
&\quad \left. + (M_h^2 - 4M_t^2 - M_{Z_B}^2) C_0(0, M_h^2, M_{Z_B}^2, M_t, M_t, M_t) \right), \\
B &= -\frac{8M_t}{(s - M_{Z_B}^2)^2} (2(2M_{Z_B}^2 + M_h^2) \Lambda(M_{Z_B}^2, M_t, M_t) - 2(M_{Z_B}^2 + 2M_h^2) \Lambda(M_h^2, M_t, M_t) \\
&\quad + (M_{Z_B}^2 - M_h^2)(6 + (4M_t^2 + M_{Z_B}^2 + M_h^2) C_0(0, M_{Z_B}^2, M_h^2, M_t, M_t, M_t))), \\
C &= \frac{2A}{M_{Z_B}^2 - M_h^2}, \\
D &= 0, \\
E &= -\frac{16M_t M_{Z_B}^2}{(M_{Z_B}^2 - M_h^2)^3} (2(2M_{Z_B}^2 + M_h^2) (\Lambda(M_{Z_B}^2, M_t, M_t) - \Lambda(M_h^2, M_t, M_t)) \\
&\quad + (M_{Z_B}^2 - M_h^2)(6 + (4M_t^2 + M_{Z_B}^2 + M_h^2) C_0(0, M_{Z_B}^2, M_h^2, M_t, M_t, M_t))). \tag{B2}
\end{aligned}$$

In the above equations, the explicit form of the loop functions are

$$\Lambda(s, M_t, M_t) = \frac{\sqrt{s(s - 4M_t^2)} \log\left(\frac{\sqrt{s(s - 4M_t^2)} + 2M_t^2 - s}{2M_t^2}\right)}{s}, \tag{B3}$$

$$C_0(0, M_h^2, M_{Z_B}^2, M_t, M_t, M_t) = \frac{\log^2\left(\frac{-M_h^2 + \sqrt{M_h^4 - 4M_h^2 M_t^2 + 2M_t^2}}{2M_t^2}\right) - \log^2\left(\frac{\sqrt{M_{Z_B}^4 - 4M_{Z_B}^2 M_t^2 + 2M_t^2 - M_{Z_B}^2}}{2M_t^2}\right)}{2(M_h^2 - M_{Z_B}^2)}. \tag{B4}$$

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