PROCEEDINGS OF SCIENCE

New neutral gauge bosons in supersymmetric $U(1)'$ models at hadron colliders

PoS(EPS-HEP2021)674

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We examine the production and decay modes of Z′ boson at hadron colliders in an U(1)′-extended MSSM. We choose a U(1)′ model with a secluded sector, where the tension between the electroweak scale and developing a large enough mass for Z′ is resolved by incorporating three additional SU(2) singlet fields into the model. We perform a detailed and systematic analysis of the production, followed by decays, including into supersymmetric particles, of a Z′ boson with mass larger than 4 TeV, with particular emphasis on its possible discovery. We choose three different scenarios consistent with the latest available experimental data and relic density constraints. We concentrate on final signals involving $2\ell + \not{E}_T$, $4\ell + \not{E}_T$ and $6\ell + \not{E}_T$. Including possible SM backgrounds, we show the likelihood of observing a Z′ boson is not promising for the HL-LHC at 14 TeV, but optimistic for 27 and 100 TeV.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

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1. Introduction

Supersymmetry (SUSY) is the most popular beyond the Standard Model (BSM) scenario. It resolves the Higgs mass/gauge hierarchy problem, and provides, in its simplest scenario, the Minimal Supersymmetric Standard Model (MSSM), a natural dark matter candidate. It does not, however, explain neutrino masses and provides no explanation for the μ problem. The μ parameter, so-called higgsino mass term entering the supersymmetric Lagrangian, is expected to be at the SUSY breaking scale but, for successful EW symmetry breaking, its value should be at the scale of the latter. Adding an U(1)′ gauge group to the SM/MSSM symmetry group resolves these problems. A singlet right-handed neutrino yield masses for the left-handed neutrinos (Dirac or Majorana) and the vacuum expectation value (VEV) of the singlet Higgs field S which breaks the U(1)′ symmetry generates the μ term dynamically, with $\mu \sim O(\langle S \rangle)$.

Models with additional U(1)′ groups extend the spectrum of MSSM minimally: in addition to the right-handed neutrino and Higgs field S, they predict the existence of an additional neutral gauge boson Z′. The physics of Z′ bosons has been extensively studied in the literature, in models without supersymmetry [1], or with [2]. The additional neutral gauge bosons have received significant attention from the experimentalist, and have been searched for extensively at the LHC. Mass limits of 4 TeV or above, depending of the particular U(1)′ scenario chosen, have hindered extensive analyses of their implications for phenomenology, as the prospects of observing them at the LHC are not promising. Even less analyses exist for Z′ bosons in supersymmetric U(1)′ models. There the mass of the Z′ boson is proportional to the VEV of the singlet Higgs boson S. Since this parameter also determines the scale of the chargino/neutralino sector, a heavy Z′ implies a heavy electroweakino sector, reducing further the interest in such models at the LHC. To avoid this relationship, we work in a secluded scenario, where the scalar sector of the U(1)′ model is augmented by three additional singlet scalars, whose role is to decouple the mass of the Z′ to the scale of chargino and neutralino masses. Thus in this model, one can still preserve a large Z′ mass while allowing for light charginos/neutralinos, and in particular, for a light dark matter candidate, which is the lightest supersymmetric particle (LSP).

The scope of this paper is indeed the investigation of the phenomenology of Z′ bosons at the LHC, assuming that they are heavy, and that they can decay into both SM and supersymmetric particles. We will examine the supersymmetric decay channels of the Z′ boson, including decays to neutralinos, charginos and sleptons which are normally neglected.

2. The secluded $U(1)'$ model

The model is based on the gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1) \otimes U(1)'$, which breaks to the SM/MSSM $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. The additional Abelian group, introduces, in addition to the MSSM superfields, three right-handed neutrino superfields $\hat{N}_i^c$ and four scalar singlets $\hat{S}$, $\hat{S}_1$, $\hat{S}_2$ and $\hat{S}_3$ and an additional neutral gauge boson and gaugino. While only one scalar field S is needed to break the symmetry, three additional singlets S_1, S_2 and S_3 (the secluded sector) are introduced to split the mass scale of the additional gauge boson from that of electroweakinos. Unfortunately, anomaly cancelation requires the presence of additional superfields with exotic quantum numbers, which are assumed to be heavy and decoupled form the rest of the spectrum. The superpotential in this model including the exotic fields is given by

$$\begin{aligned}\widehat{W} &= h_u\widehat{Q}\cdot\widehat{H}_u\widehat{U}+h_d\widehat{Q}\cdot\widehat{H}_d\widehat{D}+h_e\widehat{L}\cdot\widehat{H}_d\widehat{E}+h_s\widehat{S}\widehat{H}_u\cdot\widehat{H}_d+\frac{1}{M_R}\widehat{S}_1\widehat{L}\cdot\widehat{H}_u\mathbf{h}_\nu\widehat{N}+\bar{h}_s\widehat{S}_1\widehat{S}_2\widehat{S}_3\\ &+ \sum_{i=1}^{n_Q} h_Q^i\widehat{S}\widehat{\mathcal{Q}}_i\widehat{\overline{\mathcal{Q}}}_i+\sum_{j=1}^{n_{\mathcal{L}}} h_L^j\widehat{S}\widehat{\mathcal{L}}_j\widehat{\overline{\mathcal{L}}}_j, \end{aligned} \tag{1}$$

where the fields $\mathcal{Q}$, $\mathcal{L}$ are the exotic fermions, M_R is a large mass scale and h_ν is the Yukawa coupling responsible for generating neutrino masses.

Through spontaneous breakdown of the group $SU(2)_L\otimes U(1)\otimes U(1)'$ to $U(1)_{\rm em}$ the Higgs acquire the VEVs

$$\langle H_u\rangle=\frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_u\end{pmatrix},\quad \langle H_d\rangle=\frac{1}{\sqrt{2}}\begin{pmatrix}v_d\\ 0\end{pmatrix},\quad \langle S\rangle=\frac{v_s}{\sqrt{2}},\quad \langle S_i\rangle=\frac{v_{s_i}}{\sqrt{2}} \tag{2}$$

Here the first two VEVs are required to break the SM, and the next to break $U(1)'$. After breaking, one massless state (the photon) and two massive states (the Z, Z' bosons) arise as orthonormal combinations of W^3_μ, B'_μ and B_μ gauge bosons. The W^1_μ and W^2_μ combine to form $W^\pm_\mu$, as the only charged vector bosons in the model. Unlike in the MSSM, the Z boson is not a physical state by itself but mixes with the Z' boson. This mass mixing arises from the fact that the Higgs doublets $H_{u,d}$ are charged under each factor of $SU(2)_L\otimes U(1)_Y\otimes U(1)'$, and the associated mass-squared matrix is given by

$$M^2_{ZZ'}=\begin{pmatrix}M_Z^2 & \Delta^2\\ \Delta^2 & M^2_{Z'}\end{pmatrix}, \tag{3}$$

in the $\left(Z_\mu, Z'_\mu\right)$ basis, where the matrix elements are

$$\begin{aligned} M_Z^2 &= \frac{1}{4}g_Z^2\left(v_u^2+v_d^2\right),\\ M^2_{Z'} &= {g'_1}^2\left({Q'_{H_u}}^2v_u^2+{Q'_{H_d}}^2v_d^2+{Q'_S}^2v_s^2+\sum_{i=1}^{3}{Q'_{S_i}}^2v_{s_i}^2\right),\\ \Delta^2 &= \frac{1}{2}g_Zg'_1\left(Q'_{H_u}v_u^2-Q'_{H_d}v_d^2\right), \end{aligned} \tag{4}$$

where $g_Z^2=g_2^2+g_Y^2$. The physical neutral vector bosons, $Z_{1,2}$, are obtained by diagonalizing $M^2_{ZZ'}$:

$$\begin{pmatrix}Z_1\\ Z_2\end{pmatrix}=\begin{pmatrix}\cos\theta_{ZZ'} & \sin\theta_{ZZ'}\\ -\sin\theta_{ZZ'} & \cos\theta_{ZZ'}\end{pmatrix}\begin{pmatrix}Z\\ Z'\end{pmatrix}, \tag{5}$$

and

$$M^2_{Z_{1,2}}=\frac{1}{2}\left[M^2_{Z'}+M^2_Z\mp\sqrt{\left(M^2_{Z'}-M^2_Z\right)^2+4\Delta^4}\right], \tag{6}$$

are their masses-squared eigenstates.

3. Numerical analysis

We now proceed to the main analysis in this work, looking at the consequences of a heavy neutral gauge boson at the collider. As we shall see, and found before, Z' bosons satisfying all collider, cosmological and low energy constraints, do not offer promising prospects for observability at the present LHC, even operating at 3 ab^{-1}. Thus, we will analyze the prospects of observing a signal at the HE-LHC, operating at 27 and 100 TeV as well [3]. As the parameter space is large, choosing realistic benchmarks is a more transparent method to show physics results than a scan. The three benchmark points, and some parameters associated with them, are given in Table 1.

Parameters	BP1	BP2	BP3
g_1'	0.2	0.12	0.15
$\tan\beta$	1.345	1.198	1.175
Q_Q'	0.6	0.1	-0.81
$\mu_{\rm eff}$	260	280	250
$(h_\nu,\ h_s,\ \bar{h}_s)$	(1.0, 0.739, 0.1)	(1.0, 0.7235, 0.1)	(1.0, 0.724, 0.1)
$(v_{s_1},\ v_{s_2},\ v_{s_3})$	(8675, 8650, 8675)	(6675, 15600, 14675)	(12100, 14550, 14500)

Table 1: The parameters characterizing benchmarks BP1, BP2 and BP3 for the secluded $U(1)'$ model. The values of dimensionful parameters are given in GeV.

For each benchmark scenario, the mass spectra for the supersymmetric partners obtained are given in Table 2.

Masses	BP1	BP2	BP3
$m_{Z'}$	4250	4069	5195
$m_{\tilde{\chi}_i^0,\ i=1,\dots,5}$	$(51, 167, 262, 312, 613)$	$(48, 269, 328, 762, 763)$	$(52, 195, 264, 303, 360)$
$(m_{\tilde{\chi}_1^\pm},\ m_{\tilde{\chi}_2^\pm})$	$(256, 2004)$	$(267, 763)$	$(192, 359)$
$(m_{\tilde{e}_L},\ m_{\tilde{\mu}_L},\ m_{\tilde{\tau}_1})$	$(503, 503, 457)$	503	$(1412, 1412, 473)$
$(m_{\tilde{e}_R},\ m_{\tilde{\mu}_R},\ m_{\tilde{\tau}_2})$	$(457, 457, 503)$	1850	$(473, 473, 1412)$
$(m_{\tilde{\nu}_e},\ m_{\tilde{\nu}_\mu},\ m_{\tilde{\nu}_\tau})$	501	501	1412
$(m_{\tilde{\nu}_{eR}},\ m_{\tilde{\nu}_{\mu R}},\ m_{\tilde{\nu}_{\tau R}})$	553	3472	645

Table 2: The mass spectra (in GeV) for the supersymmetric sector of the benchmark points given in Table 1 for the Secluded $U(1)'$.

We concentrate on leptonic final states, considered as golden channels from in LHC experimental searches. To exploit these features, this study will be focused on the decays of the Z' boson into supersymmetric particles, leading to final states with leptons and missing energy. In the following, we present a study of Z' decays into leptonic final states for a given set of the secluded sector $U(1)'$ model parameters, dividing our analysis into $2\ell + \not{E}_T$, $4\ell + \not{E}_T$ and $6\ell + \not{E}_T$ signals.

PoS(EPS-HEP2021)674

Two lepton Signal: $2\ell + \not{E}_T$

The main decay modes of Z' giving rise to dilepton final states are: $Z' \to \tilde{\nu}_{\ell_R}\tilde{\nu}_{\ell_R}/\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0\tilde{\chi}_3^0/\tilde{\ell}_R\tilde{\ell}_R \to 2\ell + \not{E}_T$. In the following figures, we first plot the relevant kinematic variables signals and background at 14, 27 and 100 TeV, before any cuts were imposed.

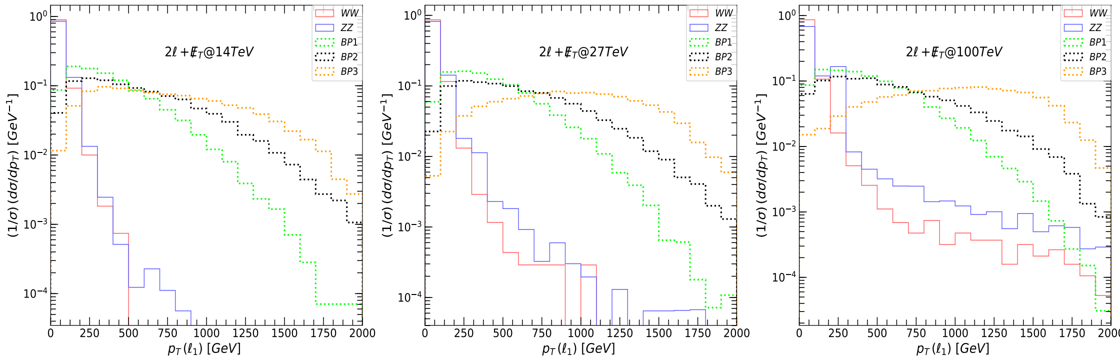

Figure 1: The transverse momentum p_T, for the leading lepton ℓ_1 for the signal and background in the $2\ell + \not{E}_T$ scenario. The main backgrounds are indicated in solid lines while the signals are plotted in dotted lines.

We show, in Fig. 1, the leading lepton transverse momentum. These graphs show clearly that at large $p_T(\ell_1)$, the signal dominates the background. We also calculate the signal significance σ_A for each benchmark, at proposed total integrated luminosity: for 14 TeV at $\mathcal{L} = 3$ ab^{-1}, for 27 TeV at $\mathcal{L} = 15$ ab^{-1} and for 100 TeV at $\mathcal{L} = 30$ ab^{-1}. While BP3 appears to be most promising, the significance for all benchmarks at 14 TeV is very low ($<1.5\sigma$), dispelling any hope for observing the Z' boson in the $2\ell + \not{E}_T$ final state.

Four lepton Signal: $4\ell + \not{E}_T$

The main decay modes of the Z' boson yielding $4\ell + \not{E}_T$ signals are: $Z' \to \tilde{\nu}_{\ell_R}\tilde{\nu}_{\ell_R}/\tilde{\ell}_R\tilde{\ell}_R \to 4\ell + \not{E}_T$. We show, in Fig. 2, the leading lepton transverse momentum, before any cuts were imposed.

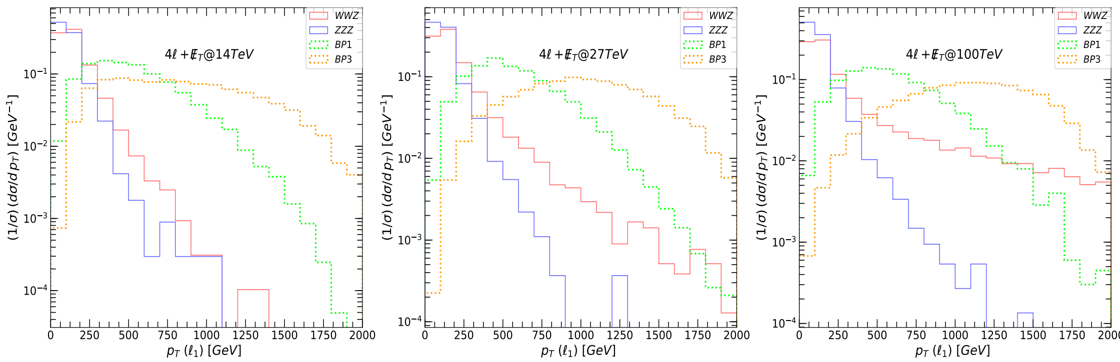

Figure 2: The transverse momentum p_T, for the leading lepton ℓ_1 for the signal and background in the $4\ell + \not{E}_T$ scenario. The main backgrounds are indicated in solid lines while the signals are plotted in dotted lines.

In all the plots, the signal from BP3 is most promising, particularly at high energy/momenta. We calculate the signal significance for each benchmark. Again, the significance for all benchmarks at 14 TeV for observing the Z' boson in the $4\ell + \not{E}_T$ final state is low. However, at 27 TeV both BP1 and BP3 show some promise, and we obtain large significances of 3σ or more for σ_A. At 100 TeV, though there are many uncertainties and unknowns, and our results should be interpreted as estimates only, both BP1 and BP3 show significant promise for observability.

Six lepton Signal: $6\ell + \not{E}_T$

The dominant decay mode of the Z' gauge boson, yielding a $6\ell + \not{E}_T$ signal is: $Z' \to \tilde{\ell}_R \tilde{\ell}_R \to 6\ell + \not{E}_T$. In Fig. 3 we plot transverse momentum p_T for the leading lepton ℓ_1.

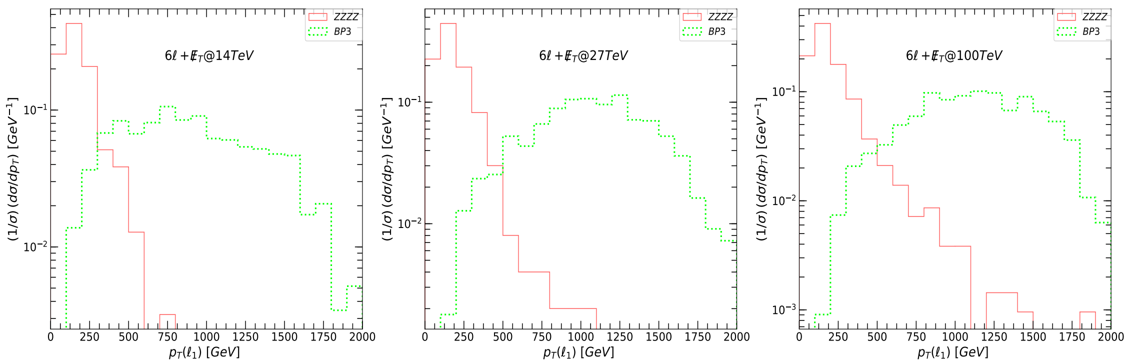

Figure 3: The transverse momentum p_T, for the leading lepton ℓ_1 for the signal and background in the $6\ell + \not{E}_T$ scenario. The main backgrounds are indicated in solid lines while the signals are plotted in dotted lines.

The main backgrounds (four-bosons) are indicated in solid lines while the dotted green line represent the signal BP3. As expected, the leading lepton p_T distribution is most promising in distinguishing this signal from background, with other lepton p_T distributions slightly less so. The signal significance can be around 3σ at 27 TeV and even greater than 8σ at 100 TeV.

Our analysis shows that the probability of observing Z' through supersymmetric decays at 14 TeV is not good, even at high total integrated luminosity $\mathcal{L} = 3$ ab^{-1}. Our findings indicate that HE/HL-LHC and FCC-hh can be promising grounds for observing consequences of both supersymmetry and extended gauge symmetry, of which an additional neutral gauge boson is one of the simplest examples.

References

[1] P. Langacker, *The Physics of Heavy Z' Gauge Bosons*, *Rev. Mod. Phys.* **81** 1199 (2009) [hep-ph/0801.1345].

[2] D. A. Demir, *Two Higgs doublet models from TeV scale supersymmetric extra U(1) models*, *Phys. Rev. D* **59**, 015002 (1999) [hep-ph/9809358].

[3] M. Frank, L. Selbuz and I. Turan, *Heavy Z' bosons in the secluded $U(1)'$ model at hadron colliders*, *Eur. Phys. J. C* **81** 466 (2021) [arXiv:2007.00676 [hep-ph]].

PoS(EPS-HEP2021)674