Z' bosons at the LHC in a modified MSSM

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I study the production of heavy neutral gauge bosons Z' at the LHC in U(1)$'$ models, inspired by Grand Unification Theories, as well as in the Sequential Standard Model, accounting for possible decays into supersymmetric channels. I shall consider the MSSM and present results on branching ratios and event rates with sparticle production at the LHC, taking particular care about final states with charged leptons and missing energy.

Heavy neutral bosons Z' are predicted in U(1)$'$ gauge groups, inspired by Grand Unification Theories (GUTs), and in the Sequential Standard Model (SSM), wherein the Z' has the same coupling to fermions and gauge bosons as the Z in the Standard Model (SM) (see, e.g., the reviews in Refs. [1, 2]). From the experimental viewpoint, searches for Z' bosons have been performed at the Tevatron [3] and at the LHC [4]. The latest LHC analyses excluded a U(1)$'$-based Z' with mass below 2.32 TeV (CMS) and 2.21 TeV (ATLAS), whereas the lower mass limits for the SSM Z' are currently about 1.49-1.69 TeV (CMS) and 1.77-1.96 TeV (ATLAS). Such results crucially rely on the assumption that the new neutral gauge bosons only decay into Standard Model final states. In this talk, following the lines of [5], I wish to investigate the possibility that the Z' can decay according to modes Beyond the Standard Model (BSM). In particular, I will consider supersymmetry and the Minimal Supersymmetric Standard Model, extending the work carried out in [6] by varying the Z' mass and scanning thoroughly the U(1)$'$ and MSSM parameter space. With respect to Refs. [7, 8], which also studied Z' decays in supersymmetry, the so-called D-term correction, due to the extra U(1)$'$ group, is added to the sfermion masses and the supersymmetric particle masses are not treated as free parameters, but they are obtained diagonalizing the corresponding mass matrices. If the branching ratios into BSM modes were to be relevant, one may have to reconsider the current exclusion limits on the Z' boson. From the point of view of supersymmetry, the production of charged-slepton or chargino pairs in Z' decays has the advantage, with respect to other production channels, that the Z' mass sets a kinematic constrain on the final-state invariant mass.

The U(1)$'$ models originate from the breaking of a rank-6 GUT group E_6 according to $E_6 \to SO(10) \times U(1)'_\psi$, followed by $SO(10) \to SU(5) \times U(1)'_\chi$. The heavy neutral bosons associated with $U(1)'_\psi$ and $U(1)'_\chi$ are thus named Z'_ψ and Z'_χ, respectively, whereas a generic Z' boson is a combination of Z'_ψ and Z'_χ, with a mixing angle θ:

$$Z'(\theta) = Z'_\psi \cos\theta - Z'_\chi \sin\theta. \tag{1}$$

Following [5], the models and the Z' bosons which will be investigated are listed in Table 1. The model Z'_η comes from the breaking of the GUT group in the SM, i.e. $E_6 \to SM \times U(1)'_\eta$; the Z'_S is present in the secluded model, wherein the SM is extended by means

of a singlet field S; the $Z'_{\rm N}$ is equivalent to the Z'_χ model, but with the 'unconventional' assignment of SM, MSSM and exotic fields in the SU(5) representations, as debated in [9]. When studying supersymmetric contributions to Z' decays, it is necessary to modify the particle content of the MSSM. First, besides the MSSM Higgs doublets, one needs an extra scalar Higgs boson to break the U(1)$'$ gauge symmetry and give mass to the Z'. After symmetry breaking, one is left with two charged Higgs bosons $H^\pm$, one neutral CP-odd A and three neutral CP-even, i.e. h and H, already present in the MSSM, and a novel H'. In the gaugino sector, two new neutralinos are to be included, for a total of six, corresponding to the supersymmetric partners of the Z' and of the extra Higgs. However, as pointed out in [5], the novel Higgs and neutralinos are typically too heavy to contribute to Z' phenomenology.

Model	θ
Z'_ψ	0
Z'_χ	$-\pi/2$
Z'_η	$\arccos\sqrt{5/8}$
$Z'_{\rm S}$	$\arctan(\sqrt{15}/9)-\pi/2$
$Z'_{\rm I}$	$\arccos\sqrt{5/8}-\pi/2$
$Z'_{\rm N}$	$\arctan\sqrt{15}-\pi/2$

Table 1: Z' bosons in the U(1)$'$ models along with the mixing angles.

In the extended MSSM, besides the SM modes, one has to consider Z' decays into slepton, squark, chargino, neutralino and Higgs pairs, as well as final states with Higgs bosons associated with a W or a Z. As in [5], I shall pay special attention to supersymmetric decays yielding charged leptons, as they are the golden channel for the experimental searches. Final states with two charged leptons and missing energy may come from primary decays into charged sleptons $Z' \to \tilde{\ell}^+\tilde{\ell}^-$, with the sleptons decaying according to $\tilde{\ell}^\pm \to \ell^\pm\tilde{\chi}^0$, with $\tilde{\chi}^0$ being a neutralino, or from primary decays into charginos $Z' \to \tilde{\chi}_2^+\tilde{\chi}_2^-$, followed by $\tilde{\chi}_2^\pm \to \ell^\pm\tilde{\chi}_1^0$. A decay chain, leading to four leptons and missing energy, is also yielded by decays into neutralinos $Z' \to \tilde{\chi}_2^0\chi_2^0$, with subsequent $\tilde{\chi}_2^0 \to \ell^\pm\tilde{\ell}^\mp$ and $\tilde{\ell}^\pm \to \ell^\pm\tilde{\chi}_1^0$. Finally, the decay into sneutrino pairs, such as $Z' \to \tilde{\nu}_2\tilde{\nu}_2^*$, followed by $\tilde{\nu}_2 \to \tilde{\chi}_2^0\nu$ and $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$, with an intermediate charged slepton, gives four charged leptons and missing energy, due to both neutrinos and neutralinos.

Following [5], I explore the Z' branching ratios by varying the Z' and slepton masses, while fixing the other parameters to the following 'Reference Point':

$$\begin{aligned} &\mu = 200\ ,\ \tan\beta = 20\ ,\ A_q = A_\ell = A_f = 500\ \text{GeV}\ , \\ &m_{\tilde{q}}^0 = 5\ \text{TeV}\ ,\ M_1 = 150\ \text{GeV}\ ,\ M_2 = 300\ \text{GeV}\ ,\ M' = 1\ \text{TeV}. \end{aligned} \tag{2}$$

In Eq. (2), μ is the parameter contained in the Higgs superpotential, $\tan\beta = v_2/v_1$ is the ratio of the vacuum expectation values of the two MSSM Higgs doublets, A_f is the coupling of the Higgs with the fermions. Furthermore, $m_{\tilde{q}}^0$ is the squark mass, assumed to be the same for all flavours at the Z' scale, before the addition of the D-term, M_1, M_2 and M' are the soft masses of the gauginos $\tilde{B}$, $\tilde{W}_3$ and $\tilde{B}'$. As for the U(1)$'$ coupling g', we shall adopt the GUT-driven convention that it is proportional to the coupling constant g_1 of U(1) via $g' = \sqrt{5/3}g_1$. In the Sequential Standard Model, the coupling of the $Z'_{\rm SSM}$ to sfermions is instead the same as in the SM, i.e. $g_{\rm SSM} = g_2/(2\cos\theta_W)$, where g_2 is the SU(2) coupling and θ_W the Weinberg angle.

An extensive analysis for all the models quoted in Table 1 has been carried out in [5]: here I just report the branching ratios for the GUT-inspired model Z'_ψ (Table 2) and for the $Z'_{\rm SSM}$ (Table 3), since they are the ones yielding the highest rates into supersymmetric channels. The branching ratios are listed for 1 TeV$< m_{Z'} <$5 TeV and for the values of $m_{\tilde{\ell}}^0$ which minimize and maximize the slepton rate, with $m_{\tilde{\ell}}^0$ being the slepton mass, assumed to be the same for all

$m_{Z'}$	$m^0_{\tilde{\ell}}$	$\mathrm{BR}_{q\bar{q}}$	$\mathrm{BR}_{\ell\ell}$	$\mathrm{BR}_{\nu\bar{\nu}}$	BR_{WW}	BR_{Zh}	$\mathrm{BR}_{\tilde{\chi}^+\tilde{\chi}^-}$	$\mathrm{BR}_{\tilde{\chi}^0\tilde{\chi}^0}$	$\mathrm{BR}_{\tilde{\nu}\tilde{\nu}^*}$	$\mathrm{BR}_{\tilde{\ell}\tilde{\ell}}$	$\mathrm{BR}_{\mathrm{BSM}}$
1.0	0.4	48.16	8.26	8.26	3.00	2.89	9.13	16.53	1.91	1.90	35.31
1.0	0.7	50.07	8.59	8.59	3.08	2.99	9.49	17.18	0.00	0.00	32.75
1.5	0.6	46.78	7.90	7.90	2.71	2.69	9.73	18.64	1.83	1.83	37.43
1.5	1.0	48.55	8.20	8.20	2.81	2.79	10.10	19.35	0.00	0.00	35.05
2.0	0.8	46.30	7.77	7.77	2.62	2.62	9.92	19.37	1.80	1.80	38.15
2.0	1.3	48.03	8.06	8.06	2.72	2.72	10.29	20.10	0.00	0.00	35.84
2.5	1.0	46.01	7.70	7.70	2.58	2.59	9.99	19.68	1.79	1.78	38.58
2.5	1.6	47.72	7.99	7.99	2.67	2.68	10.36	20.41	0.00	0.00	36.30
3.0	1.1	45.35	7.58	7.58	2.53	2.54	9.92	19.63	1.86	1.86	39.49
3.0	1.9	47.10	7.88	7.88	2.62	2.64	10.30	20.39	0.00	0.00	37.15
3.5	1.3	44.91	7.50	7.50	2.49	2.51	9.86	19.58	1.83	1.83	40.08
3.5	2.2	46.61	7.79	7.79	2.59	2.61	10.24	20.32	0.00	0.00	37.81
4.0	1.5	44.60	7.45	7.45	2.47	2.49	9.82	19.53	1.80	1.80	40.51
4.0	2.5	46.26	7.72	7.72	2.56	2.58	10.19	20.26	0.00	0.00	38.29
4.5	1.6	44.32	7.40	7.40	2.45	2.47	9.78	19.47	1.84	1.84	40.89
4.5	2.8	46.01	7.68	7.68	2.54	2.57	10.15	20.21	0.00	0.00	38.63
5.0	1.8	44.16	7.37	7.37	2.44	2.46	9.76	19.44	1.82	1.82	41.11
5.0	3.1	45.83	7.65	7.65	2.53	2.55	10.13	20.18	0.00	0.00	38.88

Table 2: Z'_ψ branching ratios for a few values of Z' and slepton masses, expressed in TeV. $\mathrm{BR}_{\mathrm{BSM}}$ is the total decay rate in BSM channels.

flavours, before the D-term addition. In the Z'_ψ case, both SM and BSM branching fractions are reported; for the SSM, only the BSM channels are quoted. From such tables, one can learn that, in the Z'_ψ scenario, the BSM modes account for about 35-40% of the total width, whereas in the SSM they can be up to 60-65%. In both cases, the dominant BSM contributions are the ones into neutralinos and charginos, whereas the slepton modes, i.e. charged sleptons or sneutrinos, can reach 4% for the Z'_ψ and 5-6% for the Z'_{SSM}. Ref. [5] also presents the branching ratios as a function of $m^0_{\tilde{\ell}}$: as expected, the slepton rates rapidly decrease as $m^0_{\tilde{\ell}}$ increases. Such spectra are not shown here for the sake of brevity.

Before concluding, in Table 4 I present the expected number of events with supersymmetric cascades (N_{casc}), i.e. production of neutralinos, charginos or sleptons, and the charged-slepton rates (N_{slep}), in the high-luminosity phase of the LHC, i.e. $\mathcal{L} = 100$ fb^{-1}, and at the centre-of-mass energy $\sqrt{s} = 14$ TeV. The parameters are fixed to the Reference Point (2), whereas the Z' is set either to 1.5 or to 2 TeV and $m^0_{\tilde{\ell}}$ to the value maximizing the slepton rate. The numbers in Table 4 are obtained in the narrow-width approximation and calculating the $pp \to Z'$ cross section at leading order, as in [5]. One finds that the cascade events can be up to $\mathcal{O}(10^5)$ and the charged sleptons up to $\mathcal{O}(10^4)$: the highest rate of production of supersymmetric particles occurs in the SSM, but even the U(1)$'$ models yield meaningful sparticle production.

In summary, I reviewed the main issues discussed in Ref. [5] and presented some results on Z' decays in the MSSM, extended by means of an extra GUT-inspired U(1)$'$ group, as well as in the SSM. In order to reconsider the Z' exclusion limits or draw a conclusive statement on the feasibility to discover supersymmetry in Z' decays at the LHC, however, it will be compulsory implementing this modelling in the framework of a Monte Carlo generator. This is in progress.

$m_{Z'}$	$m^0_{\tilde{\ell}}$	$\mathrm{BR}_{H^+H^-}$	BR_{Zh}	B_{hA}	$\mathrm{BR}_{\tilde{\chi}^+\tilde{\chi}^-}$	$\mathrm{BR}_{\tilde{\chi}^0\tilde{\chi}^0}$	$\mathrm{BR}_{\tilde{\ell}\tilde{\ell}}$	$\mathrm{BR}_{\tilde{\nu}\tilde{\nu}^*}$	$\mathrm{BR}_{\mathrm{BSM}}$
1.0	0.10	0.00	$\sim 10^{-6}$	0.00	18.31	29.30	1.89	3.77	53.27
1.0	0.50	0.00	$\sim 10^{-6}$	0.00	19.41	31.06	0.00	0.00	50.47
1.5	0.10	0.00	0.87	0.76	17.84	32.52	1.75	3.48	57.21
1.5	0.75	0.00	0.92	0.80	18.82	34.31	0.00	0.00	54.55
2.0	0.10	0.00	1.93	1.85	17.37	33.01	1.67	3.33	59.17
2.0	1.00	0.00	2.04	1.95	18.28	34.75	0.00	0.00	57.02
2.5	0.10	0.91	2.59	2.53	16.93	32.78	1.62	3.22	60.58
2.5	1.25	0.95	2.72	2.66	17.79	34.45	0.00	0.00	58.57
3.0	0.10	1.72	2.98	2.94	16.62	32.51	1.58	3.15	61.49
3.0	1.50	1.81	3.13	3.08	17.44	34.12	0.00	0.00	59.58
3.5	0.10	2.27	3.23	3.20	16.42	32.30	1.56	3.10	62.08
3.5	1.75	2.38	3.38	3.35	17.22	33.88	0.00	0.00	60.22
4.0	0.10	2.65	3.39	3.37	16.28	32.16	1.54	3.07	62.46
4.0	2.00	2.78	3.56	3.53	17.07	33.71	0.00	0.00	60.65
4.5	0.10	2.91	3.51	3.49	16.19	32.06	1.53	3.05	62.73
4.5	2.25	3.05	3.67	3.65	16.96	33.59	0.00	0.00	60.94
5.0	0.10	3.11	3.59	3.57	16.12	31.98	1.52	3.03	62.93
5.0	2.50	3.26	3.76	3.74	16.89	33.51	0.00	0.00	61.16

Table 3: As in Table 2, but for the Sequential Standard Model, including only the BSM modes.

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Model	$m_{Z'}$	$\mathrm{N}_{\mathrm{casc}}$	$\mathrm{N}_{\mathrm{slep}}$
Z'_η	1.5	13650	–
Z'_η	2.0	2344	–
Z'_ψ	1.5	10241	622
Z'_ψ	2.0	2784	162
Z'_{N}	1.5	9979	414
Z'_{N}	2.0	2705	104
Z'_{I}	1.5	8507	–
Z'_{I}	2.0	2230	–
Z'_{S}	1.5	8242	65
Z'_{S}	2.0	2146	16
Z'_{SSM}	1.5	775715	24774
Z'_{SSM}	2	19570	606

Table 4: Rates of supersymmetric cascades and charged sleptons at the LHC for an integrated luminosity of 100 fb^{-1} and a centre-of-mass energy of 14 TeV. The Z' mass is given in TeV.