

## Searching for supersymmetry in $Z'$ decays

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**Abstract.** I investigate production and decay of heavy neutral gauge bosons  $Z'$  in GUT-inspired  $U(1)'$  groups and in the Sequential Standard Model. In particular, decays into supersymmetric particles, such as slepton, chargino and neutralino pairs, as predicted in the MSSM, are accounted for, with a special interest in final states with leptons and missing energy. For a representative point of the parameter space, it is found that the inclusion of supersymmetric decay modes has an impact of 200-300 GeV on the  $Z'$  mass exclusion limits.

### 1 Introduction

Searching for heavy neutral gauge bosons  $Z'$  is one of the main goals of the LHC experiments; in fact, these bosons are particularly interesting since they are predicted by gauge models based on a  $U(1)'$  symmetry, arising in the framework of Grand Unification Theories (GUTs) [1, 2]. The Sequential Standard Model (SSM), the simplest extension of the Standard Model (SM), also contains extra heavy neutral bosons, i.e.  $Z'$  and  $W'$ , with the same couplings to fermions and bosons as the standard  $Z$  and  $W$ . The ATLAS and CMS collaborations have searched for a  $Z'$  at the LHC by looking at high-mass electron or muon pairs: in detail, with an integrated luminosity of  $20 \text{ fb}^{-1}$ , CMS set limits  $m_{Z'} > 2.96 \text{ TeV}$  and  $m_{Z'} > 2.60 \text{ TeV}$  on the mass of SSM and GUT-inherited  $Z'$  bosons [3], respectively, whereas the corresponding ATLAS limits are 2.86 TeV (SSM) and in the range 2.38-2.54 TeV ( $U(1)'$  models) [4]. However, such analyses completely rely on Standard Model  $Z'$  decays: allowing supersymmetric modes will substantially modify the search strategies and the mass exclusion limits.

In fact, several reasons makes it compelling and interesting investigating possible  $Z'$  decays beyond the Standard Model (BSM). Referring, for simplicity, to the Minimal Supersymmetric Standard Model (MSSM), possible  $Z'$  decays into pairs of the lightest neutralinos can lead to monojet or monophoton final states, which are used to look for Dark Matter candidates. From the point of view of supersymmetry,  $Z'$  decays yield a cleaner signal with respect to direct sparticle production in  $pp$  collisions, since, in events like  $Z' \rightarrow \tilde{\ell}^+ \tilde{\ell}^-, \tilde{\chi}_i^+ \tilde{\chi}_j^-, \dots, \tilde{\ell}^\pm$  and  $\tilde{\chi}_{i,j}^\pm$  being sleptons and charginos, the  $Z'$  mass gives a further kinematic constrain on the invariant mass of the supersymmetric pair. Furthermore, supersymmetric contributions to  $Z'$  decays decrease the SM branching ratios and the number of expected high-mass dimuons and dielectrons, and therefore

the exclusion limits on the  $Z'$  mass, will have to be revisited. Ideally, if for a given scenario the BSM branching ratios had to be comparable or even larger than the SM ones, one could even argue that such decay channels may have hidden the  $Z'$  in the searches carried out so far.

In this talk I will present a recent study [5] on supersymmetric contributions to  $Z'$  decays, discussing the impact which they may have on the present searches and mass exclusion limits. This investigation updates the pioneering work of Ref. [6] and improves Refs. [7, 8] by consistently including the so-called D-term correction, due to the extra  $U(1)'$  group, to the sfermion masses.

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

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

The  $Z'$  bosons and the  $\theta$  values which will be investigated are listed in Table 1. The  $Z'_\eta$  model comes from the direct breaking of the GUT group in the SM, i.e.  $E_6 \rightarrow SM \times U(1)'_\eta$ ; the  $Z'_S$  is predicted in the secluded model, wherein the SM is extended by means of a singlet field  $S$ ; the  $Z'_N$  is instead equivalent to the  $Z'_\chi$ , but with the ‘unconventional’ assignment of SM, MSSM and exotic fields in the  $SU(5)$  representations [9]. Because of the  $Z'$ , the MSSM spectrum gets somewhat modified: two extra neutralinos are present, for a total of six neutralinos ( $\tilde{\chi}_1^0, \dots, \tilde{\chi}_6^0$ ), and a novel neutral scalar Higgs, named  $H'$  in [5], must be included to give mass to the  $Z'$ . Although, for the sake of consistency, such new particles are to be taken into account in any phenomenological analysis, for reasonable choices of the points in the parameter space, they are too heavy to contribute to the  $Z'$  width and can be safely neglected [5].

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**Table 1.**  $Z'$  bosons in U(1)' gauge models

Model	$\theta$
$Z'_\psi$	0
$Z'_\chi$	$-\pi/2$
$Z'_\eta$	$\arccos \sqrt{5/8}$
$Z'_S$	$\arctan(\sqrt{15/9}) - \pi/2$
$Z'_1$	$\arccos \sqrt{5/8} - \pi/2$
$Z'_N$	$\arctan \sqrt{15} - \pi/2$

In the MSSM, the  $Z'$  can decay into slepton, squark, chargino, neutralino and Higgs pairs, as well as into final states with Higgs bosons associated with a  $W$  or a  $Z$ . Among these modes, the most interesting ones are those leading to leptonic final states via supersymmetric particles. For example, decays into charged sleptons  $Z' \rightarrow \tilde{\ell}^+ \tilde{\ell}^-$ , with the sleptons decaying according to  $\tilde{\ell}^\pm \rightarrow \ell^\pm \tilde{\chi}_1^0$ , or chargino modes like  $Z' \rightarrow \tilde{\chi}_2^+ \tilde{\chi}_2^-$ , followed by  $\tilde{\chi}_2^\pm \rightarrow \ell^\pm \tilde{\chi}_1^0$ , yield final states with two charged leptons and missing energy (neutralinos). Four leptons and missing energy are instead given by the decay chain  $Z' \rightarrow \tilde{\chi}_2^0 \tilde{\nu}_2^0$ , with subsequent  $\tilde{\chi}_2^0 \rightarrow \ell^\pm \tilde{\ell}^\mp$  and  $\tilde{\ell}^\pm \rightarrow \ell^\pm \tilde{\chi}_1^0$ . Sneutrino-pair production, i.e.  $Z' \rightarrow \tilde{\nu}_2 \tilde{\nu}_2^*$ , followed by  $\tilde{\nu}_2 \rightarrow \tilde{\chi}_2^0 \nu$  and  $\tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$ , with an intermediate charged slepton, leads to four charged leptons and missing energy (neutrinos and neutralinos) as well.

The choice of the point in the parameter space to carry out this analysis is crucial. In fact, this must be done in such a way to obtain a supersymmetric spectrum which has not been excluded yet by the searches at the LHC. Moreover, the lightest Higgs of the MSSM, which roughly plays the role of the Standard Model one, has to have a mass about 125-126 GeV, consistent with the recent discovery of a Higgs-like particle at the LHC [10]. Finally, for this investigation to be meaningful, the branching fraction of the  $Z'$  into BSM final states has to be large enough to motivate searches of the  $Z'$  within supersymmetry and claims that the  $Z'$  has not been discovered yet since its decay ratios into electron and muon pairs are substantially lower than what the Standard Model predicts.

Following [5], the following reference point can be chosen:

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

In Eq. (2) the standard MSSM notation is adopted:  $\mu$  is the parameter in the Higgs superpotential,  $\tan\beta = v_2/v_1$  is the ratio of the vacuum expectation values of the two MSSM Higgs doublets,  $A_q$  and  $A_\ell$  are the couplings of the Higgs with quarks and leptons. 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 in [5],  $m_{\tilde{\ell}}^0$ , the slepton mass before the D-term contribution, is not fixed, but it is just set to the same value for all selectrons, smuons, staus and sneutrinos, and tuned to maximize the  $Z' \rightarrow \tilde{\ell}^+ \tilde{\ell}^-$  branching fraction in each model. As for the couplings, the U(1)' and U(1) ones are taken to be proportional through  $g' = \sqrt{5/3} g_1$ , as occurs in GUTs. In the Sequential Standard Model, the coupling of the  $Z'_{SSM}$  to the fermions is the same as in the SM, i.e.  $g_{SSM} = g_2/(2 \cos \theta_W)$ , where  $g_2$  is the SU(2) coupling and  $\theta_W$  the Weinberg angle. The partial widths of the  $Z'$  into all decay channels can be found in [6]. As for the  $Z'_{SSM}$ , one assumes that its couplings to the supersymmetric particles are the same as those of the Standard Model  $Z$  boson.

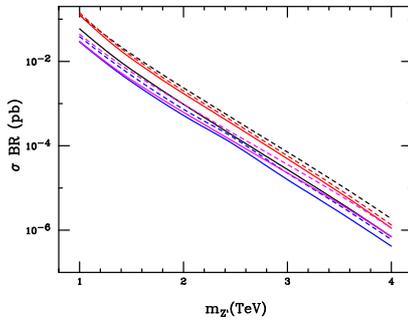
In the reference point (2), as presented in [5], the total branching ratio into BSM channels can be up to about 60% ( $Z'_{SSM}$ ), 40% ( $Z'_\psi$ ), 30% ( $Z'_\eta$  and  $Z'_N$ ), 20% ( $Z'_S$ ) and 15% ( $Z'_1$ ). Decays into charged-slepton pairs account for few percent, whereas a major role is played by final states with chargino and neutralino pairs, which can be up to 20% and 30% of the total  $Z'$  width. Also, in the model  $Z'_\eta$ , one has a non-negligible contribution of sneutrino production, which can be of the order of 10% [5].

To have an idea of the number of events with supersymmetric  $Z'$  decays at the LHC, in Table 2 I present the expected rate of supersymmetric cascades ( $N_{\text{casc}}$ ), i.e. the sum of events with neutralinos, charginos and sleptons, as well as the pure charged-slepton rates ( $N_{\text{slep}}$ ), at the LHC for an integrated luminosity  $\mathcal{L} = 20 \text{ fb}^{-1}$  and  $\sqrt{s} = 8 \text{ TeV}$ . All parameters are fixed to the reference point (2); the  $Z'$  mass is set to either 1.5 or 2 TeV, with  $m_{\tilde{\ell}}^0$  fixed to enhance the  $Z' \rightarrow \tilde{\ell}^+ \tilde{\ell}^-$  decay rate [5]. The numbers in Table 2 are obtained in the narrow-width approximation, with the  $pp \rightarrow Z'$  cross section computed using the leading-order CTEQ6L parton distribution functions. The  $Z'_\chi$  model is not taken into account, since, using the parametrization (2), it does not lead to a physical sfermion spectrum [5]. The cascade events can be  $\mathcal{O}(10^3)$  and the charged sleptons up a few dozens; the highest rate of supersymmetric particles occurs in the SSM, which enhances the  $Z'$  couplings and thus the production and decay rates, but even the U(1)' models yield meaningful sparticle production.

Before concluding, as in [11], since the experimental analyses search for high-mass dielectron and dimuon pairs, I present the results in terms of the product of the  $Z'$  production cross section ( $\sigma$ ) at the LHC ( $\sqrt{s} = 8 \text{ TeV}$ ) times the branching ratio (BR) into  $e^+ e^-$  and  $\mu^+ \mu^-$  pairs, with and without accounting for supersymmetric modes. In fact, the experimental exclusion limits are obtained by comparing data and theoretical predictions for the product  $\sigma \text{ BR}$ . Fig. 1 shows this product varying the  $Z'$  mass in the range  $1 \text{ TeV} < m_{Z'} < 4 \text{ TeV}$ , with only SM decays (dashes) and accounting for possible supersymmetric contributions (solid lines). In the BSM case, the parameters are fixed to the reference point (2), with the slepton mass  $m_{\tilde{\ell}}^0$  set as explained above [5]. One can thus note that, when including the BSM decay modes, the suppression of  $\sigma \text{ BR}$  is about 60% for the  $Z'_{SSM}$ , 40% for the  $Z'_\psi$  model, 30% for the  $Z'_\eta$  and 13% for the  $Z'_1$ . Such results point out a remarkable impact of the inclusion of the supersymmetric contribu-

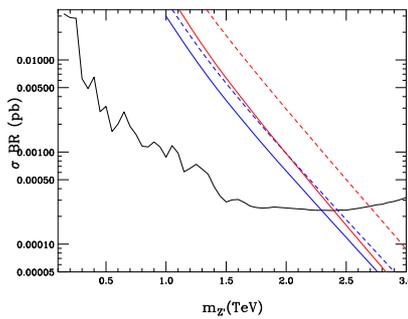
**Table 2.** Number of supersymmetric cascade events and charged sleptons at the LHC for an integrated luminosity of  $20 \text{ fb}^{-1}$  and a centre-of-mass energy of 8 TeV. The  $Z'$  mass is quoted in TeV.

Model	$m_{Z'}$	$N_{\text{casc}}$	$N_{\text{slep}}$
$Z'_\eta$	1.5	523	–
$Z'_\eta$	2	55	–
$Z'_\psi$	1.5	599	36
$Z'_\psi$	2	73	4
$Z'_N$	1.5	400	17
$Z'_N$	2	70	3
$Z'_1$	1.5	317	–
$Z'_1$	2	50	–
$Z'_S$	1.5	30	–
$Z'_S$	2	46	–
$Z'_{\text{SSM}}$	1.5	2968	95
$Z'_{\text{SSM}}$	2	462	14



**Figure 1.** Product of the cross section ( $\sigma$ ) times the branching ratio (BR) into  $e^+e^-$  and  $\mu^+\mu^-$  pairs for  $Z'$  production in  $pp$  collisions at  $\sqrt{s} = 8$  TeV, according to the models  $Z'_{\text{SSM}}$  (black on-line),  $Z'_\eta$  (blue),  $Z'_1$  (red) and  $Z'_\psi$  (magenta). The solid lines account for BSM modes, the dashes just rely on SM channels.

tions to  $Z'$  decays and that a novel analysis, taking into account such modes, may be worthwhile to be pursued.

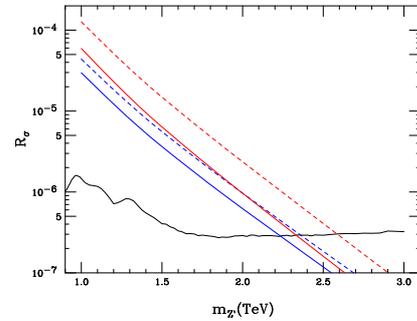


**Figure 2.** Comparison of the product  $\sigma(pp \rightarrow Z') \text{BR}(Z' \rightarrow \ell^+\ell^-)$ , as measured by the ATLAS Collaboration (black solid line) with the corresponding theory predictions including supersymmetric decays (solid lines) and only SM modes (dashes) for the  $Z'_{\text{SSM}}$  (red) and  $Z'_\psi$  (blue) models.

Finally, I compare the ATLAS (Fig. 2) and CMS (Fig. 3) data on  $\sigma$  BR with our predictions with and with-

out supersymmetric  $Z'$  decays. As for CMS in the plotted ratio  $R_\sigma$  the high-mass dilepton data are normalized to the  $\sigma$  BR product for Standard Model  $Z$  production. From such a comparison, one can learn that, in the reference point, the inclusion of supersymmetric contributions to  $Z'$  decays can have an impact of about 200-300 GeV on the mass exclusion limits.

In summary, I discussed possible supersymmetric signals in the decays of new neutral vector bosons  $Z'$ , predicted in GUT-inspired  $U(1)'$  groups and in the Sequential Standard Model, paying special attention to decay modes into sleptons, charginos and neutralinos, leading to final states with charged leptons and missing energy. For a representative point of the phase space, it was found that, especially in the SSM, the supersymmetric decays can be competitive with the standard ones, up to the point of lowering by 200-300 GeV the current limits on the  $Z'$  mass. However, in order to make a final statement on this issue, a novel experimental analysis including supersymmetric channels is compelling.



**Figure 3.** As in Fig. 2, but comparing the theory predictions with the CMS measurement of the ratio  $R_\sigma = [\sigma(pp \rightarrow Z') \text{BR}(Z' \rightarrow \ell^+\ell^-)] / [\sigma(pp \rightarrow Z) \text{BR}(Z \rightarrow \ell^+\ell^-)]$ .

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