I study the phenomenology of new heavy neutral gauge bosons $Z'$, predicted by GUT-driven $U(1)'$ gauge groups and by the Sequential Standard Model. BSM decays into supersymmetric final states are accounted for, besides the SM modes so far investigated. I give an estimate of the number of supersymmetric events in $Z'$ decays possibly expected at the LHC, as well as of the product of the $Z'$ cross section times the branching fraction into electron and muon pairs.

Heavy neutral gauge bosons $Z'$ are predicted by gauge groups $U(1)'$, which arise in the framework of Grand Unification Theories (GUTs). They are also present in the Sequential Standard Model (SSM), the simplest extension of the Standard Model (SM), as it just contains an extra heavy neutral boson with the same couplings to fermions and bosons as the $Z$. Both Tevatron and LHC experiments have searched for high-mass electron or muon pairs, which are the typical signature of $Z'$ decays. As for the LHC, CMS and ATLAS excluded a $U(1)'$-based $Z'$ with mass below 2.32 TeV and 2.21 TeV, respectively, and a SSM $Z'$ below 1.49-1.69 TeV (CMS) and 1.77-1.96 TeV (ATLAS). More recently, $\tau^+\tau^-$ pairs were also considered to exclude a $Z'$ boson with mass below 1.1-1.4 TeV.

These analyses assume, however, that the $Z'$ has only SM decay modes. Supersymmetric contributions to $Z'$ decays may possibly decrease the SM branching ratios and therefore have an impact on the exclusion limits on the $Z'$ mass. In this talk I will highlight recent results on supersymmetry signals in $Z'$ decays, referring to the Minimal Supersymmetric Standard Model (MSSM) and updating pioneering work on this topic.

Other studies lately carried out will be improved by consistently including the so-called D-term correction, due to the extra $U(1)'$ group, to the sfermion masses. In fact, the D-term can be large and negative, in such a way to drive the sfermion squared masses to become negative and thus unphysical. Furthermore, the supersymmetric particle masses will not be treated as free parameters, but will be obtained by diagonalizing the corresponding mass matrices.

The $U(1)'$ models originate from the breaking of a rank-6 GUT group $E_6$ according to $E_6 \rightarrow SO(10) \times U(1)_{\psi}^{'},$ 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 then named $Z'_{\psi}$ and $Z'_{\chi}$, whereas a generic $Z'$ boson is a combination of $Z'_{\psi}$ and $Z'_{\chi}$, with a mixing angle $\theta$:

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

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

| Model | $\theta$ |
|-------|---------|
| $Z'_\psi$ | 0 |
| $Z'_\eta$ | $-\pi/2$ |
| $Z'_N$ | $\arctan(\sqrt{15}/9) - \pi/2$ |
| $Z'_1$ | $\arctan(\sqrt{5}/8 - \pi/2$ |
| $Z'_2$ | $\arctan(\sqrt{5}/8)$ |

The $Z'$ bosons and the $\theta$ values which will be investigated are listed in Table 1. The $Z'_\psi$ model comes from the direct breaking of the GUT group in the SM, i.e. $E_6 \rightarrow \text{SM} \times \text{U}(1)'_\eta$; the $Z'_N$ is present in the secluded model, wherein the SM is extended by means of a singlet field $S$; the $Z'_1$ is instead equivalent to the $Z'_\chi$ model, but with the ‘unconventional’ assignment of SM, MSSM and exotic fields in the SU(5) representations. When extending the MSSM with a $Z'$ boson, one has two extra neutralinos, for a total of six neutralinos, and an extra neutral scalar Higgs. These new Higgs and neutralinos must be included when studying $Z'$ decays within the MSSM and U(1)' framework; however, they are typically quite heavy and therefore their contribution to the $Z'$ width is rather small.

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 $Z$. Decays yielding charged leptons are the golden channels for the experimental searches and deserve special attention. $Z'$ decays into charged sleptons $Z' \rightarrow \ell^+ \ell^-$, with the sleptons decaying according to $\tilde{\ell}^\pm \rightarrow \ell^\pm \tilde{\chi}^0$, $\tilde{\chi}^0$ being a neutralino, or chargino modes like $Z' \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_2$, followed by $\tilde{\chi}^0_2 \rightarrow \ell^\pm \tilde{\chi}^0_1$, lead to a final state with two charged leptons and missing energy. Four leptons and missing energy can be obtained by the decay chain $Z' \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1$, with subsequent $\tilde{\chi}^0_2 \rightarrow \ell^\pm \tilde{\chi}^0_1$ and $\tilde{\chi}^0_1 \rightarrow \ell^\pm \tilde{\chi}^0_1$. Finally, sneutrino-pair production, i.e. $Z' \rightarrow \tilde{\nu}_2 \tilde{\nu}_2^*$, followed by $\tilde{\nu}_2 \rightarrow \tilde{\chi}^0_2 \nu$ and $\tilde{\chi}^0_2 \rightarrow \ell^+ \ell^- \tilde{\chi}^0_1$, with an intermediate charged slepton, yields four charged leptons and missing energy (neutrinos and neutralinos).

A point in the parameter space can be chosen to compute the masses of the supersymmetric particles and study the dependence of the branching ratios on the MSSM and U(1)' parameters. Particular care has been taken about the relevance of $Z'$ and slepton masses in the decay rates in the channels eventually leading to leptons and missing energy. Hereafter, this study will be carried out setting the U(1)’/MSSM parameters to the following ‘Reference Point’:

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

In Eq. (2), $\mu$ is the well-known 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, $A_q$ and $A_\ell$ are the couplings of the Higgs with quarks and leptons, respectively. 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 $\tilde{B}'$. The U(1)' coupling $g'$, as occurs in GUTs, is proportional to the standard U(1) coupling constant $g_1$ via $g' = \sqrt{5/3} g_1$. In the Sequential Standard Model, the coupling of the $Z'_{\text{SSM}}$ to the fermions is the same as in the SM, i.e. $g_{\text{SSM}} = g_2/(2 \cos \theta_W)$, where $g_2$ is the SU(2) coupling and $\theta_W$ the Weinberg angle. As for $m_{\ell}^0$, the slepton mass before the D-term contribution, fixed to the same value for selectrons, smuons, staus and sneutrinos, it can be determined in such a way that, for a given $Z'$ mass in the range $1 \text{ TeV} < m_{Z'} < 5 \text{ TeV}$, the rate of the decay $Z' \rightarrow \ell^+ \ell^-$ is maximized. With
the parametrization (2) and this choice, the total branching ratio into BSM channels can be up to about 60% (Z′_{SSM}), 40% (Z′_ψ), 30% (Z′_η and Z′_N), 20% (Z′_I) and 15% (Z′_S). The highest branching ratios are those into chargino and neutralino pairs, which can account up to 20% and 30% of the total Z′ width, respectively. Direct decays into charged-slepton pairs have branching fractions of the order of few percent. The numbers in Table 2 are obtained in the narrow-width approximation, with the pp → Z′ cross section computed at leading order using the CTEQ6L parton distribution functions. The Z′ model is not taken into account, since, using the parametrization (2), it does not lead to a physical sfermion spectrum. One finds that the cascade events can be O(10^3) and the charged sleptons up to a few dozens: the highest rate of production of supersymmetric particles occurs in the SSM, but even the U(1)′ models yield meaningful sparticle production.

Before concluding, 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 (σ) at the LHC (√s = 8 TeV) times the branching ratio (BR) into e^+e^− and μ^+μ^− pairs, with and without accounting for supersymmetric modes. In the Sequential Standard Model, assuming only SM decays, it is BR ≃ 6.8%, like the SM Z boson: the addition of supersymmetric modes decreases the lepton rates and may therefore have an impact on the limits on the Z′ mass. In fact, the experimental exclusion limits are obtained by comparing data and theoretical predictions for σBR. Fig. 1 shows this product varying the Z′ mass in the range 1 TeV < m_{Z′} < 4 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}} fixed to the value which enhances the Z′ → \tilde{\ell}^+\tilde{\ell}− decay rate. One can thus note that, when including the BSM decay modes, the suppression of σBR is about 60% for the Z′_{SSM}, 40% for the Z′_ψ model, 30% for the Z′_η and 13% for the Z′_I. Such results point out a remarkable impact of the inclusion of the supersymmetric contributions to Z′ decays and that a novel analysis, taking into account such modes, may be worthwhile to be pursued.

In summary, I briefly discussed possible supersymmetric contributions to Z′ decays, within

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

| Model   | m_{Z′} | N_{casc} | N_{slep} |
|---------|--------|----------|----------|
| Z′_η    | 1.5    | 523      | −        |
| Z′_η    | 2      | 55       | −        |
| Z′_ψ    | 1.5    | 599      | 36       |
| Z′_ψ    | 2      | 73       | 4        |
| Z′_N    | 1.5    | 400      | 17       |
| Z′_N    | 2      | 70       | 3        |
| Z′_I    | 1.5    | 317      | −        |
| Z′_I    | 2      | 50       | −        |
| Z′_S    | 1.5    | 30       | −        |
| Z′_S    | 2      | 46       | −        |
| Z′_{SSM}| 1.5    | 2968     | 95       |
| Z′_{SSM}| 2      | 462      | 14       |
Figure 1: Product of the cross section ($\sigma$) and 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 $Z'_{SSM}$ (black online), $Z'_\eta$ (blue), $Z'_I$ (red) and $Z'_\psi$ (magenta). The solid lines account for BSM decay modes, the dashes just rely on SM channels.

the Minimal Supersymmetric Standard Model, extended by means of an extra GUT-inspired $U(1)'$ group, as well as in the Sequential Standard Model. The next step of this investigation will consist in the implementation of $Z'$ production and decay modes in the framework of a Monte Carlo event generator, in such a way to account for parton showers, hadronization, underlying event, finite-width effects and possibly detector simulations. One should then be able to compare the supersymmetry signals in $Z'$ decays with the Standard Model backgrounds. In this way, a conclusive statement on the LHC reach for $Z'$ bosons within supersymmetry can ultimately be drawn. This work is in progress.

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