PROCEEDINGS OF SCIENCE

Supersymmetric signals in Z' decays

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I present a scenario wherein heavy neutral vector bosons Z', predicted by GUT-inspired U(1)$'$ models, decay into supersymmetric final states, besides the Standard Model channels investigated at the LHC. It is found that accounting for such decays lowers the exclusion limits on the Z' mass at 13 TeV by about 200-300 GeV.

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1. Introduction

Heavy neutral gauge bosons Z' are predicted by extensions of the Standard Model (SM) based on U(1)$'$ gauge symmetries, typically inspired by Grand Unification Theories (GUT) [1, 2]. They are also present in the so-called Sequential Standard Model (SSM), the simplest extension of the SM, wherein Z' and possibly W' bosons have the same coupling to fermions as Z and W.

The LHC experiments have searched for the Z', assuming that it decays only into Standard Model channels and focusing on high-mass charged-lepton pairs or dijets. As for dileptons, by using the 13 TeV LHC data, the ATLAS Collaboration [3] set the limits $m_{Z'} > 4.5$ TeV in the SSM and $m_{Z'} > 3.8$-4.1 TeV in U(1)$'$ models, whereas CMS obtained $m_{Z'} > 4.0$ TeV (SSM) and $m_{Z'} > 3.5$ TeV (GUT-inspired models) [4]. For dijets, the limits read $m_{Z'} > 2.1$-2.9 TeV (ATLAS) [5] and $m_{Z'} > 2.7$ TeV (CMS) [6]. In this talk, I explore possible supersymmetric decays of GUT-inspired Z' bosons, within the Minimal Supersymmetric Standard Model (MSSM), along the lines of Refs. [7, 8]. In fact, the opening of new channels lowers the SM branching ratios and the exclusion limits; moreover, if a Z' were to be discovered, decay modes like $Z' \to \tilde{\ell}^+\tilde{\ell}^-$ would be an ideal place to search for supersymmetry, since the Z' mass would set a constraint on sparticle invariant masses. Also, decays of the Z' into the lightest supersymmetric particles, such as neutralinos, would be useful from the viewpoint of Dark Matter searches at colliders.

I shall first discuss the main theoretical features of the considered model and then present some results for a representative benchmark point of the parameter space. I will finally make some concluding remarks.

2. Theoretical framework

U(1)$'$ gauge groups and Z' bosons typically arise from the breaking of a rank-6 Grand Unification group E$_6$. The Z'_ψ is associated with U(1)$'_\psi$, coming from the breaking of E$_6$ into SO(10):

$$\mathrm{E}_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)'_\psi. \tag{2.1}$$

The subsequent breaking of SO(10) leads to the Z'_χ boson:

$$\mathrm{SO}(10) \to \mathrm{SU}(5) \times \mathrm{U}(1)'_\chi. \tag{2.2}$$

A generic Z' is then given by the mixing between Z'_ψ and Z'_χ bosons via an angle θ:

$$Z'(\theta) = Z'_\psi \cos\theta - Z'_\chi \sin\theta. \tag{2.3}$$

Another scenario, typical of superstring theories, consists in the breaking of E$_6$ in the SM and a U(1)$'_\eta$ group, leading to a Z'_η boson, with a mixing angle $\theta = \arccos\sqrt{5/8}$:

$$\mathrm{E}_6 \to \mathrm{SM} \times U(1)'_\eta. \tag{2.4}$$

This talk will be concentrated on the the Z'_ψ model, as it is the most promising, yielding the largest cross section. Scenarios with other values of the angle θ were discussed in detail in [7, 8].

As for the MSSM, besides the scalar Higgs doublets H_d and H_u, an extra neutral singlet S is necessary to break the U(1)$'$ gauge symmetry and give mass to the Z'. After electroweak symmetry breaking, the Higgs sector consists of one pseudoscalar A and three scalars h, H and H', where H' is a new boson, due to the extra U(1)$'$ symmetry. In the gaugino sector, two extra neutralinos are present, associated with the supersymmetric partners of Z' and H', while the charginos are unchanged. As thoroughly debated in [9], the U(1)$'$ group leads to extra D- and F-term contributions to sfermion masses, which were accounted for in [7, 8] and will be included in the results. In the following section, I shall explore the U(1)$'_\psi$ model, which exhibits the most interesting phenomenology with Z' decays into supersymmetric final states.

3. Results

The Z'_ψ model corresponds to a mixing angle $\theta = 0$; in the present analysis, the Z' mass will be set to $m_{Z'} = 2$ TeV and the coupling constants of U(1)$'$ and U(1)$_\mathrm{Y}$ proportional according to $g' = \sqrt{5/3}\ g_1$. I shall also set: $M_1 = 400$ GeV, $M' = 1$ TeV, $\tan\beta$=30, $\mu = 200$ GeV and $A_q = A_\ell = A_\lambda = 4$ TeV, where A_q and A_ℓ are the soft trilinear couplings of squarks and sleptons with the Higgs fields and A_λ is the soft Higgs trilinear coupling.

The sfermion spectrum, corresponding to soft masses at the Z' scale $m^0_{\tilde{\ell}} = m^0_{\tilde{\nu}_\ell} = 1.2$ TeV and $m^0_{\tilde{q}}$=5.5 TeV, computed by means of the SARAH [10] and SPheno [11] codes, is given in Tables 1 and 2, where $\tilde{\ell}_{1,2}$ and $\tilde{q}_{1,2}$ denote the mass eigenstates. Tables 3 and 4 contain instead the mass spectra of Higgs bosons and gauginos (charginos and neutralinos), respectively.

Table 1: Squark masses in GeV in the reference point of the MSSM.

$m_{\tilde{d}_1}$	$m_{\tilde{u}_1}$	$m_{\tilde{s}_1}$	$m_{\tilde{c}_1}$	$m_{\tilde{b}_1}$	$m_{\tilde{t}_1}$
5609.8	5609.4	5609.9	5609.5	2321.7	2397.2
$m_{\tilde{d}_2}$	$m_{\tilde{u}_2}$	$m_{\tilde{s}_2}$	$m_{\tilde{c}_2}$	$m_{\tilde{b}_2}$	$m_{\tilde{t}_2}$
5504.9	5508.7	5504.9	5508.7	2119.6	2036.3

Table 2: Mass spectrum in GeV of charged sleptons ($\ell = e, \mu$) and sneutrinos.

$m_{\tilde{\ell}_1}$	$m_{\tilde{\ell}_2}$	$m_{\tilde{\tau}_1}$	$m_{\tilde{\tau}_2}$	$m_{\tilde{\nu}_{\ell,1}}$	$m_{\tilde{\nu}_{\ell,2}}$	$m_{\tilde{\nu}_{\tau,1}}$	$m_{\tilde{\nu}_{\tau,2}}$
1392.4	953.0	1398.9	971.1	1389.8	961.5	1395.9	961.5

Table 3: Masses of neutral and charged Higgs bosons in GeV.

m_h	m_H	$m_{H'}$	m_A	$m_{H^\pm}$
125.0	1989.7	4225.0	4225.0	4335.6

In this benchmark point, the Z'_ψ branching ratios were computed in [8]: although the SM modes are still dominant, the overall branching ratio into supersymmetric final states is almost 30%. The highest supersymmetric rate is the one into chargino pairs $\tilde{\chi}^+_1\tilde{\chi}^-_1$ and accounts for about 10%; the branching ratio into the lightest neutralinos, Dark Matter candidates, is roughly 5%.

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Table 4: Masses of charginos and neutralinos in GeV.

$m_{\tilde{\chi}_1^+}$	$m_{\tilde{\chi}_2^+}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_5^0}$	$m_{\tilde{\chi}_6^0}$
204.8	889.1	197.2	210.7	408.8	647.9	889.0	6193.5

As in [8], one can consider the decay chain $pp \to Z'_\psi \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to (\tilde{\chi}_1^0 \ell^+ \nu_\ell)(\tilde{\chi}_1^0 \ell^- \bar{\nu}_\ell)$, with $\ell = \mu, e$, leading to final states with two charged leptons and missing energy. Its cross section, calculated at leading order (LO) by MadGraph [12], is given by 7.9×10^{-4} pb at 14 TeV. Hereafter, I will present some relevant leptonic distributions and compare them with decays $Z'_\psi \to \ell^+\ell^-$ and direct chargino production, namely $pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \to (\tilde{\chi}_1^0 \ell^+ \nu_\ell)(\tilde{\chi}_1^0 \ell^- \bar{\nu}_\ell)$. The hard-scattering processes will be simulated by MadGraph and matched with HERWIG 6 [13] for shower and hadronization.

Figure 1 presents the transverse-momentum spectrum of the leptons produced in all three processes. For direct $Z'_\psi \to \ell^+\ell^-$, the two leptons get the full initial-state transverse momentum and the p_T spectrum is relevant at high values; in the other cases, some (missing) transverse momentum is lent to neutrinos and neutralinos, which significantly decreases the p_T of ℓ^+ and ℓ^-. For direct chargino production, the leptons are rather soft and the spectrum is peaked at low p_T; when the charginos come from the Z', their invariant mass must be equal to $m_{Z'}$ and therefore the transverse-momentum distribution is substantial at higher p_T values.

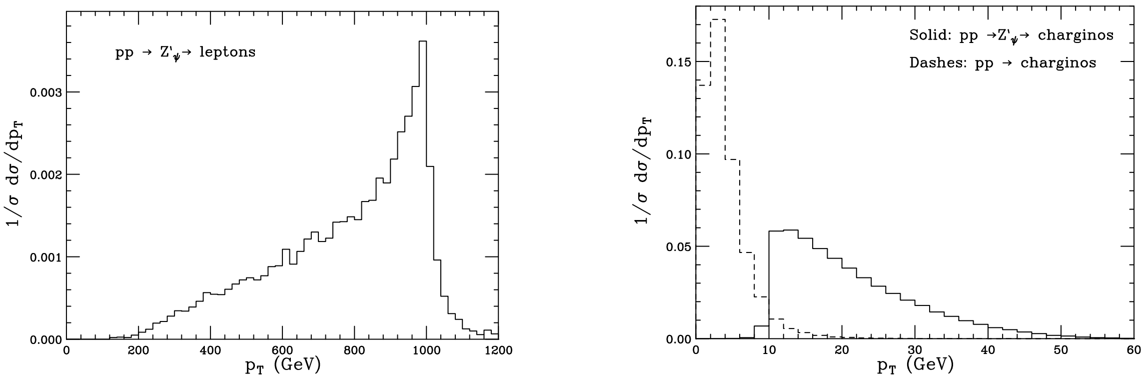

Figure 1: Lepton transverse momentum for the Z'_ψ model at $\sqrt{s} = 14$ TeV and $m_{Z'} = 2$ TeV, for a direct $Z'_\psi \to \ell^+\ell^-$ decay (left) and chains initiated by $Z'_\psi \to \tilde{\chi}_1^+ \chi_1^-$ or direct chargino production processes (right).

Figure 2 presents the dilepton invariant mass $m_{\ell\ell}$ (left), as well as the angle θ between ℓ^+ and ℓ^- (right). For Z' decays into charginos, $m_{\ell\ell}$ lies in the range 20 GeV $< m_{\ell\ell} <$ 100 GeV and is maximum at $m_{\ell\ell} \simeq 45$ GeV; for direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ production, $m_{\ell\ell}$ is peaked about 5 GeV and rapidly decreases. As for the θ spectrum, in Z'_ψ direct leptonic decays it exhibits a maximum about $\theta \simeq 3$, i.e. ℓ^+ and ℓ^- almost back-to-back; in $Z'_\psi \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$, the θ distribution is broader and peaked at a lower $\theta \simeq 2.75$; for direct chargino-pair production, ℓ^+ and ℓ^- are mostly soft and collinear and the angular distribution is peaked and substantial at smaller θ.

Decays into neutralino pairs $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ are relevant for the searches for Dark Matter candidates and exhibit a cross section $\sigma(pp \to Z'_\psi \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) \simeq 6.4 \times 10^{-3}$ pb at 14 TeV; competing processes

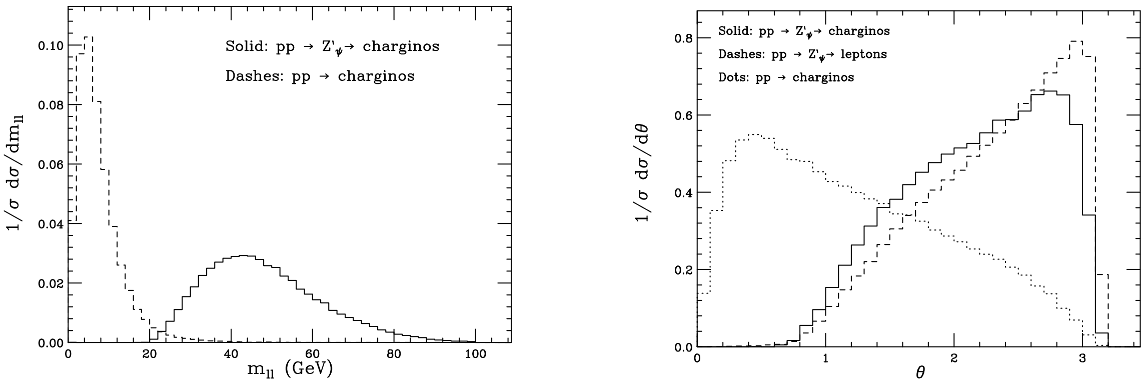

Figure 2: Left: dilepton invariant mass, with ℓ^+ and ℓ^- originated from Z'_ψ decays into charginos and for direct $pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$ production. Right: angle between $\ell^\pm$ in the laboratory frame, in all three processes.

are Z'_ψ decays into neutrino pairs. Figure 3 displays the total missing transverse energy (MET) spectrum and the contribution due to the neutrino and neutralino pairs; all spectra are normalized to the LO cross section. The shapes of all distributions are roughly the same, but the total number of events at any MET is substantially higher, by about 60%, if neutralinos contribute.

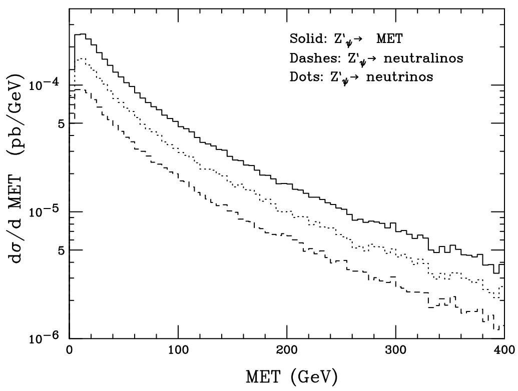

Figure 3: MET in Z'_ψ decays: plotted are the neutralino (dashes), neutrino (dots) and total (solid) rates.

Before completing this section, following [14], in Fig. 4 I compare the ATLAS data on high-mass dileptons at 13 TeV with the predictions for the Z'_ψ and Z'_η models, possibly accounting for supersymmetric decays, expressed in terms of the product $\sigma(pp \to Z')$ BR$(Z' \to \ell^+\ell^-)$. From the comparison, one learns that the impact of the supersymmetric modes on the exclusion limits on the mass of Z'_η and Z'_ψ bosons is about 200 and 300 GeV, respectively.

4. Conclusions

I investigated supersymmetric Z' decays at the LHC, for $\sqrt{s} = 14$ TeV in the $\mathrm{U}(1)'_\psi$ model. In this scenario, Z' decays into into chargino pairs lead to final states with leptons and missing energy which can be discriminated from $Z' \to \ell^+\ell^-$ processes as well as from direct chargino production. Decays into the lightest neutralinos substantially contribute to the missing transverse energy and can therefore be explored in Dark Matter searches. Comparing with the ATLAS data at 13 TeV,

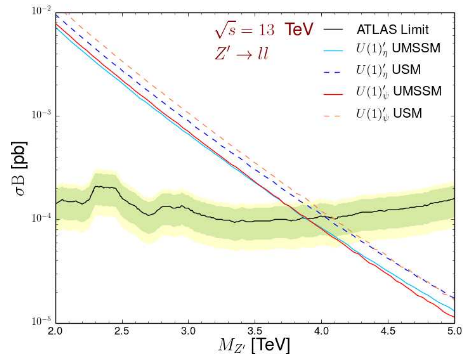

Figure 4: Comparison of ATLAS high-mass dilepton data at 13 TeV with the theoretical predictions for $\sigma(pp \to Z')\mathrm{BR}(Z' \to \ell^+\ell^-)$ in $\mathrm{U}(1)'_\psi$ and $\mathrm{U}(1)'_\eta$ models, with (UMSSM) or without (USM) supersymmetry.

one learns that the inclusion of supersymmetric modes has an impact of the order of 200-300 GeV on the Z' mass limits.

In a future perspective, a complete analysis should necessarily compare supersymmetric signals in Z' decays with the backgrounds coming from the SM and other supersymmetric processes, as well as non-supersymmetric Z' decays, and implement the detector simulation. This is in progress. Furthermore, in order to further enhance non-standard signals in Z' events, one may consider Z' supersymmetric decays in the framework of leptophobic models, wherein Z' decays into electron or muon pairs are suppressed [14].

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