Phenomenology of new heavy neutral gauge bosons in an extended MSSM

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Summary. —
An extension of Standard Model based on $U(1)'$ gauge symmetry, predicting a new heavy boson Z', in TeV mass range, is discussed in this paper. Particular attention is devoted to the Z' decays into supersymmetric channels in addition to the Standard Model modes, so far investigated. The D-term contribution, due to the breaking of $U(1)'$, is took into account for slepton and squark masses and its effect is investigated on Z' decays into sfermions. The Z' production cross section at the Large-Hadron Collider at center of mass energies 8, 14 TeV is calculated and the corresponding expected number of events containing a Z' decaying in supersymmetric particles for some integrated luminosity are predicted.

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1. – Introduction

The validity of the Standard Model (SM) of the strong and electroweak interactions has been so far experimentally tested with success using LEP, Tevatron, LHC (Large-Hadron-Collider) data. Nevertheless, many extension of the SM have been proposed, involving a gauge group of larger rank, the introduction of one extra string-inspired $U(1)'$ factor, which leads to the prediction of a new neutral gauge boson Z'(see, *e.g.*, [1]). Moreover, the Sequential Standard Model ($Z'_{\rm SSM}$), *i.e.* a heavy gauge boson with the same couplings to fermions and gauge bosons as the Z of the SM, has been, as well, investigated. The experimental limits on the new boson reached are in the range approximately 1.5 TeV for the string-inspired scenario and 1.8 TeV for the SM-like case [2], [3], [4], [5]. All these bounds on the Z' mass, $m_{Z'}$, rely on the assumption that the Z' decays into Standard Model particles, with branching ratios depending on its mass and, in the string-like case, on the parameters characterizing the specific $U(1)'$ model. But, there is no actual reason to exclude Z' decays into channels beyond the SM, such as its supersymmetric extension, the Minimal Supersymmetric Standard Model (MSSM). This new physics contributions to the Z' width significantly decreases the branching ratios into SM particles, and therefore the mass limits quoted by the experiments may have to be revisited.

The aim of this paper is the investigation of the phenomenology of Z' bosons at the LHC, assuming that they can decay into both SM and supersymmetric particles, as in the MSSM [6]. The Z' decays into supersymmetric particles, if existing, represent an excellent tool to investigate the electroweak sector at the LHC in a phase-space corner that cannot be explored by employing the usual techniques. Through this work, particular care will be taken about the decay of the Z' into leptonic final state. Here, only the main points are summarized referring to the original paper for a more extensive description [7].

2. – Z′ production and decay

In this section the extensions of the Standard Model leading to Z' bosons, allowing the decays into both standard and supersymmetric particles(MSSM) and its properties are summarized.

2·1. $U(1)'$*models*. – There are several possible extensions of the SM that can be achieved by adding an extra $U(1)'$ gauge group, typical of string-inspired theories, each model is characterized by the coupling constants, possibly of the same order as the electroweak scale, the breaking scale of $U(1)'$ and scalar particle responsible for its breaking, the quantum numbers of fermions and bosons according to $U(1)'$. The most experimentally investigated models are characterized by an angle θ and a Z' boson which can be expressed as:

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

Each value of the mixing angle θ corresponds to a $U(1)'$ group and leads to a different Z' phenomenology. The most widely used models, with their corresponding mixing angle, are: Z'_η ($\arccos\sqrt{5/8}$), Z'_ψ (0), Z'_{N} ($\arctan\sqrt{15}-\pi/2$), Z'_{I} ($\arccos\sqrt{5/8}-\pi/2$), Z'_{S} ($\arctan(\sqrt{15}/9)-\pi/2$), Z'_χ ($-\pi/2$).
The charge of a field Φ is expressed through the same mixing angle θ as: $Q'(\Phi) = Q_\psi(\Phi)\cos\theta - Q_\chi(\Phi)\sin\theta$. with Q_ψ and Q_χ charge values for standard and supersymmetric particles quoted in [6].
Another model which is experimentally investigated is the so-called Sequential Standard Model (SSM), with the new boson Z'_{SSM} heavier than the Z boson, but with the same couplings to fermions and gauge bosons as in the SM.
In the following, in addition to the SM groups coupling constants g_1, g_2 ($g_1 = g_2 \tan\theta_W$, θ_W being the Weinberg angle), is considered that to the $U(1)'$ group, $g' = \sqrt{\frac{5}{3}} g_1$ [6].
The Z and Z' are assumed to correspond, within a very good approximation, to the mass eigenstates.

2·2. *Particle content of the Minimal Supersymmetric Standard Model*. – The MSSM contains the supersymmetric partners of the SM particles: sfermions, as sleptons $\tilde{\ell}$ and $\tilde{\nu}_\ell$ ($\ell = e, \mu, \tau$), squarks $\tilde{q}$ and gauginos $\tilde{g}$, $\tilde{W}^\pm$, $\tilde{Z}$ and $\tilde{\gamma}$. It requires two Higgs doublets, which, after giving mass to W and Z bosons, lead to five scalar degrees of freedom, usually parametrized in terms of two CP-even neutral scalars, the lighter h and H, one CP-odd neutral pseudoscalar A and a pair of charged Higgs bosons $H^\pm$. Each Higgs will have a supersymmetric fermionic partner, named higgsino.

The weak gauginos mix with the higgsinos to form the corresponding mass eigenstates: two pairs of charginos ($\tilde{\chi}_1^\pm$and $\tilde{\chi}_2^\pm$) and four neutralinos ($\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$ and $\tilde{\chi}_4^0$), where $\tilde{\chi}_1^0$ is the lightest and $\tilde{\chi}_4^0$ the heaviest. The lightest neutralino, *i.e.* $\tilde{\chi}_1^0$, is often assumed to be the stable Lightest Supersymmetric Particle (LSP).

3. – Extending the MSSM with the extra $\mathbf{U(1)'}$

In this section, few relevant points are summarized important for our discussion, referring to the work in [6] for more details.

3·1. *Higgs bosons in the MSSM and* $U(1)'$ *model*. – As debated above, the MSSM itself predicts two Higgs doublets, whereas a third Higgs boson is required to break the $U(1)'$ gauge symmetry and give mass to the Z' boson. Then, the scalar components of the three Higgs bosons are two weak-isospin doublets Φ_1, Φ_2 and one singlet, Φ_3. The vacuum expectation values of the neutral Higgs bosons will be given by $\langle \phi_i^0 \rangle = v_i/\sqrt{2}$, with $v_1 < v_2 < v_3$.
The superpotential, which in the MSSM contains a Higgs coupling term giving rise to the μ parameter, because of the extra Higgs field Φ_3 presents an additional contribution $W = \lambda \Phi_1 \Phi_2 \Phi_3$, leading to a trilinear scalar potential for the neutral Higgs bosons $V_\lambda = \lambda A \phi_1^0 \phi_2^0 \phi_3^0$. The parameter λ is related to the usual μ term by means a relation, $\mu = \frac{\lambda v_3}{\sqrt{2}}$, involving the vacuum expectation value of the third Higgs [6].

After the symmetry breaking and giving mass to W, Z and Z' bosons,in the model, there are: two charged ($H^\pm$), and four neutral Higgs bosons, one pseudoscalar A and three scalars h, H and H'. The mass of the heaviest H' is typically about the Z' mass, and therefore the Z' will not be able to decay into channels containing H'. Moreover, the introduction of the extra Higgs field Φ_3 singlet has impact also on the the other Higgs masses.

3·2. *Neutralinos and charginos*. – Besides the four neutralinos of the MSSM, $\tilde{\chi}_1^0, \ldots, \tilde{\chi}_4^0$, two extra neutralinos are required, namely $\tilde{\chi}_5^0$ and $\tilde{\chi}_6^0$, associated with the Z' and with the extra neutral Higgs breaking $U(1)'$. Their mass eigenstates are obtained diagonalizing a 6×6 matrix, depending on the Higgs vacuum expectation values, on the gaugino masses M_1, M_2 and M', and on the Higgs $U(1)'$ charges. As the extra Z' and Higgs are neutral, the chargino sector of the MSSM remains unchanged even after adding the extra $U(1)'$ group.

3·3. *Sfermion masses*. – In many models for supersymmetry breaking, one typically expresses the sfermion squared mass as the sum of a soft term, m_0^2, often set to the same value for both squark and sleptons at a given scale, and a correction, called D-term, which, for the purposes of our study, consists of two contributions. A first term is a correction due to the hyperfine splitting driven by the electroweak symmetry breaking and is already present in the MSSM [7]. A second contribution to the D-term is present once one has extensions of the MSSM, such as our $U(1)'$ group, and is due to the Higgs bosons, which are necessary to break the new symmetry: $\Delta \tilde{m}_a'^2 = \frac{g'^2}{2}(Q_1' v_1^2 + Q_2' v_2^2 + Q_3' v_3^2)$, where Q_a' is the charge of the fermion a under $U(1)'$ and Q_1', Q_2' and Q_3' are the $U(1)'$ charges of the three neutral Higgs bosons. In the Sequential Standard Model, only the first contribution to the D-term will be evaluated.

Left- and right-handed sfermions in general mix, and therefore, in order to obtain the mass eigenstates, the squared mass matrix has to be diagonalized. As in ref. [6], it is assumed a common soft mass at the Z' scale and the D-term contribution it is added to it. As an example, the expression for the matrix elements in the case of an up-type squark is:

$$(M^{\tilde{u}}_{\rm LL})^2 = (m^0_{\tilde{u}_{\rm L}})^2 + m_u^2 + \left(\frac{1}{2} - \frac{2}{3}x_w\right) m_Z^2 \ \cos 2\beta + Q'_{\tilde{u}_{\rm L}} \Delta\tilde{m}'^2_{\tilde{u}_L} \tag{2}$$

$$(M^{\tilde{u}}_{\rm RR})^2 = (m^0_{\tilde{u}_R})^2 + m_u^2 + \left(\frac{1}{2} - \frac{2}{3}x_w\right) m_Z^2 \ \cos 2\beta + Q'_{\tilde{u}_R} \Delta\tilde{m}'^2_{\tilde{u}_R} \tag{3}$$

$$(M^{\tilde{u}}_{\rm LR})^2 = m_u \left(A_u - \mu \cot\beta\right). \tag{4}$$

where $x_w = \sin^2\theta_W$, $m^0_{\tilde{u}_{\rm L,R}}$ is the $\tilde{u}_{\rm L,R}$ mass at the Z' energy scale and $A_f = m_u A_u$ is the coupling constant entering in the Higgs-sfermion interaction term. The dependence on $m_{Z'}$ and the mixing angle θ is embedded in the $\Delta\tilde{m}_{D'}$ term. Analogous expressions hold for down squarks and sleptons [6]; after diagonalizing the corresponding mass matrix , the up-squark mass eigenstates are named as $\tilde{u}_1$ and $\tilde{u}_2$ and their masses as $m_{\tilde{u}_1}$ and $m_{\tilde{u}_2}$. As the mass of light quarks and leptons is very small, the mixing term, eq. (4), is negligible and the mass matrix of sleptons and light squarks is roughly diagonal.Instead the mixing term $M_{\rm LR}$ for top squarks is relevant, and therefore the stop mass eigenstates $\tilde{t}_{1,2}$ are in general different from the weak states $\tilde{t}_{\rm L,R}$. In the other cases is $\tilde{t}_{1,2} \approx \tilde{t}_{\rm L,R}$.

In conclusion, the $U(1)'$ group addition implies an additional heavy Higgs, H', two extra neutralinos are required and as for the sfermions, an extra contribution, the so-called D-term, to squark and slepton masses, depending on the $U(1)'$ sfermion charges and Higgs vacuum expectation values. This D-terms has a crucial impact on sfermion masses and, whenever large and negative, they may even lead to discarding some MSSM/$U(1)'$ scenarios.

4. – Representative Point

The analysis on Z' production and decays into SM and MSSM particles depends on $U(1)'$, MSSM several parameters, among them the Z' or MSSM masses; the experimental searches for physics beyond the Standard Model set exclusion limits on such quantities.

In the following, it is considered a specific configuration of the parameter space, the so-called 'Representative Point', to study the Z' phenomenology with non-zero branching ratios in the more relevant SM and MSSM decay channels. Then, each parameter is varied individually,fixing the others to the following values:

$$m_{Z'} = 3 \text{ TeV} \ , \ \theta = \arccos\sqrt{\frac{5}{8}} - \frac{\pi}{2}, \mu = 200 \ , \ \tan\beta = 20 \ , \ A_q = A_\ell = A_f = 500 \text{ GeV} \ ,$$
$$m^0_{\tilde{q}_L} = m^0_{\tilde{q}_R} = m^0_{\tilde{\ell}_L} = m^0_{\tilde{\ell}_R} = m^0_{\tilde{\nu}_L} = m^0_{\tilde{\nu}_R} = 2.5 \text{ TeV}, M_1 = 100 \text{ GeV} \ , \ M' = 1 \text{ TeV}.$$

where by q and ℓ denote any possible quark and lepton flavor, respectively. The gaugino masses M_1 and M_2 satisfy, within very good accuracy, the GUT-inspired relation: $\frac{M_1}{M_2} = \frac{5}{3}\tan^2\theta_W$,then M_2=200 GeV. The Beyond-Standard-Model (BSM) particle masses with eq. (5) setting are summarized in tab. I and some parameter dependence is discussed in the following. A complete study is in ref. [7].

TABLE I. – *Masses in GeV of non Standard Model particle masses in the MSSM/$U(1)'$ scenarios, at Reference Point eq. (5).*

$m_{\tilde{u}_1}$	$m_{\tilde{u}_2}$	$m_{\tilde{d}_1}$	$m_{\tilde{d}_2}$	$m_{\tilde{\ell}_1}$	$m_{\tilde{\ell}_2}$	$m_{\tilde{\nu}_1}$	$m_{\tilde{\nu}_2}$
2499.4	2499.7	2500.7	1323.1	3279.0	2500.4	3278.1	3279.1
$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_5^0}$	$m_{\tilde{\chi}_6^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$
94.6	156.5	212.2	260.9	2541.4	3541.4	154.8	262.1
m_h	m_A	m_H	$m_{H'}$	$m_{H^\pm}$			
90.7	1190.7	1190.7	3000.0	1193.4			

4·1. *Sfermion masses.* – The sfermion masses are given by the sum of a common mass, set to the same values for all squarks and sleptons at the Z' scale, as in eq. (5), and the D-term. In fact, the D-term, and then the sfermion squared masses, is expected to depend strongly on the $U(1)'$ and MSSM parameters, and can even become negative, then leading to an unphysical (imaginary) sfermion mass.

Figure (1,left), shows the remarkable dependence of all slepton masses on θ, $U(1)'$ mixing angle. The regions of small and large θ have been discarded in the plots, since they would correspond to a negative, and thus unphysical, squared mass. The squark ($\tilde{u}$ and $\tilde{d}$, $\tilde{t}$) masses dependence on θ mixing angle is also important [7]. In this particular point of parameter space (eq. (5)), the mixing term is negligible and therefore the $\tilde{t}_{1,2}$ masses are roughly equal to the masses of the other up-type squarks. The D-term correction and then sfermion masses, is also function of Z' mass, this dependence is shown in fig. (1, right).
The sfermion masses are monotonically increasing function on the $m^0_{\tilde{q},\tilde{\ell}}$ mass, as expected. being the D-term negligible for $\tilde{u}_1$, $\tilde{u}_2$, $\tilde{d}_1$ and ℓ_2.

4·2. *Neutralino and chargino masses.* – The neutralino masses, unlike the sfermion masses, depend also on M_1, M_2 and M'. The Z' decays into $\tilde{\chi}^0_5$ and $\tilde{\chi}^0_6$ are prevent for their masses, unlike those into the lighter, tab. I, then will be not considered in the

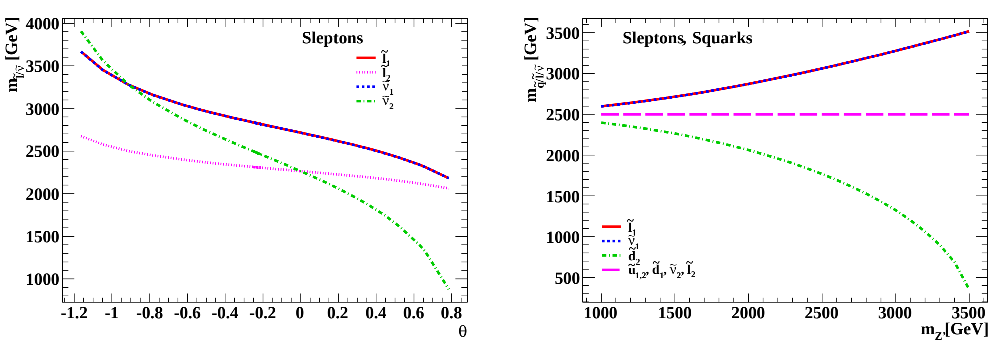


Fig. 1. – Dependence on the $U(1)'$ mixing angle θ of slepton masses (left) and sfermion masses on the Z' mass (right).

following.

The dependence of the neutralino masses on the mixing angle θ is negligible, whereas the actual value of the $m_{Z'}$ and M' affects significantly only $\tilde{\chi}^0_5$ and $\tilde{\chi}^0_6$. The masses of $\tilde{\chi}^0_5$ and $\tilde{\chi}^0_6$ are linearly increasing functions of $m_{Z'}$, whereas they exhibit opposite behavior with respect to M', as $m_{\tilde{\chi}^0_5}$ increases and $m_{\tilde{\chi}^0_6}$ decreases.
The variation of the other four neutralino masses with respect to M_1, or equivalently M_2, exhibits a step-like behavior.

As discussed before, the chargino sector stays unchanged even after the introduction of the neutral boson Z', therefore their masses don't depend on θ, $m_{Z'}$, M'.

4˙3. *Higgs masses*. – An additional Higgs, H', $U(1)'$-inherited is present respect to MSSM framework. The Z' decays into it are prevent, due to is mass about 3 TeV, approximately equal to $m_{Z'}$ in all tanβ range. The other decay channels containing Higgs are kinematically accessible, tab. I.
The mass of the lightest scalar Higgs (m$_h$) is roughly independent of both tanβ and μ, being of the order of $m_Z$and the others H, $A$and $H^{\pm}$ have a common mass of about 1190.0 GeV. The heavier MSSM Higgs H mass is physical, *i.e.* its mass squared positive only for positive values of μ. Then, in the following we only the positive space ($\mu > 0$) is discussed.

4˙4. *Branching ratios in the Representative Point*. – From sec. **4**˙1 it is possible conclude that all up-type, including the stop, and down-type squark masses are degenerate; therefore are denoted in the following as $m_{\tilde{u}_i}$ and $m_{\tilde{d}_i}$, regardless of the flavor.
At this point, it is possible calculate the Z' widths into the kinematically allowed decay channels.

The SM Z' decays are the same of Z boson, quark or lepton pairs, but in addition, due to its higher mass the WW decay is permitted.
Furthermore, the extended MSSM allows Z' decays into sfermions,*i.e.* $\tilde{f}_i\tilde{f}^*_j$ ($f = u, d, \ell, \nu$), neutralino ($\tilde{\chi}^0_{1,2,3,4}$), chargino ($\tilde{\chi}^+\tilde{\chi}^-$), or Higgs ($hh$, HH, hH, hA, HA, $H'A$, H^+H^-) pairs, as well as into states with Higgs bosons associated with W/Z, such as Zh, ZH and $H^{\pm}W^{\mp}$. Summing up all partial rates, one can thus obtain the Z' total width and the branching ratios into all allowed decay channels. Several decay channels are forbidden for phase space limitations.

The Z' kinematically not accessible decay states (from tab. I) as into up-type squarks and sleptons, the heaviest neutralinos and $U(1)'$-inherited Higgs H' have a null branching fraction. The only allowed decay into sfermion pairs is the one into down-type squarks $\tilde{d}_2\tilde{d}^*_2$. Despite is kinematically permitted, the branching ratios into up-type is null because the partial widths [6] are weighted by a null coefficient in the $Z'_{\rm I}$ model.

Since, at a scale of 3 TeV, one does not distinguish the quark or lepton flavor, the branching ratios summed over all possible flavors,in brackets, are: $u\bar{u}$ (0.0%), $d\bar{d}$ (40.67%), $\ell^+\ell^-$ (13.56 %) and $\nu\bar{\nu}$ (27.11 %). Likewise, $\tilde{u}\tilde{u}^*$ (0.0%), $\tilde{d}\tilde{d}^*$ (9.58%), $\tilde{\ell}\tilde{\ell}^*$ (0.0%) and $\tilde{\nu}\tilde{\nu}^*$ (0.0%) are their MSSM counterparts.
The most significant branching ratios into neutralinos are $\tilde{\chi}^0_2\tilde{\chi}^0_3$ (2.13), $\tilde{\chi}^0_3\tilde{\chi}^0_3$ (1.75), $\tilde{\chi}^0_3\tilde{\chi}^0_4$ (1.34), into chargino $\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_1$ (1.76) and $\tilde{\chi}^{\pm}_1\tilde{\chi}^{\mp}_2$ (1.95) The $\tilde{\chi}^0_1\tilde{\chi}^0_1$ has a small rate and is experimentally invisible.

Summarizing, at the Representative Point, the SM decays account for about the 77% of the total Z' width, and the BSM ones the remaining 23%. These are splitted into down quark decays ($\sim$ 9%) into charginos(4.2%) and neutralinos (8.4%). The Z' decays into Higgs are characterized from negligible branching fractions : H^+H^- and HA are

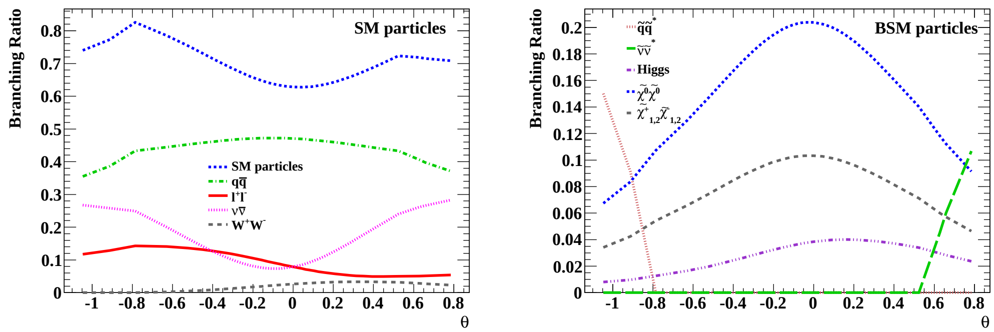


Fig. 2. – Dependence of the Z' decay rates on the U(1)' mixing angle θ (left) SM modes; BSM channels (right).

about 0.5%, $H^{\pm}W^{\mp}$only 0.1% and even more modest rate($\mathcal{O}(10^{-7})$) is due to Higgs gauge boson decays, hZ, ZH, hA.

The validity of these considerations, obtained in a particular configuration (Reference Point, eq. (5)) can be extended in a more general context. On these basis, it is possible conclude that the Z' BSM branching fractions are not negligible and consequently have to be accounted in the search for new physics.

At this point, it is interesting to investigate the dependence of the branching fractions into standard model and supersymmetric particles on the $U(1)'$ and MSSM parameters, at Reference Point (eq. (5)), varying individually one parameter at time. In fig. 2, the dependence of the branching ratios on the parameter θ, the model parameter, are presented for SM (left) and BSM (right) decays.

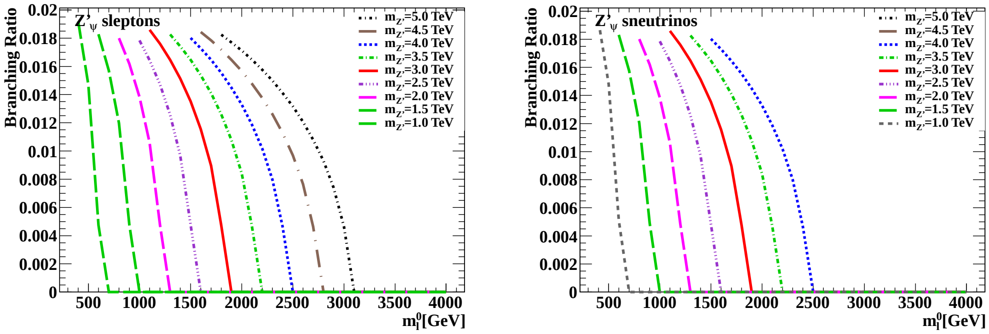
5. – Z′ decays into final states with leptons

Leptonic final states are typically the golden channels for the LHC experimental searches. Therefore, the decays of the Z' into supersymmetric particles, leading to final states with charged leptons and missing energy, due to the presence of neutralinos or neutrinos are investigated.

The two charged lepton final state may originate from primary decays $Z' \to \tilde{\ell}^+\tilde{\ell}^-$ followed by $\tilde{\ell}^{\pm} \to \ell^{\pm}\tilde{\chi}^0_1$ or from chargino chain decays $Z' \to \tilde{\chi}^{\pm}_2\tilde{\chi}^{\mp}_2$ with a subsequently decay of $\tilde{\chi}^{\pm}_2 \to \ell^{\pm}\tilde{\chi}^0_1$.

The four charged lepton final state is originated from sneutrino, $\tilde{\nu}$, decays or $Z' \to \tilde{\nu}_2\tilde{\nu}^*_2$ with a subsequent decay chain $\tilde{\nu}_2 \to \tilde{\chi}^0_2\nu$, and $\tilde{\chi}^0_2 \to \tilde{\ell}^+\tilde{\ell}^-\tilde{\chi}^{\pm}_1$ and finally $\tilde{\ell}^{\pm} \to \ell^{\pm}\tilde{\chi}^0_1$. At same four lepton final is contributing as well the Z' decays into neutralino. The SUSY decay chain is $Z' \to \tilde{\chi}^0_2\tilde{\chi}^0_2$ with subsequent $\tilde{\chi}^0_2 \to \tilde{\ell}^{\pm}\tilde{\ell}^{\mp}$ and $\tilde{\ell}^{\pm} \to \ell^{\pm}\tilde{\chi}^0_1$ processes. In the following, it is performed the study of Z' decays into leptonic final states for a given set of the MSSM and $U(1)'$ parameters, in the various models of sec. **2**·2, varying $m^0_{\tilde{\ell}}$, the initial common slepton mass, at various $m_{Z'}$ values. The same set of parameters as eq. (5) but $m_{\tilde{q}}$=5 TeV and M_1=150 TeV are used.

•*Reference Point: Model* $\mathbf{Z}'_{\eta}$. The Z' boson cannot decay into charged slepton because of phase space limitations, but the Z' decays into charginos and neutralinos are accessible, with a branching ratios about $5-6\%$ and up to $10-12\%$, respectively. Decays



Branching ratio of the Z'_ψ boson into charged slepton (left) sneutrino (right) pairs as a function of the initial condition for the slepton mass, $m^0_{\tilde\ell}$, and for several values of $m_{Z'}$.

into WW pairs, or Higgs bosons associated with Z's are also permitted, with rates about 3%. The sneutrinos branching fraction decreases at higher $m^0_{\tilde\ell}$ results in an enhancement of the SM branching ratios into $q\bar q$ and $\nu\bar\nu$ pairs. Summing up the contributions from sneutrinos, charginos and neutralinos, the branching ratio into non-standard model particles, $\mathrm{BR}_{\mathrm{BSM}}$, runs from 24 to 33%, confirming the relevance of these decays in any analysis accounting for Z' production in a supersymmetric scenario.

•*Reference Point:* $\mathbf{Z}'_\psi$. In this case, the supersymmetric decays into charged slepton and neutral slepton pairs have the same branching fractions ($\sim 2\%$). Furthermore, even the decays into gauginos are relevant, with the branching fractions into $\tilde\chi^+\tilde\chi^-$ and $\tilde\chi^0\tilde\chi^0$ being about 10 and 20% respectively. The rates into boson pairs, *i.e.* Zh and WW, are also non negligible and account for about 3% of the total decay probability.
As a whole, the Z'_ψ modeling, above depicted, yields branching ratios about 35-40% into BSM particle, and therefore it may look like being a promising scenario to investigate Z' production within the MSSM. Figure **5** finally displays the branching ratios into sneutrinos and charged sleptons as a function of $m^0_{\tilde\ell}$ and for several values of $m_{Z'}$.

•*Reference Point:* $\mathbf{Z}'_{\mathrm{N}}$. Both decays into pairs $\tilde\ell_2\tilde\ell_2^*$ and $\tilde\nu_2\tilde\nu_2^*$ are kinematically allowed, whereas $\tilde\ell_1$ and $\tilde\nu_1$ are too heavy to be produced in Z' decays. The D-term addition to the initial condition for slepton mass, $m^0_{\tilde\ell}$, has an opposite effect on the two lepton mass eigenstates; increases the $\tilde\ell_1$, $\tilde\nu_1$ values and decreases $\tilde\ell_2$. Its impact on $\tilde\nu_2$ is neglegible, consequently it is possible assume $m_{\tilde\nu_2} \simeq m^0_{\tilde\ell}$. Although, the $Z' \to \tilde\nu_2\tilde\nu_2^*$ is kinematically allowed, the coupling Z' to sneutrinos is zero, as the corresponding branching fractions. As for the other supersymmetric decay channels, the rates into charginos and neutralinos are quite significant and amount to about 9% and 18%, respectively. The decays into WW and Zh states account approximatly 1-2%, whereas the branching ratio into charged slepton pairs just about 1%, even in the most favorable case. As a whole, the rates into BSM final states run from 28 to about 35%, thus displaying a quite relevant contribution to the total Z' cross section.

• *Reference Point:* $\mathbf{Z}'_{\mathrm{I}}$. This model has been extensively discussed as Representative Point, in sec. **4**. It exhibits the property that the initial slepton mass $m^0_{\tilde\ell}$ can decreases as low few GeV, still preserving a physical scenario for the sfermion masses. D-term correction to the slepton mass is quite relevant for $\tilde\ell_1$, $\tilde\nu_1$ and $\tilde\nu_2$, especially for small values of $m^0_{\tilde\ell}$, whereas it is quite irrelevant for the $\tilde\ell_2$ case. As the D-term turns out to be positive and quite large, this has the result that the only kinematically permitted decay would $Z' \to \tilde{\ell}_2\tilde{\ell}_2^*$. Unfortunately, with the same arguments discussed for $Z'_{\rm N}$ model, the coupling of the Z' to $\tilde{\ell}_2$ is null, preventing the slepton production in Z' decays, as this scenario is concerned.

In conclusion, Z' can decay neither in neutral neither in charged slepton. Therefore, the dependence on $m^0_{\tilde{\ell}}$ is uninteresting. The total $\mathrm{BR}_{\rm BSM}$ ratio lies between 12 and 17% and is mostly due to decays into chargino ($\sim 4\%$) and neutralino ($\sim 8-9\%$) pairs. Decays involving supersymmetric Higgses as H^+H^-, WH,HA are possible, but with a negligible branching ratio at lower Z' masses, reaching at most $\sim 3\%$ for $m_{Z'} > 4$ TeV.

•*Reference Point:* $\mathbf{Z}'_{\rm S}$. As in $Z'_{\rm I}$ model, the initial slepton mass $m^0_{\tilde{\ell}}$ can reach few GeV, still having a meaningful supersymmetric spectrum. Consequently, the $m^0_{\tilde{\ell}}$ low limit is chosen at 200 GeV, on basis of direct limit set by experimental searches. The $Z'_{\rm S}$ decay rates are roughly independent of initial slepton mass. The D-term impact on slepton masses is always positive, having an important effect on $m_{\tilde{\ell}_1}$, $m_{\tilde{\nu}_1}$, $m_{\tilde{\nu}_2}$, but limited on $m_{\tilde{\ell}_2}$. Then, $Z' \to \tilde{\ell}_2\tilde{\ell}_2^*$ is the only decay kinematically allowed. in the leptonic sector. However, the branching ratio into charged sleptons is very small, about 0.1%, even for low $m^0_{\tilde{\ell}}$ values .

As for the other BSM decay modes, the most relevant are the chargino ($\sim$ 3%) and neutralino ($\sim$ 6-7%) pairs, being the others quite negigible. For $m_{Z'}$=5 TeV branching ratio into squark pairs is important, roughly 8%. The D-term for $\tilde{d}_2$-type squarks is negative, and at large values of the Z' mass, as 5 TeV, became important and allowing the decays into $\tilde{d}_2\tilde{d}_2^*$. The slepton branching ratios are small for any $m_{Z'}$ and independent of the slepton mass.

As a whole, one can say that, in this case, for $m_{Z'} < 5$ TeV the non-standard model decay rate is about 10-12%, becaming higher at larger Z' masses, even above 20%, due to the opening of the decay into squark pairs. The experimental signature of squark production is jets final state, difficult to separate from the QCD SM backgrounds. Therefore, this scenario seems, therefore, not very promising for a possible discovery of supersymmetry via Z' decays.

•*Reference Point:* $\mathbf{Z}'_\chi$. The $U(1)'$ group, Z'_χ does not lead to a meaningful sfermion scenario within our parametrization, as the sfermion masses are unphysical after the addition of the D-term. For any $m_{Z'}$, the rates into quark and neutrino pairs are the dominant ($\sim$ 40-45%), whereas the branching ratio into lepton states is approximately 12% and the other modes (WW, Zh, HA and $H^\pm H^\mp$) accounting for the remaining 1-3%. As a whole, the Z'_χ model is not adequate for possible supersymmetry analysis.

•*Reference Point:* $\mathbf{Z}'_{\rm SSM}$. This model is considered as benchmark, since the production cross section just depends only on the Z' mass, neither on the mixing angle θ, neither on possible new physics parameters, as MSSM. As for the supersymmetric sector, the sfermion masses get the D-term part originated from the hyperfine splitting contribution, and not that from MSSM further extensions. Moreover, the Z' coupling constant to the sfermions can be simply written as $g_{\rm SSM} = g_2/(2\cos\theta_W)$. As the hyperfine-splitting D-term is not too large, the sfermion spectrum is physical, even at very small $m^0_{\tilde{\ell}}$ values. At $m^0_{\tilde{\ell}} = 100$GeV, including the D-term, $m_{\tilde{\nu}_1}$ decreases by about 25%; $m_{\tilde{\ell}_1}$, $m_{\tilde{\ell}_2}$ undergo to slightly positive variation; $m_{\tilde{\nu}_2}$ is roughly unchanged. At larger $m^0_{\tilde{\ell}}$ values, D-term effect on all slepton masses is negligible and are approximatly equal to initial slepton mass, $m^0_{\tilde{\ell}}$.

The decays into non-standard model particles, $\mathrm{B}_{\rm BSM}$, exhibit rates, about 60-65%, $\mathrm{BR}_{\rm SM}$

higher than the standard model ones, 35-40%. The B_{BSM} is composed mostly from decays into neutralinos ($\sim 30\%$) and charginos ($\sim 16-18\%$), with a more limited contribution into sneutrinos($\sim 4\%$) and charged sleptons (1- 2%). Other channels involving Higgs and gauge boson are contributing as WW ($4-5\%$), H^+H^- (3%) for $m_{Z'} > 2.5$ TeV, Zh and hA (1-4 %) $m_{Z'} > 1.5$ TeV.

6. – Cross sections and event rates at the LHC

In this section, the Z' total production cross section at the LHC is presented according to the several models discussed through this paper (sec. **2**˙2), including the Sequential Standard Model. The pp collisions at two center-of-mass energies: $\sqrt{s}$= 8 TeV(2012 run) and $\sqrt{s}$= 14 TeV, the ultimate project energy ,are considered. For these two values, the cross sections are calculated and the expected number of events with Z' decaying into supersymmetric particles, with few integrated luminosities, $\int \mathcal{L}\, dt$ are estimated.

6˙1. *Leading order* $\mathbf{Z}'$ *production cross section.* – The cross sections is calculated at leading order (LO) with, for consistency, the LO parton distribution functions CTEQ6L. Different LO PDFs have a negligible impact on the cross section results. In the calculations, the factorization is set equal to the Z' mass.

As far as the total cross section is concerned, the parton-level process is analogous to Z production, *i.e.* it is the purely SM quark-antiquark annihilation $q\bar{q} \to Z'$.
Since the coupling of the Z' to the quarks depends on the specific $U(1)'$ scenario, the production rate is a function of the mixing angle θ, and of the Z' mass, but not of the MSSM parameters.

Figure 3 presents in logarithmic the total cross section for the different models, including the SSM, as a function of $m_{Z'}$ at $\sqrt{s}$= 8 TeV (fig. 3, left) and 14 TeV (fig. 3, right). The highest production cross section corresponds to SSM model, whereas the lowest to Z'_ψ model. The others model cross sections are lying between those and are indistinguishable at large $m_{Z'}$ value.
The cross section varies according $m_{Z'}$, center-of-mass energy and model.

The model choice has a more limited impact on the absolute value of cross section, but there are important differences as function of $\sqrt{s}$. The change by several order of magnitudes is present as function of Z' mass.

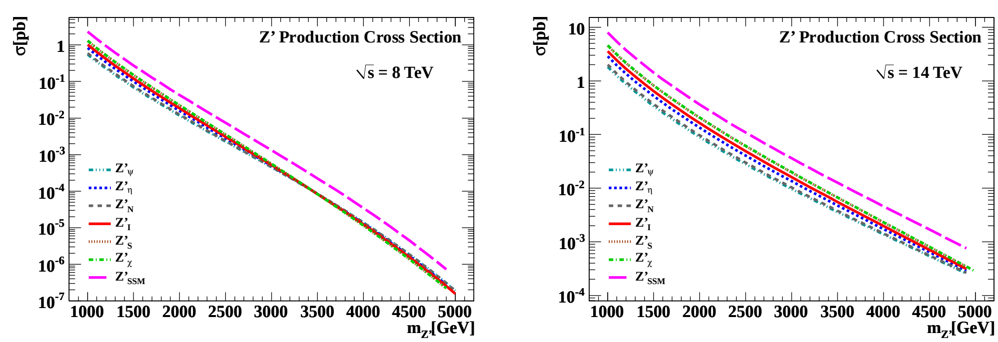


Fig. 3. – Cross section (logarithmic scale) of Z' production in pp collisions at center-of-mass energy, $\sqrt{s}$= 8 TeV (left) and $\sqrt{s}$= 14 TeV (right), for various models (see text).

TABLE II. – *Number of supersymmetric particles ($N_{\rm casc}$ and $N_{\rm slep}$) at the LHC, for Z' production in different $U(1)'$ models as well as in the Sequential Standard Model as function of $m_{Z'}$ in TeV,at $\sqrt{s}$= 8 TeV, $\int\mathcal{L}\,{\rm d}t$= 20 fb^{-1}and at $\sqrt{s}$= 14 TeV, $\int\mathcal{L}\,{\rm d}t$= 100 fb^{-1}.*

Model	$m_{Z'}$	$N_{\rm casc}^{\sqrt{s}=8\ \rm TeV}$	$N_{\rm slep}^{\sqrt{s}=8\ \rm TeV}$	$N_{\rm casc}^{\sqrt{s}=14\ \rm TeV}$	$N_{\rm slep}^{\sqrt{s}=14\ \rm TeV}$
Z'_η	1.5	523	–	13650	–
Z'_η	2	55	–	2344	–
Z'_ψ	1.5	599	36	10241	622
Z'_ψ	2	73	4	2784	162
$Z'_{\rm N}$	1.5	400	17	9979	414
$Z'_{\rm N}$	2	70	3	2705	104
$Z'_{\rm I}$	1.5	317	–	8507	–
$Z'_{\rm I}$	2	50	–	2230	–
$Z'_{\rm S}$	1.5	30	–	8242	65
$Z'_{\rm S}$	2	46	–	2146	16
$Z'_{\rm SSM}$	1.5	2968	95	775715	24774
$Z'_{\rm SSM}$	2	462	14	19570	606

6·2. *Event rates with sparticle production in* $\mathbf{Z'}$ *decays at the LHC*. – In the following, the domain where the supersymetric Z' decays would be detectable is investigated. For this purpose, two scenarios are considered: $\sqrt{s}$=8 TeV with an expected integrated luminosity,$\int\mathcal{L}\,{\rm d}t$=20 fb^{-1}, as expected in 2012 LHC data taking and a future scenario $\sqrt{s}$=14 TeV with $\int\mathcal{L}\,{\rm d}t$=100 fb^{-1}.

The number of expected events in this two scenarios is summarized in tab. II for $m_{Z'}$=1.5 and 2 TeV. As discussed in sec **6**, the leptonic final state can be yielded by direct slepton decays or by a SUSY cascade originated from primary decays into sneutrinos, charginos and neutralino pairs, ($N_{\rm casc} = N_{\tilde\nu\tilde\nu^*} + N_{\tilde\chi^+\tilde\chi^-} + N_{\tilde\chi^0\tilde\chi^0}$). Likewise, $N_{\rm slep}$ is the number of events with a Z' decaying to charged-slepton pairs.

In both luminosity (energy) regimes, due to a large cross sections, the Sequential Standard Model is the one yielding the highest number of events with production of supersymmetric particles in Z' decays, up to $\mathcal{O}(10^5-10^4)$ at $\sqrt{s}$=14 TeV with $\int\mathcal{L}\,{\rm d}t$= 100 fb^{-1}and a Z' mass $m_{Z'}$=1.5 TeV.

As already discussed (sec. **6**) in the Z'_η and $Z'_{\rm I}$ models the Z' direct slepton decays are prevented, as reflected in tab. II and the only supersymmetric decays are into sneutrino, neutralino and chargino pairs. The direct slepton decays can be produced in $Z'_{\rm N}$ model and a few hundreds of them are expected in the high luminosity phase. In the $Z'_{\rm S}$ scenario, Z' boson leads to many cascade particles in the high luminosity regime, according to the Z' mass and a few tenths of direct leptons.

Before concluding this subsection, it has to be pointed out that, although the numbers in tab. II encourage optimistic prediction on the discovery of Z' decays into sparticles specially in the high luminosity phase, however, before draw a conclusive statement on this issue, it is necessary to carry out a study taking account detector acceptance and resolution, trigger, and analysis cuts on jets and leptons. Then, the result presented through this paper should be seen a first step towards a more through investigation, which requires, above all, the implementation of the models herein discussed into a Monte Carlo event generator.

7. – Conclusions

In this paper, the production and decays of new neutral Z' boson, according to new physics models based on a $U(1)'$ gauge group and to the Sequential Standard Model is discussed. Decays in standard model and non-standard model particles are included. In this perspective, all quoted experimental limits have to be revisited.
The extension of the Minimal Supersymmetric Standard Model with $U(1)'$ group implies new features as an extra Higgs boson, two novel neutralinos and a modification of the sfermion mass by a D-term, where the new features are embedded. All these aspects have been studied as function of various $U(1)'$/MSSM parameters, *e.g.* $U(1)'$ mixing angle θ, the Z' boson mass, M_1, M_2, M', the soft masses for the gaugino etc. Only scenarios with all physical sfermion masses are considered.
A study, as function of slepton and Z' masses, has been performed on the partial widths and branching ratios of the Z', with attention to final states with charged leptons and missing energy. These configurations are favorable to experimental detection in hadronic events and can be yielded by intermediate charged sleptons or a SUSY cascade through neutralinos, chargino, sneutrinos.
Then, the LO production cross sections in all investigated models has been evaluated and an estimate of expected events at few centre-of-mass energy and integrated luminosity has been provided. The result of this study is that for some models and parametrization, one can even have $10^4 - 10^5$ events with sparticle production in Z' decays.

As additional remarks, the $Z' \to \tilde{\ell}^+\tilde{\ell}^-$ decay present two interesting issues. One for the determination slepton masses having the additional constrain of the Z' mass. The second is to explore corner of high region of slepton masses unreachable with other productions.

In summary, this can be considered a useful starting point to study Z' production and decay beyond the Standard Model, such as within supersymmetric theories, drawing a guideline for future experimental analysis.

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