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Electroweak superpartners scrutinized at the LHC in events with multi-leptons

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We analyze a multi-lepton signal plus missing transverse energy from neutrinos expected at the LHC for a bino-like neutralino as the lightest supersymmetric particle (LSP), when the left sneutrino is the next-to-LSP and hence a suitable source of binos. The discussion is carried out in the framework of the $\mu\nu$SSM, where the presence of R-parity violating (RPV) couplings involving right-handed neutrinos solves the μ problem and can reproduce simultaneously the neutrino data. Left sneutrinos/sleptons are pair-produced at pp collisions decaying to binos, with the latter decaying via RPV to $W\ell$ or $Z\nu$. This signal can be compared with LHC searches for electroweak superpartners through chargino–neutralino production. The reduced cross section of the sneutrino/slepton production in comparison with the one of the latter process, limits the sensitivity of the searches to small sneutrino/slepton masses. Although the resulting compressed spectrum typically evades the aforementioned searches, we show that analyses using recursive jigsaw reconstruction are sensitive to these scenarios. As a by-product, we find that the region of bino masses 110–120 GeV and sneutrino masses 120–140 GeV can give rise to a tri-lepton signal compatible with the local excess recently reported by ATLAS.

1. Introduction

Search for supersymmetry (SUSY) at accelerators has been focused mainly on signals with missing transverse energy (MET) inspired in R-parity conserving (RPC) models, such as the minimal supersymmetric standard model (MSSM) [1–3], where significant bounds on sparticle masses have been obtained [4]. In particular, strongly interacting sparticles have to have masses above about 1 TeV, whereas the bound for the weakly interacting sparticles is about 100 GeV, with the exception of the bino-like neutralino which is basically not constrained due to its small pair production cross section. Qualitatively similar results have also been obtained in the analysis of simplified R-parity violating (RPV) scenarios with trilinear lepton- or baryon-number violating terms [5], assuming a single channel available for the decay of the lightest supersymmetric particle (LSP). However, such assumption is not possible in other RPV scenarios, such as the 'μ from ν' supersymmetric standard model ($\mu\nu$SSM) [6,7], where the several decay branching ratios (BRs) of the LSP significantly decrease the signal. This implies that a naive extrapolation of the usual bounds on sparticle masses to the $\mu\nu$SSM is not applicable. In addition, in RPV models basically all sparticles are potential candidates for LSPs, and therefore analyses of the LHC phenomenology associated to each candidate are crucial to test them.

The only recent analyses [8,9] of signals at the LHC for LSP candidates in the $\mu\nu$SSM have been dedicated to the left sneutrino.[1] There it was shown that because the left sneutrino has several relevant decay modes, the LEP lower bound on the sneutrino mass of about 90 GeV [14–19] obtained under the assumption of BR one to leptons, via trilinear RPV couplings, is not applicable in the $\mu\nu$SSM. The same conclusion was obtained for the left slepton, given that searches for its direct decay are not relevant because it decays through an off-shell W and a sneutrino. Thus, in Ref. [8] the prospects for detection of signals with di-photon plus leptons or

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[1] The phenomenology of a neutralino LSP was analyzed in the past in Refs. [10–13].

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MET from neutrinos, and multi-leptons, from the pair production of left sneutrinos/sleptons and their prompt decays were analyzed. A significant evidence is expected only in the mass range of about 100 to 300 GeV. The mass range of 45 to 100 GeV (with the lower limit imposed not to disturb the decay width of the Z) was covered in Ref. [9], studying the displaced-vertex decays of the left sneutrino LSP producing signals with di-lepton pairs. Using the present data set of the ATLAS 8-TeV dilepton search [20], one is able to constrain the left sneutrino LSP only in some regions of the parameter space of the $\mu\nu$SSM, especially when the Yukawa couplings and mass scale of neutrinos are rather small. In order to improve the sensitivity of this search, it was proposed in [9] an optimization of the trigger requirements exploited in ATLAS based on a high level trigger that utilizes the tracker information.

All this shows that the common lore on sparticle mass bounds must be carefully re-analyzed in the light of different theoretical models. This crucial task given the current experimental results on SUSY searches, has just started in the case of the $\mu\nu$SSM, and it has been concentrated for the moment on the electroweak sector as discussed above. In this context, where basically the masses are poorly constrained or not at all, we consider crucial to take into account the recent searches at the LHC for events with multi-leptons plus MET [21–24], since they can be compared with $\mu\nu$SSM signals. This is the aim of this work.

In the $\mu\nu$SSM, when the bino-like neutralino is the LSP with the left sneutrino the next-to-LSP (NLSP), the RPC decays $\tilde{\nu} \to \nu\tilde{\chi}_1^0$ and[2] $\tilde{\ell} \to \ell\tilde{\chi}_1^0$ dominate over the RPV ones, thereby pair production of sneutrinos/sleptons at the LHC will be a source of bino pairs. Subsequently, binos will decay via RPV couplings to $W\ell$ or $Z\nu$, giving rise to signals with multi-leptons plus MET from neutrinos. In addition, we will also obtain regions of bino and sneutrino masses producing a tri-lepton signal compatible with the local excess reported by ATLAS [24]. There, this signal was studied in the context of simplified RPC models, assuming wino-like chargino–neutralino production with a bino-like LSP. This scenario was further elaborated in Refs. [25,26], including also dark matter constraints and the measured anomalous magnetic moment of the muon.

The paper is organized as follows. In Section 2, we will briefly review the $\mu\nu$SSM and its relevant parameters for our analysis of the electroweak sector. In Section 3 we will introduce the phenomenology of the bino-like LSP with the left sneutrino as the NLSP, studying their relevant pair production at the LHC, as well as the signals. On the way, we will analyze the decay widths, BRs and decay lengths of the bino. In Section 4, we will consider the recent ATLAS searches for multi-leptons plus MET, and discuss their significance on bino searches in the $\mu\nu$SSM. We will also show our prescription for recasting the ATLAS result [24] to the case of the sneutrino–bino scenario. We then will show in Section 5 the prospects for the searches at the LHC using an integrated luminosity of 100 and 300 fb^{-1}. Our conclusions and outlook will be presented in Section 6.

2. The $\mu\nu$SSM

The $\mu\nu$SSM [6,7], is a natural extension of the MSSM, where the μ problem is solved and, simultaneously, the neutrino data can be reproduced [6,7,10,11,27,28]. This is obtained through the presence of trilinear terms in the superpotential involving right-handed neutrino superfields $\hat{\nu}_i^c$, which relate the origin of the μ-term to the origin of neutrino masses and mixing. The simplest superpotential of the $\mu\nu$SSM [6,7] is built with one $\hat{\nu}^c$:

$$W = \epsilon_{ab}\left(Y_{e_{ij}}\,\hat{H}_d^a\,\hat{L}_i^b\,\hat{e}_j^c + Y_{d_{ij}}\,\hat{H}_d^a\,\hat{Q}_i^b\,\hat{d}_j^c + Y_{u_{ij}}\,\hat{H}_u^b\,\hat{Q}^a\,\hat{u}_j^c\right)$$
$$+\epsilon_{ab}\left(Y_{\nu_i}\,\hat{H}_u^b\,\hat{L}_i^a\,\hat{\nu}^c - \lambda\,\hat{\nu}^c\,\hat{H}_u^b\hat{H}_d^a\right) + \frac{1}{3}\kappa\,\hat{\nu}^c\hat{\nu}^c\hat{\nu}^c\,, \qquad (1)$$

where the summation convention is implied on repeated indices, with $a, b = 1, 2$ $SU(2)_L$ indices and $i, j = 1, 2, 3$ the usual family indices of the standard model.

The simultaneous presence of the last three terms in Eq. (1) makes it impossible to assign R-parity charges consistently to the right-handed neutrino ν_R, thus producing explicit RPV (harmless for proton decay). Note nevertheless, that in the limit $Y_{\nu_i} \to 0$, $\hat{\nu}^c$ can be identified in the superpotential as a pure singlet superfield without lepton number, similar to the next-to-MSSM (NMSSM) [29], and therefore R parity is restored. Thus, the neutrino Yukawa couplings Y_{ν_i} are the parameters which control the amount of RPV in the $\mu\nu$SSM, and as a consequence this violation is small. After the electroweak symmetry breaking induced by the soft SUSY-breaking terms of the order of TeV, and with the choice of CP conservation, the neutral Higgses develop the vacuum expectation values (VEVs) $\langle H_{d,u}\rangle = \frac{v_{d,u}}{\sqrt{2}}$, the right sneutrinos $\langle \widetilde{\nu}_R\rangle = \frac{v_R}{\sqrt{2}}$, and the left sneutrinos $\langle \widetilde{\nu}_i\rangle = \frac{v_i}{\sqrt{2}}$, where $v_R \sim$ TeV whereas $v_i \sim Y_{\nu_i} v_u \lesssim 10^{-4}$ GeV because of the small contributions $Y_{\nu_i} \lesssim 10^{-6}$ whose size is determined by the electroweak-scale seesaw of the $\mu\nu$SSM [6,7]. Note in this sense that the last term in Eq. (1) generates dynamically Majorana masses, $m_{\mathcal{M}} = 2\kappa\frac{v_R}{\sqrt{2}} \sim$ TeV. On the other hand, the fifth term in the superpotential generates the μ-term, $\mu = \lambda\frac{v_R}{\sqrt{2}} \sim$ TeV.

The new couplings and sneutrino VEVs in the $\mu\nu$SSM induce new mixing of states. The associated mass matrices were studied in detail in Refs. [7,11,8]. Summarizing, in the case of one $\hat{\nu}^c$ there are six neutral scalars and five neutral pseudoscalars (Higgses-sneutrinos), seven charged scalars (charged Higgses-sleptons), five charged fermions (charged leptons-charginos), and eight neutral fermions (neutrinos–neutralinos). In our analysis of the electroweak sector below, we are mainly interested in the scalars/pseudoscalars and neutral fermions.

The neutral fermions have the flavor composition $(\nu_i, \widetilde{B}, \widetilde{W}, \widetilde{H}_d, \widetilde{H}_u, \nu_R)$. Thus, with the low-energy bino and wino soft masses, M_1 and M_2, of the order of TeV, and the same for μ and $m_{\mathcal{M}}$ as discussed above, this generalized seesaw produces three light neutral fermions dominated by the left-handed neutrino flavor composition. One neutrino gets its mass at tree level, whereas the other two at one loop. As discussed in Ref. [9], the tree-level mass can be approximated as $m_\nu \approx \sum_i v_i^2/4M$, with $\frac{1}{M} \equiv \frac{g'^2}{M_1} + \frac{g^2}{M_2}$. The rest of neutral fermions get masses around the TeV scale. However, if M_1 is small compared with the rest of the parameters, the fourth lightest eigenstate of the mass matrix, which we identify as the lightest neutralino $\tilde{\chi}_1^0$, is mainly bino dominated and the LSP with $m_{\tilde{\chi}_1^0} \approx M_1$, since the largest off-diagonal mass entry $m_{\tilde{B}\tilde{H}_u} = \frac{1}{\sqrt{2}}g' v_u$ is small.

The neutral scalars have the flavor composition $(H_d^{\mathcal{R}}, H_u^{\mathcal{R}}, \widetilde{\nu}_R^{\mathcal{R}}, \widetilde{\nu}_i^{\mathcal{R}})$, but the off-diagonal terms of the mass matrix mixing the left sneutrinos with Higgses and right sneutrinos are suppressed by Y_ν and v_{iL}, implying that the left sneutrino states will be almost pure. The same happens for the pseudoscalar left sneutrino states $\widetilde{\nu}_i^{\mathcal{I}}$, which have in addition degenerate masses with the scalars $m_{\widetilde{\nu}_i^{\mathcal{R}}} \approx m_{\widetilde{\nu}_i^{\mathcal{I}}} \equiv m_{\widetilde{\nu}_i}$. Their approximate tree-level value is $m^2_{\widetilde{\nu}_i} \approx \frac{Y_{\nu_i} v_u}{2 v_i} v_R(-\sqrt{2}A_{\nu_i} - \kappa v_R + \frac{\lambda v_R}{\tan\beta})$, where A_{ν_i} are the trilinear

[2] In what follows, the notation slepton (lepton) will be used for a charged slepton (charged lepton), and sneutrino (neutrino) for a neutral slepton (neutral lepton). The symbol ℓ will be used for electron, muon or tau $\ell = e, \mu, \tau$, and charge conjugation of fermions is to be understood where appropriate.

parameters in the soft Lagrangian, and $\tan\beta \equiv v_u/v_d$. As discussed in Ref. [8], there is enough freedom in the $\mu\nu$SSM to tune the soft parameters in order to get light sneutrinos. Besides, the left sleptons will also be light, only a little heavier than the left sneutrinos since they are in the same $SU(2)$ doublet, with the mass splitting mainly due to the usual small D-term contribution, $-m_W^2 \cos 2\beta$.

3. Bino-like LSP phenomenology in the $\mu\nu$SSM

The pair production cross section of bino-like neutralinos at large hadron colliders is very small, since there is no direct coupling between the bino flavor state and the gauge bosons, and we are assuming that the rest of the spectrum remains decoupled. Binos are produced mainly through virtual Z bosons in the s channel exploiting their small Higgsino flavor composition, or through the t channel interchange of virtual first generation squarks, strongly suppressed by their large masses. Nevertheless, the bino-like LSP can be produced in the decay of other SUSY particles, which although heavier, have a higher production cross section at the LHC. That is the case when the left sneutrino is the NLSP. After production, the left sneutrinos decay to the bino LSP.

The dominant pair-production channels of sleptons at hadron colliders were studied in Refs. [30–35]. The main production channels at the LHC are through a virtual Z boson in the s channel for the pair production of scalar and pseudoscalar left sneutrinos $\tilde{\nu}\tilde{\nu}$, a virtual W boson for the production of a left slepton and a (scalar or pseudoscalar) sneutrino $\tilde{\ell}\tilde{\nu}$, and both virtual Z and γ for the pair production of left sleptons $\tilde{\ell}\tilde{\ell}$. Note that although the left sneutrino is lighter than its corresponding left slepton as discussed in the previous section, since the mass separation is always smaller than m_W, the phase space suppression makes the decay $\tilde{\ell} \to \tilde{\chi}_1^0 + \ell$ dominant.

In Fig. 1, we show the production channels as well as the RPC decays of the left sneutrino and left slepton to produce the bino LSP, which dominate over the RPV ones since these are suppressed by the smallness of Y_ν. The right sleptons can be also a source of bino LSP at the LHC. If their masses are similar to the ones of the left sleptons, an additional diagram as the third one of Fig. 1 will be present. However, the production cross section corresponding to this extra diagram is significantly smaller than for those shown in Fig. 1. Altogether, the number of binos produced after the decay of right sleptons is around a tenth of the number produced through left sneutrinos/sleptons.

If the mass of the bino-like neutralino lies between the Higgs and Z masses, the possible two body RPV decays are to $W\ell$ and $Z\nu$, as shown also in Fig. 1. There we only depicted the decay of each neutralino pair to W and Z, and the leptonic decays of the latter. Note nevertheless that both neutralinos can also decay to Z or W indistinctly, and that the hadronic decay of the W boson, as well as the invisible decay of one of the Z's, contribute to the signal of leptonic searches, in addition to the diagrams displayed. As we will discuss in Section 5, the latter processes can also contribute to the signal we are interested in analyzing, but with smaller yields. The bino decays are mediated through the RPV mixing between the bino and neutrinos. Although three body decays involving virtual Higgs boson or other virtual heavier scalars are possible, all of them suffer from kinematic suppression. Thus the relevant diagrams will be the two body decays, and approximate formulas for the partial decay widths are as follows:

$$\Gamma(\tilde{\chi}^0 \to W\ell_i) \approx \frac{g^2 m_{\tilde{\chi}^0}}{16\pi}\left(1-\frac{m_W^2}{m_{\tilde{\chi}^0}^2}\right)^2\left(1+\frac{m_{\tilde{\chi}^0}^2}{2m_W^2}\right)\left|U^V_{\tilde{B}\nu_i}\right|^2, \tag{2}$$

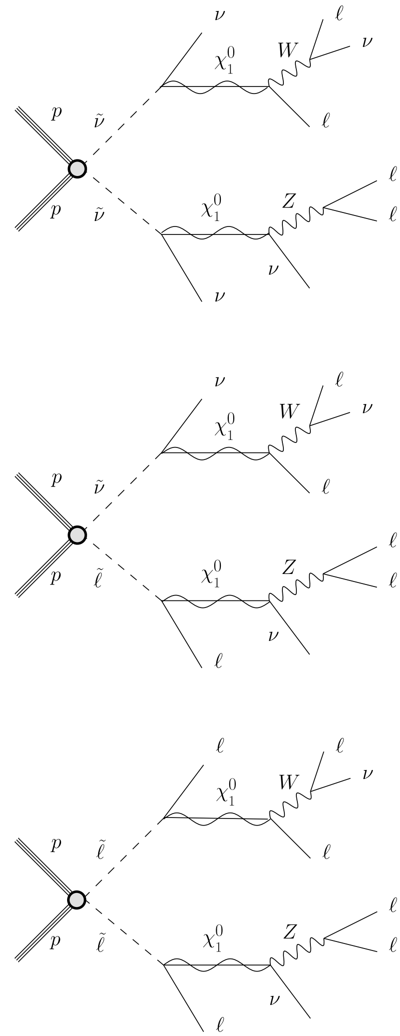

Fig. 1. Relevant diagrams of the benchmark $\mu\nu$SSM scenario of RPC left sneutrino/slepton pair production, followed by the RPV decay of the bino-like LSP, $\tilde{\chi}_1^0$.

$$\sum_i \Gamma(\tilde{\chi}^0 \to Z\nu_i) \approx \frac{g^2 m_{\tilde{\chi}^0}}{16\pi\cos^2\theta_W}\left(1-\frac{m_Z^2}{m_{\tilde{\chi}^0}^2}\right)^2 \times\left(1+\frac{m_{\tilde{\chi}^0}^2}{2m_Z^2}\right)\sum_i\left|\sum_j U^V_{\tilde{B}\nu_j}U^{V*}_{\nu_i\nu_j}\right|^2, \tag{3}$$

where U^V is the matrix that diagonalizes the mass matrix for the neutral fermions [7,8], and $U^V_{\tilde{B}\nu_i}$ can be approximated as $\frac{g'\nu_i}{M_1}$.

Since we are interested in the next sections in analyzing signals with electrons or muons in the final states, we focus now on the cases in our parameter space where the decay width of the neutralino to tau is smaller than to the two light families of leptons. This can be achieved by adjusting the sneutrino VEVs, while producing an acceptable mass scale for the neutrinos. For example, in order to optimize the signal we can use $v_1 \approx v_2 > v_3$. Then, we can compare roughly the above decay widths summing over the two light families of leptons. Taking into account the kinematic factors, we obtain for the ratio an approximate upper bound $\approx 2\cos^2\theta_W$, implying that the decay to $W\ell$ will always be at least about a factor of 1.5 larger than the decay to $Z\nu$. On the other hand, given the small value of M_1, from Eqs. (2) and (3) we can also obtain an upper bound for the total width $\gtrsim 10^{-12}$ GeV, corresponding to a proper decay length $c\tau \lesssim 0.2$ mm. This is short enough to expect most of the decays to happen inside the fiducial region defined by the values of the transverse impact parameter (d_0^{PV}) and the longitudinal impact parameter (z_0^{PV}) relative to the primary vertex, considered in prompt ATLAS and CMS searches. Subsequently, the W and Z bosons decay promptly producing leptons, neutrinos or jets. Thus the neutralino could be detectable in events including leptons, jets and/or MET.

Note that if the mass of the LSP drops below the mass of the W boson, its decay is still possible and will proceed through three-body decays mediated by off-shell gauge bosons and scalars. The total width will be in this case smaller, due to the reduced phase space, and will lead to leptons and/or quarks originated at displaced vertices. This signal cannot be tested with the usual sparticles searches, but rather with dedicated analysis. The study of this possibility, although interesting, is beyond the scope of this work.

If the mass of the bino-like neutralino is larger than the one of the Higgs boson, the decay $\tilde{\chi}^0 \to h\nu$ is also possible, with the dominant diagram mediated by the sneutrino–Higgs mixing. The approximate formula for the corresponding partial decay width is given by:

$$\sum_i \Gamma(\tilde{\chi}^0 \to h\nu_i) \approx \frac{g'^2 m_{\tilde{\chi}^0}}{64\pi}\sqrt{1-\left(\frac{m_h}{m_{\tilde{\chi}^0}}\right)^2}\sum_i\left|\sum_j Z^H_{h\tilde{\nu}_j} U^{V*}_{\nu_i\nu_j}\right|^2, \quad (4)$$

where Z^H is the matrix that diagonalizes the mass matrix for the neutral scalars [7,8]. On the one hand, the relative size of the decay of neutralino to Higgs compared to the decay to gauge bosons is suppressed by the kinematic factors. On the other hand, the contribution of the sneutrino–Higgs mixing is not necessarily small compared to the bino–neutrino mixing. Moreover, as discussed in detail in Ref. [8], the former mixing can be enhanced when the mass separation between $m_{\tilde{\nu}}$ and m_{h^0} is small. As a consequence, from the perspective of the searches using events with leptons, the opening of this channel softens the signal.

4. Electroweak searches at the LHC

As shown in the previous section, the production and decay of the sneutrino (and slepton) NLSP when the neutralino is the LSP can produce signals including up to six leptons plus MET. These $\mu\nu$SSM signals can be compared with searches for electroweak SUSY partners at the LHC.

The analyses [21,22] and [23] use the proton–proton (pp) collision data delivered by the LHC at a center-of-mass energy of $\sqrt{s} = 13$ TeV, to search for events with two or three electrons or muons and four or more electrons, muons and taus, respectively. The former analysis targets direct chargino/neutralino and slepton pair production in simplified RPC models, whereas the latter includes the study of simplified RPV scenarios with a lepton-number violating term, targeting direct pair production of chargino/neutralino, left slepton/sneutrino, and gluinos.

In the case of left sleptons/sneutrinos analyzed in Ref. [23] using an integrated luminosity of 36.1 fb^{-1}, the result extends the region of SUSY parameter space previously excluded by ATLAS [36] putting a lower bound of 1.06 TeV on their masses assuming a single RPV channel, $\lambda_{12k}\hat{L}_1\hat{L}_2\hat{e}^c_k$, available for the decay of the neutralino LSP. This assumption is not allowed in the $\mu\nu$SSM where the neutralino LSP has always decay channels to W and Z as shown in the previous section, and, in addition, the BRs of the leptonic decays of the latter are small, of order 0.1 and 0.03, respectively. Taking all this into account, we have checked that no constraint on the left sneutrino/slepton mass is obtained from this search.

Concerning the searches of Refs. [21] and [22] using 35.9 and 36.1 fb^{-1}, respectively, for chargino–neutralino pair production, they assume a wino-like production mechanism and decays with BR one to a bino-like LSP and a leptonically decaying W and Z bosons into final states with three light leptons (*electrons or muons*) or a hadronically decaying W boson and a leptonically decaying Z boson into final states with two light leptons and two jets. In this way, CMS and ATLAS obtained exclusion limits in the parameter space $m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$. For example, for a massless $\tilde{\chi}_1^0$ neutralino, $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses up to approximately 600 GeV are excluded. This analysis uses a moderate to large amount of MET to discriminate against backgrounds, thus it is not sensitive to a compressed spectrum where this amount is not large. Production cross sections for chargino/neutralino pairs at the LHC [37,38] are much larger than the production cross sections for slepton pairs [39]. Thus we have obtained that the kinematic requirement for a mass separation between sleptons and neutralinos to have enough MET, forces the sleptons in the $\mu\nu$SSM to have large masses where the expected number of pairs produced at the LCH is not enough to obtain bounds.

A novel approach for the identification of events coming from the production of sparticles in compressed spectra, where the decay products carry low momenta, is the recursive jigsaw reconstruction (RJR) technique [40,41]. This has made possible to design competitive searches for chargino–neutralino pairs even in scenarios where the mass splitting is close to the mass of the gauge bosons [24]. As we will analyze below, the same analysis can be used to put constraints on the slepton/sneutrino NLSP pair production when the neutralino is the LSP in the $\mu\nu$SSM.

The ATLAS chargino–neutralino search using RJR in Ref. [24] is based on the 13-TeV data with 36.1 fb^{-1}. All the search channels analyzed require two or three light leptons originated from the decay of the gauge bosons plus MET. The different signal regions are optimized to target specific mass splittings between the produced chargino–neutralino and the neutralino LSP, for which the initial state radiation (ISR) signal regions are designed to maximize the sensitive to the case where $\Delta m = m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$ is in the range between 100 and 160 GeV. The results extend the region of SUSY parameter space previously excluded by ATLAS searches in the high- and intermediate-mass regions. In the low-mass and ISR signal an excess of events above the standard model prediction is observed and the region of parameter space below $m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} = 200$ GeV cannot be excluded. In our case, since the production cross section of the left sneutrino/slepton is much smaller than the chargino–neutralino one, the ISR signal regions have the largest sensitivity to the mass range where the production cross section is not negligible, and $m_{\tilde{\chi}_1^0} \gtrsim m_Z$.

In the ISR signal regions, the events have to fit in the "compressed decay tree" described in Ref. [24]. A signal sparticle system S decays to a set of visible momenta V and invisible momentum I recoils from a jet-radiation system ISR. The preselection criteria require exactly two or three light leptons, and between one and three non b-tagged jets. The transverse momentum of the leptons must fulfill $p_T^{\ell_{1/2}} > 25$ and $p_T^{\ell_3} > 20$ GeV. The selection criteria applied to the events after preselection are given in Table 1.

At first at least one same-flavor opposite sign (SFOS) pair is required, and from the formed SFOS pairs the one with invariant mass closest to m_Z should be in the range $(75, 105)$. The remaining lepton is used to construct the W-boson transverse mass, m_T^W, as follows: $m_T^W = \sqrt{2p_T^\ell E_T^{miss}(1-\cos\Delta\phi)}$, where $\Delta\phi$ is the azimuthal opening angle between the lepton associated with the W boson

Table 1
Selection criteria for the 3ℓ_ISR and 2ℓ_ISR signal regions. The variables are defined in Refs. [24] and [40].

Region	$m_{\ell\ell}$ [GeV]	m_T^W [GeV]	$\Delta\phi^{CM}_{ISR,I}$	R_{ISR}	$p^{CM}_{T\ ISR}$ [GeV]	$p^{CM}_{T\ I}$ [GeV]	p^{CM}_T [GeV]
SR3ℓ_ISR	∈ (75, 105)	>100	>2.0	∈ (0.55, 1.0)	>100	>80	<25
Region	m_Z [GeV]	m_J [GeV]	$\Delta\phi^{CM}_{ISR,I}$	R_{ISR}	$p^{CM}_{T\ ISR}$ [GeV]	$p^{CM}_{T\ I}$ [GeV]	p^{CM}_T [GeV]
SR2ℓ_ISR	∈ (80, 100)	∈ (50, 110)	>2.8	∈ (0.4, 0.75)	>180	>100	<20

Table 2
Comparison between the ATLAS cutflow shown in the auxiliary figures of Ref. [24] and our implementation.

Cut applied	ATLAS yield	Implemented yield	Normalized yield
Trigger matching & Preselection	1829	1398	1829
$m_{\ell\ell} \in (75, 105)$ GeV & $m_T^W > 100$ GeV	533	406	531
$\Delta\phi^{CM}_{ISR,I} > 2.0$	408	308	403
$R_{ISR} \in (0.55, 1.0)$	157	179	234
$p^{CM}_{T\ ISR} > 100$ GeV	115	132	173
$p^{CM}_{T\ I} > 80$ GeV	114	115	150
$p^{CM}_T < 25$ GeV	73	68	89

and the missing transverse momentum. After that, the following variables are used as discriminant:

- $p^{CM}_{T\ ISR}$: The magnitude of the vector-summed transverse momenta of the jets assigned to the ISR system.
- $p^{CM}_{T\ I}$: The magnitude of the vector-summed transverse momenta of the invisible system.
- p^{CM}_T: The magnitude of the vector-summed transverse momenta of the CM system.
- $R_{ISR} \equiv \vec{p}^{\,CM}_I \cdot \hat{p}^{CM}_{T\ S}/p^{CM}_{T\ S}$: Serves as an estimate of $m_{\tilde{\chi}^0_1}/m_{\tilde{\chi}^0_2/\tilde{\chi}^\pm_1}$. This corresponds to the fraction of the momentum of the system that is carried by its invisible system I, with momentum $\vec{p}^{\,CM}_I$ in the CM frame. As $p^{CM}_{T\ S}$ grows, it becomes increasingly hard for backgrounds to possess a large value in this ratio, unlike compressed signals where this feature is exhibited [40].
- $\Delta\phi^{CM}_{ISR,I}$: The azimuthal opening angle between the ISR system and the invisible system in the CM frame.

Our analysis is implemented using the `Madanalysis v5.17` [42–44] package, and validated with simulated Monte Carlo (MC) events corresponding to the production of neutralino–chargino pairs in the context of the MSSM decaying to a neutralino LSP and leptonically decaying gauge bosons, with selected masses of $m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2} = 200$ and $m_{\tilde{\chi}^0_1} = 100$ GeV. Ten thousand events are generated using `MadGraph5_aMC@NLO v2.6.3.2` [45] at leading order (LO) of perturbative QCD simulating the production of the described process with the standard model files for the MSSM. Events are then passed for showering and hadronization to `PYTHIA v8.201` [46] using the A14 tune [47], and then to `DELPHES v3.3.3` [48] for detector simulation. The results of the events selection are compared with the cutflow table provided by the ATLAS collaboration, as shown in Table 2. The first column reproduces the unweighted yields from the ATLAS analysis, the second one presents the unweighted yields from our implementation, and the last one the same yields but normalized to the number of events in the first column. As can be seen from the table, the numbers agree within a 20% error, thus we use this implementation to obtain the efficiency map of the ATLAS search for different masses of sneutrinos/sleptons and neutralinos.

The sneutrino/slepton pair production is simulated in a similar way, but with model files generated using a suitable modified version of `SARAH` code [49–51], and the spectrum is generated using `SPheno` v3.3.6 code [52,53]. Cross sections are calculated at NLO+NLL using `Resummino v2.01` [54–57,38]. For each selected point, ten thousand MC events are generated as explained and passed through the described selection criteria. The results are then compared with the expected (S^{95}_{exp}) and observed (S^{95}_{obs}) upper limits obtained in the ATLAS search.

5. Results

We have already obtained that results [21,22] and [23] do not produce bounds on the bino-like neutralino and left sneutrino/slepton masses in the $\mu\nu$SSM. By using now the method described in the previous section, we calculate the current and potential limits on the two-dimensional parameter space $m_{\tilde{\nu}} - m_{\tilde{\chi}^0_1}$ from the 36.1 fb^{-1} ATLAS result [24], and discuss the prospects for the 100 and 300 fb^{-1} searches.

The points analyzed in the $\mu\nu$SSM parameter space show all a worse efficiency passing the selection requirements of SR2ℓ_ISR in comparison with SR3ℓ_ISR in Table 1. Thus the results discussed here are derived from the limits corresponding to the SR3ℓ_ISR signal region. Note first that the preselection requirement of exactly three light leptons, implies that the separation of masses between slepton/sneutrino and neutralino in the processes shown in Fig. 1 must be small enough to avoid the leptons produced in the decay of sleptons to contribute to the signal. Otherwise, these processes are discarded from the ATLAS searches. The processes in Fig. 1 show the highest yield of the possible combinations of neutralino decays. Other possibilities, like W decaying hadronically or both neutralinos decaying to Z bosons, with only one of them decaying leptonically, contribute also to the signal, but with smaller yields. The possibility of both neutralinos decaying to Z bosons, with the latter decaying to leptons, produce a negligible contribution caused both by the small corresponding BR and the excess of predicted signal leptons.

Our result in the mass regions considered is that no points of the $\mu\nu$SSM can be excluded from current data. Concerning the excess of events mentioned in the previous section, let us point out that the observed limit in the 3ℓ_ISR signal region ($S^{95}_{obs} = 15.3$) is significantly larger than the expected limit ($S^{95}_{exp} = 6.9^{+3.1}_{-2.2}$), due to a 3.02 sigma excess [24]. We have checked that points of our parameter space in the region $m_{\tilde{\chi}^0_1} \in (110, 120)$ and $m_{\tilde{\nu}} \in (120, 140)$ can predict a number of events similar to the observed excess. As an example, Table 3 shows a benchmark point (BP) in Sℓ3_ISR with $M_1 = 127$ GeV, and $\frac{v_{1,2}}{\sqrt{2}} = 5.2 \times 10^{-4}$ GeV, $\frac{v_3}{\sqrt{2}} = 1.07 \times 10^{-4}$ GeV. These VEVs have typical values fulfilling the minimizations

Table 3
Benchmark point of the $\mu\nu$SSM in the Sℓ3_ISR signal region. In the third row the efficiency ϵ passing the selection requirements is shown.

$m_{\tilde{\chi}^0}$	120 GeV	$m_{\tilde{\nu}}$	125 GeV	$m_{\tilde{\ell}}$	145 GeV
BR($\tilde{\ell}_i \to \ell_i \tilde{\chi}^0$) BR($\tilde{\chi}^0 \to W\tau$)	1 2.9×10^{-2}	BR($\tilde{\nu}_i \to \nu \tilde{\chi}^0$) BR($\tilde{\chi}^0 \to Z\nu$)	1 2.4×10^{-1}	BR($\tilde{\chi}^0 \to We/\mu$) $\Gamma_{\tilde{\chi}^0}$	3.5×10^{-1} 1.28×10^{-12} GeV
$\epsilon_{W_\ell Z_\ell}$	0.0092	$\epsilon_{W_h Z_\ell}$	0.0021	$\epsilon_{Z_\ell Z_\nu}$	0.0215
$\sigma(pp \to \tilde{\nu}\tilde{\nu})$	143.75 fb	$\sigma(pp \to \tilde{\nu}\tilde{\ell})$	276.32 fb	$\sigma(pp \to \tilde{\ell}\tilde{\ell})$	80.94 fb
Events above background in Sℓ3_ISR: 5.1					

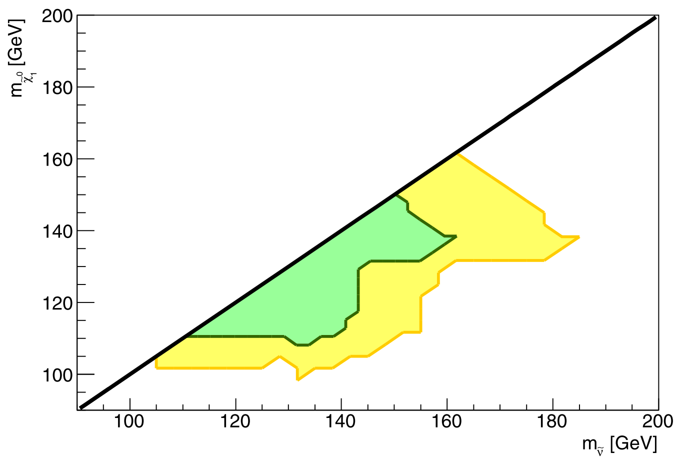

Fig. 2. Regions of the $\mu\nu$SSM that will be probed by the signal with three light leptons plus MET discussed in the text in the parameter space $m_{\tilde{\nu}} - m_{\tilde{\chi}_1^0}$ with universal sneutrino masses, for the 13-TeV search with an integrated luminosity of 100 fb^{-1} (green) and 300 fb^{-1} (yellow).

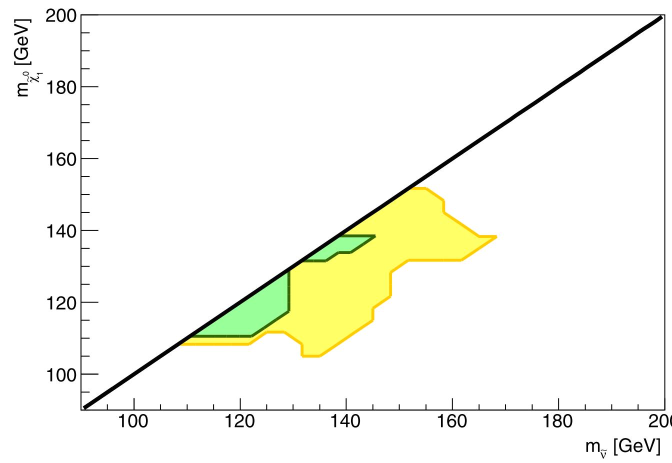

Fig. 3. The same as in Fig. 2, but for non-universal sneutrino masses as discussed in the text.

conditions, and producing the heavier neutrino mass in the experimentally constrained range $m_\nu \sim (0.05, 0.23)$ eV [58,59], given the neutrino mass formula discussed in Section 2. In particular, this BP predicts 5.1 events above background. Other parameters, whose effect on the bino-like neutralino decay properties is less significant, as can be understood from formulas in Section 3, are set to be $\lambda = 0.2$, $\kappa = 0.3$, $\tan\beta = 10$, $\frac{v_R}{\sqrt{2}} = 1350$ GeV, and $M_2 = 1$ TeV, throughout this computation. In order to optimize the signal we have assumed that the masses of the three families of left sneutrinos/sleptons are degenerated, and therefore all of them contribute to the signal. Given the sneutrino mass formula in Section 2, there is enough freedom to tune the masses in that way allowing for non-universality of the parameters Y_{ν_i} or A_{ν_i}. For this BP we set the typical values $Y_{\nu_{1,2}} = 5 \times 10^{-7}$, $Y_{\nu_3} = 1 \times 10^{-7}$ and universal $A_\nu = -396$ GeV.

If the observed local excess were due to a statistical fluctuation, and the observed upper limit converged to the expected limit, we can easily infer the potential bounds on the parameter space of the sneutrino–neutralino mass in the $\mu\nu$SSM. For 100 and 300 fb^{-1} to be reached at the end of Run 2, we just have to rescale the limits by $\sqrt{100/36.1}$ and $\sqrt{300/36.1}$, respectively. The result is shown in Fig. 2. In this plot the parameters for the BP above are used, but varying M_1 between 95 and 215 GeV, and A_ν between -470 and -376 GeV in order to obtain the range of neutralino and sneutrino masses shown. There, the solid black line shows the points where the sneutrino and neutralino are degenerated in mass. The green area encloses the excluded region for 100 fb^{-1} if no excess is observed, and the yellow area shows the same for 300 fb^{-1}. As we can see, the prospects show a potential exclusion of sneutrino masses up to 160 and 185 GeV for 100 and 300 fb^{-1}, respectively. This region extends up to the solid line, reflecting the fact that the search will be fully sensitive to the degenerated scenario.

In Fig. 2, for a given sneutrino mass, smaller value of the neutralino mass does not give rise to a worse sensitivity until the kinematic functions in Eq. (3) make the product $BR(\tilde{\chi}^0 \to Z\nu)BR(\tilde{\chi}^0 \to W\ell)$ too small and the search becomes ineffective. On the other hand, for a given neutralino mass the larger the value of the sneutrino mass the smaller the production cross section becomes, limiting the exclusion scope. Notice also that in the lower-right corner of the figure, the limits are weaker due to the larger mass separation between sneutrino and neutralino. As discussed above, the increased energy of the leptons from the decay of sleptons make them to contribute to the signal giving rise to a signature with more than three light leptons.

To discuss how general is this result in the parameter space of the $\mu\nu$SSM, we can consider a (non-optimized) signal with non-degenerate sneutrino/slepton masses. For that we can use universal $Y_{\nu_{1,2,3}} = 5 \times 10^{-7}$, producing $m_{\tilde{\nu}_3} = 2.24\, m_{\tilde{\nu}_{1,2}}$. Then, only two families of sneutrinos/sleptons contribute to the signal, and the result is shown in Fig. 3 with $m_\nu = m_{\tilde{\nu}_{1,2}}$. Obviously, the limits are less stringent, but still some regions of the parameter space can be bounded. The prospects show a potential exclusion of sneutrino masses up to 145 and 170 GeV for 100 and 300 fb^{-1}, respectively. A similar result would be obtained assuming universality of VEVs and masses, since on the one hand the latter assumption increases the signal but on the other hand the former decreases it.

6. Conclusions and outlook

There is a lack of experimental bounds on the masses of the electroweak superpartners in the $\mu\nu$SSM from accelerator searches, apart from very specific regions of a sneutrino LSP with a mass between 45 and 100 GeV [9]. In order to fill this gap in SUSY searches, it is crucial to analyze all recent results that can potentially lead to (even small) limits on sparticle masses in this model. Following this line of thought, we have discussed in this work how stringent are for the parameter space of the $\mu\nu$SSM the recent searches for electroweak superpartners at the LCH in events with multi-leptons plus MET [21–24].

We have obtained first that the results of Refs. [21,22] and [23] do not produce bounds on the bino-like neutralino and left sneutrino/slepton masses in the $\mu\nu$SSM. Concerning [24], this search uses the RJR technique and is therefore sensitive to three leptons of the two light families produced by a compressed spectrum of electroweak superpartners. This type of signal is produced in the $\mu\nu$SSM with a bino-like neutralino LSP when the left sneutrino is the NLSP. However, we have obtained that no points of the parameter space of the $\mu\nu$SSM can be excluded yet. In the region of bino (sneutrino) masses $110 - 120$ $(120 - 140)$ GeV we have found a tri-lepton signal compatible with the local excess reported by ATLAS [24]. If this excess were due to a statistical fluctuation, the prospects for the bounds on the parameter space of the sneutrino-bino mass in the $\mu\nu$SSM are shown in Figs. 2 and 3.

These limits can be complemented in the future by searches for displaced decays of the bino-like neutralino when its mass is below the threshold of the W mass. In this case, three-body decays mediated by off-shell gauge bosons and scalars will produce a small total width due to the reduced phase space, leading to signals with lepton and/or quarks originated at displaced vertices.

In this work we have focused on the bino-like LSP, but another interesting possibility would be to study the case of a wino-like LSP. The different couplings involved as well as new RPV decays could modify the sensitivity of the searches to the new compressed spectrum. We plan to carry out this analysis in a forthcoming publication [60].

Let us finally remark that our proposal in the $\mu\nu$SSM can produce signals including up to six leptons plus MET. In the region of the parameter space explored in the present work, the leptons not originated from the decay of a gauge boson will have too small transverse momentum due to the compressed nature of the spectrum. In this situation, it is unlikely that sufficient leptons would be detected to be able to use a high multiplicity of them as a powerful discriminant. On the contrary, the regions where the mass separation between neutralino–slepton/sneutrino is large enough are potentially testable requiring five or more leptons. Existing searches for events with four or more leptons [23] use a moderate associated MET or a large effective mass, to target the pair production of sleptons with masses above 500 GeV. These searches are insensitive to the small-mass slepton/sneutrino case that we were able to cover in this work. Nonetheless, the most important source of irreducible background to a signal with five or more leptons at pp colliders is the triple-gauge boson production. Specifically the ZZZ production cross section is 0.316 fb and the ZZW one is 1.073 fb at $\sqrt{s} = 13$ TeV, that means 0.07 expected background events including five or more leptons with an integrated luminosity of 36.1 fb^{-1}. In comparison, the production of slepton/sneutrino pairs with masses of 300 GeV will produce 18 events with five or more leptons with the same integrated luminosity. Thus, a dedicated experimental analysis using five or more leptons as the main discriminant might be sensitive to the slepton/sneutrino pair production in a larger mass region of the $\mu\nu$SSM. Although a similar final state is predicted assuming a single RPV channel $\lambda_{12k}\hat{L}_1\hat{L}_2\hat{e}^c_k$ in the superpotential, note however that the scenario of light sleptons/sneutrinos is already ruled out by current searches [23] unlike the case of the $\mu\nu$SSM.

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References

[1] H.P. Nilles, Supersymmetry supergravity and particle physics, Phys. Rep. 110 (1984) 1–162.
[2] H.E. Haber, G.L. Kane, The search for supersymmetry: probing physics beyond the standard model, Phys. Rep. 117 (1985) 75–263.
[3] S.P. Martin, A Supersymmetry primer, Adv. Ser. Dir. High Energy Phys. 18 (1998) 1, arXiv:hep-ph/9709356 [hep-ph].
[4] Particle Data Group Collaboration, M. Tanabashi, et al., Review of particle physics, Phys. Rev. D 98 (3) (2018) 030001.
[5] R. Barbier, et al., R-parity violating supersymmetry, Phys. Rep. 420 (2005) 1–202, arXiv:hep-ph/0406039 [hep-ph].
[6] D.E. López-Fogliani, C. Muñoz, Proposal for a supersymmetric standard model, Phys. Rev. Lett. 97 (2006) 041801, arXiv:hep-ph/0508297 [hep-ph].
[7] N. Escudero, D.E. López-Fogliani, C. Muñoz, R. Ruiz de Austri, Analysis of the parameter space and spectrum of the $\mu\nu$SSM, J. High Energy Phys. 12 (2008) 099, arXiv:0810.1507 [hep-ph].
[8] P. Ghosh, I. Lara, D.E. López-Fogliani, C. Muñoz, R. Ruiz de Austri, Searching for left sneutrino LSP at the LHC, Int. J. Mod. Phys. A 33 (18–19) (2018) 1850110, arXiv:1707.02471 [hep-ph].
[9] I. Lara, D.E. López-Fogliani, C. Muñoz, N. Nagata, H. Otono, R. Ruiz De Austri, Looking for the left sneutrino LSP with displaced-vertex searches, Phys. Rev. D 98 (7) (2018), arXiv:1804.00067 [hep-ph].
[10] P. Ghosh, S. Roy, Neutrino masses and mixing, lightest neutralino decays and a solution to the μ problem in supersymmetry, J. High Energy Phys. 04 (2009) 069, arXiv:0812.0084 [hep-ph].
[11] A. Bartl, M. Hirsch, A. Vicente, S. Liebler, W. Porod, LHC phenomenology of the $\mu\nu$SSM, J. High Energy Phys. 05 (2009) 120, arXiv:0903.3596 [hep-ph].
[12] P. Ghosh, D.E. López-Fogliani, V.A. Mitsou, C. Muñoz, R. Ruiz de Austri, Probing the μ-from-ν supersymmetric standard model with displaced multileptons from the decay of a Higgs boson at the LHC, Phys. Rev. D 88 (2013) 015009, arXiv:1211.3177 [hep-ph].
[13] P. Ghosh, D.E. López-Fogliani, V.A. Mitsou, C. Muñoz, R. Ruiz de Austri, Probing the $\mu\nu$SSM with light scalars, pseudoscalars and neutralinos from the decay of a SM-like Higgs boson at the LHC, J. High Energy Phys. 11 (2014) 102, arXiv:1410.2070 [hep-ph].
[14] DELPHI Collaboration, P. Abreu, et al., Search for supersymmetry with R-parity violating L L anti-E couplings at S**(1/2) = 183-GeV, Eur. Phys. J. C 13 (2000) 591.
[15] DELPHI Collaboration, P. Abreu, et al., Search for SUSY with R-parity violating LL anti-E couplings at s**(1/2) = 189-GeV, Phys. Lett. B 487 (2000) 36, arXiv:hep-ex/0103006 [hep-ex].
[16] L3 Collaboration, P. Achard, et al., Search for R parity violating decays of supersymmetric particles in e^+e^- collisions at LEP, Phys. Lett. B 524 (2002) 65, arXiv:hep-ex/0110057 [hep-ex].
[17] ALEPH Collaboration, A. Heister, et al., Search for supersymmetric particles with R parity violating decays in e^+e^- collisions at $\sqrt{s}$ up to 209-GeV, Eur. Phys. J. C 31 (2003) 1, arXiv:hep-ex/0210014 [hep-ex].
[18] OPAL Collaboration, G. Abbiendi, et al., Search for R parity violating decays of scalar fermions at LEP, Eur. Phys. J. C 33 (2004) 149, arXiv:hep-ex/0310054 [hep-ex].
[19] DELPHI Collaboration, J. Abdallah, et al., Search for supersymmetric particles assuming R-parity nonconservation in e+ e- collisions at s**(1/2) = 192-GeV to 208-GeV, Eur. Phys. J. C 36 (1) (2004) 1, arXiv:hep-ex/0406009 [hep-ex]; Erratum, Eur. Phys. J. C 37 (1) (2004) 129.
[20] ATLAS Collaboration, G. Aad, et al., Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, Phys. Rev. D 92 (7) (2015) 072004, arXiv:1504.05162 [hep-ex].
[21] CMS Collaboration, A.M. Sirunyan, et al., Search for new phenomena in final states with two opposite-charge, same-flavor leptons, jets, and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 03 (2018) 076, arXiv:1709.08908 [hep-ex].
[22] ATLAS Collaboration, M. Aaboud, et al., Search for electroweak production of supersymmetric particles in final states with two or three leptons at $\sqrt{s} = 13$ TeV with the ATLAS detector, arXiv:1803.02762 [hep-ex].
[23] ATLAS Collaboration, M. Aaboud, et al., Search for supersymmetry in events with four or more leptons in $\sqrt{s} = 13$ TeV pp collisions with ATLAS, Phys. Rev. D 98 (3) (2018) 032009, arXiv:1804.03602 [hep-ex].
[24] ATLAS Collaboration, M. Aaboud, et al., Search for chargino–neutralino production using recursive jigsaw reconstruction in final states with two or three charged leptons in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, arXiv:1806.02293 [hep-ex].

[25] GAMBIT Collaboration, P. Athron, et al., Combined collider constraints on neutralinos and charginos, arXiv:1809.02097 [hep-ph].

[26] M. Carena, J. Osborne, N.R. Shah, C.E.M. Wagner, Supersymmetry and LHC missing energy signals, arXiv:1809.11082 [hep-ph].

[27] J. Fidalgo, D.E. Lopez-Fogliani, C. Munoz, R. Ruiz de Austri, Neutrino physics and spontaneous CP violation in the $\mu\nu$SSM, J. High Energy Phys. 08 (2009) 105, arXiv:0904.3112 [hep-ph].

[28] P. Ghosh, P. Dey, B. Mukhopadhyaya, S. Roy, Radiative contribution to neutrino masses and mixing in $\mu\nu$SSM, J. High Energy Phys. 05 (2010) 087, arXiv:1002.2705 [hep-ph].

[29] U. Ellwanger, C. Hugonie, A.M. Teixeira, The next-to-minimal supersymmetric standard model, Phys. Rep. 496 (2010) 1–77, arXiv:0910.1785 [hep-ph].

[30] S. Dawson, E. Eichten, C. Quigg, Search for supersymmetric particles in hadron – hadron collisions, Phys. Rev. D 31 (1985) 1581, https://doi.org/10.1103/PhysRevD.31.1581.

[31] E. Eichten, I. Hinchliffe, K.D. Lane, C. Quigg, Super collider physics, Rev. Mod. Phys. 56 (1984) 579;
Addendum, Rev. Mod. Phys. 58 (1986) 1065.

[32] F. del Aguila, L. Ametller, On the detectability of sleptons at large hadron colliders, Phys. Lett. B 261 (1991) 326.

[33] H. Baer, C.-h. Chen, F. Paige, X. Tata, Detecting sleptons at hadron colliders and supercolliders, Phys. Rev. D 49 (1994) 3283, arXiv:hep-ph/9311248 [hep-ph].

[34] H. Baer, B.W. Harris, M.H. Reno, Next-to-leading order slepton pair production at hadron colliders, Phys. Rev. D 57 (1998) 5871, arXiv:hep-ph/9712315 [hep-ph].

[35] G. Bozzi, B. Fuks, M. Klasen, Slepton production in polarized hadron collisions, Phys. Lett. B 609 (2005) 339, arXiv:hep-ph/0411318 [hep-ph].

[36] ATLAS Collaboration, G. Aad, et al., Search for supersymmetry in events with four or more leptons in $\sqrt{s}$ = 8 TeV pp collisions with the ATLAS detector, Phys. Rev. D 90 (5) (2014) 052001, arXiv:1405.5086 [hep-ex].

[37] B. Fuks, M. Klasen, D.R. Lamprea, M. Rothering, Gaugino production in proton–proton collisions at a center-of-mass energy of 8 TeV, J. High Energy Phys. 10 (2012) 081, arXiv:1207.2159 [hep-ph].

[38] B. Fuks, M. Klasen, D.R. Lamprea, M. Rothering, Precision predictions for electroweak superpartner production at hadron colliders with Resummino, Eur. Phys. J. C 73 (2013) 2480, arXiv:1304.0790 [hep-ph].

[39] B. Fuks, M. Klasen, D.R. Lamprea, M. Rothering, Revisiting slepton pair production at the Large Hadron Collider, J. High Energy Phys. 01 (2014) 168, arXiv:1310.2621.

[40] P. Jackson, C. Rogan, M. Santoni, Sparticles in motion: analyzing compressed SUSY scenarios with a new method of event reconstruction, Phys. Rev. D 95 (3) (2017) 035031, arXiv:1607.08307 [hep-ph].

[41] P. Jackson, C. Rogan, Recursive Jigsaw Reconstruction: HEP event analysis in the presence of kinematic and combinatoric ambiguities, Phys. Rev. D 96 (11) (2017) 112007, arXiv:1705.10733 [hep-ph].

[42] E. Conte, B. Fuks, G. Serret, MadAnalysis 5, a user-friendly framework for collider phenomenology, Comput. Phys. Commun. 184 (2013) 222–256, arXiv:1206.1599 [hep-ph].

[43] E. Conte, B. Dumont, B. Fuks, C. Wymant, Designing and recasting LHC analyses with MadAnalysis 5, Eur. Phys. J. C 74 (10) (2014) 3103, arXiv:1405.3982 [hep-ph].

[44] B. Dumont, B. Fuks, S. Kraml, S. Bein, G. Chalons, E. Conte, S. Kulkarni, D. Sengupta, C. Wymant, Toward a public analysis database for LHC new physics searches using MADANALYSIS 5, Eur. Phys. J. C 75 (2) (2015) 56, arXiv:1407.3278 [hep-ph].

[45] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079, arXiv:1405.0301 [hep-ph].

[46] T. Sjostrand, S. Mrenna, P.Z. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026, arXiv:hep-ph/0603175 [hep-ph].

[47] ATLAS Run 1 Pythia8 Tunes, Tech. Rep. ATL-PHYS-PUB-2014-021, CERN, Geneva, Nov. 2014, https://cds.cern.ch/record/1966419.

[48] DELPHES 3 Collaboration, J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaitre, A. Mertens, M. Selvaggi, DELPHES 3, a modular framework for fast simulation of a generic collider experiment, J. High Energy Phys. 02 (2014) 057, arXiv:1307.6346 [hep-ex].

[49] F. Staub, SARAH, arXiv:0806.0538 [hep-ph].

[50] F. Staub, T. Ohl, W. Porod, C. Speckner, A tool box for implementing supersymmetric models, Comput. Phys. Commun. 183 (2012) 2165–2206, arXiv:1109.5147 [hep-ph].

[51] F. Staub, SARAH 4: a tool for (not only SUSY) model builders, Comput. Phys. Commun. 185 (2014) 1773, arXiv:1309.7223 [hep-ph].

[52] W. Porod, SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at e+ e- colliders, Comput. Phys. Commun. 153 (2003) 275, arXiv:hep-ph/0301101 [hep-ph].

[53] W. Porod, F. Staub, SPheno 3.1: extensions including flavour, CP-phases and models beyond the MSSM, Comput. Phys. Commun. 183 (2012) 2458, arXiv:1104.1573 [hep-ph].

[54] A. Buckley, J. Ferrando, S. Lloyd, K. Nordstrom, B. Page, M. Rufenacht, M. Schonherr, G. Watt, LHAPDF6: parton density access in the LHC precision era, Eur. Phys. J. C 75 (2015) 132, arXiv:1412.7420 [hep-ph].

[55] G. Bozzi, B. Fuks, M. Klasen, Transverse-momentum resummation for slepton-pair production at the CERN LHC, Phys. Rev. D 74 (2006) 015001, arXiv:hep-ph/0603074 [hep-ph].

[56] G. Bozzi, B. Fuks, M. Klasen, Threshold resummation for slepton-pair production at hadron colliders, Nucl. Phys. B 777 (2007) 157–181, arXiv:hep-ph/0701202 [hep-ph].

[57] G. Bozzi, B. Fuks, M. Klasen, Joint resummation for slepton pair production at hadron colliders, Nucl. Phys. B 794 (2008) 46–60, arXiv:0709.3057 [hep-ph].

[58] Daya Bay Collaboration, F.P. An, et al., New measurement of antineutrino oscillation with the full detector configuration at Daya Bay, Phys. Rev. Lett. 115 (11) (2015) 111802, arXiv:1505.03456 [hep-ex].

[59] Planck Collaboration, P.A.R. Ade, et al., Planck 2015 results. XIII. Cosmological parameters, Astron. Astrophys. 594 (2016) A13, arXiv:1502.01589 [astro-ph.CO].

[60] I. Lara, D.E. López-Fogliani, C. Muñoz, in preparation.