

A revisit to a compressed supersymmetric spectrum with 125 GeV Higgs

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ABSTRACT: A compressed spectrum was initially proposed as an explanation for the elusiveness of low-energy supersymmetry (SUSY). Some characteristic signals at the Large Hadron Collider (LHC), such as mono-jet + \cancel{E}_T , had been propounded as its trademark signals. However, later investigations suggested that lower limits on the supersymmetric particle masses would be quite stringent in spite of compression. Also, most compressed SUSY scenarios studied so far are only partially compressed. In this backdrop, we make an exhaustive analysis of the compressed SUSY scenarios for the 13 TeV run of LHC, keeping the level of compression in the entire spectrum as high as possible. A broad class of benchmark spectra are thus considered, after ensuring consistency with the observed Higgs mass as well as the dark matter constraints. The rates of observable events in the high-energy run are obtained through detailed simulation, for both the multi-jet + \cancel{E}_T and mono-jet + \cancel{E}_T final states. Our conclusion is that the former is still more efficient to reveal a compressed SUSY spectrum first, while the latter can serve as a useful confirmatory channel.

KEYWORDS: Supersymmetry Phenomenology, Large Hadron Collider, Multi-jets

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1 Introduction

Despite the very pertinent candidature of TeV-scale supersymmetry (SUSY) as the solution to the Higgs naturalness problem, together with the possibility of solving the dark matter (DM) puzzle with its help, the Large Hadron Collider (LHC) experiment is yet to reveal any hint of SUSY. A way of retaining one's hope in this direction is to think of some version(s) of SUSY, broken around the TeV-scale, but with such spectra as can suppress the usually expected signals. One such version assumes sparticle masses to be compressed within a rather small range, a situation whose theoretical justification and phenomenological analyses have already generated some efforts [1–4]. The compressed spectrum causes the jets and leptons produced in SUSY cascades to be relatively soft, and also downgrades the missing transverse energy (\cancel{E}_T) somewhat, thus potentially suppressing signals that pass the acceptance criteria at the LHC. One can therefore envision allowed regions in the parameter space after the 8 TeV run, with relatively low-lying superparticles but small spacing between the squark/gluino masses and that of the lightest SUSY particle (LSP)¹.

It was initially thought that the best way to look for compressed SUSY was to focus on the mono-jet + \cancel{E}_T signal [5–20]. Subsequent investigations in the context

¹The lightest neutralino ($\tilde{\chi}_1^0$) has been assumed to be the LSP in this study.

of run-I showed that the ‘conventional’ multi-jet + \cancel{E}_T signals (with or without accompanying leptons) could be more useful if appropriate event selection criteria were followed [7, 8, 10]. It is important to see how such multi-jet + \cancel{E}_T signals fare against the mono-jet + \cancel{E}_T ones in the 13 / 14 TeV runs of the LHC.

A few things, however, remain to be noted carefully in such an investigation. In many recent studies, experimental as well as theoretical, the deciding factor is assumed to be the mass splitting between the LSP and the coloured members such as gluino/squarks, the role of the rest of the spectrum being relatively inconsequential. It is also sometimes customary to focus on the mass gap between the LSP and the next-to-LSP (NLSP). This kind of an approach has often been prompted by attempts to parametrise the spectrum in terms of some ‘compression factor’ [1, 2] that straightjackets the entire spectrum in a little oversimplified manner. However, one should take an equally serious note of the rest of the minimal SUSY standard model (MSSM) spectrum where even non-coloured particles (or third family squarks) can have substantial splitting with the LSP, thus producing additional hard jets and/or leptons after all.

Another vital issue that needs to be addressed is the undeniable presence of the lighter CP-even Higgs boson around 125-126 GeV. In a SUSY extension of the standard model (SM), one can only consider spectra where this mass value is replicated, its behaviour being most likely SM-like. As we know, the mass of this scalar in the MSSM, taking radiative corrections into account, is highly dependent on the two stop masses as well as the stop left-right mixing angle. Hence the degree of compression of the entire MSSM spectra is expected to be strongly constrained, if the lighter CP-even Higgs mass has to be in the right value. Therefore, the compressed spectra proposed in the earlier works need to be revisited in the aftermath of the Higgs boson discovery. This is not thoroughly done in most existing studies; it is often implied that either the spectrum is only partly compressed [5–21], or some physics beyond MSSM is responsible for the observed value of the Higgs mass [22–24]. In contrast, we have proceeded assuming the intervention of only the MSSM fields in deciding the Higgs mass(es).

In addition, the constraints from the relic density of the universe as well as those arising from direct DM search experiments are important requirements of a SUSY spectrum. We have taken these constraints into account while selecting the benchmark points in the parameter space. For more detailed study of DM in the context of compressed SUSY scenario, see [25–27].

On the whole, given the manifold diversity of an MSSM spectrum, *we have preferred to think not in terms of some compression parameter(s) in a somewhat simplified spectrum but to work with a wide assortment of benchmark points, which reflect as many different possibilities as possible.* We have kept the heavier stop mass and/or the Higgsino mass parameter μ somewhat above the compressed spectrum in some cases. The latter choice may perhaps be justified by the observation that

μ does not have the same origin as the SUSY-breaking mass parameters; it is in fact a SUSY-invariant parameter, though destined to be in the TeV scale by the electroweak symmetry breaking requirement. In any case we have also presented results for some benchmark points where the *entire spectrum* lies tightly compressed. After a detailed study of this variety of benchmarks, we reach the conclusion that signals comprising multi-jets are likely to be more useful in the 13/14 TeV runs, as compared to those depending upon mono-jets.

In section 2, we discuss the existing experimental limits on the MSSM parameter space. We further discuss the status of compressed SUSY search at the LHC. Then we look for a truly compressed SUSY spectrum keeping the lightest CP-even Higgs boson mass in its allowed range around 125 GeV. While doing so, we carry out a detailed scan of the relevant parameter space keeping all the collider, DM and flavour physics constraints in consideration. We then provide some benchmark points to showcase our results with different squark-gluino mass hierarchy keeping the lightest neutralino as the LSP. In section 3, we explore the collider aspects of such scenarios in the context of run II of the LHC. We look for both multi-jet + \cancel{E}_T and mono-jet + \cancel{E}_T final states arising from all possible squark-gluino production channels and compare the sensitivities of these two signals to such compressed spectrum and conclude.

2 Status of SUSY search and a compressed spectrum

The generic SUSY search channels at the LHC involve the strongly interacting sector comprising of squarks (\tilde{q}) and gluino (\tilde{g}), all of which have large production rates. In the CMSSM/mSUGRA scenario, the mass spectrum for the squarks, gluino and other sparticles have a predetermined hierarchy dictated by the renormalisation group (RG) evolutions, once the free parameters are chosen at the unification scale. Once a mass-ordering is thus established, this simplifies the search strategies, since the observed jets or charged leptons originating from the SUSY cascades would carry the imprint of the mass spectrum. One usually associates the signal to contain jets and charged leptons with large transverse momenta along with substantial missing transverse energy (\cancel{E}_T) carried away by the stable lightest SUSY particle (LSP). As a result, the final states are easily separated from their respective SM backgrounds and the exclusion limits derived on the coloured sparticles come out stronger in this framework. Both CMS and ATLAS have put bounds which are close to around 1 TeV on the squark masses and 1.4 TeV on the gluino masses respectively for simplified models [28]. In the case of degenerate squarks and gluinos, the exclusion limit extends upto 1.7 TeV in CMSSM models [29].

2.1 Current limits on MSSM from ATLAS and CMS

However, the MSSM in general poses a bigger challenge for LHC to put similar exclusion limits. Since the number of free parameters increases manifold, possibilities

for different mass ordering of the SUSY particles open up. In such situations, it not only becomes very difficult to put absolute bounds on the masses of the sparticles, but the guiding principles to search for SUSY at LHC also become ambiguous. Because of this, the bounds are always associated with some simplified assumptions for the decay pattern of the produced particles and therefore, one has to be careful while implementing these limits. In such scenarios, gluino mass ($m_{\tilde{g}}$) is excluded upto 1.3 - 1.5 TeV when the lightest neutralino (LSP) mass ($m_{\tilde{\chi}_1^0}$) is not heavier than 500 - 600 GeV [29], provided the first two generation squarks are lighter than gluino. When the squarks are much heavier than the gluino, the \tilde{g} decays via off-shell squarks. The decay to three-body final state comprising of two quarks and the LSP leads to softer jets in the final state which dilute the $m_{\tilde{g}}$ exclusion limit to about 1.4 TeV for $m_{\tilde{\chi}_1^0} \leq 300$ GeV [29]. Just as above, all such available limits from run-I data of the LHC are expected to weaken further if the mass difference between the parent and daughter particles gets reduced as this would result in less \cancel{E}_T and softer jets/leptons in the final state. For example, if $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ is reasonably small, the exclusion limit on $m_{\tilde{g}}$ reduces to 550-600 GeV [29]. Thus, a light spectrum with small mass gaps among the SUSY particles might have escaped run-I scrutiny, thereby prompting increased interest in a *compressed SUSY scenario* [1, 2].

Summarising the other available bounds on MSSM, for a much heavier gluino, lighter squark (first 2 generations) masses are excluded below 850 GeV when $m_{\tilde{\chi}_1^0} \leq 350$ GeV [29]. Lighter stop masses ($m_{\tilde{t}_1}$) are excluded upto 600-700 GeV provided \tilde{t}_1 decays into a top quark (t) and $\tilde{\chi}_1^0$ where $m_{\tilde{\chi}_1^0} < 250$ GeV [30, 31]. When the \tilde{t}_1 decays into a bottom quark (b) and the lighter chargino ($\tilde{\chi}_1^\pm$), any $m_{\tilde{t}_1}$ below 500-600 GeV is excluded for $m_{\tilde{\chi}_1^0}$ below 200-250 GeV [30, 32], the exact limits being dependent on the chargino mass. For other decay modes of \tilde{t}_1 (flavour violating or > 2 -body modes), the exclusion limits reduce to 240-260 GeV [30, 32, 33]. Similarly, a lighter sbottom mass ($m_{\tilde{b}_1}$) below 620 GeV is excluded for $m_{\tilde{\chi}_1^0} \leq 150$ GeV [34]. When $m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0}$ is small, the exclusion limit on $m_{\tilde{b}_1}$ is lowered to 250 GeV [33].

Since for our present work we consider a relatively compressed spectrum, it turns out that the weakly interacting sector of MSSM has a relatively less important role to play. Therefore, we shall focus on the production and decay of the coloured sparticles. For a recent summary of SUSY search limits at the LHC, we refer the readers, for example, to Ref. [35, 36].

2.2 SUSY with the entire spectrum compressed

Compressed SUSY spectra has been studied in the context of LHC quite extensively with special emphasis on the smallness of the mass gap between the coloured sparticles and the LSP. A coloured NLSP (be it a squark or a gluino) is often assumed, and the role of the other sparticles in SUSY signals is considered to be of secondary importance. In an un-compressed spectrum one probably can accept that the significant contribution to the rates come from lightest coloured sparticle production [37]

(where the other coloured modes are heavier). Understandably, hard jets or leptons are difficult to obtain in the final state for small mass gaps. This results in weaker limits on the parameter space, when compared to the standard SUSY searches. However, such effects do not always presume the entire spectrum to be compressed. In most cases, a part of the strongly interacting sector (for example, the third family squarks) is ignored by decoupling it from the low lying spectrum. In addition, many extant studies do not pay enough attention to parts of the coloured spectrum, which may not be entirely decoupled, but whose participation vis-a-vis that of the gluino may have bearing on the SUSY signals, especially on the kinematic profiling of the events arising out of sparticle production. For example, the contribution to the final state may dominantly come from the hard processes comprising of the production of squarks in association with gluinos. Now, inspite of having a small gluino-LSP mass gap, the squarks may have a substantial mass gap with the LSP. These sparticles will then start contributing to the final state giving rise to harder jets or leptons along with relatively larger \cancel{E}_T . Hence the question we really need to ask is, how would a really compressed SUSY spectrum, with almost all sparticles rubbing shoulders with each other, play out at the LHC.

Such a SUSY spectrum, however, has to obey some guiding principles. The first of these is to reproduce the lighter neutral CP-even Higgs mass in the neighbourhood of 125 GeV. The next constraint to be taken into account is the contribution to the relic density of the universe. These, in addition to various limits arising from flavour physics and/or direct search results till date, guide one towards some allowed spectra that are either fully compressed or have to leave out some relatively heavy states above the compressed band.

We discuss these issues next, based on which we finally choose specific benchmarks from the viable parameter space that highlight different mass hierarchies among the gluino and the squark states. We use the benchmarks to carry out a detailed collider simulation for both multi-jet + \cancel{E}_T and mono-jet + \cancel{E}_T final states, to determine which search strategy may help us better to discover or rule out various SUSY spectra that are compressed to the utmost.

2.3 A spectrum constrained by Higgs mass and dark matter

We recall that the tree-level mass of the lightest CP-even Higgs boson as obtained in the MSSM framework has an upper bound:

$$m_h^{\text{tree}} \leq m_Z |\cos 2\beta| \tag{2.1}$$

where $\tan \beta = v_u/v_d$ is the ratio of the two Higgs VEVs. Since Eq. 2.1 cannot allow a Higgs mass greater than the Z boson mass, one has to rely on substantial contribution through higher order (loop) corrections to reach the neighbourhood of 125 GeV, the experimentally measured mass of what could be the lighter CP-even

neutral scalar in a SUSY scenario. The dominant higher-order contribution comes from stops in the loop due to a large Yukawa coupling of the Higgs boson with the top quark. The one-loop contribution to the m_h^{tree} is approximately [38]:

$$(\Delta m_h^2)^{1\text{-loop}} \simeq \frac{3m_t^4}{4\pi^2 v^2} \left(\ln \frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2} - \frac{X_t^4}{12M_S^2} \right), \quad (2.2)$$

where v is the up-type Higgs VEV, $M_S = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$ is the geometric mean of the stop left-right masses and $X_t = A_t - \mu \cot \beta$, which governs $\tilde{t}_L - \tilde{t}_R$ mixing as well as the splitting between the two stop mass eigenstates. Thus the radiatively corrected Higgs mass crucially depends on two parameters, namely, M_S and X_t , along with μ and $\tan \beta$. We note that in order to have one of the CP-even Higgs mass as 125 GeV Higgs boson in the theory, one requires large stop masses and large stop mixing ($X_t \simeq \pm \sqrt{6} M_S$) [39, 40].

One has the freedom to choose soft-breaking SUSY parameters in the MSSM for each sfermion generation separately. Also, maximum mass splitting is possible in the third family (due to the larger Yukawa couplings) which again contributes most significantly to the Higgs mass correction. Thus one concludes that obtaining a significant compression in the *entire spectrum* is difficult, since achieving $m_h \approx 125$ GeV requires (at least) one stop eigenstate to be heavy.

At the same time, we find a somewhat large μ , too, is favourable in achieving $m_h \approx 125$ GeV. However, this also entails the possibility of having the Higgsino-dominated chargino and neutralinos on the heavier side, thus jeopardising the degree of compression in the entire MSSM spectrum. This also affects the Higgsino component in the LSP, which in turn may reduce the annihilation rate far too much, leading to excess relic density.

We thus use the following constraints in our scan of the parameter space :

- The lightest CP-even Higgs mass should be in the range $122 < m_h < 128$ GeV [22–24].
- The LEP lower bound on the lightest chargino mass, *viz.* $m_{\tilde{\chi}_1^\pm} > 103.5$ GeV [41].
- Constraints from branching ratios of rare decays such as $\text{BR}(b \rightarrow s\gamma)$ and $\text{BR}(B_s \rightarrow \mu\mu)$ [42, 43].
- The LSP, $\tilde{\chi}_1^0$, which is the cold dark matter candidate, satisfies the observed thermal relic density, $0.092 < \Omega_{\tilde{\chi}} h^2 < 0.138$ [44].

However, for our parameter scan we have considered only the upper limit of Ωh^2 , taking the view that it is plausible to have multi-component DM [45–54]. However, substantial portions in the parameter space has been identified, where a single-component DM satisfies. We also include the constraints from direct dark matter searches, as obtained from the LUX data [55].

In order to achieve spectra which are as compressed as can be, consistent with the above constraints, we have taken into consideration the following points in our prediction of the LHC signal:

- The mass gap within the stop pair being large, overall compression can be reduced in situations where one stop eigenstate, \tilde{t}_1 , lies just above the neutralino LSP.
- Gluino can be light and both cases are considered when gluino mass is above or below the lighter stop.
- The non-strongly interacting sfermions and gauginos are assigned various orders in the compressed spectrum. Though they have less of a role in the LHC signals, they may have a bearing on the relic density as well as cascade decays.
- The heavier stop mass as well as μ are kept both outside and inside the most compressed part of the spectrum. The latter possibility (*i.e.* no sparticle outside the compressed region) works for relatively heavy spectra only.

We parameterise the compression using the mass gap between the LSP ($m_{\tilde{\chi}_1^0}$) and the heaviest sparticle (\tilde{X}) in the spectrum, defined as $\Delta M = m_{\tilde{X}} - m_{\tilde{\chi}_1^0}$, where $\tilde{X} \in [\tilde{g}, \tilde{t}_2, \tilde{b}_2, \tilde{\tau}_2, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm]$ ². We scan over the relevant parameters shown in Table 2.1.

Parameters	Ranges
M_1, M_2, M_3	(100, 2500) GeV
A_t	(-3000, 3000) GeV
$\tan \beta$	(2, 50)
$M_L = M_R$	$(M_1, M_1 + 200)$ GeV (if $M_1 < M_2$) $(M_2, M_2 + 200)$ GeV (if $M_2 < M_1$)

Table 2.1. Ranges of the relevant parameters for the scan. M_1, M_2, M_3 are the gaugino mass parameters, varied in the same range but independent of each other. M_L and M_R are the left-handed and the right-handed soft mass parameters of squarks and sleptons.

Here M_L and M_R represent the soft mass parameters of the left and right handed squarks and sleptons respectively³. Table 2.1 suggests, we chose same M_L and M_R for all flavours. For our scan, we have used SPheno(v3.3.6) [56, 57] which calculates all sparticle masses at one-loop level while the Higgs mass is calculated at two-loop in order to generate the SUSY spectrum and consequently micrOMEGAs(v4.1.7) [58]

²Note that the higgsino dominated states may lie outside our compressed spectrum when μ is chosen to be very large.

³Although the soft mass parameters for the squarks and sleptons are kept equal by choice, this does not significantly affect the hadronic signals.

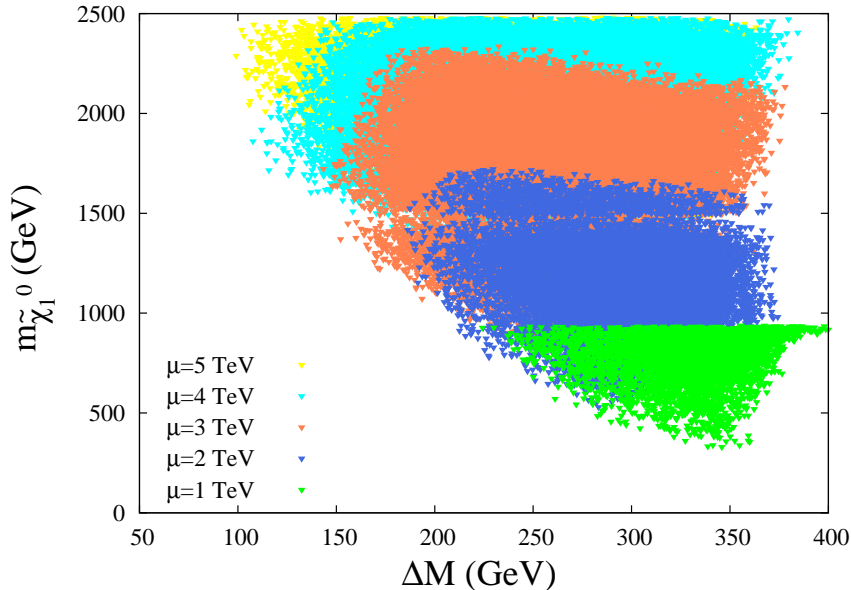


Figure 2.1. Distribution of $m_{\tilde{\chi}_1^0}$ as a function of ΔM at different μ values. The five colours (yellow, cyan, brown, blue and green) indicate five different values of μ . The points in the plot satisfy all the relevant constraints mentioned in the text.

to calculate the DM relic density and direct-detection cross-section, flavour physics constraints and muon g-2. In Fig. 2.1, we plot LSP mass $m_{\tilde{\chi}_1^0}$ as a function of compression mass gap ΔM . As evident, a μ -value close to or above 4 TeV allows a ΔM as low as 100 GeV. This figure gives a clear idea of the heaviness of the MSSM spectra as we keep compressing the whole spectrum. To give some estimate, in order to restrict the spectrum with $\Delta M \sim 100$ GeV, one obtains a lower limit on the LSP mass close to 1800 GeV for $\mu = 5$ TeV.

We examine next how the constraints from relic density (Ωh^2) and the spin-independent cross-sections (σ_{SI}) in direct search experiments affect the allowed parameter space. Since we are considering a compressed MSSM scenario, there are always some sparticles whose masses lie close enough to the LSP to produce sufficient co-annihilation to bring down the relic density to permissible limits. For a wino-like LSP, the $\tilde{\chi}_1^0$ mainly co-annihilates with the $\tilde{\chi}_1^\pm$. In addition, if there are sparticles nearby, e.g, \tilde{g} , \tilde{t}_1 , \tilde{b}_1 , $\tilde{\tau}_1$, in the spectrum, all the annihilation channels combine to produce underabundance of the DM relic density. Similar situation may occur in case of a bino-like or a bino-wino mixed LSP state. Hence Ωh^2 is not a very serious constraint for such a scenario.

Direct search limits, (σ_{SI}), however, can rule out some of the relevant parameter space. Fig. 2.2 shows the distribution of σ_{SI} as a function of the DM mass ($m_{\tilde{\chi}_1^0}$). Note

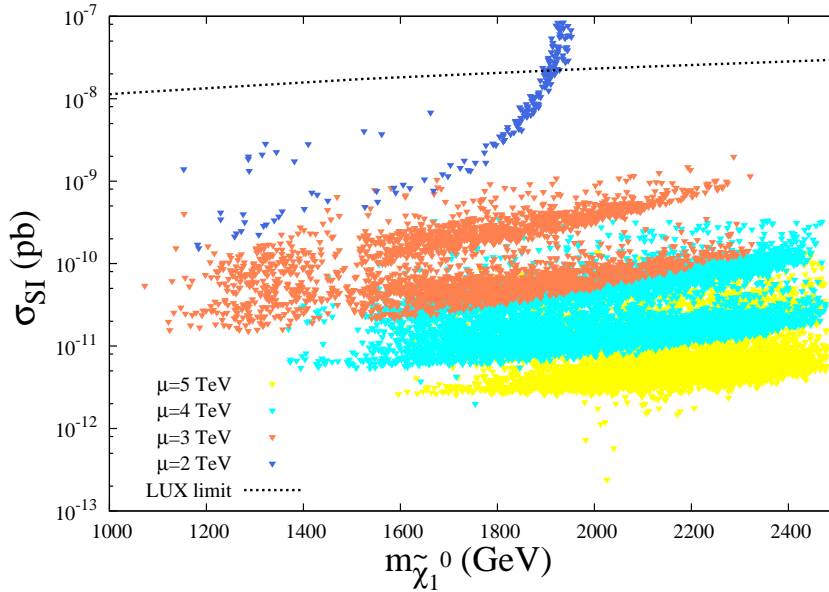


Figure 2.2. The direct detection cross-section as a function of the LSP mass. Since we are interested in small ΔM we have plotted the points only when $\Delta M \leq 200$ GeV. Colour labels follow Fig. 2.1. The black dotted line represents the most updated LUX bound.

that in this plot we only show those points in the parameter space, which produce $\Delta M \leq 200$ GeV. Understandably, there are no points corresponding to $\mu = 1$ TeV in the distribution, since Fig. 2.1 clearly shows the maximum compression we can reach in this case is close to 220 GeV. The black dotted line represents the most recent bound on σ_{SI} provided by the LUX experiment as a function of the DM mass [55]. As expected, all the points obtained in the scan with $\mu \geq 3$ TeV lie well below the exclusion line, the LSP in these scenarios have almost zero contribution from higgsino components and as a result, the Z-boson coupling of the LSP is reduced to a very small value, resulting in such small DM-nucleon scattering cross-sections. However, if we keep decreasing the μ value, σ_{SI} increases. When the bino or wino mass parameters become comparable to the μ parameter, as happens in part of the parameter space in the $\mu = 2$ TeV case⁴, the LSP turns out to be a mixed state with substantial higgsino component. This results in enhancement of σ_{SI} which is manifested in the few blue points in the figure which violate the LUX limit.

To demonstrate how the stop mixing parameters behave under the Higgs mass constraint, we chose one particular LSP mass close to 1100 GeV ($M_1 = 1100$ GeV)

⁴This is a result of our choice of the scan ranges of M_1 and M_2 as indicated in Table 2.1. In Sec. 2.4, we show two such sample benchmark points with non-negligible higgsino component (e.g. 8% in BP6). However, we have not considered higgsino-like LSP for our present work.

and vary A_t in the range $(-3000, 3000)$ GeV and \tilde{t}_L and \tilde{t}_R soft masses, $M_L^{Q_3}$ and $M_R^{U_3}$, such that $M_1 < M_L^{Q_3}(M_R^{U_3}) < M_1 + 200$ GeV.⁵ with $M_2 = 1200$ GeV. We further impose the constraint that the light stop mass ($m_{\tilde{t}_1}$) is never heavier than the LSP by more than 30 GeV. For simplicity, the gluino mass and all the other squark and slepton soft masses are kept fixed at a uniform value, about 100 GeV above the LSP mass. In principle, these sfermion masses and the gluino mass could have been anywhere in between $m_{\tilde{t}_2}$ and $m_{\tilde{\chi}_1^0}$; however, since we are interested in minimising the mass gap between $m_{\tilde{t}_2}$ and $m_{\tilde{t}_1}$ which largely determines the compression factor in the whole SUSY parameter space, we have kept them at an intermediate value in order to reduce the number of parameters to scan. The scan is carried out for two different values of $\tan\beta$, namely, 10 and 25 each for two different μ -values (2 TeV and 3 TeV) to ascertain their effect on the compression of the relevant parameter space.

Fig. 2.3 showcases the correlation between the stop mixing parameters once the Higgs boson mass constraint is implemented for two different μ values. As already discussed, the mass difference between the two stop states, $\Delta m_{\tilde{t}}$, is an important factor in enhancing the radiative Higgs mass correction. In Figs. 2.3 (a) and (b) we show the variation of $\Delta m_{\tilde{t}}$ with A_t at two different $\tan\beta$ values (Green and Blue points) for $\mu = 2$ and 3 TeV respectively. As expected, with the increase of $\tan\beta$ smaller $|A_t|$ is allowed from Higgs mass constraint as a result of increased mixing in stop sector. Fig. 2.3 (b) indicates that slightly smaller $|A_t|$ values are permissible with increase in μ . In a nutshell, the minimum allowed value of $\Delta m_{\tilde{t}}$ decreases as we increase $\tan\beta$ or μ indicating the possibility of getting more and more compressed spectrum. The minimum $\Delta m_{\tilde{t}}$ obtained is about 180 GeV with $m_{\tilde{t}_1}$ close to 1400 GeV and $\mu = 2$ TeV whereas with $\mu = 4$ TeV this minimum value reduces to about 100 GeV.

Figs. 2.3 (c) and (d) show the distribution of m_h as a function of $\Delta m_{\tilde{t}}$. These distributions give a clear idea about the range of Higgs mass we obtain for a certain value of $\Delta m_{\tilde{t}}$. Fig. 2.3 (d) shows one can squeeze $\Delta m_{\tilde{t}}$ to about 160 GeV. However, to ascertain the whole sparticle spectrum mass window, one needs to look at the difference between the LSP mass and the heaviest sparticle in the spectrum. Mass gap of the heavier stop/sbottom and the LSP is denoted as ΔM . Figs. 2.3 (e) and (f) show the distribution of m_h as a function of ΔM . As evident from the plots, the minimum $\Delta m_{\tilde{t}}$ is almost similar to the minimum ΔM that is obtained here indicating that at the periphery of this minima, $m_{\tilde{\chi}_1^0} \approx m_{\tilde{t}_1}$.

2.4 Benchmark points

In choosing the benchmark points for our collider study, we have considered a range of LSP masses varying from 840 GeV to 1862 GeV. The benchmark choices also take

⁵For the demonstration purpose, we only consider bino-like LSP, i.e, $M_1 < M_2$.

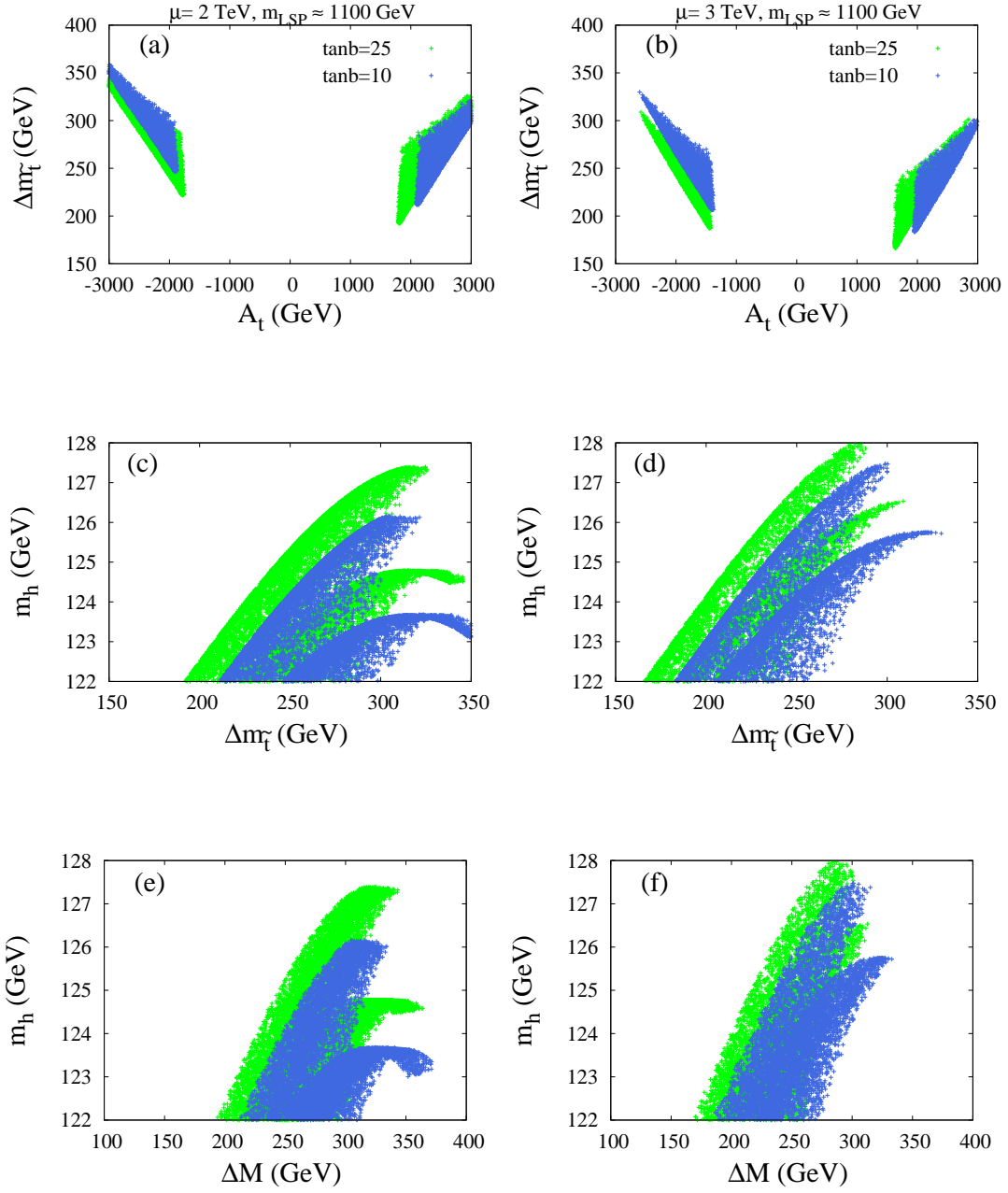


Figure 2.3. The various distributions obtained in our scan are shown. Figs. (a), (c) and (e) are obtained with $\mu = 2$ TeV while Figs. (b), (d) and (f) show the same set of plots obtained with $\mu = 3$ TeV. All the points shown in these plots respect the set of constraints mentioned in the text. The scan is done for two different $\tan\beta$ values: 25 (green points) and 10 (blue points).

into account a varied mass hierarchy for squarks and gluinos, thus allowing different

possible decay cascades down to the LSP. We also consider situations where the \tilde{g} is the NLSP instead of \tilde{t}_1 . An illustrative representation of our choice of benchmark points, keeping in mind the different ways the sparticles can be arranged in their masses, is presented in Fig. 2.4 where we have classified the benchmarks into the four types of representations as shown.

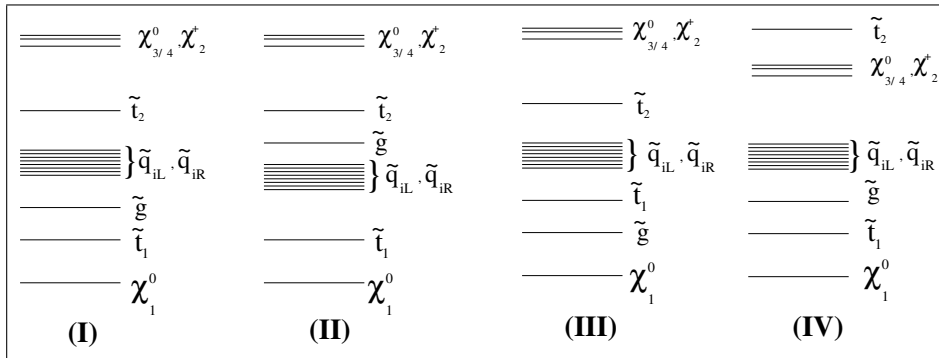


Figure 2.4. Different benchmark scenarios considered in our study: Type I (BP1, BP3, BP5, BP10), Type II (BP4, BP7, BP8, BP9), Type III (BP2) and Type IV (BP6). (In all cases, $\tilde{q}_{iL/R} = \tilde{u}_{iL/R}, \tilde{d}_{iL/R}$ with $i = 1, 2$. Sleptons, χ_2^0 and χ_1^\pm not indicated in the figure, lie below \tilde{t}_2 in all cases. Additionally, the mass gaps shown between different sparticles are not to scale).

To study the signal from the above class of spectrum within a compressed SUSY scenario, we have chosen ten benchmark points from the allowed parameter space in the model. The relevant input parameters, mass spectra and the values of the constraints are summarised in Table 2.2.

Since having at least one heavy (\sim TeV) stop in the spectrum helps in achieving a Higgs boson mass of 125 GeV, it is quite natural to expect more and more compression in the whole SUSY spectrum if we keep increasing the LSP mass. In order to showcase this, we have chosen benchmark points with different LSP masses for different choices of the μ -parameter. BP2, with the lightest LSP mass at 842.4 GeV, gives $\Delta M \sim 300$ GeV while BP6 has the heaviest $\tilde{\chi}_1^0$ at 1861.9 GeV and $\Delta M \sim 184$ GeV. However, note that in BP6, we are able to even pull down the $\tilde{\chi}_{3/4}$ and the $\tilde{\chi}_2^\pm$ masses within a 200 GeV mass window from the LSP.

A heavier spectrum with M_1 or M_2 closer to μ may give rise to more compressed spectrum, but they run into trouble with the DM direct detection constraint. In addition we note that spectra with very heavy squarks and gluino would be out of the 13/14 TeV LHC reach with perhaps some hope for the *very high luminosity* run. We also take some similar LSP masses with different squark-gluino mass hierarchies, like in BP1, BP5 and BP3, BP9 to study how the different decay modes and hardness

Parameters	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8	BP9	BP10
M_1	1470.0	850.0	1107.0	1334.5	1476.3	1890.3	1200.0	1510.0	1105.0	1730.0
M_2	1400.5	880.0	1200.0	1328.6	1402.6	1971.3	1250.0	1550.0	1150.0	1770.0
M_3	1312.0	780.0	1015.0	1405.5	1387.7	1737.1	1180.0	1420.0	1080.0	1600.0
A_t	2200.8	-1650.0	1897.0	-1535.1	1840.8	2800.2	2050.0	2300.0	2000.0	2720.0
μ	2000.0	3000.0	2000.0	3000.0	3000.0	2000.0	2500.0	3000.0	3000.0	2000.0
$\tan\beta$	20.0	20.0	25.0	23.9	24.2	16.87	18.0	20.0	20.0	35.0
$m_{\tilde{g}}$	1429.5	861.6	1112.8	1497.4	1500.4	1882.0	1276.7	1534.7	1165.6	1737.8
$m_{\tilde{q}_L}$	1476.2	893.7	1159.4	1452.3	1532.8	1912.6	1271.6	1524.5	1129.0	1790.0
$m_{\tilde{q}_R}$	1474.3	887.4	1158.1	1451.3	1531.9	1910.6	1270.2	1520.8	1130.7	1794.5
$m_{\tilde{t}_1}$	1412.3	871.7	1097.9	1330.6	1426.1	1865.0	1192.4	1507.6	1100.4	1711.3
$m_{\tilde{t}_2}$	1595.9	1136.8	1300.4	1509.0	1581.3	2045.6	1390.5	1686.6	1308.3	1903.2
$m_{\tilde{b}_1}$	1459.7	861.6	1137.1	1407.4	1493.5	1966.7	1249.6	1521.9	1130.4	1761.3
$m_{\tilde{b}_2}$	1525.3	1044.1	1224.7	1494.5	1570.3	2011.6	1323.6	1619.5	1229.4	1838.4
$m_{\tilde{\ell}_L}$	1432.7	880.9	1121.2	1400.7	1482.7	1916.4	1221.8	1543.9	1132.8	1745.8
$m_{\tilde{\ell}_R}$	1426.2	871.0	1114.7	1400.7	1482.7	1907.6	1215.4	1536.0	1121.7	1736.9
$m_{\tilde{\tau}_1}$	1430.3	890.3	1113.5	1353.2	1438.0	1893.7	1220.0	1529.1	1105.6	1725.4
$m_{\tilde{\tau}_2}$	1483.8	1003.3	1209.5	1446.6	1526.0	1928.4	1289.1	1602.2	1198.2	1803.8
$m_{\tilde{\nu}_L}$	1429.8	876.5	1117.6	1398.6	1480.6	1914.4	1218.3	1540.5	1128.9	1743.1
$m_{\tilde{\chi}_1^0}$	1406.4	842.4	1096.3	1323.9	1417.6	1862.0	1189.0	1496.3	1095.4	1709.3
$m_{\tilde{\chi}_2^0}$	1453.9	889.1	1200.8	1342.9	1463.6	1934.7	1256.9	1559.0	1158.0	1764.9
$m_{\tilde{\chi}_1^\pm}$	1406.7	889.3	1201.0	1342.9	1417.6	1929.1	1257.1	1559.1	1158.2	1764.3
m_h	122.6	122.0	122.2	122.5	122.8	123.9	122.0	122.4	122.1	124.6
Ωh^2	0.092	0.032	0.036	0.113	0.099	0.113	0.062	0.105	0.073	0.110
$\sigma_{SI} \times 10^{11}$ (pb)	115.78	50.11	35.95	4.65	9.08	744.98	7.64	0.13	9.56	280.97
ΔM (GeV)	189.5	294.4	204.1	185.1	163.7	183.6	201.5	190.3	212.9	193.9
ΔM_i (GeV)	69.8	51.3	63.1	173.5	115.2	50.6	87.7	38.4	70.2	85.2

Table 2.2. Low scale input parameters and the relevant particle masses along with the values of the relevant constraints for some of the chosen benchmark points satisfying all the collider, DM and low energy constraints discussed in this section. All the mass parameters are written in GeV unit. Here, $\Delta M_i = m_i - m_{\tilde{\chi}_1^0}$, where i represents a gluino or the $1^{st}/2^{nd}$ family squarks (whichever is the heaviest).

of jets are affected. It should be noted here that we have focussed on final states with zero lepton; one-lepton, two-lepton and three-lepton states have in general highly suppressed rates when they arise in cascade decays of coloured sparticles. Besides, the leptonic final states often entail backgrounds with harder lepton as well as \cancel{E}_T spectra, which survive the cuts in a relatively, more abundant manner. Thus the exact location of the sleptons in our spectra are somewhat inconsequential, so far as the multi-jet + \cancel{E}_T signal is concerned.

3 Probing a compressed spectrum at the LHC

We explore the possibility of finding such a scenario with jet(s) + \cancel{E}_T final state at the 13 TeV run of the LHC and also perform a detailed background simulation for the same. We consider all possible squark/gluino production channels. We must point out that among all the subprocesses contributing to the signal, the squark-gluino associated production channel has the largest cross-section closely followed by

squark pair production cross-section in most of the cases. To study the signal we look at final states with both mono-jet + \cancel{E}_T and multi-jets (≥ 2 -jets) + \cancel{E}_T in order to compare the relative statistical significance factors.

Note that there have been some significant studies [1, 2, 5–10] that deal with collider signatures of a compressed spectrum. However, all these studies consider either squark or gluino pair production and their subsequent decays into the LSP neutralino. The compression is highlighted through the mass gap between the squark/gluino and the LSP being small, begging the explanation that the final state jets in such cases are too soft to be detected at the colliders. In order to observe any signal, one then has to rely on the ISR-FSR jets and/or photons. While such an observation may shed light on a somewhat fine tuned compression in the SUSY spectrum, one cannot fathom that no other SUSY particle will be in similar mass ranges. We believe that we have already highlighted that an equally probable spectrum, where almost all SUSY particles are squeezed within a relatively small mass gap between the LSP and the heaviest coloured sparticle, meets the strictest of experimental constraints there is to offer. Such a scenario, therefore, presents a situation where one can envisage additional contributions to the final states in consideration through production of the closely lying coloured sparticles. Through this work we try to show how this could lead to modifications in the signal topologies and what optimisations in kinematic selections may be required to study such a compressed SUSY signal at the LHC.

3.1 Analysis setup and simulation details

We consider all possible production channels of the coloured sparticles, *i.e.*

$$pp \rightarrow \tilde{q}_i \tilde{q}_j, \tilde{q}_i \tilde{q}_j^*, \tilde{g} \tilde{g}, \tilde{q}_i \tilde{g}, \tilde{q}_i^* \tilde{g}$$

where the respective sparticles would cascade down to the LSP, giving a multi-particle final state comprising of leptons and quarks along with \cancel{E}_T associated with the invisible LSP. It turns out that for the compressed spectrum, the jets and charged leptons originating from cascade decays are expected to be quite soft. Therefore it becomes quite likely that events observed from such productions could be observed through jets originating from initial-state radiation (ISR). As a trigger threshold for such jets would naturally include situations where the jets may actually be coming from hard partons produced in association with the pair of SUSY particles at the parton-level. Hence one necessarily requires to produce hard jet(s) at the parton level along with the coloured sparticles and match the events with the ISR jet events. We perform a parton level event generation simulation using `MadGraph5`(v2.2.3) [59, 60]. For our analysis we have chosen `CTEQ6L` [61] as the parton distribution function (PDF). The factorisation scale is set following the default option of `MadGraph5`. The generated events are passed through `PYTHIA`(v6.4) [62] to simulate showering and hadronisation effects, including fragmentation. The matching between shower jets and jets

produced at the parton level is done using MLM matching [63, 64] based on *shower- k_T* algorithm with p_T -ordered showers. The matching scale, defined as QCUT, differs for the signal where heavy SUSY particles are produced in association with jets when compared to the scale chosen for the SM background. Typical choice of this scale is set between $\simeq 20 - 30$ GeV for the SM backgrounds, and $\simeq 100 - 120$ GeV for the MSSM processes after careful investigation of the matching plots generated for different QCUT values. Then we pass the events through Delphes(v3.2.0) [65–67] for jet formation, using *anti- k_T* jet clustering algorithm [68] (via FastJet [69]), and detector simulation with default ATLAS selection cuts.

As the signal under consideration is either mono-jet + \cancel{E}_T or multi-jet + \cancel{E}_T , we need to identify the dominant SM subprocesses that can contribute to the above. For hadronic final states, the most dominant contribution comes from the pure QCD processes such as multi-jet production where \cancel{E}_T comes either from the jets fragmenting into neutrinos or simply from mismeasurement of the jet energy. Other significantly large contributions can come from W + jets where the W decays leptonically and the charged lepton is missed, Z + jets where the Z decays to neutrinos and $t\bar{t}$ production. Additional modes that may also contribute include t + jets and VV + jets where $V = W^\pm, Z$. For reasons already stated in section 2.4, a lepton veto in the final state helps to suppress quite a few of the above backgrounds. The matching scheme has been also included for the SM background wherever necessary.

Primary selection criteria

To identify the charged leptons (e, μ), photon (γ) and jets, we put the following basic selection criteria (**C0**) on the final state particles for both signal and background:

- Leptons ($\ell = e, \mu$) are selected with $p_T^\ell > 10$ GeV, $|\eta^e| < 2.47$ and $|\eta^\mu| < 2.40$, excluding the transitional pseudorapidity region between the barrel and end cap of the calorimeter $1.37 < |\eta^\ell| < 1.52$.
- Photons are identified with $p_T^\gamma > 10$ GeV and $|\eta^\gamma| < 2.47$ excluding the same transition window as before.
- We demand hard jets having $p_T^j > 40$ GeV within $|\eta^j| < 2.5$.
- All reconstructed jets are required to have an azimuthal separation with $\vec{\cancel{E}}_T$ given by $\Delta\phi(\text{jet}, \vec{\cancel{E}}_T) > 0.2$.

Once the primary selection criteria are set for the signal and background events, we now need to identify specific kinematic characteristics that would differentiate the SUSY events from that of the SM background. To highlight the differences, we choose for illustration a few benchmark points, namely BP4, BP8 and BP10. In Fig. 3.1 we show the normalised distributions of some relevant kinematic variables where one can expect significant differences between the signal events of SUSY and

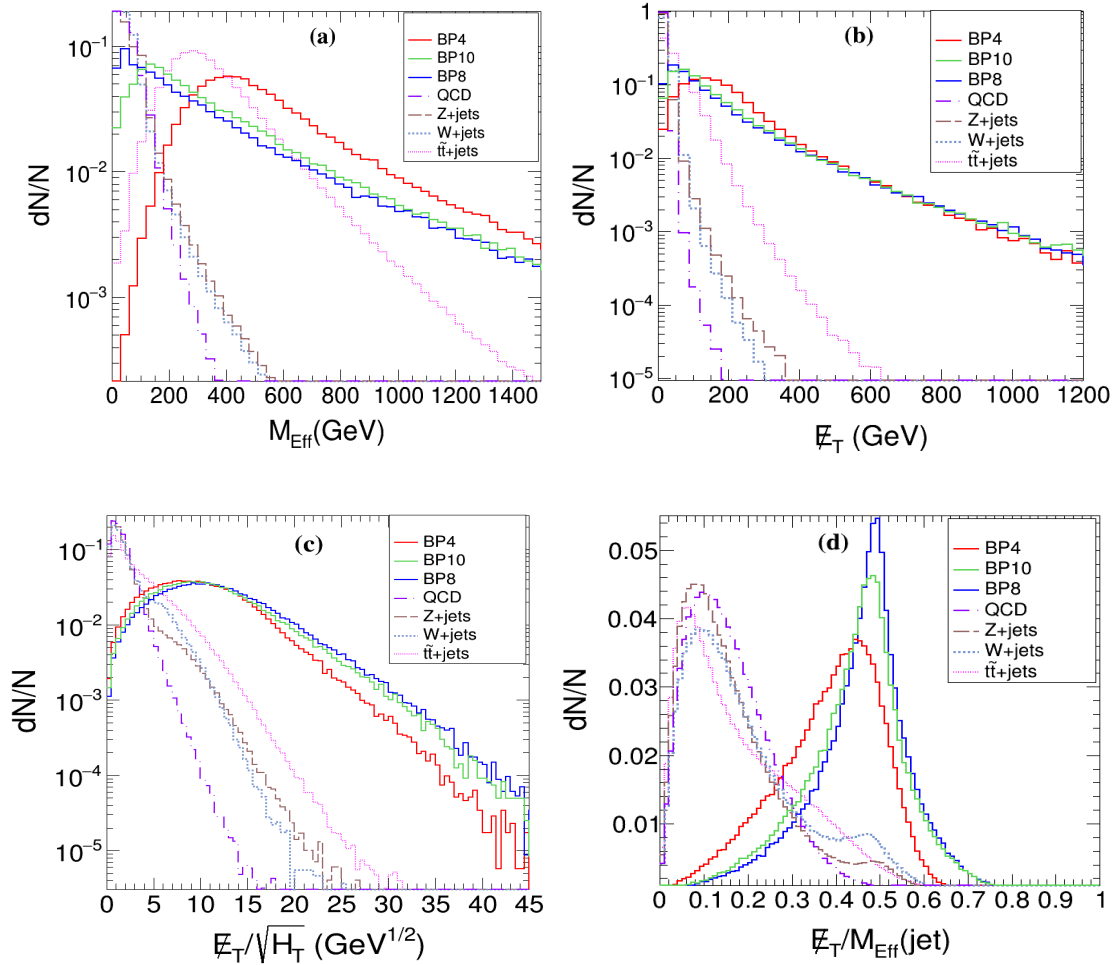


Figure 3.1. Normalised differential distributions of a few relevant kinematic variables for our analysis of compressed spectra after imposing the event selection cuts **C0**. For illustration, signals BP4, BP8 and BP10 are compared to the SM Backgrounds. See the draft for the description of $M_{Eff}(jet)$.

the SM, after imposing the above selection criteria **C0**. Note that events with all jet multiplicities have been included in these plots. As the SUSY signal arises from production of heavy coloured sparticles and is expected to carry large missing energy due to the invisible heavy LSP's in the final state, the effective mass (M_{Eff}) and \cancel{E}_T are expected to help in differentiating the SUSY events from SM. In Fig. 3.1(a) we present the effective mass (M_{Eff}) distribution for these channels where

$$M_{Eff} = \sum_i |\vec{p}_{T_i}| + \cancel{E}_T$$

and i runs over all the states present in the event including the reconstructed jets. This global variable, without utilising any topology information, can be extremely

efficacious from the understanding that, contrary to most of the SM background processes, production of heavy SUSY particles require significantly larger parton level center-of-mass (CM) energy. Thus one expects a larger M_{Eff} for all benchmark scenarios as shown in Fig. 3.1(a). In Fig. 3.1(b) we show the expected missing transverse energy distributions for the SUSY signal and SM background. Quite clearly, the distributions in both the above variables seem to peak at lower values for the SM background (except $t\bar{t}$ +jets) when compared to the SUSY signal. Note that we have plotted the normalised distributions which gives a qualitative idea on the additional cuts required on these variables, rather than a quantitative one.

In addition we find two more kinematic variables of interest used by the ATLAS Collaboration [20, 29], *viz.* $\cancel{E}_T/\sqrt{H_T}$ and $\cancel{E}_T/M_{Eff}(jet)$, which show clear difference between signal and background. These are shown in Fig. 3.1(c) and Fig. 3.1(d) respectively. Here, H_T represents the scalar sum of all isolated jet p_T 's while $M_{Eff}(jet)$ is defined to be constructed out of the first two leading jets and \cancel{E}_T :

$$M_{Eff}(jet) = p_T^{j_1} + p_T^{j_2} + \cancel{E}_T$$

These plots also show some distinct characteristic distributions for signals. We thus find that appropriate cuts on the above variables, shown in Fig. 3.1, would serve to optimise the signal vis-a-vis the SM background. We now proceed to analyse the multi-jets + \cancel{E}_T and mono-jet + \cancel{E}_T signals in the next section.

3.2 Multi-jets + \cancel{E}_T

As discussed earlier, a compressed SUSY spectra such as ours can lead to high multiplicity of jets in the final state. We observe that significant signal events are found when the jet-multiplicity (n_j) is at least two ($n_j \geq 2$) after selecting events using **C0**. This multi-jet scenario is dependent on the hardness of the selected jets and therefore one requires optimised event selection criteria to see how it stands against the SM background. We list below the different cuts which help us in achieving an improved signal to background ratio:

- **C1:** Since we are only considering squark and gluino production channels, no hard lepton or photon are expected in the final state. We, therefore, select final states with two or more jets, vetoing any qualified lepton or photon in such events.

The multi-jet signal is defined for events that satisfy **C0** + **C1**. Note that for a compressed SUSY spectrum, the jet multiplicity would start falling when more hard jets are selected in the final state. An optimised choice in our case is to have only a few very hard jets with the following requirements on their transverse momenta:

- **C2:** The hardest jet should have $p_T(j_1) > 130$ GeV and the next hardest jet $p_T(j_2) > 80$ GeV.

Signal		Effective cross-section after the cuts (in fb)						
Benchmark Points	Production cross-section(fb)	C0 + C1	C2	C3	C4	C5	C6	C7
BP1	155.56	87.38	24.32	23.34	11.49	11.29	8.28	8.22
BP2	4202.42	1877.45	588.58	564.81	260.89	255.29	176.81	175.21
BP3	835.49	414.61	126.64	121.58	58.32	57.12	40.96	40.66
BP4	126.93	118.79	62.85	59.72	20.74	19.84	9.99	9.93
BP5	93.77	81.83	41.58	39.57	13.64	13.17	7.18	7.13
BP6	29.66	14.39	5.49	5.30	2.76	2.71	2.03	2.01
BP7	364.38	248.29	82.04	77.54	32.81	31.99	20.16	20.04
BP8	95.58	40.62	12.86	12.45	6.34	6.24	4.72	4.68
BP9	731.08	453.91	117.84	112.37	55.17	53.86	35.92	35.62
BP10	29.60	19.21	5.20	4.99	2.37	2.33	1.65	1.64

Table 3.1. The cut-flow table for the (multi-jet + \cancel{E}_T) final state, showing the change in signal cross-sections for the ten different benchmark points. The cuts (**C0** – **C7**) are defined in the text in Sec. 3.2.

SM Backgrounds		Effective cross-section after the cuts (in pb)						
Channels	Production (in pb)	C0 + C1	C2	C3	C4	C5	C6	C7
$t\bar{t} + \leq 2$ jets	722.94	542.67	167.2	141.63	15.54	2.47	0.16	0.151
$t + \leq 3$ jets	330.57	227.0	36.23	29.84	1.09	0.123	0.01	0.009
QCD(≤ 4 jets)	2E+08	1.8E+07	312747	251865	2765.52	~ 0	~ 0	~ 0
$Z + \leq 4$ jets	57088	6660.86	325.92	265.45	13.39	2.10	0.666	0.666
$W + \leq 4$ jets	197271	14206.3	896.76	734.47	36.93	3.98	0.485	0.485
WZ + ≤ 2 jets	53.8	24.44	5.74	4.81	0.67	0.16	0.037	0.036
ZZ + ≤ 2 jets	13.69	5.77	0.79	0.66	0.069	0.019	0.00549	0.00548
Total background								1.352

Table 3.2. The cut-flow table for the (multi-jet + \cancel{E}_T) final state, showing the change in cross-sections for the different subprocesses contributing to the SM background. The cuts (**C0** – **C7**) are defined in the text in Sec. 3.2.

We find that the above requirement does not affect the signal significantly while giving appreciable suppression to the SM background (see Table 3.1 and Table 3.2).

- **C3:** We demand larger azimuthal separations between the leading two jets and $\vec{\cancel{E}}_T$ *i.e.* $\Delta\phi(\text{jet}, \vec{\cancel{E}}_T) > 0.4$. This requirement is necessary to reduce the chance of contamination in the \cancel{E}_T coming from missing parts of these hard jets.

We note that the above set of requirements (**C0** – **C3**) not only helps in refining the signal against the SM background but also helps us in determining more precise quantitative cuts on the kinematic variables shown in Fig. 3.1 to improve the signal

Signal	$m_{\tilde{\chi}_1^0}$ (GeV)	Statistical significance (\mathcal{S})			Required luminosity (in fb^{-1})	
		$\mathcal{L} = 100$	$\mathcal{L} = 500$	$\mathcal{L} = 1000$	$\mathcal{S} = 3\sigma$	$\mathcal{S} = 5\sigma$
BP1	1406.4	2.23	4.99	7.06	180.98	502.72
BP2	842.4	46.67	104.37	147.60	0.41	1.15
BP3	1096.3	11.00	24.61	34.80	7.44	20.66
BP4	1323.9	2.70	6.03	8.53	123.46	342.94
BP5	1417.6	1.94	4.33	6.13	239.13	664.26
BP6	1862.0	0.55	1.22	1.73	2975.21	8264.46
BP7	1189.0	5.44	12.16	17.19	30.41	84.48
BP8	1496.3	1.27	2.84	4.02	558.00	1550.00
BP9	1095.4	9.65	21.57	30.50	9.66	26.85
BP10	1709.3	0.45	1.00	1.41	4444.44	12345.68

Table 3.3. Statistical significance of the signal for different benchmark points in the multi-jet + \cancel{E}_T analysis at 13 TeV LHC. The significance is estimated for three values of integrated luminosity ($\mathcal{L} = 100, 500$ and 1000 fb^{-1}). We also estimate the required integrated luminosity to achieve a 3σ and 5σ excess for each benchmark point at LHC with $\sqrt{s} = 13 \text{ TeV}$.

significance (see Table 3.1 and Table 3.2). Naively, Fig. 3.1(d) would suggest that an appropriate cut on $\cancel{E}_T/M_{Eff}(jet)$ itself can help us completely eliminate the background. However, on close inspection, we find that the tail of the large QCD background still survives this cut. We, therefore, find a more optimised cut flow to improve the signal significance as shown below.

- **C4:** We demand $M_{Eff} > 800 \text{ GeV}$. This turns out to be quite crucial in significantly suppressing almost all contributions for the SM background while moderately affecting the signal events.
- **C5:** We demand $\cancel{E}_T > 160 \text{ GeV}$ which helps in completely eliminating the remnant QCD multi-jet background while suppressing all the other SM background channels. Note that this cut hardly affects the signal for any of the benchmark points.
- **C6:** Larger missing energy and softer jets in our scenario results in a larger $\cancel{E}_T/\sqrt{H_T}$ ratio compared to the SM background channels. We find that with $\cancel{E}_T/\sqrt{H_T} > 15 \text{ GeV}^{1/2}$ the signal significance can be improved further.
- **C7:** The ratio $\cancel{E}_T/M_{Eff}(jet)$ is shown to peak at smaller values for the SM background and therefore we demand $\cancel{E}_T/M_{Eff}(jet) > 0.35$ which further improves our signal significance.

We present the numerical results for the ten aforementioned benchmark points and the SM background to the multi-jet + \cancel{E}_T signal at LHC with $\sqrt{s} = 13$ TeV. In Table 3.1 we summarise the effects of the cuts (**C0** – **C7**) on signal cross-sections. It is worth pointing out here that we have used next-to-leading order (NLO) cross-section for the production rates of squarks and gluinos in our signal analysis by multiplying the leading-order cross-sections of `MadGraph5` by NLO K -factors obtained using `Prospino 2.1` [70–74]. The cut-flow table for the same set of cuts is shown for the SM background processes in Table 3.2. Note that we have also used the NLO cross-section for SM background processes provided in `MadGraph5` [59]. It is quite clear to see from Tables 3.1 and 3.2 that our choice of cuts is quite efficient in suppressing a seemingly huge SM background such that the signal may be observed at the LHC. The statistical significance (\mathcal{S}) of the observed signal (s) over the total SM background (b) has been calculated using

$$\mathcal{S} = \sqrt{2 \times \left[(s + b) \ln \left(1 + \frac{s}{b} \right) - s \right]}. \quad (3.1)$$

We show the significance of the signal for different benchmark points in the multi-jet + \cancel{E}_T channel in Table 3.3. We choose three different values for the integrated luminosity ($\mathcal{L} = 100, 500$ and 1000 fb^{-1}) to highlight the significance for the benchmark points. We find that the signal corresponding to BP6 and BP10 are practically scenarios within a compressed SUSY spectrum which would be very hard to observe in the multi-jet + \cancel{E}_T channel. In fact an integrated luminosity of over 3000 fb^{-1} would be required for any hope of observing a notable excess for the SUSY spectrum given by the above benchmark points. This is however understandable as the corresponding spectra is very heavy leading to smaller production rates compared to the other benchmark points. The lightest spectrum amongst all the benchmark points, *viz.* BP2 is the most robust of all and should be observable at the present run of LHC with luminosity as low as 1 fb^{-1} . The rest of the benchmark points too lead to 3σ and 5σ excess over the SM backgrounds with relatively nominal to slightly higher integrated luminosities as shown in the last two columns of Table 3.3.

3.3 Mono-jet + \cancel{E}_T

The mono-jet + \cancel{E}_T signal is considered as a favourable channel to probe a compressed spectrum at the LHC [5–13, 18, 75]. Therefore it is quite logical to explore how the mono-jet final state in our scenario stands against the SM background. Both ATLAS and CMS have investigated mono-jet signals in the context of compressed SUSY spectra [15–17, 19, 20]. Note that, these analyses consider only such scenarios where the compression is between the NLSP and LSP, and the signal arises through the NLSP pair production and its subsequent decay. Since we consider almost the entire SUSY spectrum to be compressed, all SUSY processes (dominated, of course, by coloured sparticle production channels) are of interest to us. Thus our analysis

Signal		Effective cross-section after the cuts (in fb)				
Benchmark Points	Production cross-section(fb)	C0 + D1	D2	D3	D4	D5
BP1	155.56	136.11	51.85	14.19	11.64	3.01
BP2	4202.42	3262.38	1334.47	321.74	256.86	58.14
BP3	835.49	686.61	277.70	70.70	57.26	13.76
BP4	126.93	126.70	79.36	12.06	8.22	0.88
BP5	93.77	88.93	55.13	9.16	6.23	0.78
BP6	29.66	23.81	11.58	2.58	2.13	0.58
BP7	364.38	308.97	126.35	27.61	20.34	5.15
BP8	95.58	71.47	30.46	7.48	6.20	1.63
BP9	731.08	650.39	241.20	69.16	54.65	13.63
BP10	29.60	27.11	10.32	2.91	2.32	0.60

Table 3.4. The cut-flow table for the (mono-jet + \cancel{E}_T) final state, showing the change in signal cross-sections for the ten different benchmark points. The cuts (**C0**, **D1** – **D5**) are defined in the text in Sec. 3.3.

requires revisiting the standard cuts suggested in the literature. As in the case of multi-jet + \cancel{E}_T final state, we demand a leptonically quiet mono-jet final state (after **C0**) where:

- **D1:** Events are selected having at least one hard jet in the final state with no charged lepton or photon.

Since mono-jet searches rely on hard ISR jet, the leading jet is required to be considerably hard with large transverse momentum and well separated from the direction of $\vec{\cancel{E}}_T$:

- **D2:** The leading jet has $p_T(j_1) > 130$ GeV (as before) with a significantly larger azimuthal separation with $\vec{\cancel{E}}_T$ given by $\Delta\phi(j_1, \vec{\cancel{E}}_T) > 1.0$.
- **D3:** In order to accommodate a hard jet coming from ISR, but not rule out cases with another jet arising due to its fragmentation, we demand the second hardest jet to have $p_T(j_2) < 80$ GeV, but with $\Delta\phi(j_2, \vec{\cancel{E}}_T) > 1.0$.

We thus define our mono-jet + \cancel{E}_T signal for events which satisfy cuts (**C0**, **D1** – **D3**). Moreover, for events where the leading jet is hard enough, a sizeable \cancel{E}_T is seen, which also serves as an useful discriminator for the SUSY signal from the SM background.

- **D4:** We demand $\cancel{E}_T > 160$ GeV. In our case, this decreases the SM background substantially, as opposed to the SUSY signals (see Table 3.4 and 3.5).

We also find that a hard effective mass (M_{Eff}) cut is also quite efficient in suppressing the SM background as compared to SUSY signal events for the mono-jet + \cancel{E}_T channel.

- **D5**: We set $M_{Eff} > 800$ GeV for the analysis which again helps to remove the huge QCD background as well as reduce the other dominant contributions. Although the signal events are also reduced considerably, the signal-to-background ratio improves significantly after the M_{Eff} cut.

SM Backgrounds		Effective cross-section after the cuts (in pb)				
Channels	Production (in pb)	C0 + D1	D2	D3	D4	D5
$t\bar{t} + \leq 2$ jets	722.94	573.89	171.12	21.52	2.135	0.119
$t + \leq 3$ jets	330.57	278.05	41.14	6.17	0.355	0.011
QCD(≤ 4 jets)	2E+08	7.6E+07	417461	46034	2584	~ 0
Z $+ \leq 4$ jets	57088	18924.1	446.41	52.25	6.66	0.255
W $+ \leq 4$ jets	197271	50478.5	1167.56	139.332	8.98	0.534
WZ $+ \leq 2$ jets	53.8	37.92	6.896	0.953	0.208	0.0161
ZZ $+ \leq 2$ jets	13.69	9.77	1.03	0.158	0.0498	0.00264
Total background						0.938

Table 3.5. The cut-flow table for the (mono-jet $+ \cancel{E}_T$) final state, showing the change in cross-sections for the different subprocesses contributing to the SM background. The cuts (**C0**, **D1** – **D5**) are defined in the text in Sec. 3.3.

Tables 3.4 and 3.5 summarise the effect of the cuts (**C0**, **D1** – **D5**) on the SUSY signals and SM background cross-sections respectively. For both signal and background, we have used the NLO cross-sections as before. It is clear from Tables 3.4 and 3.5 that our choice of cuts for the mono-jet $+ \cancel{E}_T$ final state, although quite helpful in suppressing the SM background to improve the signal significance is however not an improvement over the multi-jet $+ \cancel{E}_T$ channel. We show the significance of the signal for all the benchmark points in the mono-jet $+ \cancel{E}_T$ channel in Table 3.6 with the same integrated luminosity ($\mathcal{L} = 100, 500$ and 1000 fb^{-1}).

For the mono-jet $+ \cancel{E}_T$ channel too, we find that the lightest spectrum, BP2 will be discovered at the earliest. The heavier spectra, BP6 and BP10 are no more better observable in the mono-jet $+ \cancel{E}_T$ channel as they were in the multi-jet $+ \cancel{E}_T$ channel. Among others, large number of signal spectra such as, BP4, BP5, BP8, have low significances even at 1000 fb^{-1} whereas BP3, BP9, BP7 and BP1 may be observed at moderate ($\sim 45 \text{ fb}^{-1}$) to high ($\sim 1000 \text{ fb}^{-1}$) luminosities at the LHC. It is important to note that the squark-gluino masses and hierarchy dictate the hardness of the cascade jets. As per our selection criteria, **D2** rejects events with additional hard jets while retaining many more with softer accompanying jets, thereby enhancing the significance in general. However, it adversely affects cases such as BP4 which have larger mass gaps.

Thus, although the multi-jet $+ \cancel{E}_T$ channel provides increased signal significances for all the benchmark points, mono-jet $+ \cancel{E}_T$ channel still remains a viable window for

Signal	$m_{\tilde{\chi}_1^0}$ (GeV)	Statistical significance (\mathcal{S})			Required Luminosity (in fb^{-1})	
		$\mathcal{L} = 100$	$\mathcal{L} = 500$	$\mathcal{L} = 1000$	$\mathcal{S} = 3\sigma$	$\mathcal{S} = 5\sigma$
BP1	1406.4	0.98	2.19	3.10	937.11	2603.08
BP2	842.4	18.98	42.44	60.02	2.50	6.94
BP3	1096.3	4.49	10.03	14.20	44.64	124.00
BP4	1323.9	0.29	0.64	0.91	10926.44	30351.22
BP5	1417.6	0.25	0.57	0.81	14400	40000
BP6	1862.0	0.19	0.42	0.60	24930.75	69252.08
BP7	1189.0	1.68	3.76	5.31	318.88	885.77
BP8	1496.3	0.53	1.19	1.68	3203.99	8899.96
BP9	1095.4	4.45	9.95	14.07	45.44	126.25
BP10	1709.3	0.20	0.44	0.62	22500	62500

Table 3.6. Statistical significance of the signal for different benchmark points in the mono-jet + \cancel{E}_T analysis at 13 TeV LHC. The significance is estimated for three values of integrated luminosity ($\mathcal{L} = 100, 500$ and 1000 fb^{-1}). We also estimate the required integrated luminosity to achieve a 3σ and 5σ excess for each benchmark point at LHC with $\sqrt{s} = 13 \text{ TeV}$.

observing compressed spectra. Overall, the efficacy of both these channels depends on the splitting among the LSP, lighter stop, gluino and first two generation squark masses. The benchmark points where the masses of the first two generation squarks and the gluino are separated from the LSP by about 50 GeV at most are found to have better signal to background ratio in the multi-jet + \cancel{E}_T final state when compared to mono-jet + \cancel{E}_T . However, two spectra with similar \tilde{q} - \tilde{g} masses resulting in similar production cross-sections, are expected to differ in their relative sensitivities to the two final states depending upon the \tilde{q} - \tilde{g} - $\tilde{\chi}_1^0$ mass gaps. Let us consider BP5 and BP8 for example. Although the \tilde{q} 's and the \tilde{g} masses are very similar, ΔM_i in BP8 is much smaller than that in BP5 because of their different LSP masses. Naturally, BP5 provides a better signal significance than BP8 when multi-jet + \cancel{E}_T final state is considered but the situation is reversed when we do a mono-jet + \cancel{E}_T analysis. BP3 and BP9 despite having similar LSP mass, are different in terms of the \tilde{q} - \tilde{g} mass hierarchy. BP3, as a consequence of having smaller gluino mass, has a larger production cross-section, but due to the presence of more number of softer jets in BP9, it does slightly better than BP3 in terms of signal significance in the mono-jet analysis. BP4 despite having smaller production cross-section than BP1, has a better signal significance for multi-jet + \cancel{E}_T final state due to the presence of more number of harder jets. On the other hand, BP1 does better if mono-jet + \cancel{E}_T final state is considered. BP2 prevails over all the other benchmark points in terms of signal significance in both the final states due to its large production cross-section. BP6

and BP10 having very heavy $\tilde{q}\text{-}\tilde{g}$ spectrum, are unlikely to be probed even at high luminosities.

4 Summary and conclusion

In this work, we have considered the compressed SUSY scenario within the phenomenological MSSM framework that is consistent with all the present collider and DM data. We observe that achieving a substantial compression in the whole SUSY spectrum while being consistent with the observed Higgs boson mass requires relatively heavy masses for the sparticles. Since at least one of the stop masses needs to be heavy (above TeV) in order to enhance the lightest CP-even Higgs boson mass to the allowed range, better compression in the parameter space is obtained as we consider heavier LSP masses which nonetheless address the naturalness problem. Such mass ranges, we emphasize, are beyond the reach of the 8 TeV run, and therefore, warrant a close investigation in the context of 13/14 TeV LHC. We observe that having a large μ -parameter, too, can achieve tighter compression in the remaining spectrum.

We select ten representative benchmark points from the currently allowed parameter space with all kinds of mass hierarchies and explore their detection possibility at the 13 TeV run of the LHC. Similar results can be expected if the upgradation to 14 TeV takes place. We analyse both the conventional multi-jet + \cancel{E}_T channel and the mono-jet + \cancel{E}_T channel. We observe that although mono-jet + \cancel{E}_T channel may be a viable option for this kind of scenario, a multi-jet + \cancel{E}_T final state provides better statistical significance over the SM background for all our benchmark points.

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References

- [1] T. J. LeCompte and S. P. Martin, *Large Hadron Collider reach for supersymmetric models with compressed mass spectra*, *Phys. Rev.* **D84** (2011) 015004, [[arXiv:1105.4304](https://arxiv.org/abs/1105.4304)].

- [2] T. J. LeCompte and S. P. Martin, *Compressed supersymmetry after 1/fb at the Large Hadron Collider*, *Phys. Rev.* **D85** (2012) 035023, [[arXiv:1111.6897](#)].
- [3] H. Murayama, Y. Nomura, S. Shirai, and K. Tobioka, *Compact Supersymmetry*, *Phys. Rev.* **D86** (2012) 115014, [[arXiv:1206.4993](#)].
- [4] K. Nakayama and T. T. Yanagida, *Anomaly mediation deformed by axion*, *Phys. Lett.* **B722** (2013) 107–110, [[arXiv:1302.3332](#)].
- [5] D. S. M. Alves, E. Izaguirre, and J. G. Wacker, *It's On: Early Interpretations of ATLAS Results in Jets and Missing Energy Searches*, *Phys. Lett.* **B702** (2011) 64–68, [[arXiv:1008.0407](#)].
- [6] E. Alvarez and Y. Bai, *Reach the Bottom Line of the Sbottom Search*, *JHEP* **08** (2012) 003, [[arXiv:1204.5182](#)].
- [7] H. K. Dreiner, M. Kramer, and J. Tattersall, *How low can SUSY go? Matching, monojets and compressed spectra*, *Europhys. Lett.* **99** (2012) 61001, [[arXiv:1207.1613](#)].
- [8] B. Bhattacharjee and K. Ghosh, *Degenerate SUSY search at the 8 TeV LHC*, [[arXiv:1207.6289](#)].
- [9] H. Dreiner, M. Krmer, and J. Tattersall, *Exploring QCD uncertainties when setting limits on compressed supersymmetric spectra*, *Phys. Rev.* **D87** (2013), no. 3 035006, [[arXiv:1211.4981](#)].
- [10] B. Bhattacharjee, A. Choudhury, K. Ghosh, and S. Poddar, *Compressed supersymmetry at 14 TeV LHC*, *Phys. Rev.* **D89** (2014), no. 3 037702, [[arXiv:1308.1526](#)].
- [11] S. P. Martin, *Exploring compressed supersymmetry with same-sign top quarks at the Large Hadron Collider*, *Phys. Rev.* **D78** (2008) 055019, [[arXiv:0807.2820](#)].
- [12] G. Belanger, M. Heikinheimo, and V. Sanz, *Model-Independent Bounds on Squarks from Monophoton Searches*, *JHEP* **08** (2012) 151, [[arXiv:1205.1463](#)].
- [13] T. Cohen, T. Golling, M. Hance, A. Henrichs, K. Howe, J. Loyal, S. Padhi, and J. G. Wacker, *SUSY Simplified Models at 14, 33, and 100 TeV Proton Colliders*, *JHEP* **04** (2014) 117, [[arXiv:1311.6480](#)].
- [14] **ATLAS** Collaboration, T. A. collaboration, *Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum and 20.3 fb⁻¹ of $\sqrt{s} = 8$ TeV proton-proton collision data*, .
- [15] **CMS** Collaboration, S. Chatrchyan et al., *Search for New Physics with a Mono-Jet and Missing Transverse Energy in pp Collisions at $\sqrt{s} = 7$ TeV*, *Phys. Rev. Lett.* **107** (2011) 201804, [[arXiv:1106.4775](#)].
- [16] **ATLAS** Collaboration, G. Aad et al., *Search for new phenomena with the monojet and missing transverse momentum signature using the ATLAS detector in $\sqrt{s} = 7$ TeV proton-proton collisions*, *Phys. Lett.* **B705** (2011) 294–312, [[arXiv:1106.5327](#)].

- [17] **ATLAS** Collaboration, G. Aad et al., *Search for squarks and gluinos with the ATLAS detector in final states with jets and missing transverse momentum using 4.7 fb⁻¹ of $\sqrt{s} = 7$ TeV proton-proton collision data*, *Phys. Rev.* **D87** (2013), no. 1 012008, [[arXiv:1208.0949](#)].
- [18] S. Mukhopadhyay, M. M. Nojiri, and T. T. Yanagida, *Compressed SUSY search at the 13 TeV LHC using kinematic correlations and structure of ISR jets*, *JHEP* **10** (2014) 12, [[arXiv:1403.6028](#)].
- [19] **CMS** Collaboration, V. Khachatryan et al., *Search for dark matter, extra dimensions, and unparticles in monojet events in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J.* **C75** (2015), no. 5 235, [[arXiv:1408.3583](#)].
- [20] **ATLAS** Collaboration, G. Aad et al., *Search for new phenomena in final states with an energetic jet and large missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *Eur. Phys. J.* **C75** (2015), no. 7 299, [[arXiv:1502.01518](#)]. [Erratum: *Eur. Phys. J.* **C75**, no. 9, 408 (2015)].
- [21] G. Chalons and D. Sengupta, *Closing in on compressed gluino-neutralino spectra at the LHC*, [[arXiv:1508.06735](#)].
- [22] **ATLAS** Collaboration, G. Aad et al., *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett.* **B716** (2012) 1–29, [[arXiv:1207.7214](#)].
- [23] **CMS** Collaboration, S. Chatrchyan et al., *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett.* **B716** (2012) 30–61, [[arXiv:1207.7235](#)].
- [24] **ATLAS, CMS** Collaboration, G. Aad et al., *Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS Experiments*, *Phys. Rev. Lett.* **114** (2015) 191803, [[arXiv:1503.07589](#)].
- [25] S. P. Martin, *Compressed supersymmetry and natural neutralino dark matter from top squark-mediated annihilation to top quarks*, *Phys. Rev.* **D75** (2007) 115005, [[hep-ph/0703097](#)].
- [26] S. P. Martin, *The Top squark-mediated annihilation scenario and direct detection of dark matter in compressed supersymmetry*, *Phys. Rev.* **D76** (2007) 095005, [[arXiv:0707.2812](#)].
- [27] H. Baer, A. Box, E.-K. Park, and X. Tata, *Implications of compressed supersymmetry for collider and dark matter searches*, *JHEP* **08** (2007) 060, [[arXiv:0707.0618](#)].
- [28] **ATLAS** Collaboration, G. Aad et al., *Search for strong production of supersymmetric particles in final states with missing transverse momentum and at least three b-jets at $\sqrt{s} = 8$ TeV proton-proton collisions with the ATLAS detector*, *JHEP* **10** (2014) 24, [[arXiv:1407.0600](#)].
- [29] **ATLAS** Collaboration, G. Aad et al., *Search for squarks and gluinos with the*

- ATLAS detector in final states with jets and missing transverse momentum using $\sqrt{s} = 8$ TeV proton-proton collision data*, *JHEP* **09** (2014) 176, [[arXiv:1405.7875](#)].
- [30] **ATLAS Collaboration**, G. Aad et al., *Search for top squark pair production in final states with one isolated lepton, jets, and missing transverse momentum in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, *JHEP* **11** (2014) 118, [[arXiv:1407.0583](#)].
- [31] **ATLAS Collaboration**, G. Aad et al., *Search for direct pair production of the top squark in all-hadronic final states in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *JHEP* **09** (2014) 015, [[arXiv:1406.1122](#)].
- [32] **ATLAS Collaboration**, G. Aad et al., *Search for direct top-squark pair production in final states with two leptons in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *JHEP* **06** (2014) 124, [[arXiv:1403.4853](#)].
- [33] **ATLAS Collaboration**, G. Aad et al., *Search for pair-produced third-generation squarks decaying via charm quarks or in compressed supersymmetric scenarios in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *Phys. Rev.* **D90** (2014), no. 5 052008, [[arXiv:1407.0608](#)].
- [34] **ATLAS Collaboration**, G. Aad et al., *Search for direct third-generation squark pair production in final states with missing transverse momentum and two b-jets in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, *JHEP* **10** (2013) 189, [[arXiv:1308.2631](#)].
- [35] CMS, *Summary of cms susy results in sms framework*, . https://twiki.cern.ch/twiki/pub/CMSPublic/SUSYSMSSummaryPlots8TeV/barplot_ICHEP2014.pdf.
- [36] ATLAS, *Summary of atlas susy searches*, . https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/ATLAS_SUSY_Summary/ATLAS_SUSY_Summary.png.
- [37] P. Konar, K. T. Matchev, M. Park, and G. K. Sarangi, *How to look for supersymmetry under the lamppost at the LHC*, *Phys. Rev. Lett.* **105** (2010) 221801, [[arXiv:1008.2483](#)].
- [38] L. J. Hall, D. Pinner, and J. T. Ruderman, *A Natural SUSY Higgs Near 126 GeV*, *JHEP* **04** (2012) 131, [[arXiv:1112.2703](#)].
- [39] A. Djouadi, *Implications of the Higgs discovery for supersymmetry*, *EPJ Web Conf.* **95** (2015) 03006.
- [40] M. Carena, S. Heinemeyer, O. Stl, C. E. M. Wagner, and G. Weiglein, *MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios after the Discovery of a Higgs-like Particle*, *Eur. Phys. J.* **C73** (2013), no. 9 2552, [[arXiv:1302.7033](#)].
- [41] LEPSUSYWG et al., *Lep2 susy working group*, . <http://lepsusy.web.cern.ch/lepsusy/>.
- [42] **LHCb collaboration** Collaboration, R. Aaij et al., *Measurement of the*

- $B_s^0 \rightarrow \mu^+ \mu^-$ branching fraction and search for $B^0 \rightarrow \mu^+ \mu^-$ decays at the LHCb experiment, *Phys.Rev.Lett.* **111** (2013) 101805, [[arXiv:1307.5024](#)].
- [43] **CMS Collaboration** Collaboration, S. Chatrchyan et al., *Measurement of the $B(s)$ to $\mu^+ \mu^-$ branching fraction and search for B^0 to $\mu^+ \mu^-$ with the CMS Experiment*, *Phys.Rev.Lett.* **111** (2013) 101804, [[arXiv:1307.5025](#)].
- [44] **WMAP Collaboration**, G. Hinshaw et al., *Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results*, *Astrophys.J.Suppl.* **208** (2013) 19, [[arXiv:1212.5226](#)].
- [45] Z. Berezhiani and M. Y. Khlopov, *Cosmology of Spontaneously Broken Gauge Family Symmetry*, *Z.Phys.* **C49** (1991) 73–78.
- [46] C. Boehm, P. Fayet, and J. Silk, *Light and heavy dark matter particles*, *Phys.Rev.* **D69** (2004) 101302, [[hep-ph/0311143](#)].
- [47] E. Ma, *Supersymmetric Model of Radiative Seesaw Majorana Neutrino Masses*, *Annales Fond.Broglie* **31** (2006) 285, [[hep-ph/0607142](#)].
- [48] P.-H. Gu, *Unified mass origin at TeV for dark matter and Dirac neutrinos*, *Phys.Lett.* **B661** (2008) 290–294, [[arXiv:0710.1044](#)].
- [49] T. Hur, H.-S. Lee, and S. Nasri, *A Supersymmetric $U(1)$ -prime model with multiple dark matters*, *Phys.Rev.* **D77** (2008) 015008, [[arXiv:0710.2653](#)].
- [50] Q.-H. Cao, E. Ma, J. Wudka, and C.-P. Yuan, *Multipartite dark matter*, [[arXiv:0711.3881](#)].
- [51] T. Hambye, *Hidden vector dark matter*, *JHEP* **0901** (2009) 028, [[arXiv:0811.0172](#)].
- [52] M. Aoki, M. Duerr, J. Kubo, and H. Takano, *Multi-Component Dark Matter Systems and Their Observation Prospects*, *Phys.Rev.* **D86** (2012) 076015, [[arXiv:1207.3318](#)].
- [53] J. Heeck and H. Zhang, *Exotic Charges, Multicomponent Dark Matter and Light Sterile Neutrinos*, *JHEP* **1305** (2013) 164, [[arXiv:1211.0538](#)].
- [54] P. Konar, K. Kong, K. T. Matchev, and M. Park, *Dark Matter Particle Spectroscopy at the LHC: Generalizing $M(T2)$ to Asymmetric Event Topologies*, *JHEP* **04** (2010) 086, [[arXiv:0911.4126](#)].
- [55] **LUX Collaboration** Collaboration, D. Akerib et al., *First results from the LUX dark matter experiment at the Sanford Underground Research Facility*, *Phys.Rev.Lett.* **112** (2014), no. 9 091303, [[arXiv:1310.8214](#)].
- [56] 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) 275–315, [[hep-ph/0301101](#)].
- [57] W. Porod and F. Staub, *SPheno 3.1: Extensions including flavour, CP-phases and models beyond the MSSM*, *Comput. Phys. Commun.* **183** (2012) 2458–2469, [[arXiv:1104.1573](#)].

- [58] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, *micrOMEGAS₃: A program for calculating dark matter observables*, *Comput. Phys. Commun.* **185** (2014) 960–985, [[arXiv:1305.0237](#)].
- [59] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079, [[arXiv:1405.0301](#)].
- [60] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, and T. Stelzer, *MadGraph 5 : Going Beyond*, *JHEP* **06** (2011) 128, [[arXiv:1106.0522](#)].
- [61] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. M. Nadolsky, and W. K. Tung, *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* **07** (2002) 012, [[hep-ph/0201195](#)].
- [62] T. Sjostrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **05** (2006) 026, [[hep-ph/0603175](#)].
- [63] M. L. Mangano, M. Moretti, F. Piccinini, and M. Treccani, *Matching matrix elements and shower evolution for top-quark production in hadronic collisions*, *JHEP* **01** (2007) 013, [[hep-ph/0611129](#)].
- [64] S. Hoeche, F. Krauss, N. Lavesson, L. Lonnblad, M. Mangano, A. Schaliche, and S. Schumann, *Matching parton showers and matrix elements*, in *HERA and the LHC: A Workshop on the implications of HERA for LHC physics: Proceedings Part A*, 2006. [[hep-ph/0602031](#)].
- [65] **DELPHES 3** Collaboration, J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lematre, A. Mertens, and M. Selvaggi, *DELPHES 3, A modular framework for fast simulation of a generic collider experiment*, *JHEP* **02** (2014) 057, [[arXiv:1307.6346](#)].
- [66] M. Selvaggi, *DELPHES 3: A modular framework for fast-simulation of generic collider experiments*, *J. Phys. Conf. Ser.* **523** (2014) 012033.
- [67] A. Mertens, *New features in Delphes 3*, *J. Phys. Conf. Ser.* **608** (2015), no. 1 012045.
- [68] M. Cacciari, G. P. Salam, and G. Soyez, *The Anti- $k(t)$ jet clustering algorithm*, *JHEP* **04** (2008) 063, [[arXiv:0802.1189](#)].
- [69] M. Cacciari, G. P. Salam, and G. Soyez, *FastJet User Manual*, *Eur. Phys. J.* **C72** (2012) 1896, [[arXiv:1111.6097](#)].
- [70] W. Beenakker, R. Hopker, and M. Spira, *PROSPINO: A Program for the production of supersymmetric particles in next-to-leading order QCD*, [[hep-ph/9611232](#)].
<http://www.thphys.uni-heidelberg.de/~plehn/index.php?show=prospino&visible=tools>.
- [71] T. Plehn, *Measuring the MSSM Lagrangean*, *Czech. J. Phys.* **55** (2005) B213–B220, [[hep-ph/0410063](#)].

- [72] M. Spira, *Higgs and SUSY particle production at hadron colliders*, in *Supersymmetry and unification of fundamental interactions. Proceedings, 10th International Conference, SUSY'02, Hamburg, Germany, June 17-23, 2002*, pp. 217–226, 2002. [hep-ph/0211145](#).
- [73] W. Beenakker, M. Kramer, T. Plehn, M. Spira, and P. M. Zerwas, *Stop production at hadron colliders*, *Nucl. Phys.* **B515** (1998) 3–14, [[hep-ph/9710451](#)].
- [74] W. Beenakker, R. Hopker, M. Spira, and P. M. Zerwas, *Squark and gluino production at hadron colliders*, *Nucl. Phys.* **B492** (1997) 51–103, [[hep-ph/9610490](#)].
- [75] C. Han, L. Wu, J. M. Yang, M. Zhang, and Y. Zhang, *New approach for detecting a compressed bino/wino at the LHC*, *Phys. Rev.* **D91** (2015) 055030, [[arXiv:1409.4533](#)].