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Low scale supersymmetry at the LHC with jet and missing energy signature

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Abstract: If supersymmetry is broken at TeV scale, particles from sector responsible for supersymmetry breaking - goldstino and sgoldstinos - can reveal themselves already at the LHC experiments. We discuss bounds on supersymmetry breaking scale from the LHC searches for events with a jet plus missing momentum signature focusing on the case of TeV scale sgoldstinos. We show that contribution of light sgoldstinos to the cross section of of gravitino pair production with a jet can be sizable and the bounds on the gravitino mass can be stronger by up to a factor of 2 as compared to those obtained in the heavy sgoldstino limit. We compare these bounds on parameters of the model to those obtained with the results of ATLAS and CMS searches for dijet resonances.

Keywords: Supersymmetry, Phenomenology, Beyond the Standard Model, Hadronic Colliders, Supergravity Models, Supersymmetry Breaking

Contents

1 Introduction

Supersymmetry is among the most interesting and well motivated Standard Model (SM) extensions. It offers solutions to different SM problems including dark matter, naturalness and gauge couplings unification [1]. If supersymmetry is indeed a true symmetry of Nature it should be broken in some way. In the standard approach the MSSM lagrangian is supplied with so-called soft terms which break supersymmetry explicitly. All mechanisms of spontaneous supersymmetry breaking which explain existence of these terms inevitably use so-called "hidden sector" [1] where spontaneous supersymmetry breaking occurs. The information that supersymmetry is broken is then transmitted to the observable sector by means of some messenger fields. In the simplest case "hidden sector" can be decribed by one singlet chiral superfield (ϕ, ψ, F_ϕ) [1]. Here ψ is a massless Goldstone fermion called goldstino, ϕ is its scalar superpartner, sgoldstino, and F_ϕ is an auxiliary field. The scale of supersymmetry breaking is often denoted as $\sqrt{F}$, where F – is a vacuum expectation value of the auxiliary field F_ϕ. In supergravity theories, where supersymmetry is promoted to a local symmetry, goldstino becomes a longitudinal part of spin-$\frac{3}{2}$ particle – gravitino $\tilde{G}$ – due to Super-Higgs mechanism [4–6]. Gravitino mass $m_{3/2}$ is then completely determined by the scale of supersymmetry breaking $\sqrt{F}$

$$m_{3/2} = \sqrt{\frac{8\pi}{3}}\frac{F}{M_{\rm Pl}}.$$

If gravitino is sufficiently heavy, e.g. its mass is of order of electroweak scale v, then $\sqrt{F} \sim \sqrt{M_{\rm Pl}\, v} \sim 10^{10} - 10^{11}$ GeV and the effective theory near the electroweak scale is just the MSSM endowed with the soft terms. However models with relatively light gravitino (i.e. with a mass of several keV) also exist and are phenomenologically viable. In particular, this is the case of models with gauge mediated SUSY breaking [7–15] and no-scale supergravity [16–18] models where $\sqrt{F} \sim 10 - 100$ TeV. However in this study we will

[1] See [2, 3] for extensive discussion of possibility of charged "hidden sectors".

focus on the case when $\sqrt{F}$ lies even lower, i.e. when it is of order of several TeVs, which means that gravitino mass lies in sub-eV range. This can be realized in warped [19, 20] SUSY models and composite [3] models with charged "hidden sector". Although there is not a lot of models of the latter class their study is interesting for the following reasons. First of all, the couplings of particles from the "hidden sector" with other SM fields scale as powers of $1/F$. In this way, the smaller F the stronger manifestation of new physics effect would be. Second, perturbative unitarity constrains possible masses of sgoldstinos [2]. In particular, their masses cannot be significantly larger than $\sqrt{F}$ scale. If $\sqrt{F}$ is of order of several TeVs than sgoldstino mass can lie in a range, the LHC [21–23] and forthcoming experiments [24, 25] will be sensitive to. In the regime when typical collision energy is much large than the gravitino mass, i.e. $E \gg m_{3/2}$, equivalence theorem [26–28] allows to approximate gravitino interactions by interactions of its longtitudial part

$$\tilde{G} \sim \frac{\partial_\mu \psi}{m_{3/2}}.$$

Hence the effective lagrangian describing interactions of ultralight gravitino with the MSSM fields can be constructed using properties of goldstino. In this study we deal with sub-eV gravitinos being produced at the LHC at 8 TeV. Hence throughout this paper we do not make any difference between goldstino and gravitino.

Search for a signal from physics beyond the Standard Model is one of the top priority goals of the LHC experiments at the moment. Many different signatures are thoroughly scrutinized to constrain models of new physics. Although the LHC experiments do not have any significant evidence of a signal from SUSY, this class of models remains the most extensively studied. Different aspects of collider phenomenology of low scale supersymmetry breaking have been studied for instance in [22, 29–34]. Gravitino production is one of the most distinct signatures of this setup [35–42]. Due to its R-odd nature, LSP goldstino would be always produced in pairs. In this paper we discuss jet-plus-missing-momentum signature of the process of gravitino pair production at the LHC. It has been recently carefully studied in [43] where authors redid jet plus transverse missing energy analysis performed by ATLAS with a part of run-I data to constrain gravitino mass or equivalently supersymmetry breaking scale. However, in that work the limit of very heavy sgoldstino (with mass about 20 TeV) was considered. The goal of our work is to include possibility of TeV scale sgoldstino contribution.

The paper is organized as follows. In Section 2 we describe a minimal model with goldstino supermultiplet and introduce possible interactions of this supermultiplet to the SM fields. In Section 3 we discuss processes contributing to the gravitino pair production in proton-proton collisions and in particular discuss contribution of light sgoldstinos. Then we describe bounds on the parameters of the model from missing energy signature analysis performed in our work using run-I data of the LHC experiments and describe comparison of the obtained results to those obtained using dijet searches. Section 5 contains our conclusions.

2 Model description

We choose a simple Polonyi model [44] to describe dynamics of the "hidden sector"

$$\mathcal{L}_\Phi = \int d^2\theta\, d^2\bar\theta \left(\Phi^\dagger\Phi + \tilde K(\Phi^\dagger,\Phi)\right) + \left(\int d^2\theta F\Phi + \text{h.c.}\right), \tag{2.1}$$

where $\Phi = \phi + \sqrt{2}\theta\psi + \theta^2 F_\phi$ is goldstino chiral superfield and non-canonical part of the Kahler potential $\tilde K$ can be chosen in the form[2]

$$\tilde K(\Phi^\dagger,\Phi) = -\frac{m_s^2+m_p^2}{8F^2}\left(\Phi^\dagger\Phi\right)^2 - \frac{m_s^2-m_p^2}{12F^2}\Phi^\dagger\Phi\left(\Phi^2+(\Phi^\dagger)^2\right). \tag{2.2}$$

Non-renormalizable operators in this expression can be generated by integrating out some heavy states in the microscopic theory. The scalar potential of the model has the following form[3]

$$V(\phi^*,\phi) = W_\phi \overline{W}_{\phi^*} K^{-1}_{\phi\phi^*} = \frac{F^2}{1-\dfrac{m_s^2+m_p^2}{2F^2}|\phi|^2 - \dfrac{m_s^2-m_p^2}{4F^2}(\phi^2+(\phi^*)^2)} = \frac{F^2}{1-\dfrac{m_s^2s^2+m_p^2p^2}{2F^2}}. \tag{2.3}$$

This potential has a local minimum where $\langle s\rangle = \langle p\rangle = 0$ and its expansion around local minimum gives proper mass term for CP-even (s) and CP-odd (p) sgoldstinos

$$V(s,p) = F^2 + \frac{m_s^2 s^2}{2} + \frac{m_p^2 p^2}{2} + \mathcal{O}\left(\frac{1}{F^2}\right)$$

In particular, if $m_s \neq m_p$ scalar and pseudoscalar components of $\phi = \frac{1}{\sqrt{2}}(s+ip)$ get different masses. Furthermore, we see that vacuum has positive energy density, $\langle V\rangle = F^2 > 0$, so supersymmetry is spontaneously broken. Auxiliary fields F_ϕ and F_ϕ^* acquire non-zero vacuum expectation values

$$F_\phi\big|_{\text{vac}} = \left(\frac{1}{2}K_{\phi^*\phi\phi}(\psi\psi) - \overline{W}_{\phi^*}\right) K^{-1}_{\phi\phi^*}\Big|_{\text{vac}} = -F \tag{2.4}$$

As was already mentioned in the Introduction the quantity $\sqrt{F}$ has dimension of energy and has the meaning of energy scale of supersymmetry breaking.

Interaction of goldstino superfield Φ with other particles of MSSM, i.e."visible" sector, can be introduced by making use of spurion technique. Recall that soft terms in lagrangian of the MSSM formally can be written in "manifestly supersymmetric" way by using the following operators

$$S^\dagger S \Phi^\dagger \Phi\Big|_D,\ \mu S\Phi^2\big|_F,\ S\Phi^3\big|_F,\ SW^\alpha W_\alpha\big|_F,$$

[2]Here $K(\phi,\phi^*) = \phi^*\phi + \tilde K(\phi,\phi^*)$. Also we use shorthand notations

$$W_\phi = \frac{\partial W(\phi)}{\partial\phi},\ \overline{W}_{\phi^*} = \frac{\partial \overline{W}(\phi^*)}{\partial\phi^*},\ K_{\phi\phi^*} = \frac{\partial^2 K(\phi,\phi^*)}{\partial\phi\partial\phi^*},$$

[3]Hereafter we assume that all parameters in the lagrangian are real. In particular, $F = F^*$.

where $S=\theta^2 m_{\rm soft}$ is a spurion superfield, Φ is a matter chiral superfield and W^α is a gauge field strength. We promote spurion S to the dynamical field Φ, containing goldstino and sgoldstinos by the following rule

$$S \to m_{\rm soft}\frac{\Phi}{F},$$

In what follows we will be interested in interactions between invisible and QCD sectors of the MSSM. Spurion method allows to describe this interaction by the following lagrangian

$$\begin{aligned}\mathcal{L}_{\Phi-{\rm vis}} = &-\int d^2\theta d^2\theta^\dagger \frac{M^2_{\tilde{q}_L,ij}}{F^2}\Phi^\dagger\Phi Q^\dagger_{L,i}e^{2gV}Q_{L,j} - \int d^2\theta d^2\theta^\dagger \frac{M^2_{\tilde{u}_R,ij}}{F^2}\Phi^\dagger\Phi U^\dagger_{R,i}e^{2gV}U_{R,j} - \\ &-\int d^2\theta d^2\theta^\dagger \frac{M^2_{\tilde{d}_R,ij}}{F^2}\Phi^\dagger\Phi D^\dagger_{R,i}e^{2gV}D_{R,j} + \left(\frac{M_3}{2F}\int d^2\theta\ \Phi W^\alpha W_\alpha + {\rm h.c.}\right).\end{aligned} \tag{2.5}$$

Here $Q_{L,i}$, $U_{R,i}$ and $D_{R,i}$ are (s)quarks superfields, W^α is a strength tensor superfield containing gluons and gluinos, $M_{\tilde{q}_L,ij}$, $M_{\tilde{u}_R,ij}$, $M_{\tilde{d}_R,ij}$ and M_3 are respective soft masses and indices i,j run over generations of quarks. Apart from soft quark and gluino masses the above lagrangian generates a tower of interactions of goldstino with the MSSM fields. In particular it contains the following operators obtained by expansion of component field lagrangian in powers of $1/F$

$$\begin{aligned}\mathcal{L}_{\psi-{\rm vis}} \supset &\frac{M_3}{4\sqrt{2}F}\bar{\psi}\left[\gamma^\mu,\gamma^\nu\right]\lambda^a F^a_{\mu\nu} - \frac{iM^2_{\tilde{d}_R,ij}}{F}\left(\tilde{d}^\dagger_{R,i}\bar{\psi}P_R d_j - \bar{d}_j P_L\psi\tilde{d}_{R,i}\right) - \\ &-\frac{iM^2_{\tilde{u}_R,ij}}{F}\left(\tilde{u}^\dagger_{R,i}\bar{\psi}P_R u_j - \bar{u}_j P_L\psi\tilde{u}_{R,i}\right) + \frac{iM^2_{\tilde{q}_L,ij}}{F}\left(\tilde{q}^\dagger_{L,i}\bar{\psi}P_L q_j - \bar{q}_j P_R\psi\tilde{q}_{L,i}\right) - \\ &-\frac{M^2_{\tilde{d}_R,ij}}{F^2}(\bar{\psi}P_R d_i)(\bar{d}_j P_L\psi) - \frac{M^2_{\tilde{u}_R,ij}}{F^2}(\bar{\psi}P_R u_i)(\bar{u}_j P_L\psi) - \frac{M^2_{\tilde{q}_L,ij}}{F^2}(\bar{\psi}P_L q_j)(\bar{q}_i P_R\psi)\end{aligned} \tag{2.6}$$

which we will use in our study[4]. Here $\tilde{q}_{L,i}$, $\tilde{u}_{R,i}$ and $\tilde{d}_{R,i}$ denote squarks and λ^a denotes gluino field. It was shown in [45] that in the case of negligible squark mixing lagrangian (2.6) is equivalent to Goldberger-Treiman lagrangian up to some redefinition of fields

$$\mathcal{L}_{GT} = \frac{1}{F}\partial_\mu\psi^\alpha J^\mu_\alpha + {\rm h.c.}, \tag{2.7}$$

with J^μ_α being a supercurrent of the MSSM which contains all of the fermion-boson pairs from the visible sector. This equivalence means that both interaction lagrangian result in identical amplitudes for processes with a single external goldstino. Nonetheless, they give different answers for double goldstino production. Since in this study we are interested in the latter case we utilize (2.6) together with relevant part of interaction lagrangian (see Eqs. (2.1), (2.2) and (2.5)) containing scalar and pseudoscalar sgoldstinos

$$\mathcal{L}_{\phi-\psi} = \frac{m_s^2}{2\sqrt{2}F}s\bar{\psi}\psi + i\frac{m_p^2}{2\sqrt{2}F}p\bar{\psi}\gamma_5\psi - \frac{M_3}{2\sqrt{2}F}sF^{\mu\nu}_a F^a_{\mu\nu} + \frac{M_3}{2\sqrt{2}F}pF^{\mu\nu}_a\tilde{F}^a_{\mu\nu} \tag{2.8}$$

where $\tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}$ with $\epsilon_{0123}=+1$.

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[4]We make use of four-component spinors in (2.5) – (2.8). We've also redefined goldstino field $\psi \to i\gamma_5\psi$ in (2.6). This corresponds to redefinition of two-component spinor $\psi^\alpha = -i\psi^\alpha$.

3 Light gravitino production at the LHC: monojet signature

In this Section we describe main subprocesses which result in jet-plus-missing-energy signature, discuss sgoldstino contribution and obtain bounds on parameter space of the model using the LHC run-I data. To our knowledge the latest study in this direction was performed in [43] with ATLAS data at $\sqrt{s} = 8$ TeV and 10 fb^{-1}. In that study authors obtained bounds on supersymmetry breaking scale $\sqrt{F}$ in the range between 850 and 1300 GeV depending on the mass scale of superpartners and their hierarchy. Our task is to extend this analysis and include possibility of relatively light sgoldstinos. For the present study we make use of CMS data at $\sqrt{s} = 8$ TeV and 19.6 fb^{-1} and perform leading order (LO) analysis at parton level.

Three main signal subprocesses relevant for our study at LO are 1) gravitino pair production in association with a parton (quark or gluon); 2) production of single gravitino with squark or gluino; 3) SUSY QCD pair production. Here it is assumed that squarks and gluino decay mainly as $\tilde{q}(\tilde{g}) \to q(g) + \psi$. Corresponding decay widths look as

$$\Gamma(\tilde{q}(\tilde{g}) \to q(g) + \psi) = \frac{M_{\tilde{q}(3)}^5}{16\pi F^2}. \qquad (3.1)$$

In what follows we assume that $M_{\tilde{q}} = M_3$ and these decay modes are dominant. One can check that the latter assumption is actually valid for masses of squarks and gluinos and SUSY breaking scale around TeV scale. In general, if sgoldstinos have masses around TeV scale they can decay into a pair of MSSM particles and corresponding decay widths are governed by relevant soft SUSY breaking parameters [46]. However in the present analysis we consider only two decay channels: decay into a pair of gravitinos

$$\Gamma(s(p) \to \psi\psi) = \frac{m_{s(p)}^5}{32\pi F^2} \qquad (3.2)$$

or a pair of gluons

$$\Gamma(s(p) \to gg) = \frac{M_3^2 m_{s(p)}^3}{4\pi F^2}. \qquad (3.3)$$

The reason is that these decay modes are indeed dominant for a typical hierarchy of soft SUSY breaking parameters [5]. Above expressions indicate that at fixed M_3 very heavy sgoldstino decays mostly into gravitino pair, while lighter sgoldstinos prefer to decay into gluons. For discussions of sgoldstino branching patterns in more generic cases we refer an interested reader to [21, 23, 47].

Let us start with direct gravitino pair production with a single jet

$$pp \to \psi\psi + \text{jet}\,.$$

On Fig. 1 we present examples of relevant Feynman diagrams contributing to this subprocess. Here we show a diagram with sgoldstino production, diagram with four-fermion interaction and with gluino exchange in t-channel. In the heavy sgoldstino limit, the cross

[5] We disregard here possibility of sgoldstino mixing with the Higgs bosons which could result in a considerable changes of sgoldstino branching pattern [47, 48].

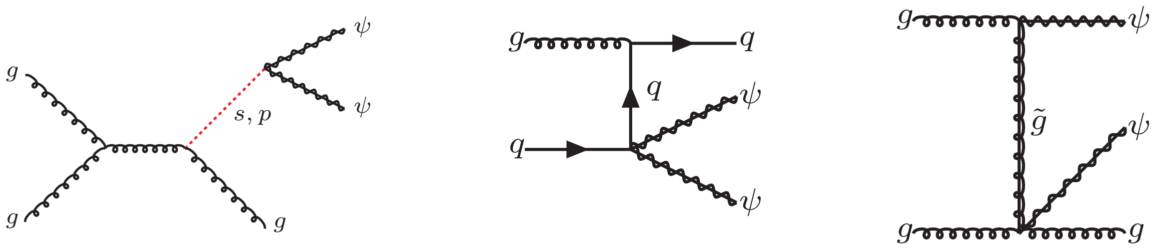

Figure 1: Examples of Feynman diagrams contributing to direct gravitino pair production with a jet.

section of this process behaves as $1/F^4$. If sgoldstinos are light they can be produced on-shell with subsequent decays into a pair of gravitinos. If sgoldstino contribution is dominant, which happens for very light sgoldstinos, corresponding cross section scales as $1/F^2$.

Next subprocess is associated gravitino production with gluino or squark (see Fig. 2)

$$pp \to \tilde{q}\psi, \tilde{g}\psi \to \psi\psi + \text{jet}\,.$$

In this case gluino or squark decay into gluino or quark, respectively, with gravitino and

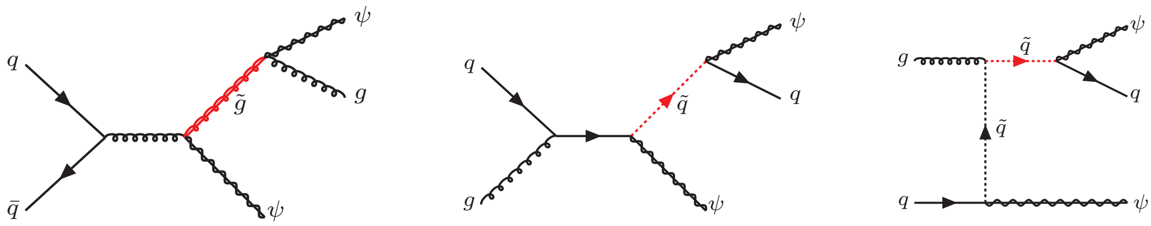

Figure 2: Examples of Feynman diagrams contributing to associated gravitino production with gluino or squark.

hence we will have two gravitinos and jet in the final state. The cross section behaves as $1/F^2$ at large values of SUSY breaking scale.

At last one has squark-squark, gluino-gluino and squark-gluino production (or SUSY QCD pair production) with their subsequent decays into gravitino and gluons or quarks (see Fig. 3)

$$pp \to \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} \to \psi\psi + 2\ \text{jets}\,.$$

The final state of these subprocesses contains in fact two jets but the event selection procedure used by ATLAS and CMS experiments for monojet searches actually admit more than one jet in a final state. It appears that SUSY QCD pair production gives quite significant contribution, thus it is important to take these processes into account especially at large values of SUSY breaking scale where they are dominant and their cross section does not depend on $\sqrt{F}$.

In the case of TeV scale sgoldstino other types of subprocesses contributing to jet-plus-missing-energy signature at tree level are possible. As it follows from (2.5) the interaction

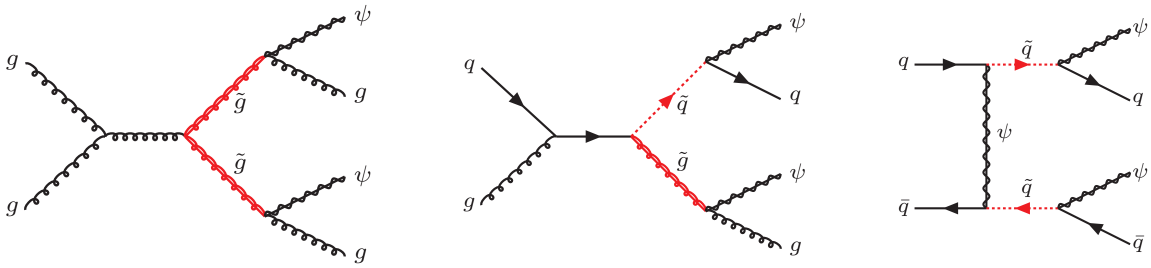

Figure 3: Examples of Feynman diagrams contributing to SUSY QCD pair (squark-squark, gluino-gluino and squark-gluino) production.

lagrangian contains higher dimensional operators of the following types

$$\frac{m_{\text{soft}}^2}{F^2}\tilde{q}\partial_\mu\phi\,\bar{q}\gamma^\mu\psi,\ \frac{m_{\text{soft}}^2}{F^2}D_\mu\tilde{q}\phi\,\bar{q}\gamma^\mu\psi,\ \text{etc.} \tag{3.4}$$

They would generate subprocesses like $qg \to \tilde{q}\phi\psi$, which after subsequent decays $\tilde{q} \to q\psi$ and $\phi \to \psi\psi$ would result in missing energy signature. However, we expect that cross section of these subprocesses will be suppressed with respect to SUSY QCD pair production and to gravitino associated production with squark(gluino) by additional power of m_{soft}/F suppression [6]. It would also endure phase space suppression due to production of two heavy particles (sgoldstino and squark). In what follows we neglect contribution of such subprocesses.

We implemented model (2.6)–(2.8) into `MadGraph` [49] and calculated cross section for the processes in question at the leading order applying all the relevant cuts from CMS monojet analysis with run-I data [51]. This CMS study selects events with at most two jets in the final state where the primary jet (j_1) should have transverse momentum $p_T(j_1) >$ 110 GeV and pseudorapidity $|\eta(j_1)| < 2.4$. The secondary jet (j_2) is also allowed if $p_T(j_2) > 30$ GeV, $|\eta(j_2)| < 4.5$ and difference in azimuthal angle $|\Delta\phi(j_1, j_2)| < 2.5$. For cross check we verify obtained cross sections using `CalcHEP` [50].

In general the model in question contains a lot of free parameters:

$$M_3,\ M_{\tilde{q}_L,ij},\ M_{\tilde{u}_R,ij},\ M_{\tilde{d}_R,ij},\ A_{d,ij},\ A_{u,ij},\ \sqrt{F},\ m_s,\ m_p,$$

were i, j is a family index. We however consider simplified class of models by making several assumptions. Firstly, we assume no mixing in squark sector, which means that $M_{\tilde{q}_L,ii}$, $M_{\tilde{u}_R,ii}$, $M_{\tilde{d}_R,ii}$ are physical squark masses. Next, we assume equal masses of gluinos and all squarks

$$M_{\tilde{q}_L,ii} = M_{\tilde{u}_R,ii} = M_{\tilde{d}_R,ii} \equiv M_{\tilde{q}} = M_3.$$

Equality of gluino and squark masses implies that these particles decay mostly into gravitinos and gluino and quark. Furthermore, we assume that scalar and pseudoscalar sgoldstinos are degenerate in mass, $m_s = m_p$ and take into account only their decays into pair of

[6]We remind that self-consistency of the effective theory we consider here implies that inequality $m_{\text{soft}} < \sqrt{F}$ must be fulfiled.

gluons and gravitinos which are dominant for TeV-scale gluinos and sgoldstinos. For calculations of cross sections we use CTEQ6L1 PDFs [52] with relevant values of renormalization and factorization scales for different subprocesses contributing to the signal. Namely, for the process of direct gravitino pair production we take $\mu_R = \mu_F = \frac{1}{2}(p_T^j + m_T^{\psi\psi})$, where $m_T^{\psi\psi} = \sqrt{m^{\psi\psi 2} + p_T^{j\,2}}$ and $m^{\psi\psi}$ is invariant mass of pair of gravitinos. For gluino/squark associated production with gravitino we take $\mu_R = \mu_F = 0.5M_{\tilde{q}} = 0.5M_3$ while for QCD pair production $\mu_R = \mu_F = M_{\tilde{q}} = M_3$. Unstable particles in the intermediate states are taken into account in narrow width approximation (NWA) which implies that the results are valid when

$$m_s \gg \frac{m_{s(p)}^5}{32\pi F^2} + \frac{M_3^2 m_{s(p)}^3}{4\pi F^2}$$

Unitarity arguments also constrain the ratio between sgoldstino masses and $\sqrt{F}$. Namely, application of optical theorem to process $\psi\psi \to \psi\psi$ yields the following constraint on sgoldstino masses [2]

$$m_s^2 + m_p^2 < \sqrt{48\pi}F,$$

which in our case of degenerate sgoldstino masses can be rewritten as $m_s(m_p) < \sqrt{2\sqrt{3\pi}}\sqrt{F} \approx 2.5\sqrt{F}$.

CMS analysis considers a number of requirements for the amount of $\not{p}_T{}^{\rm min}$ in the following set:

$$\not{p}_T^{\rm min} \in \{250, 300, 350, 400, 450, 500, 550\}\ \text{GeV}$$

We checked that for the parameter space we use here the strongest bound comes from the requirement $\not{p}_T^{\rm min} = 450$ GeV. In this case the upper limit on the visible cross section times acceptance times efficiency for non-SM production of events is about 7.8 fb. We do not take into account detector effects; corresponding efficiencies are expected to be close to unity for the selected events, see [51]. In [43] an additional cut $p_T(j_2) < 150$ GeV was imposed to decrease contribution of SUSY QCD subprocesses. It was motivated by the fact that cross section of these subprocesses is not sensitive to $\sqrt{F}$, i.e. to gravitino mass. Still as we will see below large contribution of SUSY QCD subprocesses to the signal allow us to exclude some models with relatively light masses of superpartners within framework of low scale supersymmetry breaking using missing transverse energy signature. For this reason we do not introduce any additional cuts in the phase space.

Let us briefly comment on NLO corrections. It is known that for squark and gluino productions they are large [53–55]. For instance, corresponding K-factor reaches value of 3 for gluino-gluino production [53–55]. However, our whole theory which includes gravitinos and sgoldstinos is effective and nonrenormalizable. To perform self-consistent NLO analysis one should have knowledge of microscopic theory behind it. This is beyond the scope of our work. Given the fact the NLO corrections typically increase the production cross sections we expect that our bounds will be even stronger if we include them into our analysis. Also it has been shown in previous work [43] that effects of showering on jet transverse missing energy distribution are important but rather mild. We will neglect them here in view of large expected NLO corrections.

On Fig. 4 we show cross sections of relevant subprocesses as functions of supersymmetry

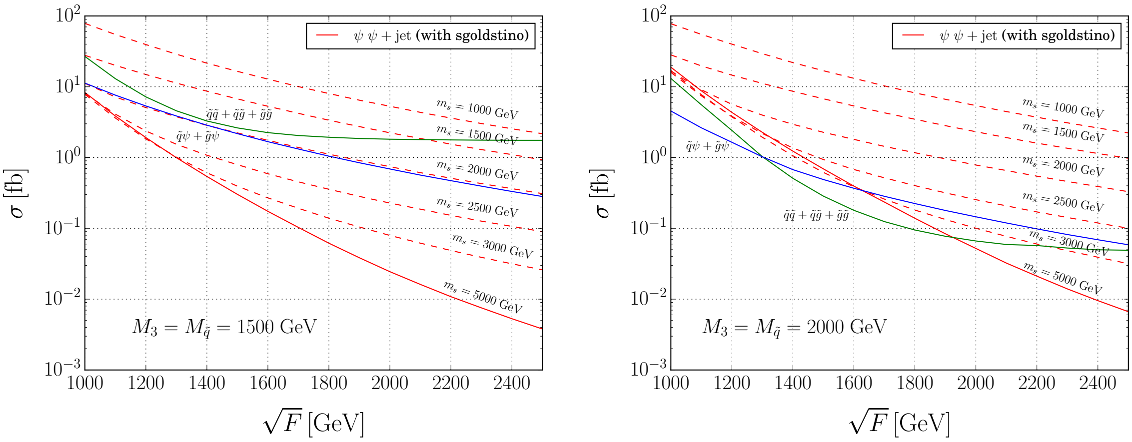

Figure 4: Cross sections of relevant subprocesses contributing to $pp \to \psi\psi$+jet $\to \not{p}_T$+jet as functions of supersymmetry breaking scale for $M_3 = M_{\tilde{q}} = 1.5$ TeV (left panel) and $M_3 = M_{\tilde{q}} = 2$ TeV (right panel).

breaking scale. On the left panel masses of superpartners are equal to 1.5 TeV and one can see that for heavy sgoldstinos the superpartner production and associated production are the dominant processes. However for sgoldstinos with masses of several TeVs corresponding cross sections can be comparable or even larger. Similar behaviour can be observed on the right panel on the Figure (where the masses of superpartners are taken to be 2 TeV) but with different hierarchy between different subprocesses. One can see that steep slope of gravitino pair production in the heavy sgoldstino mass limit becomes more flat with light sgoldstino which respects changing of cross section scaling from $1/F^4$ to $1/F^2$ with the increase of light sgoldstino contribution.

On Fig. 5 we show the same cross sections but as functions of common mass of super-

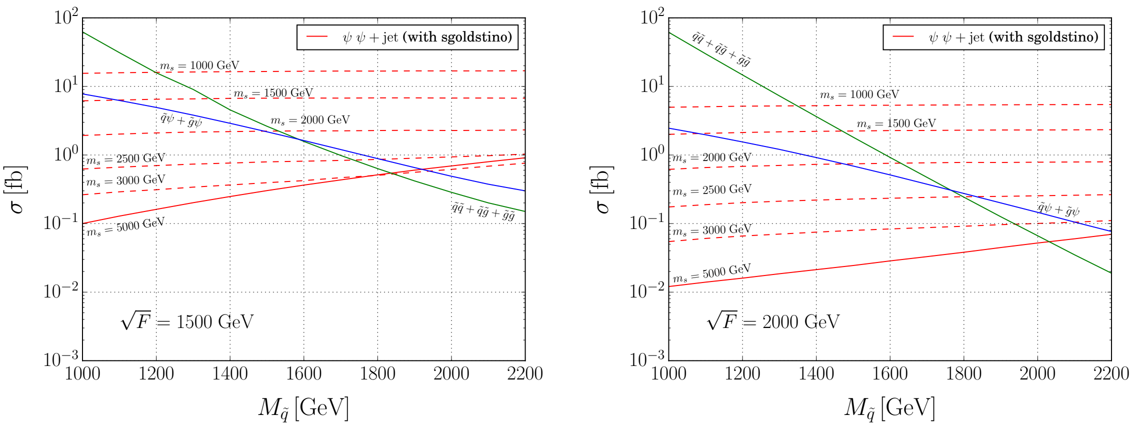

Figure 5: Cross sections of relevant subprocesses contributing to $pp \to \psi\psi + \text{jet} \to \not{p}_T + \text{jet}$ as functions of common mass of superpartners for $\sqrt{F} = 1.5$ TeV (left panel) and $\sqrt{F} = 2$ TeV (right panel).

partners at different values of SUSY breaking scale. Obviously, production cross section of superpartners decreases with increase of their masses. On the contrary, direct gravitino pair production increases and stays constant at large masses of squarks. Let us note that the contribution of light sgoldstino is prominent as compared with heavy sgoldstino limit and can increase cross section of the corresponding subprocess by almost 3 orders of magnitude.

On Fig. 6 we show exclusion plots of SUSY breaking scale $\sqrt{F}$ versus common mass

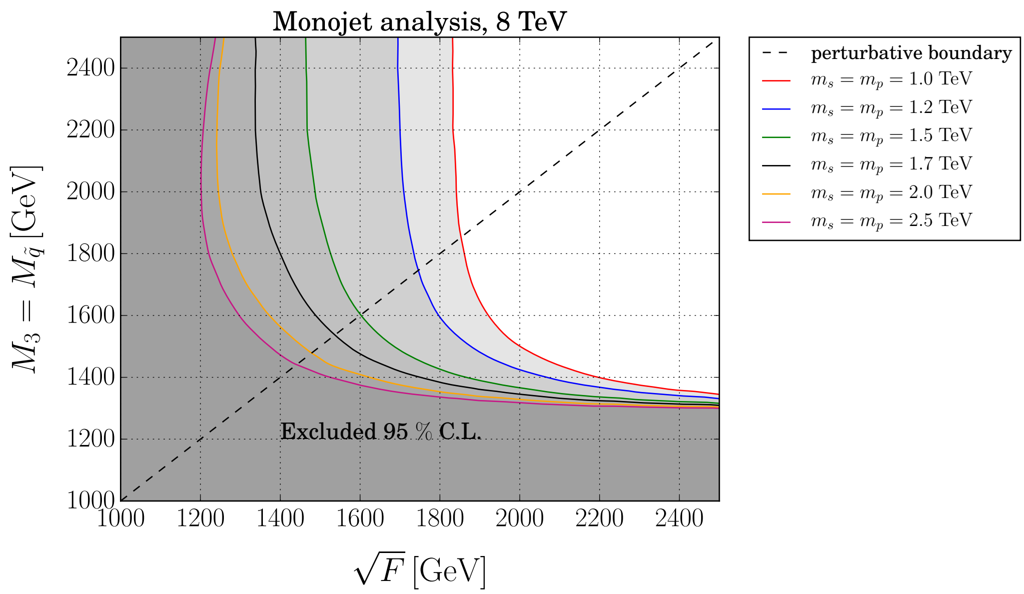

Figure 6: Exclusion plot of $\sqrt{F}$ vs $M_3 = M_{\tilde{q}}$ for different masses of sgoldstino.

of superpartners $M_3 = M_{\tilde{q}}$ at fixed values of sgoldstino masses. One can see that light sgoldstinos can change the bounds on $\sqrt{F}$ (and as consequently on the gravitino mass $m_{3/2}$) considerably. Flattening of these lines at large values of SUSY breaking scale is due to saturation of the total cross section by by pair production of superpartners, squarks and gluinos, in this limit. However, one should remember that at very large value of $\sqrt{F}$ squarks/gluinos cease to decay dominantly into quark/gluino and gravitinos (which is one of the assumptions of the present analysis) and the bounds from the monojet searches should be weakening. On the opposite end, at large $M_3 = M_{\tilde{q}}$ the contour becomes almost vertical because in this parameter region cross section is dominated by direct gravitino pair production in association with jet. In between all the subprocesses are of the same relevance. The dashed line here is the boundary of applicability of perturbation theory for our model $m_{\text{soft}} < \sqrt{F}$. Above this line the theory is in the strong coupling regime.

On Fig. 7 we present another exclusion plot but in different coordinates. Here we fix the mass scale of superpartners and vary common masses of sgoldstinos and SUSY breaking scale. One can see that sgoldstino contribution is the most important in the range of its mass from 1 TeV to 2.5 TeV where the bounds on SUSY breaking scale are strengthen by factor up to about 1.5 in comparison with those obtained in the heavy sgoldstino limit.

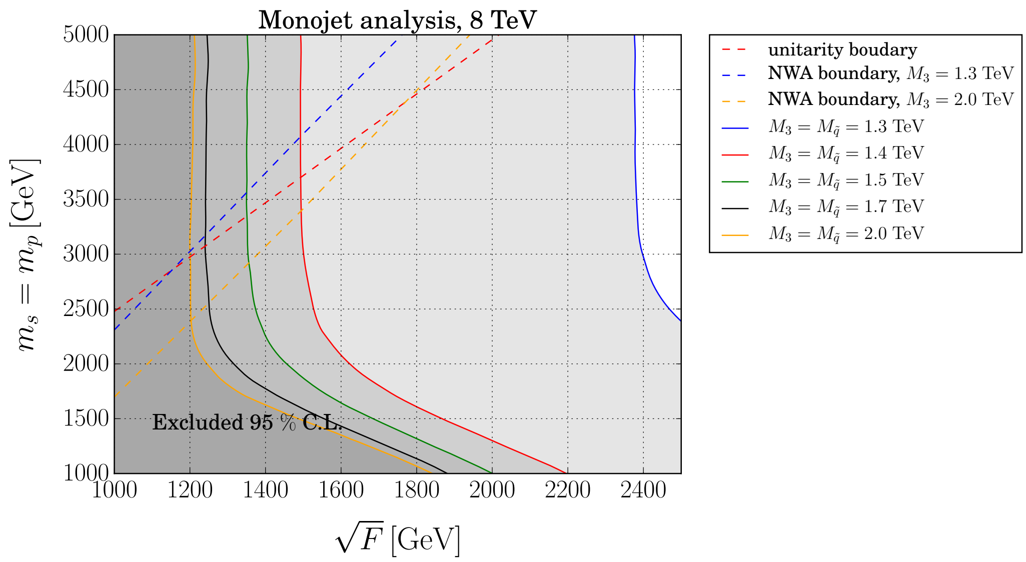

Figure 7: Exclusion plot of $\sqrt{F}$ vs $m_s = m_p$ for different scale of masses of superpartners. Above the dashed lines one of the corresponding conditions is violated: unitarity, condition for applicability of NWA. Here we depicted only lines which correspond to $M_3 = 1.3$ TeV (blue dashed) and $M_3 = 2.0$ TeV (orange dashed). All other lines which correspond to all intermediate scales lie between them.

This corresponds to a factor of 2 in limit on gravitino mass $m_{3/2}$. Let us note that for $m_s = m_p \gtrsim \sqrt{F}$ narrow width approximation which is used in this work is not applicable [7]. But in this limit sgoldstino contribution is suppressed and we do not expect considerable changes in our results.

4 Direct sgoldstino production and dijet signature

Light sgoldstinos can be produced directly in pp collisions mainly in gluon-gluon fusion [29] and after their decay into pair of gluons they can be observed as narrow dijet resonances. It is interesting to compare the bounds from monojet analysis with the bounds which can be obtained from the the LHC searches of dijet resonance. For comparison we use both ATLAS [56] and CMS [57] dijet analyses with the data obtained at $\sqrt{s} = 8$ TeV. Although new results of both experiments at $\sqrt{s} = 13$ TeV are already available [58, 59] we still use run-I data of the same statistics as we used for monojet analysis in the previous Section.

We use `MadGraph` [49] to calculate leading order cross section of the process $pp \to s(p) \to 2$ jets at the partonic level. To apply ATLAS upper limits on dijet cross section we impose the following cuts: $|\eta(j_{1,2}))| < 2.8$, $p_T(j_{1,2}) > 50$ GeV with $\frac{1}{2}|\eta(j_1) - \eta(j_2)| < 0.6$ and dijet invariant mass $m_{jj} > 250$ GeV. For the case of the CMS results we use the following set of cuts: $|\eta| < 2.5$ and scalar sum of gluon p_T, $H_T > 150$ GeV with either

[7] Unitarity condition is violated as well in this case.

$H_T > 650$ GeV or $m_{jj} > 750$ GeV with $|\eta(j_1) - \eta(j_2)| < 1.5$. In both cases additional requirement $m_{jj} > 890$ GeV should be fulfilled. We do not include detector effects and showering in view of unknown NLO corrections to the cross section.

To find excluded models we've compared calculated cross sections with the experimental upper 95 % C.L. limits on the dijet cross sections obtained by ATLAS [56] and CMS [57]. On Fig. 8 we present comparison of exclusion plots of SUSY breaking scale

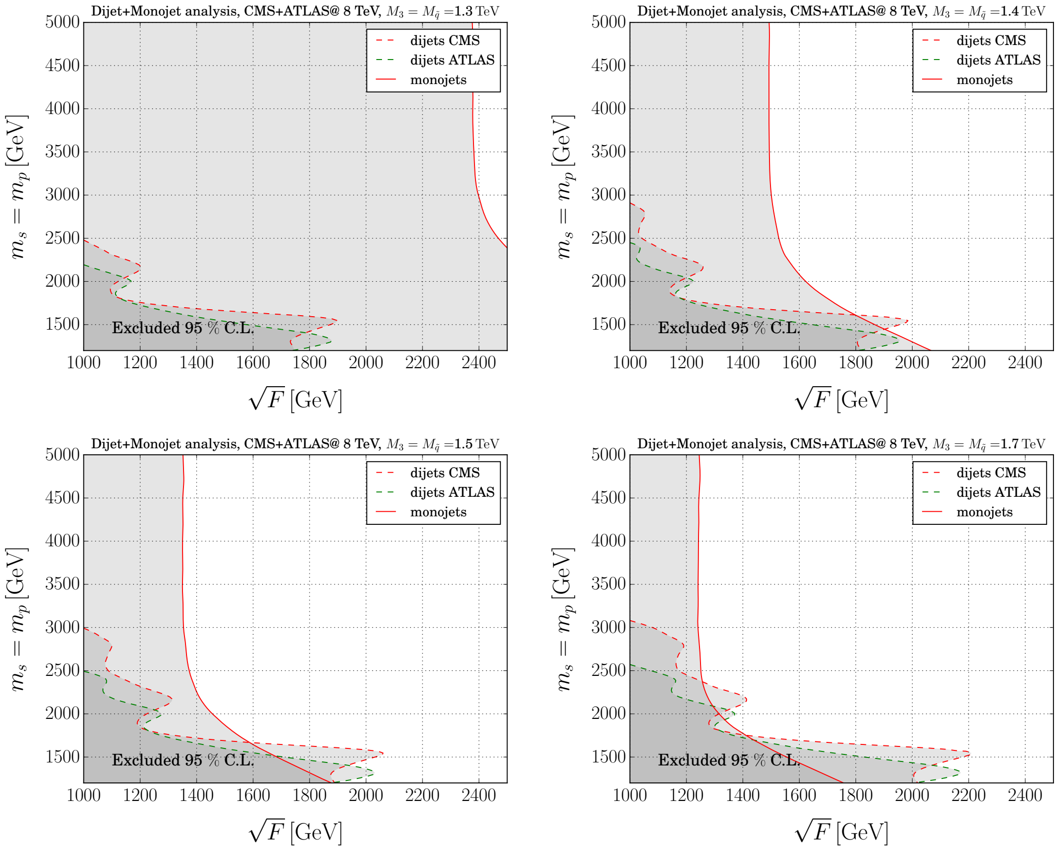

Figure 8: Exclusion plots of $\sqrt{F}$ vs $m_s = m_p$, comparison of bounds obtained from dijet resonances and missing energy searches for different values of $M_3 = M_{\tilde{q}}$: 1.3 TeV (upper left), 1.4 TeV (upper right), 1.5 TeV (lower left), 1.7 TeV (lower right).

$\sqrt{F}$ vs sgoldstino mass $m_s = m_p$ for different values of superpartners masses $M_3 = M_{\tilde{q}}$ obtained from dijet and monojet searches. One can see that for relatively small masses of squarks and gluinos monojet analysis limits this models considerably stronger than dijets. In this case the monojet cross section due to contribution of these superpartners. With the increase of masses of superpartners direct production of sgoldstinos with their subsequent decays into pair of gluons becomes more constraining. But for heavy sgoldstinos it weakens again for two reasons: on the one hand direct production of sgoldstinos becomes suppressed by its mass and on the other in this case sgoldstinos decay dominantly a into pair of gravitinos. In this way searches for monojets and dijets are complimentary to each other.

On Fig. 9 we present similar exclusion plots but in different coordinates: supersymme-

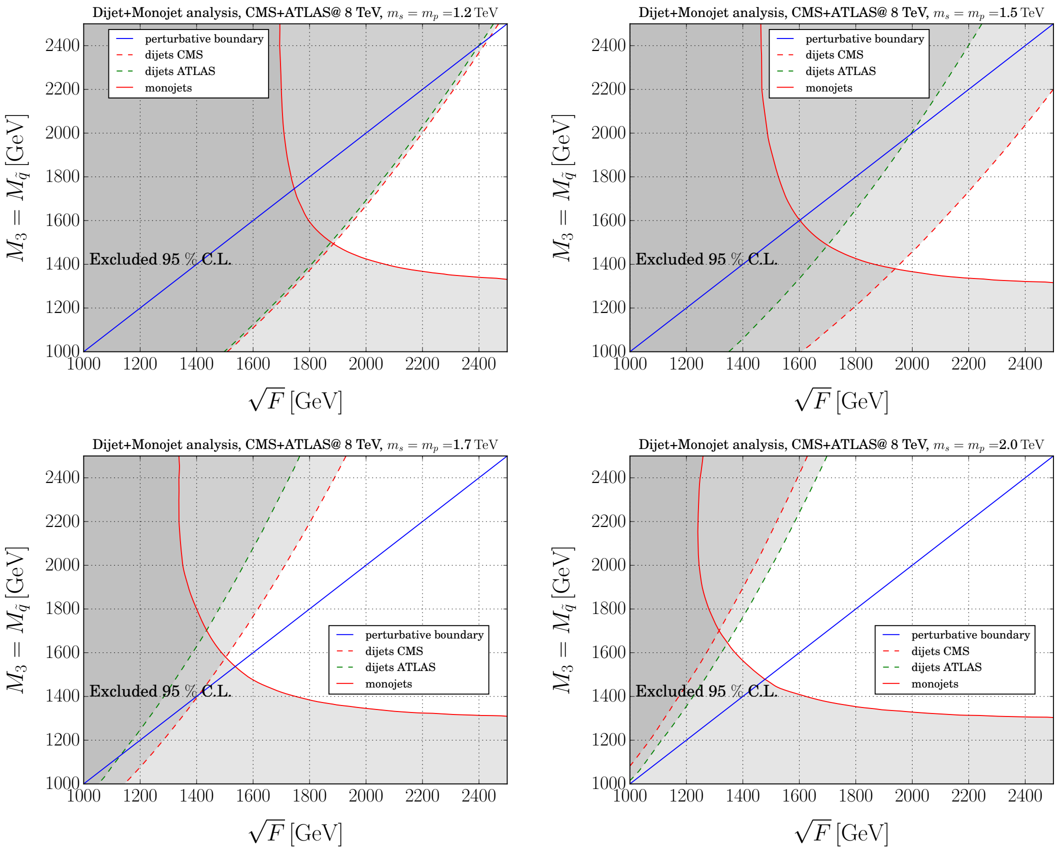

Figure 9: Exclusion plots of $\sqrt{F}$ vs $M_3 = M_{\tilde{q}}$, comparison of bounds obtained from dijet resonances and jet + missing energy searches for different values of $m_s = m_p$: 1.2 TeV (upper left), 1.5 TeV (upper right), 1.7 TeV (lower left), 2.0 TeV (lower right)

try breaking scale $\sqrt{F}$ vs $M_3 = M_{\tilde{q}}$ for different selected values of sgoldstino masses. For instance, in the upper left panel sgoldstino mass is equal to 1.2 TeV and here we see again that at small masses of superpartners the constraints from jet + missing transverse energy searches are stronger than from dijets, while for heavy superpartners it is vice versa. For sgoldstinos with mass more than $\sim$ 1.7 TeV the bounds from dijets searchs, being formally more stringent for large masses of superpartners, actually lie in a strong coupling regime of the theory $m_{\text{soft}} > \sqrt{F}$ and hence in this case constraints from monojet searches are the most relevant.

5 Conclusions

To summarize in this paper we show that in models with low scale supersymmetry breaking contribution of light sgoldstino to gravitino pair production can be considerable, although its actual size depends on the mass of sgoldstino. We calculate leading order cross sections of the processes contributing to jet and missing energy signal. We obtain bounds on the parameter space of the model within a simplified set of parameters using results of the CMS run-I searches for jet and missing transverse energy signature at $\sqrt{s} = 8$ TeV. We found that the bounds on gravitino mass in the case of light sgoldstinos can be stronger by factor of 2 as compared to those in the heavy sgoldstino limit. We compare the bounds from monojet searches with those from dijets from ATLAS and CMS data of the same collision energy and statistics. We found them complimentary in different regions of parameter space. Our final results are presented in Figs. 8 and 9. For instance, for common mass of superpartners 1.5 TeV the bound on supersymmetry breaking scale varies from about 1.35 TeV for heavy sgoldstinos to about 2 TeV for sgoldstinos with mass about 1.5 TeV. The respective bounds on $m_{3/2}$ in this case are $4.3 \cdot 10^{-13}$ eV and $9.5 \cdot 10^{-13}$ eV. It would be interesting to probe this scenario with new data at 13 TeV.

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