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Missing energy signature for low scale supersymmetry breaking

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Abstract. If the supersymmetry is broken at a scale about several TeVs particles from the sector responsible for the supersymmetry breaking - goldstino and sgoldstino - can reveal themselves already at the LHC experiments. We discuss bounds on supersymmetry breaking scale from LHC searches for jet and missing energy signature.

1 Introduction

Supersymmetry [1] still remains one of the attractive extensions of the SM and one of the main scenario of new physics which is extensively studied at the LHC experiments. If supersymmetry is indeed relevant to our Nature it should be spontaneously broken in some hidden sector with no direct interactions with the visible one. Transmission of this supersymmetry breaking can proceed in different ways. For example, it can be mediated by gravity or gauge interactions. This results in appearance of soft terms which break supersymmetry explicitly. According to supersymmetric analogue of Goldstone theorem there should exist massless fermionic degree of freedom which is called goldstino. In the simplest case goldstino is a part of a singlet chiral superfield $\left(\phi, \psi, F_\phi\right)$. Here ψ is a massless goldstino, ϕ is its scalar superpartner, sgoldstino, and F_ϕ is an auxiliary field. In the case of spontaneously broken supersymmetry the auxiliary field gets nonzero v.e.v., F and quantity $\sqrt{F}$ is called the scale of supersymmetry breaking. In supergravity theories goldstino becomes [4–6] a longitudinal part of spin-$\frac{3}{2}$ particle – gravitino, with the mass $m_{3/2} = \sqrt{\frac{8\pi}{3}}\frac{F}{M_{\rm Pl}}$.

If gravitino is very heavy then 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 (see e.g. models with gauge mediated SUSY breaking [7–12] or no-scale supergravity [13–15] where $\sqrt{F} \sim 10 - 100$ TeV). Here we consider the case when $\sqrt{F}$ is of order of several TeVs which is called low scale supersymmetry breaking. This can be realized in warped [16, 17] SUSY models and composite [3] models. According to the equivalence theorem [22–24] the effective lagrangian describing interactions of ultralight gravitino with the MSSM fields can be constructed using properties of goldstino.

Several aspects of collider phenomenology of low scale supersymmetry breaking have been studied for instance in [19, 25–30]. Gravitino production is one of the most distinct signatures of this

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setup [31–38]. Here we discuss missing energy signature of the process of gravitino pair production at the LHC. It has been recently studied in [39] where use ATLAS run-I data to obtain bounds on gravitino mass or equivalent 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 [40] is to include possibility light sgoldstinos.

2 Model

The model is described by the following lagrangian

$$\mathcal{L}_{\Phi} = \int d^2\theta\, d^2\bar{\theta} K(\Phi^\dagger, \Phi) + \left(\int d^2\theta F \Phi + \text{h.c.} \right), \tag{1}$$

where $\Phi = \phi + \sqrt{2}\theta\psi + \theta^2 F_\phi$ is goldstino chiral superfield and the Kahler potential $\tilde{K}$ is chosen as

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

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

$$V(s, p) = F^2 + \frac{m_s^2 s^2}{2} + \frac{m_p^2 p^2}{2} + O\left(\frac{1}{F^2}\right) \tag{3}$$

Auxiliary fields F_ϕ and F_ϕ^* acquire non-zero vacuum expectation values F.

Here we are interested in interactions between invisible and QCD sectors of the MSSM. Spurion method [41] allows to describe this interaction by the following lagrangian

$$\begin{gathered}\mathcal{L}_{\Phi-\text{vis}} = -\int d^2\theta d^2\theta^\dagger \frac{M^2_{\tilde{q}_L,ij}}{F^2}\Phi^\dagger\Phi Q^\dagger_{L,i} e^{2gV} Q_{L,j} - \int d^2\theta d^2\theta^\dagger \frac{M^2_{\tilde{u}_R,ij}}{F^2}\Phi^\dagger\Phi U^\dagger_{R,i} e^{2gV} U_{R,j} - \\ - \int d^2\theta d^2\theta^\dagger \frac{M^2_{\tilde{d}_R,ij}}{F^2}\Phi^\dagger\Phi D^\dagger_{R,i} e^{2gV} D_{R,j} + \left(\frac{M_3}{2F}\int d^2\theta\, \Phi W^\alpha W_\alpha + \text{h.c.}\right).\end{gathered} \tag{4}$$

Apart from soft quark and gluino masses the above lagrangian describes interactions of goldstino with the MSSM fields. In particular it contains the following operators obtained by expansion of component field lagrangian in powers of $1/F$

$$\begin{gathered}\mathcal{L}_{\psi-\text{vis}} \supset \frac{M_3}{4\sqrt{2}F}\bar{\psi}\left[\gamma^\mu, \gamma^\nu\right]\lambda^a F^a_{\mu\nu} - \frac{iM^2_{\tilde{d}_R,ij}}{F}\left(\tilde{d}^\dagger_{R,i}\bar{\psi}P_R d_j - \bar{d}_j P_L \psi \tilde{d}_{R,i}\right) - \\ - \frac{iM^2_{\tilde{u}_R,ij}}{F}\left(\tilde{u}^\dagger_{R,i}\bar{\psi}P_R u_j - \bar{u}_j P_L \psi \tilde{u}_{R,i}\right) + \frac{iM^2_{\tilde{q}_L,ij}}{F}\left(\tilde{q}^\dagger_{L,i}\bar{\psi}P_L q_j - \bar{q}_j P_R \psi \tilde{q}_{L,i}\right) - \\ - \frac{M^2_{\tilde{d}_R,ij}}{F^2}(\bar{\psi}P_R d_i)(\bar{d}_j P_L \psi) - \frac{M^2_{\tilde{u}_R,ij}}{F^2}(\bar{\psi}P_R u_i)(\bar{u}_j P_L \psi) - \frac{M^2_{\tilde{q}_L,ij}}{F^2}(\bar{\psi}P_L q_j)(\bar{q}_i P_R \psi),\end{gathered} \tag{5}$$

which we use in our study along with the following interactions of sgoldstinos

$$\mathcal{L}_{\phi-\psi} = \frac{m_s^2}{2\sqrt{2}F}s\bar{\psi}\psi + i\frac{m_p^2}{2\sqrt{2}F}p\bar{\psi}\gamma_5\psi - \frac{M_3}{2\sqrt{2}F}sF^{\mu\nu}_a F^a_{\mu\nu} + \frac{M_3}{2\sqrt{2}F}pF^{\mu\nu}_a \tilde{F}^a_{\mu\nu} \tag{6}$$

with gravitino and gluons.

3 Light gravitino production at the LHC: monojet signature

Here we describe main subprocesses which result in missing energy signature, discuss sgoldstino contribution and obtain bounds on parameter space of the model using the LHC run-I data. Our task is to extend the analysis of [39] and include possibility of light sgoldstinos. For the present study we use the 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 contribute the process in question at the LO: 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. For simplicity, we assume that squarks and gluino decay mainly as $\tilde{q}(\tilde{g}) \to q(g) + \psi$. Corresponding decay widths look as

$$\Gamma(\tilde{q}(\tilde{g}) \to q(g) + \psi) = \frac{M^5_{\tilde{q}(3)}}{16\pi F^2}. \tag{7}$$

In what follows we assume that $M_{\tilde{q}} = M_3$. 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 [41]. For the present analysis we consider only two dominant decay [1] channels: decay into a pair of gravitinos

$$\Gamma(s(p) \to \psi\psi) = \frac{m^5_{s(p)}}{32\pi F^2} \tag{8}$$

or a pair of gluons

$$\Gamma(s(p) \to gg) = \frac{M_3^2 m^3_{s(p)}}{4\pi F^2}. \tag{9}$$

Above expressions indicate that at fixed M_3 very heavy sgoldstino decays mostly into gravitino pair, while lighter sgoldstinos prefer to decay into gluons.

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

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

Examples of relevant Feynman diagrams are presented on Fig. 1. In the heavy sgoldstino limit, the cross section of this process scales as $1/F^4$. If sgoldstino contribution is dominant, which happens

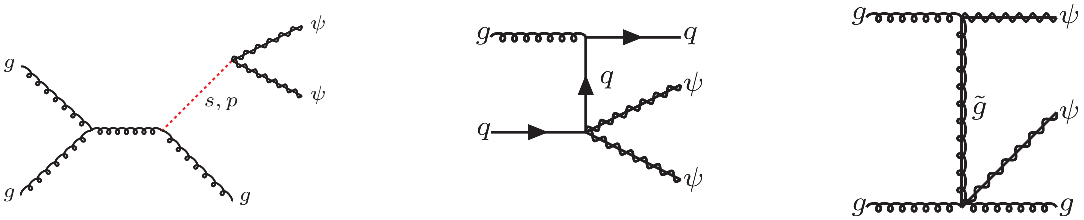

Figure 1. Examples of Feynman diagrams contributing to direct gravitino pair production with a jet.

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[1] We disregard here possibility of sgoldstino mixing with the Higgs bosons which could result in a considerable changes of sgoldstino branching pattern [42, 43].

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)

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

The cross section behaves as $1/F^2$ at large values of SUSY breaking scale. Finally, we have 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)

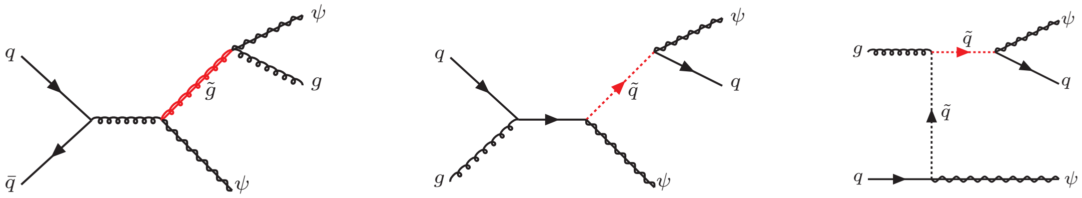

Figure 2. Examples of Feynman diagrams contributing to associated gravitino production with gluino or squark.

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

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.

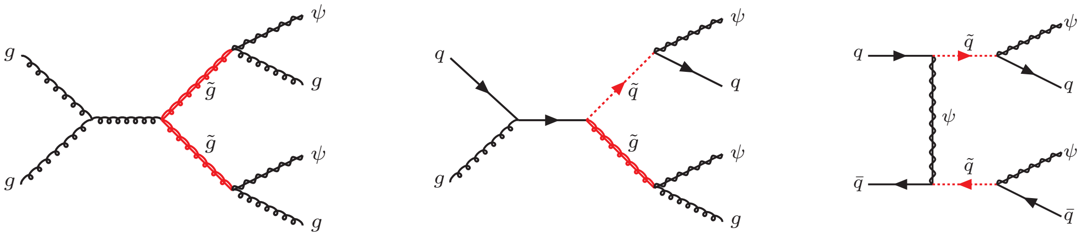

Figure 3. Examples of Feynman diagrams contributing to SUSY QCD pair (squark-squark, gluino-gluino and squark-gluino) production.

We implemented model (5)–(6) into `MadGraph` [44] 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 [45]. We decrease number of free parameters in the model by assuming that $M_{\tilde{q}_L,ii}$, $M_{\tilde{u}_R,ii}$, $M_{\tilde{d}_R,ii}$ are physical squark masses neglecting their mixing. Also we assume equal masses of squarks and gluinos and equal masses of sgoldstinos, i.e. $m_s = m_p$. For calculations of cross sections we use CTEQ6L1 PDFs [46] with relevant values of renormalization and factorization scales for different subprocesses contributing to the signal (see [40] for more details). We add cut on missing momentum, $\not{p}_T^{\min} = 450$ GeV and 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, see [45].

It is known that for squark and gluino productions NLO corrections are quite large [47–49]. However, the whole theory which includes gravitinos and sgoldstinos is nonrenormalizable. Self-consistent NLO analysis would require knowledge of microscopic theory. 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.

On Fig. 4 we show cross sections of different subprocesses as functions of $\sqrt{F}$. One can see that for sgoldstinos with masses of several TeVs corresponding cross sections can be comparable or even larger with production of superpartners. One can see that the 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.

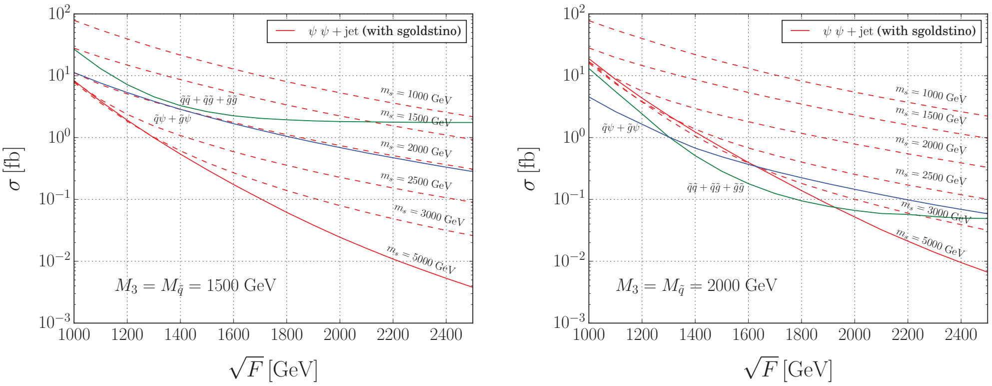

Figure 4. Cross sections of relevant subprocesses contributing to $pp \to \psi\psi + \text{jet} \to \not{p}_T + \text{jet}$ as functions of supersymmetry breaking scale for $M_3 = M_{\tilde{q}} = 1.5$ TeV (left panel) and $M_3 = M_{\tilde{q}} = 2$ TeV (right panel).

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

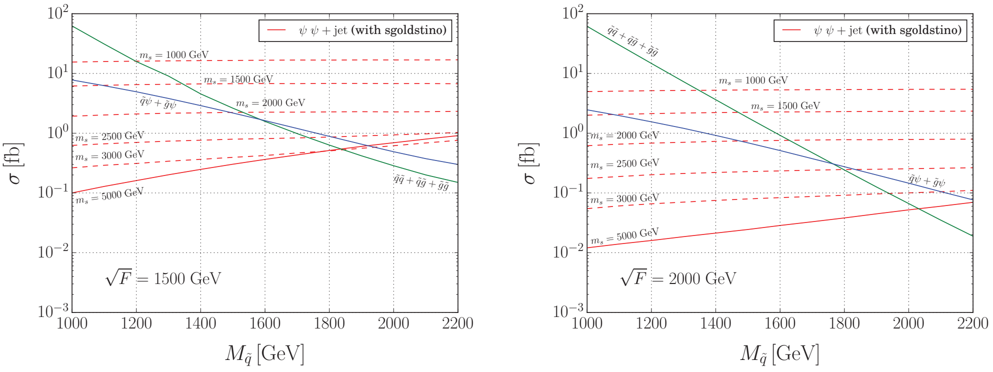

Figure 5. Cross sections of relevant subprocesses contributing to $pp \to \psi\psi + \text{jet} \to \not{p}_T + \text{jet}$ as functions of common mass of superpartners for $\sqrt{F} = 1.5$ TeV (left panel) and $\sqrt{F} = 2$ TeV (right panel).

On Fig. 6 we show exclusion plots of $\sqrt{F}$ versus $M_3 = M_{\tilde{q}}$ at fixed values of sgoldstino masses. One can see that light sgoldstinos can change the bounds on $\sqrt{F}$ considerably. Flattening of the lines at large values of $\sqrt{F}$ is due to saturation of the total cross section by the pair production of

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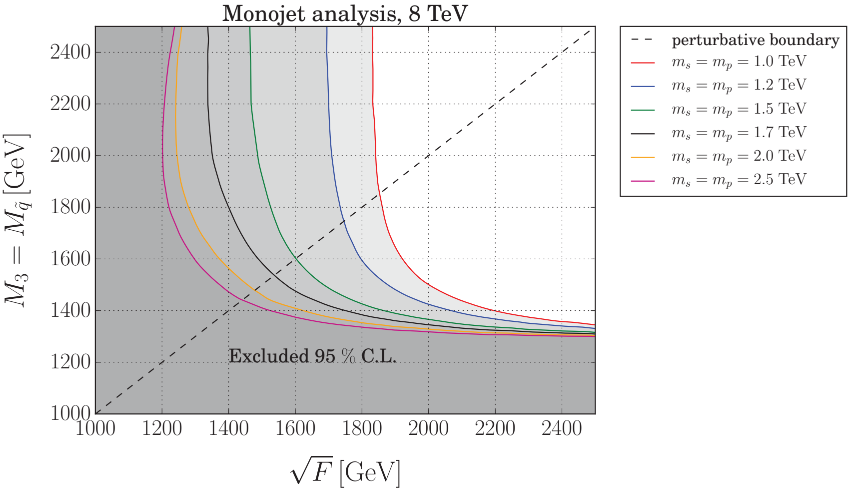

Figure 6. Exclusion plot of $\sqrt{F}$ vs $M_3 = M_{\tilde{q}}$ for different masses of sgoldstino.

superpartners, i.e. squarks and gluinos, in this limit. At large $M_3 = M_{\tilde{q}}$ the contour becomes vertical because in this limit the cross section is dominated by direct gravitino pair production in association with jet. 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 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.

4 Direct sgoldstino production and dijet signature

TeV scale sgoldstinos can be produced directly in *pp* collisions mainly in gluon-gluon fusion [25] and after their decay into pair of gluons they can be observed as narrow dijet resonances. Here we 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 [50] and CMS [51] dijet analyses with the data obtained at $\sqrt{s} = 8$ TeV.

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 [50] and CMS [51]. On Fig. 8 we present comparison of exclusion plots of $\sqrt{F}$ vs sgoldstino mass $m_s = m_p$ for different values of superpartners masses $M_3 = M_{\tilde{q}}$ obtained from dijet and monojet searches. We 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 is large 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 decreases because on the one hand direct production of sgoldstinos becomes suppressed by its mass and on the other in this

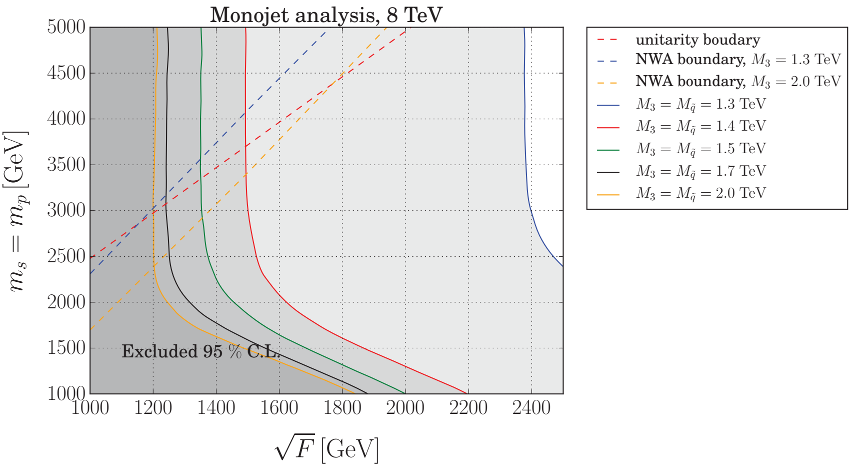

Figure 7. Exclusion plot of $\sqrt{F}$ vs $m_s = m_p$ for different scale of masses of superpartners. Above the dashed lines one of the corresponding conditions is violated: unitarity, condition for applicability of NWA. Here we depicted only lines which correspond to $M_3 = 1.3$ TeV (blue dashed) and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

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. 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 ~ 1.7 TeV the bounds from dijets searches lie in a strong coupling regime of the theory $m_{\text{soft}} > \sqrt{F}$ and hence in this case constraints from monojet searches should be used.

5 Conclusions

To conclude we show that in models with low scale supersymmetry breaking contribution of light sgoldstino to gravitino pair production can be considerable. 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 supersymmetry breaking scale in the case of light sgoldstinos can be stronger by factor of 1.5 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.

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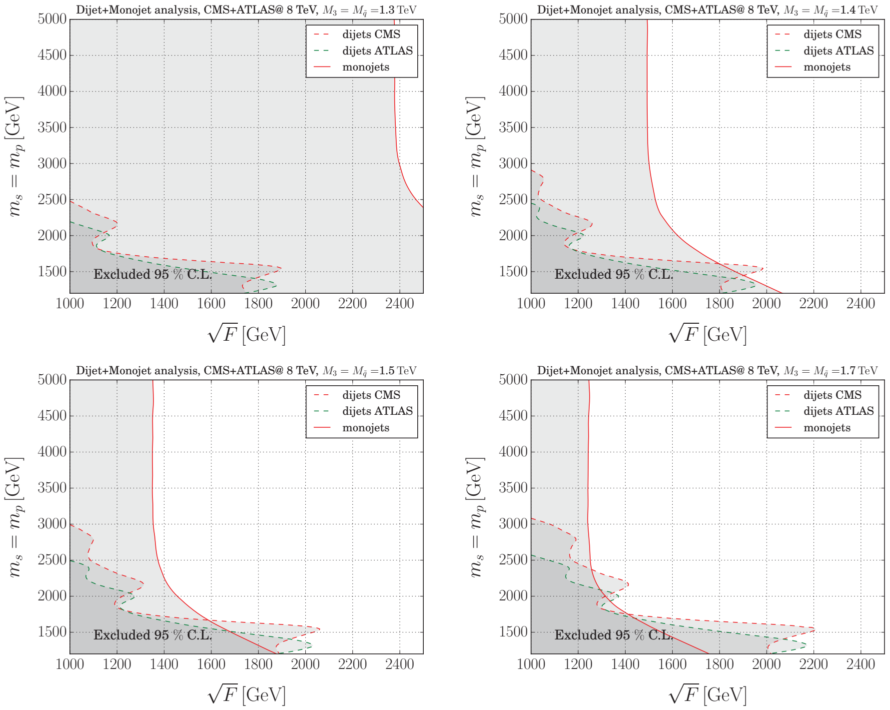

Figure 8. Exclusion plots of $\sqrt{F}$ vs $m_s = m_p$, comparison of bounds obtained from dijet resonances and missing energy searches for different values of $M_3 = M_{\tilde{q}}$: 1.3 TeV (upper left), 1.4 TeV (upper right), 1.5 TeV (lower left), 1.7 TeV (lower right).

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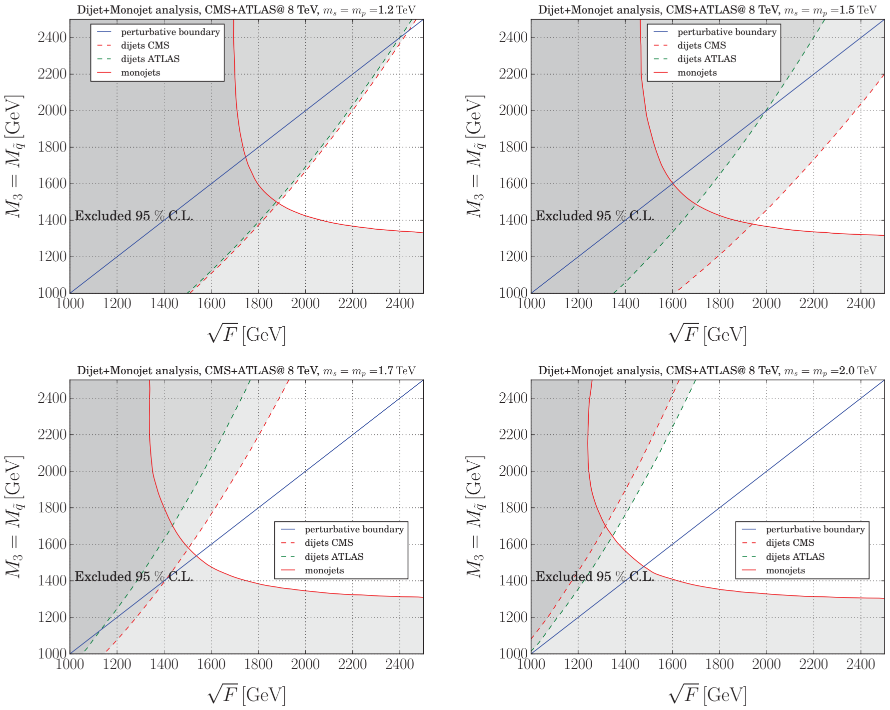

Figure 9. Exclusion plots of $\sqrt{F}$ vs $M_3 = M_{\tilde{q}}$, comparison of bounds obtained from dijet resonances and jet + missing energy searches for different values of $m_s = m_p$: 1.2 TeV (upper left), 1.5 TeV (upper right), 1.7 TeV (lower left), 2.0 TeV (lower right)

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