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# Constraining supersymmetry at the LHC with simplified models for squark production

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**ABSTRACT:** An important tool for interpreting LHC searches for new physics are simplified models. They are characterized by a small number of parameters and thus often rely on a simplified description of particle production and decay dynamics. Considering the production of squarks of the first two generations we compare the interpretation of current LHC searches for hadronic jets plus missing energy signatures within simplified models with the interpretation within a complete supersymmetric model. Although we find sizable differences in the signal efficiencies, in particular for large supersymmetric particle masses, the differences between the mass limits derived from a simplified model and from the complete supersymmetric model are moderate given the current LHC sensitivity. We conclude that simplified models provide a reliable tool to interpret the current hadronic jets plus missing energy searches at the LHC in a more model-independent way.

**KEYWORDS:** Supersymmetry Phenomenology

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**1 Introduction**

The quest for covering a large number of scenarios beyond the Standard Model (BSM) with current searches for new physics at the LHC requires efficient ways of matching experimental results with theory predictions. A particularly successful approach is the utilization of simplified models [1–4]. Recently developed program packages [5, 6] provide a convenient framework to employ simplified models for testing BSM theories at the LHC. Common to the experimental limits thus obtained is that the simplified models used for data interpretation are characterized by a small number of new particles and a simplified description of particle production and decay. The underlying assumption for this treatment is that the more model-specific details of the production and decay dynamics have little influence on the signal efficiencies. In this study we question the validity of this assumption. We focus on light flavor squark production in the minimal supersymmetric model with  $R$ -parity conservation. In supersymmetric models, squark production proceeds also through the exchange of a gluino in the  $t$ -channel and thus includes various processes with left- and right-chiral squarks and anti-squarks in the final state,  $pp \rightarrow \tilde{q}_i \tilde{q}_j^*$  and  $pp \rightarrow \tilde{q}_i \tilde{q}_j$ , with the chirality  $i, j = L, R$ . In the simplified models adopted by the ATLAS and CMS collaborations, however, the usual choice is to decouple the gluino, see, e.g., [7–9]. Consequently, the only contributing production mode is  $pp \rightarrow \tilde{q}_i \tilde{q}_i^*$ . As  $pp \rightarrow \tilde{q}_i \tilde{q}_i^*$  is in general not the dominant production channel, it is an important question whether the signal efficiencies — and hence the resulting exclusion limits — derived from this production mode are applicable to the more general case of supersymmetric models.

In this paper we compare the efficiencies for squark production and the exclusion limits for squark masses obtained by using a simplified model with those obtained in the complete

supersymmetric model. We focus on two representative all-hadronic analyses performed by CMS: one based on the discriminating variable  $\alpha_T$  [8], and one based on missing transverse energy, denoted by  $\cancel{E}_T$  [9]. As in the experimental analyses, we assume a direct decay of the squark into the neutralino. The respective topology is often referred to as T2 [10]. The simplified model with a decoupled gluino is denoted by T2 $_\infty$  in the following, while the complete supersymmetric model with a finite gluino mass is denoted by T2 $_{m_{\tilde{g}}}$ . The simplified model commonly adopted by ATLAS and CMS for the hadronic searches for squarks corresponds to T2 $_\infty$ .

We find very large deviations between the efficiencies for T2 $_\infty$  and T2 $_{m_{\tilde{g}}}$  in certain regions of parameter space, in particular for large squark masses. However, we show that for the parameter region relevant for the current exclusion limits, the differences turn out to be moderate, and the exclusion limits obtained from applying the efficiencies for T2 $_\infty$  are close to the ones for T2 $_{m_{\tilde{g}}}$ . Comparing the differences to the theoretical uncertainties of the cross section normalization, we find that both are of the same size for large regions in the considered parameter space. In addition, we compare the two analyses based on  $\alpha_T$  and  $\cancel{E}_T$  and show that the  $\alpha_T$  variable is less sensitive to the difference in the production dynamics and modes. Furthermore, whereas in the  $\cancel{E}_T$  analysis the T2 $_\infty$  efficiencies lead to an overestimation of the exclusion limits, in the  $\alpha_T$  analysis T2 $_\infty$  yields conservative limits.

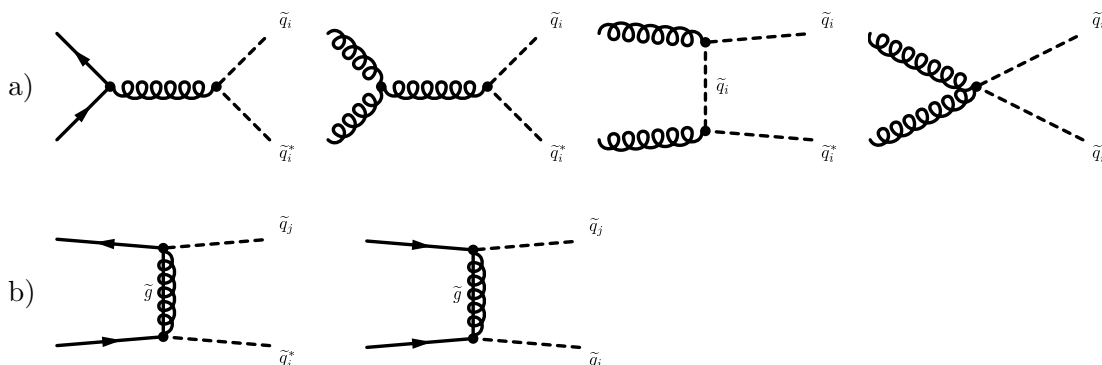
This paper is structured as follows. In section 2 we review the different squark production processes and their dependence on the gluino mass. In section 3 we introduce the two CMS searches and the parameter scan. The results for the comparison of efficiencies and squark mass limits are presented in section 4. We conclude in section 5.

## 2 Production processes of squarks at the LHC

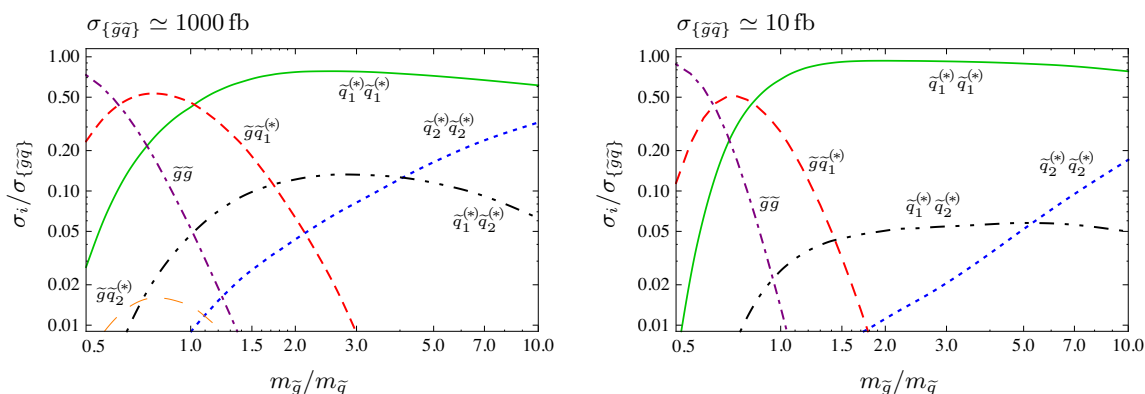
The production of strongly interacting sparticles is an important production channel for probing supersymmetry at the LHC. The strength and the kinematic distribution of squark (anti-)squark production not only depend on the mass spectrum of the squarks, but also on the gluino mass  $m_{\tilde{g}}$ , since all squark production processes — except for the case  $pp \rightarrow \tilde{q}_i \tilde{q}_i^*$ ,  $i = L, R$  — require a  $t$ -channel gluino exchange (cf. the diagrams in figure 1).

We first discuss the relative importance of different squark production processes as a function of the mass ratio  $m_{\tilde{g}}/m_{\tilde{q}}$ , where we make the convenient assumption of a common mass  $m_{\tilde{q}}$  for the squarks of the first and second generation.<sup>1</sup> The third generation is not considered here. While varying the ratio  $m_{\tilde{g}}/m_{\tilde{q}}$ , we kept the total production cross section of squarks and gluinos, denoted by  $\sigma_{\{\tilde{g}\tilde{q}\}}$ , fixed. This requirement determines  $m_{\tilde{q}}$  and  $m_{\tilde{g}}$ . We show relative cross section contributions for  $\sigma_{\{\tilde{g}\tilde{q}\}} \simeq 1000$  fb and  $\sigma_{\{\tilde{g}\tilde{q}\}} \simeq 10$  fb. These values represent typical cross section upper limits from the 8 TeV LHC null-search for regions with very small and very high sensitivities, respectively. For  $m_{\tilde{g}}/m_{\tilde{q}} \gtrsim 3$ , this corresponds to squark masses of about 500 GeV and 1 TeV, respectively. We computed the

<sup>1</sup>Here we consider  $m_{\tilde{g}}$  and  $m_{\tilde{q}}$  as free parameters defined at the TeV scale. Note, however, that a large ratio  $m_{\tilde{g}}/m_{\tilde{q}}$  is inaccessible in models where the supersymmetry breaking is mediated at a high scale. For a detailed discussion see, e.g., [11].



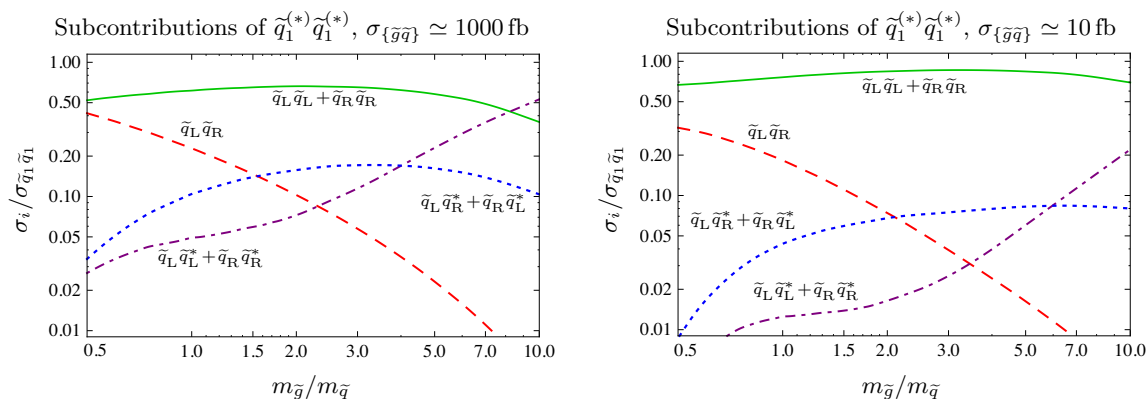
**Figure 1.** a) Production process  $pp \rightarrow \tilde{q}_i \tilde{q}_i^*$  with  $i = L, R$  with a decoupled gluino. For  $i = L$ , these graphs contribute to  $T2_\infty$ . b) Diagrams for  $pp \rightarrow \tilde{q}_i \tilde{q}_j^*$  and  $pp \rightarrow \tilde{q}_i \tilde{q}_i^*$ , with  $i, j = L, R$ . These are present if the gluino is not decoupled. Thus both types of diagrams a) and b) contribute to  $T2_{m_{\tilde{g}}}$ .



**Figure 2.** Relative contributions to the production cross section of squarks and gluinos as a function of the ratio  $m_{\tilde{g}}/m_{\tilde{q}}$  along iso-cross section curves for the 8 TeV LHC. *Left panel:* for a total production cross section  $\sigma_{\{\tilde{g}\tilde{q}\}} \simeq 1000$  fb, i.e., small  $m_{\tilde{g}}$  and  $m_{\tilde{q}}$ . *Right panel:* for  $\sigma_{\{\tilde{g}\tilde{q}\}} \simeq 10$  fb, i.e., large  $m_{\tilde{g}}$  and  $m_{\tilde{q}}$ . We take into account all production mechanisms of gluinos and of squarks of the first and second generation. These squarks are assumed to have a common mass  $m_{\tilde{q}}$ . Here we denote  $\tilde{q}_1^{(*)}$ ,  $\tilde{q}_2^{(*)}$  to be all first and second generation (anti)squarks not distinguishing between left- and right superpartners.

total production cross section at NLO with PROSPINO [12], while the individual contributions were calculated at LO with MADGRAPH 5 [13].

In figure 2 we show the relative strength of all possible combinations of first generation squark production,  $\tilde{q}_1^{(*)}$ , second generation squark production,  $\tilde{q}_2^{(*)}$ , and gluino production. In figure 3, the subcontributions to first generation squark pair production,  $\tilde{q}_1^{(*)}\tilde{q}_1^{(*)}$ , are shown. We summed processes that give equal contributions, such as  $\tilde{q}_L\tilde{q}_L$  and  $\tilde{q}_R\tilde{q}_R$ . Subcontributions that are not displayed (antisquark pair production, for instance) are below the range displayed here. From figures 2 and 3 we can draw several conclusions. First, the production of first generation squark pairs,  $\tilde{q}_1^{(*)}\tilde{q}_1^{(*)}$ , is the dominant production channel over a large range of  $m_{\tilde{g}}/m_{\tilde{q}}$ . This dominance is even more pronounced for  $\sigma_{\{\tilde{g}\tilde{q}\}} \simeq 10$  fb,



**Figure 3.** Relative contributions to the production cross section of squarks of the first generation at the 8 TeV LHC. These are the subcontributions of  $\tilde{q}_1^{(*)}\tilde{q}_1^{(*)}$  in figure 2 as a function of the ratio  $m_{\tilde{g}}/m_{\tilde{q}}$  along iso-cross section curves. *Left panel:* for a total production cross section  $\sigma_{\{g\tilde{q}\}} \simeq 1$  pb, corresponding to small squark masses. *Right panel:* for  $\sigma_{\{g\tilde{q}\}} \simeq 10$  fb, corresponding to large squark masses.

i.e., for larger  $m_{\tilde{q}}$ . Second, among its subcontributions, the channel  $\tilde{q}_L\tilde{q}_L + \tilde{q}_R\tilde{q}_R$  (with  $\tilde{q} \equiv \tilde{q}_1 = \tilde{u}, \tilde{d}$ ) is the dominant channel. Although for large  $m_{\tilde{g}}/m_{\tilde{q}}$  its contribution is suppressed through the gluino mass appearing in the  $t$ -channel propagator, the relative contributions stays dominant up to  $m_{\tilde{g}} \simeq 7m_{\tilde{q}}$  (for  $\sigma_{\{g\tilde{q}\}} \simeq 1000$  fb) and above  $m_{\tilde{g}}/m_{\tilde{q}} = 10$  (for  $\sigma_{\{g\tilde{q}\}} \simeq 10$  fb). These effects are due to the relatively large parton luminosities for  $uu$  and  $dd$  initial states when approaching large partonic center-of-mass energies in the hard scattering process. In contrast, although equally enhanced through a higher parton luminosity, the relative contribution of  $\tilde{q}_L\tilde{q}_R$  decreases rapidly with increasing  $m_{\tilde{g}}/m_{\tilde{q}}$ . This is because its cross section is suppressed by  $1/m_{\tilde{g}}^2$  compared to  $\tilde{q}_L\tilde{q}_L$  and  $\tilde{q}_R\tilde{q}_R$  in the limit of large  $m_{\tilde{g}}$ .

The subcontributions to second generation squark pair production are completely dominated by  $\tilde{q}_L\tilde{q}_L^*$  and  $\tilde{q}_R\tilde{q}_R^*$ . Its absolute contribution is dominated by the diagrams in the first row of figure 1, which are independent of the gluino mass as well as independent of the squark flavor.

In summary, even for  $m_{\tilde{g}}/m_{\tilde{q}}$  as large as 10 the channels  $\tilde{q}_L\tilde{q}_L^*$ ,  $\tilde{q}_R\tilde{q}_R^*$  are not necessarily the dominant production mode of squarks, and it is crucial to take into account other channels, in particular  $\tilde{q}_L\tilde{q}_L$  and  $\tilde{q}_R\tilde{q}_R$ . These, in turn, yield different event kinematics and thus, in principle, different signal efficiencies for the experimental searches.

### 3 Analyses and parameter scan

We consider two representative all-hadronic analyses performed by the CMS collaboration using the 8 TeV LHC data set. One analysis is based on the discriminating variable  $\alpha_T$  [8], and one is based on missing transverse energy  $\cancel{E}_T$  [9]. Among other models, these searches were interpreted in terms of the simplified model  $T2_\infty$ , which consists of squark production via the process  $pp \rightarrow \tilde{q}\tilde{q}^*$  ( $m_{\tilde{g}} \rightarrow \infty$ ), followed by a squark decay into a neutralino  $\tilde{\chi}_1^0$  (the lightest supersymmetric particle, LSP, in this model) and a quark with branching ratio 1.

bins	$H_T$ [GeV]	$\cancel{H}_T$ [GeV]
1–4	500–800	200–300; 300–450; 450–600; > 600
5–8	800–1000	200–300; 300–450; 450–600; > 600
9–12	1000–1250	200–300; 300–450; 450–600; > 600
13–15	1250–1500	200–300; 300–450; >450
16–17	>1500	200–300; > 300
0	> 500	> 200

**Table 1.** Categorization of selection regions (bins) for the  $\cancel{H}_T$  analysis [9].

### 3.1 All-hadronic analyses

The CMS analysis [9] is sensitive to the pair production of squarks (and gluinos) decaying into one (two) jets and an LSP. The search requires at least three jets, and the data is divided into several categories (3–5, 6–7, 8 jets). Consequently, the analysis is more sensitive to final states resulting from longer cascade decays of gluinos and squarks. Since we are interested in the pair production of squarks, we concentrate on the 3–5 jet analysis. The search is based on the two variables

$$H_T = \sum_{j \in \text{jets}} p_T^j \quad \text{for jets with } p_T^j > 50 \text{ GeV}, |\eta_j| < 2.5, \quad (3.1)$$

$$\cancel{H}_T = |\cancel{H}_T| = \left| - \sum_{j \in \text{jets}} \mathbf{p}_T^j \right| \quad \text{for jets with } p_T^j > 30 \text{ GeV}, |\eta_j| < 5. \quad (3.2)$$

$H_T$  characterizes the total visible hadronic activity and  $\cancel{H}_T$  the momentum imbalance in an event. The selection regions are categorized as summarized in table 1.

Further cuts are  $|\Delta\phi(\mathbf{p}_j, \cancel{H}_T)| > 0.5$  for the two hardest jets and  $|\Delta\phi(\mathbf{p}_j, \cancel{H}_T)| > 0.3$  for the third hardest jet, as well as a veto against isolated electrons and muons with  $p_T > 10$  GeV. For details see [9]. We refer to this analysis in the following as the  $\cancel{H}_T$  (MHT) analysis.

Another CMS analysis [8] is based on the variable  $\alpha_T$ , which is a powerful variable for discrimination against QCD multijet background. It rejects multijet events without significant  $\cancel{E}_T$  [14, 15]. For a dijet system,  $\alpha_T$  is defined as

$$\alpha_T = \frac{E_T^{j_2}}{M_T}, \quad M_T = \sqrt{\left(\sum_{i=1}^2 E_T^{j_i}\right)^2 - \left(\sum_{i=1}^2 p_x^{j_i}\right)^2 - \left(\sum_{i=1}^2 p_y^{j_i}\right)^2}, \quad (3.3)$$

where  $j_2$  denotes the less energetic jet.  $\alpha_T$  is 0.5 for perfectly measured dijet events that are back-to-back in  $\phi$ . If the two jets are not back-to-back and recoil against a large  $\cancel{E}_T$ ,  $\alpha_T$  becomes larger than 0.5. For suppression of mismeasured QCD background,  $\alpha_T$

is required to be larger than 0.55. For events with more than two jets, a pseudo-dijet system is formed, such that the absolute  $E_T$  difference, denoted as  $\Delta H_T$ , between the two pseudo-jets is minimized. In this case, the variable is generalized to

$$\alpha_T = \frac{1}{2} \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - \#_T^2}}, \quad (3.4)$$

where  $H_T$  is the scalar sum of the transverse energies  $E_T$  of the jets,  $H_T = \sum_j E_T^j$ ,<sup>2</sup> and  $\#_T$  is as defined in (3.2). As we consider light flavor squark-squark production, we choose the signal region using 2–3 jets without a  $b$ -tagged jet. To maximize the sensitivity, the events are divided in eight bins based on  $H_T$ : one bin in the range of 275–325 GeV, one in the range of 325–375 GeV, five bins between 375–875 GeV in steps of 100 GeV, and an open bin  $> 875$  GeV. In the following we will refer to these eight bins as bin 1 . . . 8 and to the combination of all bins as bin 0. The selection criteria for jets in the first two bins differ from the others: for bin 1 (bin 2),  $E_T^j > 37$  GeV (43 GeV) is required. In these same two bins, the two highest- $E_T$  jets are required to have  $E_T^j > 73$  GeV (87 GeV). For the other bins, the threshold for the two highest- $E_T$  jets is  $E_T^j > 100$  GeV each, and all jets are required to have  $E_T^j > 50$  GeV. In addition, for all bins jets are required to have  $|\eta| < 3$  ( $|\eta| < 2.5$  for the highest- $E_T$  jet). For details see [8]. We refer to this analysis in the following as the  $\alpha_T$  analysis.

### 3.2 Event generation and parameter scan

In order to compute signal efficiencies, we performed a Monte Carlo event simulation. We used MADGRAPH 5 [13] to simulate the hard scattering of the squarks, whereafter PYTHIA 6 [16] was used for the decays of the squarks into neutralinos as well as for showering and hadronization. As the MHT analysis requires at least three hard jets, in our model at least one jet has to arise from initial state radiation. We therefore include up to one jet in the hard scattering and performed an MLM matching [17] with initial state radiation from PYTHIA 6. We chose a matching scale  $Q_{\text{cut}} = 46$  GeV and  $p_T^{\text{jet}} > 30$  GeV in MADGRAPH 5. The gluino and squark<sup>3</sup> widths were computed with MADGRAPH 5. The branching ratios of squark decays to the neutralino were set to 1. We used DELPHES 3.0.11 [18] with FASTJET [19] for detector simulation using the standard CMS settings included in this version of DELPHES, but changed the  $b$ -tag misidentification rate to 0.01 [8, 20].

We performed parameter scans in the mass region  $m_{\tilde{\chi}_1^0} = 100 \dots 1400$  GeV and  $m_{\tilde{q}} = 500 \dots 1500$  GeV in steps of 100 GeV, with  $m_{\tilde{q}} - m_{\tilde{\chi}_1^0} \geq 100$  GeV, for two mass ratios  $m_{\tilde{g}}/m_{\tilde{q}} = 2, 4$ . For both ratios, associated gluino and gluino pair production are negligible. We computed the efficiencies for MHT and  $\alpha_T$  for all sub-channels of first generation squark production (as listed in section 2), as well as for  $\tilde{q}_1^{(*)}\tilde{q}_2^{(*)} + \tilde{q}_2^{(*)}\tilde{q}_1^{(*)}$ , or production of at least one second generation squark (or anti-squark). Finally, as a reference we computed the efficiencies for  $pp \rightarrow \tilde{q}_L\tilde{q}_L^*$  for the case  $m_{\tilde{g}} \rightarrow \infty$ , which amounts to the simplified model T2 <sub>$\infty$</sub> .

<sup>2</sup>Note that this definition differs from the one used in the MHT analysis.

<sup>3</sup>We assumed a pure bino for the computation of squark widths.

## 4 Results

In this section, we show the deviations from the simplified model  $T2_\infty$  that arise from different production mechanisms, both at the efficiency level (see section 4.1) and at the level of squark and LSP mass limits (see section 4.2). We find that although there are some substantial differences at the efficiency level, the deviations in the mass limits based on current LHC data are rather moderate.

### 4.1 Efficiencies

Comparing the signal acceptance  $\times$  efficiency  $A\epsilon$  (simply called “efficiency” in the following) for  $T2_\infty$  and the other individual production mechanisms  $M$  that contribute to  $T2_{m_{\tilde{g}}}$ , for individual bins  $i$  we found very large relative deviations

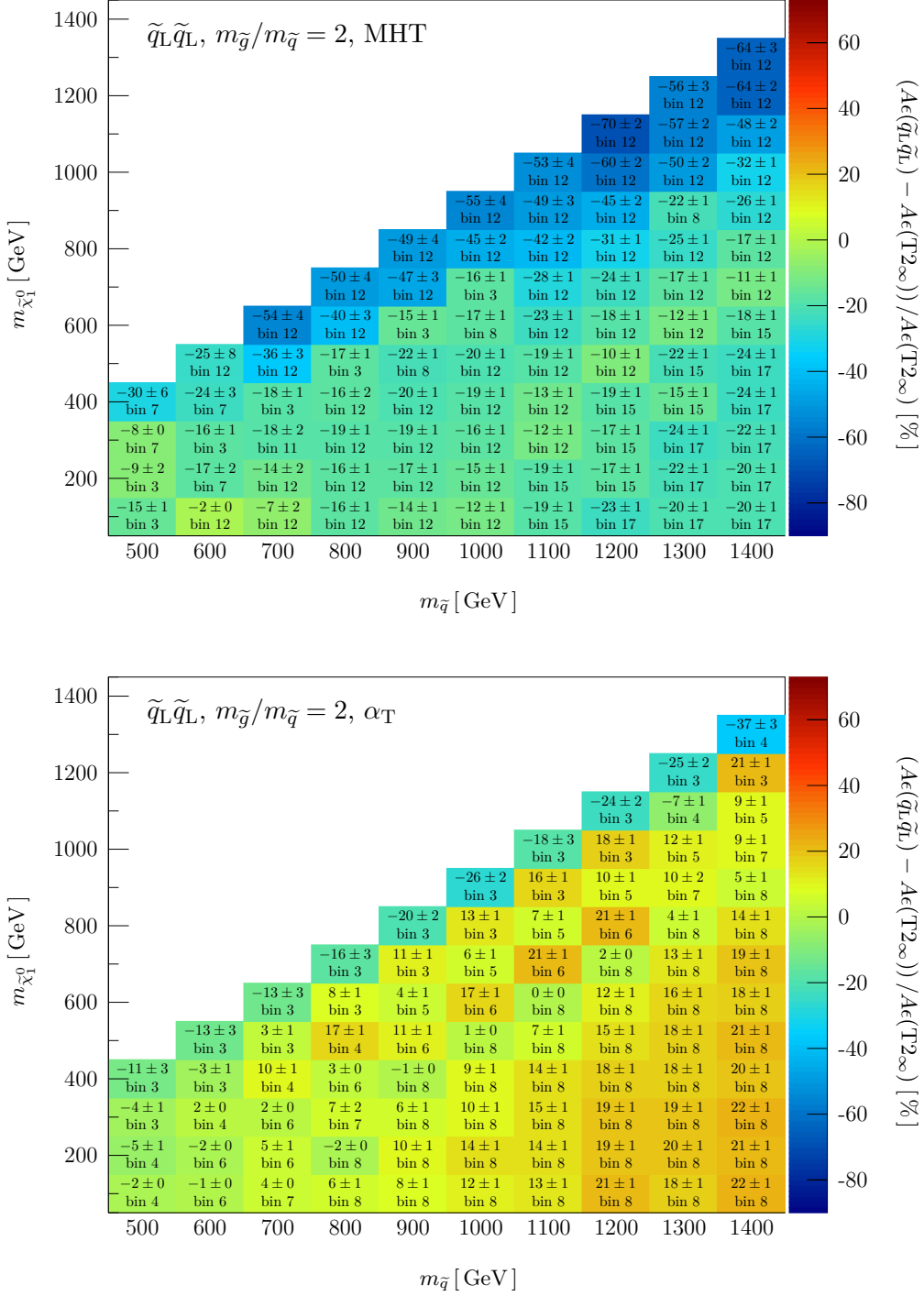
$$\frac{A\epsilon^i(M) - A\epsilon^i(T2_\infty)}{A\epsilon^i(T2_\infty)},$$

that were up to about 220%. However, not all bins are equally relevant for setting exclusion limits. In order to take this into account, we consider here the most sensitive bin only, which we define as the bin that yields the largest ratio  $S^i/S_{95\% \text{ C.L.}}^i(B)$ , where  $S^i \propto A\epsilon^i$  is the expected number of signal events in bin  $i$ , while  $S_{95\% \text{ C.L.}}^i(B)$  is the corresponding required number of signal events that would provide a 95% C.L. exclusion if the data would equal the background prediction  $B$ . Of particular interest is the production mechanism  $pp \rightarrow \tilde{q}_L \tilde{q}_L, \tilde{q}_R \tilde{q}_R$ , as it is the dominant contribution (see section 2). The deviations in the efficiencies obtained for the production mode  $pp \rightarrow \tilde{q}_L \tilde{q}_L$  from those obtained for  $T2_\infty$  are shown in figure 4 for  $m_{\tilde{g}}/m_{\tilde{q}} = 2$ .

**MHT analysis.** An overall feature for the MHT analysis is that the  $A\epsilon$  for  $M = \tilde{q}_L \tilde{q}_L$  are smaller than those for  $T2_\infty$ . The deviations range from up to  $-70\%$  in the region where  $m_{\tilde{q}} - m_{\tilde{\chi}_1^0} \approx 100 \text{ GeV}$ , to a few percent for small LSP and squark masses. For most masses bin 12 or bin 17 (for large squark and small LSP masses) are the most sensitive bins. Another important production mode is  $\tilde{q}_L \tilde{q}_R^*$  which contributes significantly to the total cross section for  $m_{\tilde{g}}/m_{\tilde{q}} \approx 2 - 5$ . For  $m_{\tilde{g}}/m_{\tilde{q}} = 2$ , the deviations are largest for  $m_{\tilde{q}} - m_{\tilde{\chi}_1^0} \approx 100 \text{ GeV}$  and reach up to  $-80\%$ . The deviations decrease to  $-5\%$  in the region  $m_{\tilde{q}} - m_{\tilde{\chi}_1^0} \approx 700 \text{ GeV}$  and increase again up to  $-20\%$  for large squark and small LSP masses. For gluino masses  $m_{\tilde{g}}/m_{\tilde{q}} = 4$ , the general features remain the same, but the absolute values of the deviations increase by a few percentage points. All deviations are negative, meaning that the  $A\epsilon$  for  $T2_\infty$  is larger than for  $\tilde{q}_L \tilde{q}_R^*$ . For  $\tilde{q}_L \tilde{q}_R$  we found deviations as large as 220%. However, the contribution of  $\tilde{q}_L \tilde{q}_R$  to the total cross section is completely negligible for  $m_{\tilde{g}}/m_{\tilde{q}} = 4$  and rather small for  $m_{\tilde{g}}/m_{\tilde{q}} = 2$ .

**$\alpha_T$  analysis.** The  $\alpha_T$  analysis turns out to be more robust towards the different production and gluino mass scenarios. The efficiencies for  $\tilde{q}_L \tilde{q}_L$  are mainly larger than for  $T2_\infty$  (with the exception of small squark/LSP masses and mass differences). The deviations are in the range of  $+20$  to  $-40\%$ . The most sensitive bin for large squark and small neutralino masses is bin 8. The deviations of the production mode  $\tilde{q}_L \tilde{q}_L^*$  from  $T2_\infty$  are around a few





**Figure 4.** Relative difference of signal efficiencies  $A\epsilon$  for  $\tilde{q}_L \tilde{q}_L$ -production with  $m_{\tilde{g}}/m_{\tilde{q}} = 2$  and  $\tilde{q}_L \tilde{q}_L^*$ -production with  $m_{\tilde{g}}/m_{\tilde{q}} \rightarrow \infty$  ( $T_{2\infty}^2$ ) for the MHT analysis (upper panel) and the  $\alpha_T$ -analysis (lower panel) at the 8 TeV LHC. The relative difference is denoted by the color code and given in percent. The error corresponds to the Monte Carlo error from event generation. For each mass point we compare the efficiencies of the bin that yields the largest sensitivity within the  $T_{2\infty}^2$  model. The corresponding bin is displayed below the relative difference.

percent. The largest deviations occur for small squark and LSP masses with around  $-10\%$ . For larger  $m_{\tilde{g}}/m_{\tilde{q}} = 4$ , the deviations become even smaller, as expected. The  $A\epsilon$  for  $\tilde{q}_L\tilde{q}_R^*$  are larger than for  $T2_\infty$ . The largest deviations are  $\approx 30\%$  for large squark masses.

## 4.2 Exclusion limits

Our final goal is to examine the effect of the different production mechanisms and gluino masses on the search sensitivity. From the efficiencies we derived 95% C.L. exclusion limits in the  $m_{\tilde{g}}-m_{\tilde{\chi}_1^0}$  plane for  $m_{\tilde{g}}/m_{\tilde{q}} = 2, 4$ , for both the simplified model  $T2_\infty$  and the complete supersymmetric model  $T2_{m_{\tilde{g}}}$ . In order to obtain the efficiencies for  $T2_{m_{\tilde{g}}}$  from the individual production channels, we compute the weighted mean of the efficiencies, where we use NLO cross sections computed with PROSPINO 2 [12] for the weights. For the determination of the most sensitive bin for  $T2_{m_{\tilde{g}}}$  and  $T2_\infty$ , we included bin 0 (the sum of all bins of the analysis). The most sensitive bin is determined, as before, on the basis of background expectation only. To obtain the exclusion limits, we compute

$$\mu^{-1} = \left( \frac{(A\epsilon)^i \times \int \mathcal{L} \times \sigma_{\text{tot}}}{S_{95\%CL}^i(\text{data})} \right)_{i = \text{most sensitive bin}}, \quad (4.1)$$

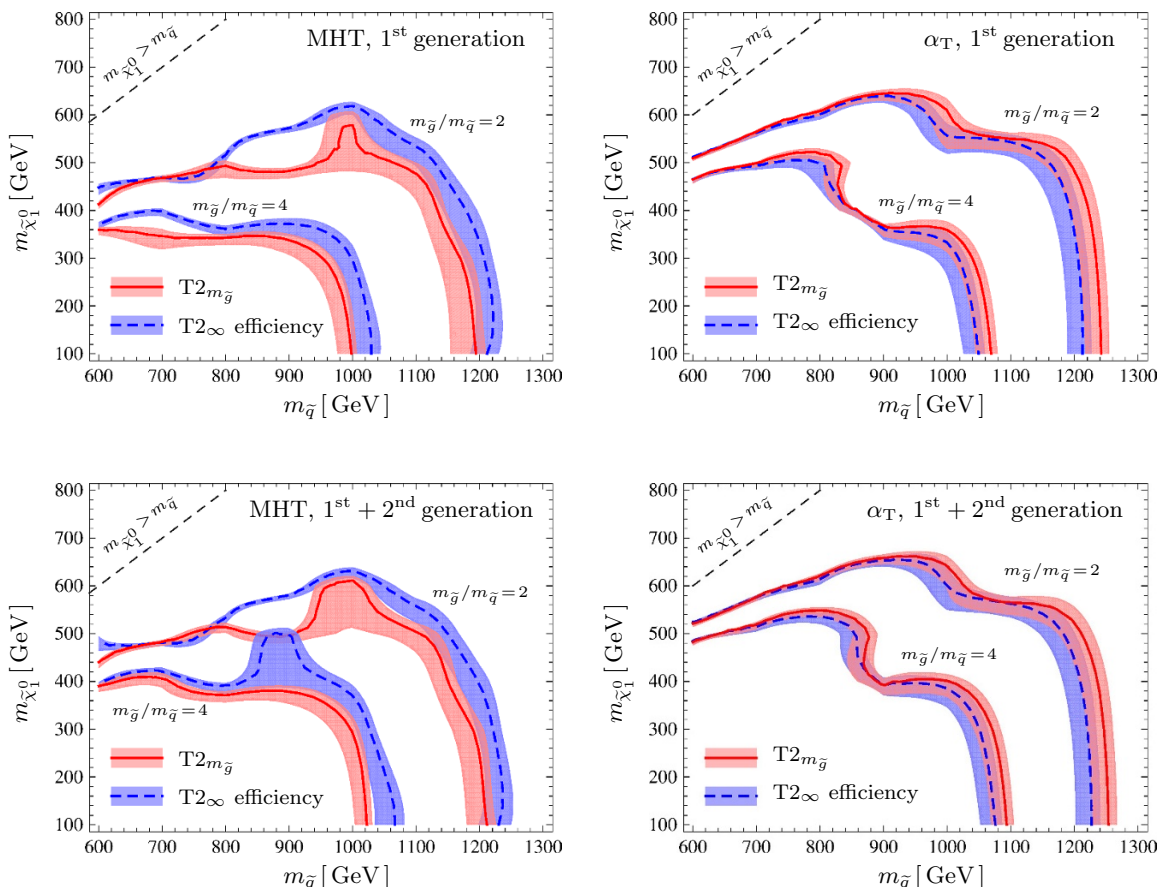
for each point in the  $m_{\tilde{g}}-m_{\tilde{\chi}_1^0}$  plane. Here,  $S_{95\%CL}^i(\text{data})$  is the required number of signal events allowing for a 95% C.L. exclusion in the presence of the measured number of events (data). The total cross section  $\sigma_{\text{tot}}$  was computed from PROSPINO 2 [12] and multiplied with NLL  $K$ -factors from NLLFAST [21].<sup>4</sup>

Figure 5 shows the 95% C.L. exclusion limits — the contours  $\mu = 1$  — for the MHT and  $\alpha_T$  analyses for first generation squarks only as well as first and second generation squarks, both for  $m_{\tilde{g}}/m_{\tilde{q}} = 2, 4$ . The shaded bands around the exclusion limits denote the uncertainties from scale variation, which we took to be  $\mu = m_{\tilde{g}}/2, 2m_{\tilde{q}}$ .<sup>5</sup>

We observe the following results: first, for both  $m_{\tilde{g}}/m_{\tilde{q}} = 2$  and 4, the deviations in the exclusion limits derived from the efficiencies taken from  $T2_\infty$  and the full supersymmetric model  $T2_{m_{\tilde{g}}}$  are of the order of the theoretical uncertainty on the cross section normalization for large regions in parameter space. Second, whereas for the  $\alpha_T$  analysis the uncertainty bands overlap throughout the exclusion limit, there are deviations in the MHT analysis in the region  $m_{\tilde{\chi}_1^0} \gtrsim m_{\tilde{q}}/2$ . The upper limit on  $m_{\tilde{\chi}_1^0}$  for  $m_{\tilde{q}} < 1$  TeV is very sensitive to small changes in the efficiencies. The  $\alpha_T$  analysis is much less sensitive to the actual production mode and thus less model-dependent. Third, while for the MHT analysis the limits from  $T2_\infty$  overestimate the exclusion limits for most of the parameter space, the  $\alpha_T$  analysis  $T2_\infty$  limits stay conservative over the complete parameter space.

<sup>4</sup>For points with  $m_{\tilde{g}} > 2500$  GeV, we used the respective  $K$ -factor for  $m_{\tilde{g}} = 2500$  GeV, as larger values are not provided in NLLFAST.

<sup>5</sup>We show here the scale variation at NLO. The information was not available at NLL accuracy for the complete parameter space considered (see footnote 4). However, although scale uncertainties at NLL are smaller than at NLO, additional uncertainties from the parton distribution functions and  $\alpha_s$  should, in principle, be taken into account. Hence, we expect the presented uncertainties to give a reasonable estimate of the over-all theoretical uncertainty.



**Figure 5.** 95% C.L. exclusion limits derived from the full  $T2_{m_{\tilde{g}}}$  model (red, solid curves) and from the efficiencies for the  $T2_{\infty}$  simplified model (blue, dashed curves). The shaded regions around the curves denote the uncertainties due to scale variation ( $\mu = m_{\tilde{q}}/2, 2m_{\tilde{q}}$ ). The  $\alpha_T$  and MHT analyses are based on an integrated luminosity of  $11.7 \text{ fb}^{-1}$  and  $19.5 \text{ fb}^{-1}$ , respectively, collected at the 8 TeV LHC.

## 5 Conclusion

In this study we investigated the validity of a simplified model description of squark production at the LHC. Concentrating on the  $T2$  topology,  $pp \rightarrow \tilde{q}^{(*)}\tilde{q}^{(*)} \rightarrow qq\tilde{\chi}_1^0\tilde{\chi}_1^0$ , we examined the effect of a varying gluino mass and thus of varying dominant production channels. We found that the often used limiting case of a simplified model with a decoupled gluino (here denoted as  $T2_{\infty}$ ) is a priori not a good description unless  $m_{\tilde{g}} \gg 10 m_{\tilde{q}}$ . For most of the relevant parameter space for  $m_{\tilde{g}} < 10 m_{\tilde{q}}$ , squark production is dominated by the production channels  $pp \rightarrow \tilde{q}_L\tilde{q}_L, \tilde{q}_R\tilde{q}_R$ ; this in contrast to the case of a decoupled gluino, where only same-flavor and same-chirality squark-anti-squark production is present. We computed the signal efficiencies for two all-hadronic analyses performed by CMS: one based on missing transverse energy (MHT), and one based on the  $\alpha_T$  variable. We found a larger sensitivity on the production channel in the MHT analysis. For the most sensitive bin in the analyses, we found relative deviations between the efficiencies from  $T2_{\infty}$  and the

dominant production mode ( $pp \rightarrow \tilde{q}_L \tilde{q}_L, \tilde{q}_R \tilde{q}_R$ ) of up to 70% for the MHT analysis and up to 40% for the  $\alpha_T$  analysis. However, both maximal differences were found in the region of large  $m_{\tilde{q}}$  and small mass splittings  $m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$ , which is far beyond the exclusion limits that could be derived from the 8 TeV LHC run. Hence, we found little deviation between the derived mass exclusion limits from the  $T2_\infty$  simplified model efficiencies and those of the full supersymmetric model  $T2_{m_{\tilde{g}}}$ . In particular, we found that limits derived from the  $\alpha_T$  analysis are much less sensitive to the production mode. For the  $\alpha_T$  analysis, the limits from  $T2_\infty$  provide conservative estimates for the limits within the full model. In contrast,  $T2_\infty$  tends to overestimate the limits in the case of the MHT analysis.

We showed our results for  $m_{\tilde{g}}/m_{\tilde{q}} = 2, 4$ . For  $m_{\tilde{g}}/m_{\tilde{q}} > 4$  and  $m_{\tilde{g}}/m_{\tilde{q}} < 2$ , the deviations in the efficiencies tend to become smaller. For the former case, the same-flavor and same-chirality squark-anti-squark production becomes more important, which is much less dependent on the gluino mass and hence resembles  $T2_\infty$  for large  $m_{\tilde{g}}/m_{\tilde{q}}$ . For  $m_{\tilde{g}}/m_{\tilde{q}} < 2$ , the production channel  $\tilde{q}_L \tilde{q}_R$  becomes important. However, the differences in the efficiencies between  $\tilde{q}_L \tilde{q}_R$  and  $T2_\infty$  tend to decrease with decreasing  $m_{\tilde{g}}/m_{\tilde{q}}$ . In particular, we found smaller differences than for  $\tilde{q}_L \tilde{q}_L$  with  $m_{\tilde{g}}/m_{\tilde{q}} = 1$ . However, for  $m_{\tilde{g}}/m_{\tilde{q}} \lesssim 1$  associated squark-gluino production becomes dominant. In this part of parameter space, the gluino mass has to be taken into account as an additional parameter in the simplified model analysis.

To conclude, the simplified model  $T2_\infty$  is a reliable tool to interpret the current hadronic jets plus missing energy searches at the LHC in a more model-independent way, in particular for analyses based on the variable  $\alpha_T$ . Larger differences between simplified model and complete supersymmetric model interpretations could, however, arise in future LHC searches for heavier squarks, depending in detail on the experimental cuts and the parameter space probed.

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