Exclusion analysis of stau production via heavy neutral Higgs bosons in the Tauphobic MSSM Scenario

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Abstract. The discovery of a Higgs-like particle at 125GeV has allowed for tighter constrains to be placed on the Higgs sectors of supersymmetric models. To this end, this work focused on excluding regions of the M_{A^0}, $\tan\beta$ parameter space in the "tau-phobic" MSSM benchmark scenario proposed in [1]. Exclusion limits were found by analysing stau production both through tree-level SM chargeless bosons and via the A^0 and H^0 in the context of existing ATLAS and CMS BSM searches at 13TeV. Of the M_{A^0} [200GeV $\rightarrow$ 1400GeV], $\tan\beta$ [$0^\circ \rightarrow 60^\circ$], region of parameter space that was explored, a sizable region at high $\tan\beta$ and $\mathrm{M_{A^0}} \approx 850\,\mathrm{GeV}$ was found to be excluded by these searches.

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1 Introduction

> If supersymmetry plays the role in physics that we suspect it does, then it is very likely to be discovered by the next generation of particle accelerators...
>
> *Ed Witten, 1999* [2]

Attempts to constrain existing models of supersymmetry [SUSY] have been painstakingly ongoing for many years. Indeed, many physicists believed that we would find evidence for SUSY prior to, or at least during, the experiments carried out at LEP and the LHC. Whilst this has not yet come to pass, the constraints on reasonable SUSY models have tightened considerably. The discovery of the Higgs boson at $125GeV$ has significantly restrained the parameter space available to theorists (at least in regimes which had previously been targeted).

Furthermore, existing studies carried out have yet to be exhaustively explored with regard to their implications for a number of SUSY scenarios, and with (hopefully) experiments set to more precisely probe the couplings of the SM Higgs in the coming decades, now is a good time to "trim the fat" and narrow our SUSY search.

To this end, this work investigates what regions of the $M_{A^0}, \tan\beta$ parameter space have been excluded in the Tauphobic MSSM scenario [1] via stau production channels through existing ATLAS and CMS studies.

2 Theory

2.1 Supersymmetry

During its circa 40 year lifetime the standard model [SM] has been immensely successful. Nonetheless, it is well known that it does not offer a truly complete, nor philosophically satisfying, description of the fundamental aspects of nature. Perhaps most notably, the SM suffers from the well-known hierarchy problem, in which perturbative corrections to the Higgs mass must be cut-off at scales many orders of magnitude greater than the Higgs boson's mass, and thus extremely precise cancellation of these corrections is required from other mechanisms in the SM. Additionally, it is also clear that an ultimate theory of quantum gravity will somehow need to assimilate the SM, but it is far from clear how this might work in practice. Of course, there are also other issues within the SM, but these were not the primary motivations in the exploration of SUSY.

Supersymmetric theories (those which realise SUSY) are perhaps the most popular extensions of the SM as they represent a "natural" extension of the SM's symmetries whilst also elegantly fixing the hierarchy problem (and others, depending on the exact details of the model being considered). SUSY comes in many forms, but for the purposes of this paper we are only interested in the minimal supersymmetric model [MSSM] [3, §10].

As other SUSY models do, the MSSM introduces numerous superpartners which are paired with SM particles in supermultiplets. These superpartners vary in spin from their SUSY counterparts by 1/2; Notably, this means that the tau's superpartners, the staus, are bosonic. One should note that the spinless nature of the bosonic superpartners does not imply the equivalence of the left and right handed partners of fermions. Instead, the MSSM contains two staus, $\tilde{\tau}_1$ and $\tilde{\tau}_2$ - one for each handedness of the tau.

2.2 The MSSM and the Tauphobic Scenario

In the MSSM there are actually two Higgs fields (also seen in two-Higgs-doublet models which do not necessarily realize SUSY), which contain a total of eight degrees of freedom [as each doublet consists of two complex scalar fields]. These mix non-trivially to produce the CP-even Higgs, h^0 and H^0, the CP-odd Higgs, A, and the charged Higgs $H^\pm$ [3, §6]. In the scheme of interest, the parameters which ultimately constrain the masses of these bosons are μ, M_{A^0} , A_t and $\tan\beta$. However, of these only M_{A^0} and $\tan\beta$ are not explicitly specified in the scenario.

m_t	173.2	M_2	200
$m_{\tilde{g}}$	1500	$M_{\tilde{q}_{1,2}}$	1500
M_{SUSY}	1500	$M_{\tilde{l}_{1,2}}$	500
$M_{\tilde{l}_3}$	1000	μ	2000
$X_t^{\bar{M}S}/M_{SUSY}$	2.9	X_t^{OS}/M_{SUSY}	2.45
A_τ	0	$A_{f\neq t,b,\tau}$	0

Table 1: Specification of the free MSSM parameters defining the tauphobic scenario. All masses are given in units of GeV. Note that M_1 is fixed by GUT relations to M_2

Ultimately the tauphobic scenario specifies the free parameters in a reduced form of the MSSM as per Table 1 (as specified in [1]). Note that under the "maximal mixing" condition, further constraints are provided by the relationship

$$A_t = X_t + \mu\cot\beta,$$

where $\tan\beta$ and X_t determine M_{h^0} such that in models where h^0 is the lightest Higgs, X_t can also be calculated for a given $\tan\beta$ in order to reproduce the 125GeV mass observed at the LHC. Figure 1 shows the form of the relationship which is used to accomplish this.

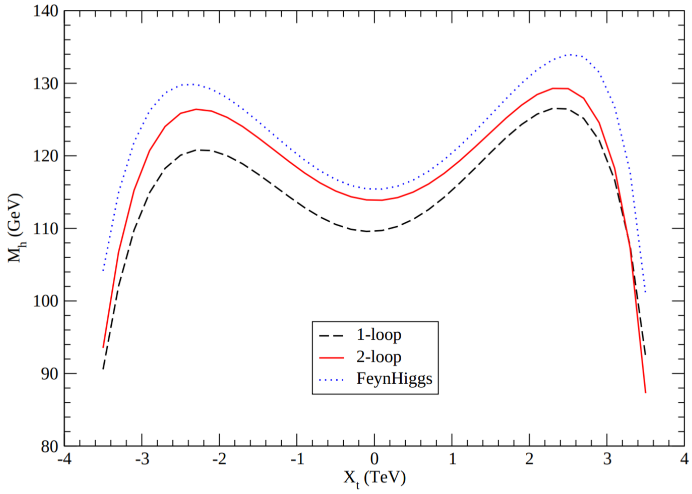
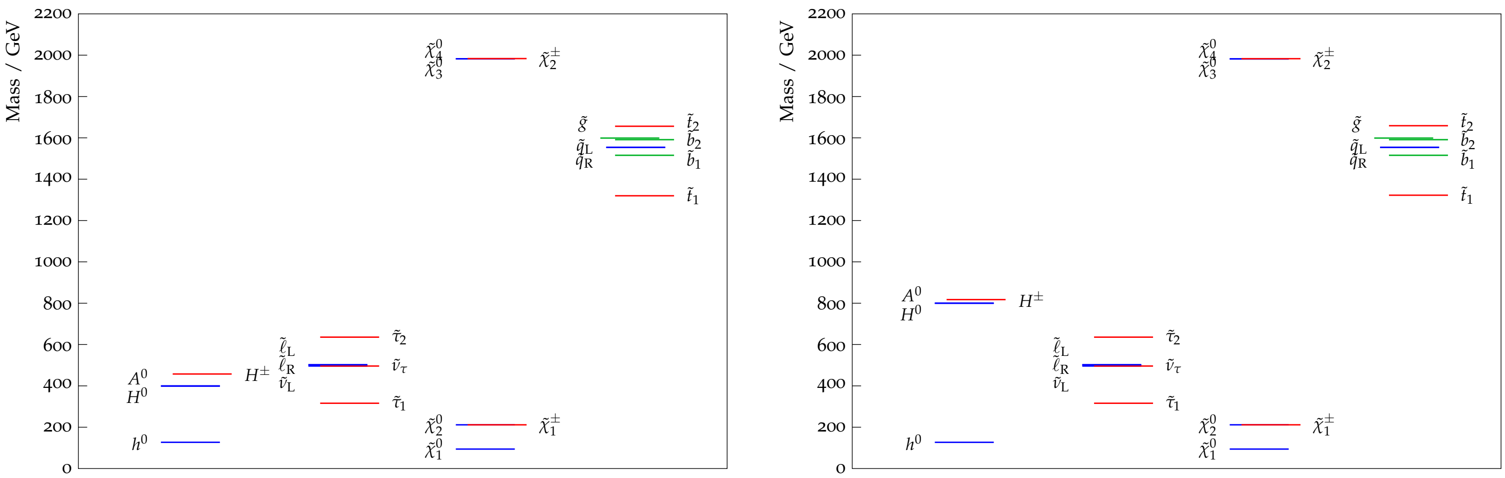


Figure 1: In scenarios where M_h represents the SM Higgs, X_t is constrained by the mass observed at the LHC for any given $\tan\beta$ (in this diagram $\tan\beta = 10°$) [4]

Additionally, for the tauphobic scenario as specified in the $\overline{MS}$ renormalization scheme [5–7] we have that $A_b = A_t$.

Looking at Figure 2, we provide visualizations of the SUSY spectrum at two different values of M_{A^0} for fixed $\tan\beta = 45°$. Note that the difference between the H^0 and A^0 masses decreases as M_{A^0} increases; this is a result of an inverse M_{A^0} dependence in the mass splitting portion of terms determining M_{H^0} [8].



(a) $M_A = 400, \tan\beta = 45°$

(b) $M_A = 800, \tan\beta = 45°$

Figure 2: Visualisations of the SUSY spectrum generated using PySLHA [9].

2.3 Stau Production Processes of Interest

For the purposes of this work, two different types of stau production channel were investigated. Firstly, those proceeding via the SM Z and γ ("direct" production) bosons, and secondly those which went via quarks and then the heavy neutral Higgs bosons, A^0, H^0. The direct production mode is shown in Figure 3 and the cross-sections for this

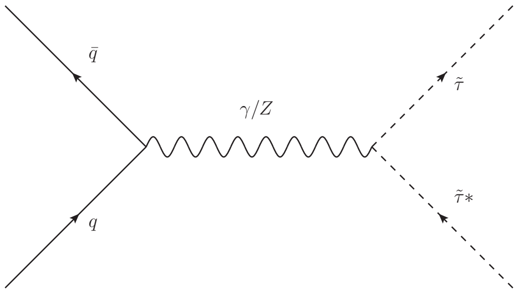
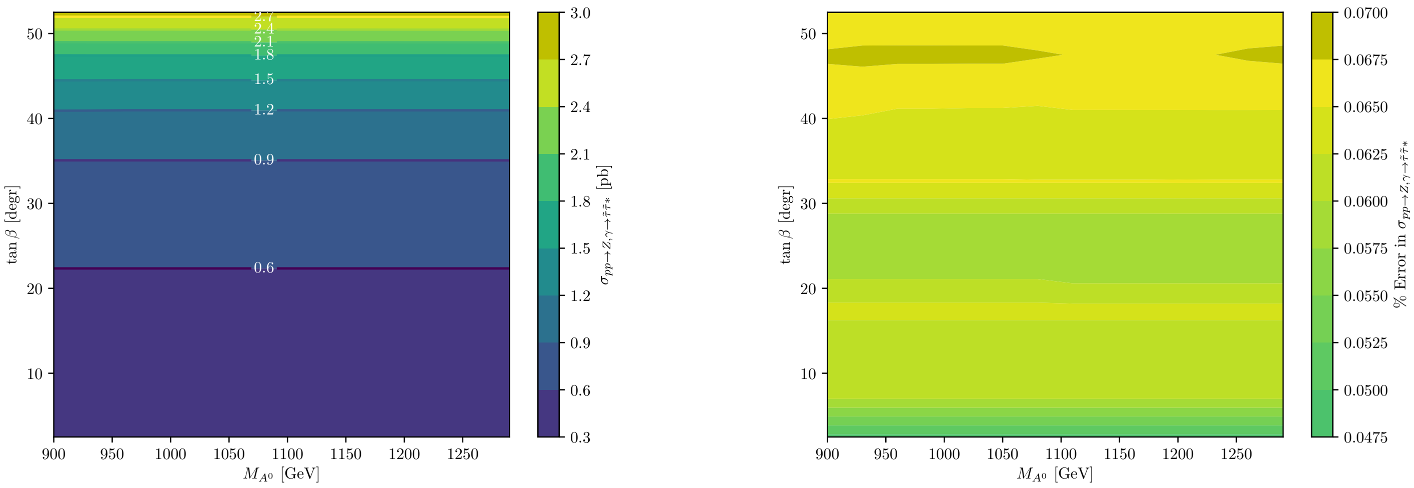


Figure 3: Direct stau production via neutral SM bosons. This is a Drell-yan like process dominated by bottom quark annihilation

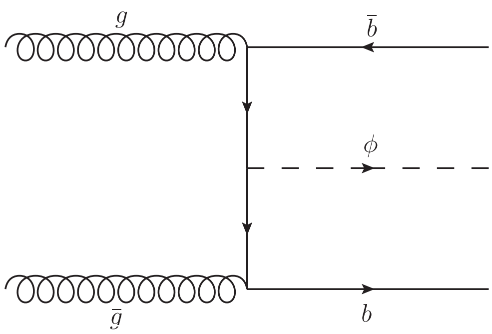
mode are presented in Figure 4. From this we see a clear a clear lack of dependence on M_{A^0} , as expected (provided there is no M_{A^0} dependency on the sfermion Yukawa coupling for the Z or γ). Additionally, we see a strong $\tan\beta$, which is primarily due to the inverse dependence of M_Z on $\tan^2\beta$ [10, §8.1].



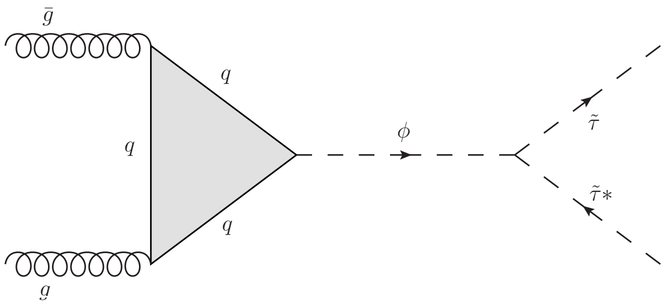
(a) Cross sections for direct stau production exhibit a clear dependence on $\tan\beta$ and no dependence on M_{A^0}

(b) The errors in cross-sections were negligible compared to other sources of error discussed in section 4

Figure 4: Cross sections for direct production of staus via Z, γ.



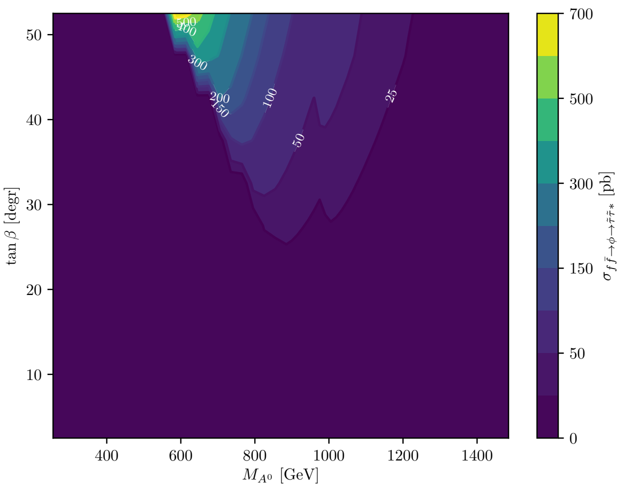
(a) The bottom quark annihilation process



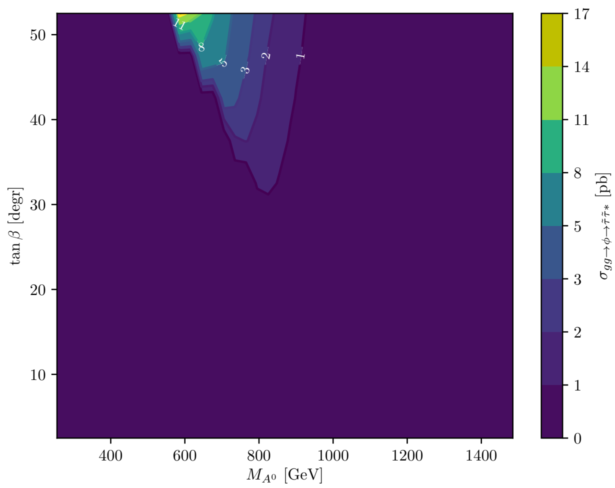
(b) Gluon fusion to SM quarks and intermediate Higgs

Figure 5: NLO Higgs production channels, with ϕ denoting A^0 or H^0

The dominant modes were intermediate Higgs production modes which proceeded through production of H^0 or A^0; Besides the fermionic annihilation channel, the NLO pathways for this mode are shown in Figure 5. Additionally, we again present the overall cross-sections for channels through fermions and gluons in Figure 6. By comparing these cross-sections to the direct ones, we see that the intermediate Higgs channels dominate the signal, and that fermionic annihilation produces the most events.



(a) Cross sections for fermions to staus via A,H



(b) Cross sections for gluon fusion of A,H decaying to staus

Figure 6: Here we see that the channels open up around $M_{A^0} = 750$GeV, and that the fermionic annihilation channel is dominant by an order of magnitude.

3 Method

3.1 Tools

The determination of exclusion points was carried out using scripts written in python. These were seperated into two stages; the first being the generation of an SLHA-format [11] file containing all relevant information about the SUSY spectrum, as well as branching ratios for all relevant modes. These files were generated by feeding an SLHA file specifying only the important parameters in the tauphobic scenario to SUSY-HIT [12], which generated the residual spectrum as well as decays. For increased accuracy in the Higgs sector, this was subsequently fed through FeynHiggs [13–19] which recalculated the parameters and branching ratios relevant to the Higgs sector. Additionally, the manipulation of SLHA files was carried out using PySLHA [9].

Subsequently, this information was then passed to CheckMATE2 [20] which took care of everything from Monte Carlo simulations through to detector simulations. CheckMATE does not natively implement all of this functionality, but instead makes use of various other programs:

- MadGraph for Monte Carlo event generation (in the direct case)[21]
- Pythia for hadronization (and event generation in the LO Higgs Processes)[22]
- Delphes for detector simulation (with CheckMATE enforcing models apt for LHC experiments)[23]
- Numerous technical packages used for specific aspects of the calculations [24–31]

3.2 Omissions

Notably, NLO Higgs generation processes were not included in the calculation. This was due to technical difficulties in attempting to automate the usage of aMCSuSHi (which would have provided such processes) via CheckMATE. Nonetheless, Pythia's LO calculations were deemed sufficient for the purposes of this project. If further precision is required on the exclusion limits, then the inclusion of higher order processes would be worth implementing for more complete physics.

Additionally, it should be noted that CheckMATE does not implement all ATLAS/CMS SUSY searches, although we did make use of a development version* which included two additional, potentially relevant, analyses: [32, 33].

*Many thanks to Daniel Dercks who implemented these analyses for us upon short notice

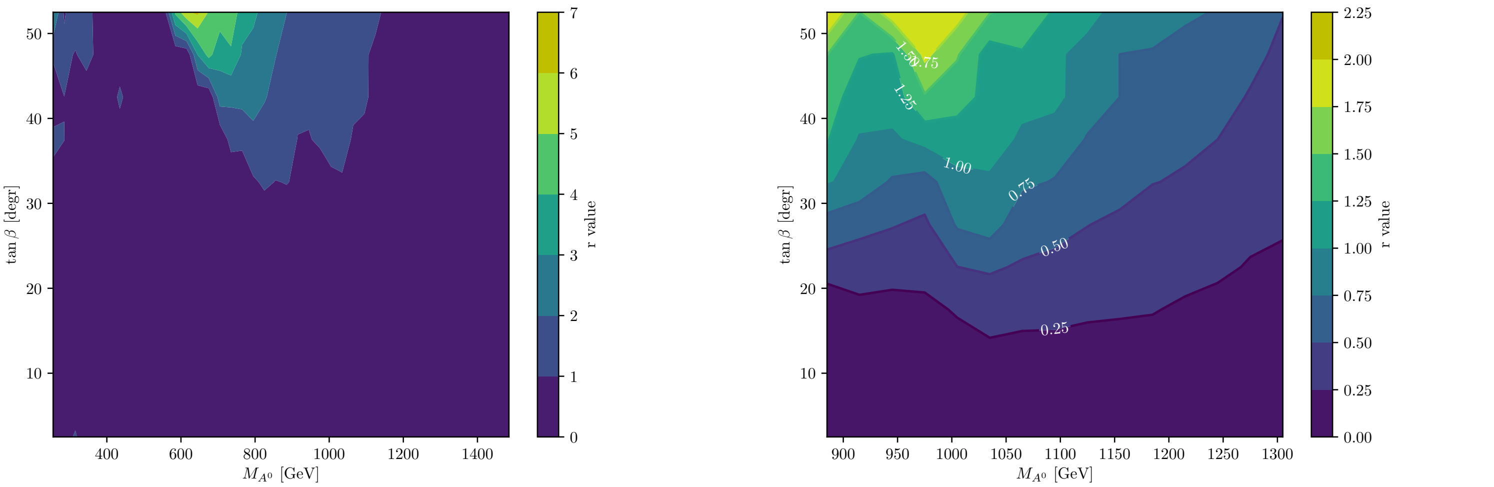
4 Results

In this section we present the exclusion limits derived from CMS and ATLAS studies at 13TeV, using the methods described in section 3. Besides the primary result shown in figure Figure 7, there are numerous cross-checks which will also be discussed in order to explain the observed exclusion region. Note that the exclusion limits are quantified in terms of an r value which is calculated as per [20], as

$$r = \frac{(S - 1.64 \cdot \Delta S)}{S95} = \frac{\text{Signal}}{95\% \text{ CL on Signal}}. \tag{1}$$

Such that r essentially quantifies the proportion of events events we would expect to observe in our scenario versus the amount that relevant searches have observed; More quantitatively $r < 1$ indicates a point which is not yet excluded, and points at $r > 1$ are excluded with increasing significance.

Looking then at Figure 7a we see that the majority of the investigated parameter space remains unconstrained by the stau decays, both through direct production and the LO Higgs production processes discussed in subsection 2.3. As $M_{\tilde{\tau}_1} = M_{\tilde{\tau}_2} = 500$GeV, the position of the dominant exclusion region with respect to M_{A^0} is unsurprising as it represents the region in which the stau channel opens up and is most dominant. Figure 8 allows us to understand the shape of the exclusion regions more exactly, by



(a) Exclusion region for all relevant channels shown over the whole parameter space.

(b) The region of interest shows that points above $\tan\beta \approx 30°$ are excluded with increasing certainty.

Figure 7: Exclusion regions for Higgs production and direction production over the $\tan\beta$, M_{A^0} parameter space.

including the stau branching ratios of both the A^0 and the H^0. As expected, above the $M_{A^0} \approx 1000$GeV threshold we see the opening up of the A^0 to stau channel.

However, it is interesting to note that the main channel for the decays occurs via the H^0, and this channel in fact opens up at $M_{A^0} \approx 600$GeV. At this energy there is some splitting in the masses of the neutral heavy Higgs, such that $M_{H^0} > M_{A^0}$, (as discussed in subsection 2.2). Furthermore, we see that after the channels become available, they are increasingly suppressed with increasing mass, as other decay modes become more relevant.

Note the shallower slope of the $H^0 \rightarrow \tilde{\tau}\tilde{\tau}*$ contours is partly due to the proportionality of the Higgs mass splitting (see Figure 2) to $\sin^2\beta$ (in the limit where $M_{A^0} >> M_Z$). There is also a cosine dependence, but this is suppressed relative to the sine dependence [8].

It should also be noted that the dominant behaviour is due to the H^0 as this is the primary source of the stau production owing to the nature of its sfermionic coupling (the coupling matrices for A^0 lack diagonal terms in a standard basis. whereas those of the H^0 do not). Additionally, we see a clear $\tan\beta$ dependence in the branching ratios, stemming from the form of the coupling.

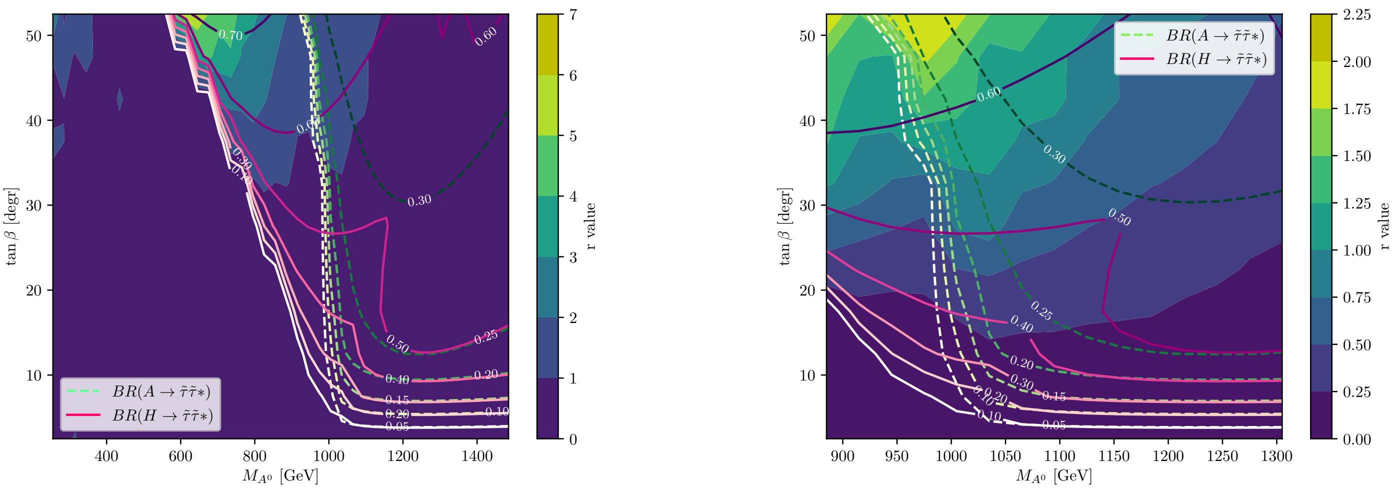


Figure 8: As in Figure 7, with branching ratios overlaid.

For the sake of completeness, we also include Figure 9, which illustrates the nature, and titles, of the the LHC analyses which provided the dominant signal contribution to the exclusion constraints at every point considered.

Finally, it is assumed that the usual theoretical uncertainty of ± 3GeV applies for M_{A^0} at all points in the parameter space; although this error is likely even more significant in our analysis for both technical reasons stemming from possible discrepancies between different steps during spectrum generation, and additionally due to the aforementioned omission of NLO and Higher order effects.

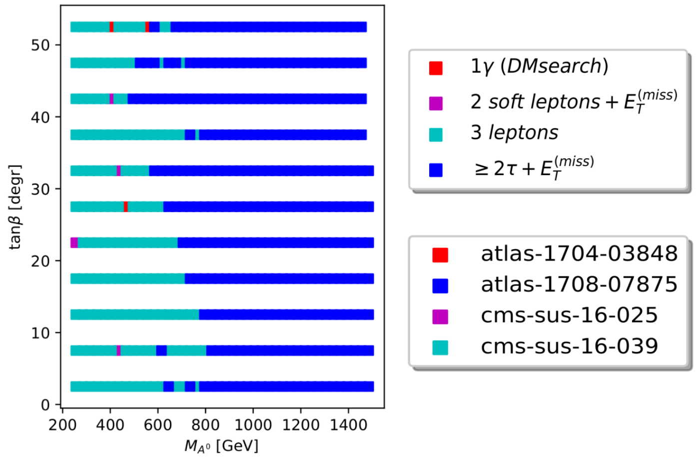


Figure 9: The searches which provided the dominant contribution to the exclusion at different points in the parameter space are shown.

5 Conclusion

It has been found that the stau decay channel through direct SM bosons and heavy neutral MSSM Higgs is largely unexcluded by existing ATLAS and CMS studies at 13TeV. However, these results are merely prelimenary; more thorough considerations of higher order effects as well as including more recent analyses and those performed at 8TeV would certainly be worthwhile. Nonetheless, the largely unconstraining nature of existing studies is likely to hold true even upon inclusion of these suggestions, in which case a directed LHC investigation of dominant stau decay modes may be deemed worthwhile.

In any event, there is much work still to be done in the investigation of existing LHC analyses with regards to their ability to constrain SUSY models, and the tools used in this work enable such research to be performed with relative ease.

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