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Setting limits on supersymmetry using simplified models

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Abstract:	Experimental limits on supersymmetry and similar theories are difficult to set because of the enormous available parameter space and difficult to generalize because of the complexity of single points. Therefore, more phenomenological, simplified models are becoming popular for setting experimental limits, as they have clearer physical interpretations. The use of these simplified model limits to set a real limit on a concrete theory has not, however, been demonstrated. This paper recasts simplified model limits into limits on a specific and complete super- symmetry model, minimal supergravity. Limits obtained under various physical assumptions are comparable to those produced by directed searches. A prescrip- tion is provided for calculating conservative and aggressive limits on additional theories. Using acceptance and efficiency tables along with the expected and observed numbers of events in various signal regions, LHC experimental results can be re-cast in this manner into almost any theoretical framework, including non-supersymmetric theories with supersymmetry-like signatures.
Author Comments:	We have two remaining editorial issues in this version of the manuscript, which I hope your editors will be able to help us with. First, Eq 1 and the text two lines after currently includes the symbol "A epsilon _ {a -> i}". We think it would be more clear (and this may have caused some of the reviewers' confusion) if it read "A epsilon _ {(a,b)->i}". Unfortunately, my version of Word does not allow me to edit those equations. Second, in a number of cases, % instead of ~ appears over the squark or gluino symbol. You can find a correct instance in the first full paragraph of page 8, fifth to last line, and two incorrect examples in the second to last line of that paragraph. Otherwise, we have revised the references and figures and kept the formatting as requested (I hope).
Additional Information:	
Question	Response

To whom it may concern:

We would like to propose the work described in “Setting limits on supersymmetry using simplified models” for publication in your journal. The experiments at the Large Hadron Collider have set limits on a number of so-called simplified models. These models were designed with the hope that they could be used to set limits on concrete models like minimal supergravity, gauge-mediated supergravity, and universal extra dimensions. This paper provides a series of protocols for constructing such limits on “real” models from the available simplified model exclusion results. We believe these protocols will be useful for theorists and phenomenologists wishing to set limits on models not considered by the LHC experiments. They should also be considered by the experiments themselves, since they require certain pieces of information that are not available for all the published search results. Indeed, since the posting of the original version of the paper on the arXiv, we have received a number of notes from interested readers asking for further instruction and guidance on using these methods.

A significantly different version of this paper was submitted to the journal Phys. Rev. D for review. However, during the review process we were contacted by one of the editors of JOVE, and we decided your journal would be a more appropriate home for the work.

The two authors of the paper essentially split the work between them. Both contributed to the construction of the method, the results, and the composition of the paper.

We hope that you will find this manuscript suitable for publication. Please do not hesitate to contact either of us if you would like to discuss the work or document.

Best Wishes,

Zachary Marshall
CERN Research Fellow
2 October 2012

Setting limits on supersymmetry using simplified models

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Abstract
Experimental limits on supersymmetry and similar theories are difficult to set because of the enormous available parameter space and difficult to generalize because of the complexity of single points. Therefore, more phenomenological, simplified models are becoming popular for setting experimental limits, as they have clearer physical interpretations. The use of these simplified model limits to set a real limit on a concrete theory has not, however, been demonstrated. This paper recasts simplified model limits into limits on a specific and complete supersymmetry model, minimal supergravity. Limits obtained under various physical assumptions are comparable to those produced by directed searches. A prescription is provided for calculating conservative and aggressive limits on additional theories. Using acceptance and efficiency tables along with the expected and observed numbers of events in various signal regions, LHC experimental results can be re-cast in this manner into almost any theoretical framework, including non-supersymmetric theories with supersymmetry-like signatures.

Keywords
Supersymmetry; LHC; ATLAS; CMS; New Physics Limits; Simplified Models

Short Abstract
This paper demonstrates a protocol for recasting experimental simplified model limits into conservative and aggressive limits on an arbitrary new physics model. Publicly available LHC experimental results can be re-cast in this manner into limits on almost any new physics model with a supersymmetry-like signature.

Introduction

One of the most promising extensions of the Standard Model, supersymmetry (SUSY)[1–14], is the central focus of many searches by the LHC experiments at CERN. The data collected in 2011 are already sufficient to push the limits of new physics beyond those of any previous collider[15–22]. As new data arrive and the exclusions are pushed still farther, it will be increasingly important to clearly communicate to the physics community what regions of the extensive supersymmetric

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parameter space have been excluded. Current limits are typically set on constrained two-dimensional planes, which frequently do not represent the diverse available SUSY parameter space and are difficult to understand as limits on physical masses or branching fractions. A large set of simplified models[23, 24] have been proposed for aiding in the understanding of these limits, and both ATLAS and CMS have provided exclusion results for several of these models[15–20].

This paper demonstrates the application of these simplified model exclusions to a full new physics model using the example of the minimal supergravity (MSUGRA, also known as the CMSSM)[25–30]. This model is chosen in order to compare the limits set using simplified models to those published independently by the experiments. The procedure is sufficiently general to be extendable to any new physics model (NPM). As this represents the first attempt to “close the loop” and set limits on SUSY using simplified models, a number of assumptions about the applicability of limits on particular simplified models are explored, resulting in recipes for setting conservative and aggressive limits on theories that have not been examined by the LHC experiments.

For setting a limit in a NPM, three separate operations are required. First, the NPM must be deconstructed into its constituent pieces, separating the various production modes and decay modes for all new particles in the model. Second, a set of simplified models must be chosen to re-create the kinematics and relevant event topologies in the NPM. Third, the available limits on these simplified models must be combined in order to produce limits on the NPM. These three procedures are described in the protocol. Some additional approximations are also provided that may expand the applicability of the already-available simplified models to a broader range of event topologies.

A complete NPM typically involves many production modes and many possible subsequent decays. The deconstruction of new physics models into their components and the application of simplified model limits to those components allows the construction of an exclusion limit directly. For any signal region, the most conservative limit can be set using the production fraction $P_{(a,b)}$ (where a,b represents the simplified model sparticle production mode) of events identical to a simplified model i and the branching fraction for the produced sparticles to decay in the manner described by the simplified model[‡], $\mathrm{BR}_{a\to i}\times\mathrm{BR}_{b\to i}$. The expected number of events in a given signal region from these simple topologies can then be written as

$$N=\sigma_{\mathrm{tot}}\times L_{\mathrm{int}}\times\sum_{\mathrm{SM}}\mathrm{A}\varepsilon_{a,b\to i}\times P_{(a,b)}\times\mathrm{BR}_{a\to i}\times\mathrm{BR}_{b\to i}\,,\quad(1)$$

where the sum is over simplified models, σ_{tot} is the total cross section for the NPM point, L_{int} is the integrated luminosity used in the search, and $\mathrm{A}\varepsilon_{a,b\to i}$ is the acceptance times efficiency for the simplified model events in the signal region being considered. This number can be compared to the expected 95 % confidence level upper limit on the number of new physics

[‡] Some simplified models now used at the LHC include associated production. While not explicitly discussed here, the equations can be trivially extended to allow for this case.

events to select the optimal search region. The model can then be excluded if N is larger than the observed number of new physics events excluded at the 95 % confidence level. Exclusions in non-overlapping regions may be combined if information about the correlations of their uncertainties is available. If this information is not available, the best signal region or analysis that provides the best expected limit can be used to attempt to exclude the model.

In order to construct concrete limits with this method, the $A\varepsilon$ for various simplified models must be made available by the LHC experiments. Both CMS and ATLAS have published figures with the $A\varepsilon$ for several models, and a few of the figures are available in the HepData database[31]. In order to demonstrate the value of publishing all such tables, we feel it is important to provide concrete limits that are comparable to those already published. Therefore we use (and describe in the protocol as an optional step) a fast detector simulation to emulate the effect of the ATLAS or CMS detector. The $A\varepsilon$ derived from the Pretty Good Simulation (PGS)[32] is compared to that published by ATLAS in a simplified model grid in Figure 1. These results are sufficiently close to one another (within roughly 25 %) that, rather than wait for all results to be public, $A\varepsilon$ results for the remaining grids are derived using PGS and used directly in the remainder of this paper. As the number of publicly available simplified model $A\varepsilon$ results grows, the need for such approximations should be significantly reduced.

Two conservative assumptions allow the inclusion of a larger number of production and decay modes in the limit. The first is that for associated production the experimental $A\varepsilon$ is at least as high as the $A\varepsilon$ for the worse of the two production modes. For inclusive searches, this is generally a good assumption. The minimum expected number of events would then be

$$N = \sigma_{\text{tot}} \times L_{\text{int}} \times \sum_{(a,b)} P_{(a,b)} \times \sum_{i} \text{BR}_{a\to i} \times \text{BR}_{b\to i} \times \min(A\varepsilon_{a\to i}, A\varepsilon_{b\to i}), \quad (2)$$

where the first sum runs over all production modes, and only those where a and b are exactly those particles from the simplified model are included in Equation 1. Similarly, the $A\varepsilon$ for decays with different legs can be assumed to be at least as high as the $A\varepsilon$ for the worse of the two legs. That is,

$$N = \sigma_{\text{tot}} \times L_{\text{int}} \times \sum_{(a,b)} P_{(a,b)} \times \sum_{i} \text{BR}_{a\to i} \times \sum_{j} \text{BR}_{b\to j} \times \min(A\varepsilon_{a\to i}, A\varepsilon_{b\to j}), \quad (3)$$

where diagrams with different decays on either side have now been included.

Two further assumptions would allow the setting of stricter limits. One can assume that the experimental $A\varepsilon$ for all production modes in the theory is similar to the average $A\varepsilon$ for the production modes covered by simplified models. In that case, the expected number of events can instead be written as

$$N = \sigma_{\text{tot}} \times L_{\text{int}} \times \sum_{(a,a)} A\varepsilon_{(a,b)} \times \frac{P_{(a,a)}}{\sum_{(a,a)} P_{(a,a)}} \times \text{BR}^2_{a\to i}, \quad (4)$$

where the sums are both over only those production modes covered by simplified models. One might further assume that the $A\varepsilon$ for all decay modes in the theory is similar to the average $A\varepsilon$ for those events covered by the simplified model topologies. Then the expected number of events may be written as:

$$N = \sigma_{\text{tot}} \times L_{\text{int}} \times \sum_i A\varepsilon_{a\to i} \times \frac{P_{(a,a)}}{\sum_{(a,a)} P_{(a,a)}} \times \left(\frac{\text{BR}_{a\to i}}{\sum_a \text{BR}_{a\to i}}\right)^2, \quad (5)$$

where again the sums run only over the simplified models. Clearly, the most aggressive MSUGRA limit is provided under this assumption, and a limit set in this manner risks claiming exlusion for regions which would not, in fact, be excluded at the 95 % confidence level by a dedicated search. Although the accuracy of these two approximations might be suspect, if the inclusive event kinematics of the simplified models compare favorably to a complete SUSY parameter space point, they may not be unreasonable.

Protocol:

1. Model Deconstruction

1.1 Generate proton-proton collision events covering a plane in the parameter space of the NPM. Any event generator configuration that includes a parton shower and hadronization model can be used. In the case of MSUGRA for example, the mass spectra are generated using Isasugra[33], and the branching fractions and decay widths are calculated using MSSMCalc[34]. For the event generation itself, MadGraph 5 1.3.9[34] with CTEQ 6L1 parton density functions[35] is used to generate matrix-element events, since it includes additional radiation in the matrix element, which can be important for small mass-splitting scenarios. In order to mimic the LHC experiments' choices of leading-order generators for MSUGRA, the additional radiation in the MadGraph matrix element is disabled when generating MSUGRA events. Pythia 6.425[36] is then used for SUSY particle (sparticle) decay, parton showering, and hadronization. Extensive documentation for any of these programs is readily available on the web.

1.2 In order to mimic an LHC detector, pass the events through PGS with an LHC-detector parameter card. The ATLAS and CMS detector cards included with MadGraph 5[34] perform well enough for search reach analysis. Where available, the experiments' parameterizations of identification and performance made public with some analyses can be used. Ideally, the experiments will provide full maps off acceptance and efficiency for a number of simplified model grids, in which case these can be used directly and this step is unnecessary.

1.3 In order to analyze the results quickly, an intermediate light-weight data format is desirable. Extracting the jets, stable leptons, missing transverse energy, and any other necessary final-state objects from the PGS output (e.g. using ExRootAnalysis[34]) in a convenient format is recommended.

1.4 In order to classify the results, correlate the PGS event results with the portion of the generator event record necessary to classify the sparticle production and decay modes for each event. Keep track of all particle masses, production mechanisms, and decay chains as well as their respective counts in order to be able to calculate their corresponding branching fraction.

1.5 Calculate the best available production cross-section calculations for the model of interest. In the case of MSUGRA, next-to-leading order cross-sections for each point can be calculated using Prospino 2.1[37] with NLL-Fast[38] using CTEQ 6.6 NLO PDFs.

2. Model Reconstruction

2.1 Based on the breakdown from the model deconstruction, choose a dictionary of simplified models so as to cover at least 50 % of the open production and decay modes of the NPM. Because of the rapidly falling cross-section of most BSM models with mass, a factor of two in acceptance typically represents only 20-50 GeV in the limit, making this sufficiently close to be within the experimental and theoretical uncertainties. Most direct decay and one-step decay models, including off-shell / three-body decays, have been considered by the LHC experiments. CMS has collected a number of simplified model exclusion results in a single paper[21]. Both ATLAS and CMS have also considered a number of heavy-flavor simplified models. The full list of models has not been made publicly available in a single place. However, the results are available from the two experiments' public webpages[39, 40]. These are the simplified models that should be selected from for reconstruction of the NPM.

2.2 In order to test the quality of the simplified model coverage, compare the kinematics of a few representative NPM points with those resulting from the simplified models used to reproduce that point. For a given NPM point, construct the relevant simplified models with the appropriate masses.

2.3 Assign a weight to each model type that includes the production fraction represented by that simplified model times the branching fraction for the decay represented by that model.

2.4 For associated production, if only pair-production simplified models are considered, divide the weight between the two relevant simplified models.

2.5 It is recommended to apply a set of physically-motivated simplifications to the NPM event topologies in order to group similar production- and decay-modes.

2.6 Normalize the sum of the weights for all the simplified models to unity.

2.7 Calculate the kinematic distributions for the representative NPM points using the event generation procedure described in the previous protocol.

2.8 If the kinematics of the NPM point after typical signal selections differ by more than $\mathcal{O}(30\%)$ from those of the combined simplified models, include additional simplified models to improve the production and decay phase-space coverage. Discrepancies on the 15 % level have negligible impact on the final exclusion results because of the rapidly falling cross-sections in most new physics models.

3. Limit Construction

3.1 Obtain the available and relevant $A\varepsilon$ and 95 % confidence level upper limit on the number of new physics events for the simplified models being considered in each experimental signal region that can be applied.

3.2 Apply Equations 1 and 3–5 to the NPM of interest at each parameter space point to determine under which (if any) assumptions the point is excluded.

3.3 Use the limit set by the signal region with the best expected performance, unless correlations between the signal regions' background uncertainties are available so that the regions can be properly combined[§].

3.4 With the comparison of kinematics performed with the previous protocol and the spread of the exclusion contours, determine the range in which the experimental exclusion should lie.

Representative Results

Having applied the model deconstruction step to a point in the parameter space of MSUGRA, a breakdown of the output can be best visualized by counting up the various production and decay modes for every generated event and plotting the corresponding production rates and branching fractions according to the relative frequencies. The branching fractions for the various production and decay modes for representative MSUGRA points are illustrated in Figures 2 and 3. A large number of similar figures for other points in SUSY parameter space are available online[41].

For the case of MSUGRA, some trends across the phase space are present, as demonstrated in Figure 4. Squark production dominates in the low-m_0, high-$m_{1/2}$ region, and gluino production dominates in the high-m_0, low-$m_{1/2}$ region. In the region where squark production dominates, direct squark decays to the lightest supersymmetric particle (LSP) are favored. In regions where gluino production dominates, however, direct decays of the gluino to the LSP never comprise more than ~ 30 % of the total decay phase space. In the interjacent region, direct chargino production makes up a non-negligible contribution, especially towards high m_0 and high $m_{1/2}$ where the squarks and gluinos are all heavy. This MSUGRA plane, therefore, can be covered by five simplified model (SM) scenarios:

- Pair-production of squarks, which directly decay to the LSP via the emission of a quark (SM 1);
- Pair-production of gluinos, which directly decay to the LSP via the emission of a two quarks (SM 2);
- Pair-production of squarks, which decay in one-step to the LSP. The squark decays to a chargino via the emission of a quark, and the chargino decays to the LSP via emission of a W-boson (SM 3);

[§] At present, no such correlations are available.

- Pair-production of gluinos, which decay in one-step to the LSP. The gluino decays to a chargino via the emission of two quarks, and the chargino decays to the LSP via emission of a W-boson (SM 4); and
- Pair-production of charginos, which directly decay to the LSP via the emission of a W-boson (SM 5).

The fraction of MSUGRA events classified as belonging to one of these five simplified models is shown in Figure 5. For the MSUGRA example, the following additional simplifying approximations are made: When the squark decays to the gluino, the gluino decay is counted in classifying the event topology, and the decay of the squark to the gluino is counted as an additional jet in the event ("plus jets"), as though it were identical to initial- or final-state radiation. When the gluino decays through a squark $g \to q\tilde{q}, \tilde{q} \to q\mathrm{X}$, however, the final state of the decay still appears as though the gluino had produced two jets and decayed directly, omitting the squark-step, save some (small) differences in kinematics. For these cases, therefore, the decay chain is classified as though the gluino decayed via the emission of a pair of quarks with no intermediate squark ($g \to qq\mathrm{X}$), rather than classifying it as the squark decay with an additional initial- or final-state radiation-like jet ($q \to q\mathrm{X}$ plus jet(s)). Associated squark-gluino production is divided evenly among the squark and gluino simplified models. With these approximations, it is possible to classify a large fraction of SUSY events as one of the five simplified models under consideration. This is the first step towards the model reconstruction.

The event kinematics for two MSUGRA parameter space points, along with a combination of simplified models used to mimic them, are shown in Figures 6, 7, and 8. These two points are deconstructed using the method described above, and the five selected simplified models are constructed and combined according to the mass spectra, production rates, and branching fractions of the points. The simplified model events were generated and analyzed in a manner identical to the MSUGRA events. Here, four of the key kinematic variables used in LHC supersymmetry searches are shown: leading jet transverse momentum (p_T), lepton p_T, missing transverse energy, and effective mass, defined as the scalar sum of the transverse momenta of the four leading jets and the lepton. Two features are visible in the effective mass, leading jet, and missing transverse energy distributions, corresponding to strong production and weakino production. In these inclusive distributions, some discrepancies are clearly visible. The low-p_T lepton tail, for example, is predominantly from tau decays that are not covered by any of the simplified models. The low missing transverse energy, low effective mass region is in part from LSP-X associated production, which is not modeled. Most kinematic features are described well enough by PGS for the purposes of a search in a parameter space with rapidly falling background. Tau fake rates remain a significant challenge to a parameterization of tau analysis results, and completely addressing that issue is beyond the scope of this protocol.

However, the cuts of most signal regions used at the LHC are such that simple decay topologies are selected over the more complex, often softer or higher multiplicity events. Thus, signal region selection tends to improve the description of event kinematics by simplified models. Comparison in a one-lepton region similar to that used in a recent ATLAS SUSY search[16] are shown in Figure 7 and 8. The agreement in both shape and tails is significantly better. The kinematics for the simplified models compare well to the *inclusive* SUSY model kinematics, suggesting that the efficiency and acceptance for a complete SUSY point may be well described by a limited combination of simplified models. Of course, the kinematics of only those SUSY events corresponding to topologies described by the simplified models are identical to their simplified model counterparts. This serves as a confirmation that those events not covered by these simplified models are either a small fraction of the total events or kinematically similar to those that are covered. This completes the model reconstruction step in the case of MSUGRA.

The limit-setting procedure under section 3 is then applied to the MSUGRA plane with $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$, using signal regions from the ATLAS zero-lepton search[16]. Five signal regions are included in this search, and the signal region with the best expected limit is used for each point. A point is considered to be excluded if the number of expected SUSY events in the optimal signal region exceeds the observed 95 % confidence level upper limit on new physics events in that signal region. The results of the simplified model exclusion are compared to the zero-lepton exclusion without systematic uncertainties on the signal, as discussed previously, in Figure 9. Four simplified model exclusion curves are shown, corresponding to Equations 1 and 3–5. In comparison to the zero-lepton exclusion limit, the most conservative simplified-model-based approach does rather poorly in the region dominated by $q\tilde{g}$ and weakino associated production, missing the correct limit by up to ~ 100 GeV. This is also in part due to the relatively complicated decay of the gluino (c.f. the large number of open modes in Figure 3). The coverage is much closer to the true limit for the region dominated by $q\tilde{q}$ and $g\tilde{g}$ production, for which the simplified model-derived limit is within 40 GeV of the true limit.

This prescription omits the treatment of theoretical uncertainties on the signal model. In fact, the LHC experiments currently do not treat these uncertainties in a consistent way, nor are all of the uncertainties included. No experiment, for example, includes any uncertainty in the calculation of visible masses from the GUT scale parameters. The limits that are presented here, therefore, should be expected to differ from the published limits. In Figure 10, the published ATLAS exclusion limits in the zero-lepton channel are compared to those obtained here without any systematic uncertainty on the signal. The limit without signal uncertainties is clearly higher than the published limit. For the remainder of the paper, the limit without systematic uncertainties on the signal will be taken as the “correct answer” to be arrived at using simplified models. The theoretical uncertainty can be added to both in the same way and will affect both limits in approximately the same way.

In order to portray the results achievable with present resources as accurately as possible, simplified model points are generated on a grid corresponding roughly to that already in use by the ATLAS experiment[17]. Between these points, $A\varepsilon$ is interpolated in the two-dimensional m_{squark} / m_{gluino}-m_{LSP} grid. Because SM 3 and SM 4 are three dimensional grids, and because it is unlikely that experiments will provide full three-dimensional $A\varepsilon$, three values of intermediate chargino mass are used: $m_{\text{chargino}} = x \times \left(m_{\text{squark/gluino}} - m_{\text{LSP}}\right) + m_{\text{LSP}}$, with $x = 0.25$, 0.5, and 0.75. To interpolate between these three two-dimensional planes, a simple quadratic fit is used. When approaching the boundaries of $m_{\text{LSP}} = m_{\text{chargino}}$ and $m_{\text{squark/gluino}} = m_{\text{chargino}}$, the decay modes naturally turn off, making more complicated interpolation unnecessary.

From comparing the exclusion curves, one can indeed see that a conservative exclusion limit set using Eq. 1 follows the "correct" exclusion limit quite well in regions of phase space that are well-covered by simplified models (c.f. Fig. 5). In regions that are not as well covered, Eq. 3 still provides a conservative limit. The aggressive limit set by Eq. 5 overestimates the exclusion by up to 40 GeV in the squark-dominated region and by up to 100 GeV in the gluino-dominated region of phase space, because the assumption that the long gluino decay chains are well-modeled by the shorter chains of the simplified models is invalid at some level. In terms of parameter-space coverage, the conservative limits under-cover by 20 %, the middle two limits under-cover by 10 %, and the aggressive limit over-covers by 10 %. Naturally, expanding the dictionary of simplified models available would improve the conservative limit and reduce the aggressive limit as more correct $A\varepsilon$ are included for more production and decay modes. However, even with this small number of simplified models, the conservative limits set are close to the "correct" result.

For demonstrative purposes, limits are also placed on an MSUGRA signal region at high $\tan(\beta)$. The limits are shown in Figure 11. Based on the agreement observed in Figure 10, the experimental exclusion should lie a bit beyond the exclusion set by Eq. 3.

In extrapolating to more exotic theories, or even in expanding the applicability of a small list of simplified models to SUSY theories, several approximations can be made:

1. That heavy-flavor jets are identical to light flavor jets for searches that do not include flavor tagging;

2. That photons are identical to jets for searches that do not identify photons;

3. That more than half the time, chargino (neutralino) decays to the LSP via emission of a W -boson (Z -boson) produce a signature functionally identical to gluino decays via emission of two quarks.

Such approximations are physically well motivated and should result in limits which are still in agreement with the full experimental results.

Figure 1
Left, the public $A\varepsilon$ for the ATLAS three jet "loose" one-lepton signal region[17]. Right, the same reproduced in the MadGraph + Pythia + PGS setup used here. Some differences are to be expected from the different generators and higher statistics used here, but the two follow one another closely.

Figure 2
Branching ratios for SUSY production mechanisms and decay modes in the MSUGRA parameter space. The top row ($m_0 = 300\text{GeV}$, $m_{1/2} = 600\text{GeV}$, $\tan(\beta) = 10$, $A_0 = 0$ GeV, and $\mu > 0$) is typical for the region in parameter space that is dominated by squark production, and the bottom row ($m_0 = 1000\text{GeV}$, $m_{1/2} = 350\text{GeV}$, $\tan(\beta) = 10$, $A_0 = 0$ GeV, and $\mu > 0$)

is typical for the region in parameter space lying somewhat in between the two extremes. For clarity, production and decay modes are only listed if their branching fraction is greater than 0.5 %. The labels “SM” with a number are given to decay modes corresponding to the simplified models discussed in the model reconstruction protocol.

Figure 3
Branching ratios for SUSY production mechanisms and decay modes in the MSUGRA parameter space. The top row ($m_0 = 300GeV$, $m_{1/2} = 500GeV$, $\tan(\beta) = 25$, $A_0 = 1500$ GeV, and $\mu > 0$) is typical for the region in parameter space that is dominated by squark production, and the bottom row ($m_0 = 2100GeV$, $m_{1/2} = 100GeV$, $\tan(\beta) = 45$, $A_0 = 500$ GeV, and $\mu > 0$) is typical for the region dominated by gluino production. For clarity, production and decay modes are only listed if their branching fraction is greater than 0.5 %. The labels “SM” with a number are given to decay modes corresponding to the simplified models discussed in the model reconstruction protocol. The models in the white regions had no events described by simplified models, with limited Monte Carlo statistics.

Figure 4
Variation of the branching ratios, in percent, of the main SUSY production and decay modes in the MSUGRA parameter space with $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$. The upper right corner, where the strong sparticles are heavy, includes a significant contribution from weakino production. The models in the white regions had no events described by simplified models, with limited Monte Carlo statistics.

Figure 5
The percentage of MSUGRA events classified as belonging to one of the five simplified models considered in this paper, for low-$\tan\beta$ (left) and high-$\tan\beta$ (right).

Figure 6
Kinematics of a squark-production-dominated MSUGRA point ($m_0 = 300$ GeV, $m_{1/2} = 600$ GeV, $\tan(\beta) = 10$, $A_0 = 0$, $\mu > 0$) and a set of five simplified models constructed using the same mass spectrum. Clockwise from the top left, leading jet p_T, leading muon p_T, effective mass, and missing transverse energy. No signal selection has been applied.

Figure 7
Kinematics of a squark-production-dominated MSUGRA point ($m_0 = 300$ GeV, $m_{1/2} = 600$ GeV, $\tan(\beta) = 10$, $A_0 = 0$, $\mu > 0$) and a set of five simplified models constructed using the same mass spectrum. Clockwise from the top left, leading jet p_T, leading muon p_T, effective mass, and missing transverse energy. A signal selection similar to the one-lepton four-jet “tight” ATLAS SUSY search has been applied.

Figure 8
Kinematics of a complex MSUGRA point ($m_0 = 1000$ GeV, $m_{1/2} = 350$ GeV, $\tan(\beta) = 10$,

$A_0 = 0$, $\mu > 0$) and a set of five simplified models constructed using the same mass spectrum. Clockwise from the top left, leading jet p_T, leading muon p_T, effective mass, and missing transverse energy. A signal selection similar to the one-lepton four-jet "tight" ATLAS SUSY search has been applied.

Figure 9
Combined zero-lepton exclusion limits for MSUGRA models with $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$ (10a) in comparison with the exclusion limit obtained using simplified models only (10b). The signal region providing the best expected limit is taken for a given point in parameter space. The expected 95 % confidence level limit is shown as a dashed blue line, and the observed limit is shown as a solid red line. Results from previous searches are also shown for comparison purposes[42–48], although some of these limits were produced using slightly different parameter choices. The simplified model limits are generated using four different sets of assumptions, corresponding to the limit equations in the main text.

Figure 10
Combined zero-lepton exclusion limits for MSUGRA models with $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$ [16] (left) in comparison with the exclusion limit obtained using PGS and without a systematic uncertainty on the signal. The signal region providing the best expected limit is taken for a given point in parameter space. The expected 95 % confidence level limit is shown as a dashed blue line, and the observed limit is shown as a solid red line. Results from previous searches are also shown for comparison purposes[42–48], although some of these limits were produced using slightly different parameter choices.

Figure 11
Exclusion limits for MSUGRA models with $\tan\beta = 40$, $A_0 = -500$ GeV and $\mu > 0$ (left) and $\tan\beta = 20$, $A_0 = 500$ GeV and $\mu > 0$ (right) obtained using simplified models only. Combined limits are obtained by using the signal region which generates the best expected limit at each point in parameter space. The simplified model limits are generated using four different sets of assumptions, corresponding to the limit equations in the main text.

Discussion

The application of simplified model limits to produce an exclusion contour in a complete new physics model has been demonstrated. Despite the apparent complexity of MSUGRA parameter space points, the kinematics can be well-reproduced by a combination of only a small number of simplified models. The kinematic agreement is further improved when looking within a particular signal region, since the searches thus far conducted at the LHC tend to favor simplified model-like event topologies with a (relatively) small number of high-p_T objects.

The exclusion contours derived from simplified models compare favorably with those already published with dedicated searches. With this procedure, it is possible to trivially recast exclusion results into more exotic SUSY theories, or even into non-SUSY theories with signatures covered by simplified models. This method additionally allows a simple route for preservation of the data and application of current searches to future theories.

Practically, this approach means a significant resource saving for the LHC experiments and a great benefit to LHC theorists and phenomenologists. By re-casting theories using information available from the matrix element and decay probabilities, no computing-intensive simulation of the model must be done. Instead, the experiments are free to straightforwardly provide exclusion results in a large variety of theoretical models which include – but may not be completely covered by – simple final state signatures. Similarly, theorists need not wait for the LHC experiments to produce limits in their favored model. Although the simplified models may not cover all the production and decay modes of a model, with a relatively small number of simplified models it is possible to cover a fairly broad range of possibilities. The exclusions acquired in this manner do not precisely overlap the results of a complete experimental search. In the current LHC search era, however, they give a critical and surprisingly accurate estimation of how much theory space has already been excluded by the already conducted searches, and how much may still be open to discovery.

Disclosures

The authors are both members of the ATLAS Collaboration. However, no ATLAS internal resources, monetary or otherwise, were used in the completion of this work.

Acknowledgments

The authors would like to thank Jay Wacker for significant discussion of simplified models and potential pitfalls. Many thanks also to Max Baak and Till Eifert for constructive criticism and encouragement whenever it was necessary. Thanks to the CERN Summer Student Program for making this collaboration possible.

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*Figure 1

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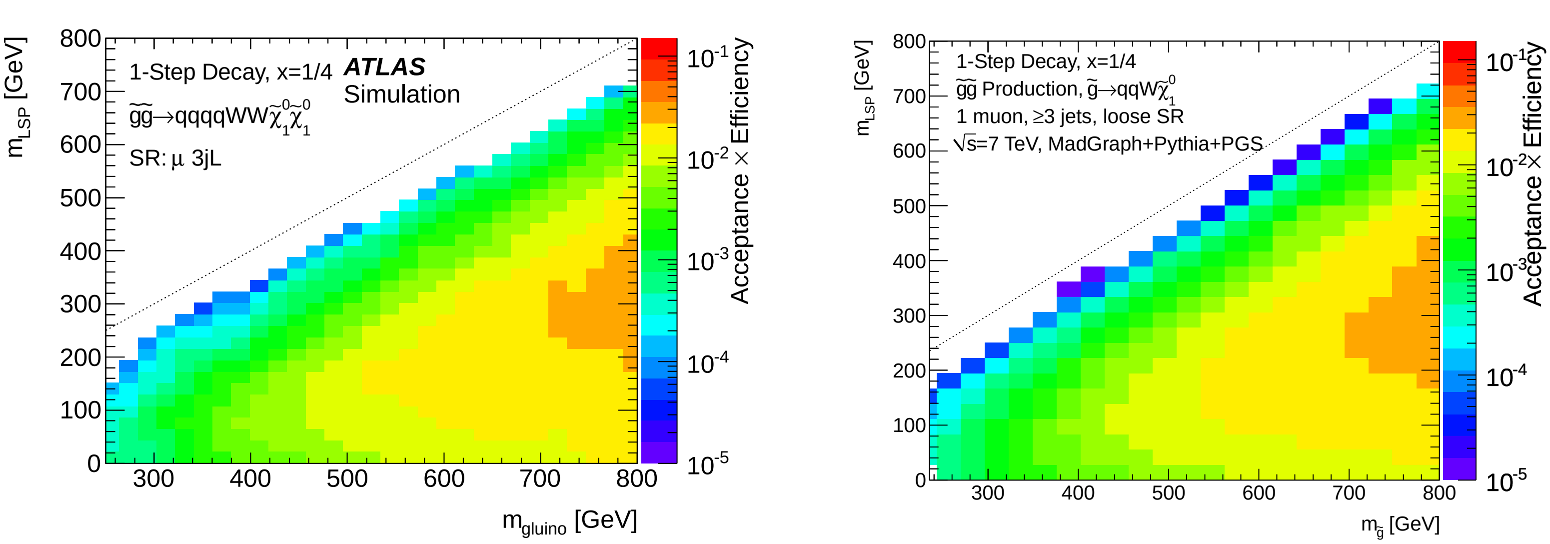

*Figure 2

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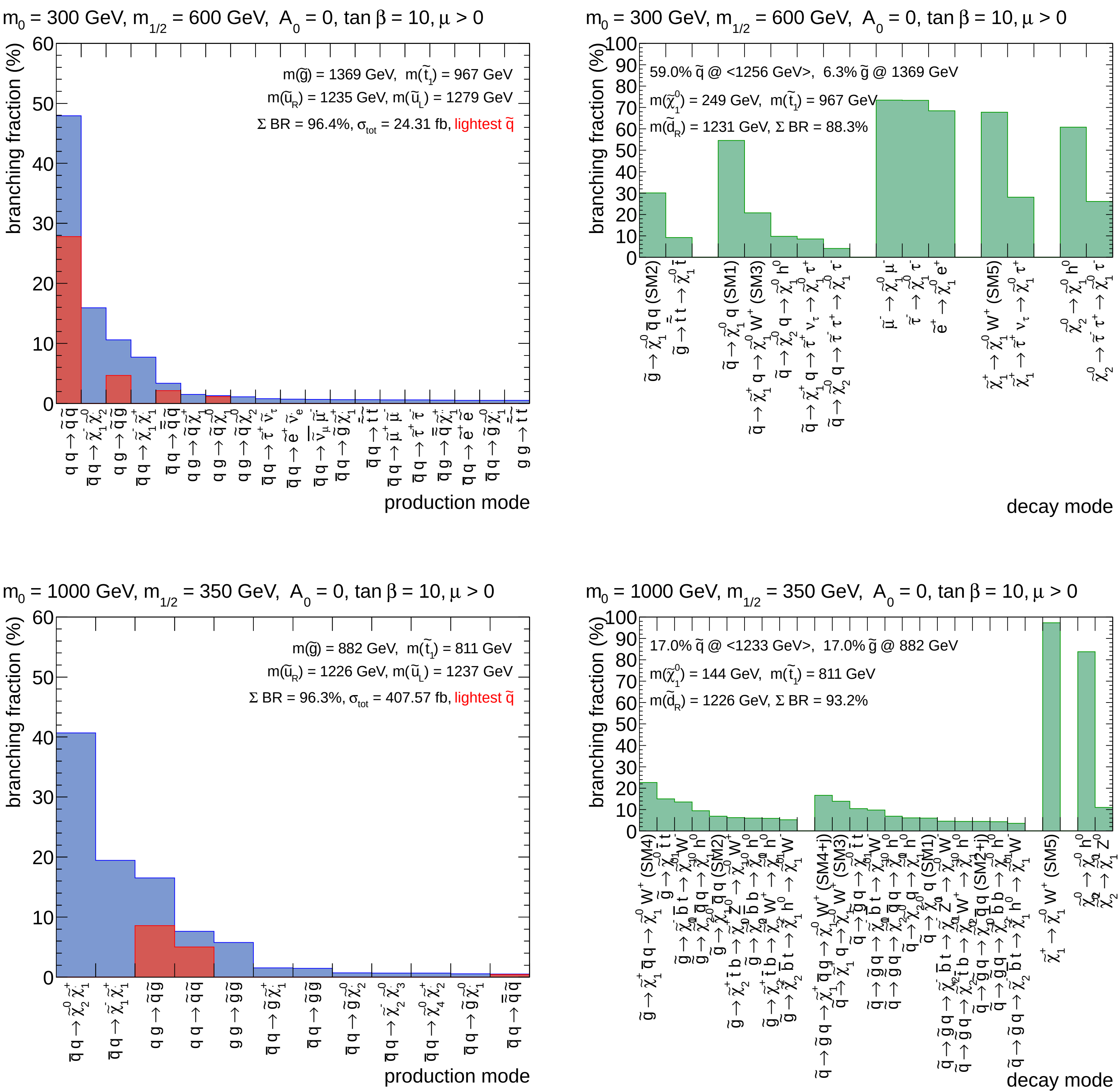

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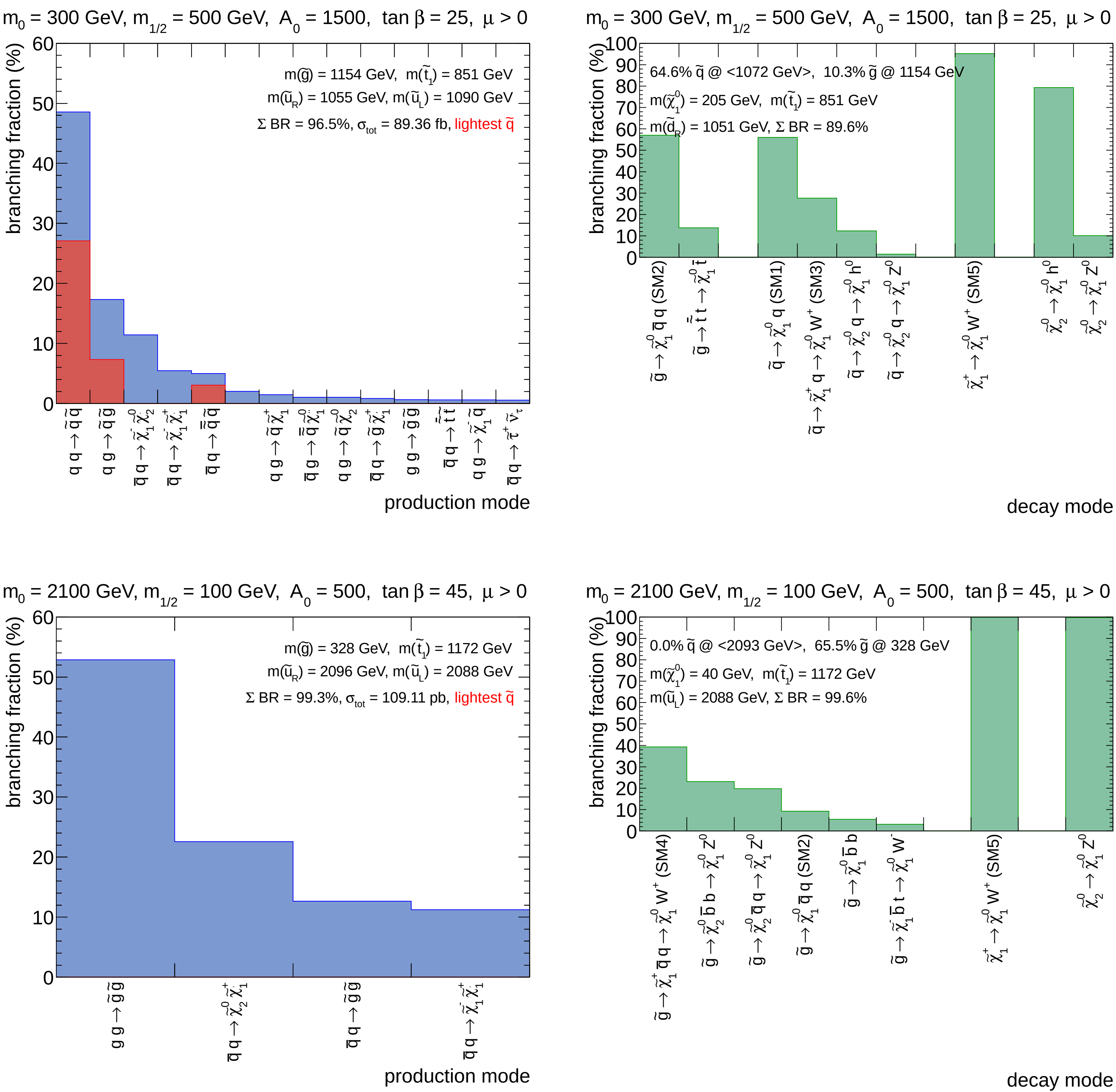

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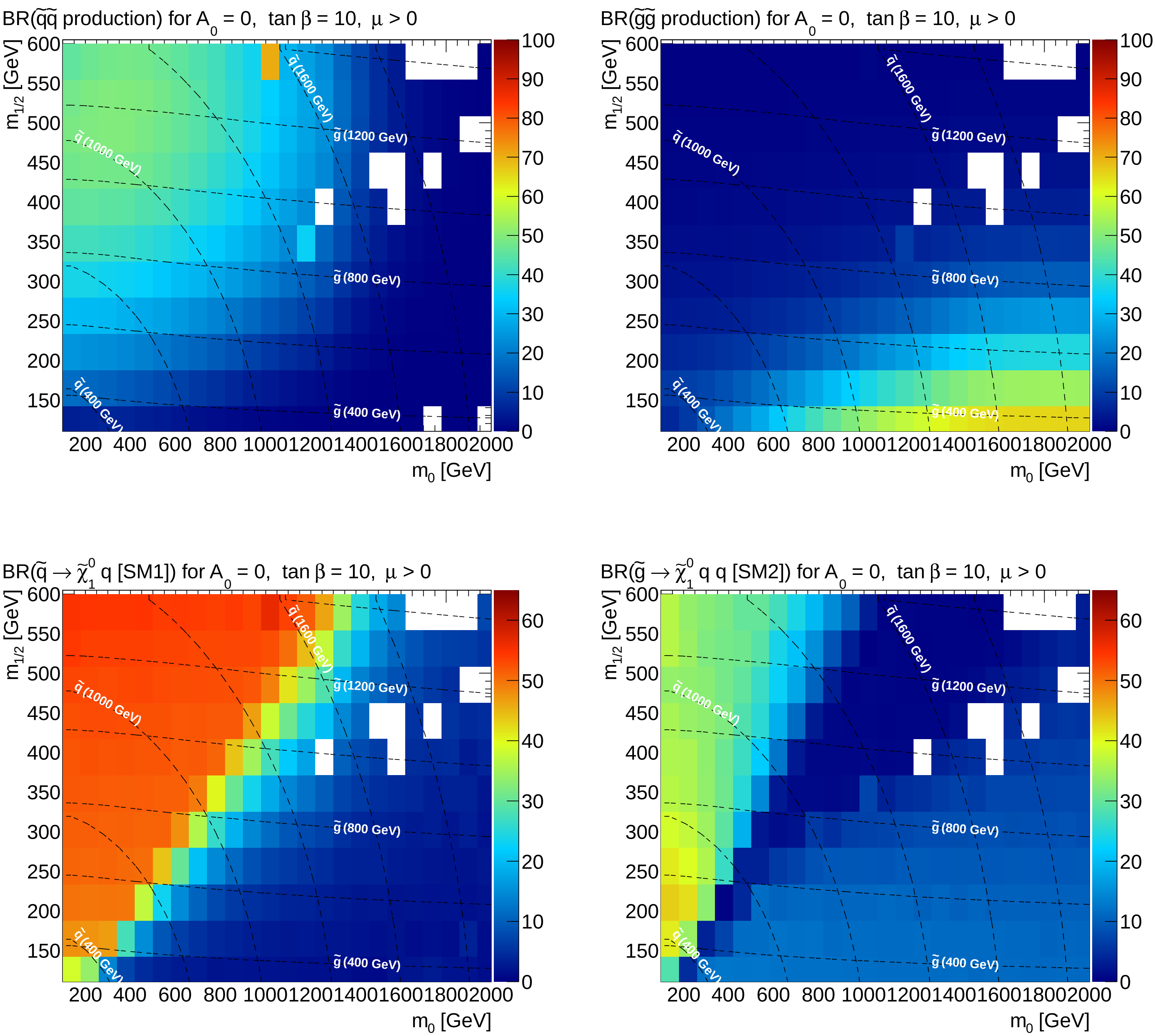

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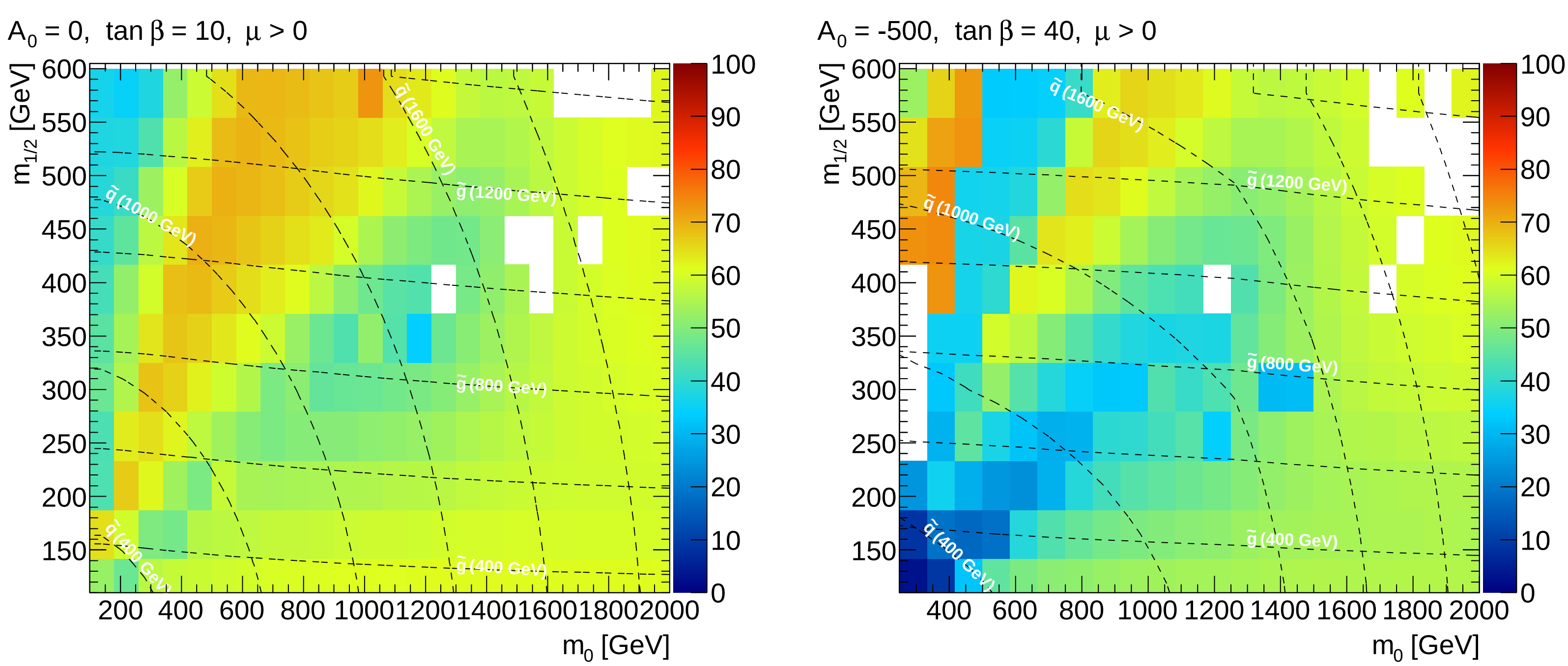

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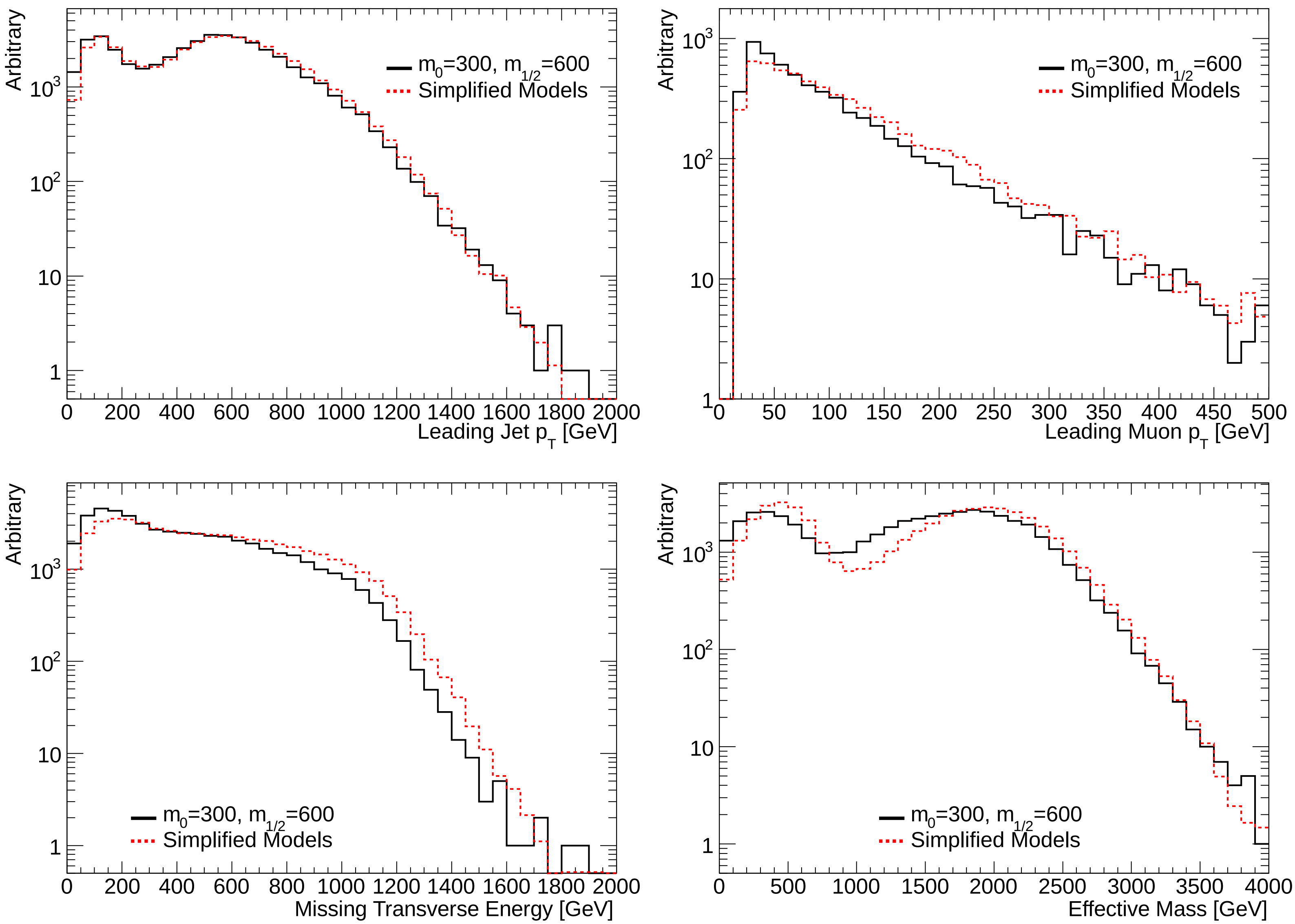

*Figure 7

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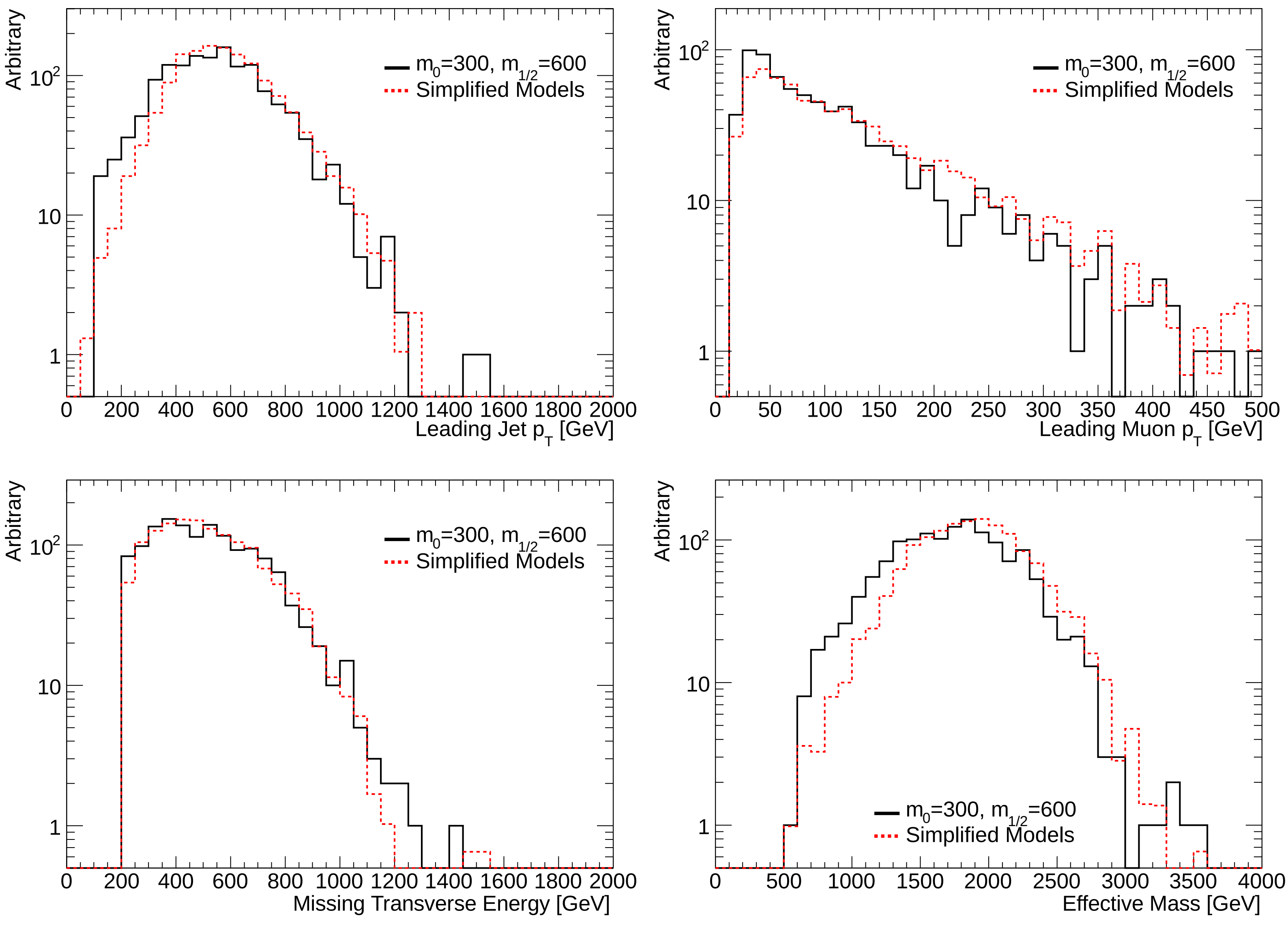

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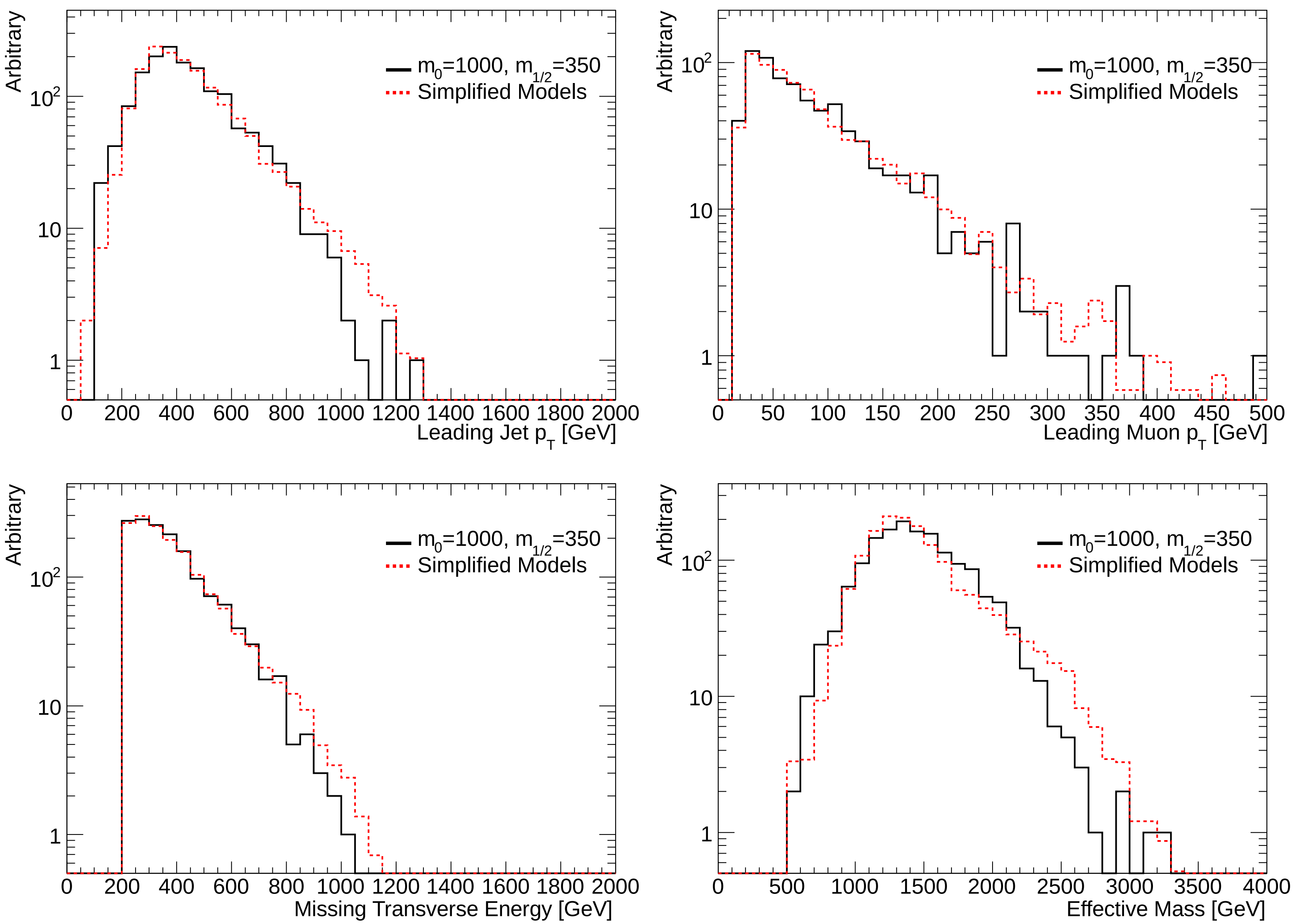

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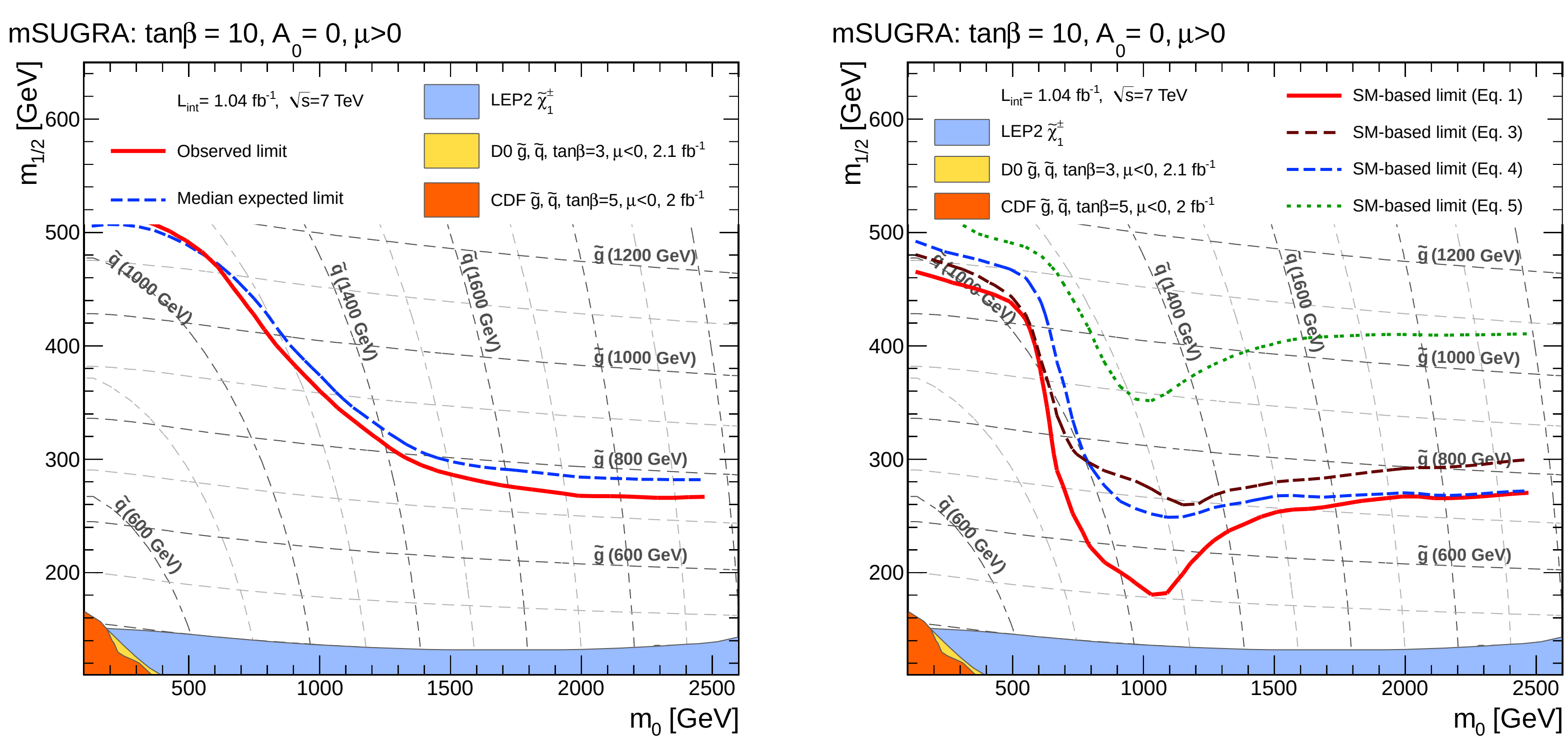

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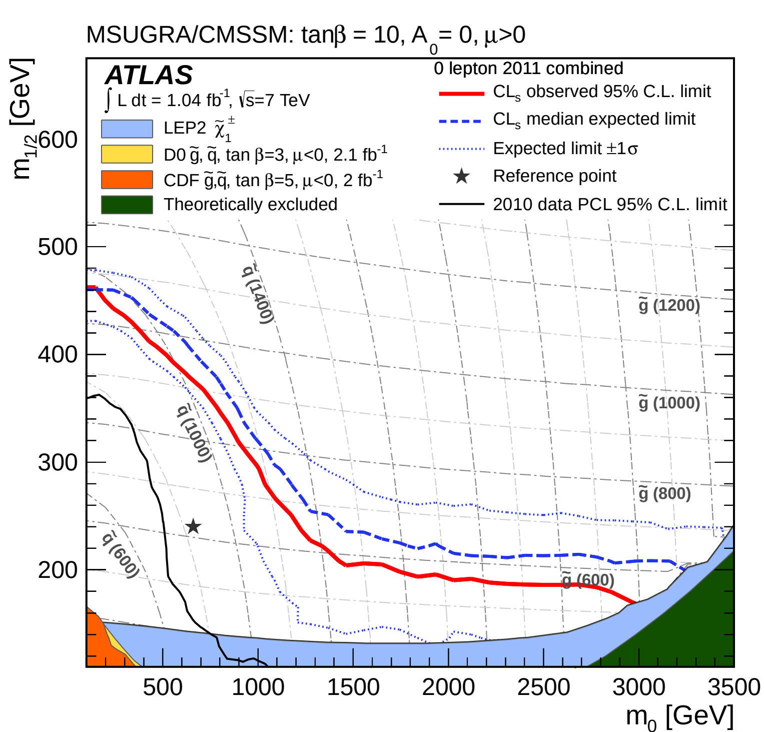

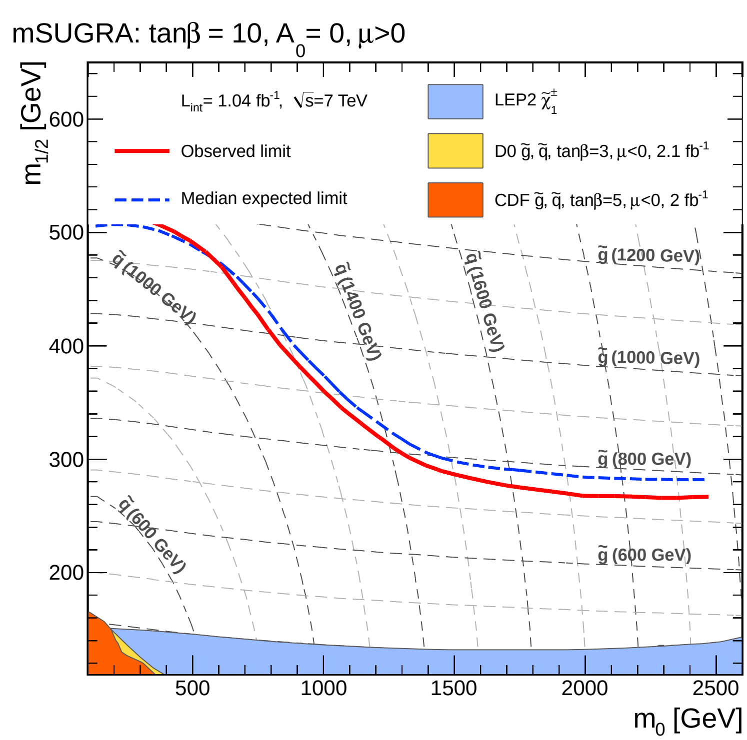

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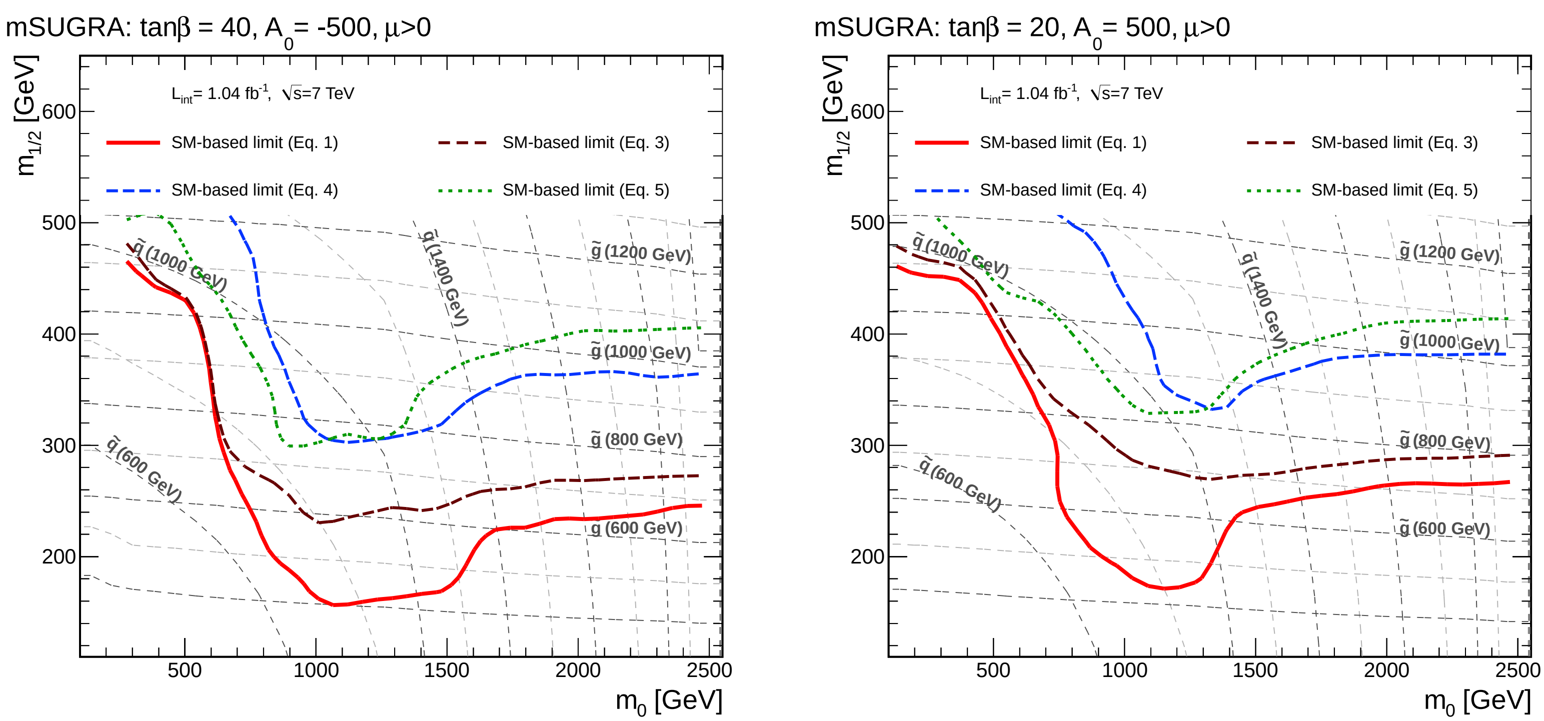

*Table of Reagents/ Materials Used
Click here to download Excel Spreadsheet- Table of Materials/Equipment: JoVE_Materials.xlsx

Name of Reagent/Material	Company	Catalog Number	Comments

This piece of the submission is being sent via mail.

Hello,

Please find attached a new draft of the paper wherein we've tried to implement all your requests. The equation formatting looks ok, except that there are a number of cases of tan beta when it should read tan(beta) (as it does elsewhere) and GeV is sometimes in the equation box and other times not. We each had a go at fixing those, but it seems neither of us have a version of word that's completely compatible with what you've got.

It looks like we're fine on the length of the protocol, so for now we've not highlighted anything.

A few replies where we thought it would be useful:

>>> 3)Several of your steps could use more detail to help viewers complete the protocol. When you use terms such as, "Generate" or "calculate" particularly, please answer the "how" question, i.e. is this step done through a computer program? What parameters are important?

Please have a peek at the document as it stands. If you like, we would be happy to add a note like: "In order to avoid obsolescence, this protocol only describes deviations from standard software settings. Complete documentation of the software described here can be found on the cited webpages."

I'm a bit worried that if we go into detail about the software we run the risk of the instructions being out of date quickly (already since writing the paper some of the software has undergone several major revisions including interface changes - but all the principles we describe hold, and nothing we've described at the moment is incorrect).

>>> 4)It appears that much of your protocol is computer work and complex calculations, could you please provide screen shots of any relevant computer programs to help our scriptwriters visualize each step of your protocol?

We're preparing these, but it will require a bit more time. I hope that we can proceed with any further draft modifications in parallel.

>>> 5)It may be helpful to write your protocol with a specific example in mind, i.e. could you pick a representative proton-proton collision event and complete all of the calculations with that event in mind? I apologize for my lack of familiarity in your field so I hope an example will be possible. If you do provide an example, you can then provide representative results using that example, i.e. show any relevant graphs or visualized metrics to help the viewer know what to expect from their results.

This is what we've tried to do, with a couple specific points that you see in Figures 5-7. I'd be happy to talk through the procedure a bit with you (by phone, by skype, by email, or how ever works best for you) to see if we can help you or any other members of the eventual editorial crew get a good handle on what we're doing - certainly I don't expect everyone to be intimately familiar with the details of high energy particle physics analyses.

Thanks,
Zach and Chris

Dear Reviewer,

Thank you for your thoughtful review of our paper. We've done our best to incorporate changes to address all of your comments in the newest draft of the paper. Please find below responses item-by-item, marked with ---> .

Cheers,
The authors

Reviewer #1:
Manuscript Summary:
The Manuscript outlines a technique for utilising Simplified Models in setting limits on searches for Supersymmetry at the Large Hadron Collider experiments.
Such a technique could find a wide range of use cases and may therefore prove to be a highly cited work of importance to this area of experimental particle physics.
Simplified Models are a widely used technique to avoid bias in optimising searches based on a single signal topology and recasting such limits into a broader range of Supersymmetry signals is crucial to guide the phenomenology community. The most highly constraining and high-profile LHC supersymmetry searches have been used as examples demonstrating the authors knowledge of the key aspects of their work.

Major Concerns:
I have no major concerns with the publication of this work.

Minor Concerns:
Some of the type-setting on the draft received is a little odd, with values appearing in the body of the text that require roman symbols having large amounts of space around them. These are too numerous to point out individually but the reviewer assumes the journal and authors are happy with the solution they will come to.

---> We agree - this is an unfortunate feature of Microsoft Word, it seems, which latex handles much better (that is why the reviewer presumably is objecting)

line 41: "is" -> "are"

---> Done (sorry)

line 86, 87: What is done if the information about correlations of uncertainties is not available?

---> The signal region or analysis with the best expected limit is used. Amended the text.

line 97: The results are considered to be "sufficiently close". What does this mean numerically?

---> Within about 25%.   The production cross-section is steeply falling, so this results in limits that are close to those of the experiments.   Amended the text to note this.

Are there any areas where the results may not be valid. Could the authors comment further on specifics of where PGS may not be a good simulator of the ATLAS/CMS detector (perhaps with tau leptons, photons or b jets?) and what should be done in such circumstances.

---> The most significant problem is the tau fake rate.   The real efficiencies are close enough, and b-tagging is straightforward to emulate when the working point is given.   We have added a note on these issues.

line 144: MSSMCalc. The reference points to the same reference as for MadGraph. I'm not familiar with this calculator, does it come as standard with MG perhaps?

---> It does indeed.

Additional Comments to Authors:
Is it possible to add a comment on the approach the authors would take to extracting a simplified model exclusion from analysis using multi-parameter fits to define their exclusion limits.

---> In our view, the manner of presentation of these limits is under considerable flux in the field.   It remains to be seen whether experiments will shortly begin providing workspaces to theorists, or whether they will in fact supply more cut-and-count type signal region analyses for purposes like those described in this paper.   We therefore wish to avoid any speculation that might go too far in anticipating the outcome of these developments.

Dear Reviewer,

Thank you for your thoughtful review of our paper. We've done our best to incorporate changes to address all of your comments in the newest draft of the paper. Please find below responses item-by-item, marked with ---> .

Cheers,
The authors

Reviewer #2:
Manuscript Summary:
In this paper on the Setting limits on
supersymmetry using simplified models, the authors
use the simplified models approach to set limits on the minimal
supergravity model.
The paper is interesting and worth publishing
but there are some issues that should be resolved/answered
before I can finally recommend publication.

Major Concerns:
It looks like the authors define BR_(a->i) in Eq. 1 of the paper
based on what they show in Figs 1-2 . Given, for instance,
what they call SM2 (gl -> chi^0 qbar q) and taking
as a reference the benchmark point given in
Fig. 2d, it looks like they define:

BR_(SM2) = BR(gl->chi^0 qbar q)

BR(gl->chi^0 qbar q) + BR(gl->chi^+ qbar q) BR (chi^+ -> chi^0 W) + ...

In this way the signal is enhanced with respect to just take:

BR_(SM2) = BR(gl->chi^0 qbar q)

---> This is only done in Eq. 4 and 5, where we explicitly write the denominator. In the first three equations, we do not normalize to the list of simplified models (as the equation indicates).

Actually this is the way in which the authors define the
branching fraction of a simplified model.

---> Defining the branching fraction this way is equivalent to making the assumption that the kinematics of the non-described decays are the same as the (weighted) kinematics of the described decays. This is indeed one of the assumptions that we explore, but it is not an assumption made in either of the first three limit configurations (which are more conservative, as can be seen from the final limits).

This way could solve the expected problem of obtaining a low signal in the large m0 region where one has many more 3 body decays of gluinos that the considered at the level of simplified models. I consider this somehow artificial since essentially by doing like that, the authors are simply saying that the gluino only decays through the processes one has simulated, which may well define a reasonable model, but one is no more in mSUGRA.

---> We agree that doing this for all limit equations would have been artificial.

Of course one may also argue that the different decays at the end of the day have similar topologies, but this is a bit stretched.
Could the authors justify this approach and comment about its applicability to models beyond the minimal supergravity scenario ?

---> Indeed, this is one of the points of the kinematic comparison that we describe later in the paper and show in Figures 6-8. If these kinematic comparisons look reasonable, then one can be much more confident in this assumption. This is discussed further in the example application section of the paper.

The authors include in the analysis the pair production of charginos but I don't understand why they have not considered the production of the second lightest neutralino as well since it has similar mass to the lightest chargino when it is wino-like which happens in a large portion of the mSUGRA parameter space.
Could the authors clarify this ?

---> The primary reason is that the analyses included in this study were 0- and 1-lepton searches for SUSY, and the neutralino decay to the LSP typically happens through a Z when it is Wino-like as you say. Generally these decays produce either two leptons (in which case they are selected by neither analysis at very high efficiency) or no leptons (in which case they are selected by the zero-lepton analysis but at a rate much lower than and with kinematics much less favorable than strong production). We therefore decided that this was not a mode that was of significant concern in modeling the events in the signal regions - and indeed, even the chargino production does not enter the signal region significantly.

---> We certainly agree that if someone wishes to include electroweak searches, both chargino and neutralino production simplified models should be included in their "dictionary".

Minor Concerns:
There is a typo in page 9, third paragraph:

m_squark-/m_gluino - m_LSP -> m_squark/m_gluino - m_LSP

---> Fixed

Dear Reviewer,

Thank you for your thoughtful review of our paper. We've done our best to incorporate changes to address all of your comments in the newest draft of the paper. Please find below responses item-by-item, marked with ---> .

Cheers,
The authors

Reviewer #3:
Manuscript Summary:
The authors describe a technique to use "simplified models" to set limits on a new physics model. MSUGRA is used as a test case and the limits calculated by the method are compared against the limits published for this particular model.

Major Concerns:
-> something has gone in the production of the pdf provided to the reviewer: the numbers of the figures do not match the content of the caption (or their reference) with the exception of Figures 10 and 11. This makes it extremely hard to understand the paper.

---> We agree and apologize. These appear to be relics of the difference between the formats the authors are familiar with and the journal requires. We have tried to repair these.

-> There are several assumptions on epsilon*A (e.g. L103, L112, L117). This should be quantified (=proven) as the authors have the machinery at hand to do so.

---> This is indeed what the "example application" attempts to do. We prefer not to anticipate the discussion too much.

-> L103: deducing associated production A*eps from the "pair production" models should be quantified. While a common i ensures that the final state looks similar, what about the production? In particular: if the SMs have s-channels, an associated production could have a t channel contribution which could change kinematics as function of the mass of the a and b particle.

---> Again, we believe that the example application follows these through, and we hope that it becomes more clear how the different assumptions affect the limits when looking at this concrete example.

-> The train from Eq.1 to Eq.5 is very hard to follow. While Eq.1 looks ok, Eq.5 seems hard to understand.

---> The trend is meant to be towards increasingly bold assumptions about the acceptance and efficiency of the models, and thus towards increasingly aggressive limits.   Of course we agree with you that at some point the limits become too aggressive and over-estimate the actual limit set by the analyses.   This is what is shown in the final section, in fact: that the most aggressive set of assumptions is too aggressive, that the most conservative is too conservative, and that the truth lies somewhere in between.

Example: there is only 1 SM: in that case the fourth factor would reduce to one, even if the production fraction of the SM is 10%. Further assuming BR=100% for simplicity, Eq. 1 and Eq 5 would differ by a factor 0.1.
Eq 1: sigma *L*A*eps *Paa
Eq 2: sigma *L*A*eps * Paa/Paa * 1/1
so something in the meaning of the indices or the sums is not clear: L80 defines sigma_tot as the NPM cross section, so if there is only a single SM which corresponds to 10% of the total cross section, Eq.5 does not seem to be correct.
L110 is also very confusing.

---> By the time Equation 5 is applied, the limit produced is likely somewhat too aggressive (confirmed later in the limit figures).   As you point out, in simple cases the limit set by equation 1 and equation 5 differ significantly - the effect is that the limit set by equation 1 makes very few assumptions about the mapping of acceptance and efficiency of simplified models to other events, and equation 5 assumes that all events in your BSM model are well represented by what ever simplified models you have chosen.   For a small list of simplified models and a complex theory, this assumption breaks down, as you point out.   However, what we've found is that a surprisingly small list of simplified models are able to represent a fairly diverse range of BSM models - one does not in fact need to create an infinite (or even very long) list.   This is why we attempt to provide guidance in choosing the dictionary of simplified models that one should begin with: without an appropriate choice, the limit given by equations 1 and 5 are dramatically different, which itself is an indication that the dictionary of simplified models chosen is inappropriate.

---> These are certainly not simply a re-writing of the same equation - they each represent different assumptions about how well the acceptance and efficiency of the simplified model events represent the acceptance and efficiency of the full SUSY (or BSM) model.

---> If you have any concrete suggestions for how we might make this more clear, we would welcome them!

-> L174: justify the 50%.

---> Done.

Minor Concerns:

The abstract needs to be revisited:
-> why are simplified models more phenomenological, when they in fact correspond to arbitrary choices on branching ratios?

---> One of the beauties of simplified models, we think, is that they correspond to no choice of branching ratio. We often see lines drawn on them that correspond to arbitrary choices, it is true, but the most important part of the limit is the excluded cross-section at any given point, which should be applicable to almost any model with the right mass spectrum (with some caveats about the manner in which the limit is set).

-> what is meant by "clearer physical implications"? The MSUGRA is well defined and has a clear physical implication for the calculation of masses, branching ratios etc. What is the added value of a simplified model?

---> We have changed "implications" to "interpretations." Too often one hears a person explain that "CMS has excluded gluinos below 1000 GeV" by looking at a plot of MSUGRA, when in fact this corresponds (as you say!) to a very specific set of masses and branching fractions. That is often a best case - too often we see a plot of MSUGRA against m0 and m1/2, two GUT scale parameters from which physically observable parameters must be derived. In the case of simplified models, on the other hand, an upper cross section limit (these are the limits of simplified models, as we've mentioned above, not the lines on the excluded cross section plots, which we agree are not terribly physical) does correspond to a generic limit on a mass times branching fraction. The limits are also presented in terms of physical masses and branching fractions, which we believe is a significant step forward from MSUGRA.

-> "direct searches" would imply dedicated analyses for MSUGRA parameter sets/points. Or do the authors rather mean "limits calculated by ATLAS/CMS"?

---> We agree this was unclear. We have changed it to read "that have not yet been examined by the LHC experiments," which we think was closer to what we meant.

-> L41 "any" is the statement also true for the production of sleptons?

---> As it appears that ATLAS and CMS now include simplified models with sleptons as well, we are pleased to be able to say "yes."

-> L62: constituent could be defined here.

---> Done

-> L203: Discrepancies..... is that true independent of the mass of the new particle? when approaching the kinematical limit due to the PDF of the proton, isn't the dependence sharper than far away?

---> In fact the limits on almost all new physics models do not approach the kinematic limit of the LHC from PDFs. They tend, even after the latest run, to be down by more than a factor of two, and sometimes more. It is partially the PDF that contributes to making the cross-section rapidly falling - but as the cross section falls more steeply against mass, 15% variations in acceptance matter less.

---> In an extreme case, imagine a very hard cut off at 4 TeV. Say also, for example, that the cross section falls by an order of magnitude between 3.99 TeV and 4 TeV. Then a 15% error on acceptance times efficiency, which will likely lead to a roughly 15% error in excluded cross-section times branching fraction, will only impact the limit on the level of 1 GeV. The faster the cross section falls, the less a 10-15% error on acceptance times efficiency will matter when mass limits are the figure of merit.

-> There are white squares in some of the figures of R(sq sq) plane?

---> These models had no events described by simplified models, up to the Monte Carlo statistics that we produced for this particular grid. We have noted this in the caption.

L294: "indication": shouldn't you be able to know this fraction from your Madgraph+PGS machinery?

---> Indeed - and it is high. We've changed this to "confirmation".

L334: "unnecessary": This is quite a strong statement. I would have thought that when mchargino gets close to mLSP, the efficiency will vary strongly. Which points have been simulated with PGS to analyze the dependence?

---> We agree, of course, that the efficiency varies strongly. The point is that as the chargino gets very close to the LSP, decay chains prefer to not include the chargino and jump straight to the LSP - particularly those decay chains that are being selected by the LHC analyses. That is why we say they are unnecessary.

Additional Comments to Authors:
N/A