SModelS extension with the CMS supersymmetry search results from Run 2

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Abstract

We present the update of the SModelS database with the simplified model results from CMS searches for supersymmetry at Run 2 with 36 fb⁻¹ of data. The constraining power of these new results is compared to that of the 8 TeV results within the context of a full model, the pMSSM. The new database, v1.1.2, is publicly available and can readily be employed for physics studies with SModelS.

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Simplified models [1, 2, 3, 4, 5] have become one of the standard methods for ATLAS and CMS to optimise analyses for specific signatures, compare the reach, and communicate the results of their searches for new particles. When simplified model results are provided in terms of cross section upper limits or efficiency maps, they can readily be re-used to constrain arbitrary beyond-the-standard-model (BSM) theories in which the same final state occurs, as long as differences in the event kinematics (e.g., from different production mechanisms or from the spin of the BSM particle) do not significantly affect the signal acceptance of the experimental analysis. This is precisely the idea behind SModelS [6, 7].

SModelS is a public tool which allows to exploit the plethora of constraints on simplified model spectra (SMS) from ATLAS and CMS searches for supersymmetry (SUSY) in an automated way. The principle of SModelS, in the current version 1.1, is to decompose BSM collider signatures featuring a $Z_2$ symmetry into simplified model topologies, using a generic procedure where each SMS is defined by the vertex structure and the SM final state particles; BSM particles are described only by their masses, production cross sections and branching ratios.

The working principle is illustrated in Fig. 1. The SModelS code and database are publicly available on GitHub at https://github.com/SModelS/ or on the SModelS wiki page, http://smodels.hephy.at/

The previous database version [3] (v1.1.1) was comprised of 186 results (125 upper limits and 61 efficiency maps) from 21 ATLAS and 23 CMS SUSY searches, covering a total of 37 simplified models. From these 44 searches, the vast majority were based on Run 1 data. Only 11 (4 from ATLAS and 7 from CMS) were based on early 13 TeV Run 2 data with 2–13 fb⁻¹ of integrated luminosity; most of these were preliminary results from ATLAS conference notes or CMS public analysis summaries.

In this note we now present the implementation of the Run 2 SUSY search results from CMS with 36 fb⁻¹, presented at the Moriond and the summer (LHCP and EPS) conferences of 2017. This extends the SModelS database by 84 new cross section upper limit (UL) maps from 19 different analyses. We give an overview which results have been included, show their validation in SModelS, and demonstrate their constraining power for the phenomenological Minimal Supersymmetric Standard Model (pMSSM) as compared to the 8 TeV data.

The v1.1.2 database presented here includes results from 19 CMS SUSY analyses from Run 2 with 36 fb⁻¹ of data, comprising in total 84 new SMS results for the full 2016 dataset. A detailed list is given in Table 1.

All these new CMS results are upper limit maps: they give the 95% confidence level (CL) upper limit values on $\sigma \times BR$ for a particular SMS as a function of the relevant parameters, usually the SUSY particle masses or slices over mass planes. They are derived from the colour maps in the simplified model limit plots of the experimental papers, which CMS systematically provides in numerical form, typically as

FIGURE 1: Schematic view of the working principle of SModelS.
**TABLE 1**: CMS 13 TeV results for 36 fb$^{-1}$ included in this SModelS database update. The last column lists the specific SMS results included, using the shorthand “txname” notation (see text for details). For brevity, only the on-shell results are listed, although the off-shell ones are always also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff). The superscript † denotes SMS with three mass parameters, for which only one mass plane is available; we also included (e.g., T1tttt in the table effectively means T1tttt and T1ttttoff).

ROOT files on the analyses’ wiki pages\footnote{Alternatively, SModelSv.1.1 can also use efficiency maps \footnote{Efficiency maps (EMs) have the advantage that contributions from different topologies to the same signal region can be combined.}}. Each included map is thoroughly validated to make sure it reproduces the limits reported in the experimental publication. Figure\footnote{Efficiency maps (EMs) have the advantage that contributions from different topologies to the same signal region can be combined.} shows some examples of validation plots; the full set is available online at http://smodels.hephy.at/wiki/Validation\footnote{Efficiency maps (EMs) have the advantage that contributions from different topologies to the same signal region can be combined.}.

We note that a few results in Table \ref{tab:results} are from CMS PASes, i.e. they are preliminary results; these will be updated to the final published results in a future release.

Inside SModelS, individual SMS results are identified by the analysis ID and the txname (see right-most column in Table \ref{tab:results}). which describes in a shorthand notation the hypothesis of SUSY process used to derive the UL map. The txnames largely follow the notation introduced in \cite{5}. For instance, ’T1’ topologies stand for gluino-pair production followed by 3-body gluino decay into the lightest SUSY particle (LSP), usually the $\tilde{\chi}^0_1$, hence:

1. $\mathrm{T1: } pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}^0_1$,
2. $\mathrm{T1bbbt: } pp \rightarrow \tilde{q}\tilde{q}, \tilde{g} \rightarrow b\tilde{\chi}^0_1$,
3. $\mathrm{T1tttt: } pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{\chi}^0_1$,

T1bbbt would mean one gluino decays into $b\tilde{\chi}^0_1$ and the other one into $t\tilde{\chi}^0_1$, but results for such asymmetric topologies are currently not available. ‘T’ also stands for gluino-pair production but with the decay proceeding via an intermediate on-shell SUSY particle (for example T5tttt: $pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow h_1, t_1 \rightarrow \tilde{\chi}^0_1$). Along the same lines, ‘T2’ and ’T6’ denote squark pair production followed by, respectively, direct or cascade decay into the LSP (e.g., T2tt: $pp \rightarrow \tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}^0_1, \tilde{g}\tilde{g}$, T6bbWW: $pp \rightarrow \tilde{b}\tilde{b}, \tilde{b} \rightarrow b\tilde{\chi}^0_1, \tilde{g}\tilde{g}$, T6WZ: $pp \rightarrow \tilde{b}\tilde{b}, \tilde{b} \rightarrow b\tilde{\chi}^0_1, \tilde{g}\tilde{g}$). A complete list of txnames and the corresponding diagrams can be consulted at http://smodels.hephy.at/wiki/SmsDictionary.

We note also that, whenever relevant, the experimental results for topologies with top quarks and/or massive gauge bosons are split into several UL maps according to different kinematic regions where the tops, Ws or Zs are on-shell or off-shell. For example, an experimental result for $pp \rightarrow \tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}^0_1$ will have two UL maps in SMODELS, one called T2tt covering the region where the $\Delta m = m_t - m_{\tilde{\chi}^0_1} \leq m_\tau - 2\Gamma_t$, $\Gamma_t$ being the top total width, and one called T2tttoff covering $m_W < \Delta m < m_t - 2\Gamma_t$. The reason is that for T2tt the final state to be constrained is $2\ell + E_T^{\text{miss}}$ while for T2tttoff it is $2\ell2W + E_T^{\text{miss}}$. (Below $\Delta m = m_W$, one enters a different regime of stop 4-body or loop decays.) The $2\ell2W + E_T^{\text{miss}}$ final state also
arises from stop decays via a chargino, $\tilde{t} \rightarrow b\tilde{\chi}^+_1 \rightarrow bW^+\tilde{\chi}^0_1$, but this has a different topology (vertex structure) and corresponds to a distinct simplified model (TobbWW). For conciseness, the “off” maps are not listed in Table 1, with the exception of PAS-SUS-16-052, which has only UL maps for compressed spectra whereWs are always off-shell.

In total, the 84 new results in the v1.1.2 database cover 25 distinct topologies (35 when counting on- and off-shell versions separately). As can also be seen in Table 1, several analyses have SMS interpretations for the same topologies (txnames). For instance, upper limits for $pp \rightarrow gg, g \rightarrow t\bar{t}X^0_1$ (T1tttt) are provided in seven of the eight searches for gluinos. Likewise, the different stop searches in the 0, 1, and 2 leptons channels all give upper limits for $pp \rightarrow t_1\bar{t}_1, t_1 \rightarrow t\bar{t}X^0_1$ (T2tt) and $pp \rightarrow t_1\bar{t}_1, \tilde{t}_1 \rightarrow b\tilde{\chi}^+_1 \rightarrow bW^+\tilde{\chi}^0_1$ (TobbWW). In principle it would be possible to compile, for each topology, the limits from different analyses into one single map, using only the strongest constraint in each mass bin. Instead, we have chosen to include all the individual results which are provided by the experimental collaboration. This makes the database larger and the evaluation slightly slower, but has the advantage of more flexibility. For instance it allows to compare the constraining power of different analyses for the same signal. When speed is a limiting factor, knowledgeable users can build a slimmer-down pickle file, applying only the subset of analyses which give the strongest constraints; see the SMo[Model$S$] v1.1 manual [8] for more details.

There is a further reason for including all individual SMS results: when using SMo[Model$S$] to constrain non-SUSY scenarios, it is possible that, depending on the selection cuts in the analyses, some SMS results do not apply. Such results should then be disregarded. Generally, the validity of the SMS assumptions depends on the concrete model under consideration, as well as details of the experimental search. It is the responsibility of the user to verify this case by case when testing new theories. In practice this means verifying that the signal acceptance as function of the BSM masses is approximately the same for the new model as for the model assumed in the experimental paper. This can be done by explicitly recasting the experimental analysis for a few benchmark points and/or by comparing the relevant kinematic distributions in the new theory and the model which underlies the SMS result.

To assess the impact of these new 13 TeV results in a general manner, we make use of the extensive scan of the pMSSM [28] with 19 free parameters from the ATLAS pMSSM study [29] (see also [30, 31, 52, 33]). The ATLAS collaboration made the whole scan, in total more than 310k parameter points with SUSY masses up to 4 TeV, publicly available on HepData [34]. These points were classified into three sets according to the nature of the LSP: bino-like (103,410 points), wino-like (80,233 points) and higgsino-like (126,684 points). They all have $m_{\tilde{t}_0} = [124, 128]$ GeV and satisfy constraints from SUSY searches at LEP and the Tevatron, flavor and electroweak precision measurements, cold dark matter relic density and direct dark matter searches. We remove from this dataset the points which contain long lived charged sparticles ($c\tau > 1$ mm), which cannot be treated in the official
SMModelS version. This has only a small effect on the bino-like and higgsino-like LSP sets (99,492 and 123,498 points remaining, respectively) but removes most of the wino-like LSP points (only 8,772 points remaining).

For this dataset, we analyse how the SMModelS exclusion improves with the new 13 TeV results as compared to the 8 TeV results. As a first overview, we list in Table 2 the total number of points studied, the number of points that can be excluded by SMModelS when using only the 8 TeV results in the database, and the number of points that can be excluded when using the full 8 TeV + 13 TeV database. As one can see, the gain is quite substantial, between a factor of 2 for the higgsino-like LSP dataset and a factor of 2.7 for the bino-like dataset.

The impact on the gluino, average squark, stop and sbottom masses is illustrated in Fig. 3. We see that gluinos with masses below 1 (1.5) TeV are now much better constrained, with only about 11% (22%) of points escaping exclusion by simplified model results in this mass range. Likewise, the SMS constraints are severely closing in on stops, sbottoms and light-flavor squarks, with around 70% of points with at least one squark below 1 TeV being excluded. Also interesting is the impact on the LSP mass, shown in Fig. 4. The 8 TeV results eliminate about 54% of the pMSSM points with LSP masses below about 100 GeV, but show a steep drop in constraining power for heavier $\tilde{\chi}_1^0$. The new 13 TeV results, on the other hand, provide strong constraints for $\tilde{\chi}_1^0$ masses up to about 600 GeV, excluding 64% of the pMSSM points in this range and more than 75% of the points with $m_{\tilde{\chi}_1^0} \lesssim 100$ GeV.

To address the question which signal topologies are most relevant for the improved constraints, Fig. 5 provides a breakdown by txnames as a function of the gluino mass. For each point excluded at 13 TeV, but not at 8 TeV, we take the txname with the highest $r$-value ($r = c_{\text{SMS}}/c_{\text{UL}}$) and then show the

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**TABLE 2:** Summary of results, listing the total number of points tested from the ATLAS pMSSM scan (without long-lived charged particles), the number of points excluded by SMModelS using only the 8 TeV database and the number of points excluded when using the full database with 8 TeV and 13 TeV results.

|                        | Bino-like LSP | Higgsino-like LSP | Wino-like LSP |
|------------------------|--------------|-------------------|--------------|
| Total number of points | 99,492       | 123,498           | 8,772        |
| # points excluded – 8 TeV results only | 23,253 | 32,219 | 1,389 |
| # points excuded – full database | 62,159 | 65,768 | 3,212 |

**FIGURE 3:** Fraction of points excluded by SMModelS for the ATLAS pMSSM scan as a function of gluino, average squark, stop and sbottom mass. Only the points without long-lived charged particles were considered. The blue histogram shows the fraction of excluded points using only the 8 TeV database, while the red histogram shows the increase of excluded points once the 13 TeV database is included.
For the standard installation, it suffices to put this tarball into the main smodels folder and explode it there. That is, the following steps need to be performed

```
mv smodels-database-v1.1.2.tar.gz <smodels folder>
```
```
cd <smodels folder>
tar -xzvf smodels-database-v1.1.2.tar.gz
```
```
rm smodels-database-v1.1.2.tar.gz
```

The v1.1.2 database will be unpacked into the smodels-database directory, replacing the previous version and the pickle file will then be automatically rebuilt on the next run of SModelS. For a clean installation, it is recommended to first remove the previous database version. If the tarball is unpacked to another location, one has to correctly set the SModelS database path when running SModelS. If using runSModelS.py, this is done in the parameters.ini file.

Alternatively, the database can also be obtained from the https://github.com/SModelS/smodels-database-release repository.

We presented the update of the SModelS database with the simplified model cross section upper limits from 19 CMS SUSY analyses from Run 2 with 36 fb⁻¹ of data. These results significantly improve previously available constraints. Using the pMSSM as a showcase for a realistic model, we demonstrated how the limits on various SUSY masses are pushed to higher values by the 13 TeV results as compared to 8 TeV results. The improved constraints affect not only the masses of colored sparticles—particularly noticeable are the much stronger constraints on LSP masses up to about 600 GeV. All in all, the number of points from the ATLAS pMSSM scan [29] which can be excluded by SModelS increases by a factor 2.3 as compared to the 8 TeV results.

The v1.1.2 database is publicly available and can readily be used in SModelS to constrain arbitrary BSM models which have a $Z_2$ symmetry, provided the SMS assumptions [6, 8] apply. The simplified model results from ATLAS searches for 36 fb⁻¹ at 13 TeV available on HEPData will be included as soon as possible.

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A couple of results from the CMS publications listed in Table 1 have not been implemented in the v1.1.2 database, because they cannot be re-used well in SModelS. This is notably
the case for SMS results with mixed decay modes, where different intermediate \( Z_2 \)-odd particles and/or different final states are summed over. They pose constraints on a very specific sum of topologies, which is not applicable to the general case. Examples are:

- Fig. 12d in SUS-16-033 and Fig. 5b in SUS-16-041: these are constraints on gluino-pair production followed by \( \tilde{g} \rightarrow q\tilde{q}_{1}^{\pm} \rightarrow qW\tilde{\chi}_{1}^{0} \) and \( \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{2}^{0} \rightarrow q\bar{q}Z\tilde{\chi}_{1}^{0} \) decays with 50% branching ratio each. CMS treats this as a T5VV \((V=W, Z)\) topology. For SModelS, however, this results represents an UL map for the weighted sum of three topologies, 25% T5WW + 25% T5ZZ + 50% T5WZ.

- Fig. 8b in SUS-16-036, Fig. 9 in SUS-16-049 and Fig. 7 in SUS-16-051: these are limits on stop-pair production for \( \text{BR}(\tilde{t} \rightarrow \tilde{b}_{\text{R}}\tilde{\chi}_{1}^{\pm}) = \text{BR}(\tilde{t} \rightarrow \tilde{t}_{\text{L}}\tilde{\chi}_{1}^{0}) = 0.5 \). As in the bullet item above, the UL applies to the weighted sum of three topologies, 25% T2tt + 25% T2bb + 50% T2tb;

- The T5Wg results in SUS-16-046 and SUS-16-047: these are actually a sum over T5WW, T5gg and T5Wg for a given branching ratio;

As discussed in [35], results for asymmetric topologies, arising from two different decays happening on the two branches of the topology diagram, would be very useful to improve the constraining power of SMS results. In principle one could try to interpolate between the UL maps for the symmetric topologies with 100% BR and the ones for 50% BRs including the mixed topologies. This would add a level of complication in the matching with the decomposition procedure, which is the most time-consuming part of the calculation. Moreover, the validation of such a procedure would require full recasting, as there are no official results for intermediate BRs to compare to. Much better and simpler would be if efficiency maps for the individual symmetric and asymmetric topologies were available. This would allow to work out the limits for arbitrary branching ratios in a fast, reliable and robust way.

Another class of results which are not included are long cascade decays (with more than one intermediate particle) where intermediate masses are fixed and/or branching ratios summed over. An example is Fig. 10 of SUS-16-034. Here, pair-produced sbottoms decay via \( b_{1} \rightarrow b_{\text{L}}\tilde{\chi}_{2}^{0} \) followed by \( \tilde{\chi}_{2}^{0} \rightarrow l^{\pm}\bar{\nu}^{\pm} \rightarrow l^{\pm}l^{\mp}\bar{\nu}^{\mp} \) or \( \tilde{\chi}_{2}^{0} \rightarrow Z^{(\pm)}\tilde{\chi}_{1}^{0} \). From the SModelS point of view this is not a simplified model topology.

Finally, the results of a number of newer CMS publications or public analysis summaries are not included, because the ROOT files for the SMS limits are not yet available. This concerns the analyses SUS-16-048 [36] (2 soft leptons), SUS-17-003 [37] (hadronic staus), and the searches in leptonic final states presented at the SUSY 2017 conference SUSY-17-002 [38] and SUS-17-009 [39]. They will be added later when the relevant ROOT files are available.

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