The impact of the ATLAS zero-lepton, jets and missing momentum search on a CMSSM fit

B.C. Allanach, T.J. Khoo, C.G. Lester, S.L. Williams

Abstract: Recent ATLAS data significantly extend the exclusion limits for supersymmetric particles. We examine the impact of such data on global fits of the constrained minimal supersymmetric standard model (CMSSM) to indirect and cosmological data. We calculate the likelihood map of the ATLAS search, taking into account systematic errors on the signal and on the background. We validate our calculation against the ATLAS determination of 95% confidence level (C.L.) exclusion contours. A previous CMSSM global fit is then re-weighted by the likelihood map, which takes a bite at the high probability density region of the global fit, pushing scalar and gaugino masses up.

Keywords: Supersymmetric Phenomenology, Markov chain Monte Carlo, Large Hadron Collider
1 Introduction

Both ATLAS [1, 2] and CMS [3] have now conducted searches for supersymmetric particles with the 35 $fb^{-1}$ of $\sqrt{s} = 7$ TeV $pp$ collision data taken in 2010. All of these searches have involved missing energy and jets, though the chosen techniques use different search variables and make differing requirements on (for example) the number of isolated leptons in each event. None of these searches has found a significant signal over the expected Standard Model (SM) background, and so they have set limits on sparticle production. The most stringent limits come from the ATLAS papers [1, 2] each of which, independently, subsumes the CMS exclusion [3] within its own.\textsuperscript{1} Within the CMSSM [9–14], the strongest limit comes from the ATLAS “0-lepton” search [1] which excludes equal mass squarks and gluinos with masses below 775 GeV at 95% C.L. limits in the $A_0 = 0$, $\tan(\beta) = 3$, $\mu > 0$ slice of CMSSM. The equivalent limit from the ATLAS “1-lepton” paper [2] is 700 GeV, while the CMS exclusion reaches 600 GeV. Data taken in 2011 is expected to extend this reach, assuming lack of any signal, up to squark and gluino masses of around 1000 GeV [15].

It is the aim of this paper to assess the impact of the ATLAS 0-lepton results on the regions of the CMSSM favoured by indirect constraints and astrophysical data. We note that an earlier study [16] performed a similar update in response to the CMS results. In that study the likelihood function of the CMS exclusion was calculated by full Monte Carlo simulation of LHC collisions. We note also that in a later study, [17], informed guesses for

\textsuperscript{1}Since both the ATLAS and CMS searches use the same amount of data, it is reasonable to ask why the ATLAS reach is so much greater than that of CMS. The answer is that ATLAS and CMS used very different experimental techniques. The CMS search [3] was based on a single cut on a variable called $\alpha_T$ (along with cuts on the transverse hadronic momenta of jets). This variable is known to strongly suppress QCD backgrounds, but is not designed with specific kinematic properties in the supersymmetric (SUSY) signals in mind. The ATLAS collaboration based its search on four sets of cuts on two different variables (the effective mass, $m_{\text{eff}}$, [4, 5] and the transverse mass $m_{T2}$, [6–8]) which have properties tailored more specifically to the kinematic properties of $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{g}$ production.
the forms of the likelihood functions of the experiments (intended to be accurate in the vicinity of the CMS 95% exclusion contour) were used to update global frequentist fits to the CMSSM and other constrained models, with similar conclusions. An analysis of the ATLAS 1-lepton search result was also included in [17].

Here, we shall only consider the ATLAS 0-lepton result, since it is more constraining than the other previous search results mentioned above. A small amount of additional constraining power could, in principle, be obtained by including the results of the other searches, but at the cost of significant complication to our analysis.

Global fits allow a good fit in one observable to be traded for a somewhat poor fit in a different observable in a statistically balanced way. Fits to constrained SUSY models typically use the anomalous magnetic moment of the muon, the dark matter relic density, direct searches for supersymmetric particles and Higgs bosons, and electroweak observables to constrain simple SUSY models simultaneously [18–35]. Variations with respect to all of the parameters of the model that have an impact on the predictions of the observables, including Standard Model (SM) parameters, are taken into account. Various algorithmic tools have now been developed to allow such a sampling of a multi-dimensional parameter space, which may be multi-modal [36–38]. The lack of robustness of the results of such fits is illustrated by their large prior dependence [19, 22, 24, 27]. There are some predictions that are prior independent however, such as the prediction of the lightest CP even Higgs mass, even in a fit to a 25 parameter version of the minimal supersymmetric standard model (MSSM) [39]. This is not surprising, since LEP data provide a strong lower bound on the Higgs mass, and the model itself imposes a close and strict upper bound. Thus, the data are constraining enough themselves to dominate the prediction. Frequentist fits to edge measurements from hypothetical LHC SUSY edge measurements showed an incorrect confidence level (C.L.) coverage of frequentist fits when the C.L.s are calculated by assuming a $\chi^2$ distribution [40]. There are no published coverage studies of global SUSY fits and, since they are expected to be less robust than fits to an LHC SUSY signal, a coverage study of the frequentist fits is necessary and long overdue. A fit to a large volume string model with only two free parameters additional to the SM (the ratio of the Higgs vacuum expectation values, $\tan \beta$, and an overall supersymmetry breaking mass scale) did display approximate prior independence [41]. On the other hand, a fit to a model with three parameters additional to the SM (minimal anomaly mediated supersymmetry breaking) showed significant prior dependence [42]. Fits to models with more than three additional parameters have also (so far) shown a lack of robustness [28, 30, 39, 42].

Despite the lack of robustness of the global fits, we still find it interesting to examine the effect of the recent search on them. Much of this effect (ruling out light sparticles) is a robust property of the data rather than of the model, and as such will be prior independent. It is useful to see to what extent the experiments are able to rule out good-fit portions of the models. Here, we exemplify in the CMSSM, a well-studied and well defined model that has phenomenological properties that many other supersymmetry breaking patterns will follow. Specialising to the CMSSM allows us to take advantage of published ATLAS 0-lepton signal rates in Ref. [43], which include next-to-leading order corrections and detector effects that we could only crudely approximate were we to simulate the events ourselves.
The cuts defining the search regions used by the ATLAS 0-lepton analysis are given in Tab. 1. Also shown for each signal region \( i \in \{A,B,C,D\} \) are the number of observed events \( n_o(i) \) that made it past cuts and the expected Standard Model backgrounds \( n_b(i) \) together with their systematic errors \( \sigma_b(i) \). The \( \sigma_b(i) \) are calculated by adding the uncorrelated background systematic and the jet energy scale systematic in quadrature. At each point in their model grids, ATLAS also detailed the predicted number of signal events \( n_s(i) \) in each signal region.

ATLAS constructed frequentist exclusion regions in SUSY parameter space using a profile likelihood ratio method, taking into account theoretical and detector systematics and using Monte Carlo toys to compute the coverage on a pair of SUSY model grids. The information from the four signal regions was combined by defining the test statistic of each parameter point to be a likelihood ratio given by the signal region demonstrating the best expected sensitivity to new physics. Results were presented as 95% confidence exclusion regions in the \((m_{\tilde{g}}, m_{\tilde{q}})\) plane for \(m_{\tilde{\chi}_1^0} = 0\) and in the \(\tan \beta = 3\), \(A_0 = 0\), \(\mu > 0\) slice of the CMSSM \([1]\). 95% confidence exclusion regions (and expected sensitivity curves) were also produced in Ref. \([43]\) for each signal region individually. We shall use these curves to validate our statistical calculation of the ATLAS 0-lepton search likelihood.

### Table 1

| Number of required jets | Region A | Region B | Region C | Region D |
|-------------------------|----------|----------|----------|----------|
| \( \geq 2 \)            | \( \geq 2 \) | \( \geq 3 \) | \( \geq 3 \) |
| Leading jet \( p_T \)   | \( > 120 \text{ GeV} \) | \( > 120 \text{ GeV} \) | \( > 120 \text{ GeV} \) | \( > 120 \text{ GeV} \) |
| Subsequent jet(s) \( p_T \) | \( > 40 \text{ GeV} \) | \( > 40 \text{ GeV} \) | \( > 40 \text{ GeV} \) | \( > 40 \text{ GeV} \) |
| \( E_T^{\text{miss}} \) | \( > 100 \text{ GeV} \) | \( > 100 \text{ GeV} \) | \( > 100 \text{ GeV} \) | \( > 100 \text{ GeV} \) |
| \( \Delta \phi (\text{jet,} P_T^{\text{miss}})_{\text{min}} \) | \( > 0.4 \) | \( > 0.4 \) | \( > 0.4 \) | \( > 0.4 \) |
| \( E_T^{\text{miss}} / m_{\text{eff}} \) | \( > 0.3 \) | - | \( > 0.25 \) | \( > 0.25 \) |
| \( m_{\text{eff}} \) | \( > 500 \text{ GeV} \) | - | \( > 500 \text{ GeV} \) | \( > 1000 \text{ GeV} \) |
| \( m_{T2} \) | - | \( > 300 \text{ GeV} \) | - | - |
| Observed                | 87       | 11       | 66       | 2        |
| Standard Model background| 118±25±32| 10±4.3±4 | 88±18±26 | 2.5±1±1 |

The paper proceeds as follows: in Section 2, we review the basic properties of the ATLAS 0-lepton search. In Section 3, we describe how we take into account correlated systematic background and signal errors in order to provide a marginalised likelihood for the ATLAS 0-lepton search. The likelihood is then validated against the 95% C.L. exclusion contours published by ATLAS. We present the effect of the ATLAS 0-lepton search on global fits in Section 4, finishing with a summary and conclusions in Section 5.

2 The ATLAS 0-lepton Search

The cuts defining the search regions used by the ATLAS 0-lepton analysis are given in Tab. 1. Also shown for each signal region \( i \in \{A,B,C,D\} \) are the number of observed events \( n_o(i) \) that made it past cuts and the expected Standard Model backgrounds \( n_b(i) \) together with their systematic errors \( \sigma_b(i) \). The \( \sigma_b(i) \) are calculated by adding the uncorrelated background systematic and the jet energy scale systematic in quadrature. At each point in their model grids, ATLAS also detailed the predicted number of signal events \( n_s(i) \) in each signal region.

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3 ATLAS 0-lepton Search Likelihood Map

ATLAS provides signal numbers throughout the CMSSM $m_0 - m_{1/2}$ (the GUT scale universal scalar and universal gaugino mass, respectively) plane for the ratio of Higgs vacuum expectation values $\tan \beta = 3$ and SUSY breaking scalar trilinear coupling $A_0 = 0$, obviating the need for us to perform a SUSY signal event simulation in order to calculate the ATLAS 0-lepton search likelihood of each point in the slice of parameter space. Given the information $\Sigma^{(i)} = (n_{s}^{(i)}, n_{b}^{(i)}, \sigma_{s}^{(i)}, \sigma_{b}^{(i)})$ for a particular CMSSM point and signal region $i$, we can model the expectation value for the number of events observed in data as

$$\lambda(\Sigma^{(i)}, \delta_{s}, \delta_{b}) = n_{s}^{(i)}(1 + \delta_{s} \cdot \sigma_{s}^{(i)}) + n_{b}^{(i)}(1 + \delta_{b} \cdot \sigma_{b}^{(i)}),$$

(3.1)

where the impact of systematic variations is accounted for by the nuisance parameters $\delta_{s}, \delta_{b}$. We have neglected the luminosity error, which is subdominant compared to the errors we include. The probability of observing $n$ events from a Poisson process which is expected to generate, on average, a mean of $\mu$ events, is given by

$$\text{Poiss}(n|\mu) = \frac{e^{-\mu}(\mu)^n}{n!}.$$  

(3.2)

Taking the nuisance parameters to have Gaussian probability distribution functions, the probability of observing $n^{(i)}_{o}$ events, with systematic deviations $\delta_{s}, \delta_{b}$ from the central value is given by

$$P_{\text{syst}}(n^{(i)}_{o}, \delta_{s}, \delta_{b}|\Sigma^{(i)}) = \frac{1}{N^{(i)}} \text{Poiss}\left(n^{(i)}_{o}|\lambda(\Sigma^{(i)}, \delta_{s}, \delta_{b})\right) e^{-\frac{1}{2}(\delta_{s}^{2} + \delta_{b}^{2})},$$

(3.3)

where we have truncated the Gaussian modelling of the systematic errors at $5\sigma$ for convenience (restricted to keep the signal and background contributions independently non-negative), leading to the normalisation factor

$$N^{(i)} = \int_{\delta_{s}^{min}(-5, -1/\sigma_{s}^{(i)})}^{\delta_{s}^{max}(-5, -1/\sigma_{s}^{(i)})} d\delta_{s} \int_{\delta_{b}^{min}(-5, -1/\sigma_{b}^{(i)})}^{\delta_{b}^{max}(-5, -1/\sigma_{b}^{(i)})} d\delta_{b} e^{-\frac{1}{2}(\delta_{s}^{2} + \delta_{b}^{2})}.$$  

(3.4)

We then calculate the probability of observing $n^{(i)}_{o}$ events

$$P_{m}(n^{(i)}_{o}|\Sigma^{(i)}) = \int_{\delta_{s}^{min}(-5, -1/\sigma_{s}^{(i)})}^{\delta_{s}^{max}(-5, -1/\sigma_{s}^{(i)})} d\delta_{s} \int_{\delta_{b}^{min}(-5, -1/\sigma_{b}^{(i)})}^{\delta_{b}^{max}(-5, -1/\sigma_{b}^{(i)})} d\delta_{b} P_{\text{syst}}(n^{(i)}_{o}, \delta_{s}, \delta_{b}).$$

(3.5)

To validate the likelihood model and signal systematic estimation, we first compute exclusion limits corresponding to the ATLAS expected and observed results in the individual signal regions C and D. The inclusive di-jet signal regions A and B are neglected for the purposes of this paper, as their contributions to the constraints on the CMSSM parameter space were sub-dominant.

At each model point considered by ATLAS for a single signal region $i$, we compute the exclusion $p$-value defined as the cumulative marginalised likelihood for $n^{(i)}_{o}$ observed events

$$p_{\text{excl}}(n^{(i)}_{o}) = \sum_{n=0}^{n^{(i)}_{o}} P_{m}(n|\Sigma^{(i)}).$$

(3.6)
This corresponds to the likelihood that the observed event count was given by a downwards fluctuation from the Poisson mean of the nominal signal hypothesis. The 95% C.L. contour corresponding to \( p_{\text{excl}} = 0.05 \) is then interpolated in the \( m_0 - m_{1/2} \) plane.

Having determined suitable estimates of the signal uncertainties, we compute a combined likelihood function that incorporates the measurements from the two signal regions C and D. Here we diverge from the ATLAS strategy of taking the single optimal signal region to determine the likelihood at each model point.

We are using as our “data” the number of events \( n_o^{(C)} \) passing cuts in ATLAS signal region C, and the number of events \( n_o^{(D)} \) passing cuts in ATLAS signal region D. To emphasise this, we notate our data as \( \vec{n} \) where \( \vec{n} = (n_o^{(C)}, n_o^{(D)}) \). The events in region D are a subset of those in region C (since the only difference between the regions is that one has a harder cut on the effective mass) so we note that the independent data that we are working with are actually the numbers \( n_o^{(D)} \) and \( n_o^{(C)} - n_o^{(D)} \). If the expected numbers of events passing the cuts in regions C and D are denoted by \( \lambda_C \) and \( \lambda_D \) respectively, then the probability of observing our data \( \vec{n} \) as a function of \( \vec{\lambda} = (\lambda_C, \lambda_D) \) is thus given by:

\[
P(\vec{n} | \vec{\lambda}) = \text{Poiss}(n_o^{(D)} | \lambda_D) \text{ Poiss}(n_o^{(D)} - n_o^{(C)} | \lambda_C - \lambda_D).
\]

(3.7)

Again, we can model the systematic uncertainties in the Poisson means,
\[
\lambda_C = \lambda(\vec{\Sigma}^{(C)}, \delta_s, \delta_b),
\]

(3.8)
\[
\lambda_D = \lambda(\vec{\Sigma}^{(D)}, \delta_s, \delta_b),
\]

(3.9)

where we keep the same \( \delta_s \) and \( \delta_b \) in both definitions, as we assume that the uncertainties are fully correlated between the two signal regions. The probability of measuring data \( \vec{n} \) incorporating systematic variations is then, using Eq. 3.7 and by analogy with Eq. 3.3,

\[
P_{\text{syst}}(\vec{n}, \delta_s, \delta_b | \vec{\Sigma}^{(C)}, \vec{\Sigma}^{(D)}) = \frac{1}{N^{(C,D)}} \text{ Poiss}\left(n_o^{(C)} | \lambda(\vec{\Sigma}^{(C)}, \delta_s, \delta_b)\right) \times \text{ Poiss}\left(n_o^{(D)} - n_o^{(C)} | \lambda(\vec{\Sigma}^{(D)}, \delta_s, \delta_b) - \lambda(\vec{\Sigma}^{(C)}, \delta_s, \delta_b)\right) e^{-\frac{1}{2} (\delta_s^2 + \delta_b^2)}
\]

(3.10)

with the normalisation factor \( N^{(C,D)} \) defined similarly to 3.4 as

\[
N^{(C,D)} = \int_{\max(-5, -1/ \max(\sigma_s^{(C)}, \sigma_s^{(D)}))}^{5} d\delta_s \int_{\max(-5, -1/ \max(\sigma_b^{(C)}, \sigma_b^{(D)}))}^{5} d\delta_b e^{-\frac{1}{2} (\delta_s^2 + \delta_b^2)}.
\]

(3.11)

Marginalising over the systematics once more produces the probability of measuring \( \vec{n} \) under the nominal signal hypothesis,

\[
P_m(\vec{n} | \vec{\Sigma}^{(C)}, \vec{\Sigma}^{(D)}) = \int_{\max(-5, -1/ \max(\sigma_s^{(C)}, \sigma_s^{(D)}))}^{5} d\delta_s \int_{\max(-5, -1/ \max(\sigma_b^{(C)}, \sigma_b^{(D)}))}^{5} d\delta_b \{ P_{\text{syst}}(\vec{n}, \delta_s, \delta_b | \vec{\Sigma}^{(C)}, \vec{\Sigma}^{(D)}) \}.
\]

(3.12)

We shall refer to \( P_m(\vec{n} | \vec{\Sigma}^{(C)}, \vec{\Sigma}^{(D)}) \) as the likelihood, or the ATLAS 0-lepton search likelihood, in what follows.
3.1 Validation of the search likelihood penalty

We validate our statistical framework (defined in the previous section) by attempting to reproduce the official ATLAS exclusion limits from Ref. [1]. A systematic error\(^2 \sigma_s^{(i)}\) on the signal was used in the ATLAS results, but the values of \(\sigma_s^{(i)}\) were not made public. In order to account for signal systematics, we vary \(\sigma_s^{(C)}\) and \(\sigma_s^{(D)}\) in order to provide a reasonable fit to the official ATLAS 95\% C.L. exclusion contours in the parameter regions most sensitive to the global fit. Varying them manually, we find that \(\sigma_s^{(C)} = 0.6\) and and \(\sigma_s^{(D)} = 0.3\) respectively, provide a reasonable fit in the most important area of the parameter plane for each signal region. We find that the exclusion contours are not so sensitive to the precise values of \(\sigma_s^{(C)}\) and \(\sigma_s^{(D)}\): changing either by 0.05 moves the contours almost imperceptibly.

The exclusion contours are interpolated in the \(m_0 - m_{1/2}\) plane after computing \(p_{\text{excl}}(n_o)\) at each model point for signal regions C and D separately (see Fig. 1).

Our solid exclusion contours are seen to match the official ATLAS dashed contours well, particularly at low \(m_0\) and high \(m_{1/2}\), i.e. in the lower right-hand corner of the plots. This is crucial, since the global fits before including ATLAS 0-lepton search results favour this region of the CMSSM parameter space, as is demonstrated below in Fig. 3, and hence the ATLAS search likelihoods will have the greatest impact in this region. Our approximations do very well at high \(m_{1/2}\), close to the favoured CMSSM point. Elsewhere, at lower values of \(m_{1/2}\) and high \(m_0\), the approximation is less good, particularly in signal region D. This is likely due to the assumption of a signal uncertainty that, within each signal region, is

\(^2\sigma_s^{(i)}\) accounts for higher order corrections and jet energy scale uncertainties among others.
Figure 2. Our approximation to the ATLAS 0-lepton search CMSSM likelihood map for tan $\beta = 3$, $A_0 = 0$. We display $\Delta \chi^2_{ATLAS}$ as the background colour density. The ATLAS 95% C.L. exclusion limit is shown as the light (green) solid line.

For the jets plus $p_T$ search (0-lepton), where the signal involves just high energy jets and missing transverse momentum, we expect the signal rate to be approximately independent of tan $\beta$ and $A_0$. This is because the signal is dominated by the strong interaction cross-sections of squark and gluino production, which do not depend to any significant degree on those parameters. The accuracy of the tan $\beta - A_0$ independence assumption was explicitly checked recently in the CMS $\alpha_T$ search [16], which is also looking for events with jets and missing transverse momentum. It was found that, for CMSSM global fits, the CMS $\alpha_T$ search likelihood is well approximated by ignoring any $A_0$ or tan $\beta$ dependence. Being able to model the dependence of the ATLAS search likelihood on $m_0$ and $m_{1/2}$, while ignoring the effect of $A_0$ and tan $\beta$ leads to a significant simplification when we come to take it into account in our global CMSSM fits. We shall neglect $A_0$ and tan $\beta$ dependence.

We investigate the combination of signal regions C and D into $P_m$ in Fig. 2.

$$\Delta \chi^2_{ATLAS} = -2 \ln(P_m/P_m(0 \text{ sig}))$$ (3.13)

is shown as the background colour density, where $P_m(0 \text{ sig})$ is the combined 0-lepton search likelihood penalty from Eq. 3.12 in the limit of no signal events. We see that the shape of the background colour density closely follows the shape of the official ATLAS exclusion limit. It is also around $\Delta \chi^2 = 5.99$, which would be the 95% C.L. exclusion in the limit.
of Gaussian statistics\(^3\). For increasing \(m_{1/2}\) GeV, we see \(\Delta \chi^2\) reaching a constant in Fig. 2 because there is no SUSY signal, since squarks and gluinos become too heavy to be produced. At large \(m_0\) and small \(m_{1/2}\), the SUSY signal is strongly dominated by gluino pair production, where the gluinos have three-body decays into squarks. Thus the dependence of \(P_m\) on \(m_0\), if it is above 1160 GeV, is negligible. We shall therefore model the likelihood as follows: we use for \(m_{1/2} > 430\) GeV, \(n^c_s = n^D_s = 0\). We also use this zero signal limit for \(m_{1/2} > 340\) GeV and \(m_0 > 430\) GeV. For \(m_0 > 1160\) GeV and \(m_{1/2} < 430\) GeV, we use the \(P_m\) value given by the \(m_0 = 1160\) line on the figure. For \(m_0 < 1160\), \(m_{1/2} < 430\), we interpolate linearly within the grid of \(\Delta \chi^2_{ATLAS}\).

4 Global CMSSM Fits Including the ATLAS Search

We shall use a previous global Bayesian fit of the CMSSM from the KISMET (Killer Inference in Supersymmetric METeorology) collaboration [22] to: the relic density of dark matter, the anomalous magnetic moment of the muon, previous direct searches for sparticles, the branching ratios \(BR(b \to s\gamma)\), \(BR(B_s \to \mu\mu)\), \(M_W\), \(\sin^2 \theta^w\), as well as 95% exclusions from LEP and Tevatron direct search data. The ranges of parameter considered were: \(2 < \tan \beta < 62\), \(|A_0|/\text{TeV} < 4\), \(60 < m_{1/2}/\text{GeV} < 2000\), \(60 < m_0/\text{GeV} < 4000\). Variations of the top mass, the strong coupling constant, the fine structure constant and the bottom mass were all included. Various different prior distributions were examined in Ref. [22], but here we shall use the example of priors flat in the parameters listed above, except for \(m_0\) and \(m_{1/2}\), which are flat in their logarithm. Using such log priors allows us to illustrate the effects of the 0-lepton search more acutely than with purely linear priors. Rigorous convergence criteria were satisfied by the fits, which were performed by ten Metropolis Markov Chains running simultaneously. For more details on the fits, we refer interested readers to Ref. [22].

We take 2.7 million points from the fits, whose densities in parameter space are proportional to their posterior probability distributions. We then re-weight each point by multiplying its global fit likelihood by \(L\) calculated from the 0-lepton search. By plotting the posterior probability distributions before and after the re-weighting, we then examine the effect of the ATLAS SUSY exclusion data on the CMSSM fits.

We display the impact of the 0-lepton search on the \(m_0 - m_{1/2}\) plane in Fig. 3. Fig. 3a shows that the search 95% contour covers much of the current region that fits indirect data well at low values of \(m_0\). We emphasise that we have used the full likelihood function and not just a simple cut based on the exclusion curve. When our approximation to the likelihood function in Fig. 2 is applied to the global fit, much of the probability mass moves to higher values of \(m_0\) and \(m_{1/2}\), despite the fact that the anomalous magnetic momentum of the muon would prefer somewhat lower values. This effect is much more pronounced in the ATLAS 0-lepton search than in the CMS \(\alpha_T\) search because of the more stringent exclusion of the ATLAS analysis, as shown by a comparison between Fig. 2 and Fig. 3 of Ref. [16]. The fits are performed under the CMSSM hypothesis, so the total probability is

\(^3\)We note here that in some regions of parameter space, the event numbers are very small and so one cannot use the Gaussian limit.
Figure 3. Global CMSSM fits in the $m_0 - m_{1/2}$ plane: (a) excluding the ATLAS 0-lepton search and (b) including the ATLAS 0-lepton search likelihood. The posterior probability of each bin is shown as the background colour, normalised to the maximum bin probability. The region to the left of the almost vertical solid green (dotted yellow) curve is excluded by the ATLAS 0-lepton search (CMS $\alpha_T$ search) at the 95% C.L. The cyan inner (outer) contour shows the 68% (95%) Bayesian credibility region.

conserved, even after the ATLAS search data have been used to constrain the model. We could quantify the difference the search has made to the Bayesian evidence of the model, but such an inference is likely to not be robust until the CMSSM is strongly constrained by supersymmetric signals. The non-robustness manifests as a high degree of prior dependence in the evidence [42].

Fig. 4 displays the effect of the 0-lepton search on the $m_{1/2} - \tan \beta$ plane. As well as moving the probability mass up in $m_{1/2}$, we see that it is moved upward in $\tan \beta$ as well. This effect is due to the positive correlation between $m_{1/2}$ and $\tan \beta$ evident in Fig. 4a in the high probability region. The correlation can be understood as a consequence of the fits preferring a positive contribution to the anomalous magnetic momentum of the muon, $\delta a_\mu$. $\delta a_\mu$ is proportional to $\tan \beta / M^2_{SUSY}$, where $M_{SUSY}$ is the mass scale of sparticles in the loop that contribute. Thus, if $M_{SUSY}$ is forced upward by the ATLAS search, to get an equivalent $\delta a_\mu$, $\tan \beta$ must also increase. The vertical arm at the left hand side of the plots corresponds to the higgs pole region, where neutralinos annihilate efficiently through an $s$ channel lightest CP even higgs boson. The higgs pole region has low $m_{1/2}$ and high $m_0$, and so isn’t yet affected much by the ATLAS search.

The effect of the ATLAS 0-lepton search [1] on individual CMSSM parameters is shown in Fig. 5, and can be understood in terms of the effect of the search on the higher dimensional parameter space: $m_0$ and $m_{1/2}$ are pushed to larger values, as is $\tan \beta$ due to the correlations mentioned above. There is almost no change in the probability distribution of $A_0$, indicating that $A_0$ isn’t strongly correlated in the global fits with the other parameters.

A change in the probability distributions in the CMSSM parameters implies a change
Figure 4. Global CMSSM fits in the $m_{1/2} - \tan \beta$: (a) excluding the ATLAS 0-lepton search and (b) including the ATLAS 0-lepton search likelihood. The posterior probability of each bin is shown as the background colour, normalised to the maximum bin probability. The cyan inner (outer) contour shows the 68% (95%) Bayesian credibility region.

in the probability distributions of sparticle masses. We display a representative sample of these in Fig. 6. The squark and gluino masses are predictably pushed to be heavier by the CMSSM search, as is the neutralino, since in the CMSSM it is controlled by the same parameter as the gluino mass ($m_{1/2}$), and is therefore highly correlated. We see a similar effect for the right-handed slepton $\tilde{e}_R$, which is strongly correlated with $m_0$ and is thus pushed to somewhat heavier values. Although in general, global fits are not expected to be robust until significant SUSY signals are detected, the moving of sparticle masses to heavier values by the ATLAS exclusion is expected to be.

We display the effect of the ATLAS 0-lepton search on the probability distribution for the total production cross-section of sparticles $\sigma_{SUSY}$ in Fig. 7. As expected, heavier sparticles mean that the cross-sections decrease somewhat.

5 Summary and Conclusions

Global fits of the CMSSM to indirect data provide us with a “weather forecast” for future sparticle production, under the CMSSM hypothesis. We use KISMET fits that take into account the anomalous magnetic moment of the muon, the dark matter relic density and electroweak observables and direct searches for supersymmetric particles and Higgs bosons. These data have the power to constrain approximately two free parameters additional to the SM: essentially, the dark matter relic density constraint is strong enough to constrain one dimension, and the combination of all of the other observables jointly constrains another. The ATLAS 0-lepton search [1] has significantly extended previous exclusion limits in the CMSSM and it has a significant effect on the global fits. The search bites off the part of the parameter space where both squarks and gluinos are light, but also has some other non-
trivial effects: for instance $\tan \beta$ is pushed to higher values. A recent CMS $\alpha_T$ search [3] based on the $\alpha_T$ variable, picked because it was thought to be more robust with respect to fluctuations in Standard Model backgrounds, also produced some of these effects on the global fits [16], although it had a slight $\sim 1\sigma$ excess in the number of events, meaning that intermediate sparticle masses were somewhat preferred. Since the ATLAS 0-lepton search did not have such an excess, there is no relative preference for intermediate sparticle masses.

The ATLAS exclusion reaches further than the one produced by CMS, with a consequently larger effect on the global fits. ATLAS had a different search strategy, relying on more standard cuts on $m_{\text{eff}}$, $p_T$ and $m_{T_2}$ which differ in different signal regions of parameter space and which have been somewhat optimised to increase the constraining power of the search. The heavier sparticles implied by the ATLAS 0-lepton exclusion means that the weather forecast for LHC sparticle production is somewhat more arid: heavier sparticles have less phase space to be produced in the collisions, and their production cross-section decreases. With a most likely $\sigma_{\text{SUSY}} = 0.1$ pb, there is still plenty of opportunity for LHC sparticle production in the coming years.

ATLAS produced a useful amount of information about their search in published aux-

**Figure 5.** Effect of the ATLAS 0-lepton, jets and missing momentum search [1] on one dimensional probability distributions of CMSSM parameters. The area of each histogram has been normalised to 1 and labeled ‘Incl. ATLAS’ (‘Excl. ATLAS’) if it includes (excludes) the ATLAS results.
Figure 6. Effect of the ATLAS 0-lepton, jets and missing momentum search [1] on the probability distributions of sparticle masses in the CMSSM. The area of each histogram has been normalised to 1 and labeled ‘Incl. ATLAS’ (‘Excl. ATLAS’) if it includes (excludes) the ATLAS results.

Figure 7. Effect of the ATLAS 0-lepton, jets and missing momentum search [1] on the total SUSY cross-section $\sigma_{SUSY}$ in the CMSSM in $pp$ collisions at $\sqrt{s} = 7$ TeV. The area of each histogram has been normalised to 1 and labeled ‘Incl. ATLAS’ (‘Excl. ATLAS’) if it includes (excludes) the ATLAS results.
iliary data, including backgrounds and uncertainties and expected signal rates throughout parameter space. The signal rates allowed us to take their search into account without having to re-perform event generation, which would be a CPU-time bottleneck and a significant complication in the analysis. We are thus also able to perform the fits implicitly taking detector effects into account.

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