Present and possible future implications for mSUGRA of the non-discovery of SUSY at the LHC

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Both ATLAS and CMS have published results of SUSY searches putting limits on SUSY parameters and masses. A non-discovery of SUSY in the next two years would push these limits further. On the other hand, precision data of low energy measurements and the dark matter relic density favor a light scale of supersymmetry. Therefore we investigate if supersymmetry – more specifically the highly constraint model mSUGRA – does at all agree with precision data and LHC exclusions at the same time, and whether the first two years of LHC will be capable of excluding models of supersymmetry. We consider the current non observation of supersymmetry with 35 pb^{-1} as well as the possible non observation with 1, 2 and 7 fb^{-1} in a global fit using the framework Fittino.

1 Introduction

Supersymmetry[1] (SUSY) provides an elegant and renormalizable solution to several current problems of the Standard Model (SM) of elementary particles: Provided its parameters are chosen appropriately, it can explain electroweak symmetry breaking, solve the hierarchy problem of the Higgs sector of the SM, and provide the correct amount and structure of Dark Matter (DM) in the universe, together with agreement of its predictions with precision measurements at various experiments. However, all these are typically only fulfilled simultaneously for very specific parameter settings and breaking assumptions.

Many previous studies of the available data before the LHC[2,3,4,5,6,7] era indicate that a mass scale of the SUSY particles below around 1.6 GeV is required at the 2 σ level to bring a highly constrained model such as mSUGRA/CMSSM in agreement with all precision results. Strong constraints are placed on details of the mass spectrum and the couplings, e.g. corresponding to a co-annihilation process to control the DM content (see e.g.[6]).

Since SUSY is already highly constrained before including the present non-observation of new physics at LHC in the fit, it is a highly non-trivial question whether SUSY can be brought in agreement with both the LHC limits and the precision data, even though the upper mass bound on the colored particles from the previous fits is considerably higher than the present LHC limits (see e.g.[8,9]), at around 800 GeV, since the precision data also put constraints on details of the model, as described above.

The analysis presented here[10] is using the mSUGRA model to answer the question of the

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level of agreement for the following reason: if this highly constrained (but well-understood) model is in agreement with the data, then more general SUSY models will be in agreement, too. If not, other breaking scenarios and generalizations of mSUGRA with weaker high-scale assumptions will have to be tested.

At LHC, SUSY can be searched in different channels asking for varying numbers of hard jets, leptons and amounts of missing transverse energy. The strongest constraints are currently stemming from very inclusive analyses asking only for jets and leptons. In addition, such analyses have the advantage that their results do depend on only few mSUGRA parameters. Therefore, a study for inclusive searches at ATLAS[11] has been modeled as a prediction for the actual results of the experiments, since the fits presented here were performed in parallel to the presently public searches by ATLAS and CMS. For other recent contributions in the same field, see e.g. Ref.[12]

2 Model, Inputs to the Fit and Statistics

The mSUGRA model used in the fit are evaluated using a Markov Chain Monte Carlo technique. The theoretical predictions are calculated using SPheno[13] for the RGE running and the spectrum calculation, and programs compiled in the mastercode package for the prediction of the low energy precision observables and the Higgs boson masses, most notably FeynHiggs, micrOmegas and SuperISO[7]. SoftSUSY[14] is used for cross-checks.

2.1 Observables from the pre-LHC era

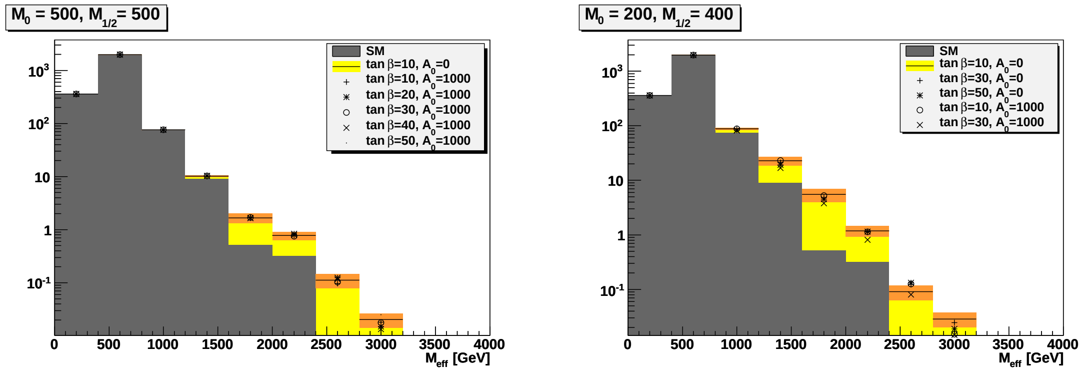
Following the Fittino[15] analysis in Ref.[6], the following set of low-energy observables and existing collider limits is used: *(i)* rare decays of B- and K-mesons; *(ii)* the anomalous magnetic moment of the muon, a_μ; *(iii)* electroweak precision measurements from LEP, SLC and the Tevatron and the Higgs boson mass limit from LEP; and *(iv)* the relic density of cold dark matter in the universe, Ω_χ. In contrast to Ref.[6], we employ the program HiggsBounds[16] and not a rigid Higgs mass limit. We refer to Ref.[6] for a detailed discussion of the low-energy inputs and the collider limits.

2.2 Modeling the ATLAS analysis

The most sensitive and at the same time rather model independent search channel for R-parity conserving SUSY at the LHC relies on jets and missing transverse energy $E_T^{\rm miss}$ for the selection. From the analyses presented in the ATLAS MC study[11], we consider the search channel with four jets, zero leptons and $E_T^{\rm miss}$. This channel drives the sensitivity, in particular for large $M_{1/2}$. For a detailed description of the selection cuts applied see Ref.[10]. As a final discriminating variable the effective mass is used. It is defined as the scalar sum of the transverse momenta of all main objects, *i.e.*

$$M_{\rm eff} = \sum_{i=1}^{N_{\rm jets}=4} p_T^{{\rm jet},i} + E_T^{\rm miss}. \qquad (1)$$

The SM background processes have been described in detail in Ref.[11]. We use the background shape of $M_{\rm eff}$ from the ATLAS analysis directly in our fit. A systematic uncertainty of 20 %, derived from Ref.[11] has been used on the background, which is also in rough agreement with the present results based on data[8]. The signal cross section is dominated by squark and gluino pair production, $pp \to \tilde{q}\tilde{q}^*, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}$ and $\tilde{g}\tilde{g}$, but all SUSY pair production processes are included in our numerical analysis. We use Herwig++[17] in combination with the parametrized fast detector simulation Delphes[18] to obtain the detector response and, in particular, the shape of the $M_{\rm eff}$ distribution for a given point in the supersymmetric parameter space. The simulation has been



(a) (b)

Figure 1: *Systematic check of the dependence of the simulated SUSY M_{eff} spectrum on the parameters A_0 and $\tan\beta$ for two different parameter points in M_0 and $M_{1/2}$. In (a), a point with low dependence on the parameters fixed in the grid are shown, showing a small variation of the predicted SUSY M_{eff} spectrum well within systematics. In (b), a point with relatively large dependence is shown, which is still in agreement with the systematics. This shows the reliability of the application of the grid in $M_0, M_{1/2}$ in the fit.*

carefully modified to match the published measured resolutions and efficiencies of the ATLAS experiment, and the resulting M_{eff} has been compared to the public spectra at an mSUGRA benchmark point. The signal estimate is normalized to the NLO+NLL QCD prediction for the inclusive squark and gluino cross sections [19].

On the signal, we apply a systematic uncertainty of 30 %, covering both the uncertainty in the calculation of the cross section and the remaining model dependence. The fit presented in Section 3 uses a grid spanned in M_0 and $M_{1/2}$ for the model prediction of the M_{eff} spectrum. In between the model points, a bi-linear interpolation is used. The variation of the M_{eff} spectrum with the remaining parameters $\tan\beta$ and A_0 is shown in Fig. 1. The variations are clearly compatible with the systematic uncertainty shown as the orange band.

2.3 Statistics

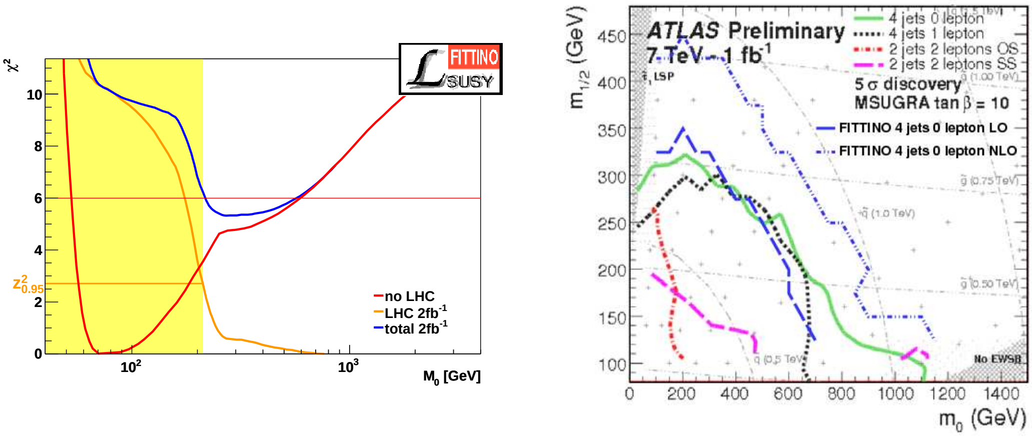
We use a likelihood ratio technique to calculate an expected CL_{s+b} for the non-observation of a signal at LHC. This confidence level is then transferred into a contribution to the χ^2 of the frequentist fit. For a detailed description of the statistical method, see Ref.[10]

As shown in Fig. (a), this technique transfers the exact statistical power of the LHC search into a contribution to the χ^2. Thus, the global fit can find the exact minimum and the exact uncertainties arising from the interplay between the LHC contribution (orange) and the contribution from pre-LHC observables (red). It can be seen that naturally LHC prefers high SUSY mass scales, whereas the precision results prefer low scales, and that the LHC contribution does not provide a considerably steeper χ^2 profile than the other results. The blue line represents the combined χ^2.

Very good agreement is achieved between the results presented here and the official ATLAS study[11]. Also, the limit derived from our implementation agrees with the actual search result for $\mathcal{L}^{int} = 35\,\text{pb}^{-1}$ of data within a $1\,\sigma$ fluctuation of the background.

3 Results

The following results are obtained from global fits of the mSUGRA to the observables described in Sec. 2. sign$\mu = +1$ is assumed for all fits due to the observed value of $(g-2)_\mu$. For a more detailed analysis of the dependence of the pre-LHC-era fit on signμ, see Ref.[6]. For the LHC,



(a) (b)

Figure 2: *(a): Interplay between the LHC and the pre-LHC contribution to the global χ^2. (b): Comparison between the discovery potential based on the ATLAS MC study (green line) and the LO result based on our implementation of the simulation of the detector and the analysis (dashed blue line).*

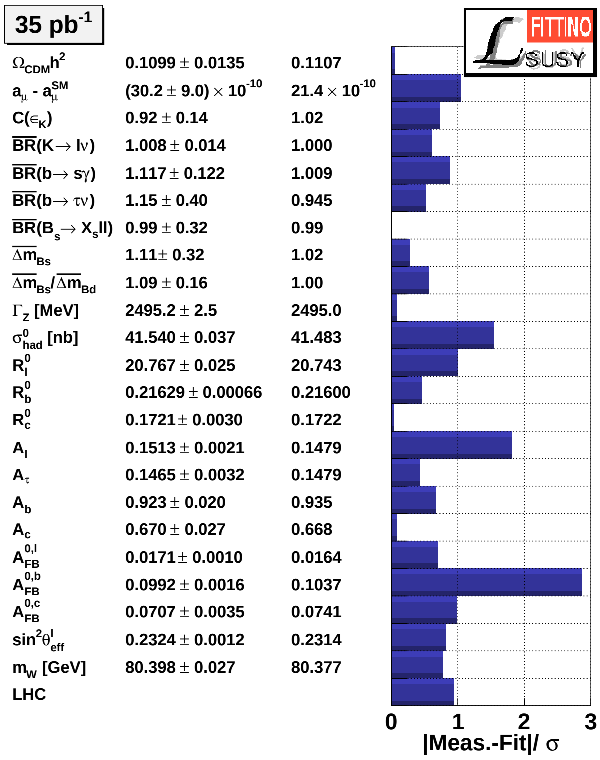
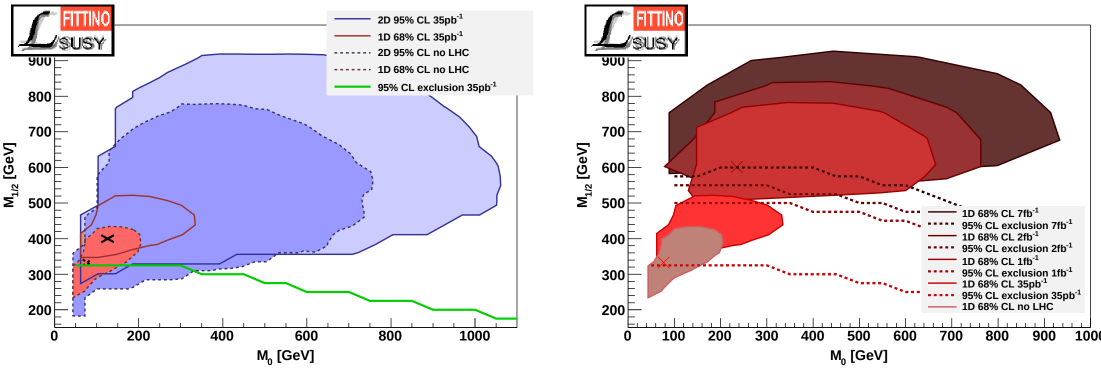


Figure 3: *All observables in the global fit and their pulls are shown for $\mathcal{L}^{int} = 35\,\mathrm{pb}^{-1}$. Excellent agreement is observed.*

integrated luminosities $\mathcal{L}^{int} = 0.035, 1, 2, 7\,\mathrm{fb}^{-1}$ are assumed, the first of those corresponding to the presently published analyses, while the last corresponds to a reasonable expectation for the available data set in 2011/2012.

For fits without LHC and for $\mathcal{L}^{int} = 35\,\mathrm{pb}^{-1}$, excellent agreement between the data and the mSUGRA model is found. The pulls of the variables in the fit are shown in Fig. 3 for $\mathcal{L}^{int} = 35\,\mathrm{pb}^{-1}$. More importantly, there still is a significant agreement between the resulting parameter ranges from the two fits, as shown in Fig. 4(a). While the LHC just excludes the



(a) (b)

Figure 4: *The allowed parameter range for the fits without LHC and for the fit with our implementation present luminosity is shown in (a). The tension between the two fits is observed to be very moderate. In (b), the evolution of the* $\Delta\chi^2 = 1$ *area with increasing luminosity is shown. As expected, it moves to higher values of* M_0 *and* $M_{1/2}$*, and in addition the uncertainties grow very significantly.*

Table 1: *Overview of the best fit points for all considered LHC luminosities. The values of* χ^2/ndf *underline that mSUGRA can not be excluded in the first 2 years of LHC.*

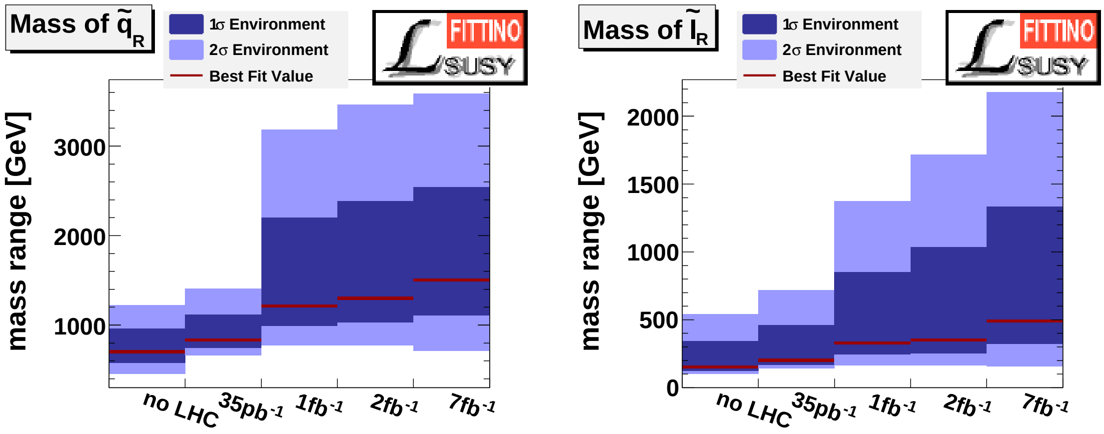
$\mathcal{L}^{int}/\text{fb}^{-1}$	M_0	$M_{1/2}$	$\tan\beta$	A_0	χ^2/ndf	$\mathcal{P}-Value$
0	77.1	332.8	12.8	426.2	18.9/20	53.1 %
0.035	125.9	399.8	17.3	742.3	20.4/21	49.8 %
1	235.1	601.0	31.1	626.8	23.7/21	30.9 %
2	254.1	647.1	30.2	770.7	24.2/21	28.3 %
7	402.7	744.1	43.1	780.7	25.0/21	24.6 %

best fit point for the fit without LHC data, the $\Delta\chi^2 = 1$ areas do still overlap significantly, and there is a large overlap in the $\Delta\chi^2 = 5.99$ area, corresponding to a 95 % CL in two dimensions.

The fact that the current LHC analyses put little pressure on SUSY is also evident from Tab. 1, which shows the best fit points of the five fits together with the observed χ^2/ndf values and the corresponding $\mathcal{P}$-values (the latter being only for completeness, since it is technically not proven that the expected fit results follow a χ^2 curve, due to significant non-linearities both in the LHC limits and in the relation between parameters and observables). In any case, the change in χ^2/ndf is very moderate when going from the fit without LHC to the fit with $\mathcal{L}^{int} = 35\,\text{pb}^{-1}$.

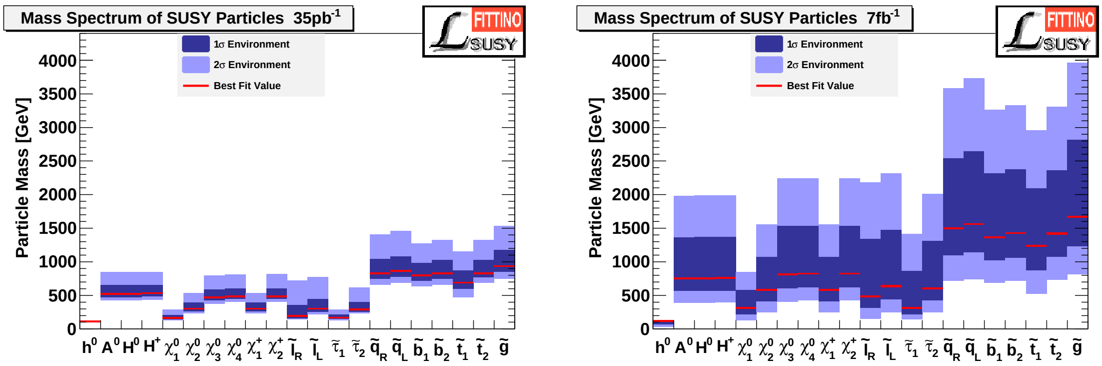
This observation contradicts the disappointment about the non-observation of SUSY at LHC with $\mathcal{L}^{int} = 35\,\text{pb}^{-1}$, which is mostly based on finetuning arguments or Bayesian discussions of the size of the available parameter space for arbitrary priors. Without those more subjective measures of the attractiveness of a theory, even the highly constrained mSUGRA is still in natural agreement with the data. To the contrary, squark masses of around 1 TeV or slightly higher are a welcome ingredient to lift the mass of the lightest, SM-like Higgs boson above the LEP limit.

For higher assumed LHC luminosities, still assuming no observation of new physics, the $\Delta\chi^2 = 1$ areas of the fits do start to deviate significantly from each other, as evident from Fig. 4(b). This corresponds to a building tension in the fit between mainly $(g-2)_\mu$ and Ω_χ, pushing mSUGRA to lower scales via the gaugino and slepton sector, and the LHC, pushing mSUGRA to higher scales via the more direct limit on the squark and gluino mass scale. This results in a degradation of χ^2/ndf, as evident from Tab. 1. However, even for $\mathcal{L}^{int} = 7\,\text{fb}^{-1}$, mSUGRA can not be excluded with the given observable set and SUSY searches alone. This tension is expected to be significantly weaker for more general SUSY models.



(a) (b)

Figure 5: *For the different LHC luminosities, this figure shows the allowed mass ranges of squarks in (a) and of sleptons in (b). While the former is quite model independent, the latter strongly depends on assumptions in the mSUGRA model.*



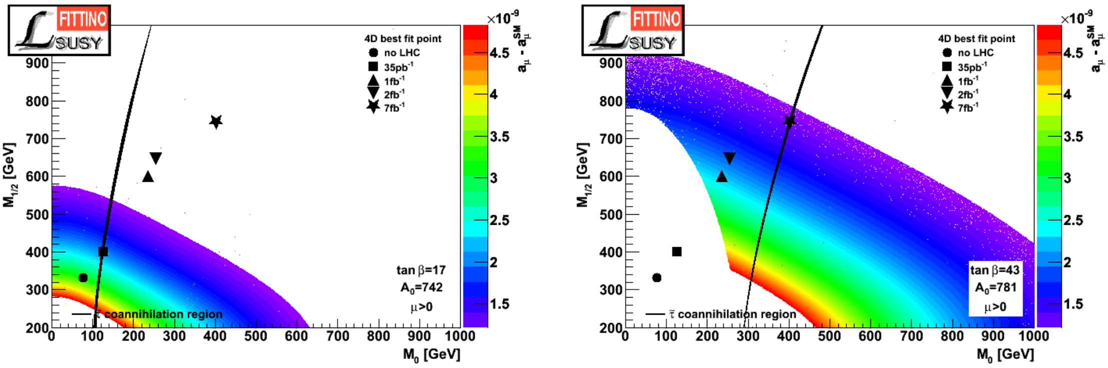
(a) (b)

Figure 6: *Comparison of the allowed mass ranges of all sparticles and Higgs bosons for the fits with* $\mathcal{L}^{int} = 35\,\mathrm{pb}^{-1}$ *in (a) and* $\mathcal{L}^{int} = 7\,\mathrm{fb}^{-1}$ *in (b).*

Even though the tension is rising, SUSY cannot be excluded at the LHC in the first two years of running. The interesting observation here is that the inclusion of the LHC exclusion to the fit only has a very moderate effect on the lower mass bound of the sparticles, as shown in Fig. 5. The by far non-trivial result from the fit, however, is the fact that the upper bound on the sparticle masses depends very strongly on including the LHC into the fit. The reason for this behavior can be seen in Fig. 2(a). The χ^2 surface is influenced by LHC only for $M_0 < 1.5$ GeV, it remains independent of the LHC luminosity above that value. However, there it is significantly more flat than close to the minimum of the fit without LHC. Including the LHC cuts away the low χ^2 values, shifting up the $\Delta\chi^2 = 4$ area significantly into shallower areas of the χ^2 profile. Therefore, non-trivially, the upper mass bounds on the sparticles increase very strongly, allowing mSUGRA to escape the LHC detection to higher mass regions.

Fig. 6 shows the same for all sparticles and Higgs bosons, but only for $\mathcal{L}^{int} = 35\,\mathrm{pb}^{-1}$ and $\mathcal{L}^{int} = 7\,\mathrm{fb}^{-1}$. The interesting observation is that the only particle of which the allowed mass range does not change is the SM-like Higgs boson h^0, which is bound in mSUGRA at $m_{h^0} < 135$ GeV. Therefore, the only chance for an exclusion of mSUGRA and many other SUSY breaking scenarios can be obtained via SM-like Higgs searches at the Tevatron and LHC.

One interesting observation is the fact that the LHC pushes the best fit point of $\tan\beta$ to



(a) (b)

Figure 7: *Explanation, of how the interplay of $(g-2)_\mu$, Ω_χ and the LHC moves the best fit point of* $\tan\beta$ *to significantly higher values for higher LHC luminosities. In (a), the situation for* $\tan\beta = 17$ *is shown, where* $(g-2)_\mu$ *and* Ω_χ *are in good agreement with the data for low* M_0 *and* $M_{1/2}$*. If LHC should exclude those low regions of* M_0 *and* $M_{1/2}$*, a higher value of* $\tan\beta$ *is necessary to reconcile* $(g-2)_\mu$ *and* Ω_χ *with the data, as shown in (b) for* $\tan\beta = 43$*.*

significantly higher values than observed for the fit without LHC. This is interesting since it is shown in Fig. 1 that the LHC limit in the chosen search channel does not depend significantly on $\tan\beta$. The increase however is an interesting showcase of an interplay between low-energy precision observables, cosmological observables and direct limits from the LHC. This is described in Fig. 7, showing the co-annihilation region which is mainly responsible for a good fit of Ω_χ (another region with some contribution from the Higgs funnel also is allowed at very large $\tan\beta$) and the predicted values of $(g-2)_\mu$ for M_0 and $M_{1/2}$. In Fig. 7(a), $\tan\beta = 17$ is used and the two observables agree with the measurements for low mass scales. In Fig. 7(b) and $\tan\beta = 43$, the low mass scales can be excluded by the LHC, retaining agreement with Ω_χ and $(g-2)_\mu$ at high mass scales. Thus, the exclusion of low mass scales pushes mSUGRA to higher values of $\tan\beta$, since only then the pre-LHC-era observables can be correctly described. This is an interesting observation, since also in the detailed study of theoretical uncertainties of mSUGRA models up to now the focus was on the low to intermediate $\tan\beta$ region. A further non-observation of SUSY at the LHC would highlight the importance of understanding SUSY precision calculations at high values of $\tan\beta$.

4 Conclusions

We have presented a global mSUGRA analysis of supersymmetric models which includes the current low-energy precision measurements, the dark matter relic density as well as potential LHC exclusion limits from direct SUSY searches in the zero-lepton plus jets and missing transverse energy channel.

We conclude that non-trivially it is possible to reconcile the supersymmetric description of low-energy observables and the dark matter relic density with a non-observation of supersymmetry in the first phase of the LHC with acceptable χ^2/ndf values, despite some tension building up in a combined fit within mSUGRA.

While our study is exploratory in the sense that it is based on one search channel only, and on a simplified description of the LHC detectors, it clearly demonstrates the potential of the first phase of LHC running at 7 TeV in 2011/12 to constrain supersymmetric models and the sparticle mass spectrum, or to discover such models.

However, the interesting fact that including LHC limits in the global fit significantly increases the upper bounds on the sparticle masses make it impossible to exclude mSUGRA in the first two years at LHC based on SUSY searches. Excluding the model could however be possible using Higgs boson searches.

Acknowledgments

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