Impact of the recent results by the CMS and ATLAS Collaborations at the CERN Large Hadron Collider on an effective Minimal Supersymmetric extension of the Standard Model*

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We discuss the impact for light neutralinos in an effective Minimal Supersymmetric extension of the Standard Model of the recent results presented by the CMS and ATLAS Collaborations at the CERN Large Hadron Collider for a search of supersymmetry in proton-proton collisions at a center-of-mass energy of 7 TeV with an integrated luminosity of 35 pb^{-1}. We find that, in the specific case of light neutralinos, efficiencies for the specific signature searched by ATLAS (jets+missing transverse energy and an isolated lepton) imply a lower sensitivity compared to CMS (which searches for jets +missing transverse energy). Focusing on the CMS bound, if squark soft masses of the three families are assumed to be degenerate, the combination of the ensuing constraint on squark and gluino masses with the experimental limit on the $b \to s + \gamma$ decay imply a lower bound on the neutralino mass m_χ that can reach the value of 11.9 GeV, depending on the gluino mass. On the other hand, when the universality condition among squark soft parameters is relaxed, the lower bound on m_χ is not constrained by the CMS measurement and then remains at the value 7.5 GeV derived in previous papers.

I. INTRODUCTION

The CMS and ATLAS Collaborations have presented their results of a search for supersymmetry (SUSY) in proton-proton collisions at the CERN Large Hadron Collider (LHC) at a center-of-mass energy of 7 TeV with an integrated luminosity of 35 pb^{-1} [1, 2]. The CMS investigation[1] consists in a search for events with jets and missing transverse energy, while ATLAS[2] searched for final states containing jets, missing transverse energy and one isolated electron or muon. Both signatures would be significant of processes due to the production in pairs of squarks and gluinos, subsequently decaying into quarks, gluons, other standard-model (SM) particles and a neutralino (interpreted as the lightest supersymmetric particle (LSP)) in a R-parity conserving SUSY theory. As reported in Ref.[1, 2] in both analyses the data appear to be consistent with the expected SM backgrounds; thus constraints are derived on the model parameters in the case of a minimal supergravity model (mSUGRA, also denoted as CMMS) [3] for the specific standard benchmark with trilinear coupling A_0=0, ratio of vacuum expectation values $\tan\beta$=3, Higgs–mixing parameter $\mu > 0$ in the plane of the universal scalar and gaugino mass parameters m_0–$m_{1/2}$. In Ref. [1]constraints are also discussed in terms of two of the conventional benchmarks within SUGRA models: those denoted by LM1 and LM0 (or SU4) in the literature [4–6]. Though these constraints depend on the specific sets of the mSUGRA parameters employed in the phenomenological analysis, the general outcome of Refs.[1, 2] is that the lower bounds on the squark and gluino masses are sizeably higher as compared to the previous limits established by the experiments D0 [7] and CDF [8] at the Tevatron.

In this paper we consider the implications of the results of Refs. [1, 2] for the supersymmetric scheme discussed in Refs. [9–11], *i. e.* for an effective MSSM scheme at the electroweak scale with the following independent parameters: $M_1, M_2, M_3, \mu, \tan\beta, m_A, m_{\tilde{q}}, m_{\tilde{l}}$ and A. Notations are as follows: M_1, M_2 and M_3 are the U(1), SU(2) and SU(3) gaugino masses (these parameters are taken here to be positive), μ is the Higgs mixing mass parameter, $\tan\beta$ the ratio of the two Higgs v.e.v.'s, m_A the mass of the CP-odd neutral Higgs boson, $m_{\tilde{q}}$ is a squark soft–mass common to all squarks, $m_{\tilde{l}}$ is a slepton soft–mass common to all sleptons, and A is a common dimensionless trilinear parameter for the third family, $A_{\tilde{b}} = A_{\tilde{t}} \equiv A m_{\tilde{q}}$ and $A_{\tilde{\tau}} \equiv A m_{\tilde{l}}$ (the trilinear parameters for the other families being set equal to zero). Since no gaugino-mass unification at a Grand Unified scale is assumed (at vari-

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ance with one of the major assumptions in mSUGRA), in this model the neutralino mass is not bounded by the lower limit $m_\chi \gtrsim 50$ GeV that is commonly derived in mSUGRA schemes from the LEP lower bound on the chargino mass (of about 100 GeV). In Refs.[9–11] it is shown that, if R-parity is conserved, a light neutralino (*i. e.* a neutralino with $m_\chi \lesssim 50$ GeV) is a very interesting candidate for cold dark matter (CDM), due to its relic abundance and its relevance in the interpretation of current experiments of search for relic particles; in Refs. [9–11] also a lower bound, $m_\chi \gtrsim$ 7-8 GeV, is obtained from the cosmological upper limit on CDM. The compatibility of these results with all experimental searches for direct or indirect evidence of SUSY (prior to the results of Refs.[1, 2]) and with other precision data that set constraints on possible effects due to supersymmetry is discussed in detail in Ref.[11]. The SUSY model described above will hereafter be denoted as Light Neutralino Model (LNM); within this model, the so-called *Scenario* $\mathcal{A}$ [11] will be considered in the present analysis. The main features of this scenario are: i) m_A must be light, 90 GeV $\leq m_A \lesssim (200 - 300)$ GeV (90 GeV being the lower bound from LEP searches); ii) $\tan\beta$ has to be large: $\tan\beta$ = 20–45, iii) the $\tilde{B} - \tilde{H}_1^\circ$ mixing needs to be sizeable, which in turn implies small values of μ: $|\mu| \sim (100 - 200)$ GeV. The purpose of this paper is to establish the novelties introduced by the outcomes of the recent CMS and ATLAS investigations on the features of the LNM, with special emphasis on the aspects concerning the neutralino as a CDM candidate. For detailed discussions of LNM models, see Refs. [9, 10] and especially Ref. [11].

First, we recall that the neutralino, defined as the linear superposition of bino $\tilde{B}$, wino $\tilde{W}^{(3)}$ and of the two Higgsino states $\tilde{H}_1^\circ$, $\tilde{H}_2^\circ$, $\chi \equiv a_1\tilde{B} + a_2\tilde{W}^{(3)} + a_3\tilde{H}_1^\circ + a_4\tilde{H}_2^\circ$, of lowest mass m_χ, is described within the minimal supersymmetric extension of the SM only through a subset of the SUSY model parameters, namely M_1, M_2, μ and $\tan\beta$. The neutral Higgs mass m_A and the slepton mass $m_{\tilde{l}}$ are instead crucial parameters intervening in the neutralino-nucleon scattering and in the neutralino pair-annihilation processes (and then also in the neutralino relic abundance) [9–11]. The three remaining parameters characterizing the LNM: M_3, $m_{\tilde{q}}$ and A, enter into play, when the large host of experimental results that constrain supersymmetry are implemented into the model [11]. This experimental information is derived from : 1) the searches at accelerators for Higgs bosons and supersymmetric charged particles (sleptons and charginos at LEP, squarks and gluinos at hadron colliders); 2) the B-meson rare decays at the Tevatron and the B-factories; 3) the muon anomalous magnetic moment; 4) the $b \to s\gamma$ decay. One further crucial requirement which guarantees that the neutralino can be interpreted as a relic particle in the Universe is that its relic abundance satisfies the cosmological bound $\Omega_\chi h^2 \leq (\Omega_{CDM} h^2)_{\rm max} \simeq 0.12$. All these data set significant constraints on the model parameters and also entail sizable correlations among some of them. In particular, various constraints and correlations involving the SUSY parameters follow from the loop correction terms, due to supersymmetry, that can affect the physical quantities involved in the items (2-4) above.

II. CORRELATIONS BETWEEN $m_{\tilde{q}}$ AND OTHER SUSY PARAMETERS WITHIN THE LNM

One of the most important constraints among those mentioned above is the one established by the branching ratio of the $b \to s + \gamma$ decay process. Indeed, in the LNM this branching ratio lies in its experimental range if the contribution of a loop diagram with a charged Higgs and the top quark is compensated by the contribution of a loop diagram with a chargino and a top squark [12]. Since our LNM (in *Scenario* $\mathcal{A}$) entails both a light charged Higgs (of mass $m^2_{H^\pm} \simeq m^2_A + m^2_W$) and a light chargino (of mass $m_{\chi^\pm} \sim \mu \sim$ 100-200 GeV), also $m_{\tilde{q}}$ has to be not too heavy. A strong correlation implied by the $b \to s + \gamma$ decay process between m_A (through $m_{H^\pm}$) and $m_{\tilde{q}}$ is shown in Fig. 1, where a scatter plot for a light neutralino population is represented by (black) dots when the $b \to s + \gamma$ constraint is not implemented, and by (red) crosses when this constraint is applied. In this second case it turns out that: i) $m_{\tilde{q}}$ and m_A are rather strongly correlated, ii) the squark mass is limited by the upper bound $m_{\tilde{q}} \lesssim 800$ GeV. Notice that the variation in the density of points of Fig. 1 is just due to a different sampling of the regions of interest in the parameter space. The relaxation of the $b \to s\gamma$ constraint is only considered here in connection with Fig. 1, for illustration purposes. This constraint is implemented in all our further discussions and results.

Since the lower bound on the neutralino mass, implied by the cosmological bound $\Omega_\chi h^2 \leq (\Omega_{CDM} h^2)_{\rm max}$, increases as m^2_A [11], the correlation between $m_{\tilde{q}}$ and m_A entails also a correlation between $m_{\tilde{q}}$ and m_χ, as displayed in Fig.2.

These correlations imply that a lower bound on $m_{\tilde{q}}$, derived from accelerator measurements could potentially have the consequence of increasing the lower bound on m_χ, as compared to the one of about 7–8 GeV, previously established within the LNM [11]. Thus, it is important to establish which lower limit on $m_{\tilde{q}}$ can be actually derived from the CMS and ATLAS results [1, 2].

Before we come to an analysis of this point, let us just

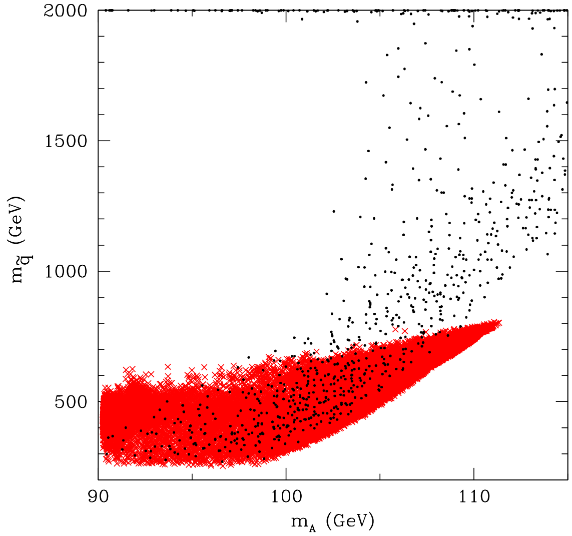

FIG. 1: Scatter plot of the light neutralino population shown in the plane $m_A - m_{\tilde{q}}$. For (black) dots the $b \to s + \gamma$ constraint is not implemented, while for (red) crosses the constraint is applied.

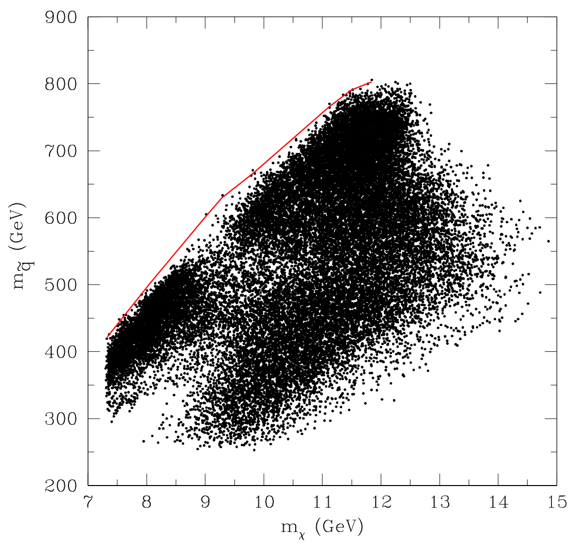

FIG. 2: Scatter plot of the light neutralino population shown in the plane $m_\chi - m_{\tilde{q}}$. The (red) line represents an interpolation of the lower boundary on m_χ as a function of $m_{\tilde{q}}$.

remark that a loop involving the chargino and the stop, as the one relevant for the $b \to s + \gamma$, is also responsible for a potentially sizable SUSY contribution to the branching ratio for the decay $B_s \to \mu^+ + \mu^-$. Indeed, this loop correction behaves as $\tan^6 \beta$ [13], thus, at large $\tan \beta$, it can overshoot the experimental upper bound: $BR(B_s \to \mu^+ \mu^-) < 5.8 \times 10^{-8}$ [14]. This can actually occur in SUGRA models, with the effect of constraining the neutralino phenomenology drastically [15]. In Ref. [11] it is shown that in the LNM this is not the case, since: (a) the chargino intervening in the relevant loop is light, and (b) the splitting in the top mass eigenstates can be small (a condition that is met whenever: $|A| \ll m_{\tilde{q}}/m_t$). This last requirement is exemplified by the lower frontier of the scatter plot of Fig. 3 displaying the correlation between A and $m_{\tilde{q}}$. In this figure the upper bound on $m_{\tilde{q}}$ is due, as already mentioned, to the bound on the $b \to s + \gamma$ decay. The point we wish to stress here is that, as shown in the numerical analysis of Ref. [11], the constraint imposed by the branching ratio for the decay $B_s \to \mu^+ + \mu^-$ is compatible with the constraints due to the branching ratio of the $b \to s + \gamma$ decay process, a feature which is not trivial, due to the different role played by the parameter $m_{\tilde{q}}$ in the two processes. However, it is clear from Fig. 3 that as the squark soft mass parameter $m_{\tilde{q}}$ gets close to its upper bound, the interplay of the two constraints entails a growing tuning of the A trilinear coupling for the highest values of $m_{\tilde{q}}$. In the same figure (black) dots show configurations for which all constraints are applied, while for (red) crosses the bound from $B \to \tau\nu$ measurements is not implemented. As discussed in Ref. [11], this latter bound is somewhat less robust than other constraints, due to the uncertainties affecting both theoretical estimates and experimental determinations related to B–meson decays. As can be seen from Fig. 3, when the $B \to \tau\nu$ constraint is not implemented the tuning affecting the trilinear coupling is eased and the upper bound on $m_{\tilde{q}}$ weakened.

III. LOWER LIMIT TO $m_{\tilde{q}}$ IMPLIED BY THE CMS AND ATLAS RESULTS WITHIN THE LNM

After appropriate cuts to reject the background and to reduce the probability of jet mismeasurements, the CMS search for events with jets and missing transverse energy derived an upper bound $N^{\rm CMS}_{\rm max} = 13$ events at 95% confidence level in the signal region for an integrated luminosity $\mathcal{L} = 35$ pb $^{-1}$. This upper bound is related to the total SUSY production cross section σ by the relation $N_{\rm max} = \epsilon \times \mathcal{L} \times \sigma$, where ϵ is the total efficiency due to selection cuts. In order to estimate $\epsilon_{\rm CMS}$ for the CMS signature we have simulated a few LNM benchmarks on the low–m_χ boundary shown in Fig. 2 using ISAJET [16], applying the same kinematic cuts as described in Ref. [1]. In this way we obtained the range $0.07 \lesssim \epsilon_{\rm CMS} \lesssim 0.2$ for the total efficiency, that can be used to convert $N^{\rm CMS}_{\rm max}$ into an upper bound $\sigma^{\rm max}_{\rm CMS}$ on the cross section, with $1.86\,{\rm pb} < \sigma^{\rm max}_{\rm CMS} < 5.31\,{\rm pb}$. On the other hand, the ATLAS collaboration searched for jets+missing transverse energy and one isolated electron or muon, and derived

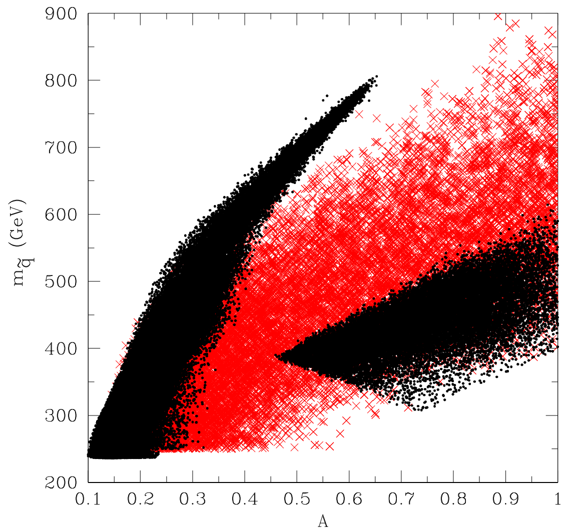

FIG. 3: Scatter plot of the light neutralino population shown in the plane $A - m_{\tilde{q}}$. (Black) dots show configurations for which all constraints are applied, while for (red) crosses the bound from $B \to \tau\nu$ measurements [11] is not implemented.

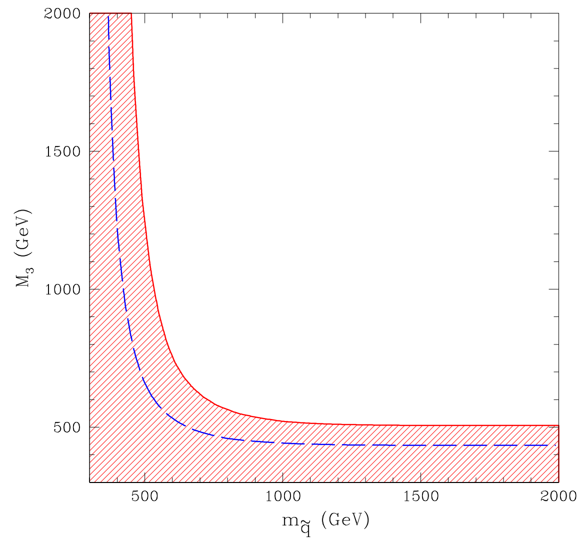

FIG. 4: Shaded area representing the region in the $m_{\tilde{q}}$-M_3 parameter space where the total SUSY production cross section at the LHC with $\sqrt{s} = 7$ TeV is larger than 1.86 pb, corresponding to the CMS upper bound of 13 SUSY events [1], and assuming an average total efficiency due to kinematic cuts equal to 0.2 for the LNM scenario. The (blue) dashed line represents the contour plot for $\sigma = \sigma_{\rm CMS}$= 5.31 pb, the value corresponding to the upper bound on the cross section when $\epsilon_{\rm CMS} = 0.07$ (see text).

an upper bound $N_{\rm max}^{\rm ATLAS}$= 2.2 events at 95% confidence level in the electron signal region (with a similar result in the muon channel) for the same integrated luminosity of CMS. Following the same procedure used for CMS and for the same LNM benchmarks, we estimated $\epsilon_{\rm ATLAS}$ for the ATLAS signature applying the same kinematic cuts as described in Ref. [2]. In this way we found the range $2 \times 10^{-4} \lesssim \epsilon_{\rm ATLAS} \lesssim 5 \times 10^{-3}$, that when converted into an upper bound on the cross section $\sigma_{\rm ATLAS}^{\rm max}$ implies $12.6\,{\rm pb} < \sigma_{\rm ATLAS}^{\rm max} < 314.3\,{\rm pb}$. Since $\sigma_{\rm ATLAS}^{\rm max} \gg \sigma_{\rm CMS}^{\rm max}$ we conclude that, within the LNM scenario, the CMS analysis is significantly more sensitive than that from ATLAS[1]. As a consequence of the above discussion, in the following we will concentrate only on the discussion of the CMS bound.

In Fig.4 the solid (red) line shows the contour plot for $\sigma = \sigma^{\rm CMS} = 1.86$ pb, while the dashed (blue) one represents the corresponding curve for $\sigma = \sigma^{\rm CMS} = 5.31$ pb; we have calculated the total SUSY production cross section for the process $p+p \to$ gluinos, squarks as a function of the squark mass $m_{\rm squark} \simeq m_{\tilde{q}}$ and the gluino mass M_3 using PROSPINO [17] with CTEQ-TEA CT10 Parton Distribution Functions [18]. The shaded area below the (red) solid line would be excluded adopting $\epsilon_{\rm CMS} = 0.2$ and represents the maximal impact of the CMS measurement on the LNM parameter space. It is important here to point out that, at variance with the SUGRA scenario, within the LNM model the gluino mass M_3 is not related to the other gaugino masses, and in particular to $m_\chi \simeq M_1$ by GUT relations. Moreover, M_3 enters in the calculation of observables for the relic neutralino only at the loop level (through radiative corrections of Higgs couplings [19]) so that within the LNM M_3 is very weakly correlated to the other parameters. This implies that within the LNM the absolute lower bound $m_{\tilde{q}} \gtrsim 450$ (370) GeV can be obtained from the contour plot of Fig. 4 by taking the limit $M_3 \to \infty$ and for $\epsilon_{\rm CMS} = 0.2(0.07)$.

IV. LOWER LIMIT TO m_χ IMPLIED BY THE CMS RESULTS WITHIN THE LNM FOR DEGENERATE SQUARK SOFT MASSES

As already mentioned before, within the LNM the $m_{\tilde{q}}$ parameter is correlated to the neutralino mass m_χ, as shown by the scatter plot of Fig.2. As a consequence, the lower bound on $m_{\tilde{q}}$ discussed in the previous Section can be converted into a lower bound on m_χ. This is shown as a function of M_3 in Fig.5, where the solid (red)

[1] We find that the particular suppression of $\epsilon_{\rm ATLAS}$ is due to the cut on the angle between the missing transverse momentum vector and the jets, applied by ATLAS to reduce the probability of jet mismeasurement [2].

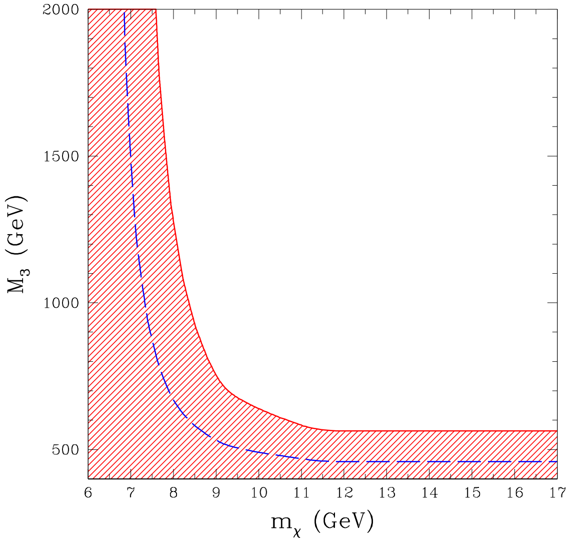

FIG. 5: Lower bound on the neutralino mass m_χ as a function of the gluino mass M_3, that can be derived from the CMS data [1] when soft mass parameters of squarks of the three families are assumed to be degenerate in the LNM. The solid (red) line is obtained adopting the efficiency $\epsilon_{\rm CMS} = 0.2$ and the dashed (blue) one corresponds to the case $\epsilon_{\rm CMS} = 0.07$.

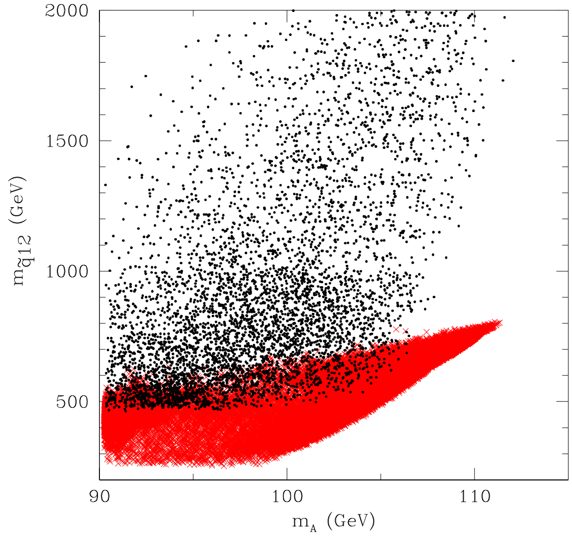

FIG. 6: Scatter plot of the light neutralino population in the plane m_A– m_{squark}. For (red) crosses the squark soft–mass parameters are assumed to be degenerate, $m_{\tilde{q}_{12}}$=$m_{\tilde{t}} \equiv m_{\tilde{q}}$, while for (black) dots $m_{\tilde{q}_{12}}$ and $m_{\tilde{t}}$ are allowed to float independently.

line corresponds to $\epsilon_{\rm CMS} = 0.2$ and the dashed (blue) one to $\epsilon_{\rm CMS} = 0.07$. In both cases the boundary shown in Fig. 2 has been used to convert the bound on $m_{\tilde{q}}$ into a limit on m_χ. Notice that, assuming degenerate soft squark masses, in the LNM the CMS limit can be combined to the upper bound $m_{\tilde{q}} < 800$ GeV obtained from the $b \to s + \gamma$ decay process to get the absolute limit $M_3 > 560$ (460) GeV for $\epsilon_{\rm CMS} = 0.2(0.07)$. For this reason the bound of Fig. 5 becomes a flat line for $m_\chi \gtrsim$ 11.8 (11.9) GeV. From this figure we also notice that the absolute lower bound on m_χ is 7.6 (6.8) GeV. This bound is increased to 11.8 (11.9) GeV when the gluino mass is close to its lower limit of 560 (460) GeV. In Fig. 5 the shaded area below the (red) solid line would be excluded adopting $\epsilon_{\rm CMS} = 0.2$ and represents the maximal impact of the CMS measurement on the LNM parameter space.

V. EXTENSION OF THE LNM BY REMOVING THE DEGENERACY IN $m_{\tilde{q}}$

According to the previous derivations we can conclude that, within the LNM described in terms of the eight SUSY parameters, the squark-mass parameter has to stay in the range (370) 450 GeV $\lesssim m_{\tilde{q}} \lesssim$ 800 GeV, with the further feature that in the high side of this range the model requires some fine-tuning. These properties are strictly related to the choice we have made before of taking a single soft mass parameter $m_{\tilde{q}}$ for all squarks; a choice originally taken to keep the number of SUSY parameters as low as possible. We consider here a minimal extension of the previous LNM, by removing this degeneracy in $m_{\tilde{q}}$. A natural (SUGRA-inspired) hierarchy among the soft squark masses might consists in introducing a common soft mass for the first two families, $m_{\tilde{q}_{12}}$, larger than the soft mass parameter for the third family, $m_{\tilde{t}}$. We expect this splitting to reduce the fine tuning discussed in the previous Sections because LHC physics is mainly sensitive to squarks of the first two families (which correspond to the flavors more abundant in colliding protons), while the dominant contribution to the $b \to s + \gamma$ decay is driven by the large Yukawa coupling of the top squark. This is confirmed by the scatter plot in Fig. 6, where (red) crosses represent the same configurations shown in Fig. 1 with $m_{\tilde{q}_{12}}$=$m_{\tilde{t}} \equiv m_{\tilde{q}}$, while (black) dots show configurations where $m_{\tilde{q}_{12}}$ and $m_{\tilde{t}}$ are allowed to float independently. In this latter case the $m_{\tilde{q}_{12}}$ parameter is no longer constrained from above for all values of m_A. As a consequence, in this case m_χ is no longer constrained by the CMS measurement.

An analysis of the capability of the LHC in exploring SUSY regions where the first generation squarks are very heavy compared to the other superpartners is performed in Ref. [20], but for models different from LNM.

VI. CONCLUSIONS

In this paper we have discussed the impact for light neutralinos in an effective Minimal supersymmetric extension of the Standard Model of the recent results presented by the CMS and ATLAS Collaborations at the CERN Large Hadron Collider for a search of supersymmetry in proton-proton collisions at a center-of-mass energy of 7 TeV with an integrated luminosity of 35 pb^{-1}. Within the LNM model we found that CMS is significantly more sensitive than ATLAS, due to the different signatures searched by the two experiments. In particular, we estimated a detection efficiency at CMS $0.07 \lesssim \epsilon_{\rm CMS} \lesssim 0.2$ after kinematic cuts, corresponding to an upper bound for the total SUSY production cross section that varies from 1.86 pb to 5.31 pb . Taking the limit $M_3 \gg m_{\tilde{q}}$ this implies an absolute lower bound of 450 (370) GeV for the squark mass when $\epsilon_{\rm CMS}$=0.2(0.07). If squark soft masses of the three families are assumed to be degenerate, we found that the combination of the CMS bound on the squark mass with the experimental constraints on the $b \to s + \gamma$ and the $B_s \to \mu^+ + \mu^-$ decays entail some tuning of the A trilinear coupling at high values of $m_{\tilde{q}}$. Moreover, when combining the CMS bound to the $b \to s + \gamma$ constraint the lower bound on the neutralino mass m_χ varies between 6.8 and 11.9 GeV, depending on the gluino mass. On the other hand, if the universality condition among squark soft parameters is relaxed the CMS measurement implies no constraint on the lower limit on m_χ, that remains at the value 7.5 GeV as derived in Ref. [11].

Acknowledgments

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