# The Next-to-Minimal Supersymmetric Standard Model: an overview

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We review the most important aspects of the NMSSM, discussing the impact of the NMSSM on low-energy observables, for dark matter, as well as NMSSM specific signatures at colliders. We also briefly consider constrained realisations of the NMSSM.

## 1 Supersymmetric extensions of the Standard Model

Among the many extensions of the Standard Model (SM) which aim at solving or easing its observational and theoretical shortcomings, supersymmetry (SUSY) is one of the most appealing possibilities. SUSY extensions of the SM offer a potential solution to the hierarchy problem, allow for radiative spontaneous electroweak (EW) symmetry breaking, and provide a possible link between the EW scale and the scale of soft-supersymmetry breaking ($M_{\mathrm{SUSY}}$). SUSY models are further motivated by an automatic unification of the running gauge coupling constants under simple SU(5) or SO(10) grand unified (GUT) models, at a scale $10^{16}$ GeV $\lesssim M_{\mathrm{GUT}} \lesssim 10^{17}$ GeV. If R-parity is conserved, the lightest SUSY particle (LSP) is stable; if neutral and colourless, it can be a candidate to explain the observed dark matter (DM) relic density of the Universe.

The minimal supersymmetric extension of the SM (MSSM) is defined by the following superpotential and supersymmetry soft-breaking Lagrangian

$$\mathcal{W} = Y_u\, \hat{H}_u\, \hat{Q}\, \hat{u} + Y_d\, \hat{H}_d\, \hat{Q}\, \hat{d} + Y_e\, \hat{H}_d\, \hat{L}\, \hat{e} + \mu\, \hat{H}_u \hat{H}_d\,, \tag{1}$$

$$-\mathcal{L}_{\mathrm{soft}} = m^2_{H_u}\, H_u^* H_u + m^2_{H_d} H_d^* H_d + (M_i \psi_i \psi_i + A_F Y_F H_i \tilde{F}\tilde{F}^* + B\mu H_u H_d + \mathrm{H.c.}) + ... \tag{2}$$

Other than squarks, sleptons and gluinos, the spectrum contains 2 charginos and 4 neutralinos, arising from the mixing of electroweak gauginos with the charged and neutral fermion components of the two Higgs superfields, $\hat{H}_d$ and $\hat{H}_u$. The Higgs sector is composed of 2 neutral scalars ($H_i$), one pseudoscalar $A$, and a pair of charged states $H^\pm$.

Despite its many appealing features, the MSSM suffers from phenomenological problems; among them, and deeply related to the Higgs sector, is the so-called "$\mu$-problem" [1]. The latter arises from the presence of a non-vanishing dimensionful term in the MSSM superpotential of Eq. (1), for which there are only two "natural" values: either 0, or then the typical scale at which the model is defined ($\sim M_{\mathrm{GUT,\,Planck}}$). However, and as we briefly discuss, neither possibility is viable. The non-observation of charginos at LEP puts a limit on their mass ($m_{\chi_1^\pm} \gtrsim 103$ GeV), and hence a lower bound on the SUSY conserving mass term, $\mu \tilde{h}_u \tilde{h}_d$, $|\mu| \gtrsim 100$ GeV. In any case, in order to ensure that the neutral components of both Higgs scalars develop non-vanishing vacuum expectation values (VEVs), $\mu \neq 0$. Moreover, a correct EW symmetry breaking implies that the SUSY conserving $\mu$ term cannot be excessively large: the $\mu$-induced mass squared for $H_u$ and $H_d$ (always positive) must not dominate over the negative soft breaking masses, which further precludes $\mu \sim M_{\mathrm{GUT,\,Planck}}$. Everything taken into account, $\mu$ must be of order of the soft SUSY breaking scale, $|\mu| \sim \mathcal{O}(M_{\mathrm{SUSY}})$, which is a very unnatural scenario.

An elegant and yet simple way to solve this problem consists in the addition of a superfield to the MSSM content, and in taking a scale-invariant superpotential where only trilinear dimensionless couplings are present. The required non-vanishing bilinear mass term for the Higgs can then be effectively generated from the VEV of the new scalar field (necessarily a singlet since the $\mu$-parameter is gauge invariant): $\mu^{\mathrm{eff}} = \lambda \langle S \rangle$. This is the so-called Next-to-Minimal supersymmetric standard model (for a recent review, see [2]).

## 2 The Next-to-Minimal Supersymmetric Standard Model

In its simplest form, the Next-to-Minimal supersymmetric standard model (NMSSM) is described by the superpotential

$$\mathcal{W}^{\mathrm{NMSSM}} = Y_u\, \hat{H}_u\, \hat{Q}\, \hat{u} + Y_d\, \hat{H}_d\, \hat{Q}\, \hat{d} + Y_e\, \hat{H}_d\, \hat{L}\, \hat{e} + \lambda\, \hat{S}\, \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa\, \hat{S}^3\,. \tag{3}$$

In the soft breaking Lagrangian, the $B\mu$ term is replaced by trilinear couplings, $A_\lambda$ and $A_\kappa$, and there is an additional soft breaking mass for the scalar, $m_S^2$. Phenomenologically viable values of $\mu_{\mathrm{eff}}$ can be easily obtained with negative soft SUSY breaking mass squared (and trilinear couplings) for the singlet. It is also important to stress that in this case, all the fermions belonging to a chiral superfield will have a supersymmetry conserving mass term in the Lagrangian arising from a trilinear (Yukawa) coupling. In particular, for the case of the higgsinos, one finds $\lambda \tilde{h}_u \tilde{h}_d S$. Since it allows for a scale invariant superpotential, as can be seen from Eq. (3), the NMSSM is in fact the simplest supersymmetric generalization of the SM in which the SUSY breaking scale is the only scale in the Lagrangian (notice that the EW scale originates exclusively from the SUSY breaking scale).

The scalar components of the singlet superfield mix with the neutral scalar components of $\hat{H}_u$ and $\hat{H}_d$, leading to an enlarged Higgs sector, which now comprises three scalars, $h_i^0$, and two pseudoscalars, $a_i^0$. Likewise, the fermionic component of $\hat{S}$ (the singlino, $\chi_S^0$) mixes with the neutral higgsinos and gauginos, so that now one has five neutralinos. Depending on the regime considered, the new states can either decouple from the rest of the spectrum (an "effective"-MSSM scenario), be mixed with the MSSM states, or even be the lightest Higgs and neutralino. One can thus have a richer and more complex phenomenology, with a potential impact for low energy physics (e.g. flavour physics), dark matter scenarios and searches at colliders.

## 3 Higgs phenomenology in the NMSSM

When compared to the MSSM, the additional states and the new couplings of the NMSSM can significantly alter the phenomenology of scalar and pseudoscalar Higgs: in the NMSSM, both $h_1^0$ and $a_1^0$ can be very light, and still comply with all collider and low-energy bounds. Firstly, if the lightest scalar has a dominant singlet component, its reduced couplings to the $Z$ boson ($\xi^Z \equiv g_{h_1 ZZ}/g^{\mathrm{SM}}_{HZZ}$) can be much smaller than in the MSSM [3]. As can be seen from the left panel of Fig. 1, depending on the value of $\xi^Z$ ($\xi = \xi^Z$), extremely light Higgs can still be in agreement with the combined results from the four experiments at LEP II.

Higgs-to-Higgs decays are an extremely interesting and peculiar feature of the NMSSM: in particular, in the presence of a light (singlet-dominated) pseudoscalar, a SM-like $h_1^0$ ($\xi^Z = 1$) can have dominant decays into a pair of light $a_1^0$ (thus reducing the $h_i^0 \to b\bar{b}$, $\tau^+\tau^-$ branching ratios). Should this be the case, then one can have $m_{h_1^0} \lesssim 114$ GeV, still in agreement with

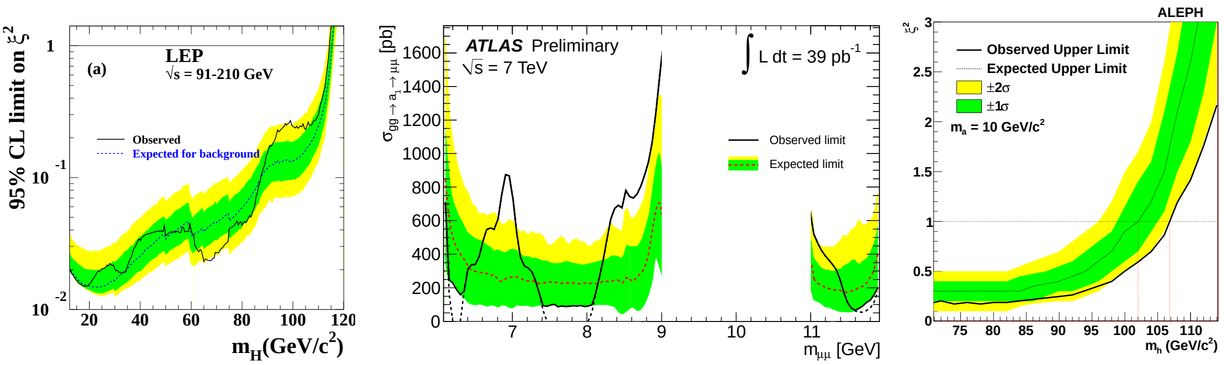

Figure 1: From left to right: upper bound on $\xi^2$ $(= {\xi^Z}^2)$ as a function of the scalar Higgs mass; upper limits on $\sigma(gg \to a_1 \to \mu\mu)$ as a function of the dimuon invariant mass; upper bound on $\xi^2$ $(= {\xi^A}^2)$ as a function of $m_H$, for $m_a = 10$ GeV.

LEP data[4,5]. Depending on the mass of $a_1^0$, it can decay to $b\bar{b}$, or into a pair of charged leptons. There are presently strong constraints on a light pseudoscalar, which we briefly summarise: for $m_{a_1^0} \gtrsim 2m_B$, LEP searches for $h_1^0 \to a_1^0 a_1^0 \to 4b$ strongly constrain $m_{h_1^0} \lesssim 100$ GeV; below the $b\bar{b}$ threshold, the most important constraints arise from $B$ and $\Upsilon$ phenomenology, with KLEO and BABAR severely constraining the regimes leading to $m_{a_1^0} \lesssim 9$ GeV (the actual bounds depending on $X_d = \cos\theta_A \tan\beta$, where $\cos\theta_A$ denotes the doublet-like component of $a_1^0$)[6]. This has been reinforced by recent ATLAS searches for a light pseudoscalar decaying into $\mu\mu$ pairs[7], as shown on the centre plot of Fig. 1. An NMSSM pseudoscalar with a mass 9 GeV $\lesssim m_{a_1^0} \lesssim 10.1$ GeV satisfies all available constraints and, if such a light state mixes with the $\eta_b$ meson, it could also explain the observed $\Upsilon(1s) - \eta_b(1s)$ hyperfine splitting[8]. On the right hand-side of Fig. 1 we display the ALEPH bounds, under the assumption that a light pseudoscalar, $m_{a_1^0} \sim 10$ GeV, is present (in this case, ${\xi^A}^2 = \frac{\sigma(e^+e^-\to Zh)}{\sigma(e^+e^-\to Zh)_{\mathrm{SM}}} \times \mathrm{BR}(h \to aa) \times \mathrm{BR}(a \to \tau^+\tau^-)^2$).

As pointed out in[9], for $m_{a_1^0} \sim 10$ GeV, and if $\mathrm{BR}(a_1^0 \to \tau^+\tau^-) \sim 80\%$ (i.e., ${\xi^A}^2 \lesssim 0.5 - 0.6$), LEP data allows a SM-like CP-even Higgs with $m_{h_1^0} \sim 100$ GeV. This interesting NMSSM regime offers the possibility to reconcile LEP Higgs searches with EW precision measurements, the latter strongly favouring $m_H \sim 100$ GeV.

Finally, it is interesting to remark that the NMSSM also offers two possible explanations for the slight excess of events ($\sim 2.3\,\sigma$) observed at LEP for $m_H \sim 95 - 100$ GeV: either the lightest Higgs has a non-vanishing singlet component[10] (leading to $\xi^Z \sim 0.4$, as can be infered from the left panel of Fig. 1), or it is indeed SM-like, but dominantly decays into a pair of light pseudoscalars[9], as discussed above.

On the theoretical side, it is also relevant to notice that in the NMSSM the mass of the SM-like Higgs can be larger than in the MSSM[11]: for large values of $\lambda$ (but $\lambda \lesssim 0.7$ to avoid a Landau pole below $M_{\mathrm{GUT}}$) and in the low $\tan\beta$ regime, one can have $m_{h_1^0} \sim 140$ GeV, where $h_1^0$ has SM-like couplings to fermions and gauge bosons ($h_1^0 \sim H^{\mathrm{SM}}$). In the limit where the lightest Higgs is singlet-like ($\xi^Z \to 0$), $h_2^0$ behaves as $H^{\mathrm{SM}}$, its mass being no larger than the above mentioned bound. However, in scenarios of maximal mixing between doublet and singlet-like states, one can have $m_{h_1^0} \gtrsim 110$ GeV and $m_{h_2^0} \lesssim 162$ GeV, stil in agreement with LEP data. Moreover, should $h_1^0$ be singlet-like and decay unconventionally (e.g. $h_1^0 \to a_1^0 a_1^0 \to 4b$), then the upper bound on the mass of the SM-like $h_2^0$ can be even further relaxed. For these regimes, Tevatron exclusion results[12] already apply to part of the NMSSM parameter space (contrary to the MSSM case).

By relaxing the upper bound on the lightest Higgs boson, and allowing for regimes where a light SM-like Higgs is still in agreement with LEP bounds, the NMSSM also renders less severe the so-called "Higgs little fine tuning problem" of the MSSM, which is related to the non-observation of a light Higgs state at LEP. In the MSSM, the mass of the lightest Higgs state is bounded from above: at tree level $m_{h_1^0} \lesssim M_Z |\cos 2\beta|$, and while the inclusion of radiative corrections allows to relax this bound, one still has $m_{h_1^0} \lesssim 130 - 135$ GeV (the limits being model dependent, and for a sparticle spectrum no heavier than a few TeV). The allowed interval for the mass of the lightest MSSM Higgs scalar is thus considerably narrower than in the NMSSM.

## 4 LHC search strategies

Having an extended and more complex Higgs sector[a] does not imply that detection of an NMSSM Higgs boson will be easier at the LHC. In the previous section we have seen that NMSSM Higgs might have escaped LEP detection, either due to non-standard couplings to SM fermions and gauge bosons, or in the presence of Higgs-to-Higgs decays. NMSSM searches at the LHC must strongly build upon LEP's lessons: the new, distinctive features of the NMSSM, especially concerning the Higgs sector, must be taken into account in devising strategies, for instance for ATLAS and CMS. The different production processes, new intermediate states in cascade decays, and unusual final-state configurations might require dedicated studies and simulations.

If Higgs-to-Higgs decays are kinematically forbidden (or marginally allowed, but with tiny branching ratios), then NMSSM Higgs searches can be carried out as in the MSSM[13]. Different couplings and new (loop) corrections should be taken into account in a (re)-evaluation of the expected production cross sections and decay rates. For some regimes, the Higgs sector can be more visible than in the MSSM (e.g., as shown in [14], up to 3 Higgs - $h^0_{1,2}$ and $a^0_1$ - can be observed, from the decays into 2 photons). Recently, it was noticed that light NMSSM Higgs, with a mass 80-100 GeV (in agreement with LEP constraints due to a large singlet component) may have a $\mathrm{BR}(h^0_1 \to \gamma\gamma)$ considerably larger than a SM-like Higgs of similar mass, $\sigma(gg \to h^0_1 \to \gamma\gamma) \sim 6 \times \sigma(gg \to H^{\mathrm{SM}} \to \gamma\gamma)$, due to a reduced coupling to $b$ quarks[15].

In recent years, many efforts have been put forward to generalise the "No-lose" theorem of the MSSM to the NMSSM: under the assumption that Higgs-to-Higgs decays are kinematically forbidden, it has been established that at least one of the NMSSM Higgs bosons can be detected at the LHC with 600 $\mathrm{fb}^{-1}$ of integrated luminosity[16].

However, not only Higgs-to-Higgs decays can occur in large regions of the NMSSM parameter space, but they also constitute one of the most interesting features of this model. If these decays are indeed present, Higgs searches at the LHC (and at the Tevatron) can be considerably more complicated, and many new channels have been considered, for the different $m_{a^0_1}$ regimes. Here we briefly comment on some dedicated strategies for regions in parameter space where the dominant decays of (light) Higgs are $h^0_1 \to a^0_1 a^0_1$, and $a^0_1 \to \tau\tau$. (For $m_{a^0_1}$ above the $b\bar{b}$ threshold, see for instance[17].) In general, it can be quite challenging to identify the four leptons in these decay modes, and final states containing as much as 8 neutrinos imply signatures of large missing energy. SM backgrounds will also be important (heavy flavour jets, vector boson and light jets, $\Upsilon$ production, etc.).

The $h^0_1 \to a^0_1 a^0_1 \to 4\tau$ channel, with the taus decaying into muons and jets, has been analysed in[18], resorting to both Higgs-strahlung (triggering on leptonic decays of $W^\pm$), and vector boson fusion (triggering on two same sign non-isolated muons). While the latter may yield a larger number of events, the former can lead to very clean, almost background free signals, so that in both cases there is a significant potential for discovery. In regions where $a^0_1 \to \mu\mu$, the $2\mu$ ($4\mu$) invariant mass allows a direct estimation of $m_{a^0_1}$ ($m_{h^0_1}$); furthermore, the extremely

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[a] We will not discuss here the impact of an extended neutralino sector for sparticle production and decay at colliders.

small background allows to rely on direct $gg$ and $b\bar{b}$ fusion for Higgs production (instead of the subdominant vector boson fusion)[19]. If the lightest Higgs is produced via central exclusive production, $pp \to h_1^0 \to p + h_1^0 + p$ (with $h_1^0 \to a_1^0 a_1^0 \to 4\tau$), the prospects for observing such an NMSSM Higgs at the LHC are good, and one could determine $m_{h_1^0}$ and $m_{a_1^0}$ on an event-to-event basis. However, this would require installing forward detectors to measure the final state protons[20]. Finally, for regimes of very low $\tan\beta$ ($\tan\beta \lesssim 2$), most of LHC (and Tevatron) discovery prospects must be reconsidered: in such regimes for $\tan\beta$, $\mathrm{BR}(a_1^0 \to \tau^+\tau^-)$ becomes increasingly reduced (accompanied by an increase of $\mathrm{BR}(a_1^0 \to gg + c\bar{c})$), so that the light pseudoscalar easily evades both ALEPH and meson physics constraints (due to small $\xi^{A^2}$ and $X_d$). However, this also implies that searches using the $a_1^0 \to \tau\tau$ and $a_1^0 \to \mu\mu$ modes will be more difficult. Nevertheless, dedicated searches at the LHC and Tevatron include direct detection of $a_1^0$ in $gg \to a_1^0 \to \mu\mu$ channel (as wel as in the other channels mentioned before)[9].

Light singlet-like Higgs are very difficult to detect (due to the smallness of their couplings). It has been noticed that in this case the process $pp \to h_1^0 +$ resolved jet $\to \tau^+\tau^- +$ jet (via gluon fusion) could allow for LHC detection with $\sqrt{s} = 14$ TeV[21].

In NMSSM scenarios with a light doublet-like CP-odd Higgs boson, the charged Higgs can be lighter than the top quark, dominantly decaying as $h^\pm \to a_1^0 W^\pm$. The search for subleading $a_1^0$ decay modes (into a pair of muons) could provide evidence for the charged Higgs, or even a discovery, with early LHC data[22]. Other channels, which are absent in the MSSM, and that deserve further investigation are, for example, $gg \to a_2^0 \to h^\pm W^\mp$ (where the $a_2^0$ has an important singlet component)[23].

It is important to re-emphasise that the discovery of MSSM-like Higgs and neutralinos does not necessarily establish that the MSSM is indeed at work: disentangling the NMSSM from the MSSM might be challenging, especially in regimes where the new states decouple and/or in the absence of a singlino LSP. In this case additional studies might be required, and unravelling the nature of the SUSY model will strongly depend on the precision of the experimental data.

## 5 Implications for Dark Matter

Due to the differences in the neutralino and Higgs sectors of the NMSSM, one can have dark matter scenarios that are very distinct from the MSSM. Depending on the regions of the parameter space, the LSP can be singlino-like (or have an important singlino component). The additional scalar and pseudoscalar Higgs bosons can have in impact on the processes leading to LSP annihilation, so that the correct relic density can be obtained in large regions of the parameter space[24]: the extra states can offer rapid annihilation via new s-channel resonances, and if light, new final states can be kinemmatically open (e.g. annihilation into $Zh_1^0$, $h_1^0 h_1^0$, $h_1^0 a_1^0$ and $a_1^0 a_1^0$). For instance, nearly pure binos can efficiently annihilate via $h_1^0$ resonances into a pair of light $a_1^0 a_1^0$. Provided there is a small higgsino component, a singlino LSP can also rapidly annihilate via the latter process and co-annihilations with heavier neutralinos, or with a nearly degenerate NLSP, are also possible. A singlino LSP can also be instrumental in recovering MSSM scenarios with a charged LSP (e.g., the lightest stau for $m_0 \ll M_{1/2}$ in the constrained MSSM).

Dark matter detection prospects can also be significantly different[b]. As discussed in[25] light NMSSM neutralinos (with a mass below the MSSM lower bound) may have an elastic scattering cross section on nucleons allowing to explain recent direct detection results (DAMA/LIBRA, CoGeNT or CDMS), provided that the spectrum contains light scalar and pseudoscalar Higgs.

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[b] This topic was also addressed in the talks of A. Goudelis and T. Delahaye.

## 6 A simple and predictive model: the constrained NMSSM

Assuming that supersymmetry is spontaneously broken in a hidden sector, and that the mediation of SUSY breaking to the observable sector occurs via flavour blind interactions (as is the case of minimal supergravity models), all soft SUSY breaking terms will be universal at some very large scale (e.g., $M_{\mathrm{GUT}}$). The scale invariant NMSSM with universal soft breaking terms is denoted the fully constrained NMSSM (cNMSSM)[26], and is one of the most appealing SUSY extensions of the SM, both for its simplicity and predictivity.

Other than the gauge and quark/lepton Yukawa couplings, the Lagrangian of the cNMSSM depends on five parameters - $m_0^2$, $M_{1/2}$, $A_0$, $\lambda$ and $\kappa$ -, the correct EW symmetry breaking reducing the parameter space from five to four degrees of freedom. However, phenomenological arguments strongly constrain the parameter space, as we proceed to briefly explain.

In order to generate a non-vanishing singlet VEV (as required by the lower bound on the effective $\mu$-term ($|\mu| \gtrsim 100$ GeV), the singlet soft breaking mass $m_S^2$ must not be too large. Since $m_S$ is hardly renormalised between the GUT and the EW scales, its value at $M_{\mathrm{GUT}}$, given by $m_0$, must also be small (compatible with $m_0 \sim 0$). While in the cMSSM a regime where $m_0 \lesssim 1/5\, M_{1/2}$ would lead to a charged LSP (the lightest stau), in the cNMSSM the additional singlino-like neutralino can be lighter than $\tilde{\tau}_1$, so that a viable dark matter candidate can be recovered for very small or even vanishing values of $m_0$. An efficient reduction of the LSP abundance can only be achieved via co-annihilations with the stau NLSP, requiring nearly degenerate LSP and NLSP ($m_{\tilde{\tau}_1} - m_{\chi_S^0} \sim$ few GeV), which implies that $A_0 \sim -1/4\, M_{1/2}$ (and furthermore $m_0 \leq 1/10\, M_{1/2}$). Under such a regime for the soft breaking parameters, LEP constraints on the Higgs sector imply that $\lambda$ must be also very small, $\lambda \lesssim 0.02$. Provided $\lambda$ is not excessively small ($\lambda \gtrsim 10^{-5}$, to allow for co-annihilation), the resulting phenomenology is largely independent of its exact value. Thus, as depicted on the left panel of Fig. 2, the parameter space of the fully constrained NMSSM is essentially determined by $M_{1/2}$ ($\tan\beta$, no longer a free parameter, is quite large, $\tan\beta > 25$). Collider constraints lead to $M_{1/2} \gtrsim 500$ GeV, while the requirement that SUSY contributions account for the discrepancy of the measured muon anomalous magnetic moment with respect to the SM prediction favours $M_{1/2} \lesssim 1$ TeV[27].

Concerning the Higgs sector of the cNMSSM, and for increasing values of $M_{1/2}$, the lightest state can be singlet-like, a doublet-singlet mixture and, for large $M_{1/2}$, SM-like (the actual cross-over range depending on the value of $m_0$). The lightest pseudoscalar (always heavier than $h_{1,2}^0$) is singlet-like, while $h_3^0$, $a_2^0$ and $h^{\pm}$ are significantly heavier and nearly degenerate. Interestingly, just below the singlet-doublet cross-over for $h_{1,2}^0$, the cNMSSM can actually account for the two LEP "excesses", with a singlet-like $h_1^0$ with mass around 100 GeV and a SM-like $h_2^0$ around 117 GeV. The cNMSSM strongly interacting sparticle spectrum, displayed on the right hand-side of Fig. 2, is quite heavy (typically $m_{\tilde{g},\tilde{q}} \gtrsim 1$ TeV), with the gluino always heavier than all squarks (and sleptons). As seen from Fig. 2, the measurement of one sparticle mass (or mass difference) would allow to predict quite accurately the remaining sparticle spectrum.

Having a singlino LSP, nearly degenerate with the NLSP, leaves a striking imprint on cNMSSM decay chains: due to the weakly coupled singlino-like LSP, all sparticle branching ratios into $\chi_S^0$ are tiny, and thus sparticles first decay into the stau NLSP. As an example, the simplest squark cascades typically are $\tilde{q} \to q\chi_2^0 \to q\tilde{\tau}_1\tau \to q\tau\tau\chi_S^0$. Hence, practically all cascade decays will go via $\tilde{\tau}_1$, leading to two $\tau$'s per decaying squark. For very small $\lambda$, or a very small NLSP-LSP mass difference, the stau lifetime can be so large that its decay vertices are visibly displaced, $\mathcal{O}$(mm - cm), a "smoking-gun" for the cNMSSM. All the above features should in principle allow to discriminate the cNMSSM from most realisations of the MSSM.

Another very appealing feature of the cNMSSM is that it can be easily ruled out. Detection of a singlino LSP relies on its non-singlet component, which is $\mathcal{O}(\lambda)$; hence direct detection (LSP-nucleon) cross sections are extremely small, and indirect detection of the products of

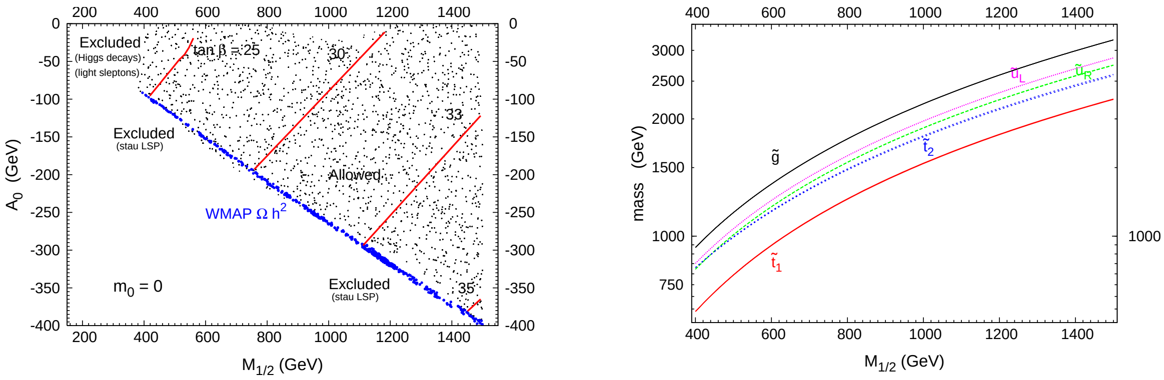

Figure 2: On the left, cNMSSM parameter space: experimentally allowed regions (scatter points) and imposing the correct DM relic density (blue). On the right, cNMSSM gluino and squark spectrum as a function of $M_{1/2}$.

LSP annihilation also appears impossible. Thus, the direct or indirect detection of a weakly interacting massive particle allows to exclude the cNMSSM.

The prospects for cNMSSM discovery at the LHC have been discussed in [28]. The dominant sparticle production modes are squark-gluino and squark pair production. Regarding the SM-like Higgs $h^0_{1,2}$, the most relevant production processes will be gluon-gluon and vector boson fusion, $gg \to$ Higgs and $qq \to qq$+Higgs, with the Higgs decaying into two photons (possibly $\tau^+\tau^-$ in the vector boson fusion process). The heavier non-singlet Higgs can be observed in associated production with $b\bar{b}$ pairs while, apart from the “cross-over” region, the singlet-like Higgs states are generally inaccessible. Dedicated cNMSSM cuts suggest that for the LHC operating at $\sqrt{s} = 14$ TeV, and for an integrated luminosity of 1 fb$^{-1}$, the signal-to-background ratio already allows for the discovery of the cNMSSM in the lower $M_{1/2}$ regime, while more luminosity will be required in the case of a heavier spectrum. Furthermore, the cNMSSM can be distinguished from the MSSM in the stau co-annihilation region.

## 7 Outlook

The NMSSM is a very interesting SUSY extension of the SM, solving in an elegant way the “$\mu$-problem” of the MSSM, and rendering its “Higgs little fine tuning problem” less severe. Since it allows for a scale invariant superpotential, the NMSSM is the simplest supersymmetric model in which the SUSY breaking scale is the only scale in the Lagrangian.

The extended Higgs and neutralino sectors of the NMSSM have an impact regarding low-energy observables (such as $B$ physics), dark matter prospects and collider phenomenology. Concerning the latter, the NMSSM allows to accommodate LEP constraints easier than the MSSM. In particular, the upper bound on the mass of the SM-like Higgs boson is relaxed, and the lightest Higgs scalar and pseudoscalar can be quite light (either due to an important singlet component, or to unconventional decays, such as $h \to aa$). Unconventional Higgs decay scenarios require dedicated studies and simulations. At present many studies are under way to ensure that at least one NMSSM Higgs will be observed at the LHC. The absence of a “No-lose” theorem should be kept in mind: a non-discovery of a Higgs boson at the LHC (potentially excluding scenarios as the cMSSM) could be a signal of the NMSSM.

The cNMSSM is perhaps one of the most simple and yet most predictive supersymmetric extensions of the SM since, in addition to all the appealing features of the NMSSM, its phenomenology is essentially described by one parameter, $M_{1/2}$. The cNMSSM predicts a heavy sparticle spectrum, with a $\tilde{\tau}_1$ appearing in all cascades, leading to a singlino-like LSP. The model can be discovered at the LHC, and be easilly ruled out by dark matter detection.

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