STATUS OF SUPERSYMMETRY WITH EXTRA SINGLETS

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We show that, in supersymmetry with extra singlets, it is easy and natural to obtain a mass of the SM scalar of ~125 GeV, well above M_Z. Moreover, several mecanisms can enhance the signal rate w.r.t. the Standard Model in the gamma gamma channel. These properties persist in various singlet extensions of the MSSM, which are briefly scetched, as well as correlations among signal rates in different channels. We discuss additional scalars in supersymmetry with extra singlets and, finally, the impact of an extra singlet (singlino) on searches for supersymmetry.

1 The SM scalar mass in supersymmetry with extra singlets

In the Standard Model (SM), the "mexican hat" potential of the complex SM scalar H is given by

$$V(H) = -m^2|H|^2 + \lambda^2|H|^4 \ . \tag{1}$$

Denoting the vacuum expectation value of the real component h of H by $v =< h >$, the tree level mass M_h^2 of the physical state h can be expressed in terms of v:

$$M_h^2 = -m^2 + 3\lambda^2 v^2 = 2\lambda^2 v^2 \tag{2}$$

The second expression is more useful, since we know v from the known W and Z masses. We see that M_h is proportional to quartic coupling λ; if we would have known the coupling λ, we could have predicted the SM scalar mass M_h.

In supersymmetry (Susy), various dimensionless couplings are related at tree level (even if supersymmetry is softly broken by mass terms of $\mathcal{O}(M_{\rm SUSY}) \sim v$).

In the Minimal Supersymmetric extension of the SM (MSSM), we have two SU(2) doublets H_u and H_d which couple to up-quarks and down-quarks/leptons, respectively. Now the quartic terms in the potential $V(H_u, H_d)$ are given by the electroweak gauge couplings g_1 and g_2:

$$V(H_u, H_d) = \frac{g_1^2 + g_2^2}{2}(H_u^2 - H_d^2)^2 + ... \tag{3}$$

In the MSSM we find two physical neutral CP-even scalars conventionally denoted by h and H. Their masses have to be obtained by diagonalising a 2×2 mass matrix of second derivatives of $V(H_u, H_d)$. We have less information on the vacuum expectation values v_u, v_d of H_u, H_d, since we know only $\sqrt{v_u^2 + v_d^2}$ from the W and Z masses, but not their ratio $\tan\beta = \frac{v_u}{v_d}$.

However, one can still derive an upper tree level bound on the mass M_h of the lighter scalar:

$$M_h^2 = \frac{g_1^2 + g_2^2}{2}\sqrt{v_u^2 + v_d^2}\cos^2 2\beta \equiv M_Z^2 \cos^2 2\beta \le M_Z^2 \tag{4}$$

This obviously violated inequality (in view of the measured mass of ~ 125 GeV) gets modified if radiative corrections to $V(H_u, H_d)$ are large enough. However, therefore one needs large ($\gtrsim 1$ TeV) Susy breaking top squark masses and/or large trilinear top squark–scalar couplings A_{top}, which can be considered as unnatural.

We recall that the origin of the problem is that, in the MSSM, no supersymmetric quartic couplings for H_u and H_d exist, except for the ones induced by the SUSY gauge interactions.

On the other hand, a supersymmetric mass term μ for the components of H_u and H_d has to exists: it is required for the (neutral and charged) higgsino masses $\mu\Psi_{H_u}\Psi_{H_d}$ (charged higgsinos with mass below ~ 100 GeV are excluded by LEP). This mass term also contributes to $V(H_u, H_d)$, but not to M_h! Its order of magnitude has to be $\mu \sim \mathcal{O}(M_{\rm SUSY}) \sim v$ which is difficult to explain; this is the so-called "μ-problem".

In supersymmetry with extra singlet(s), one generates a μ-term through the vacuum expectation value of an extra scalar singlet S with $\langle S \rangle = v_s$:

$$\mu\Psi_{H_u}\Psi_{H_d} \to \lambda S \Psi_{H_u}\Psi_{H_d} \to \lambda v_s \Psi_{H_u}\Psi_{H_d} \tag{5}$$

where v_s of $\mathcal{O}(M_{\rm SUSY})$ is automatic due to the soft Susy breaking terms involving S.

As an additional benefit one obtains an extra quartic coupling $\lambda^2 H_u^2 H_d^2$ due to supersymmetry, and thus a larger mass $M_h > M_Z$ at tree level!

With one extra singlet (the Next-to-Minimal Supersymmetric Standard Model, NMSSM) one ends up with three neutral CP-even scalars which are superpositions of H_u, H_d and S. Now their masses have to be obtained by diagonalising a 3×3 mass matrix. The tree level mass of the mostly SM like scalar h_{SM} is

$$M_{h_{SM}} = M_Z^2 \cos^2 2\beta + \lambda^2 (v_u^2 + v_d^2) \sin^2 2\beta \pm (...) \tag{6}$$

where $\pm(...)$ originates from mixing of h_{SM} with the mostly singlet like scalar h_s, which depends on unknown parameters. This contribution is positive if $M_{h_s} < M_{h_{SM}}$!

Hence, $M_{h_{SM}} > M_Z$ much easier to obtain than in the MSSM, no large radiative corrections (heavy top squarks) are required for $M_{h_{SM}} \sim 125$ GeV.

2 Impact on the diphoton signal rate, and variants of the NMSSM

In fact, in the NMSSM two distinct mechanisms can lead to an enhancement of the diphoton signal rate of the 125 GeV SM scalar. First we recall the expression for the branching fraction $BR(H \to \gamma\gamma)$ in terms of the partial widths Γ:

$$BR(H \to \gamma\gamma) = \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to bb) + \ldots} \tag{7}$$

where the denominator represents the total width of H, which is dominated by the partial width $\Gamma(H \to bb)$.

Now, due to the mixing of H_u, H_d, S it is easily possible that, in the NMSSM, the mostly SM–like scalar h_{SM} has a reduced coupling to bb, and hence a reduced width $\Gamma(h_{SM} \to bb)$ which leads to an enhanced $BR(h_{SM} \to \gamma\gamma)$. Together with nearly SM–like couplings to the top quark (whose loops induce the coupling to gluons) and to the electroweak gauge bosons, one finds that the production rates in gluon fusion and/or VBF are hardly reduced. As a result, the diphoton signal rate is enhanced—a possibility observed already in 2010 [1].

Second, we recall that in the SM, $\Gamma(h_{SM} \to \gamma\gamma)$ is induced via W-boson (and top quark) loops as shown in Fig. 1.

In the NMSSM, the singlet S couples to the (charged) higgsinos Ψ_{H_u}, Ψ_{H_d} via $\lambda S \Psi_{H_u}\Psi_{H_d}$ (recall the generation of the μ–term through $\langle S \rangle$). Hence, if h_{SM} has a S-component, charged higgsinos contribute also to the loop and to $\Gamma(h_{SM} \to \gamma\gamma)$ unless λ is small or the higgsinos are heavy!

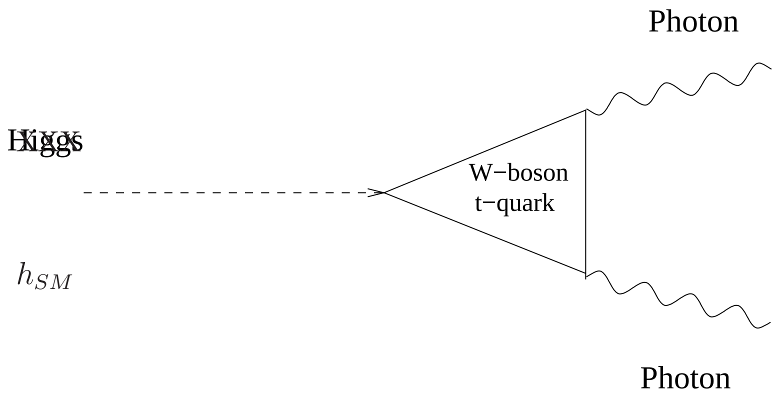

Figure 1: $\Gamma(h_{SM} \to \gamma\gamma)$ induced via W-boson (and top quark) loops

Both mechanisms for the enhancement of the $h_{SM} \to \gamma\gamma$ signal rate can occur in many variants of singlet extensions of the MSSM (see[2,3] and refs. therein):

- The "singlet" S could be charged under an extra U(1)' gauge symmetry (implying an extra Z' gauge boson); it follows, that H_u, H_d and hence at least some of the quarks and leptons must also carry U(1)' charges.
- Several singlets are possible, which implies even more states in the scalar sector (but with reduced couplings relative to the SM scalar).
- The supersymmetric terms depending on the superfield S can be dimensionful such as mass and/or tadpole terms. (If not: this version of the NMSSM is the simplest supersymmetric extension of the SM where *all* supersymmetric interactions are scale invariant!)
- The running coupling λ can remain perturbative $\lesssim 1$ up to the GUT scale. The alternative case is denoted as "λ-Susy", where a Landau singularity in the running coupling λ can indicate a compositeness scale.
- It is theoretically appealing to assume, as in supergravity, that the soft Susy breaking terms are universal at the GUT scale (not far from the Planck scale). Then one assumes universal squark, slepton masses m_0 and gaugino masses $M_{1/2}$ as in the cMSSM. If one includes the masses of H_u, H_d and S, one obtains the cNMSSM (the constrained NMSSM); if not, one obtains the "semi-constrained" sNMSSM.
- As in the MSSM, one can assume an alternative source for the soft Susy breaking terms like gauge mediation.

3 Examples in the parameter space of the semi-constrained NMSSM

A first study of the parameter space of the sNMSSM, after the measurement of the mass of the SM scalar of about 125 GeV, has been performed in[4] (other studies exist as well). Here it was required in addition that the dark matter relic density agrees with present constraints. It was assumed that the mostly SM like scalar h_{SM} is the next-to-lightest state H_2 among the three CP-even states, and it was required that the mostly singlet like state H_1 satisfies constraints from LEP[5] on its couplings.

For what follows it is convenient to define $R_2^{\gamma\gamma}(gg)$ as the $\gamma\gamma$ signal rate of H_2 in gluon fusion relative to the SM,

$$R_2^{\gamma\gamma}(gg) = \frac{\text{production cross section} \times BR(h_{SM} \to \gamma\gamma)}{\text{production cross section} \times BR(H_{SM} \to \gamma\gamma)} \tag{8}$$

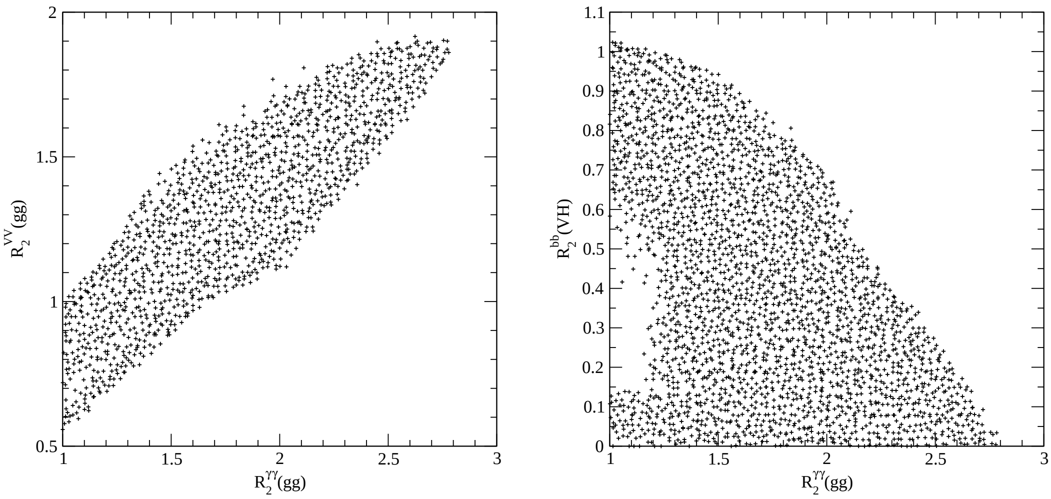

Figure 2: Left: Scatter plot of $R_2^{VV}(gg) \equiv R_2^{ZZ} \equiv R_2^{WW}$ against $R_2^{\gamma\gamma}(gg)$ in the sNMSSM. Right: Scatter plot of $R_2^{bb}(VH)$ against $R_2^{\gamma\gamma}(gg)$ in the sNMSSM

Similarly, we define $R_2^{VV}(gg)$ as the ZZ/WW signal rate of the second scalar in gluon fusion, and $R_2^{bb}(VH)$ as the bb signal rate of the second scalar in associate production with a $V = Z$ or W boson.

First we show a scatter plot of $R_2^{VV}(gg) \equiv R_2^{ZZ} \equiv R_2^{WW}$ against $R_2^{\gamma\gamma}(gg)$. This is relevant since present measurements of $R_2^{VV}(gg)$ do not show an enhancement with respect to the SM, i.e. $R_2^{VV}(gg) \approx 1$. Among the mecanisms for the enhancement of $R_2^{\gamma\gamma}(gg)$ in the NMSSM, the first one (a reduction of the width into bb) would also induce an enhancement of $R_2^{VV}(gg)$, whereas the second mecanism (an additional chargino contribution to the width into $\gamma\gamma$) would not have this effect.

From the left of Figs. 2 we see that, in principle, $R_2^{\gamma\gamma}(gg)$ can be enhanced by a factor 2 (or larger) in the sNMSSM. However, if $R_2^{\gamma\gamma}(gg) \lesssim 2$ (consistent with the presently observed excess), $R_2^{VV}(gg) \equiv R_2^{ZZ} \equiv R_2^{WW}$ is not necessarily enhanced.

Next we consider $R_2^{bb}(VH)$ against $R_2^{\gamma\gamma}(gg)$. If an enhancement of $R_2^{\gamma\gamma}(gg)$ goes hand-in-hand with a reduction of $R_2^{bb}(VH)$, the question is whether this reduction is in conflict with the SM-like signal rate $h_{SM} \to bb$. From the right of Figs. 2 it can be seen that, if $R_2^{\gamma\gamma}(gg) \lesssim 1.5$, $R_2^{bb}(VH)$ is not necessarily reduced provided that the enhancement of $R_2^{\gamma\gamma}(gg)$ results from the additional higgsino loop, not from a reduction of $\Gamma(h_{SM} \to bb)$.

4 Additional scalars in Supersymmetry with extra singlets

If h_{SM} mixes strongly with another mostly singlet-like scalar one can expect that the mass of this mostly singlet-like scalar should be not too far from $M_{h_{SM}} \sim 125$ GeV. Hence the question arises whether there are hints for – or at least weak bounds on – such an additional state. Unfortunately we also have to expect that the couplings/signal rates of such a state are typically reduced relative to the ones of h_{SM}. However, such a state can still be visible!

First, if this state H_1 has a mass below 114 GeV, we can study the bounds on the signal rate ξ^2 in $Z^* \to Z + h_{SM}$ at LEP[5] shown in Fig. 3. Here we see that $M_{H_1} \sim 95 - 100$ GeV would be compatible with $\xi^2(H_1) \sim 0.2$, a possibility pointed out in [6].

Alternatively, H_1 and H_2 could be very close in mass as discussed in [7,8].

Finally the mass of a mostly singlet-like state may be larger than 125 GeV. In the $\gamma\gamma$ channels, mild excesses can indeed be observed near 137 GeV at CMS[9] and ATLAS[10] in Figs. 4.

Likewise, mild excesses relative to the expectations from a SM like scalar at 125 GeV have

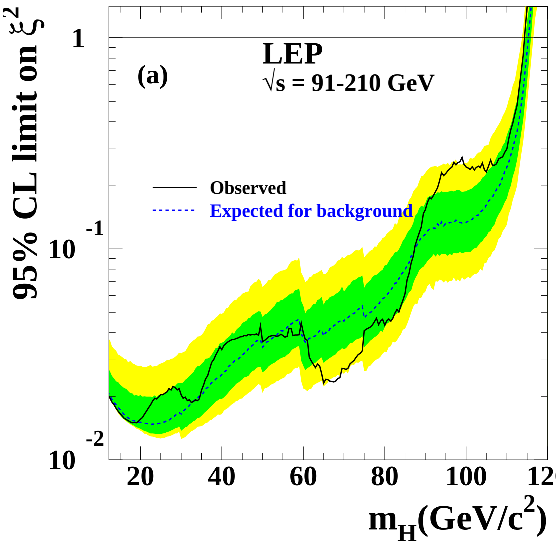

Figure 3: Upper bounds on the signal rate ξ^2 in $Z^* \to Z + h_{SM}$ at LEP

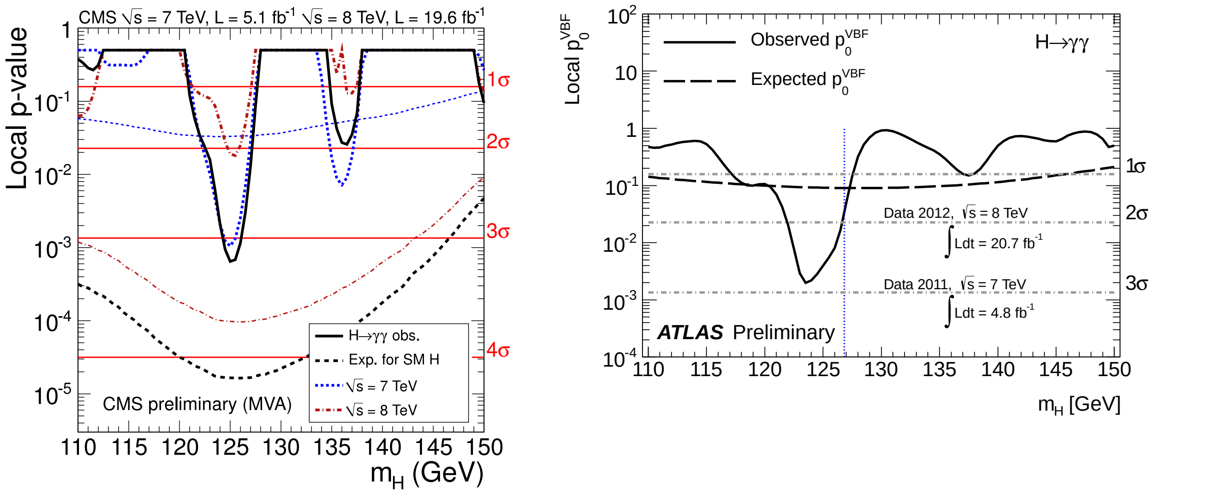

Figure 4: Local p-values from the search for $H \to \gamma\gamma$ as function of M_H at CMS (left) and ATLAS (VBF only, right)

been observed in the $H \to bb$ final state (with H production in association with a Z or W boson) for $M_H \gtrsim 130$ GeV at the Tevatron[11] and at CMS[12], see Figs. 5. Due to the low mass resolution in the $H \to bb$ channel, these excesses could be a superposition of two states at 125 and ~ 137 GeV, which is possible in the parameter space of the NMSSM[13].

In the $H \to ZZ$ and $H \to \tau\tau$ channels no excesses are observed for $M_H \sim 137$ GeV (only upper bounds on the signal rate of about 20% relative to the SM) and such a state is far from being confirmed at present; still, one should keep one's eyes wide open for possible excesses – in any channel – below and above 125 GeV!

5 Possible impact of singlet extensions of the MSSM on searches for SUSY

A singlet extension of the MSSM implies also an extended neutralino sector consisting in the bino, the neutral wino, two neutral higgsinos and a singlino, the fermionic superpartner of the singlet S. Once one imposes a dark matter relic density consistent with present bounds, one

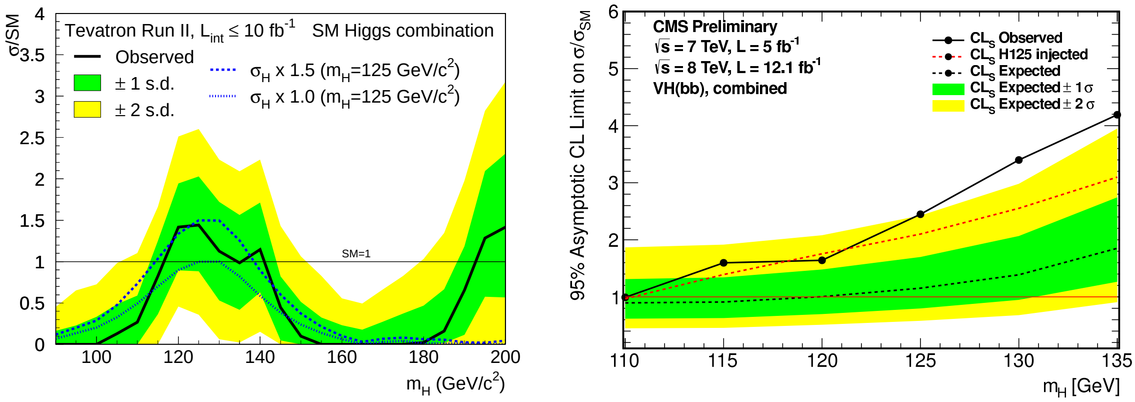

Figure 5: The signal rate $VH \to bb$ relative to the SM from the combination of the CDF and D0 experiments (left) and the corresponding 95% CL upper limits from CMS (right).

finds that these can easily be satisfied if the lighter neutralinos χ_n^0, $n = 1...3$, are mixtures of higgsinos and the singlino. (Heavy gluinos and the assumption of unified gaugino masses at the GUT scale imply also a relatively heavy bino and winos.)

Then the bino/winos decay via cascades involving χ_n^0 and $\chi_1^\pm$, and squark decay cascades are relatively long. Moreover, lighter top squarks are favored by low fine tuning and the RG equations from $M_{GUT} \to M_{weak}$ at low $\tan\beta$ as it is typically the case in the NMSSM. Then the gluinos decay via top squarks, $\tilde{g} \to t + \tilde{t} \to t + b + \chi_1^\pm \to t + b + W^\pm + \chi_1^0$. Altogether one obtains less missing E_T and less p_T per jet than in the typical cMSSM.

The question how the (c)MSSM bounds on squark/gluino masses are affected due to the additional neutralino and/or light top squarks in the sNMSSM has been studied in [14]. There, squark/gluino production was simulated in regions of the parameter space of the sNMSSM consistent with a SM like scalar mass of ~ 125 GeV, a consistent dark matter relic density, and other constraints from b physics and LEP. Cuts like the ones in ATLAS searches for 3-6 jets (7-9 jets) and missing E_T at $\sqrt{s} = 8$ TeV were applied, and it was found that, for identical values of m_0 and $M_{1/2}$, the signal efficiencies in the sNMSSM get reduced by about 50% relative to the cMSSM. In Fig. 6, the resulting bounds on $M_{\rm squark}$ versus $M_{\rm gluino}$ in the sNMSSM are compared to the ones from searches for 3-6 jets and missing E_T by ATLAS (bounds from searches for 7-9 jets and missing E_T in this plane were not shown).

We see that, for $M_{\rm gluino} \gtrsim 1200$ GeV, the bounds from searches for 3-6 jets in the sNMSSM (full red line) are somewhat weaker than in the cMSSM (full black line). For $M_{\rm gluino} \lesssim 1200$ GeV, the bounds from searches for 7-9 jets in the sNMSSM (full blue line) are somewhat stronger than bounds from 3-6 jets in the cMSSM, but they would still be weaker than the 7-9 jets bounds within the cMSSM which are not shown here.

6 Conclusions

Given the measured SM like scalar mass of about 125 GeV, it seems that the simplest singlet extension of the MSSM, the NMSSM, is the most natural supersymmetric extension of the Standard Model: here, all supersymmetric interactions are scale invariant (no need for a μ term), and a SM like scalar mass of about 125 GeV is natural in the parameter space; very heavy top squarks (or large A_{top}) are not required. All desirable properties of supersymmetric extensions of the SM are maintained: a solution of the hierarchy problem, unification of the running gauge couplings, and a promising candidate for dark matter.

Possible hints for the NMSSM include an enhanced signal rate of the SM like scalar in $\gamma\gamma$ channels, but also additional scalars with "below-the-SM" signal rates in other channels, with masses below or above 125 GeV.

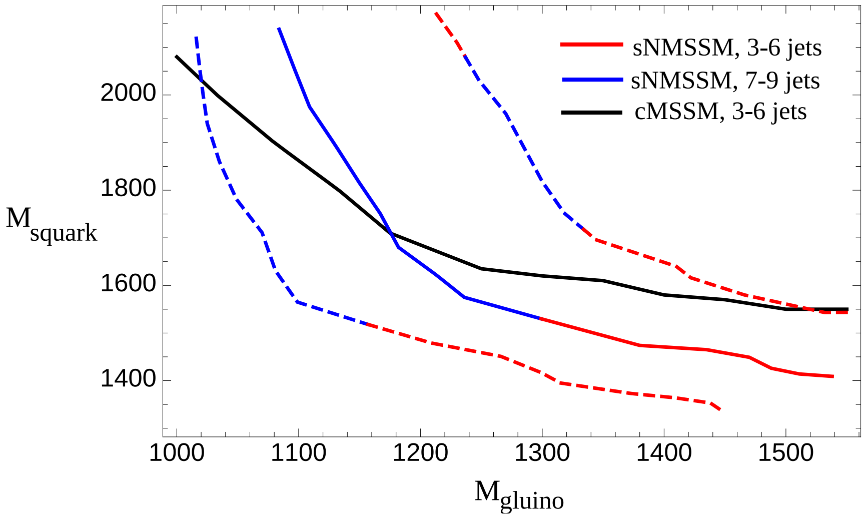

Figure 6: Bounds in the $M_{\mathrm{squark}} - M_{\mathrm{gluino}}$ plane in the sNMSSM from searches for 3-6 jets (7-9 jets) and missing E_T, compared to bounds in the cMSSM from searches for 3-6 jets and missing E_T

Finally, searches for sparticles like squarks and gluinos can be handicapped due to more complicated sparticle decay cascades, which can alleviate the bounds from unobserved signal events interpreted within the MSSM.

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