Status of SUSY with extra singlets (NMSSM)

U. Ellwanger, LPT Orsay

— The SM scalar mass in SUSY with extra singlets

— Its diphoton rate in SUSY with extra singlets

— Additional scalars in SUSY with extra singlets

— Search for SUSY in SUSY with extra singlets

Exercise I and solutions:

Consider the "mexican hat" potential of a complex scalar H:

$$V(H) = -m^2|H|^2 + \lambda^2|H|^4$$

Decompose H into its real part h and complex part a: $H = \frac{1}{\sqrt{2}}(h + i\,a)$; study the potential as function of h:

$$\longrightarrow V(h) = -\frac{m^2}{2}h^2 + \frac{\lambda^2}{4}h^4$$

Look for the minimum $h = v$ (vacuum expectation value) of $V(h)$:

$$\longrightarrow v = \frac{m}{\lambda}$$

The physical (tree level) mass M_h^2 of the scalar h is given by the second derivative of $V(h)$ evaluated at the minimum:

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

(The second expression is more useful, since we know v from the W and Z masses)

$\longrightarrow$ Larger M_h corresponds to larger λ

$\longrightarrow$ If we would have known the coupling λ, we could have predicted the scalar mass M_h

Supersymmetry relates various dimensionless couplings at tree level (even if softly broken by mass terms of $\mathcal{O}(M_{\text{SUSY}}) \sim v$)

MSSM: Two SU(2) doublets H_u and H_d, the quartic terms in $V(H_u, H_d)$ are given by the electroweak gauge couplings g_1 and g_2:

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

$\longrightarrow$ Two physical scalars h and H

$\longrightarrow$ Their masses have to be obtained by diagonalising a 2×2 mass matrix (of second derivatives of $V(H_u, H_d)$)

$\longrightarrow$ Less information, since we only know $\sqrt{v_u^2 + v_d^2}$ from the W and Z masses, but $\tan\beta = \frac{v_u}{v_d}$ unknown

$\longrightarrow$ Still: one obtains an upper tree level bound on the mass M_h of the lighter scalar:

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

$\longrightarrow$ Disaster? Not if radiative ("Coleman-Weinberg"-) corrections to $V(H_u, H_d)$ are large enough, but

$\longrightarrow$ need large ($\gtrsim 1$ TeV) soft SUSY breaking top squark masses and/or trilinear top squark–scalar couplings A_{top} ($\gtrsim 1$ TeV); unnatural?

Origin of the problem:
In the MSSM, no supersymmetric quartic couplings for H_u and H_d exist, except for the ones induced by the SUSY gauge interactions

A SUSY mass term μ for the components of H_u and H_d exists:

— required for higgsino masses $\mu \Psi_{H_u} \Psi_{H_d}$
— contributes to $V(H_u, H_d)$, but not to M_h!
— its order of magnitude $\mu \sim \mathcal{O}(M_{\text{SUSY}}) \sim v$ is difficult to explain ("μ-problem")

SUSY with extra singlets: Generate the μ-term through the vev of an extra scalar singlet S, $\langle S \rangle = v_s$:

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

(v_s of $\mathcal{O}(M_{\text{SUSY}})$ is automatic)

$\longrightarrow$ Benefit: An extra quartic coupling $\lambda^2 H_u^2 H_d^2$ due to SUSY

$\longrightarrow$ Larger mass $M_h > M_Z$ (at tree level!)

Now: Three physical scalars, superpositions of H_u, H_d and S

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

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

$\pm (\ . \ . \ . \ )$: From mixing of the mostly SM like scalar h_{SM} with the mostly singlet like scalar h_s (dep. on unknown parameters);

positive if $M_{h_s} < M_{h_{SM}}$!

$\rightarrow$ $M_{h_{SM}} > M_Z$ much easier to obtain than in the MSSM
(at low $\tan\beta \rightarrow$ large $\sin^2 2\beta$)
no large rad. corrs. (heavy top squarks) required for $M_{h_{SM}} \sim 125$ GeV

Impact on the diphoton signal rate:

1) Recall:

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

($\Gamma(H \to bb)$ gives $\sim 58\%$ of the total width for a 125 GeV scalar mass)

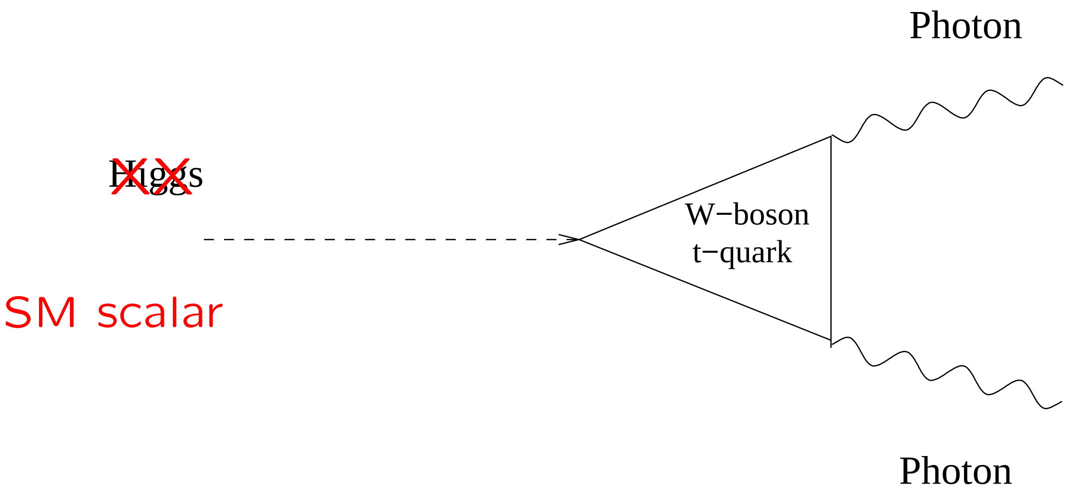
$\longrightarrow$ Due to the mixing of H_u, H_d, S it is easily possible that, in the NMSSM, the mostly SM–like scalar h_{SM} has

— a reduced coupling to bb, and hence a reduced width $\Gamma(h_{SM} \to bb)$
$\longrightarrow$ an enhanced $BR(h_{SM} \to \gamma\gamma)$

— nearly SM–like couplings to the top quark (whose loops induce the coupling to gluons) and to the electroweak gauge bosons
$\longrightarrow$ the production rates in gluon fusion and/or VBF are hardly reduced

$\to$ The diphoton signal rate is enhanced (U.E. 2010)

2) Recall: In the SM, $\Gamma(H \to \gamma\gamma)$ is induced via W-boson (and top quark) loops:



In the NMSSM, the singlet S couples to the (charged) higgsinos Ψ_{H_u}, Ψ_{H_d}:

$\lambda S \Psi_{H_u} \Psi_{H_d}$ (recall the generation of the μ–term through $\langle S \rangle$)

$\longrightarrow$ If h_{SM} has a S-component, charged higgsinos contribute to the loop and to $\Gamma(h_{SM} \to \gamma\gamma)$ unless λ is small or the higgsinos are heavy

Note: Singlet extensions of the MSSM are not unique:

— The "singlet" could be charged under an extra U(1)' gauge symmetry (implying a Z' gauge boson)
$\longrightarrow$ H_u, H_d must be charged as well
$\longrightarrow$ Quarks, leptons must be charged as well

— Several singlets are possible
($\to$ more states, but with reduced couplings)

— The SUSY S-dependent terms can be dimensionful
(mass term, tadpole term) or not

If not: This version of the NMSSM is the simplest SUSY extension of the SM where all SUSY interactions are scale invariant
(no μ-term as in the MSSM)

— The running coupling λ can remain $\lesssim 1$ up to the GUT scale
If not: "λ-SUSY", a Landau singularity in the running coupling λ can indicate a compositeness scale

— The soft SUSY breaking terms can be universal at the GUT scale:
Universal squark, slepton masses m_0 and gaugino masses $M_{1/2}$ as in the cMSSM

Including the soft SUSY breaking BEH scalar masses $\longrightarrow$ cNMSSM
or not $\longrightarrow$ "semi-constrained" sNMSSM

— The soft SUSY breaking terms can be induced by gauge mediation

The naturalness of $M_{h_{SM}} \sim 125$ GeV and the possible enhancement of the $\gamma\gamma$ signal rate hold in all these scenarios

Examples in the parameter space of the semi-constrained NMSSM

Imposing $M_{h_{SM}} \sim 125$ GeV, good dark matter relic density
The mostly SM-like scalar h_{SM} is the next-to-lightest H_2
H_1 satisfies constraints from LEP
(with C. Hugonie, arXiv:1203:5049; more studies exist)

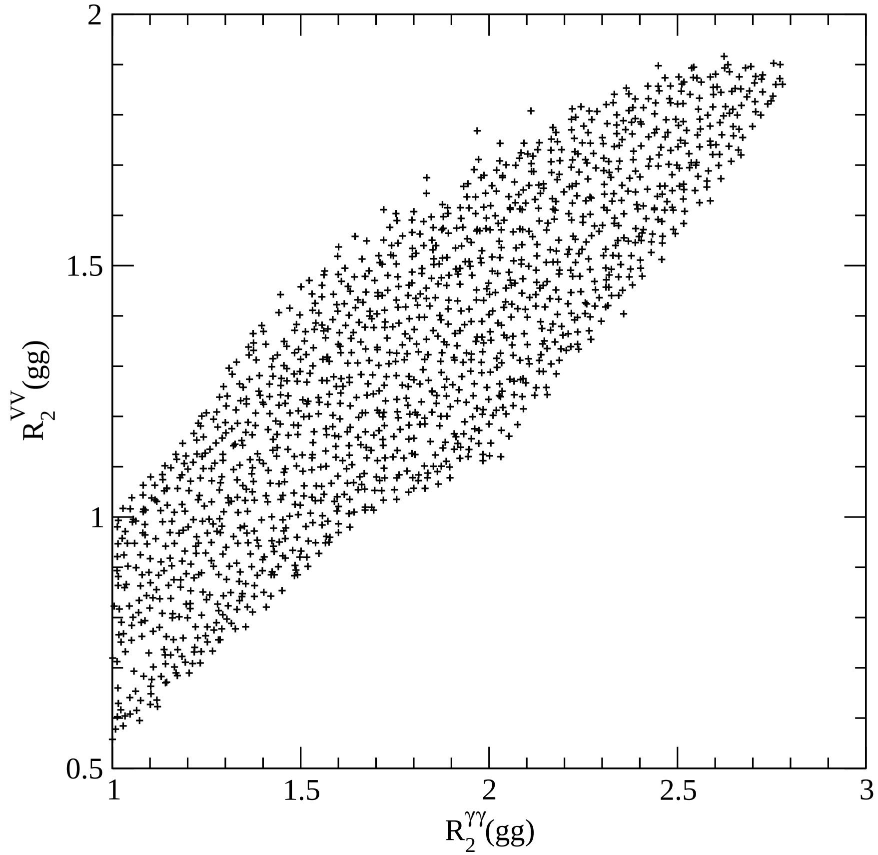
$R_2^{\gamma\gamma}(gg)$: $\gamma\gamma$ signal rate of H_2 in gluon fusion relative to the SM:

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

$R_2^{VV}(gg)$: ZZ/WW signal rate of the second scalar in gluon fusion

$R_2^{bb}(VH)$: bb signal rate of the second scalar in associate production with a $V = Z$ or W boson

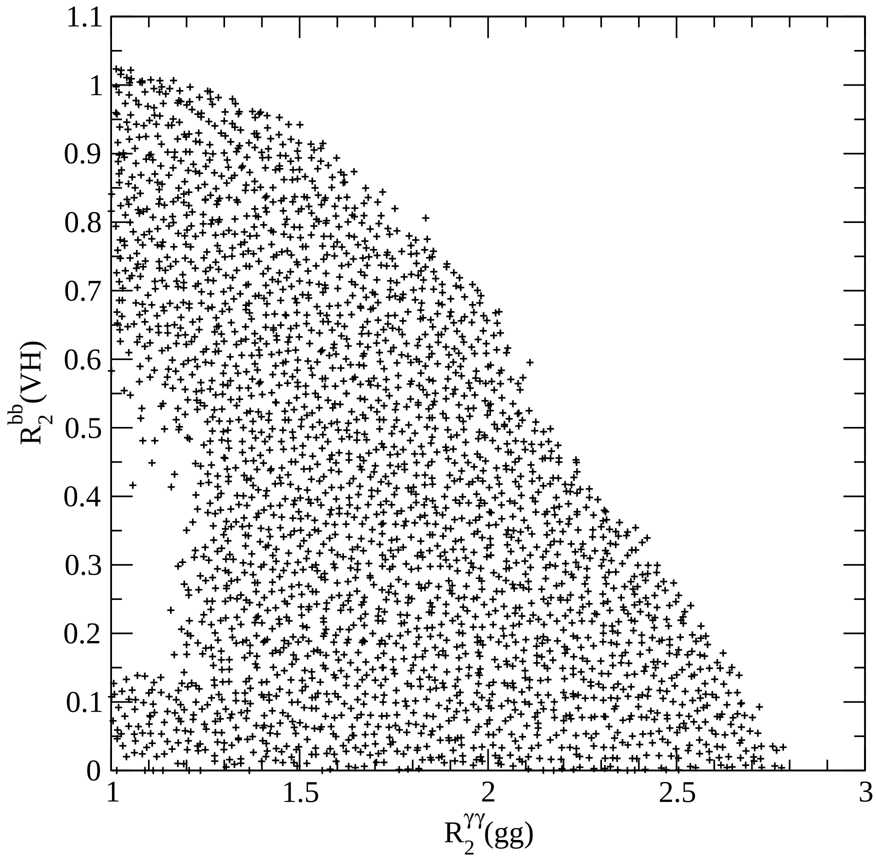
$R_2^{VV}(gg) \equiv R_2^{ZZ} \equiv R_2^{WW}$ against $R_2^{\gamma\gamma}(gg)$:



$\longrightarrow$ $R_2^{\gamma\gamma}(gg)$ can be enhanced by a factor 2 (or larger); both mechanisms 1) and 2) contribute!

$\longrightarrow$ If $R_2^{\gamma\gamma}(gg) \lesssim 2$: $R_2^{VV}(gg) \equiv R_2^{ZZ} \equiv R_2^{WW}$ is not necessarily enhanced

$R_2^{bb}(VH)$ against $R_2^{\gamma\gamma}(gg)$:
In conflict with the SM-like signal rate $h_{SM} \to bb$?



$\longrightarrow$ If $R_2^{\gamma\gamma}(gg) \lesssim 1.5$:
$R_2^{bb}(VH)$ is not necessarily reduced, the enhancement of $R_2^{\gamma\gamma}(gg)$ results from the additional higgsino loop, not from a reduction of $\Gamma(h_{SM} \to bb)$

If h_{SM} mixes strongly with another mostly singlet-like scalar: The mass of this mostly singlet-like scalar should be not too far from $M_{h_{SM}} \sim 125$ GeV

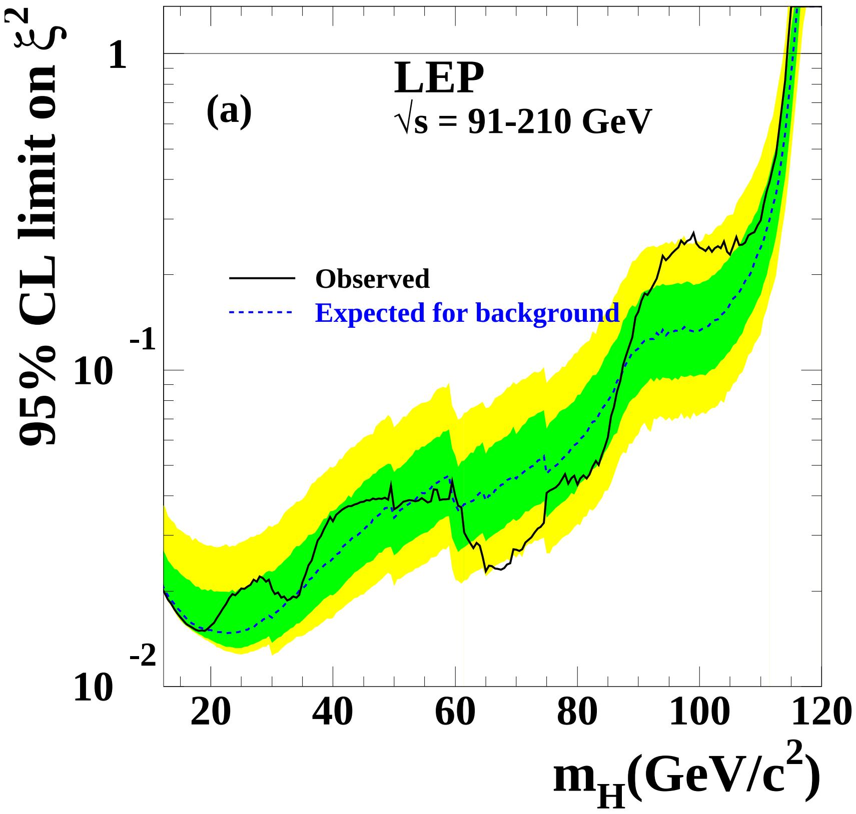
$\longrightarrow$ Are there hints for (at least weak bounds on) such a state?

Unfortunately: The couplings/signal rates of such a state are typically reduced relative to the ones of h_{SM}, but it can still be visible

If this state has a mass below 114 GeV:

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

$\longrightarrow$ If $\xi^2(H_1) \sim 0.2$:
Compatible with the weak bounds around 95 GeV (R. Dermisek, J.-F. Gunion)



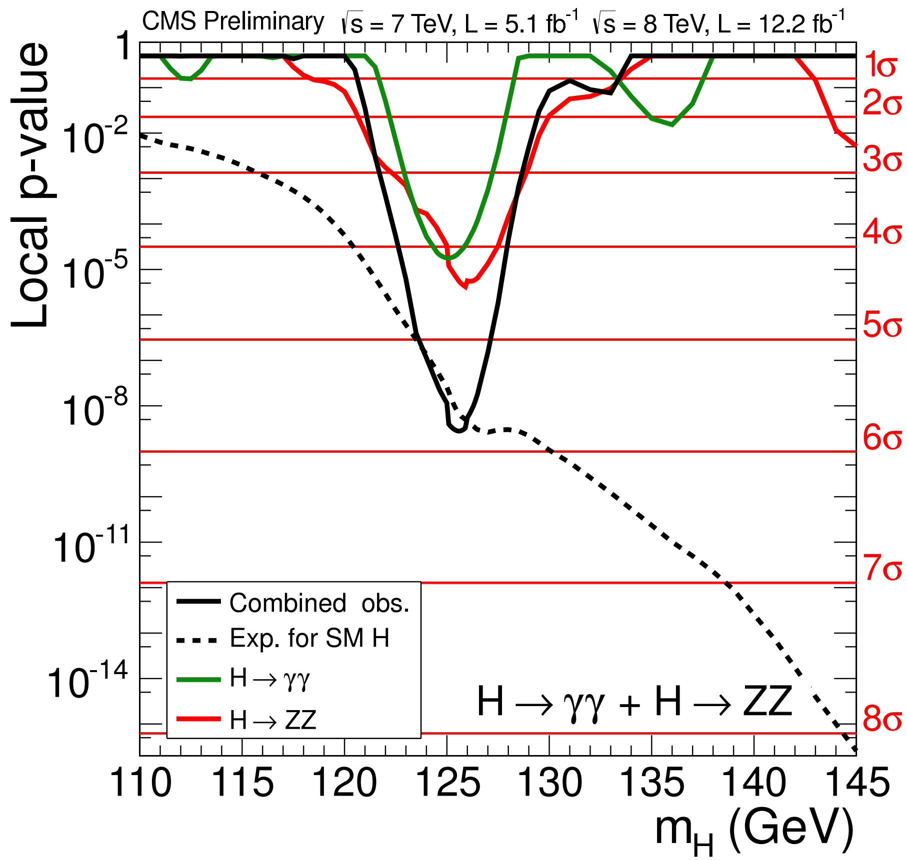
Or: could be very close to 125 GeV?

(Gunion, Jiang, Kraml, 1207.1545 and 1208.1817)

If this state has a mass above 125 GeV:

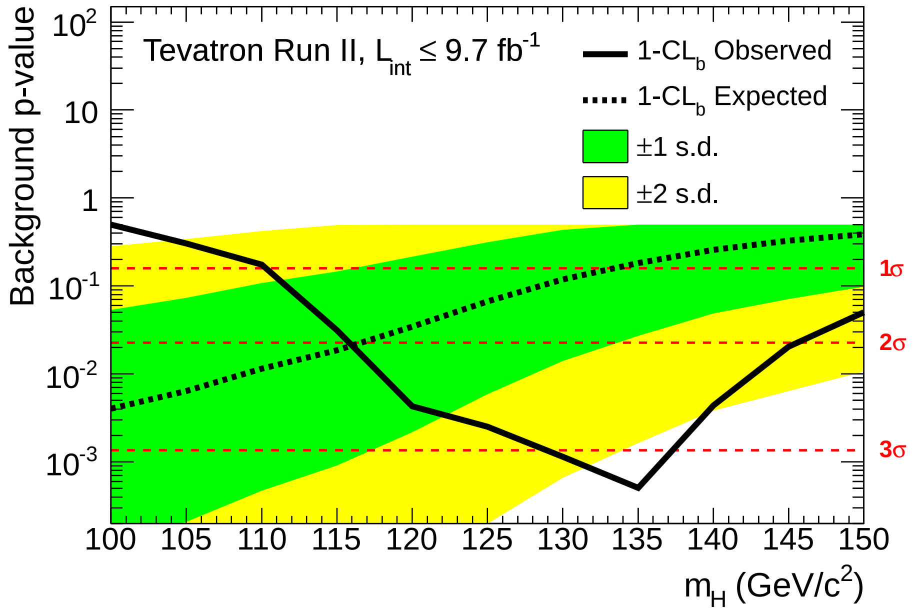
CMS (pre-Moriond):
Additional excesses at
135 GeV (in $\gamma\gamma$, $\sim 2\ \sigma$)
145 GeV (in ZZ, $\sim 2.5\ \sigma$)

BUT: Not in Atlas ...

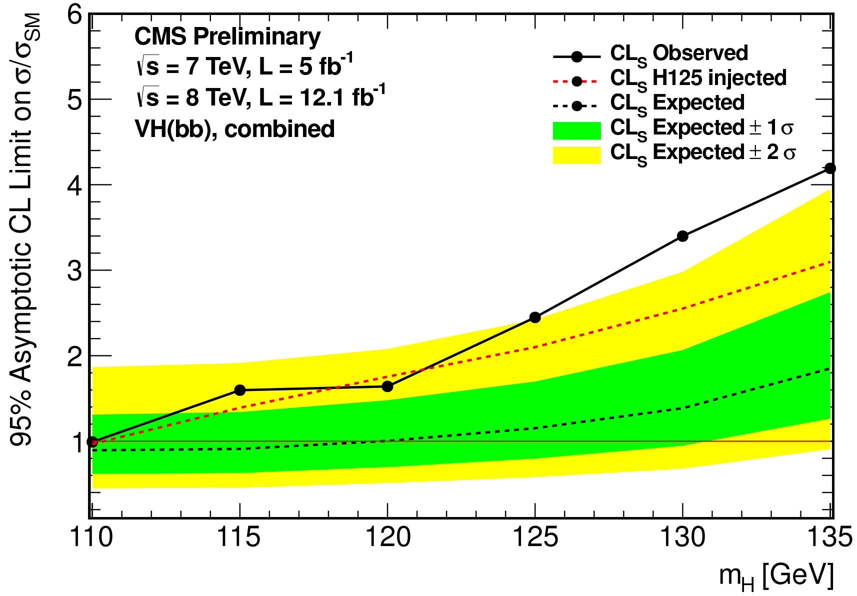


Best fits of M_H in VH with $H \to bb$ (low mass resolution):

Tevatron (1207.6436, PRL):



CMS (pre-Moriond):



$\longrightarrow$ For $M_H \sim 135$ GeV!? Due to the low mass resolution in $H \to bb$, the excesses could be a superposition of two states at 125 + 135 GeV!

$\longrightarrow$ Possible in the NMSSM! (See arXiv:1208.4952)

let's see...

Keep your eyes wide open for possible excesses – in any channel – below and above 125 GeV!

Possible impact of Singlet extensions of the MSSM on searches for SUSY:

Typically (if a good dark matter relic density is imposed):

— The lighter neutralinos χ_n^0, $n = 1...3$, are mixtures of higgsinos and the singlino (superpartner of the singlet superfield $\widehat{S}$)

— Binos/winos decay via cascades involving χ_n^0 and $\chi_1^\pm$

$\longrightarrow$ The squark decay cascades are relatively long

— Lighter top squarks are favored by low fine tuning, and the RG equations from $M_{GUT} \to M_{weak}$ at low $\tan\beta$:

$\longrightarrow$ Gluinos decay via stops: $\tilde{g} \to t + \tilde{t} \to t + b + \chi_1^\pm \to t + b + W^\pm + \chi_1^0$

$\longrightarrow$ Less missing E_T, less p_T per jet than in the typical MSSM

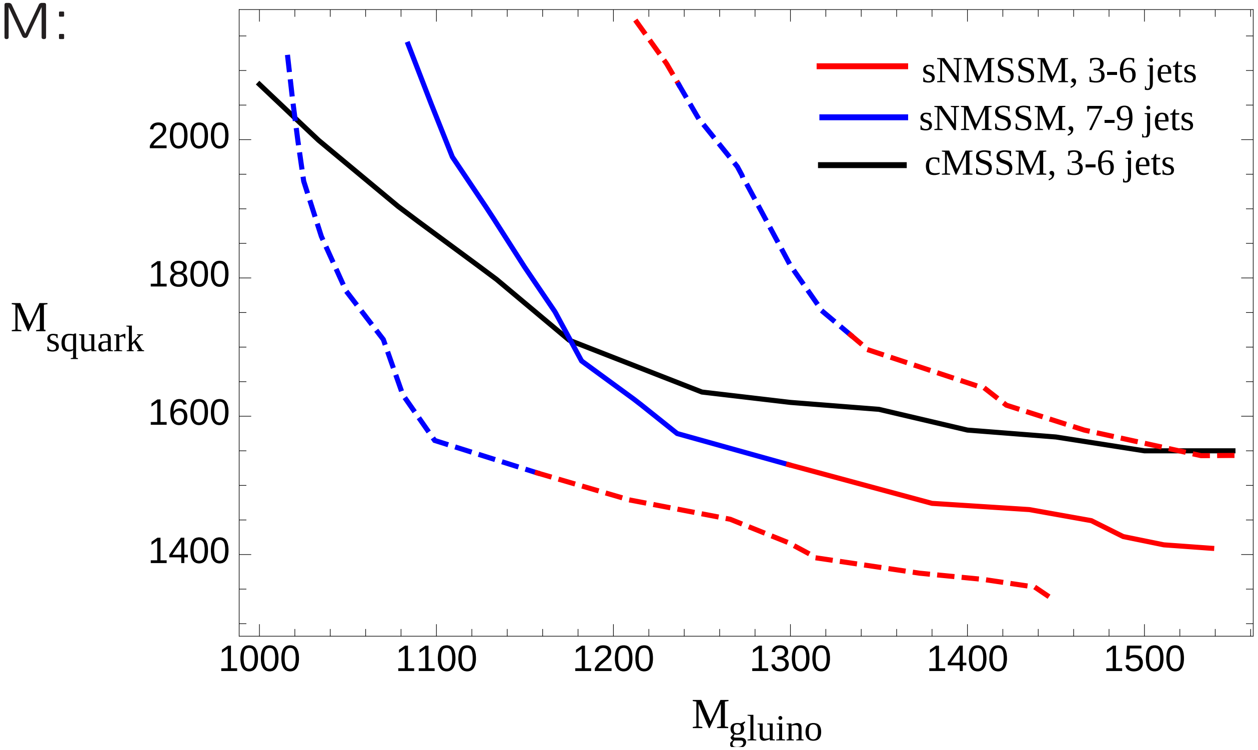
How are the (c)MSSM bounds on squark/gluino masses affected due to the additional neutralino and/or light top squarks in the sNMSSM?

With D. Das, A.M. Teixeira (arXiv:1301.7584):
Simulations of squark/gluino production in the sNMSSM
(with $M_{h_{SM}} \sim 125$ GeV, good DM relic density)

Apply the cuts of the ATLAS searches for 3-6 jets (7-9 jets) and missing E_T at $\sqrt{s} = 8$ TeV

$\longrightarrow$ Reduction of the signal efficiencies by $\sim 50\%$

Comparison of bounds on M_{squark} vs. M_{gluino} from searches for 3-6 jets and missing E_T by ATLAS (pre-Moriond) sNMSSM vs. the cMSSM:



$\longrightarrow$ For $M_{\text{gluino}} \gtrsim 1200$ 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)

$\longrightarrow$ For $M_{\text{gluino}} \lesssim 1200$ 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
(Still: weaker than the 7-9 jets bounds within the cMSSM, not shown)

Conclusions

— Given $M_{h_{SM}} \sim 125$ GeV, the NMSSM is the most natural SUSY extension of the SM: scale invariant SUSY interactions, no need for very heavy top squarks, but gauge coupling unification and a good dark matter candidate as in the MSSM

— An enhanced $\gamma\gamma$ signal rate of h_{SM} can be a hint for the NMSSM

— Additional below-the-SM signals in searches for scalars at low mass ($\lesssim 200$ GeV) can be a hint for the NMSSM

— Searches for SUSY (squarks, gluinos) can be handicapped due to more complicated sparticle decay cascades