Supersymmetry with a Singlet

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Motivations for an extra Singlet S

Replace in the superpotential $\mathcal{W}$ of the MSSM:

$$\mathcal{W}_{MSSM} = ... + \mu H_u H_d \longrightarrow \mathcal{W}_{NMSSM} = ... + \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

- Solves the μ problem of the MSSM: μ replaced by $\lambda \langle S \rangle$
- Less tuning required for a SM-like Higgs boson with $M_{H_{SM}} \simeq 125$ GeV:

$$M^2_{H_{SM}} \sim M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \frac{3 m_t^4}{4\pi^2 v^2} \left(\ln \left(\frac{M^2_{stop}}{m_t^4} \right) + ... \right)$$

$\longrightarrow$ No heavy stops are needed for $M_{H_{SM}} \sim 125$ GeV
(See the talk by M. Carena)

- Alleviates constraints from negative squark/gluino searches
- Alleviates constraints from negative dark matter searches

Extra states "Beyond the MSSM":

A CP-even scalar H_S, a CP-odd scalar A_S, a fifth neutralino ("singlino"), all of which have couplings to the SM-sector only through mixings $\sim \lambda$ with the MSSM-like Higgs(ino) states

$\longrightarrow$ Not easy to discover (even if H_S/A_S are possibly light!)

$\longrightarrow$ But: a plethora of possible exotic processes at the LHC (cf. CERN Yellow Report 4, including BM points):

- Exotic H_{125} decays:
  - $H_{125} \to H_S + H_S$ or $A_S + A_S$
  - $H_{125} \to H_S + H_S \to 4A_S$
  - $H_{125} \to \tilde{\chi}_1^0 + \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + \tilde{\chi}_1^0 + H_S$

  all with H_S or $A_S \to b\bar{b}, \tau^+\tau^-, \mu^+\mu^-, \gamma\gamma$, depending on its mass

- Direct H_S/A_S production:
  - $ggF \to H_S$ or $A_S \to b\bar{b}, \tau^+\tau^-, \mu^+\mu^-, \gamma\gamma$
  - $ggF \to H_S$ or $A_S \to \tilde{\chi}_1^0 + \tilde{\chi}_1^0$
  - $ggF \to H_S \to A_S + A_S$
  - $ggF \to H_S \to H_{125} + H_{125}$
  - $ggF \to A_S \to Z + H_S$
- Exotic MSSM-like H/A decays (or decay chains):
  - $H \to H_S + H_S$ or $H_{125} + H_S$ or $A_S + A_S$, evtl. $H_S \to A_S + A_S$
  - $H \to Z + A_S$
  - $A \to H_S + A_S$ or $H_{125} + A_S$, evtl. $H_S \to A_S + A_S$
  - $A \to Z + H_S$, evtl. $H_S \to A_S + A_S$
- Exotic neutralino decays in squark/gluino/... decay chains:
  - $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + H_S$, evtl. $H_S \to A_S + A_S$
  - $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + A_S$
- Displaced vertices from $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0$ decays, if $\tilde{\chi}_1^0$ is singlino-like and λ is very small

Note: Notably A_S can be quite light;
a pseudo-Goldstone boson of a spontaneously broken approximate global symmetry:

— A Peccei-Quinn symmetry

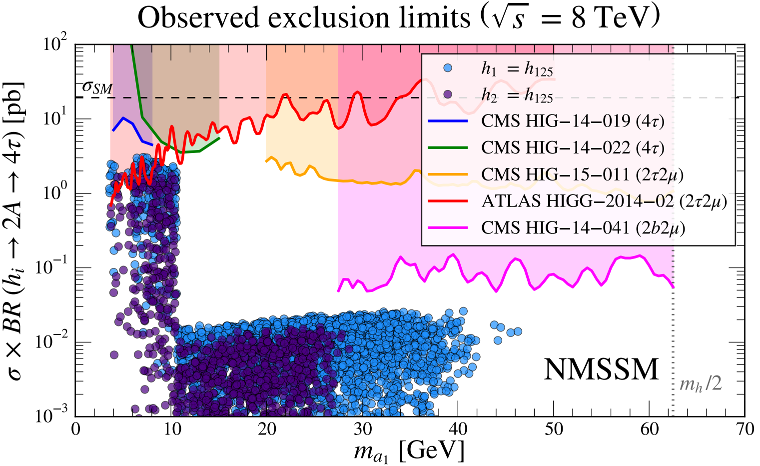
$$H_u \to H_u e^{i\varphi}, \quad H_d \to H_d e^{i\varphi}, \quad S \to S e^{-2i\varphi}$$

if the S^3 coupling $\kappa \to 0$, or

— An R-symmetry (since the superpotential is cubic) if the trilinear soft SUSY breaking terms $A_\lambda S H_u H_d \to 0$ and $\frac{1}{3} A_\kappa S^3 \to 0$

Such light states are constraint by LEP,
by the $BR(H_{125} \to A_S A_S) \lesssim 20\%$ from the measured H_{125} SM-like signal rates,
and by direct searches by ATLAS and CMS at the LHC, but not ruled out:

Searches for $H_{125} \to A_S A_S \to 4\tau$:



Dark/light blue points: viable in the NMSSM after LEP/LHC constraints

With curtesy of Robin Aggleton (thesis)

Impact of $H_{SM} - H_S$ mixing:

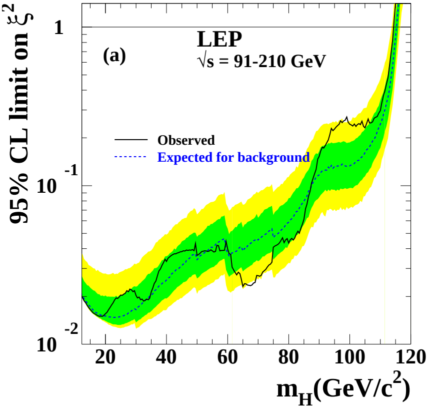
Generated by a term $\mathcal{M}^2_{H_S,H_{SM}} \sim \lambda v\,(2\lambda\,\langle S\rangle - \sin 2\beta(A_\lambda + 2\kappa\,\langle S\rangle))$ which is large for large $\tan\beta \approx 25 - 50$ where the second term is small

- If the diag. terms $M_{H_S}, M_{H_{SM}}$ in the 2×2 mass matrix satisfy $M_{H_S} > M_{H_{SM}}$: The eigenvalue corresponding to H_{SM} is reduced, not desirable!
- If $M_{H_S} < M_{H_{SM}}$: The eigenvalue corresponding to H_{SM} becomes larger, very desirable![1]
- The couplings of H_S to electroweak gauge bosons, quarks and leptons are proportional to the mixing angle $\sin\theta_{H_S - H_{SM}} \equiv \xi$
- The couplings of H_{SM} get reduced by $\sqrt{(1-\xi^2)}$
  combining the measured κ_W and κ_Z from LHC run I: $\sqrt{(1-\xi^2)} \gtrsim 0.83$,
  $\xi \lesssim 0.56$

[1] See talk by G. Weiglein

Is $M_{H_S} < 114$ GeV ruled out by LEP?

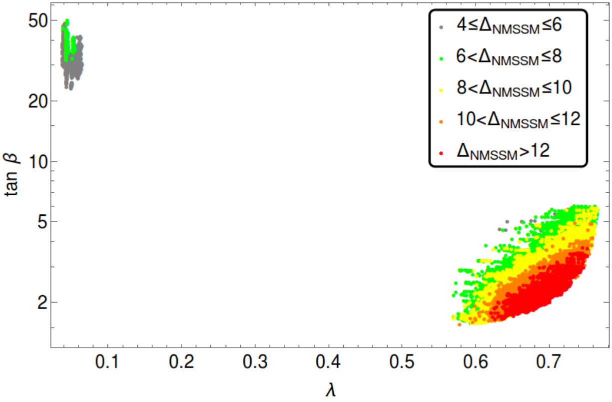
Constraints from the combined LEP experiments on a Higgs coupling $\xi\, H_{SM} ZZ$ (relative to the coupling of H_{SM}) vs. M_H:



$\rightarrow$ Not if ξ is small enough, $\xi < 0.5$ for $M_{H_S} \sim 100$ GeV

Subsequently: Assume $M_{H_S} < M_{H_{SM}}$,
an uplift Δ_{NMSSM} of $M_{H_{SM}}$
by large singlet-doublet mixing (LMIX) or large λ (LLAM) [2]:

λ-$\tan\beta$ plane showing the viable points where $\Delta_{\mathrm{NMSSM}} \gtrsim 4$ GeV:

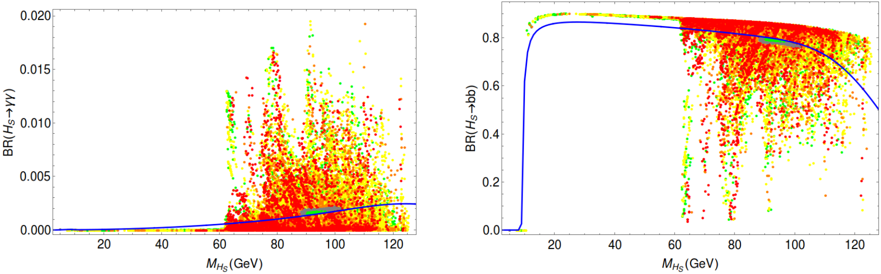


LMIX: $\lambda \lesssim 0.1$, $\tan\beta \sim 25 - 50$

LLAM: $\lambda \sim 0.6 - 0.7$, $\tan\beta \sim 2 - 5$

[2] Scan of the NMSSM parameter ranges compatible with LEP/LHC constraints with M. Rodriguez-Vazquez, 1512.04281

Branching ratios of H_S into photons (left) and $b\bar{b}$ (right) versus its mass:



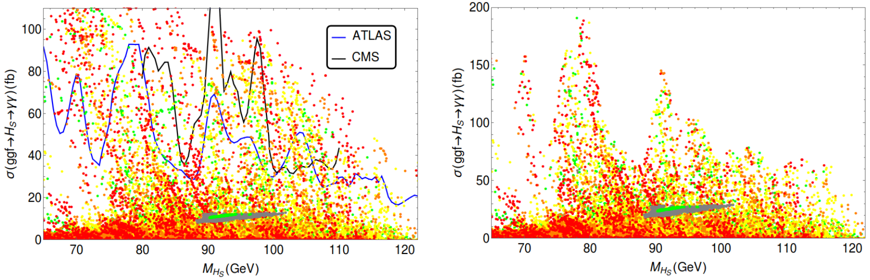
The blue line indicates the corresponding branching ratios for a SM Higgs boson of the same mass. The grey-green island corresponds to the LMIX region, in which the branching ratios are very SM-like.

$\longrightarrow$ In the LLAM region, the $BR(H_S \to \gamma\gamma)$ can be considerably enhanced!

(Due to a reduction of the $BR(H_S \to b\bar{b})$ through mixing with H_{SM} AND H_{MSSM})

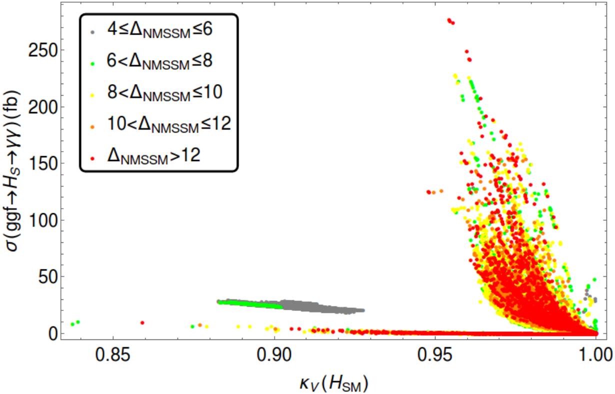
Left: possible signal rates $\sigma(gg \to H_S \to \gamma\gamma)$ at a c.m. energy of $\sqrt{s} = 8$ TeV

Blue line: Bounds from ATLAS, PRL 113 (2014) 17, 171801 (1407.6583)
Black line: Bounds from CMS, CMS-PAS-HIG-14-037
Red/yellow/green points: LLAM region, gray/green region: LMIX region.



Right: possible signal rates $\sigma(gg \to H_S \to \gamma\gamma)$ at a c.m. energy of $\sqrt{s} = 13$ TeV, after applying the ATLAS and CMS limits from $\sqrt{s} = 8$ TeV)
$\longrightarrow$ Need a sensitivity on a signal rate of ~ 20 fb in the $90 - 100$ GeV region in order to test the LMIX region at 13 TeV

Complementarity between H_S discovery via direct detection in $\gamma\gamma$ or via the reduced coupling κ_V of H_{SM}?

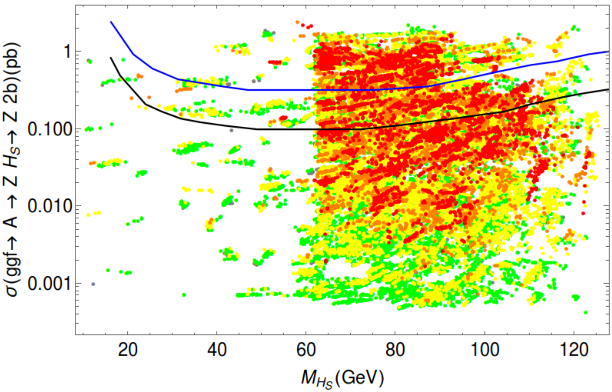


Expect at the LHC run II: $\Delta\kappa_V \sim 5\%$

$\longrightarrow$ The LMIX region can be fully tested, not the LLAM region

Prospects for H_S discovery in $A \to Z + H_S \to l^+ l^- + b\bar{b}$:

($M_A \sim 300$ GeV; LLAM region only since $M_A \gtrsim 1$ TeV for LMIX)



Lines: Expected sensitvities at 300 fb^{-1} (blue) and 3000 fb^{-1} (black)*

$\longrightarrow$ Discovery of H_S possible, but not guaranteed

* From N-E. Bomark, S. Moretti, S. Munir and L. Roszkowski, arXiv:1409.8393, JHEP

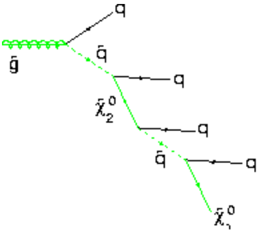
Production of H_S in Decays of Squarks/Gluinos:

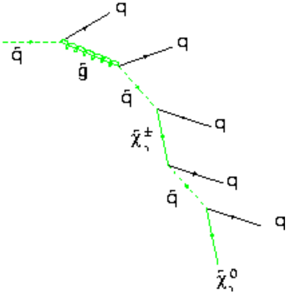
The role of neutralinos in Searches for Susy:

— The lightest among them is typically the "lightest Susy particle" (LSP), stable since odd under R-parity!

— A welcome candidate for DM

— All Susy particle decay cascades will end up in the LSP which is invisible (like neutrinos):



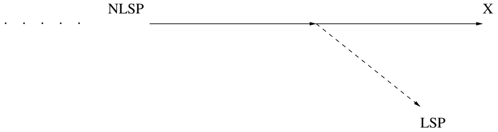


$\longrightarrow$ Susy particle (pair-) production leads to missing transverse momentum/energy!

— In the MSSM, the LSP is a mixture of bino/higgsinos/neutral wino

— In the NMSSM, the LSP can be dominantly singlino-like and light (a few GeV)
$\longrightarrow$ No sparticle wants to decay directly into the LSP

Then: possibly "Missing" missing transverse energy:
Consider an additional last step in a Susy particle decay cascade from a Next-to-Lightest Susy particle (NLSP) into a singlet-like LSP + X,



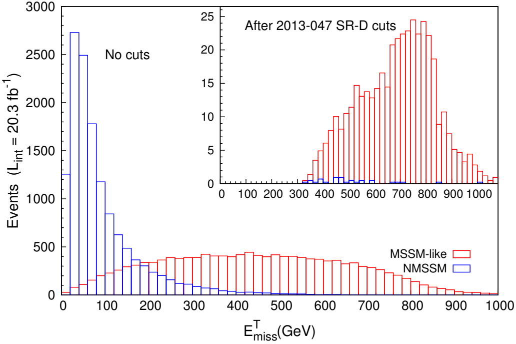
where "X" decays into SM particles (X = Higgs boson, Z,...);
notably:

"X" can be H_S!

$\longrightarrow$ If the LSP is light and $M_{H_S} \sim M_{NLSP} - M_{LSP}$, little (missing transverse) energy is transferred to the LSP; the transverse energy is carried away by H_S
$\longrightarrow$ Since H_S decays give rarely rise to E_T^{miss}, the E_T^{miss} signature gets reduced!

Example: Benchmark point: $M_{NLSP} \sim M_{bino} \sim 89$ GeV, $M_{H_S} \sim 83$ GeV,
$M_{LSP} \sim M_{singlino} \sim 5$ GeV

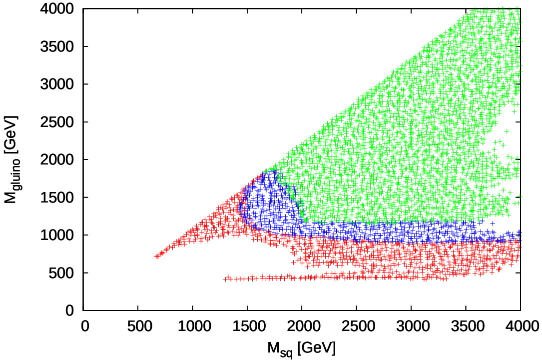
Spectrum of E_T^{miss} from ~ 1 TeV squark/gluino production at 8 TeV:
MSSM: With bino as LSP
NMSSM: With bino $\rightarrow H_S +$ singlino decay



Inlet: After cuts on E_T^{miss} and jet P_T (from an ATLAS search for squarks/gluinos)
$\longrightarrow$ In the NMSSM, hardly any events survive the cuts; the signal disappears!

Impact on lower bounds on squark/gluino masses in the NMSSM (MSUGRA):

Red: Excluded after searches by ATLAS/CMS at the run I
(due to E_T^{miss} from neutrinos from leptonic $W^{\pm}$, Z decays)
Blue: Excluded in the MSSM, but allowed in the NMSSM
Green: Allowed both in the MSSM and NMSSM



$\longrightarrow$ Alleviation of the lower bounds on squark/gluino masses due to the bino $\rightarrow H_S +$ singlino decay*

*from arXiv:1405.6647, with C. Hugonie, using 1406.7221 and 1412.6394 with A.M.Teixeira

Search for H_S via squark/gluino production in the jets $+b\bar{b}+\tau^+\tau^-$ final state:
(With A.M. Teixeira, arXiv:1406.7221 and arXiv:1412.6394)

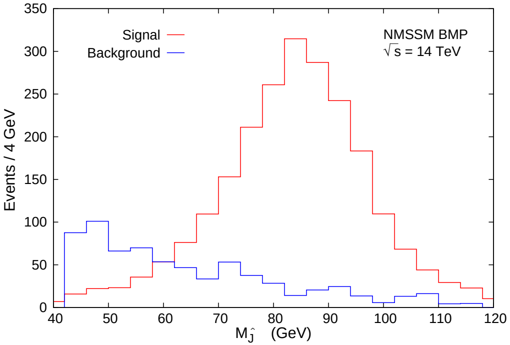
— Require four hard jets, e.g. with $P_T \geq 400,\ 200,\ 80,\ 80$ GeV
from $2 \times (\tilde{q} \to q + bino \to q + singlino + H_S$ and/or $\tilde{g} \to q + \tilde{q} \to ...)$

— Ask for two b-jets and two τ_h ($M_{2\tau} < 120$ GeV); try to reconstruct the a priori unknown Higgs (H_S) mass from two b-jets

Analyse the final state twice:

First:
— since the H_S decay products are boosted, look for two “slim” b-jets and two τ_h using anti-k_T jet-finding algorithm with small cone size $R = 0.15$
Define a $2b$ pseudo-jet $2bPJ$ as the sum of both b-tagged jets
Second:
— Apply the anti-k_T jet-finding algorithm again, with $R = 0.5$
$\to$ The two boosted b-jets tend to merge into a single fatter jet $\hat{J}$;
Look for the jet $\hat{J}$ with $p_T > 400$ GeV closest in ΔR to the previously found $2bPJ$

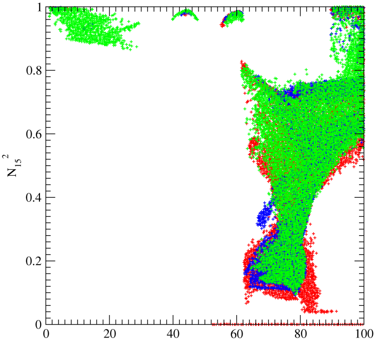
Invariant mass of $\hat{J}$ (event numbers after $100 fb^{-1}$ at 14 TeV):



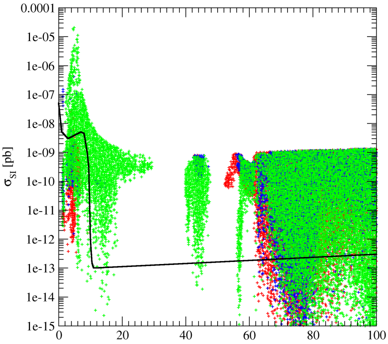
→ The signal is there! Here: $M_{H_S} = 83$ GeV, $M_{squark} \sim M_{gluino} \sim 900$ GeV
Of course: for heavier squarks/gluinos the H_S production cross section (here: ~ 5.2 pb) would go down
Dominant background from QCD: 2 jets + $b\bar{b}$ + 2 fake τ's

Dark Matter and the Singlino:

N_{15}: Singlino component of the LSP after constraints from WMAP/Planck



Direct detection cross section after constraints from LUX:
(Black line: Expected neutrino background*)



$\longrightarrow$ The direct detection rate of mostly singlino-like dark matter can fall below the expected neutrino background!

*from J. Billard, L. Strigari and E. Figueroa-Feliciano, PRD 89 (2014) 023524

A light singlino allows for a light higgsino, consistent with a good dark matter relic density ($\rightarrow$ LSP = mixture of singlino/higgsino)

A small higgsino mass parameter μ ($\equiv \lambda \langle S \rangle$ in the NMSSM) is desirable for naturalness, since $\mu^2 > 0$ contributes to the scalar Higgs mass terms $M^2_{Higgs_{u,d}}$ in the potential[3]:

$M^2_{Higgs_{u,d}} = \mu^2 + M^2_{soft_{u,d}}$ where $M^2_{soft_{u,d}}$ are the soft SUSY breaking mass terms

$\longrightarrow$ At least one $M^2_{Higgs_{u,d}}$ has to be negative (of $\mathcal{O}(M_Z^2)$); otherwise the Higgs potential is stable at $\langle H_u \rangle = \langle H_d \rangle = 0$, no electroweak symmetry breaking

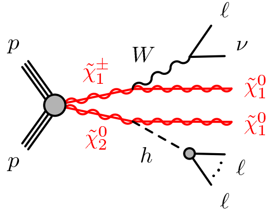
$\longrightarrow$ Expect $\mu^2,\ M^2_{soft_{u,d}} \sim \mathcal{O}(M_Z^2)$ to avoid strong cancellations

$\longrightarrow$ Expect light (neutral and charged) higgsinos, which is consistent with a good dark matter relic density in the NMSSM!

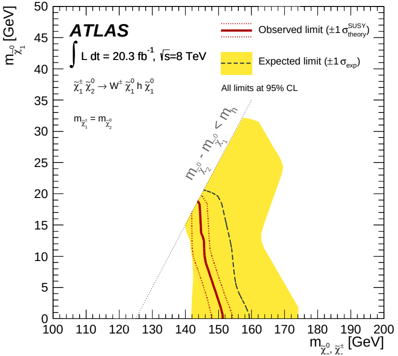
$\longrightarrow$ Visible at the LHC?

[3] See talks by H. Baer, T. Cohen

In the presence of light Higgs states, the dominant search channel are leptons + E_T^{miss} from



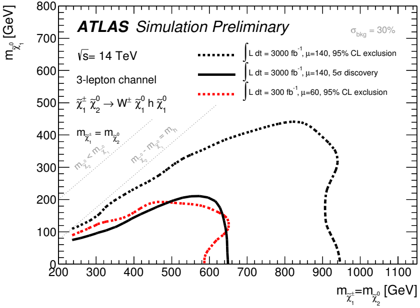
but the limits from run I are quite weak:
(here: $h = H_{125}$ assumed)



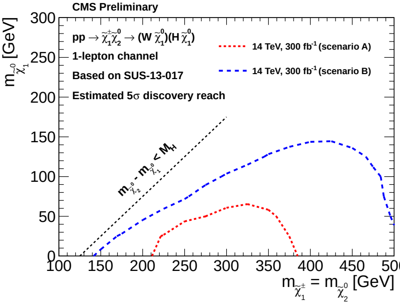
And little improvement expected at the run II:
Small cross sections for higgsinos, little E_T^{miss} for light $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$

Future prospects in the channel wino-like $\tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0$ (bino) + Higgs:

ATLAS (PHYS-PUB-2013-011)
300 fb^{-1}, 3000 fb^{-1},
$3\sigma/5\sigma$ exclusion/discovery

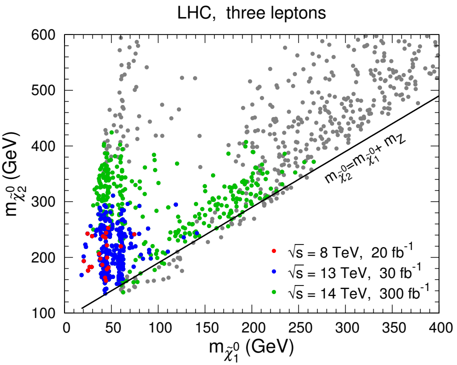


CMS (from 1307.7135)
300 fb^{-1}, 5σ discovery
depend. on trigger upgrade A/B



$\longrightarrow$ Prospects seem quite promising at first sight...

Outlook within the simplified Higgsino-Singlino scenario in the NMSSM*



Red points: Excluded from the run I of the LHC
Blue/green points: Visible at 13 TeV (30 fb^{-1}) or 14 TeV (300 fb^{-1})
Grey points: Remain invisible**

$\longrightarrow$ The complete Higgsino-Singlino scenario in the NMSSM is hard to test at the run II of the LHC, even for light higgsinos and sizeable higgsino-singlino mass splitting!

*From Quian-Fei Xiang, Xiao-Jun Bi, Peng-Fei Yin, Zhao-Huan Yu, 1606.02149
**Invisible points also found by J. Cao, Y. He, L. Shang, W. Su, Y. Zhang, 1606.04416

Conclusions:

- After the run I of the LHC, the parameter space of the NMSSM is less constrained than the one of the MSSM:
- No heavy stops needed for $H_{SM} \sim 125$ GeV
- No heavy higgsinos (large μ_{eff}) needed for dark matter consistent with WMAP/Planck
- Alleviated lower bounds on M_{squark}, M_{gluino} due to possible "missing E_T^{miss}"
- A plethora of "non-MSSM-like" signatures are possible at the run II of the LHC:
    - Additional Higgs-to-Higgs decays
    - Additional Higgs bosons in squark/gluino/chargino/neutralino decay cascades
- BUT: The discovery of sparticles (light higgsinos, squarks, gluinos, direct detection of dark matter, stops ...) in standard search channels can be even more difficult than in the MSSM; special attention may be needed!

$\rightarrow$ keep posted!

Comment on the ~ 250 models for a 750 GeV diphoton resonance by Georg Lichtenberg, German scientist and philosopher, 1742–1799:

A rather audacious philosopher, Hamlet, Prince of Denmark, I think, said that there are many things in heaven and on earth that are not mentioned in our compendia.

If the simple fellow, who as is well known was not quite in his right mind, was mocking our physics compendia, we might confidently reply to him: very well, but then there are also many things in our compendia that can be found neither in heaven nor on earth.