Review of the NMSSM phenomenology
NMSSM Workshop Orsay 2016

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Recall the Goodies of the NMSSM

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

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

$\longrightarrow$ No $>$ TeV stops are needed for $M_{H_{SM}} \sim 125$ GeV

- 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 (see the talk by M. Rodriguez):
  - $H \to H_S + H_S$ 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

Light Pseudoscalars

Notably the singlet-like pseudoscalar A_S can be quite light;
a pseudo-Goldstone boson of a spontaneously broken approximate global symmetry:

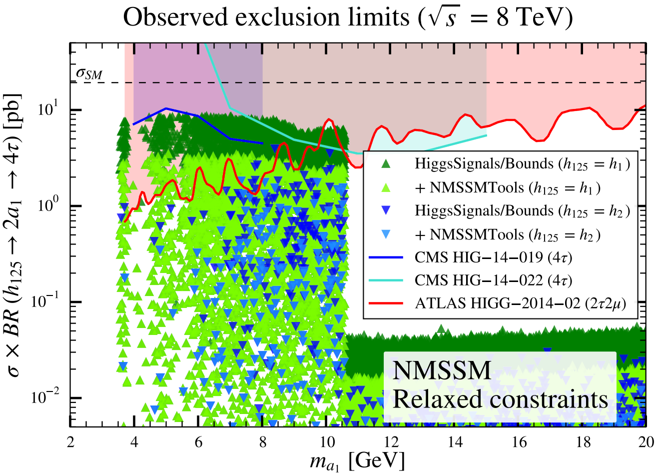
– A Peccei-Quinn symmetry $H_u \to H_u e^{i\varphi}, \quad H_d \to H_d e^{i\varphi}, \quad S \to S e^{-2i\varphi}$
if the S^3 coupling $\kappa \to 0$, or

– 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 constrained by LEP,
by the $BR(H_{125} \to A_S A_S) \lesssim 10\%$ from the measured H_{125} SM-like signal rates,
and by direct searches by ATLAS and CMS at the LHC, but not ruled out:

Run I searches for $H_{125} \to A_S A_S \to 4$ leptons

(From R. Aggleton, D. Barducci, N. Bomark, S. Moretti, C. Shepherd-Themistocleous, arXiv:1609.06089)



Light green/blue points: viable in the NMSSM after LEP/other LHC constraints

$\to$ These searches for A_S have only scratched the NMSSM parameter space

Discovery Prospects of a Light Singlet-Like CP-even Scalar H_S

With M. Rodriguez-Vazquez, arXiv:1512.04281, JHEP 1602 (2016) 096

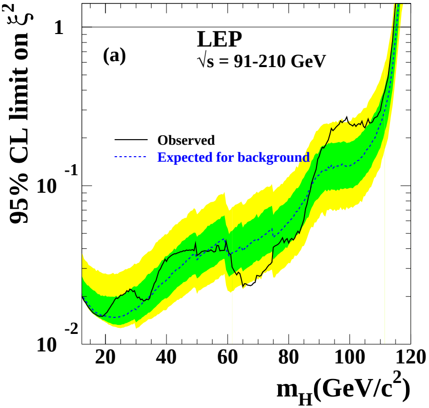
Impact of $H_{SM} - H_S$ mixing:

Generated by a term $\mathcal{M}^2_{H_S,H_{SM}} \sim \lambda v \left(2\lambda \langle S\rangle - \sin 2\beta (A_\lambda + 2\kappa \langle S\rangle)\right)$ 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! (An uplift of $M^2_{H_{SM}}$ complementary to $\lambda^2 v^2 \sin^2 2\beta$ in the diagonal of the mass^2 matrix)
- 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: $\sqrt{(1-\xi^2)} \gtrsim 0.83$,
  $\xi \lesssim 0.56$ ($\xi^2 \lesssim .31$)

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

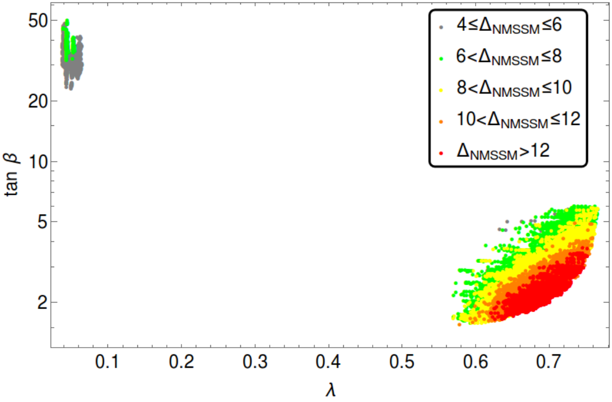
Constraints from the combined LEP experiments on a Higgs coupling $\xi \, H_{SM} ZZ$ (relative to the coupling of H_{SM}) vs. M_H:



$\rightarrow$ 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 mixing (LMIX) or large λ (LLAM)

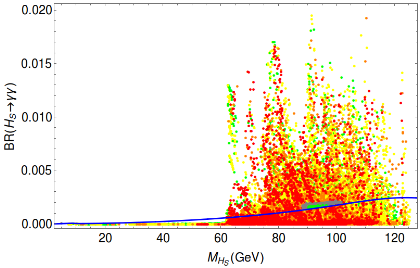
λ-tan β plane showing the viable points where $\Delta_{\mathrm{NMSSM}} \gtrsim 4$ GeV:

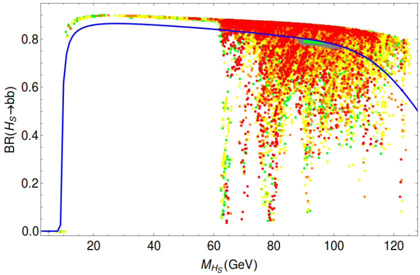


LMIX: $\lambda \lesssim 0.1$, $\tan\beta \sim 25 - 50$

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

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





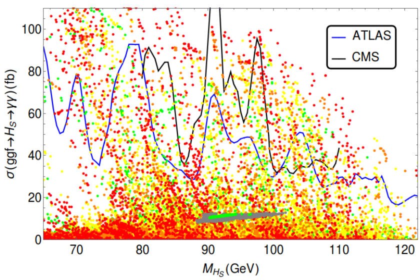
The blue line indicates the corresponding branching ratios for a SM Higgs boson of the same mass. The grey-green island corresponds to the LMIX region in which the branching ratios are very SM-like.

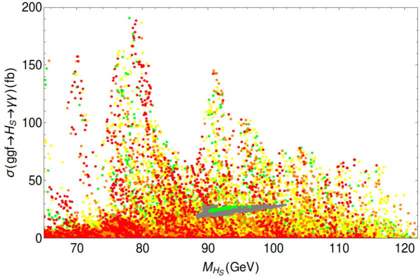
$\longrightarrow$ In the LLAM region, the $BR(H_S \to \gamma\gamma)$ can be considerably enhanced!

(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

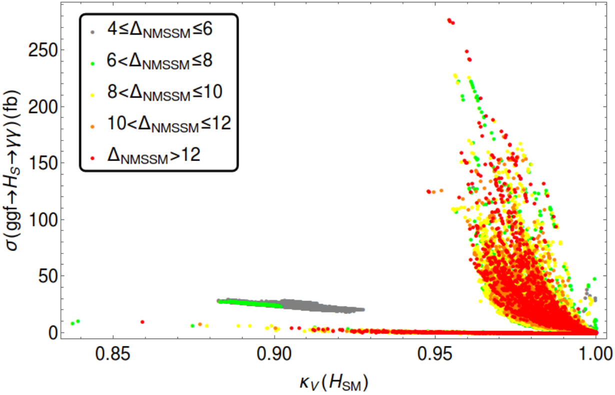
Blue line: Bounds from ATLAS, PRL 113 (2014) 17, 171801 (1407.6583)
Black line: Bounds from CMS, CMS-PAS-HIG-14-037
Red/yellow/green points: LLAM region, gray/green region: LMIX region.





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}?

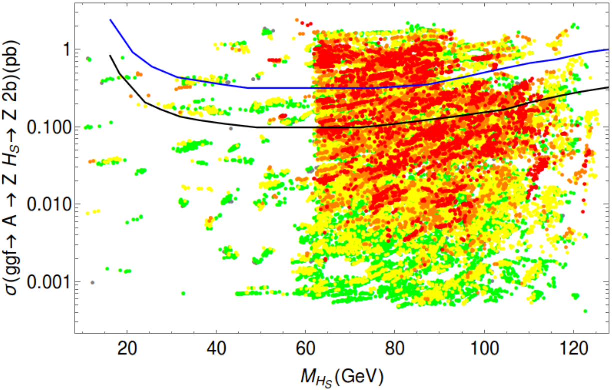


Expect at the LHC run II: $\Delta\kappa_V \sim 5\%$ ($\rightarrow \kappa_V < 0.95$ ruled out)

$\longrightarrow$ 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)*

→ A discovery of H_S is possible, but not guaranteed

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

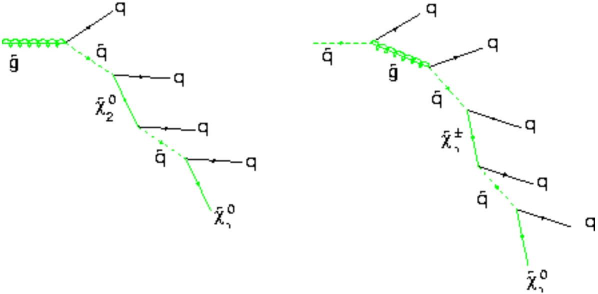
Production of H_S in Decays of Squarks/Gluinos

"Missing" missing transverse energy:

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

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

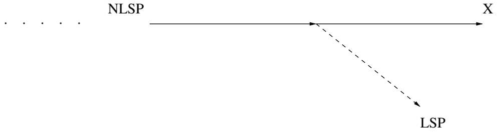


$\longrightarrow$ Susy particle (pair-) production leads to missing transverse momentum/energy

— 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)
$\rightarrow$ 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:

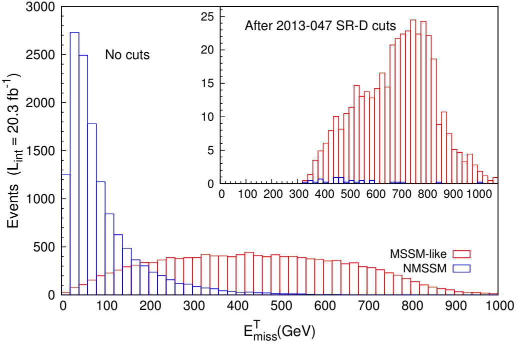
"X" can be H_S!

$\longrightarrow$ 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 (from 1406.7221 with A.M.Teixeira)

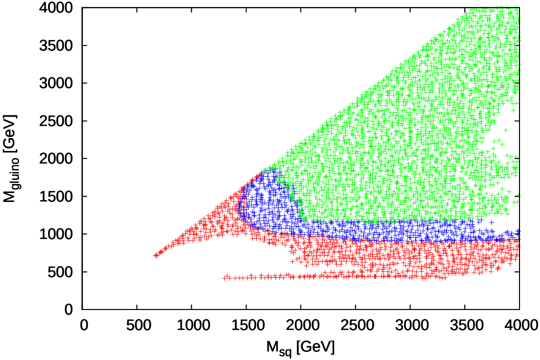
Spectrum of E_T^{miss} from ~ 1 TeV squark/gluino production at 8 TeV:
MSSM: With bino as LSP
NMSSM: With bino $\rightarrow H_S +$ singlino decay



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

Search for two H_S via squark/gluino production in the jets $+b\bar{b}+\tau^+\tau^-$ final state:*

— 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 ("subjet analysis"):

First:

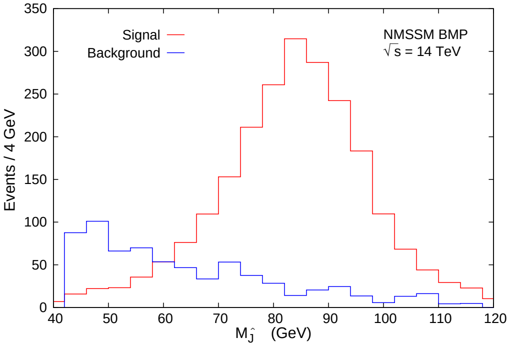
— since the H_S decay products are boosted, look for two "slim" b-jets and two τ_h using anti-k_T jet-finding algorithm with small cone size $R = 0.15$
Define a $2b$ pseudo-jet $2bPJ$ as the sum of both b-tagged jets

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 $2bPJ$

* With A.M. Teixeira, arXiv:1406.7221 and arXiv:1412.6394

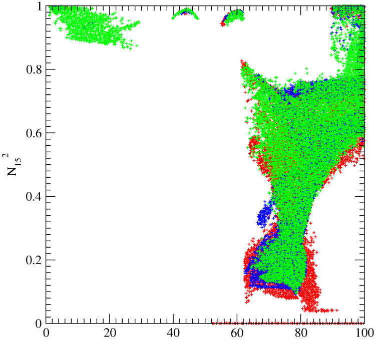
Invariant mass of $\hat{J}$ (event numbers after $100 fb^{-1}$ at 14 TeV):



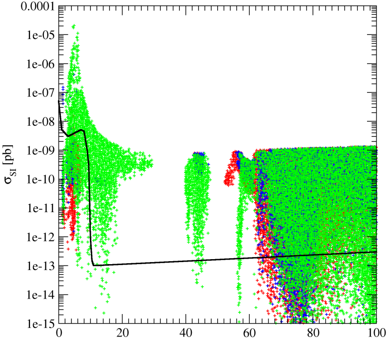
→ The signal is there! Here: $M_{H_S} = 83$ GeV, $M_{squark} \sim M_{gluino} \sim 900$ GeV
Of course: for heavier squarks/gluinos the H_S production cross section (here: ~ 5.2 pb) would go down
Dominant background from QCD: 2 jets + $b\bar{b}$ + 2 fake τ's

Dark Matter and the Singlino-Like LSP

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



Direct detection cross section after constraints from LUX (2014):
(Black line: Expected neutrino background**)



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

*from arXiv:1405.6647, with C. Hugonie

**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

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

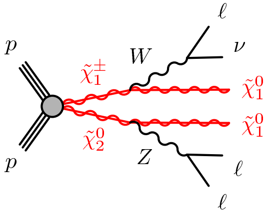
$\longrightarrow$ At least one $M^2_{Higgs_{u,d}}$ has to be negative (of $\mathcal{O}(M_Z^2)$); otherwise the Higgs potential is stable at $\langle H_u \rangle = \langle H_d \rangle = 0$, no electroweak symmetry breaking

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

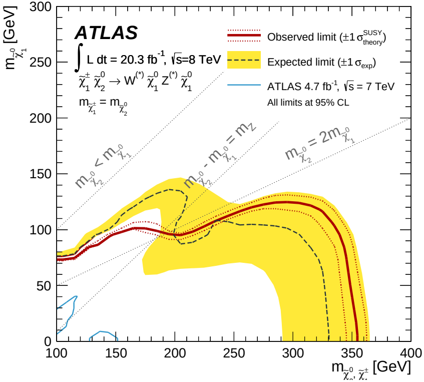
$\longrightarrow$ Expect light (neutral and charged) higgsinos, which is consistent with a good dark matter relic density in the NMSSM!

$\rightarrow$ Visible at the LHC?

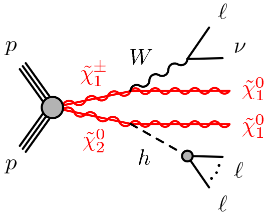
The dominant chargino/neutralino search channel: three leptons + E_T^{miss} from



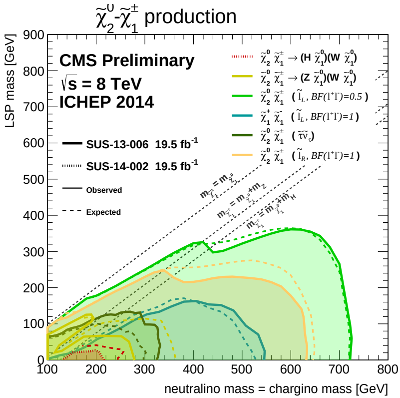
ATLAS limits from run I
assuming wino-like χ_2^0 and $\chi_1^{\pm}$:



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



Combined constraints from CMS:
(here: $h = H_{125}$ and wino-like χ_2^0 and $\chi_1^\pm$ assumed; the most stringent limits assume decays via light sleptons)



BUT: These limits have to be recasted for the singlino/higgsino scenario in the NMSSM:

- Smaller production cross sections for higgsino-like $\chi^0_{2,3}$ and $\chi^\pm_1$
- In practice: Shared branching fractions for $\chi^0_{2,3} \to \chi^0_1 + Z$, $\chi^0_{2,3} \to \chi^0_1 + H_{SM}$ and $\chi^0_{2,3} \to \chi^0_1 + H_S$ (the latter are NOT tested for $M_{H_S} \neq 125$ GeV)

Scan of the NMSSM parameter space (asking for the correct relic density, applying recent LUX/Panda limits on direct DM detection), looking for definitively excluded regions in the $M_{LSP} - M_{chargino}$ plane in the higgsino/singlino scenario*

- No excluded region from the run I of the LHC!
- Run II/high luminosity run (3000 fb^{-1}): only a small island for heavier $M_{chargino} \approx 250$ GeV can be tested
  Reason: Larger instantaneous luminosity
  $\to$ need harder triggers/cuts on lepton-p_T and E_T^{miss}
  $\to$ no longer sensitive to lighter charginos/neutralinos

$\to$ Most of the attractive light higgsino/singlino scenario within the NMSSM was and will remain untested at the LHC!

* UE, to be published

Conclusions:

- The NMSSM remains the most attractive SUSY extension of the Standard Model:
- No heavy stops needed for $H_{SM} \sim 125$ GeV
- No heavy higgsinos (large μ_{eff}) needed for dark matter consistent with WMAP/Planck
- After the run I of the LHC, the parameter space of the NMSSM is less constrained than the one of the MSSM:
  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, stops at the LHC, direct detection of dark matter ...) can be considerably more difficult than in the MSSM
  Conclusive tests of the attractive light higgsino/singlino scenario are likely to require a e^+-e^- collider!

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.