Supersymmetry: Status 2018/19

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Supersymmetry addresses the following shortcomings of the SM:

- The Hierarchy Problem
- What is Dark Matter?
- Unification of gauge couplings
  (quarks and leptons fill complete SU(5) representations, but gauge couplings do not quite unify in the Standard Model without Supersymmetry)
- Possibly: the $\sim 3\ \sigma$ deviation of the measured anomalous magnetic moment of the muon a_μ w.r.t. the Standard Model

BUT: Up to now, no significant sign for Supersymmetry at the LHC

Status of the MSSM after 36 fb^{-1} at the LHC

Better not rely on interpretations of limits within simplified models (simplified decay cascades, typically 1 step), but

- consider versions of the "pMSSM" (differ by the number of independent parameters/soft Supersymmetry breaking terms at the weak scale)
- consider all (most relevant) searches by ATLAS and CMS simultaneously, interprete with realistic branching ratios and decay cascades within these models
- require the Higgs (H_{125}) mass and couplings within present limits
  $\longrightarrow$ Need a large soft Supersymmetry breaking A_{top} and/or large soft Supersymmetry breaking stop mass terms
  $\rightarrow$ large rad. corrections to a soft Supersymmetry breaking Higgs mass term
  $\rightarrow$ a "little" finetuning problem
- Finally: derive lower limits on sparticle masses at 95% confidence level

The Dark Matter Issue

Case of generic annihilation cross sections of higgsinos/winos/binos as LSP χ_1^0:

- Higgsinos and winos annihilate too fast
  $\longrightarrow$ Relic density too small (unless $M_{\chi_1^0} \gtrsim 1$ TeV $\to M_{Squark,\ Slepton} > 1$ TeV)
- Binos annihilate too slow $\longrightarrow$ Ωh^2 too large

$\longrightarrow$ Binos as LSP/DM require enhanced annihilation cross sections:

- Large bino/wino/higgsino mixing requires tuning given the relatively small off-diagonal elements of the 4×4 neutralino mass matrix
- coannihilation with charginos/sleptons/stops ($\longrightarrow M_{\chi_1^0} > 100$ GeV since near-degeneracy is required), or
- annihilation via H_{125} or heavy H/A-funnels

$\longrightarrow$ Higgsinos/winos as LSP lighter than 1 TeV require other sources for DM (their lower relic densities would allow to alleviate constraints from direct DM detection which are strong)

Or: unconventional cosmological evolution

Recent pMSSM Scans

GAMBIT collaboration (1705.07917), pMSSM7:

- Gaugino mass ratios motivated by GUT: $M_3/\alpha_s = M_2/\alpha_2 = M_1/\alpha_1$
- Degenerate soft squark/slepton masses, but free $A_t \neq A_b$ (the muon anomalous magnetic moment a_μ cannot be fitted)
- Free soft Higgs masses M_{H_u}, M_{H_d}, $\tan\beta$ ($\to \mu$, B_μ fixed by M_Z, $\tan\beta$)
- $\Omega h^2 \lesssim 0.1189$ (smaller Ωh^2 alleviates constraints from direct DM detection, but requires additional sources of dark matter)

MasterCode (1710.11091), pMSSM11:

- Free gaugino masses
- Different soft squark/slepton masses for the first two/third generations, free $A_t = A_b$
- Free μ, $\tan\beta$, M_A
- $\Omega h^2 = 0.1186 \pm 0.004$
- With or without fits to the muon anomalous magnetic moment a_μ

Limits on sparticle masses

(Within 2σ of the "best fit point" to numerous search signal regions mainly from sparticle searches by ATLAS/CMS)

MasterCode: The parameters of the "best fit points" with or w/o a_μ are completely different!

	GAMBIT	MasterCode with a_μ	MasterCode w/o a_μ
$M_{\chi_1^0}$	$\gtrsim$ 60 GeV (H'ino)	90 – 500 GeV (bino)	$>$ 90 GeV (H'ino)
$M_{\chi_1^\pm}$	$\gtrsim$ 90 GeV	$\gtrsim$ 90 GeV	$\gtrsim$ 90 GeV
$M_{\tilde{g}}$	$\gtrsim 1,0$ TeV	$\gtrsim 1,8$ TeV	$\gtrsim 1,0$ TeV
$M_{\tilde{q}}$	$\gtrsim 1,2$ TeV	$\gtrsim 1,9$ TeV	$\gtrsim$ 800 GeV
$M_{\tilde{t}}$	$\gtrsim 0,5$ TeV	$\sim$ 500 GeV/ $\gtrsim 1,0$ TeV	$\gtrsim$ 500 GeV
$M_{\tilde{\tau}}$	$\gtrsim 1,3$ TeV	$\gtrsim$ 110 GeV	$\gtrsim$ 110 GeV
$M_{\tilde{\mu}}$	$\gtrsim 1,3$ TeV	110 – 770 GeV	$\gtrsim$ 110 GeV
M_A	$\gtrsim$ 500 GeV	$\gtrsim$ 800 GeV	$\gtrsim$ 800 GeV

No sign for "dark spots" in the combined signal regions (light sparticles escaping detection)

$\longrightarrow$ Limits on squarks/gluinos depend strongly on assumptions (possible decay cascades)

NMSSM

– Extra neutral CP-even and CP-odd scalars H_S, A_S (not degenerate!) on top of the MSSM-like heavy ∼degenerate SU(2) doublets H/A

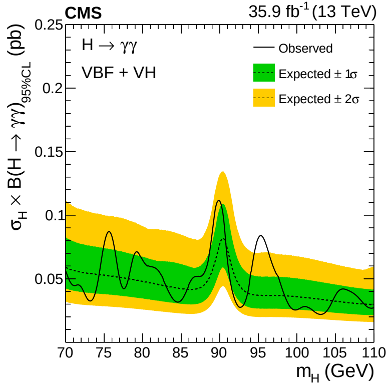
– Extra singlino $\tilde{S}$ on top of the MSSM-like charged/neutral bino/wino/higgsinos

– H_S, A_S, $\tilde{S}$ have small couplings to SM particles/MSSM sparticles, except to the Higgs sector from a coupling $\lambda \widetilde{H}_u \widetilde{H}_d \widetilde{H}_S$ in the superpotential (in terms of superfields)

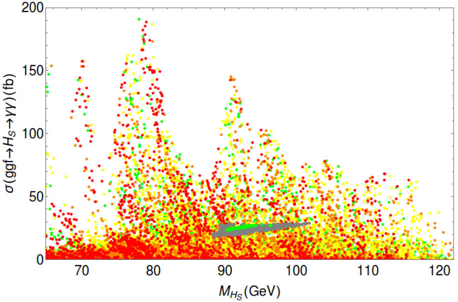
$\longrightarrow$ Small direct production cross sections proportional to mixing angles$^2 \sim \lambda^2$, but possible decay products of SM particles/MSSM sparticles

$\longrightarrow$ Still: H_S, A_S decay into SM particles like H_{125} due to mixing

$\longrightarrow$ Searches for $ggF \rightarrow H_S \rightarrow \gamma\gamma$ with $M_{H_S} < 125$ GeV are sensitive to viable cross sections $\times$ BR in the NMSSM:



From CMS-HIG-17-013 (13 TeV)

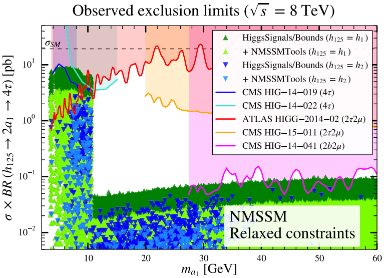


Possible Xsect$\times$BR in the NMSSM for 13 TeV using limits from 8 TeV, from 1512.04281

Searches for $H_{125} \to A_S A_S / H_S H_S$ are sensitive to BSM branching fractions of H_{125} allowed by indirect constraints from measured H_{125} couplings

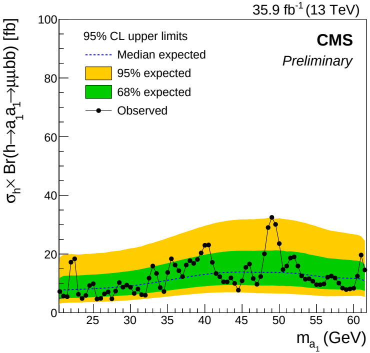
Many possible final states, many recent and ongoing searches by ATLAS/CMS

Compilation by R. Aggleton et al., JHEP 1702 (2017) 035:



Light green/blue points: viable in the NMSSM after 2017 LEP/LHC constraints

CMS-PAS-HIG-18-011:

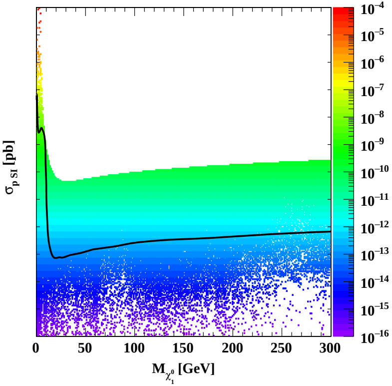


Significant improvement in the $\mu\mu bb$ channel!

If the singlino $\tilde{S}$ is the LSP (I)

A good DM candidate: a relic density $\Omega h^2 \sim 0.119$ is possible even if $\tilde{S}$ is very light (a few GeV) through annihilation via A_S funnel ($\neq$ MSSM)

Constraints from direct detection experiments:
coloured region: NMSSM points allowed by constraints from LUX/PandaX-II
$\longrightarrow$ Xsect possibly below the neutrino floor (black curve):



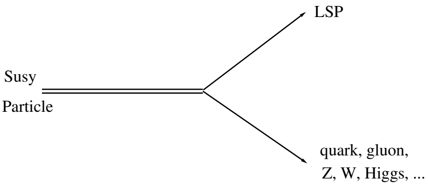
(from 1806.09478)

If the singlino $\tilde{S}$ is the LSP (II)

Every NLSP (neutralino, chargino, slepton, stop. . .) will decay into

$$\tilde{S} + H_{125}/H_S/A_S/Z, W, lepton, top \ldots,$$

the only available decay channels due to R-parity conservation



$\longrightarrow$ Impact on sparticle searches?

Notably if $\tilde{S}$ is light (a few GeV) AND $M_{NLSP} \approx M_{\tilde{S}} + M_X$, $X = H_{125}/H_S/A_S/Z$:

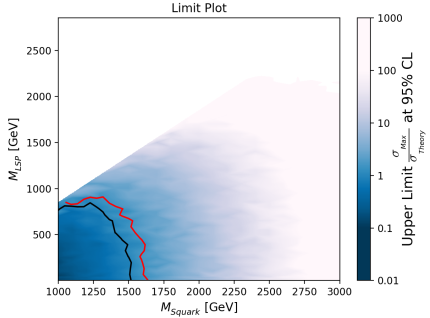
Little energy is given to $\tilde{S}$ in any decay $NLSP_{heavy} \to X_{heavy} + \tilde{S}_{light}$

$\longrightarrow$ Little E_T^{miss} from $\tilde{S}$ in all Susy searches

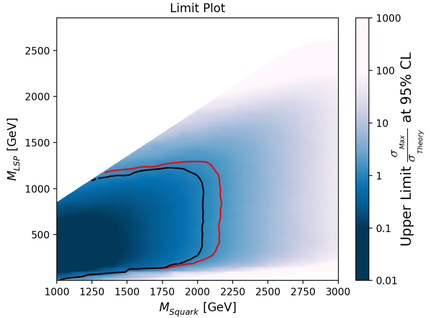
$\longrightarrow$ Reduced lower limits on sparticle masses (A.Teixeira, U.E., 1406.7221, 1412.6394)

Re-analysis of sensitivities of the CMS squark search via jets and E_T^{miss} (1802.02110, after 36 fb^{-1} at 13 TeV) by A. Titterton et al., 1807.10672:

MSSM with bino LSP
Assume $\tilde{q} \to q + bino$



NMSSM with $\tilde{q} \to q + bino \to q + \tilde{S} + H_{125}$
$M_{bino} = M_{\tilde{S}} + M_{H_{125}} + 2$ GeV



(red/black curves: expected/observed limits)

NMSSM: strong reduction of the lower limit on M_{Squark} for small $M_{LSP} = M_{\tilde{S}}$!

Given the present absence of significant excesses:

What are the constraints on the NMSSM parameter space (masses and couplings)?

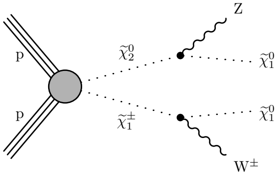
A simple but highly nontrivial question given the larger parameter space, and the possibilities of "dark spots": reduced sensitivities in case of quenched spectra, complicated decay cascades, ...

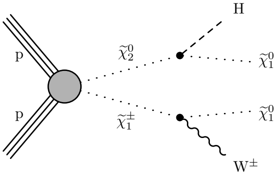
"Bottom up" approach: Start with constraints on neutralinos/charginos, the lower ends of heavier sparticle decay cascades:
Neutralino/chargino masses and couplings are needed for their simulations!

Require – as promised by Supersymmetry – a viable DM relic density consistent with constraints from direct DM detection

At the LHC, neutralinos/charginos are produced via $W^{\pm *} \to \chi_i^0 + \chi_j^\pm$ (or $Z^* \to \chi_i^\pm + \chi_j^\mp, \chi_i^0 + \chi_j^0$)

Searches by ATLAS/CMS: Trileptons from $Z + W$ (or bb from H_{125}):





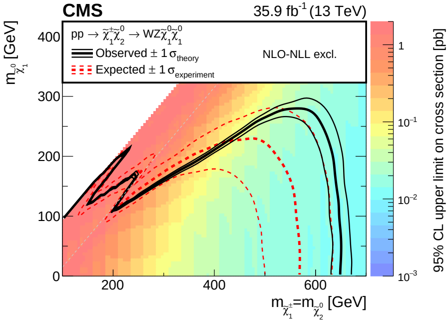
Results are typically interpreted for wino-like $\chi_2^0 + \chi_1^\pm$:
Largest cross sections $\to$ strongest constraints

But: Higgsinos have only half the cross section (even adding χ_2^0, χ_3^0)
$\to$ weaker constraints

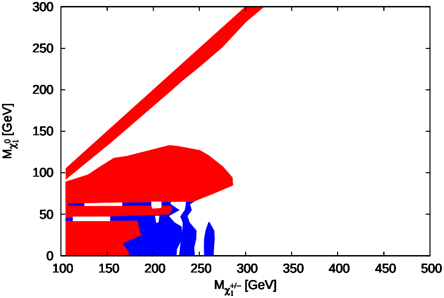
For limits on the NMSSM singlino-higgsino sector (with C. Hugonie, 1806.09478):
Scan the parameter space with singlino LSP, require a viable relic density consistent with constraints from direct DM detection, apply bounds from the CMS trilepton search in 1801.03957 (the strongest ones)

Comparison of limits the in the $M_{\chi_1^0}/M_{\chi_1^\pm} \sim M_{\chi_2^0}$ plane:

CMS, assuming wino-like χ_2^0 and $\chi_1^\pm$:



NMSSM, singlino LSP and higgsino-like χ_2^0, χ_3^0 and $\chi_1^\pm$, bino-like χ_4^0:

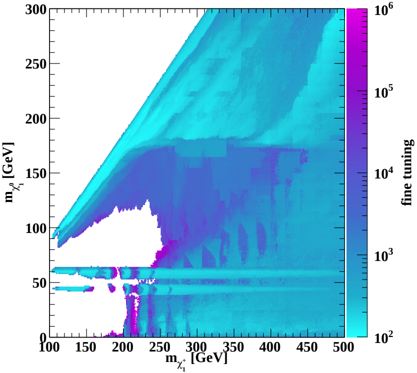


Red: Excluded by constraints on DM and by CMS

Blue: Excluded iff the bino mass satisfies $M_1 > 300$ GeV as motivated by the GUT relation $M_1 \approx M_{Gluino}/6$ and $M_{Gluino} \gtrsim 1.8$ TeV $\to$ no bino/higgsino mixing

$\longrightarrow$ Substantial reduction of limits!

Allowed regions in the plane $M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0}$ in the constrained NMSSM: universal soft susy breaking terms at the GUT scale, but non-universal soft Higgs mass terms (allows to estimate the necessary amount of finetuning):



$\longrightarrow$ Relatively low finetuning for $M_{\tilde{\chi}_1^0} \sim M_Z/2$, $M_{\tilde{\chi}_1^0} \sim M_{H125}/2$ or $M_{\tilde{\chi}_1^0} \sim M_{\tilde{\chi}_1^\pm}$ where s-channel annihilation or co-annihilation is possible

Otherwise: s-channel annihilation via A_S with $M_{\tilde{\chi}_1^0} \sim M_{A_S}/2$

$\longrightarrow$ Many regions with relatively low fine-tuning ≈ 100 remain to be tested

Dark Spots for neutralino/chargino searches:

- Mixed bino – higgsino NLSP χ_2^0: reduces production cross section further
- $\chi_{2,3}^0$ cascade decays via light H_S or A_S (escape searches for H_{125} via $b\bar{b}$)
- Light staus $\tilde{\tau}$ as NLSP: Hardly constrained by the LHC (limits from LEP), $\rightarrow$ less "Trileptons" in the final state

Hints for Excesses?

Recent searches for neutralinos/charginos by ATLAS/CMS:

Some local $2-3\,\sigma$ excesses in some bins/some signal regions
(e.g. ATLAS 1806.02293 in SR2$\ell_{low/ISR}$ and SR3$\ell_{low/ISR}$)
$\longrightarrow$ If interpreted in terms of simplified models:
No significant deviations from observed w.r.t. expected limits

GAMBIT collaboration, 1809.02097:
combine 4 ATLAS and 4 CMS electroweakino searches after 39 fb^{-1}
($\approx$ 10 signal regions each, up to $\sim$ 40 bins),
compare to simulations within a pMSSM electroweakino sector
(bino, wino, higgsinos), allowing for cascade decays
$\longrightarrow$ local 3,2 σ excess for $M_{\chi_1^0} \sim 50$ GeV, $M_{\chi_1^\pm} \sim 150$ GeV
via contributions from χ_2^0, χ_3^0 and $\chi_2^\pm$ multi-W/Z cascade decays
($M_{\chi_1^0} \sim 8-155$ GeV, $M_{\chi_1^\pm} \sim 104-259$ GeV within 95% CL)
But: Missing covariance matrices for stat. analysis including more search results

Viable relic density possible for bino-like LSP via Z/H_{125} funnels

$\rightarrow$ To confirm or to rule out!

Conclusions:

- Due to $M_{Higgs} \sim 125$ GeV the MSSM has a "little" finetuning problem of at least $\mathcal{O}(1\%)$, of $\mathcal{O}(1‰)$ with (grand) unified soft Supersymmetry breaking terms, somewhat less in the NMSSM
- Of course: even with M_{Squark}, $M_{Gluino} > 1 - 2$ TeV Supersymmetry still solves the "BIG" hierarchy problem
- To derive definite constraints on the high dimensional parameter space is a challenging task, notably in the NMSSM ($\rightarrow$ dark spots)
- But a MUST for the future – unless significant excesses appear