Supersymmetry: Status 2019

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Supersymmetry can address the following shortcomings of the SM:

- The Hierarchy Problem
- Dark Matter relic density (incl. constraints from spin dependent/independent direct detection experiments)
- 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,
  - galactic center gamma ray excess (dark matter interpretation still viable!),
  - AMS-02 anti-proton excess,
  - ATLAS 2/3 lepton + ISR excess ($\sim 2/3\ \sigma$)

To do

1) Better not rely on interpretations of limits within simplified models (simplified decay cascades, typically 1 step), but recast limits within realistic versions of the MSSM (pMSSM) or NMSSM,
preferably including the dark matter relic density

2) Try to fit at least some of the excesses without violating existing constraints

3) Provide experimentalists with new promising search channels

Recasting limits in the pMSSM:

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 $2\,\sigma$ of the "best fit point" to numerous search signal regions mainly from sparticle searches by ATLAS/CMS)

MasterCode: Some of 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	~ 500 GeV/ $\gtrsim 1,0$ TeV	$\gtrsim 500$ GeV
$M_{\tilde{\tau}}$	$\gtrsim 1,3$ TeV	$\gtrsim 110$ GeV (LEP)	$\gtrsim 110$ GeV (LEP)
$M_{\tilde{\mu}}$	$\gtrsim 1,3$ 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)

Recast limits in the NMSSM:

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

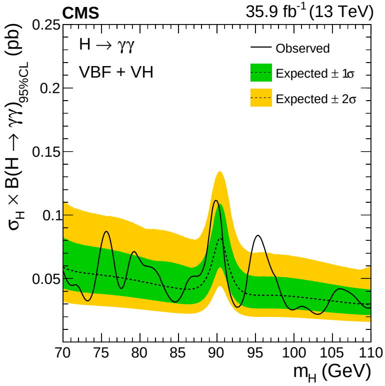
– Extra singlino $\tilde{S}$ on top of the MSSM-like charged/neutral bino/wino/higgsinos

– 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)

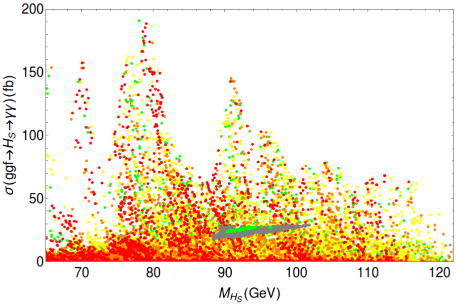
$\longrightarrow$ Small direct production cross sections proportional to mixing angles$^2 \sim \lambda^2$, but singlets can be possible decay products of Higgs bosons or sparticles

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

Searches for $ggF \to H_S \to \gamma\gamma$ with $M_{H_S} < 125$ GeV



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



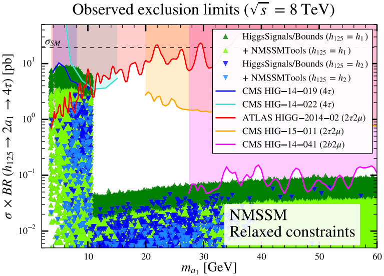
Possible Xsect$\times$BR in the NMSSM for 13 TeV using limits from 8 TeV, from 1512.04281

$\longrightarrow$ Sensitivity to viable cross sections $\times$ BR in the NMSSM!

Searches for $H_{125} \to A_S A_S / H_S H_S$

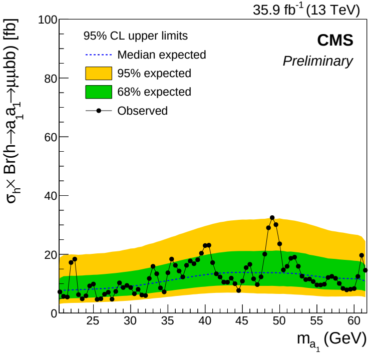
Many possible final states, many recent and ongoing searches by ATLAS/CMS

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:



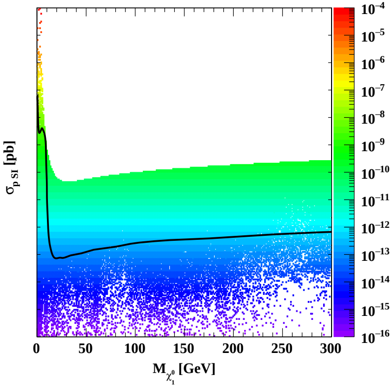
Significant improvement in the $\mu\mu bb$ channel!

$\longrightarrow$ Sensitivity to BSM branching fractions of H_{125} allowed by indirect constraints from measured H_{125} couplings!

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)

Coloured region: NMSSM points allowed by constraints from LUX/PandaX-II/Xenon (from 1806.09478 with C. Hugonie)



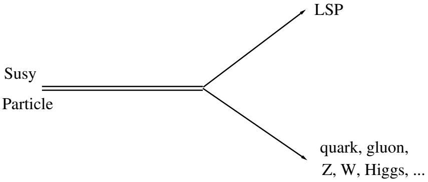
$\rightarrow$Xsection possibly below the neutrino floor (black curve)!

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

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

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

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

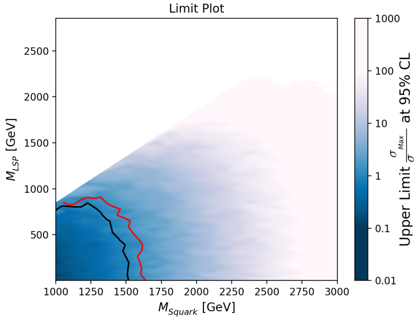
$\longrightarrow$ Reduced lower limits on sparticle masses (A.Teixeira, U.E., 1406.7221, 1412.6394)

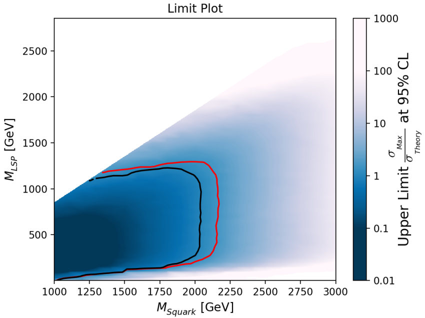
Recast limits from CMS squark search via jets and E_T^{miss} (1802.02110)

(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



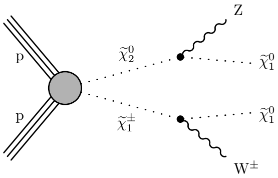


(red/black curves: expected/observed limits)

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

Recast searches by ATLAS/CMS for trileptons:

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



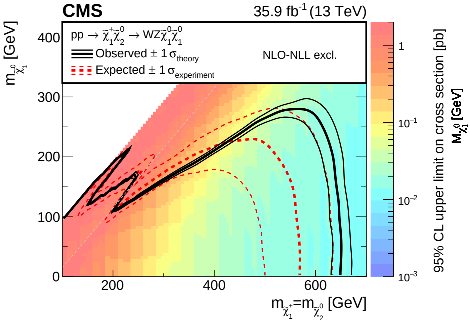
Results are typically interpreted for wino-like $\chi_2^0 + \chi_1^\pm$:
Largest cross sections $\to$ strongest constraints

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

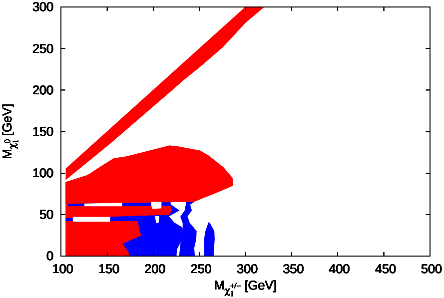
For limits on the NMSSM singlino-higgsino sector (with C. Hugonie, 1806.09478):
Scan the parameter space with singlino LSP, require a viable relic density consistent with constraints from direct DM detection, apply bounds from the CMS trilepton search in 1801.03957 (the strongest ones)

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:

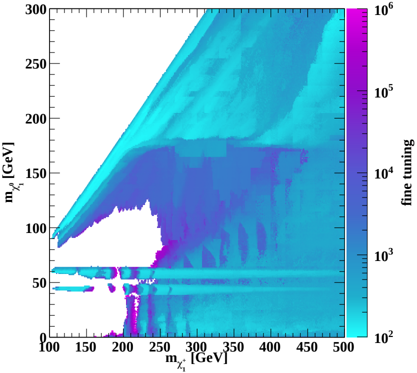


Red: Excluded by constraints on DM and by CMS

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 → no bino/higgsino mixing

→ 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 $M_{\tilde{\chi}_1^0} \sim M_{A_S}/2$

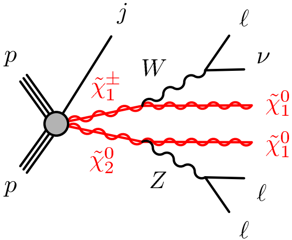
$\longrightarrow$ Many regions with relatively low fine-tuning ≈ 100 remain to be tested

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

Attempts to fit excesses

Searches for neutralinos/charginos by ATLAS using recursive jigsaw reconstruction (1806.02293), ISR jet, sensitive to small $\chi_2^0 - \chi_1^0$ mass differences:



Local $2 - 3\,\sigma$ excesses in the signal regions SR2ℓ_{low}+ISR and SR3ℓ_{low}+ISR

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} (≈ 10 signal regions each, up to ~ 40 bins), 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)

(Missing covariance matrices for stat. analysis including more search results)

M. Carena et al., 1809.11082:

Require a viable dark matter relic density and a fit of a_μ:

Bino-like χ_1^0, resonant pair annihilation via H_{SM} funnel
(requires some higgsino component for $H_{SM} - \chi_1^0 - \chi_1^0$ coupling)
Large $\tan\beta$ to suppress $H_{SM} \to \chi_1^0\chi_1^0$ decay

Suppress spin independent direct detection cross section via $\mu \cdot M_1 < 0$
But: Assume $\mu \cdot M_2 > 0$ (and large $\tan\beta$, $M_{\tilde{\nu}_\mu} < 400$ GeV) to fit a_μ

M. Carena et al., 1905.03768:

Include fit to galactic center gamma ray excess: Need $\chi_1^0\chi_1^0$ annihilation (Higgs funnel) via s-wave; then: simultaneous explanation of AMS-02 anti-proton excess from $\chi_1^0\chi_1^0 \to b\bar{b}$.

MSSM: M_1 complex $\to$ CP-violating $H_{SM} - \chi_1^0 - \chi_1^0$ coupling allows for annihilation via s-wave; but: constraints from electric dipole moments require heavy sleptons $\to$ fit of a_μ impossible

NMSSM: Relic density from χ_1^0 pair annihilation with a pseudoscalar in the s-channel

$\longrightarrow$ NMSSM benchmark point with common fit of ATLAS $3\ell_{low}$+ISR excess, a_μ, galactic center and AMS-02 anti-proton excesses!

Supersymmetry: Status 2019

- 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
- The dark matter relic density and some (mild) excesses in particle/astroparticle physics can be explained with still viable parameters in the MSSM, notably the NMSSM