Beyond Minimal SUSY

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Subjects

- The MSSM, and its problems
- The Next-to-Minimal Standard Model
- Its Higgs sector beyond the MSSM
- Possible impact on searches for SUSY
- Dark matter

Motivations for a supersymmetric extension of the SM

- Solves the hierarchy problem: the need to tune a bare Higgs mass term to 14 digits in order to cancel quadratically divergent quantum corrections
- Unification of the running gauge couplings at a GUT scale of $\sim 2 \times 10^{16}$ GeV (a numerical accident?)
- Automatically a dark matter candidate

→ Hard to give up, despite the absence of "sparticles" at the LHC
But supersymmetric extensions of the SM are not unique. The Minimal Supersymmetric extension of the SM (MSSM) is just the simplest choice (too simplistic ?), and at least some of the "pressure" is relieved in non-minimal extensions → to discuss

Minimal Supersymmetry (MSSM)

Every particle of the Standard Model (SM) has a "superpartner" with different spin: (Boson + Fermion) form a Supermultiplet
$\rightarrow$ Quantum corrections to Boson (Higgs) masses cancel

Quarks, Leptons $\leftrightarrow$ Squarks, Sleptons (Scalars)
Gauge Bosons $\leftrightarrow$ Gauginos (Fermions)
Higgs Boson(s) $\leftrightarrow$ Higgsinos (Fermions)

Need at least two Higgs doublets since one cannot couple simultaneously $H^\dagger$ to up-quarks and H to down-quarks/leptons (as in the SM)
MSSM: Two Higgs doublets H_u, H_d with VEVs v_u, v_d; $\tan\beta \equiv v_u/v_d$

Superpartners have the same dimensionless gauge and Yukawa couplings (related to quartic scalar couplings), but different " soft SUSY breaking" masses; quadratically divergent quantum corrections still cancel if Scalars (Squarks, Sleptons) and Gauginos have extra masses

All of the same order "M_{SUSY}", expected to be of $\mathcal{O}(M_{Higgs})$

Problems of the MSSM

1) The μ-Problem:

Higgsinos Ψ_{H_u} and Ψ_{H_d} – some of which are charged – have not been observed at LEP ($M_{chargino} \gtrsim 100$ GeV)

$\longrightarrow$ a higgsino mass term $\mu\, \Psi_{H_u} \Psi_{H_d}$ with $|\mu| \gtrsim 100$ GeV is required, but fermionic masses are supersymmetric, not soft SUSY breaking mass terms.

How can μ “happen” to be of the order of the other soft SUSY breaking mass terms which determine the electroweak scale?

Recall the generation of quark masses through the VEV of a Higgs scalar:

$\longrightarrow$ Generate a higgsino mass term through the VEV of an additional scalar S:

$$\mu\,\Psi_{H_u}\,\Psi_{H_d} \quad\to\quad \lambda\,S\,\Psi_{H_u}\,\Psi_{H_d}$$

S gets a VEV from $V(S) = m_S^2|S^2| + \kappa^2|S^2|^2 + \ldots,$
m_S^2 = soft SUSY breaking mass term (negative), $\left\langle S^2\right\rangle \approx -2m_S^2/\kappa^2$

$\longrightarrow$ $\lambda\,\langle S\rangle \equiv \mu_{\text{eff}}$ is of the order $|m_S| \sim M_{SUSY} \sim M_{Higgs}$ ✓

Adding S to the MSSM in a SUSY way leads to the NMSSM

2) The mass of the SM-like Higgs boson *h*:

(ϕ: Higgs doublet, *h*: its neutral CP-even component)

a) The Higgs mass in the Standard Model:

$$V(\phi) = -\mu^2 \left|\phi\right|^2 + \lambda^2 \left|\phi\right|^4 , \text{ its minimum } v_\phi \text{ is at } \left|v_\phi\right|^2 = \frac{\mu^2}{2\lambda^2}$$

v_ϕ is known since long from the W and Z masses: $v_\phi \sim 175$ GeV

The mass M_h of the physical Higgs boson is given by the second derivative of $V(h)$ at the minimum:

$M_h^2 = -2\mu^2 + 6\lambda^2 v_\phi^2 = 4\lambda^2 v_\phi^2$

$\longrightarrow$ even given v_ϕ, M_h could not be predicted since is proportional to the unknown quartic coupling λ

Now we know $M_h \sim 125$ GeV $\longrightarrow \lambda \sim 0,36$

$\longrightarrow$ If we would have known λ, we could have predicted the Higgs mass

b) The SM-like Higgs mass in the MSSM:

Recall: Two physical neutral CP-even Higgs bosons h, H where, typically, $h \sim$ mostly Standard Model-like, $M_H \sim M_A \sim M_{H^\pm}$ ($\gtrsim$ 300 GeV)

Due to SUSY, the quartic Higgs couplings are proportional to the electroweak gauge couplings $\sim g_1^2 + g_2^2$ (like M_Z in the SM)

$\longrightarrow$ The lighter state h has a mass M_h with

$$M_h^2 < M_Z^2 \cos^2 2\beta = M_Z^2 \left(\frac{\tan^2 \beta - 1}{\tan^2 \beta + 1} \right)^2$$

$\longrightarrow$ Large radiative corrections from heavy "stops" are needed in order to explain $M_h \sim 125$ GeV, but $M_h \ll M_{\text{stop}}$ becomes unnatural

$\longrightarrow$ "Little Finetuning Problem"

c) The SM-like Higgs mass in the NMSSM:

Recall: The additional singlet S has a Yukawa coupling $\lambda\, S\, \Psi_{H_u}\, \Psi_{H_d}$ to the higgsinos

→ SUSY requires additional quartic Higgs self couplings proportional to λ^2, amongst others $\lambda^2\, (H_u H_d)^2$

Due to the additional quartic coupling, the mass M_h of the mostly SM-like Higgs boson can be larger:

$$M_h^2 \simeq M_Z^2 \left(\cos^2 2\beta + \frac{2\lambda^2}{g_1^2 + g_2^2} \sin^2 2\beta \right)$$

Highly welcome, less tuning required

The Structure of the NMSSM

In terms of the superpotential W and superfields $\widehat{H}_u$, $\widehat{H}_d$ and $\widehat{S}$:

$$W_{\text{MSSM}} = \mu \widehat{H}_u \widehat{H}_d + \ldots \quad \rightarrow \quad W_{\text{NMSSM}} = \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3 + \ldots$$

where … denote the Yukawa couplings to (s)quarks and (s)leptons

Extended Higgs sector:
The physical states are linear combinations of H_u, H_d and S which form

- 3 CP-even neutral scalars, typically a mostly SM-like neutral Higgs h, a "MSSM"-like heavy scalar H, and a mostly singlet-like scalar H_S (but all states are mixtures in general)
- 2 CP-odd neutral scalars, typically a "MSSM"-like heavy pseudoscalar A and a mostly singlet-like pseudoscalar A_S
- "MSSM"-like charged scalars $H^\pm$

The "MSSM"-like states H, A and $H^{\pm}$ are nearly degenerate with masses $\gtrsim$ 300 GeV from constraints on $M_{H^{\pm}}$ from $b \to s\ \gamma$
(can be avoided assuming cancellations with SUSY diagrams)

The mostly singlet-like states H_S and A_S can have any mass; a light scalar H_S and a light pseudoscalar A_S are "natural" in the case of an approximate Peccei-Quinn symmetry where $\kappa \ll 1$.

Note: if $M_{H_S} < M_h$, mixing of H_S with h ($\overset{!}{=} H_{125}$) increases the mass of h $\to M_{H_S} < M_h$ is preferred!

Possible Phenomenological Impact of the Extended Higgs Sector

- Modified properties of the SM-like Higgs boson through mixing
- Possible detection of the additional states as a single resonance
- Possible Higgs-to-Higgs decays into light H_S/A_S

Possible modifications properties of the SM-like Higgs boson h

— Through mixing of h with H_S: all couplings of h get reduced
$\rightarrow$ Production cross sections get reduced,
but branching ratios remain unchanged

— Through mixing of h with H which has a $\tan\beta$ enhanced coupling to b-quarks/τ-leptons:
$\rightarrow$ Through negative interference,
the coupling of h to b-quarks/τ-leptons can get reduced
$\rightarrow$ The total width gets reduced
$\rightarrow$ Branching fractions into $\gamma\gamma$, ZZ and WW get enhanced

Also: if h has a singlet component, the coupling $\lambda\, S\psi_u\psi_d$ generates a charged higgsino loop contribution to $h \to \gamma\gamma$

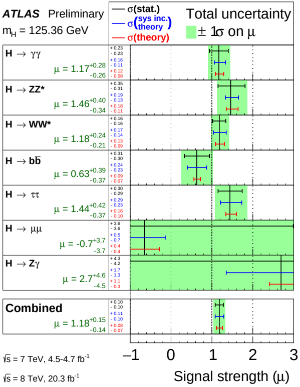
$\longrightarrow$ this branching fraction can be larger than in the Standard Model!

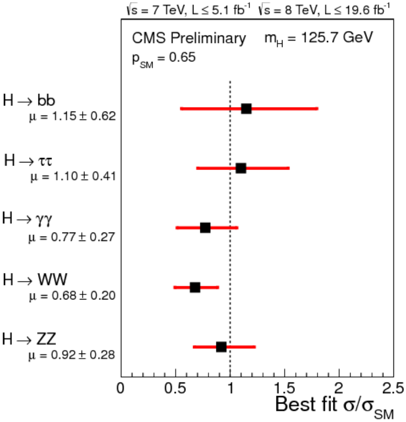
$\longrightarrow$ this can also happen for H_S!

Status of the 125 GeV Higgs couplings

Def.: Signal rates $\mu =$ (production rates)$\times$(branching fractions) relative to the Standard Model predictions

Measured averages over production modes, decomposed into final states:





→ More precise measurements could give us a hint

Search for/constraints on light H_S, A_S

H_S, A_S decay approx. like a SM-Higgs boson of similar mass:

If heavier than ~ 10 GeV: up to 85% into $b\bar{b}$, up to 8% into $\tau^+\tau^-$;

But: If H_S mixes with h and H, the coupling to $b\bar{b}$ can be suppressed → the total width gets reduced → $H_S \to \gamma\gamma$ can be enhanced by a factor ≈ 7

If 3.6 GeV $< M_{A_S}$, $M_{H_S} \lesssim$ 10 GeV: mostly into $\tau^+\tau^-$

If $M_{A_S} \lesssim 10$ GeV and $\tan\beta$ very large such that the coupling of A_S to b-quarks is not too small:
→ Constraints from $\Upsilon_{1,2} \to A_S + \gamma$ (BaBar, Belle), and possible distortions of the spectrum of the excited CP-odd η_b states

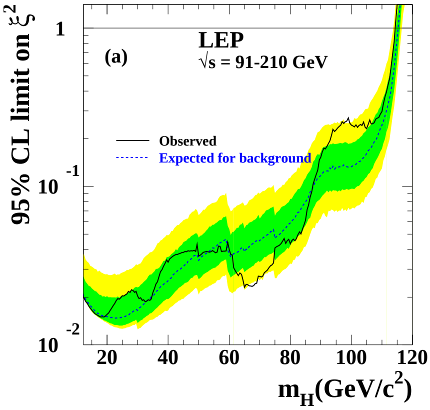
If M_{A_S}, $M_{H_S} \lesssim$ 3.6 GeV: decays into gg, $c\bar{c}$, $s\bar{s}$, $\mu^+\mu^-$

Direct production of a lighter Higgs boson at LEP:

The production of H_S in $e^+ + e^- \to Z^* \to Z + H_S$ requires some doublet component ξ of H_S

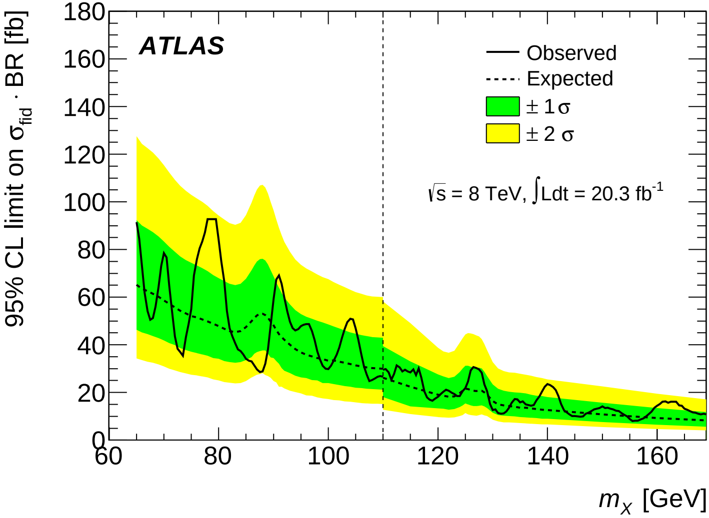
Constraints from LEP Higgs searches in the plane $\xi^2 - M_H$ (Assuming SM-like BR into $b\bar{b}$):

These allow, e.g., for $\xi \sim 0.5$ for $M_{H_1} \sim 95 - 105$ GeV!

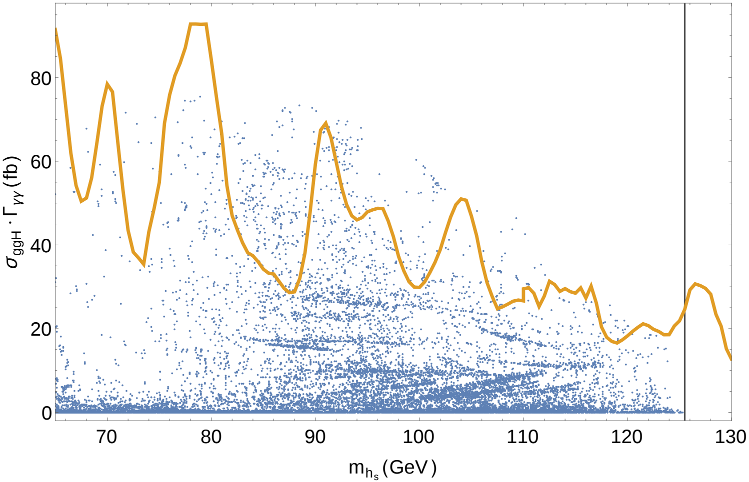


Possible detection of the additional states as a single resonance:

Searches by ATLAS in the diphoton channel:



Possible signal rates in the diphoton channel in the NMSSM, taking LEP constraints into account (from M. Rodríguez): Yellow: ATLAS limits



→ The LHC becomes more sensitive to additional light Bosons than LEP!

If $M_{A_S},\ M_{H_S} \lesssim 60$ GeV: decays of $h = H_{125} \to H_S H_S,\ A_S A_S$ are possible

Note: Large branching fractions of $H_{125} \to HH/AA$ would reduce the branching ratios of H_{125} into the observed channels, and hence the measured signal rates $\longrightarrow$ indirect constraints (from 1302.5694)!

Assuming SM-like production cross sections: $BR(H_{125} \to HH/AA) \lesssim 20\%$

Allowing for enhanced ggF production rate: $BR(H_{125} \to HH/AA) \lesssim 29\%$

(enhanced production rates in VH/VBF are practically impossible)

Again: the prospects for the discovery of $H_{125} \to 2(H_S/A_S)$ at the LHC depend strongly on the mass(es), and hence on the dominant decays of H_S/A_S:

– If $M_{H_S/A_S} \gtrsim 10$ GeV: Decays $H_S/A_S \to b\bar{b}$ are dominant, but $H_{125} \to 2(H_S/A_S) \to 2(b\bar{b})$ is very hard to see above the SM background

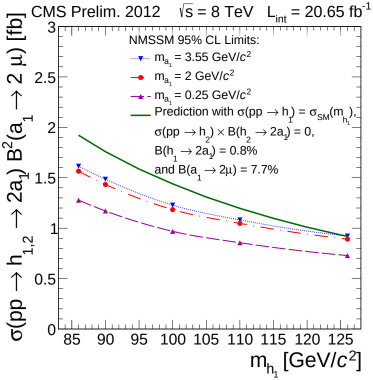
– If 3.5 GeV $\lesssim M_{H_S/A_S} \lesssim 10$ GeV: Decays $H_S/A_S \to \tau^+\tau^-$ are dominant, the prospects are better

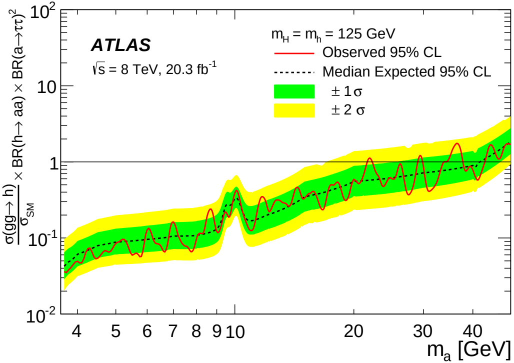
– If $M_{H_S/A_S} \lesssim 3.5$ GeV: Decays $H_S/A_S \to \mu^+\mu^-$ are dominant, much better visibility!

(Selection of) searches at run I:

Left: Search for $H_S \to A_S A_S \to 4\mu$ (CMS)

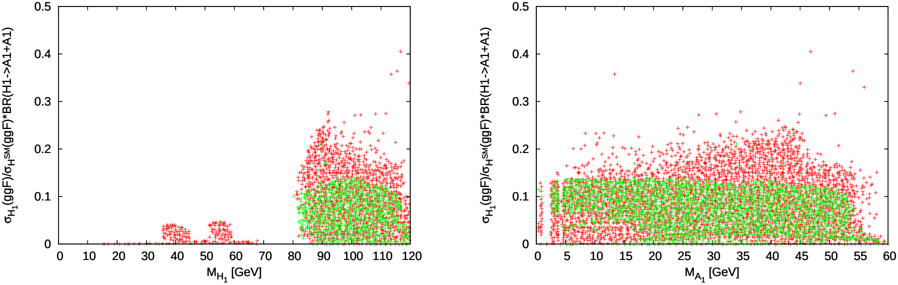
Right: Search for $h \to A_S A_S \to 4\tau$ (ATLAS)





If $M_{A_S} \lesssim M_{H_S}/2$: decays $H_S \to A_S A_S$ are typically dominant:

$\sigma_{H_S}(ggF)/\sigma_{H^{SM}}(ggF) \times BR(H_S \to A_S A_S)$ as function of M_{H_S} (left) and M_{A_S} (right) (from 1405.6647; green: favoured by MSUGRA)



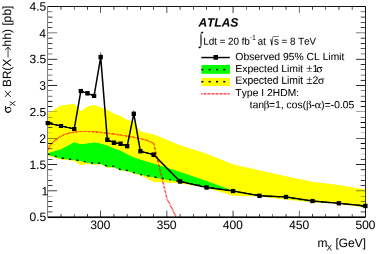
$\longrightarrow$ Must keep an eye on $ggF \to H_S \to A_S A_S$ with $M_{H_S} < 125$ GeV, or even $h \to H_S H_S \to (A_S A_S) + (A_S A_S)$!

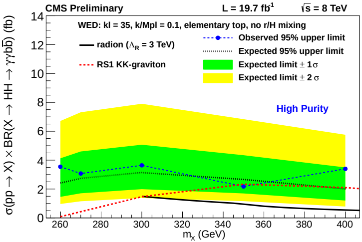
Another possibility:

Decays of H/A with $M_{H/A} \gtrsim 300$ GeV into a pair of H_S/A_S

The higher energy allows to detect H_S/A_S in $b\bar{b}$ decays

Searches for $ggF \to H/A \to h + h$ by ATLAS and CMS:

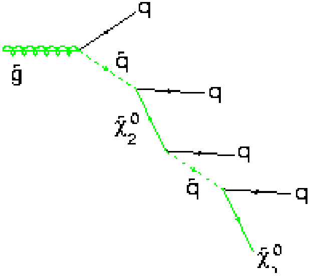


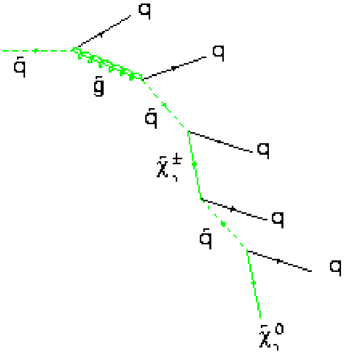


$\longrightarrow$ Interesting prospects for the run II

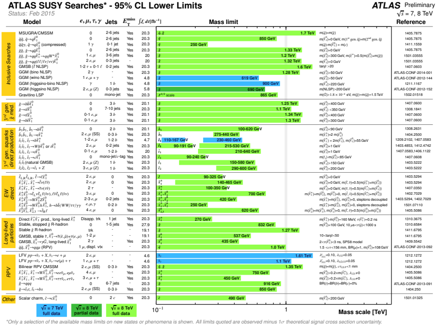
Possible Impact of BMS on Searches for SUSY

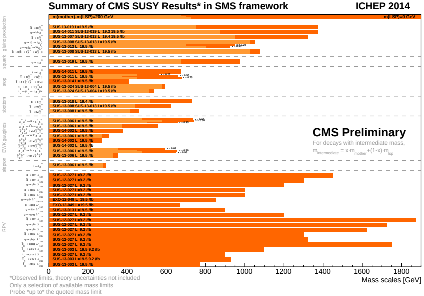
Due to R-parity, a sparticle decays always into a sparticle + SM particle(s). The lightest sparticle is stable!
Notation: $\tilde{g}$: gluino, $\tilde{q}$: squark, $\tilde{\chi}_i^0$: neutralino = bino/wino/higgsino, $\tilde{\chi}_i^\pm$: chargino = wino/higgsino,
Searches for SUSY employ cuts on E_{miss}^T, assumed to be generated by escaping invisible neutralinos χ_1^0 (LSPs) at the end of decay cascades:





→ Lower bounds on squark/gluino masses in the MSSM of up to 1.7 TeV (ATLAS, assuming MSUGRA):



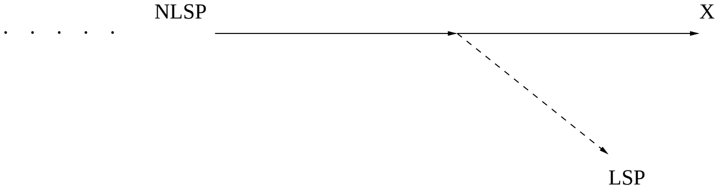


Limits depend on the assumed decay cascades!

Often: “Simplified Models” which assume heavy sparticles except for the one aimed at (gluinos, stops, ...)

And if there is a light singlino-like LSP χ_1^0 in the NMSSM?

Due to its small couplings to all sparticles, these will decay first into the NLSP χ_2^0 (typically Bino-like); only subsequently the NLSP χ_2^0 will decay into the LSP $\chi_1^0 + X$,



where "X" decays into SM particles ($X =$ Higgs boson, Z,...)

If the available phase space is narrow, $M_{NLSP} - (M_{LSP} + M_X) \ll M_{NLSP}$, the energy (momentum) E_{LSP} transferred from the NLSP to the LSP is proportional to the ratio of masses:

$$\frac{E_{LSP}}{E_{NLSP}} \simeq \frac{M_{LSP}}{M_{NLSP}}$$

$\longrightarrow$ If the LSP is light and $M_X \sim M_{NLSP} - M_{LSP}$, little (missing transverse) energy is transferred to the LSP; the transverse energy is carried away by X

$\longrightarrow$ If X decays do not give rise to E_T^{miss}, the E_T^{miss} signature disappears!

Possible states X:

Z, W: Have leptonic decays (incl. neutrinos), lead to some E_T^{miss}

H_{125}: The leptonic decays $H_{125} \to WW/ZZ \to \ldots$ lead to some E_T^{miss}

Worst case with little E_T^{miss}:

— $X = H_1$, a NMSSM specific light Higgs boson with $M_{H_1} < M_Z$
(Just occasionnaly: $H_1 \to \tau^+\tau^- \to ... +$ neutrinos)

— no Zs/Ws (decaying possibly into neutrinos) in squark decay cascades; if wino/higgsino masses $\gtrsim$ squark masses:

$\tilde{q} \to q + bino \to q + singlino + H_1$,
$\tilde{g} \to q + \tilde{q} \to ...$

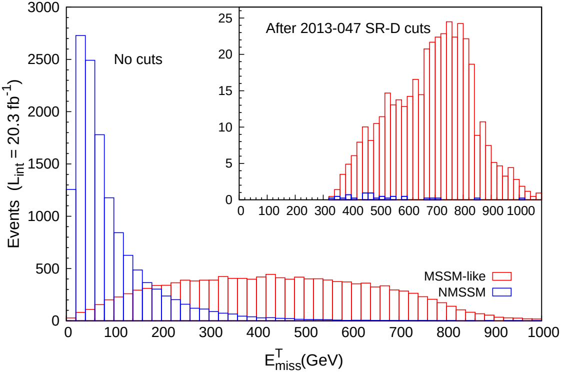
Example: $M_{NLSP} \sim M_{bino} \sim 89$ GeV, $M_{H_1} \sim 83$ GeV,
$M_{LSP} \sim M_{singlino} \sim 5$ GeV

Spectrum of E_T^{miss} from squark/gluino production at 8 TeV:

Compare

— the MSSM with a 89 GeV bino as LSP, would be ruled out!

— the NMSSM with the additional bino $\to H_1 +$ singlino cascade



Inlet: after Cuts on P_T of 5 jets, $E_T^{miss}/m_{eff} > 0.2$ where

$$m_{eff} \sim \sum |p_T|_{jets}$$

Where does the remaining E_T^{miss} come from?

H_1 has branching fractions similar to H_{SM} of the same mass:
$\sim 8\%$ into $\tau^+\tau^-$ leading to neutrinos in the final state;
$\sim 85\%$ into $b\bar{b}$ with partially leptonic decays

Still: The example with $M_{squarks} \sim 830$ GeV, $M_{gluino} \sim 860$ GeV, $M_{stops,sbottoms} \sim 810 - 1060$, $M_{charginos} \sim 830 - 950$ GeV passes all LHC constraints

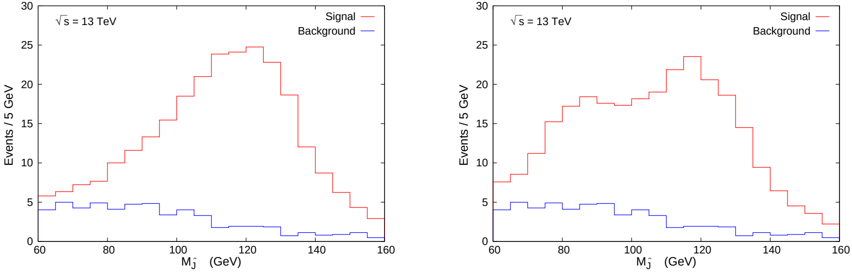
The only LHC allowed scenario with all sparticle masses below ~ 1 TeV!

What would be the signature of squark/gluino production in such a case?

Jets + the remnants of two Higgs states, but

M_H not known, e.g. $M_H = 125$ GeV, or $M_H \sim 50 - 90$ GeV

$\longrightarrow$ Look for, e.g., one $b\bar{b}$ pair and one $\tau^+\tau^-$ pair (+ cuts on p_T of jets), and a bump at the $b\bar{b}$ invariant mass:



$\hat{J}$: “Fat” jet constructed with $R = 0.5$ in the direction of two b-jets, after cuts on 4 jets with large p_T and asking for 2 τ_h
(Simulation from 1412.6394)

Left: bino → h + singlino;
right: bino → h + singlino or bino → H_S + singlino

Constraints from chargino/neutralino searches at the LHC:

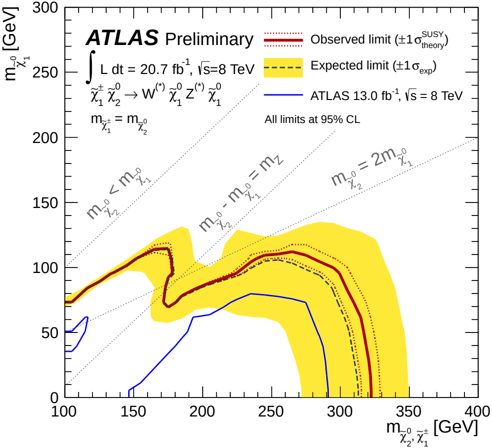
Most relevant:

$$W^* \to \chi_1^+ + \chi_2^0 \to (W_{\to lept} + \chi_1^0) + (Z_{\to 2lept} + \chi_1^0)$$

$\longrightarrow$ 3 leptons ($e^\pm$ or $\mu^\pm$) + E_T^{miss}

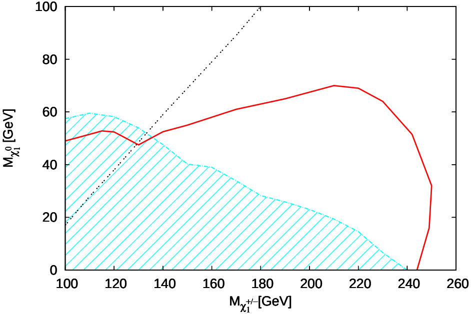
Often interpreted for χ_1^+, χ_2^0 wino-like (degenerated), χ_1^0 bino-like,
no $\chi_2^0 \to \chi_1^0$+Higgs decays ("simplified model")

From ATLAS-CONF-2013-035:



$\longrightarrow M_{\chi_1^\pm} \lesssim 320$ GeV for $M_{\chi_1^0} \lesssim 100$ GeV

Applying the same bounds to the singlino-higgsino scenario in the NMSSM:

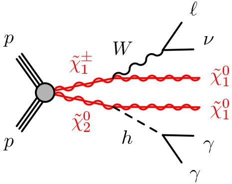


Blue hatched: excluded by LEP; red curve: excluded by ATLAS

→ $M_{\chi_1^\pm} \lesssim 240$ GeV for $M_{\chi_1^0} \lesssim 60$ GeV

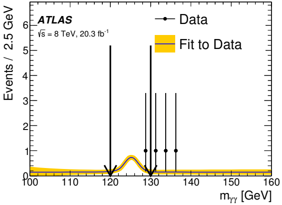
→ Alleviation of the previous bounds since the W-higgsino^2 coupling is smaller than the W-wino^2 coupling (Clebsch Gordan coeff.), and $\chi_{2,3}^0$ have some singlino component

And if χ_2^0 decays into $\chi_1^0 +$ a Higgs boson?



Look, e.g., for a lepton from W^+ and two photons from the Higgs:

From ATLAS 1501.07110:



No excess is seen since $M_{\gamma\gamma} = 125 \pm 5$ GeV was required!

Lesson: If you don't look for, you can miss additional Higgs bosons!

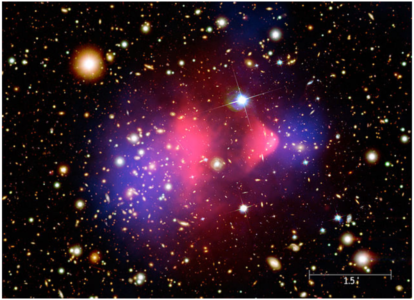
Dark Matter

From measurements of the CMB etc. by WMAP/Planck we know quite precisely the amount of Dark Matter in the present universe:

$$\Omega_c h^2 = 0.1188 \pm 0.0010$$

where Ω_c is the critical matter + dark energy density, h the Hubble constant normalised to 100 (km/sec)/Mpc.

Observation of the bullet cluster:
Red: Visible matter
Blue: Dark Matter from gravitational lensing



Searched for in direct and indirect detection experiments

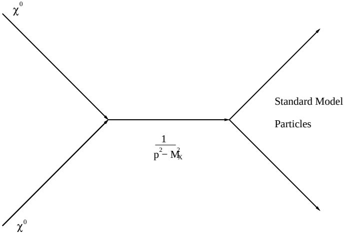
Standard lore:
The early universe is a bath of all (s)particles in chemical equilibrium.
Once temperature decreases, heavy (s)particles decay into lighter ones.
Stable (s)particles are left over, unless they pair-annihilate

→ The Dark Matter relic density depends on $\langle v\sigma(v)\rangle$ where $\sigma(v)$ is its annihilation cross section at the time of "freeze out", i.e. at temperatures $T \approx M_{\chi_1^0}/10$
(later they become too deluted due to the expanding universe)

Assuming $\langle v\sigma(v)\rangle$ independent of v (as in the case of the exchange of a heavy particle with mass $\gg M_{\chi_1^0}$):

$$\langle v\sigma(v)\rangle = \text{"thermal cross section"} \sim 3 \times 10^{-26}\ \text{cm}^3/\text{sec}$$

Its annihilation cross section today, relevant for indirect detection, can differ significantly from the thermal cross section if annihilation proceeds via a resonance X and $\langle v\sigma(v)\rangle$ depends on v:



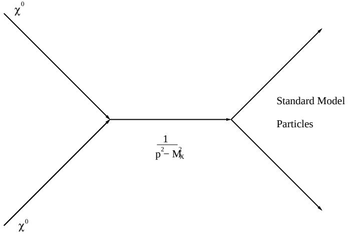
If $X =$ vector (Z) or scalar (Higgs):

$$\langle v\sigma(v)_{\text{freeze out}}\rangle \sim v^2 \gg \langle v\sigma(v)_{\text{today},\ v \ll c}\rangle$$

If $X =$ pseudoscalar like A_S (NMSSM):

$$\langle v\sigma(v)_{\text{freeze out}}\rangle \sim \text{ const } \sim \langle v\sigma(v)_{\text{today},\ v \ll c}\rangle$$

In any case, if M_X is just a bit larger than $2M_{\chi^0}$:

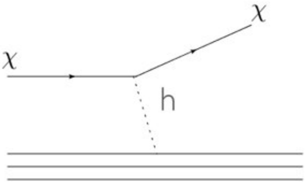


$p^2 = (p_{\chi^0} + p_{\chi^0})^2$ is close to $M_{\chi^0}^2$ at the moment of freeze-out
$(T \approx M_{\chi^0}/10)$
$\longrightarrow$ After averaging $\langle v\sigma(v)_{\text{freeze out}}\rangle$, a large contribution from the pole

Today: $\langle v\sigma(v)_{\text{today, } v \ll c}\rangle$ is below the pole, below $\langle v\sigma(v)_{\text{freeze out}}\rangle$

$\longrightarrow$ Cannot expect $\langle v\sigma(v)_{\text{today}}\rangle$ to be given by the thermal cross section

The direct detection cross section depends on its scattering cross section off protons/neutrons, generated by the exchange of Higgs boson(s)



Higgs boson(s) couple to protons/neutrons via
— the strange quark see
— a top quark loop to gluons (see ggF)

Z-exchange: generates only a spin-dependent cross section if χ_1^0 is a Majorana Fermion as in Susy

Supersymmetry

The lightest neutralino χ_1^0 is automatically a candidate for Dark Matter
Expected mass range: a few GeV ... a few hundred GeV (cold, not "warm")

MSSM: a superposition of a bino/wino/neutral higgsinos

Pure bino (most natural): No bino-bino-Z or bino-bino-Higgs couplings
$\longrightarrow$ $\sigma(v)$ too small, relic density too large
Way out: bino-slepton-lepton vertex, but requires light sleptons (constrained by the LHC)

Pure higgsino: higgsino-higgsino-Z coupling makes $\sigma(v)$ too large, relic density too small (unless $M_{\text{higgsino}} \gtrsim 1$ TeV)

Way out: mixture of bino-higgsino, still constrained by $Z \to \chi_1^0 \chi_1^0$ (LEP) if $M_{\chi_1^0} < 45$ GeV, and direct detection due to a Higgs-higgsino-bino-vertex.

NMSSM: χ_1^0 can have a large singlino (small higgsino) component

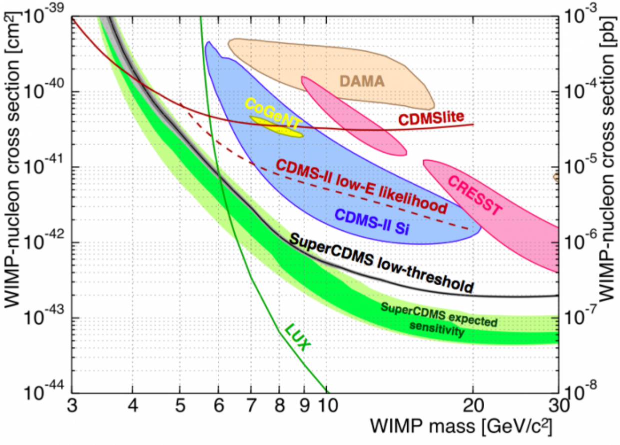
A light χ_1^0 is compatible with constraints from $Z \to \chi_1^0 \chi_1^0$,
good relic density due to pair annihilation via A_S

Direct detection cross section can be small since

— the singlino has small couplings to the exchanged Higgs boson

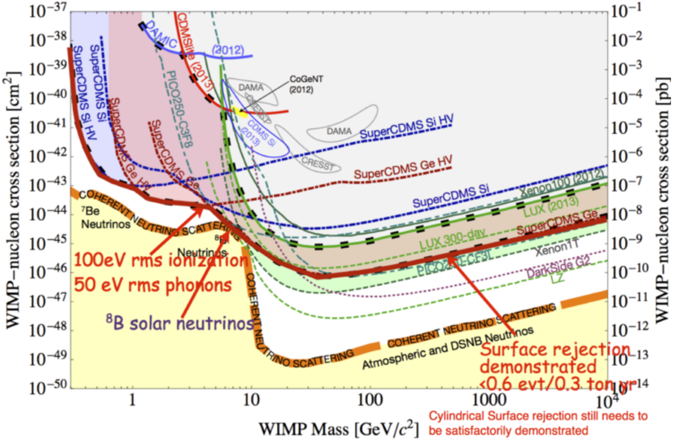
— additional Higgs boson(s) can be exchanged and interfere negatively

Occasionally one has seen hints for “light” dark matter in direct detection:



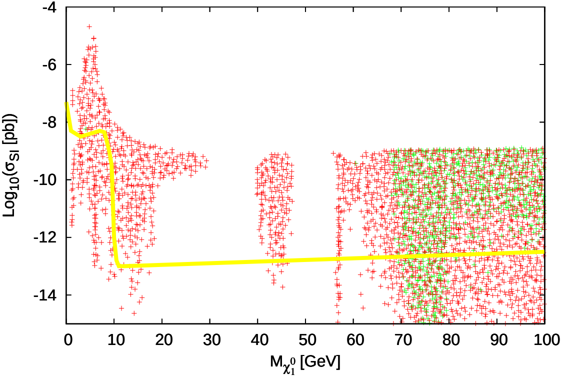
Hints for DM in the 6 - 40 GeV mass range have been ruled out by LUX, but even LUX is not very sensitive to dark matter with $M_{\chi^0} \lesssim 6$ GeV

Note: The sensitivity cannot be increased arbitrarily; at some stage direct detection experiments have to take the background from solar neutrinos into account:



Cylindrical Surface rejection still needs to be satisfactorily demonstrated

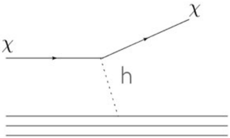
And what can we expect in the NMSSM with a mostly singlino-like LSP? Scan the parameter space, impose good relic density and constraints from LUX; possible direct detection cross sections:



A direct detection signal above the neutrino background (yellow) is not guaranteed!

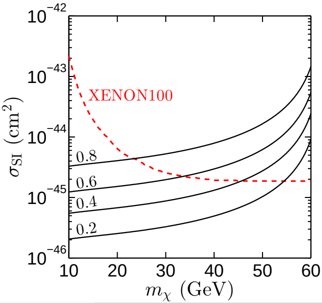
Duality between direct detection of dark matter, and production of dark matter at the LHC:

Recall the diagram for direct detection:



Turn it around by 90^o to the right → you get the diagram for $p + p \to h \to \chi^0 + \chi^0$, i.e. the production and the decay of a Higgs into dark matter (if $M_{\chi^0} < M_h/2$)

→ Constraints on invisible Higgs decays with BR $<$ 0.2...0.8 give you constraints on the direct detection cross section:



Indirect detection:

Look for remnants of dark matter annihilation into SM particles

Where? Where the dark matter density is expected to be large
$\longrightarrow$ In the center of galaxies

Our galaxy: Close, but dirty (dust), dark matter density profile subject to uncertainties

Dwarf galaxies ($\sim$ spherical): Cleaner (less dust), less uncertainties in the dark matter density profile

What? Stable SM particles in the cosmic rays, preferably those whose "astrophysics background" (pulsars, ...) is expected small:

Anti-protons, positrons

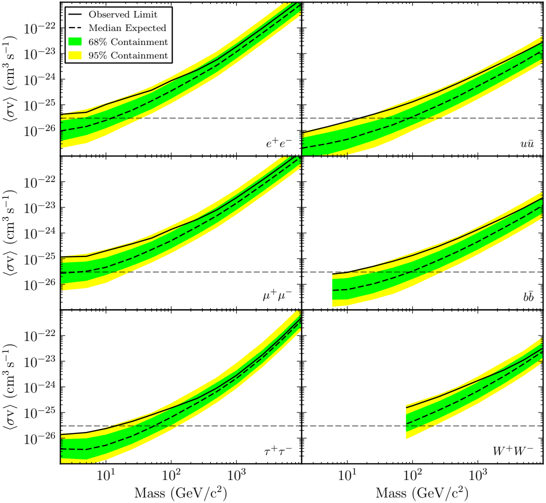
$\longrightarrow$ charged, bent trajectories in the galactic magnetic field
$\longrightarrow$ the location of production is difficult to estimate

Energetic photons (gammas) directly from the location of production

Expected flux depends on the two initially produced SM particles: $b\bar{b}$ (case of a Higgs in the s-channel), $\tau^+\tau^-$ (light Higgs), W^+W^-, $\mu^+\mu^-$, $q\bar{q}$,...

Still: astrophysics background not very well known, under debate

Hints for DM in the 6 - 40 GeV mass in the search for gamma rays from our galactic center by FermiLAT,
interpreted in terms of different SM particle pair production processes:

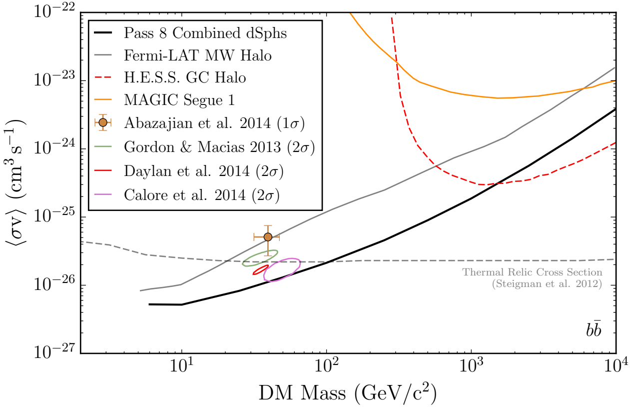


An explanation requires an annihilation cross section today similar to the thermal cross section and $M_{\chi^0} \approx 40$ GeV

$\longrightarrow$ Impossible in the MSSM

Can be explained in the NMSSM with a light singlino-like χ^0, with a good relic density from annihilation via A_S
(Cahill-Rowley et al., 1409.1573)

BUT: Recent upper bounds on gamma rays from dwarf galaxies by FermiLAT, interpreted in terms of $b\bar{b}$ SM particle pair production and compared to models explaining the "galactic center excess":



Still marginally compatible with a NMSSM singlino explaining the galactic center excess, depending on the dwarf/milky way dark matter profiles

Summary

Since Supersymmetry solves simultaneously several problems of the Standard Model, it remains an attractive scenario

Its minimal version is under pressure from the non-observation of sparticles, also – somewhat less – from the measured Higgs mass and the non-observation (direct and indirect) of dark matter

Non-minimal Supersymmetry (here: the NMSSM) alleviates this pressure, more attractive nowadays

Hints/evidence for non-minimal Supersymmetry can come from unexpected corners (at the LHC):
— Higgs bosons instead of E_{miss}^{T} in squark/gluino production
— Extra Higgs bosons with masses below/above 125 GeV
— Higgs-to-Higgs decays of H_{125} and/or extra Higgses

Stay tuned!

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.

(Georg Lichtenberg, German scientist and philosopher, 1742–1799)