SUSY@LHC

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June 20, 2015

Shortcomings of the SM	Solved by SUSY?
• What is Dark Matter?	✓
• Hierarchy Problem$^{(*)}$	✓
• Grand Unification (Quarks, leptons fill complete SU(5) representations, but gauge couplings do not quite unify)	✓
• Matter-Antimatter Asymmetry	✓
• Origin of the tiny Neutrino Masses	–
• Hierarchy/Mixing of Quark/Lepton Masses	–

– means "can be implemented", but not automatically

$(*)$ See comment on the next page

Comment on the Hierarchy Problem:

It has been proposed that, for some unknown reason, Quantum Field Theory ignores quadratic (power-like) divergencies like those contributing to scalar (Higgs) masses.

However, summing logarithmic divergencies leads often to “odd” powers, so-called anomalous dimensions of operators/corresponding couplings.

How could Quantum Field Theory distinguish between integer/odd powers of a cutoff???
Not consistent for me...

At present: No hints for SUSY nor for alternative solutions of the Hierarchy Problem

SUSY@LHC: SUSY extensions of the Standard Model are not unique! What to expect from "Naturalness"?

All SUSY extensions of the SM include at least two Higgs doublets H_u, H_d, which have fermionic partners ("higgsinos") some of which are charged

Need a supersymmetric mass term $|\mu| > 100$ GeV for the higgsinos (LEP)

$\longrightarrow$ Positive mass terms μ^2 in the potential for H_u, H_d due to SUSY

But the Higgs potential must be unstable at the origin in order to generate VEVs for H_u, H_d with $v_u^2 + v_d^2 \simeq (174\ \mathrm{GeV})^2$

$\longrightarrow$ Have to compensate the positive mass terms μ^2 by negative SUSY-breaking mass terms $m_{H_u}^2,\ m_{H_d}^2$ in the Higgs potential: $\mu^2 + m_{H_u}^2$ should give $\approx -M_Z^2/2$ (without "finetuning")

$\longrightarrow$ Expect $|\mu|$ not too far above M_Z, hence not too heavy higgsinos

In the MSSM the reason for $\mu^2 \approx |m_{H_u}^2|,\ |m_{H_d}^2|$ remains unexplained

In the MSSM the quartic H_u, H_d self couplings are proportional to the electroweak gauge couplings $g_1^2 + g_2^2$
$\longrightarrow$ $M_h < M_Z$ at tree level (h is the SM-like Higgs boson)

Heavy or largely split "stops" (scalar partners of the top quark) lead to large radiative corrections to the quartic H_u self couplings;
$m_{\mathrm{stop}_2} \gtrsim 1$ TeV is necessary in order to explain $M_h \sim 125$ GeV (in the MSSM)

But radiative corrections due to a heavy stop$_2$ lead to $m_{H_u}^2 \approx -m_{\mathrm{stop}_2}^2$!
Explains why $m_{H_u}^2 < 0$, but $|m_{H_u}^2|$ comes out too large for $m_{\mathrm{stop}_2} \gtrsim 1$ TeV

$\longrightarrow$ Again: a "little finetuning" is necessary in order to obtain $\mu^2 + m_{H_u}^2 \approx -M_Z^2/2$

In the NMSSM μ is given by the VEV of a singlet S, $\mu_{\mathrm{eff}} = \lambda \langle S \rangle$

λ is a Yukawa coupling of S to higgsinos;
$\langle S \rangle \approx |m_S|$ if the soft SUSY breaking mass $m_S^2 < 0$

$\longrightarrow$ explains $\mu_{\mathrm{eff}}^2 \approx -m_S^2 \approx |m_{H_u}^2|,\ |m_{H_d}^2|$

$\longrightarrow$ Additional contributions to the quartic H_u, H_d self couplings $\sim \lambda^2$

$\longrightarrow$ Additional contributions to the SM-like Higgs mass,
(also through possible mixing with a lighter mostly S-state)
less contributions from rad. corrs. required

$\longrightarrow$ Not so heavy stops (less "finetuning") are required

$\longrightarrow$ Expect not too heavy stops

Search Strategies for SUSY@LHC:

Assume R-parity (symmetry under sparticle $\to$ $-$sparticle)

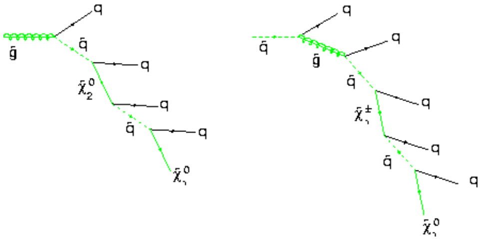
$\longrightarrow$ Each vertex contains an even number of sparticles

$\longrightarrow$ A sparticle decays always into a sparticle + SM particle(s).

$\longrightarrow$ The lightest sparticle is stable!

$\longrightarrow$ A good dark matter candidate if neutral, a "neutralino" $\tilde{\chi}_1^0$
(mixture of bino/wino/higgsino in the MSSM,
mixture of bino/wino/higgsino/singlino in the NMSSM)

Once sparticles are produced (in pairs), they decay into other sparticles, but the lightest neutralino escapes undetected and gives rise to E_{miss}^T:



Search Strategies for SUSY@LHC:

$\longrightarrow$ Searches for SUSY employ cuts on $E^T_{\text{miss}} >$ a few hundred GeV plus

- hard jets
- leptons
- *b*-quarks (from stops/sbottoms)
- τ's, photons,
- combinations thereof

Due to the various possible sparticle cascade decays, the absence (or presence) of excess events is not easy to interpret
$\longrightarrow$ use, for the interpretation, "simplified models" $\equiv$ the assumption of simple one-step sparticle cascade decays,
or specific mechanisms for SUSY breaking like MSUGRA

The largest cross sections at the LHC are the ones for up-/down-squarks and gluinos:

$\rightarrow$ Strong interactions, and the "superpartners" are present in protons

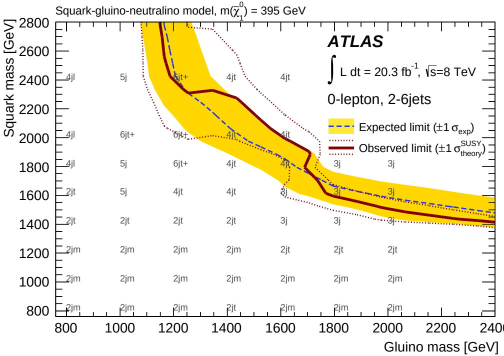
$\rightarrow$ The exchange of a gluino in the t-channel can transform quarks and gluons into squarks and gluinos

$\rightarrow$ The absence of excess events leads to the strongest bounds, e.g. from ATLAS (1405.7875), assuming simplified squark/gluino decays into jets + E^T_{miss} and $m(\tilde{\chi}^0_1) = 395$ GeV:

If $M_{squark} \sim M_{gluino}$:

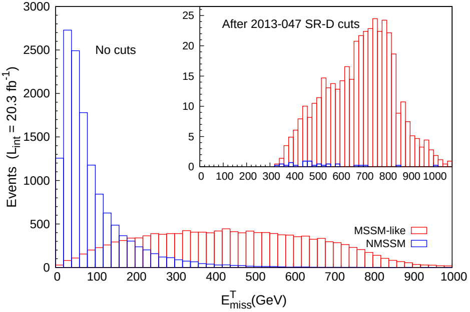
$M_{squark} \sim M_{gluino} \gtrsim 1.7$ TeV

(CMS/MSUGRA bounds are similar)



In the MSSM, $\tilde{\chi}_1^0$ is typically a "bino"
In the NMSSM, $\tilde{\chi}_1^0$ can be a very light "singlino"

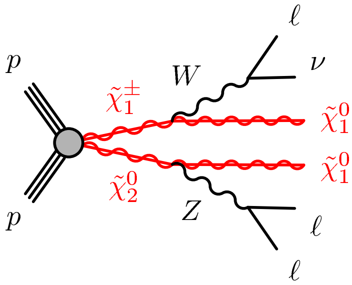
During an additional decay bino $\to$ singlino + Higgs with $M_{\rm Higgs} \lesssim M_{\rm bino}$, the bino can transfer practically all of its energy to the Higgs
$\longrightarrow$ Nearly no energy, and hence no E^T_{miss} is left for the singlino!
Simulation of squark/gluino production in 1406.7221, with A.M. Teixeira:
Red: MSSM with $\tilde{\chi}_1^0$ = bino; blue: NMSSM with an additional singlino



$\longrightarrow$ Squark $\sim$ gluino masses just below 1 TeV are not excluded!

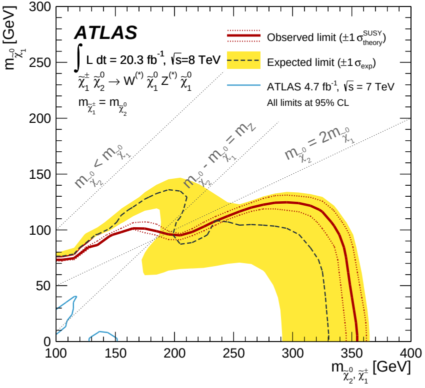
Recall: Expect light higgsinos of a few 100 GeV (charged $\tilde{\chi}_1^\pm$, neutral $\tilde{\chi}_2^0$) from "naturalness"

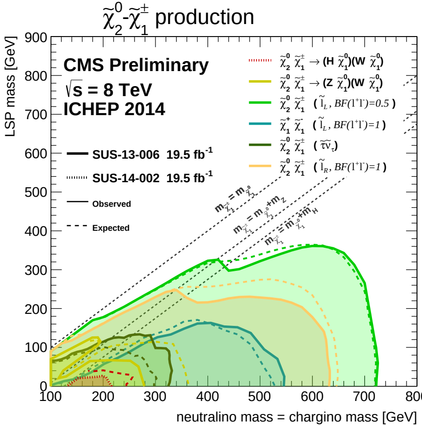
Can be pair produced via $p+p \to W^{\pm *} \to \tilde{\chi}_1^\pm + \tilde{\chi}_2^0$, and decay into $\tilde{\chi}_1^0$ via $W^\pm$ and Z:



If $W^\pm$ and Z decay leptonically: trileptons + E^T_{miss}

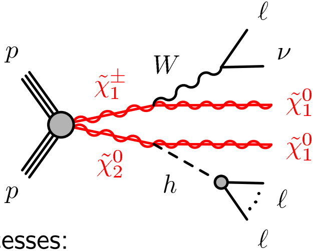
Interpreting the absence of excesses in terms of wino-like $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ (which have larger couplings to $W^\pm$ than higgsinos):



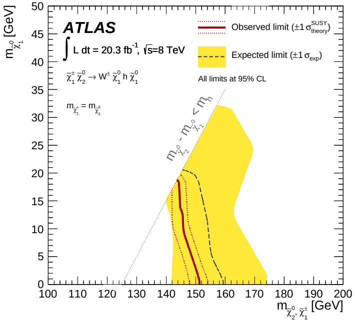


(Green limits for CMS: assume decays via light sleptons)

But: In the NMSSM,
$\tilde{\chi}_2^0 \to$ singlino ($\tilde{\chi}_1^0$) + Higgs
can alleviate the bounds



Re-interpreting the absence of trilepton-excesses:



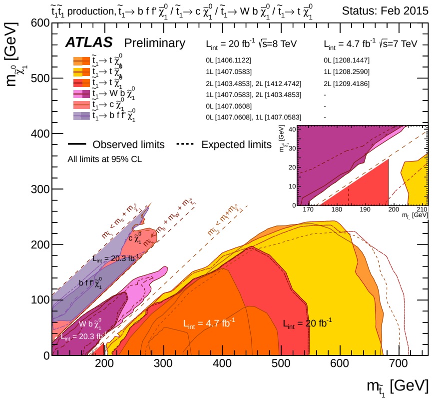
$\longrightarrow$ Much weaker bounds!
(CMS: see previous page)

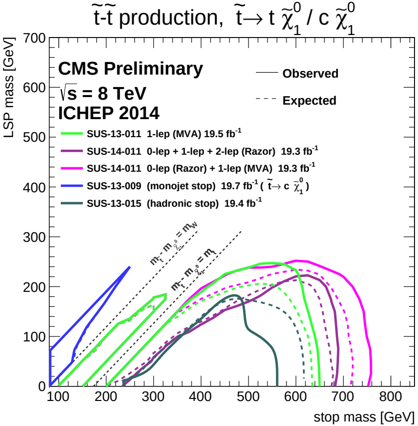
Recall: Expect light stops of a few 100 GeV from naturalness

But: Stops $\tilde{t}$ may decay in many different ways, depending on $m_{\tilde{t}}$:

- $\tilde{t} \to t + \tilde{\chi}_1^0$ if $m_{\tilde{t}} > m_{\rm top} + m(\tilde{\chi}_1^0)$
- $\tilde{t} \to b + W + \tilde{\chi}_1^0$ if $m_{\tilde{t}} > m_W + m_b + m(\tilde{\chi}_1^0)$
- $\tilde{t} \to b + q + \bar{q}' + \tilde{\chi}_1^0$ if $m_{\tilde{t}} < m_W + m_b + m(\tilde{\chi}_1^0)$
- $\tilde{t} \to b + \ell + \bar{\ell}' + \tilde{\chi}_1^0$ if $m_{\tilde{t}} < m_W + m_b + m(\tilde{\chi}_1^0)$
- $\tilde{t} \to c + \tilde{\chi}_1^0$ if $m_{\tilde{t}} < m_c + m(\tilde{\chi}_1^0)$

$\rightarrow$ Limits depend on the (lighter) stop $\tilde{t}_1$ decay mode:

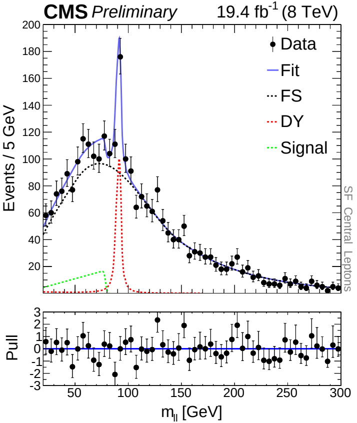




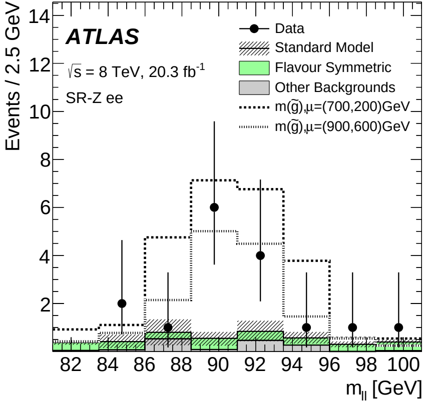
In all cases: No limits for $m_{\tilde{t}_1} \sim m_{\text{top}} + m(\tilde{\chi}^0_1)$, where $E^T_{\text{miss}} \rightarrow 0$

In searches for trileptons ($= \ell\bar{\ell} + \ell'$) $+ E^T_{\rm miss}$ + jets, possible from gluino/sbottom decay cascades with $\ell\bar{\ell}$ from Z^* or Z:

CMS, $\sim 2.6\ \sigma$ for $M_{\ell\bar{\ell}} < M_Z$: (The "edge" below M_Z!)



ATLAS, $\sim 3.0\ \sigma$ for $M_{\ell\bar{\ell}} \sim M_Z$:

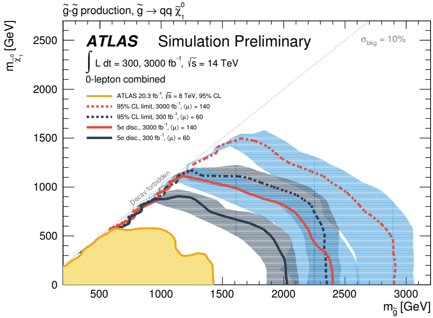


(CMS: 1502.06031, ATLAS: 1503.03290) But: $M_{\ell\bar{\ell}}$ not compatible!

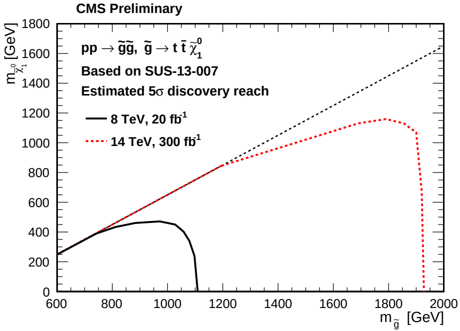
Prospects for future SUSY searches

Gluinos:

ATLAS (PHYS-PUB-2014-010)
300 fb^{-1}, 3000 fb^{-1},
95% CL exclusion/5σ discovery

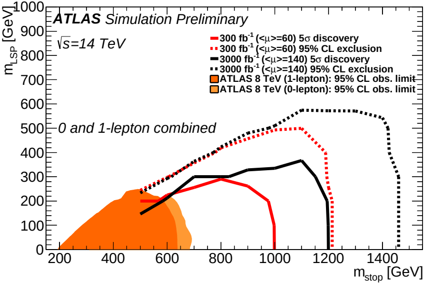


CMS (from 1307.7135)
300 fb^{-1}, 5σ discovery

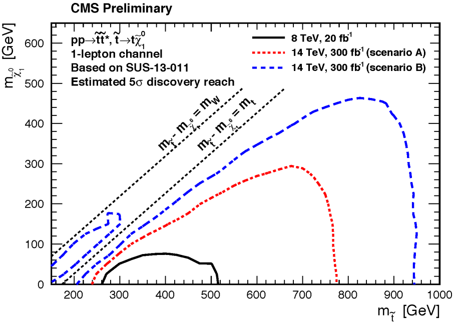


Stops:

ATLAS (PHYS-PUB-2013-011)
300 fb^{-1}, 3000 fb^{-1},
95% CL exclusion/5σ discovery



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

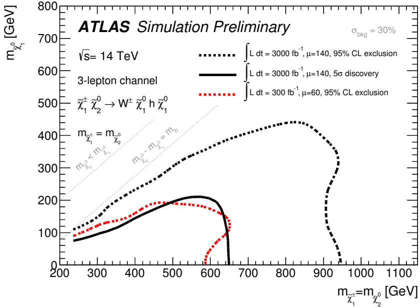


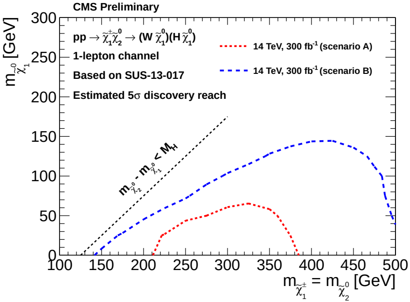
$\tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0$ (bino/singlino) + Higgs

(here: wino-like $\tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^0$; higgsino cross sects. are smaller):

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





STATUS OF SUSY AFTER THE LHC RUN I:

Limits depend on
— The SUSY extension of the Standard Model (MSSM, NMSSM, ...)
— The mechanism for SUSY breaking $\leftrightarrow$ sparticle masses, decay cascades

Simple scenarios for SUSY breaking (MSUGRA, GMSB) are under pressure from lower bounds on up-/down-squark, gluino masses:
"Little finetuning" of $\mathcal{O}(0.1\%)$ (MSSM), $\mathcal{O}(1\%)$ (NMSSM)
(Still small compared to the Standard-Model hierarchy problem ...)

Scenarios with light higgsinos, light stops which minimize finetuning ("natural SUSY") will only be tested at the run II (or after 3000 fb^{-1} integrated luminosity)

Recall the "Goodies" of SUSY from page 1:
$\longrightarrow$ Hard to give up, unless hints for alternatives appear!