APPS 2011, Amsterdam, November 2011

Implications of LHC data for theory

Michael Krämer (RWTH Aachen)

APPS 2011, Amsterdam, November 2011

Implications of LHC data for a theorist

Michael Krämer (RWTH Aachen)

Questions for the LHC:

- What is the mechanism of EWSB?

Questions for the LHC:

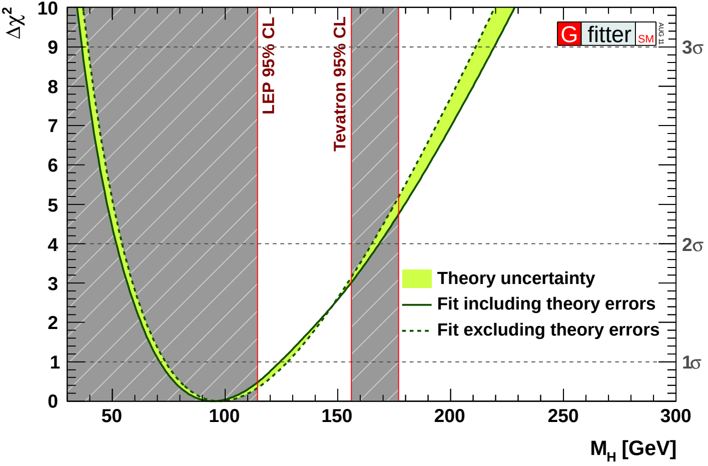
- What is the mechanism of EWSB?
- What is the dark matter in the universe?
- Is there unification of the fundamental forces?
- Are there additional spatial dimensions?
- What is the origin of the matter-antimatter asymmetry?
- ...

Questions for the LHC:

- What is the mechanism of EWSB?
- What is the dark matter in the universe?
- Is there unification of the fundamental forces?
- Are there additional spatial dimensions?
- What is the origin of the matter-antimatter asymmetry?
- ...

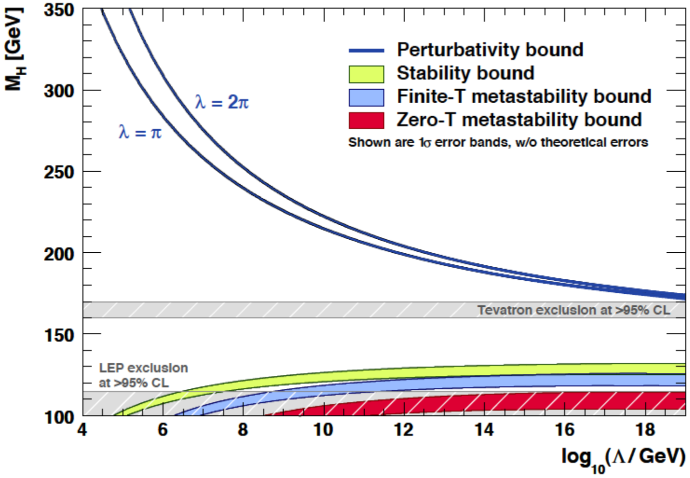
The Standard Model Higgs mechanism

Constraints from electroweak precision physics:



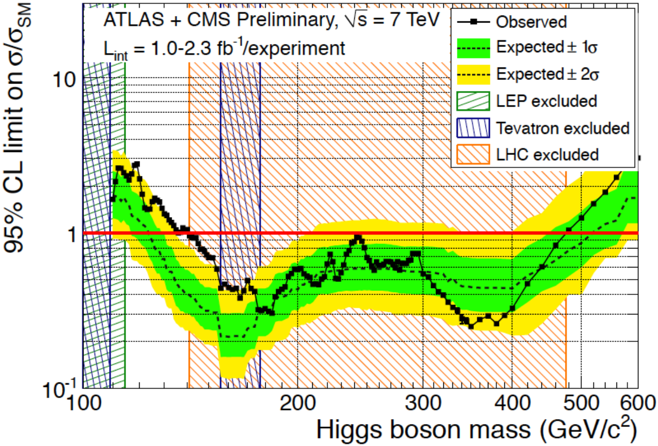
Constraints from theory:

[Ellis, Espinosa, Giudice, Hoecker, Riotto]



The Standard Model Higgs mechanism

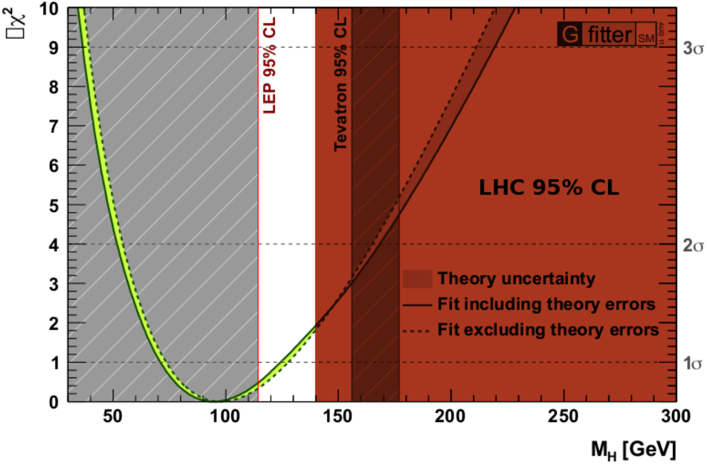
Constraints from the LHC:



$$114\ \text{GeV} < M_{\text{Higgs}} < 141\ \text{GeV} \quad \text{or} \quad M_{\text{Higgs}} > 476\ \text{GeV} \quad (95\%\text{C.L.})$$

What did we learn about the SM Higgs from the LHC?

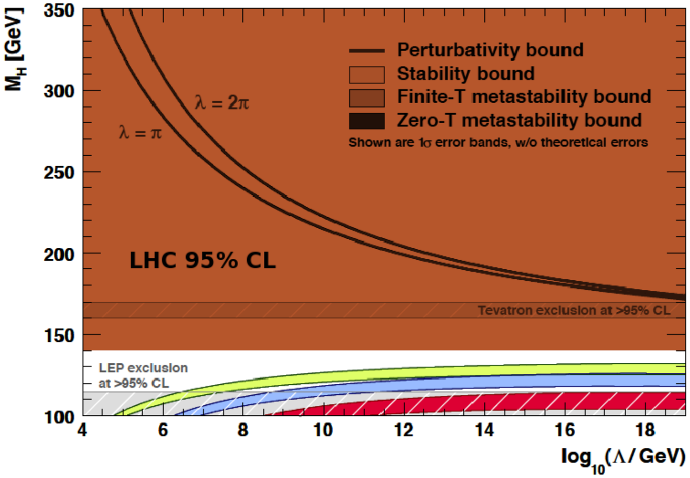
Constraints from electroweak precision physics:



What did we learn about the SM Higgs from the LHC?

Constraints from theory:

[Ellis, Espinosa, Giudice, Hoecker, Riotto]



What did we learn about the SM Higgs from the LHC?

There is strong evidence that either

- the Higgs boson is light, consistent with electroweak precision physics and theoretical prejudice
- or, the Higgs boson is very heavy and strongly self-coupled.

What did we learn about the SM Higgs from the LHC?

There is strong evidence that either

- the Higgs boson is light, consistent with electroweak precision physics and theoretical prejudice
- or, the Higgs boson is very heavy and strongly self-coupled.

However,

- the SM Higgs mechanism does not provide a dynamical explanation of EWSB;
- and what stabilizes the Higgs boson mass?

Thus, the SM Higgs mechanism points to physics beyond the SM,

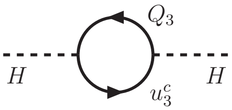
e.g. composite Higgs models, little Higgs models, higher-dimensional Higgs models, supersymmetry,. . .

New physics at the LHC?

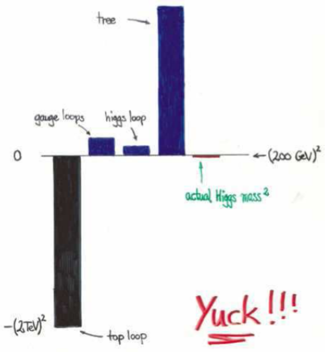
- What is the mechanism of EWSB?
- What is the dark matter in the universe?
- Is there unification of the fundamental forces?
- Are there additional spatial dimensions?
- What is the origin of the matter-antimatter asymmetry?
- ...

New physics at the LHC?

The hierarchy problem: why is $M_{\mathrm{Higgs}} \ll M_{\mathrm{Planck}}$?



$$\delta M_{\mathrm{H}}^2 \sim \frac{3\lambda_t^2}{8\pi^2}\,\Lambda_{\mathrm{UV}}^2 \sim (0.3\,\Lambda_{\mathrm{UV}})^2$$

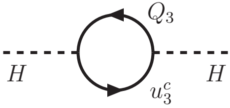


Schmaltz

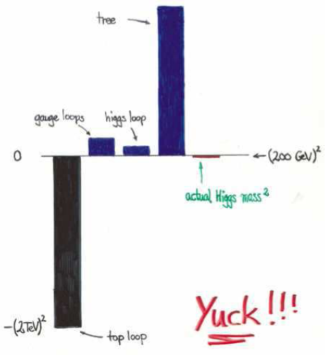
→ need new coloured top partners with mass below about 500 GeV

New physics at the LHC?

The hierarchy problem: why is $M_{\rm Higgs} \ll M_{\rm Planck}$?



$$\delta M_{\rm H}^2 \sim \frac{3\lambda_t^2}{8\pi^2}\,\Lambda_{\rm UV}^2 \sim (0.3\;\Lambda_{\rm UV})^2$$



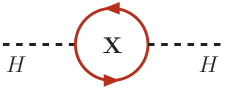
Schmaltz

$\rightarrow$ Supersymmetry? Little Higgs models? ...?

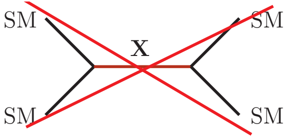
New physics at the LHC?

A dark matter connection?

The new physics should



stabilize the Higgs mass

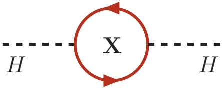


decouple from EWK physics

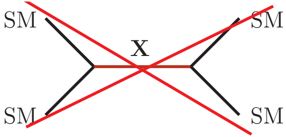
New physics at the LHC?

A dark matter connection?

The new physics should



stabilize the Higgs mass



decouple from EWK physics

Solution: impose a discrete parity

- $\rightarrow$ all interactions require pairs of new particles;
- $\rightarrow$ the lightest new particle is stable and provides a dark matter candidate.

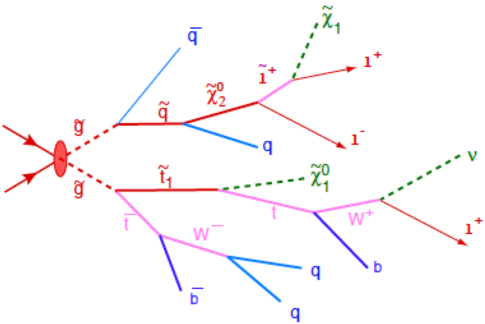
A weakly interacting massive particle (WIMP) with mass $\sim \mathcal{O}(100)$ GeV provides the correct dark matter relic abundance.

Supersymmetry and other new physics models that address

the hierarchy problem and the origin of dark matter

generically predict a spectrum of new particles at the TeV-scale with a weakly interacting & stable particle ($\leftarrow$ discrete parity)

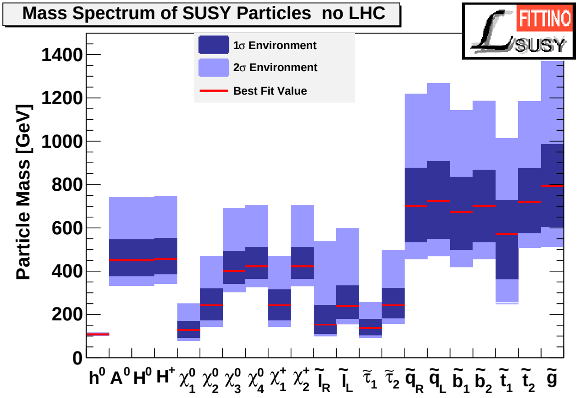
A generic BSM signature at the LHC is thus cascade decays with $E_{\mathrm{T,miss}}$



CMSSM global fit to B, K and EWK observables, $(g-2)_\mu$ and $\Omega_{\rm DM}$

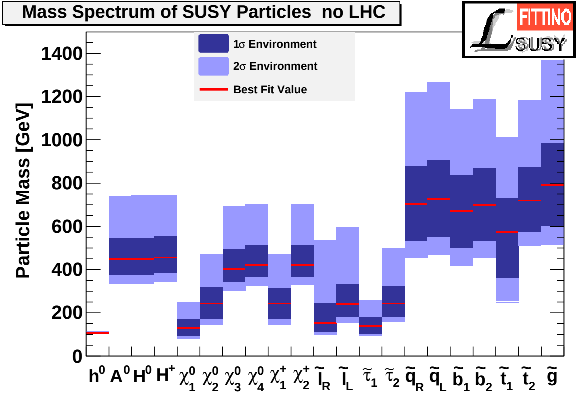
Exploring SUSY before the LHC

CMSSM global fit to B, K and EWK observables, $(g-2)_\mu$ and Ω_{DM}



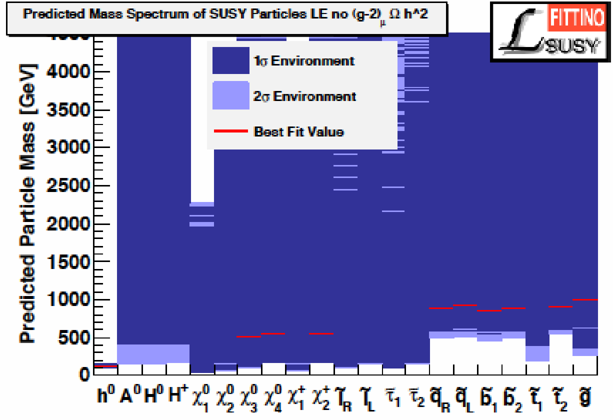
- global fits point to light sparticle spectrum with $\tilde{m} < 1$ TeV

CMSSM global fit to B, K and EWK observables, $(g-2)_\mu$ and Ω_{DM}



- global fits point to light sparticle spectrum with $\tilde{m} < 1$ TeV
- current data cannot constrain more general SUSY models

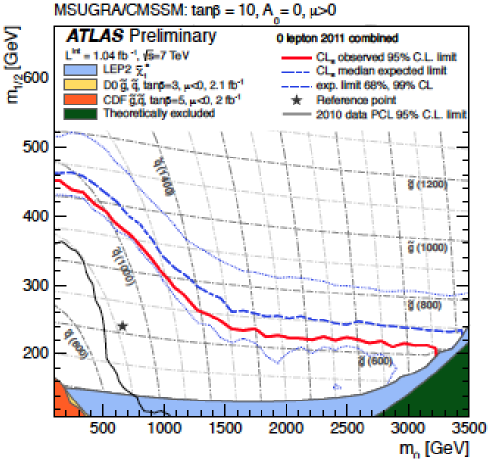
CMSSM global fit without $(g-2)_\mu$ and Ω_{DM}



- prediction of light SUSY spectrum rests on $(g-2)_\mu$ and Ω_{DM}

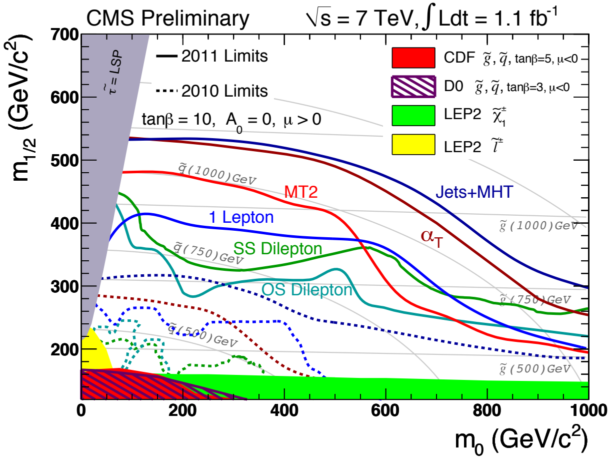
Squark and gluino searches at the LHC

ATLAS limits ($\approx$1 fb^{-1})



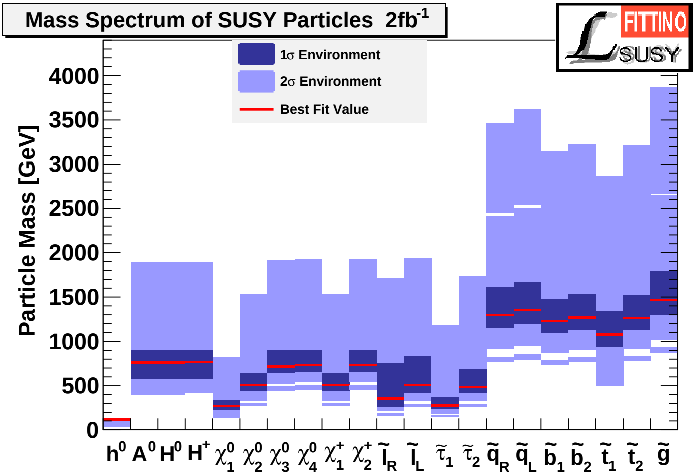
$\rightarrow m_{\tilde{q}} \approx m_{\tilde{g}} \gtrsim 980$ GeV

CMS limits ($\approx 1\ \text{fb}^{-1}$)

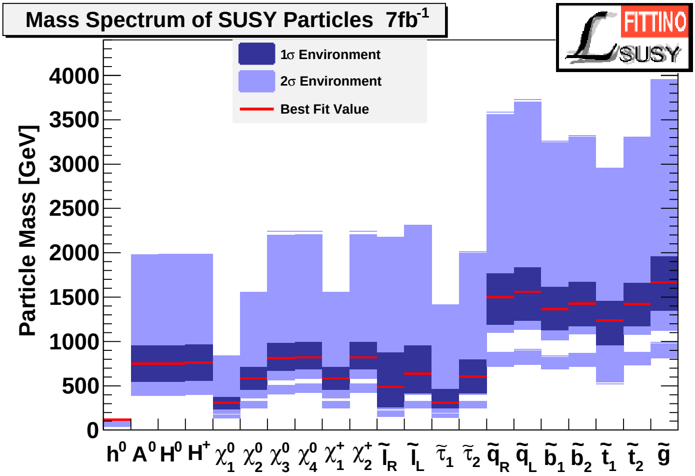


$\rightarrow m_{\tilde{q}} \approx m_{\tilde{g}} \gtrsim 1.2$ GeV

CMSSM global fit including LHC exclusions with 2 fb^{-1}



CMSSM global fit including LHC exclusions with 7 fb^{-1}



Global SUSY fits with LHC exclusions: is there a tension?

$\rightarrow$ LEOs prefer low mass scales (for non-coloured sector)

$\rightarrow$ LHC prefers high mass scales (for coloured sector)

Is there a tension building up?

Global SUSY fits with LHC exclusions: is there a tension?

→ LEOs prefer low mass scales (for non-coloured sector)

→ LHC prefers high mass scales (for coloured sector)

Is there a tension building up?

Let us look at the best fit points:

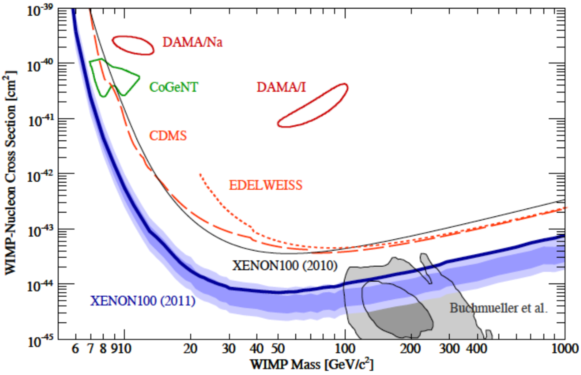
	M_0	$M_{1/2}$	A_0	$\tan\beta$	χ^2/ndf
no LHC	77^{+114}_{-31}	333^{+89}_{-87}	426^{+70}_{-735}	13^{+10}_{-8}	19/20
35 pb^{-1}	126^{+189}_{-54}	400^{+109}_{-40}	724^{+722}_{-780}	17^{+14}_{-9}	20/21
1 fb^{-1}	235^{+389}_{-103}	601^{+148}_{-63}	627^{+1249}_{-717}	31^{+19}_{-18}	24/21
2 fb^{-1}	254^{+456}_{-128}	647^{+157}_{-74}	771^{+1254}_{-879}	30^{+20}_{-19}	24/21
7 fb^{-1}	403^{+436}_{-281}	744^{+142}_{-150}	781^{+1474}_{-918}	43^{+11}_{-33}	25/21

→ even the CMSSM would "survive" the 2011/2012 LHC run

[Note: $a_\mu^{\mathrm{SUSY}} \sim \mathrm{sgn}(\mu)\tan\beta\, M_{\mathrm{SUSY}}^{-2}$ and Ω_{DM} require larger $\tan\beta$]

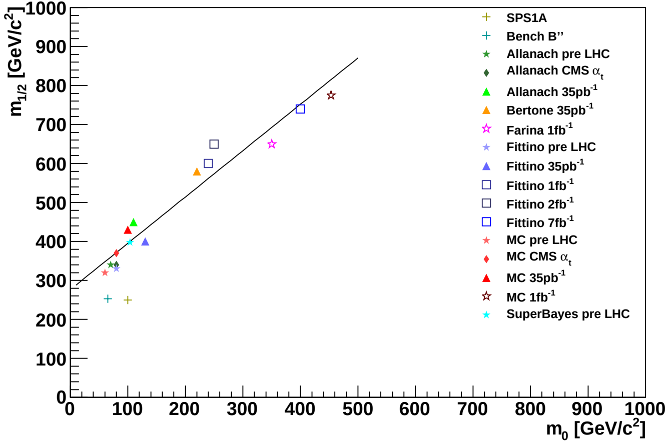
Future SUSY searches beyond pp $\rightarrow$ jets + MET

- flavour constraints, *e.g.* $B_s \rightarrow \mu\mu$ (LHCb)
- direct dark matter searches (see e.g. Aprile et al: arXiv:1104.2549)



Comparison of global CMSSM fits with and without LHC exclusions

There has been a lot of activity recently (see e.g. arXiv:1109.3859v1)



→ there is reasonable agreement between the different groups

Current and upcoming SUSY searches at the LHC

- The LHC has excluded constrained SUSY models where

  $m_{\mathrm{squark}} \approx m_{\mathrm{gluino}} \lesssim 1$ TeV

  and squarks and gluinos decay into jets and $\tilde{\chi}_1^0$

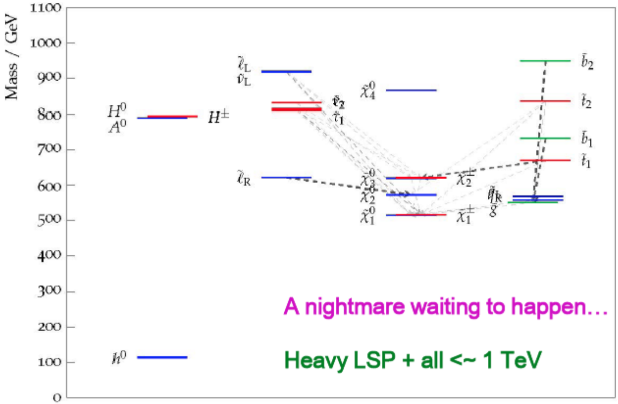
  and $m_{\tilde{\chi}_1^0} \lesssim 200$ GeV .

However,

- The current searches are not sensitive to compressed SUSY spectra

Discovery/exclusion is hard for SUSY models with long decay chains and/or compressed mass spectra

[Conley et al.]



Current and upcoming SUSY searches at the LHC

- The LHC has excluded constrained SUSY models where

  $m_{\rm squark} \approx m_{\rm gluino} \lesssim 1$ TeV

  and squarks and gluinos decay into jets and $\tilde{\chi}_1^0$

  and $m_{\tilde{\chi}_1^0} \lesssim 200$ GeV.

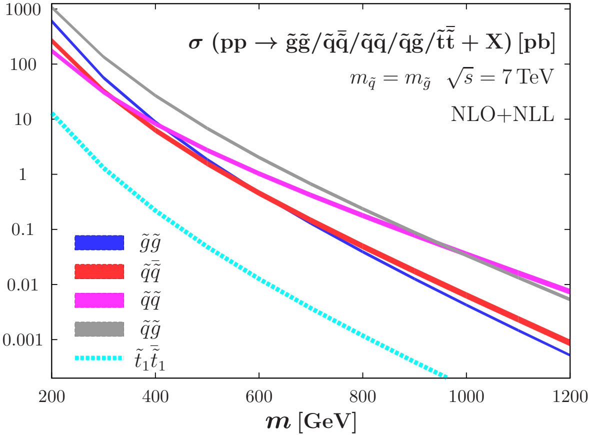
However,

- The current searches are not sensitive to compressed SUSY spectra

- The LHC has only just started to probe the third generation squarks (cf. hierarchy problem)

The direct stop/sbottom cross section is suppressed compared to the inclusive squark & gluino cross section

[Beenakker, Brensing, MK, Laenen, Kulesza, Niessen '09]



Current and upcoming SUSY searches at the LHC

- The LHC has excluded constrained SUSY models where

$$m_{\mathrm{squark}} \approx m_{\mathrm{gluino}} \lesssim 1 \text{ TeV}$$

and squarks and gluinos decay into jets and $\tilde{\chi}_1^0$

and $m_{\tilde{\chi}_1^0} \lesssim 200$ GeV .

However,

- The current searches are not sensitive to compressed SUSY spectra
- The LHC has only just started to probe the third generation squarks (cf. hierarchy problem)
- The LHC has only just started to probe electroweak sparticles (cf. $(g-2)_\mu$)

Conclusions

The LHC7 will provide crucial information on EWSB and the Higgs boson

- current data are consistent with a light Higgs as expected from electroweak precision physics and supersymmetric theories;
- the exclusion of a Higgs with $m_h \lesssim 140$ GeV would be the only way to exclude the MSSM;
- SM Higgs searches will, however, not be sufficient to exclude a light MSSM Higgs, e.g. because of invisible decays $h \to \tilde{\chi}\tilde{\chi}$;
- the Higgs sector will play a crucial role for the assessment of SUSY models in the near future!

Conclusions

The LHC7 has started to cut heavily into the landscape of new physics at the TeV-scale

- there is no sign of new physics so far;
- canonical searches with jets and MET have pushed limits on squark and gluino masses beyond 1 TeV;

Conclusions

The LHC7 has started to cut heavily into the landscape of new physics at the TeV-scale

- there is no sign of new physics so far;
- canonical searches with jets and MET have pushed limits on squark and gluino masses beyond 1 TeV;

However, the LHC searches need to

- be optimized for and interpreted in a wider class of SUSY and other BSM models;
- focus on third generation and electroweak sparticles;
- be extended to more general and complex scenarios, e.g. compressed spectra.

Unfortunately, the (canonical) BSM searches will soon run out of steam; it will be crucial to upgrade the LHC energy towards 14 TeV.

Conclusions

Personally, I am disappointed about the lack of evidence for new physics.

I did hope for early discovery of new physics in the jets+MET signature.

But we should not forget that we have not yet reached design energy and so far only looked at about 0.1% of the expected LHC data set.

We have more than 10 years of LHC physics ahead of us.

Let's enjoy the ride!