SUSY after LHC run 1

Heidi Rzehak

Albert-Ludwigs-Universität Freiburg

Frontiers of Fundamental Physics 2014, Marseille, July 17, 2014

Supersymmetry

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

$$Q = \text{supersymmetry generator}$$

$\rightarrow$ Connection between space-time and internal symmetries

Minimal Supersymmetric Standard Model (MSSM)

MSSM: Minimal supersymmetric extension of the Standard Model (SM)

Recipe:
- Standard Model particles + 2nd Higgs doublet (2HDM)
  (Generation of fermion masses, anomaly cancelations)
- Superpartners
- Explicit soft SUSY-breaking ⇒ many new (complex) parameters
  (Else: $\text{mass}_{\text{superpartner}} = \text{mass}_{\text{2HDM-particle}} \leftarrow$ exp. excluded)

(• R-Parity: discrete symmetry)

→ possible dark matter candidate

→ grand unification

→ solution to hierarchy problem

Minimal Supersymmetric Standard Model (MSSM)

Particle content:

(2HDM)-Particle	Quarks	Leptons	Gauge bosons	Higgs bosons
Superpartner	Squarks	Sleptons	Gauginos Higgsinos	

Gauginos, Higgsinos ⇓ mix

Charginos, Neutralinos

LHC run 1:

- Discovery of a Higgs boson
- Constraints from direct/indirect searches

Constrained MSSM

Soft SUSY breaking $\Rightarrow$ many new parameters $\mathcal{O}(100)$

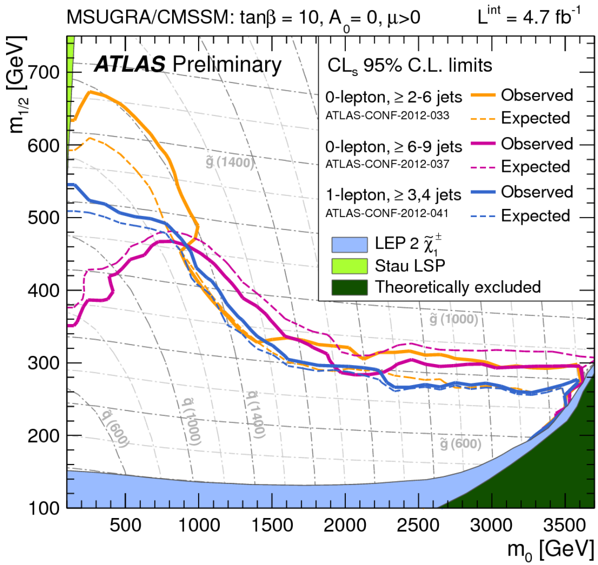
$\rightarrow$ reduction of number of parameters desirable

CMSSM (inspired by gravity-mediated SUSY breaking):

$\Rightarrow$ 4 new parameters, 1 sign

- m_0: scalar soft breaking mass parameters
- $m_{\frac{1}{2}}$: gaugino mass parameters
- A_0: scalar trilinear couplings
- $\tan\beta$: ratio of the vacuum expectation values $\frac{v_d}{v_u}$
- $\text{sign}(\mu)$: sign of Higgs superfield mixing parameter μ

Exclusion in the CMSSM

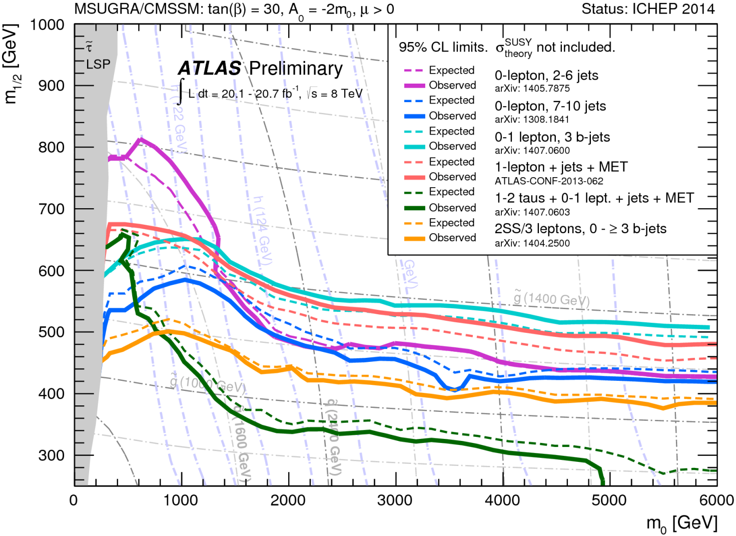


2012:

Main constraints:

from processes
with many jets

Exclusion in the CMSSM



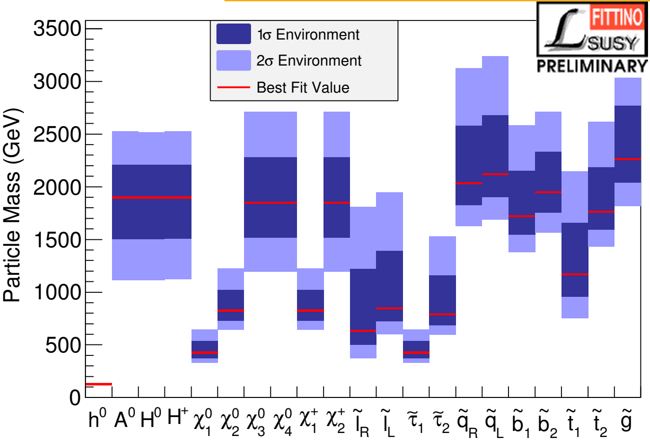
2014:

Main constraints:

from processes

- with many jets (mainly)
- with leptons:
  - ⋆ 3 charged
  - ⋆ 2 same electric charge

CMSSM fits



squarks: ~ 2 TeV

light stop:

$\gtrsim 750$ GeV

[Bechtle, Desch, Sarrazin, Uhlenbrock, Wienemann, Dreiner, Stefaniak, Hamer, Krämer, Porod, O'Leary, Prudent, arXiv:11310.3045]

see also [Kowalska, Roszkowski, Sessolo, arXiv:1302.5956; Buchmueller, Cavanaugh, De Roeck, Dolan, Ellis, Flächer, Heinemeyer, Isidori, Marrouche, Martínez Santos, Olive, Rogerson, Ronga, de Vries, Weiglein, arXiv:1312.5250; . . .]

Higgs mass and direct SUSY searches

Limits from direct searches

$\rightarrow$ heavy SUSY partner particles e.g. in CMSSM

$\Rightarrow$ good Higgs mass prediction for large SUSY mass scales M_S needed

Problem: fixed order calculation $\rightarrow$ large logs $\log \frac{M_S}{m_t}$

m_t = top quark mass

$\Rightarrow$ improve prediction by resummation of logs using RGEs

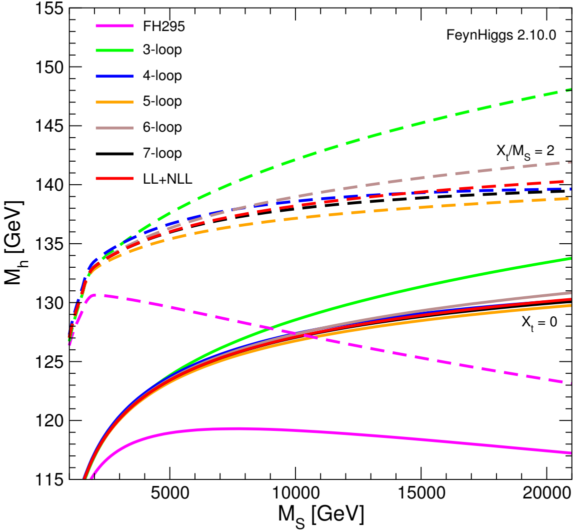
Renormalization Group Eequation

(latest RGE Higgs mass result: [Draper, Lee, Wagner, arXiv:1312.5743])

$\Rightarrow$ combination of fixed-order and RGE result

[Hahn, Heinemeyer, Hollik, HR, Weiglein, arXiv:1312.4937]

Improved Higgs mass prediction



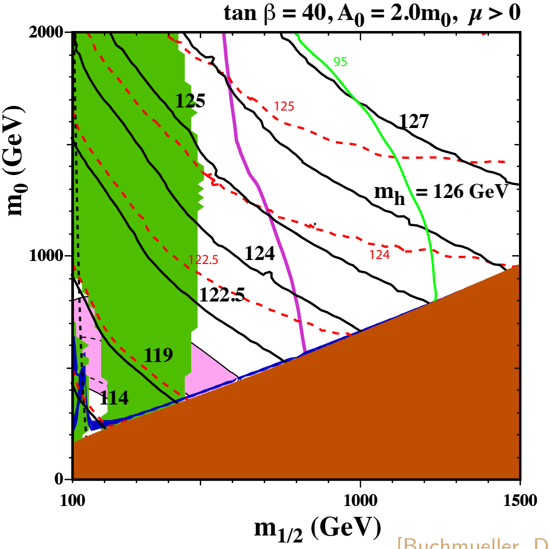
Comparison of:

- ⋆ old FeynHiggs reliable up to $M_s = \mathcal{O}(1\text{TeV})$
- ⋆ analyt. solution of RGE: 3-loop … 7-loop level: Logs of order $\mathcal{O}(\alpha_t\alpha_s^2, \alpha_t^2\alpha_s, \alpha_t^3)$ …
- ⋆ numerical solution: LL+NLL: logs resummed to all orders

$M_A = M_2 = \mu = 1$ TeV, $m_{\tilde{g}} = 1.6$ TeV, $\tan\beta = 10$

[Hahn, Heinemeyer, Hollik, HR, Weiglein, arXiv:1312.4937]

CMSSM fits and improved Higgs mass prediction



M_h: `FeynHiggs2.10.0`

[Hahn, Heinemeyer, Hollik, HR, Weiglein, Williams]

M_h: `FeynHiggs2.8.6`

95% CL limit of BR($B_s \to \mu\mu$) (CMS/LHCb)

95% CL excl. limit of ATLAS missing E_T searches

right relic density

$g-2$ favoured

BR($b \to s\gamma$) exclusion

charged LSP

[Buchmueller, Dolan, Ellis, Hahn, Heinemeyer, Hollik, Marrouche, Olive, HR, de Vries, Weiglein, arXiv:1312.5233]

Looking beyond

CMSSM: maybe too simple

- relax the assumptions:

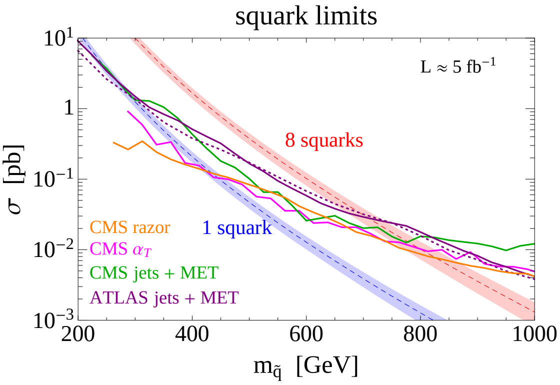
  → NoneUniversalHiggsMasses, phenomenologicalMSSMi $i \in \mathbf{N}$

- capture special features

  → simplified models

Bounds on masses of first generation squarks

Model assumptions: degenerate masses $\leftrightarrow$ non-degenerate masses



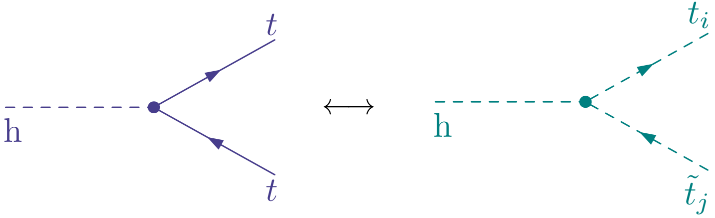
Read the fineprint!

$\tilde{q} \to q\chi_1^0$: decoupled gluino, massless neutralino

[Mahbubani, Papucci, Perez, Ruderman, Weiler, arXiv:1212.3328]

Stops

Connection to Higgs physics:



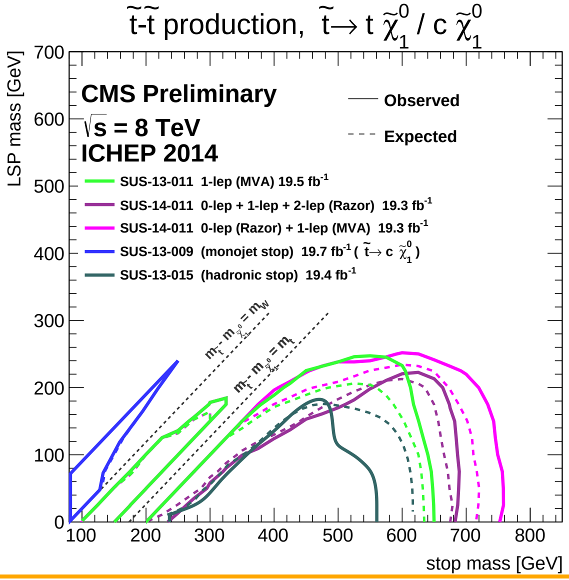
Important wrt

- Higgs mass value
- discussion of fine-tuning

Different wrt 1st, 2nd generation of squarks:

- large mixing $\propto m_t$ possible

Limits from Stop searches

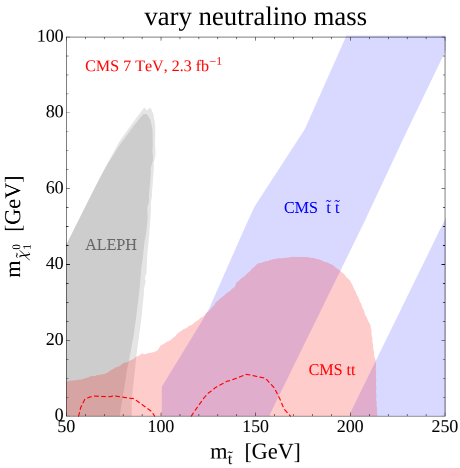


already excluding stops with mass $\lesssim$ 750 GeV (fineprint!)

But: Holes!
$\rightarrow$ separation from top quark background difficult

Stop mass ∼ top mass

Filling holes:



Use measurement of
top pair production
cross section $\sigma_{t\bar{t}}$

Note: $\sigma_{t\bar{t}}^{\text{measured}} \lesssim \sigma_{t\bar{t}}^{\text{SM}}$

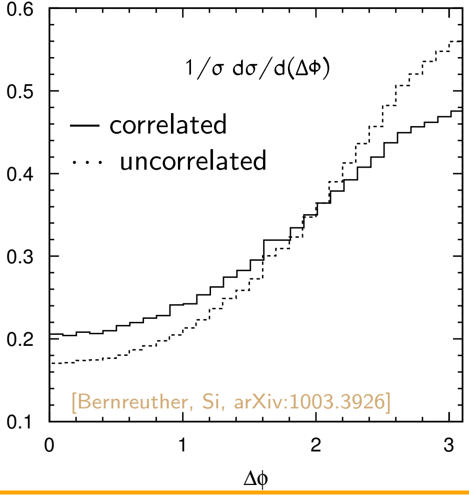
downward fluctuation

[Czakon, Mitov, Papucci, Ruderman, Weiler, arXiv:1407.1043]

Stop mass ∼ top mass

Filling holes:

complementary: spin correlations in top pair production (dilepton channel)



best:

low invariant $t\bar{t}$ mass region:

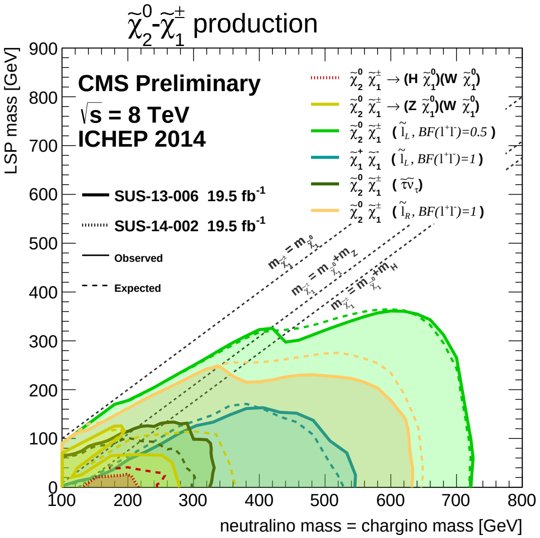
azimuthal angle difference of leptons

[Mahlon, Parke, arXiv:1001.3422]

excess of uncorrelated events?

[Han, Katz, arXiv:1310.0356; Mahbubani, Parke, HR, Winter, in preparation]

Limits on electroweak interacting SUSY particles



- no jets
  $\rightarrow$ more difficult
  to measure

- best limits from
  trilepton searches
  (low SM background)

WW cross section

- 7 TeV:
  - ⋆ ATLAS: measured: $51.9 \pm 2.0(\text{stat.}) \pm 3.9(\text{syst.}) \pm 2.0(\text{lum.})$ pb
    theory: $44.7^{+2.1}_{-1.9}$ pb
  - ⋆ CMS: measured: $52.4 \pm 2.0(\text{stat.}) \pm 4.5(\text{syst.}) \pm 1.2(\text{lum.})$ pb
    theory: 47 ± 2 pb
- 8 TeV:
  - ⋆ ATLAS: measured: $71.4 \pm 1.2(\text{stat.})^{+5.0}_{-4.4}(\text{syst.})^{+2.2}_{-2.1}(\text{lum.})$ pb
    theory: $58.7^{+3}_{-2.7}$ pb
  - ⋆ CMS: measured: $69.9 \pm 2.8(\text{stat.}) \pm 5.6(\text{syst.}) \pm 3.1(\text{lum.})$ pb
    theory: $57.6^{+2.3}_{-1.6}$ pb

SUSY hidden in WW?

- SUSY contaminating the WW background to Higgs searches?

  [Feigl, HR, Zeppenfeld, arXiv:1205.3468]

- Charginos, sleptons responsible for WW excess?

  [Curtin, Jaiswal, Meade, arXiv:1206.6888;

  Curtin, Jaiswal, Meade, Tien, arXiv:1304.7011]

- WW excess arising from stops?

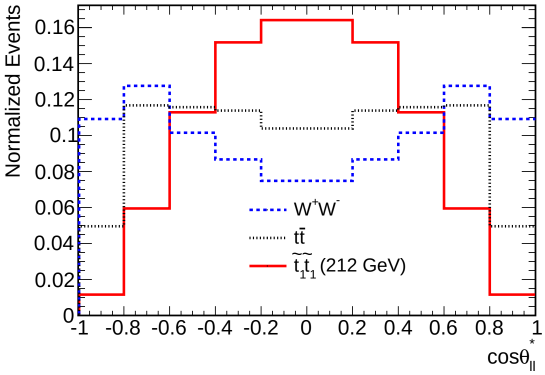
  [Rolbiecki, Sakurai, arXiv:1303.5696;

  Curtin, Meade, Tien, arXiv:1406.0848;

  Kim, Rolbiecki, Sakurai, Tattersall, arXiv:1406.0858]

SUSY hidden in WW?

Discrimination between stops and W:



$$\cos\theta^*_{ll} = \tanh\left(\frac{\Delta\eta_{ll}}{2}\right)$$

η_{ll} = pseudorapidity difference of leptons

→ different shapes for stops and W bosons

[Kim, Rolbiecki, Sakurai, Tattersall, arXiv:1406.0858]

Summary: SUSY after LHC run 1

- Discovered: A Higgs boson
- Excluded: quite a bit of SUSY parameter space
  - ⋆ by searches of jets + missing energy, also b-jets
  - ⋆ by searches of a lepton + jets + missing energy, also b-jets
  - ⋆ by trilepton searches
  - ⋆ by dedicated searches to specific characteristic scenarios
- But: still (reasonable) parameter space allowed!
- LHC run 2: a further discovery?