SUSY after LHC run 1

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Supersymmetry

\[ Q |\text{Boson}\rangle = |\text{Fermion}\rangle, \quad Q |\text{Fermion}\rangle = |\text{Boson}\rangle \]

\[ Q = \text{supersymmetry generator} \]

\[ \rightarrow \text{Connection between space-time and internal symmetries} \]
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: $\text{mass}_{\text{superpartner}} = \text{mass}_{2\text{HDM}-\text{particle}} \leftarrow \text{exp. excluded}$)
  (• 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
- Charginos
- Neutralinos

LHC run 1:
- Discovery of a Higgs boson
- Constraints from direct/indirect searches
**Constrained MSSM**

Soft SUSY breaking \(\Rightarrow\) many new parameters \(O(100)\)
\(\rightarrow\) 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
- \(m_{1/2}\): 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 \(\mu\)
Exclusion in the CMSSM

Main constraints:
from processes with many jets

2012:

ATLAS Preliminary

MSUGRA/CMSSM: tan\(\beta\) = 10, \(A_0 = 0\), \(\mu > 0\) 

\(L^{\text{int}} = 4.7\ \text{fb}^{-1}\)

CL\(_{s}\) 95\% C.L. limits

- 0-lepton, \(\geq 2\)-6 jets
- 0-lepton, \(\geq 6\)-9 jets
- 1-lepton, \(\geq 3\),4 jets

Observed
Expected

LEP 2 \(\tilde{\chi}_1^\pm\)
Stau LSP
Theoretically excluded
Main constraints:

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

squarks: \( \sim 2 \) 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

→ heavy SUSY partner particles e.g. in CMSSM

⇒ good Higgs mass prediction for large SUSY mass scales $M_S$ needed

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

$m_t = \text{top quark mass}$

⇒ improve prediction by resummation of logs using RGEs

Renormalization Group Equation

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

⇒ 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

\[ \tan \beta = 40, A_0 = 2.0m_0, \mu > 0 \]

\[ M_h: \text{FeynHiggs2.10.0} \]
[Hahn, Heinemeyer, Hollik, HR, Weiglein, Williams]

\[ M_h: \text{FeynHiggs2.8.6} \]

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

95\% CL excl. limit of ATLAS missing \( E_T \) searches

right relic density

\( g - 2 \) favoured

\( BR(b \rightarrow s\gamma) \) exclusion

charged LSP

Looking beyond

CMSSM: maybe too simple

• relax the assumptions:
  \[ \to \text{NoneUniversalHiggsMasses, phenomenologicalMSSMi \quad i \in \mathbb{N}} \]

• capture special features
  \[ \to \text{simplified models} \]
Bounds on masses of first generation squarks

Model assumptions: degenerate masses ↔ non-degenerate masses

\[ \tilde{q} \rightarrow q \chi_1^0: \text{decoupled gluino, massless neutralino} \]

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

Connection to Higgs physics:

Important wrt

- Higgs mass value
- discussion of fine-tuning

Different wrt 1\textsuperscript{st}, 2\textsuperscript{nd} generation of squarks:

- large mixing $\propto m_t$ possible
Limits from Stop searches

$t\bar{t}$ production, $t \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0$

CMS Preliminary
\[ \sqrt{s} = 8 \text{ TeV} \]
ICHEP 2014

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

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

Filling holes:

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

\[
\frac{1}{\sigma} \frac{d\sigma}{d(\Delta \phi)}
\]

- correlated
- uncorrelated

best:

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

azimuthal angle difference of leptons


excess of uncorrelated events?

[Han, Katz, arXiv:1310.0356; Mahbubani, Parke, HR, Winter, in preparation]
Limits on electroweak interacting SUSY particles

- no jets
  → more difficult to measure
- best limits from trilepton searches
  (low SM background)

CMS Preliminary
\[ \sqrt{s} = 8 \text{ TeV} \]
ICHEP 2014

![Graph showing SUSY particle production](image)

- SUSY after LHC run 1
  - Heidi Rzehak
  - July 17, 2014
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: $47 \pm 2$ 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?

- WW excess arising from stops?
Discrimination between stops and $W$:

$\cos \theta_{\parallel}^* = \tanh \left( \frac{\Delta \eta_{\parallel}}{2} \right)$

$\eta_{\parallel} = \text{pseudorapidity difference of leptons}$

$\rightarrow$ 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?