

The Standard Model and beyond (5)

SM limits and some extensions

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Quarks

Leptons

Fermions



Photon



W and Z



Gluons



Higgs boson

Bosons

Fourth lecture

Spontaneous symmetry breaking

- Interactions obey a symmetry which is not visible in the spectrum
- Ground state does not respect the symmetry
- Must expand the theory around this ground state
- For global symmetry, massless scalar particles (Goldstone bosons)

Electroweak symmetry breaking

- Triggered by addition complex scalar doublet, the Higgs field
- For gauge symmetry, yields 3 massive gauge bosons
- Symmetry breaking chosen to preserve $U(1)_{em}$ and keep massless photons
- A dof not used to give masses to W, Z : the Higgs boson H
- Couplings of H to gauge bosons and to fermions
- Experimental tests: Higgs couplings, electroweak precision observables, CKM matrix

The splendors and miseries of the Standard Model

Too successful a theory ?

SM a real success story

- Description of three fundamental interactions
- Gauge symmetry yields dynamics unambiguously
- Very good agreement with experimental data

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So, is the dinner too good and should we go to sleep ?

SM limits (1)



- QCD gauge sector : α_s, θ_{QCD}

2

- Electroweak gauge/scalar sector : g, g', μ, λ

4



- Yukawa sector

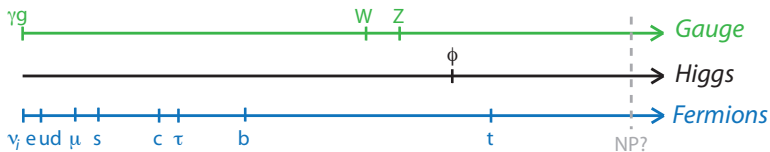
13

$m_e, m_\mu, m_\tau, m_d, m_s, m_b, m_u, m_c, m_t + 4$ param in V_{CKM}

19 free parameters

(+ neutrinos: masses/lepton mixing depending on Dirac vs Majorana)

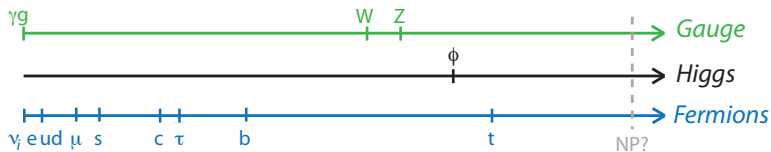
SM limits (2)



- Parameters, e.g., masses, completely **arbitrary**

$$m_e = 0.51 \text{ MeV} \rightarrow m_t = 170 \text{ GeV}$$

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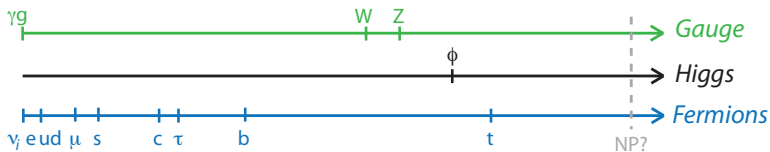
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- Origin of electroweak symmetry breaking

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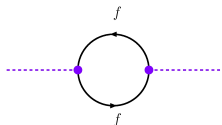
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- Hierarchy “problem” with $m_H = 125 \text{ GeV}$



$$\Delta m_H^2 = \frac{N_f m_f^2}{4\pi^2 V^2} \left[\Lambda_{NP}^2 + 6m_f^2 \log \frac{\Lambda_{NP}}{m_f} - 2m_f^2 \right] + O \left[\frac{1}{\Lambda_{NP}^2} \right]$$

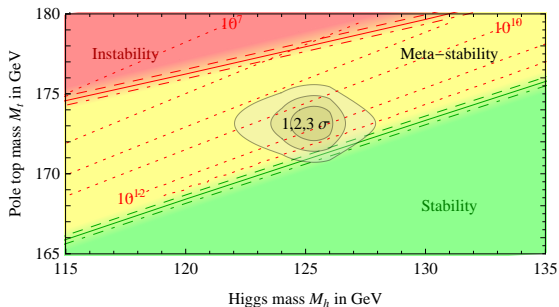
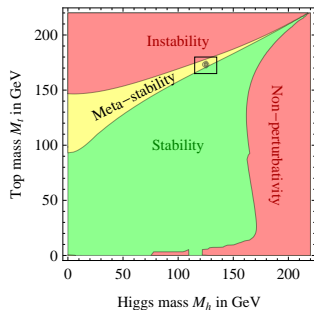
Λ_{NP} scale of new physics: **fine tuning** needed if no particle up to unification scale ($10^{16 \dots 19} \text{ GeV}$?)

SM limits (3)

Analysis of NNLO analysis of SM Higgs potential

$$M_H > 129.4 + 1.4 \left(\frac{m_t - 173.1}{0.7} \right) - 0.5 \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0 \quad M_H > 129.4 \pm 1.8 \text{ GeV}$$

for vacuum absolutely stable up to Planck scale



M_t and M_H (if SM Higgs) favour metastability of the vacuum
as well as almost vanishing of $\lambda(M_{Planck})$

SM limits (4)

- No gravitation included
- Cosmological obs: dark matter, matter-antimatter asym. . .
- No explanations for gauge group, only partial unification
- Value of the charges ? Three families ? Neutrinos ?
- Why $L \neq R$? Structure of Yukawa ? Amount of CP-violation ?
- Strong CP-problem: $\theta_{QCD} \epsilon_{\mu\nu\rho\sigma} G^{\mu\nu} G^{\rho\sigma}$ allowed, but $\theta_{QCD} \leq 10^{-10}$

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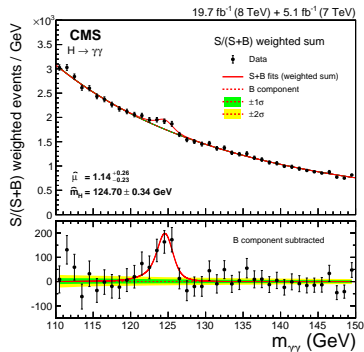
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Theorists have plenty of ideas to spice up the SM



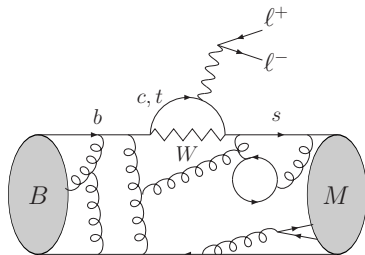
Complementary ways of observing New Physics

Relativistic path: $E = mc^2$



Collisions with enough energy
to produce directly particles
beyond the SM
Higher energy/lower intensity
“Direct” proof

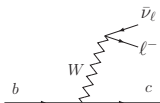
Quantum path: $\Delta E \Delta t \geq \hbar/2$



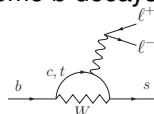
Small deviations from
intermediate states
with heavy particles
Lower energy/higher intensity
“Indirect” proof

A few signs ?

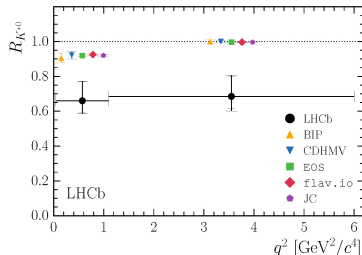
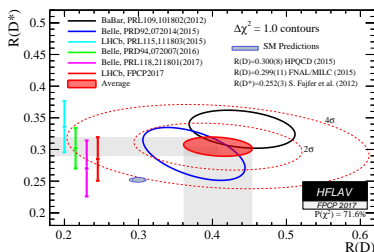
- No signal using the relativistic path at LHC
- But a few hints using the quantum path
 - anomalous magnetic moment of the muon $(g - 2)_\mu$
 - CP-violation in kaon decays (ϵ'/ϵ)
 - violation of lepton flavour universality in some b decays



$$R_{D^{(*)}} = \frac{Br(B \rightarrow D^{(*)} \tau \nu)}{Br(B \rightarrow D^{(*)} \ell \bar{\nu}_\ell)}$$



$$R_{K^{(*)}} = \frac{Br(B \rightarrow K^{(*)} \mu \mu)}{Br(B \rightarrow K^{(*)} ee)}$$



New directions to extend the SM ?

Many different directions

- Fermion content (more “matter”)
- Gauge boson content (more “interactions”)
- Scalar sector (different symmetry breakings)
- Additional symmetries
- Additional dimensions



Main constraints

- Reproduce data within experimental and theoretical uncertainties
⇒ Be close to SM up to currently tested energies
- Most new phenomena should occur only in untested processes
⇒ Modify structure of the theory to push NP in these corners
- Built as decoupling theories: recover SM when $\Lambda_{NP} \rightarrow \infty$
⇒ SM seen as effective theory, with NP corrections $O(\Lambda_{EW}/\Lambda_{NP})$

Supersymmetry

Basic idea

Let us take seriously the hierarchy problem, can we solve it ?

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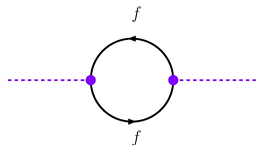
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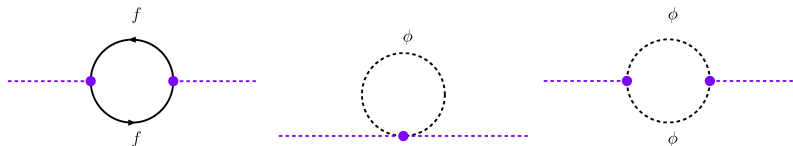


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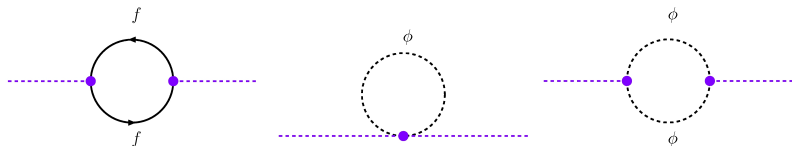
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$$\Delta m_H^2|_\phi = \frac{N_s \lambda_s}{16\pi^2} \left[-\Lambda^2 + 2m_s^2 \log \frac{\Lambda}{m_s} \right] - \frac{N_s \lambda_s^2 v^2}{16\pi^2} \left[-1 + 2 \log \frac{\Lambda}{m_s} \right] + O \left[\frac{1}{\Lambda^2} \right]$$

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- If $N_s = 2N_f$ and $\lambda_f = 2m_f^2/v^2 = -\lambda_s$ (particle content, symmetry), **cancellation of quadratic divergences**, no fine tuning needed

$$\Delta m_H^2 = \frac{N_f \lambda_f^2}{4\pi^2} \left[(m_f^2 - m_s^2) \log \frac{\Lambda}{m_f} + 3m_f^2 \log \frac{m_s}{m_f} \right] + O\left[\frac{1}{\Lambda^2}\right]$$

Supersymmetry

Such a symmetry exists, it is supersymmetry : boson \leftrightarrow fermion

$$Q|\text{Spin } S\rangle = |\text{Spin } S + 1/2\rangle \quad \{Q, Q^\dagger\} = P^\mu$$

\implies connects different spins : extension of Lorentz-Poincaré symmetry
(be careful : it is not a gauge symmetry !)

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- Quadratic terms in Λ cancel in m_H

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(even log. terms do cancel if $m_f = m_s$) \implies no fine-tuning !

- If supersymmetry not broken,
spectrum of bosons and fermions should be degenerate

MSSM

Minimal Supersymmetric Standard Model: minimal extension of SM

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- Doubling of the spectrum

Spin	SM particle	Susy partner	Spin
1/2	lepton $\ell_{R,L}$	slepton $\tilde{\ell}_{R,L}$	0
1/2	neutrino $\nu_{\ell,L}$	sneutrino $\tilde{\nu}_{\ell,L}$	0
1/2	quark $q_{R,L}$	squark $\tilde{q}_{R,L}$	0
1	bosons Z^0, W^\pm	zino, wino \tilde{Z}, \tilde{W}^\pm	1/2
1	gluons g	gluinos \tilde{g}	1/2

L, R just a label for superpartners (no helicity for such scalars)

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- Two Higgs doublets H_1, H_2 (and higgsinos \tilde{H}_1, \tilde{H}_2)

$$H_u = \begin{pmatrix} H_u^+ \\ H_d^0 \end{pmatrix} \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

[different couplings to u and d -type quarks]



MSSM : electroweak symmetry breaking

Electroweak symmetry breaking triggered by

$\langle 0|H_u^0|0\rangle \neq 0$ and $\langle 0|H_d^0|0\rangle \neq 0$, with $m_W, m_Z \dots$ depending on

- $\tan \beta = \langle H_u^0 \rangle / \langle H_d^0 \rangle$
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= 5 observable spin-0 particles



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$$m_{H^\pm} \geq m_W$$

$$m_h \leq m_A, m_Z \leq m_H$$

at leading order, implying large one-loop corrections to have $m_h \geq M_Z$

MSSM : spectrum

If same quantum number, possibility of mixing to yield physical states
 \implies Possible in various super-sectors

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- Fermions associated with electroweak sector

Photino, zino, neutral higgsinos ⇒ neutralinos

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neutralino often taken as
Dark Matter particle
if sufficiently stable !



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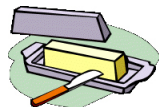
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- Scalars – squark and sleptons

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- Susy to be broken: spectrum non-degenerate with SM particles

Interactions and decays

R -parity : even number of susy particles at each vertex

- no creation/decay of a single susy particle
- lightest susy particle (LSP) is stable (**dark matter** candidate)

Many more particles, and thus many more interactions



Gauge bosons



Gaugino



Fermion (quark, lepton, Higgsinos)



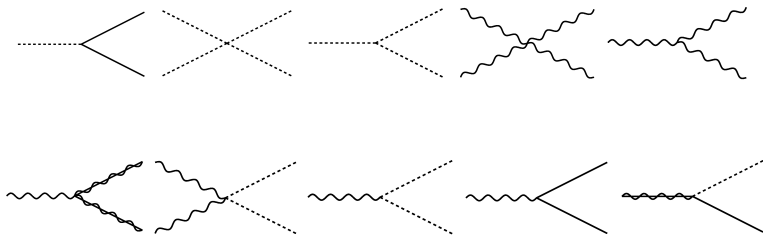
Scalar (squark, slepton, Higgs)

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governed by the same coupling constants as their SM counterparts

Supersymmetry and its “soft” breaking

Supersymmetry not a symmetry of the spectrum
⇒ mechanism to break susy and
push superpartners above TeV scale

$$\mathcal{L} = \mathcal{L}_{susy} + \mathcal{L}_{soft}$$



Supersymmetry and its “soft” breaking

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$$\mathcal{L} = \mathcal{L}_{susy} + \mathcal{L}_{soft}$$

- \mathcal{L}_{soft} must not affect the couplings involved in the cancellation of quadratic divergences \mathcal{L}_{susy}
- \mathcal{L}_{soft} : typical scale $m_{soft} = O(1 \text{ TeV})$ parametrising susy breaking
- Contribution to Δm_H^2 should vanish as $m_{soft} \rightarrow 0$

$$\Delta m_H^2 = m_{soft}^2 \left[\frac{\lambda}{16\pi^2} \log \frac{\Lambda}{m_{soft}} + \dots \right]$$

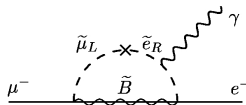
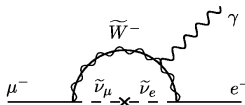
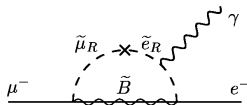
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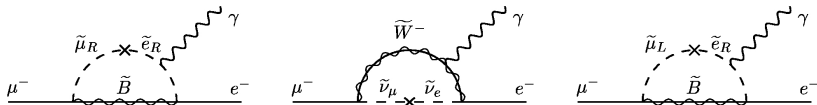
- Lepton-flavour violating processes : $\mu \rightarrow e\gamma$



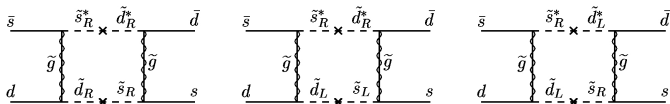
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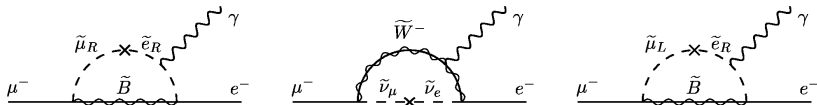
- Neutral meson mixing : $K_0 \leftrightarrow \bar{K}_0$ (i.e., $\bar{s}d \leftrightarrow s\bar{d}$)



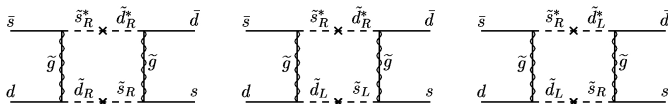
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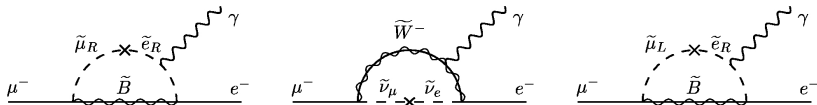


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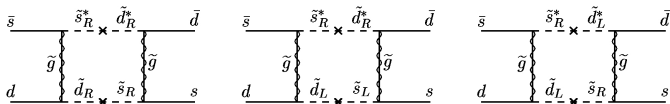
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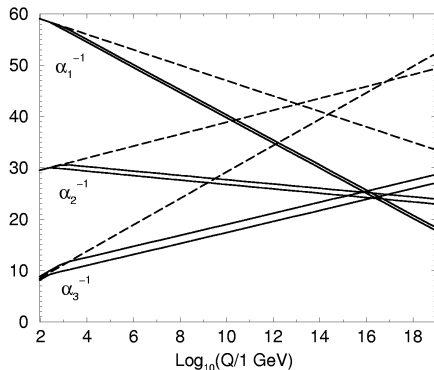
- CP-violation should remain in agreement with CKM matrix

\implies Susy-breaking terms \simeq almost flavour diagonal and blind,
identical for 3 generations and with **small sources of CP-violation**

(implemented through additional, hidden, sector
communicating susy breaking to SM via interactions)

Susy : pros

- No hierarchy “problem”: desert possible from TeV to Planck scale
- Gauge unification more satisfactory



- Lightest susy particle (if neutralino) good candidate for dark matter
- All perturbative and computable once input parameters fixed

Susy : cons

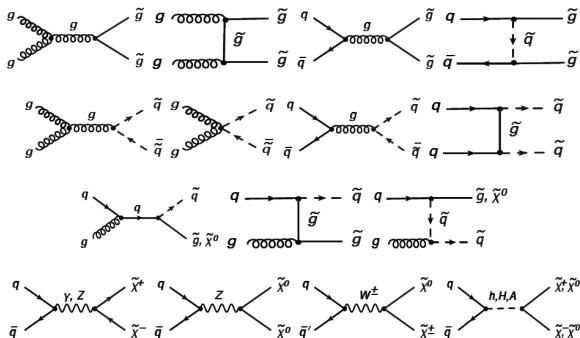
- Doubling of the spectrum, not yet observed
- Many new parameters related to susy-breaking, requiring modelling to fix them and be predictive
- No explanation for mass matrix, CP-violation. . .
- No satisfying mechanism to break susy (hidden sector ?)
- Is the desert from TeV to Planck scale such a good idea ?
- Direct searches at LHC have seen nothing up to now. . .

Susy is more **framework** than definite theory, with many extensions

- NMSSM, CNMSSM. . . with more scalars
- Grand unified versions with more gauge bosons
- R -parity violation with even more parameters
- split susy with different scales for the breakings
- . . .

Susy useful as a benchmark for discovery machines
but its "plausibility" is sometimes overstated. . .

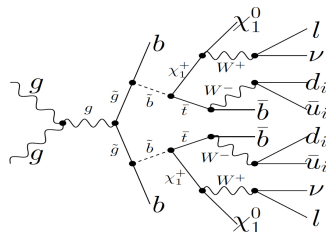
Searching for supersymmetry



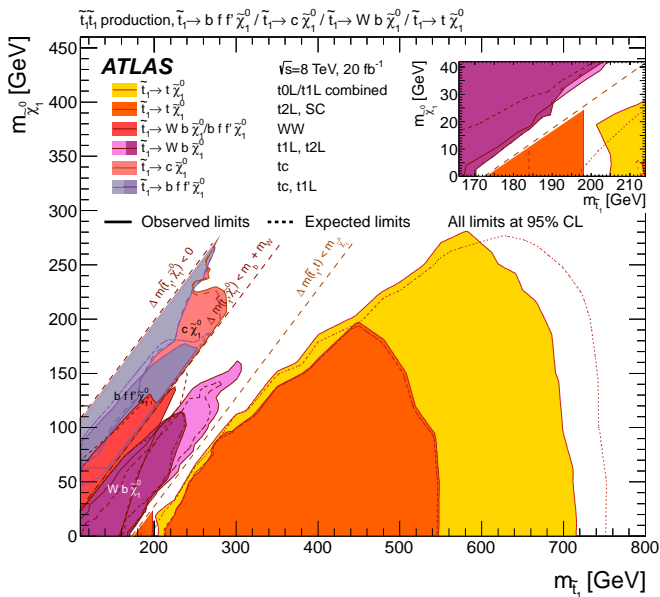
Many different production channels

If R parity, decay chain producing

- different SM particles: jets or highly energetic leptons
- LSP χ_1^0 : missing energy and missing transverse momentum



Searching for the stop (for instance)



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

ATLAS Preliminary

$\sqrt{s} = 7, 8, 13 \text{ TeV}$

Model	$\epsilon, \mu, \tau, \gamma$	Jets	E_{T}^{miss}	$L_{\text{int}} \text{ (fb}^{-1}\text{)}$	Mass limit	$\sqrt{m} = 7, 8 \text{ TeV}$	$\sqrt{m} = 13 \text{ TeV}$	Reference
Inclusive Searches								
MSUGRA/CMSSM	$0 < \epsilon, \mu < 1$	$2 < \text{jets} < 3$	Yes	20.3	\tilde{g}	1.80 TeV	$m(\tilde{g}) > m(\tilde{u}_L)$	1507.02025
$\tilde{g}, \tilde{t} \rightarrow q\bar{t}$	0	2-6 jets	Yes	3.2	\tilde{t}	810 GeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	ATLAS-COMP-2015-062
$\tilde{g}, \tilde{t} \rightarrow q\bar{t}$ (compressed)	mono-jet	1-3 jets	Yes	3.2	\tilde{t}	820 GeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	\tilde{t} -appear
$\tilde{g}, \tilde{t} \rightarrow q\bar{t}$ ($\tilde{t} \rightarrow \nu\tau/\nu\mu$)	$2 < \epsilon, \mu < 2$	2 jets	Yes	20.3	\tilde{t}	820 GeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	1501.02050
$\tilde{g}, \tilde{t} \rightarrow q\bar{t}$	0	2-6 jets	Yes	3.2	\tilde{t}	1.52 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	ATLAS-COMP-2015-062
$\tilde{g}, \tilde{t} \rightarrow q\bar{t}$ ($\tilde{t} \rightarrow \nu\tau/\nu\mu$)	$1 < \mu, \tau < 2$	2-6 jets	Yes	3.2	\tilde{t}	1.4 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	ATLAS-COMP-2015-076
$\tilde{g}, \tilde{t} \rightarrow q\bar{t}$ ($\tilde{t} \rightarrow \nu\tau/\nu\mu$)	$2 < \mu, \tau < 2$	0-3 jets	Yes	20	\tilde{t}	1.38 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	1501.02055
$\tilde{g}, \tilde{t} \rightarrow q\bar{t}$ ($\tilde{t} \rightarrow \nu\tau/\nu\mu$)	$2 < \mu, \tau < 2$	0-3 jets	Yes	20	\tilde{t}	1.4 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	1502.01194
GMSB (\tilde{t} NLSP)	$1.2 < a < 0.1$	0-2 jets	Yes	20.3	\tilde{t}	1.83 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	1407.0653
GGM (bino NLSP)	2γ	1	Yes	20.3	\tilde{t}	1.36 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	1507.05463
GGM (Higgsino-bino NLSP)	1τ	1	Yes	20.3	\tilde{t}	1.37 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	1507.05463
GGM (Higgsino-bino NLSP)	7τ	2 jets	Yes	20.3	\tilde{t}	1.3 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	1507.05463
GGM (Higgsino NLSP)	$2 < \mu, \tau < 2$	mono-jet	Yes	20.3	\tilde{t}	900 GeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	1503.02060
Gravitino LSP	0	mono-jet	Yes	20.3	\tilde{g}	963 GeV	$m(\tilde{g}) > 1.8 \times 10^{-4} \text{ eV}$	1502.01518
\tilde{t} pair								
$\tilde{t}\tilde{t} \rightarrow q\bar{t}q$	0	3 jets	Yes	20.3	\tilde{t}	1.78 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	ATLAS-COMP-2015-067
$\tilde{t}\tilde{t} \rightarrow q\bar{t}q$	$0 < \epsilon, \mu < 1$	3 jets	Yes	20.3	\tilde{t}	1.76 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	\tilde{t} -appear
$\tilde{t}\tilde{t} \rightarrow q\bar{t}q$	$0 < \epsilon, \mu < 1$	3 jets	Yes	20.3	\tilde{t}	1.37 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	1407.0650
\tilde{t} pair, squarks, dijet production								
$\tilde{t}_1\tilde{t}_1 \rightarrow q\bar{t}q$	0	2 jets	Yes	4.2	\tilde{t}_1	840 GeV	$m(\tilde{t}_1) > m(\tilde{g}) + m(\tilde{u}_L)$	ATLAS-COMP-2015-066
$\tilde{t}_1\tilde{t}_1 \rightarrow q\bar{t}q$	$2 < \mu, \tau < 2$	0-3 jets	Yes	3.2	\tilde{t}_1	325-940 GeV	$m(\tilde{t}_1) > m(\tilde{g}) + m(\tilde{u}_L)$	1602.00258
$\tilde{t}_1\tilde{t}_1 \rightarrow q\bar{t}q$	$1 < \mu, \tau < 1$	1-2 jets	Yes	4.20013	\tilde{t}_1	217-170 GeV	$m(\tilde{t}_1) > m(\tilde{g}) + m(\tilde{u}_L)$	1508.0118, 1407.02583
$\tilde{t}_1\tilde{t}_1 \rightarrow q\bar{t}q$ or \tilde{t}_1^2	$0 < \epsilon, \mu < 0.2$	mono-jet+2 jets	Yes	20.3	\tilde{t}_1	90-198 GeV	$m(\tilde{t}_1) > m(\tilde{g}) + m(\tilde{u}_L)$	1500.08616, ATLAS-COMP-2016-007
$\tilde{t}_1\tilde{t}_1 \rightarrow q\bar{t}q$ (tag)	0	0, mono-jet+tag	Yes	20.3	\tilde{t}_1	90-245 GeV	$m(\tilde{t}_1) > m(\tilde{g}) + m(\tilde{u}_L)$	1407.06508
$\tilde{t}_1\tilde{t}_1$ (inclusive GMSB)	$2 < \mu, \tau < 1$	1 jet	Yes	20.3	\tilde{t}_1	150-800 GeV	$m(\tilde{t}_1) > m(\tilde{g}) + m(\tilde{u}_L)$	1403.5232
$\tilde{t}_1\tilde{t}_1 \rightarrow q\bar{t}q + 2$	$3 < \mu, \tau < 1$	1 jet	Yes	20.3	\tilde{t}_1	290-610 GeV	$m(\tilde{t}_1) > m(\tilde{g}) + m(\tilde{u}_L)$	1403.5232
$\tilde{t}_1\tilde{t}_1 \rightarrow q\bar{t}q + b$	$1 < \mu, \tau < 1$	0 jets + 2 jets	Yes	20.3	\tilde{t}_1	300-620 GeV	$m(\tilde{t}_1) > m(\tilde{g}) + m(\tilde{u}_L)$	1508.08616
EW direct								
$\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \ell^+$	$2 < \mu, \tau < 2$	0	Yes	20.3	\tilde{L}	90-335 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1403.5294
$\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \nu$	$2 < \mu, \tau < 2$	0	Yes	20.3	\tilde{L}	140-175 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1403.5294
$\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \nu$	0	2	Yes	20.3	\tilde{L}	303 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1407.0350
$\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \nu$	$3 < \mu, \tau < 0$	0	Yes	20.3	\tilde{L}	715 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1402.7029
$\tilde{L}_R \tilde{L}_R \rightarrow W^+ Z$	$2 < \mu, \tau < 1$	0-2 jets	Yes	20.3	\tilde{L}	425 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1403.5294, 1402.7029
$\tilde{L}_R \tilde{L}_R \rightarrow W^+ Z$	$2 < \mu, \tau < 1$	0-2 jets	Yes	20.3	\tilde{L}	270 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1501.01162
$\tilde{L}_R \tilde{L}_R \rightarrow W^+ Z$	$4 < \mu, \tau < 0$	0	Yes	20.3	\tilde{L}	835 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1405.5086
GGM (wino NLSP) weak prod.	$1 < \mu, \tau < \gamma$	-	Yes	20.3	\tilde{L}	115-370 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1507.05463
Long-lived particles								
Direct $\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \ell^+$ prod., long-lived \tilde{L}_R	Disapp. trk	1 jet	Yes	20.3	\tilde{L}	270 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1310.3875
Direct $\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \nu$ prod., long-lived \tilde{L}_R	dE/dx trk	1 jet	Yes	18.4	\tilde{L}	495 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1508.02502
Stable, stopper \tilde{L}_R -hadron	dE/dx trk	0	Yes	27.9	\tilde{L}	850 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1310.6584
Metastable \tilde{L}_R -hadron	dE/dx trk	0	-	3.2	\tilde{L}	1.24 TeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	\tilde{L} -appear
GMSB, stopper \tilde{L}_R -hadron	dE/dx trk	1-2 jets	-	19.1	\tilde{L}	537 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1411.6795
GMSB, $\tilde{L}_R \rightarrow \ell^+ \nu$, long-lived \tilde{L}_R	$\ell^+ \nu$	2 jets	-	20.3	\tilde{L}	440 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1409.0126
$\tilde{g}, \tilde{t} \rightarrow q\bar{t}q$ (tag)	displ. vtx/jet	-	-	20.3	\tilde{t}	1.0 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	1504.05162
GGM $\tilde{g}, \tilde{t} \rightarrow q\bar{t}q$	displ. vtx + jets	-	-	20.3	\tilde{t}	1.0 TeV	$m(\tilde{t}) > m(\tilde{g}) + m(\tilde{u}_L)$	1504.05162
RPV								
LFV $\tilde{g} \rightarrow q\bar{q} + X, \tilde{t}_1 \rightarrow q\bar{q} + \nu\tau/\nu\mu$	$\nu\tau/\nu\mu$	-	-	20.3	\tilde{g}	1.7 TeV	$A_{12} = 0.11, A_{13} = 0.009$	1503.04420
Bilinear RPV CMSSM	$2 < \mu, \tau < 2$	0-3 jets	Yes	20.3	\tilde{t}	1.45 TeV	$A_{12} = 0.11, A_{13} < 0.1$	1404.2550
Direct $\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \ell^+$ prod., long-lived \tilde{L}_R	$4 < \mu, \tau < 0$	0	Yes	20.3	\tilde{L}	760 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1405.5086
$\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \ell^+$	$3 < \mu, \tau < 0$	0	Yes	20.3	\tilde{L}	450 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1405.5086
$\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \nu$	0	0-7 jets	Yes	20.3	\tilde{L}	917 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1502.05696
$\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \nu$	0	0-6 jets	Yes	20.3	\tilde{L}	960 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1502.05696
$\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \nu$	$2 < \mu, \tau < 1$	0-3 jets	Yes	20.3	\tilde{L}	880 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1404.2550
$\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \nu$	0	2 jets + 2 jets	Yes	20.3	\tilde{L}	320 GeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	1601.07463
$\tilde{L}_R \tilde{L}_R \rightarrow \ell^+ \nu$	$2 < \mu, \tau < 2$	0	Yes	20.3	\tilde{L}	6.4-1.0 TeV	$m(\tilde{L}) > m(\tilde{g}) + m(\tilde{u}_L)$	ATLAS-COMP-2015-015
Other								
Scalar charm, $\tau \rightarrow c\bar{c}$	$2 < \epsilon$	2 jets	Yes	20.3	\tilde{c}	510 GeV	$m(\tilde{c}) > m(\tilde{g}) + m(\tilde{u}_L)$	1501.01225

*Only a selection of the available mass limits on new states or phenomena is shown.

10^{-1}

1

Mass scale [TeV]

- Direct searches, assuming specific decay chains
- Simplifying assumptions about susy couplings and masses

End of part V

