Intro to SUSY III: MSSM

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Recap from the second lecture:

- Chiral and anti-chiral superfields

$$\bar{D}_{\dot{\alpha}} S(x, \theta, \bar{\theta}) = 0. \qquad D_\alpha S(x, \theta, \bar{\theta}) = 0$$

$$\Phi(y, \theta) = \phi(y) + \sqrt{2}\theta\psi(y) + \theta^2 F(y)$$

$$= \phi(x) + \sqrt{2}\theta\psi(x) + \theta^2 F(x)$$

$$+ i\theta\sigma^\mu\bar{\theta}\partial_\mu\phi(x) + \frac{i}{\sqrt{2}}\theta^2\partial_\mu\psi(x)\sigma^\mu\bar{\theta} - \frac{1}{4}\theta^2\bar{\theta}^2\partial_\mu\partial^\mu\phi(x)$$

Recap from the second lecture:

- Vector (real) superfield

$$S^{+}(x,\theta,\bar{\theta}) = S(x,\theta,\bar{\theta})$$

- In the Wess-Zumino gauge

$$V_{WZ}(x,\theta,\bar{\theta}) = \theta\sigma^{\mu}\bar{\theta}A_{\mu}(x) + \theta^{2}\bar{\theta}\bar{\lambda} + \bar{\theta}^{2}\theta\lambda + \theta^{2}\bar{\theta}^{2}D(x)$$

- Super-Yang-Mills

$$V \to V^{a}T^{a}$$

Recap from the second lecture:

- Strength tensor superfields

$$W_\alpha = -\frac{1}{4}\bar{D}^2 D_\alpha V,\ \bar{W}_{\dot{\alpha}} = -\frac{1}{4}D^2\bar{D}_{\dot{\alpha}}V$$

- In the Wess-Zumino gauge

$$W_\alpha = \lambda_\alpha + \theta_\alpha D + \frac{i}{2}(\sigma^\mu\bar{\sigma}^\nu\theta)_\alpha F_{\mu\nu} + i\theta^2(\sigma^\mu\partial_\mu\bar{\lambda})_\alpha$$

- SUSY invariant Lagrangians – F and D terms for chiral and vector superfields, respectively.

Nonrenormalisation theorems

M.T. Grisaru, W. Siegel and M. Rocek, ``Improved Methods for Supergraphs,” Nucl. Phys. B159 (1979) 429

$$\mathcal{L} = K\left[\Phi^{+} \mathrm{e}^{gV} \Phi\right]\Big|_{\theta^2 \bar{\theta}^2} + W(\Phi)\big|_{\theta^2} + h.c. + f(\Phi) W^{\alpha} W_{\alpha}\big|_{\theta^2} + h.c.$$

- Kahler potential $K\left[\Phi^{+} \mathrm{e}^{gV} \Phi\right]$ receives corrections order by order in perturbation theory

- Only 1-loop corrections for $f(\Phi)$

- $W(\Phi)$ is not renormalised in the perturbation theory!

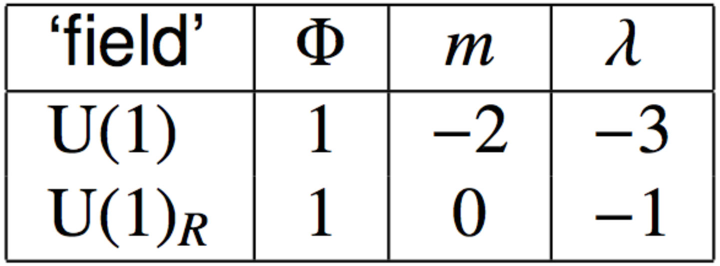
Nonrenormalisation theorems

N. Seiberg, ``Naturalness versus supersymmetric nonrenormalization theorems," Phys. Lett. B318 (1993) 469

- Consider just Wess-Zumino model:

$$W(\Phi) = \frac{m}{2}\Phi^2 + \frac{\lambda}{3}\Phi^3$$

- R-symmetry and U(1) charges:



‘field’	Φ	m	λ
$U(1)$	1	-2	-3
$U(1)_R$	1	0	-1

Nonrenormalisation theorems

N. Seiberg, ``Naturalness versus supersymmetric nonrenormalization theorems,” Phys. Lett. B318 (1993) 469

- Quantum corrected superpotential:

$$W_{eff}(\Phi) = m\Phi^2 f\left(\frac{\lambda\Phi}{m}\right) = \sum_{n\geq 0} c_n \lambda^n m^{1-n} \Phi^{n+2}$$

- Consider $\lambda \to 0 \to n \geq 0$
- Consider $m \to 0 \to n \leq 1$

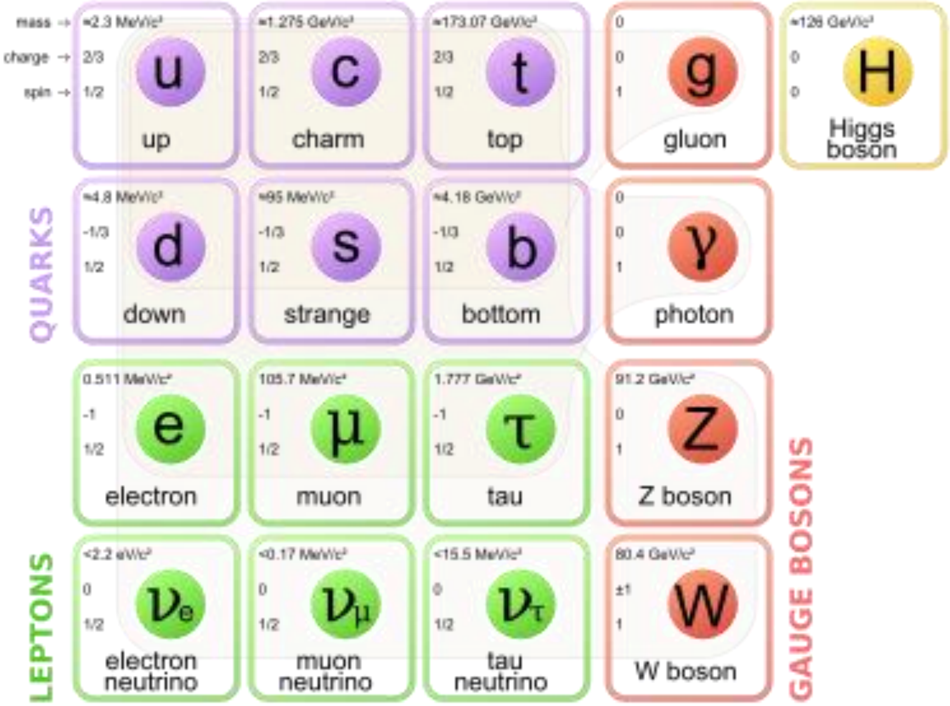
- Hence, $W_{eff}(\Phi) = W(\Phi)$

Outline of part III: MSSM

- Standard Model. Great success and some problems
- Building MSSM
- Soft supersymmetry breaking. Spontaneous supersymmetrty breaking
- Sparticle spectra
- Current data and future prospects

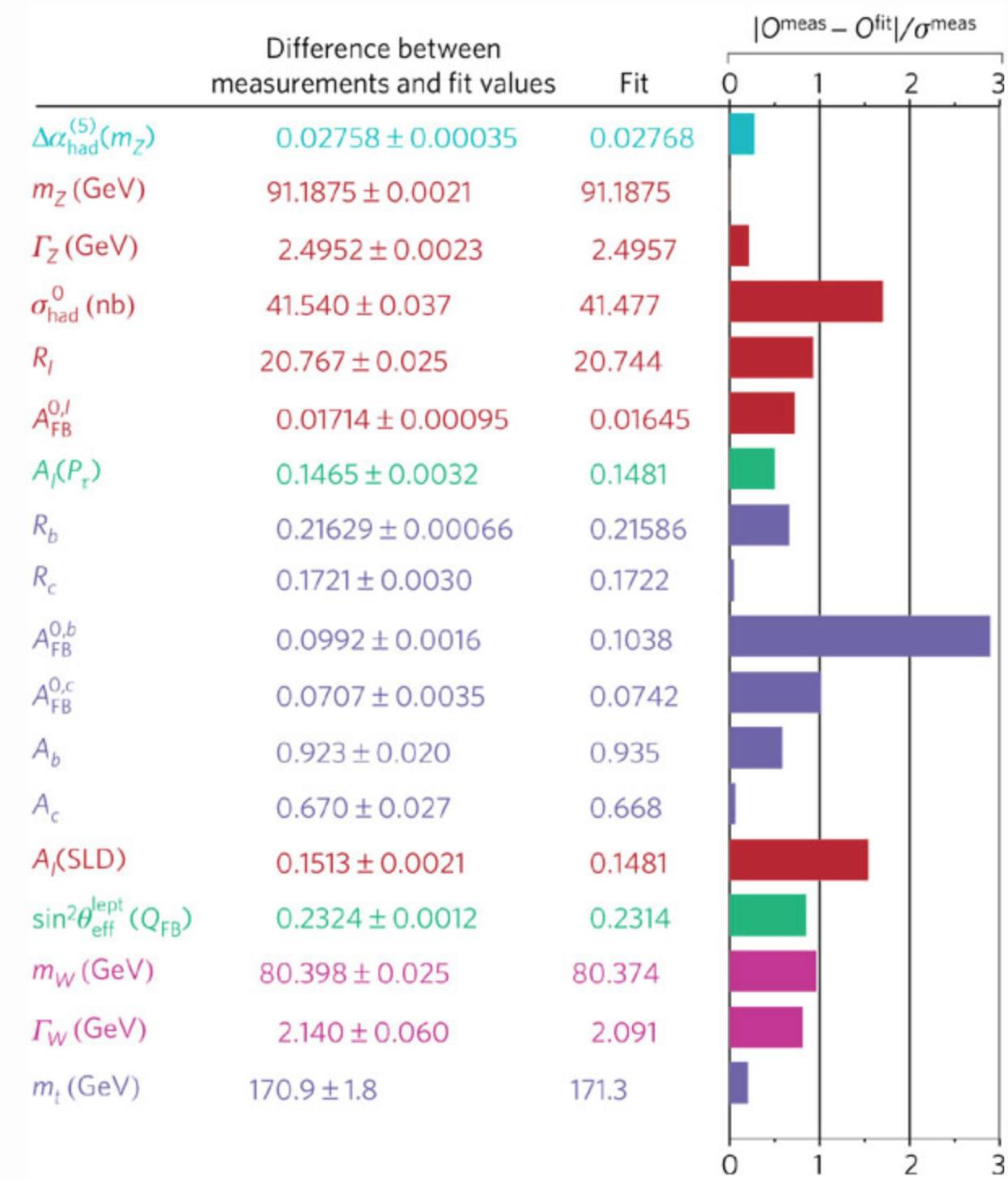
Standard Model

- Standard Model of particle physics is theoretically consistent model of known elementary particles and fundamental interactions which successfully describes (almost) all observed phenomena in particle physics.



Standard Model

The SM has been tested with very high precision (one part in a thousand)



	Difference between measurements and fit values	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z (GeV)	91.1875 ± 0.0021	91.1875
Γ_Z (GeV)	2.4952 ± 0.0023	2.4957
σ_{had}^0 (nb)	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{FB}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{FB}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{FB}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{FB})$	0.2324 ± 0.0012	0.2314
m_W (GeV)	80.398 ± 0.025	80.374
Γ_W (GeV)	2.140 ± 0.060	2.091
m_t (GeV)	170.9 ± 1.8	171.3

Standard Model

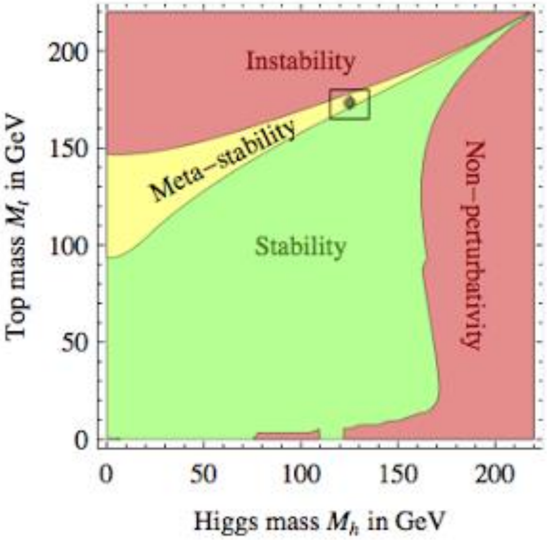
- Theoretical foundation of the Standard Model is the relativistic local quantum field theory (QFT) with local gauge invariance. QFT is the unique theory that consistently merges quantum mechanics and relativity, while local gauge invariance is the only known framework which consistently describes force career spin 1 particles.

- The basic lesson one can draw from the success the Standard Model is that symmetry principle plays a defining role in our understanding of microworld.

Problems of the Standard Model

Empirical evidence for BSM physics:

- SM can’t explain massive neutrinos
- No candidate for dark matter particle
- Current measurements of the Higgs and top quark masses indicate that the Higgs vacuum is unstable



G.Degrassi, et al., “Higgs mass and vacuum stability in the Standard Model at NNLO”, JHEP 1208 (2012) 098

Problems of the Standard Model

Theoretical evidence for BSM physics:

- The very existence of 125 GeV elementary Higgs boson is somewhat puzzling. Scalar masses do receive quantum correction from UV physics, which is proportional to the UV scale:

  $$\delta m_h^2 \sim \Lambda^2$$

  Quadratic sensitivity of the Higgs mass to high energy mass scale is known as the hierarchy problem.

- However, from Part II we know that quadratic divergences cancel out in supersymmetric theories. Thus, supersymmetric extension of the Standard Model provides natural framework for the solution of the hierarchy problem.

Problems of the Standard Model

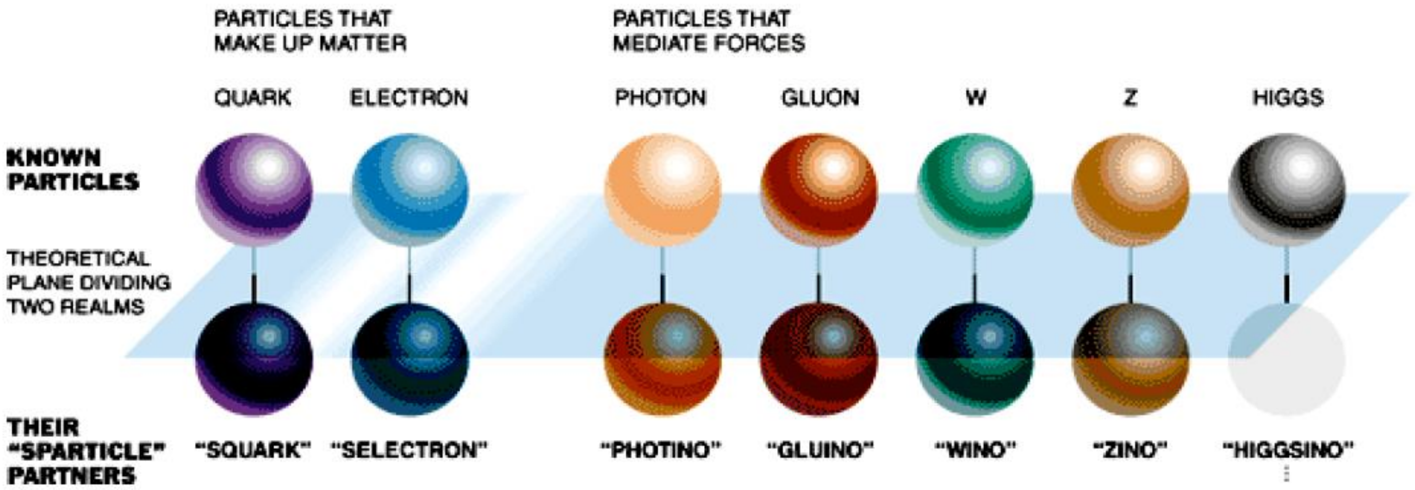
Theoretical evidence for BSM physics:

- Other hierarchies: strong CP problem, CC problem
- Too many free parameters…more symmetries, e.g. GUTs?

Supersymmetry also provides more friendly framework (gauge coupling unification) for GUTs and incorporates dark matter candidate.

Minimal Supersymmetric Standard Model (MSSM)

- Recall from Part I and II that superalgebra implies equal number of bosonic and fermionic degrees of freedom.



- The superalgebra also implies that particle and sparticle are degenerate in mass. We do not observe this. SUSY must be broken symmetry!

MSSM

- Matter fields and their superpartners are residing in chiral superfields:

$$q_L = \begin{pmatrix} \mathrm{u} \\ \mathrm{d} \end{pmatrix}_L \rightarrow Q \sim (3, 2, 1/6)$$

$$l_L = \begin{pmatrix} \nu_e \\ \mathrm{e} \end{pmatrix}_L \rightarrow L \sim (1, 2, -1/2)$$

$$u^c_L \rightarrow U \sim (3^*, 1, -2/3),\ d^c_L \rightarrow D \sim (3^*, 1, 1/3),\ e^c_L \rightarrow E\ (1, 1, 1)$$

MSSM

- SU(3), SU(2) and U(1) gauge fields and their superpartners are residing in vector superfields:

$$V_{SU(3)} \sim (8,1,1),\ V_{SU(2)} \sim (1,3,1),\ V_{U(1)} \sim (1,1,0)$$

MSSM

- The electroweak Higgs doublet can be placed in chiral superfield:

$$H_d \sim (1, 2, -1/2)$$

- However, the above superfield contains also a fermionic partner (Higgsino) with quantum numbers of the lepton doublet. Gauge anomaly cancellation than requires to introduce another Higgs superfield:

$$H_u \sim (1, 2, 1/2)$$

MSSM

- The Lagrangian of the supersymmetric Standard Model:

$$\mathcal{L}_{SUSY\ SM} = \int d\theta^2 d\bar{\theta}^2 \sum_{i=all\ chiral\ superfields} \Phi_i^+ \mathrm{e}^{\sum_a g_a V_a} \Phi_i$$

$$+ \int d\theta^2 \mathrm{Tr}\left(\sum_a \frac{1}{4g_a^2} W_a^\alpha W_{a\alpha}\right) + h.c.$$

$$+ \int d\theta^2\ \mu H_u H_d + \hat{y}_u Q U H_u + \hat{y}_d Q D H_d + \hat{y}_l L E H_d + h.c.$$

- The power of SUSY: no new parameter has been introduced! Moreover, Higgs self-coupling is defined by electroweak gauge couplings!

MSSM

- Higgs potential (neutral components):

$$V = |\mu|^2 \left(|H_u^0|^2 + |H_d^0|^2\right) + \frac{1}{8}(g^2 + g'^2)\left(|H_u^0|^2 - |H_d^0|^2\right)^2$$

- No EWSB without SUSY breaking

$$\langle H_u^0 \rangle = \langle H_d^0 \rangle = 0$$

- Since self-inteaction ~g, we expect a light Higgs,

$$m_h \sim m_Z \sim 100\ \mathrm{GeV}$$

MSSM

- Gauge invariance alone does not forbid lepton and baryon # violating interactions:

$$\hat{\lambda}' LLE + \hat{\lambda}'' LQD + \hat{\lambda}''' UDD \ .$$

- The above terms are forbidden due to R-parity:

$$(-1)^{3(B-L)+2S}$$

Ordinary particles R-even (+), sparticles R-odd (-).

MSSM

- Conservations of R-parity implies:

i. Sparticles produce in pairs;

ii. The lighest supersymmetric particle, the LSP, is stable and may be a dark matter particle (usually neutralino);

iii. Large missing energy signature at colliders.

Soft supersymmetry breaking

- We would like to break supersymmetry without introducing undesired quadratic divergences in scalar masses. There are three types of explicit soft-breaking terms:

i. Mass terms for scalar components of chiral superfields

ii. Mass terms for fermionic component of vector superfields

iii. Trilinear couplings for scalar components of chiral superfields

L. Girardello, M.T. Grisaru, ``Soft Breaking of Supersymmetry,'' Nucl. Phys. B 194 (1982) 65.

Soft supersymmetry breaking

$$
\begin{aligned}
\mathcal{L}_{soft} = -\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B} + c.c.\right) \\
-\tilde{Q}^\dagger m_Q^2\tilde{Q} - \tilde{u}^c m_u^2\tilde{u}^{c\dagger} - \tilde{d}^c m_d^2\tilde{d}^{c\dagger} - \tilde{L}^\dagger\tilde{L} - m_e^2\tilde{e}^c\tilde{e}^{c\dagger} \\
-m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (BH_uH_d + c.c)
\end{aligned}
$$

- Sparticles must be within the reach of LHC, if SUSY is indeed responsible for the solution of the hierarchy problem!

Spontaneous supersymmetry breaking

- Explicit soft SUSY breaking is problematic nevertheless:

i. Introduces ~100 new a priory unknown parameters

ii. Unacceptably large contribution to flavour changing neutral processes (SUSY flavour problem)

iii. Unacceptably large CP-violating effects (SUSY CP problem)

- It is more desirable to have spontaneous SUSY breaking:

i. Fayet-Iliopoulos mechanism – D-term breaking

ii. O' Raifeartaigh mechanism – F-term breaking

Note that upon the spontaneous SUSY breaking, Str $M^2=0$ still holds!

Supersymmetry mediation scenarios

- Standard approach to realistic SUSY breaking:

i. Break SUSY spontaneously in the “hidden sector” at high energy scale

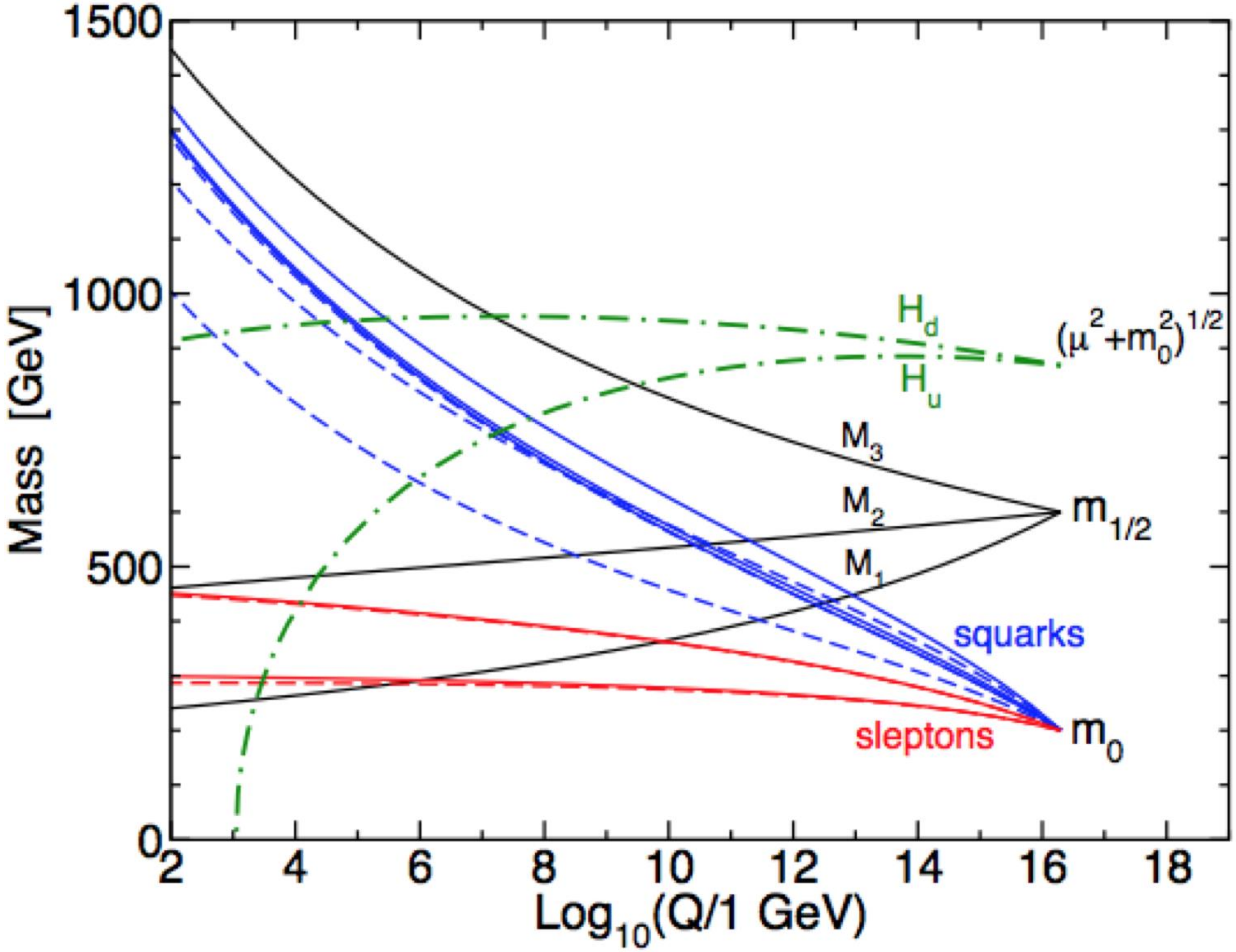
ii. Find the interactions that mediate “hidden sector” breaking to the visible sector

(a) Gravity mediation

(b) Gauge mediation

(c) Anomaly mediation

RG evolution and REWSB



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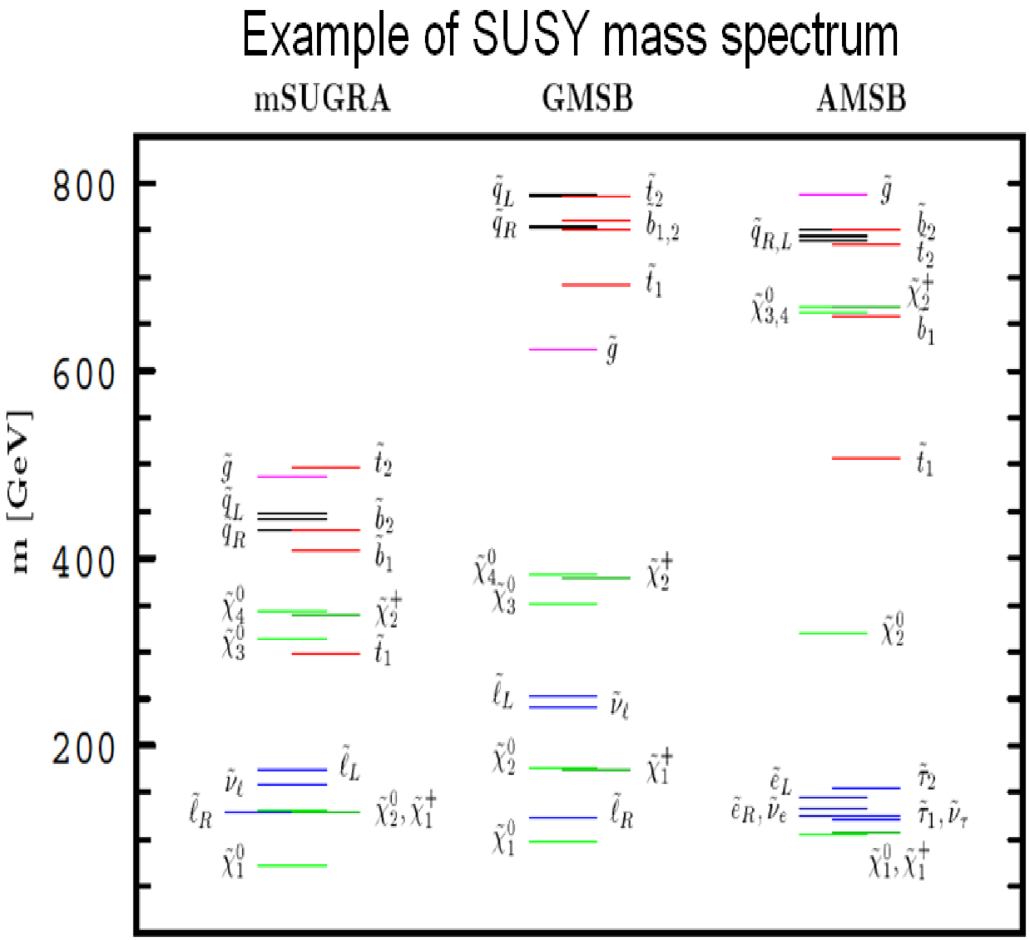
‘Typical’ sparticle spectra

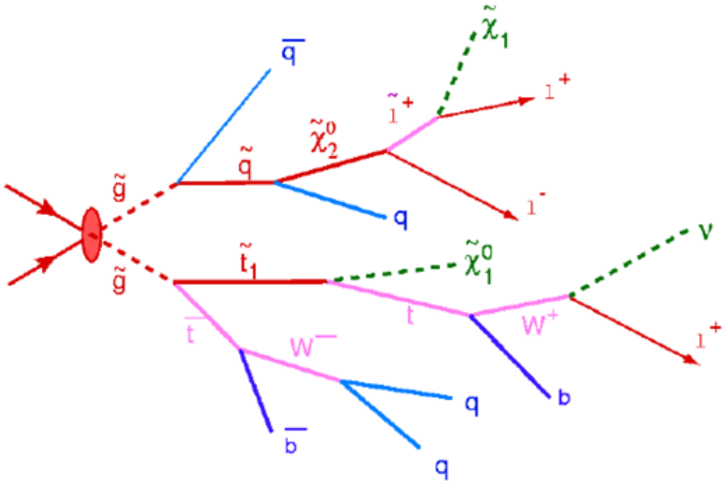
Generic features:

- Coloured particles are heavy
- Uncoloured particles are ligh

Overall SUSY breaking scale is a free parameter



Example of SUSY mass spectrum



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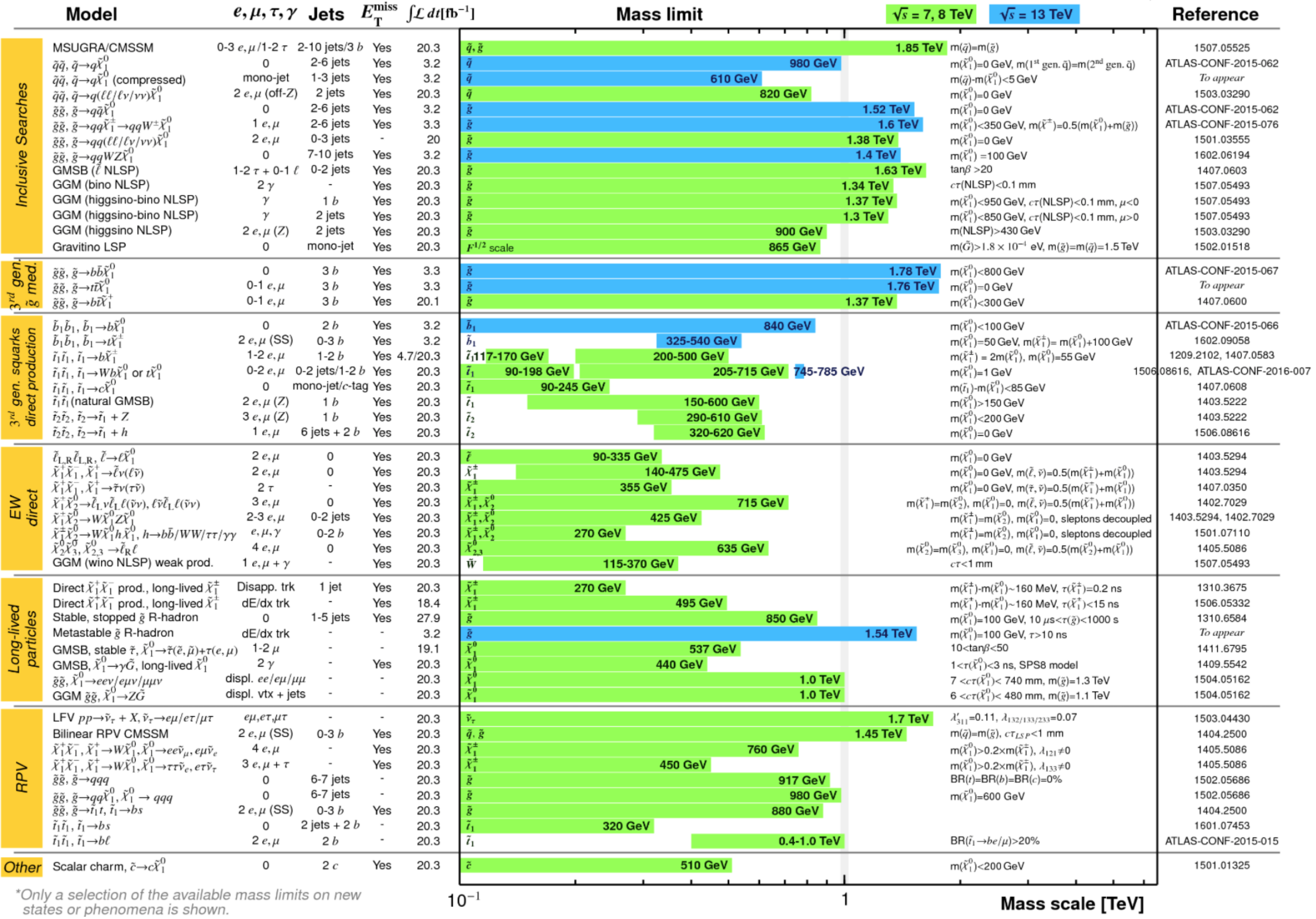
ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

ATLAS Preliminary

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



	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$	🟩 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	3.2	$\tilde{q}$	🟦 980 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2015-062
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$	🟦 610 GeV	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)<5 GeV	*To appear*
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$	🟩 820 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	3.2	$\tilde{g}$	🟦 1.52 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2015-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	1 e,μ	2-6 jets	Yes	3.3	$\tilde{g}$	🟦 1.6 TeV	m($\tilde{\chi}^0_1$)<350 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2015-076
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ	0-3 jets	-	20	$\tilde{g}$	🟩 1.38 TeV	m($\tilde{\chi}^0_1$)=0 GeV	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0	7-10 jets	Yes	3.2	$\tilde{g}$	🟦 1.4 TeV	m($\tilde{\chi}^0_1$) =100 GeV	1602.06194
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	🟩 1.63 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	🟩 1.34 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	🟩 1.37 TeV	m($\tilde{\chi}^0_1$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$	🟩 1.3 TeV	m($\tilde{\chi}^0_1$)<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	🟩 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	🟩 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	3.3	$\tilde{g}$	🟦 1.78 TeV	m($\tilde{\chi}^0_1$)<800 GeV	ATLAS-CONF-2015-067
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	3.3	$\tilde{g}$	🟦 1.76 TeV	m($\tilde{\chi}^0_1$)=0 GeV	*To appear*
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	🟩 1.37 TeV	m($\tilde{\chi}^0_1$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	3.2	$\tilde{b}_1$	🟦 840 GeV	m($\tilde{\chi}^0_1$)<100 GeV	ATLAS-CONF-2015-066
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	0-3 b	Yes	3.2	$\tilde{b}_1$	🟦 325-540 GeV	m($\tilde{\chi}^0_1$)=50 GeV, m($\tilde{\chi}^\pm_1$)= m($\tilde{\chi}^0_1$)+100 GeV	1602.09058
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$	🟩 117-170 GeV 🟩 200-500 GeV	m($\tilde{\chi}^\pm_1$) = 2m($\tilde{\chi}^0_1$), m($\tilde{\chi}^0_1$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$	🟩 90-198 GeV 🟩 205-715 GeV 🟦 745-785 GeV	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, ATLAS-CONF-2016-007
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	🟩 90-245 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	🟩 150-600 GeV	m($\tilde{\chi}^0_1$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	🟩 290-610 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	$\tilde{t}_2$	🟩 320-620 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	🟩 90-335 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1$	🟩 140-475 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}^\pm_1$	🟩 355 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1407.0350
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_\mathrm{L}\nu\tilde{\ell}_\mathrm{L}\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_\mathrm{L}\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	🟩 715 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	🟩 425 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	🟩 270 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, sleptons decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_\mathrm{R}\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}^0_{2,3}$	🟩 635 GeV	m($\tilde{\chi}^0_2$)=m($\tilde{\chi}^0_3$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}^0_2$)+m($\tilde{\chi}^0_1$))	1405.5086
	GGM (wino NLSP) weak prod.	1 $e,\mu+\gamma$	-	Yes	20.3	$\tilde{W}$	🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}^\pm_1$	🟩 270 GeV	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^\pm_1$)=0.2 ns	1310.3675
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}^\pm_1$	🟩 495 GeV	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^\pm_1$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	🟩 850 GeV	m($\tilde{\chi}^0_1$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	🟦 1.54 TeV	m($\tilde{\chi}^0_1$)=100 GeV, τ>10 ns	*To appear*
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}^0_1$	🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$	🟩 440 GeV	1<τ($\tilde{\chi}^0_1$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}^0_1$	🟩 1.0 TeV	7 <$c\tau$($\tilde{\chi}^0_1$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}^0_1$	🟩 1.0 TeV	6 <$c\tau$($\tilde{\chi}^0_1$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$	🟩 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$	🟩 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}^\pm_1$	🟩 760 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^\pm_1$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}^\pm_1$	🟩 450 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^\pm_1$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	🟩 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	🟩 980 GeV	m($\tilde{\chi}^0_1$)=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	🟩 880 GeV		1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$	🟩 320 GeV		1601.07453
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$	🟩 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$	🟩 510 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1501.01325

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

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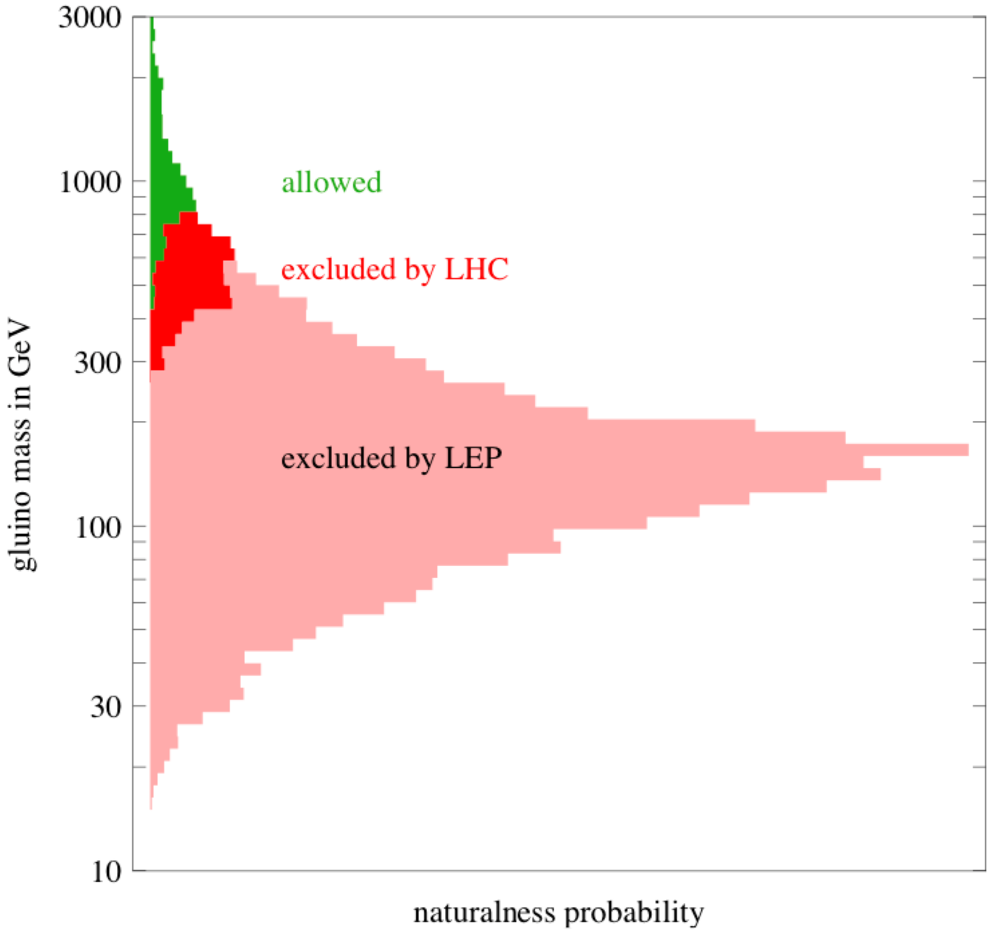
Is fine-tuning back?



A.Strumia JHEP 1104 (2011) 073

Beyond MSSM?

- Tensions: Higgs mass vs naturalness. To bring the tree level Higgs mass up to 125 GeV via radiative corrections we need massive superparticles (stop, gluino), but this results in increased fine-tuning

- Two ways to resolve the tension:

i. Extensions of MSSM with larger tree level Higgs mass – e.g., NMSSM

ii. Extra protection for the Higgs mass, e.g. Higgs as a PGB (e.g., Z. Berezhiani et al., ``Double protection of the Higgs potential in a supersymmetric little Higgs model,'' Phys. Rev. Lett. 96 (2006) 031801)

- Maybe weak scale fine-tuning (little hierarchy) is irrelevant, if an underlying UV theory is natural

Summary

- SUSY is an attractive framework for beyond the Standard Model physics:
- Low energy softly broken SUSY stabilizes the electroweak scale against radiative corrections.
- In SUSY models with R-parity the LSP may play the role of dark matter.
- Low-energy SUSY provides unification of gauge couplings and hence a framework for GUTs.
- No empirical evidence of SUSY so far. The discovery of SUSY (if it there) undoubtedly will be the major breakthrough in fundamental physics.