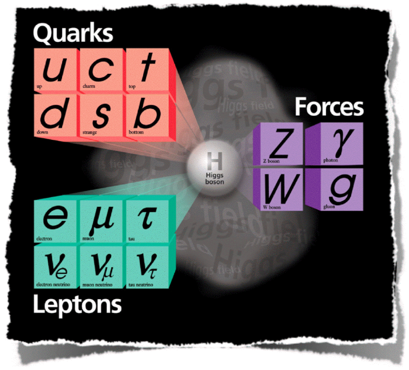
Beyond the Standard Model (or not) after LHC8

G. Ross, Dubna, February 2015

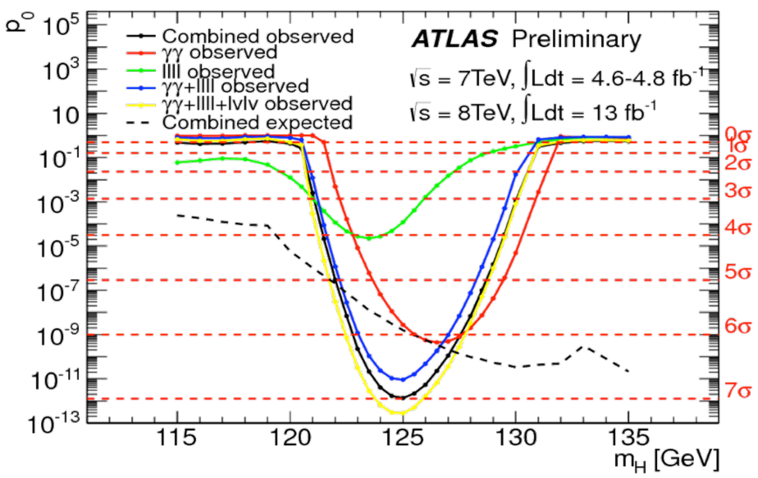
LHC 8

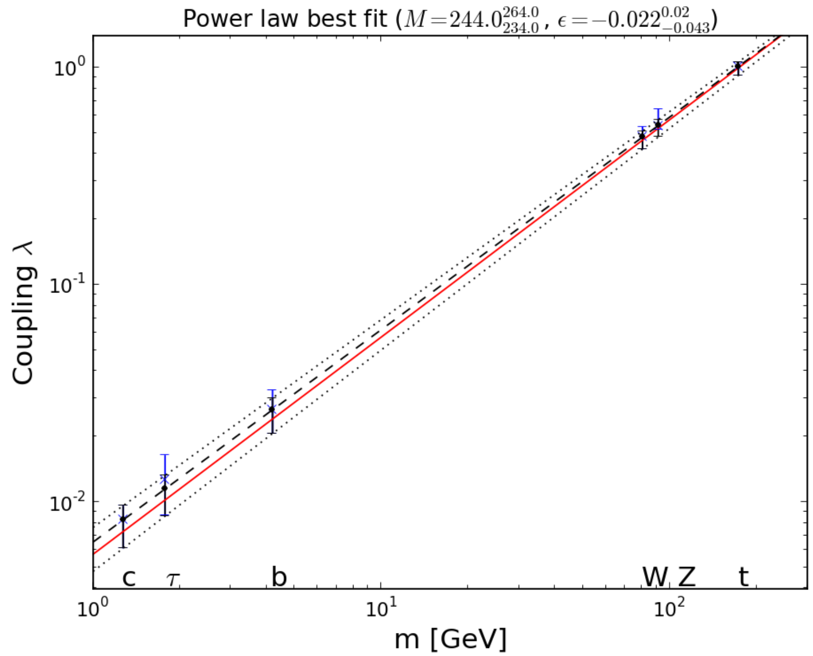
LHC 8



Higgs discovery!

…completes the Standard Model

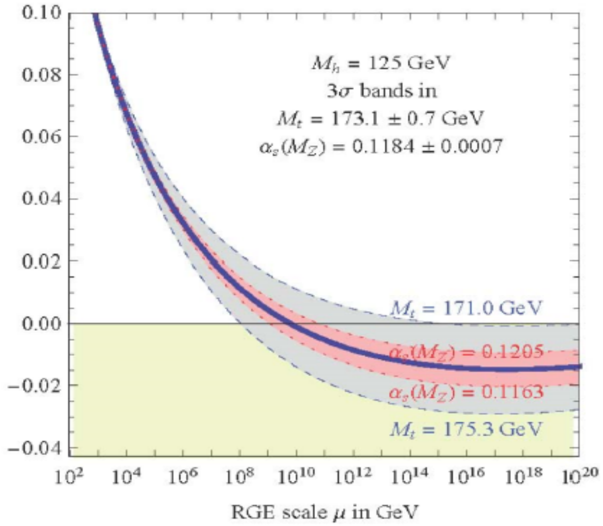




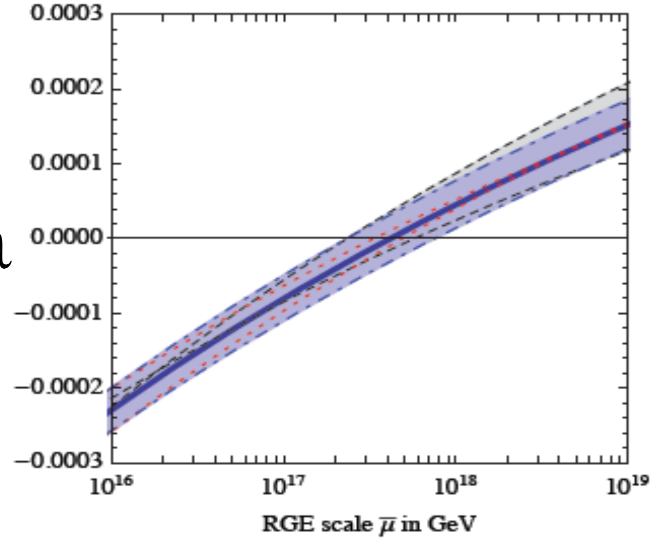
LHC 8

Higgs discovery!

λ



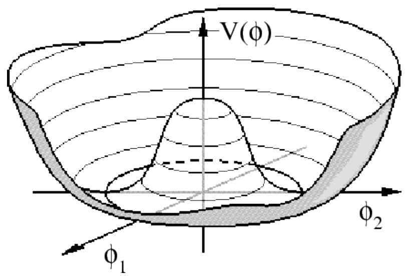
β_λ



DeGrassi et al,...

$$V(H) = -m^2 |\phi|^2 + \lambda |\phi|^4$$

$$m^2 \simeq (89 GeV^2), \lambda \simeq 0.13$$



LHC 8

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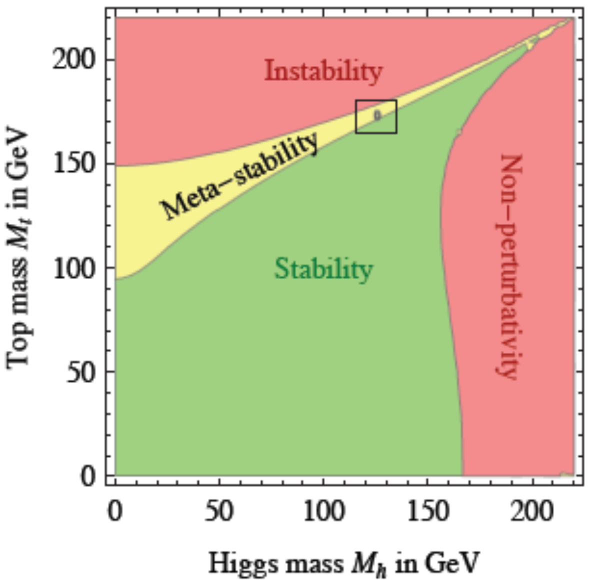

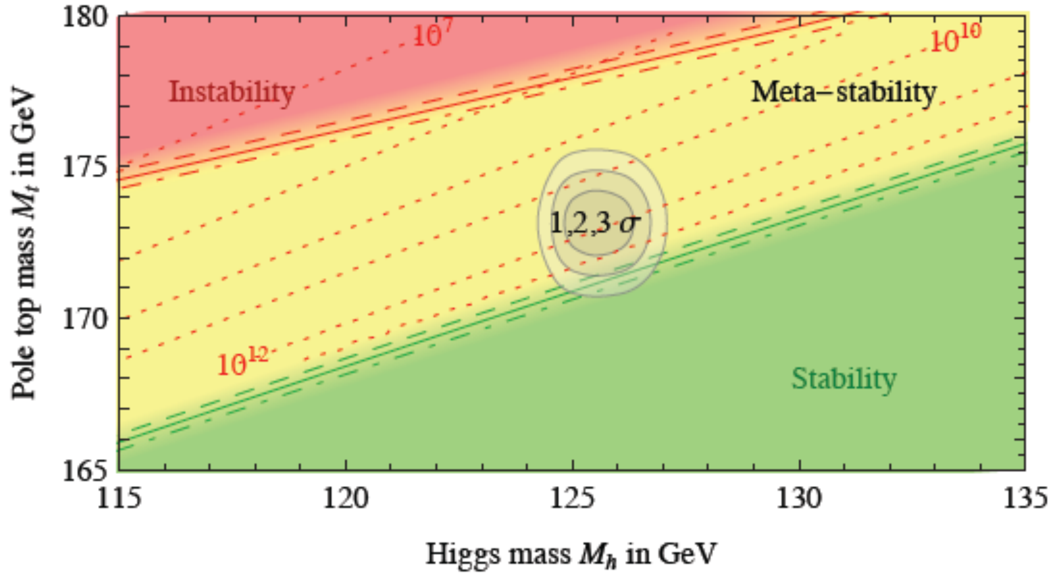

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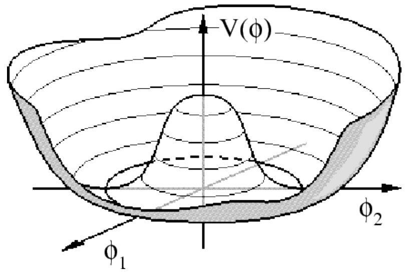
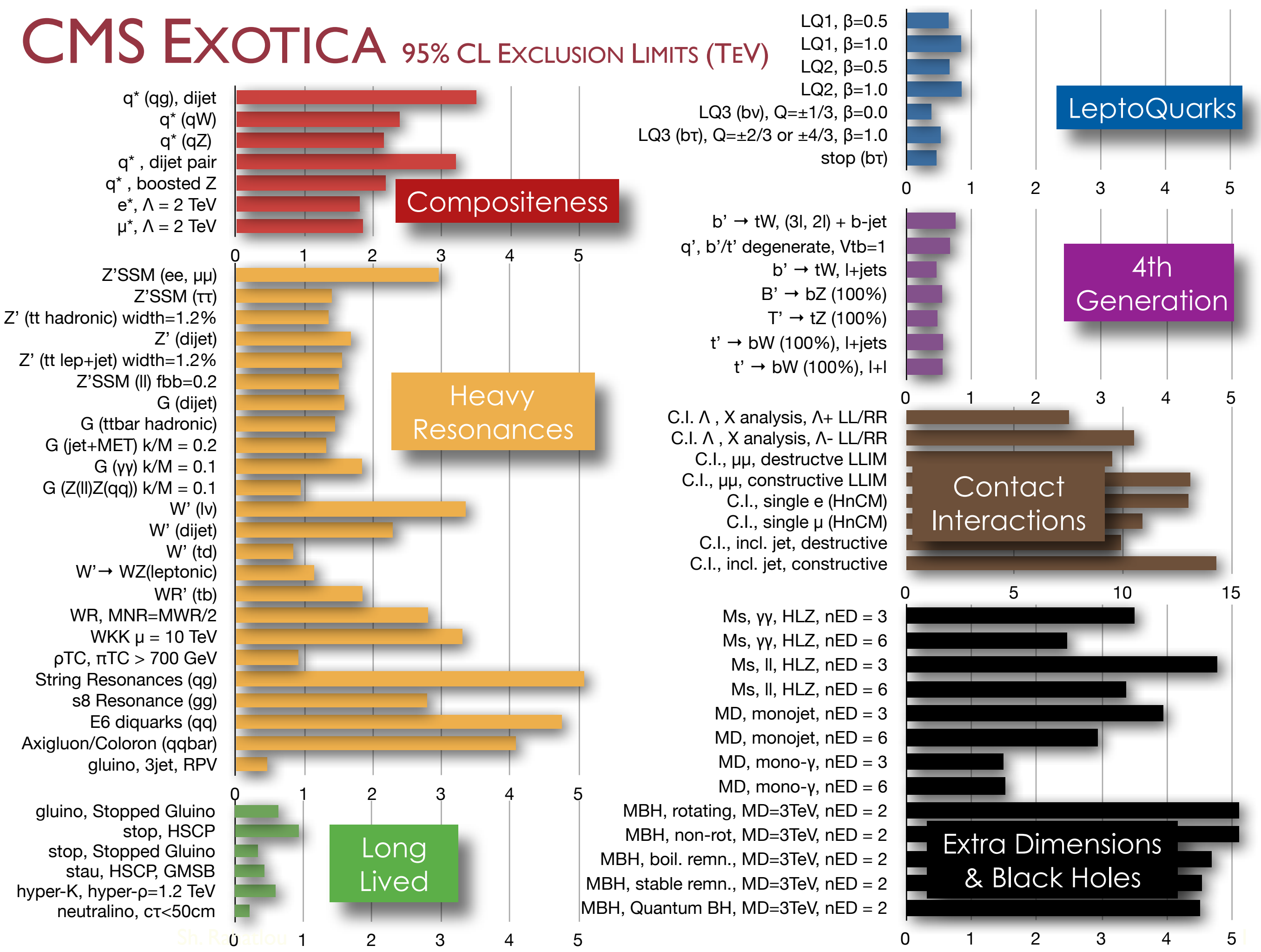


LHC 8

No evidence (yet) for BSM



The discovery of the Higgs scalar has completed the Standard Model and challenged our speculations about physics beyond the Standard Model:

- Full unification of fundamental forces now under pressure
- Could the Standard Model be all there is ?

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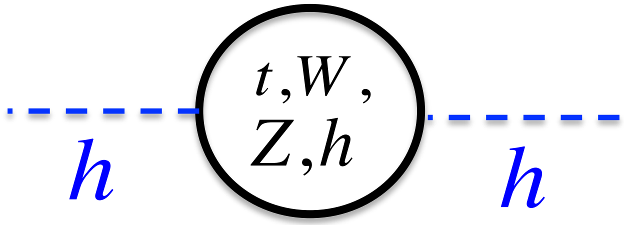
  The hierarchy problem...

The Hierarchy problem



$$\delta m_h^2 |_{SM} = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_h^2\right)\Lambda^2 = \left(\frac{\Lambda}{500GeV}\right)^2 m_h^2$$

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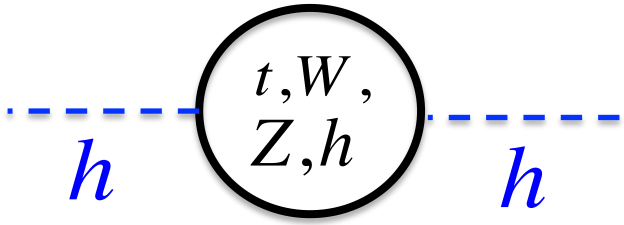

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Field theory: δm^2 not measureable

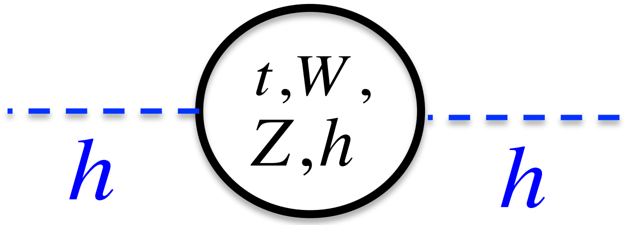
...only $m^2 = m_0^2 + \delta m^2$ "physical"

Only $m^2 = 0$ special

$$\Rightarrow \quad \frac{d\, m_H^2}{d\, \ln \mu} = \frac{3m_H^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3g_2^2}{4} - \frac{3g_1^2}{20}\right)$$

...no hierarchy problem for SM? (Landau pole?)

The Hierarchy problem



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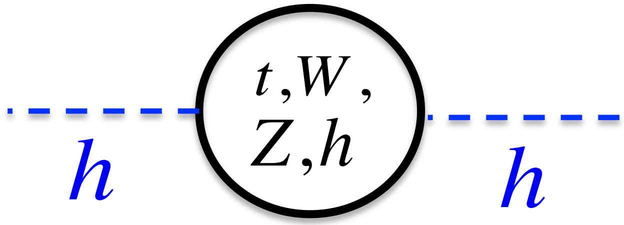
Classical scale invariance (dimensional regularisation)

The Hierarchy problem



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... but is the SM all there is?

Unification of forces and matter?

$$e.g.\quad SO(10) \supset \underset{g_5}{SU(5)} \supset \underset{g_3}{SU(3)} \otimes \underset{g_2}{SU(2)} \otimes \underset{g_1}{U(1)}$$

Georgi Glashow 1974

$(\bar{5})_L$:

$SU(3)$

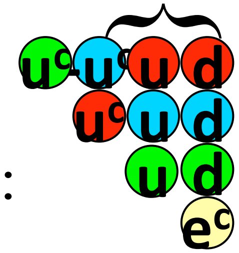
$SU(2)$

$$3Q_? + Q_{e^-} = 0$$

$$Q_{d^c} = 1/3$$

LH states SU(2) doublets

$(10)_L$:



$$(16)_L = (10)_L + (\bar{5})_L + (1)_L$$

$$\nu_{e,L}{}^c \equiv \nu_{e,R}$$

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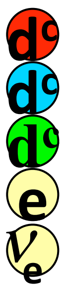

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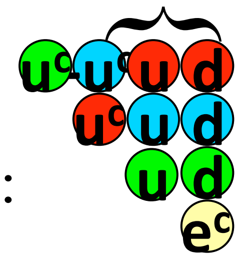

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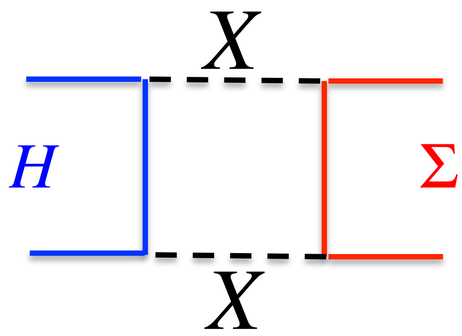
but…

$$\delta m_h^2 \propto M_X^2 \ln\left(\frac{Q^2 + M_X^2}{\Lambda^2}\right)$$

- "the real hierarchy problem"



Llewellyn-Smith, GGR

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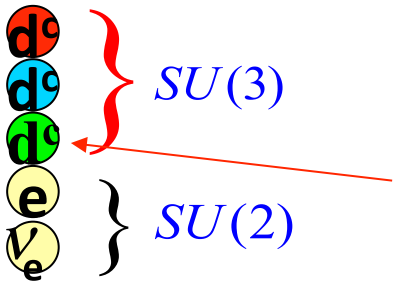

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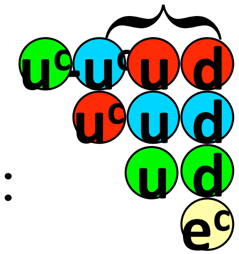
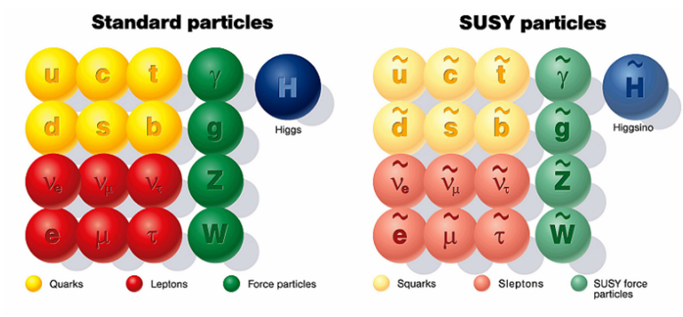
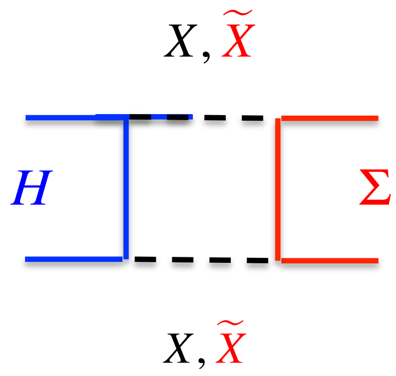


Low scale SUSY

MSSM:





SUSY GUTS: the hierarchy problem

$$\delta m^2 \propto M_{SUSY}^2$$

Unification of forces and matter?

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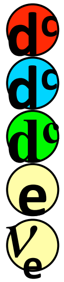

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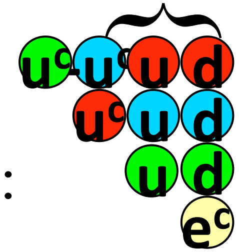

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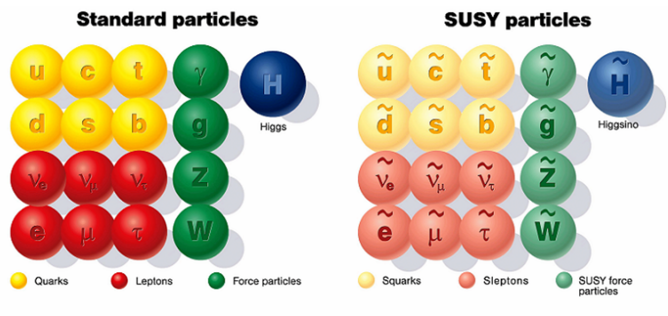

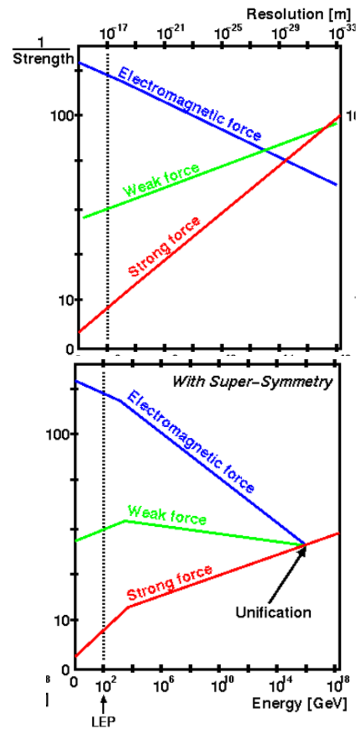

Case studies :

I. "Just" the Standard Model

II. SUSY unification

I "Just" the Standard Model

Classical scale invariance, $m_h = 0$ … origin of EW breaking?

II "Just" the Standard Model

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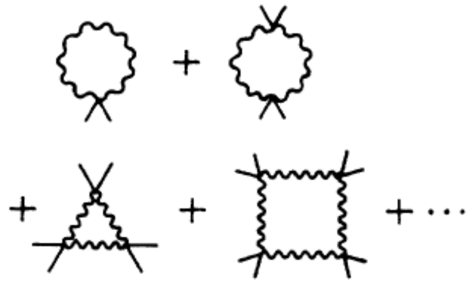
Coleman-Weinberg – dynamical symmetry breaking :

e.g. scalar elactrodynamics

$$V = \left\{ \frac{\lambda}{4!}\phi^4 + \frac{3e^4}{64\pi^2}\phi^4 \ln\frac{\phi^2}{M^2} \right\}$$

$$= \frac{3e^4}{64\pi^2}\phi^4 \left(\ln\frac{\phi^2}{\langle\phi\rangle^2} - \frac{1}{2} \right)$$



$$m_\phi^2 = \frac{3e_\phi^2}{8\pi^2}\langle\phi\rangle^2 \ll m_W^2$$

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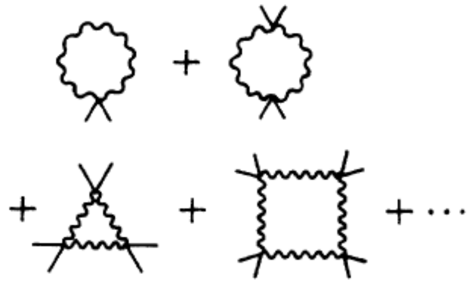

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"real" hierarchy problem

..... many models with new Higgs interactions + no heavy states

No heavy thresholds? (real hierarchy problem)

- Neutrino masses?
- Strong CP problem?
- Baryogenesis?
- Gravity/Inflation?

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- Neutrino masses?
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Neutrino masses:

Add singlet neutrinos ν_{Ra}

$$L_{mass} = h_a \bar{l}_a \nu_{Ra} H + \frac{M_{ab}}{2} \nu_{Ra}^T C \nu_{Rb}$$

$$e.g. \quad h_A^2 = 5.10^{-14}, h_B^2 = 5.10^{-15}, M_a = 20GeV$$

$$m_A \simeq 0.1 eV, \quad m_B \simeq 0.01\, eV$$

Ultra-weak:
Natural due to chiral symmetry

- Strong CP problem: $$\frac{\theta}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}, \quad \theta \leq 10^{-10} ??$$

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Make θ a dynamical variable the axion, a….θ=0 at minimum of its potential

… complex scalar field, S

$$S = (|S| + f_a) e^{i\frac{a}{f_a}}, \quad 10^{10} GeV \le f_a \le 10^{12} GeV ??$$

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DFSZ axion: 2 Higgs doublets $H_{1,2}$, complex singlet, S

$$\begin{aligned} V(H_1, H_2) &= \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 \\ &+ \lambda_4|H_1^\dagger H_2|^2 + \zeta_1|S|^2|H_1|^2 + \zeta_2|S|^2|H_2|^2 \\ &+ \zeta_3 S^2 H_1 H_2 + h.c. \end{aligned}$$

Ultra weak sector: $\zeta_{1,2,3} \le 10^{-20}\left(\frac{10^{12}\,GeV}{f_a}\right)^2$

Ultra weak sector:

ζ_i multiplicatively renormalised

(Underlying shift symmetry $S \rightarrow S + \delta$)

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(Underlying shift symmetry $S \to S + \delta$)

Origin of large vev?

Start with $m = m_0 + \delta m = 0$ (Classical scale invariance)

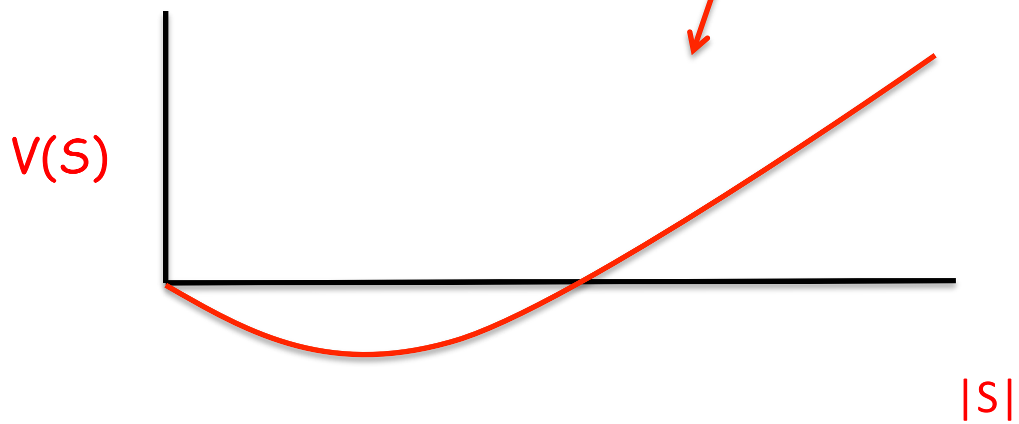
Dimensional transmutation (Coleman Weinberg)

Coleman Weinberg in DFSZ model

$\zeta_2 S^2 |H_2|^2$

$$V_{DFSZ}(H_1, H_2, S) \simeq \frac{\lambda_1}{2}\left(|H_1|^2 + \frac{\zeta_1}{\lambda_1}|S|^2\right)^2 + \frac{1}{64\pi^2}\left(\zeta_2 |S|^2\right)^2\left(-\frac{1}{2} + \ln\frac{|S|^2}{f_a^2}\right)$$

$$+\frac{\lambda_2}{2}|H_2|^4 + \zeta_3 S^2 H_1 H_2 + h.c.$$



$\langle H_1^2 \rangle = -\frac{\zeta_1}{\lambda_1}\langle S^2 \rangle$ triggers EW breaking

Coleman Weinberg in DFSZ model

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$$+\frac{\lambda_2}{2}|H_2|^4 + \zeta_3 S^2 H_1 H_2 + h.c. \quad (\zeta_2 > \zeta_1 > \zeta_3 \text{ assumed})$$

$$v_S = f_a, \quad v_{H_1} = \frac{\zeta_1}{\lambda_1} f_a, \quad v_{H_2} = \frac{\zeta_3}{2\zeta_2} v_{H_1}$$

$$m^2_{H_2^0} = m^2_{H^\pm} = m^2_X = -\frac{\zeta_2}{2\zeta_1} m_h^2$$

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$$m^2_{H_2^0} = m^2_{H^\pm} = m_X^2 = -\frac{\zeta_2}{2\zeta_1} m_h^2$$

$$m^2_{|S|} = -\left(\frac{\zeta_2^2}{32\pi^2\zeta_1}\right)^2 m_h^2 \simeq 13\left(\frac{10^{12}\,GeV}{\mathrm{v}_S}\right)^2\left(\frac{m_{H_2}}{m_h}\right)^4 eV^2$$

$|S|$ Pseudo-dilaton

K. Allison, C.Hill, GGR

Phenomenology

Collider signals

Ultra weak couplings … just 2HD model with nearly degenerate heavy Higgs

Direct (axion-like) searches for pseudo-dilaton?

Cosmology

If inflation scale below PQ phase transition $\Delta_I < 10^5 \left(\frac{10^{12} GeV}{f_a} \right)^{1/2} \left(\frac{m_{H_2}}{m_h} \right) GeV$

…. no cosmological constraints

If inflation scale above PQ phase transition

…. potential Polonyi problem:

Coughlan et al

$$V(S_I) \sim + \frac{1}{64\pi^2} \left(\zeta_2 |S_I|^2 \right)^2 \left(-\frac{1}{2} + \ln \frac{|S_I|^2}{f_a^2} \right)$$

(stored energy after inflation)

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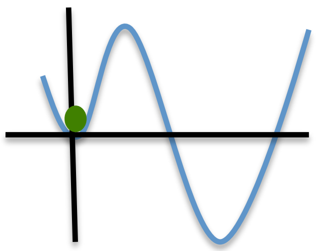
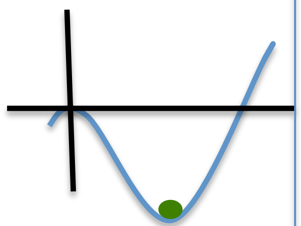
$$m^2_{s,thermal} \simeq \frac{\varsigma_2}{6}T^2$$

$$\rho_S \propto T^4$$

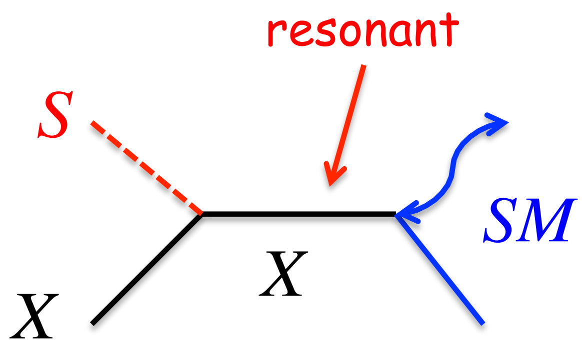


$$T \sim \Lambda_{QCD},\ m_{s,thermal} = 0$$

$$\rho_s \propto T^3$$



$$S + X \rightleftarrows SM$$



$$\rho_s \to 0, \quad \Omega_a\,?$$

- Baryogenesis - via neutrino oscillation

Akhmedov, Rubakov, Smirnov

$$L_{mass} = h_a \bar{l}_a \nu_{Ra} H + \frac{M_{ab}}{2} \nu_{Ra}^T C \nu_{Rb}$$

- ν_{Ra} produced via Yukawa interactions $\quad L_A = L_B = L_C = 0$
- ν_{Ra} oscillate $\quad \not{C}\not{P}, \quad L_{A,B,C} \neq 0, \quad L_A + L_B + L_C = 0$
- $\nu_{R\,A,B}$ in thermal equilibrium by t_{EW} when sphalerons inoperative
- $\Delta_{L\,AB} = L_A + L_B \xrightarrow[Sphalerons]{} \Delta B = \Delta_{L\,AB}/2$ ✔

ARS demonstrate mechanism viable over range of parameters -

but ν_R not dark matter – need axion as dark matter

- Gravity/Inflation

Scale invariance — Spontaneous symmetry breaking $\Longrightarrow M_P$

Hierarchy problem? — $\delta m_h^2 \sim \frac{1}{(2\pi)^4} G_N M_P^2 \rightarrow 0$ (Dimensional regularisation)

Inflation — Chaotic - $L \supset \lambda(s)s^4, \xi_S s^2 R$

- ## Gravity/Inflation

Scale invariance — Spontaneous symmetry breaking $\Longrightarrow M_P$

Hierarchy problem? — $\delta m_h^2 \sim \frac{1}{(2\pi)^4} G_N M_P^2 \to 0$ (Dimensional regularisation)

Inflation — Chaotic - $L \supset \lambda(s)s^4, \xi_S s^2 R$

Jordan frame

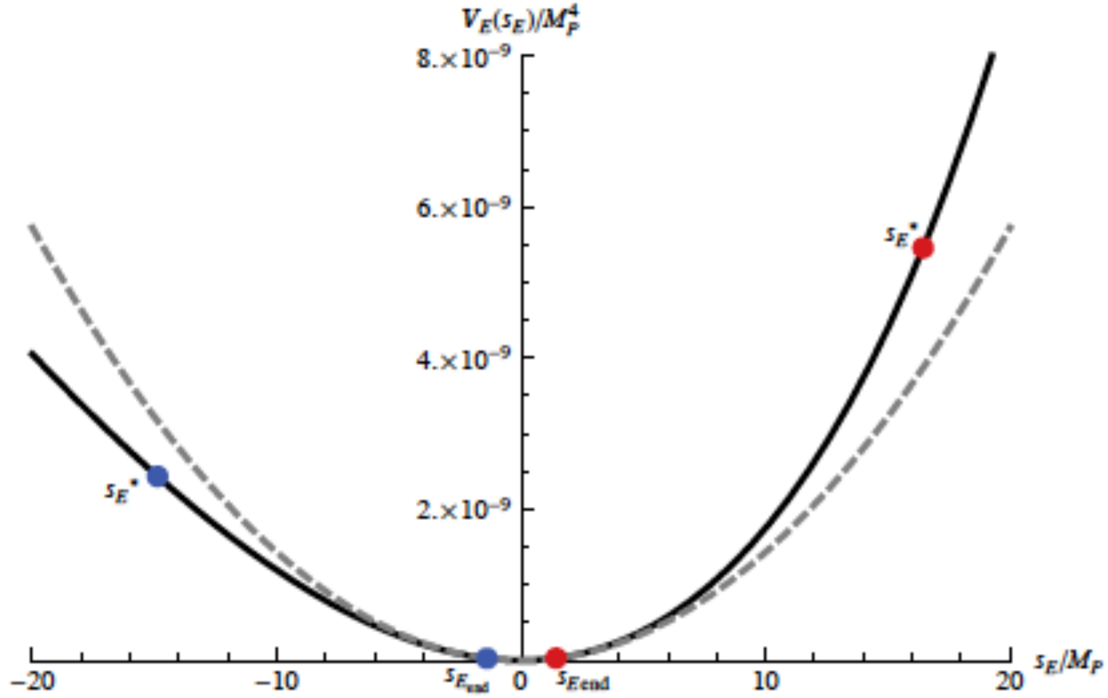
$$\sqrt{-g^J} L^J = -\frac{\xi_S}{2} s^2 R + \frac{(\partial s)^2}{2} + \lambda(s) s^4$$

$$g^E_{\mu\nu} = \Omega(s)^2 g_{\mu\nu}, \quad \Omega(s)^2 = \frac{\xi_s s^2}{M_P^2} = \frac{s^2}{v_s^2}$$

Einstein frame

$$\sqrt{-g^E} L^E = -\frac{1}{2} M_P^2 R + \frac{(\partial s_E)^2}{2} + \lambda(s_E) M_P^4$$

A simple model



$$\sqrt{-g^E}\mathscr{L}^E = \sqrt{-g^E}\left[\frac{\mathscr{L}_{\rm SM}}{\Omega(s)^4} - \frac{1}{2}\bar{M}_{\rm Pl}^2 R + \frac{(\partial s_E)^2}{2} + \frac{(\partial \sigma_E)^2}{2} + \frac{i}{2}\bar{\psi}_E^c \not{D}\psi_E + \mathscr{L}_{Y_E} - V_E\right.$$

$$\mathscr{L}_{Y_E} = \frac{1}{2}y_S v_s \bar{\psi}_E^c\psi_E + \frac{1}{2}y_\sigma \sigma_E \bar{\psi}_E^c\psi_E \equiv \frac{1}{2}m_\psi \bar{\psi}_E^c\psi_E + \frac{1}{2}y_\sigma \sigma_E \bar{\psi}_E^c\psi_E,$$

$$V_E = \frac{1}{4}\lambda_S v_s^4 + \frac{1}{4}\lambda_{S\sigma} v_s^2 \sigma_E^2 + \frac{1}{4}\lambda_\sigma \sigma_E^4 \equiv \Lambda + \frac{1}{2}m_\sigma^2 \sigma_E^2 + \frac{1}{4}\lambda_\sigma \sigma_E^4,$$

Kannike et al 1502.01334

Summary - I

- "JSM" requires ultra-weak sectors – chiral and shift symmetries

- DFSZ axion + dimensional trasmutation $\Rightarrow f_a$

  ...consistent with classical scale invariance (not KSVZ model)

- Requires two Higgs doublets (type II couplings), light pseudo-dilaton

  $$m^2_{H_2^0} = m^2_{H^\pm} = m^2_X = R^2 m^2_h \qquad m_{|S|} \simeq 0.9\left(\frac{10^{12}\,GeV}{f_a}\right) R^2 eV$$

  h ≈ SM Higgs

- SSB generates M_P and Coleman Weinberg generates hierarchy

  and inflation

Summary - I

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- Requires two Higgs doublets (type II couplings), light pseudo-dilaton

$$m_{H_2^0}^2 = m_{H^\pm}^2 = m_X^2 = R^2 m_h^2 \qquad m_{|S|} \simeq 0.9 \left(\frac{10^{12} GeV}{f_a} \right) R^2 eV$$

  h ≈ SM Higgs

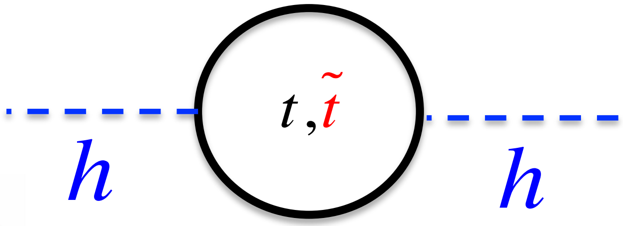
- But...

  (i) No unification of forces and matter.

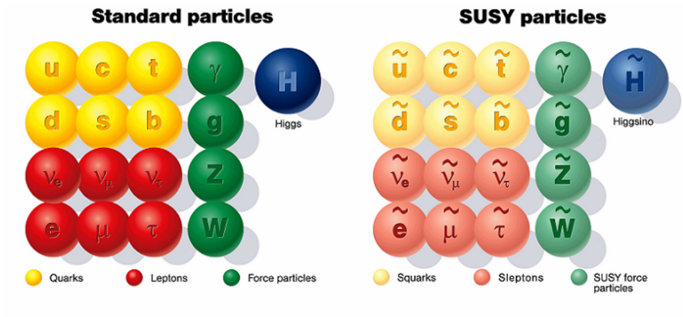
  (II) In Wilsonian sense quadratically divergent terms seem physical

II. SUSY Unification

Low scale SUSY



MSSM:



$$m_h^2 = M_Z^2 + \frac{3m_t^2 h_t^2}{4\pi^2}\left(\ln\left(m_{stop}^2 / m_t^2\right) + \delta_t\right) + \ldots \simeq 126\,GeV$$

$$\delta m_{H_u}^2 \simeq -\frac{3y_t^2}{4\pi^2}\left(m_{stop}^2 + \frac{g_s^2}{3\pi^2} m_{gluino}^2 \log\left(\frac{\Lambda}{m_{gluino}}\right)\right)\log\left(\frac{\Lambda}{m_{stop}}\right)$$

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

ATLAS Preliminary

$\int \mathcal{L}\,dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7,\ 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Data		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
Inclusive Searches	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	$\sqrt{s}$ = 8 TeV full data	any $m(\tilde{q})$	ATLAS-CONF-2013-062
Inclusive Searches	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$\sqrt{s}$ = 8 TeV full data	any $m(\tilde{q})$	1308.1841
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
Inclusive Searches	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
Inclusive Searches	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
Inclusive Searches	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
Inclusive Searches	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	$\sqrt{s}$ = 7 TeV full data	$\tan\beta$<15	1208.4688
Inclusive Searches	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	$\sqrt{s}$ = 8 TeV full data	$\tan\beta$ >18	ATLAS-CONF-2013-026
Inclusive Searches	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.28 TeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
Inclusive Searches	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	$\sqrt{s}$ = 7 TeV full data	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
Inclusive Searches	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	$\sqrt{s}$ = 7 TeV full data	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
Inclusive Searches	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	$\sqrt{s}$ = 8 TeV partial data	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
Inclusive Searches	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	$\sqrt{s}$ = 8 TeV partial data	$m(\tilde{G})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^\pm)$=2 $m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
3rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	$\sqrt{s}$ = 7 TeV full data	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
3rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-210 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	1403.4853
3rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	215-530 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853
3rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
3rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
3rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
3rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
3rd gen. squarks direct production	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
3rd gen. squarks direct production	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
EW direct	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$	140-465 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1403.5294
EW direct	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	180-330 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	700 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	1402.7029
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	420 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^0$	285 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^\pm$	270 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
Long-lived particles	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
Long-lived particles	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	$\sqrt{s}$ = 8 TeV partial data	10<$\tan\beta$<50	ATLAS-CONF-2013-058
Long-lived particles	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	$\sqrt{s}$ = 7 TeV full data	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
Long-lived particles	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	$\sqrt{s}$ = 8 TeV full data	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	$\sqrt{s}$ = 7 TeV full data	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	$\sqrt{s}$ = 7 TeV full data	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
RPV	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q},\tilde{g}$	1.2 TeV	$\sqrt{s}$ = 7 TeV full data	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
RPV	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
RPV	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	$\sqrt{s}$ = 8 TeV full data	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
RPV	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	$\sqrt{s}$ = 8 TeV full data	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
RPV	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV	$\sqrt{s}$ = 8 TeV full data		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	$\sqrt{s}$ = 7 TeV full data	incl. limit from 1110.2693	1210.4826
Other	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV	$\sqrt{s}$ = 8 TeV partial data		ATLAS-CONF-2013-051
Other	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	$\sqrt{s}$ = 8 TeV partial data	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

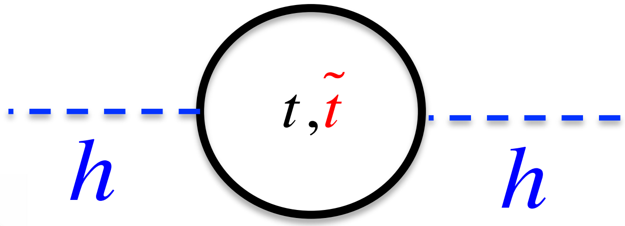
$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

10^{-1} 1 Mass scale [TeV]

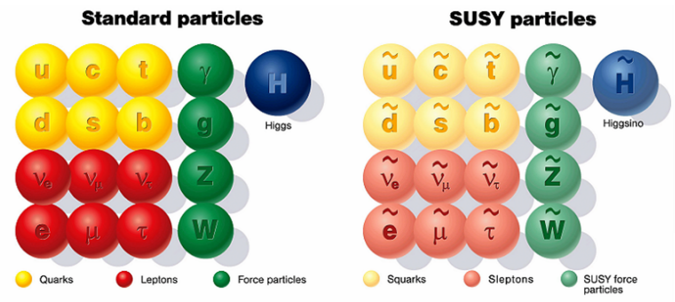
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

II. SUSY Unification

Low scale SUSY



MSSM:



$$m_h^2 = M_Z^2 + \frac{3m_t^2 h_t^2}{4\pi^2}\left(\ln\left(m_{stop}^2 / m_t^2\right)+\delta_t\right)+\ldots \simeq 126\,GeV$$

$$\Lambda \sim M_{GUT}\ ?$$

$$\delta m_{H_u}^2 \simeq -\frac{3y_t^2}{4\pi^2}\left(m_{stop}^2+\frac{g_s^2}{3\pi^2}m_{gluino}^2\log\left(\frac{\Lambda}{m_{gluino}}\right)\right)\log\left(\frac{\Lambda}{m_{stop}}\right)$$

? Little hierarchy problem

LHC8 - SUSY unification under pressure

Little hierarchy problem

e.g. MSSM: 105 +(19) Parameters

$$M_Z^2 = \sum_{\tilde{q},\tilde{l}} a_i \widetilde{m}_i^2 + \sum_{\tilde{g},\widetilde{W},\widetilde{B}} b_i \widetilde{M}_i^{\,2} + \ldots$$

$$m_{\tilde{q}} > 0.6 - 1 TeV \quad \Rightarrow \quad \Delta > a \frac{\widetilde{m}^2}{M_Z^2} \sim 100$$

(Unless light stop $m_{\tilde{t},LHC} > 250\ GeV$)

$\Rightarrow$ Correlations between SUSY breaking parameters and/or additional low-scale states

Little hierarchy problem

e.g. MSSM: 105 +(19) Parameters

$$M_Z^2 = \sum_{\tilde{q},\tilde{l}} a_i \widetilde{m}_i^2 + \sum_{\tilde{g},\widetilde{W},\widetilde{B}} b_i \widetilde{M}_i^2 + \ldots$$

$$m_{\tilde{q}} > 0.6 - 1TeV \quad \Rightarrow \quad \Delta > a\frac{\widetilde{m}^2}{M_Z^2} \sim 100$$

(Unless light stop $m_{\tilde{t},LHC} > 250\ GeV$)

$\Rightarrow$ Correlations between SUSY breaking parameters and/or additional low-scale states

Fine Tuning measure:

$$\Delta(\gamma_i) = \left| \frac{\gamma_i}{M_Z} \frac{\partial M_Z}{\partial \gamma_i} \right|,$$

$$\Delta_m = Max_{\gamma_i} \Delta(\gamma_i), \quad \Delta_q = \left(\sum \Delta_{\gamma_i}^2\right)^{1/2}$$

$$\gamma_i = \widetilde{m}_i, \widetilde{M}_i, \ldots$$

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

Fine tuning from a likelihood fit:

"Nuisance" variable

$$L(\text{data} \mid \gamma_i) \propto \int d\text{v}\, \delta\left(m_Z - m_Z^0\right) \delta\left(\text{v-} \left(-\frac{m^2}{\lambda} \right)^{1/2} \right) L(\text{data} \mid \gamma_i; \text{v})$$

$$= \frac{1}{\Delta_q} \delta\left(n_q (\ln \gamma_i - \ln \gamma_i^S)\right) L(\text{data} \mid \gamma_i; \text{v}_0)$$

Fine tuning not optional!

Ghilencea, GGR
Casas et al

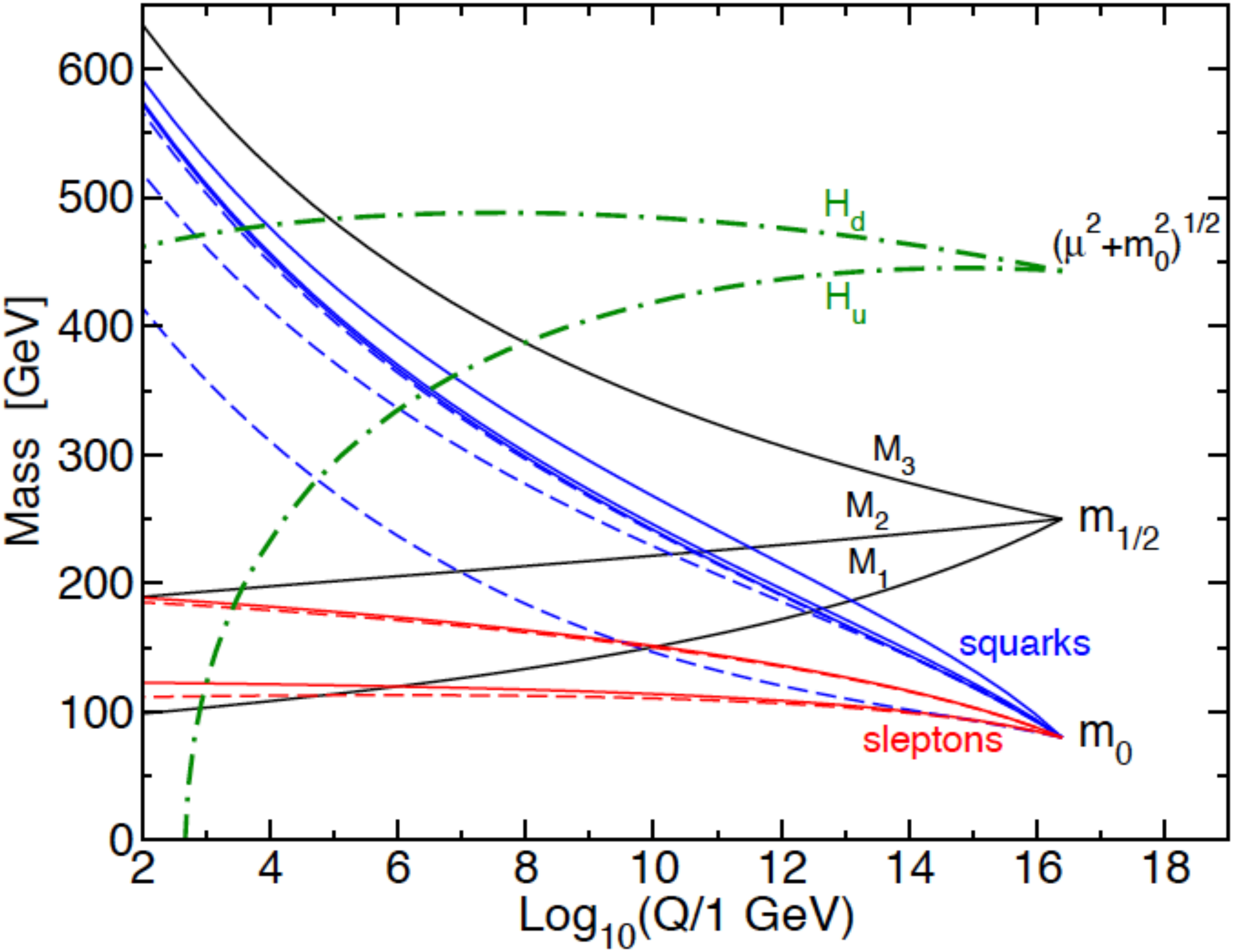
Probabilistic interpretation:

$$\chi^2_{new} = \chi^2_{old} + 2 \ln \Delta_q$$

$$\Delta_q \ll 100$$

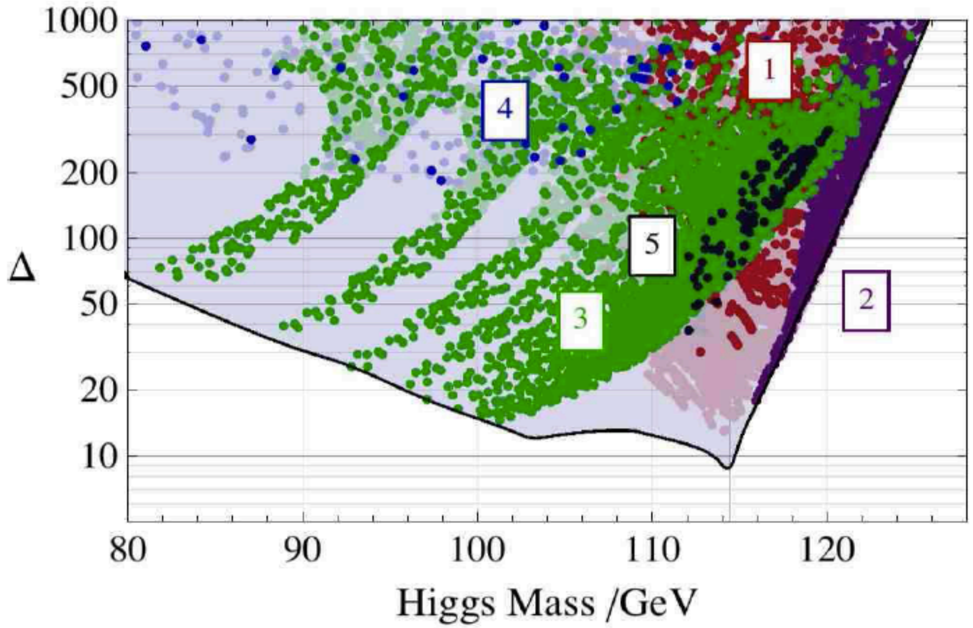
CMSSM:

$\gamma_i = \mu_0, m_0, m_{1/2}, A_0, B_0$



CMSSM: pre Higgs

$$\gamma_i = \mu_0, m_0, m_{1/2}, A_0, B_0$$



Gauge unification required

Relic density restricted

1 h^0 resonant annihilation

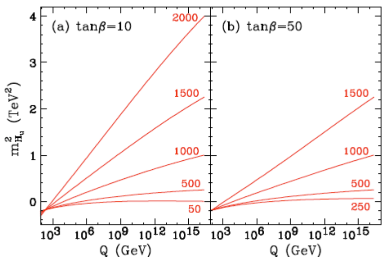
2 $\tilde{h}$ t-channel exchange

3 $\tilde{\tau}$ co-annihilation

4 $\tilde{t}$ co-annihilation

• 5 A^0 / H^0 resonant annihilation

Focus point



$$m_0^2 \qquad \frac{3}{2} m_0^2$$

$$m_{H_u}^2\left(Q^2\right) = m_{H_u}^2\left(M_P^2\right) + \frac{1}{2}\left(m_{H_u}^2\left(M_P^2\right) + m_{Q_3}^2\left(M_P^2\right) + m_{\bar{u}3}^2\left(M_P^2\right)\right)\left[\left(\frac{Q^2}{M_P^2}\right)^{\frac{3y_t^2}{4\pi^2}} - 1\right]$$

$$\simeq -\frac{2}{3}, \; Q^2 \simeq M_Z^2$$

CMSSM: post Higgs

$$\gamma_i = \mu_0, m_0, m_{1/2}, A_0, B_0$$

Gauge unification required

Relic density restricted

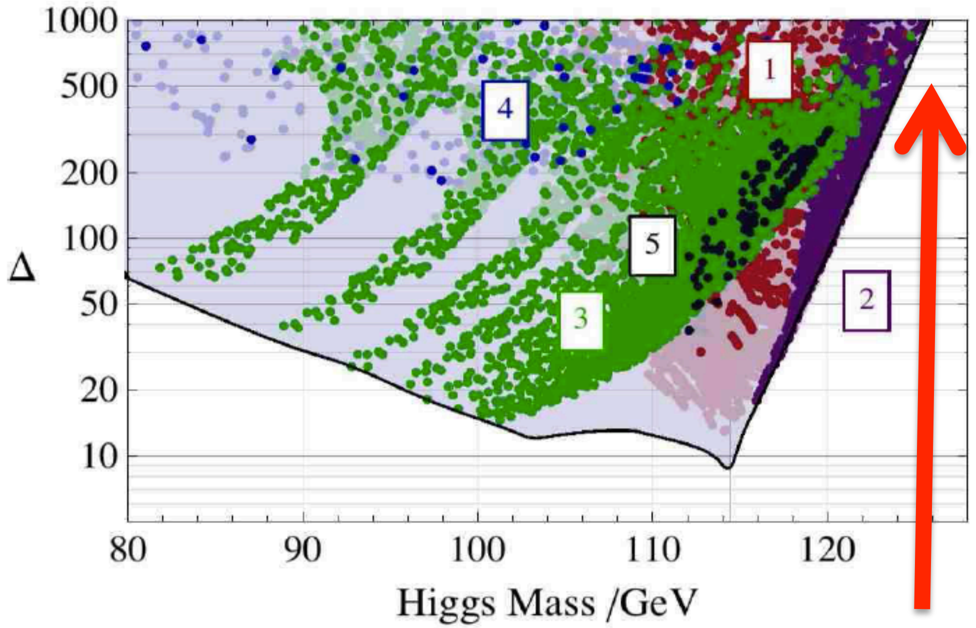
1 h^0 resonant annihilation

2 $\tilde{h}$ t-channel exchange

3 $\tilde{\tau}$ co-annihilation

4 $\tilde{t}$ co-annihilation

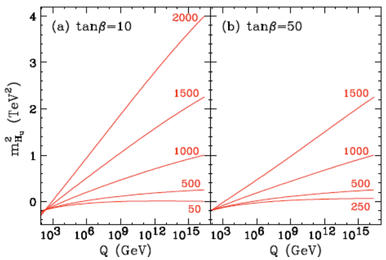
• 5 A^0 / H^0 resonant annihilation



$$\Delta_{Min} > 350, \quad m_h = 125.6 \pm 3GeV$$

Focus point

$$m_{H_u} = m_{\tilde{Q}_3} = m_{\tilde{u}_3}$$



$$m_{H_u}^2\left(Q^2\right) = m_{H_u}^2\left(M_P^2\right) + \frac{1}{2}\left(m_{H_u}^2\left(M_P^2\right) + m_{Q_3}^2\left(M_P^2\right) + m_{u3}^2\left(M_P^2\right)\right)\left[\left(\frac{Q^2}{M_P^2}\right)^{\frac{3y_t^2}{4\pi^2}} - 1\right]$$

$$\simeq -\frac{2}{3}, \; Q^2 \simeq M_Z^2$$

Beyond the CMSSM

- New states and interactions

  (additional contributions to Higgs mass)

Further

- Correlations between SUSY breaking parameters

  ^

New (heavy) states- Singlet extensions

$$W = W_{\text{Yukawa}} + \lambda S H_u H_d + \frac{\kappa}{3} S^3$$ NMSSM

$$\delta V = \lambda^2 |H_u H_d|^2$$

$$W = W_{\text{Yukawa}} + (\mu + \lambda S) H_u H_d + \frac{\mu_S}{2} S^2 + \frac{\kappa}{3} S^3 + \xi S$$ GNMSSM

$$\delta V = \frac{\mu}{\mu_S} \left(|H_u|^2 + |H_d|^2 \right) H_u H_d$$

$$\mu, \mu_s = O(m_{3/2}), \quad Z_{4,8R}$$

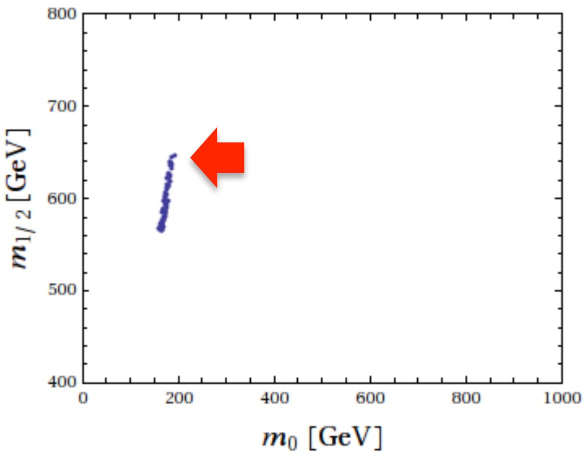
Fine tuning in the CGNMSSM $(\lambda \leq 0.7)$

$$\Delta_{Min} = 60\ (500), \quad m_h = 125.6 \pm 3GeV$$

LHC8 SUSY bounds ✗

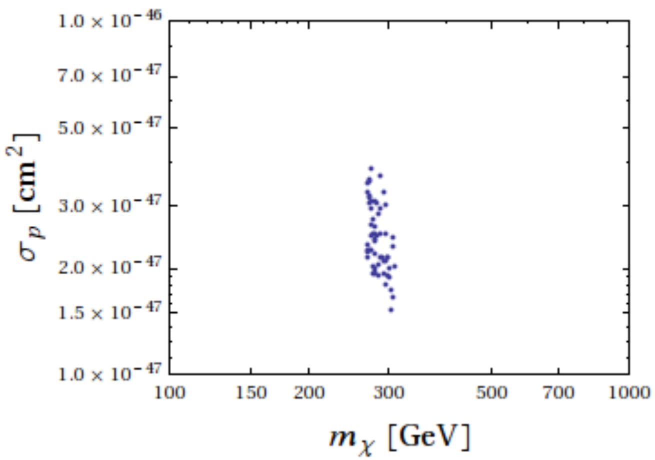
DM relic abundance ✔

DM searches ✔



LSP~Bino

Stau co-annihilation



DM searches insensitive

GGR, Schmidt-Hoberg , Staub

Correlation between SUSY breaking parameters

…non-universal gaugino masses

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3\left(2\,|y_t|^2 \,(m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}3}^2) + 2\,|a_t|^2\right) - 6 g_2^2 \,|M_2|^2 - \frac{6}{5} g_1^2 \,|M_1|^2$$

New focus point: cancellation between M_3 and M_2 contributions if $|M_2|^2 \simeq |M_3|^2$ at M_{SUSY}

Horton, GGR

(Also improves precision of gauge coupling unification)

Shifman, Roszkowski
Krippendorf, Nilles, Ratz, Winkler

Natural ratios? e.g.:

GUT: $SU(5): \quad \Phi^N \subset (24\times 24)_{symm} = 1 + 24 + 75 + 200; \quad SO(10): \quad (45\times 45)_{symm} = 1 + 54 + 210 + 770$

$\eta_3 : 1 : \eta_1$ $\qquad$ $2.7\eta_3 : 1 : 0.5\eta_1$

Representation	$M_3 : M_2 : M_1$ at M_{GUT}	$M_3 : M_2 : M_1$ at M_{EWSB}
1	1:1:1	6:2:1
24	2:(-3):(-1)	12:(-6):(-1)
75	1:3:(-5)	6:6:(-5)
200	1:2:10	6:4:10

Fine tuning in the (C)MSSM

Non-universal gaugino masses ✔

$$\Delta_{Min} = 60\ (500), \quad m_h = 125.6 \pm 3 GeV$$

LHC8 SUSY bounds ✔

DM relic abundance

DM searches ✔

Fine tuning in the (C)GNMSSM

$$\Delta_{Min} = 20, \quad m_h = 125.6 \pm 3 GeV$$

LHC8 SUSY bounds ✔

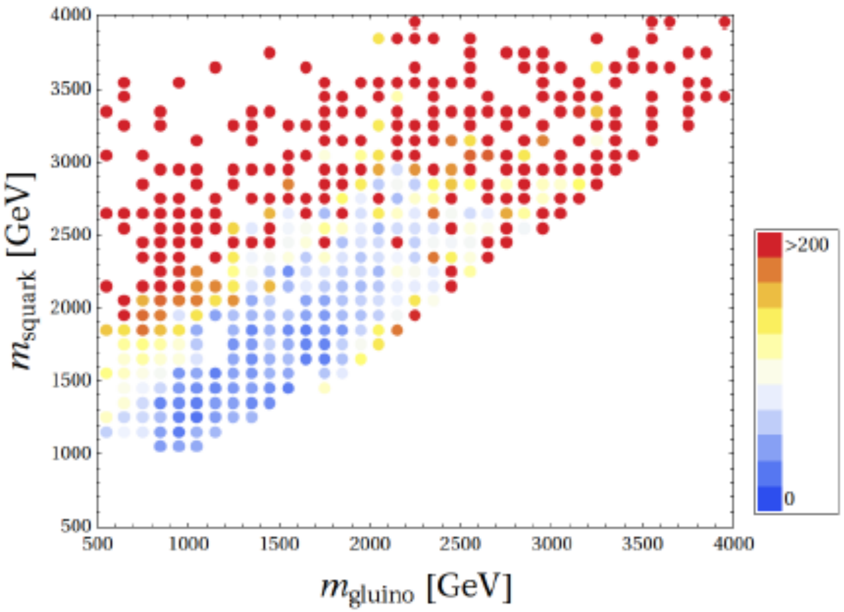
DM relic abundance ✔

DM searches ✔

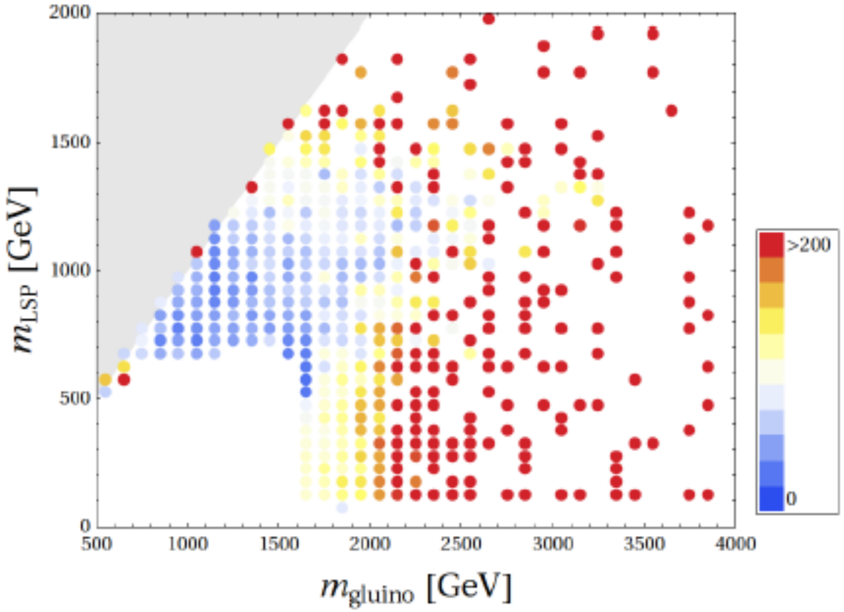
GGR, Kaminska, Schmidt-Hoberg

Masses v/s fine tuning

m_{squark}



m_{LSP}



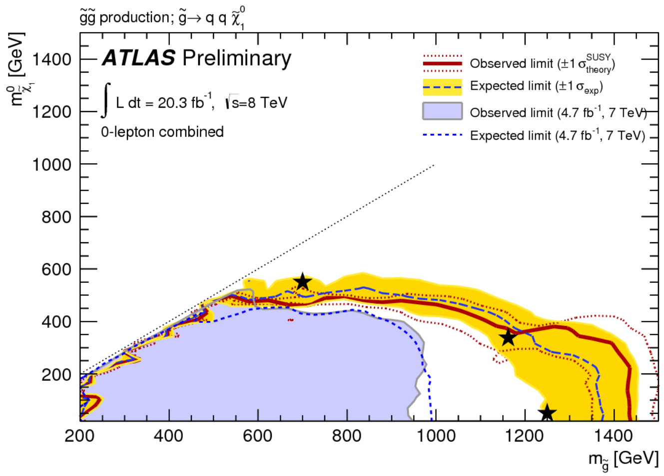
> 200

0

Δ

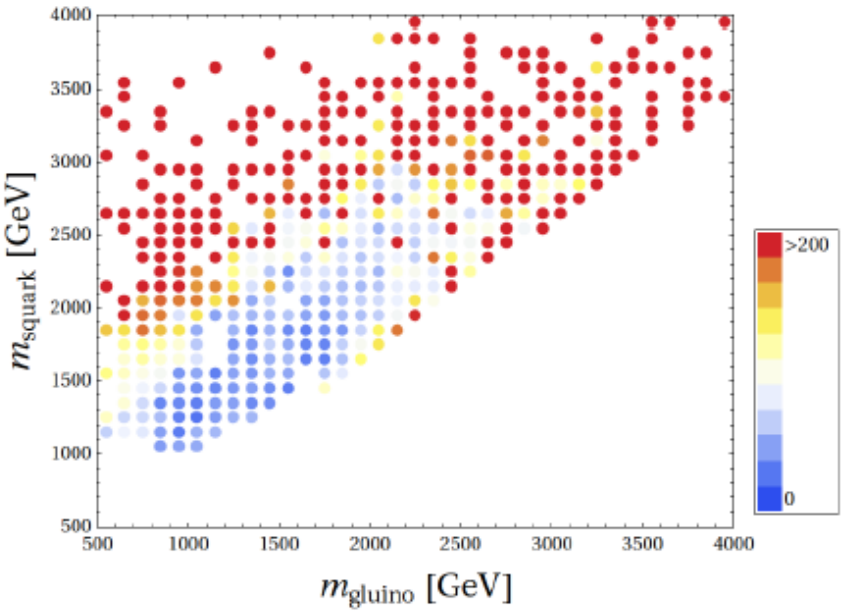
M_{gluino}

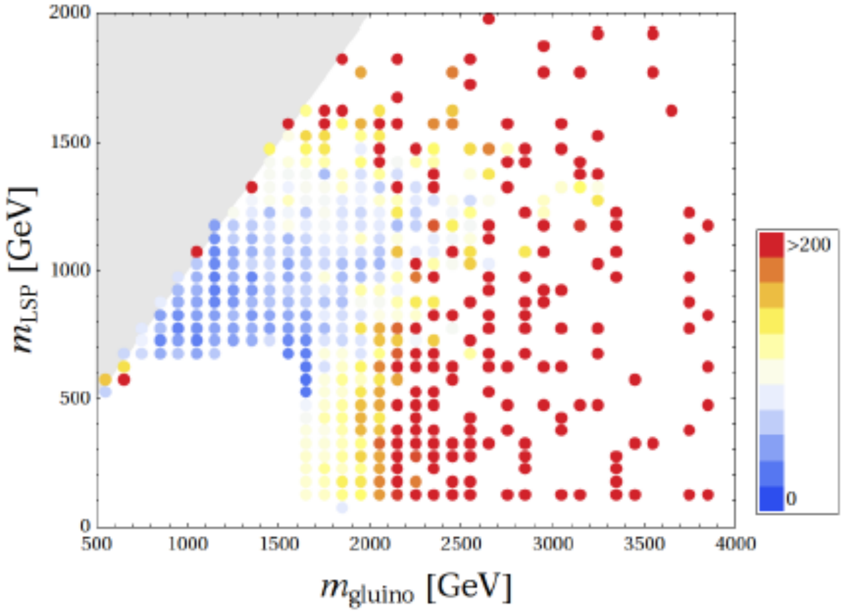
Masses v/s fine tuning



m_{squark}

m_{LSP}





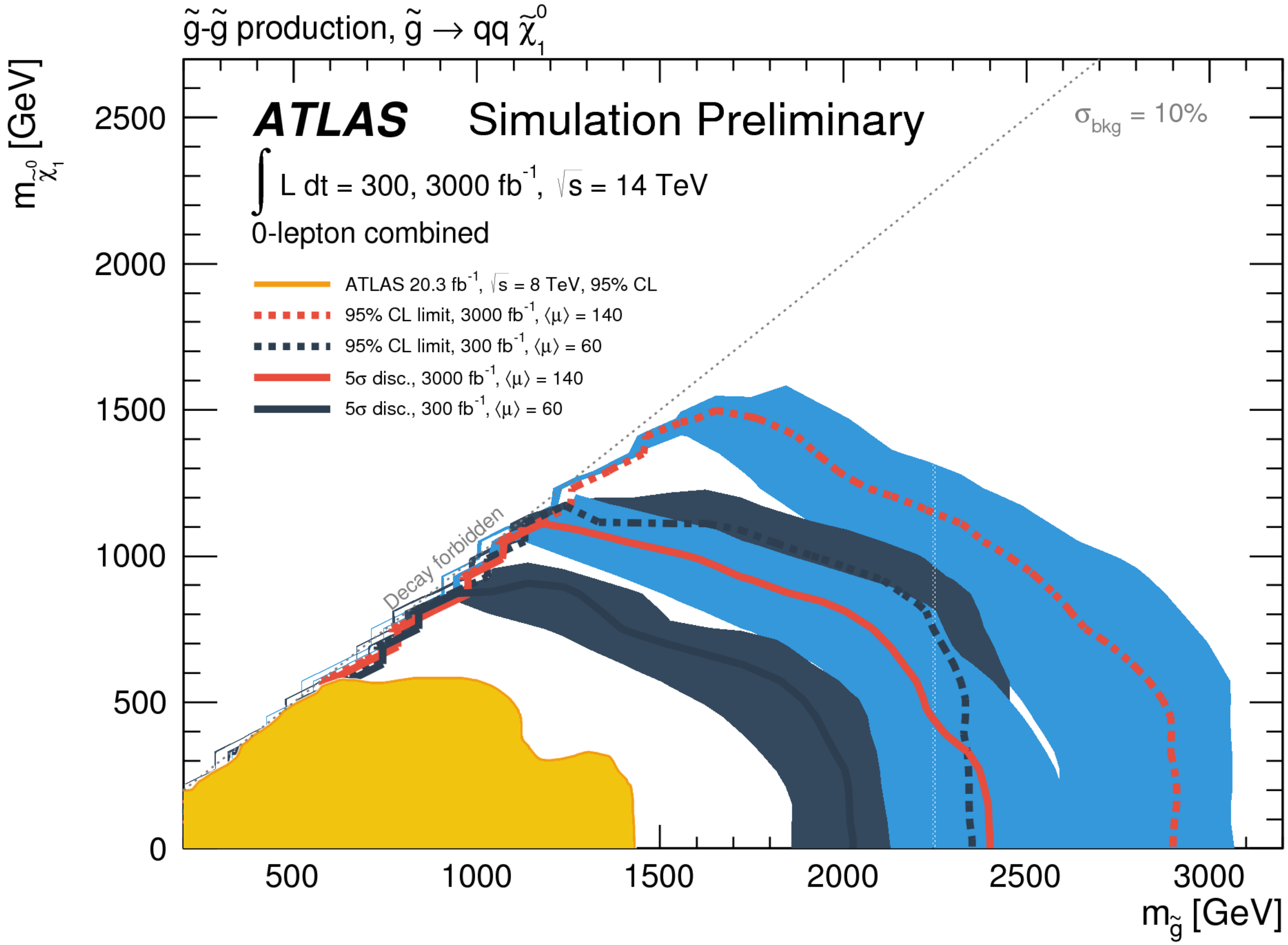
> 200

0

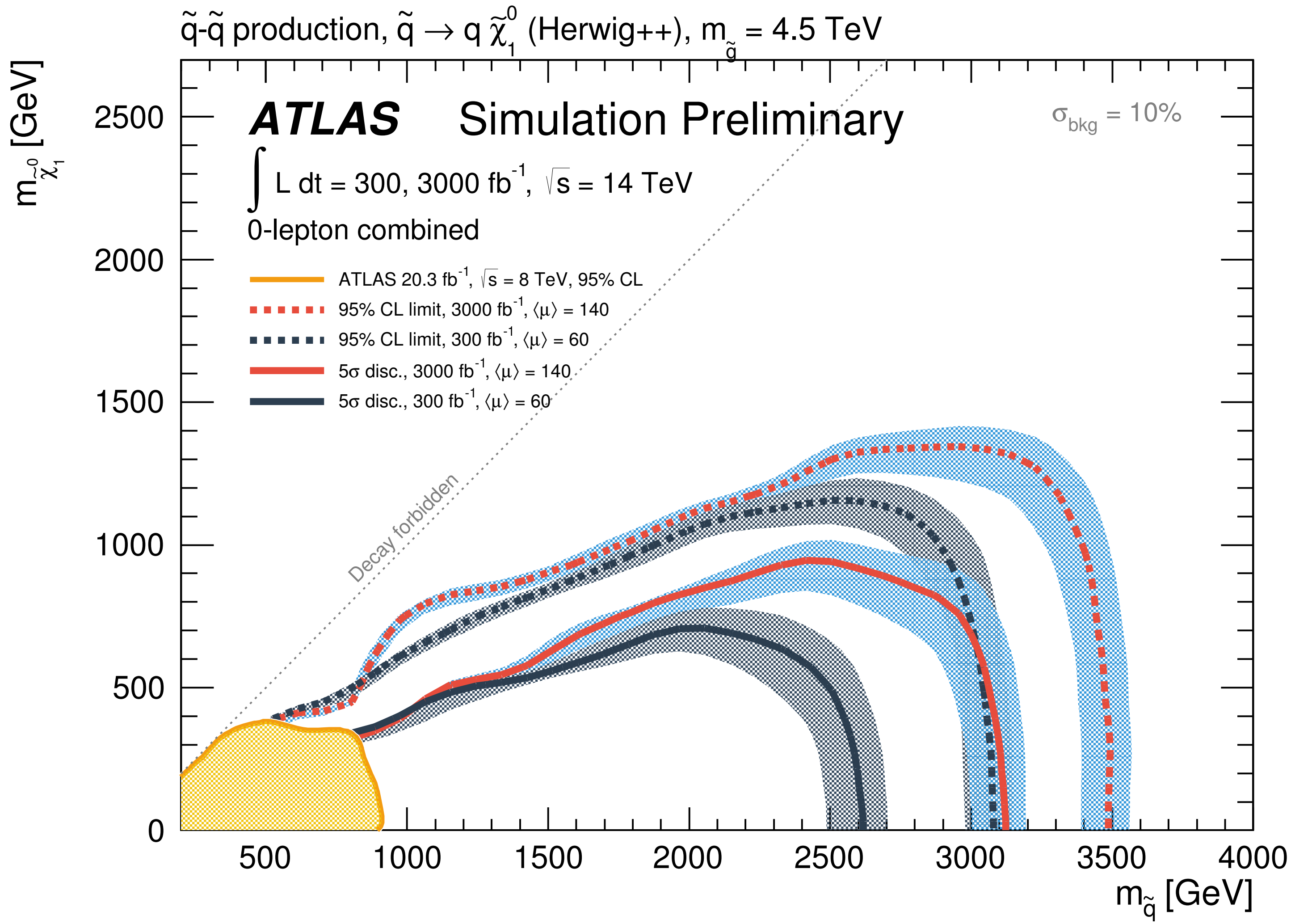
Δ

M_{gluino}

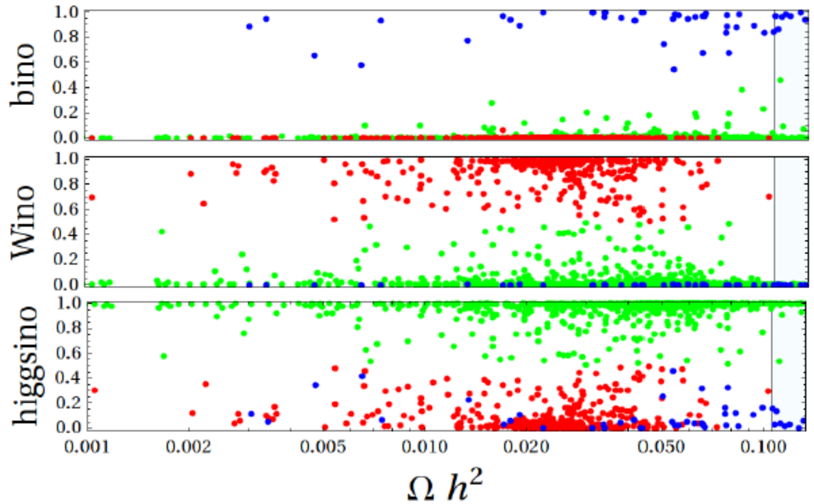
Heavy LSP reach



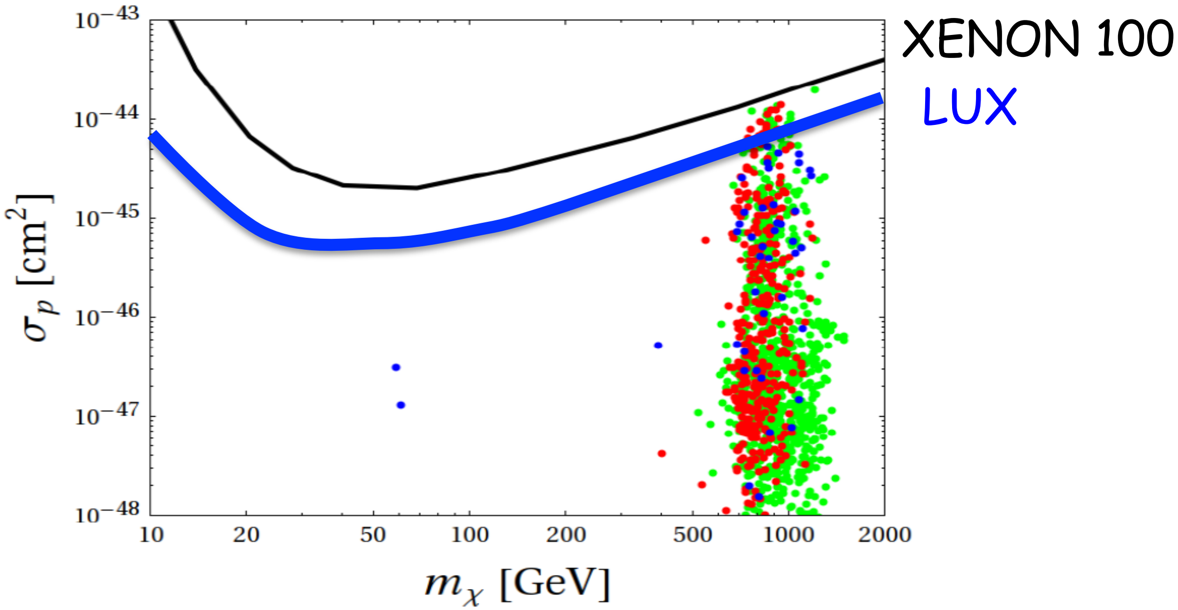
Heavy LSP reach



Dark matter



LSP composition



Direct DM searches

Summary - V

- GUTs $\Longrightarrow$ SUSY-GUTS (hierarchy problem)

  Gauge coupling unification ✔

- Fine tuning sensitive to SUSY spectrum

  ...scalar and gaugino focus points

$$\Delta^{CMSSM} > 350 \ ✗ \qquad \Delta^{(C)MSSM} > 60 \ ✔$$

$$\Delta^{CGMSSM} > 60 \ ✗ \qquad \Delta^{(C)GNMMS} > 20 \ ✔$$

$$c.f. \quad \Delta^{CMSSM}_{Low\ scale} = (10-30), \quad m_{\tilde{t}} = (1-5)TeV$$

Summary - II

- GUTs $\Longrightarrow$ SUSY-GUTS (hierarchy problem)

  Gauge coupling unification ✔

- Fine tuning sensitive to SUSY spectrum

  …scalar and gaugino focus points

  $\Delta^{CMSSM} > 350$ ✗ $\Delta^{(C)MSSM} > 60$ ✔

  $\Delta^{CGMSSM} > 60$ ✗ $\Delta^{(C)GNMMS} > 20$ ✔

  $c.f. \quad \Delta^{CMSSM}_{Low\ scale} = (10-30), \quad m_{\tilde{t}} = (1-5)TeV$

- Whither SUSY?

  ….well motivated SUSY models remain to be tested

  Compressed spectra, TeV squarks and gluinos LHC14?

  Natural SUSY

Summary BSM after LHC8

JSM v/s SUSY-GUTs

- Both require new (light) states

  More Higgs and/or Higgs interactions, pseudo-dilaton..
  SUSY partners

- Fine tuning limits $\Rightarrow$ LHC 13/14 discovery(?)

- Grand Unification still viable – but must find SUSY

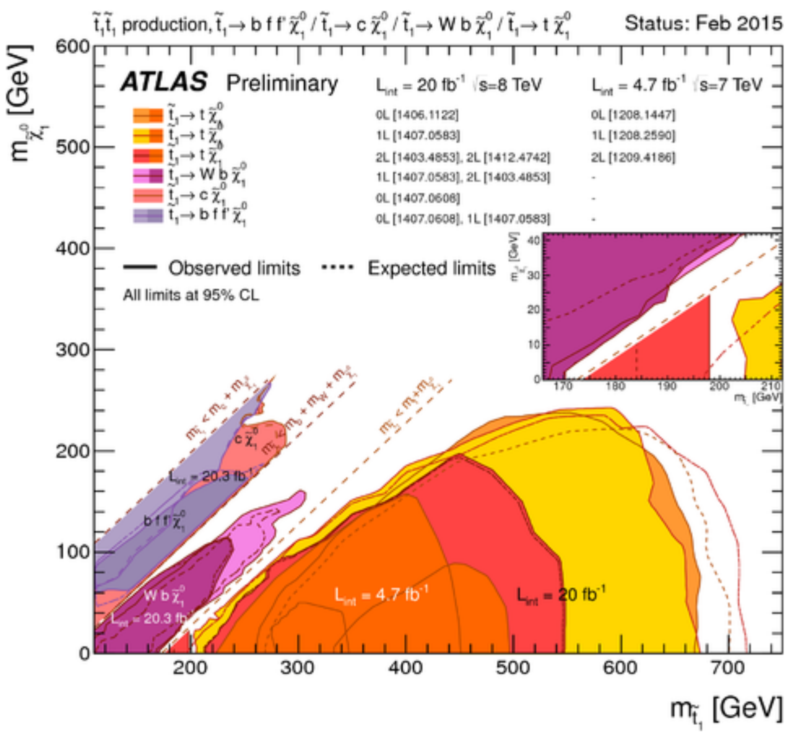
- Gravity/Inflation *may* be consistent with scale invariance

"Natural" SUSY

$$\delta m^2_{H_u}|_{\text{stop}} = -\frac{3}{8\pi^2} y_t^2 \left(m^2_{Q_3} + m^2_{U_3} + |A_t|^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$$

?

$$\sqrt{m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}} \lesssim 600\,\text{GeV} \frac{\sin\beta}{(1+x^2)^{1/2}} \left(\frac{\log(\Lambda/\,\text{TeV})}{3}\right)^{-1/2} \left(\frac{\tilde{\Delta}^{-1}}{20\%}\right)^{-1/2}$$



"Natural" SUSY

$$\delta m^2_{H_u}|_{\rm stop} = -\frac{3}{8\pi^2} y_t^2 \left(m^2_{Q_3} + m^2_{U_3} + |A_t|^2\right) \log\left(\frac{\Lambda}{\rm TeV}\right)$$

?

$$\sqrt{m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}} \lesssim 600\,{\rm GeV} \frac{\sin\beta}{(1+x^2)^{1/2}} \left(\frac{\log\left(\Lambda/\,{\rm TeV}\right)}{3}\right)^{-1/2} \left(\frac{\tilde{\Delta}^{-1}}{20\%}\right)^{-1/2}$$

- two stops and one (left-handed) sbottom, both below $500 - 700$ GeV.
- two Higgsinos, *i.e.*, one chargino and two neutralinos below $200 - 350$ GeV. In the absence of other [lighter] chargino/neutralinos, their spectrum is quasi-degenerate.
- a not too heavy gluino, below 900 GeV $-$ 1.5 TeV.

Papucci, Ruderman, Weiler 1110.6926

“Natural” SUSY

$$\delta m_{H_u}^2|_{\rm stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right) \log\left(\frac{\Lambda}{\rm TeV}\right)$$

?

$$\sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} \lesssim 600\,{\rm GeV} \frac{\sin\beta}{(1+x^2)^{1/2}} \left(\frac{\log(\Lambda/\,{\rm TeV})}{3}\right)^{-1/2} \left(\frac{\tilde{\Delta}^{-1}}{20\%}\right)^{-1/2}$$

…but

- Focus points can reduce sensitivity to $m_{\tilde{t}}, m_{\tilde{g}}$
- Additional fine tuning needed to get large $\tan\beta$

$$\Rightarrow \quad m_{\tilde{t}} \geq 800\ GeV$$

$$\tan\beta \leq 15 - 30$$

Casas, Moreno, Robles, Rolbiecki, Zaldivar 1407.6966

5^{th} Force limits