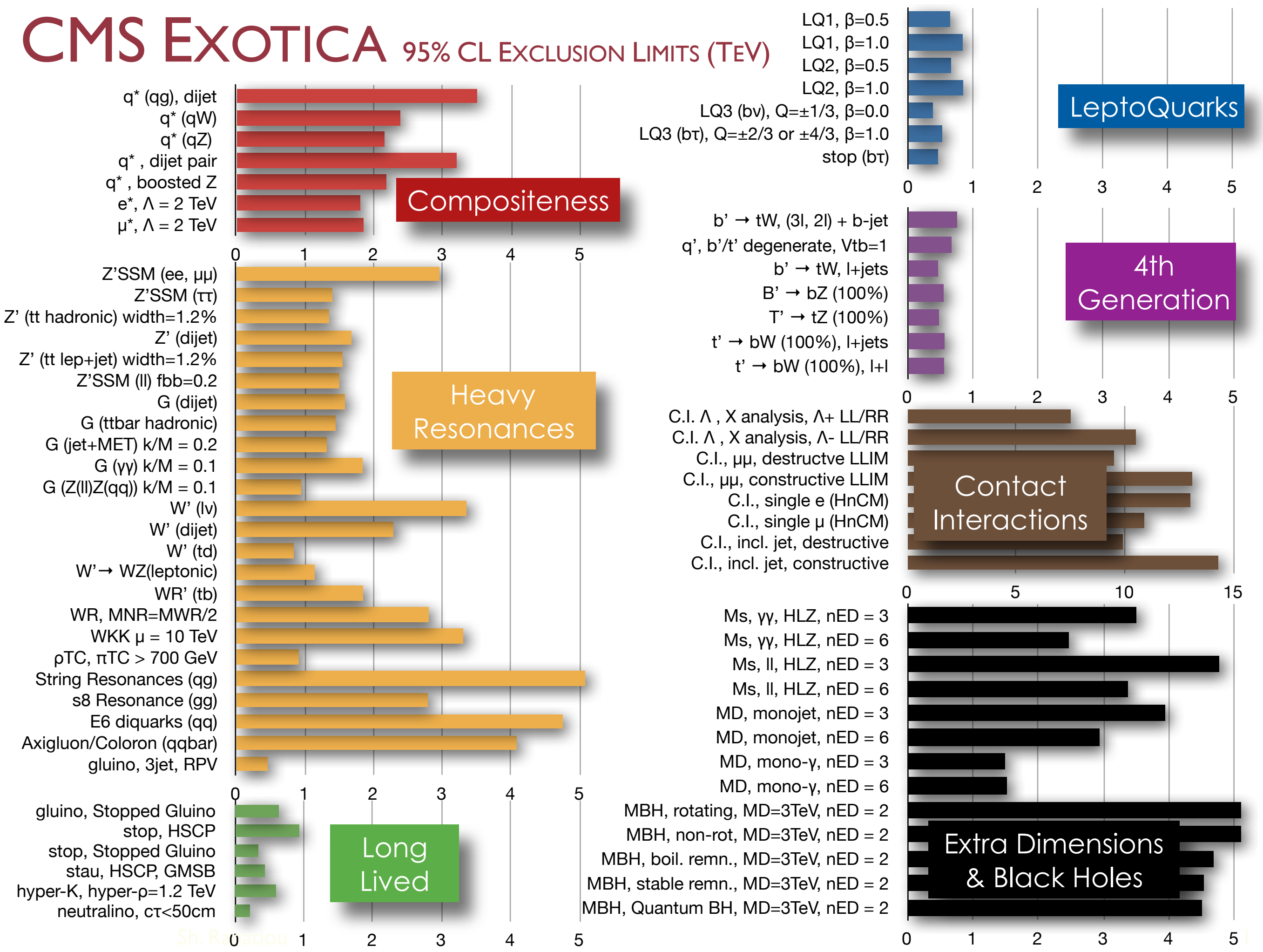
Beyond the Standard Model (or not) after the Higgs

G. Ross, Southampton, October 2014

LHC 8

No evidence (yet) for BSM



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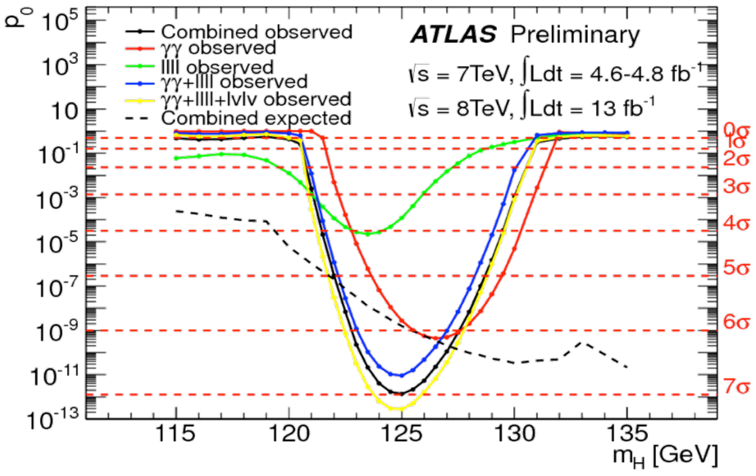

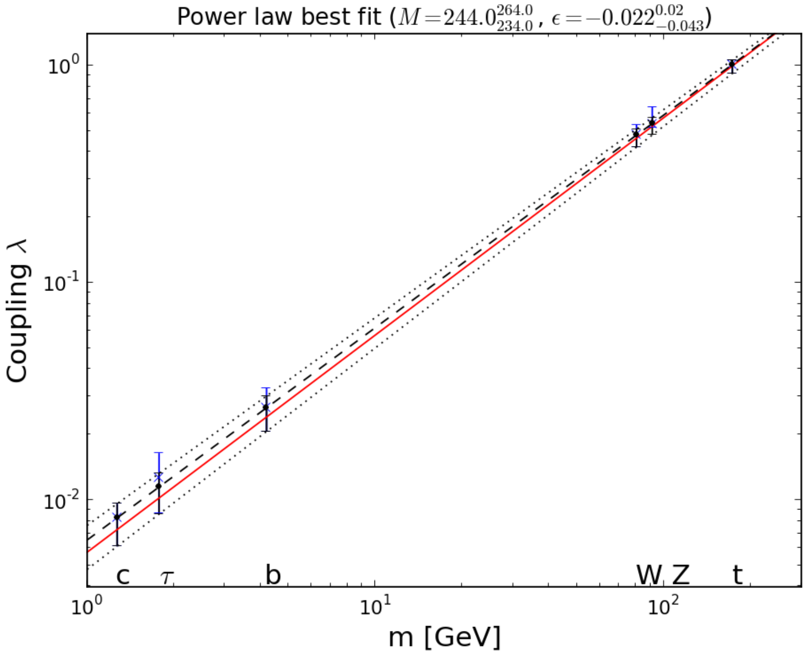

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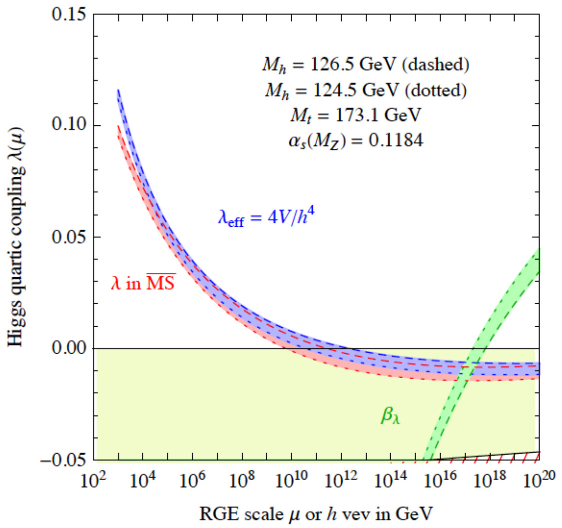
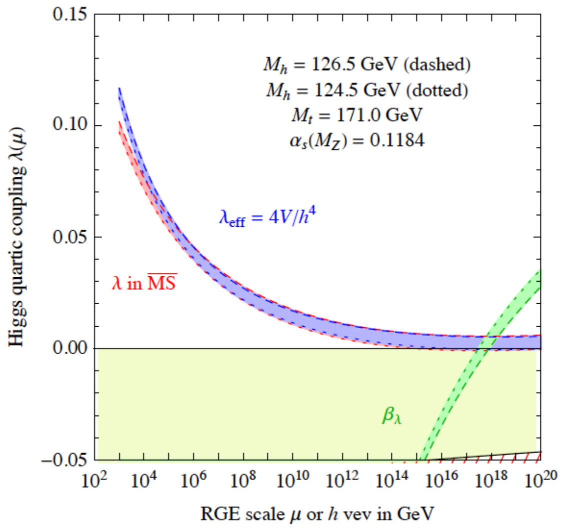
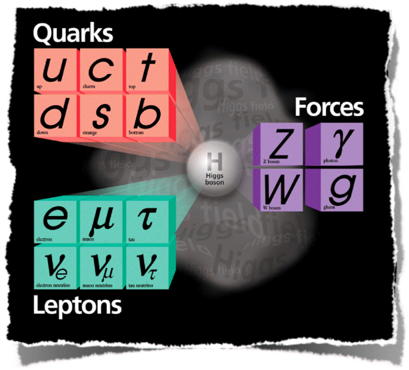
$\}$ "Just" the SM (JSM)?

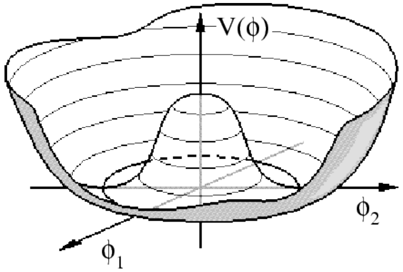






$$V(H) = -m^2 |\phi|^2 + \lambda |\phi|^4$$

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



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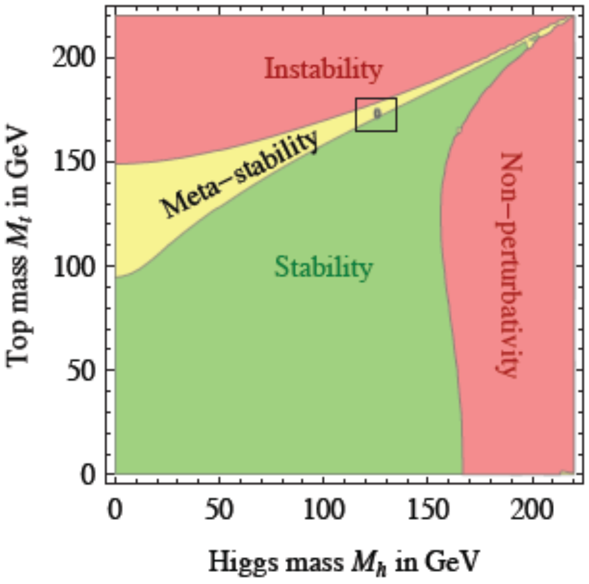

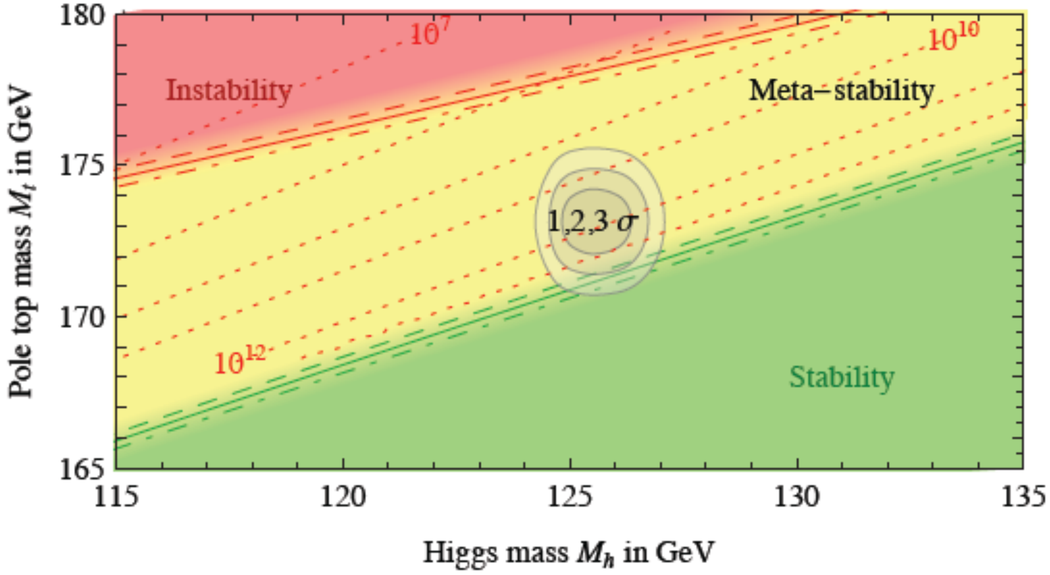

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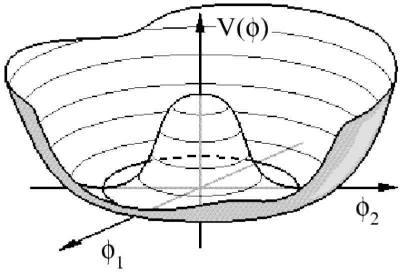
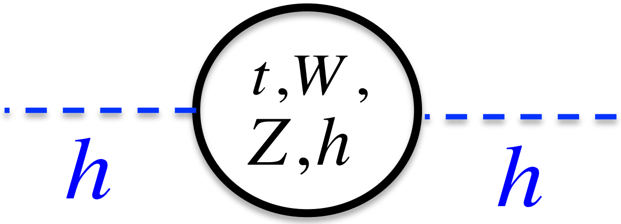


JSM - Hierarchy problem?



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

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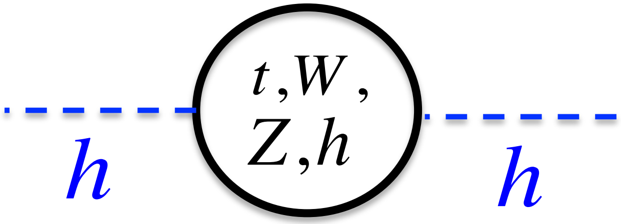

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Field theory: δm^2 not measureable

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

Only $m^2 = 0$ special ("classical" scale invariance)

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

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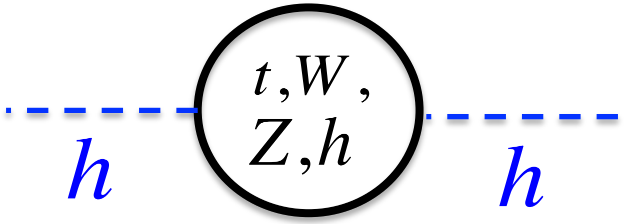

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… but is the SM all there is?

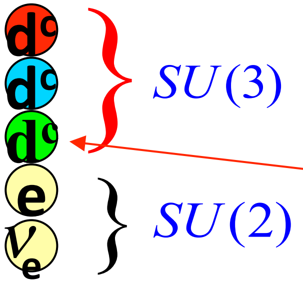
Unification of forces and matter?

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

Georgi Glashow 1974

LH states SU(2) doublets

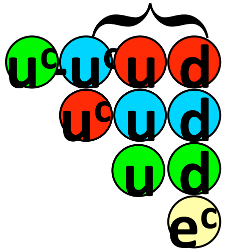
$(\bar{5})_L$:



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

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

$(10)_L$:



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

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

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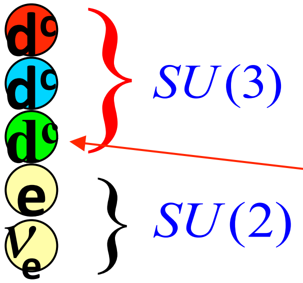

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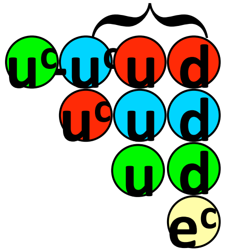


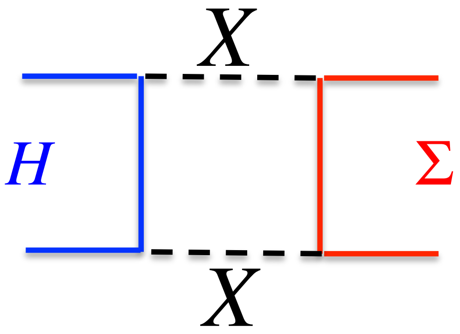
$$(16)_L = (10)_L + (\bar{5})_L + (1)_L$$

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

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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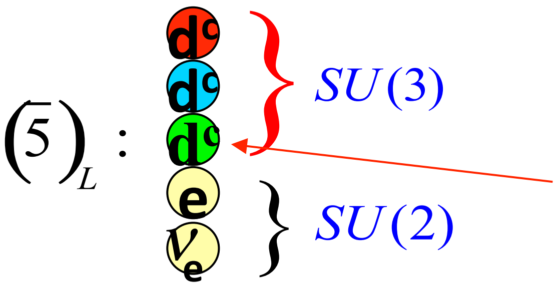

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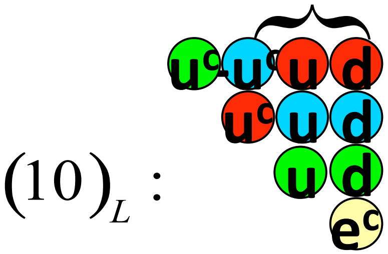
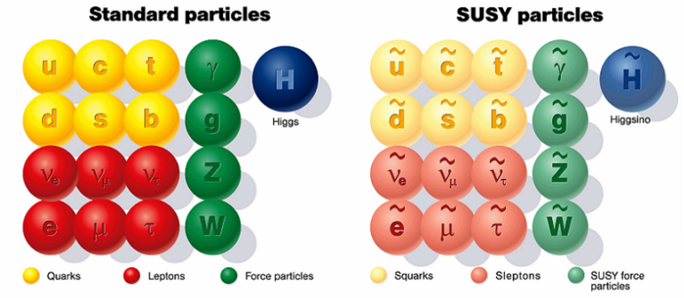
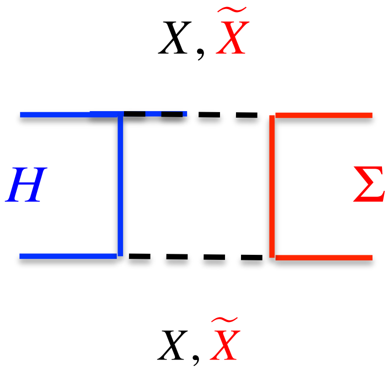


Low scale SUSY

MSSM:





SUSY GUTS: the hierarchy problem

$$\delta m^2 \propto M^2_{SUSY}$$

Unification of forces and matter?

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

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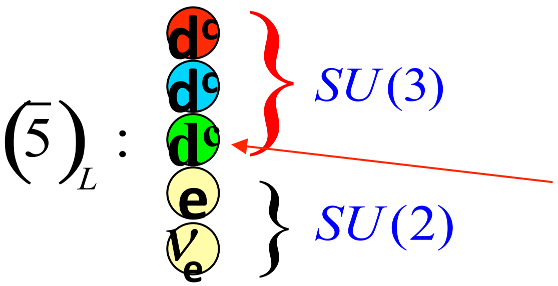

$(\bar{5})_L$:

d^c

d^c

d^c

e

ν_e

$SU(3)$

$SU(2)$

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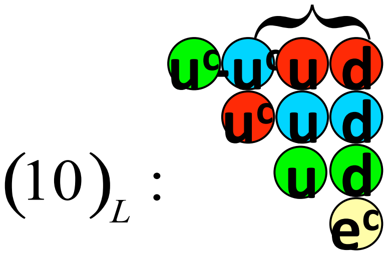

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$u^c\ u^c\ u\ d$

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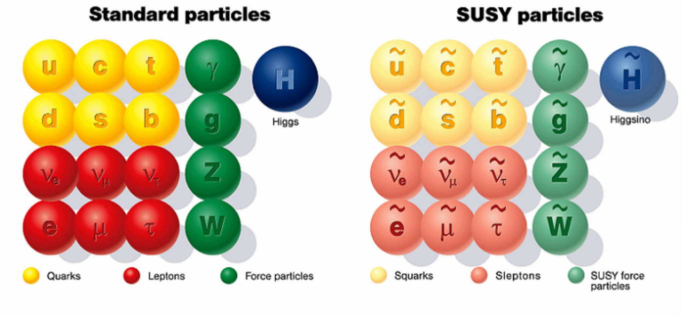

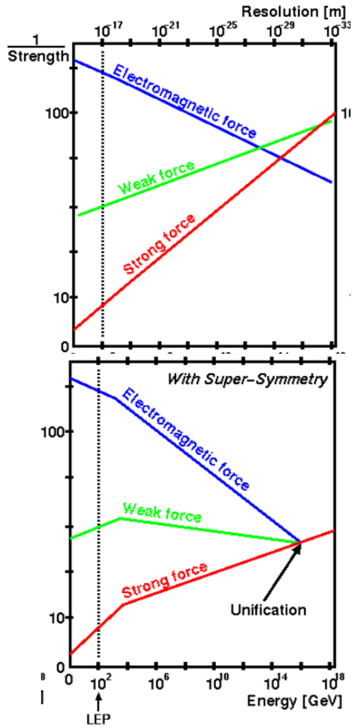

Two case studies :

I. SUSY unification

II. “Just” the Standard Model

I. SUSY Unification

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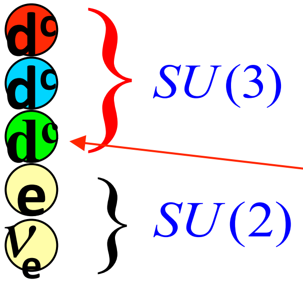

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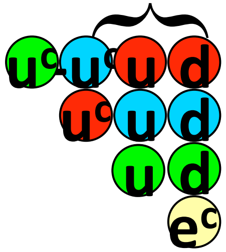

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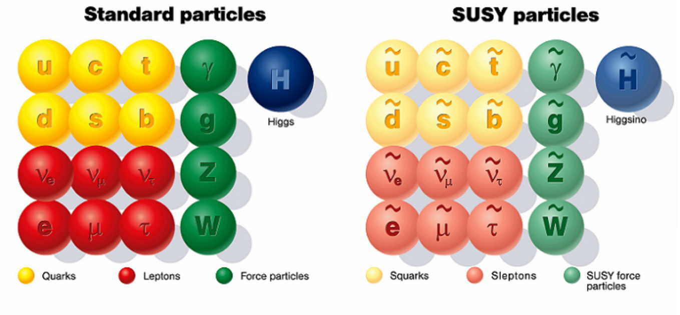

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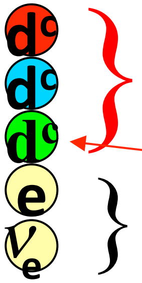

$SU(3)$

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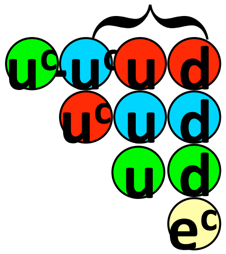

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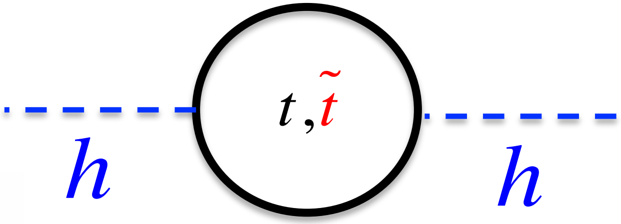

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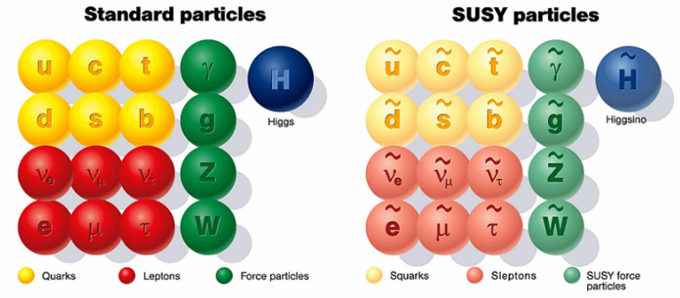


$$m_h^2 = M_Z^2 + \frac{3m_t^2 h_t^2}{4\pi^2}\left(\ln\left(m_{stop}^2 / m_t^2\right) + \delta_t\right) + \ldots \simeq 126\,GeV$$

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

$\Lambda \sim M_{GUT}$?

?

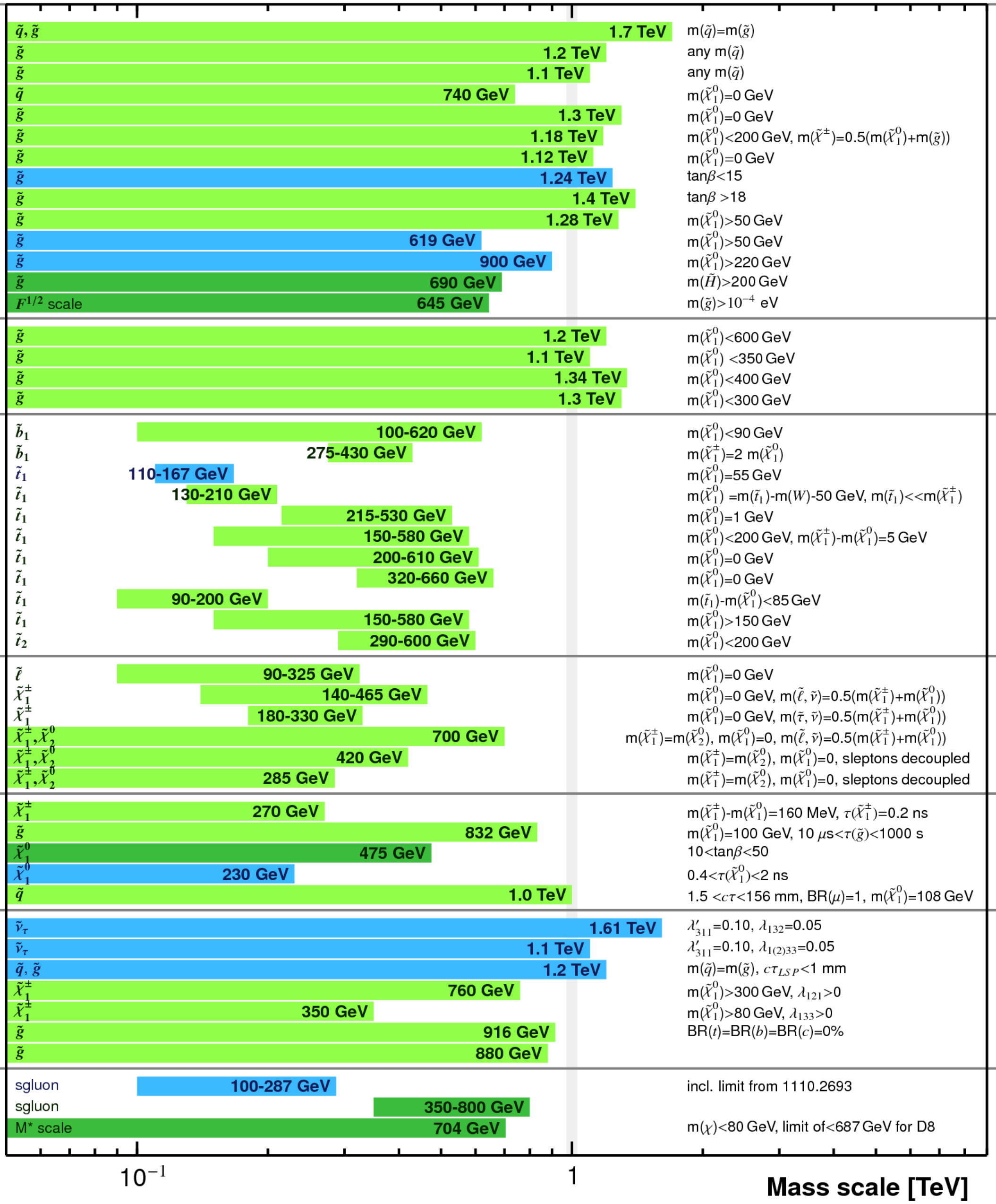
Little
hierarchy
problem

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (4.6 - 22.9) 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			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^{\pm}\rightarrow qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	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
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$	1.4 TeV	tanβ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m($\tilde{H}$)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	m($\tilde{g}$)>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\rightarrow b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	ATLAS-CONF-2013-061
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$	275-430 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$	215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$	200-610 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-200 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	140-465 GeV	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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$	180-330 GeV	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	700 GeV	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	420 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	285 GeV	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	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\rightarrow\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\rightarrow qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q},\tilde{g}$	1.2 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow ee\tilde{\nu}_\mu$, $e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$	760 GeV	m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau\tau\tilde{\nu}_e$, $e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^{\pm}$	350 GeV	m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\rightarrow qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\rightarrow\tilde{t}_1t$, $\tilde{t}_1\rightarrow bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\rightarrow q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\rightarrow t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<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**

**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.*

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

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

Fine Tuning measure:

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

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

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

Fine tuning from a likelihood fit:

"Nuisance" variable

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

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

Fine tuning not optional!

Ghilencea, GGR
Casas et al

Probabilistic interpretation:

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

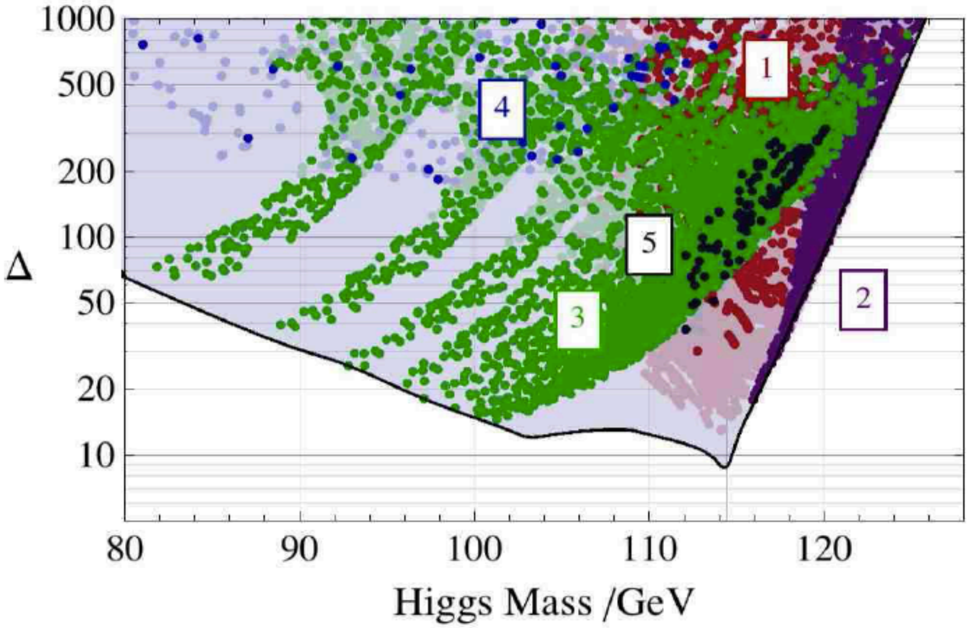
$$\Delta_q \ll 100$$

CMSSM:

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

CMSSM: pre Higgs

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



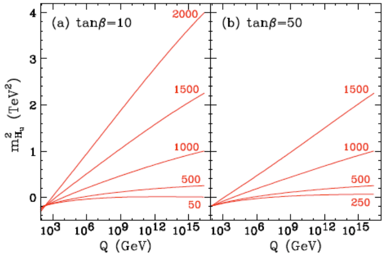
Gauge unification required

Relic density restricted

- 1 h^0 resonant annihilation
- 2 $\tilde{h}$ t-channel exchange
- 3 $\tilde{\tau}$ co-annihilation
- 4 $\tilde{t}$ co-annihilation
- $\bullet\, 5$ A^0 / H^0 resonant annihilation

Focus point

$$m_{H_u} = m_{\tilde{Q}_3} = m_{\tilde{u}3}$$



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

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

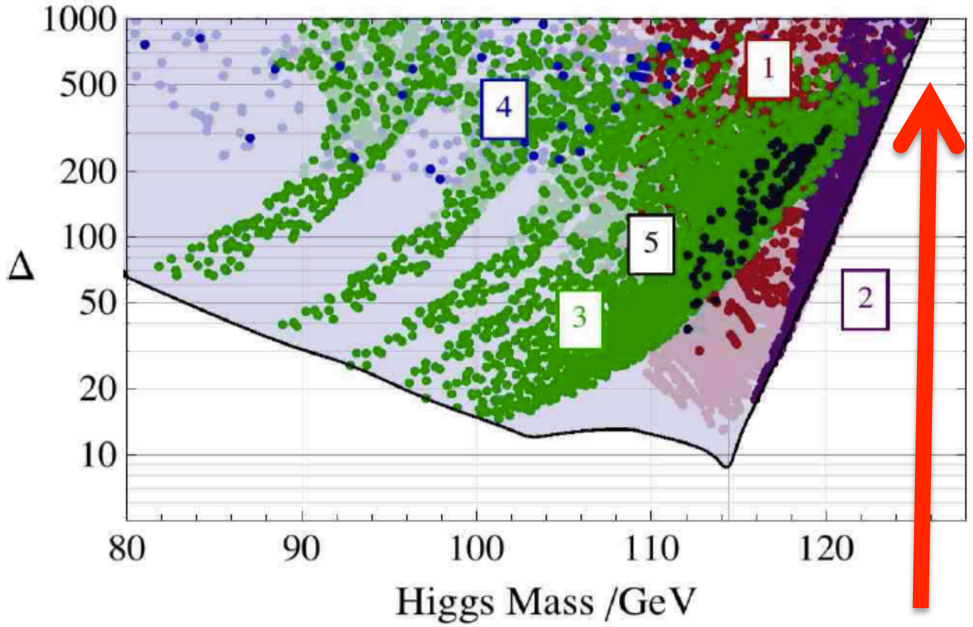
CMSSM: post Higgs

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

Gauge unification required

Relic density restricted

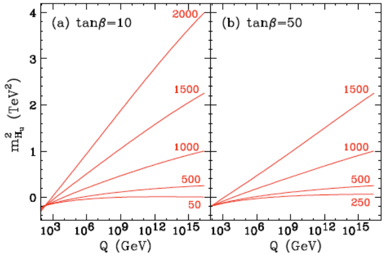
- 1 h^0 resonant annihilation
- 2 $\tilde{h}$ t-channel exchange
- 3 $\tilde{\tau}$ co-annihilation
- 4 $\tilde{t}$ co-annihilation
- • 5 A^0 / H^0 resonant annihilation



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

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)

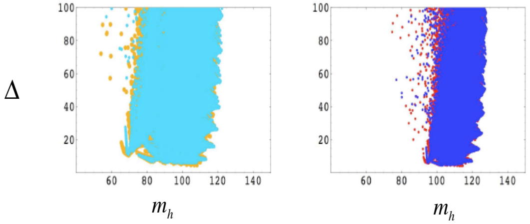
- Correlations between SUSY breaking parameters

New (heavy) states - higher dimension operators

$$\delta L_5 = \int d^2\theta \frac{1}{M_*}\left(\mu_0 + c_0 S\right)\left(H_u H_d\right)^2, \quad S = m_0\theta\theta$$

Dimension 5

$$\delta V = \varsigma_1\left(\left|h_u\right|^2 + \left|h_d\right|^2\right)h_u h_d + \varsigma_2\left(h_u h_d\right)^2; \quad \varsigma_1 = \frac{\mu_0}{M_*}, \ \varsigma_2 = \frac{c_0 m_0}{M_*}$$



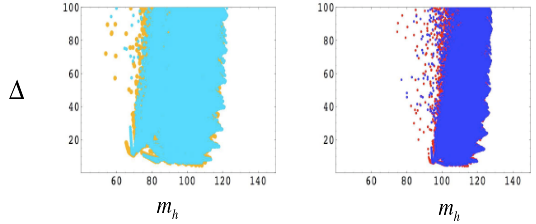
Cassel, Ghilencea, GGR
Casas, Espinosa, Hidalgo
Dine, Seiberg, Thomas
Batra, Delgardo, Tait
Kaplan,

New (heavy) states – higher dimension operators

$$\delta L_5 = \int d^2\theta \frac{1}{M_*}(\mu_0 + c_0 S)(H_u H_d)^2 , \quad S = m_0 \theta\theta$$

Dimension 5

$$\delta V = \varsigma_1\left(|h_u|^2 + |h_d|^2\right)h_u h_d + \varsigma_2 (h_u h_d)^2; \quad \varsigma_1 = \frac{\mu_0}{M_*}, \ \varsigma_2 = \frac{c_0 m_0}{M_*}$$



Singlet extensions

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

NMSSM ✗

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

GNMSSM ✓

$$\mu_S >> m_{3/2} : \quad W_{eff}^{GNMSSM} = (H_u H_d)^2 / \mu_s + \mu H_u H_d$$

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

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

Lee, Raby, Ratz, Ross, Schieren, Schmidt-Hoberg, Vaudrevange
Babu, Gogoladze,Wang

GNMSSM

NMSSM spectrum
No perturbative μ term
Commutes with SO(10)
Discrete Anomaly cancellation $(\Rightarrow q_{H_u} + q_{H_d} = 0)$

Z_{4R}

N	q_{10}	$q_{\bar{5}}$	q_{H_u}	q_{H_d}	q_s
4	1	1	0	0	2

D=5 operators

up and down Yukawas allowed

$$3q_{10} + q_{\bar{5}} + q_{H_u} + q_{H_d} = 4 \quad \text{Mod N} \quad \Rightarrow \quad 3\text{q}_{10} + q_{\bar{5}} = 0 \quad \text{Mod N} \quad \Rightarrow \quad \frac{1}{M}Q\cancel{Q}QL \quad \frac{1}{M}LLH_uH_u$$

Weinberg operator

SUSY breaking

$\langle W \rangle, \langle \lambda\lambda \rangle$ R=2 non=perturbative breaking

$Z^R_{4,8} \rightarrow Z^R_2 \quad R-parity$

Domain walls and tadpoles safe Abel

$\mu \sim m_{3/2}, \quad O(\frac{m_{3/2}}{M^2}QQQL)$

$$W = W_{MSSM} + \lambda S H_u H_d + \kappa S^3 + \Delta W$$

$$\Delta W_{Z^R_4} \sim m_{3/2} H_u H_d + m^2_{3/2} S + m_{3/2} S^2$$

$$\Delta W_{Z^R_8} \sim m^2_{3/2} S$$

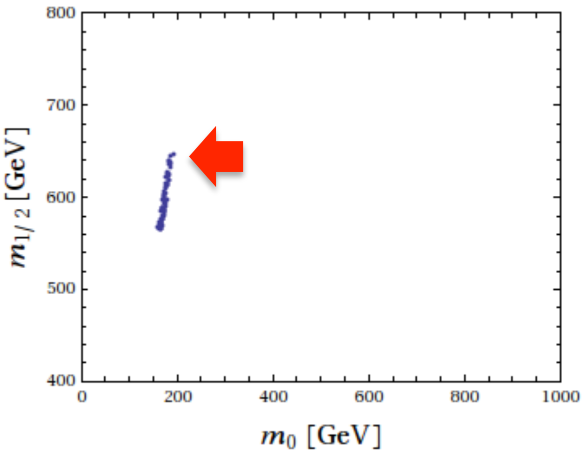
← μ term and mass term

Fine tuning in the CGNMSSM

$(\lambda \leq 0.7)$

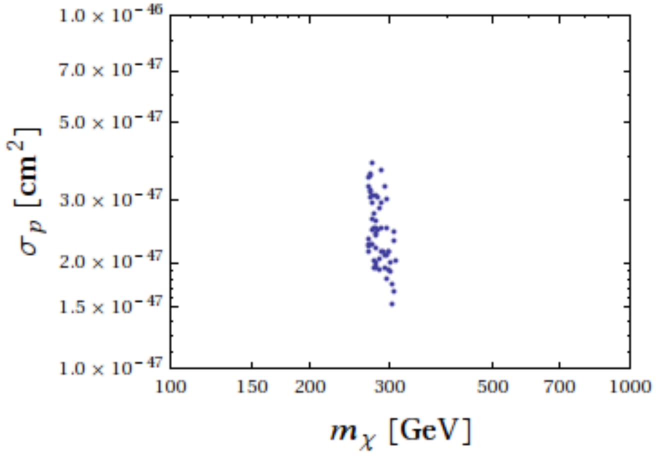
$$\boxed{\Delta_{Min} = 60\ (500), \quad m_h = 125.6 \pm 3 GeV}$$

- 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

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

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

Horton, GGR

Also improves precision of gauge coupling unification

Shifman, Roszkowski
Krippendorf, Nilles, Ratz, Winkler

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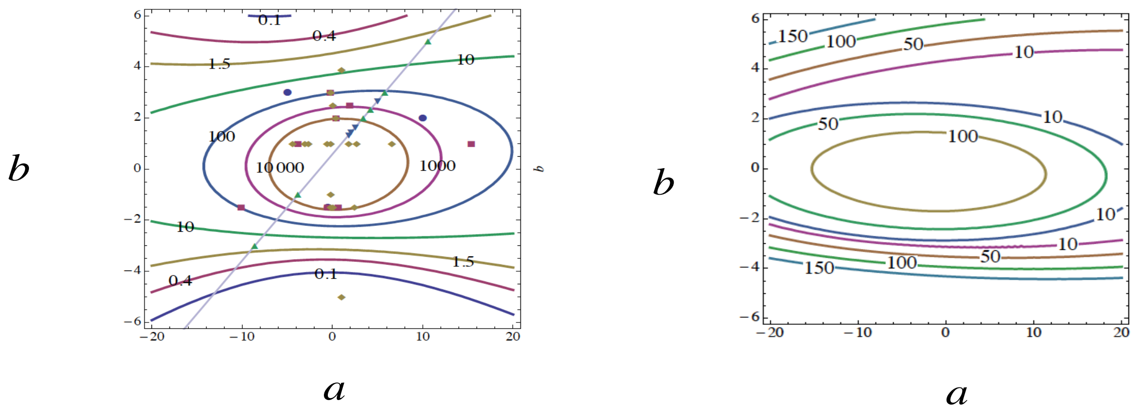

$$M_3 : M_2 : M_1 = 1 : b : a$$

Correlation between SUSY breaking parameters

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Horton, GGR

Also improves precision of gauge coupling unification

Shifman, Roszkowski
Krippendorf, Nilles, Ratz, Winkler

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

LHC8 SUSY bounds ✓

DM relic abundance ✓

DM searches ✓

Better…but still uncomfortably large

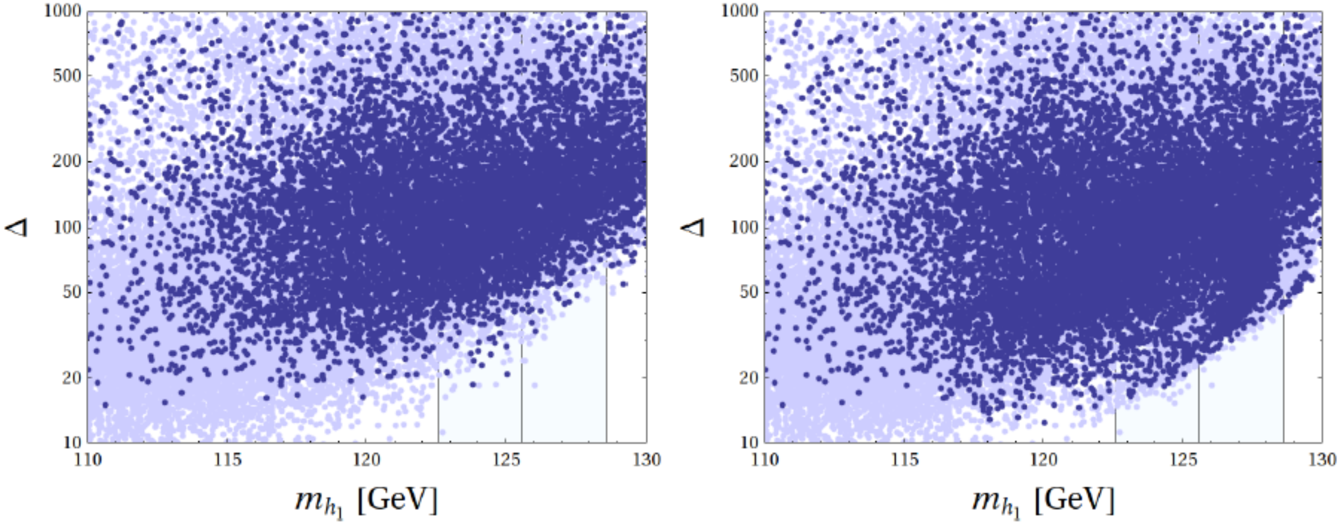
Fine tuning in the (C)GNMSSM $(\lambda \leq 0.7^{\dagger})$

Non-universal gaugino masses

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

- LHC8 SUSY bounds ✓
- DM relic abundance ✓
- DM searches ✓

Δ

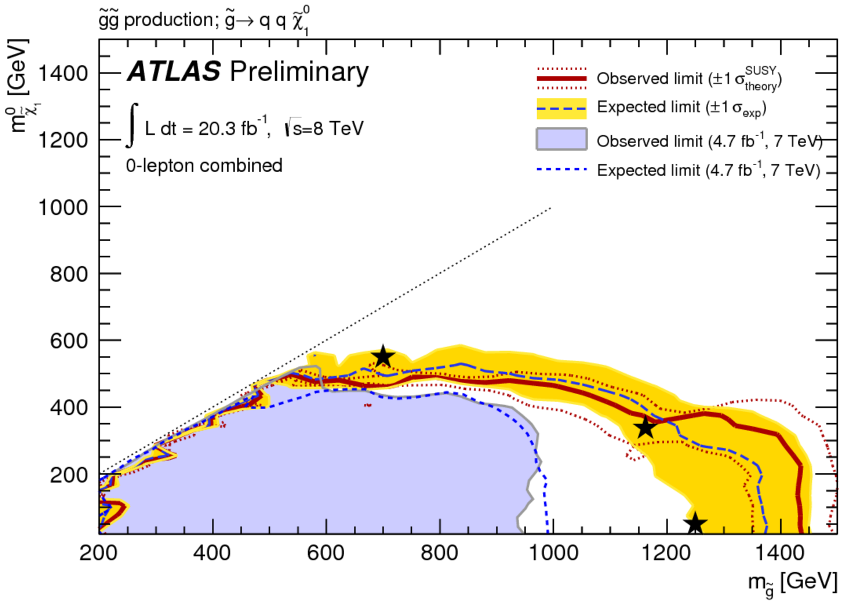


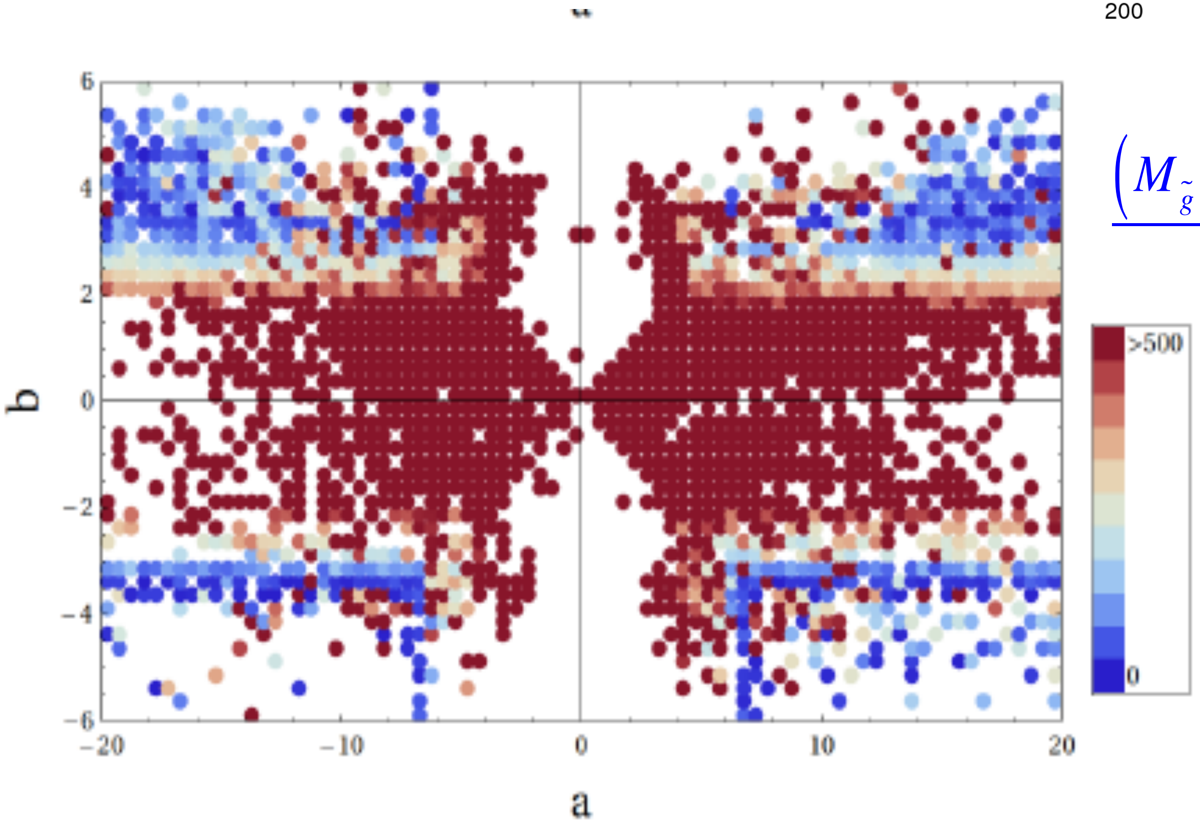
(uniform scan)

GGR, Kaminska, Schmidt-Hoberg

Compressed spectrum-

heavy LSP





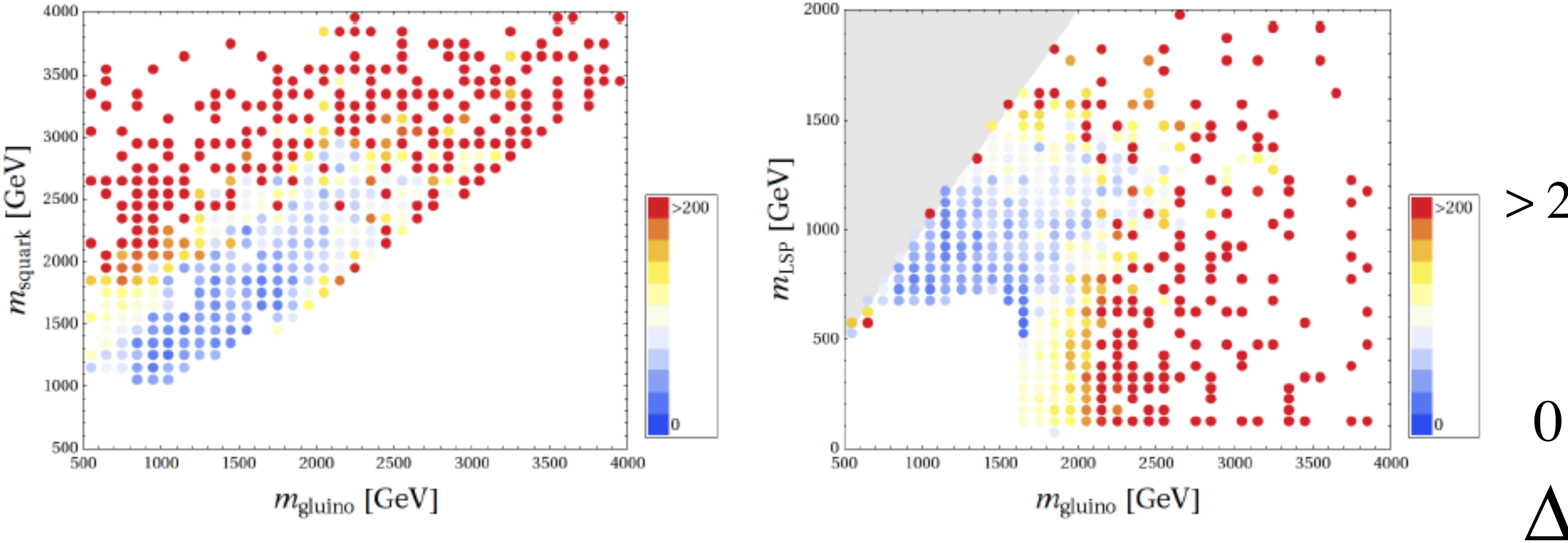
$$\frac{\left(M_{\tilde{g}} - M_{LSP}^{neutralino}\right)}{GeV}$$

> 500

0

Masses v/s fine tuning

m_{squark} m_{LSP}



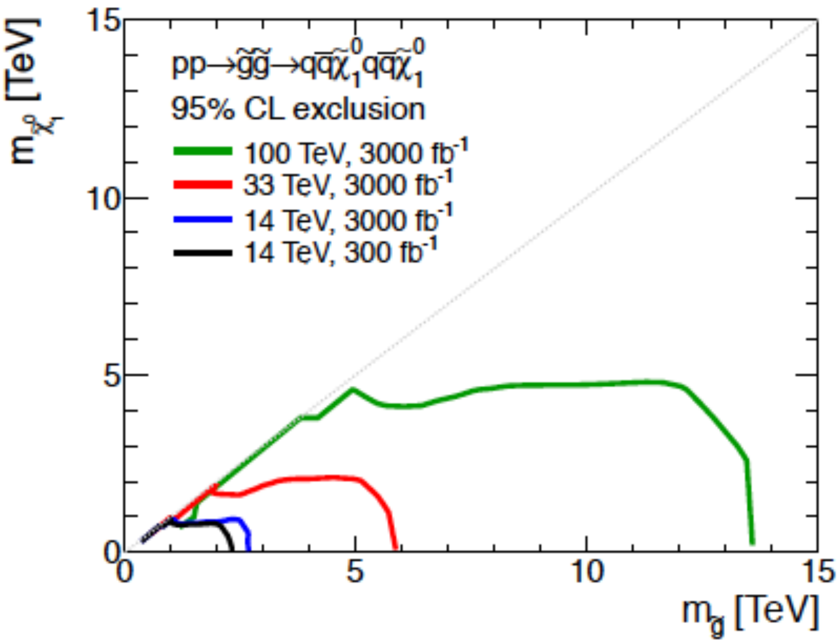
> 200

0

Δ

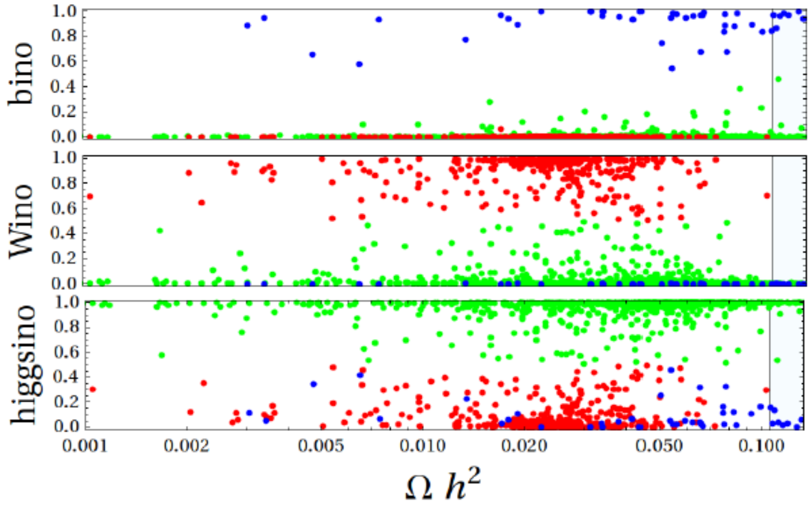
M_{gluino}

Heavy LSP reach

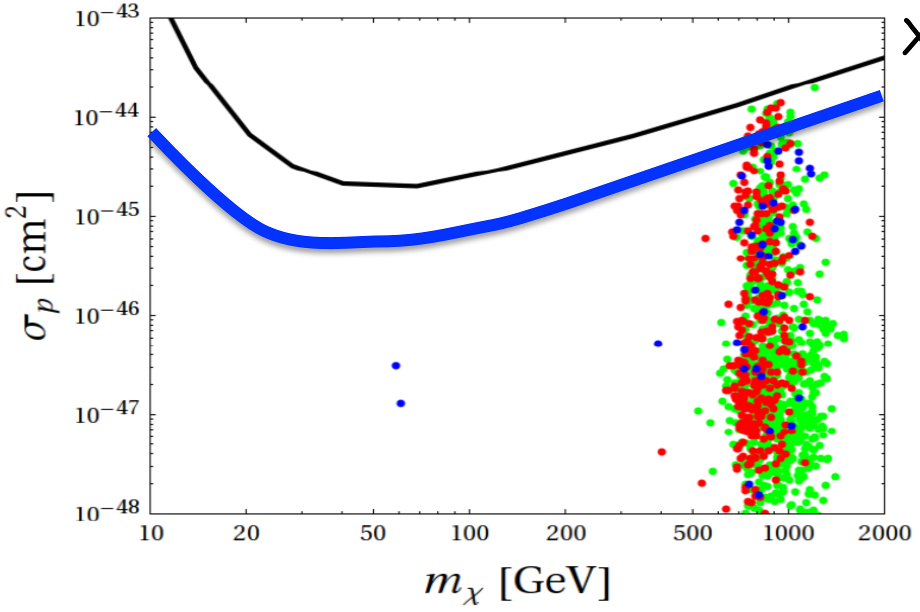


Snowmass white paper: Cohen et al

Dark matter



LSP composition



XENON 100

LUX

Direct DM searches

Summary - I

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

- Fine tuning sensitive to SUSY spectrum

  …scalar and gaugino focus points

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

  $\Delta^{CGNMSSM} > 60$ ✗ $\Delta^{(C)GNMMS} > 20$ ✓

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

Summary - I

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

- Whither SUSY?

  ….well motivated SUSY models remain to be tested

Compressed spectra, TeV squarks and gluinos LHC14?

II "Just" the Standard Model

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

II "Just" the Standard Model

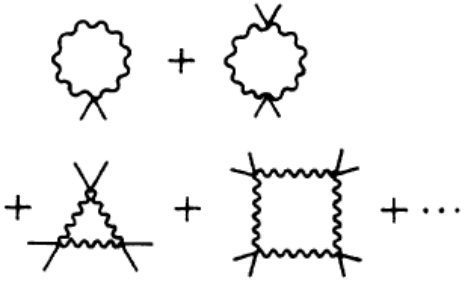
Classical scale invariance, $m_h = 0$ … origin of EW breaking?

Coleman-Weinberg - dynamical symmetry breaking :

e.g. scalar elactrodynamics

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

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



$$m_\phi^2 = \frac{3e_\phi^2}{8\pi^2} m_X^2 \ll m_X^2$$

"real" hierarchy problem

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

No heavy states?

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

No heavy thresholds?

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

Neutrino masses:

Add singlet neutrinos ν_{Ra}

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

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

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

Ultra-weak:

Natural due to chiral symmetry

Baryogenesis

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

- ν_{Ra} produced via Yukawa interactions $L_A = L_B = L_C = 0$
- ν_{Ra} oscillate $\cancel{CP}\,,\quad L_{A,B,C} \neq 0,\quad L_A + L_B + L_C = 0$
- $\nu_{R\,A,B}$ in thermal equilibrium by t_{EW} when sphalerons inoperative
- $\Delta_{L\,AB} = L_A + L_B \xrightarrow[Sphalerons]{} \Delta B = \Delta_{L\,AB} / 2$ ✓

Akhmedov, Rubakov, Smirnov

see also Shaposhnikov et al

Strong CP problem:

$$\frac{\theta}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}, \quad \theta \le 10^{-10} ??$$

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$$\frac{\theta}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}, \quad \theta \le 10^{-10} ??$$

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

… complex scalar field, S

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

Strong CP problem:

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

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

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:

$$\zeta_{1,2,3} \leq 10^{-20} \left(\frac{10^{12}\, GeV}{f_a} \right)^2$$

Ultra weak sector:

ζ_i multiplicatively renormalised

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

Origin of large vev?

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

Dimensional transmutation (Coleman Weinberg)

Coleman Weinberg in DFSZ model

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

$$+\frac{\lambda_2}{2}|H_2|^4+\zeta_3S^2H_1H_2+h.c.$$

Coleman Weinberg in DFSZ model

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

$$\mathrm{v}_S=f_a, \quad \mathrm{v}_{H_1}=\frac{\zeta_1}{\lambda_1}f_a, \quad \mathrm{v}_{H_2}=\frac{\zeta_3}{2\zeta_2}\mathrm{v}_{H_1}$$

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

Coleman Weinberg in DFSZ model

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

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

$$\mathrm{v}_S = f_a, \quad \mathrm{v}_{H_1} = \frac{\zeta_1}{\lambda_1} f_a, \quad \mathrm{v}_{H_2} = \frac{\zeta_3}{2\zeta_2}\mathrm{v}_{H_1}$$

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

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

$|S|$ 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

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

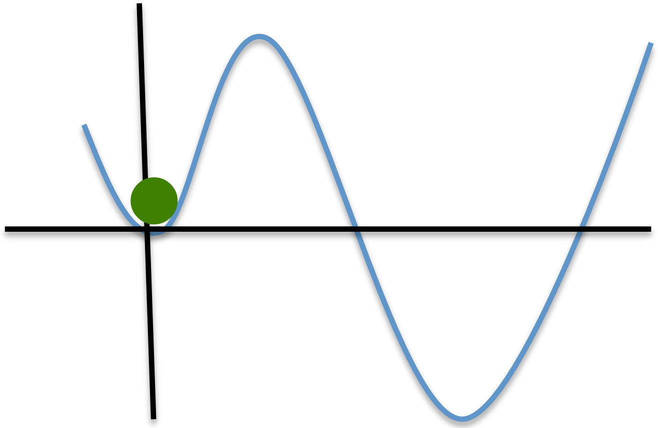
(stored energy after inflation)

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

(stored energy after inflation)

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

$$\rho_S \propto T^4$$



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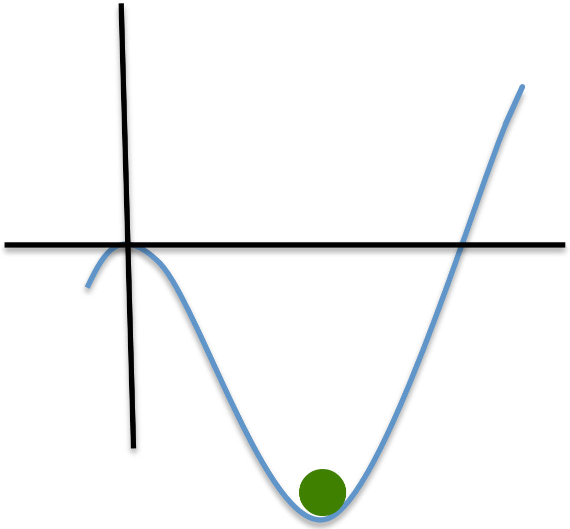

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$$T \sim \Lambda_{QCD}, m_{s,thermal} = 0$$

$$\rho_s \propto T^3 ??$$

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

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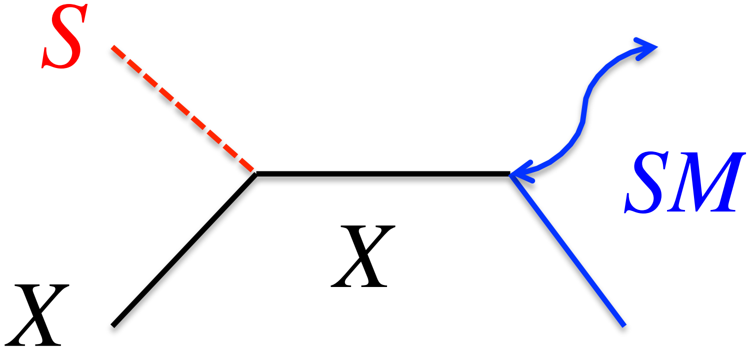
$$S + X \rightleftharpoons SM$$

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



Summary - II

- "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

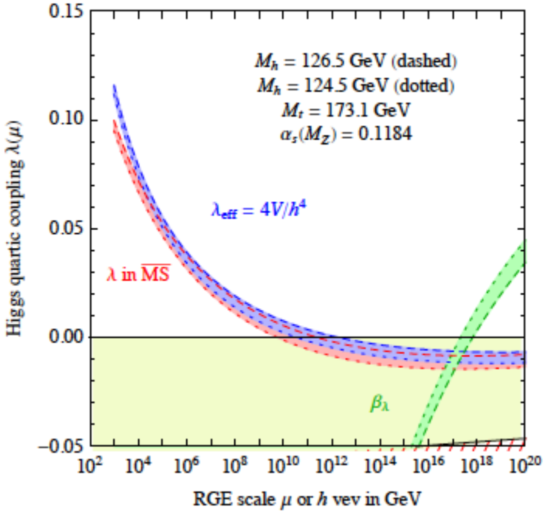
$$m^2_{H^0_2} = m^2_{H^\pm} = m^2_X = R^2 m^2_h \qquad m_{|S|} \simeq 0.9\left(\frac{10^{12}\,GeV}{f_a}\right) R^2 eV$$

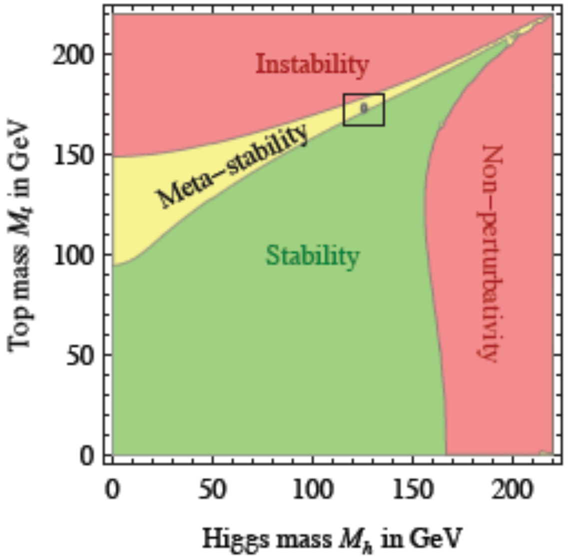
h ≈ SM Higgs

…stable vacuum?

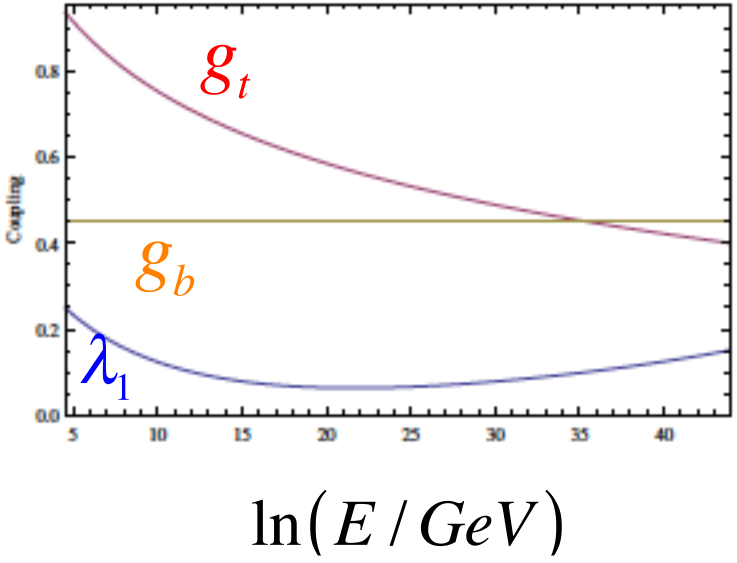
Energy dependence of couplings

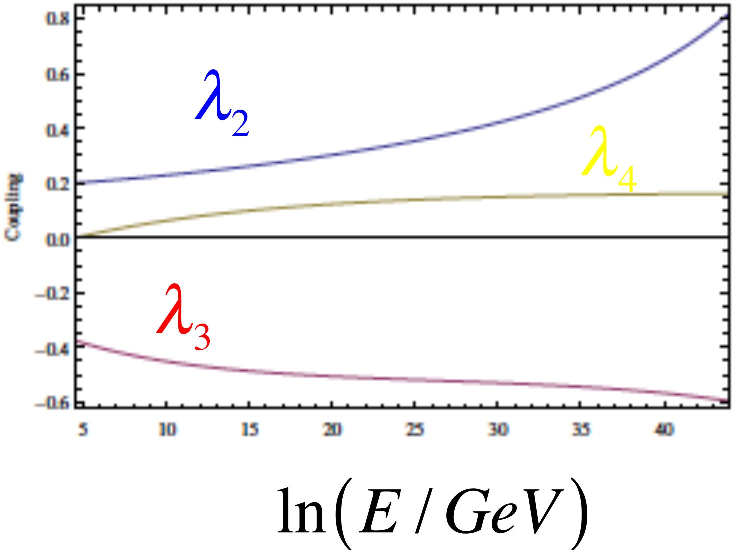
SM:





DFSZ:





Summary - II

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

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  ...stable vacuum but loses simplicity of SM

Summary - II

- "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

- But...

  (i) No unification of forces and matter.

  (II) In Wilsonian sense quadratically divergent terms seem physical