NATURAL SUSY FROM X-DIMENSIONS

FROM THE PLANCK SCALE TO THE ELECTROWEAK SCALE

PLANCK 2016, VALENCIA 23-27 MAY 2016

Mariano Quirós

ICREA/IFAE

Outline

- Introduction
- The MSSM
- Beyond the MSSM
- Scherk-Schwarz supersymmetry breaking
    - The model
    - The supersymmetric spectrum
    - The EW breaking
    - Phenomenology
- Conclusions

Introduction

- ATLAS & CMS have discovered a scalar boson with properties consistent with those of the SM Higgs and a mass 125 GeV
- Whether it actually is the SM Higgs depends on possible (future) deviations from the SM predictions in Higgs strengths (e.g. in the $\gamma\gamma$, or any other, channel)
- However the SM suffers (as any effective theory with cutoff Λ) from a naturalness problem by which the Higgs mass term receives huge (quadratic) corrections

$$\Delta m^2 \simeq -\frac{3}{32\pi^2 v^2}\left(m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right)\Lambda^2$$

- The paradigmatic solution to the problem of quadratic divergences is supersymmetry by which the previous correction cancels out

IN PARTICULAR THE MINIMAL SUPERSYMMETRIC EXTENSION OF THE SM (MSSM)

The MSSM

The MSSM has a number of theoretical drawbacks

- The MSSM has a large number ($\sim 10^2$) of free parameters in the soft supersymmetry breaking sector (many more than the SM). They lower the predictability of the theory
- The supersymmetric parameters are essentially the Yukawa couplings of the SM plus the supersymmetric Higgsino mass μ

$\Rightarrow$ the μ-problem: why $\mu = \mathcal{O}(v)$ and $m_3^2 = \mathcal{O}(v^2)$?

$$W = \mu \widehat{H}_1 \cdot \widehat{H}_2 + \dots, \quad \mathcal{L}_{soft} = -m_3^2 H_1 \cdot H_2 + h.c.$$

Supersymmetric flavor problem

- Supersymmetric partners can create FCNC and CP violating operators
- Standard way out: gravity mediation has to be subdominant ($\sim 0.1\%$ of gauge mediation) unless specific UV boundary conditions!

Little hierarchy problem

- The (running) Higgs mass is logarithmically sensitive to the stop mass

$$\Delta m_H^2 \propto L\, m_t^2 \log(m_{\tilde t}^2/m_t^2), \quad L{=}\text{loop factor}$$

- As $(m_H)^0 \lesssim m_Z$ and $(m_H)^{exp} = 125$ GeV, heavy stops are required

- However, when the stops decouple they leave threshold effects which are quadratically sensitive to the stop mass [1] and destabilize the SM vacuum (unless a fine-tuning is performed)

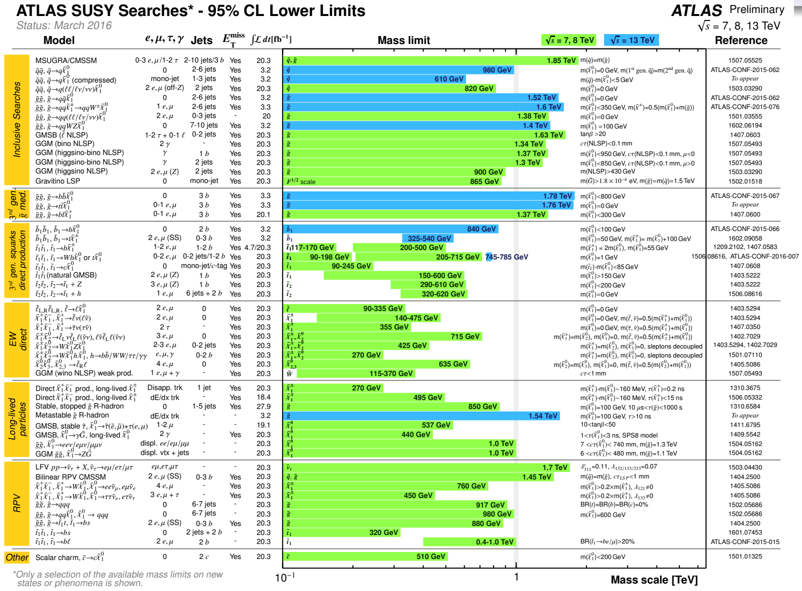
$$\lambda\Delta(v^2) \propto L\, y_t^2 m_{\tilde t}^2$$

The tension between the physical Higgs mass and the stability of the EW vacuum is dubbed: little hierarchy problem

---

[1] I Masina, G Nardini and M Q, "Electroweak vacuum stability and finite quadratic radiative corrections," arXiv:1502.06525 [hep-ph].

Still the main problem is: the absence of evidence from experimental data!



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

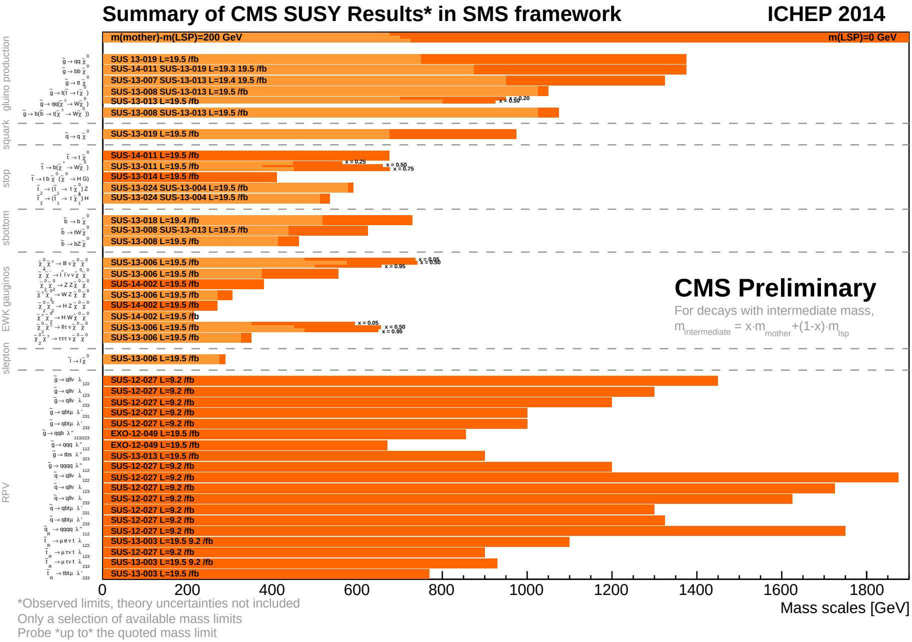
ATLAS Preliminary

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

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

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 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
	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi_1^0$	0	2-6 jets	Yes	3.2	🟦 $\tilde q$ 980 GeV	$m(\tilde\chi_1^0)$=0 GeV, m(1st gen. $\tilde q$)=m(2nd gen. $\tilde q$)	ATLAS-CONF-2015-062
	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde q$ 610 GeV	$m(\tilde q)-m(\tilde\chi_1^0)$<5 GeV	*To appear*
	$\tilde q\tilde q$, $\tilde q\to q(\ell\ell/\ell\nu/\nu\nu)\tilde\chi_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	🟩 $\tilde q$ 820 GeV	$m(\tilde\chi_1^0)$=0 GeV	1503.03290
	$\tilde g\tilde g$, $\tilde g\to q\bar q\tilde\chi_1^0$	0	2-6 jets	Yes	3.2	🟦 $\tilde g$ 1.52 TeV	$m(\tilde\chi_1^0)$=0 GeV	ATLAS-CONF-2015-062
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi_1^\pm\to qqW^\pm\tilde\chi_1^0$	1 e,μ	2-6 jets	Yes	3.3	🟦 $\tilde g$ 1.6 TeV	$m(\tilde\chi_1^0)$<350 GeV, $m(\tilde\chi^\pm)=0.5(m(\tilde\chi_1^0)+m(\tilde g))$	ATLAS-CONF-2015-076
	$\tilde g\tilde g$, $\tilde g\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde\chi_1^0$	2 e,μ	0-3 jets	-	20	🟩 $\tilde g$ 1.38 TeV	$m(\tilde\chi_1^0)$=0 GeV	1501.03555
	$\tilde g\tilde g$, $\tilde g\to qqWZ\tilde\chi_1^0$	0	7-10 jets	Yes	3.2	🟦 $\tilde g$ 1.4 TeV	$m(\tilde\chi_1^0)$ =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	$\tan\beta$ >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	$m(\tilde\chi_1^0)$<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	$m(\tilde\chi_1^0)$<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	$m(\tilde G)>1.8\times10^{-4}$ eV, $m(\tilde g)=m(\tilde q)$=1.5 TeV	1502.01518
3^{rd} gen. $\tilde g$ med.	$\tilde g\tilde g$, $\tilde g\to b\bar b\tilde\chi_1^0$	0	3 b	Yes	3.3	🟦 $\tilde g$ 1.78 TeV	$m(\tilde\chi_1^0)$<800 GeV	ATLAS-CONF-2015-067
	$\tilde g\tilde g$, $\tilde g\to t\bar t\tilde\chi_1^0$	0-1 e,μ	3 b	Yes	3.3	🟦 $\tilde g$ 1.76 TeV	$m(\tilde\chi_1^0)$=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	$m(\tilde\chi_1^0)$<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi_1^0$	0	2 b	Yes	3.2	🟦 $\tilde b_1$ 840 GeV	$m(\tilde\chi_1^0)$<100 GeV	ATLAS-CONF-2015-066
	$\tilde b_1\tilde b_1$, $\tilde b_1\to t\tilde\chi_1^\pm$	2 e,μ (SS)	0-3 b	Yes	3.2	🟦 $\tilde b_1$ 325-540 GeV	$m(\tilde\chi_1^0)$=50 GeV, $m(\tilde\chi_1^\pm)=m(\tilde\chi_1^0)$+100 GeV	1602.09058
	$\tilde t_1\tilde t_1$, $\tilde t_1\to b\tilde\chi_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7/20.3	🟩 $\tilde t_1$ 117-170 GeV 🟩 200-500 GeV	$m(\tilde\chi_1^\pm)=2m(\tilde\chi_1^0)$, $m(\tilde\chi_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde t_1\tilde t_1$, $\tilde t_1\to Wb\tilde\chi_1^0$ or $t\tilde\chi_1^0$	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	$m(\tilde\chi_1^0)$=1 GeV	1506.08616, ATLAS-CONF-2016-007
	$\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi_1^0$	0	mono-jet/c-tag	Yes	20.3	🟩 $\tilde t_1$ 90-245 GeV	$m(\tilde t_1)-m(\tilde\chi_1^0)$<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	$m(\tilde\chi_1^0)$>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	$m(\tilde\chi_1^0)$<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	$m(\tilde\chi_1^0)$=0 GeV	1506.08616
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	🟩 $\tilde\ell$ 90-335 GeV	$m(\tilde\chi_1^0)$=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	🟩 $\tilde\chi_1^\pm$ 140-475 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
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to\tilde\tau\nu(\tau\tilde\nu)$	2 τ	-	Yes	20.3	🟩 $\tilde\chi_1^\pm$ 355 GeV	$m(\tilde\chi_1^0)$=0 GeV, $m(\tilde\tau,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	1407.0350
	$\tilde\chi_1^\pm\tilde\chi_2^0\to\tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu)$, $\ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	20.3	🟩 $\tilde\chi_1^\pm,\tilde\chi_2^0$ 715 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
	$\tilde\chi_1^\pm\tilde\chi_2^0\to W\tilde\chi_1^0Z\tilde\chi_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	🟩 $\tilde\chi_1^\pm,\tilde\chi_2^0$ 425 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde\chi_1^\pm\tilde\chi_2^0\to W\tilde\chi_1^0h\tilde\chi_1^0$, $h\to b\bar b/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde\chi_1^\pm,\tilde\chi_2^0$ 270 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)$=0, sleptons decoupled	1501.07110
	$\tilde\chi_2^0\tilde\chi_3^0$, $\tilde\chi_{2,3}^0\to\tilde\ell_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde\chi_{2,3}^0$ 635 GeV	$m(\tilde\chi_2^0)=m(\tilde\chi_3^0)$, $m(\tilde\chi_1^0)$=0, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi_2^0)+m(\tilde\chi_1^0))$	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 $\tilde\chi_1^\pm$	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, $\tau(\tilde\chi_1^\pm)$=0.2 ns	1310.3675
	Direct $\tilde\chi_1^+\tilde\chi_1^-$ prod., long-lived $\tilde\chi_1^\pm$	dE/dx trk	-	Yes	18.4	🟩 $\tilde\chi_1^\pm$ 495 GeV	$m(\tilde\chi_1^\pm)-m(\tilde\chi_1^0)$~160 MeV, $\tau(\tilde\chi_1^\pm)$<15 ns	1506.05332
	Stable, stopped $\tilde g$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde g$ 850 GeV	$m(\tilde\chi_1^0)$=100 GeV, 10 μs<$\tau(\tilde g)$<1000 s	1310.6584
	Metastable $\tilde g$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde g$ 1.54 TeV	$m(\tilde\chi_1^0)$=100 GeV, τ>10 ns	*To appear*
	GMSB, stable $\tilde\tau$, $\tilde\chi_1^0\to\tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde\chi_1^0$ 537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde\chi_1^0\to\gamma\tilde G$, long-lived $\tilde\chi_1^0$	2 γ	-	Yes	20.3	🟩 $\tilde\chi_1^0$ 440 GeV	1<$\tau(\tilde\chi_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde g\tilde g$, $\tilde\chi_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde\chi_1^0$ 1.0 TeV	7 <$c\tau(\tilde\chi_1^0)$< 740 mm, $m(\tilde g)$=1.3 TeV	1504.05162
	GGM $\tilde g\tilde g$, $\tilde\chi_1^0\to Z\tilde G$	displ. vtx + jets	-	-	20.3	🟩 $\tilde\chi_1^0$ 1.0 TeV	6 <$c\tau(\tilde\chi_1^0)$< 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
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to W\tilde\chi_1^0$, $\tilde\chi_1^0\to ee\tilde\nu_\mu, e\mu\tilde\nu_e$	4 e,μ	-	Yes	20.3	🟩 $\tilde\chi_1^\pm$ 760 GeV	$m(\tilde\chi_1^0)>0.2\times m(\tilde\chi_1^\pm)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to W\tilde\chi_1^0$, $\tilde\chi_1^0\to\tau\tau\tilde\nu_e, e\tau\tilde\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	🟩 $\tilde\chi_1^\pm$ 450 GeV	$m(\tilde\chi_1^0)>0.2\times m(\tilde\chi_1^\pm)$, $\lambda_{133}\neq0$	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
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi_1^0$, $\tilde\chi_1^0\to qqq$	0	6-7 jets	-	20.3	🟩 $\tilde g$ 980 GeV	$m(\tilde\chi_1^0)$=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, $\tilde c\to c\tilde\chi_1^0$	0	2 c	Yes	20.3	🟩 $\tilde c$ 510 GeV	$m(\tilde\chi_1^0)$<200 GeV	1501.01325

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


Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
RPV
SUS 13-019 L=19.5 /fb
SUS-14-011 SUS-13-019 L=19.3 19.5 /fb
SUS-13-007 SUS-13-013 L=19.4 19.5 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-013 L=19.5 /fb
x = 0.20
x = 0.50
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-019 L=19.5 /fb
SUS-14-011 L=19.5 /fb
SUS-13-011 L=19.5 /fb
x = 0.25
x = 0.50
x = 0.75
SUS-13-014 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-024 SUS-13-004 L=19.5 /fb
SUS-13-018 L=19.4 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
SUS-13-006 L=19.5 /fb
x = 0.05
x = 0.50
x = 0.95
SUS-13-006 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-14-002 L=19.5 /fb
SUS-13-006 L=19.5 /fb
x = 0.05
x = 0.50
x = 0.95
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
EXO-12-049 L=19.5 /fb
EXO-12-049 L=19.5 /fb
SUS-13-013 L=19.5 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-13-003 L=19.5 9.2 /fb
SUS-12-027 L=9.2 /fb
SUS-13-003 L=19.5 9.2 /fb
SUS-13-003 L=19.5 /fb
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother +(1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
1600
1800
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

- One idea to alleviate the fine-tuning in the EW vacuum is if the high supersymmetry scale is the Focus Point (FP) of the RGE [2] for large $\tan\beta$
- Experimental data suggest that the decoupling scale of gluinos and sfermions is $\mathcal{Q}_0 \gg \mathcal{Q}_{EW}$
- The FP is then defined by $m^2_{H_2}(\mathcal{Q}_0) = 0$ and invariant under

$$(m^2_Q,\, m^2_U,\, m^2_{H_2},\, M_a,\, A_t) \to\ (\lambda^2\, m^2_Q,\, \lambda^2\, m^2_U,\, \lambda^2\, m^2_{H_2},\, \lambda\, M_a,\, \lambda\, A_t)$$

- and for large $\tan\beta$ the EOM is

$$\frac{m^2_H}{2} \simeq \frac{m^2_{H_1}(\mathcal{Q}_0)}{\tan^2\beta} - |\mu(\mathcal{Q}_0)|^2, \quad m^2_3 \simeq m^2_{H_1}/\tan\beta$$

- So that the fine tuning is minimized for

$$m_{H_1} \simeq \tan\beta m_H, \quad \mu \simeq m_H$$

---

[2] J L Feng, K T Matchev and T Moroi, hep-ph/9909334

Beyond the MSSM

- Independently of the EW vacuum, the experimental value of the Higgs mass (125 GeV) constrains the MSSM parameters:

- Heavy enough stops ($\gtrsim$ TeV scale)
- Large values of $\tan\beta \gg 1$, i.e. $v_2 \gg v_1$: it requires the hierarchy $m_1^2 \gg m_3^2$, $m_2^2 \simeq -m_Z^2/2$ from EW minimum
- Maximum value of LR mixing in stop sector $A_t \simeq \sqrt{6} m_{\tilde{t}}$

which re-creates a little hierarchy problem $\sim (0.1-1)\%$

- Some supersymmetric models are already ruled out by the Higgs discovery at the LHC and by the measurements of Higgs couplings to fermions and gauge bosons

An example is the MSSM from minimal gauge mediation, the paradigmatic mechanism to solve the supersymmetric flavor problem: A_t is generated only at two-loop and very heavy stops are required

An attempt to have a more natural supersymmetric theory and get rid of the little hierarchy problem is going beyond the MSSM (BMSSM) and increasing the tree level Higgs mass by a D-term [3], or an F-term [4]

D-term contribution

- An extra gauge group, on top of the SM one, has to be introduced
- The Higgs sector has to be charged under the extra gauge group
- The D-term contribution easily increases the tree level Higgs mass to cope with experimental values
- However the model requires anomaly cancellation

The simplest way, which does not require to enlarge the gauge group, is by an F term which implies enlarging the MSSM Higgs sector!

---

[3] P Batra, A Delgado, D E Kaplan and T M P Tait, "The Higgs mass bound in gauge extensions of the minimal supersymmetric standard model," hep-ph/0309149

[4] J R Espinosa and M Q, "Gauge unification and the supersymmetric light Higgs mass," Phys. Rev. Lett. **81** (1998) 516 [hep-ph/9804235].

F-term contribution

- The only possibilities are introducing gauge singlets S and/or $SU(2)_L$ triplets T_Y with hypercharge $Y=0,\pm 1$ which can couple to the Higgs sector in the superpotential as

$$W=\lambda_1 S H_1\cdot H_2+\lambda_2 H_1\cdot T_0 H_2+\chi_1 H_1\cdot T_1 H_1+\chi_2 H_2\cdot T_{-1}H_2$$

- Singlets and triplets contribute to the tree-level Higgs mass as

$$\frac{m_h^2}{v^2}=\frac{g^2+g'^2}{2}\cos^2 2\beta+(\lambda_1^2+\lambda_2^2)\sin^2 2\beta+4\chi_1^2\cos^4\beta+4\chi_2^2\sin^4\beta$$

Of course singlets are the simplest solution (NMSSM) to solve the little hierarchy problem (although they contribute only to the Higgs mass for small values of $\tan\beta$)

- However singlet tadpoles are not protected by any symmetry (once local supersymmetry is broken) and can destabilize the hierarchy when they are coupled to heavy states. Bagger, Poppitz and Randall proved [5] that there are 2-loop tadpole divergences
- Way out is if tadpoles are protected by residual symmetry, as e.g. $\mathbb{Z}_3$ but then there is a cosmological domain wall problem as Abel, Sarkar and White showed [6]
- There is not an easy solution, as e.g. introducing gauged $U(1)_R$ symmetry [7] which requires anomaly cancellation
- Tadpoles will trigger wild VEVs for singlets which will mix with the SM Higgs and can destabilize the EW vacuum

---

[5] J Bagger, E Poppitz and L Randall, hep-ph/9505244

[6] S A Abel, S Sarkar and P L White, arXiv:hep-ph/9506359

[7] S A Abel, arXiv:hep-ph/9609323

- Dropping the existence of singlets, the next solution is adding triplets with $|Y| = 0, 1$ (tadpoles forbidden by gauge symmetry)
- It is a particular phenomenologically appealing extension, which includes singly and/or doubly charged states
- Triplets have (as generic non-doublet representations) the general problem that their VEVs contribute to the ρ parameter at the tree-level, strongly constraining the model, as experimentally we know

$$\rho - 1 = \Delta\rho, \qquad -4 \times 10^{-4} < \Delta\rho < 10^{-3} \quad @ \quad 95\% CL$$

- This constraint translates into a few GeV bound on the triplet VEV
- Or into a custodial symmetry in the model in the context of non-supersymmetric [8] and supersymmetric [9] extensions of the SM

Many problems are solved going to X-dim

---

[8] H Georgi, M Machacek, NPB **262** (1985) 463; M Chanowitz, M Golden, PLB **165** (1985) 105; J Gunion, R Vega, J Wudka, PRD **42** (1990) 1673.

[9] L Cort, M Garcia-Pepin and M Q, arXiv:1308.4025 [hep-ph]

SS supersymmetry breaking

- Focus point are boundary conditions which automatically satisfy the equations of the EW minimum:

Potential and EoM

$$V = m_1^2|H_1^0|^2 + m_2^2|H_2^0|^2 - (m_3^2 H_1^0 H_2^0 + h.c.) + \frac{g^2+g'^2}{8}(|H_1^0|^2 - |H_2^0|^2)^2$$

$$\frac{g^2+g'^2}{4}v^2 = \left[\frac{m_1^2 - m_2^2}{\sqrt{(m_1^2+m_2^2)^2 - 4m_3^4}} - 1\right](m_1^2 + m_2^2)$$

- In particular if boundary conditions are such that

$$m_1^2 = m_2^2 = m_3^2 = \mathrm{arbitrary}$$

  the EoM is satisfied for $v = 0$ and breaking is radiative
- This is what happens in SS (non-maximal) breaking

The model

- The model is based on a 5D theory compactified on an interval (orbifold): $S^1/\mathbb{Z}_2$, with two 4D branes at the fixed points $y = 0, \pi R$
- Gauge bosons, at least first and second generation matter (and possibly $\tilde{\tau}_R$) and the Higgs sector are propagating in the bulk
- In the bulk there is $N = 2$ supersymmetry and matter is in $N = 2$ hypermultiplets, e.g. $\mathbb{H}_a = (H_a, H_a^c, \Psi_a, F_a, F_a^c)$ where Ψ_a are Dirac
- Zero modes have $N = 1$ (orbifold boundary conditions)
- $N = 1$ supersymmetry is broken by twisted (SS) boundary conditions with parameter $0 < \omega < 1/2$ (non-maximal): units $R \equiv 1$

$$\begin{bmatrix} H_1(x,y) & H_1^c(x,y) \\ H_2^c(x,y) & H_2(x,y) \end{bmatrix} =$$

$$e^{i\omega\sigma_2 y} \sum_{n=0}^{\infty} \sqrt{\frac{2}{\pi}} \begin{bmatrix} \cos ny\, H_1^{(n)}(x) & \sin ny\, H_1^{c(n)}(x) \\ \sin ny\, H_2^{c(n)}(x) & \cos ny\, H_2^{(n)}(x) \end{bmatrix} e^{-i\omega\sigma_2 y}$$

The spectrum

- The tree-level spectrum is [10]
  - For first and second generation sfermions (and $\tilde{\tau}_R$) and gauginos

$$M_a = m_{\tilde{f}} = \frac{\omega}{R}$$

  - For the Higgs sector

$$m_1^2 = m_2^2 = m_3^2 = \frac{\omega}{R} \quad \Longrightarrow \quad v = 0,\ \tan\beta = 1,\ m_h = 0,\ m_H = \frac{2\omega}{R}$$

- EW symmetry is unbroken at the tree level (it requires radiative breaking) and the Higgs mass is zero at tree level ($\tan\beta = 1$)

---

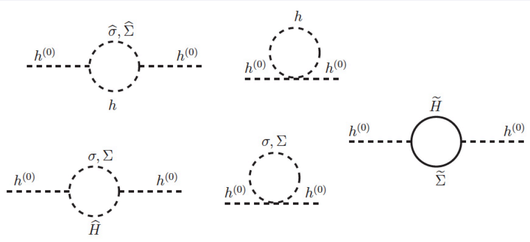
[10] I Antoniadis, S Dimopoulos, A Pomarol and M Q, hep-ph/9810410
A Delgado, A Pomarol and M Q, [hep-ph/9812489]
S Dimopoulos, K Howe and J March-Russell, arXiv:1404.7554 [hep-ph]
I G Garcia, K Howe and J March-Russell, arXiv:1510.07045 [hep-ph].

EW breaking

- Both issues are fixed by introducing Higgs triplets $\mathcal{T}_a$ in the bulk with (e.g.) $Y=0$ (which trigger a tree-level Higgs mass F-term at small values of $\tan\beta$) and coupled by a superpotential term

$$W=\left(\lambda_1^{5D}\ \mathcal{H}_1\cdot\mathcal{T}_1\mathcal{H}_2+\lambda_2^{5D}\ \mathcal{H}_1\cdot\mathcal{T}_2\mathcal{H}_2\right)\delta(y)$$

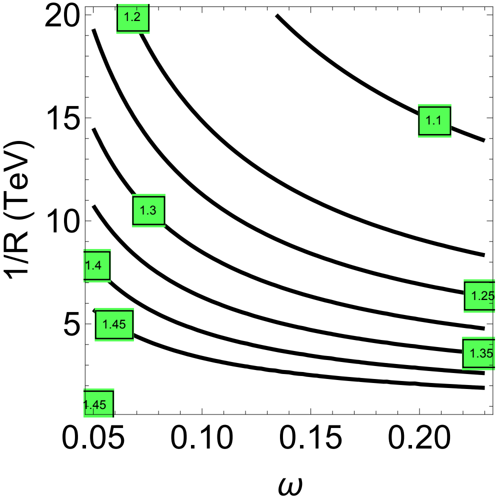
- EW breaking is triggered by one-loop radiative corrections as [11]



---

[11] A Delgado, M Garcia-Pepin, G Nardini and M Q, arXiv:1605.XXXXX

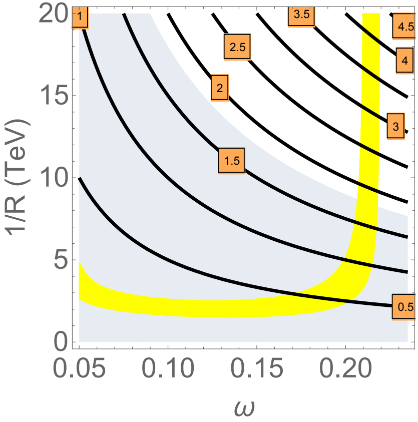
The Higgs mass is easily fixed

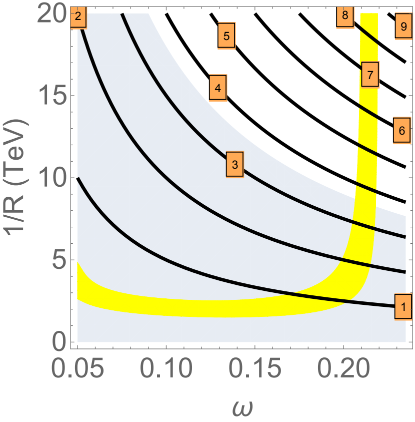


Contour plot of values of $|\lambda_1 - \lambda_2|$

- The region (yellow) of radiative EWSB is stable under $1/R \to \lambda\ 1/R$ for vertical yellow region (FP). $\lambda_1 + \lambda_2 > 0$ (inner bound)

Masses of bulk sfermions and gauginos | Heavy Higgses

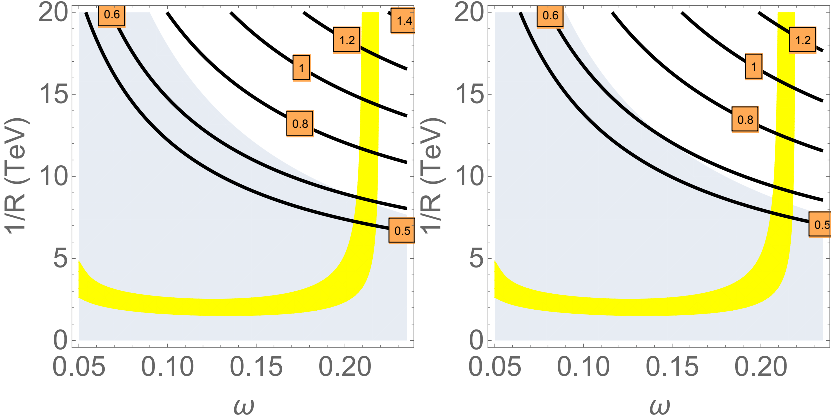




- Region of $M_3 < 1.9$ TeV (shadowed) excluded by ATLAS & CMS

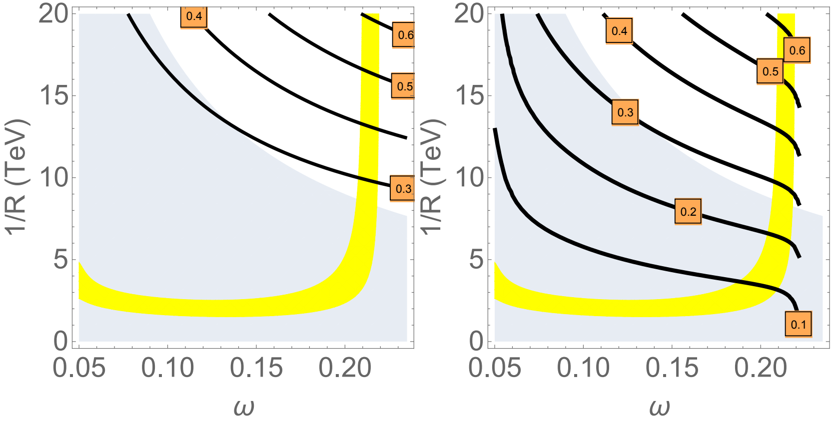
- Third generation matter is localized at the brane $y = 0$
- It is massless at the tree level
- Stops and sbottoms receive a mass from (finite) radiative corrections

Heavier stop Lighter stop



- As well as the third generation slepton doublet and light triplet

$\tilde{\ell}_3$ Light triplet



The global picture is

- Above the scale $\mathcal{Q} \sim 1/R$ the theory is 5D
- At the scale $\mathcal{Q} \sim \omega/R$ all KK modes (e.g. triplets) are integrated out and yield (finite) threshold effects triggering radiative EWSB
- Below the scale $\mathcal{Q} = \omega/R$ the theory is the 4D SM plus light scalars (e.g. stops), with masses at $\lesssim$TeV
- At the scale $m_{\tilde{t}} \simeq 600 - 800$ GeV stops decouple and yield quadratic corrections to the Higgs mass (thresholds)

$$\Delta m_H^2 \simeq \frac{12}{32\pi^2} h_t^2 m_{\tilde{t}}^2 \simeq \left(10^2 \text{ GeV}\right)^2$$

which do not destabilize the EW minimum

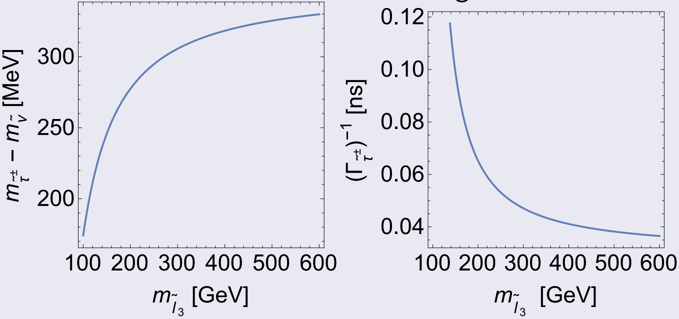
- The LSP is the third generation $\tilde{\nu}_L$
- The NLSP is the $\tilde{\tau}_L$

Phenomenology

The low energy theory is SM + $\tilde{\ell}_3$ + stops/sbottoms + scalar triplet

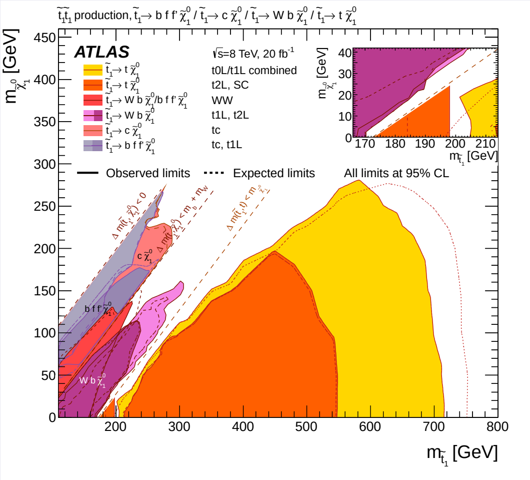
$\tilde{\ell}_3$

- The $\tilde{\tau}_L$ mass receives a QED correction and gets heavier than $\tilde{\nu}_{\tau_L}$



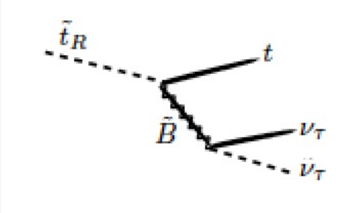
- The signal is disappearing track. ATLAS and CMS put bounds for long-lived charged particles $\Rightarrow m_{\tilde{\ell}_3} > 150$ GeV
- From gluino bounds: $m_{\tilde{\ell}_3} \gtrsim 280$ GeV

ATLAS stop searches: $\tilde{t} \to t + LSP$



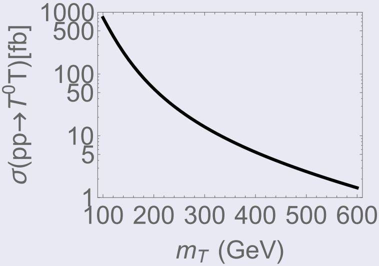
For $m_{LSP} \gtrsim 280$ GeV there is no bound on $m_{\tilde{t}}$

Stops



- The decay of light stops proceeds through off-shell gauginos.
- The rate is prompt for the scales in the model
- The signatures will involve MET
- From gluino bounds: $m_{\tilde{t}} \gtrsim 550$ GeV

Triplets (DY production cross section)



- If triplets are light they could be produced at LHC
- For heavy triplets we should go to a 100 TeV collider
- From gluino bounds: $m_T \gtrsim 280$ GeV

Conclusion

- The model has only two continuous parameters: ω and $1/R$
- The model solves automatically the μ-problem as it provides a supersymmetry breaking mass to Higgsinos
- The Higgs mass is reproduced by introducing triplets
- The model solves automatically at tree level the EoM with $\tan\beta = 1$ and $v = 0$, and triplets trigger radiative breaking with the FP property
$$\frac{1}{R} \to \lambda \frac{1}{R}$$
which allows to go to pretty heavy spectra
- First and second generation squarks (which do not enter the hierarchy problem) are much heavier than the third one $\Rightarrow$ no flavor problem
- Third generation squarks are sub-TeV $\Rightarrow$ no little hierarchy problem
- The LSP is $\tilde{\nu}_{\tau_L}$ and the NLSP the $\tilde{\tau}_L$
- The effective 4D theory is: the SM supplemented with stop/sbottom, third generation slepton doublet and one scalar triplet