Super-Natural Supersymmetry

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May 16, 2014

Outline

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Introduction

The SUSY EW Fine-Tuning Problem

The MSSM with Heavy LSP

No-Scale $\mathcal{F}$-$SU(5)$

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Conclusion

Standard Model:

- Fine-tuning problems:
  cosmological constant problem; gauge hierarchy problem; strong CP problem; SM fermion masses and mixings; ...

Standard Model:

- Fine-tuning problems:
  cosmological constant problem; gauge hierarchy problem; strong CP problem; SM fermion masses and mixings; ...
- Aesthetic problems: interaction and fermion unification; gauge coupling unification; charge quantization; too many parameters; ...

The Supersymmetric Standard Models:

- Solving the gauge hierarchy problem
- Gauge coupling unification
- Radiatively electroweak symmetry breaking
- Natural dark matter candidates
- Electroweak baryogenesis
- Electroweak precision: R parity

Problems in the MSSM:

- μ problem: $\mu H_u H_d$
- Little hierarchy problem
- CP violation and EDMs
- FCNC
- Dimension-5 proton decays

The Grand Unified Theories: $SU(5)$, and $SO(10)$

- Unification of the gauge interactions, and unifications of the SM fermions
- Charge quantization
- Gauge coupling unification in the MSSM, and Yukawa unification
- Radiative electroweak symmetry breaking due to the large top quark Yukawa coupling
- Weak mixing angle at weak scale M_Z
- Neutrino masses and mixings by seesaw mechanism

Problems:

- Gauge symmetry breaking
- Doublet-triplet splitting problem
- Proton decay problem
- Fermion mass problem: $m_e/m_\mu = m_d/m_s$

String Models:

- Calabi-Yau compactification of heterotic string theory
- Orbifold compactification of heterotic string theory

  Grand Unified Theory (GUT) can be realized naturally through the elegant E_8 breaking chain:

  $E_8 \supset E_6 \supset SO(10) \supset SU(5)$
- D-brane models on Type II orientifolds

  N stacks of D-branes gives us $U(N)$ gauge symmetry: Pati-Salam Models
- Free fermionic string model builing

  Realistic models with clean particle spectra can only be constructed at the Kac-Moody level one: the Standard-like models, Pati-Salam models, and flipped $SU(5)$ models.

$\mathcal{F}$-Theory Model Building:

- The models are constructed locally, and then the gravity should decoupled, *i.e.*, $M_{\rm GUT}/M_{\rm Pl}$ is a small number.
- The $SU(5)$ and $SO(10)$ gauge symmetries can be broken by the $U(1)_Y$ and $U(1)_X/U(1)_{B-L}$ fluxes.
- Gauge mediated supersymmetry breaking can be realized via instanton effects. Gravity mediated supersymmetry breaking predicts the gaugino mass relation.
- All the SM fermion Yuakwa couplings can be generated in the $SU(5)$ and $SO(10)$ models.
- The doublet-triplet splitting problem, proton decay problem, μ problem as well as the SM fermion masses and mixing problem can be solved.

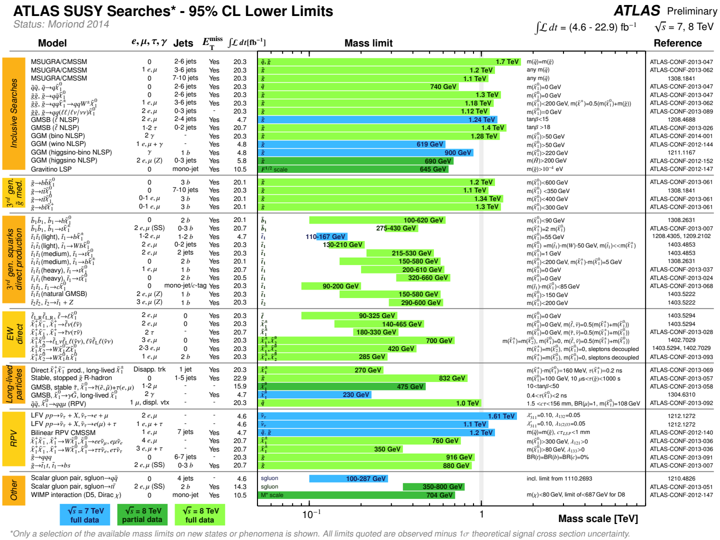
Outline

Higgs boson mass in the MSSM:

- The SM-like Higgs boson mass is around 126 GeV.
- The tree-level Higgs boson mass is smaller than M_Z.
- The Higgs boson mass is enhanced by the top quarks/squarks loop corrections.
- The maximal stop mixing is needed to relax the fine-tuning.

The LHC Supersymmetry Search Contraints:

- The gluino and squark mass low bounds are around 1.7 TeV in the CMSSM/mSUGRA
- The gluino mass low bound is around 1.3 TeV.
- The stop/sbottom mass low bounds are around 600 GeV.
- If the LSP is heavy enough, all the bounds will be gone.



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Moriond 2014

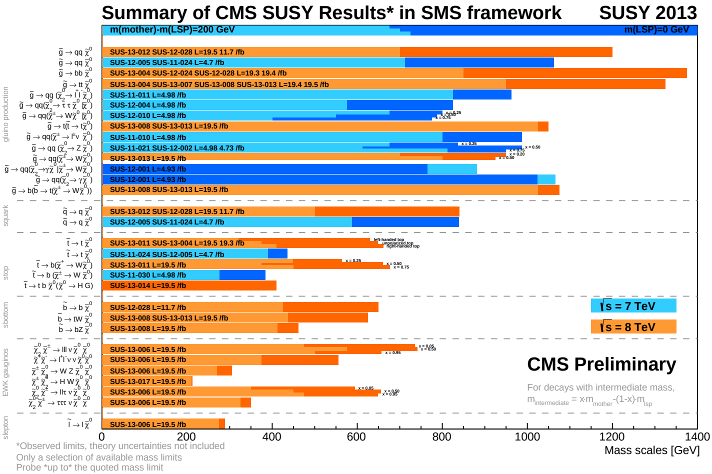
ATLAS Preliminary

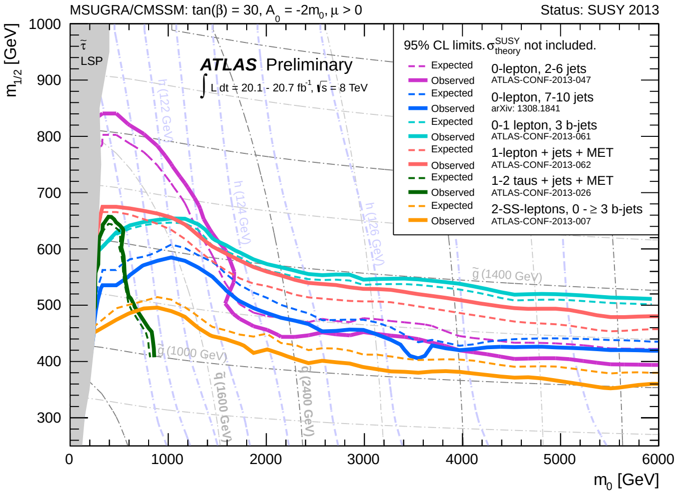
$\int \mathcal{L}\, dt$ = (4.6 - 22.9) fb^{-1} $\sqrt{s}$ = 7, 8 TeV

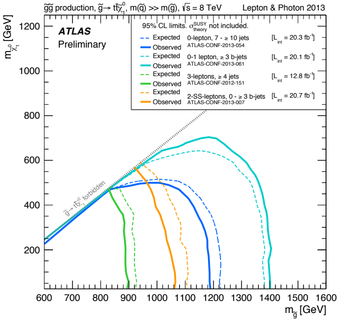
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}$, $\tilde{q} \to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	740 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g} \to qq\tilde{\chi}_1^\pm \to qqW^\pm\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	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
	$\tilde{g}\tilde{g}$, $\tilde{g} \to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	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.	$\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.2 TeV	m($\tilde{\chi}_1^0$)<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$	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
	$\tilde{g} \to b\bar{t}\tilde{\chi}_1^+$	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	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1 \to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1 \to t\tilde{\chi}_1^\pm$	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), $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$	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), $\tilde{t}_1 \to Wb\tilde{\chi}_1^0$	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), $\tilde{t}_1 \to t\tilde{\chi}_1^0$	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), $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$	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), $\tilde{t}_1 \to t\tilde{\chi}_1^0$	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), $\tilde{t}_1 \to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$	320-660 GeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1 \to c\tilde{\chi}_1^0$	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
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2 \to \tilde{t}_1 + Z$	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	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell} \to \ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+ \to \tilde{\ell}\nu(\ell\tilde{\nu})$	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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+ \to \tilde{\tau}\nu(\tau\tilde{\nu})$	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
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to \tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	700 GeV	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
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	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
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0 \to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$	285 GeV	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 $\tilde{\tau}$, $\tilde{\chi}_1^0 \to \tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0 \to \gamma\tilde{G}$, 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
	$\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0 \to qq\mu$ (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 $pp \to \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \to e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp \to \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \to e(\mu) + \tau$	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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+ \to W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$	760 GeV	m($\tilde{\chi}_1^0$)>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+ \to W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to \tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$	350 GeV	m($\tilde{\chi}_1^0$)>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g} \to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g} \to \tilde{t}_1 t$, $\tilde{t}_1 \to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$	880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	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

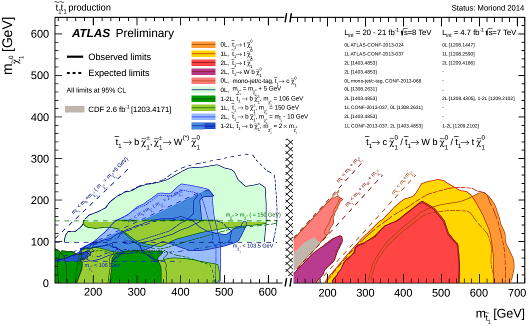
$\sqrt{s}$ = 7 TeV full data	$\sqrt{s}$ = 8 TeV partial data	$\sqrt{s}$ = 8 TeV full data

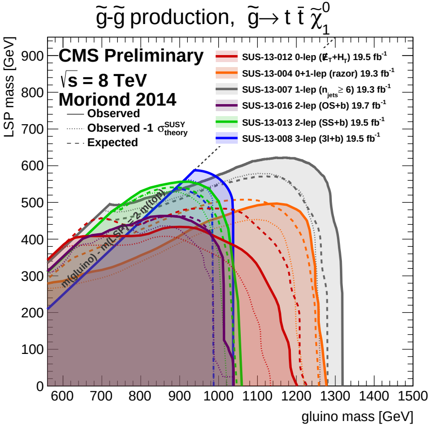
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

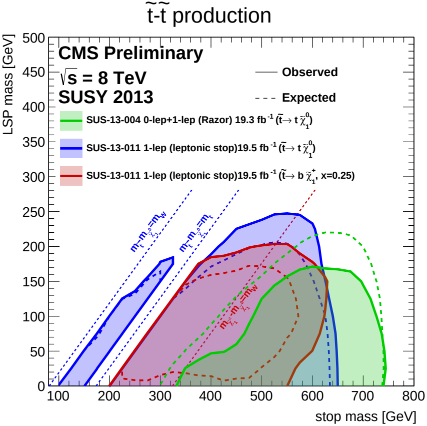

Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
squark
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
stop
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
SUS-13-014 L=19.5 /fb
sbottom
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
EWK gauginos
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
slepton
SUS-13-006 L=19.5 /fb
x = 0.25
x = 0.50
x = 0.75
x = 0.20
x = 0.05
x = 0.95
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother -(1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit


MSUGRA/CMSSM: tan(β) = 30, $A_0 = -2m_0$, μ > 0
Status: SUSY 2013
ATLAS Preliminary
$\int L\,dt = 20.1 - 20.7\ \mathrm{fb}^{-1}$, $\sqrt{s} = 8$ TeV
$\tilde{\tau}$ LSP
95% CL limits. σ^{SUSY}_{theory} not included.
Expected / Observed — 0-lepton, 2-6 jets — ATLAS-CONF-2013-047
Expected / Observed — 0-lepton, 7-10 jets — arXiv: 1308.1841
Expected / Observed — 0-1 lepton, 3 b-jets — ATLAS-CONF-2013-061
Expected / Observed — 1-lepton + jets + MET — ATLAS-CONF-2013-062
Expected / Observed — 1-2 taus + jets + MET — ATLAS-CONF-2013-026
Expected / Observed — 2-SS-leptons, 0 - ≥ 3 b-jets — ATLAS-CONF-2013-007
h (122 GeV)
h (124 GeV)
h (126 GeV)
$\tilde{g}$ (1400 GeV)
$\tilde{g}$ (1000 GeV)
$\tilde{q}$ (1600 GeV)
$\tilde{q}$ (2400 GeV)
$m_{1/2}$ [GeV]
1000
900
800
700
600
500
400
300
0
1000
2000
3000
4000
5000
6000
m_0 [GeV]


$\tilde{g}\tilde{g}$ production, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$, $m(\tilde{q}) >> m(\tilde{g})$, $\sqrt{s}$ = 8 TeV
Lepton & Photon 2013
ATLAS
Preliminary
95% CL limits. σ_{theory}^{SUSY} not included.
Expected
Observed
0-lepton, 7 - ≥ 10 jets
ATLAS-CONF-2013-054
[L_{int} = 20.3 fb^{-1}]
Expected
Observed
0-1 lepton, ≥ 3 b-jets
ATLAS-CONF-2013-061
[L_{int} = 20.1 fb^{-1}]
Expected
Observed
3-leptons, ≥ 4 jets
ATLAS-CONF-2012-151
[L_{int} = 12.8 fb^{-1}]
Expected
Observed
2-SS-leptons, 0 - ≥ 3 b-jets
ATLAS-CONF-2013-007
[L_{int} = 20.7 fb^{-1}]
$\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$ forbidden
$m_{\tilde{\chi}_1^0}$ [GeV]
1200
1000
800
600
400
200
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
$m_{\tilde{g}}$ [GeV]


$\tilde{t}_1\tilde{t}_1$ production
Status: Moriond 2014
ATLAS Preliminary
Observed limits
Expected limits
All limits at 95% CL
CDF 2.6 fb^{-1} [1203.4171]
L_{int} = 20 - 21 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
0L, $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$
0L ATLAS-CONF-2013-024
0L [1208.1447]
1L, $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$
1L ATLAS-CONF-2013-037
1L [1208.2590]
2L, $\tilde{t}_1\rightarrow t\tilde{\chi}_1^0$
2L [1403.4853]
2L [1209.4186]
2L, $\tilde{t}_1\rightarrow W b\tilde{\chi}_1^0$
2L [1403.4853]
-
0L, mono-jet/c-tag, $\tilde{t}_1\rightarrow c\tilde{\chi}_1^0$
0L mono-jet/c-tag, CONF-2013-068
-
0L, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$ + 5 GeV
0L [1308.2631]
-
1-2L, $\tilde{t}_1\rightarrow b\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm}$ = 106 GeV
2L [1403.4853]
2L [1208.4305], 1-2L [1209.2102]
1L, $\tilde{t}_1\rightarrow b\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm}$ = 150 GeV
1L CONF-2013-037, 0L [1308.2631]
-
2L, $\tilde{t}_1\rightarrow b\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1}$ - 10 GeV
2L [1403.4853]
-
1-2L, $\tilde{t}_1\rightarrow b\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = 2\times m_{\tilde{\chi}_1^0}$
1L CONF-2013-037, 2L [1403.4853]
1-2L [1209.2102]
$\tilde{t}_1\rightarrow b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm\rightarrow W^{(*)}\tilde{\chi}_1^0$
$\tilde{t}_1\rightarrow c\tilde{\chi}_1^0 / \tilde{t}_1\rightarrow W b\tilde{\chi}_1^0 / \tilde{t}_1\rightarrow t\tilde{\chi}_1^0$
$m_{\tilde{\chi}_1^\pm} > m_{\tilde{\chi}_1^0}$ (= 150 GeV)
$m_{\tilde{\chi}_1^\pm}$ < 103.5 GeV
$m_{\tilde{\chi}_1^\pm}$ < 106 GeV
$m_{\tilde{\chi}_1^0}$ [GeV]
600
500
400
300
200
100
0
200
300
400
500
600
200
300
400
500
600
700
$m_{\tilde{t}_1}$ [GeV]


$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow t\,\bar{t}\,\tilde{\chi}^0_1$
CMS Preliminary
$\sqrt{s}$ = 8 TeV
Moriond 2014
Observed
Observed -1 σ^{SUSY}_{theory}
Expected
SUS-13-012 0-lep ($\not{E}_T$+H_T) 19.5 fb^{-1}
SUS-13-004 0+1-lep (razor) 19.3 fb^{-1}
SUS-13-007 1-lep ($n_{jets} \geq 6$) 19.3 fb^{-1}
SUS-13-016 2-lep (OS+b) 19.7 fb^{-1}
SUS-13-013 2-lep (SS+b) 19.5 fb^{-1}
SUS-13-008 3-lep (3l+b) 19.5 fb^{-1}
m(gluino) - m(LSP) = 2 m(top)
LSP mass [GeV]
0
100
200
300
400
500
600
700
800
900
600
700
800
900
1000
1100
1200
1300
1400
1500
gluino mass [GeV]


$\tilde{t}$-$\tilde{t}$ production
CMS Preliminary
$\sqrt{s}$ = 8 TeV
SUSY 2013
Observed
Expected
SUS-13-004 0-lep+1-lep (Razor) 19.3 fb^{-1} ($\tilde{t} \rightarrow t\,\tilde{\chi}^0_1$)
SUS-13-011 1-lep (leptonic stop)19.5 fb^{-1} ($\tilde{t} \rightarrow t\,\tilde{\chi}^0_1$)
SUS-13-011 1-lep (leptonic stop)19.5 fb^{-1} ($\tilde{t} \rightarrow b\,\tilde{\chi}^+_1$, x=0.25)
$m_{\tilde{t}} - m_{\tilde{\chi}^0_1} = m_W$
$m_{\tilde{t}} - m_{\tilde{\chi}^0_1} = m_t$
$m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1} = m_W$
LSP mass [GeV]
0
50
100
150
200
250
300
350
400
450
500
100
200
300
400
500
600
700
800
stop mass [GeV]

Fine-Tuning Definition I:

- Electroweak symmetry breaking condition

$$\mu^2 + \frac{1}{2} M_Z^2 = \frac{\overline{m}_{H_d}^2 - \overline{m}_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} ~.$$

- Fine-tuning Definition I [1]: the quantitative measure $\Delta_{\rm FT}$ for fine-tuning is the maximum of the logarithmic derivative of M_Z with respect to all the fundamental parameters a_i at the GUT scale

$$\Delta_{\rm FT} ~=~ {\rm Max}\{\Delta_i^{\rm GUT}\} ~,~~~ \Delta_i^{\rm GUT} ~=~ \left| \frac{\partial {\rm ln}(M_Z)}{\partial {\rm ln}(a_i^{\rm GUT})} \right| ~.$$

---

[1] J. R. Ellis, K. Enqvist, D. V. Nanopoulos and F. Zwirner, Mod. Phys. Lett. A **1**, 57 (1986); R. Barbieri and G. F. Giudice, Nucl. Phys. B **306**, 63 (1988).

Fine-Tuning Definition II

- Higgs potential:

$$V = \overline{m}_h^2 |h|^2 + \frac{\lambda_h}{4} |h|^4 ~.$$

- Higgs boson mass

$$m_h^2 = -2\overline{m}_h^2 ~, \quad \overline{m}_h^2 \simeq |\mu|^2 + m_{H_u}^2|_{\rm tree} + m_{H_u}^2|_{\rm rad} ~.$$

- The fine-tuning measure [2]:

$$\Delta_{\rm FT} \equiv \frac{2\delta\overline{m}_h^2}{m_h^2} ~.$$

---

[2] R. Kitano and Y. Nomura, Phys. Lett. B **631**, 58 (2005) [hep-ph/0509039]; Phys. Rev. D **73**, 095004 (2006) [hep-ph/0602096].

Fine-Tuning Definition II

- The μ term or effective μ term is smaller than 400 GeV.
- The squar root $M_{\tilde{t}} \equiv \sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}$ of the sum of the two stop mass squares is smaller than 1.2 TeV.
- The gluino mass is lighter than 1.5 TeV.

Fine-Tuning Definition III

- The minimization condition for electroweak symmetry breaking

$$\frac{M_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \ .$$

- The fine-tuning measure [3]

$$\Delta_{\rm FT} \equiv {\rm Max}\{\frac{2C_i}{M_Z^2}\} \ .$$

---

[3] H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev and X. Tata, Phys. Rev. D **87**, no. 11, 115028 (2013) [arXiv:1212.2655 [hep-ph]].

Comments on Fine-Tuning

- Fine-Tuning Definition III is weak.
- Fine-Tuning Definition II is medium.
- Fine-Tuning Definition I is strong.

Supersymmetric SMs:

- Natural supersymmetry [4].
- Supersymmetric models with a TeV-scale squarks that can escape/relax the missing energy constraints: R parity violation [5]; compressed supersymmetry [6] ; stealth supersymmetry [7]; etc.

---

[4] S. Dimopoulos and G. F. Giudice, Phys. Lett. B **357**, 573 (1995) [hep-ph/9507282]; A. G. Cohen, D. B. Kaplan and A. E. Nelson, Phys. Lett. B **388**, 588 (1996) [hep-ph/9607394].

[5] R. Barbier, C. Berat, M. Besancon, M. Chemtob, A. Deandrea, E. Dudas, P. Fayet and S. Lavignac *et al.*, Phys. Rept. **420**, 1 (2005) [hep-ph/0406039].

[6] T. J. LeCompte and S. P. Martin, Phys. Rev. D **84**, 015004 (2011) [arXiv:1105.4304 [hep-ph]]; Phys. Rev. D **85**, 035023 (2012) [arXiv:1111.6897 [hep-ph]].

[7] J. Fan, M. Reece and J. T. Ruderman, JHEP **1111**, 012 (2011) [arXiv:1105.5135 [hep-ph]]; arXiv:1201.4875 [hep-ph].

Supersymmetric SMs:

- Supersymmetric models with sub-TeV squarks that decrease the cross sections: supersoft supersymmetry [8].
- Displaced Supersymmetry [9].
- Double Invisible Supersymmetry [10].

---

[8] G. D. Kribs and A. Martin, arXiv:1203.4821 [hep-ph], and references therein.

[9] P. W. Graham, D. E. Kaplan, S. Rajendran and P. Saraswat, JHEP **1207**, 149 (2012) [arXiv:1204.6038 [hep-ph]].

[10] J. Guo, Z. Kang, J. Li, T. Li and Y. Liu, arXiv:1312.2821 [hep-ph]; D. S. M. Alves, J. Liu and N. Weiner, arXiv:1312.4965 [hep-ph].

Outline

Why the LHC supersymmetry search constraints can be relaxed for the heavy LSP?

- $p_T^{\rm miss}$
- The energy scale of an event: h_T

$$h_T = \sum_{i=1}^{N_{jet}} p_T^i ~.$$

- The effective mass of an event: $m_{\rm eff}$

$$m_{\rm eff} = \not{E}_T + \sum_{i=1}^{N_{jet}} p_T^i ~.$$

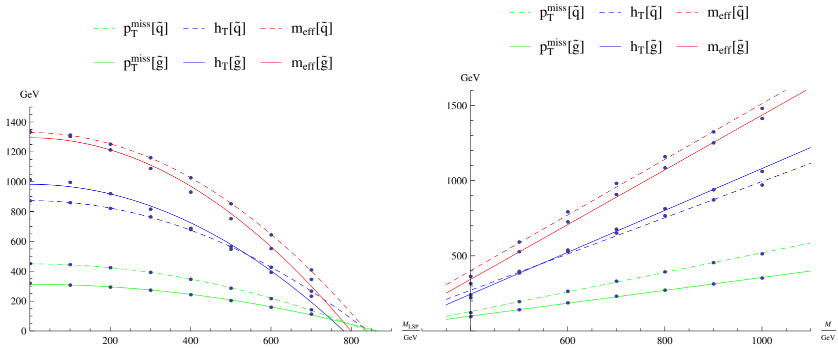


Figure : The behaviour of p_T^{miss}, h_T and $m_{\rm eff}$ for $\tilde{q}\bar{\tilde{q}}$ and $\tilde{g}\tilde{g}$ pair production, with subsequent decay $\tilde{q} \to q\tilde{\chi}$ and $\tilde{g} \to qq\tilde{\chi}$, respectively. Left: $m_{\tilde{q}/\tilde{g}} = 800$ GeV and scan over $m_{\tilde{\chi}}$ in [0,700] GeV. Right: $m_{\tilde{\chi}} = 300$ GeV and scan over $m_{\tilde{q}/\tilde{g}}$ in [400,1000] GeV. The black dots are simulated number and fitted by corresponding color line.

Parameter space scan

- The muon anomalous magnetic moment $a_\mu = (g-2)/2$

$$a_\mu \quad = \quad (28.7 \pm 8) \times 10^{-10} ~.$$

- Higgs boson mass

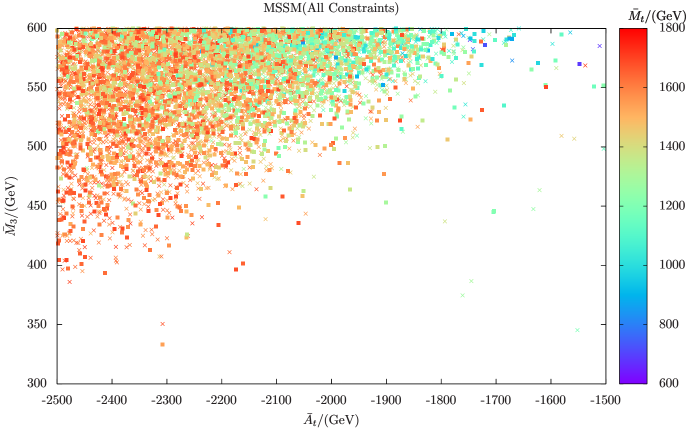
$$123.0 \text{ GeV} \leq m_h \leq 127.0 \text{ GeV} ~.$$

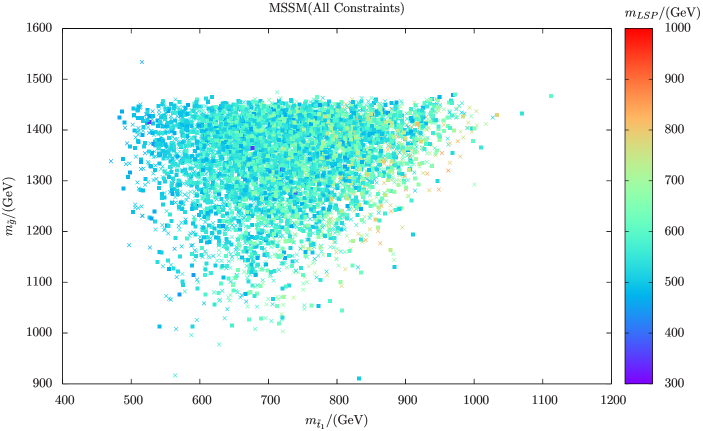
- LHCb

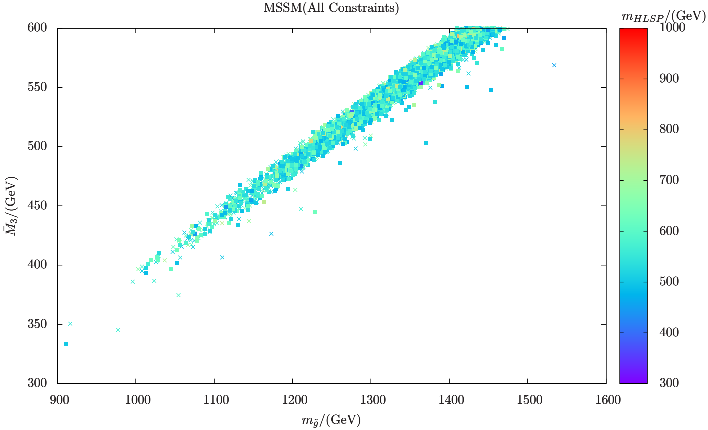
$$\mathrm{Br}(B_s \rightarrow \mu^+ \mu^-) \quad = \quad 3.2^{+1.5}_{-1.2} \times 10^{-9} ~.$$

Input parameters

$$\tan\beta : [15, 40], \quad \mu : [500, 1000]~\text{GeV}, \quad M_A : [200, 2500]~\text{GeV},$$
$$\bar{M}_1 : [1200, 2500]~\text{GeV}, \quad \bar{M}_2 : [600, 1200]~\text{GeV}, \quad \bar{M}_3 : [330, 600]~\text{GeV},$$
$$\bar{A}_t : [-2500, 2500]~\text{GeV}, \quad \bar{m}_{L_{2,3}} : [400, 1000]~\text{GeV}, \quad \bar{m}_{e_{2,3}} : [400, 1000]~\text{Ge}$$
$$\bar{m}_{Q_3} : [200, 1400]~\text{GeV}, \quad \bar{m}_{U_3} : [200, 1700]~\text{GeV}, \quad \bar{m}_{D_3} : [100, 1900]~\text{GeV},$$
$$\bar{A}_b : [-2000, 2000]~\text{GeV}, \quad \bar{A}_l = 0~\text{GeV}, \quad \bar{m}_{Q_2,U_2,D_2} : [1500, 3000]~\text{GeV}~.$$


MSSM(All Constraints)
$\bar{M}_3/(\mathrm{GeV})$
600
550
500
450
400
350
300
-2500
-2400
-2300
-2200
-2100
-2000
-1900
-1800
-1700
-1600
-1500
$\bar{A}_t/(\mathrm{GeV})$
$\bar{M}_t/(\mathrm{GeV})$
1800
1600
1400
1200
1000
800
600


MSSM(All Constraints)
$m_{LSP}/(\mathrm{GeV})$
1000
900
800
700
600
500
400
300
$m_{\tilde{g}}/(\mathrm{GeV})$
1600
1500
1400
1300
1200
1100
1000
900
$m_{\tilde{t}_1}/(\mathrm{GeV})$
400
500
600
700
800
900
1000
1100
1200


MSSM(All Constraints)
$m_{HLSP}/(\mathrm{GeV})$
1000
900
800
700
600
500
400
300
600
550
500
450
400
350
300
$\bar{M}_3/(\mathrm{GeV})$
900
1000
1100
1200
1300
1400
1500
1600
$m_{\tilde{g}}/(\mathrm{GeV})$

$\widetilde{\chi}_1^0$	629.2	$\widetilde{\chi}_1^\pm$	630.2	$\widetilde{e}_R/\widetilde{\mu}_R$	929.2	$\widetilde{t}_1$	754.1	$\widetilde{u}_R/\widetilde{c}_R$	2227.2	h^0	127.0
$\widetilde{\chi}_2^0$	733.3	$\widetilde{\chi}_2^\pm$	817.6	$\widetilde{e}_L/\widetilde{\mu}_L$	759.8	$\widetilde{t}_2$	1125.9	$\widetilde{u}_L/\widetilde{c}_L$	2272.3	A^0/H^0	1581
$\widetilde{\chi}_3^0$	798.2	$\widetilde{\nu}_{e/\mu}$	755.8	$\widetilde{\tau}_1$	722.1	$\widetilde{b}_1$	799.2	$\widetilde{d}_R/\widetilde{s}_R$	2227.2	$H^\pm$	1583.0
$\widetilde{\chi}_4^0$	827.2	$\widetilde{\nu}_\tau$	720.9	$\widetilde{\tau}_2$	874.0	$\widetilde{b}_2$	2036.7	$\widetilde{d}_L/\widetilde{s}_L$	2272.3	$\widetilde{g}$	1228.9

$$\Omega_{\chi_1^0} h^2 = 0.017,\ \Delta a_\mu = 5.27 \times 10^{-10},\ \mathrm{BR}(B_s^0 \to \mu^+\mu^-) = 3.35 \times 10^{-9},\ R_{\mathrm{MAX}} = 0.35,\ \Delta_{\mathrm{FT}} = 161.$$

Outline

Introduction

The SUSY EW Fine-Tuning Problem

The MSSM with Heavy LSP

No-Scale $\mathcal{F}$-$SU(5)$

General Super-Natural Supersymmetry Conditions

Conclusion

Flipped $SU(5) \times U(1)_X$ Models: [13]

- Doublet-triplet splitting via missing partner mechanism [11].
- No dimension-five proton decay problem.
- Little hierarchy problem in string models: $M_{\rm String} \sim 20 \times M_{\rm GUT}$

$$M_{\rm String} = g_{\rm String} \times 5.27 \times 10^{17}~{\rm GeV}~.$$

- Testable flipped $SU(5) \times U(1)_X$ models: TeV-scale vector-like particles [12].

---

[11] I. Antoniadis, J. R. Ellis, J. S. Hagelin and D. V. Nanopoulos, Phys. Lett. B **194**, 231 (1987).

[12] J. Jiang, T. Li and D. V. Nanopoulos, Nucl. Phys. B **772**, 49 (2007).

[13] S. M. Barr, Phys. Lett. B **112**, 219 (1982); J. P. Derendinger, J. E. Kim and D. V. Nanopoulos, Phys. Lett. B **139**, 170 (1984).

Flipped $SU(5) \times U(1)_X$ Models:

- Free-fermionic string construction [14].
- F-theory model building [15].
- Heterotic String Constructions: Calabi-Yau [16]; Orbifold [17].
- Orbifold GUTs [18].

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[14] J. L. Lopez, D. V. Nanopoulos and K. j. Yuan, Nucl. Phys. B **399**, 654 (1993).

[15] C. Beasley, J. J. Heckman and C. Vafa, JHEP **0901**, 059 (2009); J. Jiang, T. Li, D. V. Nanopoulos and D. Xie, Phys. Lett. B **677**, 322 (2009); Nucl. Phys. B **830**, 195 (2010).

[16] A. E. Faraggi, R. S. Garavuso and J. M. Isidro, Nucl. Phys. B **641**, 111 (2002)

[17] J. E. Kim and B. Kyae, Nucl. Phys. B **770**, 47 (2007).

[18] S. M. Barr and I. Dorsner, Phys. Rev. D **66**, 065013 (2002).

$\mathcal{F}$-$SU(5)$ Models

- The gauge group $SU(5) \times U(1)_X$ can be embedded into $SO(10)$ model.
- Generator $U(1)_{Y'}$ in $SU(5)$

$$T_{\mathrm{U(1)_{Y'}}} = \mathrm{diag}\left(-\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2}\right) ~.$$

- Hypercharge

$$Q_Y = \frac{1}{5}\left(Q_X - Q_{Y'}\right) ~.$$

- SM fermions

$$F_i = (\mathbf{10}, \mathbf{1}),~~ \bar{f}_i = (\bar{\mathbf{5}}, -\mathbf{3}),~~ \bar{l}_i = (\mathbf{1}, \mathbf{5})~,$$

$$F_i = (Q_i, D_i^c, N_i^c),~~ \overline{f}_i = (U_i^c, L_i),~~ \overline{l}_i = E_i^c~.$$

- Higgs particles:

$$H = (\mathbf{10}, \mathbf{1}),~~ \overline{H} = (\overline{\mathbf{10}}, -\mathbf{1}),~~ h = (\mathbf{5}, -\mathbf{2}),~~ \overline{h} = (\bar{\mathbf{5}}, \mathbf{2})~,$$

$$H = (Q_H, D_H^c, N_H^c)~,~~ \overline{H} = (\overline{Q}_{\overline{H}}, \overline{D}^c_{\overline{H}}, \overline{N}^c_{\overline{H}})~,$$

$$h = (D_h, D_h, D_h, H_d)~,~~ \overline{h} = (\overline{D}_{\overline{h}}, \overline{D}_{\overline{h}}, \overline{D}_{\overline{h}}, H_u)~.$$

- Flip

$$U \leftrightarrow D~,~~ N \leftrightarrow E~,~~ H_d \leftrightarrow H_u~.$$

Symmetry breaking:

- Superpotential

$$W_{\rm GUT} = \lambda_1 HHh + \lambda_2 \overline{HHh} + \Phi(\overline{H}H - M_{\rm H}^2) ~.$$

- There is only one F-flat and D-flat direction along the N_H^c and $\overline{N}_H^c$ directions: $< N_H^c > = < \overline{N}_H^c > = M_{\rm H}$.
- The doublet-triplet splitting due to the missing partner mechanism
- No dimension-5 proton decay problem.

$\mathcal{F}$-$SU(5)$ Models

- To achieve the string scale gauge coupling unification, we introduce sets of vector-like particles in complete $SU(5) \times U(1)_X$ multiplets, whose contributions to the one-loop beta functions of the $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ gauge symmetries, Δb_1, Δb_2 and Δb_3 respectively, satisfy $\Delta b_1 < \Delta b_2 = \Delta b_3$.
- To avoid the Landau pole problem for the gauge couplings, we can only introduce the following two sets of vector-like particles around the TeV scale, which could be observed at the LHC

$$Z1 : XF = (\mathbf{10}, \mathbf{1}) \equiv (XQ,~ XD^c,~ XN^c)~,~ \overline{XF} = (\overline{\mathbf{10}}, -\mathbf{1})~;$$

$$Z2 : XF~,~ \overline{XF}~,~ Xl = (\mathbf{1}, -\mathbf{5})~,~ \overline{Xl} = (\mathbf{1}, \mathbf{5}) \equiv XE^c~.$$

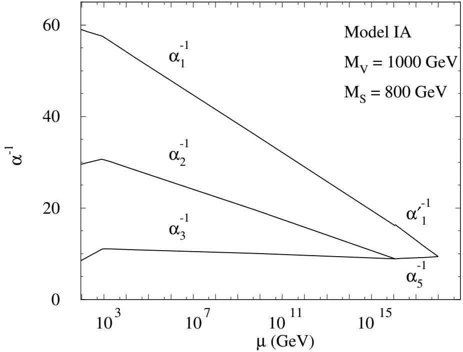


Figure : Gauge coupling unification in the Type IA model.

No-Scale Supergravity [19]:

- The vacuum energy vanishes automatically due to the suitable Kähler potential.
- At the minimum of the scalar potential, there are flat directions which leave the gravitino mass $M_{3/2}$ undertermined.
- The super-trace quantity $\mathrm{Str}\mathcal{M}^2$ is zero at the minimum.

$$K = -3\ln(T + \overline{T} - \sum_i \overline{\Phi}_i \Phi_i) ~.$$

---

[19] E. Cremmer, S. Ferrara, C. Kounnas and D. V. Nanopoulos, Phys. Lett. B **133**, 61 (1983); A. B. Lahanas and D. V. Nanopoulos, Phys. Rept. **145**, 1 (1987).

No-Scale Supergravity:

- mSUGRA/CMSSM: $M_{1/2}$, M_0, A, $\tan\beta$, $\mathrm{sign}(\mu)$.
- No-scale boundary condition: $M_{1/2} \neq 0$, $M_0 = A = B_\mu = 0$
- Natural solution to CP violation and FCNC problem.
- Disfavored by phenomenology: $M_0 = 0$ at traditional GUT scale.
- No-scale $\mathcal{F}$-$SU(5)$

No-scale supergravity can be realized in the compactification of the weakly coupled heterotic string theory [20] and the compactification of M-theory on S^1/Z_2 at the leading order [21].

---

[20] E. Witten, Phys. Lett. B **155**, 151 (1985).

[21] T. Li, J. L. Lopez and D. V. Nanopoulos, Phys. Rev. D **56**, 2602 (1997).

$\mathcal{F}$-$SU(5)$

- These models can be realized in heterotic string constructions, free fermionic string constructions, and F-theory model building.
- These models may be tested in the next LHC run.
- The Higgs boson mass can be around 126 GeV.
- The proton decay $p \to e^+\pi^0$ from the heavy gauge boson exchange is within the reach of the future DUSEL and Hyper-Kamiokande experiments for a majority of the most plausible parameter space.
- The dark matter is within the reach of the XENON1T experiment.

Miracle of Vector-Like Particles

- String scale gauge coupling unification.
- Dimension-six proton decay.
- Lifting the lightest CP-even Higgs boson mass.
- Special sparticle spectra.

Question: Super-Natural Supersymmetry

Can we propose the Super-Natural Supersymmetric SMs whose EENZ or BG fine-tuning measure will be automatically 1 or order 1 ($\mathcal{O}(1)$)?

No-Scale Supergravity

- Scalar Potential

$$V = e^K \left((K^{-1})_{\bar{j}}^{i} D_i W D^{\bar{j}} \overline{W} - 3|W|^2 \right) ~.$$

where $(K^{-1})_{\bar{j}}^{i}$ is the inverse of the Kähler metric $K_i^{\bar{j}} = \partial^2 K / \partial \Phi^i \partial \bar{\Phi}_{\bar{j}}$, and $D_i W = W_i + K_i W$.

- Automatically vanishing scalar potential

$$K ~=~ -3 \ln (T + \overline{T} - \sum_i \overline{\Phi}_i \Phi_i) ~.$$

Natural Solution to the Fine-Tuning Problem

- Fine-Tuning Definition:

$$\Delta_{\rm FT} ~=~ {\rm Max}\{\Delta_i^{\rm GUT}\}~, \quad \Delta_i^{\rm GUT} ~=~ \left| \frac{\partial {\rm ln}(M_Z)}{\partial {\rm ln}(a_i^{\rm GUT})} \right| ~.$$

- Natural Solution:

$$M_Z^n ~=~ f_n \left(\frac{M_Z}{M_{1/2}}\right)~ M_{1/2}^n ~.$$

$$\frac{\partial {\rm ln}(M_Z^n)}{\partial {\rm ln}(M_{1/2}^n)} ~\simeq~ \frac{M_{1/2}^n}{M_Z^n} \frac{\partial M_Z^n}{\partial M_{1/2}^n} ~\simeq~ \frac{1}{f_n} f_n \simeq \mathcal{O}(1) ~.$$

No-Scale $\mathcal{F}$-$SU(5)$

- μ problem [22]:

$$\mu \propto M_{1/2} \propto M_{3/2} ~.$$

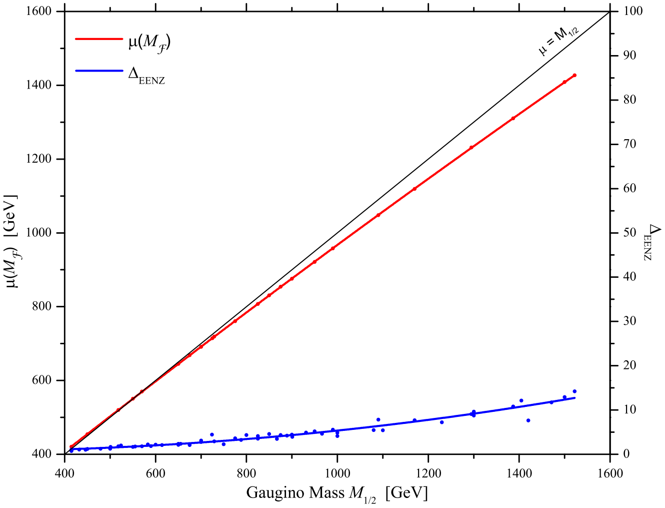
- All the mass parameters are proportional to $M_{1/2}$
- Natural solution [23]

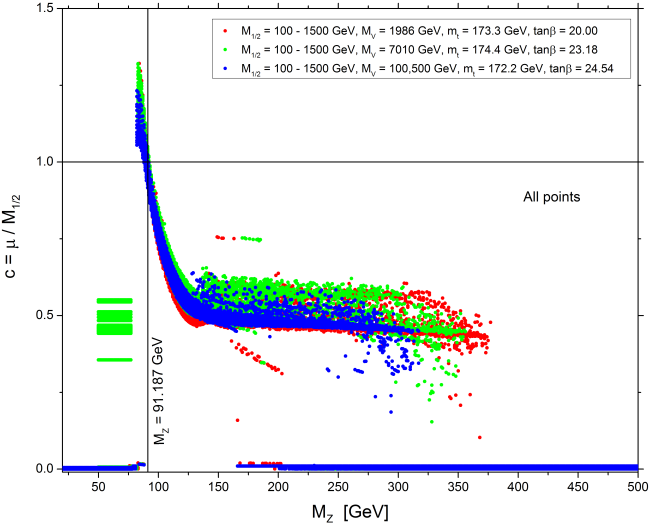
$$\mu \simeq M_{1/2} ~.$$

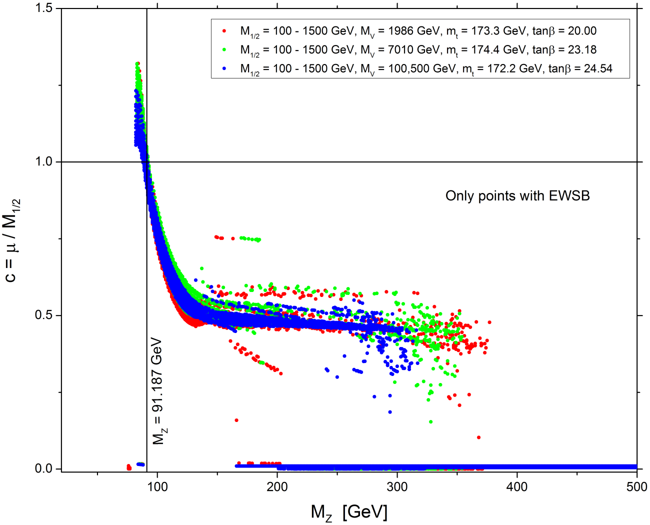
---

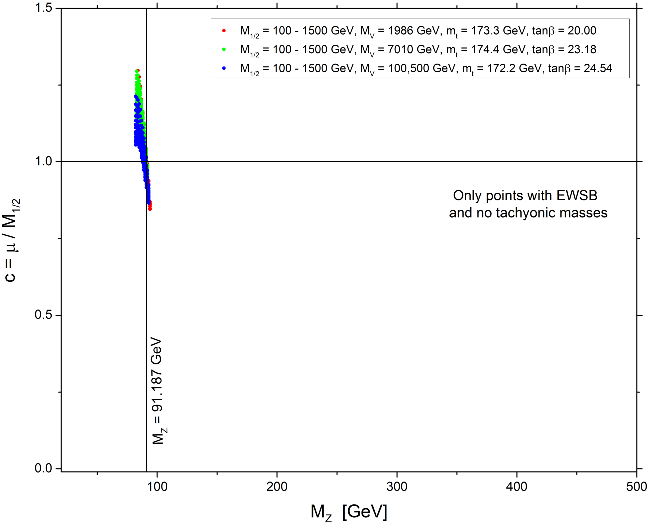
[22] G. F. Giudice and A. Masiero, Phys. Lett. B **206**, 480 (1988).

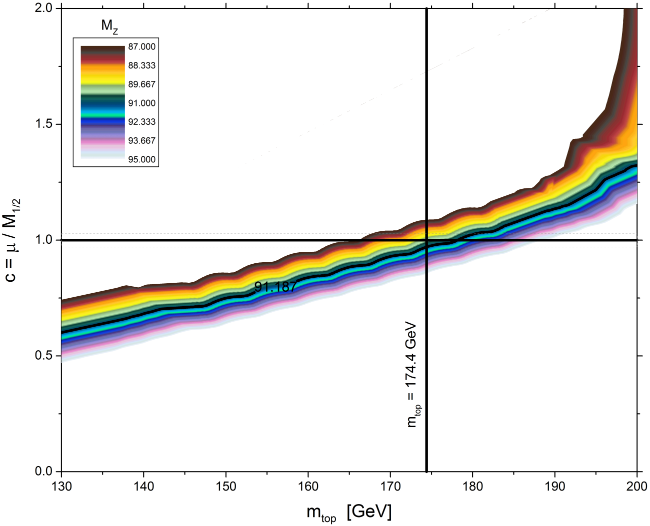
[23] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph].


$\mu(M_{\mathcal{F}})$
Δ_{EENZ}
$\mu = M_{1/2}$
$\mu(M_{\mathcal{F}})$ [GeV]
Δ_{EENZ}
Gaugino Mass $M_{1/2}$ [GeV]
1600
1400
1200
1000
800
600
400
400
600
800
1000
1200
1400
1600
100
90
80
70
60
50
40
30
20
10
0


● $M_{1/2}$ = 100 - 1500 GeV, M_V = 1986 GeV, m_t = 173.3 GeV, tanβ = 20.00
● $M_{1/2}$ = 100 - 1500 GeV, M_V = 7010 GeV, m_t = 174.4 GeV, tanβ = 23.18
● $M_{1/2}$ = 100 - 1500 GeV, M_V = 100,500 GeV, m_t = 172.2 GeV, tanβ = 24.54
All points
M_Z = 91.187 GeV
$c = \mu / M_{1/2}$
M_Z [GeV]
0.0
0.5
1.0
1.5
50
100
150
200
250
300
350
400
450
500


$M_{1/2}$ = 100 - 1500 GeV, M_V = 1986 GeV, m_t = 173.3 GeV, tanβ = 20.00
$M_{1/2}$ = 100 - 1500 GeV, M_V = 7010 GeV, m_t = 174.4 GeV, tanβ = 23.18
$M_{1/2}$ = 100 - 1500 GeV, M_V = 100,500 GeV, m_t = 172.2 GeV, tanβ = 24.54
Only points with EWSB
M_Z = 91.187 GeV
$c = \mu / M_{1/2}$
M_Z [GeV]
0.0
0.5
1.0
1.5
100
200
300
400
500


● $M_{1/2}$ = 100 - 1500 GeV, M_V = 1986 GeV, m_t = 173.3 GeV, tanβ = 20.00
● $M_{1/2}$ = 100 - 1500 GeV, M_V = 7010 GeV, m_t = 174.4 GeV, tanβ = 23.18
● $M_{1/2}$ = 100 - 1500 GeV, M_V = 100,500 GeV, m_t = 172.2 GeV, tanβ = 24.54
Only points with EWSB
and no tachyonic masses
M_Z = 91.187 GeV
c = μ / $M_{1/2}$
1.5
1.0
0.5
0.0
100
200
300
400
500
M_Z [GeV]


M_Z
87.000
88.333
89.667
91.000
92.333
93.667
95.000
91.187
m_{top} = 174.4 GeV
$c = \mu / M_{1/2}$
2.0
1.5
1.0
0.5
0.0
130
140
150
160
170
180
190
200
m_{top} [GeV]

Outline

- One and only one chiral superfield or modulus breaks supersymmetry.
- All the supersymmetry breaking soft terms are proportional to gravitino mass.
- μ term is generated via the GM mechanism after supersymmetry breaking in the MSSM, or NMSSM.
- No-scale supergravity or M-theory on S^1/Z_2 [24].

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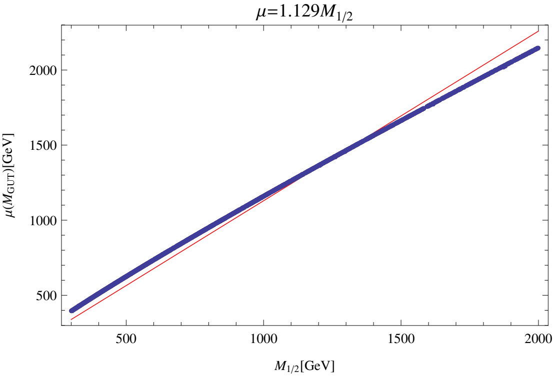
[24] T. Li, Phys. Rev. D **59**, 107902 (1999) [hep-ph/9804243].

The MSSM with No-Scale Supergravity

- $\mu \simeq 1.13 M_{1/2}$
- Fine-tuning measure is less than 15.


μ=1.129$M_{1/2}$
$\mu(M_{\rm GUT})$[GeV]
500
1000
1500
2000
$M_{1/2}$[GeV]
500
1000
1500
2000

Outline

Super-Natural Supersymmetry: the EENZ or BG fine-tuning measure is automatically $\mathcal{O}(1)$.

Thank You Very Much
for Your Attention!