The Supersymmetric Standard Models with a Pseudo-Dirac Gluino from Hybrid $F-$ and $D-$Term Supersymmetry Breakings

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R. Ding, TL, F. Staub, C. Tian and B. Zhu, arXiv:1502.03614 [hep-ph], and in preparation.

Outline

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Introduction

Motivation and Model Building

Phenomenological Study

Conclusion

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

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

String Models:

- Calabi-Yau compactification of heterotic string theory
- Orbifold compactification of heterotic string theory
- D-brane models on Type II orientifolds
- Free fermionic string model builing
- $\mathcal{F}$-Theory Model Building

Supersymmetry is a bridge between the low energy phenomenology and high-energy fundamental physics.

Particle Physics Paradigm

String Theory → String Models → GUTs → SSMs → SM

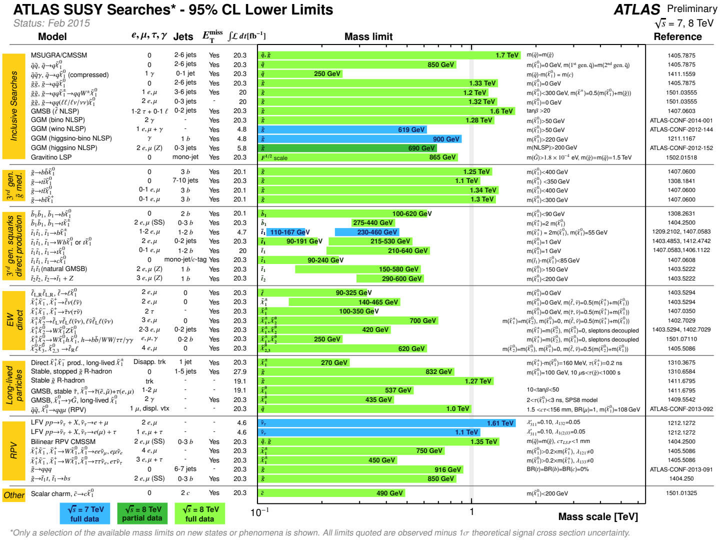
Higgs boson mass in the MSSM:

- The SM-like Higgs boson mass is around 125 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 mass $m_{\tilde{g}}$ and first two-generation squark mass $m_{\tilde{q}}$ should be heavier than about 1.7 TeV if they are roughly degenerate $m_{\tilde{q}} \sim m_{\tilde{g}}$.
- The gluino mass low bound is around 1.33 TeV for $m_{\tilde{g}} \ll m_{\tilde{q}}$.
- The first two-generation squark mass $m_{\tilde{q}}$ is heavier than about 850 GeV for $m_{\tilde{q}} \ll m_{\tilde{g}}$.
- The stop/sbottom mass low bounds are around 600-700 GeV.
- If the LSP is heavy enough, all the bounds will be gone or relaxed. All sparticles can be within 1 TeV except gluino.

The SSMs are fine-tuned!!!



ATLAS SUSY Searches* - 95% CL Lower Limits

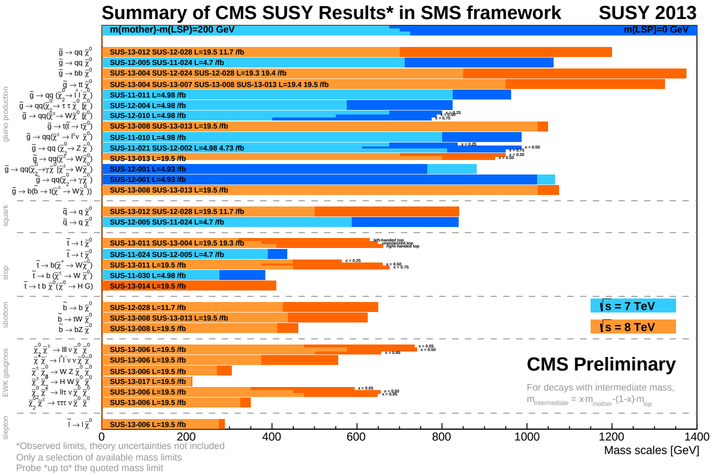
Status: Feb 2015

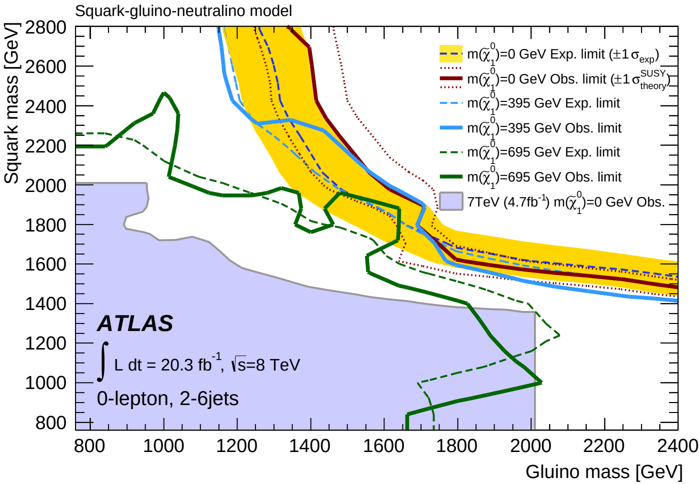
ATLAS Preliminary

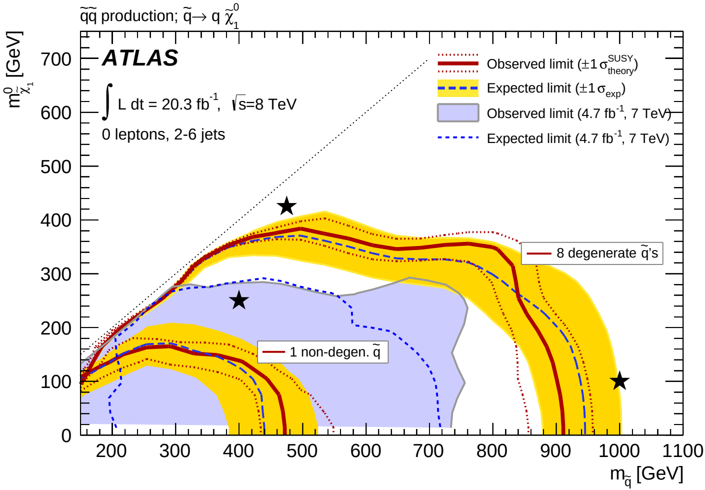
$\sqrt{s}$ = 7, 8 TeV

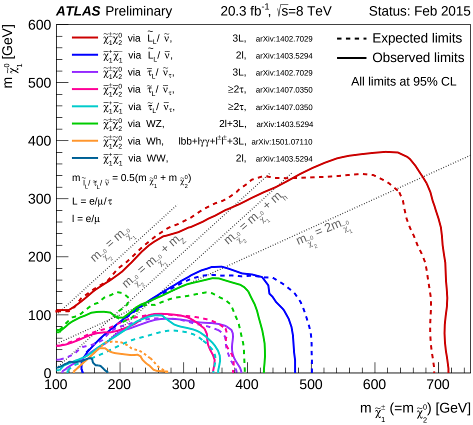
	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}\gamma, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	$m(\tilde{q})$-$m(\tilde{\chi}_1^0)$ = $m(c)$	1411.1559
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<300 GeV, $m(\tilde{\chi}^{\pm})$=0.5($m(\tilde{\chi}_1^0)$+$m(\tilde{g})$)	1501.03555
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	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(NLSP)>200 GeV	ATLAS-CONF-2012-152
	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
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	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	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<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	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^{\pm})$=2 $m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV 230-460 GeV	$m(\tilde{\chi}_1^{\pm})$ = 2$m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_1^0)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	1-2 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 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	$\tilde{t}_1$ 150-580 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	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 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	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 250 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	$\tilde{\chi}_{2,3}^0$ 620 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
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
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	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	$\tilde{\chi}_1^0$ 435 GeV	2<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (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	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 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	$\tilde{\chi}_1^{\pm}$ 750 GeV	$m(\tilde{\chi}_1^0)$>0.2×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	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×$m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 490 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. 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


Squark-gluino-neutralino model
Squark mass [GeV]
Gluino mass [GeV]
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
800
1000
1200
1400
1600
1800
2000
2200
2400
m($\tilde{\chi}_1^0$)=0 GeV Exp. limit (±1 σ_{exp})
m($\tilde{\chi}_1^0$)=0 GeV Obs. limit (±1 σ^{SUSY}_{theory})
m($\tilde{\chi}_1^0$)=395 GeV Exp. limit
m($\tilde{\chi}_1^0$)=395 GeV Obs. limit
m($\tilde{\chi}_1^0$)=695 GeV Exp. limit
m($\tilde{\chi}_1^0$)=695 GeV Obs. limit
7TeV (4.7fb^{-1}) m($\tilde{\chi}_1^0$)=0 GeV Obs.
ATLAS
$\int L\,dt$ = 20.3 fb^{-1}, $\sqrt{s}$=8 TeV
0-lepton, 2-6jets


$\tilde{q}\tilde{q}$ production; $\tilde{q}\rightarrow q\,\tilde{\chi}_1^0$
ATLAS
$\int L\,dt = 20.3\ \text{fb}^{-1}$, $\sqrt{s}$=8 TeV
0 leptons, 2-6 jets
Observed limit ($\pm1\,\sigma^{\text{SUSY}}_{\text{theory}}$)
Expected limit ($\pm1\,\sigma_{\text{exp}}$)
Observed limit (4.7 fb^{-1}, 7 TeV)
Expected limit (4.7 fb^{-1}, 7 TeV)
8 degenerate $\tilde{q}$'s
1 non-degen. $\tilde{q}$
$m_{\tilde{\chi}_1^0}$ [GeV]
0
100
200
300
400
500
600
700
200
300
400
500
600
700
800
900
1000
1100
$m_{\tilde{q}}$ [GeV]


ATLAS Preliminary
20.3 fb^{-1}, $\sqrt{s}$=8 TeV
Status: Feb 2015
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via $\tilde{L}_L/\tilde{\nu}$, 3L, arXiv:1402.7029
$\tilde{\chi}_1^+\tilde{\chi}_1^-$ via $\tilde{L}_L/\tilde{\nu}$, 2l, arXiv:1403.5294
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via $\tilde{\tau}_L/\tilde{\nu}_\tau$, 3L, arXiv:1402.7029
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via $\tilde{\tau}_L/\tilde{\nu}_\tau$, ≥2τ, arXiv:1407.0350
$\tilde{\chi}_1^+\tilde{\chi}_1^-$ via $\tilde{\tau}_L/\tilde{\nu}_\tau$, ≥2τ, arXiv:1407.0350
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ, 2l+3L, arXiv:1403.5294
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh, lbb+lγγ+l$^\pm$l$^\pm$+3L, arXiv:1501.07110
$\tilde{\chi}_1^+\tilde{\chi}_1^-$ via WW, 2l, arXiv:1403.5294
$m_{\tilde{l}_L/\tilde{\tau}_L/\tilde{\nu}} = 0.5(m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0})$
L = e/μ/τ
l = e/μ
Expected limits
Observed limits
All limits at 95% CL
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + m_Z$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + m_h$
$m_{\tilde{\chi}_2^0} = 2m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [GeV]
600
500
400
300
200
100
0
100
200
300
400
500
600
700
$m_{\tilde{\chi}_1^\pm}$ (=$m_{\tilde{\chi}_2^0}$) [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

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

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[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).

Natural Solution to the Fine-Tuning Problem

Natural Solution: if there is one and only one mass parameter M_* in the SSMs, M_Z is a trivial function of M_*

$$M_Z^n ~=~ f_n\,(c_i)~ M_*^n ~.$$

$$\frac{\partial \mathrm{ln}(M_Z^n)}{\partial \mathrm{ln}(M_*^n)} ~\simeq~ \frac{M_*^n}{M_Z^n}\frac{\partial M_Z^n}{\partial M_*^n} ~\simeq~ \frac{M_*^n}{M_Z^n}\frac{\delta M_Z^n}{\delta M_*^n} ~\simeq~ \frac{1}{f_n} f_n ~\simeq~ \mathcal{O}(1) ~.$$

Supernatural Supersymmetry [2]

- The Kähler potential and superpotential can be calculated in principle or at least inspired from a fundamental theory such as string theory with suitable compactifications. In other words, one cannot add arbitrary high-dimensional terms in the Kähler potential and superpotential, at least at leading order.
- There is one and only one chiral superfield or modulus which breaks supersymmetry. And all the supersymmetry breaking soft terms are obtained from the above Kähler potential and superpotential.
- All the other mass parameters, if there exist like the μ term in the MSSM, must arise from supersymmetry breaking.

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[2] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph]; Phys. Lett. B **740**, 66 (2015) [arXiv:1408.4459 [hep-ph]]; G. Du, T. Li, D. V. Nanopoulos and S. Raza, arXiv:1502.06893 [hep-ph].

Supernatural Supersymmetry

- The $\mathcal{F}-SU(5)$ [3] and the MSSM [4] with no-scale supergravity [5] and Giudice-Masiero Mechanism [6].
- The NMSSM [7] with M-theory soft terms [8].

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[3] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph]; Phys. Lett. B **740**, 66 (2015) [arXiv:1408.4459 [hep-ph]].

[4] G. Du, T. Li, D. V. Nanopoulos and S. Raza, arXiv:1502.06893 [hep-ph].

[5] 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).

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

[7] T. Li, S. Raza, X.-C. Wang, in preparation.

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

Fine-Tuning Definition II

- Higgs potential:

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

- Higgs boson mass

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

- The fine-tuning measure [9]:

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

---

[9] 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.

The MSSM and NMSSM with non-universal soft terms are fine.

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 [10]

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

---

[10] 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: the viable SSMs are fine-tuned.

- Fine-Tuning Definition III is weak [11].
- Fine-Tuning Definition II is medium.
- Fine-Tuning Definition I is much stronger [12].

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[11] H. Baer, V. Barger, P. Huang, A. Mustafayev and X. Tata, Phys. Rev. Lett. **109**, 161802 (2012) [arXiv:1207.3343 [hep-ph]]. 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]].

[12] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph]; Phys. Lett. B **740**, 66 (2015) [arXiv:1408.4459 [hep-ph]]; G. Du, T. Li, D. V. Nanopoulos and S. Raza, arXiv:1502.06893 [hep-ph].

Supersymmetric SMs:

- Natural supersymmetry [13].
- Supersymmetric models with a TeV-scale squarks that can escape/relax the missing energy constraints: R parity violation [14]; compressed supersymmetry [15] ; stealth supersymmetry [16]; etc.
- Supersymmetric models with sub-TeV squarks that decrease the cross sections: supersoft supersymmetry [17].

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[13] 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].

[14] 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].

[15] 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]].

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

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

Supersymmetric SMs:

- Displaced Supersymmetry [18].
- Radiative Natural Supersymmetry [19].
- Double Invisible Supersymmetry [20].
- Heavy LSP Supersymmetry [21].
- Supernatural Supersymmetry [22].

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

[19] H. Baer, V. Barger, P. Huang, A. Mustafayev and X. Tata, Phys. Rev. Lett. **109**, 161802 (2012) [arXiv:1207.3343 [hep-ph]]. 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]].

[20] 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].

[21] T. Cheng, J. Li and T. Li, arXiv:1407.0888 [hep-ph].

[22] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph]; Phys. Lett. B **740**, 66 (2015) [arXiv:1408.4459 [hep-ph]]; G. Du, T. Li, D. V. Nanopoulos and S. Raza, arXiv:1502.06893 [hep-ph].

Outline

Goal for the natural SSMs

- Naturalness, dark matter, gauge coupling unification, and Higgs boson mass.
- The LHC SUSY search constraints.
- Consistence with GUTs and/or string models.

Intuition

- The pre-LHC SSMs like the mSUGRA/CMSSM work well, what is the minimal and viable modification to these particle spectra which keep all the merits of the pre-LHC SSMs?

---

[23] G. D. Kribs and A. Martin, Phys. Rev. D **85**, 115014 (2012) [arXiv:1203.4821 [hep-ph]].

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- All the sparticles in the SSMs can still be within about 1 TeV as long as the gluino is heavier than 3 TeV, which is obviously an simple modification to the SSM spectra before the LHC.
- Such a heavy gluino will not induce the SUSY electroweak fine-tuning problem and lift the squark masses via RGE running if it is (pseudo-)Dirac like the supersoft supersymmetry [23]

$$\delta m_{H_u}^2 = -\frac{3\lambda_t^2}{8\pi^2} M_{\tilde{t}}^2 \log \frac{M_D^2}{M_{\tilde{t}}^2} .$$

---

[23] G. D. Kribs and A. Martin, Phys. Rev. D **85**, 115014 (2012) [arXiv:1203.4821 [hep-ph]].

Problems in the SSMs with Dirac gauginos [25]

- μ problem

  The Giudice-Masiero mechanism etc does not work.

- No Higgs quartic coupling from D term.

  The D-term contribution to the Higgs quartic coupling vanishes, i.e., $D = 0$.

- No dark matter

  The right-handed slepton may be the LSP.

- The SM gauge symmetry breaking

  The scalar components of adjoint superfields might be tachyonic and then break the SM gauge symmetry.

---

[24] A. E. Nelson and T. S. Roy, arXiv:1501.03251 [hep-ph].

[25] P. J. Fox, A. E. Nelson and N. Weiner, JHEP **0208**, 035 (2002) [hep-ph/0206096].

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The first three problems can be solved in gravity mediation, while the last problem was solved recently [24].

---

[24] A. E. Nelson and T. S. Roy, arXiv:1501.03251 [hep-ph].

[25] P. J. Fox, A. E. Nelson and N. Weiner, JHEP **0208**, 035 (2002) [hep-ph/0206096].

The SSMs with a Pseudo-Dirac Gluino [26]

- The hybrid $F-$ and $D-$term SUSY breakings.
- All the sparticles in the MSSM obtain SUSY breaking soft terms from the traditional gravity mediation.
- Only gluino receives an extra Dirac mass from the $D-$term SUSY breaking.
- All the MSSM sparticles except gluino can be within about 1 TeV as the pre-LHC SSMs.

---

[26] R. Ding, T. Li, F. Staub, C. Tian and B. Zhu, arXiv:1502.03614 [hep-ph].

Key points:

- The merits of the pre-LHC SSMs are preserved.

  Naturalness, dark matter, muon anomalous magnetic moment, etc
- Evading the LHC SUSY search constraints.
- Solving the problems in the SSMs with Dirac gauginos via F-term gravity mediation.

Key points:

- The merits of the pre-LHC SSMs are preserved.

  Naturalness, dark matter, muon anomalous magnetic moment, etc
- Evading the LHC SUSY search constraints.
- Solving the problems in the SSMs with Dirac gauginos via F-term gravity mediation.

Such supersymmetry breakings can be realized by an anomalous $U(1)_X$ gauge symmetry inspired from string models.

Problems:

- Gauge coupling unification?
- Higgs boson mass?

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- Gauge coupling unification?
- Higgs boson mass?

Solution: vector-like particles. Their uniform contributions to the one-loop beta functions of the SM gauge couplings: $\Delta b = 3$ and $\Delta b = 4$.

The SSM with $\Delta b = 3$

Particles	Quantum Numbers	Particles	Quantum Numbers
Φ	$(\mathbf{8}, \mathbf{1}, \mathbf{0})$	T	$(\mathbf{1}, \mathbf{3}, \mathbf{0})$
XL	$(\mathbf{1}, \mathbf{2}, -\mathbf{1/2})$	XL^c	$(\mathbf{1}, \mathbf{2}, \mathbf{1/2})$
XE_i	$(\mathbf{1}, \mathbf{1}, -\mathbf{1})$	XE_i^c	$(\mathbf{1}, \mathbf{1}, \mathbf{1})$
S	$(\mathbf{1}, \mathbf{1}, \mathbf{0})$		

Table: The extra vector-like particles and their quantum numbers in the SSM with $\Delta b = 3$. Here, $i = 1,\ 2$, and we do not have to introduce S except for Dirac gaugino case since it is an SM singlet.

The SSM with $\Delta b = 4$

Particles	Quantum Numbers	Particles	Quantum Numbers
Φ	$(\mathbf{8}, \mathbf{1}, \mathbf{0})$		
XD	$(\mathbf{3}, \mathbf{1}, -\mathbf{1/3})$	XD^c	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3})$
T_+	$(\mathbf{1}, \mathbf{3}, \mathbf{1})$	T_-	$(\mathbf{1}, \mathbf{3}, -\mathbf{1})$

Table: The extra vector-like particles and their quantum numbers in the SSM with $\Delta b = 4$.

The SSM with $\Delta b = 4$

- The $SU(2)_L \times U(1)_Y$ Dirac gaugino masses are forbidden.
- The neutrino masses and mixings can be generated via Type II seesaw mechanism.

The string realizations

- We usually do not have the vector-like particles T_+ and T_- since they arise from an symmetric **15** representations of $SU(5)$.
- The symmetric **15** representation of $SU(5)$ or flipped $SU(5)$ can indeed be obtained in the Type IIA orientifold on $\mathbf{T^6}/(\mathbf{Z_2} \times \mathbf{Z_2})$ with intersecting D6-branes [27].
- Embeding $SU(2)_L$ into a diagonal gauge group of $SU(2)_A \times SU(2)_B$ in a particular $Z_3 \times Z_3$ orbifold of the heterotic string [28].

---

[27] M. Cvetic, I. Papadimitriou and G. Shiu, Nucl. Phys. B **659**, 193 (2003) [Nucl. Phys. B **696**, 298 (2004)] [hep-th/0212177]; C. M. Chen, T. Li and D. V. Nanopoulos, Nucl. Phys. B **751**, 260 (2006) [hep-th/0604107].

[28] P. Langacker and B. D. Nelson, Phys. Rev. D **72**, 053013 (2005) [hep-ph/0507063].

Lagrangian

- The new superpotential terms with universal vector-like particles are

$$W = M_V (T_+ T_- + XD^c XD) + \lambda H_u T_- H_u + \lambda' H_d T_+ H_d \, .$$

- The corresponding SUSY breaking soft terms are

$$-\mathcal{L}_{soft} = B_T T_- T_+ + B_D XD^c XD + T_\lambda H_u T_- H_u \\ + M_D G \Phi + \mathrm{h.c.} + \tilde{\phi}^\dagger m^2_{\tilde{\phi}} \tilde{\phi}.$$

SUSY Breaking

- Inspired from string models, we shall consider the anomalous $U(1)_X$ gauge symmetry, and introduce two SM singlet fields S and S' with $U(1)_X$ charges 0 and -1.

$$V_D = \frac{g_X^2}{2} D^2 = \frac{g_X^2}{2} \left(\sum_i q_i^X |Q_i^X|^2 - |S'|^2 + \xi \right)^2 .$$

- The Fayet-Iliopoulos term is [29]

$$\xi = \frac{g_X^2 \, \mathrm{Tr} q^X}{384\pi^2} M_{\rm Pl}^2 .$$

- The superpotential via instanton effect

$$W_{\rm Instanton} = M_I S S' .$$

---

[29] M. Cvetic, L. L. Everett and J. Wang, Phys. Rev. D **59**, 107901 (1999) [hep-ph/9808321].

SUSY Breaking

- The minimum of the potential

$$\langle S \rangle = 0 \,, \quad \langle S' \rangle^2 = \xi - M_I^2/g_X^2 \,, \quad \langle F_{S'} \rangle = 0 \,,$$
$$\langle F_S \rangle = M_I \sqrt{\xi - M_I^2/g_X^2} \,, \quad \langle D \rangle = M_I^2/g_X^2 \,.$$

- Because S is neutral under $U(1)_X$, the traditional gravity mediation can be realized via the non-zero F_S. This is key difference between our model and the previous model [30].

---

[30] G. R. Dvali and A. Pomarol, Phys. Rev. Lett. **77**, 3728 (1996) [hep-ph/9607383].

SUSY Breaking Soft Terms from D-Term

- The Dirac mass for gluino/Φ and soft scalar masses for Φ and $T_{+/-}$ can be generated respectively via the following operators [31]

$$\int d^2\theta \left(\frac{\overline{D}^2 D^\alpha V'}{M_*} W_{3,\alpha}\Phi + \frac{\overline{D}^2 (D^\alpha V' D_\alpha X')}{M_*} X'' \right) .$$

- The similar operators for H_d/H_u and XD^c/XD are assumed to be suppressed by a factor 5.

---

[31] A. E. Nelson and T. S. Roy, arXiv:1501.03251 [hep-ph].

SUSY Breaking Scale

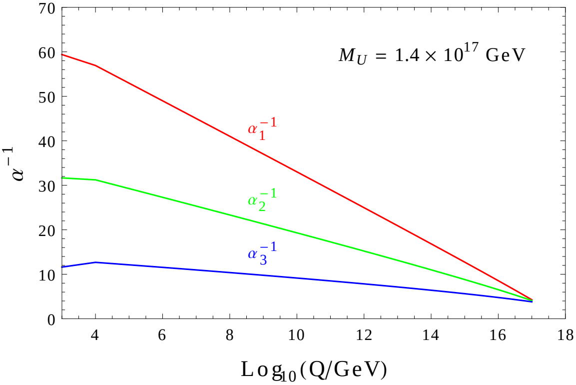
- We choose $M_* = M_{\rm Pl}$, $M_l = 10^8~{\rm GeV}$, ${\rm Tr} q^X = 2$, and $g_X = 10^{-3}/a$. So we get $D = 10^{22}/a^2~{\rm GeV}^2$ and $F_S = 5.5 a \times 10^{21}~{\rm GeV}^2$. For $a = 2^{-1/2}$, we have $D/F_S = 5.1$.
- We choose $M_l = 1.25 \times 10^5~{\rm GeV}$, ${\rm Tr} q^X = 2$, and $g_X = 0.8$. So we have $D = 2.44 \times 10^{10}~{\rm GeV}^2$ and $F_S = 5.5 \times 10^{21}~{\rm GeV}^2$. And then the messenger scale M_* around is 10^6 GeV.

The relatively heavy masses for Dirac gluino and scalar components of $T_{+/-}$ and Φ from D-term due to $D/F_S \sim 5$.

Outline

Gauge Coupling Unification and Implication

- For $M_V = M_D = 5$ TeV, the GUT scale is around 10^{17} GeV.
- To avoid the Landau pole problem for gauge couplings, we need $M_V \geq 3$ TeV and $M_D \geq 3$ TeV.
- Problem: the contribution to Higgs boson mass from $\lambda H_u T_- H_u$ will be suppressed.


70
60
50
40
30
20
10
0
4
6
8
10
12
14
16
18
α^{-1}
$\mathrm{Log}_{10}(Q/\mathrm{GeV})$
$M_U = 1.4 \times 10^{17}$ GeV
α_1^{-1}
α_2^{-1}
α_3^{-1}

Non-Decoupling Effect

- For $m_{T_+} \geq M_V$, the Higgs boson mass is increased by

$$\Delta m_h^2 = \lambda_{\text{eff}}^2 \sin^4 \beta v^2 \ , \ \lambda_{\text{eff}}^2 \equiv \lambda^2 (m_{T_+}^2 / (M_V^2 + m_{T_+}^2)) \, .$$

- Unlike the Dirac NMSSM [32], this contribution does not vanish at large $\tan\beta$ limit, which is properly accommodated with some interesting low energy constraints such as the following Δa_μ.

---

[32] X. Lu, H. Murayama, J. T. Ruderman and K. Tobioka, Phys. Rev. Lett. **112**, 191803 (2014) [arXiv:1308.0792 [hep-ph]].

Codes

- We implement our model in the Mathematica package `SARAH`, which is used to generate the various relevant outputs necessary for our analysis.
- We use the Fortran modules for `SPheno` to calculate the mass spectra and precision observables, and the model files for `CalcHEP` which are used together with `micrOMEGAs` to calculate the dark matter relic density and direct detection rates.

Phenomenological Constraints:

- All the current experimental constraints from the LEP, LHC, and B physics experiments, etc.
- The Higgs mass range is taken from 123 GeV to 127 GeV.
- The anomalous magnetic moment of the muon [33]

$$\Delta a_{\mu} \equiv a_{\mu}(\mathrm{exp}) - a_{\mu}(\mathrm{SM}) = (28.6 \pm 8.0) \times 10^{-10}.$$

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[33] M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C **71**, 1515 (2011) [Eur. Phys. J. C **72**, 1874 (2012)] [arXiv:1010.4180 [hep-ph]]; K. Hagiwara, R. Liao, A. D. Martin, D. Nomura and T. Teubner, J. Phys. G **38**, 085003 (2011) [arXiv:1105.3149 [hep-ph]].

The Input parameters

$\tan\beta$	$\lambda_{\rm eff}$	μ	B_μ	M_1	M_2
$[5, 60]$	$[0.1, 0.7]$	$[0.3, 1]$	$[10^{-3}, 1]$	$[0.01, 0.1]$	$[0.5, 1]$
M_D	$m_{\tilde{Q},1\&2}$	$m_{\tilde{Q},3}$	$m_{\tilde{L},1\&2}$	$m_{\tilde{L},3}$	m_Φ
$[3, 5]$	$[0.8, 0.9]$	$[0.4, 0.7]$	$[0.1, 0.5]$	$[0.07, 0.16]$	$[\sqrt{3}, \sqrt{5}]$

Table: The input parameter ranges or values used in our scans. All the mass parameters are given in appropriate power of TeV. Here, M_i are gaugino masses, μ is the bilinear Higgs mass in the superpotential and B_μ is the corresponding soft mass. We consider the universal scalar mass for the left- and right-handed squarks (sleptons) $\tilde{Q} \in \{\tilde{q}, \tilde{d}, \tilde{u}\}$ ($\tilde{L} \in \{\tilde{l}, \tilde{e}\}$) and the degenerated first and second generations. We choose $M_3 = 0.6$ TeV and the vanishing trilinear soft terms for three generations.

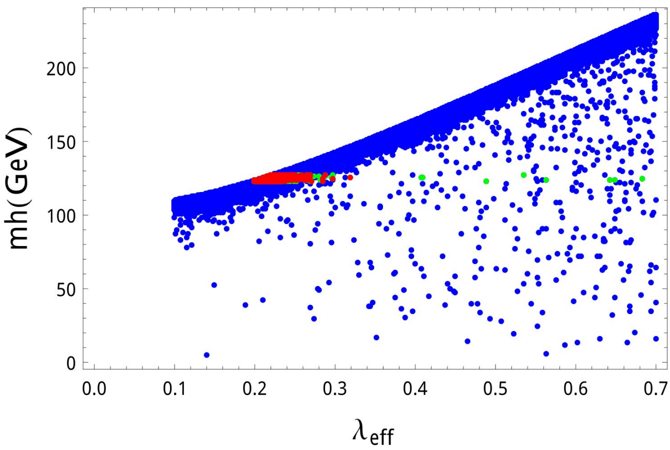

Figure: The Higgs mass versus λ_{eff}. The blue points provide the spectra without tachyons. In addition to satisfy the Higgs mass requirement, the green and red points have Δa_μ within 3σ and 1σ ranges, respectively.

Points:

- For moderate values of λ_{eff} around $0.2 - 0.3$, Δa_μ can be within 1σ range and the Higgs mass falls into the desirable range.
- The electroweak symmetry breaking can be realized even in the range of small μ, which alleviates the following fine-tuning problem.

The Fine-Tuning Measure: The Third Definition

$$\Delta_{\rm EW} = \frac{2}{M_Z^2} \max(C_{H_d}, C_{H_u}, C_{\mu}, C_{B_\mu}, C_{\delta m_{H_u}^2}) ~,$$

where

$$\begin{aligned} C_{H_d} &= \left| \frac{m_{H_d^2}}{\tan^2\beta - 1} \right| , ~ C_{H_u} = \left| \frac{m_{H_u^2} \tan^2\beta}{\tan^2\beta - 1} \right| , \\ C_{\mu} &= \left| \mu^2 \right| , ~ C_{B_\mu} = \left| B_\mu \right| , \\ C_{\delta m_{H_u}^2} &= \frac{(\lambda M_V)^2}{16\pi^2} \log \left(\frac{M_V^2 + m_{T_+}^2}{M_V^2} \right) ~. \end{aligned}$$

The Fine-Tuning Measure

- The entire fine-tuning measure is given by C_μ while the other terms $C_{H_{d,u}}$, C_{B_μ} and $C_{\delta m^2_{H_u}}$ are negligible.
- The fine-tuning measure can be as low as 50 for the viable parameter space.
- It seems that the fine-tuning measure from high energy definition will be small as well.

Dark Matter

- The LSP neutralino-stau coannihilation scenario and the 2σ interval combined range $0.1153 < \Omega_{CDM} h^2 < 0.1221$.
- The input parameters

  $\mu = 0.5$ TeV, $B_\mu = 0.15$ TeV^2, $M_2 = 0.5$ TeV, $M_3 = 0.6$ TeV, $M_D = 3$ TeV, $\lambda_{\rm eff} = 0.22$, $m_\Phi =$ 2 TeV, $m_{\tilde{Q},1\&2} = m_{\tilde{L},1\&2} = 1$ TeV, $m_{\tilde{Q},3} = 0.404$ TeV,

  $5 < \tan\beta < 30$, 10 GeV $< M_1 <$ 300 GeV, 90 GeV $< m_{\tilde{L},3} <$ 300 GeV.
- The relatively large values for μ and M_2 of 500 GeV to suppress the Higgsino and wino components of the LSP neutralino and the direct detection rates.
- A small mass splitting between the light stau and LSP neutralino to get an efficient coannihilation and to soften the LEP bounds on SUSY searches.
- The fine-tuning measure is $\Delta_{\rm EW} \simeq 60$.

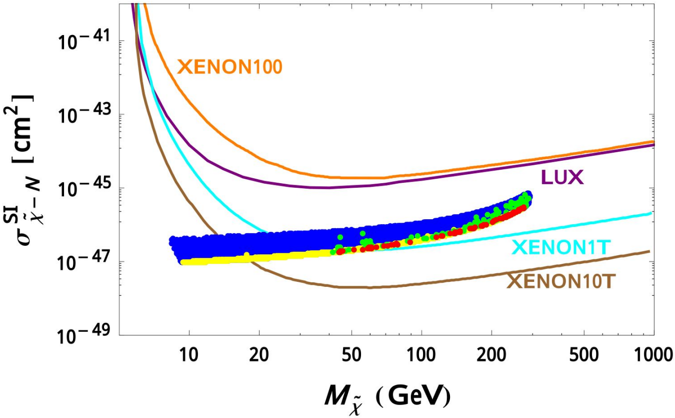

Figure: The spin-independent LSP neutralino-nucleon cross section versus the LSP mass. The blue points have the particle spectra without tachyons. The yellow points satisfy the Higgs mass requirement and have Δa_μ within 3σ range. The green points have the correct relic density. And the red points satisfy all the current constraints.

Properties

- The spin-independent cross sections are about one or two orders of magnitude below the current best limit provided by the LUX experiment.
- The points with the LSP masses above 22 (15) GeV are within the reach of the projected XENON1T (XENON10T) sensitivity.
- The current constraints on spin-dependent cross sections are much weaker.

$\widetilde{\chi}_i^0$	$\widetilde{\chi}_i^{\pm}$	$\widetilde{\nu}_e,\widetilde{\nu}_\tau$	$\widetilde{e}_R,\ \widetilde{e}_L$	$\widetilde{\tau}_i$
(204,446,502,561)	(446,561)	(800,257)	(802,805)	(211,309)
$\widetilde{u}_R,\widetilde{u}_L$	$\widetilde{t}_i$	$\widetilde{d}_R,\widetilde{d}_L$	$\widetilde{b}_i$	$H^{0,\pm}/A^0$
(956,958)	(920,927)	(957,962)	(897,938)	$\simeq 705$

Table: The particle spectrum (in GeV) for a benchmark point with pseudo-Dirac gluino masses 2927 GeV and 3470 GeV for $\tan\beta = 29$, $M_1 = 0.21$ TeV, $\mu = 0.5$ TeV, $B_\mu = 0.02$ TeV^2, $M_2 = 0.5$ TeV, $M_3 = 0.6$ TeV, $M_D = 3$ TeV, $\lambda_{\text{eff}} = 0.22$, $m_\Phi = 1.92$ TeV, $m_{\tilde{Q},1\&2} = 0.6$ TeV, $m_{\tilde{L},1\&2} = 0.8$ TeV $m_{\tilde{L},3} = 0.26$ TeV, $m_{\tilde{Q},3} = 0.55$ TeV. In this benchmark point, we have $m_h = 124.8$ GeV, $\Delta_{\text{EW}} = 60.4$, $\Omega_{\widetilde{\chi}_1^0} h^2 = 0.1187$, $\Delta a_\mu = 9.96 \times 10^{-10}$, and the spin independent cross section $\sigma^{\rm SI}_{\widetilde{\chi}-N} = 2.85 \times 10^{-46}\ {\rm cm}^2$.

The ATLAS $Z + E_T^{\rm miss}$ Excess

- A recent ATLAS search in a channel with two leptons, consistent with the production of a Z-boson, large missing transverse momentum ($E_T^{\rm miss}$), and at least two jets, reports a 3σ excess for 20.3 fb^{-1} of integrated luminosity at a center of mass energy of 8 TeV.
- The similar search at the CMS has no excess.
- The cuts used in the two searches are different, and the observed ATLAS excess may be consistent with the CMS results.

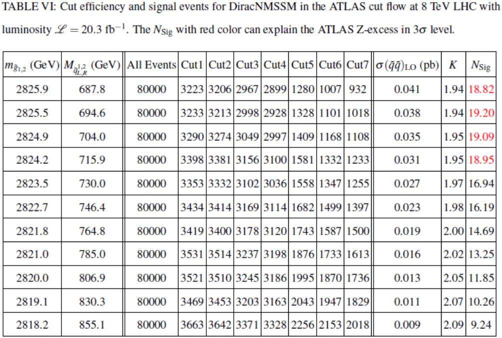

TABLE VI: Cut efficiency and signal events for DiracNMSSM in the ATLAS cut flow at 8 TeV LHC with luminosity $\mathscr{L} = 20.3\ \text{fb}^{-1}$. The N_{Sig} with red color can explain the ATLAS Z-excess in 3σ level.

$m_{\tilde{g}_{1,2}}$ (GeV)	$M_{\tilde{q}^{1,2}_{L,R}}$ (GeV)	All Events	Cut1	Cut2	Cut3	Cut4	Cut5	Cut6	Cut7	$\sigma(\bar{q}\bar{q})_{\text{LO}}$ (pb)	K	N_{Sig}
2825.9	687.8	80000	3223	3206	2967	2899	1280	1007	932	0.041	1.94	18.82
2825.5	694.6	80000	3233	3213	2998	2928	1328	1101	1018	0.038	1.94	19.20
2824.9	704.0	80000	3290	3274	3049	2997	1409	1168	1108	0.035	1.95	19.09
2824.2	715.9	80000	3398	3381	3156	3100	1581	1332	1233	0.031	1.95	18.95
2823.5	730.0	80000	3353	3332	3102	3036	1558	1347	1255	0.027	1.97	16.94
2822.7	746.4	80000	3434	3414	3169	3114	1682	1499	1397	0.023	1.98	16.19
2821.8	764.8	80000	3419	3400	3178	3120	1743	1587	1500	0.019	2.00	14.69
2821.0	785.0	80000	3531	3514	3237	3198	1876	1733	1613	0.016	2.02	13.25
2820.0	806.9	80000	3521	3510	3245	3186	1995	1870	1736	0.013	2.05	11.85
2819.1	830.3	80000	3469	3453	3203	3163	2043	1947	1829	0.011	2.07	10.26
2818.2	855.1	80000	3663	3642	3371	3328	2256	2153	2018	0.009	2.09	9.24

Figure: Preliminary results: the ATLAS $Z + E_T^{\text{miss}}$ Excess from squark productions.

Outline

- The SSMs with a pseudo-Dirac gluino from hybrid $F-$ and $D-$term SUSY breakings, which can be achieved via an anomalous $U(1)_X$ gauge symmetry inspired from string models.
- All the MSSM particles obtain the SUSY breaking soft terms from the traditional gravity mediation and can have masses within about 1 TeV except gluino, which has a heavy Dirac mass above 3 TeV from $D-$term SUSY breaking.
- The gauge coupling unification and Higgs boson mass can be obtained by introducing extra vector-like particles.
- This kind of models keeps the merits of pre-LHC SSMs and solves the possible problems in the SSMs with Dirac gauginos.