The Super-Natural Supersymmetry

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References:

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- Papers in preparations.

Outline

Outline

The Standard Model

The Standard Model (SM) is a model that describes the elementary particles in the nature and the fundamental interactions between them.

Fundamental Interactions

Interactions	Invariant	Symmetry	Fields	Spin
Gravity	Diffeomorphism		Graviton	2
Strong	Gauge	$SU(3)_C$	Gluon	1
Weak	Gauge	$SU(2)_L$	$W^{\pm}$, W^0	1
Hypercharge	Gauge	$U(1)_Y$	B^0	1

Properties for the theories

Gauge theory is renormalizable, and described by quantum field theory which is consistent with both quantum mechanics and special relativity. However, gravity theory is non-renormalizable, and we do not have a correct quantum gravity theory.

Elementary Particles

- Three families of SM fermions:

$$\textbf{Quarks}:\ Q_1=\left(\begin{array}{ccc} U & U & U \\ D & D & D \end{array}\right)_{\rm L},\ (U\ \ U\ \ U)_R,\ (D\ \ D\ \ D)_R\ .$$

$$\textbf{Leptons}:\qquad L_1=\left(\begin{array}{c} \nu \\ E \end{array}\right)_{\rm L},\quad E_R\ .$$

- One Higgs doublet

$$H\ =\ \left(\begin{array}{c} H^0 \\ H^- \end{array}\right)\ .$$

Lagrangian

$$\begin{aligned}\mathcal{L}_{MSM} = & -\frac{1}{2g_s^2}\mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}\, W_{\mu\nu}W^{\mu\nu} \\ & -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R \\ & +|D_\mu H|^2 + \bar{Q}_i i\not{D} Q_i + \bar{U}_i i\not{D} U_i + \bar{D}_i i\not{D} D_i \\ & +\bar{L}_i i\not{D} L_i + \bar{E}_i i\not{D} E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \\ & -\left(h_u^{ij} Q_i U_j \tilde{H} + h_d^{ij} Q_i D_j H + h_l^{ij} L_i E_j H + c.c.\right)\ ,\end{aligned}$$

where $\tilde{H} \equiv i\sigma_2 H^*$. **The SM has 20 parameters (19 without gravity):** 3 gauge couplings, 1 Planck scale, 1 strong CP phase, 6 quark masses, 3 charged lepton mass, 3 CKM mixing angles, 1 CKM CP phase, 2 Higgs parameters.

The Higgs potential is

$$V_{\rm Higgs} = \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 ~.$$

At minimum, Higgs field has a non-zero VEV

$$\langle H^0 \rangle = \frac{v}{\sqrt{2}} ~.$$

All the gauge symmetries, under which H^0 is charged, are broken after Higgs mechanism.

Symmetry Breaking

- $SU(2)_L \times U(1)_Y$ is broken down to the $U(1)_{\rm EM}$ symmetry.
- $W^{\pm}$ and Z^0 become massive, and γ is massless

$$Z^0 ~=~ \cos\theta_W W^0 - \sin\theta_W B^0 ~, ~~~ \gamma ~=~ \sin\theta_W W^0 + \cos\theta_W B^0 ~.$$

- The SM quarks and leptons obtain masses via Yukawa couplings, except the neutrinos.
- Higgs boson with mass around 125.5 GeV.

The SM explains existing experimental data very well, including electroweak precision tests.

The Standard Model

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

The Standard Model

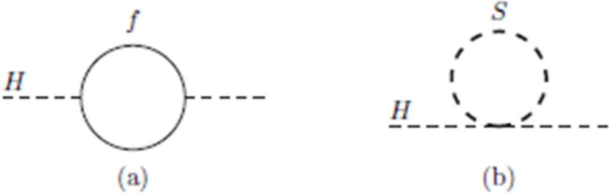
- Fine-tuning problems
  cosmological constant problem; gauge hierarchy problem; strong CP problem; SM fermion masses and mixings; ...
- Aesthetic problems interaction and fermion unification; gauge coupling unification; charge quantization; too many parameters; ...

Gauge Hierarchy Problem

$$-\mathcal{L} = \lambda_f H \bar{f} f + \lambda_S |H|^2 |S|^2 ~.$$

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2 + \frac{\lambda_S}{16\pi^2}\Lambda_{\rm UV}^2 ~.$$

Gauge Hierarchy Problem



Solutions

- Techicolor: the Higgs is a condensation of new fermions. Point: no fundamental scalar.
- Larger extra dimension(s): Arkani-Hamed-Dimopoulos-Dvali (ADD) and Randall-Sundrum (RS). Point: the high-dimensional Planck scale is close to the TeV.
- Supersymmetry.
- Little Higgs model, effective theories for compositeness, the anthropic solution, etc.

Supersymmetry

- A supersymmetry transformation turns a bosonic state into a fermionic state, and vice versa.

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle, \qquad Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle.$$

- Algebra: supersymmetry generator Q is a fermionic operator with spin-1/2.

$$\begin{aligned} \{Q, Q^\dagger\} &= P^\mu, \\ \{Q, Q\} &= \{Q^\dagger, Q^\dagger\} = 0, \\ [P^\mu, Q] &= [P^\mu, Q^\dagger] = 0. \end{aligned}$$

- Each supermultiplet contains an equal number of fermion and boson degrees of freedom.

The Supersymmetry Standard Model

- Four-dimesional $N = 1$ supersymmetry: Kähler potential, superpotential, gauge kinetic function.
- A chiral SM fermion has a complex scalar partner.
- A gauge boson has a spin $1/2$ partner.
- A graviton has a spin $3/2$ partner.

The Supersymmetry Standard Model

- Two Higgs doublet.
- R symmetry: $R = (-1)^{3B-L+2s}$.
- The SM particle are even while the supersymmetric particles are odd.
- Dark matter: neutralino, sneutrino, gravitino, etc.
- Solution to the proton decay problem.

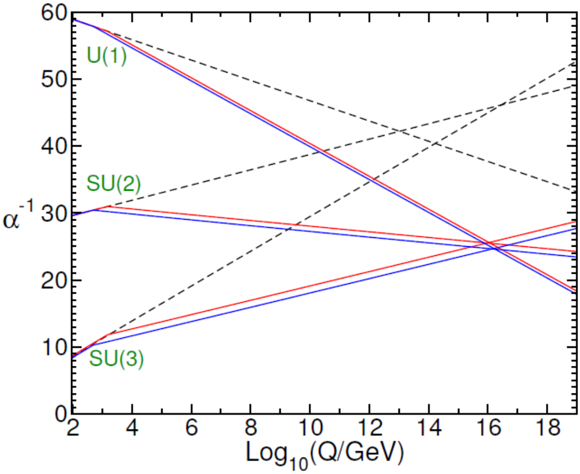
Names		spin 0	spin 1/2	$SU(3)_C$, $SU(2)_L$, $U(1)_Y$
squarks	Q	$(\widetilde{u}_L \quad \widetilde{d}_L)$	$(u_L \quad d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
quarks	$\overline{u}$	$\widetilde{u}_R^*$	$u_R^\dagger$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}_R^*$	$d_R^\dagger$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons	L	$(\widetilde{\nu} \quad \widetilde{e}_L)$	$(\nu \quad e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
leptons	$\overline{e}$	$\widetilde{e}_R^*$	$e_R^\dagger$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs	H_u	$(H_u^+ \quad H_u^0)$	$(\widetilde{H}_u^+ \quad \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
Higgsinos	H_d	$(H_d^0 \quad H_d^-)$	$(\widetilde{H}_d^0 \quad \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Table: Chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars, and the spin-1/2 fields are left-handed two-component Weyl fermions.

Names	spin 1/2	spin 1	$SU(3)_C$, $SU(2)_L$, $U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^{\pm}$ $\widetilde{W}^0$	$W^{\pm}$ W^0	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Table: Gauge supermultiplets in the Minimal Supersymmetric Standard Model.

Gauge Coupling Unification for the SM and MSSM



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.

Supersymmetry

- The most promising new physics beyond the Standard Model.
- Gauge coupling unification strongly suggests the Grand Unified Theories (GUTs), and the SUSY GUTs can be constructed from superstring theory.

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

Outline

Introduction

The SUSY EW Fine-Tuning Problem

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

No-Scale MSSM

The Super-Natural Supersymmetry and Its Generalizations

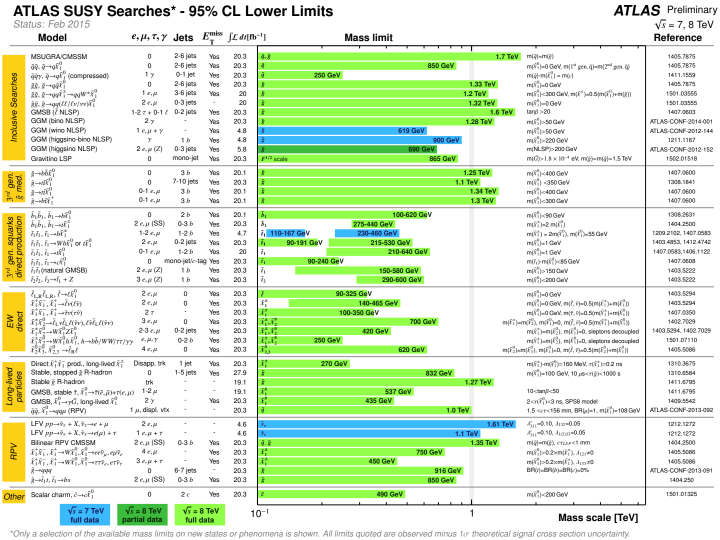
Conclusion

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: Feb 2015

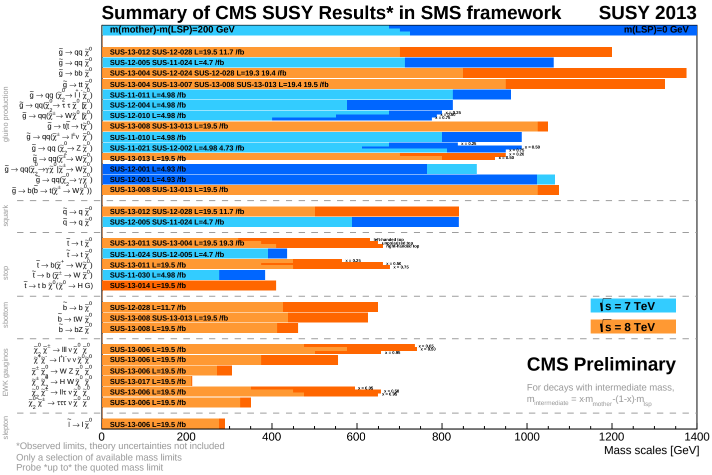
ATLAS Preliminary

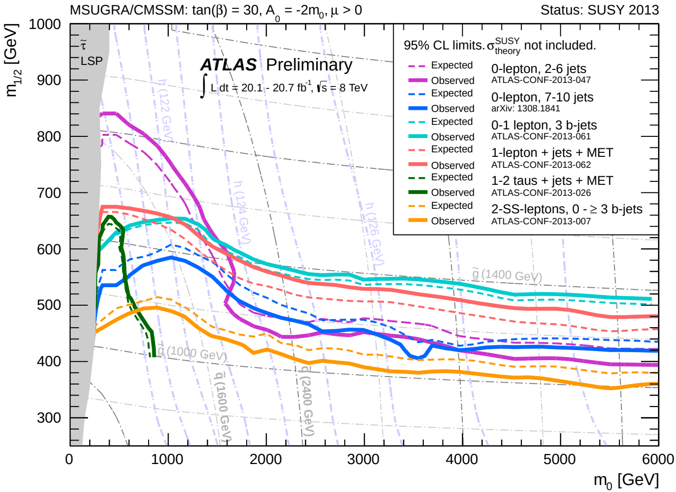
$\sqrt{s}$ = 7, 8 TeV

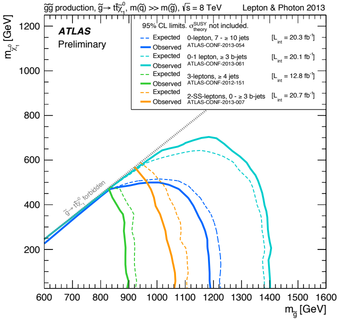
	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 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
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 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
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	20.3	$\tilde{b}_1$ 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

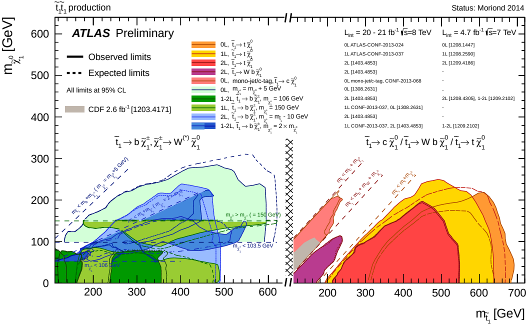
🟦 $\sqrt{s}$ = 7 TeV full data	🟩 $\sqrt{s}$ = 8 TeV partial data	🟩 $\sqrt{s}$ = 8 TeV full data

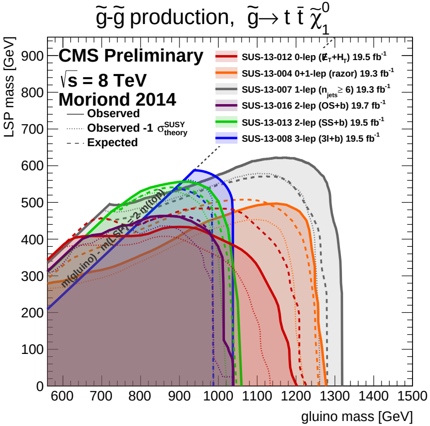
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

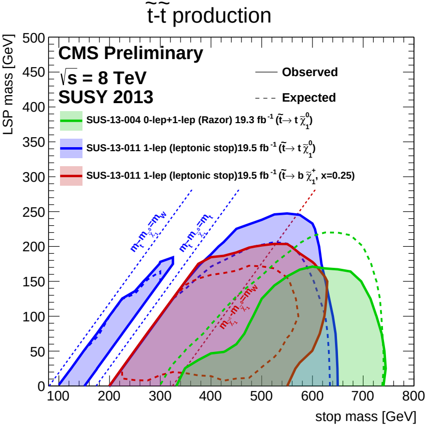

Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
$\tilde{g} \to qq\,\tilde{\chi}^0$ SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
$\tilde{g} \to qq\,\tilde{\chi}^0$ SUS-12-005 SUS-11-024 L=4.7 /fb
$\tilde{g} \to bb\,\tilde{\chi}^0$ SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
$\tilde{g} \to tt\,\tilde{\chi}^0$ SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
$\tilde{g} \to qq\,(\tilde{\chi}_2^0 \to l^+l^-\tilde{\chi}^0)$ SUS-11-011 L=4.98 /fb
$\tilde{g} \to qq(\tilde{\chi}_2^0 \to \tau\tau\tilde{\chi}^0 |\tilde{\chi}^0)$ SUS-12-004 L=4.98 /fb
$\tilde{g} \to qq(\tilde{\chi}^\pm \to W\tilde{\chi}^0 |\tilde{\chi}^0)$ SUS-12-010 L=4.98 /fb
x = 0.25
x = 0.50
x = 0.75
$\tilde{g} \to t(\tilde{t} \to t\tilde{\chi}^0)$ SUS-13-008 SUS-13-013 L=19.5 /fb
$\tilde{g} \to qq(\tilde{\chi}^\pm \to l^\pm\nu\,\tilde{\chi}^0)$ SUS-11-010 L=4.98 /fb
$\tilde{g} \to qq\,(\tilde{\chi}_2^0 \to Z\,\tilde{\chi}^0)$ SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
x = 0.25
x = 0.50
x = 0.75
x = 0.20
$\tilde{g} \to qq(\tilde{\chi}^\pm \to W\tilde{\chi}^0)$ SUS-13-013 L=19.5 /fb
x = 0.50
$\tilde{g} \to qq(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}^0 |\tilde{\chi}^\pm \to W\tilde{\chi}^0)$ SUS-12-001 L=4.93 /fb
$\tilde{g} \to qq(\tilde{\chi}_2^0 \to \gamma\tilde{\chi}^0)$ SUS-12-001 L=4.93 /fb
$\tilde{g} \to b(\tilde{b} \to t(\tilde{\chi}^\pm \to W\tilde{\chi}^0))$ SUS-13-008 SUS-13-013 L=19.5 /fb
squark
$\tilde{q} \to q\,\tilde{\chi}^0$ SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
$\tilde{q} \to q\,\tilde{\chi}^0$ SUS-12-005 SUS-11-024 L=4.7 /fb
stop
$\tilde{t} \to t\,\tilde{\chi}^0$ SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
$\tilde{t} \to t\,\tilde{\chi}^0$ SUS-11-024 SUS-12-005 L=4.7 /fb
$\tilde{t} \to b(\tilde{\chi}^+ \to W\tilde{\chi}^0)$ SUS-13-011 L=19.5 /fb
x = 0.25
x = 0.50
x = 0.75
$\tilde{t} \to b\,(\tilde{\chi}^\pm \to W\,\tilde{\chi}^0)$ SUS-11-030 L=4.98 /fb
$\tilde{t} \to t\,b\,\tilde{\chi}^0(\tilde{\chi}^0 \to H\,G)$ SUS-13-014 L=19.5 /fb
sbottom
$\tilde{b} \to b\,\tilde{\chi}^0$ SUS-12-028 L=11.7 /fb
$\tilde{b} \to tW\,\tilde{\chi}^0$ SUS-13-008 SUS-13-013 L=19.5 /fb
$\tilde{b} \to bZ\,\tilde{\chi}^0$ SUS-13-008 L=19.5 /fb
EWK gauginos
$\tilde{\chi}_2^0\tilde{\chi}^\pm \to lll\,\nu\,\tilde{\chi}^0\,\tilde{\chi}^0$ SUS-13-006 L=19.5 /fb
x = 0.05
x = 0.50
x = 0.95
$\tilde{\chi}^+\tilde{\chi}^- \to l^+l^-\nu\,\nu\,\tilde{\chi}^0\tilde{\chi}^0$ SUS-13-006 L=19.5 /fb
$\tilde{\chi}^\pm\,\tilde{\chi}_2^0 \to W\,Z\,\tilde{\chi}^0\,\tilde{\chi}^0$ SUS-13-006 L=19.5 /fb
$\tilde{\chi}^\pm\,\tilde{\chi}_2^0 \to H\,W\,\tilde{\chi}^0\,\tilde{\chi}^0$ SUS-13-017 L=19.5 /fb
$\tilde{\chi}_2^0\,\tilde{\chi}^\pm \to ll\tau\,\nu\,\tilde{\chi}^0\,\tilde{\chi}^0$ SUS-13-006 L=19.5 /fb
x = 0.05
x = 0.50
x = 0.95
$\tilde{\chi}_2^0\,\tilde{\chi}^\pm \to \tau\tau\tau\,\nu\,\tilde{\chi}^0\,\tilde{\chi}^0$ SUS-13-006 L=19.5 /fb
slepton
$\tilde{l} \to l\,\tilde{\chi}^0$ SUS-13-006 L=19.5 /fb
$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 8 TeV
CMS Preliminary
For decays with intermediate mass,
$m_{intermediate} = x{\cdot}m_{mother} - (1-x){\cdot}m_{lsp}$
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, A0 = -2m0, μ > 0
Status: SUSY 2013
τ̃ LSP
ATLAS Preliminary
∫ L dt = 20.1 - 20.7 fb-1, √s = 8 TeV
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)
g̃ (1400 GeV)
g̃ (1000 GeV)
q̃ (1600 GeV)
q̃ (2400 GeV)
m1/2 [GeV]
1000
900
800
700
600
500
400
300
0
1000
2000
3000
4000
5000
6000
m0 [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. $\sigma_{\mathrm{theory}}^{\mathrm{SUSY}}$ 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]
0L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
1L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
2L, $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
2L, $\tilde{t}_1 \rightarrow W\,b\,\tilde{\chi}_1^0$
0L, mono-jet/c-tag, $\tilde{t}_1 \rightarrow c\,\tilde{\chi}_1^0$
0L, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$ + 5 GeV
1-2L, $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm}$ = 106 GeV
1L, $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm}$ = 150 GeV
2L, $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1}$ - 10 GeV
1-2L, $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^\pm$, $m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$
L_{int} = 20 - 21 fb^{-1} $\sqrt{s}$=8 TeV
0L ATLAS-CONF-2013-024
1L ATLAS-CONF-2013-037
2L [1403.4853]
2L [1403.4853]
0L mono-jet/c-tag, CONF-2013-068
0L [1308.2631]
2L [1403.4853]
1L CONF-2013-037, 0L [1308.2631]
2L [1403.4853]
1L CONF-2013-037, 2L [1403.4853]
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
-
-
-
2L [1208.4305], 1-2L [1209.2102]
-
-
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
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^\pm}$ ($m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$+5 GeV)
$m_{\tilde{t}_1} < m_c + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ [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, $\tilde{g}\to t\,\bar{t}\,\tilde{\chi}^0_1$
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]
gluino mass [GeV]
0
100
200
300
400
500
600
700
800
900
600
700
800
900
1000
1100
1200
1300
1400
1500


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

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).

Fine-Tuning Definition II

- Higgs potential:

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

- Higgs boson mass

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

- The fine-tuning measure [2]:

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

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[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 $M_{\tilde{t}} \equiv \sqrt{m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}}$ 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]

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

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[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.

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[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].

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[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

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].

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[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

$$Z1 : XF = (\mathbf{10}, \mathbf{1}) \equiv (XQ,~ XD^c,~ XN^c)~,~ \overline{XF} = (\overline{\mathbf{10}}, -\mathbf{1})~;$$
$$Z2 : XF~,~ \overline{XF}~,~ Xl = (\mathbf{1}, -\mathbf{5})~,~ \overline{Xl} = (\mathbf{1}, \mathbf{5}) \equiv XE^c~.$$

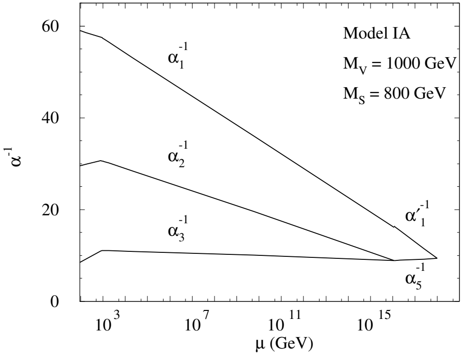

Figure: Gauge coupling unification in the Type IA model.

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.

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

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[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].

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[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

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

where $(K^{-1})^i_{\bar{j}}$ is the inverse of the Kähler metric $K^{\bar{j}}_i = \partial^2 K / \partial \Phi^i \partial \bar{\Phi}_{\bar{j}}$, 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:

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

- Natural Solution:

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

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

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]

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

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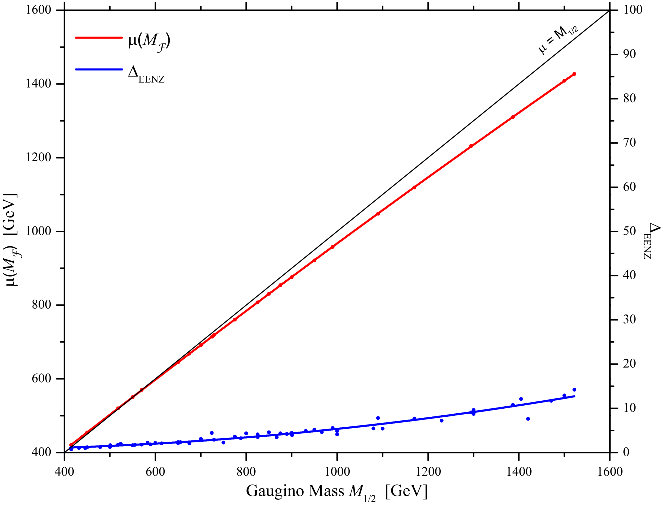
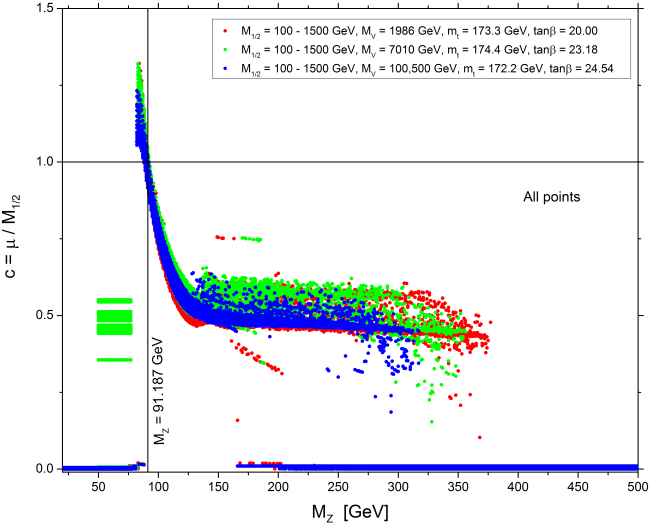
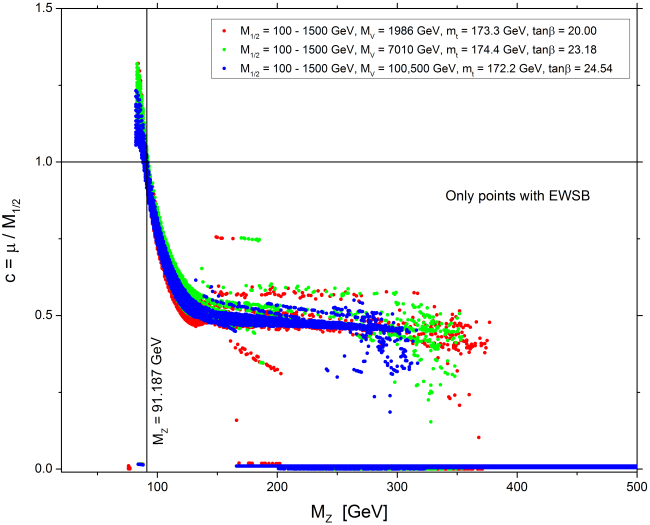
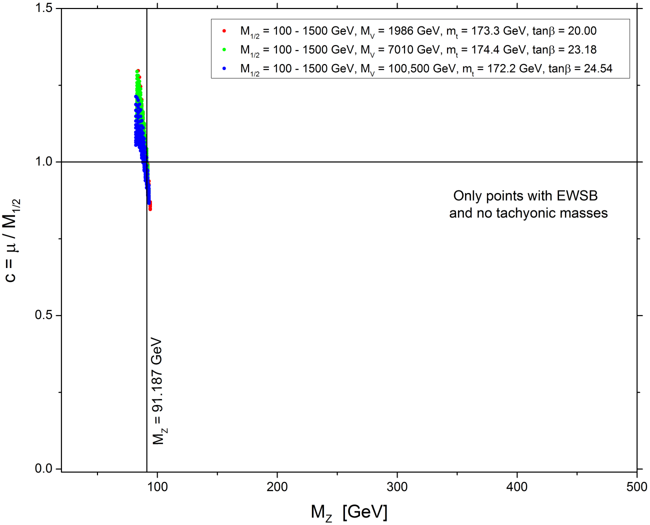
[22] G. F. Giudice and A. Masiero, Phys. Lett. B **206**, 480 (1988).

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


μ(M_F)
Δ_EENZ
μ = M_1/2
1600
1400
1200
1000
800
600
400
μ(M_F) [GeV]
100
90
80
70
60
50
40
30
20
10
0
Δ_EENZ
400
600
800
1000
1200
1400
1600
Gaugino Mass M_1/2 [GeV]


● $M_{1/2}$ = 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
$c = \mu / M_{1/2}$
0.0
0.5
1.0
1.5
50
100
150
200
250
300
350
400
450
500
M_Z [GeV]


● $M_{1/2}$ = 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



Only points with EWSB
and no tachyonic masses

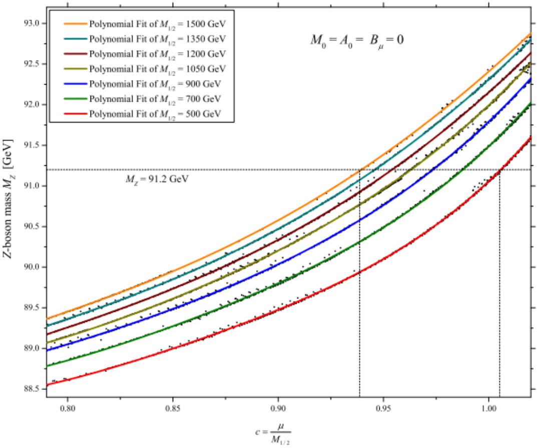


Figure: The Z-boson mass is shown as a function of the dimensionless parameter c for seven different values of $M_{1/2}$.

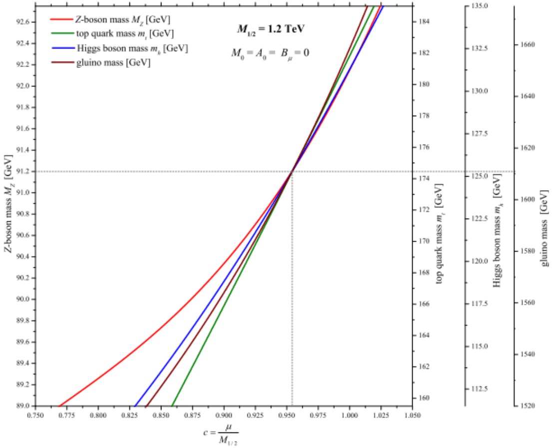


Figure: Depiction of the correlation between the Z-boson mass M_Z, top quark mass m_t, Higgs boson mass m_h, and gluino mass $m_{\widetilde{g}}$, as a function

Outline

- In the $\mathcal{F}$-$SU(5)$, there is a mass parameter: vector-like particle mass M_V.
- The MSSM with no-scale supergravity and Giudice-Masiero mechanism.
- Problem: the light stau is the lightest supersymmetric particle (LSP).
- Solution: axino as the LSP.

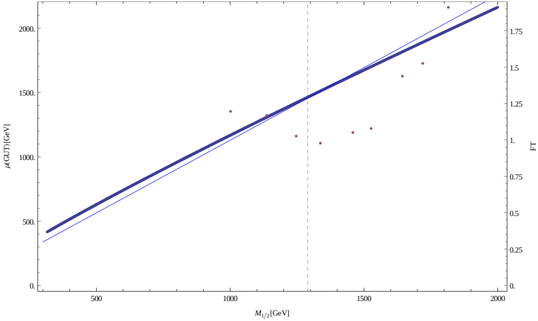


Figure: $\mu(GUT)$ (left-vertical axis) and EWFT measure Δ_{EENZ} (right-vertical axis) versus $M_{1/2}$.

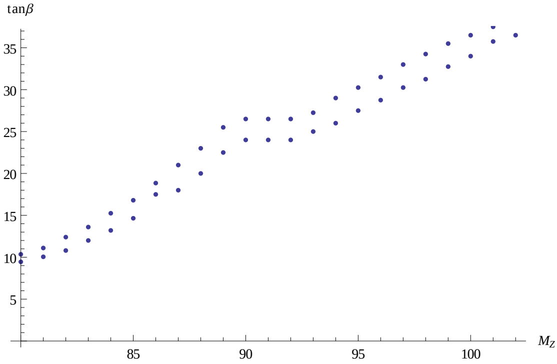


Figure: Plot in the $\tan\beta$-M_Z plane.

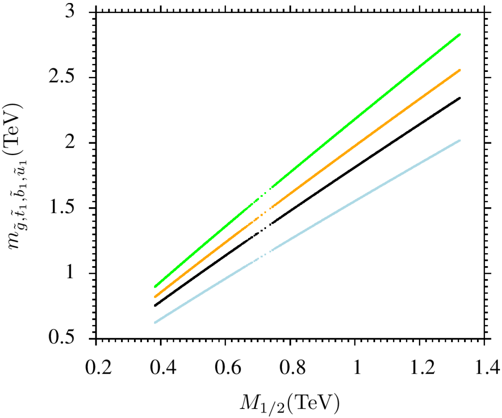


Figure: The green, purple, orange and black points represent $m_{\tilde{g}}$, $m_{\tilde{t}_1}$, $m_{\tilde{u}_1}$ and $m_{\tilde{b}_1}$, respectively.

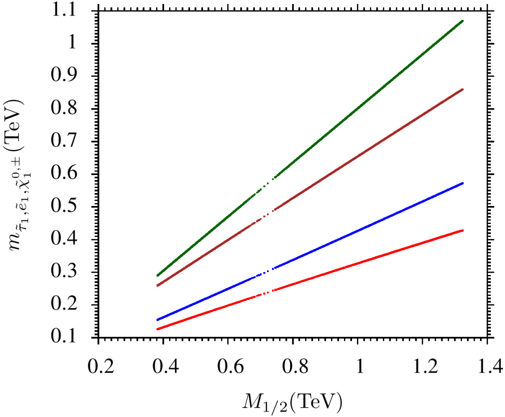


Figure: The dark green, blue, red, and brown lines represent $m_{\tilde{\chi}_1^{\pm}}$, $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\tau}_1}$, $m_{\tilde{e}_1}$, respectively.

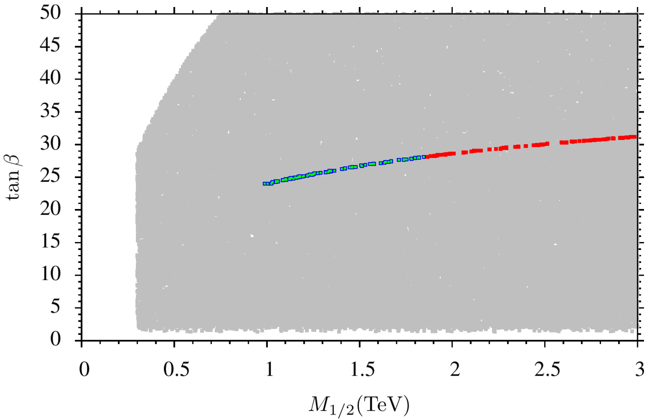


Figure: The viable parameter spaces in $M_{1/2} - \tan\beta$ plane.

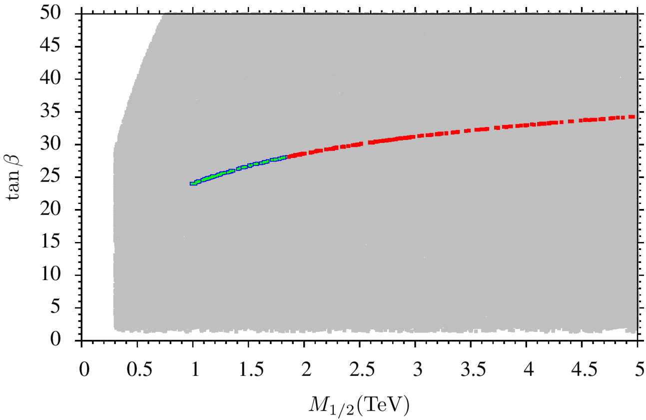


Figure: The viable parameter spaces in $M_{1/2} - \tan\beta$ plane.

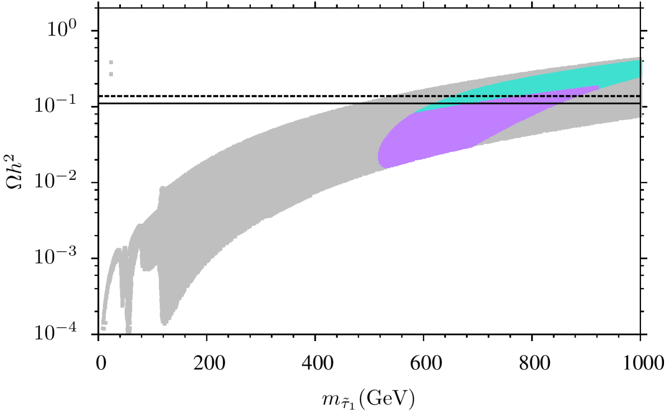


Figure: $m_{\tilde{\tau}_1}$ versus Ωh^2.

	Point 1	Point 2	Point 3
$M_{1/2}$	1865.849	2725.144	4588.77
m_0	0.0	0.0	0.0
A_0	0.0	0.0	0.0
$\tan\beta$	28.129	30.594	33.822
B_0(GUT)	0.599	0.251	-0.716
μ(GUT)	1991	2788	4431
B_0(EWSB)	92	118	4292
μ(EWSB)	1970	2735	166
m_h	123	125	127
m_H	2054	2816	4321
m_A	2054	2815	4321
$m_{H^\pm}$	2056	2816	4322

	Point 1	Point 2	Point 3
$m_{\tilde{\chi}^0_{1,2}}$	820, 1520	1219, 2238	2100, 3802
$m_{\tilde{\chi}^0_{3,4}}$	1978, 1985	2747, 2753	4310, 4317
$m_{\tilde{\chi}^\pm_{1,2}}$	1520, 1985	2238, 2753	3802, 4317
$m_{\tilde{g}}$	3895	5546	9030
$m_{\tilde{u}_{L,R}}$	3505, 3358	4968, 4746	8035, 7604
$m_{\tilde{t}_{1,2}}$	2786, 3225	3957, 4554	6411, 7343
$m_{\tilde{d}_{L,R}}$	3506, 3356	4968, 4717	8035, 7604
$m_{\tilde{b}_{1,2}}$	3205, 3247	4530, 4574	7268, 7364
$m_{\tilde{\nu}_{1,2}}$	1199	1737	2889
$m_{\tilde{\nu}_3}$	1177	1701	2819
$m_{\tilde{e}_{L,R}}$	1202, 679	1739, 987	2890, 1653
$m_{\tilde{\tau}_{1,2}}$	587,1184	841, 1705	1374, 2822

Outline

The Super-Natural Supersymmetry and Its Generalizations

- 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.
- There is one and only one chiral superfield or modulus whose F-term 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 such as the μ term in the MSSM, must arise from supersymmetry breaking.

The Super-Natural Supersymmetry and Its Generalizations

- The EW Symmetry Breaking and Determination of M_* from Z Boson Mass.
- New μ Problem in the MSSM and $\mathcal{F}$-$SU(5)$ Model. Solution: M-theory inspired NMSSM.
- Symmetry for Super-Natural Supersymmetry: scale symmetry.
- Multi F-Term SUSY Breakings.
- Effective Super-Natural SUSY.

Outline

The Super-Natural Supersymmetry

- The EENZ or BG fine-tuning measure is automatically $\mathcal{O}(1)$.
- The MSSM and $\mathcal{F}$-$SU(5)$ Model with no-scale supergravity and Giudice mechanism.
- The NMSSM with M-theory inspired supergravity.
- Gauge mediations.

Thank You Very Much for Your Attention!