

THE IMPLICATIONS OF THE LHC HIGGS SEARCHES IN THE SUPERSYMMETRIC STANDARD MODELS

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I. Supersymmetric Standard Model Overview

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III. Supersymmetric Standard Models

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I. SUPERSYMMETRIC STANDARD MODEL OVERVIEW

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; ...

Supersymmetric Standard Model:

- Solving the gauge hierarchy problem
- Gauge coupling unification
- Radiatively electroweak symmetry breaking
Large top quark mass
- Natural dark matter candidates
Neutralino, sneutrino, gravitino, ...
- Electroweak baryogenesis
- Electroweak precision: R parity

Problems in the MSSM:

- μ problem

$$\mu H_u H_d$$

- Little hierarchy problem

Fine-tuning for the lightest CP even Higgs mass

- CP violation and EDMs
- FCNC
- Dimension-5 proton decays

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

- Unification of the gauge interactions, and unifications of the SM fermions
- Charge quantization
- Gauge coupling unification in the MSSM, and Yukawa unification

$$y_t = y_b = y_\tau$$

- 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

Higgs particles do not form complete GUT multiplet at low energy

- Proton decay problem
- Fermion mass problem

GUT relation $m_e/m_\mu = m_d/m_s$

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 building

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 be decoupled, *i.e.*, $M_{\text{GUT}}/M_{\text{Pl}}$ 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 Yukawa 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.

Phenomenological constraints:

- The colored supersymmetric particles (sparticles) such as squarks and gluinos (at least the first two generation squarks) must have masses around the 1.5 TeV or larger from the ATLAS and CMS Collaborations at the LHC.
- The Higgs boson mass is $126.0 \pm 0.4(\text{stat}) \pm 0.4(\text{sys})$ GeV and $125.3 \pm 0.4(\text{stat}) \pm 0.5(\text{sys})$ GeV from the ATLAS and CMS Collaborations at the LHC, respectively.
- The cold dark matter relic density is 0.112 ± 0.0056 from the seven-year WMAP measurements.
- The spin-independent elastic dark matter-nucleon scattering cross-sections are smaller than about 2×10^{-45} cm² for the dark matter mass around 55 GeV from XENON100 experiment at 90% C.L..

- The experimental limit on the Flavor Changing Neutral Current (FCNC) process, $b \rightarrow s\gamma$. The limits, where the experimental and theoretical errors are added in quadrature, are

$$2.86 \times 10^{-4} \leq \text{BR}(b \rightarrow s\gamma) \leq 4.18 \times 10^{-4}.$$

- The anomalous magnetic moment of the muon $(g_\mu - 2)/2$. The experimental value of the muon $(g_\mu - 2)/2$ is
 $\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (26.1 \pm 8.0) \times 10^{-10}$.
- The experimental limit on the process $B_s \rightarrow \mu^+ \mu^-$. The upper bound on $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ is $4.5(3.8) \times 10^{-9}$ at 95% (90%) C.L. from the CMS and LHCb collaborations.
- The experimental limit on the process $B_u \rightarrow \tau \bar{\nu}_\tau$ is
 $0.85 \leq \text{BR}(B_u \rightarrow \tau \bar{\nu}_\tau)/\text{SM} \leq 1.65$.

The squarks might be heavy while the sleptons and electroweak gauginos may be light.

Supersymmetric SMs:

- Natural supersymmetry ^a.
- Supersymmetric models with sub-TeV squarks that can escape/relax the missing energy constraints: R parity violation ^b; compressed supersymmetry ^c ; stealth supersymmetry ^d; etc.
- Supersymmetric models with sub-TeV squarks that decrease the cross sections: supersoft supersymmetry ^e.

^aS. 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].

^b 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].

^c 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]].

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

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

Dark Matter in Supersymmetric Standard Model:

- Supersymmetry was proposed to solve the gauge hierarchy problem.
- The lightest supersymmetric particle (LSP) needs not to provide the observed dark matter density.
- The LSP needs not to be a dark matter candidate: R -parity violations.
- The elegant solution to the strong CP problem is Peccei-Quinn (PQ) mechanism, and the invisible axion is a good cold dark matter candidate with correct dark matter density.

Natural supersymmetry conditions::

- The μ term or effective μ term is smaller than 300 GeV.
- The square 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. Consequently, we can show that the light sbottom mass is smaller than $m_{\tilde{t}_2}$.
- The gluino mass is lighter than 1.5 TeV.

II. HIGGS PHYSICS

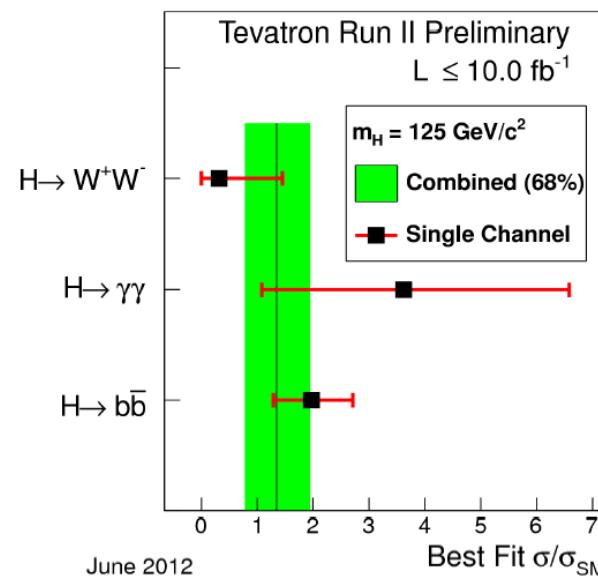
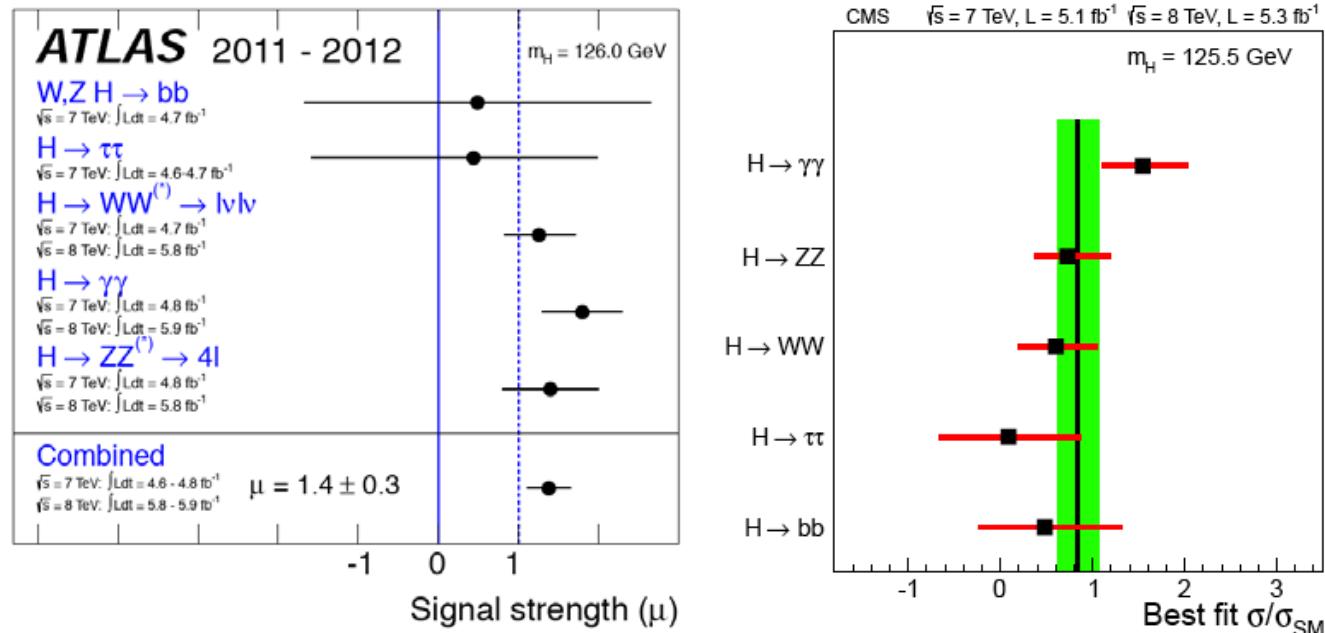


Figure 1: Measured relative signal strength μ in various channels of the ATLAS, CMS, and Tevatron Higgs searches.

Properties:

- The Higgs boson mass is about 125.5 GeV.
- There exists excesses for Higgs decays to two gamma: the signal strength is about $1.6^{+0.4}_{-0.4}$ and $2.3^{+1.0}_{-0.9}$ for gluon-gluon fusion and vector-boson fusion, respectively.
- The signal strengths for Higgs decays to VV are about $1.0^{+0.3}_{-0.3}$.
- The signal strengths for Higgs decays to $b\bar{b}$ and $\tau^-\tau^+$ are about 0.5.

Higgs boson mass:

- In the MSSM, the lightest CP-even Higgs boson mass at tree level is smaller than $M_Z |\cos 2\beta|$ since the Higgs quartic coupling is determined by the $SU(2)_L \times U(1)_Y$ gauge couplings from D-terms.
- The Higgs boson mass can be lifted radiatively due to large top quark Yukawa couplings in the MSSM.
- The Higgs boson mass can be lifted: singlet or triplet Higgs fields at tree level, additional $U(1)'$ gauge symmetry, or vector-like particles at one-loop level.

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} \frac{m_t^4}{v^2} \left[\frac{1}{2} \tilde{X}_t + t + \frac{1}{16\pi^2} \left(\frac{3}{2} \frac{m_t^2}{v^2} - 32\pi\alpha_3 \right) (\tilde{X}_t t + t^2) \right] ,$$

where

$$t = \log \frac{M_{\text{SUSY}}^2}{m_t^2} ,$$

$$\begin{aligned} \tilde{X}_t &= \frac{2\tilde{A}_t^2}{M_{\text{SUSY}}^2} \left(1 - \frac{\tilde{A}_t^2}{12M_{\text{SUSY}}^2} \right) , \\ \tilde{A}_t &= A_t - \mu \cot \beta . \end{aligned}$$

The maximum is at large values of $\tan \beta$ and $\tilde{A}_t = \sqrt{6}M_{\text{SUSY}}$.

III. SUPERSYMMETRIC STANDARD MODELS

Minimal Supersymmetric Standard Model (MSSM):

- The Higgs couplings to SM fermions in the units of SM couplings:

$$y'_t = \cos \alpha / \sin \beta, y'_b = y'_{\tau} = -\sin \alpha / \cos \beta.$$

$$h = \cos \alpha H_u^0 - \sin \alpha H_d^0.$$

- The Higgs decays to $b\bar{b}$ and $\tau^-\tau^+$ can be suppressed.
- The Higgs decays to VV and $\gamma\gamma$ can be enhanced similarly.
- To explain the ATLAS and CMS data, we need to decrease the Higgs decays to VV while increase the Higgs decays to $\gamma\gamma$.

Minimal Supersymmetric Standard Model (MSSM): A Radiatively Light Stop ^a

- The best global fit gives ^b

$$c_g^2 = \frac{\Gamma(h \rightarrow gg)}{\Gamma^{\text{SM}}(h \rightarrow gg)} \approx 0.7, \quad c_\gamma^2 = \frac{\Gamma(h \rightarrow \gamma\gamma)}{\Gamma^{\text{SM}}(h \rightarrow \gamma)} \approx 2.1 .$$

- The very light stop can change the reduced couplings of hGG and $h\gamma\gamma$ simultaneously. ^c

$$c_g \approx 1 + \frac{1}{4} \left(\frac{m_t^2}{m_{\tilde{t}_1}^2} - \eta_t^2 \frac{m_t^2}{m_{\tilde{t}}^2} \right) \sim -0.84,$$

$$c_\gamma \approx 1.28 - 0.28c_g .$$

- This is valid for $m_h \simeq 125$ GeV and $c_V \simeq 1..$
- The possible problem: the $SU(3)_C$ symmetry breaking.

^a Z. Kang, TL, J. Li and Y. Liu, arXiv:1208.2673 [hep-ph].

^b P. P. Giardino, K. Kannike, M. Raidal and A. Strumia, arXiv:1207.1347; M. R. Buckley and D. Hooper, arXiv:1207.1445; D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, arXiv:1207.1718.

^cK. Blum, R. T. D'Agnolo and J. Fan, arXiv:1206.5303.

Points:

- The light stop running mass is used in the Higgs boson mass calculations.
- The light stop physical mass is used in the Higgs decays.

$$\omega_t \approx 1 + \frac{2\alpha_s}{3\pi} \left[\frac{2M_3^2}{m_{\tilde{t}_1}^2(Q)} \left(1 - \ln \frac{M_3^2}{Q^2} \right) - \frac{m_{\tilde{t}_2}^2(Q)}{2m_{\tilde{t}_1}^2} \left(1 - \ln \frac{m_{\tilde{t}_2}^2(Q)}{Q^2} \right) \right]_{Q=m_{\tilde{t}_L}} .$$

Increasing the Higgs boson mass and Higgs boson decays to $\gamma\gamma$ simultaneously.

The Next to the Minimal Supersymmetric Standard Model (NMSSM):^a

- An extra SM singlet Higgs field S and a Z_3 symmetry: $\lambda S H_d H_u$ and $\kappa S^3/3$.
- Scenario I: R -parity is conserved and the LSP neutralino relic density is around the observed value.
- Scenario II: R -parity is conserved and the LSP neutralino relic density is smaller than the observed value.
- Scenario III: R -parity is violated and then the LSP neutralino is not stable.

^a T. Cheng, J. Li, TL, X. Wan, Y. k. Wang and S. -h. Zhu, arXiv:1207.6392 [hep-ph].

The SM-like Higgs field is:

$$\begin{aligned}H_1 &= S_{1,d}H_d^0 + S_{1u}H_u^0 + S_{1s}S, \\H_2 &= S_{2,d}H_d^0 + S_{2u}H_u^0 + S_{2s}S.\end{aligned}$$

The most general renormalizable, gauge and Z_3 invariant, and R -parity odd superpotential terms in the NMSSM are

$$W_{\text{RPV}} = \lambda_i S L_i H_u + \frac{1}{2} \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \frac{1}{2} \lambda''_{ijk} U_i^c D_j^c D_k^c.$$

The NMSSM:

- χ^2 analyses for all the phenomenological results: Scenario I has 13 degrees of freedom while Scenarios II and III have 12.
- Fine-tuning Δ_F : the maximum of the logarithmic derivative of M_Z with respect to all the fundamental parameters a_i at the GUT scale

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

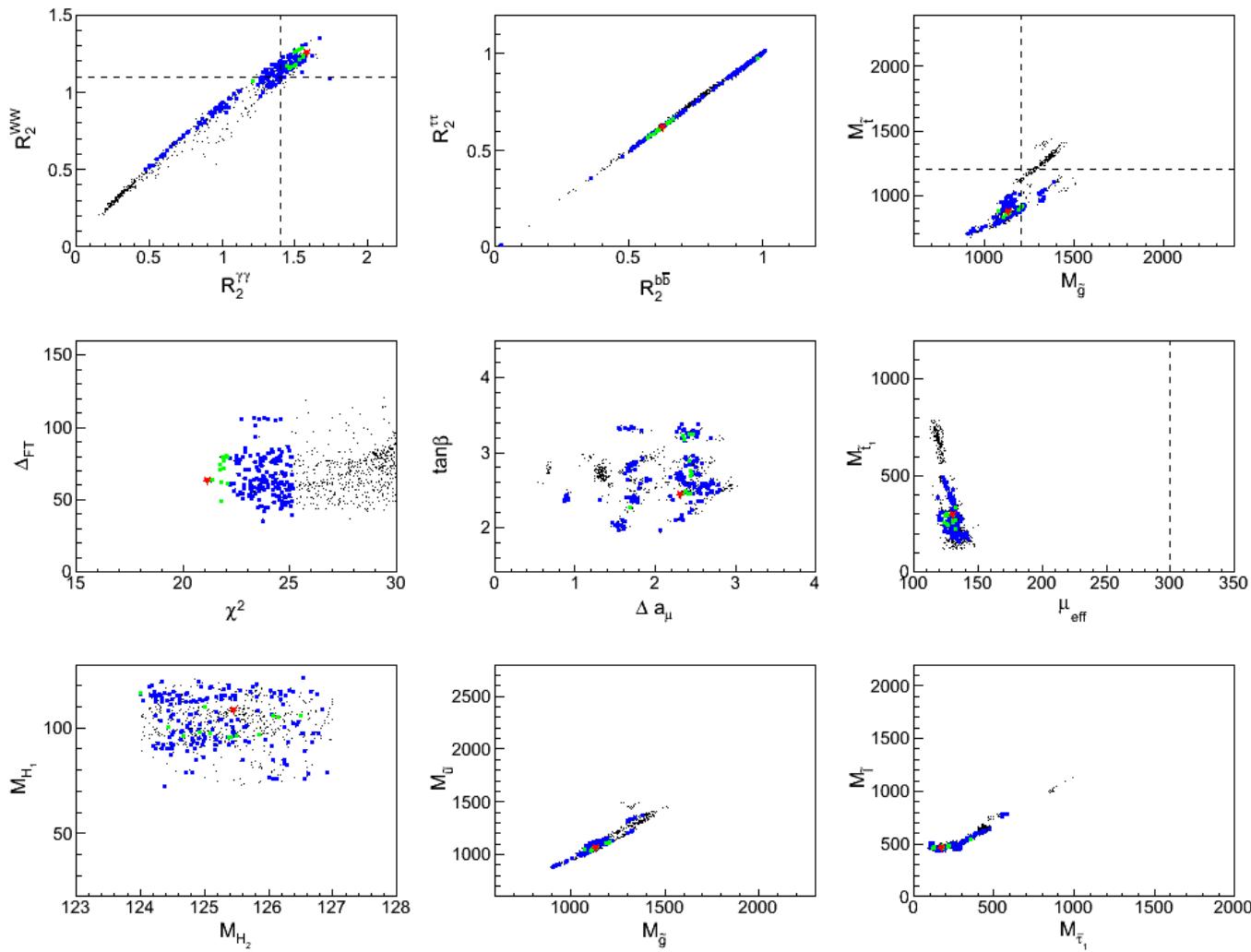


Figure 2: The fitting results for Scenario I with relic density included in the χ^2 . The red stars show the best-fitted benchmark point with minimal $\chi^2_{min} = 21.16$. The green, blue, and black regions are respectively one, two, and three standard deviation regions with $\chi^2 < \chi^2_{min} + 1, \chi^2_{min} + 4$ and $\chi^2_{min} + 9$.

$\tan \beta$	2.456	2.851	2.910	3.293	ℓ	875	857	1042	955
λ	0.601	0.550	0.564	0.536	\tilde{b}_1	783	768	994	880
κ	0.245	0.249	0.268	0.243	\tilde{b}_2	983	979	1296	1114
A_0	-1180	-1253	-1779	-1441	\tilde{u}_R/\tilde{c}_R	1053	1052	1397	1197
A_λ	-315	-230	-628	-193	\tilde{u}_L/\tilde{c}_L	1059	1057	1398	1206
A_κ	-1.904	-2.028	-218.408	-1.900	\tilde{d}_R/\tilde{s}_R	1014	1013	1342	1153
μ_{eff}	130	124	123	128	\tilde{d}_L/\tilde{s}_L	1061	1059	1399	1208
M_1	207	204	266	242	H_1^0	108.5	95.5	111.7	91.7
M_2	384	380	493	449	H_2^0	125.5	125.4	125.2	124.2
M_3	1091	1081	1368	1259	H_3^0	359.7	396.3	385.6	461.1
$\tilde{\chi}_1^0$	75	70	77	76	A_1	99.6	123.8	91.7	138.4
$\tilde{\chi}_2^0$	163	-156	-156	-158	A_2	353.4	390.0	377.9	455.9
$\tilde{\chi}_3^0$	-168	163	172	171	H^\pm	343.9	383.2	371.3	450.2
$\tilde{\chi}_4^0$	219	216	273	250	$\Omega \hbar^2$	0.110	0.104	0.103	0.109
$\tilde{\chi}_5^0$	415	410	521	475	$\Delta_{a_\mu} [10^{-10}]$	2.317	2.586	1.157	1.823
$\tilde{\chi}_1^\pm$	114	109	113	117	$\sigma^{si}(p) [10^{-10} \text{ pb}]$	7.468	1.137	3.208	39.683
$\tilde{\chi}_2^\pm$	414	409	520	475	$\text{Br}^{(b \rightarrow s\gamma)} [10^{-4}]$	3.342	2.633	2.714	2.747
\tilde{g}	1134	1125	1436	1305	Δ_{FT}	62.7	74.0	109.3	101.5
$\tilde{\nu}_{e/\mu}$	457	472	741	497	$R_2^{\gamma\gamma}_{\text{VBF}}$	1.48	1.60	1.75	1.46
$\tilde{\nu}_\tau$	456	471	740	496	$R_2^{\gamma\gamma}$	1.58	1.43	1.45	1.31
$\tilde{e}_D/\tilde{\mu}_D$	178	216	482	126	R_2^{WW}	1.25	1.10	1.07	1.09

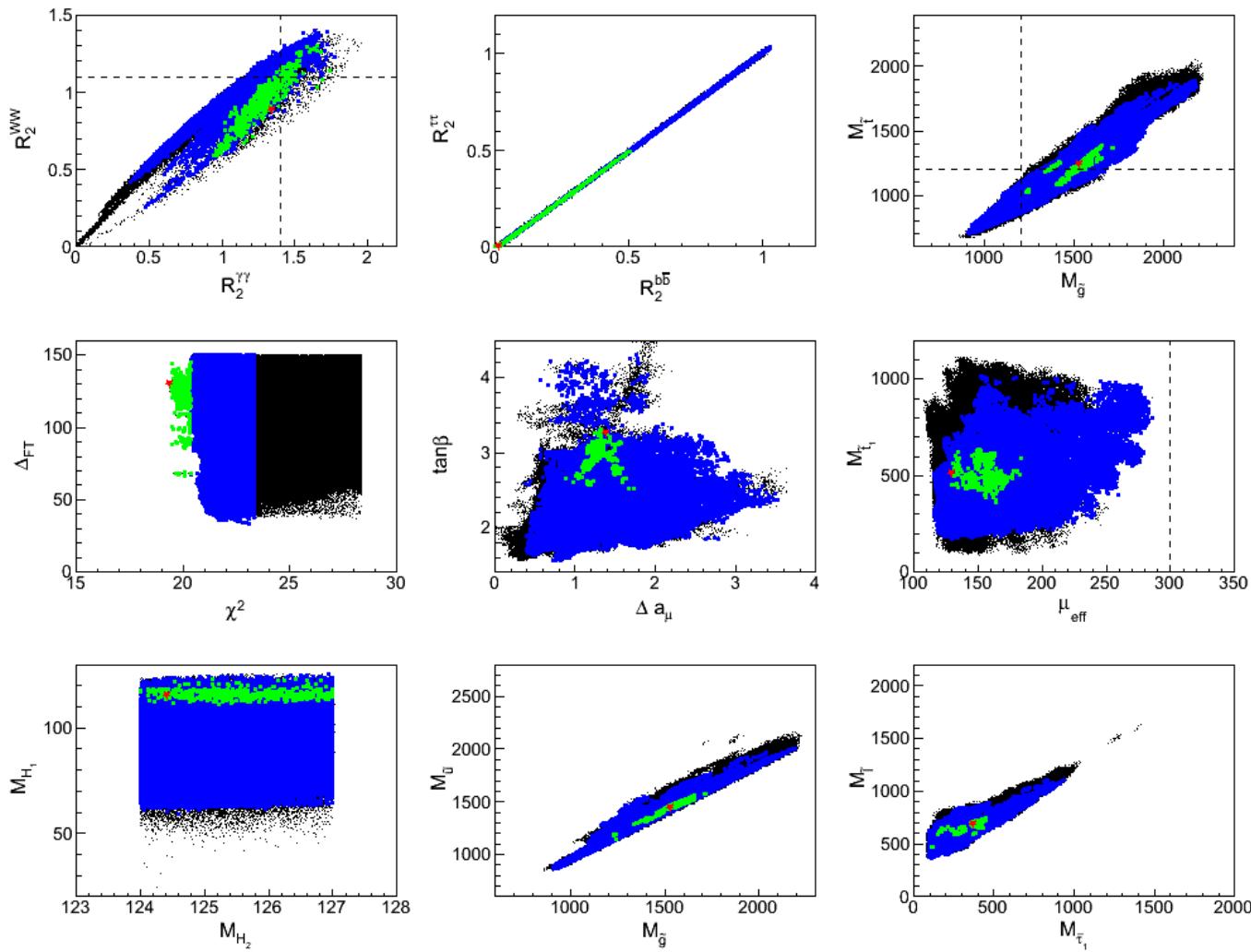


Figure 3: The fitting results for Scenario II with relic density smaller than the 95% C.L. upper limit. The red stars show the best-fitted benchmark point with minimal $\chi^2_{min} = 19.35$. The green, blue, and black regions are respectively one, two, and three standard deviation regions with $\chi^2 < \chi^2_{min} + 1$, $\chi^2_{min} + 4$, and $\chi^2_{min} + 9$.

$\tan \beta$	3.267	2.518	2.468	1.820	t	1257	717	950	994
λ	0.452	0.617	0.582	0.584	\tilde{b}_1	1093	654	880	866
κ	0.214	0.295	0.247	0.172	\tilde{b}_2	1348	835	1153	1058
A_0	-1520	-1090	-1519	-986	\tilde{u}_R/\tilde{c}_R	1434	898	1240	1127
A_λ	-296	-248	-618	-380	\tilde{u}_L/\tilde{c}_L	1445	903	1237	1135
A_κ	-1.354	-1.049	-253.408	-1.707	\tilde{d}_R/\tilde{s}_R	1384	865	1192	1086
μ_{eff}	130	129	118	123	\tilde{d}_L/\tilde{s}_L	1446	905	1239	1136
M_1	287	173	224	224	H_1^0	115.2	106.5	99.7	98.0
M_2	530	324	416	416	H_2^0	124.4	126.2	124.7	126.0
M_3	1467	933	1169	1173	H_3^0	440.5	363.1	332.7	290.1
$\tilde{\chi}_1^0$	87	70	69	74	A_1	66.1	145.4	103.3	74.6
$\tilde{\chi}_2^0$	-152	-166	-156	133	A_2	435.0	355.4	325.3	288.4
$\tilde{\chi}_3^0$	167	170	158	-166	H^\pm	433.6	345.6	316.3	275.7
$\tilde{\chi}_4^0$	292	194	233	233	$\Omega \hbar^2$	0.038	0.001	0.072	0.070
$\tilde{\chi}_5^0$	557	358	446	444	$\Delta_{a_\mu} [10^{-10}]$	1.385	3.410	1.100	1.513
$\tilde{\chi}_1^\pm$	122	107	104	107	$\sigma^{si}(p) [10^{-10} \text{ pb}]$	59.671	39.947	22.116	28.064
$\tilde{\chi}_2^\pm$	556	357	446	444	$\text{Br}^{(b \rightarrow s\gamma)} [10^{-4}]$	3.553	2.294	2.914	4.123
\tilde{g}	1529	968	1235	1218	Δ_{FT}	130.4	48.8	75.7	59.6
$\tilde{\nu}_{e/\mu}$	680	377	710	489	$R_2^{\gamma\gamma}_{\text{VBF}}$	1.08	1.68	1.53	1.24
$\tilde{\nu}_\tau$	679	377	709	489	$R_2^{\gamma\gamma}$	1.34	1.45	1.42	1.42
$\tilde{e}_D/\tilde{\mu}_D$	376	122	510	191	R_2^{WW}	0.89	1.09	1.10	1.09

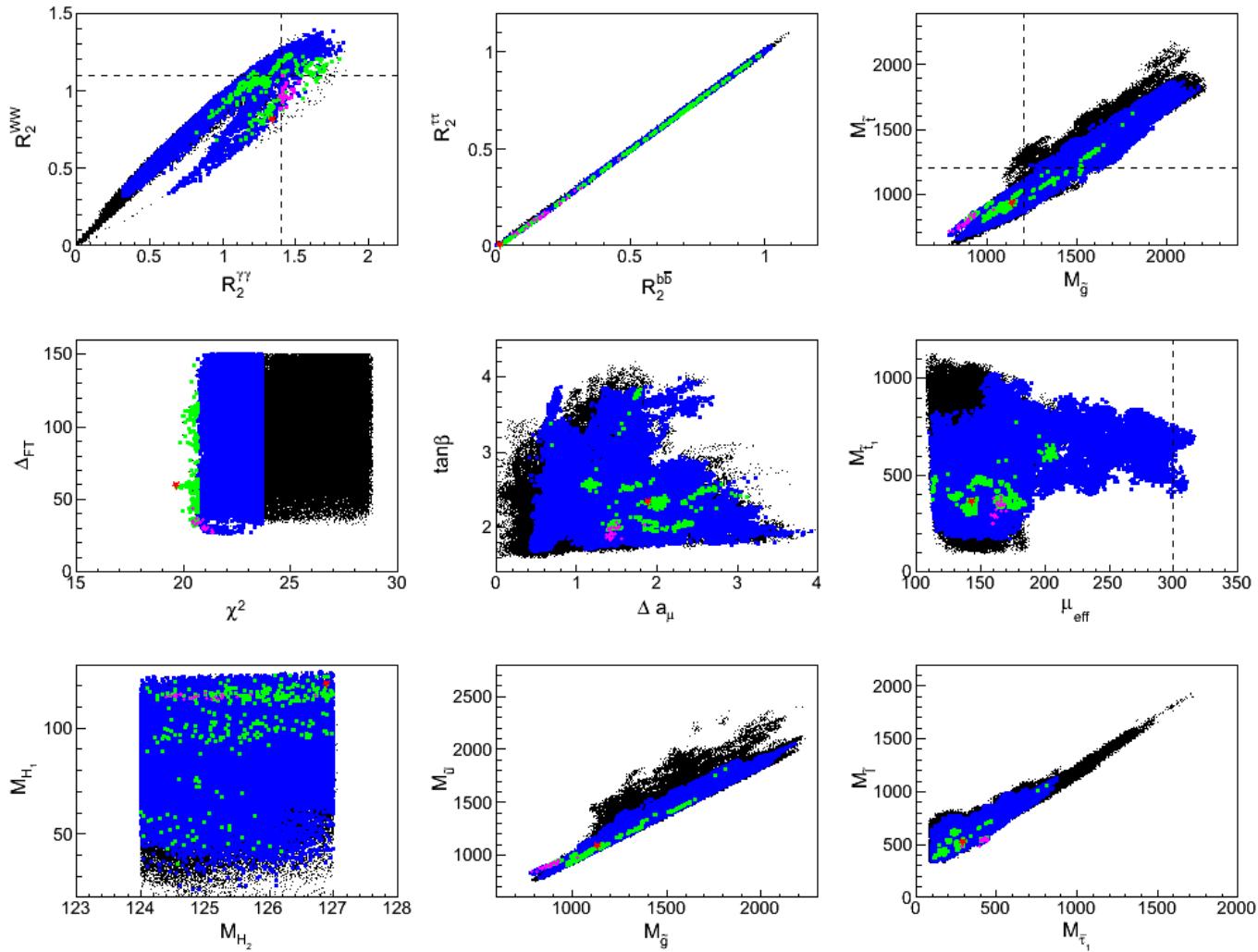


Figure 4: The fitting results for Scenario III without R -parity. The red stars show the best-fitted benchmark point with minimal $\chi^2_{min} = 19.67$. The magenta region corresponds to $R_{\gamma\gamma} > 1.4$, $R_{VV} < 1.1$, $R_{bb} < 1.0$, $R_{\tau\tau} < 1.0$, $M_{\tilde{t}} = \sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2} < 1.2 \text{ TeV}$, $\mu_{\text{eff}} < 300 \text{ GeV}$, $M_{\tilde{g}} < 1.2 \text{ TeV}$, $\chi^2 < \chi^2_{min} + 4$, and $\Delta_{FT} < 50$.

$\tan \beta$	2.541	1.853	2.731	2.039	ℓ	925	694	832
λ	0.604	0.589	0.623	0.614	\tilde{b}_1	814	610	793
κ	0.295	0.364	0.288	0.318	\tilde{b}_2	1012	778	1020
A_0	-1063	-372	-1322	-620	\tilde{u}_R/\tilde{c}_R	1078	827	1097
A_λ	-329	-161	-267	-9.93×10^{-6}	\tilde{u}_L/\tilde{c}_L	1083	823	1101
A_κ	-128.134	-628.214	-0.877	-1.459	\tilde{d}_R/\tilde{s}_R	1039	798	1056
μ_{eff}	144	162	150	166	\tilde{d}_L/\tilde{s}_L	1085	825	1103
M_1	207	136	212	186	H_1^0	120.5	114.3	119.6
M_2	384	255	393	346	H_2^0	126.9	124.6	124.9
M_3	1090	745	1114	990	H_3^0	367.8	342.7	436.6
$\tilde{\chi}_1^0$	91	86	92	107	A_1	154.3	300.6	157.1
$\tilde{\chi}_2^0$	-177	160	-184	195	A_2	360.0	335.1	430.1
$\tilde{\chi}_3^0$	187	-189	191	-197	H^\pm	352.6	330.2	421.7
$\tilde{\chi}_4^0$	222	232	228	221	$\Omega \hbar^2$	\times	\times	\times
$\tilde{\chi}_5^0$	417	310	425	384	$\Delta_{a_\mu} [10^{-10}]$	1.893	1.587	2.207
$\tilde{\chi}_1^\pm$	126	122	133	141	$\sigma^{si}(p) [10^{-10} \text{ pb}]$	\times	\times	\times
$\tilde{\chi}_2^\pm$	416	306	425	383	$\text{Br}^{(b \rightarrow s\gamma)} [10^{-4}]$	3.586	3.413	2.560
\tilde{g}	1138	796	1162	1035	Δ_{FT}	59.5	27.0	68.4
$\tilde{\nu}_{e/\mu}$	513	502	514	475	$R_2^{\gamma\gamma}_{\text{VBF}}$	0.88	0.93	1.60
$\tilde{\nu}_\tau$	512	502	514	475	$R_2^{\gamma\gamma}$	1.34	1.46	1.41
$\tilde{e}_R/\tilde{\mu}_R$	291	395	273	289	R_2^{WW}	0.81	0.95	1.08

Properties:

- The benchmark points in Scenarios I and II have fine-tuning from about 1% to 2%, while the benchmark points in Scenario III have fine-tuning from about 2% to 3.7%.
- In the best benchmark point IIIA we have $\chi^2 = 21.31$, and $\Delta_{FT} = 27.0$, *i.e.*, 3.7% fine-tuning. Also, all the supersymmetric particles are lighter than 830 GeV.
- All the benchmark points except $\Pi\chi^2_{min}$ satisfy the naturalness conditions: $\mu_{\text{eff}} < 300$ GeV, $M_{\tilde{t}} < 1.2$ TeV, and $M_{\tilde{g}} \leq 1.5$ TeV. Note that $\Delta_{FT} = 130.4$ in benchmark point $\Pi\chi^2_{min}$, the two fine-tuning definitions in Section II are compatible.

Properties:

- The SM-like Higgs boson is H_2^0 .
- $\tan \beta$ is generically smaller than about 4.5, and then we have the small anomalous magnetic moment of the muon $(g_\mu - 2)/2$, *i.e.*, $\Delta a_\mu < 4.0 \times 10^{-10}$.
- The correlation between $R_2^{\gamma\gamma}$ and R_2^{VV} roughly is $R_2^{\gamma\gamma} \sim 1.27 \times R_2^{VV}$.
- We do have some viable parameter space which indeed have $R_2^{\gamma\gamma} \geq 1.4$ and $R_2^{VV} \leq 1.1$. The Higgs decays to $\gamma\gamma$ can be enhanced due to the light stops and Higgsinos.

- The generic features for the parameter space with small χ^2 are that the light stop is around 500 GeV or smaller, the singlino and Higgsino are light neutralinos and chargino, the Wino-like chargino is heavy, and the Bino-like and Wino-like neutralinos are the second heaviest neutralino and the heaviest neutralino, respectively.
- In Scenario III, the constraints from the LHC supersymmetry searches and XENON100 experiment can be escaped, and the R -parity violating λ_{ijk} and λ'_{ijk} terms can increase $(g_\mu - 2)/2$ and generate the neutrino masses and mixings. Therefore, Scenario III with R -parity violation is more natural and realistic than Scenarios I and II.

IV. ELECTROWEAK SUPERSYMMETRY

Electroweak Supersymmetry ^a

- String model building strongly implies that the three families of the SM fermions have the same origin. Thus, all the squarks may be heavier.
- The LHC supersymmetry and Higgs searches and B physics constraints imply the heavy squarks.
- To explain the $(g_\mu - 2)/2$ results, the smuon may need to be light. Thus, the sleptons may be light.
- The observed dark matter density can be realized via the LSP neutralino and stau coannihilations.
- XENON100 constraints: small Higgsino/ \tilde{W}^0 component for LSP neutralino, and relatively heavy squarks.

^a T. Cheng, J. Li, TL, D. V. Nanopoulos and C. Tong, arXiv:1202.6088 [hep-ph].

Electroweak Supersymmetry:

The squarks and/or gluinos are heavy around a few TeV while the sleptons, bino and winos are light and within one TeV. The Higgsinos (or μ term) can be either heavy or light.

- M_3 is about a few TeV while the squark soft masses are small.
- M_3 is small while the squark soft masses are about a few TeV.
- Both M_3 and squark soft masses are heavy.

GmSUGRA can realize electroweak supersymmetry.

mSUGRA: Grand Unified Theories with Gravity Mediated Supersymmetry Breaking^a

$$\frac{1}{\alpha_3} = \frac{1}{\alpha_2} = \frac{1}{\alpha_1},$$

$$\frac{M_3}{\alpha_3} = \frac{M_2}{\alpha_2} = \frac{M_1}{\alpha_1}.$$

^aA. H. Chamseddine, R. L. Arnowitt and P. Nath, Phys. Rev. Lett. **49**, 970 (1982); H. P. Nilles, Phys. Lett. B **115**, 193 (1982); L. E. Ibanez, Phys. Lett. B **118**, 73 (1982); R. Barbieri, S. Ferrara and C. A. Savoy, Phys. Lett. B **119**, 343 (1982); H. P. Nilles, M. Srednicki and D. Wyler, Phys. Lett. B **120**, 346 (1983); J. R. Ellis, D. V. Nanopoulos and K. Tamvakis, Phys. Lett. B **121**, 123 (1983); J. R. Ellis, J. S. Hagelin, D. V. Nanopoulos and K. Tamvakis, Phys. Lett. B **125**, 275 (1983); L. J. Hall, J. D. Lykken and S. Weinberg, Phys. Rev. D **27**, 2359 (1983).

Observations:

- Gauge coupling unification and gaugino mass unification.
- $1/\alpha_i$ and M_i/α_i satisfy the same equation $x_3 = x_2 = x_1$ at the GUT scale.
- M_i/α_i are constant under one-loop RGE running, so the above gaugino mass relation is valid from the GUT scale to the electroweak scale at one loop.
- Two-loop RGE running effects on gaugino masses are very small, thus, this gaugino mass relation may be tested at the LHC and ILC where the gaugino masses can be measured ^a.

^aW. S. Cho, K. Choi, Y. G. Kim and C. B. Park, Phys. Rev. Lett. **100**, 171801 (2008); M. M. Nojiri, Y. Shimizu, S. Okada and K. Kawagoe, JHEP **0806**, 035 (2008); V. D. Barger, T. Han, T. Li and T. Plehn, Phys. Lett. B **475**, 342 (2000).

Modification of Gauge Coupling Unification:^a

- The SM gauge couplings need not be unified at the GUT Scale due to the high-dimensional operators

$$\mathcal{L} \supset \frac{c}{M_*} \text{Tr} (\Phi F_{\mu\nu} F^{\mu\nu}) .$$

$$\delta(1/g_3^2) : \delta(1/g_2^2) : \delta(1/g_1^2) = 2 : -3 : -1$$

- M_* can be the reduced Planck scale, string scale, or compactification scale.

^a C. T. Hill, Phys. Lett. B **135**, 47 (1984); Q. Shafi and C. Wetterich, Phys. Rev. Lett. **52**, 875 (1984). J. R. Ellis, C. Kounnas and D. V. Nanopoulos, Nucl. Phys. B **247**, 373 (1984); J. R. Ellis, K. Enqvist, D. V. Nanopoulos and K. Tamvakis, Phys. Lett. B **155**, 381 (1985); M. Drees, Phys. Lett. B **158**, 409 (1985).

- In the GUTs with large number of fields, the renormalization effects significantly decrease the scale at which quantum gravity (or fundamental scale) becomes strong ^a

$$M_* = \frac{M_{\text{Pl}}}{\Delta}, \quad \Delta = \sqrt{1 + \frac{N}{12\pi}}, \quad N = N_0 + N_{1/2} - 4N_1.$$

Questions:

- How to define the GUT scale?
- What is the gaugino mass relation? ^b

^a X. Calmet, S. D. H. Hsu and D. Reeb, Phys. Rev. Lett. **101**, 171802 (2008).

^b J. R. Ellis, K. Enqvist, D. V. Nanopoulos and K. Tamvakis, Phys. Lett. B **155**, 381 (1985).

GmSUGRA: two supersymmetry breaking fields S and T ^a:

$$f_i = S + \epsilon a_i T .$$

- mSUGRA if $a_1 = a_2 = a_3$
- Gauge coupling relation and gaugino mass relation

$$\frac{a_1 - a_2}{\alpha_3} + \frac{a_3 - a_1}{\alpha_2} + \frac{a_2 - a_3}{\alpha_1} = 0 .$$

$$\frac{(a_1 - a_2)M_3}{\alpha_3} + \frac{(a_3 - a_1)M_2}{\alpha_2} + \frac{(a_2 - a_3)M_1}{\alpha_1} = 0 .$$

^a TL and D. V. Nanopoulos, Phys. Lett. B **692**, 121 (2010) [arXiv:1002.4183 [hep-ph]].

GmSUGRA:

Gauge coupling relation

$$\frac{1}{\alpha_2} - \frac{1}{\alpha_3} = k \left(\frac{1}{\alpha_1} - \frac{1}{\alpha_3} \right) ,$$

Gaugino mass relation

$$\frac{M_2}{\alpha_2} - \frac{M_3}{\alpha_3} = k \left(\frac{M_1}{\alpha_1} - \frac{M_3}{\alpha_3} \right) ,$$

$$k \equiv \frac{a_2 - a_3}{a_1 - a_3} .$$

Index k might be obtained from the LHC and ILC.

$SU(5)$	a_1	a_2	a_3	k
1	1	1	1	∞
24	$-1/2$	$-3/2$	1	$5/3$
75	-5	3	1	$-1/3$
200	10	2	1	$1/9$

Table 4: a_i and k for each irreducible representation in $SU(5)$ models.

Comments:

The non-universal gaugino masses in gravity mediated supersymmetry breaking:^a

$$\frac{M_3}{a_3\alpha_3} = \frac{M_2}{a_2\alpha_2} = \frac{M_1}{a_1\alpha_1}.$$

Differences from GmSUGRA: both gauge coupling relation and gaugino masses.

^a G. Anderson, H. Baer, C. h. Chen and X. Tata, Phys. Rev. D **61**, 095005 (2000); N. Chamoun, C. S. Huang, C. Liu and X. H. Wu, Nucl. Phys. B **624**, 81 (2002); J. Chakrabortty and A. Raychaudhuri, Phys. Lett. B **673**, 57 (2009); S. P. Martin, Phys. Rev. D **79**, 095019 (2009); S. Bhattacharya and J. Chakrabortty, Phys. Rev. D **81**, 015007 (2010); N. Chamoun, C. S. Huang, C. Liu and X. H. Wu, arXiv:0909.2374 [hep-ph].

F-Theory GUTs:^a

- The $SU(5)$ gauge symmetry is broken down to the SM gauge symmetry by turning on the $U(1)_Y$ flux ^b.
- The $SO(10)$ gauge symmetry is broken down to the Flipped $SU(5) \times U(1)_X$ gauge symmetry by turning on the $U(1)_X$ flux ^c.
- The $SO(10)$ gauge symmetry is broken down to the $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge symmetry by turning on the $U(1)_{B-L}$ flux ^d.

^aR. Donagi and M. Wijnholt, arXiv:0802.2969 [hep-th]; arXiv:0808.2223 [hep-th]; C. Beasley, J. J. Heckman and C. Vafa, JHEP **0901**, 058 (2009); JHEP **0901**, 059 (2009).

^bC. Beasley, J. J. Heckman and C. Vafa, JHEP **0901**, 059 (2009); T. Li, arXiv:0905.4563 [hep-th].

^cC. 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); arXiv:0905.3394 [hep-th].

^dA. Font and L. E. Ibanez, JHEP **0902**, 016 (2009); T. Li, arXiv:0905.4563 [hep-th].

Gauge kinetic functions:

- *SU(5) Models with $U(1)_Y$ flux* ^a

$$f_3 = \tau + \frac{1}{2}\alpha S, \quad f_2 = \tau + \frac{1}{2}(\alpha + 2)S, \quad f_1 = \tau + \frac{1}{2}\left(\alpha + \frac{6}{5}\right)S.$$

- *SO(10) Models with $U(1)_X$ flux* ^b

$$f_5 = f_{1X} = \tau + \alpha S.$$

^a R. Donagi and M. Wijnholt, arXiv:0808.2223 [hep-th]; R. Blumenhagen, Phys. Rev. Lett. **102**, 071601 (2009).

^b J. Jiang, T. Li, D. V. Nanopoulos and D. Xie, arXiv:0905.3394 [hep-th].

- *SO(10) Models with $U(1)_{B-L}$ flux*^a

$$\begin{aligned} f_{SU(3)_C} &= f_{U(1)_{B-L}} = \tau + S , \quad f_{SU(2)_L} = f_{SU(2)_R} = \tau , \\ f_{U(1)_Y} &= \frac{3}{5}f_{SU(2)_R} + \frac{2}{5}f_{U(1)_{B-L}} = \tau + \frac{2}{5}S . \end{aligned}$$

The index for $SU(5)$ Models with $U(1)_Y$ flux and $SO(10)$ Models with $U(1)_{B-L}$ flux is 5/3.

^a T. Li, arXiv:0905.4563 [hep-th].

Solutions to the fermion mass problem in the GUTs ^a

- The high-dimensional operators in the superpotential.
- The high-dimensional operators in the Kähler potential.

^aC. Balazs, TL, D. V. Nanopoulos and F. Wang, JHEP **1102**, 096 (2011) [arXiv:1101.5423 [hep-ph]].

Supersymmetry breaking soft terms ^a

mSUGRA

$$W = \frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k + \alpha \frac{S}{M_*} \left(\frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k \right) ,$$

$$K = \phi_i^\dagger\phi_i + \beta \frac{S^\dagger S}{M_*^2} \phi_i^\dagger\phi_i .$$

The universal supersymmetry breaking scalar mass m_0 and trilinear soft term A of

$$m_0^2 = \beta \frac{|F_S|^2}{M_*^2} , \quad A = \alpha \frac{F_S}{M_*} .$$

^aC. Balazs, TL, D. V. Nanopoulos and F. Wang, JHEP **1009**, 003 (2010) [arXiv:1006.5559 [hep-ph]].

GmSUGRA: Superpotential and Kähler potential

$$W = \frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k + \frac{1}{6}\left(h^{ijk}\frac{\Phi}{M_*}\phi_i\phi_j\phi_k\right) + \alpha\frac{S}{M_*}\left(\frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k\right) \\ + \alpha'\frac{T}{M_*}\left(\frac{1}{6}y^{ijk}\frac{\Phi}{M_*}\phi_i\phi_j\phi_k\right),$$

$$K = \phi_i^\dagger\phi_i + \frac{1}{2}h'\phi_i^\dagger\left(\frac{\Phi}{M_*} + \frac{\Phi^\dagger}{M_*}\right)\phi_i + \beta\frac{S^\dagger S}{M_*^2}\phi_i^\dagger\phi_i \\ + \frac{1}{2}\beta'\frac{T^\dagger T}{M_*^2}\phi_i^\dagger\left(\frac{\Phi}{M_*} + \frac{\Phi^\dagger}{M_*}\right)\phi_i.$$

$SU(5)$ Model with an adjoint Higgs field Φ_{24}

Scalar masses:

- Group Theory

$$\bar{\mathbf{5}} \otimes \mathbf{5} = \mathbf{1} \oplus \mathbf{24} ,$$

$$\overline{\mathbf{10}} \otimes \mathbf{10} = \mathbf{1} \oplus \mathbf{24} \oplus \mathbf{75} .$$

- The Φ_{24} VEV

$$\langle \Phi_{24} \rangle = v \sqrt{\frac{3}{5}} \text{diag} \left(-\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3}, \frac{1}{2}, \frac{1}{2} \right) ,$$

$$\langle \Phi_{24} \rangle = v \sqrt{\frac{3}{5}} \text{diag}(\underbrace{-\frac{2}{3}, \dots, -\frac{2}{3}}_3, \underbrace{\frac{1}{6}, \dots, \frac{1}{6}}_6, 1) .$$

Supersymmetry breaking scalar masses:

$$\begin{aligned}
m_{\tilde{Q}_i}^2 &= (m_0^U)^2 + \sqrt{\frac{3}{5}} \beta'_{\mathbf{10}} \frac{1}{6} (m_0^N)^2, \quad m_{\tilde{U}_i^c}^2 = (m_0^U)^2 - \sqrt{\frac{3}{5}} \beta'_{\mathbf{10}} \frac{2}{3} (m_0^N)^2, \\
m_{\tilde{E}_i^c}^2 &= (m_0^U)^2 + \sqrt{\frac{3}{5}} \beta'_{\mathbf{10}} (m_0^N)^2, \\
m_{\tilde{D}_i^c}^2 &= (m_0^U)^2 + \sqrt{\frac{3}{5}} \beta'_{\bar{\mathbf{5}}} \frac{1}{3} (m_0^N)^2, \quad m_{\tilde{L}_i}^2 = (m_0^U)^2 - \sqrt{\frac{3}{5}} \beta'_{\bar{\mathbf{5}}} \frac{1}{2} (m_0^N)^2, \\
m_{\tilde{H}_u}^2 &= (m_0^U)^2 + \sqrt{\frac{3}{5}} \beta'_{Hu} \frac{1}{2} (m_0^N)^2, \quad m_{\tilde{H}_d}^2 = (m_0^U)^2 - \sqrt{\frac{3}{5}} \beta'_{Hd} \frac{1}{2} (m_0^N)^2,
\end{aligned}$$

where

$$(m_0^U)^2 \equiv \frac{\beta}{M_*^2} F_S^* F_S, \quad (m_0^N)^2 = \frac{v}{M_*^3} F_T^* F_T.$$

The sfermion mass relations at the GUT scale

$$3m_{\tilde{D}_i^c}^2 + 2m_{\tilde{L}_i}^2 = 4m_{\tilde{Q}_i}^2 + m_{\tilde{U}_i^c}^2 = 6m_{\tilde{Q}_i}^2 - m_{\tilde{E}_i^c}^2 = 2m_{\tilde{E}_i^c}^2 + 3m_{\tilde{U}_i^c}^2.$$

Choosing slepton masses as input parameters, we can parametrize the squark masses as follows

$$\begin{aligned} m_{\tilde{Q}_i}^2 &= \frac{5}{6}(m_0^U)^2 + \frac{1}{6}m_{\tilde{E}_i^c}^2, \\ m_{\tilde{U}_i^c}^2 &= \frac{5}{3}(m_0^U)^2 - \frac{2}{3}m_{\tilde{E}_i}^2, \\ m_{\tilde{D}_i^c}^2 &= \frac{5}{3}(m_0^U)^2 - \frac{2}{3}m_{\tilde{L}_i}^2. \end{aligned}$$

If the slepton masses are much smaller than the universal scalar mass, we obtain $2m_{\tilde{Q}_i}^2 \sim m_{\tilde{U}_i^c}^2 \sim m_{\tilde{D}_i^c}^2$.

Trilinear soft A terms:

- Group Theory

$$\begin{aligned}
 \mathbf{10} \otimes \mathbf{10} \otimes \mathbf{5} &= (\bar{\mathbf{5}} \oplus \bar{\mathbf{45}} \oplus \bar{\mathbf{50}}) \otimes \mathbf{5} \\
 &= (\mathbf{1} \oplus \mathbf{24}) \oplus (\mathbf{24} \oplus \mathbf{75} \oplus \mathbf{126}) \oplus (\mathbf{75} \oplus \mathbf{175}') , \\
 \mathbf{10} \otimes \bar{\mathbf{5}} \otimes \bar{\mathbf{5}} &= \mathbf{10} \otimes (\bar{\mathbf{10}} \oplus \bar{\mathbf{15}}) = (\mathbf{1} \oplus \mathbf{24} \oplus \mathbf{75}) \oplus (\mathbf{24} \oplus \bar{\mathbf{126}}) .
 \end{aligned}$$

- Superpotential

$$\begin{aligned}
 W \supset & \left(h^{Ui} \epsilon^{mnpql} (F'_i)_{mn} (F'_i)_{pq} (h')_k (\Phi_{\mathbf{24}})_l^k + h'^{Ui} \epsilon^{mnpkl} (F'_i)_{mn} (F'_i)_{pq} (h')_k (\Phi_{\mathbf{24}})_l^q \right. \\
 & + h^{DEi} (F'_i)_{mn} (\bar{f}'_i \otimes \bar{h}')_{Sym}^{ml} (\Phi_{\mathbf{24}})_l^n + h'^{DEi} (F'_i)_{mn} (\bar{f}'_i \otimes \bar{h}')_{Asym}^{ml} (\Phi_{\mathbf{24}})_l^n \Big) \\
 & + \alpha' \frac{T}{M_*} \left(y^{Ui} \epsilon^{mnpql} (F'_i)_{mn} (F'_i)_{pq} (h')_k (\Phi_{\mathbf{24}})_l^k \right. \\
 & + y'^{Ui} \epsilon^{mnpkl} (F'_i)_{mn} (F'_i)_{pq} (h')_k (\Phi_{\mathbf{24}})_l^q + y^{DEi} (F'_i)_{mn} (\bar{f}'_i \otimes \bar{h}')_{Sym}^{ml} (\Phi_{\mathbf{24}})_l^n \\
 & \left. \left. + y'^{DEi} (F'_i)_{mn} (\bar{f}'_i \otimes \bar{h}')_{Asym}^{ml} (\Phi_{\mathbf{24}})_l^n \right) . \right)
 \end{aligned}$$

- Yukawa couplings

$$W \supset \frac{v}{M_*} \sqrt{\frac{3}{5}} \left(-2h^{Ui} Q_i U_i^c H_u - h'^{Ui} Q_i U_i^c H_u \right. \\ \left. - \frac{1}{6} h'^{DEi} Q_i D_i^c H_d - h'^{DEi} L_i E_i^c H_d \right) .$$

- Soft A terms

$$-\mathcal{L} \supset \alpha' \frac{F_T v}{M_*^2} \sqrt{\frac{3}{5}} \left(-2y^{Ui} \tilde{Q}_i \tilde{U}_i^c H_u - y'^{Ui} \tilde{Q}_i \tilde{U}_i^c H_u \right. \\ \left. - \frac{1}{6} y'^{DEi} \tilde{Q}_i \tilde{D}_i^c H_d - y'^{DEi} \tilde{L}_i \tilde{E}_i^c H_d \right) .$$

- Soft A terms

$$A_U = A_0^U + (2\gamma_U + \gamma'_U) A_0^N ,$$

$$A_D = A_0^U + \frac{1}{6} \gamma_D A_0^N ,$$

$$A_E = A_0^U + \gamma_D A_0^N .$$

A_U , A_D and A_E can be free parameters in general in the GmSUGRA.

Supersymmetry breaking soft terms in $SU(5)$ model with an adjoint Higgs field Φ_{24}

- Two gaugino masses M_i .
- Five scalar masses: m_0^U , $m_{\tilde{E}_i^c}$, $m_{\tilde{L}_i}$, $m_{\tilde{H}_u}^2$ and $m_{\tilde{H}_d}^2$.
- Three trilinear soft terms: A_U , A_D , and A_E .

Gauge coupling unification:

$$\frac{1}{\alpha_2} - \frac{1}{\alpha_3} = \frac{5}{3} \left(\frac{1}{\alpha_1} - \frac{1}{\alpha_3} \right) .$$

- Worst case: the Higgsinos are light while the gluinos are heavy.
- Assumption: the masses for the sleptons, bino, winos and Higgsinos are universal, and the masses for the squarks and gluinos are universal.
- Proof: for the renormalization scale from the slepton mass to the squark mass, the one-loop beta functions for $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ are respectively $b_1 = 27/5$, $b_2 = -4/3$, $b_3 = -7$. Because $b_1 - b_2 = 101/15$ is larger than $b_2 - b_3 = 17/3$, the gauge coupling relation at the GUT scale can be realized properly.

Supersymmetry breaking soft terms in GmSUGRA:

- **Gaugino Masses**

$$M_1 = M_1, \quad M_2 = M_2, \quad M_3 = \frac{5}{2}M_1 - \frac{3}{2}M_2 .$$

- **Scalar masses:**

$$m_{\tilde{Q}_i}^2 = \frac{5}{6}(m_0^U)^2 + \frac{1}{6}m_{\tilde{E}_i^c}^2 ,$$

$$m_{\tilde{U}_i^c}^2 = \frac{5}{3}(m_0^U)^2 - \frac{2}{3}m_{\tilde{E}_i}^2 ,$$

$$m_{\tilde{D}_i^c}^2 = \frac{5}{3}(m_0^U)^2 - \frac{2}{3}m_{\tilde{L}_i}^2 .$$

- **Trilinear soft terms:** $A_U = A_D, A_E$

Scenarios:

- Scenario I: RPC + WMAP
- Scenario II: RPC + Multicomponent DM
- Scenario III: RPV

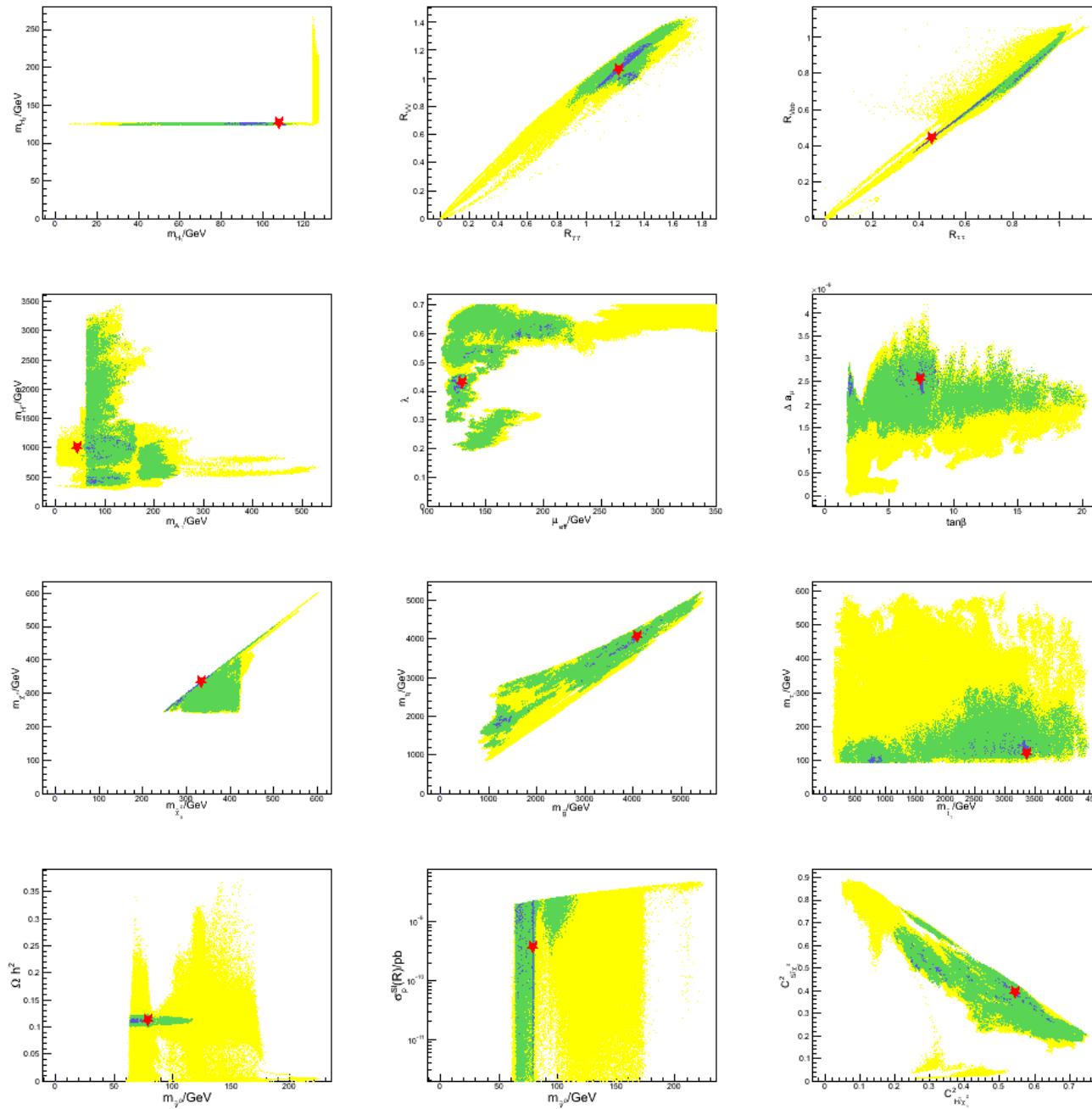


Figure 5: Scenario I: $\chi^2_{min} = 19.44$. Red pentagram: best-fitted point; green: 2σ region; purple: 1σ region

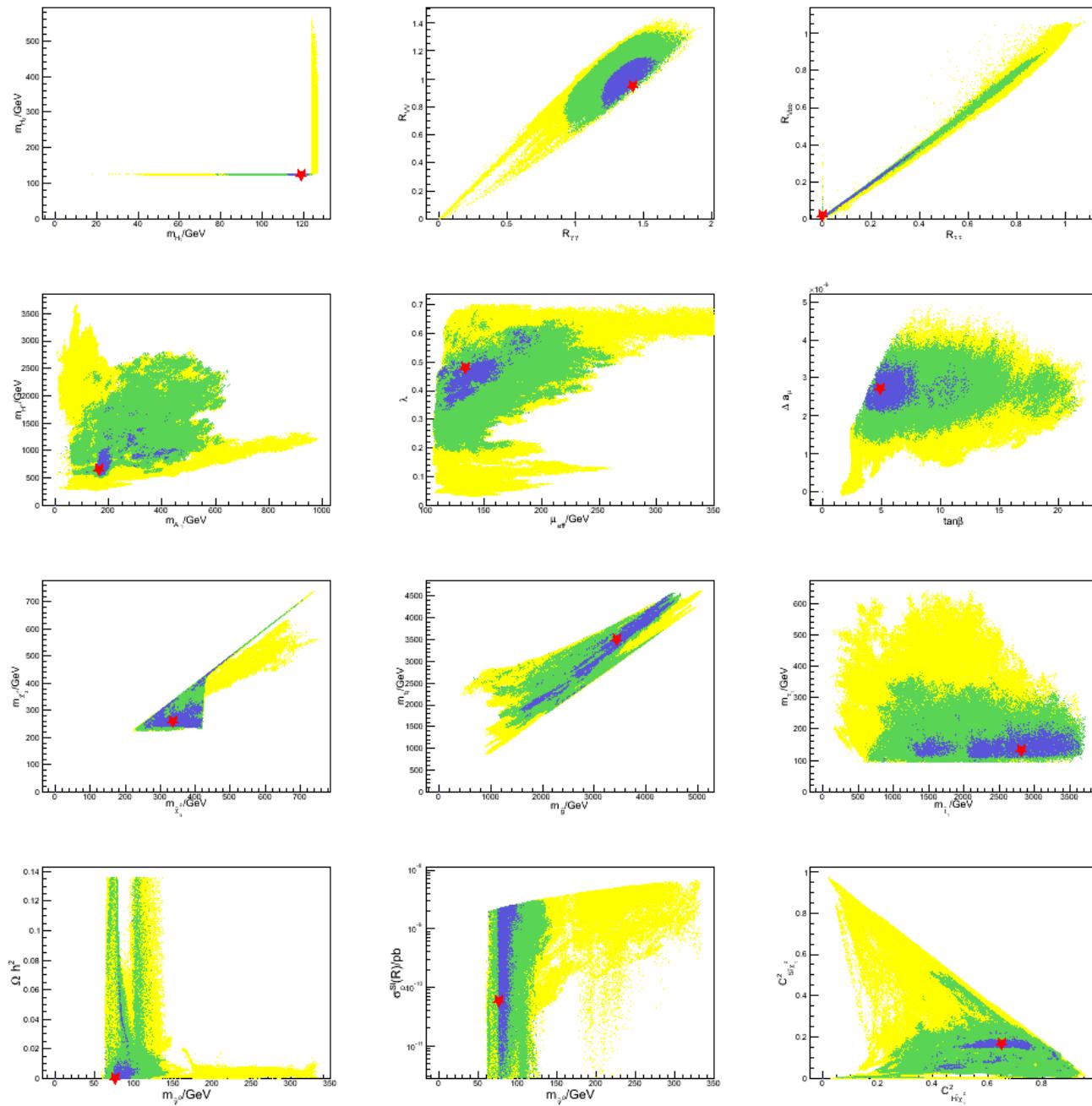


Figure 6: Scenario II: $\chi^2_{min} = 17.44$.

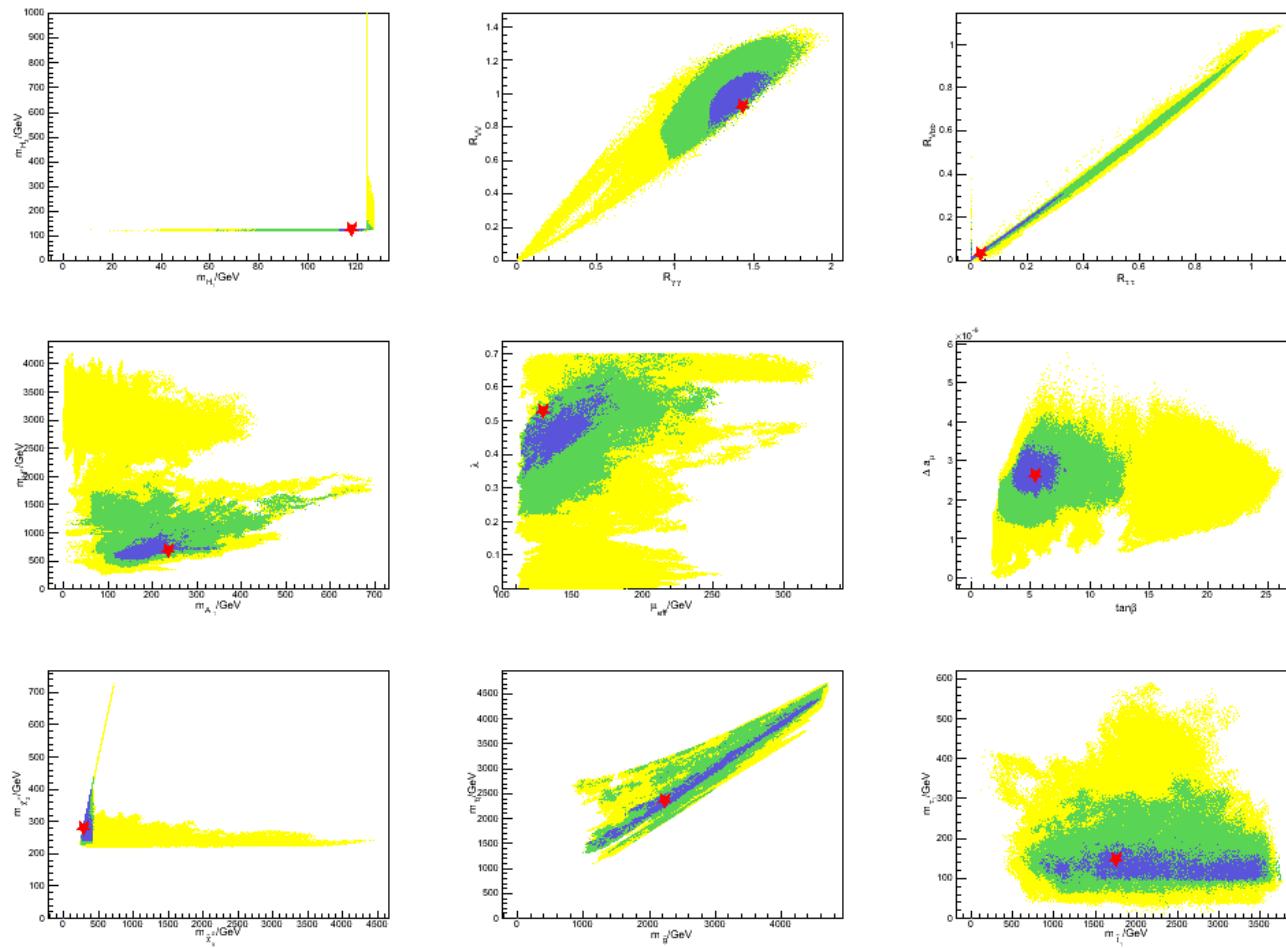


Figure 7: Scenario III: $\chi^2_{min} = 17.27$.

M_L	272	130	15	$\tilde{e}_R/\tilde{\mu}_R$	483	461	268
M_E	359	385	160	$\tilde{e}_L/\tilde{\mu}_L$	134	135	148
M_1	-560	795	579	$\tilde{\tau}_1$	121	132	146
M_2	312	286	312	$\tilde{\tau}_2$	476	460	266
M_3	-1864	1557	981	\tilde{t}_1	3364	2813	1754
A_0	846	-489	-1186	\tilde{t}_2	3486	2944	1903
A_E	-490	-227	-56	\tilde{b}_1	3385	2848	1822
A_λ	2743	-52	-25	\tilde{b}_2	4666	4054	2744
A_κ	1091	-0.93	-17	\tilde{u}_R/\tilde{c}_R	4689	4073	2763
Param. at M_{SUSY} :				\tilde{u}_L/\tilde{c}_L	4076	3504	2347
λ	0.429718	0.477	0.527	\tilde{d}_R/\tilde{s}_R	4704	4083	2767
κ	0.189889	0.276	0.38	\tilde{d}_L/\tilde{s}_L	4077	3505	2349
$\tan \beta$	7.39249	4.86	5.39	Pheno.			
μ_{eff}	130	135	160	$R_{\gamma\gamma}$	1.22	1.43	1.43
Spectrum:(GeV)				$R_{\gamma\gamma}^{gg}$	1.24	1.48	1.48
H_1^0	108	119	118	$R_{\gamma\gamma}^{VBF}$	1.17	1.2	1.18
H_2^0	126.3	124.5	125	R_{VV}	1.06	0.95	0.92
H_3^0	1013	648	688	R_{Vbb}	0.44	0.02	0.03
A_1	45	164	235	R_{bb}	0.46	0.02	0.04
A_2	1012	644	684	$R_{\tau\tau}$	0.46	6.7e-6	0.03

M_L	1.88583	27.7631	29.7436	$\tilde{e}_R/\tilde{\mu}_R$	210.387	127.992
M_E	332.69	184.266	325.658	$\tilde{e}_L/\tilde{\mu}_L$	235.435	136.779
M_1	347.521	274.159	327.307	$\tilde{\tau}_1$	98.252	103.165
M_2	241.184	203.472	192.406	$\tilde{\tau}_2$	226.631	147.028
M_3	507.027	380.19	529.658	\tilde{t}_1	578.747	516.556
A_0	-2219.16	-2178.56	-2458.82	\tilde{t}_2	888.68	748.272
A_E	-8974.16	-2434.99	-7497.61	\tilde{b}_1	837.829	680.188
A_λ	-626.151	-696.892	-861.797	\tilde{b}_2	1999.49	2071.85
A_κ	-0.0182404	-0.00906699	-0.027	\tilde{u}_R/\tilde{c}_R	2023.55	2087.01
Param. at M_{SUSY} :				Pheno.		
λ	0.630814	0.631714	0.62998	$R_{\gamma\gamma}$	1.24077	1.28908
κ	0.0734611	0.14492	0.0676808	$R_{\gamma\gamma}^{gg}$	1.24361	1.304
$\tan \beta$	2.04129	1.93553	1.88946	$R_{\gamma\gamma}^{VBF}$	1.22564	1.20442
μ_{eff}	213.478	199.934	222.791	R_{VV}	1.02234	1.0456
Spectrum:(GeV)				R_{Vbb}	0.965538	0.797919
H_1^0	83.3888	96.8521	96.8172	R_{bb}	0.97746	0.854005
H_2^0	125.248	126.997	126.681	$R_{\tau\tau}$	0.976746	0.850748
H_3^0	527.913	474.168	528.363			
A_1	117.208	148.303	87.6805			
A_2	532.546	476.502	533.429			

CONCLUSION

Supersymmetry:

- Consistent with all the current experiments, especially the Higgs boson masses and decays.
- Consistent with the string model building.
- With R -parity violation, the supersymmetric SMs are still an elegant and natural solution to the gauge hierarchy problem.

The Implications of the LHC Higgs Searches in the Supersymmetric Standard Models

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Abstract

The particle spectra for both the NMSSM and the NMSSM with EWSUSY for Scenarios I, II and III.

PACS numbers:

Point	$I\chi^2_{min}$	IA	IB	IC	Point	$I\chi^2_{min}$	IA	IB	IC
M_0	264	294	562	249	\tilde{t}_1	294	210	186	257
$M_{1/2}$	489	484	624	571	\tilde{t}_2	822	810	1026	920
$\tan \beta$	2.436	2.851	2.910	3.293	\tilde{t}	873	837	1042	955
λ	0.601	0.550	0.564	0.536	\tilde{b}_1	783	768	994	880
κ	0.245	0.249	0.268	0.243	\tilde{b}_2	983	979	1296	1114
A_0	-1180	-1253	-1779	-1441	\tilde{u}_R/\tilde{c}_R	1053	1052	1397	1197
A_λ	-315	-230	-628	-193	\tilde{u}_L/\tilde{c}_L	1059	1057	1398	1206
A_κ	-1.904	-2.028	-218.408	-1.900	\tilde{d}_R/\tilde{s}_R	1014	1013	1342	1153
μ_{eff}	130	124	123	128	\tilde{d}_L/\tilde{s}_L	1061	1059	1399	1208
M_1	207	204	266	242	H_1^0	108.5	95.5	111.7	91.7
M_2	384	380	493	449	H_2^0	125.5	125.4	125.2	124.2
M_3	1091	1081	1368	1259	H_3^0	359.7	396.3	385.6	461.1
$\tilde{\chi}_1^0$	75	70	77	76	A_1	99.6	123.8	91.7	138.4
$\tilde{\chi}_2^0$	163	-156	-156	-158	A_2	353.4	390.0	377.9	455.9
$\tilde{\chi}_3^0$	-168	163	172	171	H^\pm	343.9	383.2	371.3	450.2
$\tilde{\chi}_4^0$	219	216	273	250	$\Omega \hbar^2$	0.110	0.104	0.103	0.109
$\tilde{\chi}_5^0$	415	410	521	475	$\Delta_{a_\mu} [10^{-10}]$	2.317	2.586	1.157	1.823
$\tilde{\chi}_1^\pm$	114	109	113	117	$\sigma^{si}(p) [10^{-10} \text{ pb}]$	7.468	1.137	3.208	39.683
$\tilde{\chi}_2^\pm$	414	409	520	475	$\text{Br}^{(b \rightarrow s\gamma)} [10^{-4}]$	3.342	2.633	2.714	2.747
\tilde{g}	1134	1125	1436	1305	Δ_{FT}	62.7	74.0	109.3	101.5
$\tilde{\nu}_{e/\mu}$	457	472	741	497	$R_2^{\gamma\gamma}_{\text{VBF}}$	1.48	1.60	1.75	1.46
$\tilde{\nu}_\tau$	456	471	740	496	$R_2^{\gamma\gamma}$	1.58	1.43	1.45	1.31
$\tilde{e}_R/\tilde{\mu}_R$	178	216	482	126	R_2^{WW}	1.25	1.10	1.07	1.09
$\tilde{e}_L/\tilde{\mu}_L$	461	477	744	502	R_2^{ZZ}	1.25	1.10	1.07	1.09
$\tilde{\tau}_1$	176	213	479	116	R_2^{Vbb}	0.59	0.59	0.50	0.70
$\tilde{\tau}_2$	461	476	744	501	R_2^{bb}	0.63	0.53	0.41	0.63
χ^2	21.16	24.85	25.92	23.37	$R_2^{\tau\tau}$	0.62	0.53	0.41	0.62

TABLE I: Particle spectra (in GeV) and parameters for benchmark points in Scenario I.

Point	$\text{II}\chi^2_{min}$	IIA	IIB	IIC	Point	$\text{II}\chi^2_{min}$	IIA	IIB	IIC
M_0	454	208	576	279	\tilde{t}_1	513	157	184	432
$M_{1/2}$	673	413	528	527	\tilde{t}_2	1126	700	912	895
$\tan \beta$	3.267	2.518	2.468	1.820	\tilde{t}	1237	717	930	994
λ	0.452	0.617	0.582	0.584	\tilde{b}_1	1093	654	880	866
κ	0.214	0.295	0.247	0.172	\tilde{b}_2	1348	835	1153	1058
A_0	-1520	-1090	-1519	-986	\tilde{u}_R/\tilde{c}_R	1434	898	1240	1127
A_λ	-296	-248	-618	-380	\tilde{u}_L/\tilde{c}_L	1445	903	1237	1135
A_κ	-1.354	-1.049	-253.408	-1.707	\tilde{d}_R/\tilde{s}_R	1384	865	1192	1086
μ_{eff}	130	129	118	123	\tilde{d}_L/\tilde{s}_L	1446	905	1239	1136
M_1	287	173	224	224	H_1^0	115.2	106.5	99.7	98.0
M_2	530	324	416	416	H_2^0	124.4	126.2	124.7	126.0
M_3	1467	933	1169	1173	H_3^0	440.5	363.1	332.7	290.1
$\tilde{\chi}_1^0$	87	70	69	74	A_1	66.1	145.4	103.3	74.6
$\tilde{\chi}_2^0$	-152	-166	-156	133	A_2	435.0	355.4	325.3	288.4
$\tilde{\chi}_3^0$	167	170	158	-166	H^\pm	433.6	345.6	316.3	275.7
$\tilde{\chi}_4^0$	292	194	233	233	Ωh^2	0.038	0.001	0.072	0.070
$\tilde{\chi}_5^0$	557	358	446	444	$\Delta_{a_\mu} [10^{-10}]$	1.385	3.410	1.100	1.513
$\tilde{\chi}_1^\pm$	122	107	104	107	$\sigma^{si}(p) [10^{-10} \text{ pb}]$	59.671	39.947	22.116	28.064
$\tilde{\chi}_2^\pm$	556	357	446	444	$\text{Br}^{(b \rightarrow s\gamma)} [10^{-4}]$	3.553	2.294	2.914	4.123
\tilde{g}	1529	968	1235	1218	Δ_{FT}	130.4	48.8	75.7	59.6
$\tilde{\nu}_{e/\mu}$	680	377	710	489	$R_2^{\gamma\gamma}_{\text{VBF}}$	1.08	1.68	1.53	1.24
$\tilde{\nu}_\tau$	679	377	709	489	$R_2^{\gamma\gamma}$	1.34	1.45	1.42	1.42
$\tilde{e}_R/\tilde{\mu}_R$	376	122	510	191	R_2^{WW}	0.89	1.09	1.10	1.09
$\tilde{e}_L/\tilde{\mu}_L$	683	383	713	492	R_2^{ZZ}	0.89	1.09	1.10	1.09
$\tilde{\tau}_1$	372	118	509	190	R_2^{Vbb}	0.01	0.57	0.72	0.65
$\tilde{\tau}_2$	683	383	712	492	R_2^{bb}	0.01	0.49	0.67	0.74
χ^2	19.35	24.19	23.86	23.70	$R_2^{\tau\tau}$	0.00	0.49	0.66	0.73

TABLE II: Particle spectra (in GeV) and parameters for benchmark points in Scenario II.

Point	$\text{III}\chi^2_{min}$	IIIA	IIIB	IIIC	Point	$\text{III}\chi^2_{min}$	IIIA	IIIB	IIIC
M_0	352	431	344	337	\tilde{t}_1	365	252	184	391
$M_{1/2}$	489	326	500	441	\tilde{t}_2	850	647	832	795
$\tan \beta$	2.341	1.853	2.731	2.039	\tilde{t}	925	694	852	886
λ	0.604	0.589	0.623	0.614	\tilde{b}_1	814	610	793	760
κ	0.295	0.364	0.288	0.318	\tilde{b}_2	1012	778	1020	929
A_0	-1063	-372	-1322	-620	\tilde{u}_R/\tilde{c}_R	1078	827	1097	985
A_λ	-329	-161	-267	-9.93×10^{-6}	\tilde{u}_L/\tilde{c}_L	1083	823	1101	990
A_κ	-128.134	-628.214	-0.877	-1.459	\tilde{d}_R/\tilde{s}_R	1039	798	1056	952
μ_{eff}	144	162	150	166	\tilde{d}_L/\tilde{s}_L	1085	825	1103	992
M_1	207	136	212	186	H_1^0	120.5	114.3	119.6	116.6
M_2	384	255	393	346	H_2^0	126.9	124.6	124.9	125.7
M_3	1090	745	1114	990	H_3^0	367.8	342.7	436.6	382.5
$\tilde{\chi}_1^0$	91	86	92	107	A_1	154.3	300.6	157.1	247.6
$\tilde{\chi}_2^0$	-177	160	-184	195	A_2	360.0	335.1	430.1	376.3
$\tilde{\chi}_3^0$	187	-189	191	-197	H^\pm	352.6	330.2	421.7	369.3
$\tilde{\chi}_4^0$	222	232	228	221	$\Omega \hbar^2$	×	×	×	×
$\tilde{\chi}_5^0$	417	310	425	384	$\Delta_{a_\mu} [10^{-10}]$	1.893	1.587	2.207	1.848
$\tilde{\chi}_1^\pm$	126	122	133	141	$\sigma^{si}(p) [10^{-10} \text{ pb}]$	×	×	×	×
$\tilde{\chi}_2^\pm$	416	306	425	383	$\text{Br}^{(b \rightarrow s\gamma)} [10^{-4}]$	3.586	3.413	2.560	3.659
\tilde{g}	1138	796	1162	1035	Δ_{FT}	59.5	27.0	68.4	44.1
$\tilde{\nu}_{e/\mu}$	513	502	514	475	$R_2^{\gamma\gamma}_{\text{VBF}}$	0.88	0.93	1.60	1.16
$\tilde{\nu}_\tau$	512	502	514	475	$R_2^{\gamma\gamma}$	1.34	1.46	1.41	1.42
$\tilde{e}_R/\tilde{\mu}_R$	291	395	273	289	R_2^{WW}	0.81	0.95	1.08	1.10
$\tilde{e}_L/\tilde{\mu}_L$	517	505	519	479	R_2^{ZZ}	0.81	0.95	1.08	1.10
$\tilde{\tau}_1$	289	395	270	288	R_2^{Vbb}	0.01	0.10	0.55	0.37
$\tilde{\tau}_2$	517	505	518	479	R_2^{bb}	0.02	0.16	0.48	0.46
χ^2	19.67	21.31	23.85	20.53	$R_2^{\tau\tau}$	0.00	0.14	0.47	0.44

TABLE III: Particle spectra (in GeV) and parameters for benchmark points in Scenario III.

χ^2_{min} Points:	I	II	III	χ^2_{min} Points:	I	II	III
Param. at $M_{GUT}:(\text{GeV})$							
M_0	2572.75	2291	1606	$\tilde{\nu}_{e/\mu}$	111	113	128
M_L	272	130	15	$\tilde{\nu}_\tau$	95	110	126
M_E	359	385	160	$\tilde{e}_R/\tilde{\mu}_R$	483	461	268
M_1	-560	795	579	$\tilde{e}_L/\tilde{\mu}_L$	134	135	148
M_2	312	286	312	\tilde{t}_1	121	132	146
M_3	-1864	1557	981	\tilde{t}_2	476	460	266
A_0	846	-489	-1186	\tilde{t}_1	3364	2813	1754
A_E	-490	-227	-56	\tilde{t}_2	3486	2944	1903
A_λ	2743	-52	-25	\tilde{b}_1	3385	2848	1822
A_κ	1091	-0.93	-17	\tilde{b}_2	4666	4054	2744
Param. at $M_{SUSY}:$							
λ	0.429718	0.477	0.527	\tilde{u}_R/\tilde{c}_R	4689	4073	2763
κ	0.189889	0.276	0.38	\tilde{u}_L/\tilde{c}_L	4076	3504	2347
$\tan \beta$	7.39249	4.86	5.39	\tilde{d}_R/\tilde{s}_R	4704	4083	2767
μ_{eff}	130	135	160	\tilde{d}_L/\tilde{s}_L	4077	3505	2349
Spectrum:(GeV)							
H_1^0	108	119	118	Pheno.			
H_2^0	126.3	124.5	125	$R_{\gamma\gamma}$	1.22	1.43	1.43
H_3^0	1013	648	688	$R_{\gamma\gamma}^{gg}$	1.24	1.48	1.48
A_1	45	164	235	$R_{\gamma\gamma}^{VBF}$	1.17	1.2	1.18
A_2	1012	644	684	R_{VV}	1.06	0.95	0.92
H^\pm	1011	642	681	R_{Vbb}	0.44	0.02	0.03
$\tilde{\chi}_1^0$	79	76	75	R_{bb}	0.46	0.02	0.04
$\tilde{\chi}_2^0$	-146	-160	-155	$R_{\tau\tau}$	0.46	6.7e-6	0.03
$\tilde{\chi}_3^0$	170	192	224	$\text{BR}(b \rightarrow s\gamma)/10^{-4}$	3.43	3.64	3.56
$\tilde{\chi}_4^0$	-237	254	238	$\text{BR}(b \rightarrow \tau\nu)/10^{-4}$	1.31	1.31	1.31
$\tilde{\chi}_5^0$	334	336	288	$\text{BR}(B_s \rightarrow \mu^+\mu^-)/10^{-9}$	3.68	3.67	3.67
$\tilde{\chi}_1^\pm$	119	104	107	$\Delta a_\mu/10^{-9}$	2.55	2.72	2.62
$\tilde{\chi}_2^\pm$	334	257	279	Ωh^2	0.112	0.00015	—
\tilde{g}	-4086	3452	2243	$\sigma_p^{SI}/10^{-9} pb$	0.37	43.9	—
				Δ_{FT}	578	423	204
				5 χ^2	19.44	17.44	17.27

TABLE IV: χ^2_{min} benchmark points for three scenarios. $\chi^2_{min}(\text{I})=19.44$, $\chi^2_{min}(\text{II})=17.44$, $\chi^2_{min}(\text{III})=17.27$.

Points:	I	II	III
Param. at $M_{GUT}:(\text{GeV})$			
M_0	1374.34	1515.18	1463.92
M_L	1.88583	27.7631	29.7436
M_E	332.69	184.266	325.658
M_1	347.521	274.159	327.307
M_2	241.184	203.472	192.406
M_3	507.027	380.19	529.658
A_0	-2219.16	-2178.56	-2458.82
A_E	-8974.16	-2434.99	-7497.61
A_λ	-626.151	-696.892	-861.797
A_κ	-0.0182404	-0.00906699	-0.027
Param. at $M_{SUSY}:$			
λ	0.630814	0.631714	0.62998
κ	0.0734611	0.14492	0.0676808
$\tan \beta$	2.04129	1.93553	1.88946
μ_{eff}	213.478	199.934	222.791
Spectrum:(GeV)			
H_1^0	83.3888	96.8521	96.8172
H_2^0	125.248	126.997	126.681
H_3^0	527.913	474.168	528.363
A_1	117.208	148.303	87.6805
A_2	532.546	476.502	533.429
H^\pm	519.396	464.861	520.578
$\tilde{\chi}_1^0$	65.4309	70.9172	62.9633
$\tilde{\chi}_2^0$	124.263	122.642	112.29
$\tilde{\chi}_3^0$	163.166	143.935	143.091
$\tilde{\chi}_4^0$	-251.983	-235.379	-260.193
$\tilde{\chi}_5^0$	292.303	272.964	285.1
$\tilde{\chi}_1^\pm$	131.302	107.801	108.825
$\tilde{\chi}_2^\pm$	284.302	264.126	275.393
\tilde{g}	1236.58	966.878	1291.97

Points:	I	II	III
$\tilde{\nu}_{e/\mu}$	227.353	123.096	218.902
$\tilde{\nu}_\tau$	197.081	119.209	200.021
$\tilde{e}_R/\tilde{\mu}_R$	210.387	127.992	161.709
$\tilde{e}_L/\tilde{\mu}_L$	235.435	136.779	226.627
$\tilde{\tau}_1$	98.252	103.165	70.3972
$\tilde{\tau}_2$	226.631	147.028	220.787
\tilde{t}_1	578.747	516.556	527.772
\tilde{t}_2	888.68	748.272	883.928
\tilde{b}_1	837.829	680.188	840.973
\tilde{b}_2	1999.49	2071.85	2117.56
\tilde{u}_R/\tilde{c}_R	2023.55	2087.01	2147.75
\tilde{u}_L/\tilde{c}_L	1595.7	1559.77	1682.16
\tilde{d}_R/\tilde{s}_R	2022.4	2087.34	2143.42
\tilde{d}_L/\tilde{s}_L	1596.86	1560.92	1683.18
Pheno.			
$R_{\gamma\gamma}$	1.24077	1.28908	1.37
$R_{\gamma\gamma}^{gg}$	1.24361	1.304	1.38
$R_{\gamma\gamma}^{VBF}$	1.22564	1.20442	1.33
R_{VV}	1.02234	1.0456	1.0
R_{Vbb}	0.965538	0.797919	0.88
R_{bb}	0.97746	0.854005	0.91
$R_{\tau\tau}$	0.976746	0.850748	0.91
$\text{BR}(b \rightarrow s\gamma)/10^{-4}$	3.54	3.56	3.53
$\text{BR}(b \rightarrow \tau\nu)/10^{-4}$	1.32	1.32	1.32
$\text{BR}(B_s \rightarrow \mu^+\mu^-)/10^{-9}$	3.67	3.67	3.67
$\Delta a_\mu/10^{-9}$	1.9	2.7	2.3
Ωh^2	0.114927	0.0006	—
$\sigma_p^{SI}/10^{-9} pb$	1.48	4.9	—
Δ_{FT}	77	89	79
6 χ^2	22	20	20

TABLE V: Points with appropriate fine-tuning.