SUSY Models

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The Conference Announcement

The XXVIII International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2020), July 27-31, 2020, China National Convention Center, Beijing, P. R. China

Pre-SUSY 2020, July 20-24, 2020, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing, P. R. China

Motivation for New Physics beyong the Standard Model

- The convincing evidence

  Dark energy; dark matter; neutrino masses and mixing; baryon asymmetry; inflation; ...

- Fine-tuning problems

  cosmological constant problem; gauge hierarchy problem; strong CP problem; SM fermion masses and mixings; ...

- Aesthetic problems

  Interaction and fermion unification; gauge coupling unification; charge quantization; too many parameters; ...

- The electroweak vacuum stability problem

  The stability problem can be easily solved in the new physics models.

- New Physics beyond the SM!
- Question: why do we still believe in supersymmetry?

Anomalies or Excesses

- B physics anomalies?
- The muon and electron anomalous magnetic moments
- MiniBoone experiment?
- ANITA experiment?
- H_0 tension
- ...

They might be time dependent and might be gone with the wind in the near future?

Motivations for Supersymmetry

- Generalization of the Poincare Algebra; The most general symmetry of the S-matrix; The local supersymmetry includes gravity naturally, *i.e.*, supergravity, etc.
- Supersymmetry provides a natural solution to the gauge hiearchy problem.
- Supersymmetry partially solves the cosmological constant problem: $M_{\rm Pl} \to M_{SUSY}$.
- Supersymmetry is a bridge between the promising low energy phenomenology and the high-energy fundamental physics such as the Grand Unified Theory and String Theory.

The Supersymmetric Standard Models (SSMs)

- Solving the gauge hierarchy problem
- Gauge coupling unification
- Radiatively electroweak symmetry breaking
- Natural dark matter candidates
- Electroweak baryogenesis
- Electroweak precision: R parity
- μ problem in the MSSM: $\mu H_d H_u$.

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
- Prediction: dim-6 proton decay via heavy gauge boson exchange.

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
- D-brane models on Type II orientifolds
- Free fermionic string model builing
- $\mathcal{F}$-Theory Model Building

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

Particle Physics Paradigm

String Theory → String Models → GUTs → SSMs → SM

Higgs Boson Mass in the MSSM

- The SM-like Higgs boson mass is around 125 GeV.
- The tree-level Higgs boson mass is smaller than M_Z.
- The Higgs boson mass is enhanced by the top quarks/squarks loop corrections.
- The maximal stop mixing is needed to relax the fine-tuning.

Problem: the $SU(3)_C \times U(1)_{EM}$ symmetry breaking.

The LHC Supersymmetry Search Contraints

- The first two-generation squark mass low bounds are around 1.6 (1.75) TeV.
- The gluino mass low bound is around 2.25 (2.46) TeV.
- The stop and sbottom mass low bounds are around 1.16 (1.3) and 1.35 (1.45) TeV, respectively.

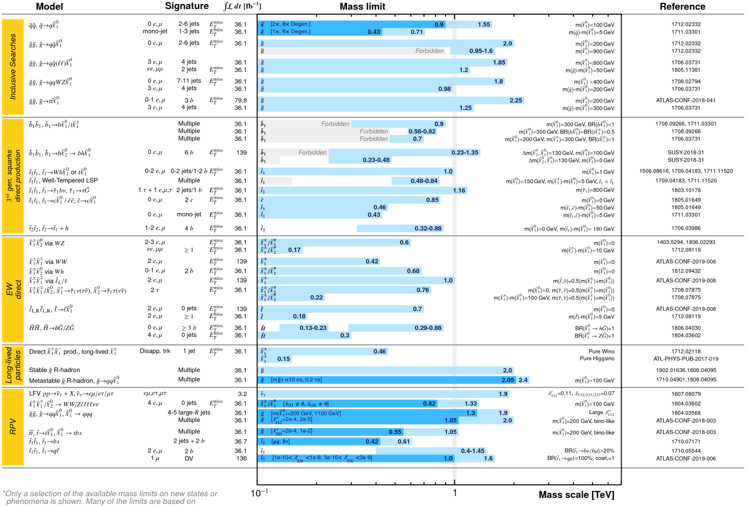
The SSMs are fine-tuned!!!

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2019

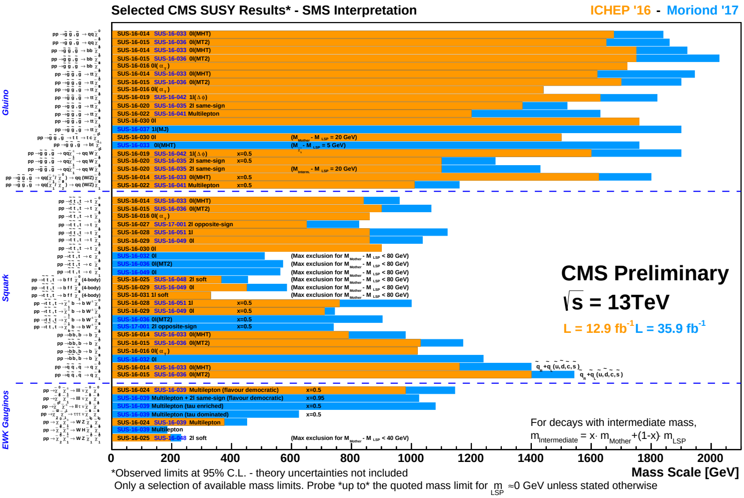
ATLAS Preliminary

$\sqrt{s}$ = 13 TeV



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	36.1	$\tilde{q}$ [2×, 8× Degen.] 0.9 1.55	m($\tilde{\chi}^0_1$)<100 GeV	1712.02332
		mono-jet	1-3 jets	E_T^{miss}	36.1	$\tilde{q}$ [1×, 8× Degen.] 0.43 0.71	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0 e,μ	2-6 jets	E_T^{miss}	36.1	$\tilde{g}$ 2.0	m($\tilde{\chi}^0_1$)<200 GeV	1712.02332
						$\tilde{g}$ Forbidden 0.95-1.6	m($\tilde{\chi}^0_1$)=900 GeV	1712.02332
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}^0_1$	3 e,μ	4 jets		36.1	$\tilde{g}$ 1.85	m($\tilde{\chi}^0_1$)<800 GeV	1706.03731
		$ee,\mu\mu$	2 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.2	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.11381
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0 e,μ	7-11 jets	E_T^{miss}	36.1	$\tilde{g}$ 1.8	m($\tilde{\chi}^0_1$) <400 GeV	1708.02794
		3 e,μ	4 jets		36.1	$\tilde{g}$ 0.98	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=200 GeV	1706.03731
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	E_T^{miss}	79.8	$\tilde{g}$ 2.25	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2018-041
		3 e,μ	4 jets		36.1	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}^0_1$)=300 GeV	1706.03731
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1/t\tilde{\chi}^\pm_1$		Multiple		36.1	$\tilde{b}_1$ Forbidden 0.9	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=1	1708.09266, 1711.03301
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.58-0.82	m($\tilde{\chi}^0_1$)=300 GeV, BR($b\tilde{\chi}^0_1$)=BR($t\tilde{\chi}^\pm_1$)=0.5	1708.09266
			Multiple		36.1	$\tilde{b}_1$ Forbidden 0.7	m($\tilde{\chi}^0_1$)=200 GeV, m($\tilde{\chi}^\pm_1$)=300 GeV, BR($t\tilde{\chi}^\pm_1$)=1	1706.03731
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_2\to bh\tilde{\chi}^0_1$	0 e,μ	6 b	E_T^{miss}	139	$\tilde{b}_1$ Forbidden 0.23-1.35	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=100 GeV	SUSY-2018-31
						$\tilde{b}_1$ 0.23-0.48	Δm($\tilde{\chi}^0_2,\tilde{\chi}^0_1$)=130 GeV, m($\tilde{\chi}^0_1$)=0 GeV	SUSY-2018-31
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	E_T^{miss}	36.1	$\tilde{t}_1$ 1.0	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP		Multiple		36.1	$\tilde{t}_1$ 0.48-0.84	m($\tilde{\chi}^0_1$)=150 GeV, m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=5 GeV, $\tilde{t}_1\approx\tilde{t}_L$	1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1 τ + 1 e,μ,τ	2 jets/1 b	E_T^{miss}	36.1	$\tilde{t}_1$ 1.16	m($\tilde{\tau}_1$)=800 GeV	1803.10178
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}^0_1$	0 e,μ	2 c	E_T^{miss}	36.1	$\tilde{c}$ 0.85	m($\tilde{\chi}^0_1$)=0 GeV	1805.01649
						$\tilde{t}_1$ 0.46	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=50 GeV	1805.01649
		0 e,μ	mono-jet	E_T^{miss}	36.1	$\tilde{t}_1$ 0.43	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}^0_1$)=5 GeV	1711.03301
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+h$	1-2 e,μ	4 b	E_T^{miss}	36.1	$\tilde{t}_2$ 0.32-0.88	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)= 180 GeV	1706.03986
EW direct	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via WZ	2-3 e,μ		E_T^{miss}	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.6	m($\tilde{\chi}^0_1$)=0	1403.5294, 1806.02293
		$ee,\mu\mu$	≥ 1	E_T^{miss}	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.17	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=10 GeV	1712.08119
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via WW	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^\pm_1$ 0.42	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ via Wh	0-1 e,μ	2 b	E_T^{miss}	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.68	m($\tilde{\chi}^0_1$)=0	1812.09432
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		E_T^{miss}	139	$\tilde{\chi}^\pm_1$ 1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2019-008
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2$, $\tilde{\chi}^+_1\to\tilde{\tau}_1\nu(\tau\tilde{\nu})$, $\tilde{\chi}^0_2\to\tilde{\tau}_1\tau(\nu\tilde{\nu})$	2 τ		E_T^{miss}	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.76	m($\tilde{\chi}^0_1$)=0, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1708.07875
						$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ 0.22	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)=100 GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	1708.07875
	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0 jets	E_T^{miss}	139	$\tilde{\ell}$ 0.7	m($\tilde{\chi}^0_1$)=0	ATLAS-CONF-2019-008
		2 e,μ	≥ 1	E_T^{miss}	36.1	$\tilde{\ell}$ 0.18	m($\tilde{\ell}$)-m($\tilde{\chi}^0_1$)=5 GeV	1712.08119
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	E_T^{miss}	36.1	$\tilde{H}$ 0.13-0.23 0.29-0.88	BR($\tilde{\chi}^0_1\to h\tilde{G}$)=1	1806.04030
		4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{H}$ 0.3	BR($\tilde{\chi}^0_1\to Z\tilde{G}$)=1	1804.03602
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	E_T^{miss}	36.1	$\tilde{\chi}^\pm_1$ 0.46	Pure Wino	1712.02118
						$\tilde{\chi}^\pm_1$ 0.15	Pure Higgsino	ATL-PHYS-PUB-2017-019
	Stable $\tilde{g}$ R-hadron		Multiple		36.1	$\tilde{g}$ 2.0		1902.01636,1808.04095
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}^0_1$		Multiple		36.1	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns, 0.2 ns] 2.05 2.4	m($\tilde{\chi}^0_1$)=100 GeV	1710.04901,1808.04095
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$			3.2	$\tilde{\nu}_\tau$ 1.9	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	$\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^0_2\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	E_T^{miss}	36.1	$\tilde{\chi}^\pm_1/\tilde{\chi}^0_2$ [$\lambda_{i33}\neq 0,\lambda_{12k}\neq 0$] 0.82 1.33	m($\tilde{\chi}^0_1$)=100 GeV	1804.03602
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$		4-5 large-R jets		36.1	$\tilde{g}$ [m($\tilde{\chi}^0_1$)=200 GeV, 1100 GeV] 1.3 1.9	Large λ''_{112}	1804.03568
			Multiple		36.1	$\tilde{g}$ [λ''_{112}=2e-4, 2e-5] 1.05 2.0	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to tbs$		Multiple		36.1	$\tilde{g}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}^0_1$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		36.1	$\tilde{t}_1$ 0.4-1.45	BR($\tilde{t}_1\to be/b\mu$)>20%	1710.05544
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	ATLAS-CONF-2019-006

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.


Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
SUS-16-014 SUS-16-033 0l(MHT)
SUS-16-015 SUS-16-036 0l(MT2)
SUS-16-014 SUS-16-033 0l(MHT)
SUS-16-015 SUS-16-036 0l(MT2)
SUS-16-016 0l(α_T)
SUS-16-014 SUS-16-033 0l(MHT)
SUS-16-015 SUS-16-036 0l(MT2)
SUS-16-016 0l(α_T)
SUS-16-019 SUS-16-042 1l(Δφ)
SUS-16-020 SUS-16-035 2l same-sign
SUS-16-022 SUS-16-041 Multilepton
SUS-16-030 0l
SUS-16-037 1l(MJ)
SUS-16-030 0l (M_Mother - M_LSP = 20 GeV)
SUS-16-033 0l(MHT) (M_χ̃1 - M_LSP = 5 GeV)
SUS-16-019 SUS-16-042 1l(Δφ) x=0.5
SUS-16-020 SUS-16-035 2l same-sign x=0.5
SUS-16-020 SUS-16-035 2l same-sign (M_Interm. - M_LSP = 20 GeV)
SUS-16-014 SUS-16-033 0l(MHT) x=0.5
SUS-16-022 SUS-16-041 Multilepton x=0.5
SUS-16-014 SUS-16-033 0l(MHT)
SUS-16-015 SUS-16-036 0l(MT2)
SUS-16-016 0l(α_T)
SUS-16-027 SUS-17-001 2l opposite-sign
SUS-16-028 SUS-16-051 1l
SUS-16-029 SUS-16-049 0l
SUS-16-030 0l
SUS-16-032 0l (Max exclusion for M_Mother - M_LSP < 80 GeV)
SUS-16-036 0l(MT2) (Max exclusion for M_Mother - M_LSP < 80 GeV)
SUS-16-049 0l (Max exclusion for M_Mother - M_LSP < 80 GeV)
SUS-16-025 SUS-16-048 2l soft (Max exclusion for M_Mother - M_LSP < 80 GeV)
SUS-16-029 SUS-16-049 0l (Max exclusion for M_Mother - M_LSP < 80 GeV)
SUS-16-031 1l soft (Max exclusion for M_Mother - M_LSP < 80 GeV)
SUS-16-028 SUS-16-051 1l x=0.5
SUS-16-029 SUS-16-049 0l x=0.5
SUS-16-036 0l(MT2) x=0.5
SUS-17-001 2l opposite-sign x=0.5
SUS-16-014 SUS-16-033 0l(MHT)
SUS-16-015 SUS-16-036 0l(MT2)
SUS-16-016 0l(α_T)
SUS-16-032 0l
SUS-16-014 SUS-16-033 0l(MHT) q̃_R+q̃_L(ũ,d̃,c̃,s̃)
SUS-16-015 SUS-16-036 0l(MT2) q̃_R+q̃_L(ũ,d̃,c̃,s̃)
SUS-16-024 SUS-16-039 Multilepton (flavour democratic) x=0.5
SUS-16-039 Multilepton + 2l same-sign (flavour democratic) x=0.95
SUS-16-039 Multilepton (tau enriched) x=0.5
SUS-16-039 Multilepton (tau dominated) x=0.5
SUS-16-024 SUS-16-039 Multilepton
SUS-16-039 Multilepton
SUS-16-025 SUS-16-048 2l soft (Max exclusion for M_Mother - M_LSP < 40 GeV)
CMS Preliminary
√s = 13TeV
L = 12.9 fb⁻¹ L = 35.9 fb⁻¹
For decays with intermediate mass,
m_Intermediate = x· m_Mother +(1-x)· m_LSP
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_LSP ≈0 GeV unless stated otherwise

Supersymmetry at the Current and Future Colliders

- The wrong impression is that supersymmetry was excluded at the LHC?
- Can we rule out supersymmetry at the LHC, VLHC, $\mathrm{FCC_{hh}}$ and SppC?
  No! No!! No!!!
- Points: supersymmetry breaking soft mass scale can be pushed to be much higher than 1 TeV, while gauge coupling unification can still be realized due to the logarithmic RGE running and threshold corrections around the GUT scale.
- Conclusion: supersymmetry will defintely not die in the near future!!!

The interesting question: can we rule out the natural supersymmetry at the $\mathrm{FCC_{hh}}$ and SppC? Or can we solve the supersymmetry electroweak fine-tuning problem?

Classifications of SUSY Models: Particle Content

- The Minimal Supersymmetric Standard Model (MSSM)

  Two Higgs doublets due to anomaly cancellations and holomorphic superpotential.

- The Next-to-MSSM (NMSSM): S and Z_3.

  Lifting Higgs boson mass, and solution to the μ problem.

- The SSMs with Dirac gauginos [1] or a pseudo-Dirac gluino [2]

  Supersoft supersymmetry.

- New gauge symmetries: SUSY $U(1)'$ Model [3], etc.

  Lifting Higgs boson mass, and solution to the μ problem.

- Vector-like particles [4]

  Lifting Higgs boson mass, dim-6 proton decay, and string-scale gauge coupling unification, etc.

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[1] P. J. Fox, A. E. Nelson and N. Weiner, JHEP **0208**, 035 (2002); G. D. Kribs and A. Martin, Phys. Rev. D **85**, 115014 (2012).

[2] R. Ding, T. Li, F. Staub, C. Tian and B. Zhu, Phys. Rev. D **92**, no. 1, 015008 (2015).

[3] J. Erler, P. Langacker and T. Li, Phys. Rev. D **66**, 015002 (2002).

[4] J. Jiang, T. Li and D. V. Nanopoulos, Nucl. Phys. B **772**, 49 (2007) [hep-ph/0610054].

SUSY Breaking Soft Terms

- The mSUGRA/CMSSM: $M_{1/2}$, M_0, A_0, $\tan\beta$, and sign(μ).

  The mSUGRA has $B = A - M_0$; NUHM1 with $m^2_{H_u} = M^2_{H_d} \neq M^2_0$; NUHM2 with $M^2_{H_u}$ and $M^2_{H_d}$.
- GmSUGRA [5]

  M_1, M_2, M_0, $M_{\tilde{L}}$, $M_{\tilde{E}^c}$, M_{H_u}, M_{H_d}, A_U, A_D, A_E, $\tan\beta$, and sign(μ).
- The phenomenological MSSM (pMSSM) [6]

  19 low energy parameters: all the parameters relevant for collider physics, and a more general description of the parameter space.
- String models

  No-scale supergravity [7]; M-theory on S^1/Z_2; Intersecting D-brane models, etc.
- Split SUSY [8]
- Universal high-scale SUSY [9]

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[5] TL and Nanopoulos, 2010; Balazs, TL, Nanopoulos and Wang, 2010.

[6] Berger, Gainer, Hewett and Rizzo, 2009.

[7] 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).

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[9] V. Barger, C. W. Chiang, J. Jiang and T. Li, Nucl. Phys. B **705**, 71 (2005) [hep-ph/0410252]; V. Barger, J. Jiang, P. Langacker and T. Li, Phys. Lett. B **624**, 233 (2005) [hep-ph/0503226]; V. Barger, J. Jiang, P. Langacker and T. Li, Nucl. Phys. B **726**, 149 (2005) [hep-ph/0504093]; L. J. Hall and Y. Nomura, JHEP **1003**, 076 (2010) [arXiv:0910.2235 [hep-ph]].

Natural Supersymmetry

The interesting question: can we rule out the natural supersymmetry at the $\mathrm{FCC_{hh}}$ and SppC? Or can we solve the supersymmetry electroweak fine-tuning problem?

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 [10]: the quantitative measure $\Delta_{\rm FT}^{\rm EENZ-BG}$ 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

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

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

Fine-Tuning Definition II

- Higgs potential:

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

- Higgs boson mass

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

- The fine-tuning measure [11]:

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

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[11] 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: Natural Supersymmetry [13]

- The first two generation squarks can be very heavy: no effects on fine-tuning.
- The light Higgsino: the μ term or effective μ term is smaller than 400 GeV.
- The squar root $M_{\tilde{t}} \equiv \sqrt{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2}$ of the sum of the two stop mass squares is smaller than 1.2 TeV. The left-handed sbottom should be light as well.
- The gluino mass is lighter than 1.5 TeV.

Comment: these bounds can be relaxed a little bit if we do the precise calculations and consider low mediation scale [12].

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[12] M. R. Buckley, A. Monteux and D. Shih, JHEP **1706**, 103 (2017) [arXiv:1611.05873 [hep-ph]].

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

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 [14]

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

- The HS fine-tuning measure [15]

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

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[14] 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]].

[15] H. Baer, V. Barger, P. Huang, D. Mickelson, A. Mustafayev and X. Tata, Phys. Rev. D **87**, no. 3, 035017 (2013) [arXiv:1210.3019 [hep-ph]].

The Third Definition: Radiative Natural Supersymmetry [16]

- The first two generation squarks can be heavy.
- The gluino and stop can be heavy as well.
- The Higgsino are light.

The LHC searches: Higgsinos.

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[16] 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 smilar to III.
- Fine-Tuning Definition I is strong.
- We shall focus on Fine-Tuning Definition I, *i.e.*, the EENZ-BG fine-tuning measure.
- The other reason is that we have a big particle physics paradiagm:
  String Theory → String Models → GUTs → SSMs → SM

Supersymmetric Standard Models (SSMs)

- Natural supersymmetry [17].
- The SSMs which can escape/relax the missing energy constraints: R parity violation [18]; compressed supersymmetry [19] ; stealth supersymmetry [20]; etc.

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[17] 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].

[18] 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].

[19] 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]].

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

Supersymmetric Standard Models (SSMs)

- The SSMs which can decrease the production cross sections: supersoft supersymmetry [21].
- Displaced Supersymmetry [22].
- Double Invisible Supersymmetry [23].
- Radiative Natural Supersymmetry [24].

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

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

[23] 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].

[24] 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]].

Supersymmetric Standard Models (SSMs)

- Maximally Natural Supersymmetry [25].
- Super-Natural Supersymmetry [26].
- Folded Supersymmetry (neutral naturalness) [27].

  The top quark partner is charged under another $SU(3)$ but not $SU(3)_C$, so its production cross section is highly suppressed.
- Relaxation mechanism [28] and Relaxing Split SUSY [29]

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[25] S. Dimopoulos, K. Howe and J. March-Russell, Phys. Rev. Lett. **113**, 111802 (2014) [arXiv:1404.7554 [hep-ph]].

[26] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph]; Phys. Lett. B **740**, 66 (2015) [arXiv:1408.4459 [hep-ph]]; G. Du, T. Li, D. V. Nanopoulos and S. Raza, Phys. Rev. D **92**, no. 2, 025038 (2015) [arXiv:1502.06893 [hep-ph]]; T. Li, S. Raza and X. C. Wang, Phys. Rev. D **93**, no. 11, 115014 (2016) [arXiv:1510.06851 [hep-ph]].

[27] G. Burdman, Z. Chacko, H. S. Goh and R. Harnik, JHEP **0702**, 009 (2007) [hep-ph/0609152]; N. Craig, S. Knapen and P. Longhi, Phys. Rev. Lett. **114**, no. 6, 061803 (2015) [arXiv:1410.6808 [hep-ph]].

[28] P. W. Graham, D. E. Kaplan and S. Rajendran, Phys. Rev. Lett. **115**, no. 22, 221801 (2015) [arXiv:1504.07551 [hep-ph]].

[29] B. Batell, G. F. Giudice and M. McCullough, JHEP **1512**, 162 (2015) doi:10.1007/JHEP12(2015)162 [arXiv:1509.00834 [hep-ph]].

Question: Super-Natural Supersymmetry

Can we propose a supersymmetry scenario whose the EENZ-BG fine-tuning measure is automatically 1 or order 1 ($\mathcal{O}(1)$)?

Fundamental physics principles: simplicity and naturalness.

Super-Natural Supersymmetry [30]

- Fine-Tuning Definition:

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

- Natural Solution:

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

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

- For no-scale supergravity and M-theory on S^1/Z_2, we have $M_* = M_{1/2}$ and $M_* = M_{3/2}$, respectively.

---

[30] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph]; Phys. Lett. B **740**, 66 (2015) [arXiv:1408.4459 [hep-ph]]; G. Du, T. Li, D. V. Nanopoulos and S. Raza, Phys. Rev. D **92**, no. 2, 025038 (2015) [arXiv:1502.06893 [hep-ph]]; T. Li, S. Raza and X. C. Wang, Phys. Rev. D **93**, no. 11, 115014 (2016) [arXiv:1510.06851 [hep-ph]].

Supernatural Supersymmetry

- The $\mathcal{F}-SU(5)$ [31] and the MSSM [32] with no-scale supergravity [33] and Giudice-Masiero Mechanism [34].

  No-scale Supergravity: $M_{1/2} \neq 0$, and $M_0 = A_0 = B_\mu = 0$.

  Giudice-Masiero Mechanism: generating μ term from supersymmetry breaking effect, *i.e.*, $\mu \propto M_{1/2}$.

  Prolem: we cannot predict the exact mass ratio $\mu / M_{1/2}$?

- The NMSSM [35] with supersymmetry breaking soft terms from M-theory on S^1/Z_2 [36].

  The NMSSM: an singlet S, and a discrete Z_3 symmetry.

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

[32] G. Du, T. Li, D. V. Nanopoulos and S. Raza, Phys. Rev. D **92**, no. 2, 025038 (2015) [arXiv:1502.06893 [hep-ph]].

[33] 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).

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

[35] T. Li, S. Raza and X. C. Wang, Phys. Rev. D **93**, no. 11, 115014 (2016) [arXiv:1510.06851 [hep-ph]].

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

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

- The Flipped $SU(5)$ model with TeV-scale vector-like particles.
- These models can be constructed in the heterotic string string theory, M-theory on S^1/Z_2, free fermionic string constructions, and F-theory model building.
- String-scale gauge coupling unification; Dimension-six proton decay; Lifting the lightest CP-even Higgs boson mass; Special sparticle spectra.
- Natural solution [37]

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

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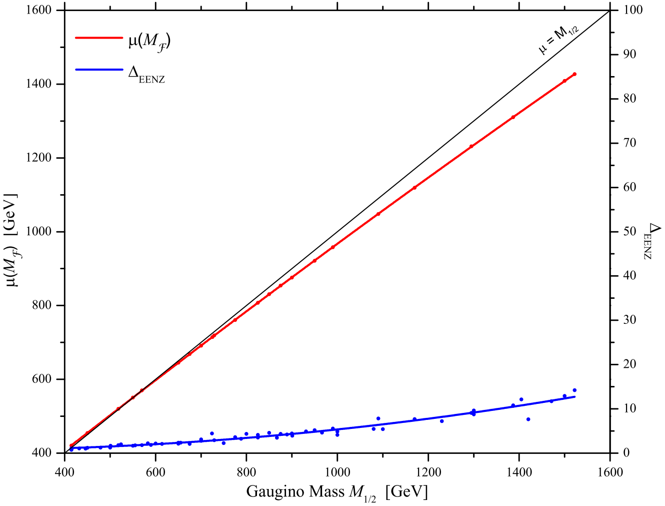
[37] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph].


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

M-theory inspired NMSSM: the Classic Example [39]

- Question: we cannot obtain the exact mass ratio $\mu/M_{1/2}$ from the GM mechanism.
- The NMSSM with an singlet S and Z_3 symmetry is scale invariant.
- M-theory supergravity: non-zero M_0 and A_0 [38].
- Consistent with all the current experiments.

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

[39] T. Li, S. Raza and X. C. Wang, Phys. Rev. D **93**, no. 11, 115014 (2016) arXiv:1510.06851 [hep-ph].

The Super-Natural Supersymmetry

- 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 Effective Super-Natural Supersymmetry

There exist the correlations among the GUT-scale parameters with large fine-tuning measures [40].

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[40] R. Ding, T. Li, F. Staub and B. Zhu, Phys. Rev. D **93**, no. 9, 095028 (2016) doi:10.1103/PhysRevD.93.095028 [arXiv:1510.01328 [hep-ph]].

The Predictions of Super-Natural Supersymmetry [41]

- No-scale supergravity

  The Bino LSP and the right-handed sleptons are light, the natural LSP-stau coanihilation.

- M-theory on S^1/Z_2

  The LSP-stau coanihilation, and Higgs resonance.

The LHC searches: Bino and right-handed sleptons.

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[41] T. Leggett, T. Li, J. A. Maxin, D. V. Nanopoulos and J. W. Walker, arXiv:1403.3099 [hep-ph]; Phys. Lett. B **740**, 66 (2015) [arXiv:1408.4459 [hep-ph]]; G. Du, T. Li, D. V. Nanopoulos and S. Raza, Phys. Rev. D **92**, no. 2, 025038 (2015) [arXiv:1502.06893 [hep-ph]]; T. Li, S. Raza and X. C. Wang, Phys. Rev. D **93**, no. 11, 115014 (2016) [arXiv:1510.06851 [hep-ph]].

The Interesting Questions?

- The SUSY electroweak fine-tuning problem can be solved by the super-natural supersymmetry or effective super-natural supersymmetry.
- Is there an upper bound on the sparticle mass?
- What is the implication from the grand unified theory or string theory?

Split SUSY and Universal High-Scale SUSY.

Split SUSY [42]

- The gauginos and Higgsinos are light around the TeV scale.
- The scalar particles are heavy except one light SM Higgs particle.
- Gauge coupling unification and dark matter.
- The tree-level Higgs quartic coupling is defined at the SUSY breaking scale M_S is

$$\lambda(M_S) = \frac{g_Y^2 + g_2^2(M_S)}{4} \cos 2\beta \ , \quad \text{where } g_Y^2 \ = \ \frac{3}{5} g_1^2 \ .$$

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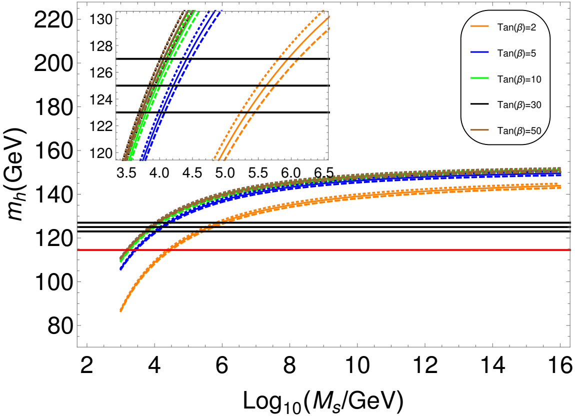
[42] J. D. Wells, Phys. Rev. D **71**, 015013 (2005) [hep-ph/0411041]; N. Arkani-Hamed and S. Dimopoulos, JHEP **0506**, 073 (2005) [hep-th/0405159]; G. F. Giudice and A. Romanino, Nucl. Phys. B **699**, 65 (2004) Erratum: [Nucl. Phys. B **706**, 487 (2005)] [hep-ph/0406088].

The Predicted Higgs Boson Mass m_h versus M_S



The Numerical Results from Higgs Boson Mass [43]

- For m_h from 123 GeV to 127 GeV, the corresponding upper bound on M_S is from $10^{5.2}$ GeV to $10^{6.2}$ GeV for $\tan\beta = 2$.
- For $\tan\beta = 50$, we have M_S ranges from $10^{3.6}$ to $10^{4.2}$ GeV. In particular, $M_S \lesssim 10^{4.5}$ GeV for $\tan\beta \gtrsim 4$.
- In short, for $\tan\beta \gtrsim 2$ and 4, we have $M_S \lesssim 10^{6.2}$ GeV and $M_S \lesssim 10^{4.5}$ GeV, respectively.

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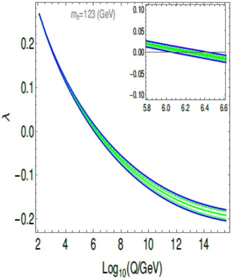
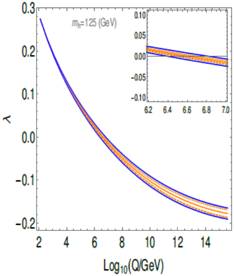
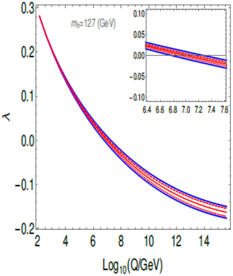
[43] W. Ahmed, A. Mansha, T. Li, S. Raza, J. Roy and F. Z. Xu, arXiv:1901.05278 [hep-ph].

The Electroweak Vacuum Stability Bound







The Numerical Results from the Electroweak Vacuum Stability Bound [44]

- For $m_h = 123$ GeV, we obtain $M_S \leq 10^{6.1}$ GeV.
- For $m_h = 125$ GeV, we obtain $M_S \leq 10^{6.8}$ GeV.
- For $m_h = 127$ GeV, we obtain $M_S \leq 10^{7.3}$ GeV.
- The key point is the extra contributions to the Renormalization Group Equation (RGE) running from the couplings among Higgs boson, Higgsinos, and gauginos.

The PeV-Scale Split SUSY.

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[44] W. Ahmed, A. Mansha, T. Li, S. Raza, J. Roy and F. Z. Xu, arXiv:1901.05278 [hep-ph].

The Universal High-Scale SUSY [46]

- All the sparticles are heavy, and the LSP can still be the dark matter [45].
- There is one and only one light SM-like Higgs field .
- Principle: gauge coupling unification within 3% uncertainty

$$\alpha_{\rm GUT}^{-1} \equiv \alpha_1^{-1} = \frac{\alpha_2^{-1} + \alpha_3^{-1}}{2} ~.$$

- Proton decay constraint: $M_{\rm GUT} \geq 1.0 \times 10^{16}~{\rm GeV}$.

$$\tau_p(e^+\pi^0) \simeq 1.0 \times 10^{34} \times \left(\frac{2.5}{A_R}\right)^2 \times \left(\frac{0.04}{\alpha_{\rm GUT}}\right)^2 \times \left(\frac{M_{\rm GUT}}{1.0 \times 10^{16}~{\rm GeV}}\right)^4 ~{\rm years}$$

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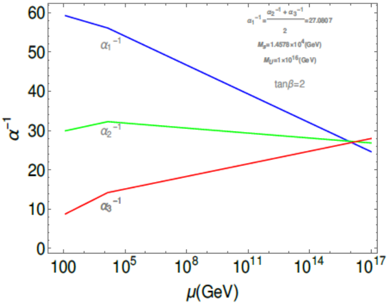
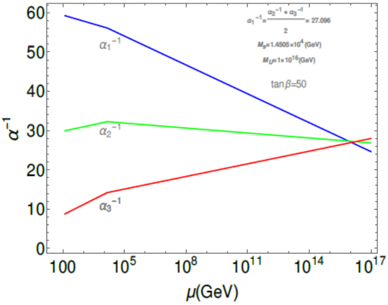
[45] W. Ahmed, TL, S. Raza, and H. Zhou, in preparation.

[46] V. Barger, C. W. Chiang, J. Jiang and T. Li, Nucl. Phys. B **705**, 71 (2005) [hep-ph/0410252]; V. Barger, J. Jiang, P. Langacker and T. Li, Phys. Lett. B **624**, 233 (2005) [hep-ph/0503226]; V. Barger, J. Jiang, P. Langacker and T. Li, Nucl. Phys. B **726**, 149 (2005) [hep-ph/0504093]; L. J. Hall and Y. Nomura, JHEP **1003**, 076 (2010) [arXiv:0910.2235 [hep-ph]].

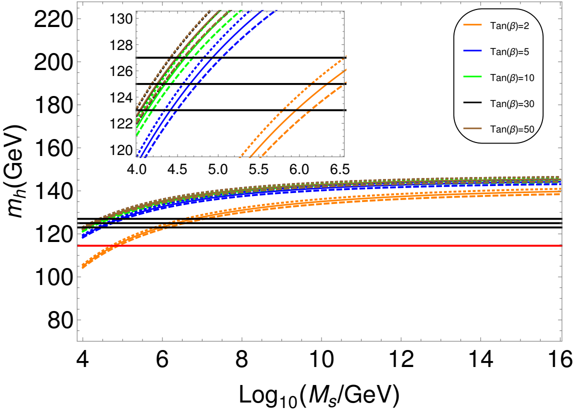
The Universal High-Scale SUSY





Prediction: $M_S \leq 1.46 \times 10^4$ GeV!

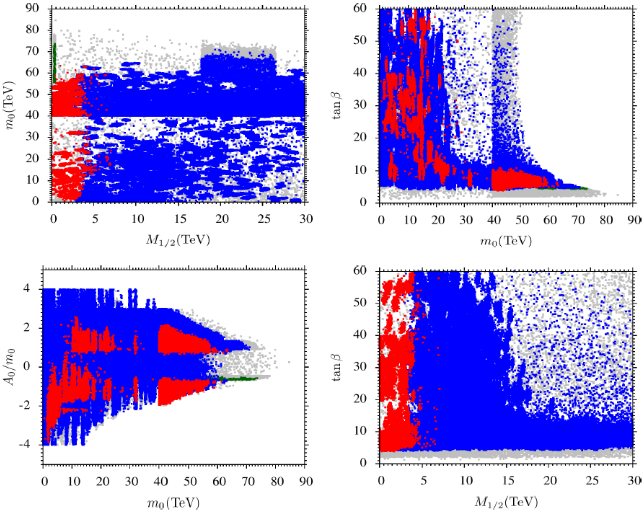
The Universal High-Scale SUSY



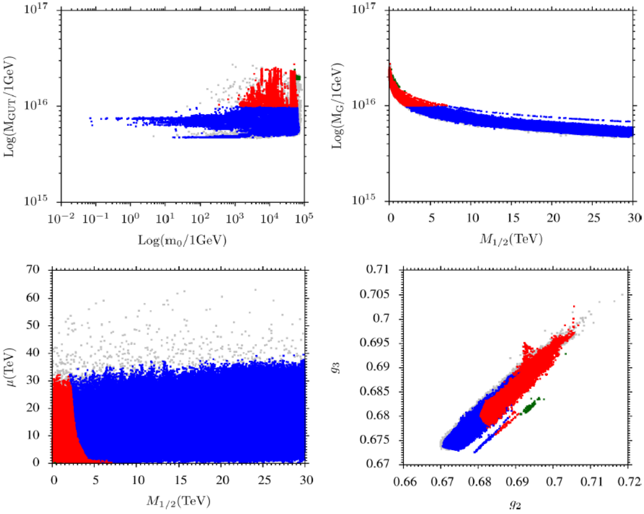
The Numerical Results from the Higgs Mass Bound for $m_h = 127$ GeV

- For $\tan\beta = 2$, we obtain $M_S \leq 10^{6.57}$ GeV.
- For $\tan\beta = 5$, we obtain $M_S \leq 10^{4.9}$ GeV.
- For $\tan\beta = 50$, we obtain $M_S \leq 10^{4.5}$ GeV.

The mSUGRA/CMSSM



The mSUGRA/CMSSM



ISAJET

- The ISAJET can still work for (mildly) high-scale supersymmetry breaking soft mass terms.
- We find that M_0 can be large up to 66 TeV, while gaugino mass and μ term are smaller than 8 and 30 TeV, respectively.

Summary

- Supersymmetry is well motivated from theoretical and phenomenological points of view.
- The supersymmetry electroweak fine-tuning problem can be solved elegantly in (or effective) super-natural supersymmetry.
- We obtain the mildly split SUSY and universal high-scale SUSY from the Higgs boson mass, gauge coupling unifcation, and proton decay, etc.

Thank You Very Much for Your Attention!