The New Phyiscs beyond the Standard Model

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Outline

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The Standard Model

- Gauge symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Fermions: Q_i, U_i^c, D_i^c, L_i, E_i^c
- Higgs: H

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

The New Physics beyond the SM

- New particles: scalars, fermions, ...
- New gauge symmetries: $U(1)'$, $SU(2)$, $SU(N)$, ...

The particle physics model building: principle and motivations!!!
Focus: the new physics can be tested at the LHC!

The convincing evidence for physics beyond the SM:

- Dark energy
- Dark matter
- Neutrino masses and mixings
- Baryon asymmetry
- Inflation

The SM is incomplete!

Major Theoretical Problems in the SM

- Fine-tuning problems
- Aesthetic Problems

Fine-Tuning Problems:

- Cosmological constant problem

$$\Lambda_{\rm CC} \sim 10^{-122} M_{\rm Pl}^4 \ .$$

- Gauge hierarchy problem

$$M_{\rm EW} \sim 10^{-16} M_{\rm Pl} \ .$$

- Strong CP probelm

$$\theta < 10^{-9} \ .$$

- The SM fermion masses and mixings

$$m_{\rm electron} \sim 10^{-5} m_{\rm top} \ .$$

Aesthetic Problems:

- Interaction unification
- Fermion unification
- Charge quantization
- Gauge coupling unification

The first three prolems can be solved when we embed the SM into the Grand Unified Theories (GUTs) and string models.

Outline

Fine-tuning Problems:

- ## Cosmological constant problem

  Let us introduce N scalar fields and assume that each scalar field has two vacua with different VEVs. Thus, there are 2^N vacuua. Similar to the string landscape, we might solve the cosmological constant problem. These scalar fields can be produced via Higgs portal and decay to the SM light fermions as well. See Nima's talk at the IHEP on December 15, 2015.

- ## Strong CP probelm

  CPT violation, private discussions with Shouhua.

- ## The SM fermion masses and mixings

  The low energy Froggat-Nielsen meschanism or the large extra dimensions.

New Physics: Baryon Asymmetry

- Electroweak baryogensis: addition SM scalar singlets for the first order electroweak phase transition.
- Leptogenesis: right-handed neutrinos via resonant leptogenesis

New Physics: Dark Matter

- The real scalar field S with Z_2 symmetry.

$$\mathcal{L}_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!} S^4 \ .$$

- The Majorana fermion.
- The massive gauge boson.
- The higher spin particles: non-renormalizable theory!

New Physics: Neutrino Masses and Mixings

- Type I seesaw mechanism: two or more right-handed neutrinos
- Baryon asymmetry: resonant leptogenesis.
- Type II seesaw mechanism: a triplet scalar Φ with quantum numbers $(\mathbf{1}, \mathbf{3}, \mathbf{1})$.
- Radiatively generated neutrino masses: Zee model, Babu-Zee model, scotogenic models, etc.

Theoretical Motivations: Additional gauge symmetries

- In the SM, there exist two global $U(1)$ symmetries: $U(1)_B$ and $U(1)_L$. And the sphaleron process violates $U(1)_{B+L}$ but preserves $U(1)_{B-L}$. Also, $U(1)_{B-L}$ can be realized in the string models easily. Thus, why $U(1)_{B-L}$ is not a gauge symmetry at the low energy?

  The $SU(3)_C \times SU(2)_L \times U(1)_{I3R} \times U(1)_{B-L}$ model.

- There is a $SU(2)_L$ gauge symmetry, why not $SU(2)_R$?

  The $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ model.

Gauge Coupling Unification

- In the four-dimensional non-SUSY GUTs: adding the vector-like particles to achieve gauge coupling unification.

  For example, the vector-like fermions: (XQ, XQ^c) and (XD, XD^c)

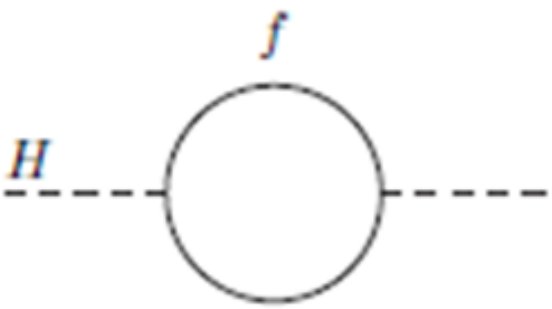
- In the four-dimensional non-SUSY GUTs: considering two-step unification, for example, non-supersymmetric $SO(10)$ models.
- In the high-dimensional GUTs: non-Canonical $U(1)_Y$ nomalization, $k_Y = 4/3$.

Gauge Hierarchy Problem

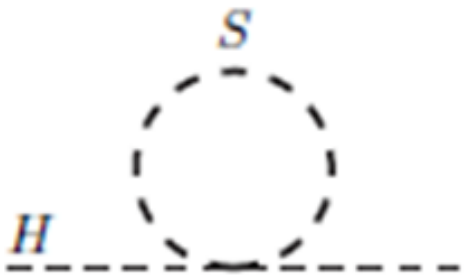
$$-\mathcal{L} = \lambda_f H \bar{f} f + \lambda_S |H|^2 |S|^2 \ .$$

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

Gauge Hierarchy Problem



(a)



(b)

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 string landscape with anthropic solution, etc.

Outline

Supersymmetry

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

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

- 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.
- Gauge bosons and Higgs fields have a spin 1/2 partner.
- Graviton has a spin 3/2 partner.

The Minimal Supersymmetry Standard Model (MSSM)

- Two Higgs doublets: holomorphic superpotential and anomaly cancellation.
- Unlike the SM, proton can decay at the renormalizable level in the SSMs. To forbid the proton decay operaors, we introduce a Z_2 R symmetry: $R = (-1)^{3B-L+2s}$.
- The SM particle are even while the supersymmetric particles are odd.
- Dark matter: neutralino, sneutrino, gravitino, etc.
- Other solutions: R symmetry is violated while $U(1)_B$ or $U(1)_L$ is preserved.

No missing energy at the LHC.

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	$(H_d^0 \quad H_d^-)$	$(\widetilde{H}_d^0 \quad \widetilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

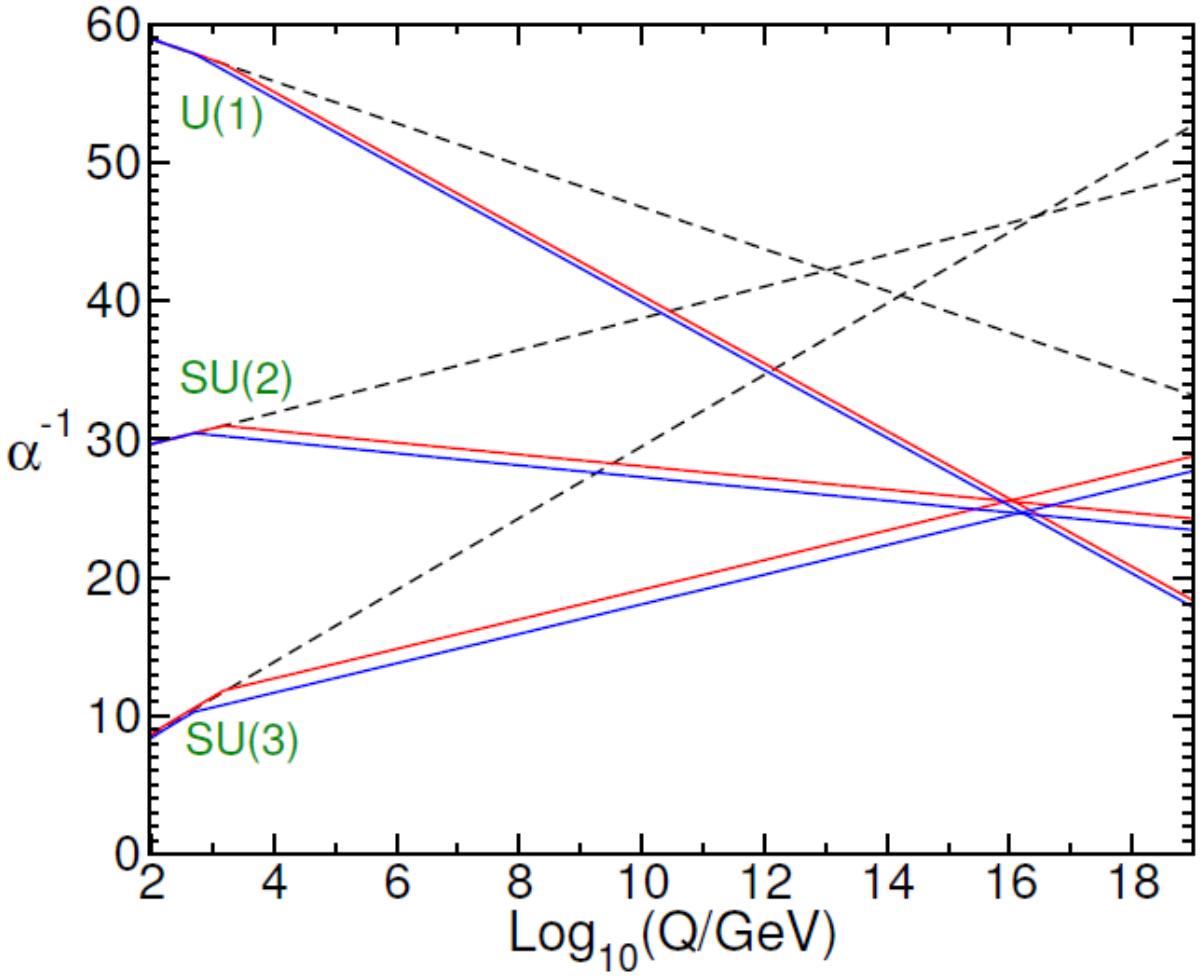
Table : Chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars, and the spin-1/2 fields are left-handed two-component Weyl fermions.

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.

Neutralinos: neutral Higgsinos, Wino and Bino.
Chargino: charged Higgsinos and Wino.

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

μ Problem:

- The next-to-MSSM (NMSM): an SM singlet S, and Z_3 symmetry to forbid the $\mu H_d H_u$ term

$$\phi \longrightarrow \omega\phi \ , \quad W \ = \ \lambda S H_d H_u .$$

  where $\omega^3 = 1$.
- The supersymmetric $U(1)'$ model
- Giudice-Masiero mechanism in gravity mediation!

Supersymmetry Breaking and Mediation:

- The supersymmetry breaking is broken in the hidden sector via F-term and/or D-term.
- The supersymmetry breaking mediations: gravity mediation, gauge mediation, anomaly mediation, and Yukawa mediation, etc.

Dark Matter Constraints from the LUX and PANDAX Experiments:

- The light stau and LSP neutralino coannihilation scenario.
- Higgs funnel: two LSP annihilate via a resonant Higgs field.
- Higgsino LSP: very small density.

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

Higgs boson mass in the MSSM:

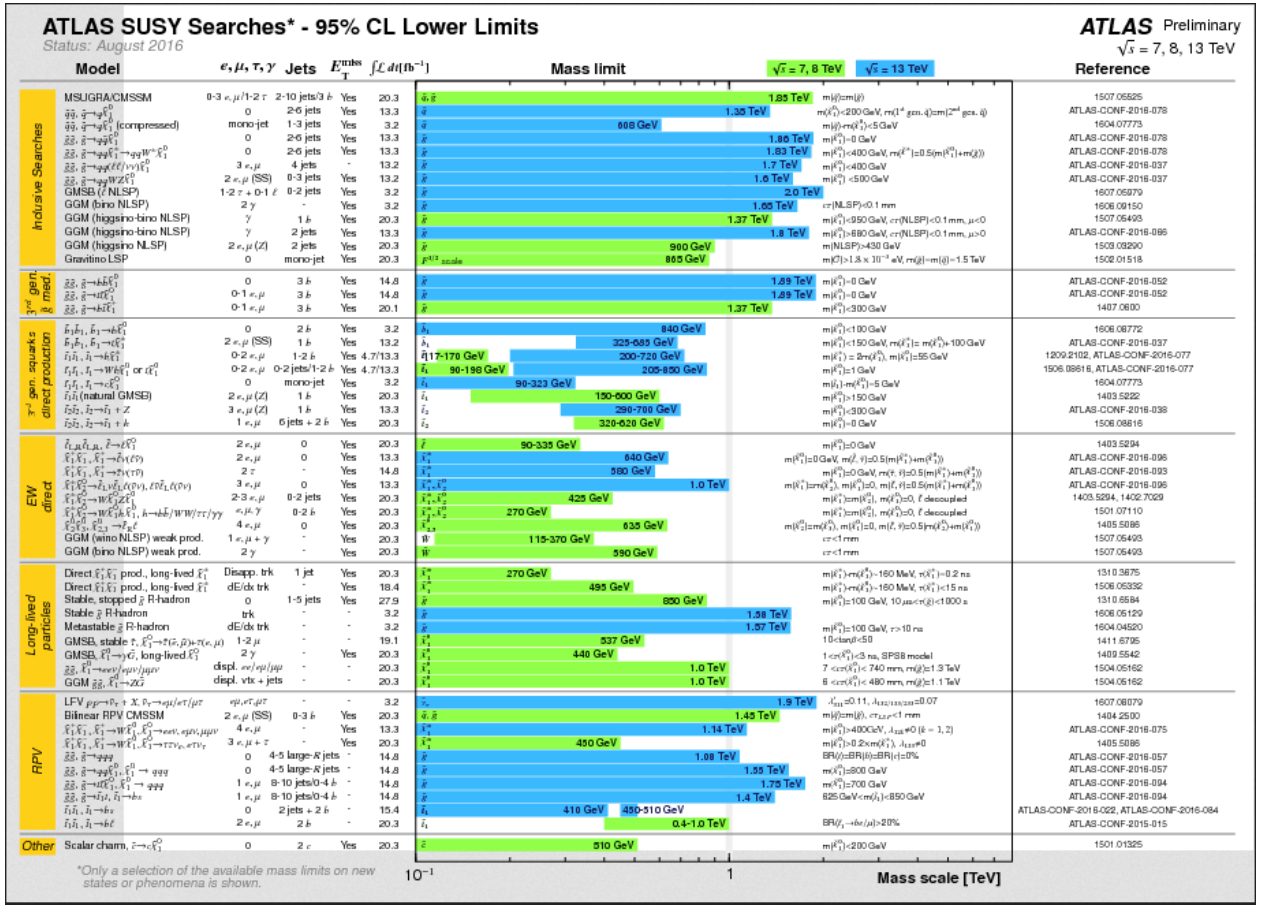
- The SM-like Higgs boson mass is around 125 GeV.
- The tree-level Higgs boson mass is smaller than M_Z.
- The Higgs boson mass is enhanced by the top quarks/squarks loop corrections.
- The maximal stop mixing is needed to relax the fine-tuning.

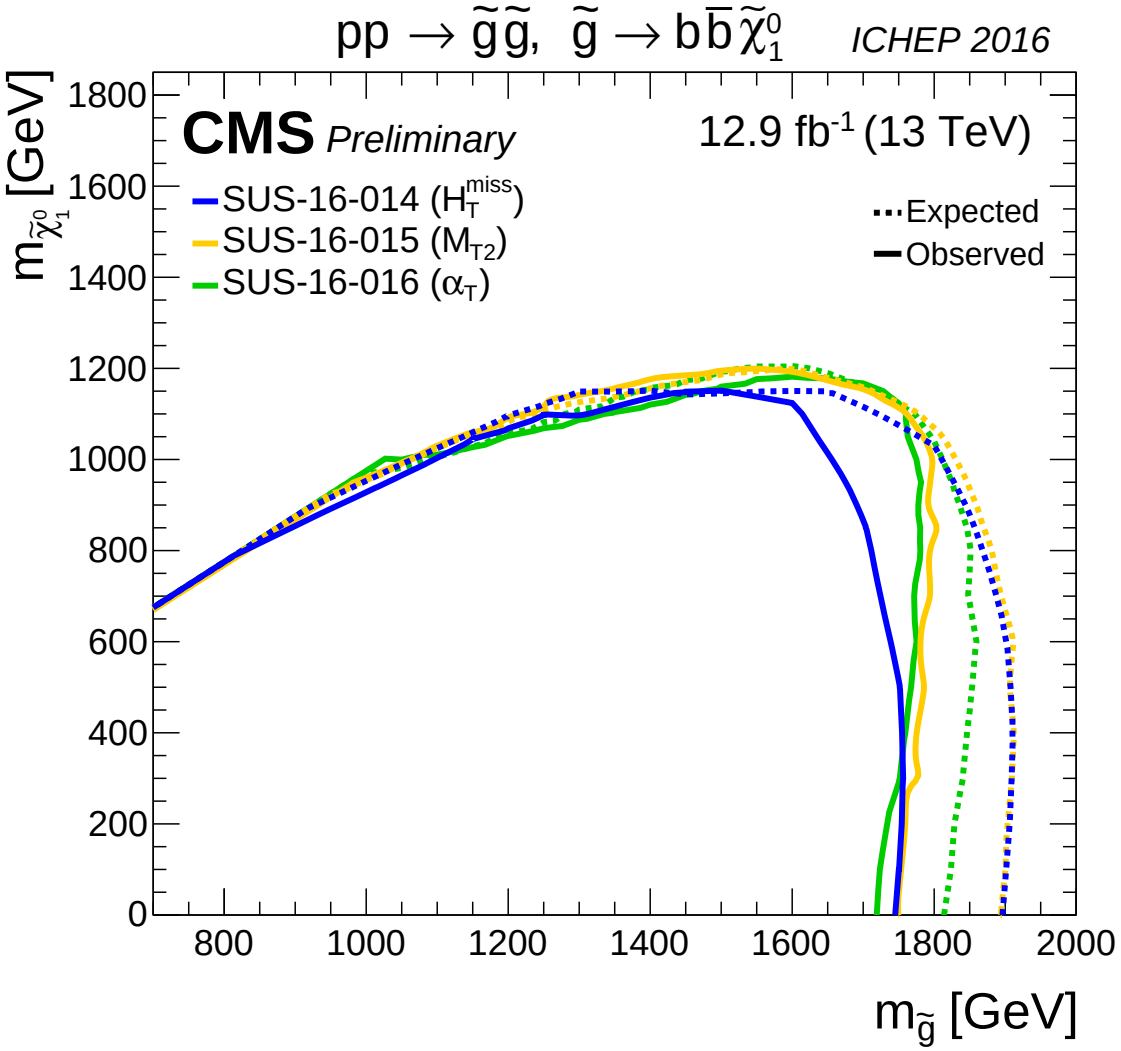
Problem: the $SU(3)_C \times U(1)_{EM}$ symmetry breaking.

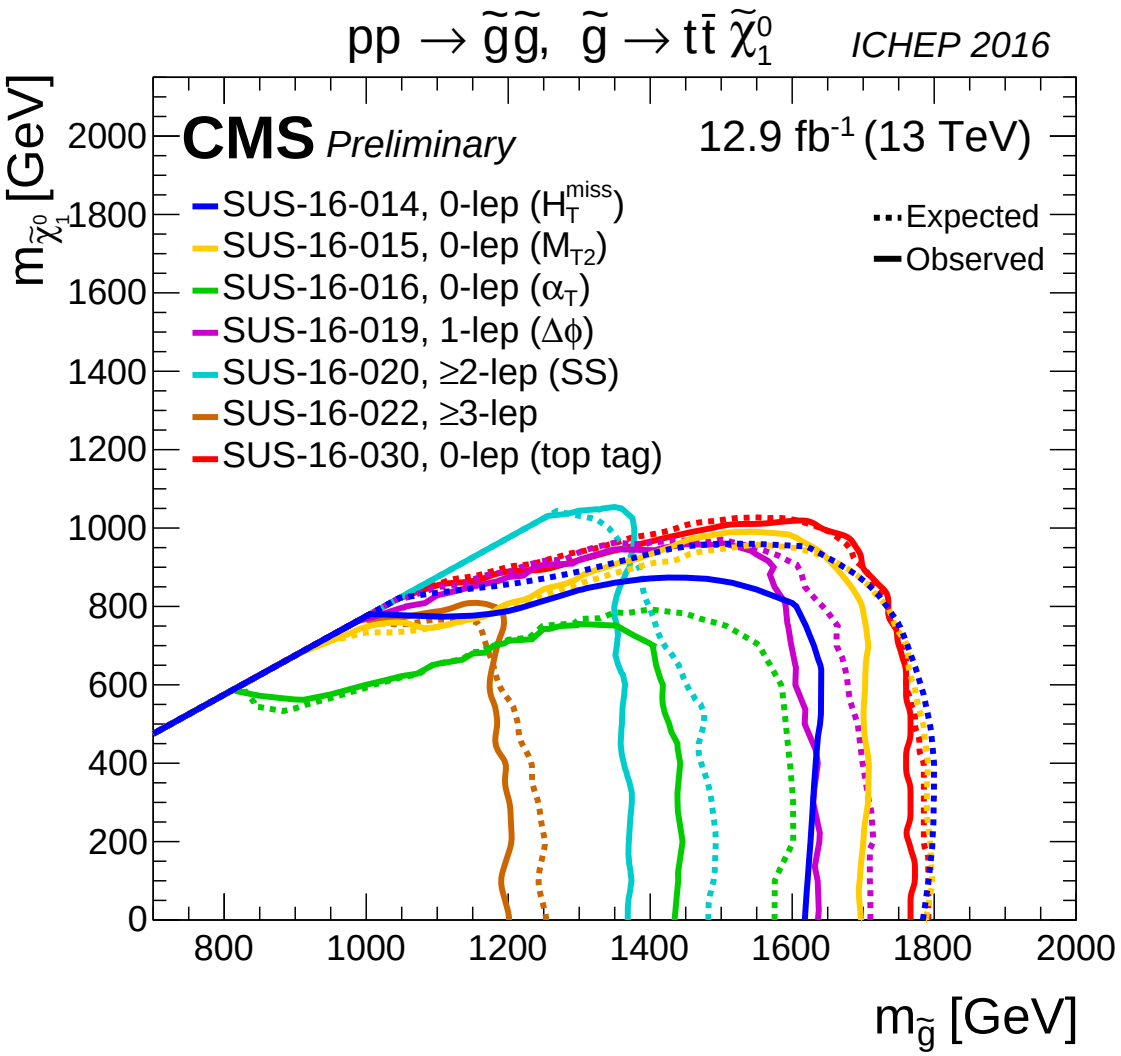
The LHC Supersymmetry Search Contraints:

- The first two-generation squark mass low bounds are around 1.2-1.4 TeV in the CMSSM/mSUGRA
- The gluino mass low bound is around 1.6-1.9 TeV.
- The stop and sbottom mass low bounds are around 800-900 GeV and 800-1000 GeV, respectively.

The SSMs are fine-tuned!!!


ATLAS SUSY Searches* - 95% CL Lower Limits
Status: August 2016
ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV
Model
e, μ, τ, γ
Jets
E_T^{miss}
$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$
Mass limit
$\sqrt{s}$ = 7, 8 TeV
$\sqrt{s}$ = 13 TeV
Reference
Inclusive Searches
MSUGRA/CMSSM
$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)
$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$
GMSB ($\tilde{\ell}$ NLSP)
GGM (bino NLSP)
GGM (higgsino-bino NLSP)
GGM (higgsino NLSP)
Gravitino LSP
gen. med.
$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$
$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$
$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$
gen. squarks direct production
$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to t\tilde{\chi}_1^0$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^+$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$
$\tilde{t}_1\tilde{t}_1$ (natural GMSB)
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$
EW direct
$\tilde{\ell}_L\tilde{\ell}_L, \tilde{\ell}\to\ell\tilde{\chi}_1^0$
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\ell\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\ell\nu)$
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$
$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_2^0\tilde{\chi}_3^0\to\tilde{\ell}_R\ell$
GGM (wino NLSP) weak prod.
GGM (bino NLSP) weak prod.
Long-lived particles
Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$
Direct $\tilde{\ell}_1\tilde{\ell}_1$ prod., long-lived $\tilde{\ell}_1^\pm$
Stable, stopped $\tilde{g}$ R-hadron
Stable $\tilde{g}$ R-hadron
Metastable $\tilde{g}$ R-hadron
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$
GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$
$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to eev/e\mu\nu/\mu\mu\nu$
GGM $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$
RPV
LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$
Bilinear RPV CMSSM
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$
$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$
$\tilde{g}\tilde{g}, \tilde{g}\to qqq$
$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$
$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$
$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1t, \tilde{t}_1\to bs$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$
Other
Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$
*Only a selection of the available mass limits on new states or phenomena is shown.
10^{-1}
1
Mass scale [TeV]


$pp \to \tilde{g}\tilde{g},\ \tilde{g} \to b\bar{b}\tilde{\chi}_1^0$
ICHEP 2016
CMS Preliminary
12.9 fb^{-1} (13 TeV)
SUS-16-014 (H_T^{miss})
SUS-16-015 (M_{T2})
SUS-16-016 (α_T)
Expected
Observed
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
2000


pp → g̃g̃, g̃ → tt̄ χ̃⁰₁
ICHEP 2016
CMS Preliminary
12.9 fb-1 (13 TeV)
SUS-16-014, 0-lep (H_T^miss)
SUS-16-015, 0-lep (M_T2)
SUS-16-016, 0-lep (α_T)
SUS-16-019, 1-lep (Δφ)
SUS-16-020, ≥2-lep (SS)
SUS-16-022, ≥3-lep
SUS-16-030, 0-lep (top tag)
Expected
Observed
m_χ̃⁰₁ [GeV]
m_g̃ [GeV]
0
200
400
600
800
1000
1200
1400
1600
1800
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1000
1200
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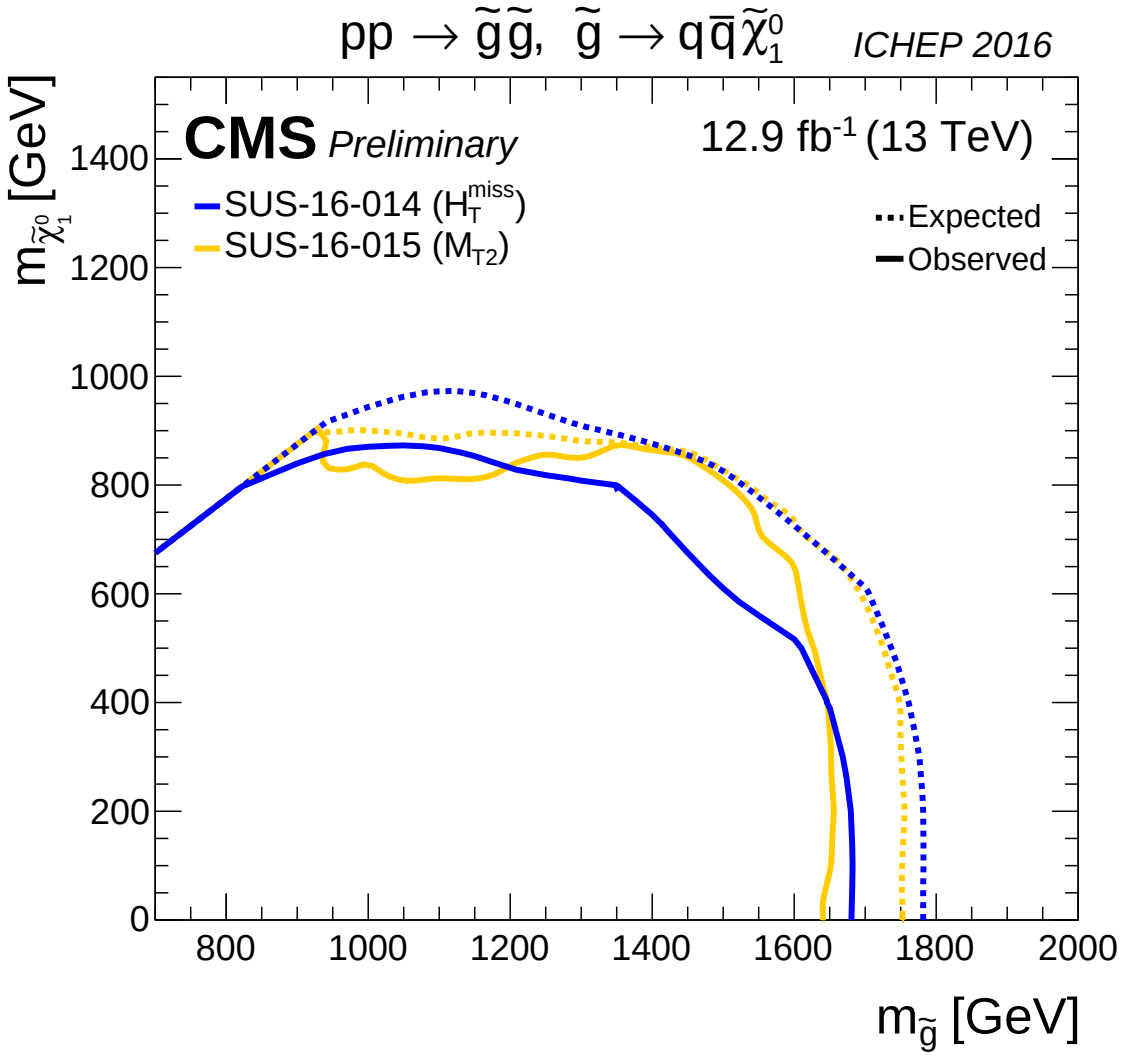
1600
1800
2000


$pp \to \tilde{g}\tilde{g},\ \tilde{g} \to q\bar{q}\tilde{\chi}_1^0$
ICHEP 2016
CMS Preliminary
12.9 fb^{-1} (13 TeV)
SUS-16-014 (H_T^{miss})
SUS-16-015 (M_{T2})
Expected
Observed
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{g}}$ [GeV]
0
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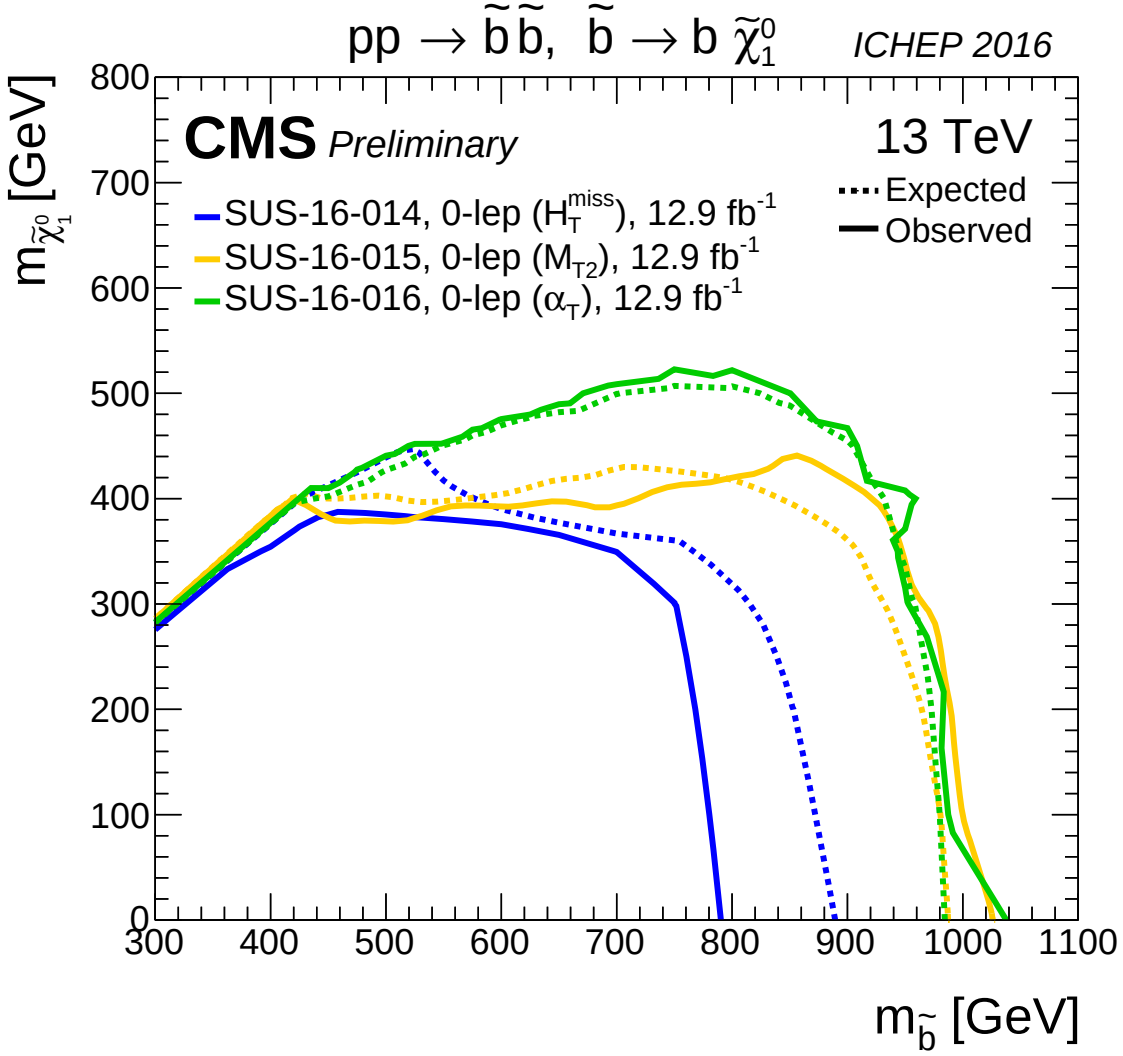
800
1000
1200
1400
1600
1800
2000


pp → b̃b̃, b̃ → b χ̃⁰₁
ICHEP 2016
CMS Preliminary
13 TeV
Expected
Observed
SUS-16-014, 0-lep (H_T^miss), 12.9 fb^-1
SUS-16-015, 0-lep (M_T2), 12.9 fb^-1
SUS-16-016, 0-lep (α_T), 12.9 fb^-1
m_χ̃⁰₁ [GeV]
m_b̃ [GeV]
0
100
200
300
400
500
600
700
800
300
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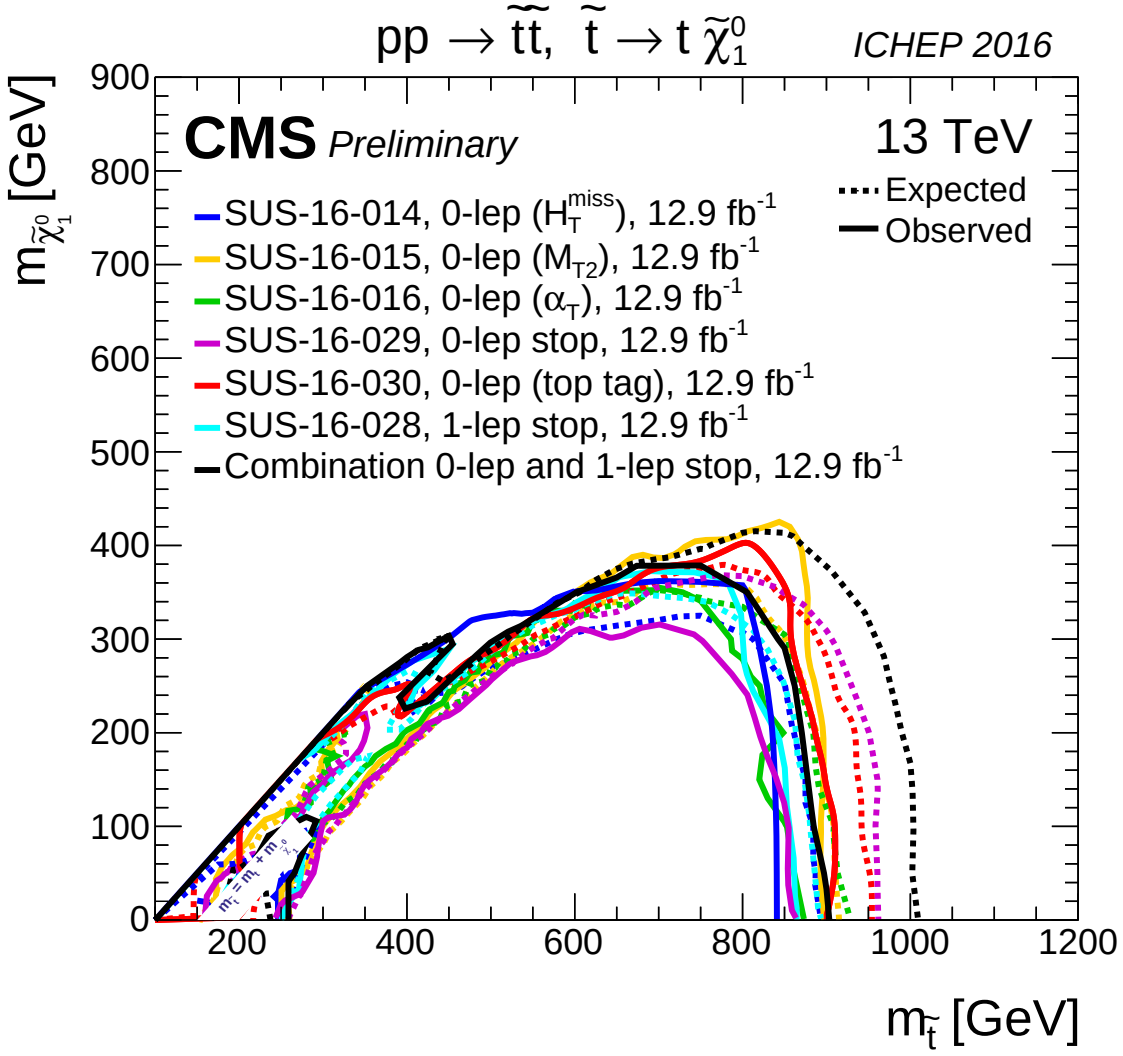
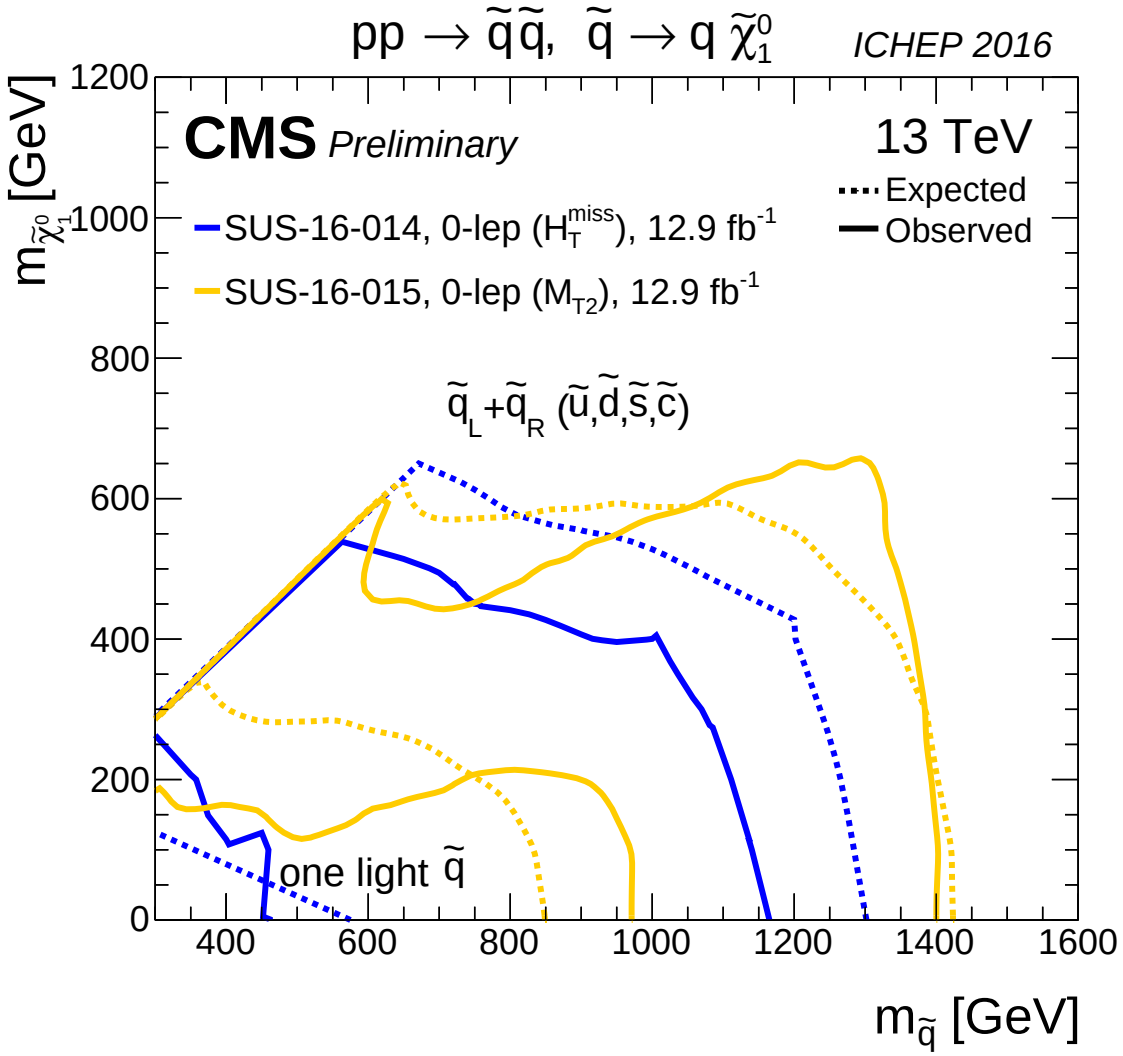
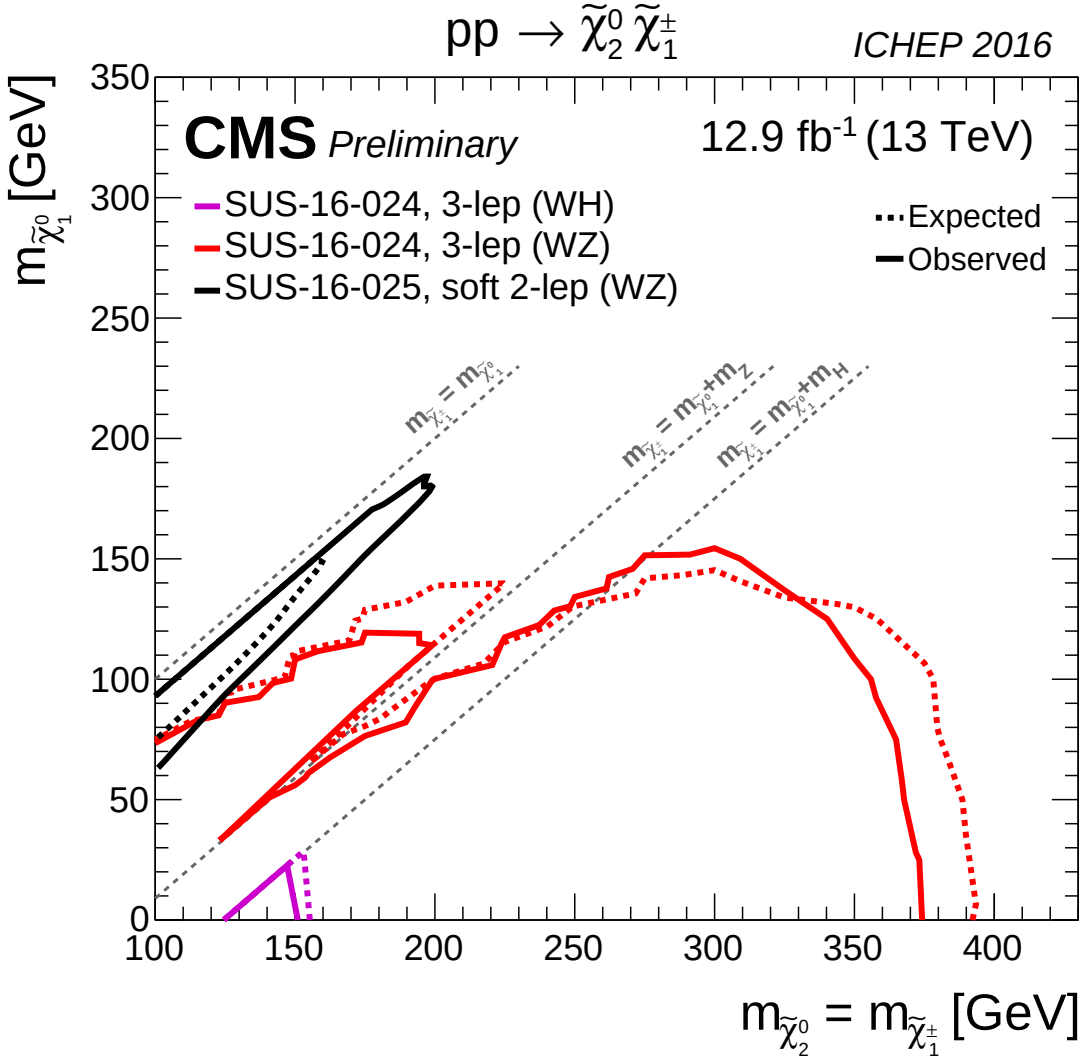
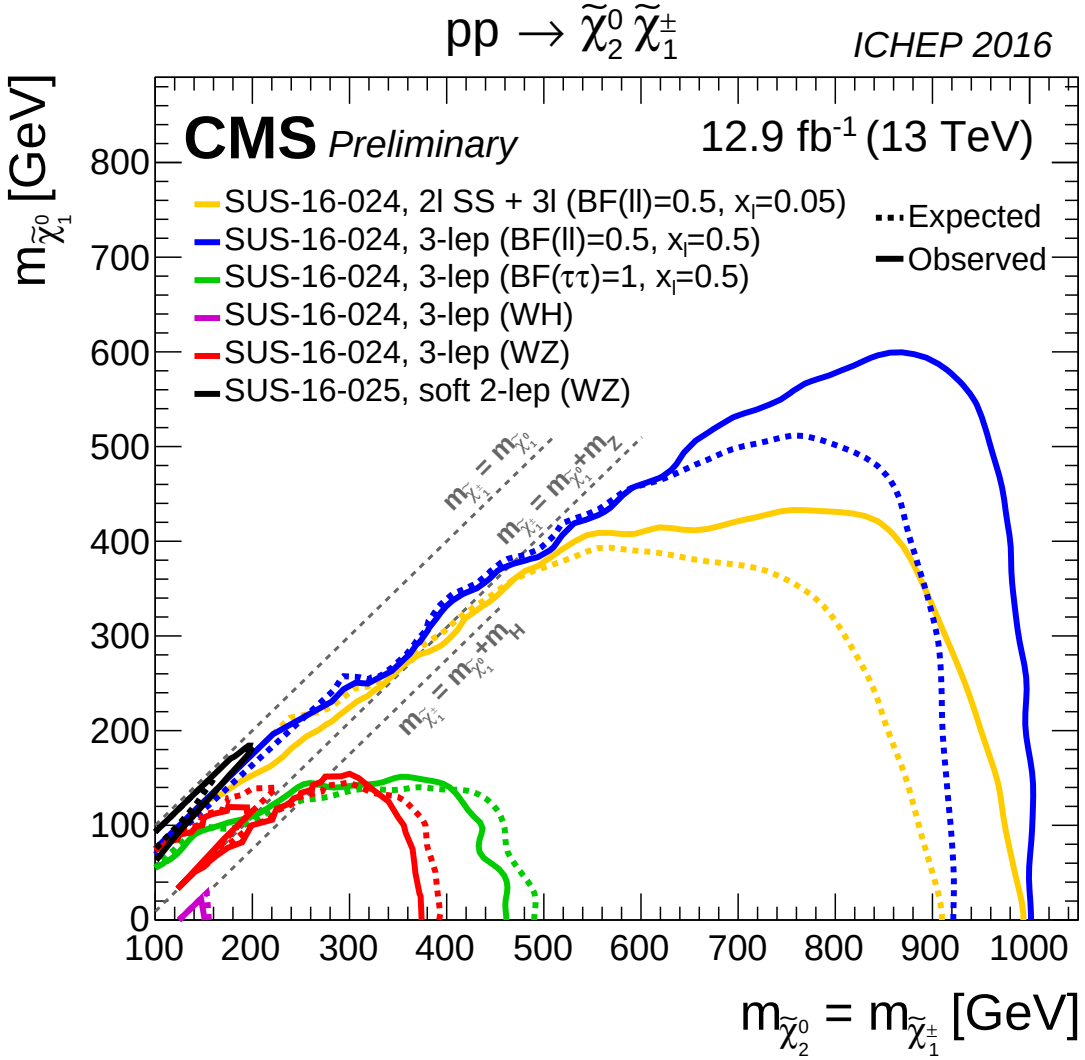
500
600
700
800
900
1000
1100


pp → t̃t̃, t̃ → t χ̃⁰₁
ICHEP 2016
CMS Preliminary
13 TeV
Expected
Observed
SUS-16-014, 0-lep (H_T^miss), 12.9 fb^-1
SUS-16-015, 0-lep (M_T2), 12.9 fb^-1
SUS-16-016, 0-lep (α_T), 12.9 fb^-1
SUS-16-029, 0-lep stop, 12.9 fb^-1
SUS-16-030, 0-lep (top tag), 12.9 fb^-1
SUS-16-028, 1-lep stop, 12.9 fb^-1
Combination 0-lep and 1-lep stop, 12.9 fb^-1
m_χ̃⁰₁ [GeV]
m_t̃ [GeV]
0
100
200
300
400
500
600
700
800
900
200
400
600
800
1000
1200


pp → q̃q̃, q̃ → q χ̃⁰₁
ICHEP 2016
CMS Preliminary
13 TeV
Expected
Observed
SUS-16-014, 0-lep (H_T^miss), 12.9 fb^-1
SUS-16-015, 0-lep (M_T2), 12.9 fb^-1
q̃_L+q̃_R (ũ,d̃,s̃,c̃)
one light q̃
m_χ̃⁰₁ [GeV]
m_q̃ [GeV]
0
200
400
600
800
1000
1200
400
600
800
1000
1200
1400
1600


pp → $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$
ICHEP 2016
CMS Preliminary
12.9 fb^{-1} (13 TeV)
SUS-16-024, 3-lep (WH)
SUS-16-024, 3-lep (WZ)
SUS-16-025, soft 2-lep (WZ)
Expected
Observed
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + m_Z$
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} + m_H$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$ [GeV]
0
50
100
150
200
250
300
350
400


pp → $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$
ICHEP 2016
CMS Preliminary
12.9 fb^{-1} (13 TeV)
SUS-16-024, 2l SS + 3l (BF(ll)=0.5, x_l=0.05)
SUS-16-024, 3-lep (BF(ll)=0.5, x_l=0.5)
SUS-16-024, 3-lep (BF(ττ)=1, x_l=0.5)
SUS-16-024, 3-lep (WH)
SUS-16-024, 3-lep (WZ)
SUS-16-025, soft 2-lep (WZ)
Expected
Observed
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}+m_Z$
$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}+m_H$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm}$ [GeV]
0
100
200
300
400
500
600
700
800
900
1000

Supersymmetry at the Current and Future Colliders

- Can we rule out supersymmetry at the LHC, VLHC, and SPPC?
  No! No!! No!!!
- Points: supersymmetry breaking soft mass scale can be pushed to be much higher than 1 TeV, for example, 100 TeV, while gauge coupling unification can still be realized due to 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? 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 [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

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

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

Fine-Tuning Definition II

- Higgs potential:

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

- Higgs boson mass

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

- The fine-tuning measure [2]:

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

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

Fine-Tuning Definition II

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

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

Fine-Tuning Definition III

- The minimization condition for electroweak symmetry breaking

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

- The fine-tuning measure [3]

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

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

Comments on Fine-Tuning

- Fine-Tuning Definition III is weak.
- Fine-Tuning Definition II is smilar to III.
- Fine-Tuning Definition I is strong.

Question: the Natural SSMs?

Supersymmetric SMs:

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

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

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

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

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

Supersymmetric SMs:

- Supersymmetric models with sub-TeV squarks that decrease the cross sections: supersoft supersymmetry [8].
- Displaced Supersymmetry [9].
- Double Invisible Supersymmetry [10].
- Radiative Natural Supersymmetry
- Maximally Natural Supersymmetry.
- Folded Supersymmetry (neutral naturalness)

  The top quark partner is charged under another $SU(3)$ but not $SU(3)_C$, so its production cross section is highly suppressed.

[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].

Supersymmetric SMs:

- Supersymmetric models with sub-TeV squarks that decrease the cross sections: supersoft supersymmetry [11].
- Displaced Supersymmetry [12].
- Double Invisible Supersymmetry [13].
- Radiative Natural Supersymmetry [14].
- Maximally Natural Supersymmetry [15].

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

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

[13] 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].

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

Supersymmetric SMs:

- Super-Natural Supersymmetry [16].
- Folded Supersymmetry (neutral naturalness) [17].

  The top quark partner is charged under another $SU(3)$ but not $SU(3)_C$, so its production cross section is highly suppressed.

[16] 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]].

[17] 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]].

The Second Definition: Natural Supersymmetry [18].

- The first two generation squarks can be very heavy: no effects on fine-tuning!
- The gluino and stop are light, possible one sbottom.
- The Higgsino are light.

The LHC searches: gluino, stop and Higgsinos.

[18] 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].

The Third Definition: Radiative Natural Supersymmetry [19].

- 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.

[19] 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]].

The First Definition: Non-Universal Gaugino Masses [20].

- Higgsino LSP.
- The right-handed sleptons are light.
- The Bino might be light as well.

The LHC searches: Higgsinos, right-handed sleptons, and Bino.

[20] S. Antusch, L. Calibbi, V. Maurer, M. Monaco and M. Spinrath, JHEP **1301**, 187 (2013) [arXiv:1207.7236 [hep-ph]]; L. Calibbi, T. Li, A. Mustafayev and S. Raza, Phys. Rev. D **93**, no. 11, 115018 (2016) [arXiv:1603.06720 [hep-ph]].

The First Definition: Super-Natural Supersymmetry [21].

- Bino LSP.
- The right-handed sleptons are light.

The LHC searches: Bino and right-handed sleptons.

[21] 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]].

Natural Solution to the Fine-Tuning Problem

- Fine-Tuning Definition:

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

- Natural Solution:

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

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

Supersymmetry Mediation

- Gravity mediation
- Gauge mediation
  Gravitino is the LSP, the NLSP can be Wino, Higgsino, Bino, sneutrino, slepton, and stop/sbottom in general.
- Anomaly mediation
  Wino can be the LSP, but its density should smaller than the observed value.

Thank You Very Much for Your Attention!