Non-standard supersymmetry breaking and Dirac gaugino masses without supersoftness

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Supersymmetry (SUSY)

- SUSY extension = one of the candidate of beyond the Standard Model (SM)

  (DM candidate, hierarchy problem btw EW and Planck, Grand Unification and etc..)

  SUSY = Symmetry btw bosons and fermions

  However, no one see SUSY partners => SUSY should be broken

Softly broken Lagrangian (= Only including dimensionful parameters)

for Minimal Supersymmetric Standard Model (MSSM)

$$
\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} = & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& -\left(\widetilde{U^C}\mathbf{a}_u\widetilde{Q}H_u - \widetilde{D^C}\mathbf{a}_d\widetilde{Q}H_d - \widetilde{E^C}\mathbf{a}_e\widetilde{L}H_d + \text{c.c.}\right) \\
& -\left(\widetilde{Q}^\dagger\mathbf{m}_Q^2\widetilde{Q} + \widetilde{L}^\dagger\mathbf{m}_L^2\widetilde{L} + \widetilde{U^C}\mathbf{m}_{U^C}^2\widetilde{U^C}^\dagger + \widetilde{D^C}\mathbf{m}_{D^C}^2\widetilde{D^C}^\dagger + \widetilde{E^C}\mathbf{m}_{E^C}^2\widetilde{E^C}^\dagger\right) \\
& -\left(m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d + (bH_uH_d + \text{c.c.})\right)
\end{aligned}
$$

Softly broken Lagrangian (= Only including dimensionful parameters)

The standard soft mass parameters

$$
\begin{aligned}
\mathcal{L}_{\mathrm{soft}}^{\mathrm{MSSM}} = & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \mathrm{c.c.}\right) \\
& - \left(\widetilde{U^C}\mathbf{a}_u\widetilde{Q}H_u - \widetilde{D^C}\mathbf{a}_d\widetilde{Q}H_d - \widetilde{E^C}\mathbf{a}_e\widetilde{L}H_d + \mathrm{c.c.}\right) \\
& - \left(\widetilde{Q}^\dagger\mathbf{m}_Q^2\widetilde{Q} + \widetilde{L}^\dagger\mathbf{m}_L^2\widetilde{L} + \widetilde{U^C}\mathbf{m}_{U^C}^2\widetilde{U^C}^\dagger + \widetilde{D^C}\mathbf{m}_{D^C}^2\widetilde{D^C}^\dagger + \widetilde{E^C}\mathbf{m}_{E^C}^2\widetilde{E^C}^\dagger\right) \\
& - \left(m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d + (bH_uH_d + \mathrm{c.c.})\right)
\end{aligned}
$$

Majorana Gaugino masses

Holomorphic soft couplings

Non-holomorphic soft masses

The non-standard soft parameters

- Dirac Gaugino Masses
- non-holomorphic scalar cubic
- etc..

Framework of Dirac Gaugino Fox, Nelson, Weiner (2002)

Enlarging the gauge sector to N=2 SUSY,
but remaining the matter sector N=1 SUSY (for chiral gauge theory).

$\mathcal{N}=2$

A^a_μ, λ^a Gauge multiplets

ϕ^a, ψ^a Adjoint multiplets

$\mathcal{N}=1$

Quark, Lepton multiplets

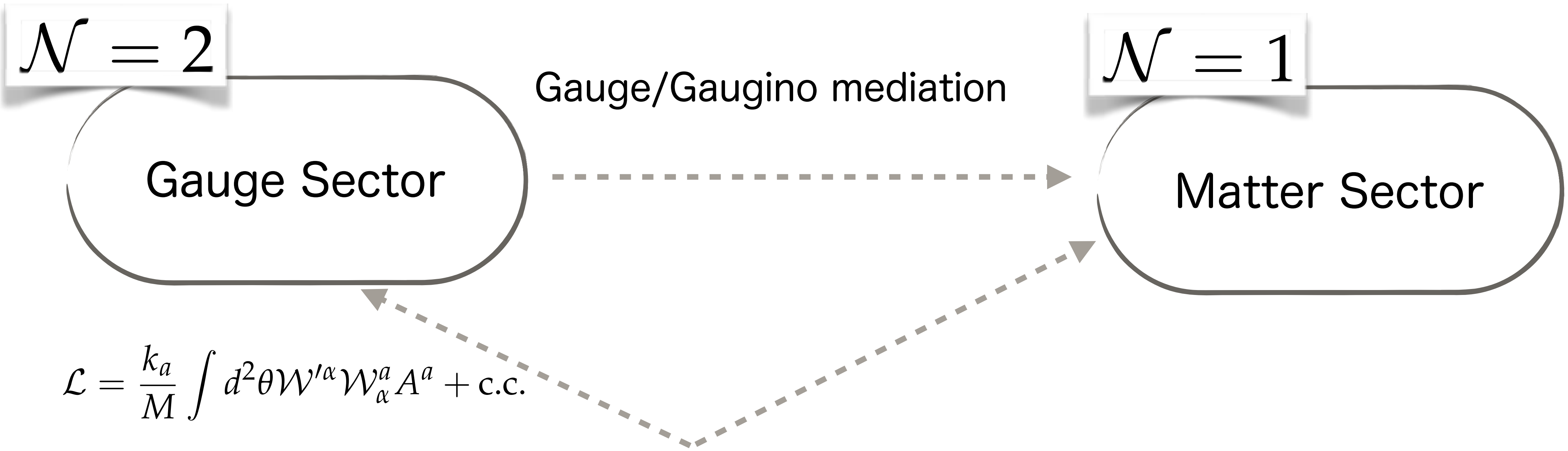
Higgs multiplets?

Realization

- Partially broken global SUSY (Hughes, Polchinski,1986)?
- Phenomenological 5D N=1 SUSY?

Framework of Dirac Gaugino

SUSY Breaking (example: D-term breaking)



SUSY breaking is triggered by D-term of additional U(1) gauge superfield

Scalar potential in SUSY $\quad V = \frac{1}{2} D^a D^a + \sum_i |F_i|^2$

Features of Dirac Gaugino

Fox, Nelson, Weiner (2002)

- Next supersymmetric extension of the standard model
- Radiatively finite soft masses (supersoftness)
  -> insensitive to the UV physics
- Evading the collider constraint (Kribs&A.Martin 2012)
- no Fine-tuning for the electro-weak scale
- However, there are several problems
  (several extensions are proposed in order to avoid these problems)

Contents

- Introduction
- Dirac gaugino masses from F-term VEVs
- Other Lagrangian terms and model-building criteria
- Renormalization group running effects

Dirac Gaugino Masses from F-term VEVs

Minimal scenario (Dirac gaugino masses from D-term VEV)

P.J.Fox, A.E.Nelson,N.Weiner (2002)

In hidden sector, we assume the presence of an hidden U(1)'

$$\mathcal{L} = \frac{k_a}{M}\int d^2\theta \mathcal{W}'^{\alpha}\mathcal{W}^a_{\alpha}A^a + \text{c.c.}$$

M: mediation scale

W': field strength of hidden U(1)

A: adjoint chiral superfield

SUSY breaking (D-term) VEV

$$\mathcal{W}'^{\alpha} = \langle D\rangle\,\theta^{\alpha}$$

In terms of component fields,

$$\mathcal{L} = -m_{D_a}(\psi_a\lambda^a + \text{c.c.}) + \sqrt{2}m_{D_a}D^a(\phi^a + \phi^{a*}) + g_a D^a(\phi_i^* T^a\phi_i) + \frac{1}{2}D^a D^a$$

Dirac gaugino mass $\quad m_{D_a} = \dfrac{k_a\langle D\rangle}{\sqrt{2}M}$

Several problems for Dirac gaugino via D-term breaking

After integrating out D^a,

$$\mathcal{L} = -m_{D_a}(\psi_a \lambda^a + \text{c.c.}) \underline{- 2m_{D_a}^2 R^a R^a - 2g_a m_{D_a} R^a(\phi_i^* T^a \phi_i) - \frac{1}{2} g_a^2 (\sum_i \phi_i^* T^a \phi_i)^2}$$

$$-\frac{1}{2}\left(2m_{D_a} R^a + g_a(\phi_i^* T^a \phi_i)\right)^2$$

R^a and I^a are the real and imaginary part of adjoint scalar,

$$R^a \equiv \frac{1}{\sqrt{2}}(\phi^a + \phi^{a*})$$

$$I^a \equiv \frac{-i}{\sqrt{2}}(\phi^a - \phi^{a*})$$

Problems

- massless I^a and no appearance of SUSY breaking interaction of I^a
- no scalar quartic coupling below the R^a mass scale

  (= Effective theory with no Higgs quartic coupling)

We expected that the higher-dim. op.

$$\mathcal{L} = \frac{k_a^{\mathrm{LT}}}{M^2}\int d^2\theta \mathcal{W}'^{\alpha}\mathcal{W}'_{\alpha}A^a A^a + \text{c.c.} = -k_a^{\mathrm{LT}}\frac{\langle D\rangle^2}{M^2}\left(I^a I^a - R^a R^a\right)$$

gives additional contribution to adjoint scalar masses.

Even if there exists this term “lemon-twist operator”,

there remain several problems..

Problems

When $k_a^{\mathrm{LT}} < 0$ tachyonic I^a if no additional contribution.

When $k_a^{\mathrm{LT}} > k_a^2$ tachyonic R^a if no additional contribution.

Simple UV completions may have tachyonic R^a w/o fine-tuning.

Fox, Nelson, Weiner (2002)
Benakli, Goodsell (2010)
Csaki, Goodman, Pavesi, Shirman (2013)

Dirac gaugino via F-term breaking

In this paper, the Dirac gaugino masses come from an F-term VEV

$$X = \theta^2 \langle F \rangle$$

The Lagrangian term

$$\mathcal{L} = -\frac{c_a^{(1)}}{\sqrt{2}M^3}\int d^4\theta X^\dagger X \mathcal{W}^{a\alpha}\nabla_\alpha A^a = -m_{D_a}\psi^a\lambda^a$$

$$m_{D_a} = \frac{c_a^{(1)}|\langle F\rangle|^2}{M^3}$$

For simplicity, <F> is assumed to be real.

Feature

- Non-holomorphic source for Dirac gaugino masses
- Dirac gaugino masses are not accompanied by the supersoft scalar couplings

Contents

Other Lagrangian terms & Model building criteria

1/M3 suppressed terms can be subdominant.

Even if X carries a conserved charge,

non-holomorphic scalar masses are generated by

$$\mathcal{L} = -\frac{k_{ij}}{M^2}\int d^4\theta X^\dagger X \Phi_i^\dagger e^V \Phi_j$$

(Masses for squarks, sleptons, and MSSM Higgs)

Holomorphic scalar masses for vector-like multiplets also arise from

$$\mathcal{L} = -\frac{1}{M^2}\int d^4\theta X^\dagger X (k_{AA} A^a A^a + k_{H_u H_d} H_u H_d)$$

These mass scales $m \sim \langle F \rangle / M$

Naive estimation,

Gaugino masses ~ 1TeV and couplings k ~ O(1)

Then, $m \sim \sqrt{M \cdot m_{D_a}} \sim 10^{11}\mathrm{GeV}$ (if $M \sim M_{\mathrm{Pl}}$)

Split type SUSY breaking

However,
we adopt SUSY as the solution of the hierarchy problem.

$\Rightarrow$ $1/M^2$ terms are forbidden or suppressed by any mechanism

Symmetry?

$$\mathcal{L} = -\frac{c_a^{(1)}}{\sqrt{2}M^3}\int d^4\theta X^\dagger X \mathcal{W}^{a\alpha}\nabla_\alpha A^a \qquad \mathcal{L} = -\frac{k_{ij}}{M^2}\int d^4\theta X^\dagger X \Phi_i^\dagger e^V \Phi_j$$

Small M?

If mediation scale M is small, the scalar mass squared can be light

$$m \sim \sqrt{M \cdot m_{D_a}}$$

However, the adjoint or messenger multiplets also have light mass

$\Rightarrow$ Spoiling the perturbative coupling unification

(Deconstructing) gaugino mediation?

Non-holomorphic scalar squared masses are highly suppressed
compared to the Dirac gaugino masses.

Model-building Criteria

(i) X carries a conserved charge.

Forbidding the term $\mathcal{L} = -\frac{1}{M}\int d^2\theta\, X\, \mathcal{W}^{a\alpha}\mathcal{W}^a_\alpha + \text{c.c.}$

(ii) All int. terms btw spurion X, X† and MSSM sector are suppressed by 1/M^3.

(iii) Spurion interactions respect to the (approx.) flavor symmetry

(iv) v.s. Anomaly-mediated contribution

Assumption: the anomaly-mediated gaugino masses are sub-dominant.

$$M^{\text{AMSB}} \sim \beta \frac{\langle F \rangle}{M_{\text{Pl}}} \lesssim \frac{\langle F \rangle^2}{M^3} \sim m_D$$

and we impose

$$m_D \sim 1\,\text{TeV} \quad \Rightarrow \quad M \lesssim 10^{(12-13)}\,\text{GeV}$$

Model-building Criteria

Comment on the criteria

- SUSY breaking is communicated at a scale below the Planck scale

  Mediation scale $M \lesssim 10^{(12-13)}\,\mathrm{GeV}$

- The author admits that:
  “I don't know any UV completion that guarantees all of these criteria”

Other Lagrangian terms

In general, the $1/M^3$ suppressed terms

$$\mathcal{L} = -\frac{c_a^{(1)}}{\sqrt{2}M^3}\int d^4\theta X^\dagger X \mathcal{W}^{a\alpha}\nabla_\alpha A^a$$

$$\mathcal{L} = \frac{c_a^{(2)}}{\sqrt{2}M^3}\int d^4\theta X^\dagger X A^a \nabla_\alpha \mathcal{W}^{a\alpha}$$

$$\mathcal{L} = -\frac{c_a^{(3)}}{2M^3}\int d^4\theta X^\dagger X \mathcal{W}^{a\alpha}\mathcal{W}^a_\alpha$$

$$\mathcal{L} = -\frac{c_a^{(4)}}{4M^3}\int d^4\theta X^\dagger X \nabla^\alpha A^a \nabla_\alpha A^a$$

$$\mathcal{L} = -\frac{c_a^{(5)}}{4M^3}\int d^4\theta X^\dagger X A^a \nabla^\alpha \nabla_\alpha A^a$$

$$\mathcal{L} = -\frac{c_a^{(6)}}{4M^3}\int d^4\theta X^\dagger X A^{a*}(e^V \nabla^\alpha \nabla_\alpha A)^a$$

$$\mathcal{L} = -\frac{c^{(7)}}{2M^3}\int d^4\theta X^\dagger X \nabla^\alpha H_u \nabla_\alpha H_d$$

$$\mathcal{L} = -\frac{c^{(8)}}{4M^3}\int d^4\theta X^\dagger X H_u \nabla^\alpha \nabla_\alpha H_d$$

$$\mathcal{L} = -\frac{c^{(9)}}{4M^3}\int d^4\theta X^\dagger X H_d \nabla^\alpha \nabla_\alpha H_u$$

$$\mathcal{L} = -\frac{c^{(10)}}{4M^3}\int d^4\theta X^\dagger X H_u^* e^V \nabla^\alpha \nabla_\alpha H_u$$

$$\mathcal{L} = -\frac{c^{(11)}}{4M^3}\int d^4\theta X^\dagger X H_d^* e^V \nabla^\alpha \nabla_\alpha H_u$$

Other Lagrangian terms

In general, the $1/M^3$ suppressed terms

$$\mathcal{L} = -\frac{c_a^{(1)}}{\sqrt{2}M^3}\int d^4\theta X^\dagger X \mathcal{W}^{a\alpha}\nabla_\alpha A^a$$

Dirac Gaugino mass

$$\mathcal{L} = \frac{c_a^{(2)}}{\sqrt{2}M^3}\int d^4\theta X^\dagger X A^a \nabla_\alpha \mathcal{W}^{a\alpha}$$

(Optional) Supersoft interaction

$$\mathcal{L} = -\frac{c_a^{(3)}}{2M^3}\int d^4\theta X^\dagger X \mathcal{W}^{a\alpha}\mathcal{W}^a_\alpha$$

$$\mathcal{L} = -\frac{c_a^{(4)}}{4M^3}\int d^4\theta X^\dagger X \nabla^\alpha A^a \nabla_\alpha A^a$$

Majorana Gaugino/adj. Fermion masses

$$\mathcal{L} = -\frac{c_a^{(5)}}{4M^3}\int d^4\theta X^\dagger X A^a \nabla^\alpha \nabla_\alpha A^a$$

$$\mathcal{L} = -\frac{c_a^{(6)}}{4M^3}\int d^4\theta X^\dagger X A^{a*}(e^V \nabla^\alpha \nabla_\alpha A)^a$$

Scalar Adjoint Mass

Other Lagrangian terms

In general, the $1/M^3$ suppressed terms

Solution to μ-problem

Nelson-Roy type μ parameters

MSSM scalar couplings

(A-terms and B_μ term)

$$\mathcal{L} = -\frac{c^{(7)}}{2M^3}\int d^4\theta X^\dagger X \nabla^\alpha H_u \nabla_\alpha H_d$$

$$\mathcal{L} = -\frac{c^{(8)}}{4M^3}\int d^4\theta X^\dagger X H_u \nabla^\alpha \nabla_\alpha H_d$$

$$\mathcal{L} = -\frac{c^{(9)}}{4M^3}\int d^4\theta X^\dagger X H_d \nabla^\alpha \nabla_\alpha H_u$$

$$\mathcal{L} = -\frac{c^{(10)}}{4M^3}\int d^4\theta X^\dagger X H_u^* e^V \nabla^\alpha \nabla_\alpha H_u$$

$$\mathcal{L} = -\frac{c^{(11)}}{4M^3}\int d^4\theta X^\dagger X H_d^* e^V \nabla^\alpha \nabla_\alpha H_u$$

Other Lagrangian terms

Comment

- Not impose an exact U(1) R symmetry

  otherwise all but $c_a^{(1)}$ and $c_a^{(2)}$ vanish
- For simplicity, not consider terms of the form

$$\frac{1}{M^3}\int d^4\theta X^\dagger X\Phi^3 + \text{c.c.}$$

$$\frac{1}{M^3}\int d^4\theta X^\dagger X\Phi^2\Phi^\dagger + \text{c.c.}$$

  where Φ denotes adj. and Higgs chiral superfields.
- Neglect the effects of any superpotential terms not involving MSSM quark and lepton superfields
  - no supersymmetric μ-term
  - no superpotential couplings of adjoints

Optional supersoft interactions

$$\mathcal{L} = \frac{c_a^{(2)}}{\sqrt{2}M^3} \int d^4\theta X^\dagger X A^a \nabla_\alpha \mathcal{W}^{a\alpha}$$ → (Optional) Supersoft interaction

$$\mathcal{L} = m_{R_a} D^a R^a, \qquad \begin{cases} R^a = \dfrac{1}{\sqrt{2}}(\phi^a + \phi^{a*}) \\ m_{R_a} = \dfrac{2c_a^{(2)} \langle F \rangle^2}{M^3} \end{cases}$$

After integrating out the auxiliary fields,

$$\mathcal{L} = -\frac{1}{2}\left(m_{R_a} R^a + g_a(\phi_i^* T^a \phi_i)\right)^2$$

Solution to the missing (scalar)^4 coupling

⇨ If m_{Ra} is smaller than m_{Da},
(scalar)^4 coupling can appear in the superset case

General gaugino masses

$$\mathcal{L} = -\frac{c_a^{(3)}}{2M^3}\int d^4\theta X^\dagger X \mathcal{W}^{a\alpha}\mathcal{W}^a_\alpha$$

$$\mathcal{L} = -\frac{c_a^{(4)}}{4M^3}\int d^4\theta X^\dagger X \nabla^\alpha A^a \nabla_\alpha A^a$$

Majorana Gaugino/adj. Fermion masses

$$\mathcal{L} = -\frac{1}{2}M_a\lambda^a\lambda^a - \frac{1}{2}\mu_a\psi^a\psi^a + \text{c.c.}$$

$$M_a = \frac{c_a^{(3)}\langle F\rangle^2}{M^3}$$

$$\mu_a = \frac{c_a^{(4)}\langle F\rangle^2}{M^3}$$

- Gluino will be Dirac-like (Majorana-like) when $|c_a^{(3)}|,|c_a^{(4)}| \ll |c_a^{(1)}|$ ($|c_a^{(3)}|,|c_a^{(4)}| \gg |c_a^{(1)}|$)
- For EW gauginos, more complicated due to mixing with Higgsino

Scalar Adjoint Mass

$$\mathcal{L} = -\frac{c_a^{(5)}}{4M^3}\int d^4\theta X^\dagger X A^a \nabla^\alpha \nabla_\alpha A^a$$

$$\mathcal{L} = -\frac{c_a^{(6)}}{4M^3}\int d^4\theta X^\dagger X A^{a*} (e^V \nabla^\alpha \nabla_\alpha A)^a$$

Scalar Adjoint Mass

From 1st op.

$$\mathcal{L} = m_{S_a} \phi^a F_a + \text{c.c.} \to -|m_{S_a}|^2 |\phi^a|^2 = -\frac{1}{2}|m_{S_a}|^2 (I^a I^a + R^a R^a)$$

This gives a common positive contribution to the adj. scalar @ tree-level.

$$m_{S_a} = \frac{c_a^{(5)} \langle F \rangle^2}{M^3}$$

R^a and I^a split due to the contribution from $c_a^{(2)}$ as mentioned.

Scalar Adjoint Mass

$$\left.\begin{aligned}\mathcal{L} &= -\frac{c_a^{(5)}}{4M^3}\int d^4\theta X^\dagger X A^a \nabla^\alpha \nabla_\alpha A^a \\ \mathcal{L} &= -\frac{c_a^{(6)}}{4M^3}\int d^4\theta X^\dagger X A^{a*} (e^V \nabla^\alpha \nabla_\alpha A)^a\end{aligned}\right\} \rightarrow \text{Scalar Adjoint Mass}$$

From 1st and 2nd ops.

$$\mathcal{L} = (m_{S_a}\phi^a + m'_{S_a}\phi^{a*})F_a + \text{c.c.} \rightarrow -(|m_{S_a}|^2 + |m'_{S_a}|^2)|\phi^a|^2 - (m_{S_a} m'^*_{S_a}\phi^{a2} + \text{c.c.})$$

$$m_{S_a} = \frac{c_a^{(5)} \langle F \rangle^2}{M^3}, \quad m'_{S_a} = \frac{c_a^{(6)} \langle F \rangle^2}{M^3}$$

This also gives positive semi-definite squared mass matrix:

Squared mass eigenvalues $\quad m^2 = (|m_{S_a}| \pm |m'_{S_a}|)^2$

Solution to μ-problem

Solution to μ-problem

Nelson-Roy type μ parameters

$$\mathcal{L} = -\frac{c^{(7)}}{2M^3}\int d^4\theta X^\dagger X \nabla^\alpha H_u \nabla_\alpha H_d$$

$$\mathcal{L} = -\frac{c^{(8)}}{4M^3}\int d^4\theta X^\dagger X H_u \nabla^\alpha \nabla_\alpha H_d$$

$$\mathcal{L} = -\frac{c^{(9)}}{4M^3}\int d^4\theta X^\dagger X H_d \nabla^\alpha \nabla_\alpha H_u$$

Higgsino mass term

$$\mathcal{L} = -\tilde{\mu}\widetilde{H}_u\widetilde{H}_d + \text{c.c.} \qquad \tilde{\mu} = \frac{c^{(7)}\langle F\rangle^2}{M^3}$$

Higgs mass terms

MSSM-like non-holomorphic scalar cubic

$$\begin{cases} \mathcal{L} = \mu_u H_u F_{H_d} + \text{c.c.} \\ \mathcal{L} = \mu_d H_d F_{H_u} + \text{c.c.} \end{cases} \rightarrow \quad \mathcal{L} = -|\mu_u|^2|H_u|^2 - |\mu_d|^2|H_d|^2 + \cdots$$

$$\begin{cases} \mu_u = \dfrac{c^{(8)}\langle F\rangle^2}{M^3} \\ \mu_d = \dfrac{c^{(9)}\langle F\rangle^2}{M^3} \end{cases}$$

$\tilde{\mu}$ is independent of the Higgs scalar potential

Higgsino can be decoupled from EW-scale naturalness

Solution to μ-problem

Holomorphic scalar squared mass

$$\mathcal{L} = -bH_uH_d + \text{c.c.}$$

can be given rise to by the RG evolution from $\widetilde{\mu}$

⇨ EWSB occurs if b is sufficiently large
i.e. Heavy higgsino scenario is preferred

This also arises from the other Lagrangian -> Next

MSSM Scalar (Holomorphic) Coupling

MSSM scalar couplings
(A-terms and B$_\mu$term)

$$\mathcal{L} = -\frac{c^{(8)}}{4M^3}\int d^4\theta X^\dagger X H_u \nabla^\alpha \nabla_\alpha H_d$$

$$\mathcal{L} = -\frac{c^{(9)}}{4M^3}\int d^4\theta X^\dagger X H_d \nabla^\alpha \nabla_\alpha H_u$$

$$\mathcal{L} = -\frac{c^{(10)}}{4M^3}\int d^4\theta X^\dagger X H_u^* e^V \nabla^\alpha \nabla_\alpha H_u$$

$$\mathcal{L} = -\frac{c^{(11)}}{4M^3}\int d^4\theta X^\dagger X H_d^* e^V \nabla^\alpha \nabla_\alpha H_u$$

Furthermore, if we include the terms prop. to c$^{(10)}$ and c$^{(11)}$,

$$\mathcal{L} = (\mu_u H_u + \mu_d' H_d^*)F_{H_d} + (\mu_d H_d + \mu_u' H_u^*)F_{H_u} + \text{c.c.}$$

$$\begin{cases} \mu_u' = \dfrac{c^{(10)}\langle F\rangle^2}{M^3} \\ \mu_d' = \dfrac{c^{(11)}\langle F\rangle^2}{M^3} \end{cases}$$

the holomorphic scalar couplings are generated after integrating out Fs

$$\mathcal{L} = -\left(H_u \widetilde{\bar{u}}\mathbf{a}_u \widetilde{Q} - H_d \widetilde{\bar{d}}\mathbf{a}_d \widetilde{Q} - H_d \widetilde{\bar{e}}\mathbf{a}_e \widetilde{L} + bH_u H_d + \text{c.c}\right)$$
$$-\left(|m_{H_u}|^2 |H_u|^2 + |m_{H_d}|^2 |H_d|^2\right)$$

MSSM Scalar (Holomorphic) Coupling

The holomorphic scalar couplings are generated after integrating out Fs

$$
\begin{aligned}
\mathcal{L} = &- \left(H_u \tilde{\bar{u}} \mathbf{a}_u \tilde{Q} - H_d \tilde{\bar{d}} \mathbf{a}_d \tilde{Q} - H_d \tilde{\bar{e}} \mathbf{a}_e \tilde{L} + b H_u H_d + \mathrm{c.c}\right) \\
&- \left(|m_{H_u}|^2 |H_u|^2 + |m_{H_d}|^2 |H_d|^2\right)
\end{aligned}
$$

Scalar squared masses and B$_\mu$-term

$$
\begin{cases}
|m_{H_u}|^2 &= |\mu_u|^2 + |\mu'_u|^2 \\
|m_{H_d}|^2 &= |\mu_d|^2 + |\mu'_d|^2 \\
b &= \mu_u \mu'^*_d + \mu_d \mu'^*_u
\end{cases}
$$

A-term

$$
\begin{cases}
\mathbf{a}_u &= \mu'^*_u \mathbf{Y}_u \\
\mathbf{a}_d &= \mu'^*_d \mathbf{Y}_d \\
\mathbf{a}_e &= \mu'^*_d \underline{\mathbf{Y}_e}
\end{cases}
$$

Contents

Renormalization group running effects

Gauge coupling unification

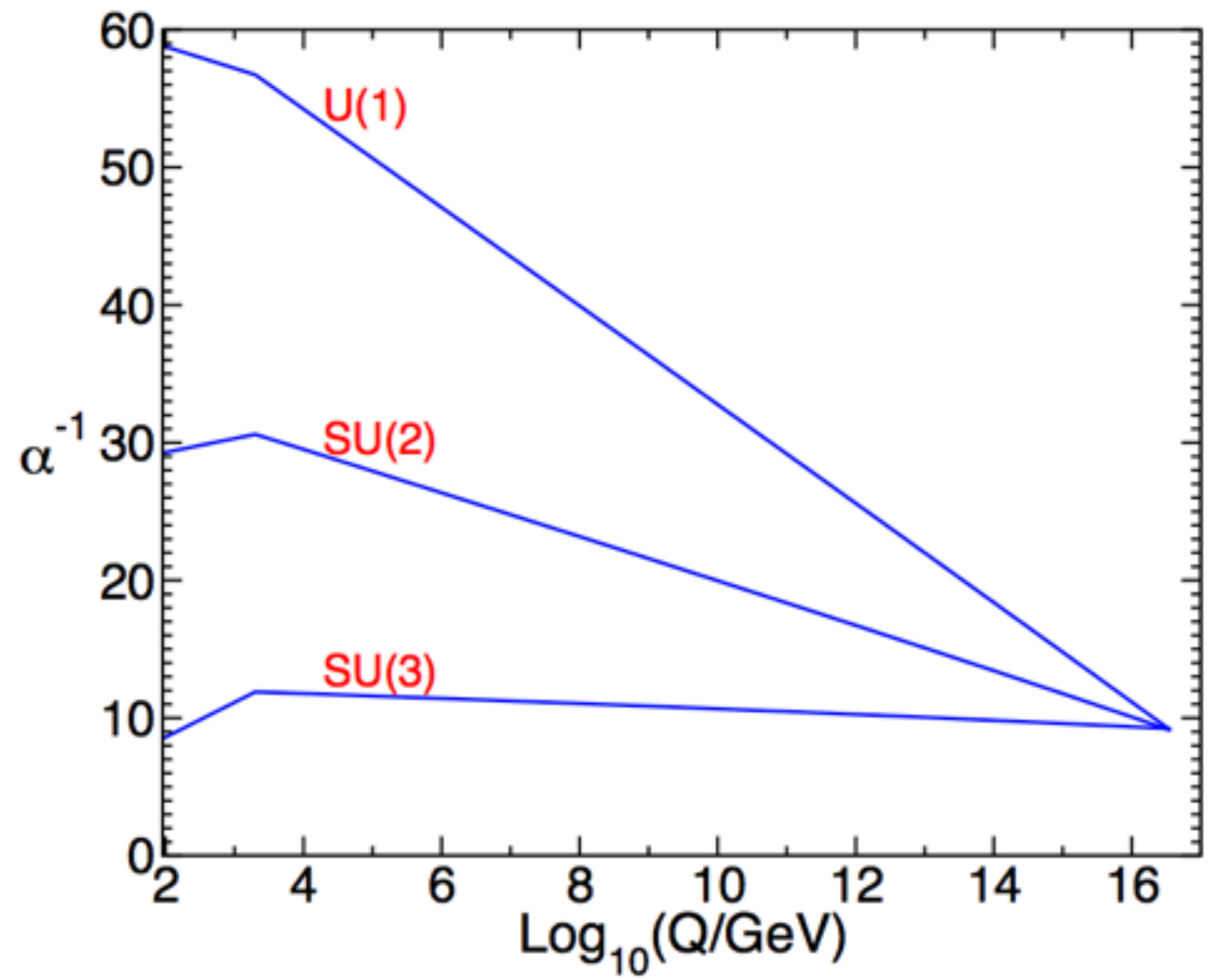
If adjoint multiplets are light (~TeV),

gauge couplings do not unify
(in minimal setup)

By adding vector-like multiplets

$$L+\overline{L}+2[E+\overline{E}]$$

the coupling unification is realized
even if adjs. are light.



MSSM+adj.+vector-like (Mass~2TeV)
with 2-loop RGEs

IR Fixed Point

Supersoft case

> The scalar masses receive no div. (even log div.)
> i.e. the scalar masses don't evolve via RGEs.

Infrared Fixed Point (IRFP)

F-term Dirac gaugino model: more general case

Question:
Is IRFP (Supersoft case) attractive and stable @ IR ?

Consider the Lagrangian

$$\mathcal{L} = -\left[\cancel{\frac{1}{2}M_a\lambda^a\lambda^a} + \cancel{\frac{1}{2}\mu_a\psi^a\psi^a} + m_{D_a}\psi^a\lambda^a + \sqrt{2}g_a m_{D_a}N_a\phi^a(\phi_i^* T^a\phi_i) + \frac{1}{2}b_a(\phi^a)^2 + \text{c.c.}\right] - m_a^2|\phi^a|^2$$

pure Dirac gaugino case

Define

$$m_a^2 \equiv 2E_a|m_{D_a}|^2, \quad b_a \equiv 2B_a m_{D_a}^2$$

Stability of IRFP

$$\mathcal{L} = -\left[m_{D_a}\psi^a\lambda^a + \sqrt{2}g_a m_{D_a} N_a \phi^a(\phi_i^* T^a \phi_i) + B_a m_{D_a}(\phi^a)^2 + \text{c.c.}\right] - 2E_a|m_{D_a}|^2|\phi^a|^2$$

Supersoft case: (cf. D-term breaking)

$$\boxed{N_a = B_a = E_a = 1}$$

RGEs (Notation)

$$\frac{d\lambda}{d\ln\mu} \equiv \beta_\lambda = \frac{g_a^2}{16\pi^2} b_\lambda$$

$$\begin{aligned} b_{N_a} &= 4C(G)(N_a - 1) \\ b_{E_a} &= [2T_a(R_F)(N_a^2 - E_a) + 8C(G)(E_a - 1)] \\ b_{B_a} &= [2T_a(R_F)(N_a^2 - B_a) + 4C(G)(B_a - 1)] \end{aligned}$$

Properties

- N_1 doesn't run, N_2=1 and N_3=1 stable @ IR
- $E_1=N_1^2$, $B_1=N_1^2$ unstable @ IR
- E_3=1 stable @ IR
- B_3=1 & E_2=1 unstable @ IR

Is IRFP Attractive or not?

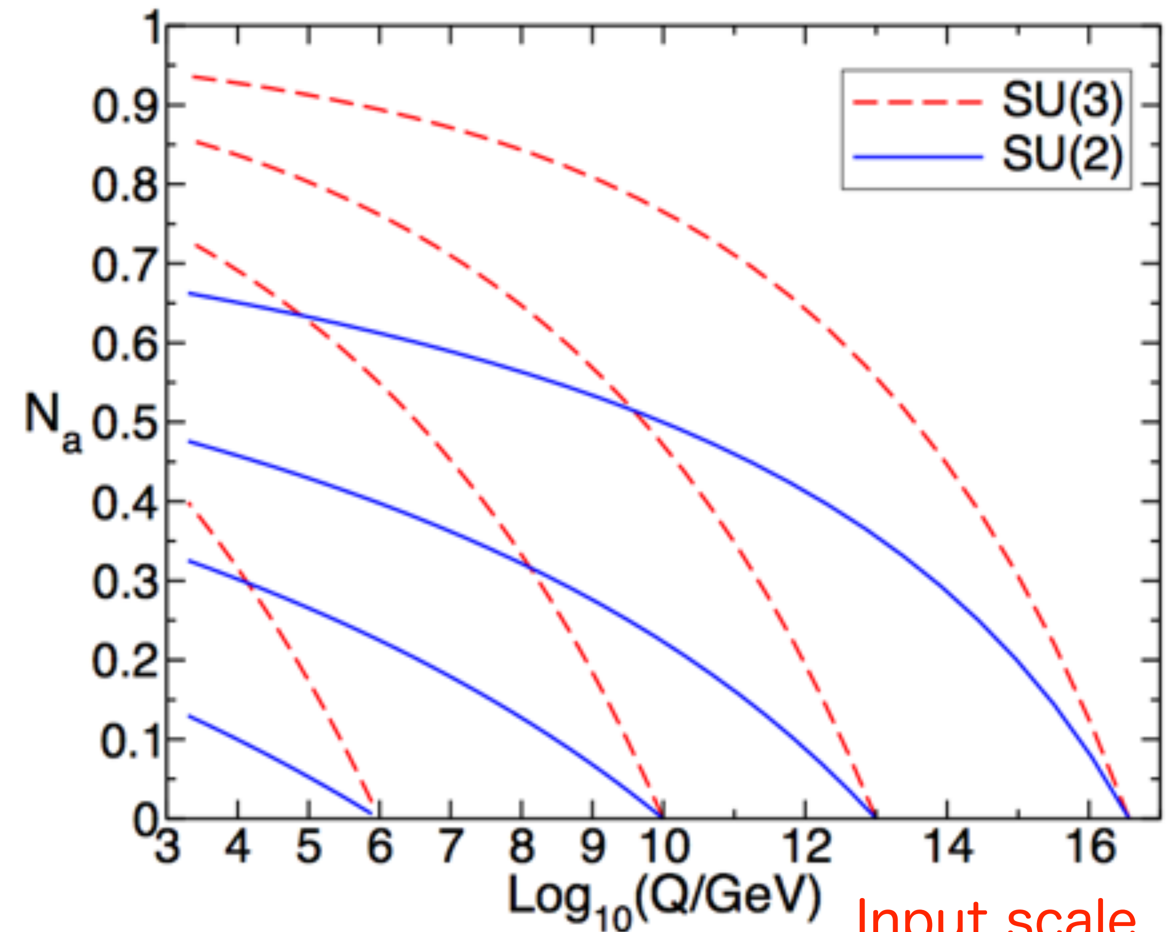
RGEs

$$\frac{d\lambda}{d\ln\mu} \equiv \beta_\lambda = \frac{g_a^2}{16\pi^2} b_\lambda$$

$$b_{N_a} = 4C(G)(N_a - 1)$$

Assumption:

$N_3 = N_2 = 0$ @ Input scale

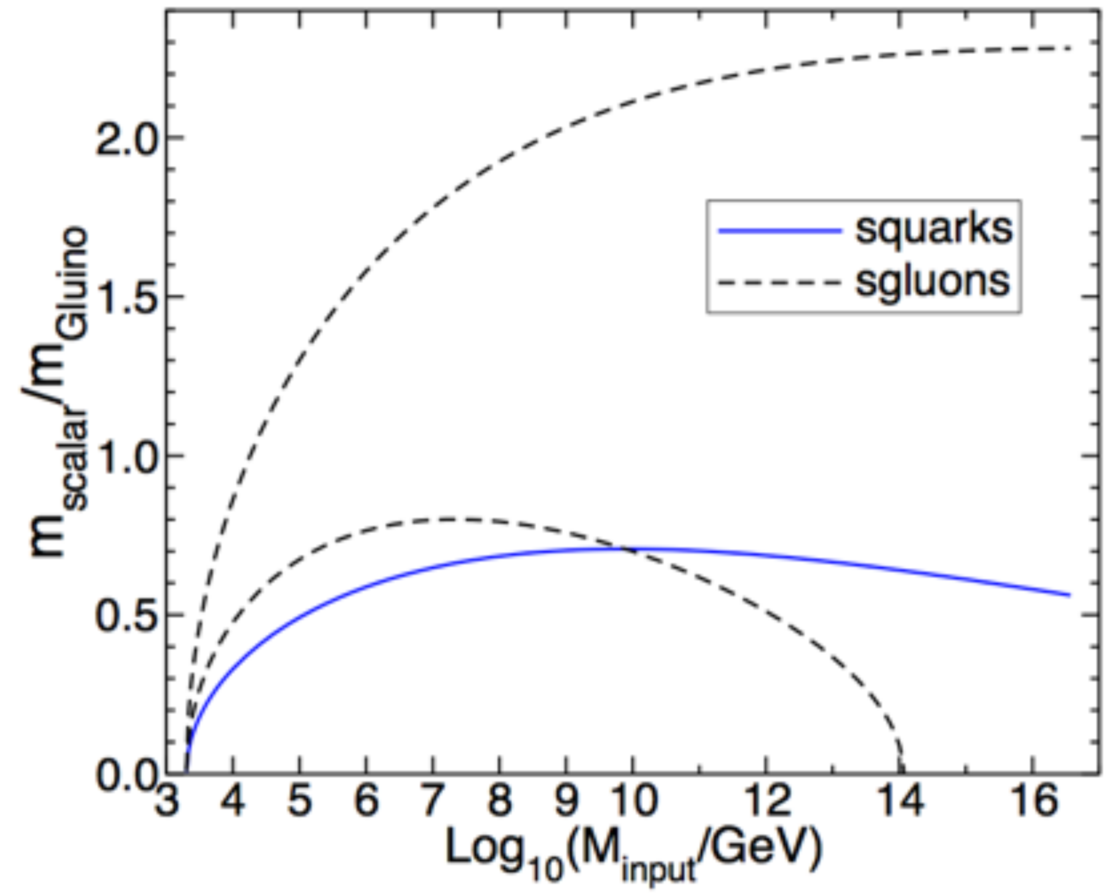


1-loop running of scalar cubic int.

- The attractive FP @N_3=1, N_2=1 is not actually approached
- SU(2) is less attractive than SU(3), due to Casimir invariant
- The input scale Q should be less than 10^{13}GeV, if AMSB contribution is smaller than Dirac Gaugino mass
- IRFP for U(1) is not attractive (N_1 doesn't run)

Scalar masses v.s. gluino mass

$$\frac{d(m^2)_i^j}{d\ln\mu} = \frac{g_a^2}{16\pi^2} 8C_a(i)\delta_i^j[(|N_a|^2-1)|m_{D_a}|^2 - |M_a|^2] + \cdots$$



$E_3=B_3=N_3=0$ @Input scale

- zero mass of adj. scalar
- no Majorana masses

- RG running is enough to generate sufficient squark and gluon masses (M_{input}~10^{10}GeV)
- Both sgluons masses: $(m_{sgluon})^2>0$ if $M_{input}<10^{14}$GeV.

Conclusions

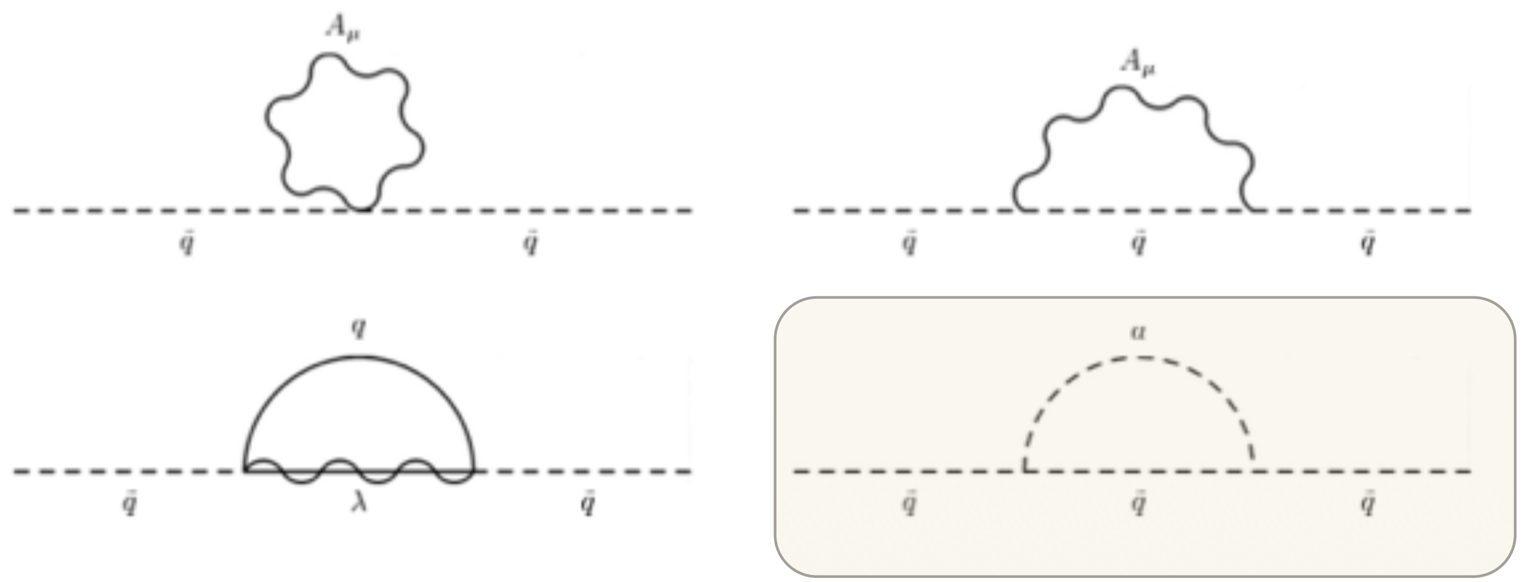
- We discussed the possibility of non-standard SUSY breaking and Gaugino masses via F-term breaking.
- In general, Dirac gaugino mass parameters need not be accompanied by superset scalar interactions.
- Both adjoint scalars have the positive squared mass: no tachyonic mode
- However, the supersoft mechanisms are diminished.
- The squarks and sleptons obtain positive RG corrections to their masses from gauginos, unlike in the supersoft case (no RG running).
- Can the model-building criteria be realized in a full UV completion?

Backups

Supersoftness

Fox, Nelson, Weiner (2002)

Squark masses arise from gauge/gaugino loops @1-loop



additional contribution

$$m^2 = 4g_i^2 C_i(r) \int \frac{d^4k}{(2\pi)^4}\left(\frac{1}{k^2} - \frac{1}{k^2 - m_i^2} + \frac{m_i^2}{k^2(k^2-\delta_i^2)}\right)$$
$$= \frac{C_i(r)\alpha_i m_i^2}{\pi}\ln\left(\frac{\delta_i^2}{m_i^2}\right)$$

δ : Adj. scalar mass

m: Dirac gaugino mass

Log div. for gaugino mass also cancels out log div. from adj. scalar mass

Supersoftness

Fox, Nelson, Weiner (2002)

Formally, the squark masses arising from D-term

$$\int d^2\theta \frac{(\mathcal{W}'\mathcal{W}')^\dagger(\mathcal{W}'\mathcal{W}')}{M^6} Q^\dagger Q$$

So, the divergent corrections arising from gauge sector should form as

$$\int d^2\theta \frac{\theta^2\bar{\theta}^2 m_D^4}{\Lambda^2} Q^\dagger Q$$

$$\mathcal{W}'^\alpha = \langle D \rangle \theta^\alpha$$

Λ: cutoff

$$m_D = \frac{D}{M}$$

Supersymmetric & gauge invariant counterterm for masses involving spurion.

Thus, the divergence should be vanished when Λ->∞

Nelson-Roy type μ-term Nelson, Roy (2015)

In D-term breaking Dirac gaugino scenario:

By adding the operators,

$$-\frac{k_{ij}}{4M}\int d^2\theta\overline{D}^2(D^\alpha V' D_\alpha \Phi_i)\Phi_j$$

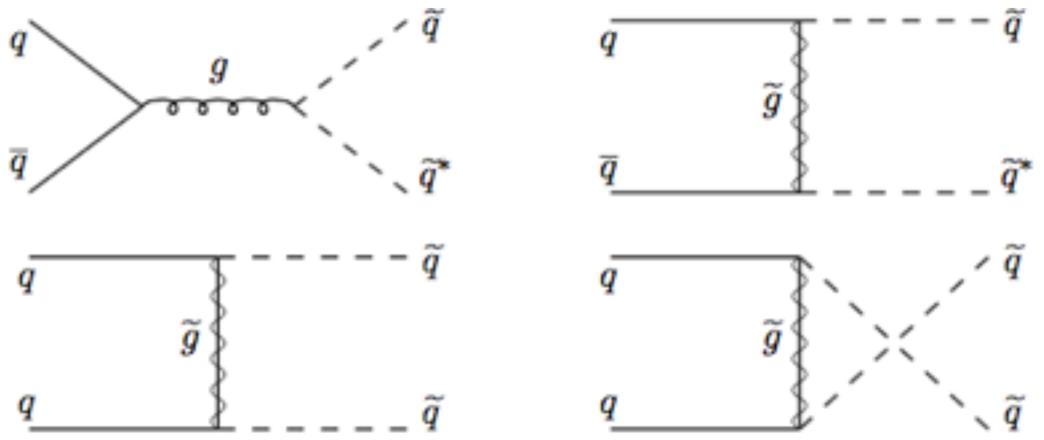
the scalar component of Φ_j obtain the mass term as

$$\mathcal{L} = \frac{\mu_{\phi_j}}{2}\tilde{\phi}_i\tilde{\phi}_j + |\mu_{\phi_j}|^2|\phi_j|^2 \qquad \mu_{\phi_j} = \frac{2k_{ij}D'}{M}$$

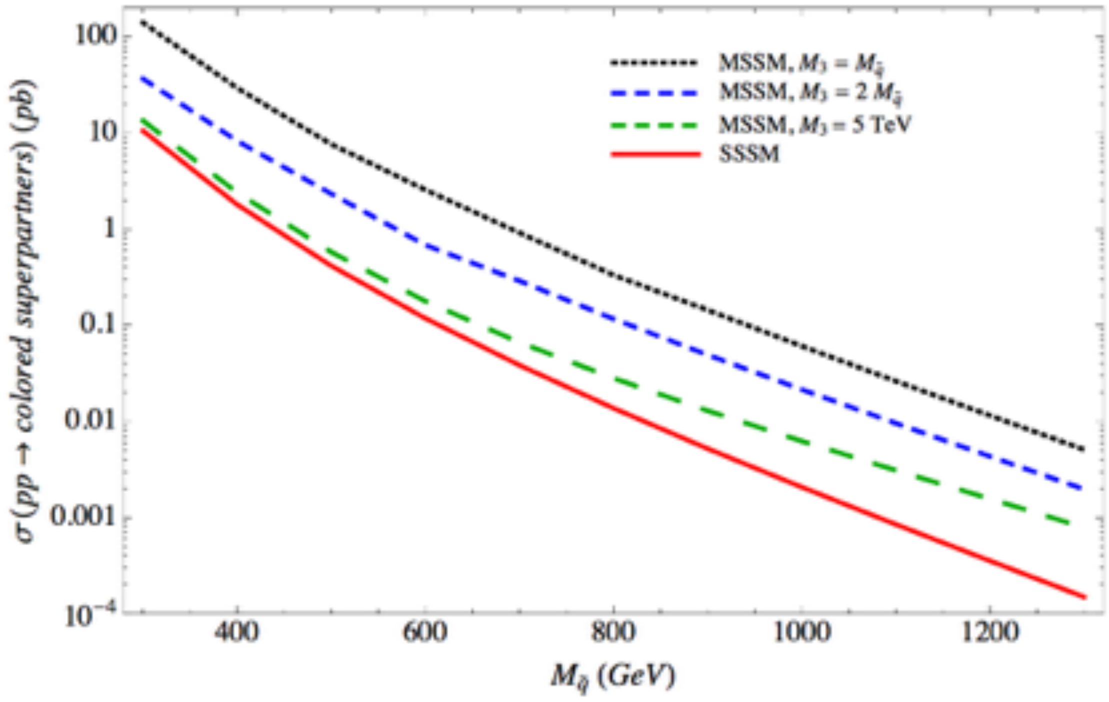
So, if k_{HuHd} and k_{HdHu} are non-zero,

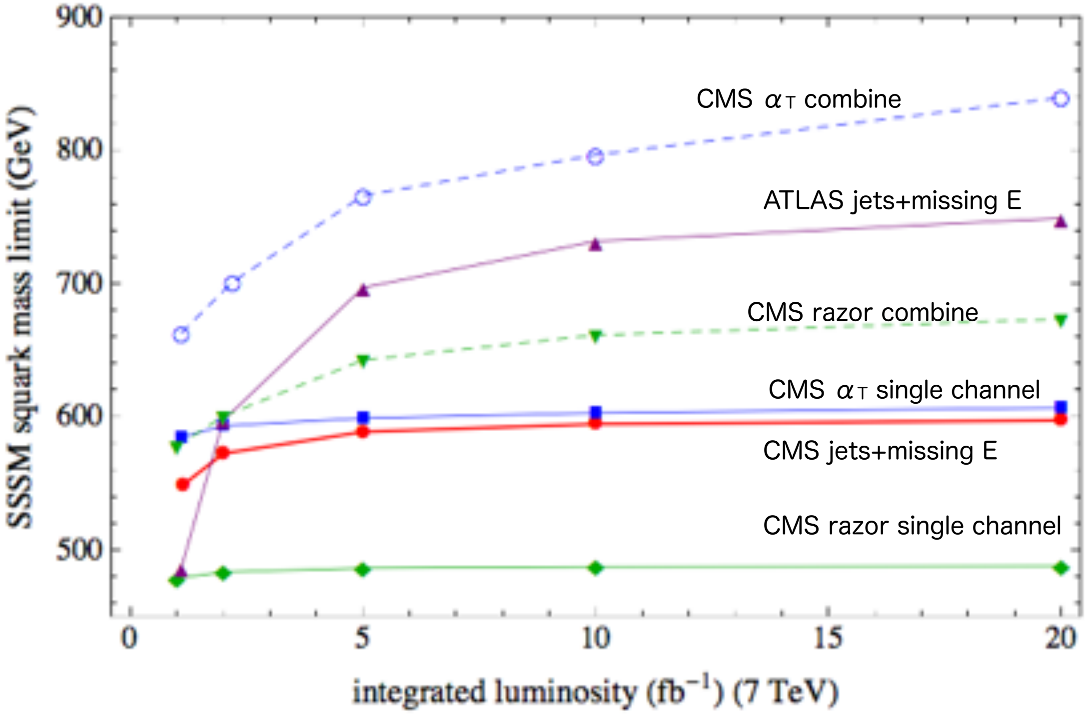
$$\mathcal{L} = \frac{1}{2}(\mu_u + \mu_d)\tilde{H}_u\tilde{H}_d + |\mu_u|^2|H_u|^2 + |\mu_d|^2|H_d|^2$$

Suppressed cross section



heavy gluino
=> Suppression of gluino mediated squark production





G.D.Kribs and A.Martin (2012)

RGEs

$$\frac{d\lambda}{d\ln\mu} \equiv \beta_\lambda = \frac{g_a^2}{16\pi^2} b_\lambda$$

Lagrangian

$$\mathcal{L} = -\left[\frac{1}{2}M_a\lambda^a\lambda^a + \frac{1}{2}\mu_a\psi^a\psi^a + m_{D_a}\psi^a\lambda^a + \sqrt{2}g_a m_{D_a} N_a\phi^a(\phi_i^* T^a\phi_i) + \frac{1}{2}b_a(\phi^a)^2 + \text{c.c.}\right] - m_a^2|\phi^a|^2$$

$$\begin{aligned}
b_{g_a} &= g_a[T_a(R_F) - 2C(G_a)] \\
b_{M_a} &= 2M_a[T_a(R_F) - 2C(G_a)] \\
b_{\mu_a} &= \mu_a[-4C(G_a)] \\
b_{m_{D_a}} &= m_{D_a}[T_a(R_F) - 4C(G_a)] \\
b_{N_a} &= 4C(G_a)(N_a - 1) \\
b_{m_a^2} &= 4[T_a(R_F)|N_a|^2|m_{D_a}|^2 - 2C(G_a)(|M_a|^2 + |\mu_a|^2 + 2|m_{D_a}|^2)] \\
b_{b_a} &= 4[T_a(R_F)N_a^2 m_{D_a}^2 - C(G_a)(2M_a\mu_a - 2m_{D_a}^2 - b_a)]
\end{aligned}$$

RGEs for IRFP analysis

$$\frac{d\lambda}{d\ln\mu} \equiv \beta_\lambda = \frac{g_a^2}{16\pi^2} b_\lambda$$

for U(1) (SU(5) normalization)

$$b_{N_1} = 0$$
$$b_{B_1} = \frac{6}{5}(11 + n_L + 2n_E)(N_1^2 - B_1)$$
$$b_{E_1} = \frac{6}{5}(11 + n_L + 2n_E)(N_1^2 - E_1)$$

for SU(2)

$$b_{N_2} = 2(N_2 - 1)$$
$$b_{B_2} = 2(7 + n_L)(N_2^2 - B_2) + 8(B_2 - 1)$$
$$b_{E_2} = 2(7 + n_L)(N_2^2 - E_2) + 16(E_2 - 1)$$

for SU(3)

$$b_{N_3} = 3(N_3 - 1)$$
$$b_{B_3} = 12(N_3^2 - 1)$$
$$b_{E_3} = 12(N_3^2 + E_3 - 2)$$

Properties

- N_1 doesn't run, N_2=1 and N_3=1 stable @ IR
- $E_1=N_1^2$, $B_1=N_1^2$ unstable @ IR
- E_3=1 stable @ IR
- B_3=1 & E_2=1 unstable @ IR