Work done in collaboration with ***Tuhin Roy****, arXiv:1501.03251*

Generalized supersoft supersymmetry breaking

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Fermilab theory seminar

Motivation: SUSY

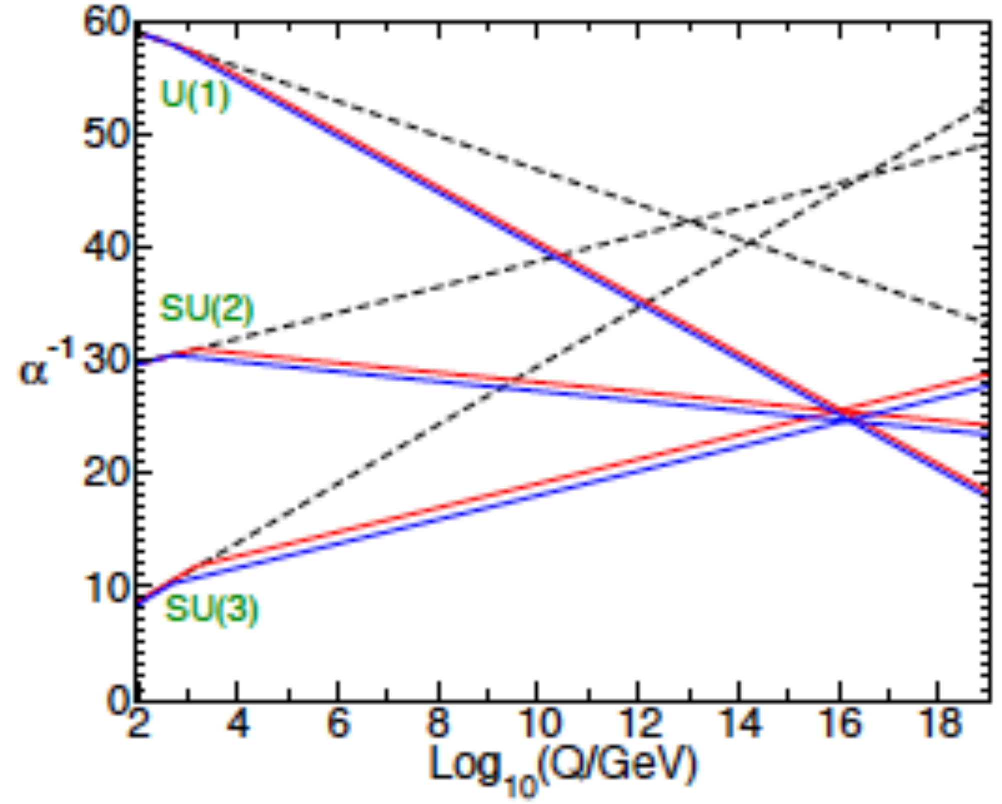
- Standard Model (to very high scale): Higgs mass squared is quadratically UV cutoff sensitive.
- Origin of Electroweak scale « Planck scale
  - Some mysterious finetuning we will never probe experimentally?
  - anthropic landscape?
- Softly Broken SUSY has reduced UV sensitivity (at most log UV)
  - electroweak scale related to SUSY breaking scale
  - dynamical SUSY breaking produces exponential hierarchy

SUSY=Path towards unification and computing “fundamental” parameters

(e.g. successful prediction $sin^2\theta_w$=0.23 in minimal susy unification)

From S. Martin

Figure 6.8: Two-loop renormalization group evolution of the inverse gauge couplings $\alpha_a^{-1}(Q)$ in the Standard Model (dashed lines) and the MSSM (solid lines). In the MSSM case, the sparticle masses are treated as a common threshold varied between 500 GeV and 1.5 TeV, and $\alpha_3(m_Z)$ is varied between 0.117 and 0.121.



(Top down)SUSY model building

- Three sectors: Visible, SUSY Breaking, and messenger

1. Integrate out messengers (could be Planck scale)
2. Renormalization group evolve effective operators to SUSY breaking scale

   hidden sector dynamics important! (Roy and Schmaltz)
3. replace hidden sector fields by vevs, obtain visible sector model with softly broken SUSY
4. Renormalization group evolve to weak scale

Breaking SUSY in the MSSM

Break SUSY in Hidden sector via non zero *F*-component of superfield(s) *S*

$$\langle S \rangle = \theta^2 F_S$$

"Messenger Scale" *M*

effective interactions between Hidden and visible sector from integrating out messengers produce soft supersymmetry breaking terms at scale $\frac{F_S}{M}$

S must be gauge singlet to allow Majorana gaugino mass from

$$\int d^2\theta \frac{F_S}{M} W_\alpha W^\alpha$$

Where should the superpartners be?

- Naturalness: opposite of fine-tuning
  - In softly broken susy, the parameters are at most log sensitive to short distances
    - computable log enhanced corrections dominate
    - meaningful to talk about size of renormalization
  - superpartner masses should lie in range where corrections to parameters do not require huge cancellations

Top Squarks

- Softly broken SUSY: Large (and negative) Higgs mass^2 corrections, sensitive to top squark mass^2
- Naturalness:
  - scale of top squark mass generation should not be really high
  - top squark should not be **too** heavy (~TeV)

$$\frac{dm_{h_u}^2}{d\ln\mu} \propto \frac{3y_t^2}{8\pi^2}(m_{h_u}^2 + m_{Q_3}^2 + m_{\bar{t}}^2 + A_t^2) + \ldots$$

Gluino

- Light top squark + naturalness implies a not too heavy gluino (~TeV)

$$\frac{dm^2_{Q_3}}{d\ln\mu} \propto -\frac{2g_3^2}{3\pi^2}(M_3^2) + \ldots$$

Higgsino

$$\int d^2\theta \mu H_u H_d \sim \int d^4\theta \frac{S}{M} H_u H_d$$

- SUSY: 2 Higgs doublet supermultiplets,

$$\langle S \rangle = \theta^2 F_S$$

  - 5 scalar bosons H±, H,h A

$$\mu = \frac{F_S}{M}$$

  - sufficiently large mass term required for Higgsinos
- "μ problem":
  - Higgsino mass term is a supersymmetric term, gives equal mass to the Higgs scalars and Higgsinos
  - Giudice-Masiero mechanism: susy breaking term gives identical result as μ term
  - making unwanted scalars and fermions heavy increases Higgs mass finetuning at tree level

➡ Naturalness: relatively light Higgsino (≪TeV)

Other superpartners:

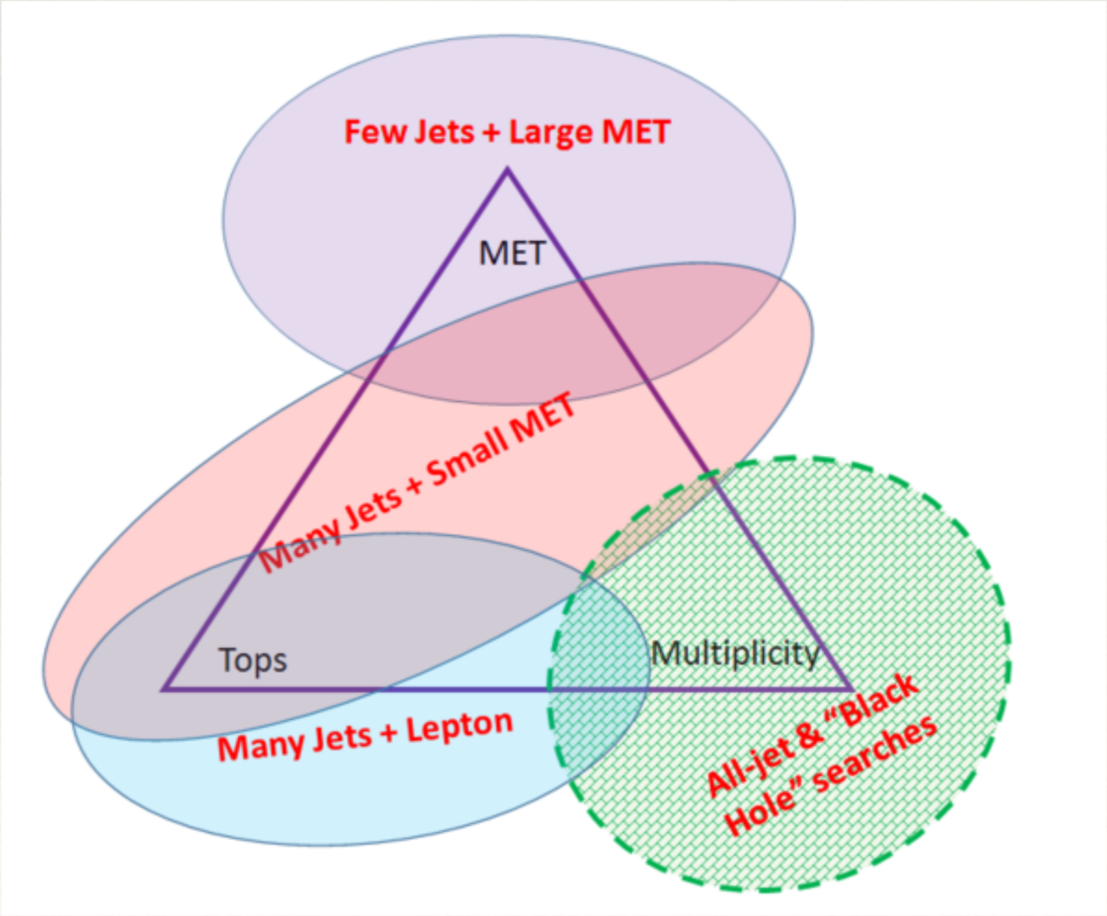
- sleptons, squarks (other than stop), electroweakinos
  - relatively small effect on Higgs mass
  - could be several TeV without finetuning
- much lower direct production rate
- Many (~100) free parameters!!

B

"We argue that combining just a handful of searches for new physics at Run I of the LHC is sufficient to exclude most supersymmetric extensions of the Standard Model **in which the gluino is kinematically accessible** and the spectrum is natural. "

–Jared A. Evans , Yevgeny Kats, David Shih, Matthew J. Strassler,

JHEP 1407 (2014) 101



Ingredients of EKSS argument

- Light-ish top squark (<~ 1 TeV) + naturalness implies kinematically accessible gluino (between 1 and 1.5 TeV in run I of LHC)
- Lighter Higgsino
- Various possibilities for other SUSY particles including hidden sector
- gluino decay chains involving one or more of
  - tops
  - MET
  - extra jets
  - leptons
  - bottom

"Supersoft" Supersymmetry Breaking

P.Fox, A.E.N., N. Weiner, JHEP 0208, 035 (2002), arXiv:hep-ph/0206096

- SUSY broken in hidden sector with no chiral singlets by Hidden sector D-term $\langle V \rangle = D' \theta^4$
- Dirac gaugino masses (requires additional chiral superfields A_i in Adjoint represention) $\int d^2\theta \frac{\bar{D}^2 D_\alpha V}{M} W_i^\alpha A_i$
- Dirac gaugino masses give **finite** correction to scalar masses squared! (protected by hidden sector gauge invariance)
- Gluinos can be naturally ~5 times heavier than squarks

Virtues of Heavy Dirac gauginos

- Flavor. In the original Supersoft theory, squark and slepton masses arise from finite, calculable, flavor universal radiative corrections
- no SUSY breaking scalar trilinears
- Graham D. Kribs, Erich Poppitz, Neal Weiner, Phys.Rev.D78:055010,2008, arXiv:0712.2039
  - Dirac gauginos allow $U(1)_R$ symmetry
  - Even with O(1) flavor violation, $U(1)_R$ suppresses FCNC and EDMs

More Virtues of heavy Dirac gluinos

- "super-safeness" G. Kribs, A. Martin, arXiv:1203.4821, Phys.Rev.D.85.115014
  - jets + MET searches do not severely constrain squark mass at LHC
  - no gluino cascades
  - no gluino contribution to squark production

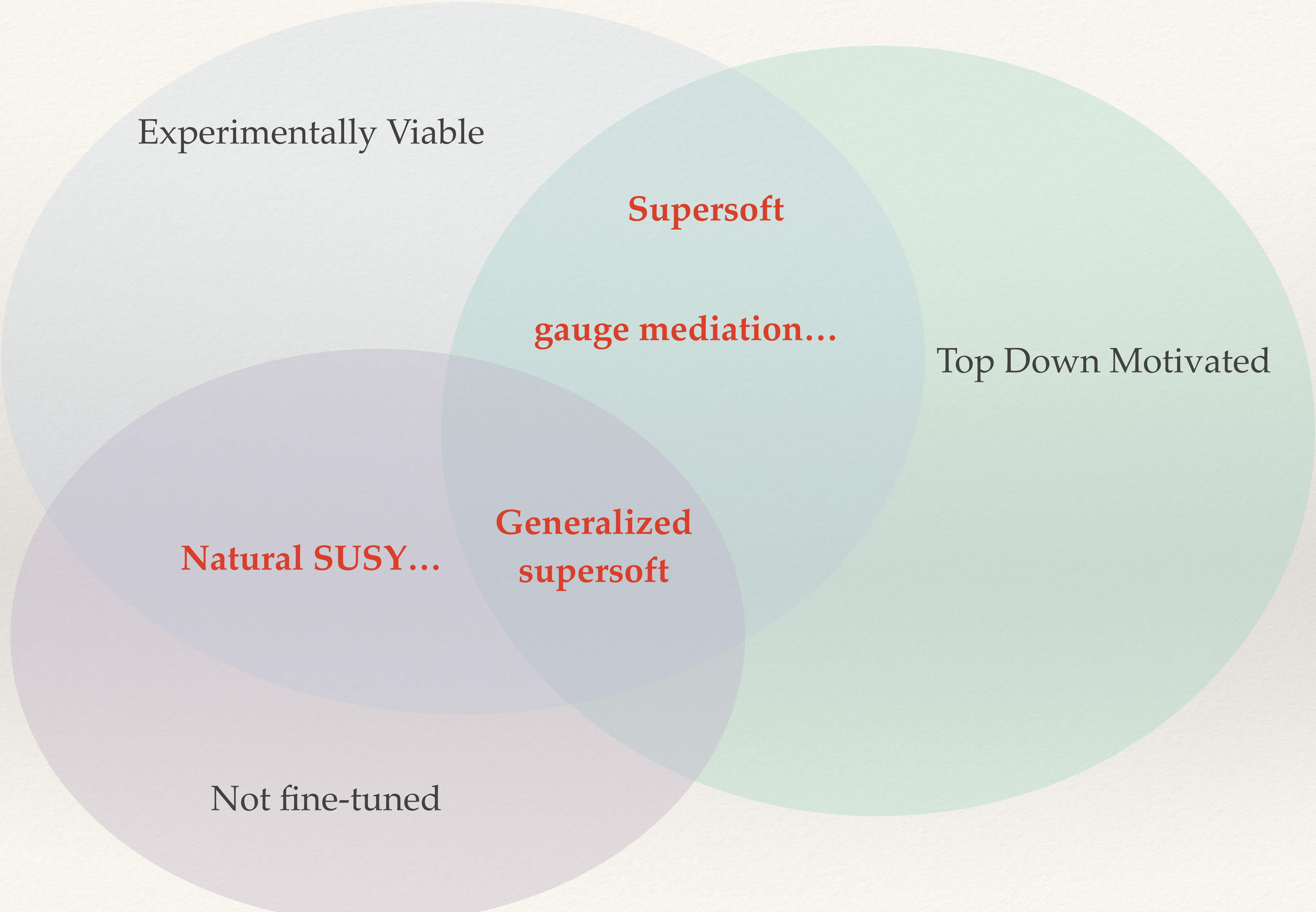
Supersoft issues:

- Landau pole below GUT scale with SU(5) unification
  - $SU(3)^3$ unification fine
- No Giudice-Masiero mechanism for μ term
- No quartic for Higgs from gauge D-term (hard to get Higgs to 125 GeV with just quartic from superpotential+ stop mass!)
- in gauge mediated supersoft, also generate “lemon twist” which can give vevs to scalar adjoints (prevent with “GoGa” mechanism: Alves,Galloway, McCullough, Weiner, arxiv:1502.03819)

$$\int d^2\theta \frac{\bar{D}^2 D_\alpha V \bar{D}^2 D^\alpha V}{M^2} A_i A_i$$

“Generalized D-term Supersymmetry Breaking”

- general study of supersymmetry breaking in hidden sector with susy breaking D-terms of vector superfields. Do not insist on hidden sector gauge invariance (could have fields charged under hidden sector U(1)
- allows: any type of susy spectrum including split susy.
- does not allow:
  1. Giudice-Masiero μ term
  2. usual gaugino Majorana mass
  3. usual non susy scalar trilinears
- Allows: New term for μ parameter
  - non susy
  - allows heavy Higgsinos + H_d with no mass for H_u



Experimentally Viable
Supersoft
gauge mediation…
Top Down Motivated
Generalized
supersoft
Natural SUSY…
Not fine-tuned

Supersoft, (selectively) generalized

- Important new ingredients:
  - TeV scale non susy Higgsino mass
  - TeV scale Chiral Adjoint mass
  - weak scale soft squark and slepton masses

    (required for self-consistent RG running with Higgsino mass)

Higgsino mass term

$$\int d^2\theta \frac{\bar{D}^2 \left(D^\alpha V D_\alpha H_u\right)}{M} H_d$$

- No mass for H_u scalar!
  - could add similar term with $H_u \Leftrightarrow H_d$
- for $\mu_d >> \mu_u$ $\quad (\mu_u + \mu_d)\, \tilde{H}_u \tilde{H}_d \; + \; |\mu_u|^2 |h_u|^2 + |\mu_d|^2 |h_d|^2$
  - large tan β
  - Heavy higgsinos
- not supersoft— scalar mass^2 terms log UV sensitive unless $\mu_d = \mu_u$
  - technically natural to have light scalars compared with gauginos, Higgsino

Chiral Adjoint Mass Term $\int d^2\theta \frac{\bar{D}^2 \left(D^\alpha V D_\alpha A_i\right)}{M} A_i$

- mass term for chiral adjoints (scalars and fermions)
- gaugino mass possibilities
  - pseudo Dirac
  - mixed Majorana / Dirac
  - seesaw (lightest gaugino is MSSM-like Majorana particle)

Superpotential additions

$$\lambda_1 H_u A_1 H_d + \lambda_2 H_u A_2 H_d + \frac{\lambda_3}{3} A_3^3 + \frac{\lambda_4}{2} A_2^2 A_1 + \frac{\lambda_5}{3} A_1^3 + \frac{\lambda_6}{2} A_3^2 A_1$$

- λ_1 gives important contribution to Higgs quartic
- other terms are optional (and have big effect on renormalization)
- $\lambda_{1,2}$ could be motivated from "N=2" gauge/higgs sector

Gluino

$$\int d^2\theta \frac{\bar{D}^2 \left(D^\alpha V D_\alpha A_3\right)}{M} A_3$$

- Chiral Adjoint mass should not be large compared with Dirac mass to preserve small corrections to top squark mass— gluino is pseudo-Dirac or mixed.

Electroweakinos

$$\int d^2\theta \frac{\bar{D}^2\left(D^\alpha V D_\alpha A_2\right)}{M} A_2\,, \quad \int d^2\theta \frac{\bar{D}^2\left(D^\alpha V D_\alpha A_1\right)}{M} A_1$$

- no naturalness upper bound
- If chiral adjoint mass large compared with Dirac mass, restore gauge contribution to Higgs quartic
- 125 GeV Higgs from combination of superpotential, top squark and electroweak gauge contribution
- Implies relatively light Bino and Winos from seesaw
- Bino Dark Matter from coannihilation with light sleptons?

Summary

- LHC searches for gluinos are highly constraining
  - especially when the Higgsino is light.
- Supersoft supersymmetry breaking allows the gauginos to be Dirac particles which are much heavier than squarks and leptons without fine-tuning.
- New class of D-term supersymmetry breaking terms can give
  1. a Higgsino mass distinct from Higgs mass

     allows heavy Higgsino w/o fine tuning
  2. mass term for the chiral adjoints
     - restores gauge contribution to Higgs quartic
     - allows lighter, Majorana electroweakinos
- gluinos, Higgsinos and additional Higgs bosons can naturally be substantially heavier than the squarks and sleptons without fine-tuning.