Viable Supersoft SUSY

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Work done with Adam Martin, Tuhin S. Roy

Motivation

SM: Higgs mass is quadratically sensitive to UV scale

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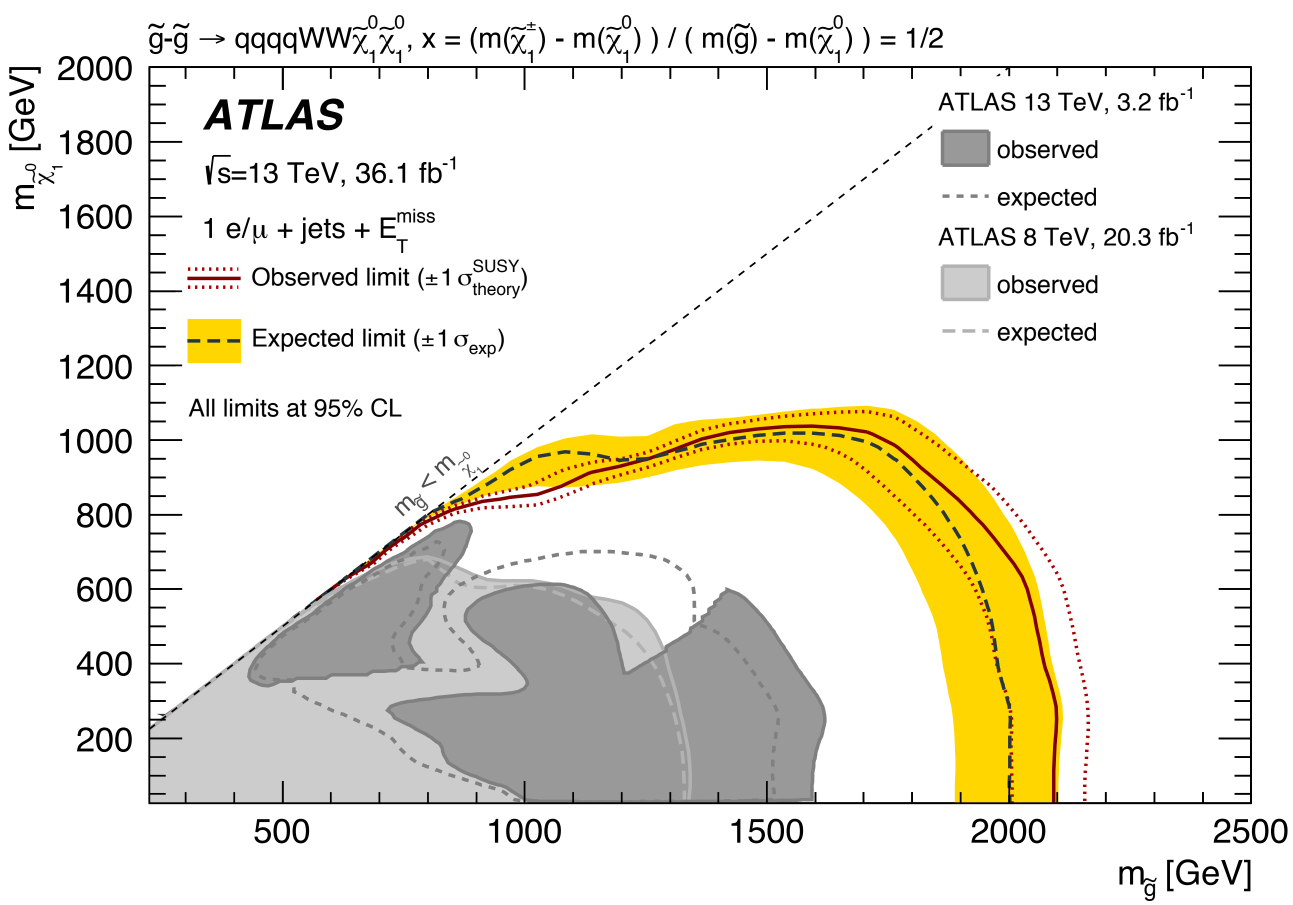
Softly broken SUSY (e.g. MSSM) reduces UV sensitivity



$$\delta m^2_{H_u} \equiv -\frac{3}{8\pi^2} y_t^2 \tilde{m}^2_{Q_3} \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

$$\frac{d}{dt}\tilde{m}^2_{Q_3} \equiv \frac{2}{3}\frac{dM_3^2}{dt}$$

Leads to

$$\delta m^2_{H_u} \equiv \# \frac{M_3^2}{\pi^2}\frac{\alpha_S}{\pi} \log^2\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

Other problematic issues: FCNS, Additional CP violating Phases.....

Talk by Michihisa Takeuchi and Xerxes Tata

Generalised Suspersoft SUSY

SUSY breaking is D-type

1. No Majorana Gaguino masses:

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

2. Gauginos have to be Dirac:

$$\int d^2\theta \frac{\omega_a}{\Lambda_{\rm mess}} \bar{D}^2 D^\alpha \mathcal{R} W_{\alpha,a} \Sigma_a \to M_{D_a} \lambda_a \psi_a$$

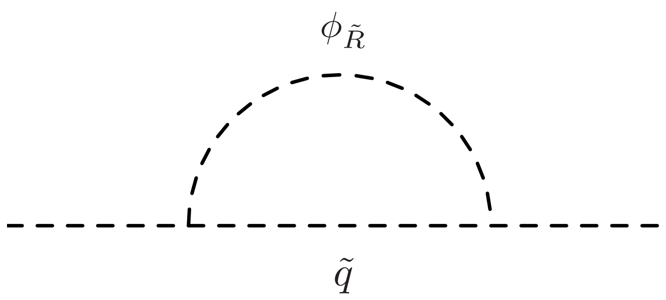
$$\bar{D}^2 D^\alpha \mathcal{R} \supset \theta^\alpha \langle \mathcal{D} \rangle \qquad W_\alpha \supset T_a \lambda^a_\alpha \qquad \Sigma_i \supset \sqrt{2}\theta\psi_i$$

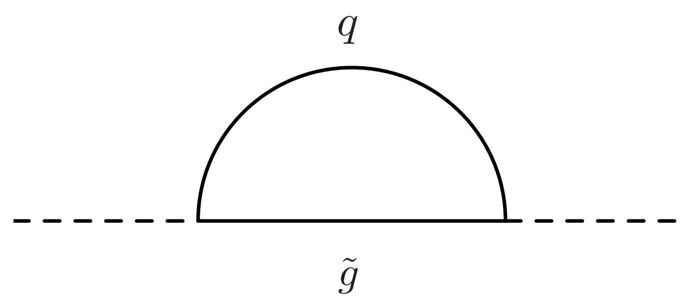
$$\boxed{M_{D_a} = \omega_a \frac{\langle \mathcal{D} \rangle}{\Lambda_{\rm mess}}}$$

Ref: Fox, Nelson, Weiner, JHEP 0208 (2002) 035

What do we gain ?

1. Supersoft: Ref: Fox, Nelson, Weiner, JHEP 0208 (2002) 035

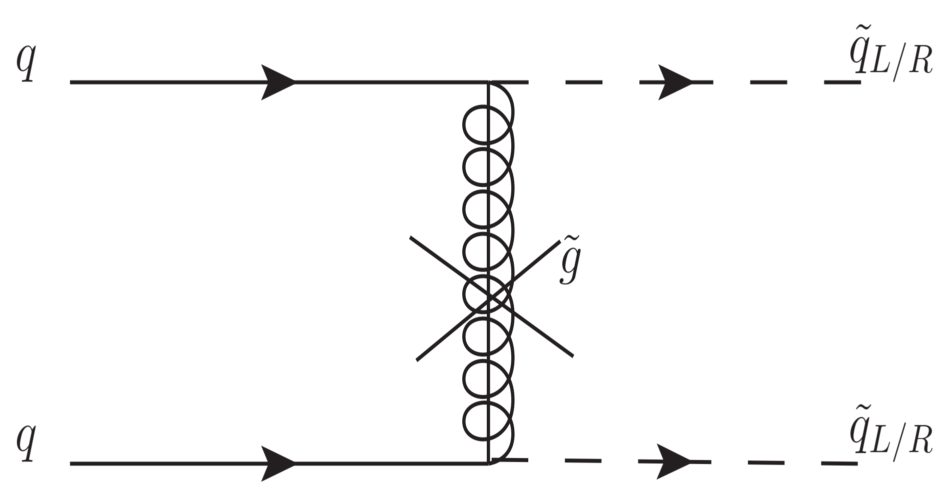


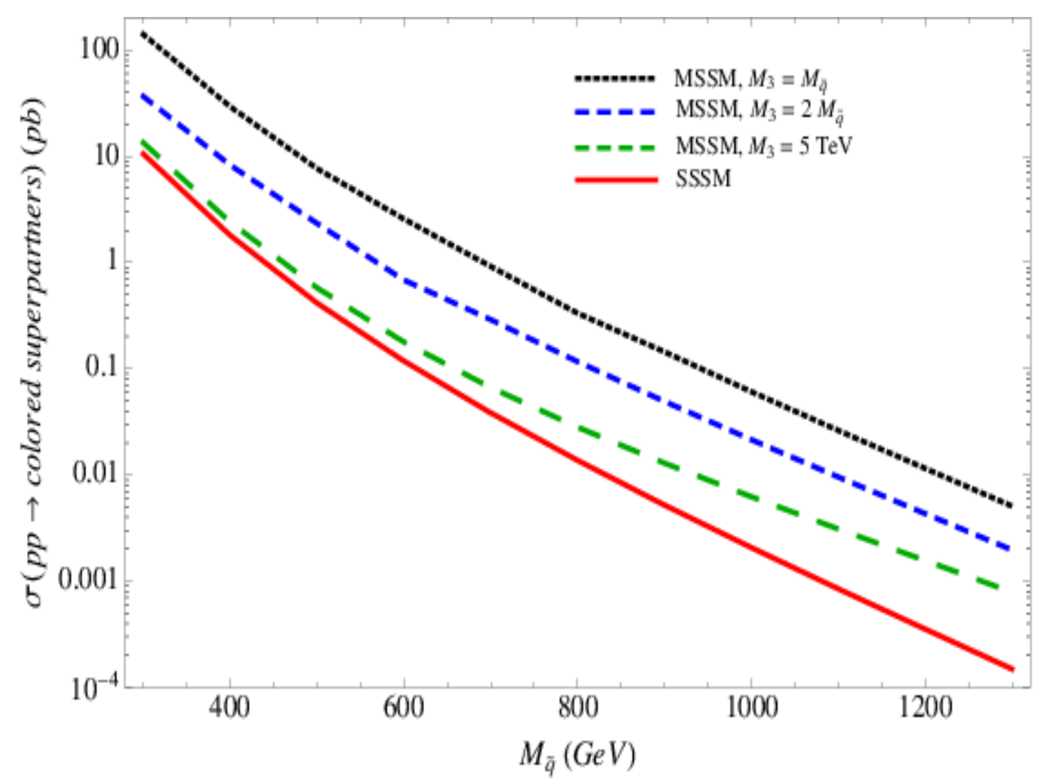


$$\delta m_{\tilde q}^2 \sim \# \frac{\alpha_S}{4\pi} M_{D_3}^2 \log\left(\frac{M_{D_3}^2}{m_{\phi_3}^2}\right)$$

UV insensitive, finite

2. Supersafe: Ref: Kribs and Martin, PRD85, 115014





Generalised Supersoft SUSY

3. Lemon-twist operator: Ref: Fox, Nelson, Weiner, JHEP 0208 (2002) 035

$$\int d^2\theta \frac{\omega_2}{4} \frac{\left(\frac{1}{4}\bar{D}^2 D\mathcal{R}\right)^2}{\Lambda_{\rm mess}^2} \Sigma_i^2 \to \left(\frac{\omega_2}{2} \frac{\mathcal{D}^2}{\Lambda_{\rm mess}^2}\right) \frac{\sigma_i^2}{2}$$

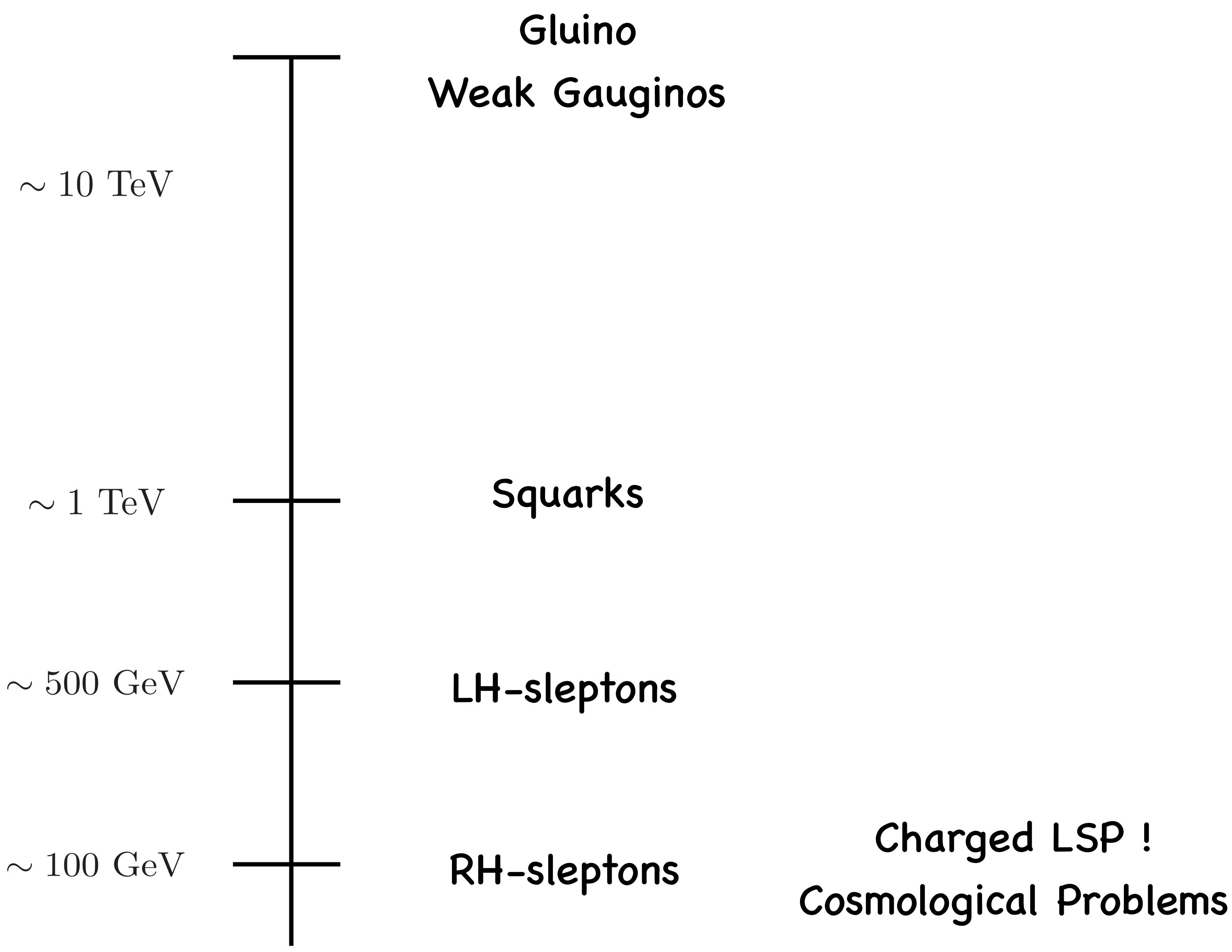
4. "Mu-term": Ref: Nelson, Roy, PRL. 114 (2015) 201802

$$\int d^2\theta \frac{\omega_3}{\Lambda_{\rm mess}} \bar{D}^2 \left(D^\alpha \mathcal{R} D_\alpha Q\right) Q' \to \mu_{Dqq'} \left(\frac{1}{2}\psi_q \psi'_q + F_Q \phi_q\right)$$

$$\boxed{\mu_{Dqq'} = \omega_3 \frac{\langle \mathcal{D} \rangle}{\Lambda_{\rm mess}}}$$

$$\mathcal{L} \supset \frac{1}{2}\left(\mu_u + \mu_d\right) \tilde{H}_u \tilde{H}_d + \left|\mu_u\right|^2 \left|h_u\right|^2 + \left|\mu_d\right|^2 \left|h_d\right|^2 + \ldots.$$

Spectrum



Goal is to solve this issue

Solution

NR operator: $$\int d^2\theta \frac{\omega_3}{\Lambda_{\text{mess}}} \bar{D}^2 \left(D^\alpha \mathcal{R} D_\alpha Q\right) Q' \to \mu_{Dqq'} \left(\frac{1}{2}\psi_q \psi'_q + F_Q \phi_q\right)$$

After eliminating the auxiliary fields

$$\left|\frac{\partial W}{\partial Q} + \mu_{Dqq'} \phi'_Q\right|^2$$

$$\to \mathcal{L} \supset \frac{1}{2}\left(\mu_u + \mu_d\right) \tilde{H}_u \tilde{H}_d + \left|m_{h_u}\right|^2 \left|h_u\right|^2 + \left|m_{h_d}\right|^2 \left|h_d\right|^2 + \underbrace{Y_u \mu_d^* h_d^\dagger \tilde{q}\tilde{u} + Y_d \mu_u^* h_u^\dagger \tilde{q}\tilde{u}}$$

Known Structure: $$\mu_u = \mu_d = \mu$$

Non-standard soft ~~SUSY~~ terms, Different from A-terms

Effects of Non-standard terms: Talk by U. Chattopadhyay and Abhishek Day

UV inputs

1. Dirac Gaugino Masses M_{D_i}

2. "Mu" parameter μ^0

3. Scalar Masses $\tilde{m}_\phi^2 = 0$

4. Higgs soft mass $\tilde{m}_{h_u}^2 = |\mu_u^0|^2 - |\mu^0|^2$

Hypercharge D-term $\mathcal{S} = \frac{1}{2}\sum_\phi q_\phi \tilde{m}_\phi^2 = \frac{1}{2}\left(|\mu_u^0|^2 - |\mu_d^0|^2\right)$

RGE's

Scalar Masses Ex: Right handed sleptons

$$\mathcal{C}_1 \equiv \frac{g'^2}{16\pi^2}\mathcal{S} \qquad \mathcal{C}_{2,3} \equiv \frac{y^2}{16\pi^2}\left(\xi^2, \mu^2\right)$$

$$16\pi^2 \beta\left[m_{\tilde{e}}^2\right] = 4\left[m_{h_d}^2 + m_{\tilde{e}}^2 + m_{\tilde{L}}^2 + \xi_d^2 - 2\left|\mu\right|^2\right] y_e^2 + 2g'^2\mathcal{S}$$

$$\downarrow$$

In terms of
Soft ~~SUSY~~ breaking terms

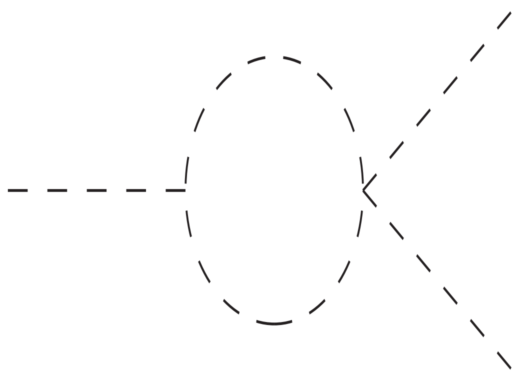
$$16\pi^2 \beta\left[\tilde{m}_{\tilde{e}}^2\right] = 4\left[\tilde{m}_{h_d}^2 + m_{\tilde{e}}^2 + m_{\tilde{L}}^2 + \left(\xi_d^2 - \left|\mu\right|^2\right)\right] y_e^2 + 2g'^2\mathcal{S}$$

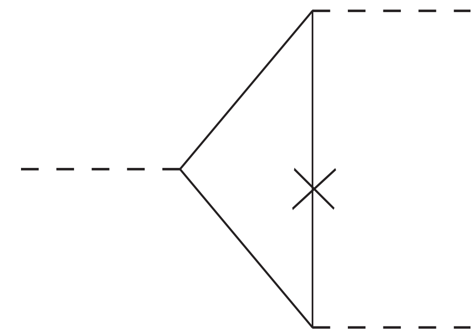
Consistency Check: SUSY limit

$\xi_d \to \mu$ We get back the traditional RGEs

Right slepton masses at IR $\quad \tilde{m}_e^2 \simeq -\frac{6}{5}\mathcal{S}_0 \frac{\alpha_1}{4\pi}\log\left(\frac{\Lambda}{\text{TeV}}\right)$

Running of trilinear Terms





$$16\pi^2 \beta\left[\xi_u\right] = 3y_t^2 \xi_u + y_b^2\left[4\mu - 2\xi_d + \xi_u\right] + \left(\xi_u - 2\mu\right)\left(3g^2 + g'^2\right)$$

Again consistency check

$$\xi_u = \xi_d = \mu$$

Reduces to the running of the Mu-term

Story so far

1. Dominant contribution for squark and left-slepton masses are through finite corrections

2. Right handed sleptons get mass through RGEs (hypercharge-D term mainly), Controlled by the parameter $\mathcal{S}(\Lambda) = |\mu_u|^2 - |\mu_d|^2$

3. Higgsino masses at UV $\mu = \frac{1}{2}(\mu_u + \mu_d)$

4. Higgs mass parameter: $\delta m_{H_u}^2 \equiv \# \frac{\alpha_1}{4\pi} \mathcal{S}(\Lambda) \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$

R $\sim 10 \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$

MSSM case: $\delta m_{H_u}^2 \equiv \# \frac{\alpha_S}{\pi} \frac{M_3^2}{\pi^2} \log^2\left(\frac{\Lambda}{\mathrm{TeV}}\right)$

DM issue

Dirac mass operator

$$\begin{pmatrix}\tilde{b} & \tilde{S}\end{pmatrix}\begin{pmatrix}0 & M_{D_1} \\ M_{D_1} & M_{\Sigma_1}\end{pmatrix}\begin{pmatrix}\tilde{b} \\ \tilde{S}\end{pmatrix}.$$

Nelson-Roy operator

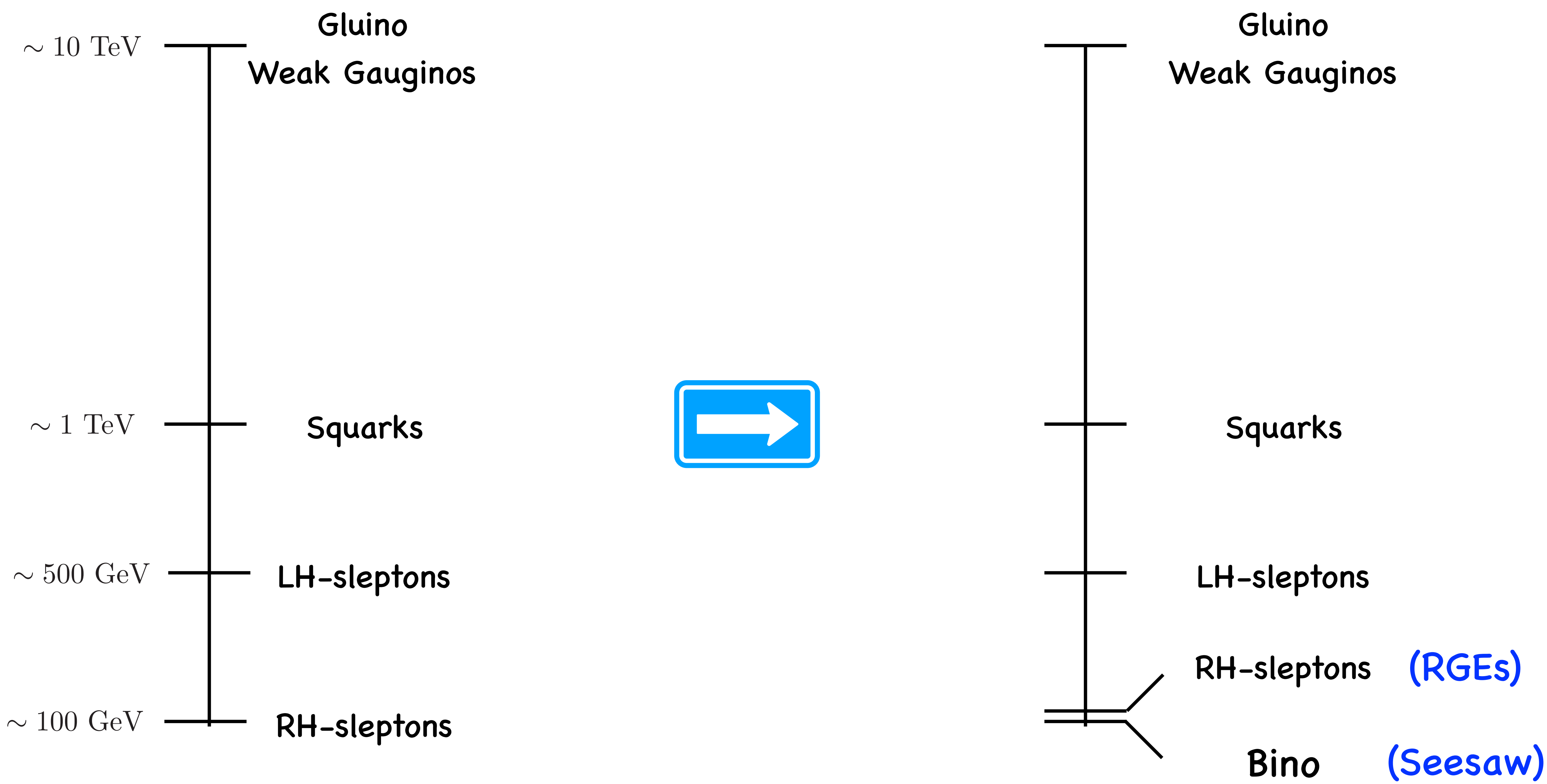
$$m_{\tilde{\chi}_1^0} \sim \frac{M_{D_1}^2}{M_{\Sigma_1}}$$

Constraints:

1. DM direct detection fixes Higgsino Mass at IR and thus $\mu = \frac{1}{2}\left(\mu_u + \mu_d\right)$

2. LEP and LHC limits fixes IR slepton mass and thus $\mu_u - \mu_d$

Spectrum: Past and Present

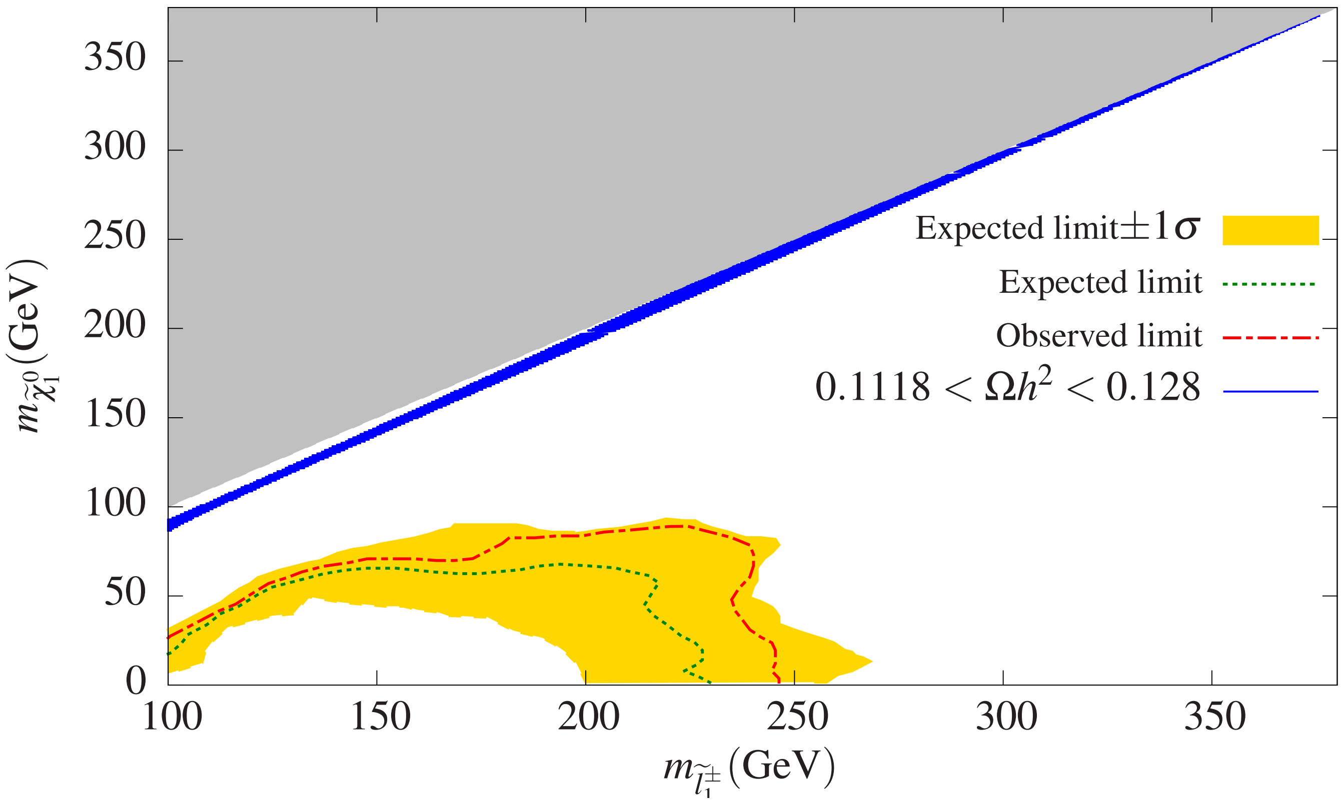


DM & Higgs mass

Bino DM suffers from overabundance

Bino-right slepton coannihilation

$$\frac{m_{\tilde{e}} - m_{\tilde{\chi}_1^0}}{m_{\tilde{\chi}_1^0}} = \frac{T_f}{m_{\tilde{\chi}_1^0}} \sim 5\%$$



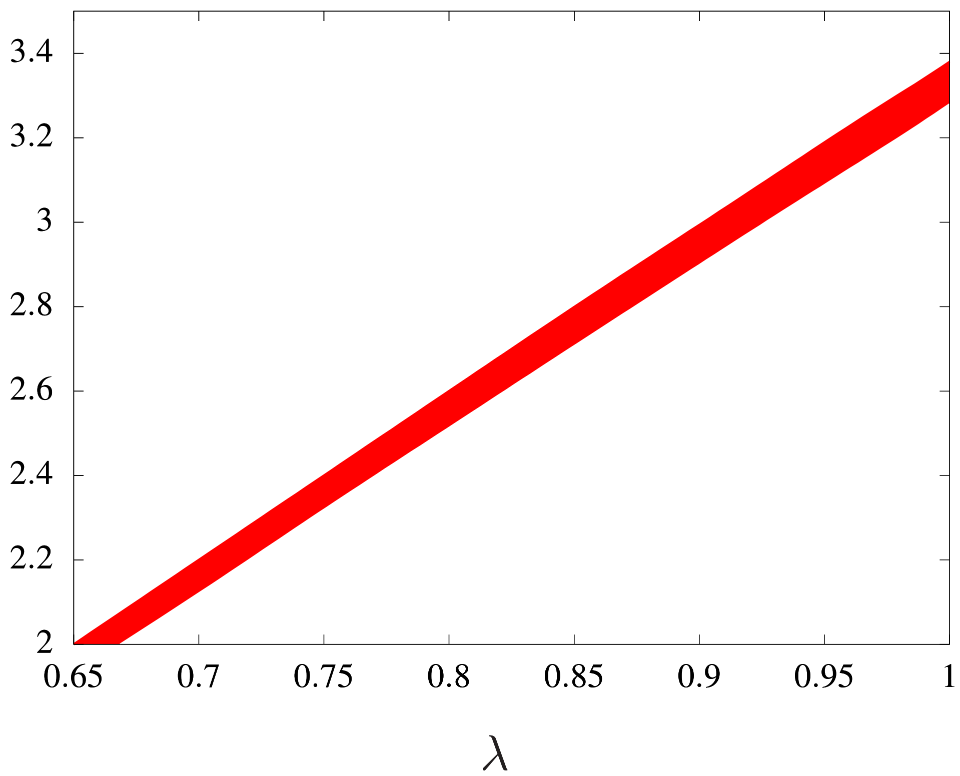
Higgs quartic is different from the Standard MSSM case

$$\mathcal{L}_{\rm eff} \supset \frac{M_{\Sigma_2}^2}{M_{\Sigma_2}^2 + 4M_{D_2}^2} \frac{g_2^2}{8} \sum_k (q_k^* t_a q_k)^2$$

Standard quartic is depleted unless

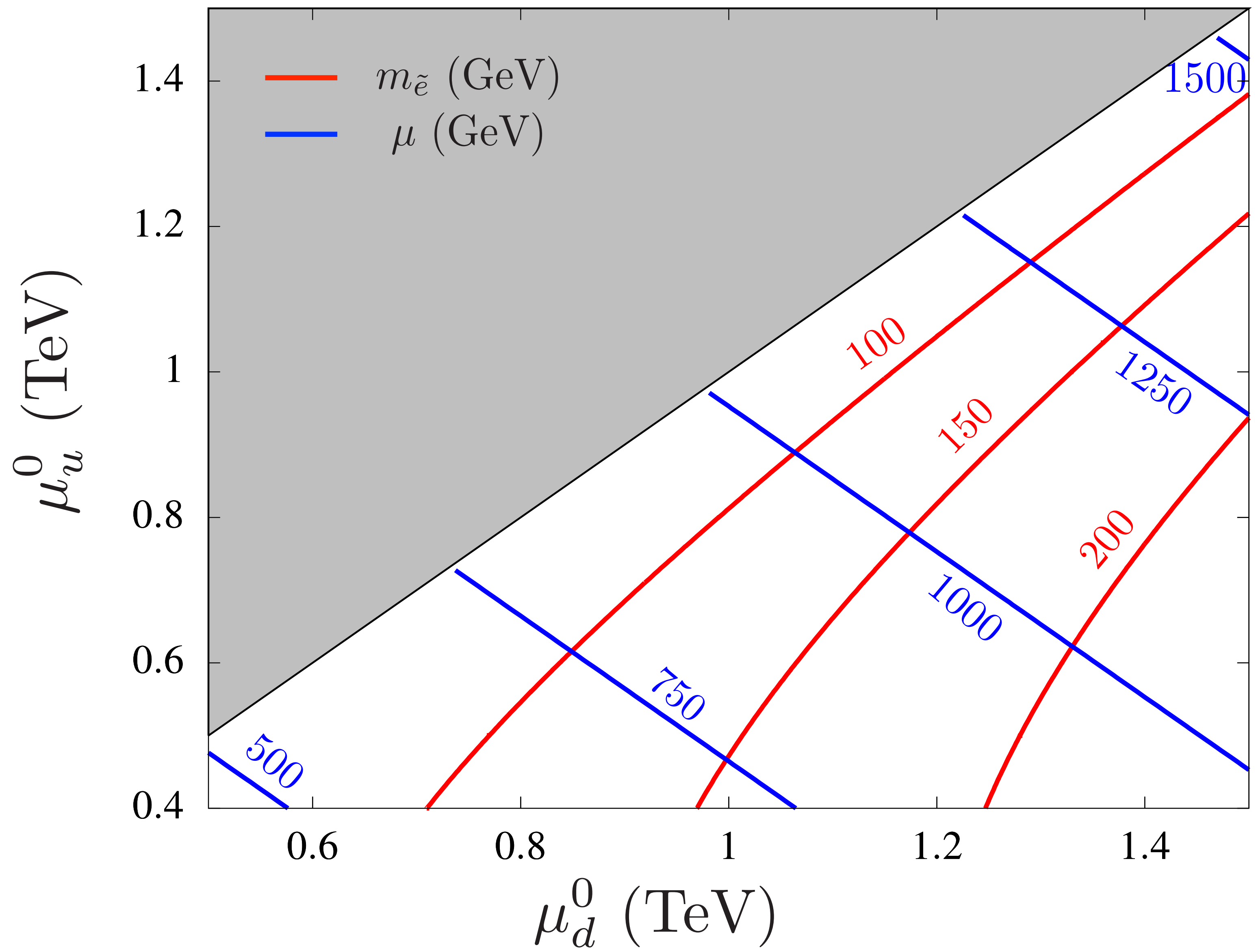
$$M_{\Sigma_2} \gg M_{D_2}$$

Another option: ala NMSSM



$$M_h^2 = \lambda^2 v^2 \sin^2 2\beta + ...$$

Viable parameters



Conclusion

1. The non-zero Hypercharge D-terms turn out to be a feature

2. Generates right slepton masses through RGEs

3. All the other scalar masses are due to finite corrections from gauginos

4. Lightest bino-like neutralino from Seesaw effect

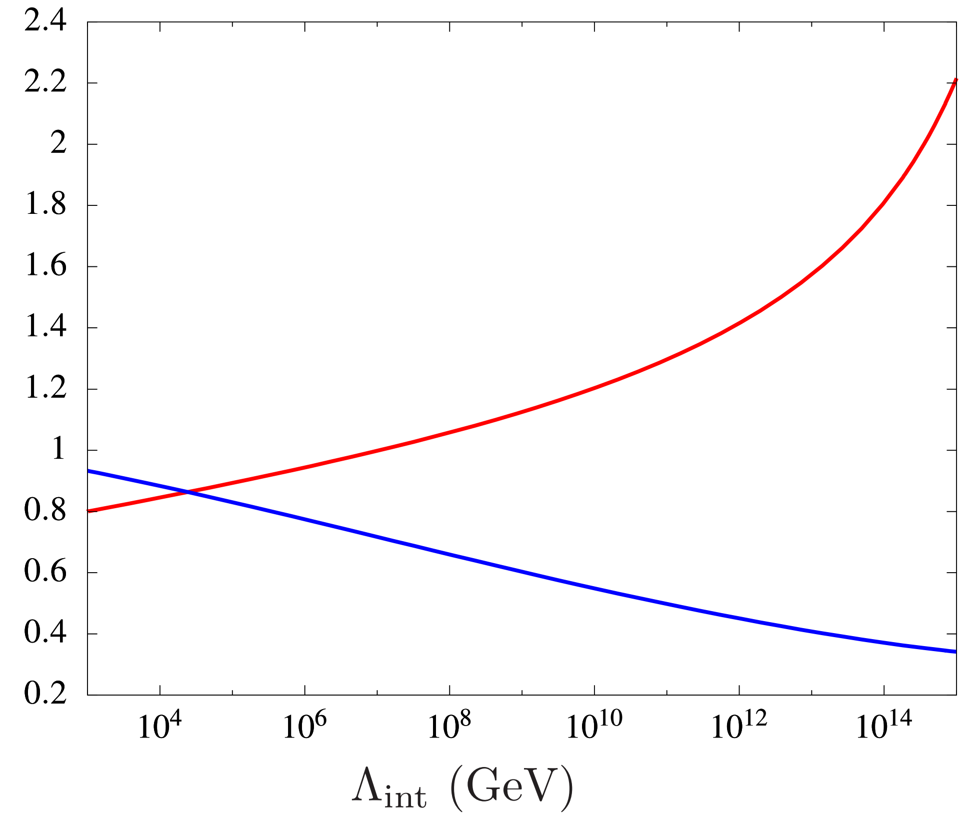
5. Bino-slepton coannihilation makes it viable from DM constraints

6. Validity from Higgs mass and collider data has been checked

Thanks!

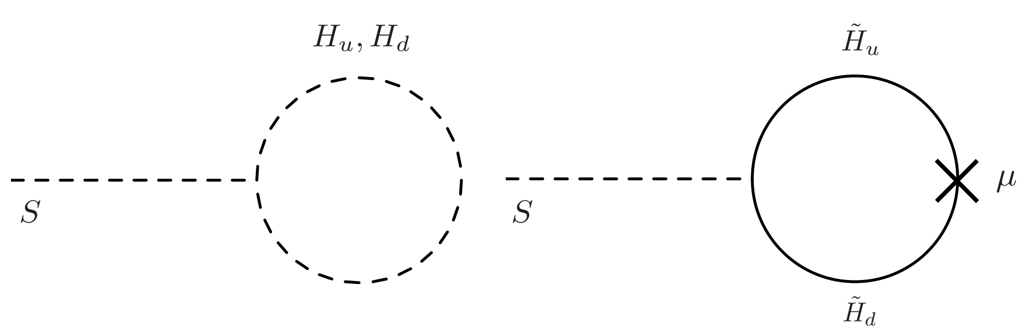
Issues with singlet coupling

- Large coupling increases Higgsino-bino mixing, Constraints from direct detection
- ✓ Heavy Higgsinos ~ 1 TeV



- Landau Pole and constraints from Higgs?
- ✓ OK up-to GUT scale

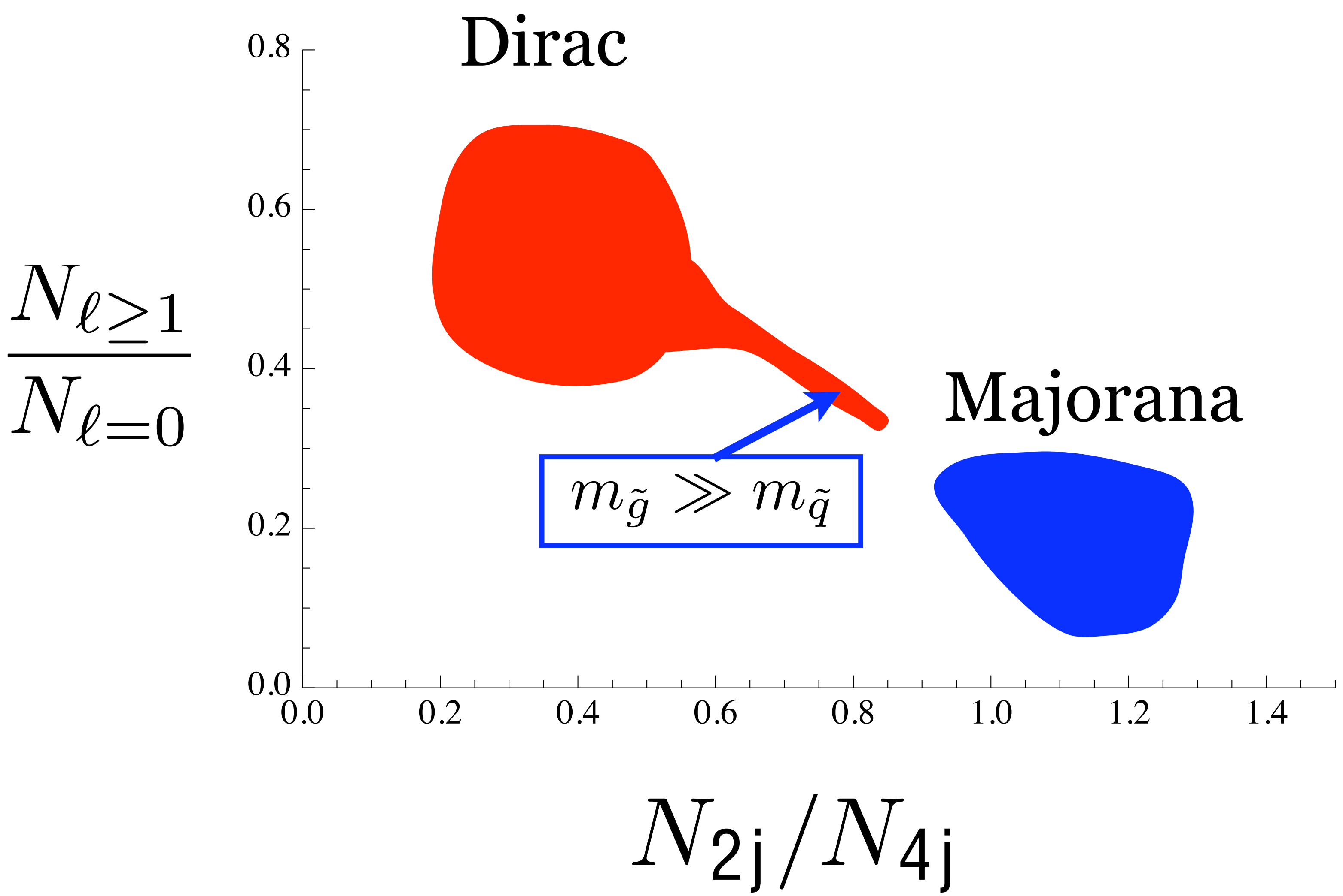
- Issues with Tadpoles as non-standard SUSY breaking terms are present



$$\delta_S = \frac{\lambda_S}{16\pi^2}\Lambda_{\rm int}^2\left[\mu\left(\Lambda_{\rm int}\right) - \left(\frac{\mu_u^0+\mu_d^0}{2}\right)\right]$$

✓ Saves the day!

How many SUSY



Matti Heikinheimo, Moshe Kellerstein and Veronica Sanz, 1111.4322