How high could SUSY go?

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Based on works realised in collaboration with K. Benakli, M. Goodsell and P. Slavich (1312.5220, 1508.02534 and 1511.02044)

Introduction

What wants SUSY at the EW scale?

- Hierarchy problem
  - Need to keep all SUSY particles at EW scale to control the Higgs mass (if not, little hierarchy problem)
- Gauge coupling unification
- Dark Matter candidate (WIMP)

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Split SUSY idea $\longrightarrow$ keep only the SUSY fermions (higgsinos and gauginos) at EW scale, but have all scalar superpartners heavy at SUSY scale M_S

- Can experimental measurements say something about M_S?

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- Can experimental measurements say something about M_S?

What is your splitting?

- Split SUSY leaves aside a "little hierarchy problem" since $M_S \gg$ EW scale.
- M_S is still constrained by
  - The Higgs mass measurement (Section 1)
  - DM and cosmology (Section 2)
- In usual Split SUSY models, "Mini-Split" $\longrightarrow M_S \lesssim 10^6$ GeV
- In Fake Split SUSY models (FSSM) , "Mega-Split":
  - Higgs mass $\longrightarrow$ No constraint
  - Assuming standard Cosmology $\longrightarrow M_S \lesssim 10^{10}$ GeV
- Main difference $\longrightarrow$ Yukawa couplings of the SUSY fermions.

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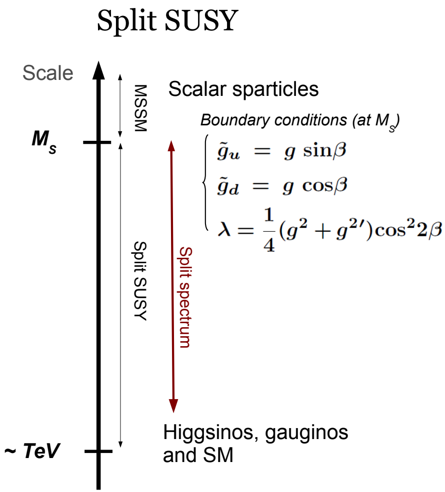
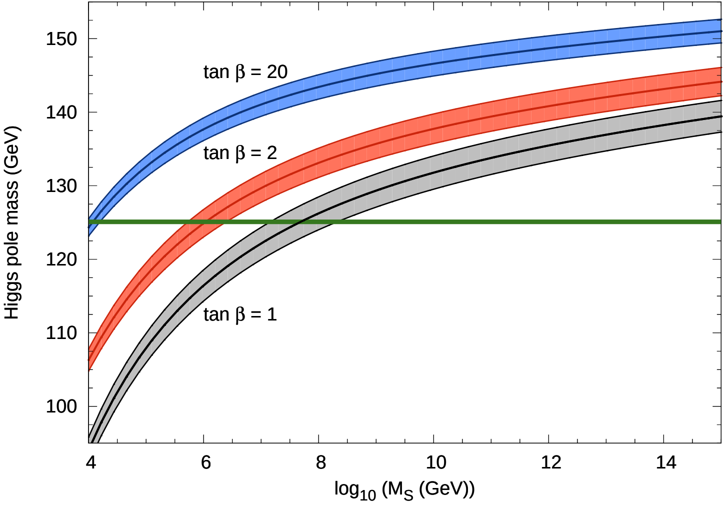
Recovering the Higgs mass

Split SUSY and Higgs mass



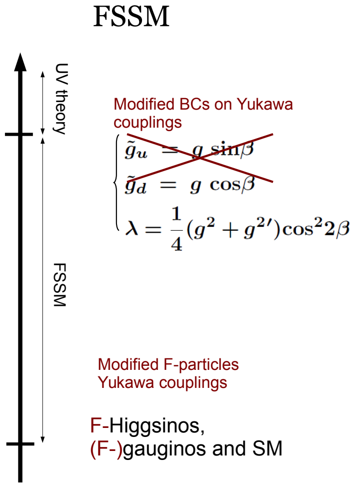
- A "prediction" for the SM-like Higgs mass $M_H^2 = 2\lambda v^2$ since:
  - experiment gives us SM-Higgs VEV v
  - boundary conditions at M_S gives us $\lambda = \frac{1}{4}\left[g'^2 + g^2\right] \cos^2 2\beta$ at tree level.
- Fine-tuning a light Higgs gives $\tan\beta = \sqrt{\frac{m_{H_d}^2 + \mu^2}{m_{H_u}^2 + \mu^2}} \simeq \sqrt{\frac{m_{H_d}^2}{m_{H_u}^2}}$
- If $m_{H_d} = m_{H_u}$ at the GUT scale, then $\tan\beta \gtrsim 2 - 3$

Higgs mass prediction - Split SUSY



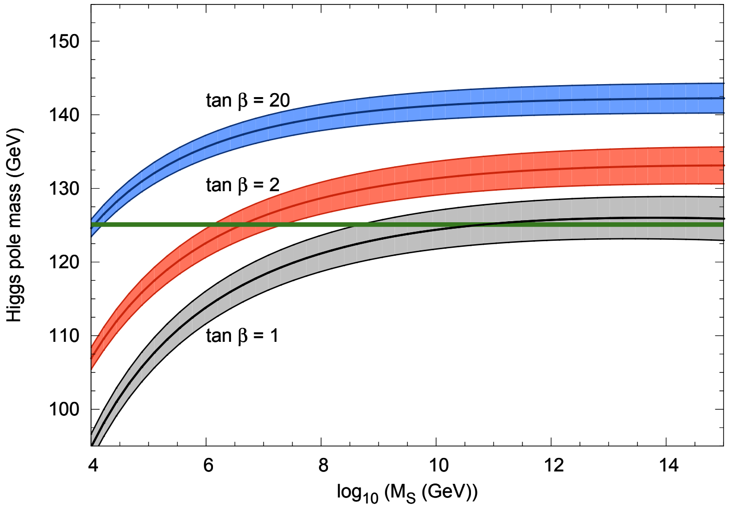
Higgs-mass function of M_S for Split SUSY for $\tan\beta = 1, 2$ or 20.

Fake Split SUSY Models (FSSM)



- Replace higgsinos (and possibly gauginos) by F-higgsinos (and F-gauginos) with same quantum numbers but suppressed Yukawa couplings.
  - "Real" higgsinos (and gauginos) are heavy.
- Approximate global symmetry to protect the splitting.
  - A $U(1)_F$ for both F-gauginos and F-higgsinos (FSSM-I)
  - An R symmetry for F-higgsinos only (FSSM-II)

FSSM - Higgs mass

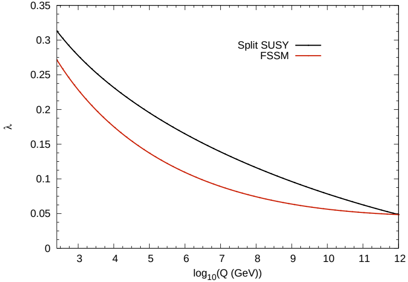


Higgs-mass function of M_S for the FSSM. $\tan\beta = 1, 2$ or 20.

Origin of the new behaviour

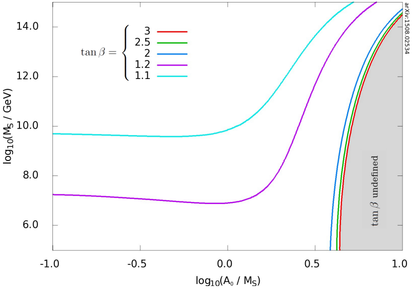
- Suppressed Yukawas for F-particles

$$\beta_\lambda = \frac{1}{16\pi^2}\left[\beta_{\text{quartic}} + \underbrace{(\cdots g^4 \cdots)}_{\equiv \beta_g} - \underbrace{(\cdots \tilde{g}^4 \cdots)}_{\equiv \beta_{\tilde{g}}} - \underbrace{12 y_t^4}_{\equiv \beta_t}\right]$$



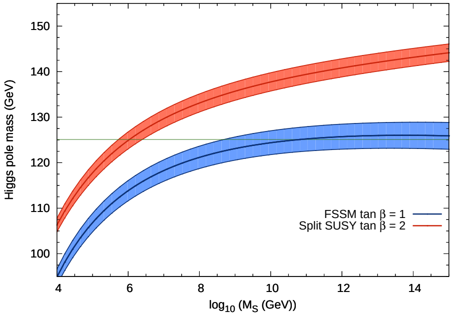
Running of λ in Split SUSY and FSSM. $M_S = 2 \times 10^{12}$ GeV.

- "Real" higgsinos are heavy: $m_{H_{d,u}} \sim \mu \sim \mathcal{O}(M_S)$:
  - $\tan\beta = \sqrt{\frac{m_{H_d}^2 + \mu^2}{m_{H_u}^2 + \mu^2}} \sim 1$



$\tan\beta$ function of M_S and of the trilinear at M_S.

Summary - Higgs mass



Higgs-mass function of M_S for the FSSM $(\tan\beta = 1)$ and Split SUSY $(\tan\beta = 2)$.

- FSSM models: simple modification of the effective theory below M_S
  - FSSM-I, SM, F-higgsinos and F-gauginos
  - FSSM-II, SM, F-higgsino and gauginos
- In both cases, Higgs mass “prediction” drastically different than Split SUSY.

SUSY scale and cosmology

F-gluino life-time

- Long-lived gluinos are basically ruled out by observations (heavy isotopes searches,CMB, diffuse gamma ray background and BBN).
- In FSSM-II, gluinos are long-lived as Split SUSY (since decay through squarks are suppressed).
  - $\tau_{\tilde{g}'} \sim 4 \text{ sec} \times \left(\frac{M_S}{10^9 \text{GeV}}\right)^4 \times \left(\frac{1 \text{ TeV}}{m_{fg}}\right)^5$.
  - Imply $M_S \lesssim 10^{10}$ GeV
- In FSSM-I, F-gluinos are even more long-lived (couplings suppressed by the approximate symmetry which keeps them light).
  - $\tau_{\tilde{g}'} \sim 4 \text{ sec} \times \left(\frac{M_S}{10^7 \text{GeV}}\right)^6 \times \left(\frac{1 \text{ TeV}}{m_{fg}}\right)^7$.
  - Imply $M_S \lesssim 10^8$ GeV

Dark Matter in FSSM

- Since FSSM have the same gauge interactions than Split SUSY, we expect rather similar DM candidates. Using micrOMEGAs, we find the correct relic density for:
  - F-Higgsino LSP with mass 1.1 TeV
  - (F-)Wino LSP with mass 2.4 TeV
- Interesting issue
  - F-higgsinos LSP are inelastic Dark Matter

Inelastic scattering of F-higgsinos

- Splitting between F-higgsinos suppressed by the approximate symmetry which keeps them light.
  - Inelastic scattering over nucleons allowed $\longrightarrow$ direct detection possible!
  - We took a conservative bound of 300 keV from LUX analysis
- F-higgsinos mass splitting is
  - FSSM-I, $\delta \sim 200 \text{ keV} \cdot \left(\frac{400 \text{ TeV}}{M_S}\right)^2 \left(\frac{m_{fg}}{4 \text{ TeV}}\right)$
  - FSSM-II, $\delta \sim 200 \text{ keV} \cdot \left(\frac{10^7 \text{ GeV}}{M_S}\right) \left(\frac{\mu}{1 \text{ TeV}}\right) \left(\frac{4 \text{ TeV}}{m_{fg}}\right)$
- Therefore if F-higgsinos Dark Matter, M_S is bounded:
  - FSSM-I, $M_S \lesssim 10^6$ GeV
  - FSSM-II, $M_S \lesssim 10^8$ GeV

Conclusions

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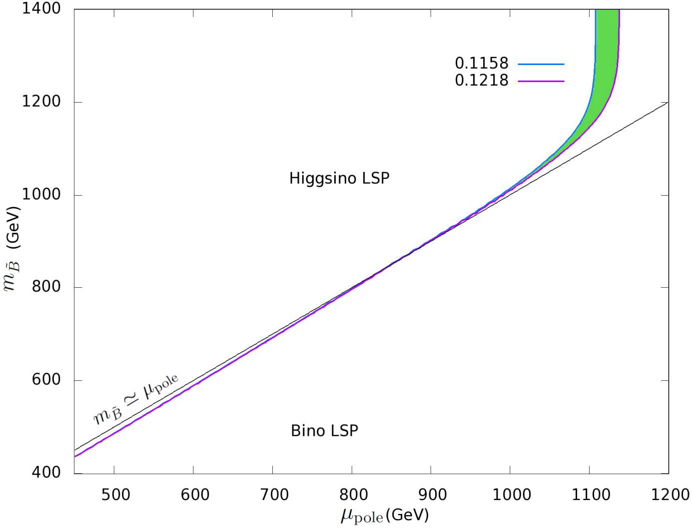
- In FSSM, the measured Higgs mass is not a constraint anymore, stark contrast with usual Split SUSY models.
- Cosmology constraints are very relevant for this class of models, especially gluino life-time.
  - We still can have a "Mega-Split" spectrum with M_S up to 10^{10} GeV
- If new light fermions discovered at LHC, we need to study their Yukawas!
- Collider phenomenology ?

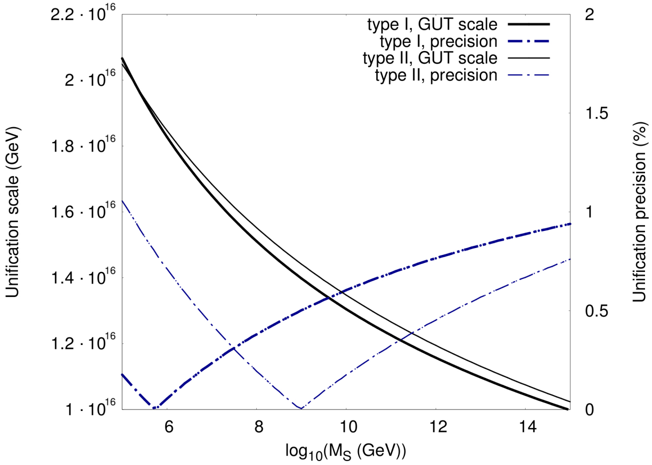
Backup slides

Well-tempered Bino/Higgsinos



Relic density as a function of F-Higgsino pole mass and Bino pole mass.

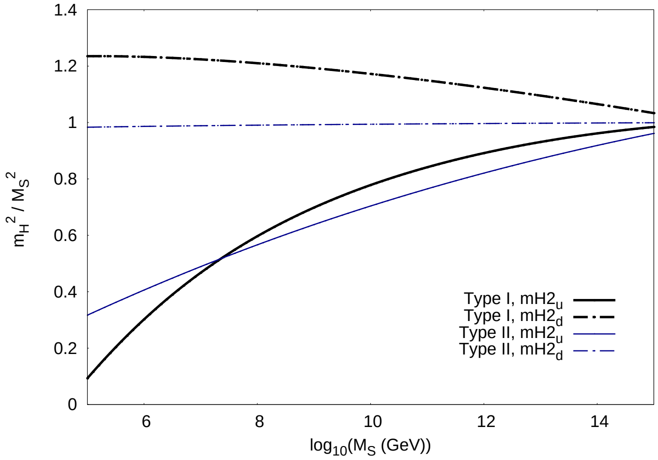
Gauge coupling unification



GUT scale and unification precision $\frac{|g_3 - g_1|}{g_1}$ in percentage for FSSM-I and FSSM-II.

From 1508.02534

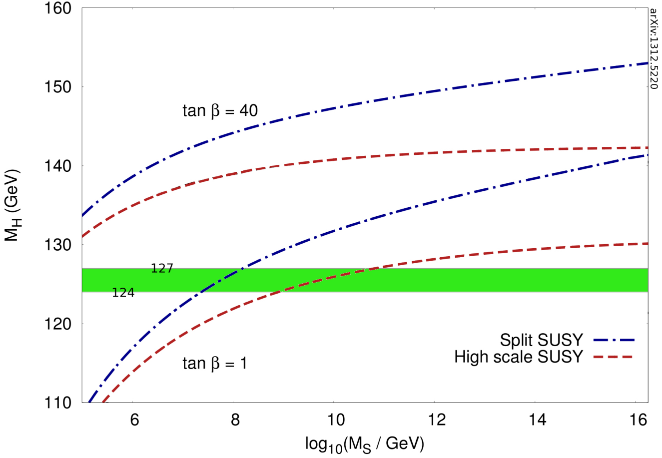
Tachyonic Higgs soft masses



RGE for Higgs sector soft masses for $M_S = 10^5$ GeV in type-I and type-II FSSM.

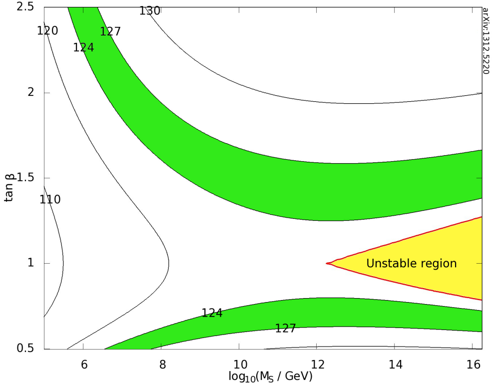
From 1508.02534

Higgs mass prediction - High scale SUSY



Higgs-mass function of M_S for High-scale SUSY, Split SUSY and FSSM. $M_{\tilde{g}'} = \mu = 2$ TeV (when relevant) and $\tan\beta = 1$ or 40.

Stability in FSSM



Contour plot of the Higgs mass on the $M_S - \tan\beta$ plane, $M_{\tilde{g}'} = \mu = 2$ TeV. Yellow-shaded region indicates where λ becomes negative during its running.

Realisation of FSSM-I: Dirac Gauginos

Toward a microscopic description:

- Above M_S, add to MSSM chiral multiplets in the adjoint representation of each gauge group (Dirac gauginos) $\rightarrow$ fermions are called *F-gauginos*[1].
- Also two Higgs-like $SU(2)_W$ doublets $\rightarrow$ fermions are called *F-higgsinos*
- Suppose no R-symmetry ($\neq$ from Split-SUSY style) protects gauginos and higgsinos masses $\rightarrow$ get masses at M_S

[1] Also arXiv:1312.2011 by E. Dudas, M. Goodsell, L. Heurtier, P. Tziveloglou

Realisation of FSSM-I: Getting light sfermions

- Use an approximate $U(1)$ symmetry with only the “fake” particles charged under it (Froggatt-Nielsen style).
- The gaugino (λ)/F-gaugino (χ) mass terms are of the form.

$$-\Delta\mathcal{L}_{\text{gauginos}} = M_S \left[\frac{1}{2}\lambda\lambda + \mathcal{O}(\varepsilon)\,\lambda\chi + \mathcal{O}(\varepsilon^2)\chi\chi + \text{h.c.} \right],$$

  leading to light F-gaugino-like eigenstate and heavy gauginos-like eigenstate.
- SUSY-breaking mass terms of the usual MSSM scalars, fake adjoint scalars and F-Higgs scalars are not protected $\rightarrow$ heavy.
- We need to fine-tune the weak scale.

Realisation of FSSM-I: We end up with

- The SM Higgs boson H is a linear combination of the original Higgs H_u, H_d and F-Higgs H'_u, H'_d doublets.

$$H \approx \cos\beta \; i\sigma^2 H_d^* + \sin\beta H_u + \mathcal{O}(\varepsilon) i\sigma^2 {H_u}'^* + \mathcal{O}(\varepsilon) {H_d}'$$

- We have F-higgsinos and F-gauginos at low energy instead of Higgsinos and gauginos:
- $\varepsilon \sim \sqrt{\frac{\mathrm{TeV}}{M_S}}$ determined by requiring TeV-scale F-particles.
- Same particle content as Split SUSY, but suppressed Higgsino and gauginos couplings. Realisation of weakly-coupled FSSM.

Practical derivation

- We want the RG evolution of λ between M_Z and the GUT scale.
- Make use of perturbative situation: algorithmic procedure
  1. Start with SM values and crude approximations at M_Z, evolve it up to GUT scale, fix unified input there.
  2. Run it down to M_S, apply FSSM boundary conditions
  3. Iterate this procedure above M_S until CV (very fast)
  4. Run it down to M_Z, apply again SM boundary conditions
  5. Iterate the procedure below M_S until CV (very fast).
  6. Iterate the whole thing until CV (again very fast)
  7. Calculate Higgs mass at M_{top}

Precision

- Concerning our precision, the most salient points are:
  - Two-loop QCD contributions while converting top pole mass to its $\overline{MS}$ counterpart.
  - Full Split-SUSY two-loop RGEs.
  - Dominant two-loop Higgs self-energy to obtain the pole mass, we also include leading-log contribution from three-loop diagrams with (F-)gluinos.
  - We did not included threshold corrections at M_S but have estimated them as a GeV effect for $M_S \gtrsim 10^8$ GeV.