Distribution of supersymmetry μ parameter and Peccei-Quinn scale f_a from the landscape arXiv: 2104.03803

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Intro

SUSY μ problem

- SUSY-preserving term $W \supset \mu H_u H_d$ generically suggests $\mu \sim \mathcal{O}(m_P)$
- Phenomenology requires $\mu \sim \mathcal{O}(100)$ GeV
- Usually forbid μ by some symmetry, then generate effective μ term by some mechanism to give weak scale value
- Can generically measure tuning by fixing m_Z to experimental value - each EWSB contribution should be comparable to m_Z!

SUSY EWSB conditions

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - \left(m_{H_u}^2 - \Sigma_u^u\right)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$
$$\simeq -m_{H_u}^2 - \Sigma_u^u\left(\tilde{t}_{1,2}\right) - \mu^2$$

Δ_{EW} definition

$$\Delta_{EW} \equiv |\text{max EWSB rhs}|/(m_Z^2/2)$$

The string landscape

- String landscape provides $\gtrsim \mathcal{O}(10^{500})$ vacua - need statistical studies
- Perturbative SUSY breaking assumed a power law pull on soft terms, with exponent $2n_F + n_D - 1$ depending on hidden sector (Denef & Douglas)
- Arguments by Agrawal et al. (Phys. Rev. D 57, 5480) suggest that if m_{weak} were $2 - 5$ times larger, atoms would be unable to form
- Veto solutions with weak scale outside those bounds (anthropics)
- Distribution of Λ independent of SUSY breaking scale - allows us to ignore f_{CC} and focus on f_{SUSY} and f_{EWFT}

Landscape distributions

$$f_{SUSY} \sim m_{\text{soft}}^{2n_F+n_D-1}$$

$$f_{EWFT} \sim \Theta(N \cdot m_{\text{weak}}^{OU} - m_{\text{weak}}^{PU})$$

$$dN_{\text{vac}}(m_{\text{hidden}}^2, m_{\text{weak}}, \Lambda) = f_{SUSY} \cdot f_{EWFT} \cdot f_{CC} \cdot dm_{\text{hidden}}^2$$

(arXiv: hep-th/0405279)

Our procedure

- Take 2 solutions to μ problem:
  1. Gravity-Safe Peccei-Quinn (GSPQ)
  2. Giudice-Masiero (GM)
- Scan over appropriate soft terms, and veto points with $m_{\text{weak}}^{PU} > 4m_{\text{weak}}^{OU}$ (corresponds to $\Delta_{\text{EW}} \gtrsim 30$)
- Veto points with either CCB minima or no EWSB
- We end up with a μ distribution predicted by string landscape
- Since GSPQ also has PQ sector, also have f_a distribution

Landscape distributions

$$f_{SUSY} \sim m_{\text{soft}}^{2n_F+n_D-1}$$

$$f_{EWFT} \sim \Theta(30 - \Delta_{\text{EW}})$$

(see e.g. Baer et al. arXiv: 2005.13577)

GSPQ

GSPQ Model

- GSPQ model introduces PQ fields $X, \; Y$ charged under $\mathbb{Z}_{24}^R$ where $U(1)_{PQ}$ emerges as an accidental, approximate global symmetry (see e.g. Baer, Barger, Sengupta arXiv: 1810.03713)

$$W \supset \frac{\lambda_\mu}{m_P} X^2 H_u H_d + \frac{f}{m_P} X^3 Y$$

- Additional non-renormalizable terms suppressed by $\mathcal{O}(m_P^8)$
- F-term and soft terms give relevant contributions:

$$V_F \supset |f\,\phi_X^3/m_P|^2 + |3f\,\phi_X^2 \phi_Y/m_P|^2,$$
$$V_{\text{soft}} \supset m_X^2\,|\phi_X|^2 + m_Y^2\,|\phi_Y|^2 + (f\,A_f\,\phi_X^3 \phi_Y/m_P + \text{h.c.})$$

- Breaking $\mathbb{Z}_{24}^R$ with large $-A_f$ (also breaking PQ) induces μ term, with $\mu \sim \frac{\lambda_\mu}{m_P} v_X^2$
- Gives us μ term and a DFSZ axion

Minimization

V_{GSPQ} minimization conditions

$$0 = \frac{9|f|^2}{m_P^2}\left|v_X^2\right|^2 v_Y + \frac{f^* A_f^*}{m_P} v_X^{*3} + m_Y^2 v_Y$$

$$0 = \frac{3|f|^2}{m_P^2}\left|v_X^2\right|^2 v_X + \frac{18|f|^2}{m_P^2}|v_X|^2|v_Y|^2 v_X + \frac{3f^* A_f^*}{m_P} v_X^{*2} v_Y^* + m_X^2 v_X$$

- Taking $A_f, f \in \mathbb{R}$ gives $v_X, v_Y \in \mathbb{R}$
- Further assume common scalar mass $m_X = m_Y = m_{3/2} \equiv m_0$ and set $f = 1$
- Solving resulting minimization conditions for given m_0, A_f gives values of v_X, v_Y
- This then gives us $\mu = \frac{\lambda_\mu}{m_P} v_X^2$ for a given $\lambda_\mu \sim \mathcal{O}(0.01 - 1)$
- No solutions for $|A_f|/m_0 < \sqrt{12}$ - gives lower bound for μ for given A_f!

Parameter space scan

- Non-universal Higgs SUSY model (NUHM2) parameter space specified by

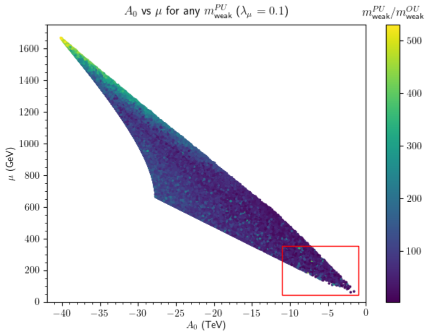
$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu,\ m_A$$

- GSPQ sector adopts $m_X = m_Y = m_0$ and $A_f = 2.5A_0$
- Soft terms take $n = 1$ statistical draw, $\tan\beta$ takes uniform statistical draw
- 3 samples, taking $\lambda_\mu = 0.05, 0.1, 0.2$
- Calculate v_X, v_Y from minimization conditions, then use derived μ values in Isajet to calculate MSSM spectra and Δ_{EW}
- Also calculate $f_a = \sqrt{v_X^2 + 9v_Y^2}$

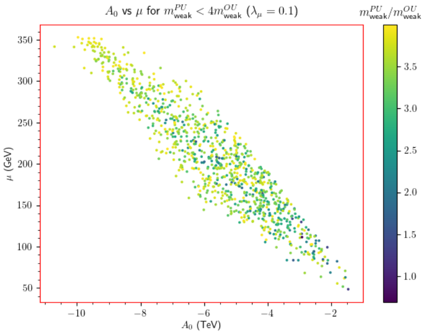
Parameter space

$$m_0 \in [0.1, 20]\ \text{TeV}$$
$$m_{1/2} \in [0.5, 5]\ \text{TeV}$$
$$-A_0 \in [0, 50]\ \text{TeV}$$
$$m_A \in [0.3, 10]\ \text{TeV}$$
$$\tan\beta \in [3, 60]$$

Results ($\lambda_\mu = 0.1$)

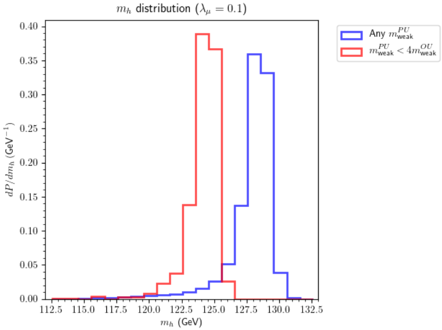


All points with appropriately broken symmetry

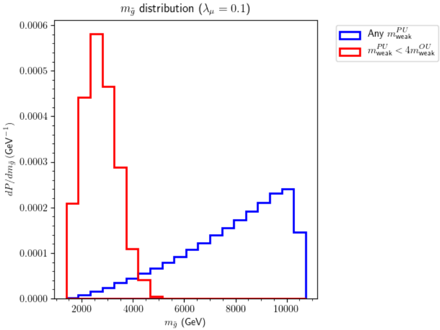


Anthropically allowed points (blowup of left fig)

Results ($\lambda_\mu = 0.1$)

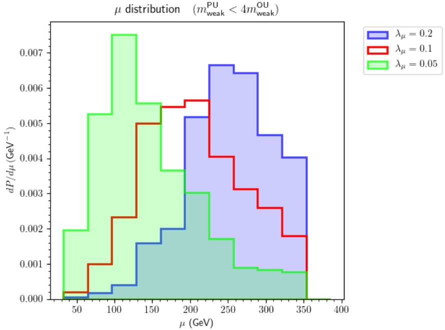


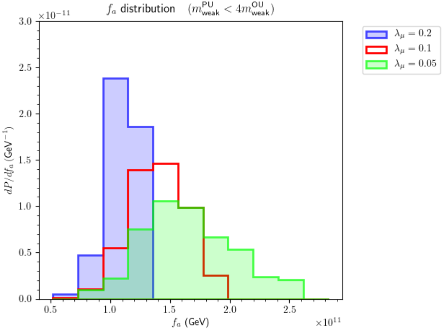
Higgs peak $\sim$ 124 GeV



Gluino peak $\sim$ 2.7 TeV

Results (comparing λ_μ)





μ distribution gets pulled up by λ_μ and capped by $m_{\text{weak}}^{PU} < 4m_{\text{weak}}^{OU}$

Predicts axion with mass $\mathcal{O}(100)$ μeV

Giudice-Masiero

Giudice-Masiero

- Most common mechanism is Giudice-Masiero (GM) mechanism
- MSSM μ term forbidden by some symmetry, but Kähler potential has Planck suppressed coupling to hidden sector h
- F-term of h acquires VEV $\sim m^2_{\text{hidden}}$

  $\Rightarrow$ induces μ term with $\mu \sim \lambda_{GM} \frac{m^2_{\text{hidden}}}{m_P}$
- Since μ_{GM} comes from single F-term, takes soft term $n = 1$ statistical draw
- Take $\lambda_{GM} = 1$
- Similar procedure to GSPQ (same anthropics)

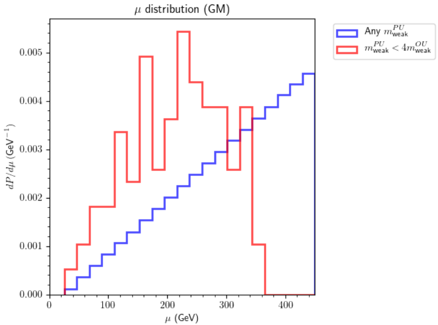
GM Kähler potential

$$K \supset \frac{\lambda_{GM}}{m_P} h^\dagger H_u H_d + \text{h.c.}$$

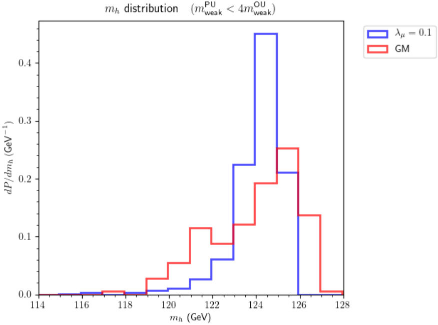
Parameter space

$$\begin{aligned} m_0 &\in [0.1, 20] \text{ TeV} \\ m_{1/2} &\in [0.5, 5] \text{ TeV} \\ -A_0 &\in [0, 50] \text{ TeV} \\ \mu &\in [25, 450] \text{ GeV} \\ m_A &\in [0.3, 10] \text{ TeV} \\ \tan\beta &\in [3, 60] \end{aligned}$$

Results



μ before and after anthropic selection



m_h for GM compared to GSPQ

Conclusion

Summary

- Both GSPQ and Giudice-Masiero solutions to μ problem have phenomenologically viable distributions in the landscape
- $m_h \sim 125$ GeV after anthropic selection in both, and sparticles tend to be pulled beyond current LHC reach
- In addition, GSPQ predicts PQ scale neatly confined to $f_a \sim (0.5 - 2.5) \times 10^{11}$ GeV

Questions?

Summary

Thanks!