Higgs and *Sparticle* mass predictions from the String Landscape

http://dx.doi.org/10.1103/PhysRevD.103.035031

Shadman Salam[1] Howard Baer[1] Dibyashree Sengupta[3] Vernon Barger[2]

[1]University of Oklahoma
[2]University of Wisconsin
[3]National Taiwan University

May 25th, Pheno 2021

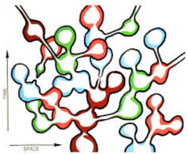
The UNIVERSITY of OKLAHOMA

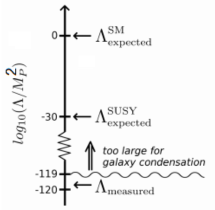
Table of Contents

Table of Contents

Anthropics + Landscape

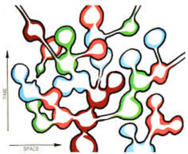
- The Λ_{cc} problem: Why $\Lambda_{cc} \simeq 10^{-120} M_P^2 \ll M_P^2$?

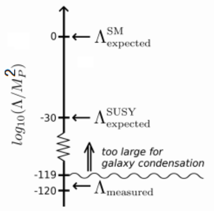




Anthropics + Landscape

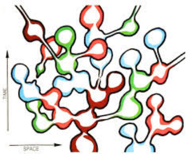
- The Λ_{cc} problem: Why $\Lambda_{cc} \simeq 10^{-120} M_P^2 \ll M_P^2$?
- Resolution in the String Landscape: We live in a Pocket Universe(PU) within an Eternally Inflating Multiverse $\Rightarrow$ a wide range of Λ_{cc} values for each PU.

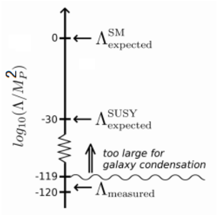




Anthropics + Landscape

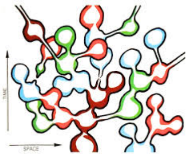
- The Λ_{cc} problem: Why $\Lambda_{cc} \simeq 10^{-120} M_P^2 \ll M_P^2$?
- Resolution in the String Landscape: We live in a Pocket Universe(PU) within an Eternally Inflating Multiverse $\Rightarrow$ a wide range of Λ_{cc} values for each PU.
- Weinberg's solution: Of Λ_{cc}^{PU} in the range $[-M_P^2, M_P^2]$, only $\Lambda_{cc}^{PU} \lesssim 10^{-120} M_P^2$ results in a livable PU.

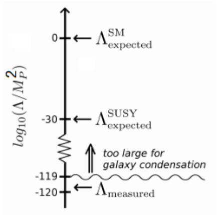




Anthropics + Landscape

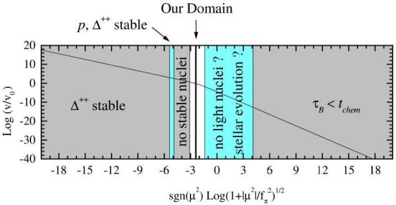
- The Λ_{cc} problem: Why $\Lambda_{cc} \simeq 10^{-120} M_P^2 \ll M_P^2$?
- Resolution in the String Landscape: We live in a Pocket Universe(PU) within an Eternally Inflating Multiverse $\Rightarrow$ a wide range of Λ_{cc} values for each PU.
- Weinberg's solution: Of Λ_{cc}^{PU} in the range $[-M_P^2, M_P^2]$, only $\Lambda_{cc}^{PU} \lesssim 10^{-120} M_P^2$ results in a livable PU.
- Much larger a value of $\Lambda_{cc} \Rightarrow$ no galaxy formation $\Rightarrow$ non-livable PU.





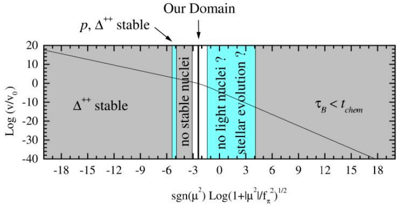
Anthropics + Landscape

- Similarly $m_{weak} \ll M_P$: Donoghue *et al.* $\Rightarrow$ if $m_{weak}^{PU} \gtrsim (2-5) m_{weak}^{OU} \Rightarrow$ violates **atomic principle** $\Rightarrow$ no observers as we know them.



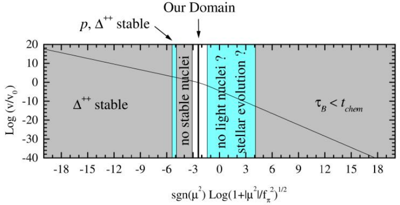
Anthropics + Landscape

- Similarly $m_{weak} \ll M_P$: Donoghue *et al.* $\Rightarrow$ if $m_{weak}^{PU} \gtrsim (2-5) m_{weak}^{OU} \Rightarrow$ violates **atomic principle** $\Rightarrow$ no observers as we know them.
- Large negative values correspond to bigger weak scale.



Anthropics + Landscape

- Similarly $m_{weak} \ll M_P$: Donoghue *et al.* $\Rightarrow$ if $m_{weak}^{PU} \gtrsim (2-5)m_{weak}^{OU} \Rightarrow$ violates **atomic principle** $\Rightarrow$ no observers as we know them.
- Large negative values correspond to bigger weak scale.
- We live in a narrow band $\leftrightarrow (2-5)m_{weak}^{OU}$ which corresponds to $\Delta_{EW} \lesssim 30$.



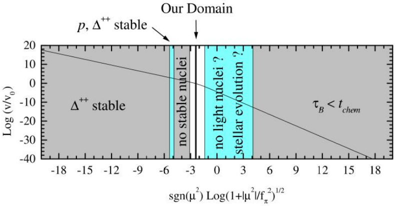
Anthropics + Landscape

- Similarly $m_{weak} \ll M_P$: Donoghue *et al.* $\Rightarrow$ if $m_{weak}^{PU} \gtrsim (2-5)m_{weak}^{OU} \Rightarrow$ violates **atomic principle** $\Rightarrow$ no observers as we know them.
- Large negative values correspond to bigger weak scale.
- We live in a narrow band $\leftrightarrow (2-5)m_{weak}^{OU}$ which corresponds to $\Delta_{EW} \lesssim 30$.
- Δ_{EW} is a model-independent measure of naturalness calculated from:

$$\frac{m_Z^2}{2} \simeq -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2})$$

and

$$\Delta_{EW} = |(\text{max RHS contribution})| / \left(\frac{m_Z^2}{2}\right).$$



Anthropics + Landscape

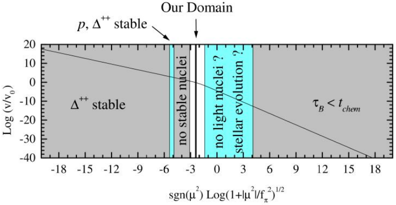
- Similarly $m_{weak} \ll M_P$: Donoghue *et al.* $\Rightarrow$ if $m_{weak}^{PU} \gtrsim (2-5)m_{weak}^{OU} \Rightarrow$ violates **atomic principle** $\Rightarrow$ no observers as we know them.
- Large negative values correspond to bigger weak scale.
- We live in a narrow band $\leftrightarrow (2-5)m_{weak}^{OU}$ which corresponds to $\Delta_{EW} \lesssim 30$.
- Δ_{EW} is a model-independent measure of naturalness calculated from:

$$\frac{m_Z^2}{2} \simeq -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2})$$

and

$$\Delta_{EW} = |(\text{max RHS contribution})| / \left(\frac{m_Z^2}{2}\right).$$

- For landscape, the condition is $(m_Z^{PU})^2/2$ and $m_Z^{PU} \neq m_Z^{OU} = 91.2$ GeV.



SUSY Breaking Scale

- For a fertile patch of the landscape with MSSM as low energy EFT, the distribution of PU vacua is given by m^2_{hidden}

$$dN_{vac}(m^2_{hidden}, m_{weak}, \Lambda_{cc}) = f_{SUSY} \cdot f_{EWSB} \cdot f_{cc} \cdot dm^2_{hidden}$$

with $m_{soft} \sim m^2_{hidden}/M_P$.

SUSY Breaking Scale

- For a fertile patch of the landscape with MSSM as low energy EFT, the distribution of PU vacua is given by m^2_{hidden}

$$dN_{vac}(m^2_{hidden}, m_{weak}, \Lambda_{cc}) = f_{SUSY} \cdot f_{EWSB} \cdot f_{cc} \cdot dm^2_{hidden}$$

with $m_{soft} \sim m^2_{hidden}/M_P$.

- It was advocated by Douglas, Susskind and Arkani-Hamed *et al.* that SUSY breaking scales should follow a power-law distribution

$$f_{SUSY}\left(m^2_{hidden}\right) \sim \left(m^2_{hidden}\right)^{2n_F+n_D-1}$$

then one expects a bias towards large soft terms i.e.

$$f_{SUSY} \sim m^n_{soft}$$

with $n = 2n_F + n_D - 1$.

SUSY Breaking Scale

- For a fertile patch of the landscape with MSSM as low energy EFT, the distribution of PU vacua is given by m^2_{hidden}

$$dN_{vac}(m^2_{hidden}, m_{weak}, \Lambda_{cc}) = f_{SUSY} \cdot f_{EWSB} \cdot f_{cc} \cdot dm^2_{hidden}$$

with $m_{soft} \sim m^2_{hidden}/M_P$.

- It was advocated by Douglas, Susskind and Arkani-Hamed *et al.* that SUSY breaking scales should follow a power-law distribution

$$f_{SUSY}\left(m^2_{hidden}\right) \sim \left(m^2_{hidden}\right)^{2n_F+n_D-1}$$

then one expects a bias towards large soft terms i.e.

$$f_{SUSY} \sim m^n_{soft}$$

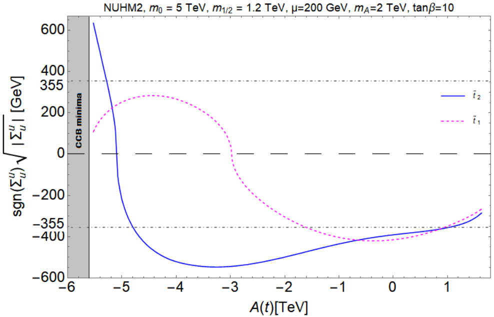
with $n = 2n_F + n_D - 1$.

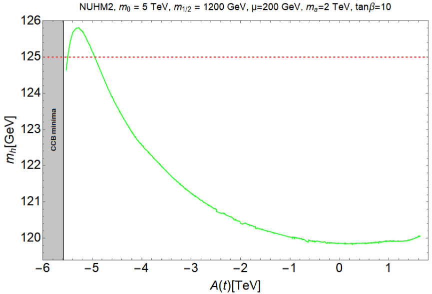
- The EWFT distribution f_{EWSB} is taken as

$$f_{EWSB} = \Theta(30 - \Delta_{EW})$$

which $\rightarrow$ large $A_t \rightarrow m_h \sim 125$ GeV, proper EWSB and $m^{PU}_{weak} \sim 4m^{OU}_{weak}$.

Consequence of Anthropics and Power law Distribution





Large negative $A(t) \Rightarrow$ smaller $\sqrt{\Sigma_u^u(\tilde{t}_{1,2})}$ contributions to the weak scale $\rightarrow$ bigger higgs mass.

Table of Contents

Alternative Soft-term Distribution

- Extra Dimensional theories $\rightarrow$ Compactification on some manifold (e.g. Calabi-Yau) $\rightarrow$ scalar fields (**moduli**).

Alternative Soft-term Distribution

- Extra Dimensional theories → Compactification on some manifold (e.g. Calabi-Yau) → scalar fields (**moduli**).
- Consistent low-energy EFT's require these moduli to be stablized (e.g. by gaining non-zero VEV ⇒ massive).

Alternative Soft-term Distribution

- Extra Dimensional theories → Compactification on some manifold (e.g. Calabi-Yau) → scalar fields (**moduli**).
- Consistent low-energy EFT's require these moduli to be stablized (e.g. by gaining non-zero VEV ⇒ massive).
- Broeckel *et al.* [1] investigated **moduli stabilization** in string models and derived the expected soft term distributions.

Alternative Soft-term Distribution

- Extra Dimensional theories → Compactification on some manifold (e.g. Calabi-Yau) → scalar fields (**moduli**).
- Consistent low-energy EFT's require these moduli to be stablized (e.g. by gaining non-zero VEV ⇒ massive).
- Broeckel *et al.* [1] investigated **moduli stabilization** in string models and derived the expected soft term distributions.
- They propose K*ä*hler moduli stabilization via:

Alternative Soft-term Distribution

- Extra Dimensional theories → Compactification on some manifold (e.g. Calabi-Yau) → scalar fields (**moduli**).
- Consistent low-energy EFT's require these moduli to be stablized (e.g. by gaining non-zero VEV ⇒ massive).
- Broeckel *et al.* [1] investigated **moduli stabilization** in string models and derived the expected soft term distributions.
- They propose K*ä*hler moduli stabilization via:
  1. KKLT (non-perturbative effects in flux compactifications) $\xrightarrow{\textit{leads to}}$ a power-law draw on soft terms i.e.

$$f_{SUSY} = m^n_{soft}.$$

Alternative Soft-term Distribution

- Extra Dimensional theories → Compactification on some manifold (e.g. Calabi-Yau) → scalar fields (**moduli**).
- Consistent low-energy EFT's require these moduli to be stablized (e.g. by gaining non-zero VEV ⇒ massive).
- Broeckel *et al.* [1] investigated **moduli stabilization** in string models and derived the expected soft term distributions.
- They propose K*ä*hler moduli stabilization via:
  1. KKLT (non-perturbative effects in flux compactifications) $\xrightarrow{\textit{leads to}}$ a power-law draw on soft terms i.e.
  $$f_{SUSY} = m_{soft}^n.$$
  2. Large Volume Scenario (LVS) (Perturbative & Non-perturbative) $\xrightarrow{\textit{leads to}}$ a logarithmic draw, i.e.
  $$f_{SUSY} = \log(m_{soft}).$$

Table of Contents

What does the Landscape & LHC data allude to?

- We investigate the phenomenology of LVS vs KKLT SUSY breaking scales [2].

What does the Landscape & LHC data allude to?

- We investigate the phenomenology of LVS vs KKLT SUSY breaking scales [2].
- Results presented within gravity-mediated Non-Universal 3 Higgs Doublet Model (NUHM3) with parameters:

$$m_0(1,2),\ m_0(3),\ m_{1/2},\ A_0,\ tan\beta,\ \mu,\ m_A$$

What does the Landscape & LHC data allude to?

- We investigate the phenomenology of LVS vs KKLT SUSY breaking scales [2].
- Results presented within gravity-mediated Non-Universal 3 Higgs Doublet Model (NUHM3) with parameters:

$$m_0(1,2),\ m_0(3),\ m_{1/2},\ A_0,\ tan\beta,\ \mu,\ m_A$$

- Only points with $\Delta_{EW} \lesssim 30$ are considered (naturalness resulting from anthropics).

What does the Landscape & LHC data allude to?

- We investigate the phenomenology of LVS vs KKLT SUSY breaking scales [2].
- Results presented within gravity-mediated Non-Universal 3 Higgs Doublet Model (NUHM3) with parameters:

$$m_0(1,2),\ m_0(3),\ m_{1/2},\ A_0,\ tan\beta,\ \mu,\ m_A$$

- Only points with $\Delta_{EW} \lesssim 30$ are considered (naturalness resulting from anthropics).
- Using these parameters, Higgs and sparticle mass spectrum were calculated using ISAJET code.

What does the Landscape & LHC data allude to?

- We investigate the phenomenology of LVS vs KKLT SUSY breaking scales [2].
- Results presented within gravity-mediated Non-Universal 3 Higgs Doublet Model (NUHM3) with parameters:

$$m_0(1,2),\ m_0(3),\ m_{1/2},\ A_0,\ tan\beta,\ \mu,\ m_A$$

- Only points with $\Delta_{EW} \lesssim 30$ are considered (naturalness resulting from anthropics).
- Using these parameters, Higgs and sparticle mass spectrum were calculated using ISAJET code.
- The results are then compared to $f_{SUSY} = m_{soft}^n$ draw with $n = 0$ (uniform distribution) and $n = 1$ (text book example of a single F-breaking field distributed as a complex number in the landscape).

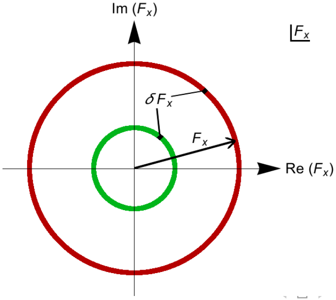
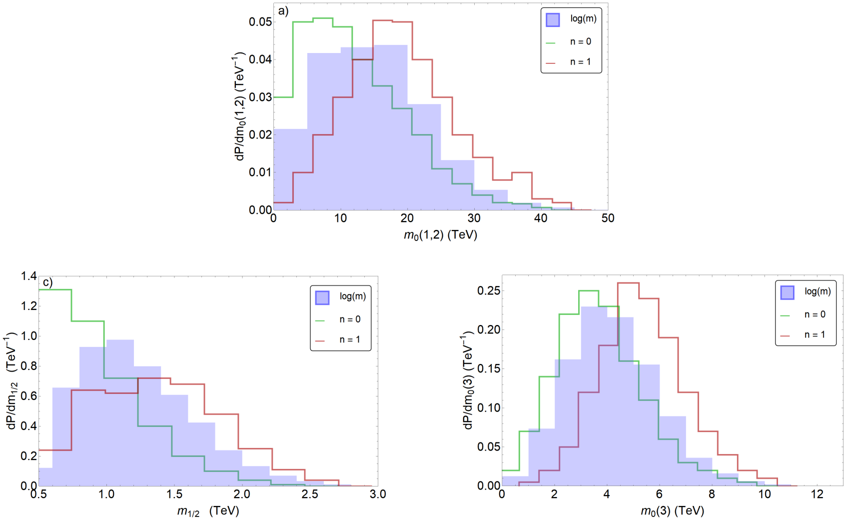
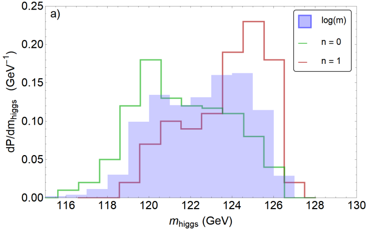


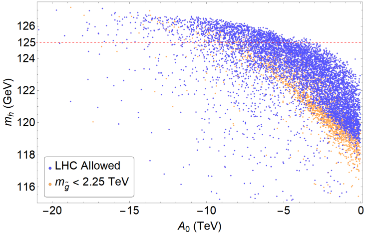
Table of Contents

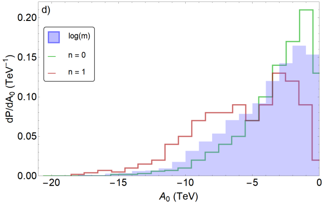
Results


a)
log(m)
n = 0
n = 1
dP/dm$_0$(1,2) (TeV^{-1})
m_0(1,2) (TeV)
c)
dP/dm$_{1/2}$ (TeV^{-1})
$m_{1/2}$ (TeV)
dP/dm$_0$(3) (TeV^{-1})
m_0(3) (TeV)

Results





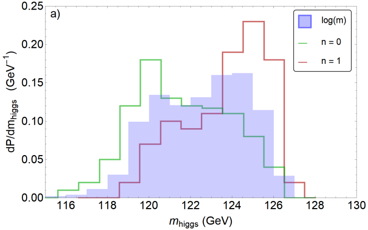


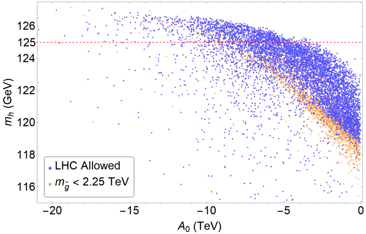
- $n = 0$ scan prefers smaller A_0 while log-draw and $n = 1$ draw are stretched to higher values.

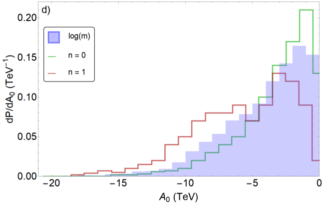
Higgs and *Sparticle* mass predictions from the String Landscape

Baer, Barger, Salam, Sengupta

Results

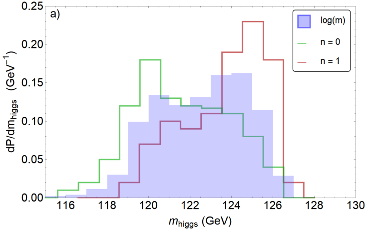


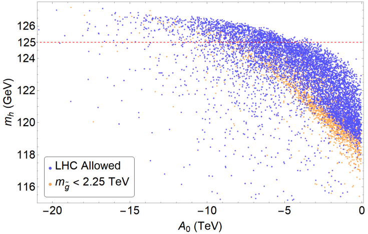


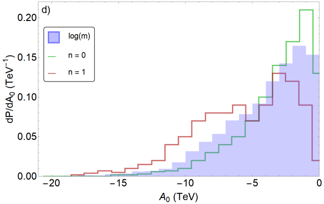


- $n = 0$ scan prefers smaller A_0 while log-draw and $n = 1$ draw are stretched to higher values.
- Larger $A_0 \Rightarrow$ large stop mixing $\Rightarrow$ large radiative corrections to $m_h \Rightarrow$ peak of higgs distribution 125 GeV.

Results

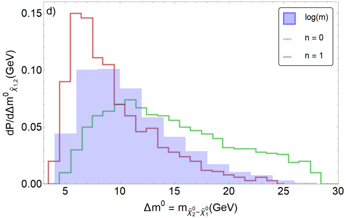


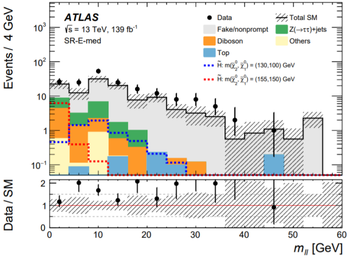


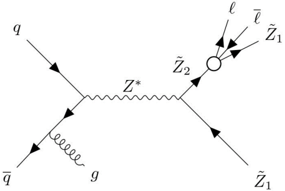


- $n = 0$ scan prefers smaller A_0 while log-draw and $n = 1$ draw are stretched to higher values.
- Larger $A_0 \Rightarrow$ large stop mixing $\Rightarrow$ large radiative corrections to $m_h \Rightarrow$ peak of higgs distribution 125 GeV.
- This is a testable prediction of the string landscape: A SM-like higgs $m_h \sim 125$ GeV is reflective of large mixing in the stop sector.

Results-Soft Dilepton Signal

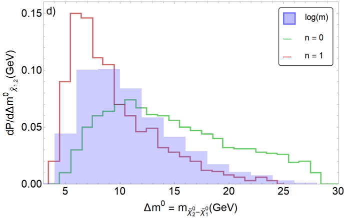


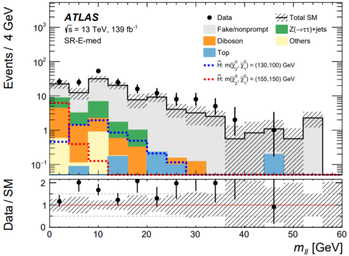


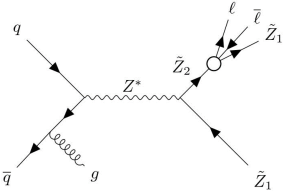


- $m_Z^2/2 \simeq -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde t_{1,2}) \rightarrow \mu$ is SUSY conserving $\Rightarrow$ too big a value of $\mu \rightarrow$ too big m_{weak} unless one finetunes.

Results-Soft Dilepton Signal

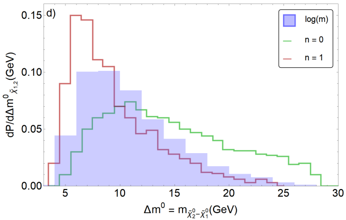


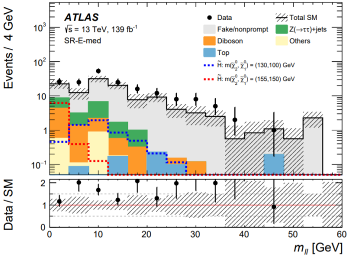


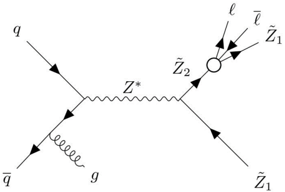


- $m_Z^2/2 \simeq -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde t_{1,2}) \rightarrow \mu$ is SUSY conserving $\Rightarrow$ too big a value of $\mu \rightarrow$ too big m_{weak} unless one finetunes.
- String landscape favors $\mu(\sim 100 - 350\text{GeV}) \ll m_{soft} \Rightarrow$ small $\mu \rightarrow$ **light higgsinos**.

Results-Soft Dilepton Signal

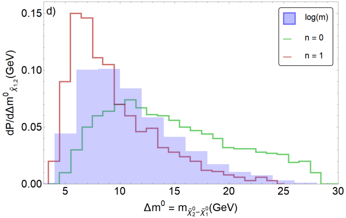


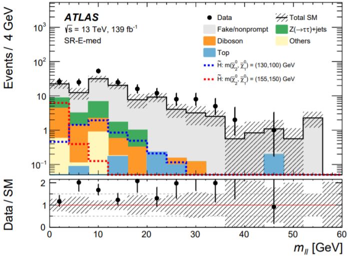


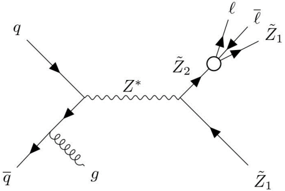


- $m_Z^2/2 \simeq -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \to \mu$ is SUSY conserving $\Rightarrow$ too big a value of $\mu \to$ too big m_{weak} unless one finetunes.
- String landscape favors $\mu(\sim 100 - 350\text{GeV}) \ll m_{soft} \Rightarrow$ small $\mu \to$ **light higgsinos**.
- Small μ has a signature in the higgsino pair-production channel.

Results-Soft Dilepton Signal

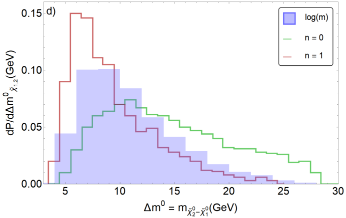


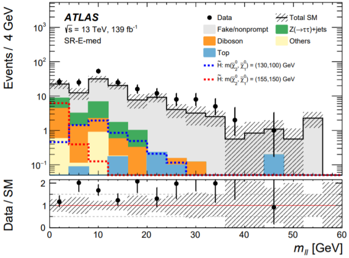


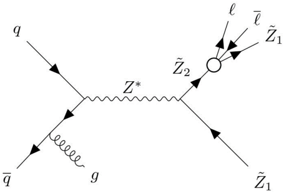


- $m_Z^2/2 \simeq -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde{t}_{1,2}) \to \mu$ is SUSY conserving $\Rightarrow$ too big a value of $\mu \to$ too big m_{weak} unless one finetunes.
- String landscape favors $\mu(\sim 100 - 350\text{GeV}) \ll m_{soft} \Rightarrow$ small $\mu \to$ **light higgsinos**.
- Small μ has a signature in the higgsino pair-production channel.
- The log-draw gives a broad peak structure $\sim 8 - 12$ GeV.

Results-Soft Dilepton Signal

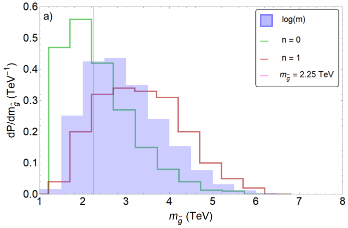


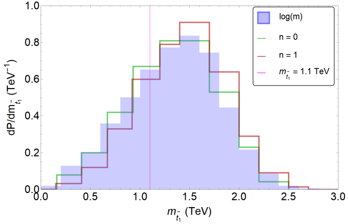


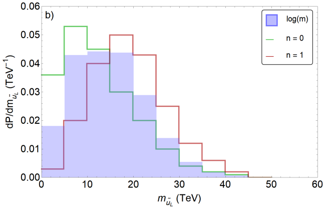


- $m_Z^2/2 \simeq -m_{H_u}^2 - \mu^2 - \Sigma_u^u(\tilde t_{1,2}) \to \mu$ is SUSY conserving $\Rightarrow$ too big a value of $\mu \to$ too big m_{weak} unless one finetunes.
- String landscape favors $\mu(\sim 100 - 350\text{GeV}) \ll m_{soft} \Rightarrow$ small $\mu \to$ **light higgsinos**.
- Small μ has a signature in the higgsino pair-production channel.
- The log-draw gives a broad peak structure $\sim 8 - 12$ GeV.
- Current search results from ATLAS with $139 fb^{-1}$ data $\to$ slight excess in bins with $m_{ll} \sim 5 - 10$ GeV.[3]

Results

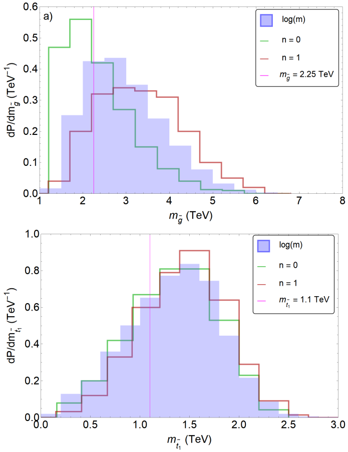


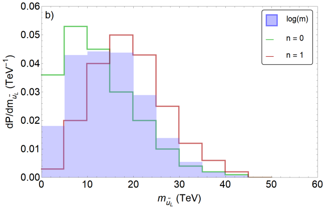




- Log-draw and $n = 1$ draw both pull the gluino mass up to peaks roughly $2.5 - 3$ TeV and $3 - 6$ TeV.

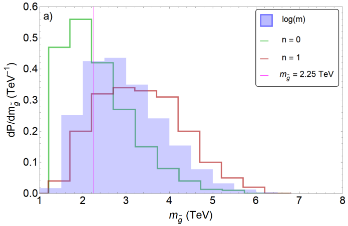
Results

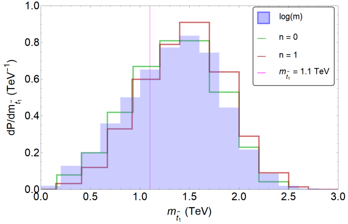


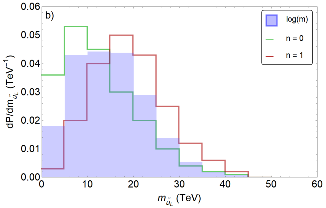


- Log-draw and $n = 1$ draw both pull the gluino mass up to peaks roughly $2.5 - 3$ TeV and $3 - 6$ TeV.
- Currently LHC excludes $m_{\tilde{g}} \lesssim 2.25$ TeV.

Results

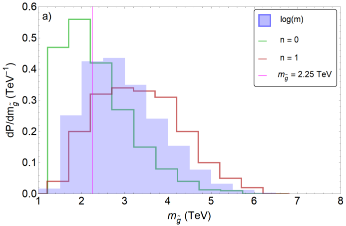


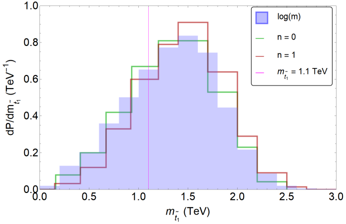


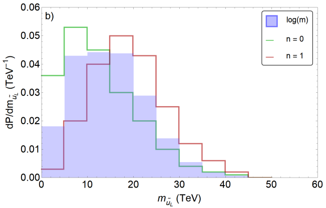


- Log-draw and $n = 1$ draw both pull the gluino mass up to peaks roughly $2.5 - 3$ TeV and $3 - 6$ TeV.
- Currently LHC excludes $m_{\tilde{g}} \lesssim 2.25$ TeV.
- Top squark distribution peaks around 1.5 TeV, beyond current bounds at $\gtrsim 1.1$ TeV.

Results







- Log-draw and $n = 1$ draw both pull the gluino mass up to peaks roughly $2.5 - 3$ TeV and $3 - 6$ TeV.
- Currently LHC excludes $m_{\tilde{g}} \lesssim 2.25$ TeV.
- Top squark distribution peaks around 1.5 TeV, beyond current bounds at $\gtrsim 1.1$ TeV.
- First and Second generation squarks yield peaks in the $10 - 40$ TeV range $\rightarrow$ decoupling solution to the SUSY flavor and CP problem.

Table of Contents

Conclusions

- Why String Landscape?

Conclusions

- Why String Landscape?
  1. Emerges automatically in IIB flux compactifications.

Conclusions

- Why String Landscape?
  1. Emerges automatically in IIB flux compactifications.
  2. String Theory is predictive in a statistical sense from the string landscape.

Conclusions

- Why String Landscape?
  1. Emerges automatically in IIB flux compactifications.
  2. String Theory is predictive in a statistical sense from the string landscape.
  3. Successful in solving Λ_{cc} problem when combined with anthropics.

Conclusions

- Why String Landscape?
  1. Emerges automatically in IIB flux compactifications.
  2. String Theory is predictive in a statistical sense from the string landscape.
  3. Successful in solving Λ_{cc} problem when combined with anthropics.

Conclusions

- Why String Landscape?
  1. Emerges automatically in IIB flux compactifications.
  2. String Theory is predictive in a statistical sense from the string landscape.
  3. Successful in solving Λ_{cc} problem when combined with anthropics.
- Various statistical distributions for different moduli stabilization models (KKLT, LVS, etc) have been proposed.

Conclusions

- Why String Landscape?
  1. Emerges automatically in IIB flux compactifications.
  2. String Theory is predictive in a statistical sense from the string landscape.
  3. Successful in solving Λ_{cc} problem when combined with anthropics.
- Various statistical distributions for different moduli stabilization models (KKLT, LVS, etc) have been proposed.
- Here we have examined the soft-term draw of $\log(m_{soft})$ as proposed by Broeckel *et. al.*

Conclusions

- Why String Landscape?
  1. Emerges automatically in IIB flux compactifications.
  2. String Theory is predictive in a statistical sense from the string landscape.
  3. Successful in solving Λ_{cc} problem when combined with anthropics.
- Various statistical distributions for different moduli stabilization models (KKLT, LVS, etc) have been proposed.
- Here we have examined the soft-term draw of $\log(m_{soft})$ as proposed by Broeckel *et. al.*
- Statistics of the SUSY-breaking scale from the landscape successfully validates what the LHC sees:
  -**A SM-like Higgs with $m_h \simeq 125$ GeV with sparticles lifted beyond current LHC limits other than the elusive light *higgsinos***.
  -**The *gluino* and *top squarks* have peak distributions beyond current LHC limits**.

Conclusions

- Why String Landscape?
  1. Emerges automatically in IIB flux compactifications.
  2. String Theory is predictive in a statistical sense from the string landscape.
  3. Successful in solving Λ_{cc} problem when combined with anthropics.
- Various statistical distributions for different moduli stabilization models (KKLT, LVS, etc) have been proposed.
- Here we have examined the soft-term draw of $\log(m_{soft})$ as proposed by Broeckel *et. al.*
- Statistics of the SUSY-breaking scale from the landscape successfully validates what the LHC sees:
  -A SM-like Higgs with $m_h \simeq 125$ GeV with sparticles lifted beyond current LHC limits other than the elusive light *higgsinos*.
  -The *gluino* and *top squarks* have peak distributions beyond current LHC limits.
- Dark matter content: higgsino-like WIMP and *axion*.

References

I. Broeckel, M. Cicoli, A. Maharana, K. Singh, K. Sinha, Moduli stabilisation and the statistics of susy breaking in the landscape, Journal of High Energy Physics 2020 (10) (Oct 2020). doi:10.1007/jhep10(2020)015.
URL http://dx.doi.org/10.1007/JHEP10(2020)015

H. Baer, V. Barger, S. Salam, D. Sengupta, Landscape higgs boson and sparticle mass predictions from a logarithmic soft term distribution, Phys. Rev. D 103 (2021) 035031. doi:10.1103/PhysRevD.103.035031.
URL https://link.aps.org/doi/10.1103/PhysRevD.103.035031

G. Aad, B. Abbott, D. Abbott, A. Abed Abud, K. Abeling, D. Abhayasinghe, S. Abidi, O. AbouZeid, N. Abraham, H. Abramowicz, et al., Searches for electroweak production of supersymmetric particles with compressed mass spectra in s=13tev pp collisions with the atlas detector, Physical Review D 101 (5) (Mar 2020). doi:10.1103/physrevd.101.052005.
URL http://dx.doi.org/10.1103/PhysRevD.101.052005