SUSY Prospects at the HL-LHC

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Problems of the Standard Model

- **Gauge Hierarchy Problem (GHP)**
  - The Higgs boson is a fundamental *scalar* – m_h has no custodial symmetry:
  - Quadratic sensitivity of Higgs mass parameter:

$$\delta m_h^2 \simeq \frac{3}{4\pi^2}\left(-y_t^2 + \frac{g^2}{4} + \frac{g^2}{8\cos^2\theta_w} + \lambda\right)\Lambda^2 + \cdots$$

  - With $\Lambda \sim M_{\mathrm{GUT}}$ or M_{Pl}, Higgs mass is destabilized.
  - Requires fine-tuning at level $\sim m_Z^2/\Lambda^2 \ll 1$.
- **Driver of Electroweak Symmetry Breaking (EWSB)**
  - We know $SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{EM}}$ at $v \simeq 246$ GeV.
  - But in the SM, the Higgs potential is put in by hand:

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4$$

  - Open question: *what dynamics drives spontaneous symmetry breaking (SSB)?*
  - Why does EWSB occur at the weak scale, not at GUT/Planck scales?

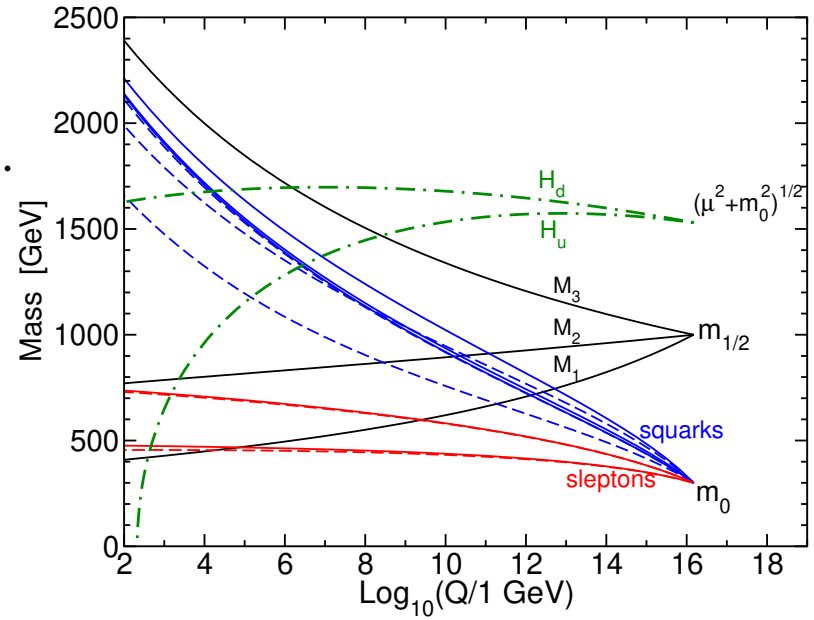
Supersymmetry as a Candidate Solution

- **Stabilizing the weak scale – SUSY soft parameters not far away from weak scale**
  - Boson–fermion symmetry cancels quadratic divergences if SUSY is broken softly.
- **Radiative EWSB**
  - Large top Yukawa y_t drives $m^2_{H_u}$ negative through RGE running:

$$\frac{dm^2_{H_u}}{d\ln Q} \sim -\frac{3y_t^2}{8\pi^2}\left(m^2_{Q_3} + m^2_{U_3} + A_t^2\right) + \cdots$$

  - $m_t \sim 100 - 200$ GeV required for radiative EWSB. Already predicted in 1982 long before top was discovered in 1995!

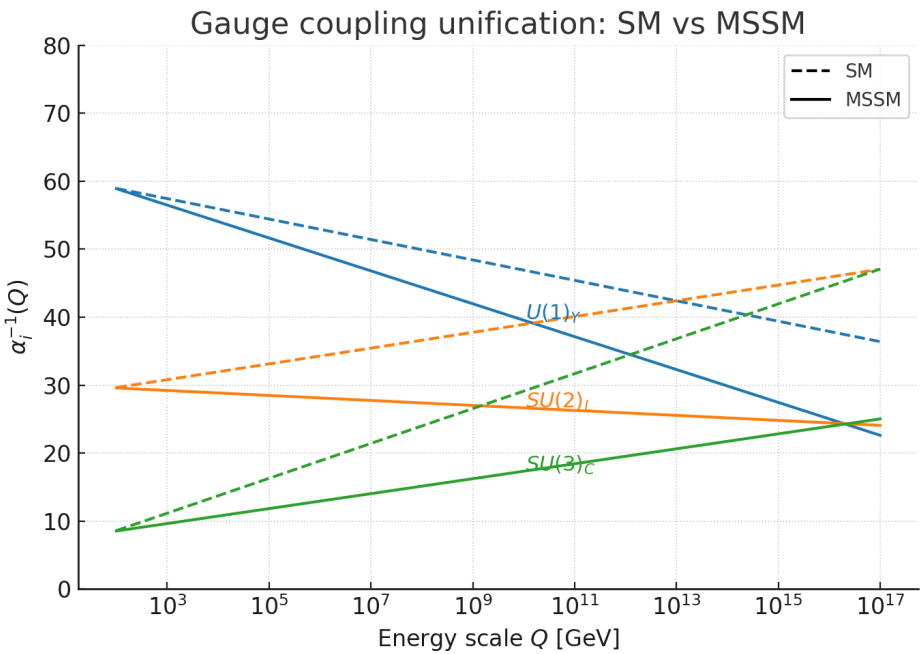
    [L E. Ibanez, G G. Ross 1982, Alvarez-Gaume et al. 1983]
  - Dynamical origin of Higgs VEV at

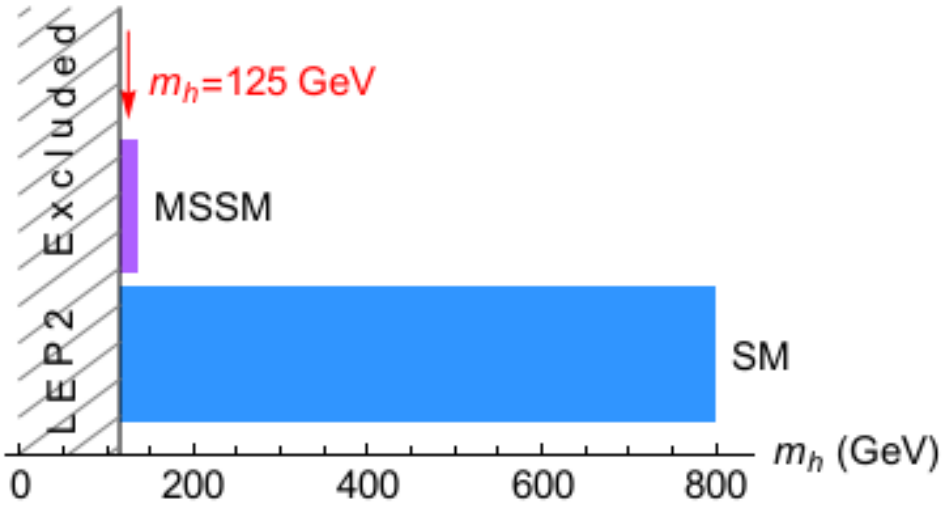


[arXiv:hep-ph/9709356]

Supersymmetry as a Candidate Solution

- **Gauge coupling unification**
- **Higgs mass "just right"**
  - MSSM: $m_h \lesssim 130$ GeV vs. SM: $m_h \lesssim 800$ GeV (unitarity).
  - Tree-level: $m_h \lesssim m_z \cos 2\beta$, but loop corrections from top/stop break this relationship.





Motivations – Criteria for a Good MSSM Model

1. Phenomenologically viable.
2. Stabilize the weak scale – low fine tuning / naturalness.
3. Support gauge coupling unification.
4. Support radiative EWSB. ($m^2_{H_u}$ barely negative at weak scale)

- *pMSSM approach often missed or unable to address.
- *The majority of pMSSM parameter scan space are either
  - leave $m^2_{H_u} > 0$, leaving EW symmetry unbroken or
  - drive $m^2_{H_u} \ll 0$ breaking charge and color symmetry (CCB)
  - – not a livable universe.

Quantifying Fine Tuning from bottom-up: Δ_{EW} – Practical Naturalness

- From the minimization of the Higgs potential:

$$m_Z^2/2 = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

- Σ_u^u and Σ_d^d terms contain one and two loop corrections.
-

$$\Delta_{EW} \equiv max|\text{terms on RHS}|/(\text{m}_\text{Z}^2/2)$$

- Interpretation:
  - Each independent contribution should be $\lesssim m_Z^2/2$.
  - Only weak-scale parameters used: model-independent & conservative. Can also be implemented in pMSSM study.
  - $\Delta_{EW} \sim 30 \Rightarrow 3\%$ fine tuning (Δ_{EW} upper bound).
  - $\Rightarrow \mu \lesssim 350$ GeV.

Natural MSSM Spectrum (Bottom-up View)

State	Bounds from naturalness (3%)
μ (higgsinos)	$\lesssim$ 350 GeV
$\tilde{t}_1$	$\lesssim$ 3 TeV
$\tilde{g}$	$\lesssim$ 6 TeV
First/second gen. scalars	$\lesssim$ 40 TeV

- Light higgsinos LSP is the key prediction of *natural SUSY.*

The Little Hierarchy Problem

- **m_h is too "light" yet too "heavy":**
  - 1-loop contribution by top / stop:

$$\Delta m_h^2 \simeq \frac{3m_t^4}{2\pi^2 v^2}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}_1} m_{\tilde{t}_2}}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}}\right)\right],$$

    where $X_t = A_t - \mu \cot\beta$ is the stop mixing parameter.
  - Either $\tilde{t}$ needs to be very heavy $\Rightarrow$ destabilize m_{weak}
  - or $\tilde{t}$ are in maximal mixing states (fine tuning?).

- **The μ problem:**
  - $\mu H_u H_d$ is SUSY-conserving $\Rightarrow \mu \sim M_{\text{Pl}}$.
  - But phenomenology requires $\mu \sim \mathcal{O}(100)$ GeV.

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    where $X_t = A_t - \mu \cot\beta$ is the stop mixing parameter.
  - Either $\tilde{t}$ needs to be very heavy $\Rightarrow$ destabilize m_{weak}
  - or $\tilde{t}$ are in maximal mixing states (fine tuning?).
    - **No:** all it said is $A_t \gg \mu$.
    - Large A_t also tends to suppress Δ_{EW} (cancellation between terms in stop loop contribution).

- **The μ problem:**
  - μ term is SUSY-conserving $\Rightarrow$ not arise from SUSY breaking.
  - Many solutions exist (e.g., Kim-Nilles mechanism (KN) ...).

Lessons from Top-down I – SUSY Breakings

- SUSY spectrum arise from *SUSY breaking* $\Rightarrow$ sensible way to study collider phenomenology from SUSY breakings.
- Criteria Refresh:
  1. phenomenologically viable
     - Supports $m_h \sim 125$ GeV (support large A_0 term)
     - Flavor constraints, ...
  2. low fine tuning ($\Delta_{EW} \lesssim 30$)
  3. gauge unification compatible
  4. radiative EWSB

Failed to satisfy criteria:

- CMSSM / mSUGRA
- GMSB (gravitino problems)
- mAMSB / Split / PeV SUSY (A_0 suppressed, generated from loop level.)
- gaugino MSB (A_0 suppressed, stau LSP ruled out.)

Workable:

- NUHM2–4
- Natural AMSB (nAMSB) – presence of bulk trilinear term, unlike mAMSB.
- Generalized Mirage Mediation (GMM) – a mixture of NUHM & nAMSB

Lessons from Top-down I – SUSY Breakings

- Study from SUSY breaking models (NUHM, nAMSB, GMM) involve much less parameters than pMSSM (19 parameters) and also much narrower ranges.

Framework	Independent input parameters at GUT scale
NUHM2-4	$m_0(i)$, $m_{1/2}$, A_0, $\tan\beta$, $m_{H_u}^2$, $m_{H_d}^2$
nAMSB	$m_0(i)$, $m_{3/2}$, A_0, $\tan\beta$, $m_{H_u}^2$, $m_{H_d}^2$

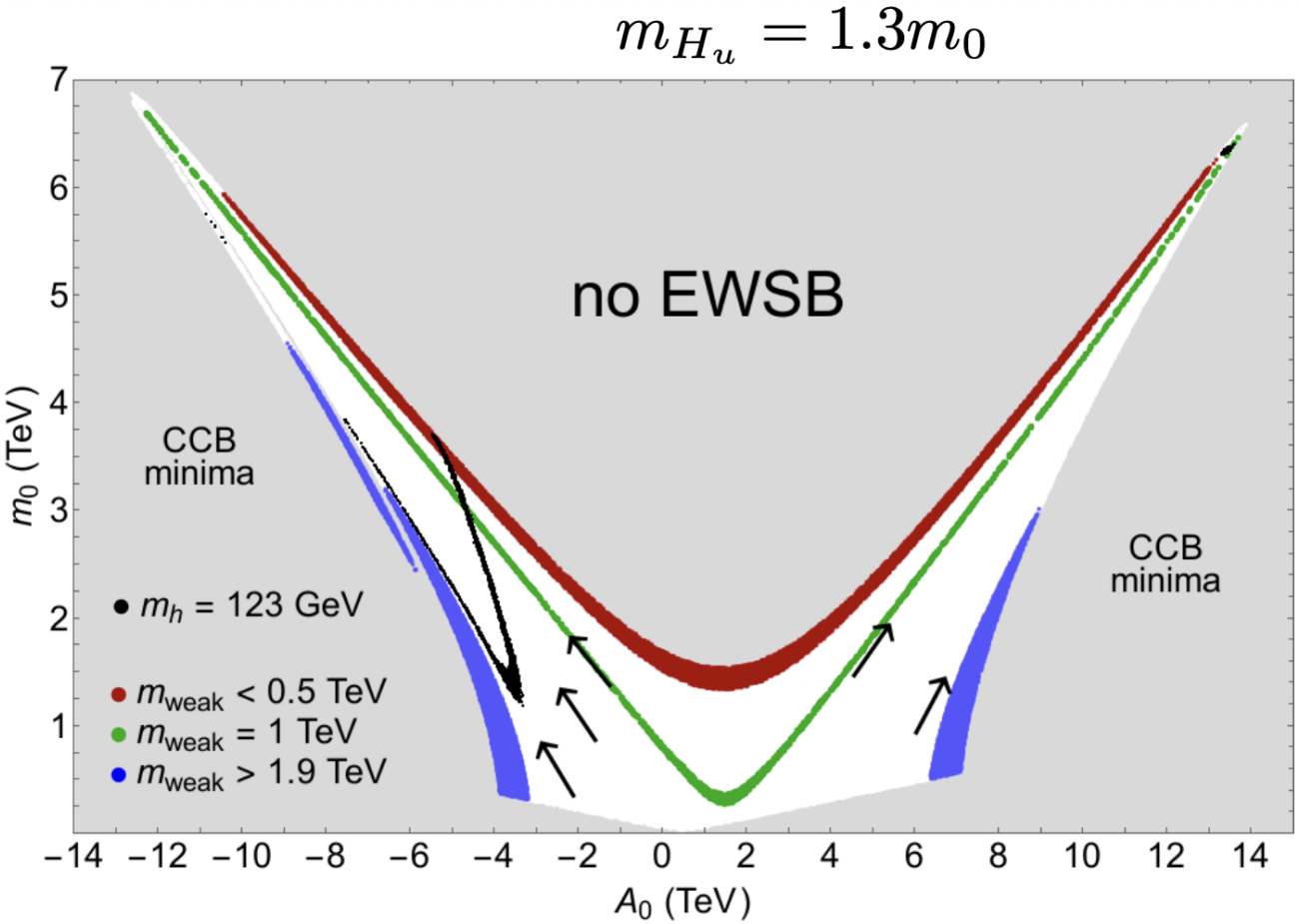
- $m_{H_u}^2$, $m_{H_d}^2$ at GUT scale can be exchanged for μ, m_A at weak scale.
- 6-8 parameters $\Rightarrow$ weak scale MSSM spectrum completely fixed.
- **gauge unification & radiative EWSB are guaranteed.**
- Naturalness further imposes 100 GeV $\lesssim \mu \lesssim$ 350 GeV.
- $m_h \sim 125$ GeV imposes A_0 multi-TeV while tens-TeV A_0 always leads CCB.
- many existing computation packages to run RGE to generate weak scale spectrum: Isajet, SOFTSUSY, ...

Lessons from Top-down II – Stringy Naturalness

- **Landscape picture:** Vast ensemble of vacua (10^{500} arise from string compactification into 4D) with SUSY breaking mediated in many ways.
  - Visible sector contains MSSM as LEFT.
- **Statistical bias:** In fertile patch of vacua with MSSM as weak scale effective theory but with no preferred SUSY breaking scale:
  - $dN_{vac} \sim f_{SUSY} \cdot f_{EWSB} \cdot dm_{sosft}$
  - Douglas ansatz: $f_{SUSY} \sim m^{2n_F+n_D-1}$
- **Anthropic veto:**
  - Balanced by anthropic principle[2]. Too large $m_{\rm soft} \Rightarrow$ no viable EWSB, universe inhospitable.
  - ABDS window: pocket universe arise from landscape: $m_{weak}^{PU} \sim (0.5-5) m_{weak}^{OU}$.
  - Out of ABDS window: complex nuclei unable to form.
- **Takeaway Message:** Landscape provides a dynamical reason that SUSY soft terms tend to be pulled to largest possible value that does not destabilize the weak scale

[2] As Weinberg used it to solve the cosmological constant problem – another fine-tuning problem plagued the SM

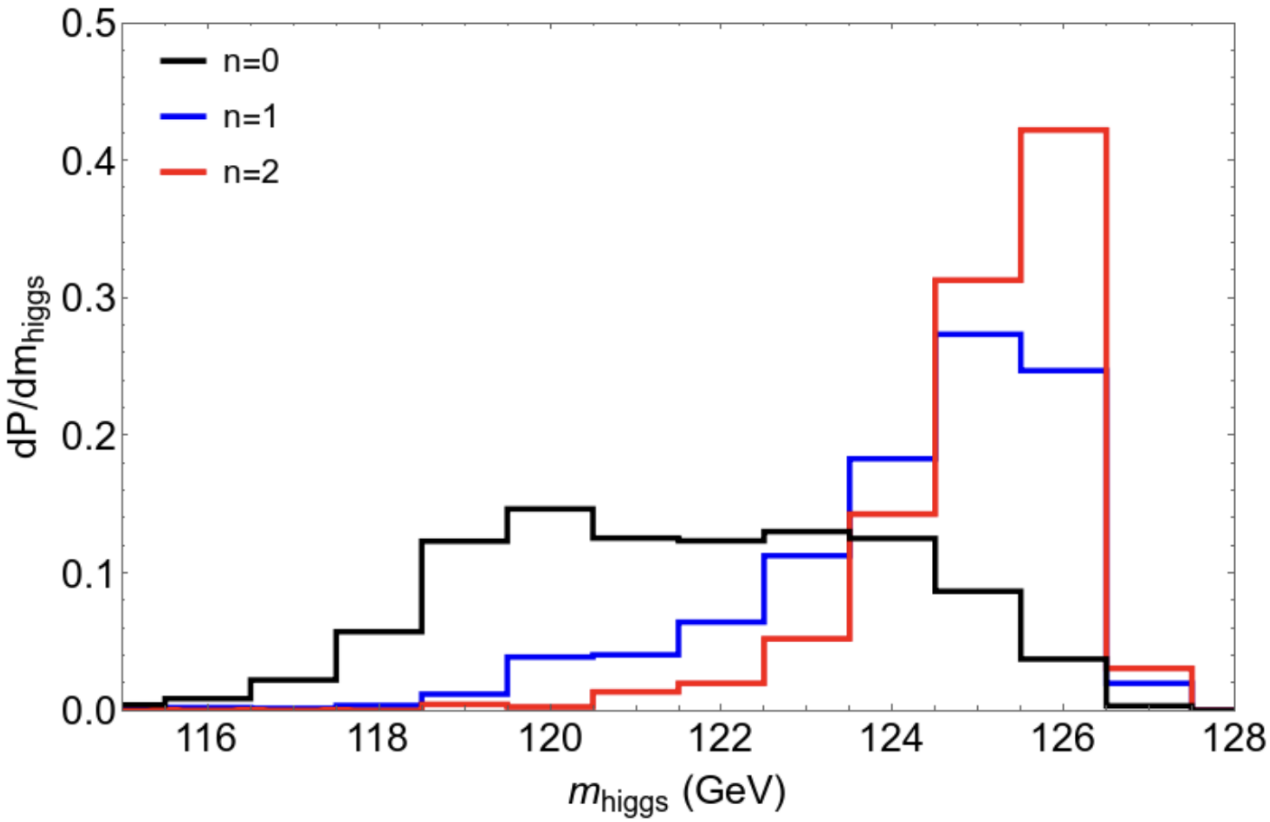
Lessons from Top-down II – Stringy Naturalness



statistical draw to large soft terms balanced by anthropic draw toward red (m(weak)~100 GeV): then m(Higgs)~125 GeV and natural SUSY spectrum!

[Baer, Barger, Savoy, Serce, PLB758 (2016) 113]

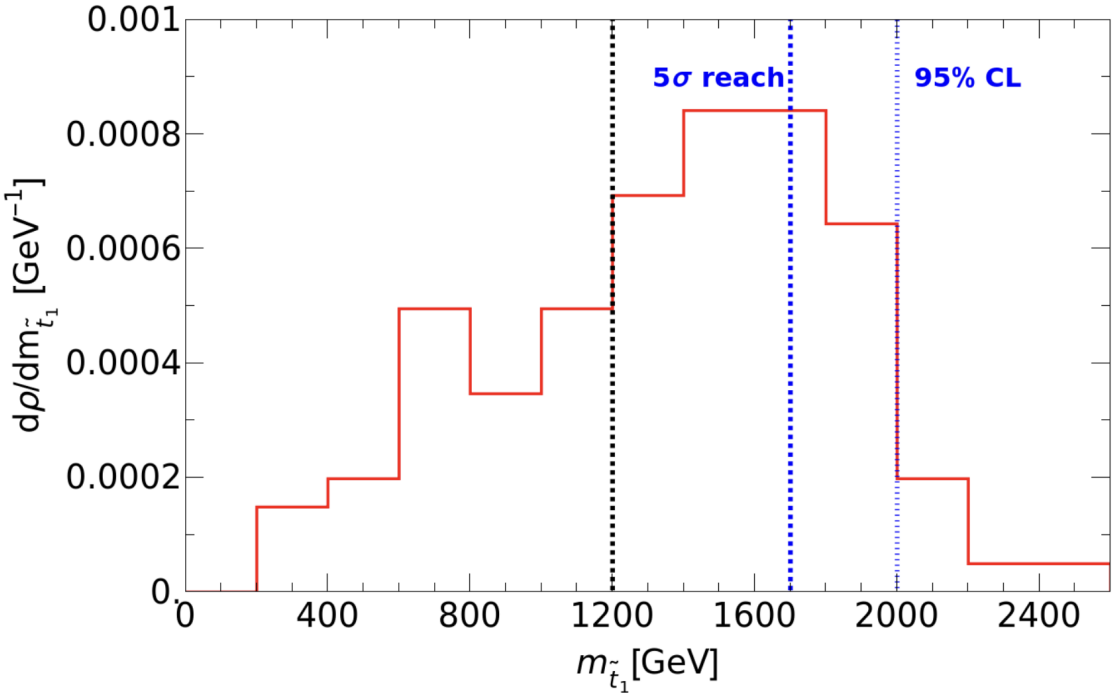
Landscape Prediction: the Higgs Mass



Probability distribution for m_h in landscape scans: peak at 124–126 GeV for $n = 1, 2$ power law draw.

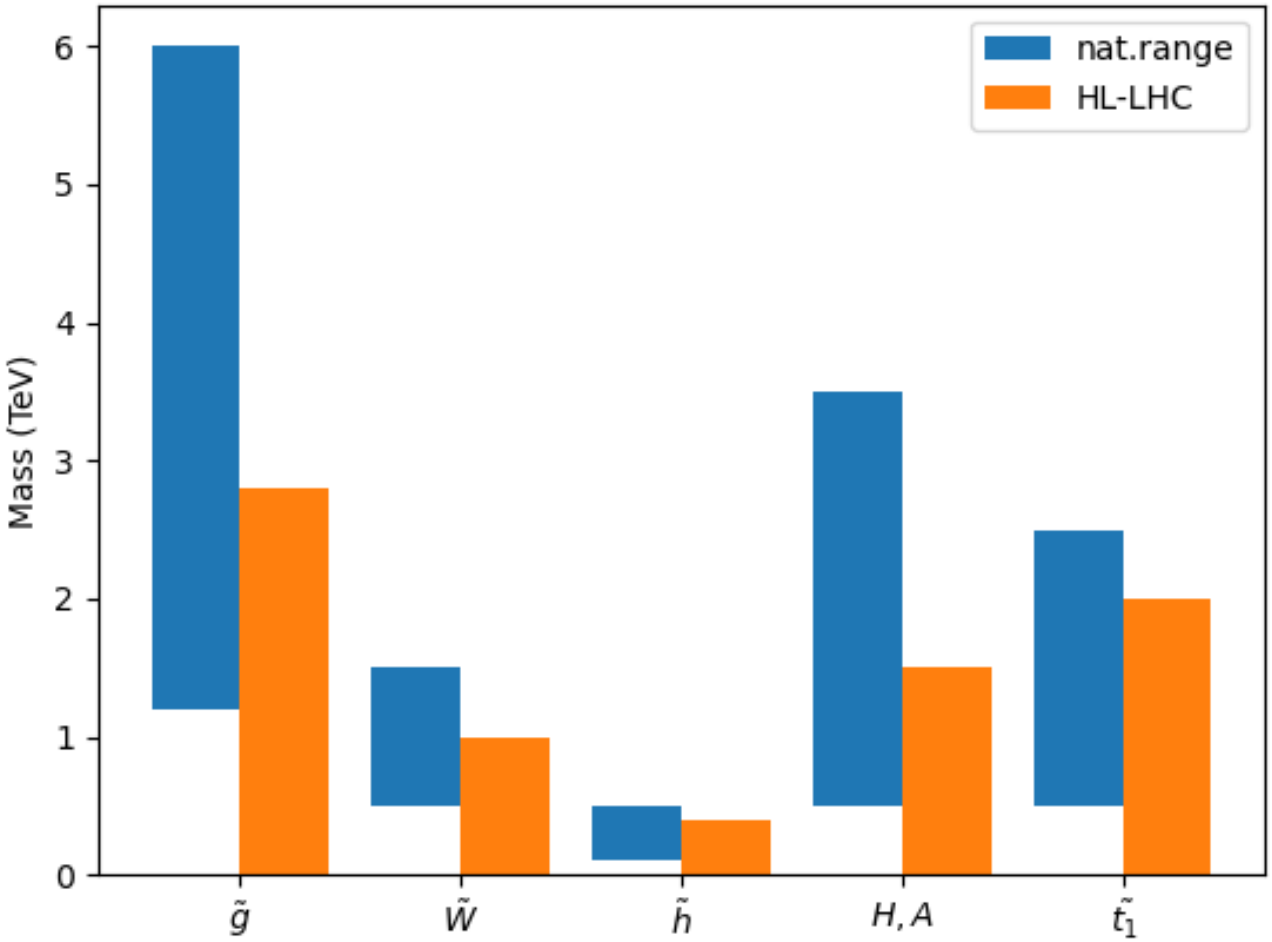
[Baer, Barger, Savoy, Serce, PLB758 (2016) 113]

Landscape Prediction: the Stop Mass – Best Chance



- Probability distribution for $m_{\tilde{t}_1}$ in landscape scans for $n = 1$ power law draw.
- Blue vertical lines are projections reach for HL-LHC.
- Fully accessible in HL-LHC – either something shows up or natural SUSY ruled out!

Landscape Spectrum vs. HL-LHC Overview



[arXiv:2502.10879]

Hints of natural SUSY? higgsino excess

- Spectrum: $\tilde{\chi}_1^0,\ \tilde{\chi}_2^0,\ \tilde{\chi}_1^\pm \approx \mu$ with $\Delta m \sim$ 5–20 GeV.
- Signature: soft leptons/jets; ISR-boosted; $m_{\ell\ell}$ edge $\sim \Delta m$.
- Run 2: $\sim 2\sigma$ hints in soft-ℓ channels; HL-LHC will be decisive.

Conclusions

- SUSY breaking mechanism provides a more convenient tool to study MSSM spectrum.
- Δ_{EW} is the guiding criterion for naturalness.
- Light higgsinos mandatory by naturalness;
- Landscape perspective:
  - $m_h \sim 125$ GeV predicted.
  - the lightest stop fully within HL-LHC reach.
- Hints: higgsino excess the current LHC search.

Backup: Kim-Nilles Mechanism (KN)

- DFSZ-type axion models, PQ field ϕ couples to the two Higgs doublets via $\phi^2 H_u H_d$ – reminiscent of the SUSY μ term $\mu H_u H_d$.
- KN: If H_u and H_d carry the same PQ charges, then the SUSY μ term is forbidden, but regenerated by PQ symmetry breaking due to the presence of the following non-renoremalizable operator

$$W_{KN} \ni \frac{\lambda_\mu}{M_P} X Y H_u H_d.$$

- Once the PQ symmetry is broken by hidden sector fields X, Y developing a VEV $\langle X \rangle, \langle Y \rangle \sim f_a$, an effective μ term is induced

$$\mu \sim \lambda_\mu f_a^2 / m_P.$$

- $\mu \sim m_{weak} \sim \mathcal{O}(100\ \text{GeV})$, $\lambda_\mu \sim \mathcal{O}(1) \Rightarrow f_a \sim 10^{11}$ GeV – Cosmological Favored Value!