Searching for top squarks from the string landscape at HL-LHC

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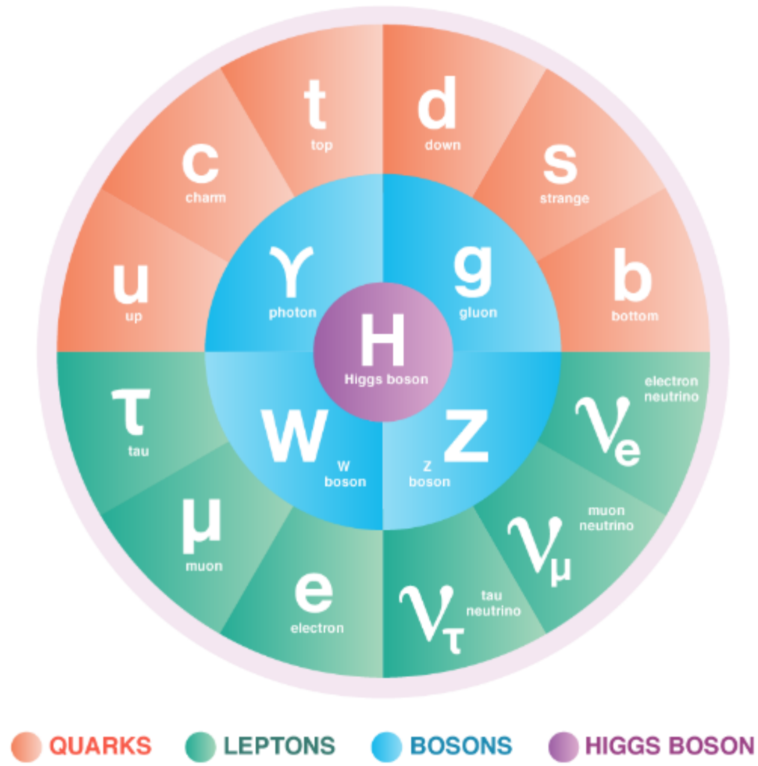
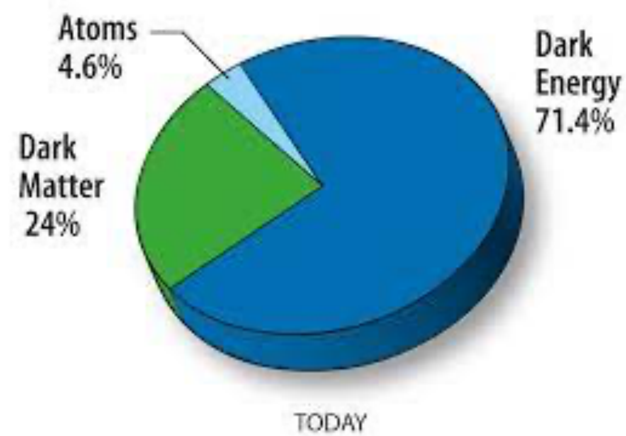
The Standard Model of Particle Physics



The Standard Model of Particle Physics, FERMILAB

Why New Physics?

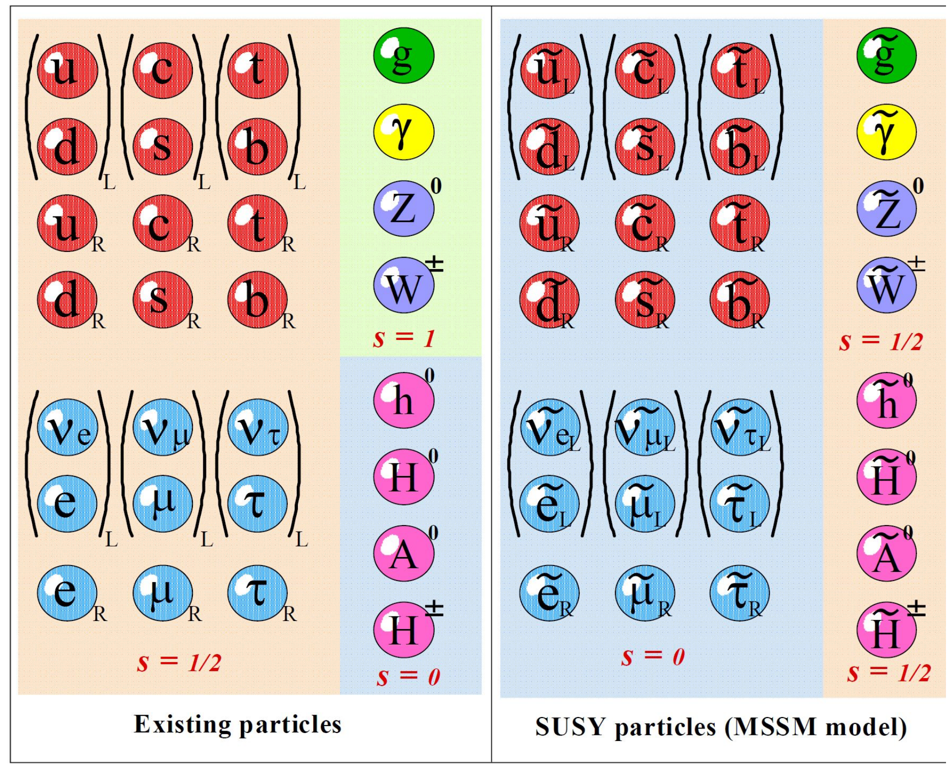
- Gauge hierarchy problem
- Dark Matter
- Dark Energy
- Non-zero neutrino masses
- Matter-antimatter asymmetry
- Gravity



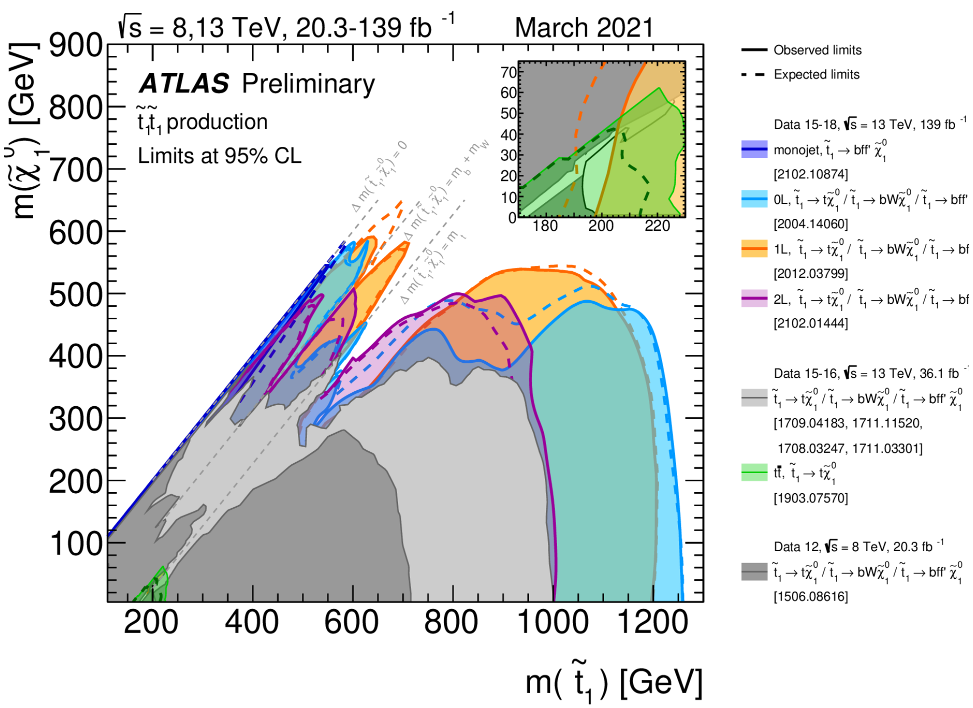
NASA.

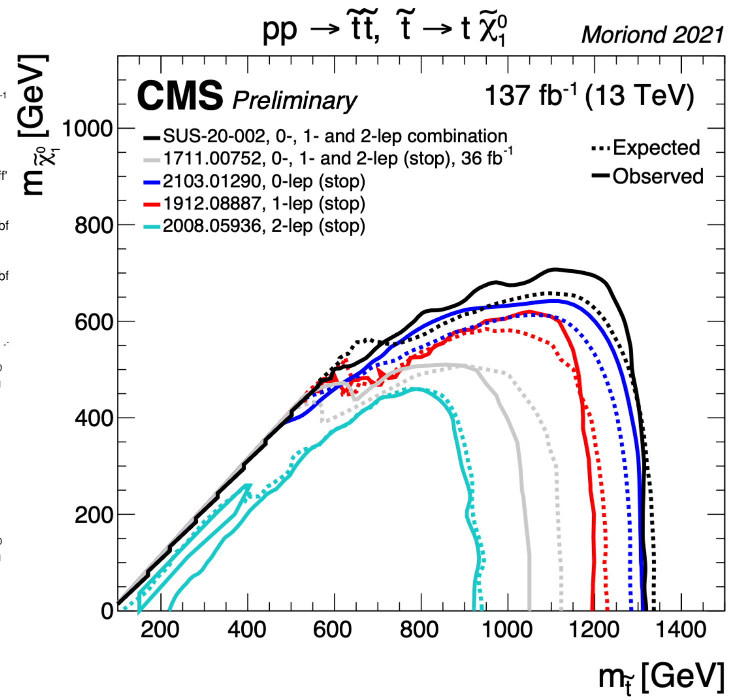
Supersymmetry

- Special symmetry providing a super partner to SM particles differing by spin-1/2 => Minimal Supersymmetric Standard Model (MSSM).
- Resolves big Hierarchy problem.
- R-parity, a discrete symmetry, when conserved provides a dark matter candidate.
- Gauge coupling unification.
- Minimal extensions also address neutrino masses.



Current Status from LHC: lightest stop





Limits of $m_{\tilde{t}_1} > 1.3$ TeV for massless $\tilde{\chi}_1^0$ from simplified model analyses assuming 100% decay modes.

Expectations from Naturalness measures for SUSY

- Light stops are a lucrative target for high luminosity LHC.
- Early estimates of naturalness such as by Barbieri-Gudice, $\Delta_{BG} = max_i |\frac{p_i \partial m_Z^2}{m_Z^2 \partial d p_i}|.$ R. Barbieri and G. F. Giudice, Nucl. Phys. B 306 (1988)
- Stringent upper limits on third generation squarks around ~450 GeV. p_i **independent soft terms at high scale.**
- Assumes soft terms are independent, however not true for eg, in UV complete scenario such as SUGRA.
- More conservative measures of naturalness: Δ_{EW} , the ratio of the largest term on the right-hand-side (below) to $m_Z^2/2$:

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

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

Limits on particles for 3% Δ_{BG} ($\Delta_{BG} < 30$) fine-tuning and for $\Delta_{EW} < 30$.

Mass	BG/DG	Δ_{EW}
μ	<350 GeV	<350 GeV
$m_{\tilde{g}}$	<400 – 600 GeV	<6 TeV
$m_{\tilde{t}_1}$	<450 GeV	<3 TeV
$m_{\tilde{q},\tilde{\ell}}$	<550 – 700 GeV	<10 – 30 TeV

Baer, et.al, 2202.11578

The Minimal Supersymmetric Standard Model from the landscape

- Motivated by Weinberg's anthropic solution to the cosmological constant, one tries to address the origin of the SUSY breaking scale in the string landscape where 10^{500} vacua solutions arise from compactification from 10 to 4 spacetime dimensions.

Weinberg, Phys. Rev. Lett. 59, 2607

- Supersymmetric models with low electroweak fine-tuning are expected to be more prevalent on the string landscape than fine-tuned models.

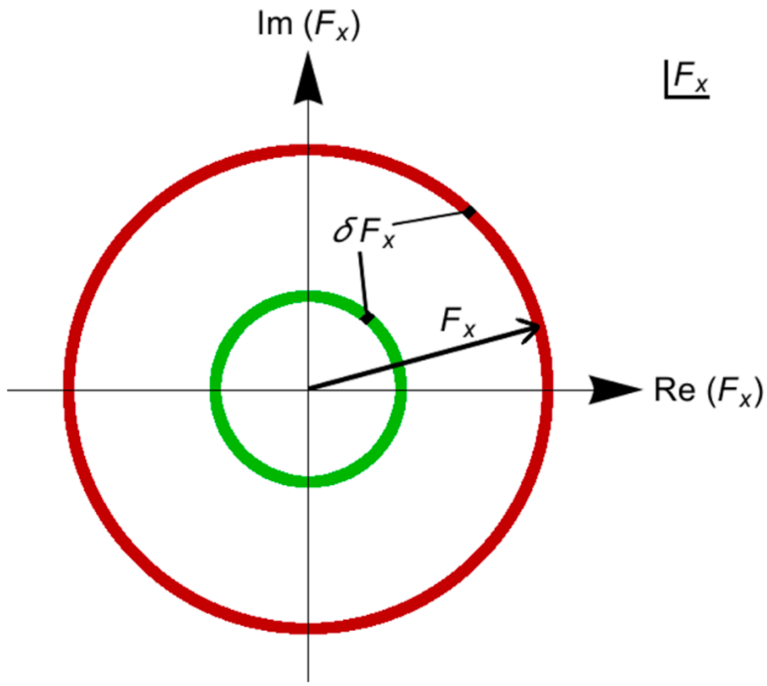
Baer, et.al, 2202.11578

- Douglas et.al, proposed a probabilistic view of naturalness, *stringy naturalness,* by identifying the statistical trends for the observables over the many landscape vacua solution we are likely to be in.

Douglas,Comptes Rendus Physique 5 (2004) 965–977

- Stringy naturalness: an observable $\mathcal{O}_2$ is more natural than $\mathcal{O}_1$ if more phenomenological vacua lead to $\mathcal{O}_2$ than $\mathcal{O}_1$.

- For $n_F = 1$, $n_D = 0$, linear statistical draw to soft terms.



Baer, et.al, 2202.11578

Annuli of the complex F_X plane giving rise to linearly increasing selection of soft SUSY breaking terms.

- This stringy statistical draw must be compensated for by requiring that the derived value for the weak scale in each pocket universe of the multiverse be not too far from our measured value, so that complex nuclei and hence atoms arise in any anthropically allowed pocket universe => ABDS window.

Agrawal et.al, Phys. Rev. D 57 (1998) 5480–5492

- We restrict ourselves to landscape vacua with MSSM as the low energy theory.

- Assume a linear draw for the soft terms $m_0(1,2), m_0(3), A_0, m_A$ which scan independently in the string landscape.

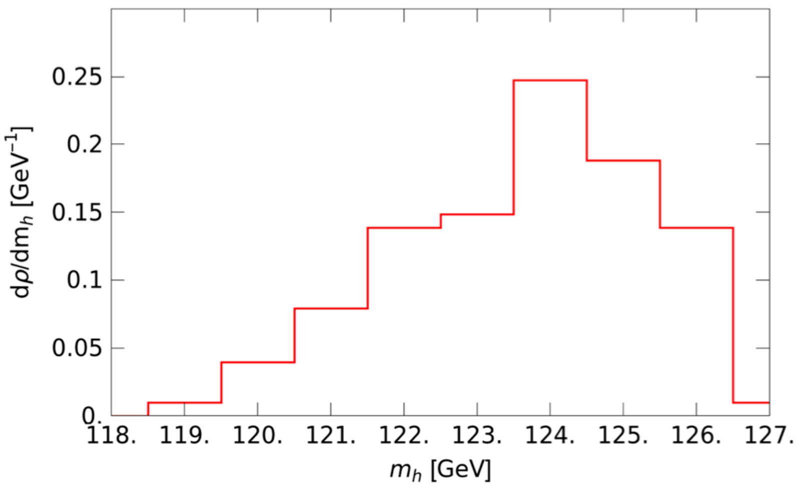
- The soft terms scan as $f_{SUSY} \sim m_{soft}^n$, where $n = 2n_F + n_D - 1$.

Non Universal Higgs Model (NUHM(3)): Global Scan

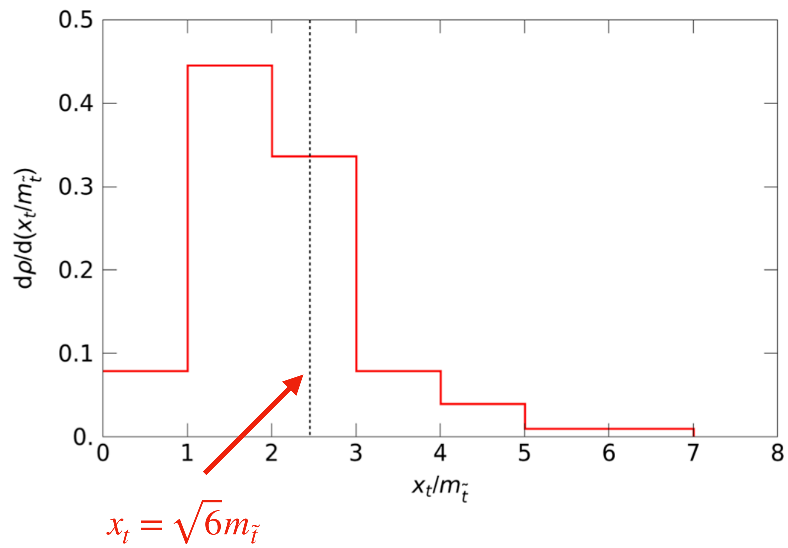
- Free parameters: $m_0(1,2), m_0(3), \tan\beta, A_0, \mu, m_A$
- Global scan:
  - $m_0(1,2)$: $0.1 - 45$ TeV,
  - $m_0(3)$: $0.1 - 10$ TeV,
  - $m_{1/2}$: $0.5 - 3$ TeV,
  - A_0 : $0 - (-20)$ TeV,
  - $\tan\beta$: $3 - 60$ TeV (uniform scan),
  - m_A : $0.3 - 10$ TeV,

with fixed $\mu = 200$ GeV and the upper bounds on the parameters are set beyond the upper bounds derived from the ABDS window.

Probability distributions: Higgs



Probability distribution for lightest higgs mass for n=1.



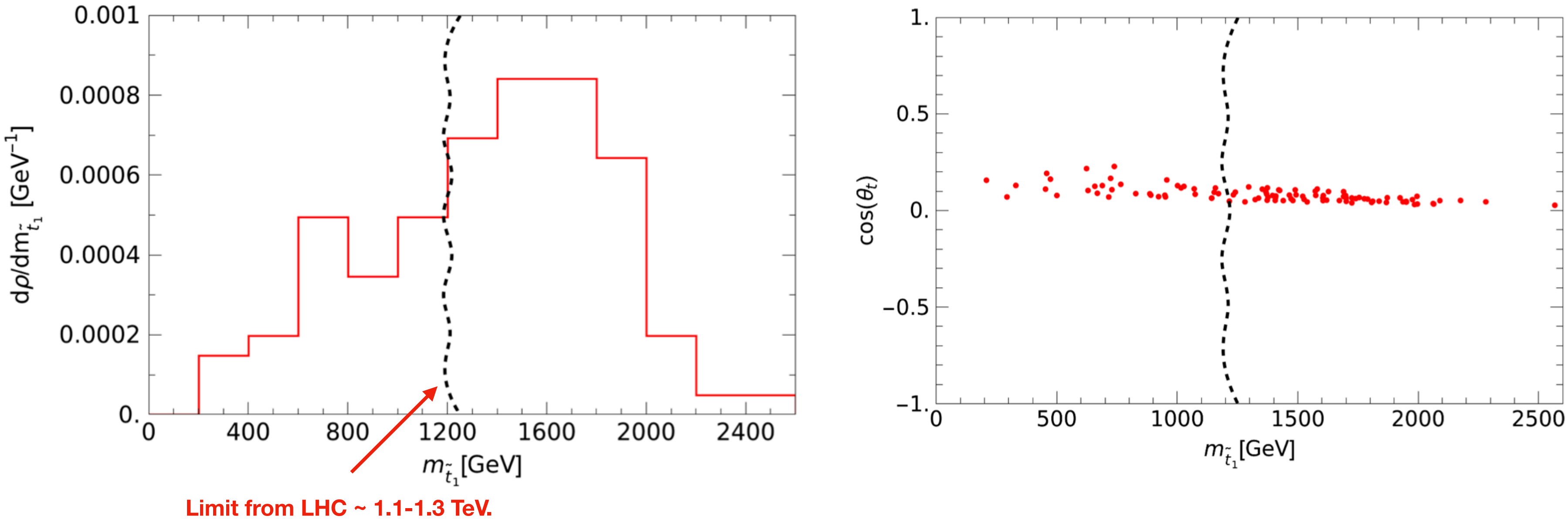
Probability distribution of $x_t/m_{\tilde{t}_1}$ for n=1.

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3g^2}{8\pi^2}\frac{m_t^4}{m_W^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{x_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{x_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

$$x_t = A_t - \mu \cot\beta$$

$$m_{\tilde{t}}^2 = m_{Q_3} m_{U_3}$$

Properties of the Stop Sector from the landscape



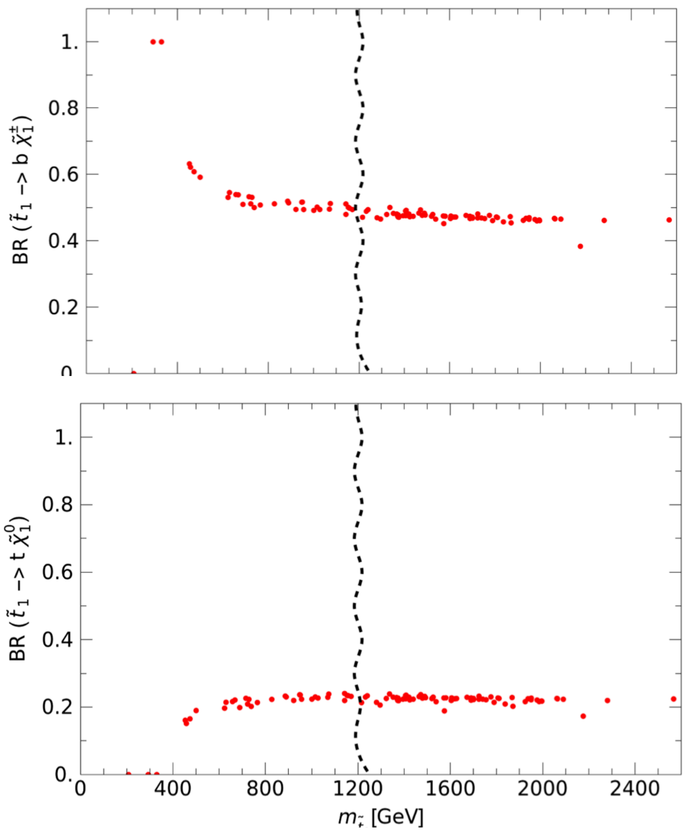
$$\tilde{t}_1 = \cos\theta_t \tilde{t}_L - \sin\theta_t \tilde{t}_R$$

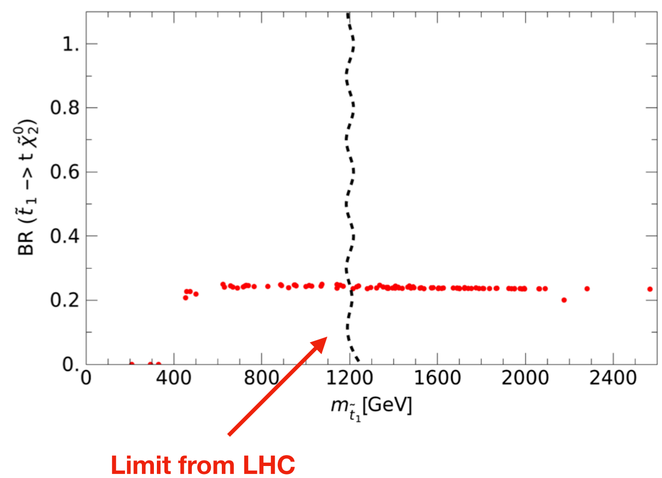
The lightest stop mass = 1-2.5 TeV and mostly right-handed.

Also consistent with the lightest CP-even Higgs mass~125 GeV.

Decays of the stops

- Lightest stop, mostly right-handed, hence decays to $b\widetilde{\chi}_1^{\pm}$, $t\widetilde{\chi}_1^0$, $t\widetilde{\chi}_2^0$: 2:1:1





Phys.Rev.D **108 (2023) 7, 075027**

Benchmark point

Natural spectra characterized by

- gluinos = 2-6 TeV
- light stops =1-2.5 TeV,
- higgsinos = 100-400 GeV

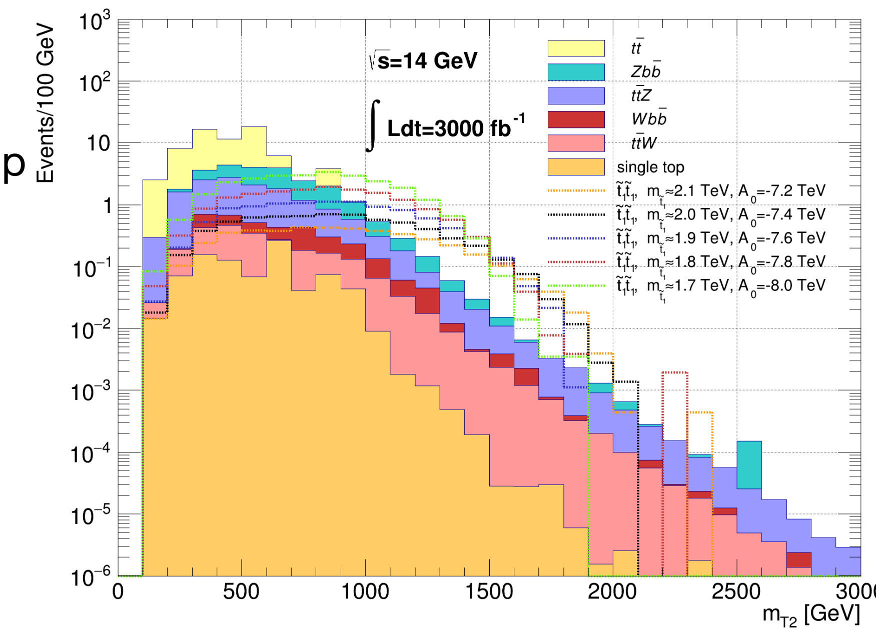
consistent with $\Delta_{EW} \leq 30$.

Parameter	Stringy natural BM point
m_0	5 TeV
$m_{1/2}$	1.2 TeV
A_0	−8 TeV
$\tan\beta$	10
μ	250 GeV
m_A	2 TeV
$m_{\tilde{g}}$	2830 GeV
$m_{\tilde{u}_L}$	5440 GeV
$m_{\tilde{u}_R}$	5561 GeV
$m_{\tilde{e}_R}$	4822 GeV
$m_{\tilde{t}_1}$	1714 GeV
$m_{\tilde{t}_2}$	3915 GeV
$m_{\tilde{b}_1}$	3949 GeV
$m_{\tilde{b}_2}$	5287 GeV
$m_{\tilde{\tau}_1}$	4746 GeV
$m_{\tilde{\tau}_2}$	5110 GeV
$m_{\tilde{\nu}_\tau}$	5107 GeV
$m_{\tilde{\chi}_1^\pm}$	261.7 GeV
$m_{\tilde{\chi}_2^\pm}$	1020.6 GeV
$m_{\tilde{\chi}_1^0}$	248.1 GeV
$m_{\tilde{\chi}_2^0}$	259.2 GeV
$m_{\tilde{\chi}_3^0}$	541.0 GeV
$m_{\tilde{\chi}_4^0}$	1033.9 GeV
m_h	124.7 GeV
$\Omega_{\tilde{\chi}_1}^{std} h^2$	0.016
$BR(b \to s\gamma) \times 10^4$	3.1
$BR(B_s \to \mu^+\mu^-) \times 10^9$	3.8
$\sigma^{SI}(\tilde{\chi}_1^0, p)$ (pb)	2.2×10^{-9}
$\sigma^{SD}(\tilde{\chi}_1^0, p)$ (pb)	2.9×10^{-5}
$\langle\sigma v\rangle\|_{v\to 0}$ (cm^3/ sec)	1.3×10^{-25}
Δ_{EW}	22

Phenomenology

- Signal topologies: $tb + \not{E}_T, tt + \not{E}_T, bb + \not{E}_T$
- Key SM backgrounds: $b\bar{b}Z, t\bar{t}Z, t\bar{t}W, t\bar{t}$, single top suppressed using highly boosted top-jets:
- For $tb + \not{E}_T$: $p_T(top - jet) > 400$ GeV, R=1.5.
- Cuts: $\not{E}_T > 400$ GeV,
    - $H_T > 1.4$ TeV, $L_T > 1.8$ TeV,
    - min($m_T(b_1, \not{E}_T), m_T(b_2, \not{E}_T) > 175$ GeV,
    - $\Delta\Phi(b, \not{E}_T) > 40°, \Delta\Phi(J, \not{E}_T) > 30°$.

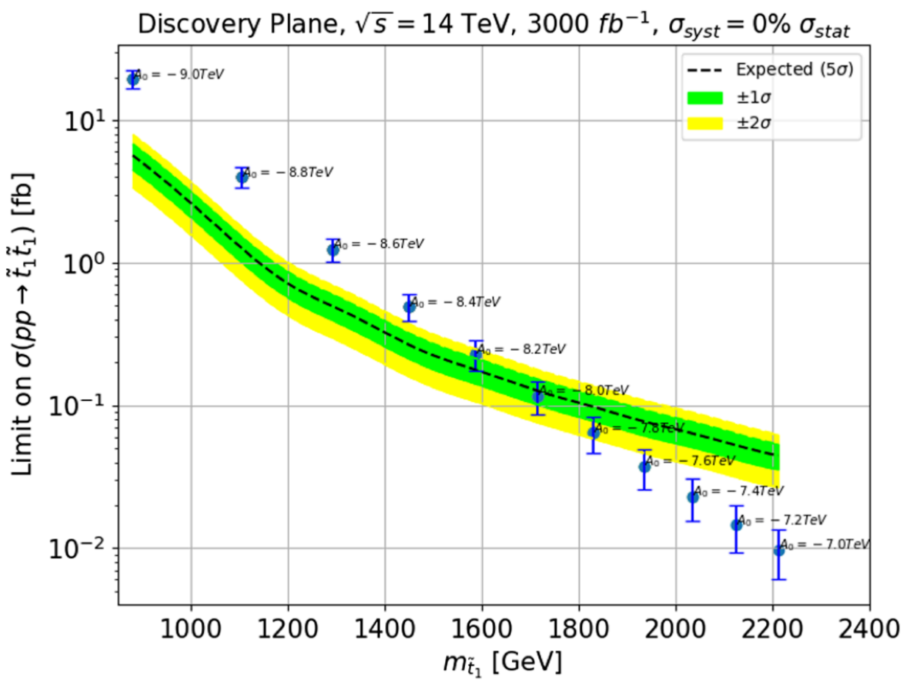
Similar cuts for $tt + \not{E}_T$ and $bb + \not{E}_T$.

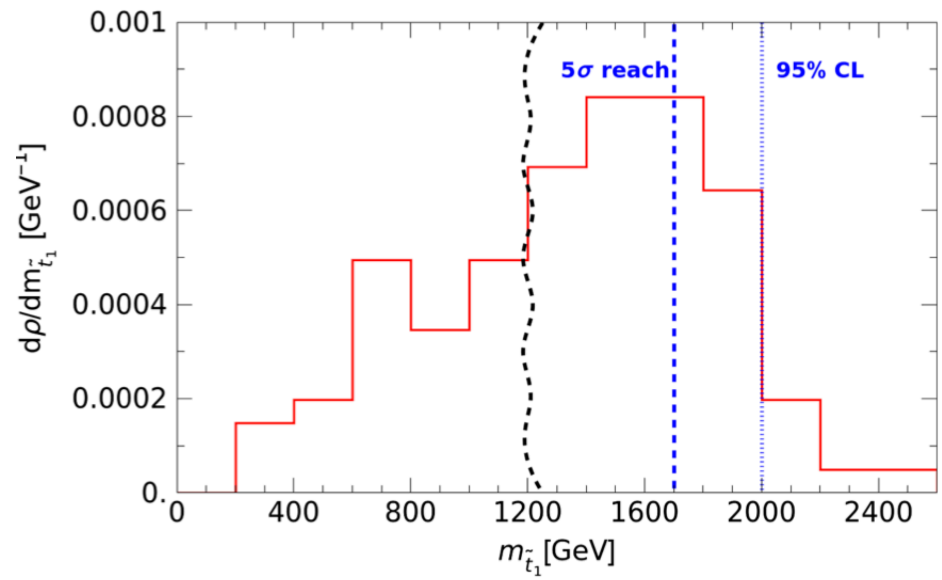


Distribution for m_{T_2} in the *tb* + MET final state.

Key kinematic variable for discrimination between signal and background m_{T_2} after cuts.

Results





Probability distribution of the lightest stop with the predicte reach at HL-LHC.

Combined reach of stops ~1.65 TeV at 5σ and ~1.95 TeV, at 95% C.L., covering most of the region allowed from the string landscape!

Summary

- We examined top squark masses and other properties are expected from the string landscape where a power-law draw to large soft terms is expected.
- The derived value of the weak scale must lie within the ABDS window in order to allow for complex nuclei (and hence atoms) in each anthropically-allowed pocket universe.
- Under the stringy naturalness requirement, we find $m_{\tilde{t}_1}$= 1-2.5 TeV with large mixing. The large mixing helps boost m_h to 125 GeV while minimizing the top squark contributions to the weak scale.
- In spite of the large mixing, the lightest top-squark is mainly right-handed, thus leading to mixed final states of $tb + \not{E}_T$, $tt + \not{E}_T$, $bb + \not{E}_T$.
- The top-squark pair production is revealed as an enhancement in the m_{T_2} distribution at high values of m_{T_2}.
- A combined reach of all channels at HL-LHC lead to a reach of ~1.65 TeV at 5σ and ~1.95 TeV at 95%CL.

Thank You!