Searching for top squarks from the landscape at HL-LHC

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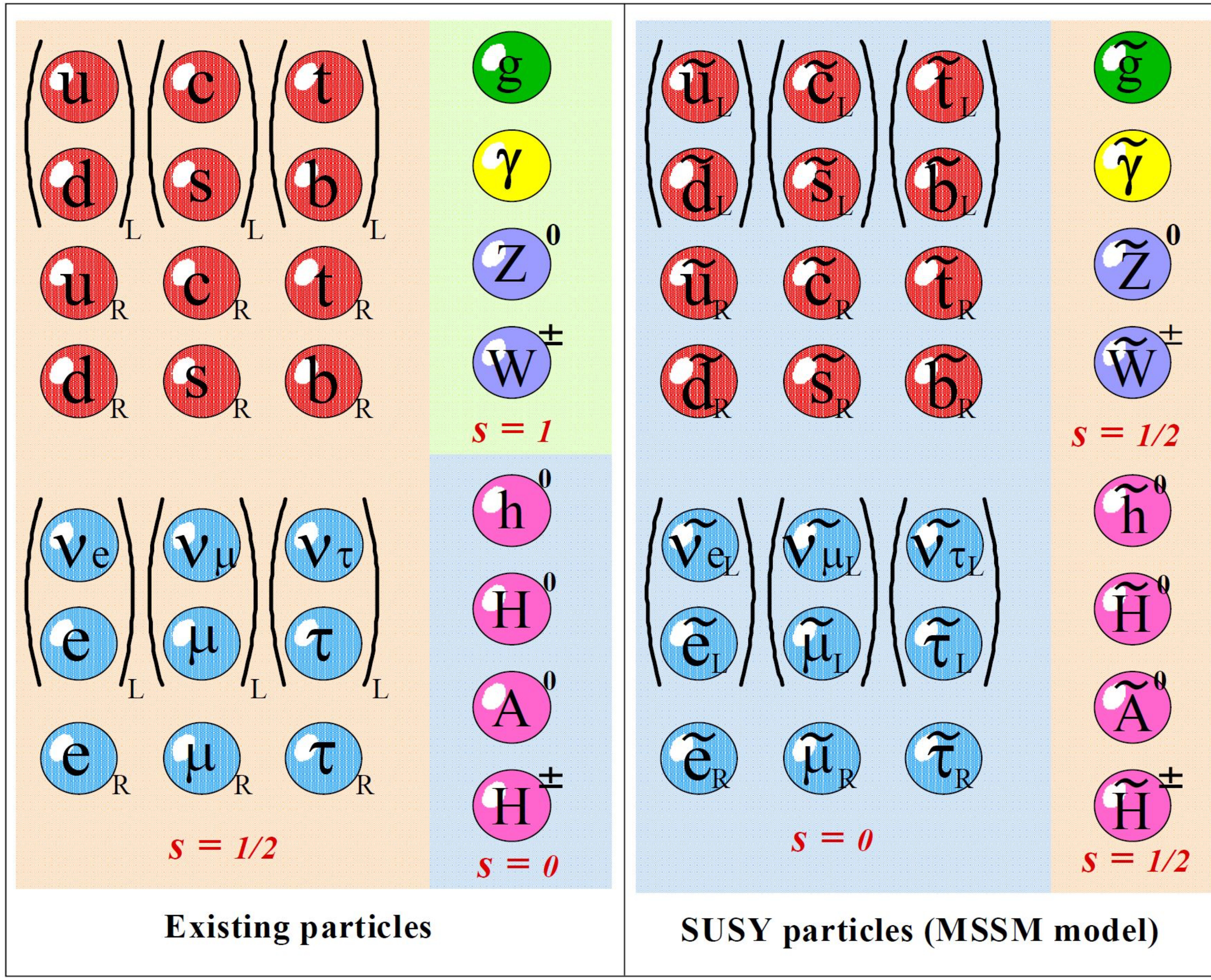
Supersymmetry, in a nutshell..

- Special symmetry providing a super partner to SM particles differing by spin-1/2.
- Resolves naturalness problem.
- R-parity, a discrete symmetry, when conserved provides a dark matter candidate.
- Gauge coupling unification.
- Minimal extensions also address neutrino masses.



Motivation

- Early estimates of naturalness $\implies$ stringent upper limits on gluinos and third generation squarks around ~450 GeV.

- More conservative measures of naturalness: Δ_{EW} , the ratio of the largest term on the right-hand-side of:

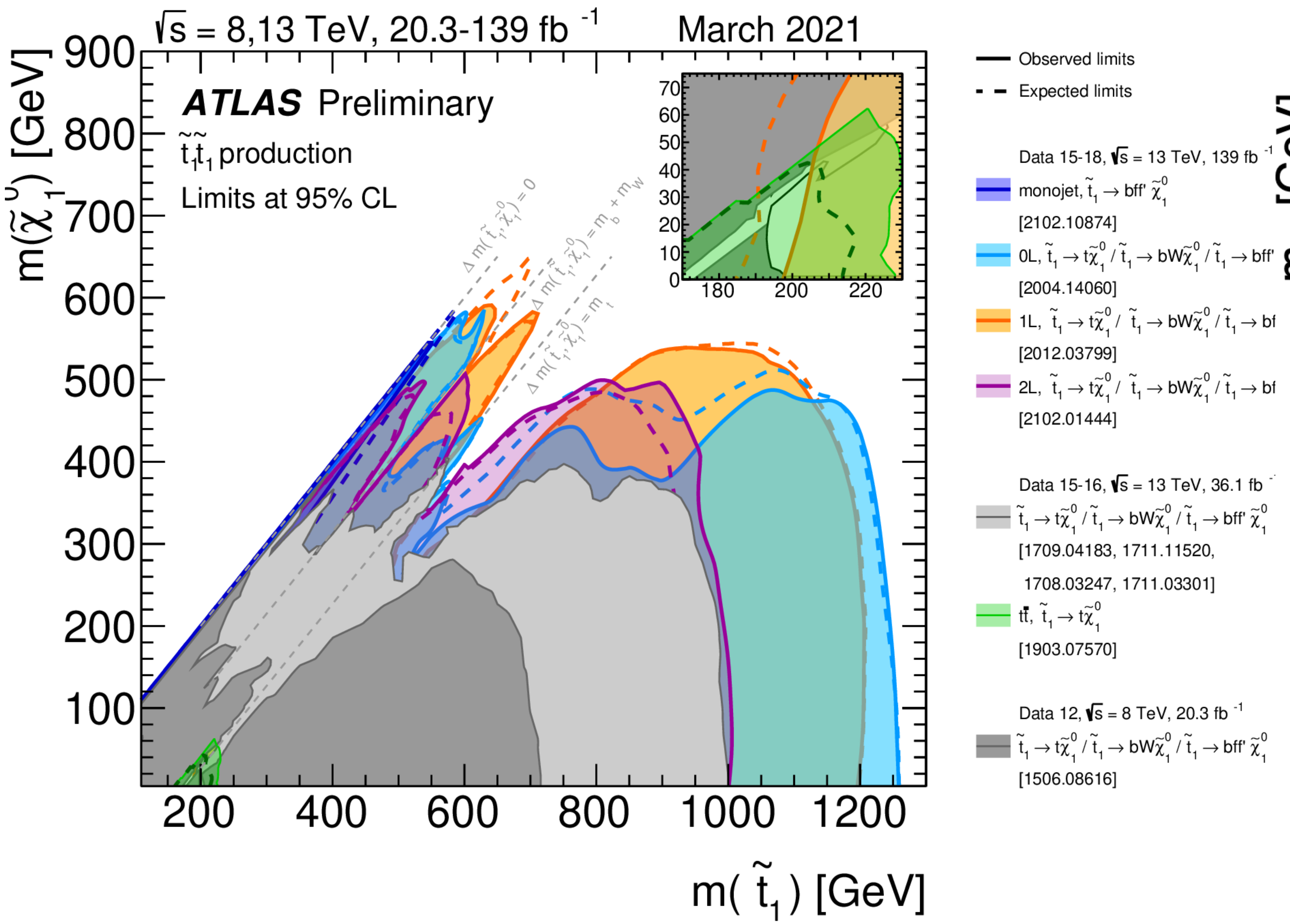
$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan_\beta^2)}{\tan_\beta^2 - 1} - \mu^2$$

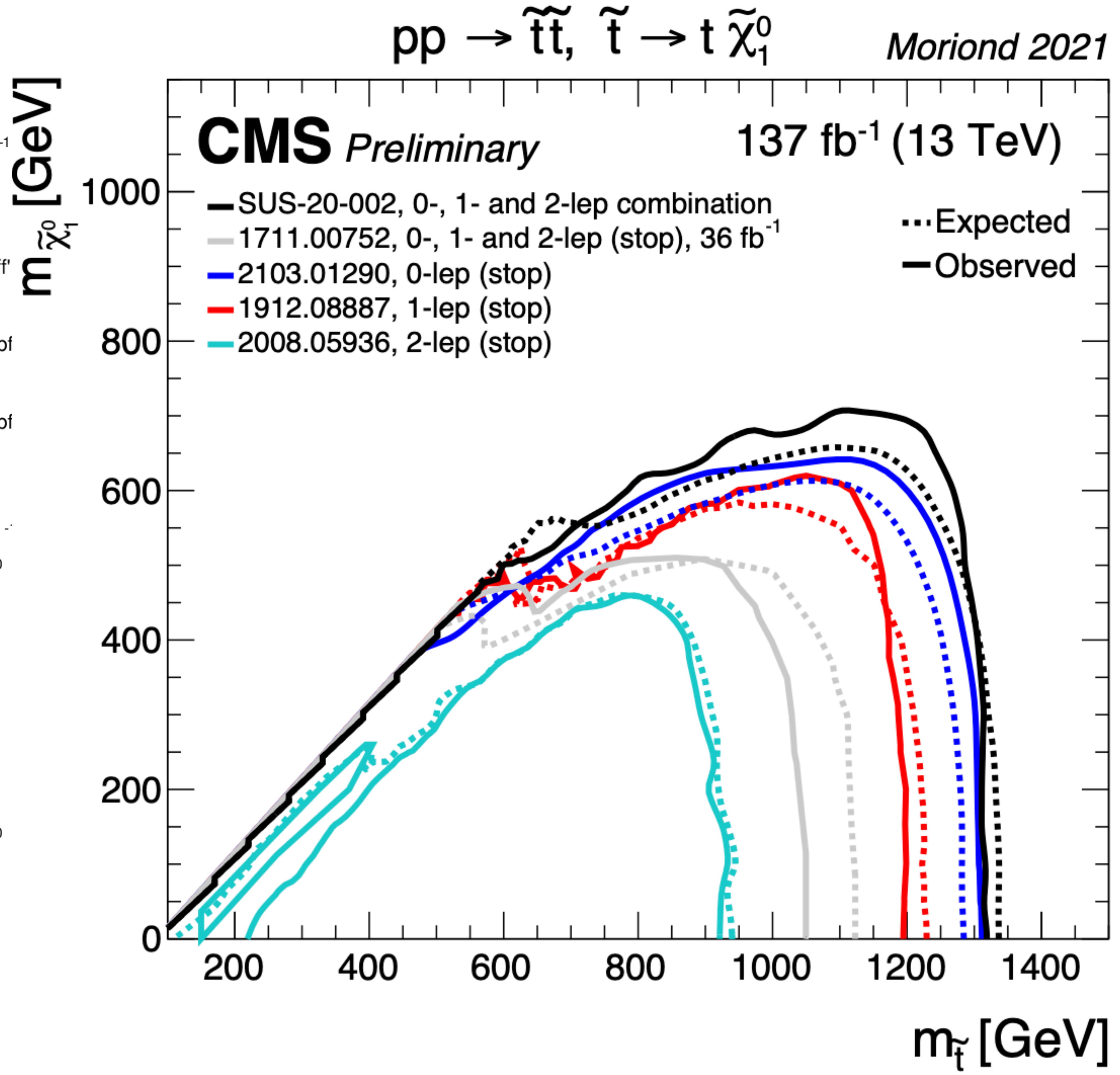
Mass	BG/DG	Δ_{EW}
μ	<350 GeV	<350 GeV
$m_{\tilde{g}}$	<400 – 600 GeV	<6 TeV
$m_{\tilde{t}_1}$	<450 GeV	<3 TeV
$m_{\tilde{q},\tilde{\ell}}$	<550 – 700 GeV	<10 – 30 TeV

Limits on particles for 3% Δ_{BG} fine-tuning and for $\Delta_{EW} \leq 30$

Baer, et.al, 2202.11578

Current Status from LHC





MSSM from the landscape

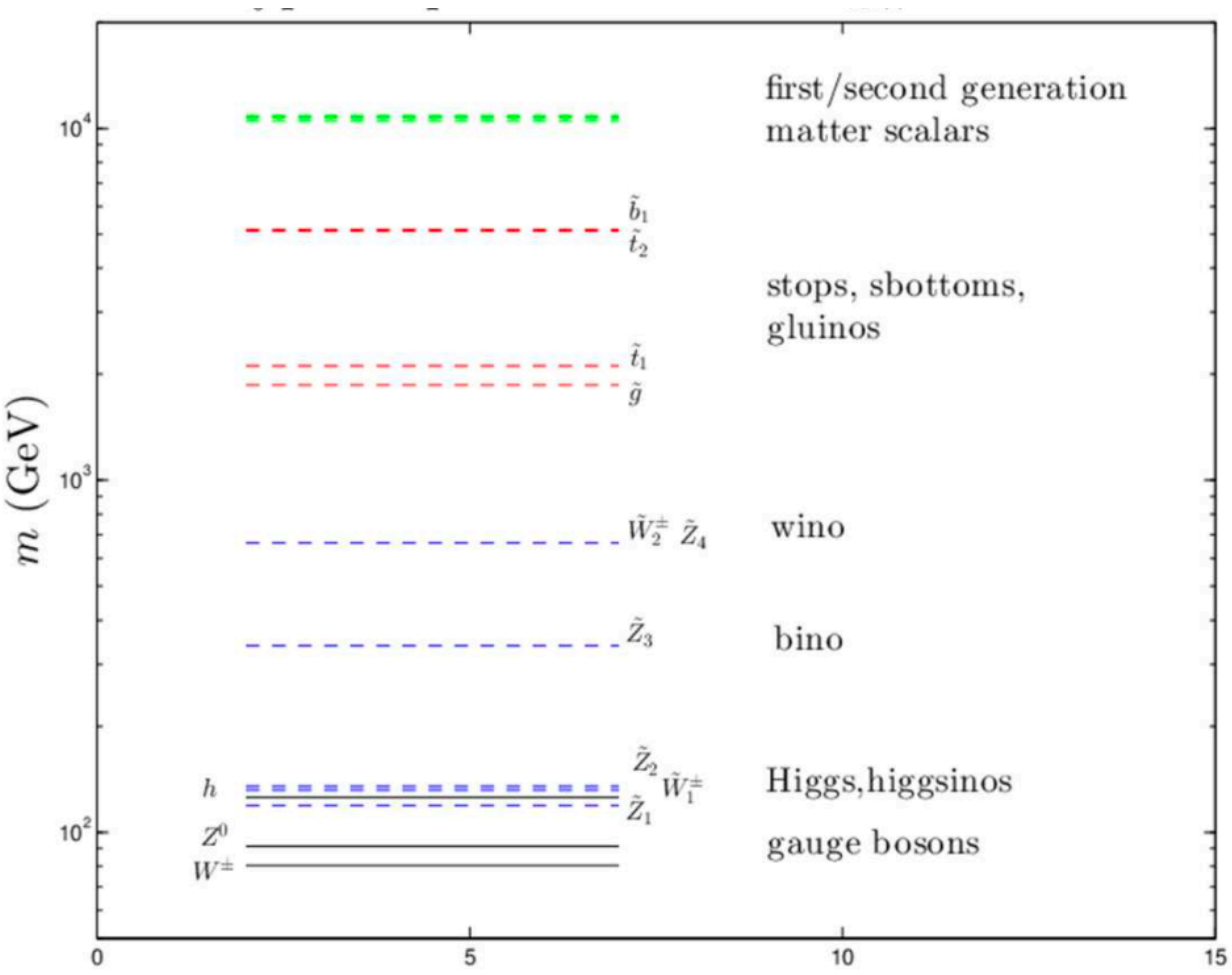
- Supersymmetric models with low electroweak fine-tuning are expected to be more prevalent on the string landscape than fine-tuned models.

- 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

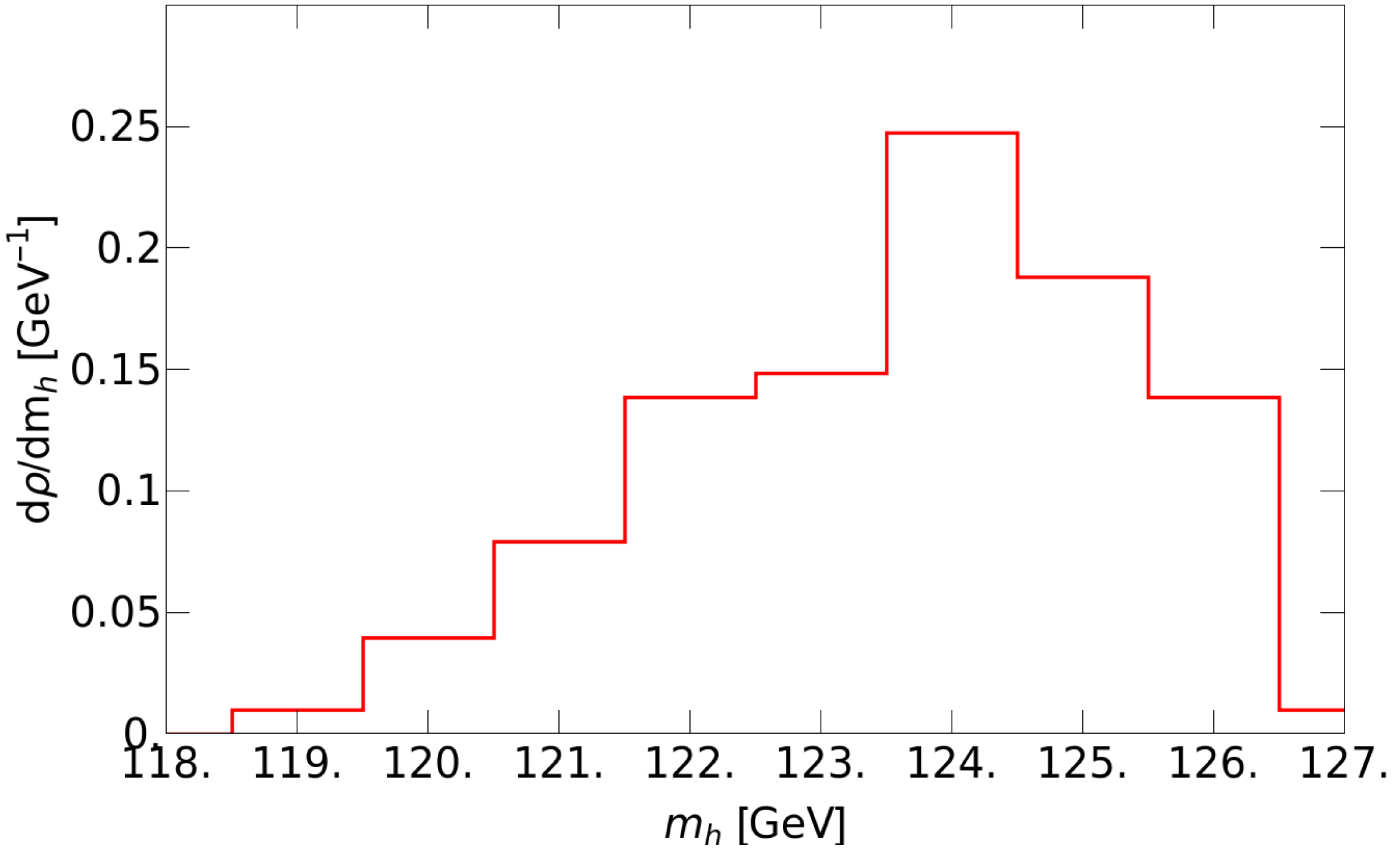
- Douglas et.al, proposed a probabilistic view of naturalness, *stringy naturalness,* by identifying the statistical trends for the many landscape vacua solution we are likely to be in.

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

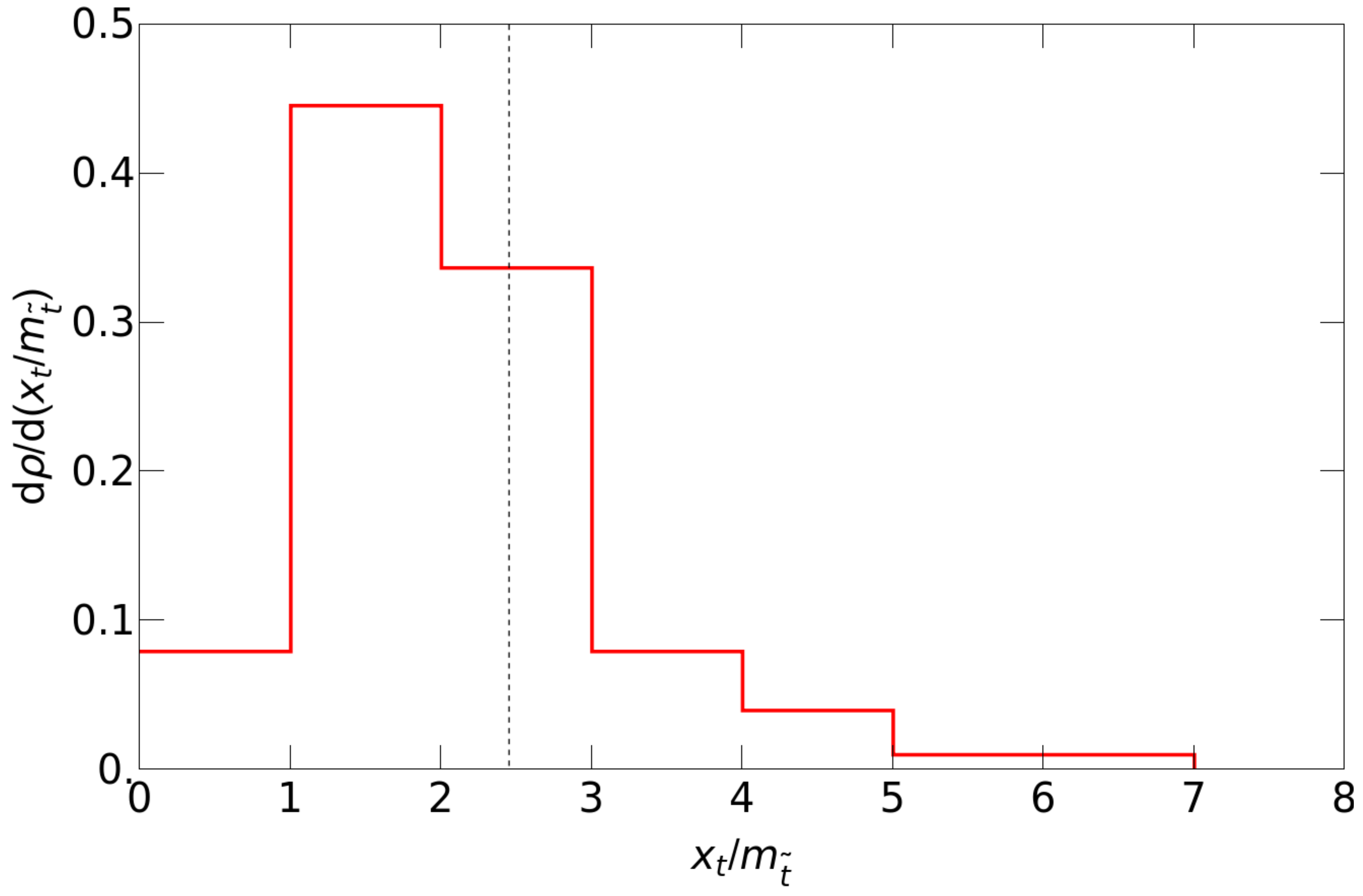


Typical spectra for low Δ_{EW}

Probability distributions



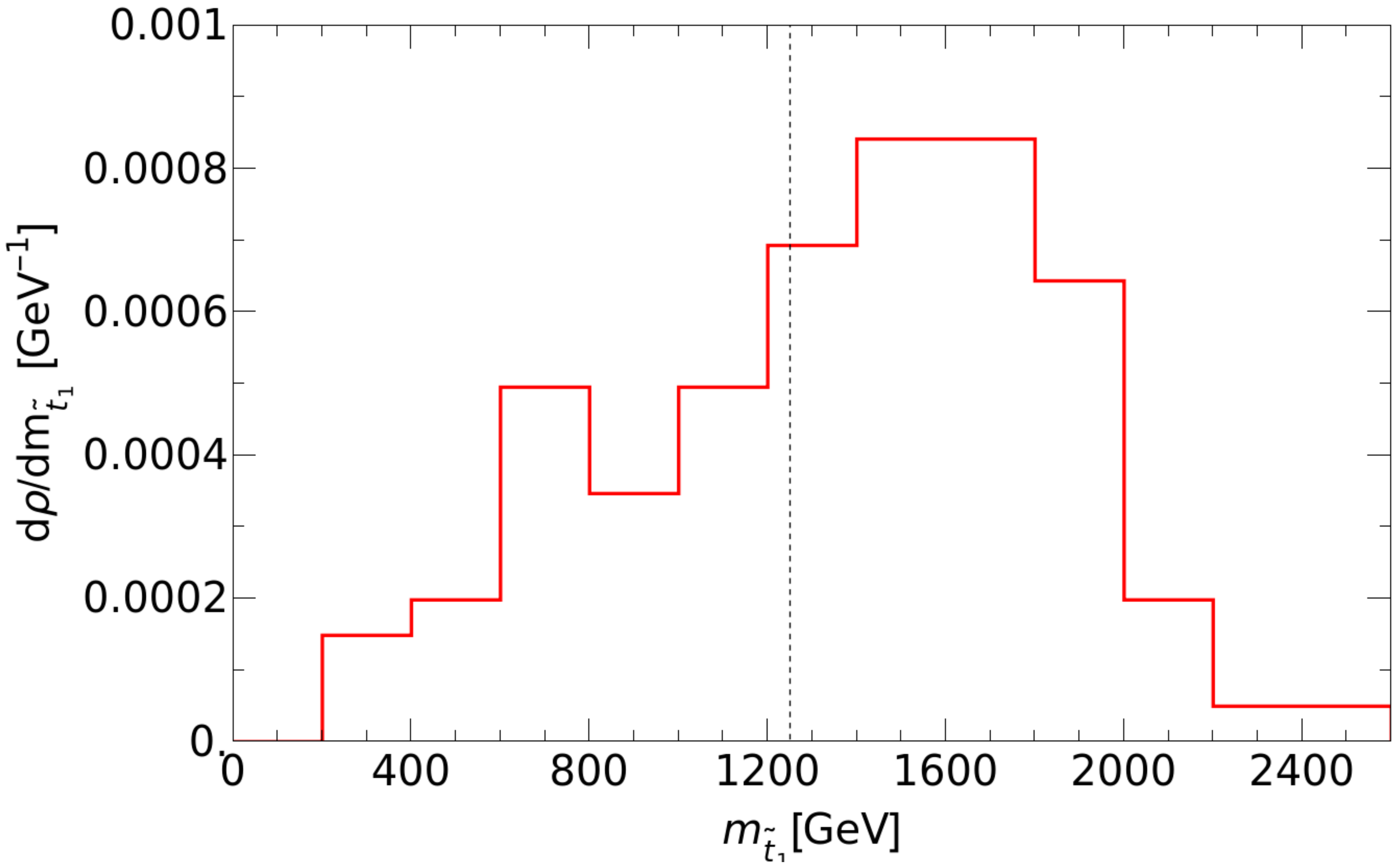
Probability distribution for the lightest CP-even Higgs mass.



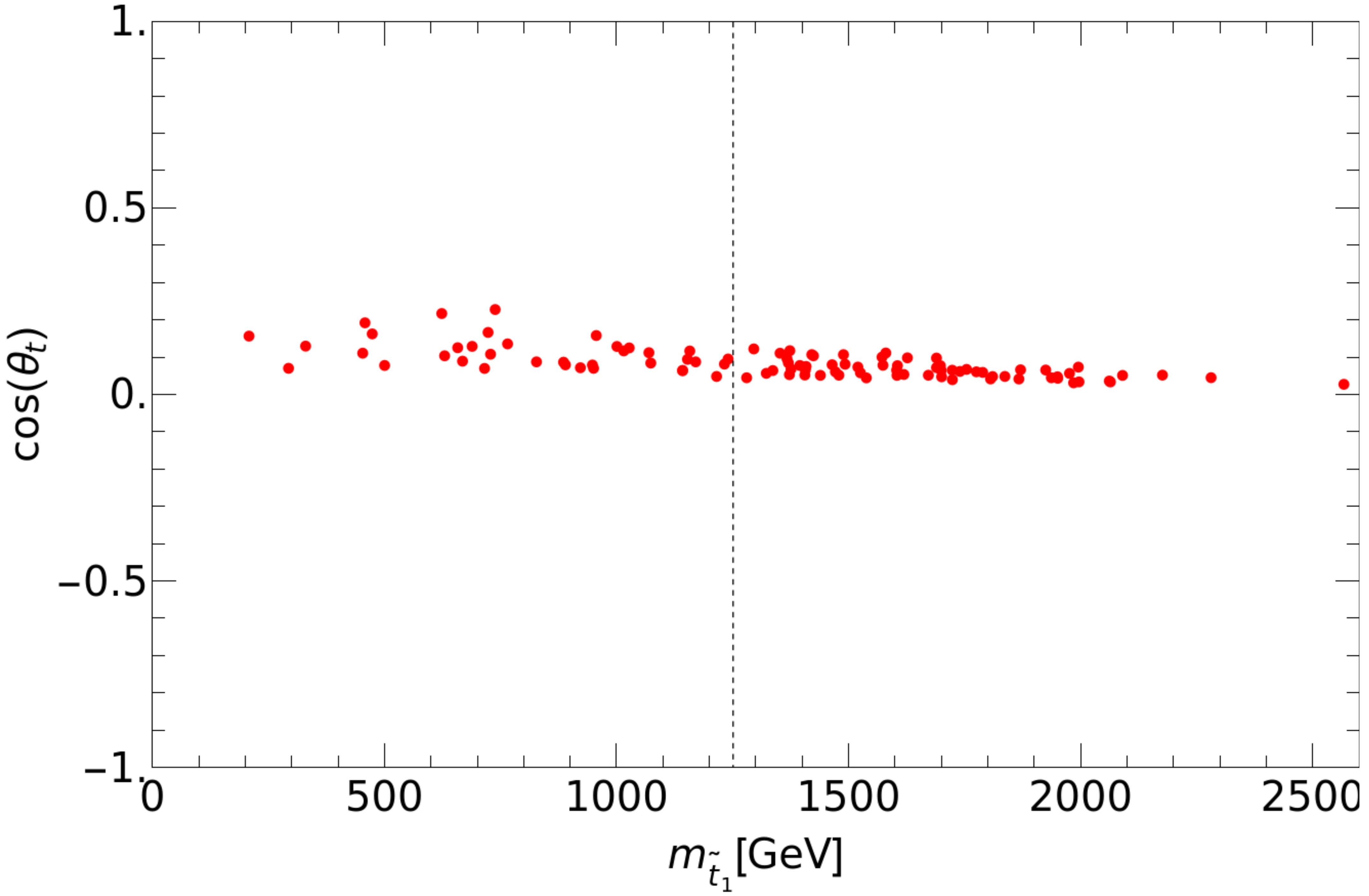
Probability distribution for the mixing in the stop sector.

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

Properties of the Stop Sector from the landscape



Probability distribution of the lightest stop mass.



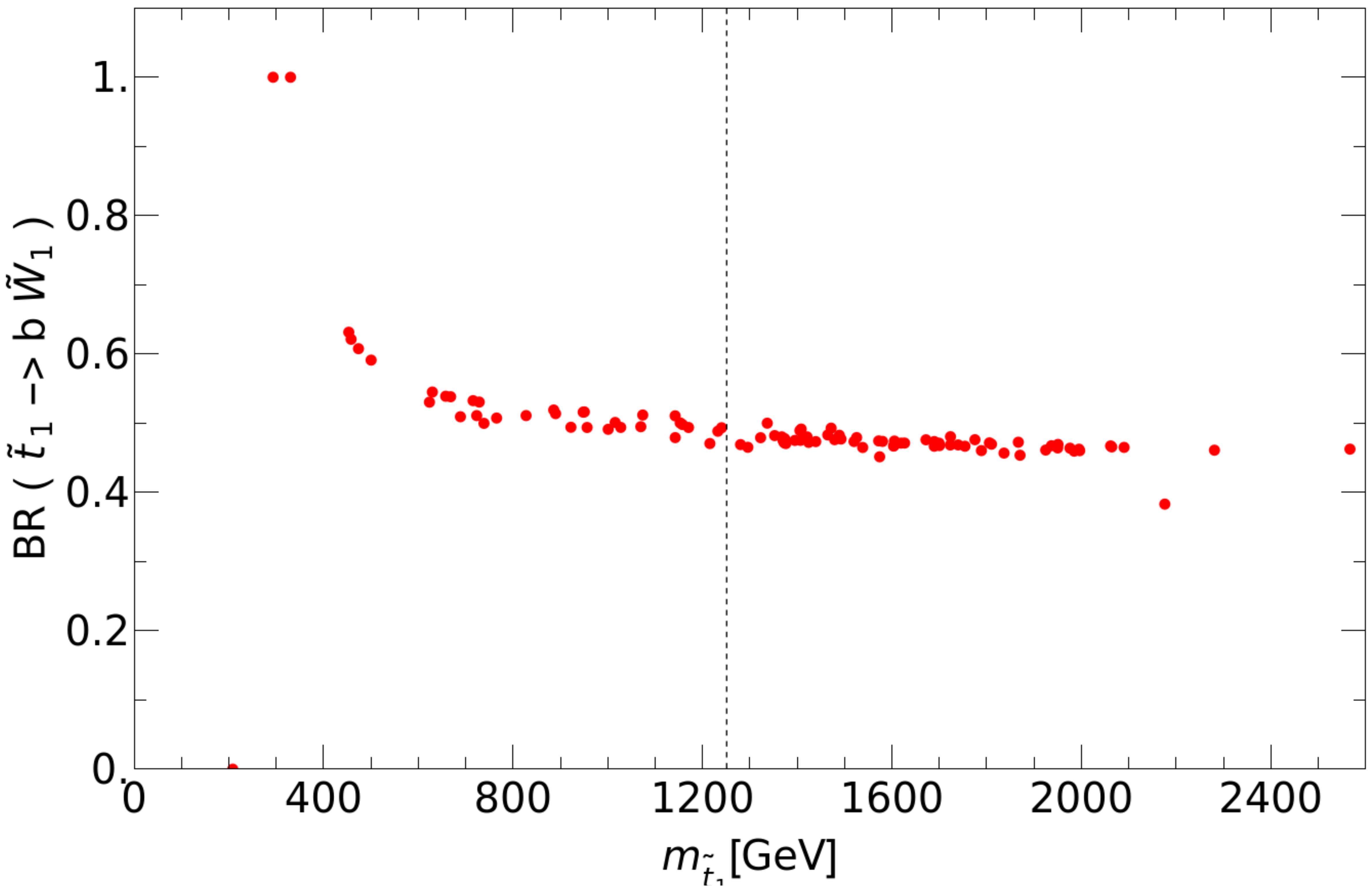
Variation of the cosine of the stop mixing angle with mass of the lightest stop.

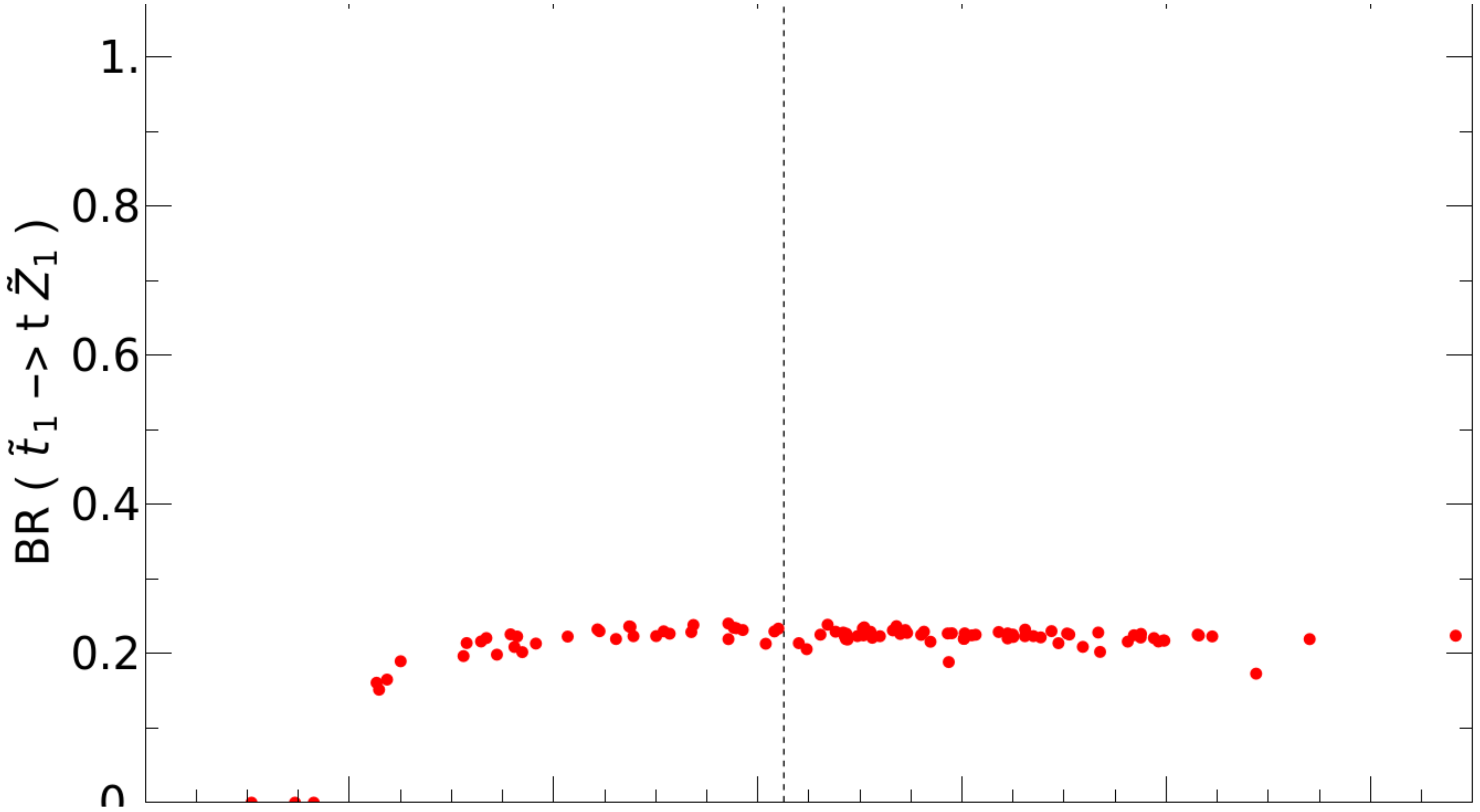
$$\tilde{t}_1 = \cos\theta_t \tilde{t}_L - \sin\theta_t \tilde{t}_R$$

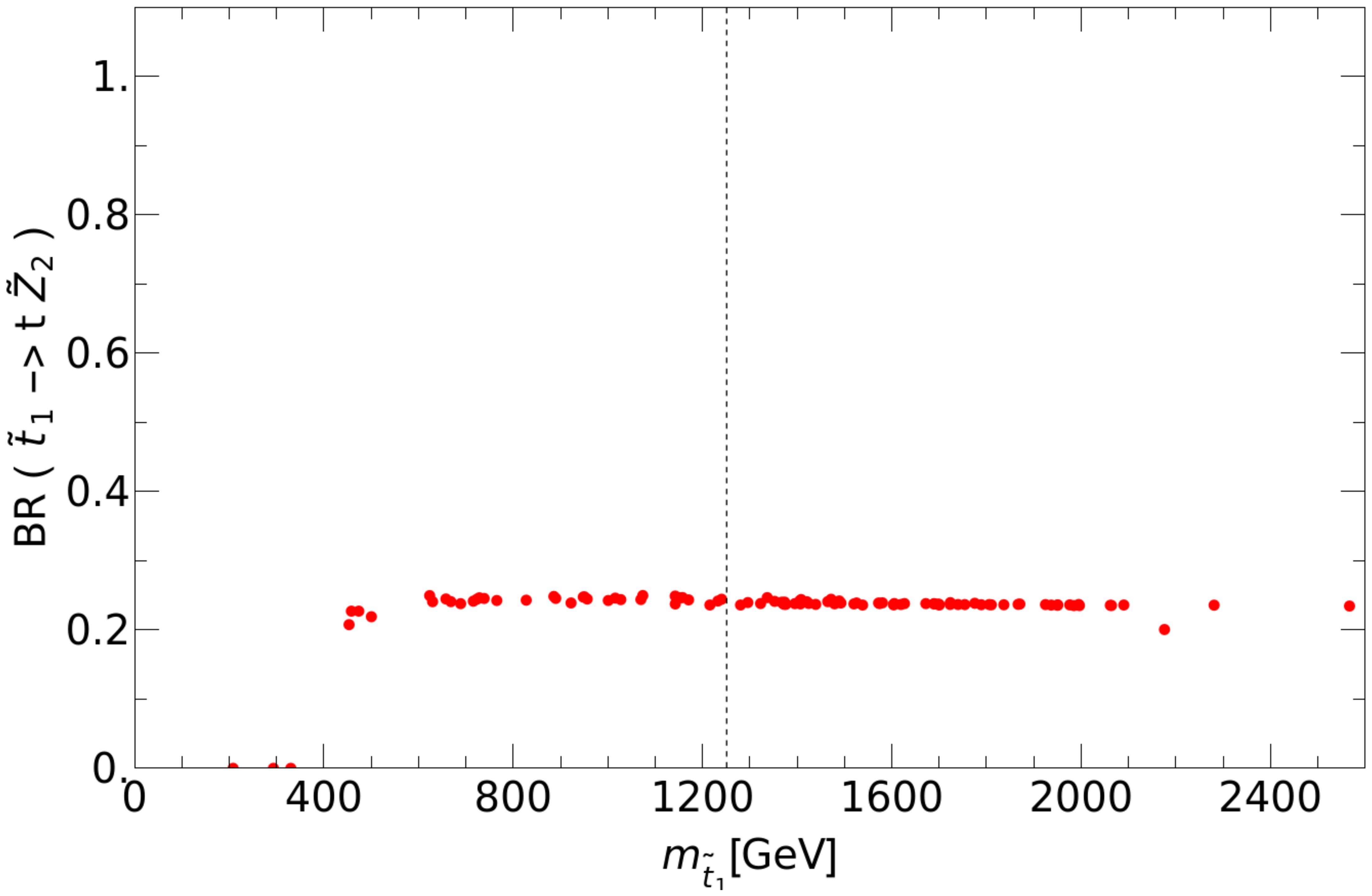
The lightest stop mass = 1-2.5 TeV and mostly right-handed.

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

Decay Modes:


BR ($\tilde{t}_1$ -> b $\tilde{W}_1$)
1.
0.8
0.6
0.4
0.2
0.
0
400
800
1200
1600
2000
2400
$m_{\tilde{t}_1}$ [GeV]

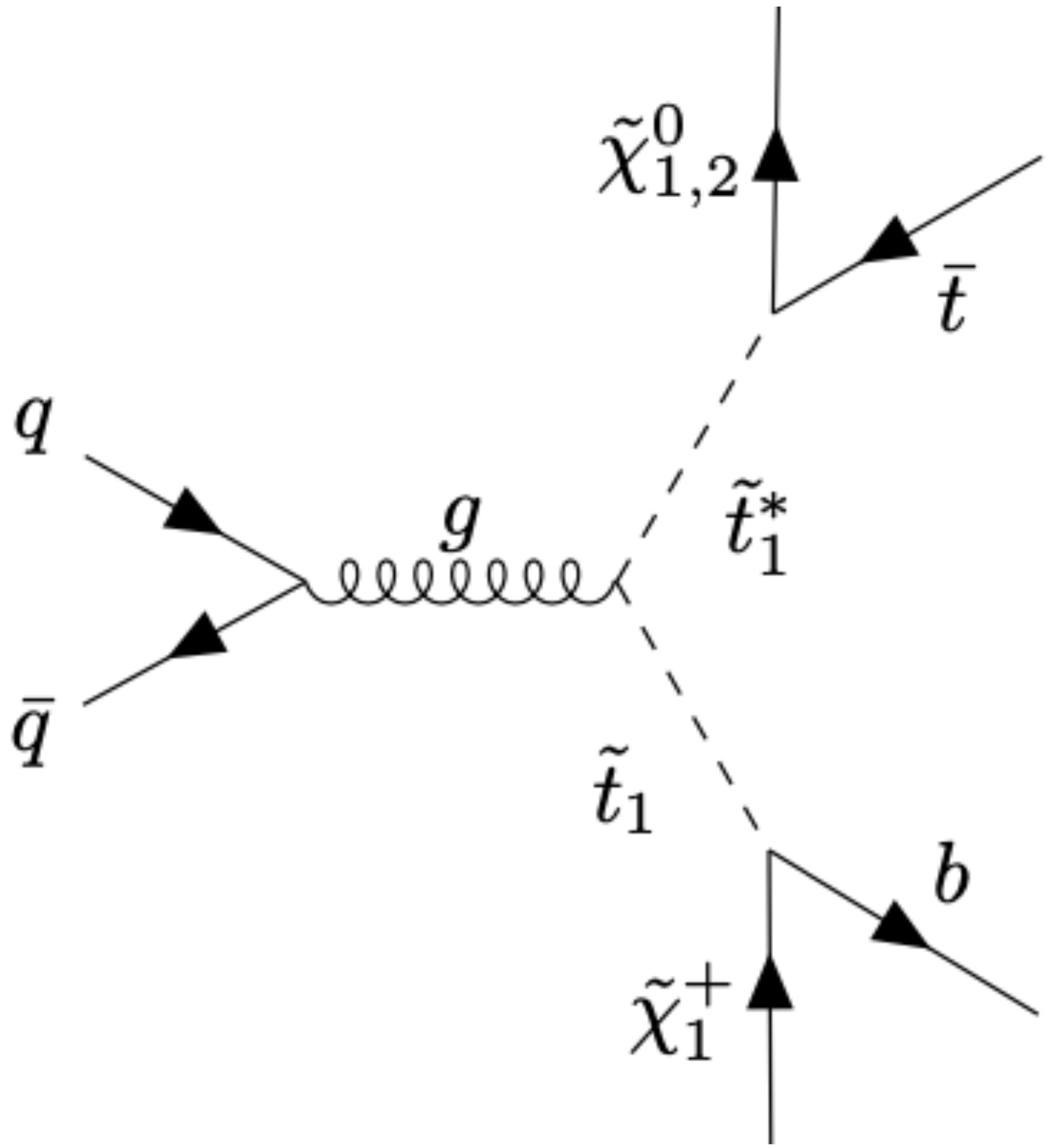

BR ($\tilde{t}_1$ -> t $\tilde{Z}_1$)
1.
0.8
0.6
0.4
0.2
0


BR ($\tilde{t}_1$ -> t $\tilde{Z}_2$)
1.
0.8
0.6
0.4
0.2
0.
0
400
800
1200
1600
2000
2400
$m_{\tilde{t}_1}$ [GeV]

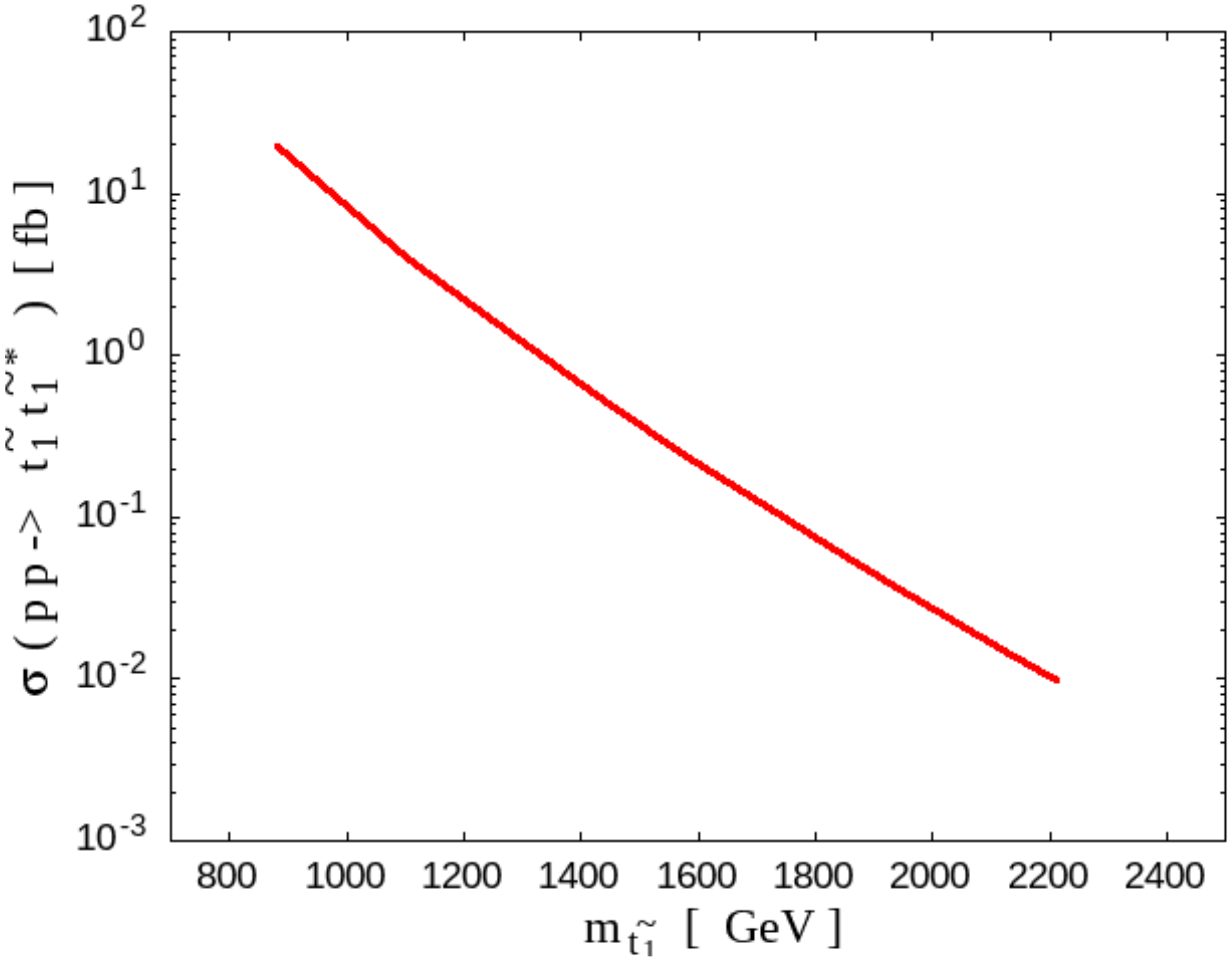
Parameters	Benchmark point
m_0	5 TeV
$m_{1/2}$	1.2 TeV
A_0	-8 TeV
$\tan\beta$	10
μ	250 GeV
m_A	2 TeV
$m_{\tilde{g}}$	2830 GeV
$m_{\tilde{t}_1}$	1714 GeV
$m_{\tilde{t}_2}$	3915 GeV
$m_{\tilde{\chi}_1^\pm}$	261.7 GeV
$m_{\tilde{\chi}_2^\pm}$	1020.6 GeV
$m_{\tilde{\chi}_1^0}$	248.1 GeV
$m_{\tilde{\chi}_2^0}$	259.2 GeV
$m_{\tilde{\chi}_3^0}$	541.0 GeV
$m_{\tilde{\chi}_4^0}$	1033.9 GeV
m_h	124.7 GeV

m_h	124.7 GeV
$\Omega^{std}_{\tilde{\chi}_1}h^2$	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}
$\Delta_{\rm EW}$	22

Collider Phenomenology



Pair production process of stop pair at LHC.



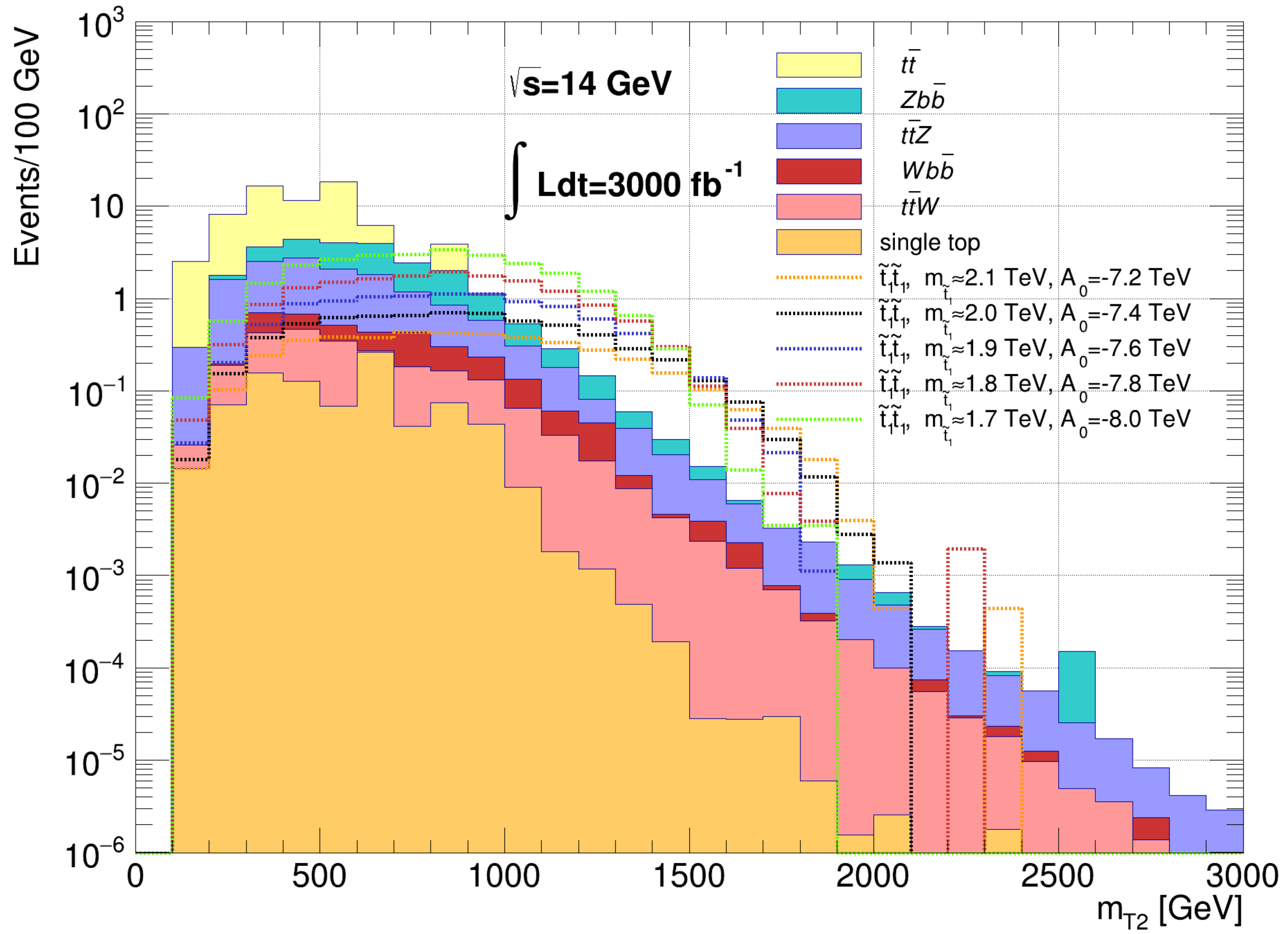
Production cross-section for stop masses in the range 800-2200 GeV at 14 TeV LHC at NLO.

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

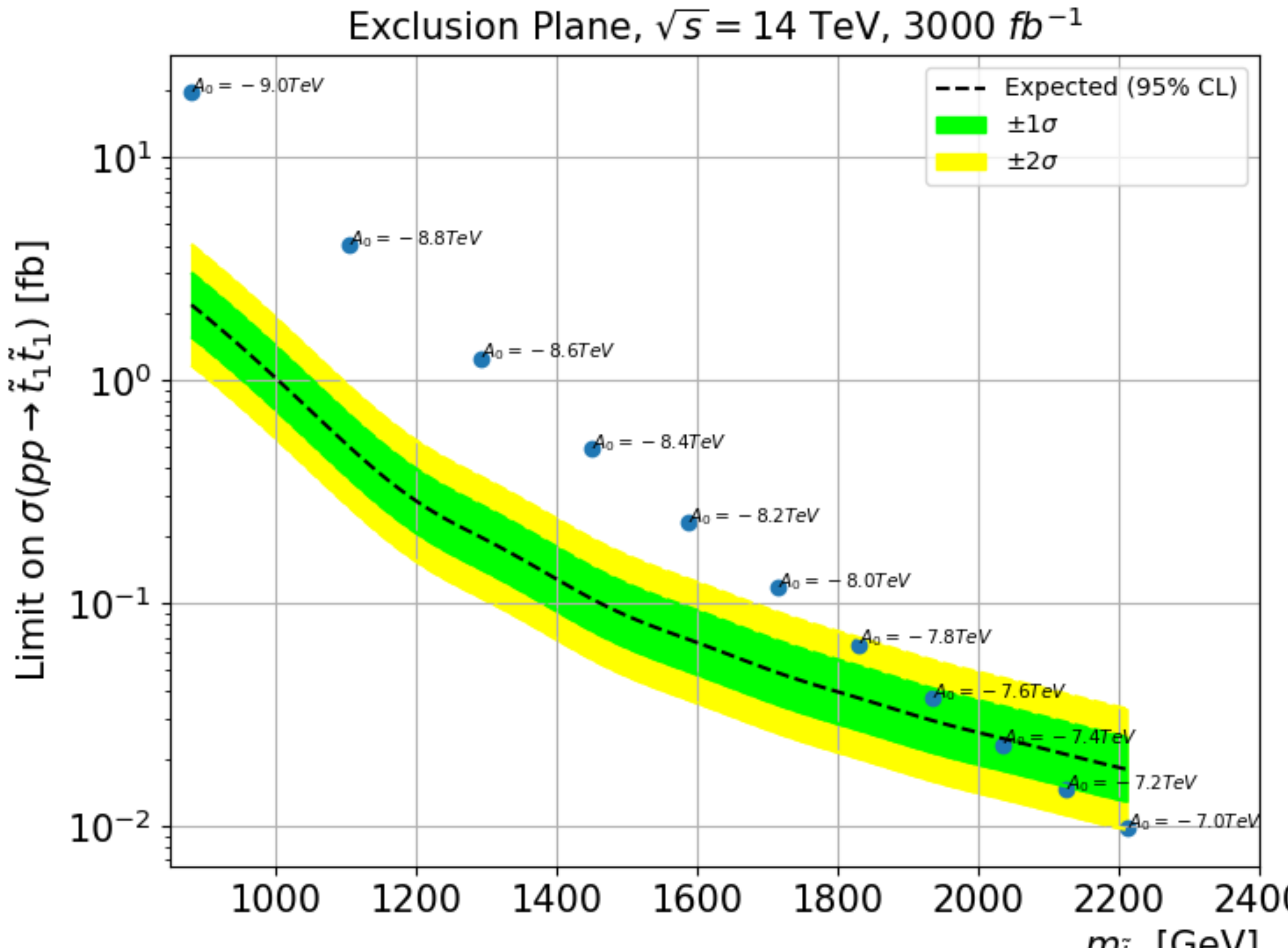
- Signal topologies: $tb + \not{E}_T, tt + \not{E}_T, bb + \not{E}_T$

- Key SM backgrounds: bbZ, ttZ, ttW, single top, tt suppressed using highly boosted top-jets $(p_T > 400,\ \not{E}_T > 400 GeV, H_T > 1.4 TeV,$ $L_T > 1.8 TeV$, $\min(m_T(b_1, \not{E}_T), m_T(b, \not{E}_T)) > 175.0,$ $\Delta_\Phi(b, \not{E}_T) > 40°, \Delta_\Phi(J, \not{E}_T) > 30°$ for $tb + \not{E}_T$ channel. Similar cuts for the other two channels.

- Key kinematic variable for discrimination between signal and background m_{T_2}, sets combined reach of stops 1.7 TeV at 5σ and 2 TeV, at 2σ, covering most of the region allowed from the string landscape!



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



Summary

- String landscape provides a way to understand origin of the SUSY breaking scale motivated from Weinberg's cosmological constant solution.

- The MSSM considered a low-energy EFT consistent with the ABDS window to ensure the atomic principle.

- Stops predicted within 1-2.5 TeV range and consistent with the 125 GeV Higgs.

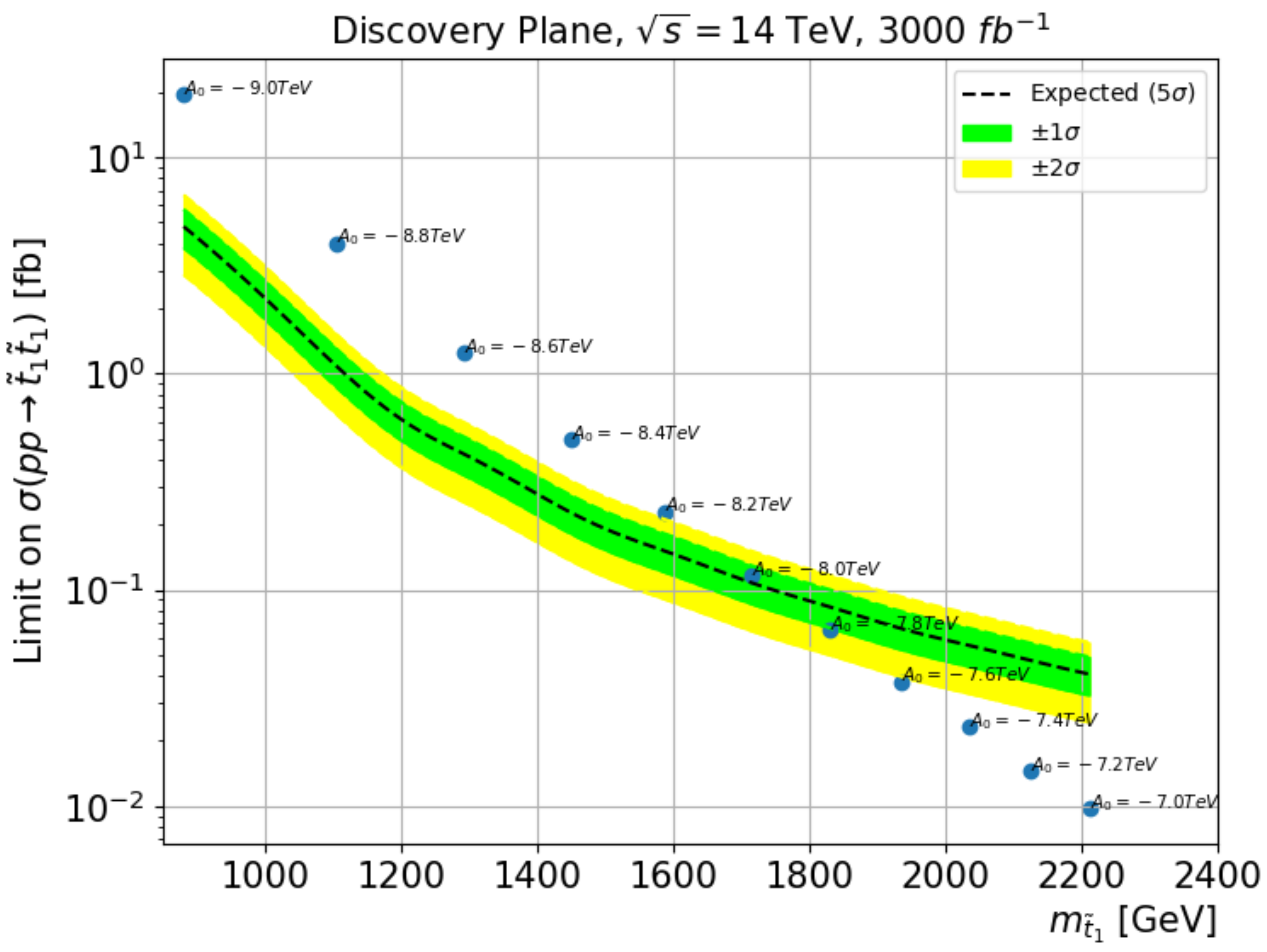
- Mostly right-handed stops lead to $tb + \not{E}_T$, $tt + \not{E}_T$, $bb + \not{E}_T$.

- Reach for stops upto 1.7 TeV at 5σ and 2.0 TeV at 2σ, covering almost all of the allowed region predicted by the landscape at HL-LHC!

Thank You

Backup

Discovery limits on stop pair production



- Significant reach for light stops (~2 TeV at 95% CL) at HL-LHC.

Measures of Naturalness

- Barbieri-Guidice: p_i **are the fundamental parameters of the theory**

$$\Delta_{BG} \equiv max_i\,[c_i] \quad \text{where} \quad c_i = \left|\frac{\partial \ln m_Z^2}{\partial \ln p_i}\right| = \left|\frac{p_i}{m_Z^2}\frac{\partial m_Z^2}{\partial p_i}\right|$$

Barbieri et.al, Nucl. Phys. B306 (1988) 63–76}

Guidice et al.hep-ph/9507282