Mirage Models Confront LHC Data

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Motivation

- First 20 fb^{-1} provide a lot of information for SUSY phenomenologists
  - ⋆ No superpartners observed, but...
  - ⋆ SM-like Higgs in the SUSY preferred window with $m_h \simeq 126\,\mathrm{GeV}$
- Add this to what we already know
  - ⋆ FCNC and rare decays in line with SM predictions
  - ⋆ If neutralino is stable we have an upper bound on its relic density, etc.
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  - ⋆ If neutralino is stable we have an upper bound on its relic density, etc.
- Might think that this information is not too useful – just push up the scale?
- But in a theory with a legitimate UV completion these scales are not arbitrary
- String models are highly constrained and inter-connected – in these models the LHC data is already telling is something very meaningful about the underlying theory
- String models provide a rich laboratory for exploring how LHC data impacts models of supersymmetry breaking generally

What is a ‘Mirage Model’?

⇒ Operational definition: a *mirage model* is any model in which soft supersymmetry breaking gaugino masses take a specific form

- Mirage pattern of gaugino masses at EW scale – a one-parameter family:

$$M_1 : M_2 : M_3 \simeq (1 + 0.66\alpha) : (2 + 0.2\alpha) : (6 - 1.8\alpha)$$

- A logical departure from ‘unified’ models
  - ⋆ Easy to understand and visualize
  - ⋆ Interpolates between mSUGRA ($\alpha = 0$) and AMSB limit ($\alpha \to \infty$)
  - ⋆ Motivated by a variety of constructions, including string theory (heterotic and Type II) as well as “deflected” AMSB

- **All** values of α correspond to a unified pattern – the only issue is at which *energy scale* they unify
  - ⋆ When $\alpha = 0$ gaugino masses unify at $M_{\rm GUT} \simeq 2 \times 10^{16}$ GeV
  - ⋆ Other α values give effective unification scale elsewhere (hence “mirage”)
  - ⋆ Example: $\alpha = 2$ gives $M_1 \simeq M_2 \simeq M_3$ at low-energy scale
  - ⋆ Effective unification scale is now at

$$\Lambda_{\rm mir} = \Lambda_{\rm GUT} \left(\frac{m_{3/2}}{M_{\rm PL}} \right)^{\alpha/2}$$

Heterotic versus Type IIB String Theory

$\Rightarrow$ Moduli stabilization generally produces distinctive patterns of SUSY breaking

$\Rightarrow$ Mirage pattern arises when $\langle V \rangle = 0$ achieved by non-perturbative effects

Heterotic versus Type IIB String Theory

⇒ Moduli stabilization generally produces distinctive patterns of SUSY breaking

⇒ Mirage pattern arises when $\langle V \rangle = 0$ achieved by non-perturbative effects

- A single un-stabilized geometrical modulus in 4D effective supergravity theory
  - ⋆ Heterotic: dilaton superfield S
  - ⋆ Type IIB: an overall Kähler modulus T
- Tree-level gauge kinetic function determined by this field
  - ⋆ Heterotic: $f_a^0 = S$
  - ⋆ Type IIB: $f_a^0 = T$ for gauge fields arising from $D7$-branes
- This modulus stabilized via non-perturbative contributions to the superpotential
  - ⋆ Heterotic: gaugino condensation in hidden sector (subgroups of E_8)

$$W_{\rm np} = \sum_i A_i e^{-S/b_i}$$

  - ⋆ Type IIB: Gaugino condensation and/or Euclidean $D3$-instantons

$$W_{\rm np} = W_0 + \sum_i A_i e^{-a_i T}$$

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⇒ Mirage pattern arises when $\langle V \rangle = 0$ achieved by non-perturbative effects

- Vanishing vacuum energy $\langle V \rangle = 0$ engineered through additional non-perturbative effects/explicit supersymmetry breaking
  - ⋆ Heterotic: instanton corrections to dilaton action
  - ⋆ Type IIB: explicit SUSY breaking in an 'uplift' sector
    KKLT: $\bar{D}3$-branes at tip of Klebanov-Strassler throat
- Hierarchies in SUSY breaking $\langle F \rangle \sim m_{3/2}/16\pi^2$ related to condensate parameter (let "+" represent largest confining group):
  - ⋆ Heterotic: $\langle F_S \rangle / m_{3/2} \sim g_s^2 b_+ / (1 + g_s^2 b_+)$
  - ⋆ Type IIB: $\langle F_T \rangle / m_{3/2} \sim g_s^2 / a_+$
- Key difference: non-universality parameter α that defines the mirage pattern determined by how vacuum energy is handled
  - ⋆ Heterotic: same mechanism as stabilization, therefore $\alpha = \alpha(\beta_+)$
  - ⋆ Type IIB: depends on $(T + \overline{T})$-dependence of uplift mechanism

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⇒ **Kähler stabilized heterotic model far more constrained than Type IIB flux-compactified model**

Kähler-Stabilized Heterotic Parameter Space

⇒ Soft terms set by two (quasi-)independent parameters: β_+ and $m_{3/2}$

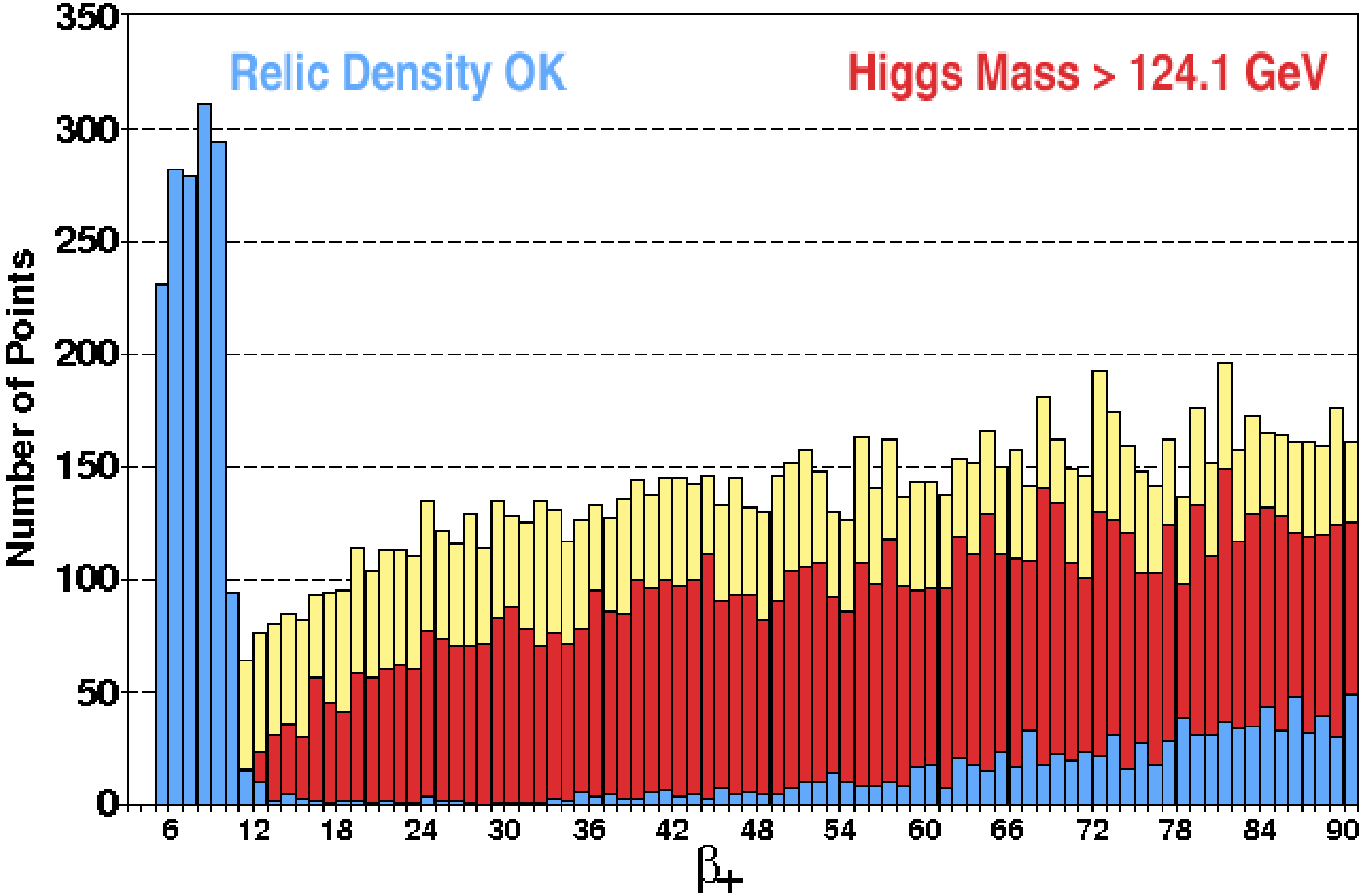
$$\beta_+ = \left(3C_+ - \sum_i C_+^i \right) , \qquad b_+ = \frac{2}{3} \left(\frac{\beta_+}{16\pi^2} \right)$$

- Largest the hidden sector can be is E_8, so $\beta_+ = 90$
- Achieving the Standard Model gauge group generally involves Wilson lines, so expect a hidden sector no bigger than E_6 ($\beta_+ = 36$) or $SO(10)$ ($\beta_+ = 24$)
- Even smaller values tend to be favored from realistic constructions

⇒ Soft terms show mirage pattern in dimension-one terms only

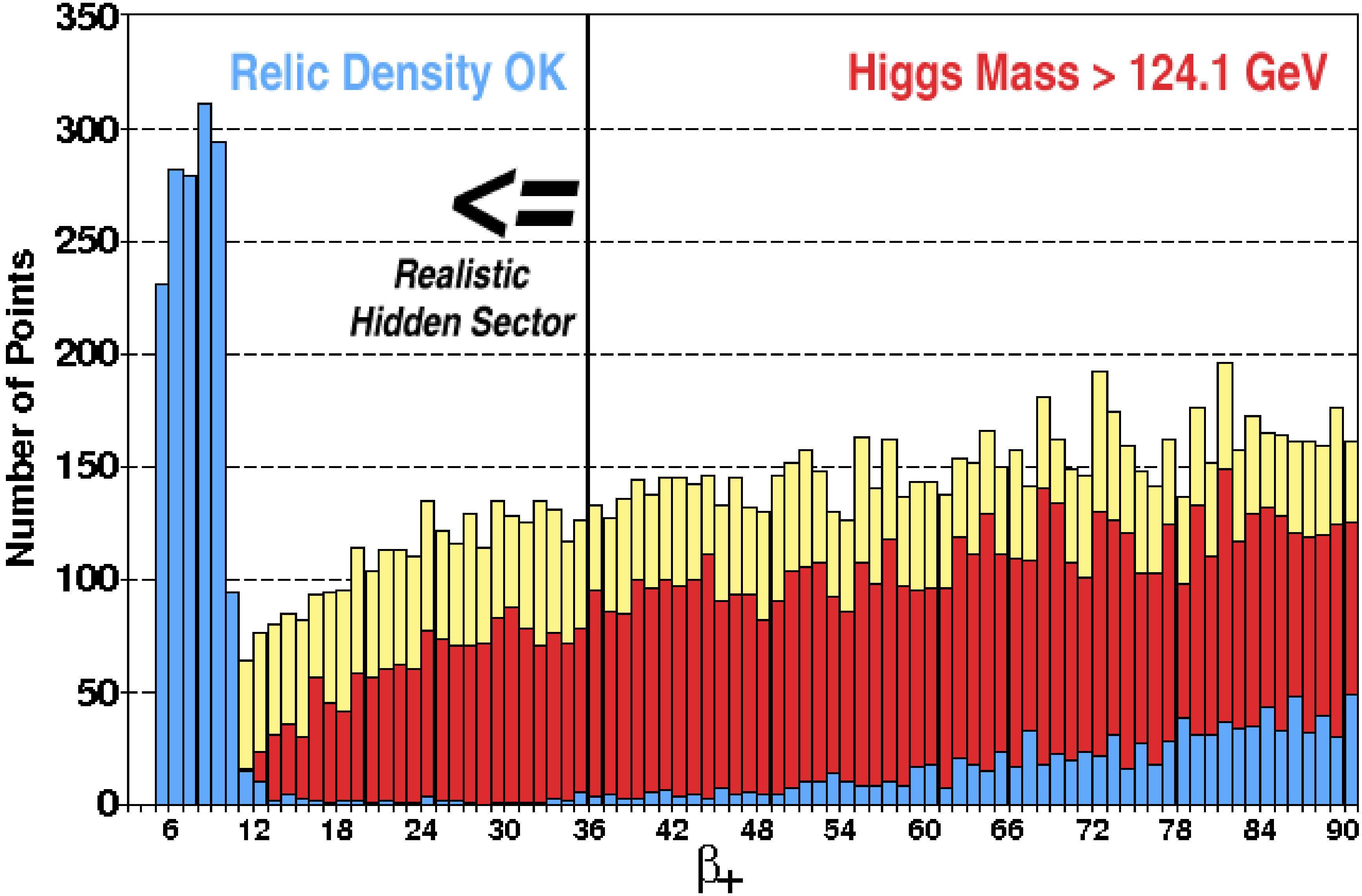
$$\begin{aligned} M_a &\sim F_S + \frac{\beta_a}{16\pi^2} m_{3/2} \\ A_{ijk} &\sim -F^S + (\gamma_i + \gamma_j + \gamma_k)\, m_{3/2} \\ m_i^2 &\sim (1 + \gamma_i)\, m_{3/2}^2 - \widetilde{\gamma}_i \left(\frac{m_{3/2} F^S}{2} + \text{ h.c.} \right) \end{aligned}$$

Higgs Mass versus Dark Matter



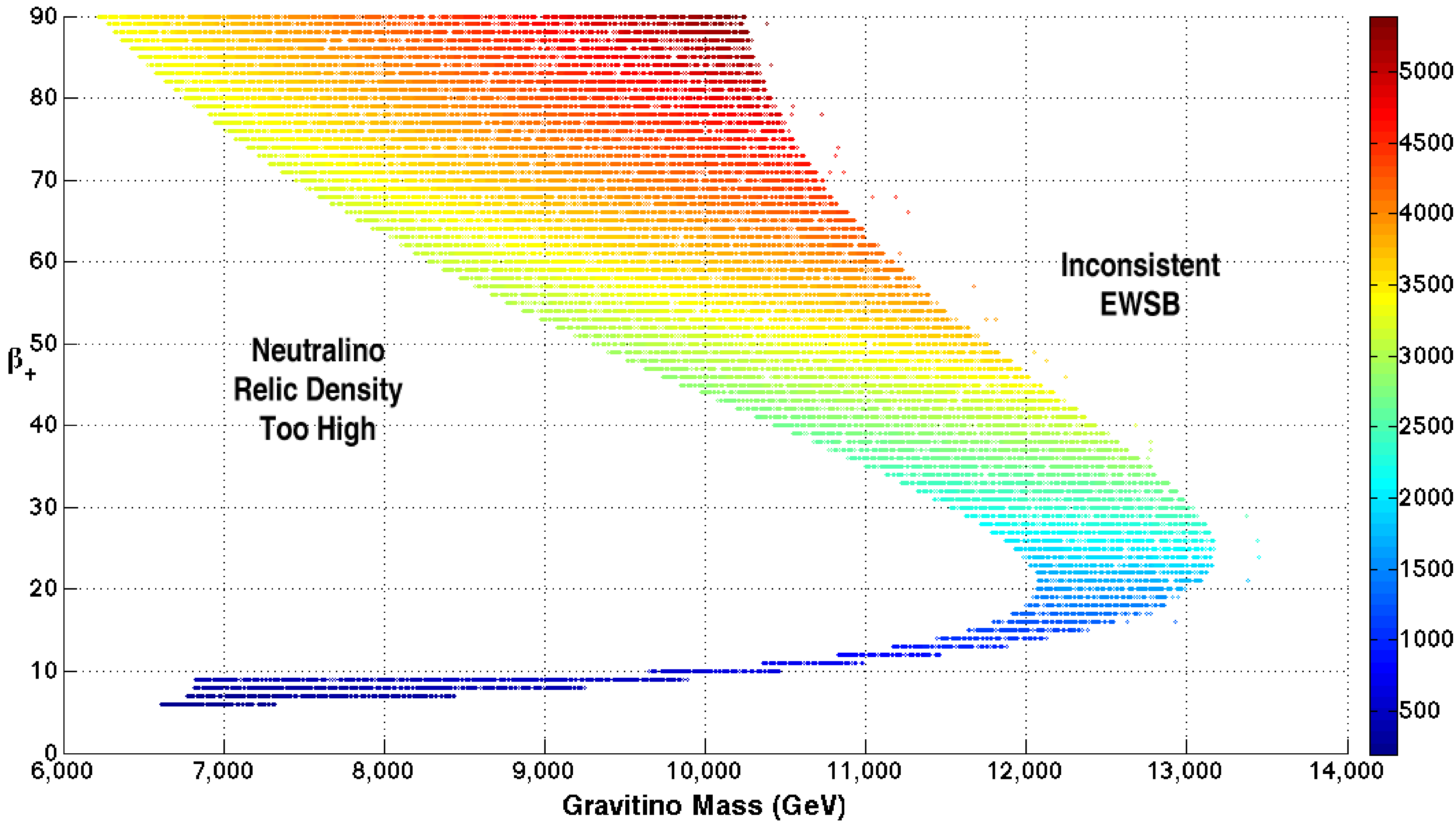
- Tension between correct LSP relic density and LHC Higgs mass measurement
- 'Automatic' dark matter for wino-like WIMP at $\beta_+ \lesssim 9$ now strongly disfavored

Higgs Mass versus Dark Matter



- Hidden sector of pure E_6 (no matter) has $\beta_+ = 36$
- Will need to boost Higgs mass by going to high $\tan\beta$

Parameter Space for $\tan\beta = 42$ with Gluino Mass



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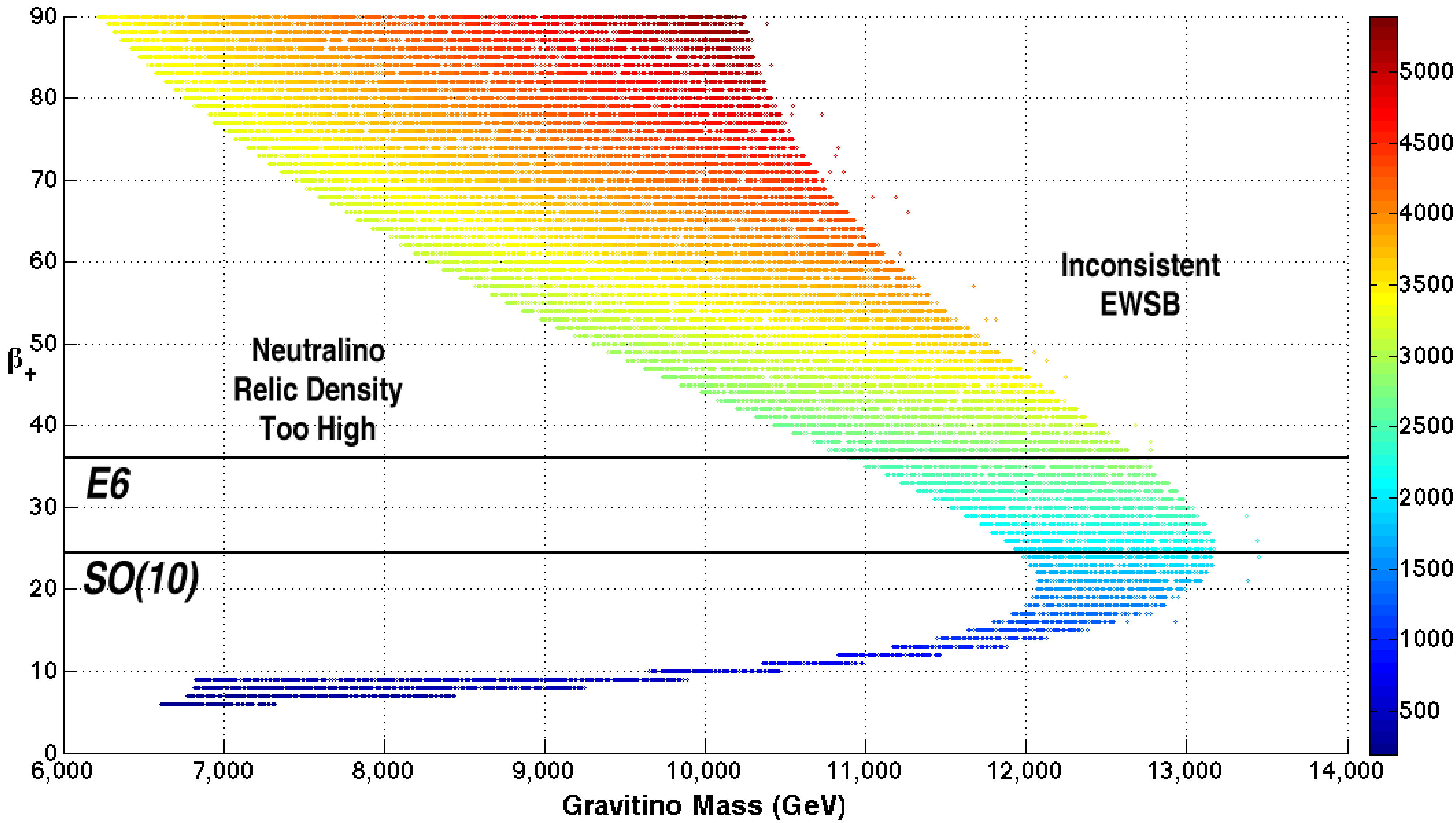

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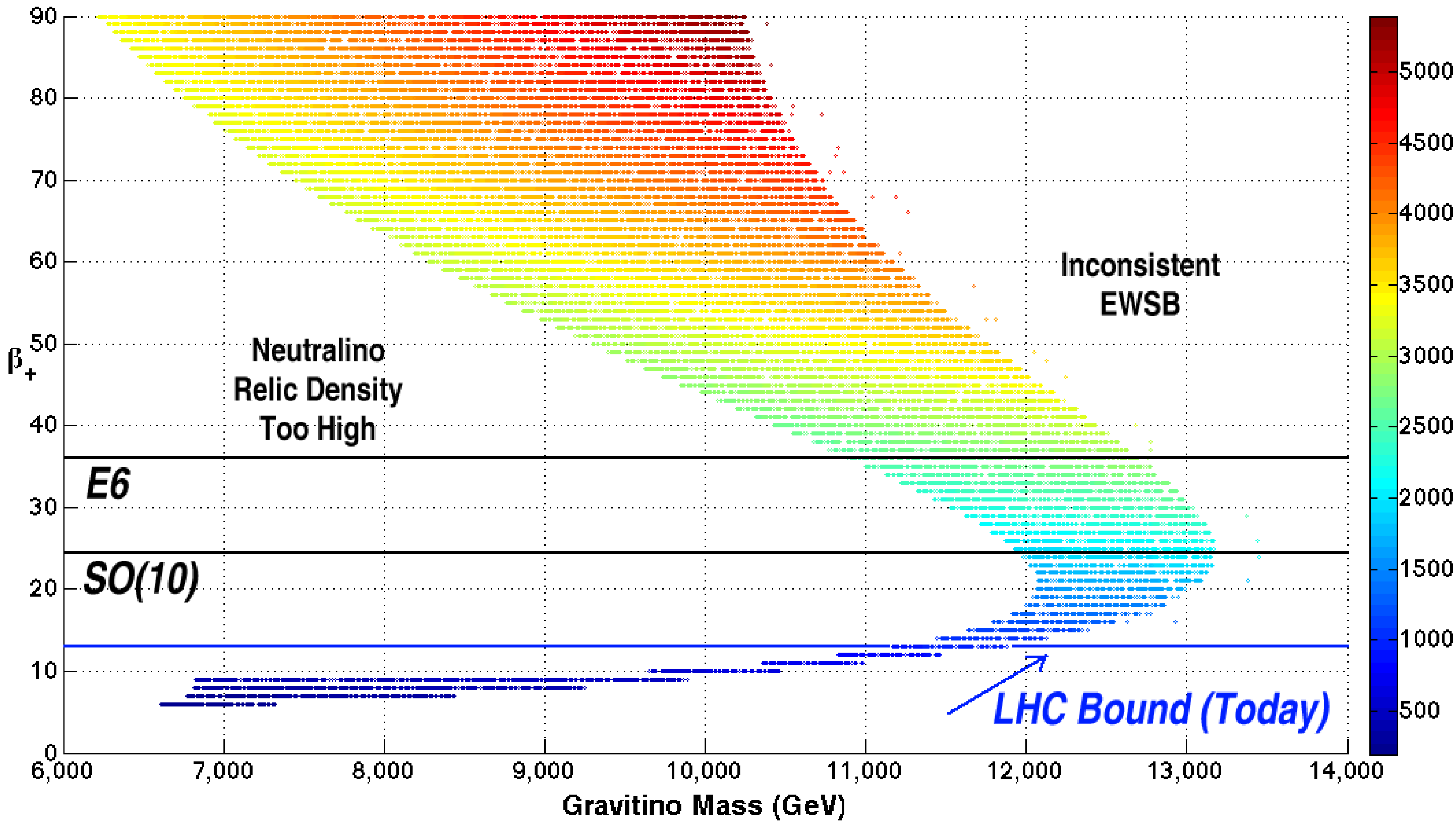

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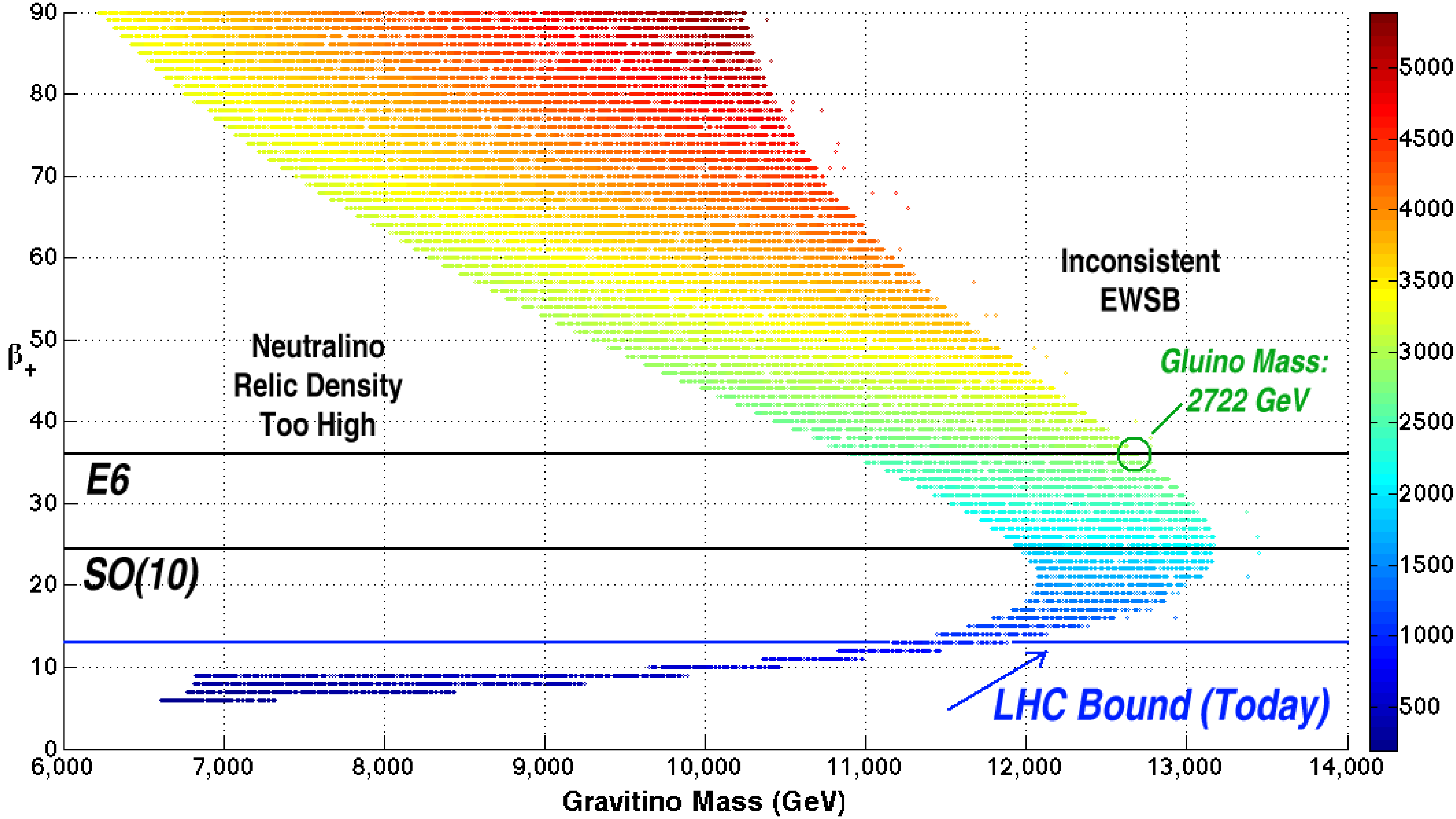


8 TeV LHC Results

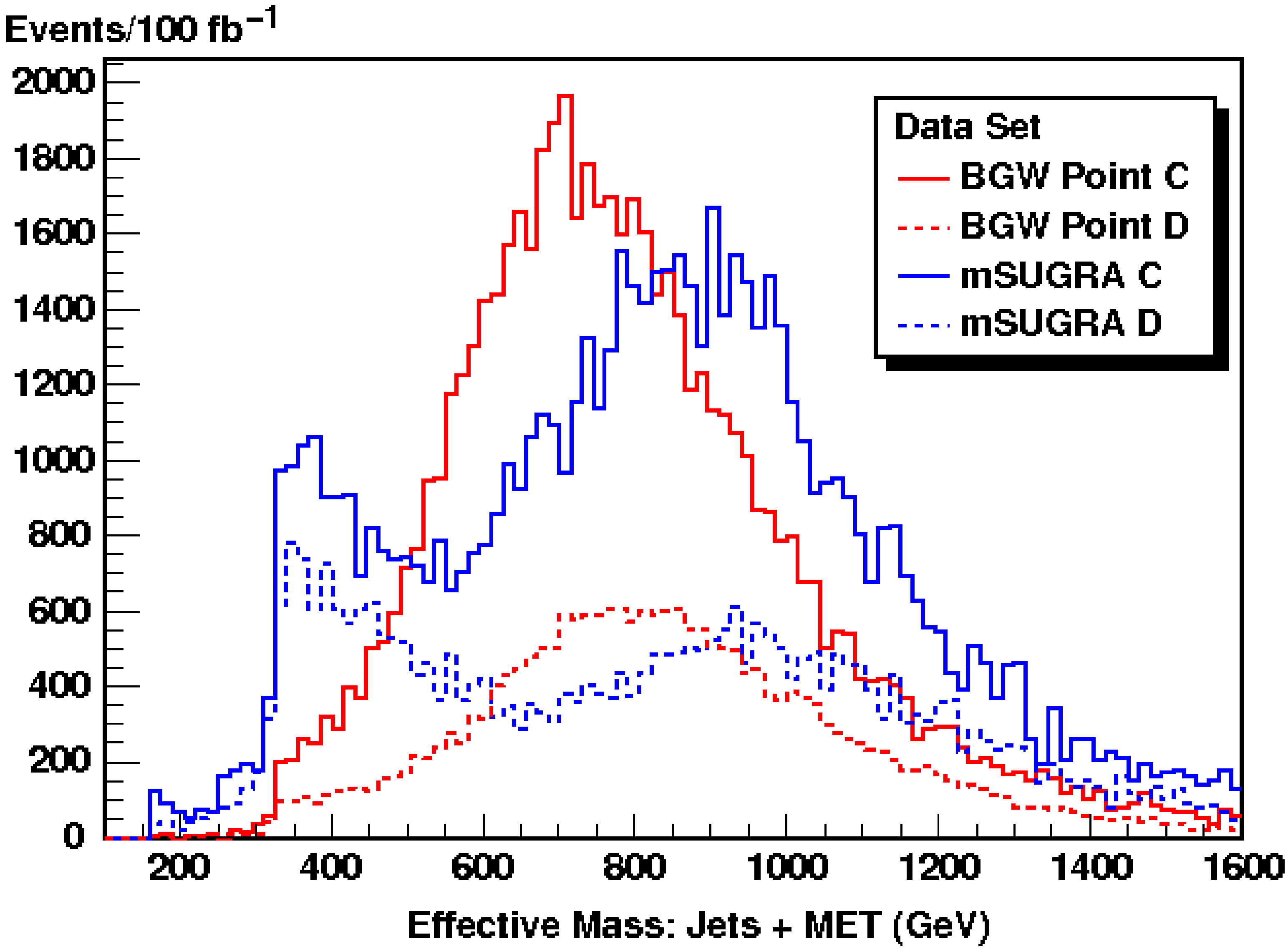
			Low Multiplicity Jets					Leptonic Channels						
			2 Jets		4 Jets			1 Lepton		SS Dilepton		SS 2ℓ, B-Jets		
Point	β_+	$m_{\tilde{g}}$	M	T	L	M	T	$1e$	1μ	$e\,\mu$	$\mu\,\mu$	0b	1b	3b
A	9	498	24	**9**	**101**	**27**	**5**	2	**12**	**6**	1	**24**	**15**	2
B	10	628	6	1	39	11	1	2	**11**	**6**	1	**33**	**68**	**21**
C	11	699	4	1	23	7	–	1	**7**	**8**	**4**	**22**	**44**	**13**
D	12	808	2	–	13	3	–	1	4	**6**	**3**	**12**	**33**	**9**
E	13	913	2	–	7	2	–	1	2	3	2	**7**	**18**	4
F	14	1050	2	–	4	2	–	–	2	1	1	2	6	1
G	15	1114	1	–	2	1	–	–	1	1	1	2	4	1
H	18	1392	–	–	–	–	–	–	–	–	–	–	1	–
		Observed	111	10	156	31	1	10	4	2	1	5	8	4
		N_{BSM}	34	9	66	18	3	10	6	6	3	7	11	7

Table 1: **Event Counts for BGW Benchmark Points at $\sqrt{s} = 8\,\mathrm{TeV}$ for Selected ATLAS Searches.** Table entries in boldface indicate a channel which would have produced a discovery for that point.

$\Rightarrow$ Greatest reach from same-sign dilepton with b-tagged jets (**ATLAS-CONF-2013-007**)

- At least two leptons (e or μ) with the same sign and $p_T > 20\,\mathrm{GeV}$
- Requires 0, 1 and 3^+ b-tagged jets with $p_T > 40\,\mathrm{GeV}$
- Missing transverse energy $E_T^{\mathrm{mis}} > 150\,\mathrm{GeV}$
- Total effective mass cut $M_{\mathrm{eff}} > 700\,\mathrm{GeV}$

Effective Mass Distribution



⇒ Softer decay products implies 100-200 GeV less reach in $m_{\tilde{g}}$ relative to mSUGRA benchmarks

Type IIB (à la KKLT) Parameter Space

- Soft terms set by two truly independent parameters
  - ⋆ Can choose two mass scales $M_0 \equiv \left\langle F_T/(T+\overline{T})\right\rangle$ and $m_{3/2}$
  - ⋆ Or choose one mass scale and the parameter $\alpha \equiv \frac{m_{3/2}}{M_0 \ln\left(M_{\rm PL}/m_{3/2}\right)}$

⇒ For certain choices of uplift sector, α becomes a *prediction*

- Example: consider modifying effective supergravity Lagrangian as follows

$$\mathcal{L} \ni -2\int \mathrm{d}^4\theta E \to -2\int \mathrm{d}^4\theta \left[E + P(T,\overline{T})\right] , \quad P(T,\overline{T}) = C(T+\overline{T})^n$$

- Now α given by a rational number

$$\alpha = \frac{1}{1-n/2} + \mathcal{O}\left(1/\ln(M_{\rm PL}/m_{3/2})\right)$$

- Note that for original KKLT suggestion of $\overline{D3}$-branes, $n = 0 \longrightarrow \alpha = 1$

Flux-Compactified Type IIB: Soft Terms

⇒ Our analysis chose to scan on parameters α and M_0

- M_0 most directly tied to overall superpartner masses; α is the parameter of most interest theoretically
- Soft terms are more easily expressed in terms of M_0 and $m_{3/2}$, however

$$\begin{aligned} M_a &\sim M_0 + \frac{\beta_a}{16\pi^2} m_{3/2} \\ A_{ijk} &\sim -(3 - n_i - n_j - n_k) M_0 + (\gamma_i + \gamma_j + \gamma_k)\, m_{3/2} \\ m_i^2 &\sim (1 - n_i) M_0^2 - \theta_i M_0 m_{3/2} - \dot{\gamma}_i m_{3/2}^2 \end{aligned}$$

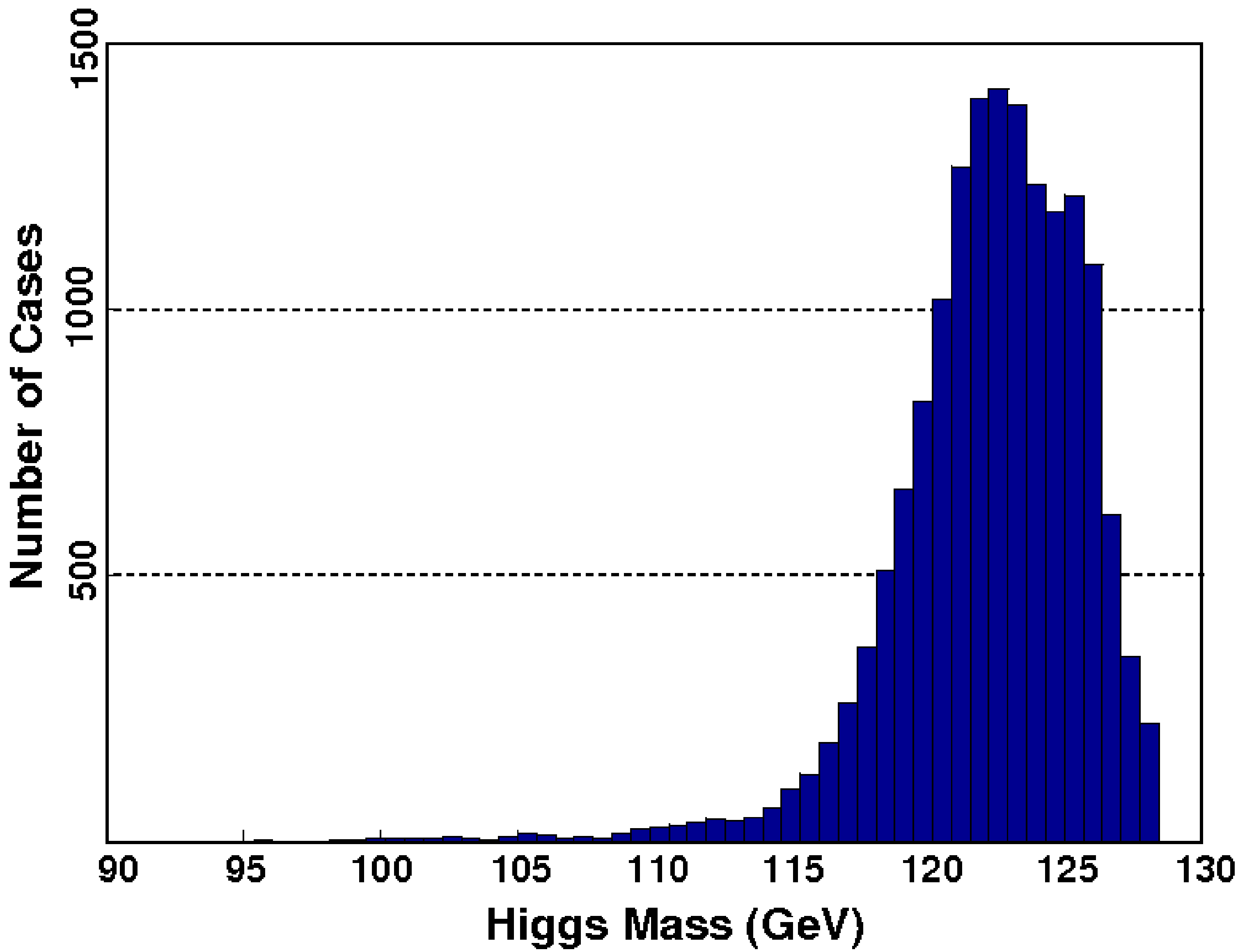
⇒ Expressions for scalar fields involve the *modular weight* n_i

- Indicates the non-canonical nature of the kinetic terms for scalar fields

$$K_{i\bar{j}} = \frac{\delta_{i\bar{j}}}{(T + \overline{T})^{n_i}}$$

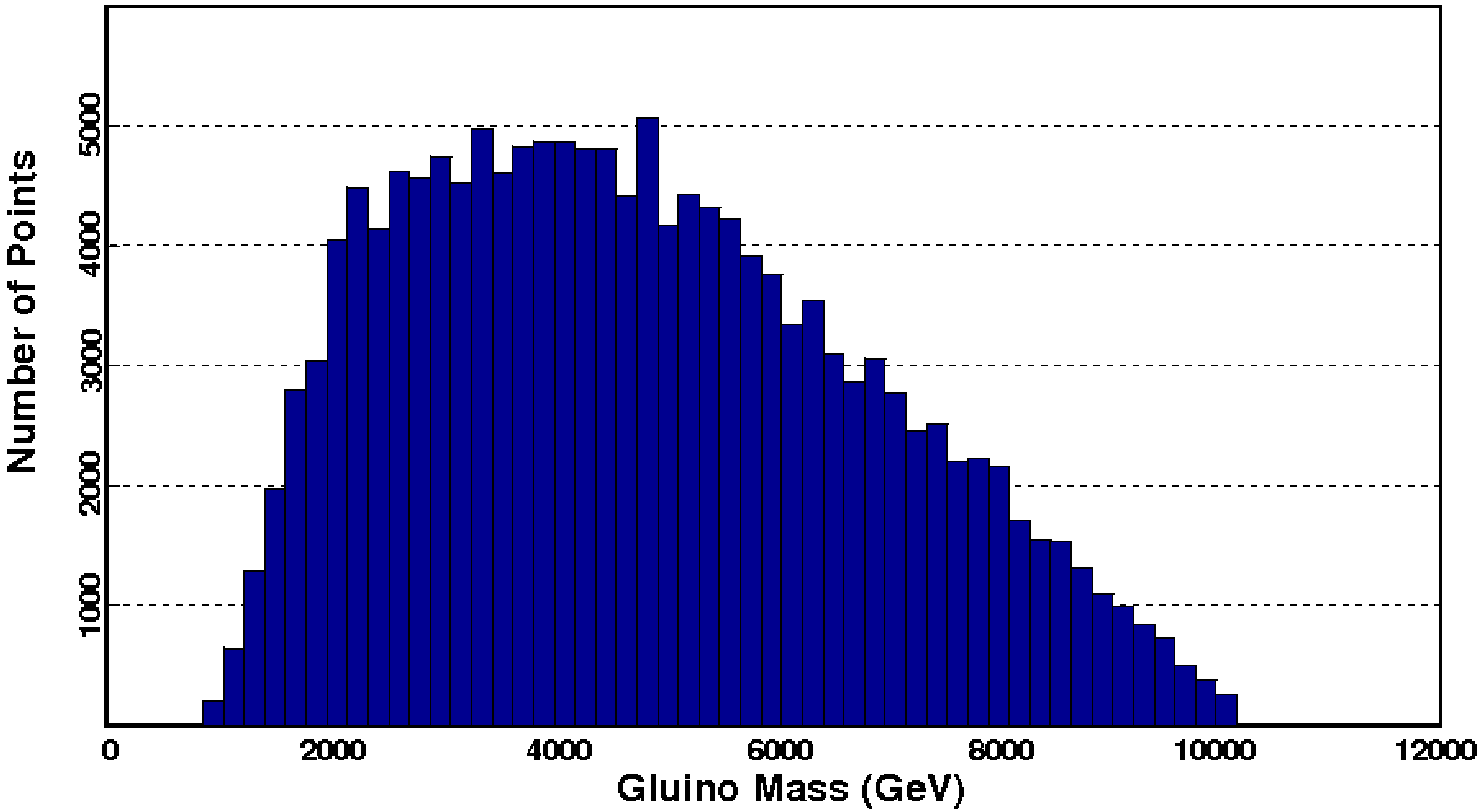
- Depends on how SM fields are realized locally on stacks of D-branes
  - ⋆ $n_i = 1$ for $D3$-brane fields, $n_i = 0$ for $D7$-brane fields
  - ⋆ $n_1 = 1/2$ for twisted sectors stretched between $D3/D7$ branes, or different stacks of $D7$-branes

Higgs Mass Distribution: All Modular Weights



$\Rightarrow$ Once requirement $\Omega_\chi h^2 \leq 0.128$ imposed, distribution on Higgs mass favors LHC measured values

Gluino Mass Distribution: All Modular Weights



⇒ Before imposing Higgs mass and dark matter requirements

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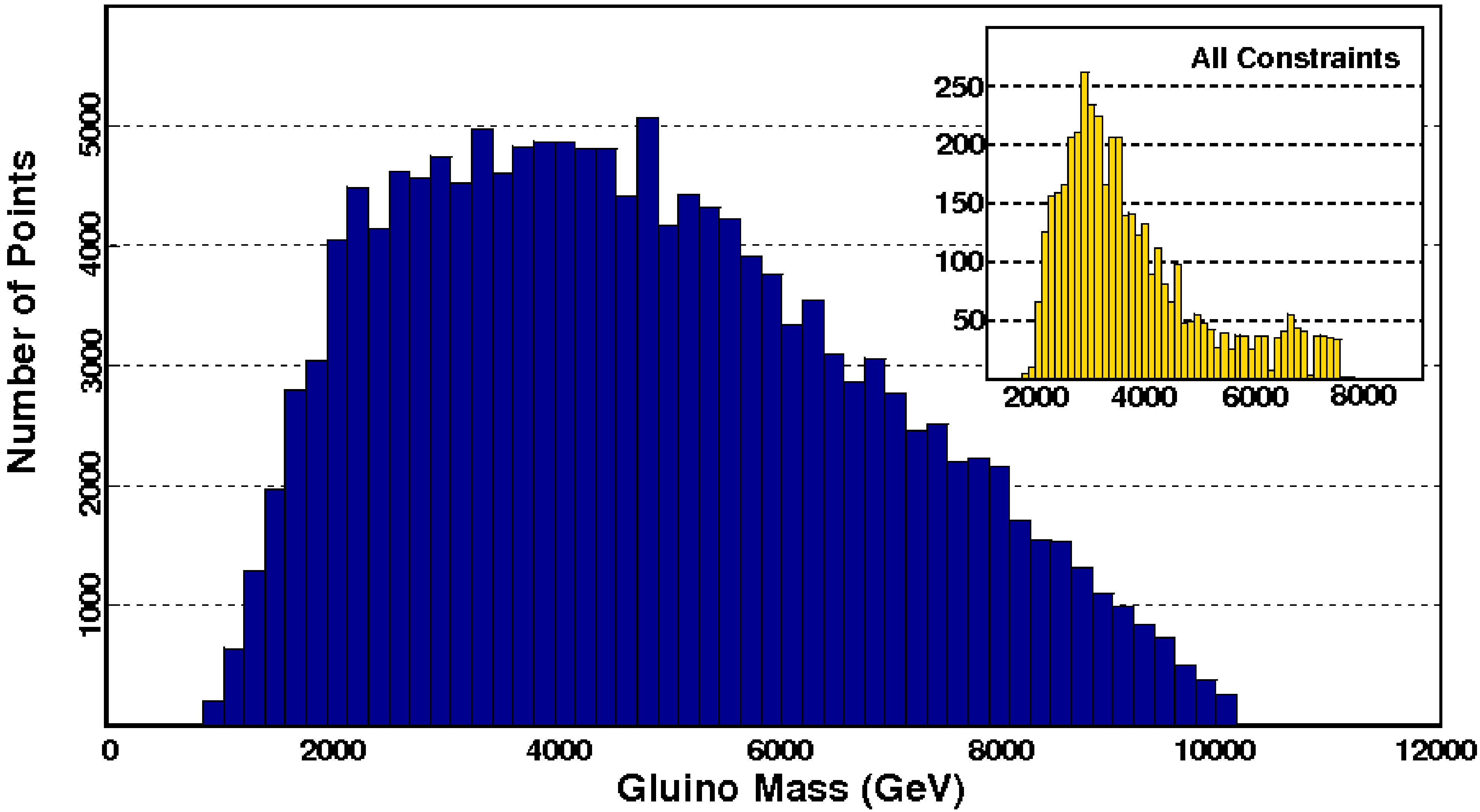
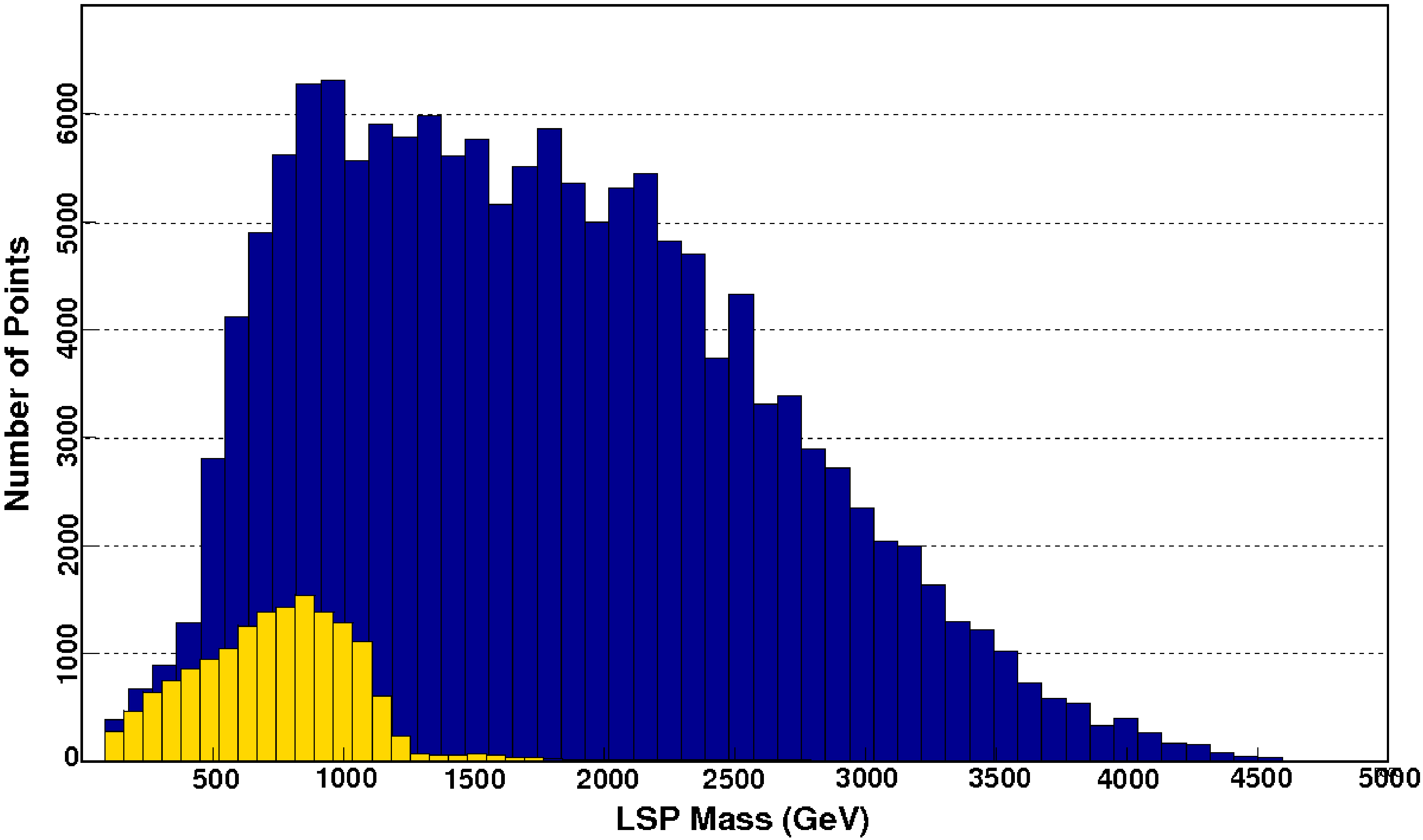


⇒ After imposing $124.2\,\mathrm{GeV} \leq m_h \leq 127.0\,\mathrm{GeV}$ and $\Omega_\chi h^2 \leq 0.128$

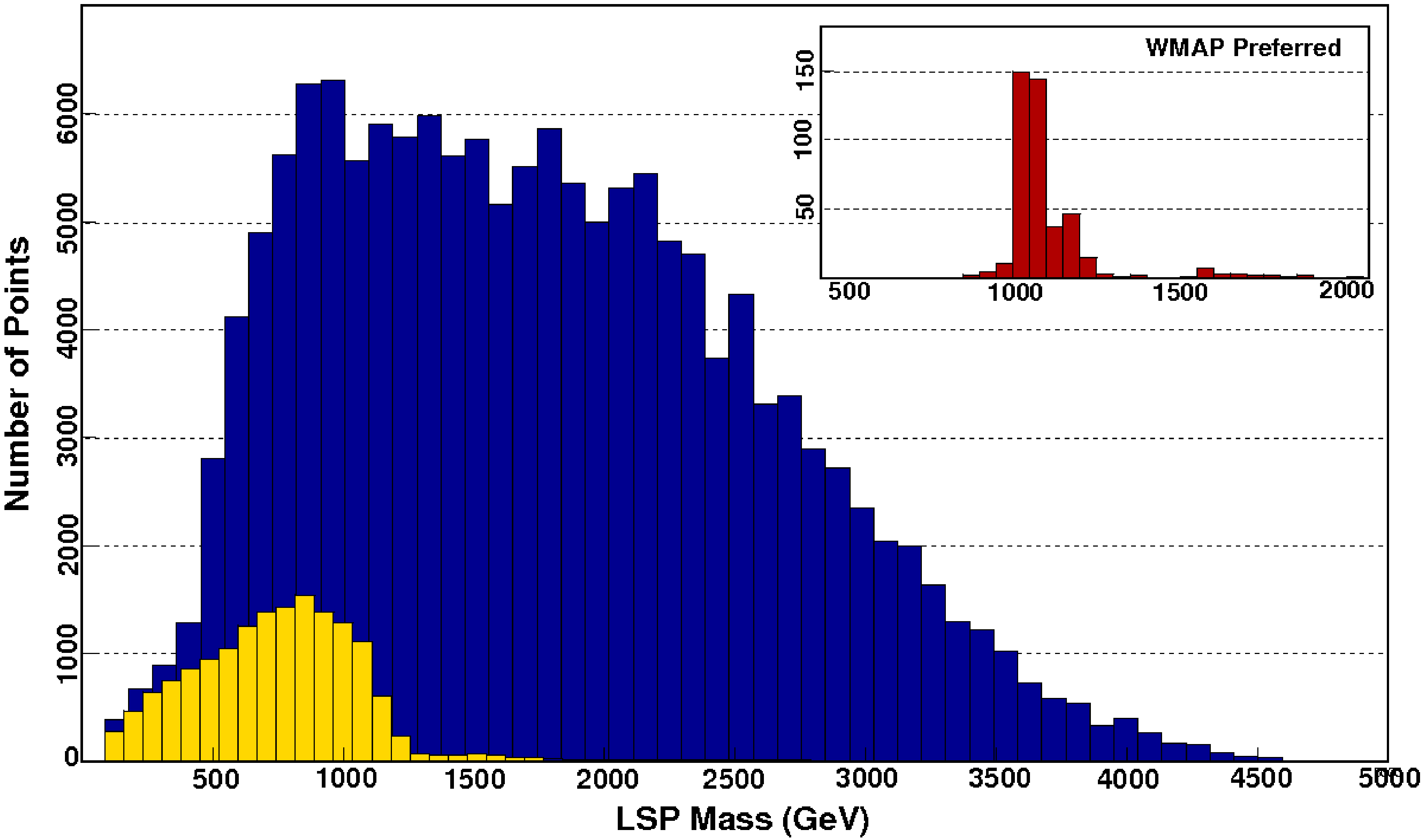
LSP Mass Distribution: All Modular Weights



⇒ Blue histogram: before Higgs mass and dark matter requirements

⇒ Yellow histogram: requiring $124.2\,\mathrm{GeV} \leq m_h \leq 127.0\,\mathrm{GeV}$ and $\Omega_\chi h^2 \leq 0.128$

LSP Mass Distribution: All Modular Weights

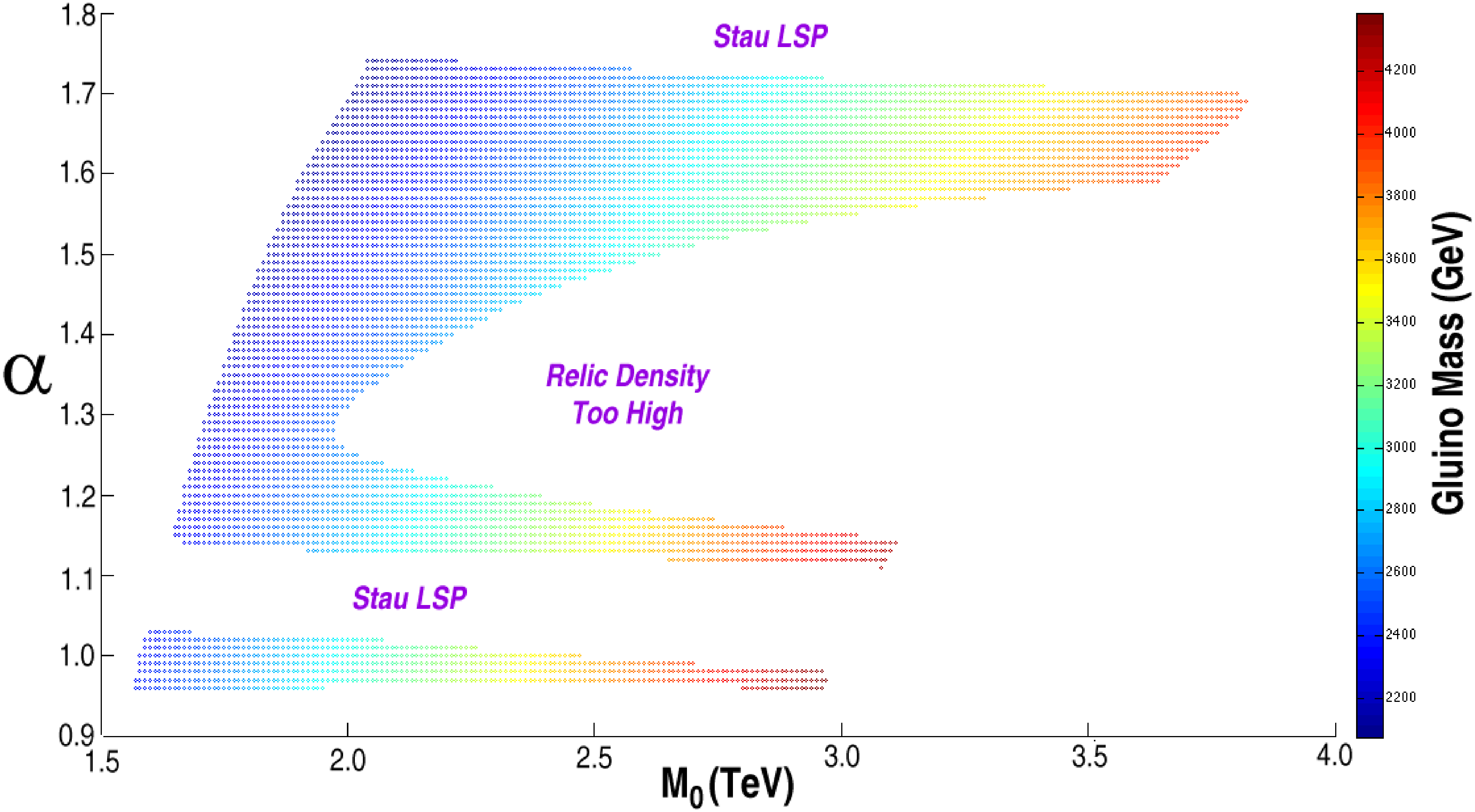


⇒ Blue histogram: before Higgs mass and dark matter requirements

⇒ Yellow histogram: requiring $124.2\,\mathrm{GeV} \leq m_h \leq 127.0\,\mathrm{GeV}$ and $\Omega_\chi h^2 \leq 0.128$

⇒ Red histogram: requiring $\Omega_\chi h^2 = 0.1199 \pm 0.0027$

Example: Modular Weights $(n_M, n_H) = (1/2, 0)$



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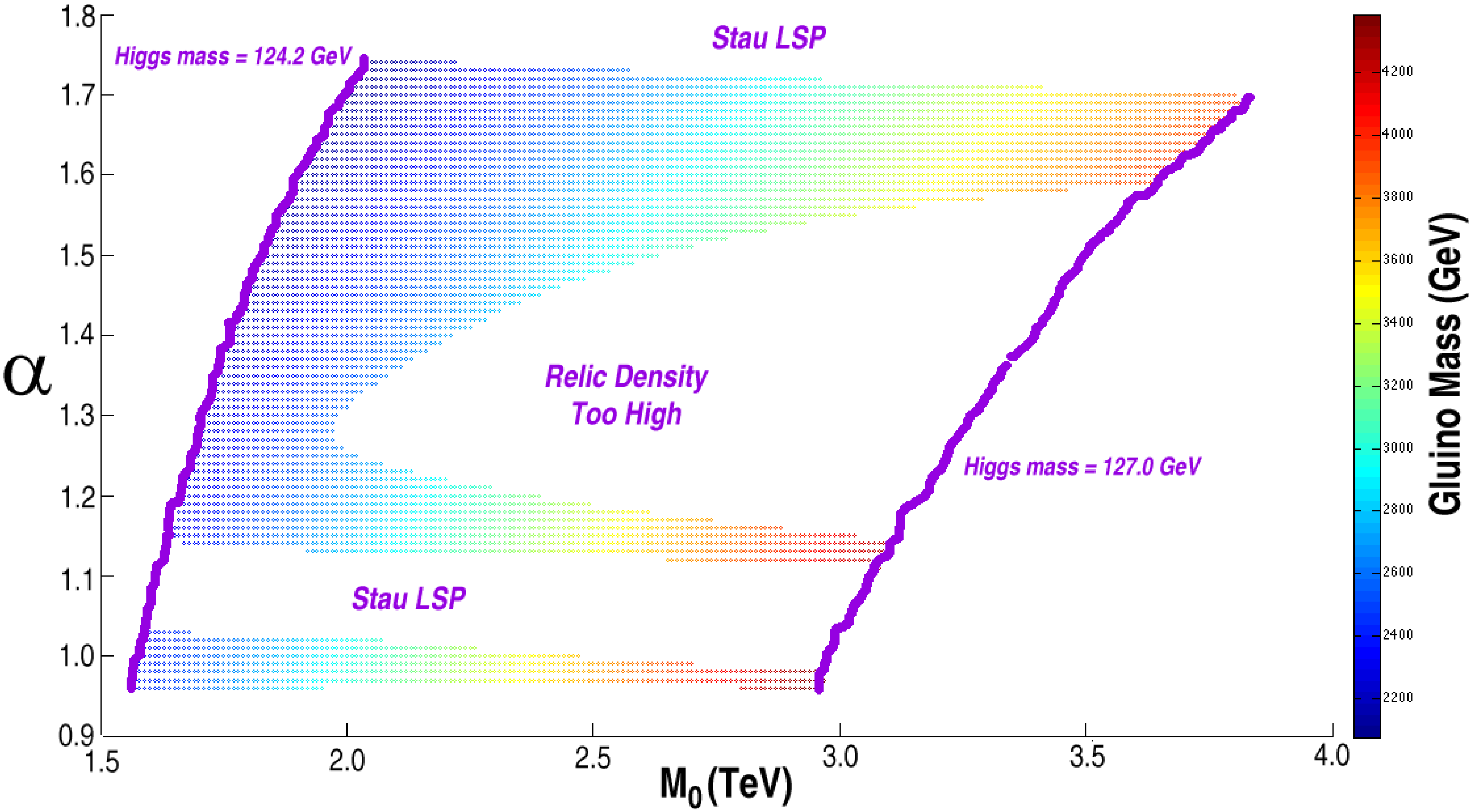

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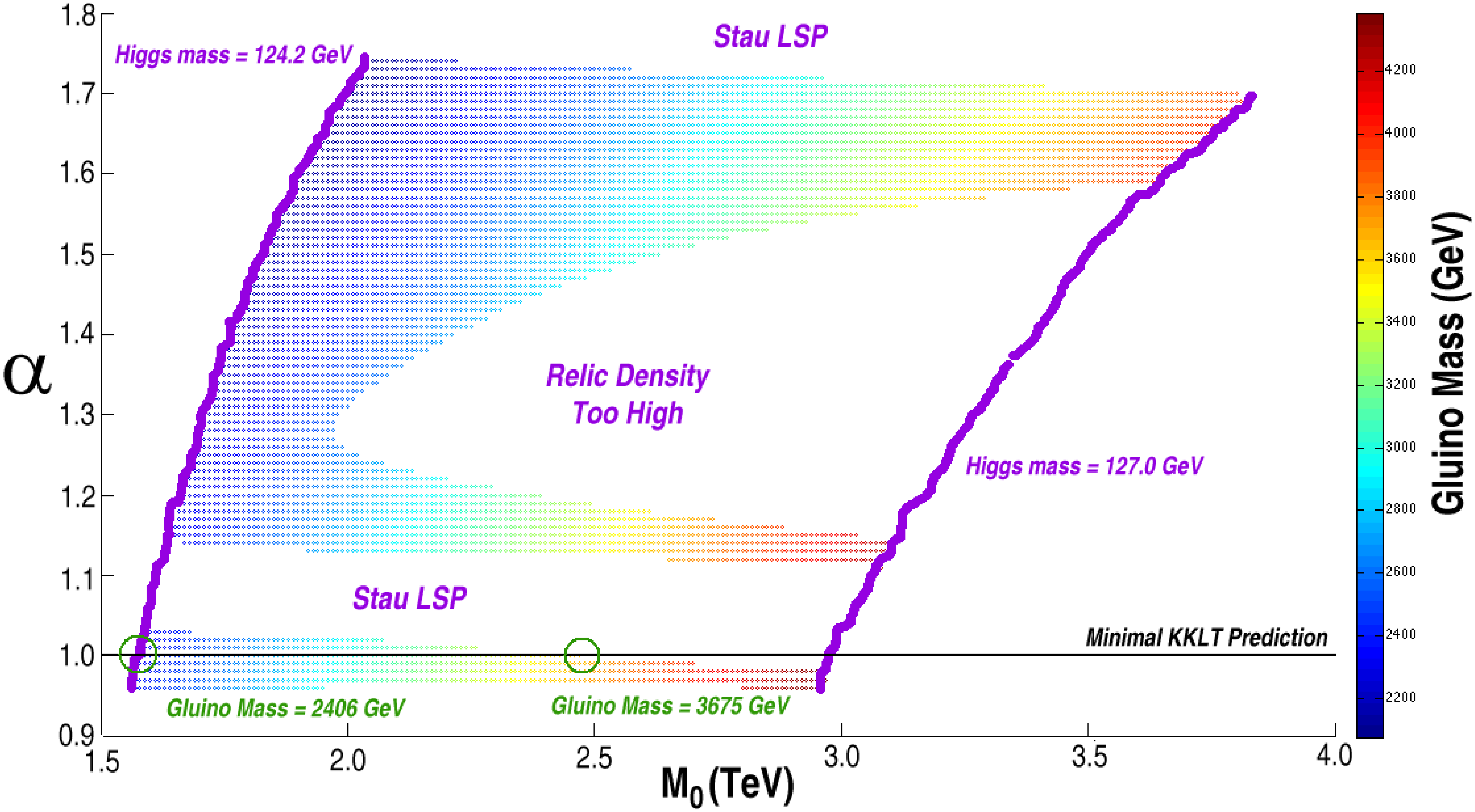

Summary of Modular Weight Results

	$n_H = 0$	$n_H = 1/2$	$n_H = 1$
$n_M = 0$	$1.08 \leq \alpha \leq 1.19$ $1.96 \leq \alpha \leq 2.0$ $1200 \leq M_0 \leq 3410$ $1770 \leq m_{\tilde{g}} \leq 5400$ $\sigma_{\mathrm{SUSY}}^{14\mathrm{TeV}} = 39.1$ fb	$0.50 \leq \alpha \leq 0.62$ $1.85 \leq \alpha \leq 2.0$ $1290 \leq M_0 \leq 2600$ $1860 \leq m_{\tilde{g}} \leq 4330$ $\sigma_{\mathrm{SUSY}}^{14\mathrm{TeV}} = 21.3$ fb	$0 \leq \alpha \leq 0.20$ $1700 \leq M_0 \leq 2800$ $3470 \leq m_{\tilde{g}} \leq 5710$ $\sigma_{\mathrm{SUSY}}^{14\mathrm{TeV}} = 15.8$ fb
$n_M = 1/2$	$0.97 \leq \alpha \leq 1.03$ $1.10 \leq \alpha \leq 1.74$ $1570 \leq M_0 \leq 3820$ $1990 \leq m_{\tilde{g}} \leq 4390$ $\sigma_{\mathrm{SUSY}}^{14\mathrm{TeV}} = 2.2$ pb	$0.72 \leq \alpha \leq 0.82$ $1.46 \leq \alpha \leq 1.79$ $1290 \leq M_0 \leq 5090$ $2580 \leq m_{\tilde{g}} \leq 5550$ $\sigma_{\mathrm{SUSY}}^{14\mathrm{TeV}} = 1.1$ pb	$1.95 \leq \alpha \leq 2.0$ $4600 \leq M_0 \leq 6000$ $3900 \leq m_{\tilde{g}} \leq 5200$ $\sigma_{\mathrm{SUSY}}^{14\mathrm{TeV}} = 4.5$ fb
$n_M = 1$	$0.62 \leq \alpha \leq 0.78$ $1200 \leq M_0 \leq 3410$ $2250 \leq m_{\tilde{g}} \leq 4410$ $\sigma_{\mathrm{SUSY}}^{14\mathrm{TeV}} = 4.4$ pb	$0.77 \leq \alpha \leq 0.88$ $1290 \leq M_0 \leq 2600$ $3300 \leq m_{\tilde{g}} \leq 6000$ $\sigma_{\mathrm{SUSY}}^{14\mathrm{TeV}} = 0.6$ pb	$1.09 \leq \alpha \leq 1.15$ $1700 \leq M_0 \leq 2800$ $4860 \leq m_{\tilde{g}} \leq 6000$ $\sigma_{\mathrm{SUSY}}^{14\mathrm{TeV}} = 6.7$ pb

Table 2: **Summary Table for All Modular Weight Combinations**. All mass values in GeV. Total SUSY production cross-section at $\sqrt{s} = 14\ \mathrm{TeV}$ for parameter set with smallest $m_{\tilde{g}}$ value.

Conclusions

⇒ LHC data starting to put the screws to semi-realistic models from string theory

- Theories with a meaningful UV completion have less room to maneuver
- Cannot simply increase the overall mass scale arbitrarily – tied to underlying theory parameters

⇒ Kähler stabilized heterotic models (the generalized dilaton domination scenario) already under stress

- Key parameter region will be tested early in LHC at $\sqrt{s} = 13 - 14\,\mathrm{TeV}$
- Expect direct dark matter detection signals within one ton-year of exposure on liquid Xenon

⇒ Type IIB flux compactification models (the generalized modulus domination scenario) not yet being probed at LHC

- Model building prefers $n_M,\, n_H$ = 0,1/2 – these models may have gluinos accessible at $\sqrt{s} = 13 - 14\,\mathrm{TeV}$
- $n_M = 1$ has light EW gauginos – accessible at ILC and/or dark matter detection experiments