Mirage Models Confront LHC Data

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- ullet First 20 fb $^{-1}$ provide a lot of information for SUSY phenomenologists
 - No superpartners observed, but...
 - \star 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

- ⇒ 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
 - \star 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
 - \star When $\alpha=0$ gaugino masses unify at $M_{\text{GUT}}\simeq 2\times 10^{16}~\text{GeV}$
 - \star Other α values give effective unification scale elsewhere (hence "mirage")
 - \star Example: $\alpha=2$ gives $M_1\simeq M_2\simeq M_3$ at low-energy scale
 - * Effective unification scale is now at

$$\Lambda_{
m mir} = \Lambda_{
m GUT} \left(rac{m_{3/2}}{M_{
m PL}}
ight)^{lpha/2}$$

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

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

 \star Type IIB: Gaugino condensation and/or Euclidean D3-instantons

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

- ⇒ Moduli stabilization generally produces distinctive patterns of SUSY breaking
- \Rightarrow 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
 - \star Type IIB: explicit SUSY breaking in an 'uplift' sector KKLT: $\bar{D3}$ -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: $\langle F_S \rangle / m_{3/2} \sim g_s^2 b_+ / (1 + g_s^2 b_+)$
 - \star 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
 - \star Heterotic: same mechanism as stabilization, therefore $\alpha = \alpha(\beta_+)$
 - \star 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

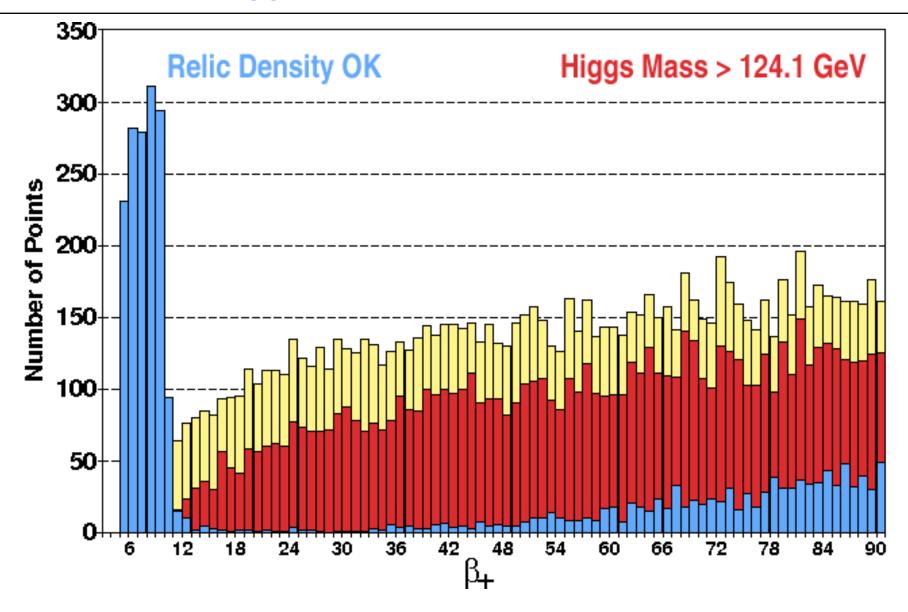
Kähler-Stabilized Heterotic Parameter Space

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

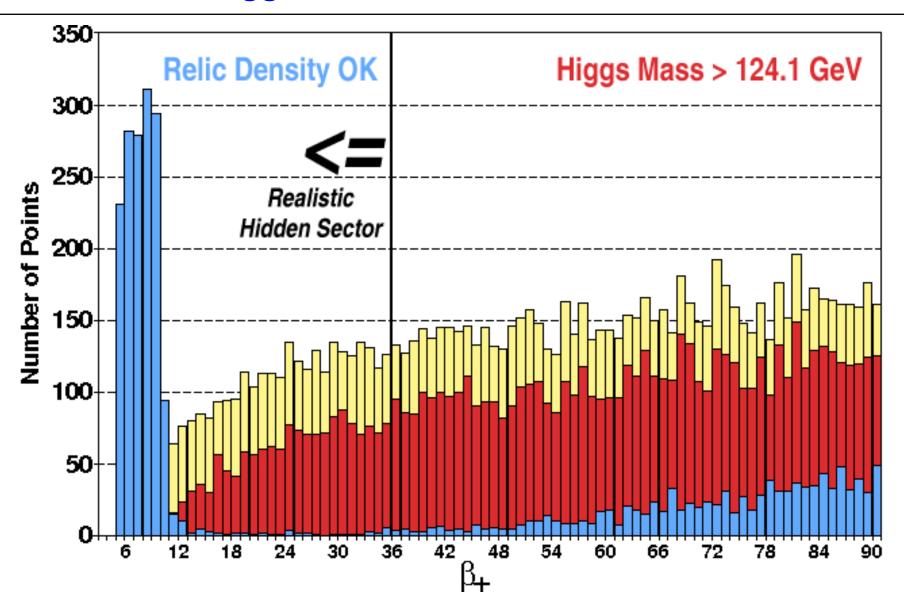
$$\beta_{+} = \left(3C_{+} - \sum_{i} C_{+}^{i}\right), \qquad b_{+} = \frac{2}{3} \left(\frac{\beta_{+}}{16\pi^{2}}\right)$$

- 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

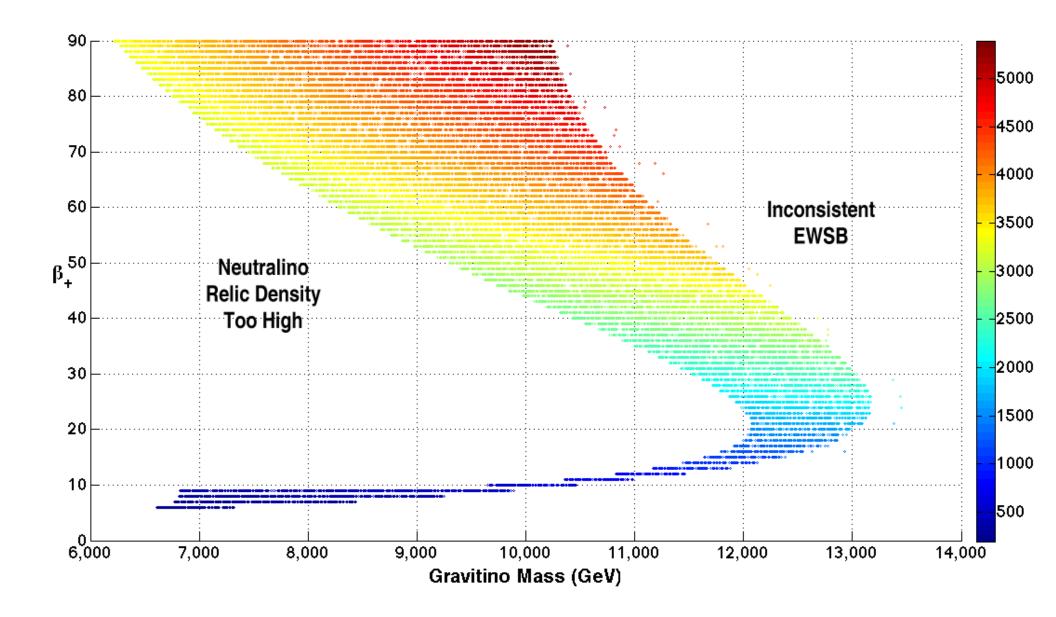
$$M_a \sim F_S + \frac{\beta_a}{16\pi^2} m_{3/2}$$
 $A_{ijk} \sim -F^S + (\gamma_i + \gamma_j + \gamma_k) m_{3/2}$
 $m_i^2 \sim (1 + \gamma_i) m_{3/2}^2 - \widetilde{\gamma}_i \left(\frac{m_{3/2} F^S}{2} + \text{h.c.}\right)$

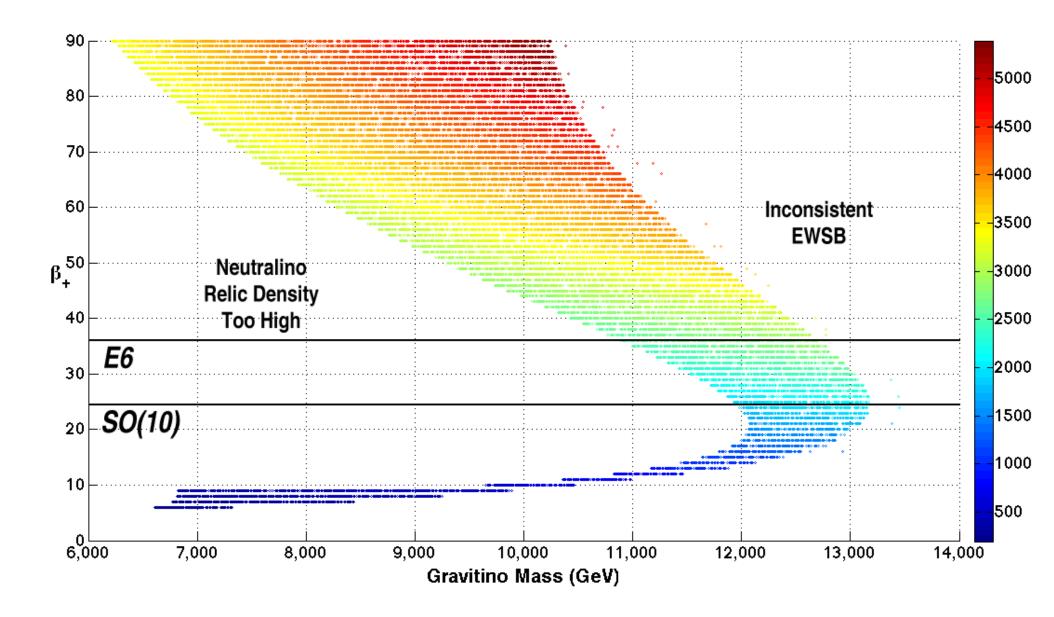


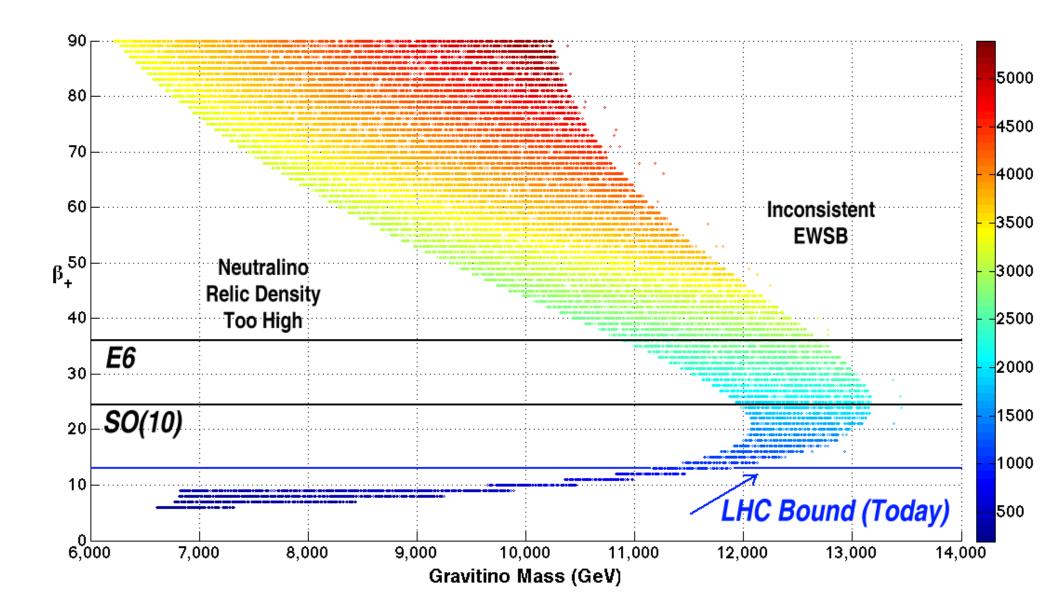
- Tension between correct LSP relic density and LHC Higgs mass measurement
- ullet 'Automatic' dark matter for wino-like WIMP at $eta_+ \lesssim 9$ now strongly disfavored

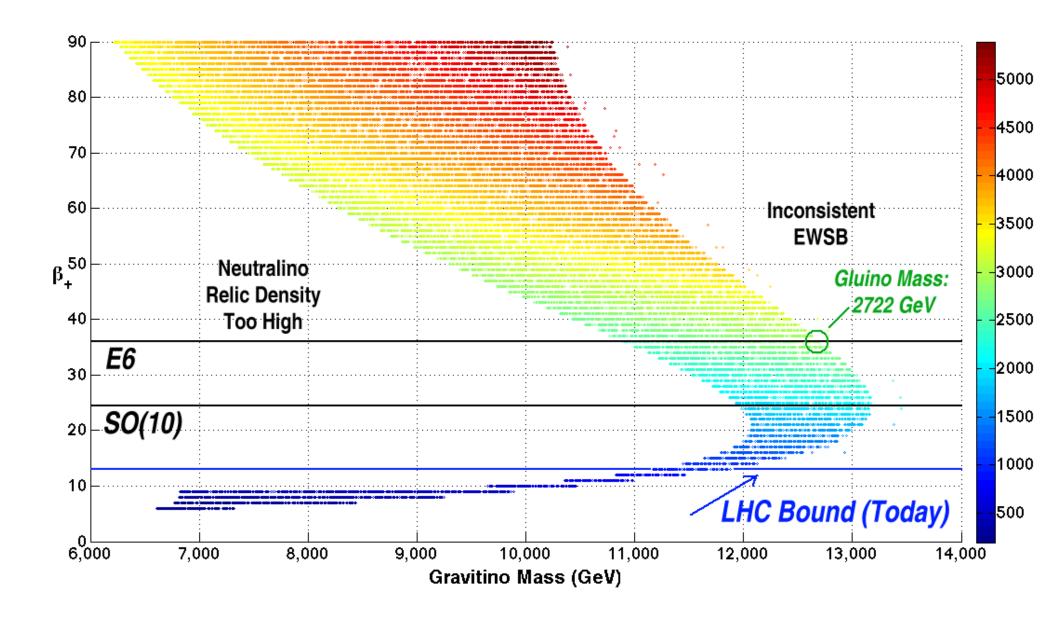


- Hidden sector of pure E_6 (no matter) has $\beta_+ = 36$
- Will need to boost Higgs mass by going to high $\tan \beta$





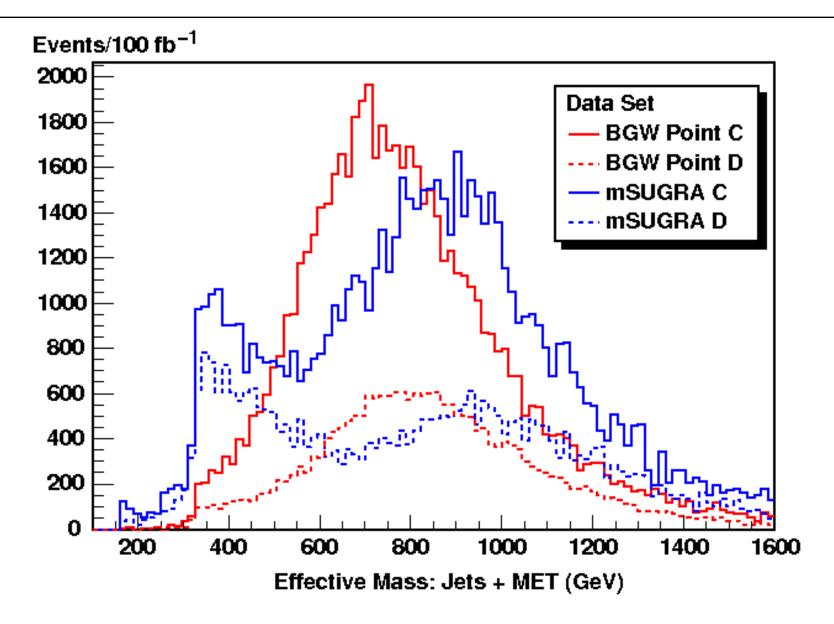




			Low Multiplicity Jets					Leptonic Channels						
			2 Jets		4 Jets			1 Lepton		SS Dilepton		SS 2ℓ, B-Jets		
Point	β_+	$m_{ ilde{g}}$	М	Т	L	М	T	1 <i>e</i>	1 μ	$e \mu$	$\mu \mu$	0b	1b	3b
Α	9	498	24	9	101	27	5	2	12	6	1	24	15	2
В	10	628	6	1	39	11	1	2	11	6	1	33	68	21
С	11	699	4	1	23	7	_	1	7	8	4	22	44	13
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
Н	18	1392	_	_	_	_	_	_	_	_	_	_	1	_
Observed		111	10	156	31	1	10	4	2	1	5	8	4	
$N_{ m BSM}$		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.

- ⇒ 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 $p_T > 20 \, {\rm GeV}$
- Requires 0, 1 and 3⁺ b-tagged jets with $p_T > 40 \, {\rm GeV}$
- Missing transverse energy $E_T^{
 m mis} > 150\,{
 m GeV}$
- Total effective mass cut $M_{\rm eff} > 700 \, {\rm GeV}$



 \Rightarrow 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
 - \star Can choose two mass scales $M_0 \equiv \left\langle F_T/(T+\overline{T}) \right
 angle$ and $m_{3/2}$
 - \star Or choose one mass scale and the parameter $lpha \equiv rac{m_{3/2}}{M_0 \ln \left(M_{
 m PL}/m_{3/2}
 ight)}$
- \Rightarrow For certain choices of uplift sector, α becomes a *prediction*
- Example: consider modifying effective supergravity Lagrangian as follows

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

• 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

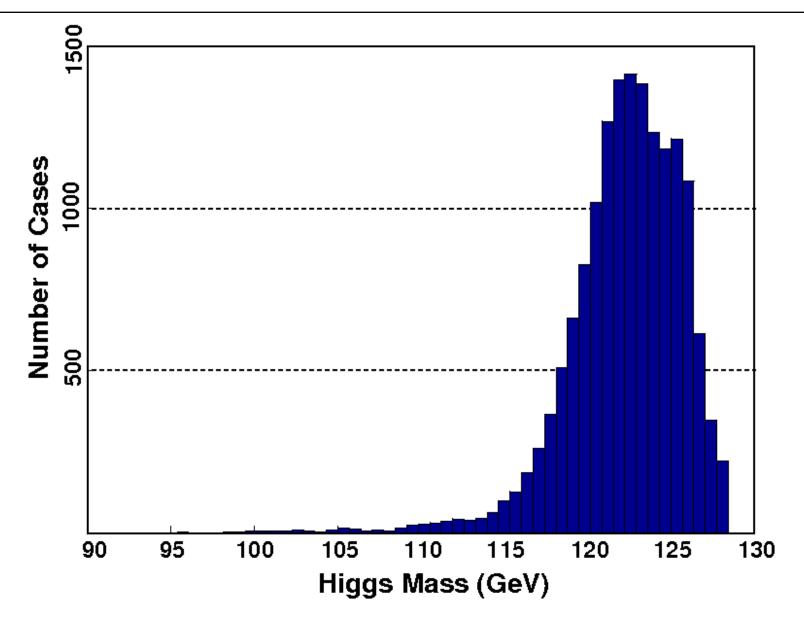
- \Rightarrow Our analysis chose to scan on parameters α and M_0
- M_0 most directly tied to overall superpartner masses; α is the parameter of most interest theoretically
- Soft terms are more easily expressed in terms of M_0 and $m_{3/2}$, however

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

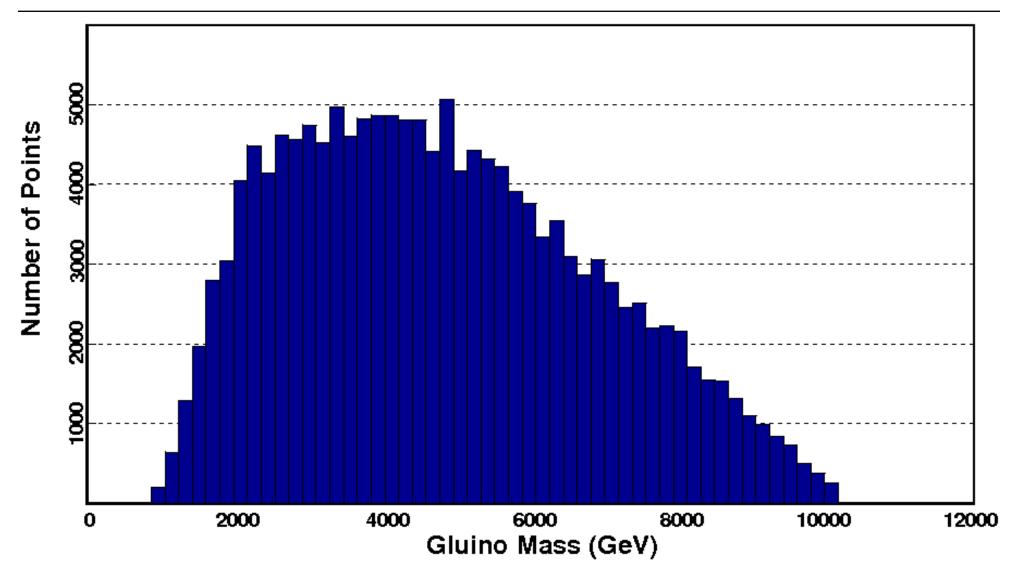
- \Rightarrow Expressions for scalar fields involve the modular weight n_i
- Indicates the non-canonical nature of the kinetic terms for scalar fields

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

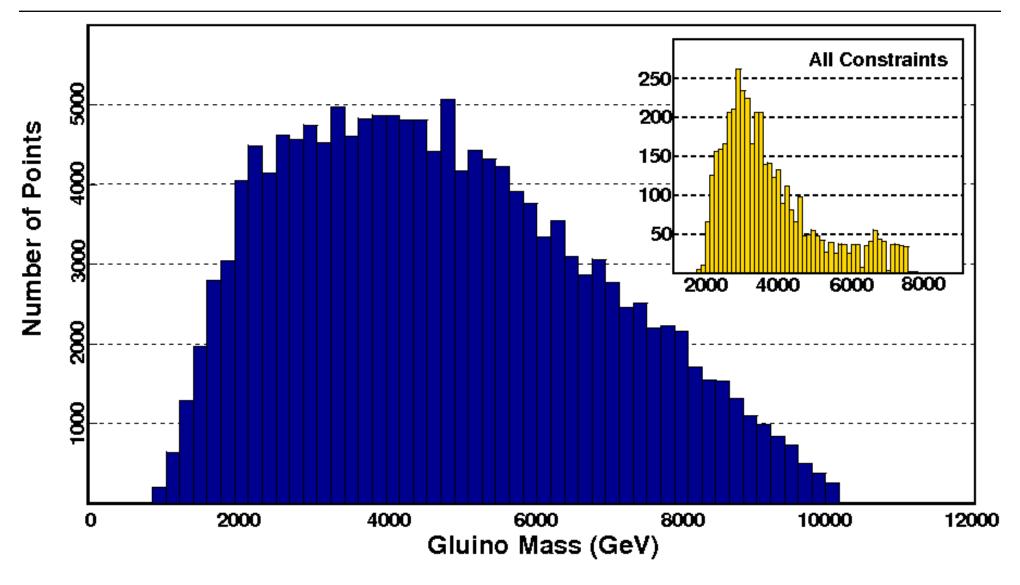
- Depends on how SM fields are realized locally on stacks of D-branes
 - \star $n_i = 1$ for D3-brane fields, $n_i = 0$ for D7-brane fields
 - \star $n_1=1/2$ for twisted sectors stretched between D3/D7 branes, or different stacks of D7-branes



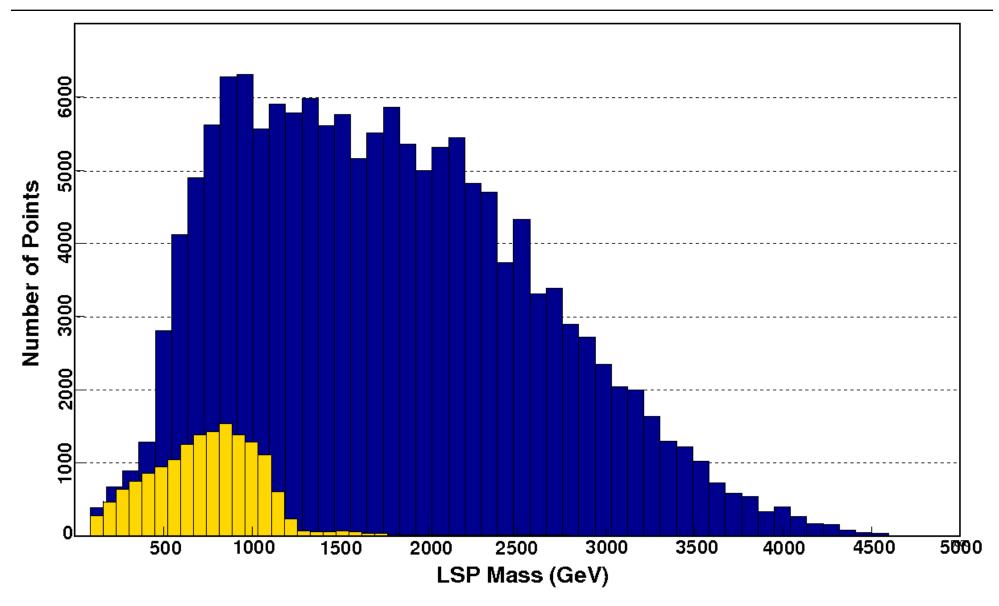
 \Rightarrow Once requirement $\Omega_\chi h^2 \leq 0.128$ imposed, distribution on Higgs mass favors LHC measured values



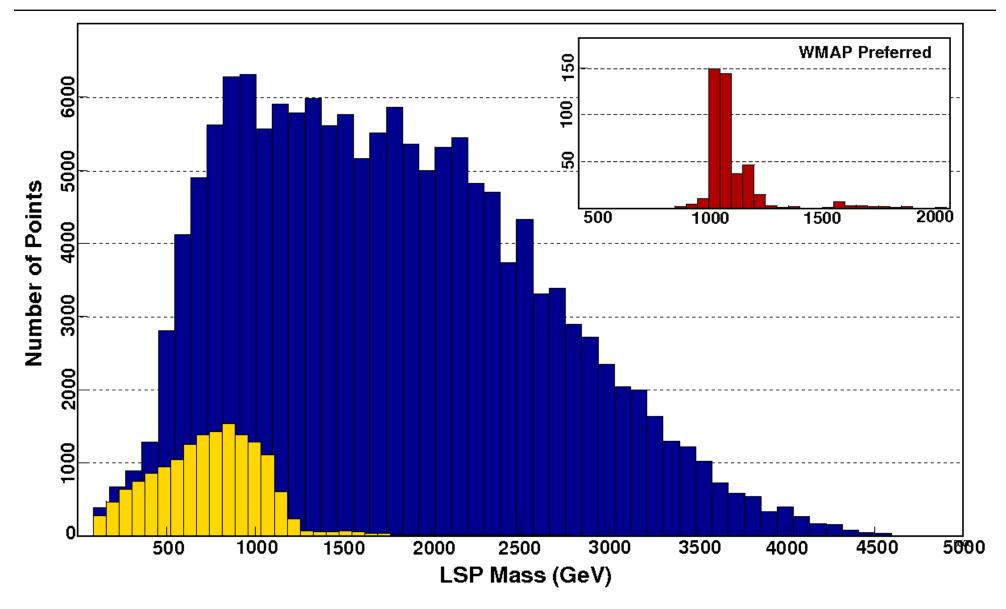
⇒ Before imposing Higgs mass and dark matter requirements



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

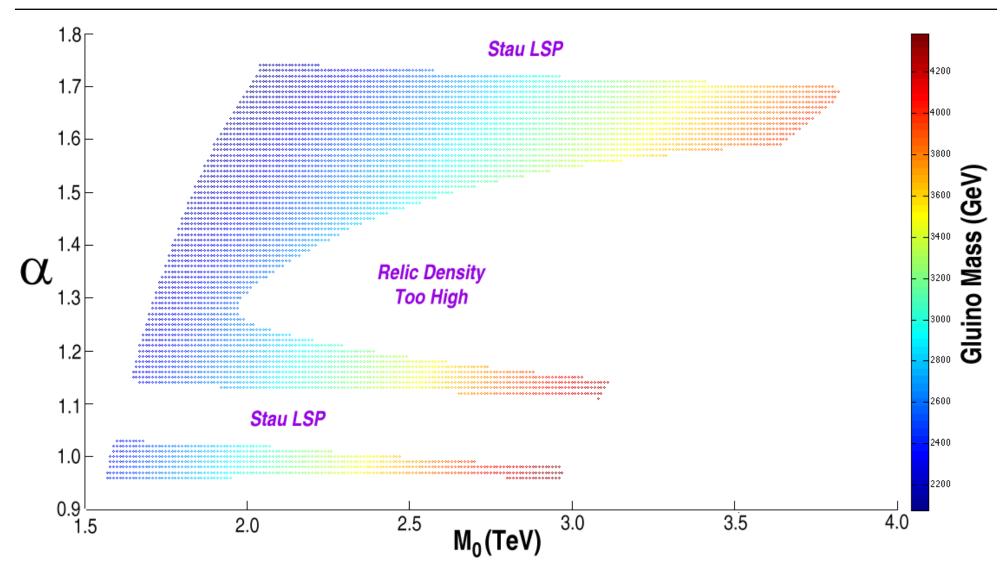


- ⇒ Blue histogram: before Higgs mass and dark matter requirements
- \Rightarrow Yellow histogram: requiring $124.2\,\mathrm{GeV} \leq m_h \leq 127.0\,\mathrm{GeV}$ and $\Omega_\chi h^2 \leq 0.128$

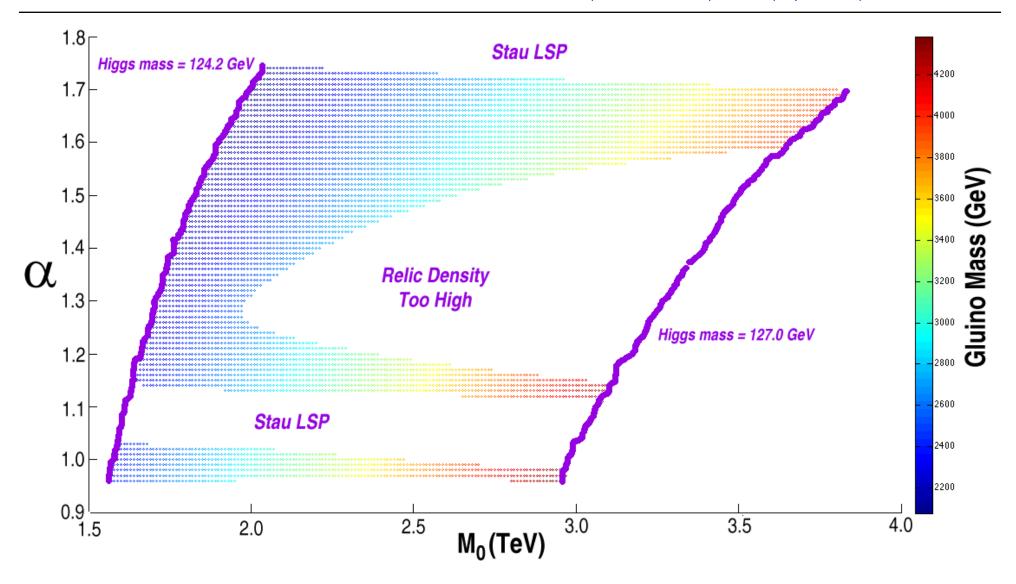


- ⇒ Blue histogram: before Higgs mass and dark matter requirements
- \Rightarrow Yellow histogram: requiring $124.2\,\mathrm{GeV} \leq m_h \leq 127.0\,\mathrm{GeV}$ and $\Omega_\chi h^2 \leq 0.128$
- \Rightarrow Red histogram: requiring $\Omega_{\chi}h^2=0.1199\pm0.0027$

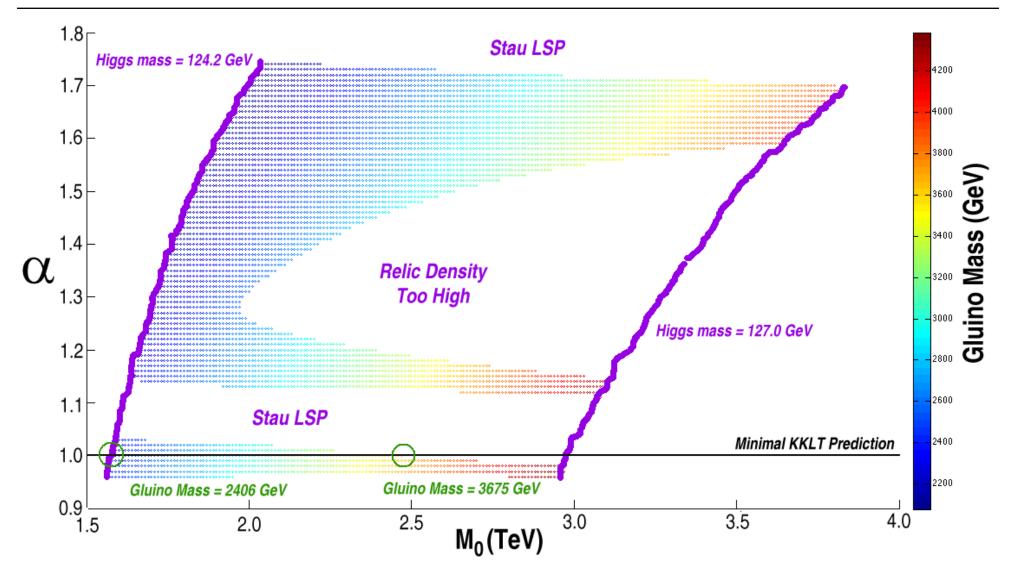
Example: Modular Weights $(n_M, n_H) = (1/2, 0)$



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Summary of Modular Weight Results

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

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