

# Beyond the Standard Paradigm



- The standard paradigm
- Uniqueness or environment
- The string landscape
- Extended MSSM quivers
- String remnants

# The Standard Paradigm

- **MSSM at TeV scale** (no LHC signal)
- **LSP WIMPs** (no unambiguous signal)
- (Possibly) **GUT at unification scale** (gauge unification)
- **Seesaw model for  $m_\nu$** 
  - **Leptogenesis**
  - (Possibly) **GUT relations for couplings** (large representations?)
  - **Flavor symmetries** (discrete, global, gauge)
- **SUSY breaking in hidden sector**
- **Assumptions of naturalness, uniqueness, minimality**

## Beyond the MSSM

Even if TeV-supersymmetry found, MSSM may not be the full story

Most of the problems of standard model remain, new ones introduced  
(FCNC, EDM, proton decay if no  $R_P$ )

$\mu$  problem introduced:  $W_\mu = \mu \hat{H}_u \cdot \hat{H}_d$ ,  $\mu = \mathcal{O}(\text{electroweak})$

Remnants of GUT/Planck scale physics may survive to TeV scale

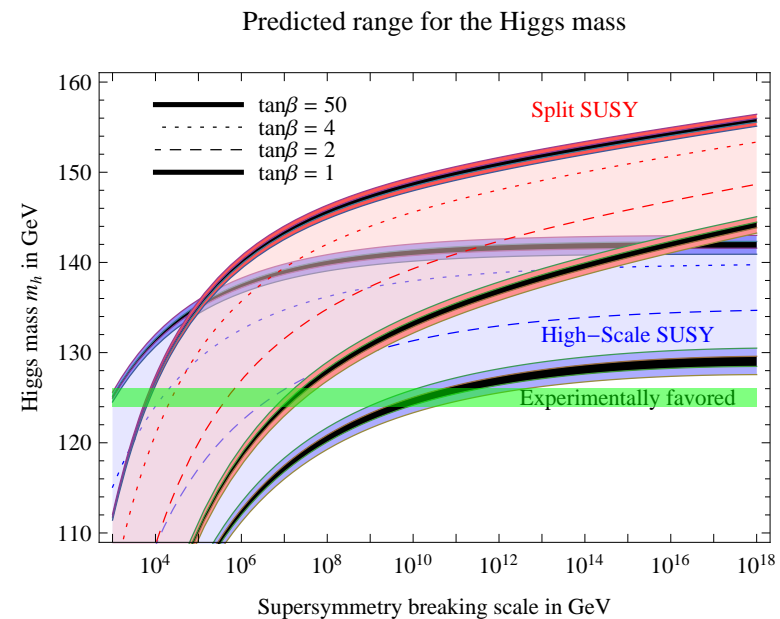
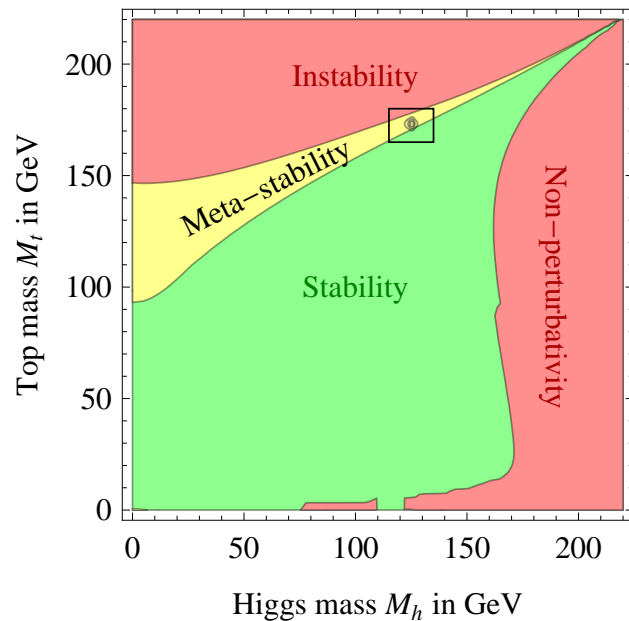
Specific string constructions often have extended gauge groups,  
exotics, extended Higgs/neutralino sectors (defect or hint?)

Ingredients of 4d GUTs hard to embed in string, especially large  
Higgs representations, Yukawa relations

Important to explore alternatives/extensions to MSSM

# Naturalness or Tuning

- ATLAS/CMS: no sign of supersymmetry or other new physics
- Higgs-like particle: consistent with elementary Higgs
  - SM: rather light (metastable vacuum or new physics below  $10^{11}$  GeV)
  - MSSM: rather heavy (need heavy stop or large mixing)



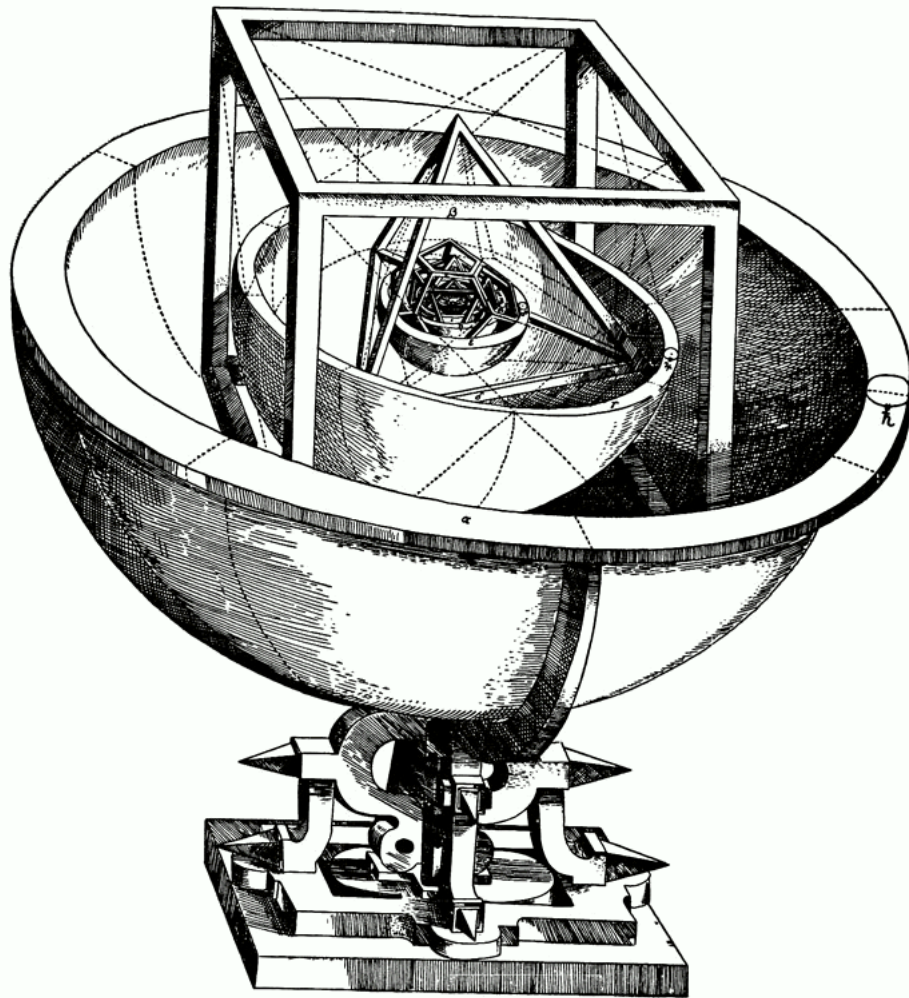
Degrassi et al, 1205.6497

- Higgs mass<sup>2</sup> very unnatural (tuning by  $10^{34}$ ) unless TeV physics  
(supersymmetry, alternative EWSB, large dimensions)
- Is naturalness a good guide? cf dark energy (tuning by  $10^{120}$ )  
(environmental solution?)
- Even for higher-scale new physics: little (baby) hierarchy problem  
(but reduces FCNC, EDM constraints)

## Uniqueness or Environment

- **Gauge interactions: determined by symmetry**  
(but groups, representations, SSB)
- **Yukawa interactions (flavor physics): apparently unconstrained, unless new symmetries/principles** (local, global, discrete, stringy)
- **The uniqueness paradigm** (cf., Kepler's *Mysterium Cosmographicum*)
  - **Enormous effort (especially  $\nu$ ) to understand spectrum/mixings by flavor symmetries/textures, usually in seesaw context**  
(tri-bimaximal, bimaximal, complementarity, GUT + flavor, lopsided, Froggatt-Nielsen, haze, loops,  $\mathcal{R}_p$ )
  - $\theta_{13} \neq 0, \theta_{23} \neq 45^\circ$  excludes many models or requires perturbations

# Kepler's *Mysterium Cosmographicum*



*MPI, Munich (9/13)*



*Paul Langacker (IAS/Princeton)*

- **The environmental paradigm** (cf., planetary orbits)
  - No simple explanation of parameters  
(but scales/hierarchies by FN-like powers or exponentials?)
  - String landscape: may be  $\gtrsim 10^{600}$  vacua with no known selection principle
  - Subset habitable, with different groups, remnants, hierarchy mechanisms, parameters
  - Multiverse sampled by eternal inflation?
  - Environmental selection? (A word?)



## Early Speculations

**Horatio:**

*O day and night, but this is wondrous strange!*

**Hamlet:**

*And therefore as a stranger give it welcome.*

*There are more things in heaven and earth, Horatio,  
Than are dreamt of in your philosophy.*

**(William Shakespeare: Hamlet, 1603)**

- **The environmental paradigm** (contd.)
  - Underlying constraints often too complicated to unravel
  - Version of anarchy
- **Distinction of paradigms critical**

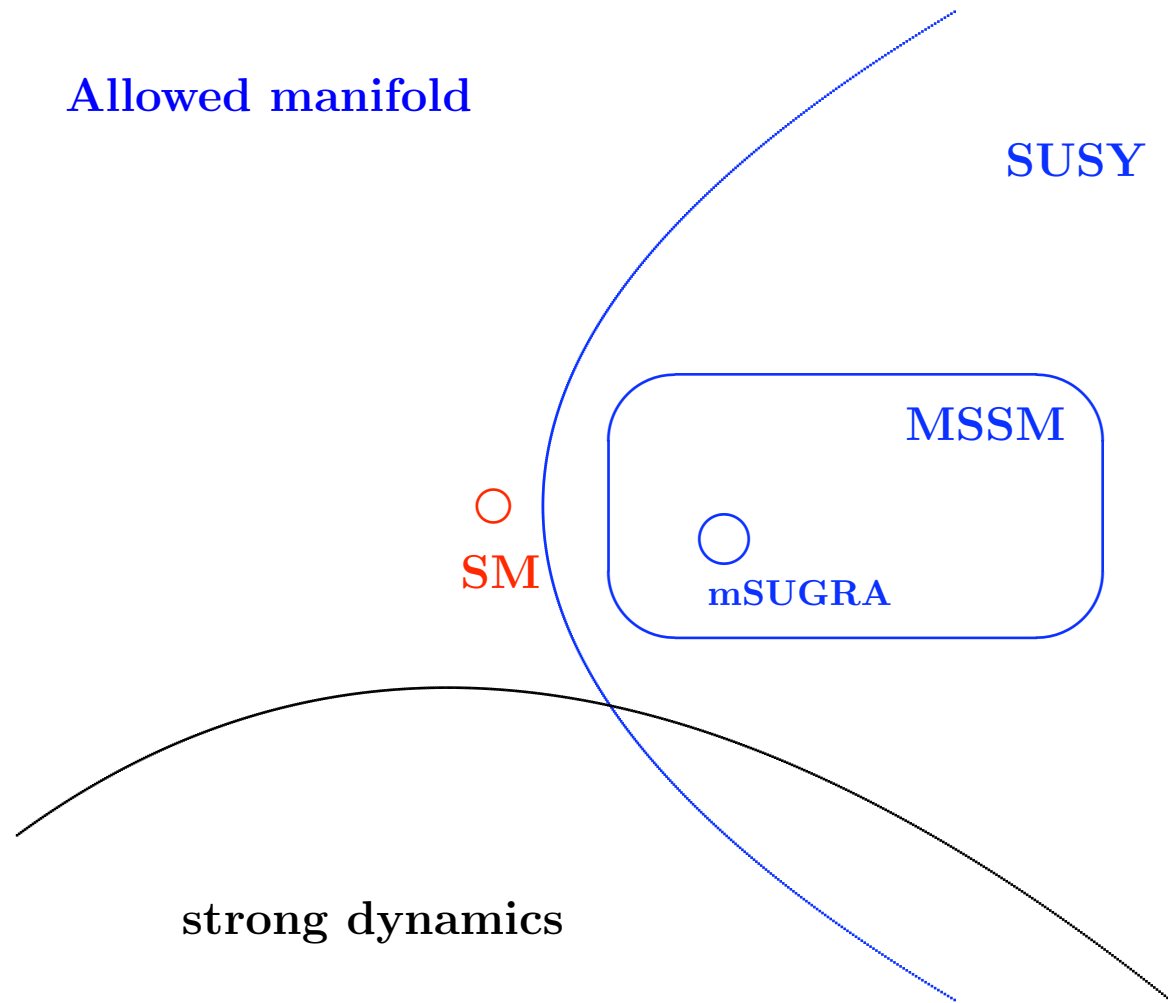
# The String Landscape

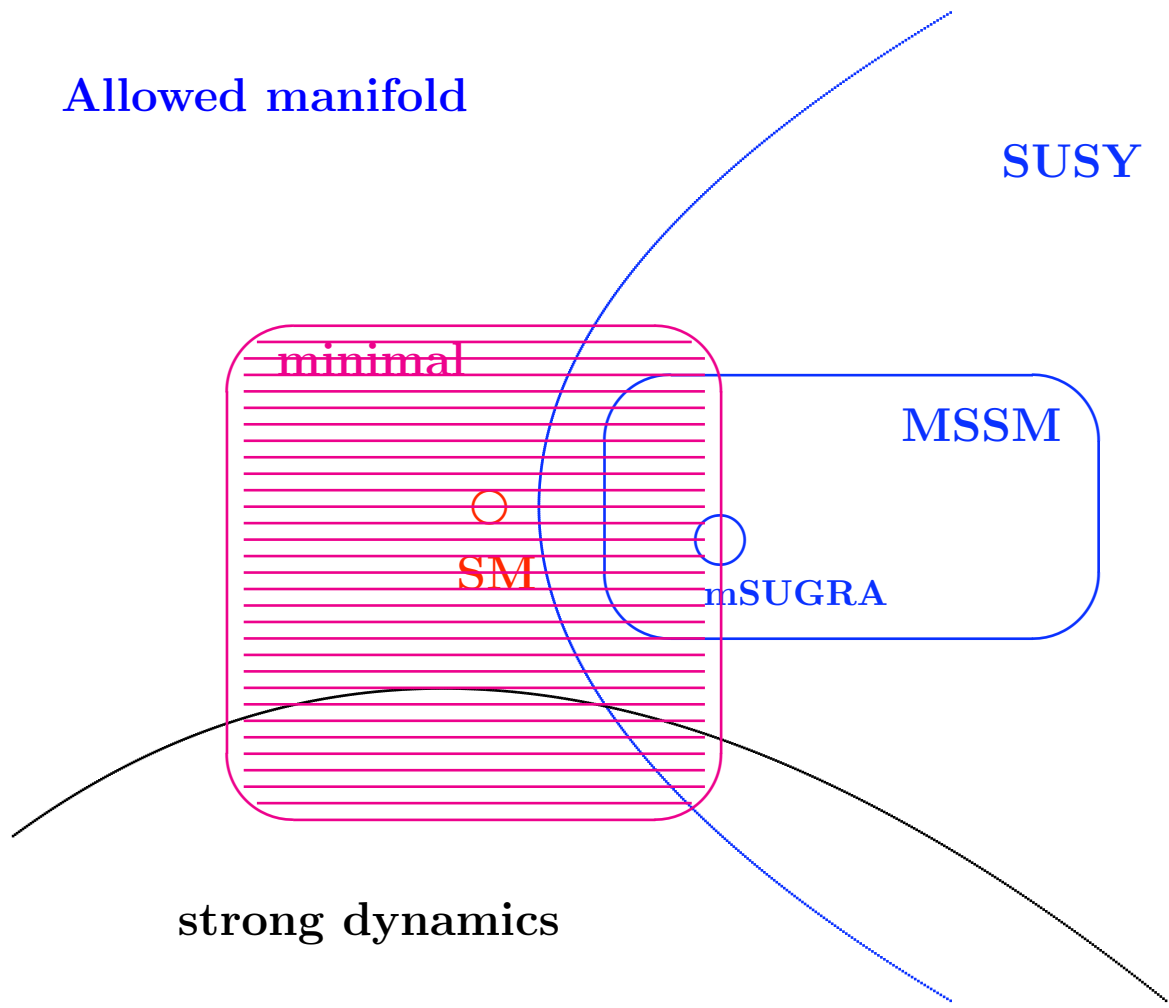
- **String theory very promising** (finite quantum gravity & other interactions)
- **However, may be enormous *landscape of vacua*** ( $> 10^{600}$ )
- **Many contain SM or MSSM**
- **Many involve TeV-scale *remnants*** (e.g.,  $Z'$ , exotics, extended Higgs, quasi-hidden sectors) **beyond the MSSM** (hint?)
- **Top-down remnants may not be minimal or motivated by SM problems**

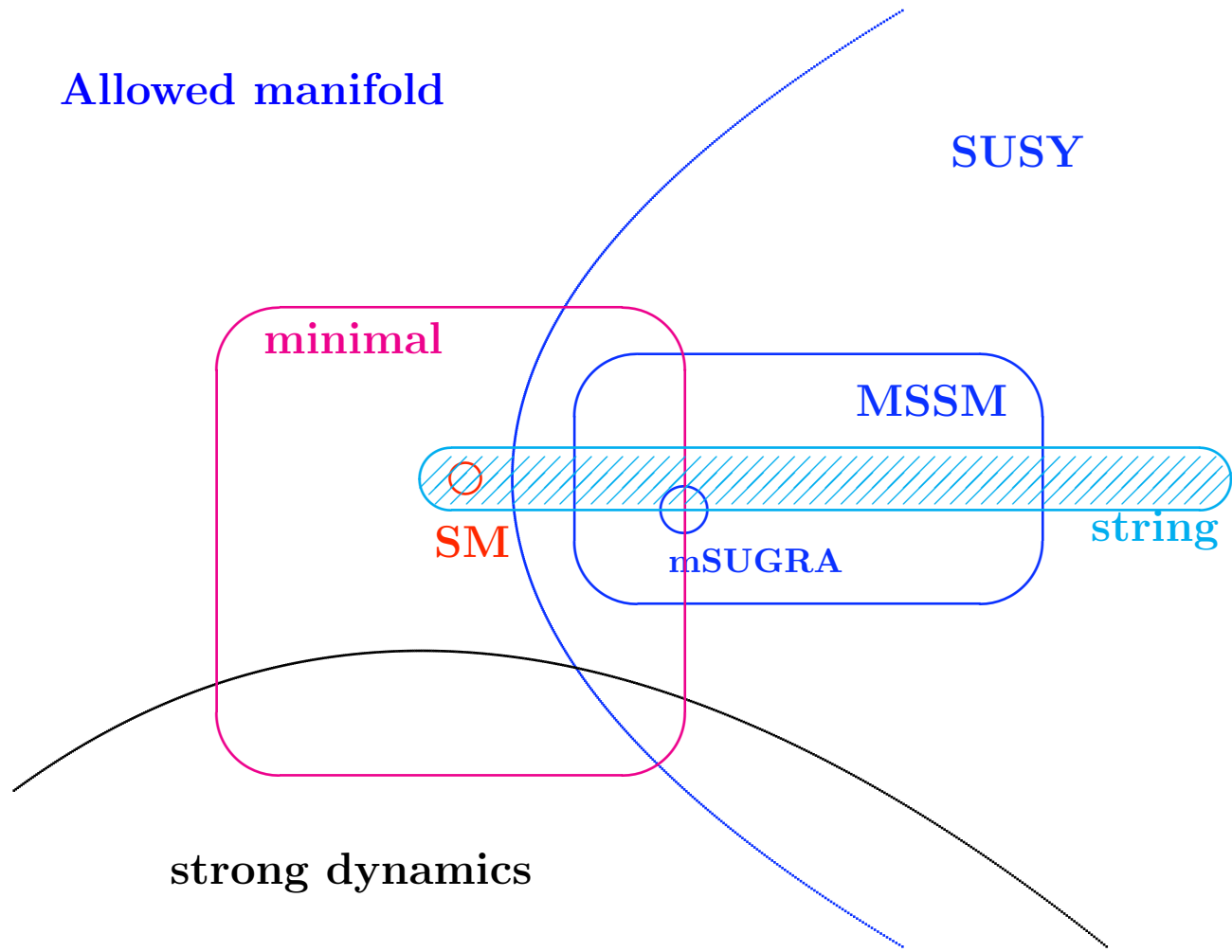
# Minimality or Remnants



- **Some bottom-up ideas unlikely to emerge from simple/perturbative string constructions** (e.g., high-dimensional representations)
- **Top-down may suggest new physical mechanisms** (e.g., string instantons: exponentially suppressed  $\mu$ , Majorana or Dirac  $m_\nu$ , etc)
- **Important to map string-likely or unlikely classes of new physics and mechanisms** (and contrast with field theory)









## Typical Stringy Effects

- $Z'$  (or other gauge)
- Extended Higgs/neutralino (doublet, singlet)
- Quasi-chiral Exotics
- Leptoquark, diquark,  $\mathcal{R}_P$  couplings
- Family non-universality (from different origins) (Yukawas,  $U(1)'$ )
- Various  $\nu$  mass mechanisms (HDO, string instantons: non-minimal seesaw, Weinberg op, Dirac, sterile)
- (Quasi-)hidden sectors (strong coupling? SUSY breaking? dark matter? random?); may be portals (exotics,  $Z'$ , Higgs)

- ***Perturbative* global symmetries from anomalous  $U(1)'$**   
(exponentially-suppressed breaking)
- **Nonstandard hypercharge embeddings/normalizations**
- **Fractionally charged color singlets** (e.g.,  $\frac{1}{2}$ )  
(confined?, stable relic? millicharged?)
- **Large/warped dimensions, low string scale**  
(TeV black holes, stringy resonances)
- **Time/space/environment-varying couplings**
- **LIV, VEP** (speeds, decays, [oscillations] of HE  $\gamma$ ,  $e$ , gravity waves, [ $\nu$ 's])

## Surveying the Landscape

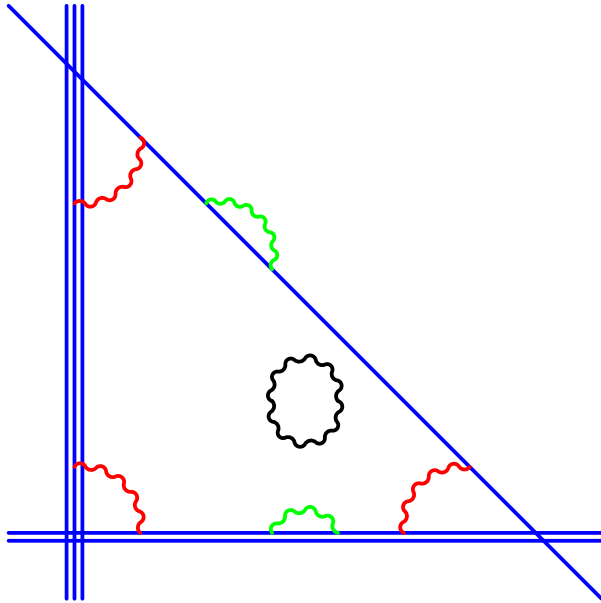
- Counting of group factors, families, etc; MSSM and beyond

- Denef, Douglas [0404116, 0411183]
- Kumar, Wells [0409218]
- DeWolfe, Giryavets, Kachru, Taylor [0411061]
- Blumenhagen, Gmeiner, Honecker, Lust, Weigand [0411173, 0510170]
- Dienes, Dudas, Gherghetta [0412185]
- Arkani-Hamed, Dimopoulos, Kachru [0501082]
- Kumar [0601053]
- Dienes [0602286]; Dienes, Lennek, Senechal, Wasnik [0704.1320]
- Anastasopoulos, Dijkstra, Kiritsis, Schellekens [0605226]
- Shelton, Taylor, Wecht [0607015]
- Gmeiner [0608227]; Gmeiner, Honecker [0708.2285]
- Douglas, Kachru [0610102]
- Blumenhagen, Kors, Lust, Stieberger [0610327]
- Denef, Douglas, Kachru [0701050]
- AbdusSalam, Conlon, Quevedo, Suruliz [0709.0221]
- Balasubramanian, de Boer, Naqvi [0805.4196]
- Gabella, He, Lukas [0808.2142]
- Anderson, Gray, Lukas, Palti [1106.4804]
- Schellekens [1306.5083]
- Nibbelink, Loukas [1308.5145]

- **MSSM-like**

- Remnants common **(but often explicitly excluded)**
- Extensions of MSSM quivers needed by stringy constraints

# Intersecting Brane (Type IIA) Constructions



- $U(N)$  from  $N$  D6 branes (fill 3 of the 6 extra dimensions)
- Adjoints, bifundamentals (open); gravitons (closed)
- Also, symmetric, antisymmetric;  $SO(2N)$ ,  $Sp(2N)$
- Families from multiple intersections (3-cycles wrapping 6d)

- Yukawa interactions  $\sim \exp(-A_{ijk}) \rightarrow$  hierarchies
- Existing models: additional gauge factors, Higgs, chiral matter
- Global  $U(1)$ 's (may be broken by nonperturbative string instantons)

# Tadpoles and Extended MSSM Quivers

Implications of String Constraints for Exotic Matter and  $Z$ 's Beyond the Standard Model, M. Cvetič, J. Halverson, PL, JHEP 1111,058 (arXiv:1108.5187)

- **Intersecting brane type IIA constructions (and others):  
tadpole cancellation conditions stronger than anomaly cancellation  
in augmented field theory (for  $N_a = 1, 2$ )**

(FT with anomalous  $U(1)$ 's and Chern-Simons terms)

–  $U(N_a)$  from stack of  $N_a$  D6 branes:

$$N_a \geq 2 : \quad \#a - \#\bar{a} + (N_a + 4) (\#\square_a - \#\bar{\square}_a) + (N_a - 4) (\#\boxplus_a - \#\bar{\boxplus}_a) = 0$$

$$N_a = 1 : \quad \#a - \#\bar{a} + (N_a + 4) (\#\square_a - \#\bar{\square}_a) = 0 \pmod{3},$$

–  $SU(N_a)^3$  triangle anomaly condition for  $N_a \geq 3$

– Landscape view: all vacua must be consistent

- “Anomalous”  $U(1)$  from trace generator of  $U(N)$  usually acquires Stuckelberg mass near string scale  $M_s$

- Anomalies cancelled by Chern-Simons
- $U(1) \Rightarrow$  global symmetry on (perturbative) superpotential
- May be broken by non-perturbative D-instantons (exponentially suppressed)

- Linear combination  $\sum q_x U(1)_x$  may be massless, non-anomalous if

$$- q_a N_a (\#\square_a - \#\bar{\square}_a + \#\square_a - \#\bar{\square}_a) + \sum_{x \neq a} q_x N_x (\#(a, \bar{x}) - \#(a, x)) = 0, \quad N_a \geq 2$$

$$q_a \frac{\#(a) - \#(\bar{a}) + 8(\#\square_a) - \#\bar{\square}_a}{3} + \sum_{x \neq a} q_x N_x (\#(a, \bar{x}) - \#(a, x)) = 0, \quad N_a = 1$$

- Require one linear combination  $\Rightarrow$  weak hypercharge,  $Y$
- May be additional massless combinations, broken by Higgs singlet VEVs  $\Rightarrow$  TeV-scale  $Z'$  (even for  $M_s = \mathcal{O}(M_{pl})$ )

# MSSM hypercharge embeddings

(Ibanez, Marchesano, Rabadan; Anastasopoulos, Dijkstra, Kiritsis, Schellekens)

- **Three-node embeddings** ( $U(3)_a \times U(2)_b \times U(1)_c$ )

Madrid: 
$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c$$

non-Madrid: 
$$U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b$$

- **Four-node embeddings** ( $U(3)_a \times U(2)_b \times U(1)_c \times U(1)_d$ )

$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c + \frac{1}{2}U(1)_d \quad U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b + \frac{1}{2}U(1)_d$$

$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c + \frac{3}{2}U(1)_d \quad U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b$$

$$U(1)_Y = \frac{1}{6}U(1)_a + \frac{1}{2}U(1)_c \quad U(1)_Y = -\frac{1}{3}U(1)_a - \frac{1}{2}U(1)_b + U(1)_d,$$



## New Matter and $Z$ 's

- Most quivers with just MSSM chiral matter don't satisfy tadpole constraints (none for 3 nodes with no vector pairs)
- Systematically add matter to MSSM quivers to satisfy tadpole and hypercharge conditions
  - Up to 5 additional fields
  - Don't allow purely vector pairs (typically acquire  $M_s$ -scale masses)
  - Allow quasi-chiral pairs (vector under MSSM; chiral under “anomalous” or additional non-anomalous  $U(1)$ 's)
  - Suggestive of quasi-chiral types,  $U(1)$ 's (often family non-universal  $\Rightarrow$  tree-level neutral  $B_s$  effects)
  - $H_d - L$  distinction (necessary for  $L$  and  $R$ -parity conservation)
  - MSSM singlets (NMSSM-type,  $\nu_L^c$ -type, or neither)

• 105 Madrid 3-node quivers ( $\leq 5$  additions)

Multiplicity	Matter Additions				
4	$\square b, (1, 3)_0$	$\square b, (1, 3)_0$	$\boxplus b, (1, 1)_0$	$(a, \bar{b}), (3, 2)_{\frac{1}{6}}$	$(\bar{a}, \bar{b}), (\bar{3}, 2)_{-\frac{1}{6}}$
4	$\square b, (1, 3)_0$	$\boxplus b, (1, 1)_0$			
4	$\square\bar{b}, (1, 3)_0$	$\boxplus b, (1, 1)_0$			
4	$\square b, (1, 3)_0$	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$	$(b, \bar{c}), (1, 2)_{-\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$
4	$\square\bar{b}, (1, 3)_0$	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$	$(b, \bar{c}), (1, 2)_{-\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$
4	$\square b, (1, 3)_0$	$\bar{\boxplus} b, (1, 1)_0$	$\bar{\boxplus} b, (1, 1)_0$	$(a, \bar{b}), (3, 2)_{\frac{1}{6}}$	$(\bar{a}, \bar{b}), (\bar{3}, 2)_{-\frac{1}{6}}$
4	$\bar{\boxplus} b, (1, 1)_0$	$\bar{\boxplus} b, (1, 1)_0$			
4	$\bar{\boxplus} b, (1, 1)_0$	$(b, \bar{c}), (1, 2)_{-\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$		
4	$(b, \bar{c}), (1, 2)_{-\frac{1}{2}}$	$(b, \bar{c}), (1, 2)_{-\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$	
4	$(a, \bar{b}), (3, 2)_{\frac{1}{6}}$	$\boxplus a, (\bar{3}, 1)_{\frac{1}{3}}$	$(b, \bar{c}), (1, 2)_{-\frac{1}{2}}$	$(\bar{a}, \bar{c}), (\bar{3}, 1)_{-\frac{2}{3}}$	$\square c, (1, 1)_1$
4	$\square b, (1, 3)_0$	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$
4	$\square\bar{b}, (1, 3)_0$	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$
4	$\square\bar{b}, (1, 3)_0$	$\bar{\boxplus} b, (1, 1)_0$	$\bar{\boxplus} b, (1, 1)_0$		
4	$\square\bar{b}, (1, 3)_0$	$\bar{\boxplus} b, (1, 1)_0$	$(b, \bar{c}), (1, 2)_{-\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$	
4	$\square\bar{b}, (1, 3)_0$	$(b, \bar{c}), (1, 2)_{-\frac{1}{2}}$	$(b, \bar{c}), (1, 2)_{-\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$
4	$\boxplus b, (1, 1)_0$				
4	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$	$(b, \bar{c}), (1, 2)_{-\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$	
4	$\square\bar{b}, (1, 3)_0$	$\square\bar{b}, (1, 3)_0$	$\bar{\boxplus} b, (1, 1)_0$	$\bar{\boxplus} b, (1, 1)_0$	
4	$\square\bar{b}, (1, 3)_0$	$\square\bar{b}, (1, 3)_0$	$\bar{\boxplus} b, (1, 1)_0$	$(b, \bar{c}), (1, 2)_{-\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$
4	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$	$\boxplus b, (1, 1)_0$	

Multiplicity	Matter Additions				
4	$\overline{\square}b, (1, 3)_0$	$\overline{\square}b, (1, 3)_0$	$\overline{\square}b, (1, 3)_0$	$\overline{\square}b, (1, 1)_0$	$\overline{\square}b, (1, 1)_0$
4	$\overline{\square}b, (1, 3)_0$	$\overline{\square}b, (1, 3)_0$	$\square b, (1, 1)_0$		
1	$\square a, (\overline{3}, 1)_{\frac{1}{3}}$	$\square b, (1, 3)_0$	$\square b, (1, 1)_0$	$(a, \overline{c}), (3, 1)_{-\frac{1}{3}}$	
1	$\overline{\square}a, (\overline{3}, 1)_{-\frac{1}{3}}$	$\square b, (1, 3)_0$	$\square b, (1, 1)_0$	$(\overline{a}, c), (\overline{3}, 1)_{\frac{1}{3}}$	
1	$\square a, (\overline{3}, 1)_{\frac{1}{3}}$	$\overline{\square}b, (1, 3)_0$	$\square b, (1, 1)_0$	$(a, \overline{c}), (3, 1)_{-\frac{1}{3}}$	
1	$\overline{\square}a, (\overline{3}, 1)_{-\frac{1}{3}}$	$\overline{\square}b, (1, 3)_0$	$\square b, (1, 1)_0$	$(\overline{a}, c), (\overline{3}, 1)_{\frac{1}{3}}$	
1	$\square a, (\overline{3}, 1)_{\frac{1}{3}}$	$\overline{\square}b, (1, 1)_0$	$\overline{\square}b, (1, 1)_0$	$(a, \overline{c}), (3, 1)_{-\frac{1}{3}}$	
1	$\overline{\square}a, (\overline{3}, 1)_{-\frac{1}{3}}$	$\overline{\square}b, (1, 1)_0$	$\overline{\square}b, (1, 1)_0$	$(\overline{a}, c), (\overline{3}, 1)_{\frac{1}{3}}$	
1	$\square a, (\overline{3}, 1)_{\frac{1}{3}}$	$\overline{\square}b, (1, 1)_0$	$(b, \overline{c}), (1, 2)_{-\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$	$(a, \overline{c}), (3, 1)_{-\frac{1}{3}}$
1	$\overline{\square}a, (\overline{3}, 1)_{-\frac{1}{3}}$	$\overline{\square}b, (1, 1)_0$	$(b, \overline{c}), (1, 2)_{-\frac{1}{2}}$	$(b, c), (1, 2)_{\frac{1}{2}}$	$(\overline{a}, c), (\overline{3}, 1)_{\frac{1}{3}}$
1	$(a, \overline{b}), (3, 2)_{\frac{1}{6}}$	$(b, \overline{c}), (1, 2)_{-\frac{1}{2}}$	$(\overline{a}, c), (\overline{3}, 1)_{\frac{1}{3}}$	$(\overline{a}, \overline{c}), (\overline{3}, 1)_{-\frac{2}{3}}$	$\square c, (1, 1)_1$
1	$\square a, (\overline{3}, 1)_{\frac{1}{3}}$	$\overline{\square}b, (1, 3)_0$	$\overline{\square}b, (1, 1)_0$	$\overline{\square}b, (1, 1)_0$	$(a, \overline{c}), (3, 1)_{-\frac{1}{3}}$
1	$\overline{\square}a, (\overline{3}, 1)_{-\frac{1}{3}}$	$\overline{\square}b, (1, 3)_0$	$\overline{\square}b, (1, 1)_0$	$\overline{\square}b, (1, 1)_0$	$(\overline{a}, c), (\overline{3}, 1)_{\frac{1}{3}}$
1	$\square a, (\overline{3}, 1)_{\frac{1}{3}}$	$\square a, (\overline{3}, 1)_{\frac{1}{3}}$	$\square b, (1, 1)_0$	$(a, \overline{c}), (3, 1)_{-\frac{1}{3}}$	$(a, \overline{c}), (3, 1)_{-\frac{1}{3}}$
1	$\overline{\square}a, (\overline{3}, 1)_{-\frac{1}{3}}$	$\overline{\square}a, (\overline{3}, 1)_{-\frac{1}{3}}$	$\square b, (1, 1)_0$	$(\overline{a}, c), (\overline{3}, 1)_{\frac{1}{3}}$	$(\overline{a}, c), (\overline{3}, 1)_{\frac{1}{3}}$
1	$\square a, (\overline{3}, 1)_{\frac{1}{3}}$	$\square b, (1, 1)_0$	$(a, \overline{c}), (3, 1)_{-\frac{1}{3}}$		
1	$\overline{\square}a, (\overline{3}, 1)_{-\frac{1}{3}}$	$\square b, (1, 1)_0$	$(\overline{a}, c), (\overline{3}, 1)_{\frac{1}{3}}$		
1	$\square a, (\overline{3}, 1)_{\frac{1}{3}}$	$\overline{\square}b, (1, 3)_0$	$\overline{\square}b, (1, 3)_0$	$\square b, (1, 1)_0$	$(a, \overline{c}), (3, 1)_{-\frac{1}{3}}$
1	$\overline{\square}a, (\overline{3}, 1)_{-\frac{1}{3}}$	$\overline{\square}b, (1, 3)_0$	$\overline{\square}b, (1, 3)_0$	$\square b, (1, 1)_0$	$(\overline{a}, c), (\overline{3}, 1)_{\frac{1}{3}}$

- **Eight 3 and 4-node hypercharge embeddings ( $\leq 5$  additions)**
  - **MSSM singlets with anomalous  $U(1)$  charge; isotriplets ( $Y = 0$ )**
  - **Quasi-chiral pairs: lepton/Higgs doublets; down-type quark isosinglets; nonabelian singlets ( $Y = Q = \pm 1$ )**  
**(+ some up-type quark isosinglets, quark isodoublets, shifted lepton/Higgs doublets ( $Q = (\pm 1, \pm 2)$ ))**
  - **Small number fractional charges, chiral fourth family (Landau poles), shifted fourth families:**  
 $(\mathbf{3}, \mathbf{2})_{-\frac{5}{6}}, (\bar{\mathbf{3}}, \mathbf{1})_{\frac{1}{3}}, (\bar{\mathbf{3}}, \mathbf{1})_{\frac{4}{3}}, (\mathbf{1}, \mathbf{2})_{-\frac{3}{2}}, (\mathbf{1}, \mathbf{3})_1$

SM Rep	Total Multiplicity	Int. El.	4 <sup>th</sup> Gen. Removed	Shifted 4 <sup>th</sup> Gen. Also Removed
$(1, 1)_0$	174276	173578	173578	173578
$(1, 3)_0$	48291	48083	48083	48083
$(1, 2)_{-\frac{1}{2}}$	39600	39560	38814	38814
$(1, 2)_{\frac{1}{2}}$	38854	38814	38814	38814
$(\bar{3}, 1)_{\frac{1}{3}}$	25029	25007	24261	24241
$(3, 1)_{-\frac{1}{3}}$	24299	24277	24277	24241
$(1, 1)_1$	15232	15228	14482	14482
$(1, 1)_{-1}$	14486	14482	14482	14482
$(\bar{3}, 1)_{-\frac{2}{3}}$	3501	3501	2755	2755
$(3, 1)_{\frac{2}{3}}$	2755	2755	2755	2755
$(3, 2)_{\frac{1}{6}}$	1784	1784	1038	1038
$(\bar{3}, 2)_{-\frac{1}{6}}$	1038	1038	1038	1038
$(1, 2)_0$	852	0	0	0
$(1, 2)_{\frac{3}{2}}$	220	220	220	184
$(1, 2)_{-\frac{3}{2}}$	204	204	204	184
$(1, 1)_{\frac{1}{2}}$	152	0	0	0
$(1, 1)_{-\frac{1}{2}}$	152	0	0	0
$(3, 1)_{\frac{1}{6}}$	124	0	0	0
$(\bar{3}, 1)_{-\frac{1}{6}}$	124	0	0	0
$(3, 1)_{-\frac{4}{3}}$	36	36	36	0
$(1, 3)_{-1}$	36	36	36	0
$(\bar{3}, 2)_{\frac{5}{6}}$	36	36	36	0
$(\bar{3}, 1)_{\frac{4}{3}}$	20	20	20	0
$(1, 3)_1$	20	20	20	0
$(3, 2)_{-\frac{5}{6}}$	20	20	20	0

- Quasi-chiral pairs

- Mass by  $SX\bar{X}$  ( $S$  =MSSM singlet) or  $X\bar{X}$  (D-instantons)
- Produce quarks/scalar partners by QCD
- Cascade decays to lightest
- Decay: mixing, lepto/di-quark, HDO (rapid, delayed, quasi-stable)

Hypercharge	Multiplicity of Quivers					
	Total	Int. El.	$H_d$ Candidate	No 4th Gen	$S_\mu H_u H_d$	$\nu_L^c H_u L$
$(-\frac{1}{3}, -\frac{1}{2}, 0)$	41	41	0	0	0	0
$(\frac{1}{6}, 0, \frac{1}{2})$	105	105	0	0	0	0
$(-\frac{1}{3}, -\frac{1}{2}, 0, 0)$	6974	6974	4954	4938	1824	2066
$(-\frac{1}{3}, -\frac{1}{2}, 0, \frac{1}{2})$	70	0	0	0	0	0
$(-\frac{1}{3}, -\frac{1}{2}, 0, 1)$	4176	4176	1842	1792	0	80
$(\frac{1}{6}, 0, \frac{1}{2}, 0)$	480	16	0	0	0	0
$(\frac{1}{6}, 0, \frac{1}{2}, \frac{1}{2})$	77853	77853	54119	53654	16754	15524
$(\frac{1}{6}, 0, \frac{1}{2}, \frac{3}{2})$	265	265	0	0	0	0

- Remove quivers leading to fractionally charged color singlets
- Require  $H_d$  quiver-distinct from 3  $L$ -doublets  
(necessary for  $L$ ,  $R$ -parity conservation)
- Perturbative NMSSM-like singlet ( $S_\mu H_u H_d$ ) (alternative: D-instanton)
- Perturbative  $\nu_L^c$ -like singlet ( $\nu_L^c H_u L$ )  
(alternative: Dirac or Weinberg op by D-instanton)

Hypercharge	Multiplicity of Quivers				
	$U(1)'$	$H_d$ Candidate	Fam. Univ	$S_\mu H_u H_d$	$LH_u \nu_L^c$
$(-\frac{1}{3}, -\frac{1}{2}, 0)$	0	0	0	0	0
$(\frac{1}{6}, 0, \frac{1}{2})$	1	0	0	0	0
$(-\frac{1}{3}, -\frac{1}{2}, 0, 0)$	198	146	56	70	94
$(-\frac{1}{3}, -\frac{1}{2}, 0, \frac{1}{2})$	0	0	0	0	0
$(-\frac{1}{3}, -\frac{1}{2}, 0, 1)$	78	16	10	0	5
$(\frac{1}{6}, 0, \frac{1}{2}, 0)$	0	0	0	0	0
$(\frac{1}{6}, 0, \frac{1}{2}, \frac{1}{2})$	1803	1466	629	610	600
$(\frac{1}{6}, 0, \frac{1}{2}, \frac{3}{2})$	82	0	0	0	0

- Quivers with additional  $U(1)'$  gauge symmetry
- $\lesssim 50\%$  are family universal for  $q_L$ ,  $L$ ,  $u_L^c$ ,  $d_L^c$ , and  $e_L^c$
- Family non-universal (quiver distinct): GIM violation, FCNC ( $B_s$  anomalies?)

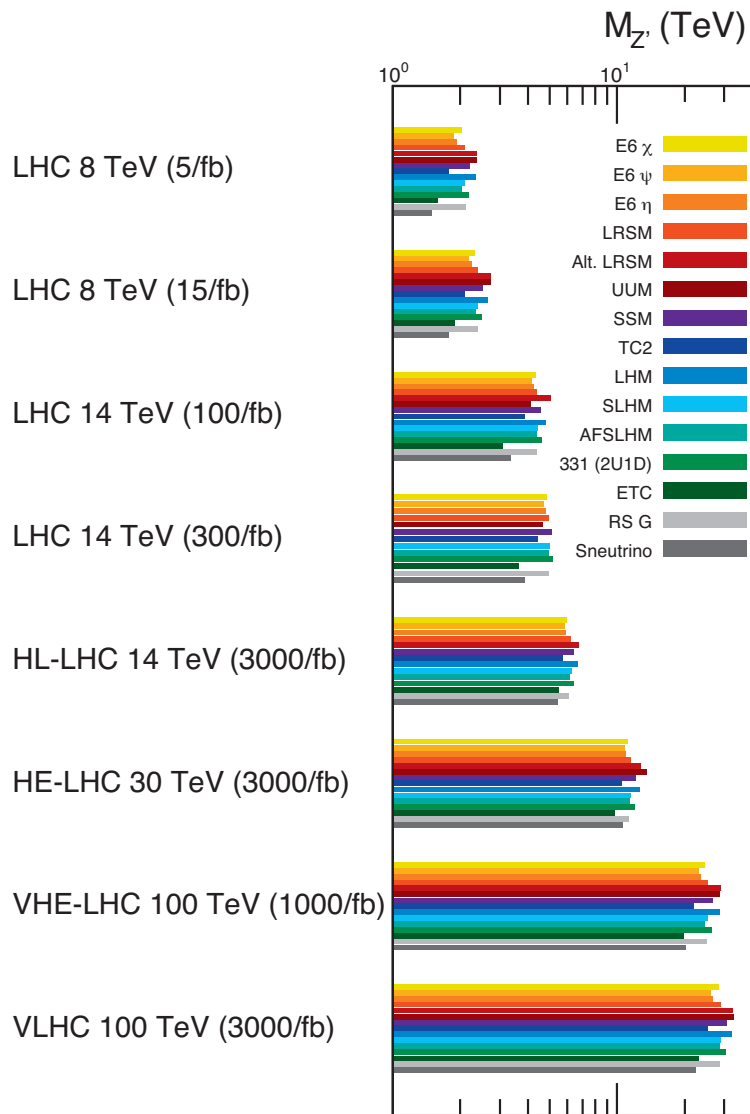


SM Rep	Total Multiplicity	4 <sup>th</sup> Gen. Removed	Shifted 4 <sup>th</sup> Gen. Also Removed
$(1, 1)_0$	4556	4556	4556
$(1, 3)_0$	1290	1290	1290
$(1, 2)_{-\frac{1}{2}}$	631	619	619
$(1, 2)_{\frac{1}{2}}$	619	619	619
$(\bar{3}, 1)_{\frac{1}{3}}$	478	466	458
$(3, 1)_{-\frac{1}{3}}$	458	458	458
$(1, 1)_1$	262	250	250
$(1, 1)_{-1}$	250	250	250
$(1, 2)_{-\frac{3}{2}}$	101	101	93
$(1, 2)_{\frac{3}{2}}$	93	93	93
$(3, 2)_{\frac{1}{6}}$	46	34	34
$(\bar{3}, 2)_{-\frac{1}{6}}$	34	34	34
$(\bar{3}, 1)_{-\frac{2}{3}}$	30	18	18
$(3, 1)_{\frac{2}{3}}$	18	18	18
$(1, 3)_1$	8	8	0
$(3, 2)_{-\frac{5}{6}}$	8	8	0
$(\bar{3}, 1)_{\frac{4}{3}}$	8	8	0

## A TeV-Scale $Z'$

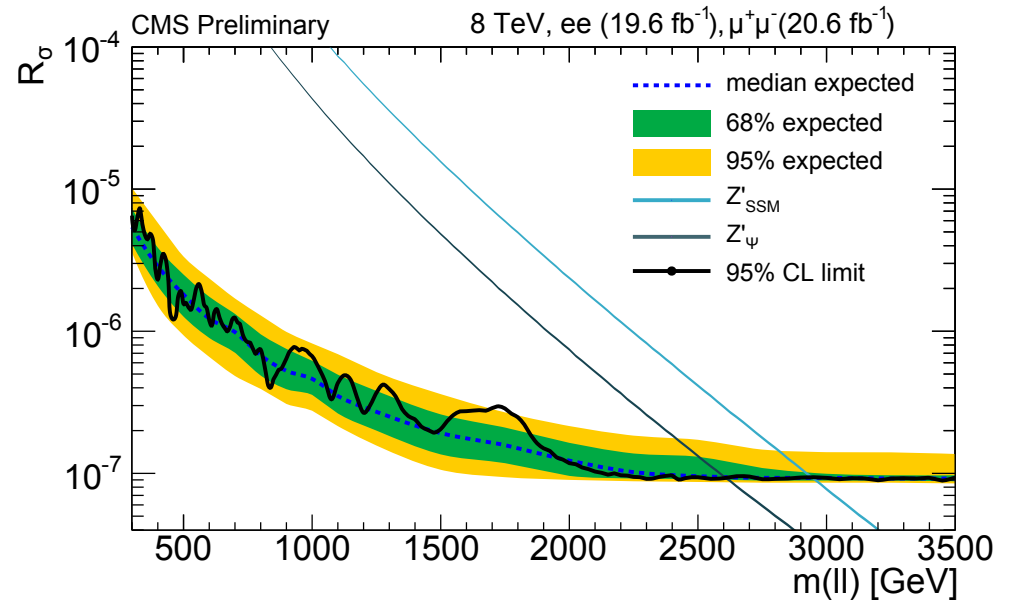
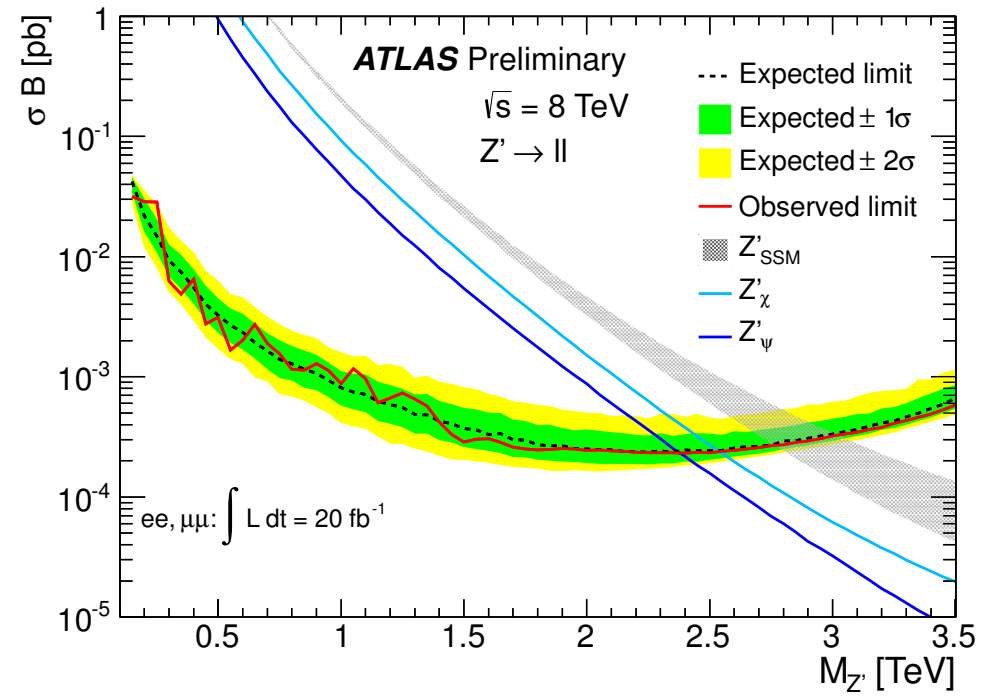
Review: Rev.Mod.Phys.81,1199 (arXiv:0801.1345)

- **Strings, GUTs, DSB, little Higgs, LED often involve extra  $Z'$**   
(harder to break  $U(1)'$  factors than non-abelian: remnants)
- **Typically  $M_{Z'} \gtrsim 2 - 3$  TeV for electroweak coupling**  
(LHC, Tevatron, LEP 2, WNC);  $|\theta_{Z-Z'}| < \text{few} \times 10^{-3}$  ( $Z$ -pole)
- **Discovery to  $M_{Z'} \sim 5 - 6$  TeV at LHC-14, higher in  $e^-e^+$**   
( $pp \rightarrow \mu^+\mu^-, e^+e^-, q\bar{q}$ ) (depends on couplings, exotics, sparticles)
- **LHC diagnostics to 1-3 TeV** (BR's, asymmetries, polarizations,  
 $y$  distributions, associated production, rare decays);  
**higher for ILC/CLIC/TLEP**
- **Light (150-300 GeV) leptophobic, TeV-scale (FCNC), or very light**  
( $\lesssim 10$  GeV)  $Z'$  portal suggested by recent anomalies/DM



Godfrey, Martin, 1309.1688

MPI, Munich (9/13)



Paul Langacker (IAS/Princeton)

## String $Z'$

- **Non-anomalous, descending through non-abelian group** ( $E_6, SO(10)$ , Pati-Salam (may be  $T_{3R}, T_{BL}, E_6$  or “random”))
- **Anomalous  $U(1)'$ , e.g., from  $U(n)$  or  $U(1)$  branes**
  - Stüeckelberg masses  $\sim M_{str}$
  - $Z'$  and Chern-Simons term may be observable for  $M_{str} \sim \text{TeV}$
  - Large  $M_{str}$ : may be anomaly-free combinations (in addition to  $Y$ ); often family non-universal

## Implications of a TeV-scale $U(1)'$

- **Couplings**  $\rightarrow$  clues about embedding into underlying theory
- **Natural solution to  $\mu$  problem:**  $W \sim h_s S H_u H_d \rightarrow \mu_{eff} = h_s \langle S \rangle$   
(“stringy version” of NMSSM)
- **Supersymmetry:**  $SU(2) \times U(1)$  and  $U(1)'$  breaking scales *both* set by SUSY breaking scale (unless flat direction)
- **Extended Higgs sector**
  - Relaxed mass limits, couplings, parameters (e.g.,  $\tan \beta \sim 1$ )
  - Higgs singlets needed to break  $U(1)'$
  - Doublet-singlet mixing, extended neutralino sector  
( $\rightarrow$  non-standard collider signatures)

- **Extended neutralino sector**
  - Additional neutralinos, non-standard couplings, e.g., light singlino-dominated, extended cascades
  - Additional cold dark matter,  $g_\mu$  – 2 possibilities
- **Exotics (anomaly-cancellation)**
  - Non-chiral wrt SM but chiral wrt  $U(1)'$
  - May decay by mixing; by diquark or leptoquark coupling; or be quasi-stable
- **$Z'$  decays into sparticles/exotics (SUSY factory)**
- **Flavor changing neutral currents** (for non-universal  $U(1)'$  charges)
  - Tree-level effects in  $B$  decay competing with SM loops  
(or with enhanced loops in MSSM with large  $\tan \beta$ )
  - $B_s - \bar{B}_s$  mixing,  $B_d$  penguins
  - $t\bar{t}$  forward-backward asymmetry (probably excluded)

- **Non-universal charges: MSW-type effects** (apparent CPT violation)
- $Z' - \tilde{Z}'$  mediation of SUSY breaking
- **Constraints on neutrino mass generation**
  - Various versions allow or exclude Type I or II seesaws, extended seesaw, small Dirac by HDO or non-holomorphic soft; stringy Weinberg operator, Majorana seesaw, small Dirac by string instantons; sterile mixing  
(e.g., Kang, PL, Li; Phys. Rev. D 71, 015012 (2005) [hep-ph/0411404])
- **Large  $A$  term and possible tree-level  $CP$  violation**  
(no new EDM constraints)  $\rightarrow$  **electroweak baryogenesis**

## Extended Higgs Sector

- Standard model singlets  $S_i$  and additional doublet pairs  $H_{u,d}$  very common
- Additional doublet pairs
  - Richer spectrum, decay possibilities (anomalies?)
  - May be needed (or expand possibilities for) quark/lepton masses/mixings (e.g., stringy symmetries may restrict single Higgs couplings to one or two families)
  - Extra neutral Higgs  $\rightarrow$  FCNC (suppressed by Yukawas)
  - Significantly modify gauge unification (unless compensated)



## Higgs singlets $S_i$

- Standard model singlets common in string constructions
- Needed to break extra  $U(1)'$  gauge symmetries
- Solution to  $\mu$  problem ( $U(1)'$ , NMSSM, nMSSM, sMSSM)

$$W \sim h_s S H_u H_d \rightarrow \mu_{eff} = h_s \langle S \rangle$$

- $F(D)$  terms allow larger MSSM-like Higgs mass
- Modified couplings, parameter ranges, branching ratios
- Singlet-doublet mixing
- Large  $A$  term and possible tree-level  $CP$  violation  $\rightarrow$  electroweak baryogenesis

## Quasi-Chiral Exotics

- Often find exotic (wrt  $SU(2) \times U(1)$ ) quarks/leptons at TeV scale
  - Assume non-chiral wrt SM gauge group (strong constraints on SM chiral from large Yukawas ( $\Rightarrow$  Landau poles), precision EW)
  - Can be chiral wrt extra  $U(1)$ 's or other extended gauge
  - Usually needed for  $U(1)$ ' anomaly cancellation
  - Modify gauge unification unless in complete GUT multiplets
  - Strings typically yield (anti-) (bi-) fundamentals, adjoints, (anti-) symmetric
  - May also be quasi-hidden, shifted charges, or fractional charges

- Examples in 27-plet of  $E_6$

- $D_L + D_R$  ( $SU(2)$  singlets, chiral wrt  $U(1)'$ )

- $\begin{pmatrix} E^0 \\ E^- \end{pmatrix}_L + \begin{pmatrix} E^0 \\ E^- \end{pmatrix}_R$  ( $SU(2)$  doublets, chiral wrt  $U(1)'$ )

- Pair produce  $D + \bar{D}$  by QCD processes (smaller rate for exotic leptons)

- $D$  or  $\tilde{D}$  decay by

- $D \rightarrow u_i W^-$ ,  $D \rightarrow d_i Z$ ,  $D \rightarrow d_i H^0$  if driven by  $D - d$  mixing (not in minimal  $E_6$ ; FCNC)

- $\tilde{D} \rightarrow$  quark jets if driven by diquark operator  $\bar{u}\bar{u}\tilde{D}$ , or quark jet + lepton for leptoquark operator  $lq\tilde{D}$  (still have stable LSP)

- May be stable at renormalizable level due to accidental symmetry (e.g., extended gauge group)  $\rightarrow$  hadronizes and escapes or stops in detector (quasi-stable from HDO  $\rightarrow \tau < 1/10$  yr)  
(Kang, PL, Nelson, Phys.Rev. D77, 035003 (arXiv:0708.2701))

- Applications:  $H \rightarrow \gamma\gamma$ , dark matter, baryogenesis,  $B$ -mixing/decays, FCNC, flavor structure,  $A_{FB}^b$ , gauge mediation

- PL, London [PR D38,886]
- Choudhury, Tait, Wagner [0109097]
- del Aguila, de Blas, Perez-Victoria [0803.4008]
- Endo, Hamaguchi, Ishikawa, Iwamoto, Yokozaki [1108.3071,1112.5653,1212.3935]
- Martin, James D. Wells [1206.2956]
- Bonne, Moreau [1206.3360]
- Joglekar, Schwaller, Wagner [1207.4235,1303.2969]
- Botella, Branco, Nebot [1207.4440]
- Arkani-Hamed, Blum, D’Agnolo, Fan [1207.4482]
- Kearney, Pierce, Weiner [1207.7062 ]
- Batell, Gori, Wang [1209.6382]
- Cacciapaglia, Deandrea, Perries, Sordini, Panizzi [1211.4034]
- Garberson, T. Golling [1301.4454]
- Buras, Girschbach, Ziegler [1301.5498]
- Aguilar-Saavedra, Benbrik, Heinemeyer, Perez-Victoria [1306.0572]
- Alves, Barreto, Camargo, Dias [1306.1275]
- Aguilar-Saavedra [1306.4432]
- Ishiwata, Wise [1307.1112]
- Alloul, Frank, Fuks, de Trautenberg [1307.1711]
- Fairbairn, Philipp Grothaus [1307.8011]
- Altmannshofer, Bauer, Carena [1308.1987]
- Halverson [tbp]

## Small neutrino masses

- Many mechanisms for small  $m_\nu$ , both Majorana and Dirac
- Minimal Type I seesaw
  - Bottom-up motivation: no gauge symmetries prevent large Majorana mass for  $\nu_R$
  - Connection with leptogenesis
  - **Argument that  $L$  must be violated is misleading**  
[non-gravity: large 126 of  $SO(10)$  or HDO added by hand]  
[gravity:  $m_\nu \lesssim \nu_{EW}^2 / \overline{M}_P \sim 10^{-5}$  eV (unless LED); often much smaller]
  - **New TeV or string scale physics/symmetries/constraints may invalidate assumptions**  
[No 126 in string-derived  $SO(10)$ ]
- Bottom-up alternatives: Higgs (or fermion) triplets, extended (TeV) seesaws, loops,  $R_p$  violation

- **String-motivated alternatives**

(review: ARNPS, 62, 215; arXiv:1112.5992)

- **Higher-dimensional operators (HDO)**

[non-minimal seesaw (not GUT-like), direct Majorana (Weinberg op), small Dirac, mixed (LSND, MiniBooNE)]

- **String instantons (exponential suppressions)**

[non-minimal seesaw, direct Majorana, small Dirac]

- **Geometric suppressions (large dimensions)** [small Dirac]

- **Alternatives often associated with new TeV physics, electroweak baryogenesis, etc.**

## Conclusions

- String landscape/eternal inflation: physics may be (partially) environmental
- **From bottom up:** there may be more at TeV scale than MSSM
- **From top down:** there may be more at TeV scale than MSSM (e.g.,  $Z'$ , extended Higgs/neutralino, quasi-chiral exotics, nonstandard  $\nu$ )
- Important to delineate difference between string possibilities and field theory possibilities