Standard Model Searches on Intersecting D-Branes

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Why String Theory?

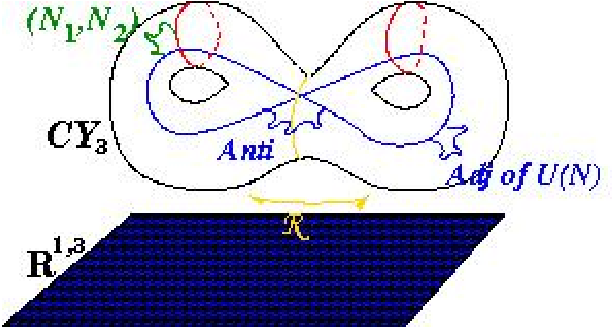
- Vibrating strings carry spin-1 *vector bosons*, spin-2 *graviton*
  $\Rightarrow$ a quantised theory of all fundamental forces
- also spin-0 *scalar bosons* and spin-$1/2$ *fermions* (and spin-3/2 *gravitini*)
  $\Rightarrow$ playground for Particle Physics

- Superstrings live in 10D $\Rightarrow$ need compact 6D
- $\mathcal{N} = 1$ supersymmetry (SUSY) in 4D requires special compact 6D: 'Calabi-Yau' (or 'orbifolds')
- String theoretic equations of motion (Bianchi identities) $\Rightarrow$ 4D gauge theory is **anomaly-free**
- string theory encorporates ideas **Beyond The Standard Model**: SUSY, extended Higgs sector, exotic particles, Z' gauge bosons, extra dimensions
- applications to cosmology: scalar potentials, dark matter

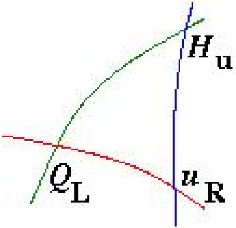
Intersecting D-Branes

- Open strings end on **D-branes**
- A single **D-brane** carries the gauge group $U(1)$,
  N coincident D-branes have $U(N)$
  $\Rightarrow$ construct the Standard Model gauge group
- Open strings with endpoints on two different D-branes carry charge $(\mathbf{N}_1, \bar{\mathbf{N}}_2)$ under $U(N_1) \times U(N_2)$
  $\Rightarrow$ engineer quarks and leptons
- Dimension of the D-branes depends on IIA/IIB string theory: even/odd
- D6-branes have a very intuitive geometrical description
- SUSY models require so-called 'orientifold planes'

- D6-branes span 4D Minkowski space
- wrap 3 of the 6 compact dimensions
- D6-branes intersect in *points*



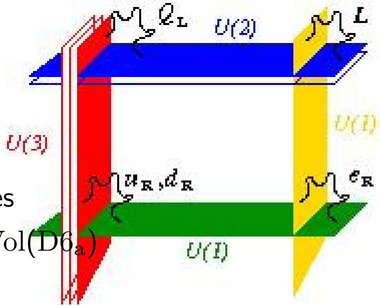
- *Intersections* at angles $\Rightarrow$ chiral matter in bi-fundamental rep. (two ends of open strings)
- SUSY for appropriate angles
- Equations of motion constrain number and position of D6-branes
- Yukawa couplings have geometric interpretation
  $Y_u \sim f(\mathrm{Angle}) \times e^{-\mathrm{Area}}$



The Standard Model in (Type II) String Theory

Gauge group: $U(3)_a \times U(2)_b \times U(1)_c \times U(1)_d$

- $U(1)_{a,\mathrm{diag}}$: gauged baryon number
- $U(1)_c$: 'right-brane': right-handed quarks
- $U(1)_d$: 'leptonic brane': left-handed leptons
- hyper charge is the massless linear combination of a, c, d, all other $U(1)$ symmetries massive
- **Higgs** on $U(2)_b \times U(1)_c$
- **Family replication** due to multiple brane intersections
- **Yukawa couplings** from triangles
- **Gauge couplings** $\frac{1}{g_a^2} = \frac{M_{\mathrm{Planck}}}{M_{\mathrm{string}}} \mathrm{Vol}(\mathrm{D6_a})$



Grand Unified Theories (GUTs)

- $SU(5)$ in principle possible - in practice not found
- Pati-Salam $SU(4) \times SU(2)_L \times SU(2)_R$
- NOT $SO(10)$ (no spinor representation on D-branes)
- NOT E_6, E_7, E_8 (no exceptional gauge groups)
- more D-branes than Standard Model: hidden sector if **no chiral matter** with SM charges exists

Constructions on

- smooth Calabi-Yaus: difficult since background metric is unkown
- $\mathbb{Z}_N$ orbifolds of the torus: have singular points
- on orbifolds one can use Conformal Field Theory techniques
- Spectrum and couplings *in principle* computable
- scan through various orbifolds: $\mathbb{Z}_6'$ gives best results

What can we compute?

The gauge group & *chiral* matter if 3-cycles are known
On orbifolds also

- the *non-chiral* matter
- ratios of tree level gauge couplings
- gauge threshold corrections from massive strings at the string scale M_{string}
- in principle Yukawa couplings, scattering amplitudes

Rest of the talk:

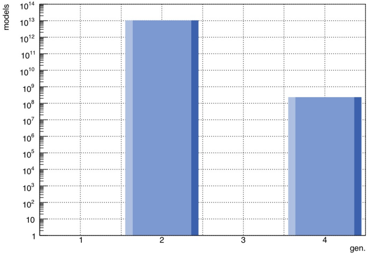
- study one orbifold $T^6/\mathbb{Z}_6'$ in detail
- solve equations of motion and SUSY condition
- investigate solutions that have 3 Standard Model generations
- statistical analysis: correlations of properties

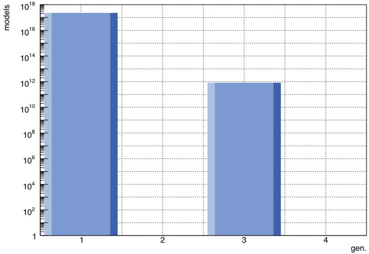
Some Statistics of Intersecting D-Branes

Florian Gmeiner, G.H. since '07

Number of generations on the $T^6/\mathbb{Z}_6'$ background:

$SU(5)$ $\qquad$ $SU(4) \times SU(2)_L \times SU(2)_R$

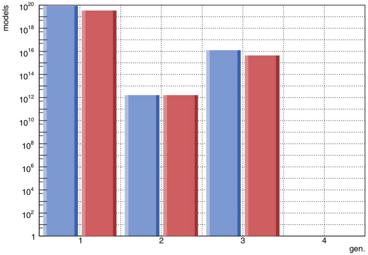




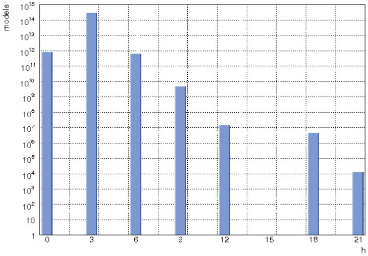
- $SU(5)$ GUTs on $T^6/\mathbb{Z}_6'$ only with 2 or 4 generations and exotic particles in **15** rep.
- Pati-Salam models only with 1 or 3 generations: rich structure, details not yet explored

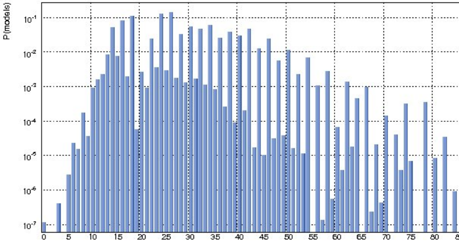
$SU(3) \times SU(2) \times U(1)_Y$ with hyper charge massive or massless:

- only 1,2,3 generations
- 10^{15} models with 3 generations
- abundance of chiral exotics
- only 10^7 models without chiral exotics
- at string tree-level: three sets of chiral SM spectra and gauge couplings, 16 classes of spectra without or with hidden sectors
- at 1-loop in string coupling: 10 sets of beta-functions



SUSY Higgs $H_u + H_d$ families h (or vector-like lepton pairs)



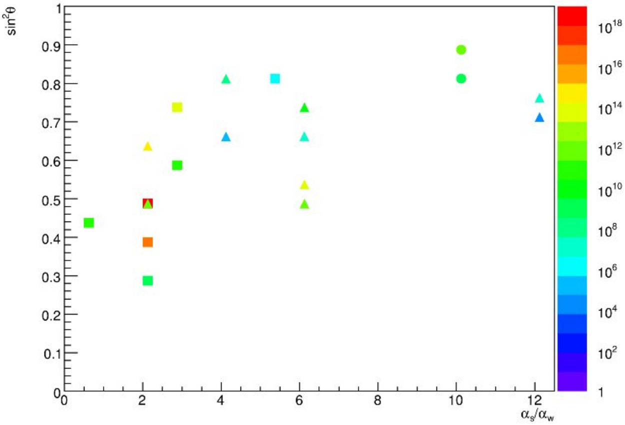


Number of chiral exotics

- no model with 1 Higgs family: multiples of 3
- faction 10^{-7} of models without chiral exotics
- Correlation: no chiral exotics only with very extended Higgs sector $h = 12, 18, 21$

Ratios of tree level gauge couplings at the string scale

$$\frac{1}{\alpha_a(\mu)} = \frac{M_{\text{Planck}}}{M_{\text{string}}} \text{Vol}(D6_a) + \frac{b_a}{4\pi} \ln \left(\frac{M^2_{\text{string}}}{\mu^2} \right) + \frac{\Delta_a}{4\pi}$$



compare to GUT relations

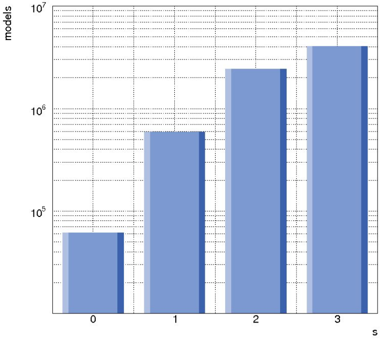
$\frac{\alpha_s}{\alpha_w} = 1,$

$\sin^2 \theta_w = \frac{3}{8}$

3 generations: triangles

Hidden sector gauge groups:

- the number of hidden sector branes



- total rank: 0,1,3
- interact gravitationally with Standard Model
- if gaugino condensation occurs, it may break SUSY

Correlations for models **without chiral exotics**

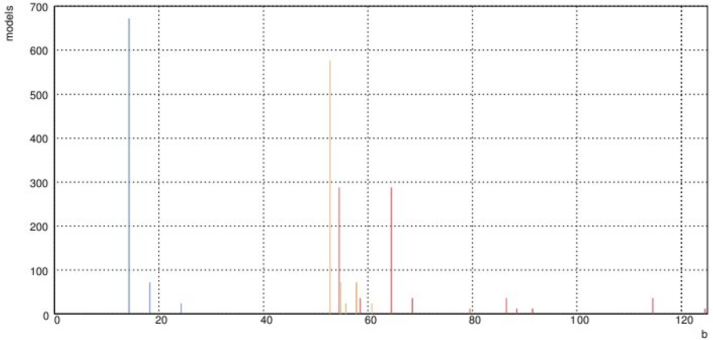
- all models have a massless $B-L$ symmetry which distinguishes among $H_u + H_d$ and $L + \bar{L}$
- $h = 12$: 9 Higgs families + 3 vector-like lepton pairs
  tree level gauge couplings: $\alpha_s/\alpha_w = 6$, $\sin^2\theta_w = 0.654$
  hidden sector gauge groups with rank 1 or 3
- $h = 18$: 6 Higgs families + 12 vector-like lepton pairs
  tree level gauge couplings: $\alpha_s/\alpha_w = 4$, $\sin^2\theta_w = 0.667$
  no hidden sector
- $h = 21$: 18 Higgs families + 3 vector-like lepton pairs
  tree level gauge couplings: $\alpha_s/\alpha_w = 12$, $\sin^2\theta_w = 0.720$
  no hidden sector

Example for a model:

- SM gauge group $SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$
- chiral spectrum: three quark-lepton generations with right-handed neutrinos $3 \times [Q_L + u_R + d_R + L + e_R + \nu_R]$
- hidden gauge group: $Sp(6)$
- non-chiral spectrum: $(9+2_m)(H_u + H_d) + \left[Q_L + (4+2_m)d_R + 3u_R^* + (1+3_m)L + 1_m e_R + 1_m e_R^* + 1_m \nu_R + 3 \cdot \mathbf{3}_{SU(2)_L} + (5+2_m)\mathbf{1} + (\mathbf{1},\mathbf{6})_{1/2,0} + c.c.\right] + 2 \cdot \mathbf{15}_{Sp(6)} + 2 \cdot (\mathbf{2}_{SU(2)_L}, \mathbf{6}_{Sp(6)})$
- mass terms for green states known
- $*$ denotes correct $SU(3) \times SU(2)_L \times U(1)_Y$ charge, but non-standard $B - L$
- beta-function coefficients: $(b_{SU(3)}, b_{SU(2)}, b_Y, b_{B-L}) = (12 + 2, 59 + 5, 33 + \frac{31}{3}, 72 + \frac{64}{3})$

1-loop beta function coefficients

$$\frac{1}{\alpha_a(\mu)} = \frac{M_{\rm Planck}}{M_{\rm string}} {\rm Vol}(D6_a) + \frac{b_a}{4\pi} \ln\left(\frac{M^2_{\rm string}}{\mu^2}\right) + \frac{\Delta_a}{4\pi}$$

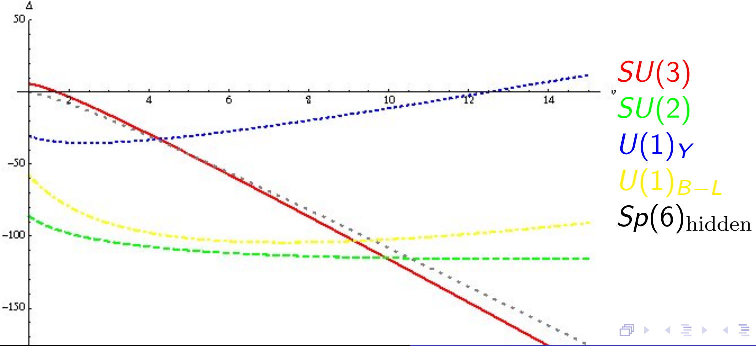


compare with MSSM values $(SU(3), SU(2), U(1)_Y) = (-3, 1, 11)$

Threshold corrections: at the string scale M_{string}, massive strings change the gauge coupling

$$\frac{1}{\alpha_a(\mu)} = \frac{M_{\text{Planck}}}{M_{\text{string}}} \text{Vol}(D6_a) + \frac{b_a}{4\pi} \ln \left(\frac{M_{\text{string}}^2}{\mu^2} \right) + \frac{\Delta_a(v)}{4\pi}$$

depend on the size v of compact dimensions



- gauge thresholds Δ depend on compact volume v, Wilson lines τ and distances σ
- for $\tau = \sigma = 0$

$$\Delta_{SU(3)_a} = \ln \left(v^8 \eta^{16}(iv)\eta^{16}(i2v) \left| e^{-\pi v/4} \frac{\vartheta_1(\frac{1-i}{2}\, v, iv)}{\eta(iv)} \right|^2 \right) + 22$$

- asymptotic linear (negative) growth with volume v
- since $\frac{1}{\alpha_{a,\mathrm{tree}}(\mu)} = \frac{M_{\mathrm{Planck}}}{M_{\mathrm{string}}} \mathrm{Vol}(D6_a)$, they are only significant for large M_{string}

Conclusions & Outlook

- String theory offers a rich playground for particle physics, beyond the standard model, SUSY, extra dimensions ... detection at LHC???
- Exactly the (MS)SM is hard to engineer: gauge group enhancements, e.g. by $B - L$ symmetry, exotic chiral and non-chiral matter, gauge couplings don't unify
- SUSY $\mathbb{Z}_6'$ examples: 16 inequivalent spectra, some with strongly coupled hidden gauge groups $\Rightarrow$ SUSY breaking via a gaugino condensate?
- Field theory of string compactifications needs better understanding!