The string landscape: viewing into it and bypassing around it at the LHC

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Introduction:

Count the number of consistent string vacua ➤

Vast landscape with \( N_{sol} = 10^{500–1500} \) vacua!

(Kawai, Lewellen, Tye (1986); Lerche, Lüst, Schellekens (1986);
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Two (complementary) issues:

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- Can we view into the landscape?

⇒ information about other vacua?
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- Can we view into the landscape?
  ⇒ information about other vacua?
- Can we by-pass the landscape?
  ⇒ look for green (promising) spots
  - model independent predictions?

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Outline

- Viewing into the landscape
- By-passing the landscape:
  Stringy signatures at LHC
  
  (The LHC string hunter’s companion)
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Low TeV string scale compactifications:

- Alternative to low energy supersymmetry
- Realization large extra dimension scenario (ADD)
- String perturbation theory valid at 1-10 TeV

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c) Constraints from mathematical consistency:
   generalized geometry
Consider a theory with $N$ species of particles with mass $M$:

$$N < N_{\text{max}} = \frac{M_{\text{Planck}}^2}{M^2}$$

$M$: scale of new physics

(A quantum black hole can emit at most $N_{\text{max}}$ different particles)

This bound must be satisfied in every effective string vacuum that is consistently coupled to gravity!

E.g. if a scalar field in the effective potential gives mass to $N$ particles via the Higgs effect: $M = M(\phi)$

$$M(\phi)^2 < \frac{M_{\text{Planck}}^2}{N}$$

Bound forbids essentially large trans-planckian vevs:
E.g: \[ N = 10^{32} \implies M < 10^{-16} M_{Planck} \approx 1 \text{ TeV} \]

This bound gives also a possible explanation of the hierarchy problem:

\[ M \text{ can be seen as the fundamental scale of gravity, which is diluted by the presence on the } N \text{ particle species.} \]
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Is there a stringy realization of the large \( N \) species scenario?
b) Transitions between different vacua:

These transitions are due to domain wall solutions that interpolate between different vacua.


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C) **Generalized geometry:** new supersymmetric, warped type II $AdS_4$ vacua:

Consider backgrounds of the form:

$$AdS_4 \times_w M_6$$

plus Ramond & NS fluxes

Type II: two globally defined internal spinors $\theta_1, \theta_2$

Non-vanishing warp factor: $\theta_1, \theta_2$ must be non-vanishing

$\Rightarrow M_6$ possesses a SU(3) x SU(3) group structure

Generalized CY condition: $d\Psi_\pm = 0$ ($\Psi_\pm \simeq \theta_1^+(\theta_2^\pm)^\dagger$)

Unwarped IIA: **Strict SU(3) structure:** $\theta_1, \theta_2$ parallel

(Berndt, Cvetic (2000/04); Lüst, Tsimpis (2004); Tomasiello (2007); Koerber, Lüst, Tsimpis (2008); Aldazabel, Font (2008)).

$M_6 :$ coset space $G/H.$

Unwarped IIB: **Static SU(2) structure:** $\theta_1, \theta_2$ orthogonal
New classes of sourceless warped AdS4 solutions:


\[ ds^2 = e^{2A} ds^2 (AdS_4) + ds^2 (M_6) \]

\( M_6 \) is a co-dimension one foliation:

\[ ds^2 (M_6) = d\chi^2 + ds^2_\chi (M_5) \]

\( M_5 \) admits an Sasaki-Einstein structure.

All SUSY and Bianchi identities are automatically satisfied (generalization of CY conditions)
Interpolating domain wall solutions:


Metric and fluxes depend on an additional coordinate $r$:

\[
\begin{align*}
\text{ds}^2 &= e^{2\hat{A}(r)} \ dx^\mu d_\mu + \text{ds}^2 (\mathcal{M}_7) \\
&= e^{Z(r)} (e^{2A(r)} \ dx^\mu d_\mu + dr^2) + \text{ds}^2 (\mathcal{M}_6)
\end{align*}
\]

$\Rightarrow$ Generalized $G_2 \times G_2$ group structure on $\mathcal{M}_7$

Supersymmetry conditions (flow equations):

\[
d\Psi_\pm = f(r)
\]

- These can be also obtained from an eff. 4D action!
- c-theorem, also relevant for flow between CFT3's!
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(The LHC string hunter’s companion)

(D. Lüst, S. Stieberger, T. Taylor, arXiv:0807.3333;
D. Härtl, D. Lüst, O. Schlotterer, S. Stieberger, T. Taylor, to appear)
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- Can we test stringyness of physics?
  Measure excited string states in experiment?
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We consider type IIA/B orientifolds with intersecting D6/D7-branes:

Realization of the SM without chiral exotics! (Gmeiner, Honecker)

Open string Standard Model Quiver, wrapped around internal p-cycles:

(Baryon number is (anomalous) U(1) gauge symmetry!)
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So far: \(n=4,5; \ g=0\)
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**Scale of wrapped D(p+3)-branes:**  
\[(3) : \quad M_p^\parallel = \frac{1}{(V_p^\parallel)^{1/p}}\]
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Strength of 4D gravitational interactions:

\[ (A) : \quad M_{\text{Planck}}^2 \sim M_s^8 V_6 \sim 10^{19} \text{ GeV} \]

Strength of 4D gauge interactions:

\[ (B) : \quad g_{Dp}^{-2} \sim M_s^p V_p^\parallel \sim \mathcal{O}(1) \]

\[ \implies (V_p^\parallel)^{-1/p} \sim M_s \]
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\( M_s \) is a free parameter!
Low string scale scenario:
(Antoniadis, Arkani-Hamed, Dimopoulos, Dvali)

\[ M_s \equiv M_{SM} \simeq 10^3 \text{ GeV} \]

Stringy realization by Swiss cheese Calabi-Yau‘s:

(Abdussalam, Allanach, Balasubramanian, Berglund, Cicoli, Conlon, Kom, Quevedo, Suruliz; Blumenhagen, Moster, Plauschinn; for model building and phenomenological aspects see: Conlon, Maharana, Quevedo, arXiv:0810.5660)
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2 requirements:
- Negative Euler number.
- SM lives on D7-branes around small cycles of the CY. One needs at least one blow-up mode (resolves point like singularity).
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**Stringy Regge excitations:**

\[ M_{\text{Regge}} = M_s = \frac{M_{\text{Planck}}}{\sqrt{V_6'}} \]

Open string excitations: completely universal (model independent), carry SM gauge quantum numbers

\[ M_{\text{n}}^2 = M_s^2 \left( \sum_{k=1}^{n} \alpha_{-k}^{\mu} \alpha_{k}^{\nu} - 1 \right) = (n - 1) M_s^2, \quad (n = 1, \ldots, \infty) \]
D-brane cycle Kaluza Klein excitations:

\[
M_{KK}^\parallel = \frac{1}{(V_p^\parallel)^{1/p}} \simeq M_s = \frac{M_{\text{Planck}}}{(V_6')^{1/2}}
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The string Regge excitations and the D-brane cycle KK modes are charged under the SM and have mass of order \( M_s \). Can they be seen at LHC?!
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Low string scale compactification is a concrete realization of the large number of species scenario at 1 TeV!

\[ 10^{32} \quad \text{KK (bulk) gravitons at the string scale.} \]
Test of D-brane models at the LHC:

\[ gg, qq, qg \longrightarrow X \longrightarrow g, \gamma, Z, W, q, l \]

In string perturbation theory production of:
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- Regge excitations of higher spin:

  \[ g^* \text{ spin } 0,1,2 \quad \& \quad q^* \text{ spin } 1/2, 3/2 \]
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(- Z' gauge bosons, black holes)

One has to compute the parton model cross sections of SM fields into new stringy states!
The string scattering amplitudes exhibit some interesting properties:

- Interesting mathematical structure
- They go beyond the N=4 Yang-Mills amplitudes:
  
  (i) The contain quarks & leptons in fundamental repr.
  
  **Quark, lepton vertex operators:**

  \[
  V_{q,l}(z, u, k) = u^\alpha S_\alpha(z) \Xi^{a \cap b}(z)e^{-\phi(z)/2} e^{ik \cdot X(z)}
  \]

  Fermions: boundary changing (twist) operators!

  Striking relation between quark and gluon amplitudes!

  (ii) They contain stringy corrections.
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Disk amplitude among 4 external SM fields \((q, l, g, \gamma, Z^0, W^\pm)\):

\[
\mathcal{A}(\Phi^1, \Phi^2, \Phi^3, \Phi^4) = < V_{\Phi^1}(z_1) V_{\Phi^2}(z_2) V_{\Phi^3}(z_3) V_{\Phi^4}(z_4) >_{disk}
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These amplitudes are dominated by the following poles:

- Exchange of SM fields
- Exchange of string Regge resonances (Veneziano like ampl.)

\[\Rightarrow\] new contact interactions:

\[
\mathcal{A}(k_1, k_2, k_3, k_4; \alpha') \sim - \frac{\Gamma(-\alpha's) \ \Gamma(1-\alpha'u)}{\Gamma(-\alpha's - \alpha'u)} = \sum_{n=0}^{\infty} \frac{\gamma(n)}{s - M^2_n} \sim \frac{t}{s} - \frac{\pi^2}{6} \ t \ u \ (\alpha')^2 + \ldots
\]

\[
V_s(\alpha') = \frac{\Gamma(1-s/M^2_{\text{string}}) \Gamma(1-u/M^2_{\text{string}})}{\Gamma(1-t/M^2_{\text{string}})} = 1 - \frac{\pi^2}{6} M^{-4}_{\text{string}} s u - \zeta(3) M^{-6}_{\text{string}} s t u + \cdots \rightarrow 1|_{\alpha' \to 0}
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- **Exchange of KK and winding modes (model dependent)**
n-point tree amplitudes with 0 or 2 open string fermions (quarks, leptons) and n or n-2 gauge bosons (gluons) are completely model independent.

⇒ Information about the string Regge spectrum.

(Computation of higher point amplitudes for LHC: D. Härtl, D. Lüst, O. Schlotterer, S. Stieberger, T. Taylor, work in progress).
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• KK modes are seen in scattering processes with more than 2 fermions.

⇒ Information about the internal geometry.

KK modes are exchanged in t- and u-channel processes and exhibit an interesting angular distribution.


Five point scattering amplitudes (3 jet events):

5 gluons:

\[ \mathcal{A}(g_1^-, g_2^-, g_3^+, g_4^+, g_5^+) = (V^{(5)}(\alpha', k_i) - 2i \epsilon(1, 2, 3, 4)P^{(5)}(\alpha', k_i)) \times M_{YM}^{(5)} \]

Field theory factors:

\[ M_{YM}^{(5)} = \frac{4g_{YM}^3 \langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \cdots \langle 51 \rangle} \]

3 gluons, 2 quarks:

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\[ N_{YM}^{(5)} = \frac{4g_{YM}^3 \langle 15 \rangle \langle 14 \rangle^3}{\langle 12 \rangle \langle 23 \rangle \cdots \langle 51 \rangle} \]

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\( \mathcal{A}(g_{1}, g_{2}, g_{3}, g_{4}, g_{5})_{\alpha' \rightarrow 0} \rightarrow \mathcal{M}_{YM}^{(5)}, \quad (V^{(5)} = 1 + \zeta(2)\mathcal{O}(\alpha'^{2}), \quad P^{(5)} = \zeta(2)\mathcal{O}(\alpha'^{2})) \)

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The two kinds of amplitudes are universal: the same Regge states are exchanged:
2 gauge boson - two fermion amplitude:

Only string Regge resonances are exchanged \( \Rightarrow \)

These amplitudes are completely model independent!

\[
|\mathcal{M}(qg \to qg)|^2 = g_3^4 \frac{s^2 + u^2}{t^2} \left[ V_s(\alpha') V_u(\alpha') - \frac{4}{9} \frac{1}{su} (sV_s(\alpha') + uV_u(\alpha'))^2 \right]
\]

\( \Rightarrow \) dijet events

\[
|\mathcal{M}(qg \to q\gamma(Z^0))|^2 = -\frac{1}{3} g_3^4 Q_A^2 \frac{s^2 + u^2}{su t^2} (sV_s(\alpha') + uV_u(\alpha'))^2
\]

Note: Cullen, Perelstein, Peskin (2000) considered:

\( e^+ e^- \to \gamma\gamma \)
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\[ \alpha' \rightarrow 0 : \text{agreement with SM!} \]

\[
|M(qg \rightarrow qg)|_{\alpha' \rightarrow 0}^2 = g_3^4 \frac{s^2 + u^2}{t^2} \left[ 1 - \frac{4}{9} \frac{1}{su} (s + u)^2 \right] \]

\[
|M(qg \rightarrow q\gamma(Z^0))|_{\alpha' \rightarrow 0}^2 = -\frac{1}{3} g_3^4 Q_A^2 \frac{s^2 + u^2}{su t^2} (s + u)^2 \]
These stringy corrections can be seen in dijet events at LHC:


\[M_{\text{Regge}} = 2 \text{ TeV}\]
\[\Gamma_{\text{Regge}} = 15 - 150 \text{ GeV}\]

Widths can be computed in a model independent way!

\[(\text{Anchordoqui, Goldberg, Taylor, arXiv:0806.3420})\]

There would be a clear signal at LHC during the first run with

\[E = 10 \text{ TeV}, \quad \mathcal{L} = 100 \text{ pb}^{-1}\]

KK modes are seen in scattering processes with more than 2 fermions.


Squared 4-quark amplitude with identical flavors:

$$|A(qq \rightarrow qq)|^2 = \frac{2}{9} \frac{1}{t^2} \left[ (sF_{tu}^{bb}(\alpha'))^2 + (sF_{tu}^{cc}(\alpha'))^2 + (uG_{ts}^{bc}(\alpha'))^2 + (uG_{ts}^{cb}(\alpha'))^2 \right] + \frac{2}{9} \frac{1}{u^2} \left[ (sF_{ut}^{bb}(\alpha'))^2 + (sF_{ut}^{cc}(\alpha'))^2 + (tG_{us}^{bc}(\alpha'))^2 + (tG_{us}^{cb}(\alpha'))^2 \right] - \frac{4}{27} \frac{s^2}{tu} \left[ F_{tu}^{bb}(\alpha') F_{ut}^{bb}(\alpha') + F_{tu}^{cc}(\alpha') F_{ut}^{cc}(\alpha') \right]$$

Squared 4-quark amplitude with different flavors:

$$|A(qq' \rightarrow qq')|^2 = \frac{2}{9} \frac{1}{t^2} \left[ (sF_{tu}^{bb}(\alpha'))^2 + (s\tilde{G}_{tu}^{cc}(\alpha'))^2 + (uG_{ts}^{bc}(\alpha'))^2 + (uG_{ts}^{cb}(\alpha'))^2 \right]$$

Dijet angular contribution by t-channel exchange:

CMS detector simulation: \( M_s = 5 \text{ TeV}, \ M_{KK} = 3.5 \text{ TeV} \)

Luminosity \( 1 \text{ fb}^{-1} \) \hspace{1cm} \( 10 \text{ fb}^{-1} \)
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Computations done at weak string coupling!

Black holes are heavier than Regge states: $M_{b.h.} = \frac{M_{\text{string}}}{g^2_{\text{string}}}$
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  Question: do loop and non-perturbative corrections change tree level signatures? Onset of n.p. physics: $M_{\text{b.h.}}$
If nature chooses weakly coupled strings with a string scale at a few TeV, LHC should find them until 2012.