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

Dieter Lüst, LMU (Arnold Sommerfeld Center) and MPI München
Count the number of consistent string vacua ➤

Vast landscape with $N_{sol} = 10^{500-1500}$ vacua!

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Antoniadis, Bachas, Kounnas (1986); Douglas (2003))
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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?

Boston, SUSY 2009, 10. June 2009
Outline

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

In general: constraints on the landscape of effective theories by consistent embedding in quantum gravity (swampland approach) (Vafa et al.)
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a) Bounds on the landscape from decays of black holes:

⇒ information on particle masses and vacuum expectation values in some vacua
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Need non-perturbative effects as telescopes:

a) Bounds on the landscape from decays of black holes:
   ⇒ information on particle masses and vacuum expectation values in some vacua

b) Transitions between vacua due to domain walls:
   ⇒ information on life times of particle of some vacua
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: $M = M(\phi)$

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

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E.g: \( N = 10^{32} \implies M < 10^{-16} M_{\text{Planck}} \approx 1 \text{ TeV} \)

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

\( M \) can be seen as the fundamental scale of gravity, which is diluted by the presence on the \( N \) particle species.
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$\Rightarrow$ dramatic effects at the LHC.
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Is there a stringy realization of the large N species scenario?
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- De Sitter vacua - inflation: Consider inflaton field $\phi$

$$\ddot{\phi} + 3H \dot{\phi} + V(\phi)' = 0$$

$\phi$ is coupled to species of mass $M$:

Black hole bound: $M(\phi) < \frac{M_P}{(H^{-1}(\phi)M_P)^{\frac{1}{3}}}$
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Chaotic inflation:

$V(\phi) = \frac{1}{2} m^2 \phi^2 + g\phi \bar{\psi}_j \psi_j$

slow roll condition: $\dot{\phi} \geq M_P$

$g\phi \leq M_P \left( \frac{m\phi}{M_P^2} \right)^{\frac{1}{3}}$

$\phi$ cannot be arbitrarily large!

Bound forbids essentially large trans-planckian vevs:
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- **Metastable vacua - susy breaking**
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\[
\Rightarrow \text{ Problem to see gravitational waves?}
\]

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b) Transitions between different vacua:

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

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E.g. from M4 to AdS4:

- **non-zero fluxes**
- **zero fluxes**
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• Viewing into the landscape

• By-passing the landscape: Stringy signatures at LHC

(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)
II) By-passing the landscape by making model independent predictions:

Consider (only) those vacua that realize the Standard Model.

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- Go to the field theory limit - decouple gravity!

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We consider type IIA/B orientifolds with intersecting D6/D7-branes:

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We want to compute all n-point, g-loop string amplitudes of SM model open string fields.
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Realization of the SM without chiral exotics!

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So far: $n=4,5; \quad g=0$
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String scale:

(1) \[ M_s = \frac{1}{\sqrt{\alpha'}} \]
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Scale of wrapped D(p+3)-branes: \( M^\parallel_p = \frac{1}{(V_p^\parallel)^{1/p}} \)

Strength of 4D gravitational interactions:

\( M_{\text{Planck}}^2 \simeq M_s^8 V_6 \simeq 10^{19} \text{ GeV} \)

Strength of 4D gauge interactions:

\( g_{Dp}^{-2} \simeq M_s^p V_p^\parallel \simeq O(1) \)

\( \implies (V_p^\parallel)^{-1/p} \simeq M_s \)
There are 3 basic mass scales in D-brane compactifications:

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**Scale of wrapped D(p+3)-branes:** \( M_p^\parallel = \frac{1}{(V_p^\parallel)^{1/p}} \)

\( M_s \) is a free parameter!
Low string scale scenario:

\( M_s \equiv M_{SM} \simeq 10^3 \text{ GeV} \)

\( M_s \) is the Standard Model (TeV) scale:

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).
There are several generic types of particles:
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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

\[
M_n^2 = M_s^2 \left( \sum_{k=1}^{n} \alpha^\mu_{-k} \alpha^\nu_k - 1 \right) = (n - 1) M_s^2, \quad (n = 1, \ldots, \infty)
\]
D-brane cycle Kaluza Klein excitations:

\[ M_{KK} = \frac{1}{(V_p^||)^{1/p}} \simeq M_s = \frac{M_{\text{Planck}}}{(V'_6)^{1/2}} \]

Open strings, depend on the details of the internal geometry, carry SM gauge quantum numbers.
D-brane cycle Kaluza Klein excitations:

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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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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 ?!

Low string scale compactification is a concrete realization of the large number of species scenario at 1 TeV!

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

In string perturbation theory production of:
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- Regge excitations of higher spin
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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.
Parton model cross sections of SM-fields:
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Disk amplitude among 4 external SM fields \((q, l, g, \gamma, Z^0, W^\pm)\):

\[
A(\Phi^1, \Phi^2, \Phi^3, \Phi^4) = \langle V_{\Phi^1}(z_1) \; V_{\Phi^2}(z_2) \; V_{\Phi^3}(z_3) \; V_{\Phi^4}(z_4) \rangle_{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.)**

⇒ new contact interactions:

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

\[
V_s(\alpha') = \frac{\Gamma(1 - s/M_{\text{string}}^2) \ \Gamma(1 - u/M_{\text{string}}^2)}{\Gamma(1 - t/M_{\text{string}}^2)} = 1 - \frac{\pi^2}{6} \ M_{\text{string}}^{-4} \ su - \zeta(3) M_{\text{string}}^{-6} \ stu + \cdots \to 1|_{\alpha' \to 0}
\]
Parton model cross sections of SM-fields:

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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.


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Five point scattering amplitudes (3 jet events):

Field theory factors:

\[ \mathcal{M}_{YM}^{(5)} = \frac{4g_{YM}^3 \langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \ldots \langle 51 \rangle} \]

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

3 gluons, 2 quarks:

\[ \mathcal{N}_{YM}^{(5)} = \frac{4g_{YM}^3 \langle 15 \rangle \langle 14 \rangle^3}{\langle 12 \rangle \langle 23 \rangle \ldots \langle 51 \rangle} \]

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(Stieberger, Taylor (2006))

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Five point scattering amplitudes (3 jet events):

5 gluons:

\[ \mathcal{A}(g_1^-, g_2^+, g_3^+, g_4^+, g_5^+) \alpha' \rightarrow 0 \rightarrow \mathcal{M}^{(5)}_{YM}, \quad (V^{(5)} = 1 + \zeta(2) \mathcal{O}(\alpha'^2), \quad P^{(5)} = \zeta(2) \mathcal{O}(\alpha'^2)) \]

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\[ A(g_1^-, g_2^+, g_3^+, g_4^+, g_5^+) \alpha' \to 0 \to M^{(5)}_{YM} , \quad (V^{(5)} = 1 + \zeta(2) O(\alpha'^2), \ P^{(5)} = \zeta(2) O(\alpha'^2)) \]

Field theory factors:

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(A. Stieberger, T. Taylor (2006))

(D. Lüst, O. Schlotterer, S. Stieberger, T. Taylor, work in progress).
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!

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

\( \Rightarrow \) dijet events

\[
|M(qg \rightarrow q\gamma(Z^0))|^2 = -\frac{1}{3} g_3^4 Q_A^2 \frac{s^2 + u^2}{s u t^2} (s V_s(\alpha') + u V_u(\alpha'))^2
\]

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

\(e^+e^- \rightarrow \gamma\gamma\)
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Only string Regge resonances are exchanged  \( \Rightarrow \)

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\[ \alpha' \rightarrow 0 : \text{agreement with SM}! \]

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

\[ |M(qg \rightarrow q\gamma(Z^0))|_{\alpha' \rightarrow 0}^2 = -\frac{1}{3} g_3^4 Q_A^2 \frac{s^2 + u^2}{sut^2} (s + u)^2 \]

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

\[ e^+ e^- \rightarrow \gamma\gamma \]
These stringy corrections can be seen in dijet events at LHC:

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

Widths can be computed in a model independent way!

\[ M_{\text{Regge}} = 2 \text{ TeV} \]


(Anchordoqui, Goldberg, Taylor, arXiv:0806.3420)
- KK modes are seen in scattering processes with more than 2 fermions.


Squared 4-quark amplitude with identical flavors:

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

Squared 4-quark amplitude with different flavors:

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

\[ F_{tu}^{bb} = 1 + \frac{g_b^2 t}{g_a^2 u} + \frac{g_b^2 t}{g_a^2} \frac{N_p \Delta}{u - M_{ab}^2} \]

\[ G_{tu}^{bc} = \tilde{G}_{tu}^{bc} = 1 \]

\[ M_{ab}^2 = (M_{KK}^{(b)})^2 + (M_{\text{wind.}}^{(a)})^2, \quad \Delta \sim e^{-M_{ab}^2/M_s^2} \]

\[ M_{ab} : \quad \text{KK of SU(2) branes and winding} \]
\[ \text{modes of SU(3) branes:} \quad M_{ab} = 0.7 M_s \]

\[ N_p : \quad \text{Degeneracy of KK-states; take} \quad N_p = 3 \]

\[ \Delta : \quad \text{Thickness of D-branes} \]
Dijet angular contribution by t-channel exchange:

CMS detector simulation:

Luminosity \(1\text{fb}^{-1}\) and \(10\text{fb}^{-1}\)
Conclusions
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- There exists many ISB models with SM like spectra without chiral exotics.
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- One can make some model independent predictions:
  (Independent of amount of (unbroken) supersymmetry!)
  String tree level, 4-point processes with 2 or 4 gluons
  observable at LHC ?? - $M_{\text{string}}$ ??
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Computations done at weak string coupling!
Black holes are heavier than Regge states: \( M_{\text{b.h.}} = \frac{M_{\text{string}}}{g_{\text{string}}} \)
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Question: do loop and non-perturbative corrections change tree level signatures? Onset of n.p. physics: $M_{b.h.}$
Conclusions

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   INTERESTING TIMES FOR STRING PHENOMENOLOGY ARE AHEAD OF US.

   THANK YOU!!

Question: do loop and non-perturbative corrections change tree level signatures? Onset of n.p. physics: $M_{b.h.}$