Strings at the LHC

Dieter Lüst, LMU (Arnold Sommerfeld Center) and MPI München
Suppose you are interested in string theory ....
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... you should be also interested in the question
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What is string theory good for?
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Where is the string scale $M_s$ ?
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(ii) Hadrons are strings: AdS/CFT
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D. Lüst, Strings at the LHC, KITP, 14th April 2010
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(J. Scherk, J. Schwarz, 1974)

$$M_s \simeq M_{\text{Planck}} \simeq 10^{19} \text{ GeV}$$

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(iii) Elementary particles are strings: Quantum gravity
     Actually this is not even necessary, but rather
     
     \[ M_s \simeq 1 \text{ TeV} - 10^{19} \text{ GeV} \]

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Low string scale compactifications

Suppose that the fundamental scale of gravity, i.e. the string scale is around 1 TeV:

\[ M_{\text{Grav.}} = M_s \simeq 1 \text{ TeV} \]

\[ M_{n}^2 = M_s^2 \left( \sum_{k=1}^{n} \alpha_{-k}^{\mu} \alpha_{k}^{\nu} - 1 \right) = (n - 1) M_s^2, \quad (n = 1, \ldots, \infty) \]
Then the following double string picture arises:

(i) Hadron spectrum at 1 GeV: String like objects (described by AdS/CFT)

(ii) Elementary (open) strings:

- Zero modes: quarks, gluons, etc
- Excited quarks, gluons etc at 1 TeV

\[ g^* \text{ spin } 0, 1, 2 \quad \& \quad q^* \text{ spin } 1/2, 3/2 \]

⇒ Two different kinds of Regge trajectories!
How does string theory meet collider physics?

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Collision of quarks and gluons:

- QCD is valid at low energies
- Corrections at higher energies from strings due to new colored objects:
  - New stringy physics at the collider in case $M_s = \mathcal{O}(\text{TeV})$
    - Discovery of universal heavy string excitations!
Outline

- Mass scales in D-brane compactifications

- Test of D-brane models at the LHC
  (The LHC string hunter’s companion)

(D. Lüst, S. Stieberger, T. Taylor, arXiv:0807.3333;
II) Mass scales in D-brane compactifications:
Recall basic set-up of type IIA/B orientifolds:
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Recall basic set-up of type IIA/B orientifolds:

- Compactification on a 6-dimensional space $M_6$

$$M_{10} = R^{3,1} \otimes M_6$$

- Wrapped (3+p)-dimensional D-branes
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Large landscape of consistent D-brane compactifications!

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   (a) baryonic U(2)
   (d) leptonic U(1)_L

(ii) Consider D-brane compactifications which allow for low string scale (solve hierarchy problem without SUSY)

⇒ Low scale for quantum gravity & large extra dimensions.
3 basic assumptions:

(i) Consider D-brane compactifications which realize the SM, i.e. contain the SM D-brane quiver:

(b) left \( W^\pm \)

(c) right \( g, \pi, \overline{d} \)

(a) baryonic \( U(2) \)

(d) leptonic \( U(1)_R \)

(ii) Consider D-brane compactifications which allow for low string scale (solve hierarchy problem without SUSY):

\( \Rightarrow \) Low scale for quantum gravity & large extra dimensions.

(iii) Perturbation theory is valid, i.e. small string coupling.
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(Discussion of warped case: Perelstein, Spray, arXiv:0907.3496)
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⇒ Universal predictions that are true for all points in the landscape, i.e. independent from any details of the compact space!

D. Lüst, Strings at the LHC, KITP, 14th April 2010
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**String scale:**

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Scale of wrapped D(p+3)-branes (e.g. II\(B\): \(p=0,4\)), (II\(A\): \(p=3\)):

\[ M_p^\parallel = \frac{1}{(V_p^\parallel)^{1/p}} \] \quad (3)

\[ M_6^{p-6} = \frac{1}{(V_6^{p-6})^{1/(6-p)}} \] \quad (3')

\[ V_6 = V_p^\parallel V_6^{p-6} \]
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**Strength of 4D gauge interactions:**

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

\[\implies (V_p^\parallel)^{-1/p} \simeq M_s\]
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\[\implies (V^\parallel_p)^{-1/p} \simeq M_s\]

(A) and (B): leave one free parameter.

\(M_s\) is a free parameter in D-brane compactifications!
There are 4 natural scenarios for the string scale:

(o) Planck scale scenario:

\[ M_s \] is the gravitational 4D Planck scale

\[ M_s \equiv M_{\text{Planck}} \sim 10^{19} \text{ GeV} \]
(i) GUT scale scenario:

\[ M_s \equiv M_{GUT} \simeq 10^{16} \text{ GeV} \]

\( M_s \) is the 4D scale of gauge coupling unification.
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Recent GUT string model building in F-theory and IIB orientifolds:

- D7-branes wrapped on del Pezzo surfaces
- GUT gauge group is broken by \( U(1)_Y \) flux

(Beasley, Heckman, Marsano, Saulina, Schafer-Nameki, Vafa; Donagi, Wijnholt; Blumenhagen, Braun, Grimm, Weigand)
(ii) SUSY breaking scenario:

\( M_s \) is the intermediate 4D scale of supersymmetry breaking

\[
M_s \equiv M_{SUSY} \simeq 10^{11} \text{ GeV}
\]

Gravity mediation:

\[
M_{SUSY} \sim \sqrt{M_{SM} M_{\text{Planck}}}
\]

(e.g. Domain wall SUSY breaking by fluxes)

(iii) Low string scale scenario:

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

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

(Effective scale of gravity is high (i.e. gravity is weak), since the gravitons can propagate into the large 6-dim. bulk space!)
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Dimensionless volumes in string units, corresponding to the four scenarios:

\[ V_6' = V_6 M_s^6 = \frac{M_{\text{Planck}}^2}{M_s^2} = 1, 10^6, 10^{16}, 10^{32} \]
There are 4 generic types of particles:
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(i) Stringy Regge excitations:

\[ M_{\text{Regge}} = \sqrt{n} M_s = \sqrt{\frac{n}{V_6'}} M_{\text{Planck}}, \quad (n = 1, \ldots, \infty) \]

Open string excitations: completely universal (model independent), carry SM gauge quantum numbers: higher spin excitations of \( g, W, Z, \gamma, q, l \)
(ii) D-brane cycle Kaluza Klein excitations:

\[ M_{KK}^\parallel = \frac{m}{(V_p^\parallel)^{1/p}} \simeq m M_s = m \frac{M_{\text{Planck}}}{(V_6')^{1/2}} \quad (m = 1, \ldots, \infty) \]

Open strings, depend on the details of the internal geometry, carry SM gauge quantum numbers

Internal momenta excitations of \( g, W, Z, \gamma, q, l \)
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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 ?!
(iii) Overall volume modulus:

\[ M_T = \frac{M_{\text{Planck}}}{(V_6')^{3/2}} = 10^{19}, 10^{10}, 10^{-5}, 10^{-29} \text{ GeV} \]

Closed string, model independent, neutral under the SM, interacts only gravitationally

Problem: the very light mass causes a fifth force.

Would rule out TeV string scale!
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But one expects a mass shift by radiative corrections:

\[ \Delta M_T \sim \frac{\langle T_{\mu}^{\mu} T_{\mu}^{\mu} \rangle}{M_{\text{Planck}}^2} \sim \frac{M_s^4}{M_{\text{Planck}}^2} \sim 10^{-13} \text{ GeV} \]

(G. Dvali, D. Lüst, arXiv:0912.3167)
(iv) Mini black holes (string balls):

These are non-perturbative states, associated to the higher dimensional gravity scale:

\[ M_{b.h.} = \frac{M_s}{g_s^2} \gg M_s \quad \text{if} \quad g_s < 1 \]

Weakly coupled string theory: gravity effects occur much above \( M_s \)!

Regge excitations: \( M_{\text{Regge}} \sim M_s \sqrt{n} \)

If \( g_s = 0.1 \) \( \Rightarrow \)

\[ n = \frac{1}{g_s^4} \sim 10^4 \quad \text{string states before one reaches black hole!} \]
Low string scale models:

⇒ General framework: Large species models:

\[ M_{\text{Planck}}^2 = N M_{\text{Grav}}^2 \quad (N: \# \text{ of species}) \]

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

This relation arises from natural bounds on black hole decays.

\( M_{\text{Grav}} \) can be seen as the fundamental scale of gravity, which is diluted by the presence on the \( N \) particle species.
Is there a stringy realization of the large N species scenario?

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D. Lüst, Strings at the LHC, KITP, 14th April 2010
(i) Large volume compactifications

(Antoniadis, Arkani-Hamed, Dimopoulos, Dvali (1998))

\[ N = V'_6 = \# \text{ of KK states} = 10^{32} \]

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)

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 even exist an alternative to large volume compactifications:

Super weakly coupled strings:
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Super weakly coupled strings:

(ii) String scale compactification: \( V'_{6} = 1 \)

(G. Dvali, D. Lüst, arXiv:0912.3167)

\( N \) is the effective number of string states that contribute to the black hole bound:

\[
N = \frac{1}{g_s^2} = 10^{32}
\]
There even exist an alternative to large volume compactifications:

Super weakly coupled strings:

(ii) String scale compactification: \( V'_{6} = 1 \)

\[ N = \frac{1}{g_s^2} = 10^{32} \]

(i) and (ii) are in agreement with the known relation:

\[ M_{\text{Planck}}^2 = \frac{1}{g_s^2} V'_6 M_s^2 \]
III) Test of D-brane models at the LHC:

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

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

First resonances: $g^*$ spin 0,1,2 & $q^*$ spin 1/2, 3/2
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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 (mathematical) properties:

• 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 relations between quark and gluon amplitudes!

  (ii) They contain stringy corrections:
• 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.

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

⇒ Information about the internal geometry.
Disk amplitudes among external SM fields \((q, l, g, \gamma, Z^0, W^\pm)\):

\[(1) \quad n=4: \quad \mathcal{A}(\Phi^1, \Phi^2, \Phi^3, \Phi^4) = \langle V_{\Phi^1}(z_1) V_{\Phi^2}(z_2) V_{\Phi^3}(z_3) V_{\Phi^4}(z_4) \rangle_{\text{disk}}\]
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- **Exchange of SM fields**
- **Exchange of string Regge resonances (Veneziano like ampl.)**

\( \Rightarrow \) new contact interactions:

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

\[
V_s(\alpha') = \frac{\Gamma(1-s/M_{\text{string}}^2) \, \Gamma(1-u/M_{\text{string}}^2)}{\Gamma(1-t/M_{\text{string}}^2)} = 1 - \frac{\pi^2}{6} M_{\text{string}}^{-4} \, su - \zeta(3) M_{\text{string}}^{-6} \, stu + \ldots \rightarrow 1 |_{\alpha' \rightarrow 0}
\]

D. Lüst, Strings at the LHC, KITP, 14th April 2010
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\]

\[
V_s(\alpha') = \frac{\Gamma(1 - s/M_{\text{string}}^2)\Gamma(1 - u/M_{\text{string}}^2)}{\Gamma(1 - t/M_{\text{string}}^2)} = 1 - \frac{\pi^2}{6} M_{\text{string}}^{-4} su - \zeta(3) M_{\text{string}}^{-6} stu + \ldots \rightarrow 1 |_{\alpha'\rightarrow 0}
\]

- Exchange of KK and winding modes (model dependent)

D. Lüst, Strings at the LHC, KITP, 14th April 2010
4 gauge boson amplitudes:

Disk amplitude:
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Only string Regge resonances are exchanged  ⇒
These amplitudes are completely model independent!
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Examples:
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Examples:

\[ |\mathcal{M}(gg \to gg)|^2 = g_3^4 \left( \frac{1}{s^2} + \frac{1}{t^2} + \frac{1}{u^2} \right) \left[ \frac{9}{4} s^2 V_s^2(\alpha') - \frac{1}{3} (s V_s(\alpha'))^2 + (s \leftrightarrow t) + (s \leftrightarrow u) \right] \]

⇒ dijet events

\[ |\mathcal{M}(gg \to g\gamma(Z^0))|^2 = g_3^4 \frac{5}{6} Q_A^2 \left( \frac{1}{s^2} + \frac{1}{t^2} + \frac{1}{u^2} \right) (s V_s(\alpha') + t V_t(\alpha') + u V_u(\alpha'))^2 \]

Observable at LHC for \( M_{\text{string}} = 3 \text{ TeV} \)

D. Lüst, Strings at the LHC, KITP, 14th April 2010

(Stieberger, Taylor)

(Anchordoqui, Goldberg, Nawata, Taylor, arXiv:0712.0386)
4 gauge boson amplitudes:

Only string Regge resonances are exchanged ⇒
These amplitudes are completely model independent!

Examples:

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

\[
|\mathcal{M}(gg \rightarrow gg)|^{2}_{\alpha' \rightarrow 0} \rightarrow \left( \frac{1}{s^2} + \frac{1}{t^2} + \frac{1}{u^2} \right) \frac{9}{4} \left( s^2 + t^2 + u^2 \right)
\]

\[
|\mathcal{M}(gg \rightarrow \gamma(Z^0))|^{2}_{\alpha' \rightarrow 0} \rightarrow 0
\]
2 gauge boson - two fermion amplitude:

Only string Regge resonances are exchanged $\Rightarrow$

These amplitudes are completely model independent!

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

$\Rightarrow$ dijet events

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

Note: Cullen, Perelstein, Peskin (2000) considered: $e^+ e^- \rightarrow \gamma \gamma$
2 gauge boson - two fermion amplitude:

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

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\[
|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]
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These stringy corrections can be seen in dijet events at LHC:

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

Widths can be computed in a model independent way!

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

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4 fermion amplitudes:

Exchange of Regge, KK and winding resonances.

These amplitudes are more model dependent and test the internal CY geometry.

Constrained by FCNC's  

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

depend on internal geometry

4 fermion amplitudes:

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\( \alpha' \to 0 : \) agreement with SM!

\[
|M(qq \to qq)|_{\alpha' \to 0}^2 = \frac{4}{9} \left[ \frac{s^2 + u^2}{t^2} \right] + \frac{4}{9} \left[ \frac{s^2 + t^2}{u^2} \right] - \frac{8}{27} \frac{s^2}{t u}
\]

Dominant contribution:

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

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

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

\( M_{ab} \): KK of SU(2) branes and winding modes of SU(3) branes:

\[ M_{ab} = 0.7 M_s \]

\( N_p \): Degeneracy of KK-states; take \( N_p = 3 \)

\( \Delta \): Thickness of D-branes
Dijet angular contribution by t-channel exchange:

CMS detector simulation:

Luminosity $1\text{fb}^{-1}$  $10\text{fb}^{-1}$

D. Lüst, Strings at the LHC, KITP, 14th April 2010
(2) Five point scattering amplitudes (3 jet events):


They depend on two characteristic functions:

(i) 5 gluons:

\[ \mathcal{A}(g_1^-, g_2^-, g_3^+, g_4^+, g_5^+) = (V^{(5)}(\alpha', k_i) z_2 - 2i\epsilon(1, 2, 3, 4) P^{(5)}(\alpha', k_i)) \times \mathcal{M}_YM^{(5)} \]

(Stieberger, Taylor (2006))

(ii) 3 gluons, 2 quarks:

\[ \mathcal{A}(g_1^-, g_2^+, g_3^+, q_4^-, \overline{q}_5^+) = (V^{(5)}(\alpha', k_i) - 2i\epsilon(1, 2, 3, 4) P^{(5)}(\alpha', k_i)) \times \mathcal{N}_YM^{(5)} \]

Field theory factors:

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

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

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\[\mathcal{A}(g_1^-, g_2^-, g_3^+, g_4^+, g_5^+)_{\alpha'\to 0} \to \mathcal{M}^{(5)}_{YM}, \quad (V_{z_2}^{(5)} = 1 + \zeta(2)\mathcal{O}(\alpha'^2), \quad P^{(5)} = \zeta(2)\mathcal{O}(\alpha'^2))\]

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\[\mathcal{A}(g_1^-, g_2^+, g_3^+, q_4^-, \bar{q}_5^+)_{\alpha'\to 0} \to \mathcal{N}^{(5)}_{YM}\]
The two kinds of amplitudes are universal: the same Regge states are exchanged:

\[ | k; n \rangle | k'; n' \rangle \]
(iii) 1 gluon, 4 quarks:

This amplitude has a similar structure as the 4 quark amplitude: exchange of Regge and KK modes.

Factorization on the 4 quark amplitude:

Factorization on the 2 quark - 2 gluon amplitude:
Conclusions (for low string scale models):
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- One can make some model independent predictions:

  True for a large class of models in the string landscape!
  (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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  String cross sections for direct production of heavy modes.

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- Can one get (mirage) gauge coupling unification?
- What is the cosmology of low string scale models?
If nature choses weakly coupled strings with a string scale at a few TeV, LHC should find them!
Thank you !