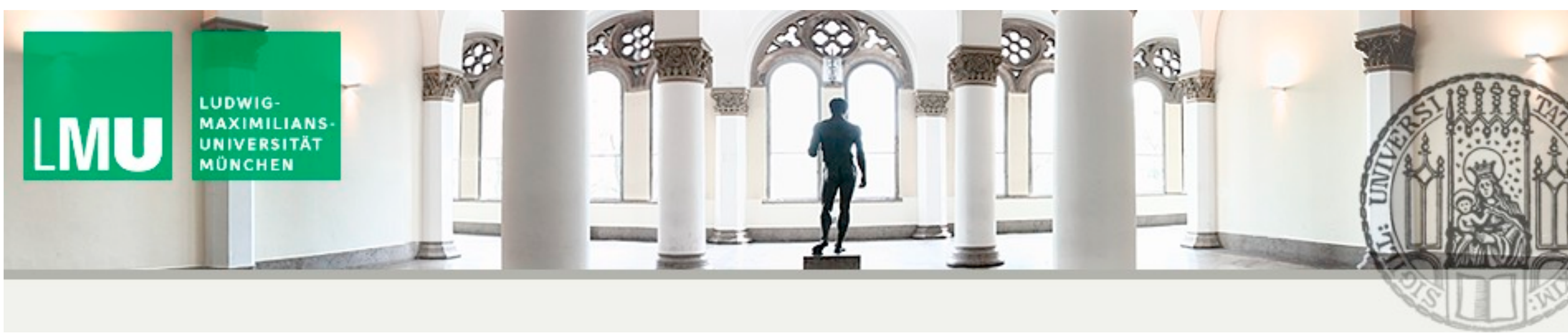
The string landscape: viewing into it and bypassing around it at the LHC

Dieter Lüst, LMU (Arnold Sommerfeld Center) and MPI München



Warsaw, StringPheno 2009, 15. June 2009

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

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- Can we view into the landscape?

  $\Rightarrow$ information about other vacua?

- Can we by-pass the landscape?

  $\Rightarrow$ look for green (promising) spots

  - model independent predictions?

Outline

- Viewing into the landsape

- By-passing the landscape:
  Stringy signatures at LHC

(The LHC string hunter's companion)

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☛ Alternative to low energy supersymmetry

☛ Realization large extra dimension scenario (ADD)

☛ String perturbation theory valid at 1-10 TeV

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b) Transitions between vacua due to domain walls:

$\Rightarrow$ information on life times of particle of some vacua

a) Bounds from black hole decays:

(G. Dvali, arXiv:0706.2050; G. Dvali, D. Lüst, arXiv:0801.1287)

Consider a theory with N species of particles with mass M:

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

M: scale of new physics

(A quantum black hole can emit at most N_{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: $M = M(\phi)$

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

$\Rightarrow$ Implications for inflation (gravitational waves)!

E.g: $N = 10^{32} \quad \Longrightarrow \quad M < 10^{-16} M_{Planck} \simeq 1\, TeV$

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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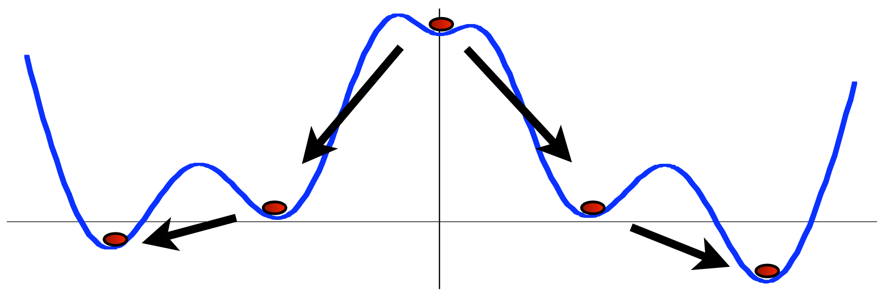
Is there a stringy realization of the large N species scenario?

b) Transitions between different vacua:



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

Described by generalized geometry and flow equations:

(Behnrdt, Cvetic;
Ceresole, Dall'Agata, Giryavets, Kallosh, Linde, hep-th/0605266;
Kounnas, Lüst, Petropoulos, Tsimpis, arXiv:0707.4270;
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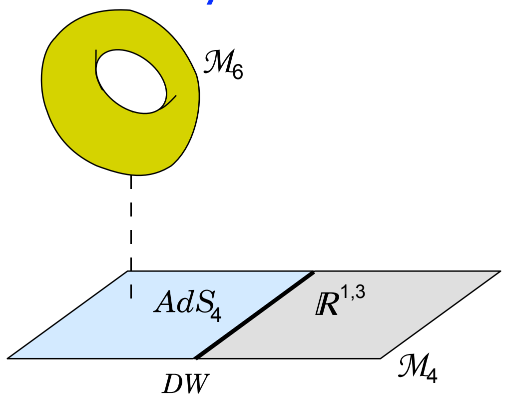
E.g. from M4 to AdS4:



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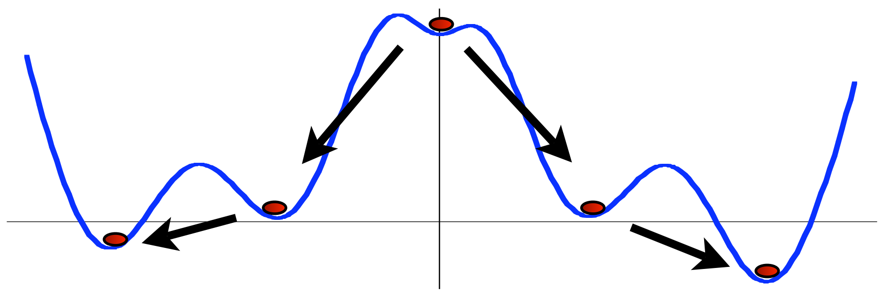

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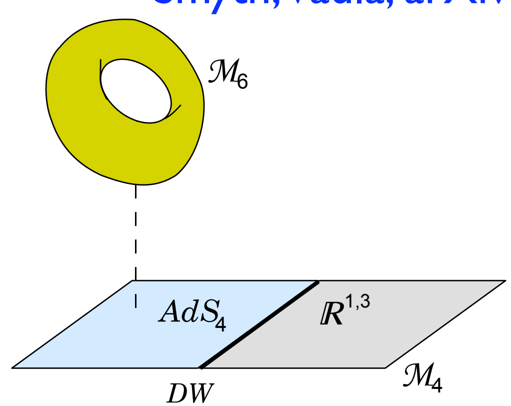

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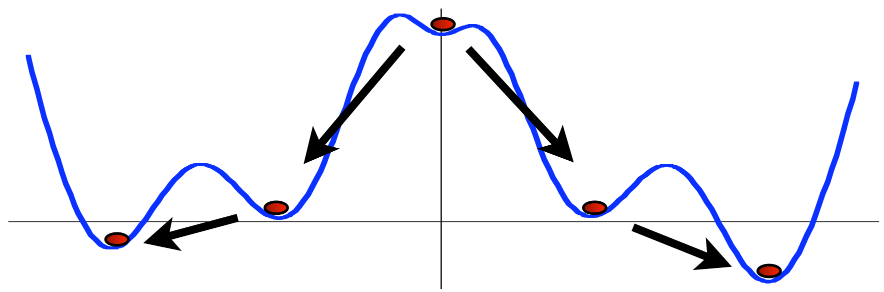

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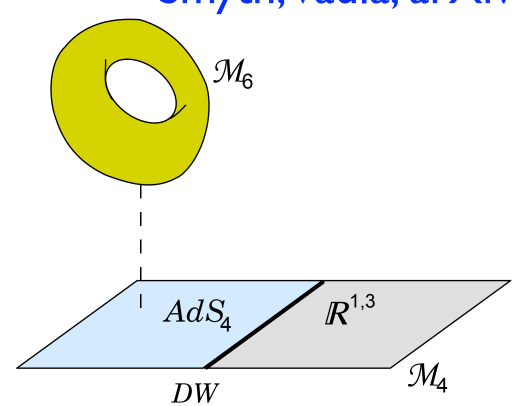

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(D. Lüst, S. Stieberger, T. Taylor, arXiv:0807.3333;
L. Anchordoqui, H. Goldberg, D. Lüst, S. Nawata, S. Stieberger, T. Taylor, arXiv:0808.0497 [hep-ph]; arXiv:0904.3547 [hep-ph]
D. Härtl, D. Lüst, O. Schlotterer, S. Stieberger, T. Taylor, to appear)

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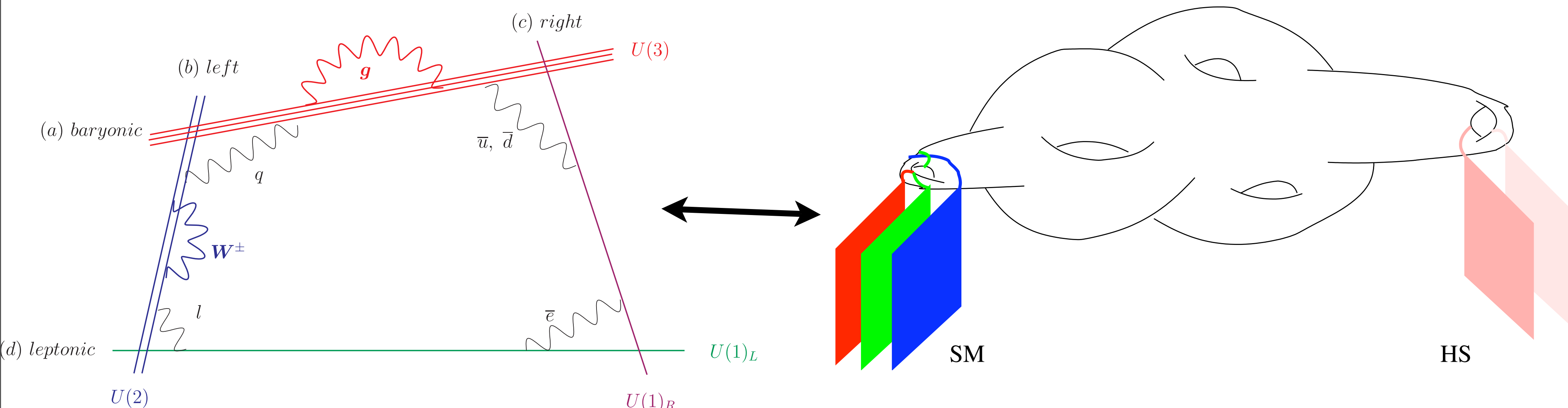
(Review: Blumenhagen, Körs, Lüst, Stieberger, hep-th/0610327)

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

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



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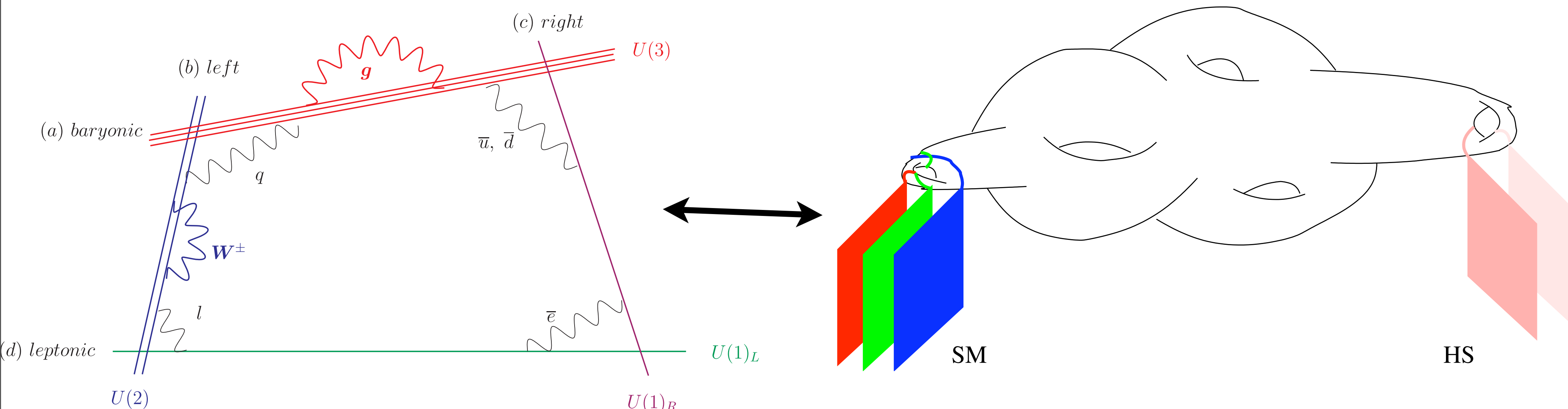

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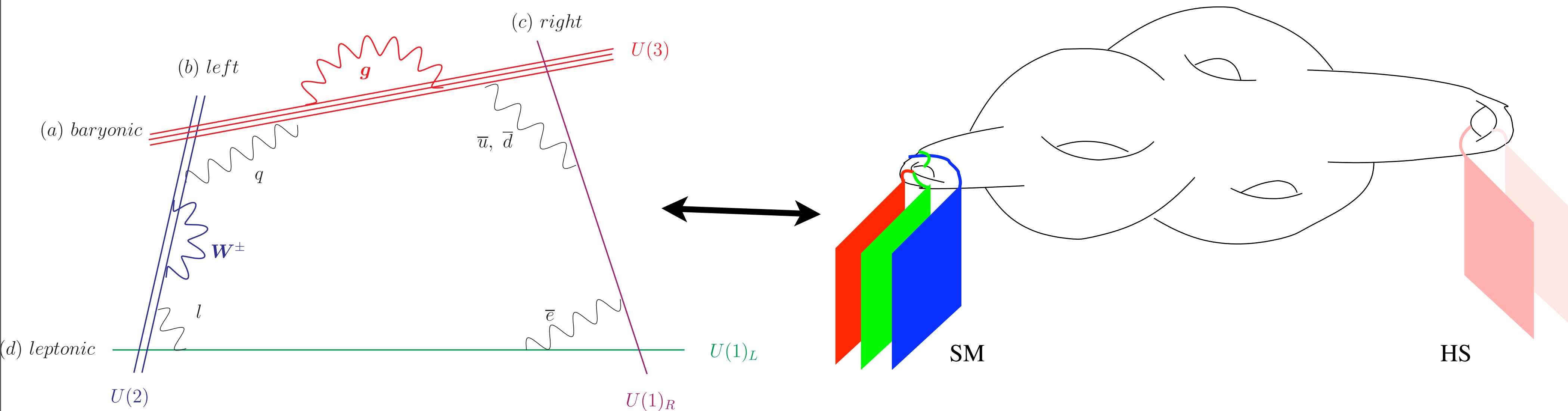

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So far: n=4,5; g=0

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Strength of 4D gravitational interactions:

$$(A): \quad M_{\mathrm{Planck}}^2 \simeq M_s^8 V_6 \simeq 10^{19}\ \mathrm{GeV}$$

Strength of 4D gauge interactions:

$$(B): \quad g_{Dp}^{-2} \simeq M_s^p V_p^{\|} \simeq \mathcal{O}(1)$$

$$\Longrightarrow \quad (V_p^{\|})^{-1/p} \simeq M_s$$

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M_s is a free parameter!

Low string scale scenario:

(Antoniadis, Arkani-Hamed, Dimopoulos, Dvali)

M_s is the Standard Model (TeV) scale:

$$\mathrm{M}_s \equiv M_{SM} \simeq 10^3 \ \mathrm{GeV} \,, \quad M_s^6 V_6 = 10^{32}$$

Stringy realization by Swiss cheese Calabi-Yau's:

(Abdussalam, Allanach, Balasubramanian, Berglund, Cicoli, Conlon, Kom, Quevedo, Suruliz;
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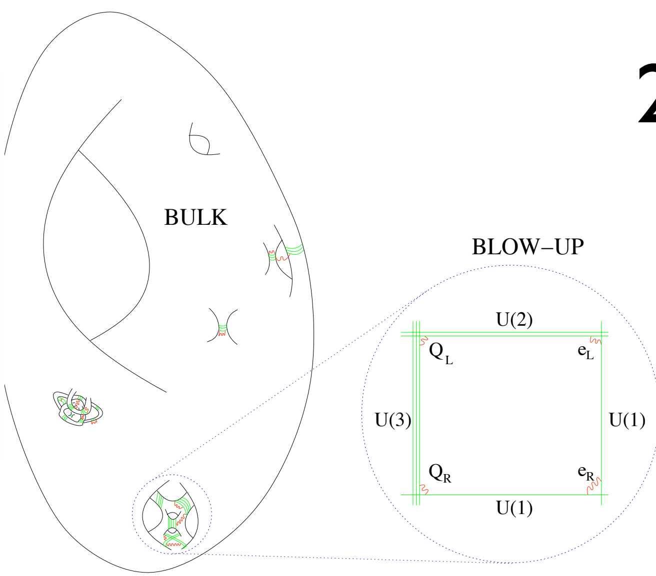

2 requirements:

- 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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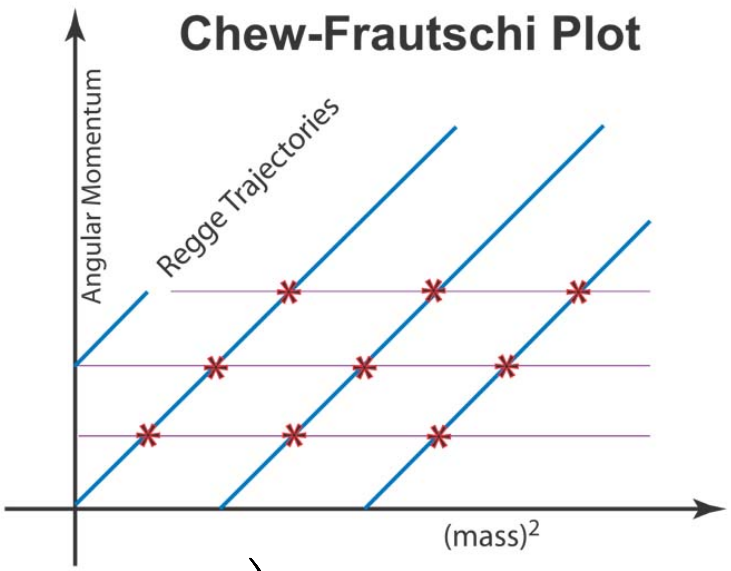
Stringy Regge excitations:

$$\mathrm{M}_{\mathrm{Regge}} = M_s = \frac{M_{\mathrm{Planck}}}{\sqrt{V_6'}}$$

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



$$M_n^2 = M_s^2 \left(\sum_{k=1}^{n} \alpha_{-k}^{\mu} \alpha_k^{\nu} - 1 \right) = (n-1)\, M_s^2 \,, \quad (n = 1, \ldots, \infty)$$

D-brane cycle Kaluza Klein excitations:

$$M_{KK}^{\|} = \frac{1}{(V_p^{\|})^{1/p}} \simeq M_s = \frac{M_{\rm Planck}}{(V_6')^{1/2}}$$

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

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

10^{32} KK (bulk) gravitons at the string scale.

Test of D-brane models at the LHC:

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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 $(q, l, g, \gamma, Z^0, W^{\pm})$:

$$\mathcal{A}(\Phi^1, \Phi^2, \Phi^3, \Phi^4) = < V_{\Phi^1}(z_1)\ V_{\Phi^2}(z_2)\ V_{\Phi^3}(z_3)\ V_{\Phi^4}(z_4) >_{disk}$$

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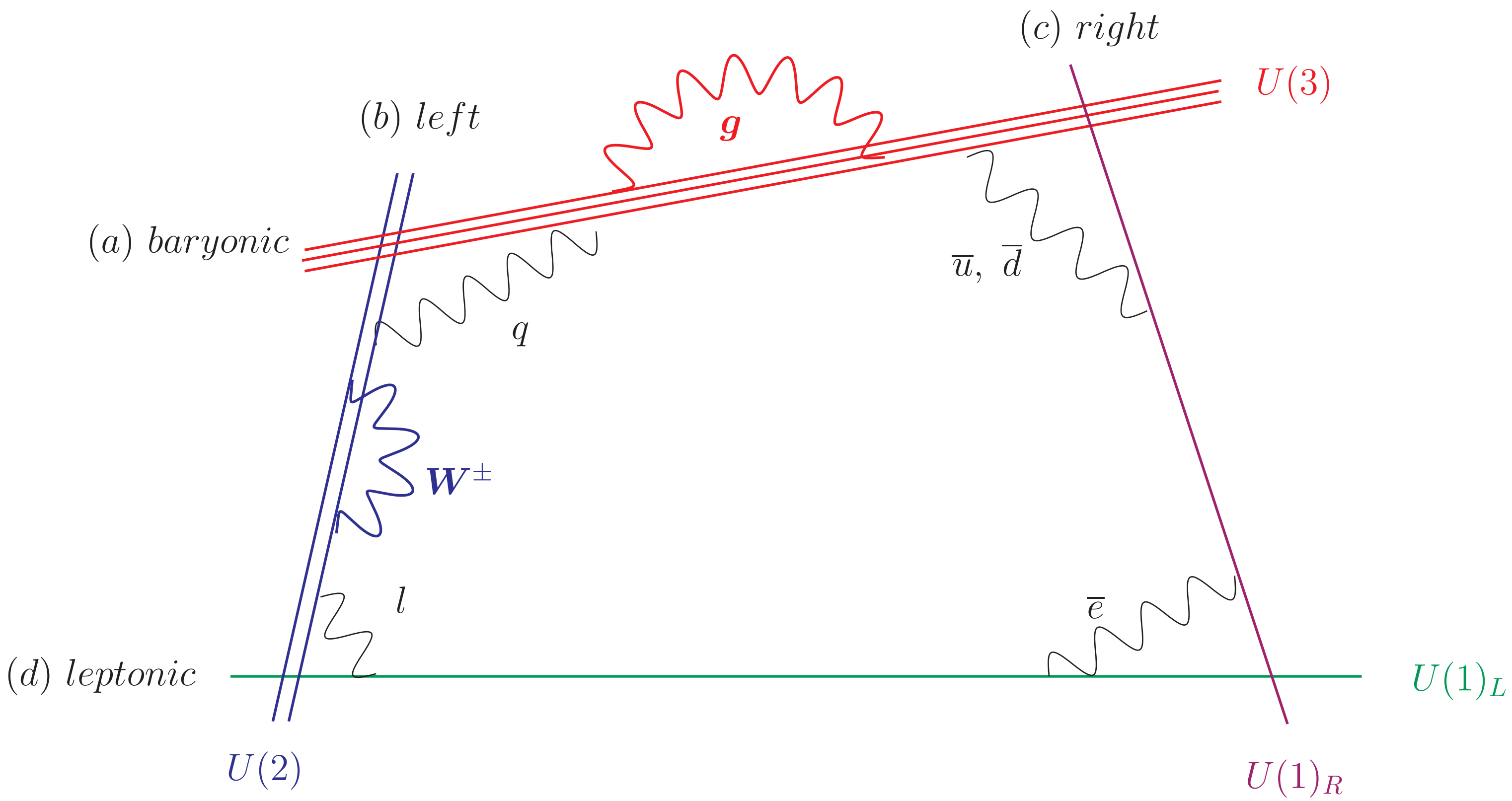

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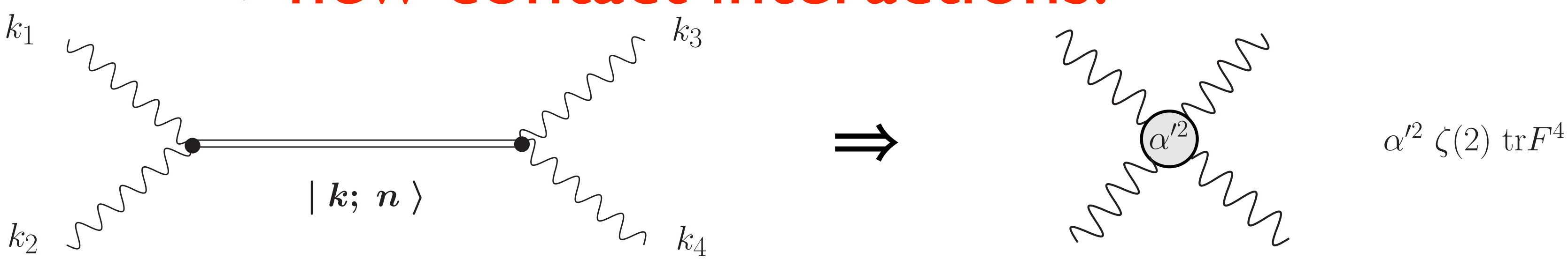
- Exchange of SM fields
- Exchange of string Regge resonances (Veneziano like ampl.)

$\Rightarrow$ new contact interactions:



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

$$V_s(\alpha') = \frac{\Gamma(1 - s/M^2_{\text{string}})\Gamma(1 - u/M^2_{\text{string}})}{\Gamma(1 - t/M^2_{\text{string}})} = 1 - \frac{\pi^2}{6} M^{-4}_{\text{string}} su - \zeta(3) M^{-6}_{\text{string}} stu + \cdots \to 1|_{\alpha' \to 0}$$

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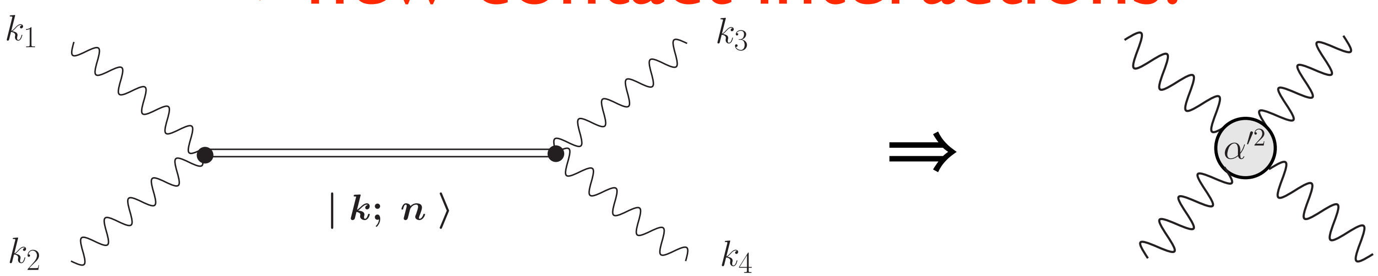

$\alpha'^2\ \zeta(2)\ \mathrm{tr}F^4$

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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.

$\Rightarrow$ Information about the string Regge spectrum.

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

$\Rightarrow$ Information about the internal geometry.

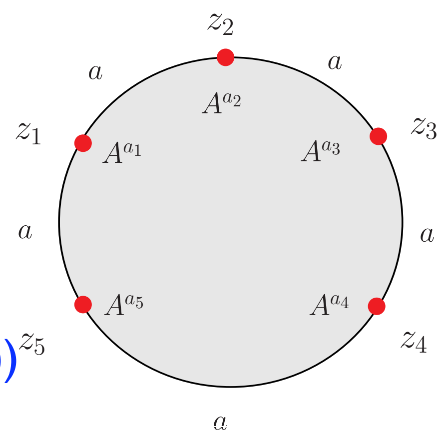
KK modes are exchanged in t- and u-channel processes and exhibit an interesting angular distribution.

(L. Anchordoqui, H. Goldberg, D. Lüst, S. Nawata, S. Stieberger, T. Taylor, arXiv:0904.3547 [hep-ph])

Five point scattering amplitudes (3 jet events):

5 gluons:

(Stieberger, Taylor (2006))



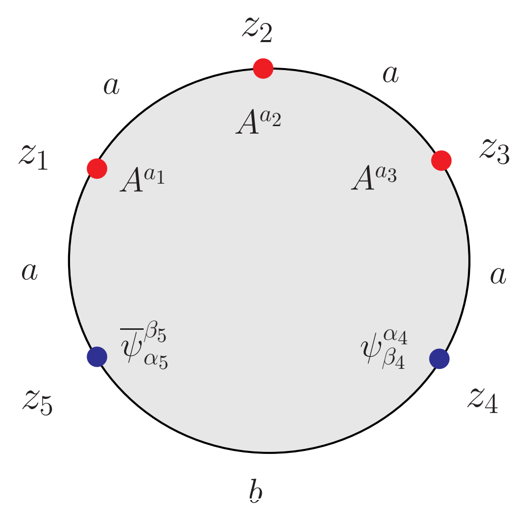
Field theory factors:

$$\mathcal{M}^{(5)}_{\mathrm{YM}} = \frac{4g^3_{\mathrm{YM}}\langle 12\rangle^4}{\langle 12\rangle\langle 23\rangle\ldots\langle 51\rangle}$$

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

3 gluons, 2 quarks:

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



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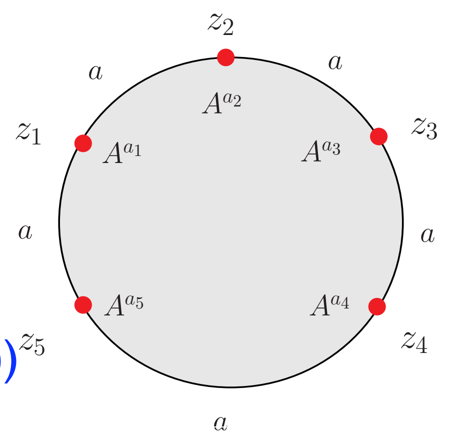

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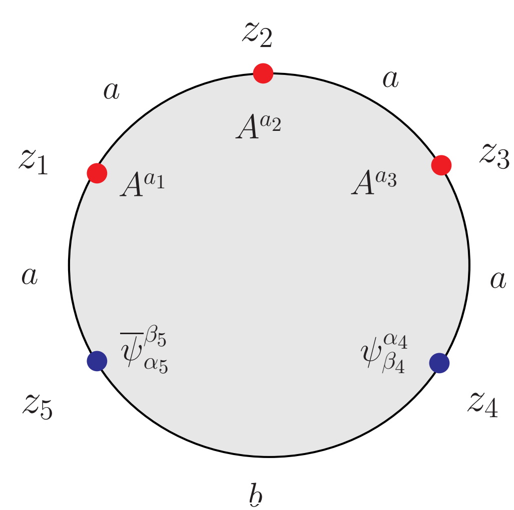

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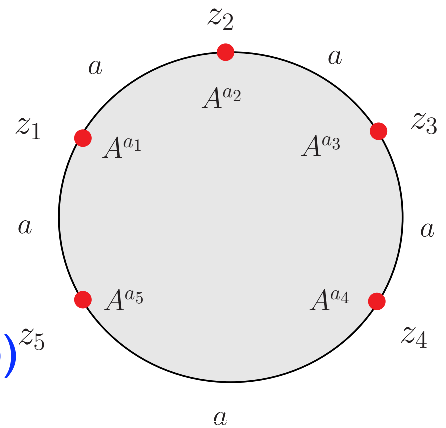

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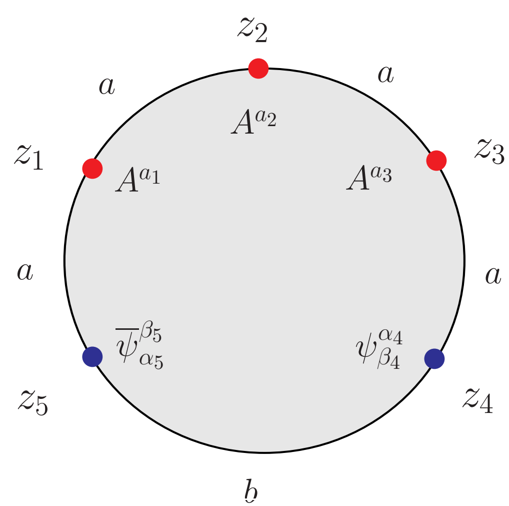

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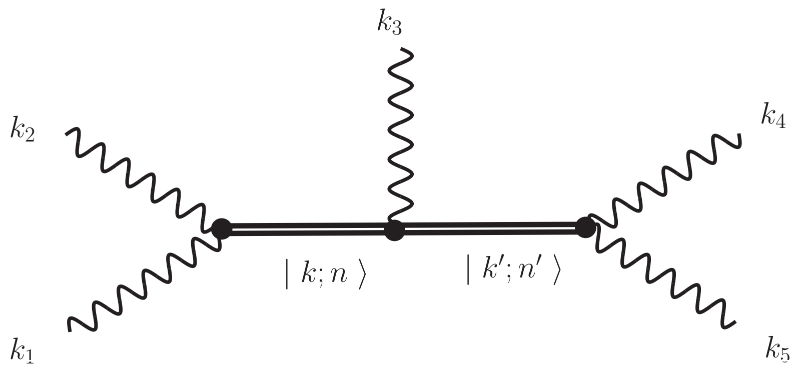
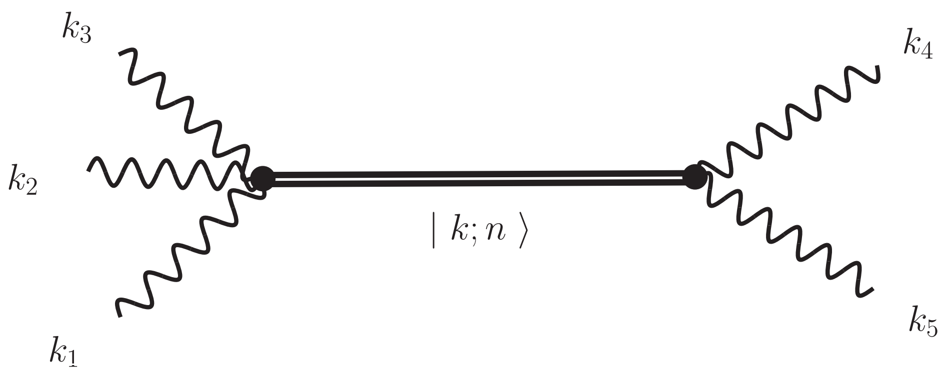
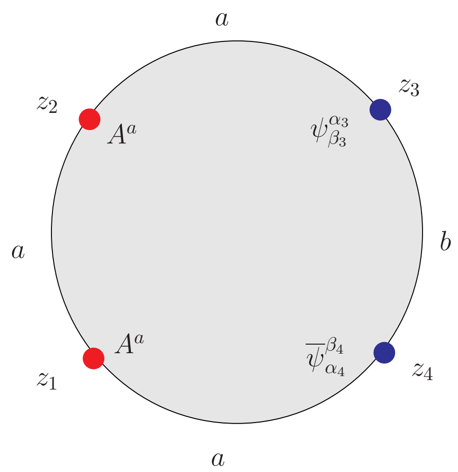
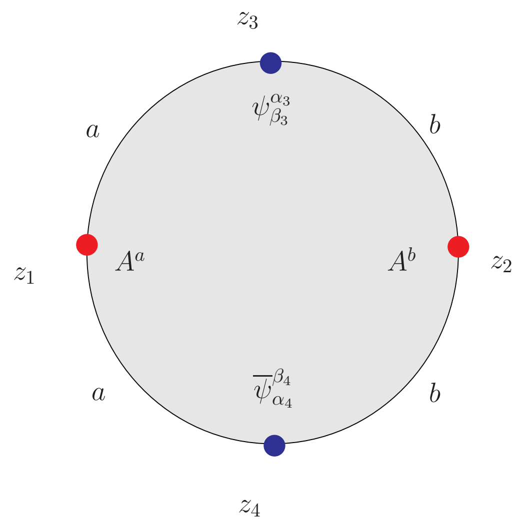
The two kinds of amplitudes are universal: the same Regge states are exchanged:





2 gauge boson - two fermion amplitude:





Note: Cullen, Perelstein, Peskin (2000) considered: $e^+e^- \to \gamma\gamma$

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

$$|\mathcal{M}(qg \to q\gamma(Z^0))|^2 = -\frac{1}{3} g_3^4 Q_A^2 \frac{s^2+u^2}{sut^2}(sV_s(\alpha') + uV_u(\alpha'))^2$$

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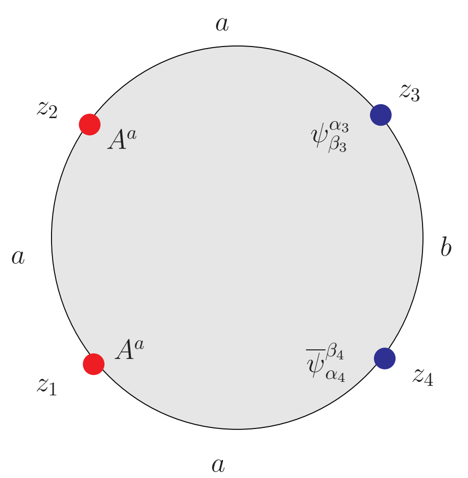

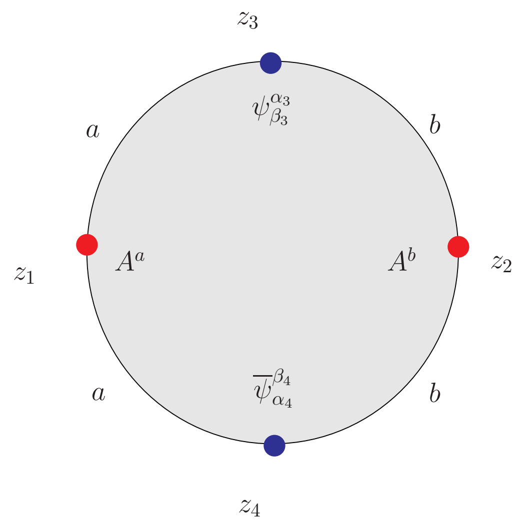

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$\alpha' \to 0$: agreement with SM !

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

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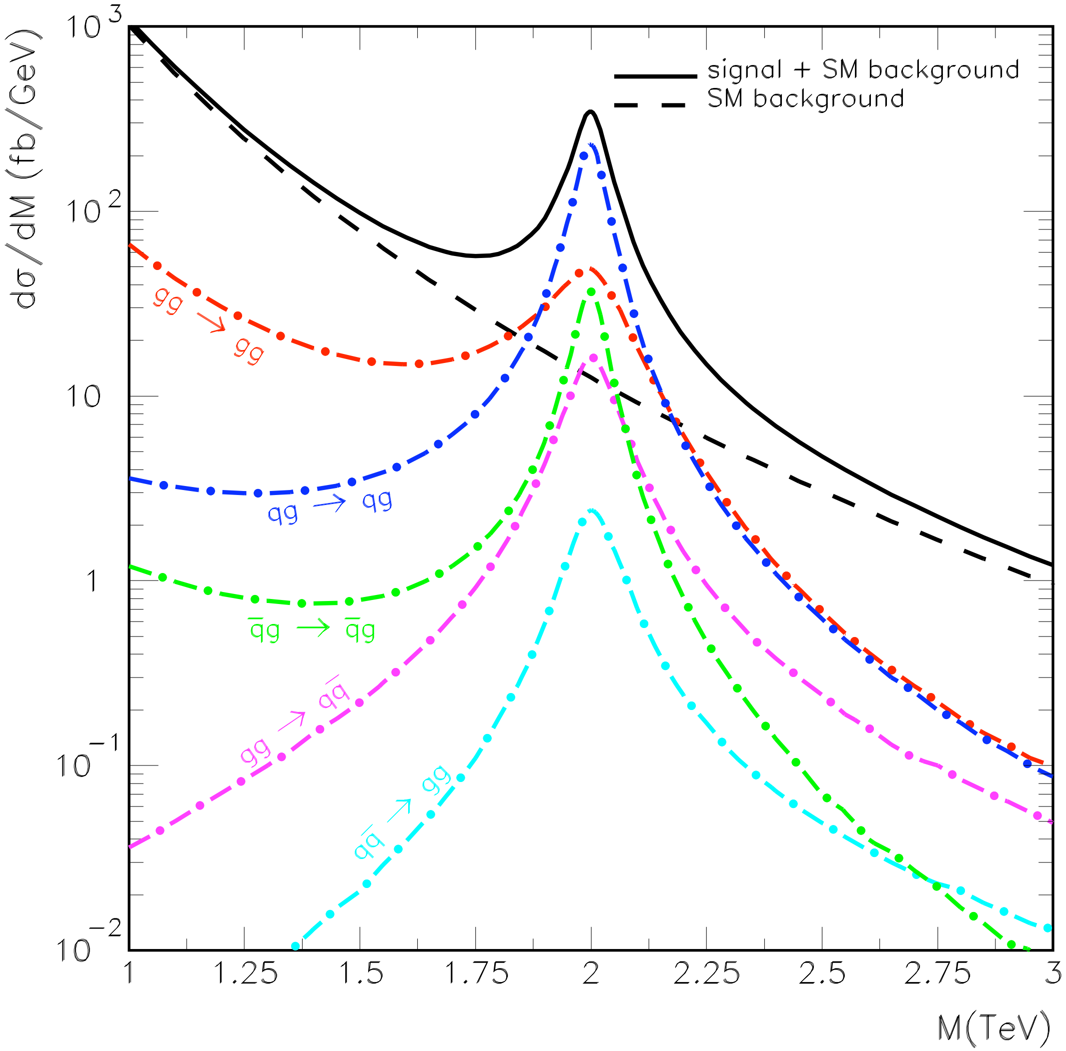
These stringy corrections can be seen in dijet events at LHC:

(Anchordoqui, Goldberg, Lüst, Nawata, Stieberger, Taylor, arXiv:0808.0497[hep-ph])



$$M_{\text{Regge}} = 2\ \text{TeV}$$

$$\Gamma_{\text{Regge}} = 15 - 150\ \text{GeV}$$

Widths can be computed in a model independent way !

(Anchordoqui, Goldberg, Taylor, arXiv:0806.3420)

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

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

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(L. Anchordoqui, H. Goldberg, D. Lüst, S. Nawata, S. Stieberger, T. Taylor, arXiv:0904.3547 [hep-ph])

Squared 4-quark amplitude with identical flavors:

$$|\mathcal{A}(qq \to qq)|^2 = \frac{2}{9}\frac{1}{t^2}\Big[\big(sF^{bb}_{tu}(\alpha')\big)^2 + \big(sF^{cc}_{tu}(\alpha')\big)^2 + \big(uG^{bc}_{ts}(\alpha')\big)^2 + \big(uG^{cb}_{ts}(\alpha')\big)^2\Big] + \frac{2}{9}\frac{1}{u^2}\Big[\big(sF^{bb}_{ut}(\alpha')\big)^2 + \big(sF^{cc}_{ut}(\alpha')\big)^2 + \big(tG^{bc}_{us}(\alpha')\big)^2 + \big(tG^{cb}_{us}(\alpha')\big)^2\Big] - \frac{4}{27}\frac{s^2}{tu}F^{bb}_{tu}(\alpha')F^{bb}_{ut}(\alpha') + F^{cc}_{tu}(\alpha')F^{cc}_{ut}(\alpha'))$$

Squared 4-quark amplitude with different flavors:

$$|\mathcal{A}(qq' \to qq')|^2 = \frac{2}{9}\frac{1}{t^2}\Big[\big(sF^{bb}_{tu}(\alpha')\big)^2 + \big(s\tilde{G}^{cc'}_{tu}(\alpha')\big)^2 + \big(uG^{bc}_{ts}(\alpha')\big)^2 + \big(uG^{bc'}_{ts}(\alpha')\big)^2\Big]$$

Dominant contribution:

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

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

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

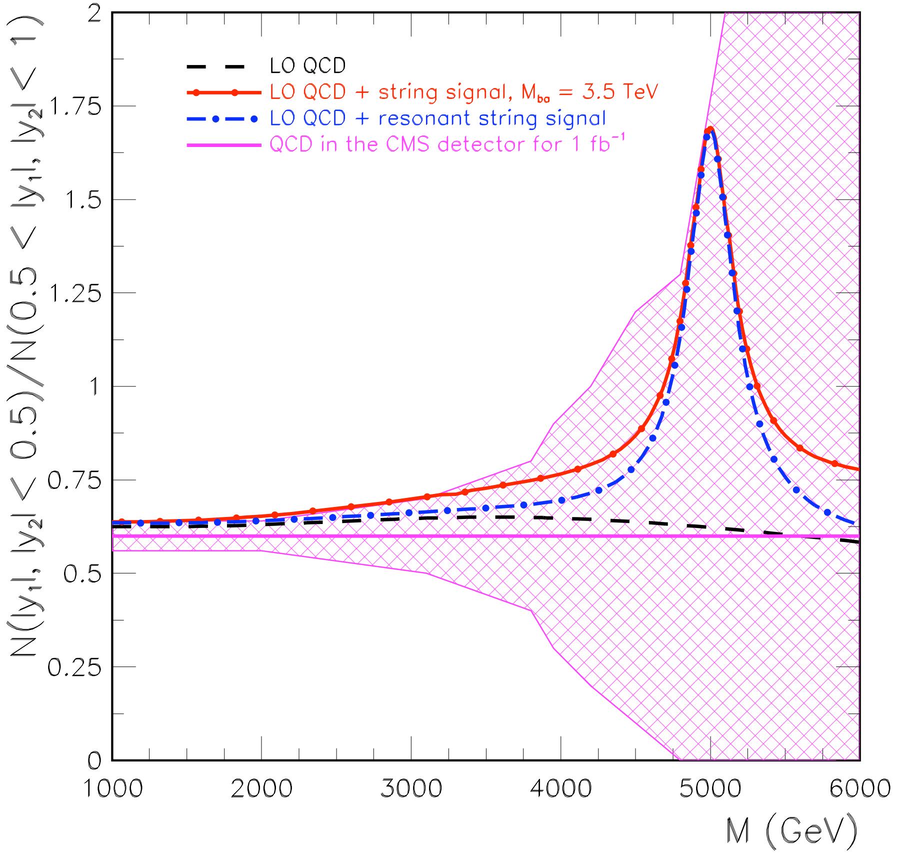
M_{ab} : KK of SU(2) branes and winding modes of SU(3) branes: $M_{ab} = 0.7 M_s$

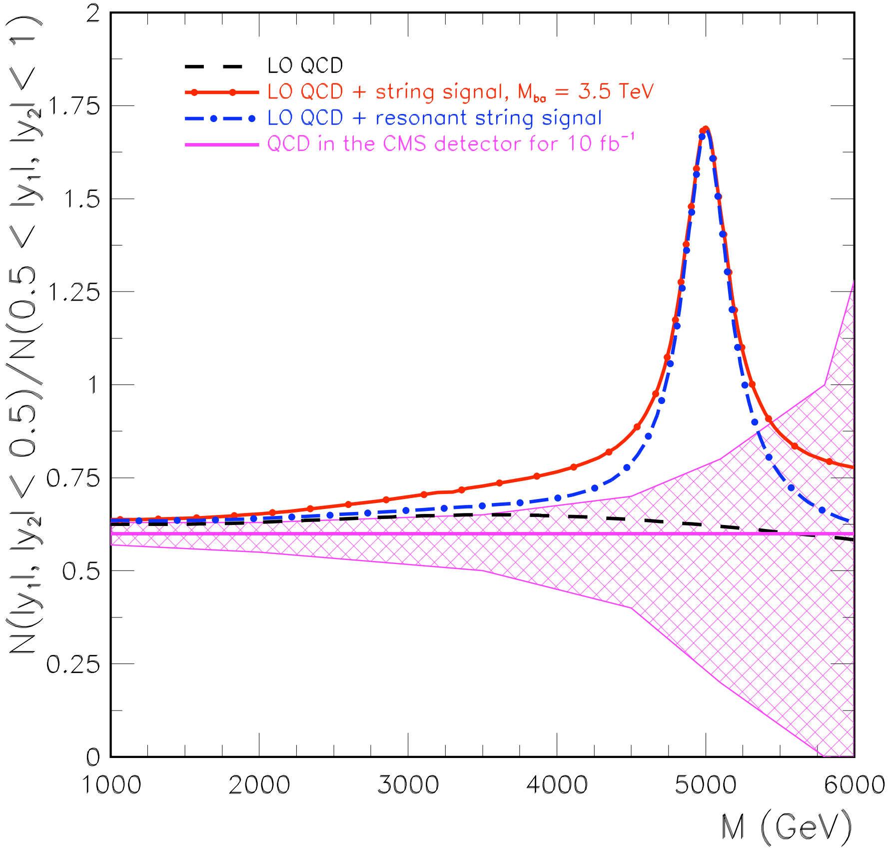
N_p : Degeneracy of KK-states; take $N_p = 3$

Δ : Thickness of D-branes

Dijet angular contribution by t-channel exchange:

CMS detector simulation:





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

Conclusions

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(Independent of amount of (unbroken) supersymmetry!)

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

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- There exists many ISB models with SM like spectra without chiral exotics.

- One ... ons:

(Indep ... etry!)

String ... ns

?

Comput ... M_{string}

Black h ... string

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: $M_{b.h.}$