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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(J. Scherk, J. Schwarz, 1974)

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

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Actually this is not even necessary, but rather

$$M_s \simeq 1 \text{ TeV} - 10^{19} \text{ GeV}$$

The solution of the Hierarchy Problem hints at

new physics in the TeV region (visible at the LHC?).

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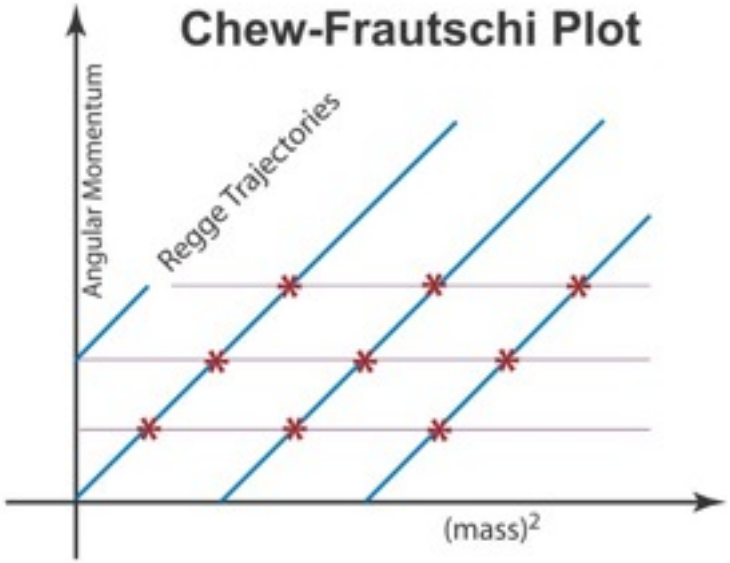
Low string scale compactifications

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

$$M_{\mathrm{Grav.}} = M_s \simeq 1\,\mathrm{Tev}$$

$\Rightarrow$ Stringy Regge excitations at 1 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^* spin 0,1,2 & q^* spin 1/2, 3/2

$\Rightarrow$ Two different kinds of Regge trajectories!

How does string theory meet collider physics?

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Collision of quarks and gluons:

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- Corrections at higher energies from strings due to new colored objects:

- New stringy physics at the collider in case $M_s = \mathcal{O}(\mathrm{TeV})$

  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;
L. Anchordoqui, H. Goldberg, D. Lüst, S. Nawata, S. Stieberger, T. Taylor, arXiv:0808.0497 [hep-ph]; arXiv:0904.3547 [hep-ph]
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Recall basic set-up of type IIA/B orientifolds:

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- 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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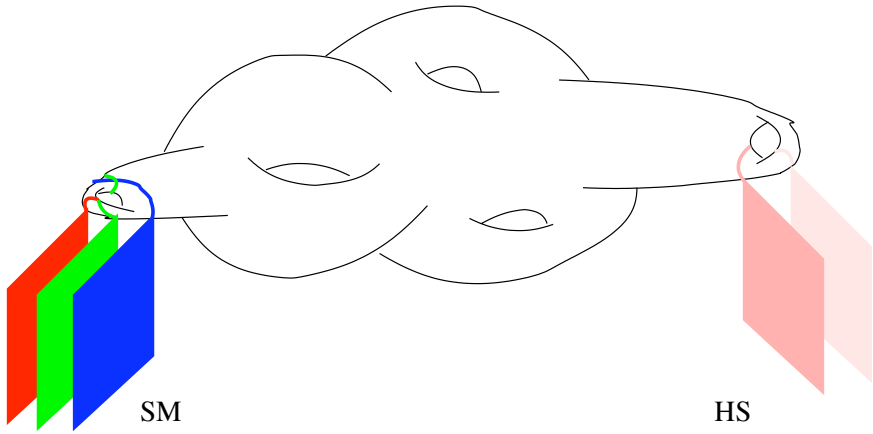

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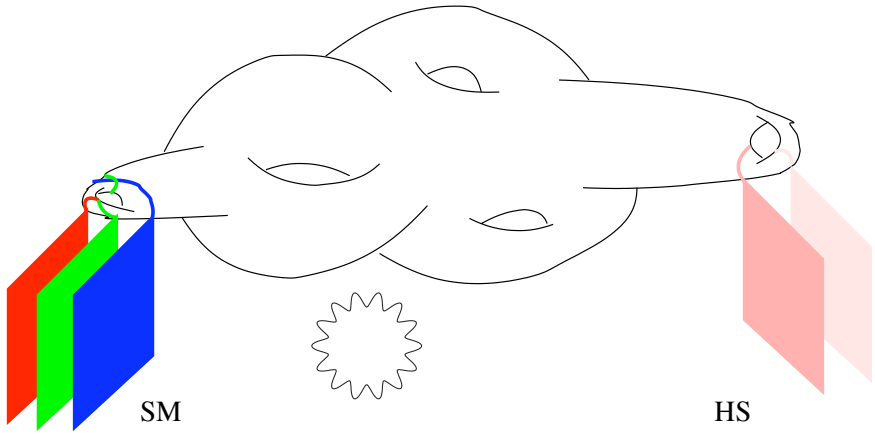

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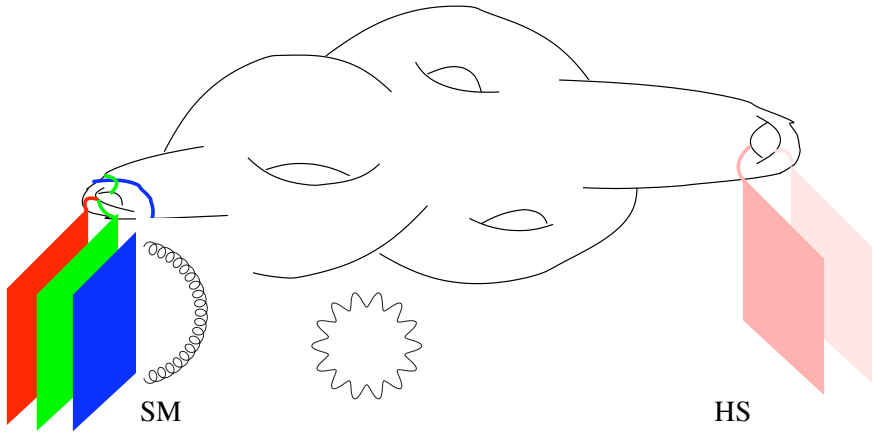

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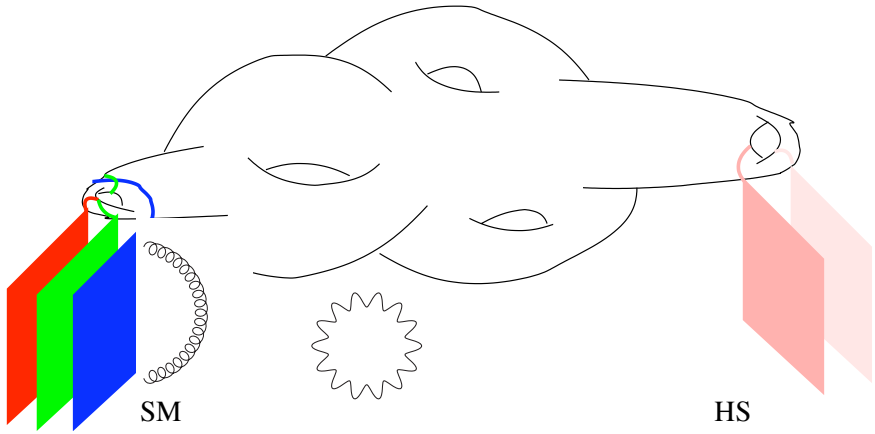

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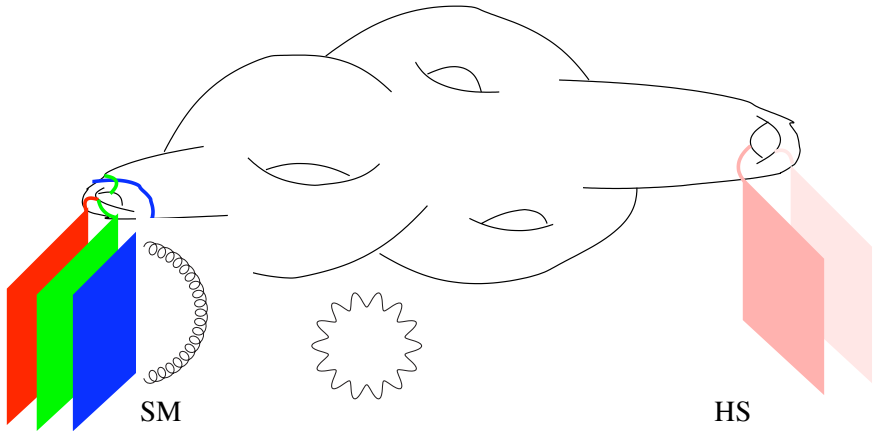

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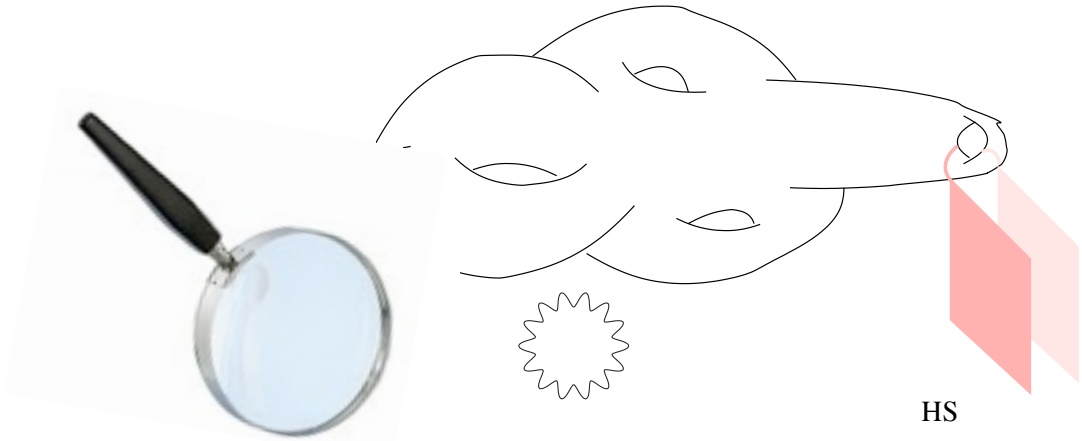

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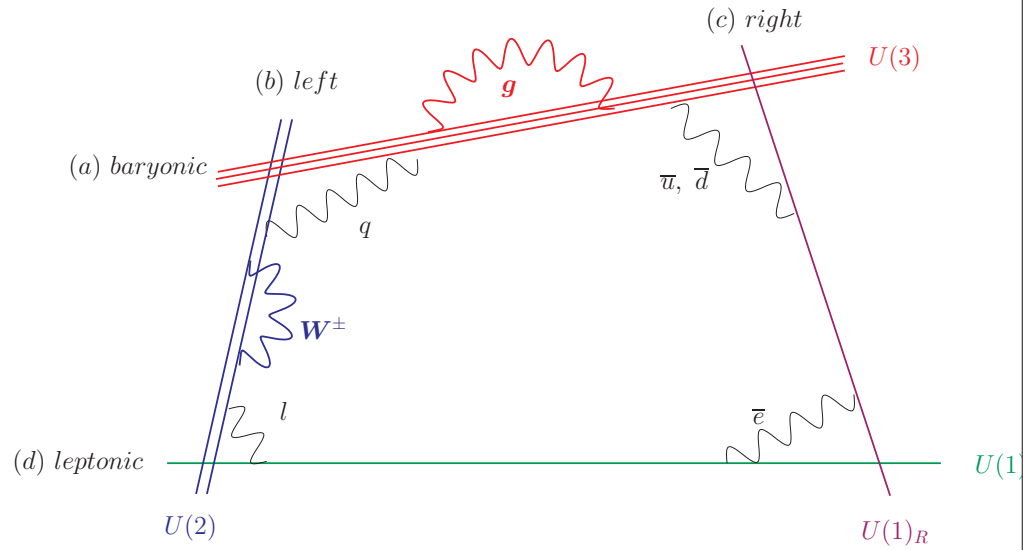

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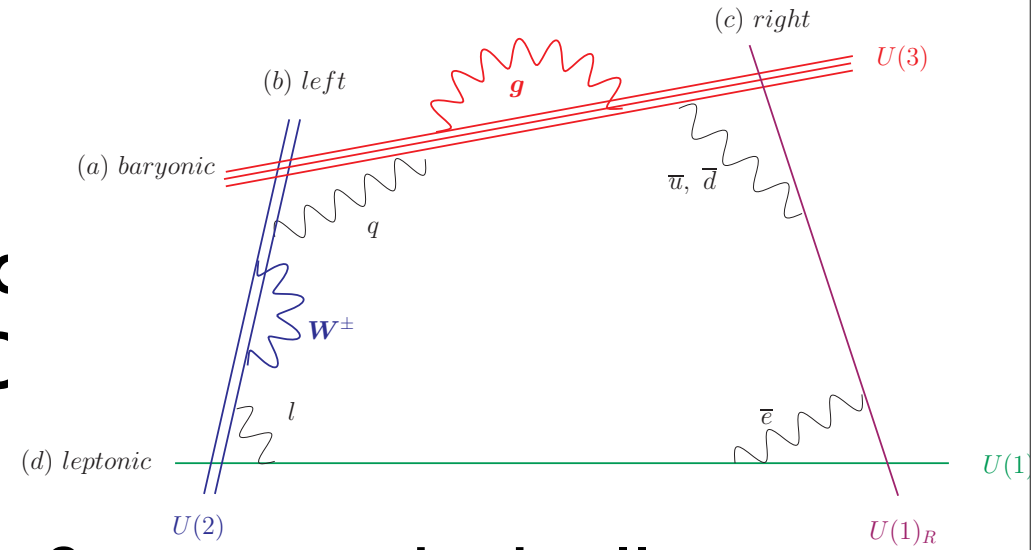

(ii) Consider D-brane compactifications which allow for low string scale (solve hierarchy problem without SUSY)

⇒ Low scale for quantum gravity & large extra dimensions.

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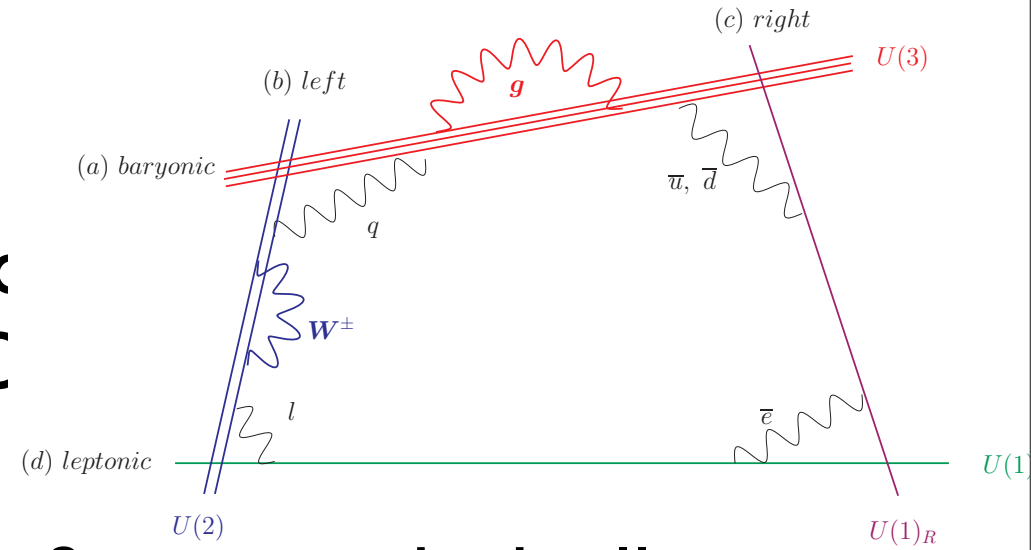

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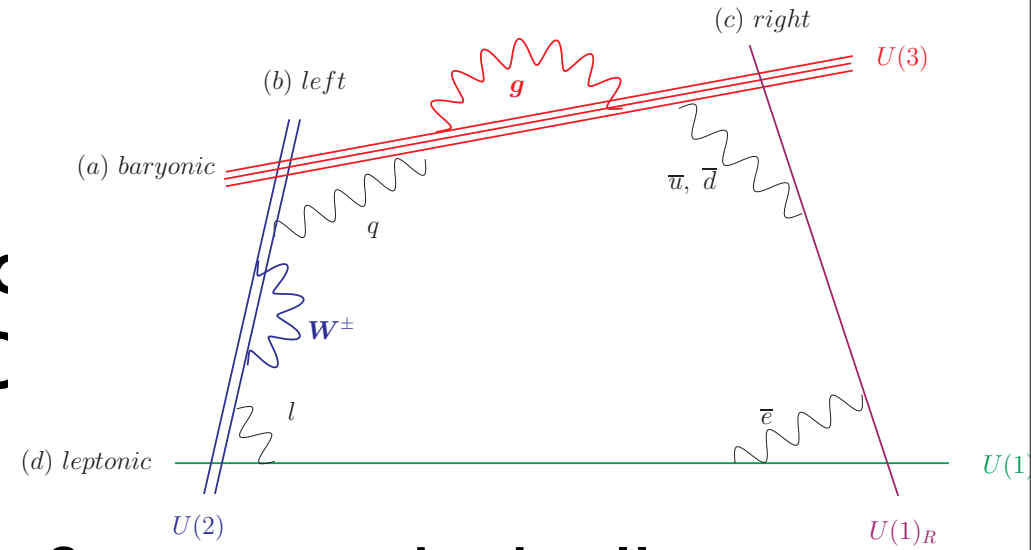

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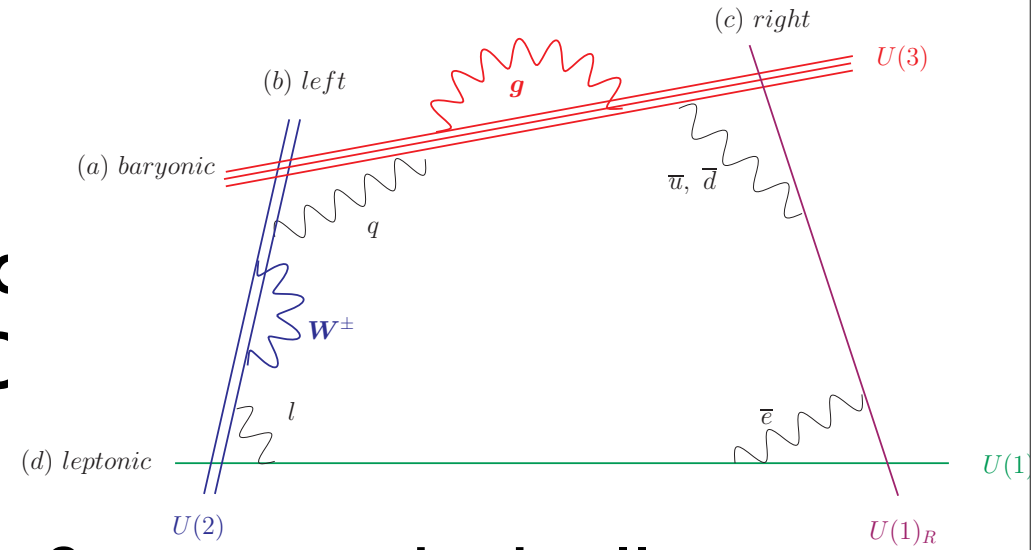

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⇒ Universal predictions that are true for all points in the landscape, i.e. independent from any details of the compact space!

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Scale of wrapped D(p+3)-branes (e.g. IIB: p=0,4), (IIA: p=3):

$$(3): \quad M_p^{\parallel} = \frac{1}{(V_p^{\parallel})^{1/p}}\,, \qquad (3'): \quad M_{6-p}^{\perp} = \frac{1}{(V_{6-p}^{\perp})^{1/(6-p)}}$$

$$V_6 = V_p^{\parallel} V_{6-p}^{\perp}$$

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(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

$$\mathrm{M}_s \equiv M_{\mathrm{Planck}} \simeq 10^{19}\ \mathrm{GeV}$$

(i) GUT scale scenario:

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:

(Beasly, Heckman, Marsano, Saulina, Schafer-Nameki, Vafa; Donagi, Wijnholt; Blumenhagen, Braun, Grimm, Weigand)

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

(ii) SUSY breaking scenario:

M_s is the intermediate 4D scale of supersymmetry breaking

(Balasubramanian, Conlon, Quevedo, Suruliz, ...)

$$\mathrm{M}_s \equiv M_{SUSY} \simeq 10^{11}\ \mathrm{GeV}$$

Gravity mediation:

$$\mathrm{M}_{SUSY} \sim \sqrt{M_{SM} M_{\mathrm{Planck}}}$$

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

(D. Lüst, F. Marchesano, L. Martucci, D. Tsimpis, arXiv:0807.4540;
J. Held, D. Lüst, F. Marchesano, L. Martucci, arXiv:1004.0867)

(iii) Low string scale scenario:

M_s is the Standard Model (TeV) scale:

$$\mathrm{M}_s \equiv M_{SM} \simeq 10^3 \ \mathrm{GeV}$$

(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:

$$\mathrm{V}_6' = V_6 M_s^6 = \frac{M_{\mathrm{Planck}}^2}{M_s^2} = 1, 10^6, 10^{16}, 10^{32}$$

There are 4 generic types of particles:

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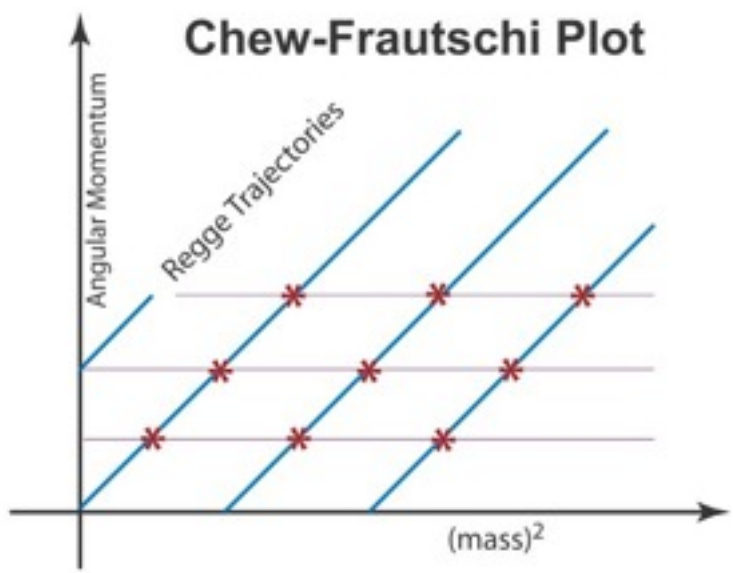
(i) Stringy Regge excitations:

$$\mathrm{M}_{\mathrm{Regge}} = \sqrt{n}\, M_s = \sqrt{\frac{n}{V_6'}}\, M_{\mathrm{Planck}}\,, \qquad (n = 1, \ldots, \infty)$$

Open string excitations: completely universal (model independent), carry SM gauge quantum numbers:
higher spin excitations of $\mathrm{g}, \mathrm{W}, \mathrm{Z}, \gamma, q, l$



(ii) D-brane cycle Kaluza Klein excitations:

$$M_{KK}^{\parallel} = \frac{m}{(V_p^{\parallel})^{1/p}} \simeq m\, M_s = m\, \frac{M_{\rm Planck}}{(V_6')^{1/2}} \qquad (m = 1, \ldots, \infty)$$

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

Internal momenta excitations of g, W, Z, γ, 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:

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

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:

(G. Dvali, D. Lüst, arXiv:0912.3167)

$$\Delta M_T \simeq \frac{< T^\mu_\mu T^\mu_\mu >}{M^2_{\rm Planck}} \simeq \frac{M_s^4}{M^2_{\rm Planck}} \simeq 10^{-13}\ {\rm GeV}$$

(iv) Mini black holes (string balls):

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

$$M_{b.h.} = \frac{M_s}{g_s^2} >> M_s \quad \text{if} \quad g_s < 1$$

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

Regge excitations: $M_{\text{Regge}} \simeq M_s \sqrt{n}$

If $g_s = 0.1 \quad \Longrightarrow$

$n = 1/g_s^4 \sim 10^4$ string states before one reaches black hole !

Low string scale models:

$\Rightarrow$ General framework: Large species models:

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

$$M_{\rm Planck}^2 = N\, M_{\rm Grav}^2 \quad \text{(N: \# of species)}$$

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

This relation arises from natural bounds on black hole decays.

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

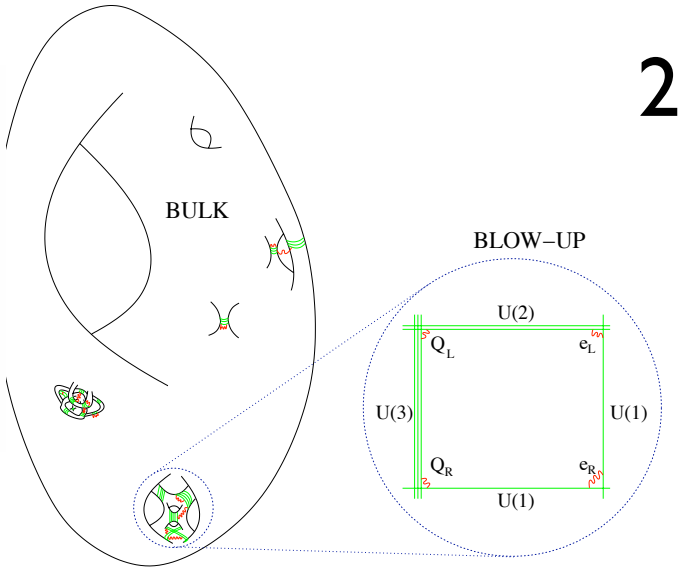
(i) Large volume compactifications

(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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(ii) String scale compactification: $V_6' = 1$

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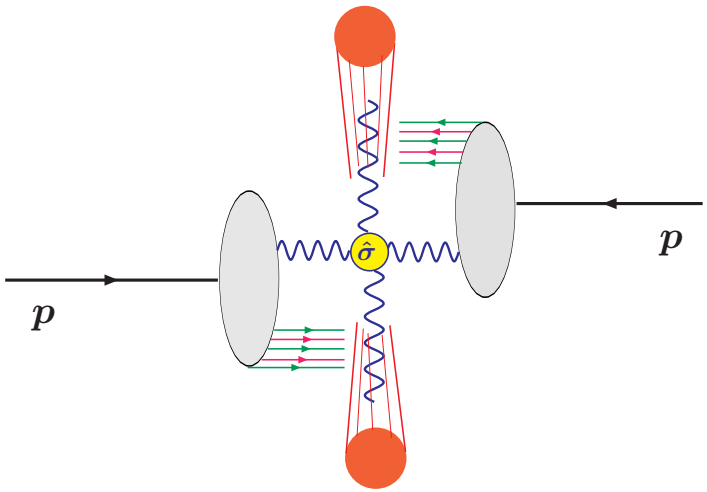
(i) and (ii) are in agreement with the known relation

$$M_{\rm Planck}^2 = \frac{1}{g_s^2} V_6' \, M_s^2$$

III) 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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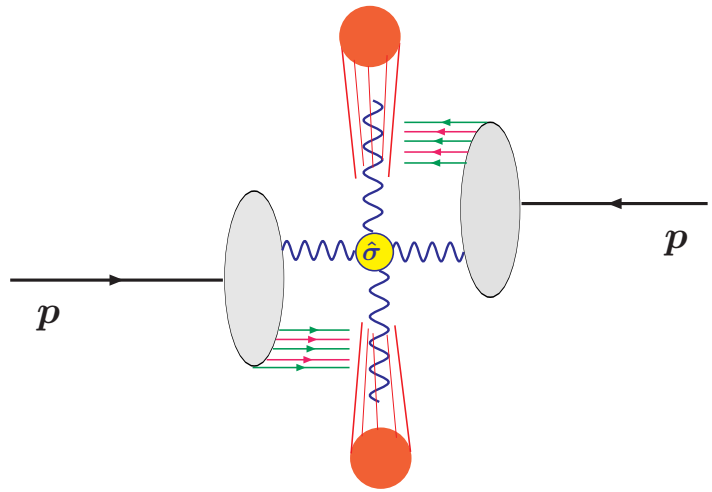

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First resonances: g^* spin 0,1,2 & q^* spin 1/2, 3/2

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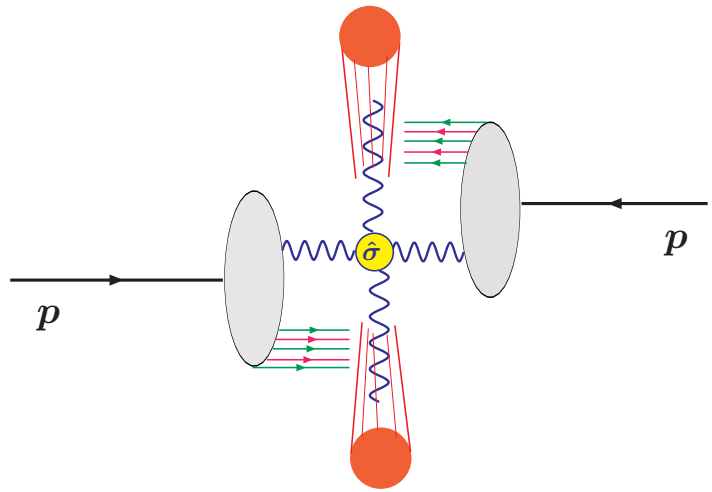

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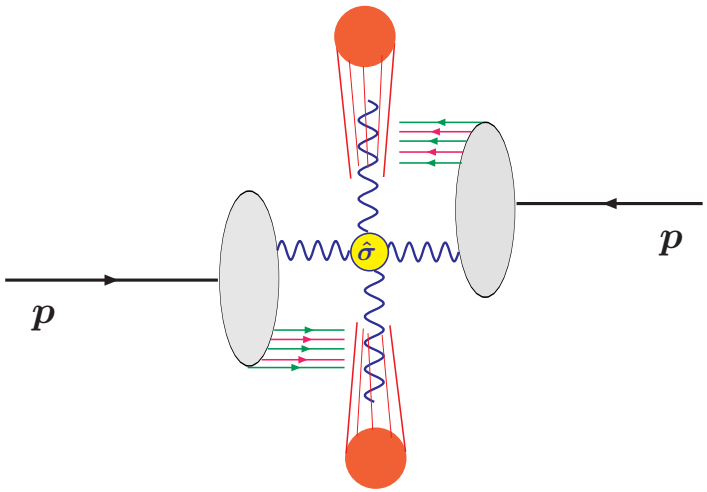

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One has to compute the parton model cross sections of SM fields into new stringy states !

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.

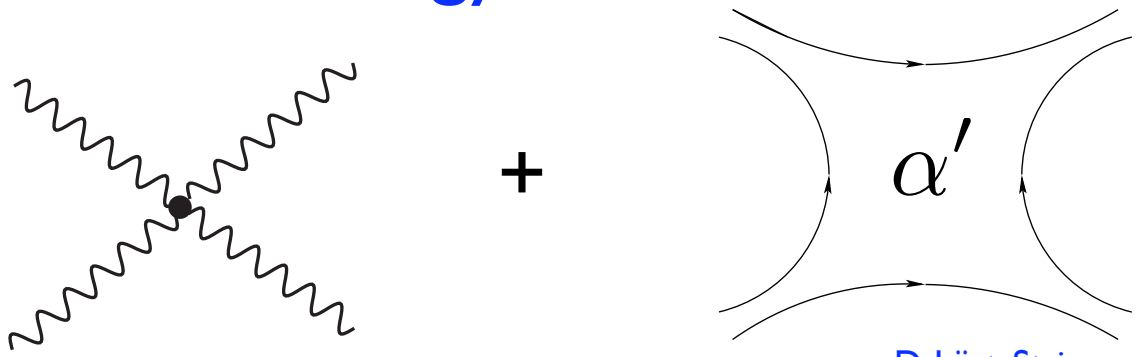
Quark, lepton vertex operators:

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

Fermions: boundary changing (twist) operators!

Striking relations between quark and gluon amplitudes!

(ii) They contain stringy corrections:

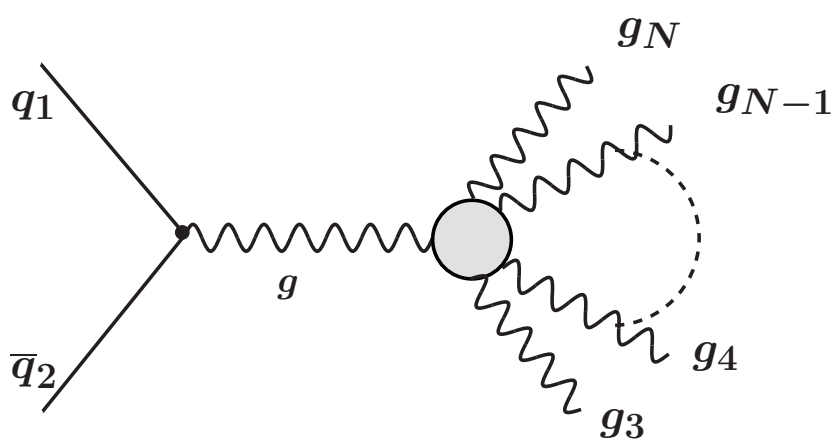


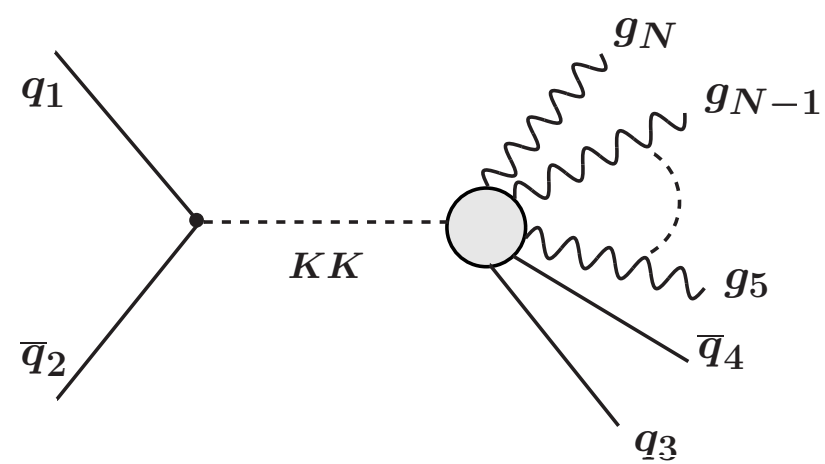
- n-point tree amplitudes with 0 or 2 open string fermions (quarks, leptons) and n or n-2 gauge bosons (gluons) are completely model independent.

  $\Rightarrow$ Information about the string Regge spectrum.

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

  $\Rightarrow$ Information about the internal geometry.





Disk amplitudes among external SM fields $(q, l, g, \gamma, Z^0, W^\pm)$:

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

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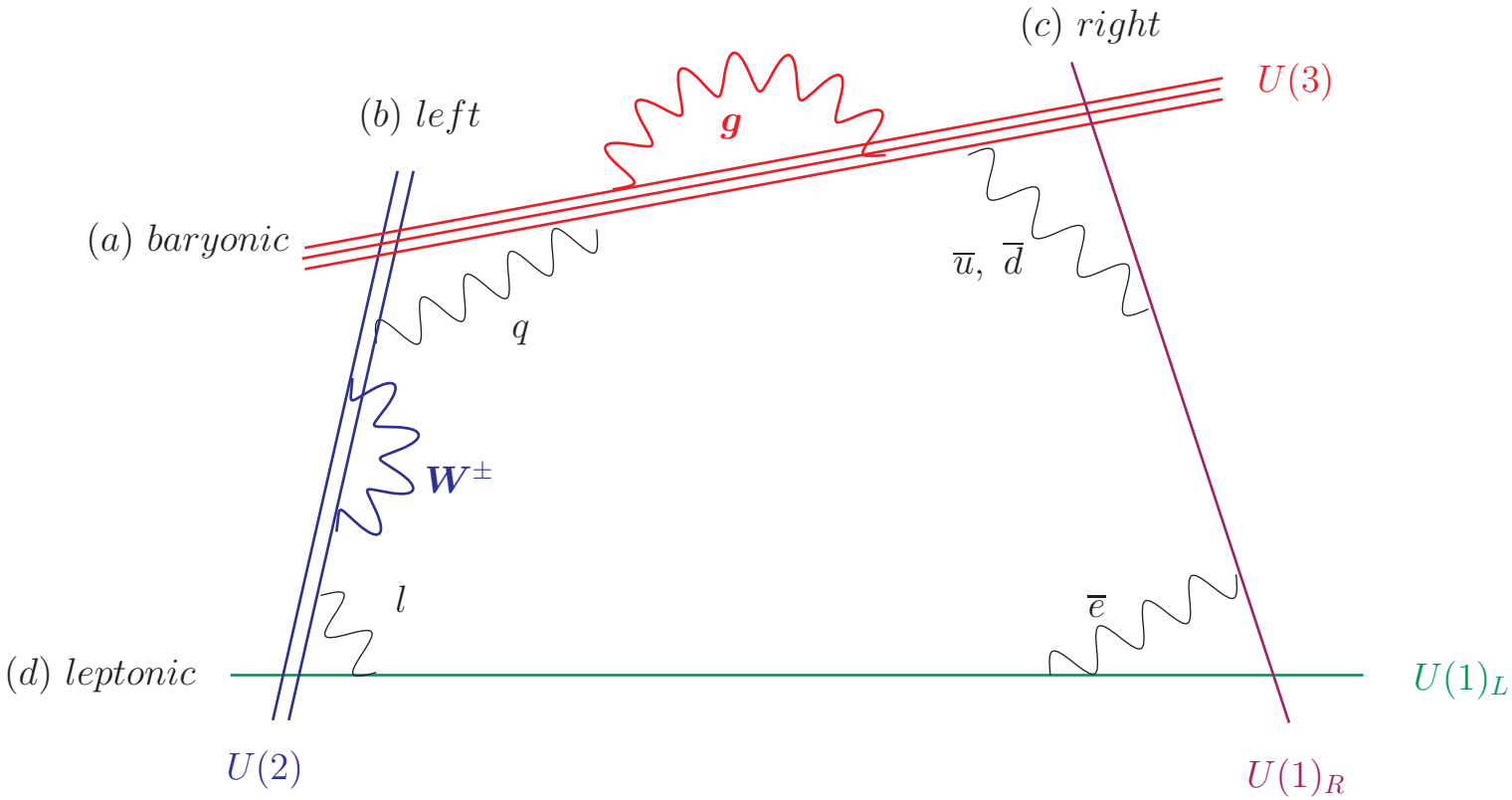

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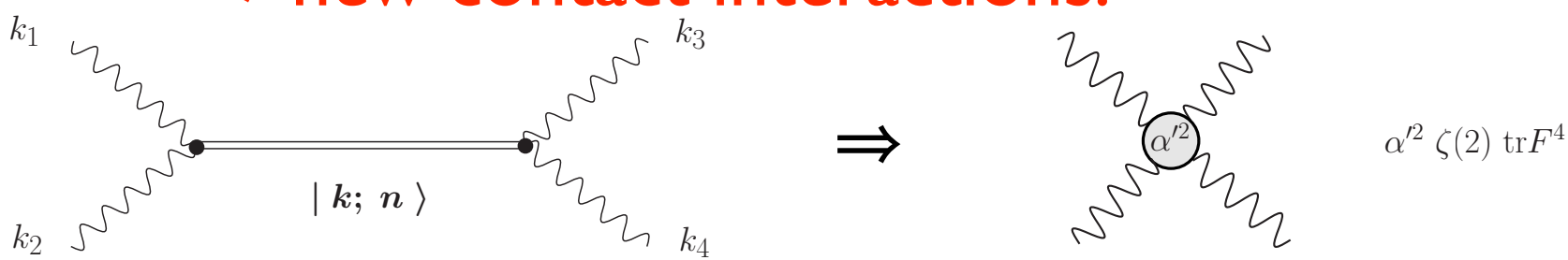
- Exchange of string Regge resonances (Veneziano like ampl.

$\Rightarrow$ new contact interactions:



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

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

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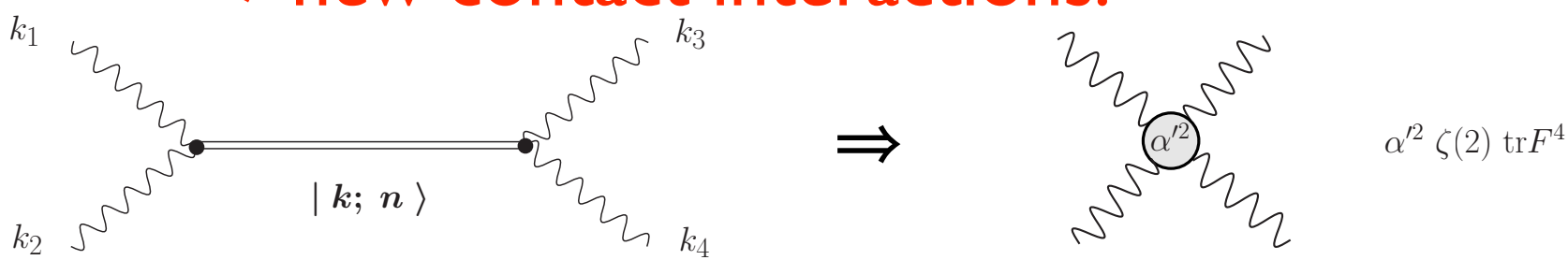

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- Exchange of KK and winding modes (model dependent)

4 gauge boson amplitudes:

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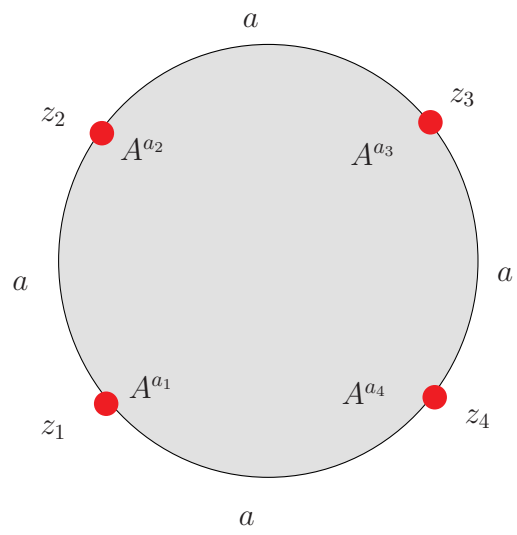

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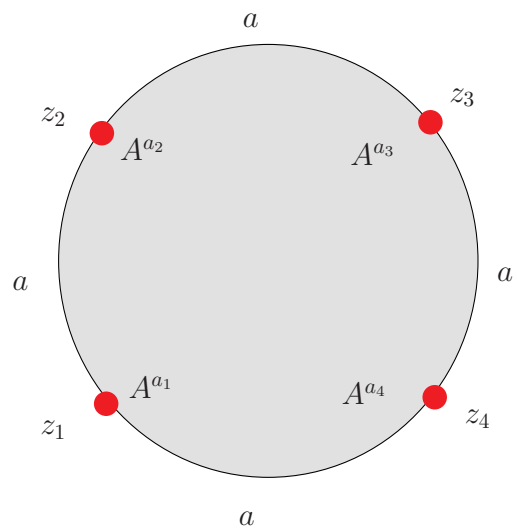

Only string Regge resonances are exchanged $\Rightarrow$

These amplitudes are completely model independent!

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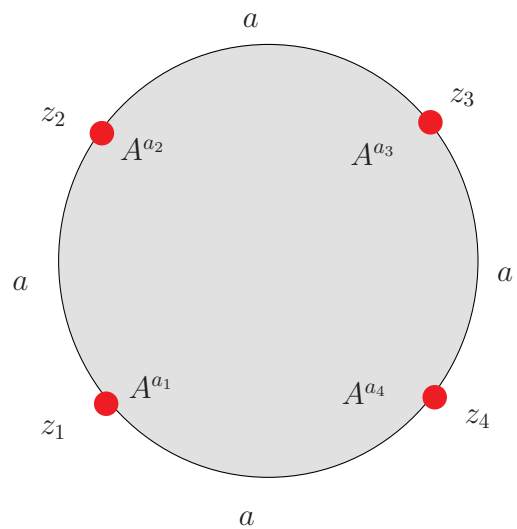

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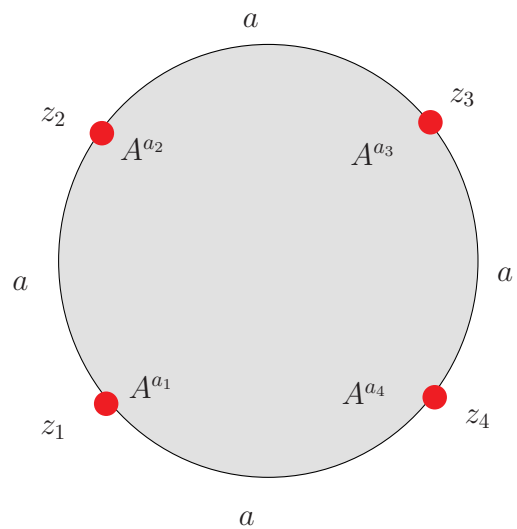

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$$|\mathcal{M}(gg \to gg)|^2 = g_3^4 \left(\frac{1}{s^2} + \frac{1}{t^2} + \frac{1}{u^2} \right) \left[\frac{9}{4} s^2 V_s^2(\alpha') - \frac{1}{3} \left(s V_s(\alpha') \right)^2 + (s \leftrightarrow t) + (s \leftrightarrow u) \right]$$

(Stieberger, Taylor)

$\Rightarrow$ dijet events

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

(Anchordoqui, Goldberg, Nawata, Taylor, arXiv:0712.0386)

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

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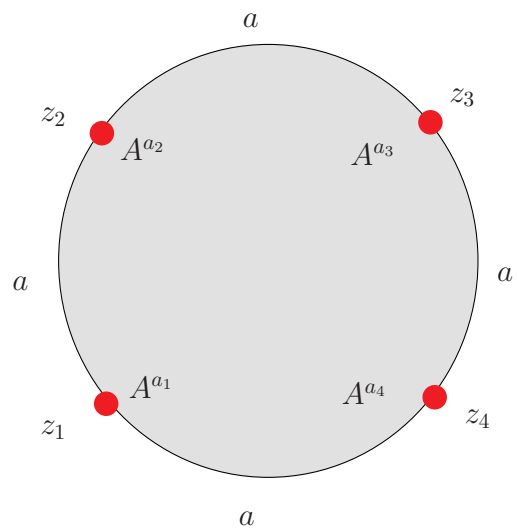

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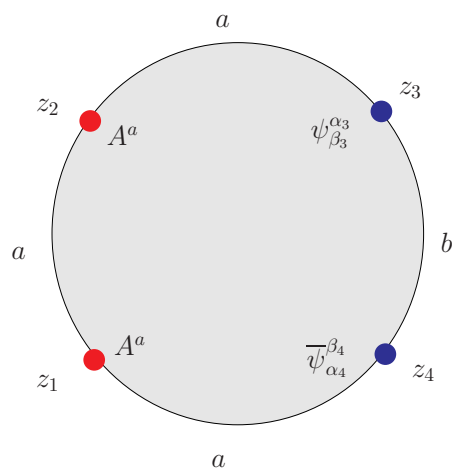
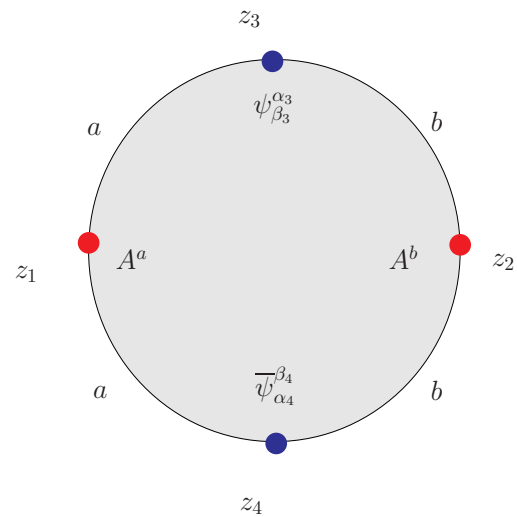
2 gauge boson - two fermion amplitude:





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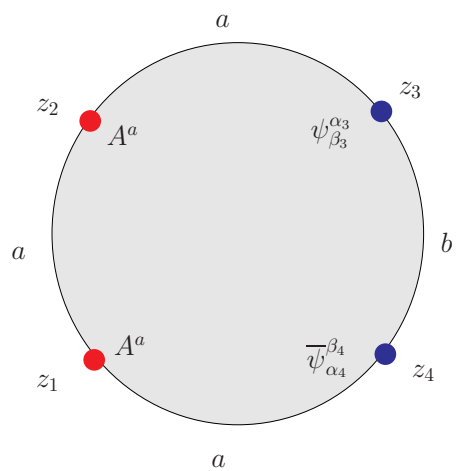

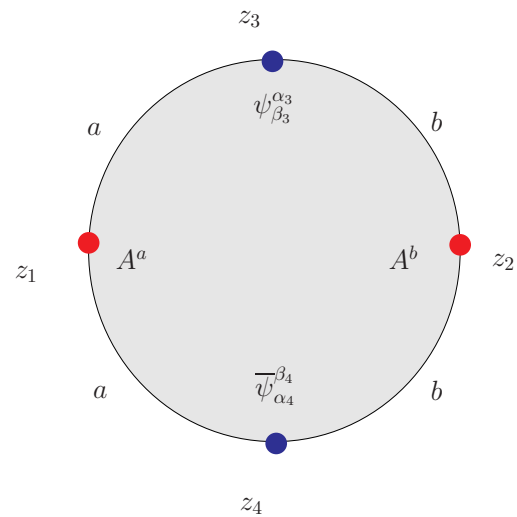

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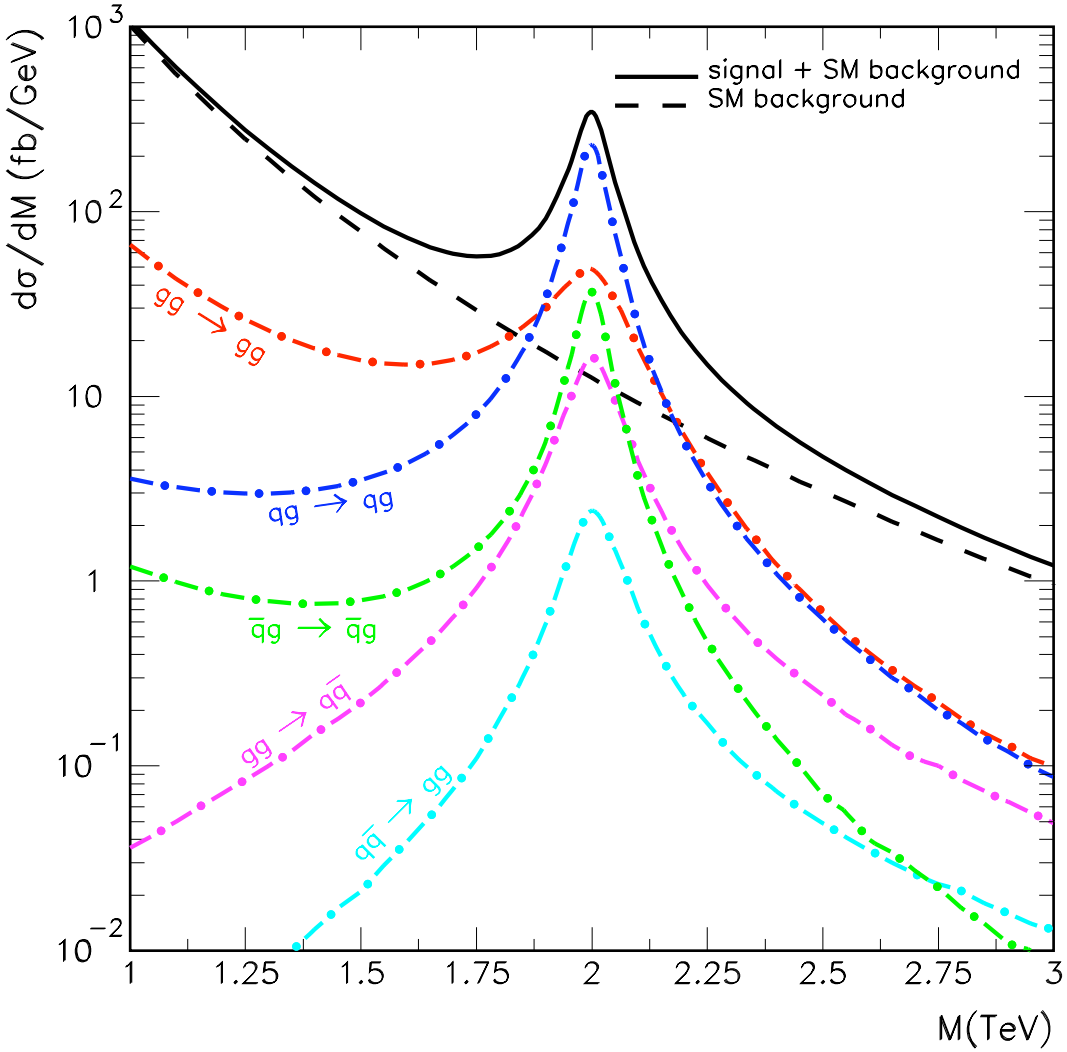

(Anchordoqui, Goldberg, Lüst, Nawata, Stieberger, Taylor, arXiv:0808.0497[hep-ph])

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

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

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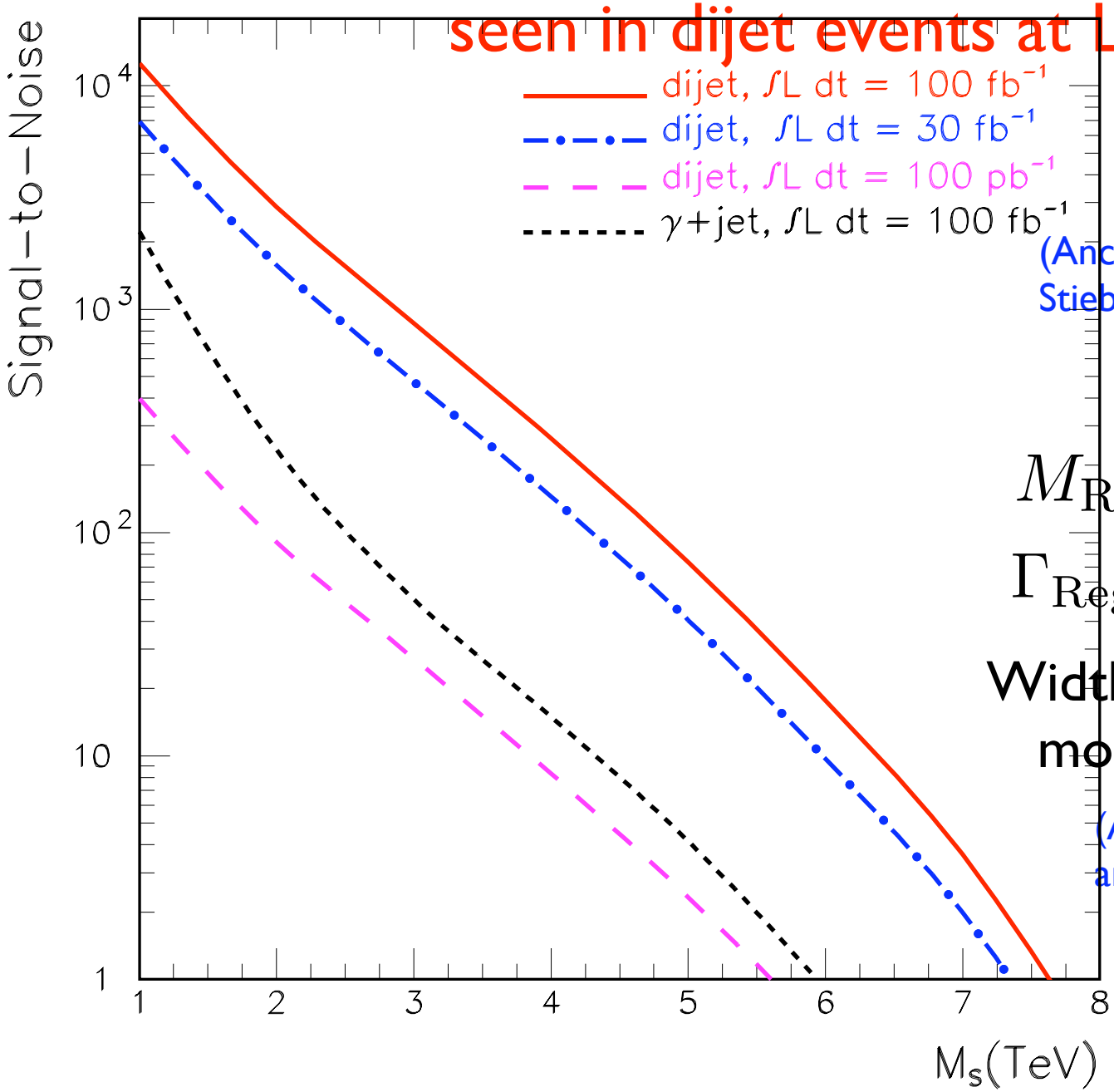

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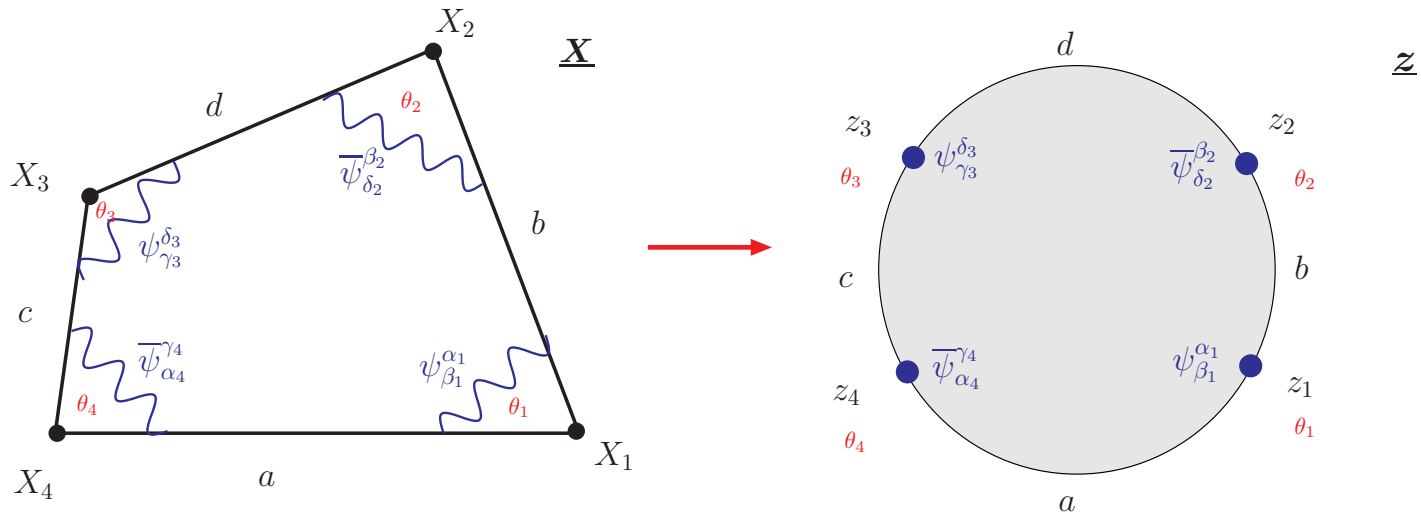

Exchange of Regge, KK and winding resonances.

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

Constrained by FCNC's (Abel, Lebedev, Santiago, hep-th/0312157)

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

depend on internal geometry

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

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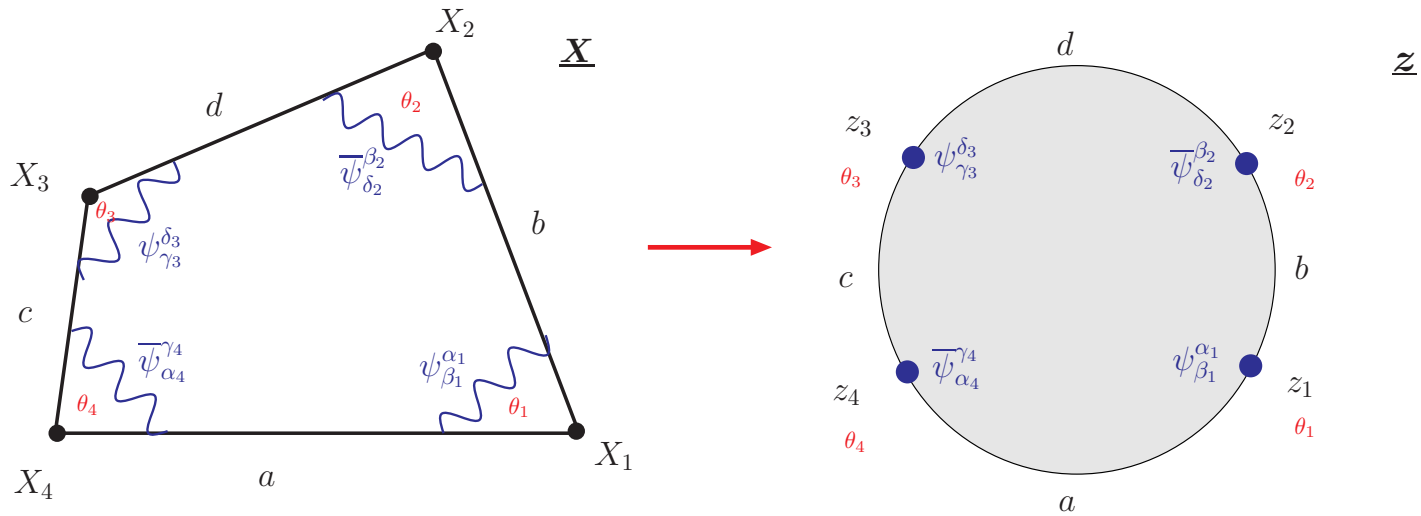

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(see: L. Anchordoqui, H. Goldberg, D. Lüst, S. Nawata, S. Stieberger, T. Taylor, arXiv:0904.3547 [hep-ph])

Dominant contribution:

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

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

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

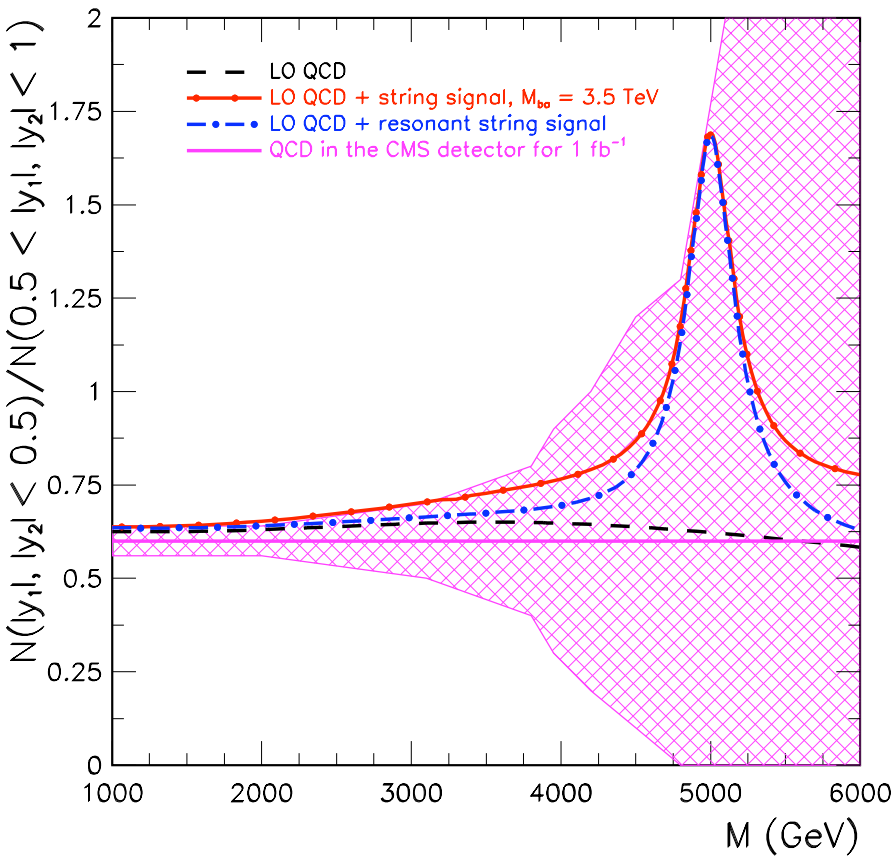
M_{ab} : KK of SU(2) branes and winding modes of SU(3) branes: $M_{ab} = 0.7 M_s$

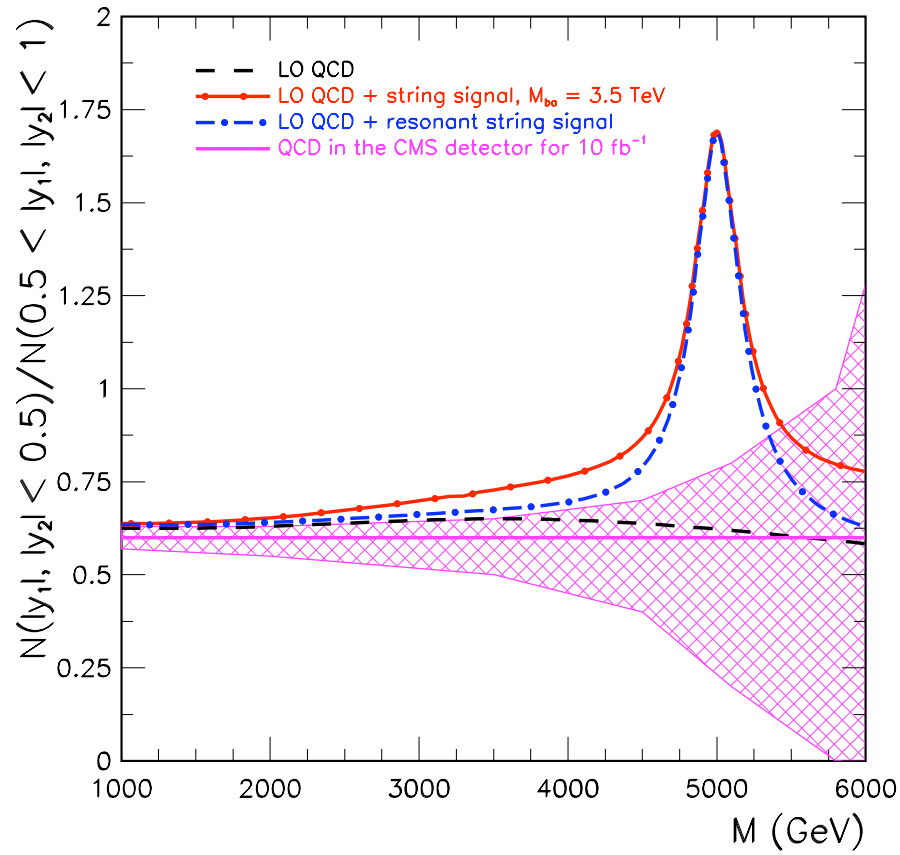
N_p : Degeneracy of KK-states; take $N_p = 3$

Δ : Thickness of D-branes

Dijet angular contribution by t-channel exchange:

CMS detector simulation:





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

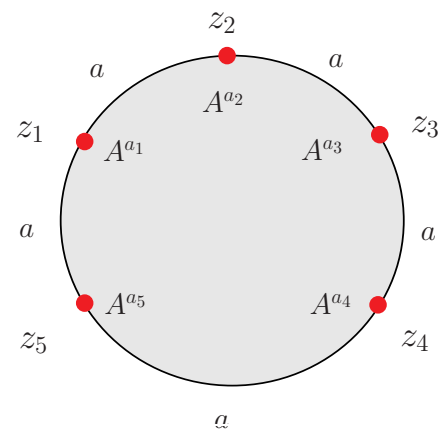
(2) Five point scattering amplitudes (3 jet events):

(Computation of higher point amplitudes for LHC: D. Lüst, O. Schlotterer, S. Stieberger, T. Taylor, arXiv:0908.0409).

They depend on two characteristic functions:

(i) 5 gluons:

(Stieberger, Taylor (2006))



Field theory factors:

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

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

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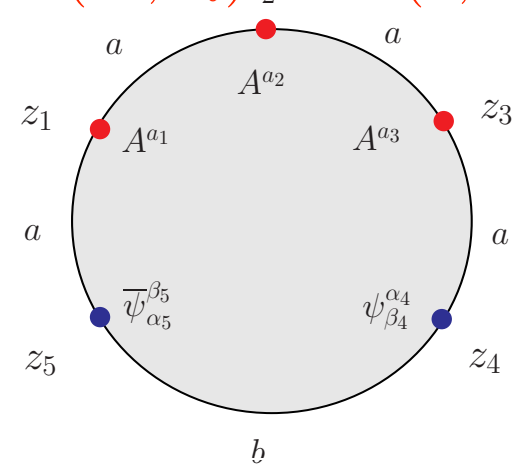

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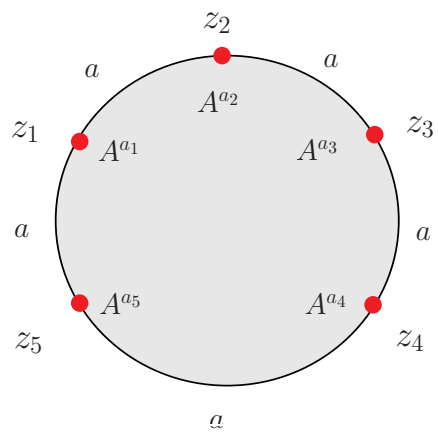

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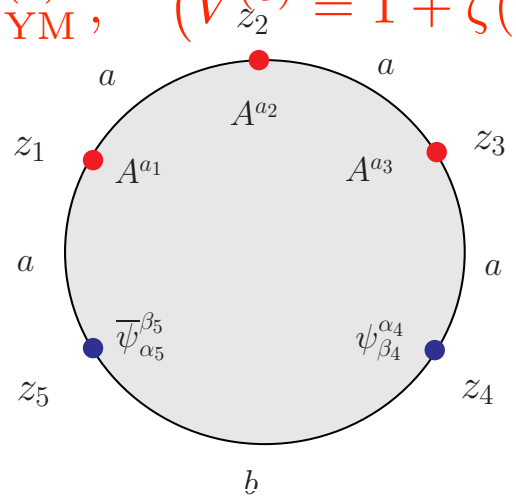


$$\mathcal{N}^{(5)}_{\rm YM} = \frac{4g^3_{\rm YM}\langle 15\rangle\langle 14\rangle^3}{\langle 12\rangle\langle 23\rangle\ldots\langle 51\rangle}$$

$$\mathcal{A}(g_1^-, g_2^+, g_3^+, q_4^-, \overline{q}_5^+) = \left(V^{(5)}(\alpha', k_i) - 2i\epsilon(1,2,3,4)P^{(5)}(\alpha', k_i)\right) \times \mathcal{N}^{(5)}_{\rm YM}$$

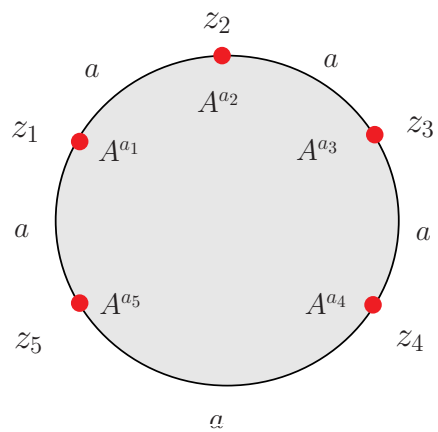
(2) Five point scattering amplitudes (3 jet events):

(Computation of higher point amplitudes for LHC: D. Lüst, O. Schlotterer, S. Stieberger, T. Taylor, arXiv:0908.0409).

They depend on two characteristic functions:

(i) 5 gluons:

(Stieberger, Taylor (2006))

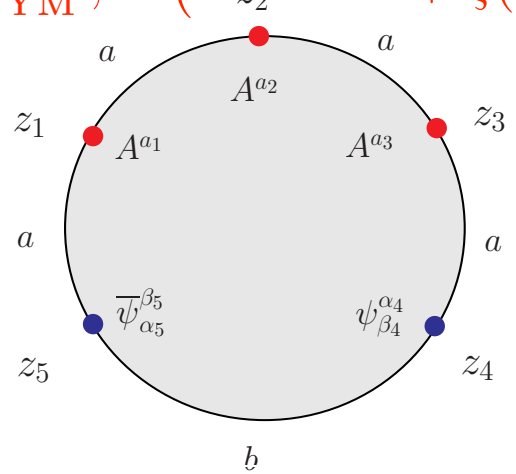


Field theory factors:

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

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

(ii) 3 gluons, 2 quarks:



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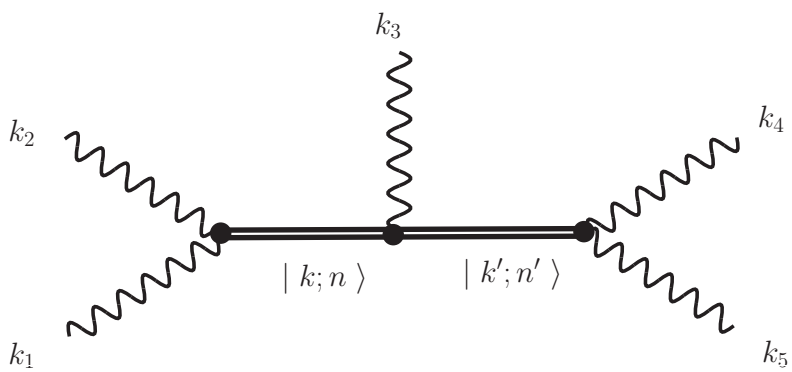
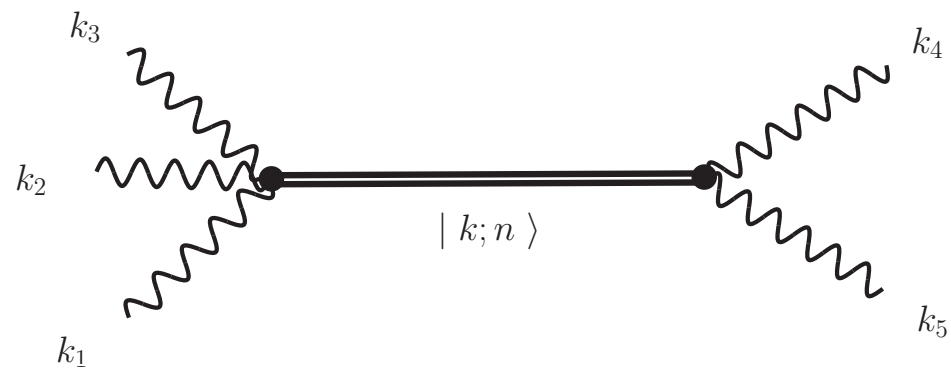
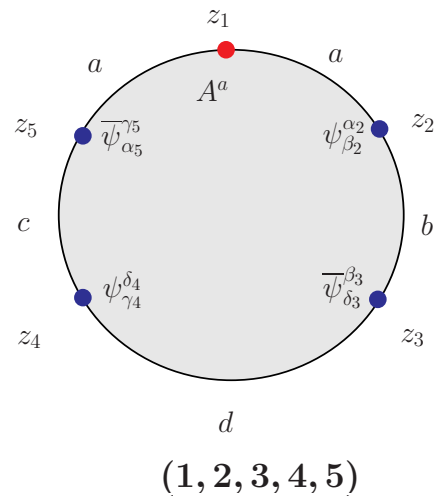
The two kinds of amplitudes are universal: the same Regge states are exchanged:



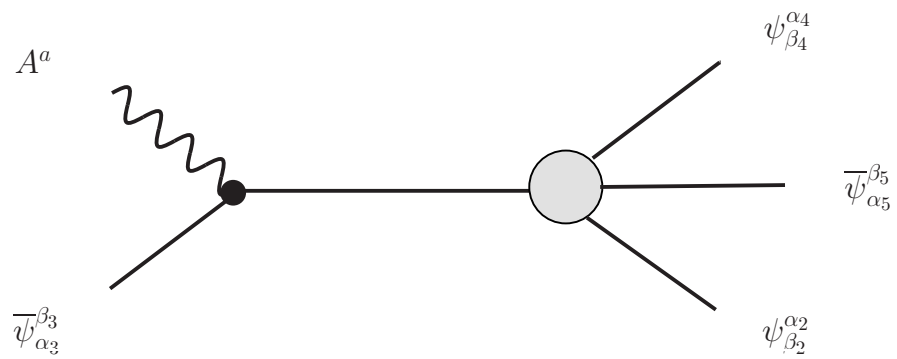


(iii) 1 gluon, 4 quarks:

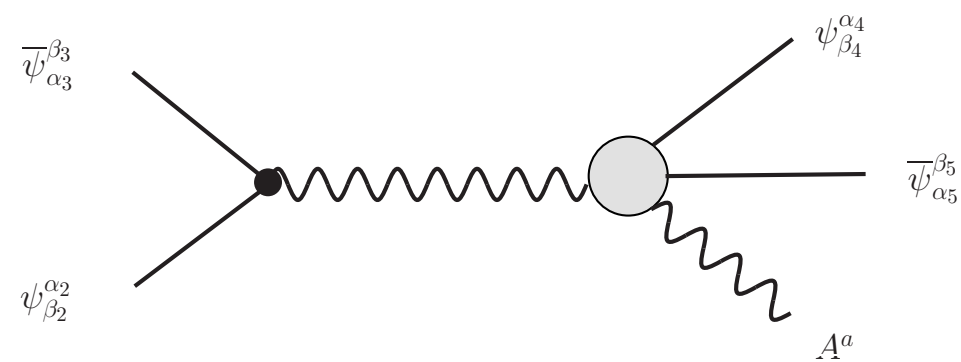


This amplitude has a similar structure as the 4 quark amplitude: exchange of Regge and KK modes.

Factorization on the 4 quark amplitude:



Factorization on the 2 quark - 2 gluon amplitude:



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True for a large class of models in the string landscape!

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String tree level, 4-point processes with 2 or 4 gluons

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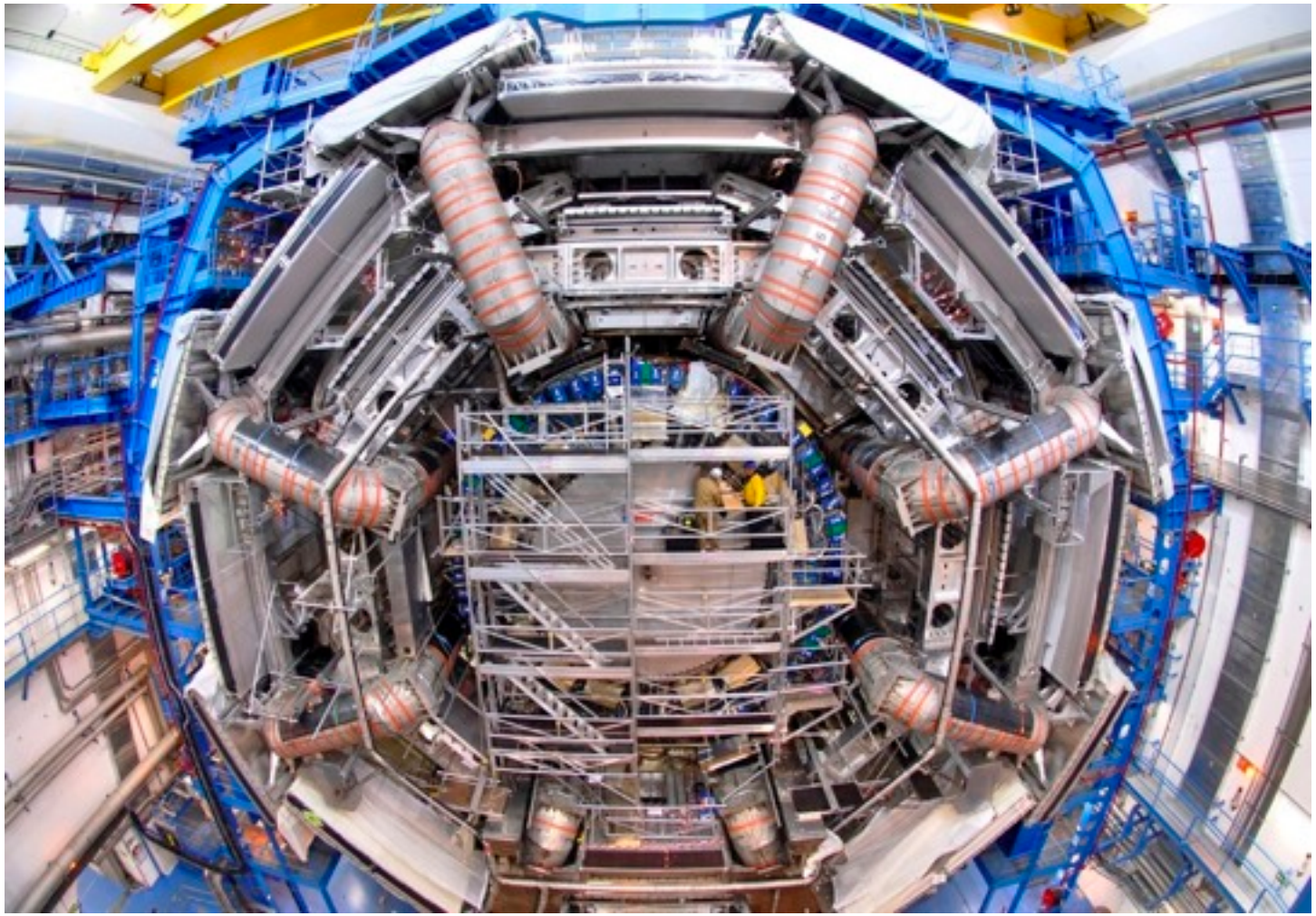
- Can one get (mirage) gauge coupling unification?
- What is the cosmology of low string scale models?

If nature choses weakly coupled strings with a string scale at a few TeV, LHC should find them !



Thank you !