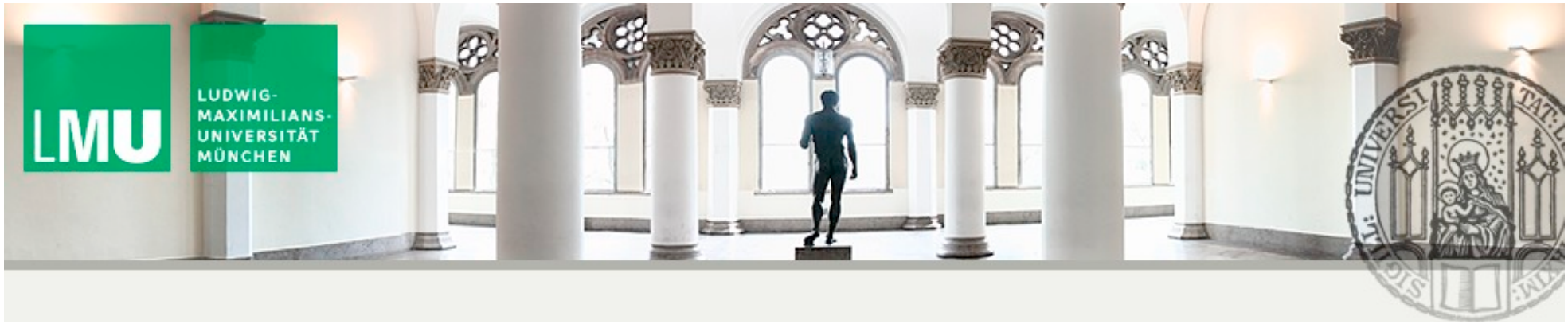
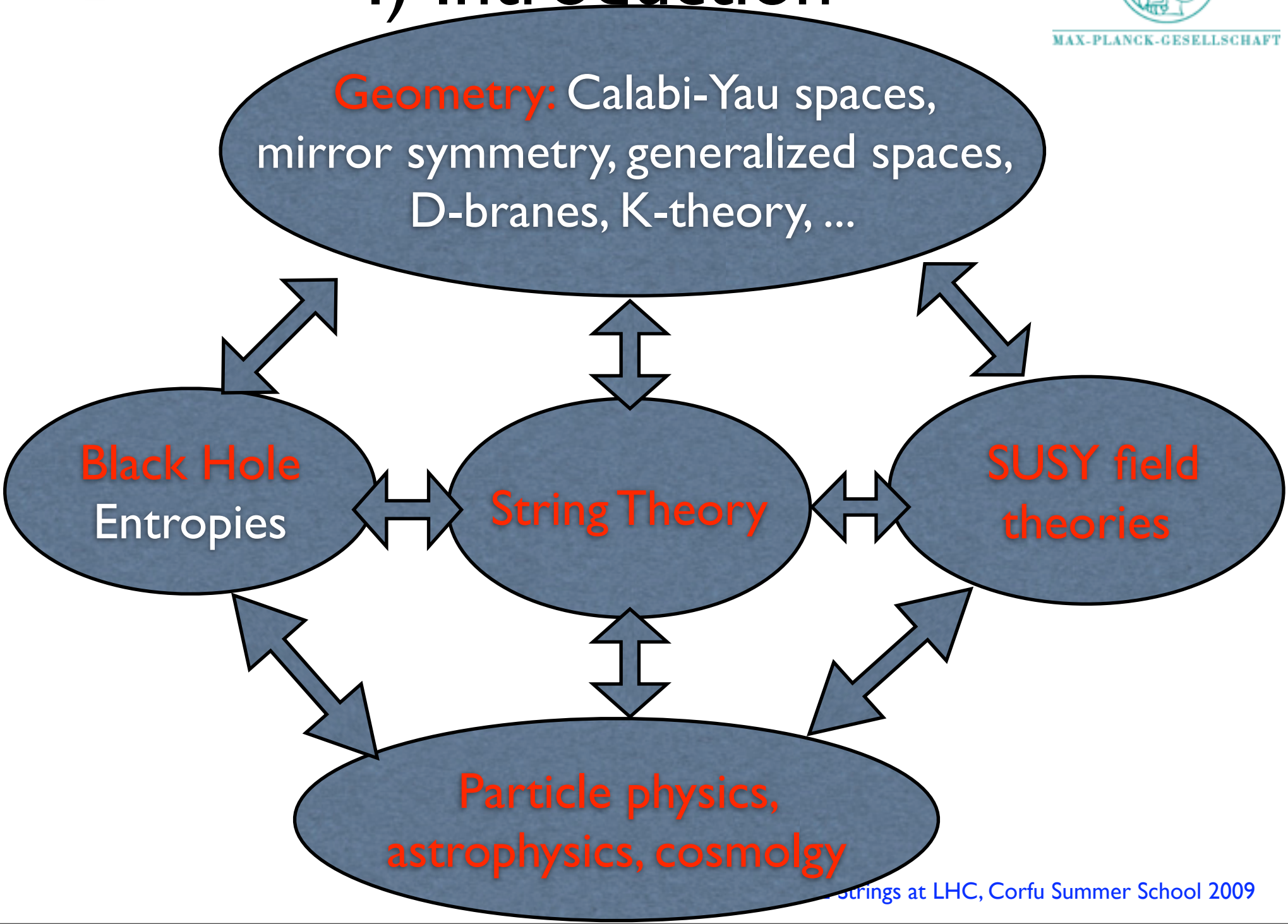
Orientifold/Flux String vacua, supersymmetry breaking and Strings at the LHC

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



I) Introduction



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Count the number of consistent string vacua ➤

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

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- Can we by-pass the landscape?

  $\Rightarrow$ look for green (promising) spots

  - model independent predictions?

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Outline

- Intersecting D-brane models (type II orientifolds)

  (Lecture I)

  Intersecting brane models and their statistics

  D-instantons: non-perturbative couplings

- Stringy signatures at LHC

  (Lecture II)

  (The LHC string hunter's companion)

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(⇨ Heterotic constructions: Talks by Faraggi, Rizos, Vaudrevange)

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(diophantic equations with finite no. of solutions!)

Orientifold with space-time filling D-branes:

IIA: special lagrangian submanifolds: D6 on 3-cycles at angles

⇕ Mirror symmetry (SYZ)

IIB: points, (complex lines), divisors, (CY) with gauge bundle

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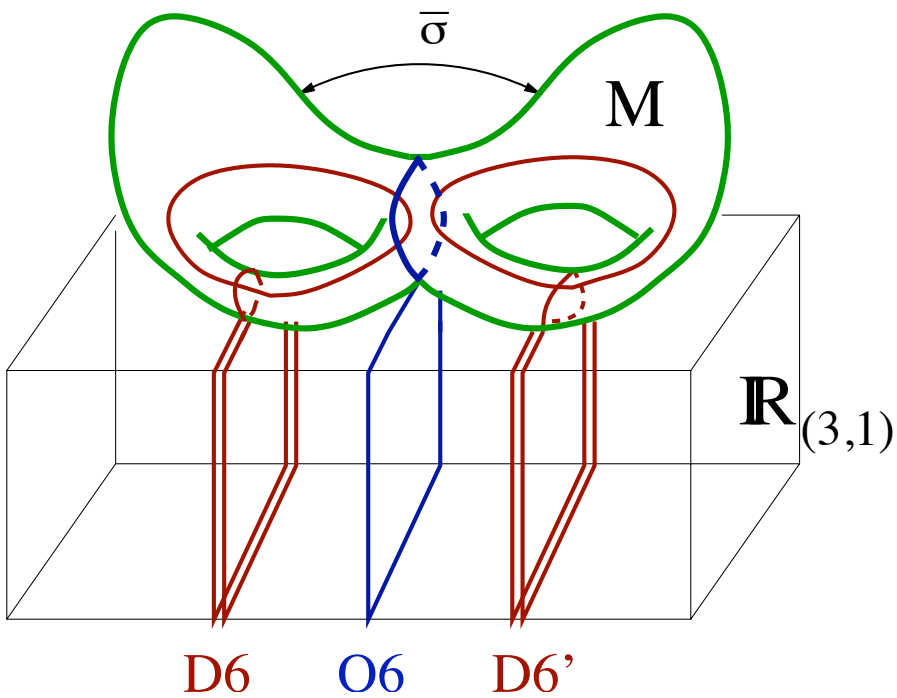


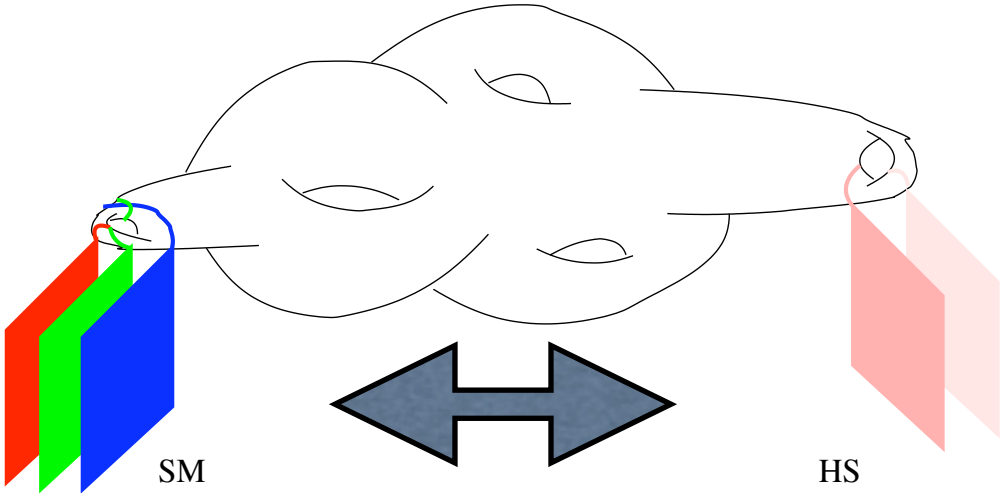
Orientifold projection:

$$\mathcal{M}_{10} = (R^{3,1} \times \mathcal{M}_6)/(\Omega\bar{\sigma})$$

Ω : world sheet parity

$\bar{\sigma}$: spatial reflection

Realization of the SM with G=SU(3) x SU(2) x U(1) and 3 generations of quarks and lepton:



Soft SUSY breaking

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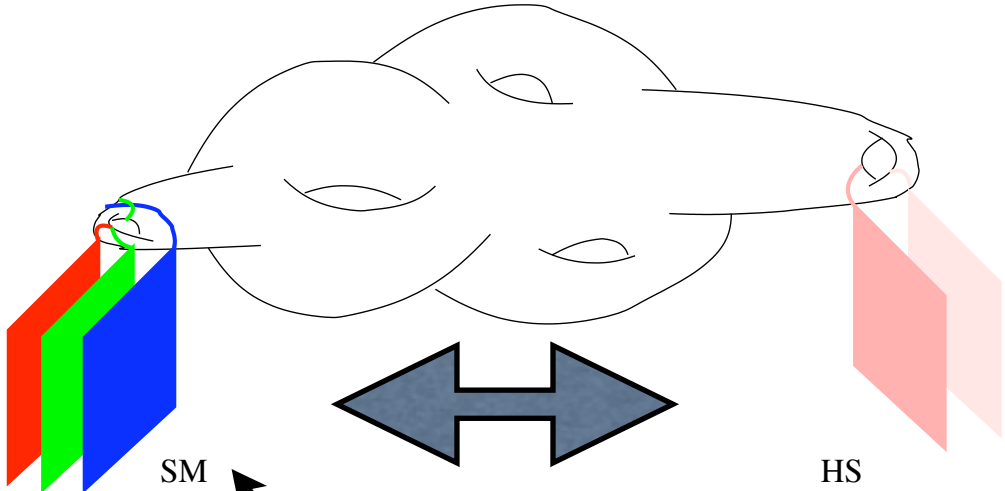
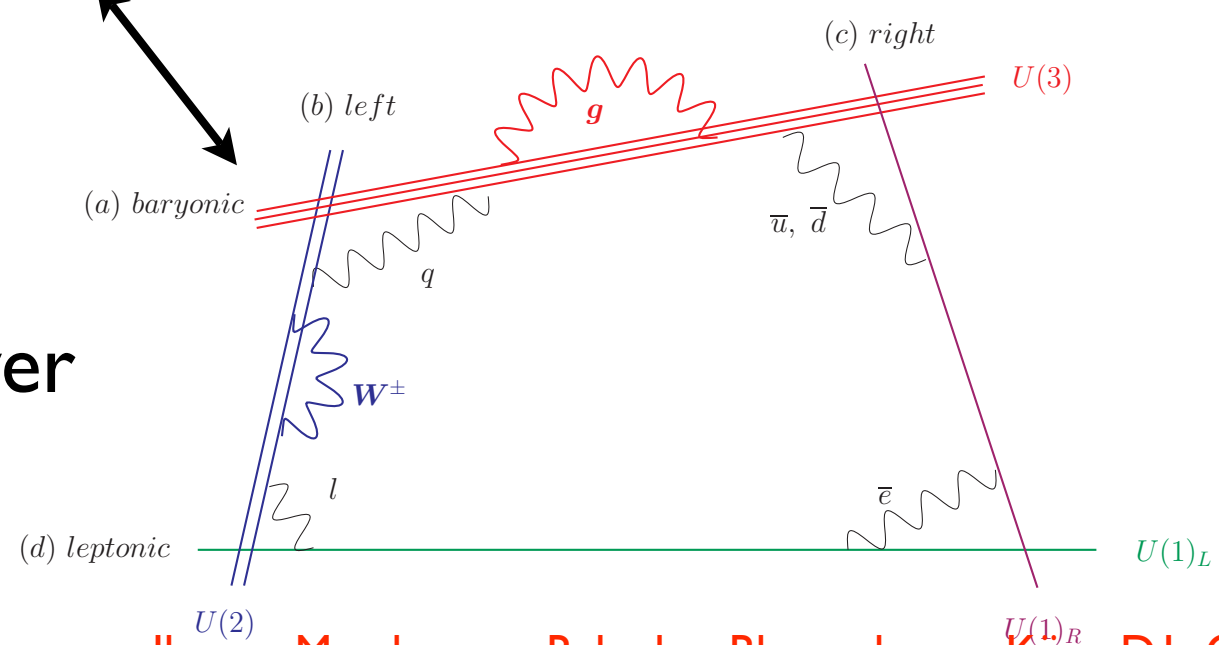


Natural
D-brane quiver
of the SM:



(Antoniadis, Kiritsis, Rizos, Tomaras; Ibanez, Marchesano, Rabadan; Blumenhagen, Kors, D.L. Ott, ...)

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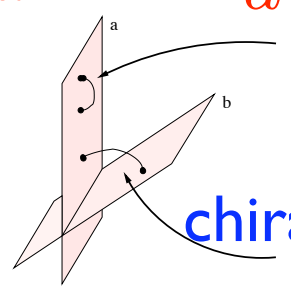

U(N)

chiral matter fields

Open string 4-dim. gauge group: $G = \prod_{a=1}^{k} U(N_a)$

4-dim. massless fermions from open strings at intersection points: $N_{a,b}^F = \Pi_a \circ \Pi_b = X_a^I Y_b^I - X_b^I Y_a^I$

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Large, but finite number of solutions. D-brane statistics!

(R. Blumenhagen, F. Gmeiner, G. Honecker, D. L., M. Stein, T. Weigand;
M. Douglas, W. Taylor; T. Dijkstra, L. Huiszoon, A. Schellekens)

(Intersecting) D-brane statistics

How many orientifold models exist which come close to the (spectrum of the) MSSM?

(Blumenhagen, Gmeiner, Honecker, Lüst, Stein, Weigand, hep-th/0411173, hep-th/0510170, hep-th/0703011; related work: Dijkstra, Huiszoon, Schellekens, hep-th/0411129; Anastasopoulos, Dijkstra, Kiritsis, Schellekens, hep-th/0605226; Douglas, Taylor, hep-th/0606109; Dienes, Lennek, hep-th/0610319; Rosenhaus, Taylor, arXiv:0905.1951)

(i) Example: $\mathcal{M}_6 = T^6/(Z_2 \times Z_2)$ IIA orientifold:

Systematic computer search (NP complete problem):

Look for solutions of a set of diophantic equations:

There exist about $1.66 \cdot 10^8$ susy D-brane models on this orbifold (with restricted complex structure)!

- Finiteness of models was proven by Douglas, Taylor.

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Restriction	Factor
gauge factor $U(3)$	0.0816
gauge factor $U(2)/Sp(2)$	0.992
No symmetric representations	0.839
Massless $U(1)_Y$	0.423
Three generations of quarks	2.92×10^{-5}
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Total	1.3×10^{-9}

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However always chiral, massless exotics!

(ii) Z6-orientifold: (exceptional, blowing-up 3-cycles!)

(Gmeiner, Lüst, Stein, hep-th/0703011)

In total $3.4 \cdot 10^{28}$ susy D-brane models.

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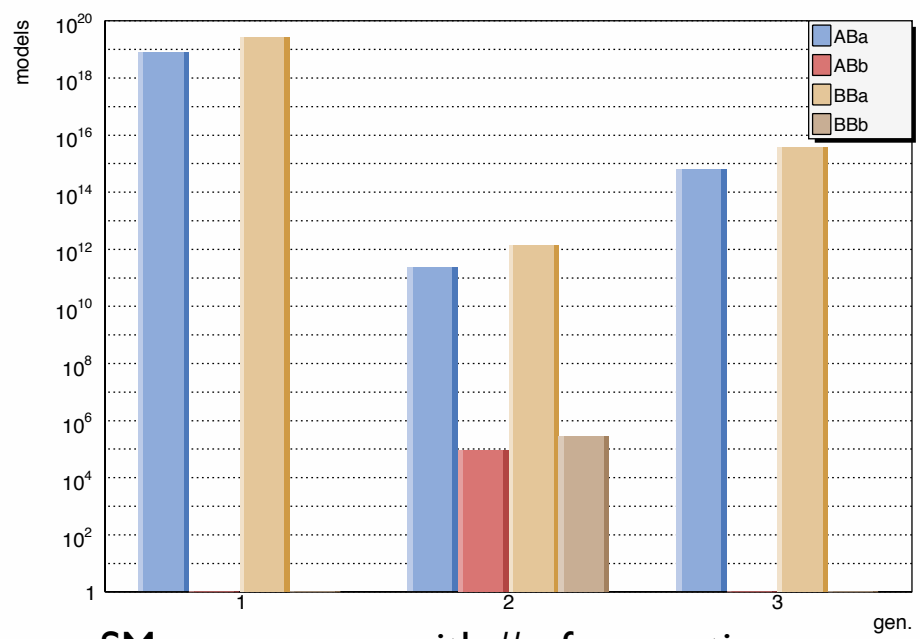

SM gauge group with # of generations

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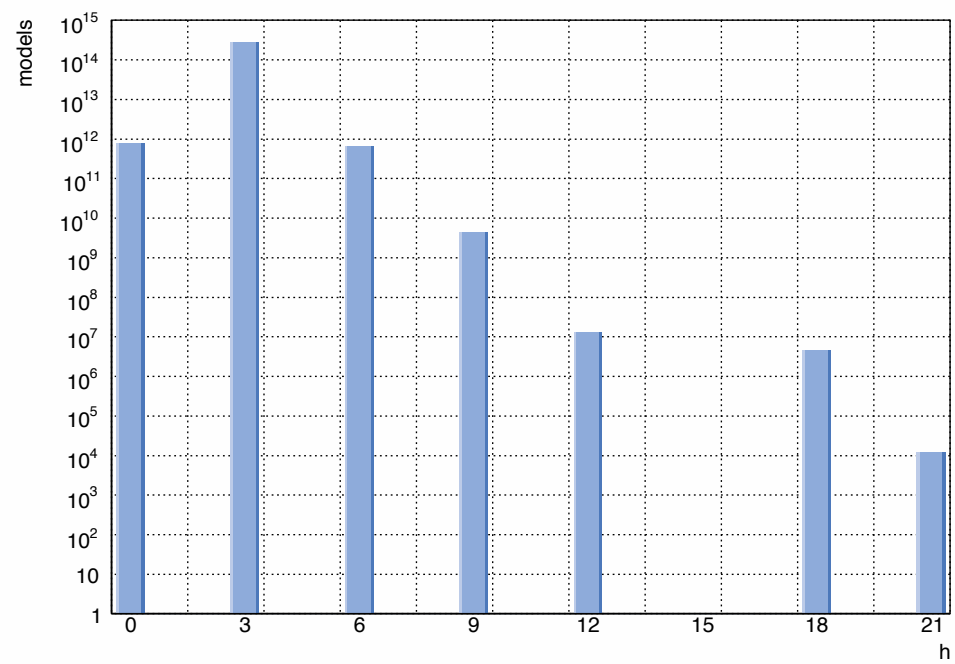

SM gauge group, 3 generations with # of Higgses

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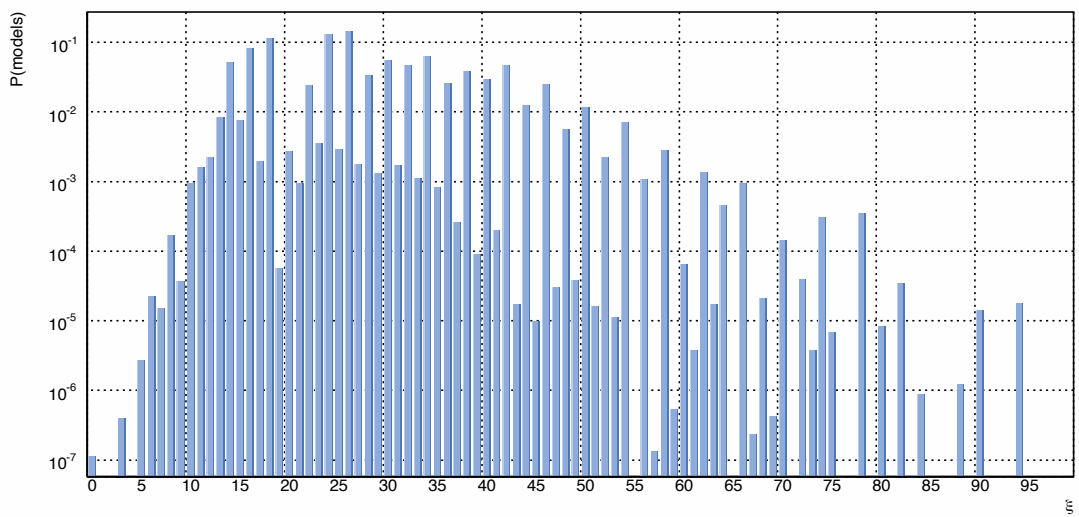

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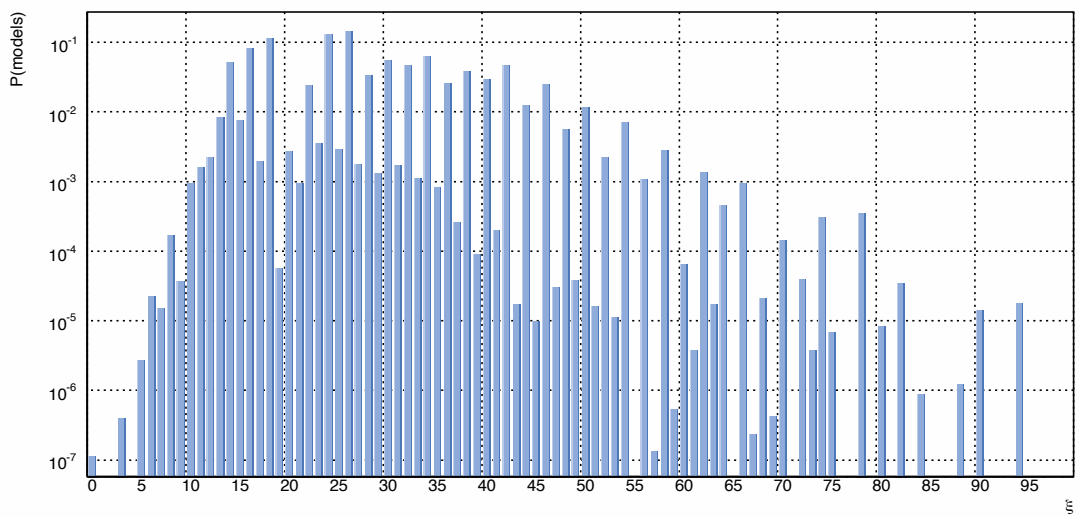

SM gauge group, 3 generations with # of chiral exotics

ISB models with no chiral exotics are possible!

Problem of realizing other GUT theories in perturbative orientifolds:

- SO(10) GUT: no spinor (16) representations from open strings

- No exceptional gauge groups from open strings.

Additional problem:

- SU(5): Some (up or down type) Yukawa couplings are absent in perturbation theory.

Non-perturbative D-instantons:

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Take into account non-perturbative instanton corrections to the effective action!

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(S. Kachru, R. Kallosh, A. Linde, S. Trivedi (2003); F. Denef, M. Douglas, B. Florea, A. Grassi, S. Kachru (2005); R. Blumenhagen, M. Cvetic, T. Weigand; D.L., S. Reffert, E. Scheidegger, W. Schulgin, S. Stieberger; Ibanez, Uranga (2006)....)

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IIA: special lagrangian submanifolds: E2 on 3-cycles

$\Updownarrow$ Mirror symmetry (SYZ)

IIB: points, (complex lines), divisors, (CY)

E(-1) (E1) E3 (E5)

Non-perturbative Yukawa couplings:

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Consider two stack a and b of D6-branes:

$$G = U(5)_a \times U(1)_b = SU(5)_a \times U(1)_a \times U(1)_b$$

Open strings:

sector	number	$U(5)_a \times U(1)_b$ reps.	$U(1)_X$
(a', a)	$3 + (1,1)$	$\mathbf{10}_{(2,0)}$	$\frac{1}{2}$
(a, b)	3	$\overline{\mathbf{5}}_{(-1,1)}$	$-\frac{3}{2}$
(b', b)	3	$\mathbf{1}_{(0,-2)}$	$\frac{5}{2}$
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Abelian symmetries: $U(1)_a \times U(1)_b$

One anomalous linear combination: global symmetry

One anomaly free linear combination $U(1)_X$

From $U(1)_X$ charges it follows that:

Perturb. allowed couplings(e.g. u,c,t-quarks): $\langle \mathbf{10}_{(2,0)}\, \bar{\mathbf{5}}_{(-1,1)}\, \bar{\mathbf{5}}^H_{(-1,-1)} \rangle$,

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(⇨ Talks by Anastasopolous, Blumenhagen)

Non-perturbative constructions:

(i) IIA orientifolds with intersecting D6-branes

$\Rightarrow$ M-theory on 7-dim. G2 manifolds

(Acharya, Atiyah, Witten, ...)

- Gauge bosons live on 3-dimensional singularities Q3

$\Leftrightarrow$ D6-branes

- Chiral fermions live on 0-dimensional conical singularities (points on 7-dim manifolds)

$\Leftrightarrow$ Intersections of D6-branes

Local ALE fibrations over Q3 were recently constructed: Pantev, Wijnholt, arXiv:0905.1968.

(ii) IIB orientifolds with intersecting D7-branes ⇒

F-theory on 8-dim. CY 4-folds (GUT models)

(Beasly, Heckman, Vafa; Donagi, Wijnholt, ...)

Local set up:

- Gauge bosons live on 4-dimensional ADE-singularities

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☺ matter in spinor representations

☺ non zero Yukawa coupl. (intersections of 3 matter curves)

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Marsano, Saulina, Schafer-Nameki, arXiv:0906.4672, arXiv:0904.3932.

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(⇨ Talks by Blumenhagen, Klemm, Tatar, Wijnholt)

Outline

- Intersecting D-brane models

(Lecture I)

- Stringy signatures at LHC

(The LHC string hunter's companion)

(Lecture II)

(D. Lüst, S. Stieberger, T. Taylor, arXiv:0807.3333;
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(⇨ Talk by Antoniadis)

II) The LHC String Hunter's Companion:

Recall basic set-up of type IIA/B orientifolds:

- Gravitons live as closed strings in 10-dimensional bulk.
- Non-Abelian gauge bosons live as open strings on lower dimensional D-branes.
- Chiral fermions are open strings on the intersection locus of two D-branes:

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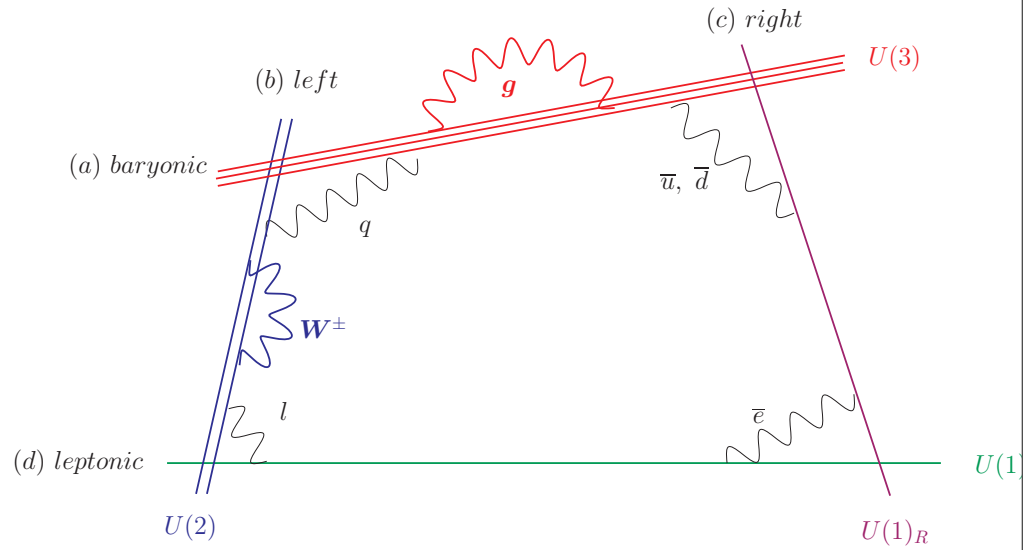

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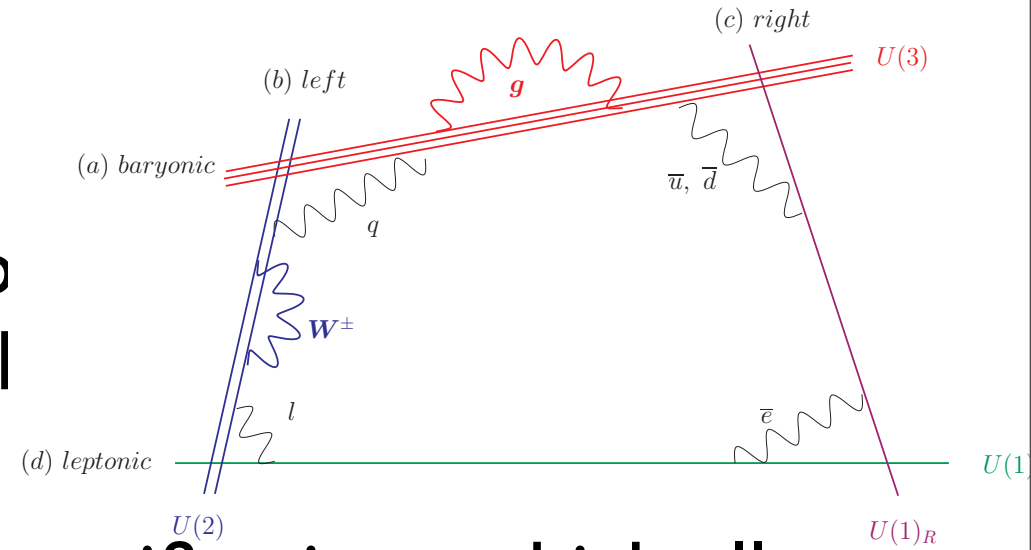

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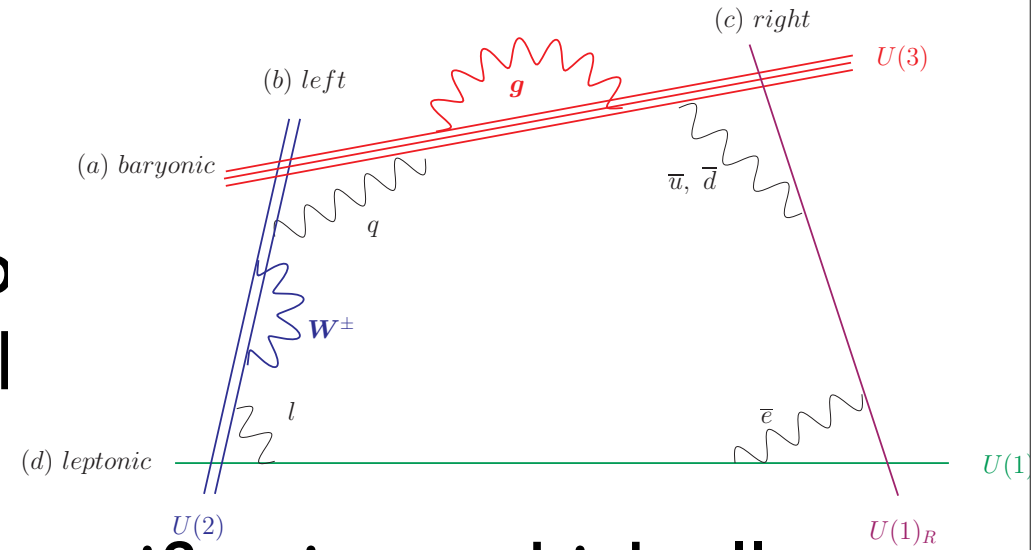

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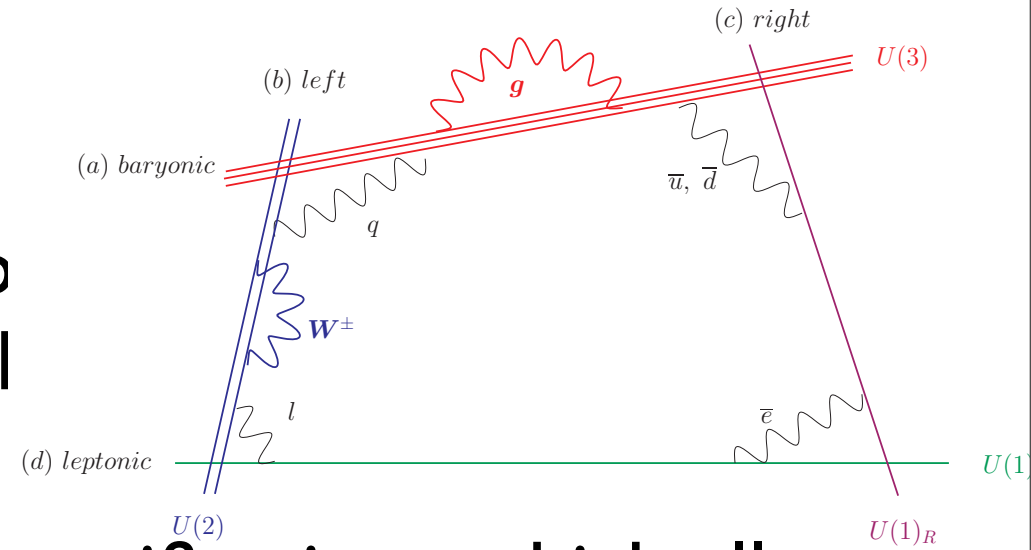

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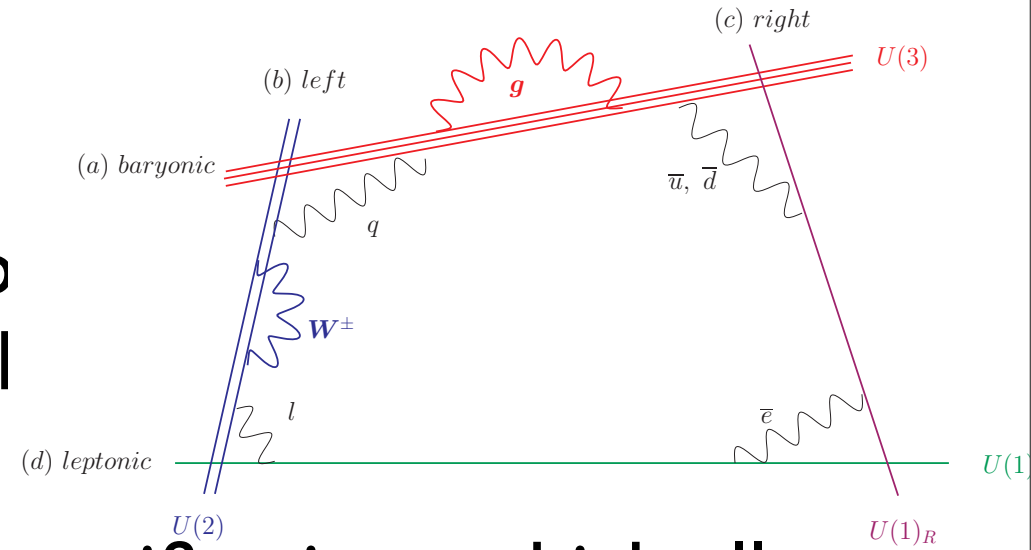

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⇒ Universal predictions that are true for all points in the landscape, i.e. independent from any details of the compact space!

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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:

There are 4 natural scenarios for the string scale:

(o) Planck scale scenario:

M_s is the gravitational 4D Planck scale

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

Gauge coupling unification at the Planck scales needs further effects (string threshold corrections, ...)

Alternatively relate the string scale to particles physics mass scales.

(i) GUT scale scenario:

M_s is the 4D scale of gauge coupling unification

$$\mathrm{M}_s \equiv M_{GUT} \simeq 10^{16}\ \mathrm{GeV}$$

$$\mathrm{M}_{GUT} = M_{SM} \exp\left(\frac{g_{Dp}^{-2}(M_{SM}) - g_{Dp}^{-2}(M_{GUT})}{b_p} \right)$$

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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:

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

(No natural gauge coupling unification!)

(iii) Low string scale scenario:

(Antoniadis, Arkani-Hamed, Dimopoulos, Dvali)

M_s is the Standard Model (TeV) scale:

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

(No natural gauge coupling unification!)

(Effective scale of gravity is high (i.e. gravity is weak), since the gravitons can propagate into the large 6-dim. bulk space!)

Dimensionless volumes in string units, corresponding to the four scenarios:

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

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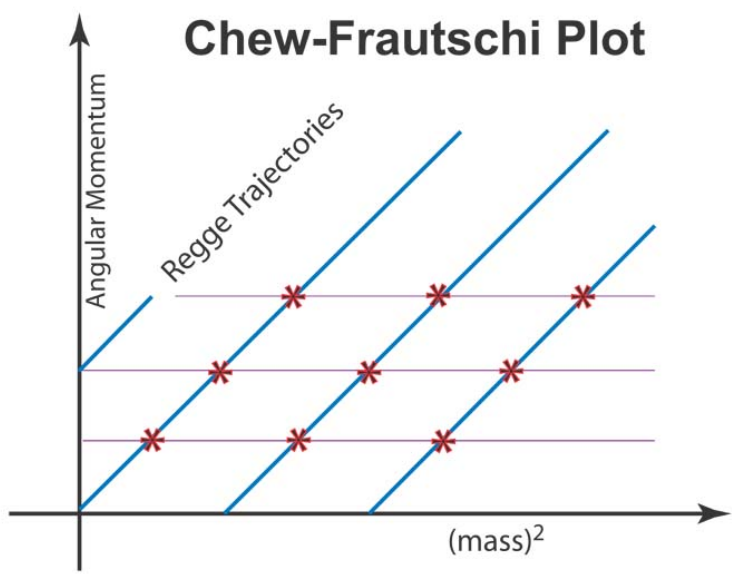
(i) Stringy Regge excitations:

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

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:

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

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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:

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

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

Problem: the very light mass causes a fifth force.

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

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Would rule out TeV string scale !

But one expects a mass shift by radiative corrections:

(G. Dvali, D. Lüst, work in progress)

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

(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 !

Type IIB orientifolds: Realization of low string scale compatifications on „Swiss Cheese“ Manifolds:

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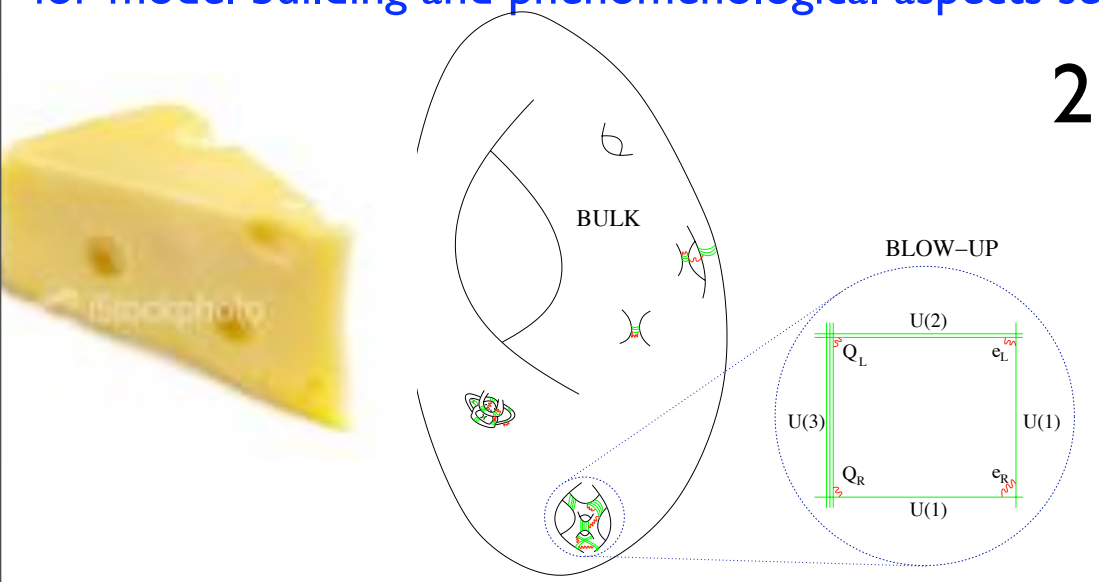

2 requirements:

- 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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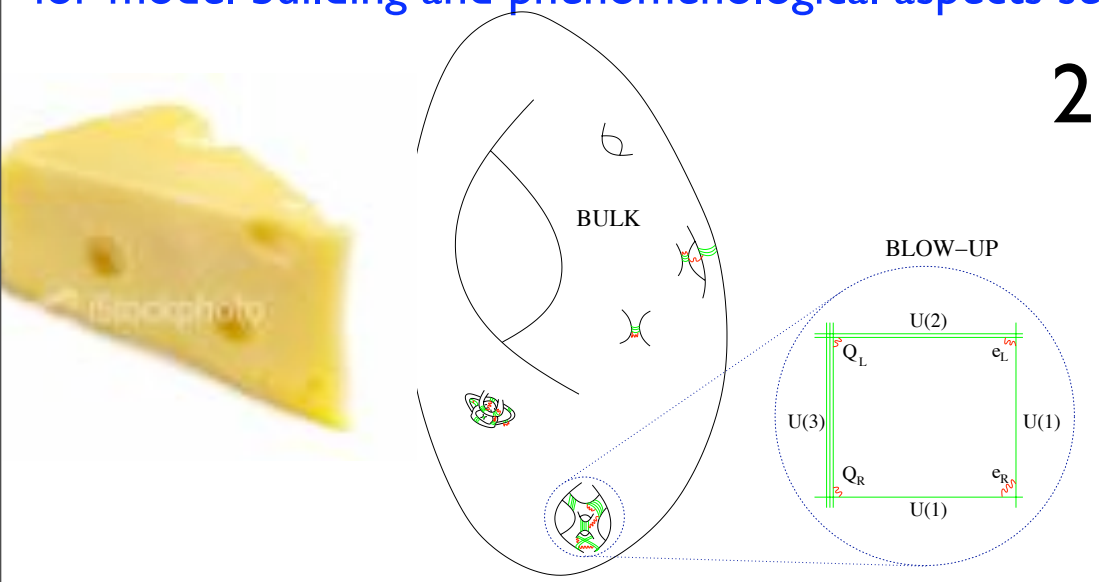

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Moduli potential:

Kähler potential: $$K = K_{cs} - 2\log\left(V_6 + \frac{\xi}{2g_s^{\frac{3}{2}}}\right)$$ (Becker, Becker, Haack, Louis)

Superpotential: $$W = W_{cs} + \sum A_i \exp(-a_i t_i)$$

Moduli stabilization ➢

Minima: Large hierarchical scales with $V_6 M_s^6 = 10^{16}, 10^{32}$

In general:

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

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

Bounds from black hole decays:

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

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: $M = M(\phi)$

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

Bound forbids essentially large trans-planckian vevs:

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?

(G. Dvali, D. Lüst, work in progress)

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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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 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!

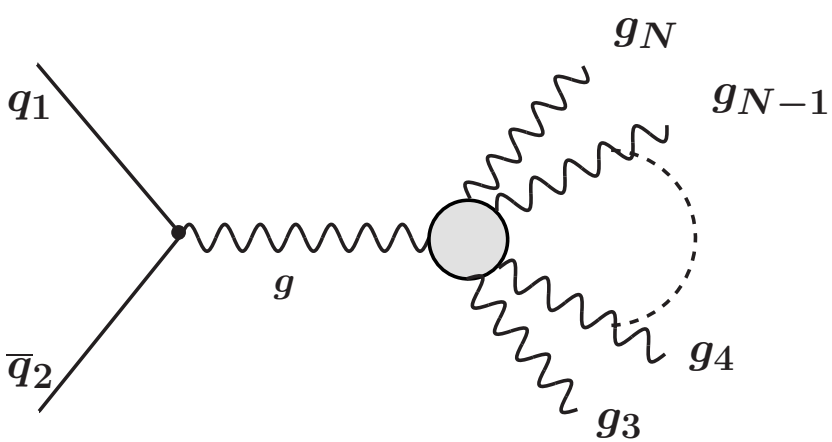
(ii) They contain stringy corrections.

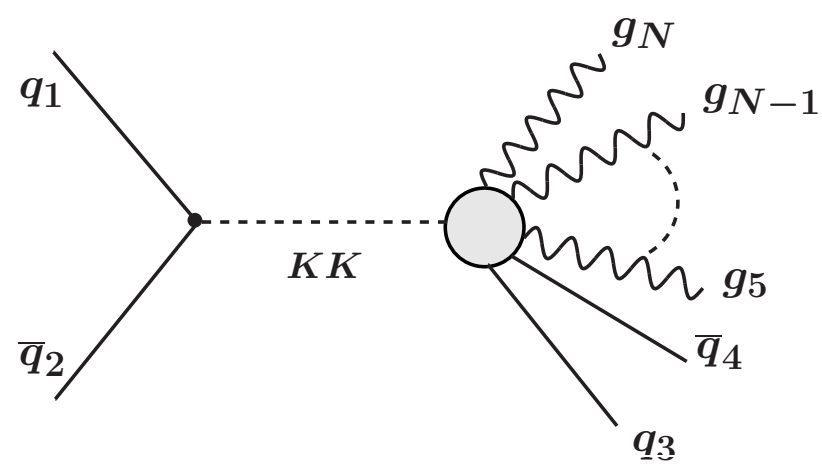
- n-point tree amplitudes with 0 or 2 open string fermions (quarks, leptons) and N or N-2 gauge bosons (gluons) are completely model independent.

  $\Rightarrow$ Information about the string Regge spectrum.

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

  $\Rightarrow$ Information about the internal geometry.





Parton model cross sections of SM-fields:

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

e.g. 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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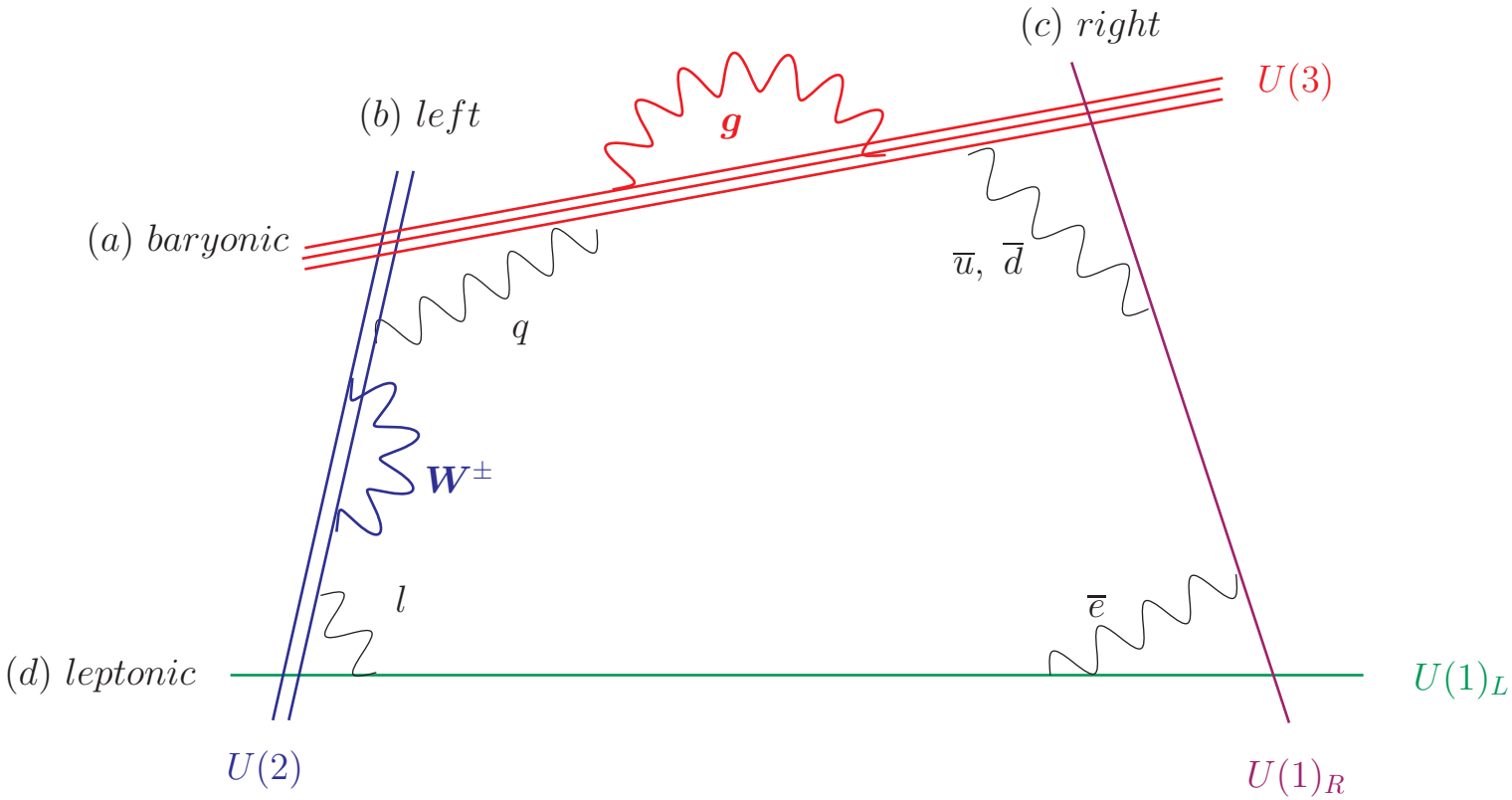

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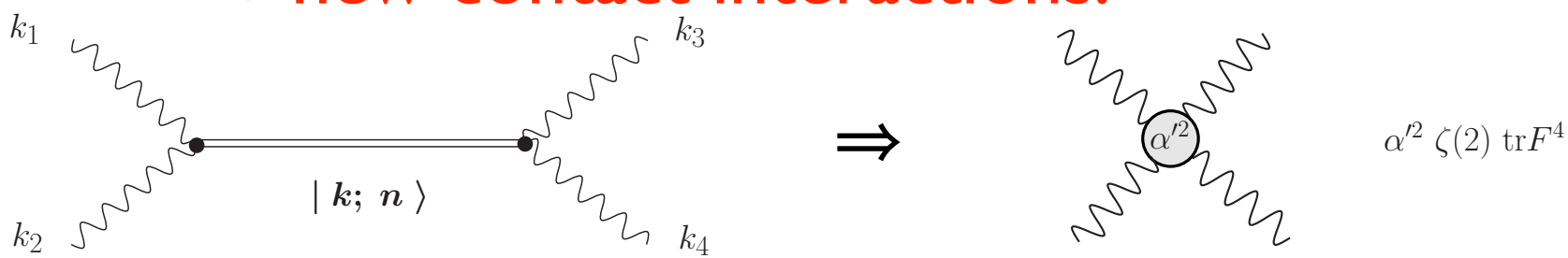
- Exchange of string Regge resonances (Veneziano like ampl.)

$\Rightarrow$ 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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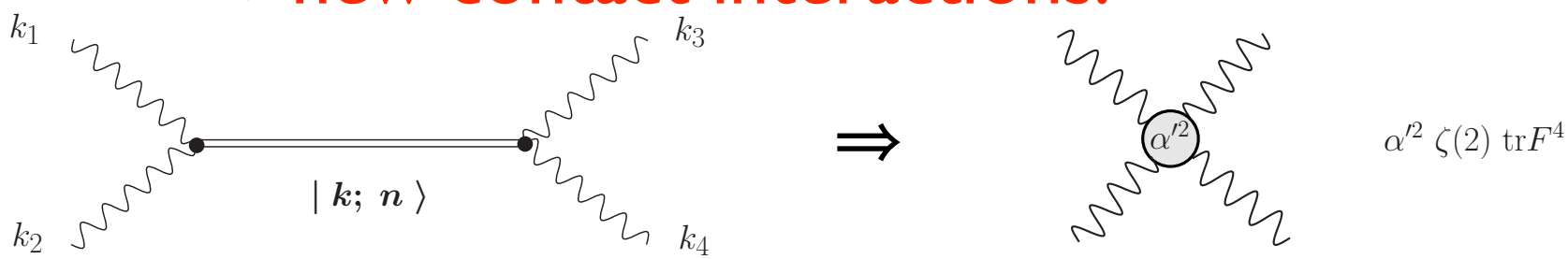

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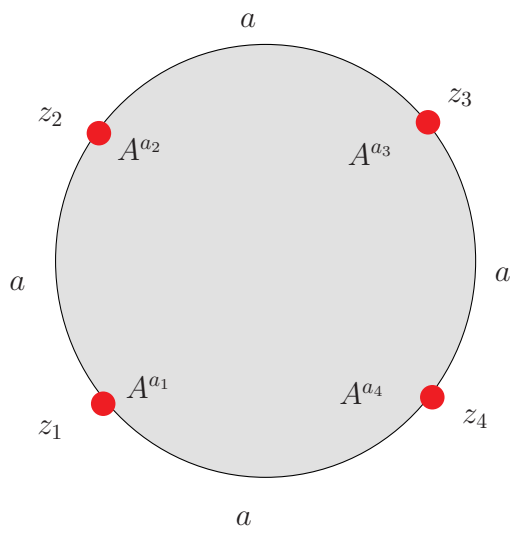
- Exchange of KK and winding modes (model dependent)

4 gauge boson amplitudes:

Disk amplitude:



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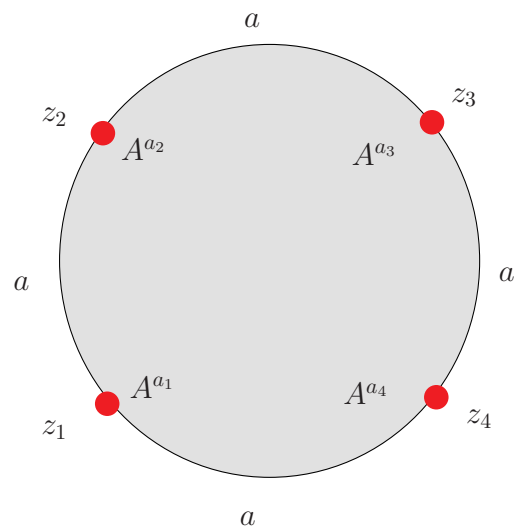

Only string Regge resonances are exchanged $\Rightarrow$

These amplitudes are completely model independent!

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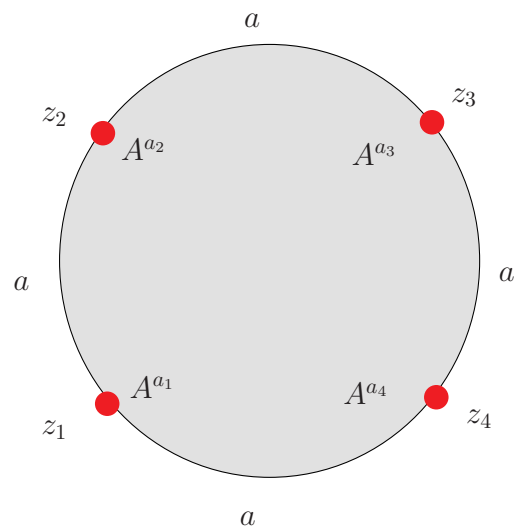

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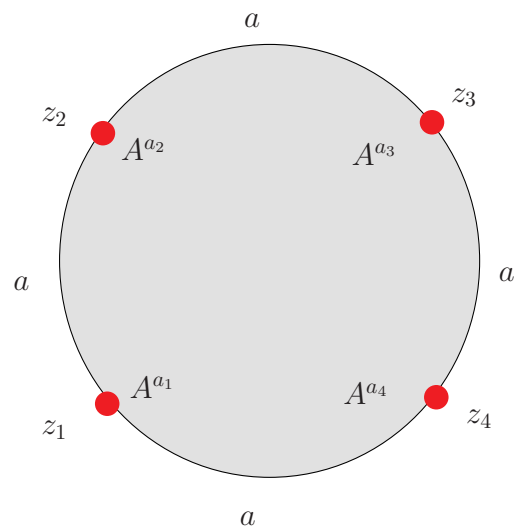

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$$|\mathcal{M}(gg \to gg)|^2 = g_3^4 \left(\frac{1}{s^2} + \frac{1}{t^2} + \frac{1}{u^2} \right) \left[\frac{9}{4} s^2 V_s^2(\alpha') - \frac{1}{3} \left(s V_s(\alpha') \right)^2 + (s \leftrightarrow t) + (s \leftrightarrow u) \right]$$

(Stieberger, Taylor)

$\Rightarrow$ dijet events

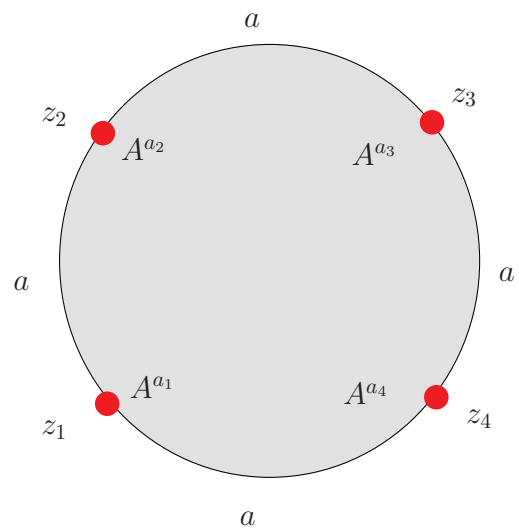
$$|\mathcal{M}(gg \to g\gamma(Z^0))|^2 = g_3^4 \frac{5}{6} Q_A^2 \left(\frac{1}{s^2} + \frac{1}{t^2} + \frac{1}{u^2} \right) \left(s V_s(\alpha') + t V_t(\alpha') + u V_u(\alpha') \right)^2$$

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

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

4 gauge boson amplitudes:

Disk amplitude:



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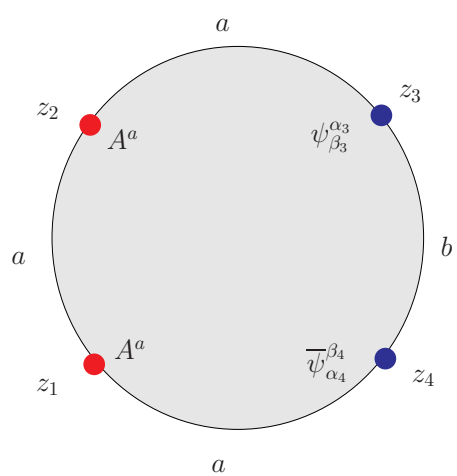
Examples:

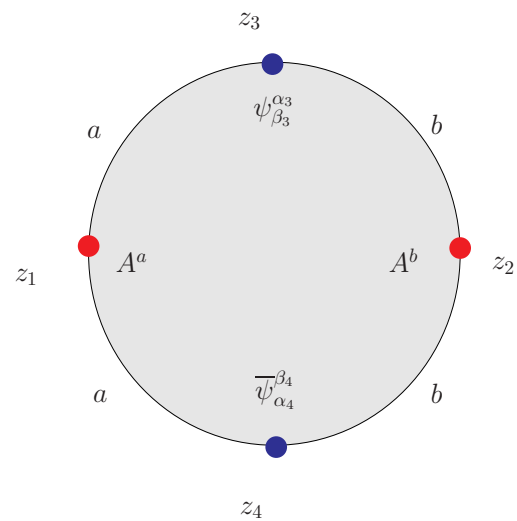
$\alpha' \to 0$: agreement with SM!

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

$$|\mathcal{M}(gg \to \gamma(Z^0))|^2_{\alpha' \to 0} \to 0$$

2 gauge boson - two fermion amplitude:





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

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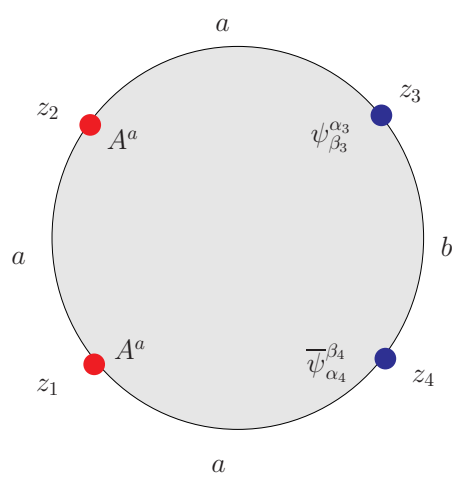

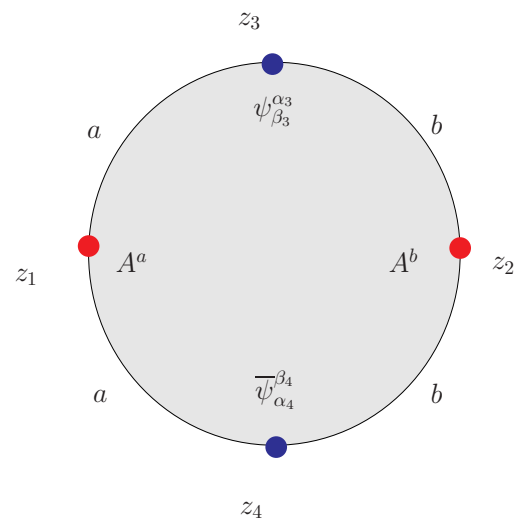

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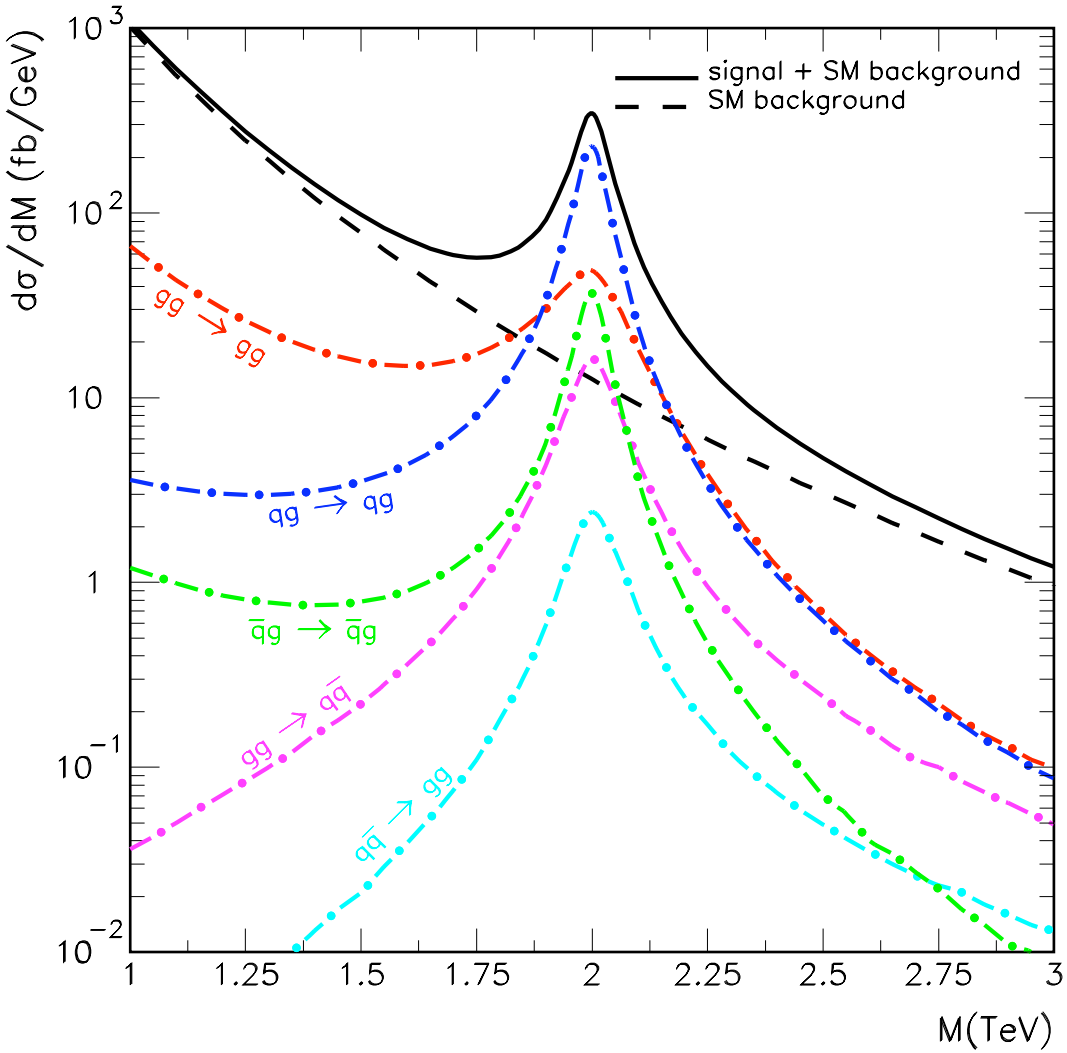
These stringy corrections can be seen in dijet events at LHC:



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

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

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

Widths can be computed in a model independent way !

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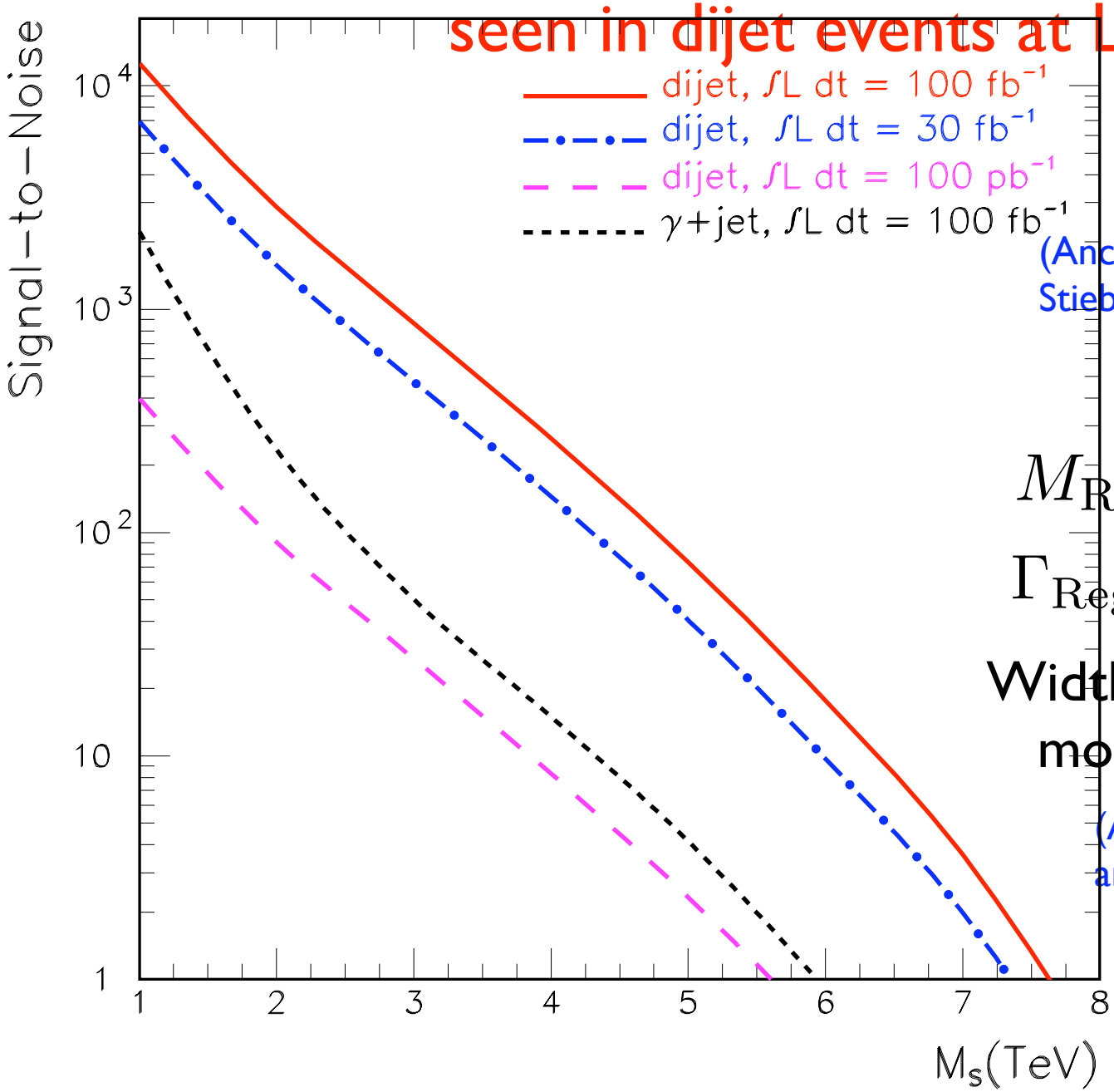

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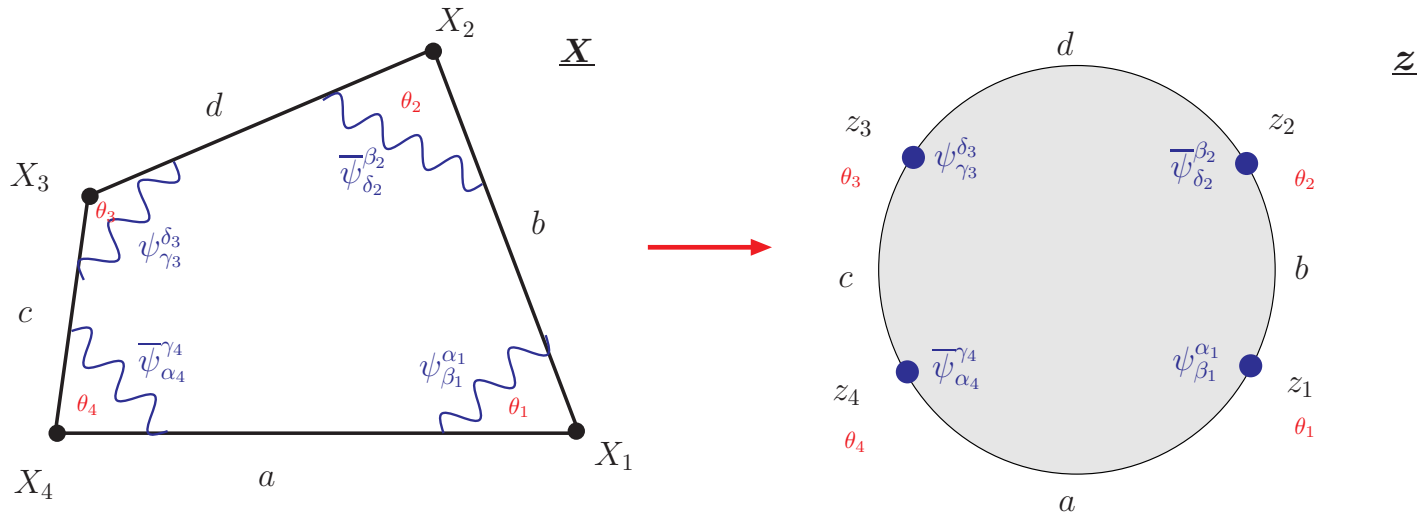

Exchange of Regge, KK and winding resonances.

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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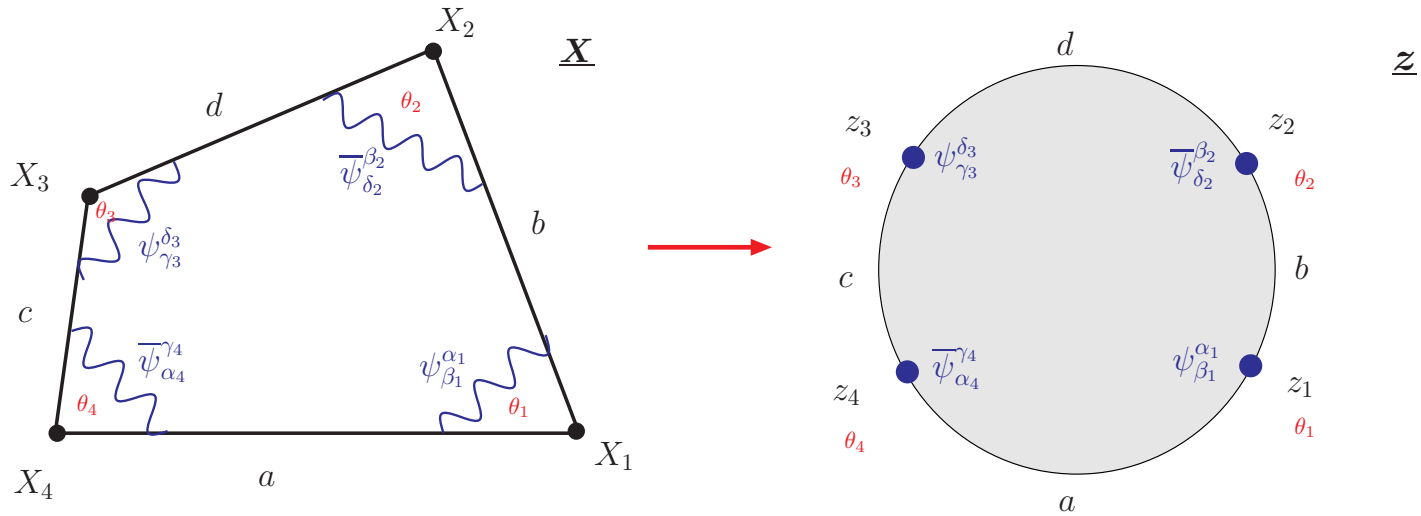

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Squared 4-quark amplitude with identical flavors:

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

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:

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

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

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

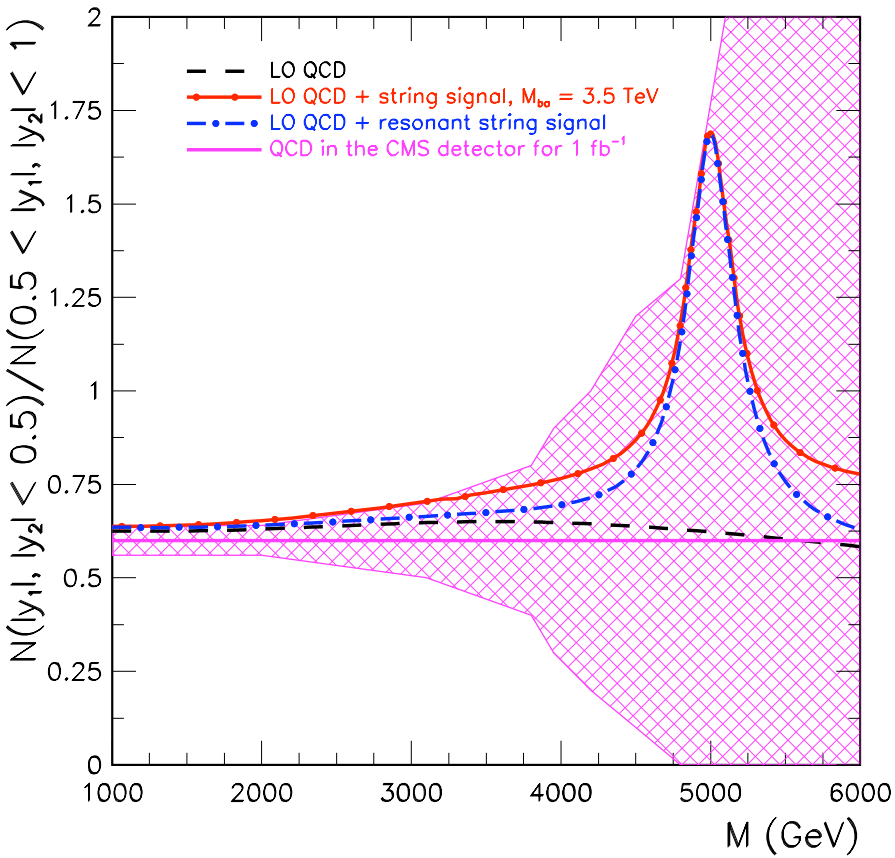
M_{ab} : KK of SU(2) branes and winding modes of SU(3) branes: $M_{ab} = 0.7 M_s$

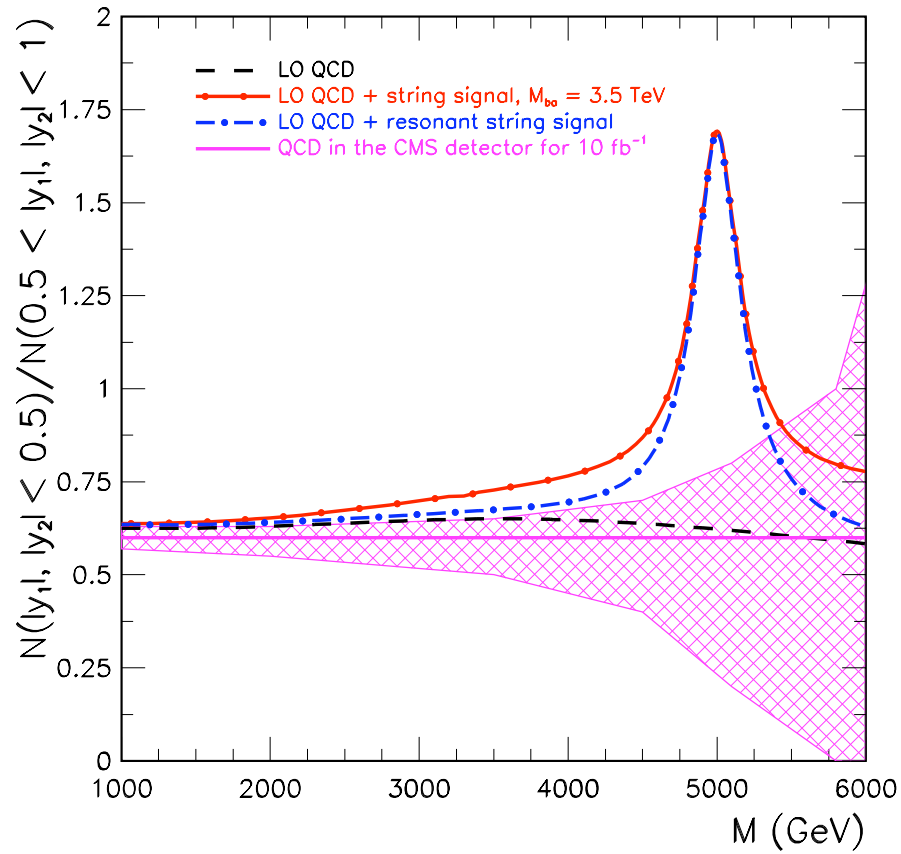
N_p : Degeneracy of KK-states; take $N_p = 3$

Δ : Thickness of D-branes

Dijet angular contribution by t-channel exchange:

CMS detector simulation:





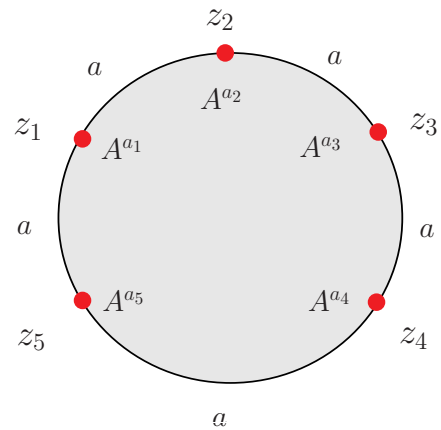
Luminosity $1\mathrm{fb}^{-1}$ $10\mathrm{fb}^{-1}$

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).

(i) 5 gluons:

(Stieberger, Taylor (2006))

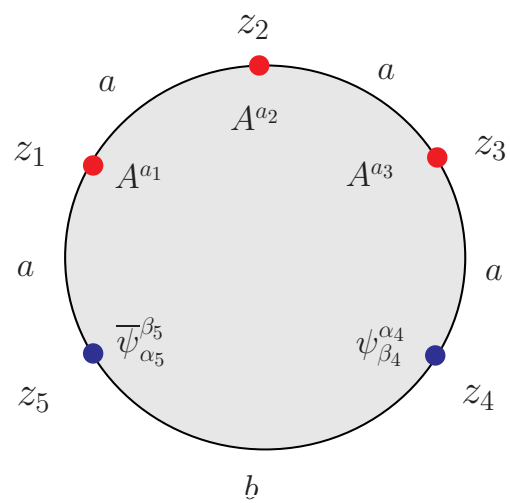


Field theory factors:

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

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

(ii) 3 gluons, 2 quarks:



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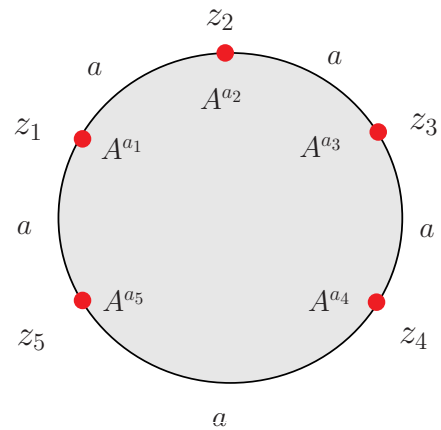

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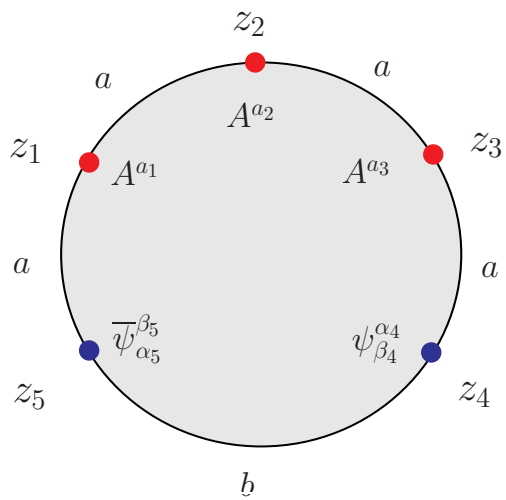

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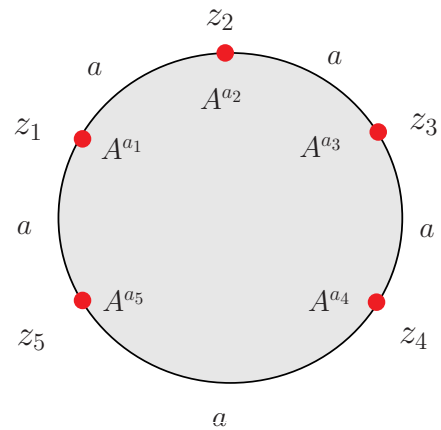

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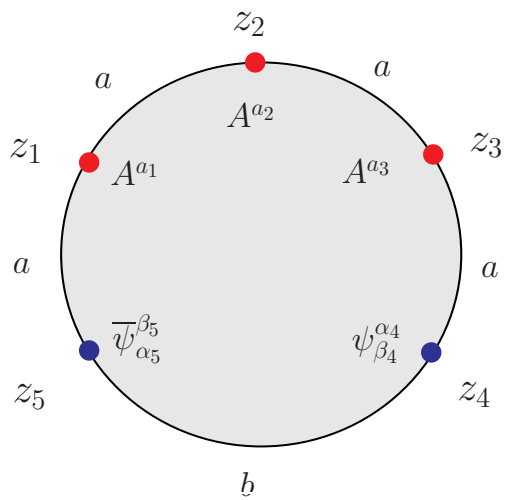

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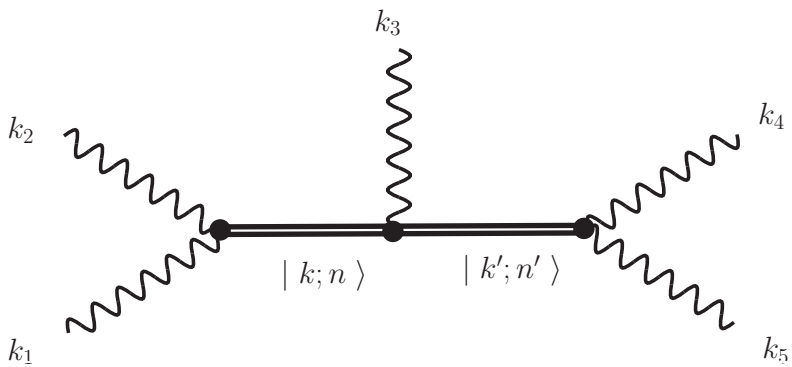
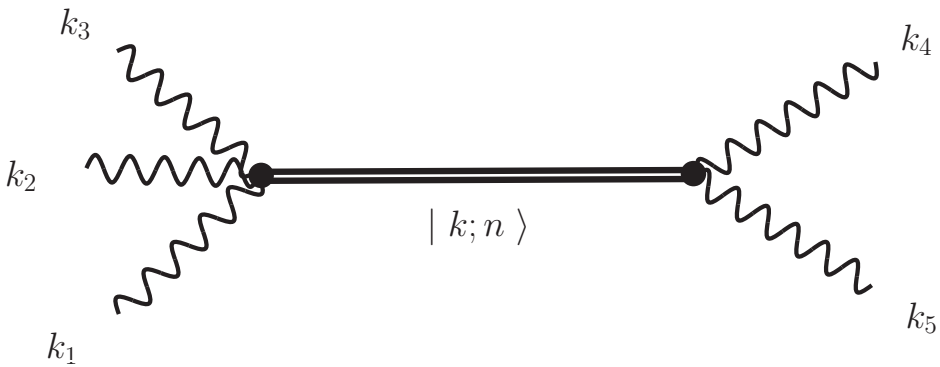
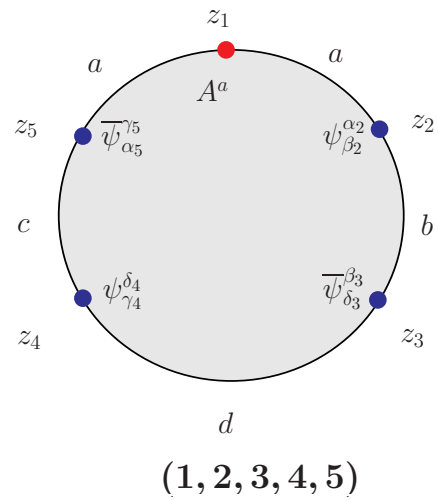
The two kinds of amplitudes are universal: the same Regge states are exchanged:



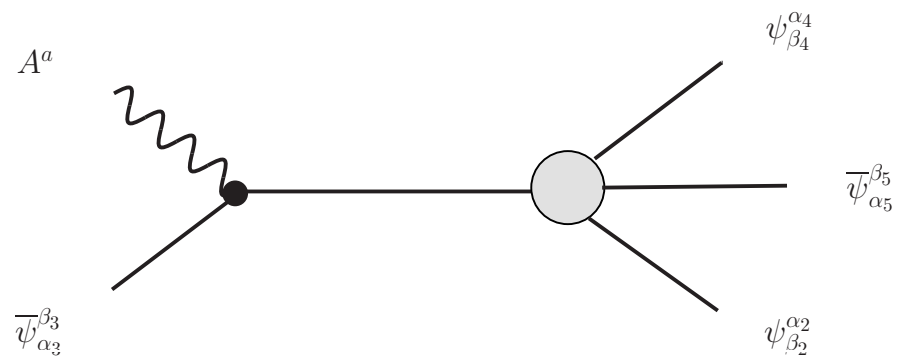


(iii) 1 gluon, 4 quarks:

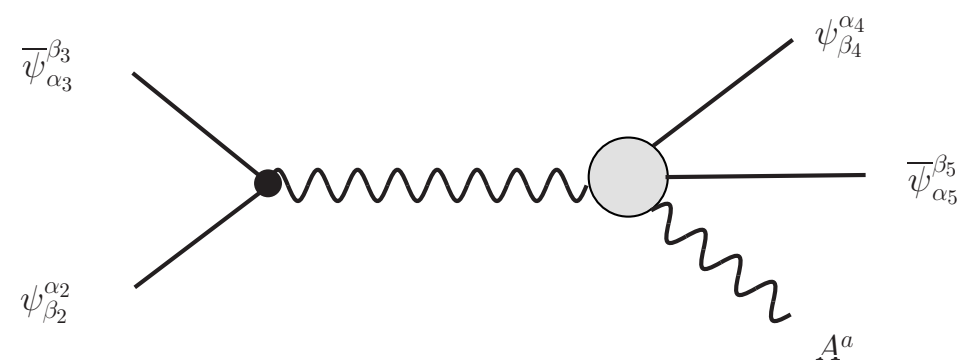


This amplitude has a similar structure as the 4 quark amplitude: exchange of Regge and KK modes.

Factorization on the 4 quark amplitude:



Factorization on the 2 quark - 2 gluon amplitude:



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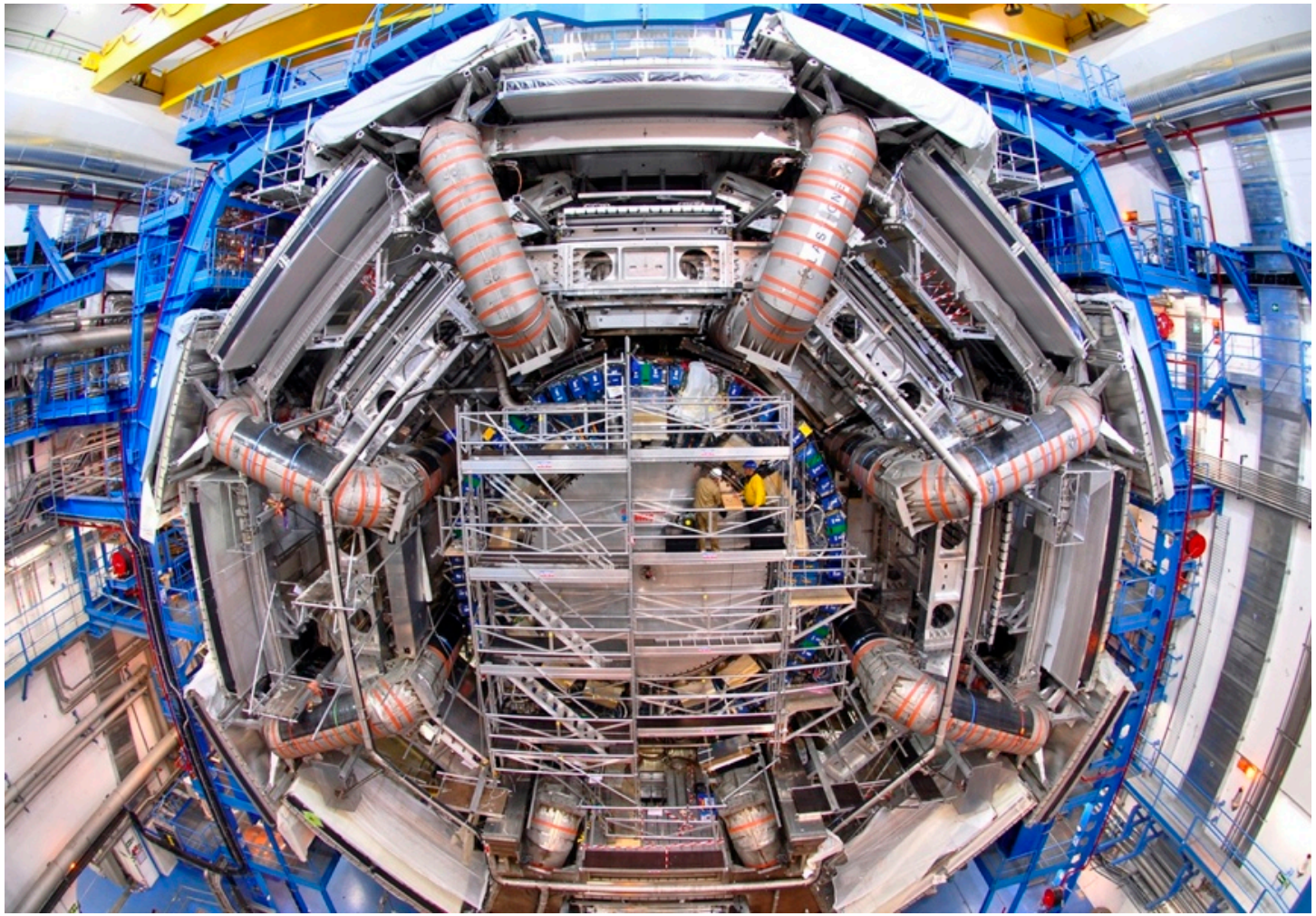
Computations done at weak string coupling !
Black holes are heavier than Regge states:

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

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



Thank you !