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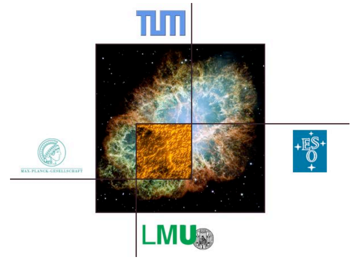

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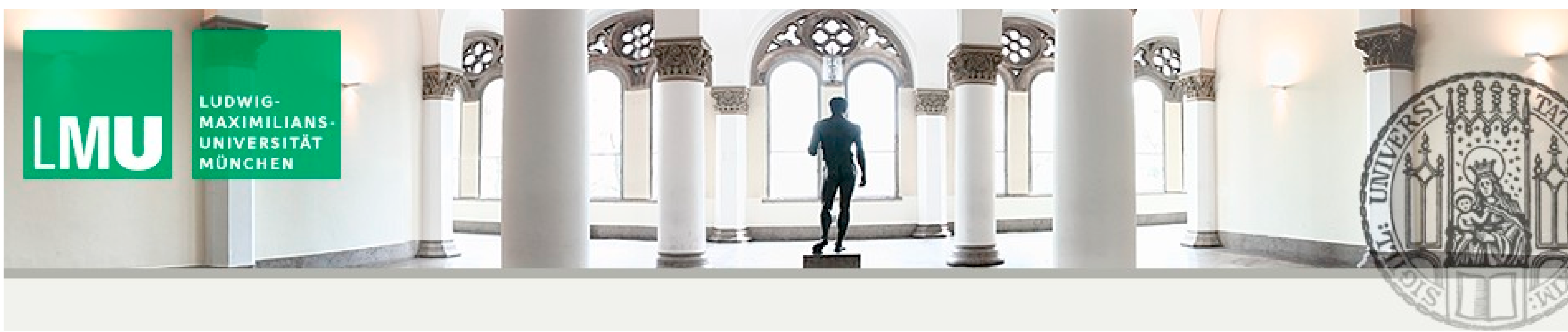
The Landscape of String theory: Intersecting branes (statistics and collider signatures) and AdS flux vacua

Dieter Lüst, LMU (ASC) and MPI München



CERN TH-Colloquium, July 23, 2008

String theory: math/phys collaboration

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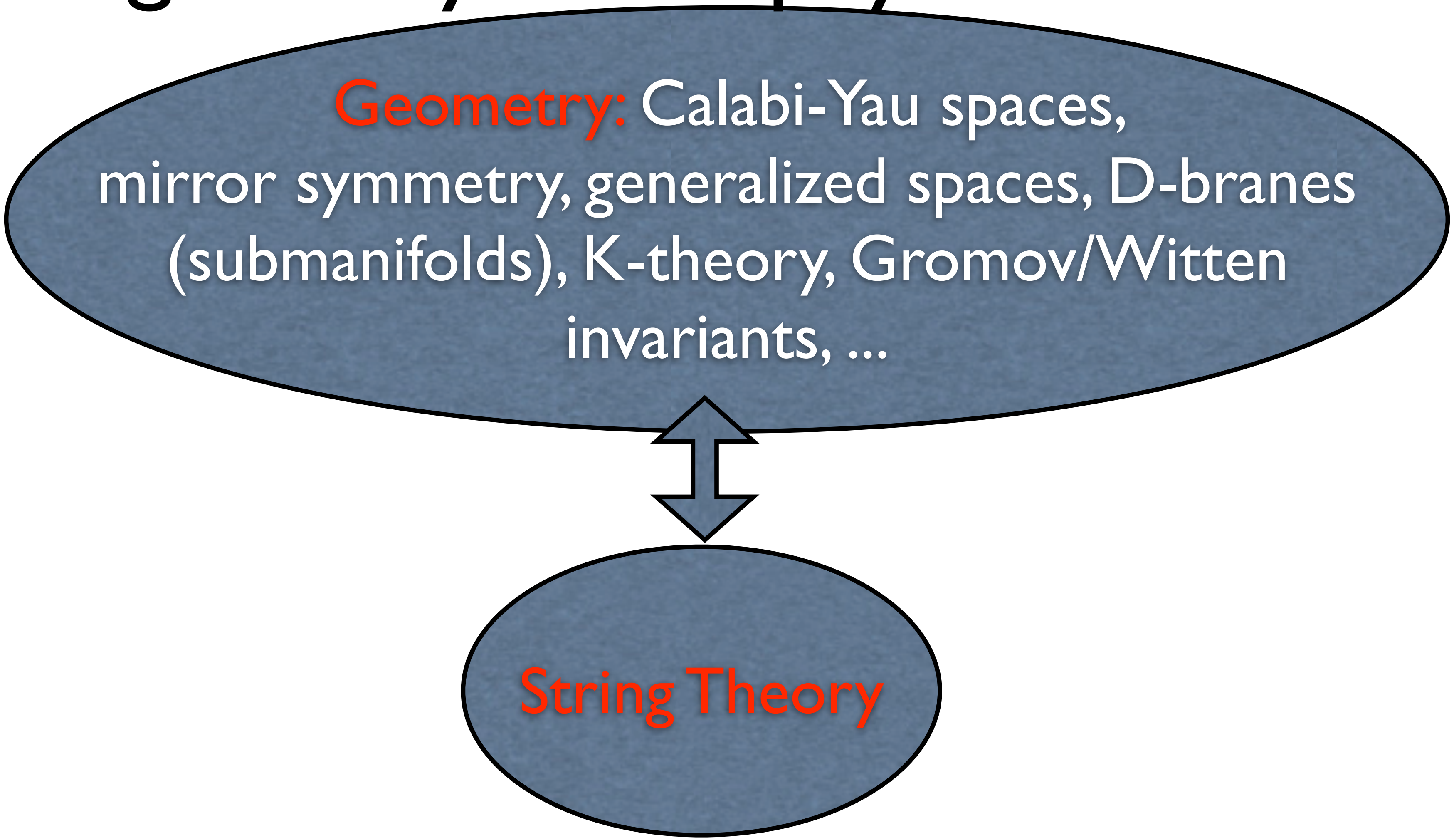

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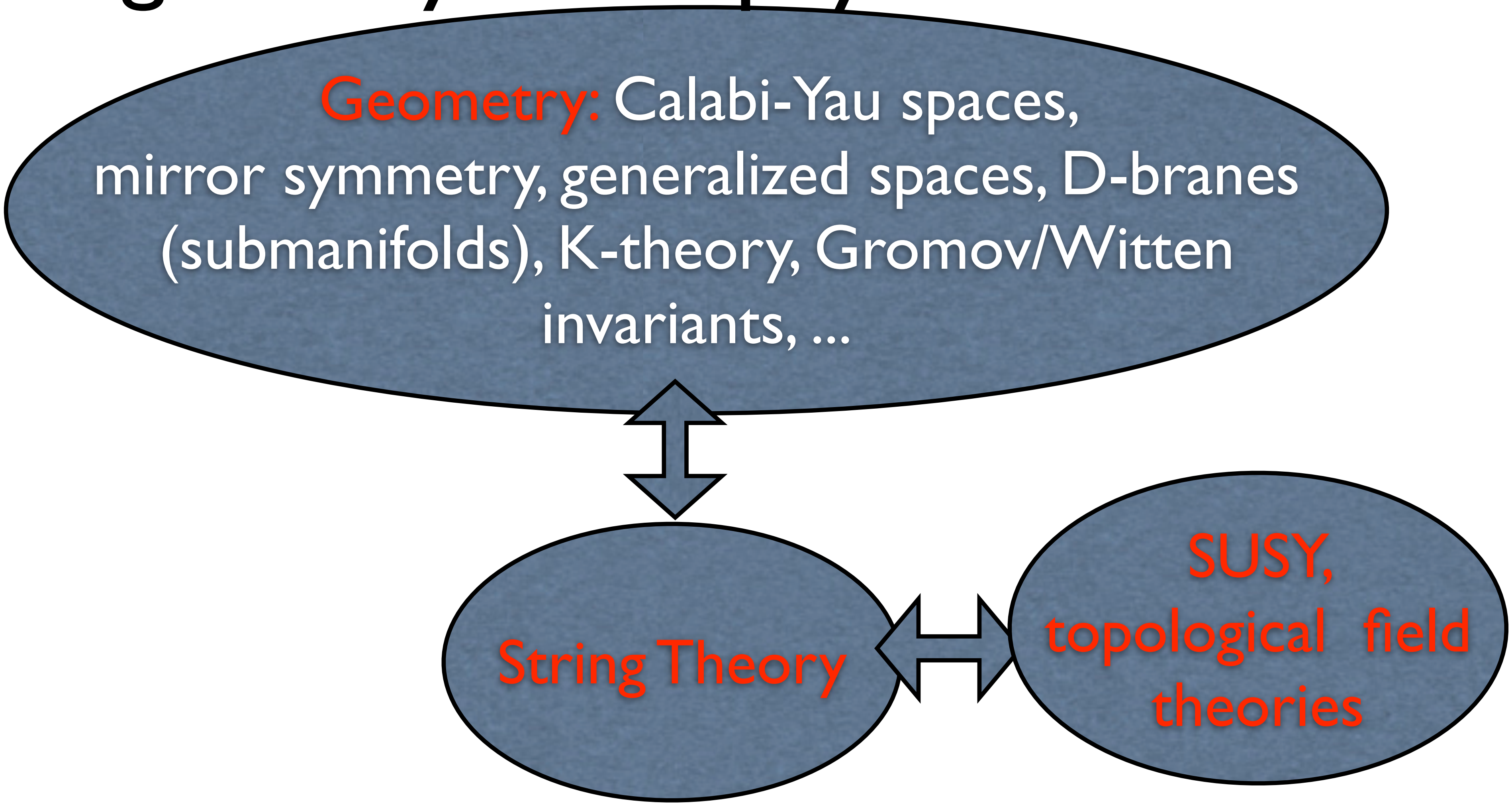

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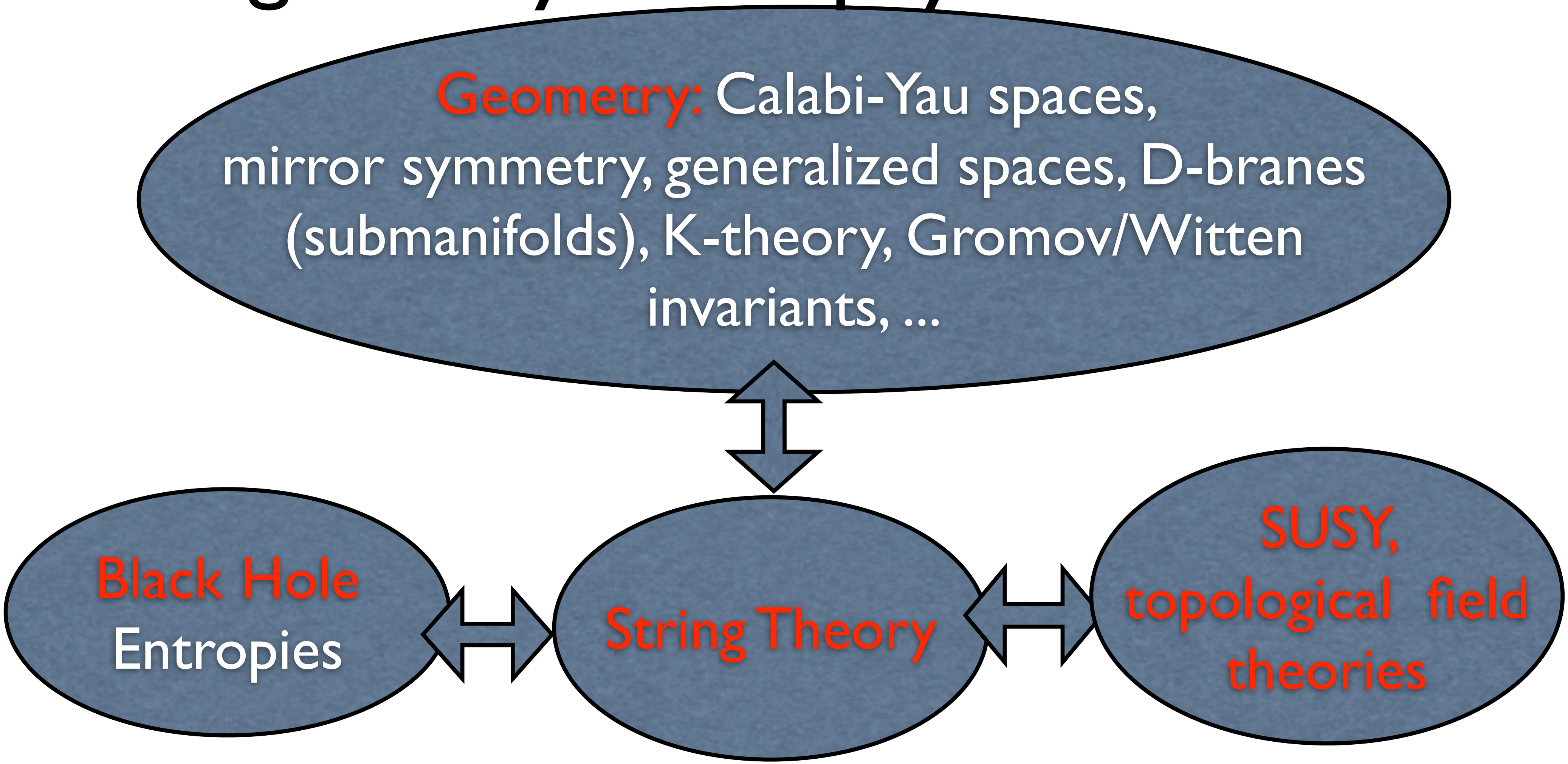

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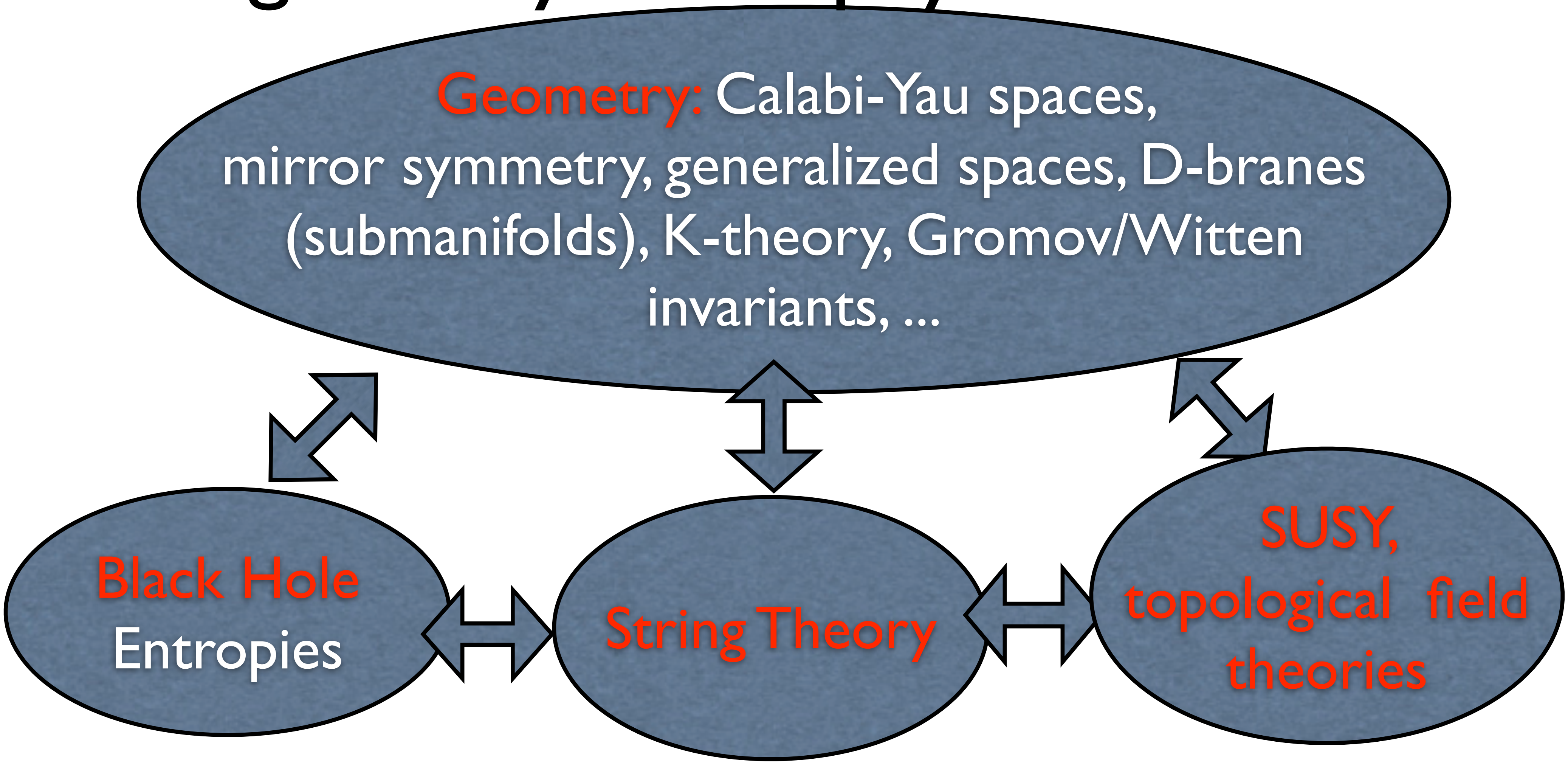

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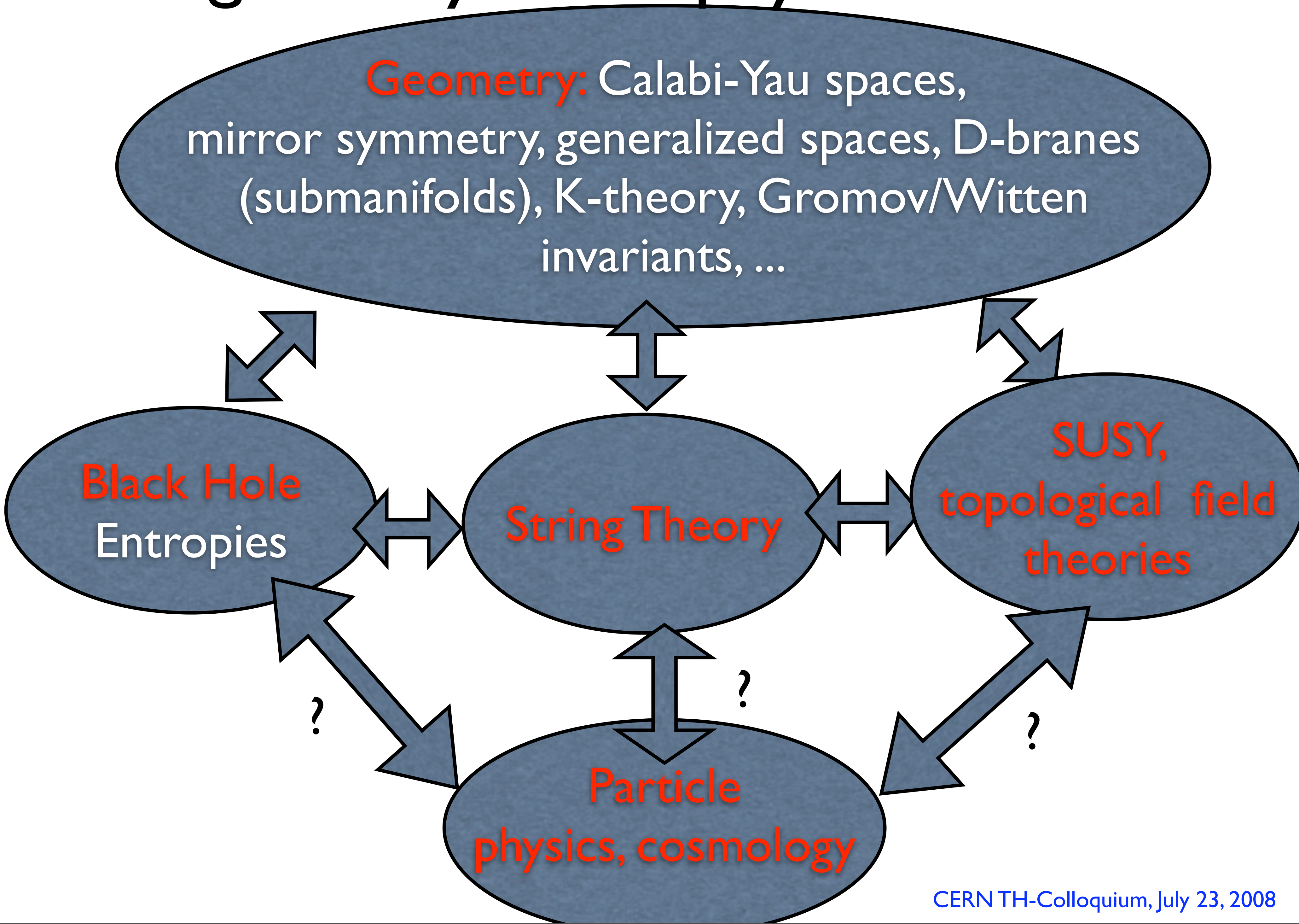

Introduction:

Count the number of consistent string vacua ➤

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

(Lerche, Lüst, Schellekens (1986), Douglas (2003))

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Two strategies to find something interesting:

- Explore all mathematically consistent possibilities: top down approach (quite hard), string statistics.

- Do not look randomly - look for green (promising) spots in the landscape ➠ model building, bottom up approach.

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Today: We will discuss some aspects of the landscape of intersecting branes and fluxes

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Geometrization of particles and their interactions!

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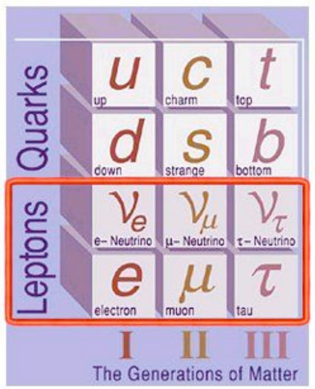
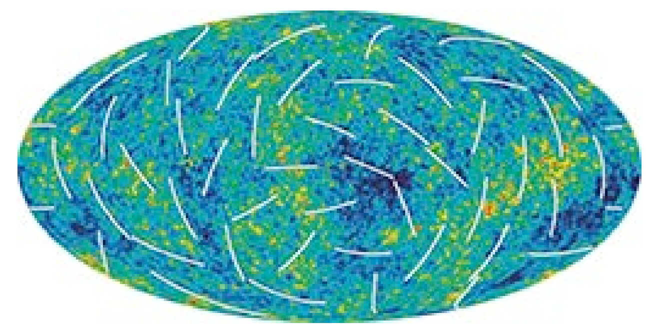
Dictionary:

Particles physics | Cosmology



Gauge interactions:

$$G = SU(3) \times SU(2) \times U(1)$$



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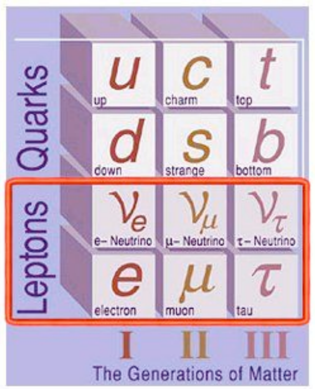

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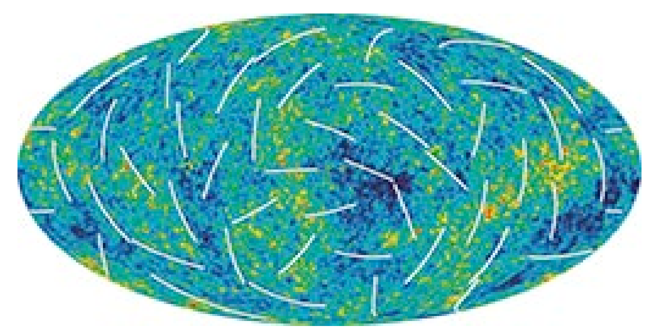
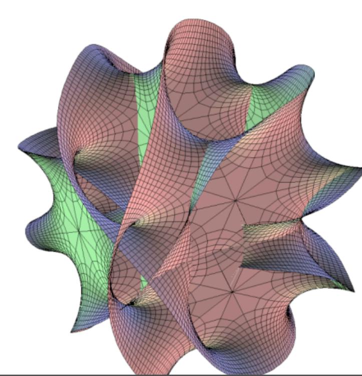


geometry & topology of strings and branes



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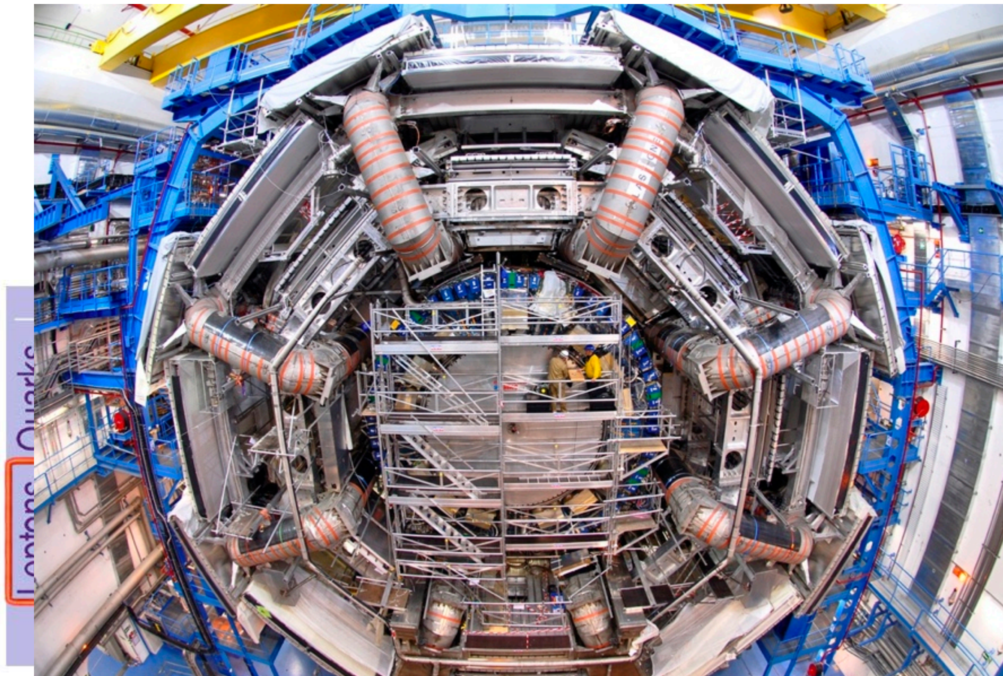

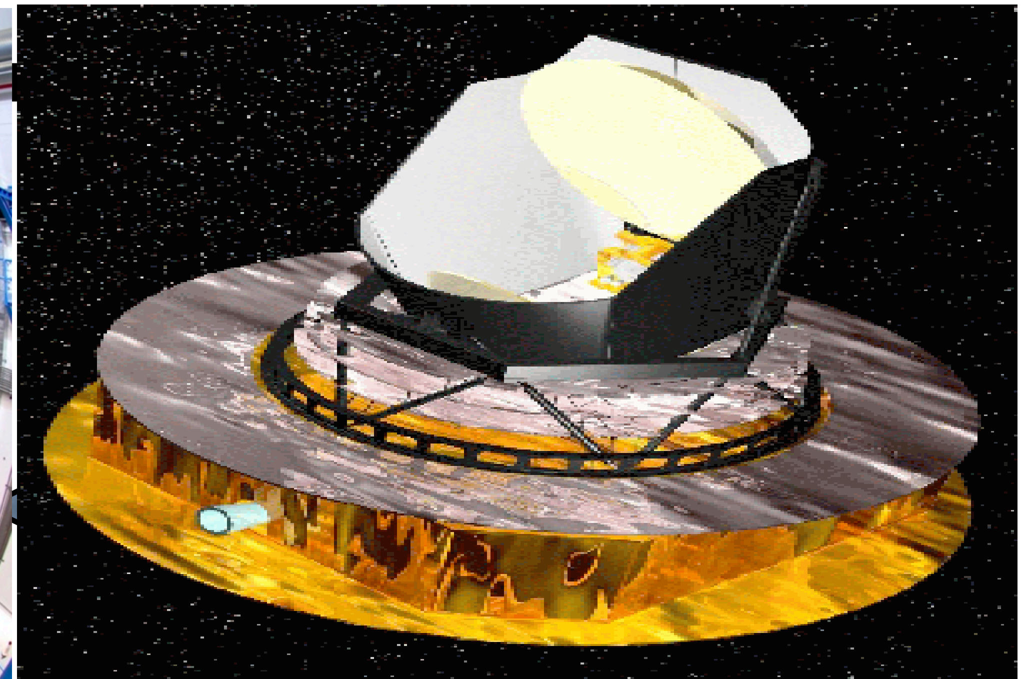

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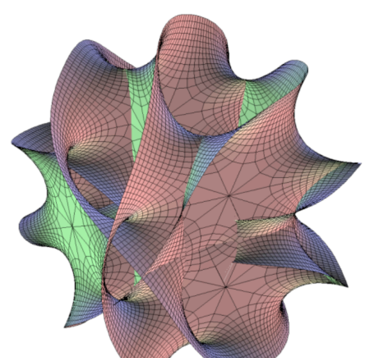

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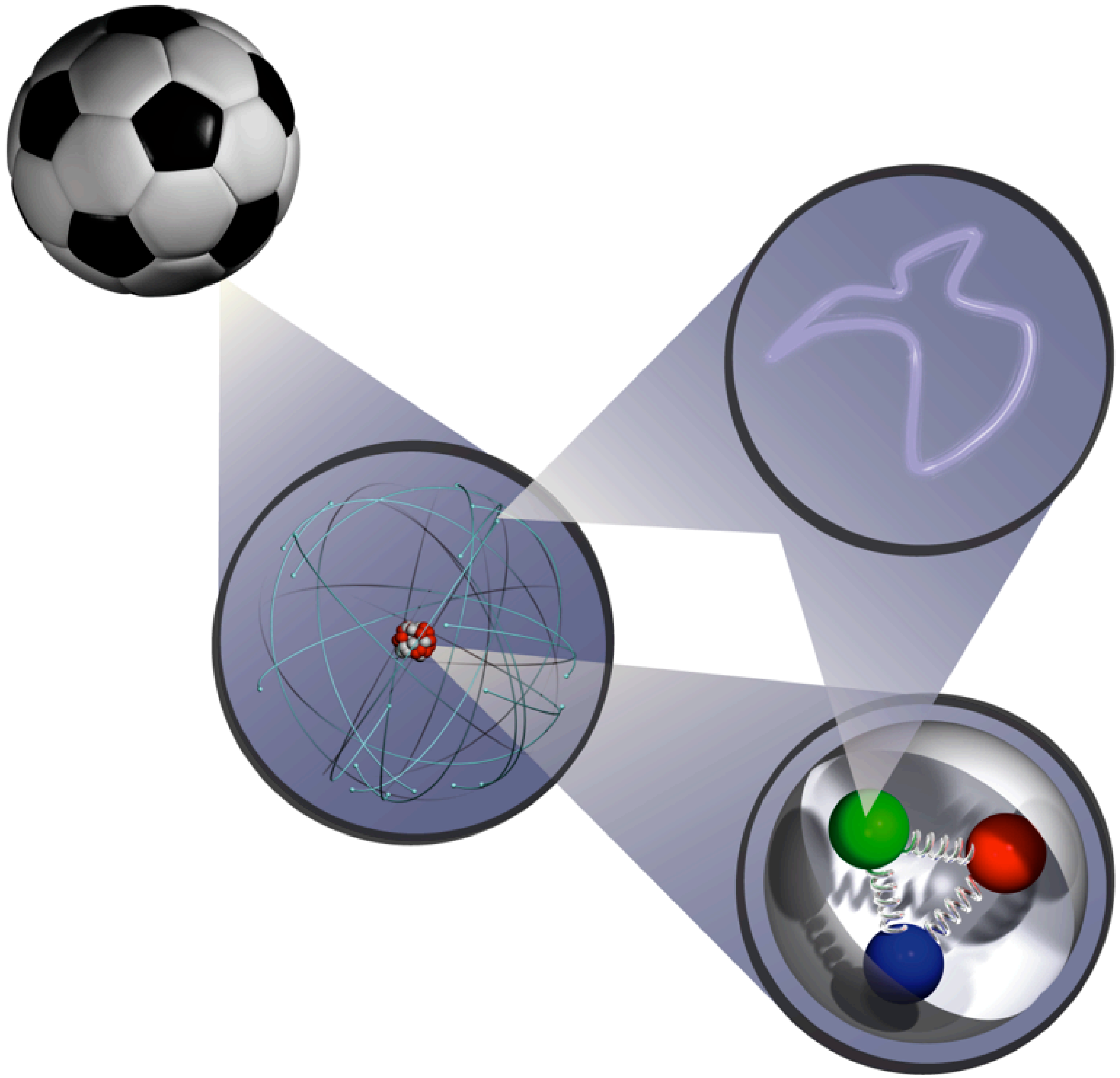
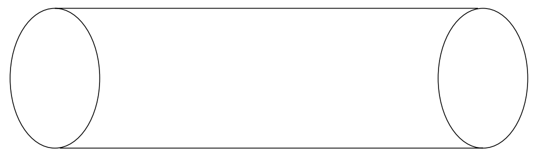


String theory:

- Unification of all particles and forces (including gravity)

(i) Closed string:



$$X^\mu(\sigma,\tau): \quad \Sigma_g \longrightarrow \mathcal{M}^D$$

$$S_{2d} = -\frac{T}{2}\int_{\Sigma_g} d\tau d\sigma\, \partial_\alpha X^\mu(\sigma,\tau)\partial_\beta X^\nu(\sigma,\tau)\big(\delta^{\alpha\beta}G_{(\mu\nu)} + \epsilon^{\alpha\beta}B_{[\mu\nu]}\big)$$

Background space:

$G_{(\mu\nu)}$: metric of $\mathcal{M}^D$

$B_{[\mu\nu]}$: antisym. tensor field, $H = dB$

- Massless string excitations: background fluctuations: $g_{\mu\nu}$,

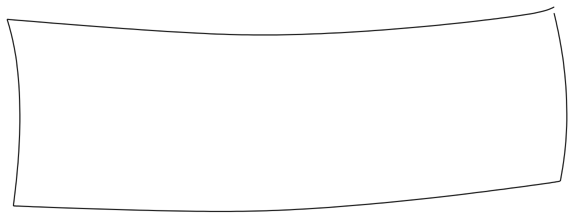
+ infinitely many massive Regge excitations:

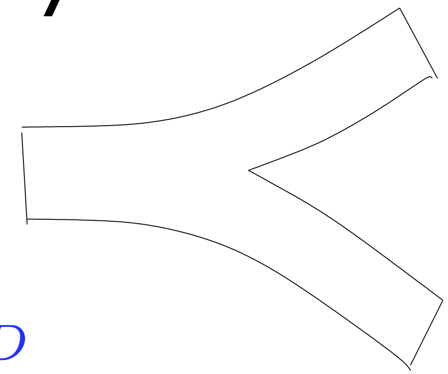
$$M_n = M_{\text{string}}\, n = \frac{1}{\sqrt{\alpha'}}\, n$$

- Conformal invariance $S_{2d} \quad \Longrightarrow \quad D = 10$

(ii) Open strings (type II/I):

World sheets with boundary:





$$X^\mu(\sigma,\tau): \quad \widetilde{\Sigma}_g \longrightarrow \mathcal{M}^D$$

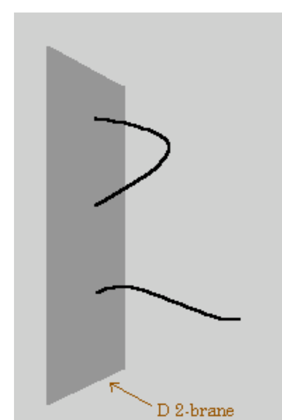
Boundary action: $S_b = \int_{\partial\widetilde{\Sigma}_g} ds\, \partial_s X^\mu(\sigma,\tau) A_\mu(X)$

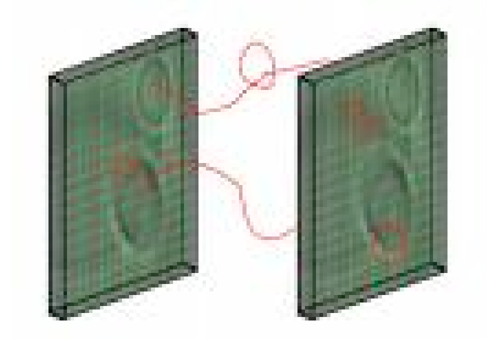
Background gauge field: $A_\mu(X)\,,\ F = dA$

D(p)-branes:

(Polchinski (1995))

p-dimensional hypersurfaces π_{D_p}, on which open string end points move:





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Facts about open strings and D-branes:

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- Massless open string excitations on D-branes are gauge fields A_μ

Dp-brane:

- electric & magnetic sources for additional (Ramond) background fields:

$$A_{[\mu_1\ldots\mu_{p+1}]} \quad \Rightarrow \quad F^{p+2} = dA^{p+1} \qquad e = \int_{\pi^T_{D_p}} {}^*F^{p=2}$$

- Gravitating objects: open closed interactions

- Curve space and induce closed string background:

$$G_{\mu\nu} \neq \eta_{\mu\nu}\,, \quad F^{p+2} \neq 0$$

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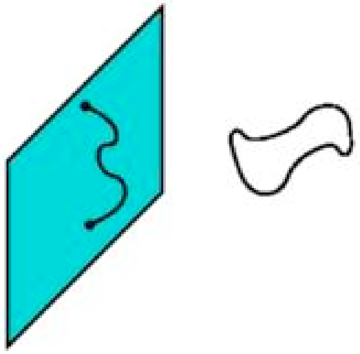

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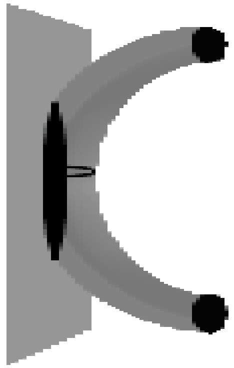

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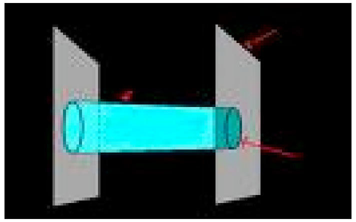

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- Type II orientifolds models

  Intersecting brane models and their statistics

- Stringy signatures at LHC

  (The LHC string hunter's companion)

- Flux compactifications and AdS4 string vacua

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- Chiral fermions are open strings on the intersection locus of two D-branes: $N_F = I_{ab} \equiv \#(\pi_a \cap \pi_b) \equiv \pi_a \circ \pi_b$

Perturbative type II orientifolds contain:

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

- Closed string 6-dimensional background geometry:

  -Torus, orbifold, Calabi-Yau space,
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- Strong consistency conditions:

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D6 wrapped on 3-cycles π_a angles θ_{ab}

Tadpole condition: $$\sum_a N_a \pi_a = \pi_{O6}$$

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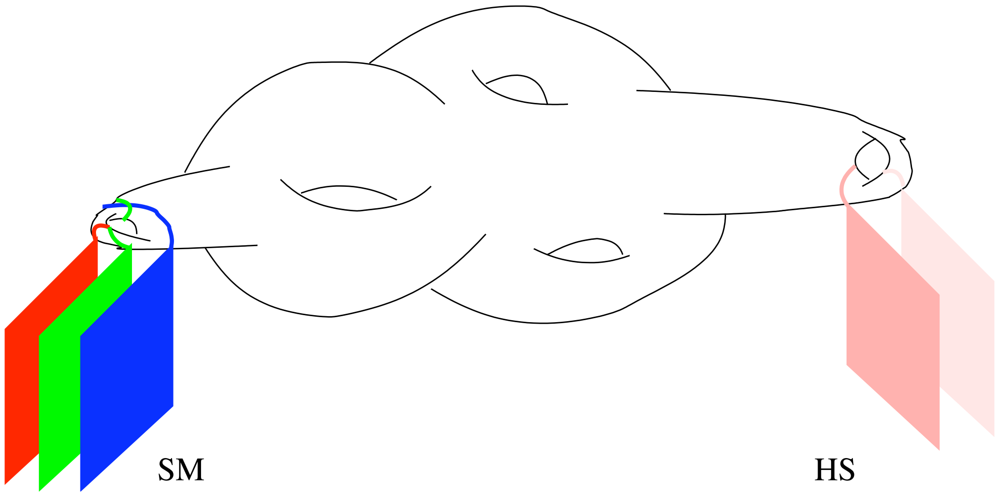

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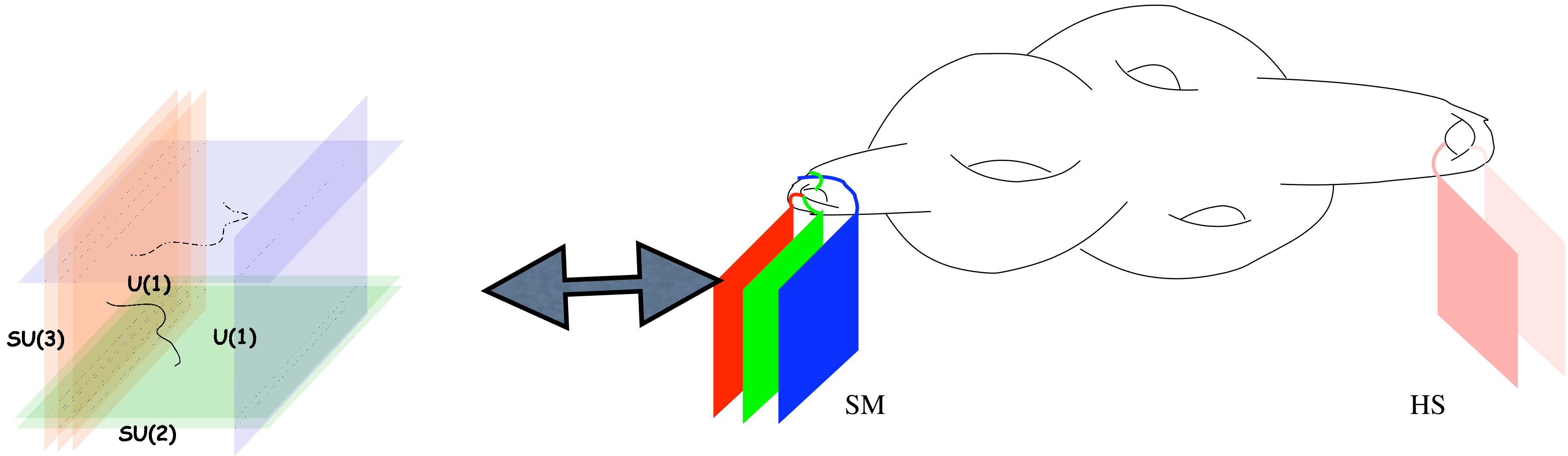

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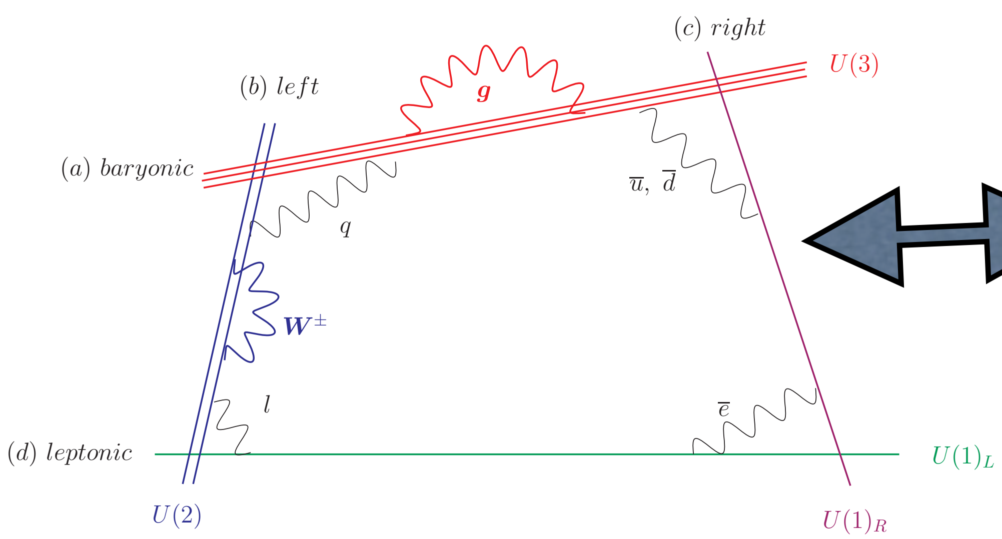

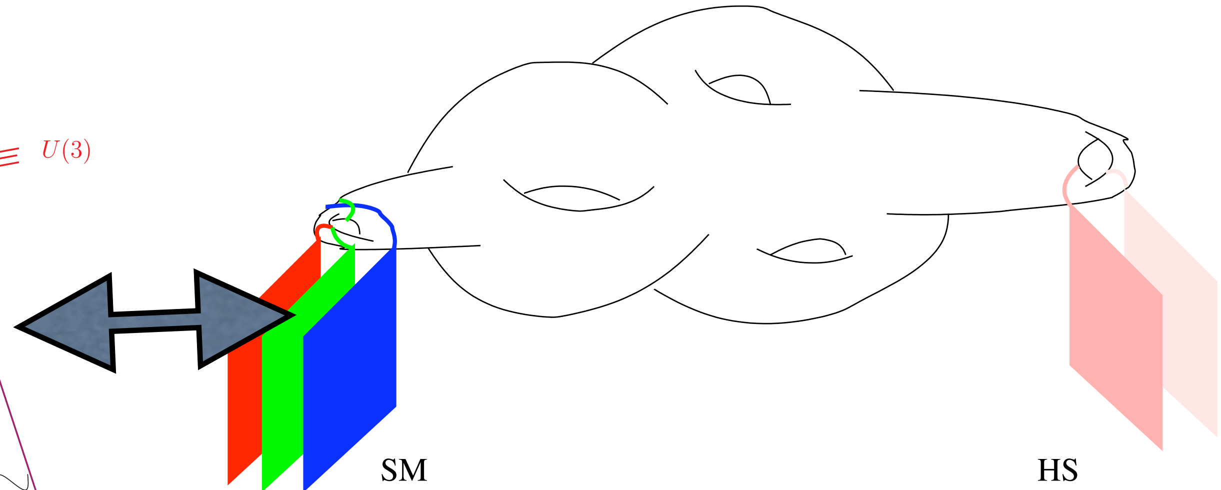

(Ibanez,Marchesano, Rabadan, hep-th/0105155;
Blumenhagen, Körs, Lüst, Ott, hep-th/0107138)

(Intersecting) D6-brane statistics

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

(Blumenhagen, Gmeiner, Honecker, Lüst, Stein, Weigand; 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)

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

Systematic computer search (NP complete problem):

Look for solutions of a set of diophantic equations:

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(i) First study: $Z_2 \times Z_2$ orientifold:

(Blumenhagen, Gmeiner, Honecker, Lüst, Stein, Weigand, hep-th/0411173 & 0510170)

One in a billion models gives rise to a MSSM like vacuum!

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.

$5.7 \cdot 10^{6}$ of them possess MSSM like spectra!

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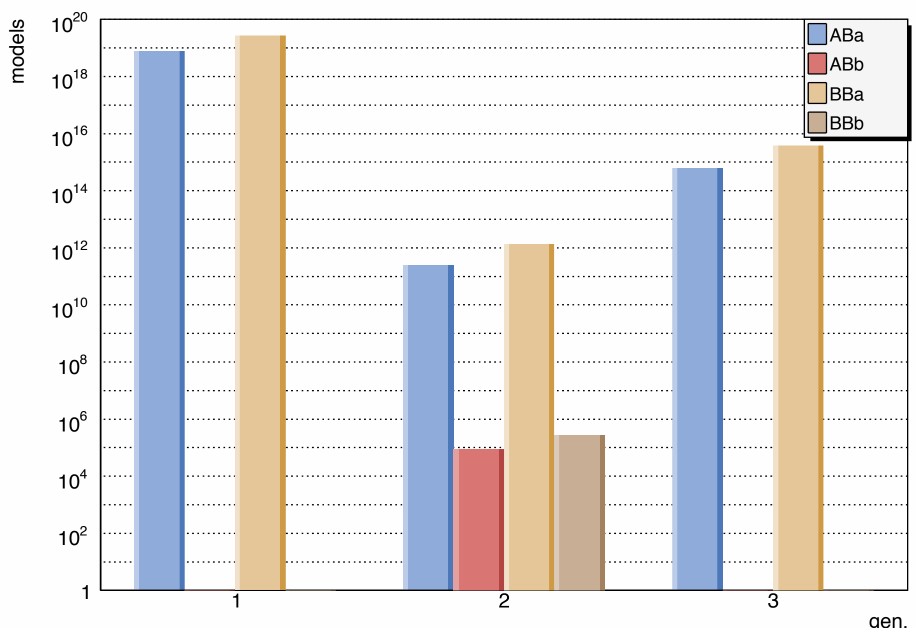

SM gauge group with # of generations

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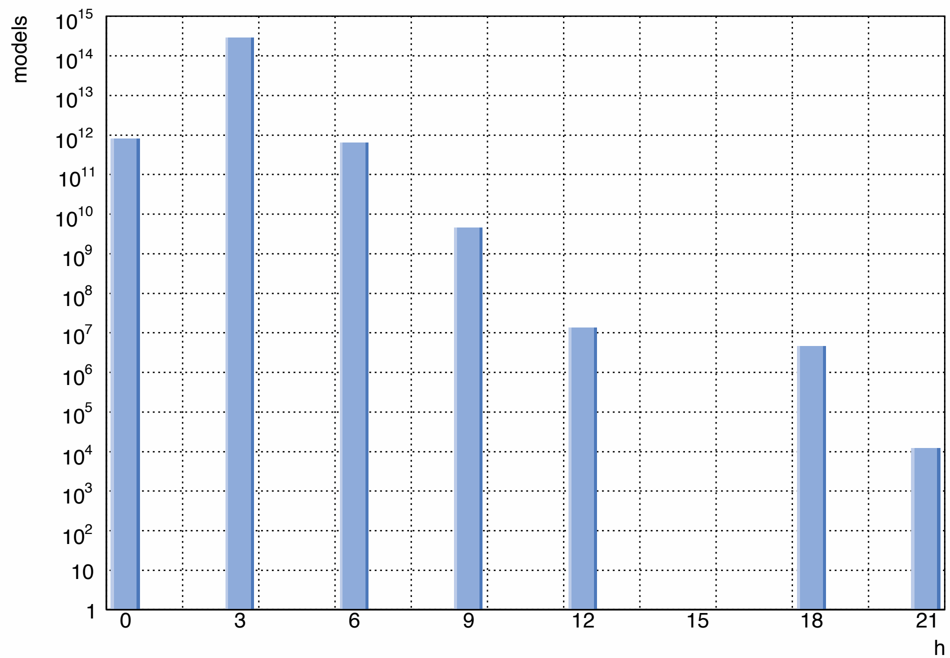

SM gauge group, 3 generations with # of Higgses

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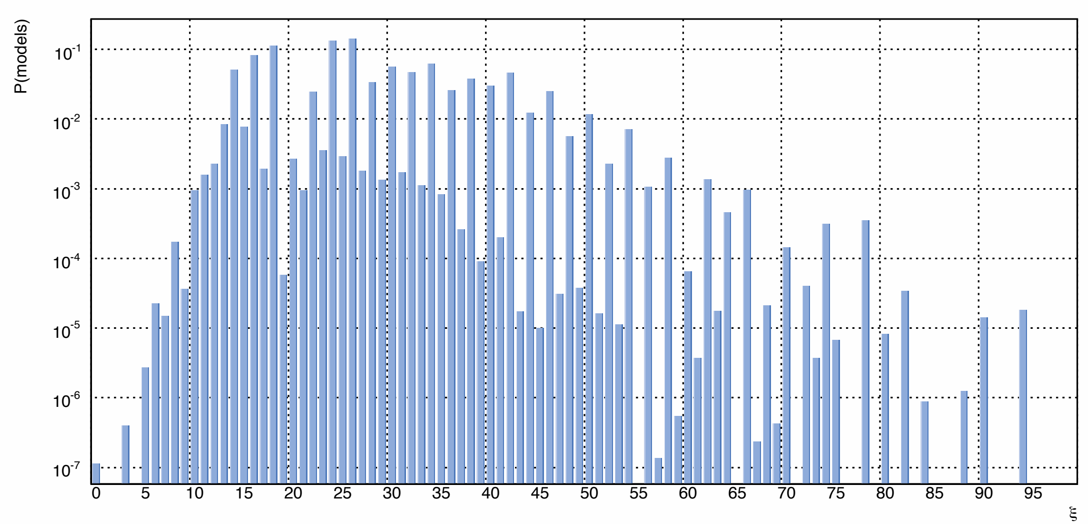

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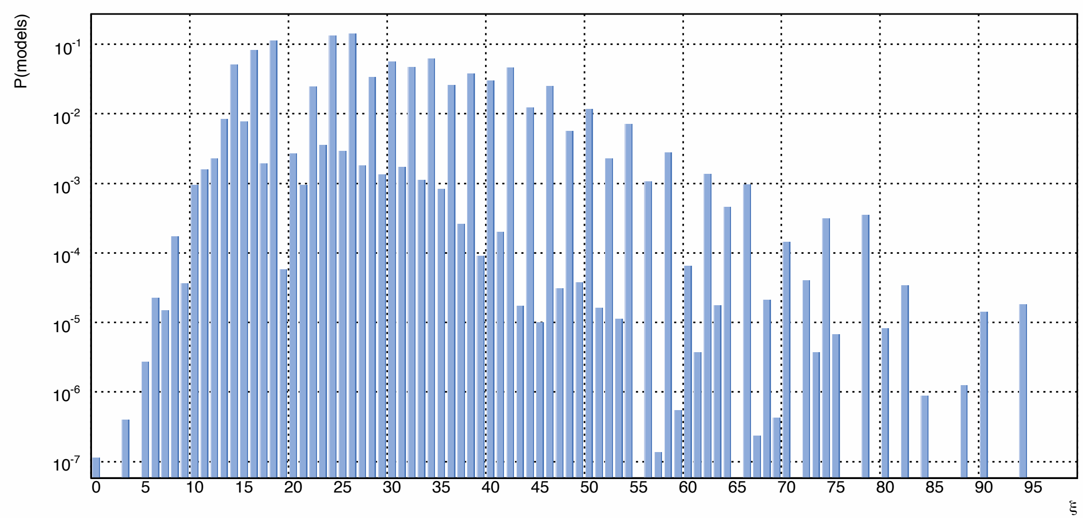

SM gauge group, 3 generations with # of chiral exotics

ISB models with no chiral exotics are possible!

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- Study of non-perturbative effects by gaugino condensation & D-instantons:

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→ moduli stabilization

→ non-perturbative couplings (Majorana neutrino masses, Yukawa couplings, ..)

- Comparison of ISB with old model by Bachas (1995):
  ⇔ orientifolds without vector structures.

(Bachas, Bianchi, Blumenhagen, Lüst, Weigand, arXiv:0805.3696)

Outline

- Type II orientifolds models

  Intersecting brane models and their statistics

- Stringy signatures at LHC

  (The LHC string hunter's companion)

- Flux compactifications and AdS4 string vacua

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(D. Lüst, S. Stieberger, T. Taylor, arXiv:0807.3333)
(Anchordoqui, Goldberg, Lüst, Nawata, Stieberger, T. Taylor, to appear)

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III) LHC String Hunter's Companion -

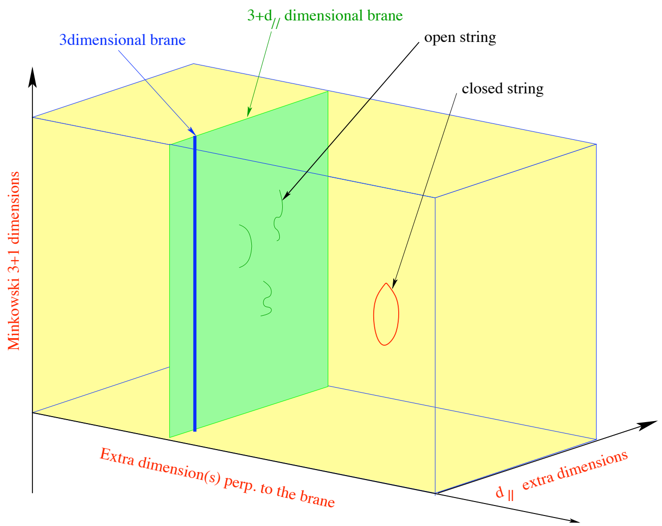
Test of D-brane models at the LHC:

New stringy physics of beyond the SM:

New massive particles:

- Z'
- Massive black holes
- Regge excitations of higher spin
- Kaluza Klein (KK) and winding modes

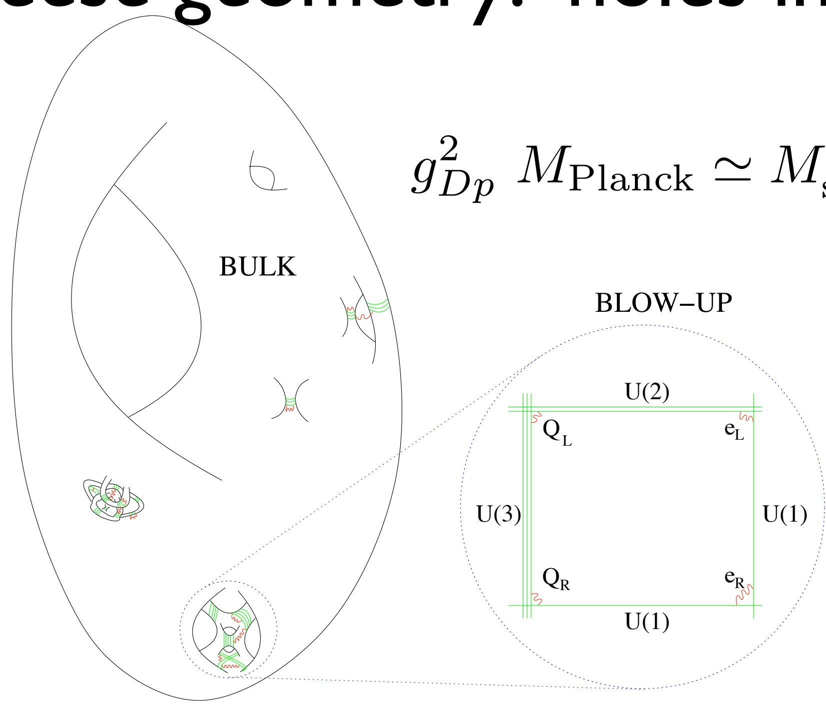
Low string scale and large extra dimensions (ADD):



$$M^2_{\text{Planck}} \simeq M^8_{\text{string}} \, V_6$$

$$V_6 M^6_{\text{string}} = \mathcal{O}(10^{16}) \Rightarrow M_{\text{string}} = \mathcal{O}(1 \text{ TeV})$$

Swiss cheese geometry: holes in a Calabi-Yau space:



$$g^2_{Dp} \, M_{\text{Planck}} \simeq M^{7-p}_{\text{string}} \left(\prod_{j=1}^{d_\perp} R_j^\perp \right)^{1/2} \left(\prod_{i=1}^{d_\parallel} R_i^\parallel \right)^{-1/2} .$$

(Balasubramanian, Berglund, Conlon, Quevedo, hep-th/0502058)

SM lives on small cycles of the CY!

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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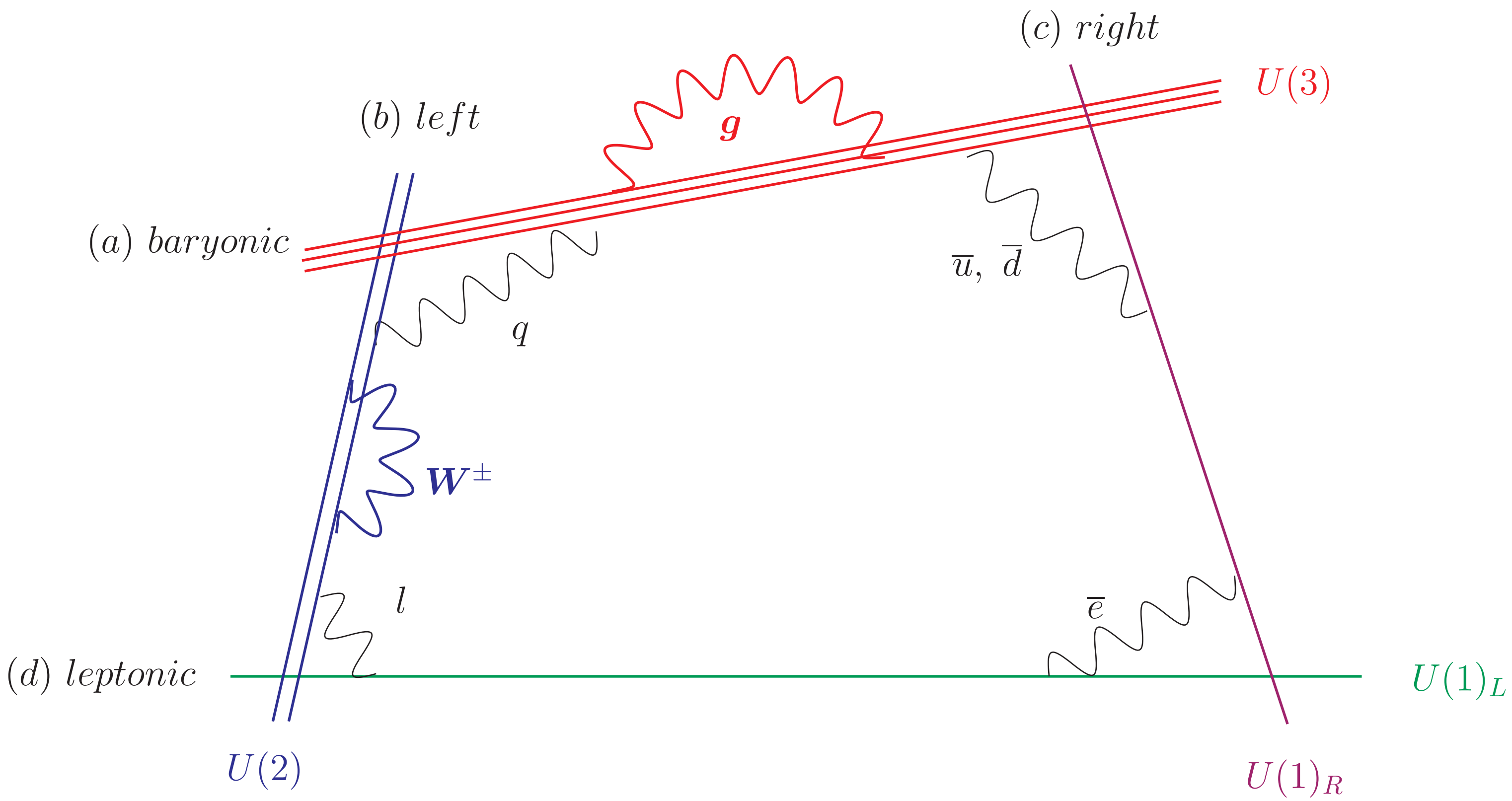

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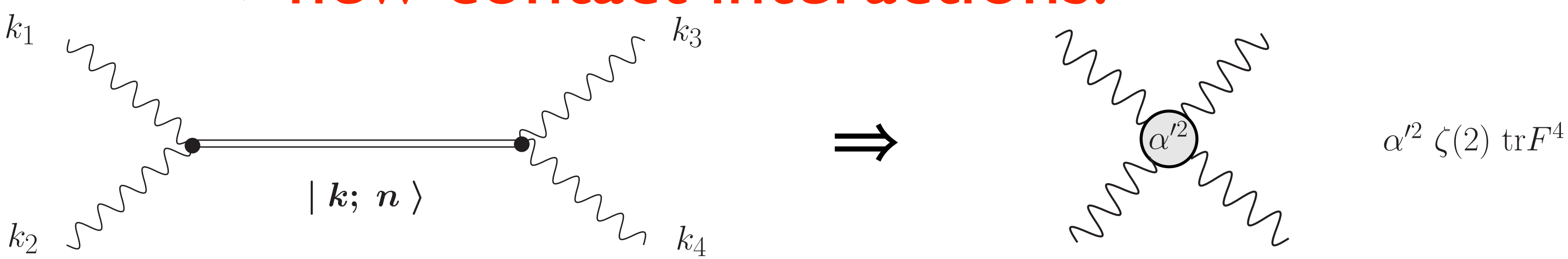
- Exchange of string Regge resonances (Veneziano like ampl.)

$\Rightarrow$ 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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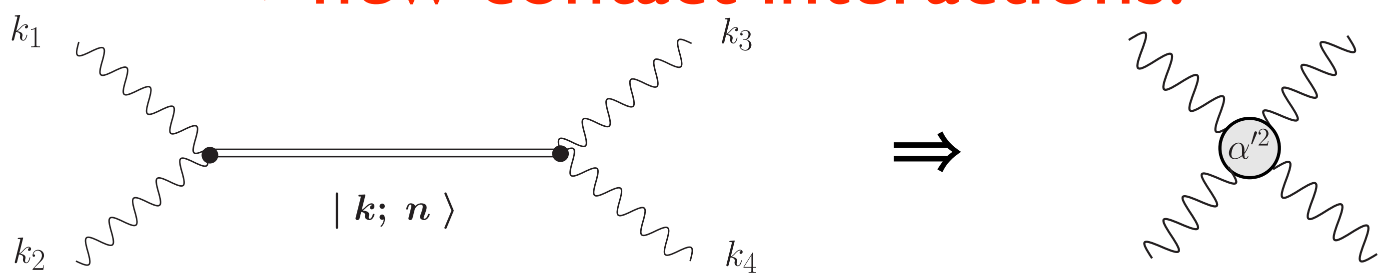

$\alpha'^2\ \zeta(2)\ \mathrm{tr}F^4$

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- Exchange of KK and winding modes (model dependent)

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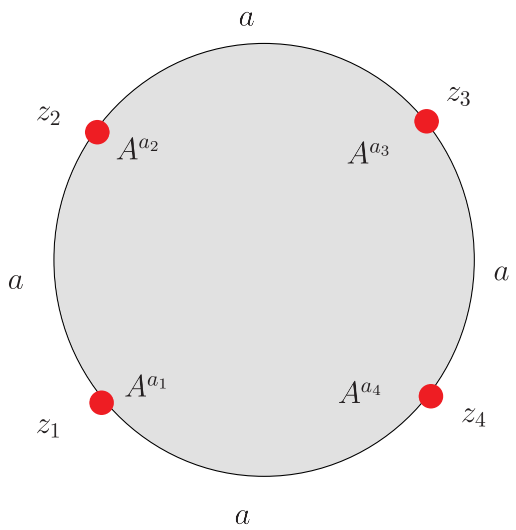
Disk amplitude:



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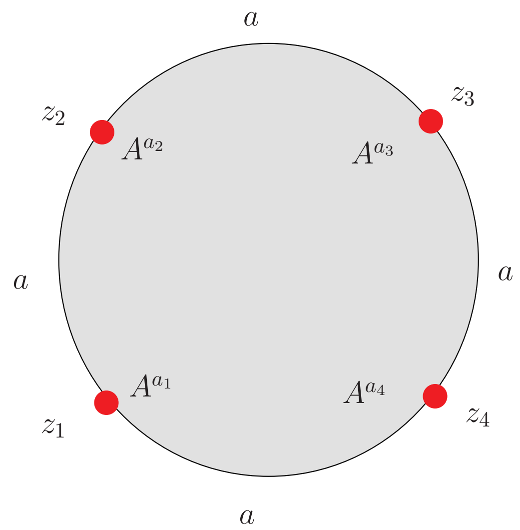

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These amplitudes are completely model independent!

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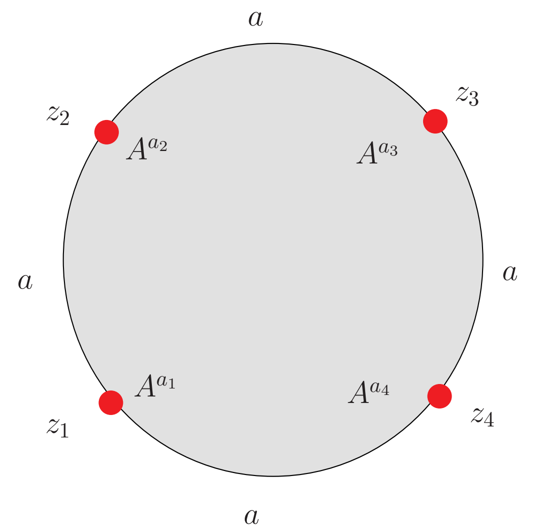

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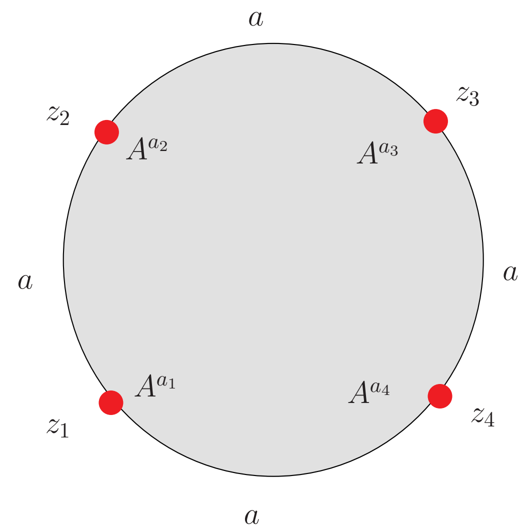

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$$|\mathcal{M}(gg\to gg)|^2 = g_3^4\left(\frac{1}{s^2}+\frac{1}{t^2}+\frac{1}{u^2}\right)\left[\frac{9}{4}s^2V_s^2(\alpha')-\frac{1}{3}\left(sV_s(\alpha')\right)^2+(s\leftrightarrow t)+(s\leftrightarrow u)\right]$$

(Stieberger, Taylor)

$\Rightarrow$ dijet events

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

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

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

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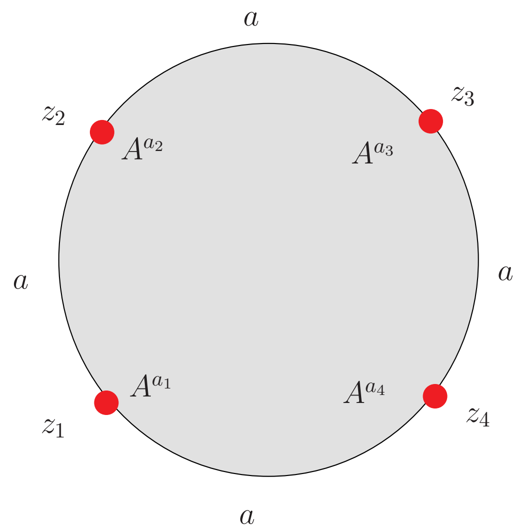

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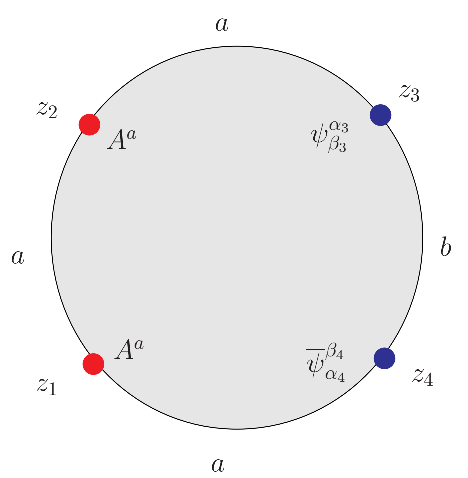
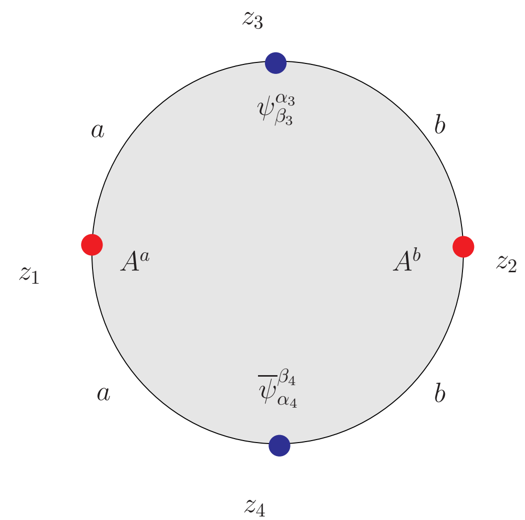
$\alpha' \longrightarrow 0$: agreement with SM!

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

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

2 gauge boson - two fermion amplitude:





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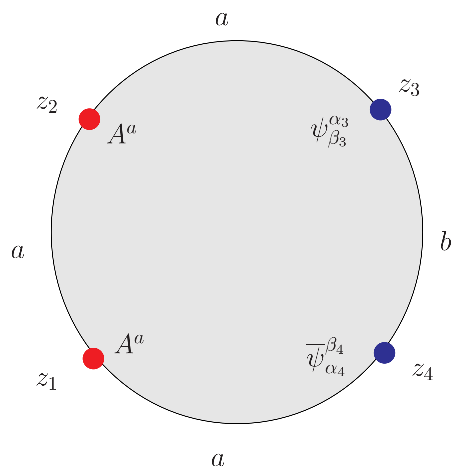

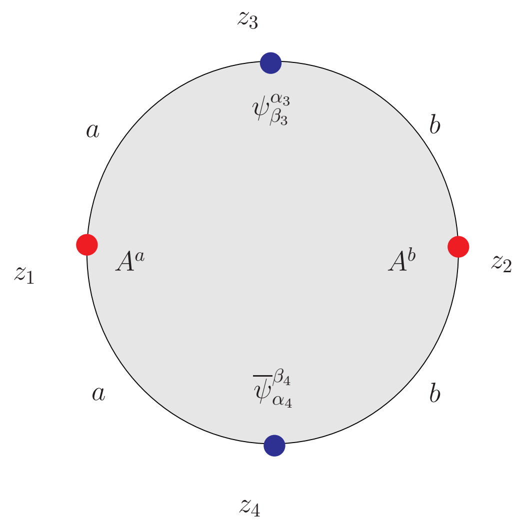

Fermions: boundary changing operators!

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

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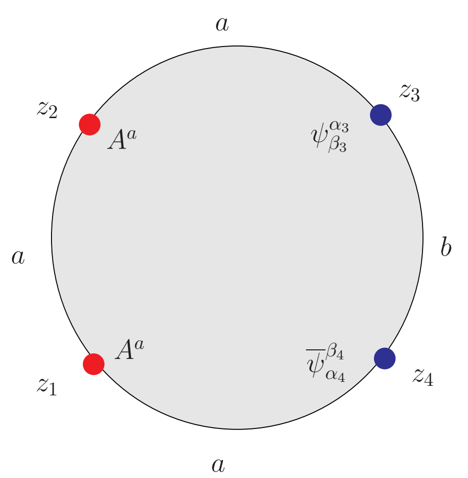

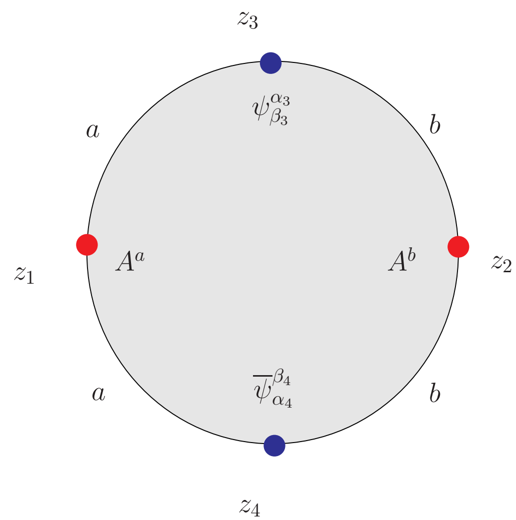

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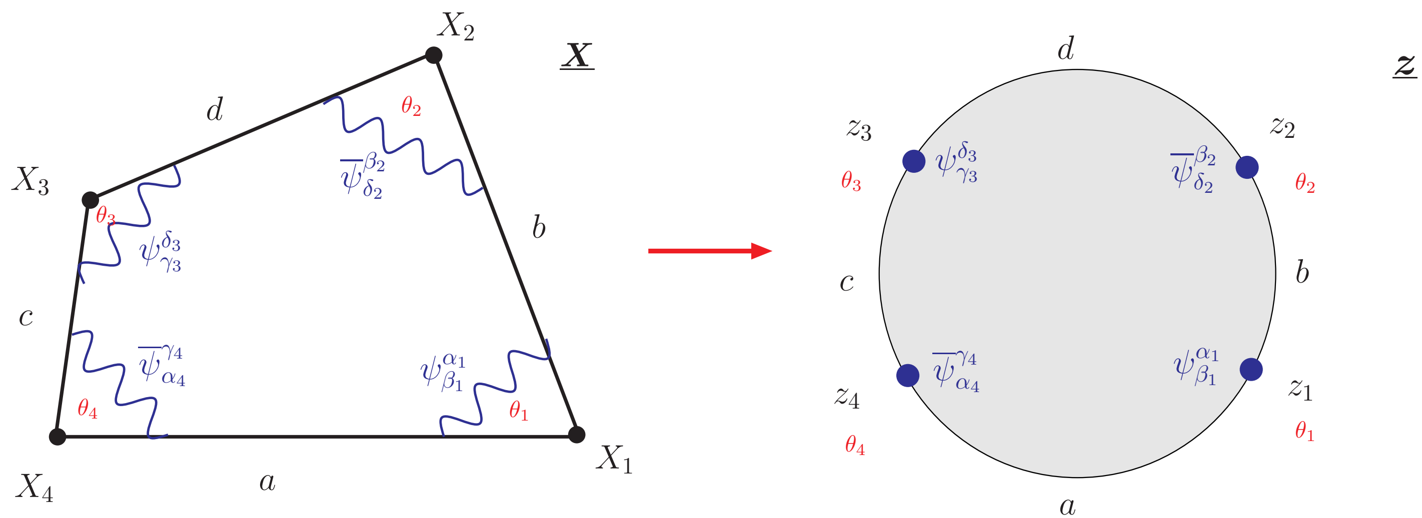

Exchange of Regge, KK and winding resonances.

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

Constrained by FCNC's and/or proton decay.

(Klebanov, Witten, hep-th/0304079; Abel, Lebedev, Santiago, hep-th/0312157)

E.g.

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

depend on internal geometry

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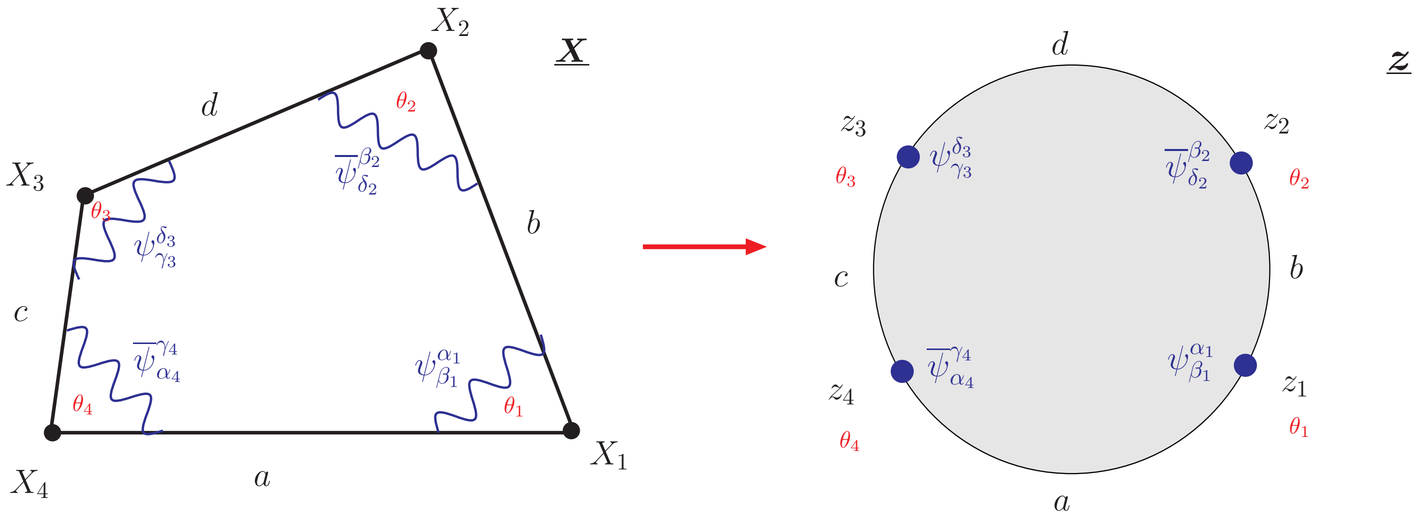

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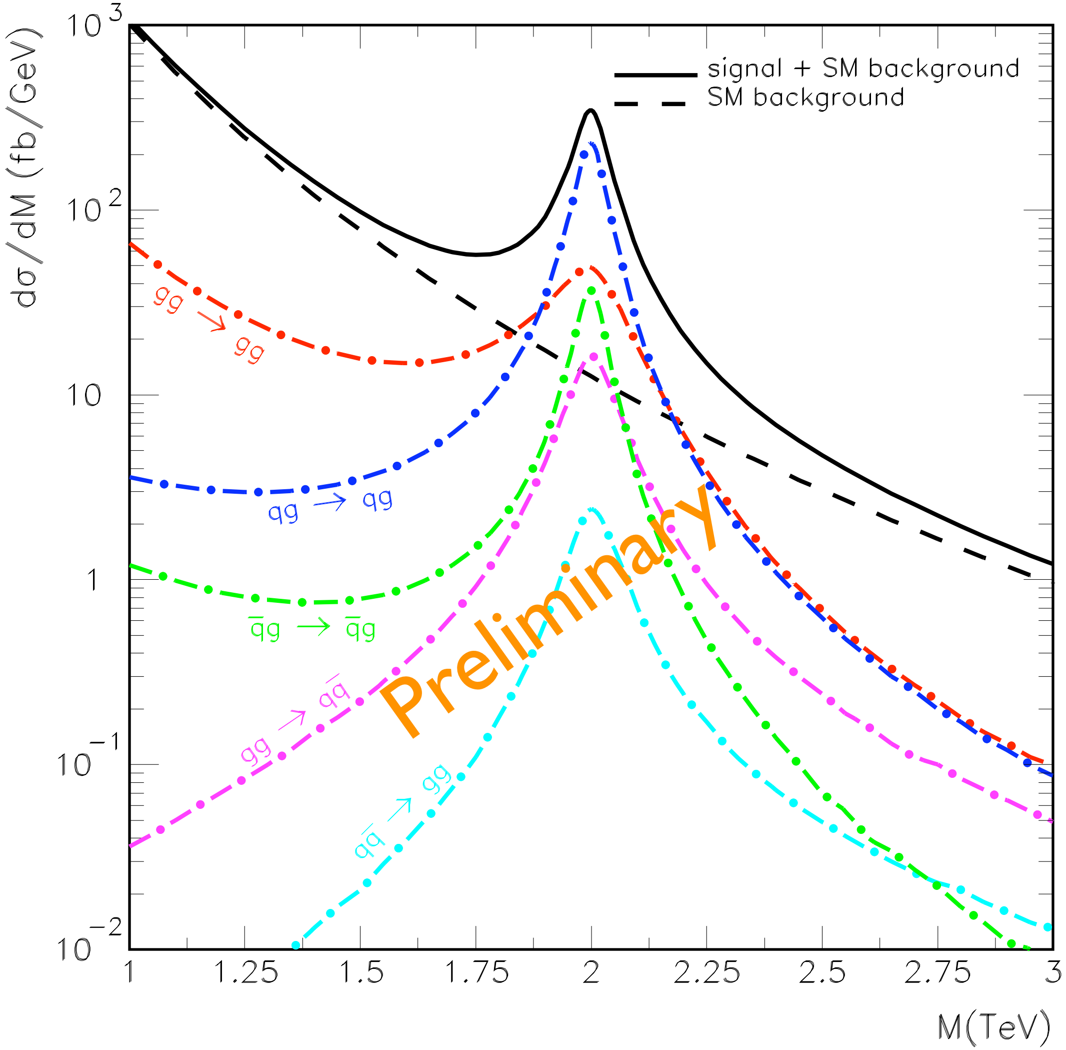
These stringy corrections can be seen in dijet events at LHC:



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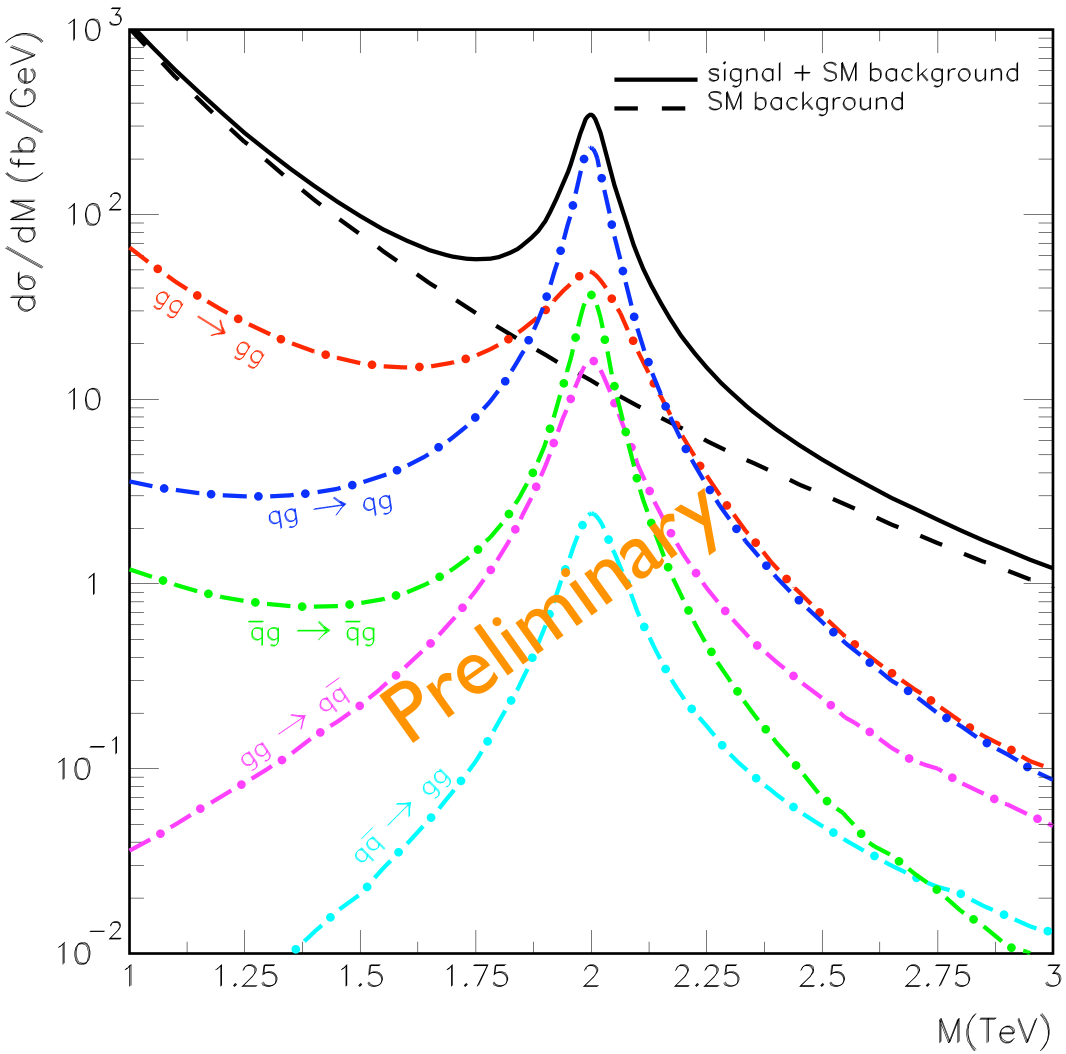

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There are possible also stringy Drell-Yan processes like

$$q\bar{q} \to l\bar{l}$$

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  (Kounnas, Lüst, Petropoulus, Tsimpis, arXiv:0707.4270)

  (Koerber, Lüst, Tsimpis, arXiv:0804.0614)

  (Caviezel, Koerber, Körs, Lüst, Tsimpis, Zagermann, arXiv:0806.3458)

  (Lüst, Marchesano, Martucci, Tsimpis, to appear)

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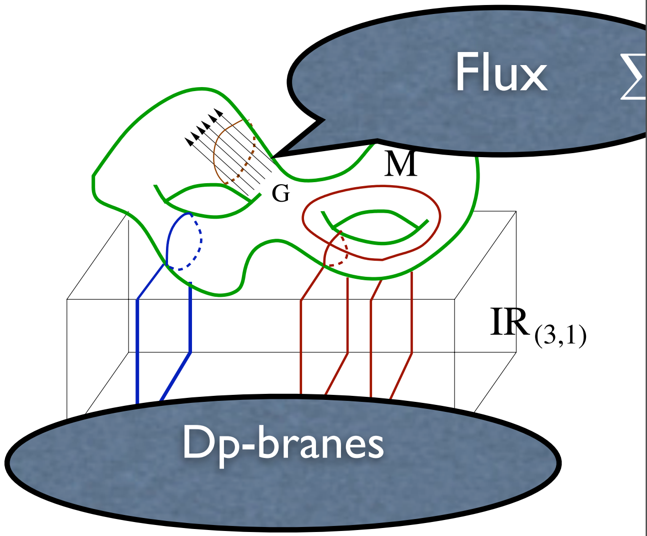
Now flux backgrounds: $\oint_{\Sigma} F^{p+2}, H \neq 0$

internal space: non-CY

external: max sym. space: e.g. dS_4, AdS_4



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  $\Rightarrow$ Transitions in the landscape.

  (similar to Coleman/de Luccia)

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- AdS_4/CFT_3 correspondence

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3-form fluxes on (warped) Calabi-Yau manifolds:

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Dilaton and complex structure moduli U are stabilized with 3-form fluxes, Kähler moduli T are fixed by non-perturbative effects → SUSY AdS4 vacuum.

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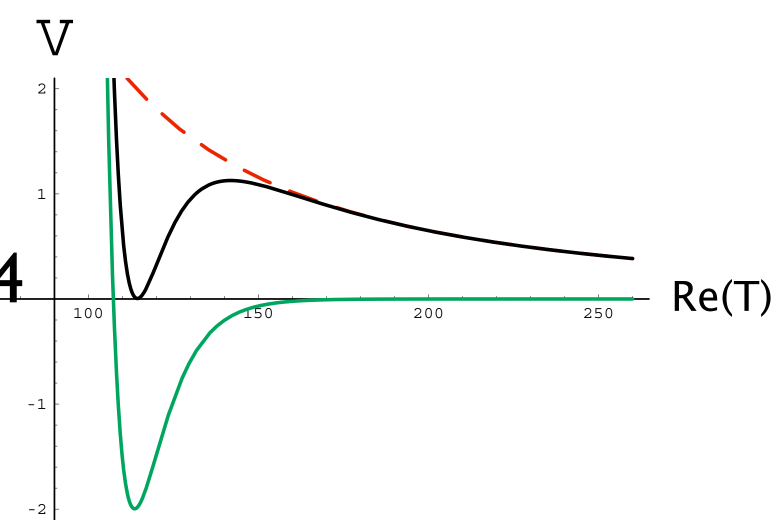
Step 2: Lift the minimum of the potential to a positive value by introducing $\overline{D3}$ branes or D7-branes with F-flux → metastable dS4 vacuum.



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- Large volume compactifications:

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Large CY-volume after quantum effects:

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LMU KKLT IIB examples with all moduli stabilized:

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- Toric Calabi-Yau orientifolds (blown-up orbifolds):

(Denef, Douglas, Florea, Grassi, Kachru, hep-th/0503124, Lüst, Reffert, Schulgin, Stieberger, hep-th/0506090; Lüst, Reffert, Schulgin, Scheidegger, Stieberger, hep-th/060913,hep-th/0609014)

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- Orientifold of $K3 \times T^2$:

(Sen, hep-th/9702165)
(Angelantonj, D´Auria, Ferrara, Trigiante, hep-th/0312019)
(Lüst, Mayr, Reffert, Stieberger, hep-th/0501139)
(Aspinwall, Kallosh, hep-th/0506014)

3-form fluxes: break N=2 SUSY to N=1

stabilize S and U fields

gaugino condensation on D7-branes:

stabilize volume of K3

In fact, one does not need non-perturbative effects to stabilize all moduli !

Need only fluxes (F,H) & geometrical fluxes ⇒ AdS4 vacua

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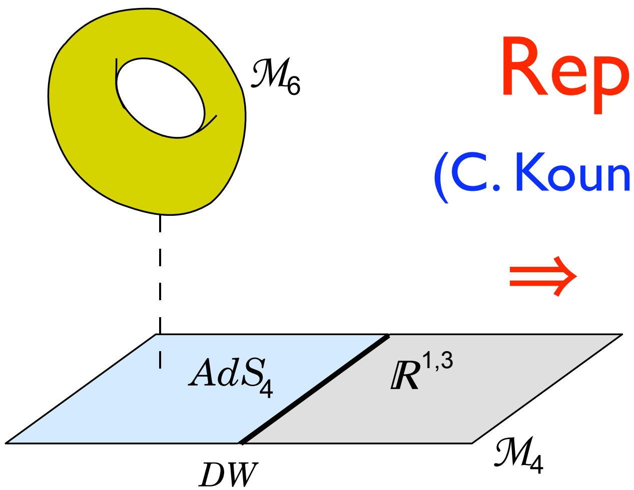

Replace fluxes by (2+p)-dim. branes (sources):

(C. Kounnas, D. Lüst, M. Petropoulos, D. Tsimpis, arXiv:0707.4270)

$\Rightarrow$ AdS4 Domain wall solutions

The corresponding sources are intersecting D4, NS5 and D8-branes:

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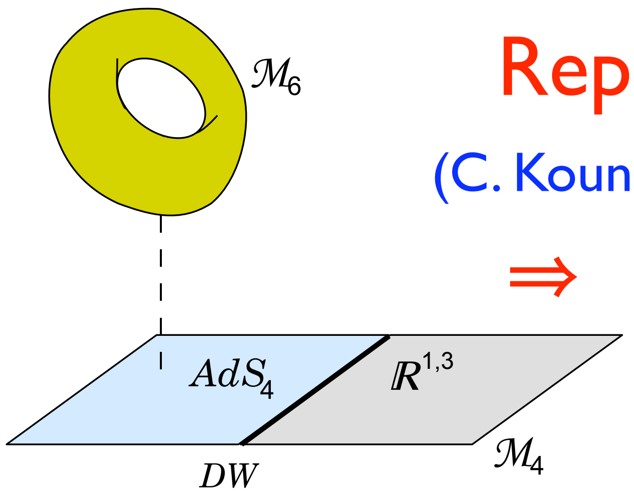

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(Aldazabal, Font, arXiv:0712.1021; Tomasiello, arXiv:0712.1396; Koerber, Lüst, Tsimpis, arXiv:0804.0614)

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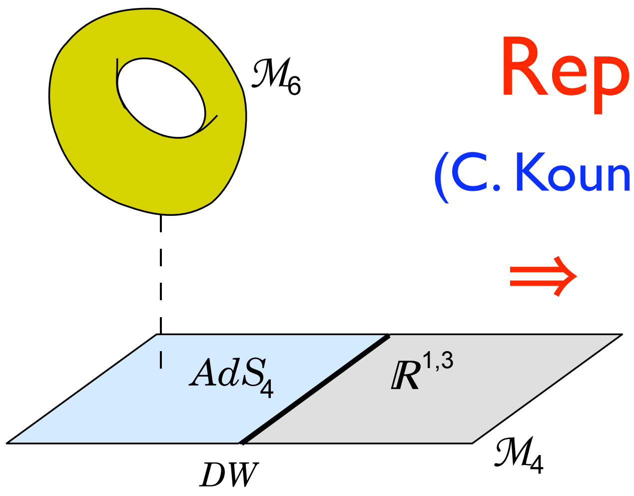

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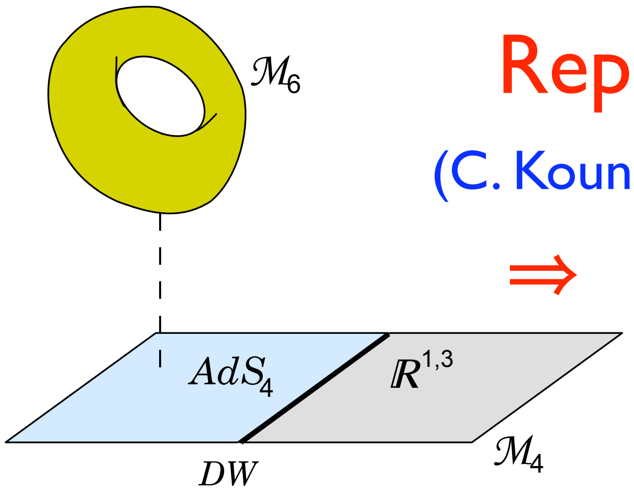

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They all fall in category of non CY-spaces, i.e. generalized geometries with torsion!

☛ talk Louis

Some new developments:

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- Non-susy flux compactifications

(Camara, Grana, arXiv:0710.4577; Lüst, Marchesano, Martucci, Tsimpis, to appear)

☛ talks Camara, Choi, Nilles

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Compute phenomenological (experimental) quantities:

$$n_S, \ r = n_T / n_S, \ G\mu$$

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Examples:

(i) IIA Nilmanifold with D4-branes

(Silverstein, Westphal, arXiv:0803.3085)

$$V(\phi) \sim \phi^{2/3}$$

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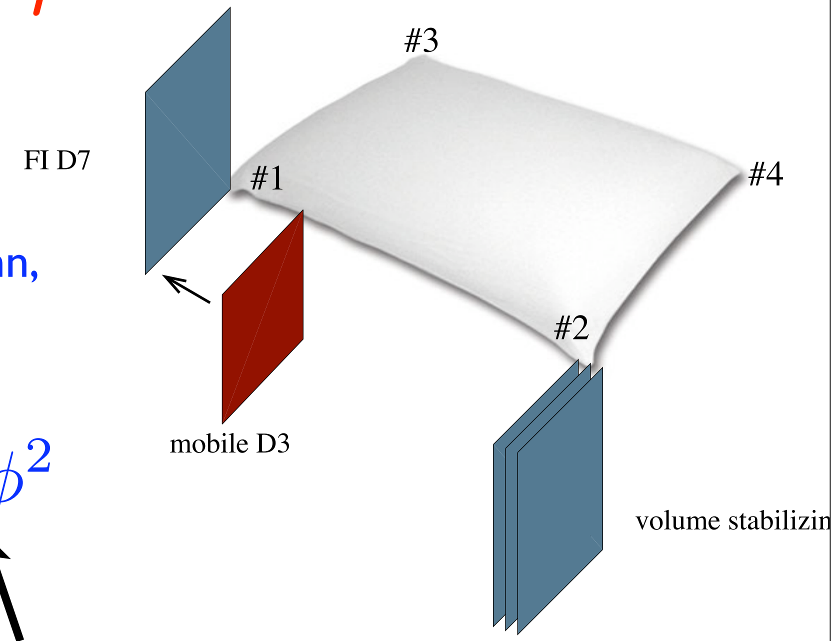
Examples:

(ii) K3 x T2 with D3/D7-branes

(Haack, Kallosh, Krause, Linde, Lüst, Zagermann, arXiv:0804.3961)



$$V = \frac{g^2 \xi^2}{2} \left(1 + \frac{g^2}{4\pi^2} \ln \frac{\phi}{\sqrt{\xi}} \right) - \frac{m^2}{2} \phi^2$$

D-term n.p. F-term

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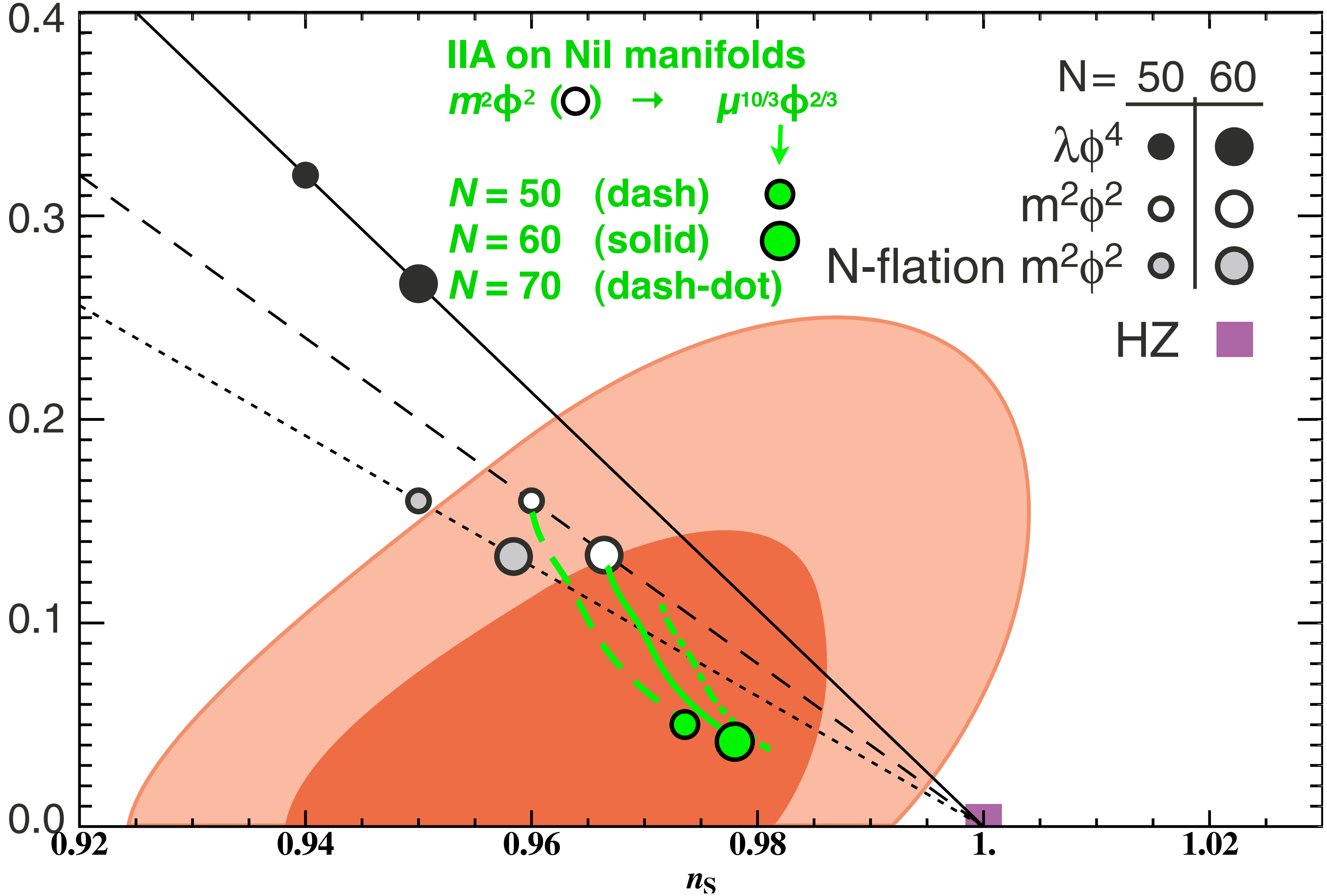
Chaotic Inflation



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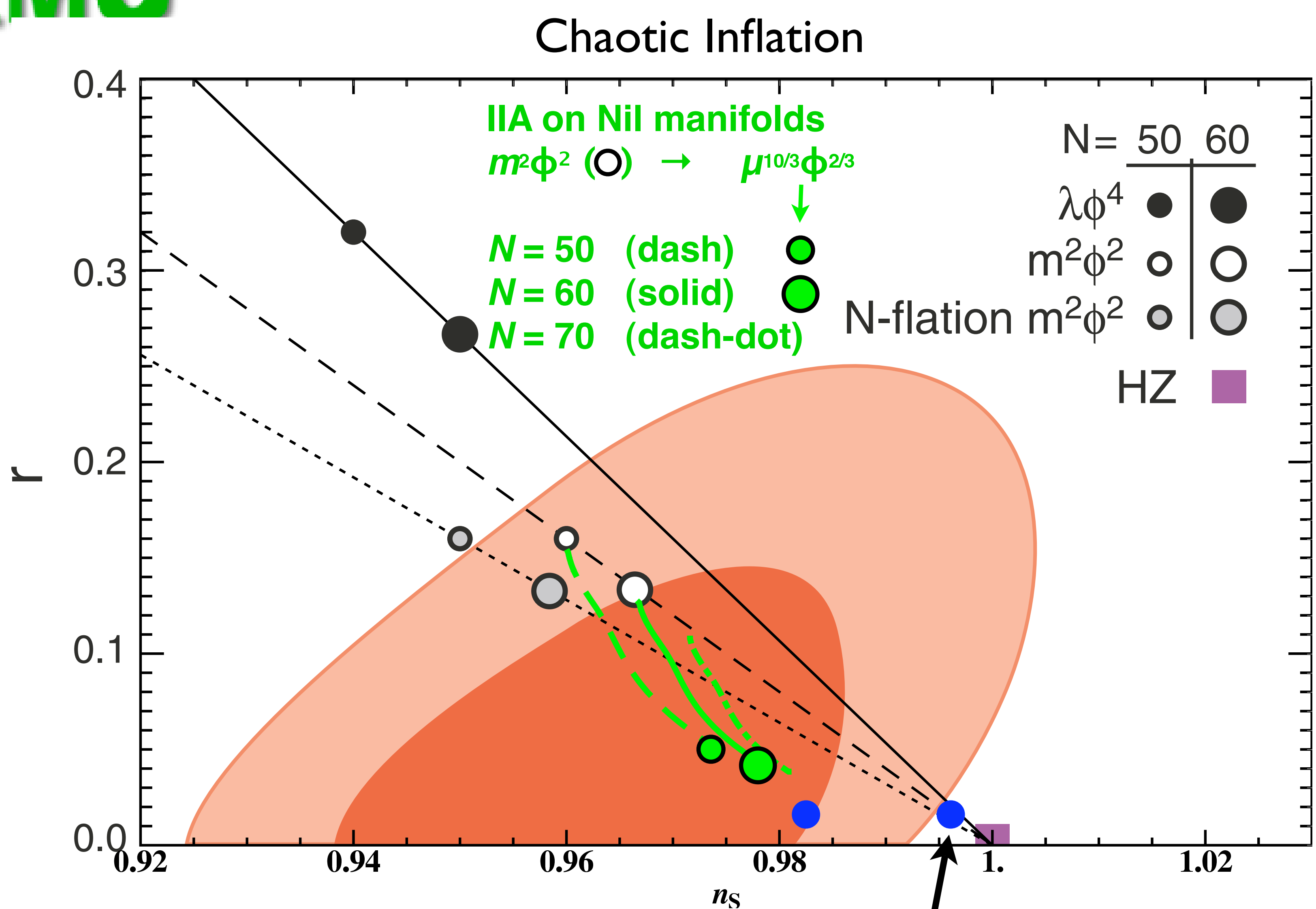

K3 x T2 orientifold

In addition cosmic strings $G\mu = 7 \times 10^{-7}$

Conclusions

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

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- One can make some model independent predictions:

(Independent of amount of (unbroken) supersymmetry!)

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

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Black holes are heavier than Regge states: $M_{b.h.} = \frac{M_{\text{string}}}{g_{\text{string}}}$

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- Further informations by cosmology (Planck satellite, ..)

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(Inde … metry!)

Strin … ons

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Compu …

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Questi … s

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INTERESTING TIMES FOR STRING PHENOMENOLOGY ARE AHEAD OF US.

THANK YOU !!

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