STRINGY SIGNATURES AT THE LHC

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

D. Lüst, String Phenomenology 2016, Ioannina, 22nd. June 2016

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Work in collaboration with L. Anchordoqui, I. Antoniadis, A. Celis, W. Feng, H. Goldberg, X. Huang, S. Nawata, O. Schlotterer, S. Stieberger, T. Taylor, B. Vclek

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LMU

MAX-PLANCK-GESELLSCHAFT

In the following we will discuss 3 kind of searches for string theory at the LHC collider:

- Direct search for heavy string resonances
  - ☞ dijets (ATLAS/CMS)
- New Z' gauge bosons
  - ☞ dibosons, dijet excesses (ATLAS/CMS)
  - ☞ rare decays (LHCb)
- New non-renormalizable contact interactions
  - ☞ diphoton events (ATLAS/CMS)

Basic set-up of type IIA/B/F-theory compactifications:

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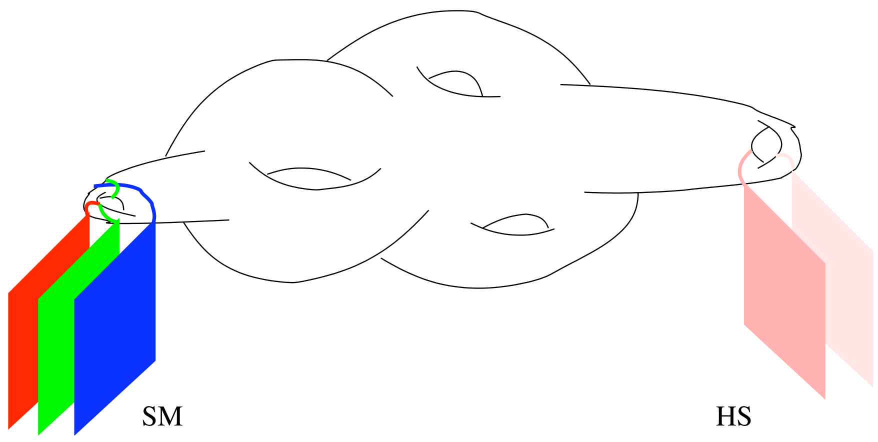
- Compactification on a 6-dimensional space M_6

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

- Wrapped (3+p)-dimensional D-branes

Basic set-up of type IIA/B/F-theory compactifications:



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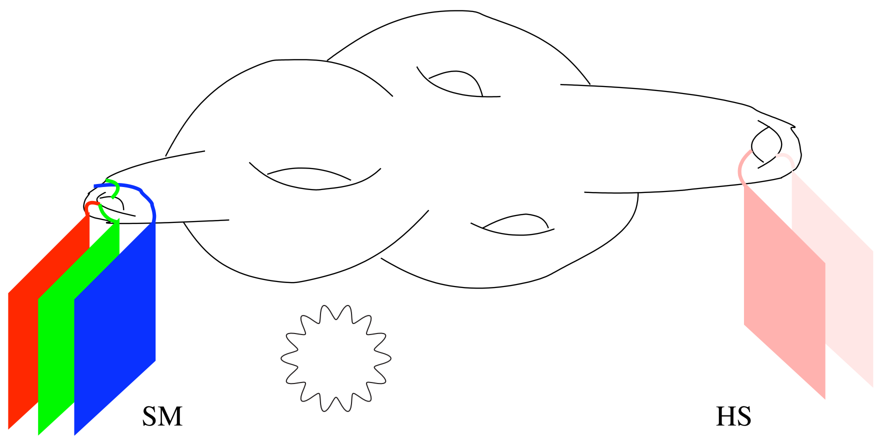

- Gravitons live as closed strings in 10-dimensional bulk.

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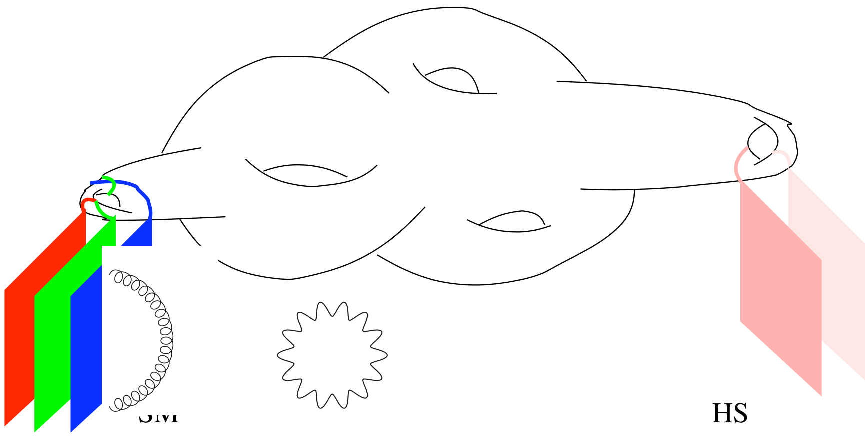

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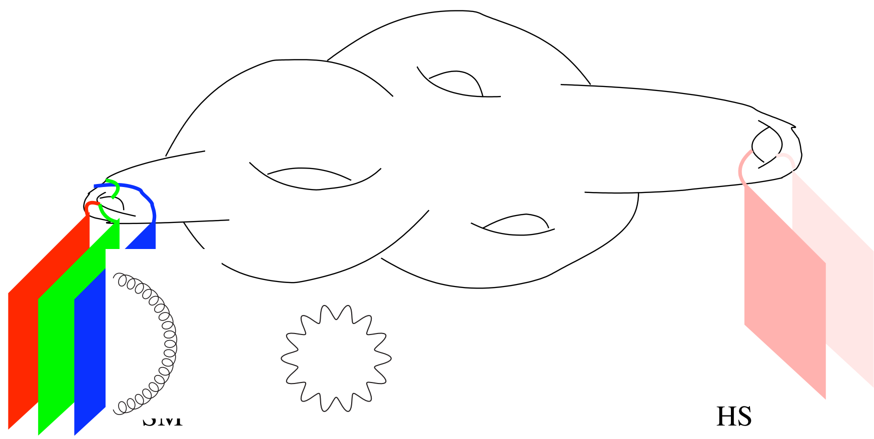

- Gravitons live as closed strings in 10-dimensional bulk.
- Non-Abelian gauge bosons live as open strings on lower dimensional D-branes.
- Chiral fermions are open strings on the intersection locus of two D-branes:

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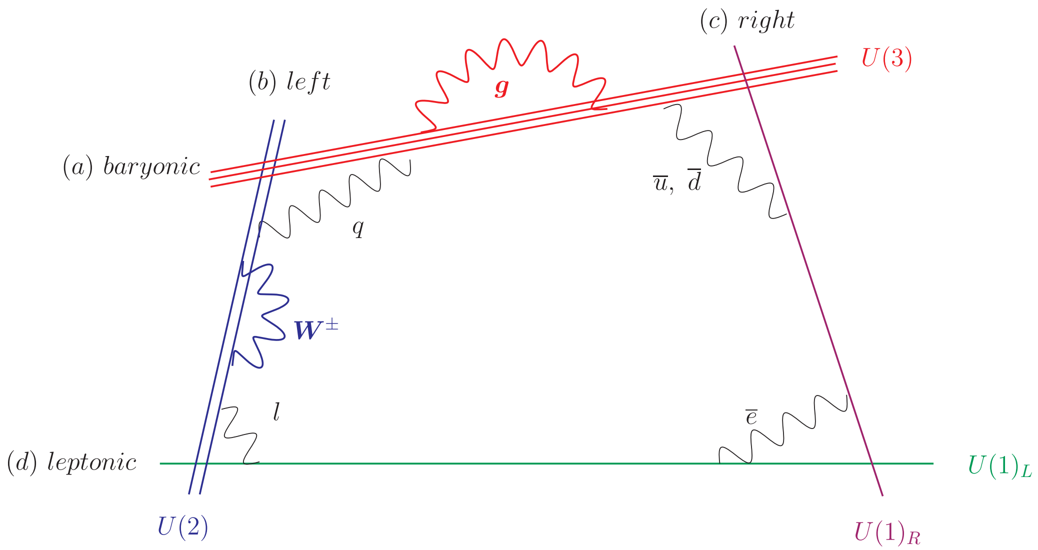
(i) Consider D-brane models which realize the SM, i.e. contain the SM D-brane quiver:



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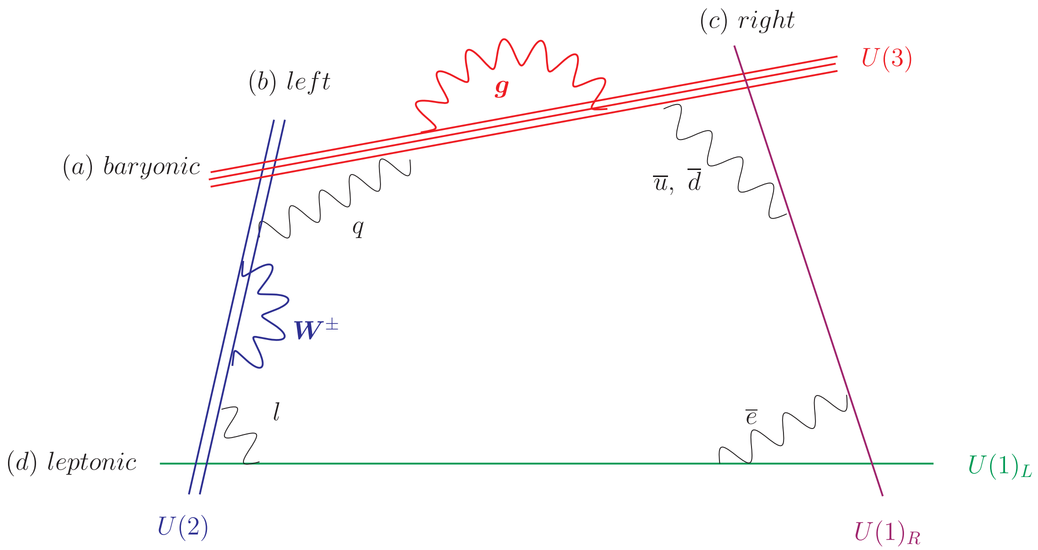


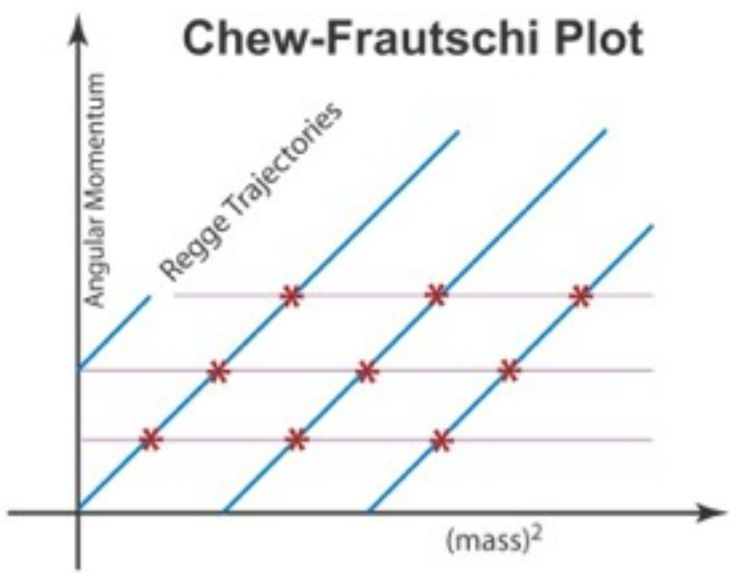
(ii) Consider D-brane compactifications which allow
for low string scale (solve hierarchy problem without SUSY)

⇒ Low scale for quantum gravity & large extra dimensions.

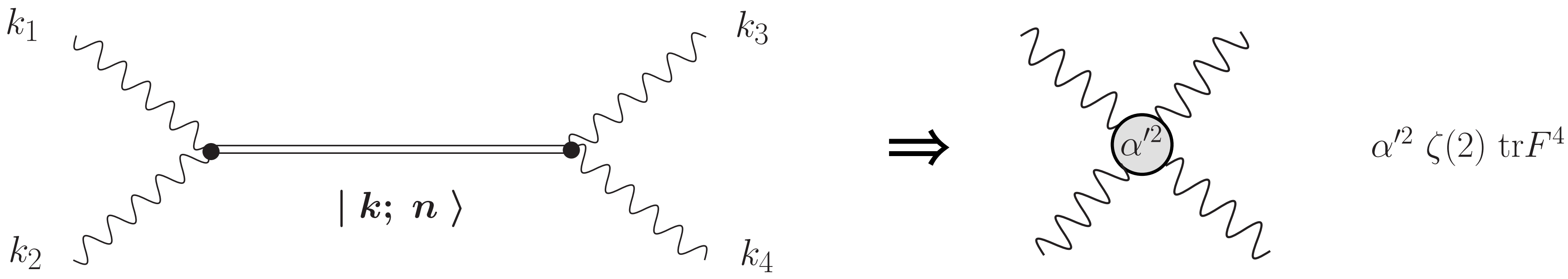
I) Stringy Regge excitations:

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

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



- Exchange of string Regge resonances in hadronic scattering processes at LHC



$$\mathcal{A} \sim V(\alpha') \approx \frac{\Gamma(-\alpha' s)\ \Gamma(1-\alpha' u)}{\Gamma(-\alpha' s - \alpha' u)} \approx \frac{1}{s - nM_s^2} \times \frac{M_s^{2-2n}}{(n-1)!} \prod_{J=0}^{n-1} (u + M_s^2 J)$$

One needs a low string scale and large extra dimensions!

2008: String Hunter I: (D. Lüst, S. Stieberger, T. Taylor, arXiv:0807.3333; L. Anchordoqui, H. Goldberg, D. Lüst, S. Nawata, S. Stieberger, T. Taylor, arXiv:0808.0497, arXiv:0904.3547)

Universal 4 parton amplitudes from Regge recurrences ⇒

Universal s-channel Regge production - Dijet (discovery?) cross section for LHC.

2009: String Hunter II:

(D. Lüst, O. Schlotterer, S. Stieberger, T. Taylor, arXiv:0908.0409)

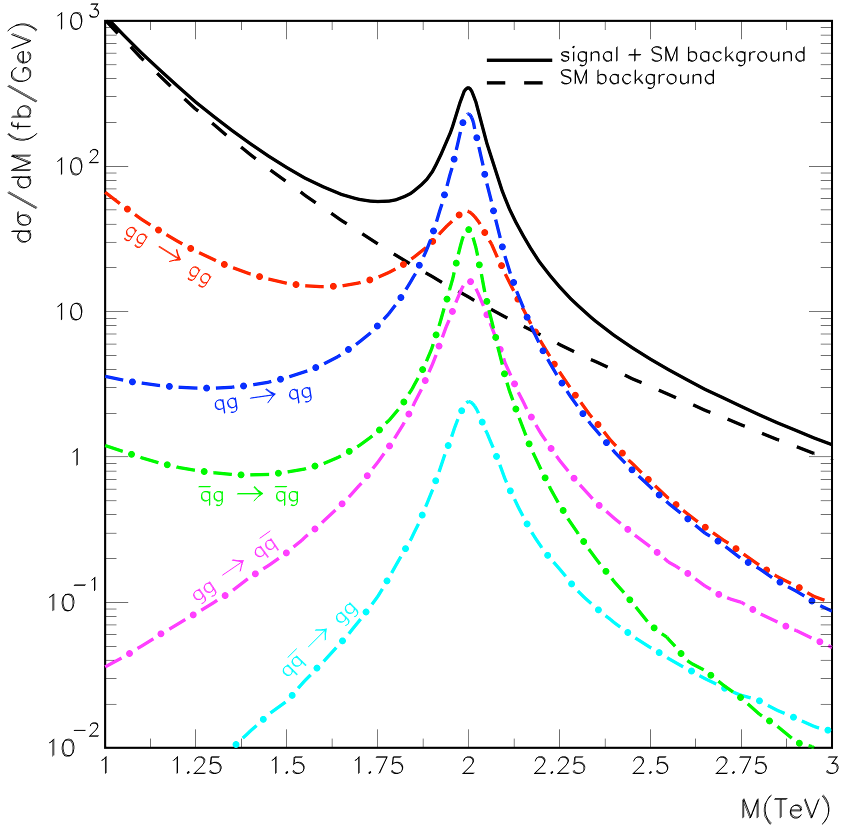
Universal 5 parton amplitudes from Regge recurrences.

(Non-universal) t-channel KK exchange at LHC.

2010: String Hunter III: (W. Feng, D. Lüst, O. Schlotterer, S. Stieberger, T. Taylor;) arXiv:1007.5254

Universal string amplitudes w. external massive Regge states.

Possible dijet signature:



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

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

From: L. Anchordoqui, H. Goldberg, D. Lüst, S. Nawata, S. Stieberger, T. Taylor, arXiv:0808.0497.

Updated curves in 1407.8120

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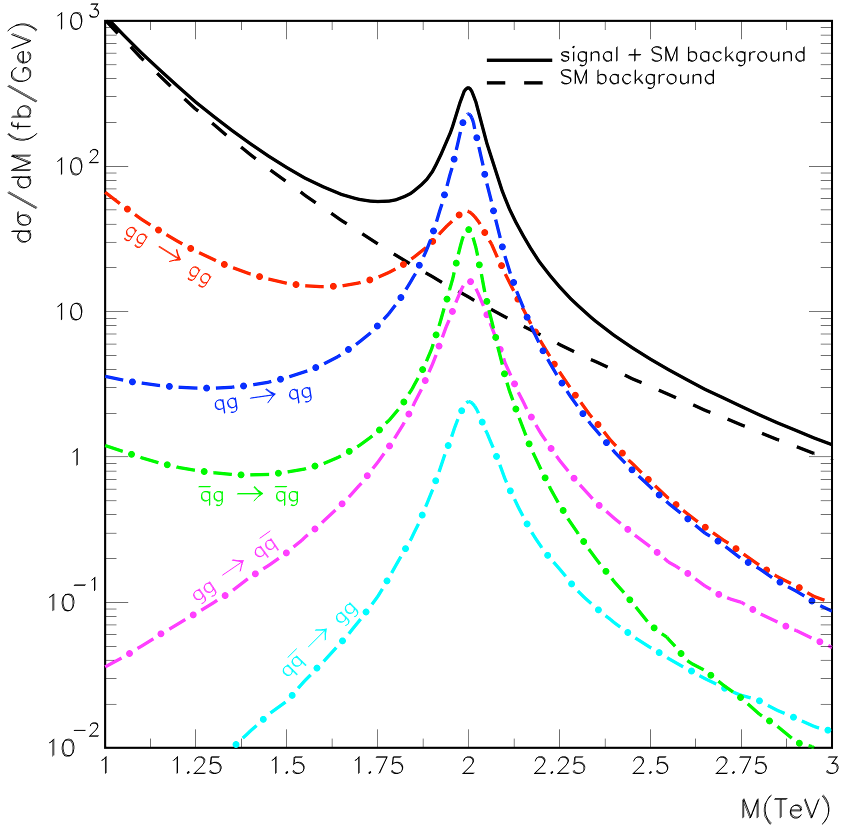

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Latest bound on the string scale:

LHC(13) (ATLAS/CMS): $M_s^{LHC} \geq 7 \ \mathrm{TeV}$

(CMS collaboration at 13TeV, arXiv:1512.01224 [hep-ex])

II) Massive Z‘ gauge bosons:

L. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D.L., T. Taylor, (B. Vclek),
arXiv:1107.4309, (1206.2537), 1507.05299

- They are generic in all intersecting and F-theory models.
- In four dimensions, the associated U(1)‘s can be anomaly free or anomalous.
- Their masses are typically of the order of the string scale or slightly heavier or lower.

$$\begin{aligned} \text{anomalous } U(1)_a: \quad M_{Z'} &= g'_a M_s\,, \\ \text{non} - \text{anomalous } U(1)_a: \quad M_{Z''} &= g'_a M_s^3 V_2 \end{aligned}$$

- They couple to weak and electromagnetic gauge bosons.

$$\left(-\frac{1}{2g'_c}\right)^2 = \frac{1}{g_Y^2} - \left(\frac{c_1}{6g'_a}\right)^2 - \left(\frac{1}{2g'_d}\right)^2$$

- They couple to fermions with non-universal couplings that depend on the D-brane quiver:

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}\sqrt{g_Y^2 + g_2^2}\sum_f \left(\epsilon_{f_L}\bar{\psi}_{f_L}\gamma^\mu\psi_{f_L} + \epsilon_{f_R}\bar{\psi}_{f_R}\gamma^\mu\psi_{f_R}\right) Z'_\mu \\ &= \sum_f \left((g_{Y'}Q_{Y'})_{f_L}\bar{\psi}_{f_L}\gamma^\mu\psi_{f_L} + (g_{Y'}Q_{Y'})_{f_R}\bar{\psi}_{f_R}\gamma^\mu\psi_{f_R}\right) Z'_\mu\end{aligned}$$

(i) Direct production and discovery of Z‘:

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Z‘ production cross section at the LHC:

$$\sigma(pp \to Z') \simeq 5.2 \left(\frac{2\Gamma(Z' \to u\bar{u}) + \Gamma(Z' \to d\bar{d})}{\mathrm{GeV}} \right) \text{ fb}$$

J. Hisano, N. Nagata, Y. Omura, arXiv:1506.03931

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Z' decay rates:

$$\Gamma(Z' \to f\bar{f}) = \frac{G_F M_Z^2}{6\pi\sqrt{2}} N_c C(M_{Z'}^2) M_{Z'} \sqrt{1-4x}\left[v_f^2(1+2x) + a_f^2(1-4x)\right] \quad (x = m_f^2/M_{Z'}^2)$$

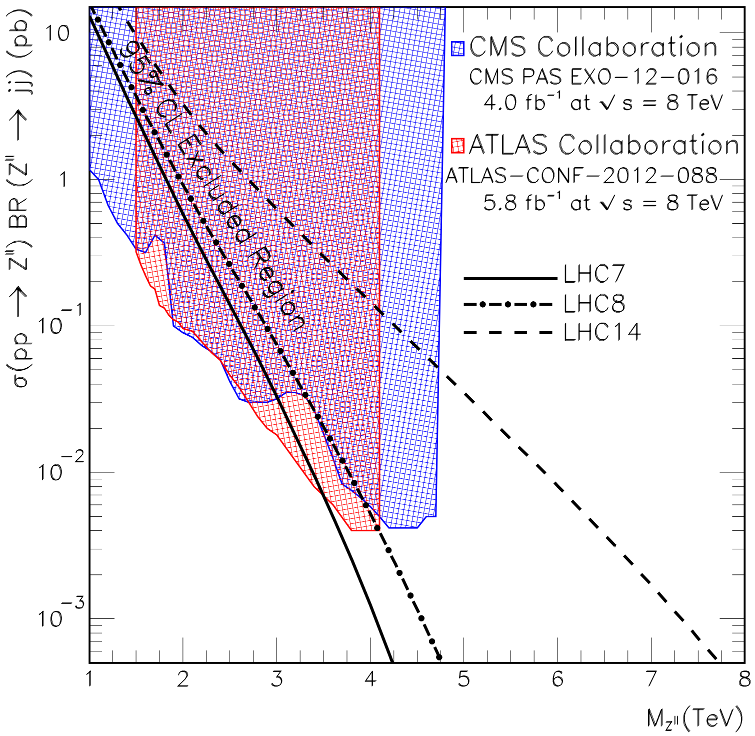
$$\Gamma(Z' \to ZZ) = \frac{c_1^2 \sin^2\theta_W M_{Z'}^3}{192\pi M_Z^2}\left(1 - \frac{4M_Z^2}{M_{Z'}^2}\right)^{5/2} \approx c_1^2\ (45\ \mathrm{GeV})\left(\frac{M_{Z'}}{\mathrm{TeV}}\right)^3 + \cdots,$$

$$\Gamma(Z' \to W^+W^-) = \frac{c_2^2 M_{Z'}^3}{48\pi M_W^2}\left(1 - \frac{4M_W^2}{M_{Z'}^2}\right)^{5/2} \approx c_2^2\ (1.03\ \mathrm{TeV})\left(\frac{M_{Z'}}{\mathrm{TeV}}\right)^3 + \cdots,$$

$$\Gamma(Z' \to Z\gamma) = \frac{c_1^2 \cos^2\theta_W M_{Z'}^3}{96\pi M_Z^2}\left(1 - \frac{M_Z^2}{M_{Z'}^2}\right)^3\left(1 + \frac{M_Z^2}{M_{Z'}^2}\right) \approx c_1^2\ (307\ \mathrm{GeV})\left(\frac{M_{Z'}}{\mathrm{TeV}}\right)^3 + \cdots.$$

I. Antoniadis, A. Boyarsky, S. Espahbodi, O. Ruchayskiy. J. Wells, arXiv:0901.0639

Upper limits on Z‘ cross sections times branching fraction into two jets from LHC(8):



LHC(8) from ATLAS and CMS in 2012

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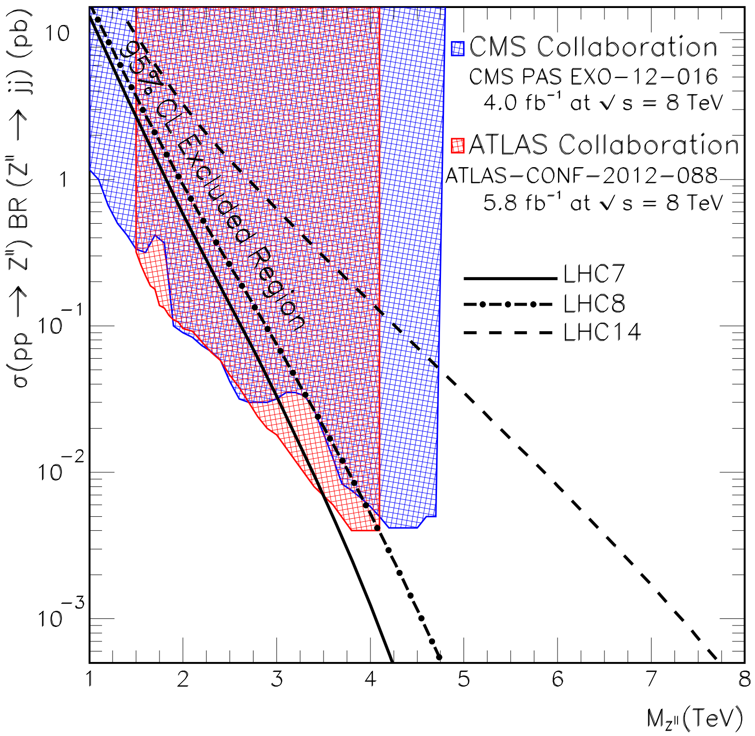

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Compare with our string model for typical parameters:

$$M_{Z''} \geq 3\ \mathrm{TeV}$$

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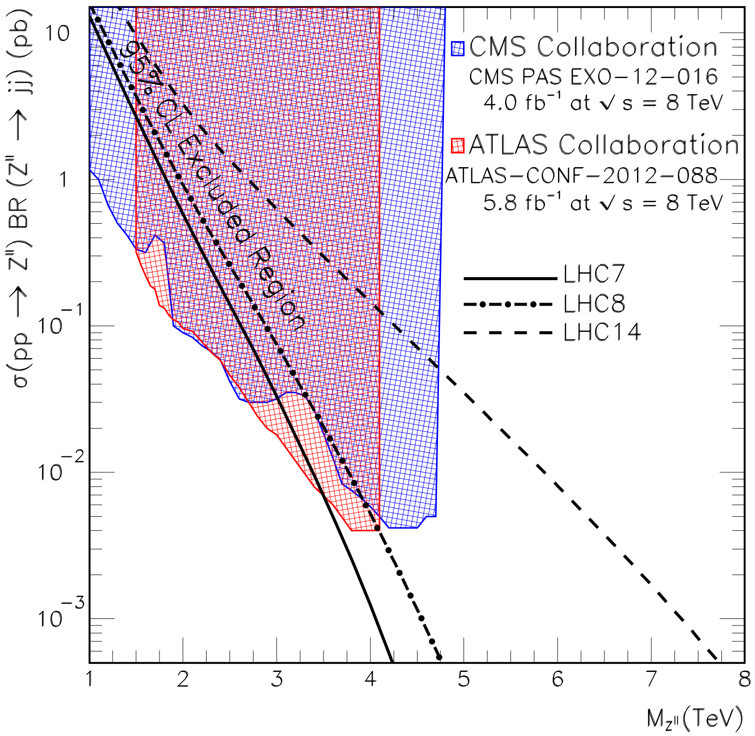

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Discovery potential for LHC(14): $M_{Z''} \leq 5 \text{ TeV}$

LHC(8): possible diboson , dijet excess at 1.8 - 2.0 TeV:

ATLAS 3.4 sigma excess. ATLAS, arXiv: 1506.00962

CMS 1.9 sigma excess. CMS, arXiv: 1506.00962

Benchmarks:

J. Brehmer, J. Hewett, J. Kopp, T. Rizzo, J. Tattersall, arXiv:1507:0013

$$\sigma(pp \to Z') \times \mathcal{B}(Z' \to ZZ/WW) \sim 5.5^{+5.1}_{-3.7}\ \text{fb}$$

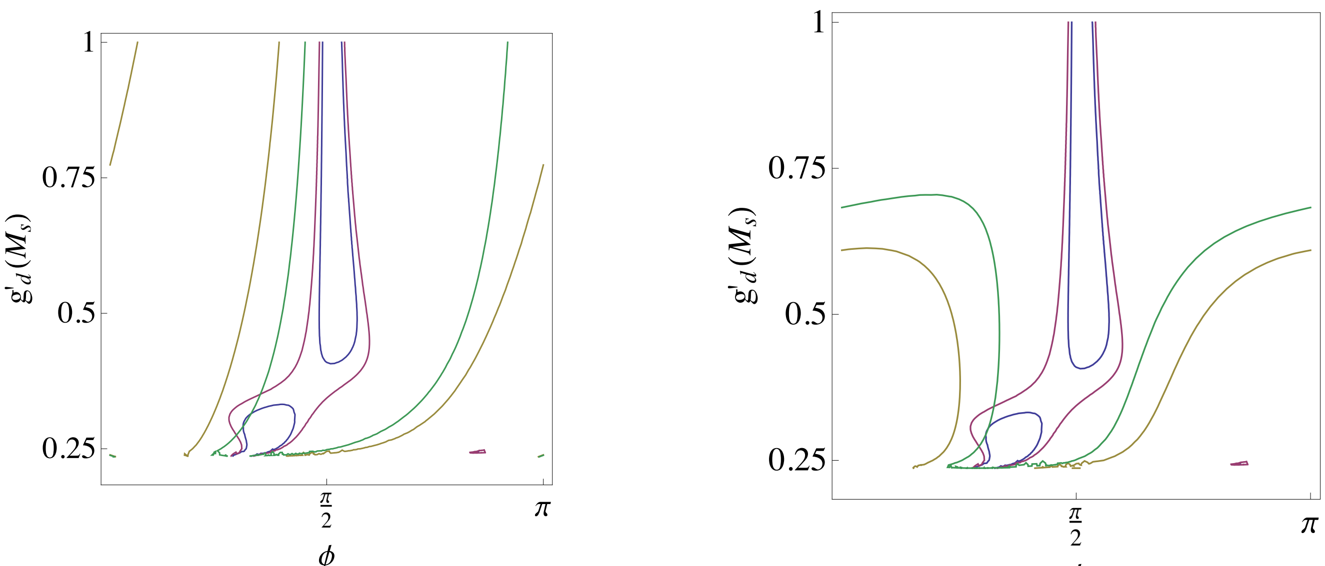
$$\sigma(pp \to Z') \times \mathcal{B}(Z' \to jj) \sim 91^{+53}_{-45}\ \text{fb}$$

$$\sigma(pp \to Z') \times \mathcal{B}(Z' \to e^+e^-) < 0.2\ \text{fb}\ (95\%\ \text{C.L.}),$$

$$\sigma(pp \to Z') \times \mathcal{B}(Z' \to HZ) < 12.9\ \text{fb}\ (95\%\ \text{C.L.})$$

These cross sections can be in principle explained by a leptophobic Z' gauge boson of mass 1.8 TeV - 2 TeV.

Scan through the parameter space to see if one can fit these date. L. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D.L., T. Taylor, arXiv:1507.05299



Best fit of cross section contourspp $\to Z'$ times branching into dijet/leptons (left) and $pp \to Z'$ times branching into dibosons (right), for $M_{Z'} \simeq 1.8$ TeV and $\sqrt{s} = 8$ TeV. The blue and red contours correspond to $\sigma(pp \to Z') \times \mathcal{B}(e^+e^-) = 0.2$ and 0.3 fb, respectively. The yellow and green contours on the left correspond to $\sigma(pp \to Z') \times \mathcal{B}(jj) = 91$ and 123 fb, respectively.

The yellow and green contours on the right correspond to $\sigma(pp \to Z') \times \mathcal{B}(W^+W^-) = 4$ and 4.5 fb.

(ii) Rare b-decays

Flavor changing neutral currents, processes like

$$b \rightarrow s\ l^+\ l^-$$

$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma(B^+ \rightarrow K^+ e^+ e^-)}{dq^2} dq^2}$$

SM prediction: $R_K \simeq 1$

LHCb measurement: $R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$

2.6σ deviation from the SM !

Sample calculation in 5 stack intersecting brane model

A. Celis, W. Feng, D.L. arXiv:1512.02218

$$M_{Z'} \sim 3.5 - 5.5 \text{ TeV}$$

We find that

$$\text{Br}(Z' \to \mu^+\mu^-)/\text{Br}(Z' \to e^+e^-) \sim [0.5, 0.9]$$

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The resonance was seen in the at center of mass energy: $\sqrt{s} = 13 \text{ TeV}$

ATLAS: $3.2 \text{ fb}^{-1}, \quad 3.9\sigma$ ATLAS-CONF-2015-081

CMS: $2.6 \text{ fb}^{-1}, \quad 2.6\sigma$ CMS-PAS-EXO-15-004

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$$\sigma_{\text{LHC13}}(pp \to \varphi + \text{anything}) \times \mathcal{B}(\varphi \to \gamma\gamma) \approx \begin{cases} (10 \pm 3) \text{ fb} & \text{ATLAS} \\ (6 \pm 3) \text{ fb} & \text{CMS} \end{cases}$$

R. Francescini et al., arXiv:1512.04933; J. Ellis, S. Ellis, J. Quevillon, V. Sanz, T. You, arXiv:1512.05327; ...

Various stringy explanations:

F-theory and F-theory GUT's

Realistic D-brane models

Open strings, vector like exotics

Heterotic string models

Stringy Axions

KK particles, ...

J. Heckmann, arXiv:1512.06773; M. Cvetic, J. Halverson, P. Langacker, arXiv:1512.07622 & 1602.06257; L. Ibanez, V. Martin-Lozano, arXiv:1512.08777; E. Palti, arXiv:1601.00285; A. Karozas, S. King, G. Leontaris, A. Meadowcroft, arXiv:1601.00285; A. Faraggi, J. Rizos, arXiv:1601.00285; A.Abel, V. Khoze, arXiv:1601.07167 P. Anastasopoulos, M. Bianchi, arXiv:1601.07584; T. Li, A. Maxin, V. Mayes, D. Nanopoulos, arXiv:1602.09099; G. Leontaris, Q. Shafi, arXiv:1603.06962; A. Adazzi, arXiv:1604.06799; J. Ashfaque, L. Delle Rose, A. Faraggi, arXiv:1606.01052; A. Belhai, S. Ennadifi, arXiv:1606.02956

We discussed that φ is a closed (pseudo) scalar string state.

L. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D.L., T. Taylor, arXiv:1512.08502 & 1603.08294

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L. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D.L., T. Taylor, arXiv:1512.08502 & 1603.08294

Non-renormalizable, dimension 5 operators are generic in string theory.

Couplings of neutral (pseudo) scalars to gauge bosons:

$$\mathcal{L} \sim \frac{c}{M_s}\varphi F^2 \, , \frac{c}{M_s}\varphi F\tilde{F}$$ F .... photons or gluons

φ : closed string (NS or Ramond) scalar.

Assume: $M_\varphi \approx 750 \text{ GeV}$ (small compared to M_s)

In our first paper we have considered production of φ via photon fusion and decay into photos:

C. Csaki, J. Hubisz, J. Terning, arXiv:1512.05776

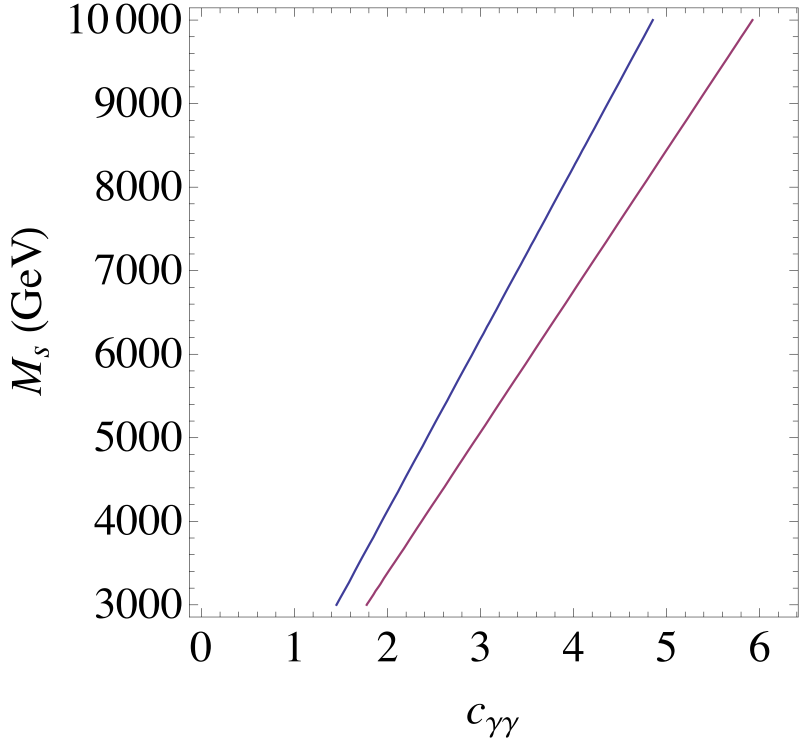
$$\Gamma_{\gamma\gamma} = \frac{c_{\gamma\gamma}^2}{4\pi}\frac{M_\varphi^3}{M_s^2}$$

$$\sigma(pp \to pp\gamma\gamma) = \frac{8\pi^2}{M_\varphi}\frac{\Gamma_{\gamma\gamma}^2}{\Gamma_{total}}\int dx_1\ dx_2\ f_s^\gamma(x_1)\ f_s^\gamma(x_2)\ \delta(x_1 x_2 s - M_\varphi^2)$$

$$\sigma_{\sqrt{s}=13\ \mathrm{TeV}} = 162(73)\ \mathrm{fb}\ \left(\frac{\Gamma_{total}}{45\ \mathrm{GeV}}\right)\mathcal{B}^2(\varphi \to \gamma\gamma)$$

$$\mathcal{B}^2(\varphi \to \gamma\gamma) = \frac{2.3\times 10^6 c_{\gamma\gamma}^2}{\pi {M_s}_{\mathrm{GeV}}^2}$$

Scan in the parameter space:



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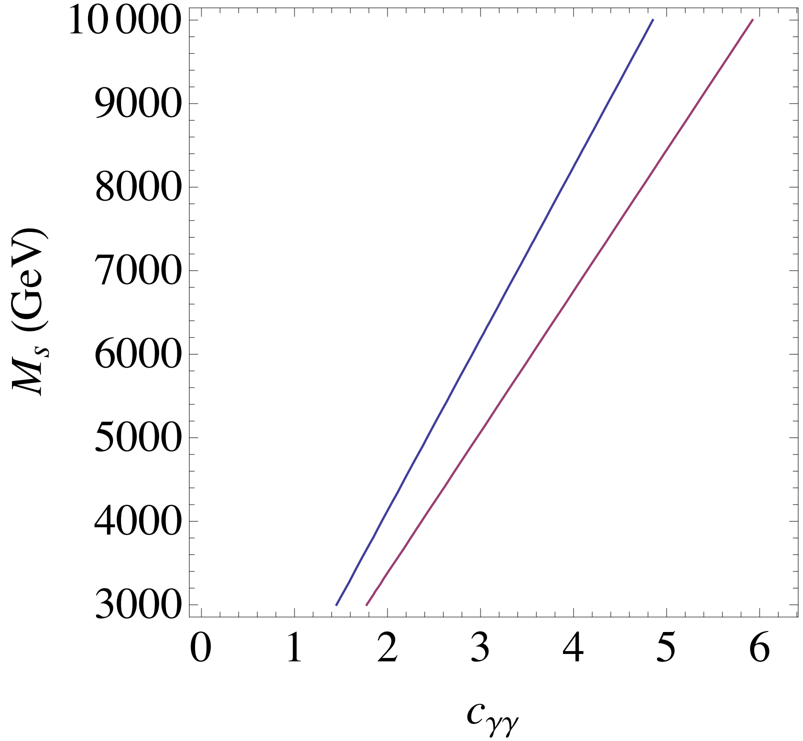


For a string scale $M_s \geq 7\ \mathrm{TeV}$ and a reasonably large $c_{\gamma\gamma}$ one gets

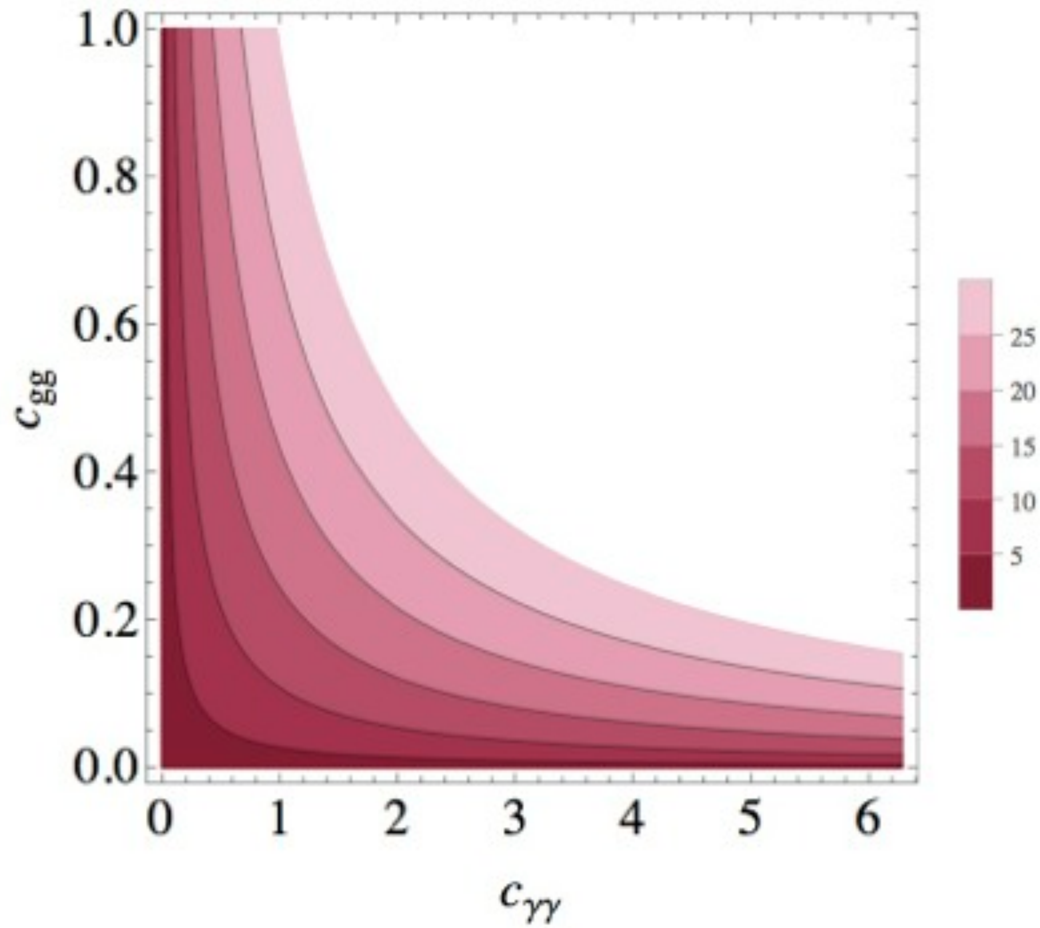
$$\sigma_{\sqrt{s}=13\ \mathrm{TeV}} \sim 5\ \mathrm{fb}$$

$$\mathcal{B}(\varphi \to \gamma\gamma) \sim 0.17(0.26) \qquad \Gamma_{\gamma\gamma} = 8(12)\ \mathrm{GeV}$$

Couplings to gluons:

$$\Gamma_{gg} = 8\frac{c_{gg}^2}{4\pi}\frac{M_\varphi^3}{M_s^2}$$

$$\sigma_{\mathrm{LHC13}}(gg \to \varphi \to \gamma\gamma) = 5.8 \times 10^3 \text{ pb } c_{gg}^2 \frac{M_s}{\text{TeV}}^{-2} \mathcal{B}(\varphi \to \gamma\gamma)$$

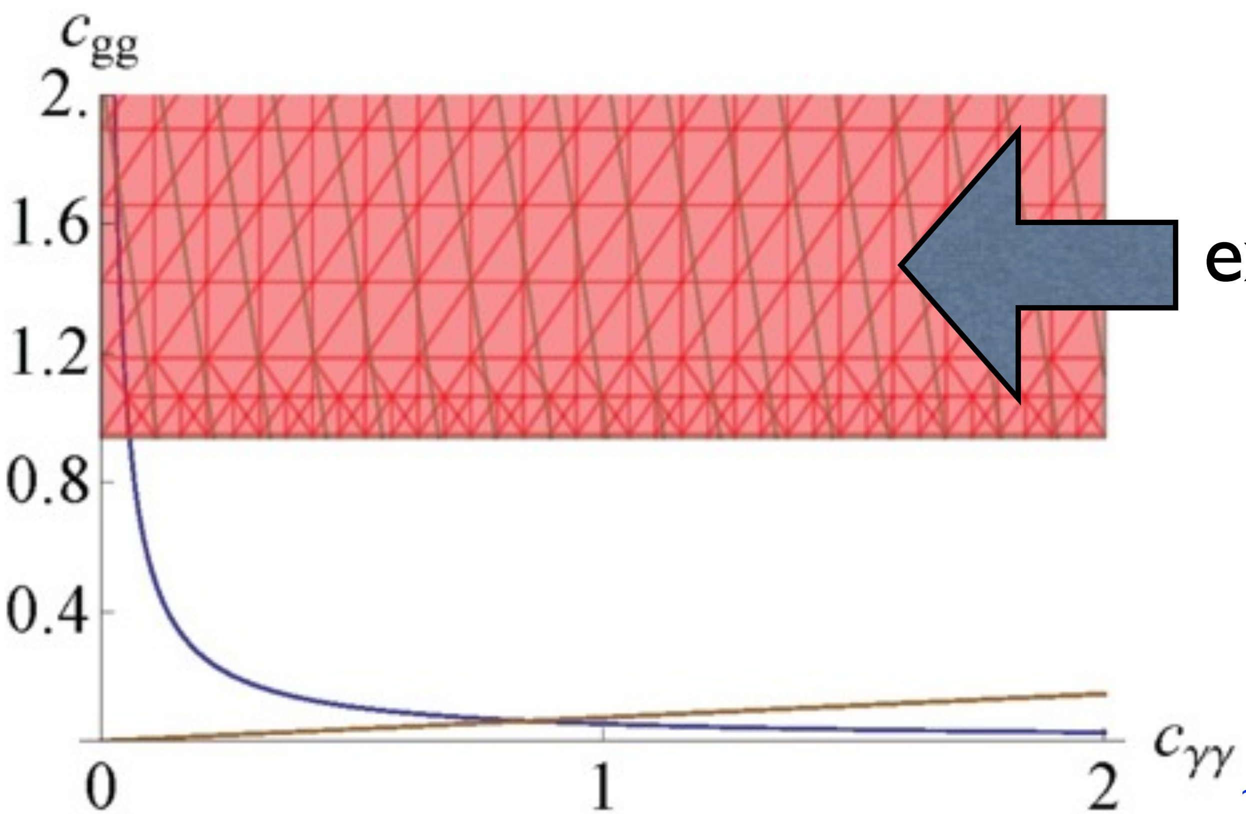


Contours of constant M_s

The 750 GeV were not seen at LHC(8TeV) run.

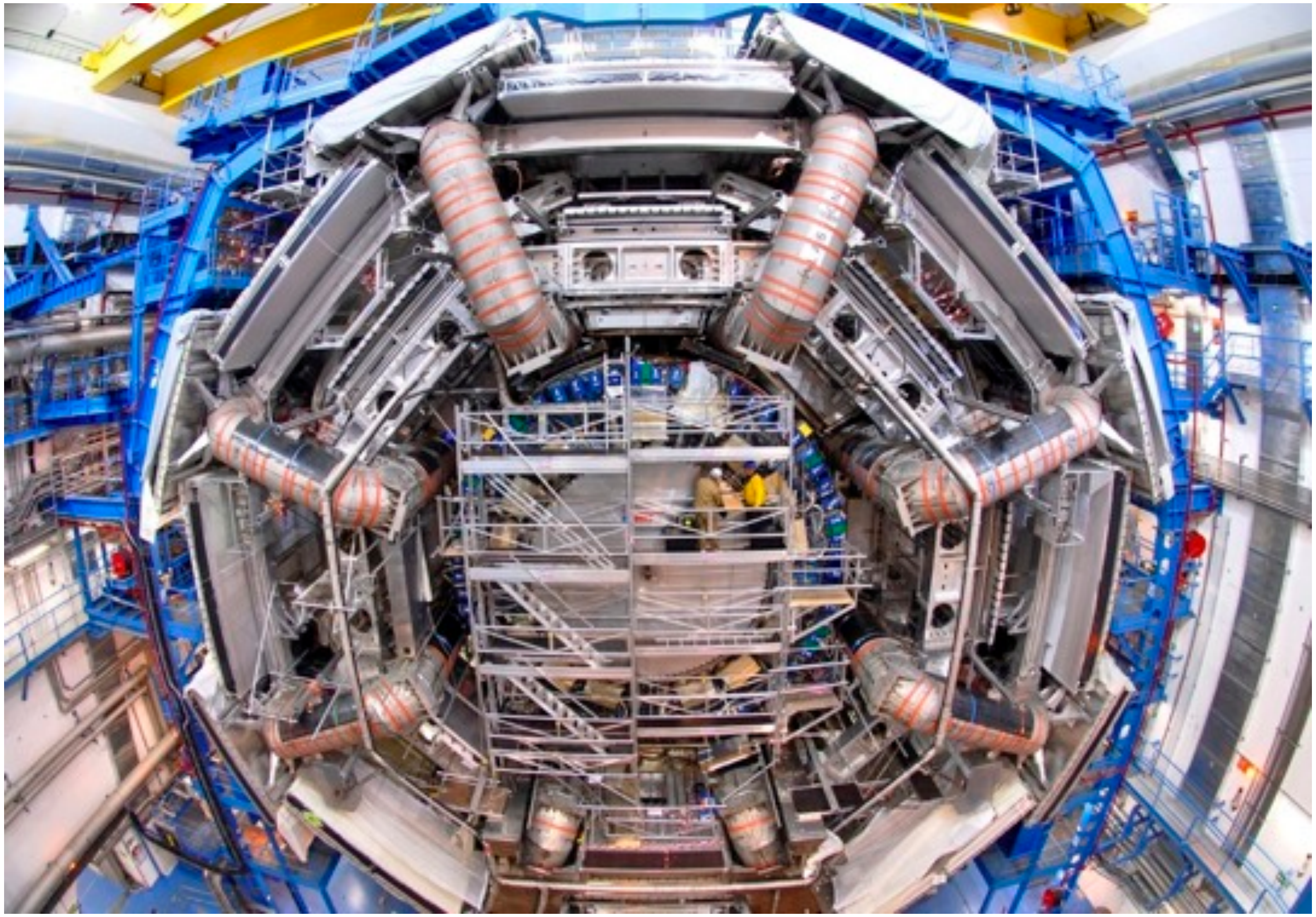
ATLAS, arXiv:1504.05511; CMS, arXiv: 1506.02301

In fact, LHC(13) prefers a cross section that is roughly 16 times larger than at 8 TeV.



$M_s = 7$ TeV

If nature choses strings with a string scale at a few TeV, there is a chance that LHC can find them !



Thank you !