

Aspects of string phenomenology in particle physics and cosmology

I. Antoniadis

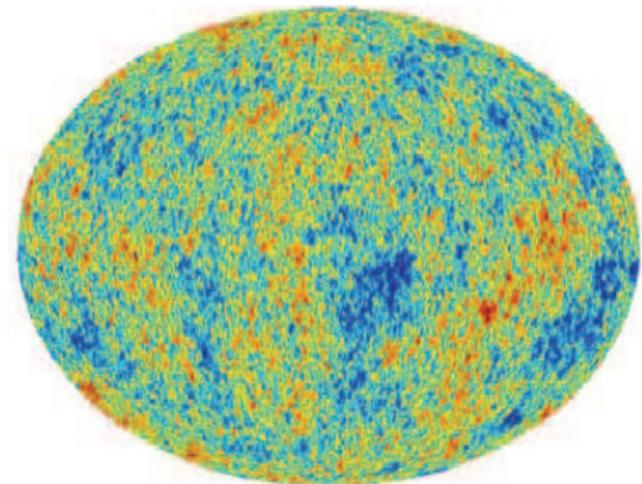
Albert Einstein Center, Bern University
and LPTHE, UPMC/CNRS, Paris

String Phenomenology, Kolymbari, Crete, Greece, 6-14 July 2016



String theory

- Is it a tool for strong coupling dynamics or a theory of fundamental forces?
- If theory of Nature can it describe both particle physics and cosmology?



An interesting possibility: string scale at low energies

I.A.-Arkani-Hamed-Dimopoulos-Dvali '98

Accelerator signatures of TeV strings: 4 different scales

- Gravitational radiation in the bulk \Rightarrow missing energy

present LHC bounds: $M_* \gtrsim 4 - 9 \text{ TeV}$

- Massive string vibrations \Rightarrow e.g. resonances in dijet distribution [5]

$$M_j^2 = M_0^2 + M_s^2 j \quad ; \quad \text{maximal spin : } j+1$$

higher spin excitations of quarks and gluons with strong interactions

present LHC limits: $M_s \gtrsim 7 \text{ TeV}$

- Large TeV dimensions \Rightarrow KK resonances of SM gauge bosons I.A. '90

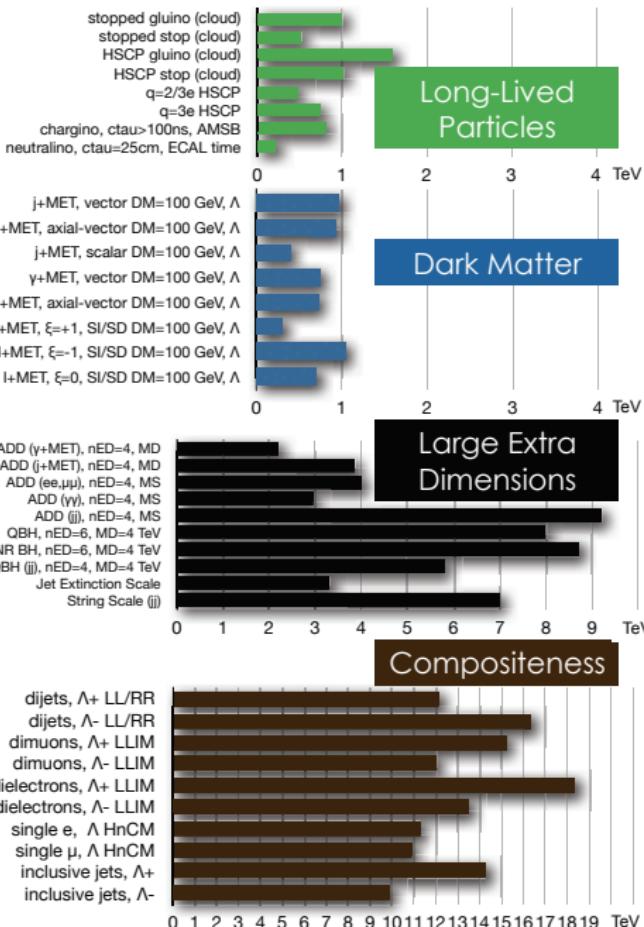
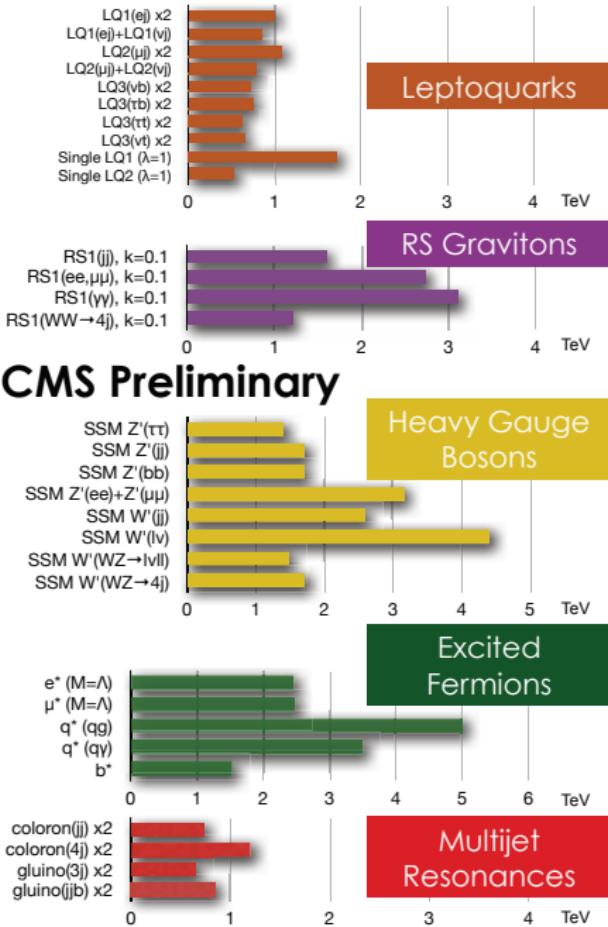
$$M_k^2 = M_0^2 + k^2/R^2 \quad ; \quad k = \pm 1, \pm 2, \dots$$

experimental limits: $R^{-1} \gtrsim 0.5 - 4 \text{ TeV}$ (UED - localized fermions)

- extra $U(1)$'s and anomaly induced terms

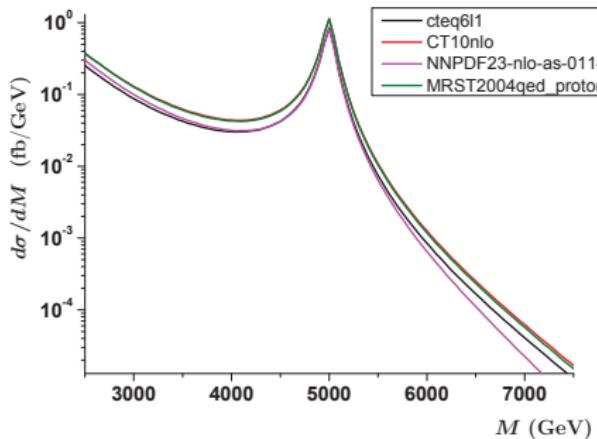
masses suppressed by a loop factor from M_s [7]

CMS Preliminary

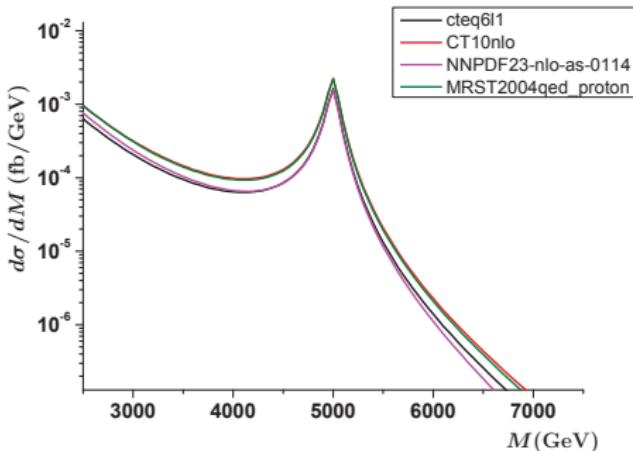


String Resonances production at Hadron Colliders

I.A.-Anchordoqui-Dai-Feng-Goldberg-Huang-Lüst-Stojkovic-Taylor '14



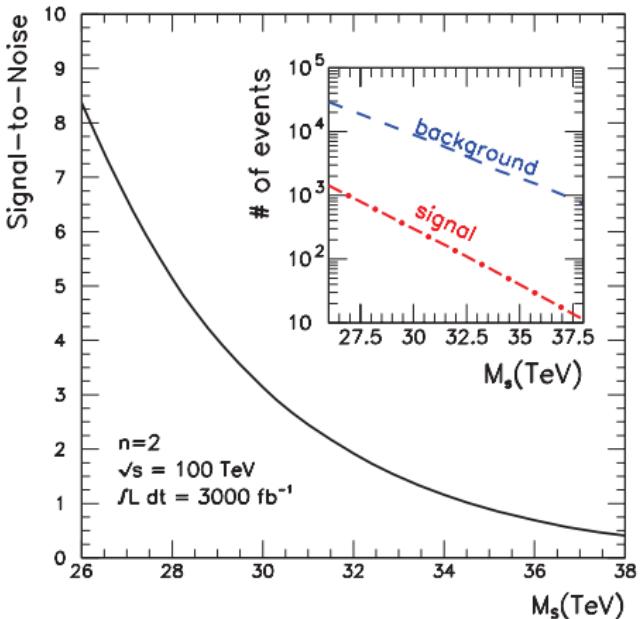
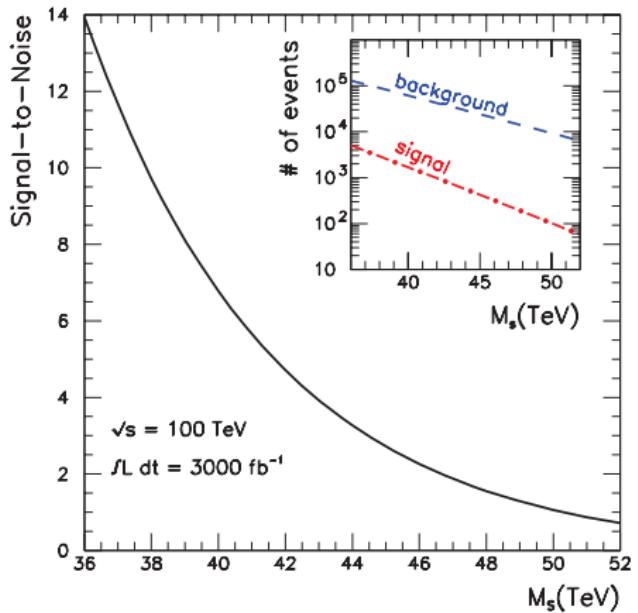
$M_s = 5 \text{ TeV}$: dijet at LHC14



$\gamma + \text{jet}$ [3]

String Resonances production at Hadron Colliders

I.A.-Anchordoqui-Dai-Feng-Goldberg-Huang-Lüst-Stojkovic-Taylor '14

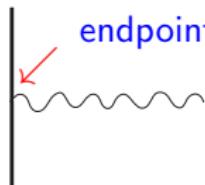


[3]

D-brane spectrum

Generic spectrum: N coincident branes $\Rightarrow U(N)$

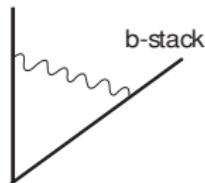
a-stack



endpoint transformation: N_a or \bar{N}_a $U(1)_a$ charge: +1 or -1
 \Rightarrow "baryon" number

- open strings from the same stack \Rightarrow adjoint gauge multiplets of $U(N_a)$
- stretched between two stacks \Rightarrow bifundamentals of $U(N_a) \times U(N_b)$

a-stack



non-oriented strings \Rightarrow also:

- orthogonal and symplectic groups $SO(N), Sp(N)$
- matter in antisymmetric + symmetric reps

Extra $U(1)$'s and anomaly induced terms

masses suppressed by a loop factor

usually associated to known global symmetries of the SM

(anomalous or not) such as (combinations of)

Baryon and Lepton number, or PQ symmetry

Two kinds of massive $U(1)$'s:

I.A.-Kiritsis-Rizos '02

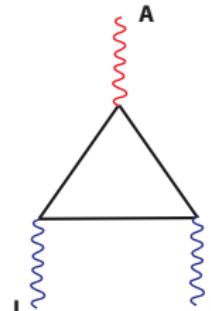
- 4d anomalous $U(1)$'s: $M_A \simeq g_A M_s$

- 4d non-anomalous $U(1)$'s: (but masses related to 6d anomalies)

$$M_{NA} \simeq g_A M_s V_2 \xleftarrow{(6d \rightarrow 4d) \text{ internal space}} \Rightarrow M_{NA} \geq M_A$$

or massless in the absence of such anomalies [10]

Green-Schwarz anomaly cancellation


$$= k_I^A \sim \text{Tr} Q_A Q_I^2 \rightarrow \text{axion } \theta : \delta A = d\Lambda \quad \delta\theta = -m_A \Lambda$$
$$-\frac{1}{4g_I^2} F_I^2 - \frac{1}{2} (d\theta + m_A A)^2 + \frac{\theta}{m_A} k_I^A \text{Tr} F_I \wedge F_I$$

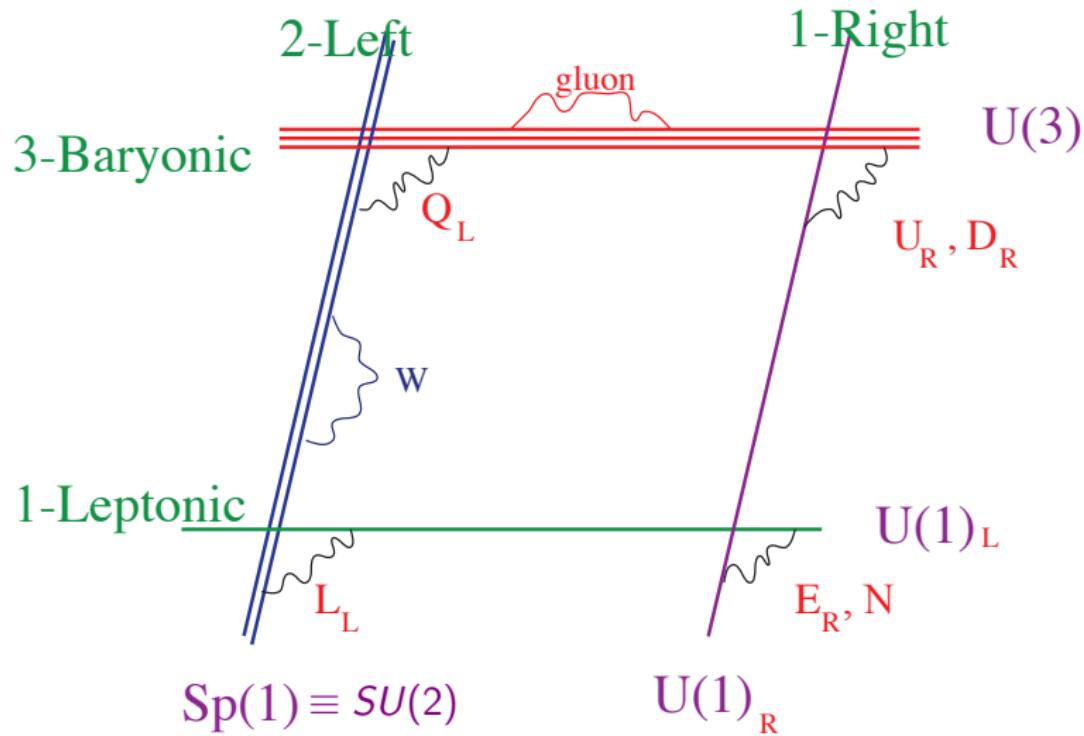
cancel the anomaly

D-brane models: $U(1)_A$ gauge boson acquires a mass
but global symmetry remains in perturbation theory

GS anomaly cancellation \Rightarrow extra scalars and axion-like particles (ALP) [11]

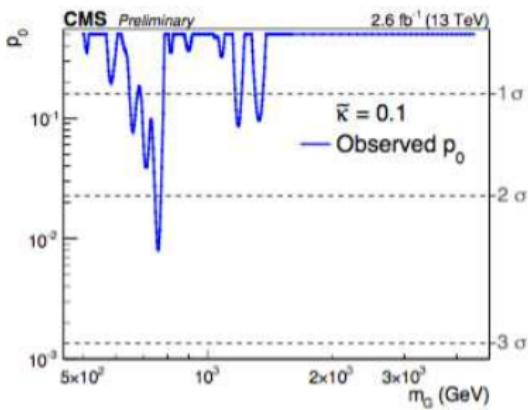
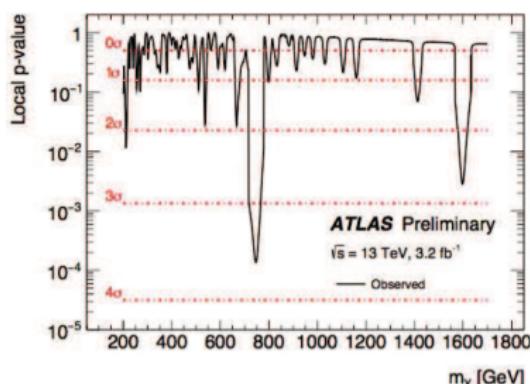
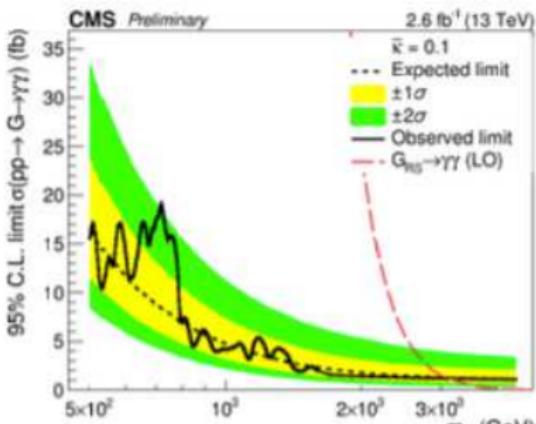
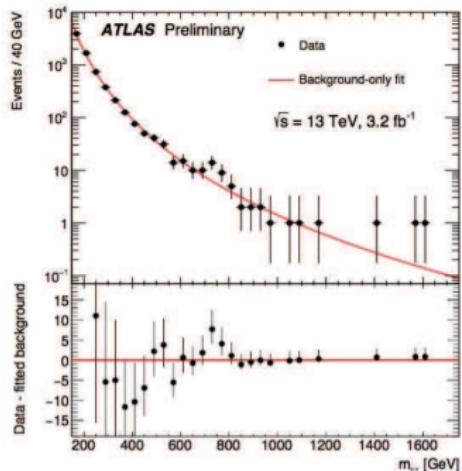
- coupled to gauge kinetic terms
- lighter than the string scale (masses loop-factor suppressed)

Standard Model on D-branes : SM⁺⁺



$$U(1)^3 \Rightarrow \text{hypercharge } (Y = \frac{1}{2}(R - L) + \frac{1}{6}B) + B, L \quad [13]$$

Diphoton excess at LHC: $M \sim 750$ GeV $\Gamma \approx 45$ GeV



Main data

- ATLAS 3.2 fb^{-1} data \Rightarrow best fit: $M \sim 750 \text{ GeV}$, $\Gamma \approx 45 \text{ GeV}$
spin-0 \Rightarrow significance 3.9σ local / 2.0σ global
spin-2 \Rightarrow significance 3.6σ local / 1.8σ global
- CMS 3.3 fb^{-1} data \Rightarrow best fit: $M \sim 760 \text{ GeV}$, $\Gamma \approx 11 \text{ GeV}$
spin-0 \Rightarrow 2.8σ local / $< 1.0\sigma$ global
spin-2 \Rightarrow significance 2.9σ local / $< 1.0\sigma$ global
combined LHC13/8 $\Rightarrow M \sim 750 \text{ GeV}$, $\Gamma \approx 0.1 \text{ GeV}$
local significance 3.4σ / global 1.6σ

$$\sigma_{\text{LHC13}}(pp \rightarrow \varphi + X) \times \mathcal{B}(\varphi \rightarrow \gamma\gamma) \sim 10 \pm 3/6 \pm 3 \text{ fb ATLAS/CMS}$$

but $\sigma_{\text{LHC8}} < 2 \text{ fb } 95\% \text{ CL}$

\Rightarrow need more statistics for a firm conclusion

Proposal: closed string state coupled to F_γ^2 or $F_\gamma \tilde{F}_\gamma$

Anchordoqui-IA-Goldberg-Huang-Lüst-Taylor '15, '16

Requirements:

- coupling to 2 photons: $f_\varphi \varphi F_\gamma^2$ (dilaton-like) or $f_\varphi \varphi F_\gamma \wedge F_\gamma$ (axion-like)
- suppressed couplings to $SU(3)$ and $SU(2)$
- suppressed mass compared to the string scale $M_s \gtrsim 7$ TeV

For instance:

modulus associated to the wrapping cycles of $U(1)_R$ and $U(1)_L$ [10]

with a loop factor suppressed mass due to anomalies

φ localized in the bulk at the orbifold singularity \Rightarrow

coupling strength set by the string scale and not the Planck mass

$$f_\varphi = \frac{c_{\gamma\gamma}}{M_s} \Rightarrow \text{partial width } \Gamma_{\gamma\gamma} = \frac{c_{\gamma\gamma}^2}{4\pi} \frac{M_\varphi^3}{M_s^2}$$

production via photon fusion

$$\sigma_{\text{LHC13}}(\gamma\gamma \rightarrow \varphi \rightarrow \gamma\gamma) \simeq 4.1 \text{ pb} \left(\frac{\Gamma_t}{45 \text{ GeV}} \right) \mathcal{B}^2(\varphi \rightarrow \gamma\gamma)$$

Harland-Lang, V.A.Khoze, Ryskin '16

$$\mathcal{B}(\varphi \rightarrow \gamma\gamma) = \frac{2.3 \times 10^6 c_{\gamma\gamma}^2}{\pi} \left(\frac{M_s}{\text{GeV}} \right)^{-2} \left(\frac{\Gamma_t}{45 \text{ GeV}} \right)^{-1}$$

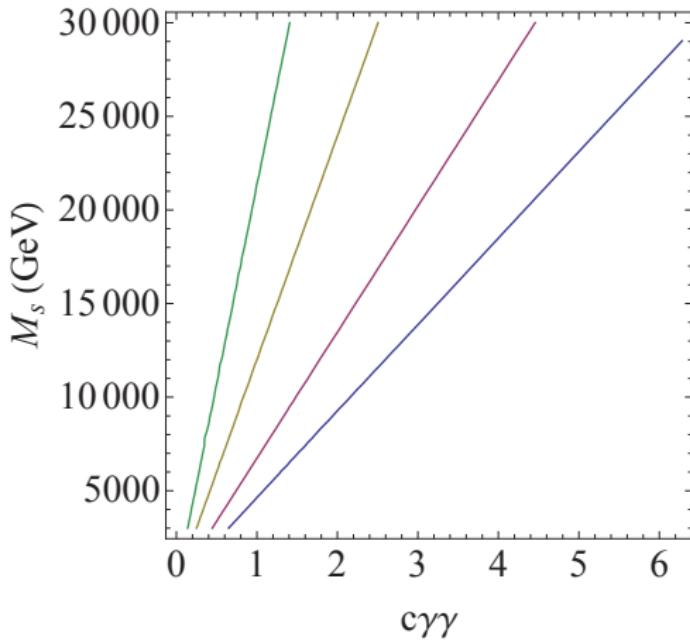
photon distribution function at small x :

$$f_s^\gamma(x) = \frac{1}{x} \frac{2\alpha}{\pi} \log \left[\frac{q_*}{m_p} \frac{1}{x} \right]$$

m_p : proton mass , $130 \text{ MeV} < q_* < 170 \text{ MeV}$

Fichet-Gersdorff-Royon '15, Csaki-Hubisz-Terning '15

Scan of the parameter space for γ -fusion



Best fit contours of diphoton cross section $\sigma_{\text{LHC13}} \sim 5 \text{ fb}$ via γ -fusion, for $\Gamma_t = 45, 10, 1, 0.1 \text{ GeV}$

Comments

- If φ couples to hypercharge \Rightarrow

additional decay channels $\varphi \rightarrow \gamma Z, ZZ$:

$$\frac{\Gamma_{\gamma Z}}{\Gamma_{\gamma\gamma}} = 2 \tan^2 \theta_W \approx 0.6 \quad ; \quad \frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}} = \tan^4 \theta_W \approx 0.08$$

- Partial width $\Gamma_{\gamma\gamma} \simeq 10 \text{ GeV}$

Missing width (if Γ_{tot} large): invisible decays to bulk fields?

KK gravitons suppressed but bulk fermions can do the job

may also be dark matter component

Dienes-Thomas '12

production via gluon fusion

φ coupling to gluon kinetic terms $\frac{c_{gg}}{M_s} \varphi G^2$

\Rightarrow partial decay width to dijets $\Gamma_{gg} = 8 \frac{c_{gg}^2}{4\pi} \frac{M_\varphi^3}{M_s^2}$

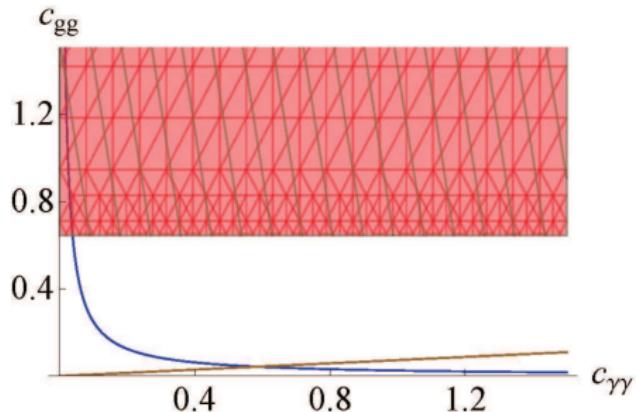
$$\sigma_{\text{LHC13}}(gg \rightarrow \varphi \rightarrow \gamma\gamma) \simeq 5.8 \times 10^3 \text{ pb } c_{gg}^2 \left(\frac{M_s}{\text{TeV}} \right)^{-2} \mathcal{B}^2(\varphi \rightarrow \gamma\gamma)$$

$$\sigma_{\text{LHC8}}(gg \rightarrow \varphi \rightarrow gg) \simeq 7.6 \times 10^3 \text{ pb } c_{gg}^4 \left(\frac{M_s}{\text{TeV}} \right)^{-4} \left(\frac{\Gamma_t}{45 \text{ GeV}} \right) < 2.5 \text{ pb}$$

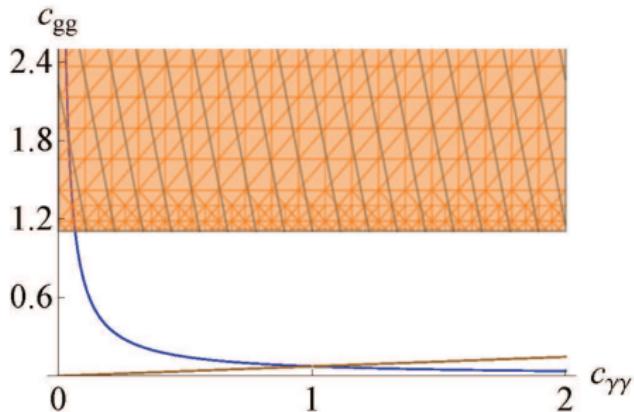
$\sigma_{\text{LHC13}}/\sigma_{\text{LHC8}} \simeq 4.7 \Rightarrow$ consistent with no excess in LHC8 data [24]

Scan of the parameter space c_{gg} vs $c_{\gamma\gamma}$ ($\Gamma_t = 10$ GeV)

$M_s = 7$ TeV



$M_s = 12$ TeV



blue curve: best fit contour of diphoton cross section $\sigma_{\text{LHC13}} \sim 5$ fb

shaded regions: excluded at 95% CL by dijet bounds

slanted curve: transition between gluon (above) and γ -fusion dominance

Cosmological observables

Power spectrum of temperature anisotropies

(adiabatic curvature perturbations \mathcal{R})

$$\mathcal{P}_{\mathcal{R}} = \frac{H^2}{8\pi^2 M_*^2 \epsilon} \simeq \mathcal{A} \times 10^{-10} \quad ; \quad \mathcal{A} \approx 22$$

\downarrow
 $-\dot{H}/H^2$

Power spectrum of primordial tensor anisotropies $\mathcal{P}_t = 2 \frac{H^2}{\pi^2 M_*^2}$

$$\Rightarrow \text{tensor to scalar ratio } r = \mathcal{P}_t / \mathcal{P}_{\mathcal{R}} = 16\epsilon$$

measurement of \mathcal{A} and $r \Rightarrow$ fix the scale of inflation

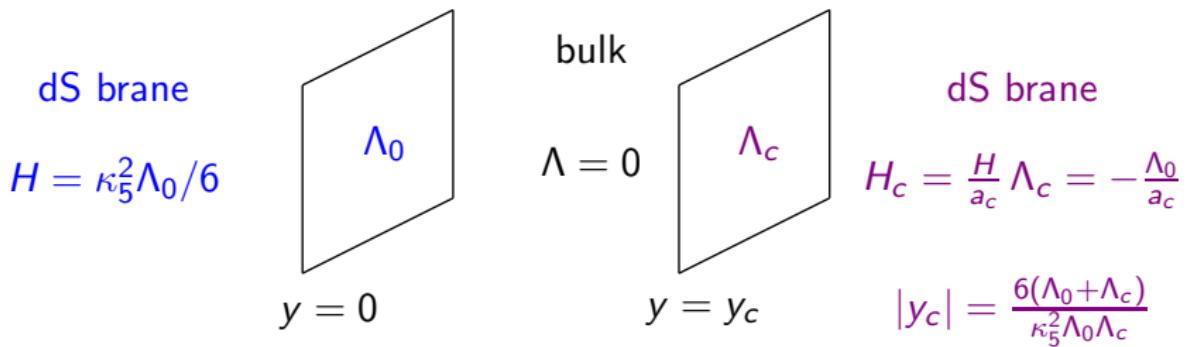
$$H \text{ in terms of } M_* \quad : \quad \frac{H}{M_*} = \left(\frac{\pi^2 \mathcal{A} r}{2 \times 10^{10}} \right)^{1/2} \equiv \Upsilon \approx 1.05\sqrt{r} \times 10^{-4}$$

- M_* may be different than M_{Planck} at the time of inflation

5D brane-world realisation: empty bulk with two boundary dS branes

$$ds^2 = \frac{(1 - H|y|)^2}{H^2\tau^2} (-d\tau^2 + dx_1^2 + dx_2^2 + dx_3^2) + dy^2$$

$|y| < 1/H$: avoid Riddler singularity $a(y) = 1 - H|y| > 0$



spectrum and couplings

4d Planck mass: $M_{Pl} \sim 1/(2H\kappa_5^2)$ y_c large

Spectrum:

0-mode (4d graviton): wave function $\phi_0 \sim (2H)^{1/2} e^{-2z}$ $z \equiv -\ln a(y) > 0$

KK-modes: $m_n^2 = H_y^2 \left(\frac{9}{4} + \pi^2 \frac{n^2}{z_c^2} \right)$ $H_y \equiv H/a(y)$: Hubble constant at y

wave functions $\phi_n \sim \frac{H}{2m_n} \left(\frac{H}{z_c} \right)^{1/2} e^{-z/2} \left[3 \sin \left(\frac{n\pi z}{z_c} \right) + \frac{2\pi n}{z_c} \cos \left(\frac{n\pi z}{z_c} \right) \right]$

⇒ KK-modes couple much stronger than 0-mode at y_c :

$$|\phi_n|/|\phi_0| = \frac{\pi n}{\sqrt{2} z_c^{3/2}} \frac{H_c}{m_n} e^{3z_c/2}$$

similar result for bulk scalars

Power spectrum

0-mode as before:

$$\mathcal{P}_0 = \frac{2}{\pi^2} \frac{H_c^2}{M_{Pl}^2}$$

KK-modes:

$$\mathcal{P}_n = \mathcal{P}_0 \frac{\pi^2 n^2}{2 z_c^3} e^{3z_c} \left(\frac{H_c}{m_n} \right)^3 \left(\frac{k}{a_{dS} H_c} \right)^3 \simeq \mathcal{P}_0 \frac{\pi^2 n^2}{2 z_c^3} \left(\frac{H_c}{m_n} \right)^3 e^{3(z_c - N)}$$

N : number of e-foldings

Riotto '02

$$\mathcal{P}_0 \lesssim \mathcal{P}_n \Rightarrow e^N \lesssim e^{z_c} / z_c$$

satisfied for TeV scale inflation ($N \gtrsim 35$, $H_c \sim M_5 \sim \text{TeV}$)

Power spectrum

$$\mathcal{P}_{\text{KK}} = \sum_n^{m_n < M_5} \mathcal{P}_n = \mathcal{P}_0 e^{3(z_c - N)} \frac{1}{2\pi} \ln \frac{M_5 z_c}{\pi H_c}$$
$$\gtrsim \mathcal{P}_0 \Rightarrow N \lesssim z_c$$

Allowed range of parameters:

$$M_{Pl}^2 \simeq \frac{M_5^3}{H_c} e^{z_c} \Rightarrow e^{z_c} \simeq \frac{M_{Pl}^2 H_c}{M_5^3} \lesssim \frac{M_{Pl}^2}{M_5^2} \quad H_c \lesssim M_5$$

$$e^{N_{\min}} = 10^{13} \times \frac{H_c}{1 \text{ GeV}} \lesssim e^{z_c}$$

$$\Rightarrow 1 \text{ TeV} \lesssim H_c \lesssim 10^8 \text{ GeV} \text{ and } 1 \text{ TeV} \lesssim M_5 \lesssim 10^{10} \text{ GeV}$$

Conclusions

String phenomenology:

Consistent framework for particle phenomenology and cosmology
several very different scales involved

Low scale gravity and strings at the (multi-)TeV scale:

- offer connection of scales and spectacular new physics to discover production of string and KK resonances, gravity emission, extra $U(1)$ s, dilaton and axion like particles
may be already hidden in LHC excesses...
- also allowed by cosmological observations
offering now possibilities for inflationary models