On the possibility of light string resonances at the LHC and Tevatron from Randall-Sundrum throats

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Abstract

In string realizations of the Randall-Sundrum scenario, the higher-spin Regge excitations of Standard Model states localized near the IR brane are warped down to close to the TeV scale. We argue that, as a consequence of the localization properties of Randall-Sundrum models of flavour, the lightest such resonance is the spin-3/2 excitation, t_R*, of the right-handed top quark over a significant region of parameter space. A mild accidental cancellation allows the t_R* to be as light or lighter than the Kaluza-Klein excitations of the Standard Model states. We consider from a bottom-up effective theory point of view the production and possible observability of such a spin-3/2 excitation at the LHC and Tevatron. Current limits are weaker than might be expected because of the excess of *WWjj* events at the Tevatron reported by CDF at $M_{\rm inv}$~ 400-500 GeV.

Motivation

• The five-dimensional Randall-Sundrum (RS) model provides an elegant explanation for the hierarchy between the electroweak and Planck scales;

• The inclusion of bulk fermions provides insight on the observed fermion mass hierarchy;

• Warped throats are generic in string theory compactifications and reproduce the main features of the RS construction, including bulk matter fields;

• The study of higher-spin string excitations of SM fields in the RS model is a useful guide to the behaviour of warped string compactifications;

• The exponential warping may bring individual Regge excitations below the Kaluza-Klein (KK) scale (~TeV), although generically string excitations will be heavier than KK modes;

• Following an effective field-theory approach, we focus on the observability of spin-3/2 excitations of SM fermions at the Tevatron and the LHC, in particular the one associated with the right-handed (rhd) top quark.

Spin-3/2 excitations in the Randall-Sundrum model

- Randall-Sundrum model with finite extra-dimension $0 < y < L$ and curvature k:

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$

- 5D-Rarita-Schwinger action for spin-3/2 field with mass $M_\Psi = ck$:

$$S_5 = \int d^4x \int dy \sqrt{-G}\bar{\Psi}_M \Gamma^{MNP}\left(D_N + \frac{1}{3}M_\Psi \Gamma_N\right)\Psi_P$$

- KK-mode expansion and equations (*analogous to spin-1/2 case*):

$$\Psi_\mu^{L,R}(x,y) = \frac{1}{\sqrt{L}}\sum_n \psi_{\mu n}^{L,R}(x)e^{2ky}f_n^{L,R}(y)$$

$$(\partial_5 + M_\Psi)f_n^R = m_n e^{ky} f_n^L \ , \qquad (-\partial_5 + M_\Psi)f_n^L = m_n e^{ky} f_n^R$$

- Impose mixed boundary conditions to avoid phenomenologically dangerous zero-modes;

- Bulk mass for resonance i:

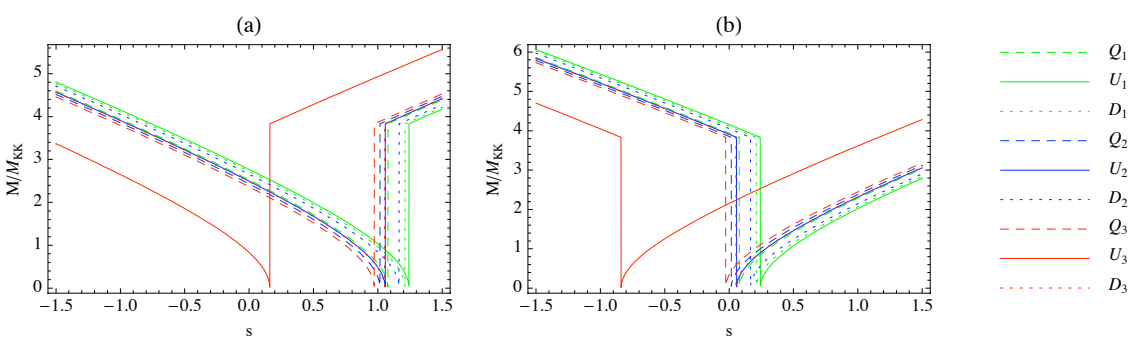
$$c_i = c_{0i} + s$$

spin-1/2 SM fermion

string contribution (flavour-blind and $\mathcal{O}(1)$)

- Consider set of spin-1/2 bulk mass parameters consistent with quark masses and mixings;

- Mass spectrum of spin-3/2 quark excitations (first KK mode):



Spectrum of quark resonances for (a) (-,+) and (b) (+,-) boundary conditions in the (UV,IR) branes for left-handed doublet states, normalized to the KK mass scale.

- Lepton and first two families of quark resonances have comparable masses;

- IR brane-localized Yukawa operators give sub-leading contributions which are further suppressed for specific choices of boundary conditions.

The rhd top spin-3/2 resonance is lighter than all others in a large region of parameter space and it may even lie below the KK scale
(due to the IR-localization of the rhd top wave-function)

Spin-3/2 right-handed top interactions

- Minimal coupling (*leading interaction for pair production*):

$$\mathcal{L}_4 = i\bar{\psi}_\mu \gamma^{\mu\nu\rho} D_\nu \psi_\rho + M \bar{\psi}_\mu \gamma^{\mu\rho} \psi_\rho$$

- Dimension-5 strong, weak and e.m. interactions (*leading interaction for single production*):

$$\mathcal{L}_5 \quad = \quad i\frac{a_i}{\Lambda}\bar{\psi}_\mu(\eta^{\mu\alpha} + z\gamma^\mu\gamma^\alpha)F_{\alpha\beta}\gamma^\beta P_R\chi + \text{h.c.}\ , \qquad a_i \sim g_i$$

cut-off scale — gauge field strength — rhd top quark — gauge coupling

- Dimension-4 weak interactions arise from Yukawa mixing between the spin-1/2 and spin-3/2 sectors, but are suppressed by $v/M_{K.K}$, v being the Higgs vev (and *possibly further suppressed for particular choices of boundary conditions*);

- FCNC from Yukawa terms are suppressed by similar mechanism that suppresses the couplings of KK fermions and SM states in RS models;

- Low-energy and electroweak observables can easily accommodate a spin-3/2 rhd top excitation below the TeV scale.

Experimental signatures I

- Main decay modes of t_R* (*may have comparable branching ratios*):

$$t_R^* \to tg,\ Wd_i\ ,\ Zt,\ Ht$$

- Use narrow width approximation:

$$\frac{\Gamma_{tg}}{M} \simeq \frac{a_3^2}{48\pi^2}\left(\frac{M}{\Lambda}\right)^2 \ll 1$$

- Unitarity bound (*s-wave*):

$$\sqrt{s} \lesssim 7M$$

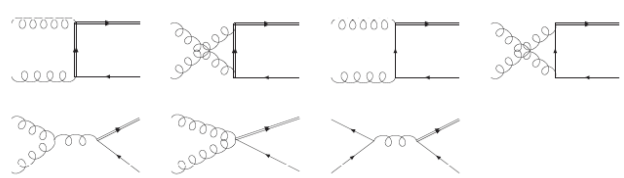
- Tevatron limits:

  - M > 340 GeV (@2σ, *BR(Wb)=1*);

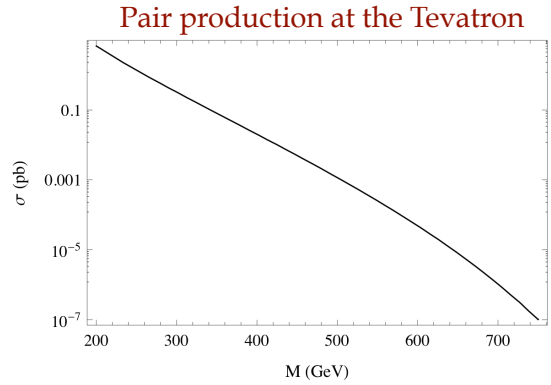
  - M ~ 400 GeV may explain mild excess in *WWjj* events (*better than standard top-prime*).

Pair production

Single production

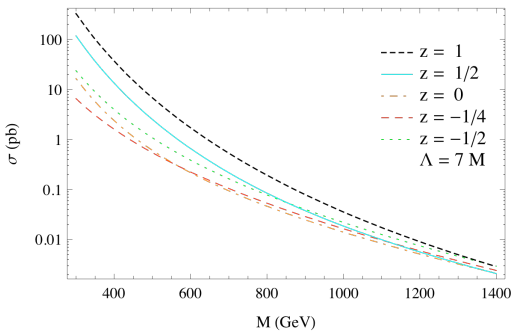


Pair production at the Tevatron

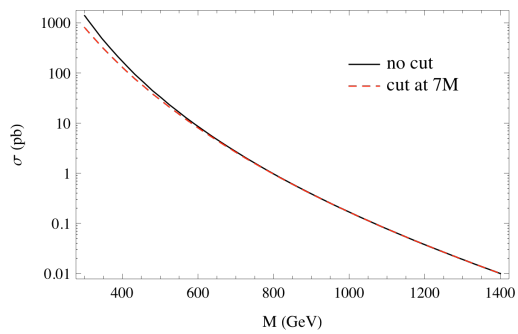


Experimental signatures II

Single production at the LHC



Pair production at the LHC



- Pair production is dominant (*even with unitarity cut at the parton level*);
- S/N ≥ 5 for M ≤ 1.35 TeV if W^+b is the dominant decay mode of t_R*
  (M ≤ 1.1 TeV for an analogous spin-1/2 resonance).

Conclusions

- Higher-spin Regge excitations of SM fermions are warped down to close to the TeV scale in string realizations of the Randall-Sundrum model;
- Due to the IR-localization of the rhd top quark, its spin-3/2 excitation is the lightest such resonance in a significant region of parameter space and may even lie below the KK scale;
- Direct searches at the Tevatron constrain such states to be heavier than 340 GeV, although a 400 GeV resonance might explain the reported excess of *WWjj* events;
- Such states should be observable at the LHC if M < 1.35 TeV (dominant decay into W^+b) and we are preparing a detailed analysis of their production and detection.

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