Four Boosted Tops from a Regge Gluon

arXiv:0907.3496, 1106.2171

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Supersymmetry 2011, 29th August, 2011

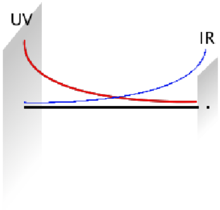
Outline

1. Introduction & Background
   - Randall-Sundrum Models
   - String Theory
2. The Warped Space Regge Gluon
   - Kaluza-Klein Expansion
   - Interactions with Standard Model
3. LHC Phenomenology
   - Decays of the Regge Gluon
   - Signals and Backgrounds

Randall-Sundrum Models
Background, Notation and Conventions

Randall-Sundrum models have 5D warped geometry:

$$\mathrm{d}s^2 = \exp(-2k\,|y|)\,\mathrm{d}x^\mu\,\mathrm{d}x_\mu - \mathrm{d}y^2; \quad y \in [0, L].$$



- Relevant Scales:
  $k \sim$ Planck; $kL \sim 35$;
  $\Lambda \equiv k\exp(-kL) \sim$ TeV.
- Higgs localised at $y = L$ (IR);
  Natural mass scale Λ.
- Other SM fields propagate in bulk;
- KK scale $\sim$ a few times Λ.
- Warping $\Rightarrow$ light stringy effects?

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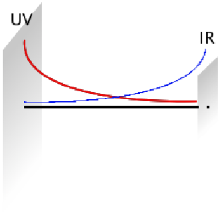

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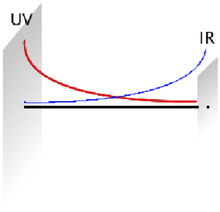

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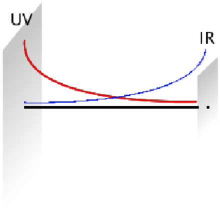

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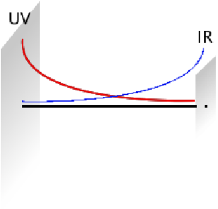

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String Theory in General and in RS

Regge States and Veneziano Amplitudes

We (I?) can't do String Theory in RS.

- Warped backgrounds not under theoretical control

High Spin (Regge) States!

- Characteristic of stringy physics
- Bosonic string: nth harmonic:
- Veneziano amplitudes:

  $$A \propto \frac{\Gamma(1-\alpha' s)\Gamma(1-\alpha' t)}{\Gamma(1-\alpha' s-\alpha' t)}$$

- Regge poles at $s = n M_S^2$

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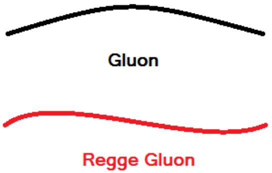

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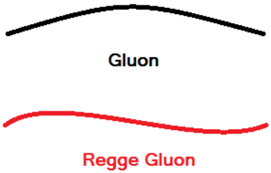
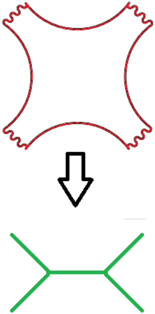


An Effective Field Theory Perspective

Model-Building Philosophy



1. Take toy string model of QCD in flat space
2. Compute scattering amplitudes $\mathcal{A}$
3. Factorise on first Regge pole
4. Construct EFT that reproduces stringy $\mathcal{A}$
   - (Focus on spin 2 gluon partner)
5. Covariantly generalise theory to RS
6. Integrate over extra dimension
   - (KK expansion)

Warning! Not a well-defined approximation to string theory!

See Rosa et al, 0904.4108 for spin-3/2 top partner

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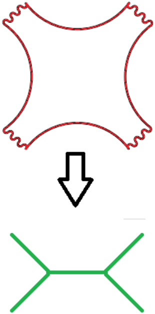

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Spin-Two Quadratic Terms

Free tensor action in RS:

$$\mathcal{L}_2 = \frac{1}{4} H_{LMN} H^{LMN} - \frac{1}{2} H_{LM}{}^{M} H^{LN}{}_{N} + \frac{1}{2}(3k^2 + m^2)\Big((B_M{}^M)^2 - B_{MN}B^{MN}\Big) - k\big[\delta(y) - \delta(y-L)\big]\Big((B_\mu{}^\mu)^2 - B_{\mu\nu}B^{\mu\nu}\Big).$$

- M (μ) 5D (4D) coordinates
- Field Strength Tensor $H_{LMN} \equiv \nabla_L B_{MN} - \nabla_M B_{LN}$
- Terms involving k are kinetic, from curvature tensors
- Gauge symmetry: $\delta B_{MN} = \nabla_M \beta_N + \nabla_N \beta_M$
- Implied boundary conditions:

$$\big(\partial_y \pm 2k\big) B_{\mu\nu} = 0 \text{ at } y = 0, L$$

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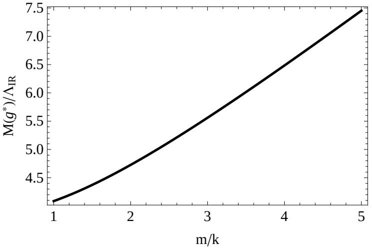
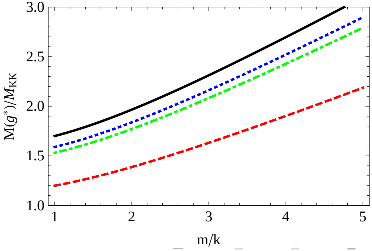
The Spectrum and Kaluza-Klein Functions

- Standard Kaluza-Klein Expansion:

$$B_{\mu\nu}(x,y) = \frac{1}{\sqrt{L}} \sum_{n=1}^{\infty} B_{\mu\nu}^{(n)}(x) f^{(n)}(y).$$

- Lightest states localised near $y = L$ (of course ...)
- Note mass $\geq$ KK gluon, quark masses for $m \gtrsim 2.2k$





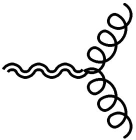
Coupling to the Gluon

- B–B–g coupling from kinetic term
- More interesting: B–g–g coupling

$$S_{ggB} = \frac{g_5}{\sqrt{2}M_S^*} \int \mathrm{d}^5x \sqrt{|G|}\, C^{abc} \left(F^{aLM} F^{b}{}_{L}{}^{N} - \frac{1}{4} F^{aLK} F^{b}{}_{LK} G^{MN} \right) B^c_{MN}$$

- $C^{abc} = 2\,\mathrm{Tr}\left[t^a\{t^b, t^c\}\right]$

$g_\sigma, g_\sigma^{(1)}$

$B_{\mu\nu}$ 

$g_\rho, g_\rho^{(1)}$

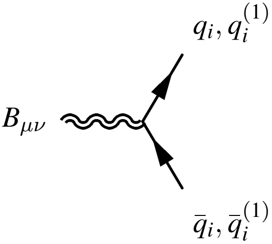
$B-g-g$	$B-g-g^{(1)}$	$B-g^{(1)}-g^{(1)}$
$1/\sqrt{kL}$	1	$\sqrt{kL}$

Coupling to the Quarks

- Also a q–$\bar{q}$–B coupling, relevant for production & decay

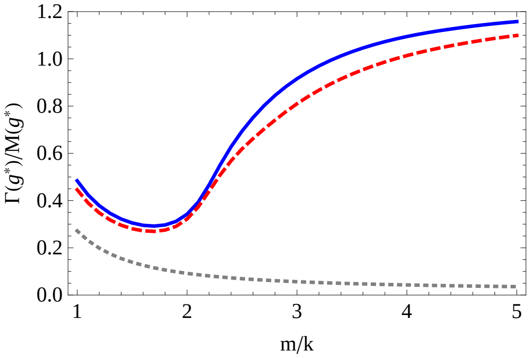
$$\mathcal{S}_{q\bar{q}B} = -\frac{\mathrm{i}\, g_5}{\sqrt{2}M_S^*} \int \mathrm{d}^5x \sqrt{|G|}\, G^{LM} E_n^N \left(\bar{Q}_i \Gamma^n \tilde{B}_{LN} \mathcal{D}_M Q_i - h.c. \right).$$

- $\tilde{B}_{MN} \equiv t^a B^a_{MN}$



$B-q-\bar{q}$	$B-q-\bar{q}^{(1)}$	$B-q^{(1)}-\bar{q}^{(1)}$
$\frac{\sqrt{kL}(1-2c)}{1-\exp[(2c-1)kL]}$	$\sqrt{\frac{kL(1-2c)}{1-\exp[(2c-1)kL]}}$	$\sqrt{kL}$

Total Decay Width



- Note width $\gtrsim$ mass for $m \gtrsim 2.2k$
- Assumed Regge gluon on-shell (to factorise Veneziano $\mathcal{A}$)
- Restrict ourselves to m below this cut-off

Branching Fractions

Figure: Higgsed

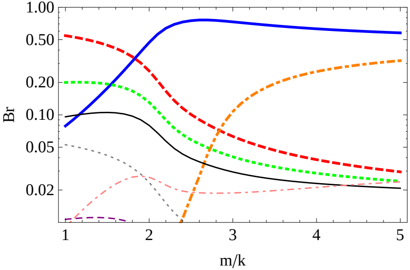
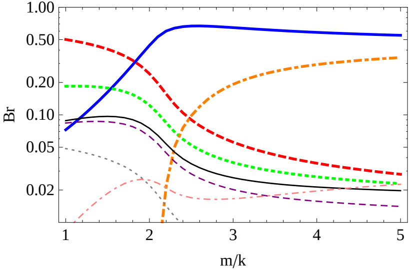


Figure: Higgsless



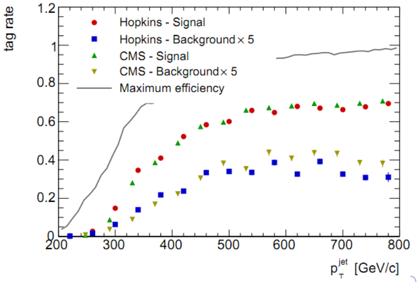
- Decay to SM ($t\bar{t}$) only dominates for $m \lesssim 1.5k$
- Decay to two KK gluons (one off-shell) dominant otherwise
- Decay chain $B \to g^{(1)} g^{(1)} \to t\bar{t}t\bar{t}$

Identifying Energetic Tops

Top Tagging Algorithms

- Regge gluon mass $\gtrsim 1.5$ TeV
- Tops typically have $E \gtrsim$ 400 GeV, highly boosted
- Decay products collimate into "top jets"
- Need to distinguish top jets from ordinary QCD jets

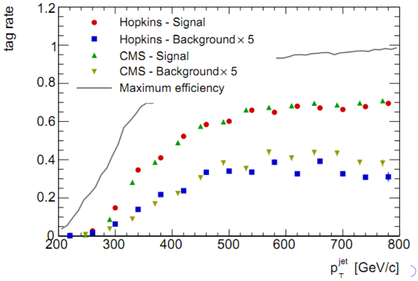
- Many tools to do this, using jet substructure
- Trade off between acceptance and purity
- Use existing studies of tagging algorithms and apply to our model (BOOST 2010, 1012.5412)



Defining the Signal and Backgrounds

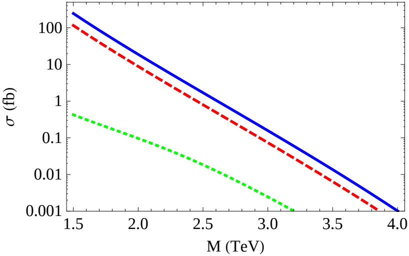
- Cannot* put Regge gluon into event generator
- "Generate" signal by assuming:
  - Regge gluon produced approximately at rest;
  - Decays to two KK gluons approximately at rest;
  - KK gluons decay isotropically to tops
- This gives top p_T distribution

- Background: QCD, n jets + $(4-n)$ tops
- Dominated by $jjjj$
- Demand four tags . . .
- . . . but high tagger eff.
- Fix fake rate (no p_T dependence)



Signal Cross Sections: 7 TeV

Figure: Higgsed



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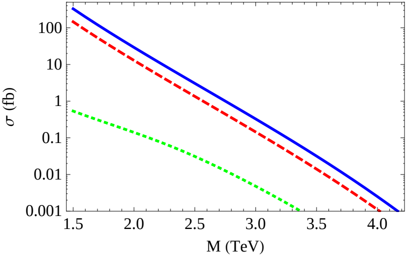
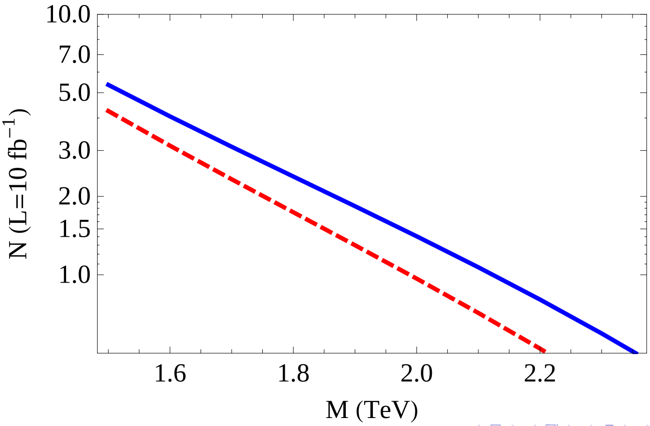


- Total cross section $\sim$ 100s of fb
- Cross section less than 1 fb after cuts

Prospects for Detection: 7 TeV

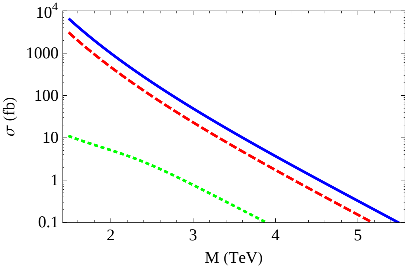
Number of Signal Events in 10 fb

- Negligible backgrounds ($\lesssim 0.1$ events)



Signal Cross Sections: 14 TeV

Figure: Higgsed



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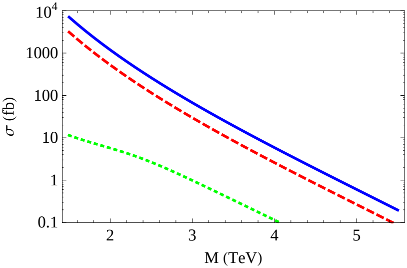
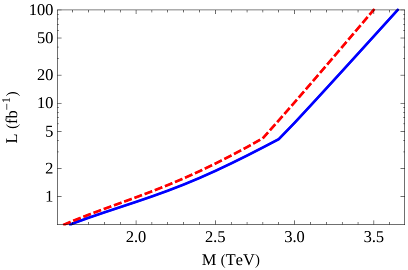


- Total cross section 1–10 pb
- Cross section 1–10 fb after cuts

Prospects for Detection: 14 TeV

Luminosity for Discovery

- Backgrounds ~ 0.24 fb



- For $M \lesssim 2.7$ TeV, limited by number of events
- Otherwise demand $S/\sqrt{B} \geq 5$
- In all region plotted, signal $\geq$ background

Conclusions and Future Directions

- String Theory + Randall-Sundrum suggests TeV-scale, high-spin partners of SM
- Regge gluon decays to four highly boosted top quarks
- Difficult to see at 7 TeV LHC; detectable at 14 TeV LHC
- Obvious next step: Implement model in event generators