

# *Flavor Violation in Warped Extra Dimensions at the LHC*

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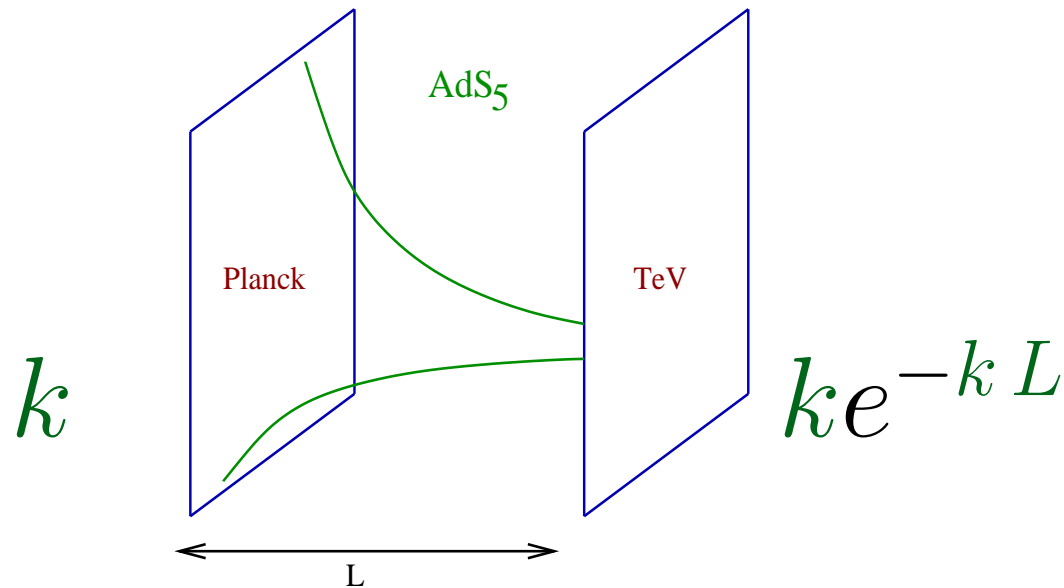
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# Outline

- Flavor Violation in Warped Extra Dimension: Solution to the fermion mass hierarchy. (Randall-Sundrum scenario, with matter/gauge fields in the bulk).
- Preliminary results for
  - $t\bar{t}$  resonances
  - $pp \rightarrow t j$  from flavor violation vertex

# Warped Extra Dimensions

- One compact extra dimension. Non-trivial metric induces small energy scale from Planck scale! (L. Randall, R. Sundrum).



- Geometry of extra dimension generates hierarchy exponentially!

$$\Lambda_{\text{TeV}} \sim M_{\text{Planck}} e^{-k L}$$

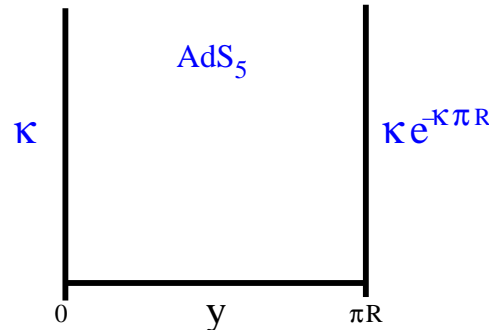
with  $k$  the curvature

# Warped Extra Dimensions

- Warped 5D metric in RS

$$ds^2 = e^{-2\kappa|y|} \eta^{\mu\nu} dx_\mu dx_\nu + dy^2$$

- Compactified on  $S_1/Z_2$  with  $L = \pi R$



and  $k \lesssim M_P$ ,  $AdS_5$  curvature.

- For  $kR \simeq (11 - 12)$

$$\longrightarrow \kappa e^{-\kappa\pi R} \simeq O(\text{TeV}).$$

# Bulk Life in WED

- In original proposal, *only gravity* propagates in 5D bulk.
- **RS** is a solution of the hierarchy problem. But origin of **EWSB**?  
And flavor ? ...
- Allowing gauge fields and matter to propagate in the bulk opens many possibilities: models of EWSB, GUTs, flavor, ...
- The 5D mass of a bulk fermion  $\Rightarrow$  *localization* of zero-mode.
- If Higgs remains on TeV brane:  
Fermions localized toward TeV brane are more massive  
Fermions localized toward the Planck brane are lighter

$\Rightarrow$  **Fermion Geography**

# Gauge Fields in the 5D bulk

- Gauge Fields in the 5D bulk: KK decomposition in 4D (for  $A_y = 0$  gauge):

$$A_\mu(x, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=0}^{\infty} A_\mu^{(n)}(x) \chi^{(n)}(y),$$

Zero-mode  $A_\mu(x)^{(0)}$  + KK tower of massive gauge bosons for  $n > 0$ ,  
with masses

$$m_n \simeq (n - O(1)) \times \pi \kappa e^{-\kappa \pi R}$$

I.e. for appropriate choice of  $\kappa R$  1st KK excitations are  $O(\text{TeV})$ .

- 1st KK excitations have  $\chi^{(n)}(y)$  localized toward TeV fixed point.
- The Gauge Symmetry usually either is or embeds the SM:  
e.g.  $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$  (restores custodial symm.)

# WED and Flavor

- Fermion Fields in the bulk: 5D fermion field KK decomposition

$$\Psi_{L,R}(x, y) = \frac{1}{\sqrt{2\pi R}} \sum_{n=0} \psi_n^{L,R}(x) e^{2\kappa|y|} f_n^{L,R}(y)$$

- 5D fermion bulk mass term  $\longrightarrow$  localization of fermion fields:

$$S_f = \int d^4x dy \sqrt{-g} \{ \dots - c \kappa \bar{\Psi}(x, y) \Psi(x, y) \} ,$$

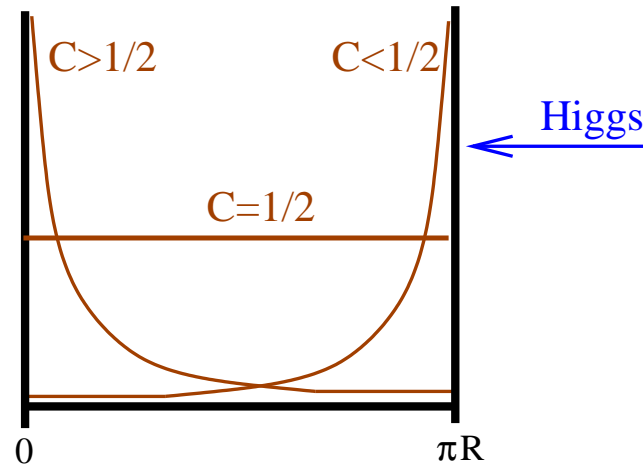
with  $c \simeq O(1)$ .

- $\Rightarrow$  Fermion zero-modes can be localized by choosing  $c$  :

$$f_0^{R,L}(y) = \sqrt{\frac{\kappa\pi R (1 \pm 2c)}{e^{\kappa\pi R(1 \pm 2c)} - 1}} e^{\pm c \kappa y}$$

# Flavor Models in WED

- $O(1)$  flavor breaking in bulk can generate fermion mass hierarchy:



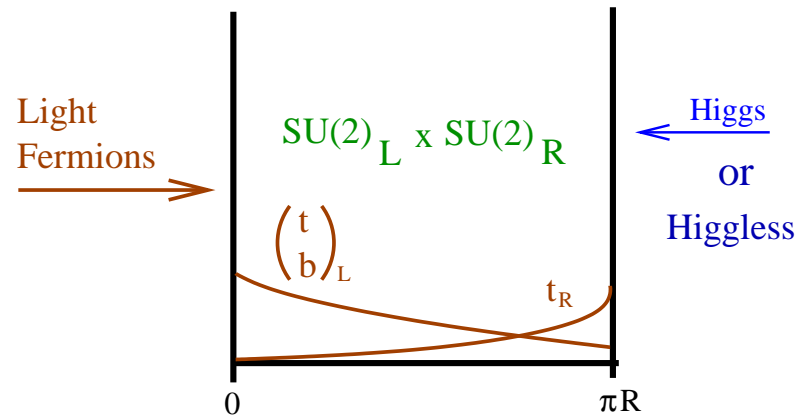
Fermions localized toward the TeV brane can have larger Yukawas, Those localized toward the Planck brane have highly suppressed ones.

- But fermions at  $\simeq \pi R \Rightarrow$  strong couplings to 1st KK gauge bosons!  
E.g: 3rd generation quarks might have large couplings  $\rightarrow$  flavor violation.



# Electroweak Symmetry Breaking and WED

Several possibilities for model building:



- Higgs or Higgsless (BC breaking)
- Light fermions on Planck brane or off (reduces  $S$ )
- Third generation remains a challenge

# Flavor Violation in WED

Non-Universal quark couplings  $\Rightarrow$  **Flavor Violation at Tree Level**

E.g.:

$$G_{\mu}^{(1)} t\bar{t} \text{ coupling} = g_t$$

such that

$$g_t \gg g_q, \text{ for } q = u, d, s, c, b_R$$

To get  $m_t$  right and avoid  $Z \rightarrow b\bar{b}$  constraints:

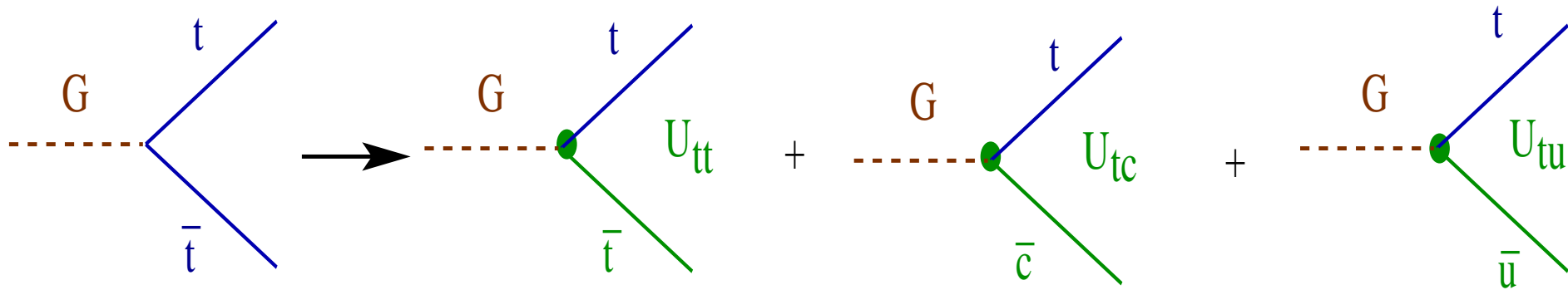
$$g_{t_L} = g_{b_L} = (1.0, 2.8) * g_s$$

$$g_{t_R} = (1.5, 5.0) * g_s$$

$$g_{q_L} = g_{q_R} = g_{b_R} \simeq -0.20 * g_s$$

# Flavor Violation in WED

After diagonalizing the quark mass matrix with  $U_L$  and  $U_R$



If we take  $U_L \sim V_{\text{CKM}}$ , then bulk mass parameters give some indication of  $U_R$ . We'll take

$$U_L^{tc} \simeq \lambda^2 \simeq 0.05$$

and leave  $U_R^{tc}$  as a free parameter (typically of  $O(1/10)$ ).

# Signals: KK Gluon as $t\bar{t}$ resonance

- Parameters allow narrow or broad resonance

$$\Gamma = \frac{\alpha_s}{12} M_G (\tilde{g}_q^2 * 9 + \tilde{g}_{t_L}^2 * 2 + \tilde{g}_t^2)$$



$$\Gamma_{\min.} = 0.04 M_G$$

$$\Gamma_{\max.} = 0.35 M_G$$

- Phenomenology (mostly  $Z \rightarrow b\bar{b}$ ) prefers

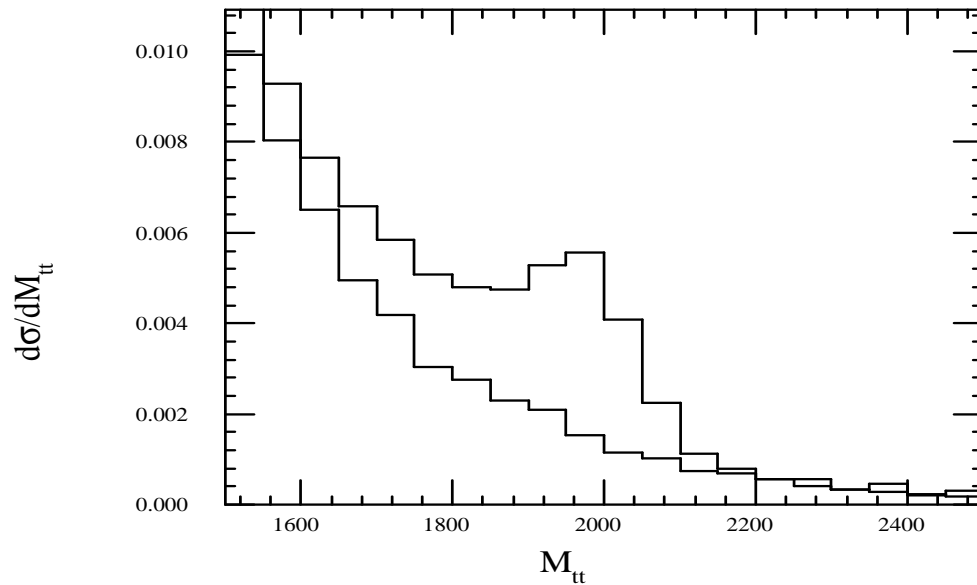
$$M_G \simeq (2 - 4) \text{ TeV.}$$

# Signals: KK Gluon as $t\bar{t}$ resonance

Standard Cuts:

$$p_T > 20 \text{ GeV}, \quad |\eta_\ell| < 2.5, \quad |\eta_j| < 3.2, \quad \Delta R = 0.4$$

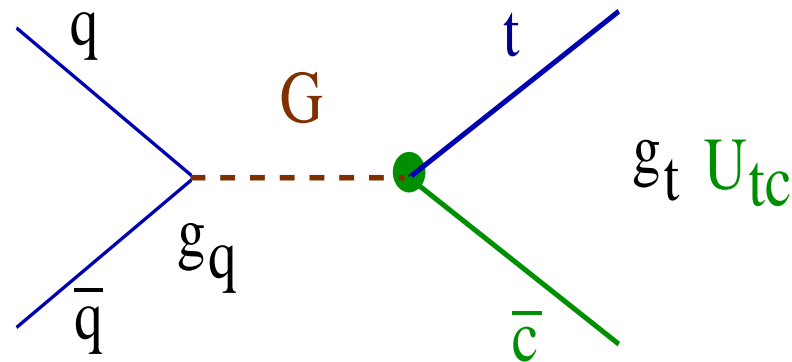
(MADGRAPH/MADEVENT)



# Signals: KK Gluon as $t\bar{t}$ resonance

- Narrow Resonance can be seen up to  $\simeq 3$  TeV ( $\sigma * BR \sim 200 fb^{-1}$ ).
- Broad Resonance probably hopeless.
- But seeing a resonance in  $t\bar{t}$  does not mean seeing flavor violation. We would only see  $t\bar{t}$  even if model is flavor conserving.
- We need to see the Flavor Violating vertex !

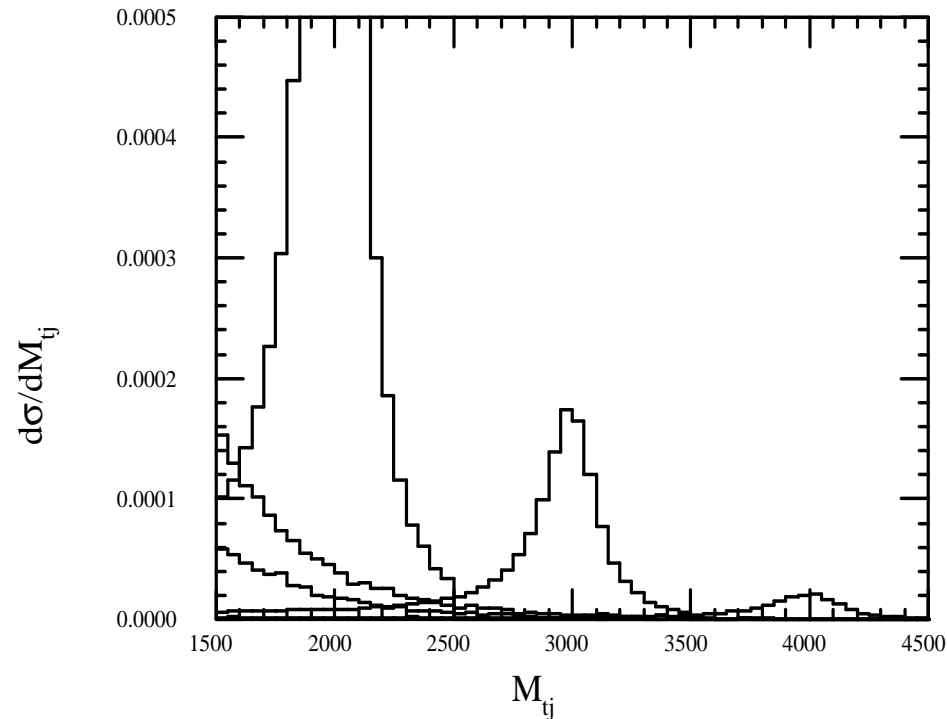
# Single Top Production at High Invariant Mass



- Signal:  $t + \text{jet}$ , very large invariant mass ( $>1.5$  TeV).
- Backgrounds:
  - Single Top Production -  $Wg$  fusion: If miss extra jet. But invariant mass smaller.
  - Single Top Production -  $W^*$ : Also smaller IM.
  - $t\bar{t}$ : In lepton + jets, miss a lepton. Eliminated by cut on visible energy.

# Single Top Production at High Invariant Mass

E.g. For  $\Gamma_{\min.}$  and  $U_L^{tc} = 0.33$ :



But now, even for  $\Gamma_{\max.}$  we get limits.



# Single Top Production at High Invariant Mass

Reach: Assuming 10 Events for  $30 fb^{-1}$ :

$M_G$ [TeV]	$\Gamma$	$U_R^{tc}$
2	Max.	0.07
	Min.	0.06
3	Max.	0.19
	Min.	0.16
4	Max.	0.40
	Min.	0.37

Encouraging. But more work is needed.