Flavor Violation in Warped Extra Dimensions at the LHC

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Outline

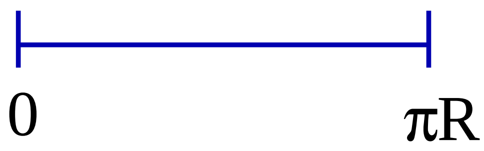
- Generalities of the Bulk Randall-Sundrum Models.
- Flavor Violation in Warped Extra Dimension: Solution to the fermion mass hierarchy.
- What are the signals for this theory of flavor ? Can they be seen at the LHC ?
- Here we consider
  - $t\bar{t}$ resonances
  - $pp \to t\ j$ from flavor violation vertex

The Hierarchy Problem in AdS_5

- Randal-Sundrum: Exponential Separation of energy scales induced by bulk metric.
- Warped 5D metric in RS

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

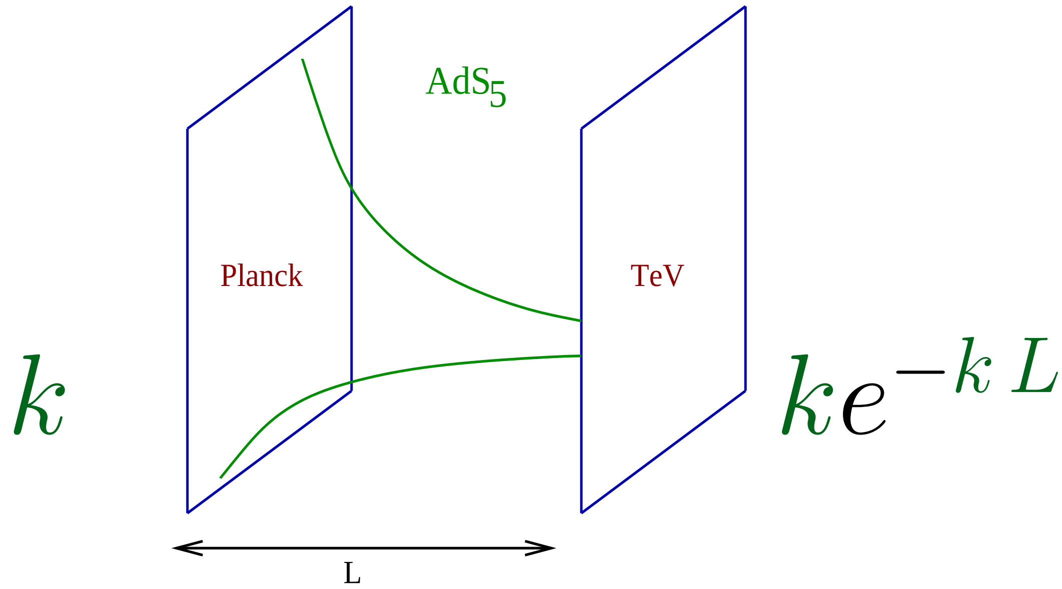
- Compactified on S_1/Z_2 with $L = \pi R$



and $k \lesssim M_P$, AdS_5 curvature.

Warped Extra Dimensions

- One compact extra dimension. Non-trivial metric induces small energy scale from Planck scale.



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

$$\boxed{\Lambda_{\rm TeV} \sim M_{\rm Planck}\, e^{-k\,L}}$$ with k the curvature

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 $=>$ *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

$\Longrightarrow$ 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 κR 1st KK excitations are $O(\mathrm{TeV})$.

- 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:

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

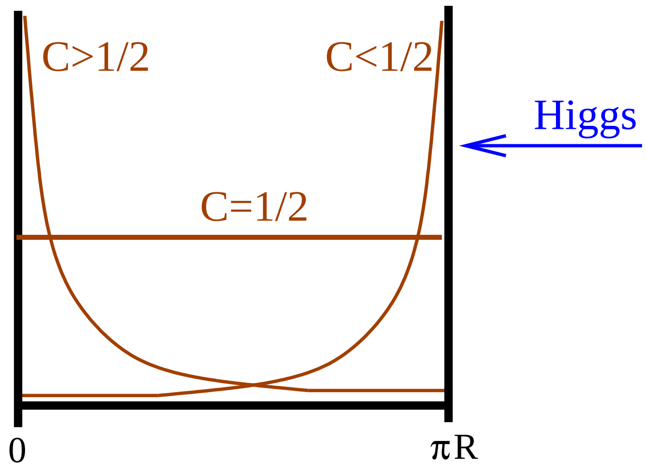
with $c \simeq O(1)$.

- $=>$ 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:

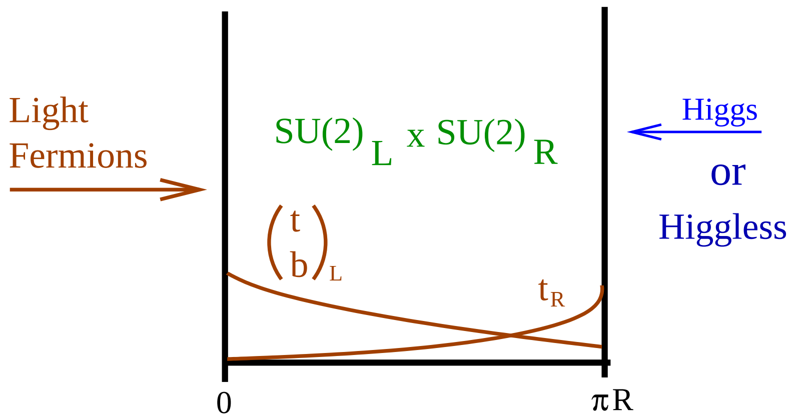


Fermions localized toward the TeV brane can have larger Yukawas, Those localized toward the Planck brane have highly suppressed ones.

- But fermions at $\simeq \pi R =>$ 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 or towardsPlanck brane
- Third generation needs special care ($Z \to b\bar{b}$).

Signals for a Theory of Flavor

- Assume a generic RS bulk model:
  - Bulk fermions and gauge bosons.
  - Bulk masses ($c's$) $\Rightarrow$ Fermion masses / CKM.
- Model(s) satisfy all EWPC (S, T, $Z \to b\bar{b}$, etc.).
- Assume typical masses $m_{KK} \simeq O(1)$ TeV

How do we test this flavor theory at the LHC ?

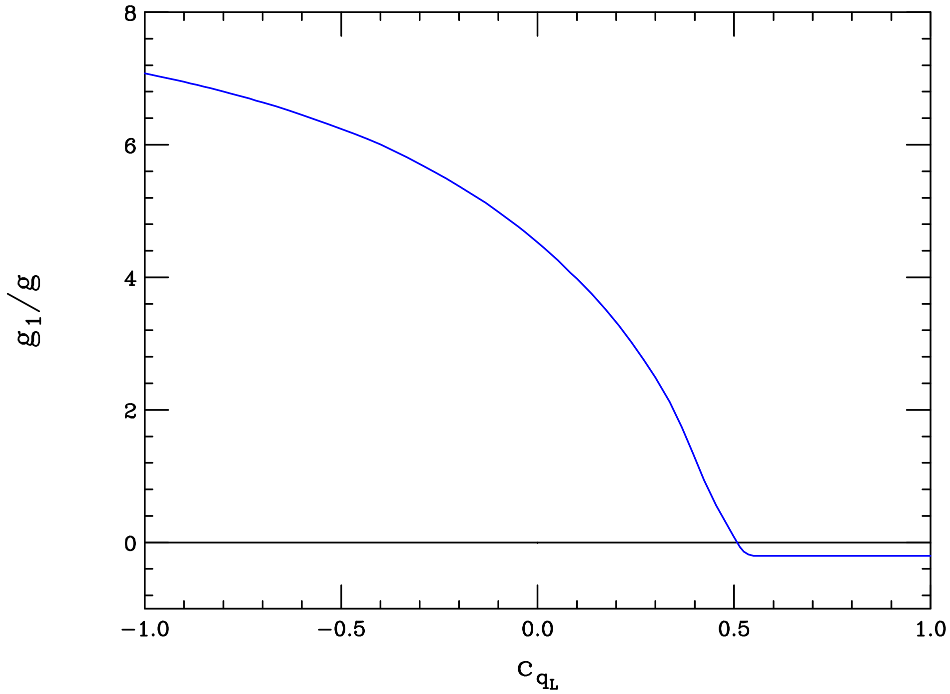
Flavor Violation in WED

The effective 4D couplings of the KK gauge bosons to the zero-mode fermions are flavor violating.
Compute the coupling of the 1st KK gauge boson to ZM fermions.
From:

- $$\int d^4x\, dy\, \sqrt{-g}\, g_5\, \bar{\Psi}(x,y)\, i\gamma_\mu\, A_\mu(x,y)\, \Psi(x,y)$$

  we get $g^{(1)}$.
- For the 3rd generation, $g^{(1)}/g$ can be large ($g = g_5/\sqrt{2\pi R}$).
- $g^{(1)}$ depends on the bulk masses $c's$.

oupling of KK Gauge Boson to Zero-Mode Ferm



For $c_{q_L} < 1/2$ coupling of 1st KK Gauge boson o zero-mode fermion can be large.

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

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

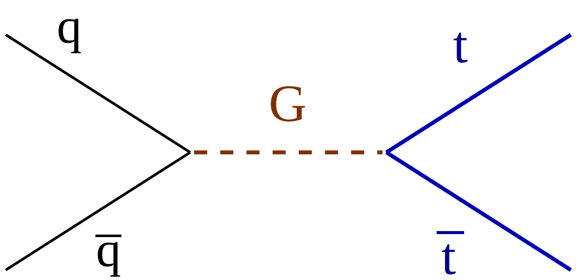
To get m_t right and avoid $Z \to b\bar{b}$ constraints:

$$\begin{aligned} g_{t_L} &= g_{b_L} = (1.0, 2.8) * g_s \\ g_{t_R} &= (1.5, 5.0) * g_s \\ g_{q_L} &= g_{q_R} = g_{b_R} \simeq -0.20 * g_s \end{aligned}$$

Signals for Flavor Violation

What is the best signal for flavor violation ?

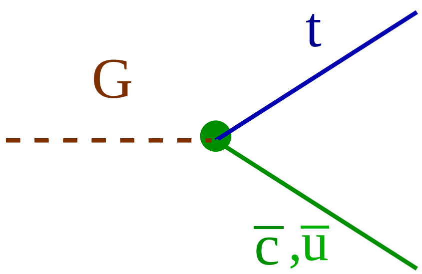
- Flavor diagonal vertices:



Compare $t\bar{t}$ resonances with light quark resonances.
Observing these is hard.

Signals for Flavor Violation

- Or Direct observation of flavor violating vertices:



  - Flavor violation suppressed by some mixing.
  - Backgrounds too large ? E.g. Single top ($> 300pb$).

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

- Parameters allow narrow or broad resonance

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

-

$$\begin{aligned} \Gamma_{\text{min.}} &= 0.04\, M_G \\ \Gamma_{\text{max.}} &= 0.35\, M_G \end{aligned}$$

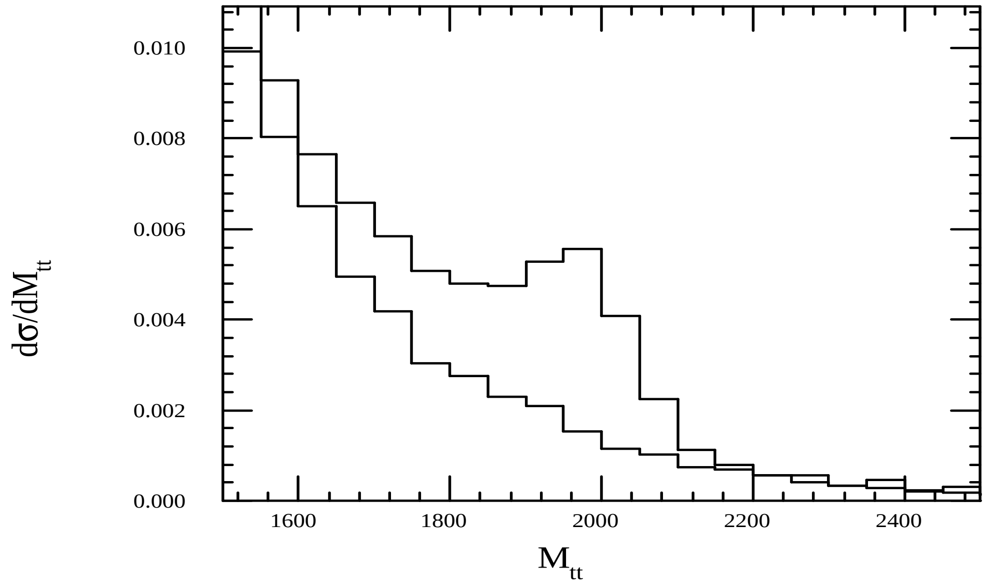
- We take

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

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

Standard Cuts:

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

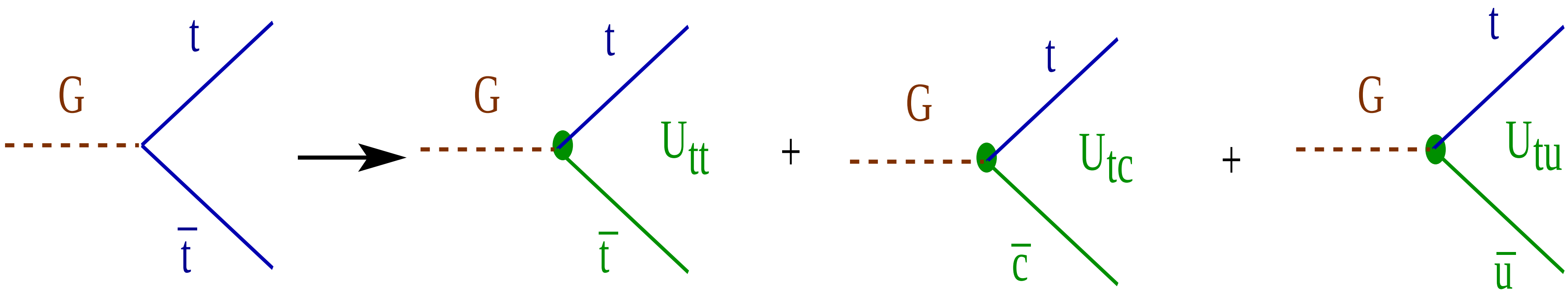


Signals: KK Gluon as $t\bar{t}$ resonance

- Narrow Resonance can be seen up to $\simeq 3$ TeV ($\sigma * BR \sim 200 fb{-}1$).
- Broad Resonance probably hopeless.
- Seeing a resonance in $t\bar{t}$ does not necessarily mean seeing flavor violation, seeing the light quark resonances might be challenging.
- We might need to see the flavor violating vertex.

Flavor Violating Vertices

After diagonalizing the quark mass matrix with U_L and U_R



If we take $U_L \sim V_{\rm CKM}$, 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 $O(1/10)$).

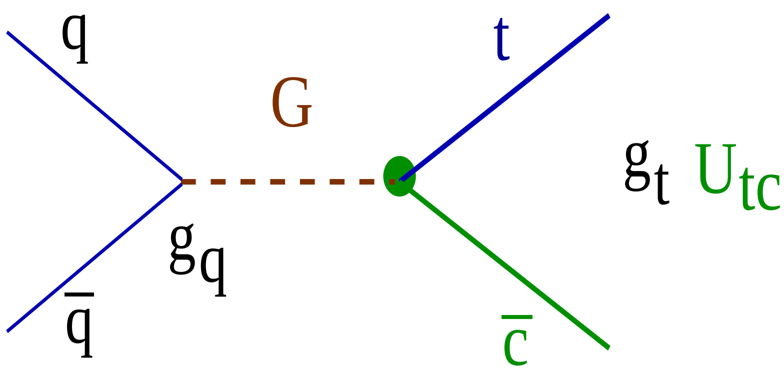
Tree Level Flavor Violation

Constraints from low energy/flavor physics ?
Potentially, deviations in

- CP asymmetries in B decays (G.B. '03)
- $b \to s\ell^+\ell^-$ (G.B. '02; G.B., Y.Nomura '03; K. Agashe, G. Perez, A. Soni '04)
- ϵ_K (K. Agashe, G. Perez, A. Soni '04)
- Δm_{B_s}
- $D^0 - \bar{D}^0$ mixing (G.B., I. Shipsey '03)

But for $M_{KK} \gtrsim 2$ TeV, and/or adjusting the down-quark rotation matrices $D_{L,R}$, these bounds can be evaded.

Single Top Production at High Invariant Mass

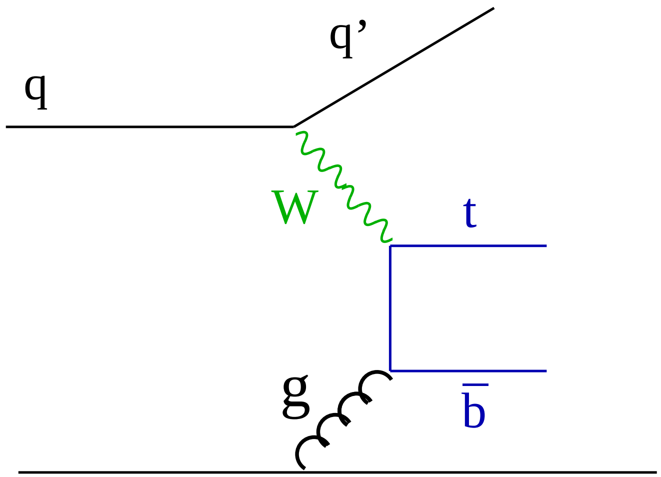


- Signal: t + jet, very large invariant mass (>1.5 TeV).
- Use $t \longrightarrow b\ell\nu$.
- Typically few hundred fb^{-1}.

Backgrounds I

Single Top Production - Wg fusion:

- 250 pb.
- Problem if miss extra jet.

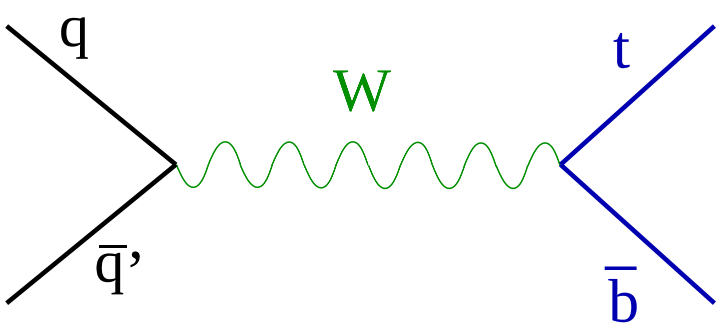


But smaller invariant mass.

Backgrounds II

Single Top Production - W^*:

- $\simeq 60$ pb
- Misstag b

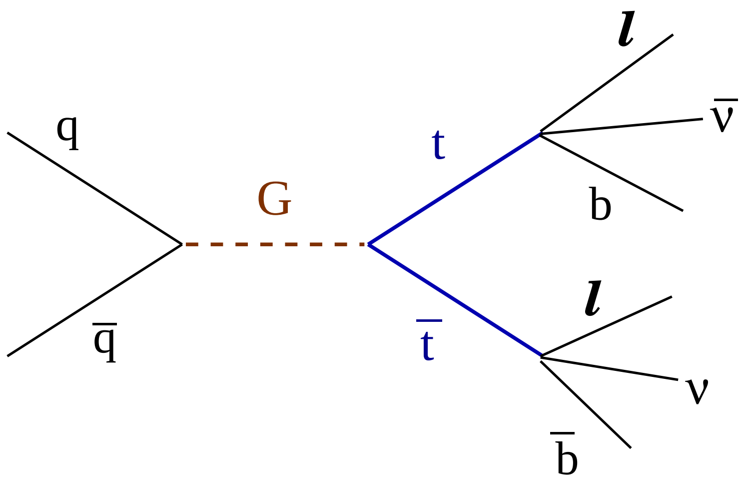


Also smaller invariant mass.

Backgrounds III

KK Gluon$\rightarrow t\bar{t}$:

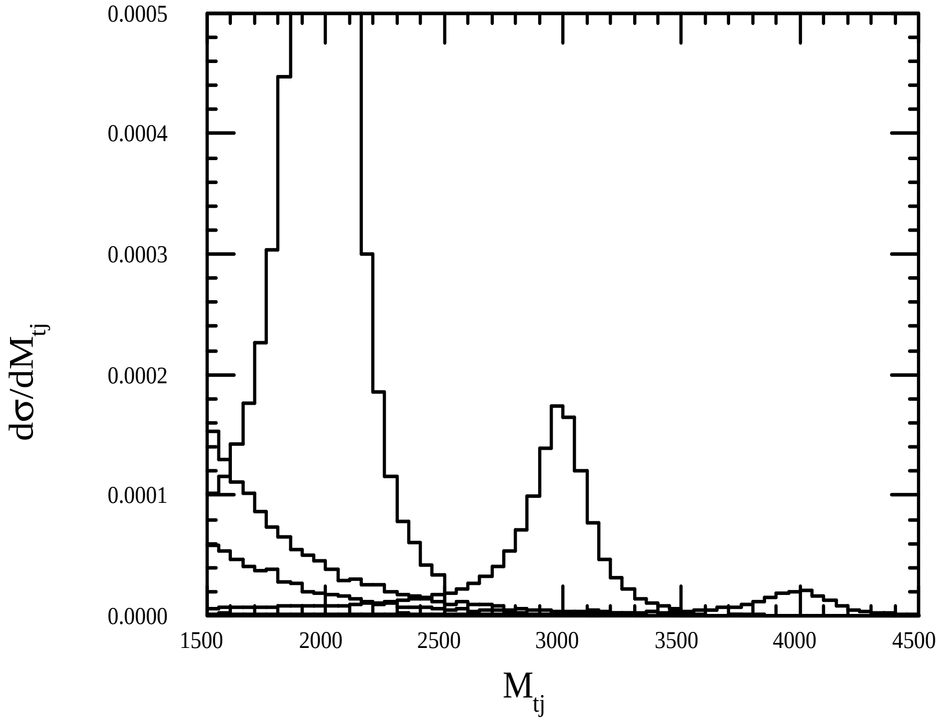
- In lepton + jets, miss a lepton ($|\eta_\ell| > 2.5$)
- Misstag b



Can be eliminated by cut on visible energy.

Single Top Production at High Invariant Mass

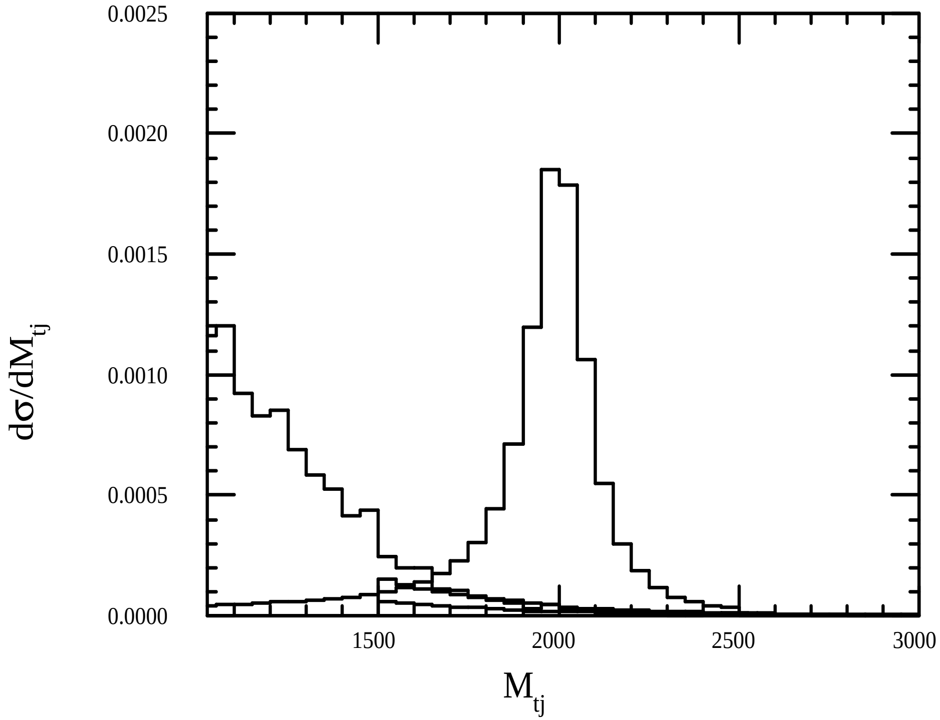
E.g. For $\Gamma_{\mathrm{min.}}$ and $U_R^{tc} = 0.3$:



M_G-independent Backgrounds (W^* and Wg fusion) included.

Single Top Production at High Invariant Mass

E.g. For $\Gamma_{\mathrm{min.}}$ and $U_R^{tc} = 0.3$:



Including the $t\bar{t}$ background for $M_G = 2$ TeV.

Single Top Production at High Invariant Mass

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

M_G[TeV]	Γ	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.

More work is needed, especially for the high luminosity stage.

Summary/Outlook

- Flavor violation at tree level is present in a broad variety of RS models. Always present if bulk RS models include a theory of flavor.
- It is possible to observe flavor violation signals at the LHC, even at low luminosity and for various values of M_{KK} and the mixing parameters.
- What's the reach at high luminosity ?