A Signal for a Theory of Flavor at the LHC

P. Aquino, G. Burdman, and O. Éboli

May 7, 2007

UNIVERSIDADE DE SÃO PAULO

SCIENTIA VINCES

Our Goal:

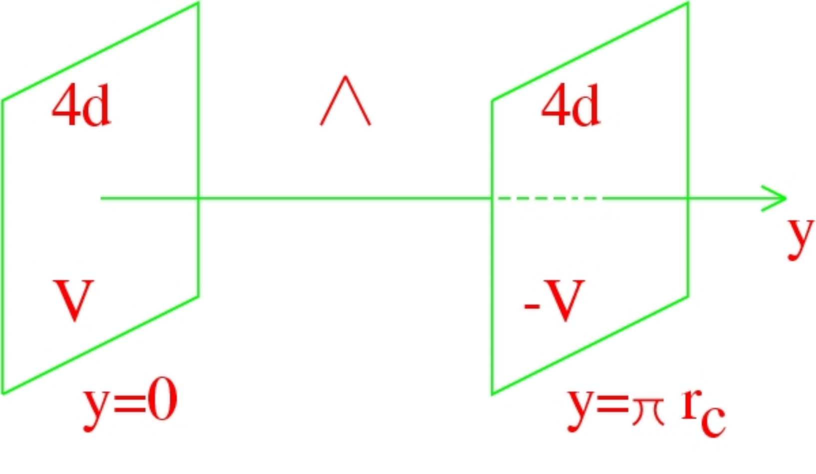
to investigate the potential of the LHC to observe flavor violation in single top production at very high invariant masses, providing a test at tree level for a theory of flavor in extra dimensions.

Warped Extra Dimensions

(Randall–Sundrum)

- One compact extra dimension compactified on $\mathbf{S^1/Z_2}$ with $\mathbf{L = \pi r}$

$$\mathbf{ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2}$$



- $\mathbf{k}$ is the AdS$_5$ curvature
- $\mathbf{M_P^2 = \frac{M_5^3}{k}(1 - e^{-2kL})}$

- Geometry $\Longrightarrow$ hierarchy $\mathbf{\Lambda_{TeV} \simeq M_P e^{-kL}}$

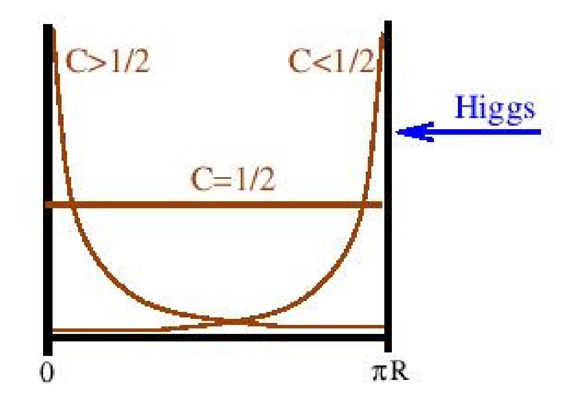
- The gauge hierarchy problem is solved for $\mathbf{kr \simeq 12}$

- Only gravity propagates in the 5D bulk in the original scenario

- Gauge and matter in the bulk $\Longrightarrow$ models for EWSB, flavor, etc. (Agashe et al; Csaki et al; Pomarol et al; ....)

- Basic idea: 5D fermion mass ($\mathbf{ck}$) leads to localization of the zero mode

- Assuming that the Higgs lives in the TeV brane:



1. fermions localized near the TeV brane are more massive
2. fermions localized near the Planck brane are lighter

- This mechanism avoids fine tuning of Yukawa couplings.

Fermions in the bulk

- The action for fermion fields is

$$\mathbf{S} = \int \mathbf{d^4 dy}\,\sqrt{\mathbf{g}}\;\bar{\Psi}\left(\mathbf{i\Gamma^M D_M} + \mathbf{ck}\ \text{sign}(\mathbf{y})\right)\Psi \quad \text{with} \quad c \simeq \mathcal{O}(1)$$

- Defining $\Psi_{L,R} = \frac{1}{2}(1 \mp \gamma_5)\Psi$ we write its KK decomposition as

$$\Psi_{L,R}(x,y) = \frac{1}{\sqrt{2\pi r}}\sum_{n=0}\psi_n^{L,R}(x)\,e^{2\sigma}f_n^{L,R}(y) \quad \text{with} \quad \sigma \equiv k|y|$$

- The zero modes are, with only one allowed by boundary conditions,

$$f_0^{R,L}(y) = \sqrt{\frac{2k\pi r\,(1 \pm 2c_{R,L})}{e^{k\pi r(1\pm 2c_{R,L})} - 1}}\; e^{\pm c_{R,L}\,k\,y}$$

- The bulk Yukawa couplings are

$$\mathbf{S_Y} = \int \mathbf{d^4x\,dy}\,\sqrt{-\mathbf{g}}\,\frac{\lambda^{\mathbf{5D}}_{\mathbf{ij}}}{\mathbf{2\,M_5}}\,\bar{\mathbf{\Psi}}_{\mathbf{i}}(\mathbf{x},\mathbf{y})\delta(\mathbf{y}-\pi\mathbf{r})\mathbf{H}(\mathbf{x})\mathbf{\Psi}_{\mathbf{j}}(\mathbf{x},\mathbf{y})$$

- This leads to the 4D mass matrix for the zero modes

$$\mathbf{M_{ij}} = \frac{\lambda^{\mathbf{5D}}_{\mathbf{ij}}\,\mathbf{v}}{\mathbf{2}\pi\mathbf{r}\,\mathbf{M_5}}\,\mathbf{f^L_{0i}}(\pi\mathbf{r})\,\mathbf{f^R_{0j}}(\pi\mathbf{r})$$

- Since $\mathbf{k}/\mathbf{M_5} \simeq \mathcal{O}(\mathbf{1}) \implies \frac{\lambda^{\mathbf{5D}}_{\mathbf{ij}}\,\mathbf{k}}{\mathbf{M_5}} \simeq \mathcal{O}(\mathbf{1})$

- Localizing the zero modes towards the Planck or TeV branes can leads to a natural solution for the fermion mass hierarchy problem ($|\lambda^{\mathbf{5D}}_{\mathbf{ij}}| \sim \mathbf{O}(\mathbf{1})$)

- Mass matrix diagonalization $\implies$ $\mathbf{U_L}$, $\mathbf{U_R}$, and $\mathbf{D_L}$ with $\mathbf{V_{CKM}} = \mathbf{U^\dagger_L D_L}$.

Gauge Fields in the Bulk

- The KK expansion of a gauge field is (in the gauge $\mathbf{A_y = 0}$)

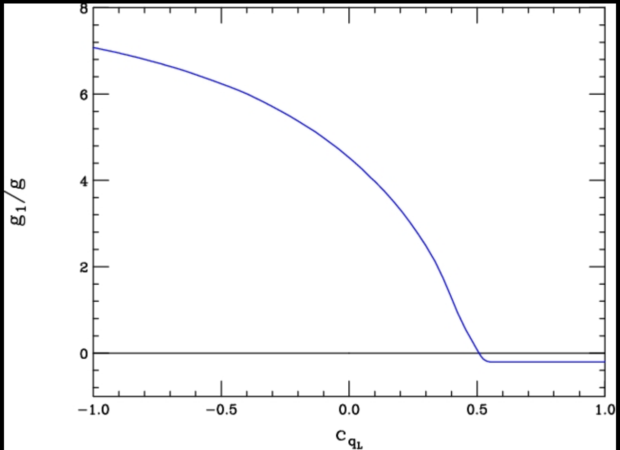
$$\mathbf{A}_\mu(\mathbf{x},\mathbf{y}) = \frac{\mathbf{1}}{\sqrt{\mathbf{2}\pi\mathbf{r}}} \sum_{\mathbf{n=0}} \mathbf{A}_\mu^{(\mathbf{n})}(\mathbf{x})\chi^{(\mathbf{n})}(\mathbf{y})$$

- The $\mathbf{n} > \mathbf{0}$ modes are massive with $\mathbf{m_1} \simeq \mathcal{O}(\mathbf{1})$ TeV.
- For the first excitations, $\chi^{(\mathbf{1})}$ is localized towards the TeV brane.
- 4D gauge coupling to fermions come from

$$\mathbf{g_5} \int \mathbf{d^4x} \int \mathbf{dy}\, \sqrt{\mathbf{g}}\, \bar{\mathbf{\Psi}}(\mathbf{x},\mathbf{y})\mathbf{\Gamma}^\mu \mathbf{T^a} \mathbf{G}_\mu^{\mathbf{a}}(\mathbf{x},\mathbf{y})\mathbf{\Psi}(\mathbf{x},\mathbf{y})$$

- The couplings are not universal.

- Fermions localized at the TeV brane have strong couplings with the first KK gauge bosons.



- We assumed light quarks and b_R are localized on the Planck brane.
- Electroweak precision measurements and $Z \to b\bar{b}$ can be used to constrain the parameters of the model. (Agashe et al. 03; Agashe et al 06)
- 1 TeV KK scale can be accommodated (Cacciapaglia et al 06)
- We considered $c_L^3 \in [0.3, 0.4]$ and $c_R^t \in [-0.4, 0.1]$ $\Longrightarrow$ correct top mass and no conflict with electroweak measurements.
- Seeing a $t\bar{t}$ resonance does not mean seeing flavor violation.

Flavor Violation

- Wave function in the extra dimension $\Longrightarrow$ couplings. The flavor diagonal couplings $\mathbf{G^{(1)}qq}$ in units of $\mathbf{g_s}$ are

$$\mathbf{\tilde{g}_l^q = \tilde{g}_R^q = \tilde{g}_R^b \simeq -0.2 \quad ; \quad \tilde{g}_L^t = \tilde{g}_L^b = [1.0, 2.8] \quad ; \quad \tilde{g}_R^t = [1.5, 5]}$$

- The width of the first KK gluon is $\mathbf{\Gamma \simeq \frac{\alpha_s}{12} M_G \left(9\, \tilde{g}_q^2 + 2\, \tilde{g}_{t_L}^2 + \tilde{g}_{t_R}^2\right)}$
- The minimum width is $\mathbf{\Gamma_{min.} \simeq 0.04\, M_G}$ while the maximum width is $\mathbf{\Gamma_{max.} \simeq 0.35\, M_G}$
- We are interested in the flavor violation couplings of the first KK excitation of the gluons
- Rotation to quark mass eigenstates $\Longrightarrow$ flavor changing couplings
- Currents: $\mathbf{(U_L^{tt})^2\, (\bar{t}_L T^a \gamma_\mu t_L)}$, $\mathbf{U_L^{tc} U_L^{tt}\, (\bar{t}_L T^a \gamma_\mu c_L)}$ and $\mathbf{U_L^{tu} U_L^{tt}\, (\bar{t}_L T^a \gamma_\mu u_L)}$.

- Similarly, $(\mathbf{U_R^{tt}})^2\,(\bar{\mathbf{t}}_\mathbf{R}\mathbf{T^a}\gamma_\mu\mathbf{t_R})$, $\mathbf{U_R^{tc}U_R^{tt}}\,(\bar{\mathbf{t}}_\mathbf{R}\mathbf{T^a}\gamma_\mu\mathbf{c_R})$ and $\mathbf{U_R^{tu}U_R^{tt}}\,(\bar{\mathbf{t}}_\mathbf{R}\mathbf{T^a}\gamma_\mu\mathbf{u_R})$

- the rotation matrices $\mathbf{U}$ are not observable in the SM.

- We can assume that $\mathbf{U_L} \simeq \sqrt{\mathbf{V}_{\mathrm{CKM}}}$, and similarly for $\mathbf{D_L}$
  $\implies\ \mathbf{U_L^{tc}} \simeq \mathbf{V_{cb}} \simeq \mathbf{0.04}$ and $\mathbf{U_L^{tu}} \simeq \mathbf{V_{ub}} \simeq \mathbf{0.004}$

- There is no bias from the SM on the entries of U_R. We consider $\mathbf{U_R^{tc}}$ and $\mathbf{U_R^{tu}}$ as free parameters, defining $\mathbf{U_R^{tq}} \equiv \sqrt{(\mathbf{U_R^{tc}})^2 + (\mathbf{U_R^{tu}})^2}$.

LHC Discovery Potential

- We studied the flavor violating process

$$\mathbf{pp} \to \mathbf{G}_{\mu}^{\mathbf{a}(1)} \to \mathbf{tq} \to \mathbf{b}\ell^{\pm}\nu_{\ell}\mathbf{q} \quad \text{with} \quad \mathbf{q} = \mathbf{u}\,,\ \mathbf{c}$$

Event characteristics

- one light jet
- one b tagged jet
- one charge lepton ($\mathbf{e}^{\pm}\,,\ \mu^{\pm}$)
- missing $\mathbf{p_T}$

✪ The main backgrounds are

- $\mathbf{pp} \to \mathbf{t\bar{t}} \to \mathbf{b}\ell^+\nu_\ell\mathbf{\bar{b}}\ell^-\bar{\nu}_\ell$
  - ⋆ one of the b jets is mistagged
  - ⋆ one of the charged leptons is either lost or embedded in the jets.
  - ⋆ the flavor-conserving signal for $\mathbf{G}_\mu^{\mathbf{a}(1)}$ decaying to $t\bar{t}$ is a background

- $\mathbf{pp} \to \mathbf{W}^\pm\mathbf{jj} \to \ell^\pm\nu\mathbf{jj}$
  - ⋆ one of the light jets is tagged as a b jet.

- $\mathbf{pp} \to \mathbf{W}^\pm\mathbf{b\bar{b}} \to \ell^\pm\nu\mathbf{b\bar{b}}$
  - ⋆ one of the b jets is mistagged.

- $\mathbf{pp} \to \mathbf{W}^{*\pm} \to \mathbf{t\bar{b}} + \mathbf{\bar{t}b} \to \mathbf{b\bar{b}}\ell^\pm\nu$
  - ⋆ where one of the b jet is mistagged.

- $\mathbf{pp} \to \mathbf{tbj} \to \mathbf{b\bar{b}j}\ell^{\pm}\nu$
  - ⋆ one of the jets is lost and just one jet is tagged as a b jet.

- Signal and backgrounds simulated with Madevent

- Lepton and jet acceptance cuts

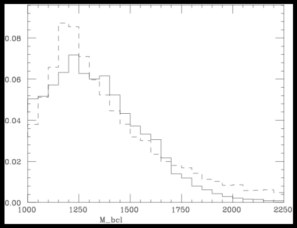
$$\begin{array}{lcll} p_T^j > 20 \text{ GeV} & , & |y_j| < 2.5 & , \\ p_T^\ell \geq 20 \text{ GeV} & , & |y_\ell| \leq 2.5 & \\ \Delta R_{\ell j} \geq 0.63 & , & \Delta R_{\ell\ell} \geq 0.63 & , \end{array}$$

✪ Further cuts:

1. The invariant mass of the visible particles should be in

$$\mathbf{M_{G^{(1)}} - \Delta \leq M_{bj\ell} \leq M_{G^{(1)}} + \Delta}$$

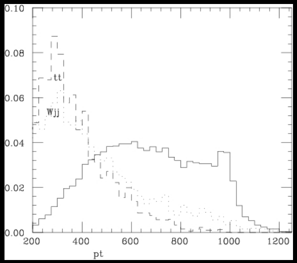
$\mathbf{\Delta = 120}$ (250) GeV for $\mathbf{M_{G^{(1)}} = 1}$ (2) TeV.

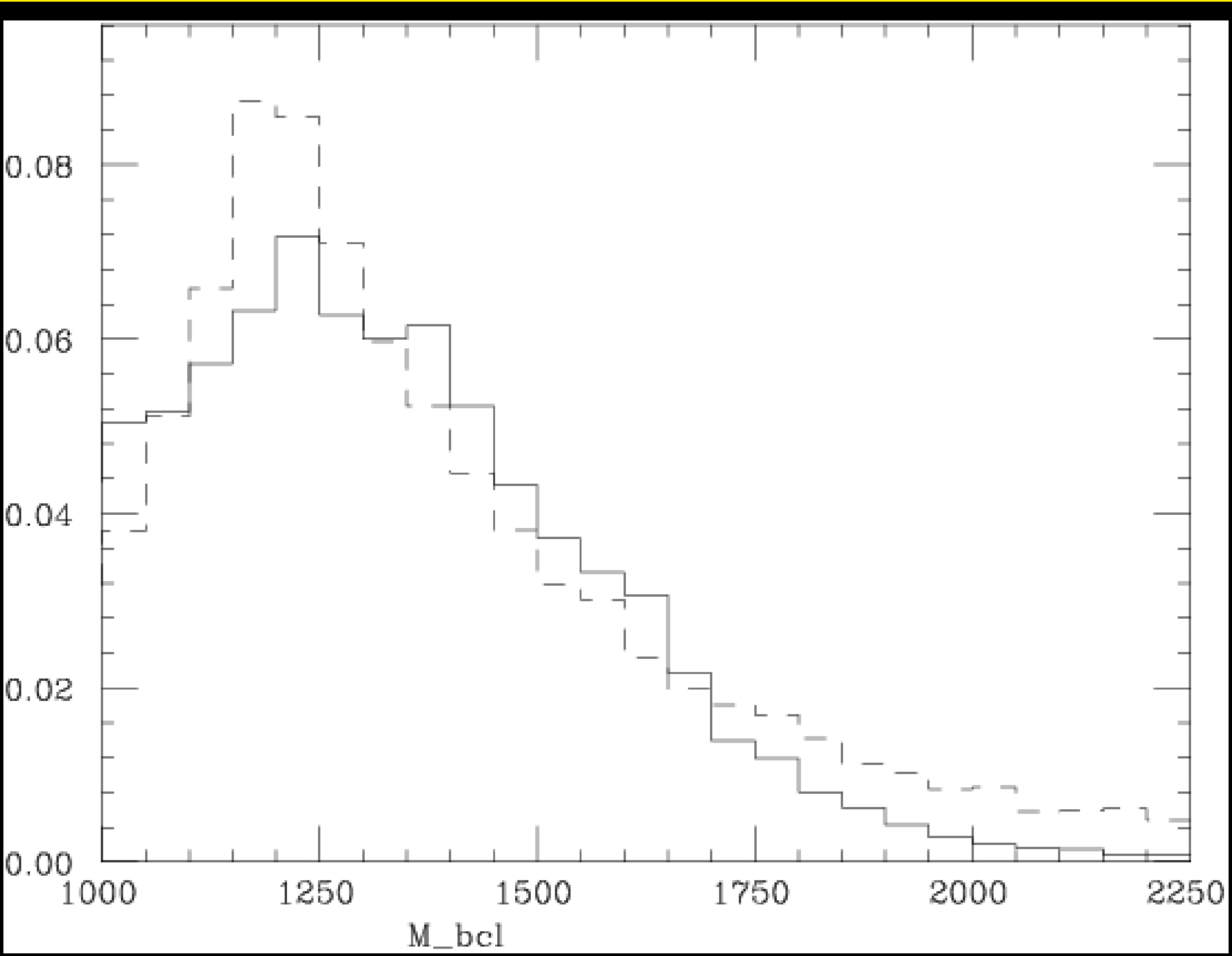


2. The transverse momentum of the light jet must satisfy

$$\mathbf{p_{j\ light} \geq p_{cut}}$$

where $\mathbf{p_{cut} = 350}$ (650) GeV for $\mathbf{M_{G^{(1)}} = 1}$ (2) TeV.



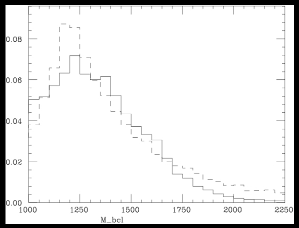

0.08
0.06
0.04
0.02
0.00
1000
1250
1500
1750
2000
2250
M_bcl

✪ Further cuts:

1. The invariant mass of the visible particles should be in

$$\mathbf{M_{G^{(1)}} - \Delta \le M_{bj\ell} \le M_{G^{(1)}} + \Delta}$$

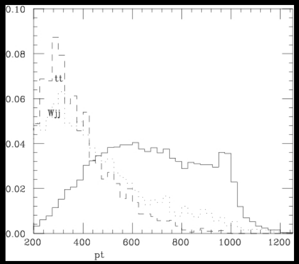
$\mathbf{\Delta = 120}$ (250) GeV for $\mathbf{M_{G^{(1)}} = 1}$ (2) TeV.

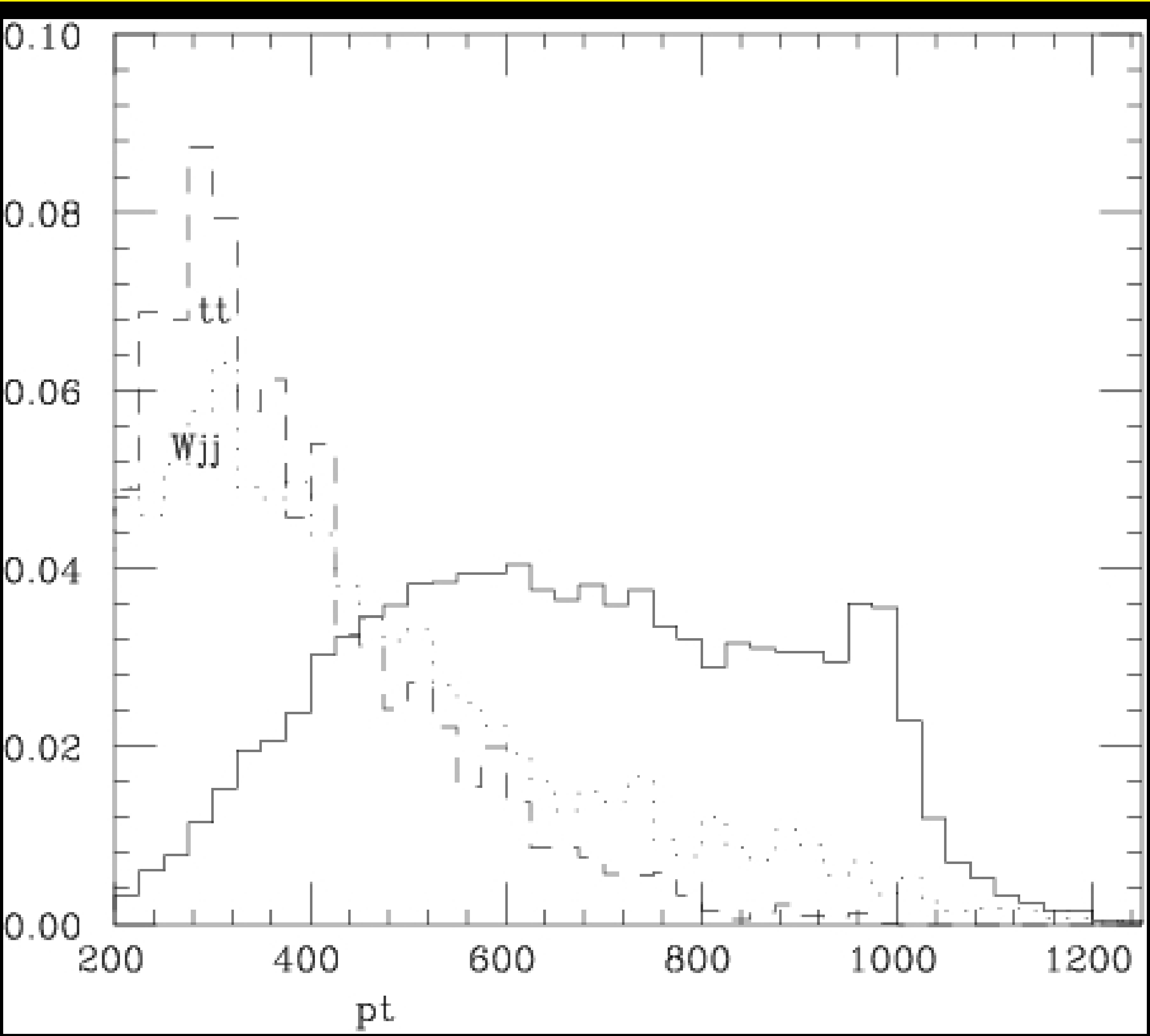


2. The transverse momentum of the light jet must satisfy

$$\mathbf{p_{j\ light} \ge p_{cut}}$$

where $\mathbf{p_{cut} = 350}$ (650) GeV for $\mathbf{M_{G^{(1)}} = 1}$ (2) TeV.



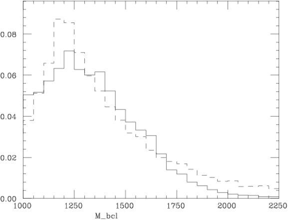

0.10
0.08
0.06
0.04
0.02
0.00
200
400
600
800
1000
1200
pt
tt
Wjj

✪ Further cuts:

1. The invariant mass of the visible particles should be in

$$\mathbf{M_{G^{(1)}} - \Delta \le M_{bj\ell} \le M_{G^{(1)}} + \Delta}$$

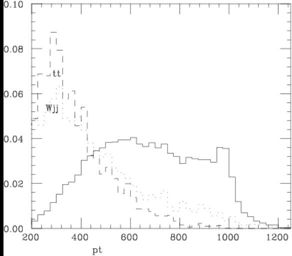
$\mathbf{\Delta = 120}$ (250) GeV for $\mathbf{M_{G^{(1)}} = 1}$ (2) TeV.



2. The transverse momentum of the light jet must satisfy

$$\mathbf{p_{j\ light} \ge p_{cut}}$$

where $\mathbf{p_{cut} = 350}$ (650) GeV for $\mathbf{M_{G^{(1)}} = 1}$ (2) TeV.



3. The invariant mass of the charged lepton and the b tagged jet must obey

$$\mathbf{M_{b\ell} \le 250}\ \text{GeV}$$

- Background and signal cross section after cuts for $\mathbf{M_{G^{(1)}} = 2}$ TeV

Process	$\mathbf{M_{bjl}}$	$\mathbf{p_{j\ light}^T}$	$\mathbf{M_{b\ell}}$
$\mathbf{pp \to tj}$	5.10 fb	2.18 fb	2.18 fb
$\mathbf{pp \to Wjj}$	25.4 fb	3.79 fb	0.95 fb
$\mathbf{pp \to t\bar{t}}$	1.60 fb	0.29 fb	0.24 fb
$\mathbf{pp \to Wbb}$	0.97 fb	0.45 fb	0.06 fb
$\mathbf{pp \to tb}$	0.04 fb	0.02 fb	0.02 fb
$\mathbf{Wg}$ fusion	1.20 fb	0.10 fb	0.10 fb

- Signal obtained using $\mathbf{U_L^{tq} = 0}$ and $\mathbf{U_R^{tq} = 1}$

- Bulk masses such that $\mathbf{\Gamma_G = 0.04\ M_G}$

- Reach in $\mathbf{U_R^{tq}}$ assuming $\mathbf{\Gamma_G^{min}}$ requiring a significance of $\mathbf{5}\,\sigma$ for the signal

$\mathbf{M_G}$ [TeV]	30 fb^{-1}	100 fb^{-1}	300 fb^{-1}
1	0.24	0.18	0.14
2	0.65	0.50	0.36

Conclusions

☆ We showed that the LHC is able to study flavor violation in the single production of tops at high energy.

☆ The signal requires that gauge fields and matter propagate in the bulk.

☆ This observation can only be a consequence of the tree-level flavor violation characteristic in extra dimension models.

☆ The LHC has the potential to observe this phenomenon up to KK gluon masses of at least $\mathbf{M_{G^{(1)}} = 2}$ TeV for interesting values of the parameter $\mathbf{U_R^{tq}}$.