Applications of MUED to rare top quark processes

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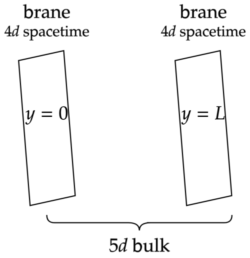
Outline

Introduction: MUED

(Minimal) Universal Extra Dimensions:

- Appelquist *et al.*, 2001
- $4 + n$ flat compactified extra dimensions
  $n = 1$: on circle
  $n = 2$: on torus
  In this work, $n = 1$.

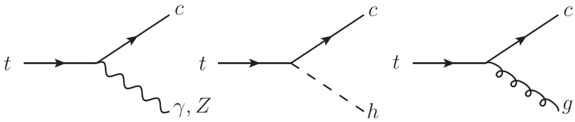


- Universal because all fields are allowed to live in bulk.
- Effective field theory: dimensionful couplings.
- Boundary-localized terms: Terms proportional to $\delta(y) + \delta(y - L)$ are absent in minimal model.
- Parameters of the model: L, size of extra dimension, and Λ, cut-off scale.

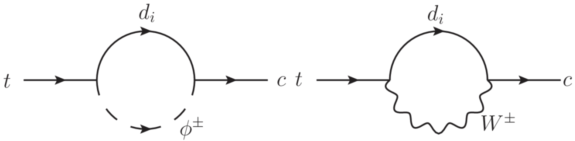
Introduction: Top physics

Main decay mode: $t \to bW$, $\Gamma = 1.54$ GeV

Rare decay modes: $t \to cX$, $X = \gamma, g, h, Z, gg$, Br $\sim 10^{-12}$



These interactions (flavor-changing neutral currents) are absent at tree level in Standard Model. Instead, they contain a loop:



Matrix element *almost* vanishes:

$$-i\mathscr{M} = \sum_{i=1}^{3} [\cdots] \frac{\not{k} + m_{d_i}}{k^2 - m_{d_i}^2} V_{ti} V_{ci}^* [\cdots]$$

Introduction: Top physics

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Table: Comparison of decay widths between SM calculation and observation

Process	Γ_{SM} (GeV)	Γ_{exp} (GeV)
$t \to c\gamma$	0.389×10^{-12}	$< 2.6 \times 10^{-3}$
$t \to ch$	0.956×10^{-13}	$< 2.5 \times 10^{-3}$
$t \to cZ$	0.110×10^{-12}	$< 0.37 \times 10^{-3}$

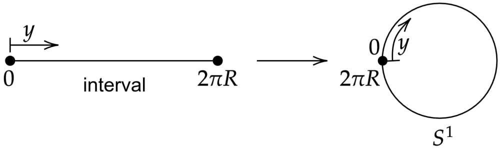
Can we hope to fill the gap using new physics?

Formalism: Construction of 5d universe

Promote Lorentz indices:

$$\mu, \nu, \ldots = 0, 1, 2, 3 \to M, N, \ldots = 0, 1, 2, 3, 5$$
$$x^\mu \to x^M = (x^\mu, x^5) =: (x^\mu, y)$$
$$\partial_\mu \to \partial_M = (\partial_\mu, \partial_5)$$

Domain of extra dimension:



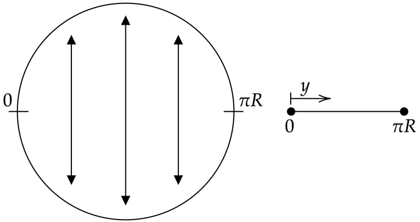
Size of extra dimensions (Deutschmann *et al.*, 2017):

$$0.5 \text{ TeV} < R^{-1} < 1.0 \text{ TeV}$$

Formalism: Construction of 5d universe

$$V^\mu(x^\nu) \to V^M(x^\nu, y) = (V^\mu(x^\nu, y), \underbrace{V^5(x^\nu, y)}_{\substack{\text{new}\\ \text{degree of}\\ \text{freedom}}})$$

Redundant degrees of freedom and chiral fermions: Z_2 symmetry



S^1/Z_2

$$\equiv \begin{cases} \Phi|_{y=0,\pi R} = 0 \\ \partial_5 \Phi|_{y=0,\pi R} = 0 \end{cases}$$

Formalism: Case of a free massive scalar

$$\mathscr{L} = \frac{1}{2}(\partial_M \phi)^2 - \frac{1}{2}m^2\phi^2 \Rightarrow (\Box - \partial_5^2 + m^2)\phi(x^\mu, y) = 0$$

$\phi(x^\mu, y) = \sum_{n\geq 0} \phi_n(x^\mu) f_n(y)$ Kaluza-Klein (KK) decomposition

n : KK number, $n = 0$ SM mode, $n > 0$ KK partners

ϕ_n : physical states, f_n : mode functions

$$\Box\phi_n(x^\mu) = -m_n^2 \phi_n(x^\mu)$$

$$f_n(y) = \begin{cases} \sqrt{\frac{2}{\pi R}} \sin M_n y, & n \in \mathbb{N}^+ \text{ if } \phi(x^\mu, y)|_{y=0,\pi R} = 0 \\ \sqrt{\frac{2}{\pi R}} \cos M_n y, & n \in \mathbb{N} \text{ if } \partial_5 \phi(x^\mu, y)|_{y=0,\pi R} = 0 \end{cases}$$

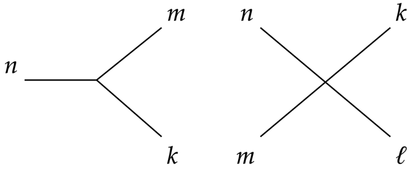
$m_n^2 = \underbrace{m^2}_{\text{SM mass}} + \underbrace{M_n^2}_{\text{geometrical mass}}$, $M_n = \frac{n}{R}$ universal mass term

Formalism: Features of MUED

New quantum number: KK parity, $(-1)^n$

$$\tau : y \to y + \pi R \Rightarrow \tau f_n(y) = (-1)^n f_n$$

Only in the minimal version: Conservation of KK number, $\sum_{\text{in}} n = \sum_{\text{out}} n$



$n = m + k$ $\quad\quad$ $n + m = k + \ell$

Formalism: Standard Model in 5d

Standard Model Lagrangian promoted to 5d:

$$\begin{aligned}
\mathscr{L} &= \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{fermion}} + \mathscr{L}_{\text{Yukawa}} + \mathscr{L}_{\text{ghost}} \\
\mathscr{L}_{\text{gauge}} &= \sum_{a=1}^{8} -\frac{1}{4}\left(G^a_{MN}\right)^2 + \sum_{i=1}^{3} -\frac{1}{4}\left(W^i_{MN}\right)^2 - \frac{1}{4}\left(B_{MN}\right)^2 \\
\mathscr{L}_{\text{Higgs}} &= \left|\mathscr{D}_M H\right|^2 + \mu_5^2 \left|H\right|^2 - \lambda_5 \left|H\right|^4 \\
\mathscr{L}_{\text{fermion}} &= \sum_{\psi=Q,U,D,L,E} \bar{\psi} i \Gamma^M \mathscr{D}_M \psi \\
\mathscr{L}_{\text{Yukawa}} &= -y_{u5}\bar{Q}U\tilde{H} - y_{d5}\bar{Q}DH - y_{e5}\bar{L}EH + \text{h.c.}
\end{aligned}$$

Gauge-fixing terms are determined after obtaining mass states.

Ghosts are irrelevant at the moment.

Formalism: Standard Model in $5d$

$5d$ field strength tensors:

$$G^a_{MN} = \partial_M G^a_N - \partial_N G^a_M - g_{s5} f^{abc} G^b_M G^c_N$$
$$W^i_{MN} = \partial_M W^i_N - \partial_N W^i_M - g_{w5} \epsilon^{ijk} W^j_M W^k_N$$
$$B_{MN} = \partial_M B_N - \partial_N B_M$$

$5d$ covariant derivative:

$$\mathscr{D}_M = \partial_M + i g_{s5} \vec{T}_s \cdot \vec{G}_M + i g_{w5} \vec{T}_w \cdot \vec{W}_M + i g_{y5} T_y B_M$$

$5d$ Dirac matrices:

$$\Gamma^M = (\gamma^\mu, i\gamma_5), \; \left\{ \Gamma^M, \Gamma^N \right\} = 2\eta^{MN}$$

$5d$ Higgs doublet:

$$H = \begin{pmatrix} i\phi^+ \\ \frac{1}{\sqrt{2}}(h + v_5 + i\phi^3) \end{pmatrix}$$

Formalism: Effective Lagrangian

MUED is an effective field theory since couplings are dimensionful:

$$g = \frac{g_5}{\sqrt{\pi R}}$$

Introduce a cut-off scale, Λ:

$$\Lambda R = n_{\max}$$

Perturbation theory and study of Higgs vacuum stability (Datta & Raychaudhuri, 2013):

$$n_{\max} = 6$$

This leave MUED with only one free parameter, the size of extra dimension, R.

Results: Particle spectrum

- Vector spectrum:

$$g_0, W_0^{\pm}, Z_0, A_0$$

$$g_n, W_n^{\pm}, Z_n, A_n$$

- Scalar spectrum:

$$h_0, \phi_0^{\pm}, \phi_0^3$$

$$h_n, a_n, a_n^{\pm}, G_{5n}, G_n^{\pm}, G_{Zn}, G_{An}$$

- Fermion spectrum:

$$e_0^i, \nu_0^i, u_0^i, d_0^i$$

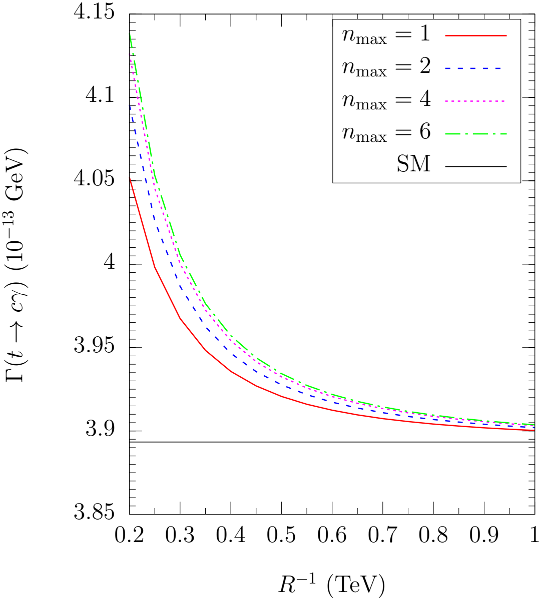
$$e_n^{(1,2)i}, \nu_n^{(1,2)i}, d_n^{(1,2)i}, u_n^{(1,2)i}$$

Results: Processes considered

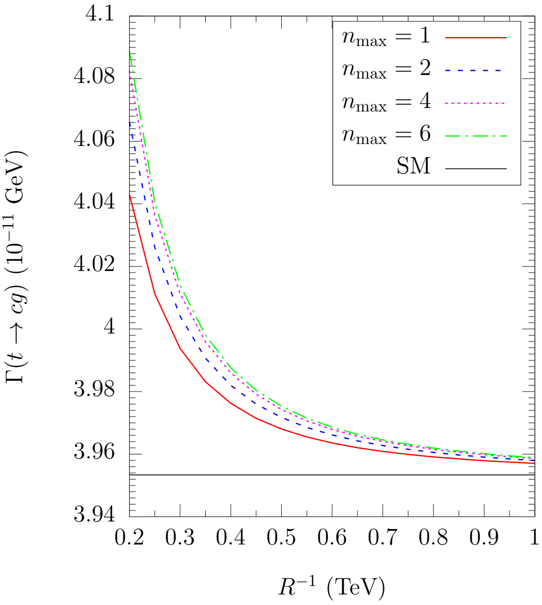
Rare top decays:	Rare single top production:
$t \to c\gamma$	$cg \to t\gamma$
$t \to cg$	$cg \to tg$
$t \to ch$	$cg \to th$
$t \to cZ$	$cg \to tZ$
$t \to cgg$	$gg \to t\bar{c}$

Production channels have original results.

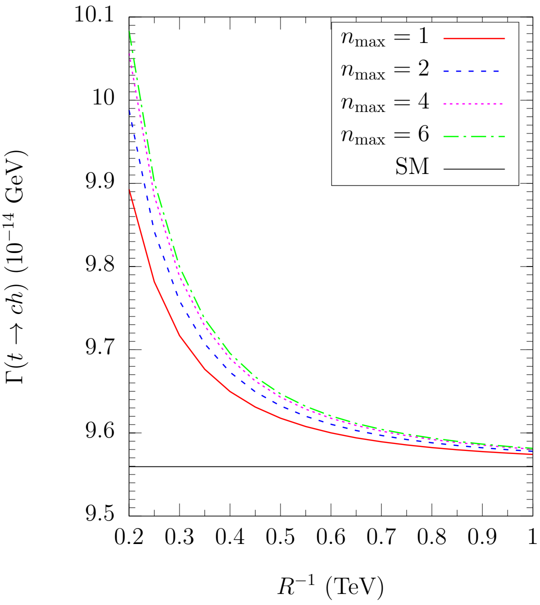
Results: $t \to c\gamma$



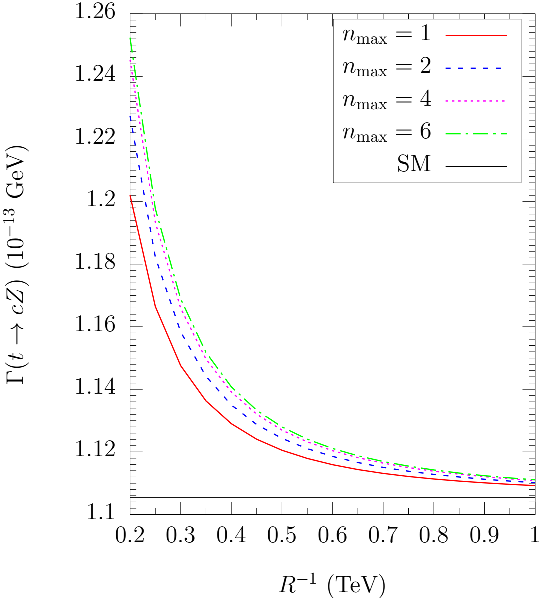
Results: $t \to cg$



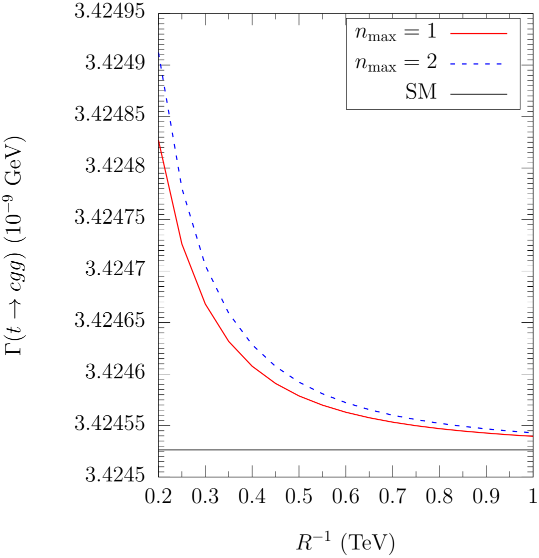
Results: $t \to ch$



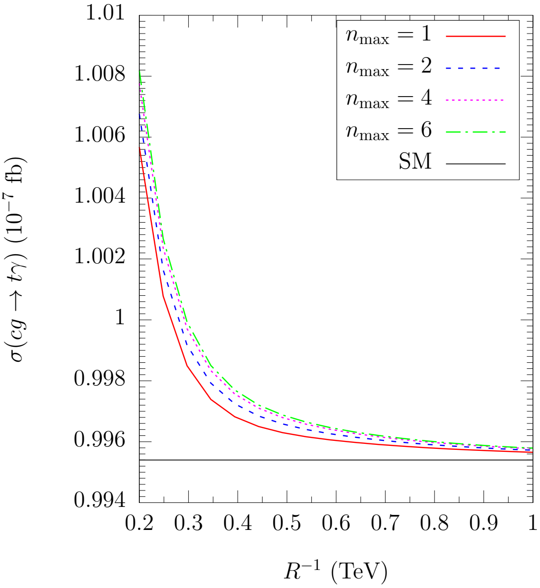
Results: $t \to cZ$



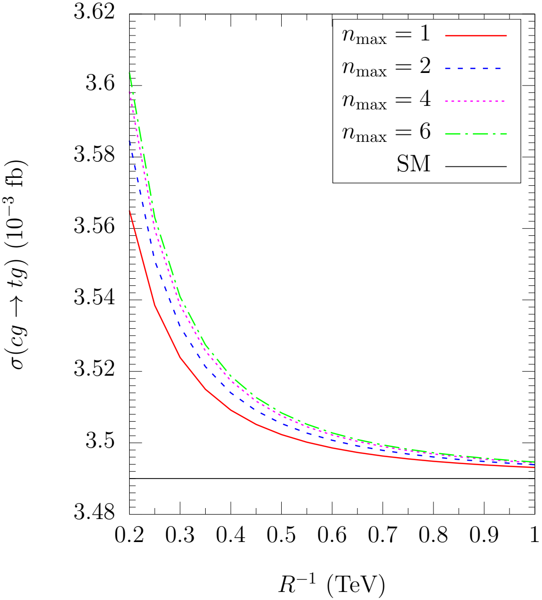
Results: $t \to cgg$



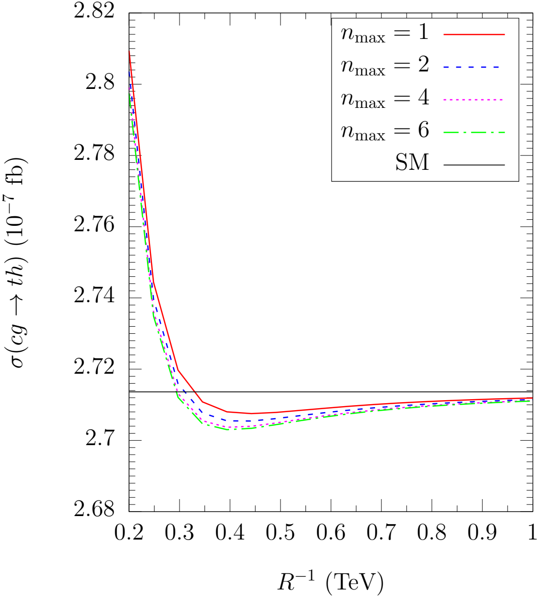
Results: $cg \to t\gamma$



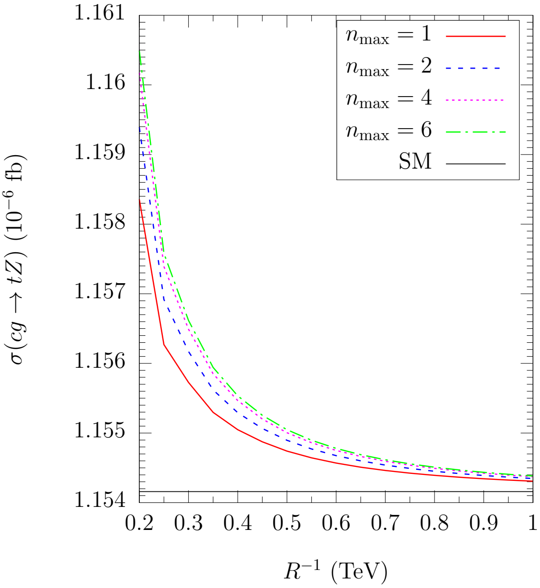
Results: $cg \to tg$



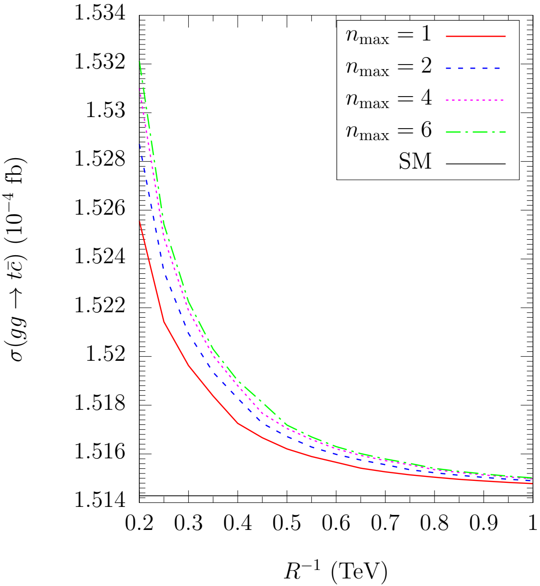
Results: $cg \to th$



Results: $cg \to tZ$



Results: $gg \to t\bar{c}$



In conclusion,

- Only one free parameter, model is predictable.
- Contributions are small.

On-going research: *Non*minimal universal extra dimensions

- New free parameters, extended parameter space.

$$\mathscr{L} \supset \frac{1}{2} r_\phi [\delta(y) + \delta(y - \pi R)] (\partial_\mu \phi)^2 + \text{etc.}$$

- No more conservation of KK number, richer phenomenology is possible.
- Larger contributions are expected.

Papers

This work:

- K. Şimşek, "Exploring extra dimensions through rare processes", M.Sc. Thesis, Inst. of Nat. and Appl. Sciences, Middle East Tech. Uni., Ankara, Turkey, 2019.
- K. Şimşek, İ. Turan, "Applications of MUED to rare top physics" [pre-print], 2020.

Important papers:

- T. Appelquist, H.-C. Cheng, & B. A. Dobrescu, "Bounds on Universal Extra Dimensions", Phys. Rev. D **64**(3), 035002, 2001.
- N. Deutschmann, T. Flacke, & J. S. Kim, "Current LHC constraints on minimal universal extra dimensions", Phys. Lett. B **771**, 515-520, 2017.
- A. Datta & S. Raychaudhuri, "Vacuum stability constraints and LHC searches for a model with a universal extra dimension", Phys. Rev. D **87**(3), 035018, 2013.