Top-Quark Pair Production in Randall-Sundrum Models:

The Forward-Backward Asymmetry and Prospects at the ILC

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

International Workshop on Linear Colliders 2010
CERN and CICG, 20.10.2010

M. Bauer, FG, U. Haisch, T. Pfoh and S. Westhoff, arXiv:1008.0742[hep-ph],...

Outline

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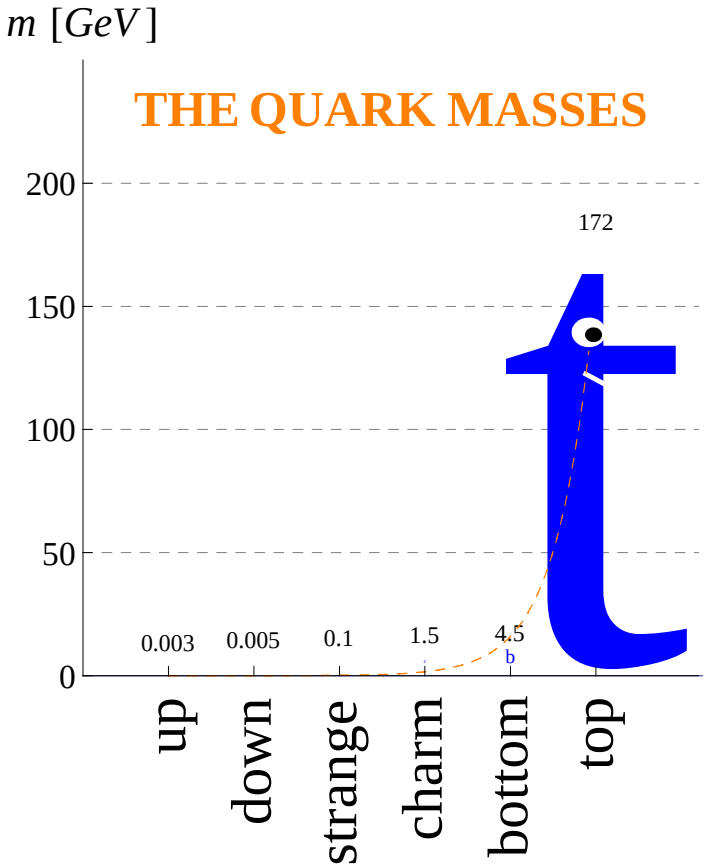
The Top Quark . . .

- . . . is the only SM fermion with a Yukawa coupling of $\mathcal{O}(1)$



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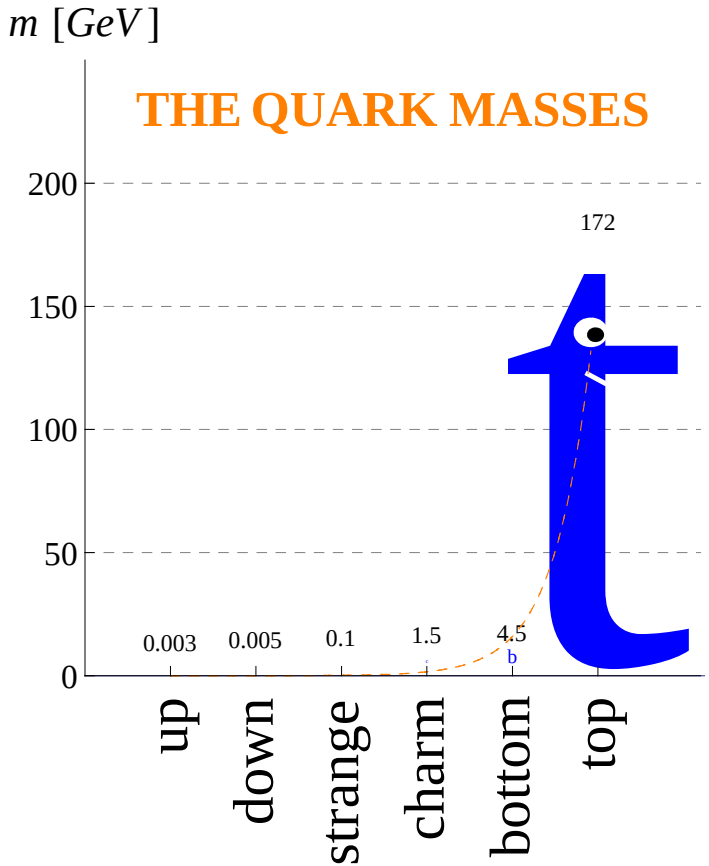
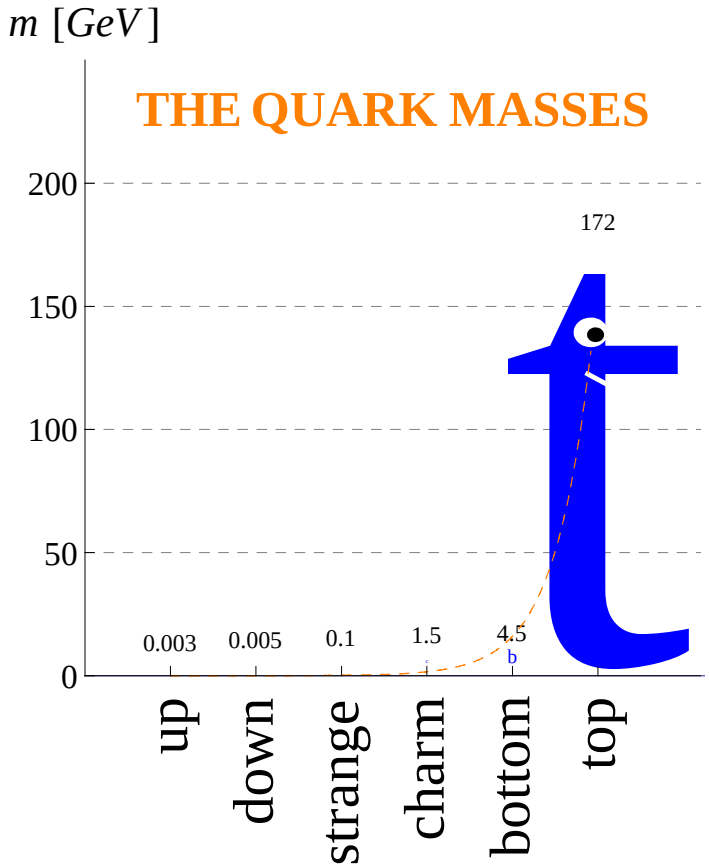


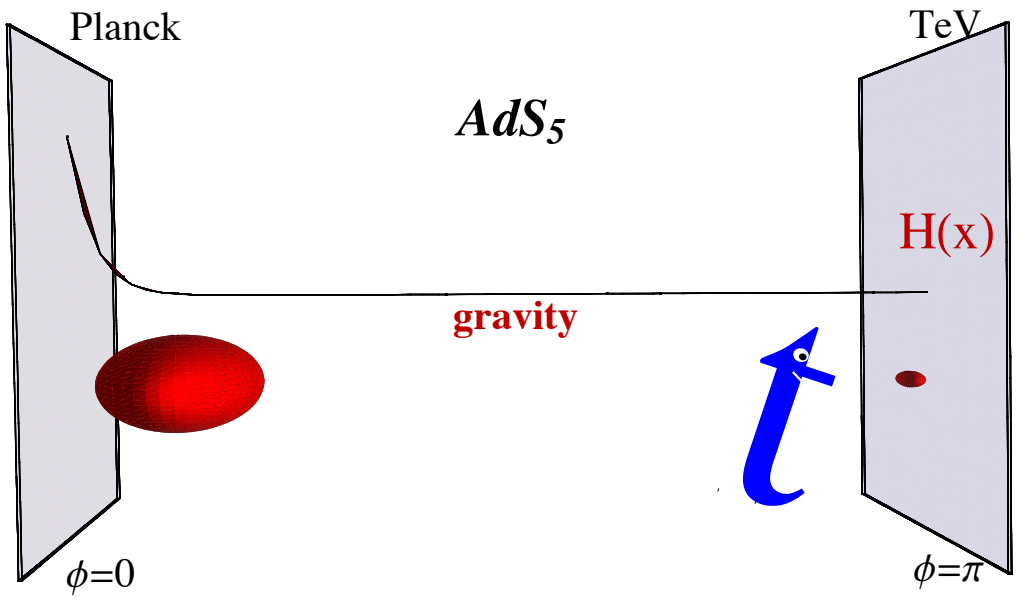
The Top Quark ...

- ... is the only SM fermion with a Yukawa coupling of $\mathcal{O}(1)$
- ... might be deeply connected to the mechanism of electroweak symmetry breaking
- ... has been detected thousands of times at the Tevatron, which allows for a determination of its mass, total production cross section and kinematic distributions with reasonable accuracy

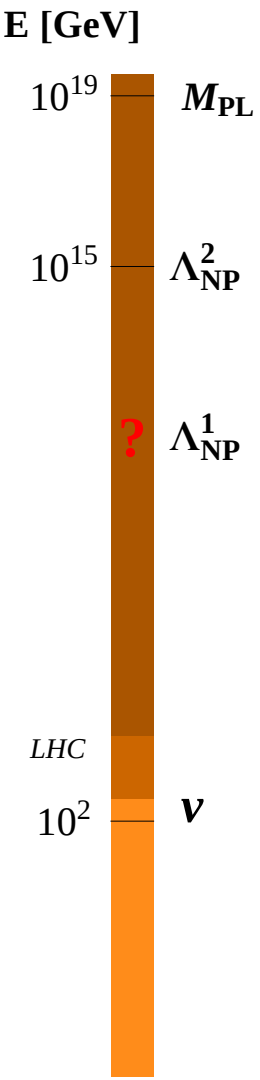


The Top Quark in Warped Extra Dimensions...

... is even more special



Why wXD: Gauge Hierarchy Problem and Flavor Puzzle



- Higgs mass receives quadratically divergent corrections $\Rightarrow$ expect $m_h^2 \sim \max[\Lambda_i]^2$
- Gauge bosons: gauge symmetry
- Fermions: $SU(2)_L$

} small masses natural

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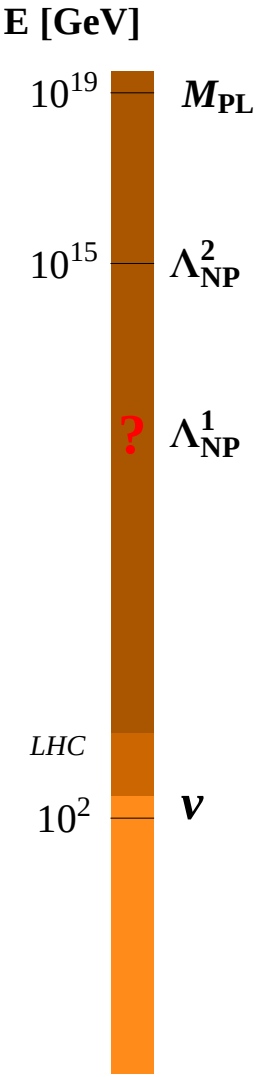

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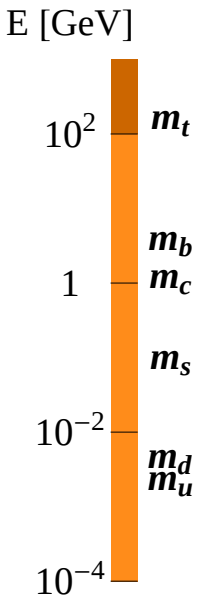

$m_u/m_t \sim 10^{-5}$

$$\mathbf{V}_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

$\lambda \sim 0.2$

The Randall-Sundrum (RS) Model hep-ph/9905221

- Solution to the gauge hierarchy problem in 5D spacetime

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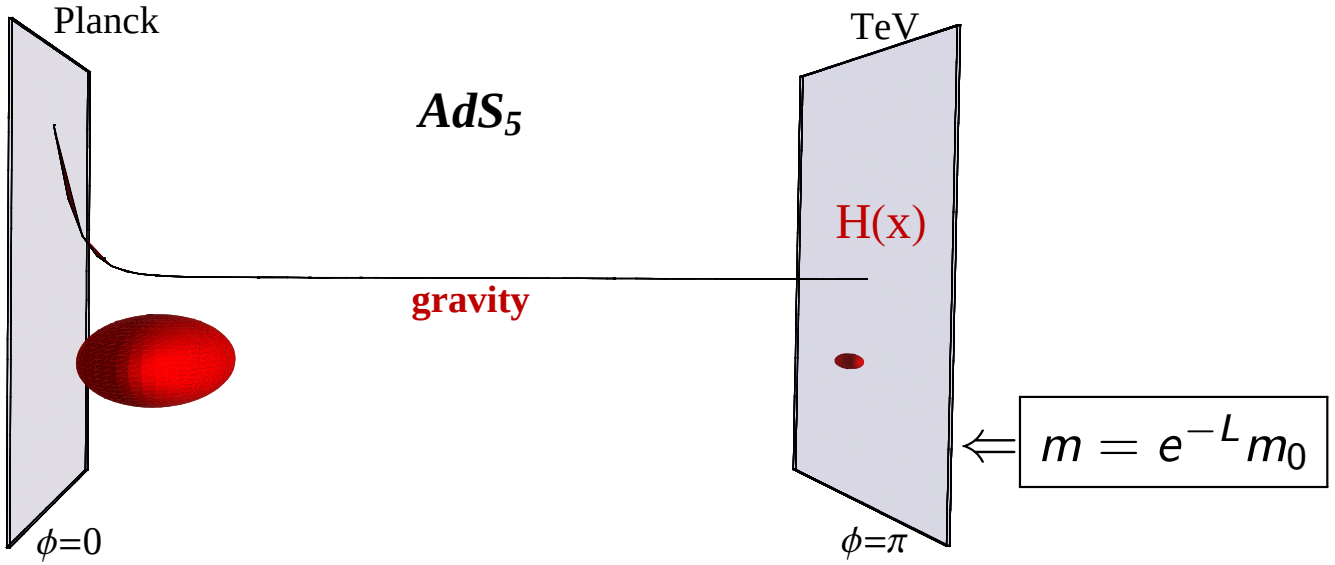

$$L = kr\pi \approx 37 \gg 1$$

many observables enhanced by L

$$\Leftarrow m = e^{-L} m_0$$

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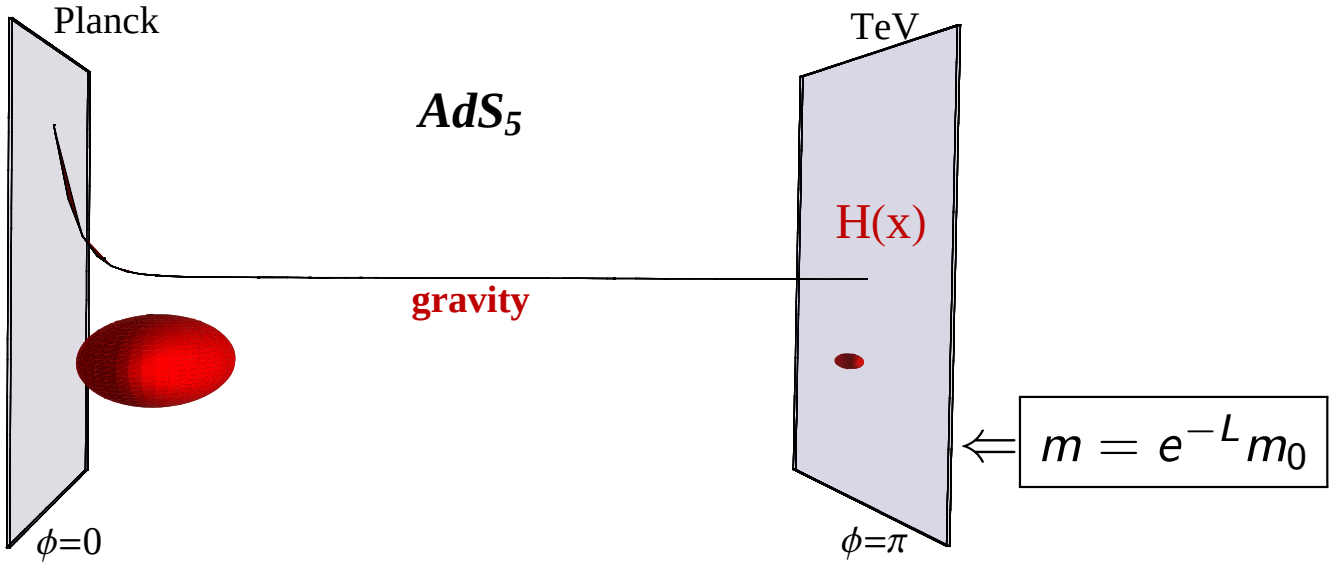

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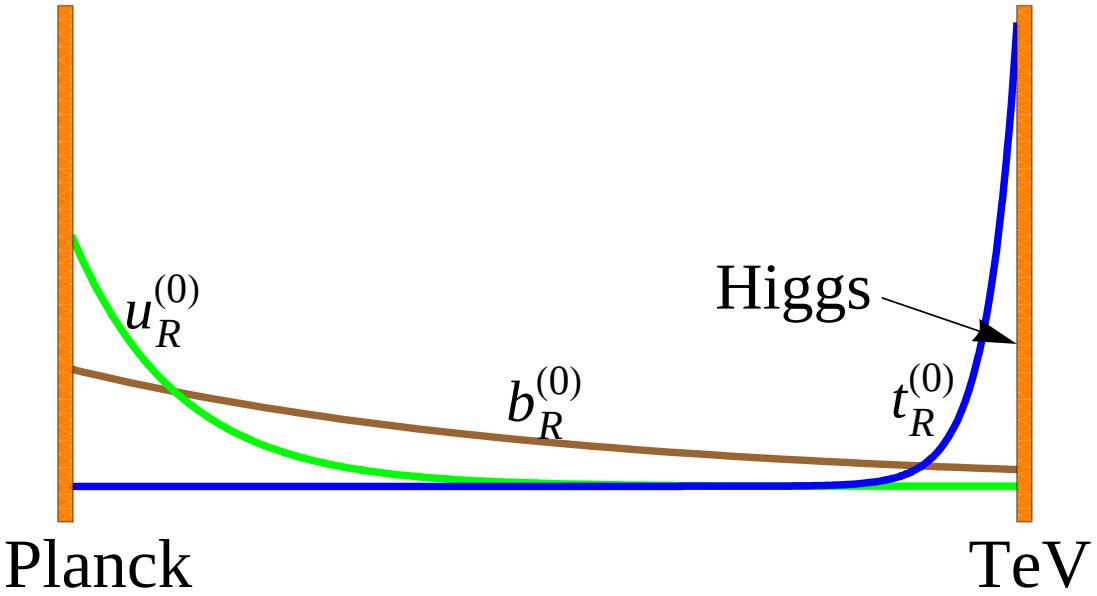
- All fundamental mass parameters of $\mathcal{O}(M_{PL})$

The Standard Model in AdS_5

Just the Higgs boson has to be localized at (close to) the TeV brane in order to solve the hierarchy problem $\Rightarrow$ *Bulk-SM*

Davoudiasl, Hewett, Rizzo, hep-ph/9911262,
Grossman, Neubert, hep-ph/9912408



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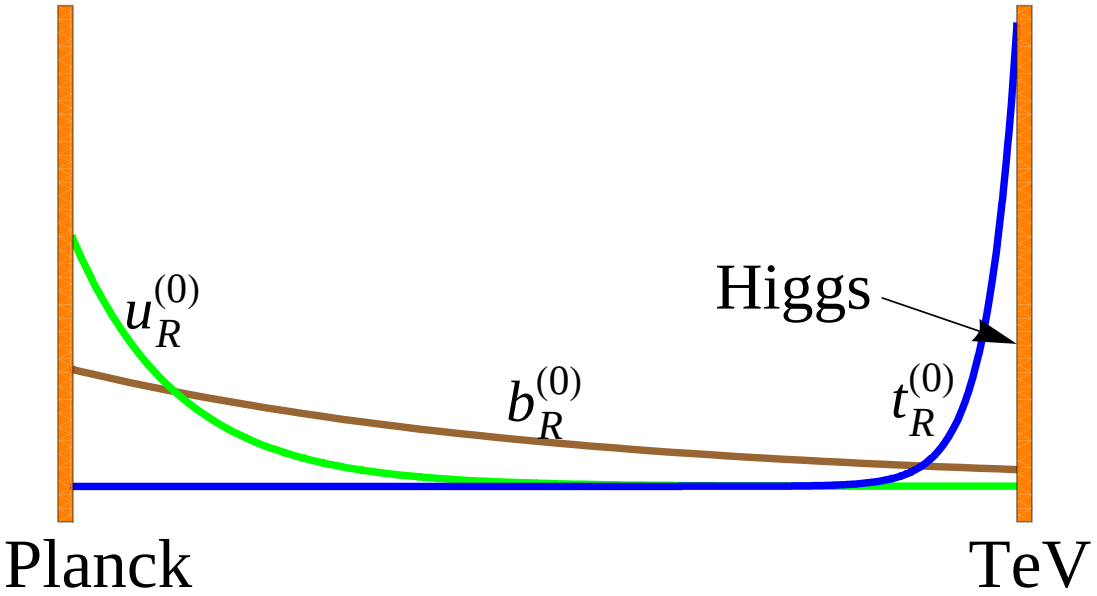

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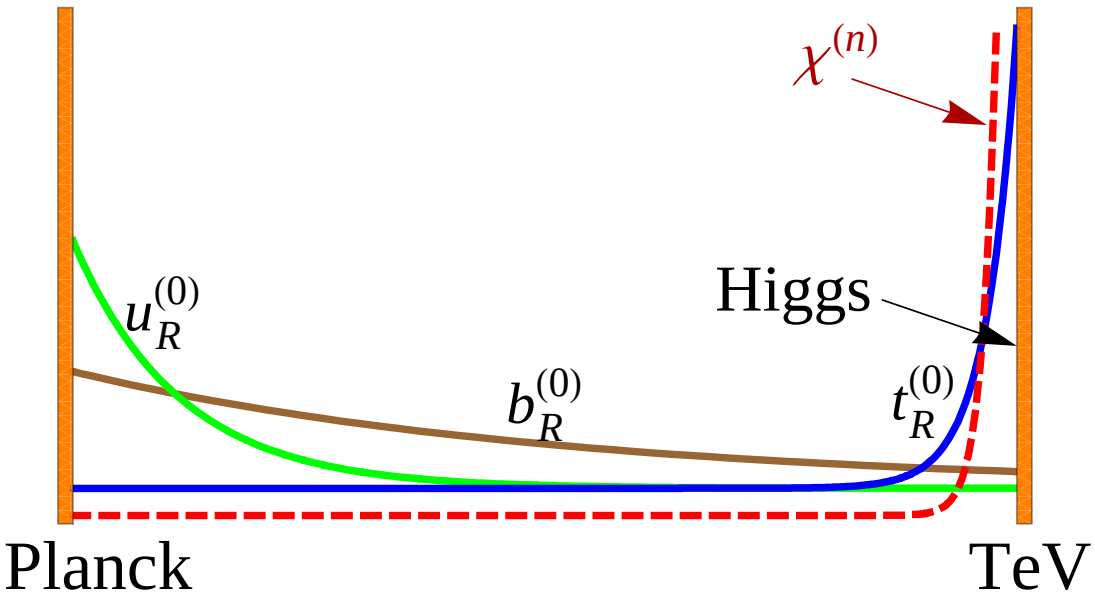

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gauge bosons have flat profiles only if gauge symmetry is not broken

$m^{(1)} \approx 2.5\, M_{\rm KK}$

$M_{\rm KK} = ke^{-L} \sim TeV$

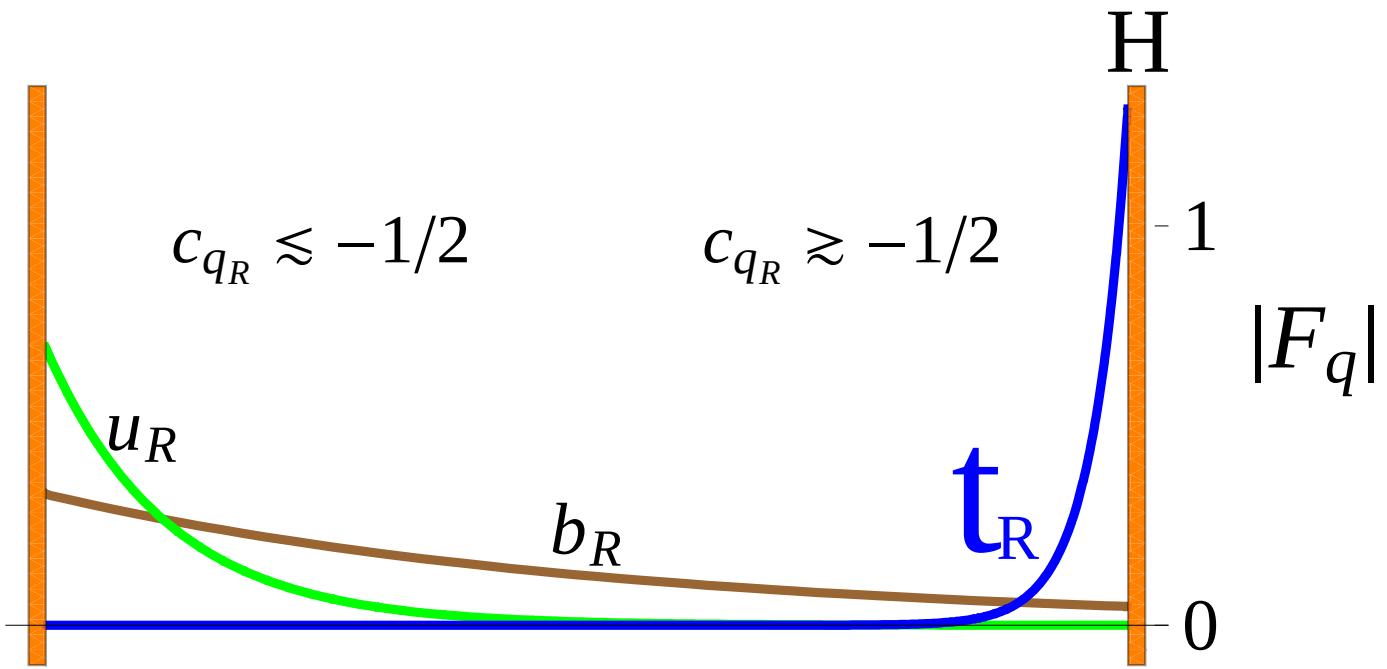
Non-trivial overlaps + doublet-singlet mixing

$\Rightarrow$ fields with same QN under unbroken symmetry have different couplings to gauge bosons of broken symmetry $\Rightarrow$ tree FCNCs

RS as a Solution to the Flavor Puzzle

- RS offers an explanation for the fermion mass hierarchies and small CKM mixing angles with anarchic 5D Yukawa couplings

Huber, Shafi, hep-ph/0010195; Huber, hep-ph/0303183; Casagrande, FG, Haisch, Neubert, Pfoh, 1005.4315



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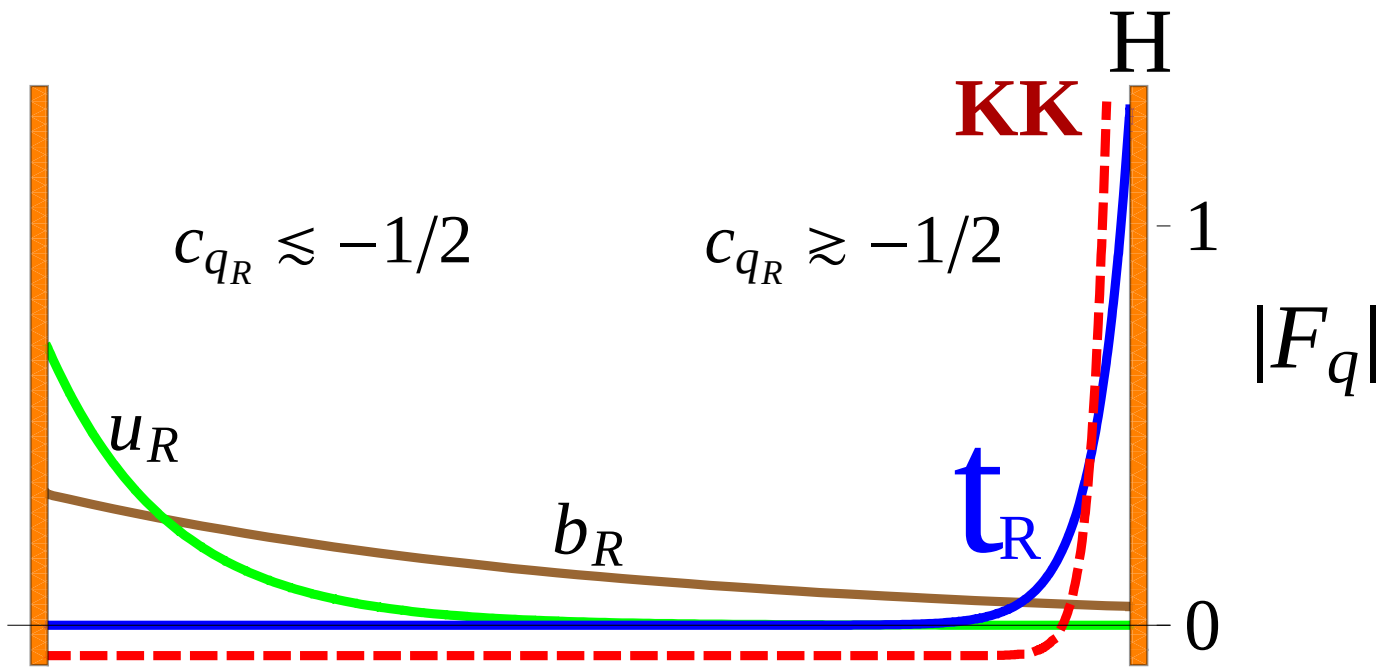

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Couplings of KK gauge bosons to **top quarks** enhanced by factor $\sqrt{L}$

The Top Quark in Warped Extra Dimensions

- Couplings involving third generation quarks could provide possibility to test the model
- Study top quark pair production, asymmetries

Outline

The Forward-Backward Asymmetry of the Top Quark

The top-quark forward-backward asymmetry measured at CDF,

$$\left(A_{\rm FB}^t\right)_{\rm exp}^{p\bar{p}} = \left(15.0 \pm 5.0_{\,\rm stat.} \pm 2.4_{\,\rm syst.}\right),$$

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CDF/ANAL/TOP/PUBLIC/10224
Antunano, Kühn, Rodrigo, 0709.1652
DØ6062-CONF

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- Expect to see RS signatures in 3rd generation observables $\longrightarrow$ anomaly due to warped extra dimensions?

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Important constraints: reproduction of SM-like $\sigma_{t\bar{t}}$ and $d\sigma_{t\bar{t}}/dM_{t\bar{t}}$

The Forward-Backward Asymmetry of the Top Quark

$$A_{\mathrm{FB}}^{t} \equiv \frac{\displaystyle\int_0^1 d\cos\theta\, \frac{d\sigma^{p\bar{p}\to t\bar{t}X}}{d\cos\theta} - \int_{-1}^0 d\cos\theta\, \frac{d\sigma^{p\bar{p}\to t\bar{t}X}}{d\cos\theta}}{\displaystyle\int_0^1 d\cos\theta\, \frac{d\sigma^{p\bar{p}\to t\bar{t}X}}{d\cos\theta} + \int_{-1}^0 d\cos\theta\, \frac{d\sigma^{p\bar{p}\to t\bar{t}X}}{d\cos\theta}}$$

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$$\frac{d\sigma_{a(s)}}{d\cos\theta} \equiv \frac{1}{2}\left[\frac{d\sigma^{p\bar{p}\to t\bar{t}X}}{d\cos\theta} \underset{(+)}{-} \frac{d\sigma^{p\bar{p}\to \bar{t}tX}}{d\cos\theta}\right]$$

used C-symmetry of QCD: $\left.\frac{d\sigma^{p\bar{p}\to \bar{t}tX}}{d\cos\theta}\right|_{\cos\theta=c} = \left.\frac{d\sigma^{p\bar{p}\to t\bar{t}X}}{d\cos\theta}\right|_{\cos\theta=-c}$

The Forward-Backward Asymmetry of the Top Quark

Charge asymmetric contribution to cross section given by convolution of parton luminosity functions with charge-asymmetric hard scattering kernels

$$\sigma_a = \frac{\alpha_s}{m_t^2} \sum_{i,j} \int_{4m_t^2}^{s} \frac{d\hat{s}}{s} \, ff_{ij}\left(\hat{s}/s, \mu_f\right) A_{ij}\left(\frac{4m_t^2}{\hat{s}}\right) \qquad (\sigma_s : A_{ij} \to S_{ij})$$

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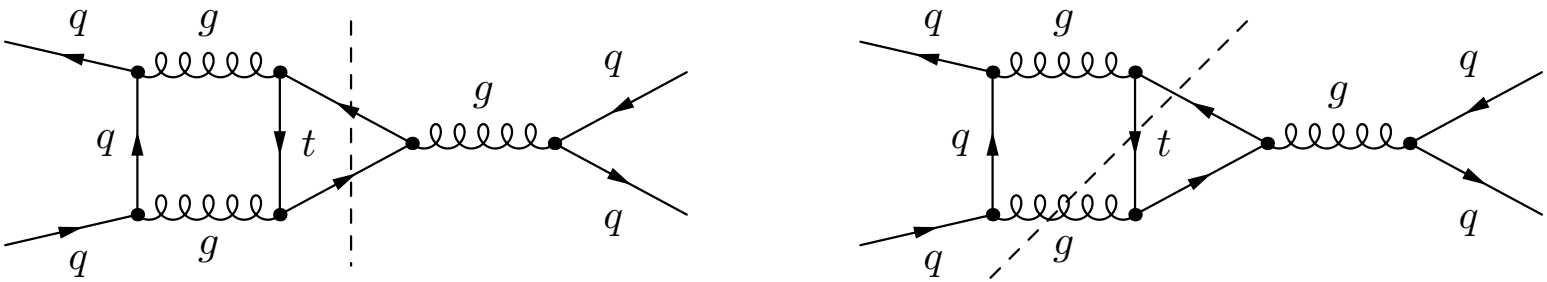
- At NLO non zero coefficient $A_{q\bar{q}}^{(1)}$ generated through interference of tree level gluon exchange with QCD box diagram and ISR/FSR



New Physics Contributions to A_{FB}^t

Consider effective dim-6 Lagrangian

$$\mathcal{L}_{\mathrm{eff}} = \sum_{q,u} \sum_{A,B=L,R} \Big[C_{q\bar{q},AB}^{(V,8)} Q_{q\bar{q},AB}^{(V,8)} + C_{t\bar{u},AB}^{(V,8)} Q_{t\bar{u},AB}^{(V,8)} + C_{t\bar{u},AB}^{(V,1)} Q_{t\bar{u},AB}^{(V,1)} + C_{t\bar{u},AB}^{(S,1)} Q_{t\bar{u},AB}^{(S,1)} \Big]$$

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$$Q^{(V,8)}_{q\bar{q},AB} = (\bar{q}\gamma_\mu T^a P_A q)(\bar{t}\gamma^\mu T^a P_B t) \quad Q^{(V,8)}_{t\bar{u},AB} = (\bar{u}\gamma_\mu T^a P_A t)(\bar{t}\gamma^\mu T^a P_B u)$$

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appropriate for broad class of BSM models

New Physics Contributions to $A_{\rm FB}^t$: LO

Corrections to LO asymmetric/symmetric kernels given by interference between SM-gluon exchange and s- and t-channel new physics contributions

$$A^{(0)}_{u\bar{u},\rm NP} = \frac{\beta^2\rho}{144}\,\hat{s}\,\left[C^{(V,8)}_{u\bar{u},\parallel} - C^{(V,8)}_{u\bar{u},\perp} + \frac{1}{3}\,C^{(V,8)}_{t\bar{u},\parallel}\right] + \text{EW contributions}\,,$$

$$S^{(0)}_{u\bar{u},\rm NP} = \frac{\beta\rho}{216}\,(2+\rho)\,\hat{s}\,\left[C^{(V,8)}_{u\bar{u},\parallel} + C^{(V,8)}_{u\bar{u},\perp} + \frac{1}{3}\,C^{(V,8)}_{t\bar{u},\parallel}\right] + \text{EW contributions}$$

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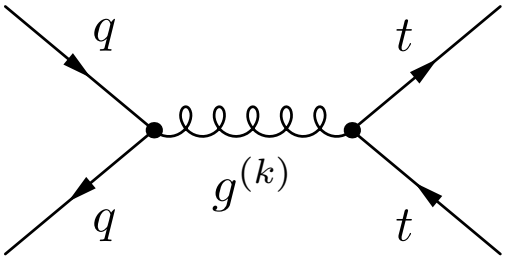
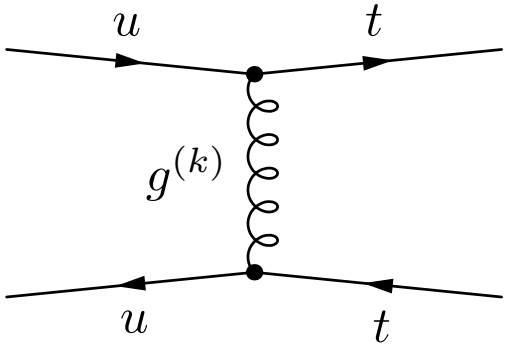
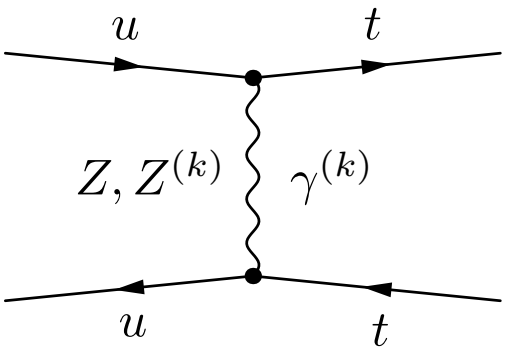
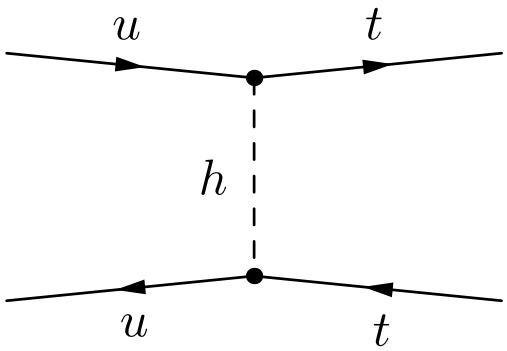
RS Contributions to A_{FB}^t: LO

RS contributions to the Wilson coefficients introduced before:



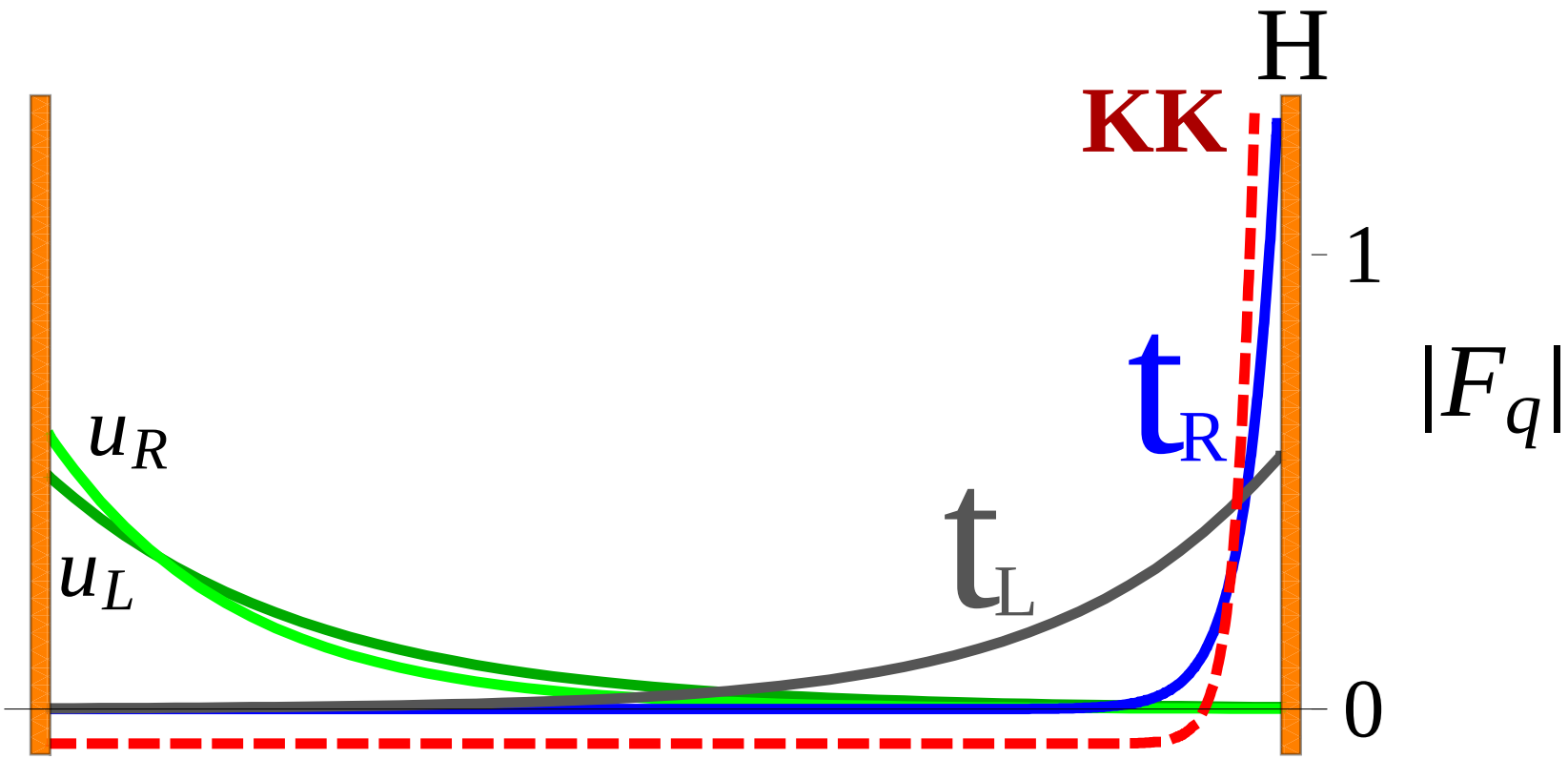






RS Contributions to A_{FB}^{t}: LO

Axial-vector couplings of quarks to gluons arise in the RS model due to the different profiles of right- and left-handed (singlet/doublet) quark zero modes



RS Contributions to $A_{\rm FB}^t$: LO

Expansion in $v^2/M_{\rm KK}^2$ and small difference of light quark bulk mass parameters leads to

$$S_{u\bar{u},\rm RS}^{(0)} \sim \frac{4\pi\alpha_s}{M_{\rm KK}^2}\, 2\,(1+c_{t_L}+c_{t_R}) > 0\,,$$

$$A_{u\bar{u},\rm RS}^{(0)} \sim \frac{4\pi\alpha_s}{M_{\rm KK}^2}\, 2L\, e^{L(1+c_{u_L}+c_{u_R})}\,(1+c_{u_L}+c_{u_R}) \times \left\{\left(2+\frac{1}{3}\right) L\,(c_{t_L}-c_{t_R})\,(c_{u_L}-c_{u_R}) + \frac{1}{3}\,(1+c_{t_L}+c_{t_R})\right\}$$

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$$\times \left\{ \left(2 + \frac{1}{3}\right) L\,(c_{t_L} - c_{t_R})\,(c_{u_L} - c_{u_R}) + \frac{1}{3}\,(1 + c_{t_L} + c_{t_R}) \right\}$$

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- Positive shift in σ_a possible, but LO contributions tiny due to elementary nature (UV localization: $c_a < -1/2$) and nearly vector like couplings of **light quarks** (keep in mind: still has to divide by σ_s)

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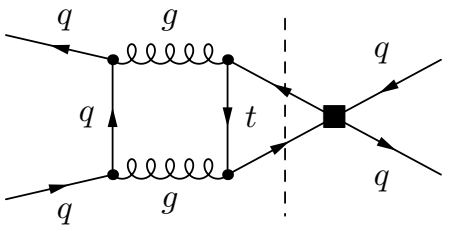
- Positive shift in σ_a possible, but LO contributions tiny due to elementary nature (UV localization: $c_a < -1/2$) and nearly vector like couplings of **light quarks** (keep in mind: still has to divide by σ_s)
- Given the smallness of the LO contribution: look at NLO

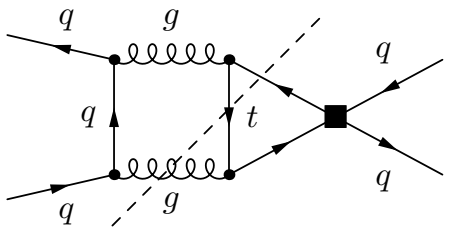
New Physics Contributions to A_{FB}^t: NLO

At NLO: σ_a gets contributions from vector-currents

$$\left[d_{abc}^2 = \left(2\,\mathrm{Tr}\left(\{T^a, T^b\}T^c\right)\right)^2 \text{terms}\right]$$

Kühn, Rodrigo, hep-ph/9802268, hep-ph/9807420





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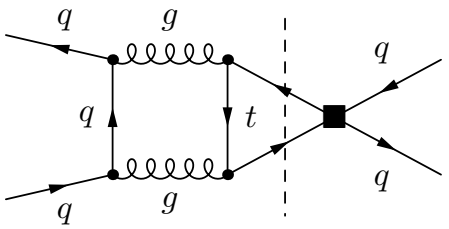

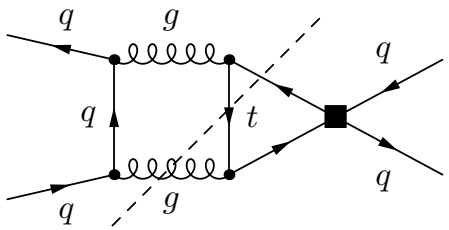

- In models with small axial-vector couplings to light quarks and no significant FCNC effects in the t-channel, e.g. models which solve the flavor puzzle by (geometrical) sequestering, the NLO corrections often exceed the LO ones

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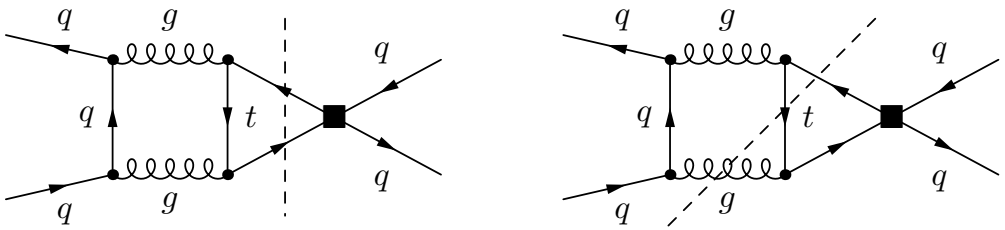

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$$\frac{\alpha_s}{4\pi}\left(1 + c_{t_L} + c_{t_R}\right) \gtrsim L\, e^{L(1+c_{u_L}+c_{u_R})}$$

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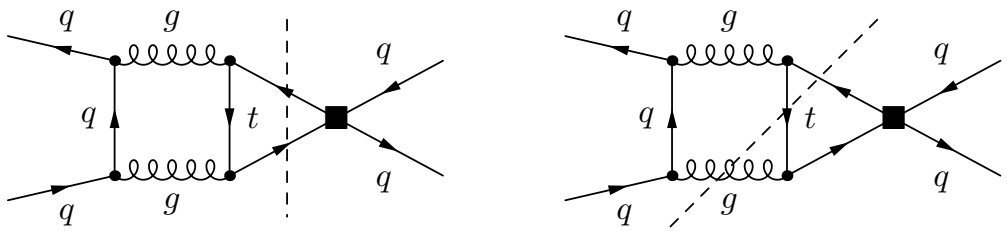

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$$\frac{\alpha_s}{4\pi}\left(1 + c_{t_L} + c_{t_R}\right) \gtrsim L\, e^{L(1+c_{u_L}+c_{u_R})}$$

- For typical bulk masses: $\sigma_a^{(1)}/\sigma_a^{(0)} \sim 25$ (IR localization of **top**)

RS Contributions to $A_{\rm FB}^t$: NLO

c_{t_L}	c_{t_R}	$\tilde{C}^V_{u\bar{u}}/\alpha_s$	$\tilde{C}^A_{u\bar{u}}/\alpha_s$	$\tilde{C}^V_{d\bar{d}}/\alpha_s$	$\tilde{C}^A_{d\bar{d}}/\alpha_s$	$\tilde{C}^V_{t\bar{u}}/\alpha_s$	$\tilde{C}^S_{t\bar{u}}$
-0.41	0.09	4.50	$0.71 \cdot 10^{-2}$	0.68	$-1.40 \cdot 10^{-3}$	$-1.35 \cdot 10^{-4}$	$8.2 \cdot 10^{-7}$
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$\tilde{C}^P_{q\bar{q}} \equiv 1\,\mathrm{TeV}^2\, C^P_{q\bar{q}}$, $\tilde{C}^V_{t\bar{u}} \equiv 1\,\mathrm{TeV}^2\,(1/3\, C^{(V,8)}_{t\bar{u},\parallel} - 2\, C^{(V,1)}_{t\bar{u},\parallel})$, scale as $(1\,\mathrm{TeV}/M_{\rm KK})^2$ $\left((1\,\mathrm{TeV}/M_{\rm KK})^4\right)$

$$(A_{\rm FB}^t)^{p\bar{p}}_{\rm RS} = \left[\frac{1 + 0.22\,\tilde{C}^A_{u\bar{u}} + 0.034\,\tilde{C}^V_{u\bar{u}} + \ldots}{1 + 0.053\,\tilde{C}^V_{u\bar{u}} + \ldots}\right] \left(5.6^{+0.8}_{-1.0}\right)\,\%\,,$$

RS Contributions to $A_{\rm FB}^t$: NLO

c_{t_L}	c_{t_R}	$\tilde{C}^V_{u\bar{u}}/\alpha_s$	$\tilde{C}^A_{u\bar{u}}/\alpha_s$	$\tilde{C}^V_{d\bar{d}}/\alpha_s$	$\tilde{C}^A_{d\bar{d}}/\alpha_s$	$\tilde{C}^V_{t\bar{u}}/\alpha_s$	$\tilde{C}^S_{t\bar{u}}$
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- SM-like forward-backward asymmetry

RS Contributions to $A_{\rm FB}^t$: NLO

c_{t_L}	c_{t_R}	$\tilde{C}^V_{u\bar{u}}/\alpha_s$	$\tilde{C}^A_{u\bar{u}}/\alpha_s$	$\tilde{C}^V_{d\bar{d}}/\alpha_s$	$\tilde{C}^A_{d\bar{d}}/\alpha_s$	$\tilde{C}^V_{t\bar{u}}/\alpha_s$	$\tilde{C}^S_{t\bar{u}}$
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- SM-like forward-backward asymmetry
- NLO corrections are important

RS Contributions to $A_{\rm FB}^t$: NLO

c_{t_L}	c_{t_R}	$\tilde{C}^V_{u\bar{u}}/\alpha_s$	$\tilde{C}^A_{u\bar{u}}/\alpha_s$	$\tilde{C}^V_{d\bar{d}}/\alpha_s$	$\tilde{C}^A_{d\bar{d}}/\alpha_s$	$\tilde{C}^V_{t\bar{u}}/\alpha_s$	$\tilde{C}^S_{t\bar{u}}$
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- SM-like forward-backward asymmetry
- NLO corrections are important
- Small corrections generically negative (for positive $\tilde{C}^V_{u\bar{u}}$)

RS Contributions to $A_{\rm FB}^t$: NLO

c_{t_L}	c_{t_R}	$\tilde{C}^V_{u\bar{u}}/\alpha_s$	$\tilde{C}^A_{u\bar{u}}/\alpha_s$	$\tilde{C}^V_{d\bar{d}}/\alpha_s$	$\tilde{C}^A_{d\bar{d}}/\alpha_s$	$\tilde{C}^V_{t\bar{u}}/\alpha_s$	$\tilde{C}^S_{t\bar{u}}$
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$$(A_{\rm FB}^t)^{p\bar{p}}_{\rm RS} = \left[\frac{1 + 0.22\,\tilde{C}^A_{u\bar{u}} + 0.034\,\tilde{C}^V_{u\bar{u}} + \ldots}{1 + 0.053\,\tilde{C}^V_{u\bar{u}} + \ldots}\right] \left(5.6^{+0.8}_{-1.0}\right)\,\%\,,$$

- SM-like forward-backward asymmetry
- NLO corrections are important
- Small corrections generically negative (for positive $\tilde{C}^V_{u\bar{u}}$)
- Not very sensitive to realization of EW-, Higgs- and fermion sectors

RS Contributions to $A_{\rm FB}^t$: NLO

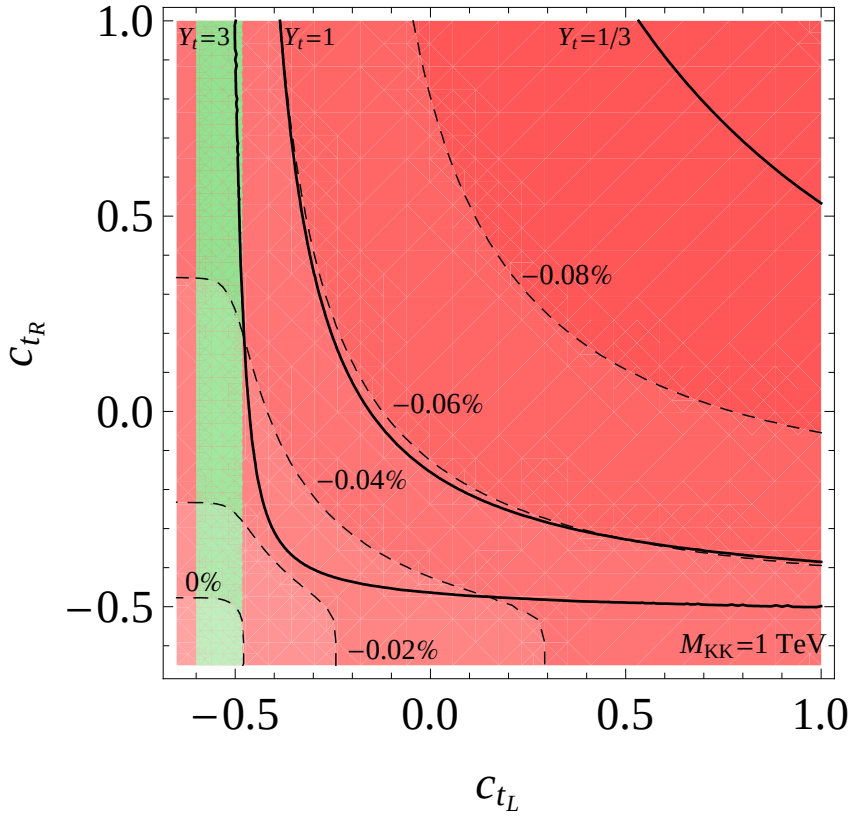
c_{t_L}	c_{t_R}	$\tilde{C}_{u\bar{u}}^V/\alpha_s$	$\tilde{C}_{u\bar{u}}^A/\alpha_s$	$\tilde{C}_{d\bar{d}}^V/\alpha_s$	$\tilde{C}_{d\bar{d}}^A/\alpha_s$	$\tilde{C}_{t\bar{u}}^V/\alpha_s$	$\tilde{C}_{t\bar{u}}^S$
-0.41	0.09	4.50	$0.71 \cdot 10^{-2}$	0.68	$-1.40 \cdot 10^{-3}$	$-1.35 \cdot 10^{-4}$	$8.2 \cdot 10^{-7}$
-0.47	0.48	4.95	$0.22 \cdot 10^{-2}$	0.27	$-0.03 \cdot 10^{-3}$	$-0.70 \cdot 10^{-4}$	$4.1 \cdot 10^{-7}$
-0.49	0.90	5.31	$1.79 \cdot 10^{-2}$	0.08	$-0.64 \cdot 10^{-3}$	$-2.45 \cdot 10^{-4}$	$122 \cdot 10^{-7}$

$\tilde{C}_{q\bar{q}}^P \equiv 1\,\mathrm{TeV}^2\, C_{q\bar{q}}^P$, $\tilde{C}_{t\bar{u}}^V \equiv 1\,\mathrm{TeV}^2\,(1/3\, C_{t\bar{u},\parallel}^{(V,8)} - 2\, C_{t\bar{u},\parallel}^{(V,1)})$, scale as $(1\,\mathrm{TeV}/M_{\rm KK})^2$ $\left((1\,\mathrm{TeV}/M_{\rm KK})^4\right)$

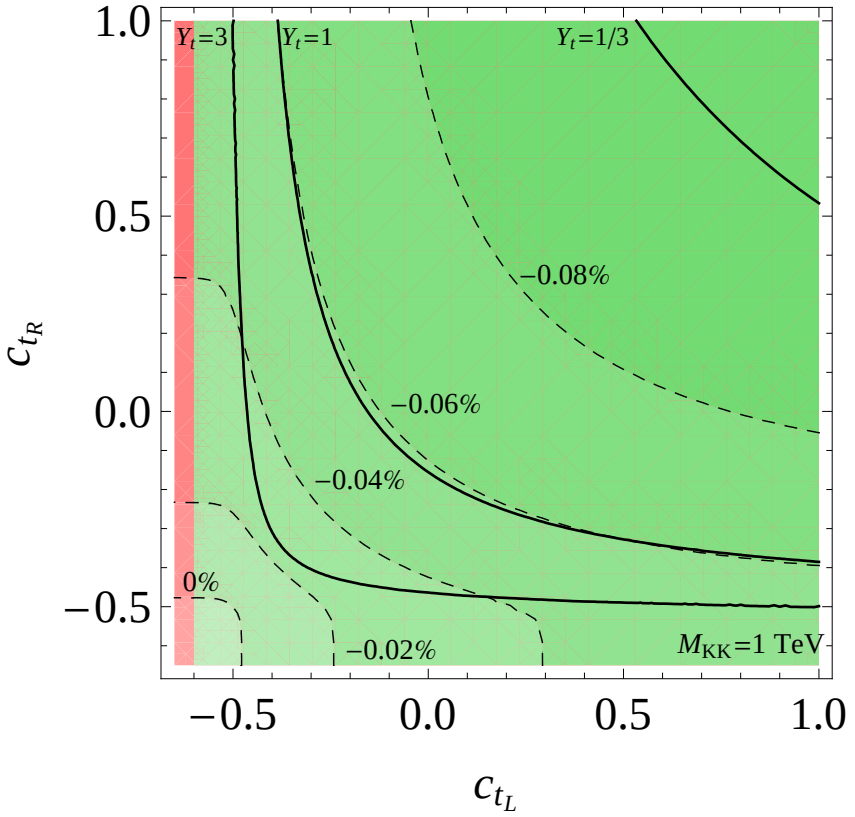
$$(A_{\rm FB}^t)_{\rm RS}^{p\bar{p}} = \left[\frac{1 + 0.22\,\tilde{C}_{u\bar{u}}^A + 0.034\,\tilde{C}_{u\bar{u}}^V + \ldots}{1 + 0.053\,\tilde{C}_{u\bar{u}}^V + \ldots}\right] \left(5.6^{+0.8}_{-1.0}\right)\,\%\,,$$

- SM-like forward-backward asymmetry
- NLO corrections are important
- Small corrections generically negative (for positive $\tilde{C}_{u\bar{u}}^V$)
- Not very sensitive to realization of EW-, Higgs- and fermion sectors
- RS model as a prototype: considerations hold for general class of models with new heavy vector states with suppressed axial-vector couplings to light quarks and suppressed FCNCs

RS Contributions to A_{FB}^t: NLO



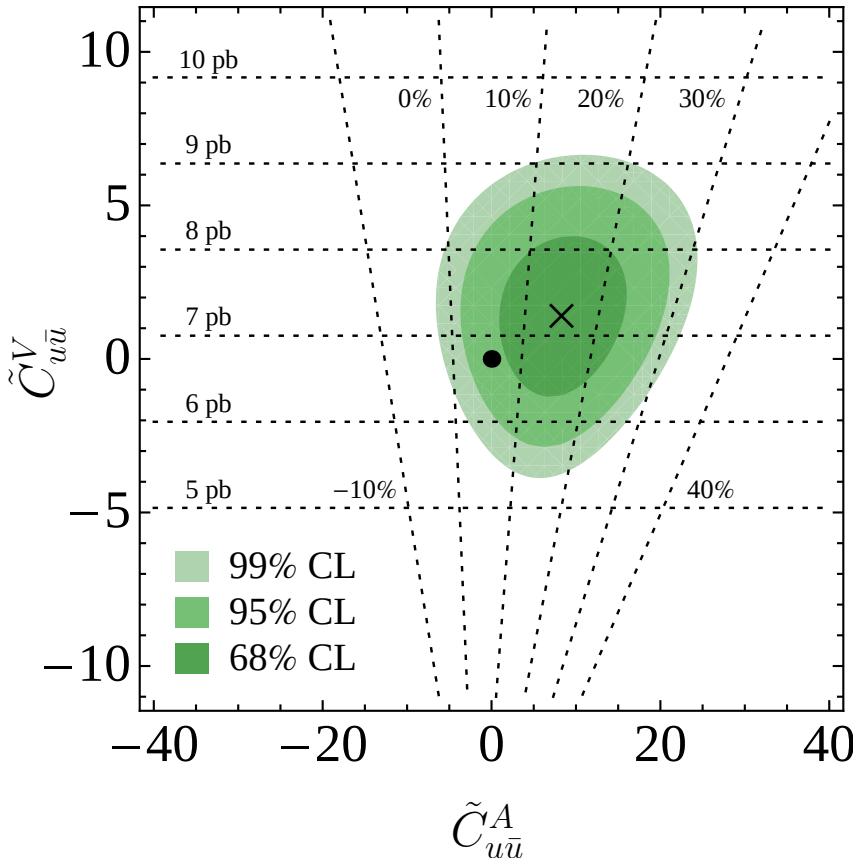
SM gauge group



custodial model

- Red: excluded by $Z \to b\bar{b}$
- RG running from M_{KK} to m_t, $\mu_r = \mu_f = m_t = 173.1\ \mathrm{GeV}$, $\alpha_s(m_t) = 0.126$

Combined Experimental Constraints



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- $\tilde{C}^V_{u\bar{u}}$ constrained by $\sigma_{t\bar{t}}$ and $\frac{d\sigma_{t\bar{t}}}{dM_{t\bar{t}}}$
- Need sizable axial-vector contributions with different signs (or sizable FCNCs) to explain discrepancy

$$(\sigma_{t\bar{t}})_{\mathrm{exp}} = (7.50 \pm 0.31_{\mathrm{sta.}} \pm 0.34_{\mathrm{sys.}} \pm 0.15_{\mathrm{lu.}})\ \mathrm{pb}; \quad \left(\frac{\mathrm{d}\sigma_{\mathrm{t\bar{t}}}}{\mathrm{dM_{t\bar{t}}}}\right)^{[0.8,1.4]\ \mathrm{TeV}}_{\mathrm{exp}} = (0.068 \pm 0.032_{\mathrm{sta.}} \pm 0.015_{\mathrm{sys.}} \pm 0.004_{\mathrm{lu.}})\ \frac{\mathrm{fb}}{\mathrm{GeV}}$$

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CDF Collaboration, Conference Note 9913; CDF Collaboration, 0903.2850

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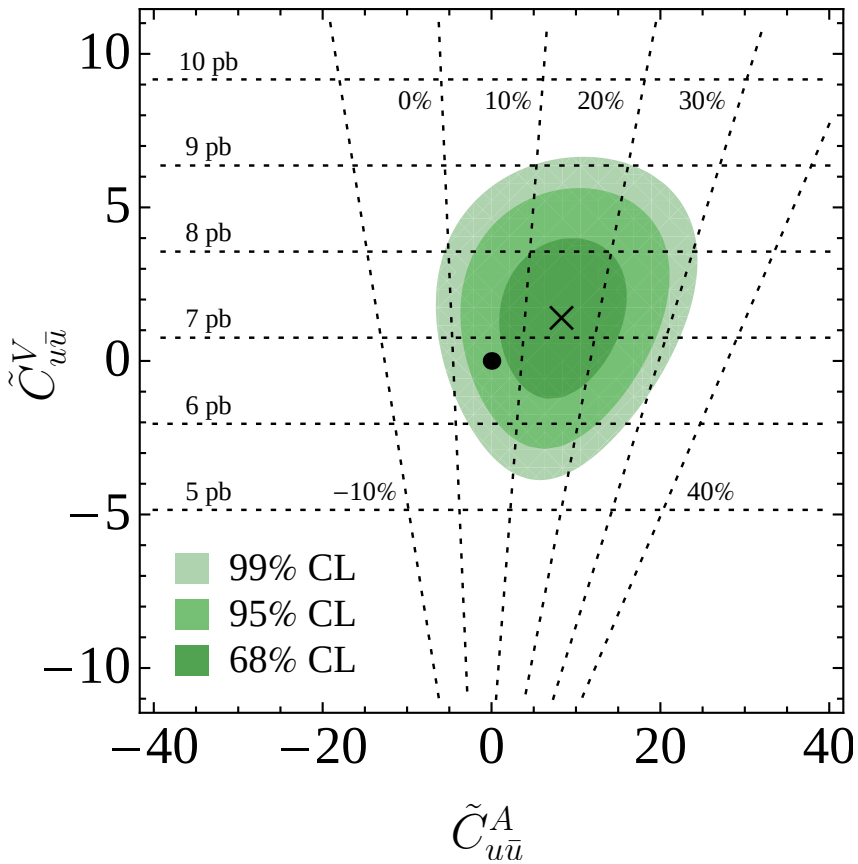

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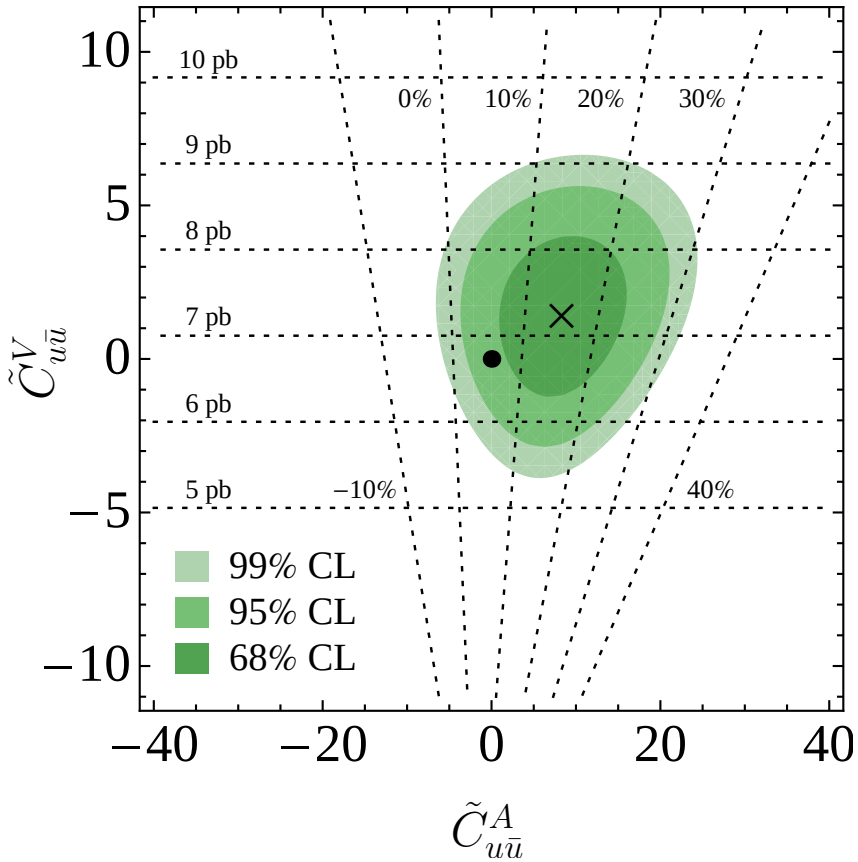

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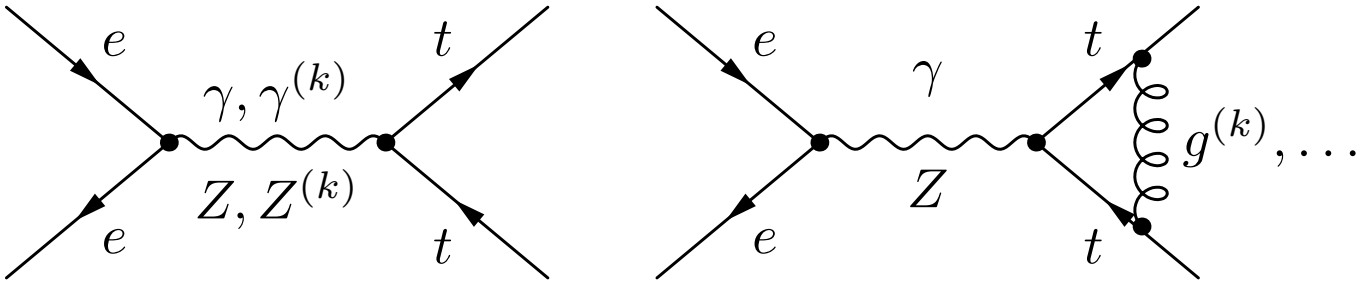

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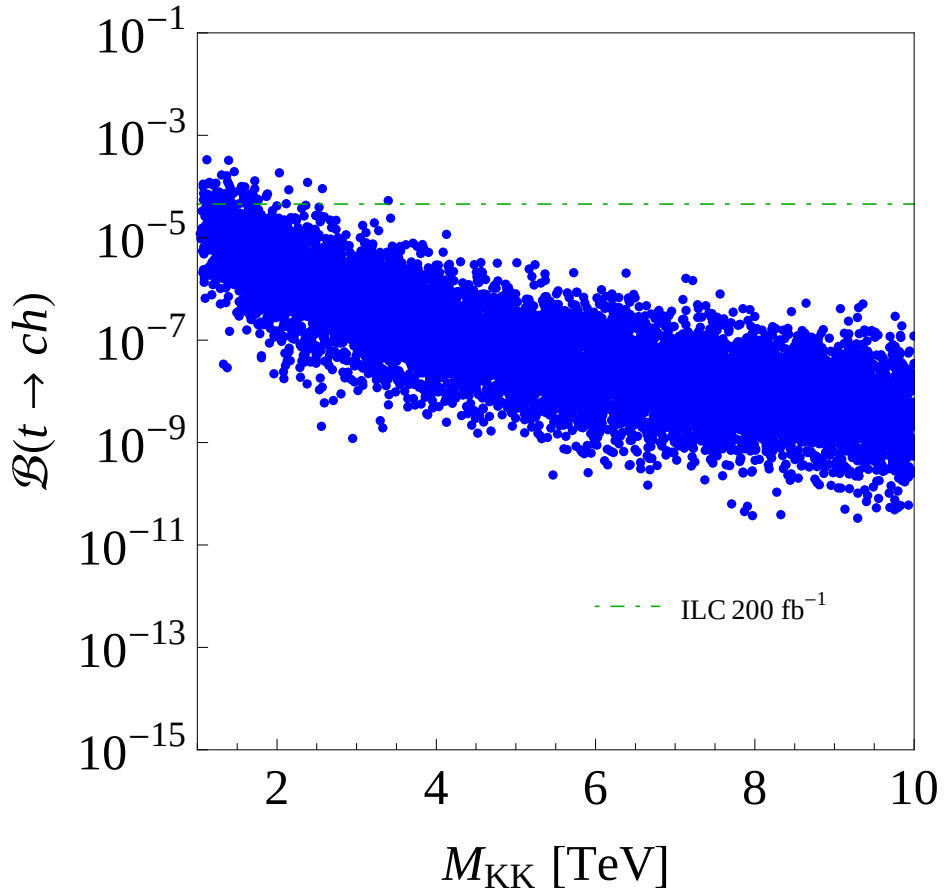
Rare Top Decays

Significant effects possible in $t \longrightarrow c\,Z$ and $t \longrightarrow ch$



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Summary

Thank you for your attention!

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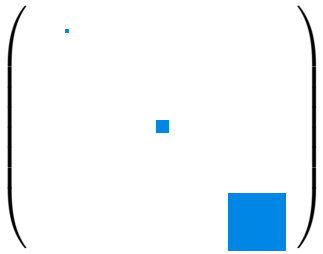

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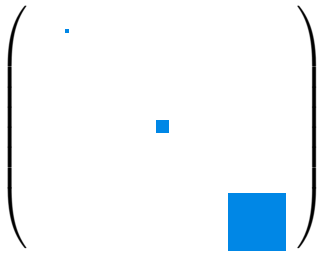

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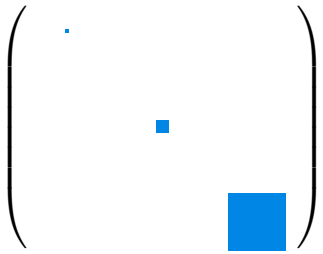

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one-to-one correspondence to Froggatt-Nielsen mechanism

Froggatt, Nielsen, Nucl. Phys. B 147, 277 (1979)
S. Casagrande, FG, U. Haisch, M. Neubert, T. Pfoh, 1005.4315

Backup: Custodial Protection

Implement custodial protection by extending the SM gauge group

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \times P_{LR}$$

- $SU(2)_R \times U(1)_X \xrightarrow{\text{UV}} U(1)_Y$
- P_{LR} : interchange $SU(2)_L \leftrightarrow SU(2)_R$
- T parameter protected
- $b_L \in (2,2)_{2/3} \rightarrow Zb_L\bar{b}_L$ protected

Agashe, Delgado, May, Sundrum, hep-ph/0308036,

Agashe, Contino, Da Rold, Pomarol, hep-ph/0605341

alternative option: heavy Higgs, Casagrande, FG, Haisch, Neubert, Pfoh, 0807.4937

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