The Quest for Extra Dimensions.

The Impact of Universal Extra Dimension on the Unitarity Triangle and Rare Decays

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In collaboration with:

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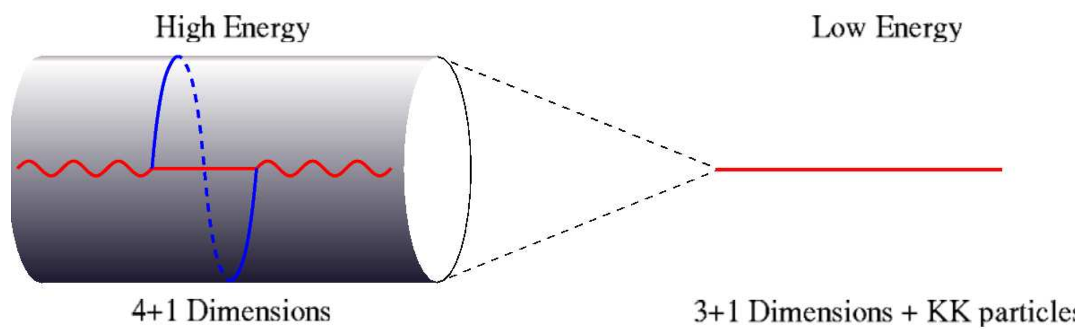
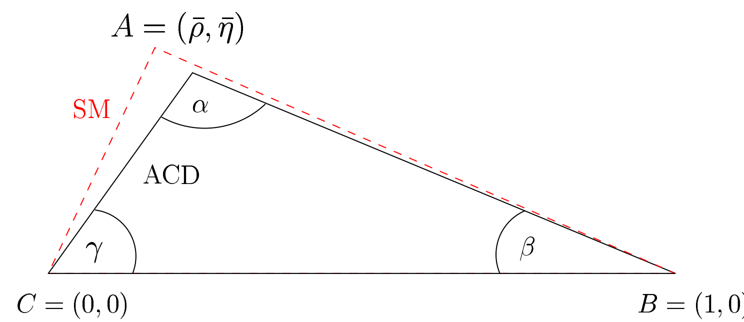
Overview

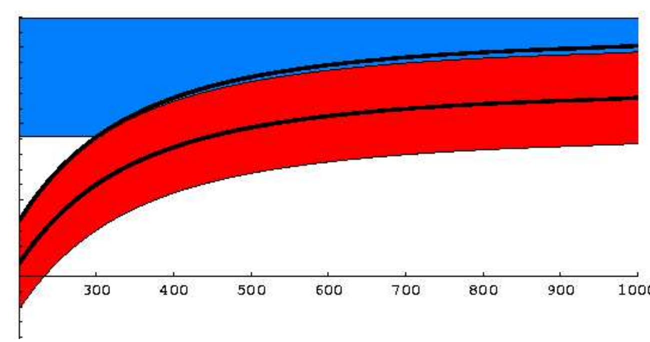
- Introduction to the model



- Impact on the unitarity triangle



- Predictions for rare decays



- Conclusions and outlook

Introduction to the model

Kaluza (1921) and Klein (1926)
Unification of gravity and electrodynamics in $D = 5$ compactified on S^1.

Some extra dimensional Models:

- brane world: SM on brane, gravity in the bulk, localization mechanism
- gravity and gauge bosons in bulk, fermions on brane $R^{-1} >$ few TeV, localization mechanism
- Universal extra dimensions (UED): everything in the bulk, no localization mechanism required, gravity not considered

ACD Model

Appelquist, Cheng, and Dobrescu (ACD)

hep-ph/0012100

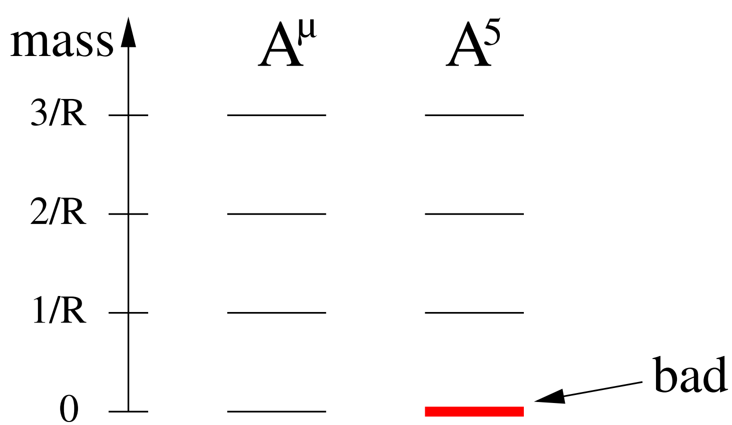
- All SM fields live in the bulk $D = 4 + 1$, Gravity not considered.
- Orbifold: Replace S^1 by S^1/Z_2
- Simple extension of SM, 1 extra parameter (R, radius of ED), boundary terms set to zero
- provides excellent dark-matter candidate
  Servant,Tait '02; Cheng,Feng,Matchev '02
- bounds on $1/R$ are rather weak
  $1/R \gtrsim 250$ GeV, $M_H > 250$ GeV,
  $1/R \gtrsim 300$ GeV, $M_H < 250$ GeV. Appelquist,Yee '02

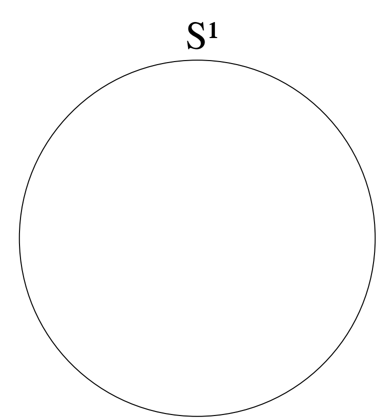
S^1 as the extra dimension

Extra dimension is compact. Kaluza-Klein Expansion, many new $4D$ fields with masses n/R ($x = x^\mu, \mu = 0, \ldots, 3$; $y = x^5$)

$$A^\mu(x,y) = \underbrace{A^\mu_{(0)}(x)}_{good} + \sum_{n=1}^{\infty} \left[A^\mu_{(n)}(x) \cos\frac{ny}{R} + A^\mu_{(n)}(x) \sin\frac{ny}{R} \right],$$

$$A^5(x,y) = \underbrace{A^5_{(0)}(x)}_{bad} + \sum_{n=1}^{\infty} \left[A^5_{(n)}(x) \cos\frac{ny}{R} + A^5_{(n)}(x) \sin\frac{ny}{R} \right].$$





Orbifold S^1/Z_2

Compactify on Orbifold S^1/Z_2 instead. Identify $y \leftrightarrow -y$ and thus require $A_\mu(-y) = A_\mu(y)$ and $A_5(-y) = -A_5(y)$.

$$
\begin{aligned}
A^\mu(x,y) &= A^\mu_{(0)}(x) + \sum_{n=1}^{\infty} \left[A^\mu_{(n)}(x) \cos\frac{ny}{R} + \cancel{A^\mu_{(n)}(x) \sin\frac{ny}{R}} \right], \\
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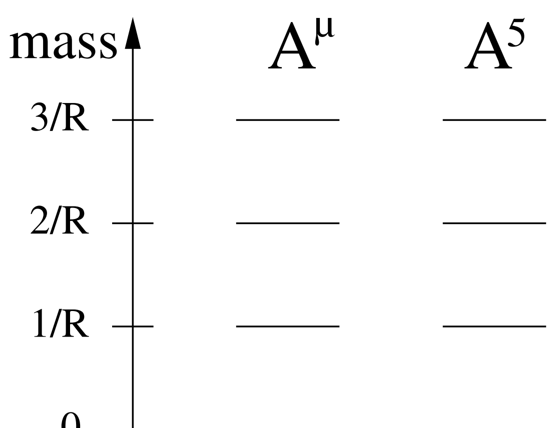
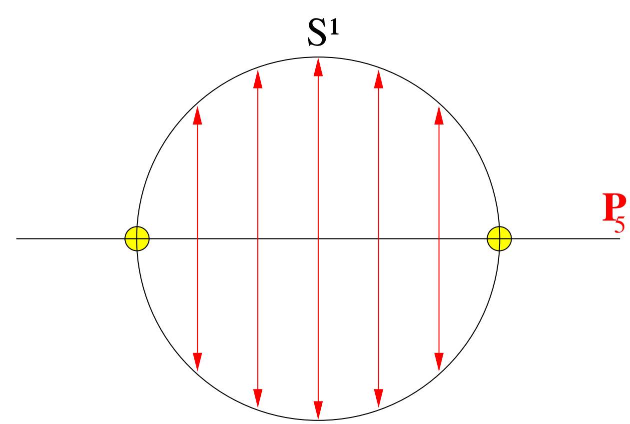
$$





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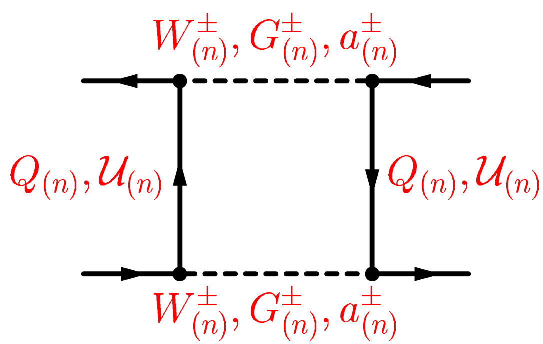
- Same mechanism in fermion representation involving γ_5 $\rightarrow 4D$ chiral theory
- Continuous translational symmetry in y direction broken, remnant $y \rightarrow y + \pi R$ gives KK parity (similar to R parity in the MSSM).
- Many similarities to MSSM:
  KK particles $\leftrightarrow$ Superpartners, LKP $\leftrightarrow$ LSP,
  bosonic ED $\leftrightarrow$ fermionic ED
  but: KK spectrum highly degenerate, infinite towers of extra particles, UV completion necessary for $\Lambda \gg 1/R$

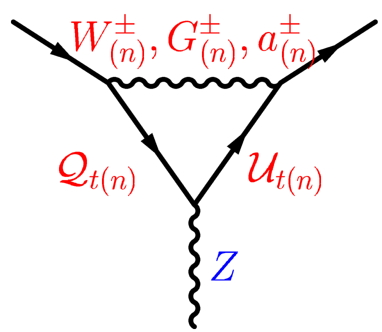
Strategy of the calculation

- Fields: replica of SM with masses $m^2_{(n)} = m^2_{\rm SM} + \frac{n^2}{R^2}$
  + charged scalar $a^\pm$ (from $5^{\rm th}$ component of $W^\pm_M$).
- KK parity: No tree level contributions.
- MFV model, no new relevant operators compared to SM
  calculate corrections to Inami-Lim functions
  $F(x_t, 1/R) = \underbrace{F_0(x_t)}_{SM} + \sum_n F_n(x_t, \frac{n}{R})$

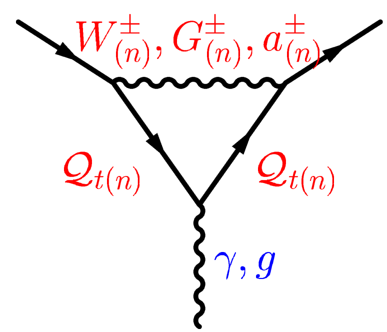
$$F = S, B, C, D, D', E, E'$$



S,B



C



γ: D,D', g: E,E'

Impact on the unitarity triangle (UT)

SM and ACD have common universal UT (UUT).

1. R_t from ΔM_d and ΔM_s:

$$\boxed{R_t = 0.87\sqrt{\frac{\Delta M_d}{0.50/\text{ps}}}\sqrt{\frac{18.4/\text{ps}}{\Delta M_s}}\left[\frac{\xi}{1.18}\right], \xi = \frac{\sqrt{\hat{B}_s}F_{B_s}}{\sqrt{\hat{B}_d}F_{B_d}}, \Delta M_s > 14.4/\text{ps} \text{ @ } 95\%\text{C.L.}}$$

No $1/R$ dependence.

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No $1/R$ dependence.

2. $B_d^0 - \bar{B}_d^0$ Mixing only:

$$R_t = 0.86\left[\frac{0.041}{|V_{cb}|}\right]\sqrt{\frac{\Delta M_d}{0.051/ps}}\left[\frac{230\,\text{MeV}}{\sqrt{\hat{B}_d}F_{B_d}}\right]\sqrt{\frac{0.55}{\eta_B^{QCD}}}\sqrt{\frac{2.4}{S(x_t,1/R)}}$$

but here: $S(x_t, 1/R)^{ACD} \neq S_0(x_t)^{SM} = 2.4$,

Impact on the unitarity triangle (UT)

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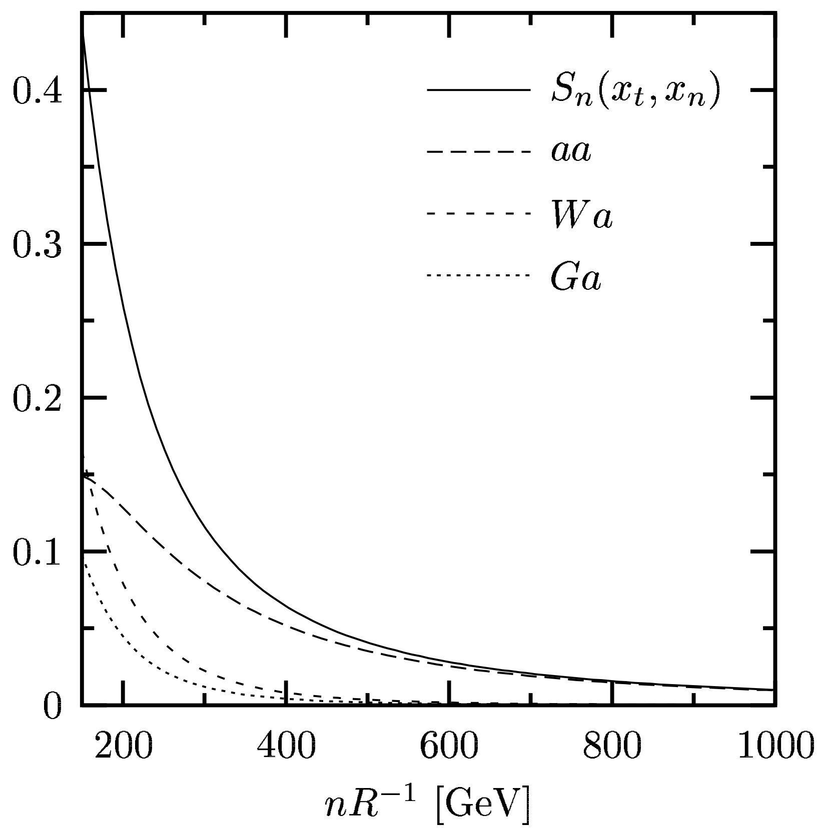

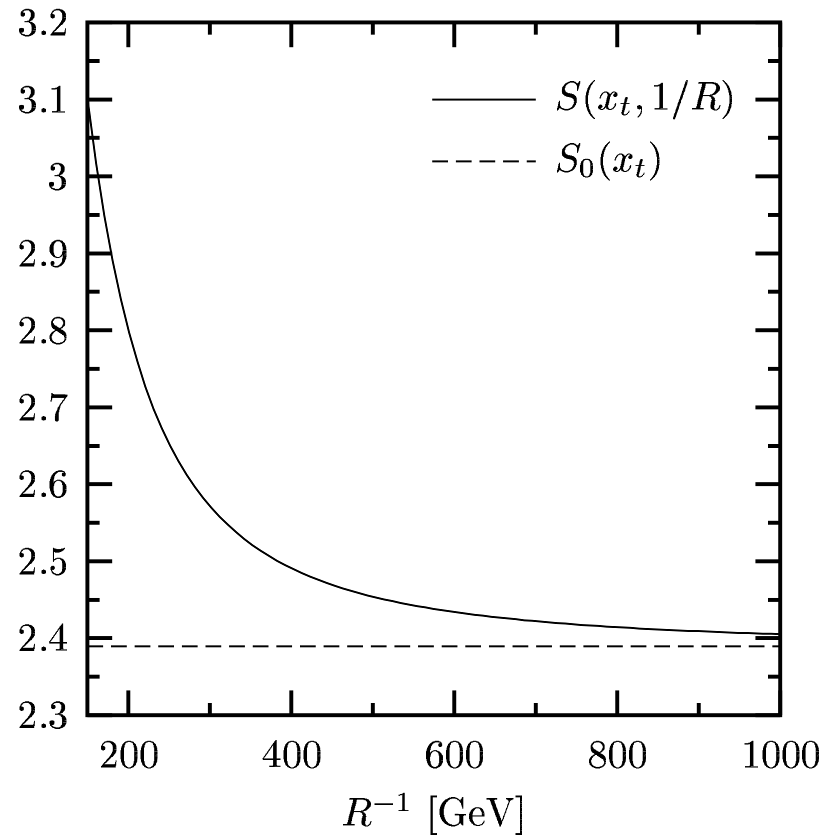

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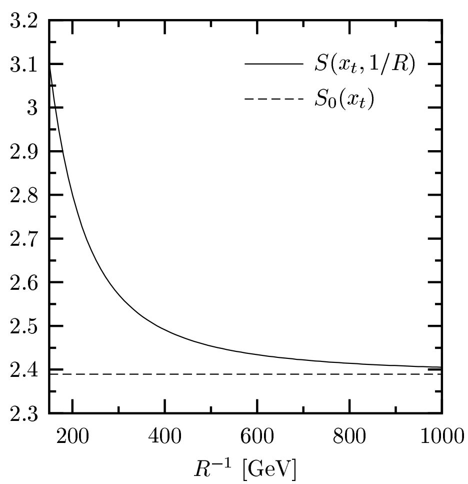

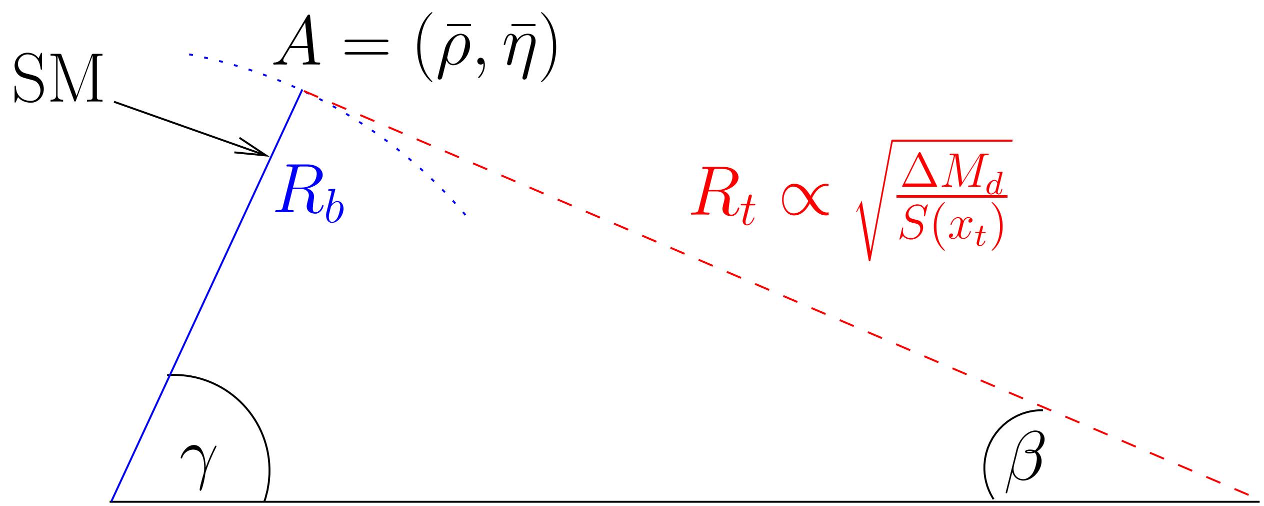

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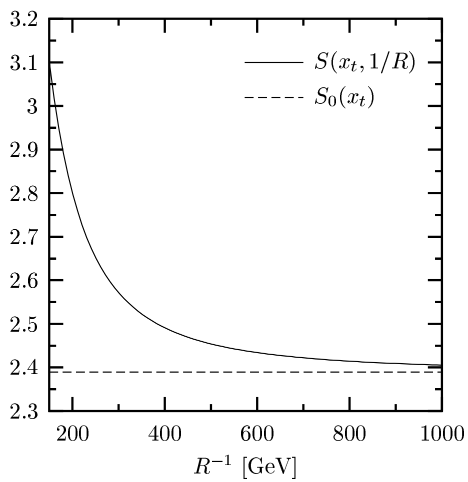
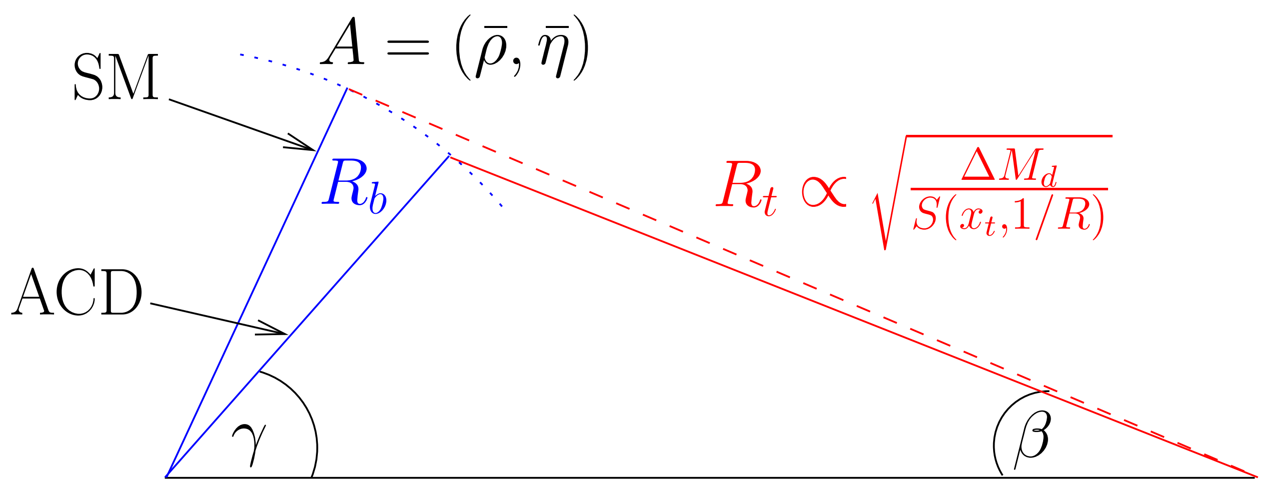




$1/R = 200$ GeV : $\gamma_{\mathrm{SM}} = 65^\circ \rightarrow \gamma_{\mathrm{ACD}} = 49^\circ$

$1/R = 300\ (400)$ GeV : $\gamma_{\mathrm{ACD}} = 60^\circ\ (63^\circ)$

CKM fit

	ACD ($1/R = 200\,\mathrm{GeV}$)	SM
$\bar{\eta}$	0.342 ± 0.027	0.357 ± 0.027
	$(0.288 - 0.398)$	$(0.305 - 0.411)$
$\bar{\rho}$	0.197 ± 0.047	0.173 ± 0.046
	$(0.102 - 0.296)$	$(0.076 - 0.260)$
$\sin 2\alpha$	-0.23 ± 0.25	-0.09 ± 0.25
	$(-0.70 - 0.27)$	$(-0.54 - 0.40)$
γ	59.5 ± 7.0	63.5 ± 7.0
(degrees)	$(45.3 - 74.8)$	$(51.0 - 79.0)$
ΔM_s	$18.6^{+1.9}_{-1.5}$	$18.0^{+1.7}_{-1.5}$
(ps^{-1})	$(15.7 - 26.2)$	$(15.4 - 21.7)$
$\lvert V_{td}\rvert$ (10^{-3})	7.80 ± 0.42	8.15 ± 0.41
	$(6.96 - 8.69)$	$(7.34 - 8.97)$

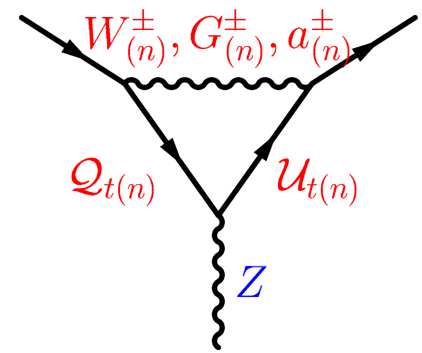
Rare Decays - Z_0 Penguin

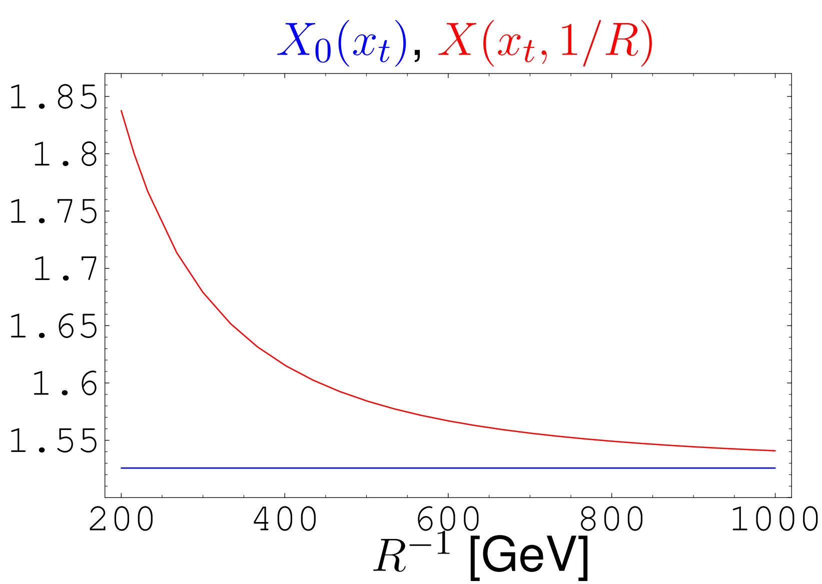
$K^+ \to \pi^+ \nu\bar{\nu}$
$K^+ \to \pi^0 \nu\bar{\nu}$
$B \to X_{s,d} \nu\bar{\nu}$

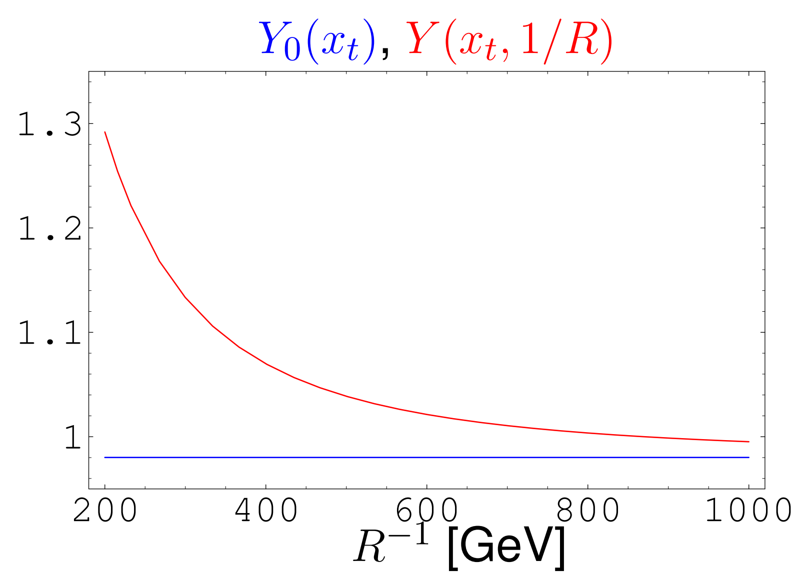
$$X = \underbrace{X_0(x_t)}_{C_0(x_t) - 4B_0(x_t)} + \sum_n C_n(x_t, n/R)$$

$B_{s,d} \to \mu^+\mu^-$
$K_L \to \mu^+\mu^-$

$$Y = \underbrace{Y_0(x_t)}_{C_0(x_t) - B_0(x_t)} + \sum_n C_n(x_t, n/R)$$







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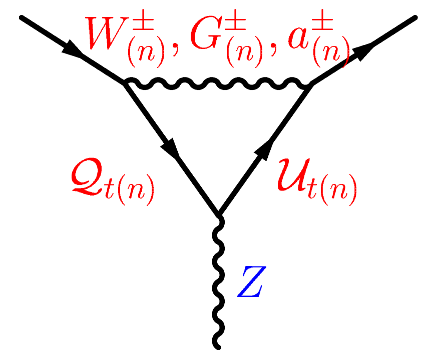

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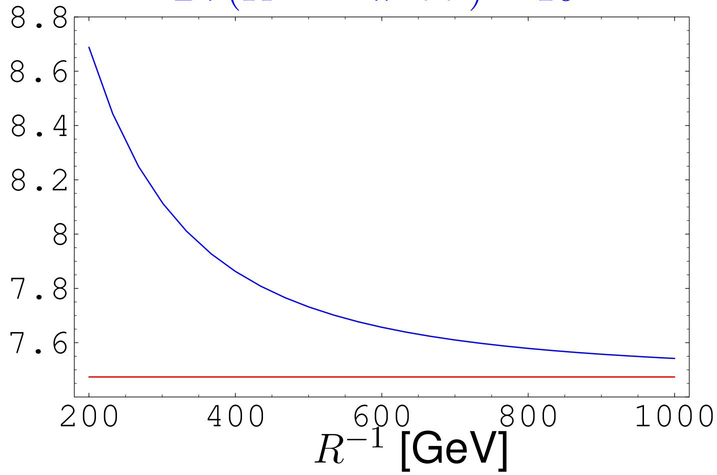
Enhancements at $1/R = 200\ (300)$ GeV

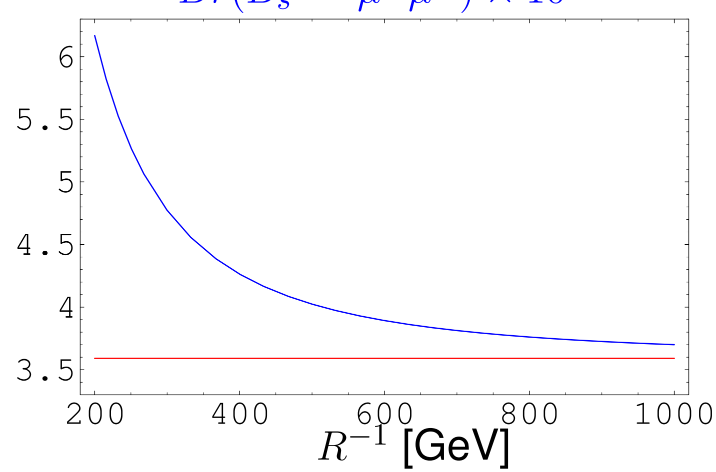
$Br(K^+ \to \pi^+\nu\bar{\nu}) \propto |\mathrm{Charm} + V_{td}X|^2 \to 16\ (9)\%$

$Br(K^+ \to \pi^+\nu\bar{\nu}) \times 10^{11}$



$Br(B_s \to \mu^+\mu^-) \propto |V_{ts}Y|^2 \to 72\ (33)\%$

$Br(B_s \to \mu^+\mu^-) \times 10^9$



Rare Decays - Z_0 Penguin

Enhancements at $1/R = 200\ (300)$ GeV

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) \propto |\mathrm{Charm} + V_{td}X|^2 \to 16\ (9)\%$$
$$Br(B \to X_d \nu\bar{\nu}) \propto |V_{td}X|^2 \to 17\ (10)\%$$
$$Br(K_L \to \mu^+\mu^-) \propto |\mathrm{Charm} + V_{td}Y|^2 \to 22\ (12)\%$$
$$Br(B \to X_s \nu\bar{\nu}) \propto |V_{ts}X|^2 \to 44\ (21)\%$$
$$Br(B_d \to \mu\bar{\mu}) \propto |V_{td}Y|^2 \to 46\ (23)\%$$
$$Br(B_s \to \mu\bar{\mu}) \propto |V_{ts}Y|^2 \to 72\ (33)\%$$

$$\Delta M_s \propto |V_{ts}|^2\, S \to 17\ (8)\%$$

Rare Decays - Z_0 Penguin

$1/R$	200 GeV	250 GeV	300 GeV	400 GeV	SM
$Br(K^+ \to \pi^+ \nu\bar{\nu}) \times 10^{11}$	8.70	8.36	8.13	7.88	7.49
$Br(K_{\mathrm{L}} \to \pi^0 \nu\bar{\nu}) \times 10^{11}$	3.26	3.17	3.09	2.98	2.80
$Br(K_{\mathrm{L}} \to \mu^+\mu^-)_{\mathrm{SD}} \times 10^{9}$	1.10	1.00	0.95	0.88	0.79
$Br(B \to X_s \nu\bar{\nu}) \times 10^{5}$	5.09	4.56	4.26	3.95	3.53
$Br(B \to X_d \nu\bar{\nu}) \times 10^{6}$	1.80	1.70	1.64	1.58	1.47
$Br(B_s \to \mu^+\mu^-) \times 10^{9}$	6.18	5.28	4.78	4.27	3.59
$Br(B_d \to \mu^+\mu^-) \times 10^{10}$	1.56	1.41	1.32	1.22	1.07

Rare Decays - γ, G magnetic Penguins

Suppression of γ-magnetic and chromo-magnetic penguins.

$$
\begin{aligned}
\bar{s}\gamma' b &= i\bar{\lambda}_t \frac{G_\mathrm{F}}{\sqrt{2}} \frac{e}{8\pi^2} D'(x_t, 1/R) \bar{s}[i\sigma_{\mu\lambda} q^\lambda [m_b(1+\gamma_5)]]b\,, \\
\bar{s}G'^a b &= i\bar{\lambda}_t \frac{G_\mathrm{F}}{\sqrt{2}} \frac{g_s}{8\pi^2} E'(x_t, 1/R) \bar{s}_\alpha[i\sigma_{\mu\lambda} q^\lambda [m_b(1+\gamma_5)]]T^a_{\alpha\beta} b_\beta\,.
\end{aligned}
$$

Work in progress...

Suppressed:
$B \to X_s \mathrm{gluon}$,
$B \to X_s \gamma$,
ϵ'/ϵ

Enhanced:
$K_L \to \pi^0 e^+ e^-$,
$B \to X_s l^+ l^-$

Comparison with other models

	ACD	MSSM large $\tan\beta$	MSSM low $\tan\beta$
$Br(K^+ \to \pi^+ \nu\bar{\nu})$	$\uparrow$	no effect	$\Downarrow$
$Br(K_{\rm L} \to \pi^0 \nu\bar{\nu})$	$\uparrow$	no effect	$\Downarrow$
$Br(B_s \to \mu^+\mu^-)$	$\Uparrow$	$\Uparrow\Uparrow\Uparrow$	$\Uparrow\Downarrow$
ΔM_s	$\uparrow$	$\Downarrow$	$\Uparrow$

Compare to:

Cheng, Matchev, Schmaltz - Bosonic supersymmetry? Getting fooled at the LHC, hep-ph/0205314

Conclusions and Outlook

- Relatively small impact on UT, impossible to see difference in view of hadronic uncertainties
- For $1/R = 250$ GeV consistent with present data of $K^+ \to \pi^+\nu\bar{\nu}$, $B \to X_{s,d}\nu\bar{\nu}$, $B_{s,d} \to \mu^+\mu^-$ and $\Delta M_{s,d}$

  ($\Delta M_{s,d}$ result verified by Chakraverti, Huitu and Kundu '02; dominant term of the Z_0 penguin verified by Oliver, Papavassiliou, Santamaria '02)
- Enhancement of $Br(K^+ \to \pi^+\nu\bar{\nu})$ could be welcome
- Analysis of $B \to X_s\gamma$, $B \to X_s\mathrm{gluon}$, $B \to X_s l^+l^-$ and ϵ'/ϵ in progress

The End

Thank you for your interest!

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Credits:

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