Flavor physics in Universal Extra Dimensions

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Overview

- Introduction to Extra Dimensions
- UED scenario
- Predictions for rare decays
- $B \to X_s\gamma$, $B \to X_s g$ and $B \to X_s\mu^+\mu^-$
- Conclusions

Extra Dimensions

Extra Dimensions provide possible solutions to problems of the SM.

- Hierarchy problem: EW scale $\leftrightarrow$ Planck scale
- Gauge unification
- Fermion mass hierarchy and mixing matrices
- Dark matter

Many models on the market, none solves all of these problems (in a "natural" way).

Additional motivation by string theory.

Extra Dimensions

Many different scenarios

- # of dimensions
- Geometry of compactification $\rightarrow$ orbifolding / size / metric
- Particle content in ED
- SUSY / non-SUSY

Three major types of models

- Warped ED - Randall, Sundrum (RS)
- Large ED - Arkani-Hamed, Dimopoulos, Dvali (ADD)
- Universal ED - Appelquist, Cheng, Dobrescu (UED)

ED vs. MSSM

ED are not all that different from the MSSM

ED	MSSM
bosonic extra dimensions	fermionic extra dimensions
KK excitations	superpartners
LKP	LSP
brane terms	SUSY breaking parameters
abundance of models	SUSY breaking mechanisms, NMSSM etc.
non-renormalizable $\rightarrow$ cut-off dependence but: Dimensional Deconstruction (DD)	renormalizable

Effective theories valid up to a cut-off scale!

Universal Extra Dimensions

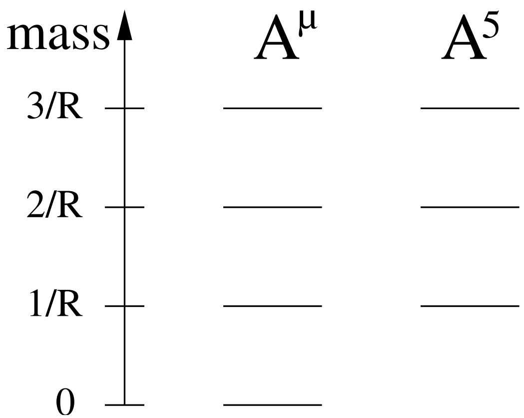
- One flat extra dimension; all SM fields live in the bulk $D = 4 + 1$
- Simple extension of SM, 1 extra parameter (radius of ED: R), boundary terms set to zero
- Chiral fermions $\rightarrow$ orbifold compactification S^1/Z_2
- KK mode expansions of fields
  Zero modes: SM particles; higher modes: KK excitations
- Bounds from electroweak precision measurements are rather weak
  $1/R \gtrsim 250$ GeV, $M_H > 250$ GeV, $1/R \gtrsim 300$ GeV, $M_H < 250$ GeV
  Appelquist,Yee '02
- LKP: excellent dark-matter candidate Servant,Tait '02; Cheng,Feng,Matchev '02

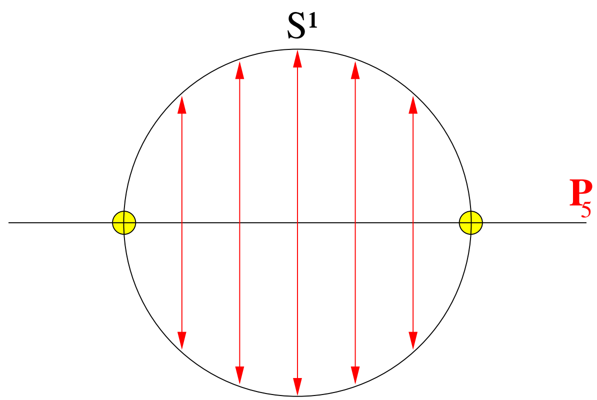
Orbifold S^1/Z_2

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

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

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





Orbifold S^1/Z_2

- Similar mechanism for fermions involving $\gamma_5 \rightarrow 4D$ chiral theory
- Continuous translational symmetry in y direction broken. Discrete symmetry left: KK parity $y \rightarrow y + \pi R$ / $y \rightarrow \pi R$ - y (similar to R parity in the MSSM).
- KK spectrum highly degenerate, infinite towers of extra particles, UV completion necessary for $\Lambda \gg 1/R$
- The compactification yields a discrete and uniform mass spectrum for the KK modes:

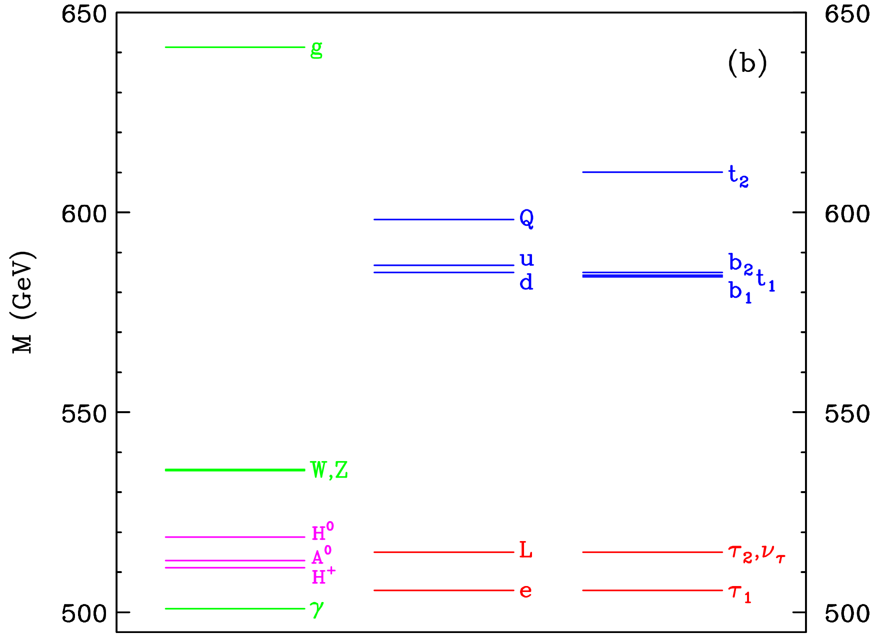
$$\partial_5 \Phi(x, y) \longrightarrow m_{(n)}^{\mathrm{KK}} = \frac{n}{R}$$

- Together with Yukawa mass terms:

$$m_{(n)}^2 = m_0^2 + \frac{n^2}{R^2}$$

Kaluza-Klein masses

Degeneracy lifted by loop corrections Cheng,Matchev,Schmaltz '02

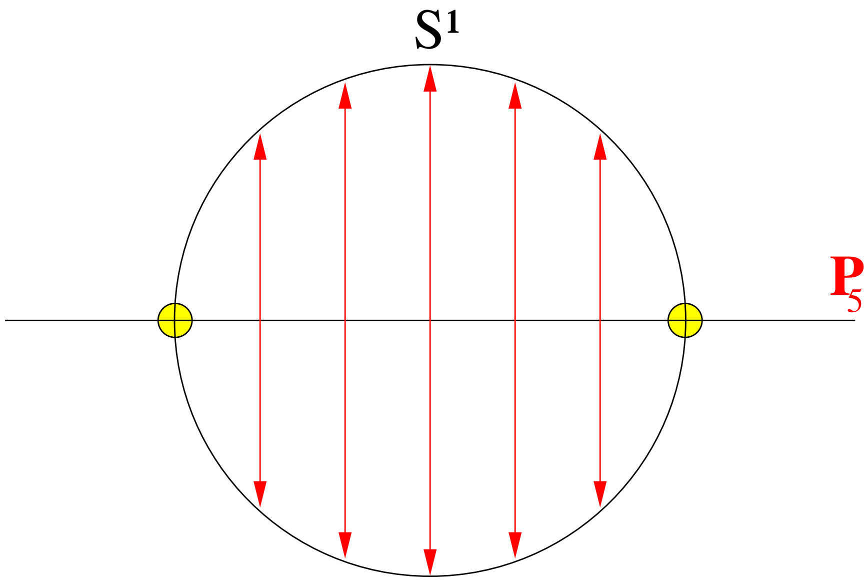


Assumptions:

- $R^{-1} = 500$ GeV, $\Lambda R = 20$
- Brane terms zero at cut-off scale, only induced by radiative corrections

KK parity

KK parity: $y \longrightarrow y + \pi R$ / $y \longrightarrow \pi R$ - y. Reflection symmetry about the midpoint



KK parity

KK parity: $y \to y + \pi R$ / $y \to \pi R$ - y. Reflection symmetry about the midpoint

- Electroweak observables
- GIM removes sensitivity on cut-off
- Dark matter

Present in particular ED models:

- UED: with symmetric brane-localized interactions
- DD: difficult with chiral fermions, but restored in continuum limit
- RS: not generic, but realized in IR-UV-IR / UV-IR-UV setup
  Agashe, Falkowski, Low, Servant, arXiv:0712.2455

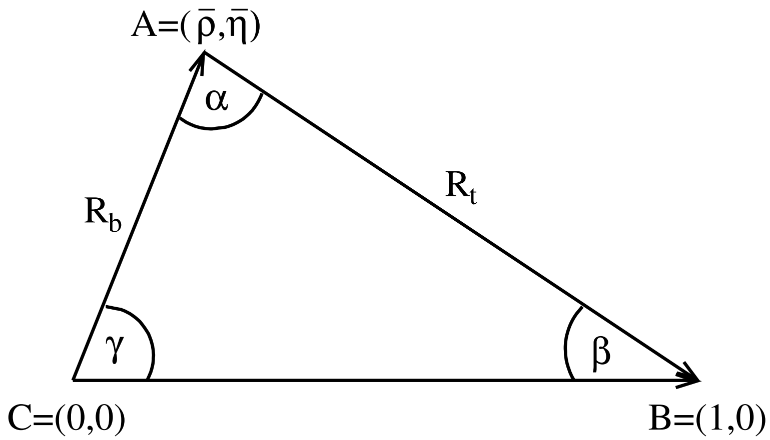
Flavor Physics

Transitions between different quark flavors are parametrized by Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Three mixing angles + one CP-violating complex phase.

Unitarity triangle



In the SM no Flavor Changing Neutral Currents (FCNC) at tree level.

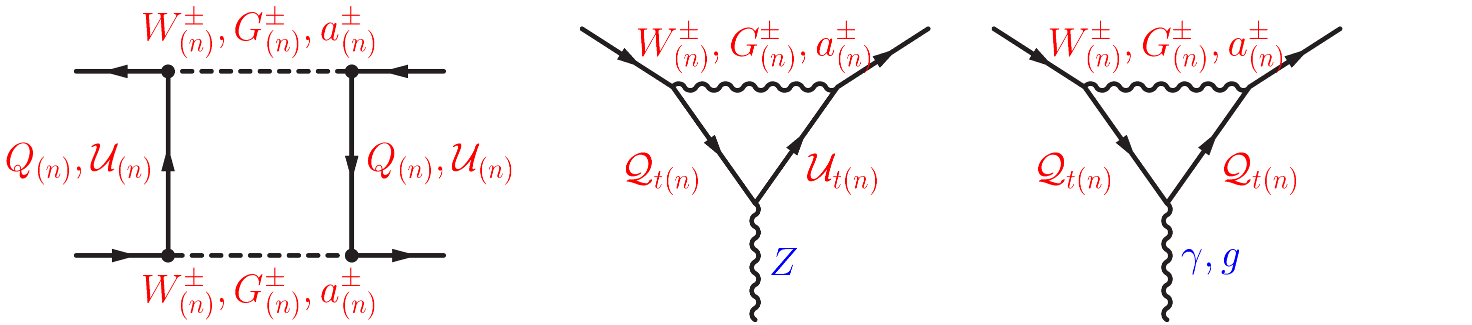
Flavor Physics in ED

- Bottom-up approach: Determine ED parameters (R) from flavor observables
- Top-down approach: Build models that explain fermion mass hierarchy and mixing:
  - GIM mechanism from Extra Dimensions
    Cacciapaglia, Csaki, Galloway, Marandella, Terninga,Weiler
    arXiv:0709.1714
  - Flavor from Minimal Flavor Violation & a viable Randall-Sundrum Model
    Fitzpatrick, Perez, Randall, arXiv:0710.1869

Strategy of calculations

- 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 # conserved at tree-level
- MFV model, GIM, no new relevant operators compared to SM, calculate corrections to Inami-Lims $F = S, C, E, D, D', E, E'$

$$F(x_t, 1/R) = \underbrace{F_0(x_t)}_{SM} + \underbrace{\sum_n F_n(x_t, \frac{n}{R})}_{UED}, \qquad F = S, B, C, \ldots$$

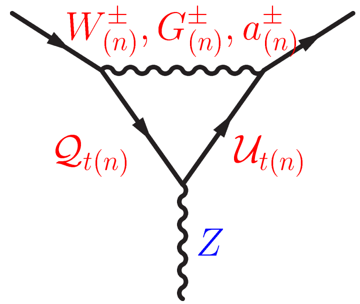


S,B   C γ: D,D', g: E,E'

Rare Decays - Z_0 Penguin

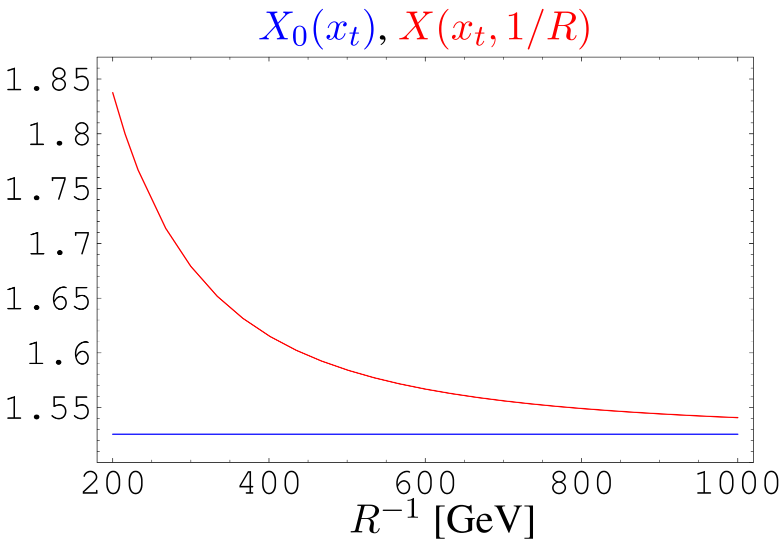
$$K^+ \to \pi^+ \nu\bar{\nu}$$
$$K^+ \to \pi^0 \nu\bar{\nu}$$
$$B \to X_{s,d} \nu\bar{\nu}$$

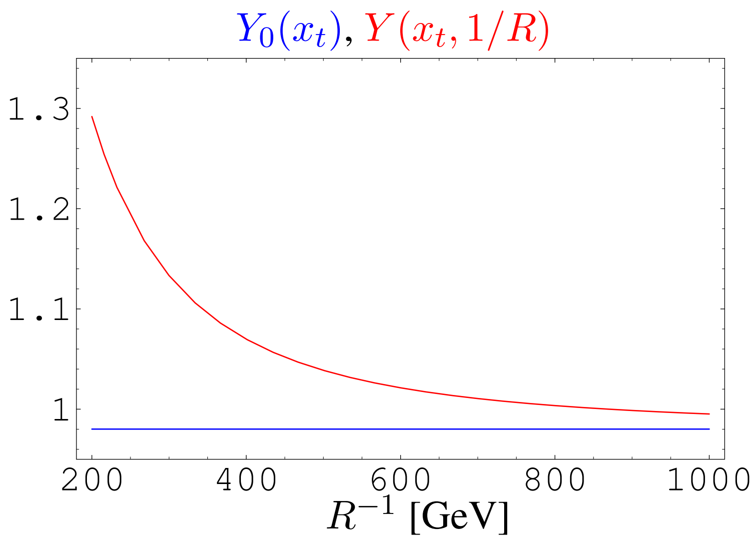
$$X = \underbrace{X_0(x_t)}_{C_0(x_t) - 4B_0(x_t)} + \sum_n C_n(x_t, n/R)$$



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

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





Buras, MS, Weiler, hep-ph/0212143

Rare Decays - Z_0 Penguin

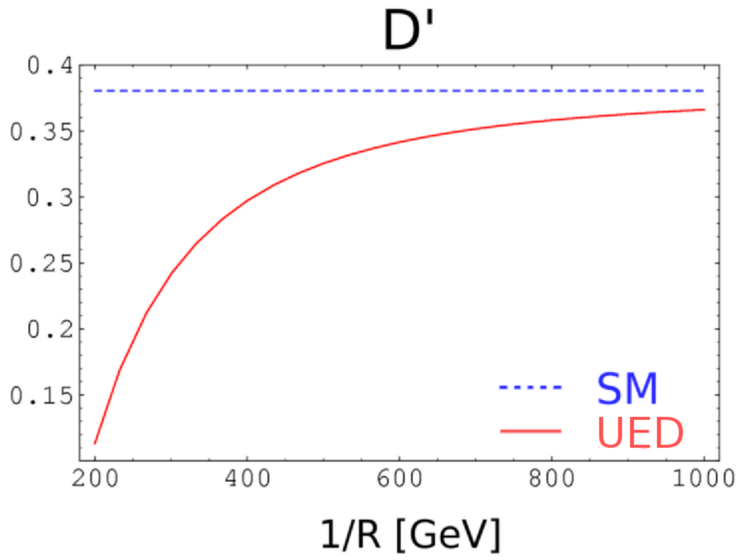
Enhancements at $1/R = 300$ GeV:

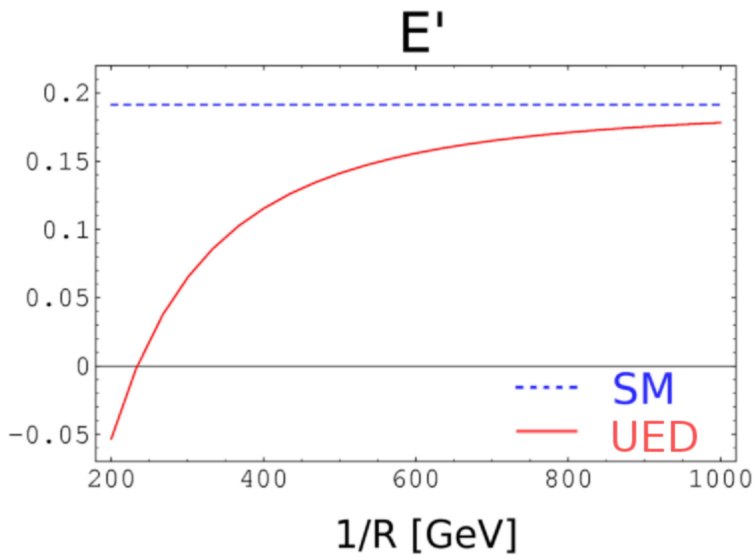
$$
\begin{aligned}
&Br(K^+ \to \pi^+ \nu\bar{\nu}) \propto |\text{Charm} + V_{td}X|^2 \to 9\% \\
&Br(B \to X_d \nu\bar{\nu}) \propto |V_{td}X|^2 \to 10\% \\
&Br(K_L \to \mu^+\mu^-) \propto |\text{Charm} + V_{td}Y|^2 \to 12\% \\
&Br(B \to X_s \nu\bar{\nu}) \propto |V_{ts}X|^2 \to 21\% \\
&Br(B_d \to \mu\bar{\mu}) \propto |V_{td}Y|^2 \to 23\% \\
&Br(B_s \to \mu\bar{\mu}) \propto |V_{ts}Y|^2 \to 33\%
\end{aligned}
$$

For even larger $1/R$: UED rapidly approaching the SM

Radiative Decays - γ, g Penguins

Suppression of γ-magnetic and chromo-magnetic penguins.





$$\bar{s}\gamma' b = i\bar{\lambda}_t \frac{G_{\mathrm{F}}}{\sqrt{2}} \frac{e}{8\pi^2} D'(x_t, 1/R) \bar{s}[i\sigma_{\mu\lambda} q^\lambda [m_b(1+\gamma_5)]]b\,,$$

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

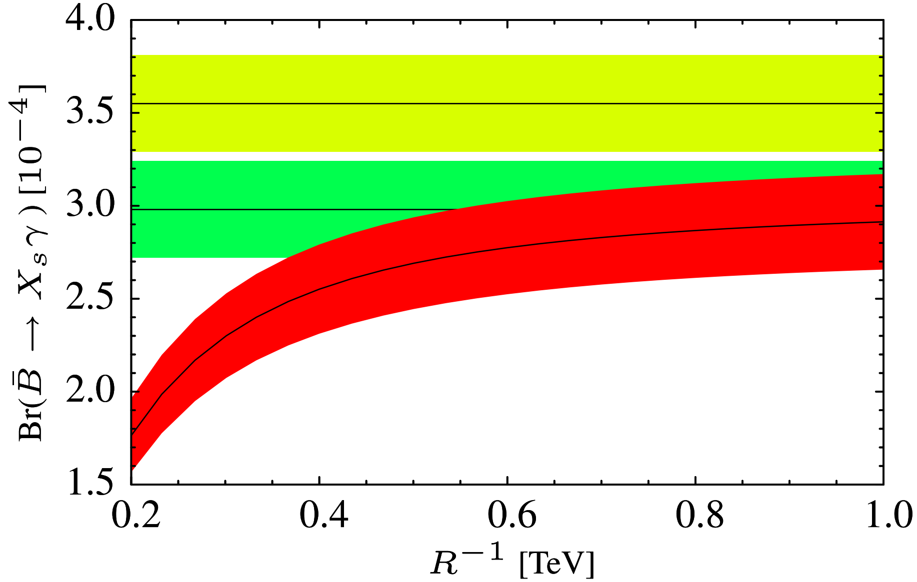
Radiative Decays - $B \to X_s\gamma$

Experimental average HFAG (CLEO, BaBar, Belle)

$$Br(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6 \text{ GeV}} = (3.55 \pm 0.24^{+0.09}_{-0.10} \pm 0.03) \times 10^{-4}$$

SM at NNLO QCD

$$Br(\bar{B} \to X_s\gamma)_{E_\gamma > 1.6 \text{ GeV}} = (2.98 \pm 0.26) \times 10^{-4}$$



Buras, Poschenrieder, MS, Weiler, hep-ph/0306158; Haisch, Weiler, hep-ph/0703064

$B \to X_s g$

Experimental value CLEO, Kagan '98

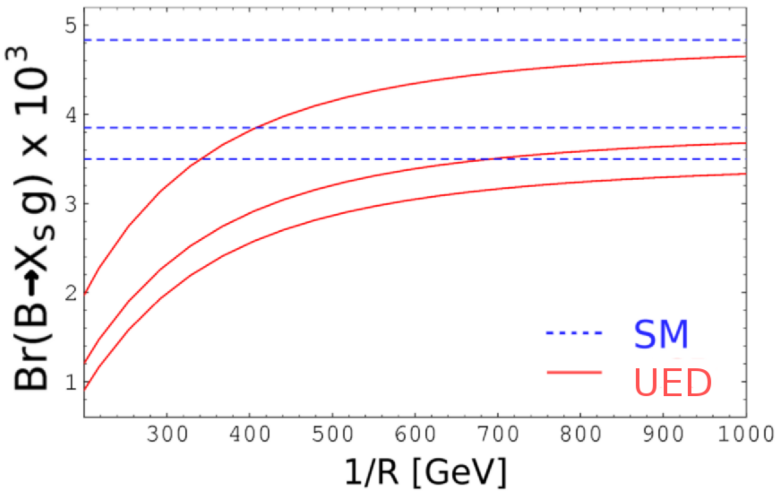
$$Br(B \to X_s g) < 9.0 \times 10^{-2} \ (90\% \text{c.l.})$$

SM using $m_c/m_b = 0.22$ Gambino, Misiak

$$Br(B \to X_s g) = (4.1 \pm 0.7) \times 10^{-3}$$

Greub, Liniger

For $m_c/m_b = 0.22$ and $\mu_b = 2.5, 5, 7.5$ GeV:



Buras, Poschenrieder, MS, Weiler, hep-ph/0306158

$B \to X_s \mu^+ \mu^-$

Branching ratio for full dilepton mass spectrum (HFAG):

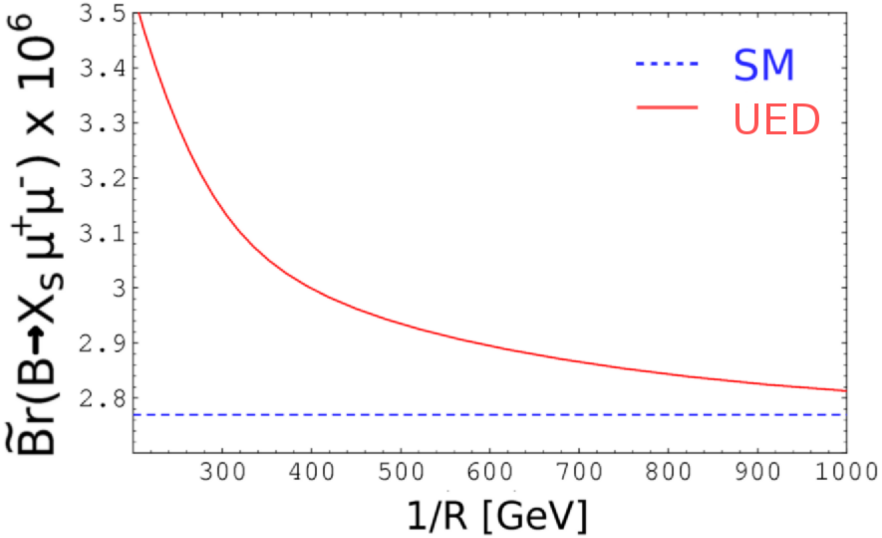
$$Br(B \to X_s \mu^+ \mu^-) \;=\; (4.3 \pm 1.2) \times 10^{-6}$$

SM Ali,Greub, Hiller, Lunghi, NNLL Ghinculov, Hurth, Isidori, Yao :

$$Br(B \to X_s \mu^+ \mu^-) \;=\; (4.1 \pm 0.7) \times 10^{-6}$$

UED $1/R = 300\,\mathrm{GeV}$ Buras, Poschenrieder, MS, Weiler, hep-ph/0306158 :

$$Br(B \to X_s \mu^+ \mu^-) \;=\; (4.8 \pm 0.8) \times 10^{-6}$$



Forward-Backward Asymmetry

Angle between μ^+ and B meson momenta in center of mass frame: θ_l

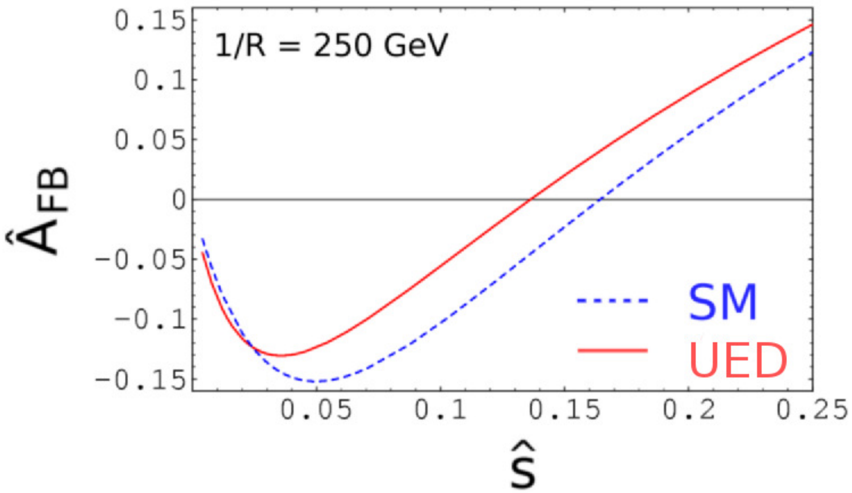
$$A_{\mathrm{FB}}(\hat{s}) = \frac{1}{\Gamma(b\to ce\bar{\nu})} \int_{-1}^{1} d\cos\theta_l \frac{d^2\Gamma(b\to s\mu^+\mu^-)}{d\hat{s}\,d\cos\theta_l} \mathrm{sgn}(\cos\theta_l)$$

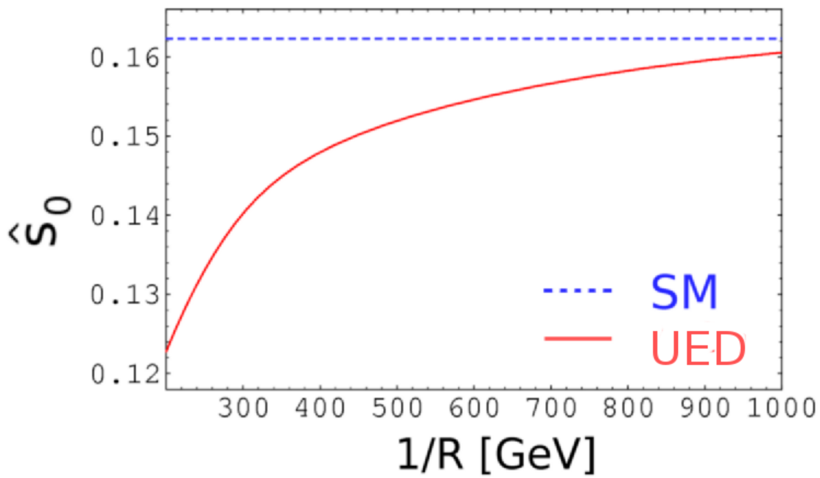
$$A_{\mathrm{FB}}(\hat{s}) \approx -3\tilde{C}_{10} \frac{\left[\hat{s}\mathrm{Re}\,\tilde{C}_9^{\mathrm{eff}}(\hat{s}) + 2C_{7\gamma}^{(0)\mathrm{eff}}\right]}{U(\hat{s})}$$

- $A_{\mathrm{FB}}(\hat{s})$ non-zero at NLO
- Sensitive to short-distance physics
- Very small non-perturbative uncertainties
- Hard to measure, $B \to K^* l^+ l^-$ Belle hep-ex/0603018

Forward-Backward Asymmetry

Zero of $A_{\text{FB}}(\hat{s})$ is given by: $$\hat{s}_0\ \mathrm{Re}\tilde{C}_9^{\text{eff}}(\hat{s}_0) + 2C_{7\gamma}^{(0)\text{eff}} = 0$$





$$\begin{cases} \hat{s}_0^{NLO} & = 0.142 \pm 0.02 \\ \hat{s}_0^{NNLO} & = 0.162 \pm 0.008 \\ \hat{s}_0^{UED}\ (600\,\text{GeV}) & = 0.154 \pm 0.01 \end{cases}$$

- $\hat{s}_0^{NLO}$: Ali,Mannel,Morozumi
- $\hat{s}_0^{NNLO}$: Ghinculov,Hurth,Isidori,Yao; Asatrian,Greub,Walker,Bieri,Hovhannisyan
- $\hat{s}_0^{UED}$ (600 GeV): Buras,Poschenrieder,MS,Weiler

Conclusions

- Flavor physics is important tool for constraining ED
- In UED all present data on FCNC processes consistent with $1/R \geq 600$ GeV at 95% CL
- Strongest bound on UED from $B \to X_s\gamma$, independent of Higgs mass
- Enhancement of $Br(K^+ \to \pi^+\nu\bar{\nu})$, $Br(K_L \to \pi^0\nu^+\nu^-)$, $Br(B \to X_s\mu^+\mu^-)$, $Br(B \to X_d\nu^+\nu^-)$, $Br(B \to X_s\nu^+\nu^-)$, $Br(K_L \to \mu^+\mu^-)$, $Br(B_d \to \mu^+\mu^-)$, $Br(B_s \to \mu^+\mu^-)$
- Suppression of $Br(B \to X_s\gamma)$, $Br(B \to X_s\,\text{gluon})$, ϵ'/ϵ, $\hat{s}_0$