B-FACTORY SIGNALS FOR A WARPED EXTRA DIMENSION

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• INTRODUCTION

Flavor *puzzle* of SM: no understanding of hierarchy of fermion masses and mixings

Flavor changing neutral currents (FCNC's) involving 1st and 2nd generations suppressed due to Glashow-Iliopoulos-Maiani (GIM) mechanism

GIM violated by m_t in B-meson mixing and ϵ_K

Solutions to Planck ($\sim 10^{18}$ GeV) - weak ($\sim$ TeV) hierarchy problem of SM:

new particles at weak scale spoil GIM mechanism

$\rightarrow$ flavor *problem*, e.g. generic SUSY model

OUTLINE AND SUMMARY

- ***Non*-SUSY solution based on warped extra dimension (Randall-Sundrum model)**

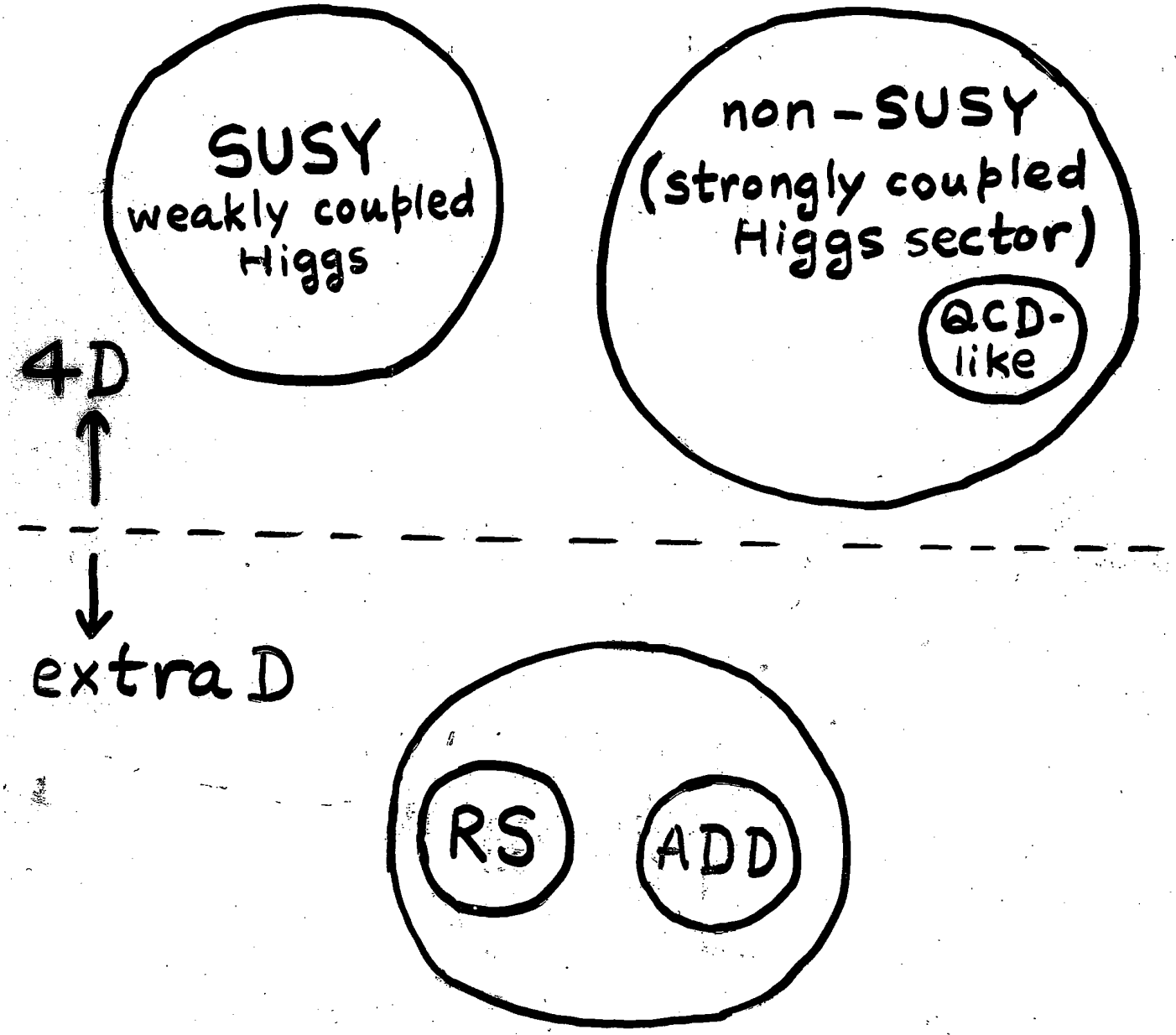
Profiles of SM fermions in extra dimension explain hierarchy of fermion masses with*out* hierarchies in fundamental ($5D$) parameters: flavor puzzle *solved*

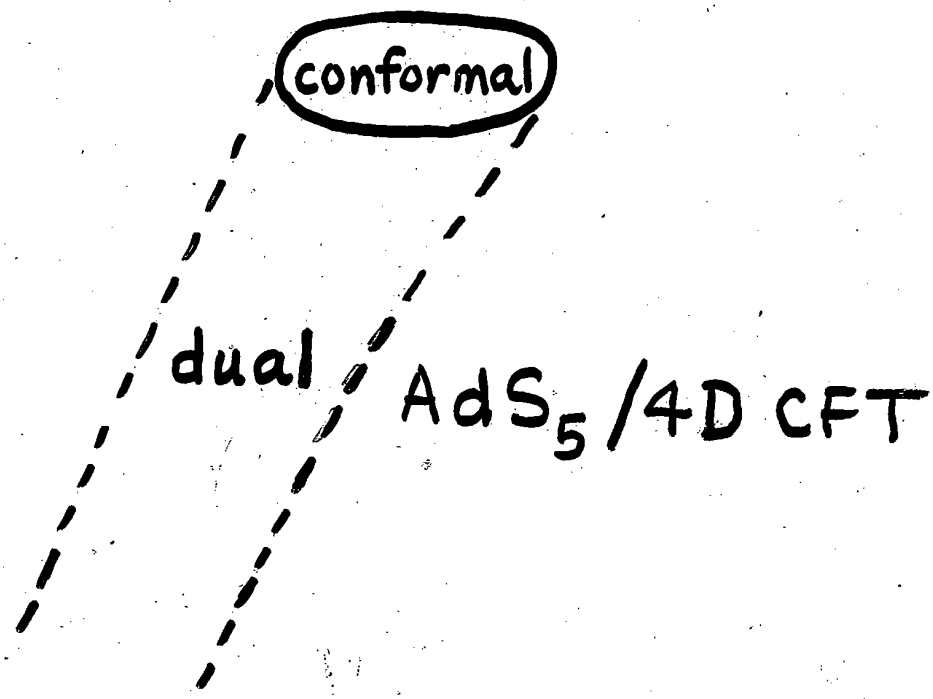
With 1st and 2nd generations, GIM mechanism preserved due to *same* profiles: *no* flavor problem

Couplings of *left*-handed b (and $t_{L,\,R}$) violate GIM due to m_t (just as in SM) $\rightarrow$ signals at B-factories

AdS/CFT correspondence: $4D$ composite Higgs model solves flavor puzzle + no flavor problem + test at B-factories

Solutions to Planck-weak hierarchy problem

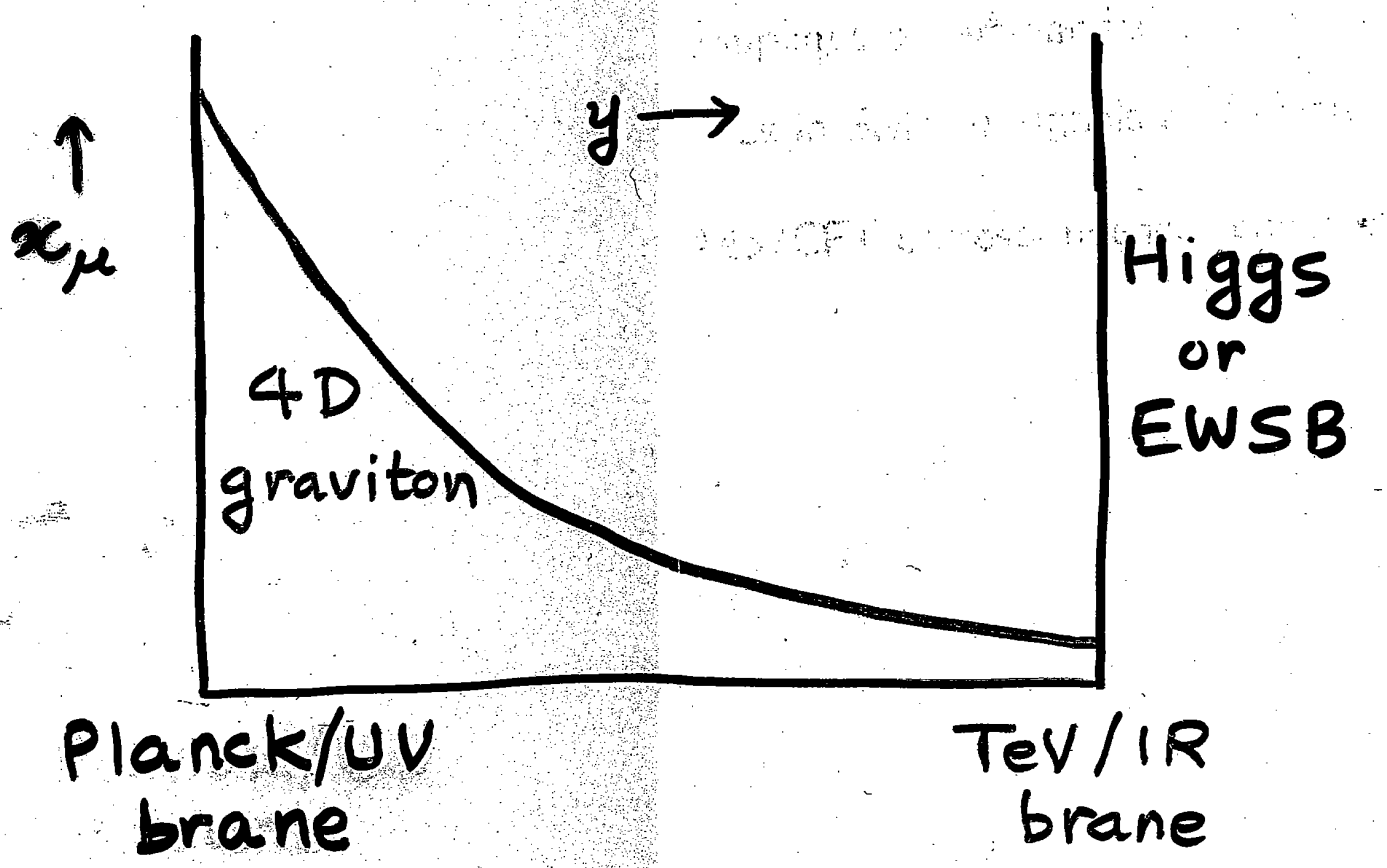




RS is a (weakly coupled) tool to calculate in a 4D strongly coupled Higgs sector

RANDALL-SUNDRUM (RS1) MODEL

Locality in 5th dimension prevents "talk" between effective UV cut-off ~ TeV for Higgs mass and new physics (4D quantum gravity) at $M_{Pl.}$



mass scale ~ $M_{Pl.}$ ← due to curvature → mass scale ~ TeV

(results valid for Higgsless models also)

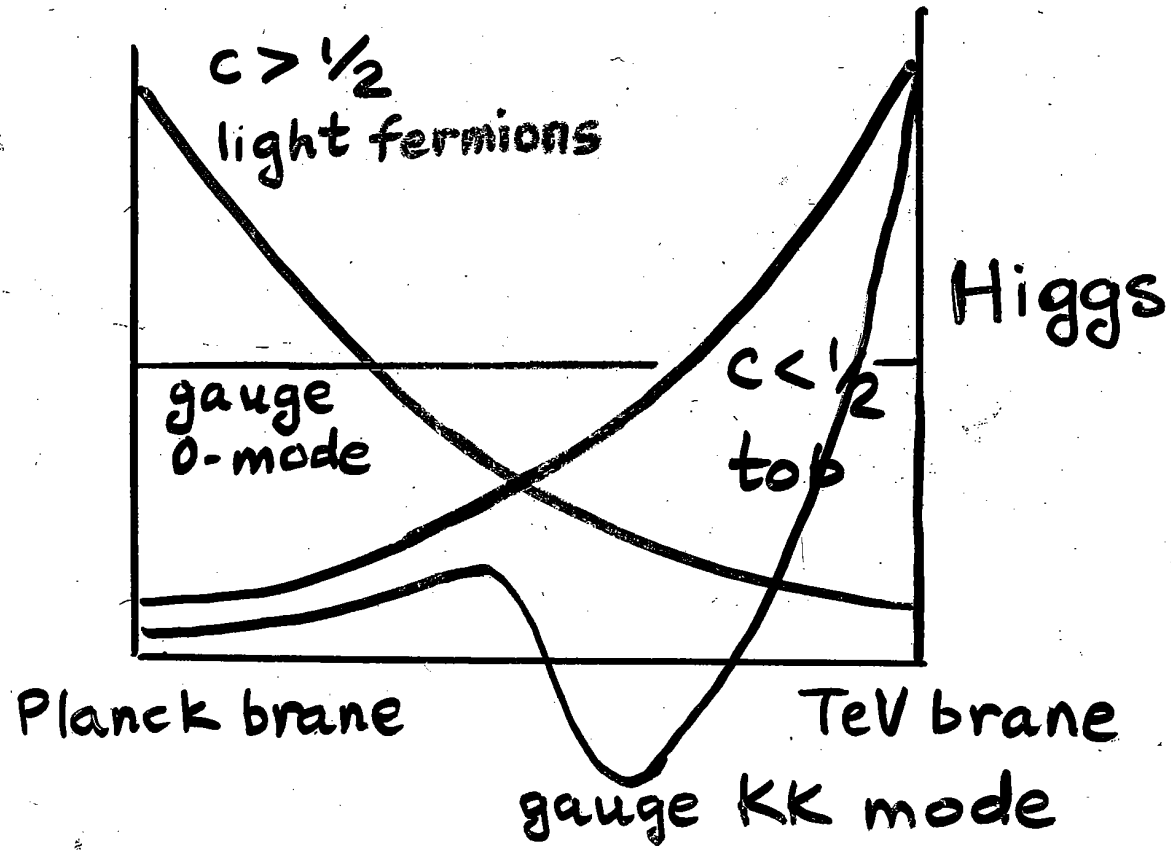
- BULK FERMIONS

c parameter localizes zero modes (SM fermions):

$c > (<) \frac{1}{2} \rightarrow$ zero mode is near Planck (TeV) brane

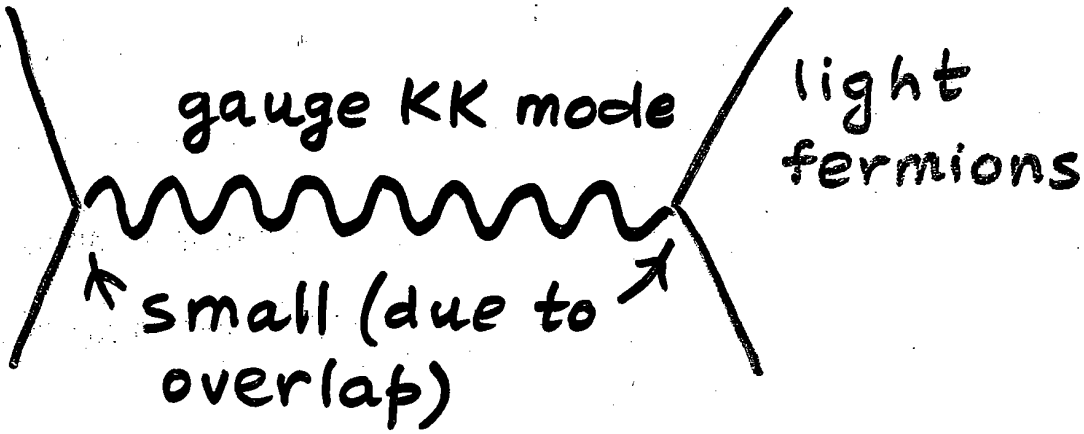
Anarchy (no structure) in O(1) 5D Yukawa : 4D Yukawa hierarchical due to wavefunctions near TeV brane

- $c > \frac{1}{2}$ for light fermions, $c \ll \frac{1}{2}$ for top (see later)



- FLAVOR CHANGING NEUTRAL CURRENTS (FCNC)

Exchange of gauge KK modes (localized near TeV brane)



Coupling to light fermions flavor dependent but small (same reason why they are light)

$\Rightarrow$ FCNC's small (correlated with small fermion masses)

- built-in GIM mechanism!

In SM, Δm_K suppressed by $m_c \ll M_W$, not $m_c \sim m_u$

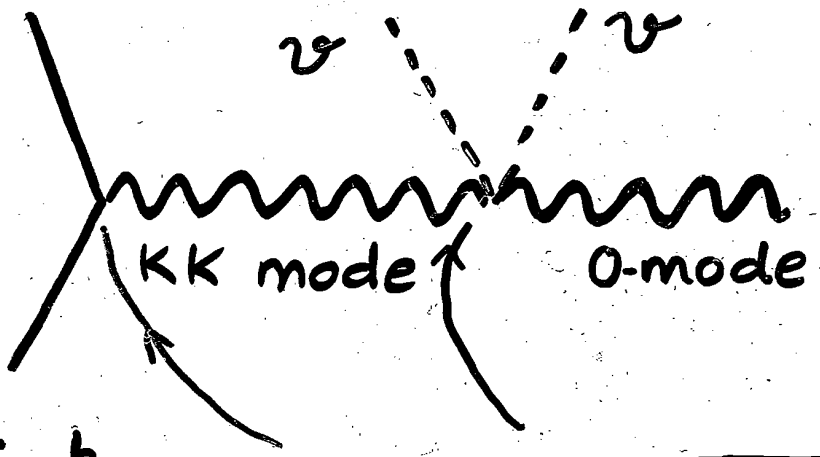
- **Top quark violates GIM (as in SM!)**

Heavy t_L prefers $c < 1/2$ (near TeV brane)

$\rightarrow b_L$ near TeV brane

$\Rightarrow$ shift in coupling of b_L to Z

KK decomposition without Higgs vev,
Higgs vev mixes zero and KK modes of W, Z

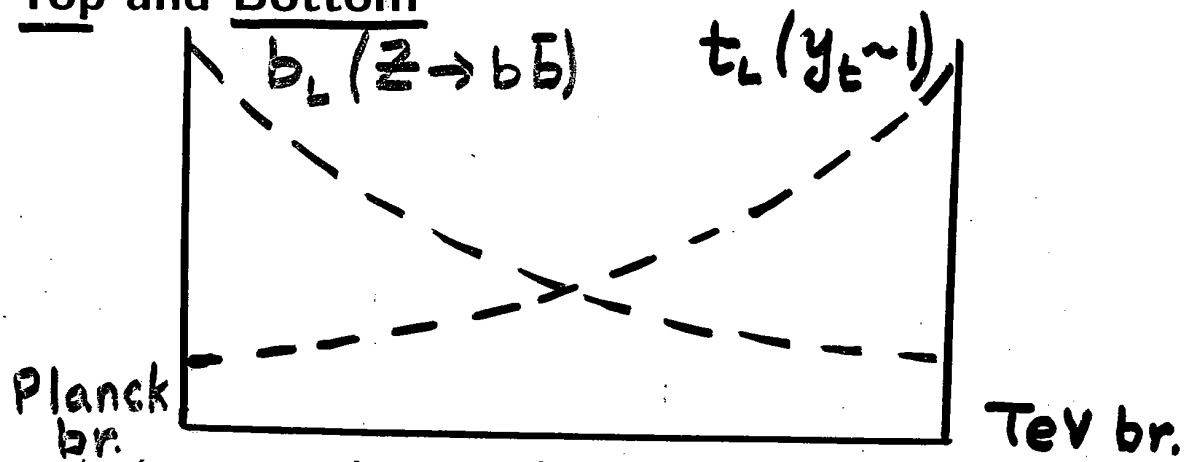


$$\delta g_Z^{b_L} \sim g_{KK}(c) \sqrt{\log(M_{Pl}/TeV)} \frac{m_Z^2}{m_{KK}^2}$$

$$\lesssim 1\% \text{ (LEP1)}$$

- Higgs coupling to gauge KK mode is enhanced (both near TeV brane or composites in CFT picture)

- **Top and Bottom**



$c > 1/2$ ($\leftrightarrow \lambda \ll 1$) for b_L (small coupling to KK modes) to be consistent with $Z \to b\bar{b}$

$c \ll 1/2$ ($\leftrightarrow \lambda \sim 1$) for t_L to obtain $y_t \sim 1$

- Tension: same c ($\leftrightarrow \lambda$) for t_L and b_L by $SU(2)_L$ symmetry

- : **Compromise**

c for $(t,b)_L \sim 0.3 - 0.4$ (a *bit* near TeV brane) $\rightarrow$ coupling of b_L to gauge KK modes $\sim G/10 \sim g_{SM}$: can*not* be larger or smaller ("live on the edge") $\rightarrow$ $y_{5D} \sim 4$ + $\delta g_Z^{b_L}/g_Z^{b_L} \sim 1\%$ for $m_{KK} \sim 3 - 4$ TeV (S, T OK with custodial isospin)

- due to m_t, c for b_L smaller (b_L nearer TeV brane, g_{KK} larger) than expected from m_b (i.e., $c > 1/2$)

3 classes of signals (related to compromise)

RS1 contribution $\sim$ SM in processes dominated by *top* loop:

(i) $\Delta F = 2$

(ii) $\Delta F = 1$ Z penguin

(iii) Radiative B decays

RS1 contribution can*not* compete with SM *tree*-level and *QCD* penguin

"little" hierarchy problem

Previous studies: ~10 TeV KK masses due to EW precision data → no signals

With custodial isospin, few TeV KK masses allowed (K.A. et al. (2003))

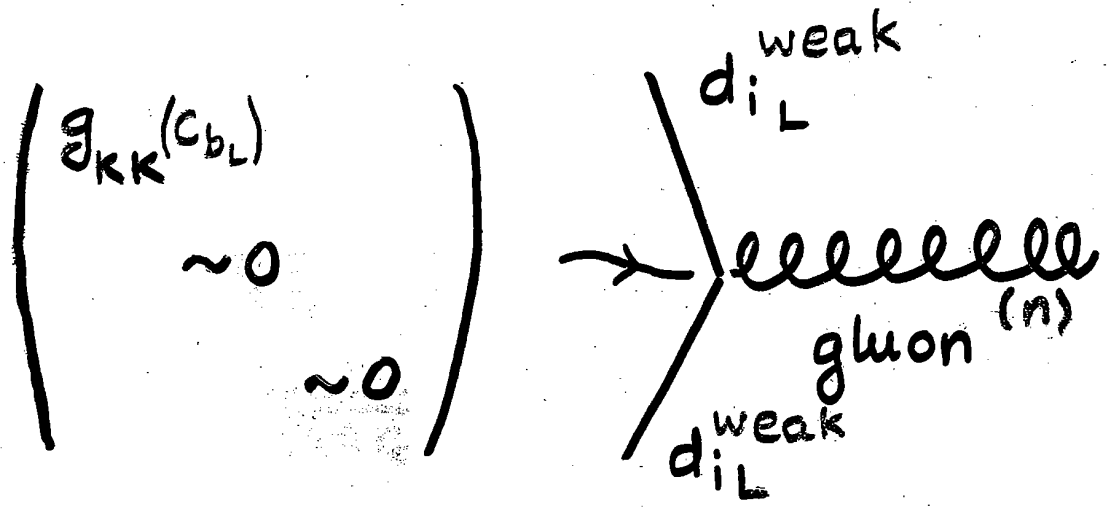
Burdman (2003): few TeV KK masses shift in coupling of b_L to Z not incorporated +
hierarchies in 5D Yukawa allowed

Flavor violation due to non-universal couplings to gauge KK modes

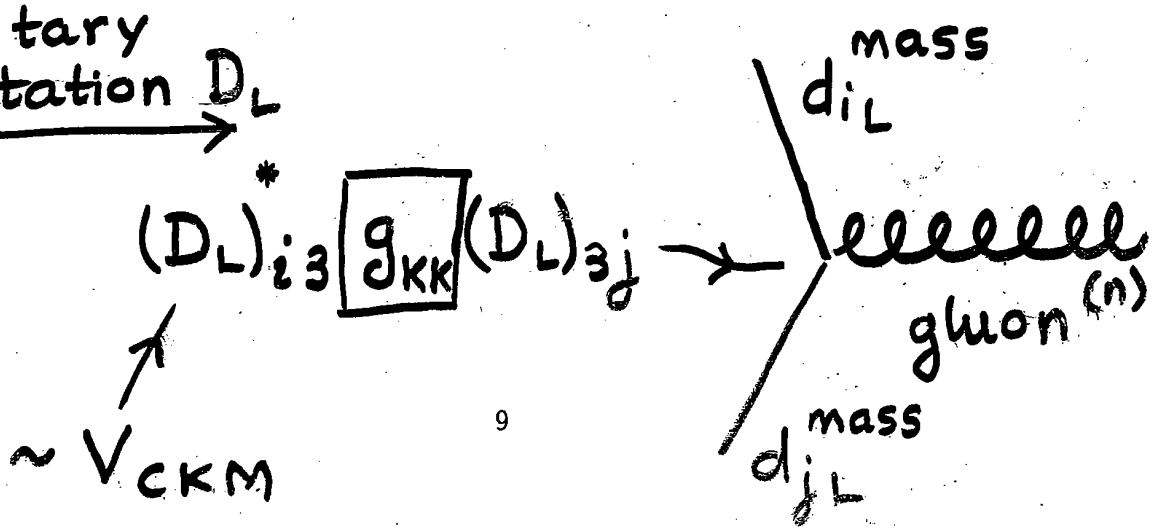
- **KK gluon**

KK gluon coupling to *weak* eigenstate $b_L \gg$ coupling to s_L, d_L

$\Rightarrow$ flavor-*violating* coupling to KK gluon after rotating to *mass* eigenstate basis (from gauge basis)

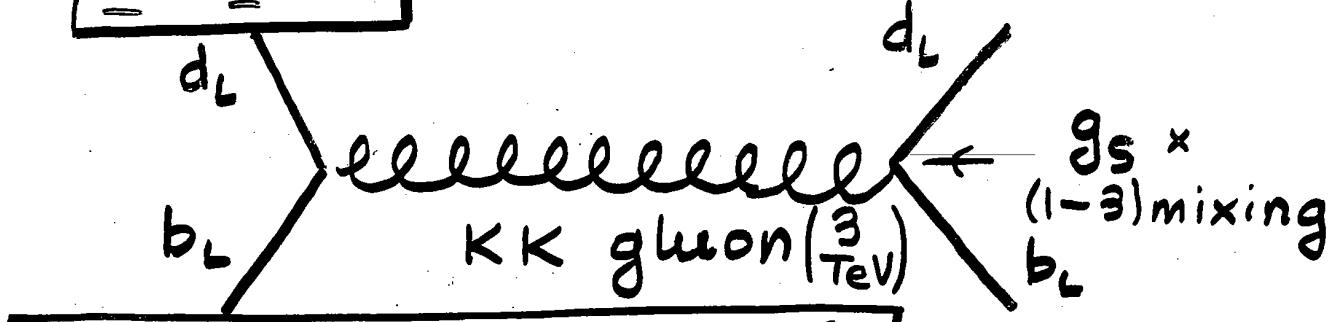


unitary rotation D_L



(due to anarchic λ_{5D})

- $B_d - \bar{B}_d$ mixing



gluon KK exchange $\sim$ SM box diagram for $m_{KK} \sim 3 - 4$ TeV

SM	RS1
Loop	Tree
$g/m_W \sim v$	KK masses $\sim 4\pi v$
$\frac{m_t^2}{m_W^2}$	$g_{KK} \sim g_{SM}$ ←
(no GIM)	(c for $(t,b)_L \sim 0.3 - 0.4$)

- Due to large m_t, c for b_L smaller (g_{KK} *larger*) than expected from m_b

  in SM, no GIM suppression (due to $m_t \sim m_W$) in $b \to s, d$ and *imaginary* part of $s \to d$ (unlike in *real* part of $s \to d$)

Coincidence problem via (1-3) x (2-3) mixing

KK gluon contribution to $\epsilon_K \sim$ SM (as in $B_d - \bar{B}_d$)

- *New* phases in ϵ_K and $B_d - \bar{B}_d$ mixing (from d_L mass mixing) $\rightarrow$ fit to data possible: (Im)

  (ρ, η) *weakly* constrained by tree-level + unitarity

  requires (ρ, η) *different* than in SM fit

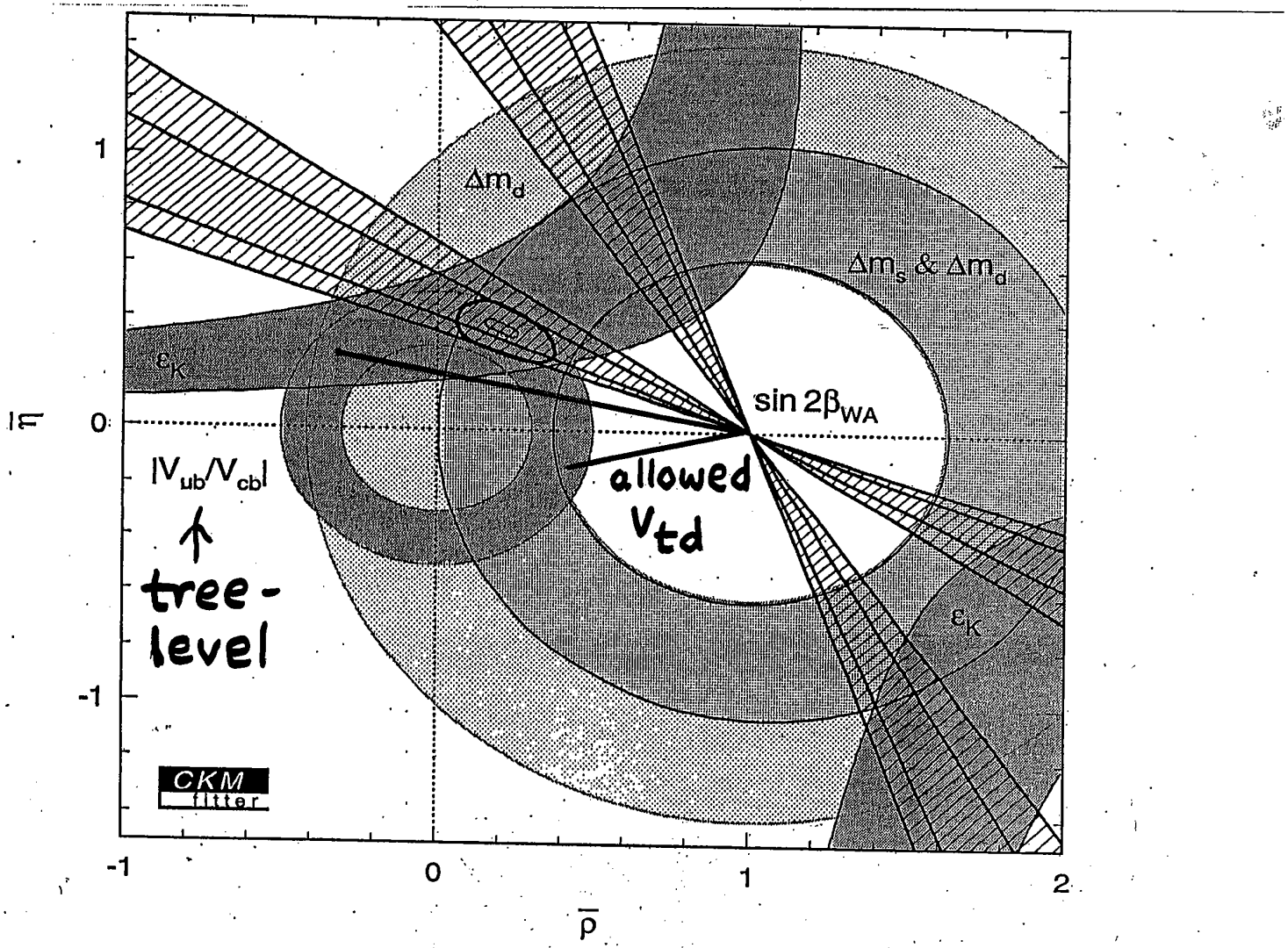
  No unnaturally small $5D$ Yukawa's or CP violating phases required to fit data

$\Rightarrow$ good $\rho - \eta$ fit to data in SM is an accident

Not severe as of now: $O(1)$ uncertainties in RS1 $\rightarrow$ from y_{5D} contributions + $O(20\%)$ uncertainties in hadronic matrix elements for ϵ_K and Δm_{B_d}

KK masses $\gtrsim 3 - 4$ TeV suppress RS1 contributions $\rightarrow$ fine-tuning/little hierarchy problem

γ in this model $\neq (\gamma)_{SM\,fit}$ $\rightarrow$ CP asymmetries in $B \rightarrow \rho\rho, DK$ deviate from SM expectation


1
0
-1
-1
0
1
2
$\bar{\eta}$
$\bar{\rho}$
Δm_d
Δm_s & Δm_d
ε_K
$\sin 2\beta_{WA}$
allowed
V_{td}
$|V_{ub}/V_{cb}|$
tree-
level
ε_K
CKM
fitter

KK gluon contribution to $B_s - \bar{B}_s$ mixing $\sim$ SM

$\uparrow V_{ts}$ constrained

Smoking gun signals

O(1) effect in

- Δm_{B_s} measurable at Run II of Tevatron
- $O(1)$ phase in $B_s - \bar{B}_s$ (due to *new* phases in D_L) $\Rightarrow$

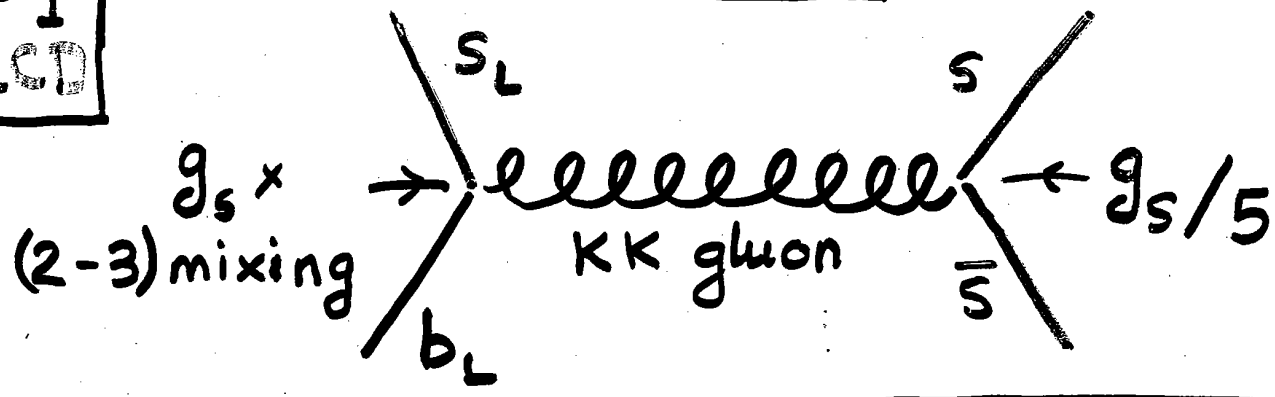
  $O(1)$ mixing-induced, time-dependent CP asymmetry in $B_s \to J/\psi\phi$

  (a la $B_d \to J/\psi K_s$ in SM)

in SM, CP asymmetry small due to phase in $B_s - \bar{B}_s$ mixing $\sim O\left(\lambda_c^2\right)$

ΔF = 1 QCD

• $B \to \phi K_S$ anomaly (?): $b \to s\bar{s}s$



coupling of (mostly fundamental) s to gauge KK mode (via "$\gamma - \rho$" mixing) $\sim g_s/5 \to$

$\mathcal{A}(b \to s\bar{s}s) \propto (2-3)$ mixing $\times\, g_s^2/m_{KK}^2 \times 1/5$

SM contribution from QCD penguin

$\sim (2-3)$ mixing $g^2/(16\pi^2)\ g_s^2 \times m_t^2/m_W^4$

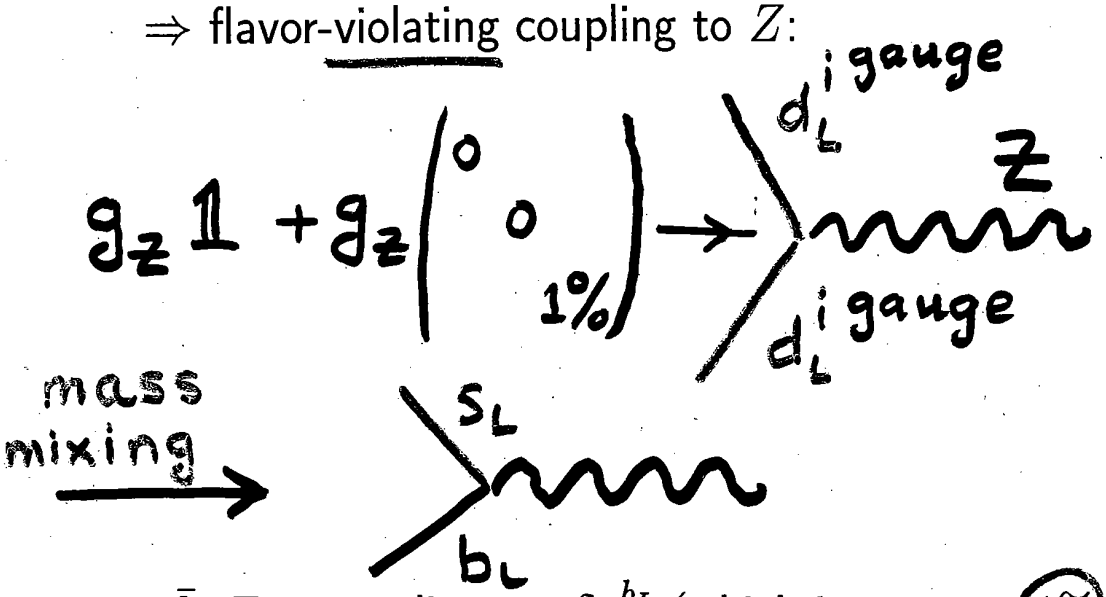
$\Rightarrow$ gluon KK exchange $\sim 1/5 \times$ SM QCD penguin

(also, dilution in RG scaling from $\sim$ TeV to m_b)

ΔF=1 Z

- coupling of b_L to physical Z different from that of s_L, d_L by $\sim 1\%$

  $\Rightarrow$ flavor-violating coupling to Z:



$\bar{b}_L Z s_L$ coupling $\sim \delta g_Z^{b_L}$ (which is $\sim g_Z \times 1\%$

$\times (2-3)$ mixing (3)

$$\mathcal{A}(b \to s f \bar{f}) \propto (2-3) \text{ mixing} \times g_Z^2/m_Z^2 \times 1\%$$

SM electroweak penguin

$$\propto (2-3) \text{ mixing} \, g^2/(16\pi^2) \, g_Z^2/m_Z^2$$

- new physics in $b \to s f \bar{f}$ $\sim$ SM electroweak penguin!

(see also Burdman, Nomura)

Smoking gun signal: $b \to s l^+ l^-$: theory $\sim 15\%$,

experiment $\sim 30\%$

Not just effect on BR:

RS1 effect in $...\bar{l}\gamma_\mu\gamma_5 l$ (coupling of Z to l is axial)

not in $...\bar{l}\gamma_\mu l$: no effect in γ penguin (vector-like coupling)

$\Rightarrow$ l^+l^--spectrum, forward-backward asymmetry affected

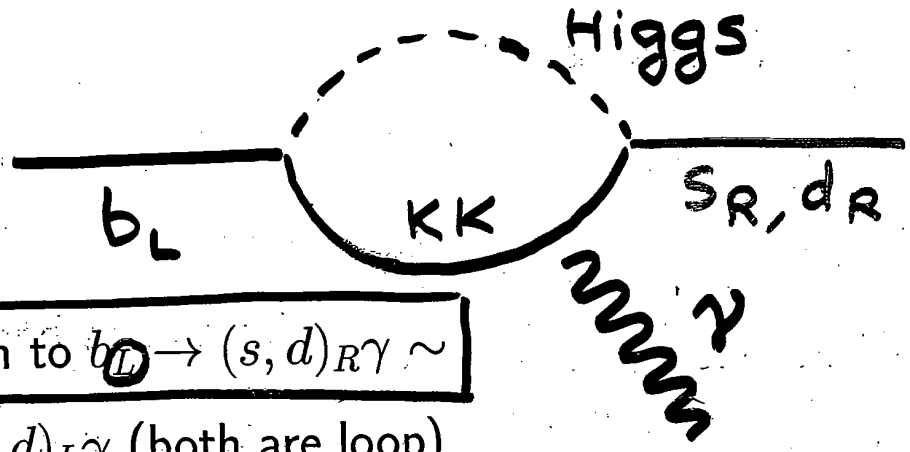
direct CP violation : RS1 effect does not have strong phase

$b \to s\bar{s}s$: contribution of *SM* QCD penguin larger by

$\sim g_s^2/g_Z^2 \to \sim 20\%$ effect

SUSY : solutions to flavor problem typically suppress signals

Radiative decays: loop diagrams with Higgs and KK fermions (couplings of KK fermions to Higgs enhanced)



- RS1 contribution to $b_L \to (s,d)_R\gamma \sim$ SM $b_R \to (s,d)_L\gamma$ (both are loop)

SM	RS1
$g/m_W \sim v$	KK masses $\sim 4\pi v$
$\frac{m_t^2}{m_W^2}$	KK coupling $\sim y_{5D} \sim 4$
(no GIM)	(required for m_t)
$V_{ts} \sim 0.04$	$(D_R)_{23} \sim 1$

anarchic $y_{5D} \Rightarrow \boxed{\frac{m_s}{m_b} \sim (D_L)_{23} \times (D_R)_{23}}$

$$\frac{50\ \text{MeV}}{2\ \text{GeV}} \sim V_{ts} \times (D_R)_{23} \qquad (4)$$

$\to \boxed{(D_R)_{23} \sim 1}$ (similarly, $(D_R)_{13} \sim 1/6$)

(RS1 contribution to $b_R \to (s,d)_L\gamma$ smaller)

Smoking gun signal

- $O(1)$ mixing induced CP violation in

  $B \to K^*\gamma$, $B_s \to \phi\gamma$ $(b \to s)$

  $B \to \rho\gamma$, $B_s \to K^*\gamma$ $(b \to d)$ ← SM

  (interference between $b_R \to (s,d)_L\gamma$ and

  RS1 → $b_L \to (s,d)_R\gamma$ amplitudes)

  (BABAR, hep-ex/0405082 : 0.25 ± 0.7)

  $O[(m_s, m_d)/m_b]$ in SM due to smaller $b_L \to (s,d)_R\gamma$

EDM's from similar loop diagram

Naively : 20 x expt. limit !

In detail : no flavor diagonal effect

→ EDM's suppressed by mixing

- No RS1 CP problem !