The Flavour Puzzle(s) (in the SM and Beyond)

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What is Flavour Physics?

Interactions that distinguish among the 3 generations of fermions:

✓ (SM) Yukawa int. between the Higgs and fermions

✗ gauge int. (at least before EW sym. breaking)

✗ Higgs self-interactions

First Remark: flavour physics is intimately connected to the Higgs sector and hence to physics beyond the SM.

First Question: given the exp. constraints, is there room for any other new interactions that are generation sensitive? i.e., is there any new flavor parameters beyond the Yukawa's?

some interesting but non-flavour questions:

- Why 3 generations?
- Why the particular quantum numbers of the different fermions?
- Why chiral representations only for broken gauge symmetries?

What is Flavour Physics?

Interactions that distinguish among the 3 generations of fermions:

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$$SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R} \times SU(3)_{E_L} \times SU(3)_{E_R}$$

explicit breaking
by renormalizable interactions

$$\Downarrow$$

$$U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

new int.? instanton? quantum gravity?
@ which scale?

$$\Downarrow$$

$\emptyset$?

SM Flavour Puzzle(s)

- Small parameters & Hierarchy of masses

$$\begin{array}{ccc} Y_t \sim 1 & Y_c \sim 7\cdot 10^{-3} & Y_u \sim 3\cdot 10^{-5} \\ Y_b \sim 2\cdot 10^{-2} & Y_s \sim 7\cdot 10^{-4} & Y_d \sim 5\cdot 10^{-5} \\ Y_\tau \sim 1\cdot 10^{-2} & Y_\mu \sim 6\cdot 10^{-4} & Y_e \sim 3\cdot 10^{-6} \end{array}$$

what is the origin of this 6 order of magnitude hierarchy?

- Hierarchy of mixing angles $(\lambda \sim \sin\theta_c \sim 0.2)$

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

why are the angles hierarchical?

why are they align with the masses?
(u- and d-type quarks are almost diagonal in the same basis)

- Why is the mixing structure different in the leptonic sector?

$$V_{PMNS} \sim \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

exact tri-bimaximal mixing?

- ...

SM Flavour Puzzle(s)

- Why so many parameters?

$$Y_u^{ij} \bar{Q}_{L_i} H^\dagger U_{R_j}$$
$$Y_d^{ij} \bar{Q}_{L_i} H D_{R_j}$$

2 (3x3) complex matrices = { 18 real parameters, 18 phases }

not all par. are physical since we can perform field rotations

$$Q_L \to U_{Q_L} Q_L$$
$$U_R \to U_{U_R} U_R$$
$$D_R \to U_{D_R} D_R$$

3 (3x3) unitary matrices = 9 real par. + 18 phases

baryon number conservation: 1 phase cannot be removed

10 phys. parameters: 6 masses, 3 mixing angles, 1 CP phase

$$Y_e^{ij} \bar{E}_{L_i} H E_{R_j}$$
$$\frac{Y_\nu^{ij}}{M} \bar{E}^c_{L_i} H H E_{L_j}$$

1 (3x3) complex matrix + 1 (3x3) symmetric matrix = { 15 real parameters, 15 phases }

field rotations: 2 (3x3) unitary matrix = 6 real par. + 12 phases

12 phys. par.: 6 masses, 3 mixing angles, 1 CP phase, 2 Maj. phases

No unified structure; No predictive power

Hierarchy from a flavor symmetry

[Froggatt, Nielsen '79]

introduce an horizontal/flavour symmetry

(i.e. different charges for the different generations)

U(1)$_F$

a flavon field: F of charge -1

$$Y_{u_{ij}} \left(\frac{F}{\Lambda}\right)^{-q_i-h+u_j} \bar{Q}_{L_i} H^\dagger U_{R_j} \xrightarrow[\langle F \rangle]{\cancel{U(1)_F}} Y^{eff}_{u_{ij}} = Y_{u_{ij}} \left(\frac{\langle F \rangle}{\Lambda}\right)^{-q_i-h+u_j}$$

easy to reproduce the mass hierarchy with charges O(1)

but need new field, new symmetry:

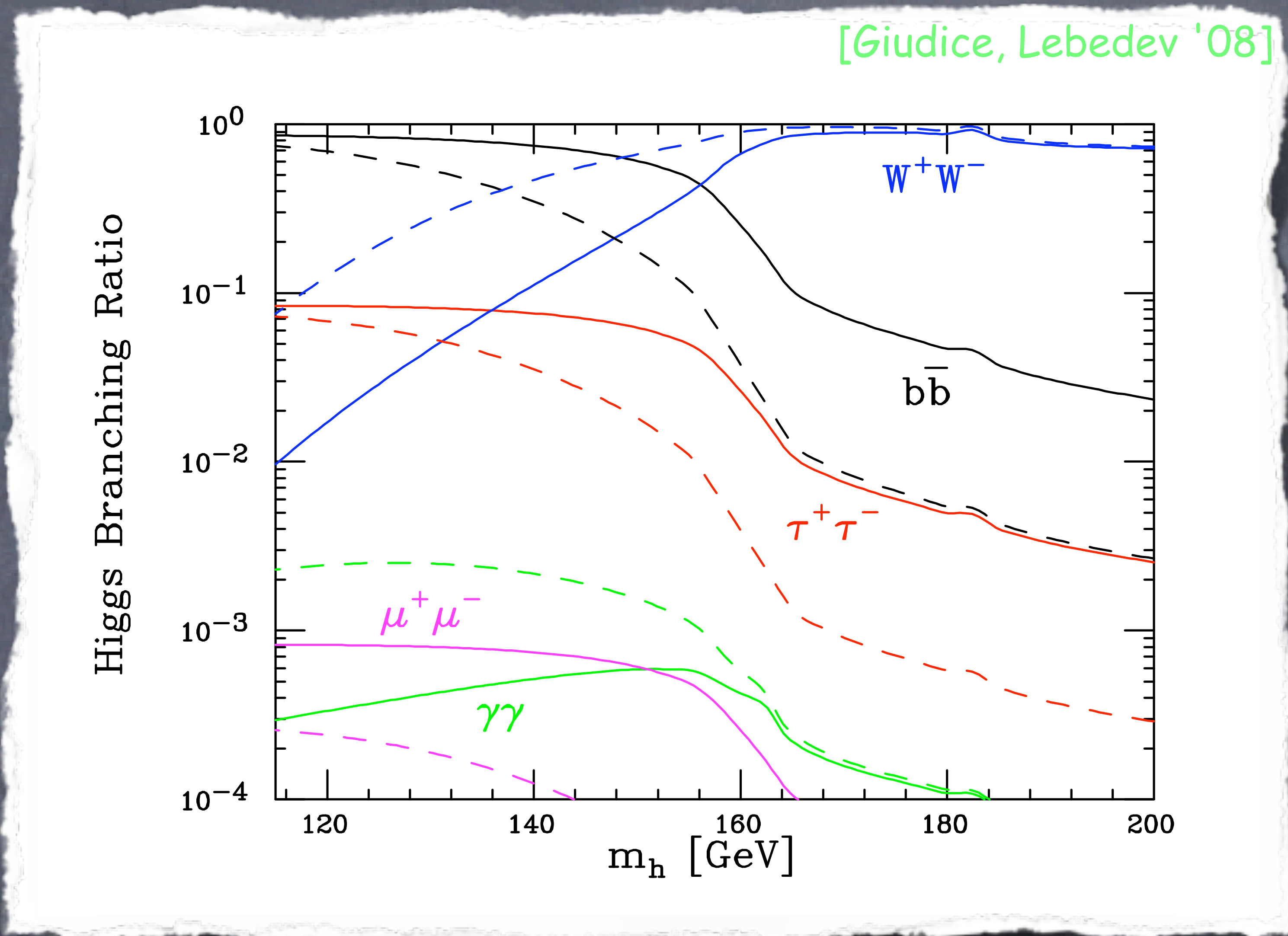
had hoc construction difficult to probe

(though, there are hints to relate U(1)$_F$ to modular symmetries of SUGRA theories)

Recent construction [Giudice, Lebedev '08]: uses the Higgs as a flavon

➲ interesting signatures in Higgs physics ⊂

- - - - SM —— Higgs-dependent Yukawa's

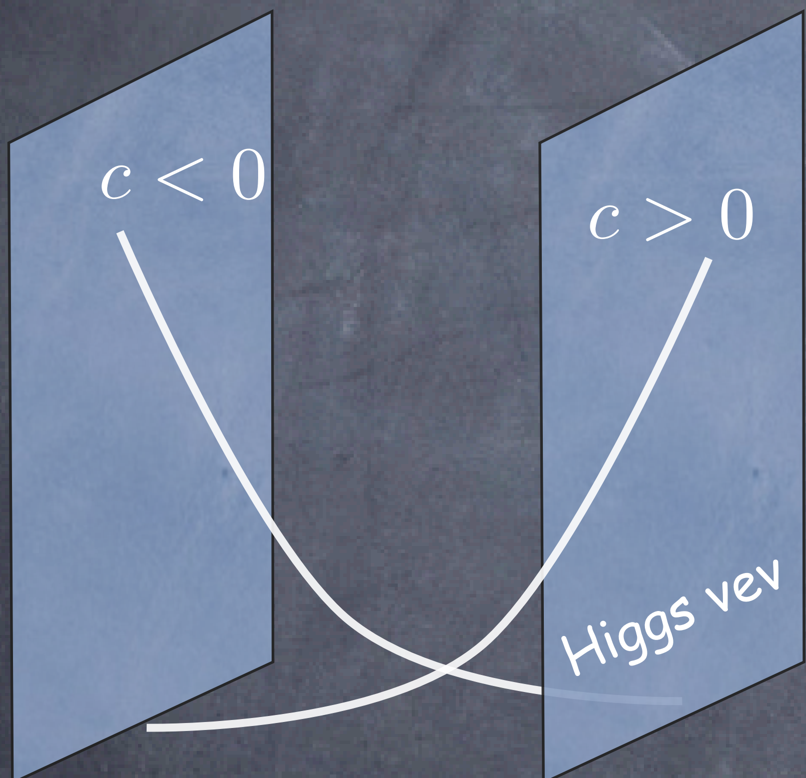


$$\frac{\Gamma(h\to b\bar{b})}{\Gamma(h\to b\bar{b})_{SM}} = \frac{\Gamma(h\to c\bar{c})}{\Gamma(h\to c\bar{c})_{SM}} = \frac{\Gamma(h\to \tau^+\tau^-)}{\Gamma(h\to \tau^+\tau^-)_{SM}} = 9 \qquad \frac{\Gamma(h\to \mu^+\mu^-)}{\Gamma(h\to \mu^+\mu^-)_{SM}} = 25$$

Hierarchy w/o sym. from extra-dimension

[Arkani-Hamed, Schmaltz '99]

x-dim. is a priori a bad starting point due to the absence of chirality but chirality is easily obtained on orbifold (or boundary conditions)



fermion zero-mode has
an exponential profile in the bulk

$$\chi(z) = \sqrt{\frac{2c}{(e^{2c}-1)L}}\, e^{cz/L}$$

Higgs localized at z=L

$$\Rightarrow \quad Y_u^{eff} = Y_u^\star \chi_q(L)\chi_u(L)$$

Froggatt-Nielsen pattern without symmetry

$Y_t^{eff} \sim \mathcal{O}(1)$ if top is also localized on the Higgs brane

$Y_{u,d}^{eff} \ll 1$ if u,d are localized on the other brane

hierarchic Yuakawa's produced
by O(1) numbers associated to the bulk dynamics

Anarchy: mixing angles from mass hierarchy

[Froggatt, Nielsen '79]

$$\boxed{Y^{eff}_{d_{ij}} = Y^{\star}_{d_{ij}} f_{q_i} f_{d_j}} \qquad \boxed{Y^{eff}_{u_{ij}} = Y^{\star}_{d_{ij}} f_{q_i} f_{u_j}}$$

Y_u, Y_d ~O(1): anarchic structure f_i: hierarchic structure: $f_1 \ll f_2 \ll f_3$

Not only, it leads to a hierarchical spectrum

$$\boxed{m_{u_i} \propto f_{q_i} f_{u_i}} \qquad \boxed{m_{d_i} \propto f_{q_i} f_{d_i}}$$

It also gives hierarchical angles

$$U_{uL}\, Y_u^{eff}\, U^{\dagger}_{uR} = \mathrm{diag} \qquad U_{dL}\, Y_d^{eff}\, U^{\dagger}_{dR} = \mathrm{diag}$$

with (for i < j)

$$U^{ij}_{uL,dL} \sim f_{q_i}/f_{q_j} \qquad U^{ij}_{uR} \sim f_{u_i}/f_{u_j} \qquad U^{ij}_{dR} \sim f_{d_i}/f_{d_j}$$

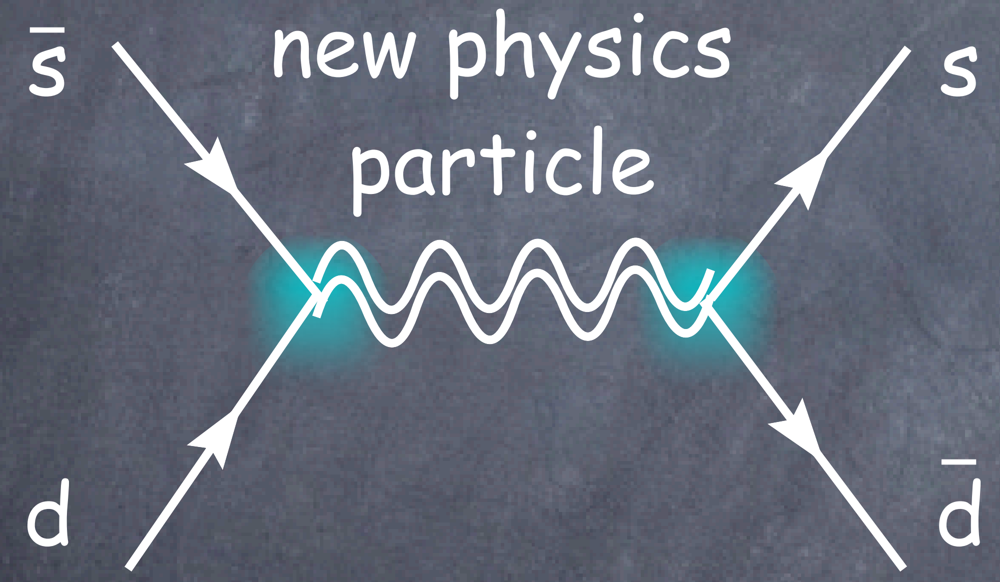
and therefore, we also get

$$\boxed{V^{ij}_{CKM} \sim f_{q_i}/f_{q_j}}$$

➲ alignment angles/masses nicely explained ⊂

SM to BSM Flavour Puzzle(s)

new physics can nicely explain SM puzzle(s)
but we have to make sure that
it does not destroy good features of SM
in particular the absence of FCNC

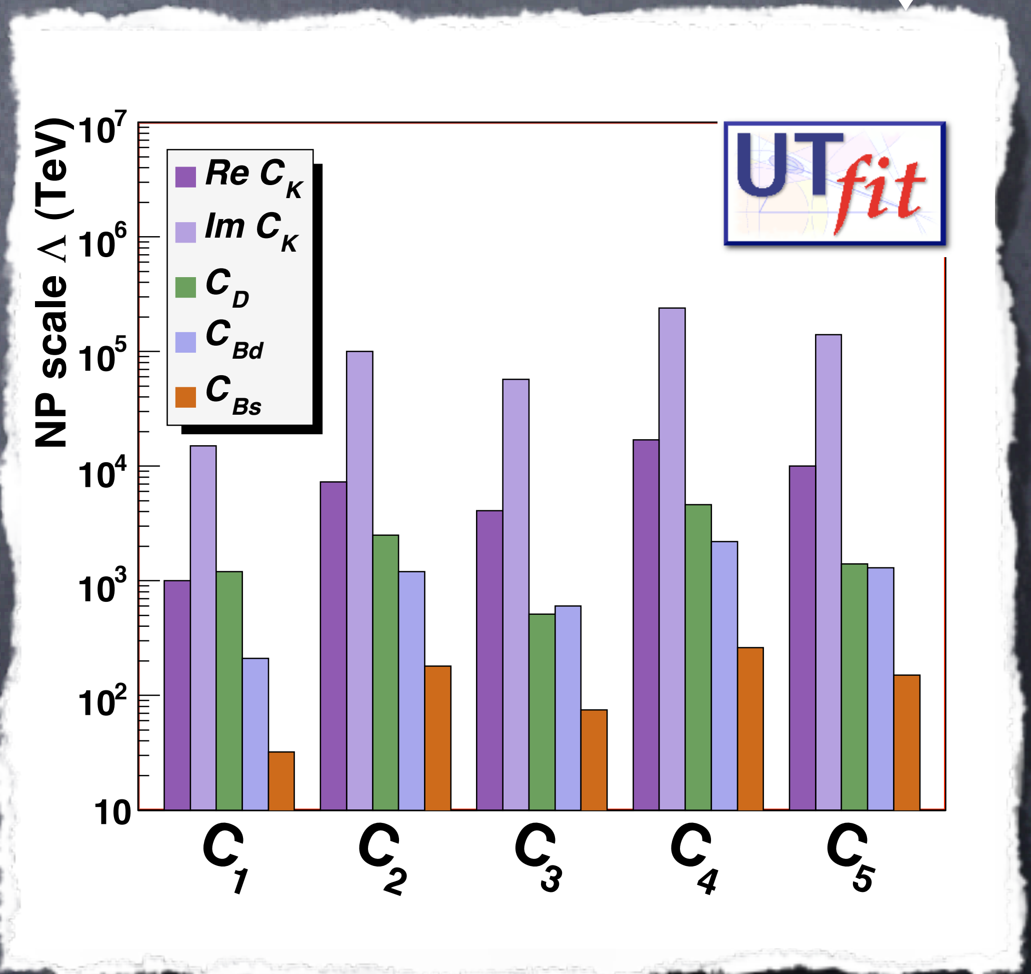


is new physics flavor blind?

or

does it know FC int. have to be small?

bound on scale of flavour-blind new physics ⇓



Beyond SM Flavour Puzzle(s)

the SM flavour hierarchy is radiatively stable
but the EW/M_{Pl} hierarchy is not

$$m_H^2 \sim m_0^2 - (115\ \mathrm{GeV})^2 \left(\frac{\Lambda}{400\ \mathrm{GeV}}\right)^2$$

need new degrees of freedom around the TeV scale to cancel the Λ^2 divergences

Clash of Scales

Flavour	?	Higgs sector
Λ > 10^5 TeV	$\Longleftrightarrow$	Λ < 3-4 TeV

the higher the scale of new physics,
the more fine-tuned the Higgs, the less likely a discovery at LHC

BSM Flavour Puzzle(s): 4-Fermi Operators

model-independent analysis: effective theory approach:

$$\frac{C^1_{ij}}{\Lambda^2}\left(\bar{Q}^i_L\gamma^\mu Q^j_L\right)^2+\frac{C^4_{ij}}{\Lambda^2}\left(\bar{d}^j_R Q^i_L\right)\left(\bar{Q}^j_L d^i_R\right)+\frac{C^5_{ij}}{\Lambda^2}\left(\bar{Q}^j_L d^i_R\right)\left(\bar{d}^j_R Q^i_L\right)$$

$$\frac{\Delta m_K}{m_K}=\frac{C^1_{sd}}{3\Lambda^2}f_K^2 \quad \left\{\begin{array}{l}\dfrac{\Delta m_K}{m_K}\sim 7\cdot 10^{-15}\\ f_K\sim 0.16\ \text{GeV}\end{array}\right. \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{C^1_{sd}}}>1100\ \text{TeV}$$

$$\frac{\Delta m_D}{m_D}<2\cdot 10^{-14} \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{C^1_{cu}}}>900\ \text{TeV}$$

$$\frac{\Delta m_{B_d}}{m_{B_d}}\sim 6\cdot 10^{-14} \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{C^1_{bd}}}>400\ \text{TeV}$$

$$\frac{\Delta m_{B_s}}{m_{B_s}}\sim 2\cdot 10^{-12} \quad \Rightarrow \quad \frac{\Lambda}{\sqrt{C^1_{bs}}}>80\ \text{TeV}$$

1

generic flavour structure

$C_{ij} \sim O(1)$

requires "heavy" new physics

$\Lambda > 10^{4-5}$ TeV

Fine-tuning pb in Higgs sector

LHC won't see anything

2

non-trivial flavour structure

can accommodate "light" new physics

$$C_{ij}<10^{-4}-10^{-6}\left(\frac{\Lambda}{\text{TeV}}\right)^2$$

result of a dynamic?

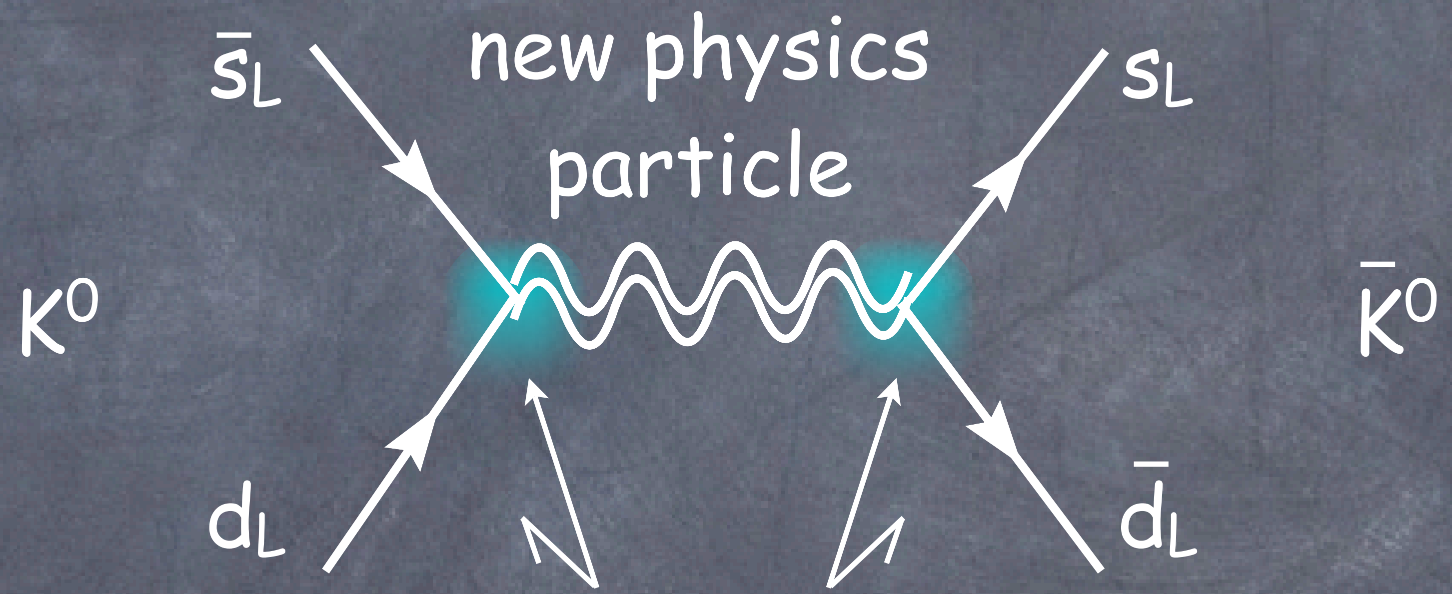
result of a symmetry?

A solution : Minimal Flavour Violation

the Yukawa's are the only source of flavour violation

i.e. all interactions breaking $SU(3)_Q \times SU(3)_U \times SU(3)_D$ are prop. to Yu, Yd

under $SU(3)_Q \times SU(3)_U \times SU(3)_D$: $Yu \sim (3,\bar{3},1)$ & $Yd \sim (3,1,\bar{3})$



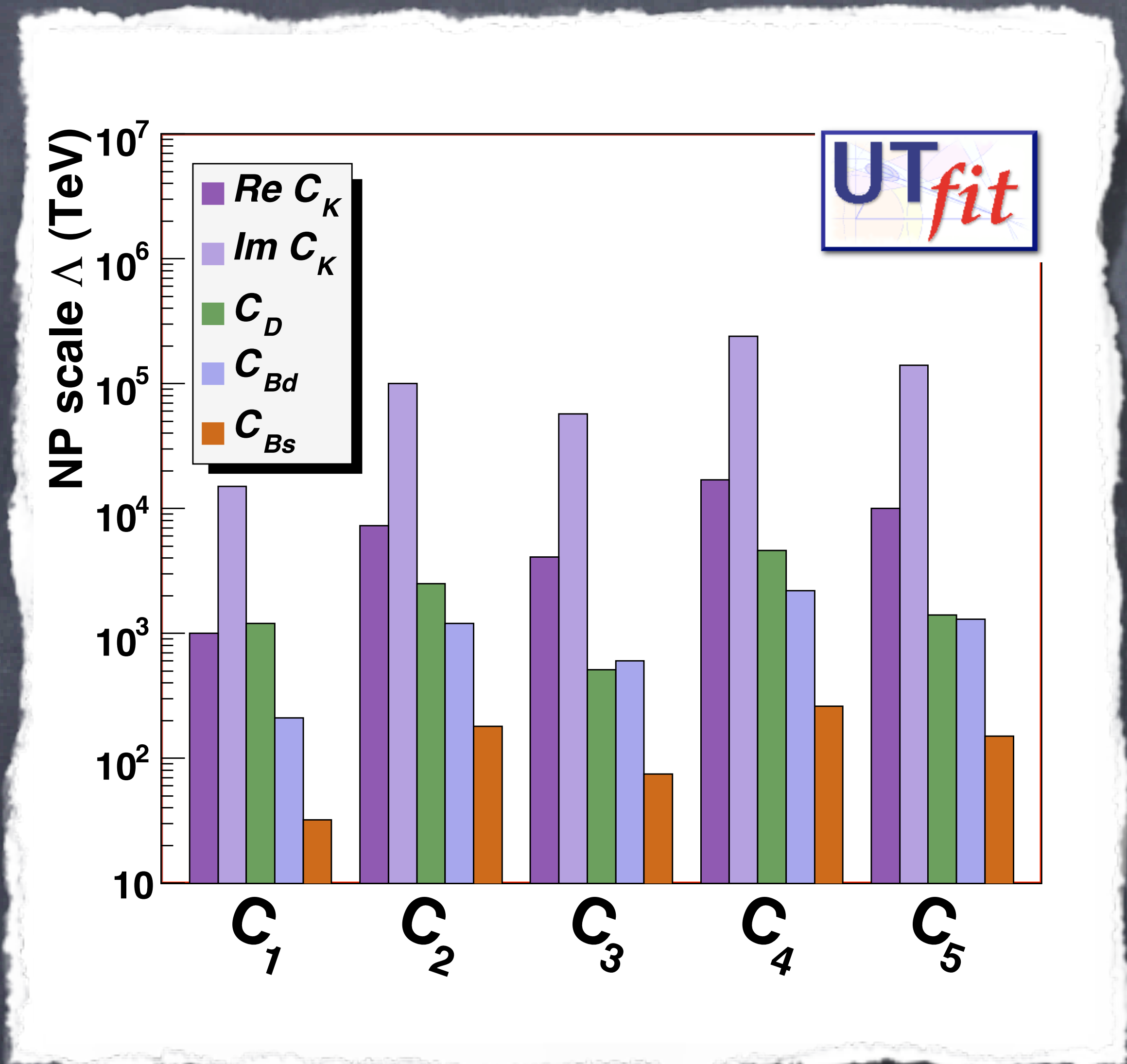
new int. that violate flavour

must involve some Yukawa's factors

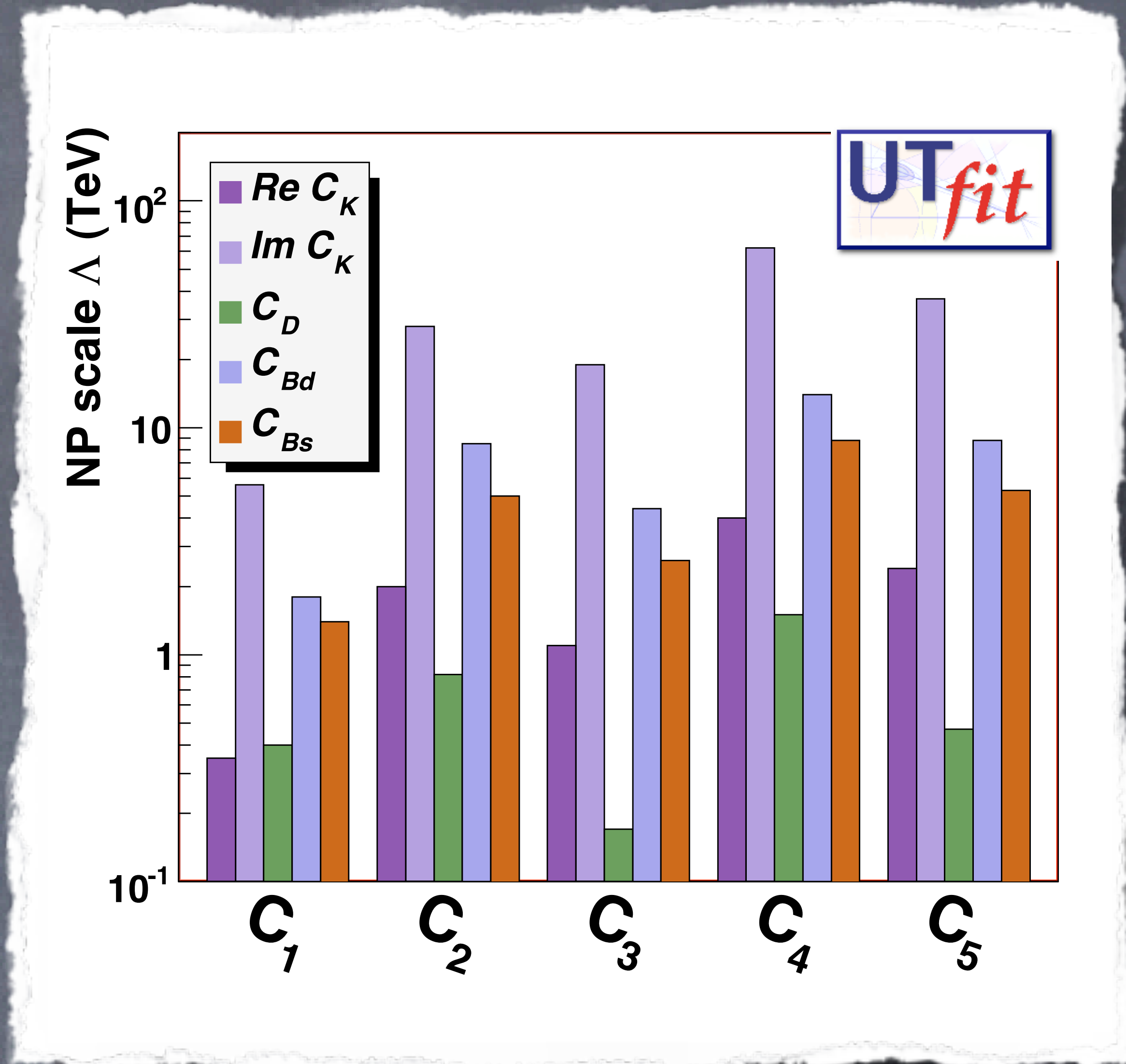
$(d\bar{s})$ transforms as (8,1,1) so the int. should be prop. to $(Y_u Y_u^\dagger)_{12} = y_t^2 V_{td} V_{ts}^*$

$$C^1_{sd} \propto g_\star^2 y_t^4 |V_{td}|^2 |V_{ts}|^2 \sim 10^{-7} g_\star^2$$

bound on the scale of new physics is reduced by $\sqrt{10^{-7}}$: 1100 TeV $\Rrightarrow$ 350 GeV



MFV



~ Supersymmetry ~

gauge-, gaugino-, anomaly-mediated susy breaking have MFV structure

gravity-mediated doesn't

~ Other models of EW symmetry breaking ~

?

Flavour Structure in EWSB Models

- Is there a flavour structure built-in in the new models of EWSB?
- Is an additional flavour structure needed?

They are clearly model-dependent questions
Nonetheless generic features emerge

Weakly coupled models

prototype: Susy

susy partners ~ 100 GeV

Can exhibit MFV structure

Strongly coupled models

prototype: Technicolor

rho meson ~ 1 TeV

Notoriously difficult for old TC models:

1/ to generate flavour hierarchy

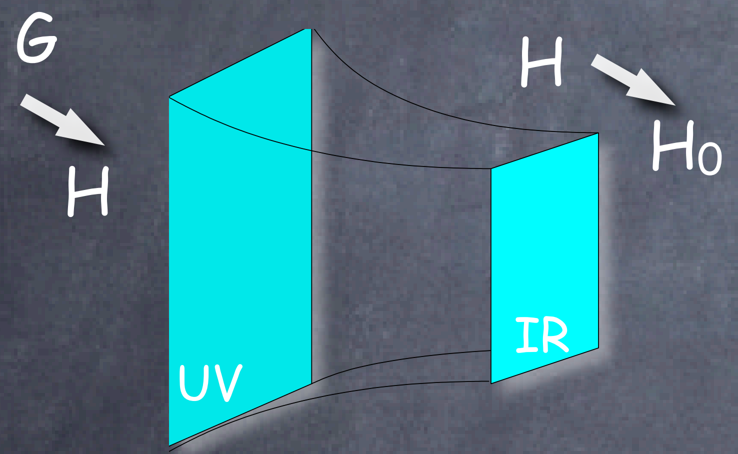
2/ to implement flavour symmetry to suppress FCNC

New twist thanks to 5D holographic approach

Holographic Approach to Strong Sector

"AdS/CFT" correspondence for model-builder

Warped gravity with fermions and gauge field in the bulk and Higgs on the brane ⟺ Strongly coupled theory with slowly-running couplings in 4D



AdS = warped space

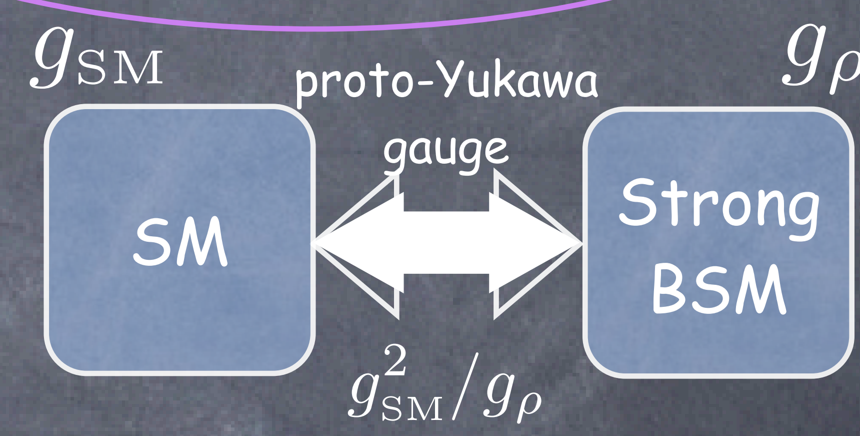
curvature ~ $1/M_{Pl}$

size ~ $40/M_{Pl}$

$$ds^2 = \left(\frac{R}{z}\right)^2 (dx^2 - dz^2)$$

exponential red-shift

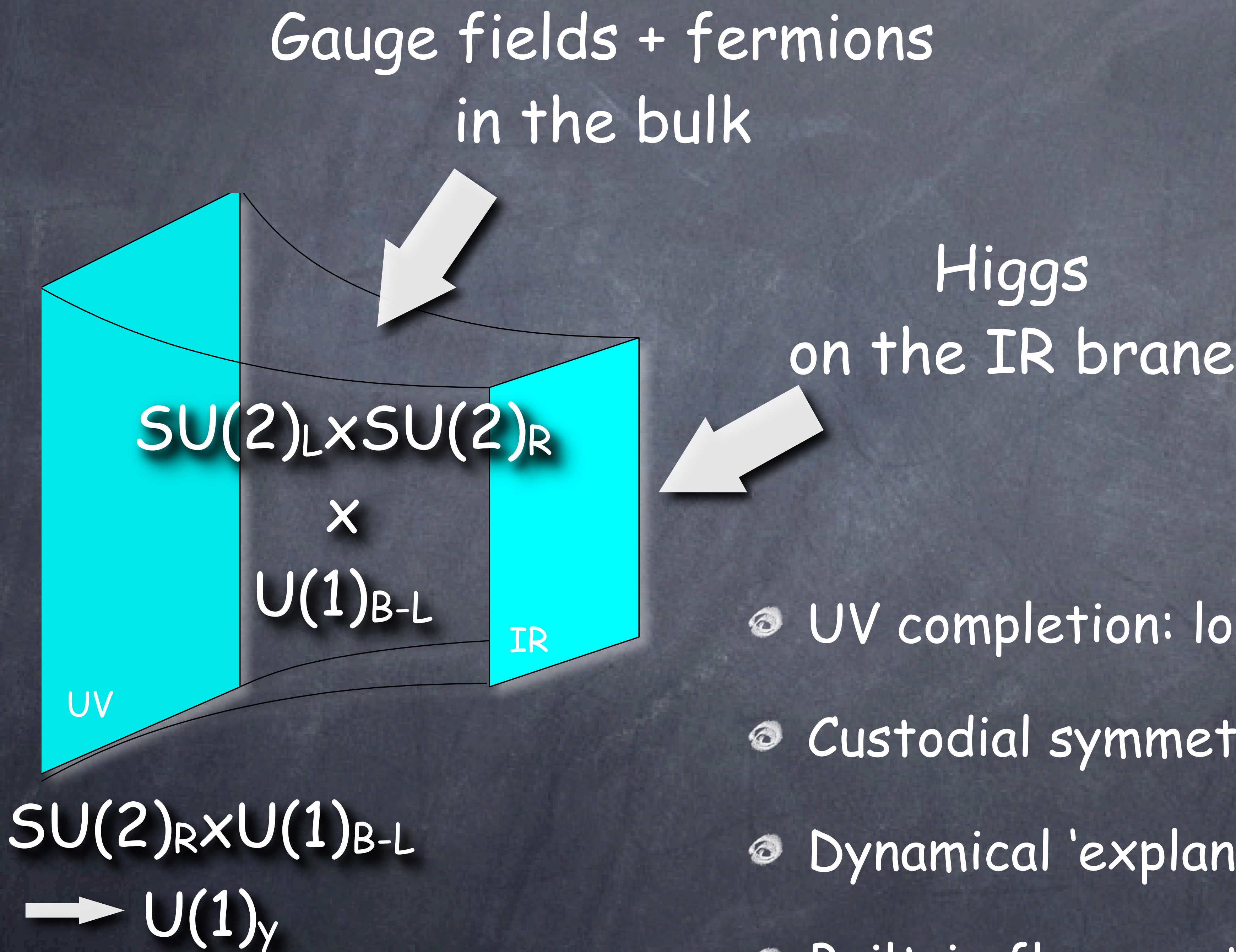
$$\frac{R_{UV}}{R_{IR}} \sim 10^{-16}$$



5D	4D
KK modes	vector resonances (ρ mesons in QCD)
motion along 5th dim	RG flow
UV brane	UV cutoff
IR brane	break. of conformal inv.
bulk local sym.	global sym.

Holographic Models of EWSB

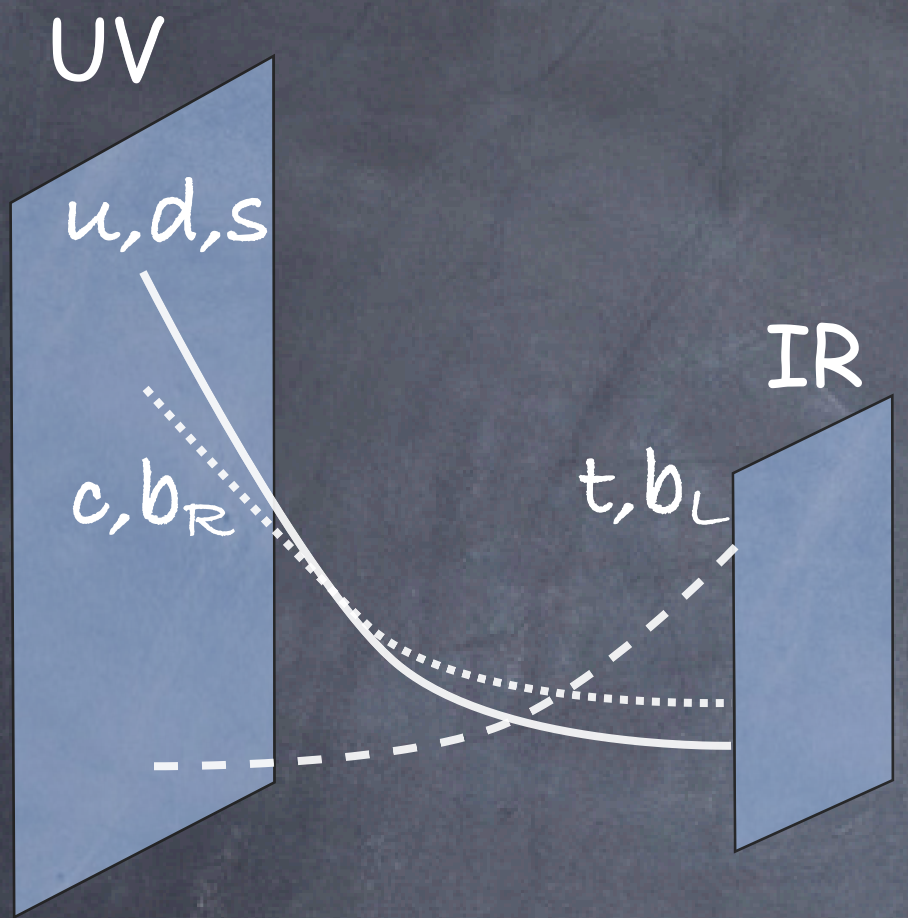
Brane SM fields: [Randall,Sundrum, '99]
Bulk gauge fields: [Pomarol, '00]
Holographic technicolor=Higgsless: [Csaki et al., '03]
Holographic composite Higgs: [Agashe et al., '04]



- UV completion: log running of gauge couplings
- Custodial symmetry from bulk $SU(2)_R$
- Dynamical 'explanation' of fermion masses
- Built-in flavour structure

Masses from IR overlaps

[Grossman and Neubert, '00]
[Gherghetta and Pomarol, '00]
[Huber, '03]



fermion zero-mode has an exponential profile in the bulk

$$\chi(z) = \frac{f_c}{\sqrt{R'}}\left(\frac{z}{R}\right)^2\left(\frac{z}{R'}\right)^{-c}$$

f_c is the "value" of wavefct. on the IR:

$$f_c = \sqrt{\frac{1-2c}{1-(R/R')^{1-2c}}}$$

c < 1/2: heavy fermion $f_c \sim \mathcal{O}(1)$

c > 1/2: light fermion $f_c \sim (R/R')^{c-1/2} \ll 1$

light fermion exponentially localized on the UV brane

➲ overlap with Higgs vev on the IR tiny

➲ exponentially small 4D mass

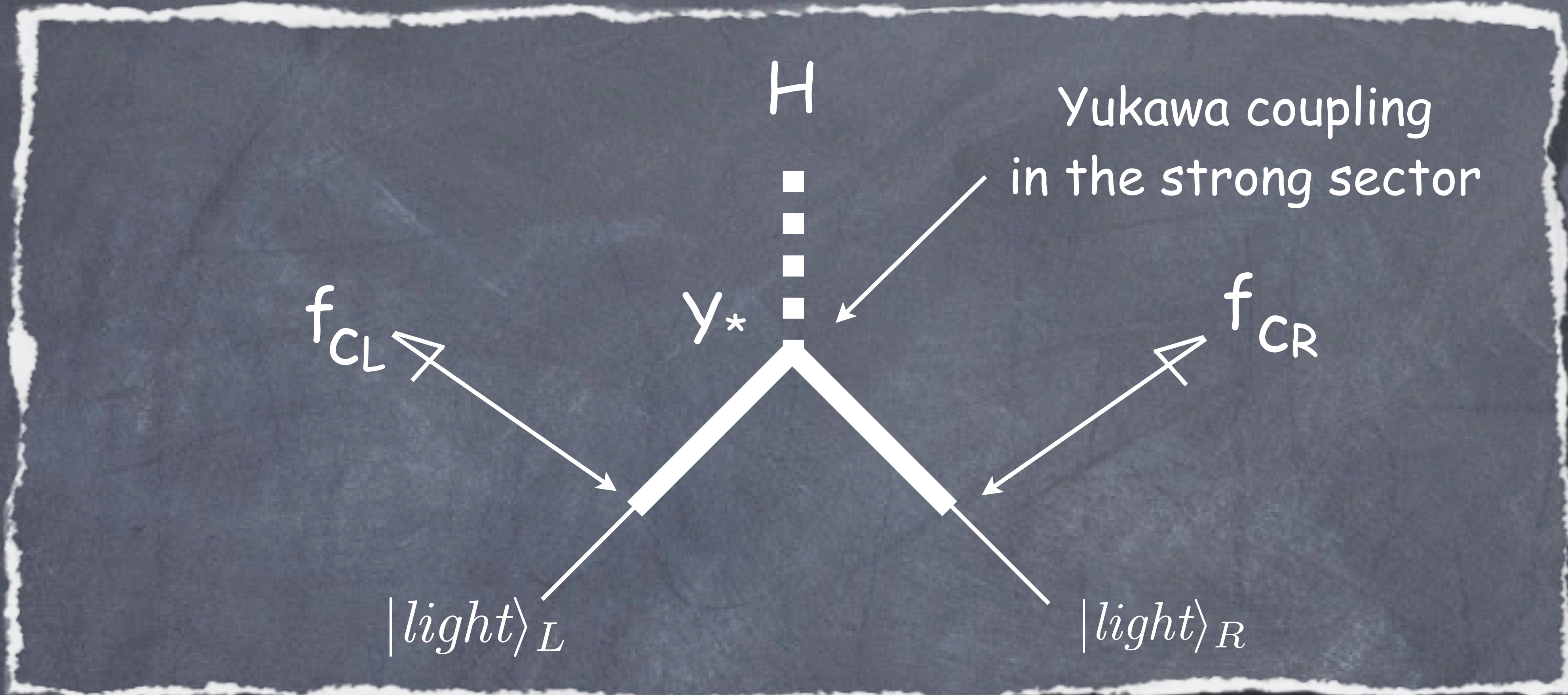
partial compositeness

zero is mixture of elementary and composite fermion

f_c is the amount of compositness

Partial Compositeness: Yukawa Couplings

Higgs part of the strong sector: it couples only to composite fermions



when the Higgs gets a vev, the light dof will acquire a mass prop. to

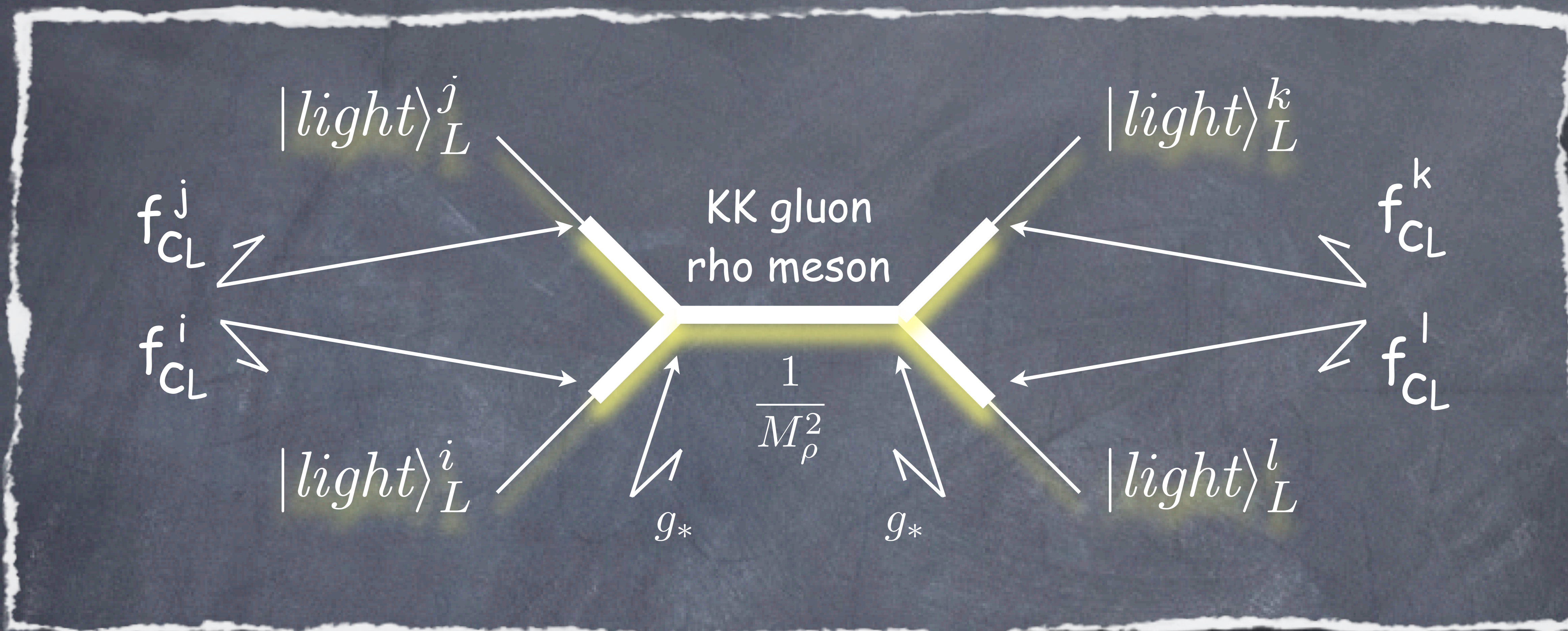
$$Y^{eff} = Y_\star \, f_{c_L} f_{c_R}$$

Yukawa hierarchy comes from the hierarchy of compositeness

~ the 5D picture gives a rationale for hierarchical f_c ~

FCNC from KK gluons/rho meson

Agashe, Perez, Soni '04
Contino, Kramer, Son, Sundrum '06



$$\mathcal{A}^{ijkl}_{LL} \sim \frac{g_\star^2}{m_\rho^2} f_{c^i_L} f_{c^j_L} f_{c^k_L} f_{c^l_L}$$

Built-in GIM supression

smaller the mass ⊃ smaller the compositness ⊃ smaller the amplitude

structure similar to the general set-up recently proposed by Davidson et al.

"Solving the flavour problem with hierarchical fermion wave functions", 0711.3376

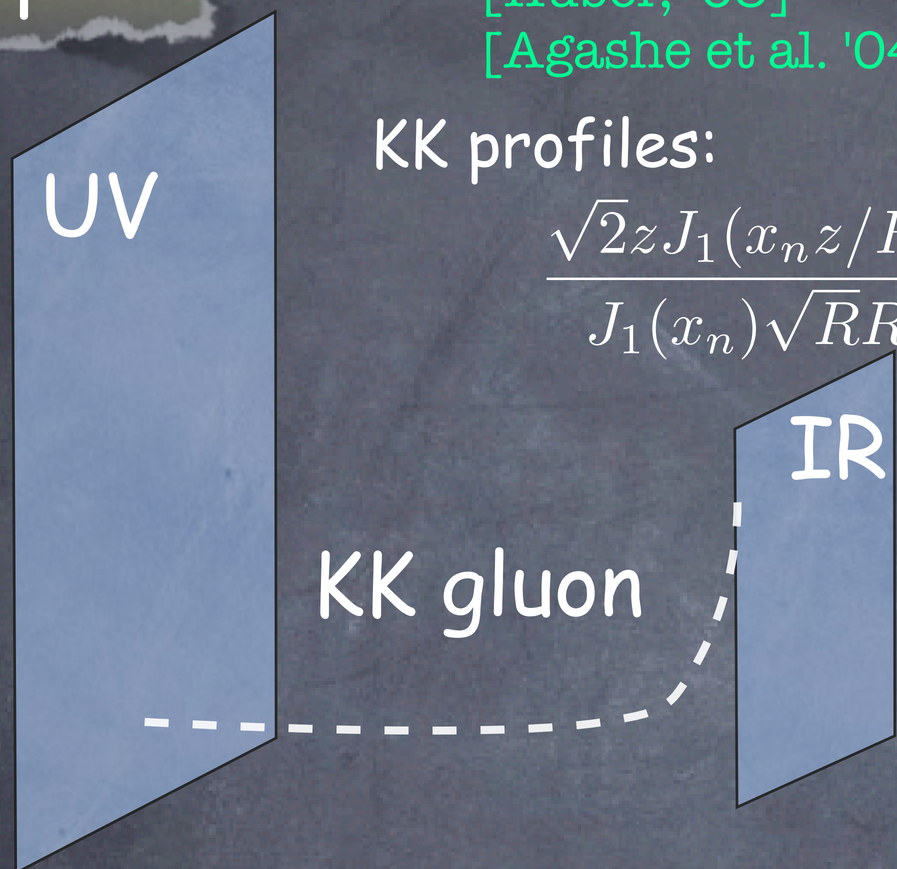
RS-GIM suppression of FCNC

warped

[Gherghetta, Pomarol '00]
[Huber, '03]
[Agashe et al. '04]

KK profiles:

$$\frac{\sqrt{2} z J_1(x_n z/R')}{J_1(x_n)\sqrt{R R'}}$$



KK gluons are flat in UV ⊃ flavor universal
flavor violation are coming from IR
FCNC are suppressed for light fermions

$$g_{\tilde{g}_{KK} Q^i_L Q^i_L} \sim g_\star \left(-\frac{\mathcal{O}(1)}{\log R'/R} + \mathcal{O}(1) f^2_{c^i_L} \right)$$

$$\Downarrow$$

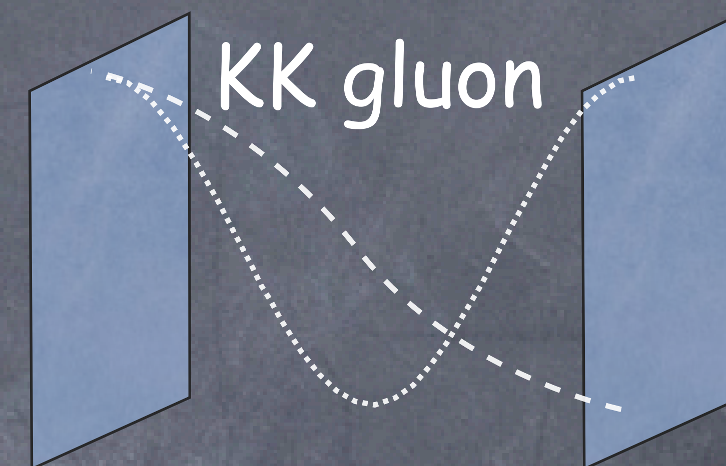
$$g_{\tilde{g}_{KK} Q^i_L Q^j_L} \propto g_\star f_{c^i_L} f_{c^j_L}$$

"low" KK scale allowed

flat

KK profiles:

$$\sqrt{\frac{2}{L}} \cos(n\pi z/L)$$



KK gluons are spread along the extra-dim.
feel all differences in fermion profiles
maximal flavour violation

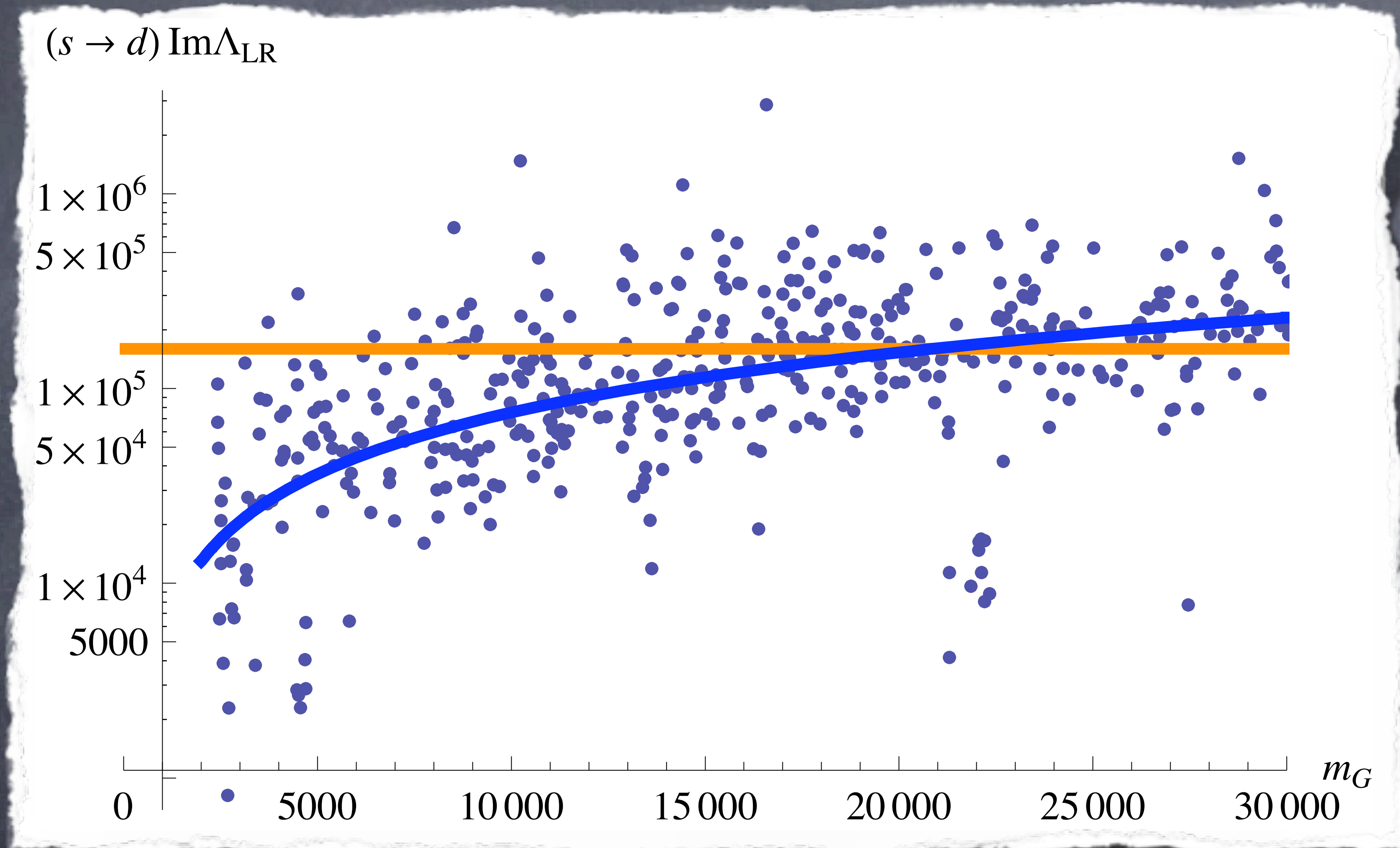
"high" KK scale required

Flavour Bounds in RS

[Csaki et al. '08]
[Neubert's group, '08]
[Buras' group, '08]

more stringent constraint from LR operator in K sector (ε_K)

exp. bound



$$\mathcal{A}_{LR}^{ds} \approx \mathcal{A}_{SM}\left(1 + 0.5\left(\frac{21 \text{ TeV}}{m_{KK}}\right)\right)$$

generically: flavour bounds are safe if KK gluon > 21 TeV

few (exceptional?) points pass flavour constraints with lower m_{KK}

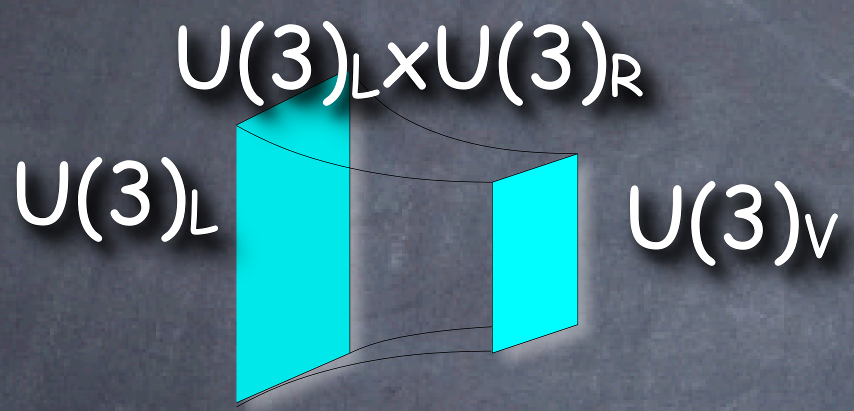
any rationale to live at those points?

Adding Flavour Structure to RS-GIM

- Minimal Flavour Violation in RS [Fitzpatrick, Perez, Randall '07]

  follows from additional alignment of bulk masses and brane Yukawa

- Exact GIM structure [Cacciapaglia et al. '07]



  flavour sym. in the bulk
  universal IR brane masses
  flavour violation only on the UV brane
  ... but fermion mass hierarchy put by hand

- Minimal flavour protection [Santiago '08]

  U(3) flavour symmetry broken on the IR brane

- Simple flavour protection [Csaki, Falkowski, Weiler '08]

  U(1) flavour sym. in down sector in bulk and IR broken on UV
  most of flavour violation is moved to the up sector

- ...[more models to be build]

Conclusions

New Physics can help to solve the SM flavour puzzle(s)

but generically will give rise to large FCNC

This is the BSM flavour problem

Some models of EW symmetry breaking automatically incorporate
a dynamical suppression of FCNC à la GIM
Other models require additional flavor structure/symmetry

LHC might be start telling us the structure of flavor in new physics

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... let us wait until tomorrow