Review of flavor in warped models

Andreas Weiler
CERN

Moriond 2011

16/3/2011

1) Can we have a sensible flavor sector without an (elementary) Higgs?

2) Does it survive the constraints from Kaon physics and the B factories?

3) Predictions for the LHC?

Weak scale is unstable

elementary scalar Higgs

$$\mathcal{L}_{Higgs} = \Lambda^2 H^2 + \ldots$$ ✘

Solution: no elementary scalar

composite Higgs (bound-state, like pion in QCD)

$$\mathcal{H} \to \langle \psi_{TC} \psi_{TC}^c \rangle \qquad [\mathcal{H}] \approx 3$$

Solution: no elementary scalar

composite Higgs (bound-state, like pion in QCD)

$$\mathcal{H} \to \langle \psi_{TC} \psi^c_{TC} \rangle \qquad [\mathcal{H}] \approx 3$$

$$\mathcal{L}_{Higgs} = \frac{1}{\Lambda^2}\mathcal{H}^2 + \ldots$$ ✔

Flavor without an elementary Higgs

Yukawas (CKM, masses)

$$y_{ij}\,\bar{\psi}_i H \psi_j$$

SM

Flavor without an elementary Higgs

Yukawas (CKM, masses)

$$[\mathcal{H}] \approx 3$$

$$y_{ij}\,\bar{\psi}_i H \psi_j \;\Rightarrow\; \frac{1}{\Lambda^2} y_{ij}\,\bar{\psi}_i \mathcal{H} \psi_j$$

SM

composite

Flavor problem

$$\frac{1}{\Lambda^2} y_{ij}\, \bar{\psi}_i \mathcal{H} \psi_j + \frac{1}{\Lambda^2} c_{ijkl}\, \bar{\psi}_i \psi_j \bar{\psi}_k \psi_l$$

can't be too small,
because top mass
large

$$\Lambda = \mathcal{O}(\mathrm{TeV})$$

Flavor problem

$$\frac{1}{\Lambda^2} y_{ij}\, \bar{\psi}_i \mathcal{H} \psi_j + \frac{1}{\Lambda^2} c_{ijkl}\, \bar{\psi}_i \psi_j \bar{\psi}_k \psi_l$$

can't be too small, because top mass large

must be very small because this leads to FCNCs

$K^0 - \bar{K}^0$

$$\Lambda = \mathcal{O}(\mathrm{TeV})$$

$$\Lambda > 10^5\ \mathrm{TeV}$$

Two ways of giving mass to fermions…

Bi-linear (like SM):

$$\mathcal{L} = y f_L \mathcal{O}_H f_R, \quad \mathcal{O}_H \sim (1,2)_{\frac{1}{2}}$$

Linear:

D.B. Kaplan '91

$$\mathcal{L} = y f_L \mathcal{O}_R + y_R f_R \mathcal{O}_L + m \mathcal{O}_L \mathcal{O}_R, \quad \mathcal{O}_R \sim (3,2)_{\frac{1}{6}}$$

Partial compositeness

$$|SM\rangle = \cos\phi|elem.\rangle + \sin\phi|comp.\rangle$$

$$|heavy\rangle = -\sin\phi|elem.\rangle + \cos\phi|comp.\rangle$$

Composites are heavy ($m_\rho \approx \mathrm{TeV}$).

Light quarks have very little composite admixture.

strong sector

elementary fields

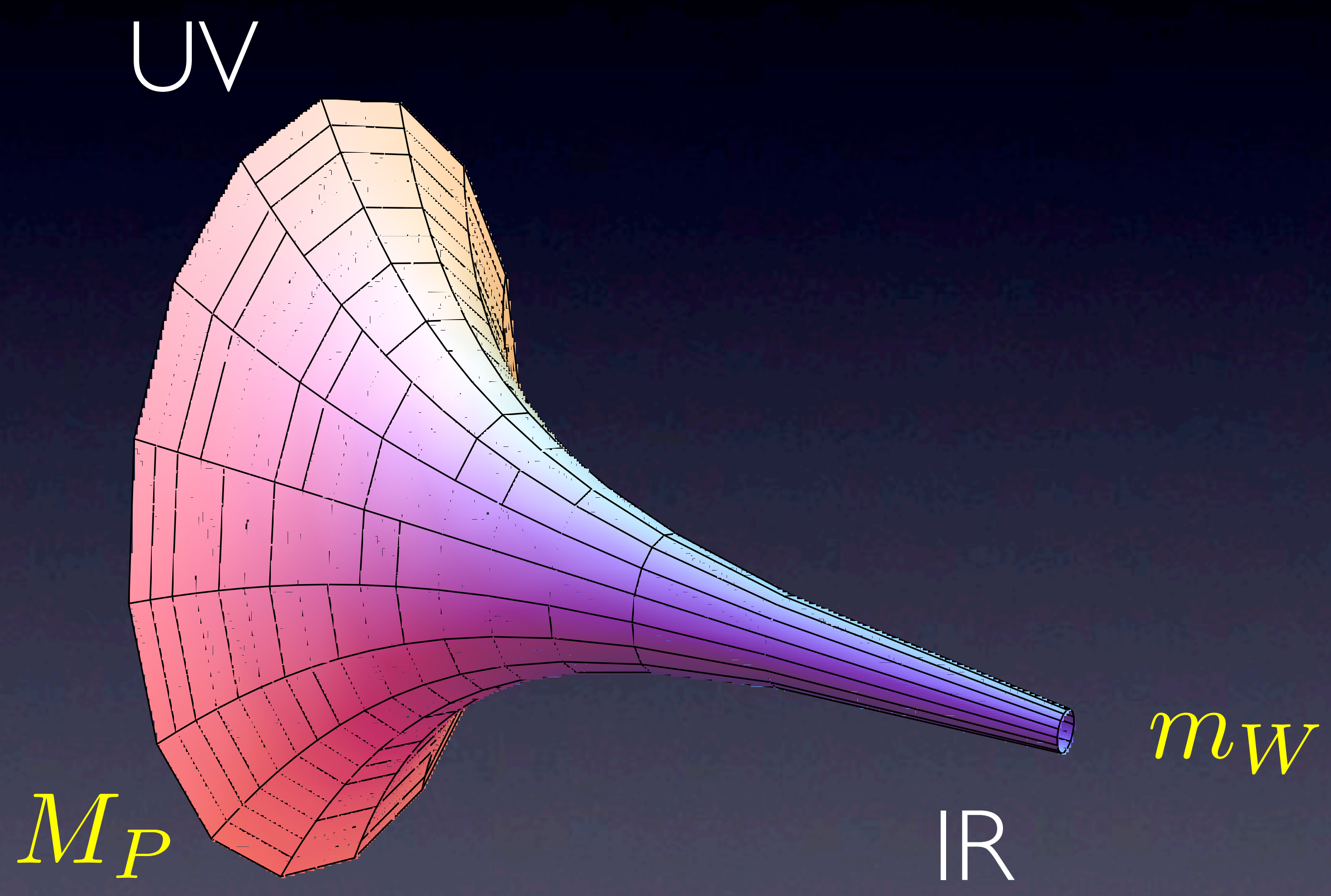
u, d, c, s, b, A_μ

$g_*,\ m_\rho$

$1 \lesssim g_* \lesssim 4\pi$

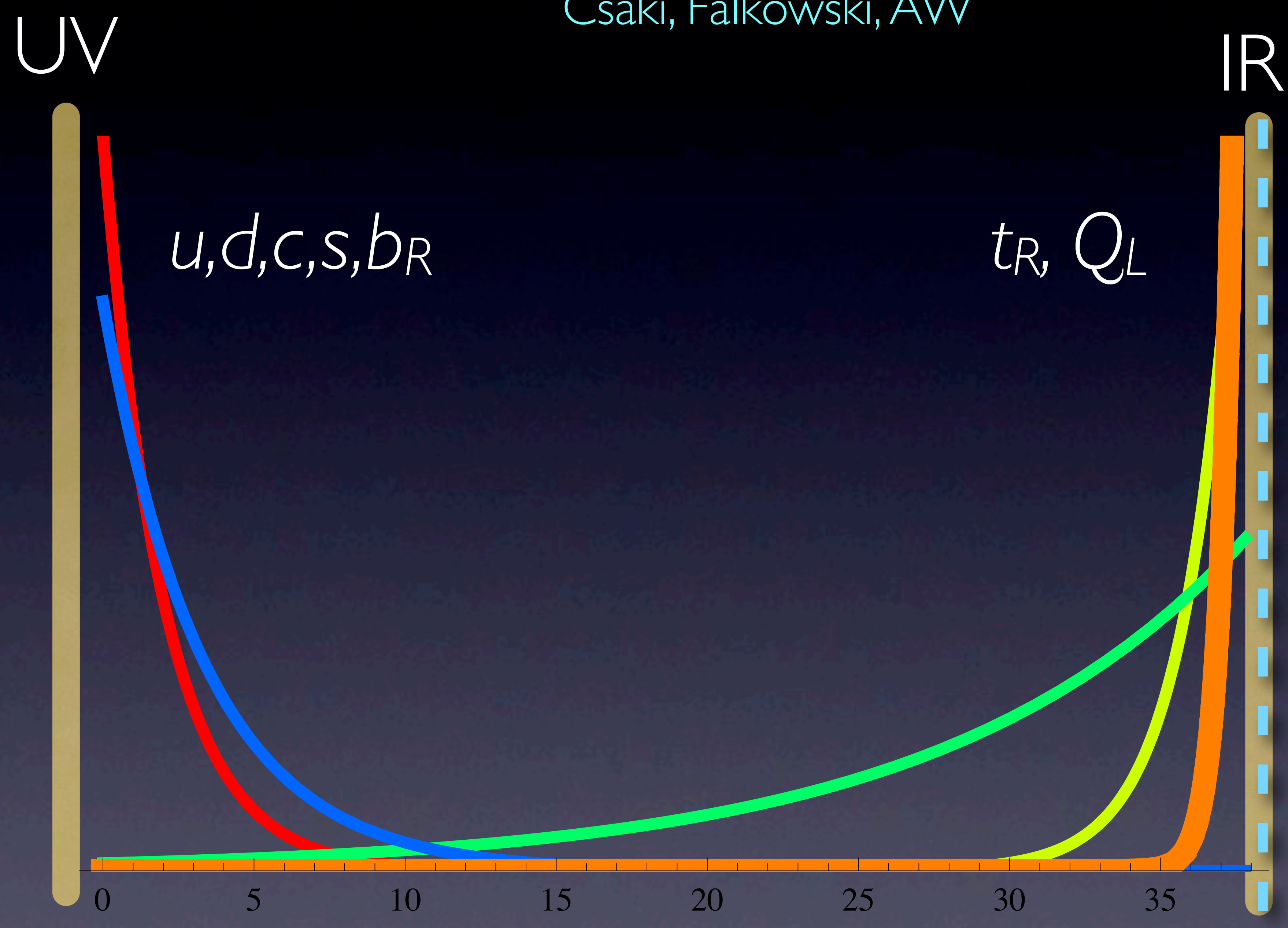
AdS/CFT => Randall Sundrum

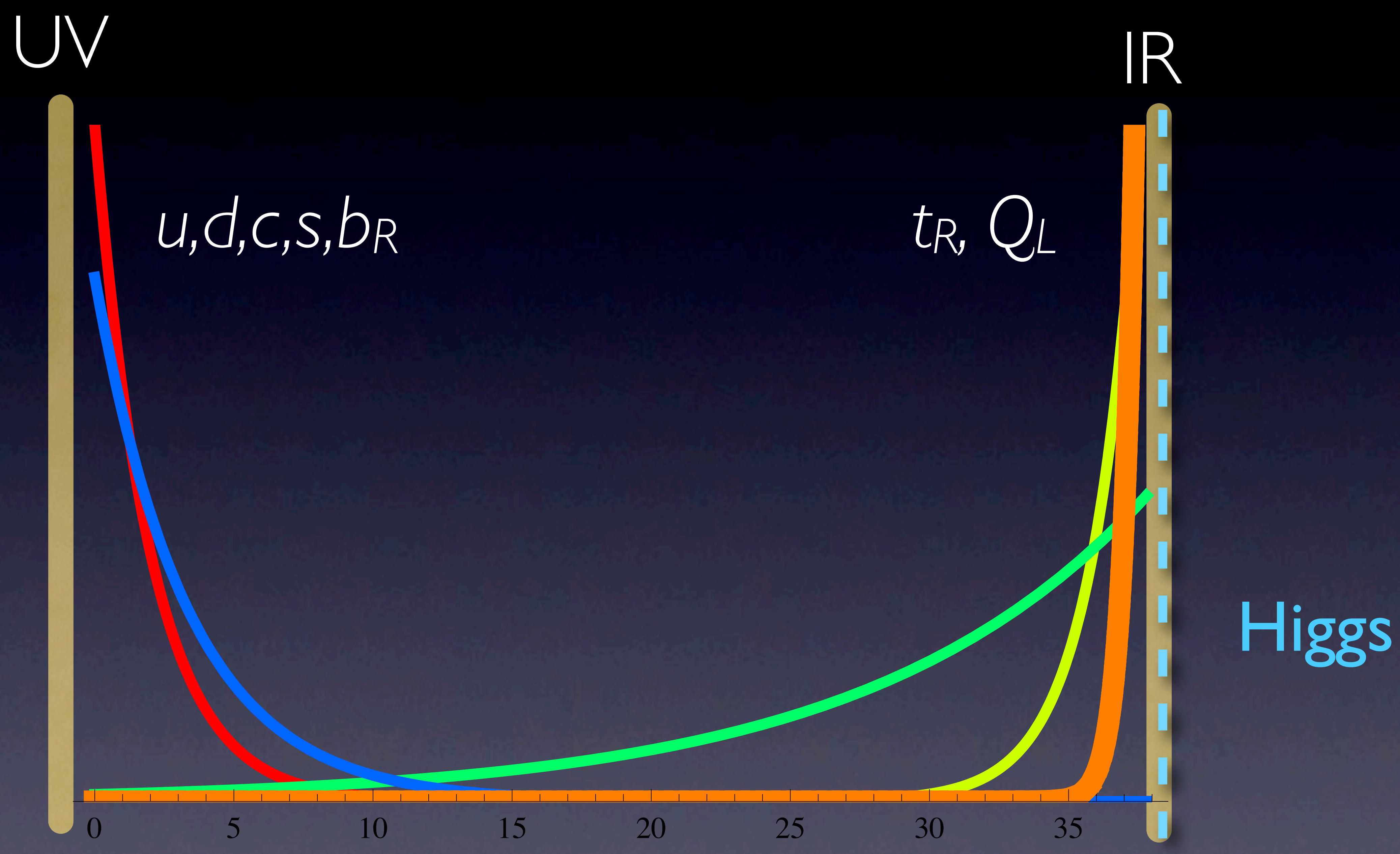
$$ds^2 = \left(\frac{R}{z}\right)^2 (dx_\mu dx_\nu - dz^2)$$

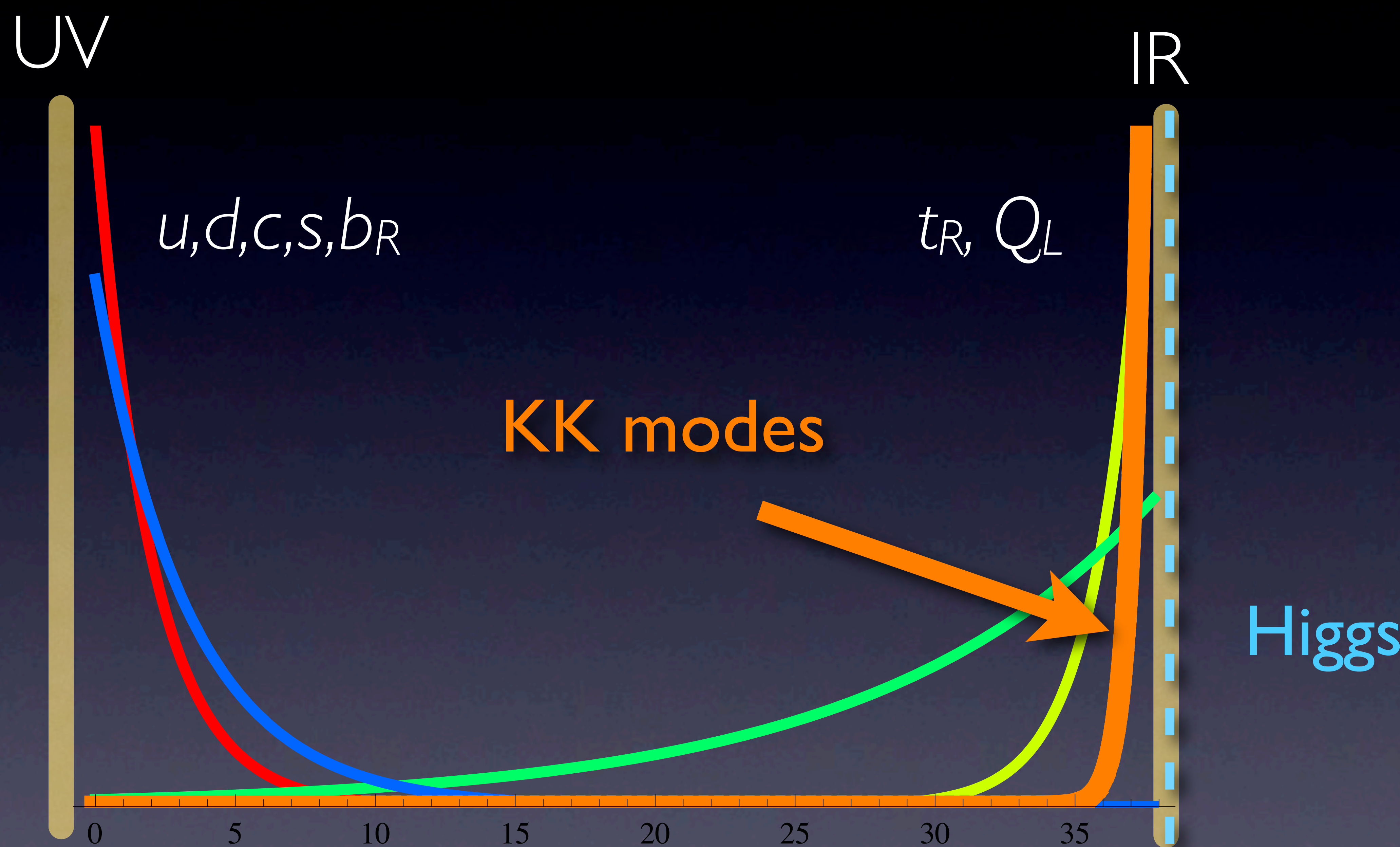


Geometrical sequestering in RS

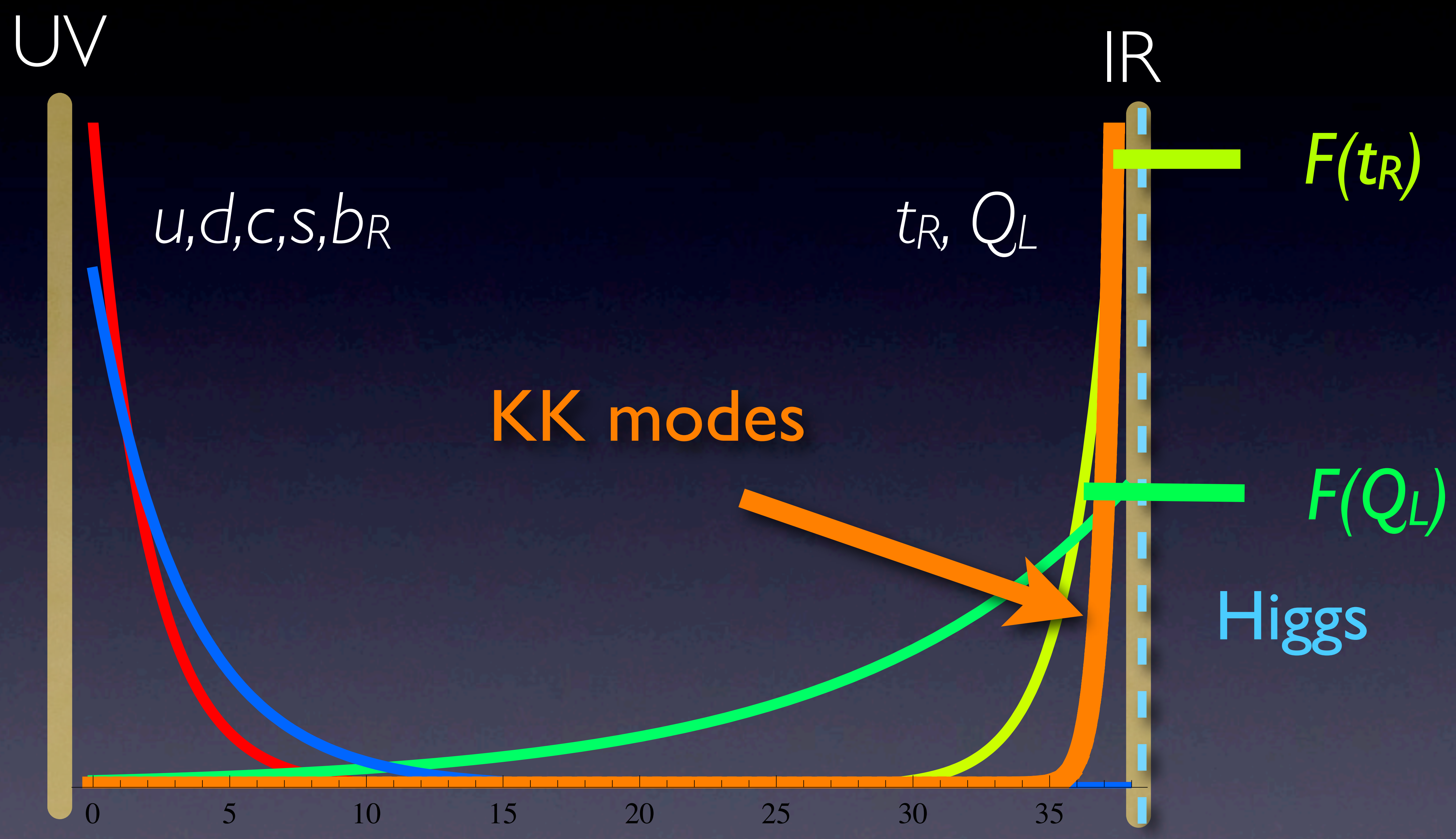
Gherghetta, Pomarol; Huber, Shafi; Agashe et. al
Csaki, Falkowski, AW



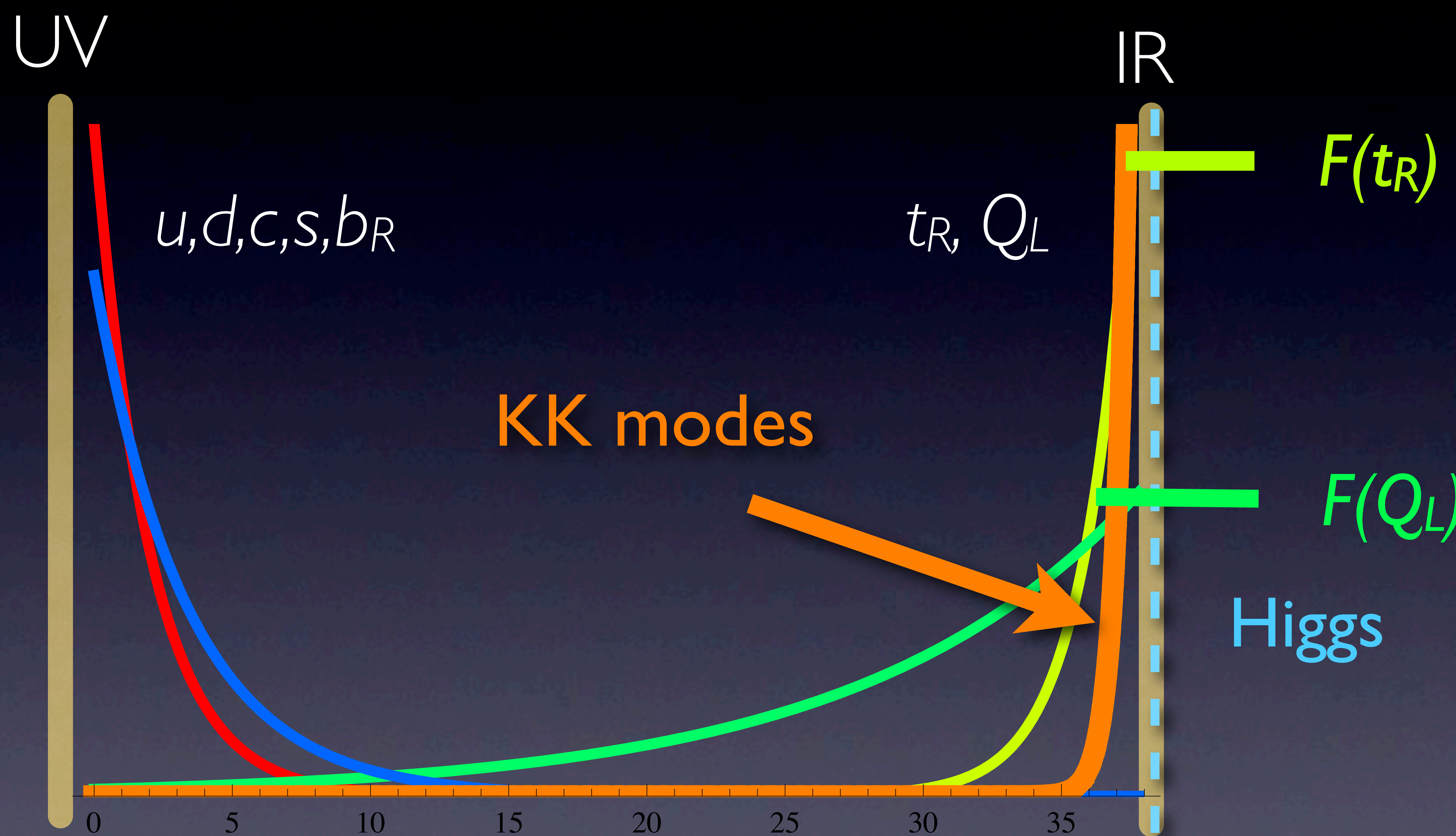

UV
IR
u,d,c,s,bR
tR, QL
Higgs
0
5
10
15
20
25
30
35



UV
IR
u,d,c,s,bR
tR, QL
KK modes
Higgs
0
5
10
15
20
25
30
35

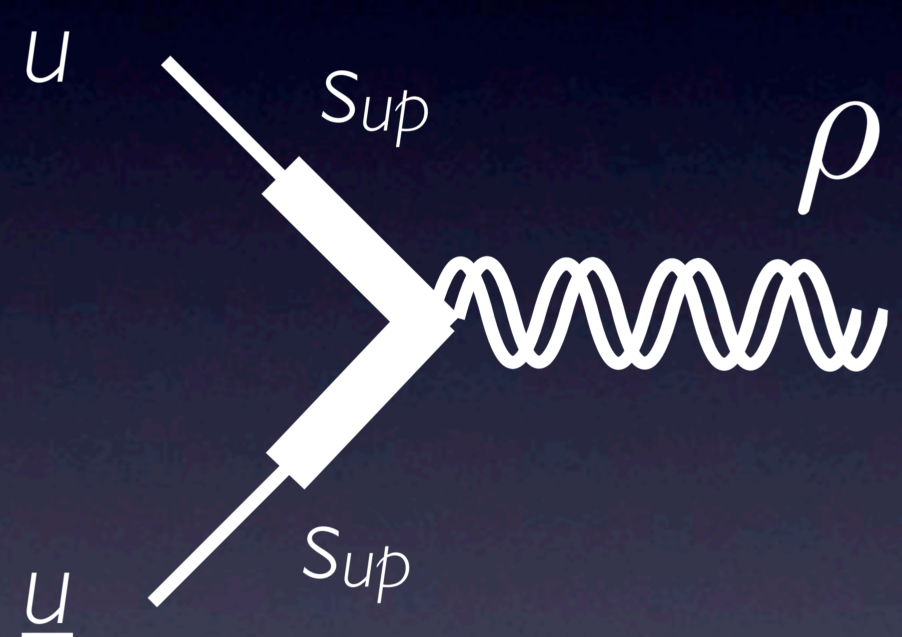

UV
IR
u,d,c,s,b_R
t_R, Q_L
$F(t_R)$
KK modes
$F(Q_L)$
Higgs
0
5
10
15
20
25
30
35

Degree of compositeness: $\sin\phi = F(c) \sim \left(\frac{\mathrm{TeV}}{\mathrm{M}_{\mathrm{pl}}}\right)^{c-\frac{1}{2}}$



LHC implications

Resonance production (option 1)



$$\sim g_*^2 \sin^2 \theta_{u_R}$$

strongly suppressed for light quarks!

LHC implications

Resonance production (option 2)

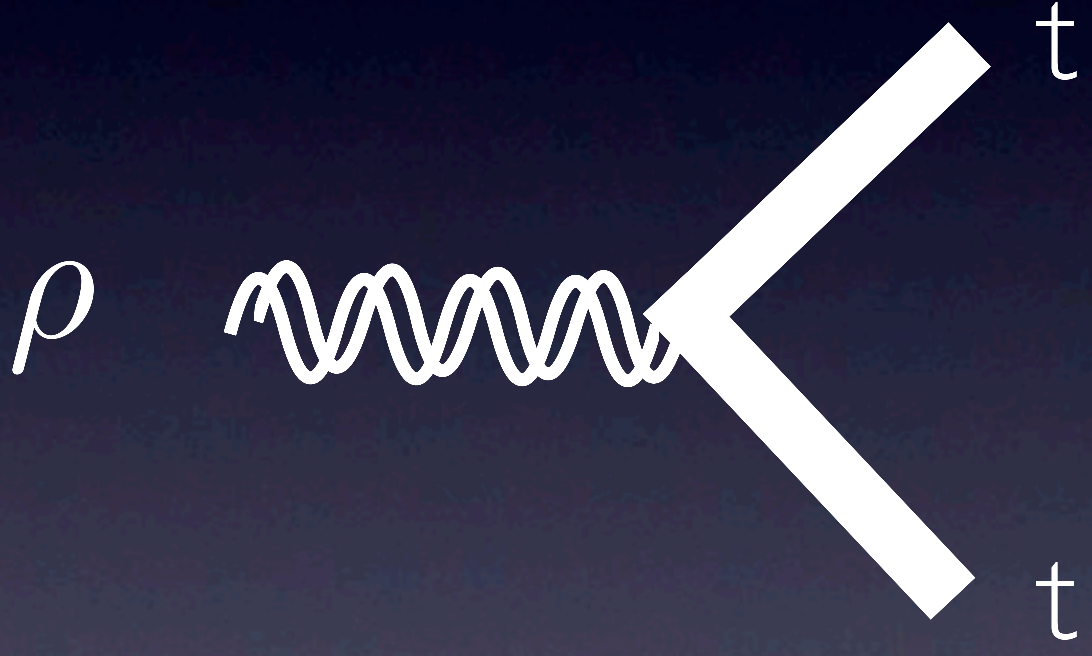
$$\sim \frac{g_s}{g*}$$

similar to $\gamma - \rho$ mixing

NB, gluon-rho-rho = 0

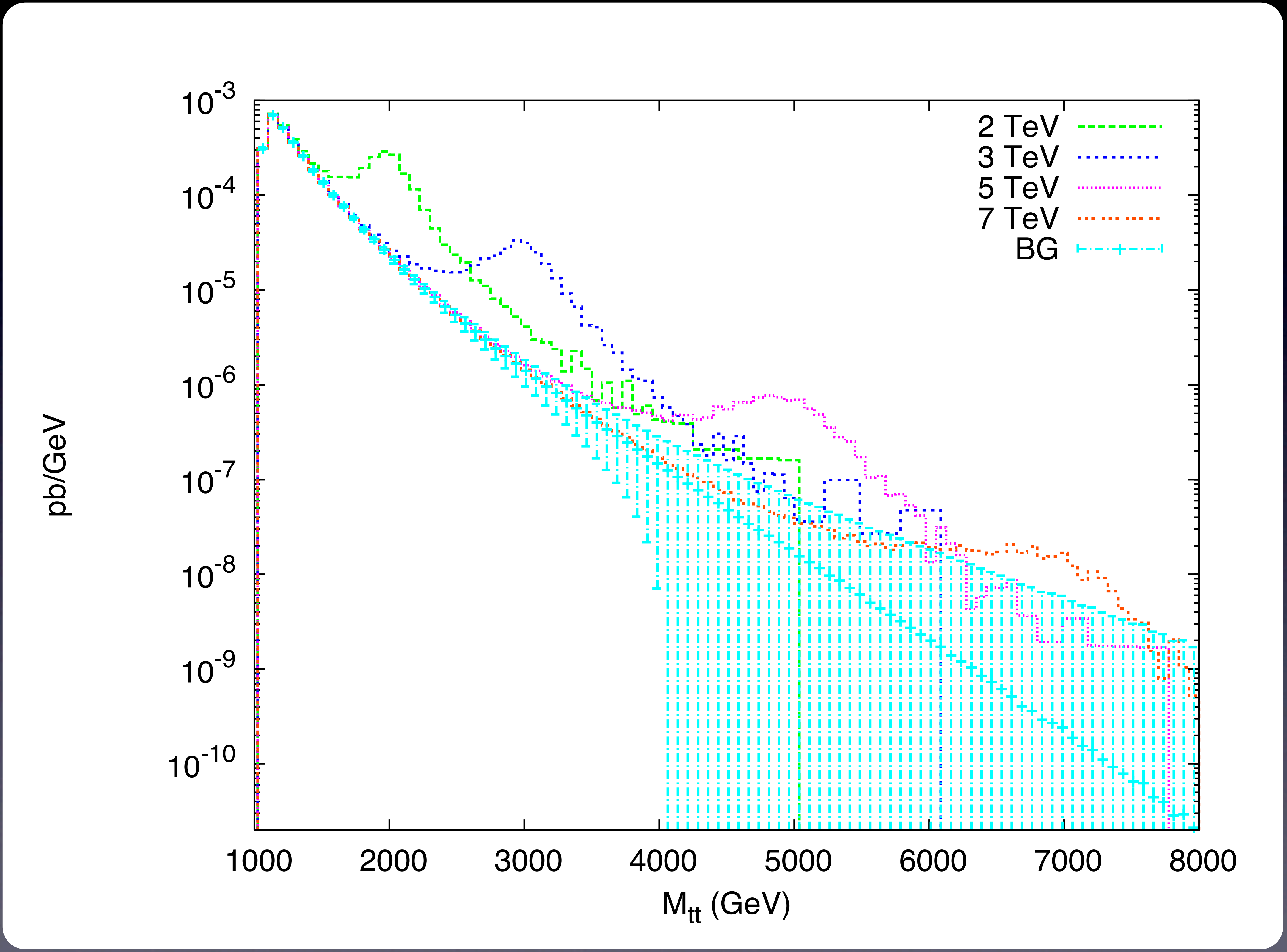
LHC implications

Resonance decay



decays dominantly into 3rd generation (tt, bt, bb)

tops mostly collimated, need sub-jet top tagger

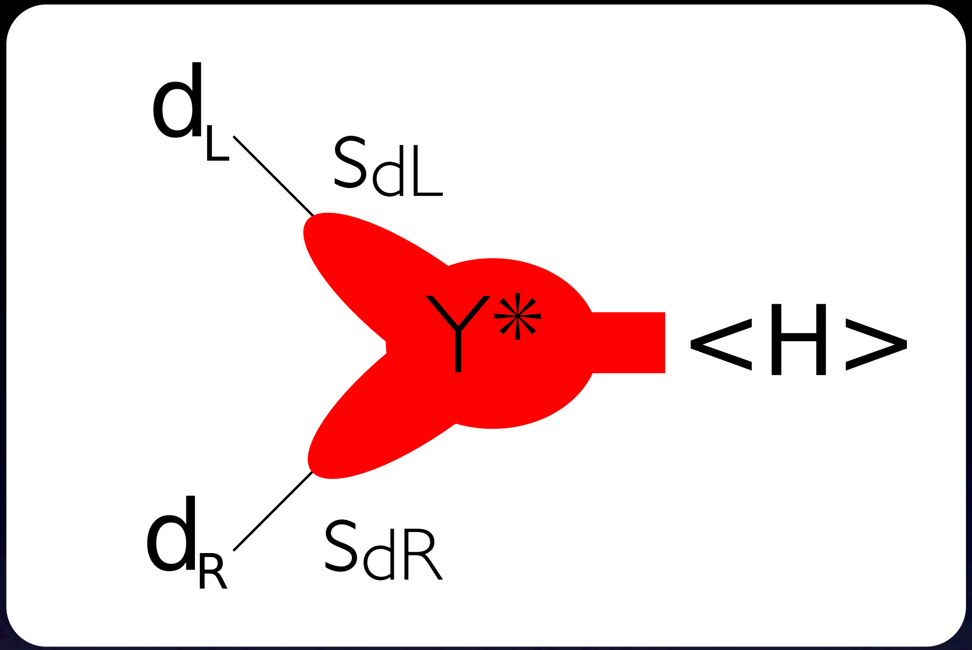


Agashe et al, Lillie et al

FCNCs

FCNC protection

Gherghetta, Pomarol; Huber;Agashe, Perez, Soni;



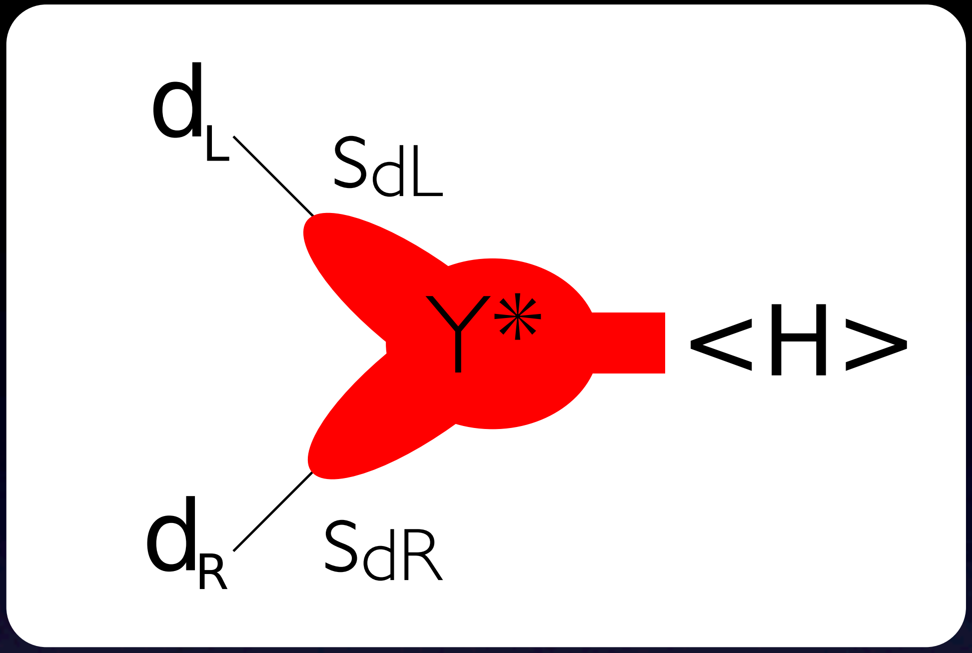
masses from mixing in composites

$$m_d \sim v \sin\theta_{d_L} Y^* \sin\theta_{d_R}$$

$$K^0 - \bar{K}^0$$

FCNC protection

Gherghetta, Pomarol; Huber;Agashe, Perez, Soni;



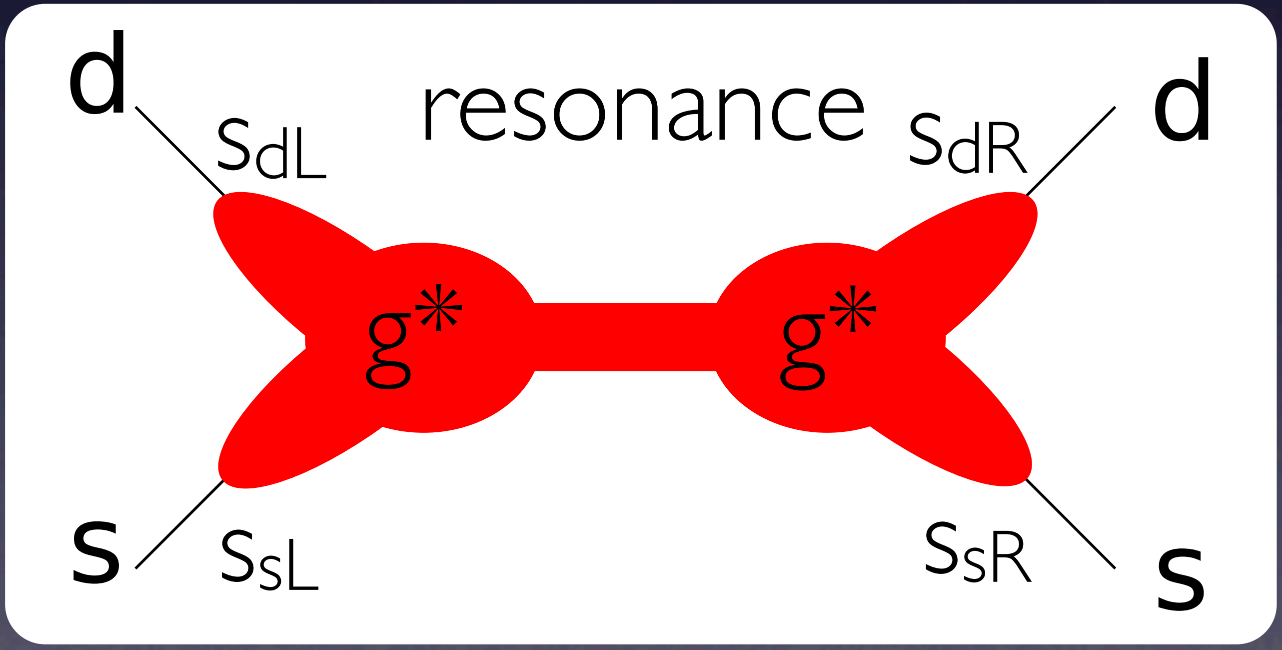
masses from mixing in composites

$$m_d \sim v \sin\theta_{d_L} Y^* \sin\theta_{d_R}$$

FCNCs suppressed by the same mixings

$$\sim \frac{g_*^2}{M_\rho^2} s_{d_L} s_{d_R} s_{s_L} s_{s_R}$$

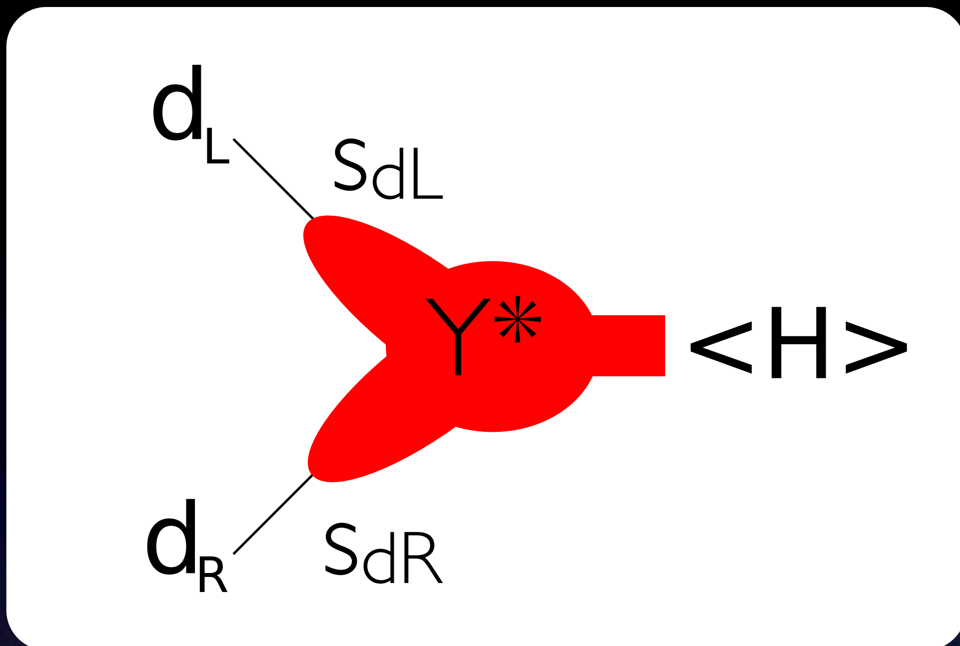
$$\sim \frac{g_*^2}{M_\rho^2} \frac{m_d m_s}{v Y_*^2}$$



$$K^0 - \bar{K}^0$$

FCNC protection

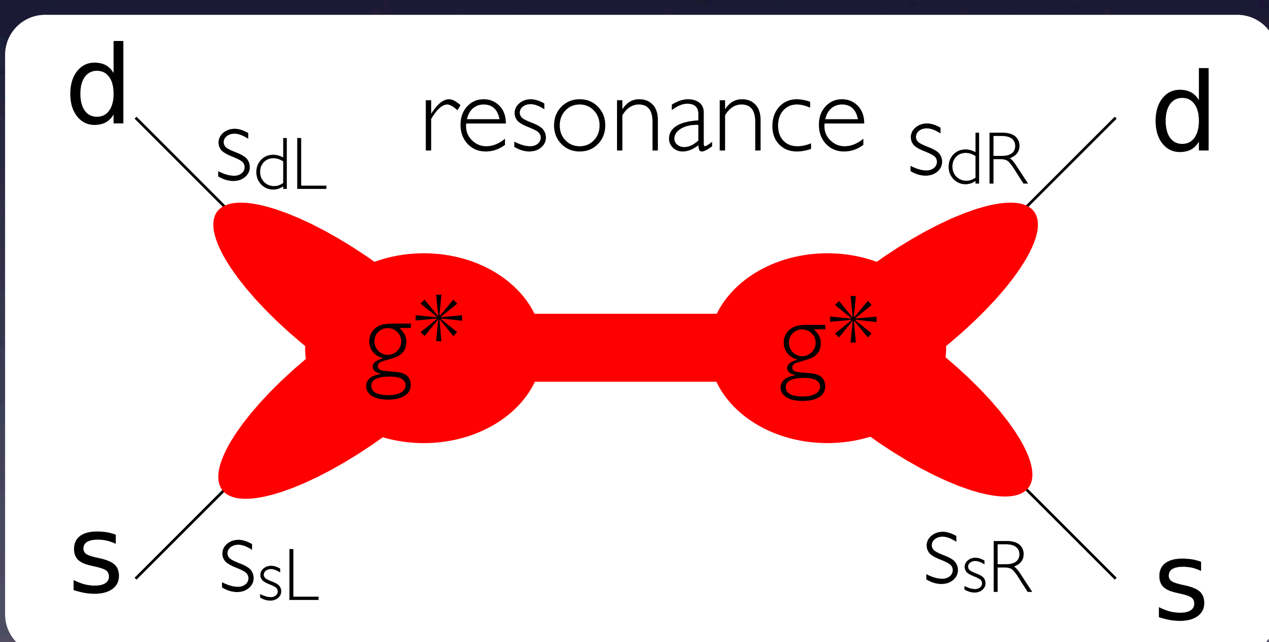
Gherghetta, Pomarol; Huber;Agashe, Perez, Soni;



masses from mixing in composites

$$m_d \sim v \sin\theta_{d_L} Y^* \sin\theta_{d_R}$$

FCNCs suppressed by the same mixings



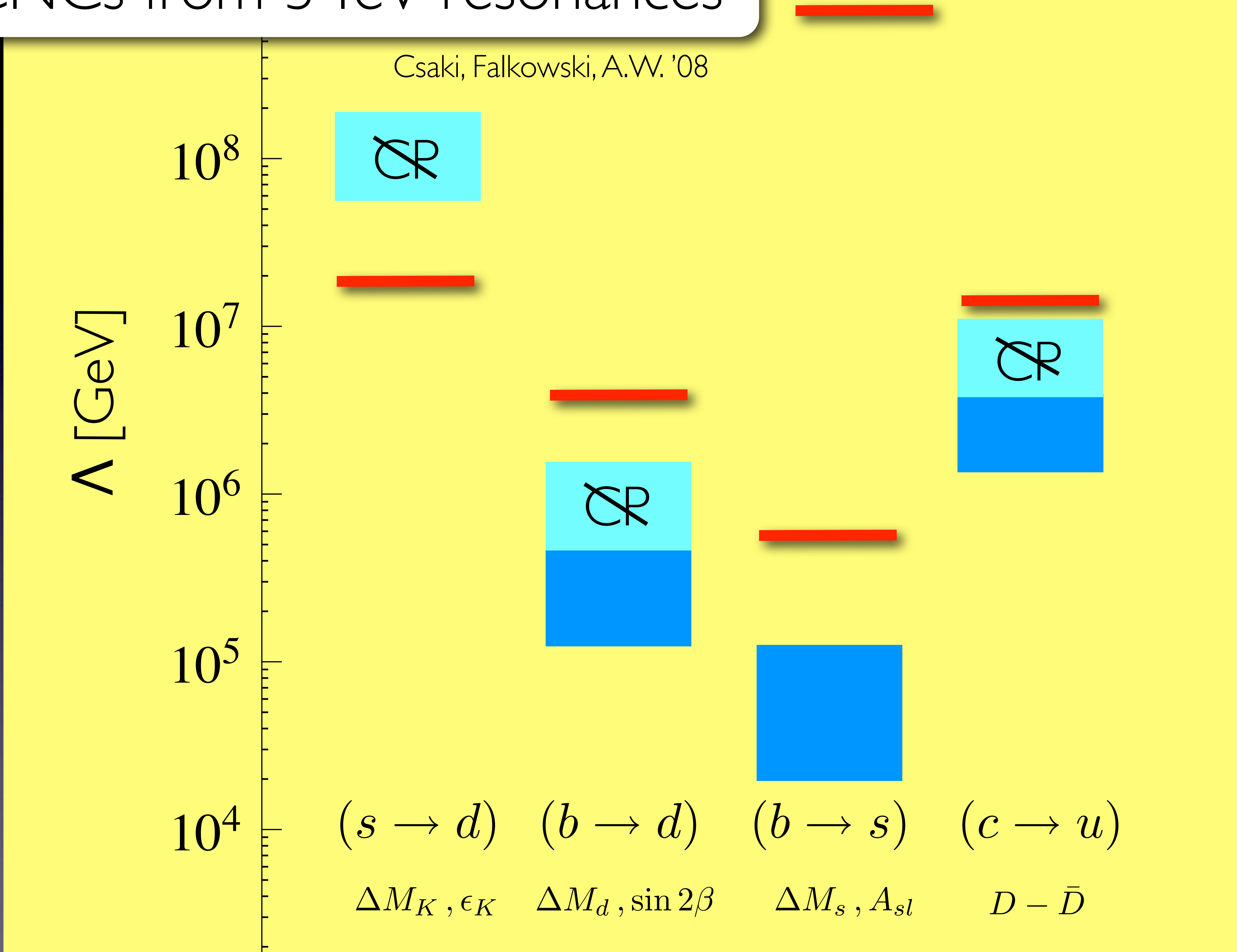
$$\sim \frac{g_*^2}{M_\rho^2} s_{d_L} s_{d_R} s_{s_L} s_{s_R}$$

$$\sim \frac{g_*^2}{M_\rho^2} \frac{m_d m_s}{v Y_*^2}$$

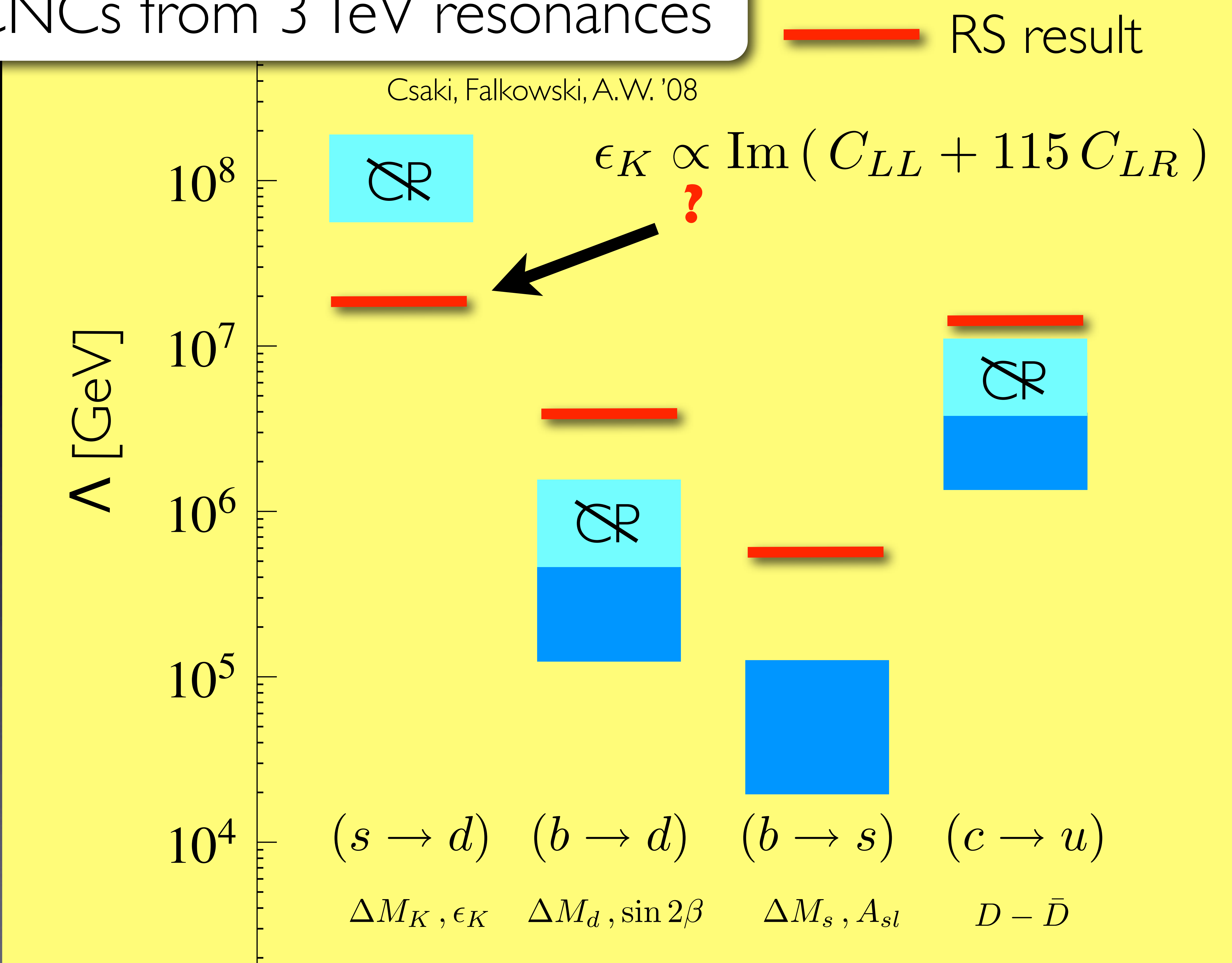
RS-GIM

$$K^0 - \bar{K}^0$$

FCNCs from 3 TeV resonances



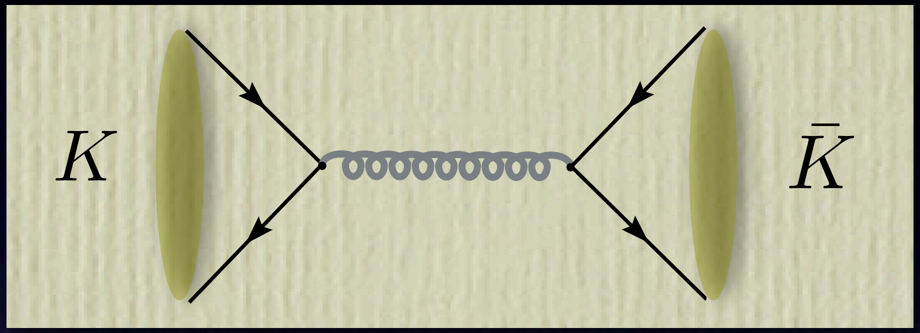
FCNCs from 3 TeV resonances



CP constraints on composite mass

Csaki, Falkowski, AW; Buras et al; Casagrande et al

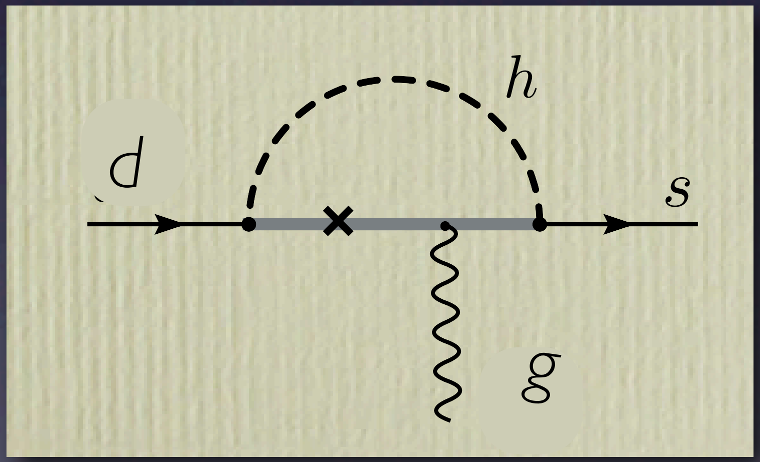
$\Delta F = 2$ (strongest constraint from ϵ_K)



$$M_* \gtrsim 10 \left(\frac{g_*}{Y_*}\right) \text{TeV}$$

$\Delta F = 1$ (strongest constraint from ϵ'/ϵ)

Gedalia et. al



$$M_* \gtrsim 1.3\, Y_* \text{ TeV}$$

$\Delta F = 0$ neutron EDM

$$M_* \geq 2.5\, Y_* \text{ TeV}$$

Agashe et. al, Delaunay et. al, Redi, AW

Flavor triviality: dynamical MFV

Cacciapaglia, Csaki, Galloway, Marandella, Terning, A.W.

strong sector $SU(3)_Q \times SU(3)_u \times SU(3)_d$

mixing ~ Yukawas

$s_u, s_d \sim Y_u, Y_d$

Delaunay et al

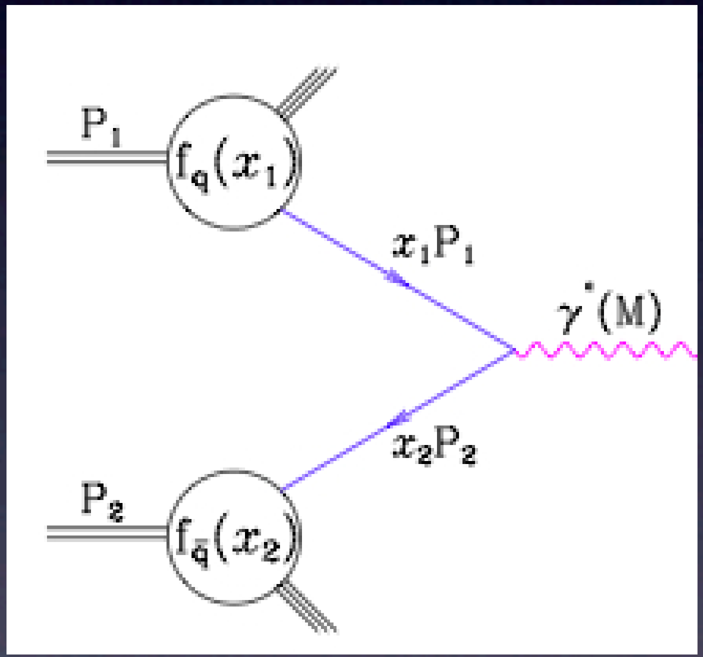
sweet spot if MFV "shines" into the bulk, $m_\rho \approx 2\,\mathrm{TeV}$

=> flavor gauge bosons predicted

Flavor gauge bosons at LHC

$$g_{\text{eff}} G_\mu^{(1)\text{KK}} \bar{\psi}\psi$$

flavor gauge bosons do not have massless modes (flavor is broken)



no $\gamma - \rho$ mixing !

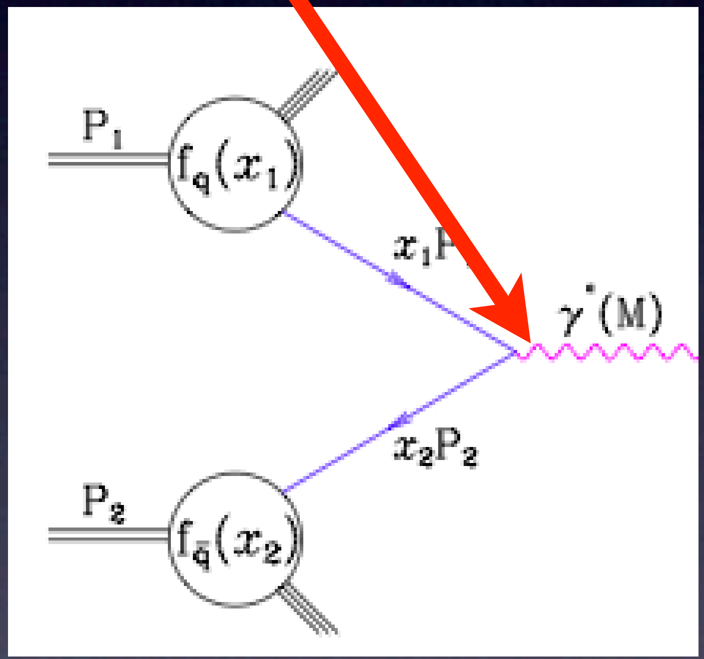
But quark composite mixing can be flavor universal & large

$$\sim g_*^2 \sin^2 \theta_{u_R}$$

Flavor gauge bosons at LHC

$g_{\rm eff} G_\mu^{(1){\rm KK}} \bar\psi\psi$

flavor gauge bosons do not have massless modes (flavor is broken)



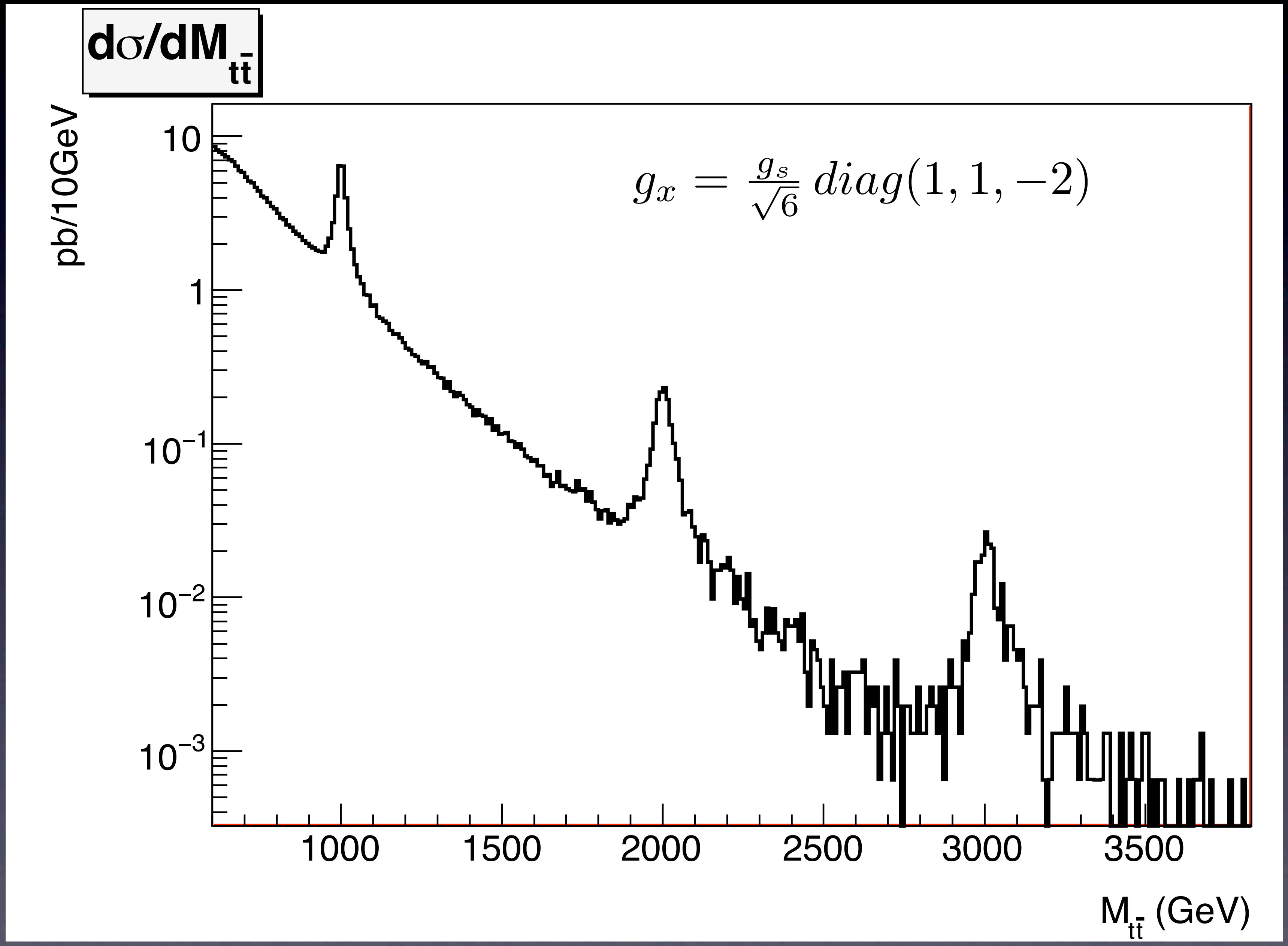
no $\gamma - \rho$ mixing !

But quark composite mixing can be flavor universal & large

$$\sim g_*^2 \sin^2\theta_{u_R}$$

Flavor scalars & gauge bosons

Csaki, Kagan, Lee, Perez, AW in preparation



see also Grinstein et. al.

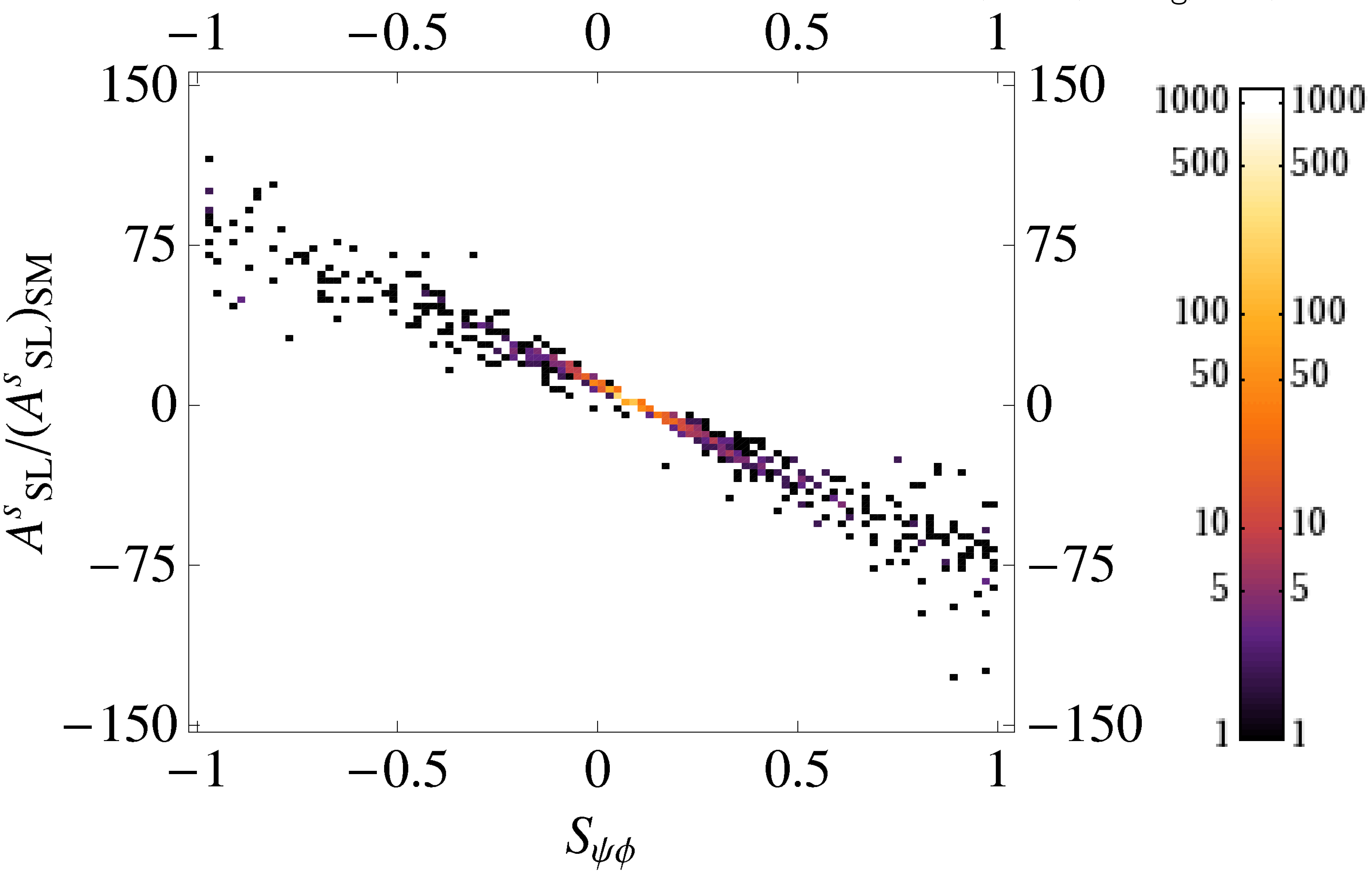
possible explanation of FB asymmetry at Tevatron

Outlook

more on warped Models:

Suzanne Westhoff - Top FB Asymmetry (next)
Florian Goertz - Higgs physics (YSF2)
Torsten Pfoh - CPV in B_S (YSF3)

Blanke, Buras, Duling, Gori, AW



Indirect tests: new physics C.S.I.

SM has accidental symmetries (B, L), e.g.

$$\mathcal{L}_{SM} + \frac{C_{\not B}}{\Lambda^2}(\bar{u}^c u)(\bar{e}^+ d)$$

$p \to e^+ \pi^0$

⇒ ***absence*** of violation probes very high scales

Flavor symmetries are only weakly broken (except top) & FCNCs require 1-loop

$$\mathcal{L}_{SM} + \frac{C_{\not{\text{flavor}}}}{\Lambda^2}(\bar{b}d)(\bar{b}d)$$

$\bar{B}^0 \leftrightarrow B^0$

⇒ ***smallness*** of violation probes high scales

The SM flavor puzzle

$$Y_D \approx \mathrm{diag}\left(2\cdot 10^{-5} \quad 0.0005 \quad 0.02\right)$$

$$Y_U \approx \begin{pmatrix} 6\cdot 10^{-6} & -0.001 & 0.008+0.004i \\ 1\cdot 10^{-6} & 0.004 & -0.04+0.001 \\ 8\cdot 10^{-9}+2\cdot 10^{-8}i & 0.0002 & 0.98 \end{pmatrix}$$

Why this structure? Small & hierarchical.

Other dimensionless parameters of the SM:

$g_s \sim 1$, $g \sim 0.6$, $g' \sim 0.3$, $\lambda_{Higgs} \sim 1$, $|\theta| < 10^{-9}$

UTfit 08, Isidori et. al '10

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

UTfit 08, Isidori et. al '10

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

Very strong suppression! New flavor violation must either approximately follow SM pattern…

UTfit 08, Isidori et. al '10

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}

Very strong suppression! New flavor violation must either approximately follow SM pattern…

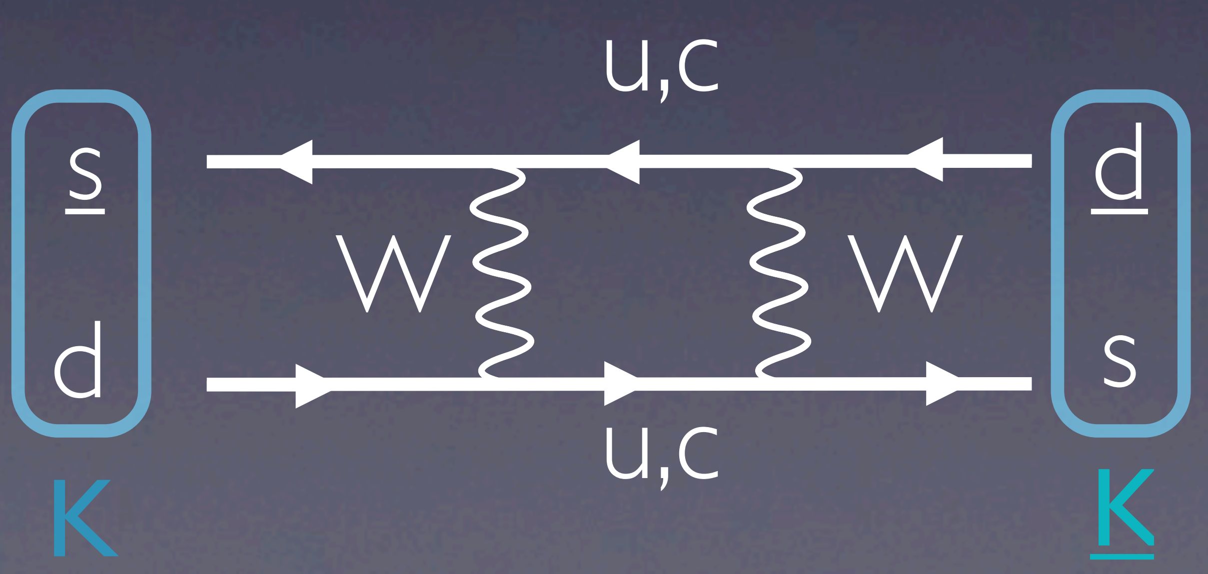
… or exist only at very high scales (10^2 - 10^5 TeV)

Why are FCNCs so suppressed in the SM?

no tree FCNCs: $g^4/(4\pi)^2$ $\sim (1/30)^2$

mixing & GIM: $\dfrac{m_c^2 - m_u^2}{m_W^2} \sin^2\theta_C$ $\sim (1/400)^2$

$$\Rightarrow \quad \frac{1}{(30 \cdot 400)^2} \frac{1}{m_W^2} \sim \frac{1}{(10^3\ \mathrm{TeV})^2}$$



Flavor and CP in the SM

Experimental picture

+ spectrum, *BR*, A_{CP}, particle-antiparticle oscillations
+ determine masses, mixing angles and phases

Theorist's view

+ In the absence of Yukawas, SM globally $SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$ symmetric

$$v\,Y_u = U_u \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} V_u \qquad v\,Y_d = U_d \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} V_d$$

Flavor and CP in the SM

Experimental picture

+ spectrum, *BR*, A_{CP}, particle-antiparticle oscillations
+ determine masses, mixing angles and phases

Theorist's view

+ In the absence of Yukawas, SM globally $SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$ symmetric

$$v\,Y_u = U_u \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} V_u \qquad v\,Y_d = U_d \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} V_d$$

Flavor and CP in the SM

Experimental picture

+ spectrum, *BR*, A_{CP}, particle-antiparticle oscillations
+ determine masses, mixing angles and phases

Theorist's view

+ In the absence of Yukawas, SM globally
  $SU(3)_{Q_L} \times SU(3)_{u_R} \times SU(3)_{d_R}$ symmetric

$$v\,Y_u = U_u \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \cancel{V_u} \qquad v\,Y_d = \cancel{U_d} \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \cancel{V_d}$$

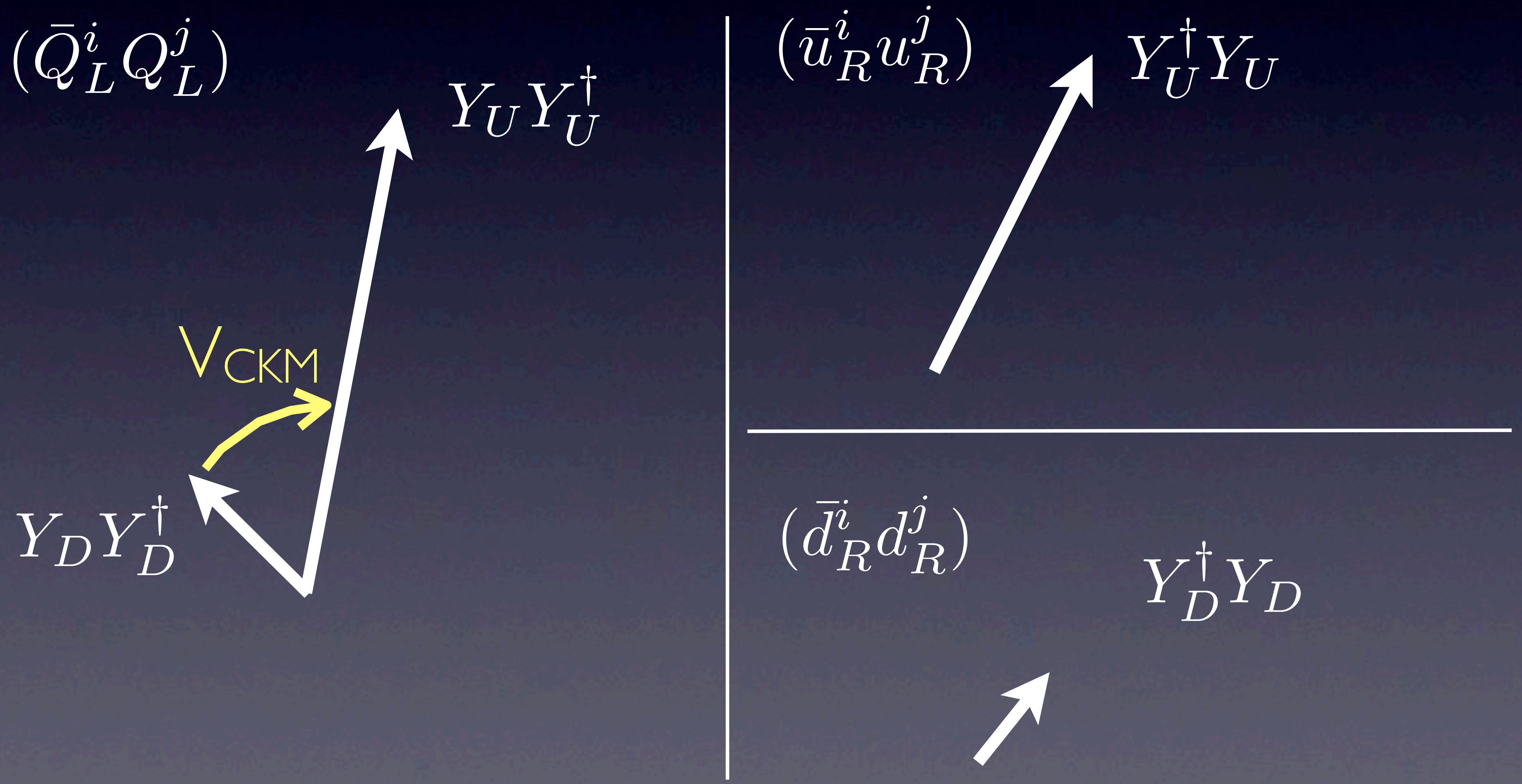
$\Downarrow$

V_{ckm}

unphysical due to $SU(3)^3$!

Flavor and CP in the SM

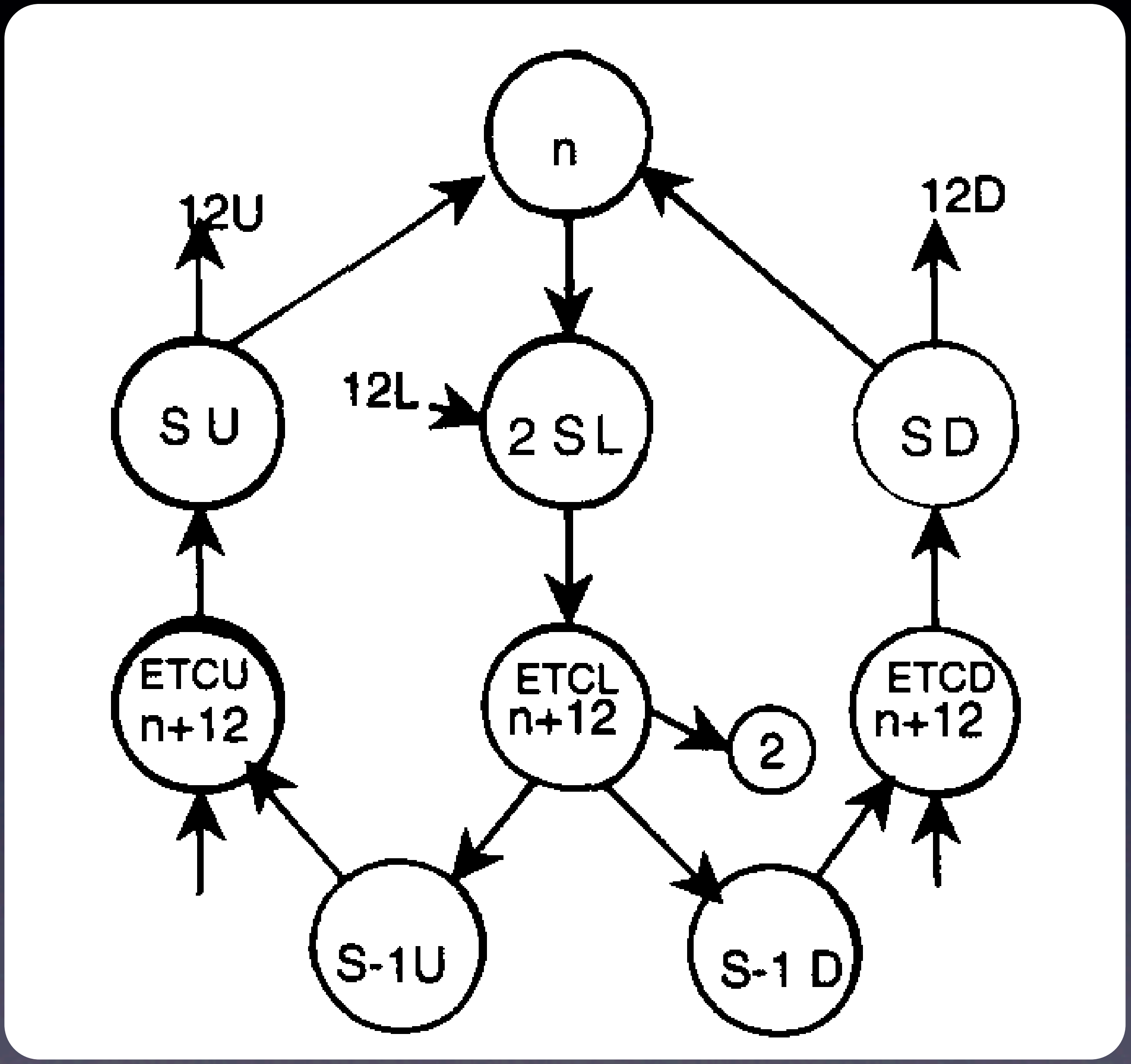
Yukawa matrices Y_U & Y_D encode flavor violation



+ LR, RL

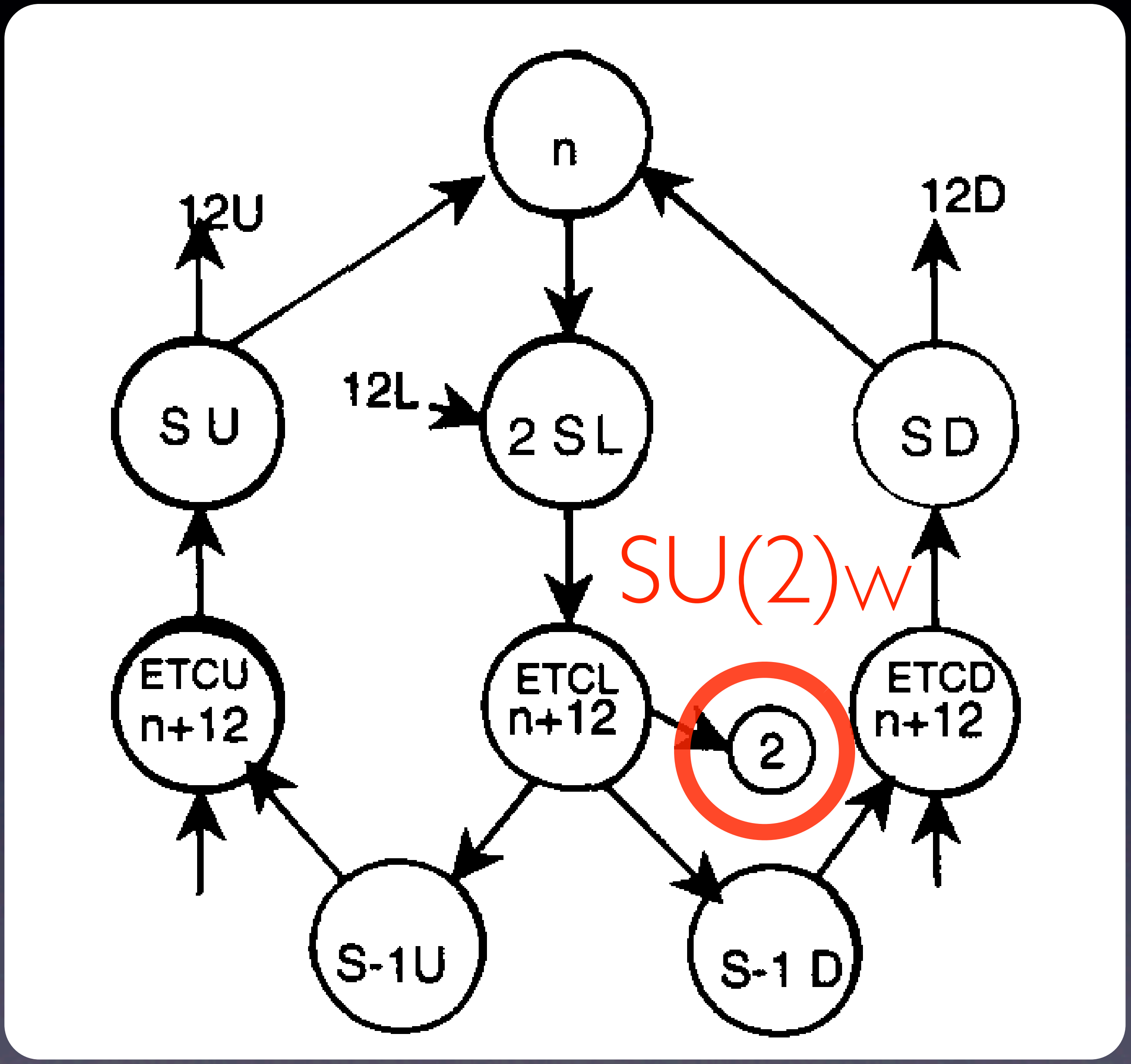
MFV Technicolor?

Chivukula, Georgi '87; Chivukula, Georgi,Randall '87; Randall '93; Georgi '94, Skiba '96



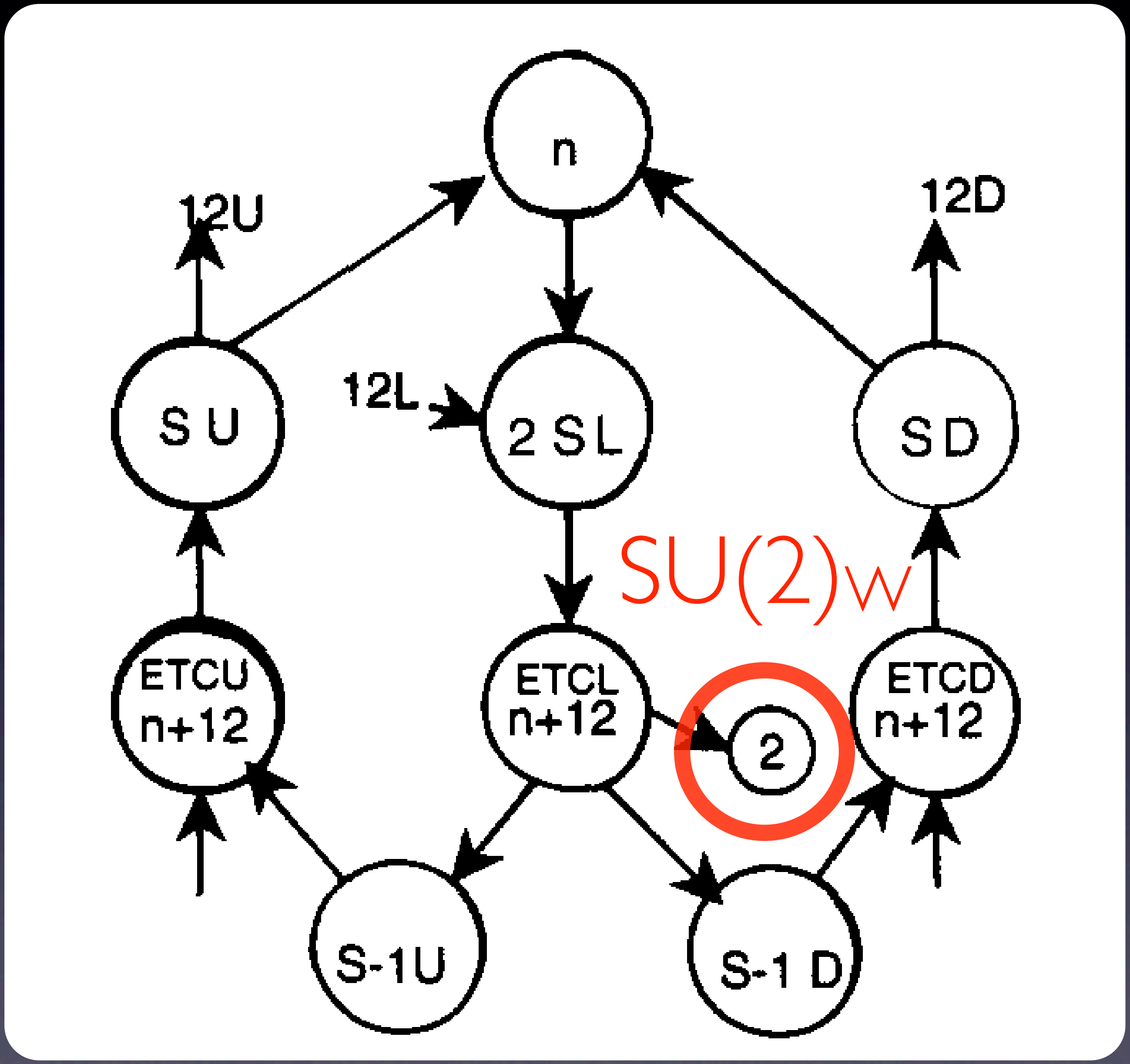
MFV Technicolor?

Chivukula, Georgi '87; Chivukula, Georgi,Randall '87; Randall '93; Georgi '94, Skiba '96



MFV Technicolor?

Chivukula, Georgi '87; Chivukula, Georgi,Randall '87; Randall '93; Georgi '94, Skiba '96



Simpler proposal:

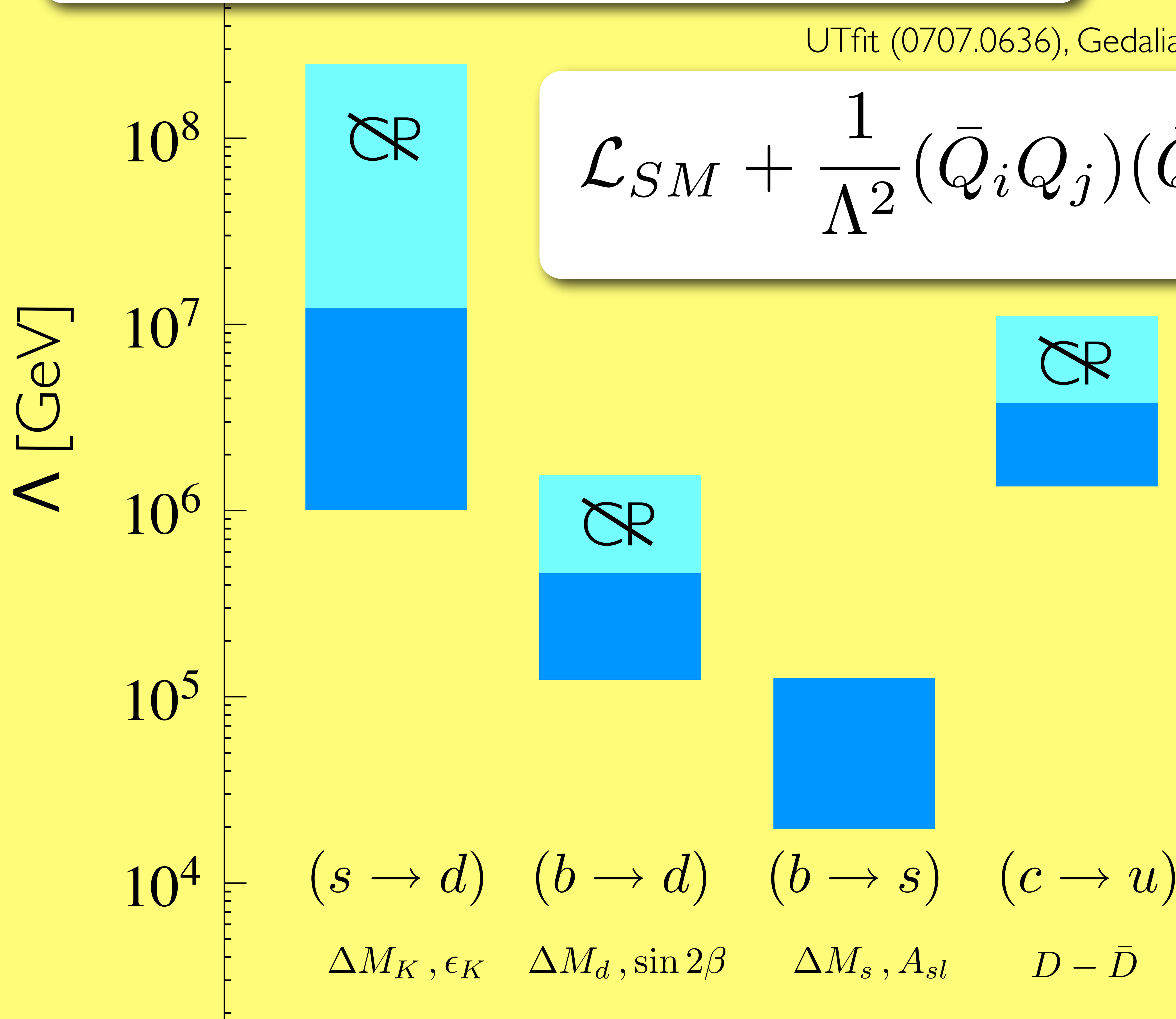
AdS/CFT construction : 5D GIM mechanism

Cacciapaglia, Csaki, Galloway, Marandella, Terning, A.W., '08

Bounds on generic flavor violation

UTfit (0707.0636), Gedalia et al '09

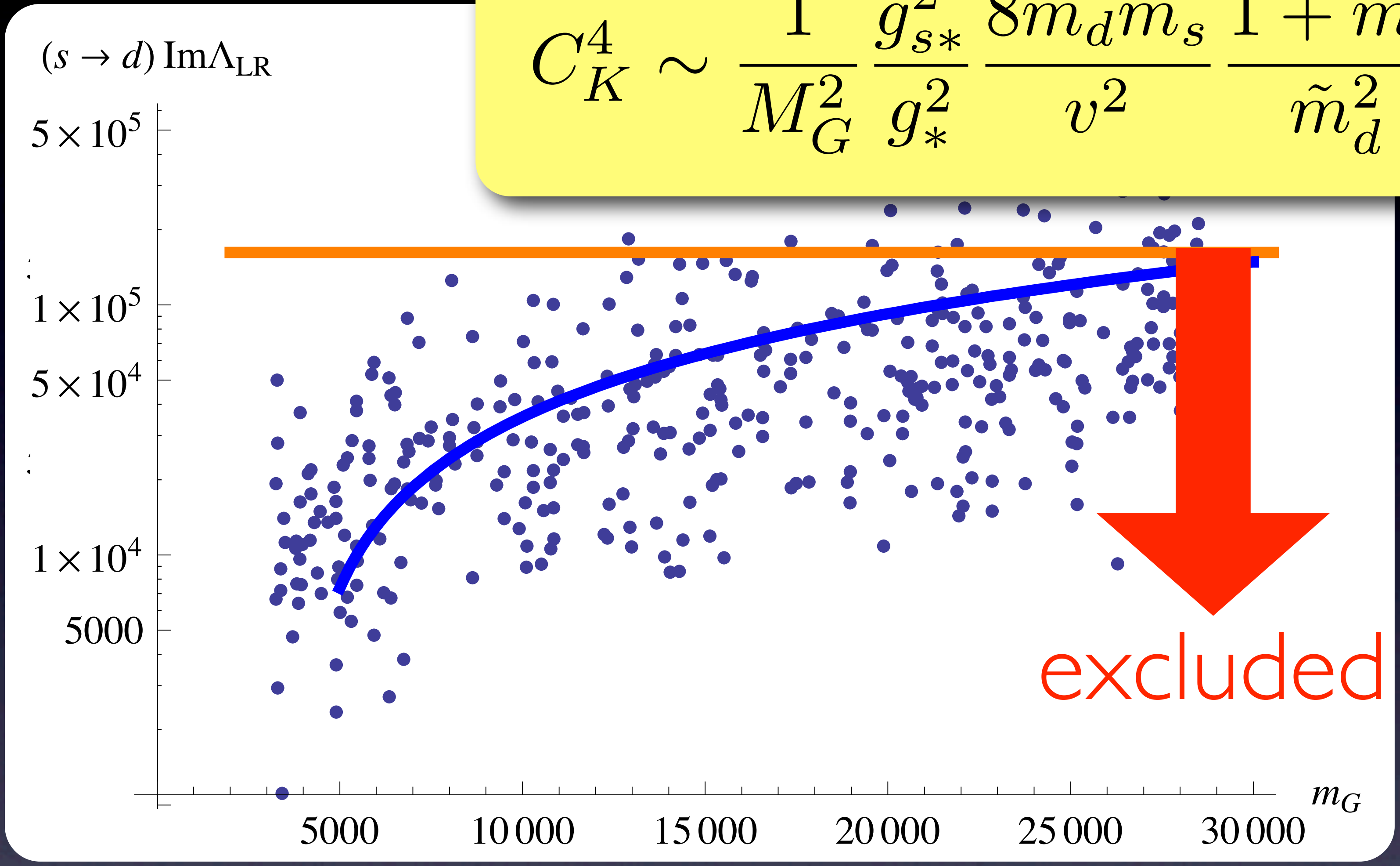
$$\mathcal{L}_{SM} + \frac{1}{\Lambda^2}(\bar{Q}_i Q_j)(\bar{Q}_i Q_j)$$



Bound for pGB Higgs

Csaki, Falkowski, A.W.;

$$C_K^4 \sim \frac{1}{M_G^2}\frac{g_{s*}^2}{g_*^2}\frac{8m_d m_s}{v^2}\frac{1+m^2}{\tilde{m}_d^2}$$



$M_{KK} > 30$ TeV

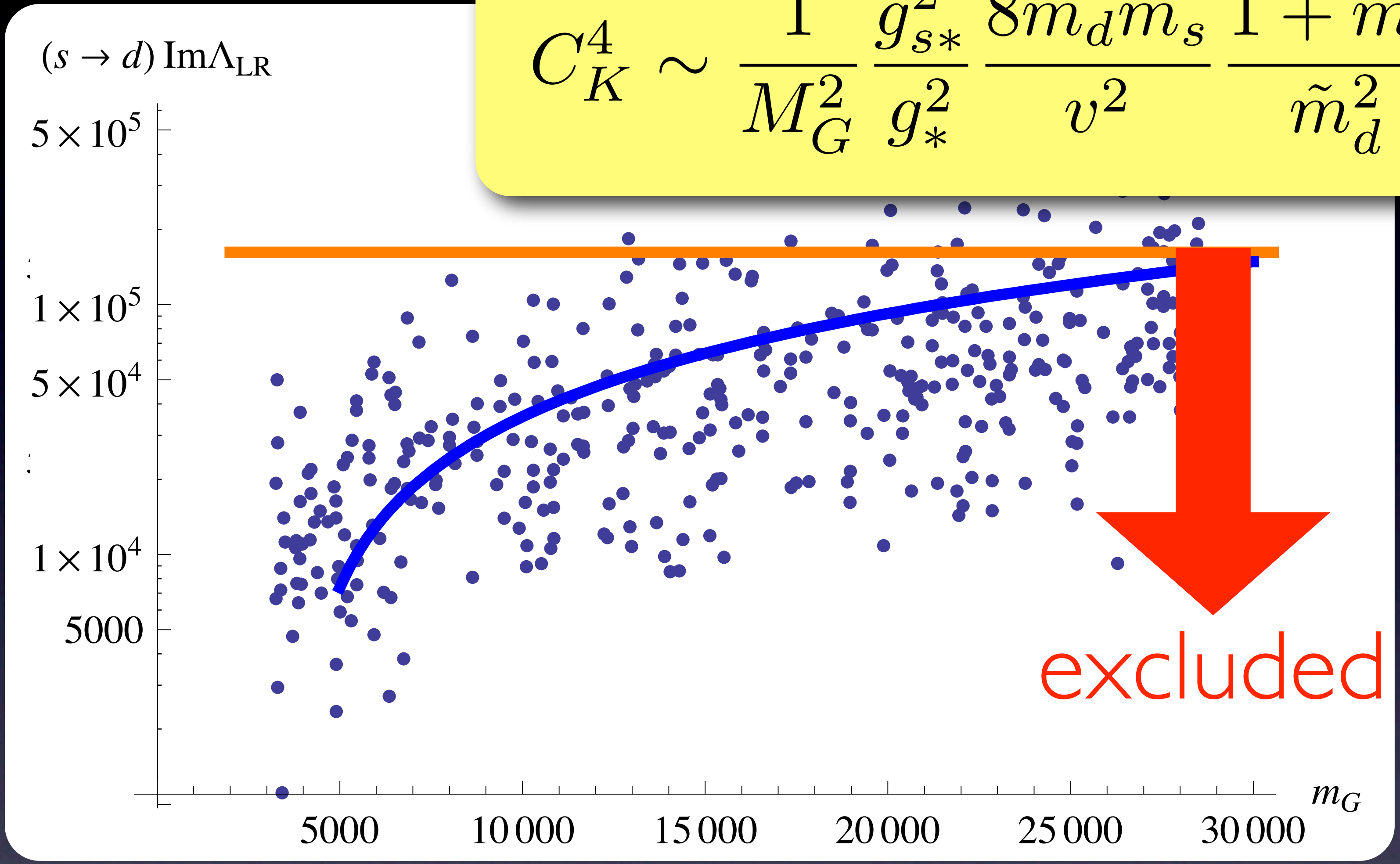
FCNC constraint more severe in composite pGB!

Why? $Y^* \to g_* / 2$ & fermionic kinetic mixings

Bound for pGB Higgs

Csaki, Falkowski, A.W.;

$$C_K^4 \sim \frac{1}{M_G^2} \frac{g_{s*}^2}{g_*^2} \frac{8 m_d m_s}{v^2} \frac{1+m^2}{\tilde{m}_d^2}$$



$M_{KK} > 30$ TeV

FCNC constraint more severe in composite pGB!

Why? $Y^* \to g_* / 2$ & fermionic kinetic mixings