Flavor & New Physics

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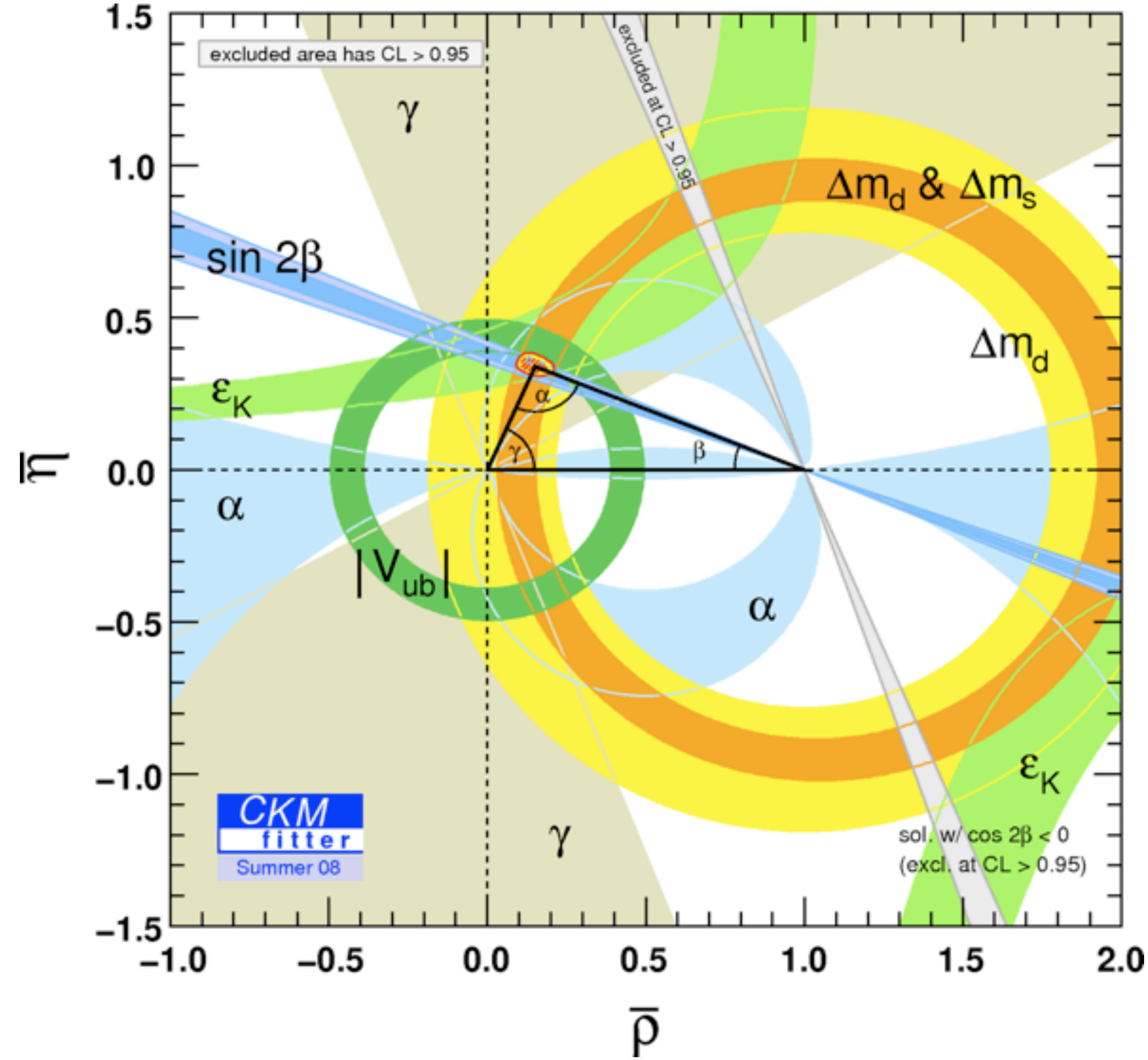
Aspen Winter Conference 2009
The Year of the Ox

New Era in 2009+x

We will probe the origin of EWSB.

Will we be able to learn about the origin of flavor in the era of the LHC?

Does the mechanism stabilizing the weak scale have non-trivial flavor content?



excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
|V_ub|
CKM fitter
Summer 08
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
2.0

Flavor and CP in the SM

Experimentalist's view

+ spectrum, BR, A_{CP}
+ measure 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

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

Charged currents:

measure only **LH misalignment**

$$v\,Y_u = \cancel{U_u} \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \cancel{V_u}$$

$$v\,Y_d = \boxed{V_{\mathrm{CKM}}} \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \cancel{V_d}$$

Charged currents:

measure only **LH misalignment**

Neutral currents:

enhanced flavor symmetry

$SU(3)_Q \to SU(3)_{u_L} \times SU(3)_{d_L}$

Yukawas diagonal, **no (tree-level) flavor violation**

$$v\, Y_u = \cancel{U_u} \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \cancel{V_u}$$

$$v\, Y_d = \cancel{V_{\mathrm{CKM}}} \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \cancel{V_d}$$

Smallness & hierarchy

$$Y_D \approx (10^{-5}, 0.0005, 0.026)$$

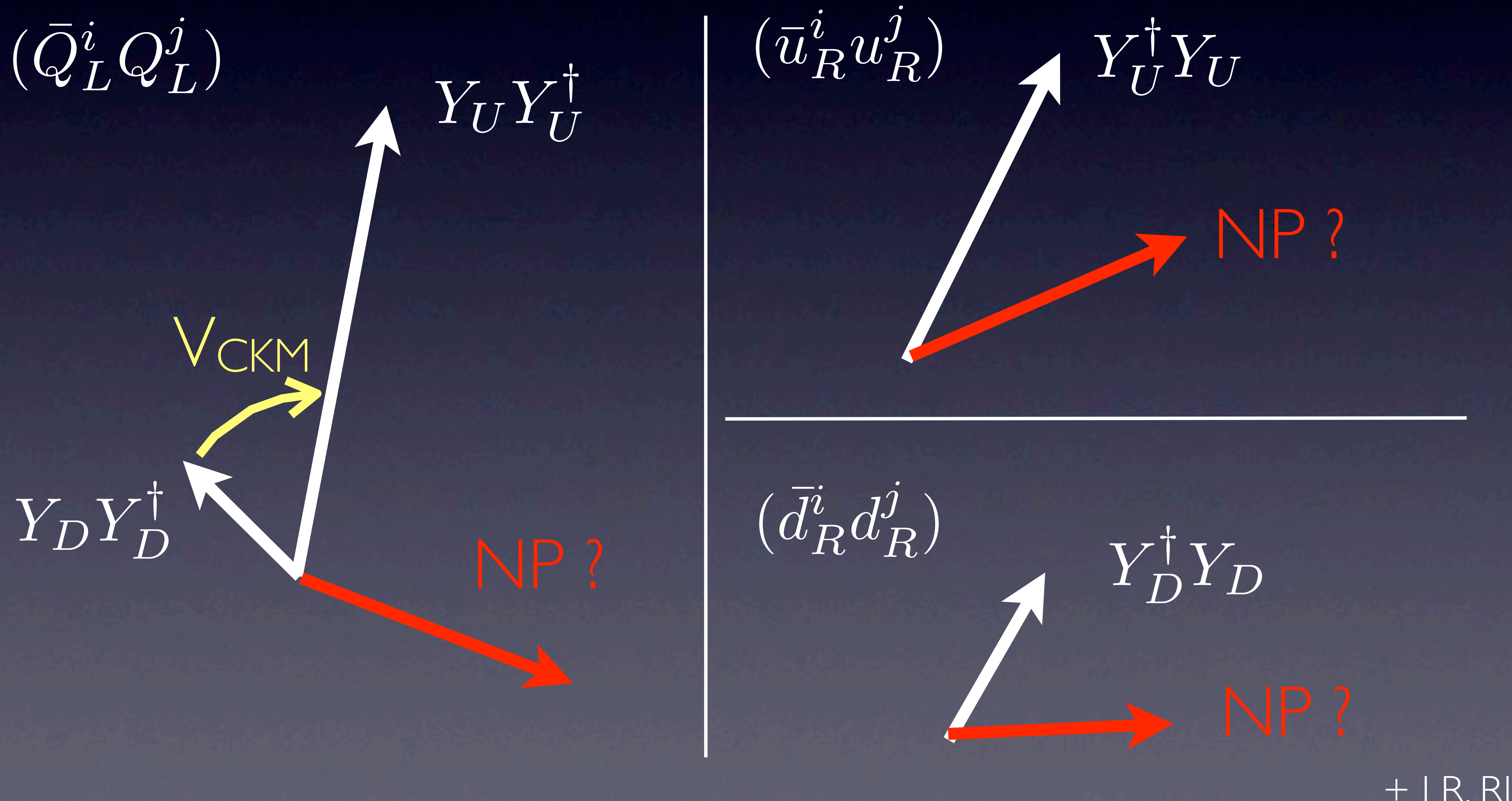
$$Y_U \approx \begin{pmatrix} 10^{-5} & -0.002 & 0.007 + 0.004i \\ 10^{-6} & 0.007 & -0.04 + 0.0008i \\ 10^{-8} + 10^{-7}i & 0.0003 & 0.96 \end{pmatrix}$$

The SM flavor parameters have structure:
smallness & hierarchy.
Why? The SM flavor puzzle.

Compare to: $g_s \sim 1$, $g \sim 0.6$, $g \sim 0.3$, $\lambda_{Higgs} \sim 1$

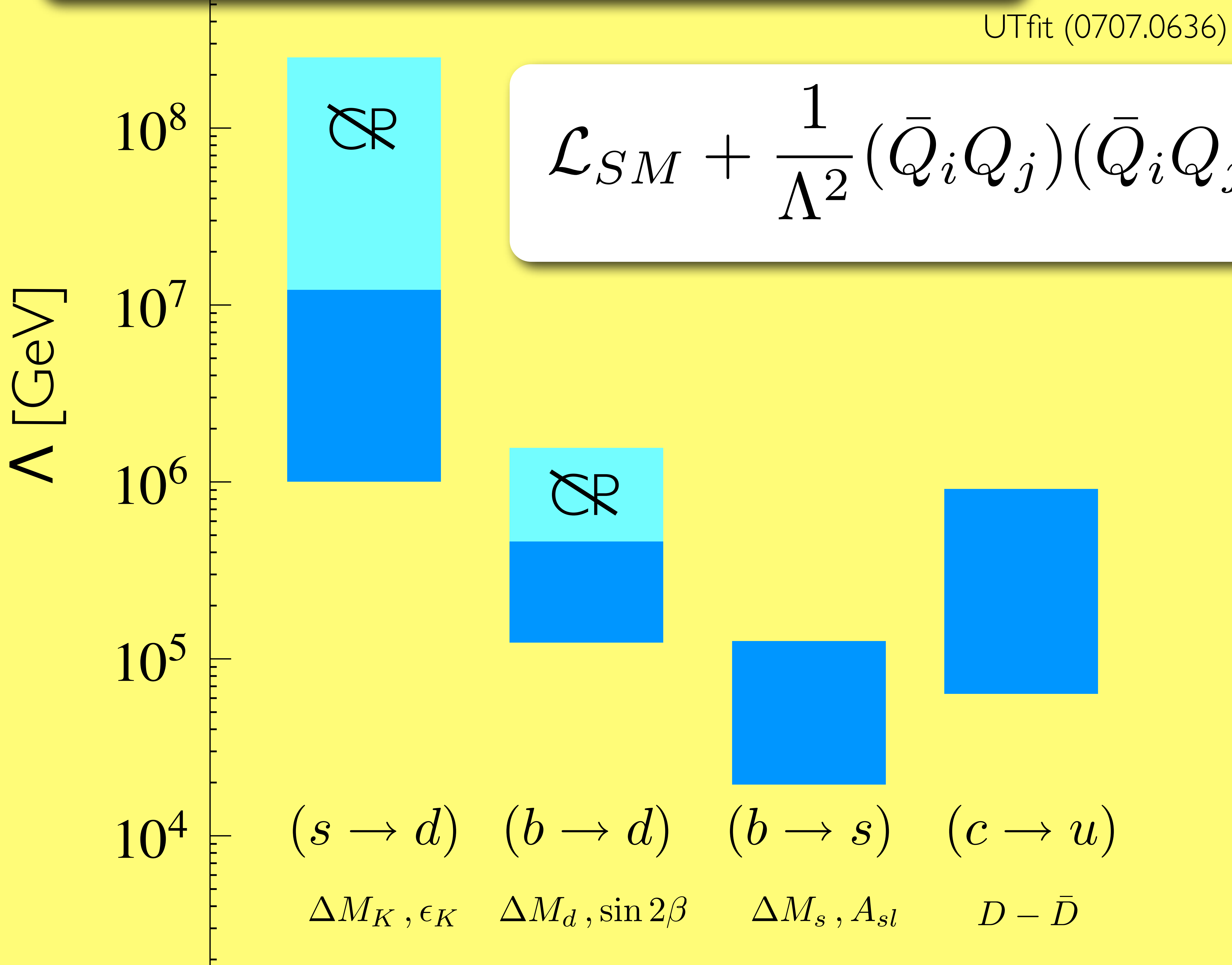
Flavor and CP in the SM

Yukawa matrices Y_U & Y_D contain everything



Bounds on generic flavor violation

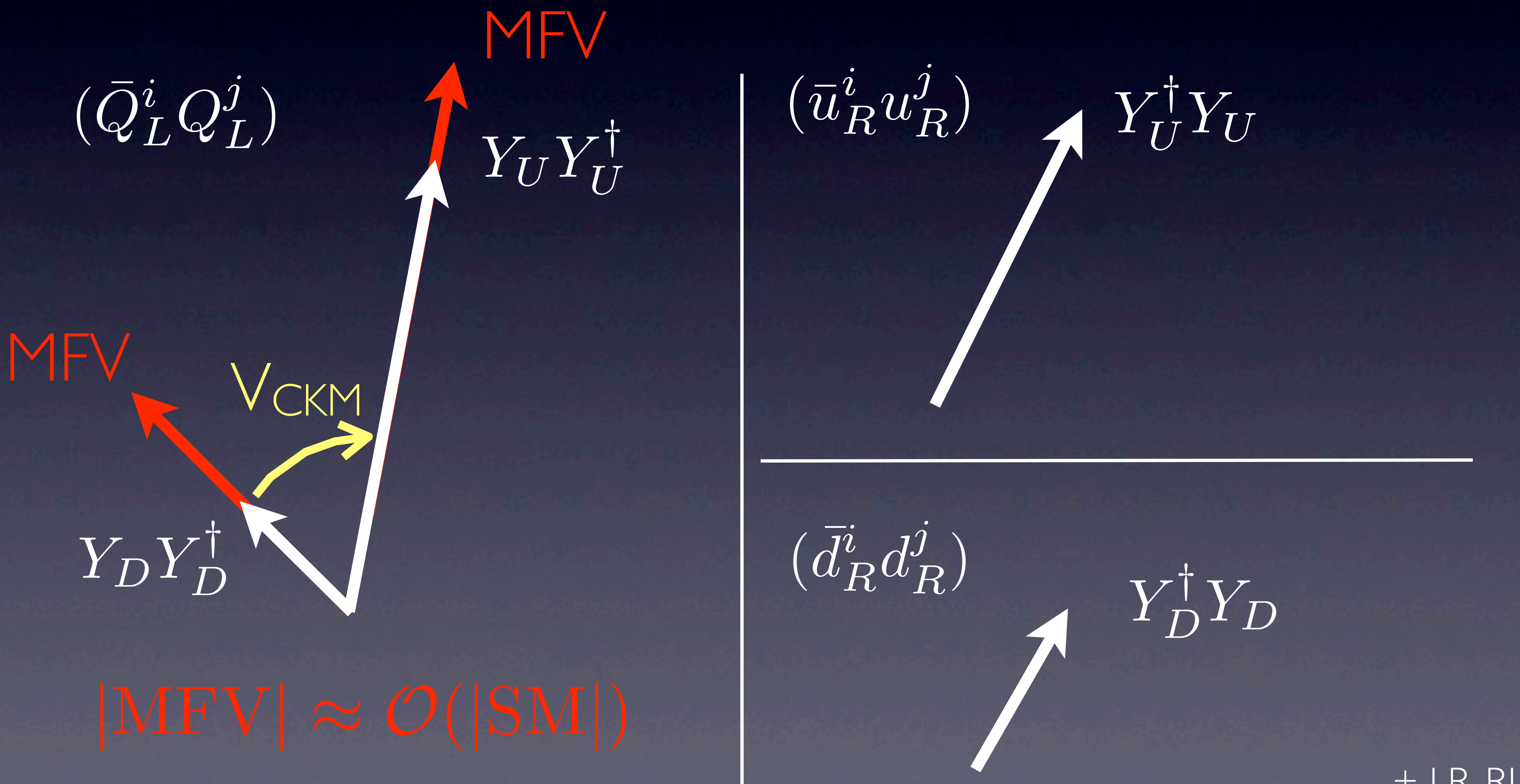
$$\mathcal{L}_{SM} + \frac{1}{\Lambda^2}(\bar{Q}_i Q_j)(\bar{Q}_i Q_j)$$



How can we protect TeV physics from these bounds?

A radical cure: MFV

New particles/interactions, but flavor structure ~ V_{CKM}



caveat: large tanβ see Carlos Wagner's talk

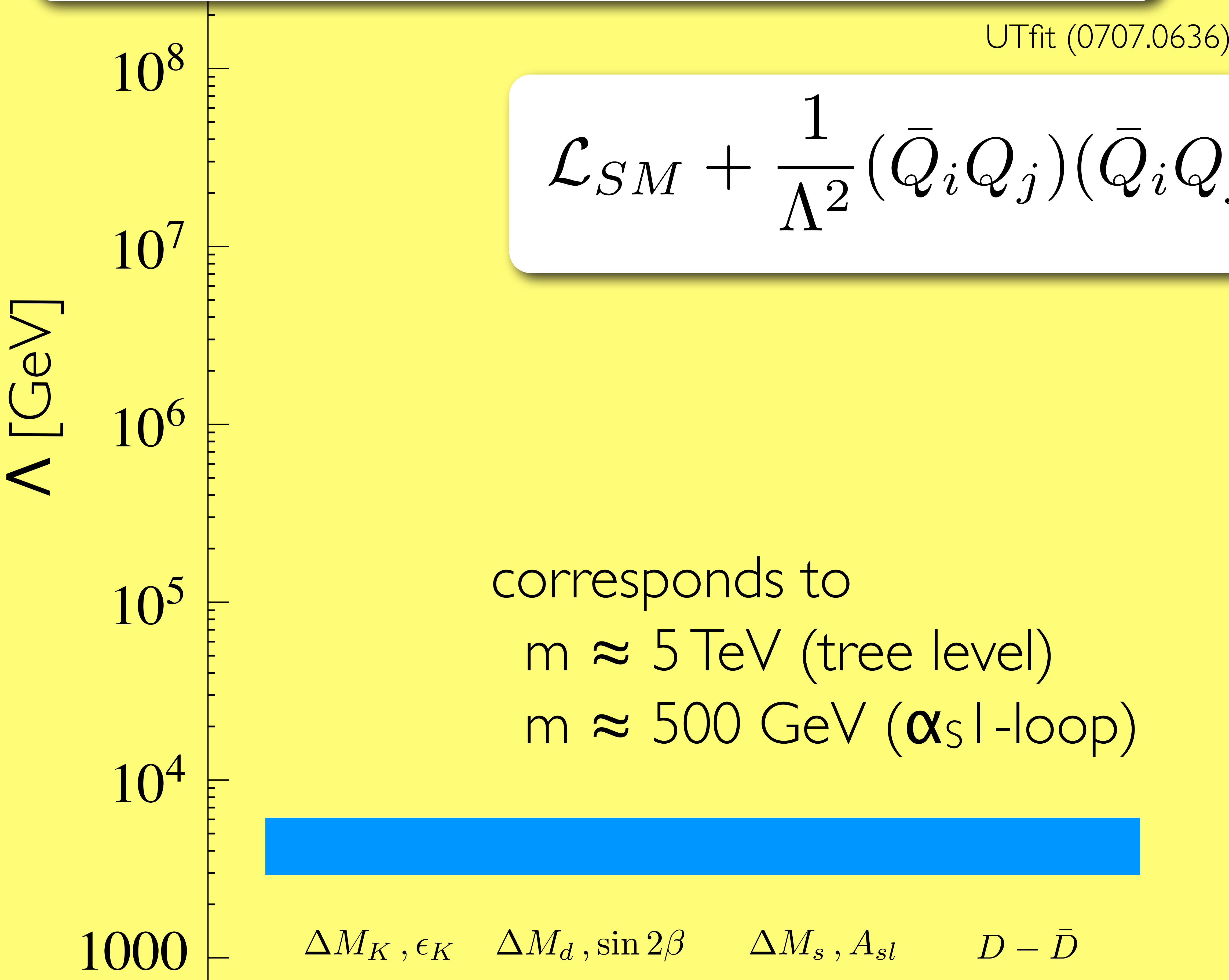
Model independent ΔF=2 MFV Bound

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

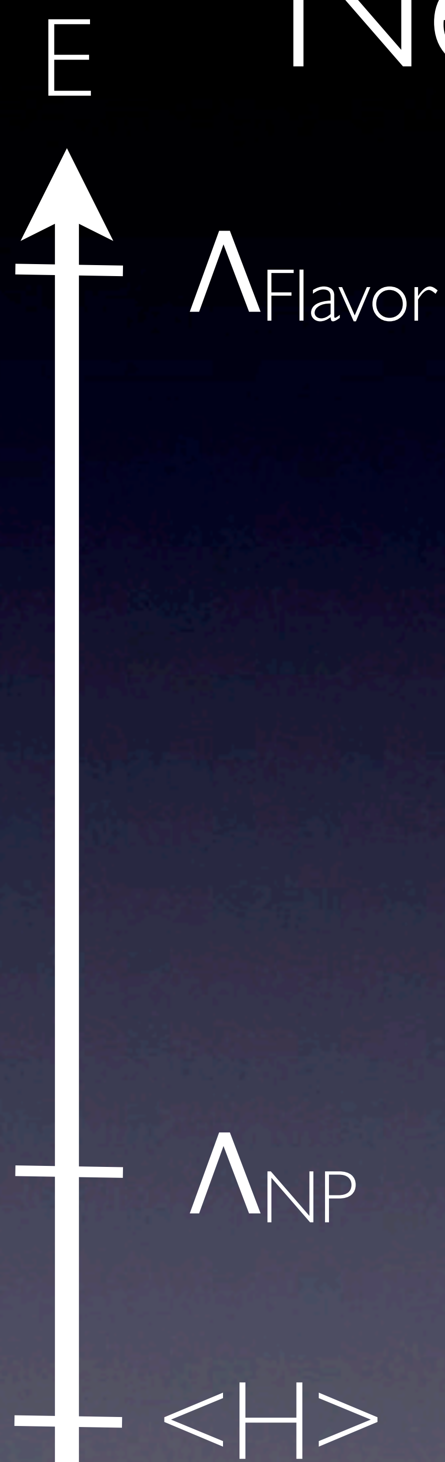
corresponds to

m ≈ 5 TeV (tree level)

m ≈ 500 GeV (α_S 1-loop)



New physics is MFV, if...



Origin of flavor structure decoupled

$\Lambda_{Flavor} >> \Lambda_{NP}$

NP below Λ_{Flavor} is flavor degenerate (or flavor like in SM)

But : little learned about the origin of flavor ☹

MFV example: SUSY

MSSM with unbroken SUSY is already MFV!

=> MSSM is MFV if ~~SUSY~~ is flavor blind

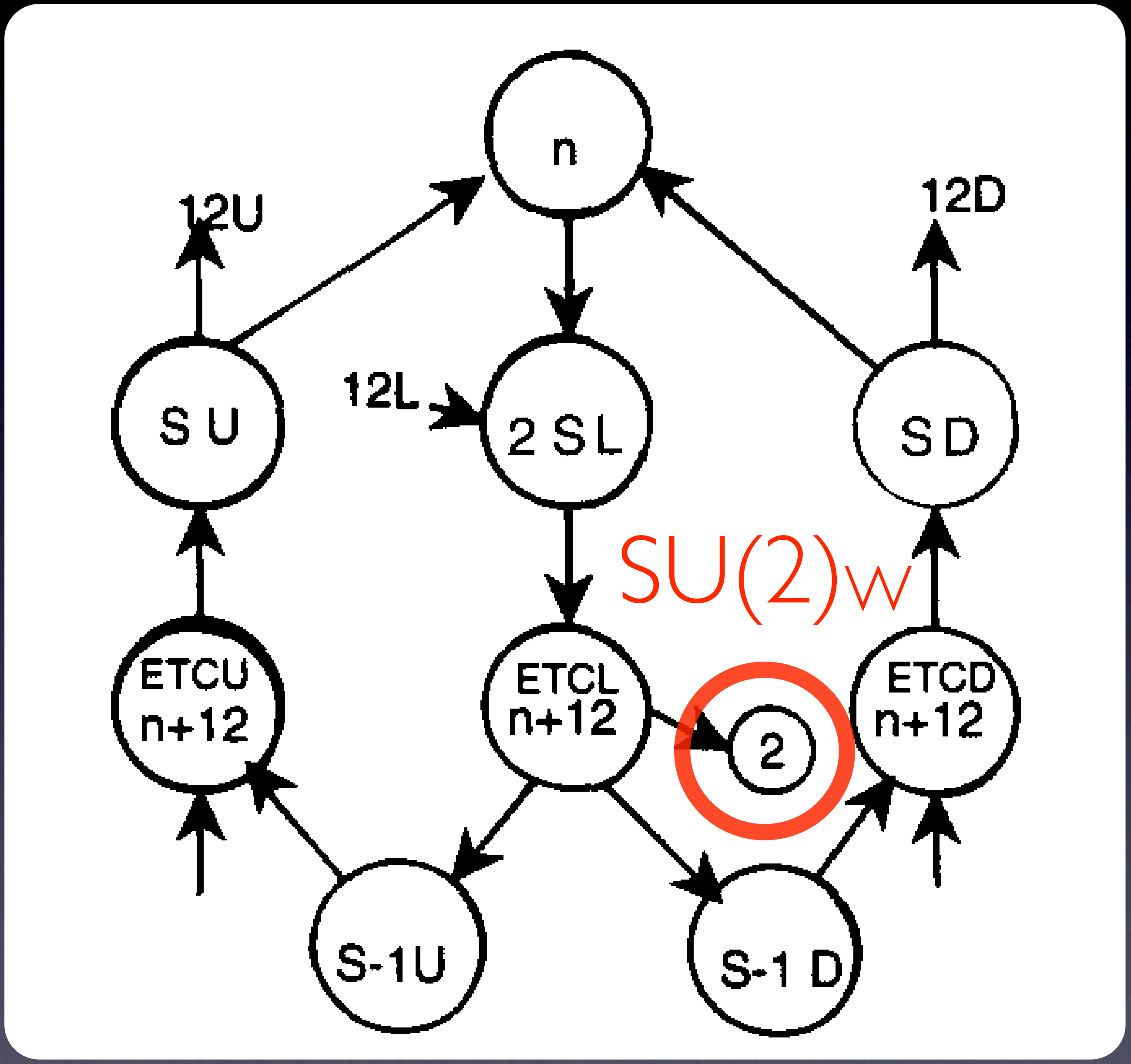
Example: Gauge mediation with $M_{mess} << \Lambda_{flavor}$

Gravity mediation in general not MFV, mSUGRA not a good starting point to study flavor!

MFV SUSY alternatives: UED and the Littlest Higgs with appropriate UV completions.

MFV Technicolor?

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



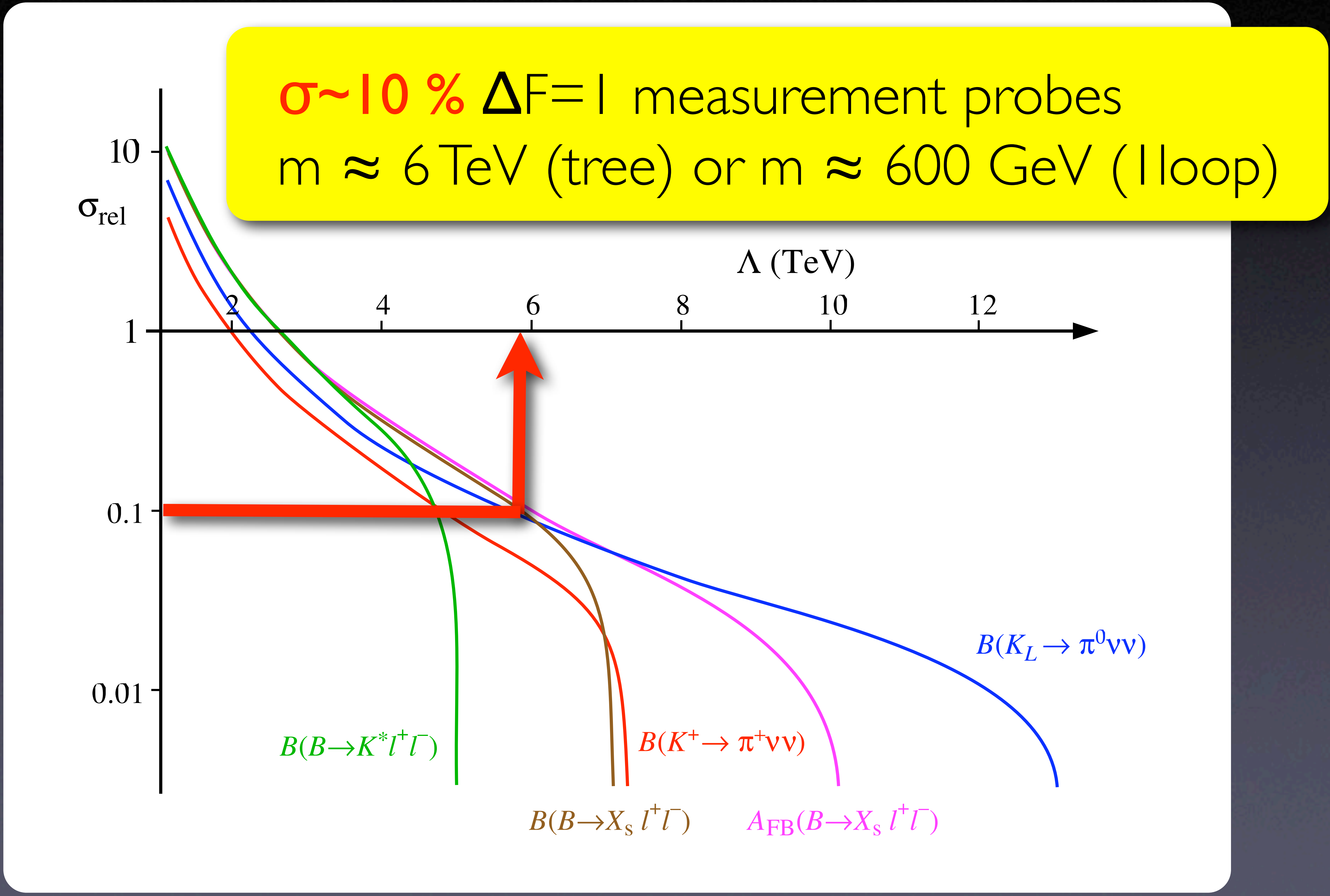
Simpler alternative:

AdS/CFT interpretation of RS : 5D GIM mechanism

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

Distinguishing MFV & SM is hard

D'Ambrosio, Giudice, Isidori, Strumia '02; Buras,Bryman, Isidori, Littenberg '05



Falsifying MFV is easy...

...once you have shown that the SM is dead

Bobeth, Bona, Buras, Ewerth, Pierini, Silvestrini, A.W.

MFV falsified by violating "sum rules"

already in the data? Lunghi, Soni '08

New CP phases

MFV@LHC: Grossman, Nir, Thaler, Volansky, Zupan

At the LHC: $Br(q_3) \sim Br(q_{1,2})$

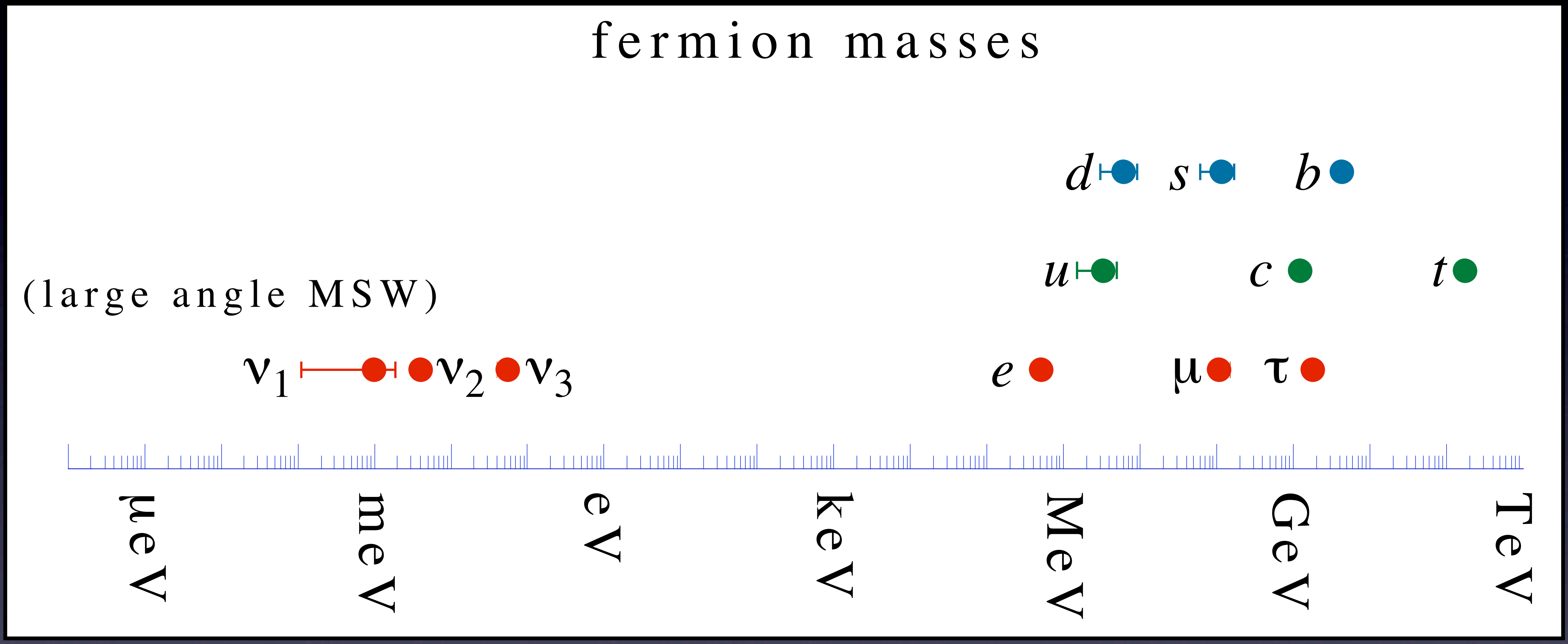
Top FCNCs

...

A theory of flavor at the LHC?

Froggat-Nielsen vs.
Higgs dependent Yukawas
RS/holographic technicolor

Fermion masses & mixings



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

$$\lambda \approx 0.23$$

Hierarchies from symmetries

Froggatt, Nielsen '79

Add horizontal $U(1)_F$, flavon Φ_F ($m_\Phi \sim \Lambda$, $q_F = -1$)

$$Y_d^{ij} \left(\frac{\Phi_F}{\Lambda} \right)^{-q_i+h+d_j} \bar{Q}_L^i H D_R^j$$

↓ $U(1)_F$ broken by $F = \langle \Phi_F \rangle$, $F < \Lambda$

$$Y_{eff,d}^{ij} = Y_d^{ij} \left(\frac{F}{\Lambda} \right)^{-q_i+h+d_j}$$ => hierarchies

But: hard to probe, flavon must be heavy $m_\Phi \gg$ TeV

Higgs as flavon

Babu, Nandi '99; Giudice, Lebedev '08

"Higgs dependent Yukawas"
Yukawas effective interaction after integrating out heavy physics. Postulate leading terms are absent

$$\mathcal{L}_Y = Y^u_{ij}(H)\ \bar{q}_{Li} u_{Rj} H^c + Y^d_{ij}(H)\ \bar{q}_{Li} d_{Rj} H$$

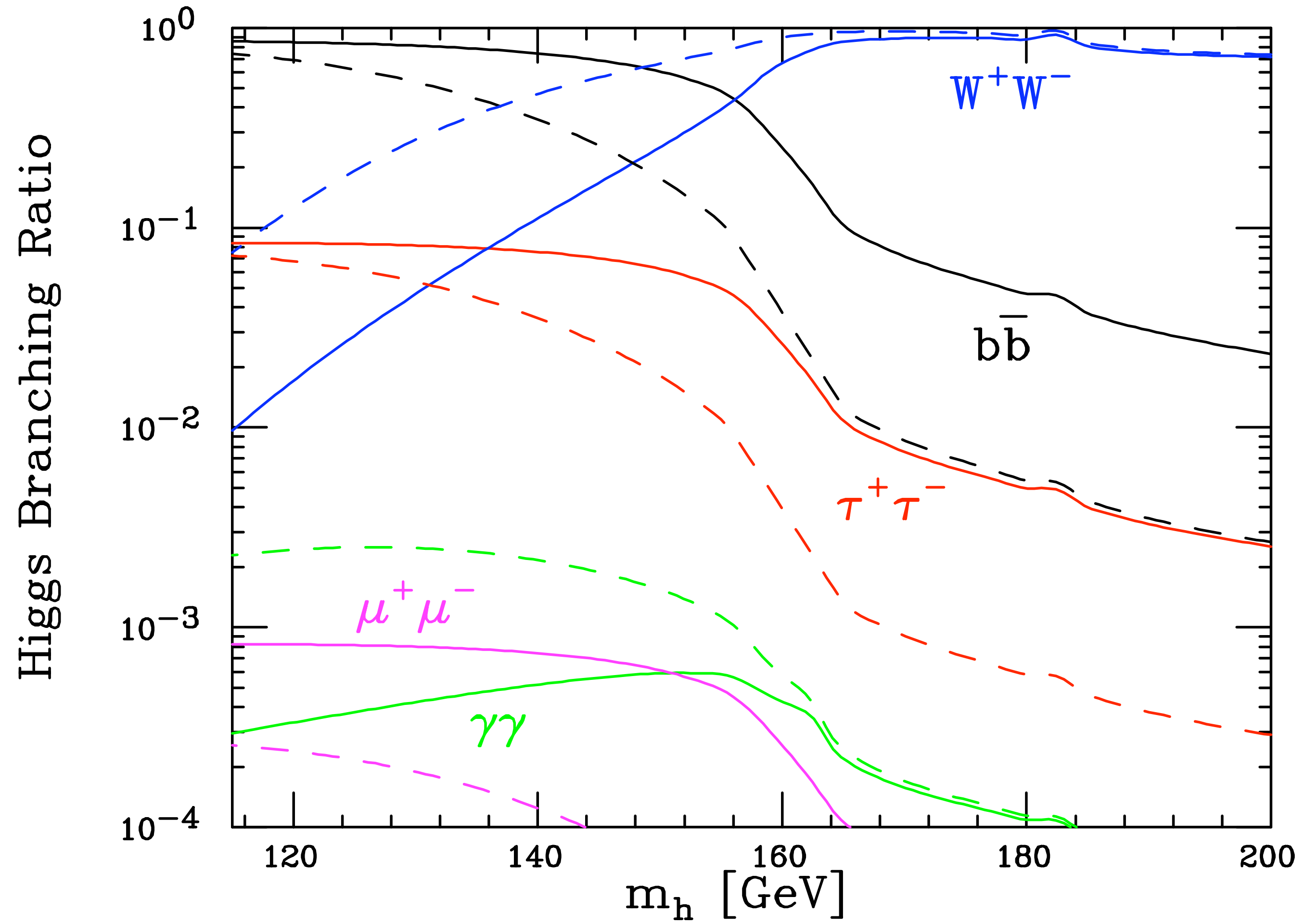
$$Y^{u,d}_{ij}(H) = c^{u,d}_{ij} \left(\frac{H^\dagger H}{M^2}\right)^{n^{u,d}_{ij}}$$

n_{ij} generation dependent integer, determines mass hierarchy

$v^2/M^2 \approx m_b^2/m_t^2$ => $M \approx 1-2\,\mathrm{TeV}$

Higgs as flavon: signals

Giudice, Lebedev '08



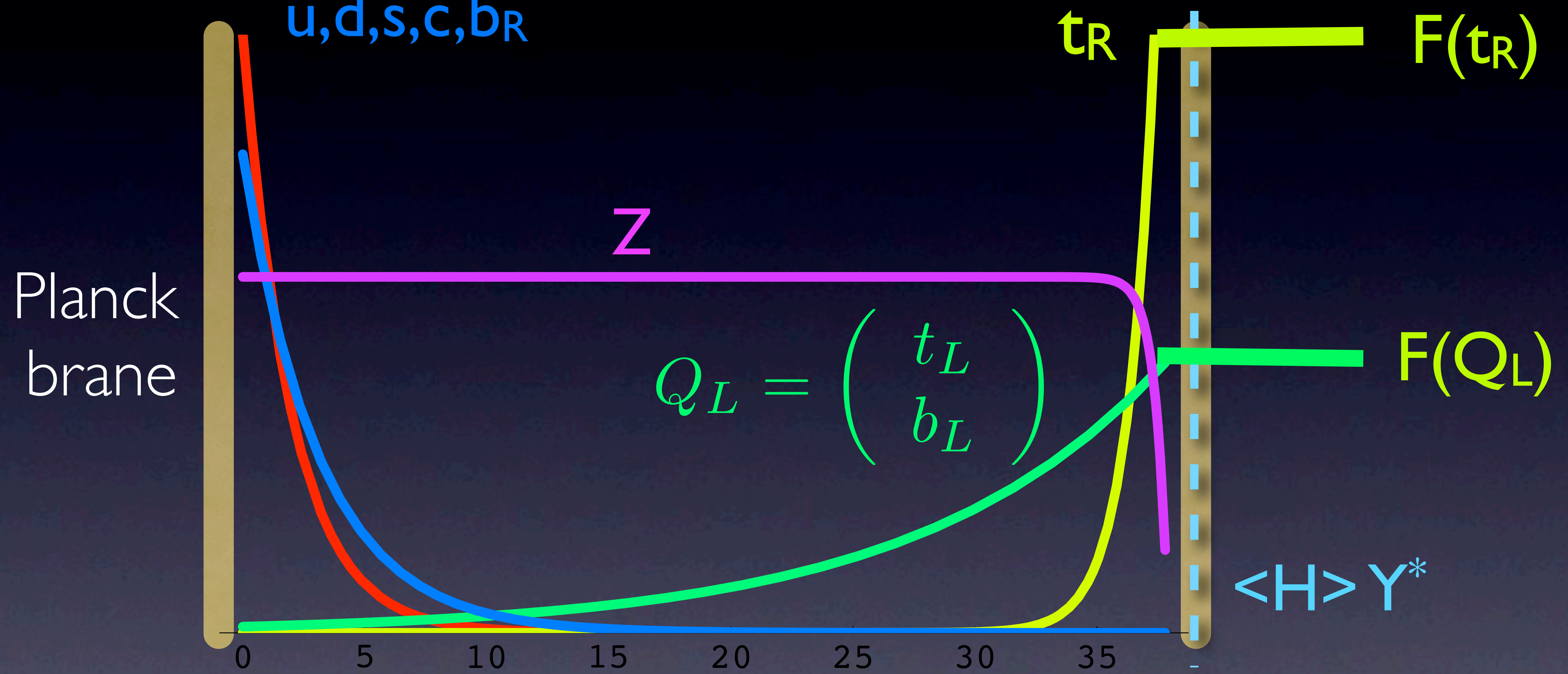
Higgs dependent Yukawas

SM

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

Hierarchies without symmetries

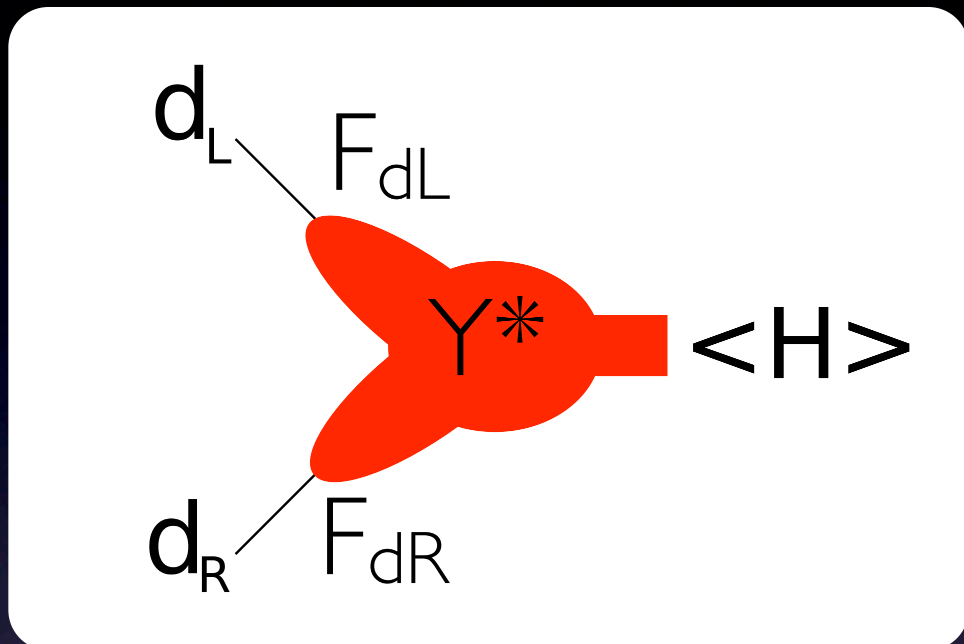
Arkani-Hamed, Schmaltz; Grossman, Neubert;
Gherghetta, Pomarol



Localization in extra dimension determines overlap $F(q_i)$ with Higgs.

Masses, mixings and FCNCs

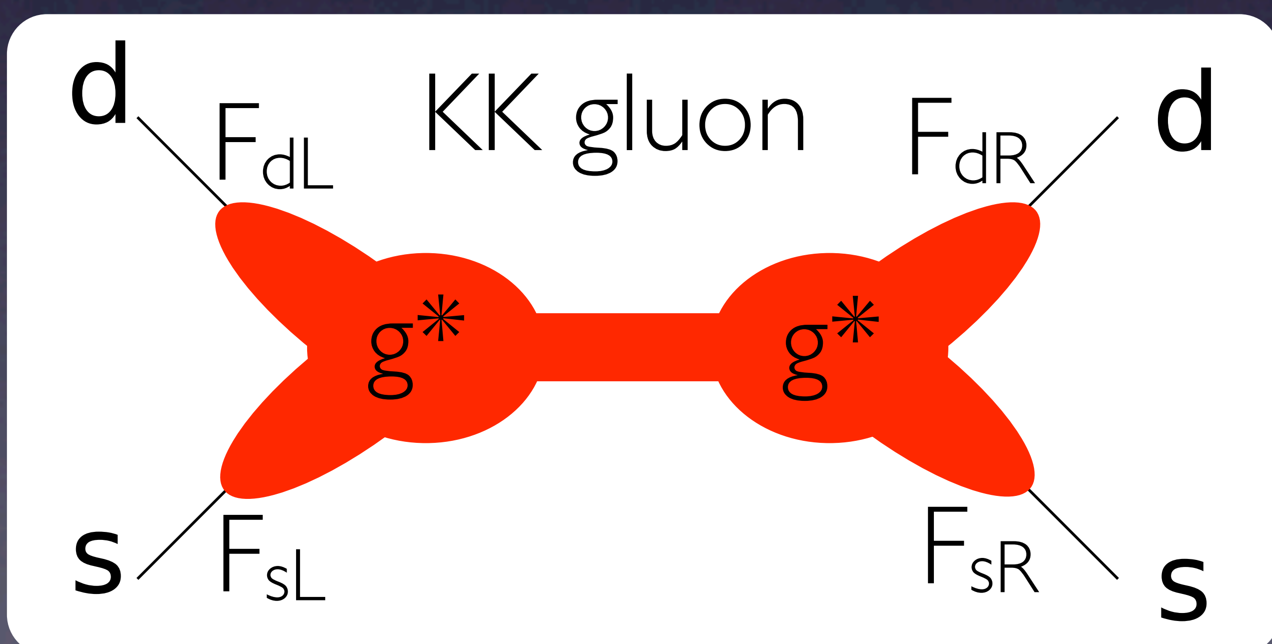
Gherghetta, Pomarol; Agashe, Perez, Soni



masses and mixings from hierarchical overlaps

$$m_d \sim v\, F_{d_L} Y^* F_{d_R}$$

RS GIM



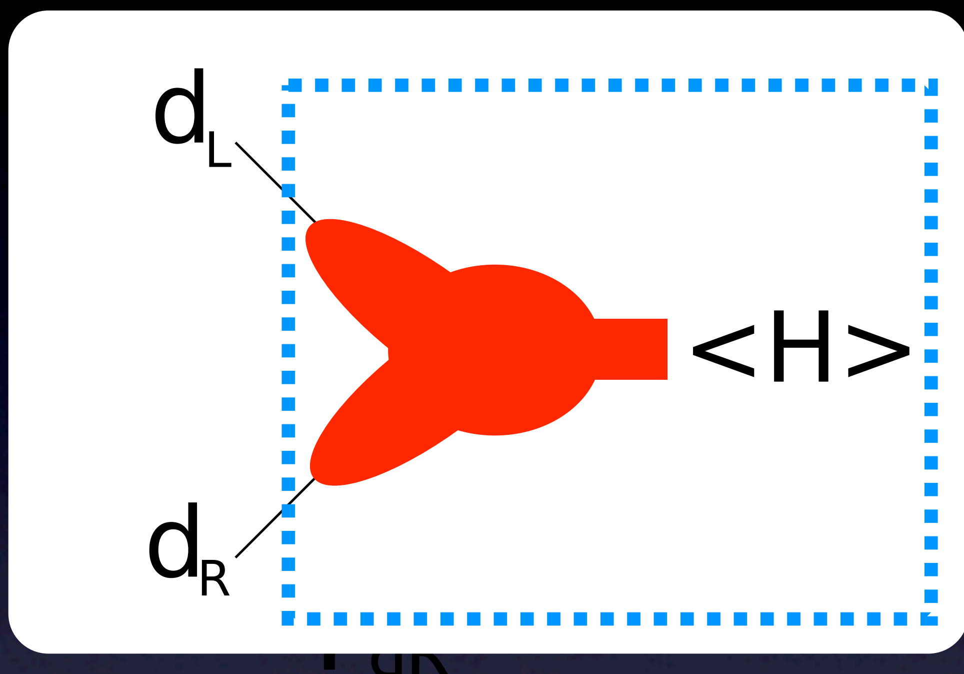
KK gluon FCNCs due to the same small overlaps F_i :

$$\sim \frac{(g^*)^2}{M_{KK}^2} F_{d_L} F_{d_R} F_{s_L} F_{s_R}$$

$$\sim \frac{(g^*)^2}{M_{KK}^2} \frac{m_d\, m_s}{(vY^*)^2}$$

DUAL PICTURE

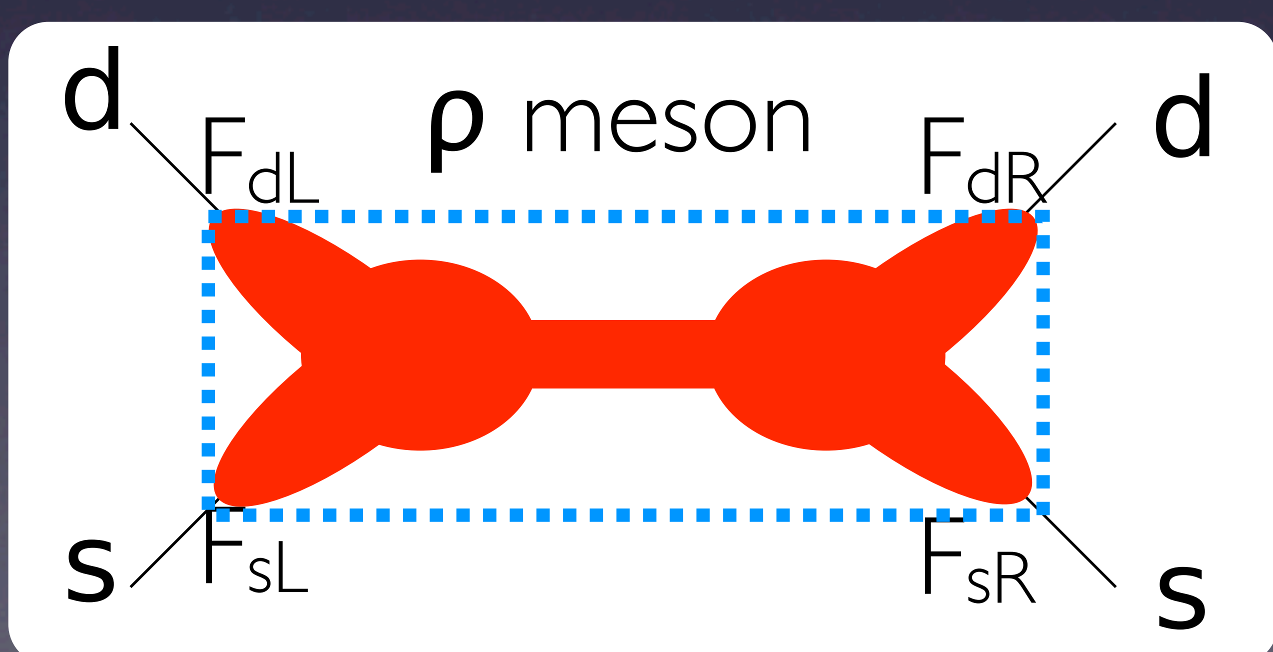
Partial compositeness



Higgs is part of the strong sector, couples only to composites

$$m_d \sim \langle H \rangle Y^* F_{dL} F_{dR}$$

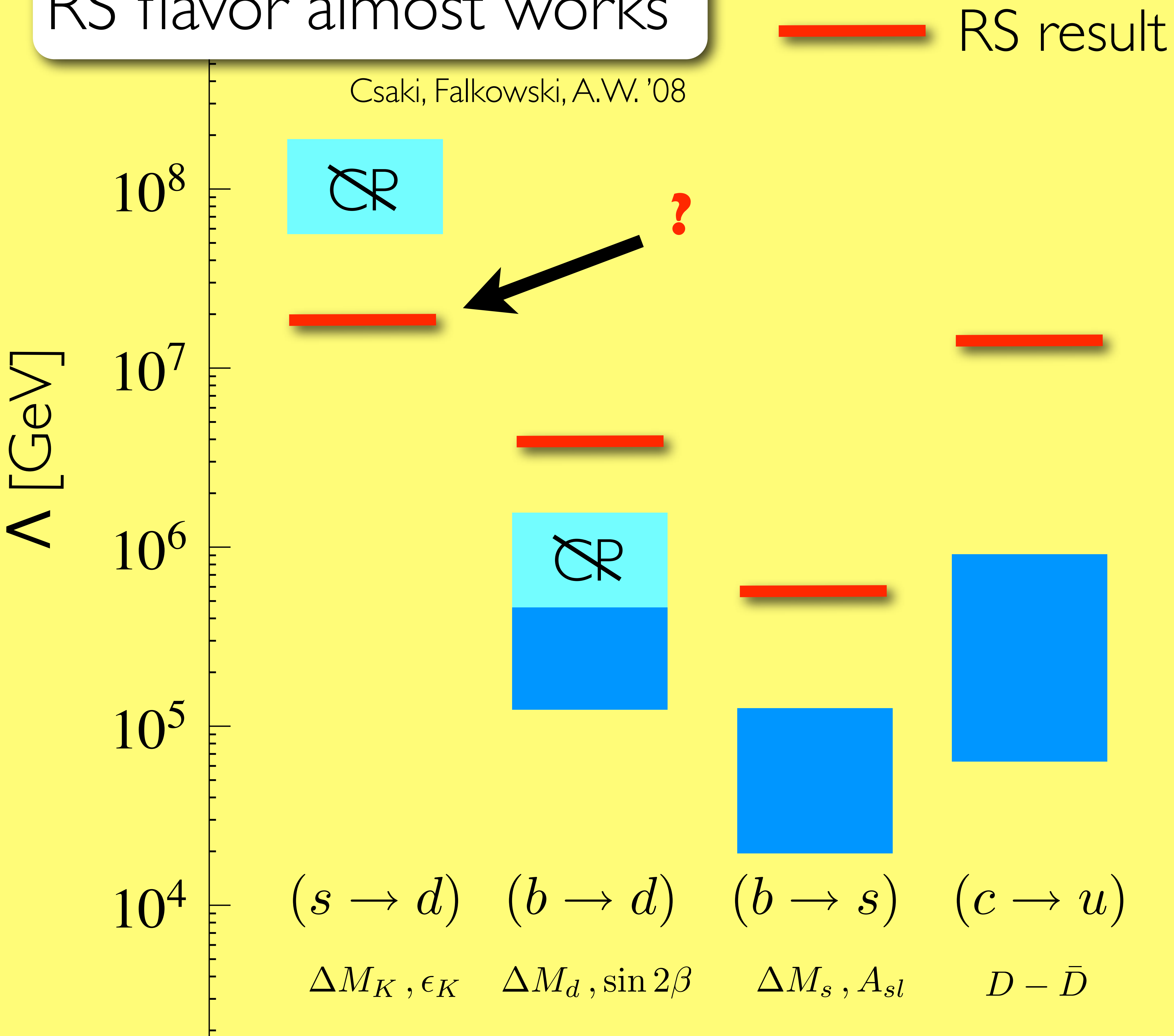
F_i amount of compositeness



The smaller the mass,
the smaller the compositeness,
the smaller the FCNC

$$\sim F_{dL} F_{sL} F_{dR} F_{sR}$$
$$\sim m_d m_s / (\langle H \rangle Y^*)^2$$

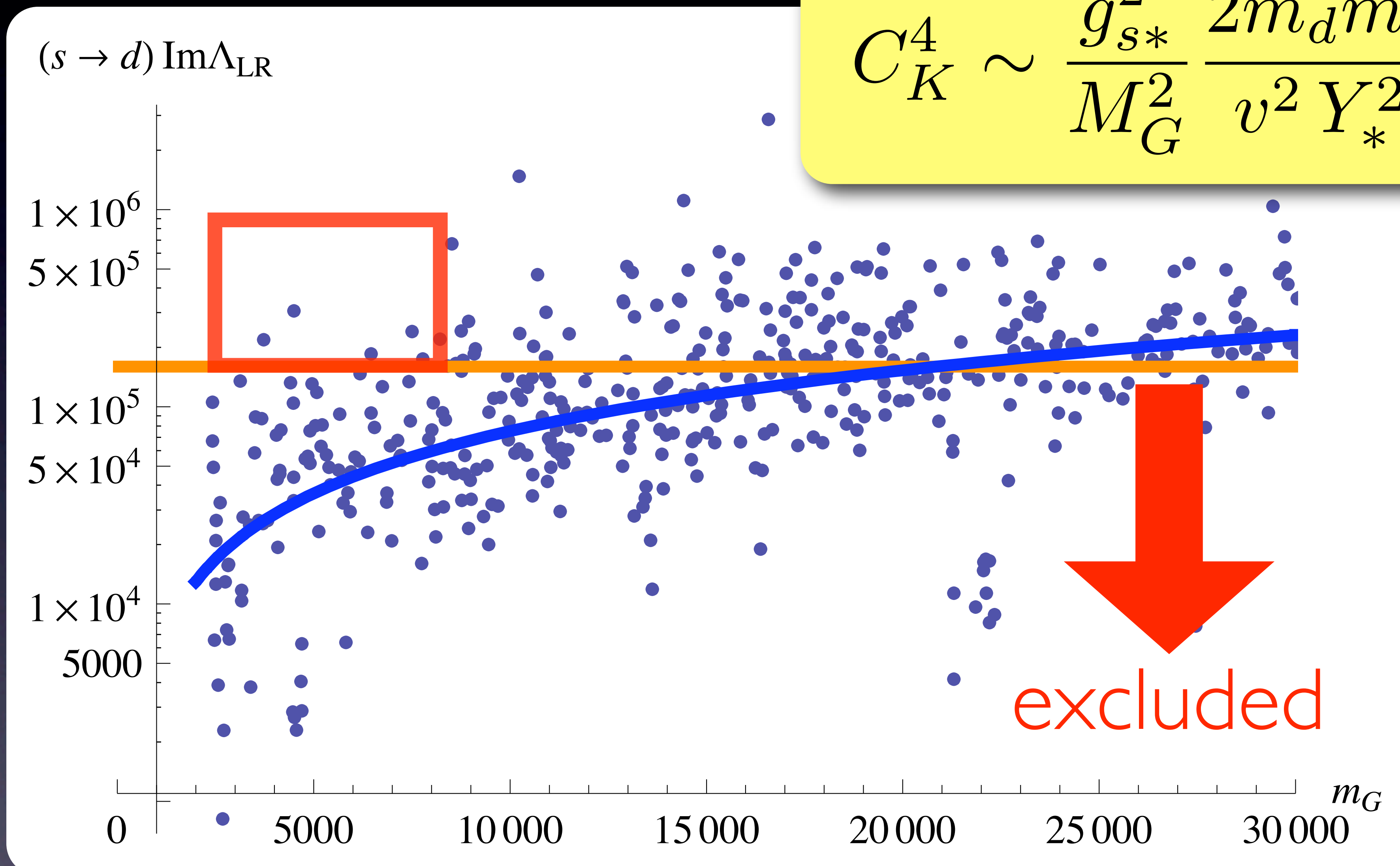
RS flavor almost works



Bound on the KK gluon mass

Csaki, Falkowski, A.W.; Casagrande et al.; Buras et. al.

$$C_K^4 \sim \frac{g_{s*}^2}{M_G^2}\,\frac{2 m_d m_s}{v^2\, Y_*^2}$$



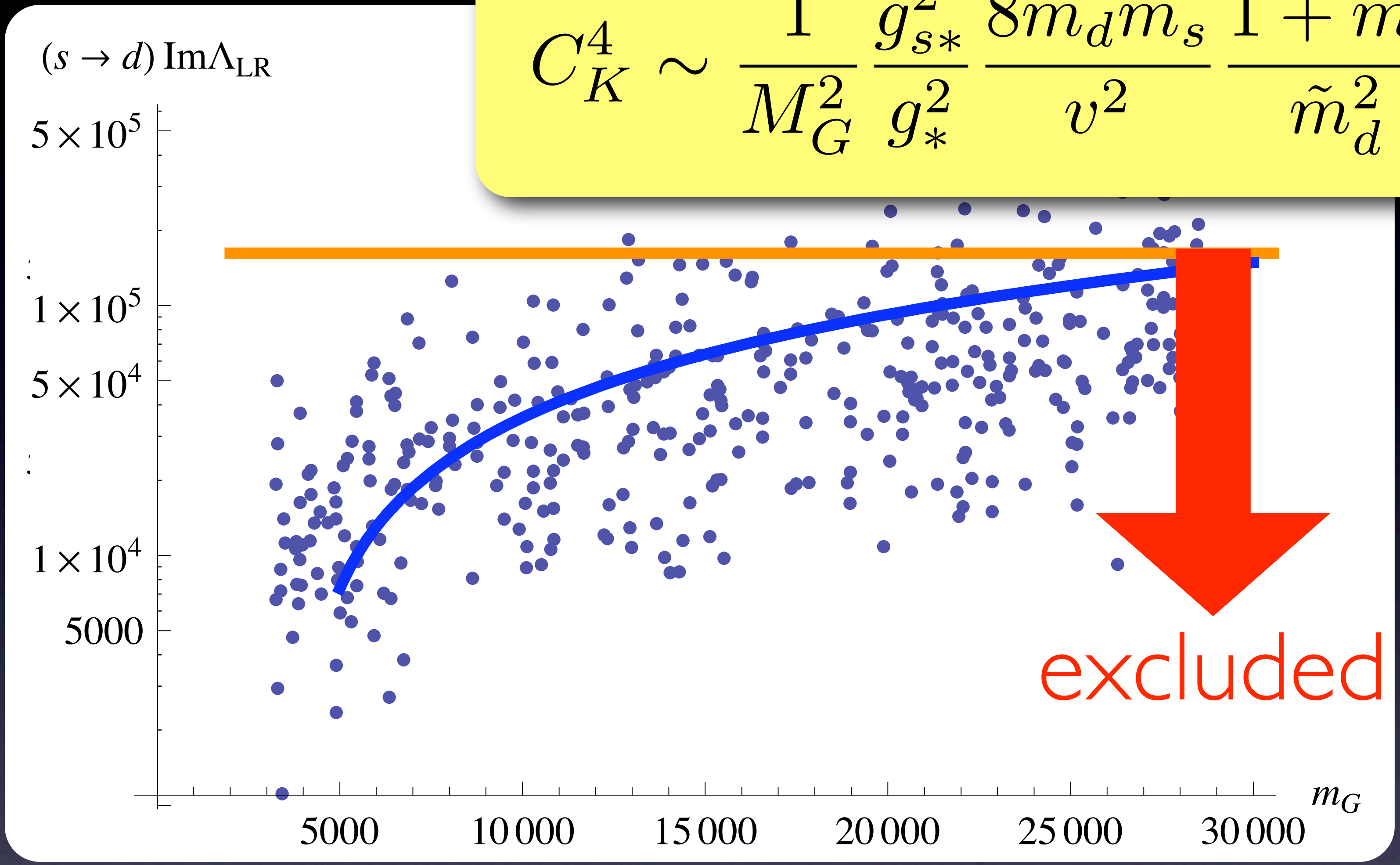
Some points above the bound: any rationale to live here? Radiative stability?

☞ more in M. Neubert's talk

Bound in the composite pGB

Csaki, Falkowski, A.W.;

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



more flavor violation in composite pGB:

Y* → g* / 2 & fermionic kinetic mixings

$M_{KK} > 30$ TeV

Conclusions

Flavor searches are complementary to direct searches at the LHC.

We have learned that NP must have a highly non-generic flavor sector.

Finding deviations from MFV can give us insights into the origin of the Yukawa couplings.

I am looking forward to the era of precision flavor physics driven by CDF, D0,LHCb, NA48/3, E391, SuperB, ATLAS, CMS & theoretical efforts.

Low KK scale w/o adding flavor structure

+ live with fine-tuned Yukawas (large radiative corrections)

or

Agashe, Azatov, Zhu

+ bulk Higgs model (not applicable to pGB), push Yukawa to perturbative limit $Y^* > 6$ and g_{s^*} as small as possible (1-loop matching)

$$M_{KK} > \frac{g_{s*}}{Y^*}\frac{\sqrt{2m_d m_s}}{v}\Lambda_4$$

With some tuning $M_{KK} \sim 5$ TeV possible
Testable at LHC?

Low KK scale by adding flavor structure

Cacciapaglia, Csaki, Galloway, Marandella, Terning, AW

+ exact GIM structure
  flavor symmetry in bulk and IR brane, UV kinetic terms generate flavor, no explanation for fermion masses (likely the only way for Higgsless)

Csaki, Falkowski, AW

+ Add horizontal U(1)'s

Fitzpatrick, Randall, Perez

+ 5D MFV only two flavor spurions (Y_U, Y_D)
  Need to tune to align bulk and brane matrices.