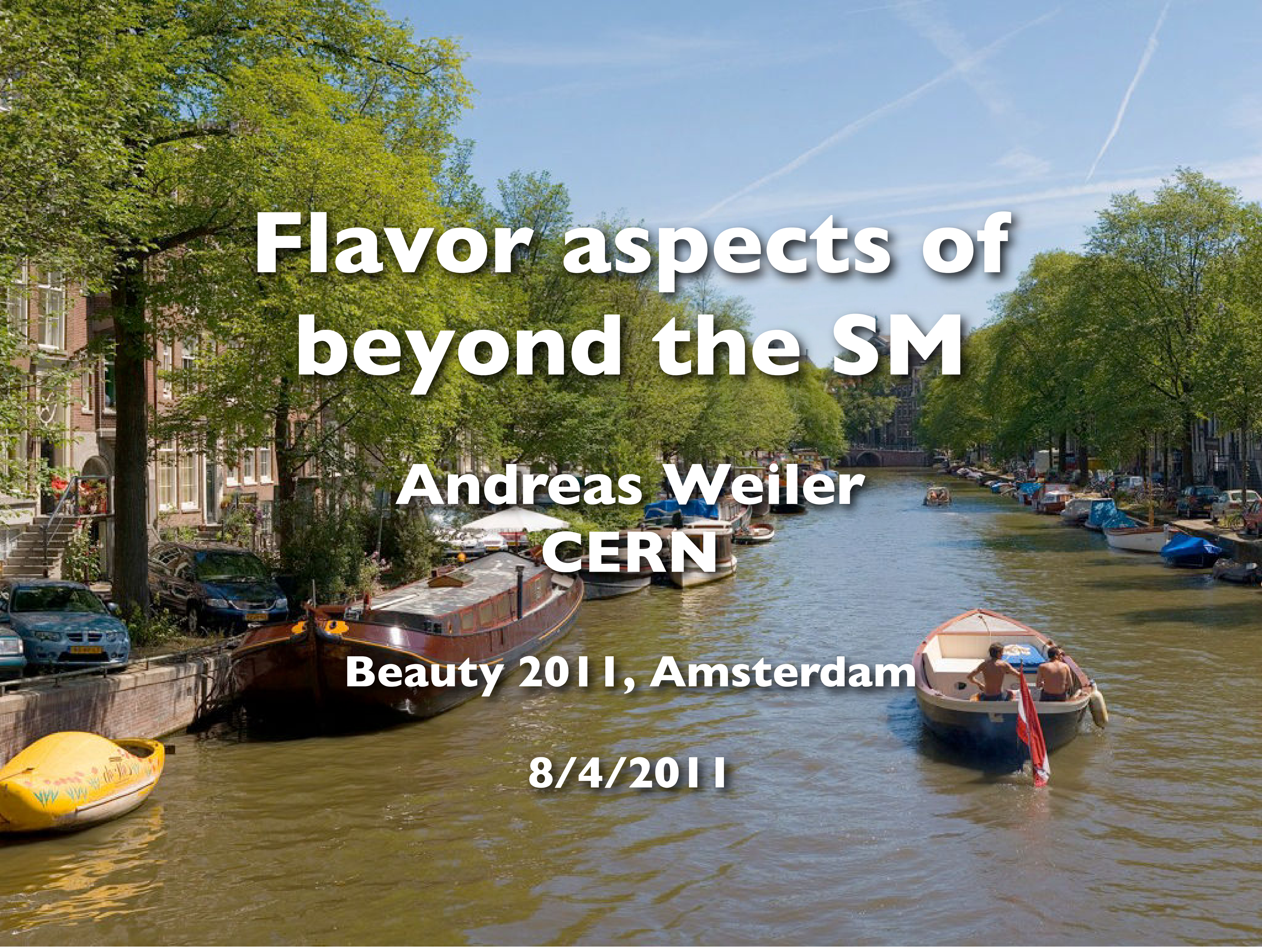

Flavor aspects of beyond the SM

Andreas Weiler
CERN

Beauty 2011, Amsterdam

8/4/2011

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

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

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$\Downarrow$

V_{ckm}

unphysical due to SU(3)^3!

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

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

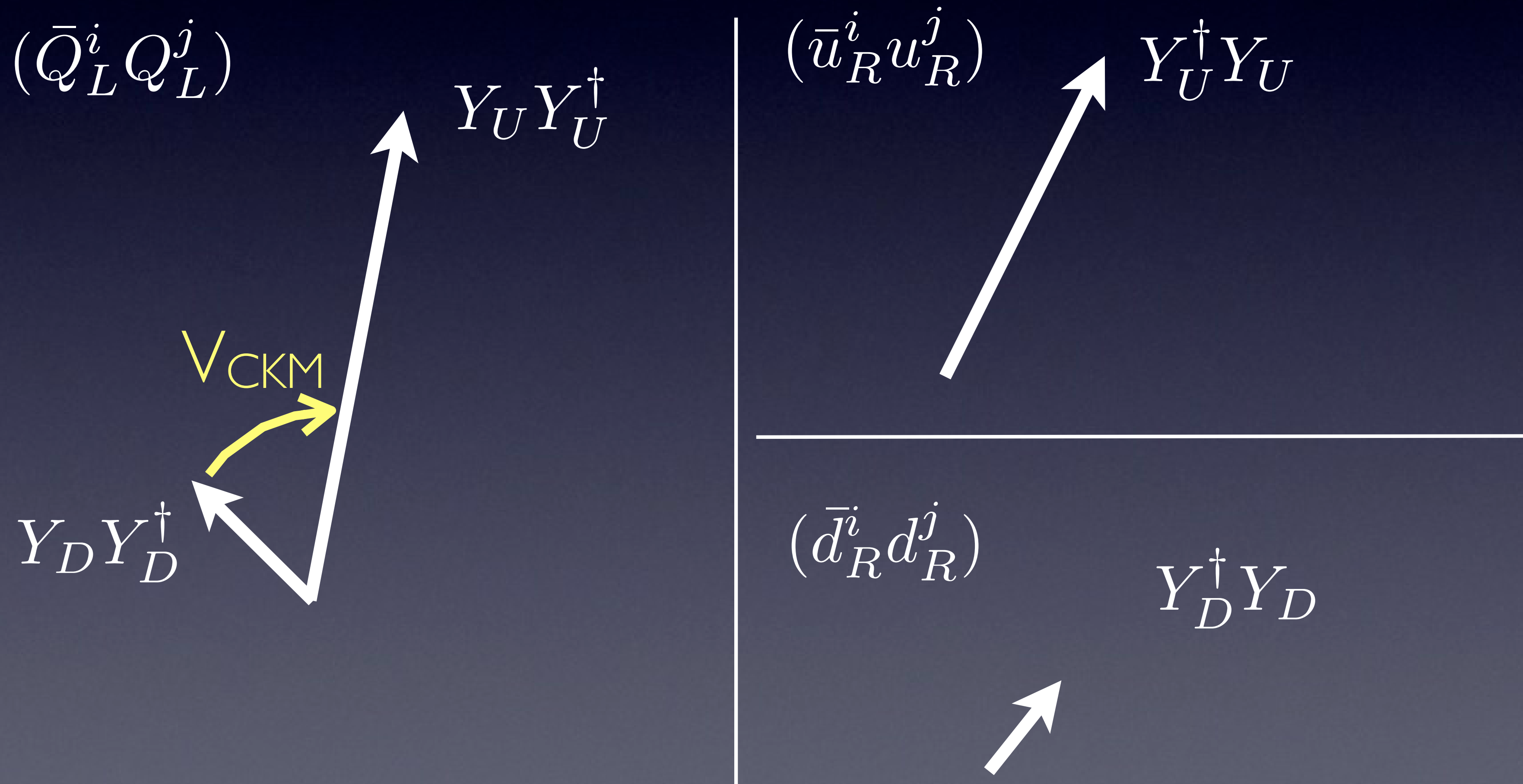
Yukawas diagonal, **no (tree-level) flavor violation**

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

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

Flavor and CP in the SM

Yukawa matrices Y_U & Y_D encode flavor violation



+ LR, RL

Flavor and CP in the SM

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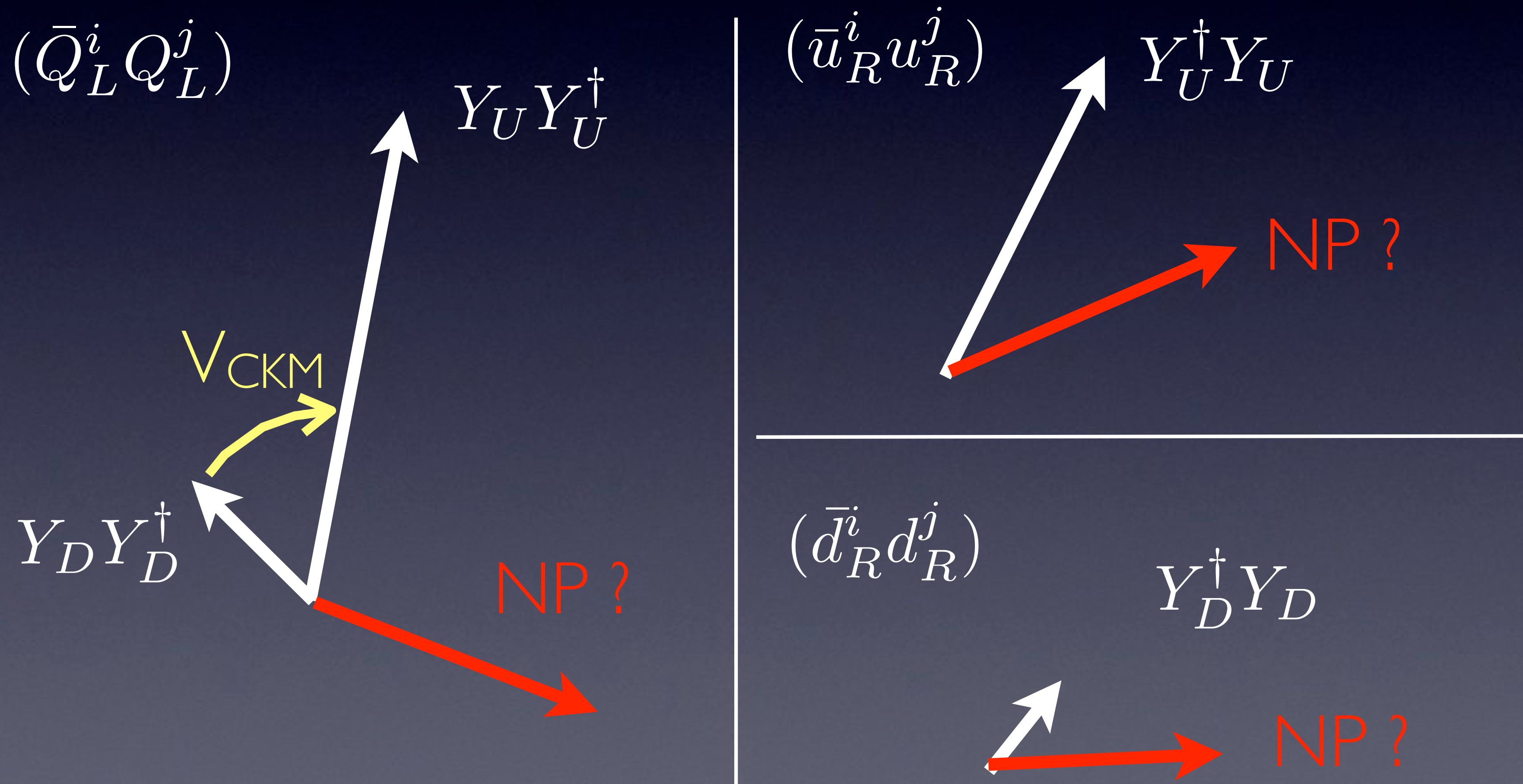
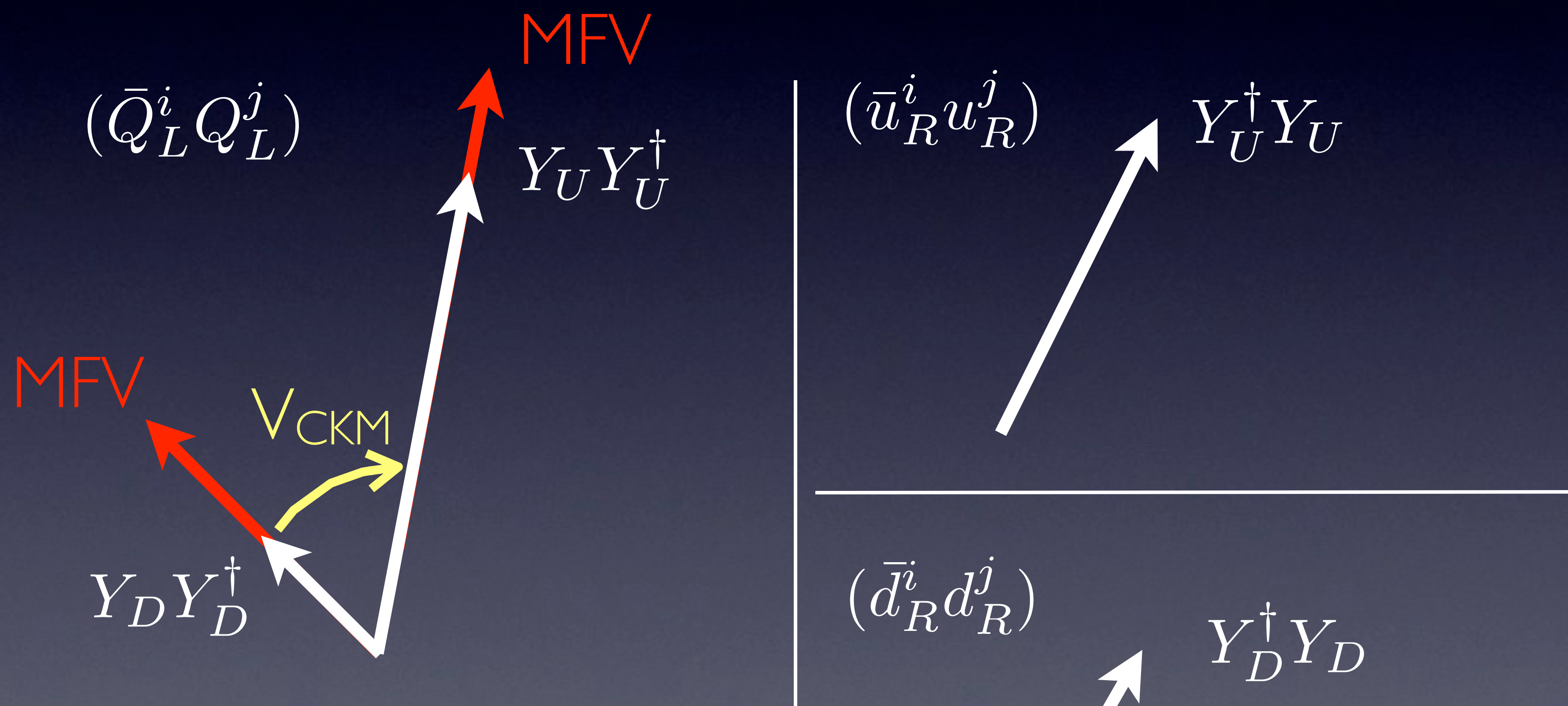


+ LR, RL

Minimal flavor violation

Chivukula Georgi; Buras et. al; D'Ambrosio et. al

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



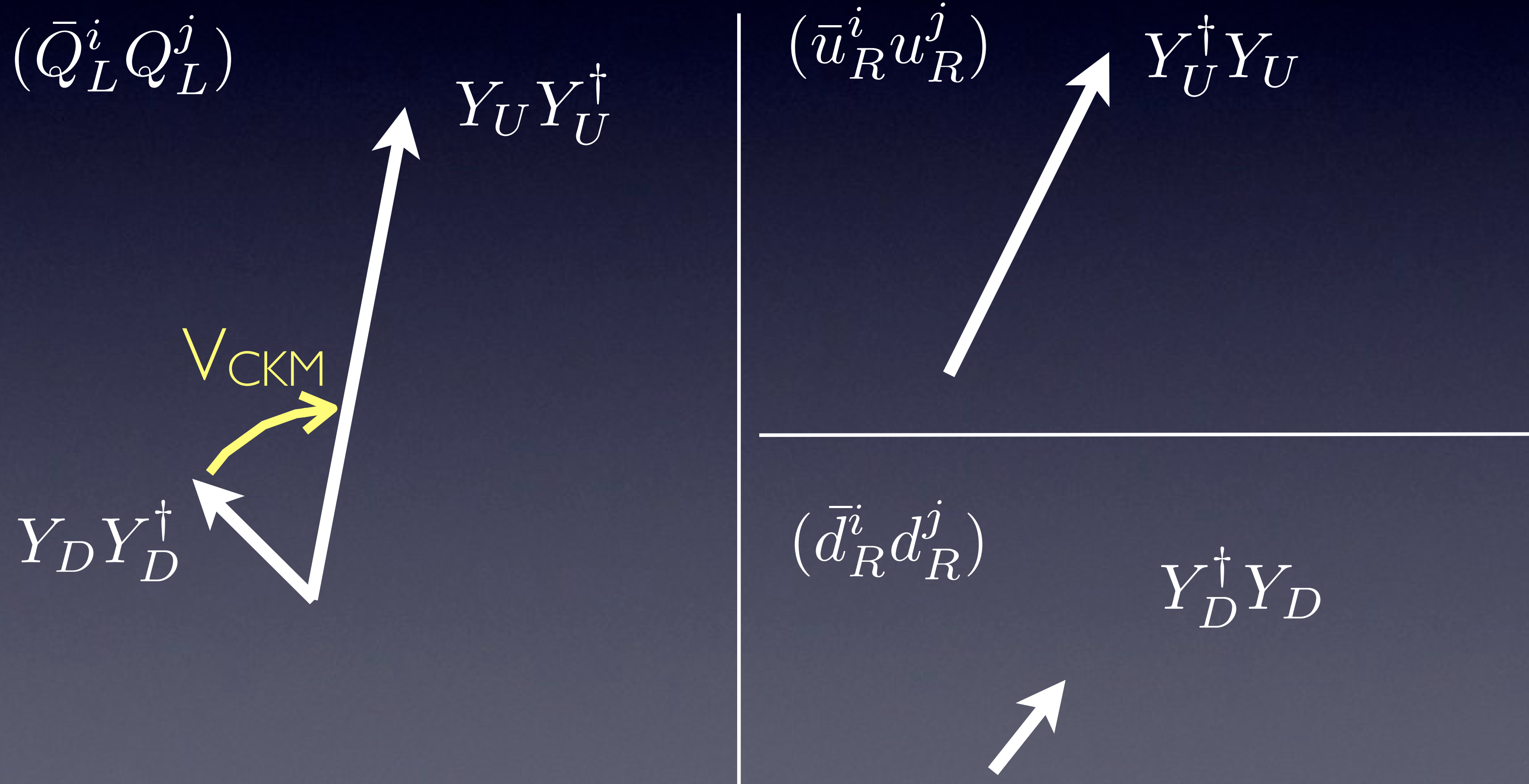
$$|\mathrm{MFV}| \approx \mathcal{O}(|\mathrm{SM}|)$$

condition: moderate tanß or small $U(1)_{PQ}$ breaking

+ LR, RL

NP Flavor dynamics

Dynamics that generates hierarchies in masses & mixings usually partially aligned with SM



+ LR, RL

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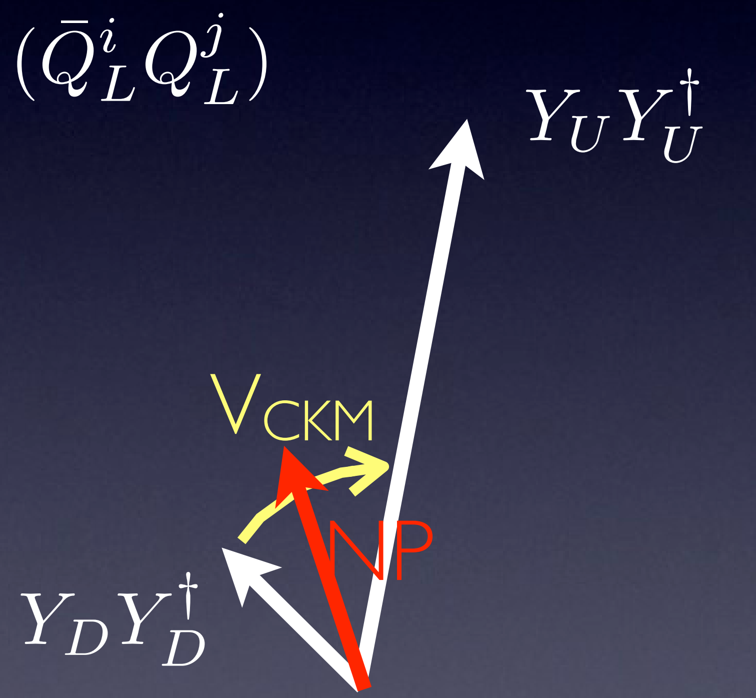

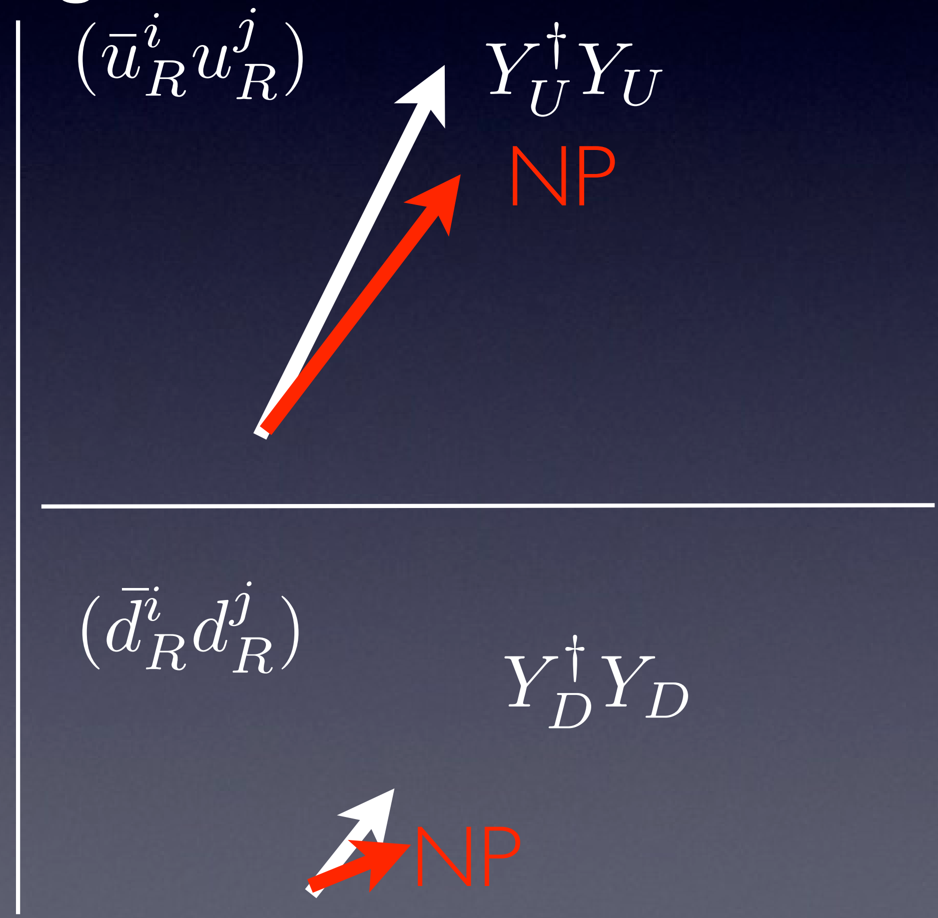

+ LR, RL

NP Flavor dynamics

Dynamics that generates hierarchies in masses & mixings usually partially aligned with SM

$(\bar{Q}_L^i Q_L^j)$ $Y_U Y_U^\dagger$

$(\bar{u}_R^i u_R^j)$ $Y_U^\dagger Y_U$ NP

Effects are O(SM) but not MFV, still possible for M ~ TeV: expect signatures also in direct tests!

NP

+ LR, RL

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?

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}	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}

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

UTfit 08, Isidori et. al '10

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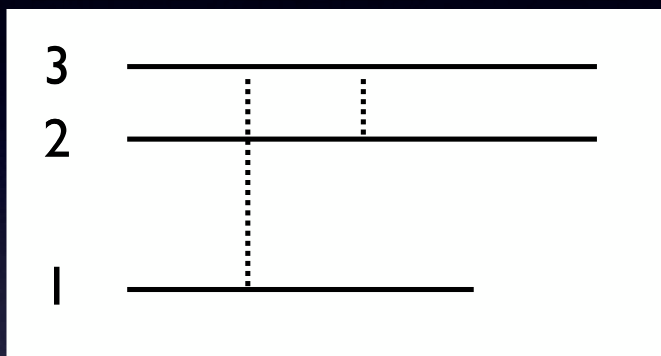
Very strong suppression! New flavor violation must either approximately follow SM pattern…

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

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

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

Analog to mysterious spectral lines before QM



$$\nu = \left(\frac{1}{n^2} - \frac{1}{m^2}\right) R$$

Explained by Bohr

$$E_n = -\frac{2\pi^2 e^4 m_e}{h^2 n^2}$$

Is there an analogue to the Bohr atom, we might discover at the LHC?

Log(SM flavor puzzle)

$$-\log|Y_D| \approx \mathrm{diag}\,(11 \quad 8 \quad 4)$$

$$-\log|Y_U| \approx \begin{pmatrix} 12 & 7 & 5 \\ 14 & 6 & 3 \\ 18 & 9 & 0 \end{pmatrix}$$

If $Y = e^{-\Delta}$, then the Δ don't look crazy.

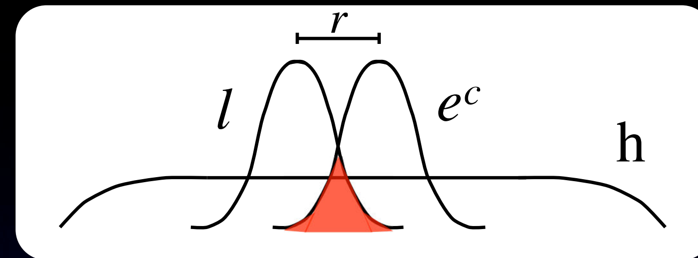
anarchic (“structure-less”)

$$\mathrm{Mass}_{ij} \propto Y_{ij} e^{-MR(c_i+c_j)} \quad \text{split fermions/RS}$$

$$\propto Y_{ij} \left(\frac{\mu_{\mathrm{low}}}{\mu_{\mathrm{high}}}\right)^{\gamma^i+\gamma^j} \quad \text{strong dynamics}$$

$$\propto Y_{ij} \left(\frac{\langle\Phi\rangle}{M_{\mathrm{mess}}}\right)^{Q^i-Q^j} \quad \text{Froggatt-Nielsen}$$

anarchic ("structure-less")



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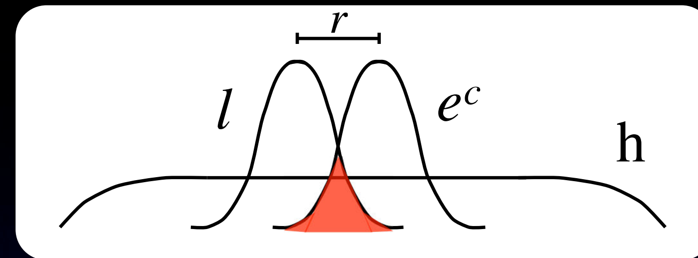

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strong dynamics

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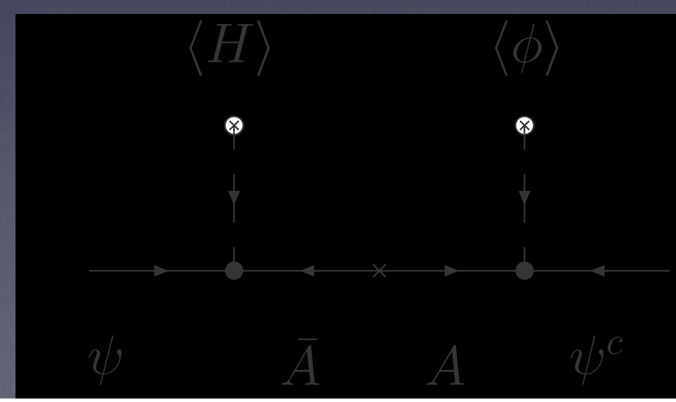
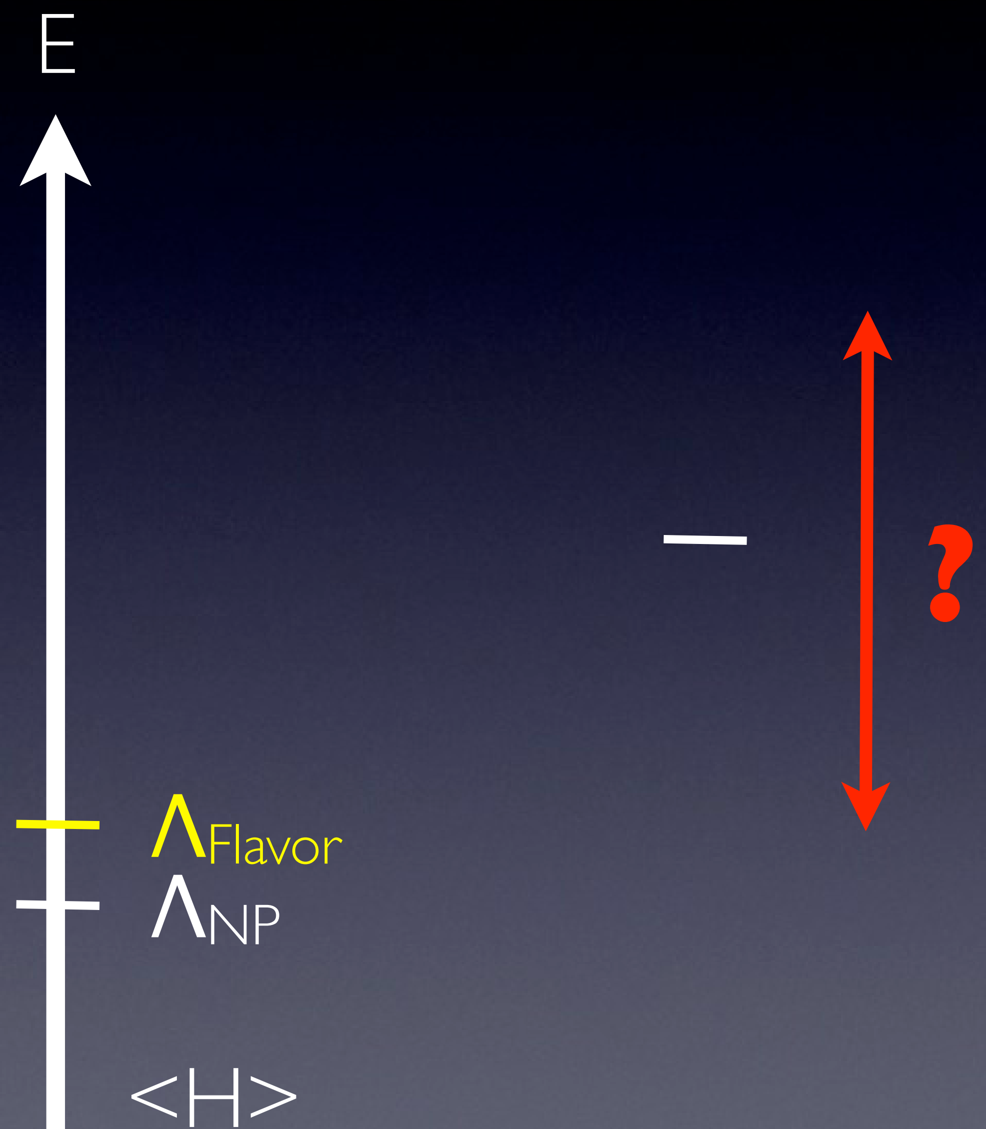
Froggatt-Nielsen



EWSB & Flavor

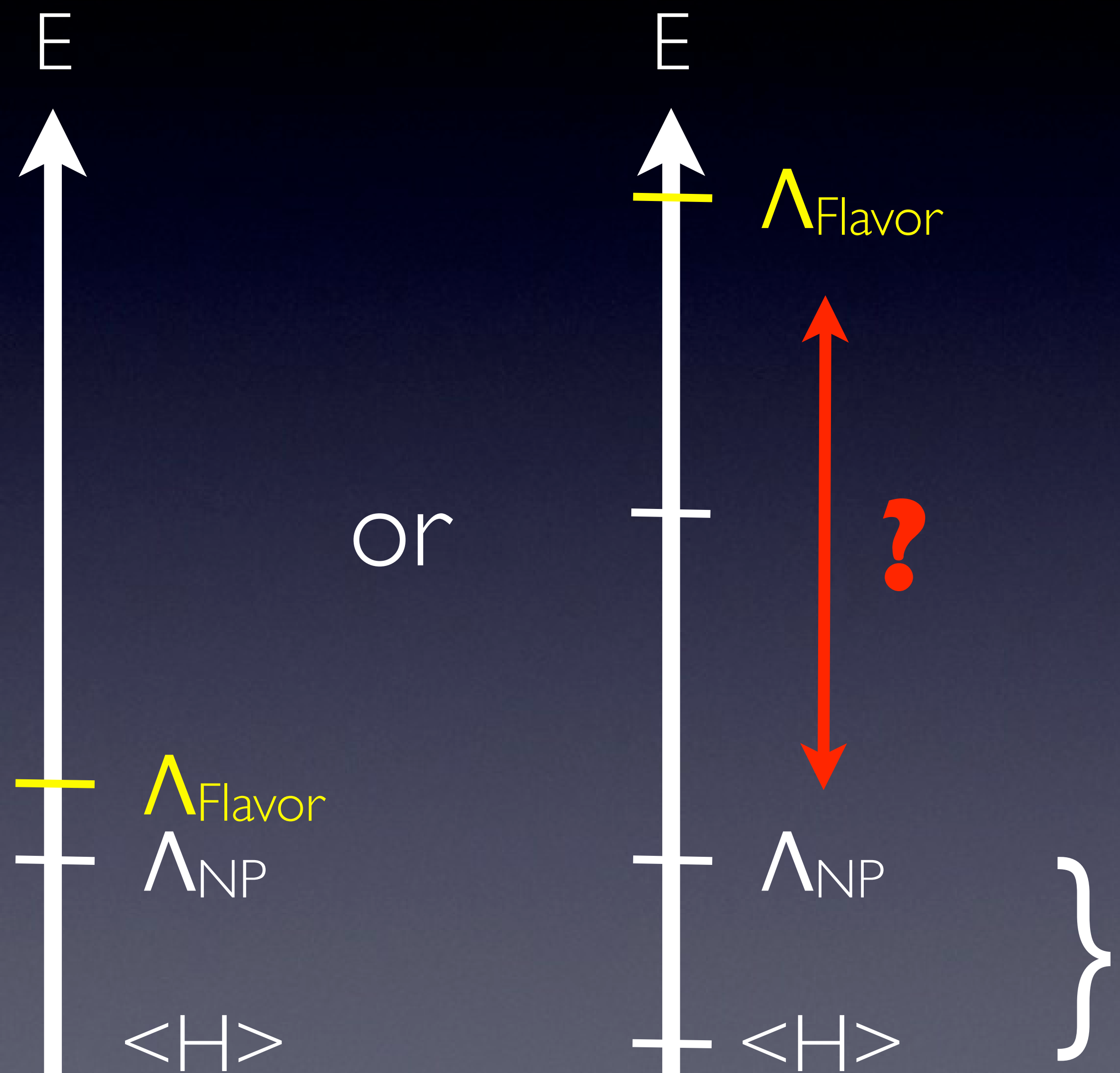


$$\frac{1}{\Lambda^2_{\text{Flavor}}}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

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

naturalness

EWSB & Flavor



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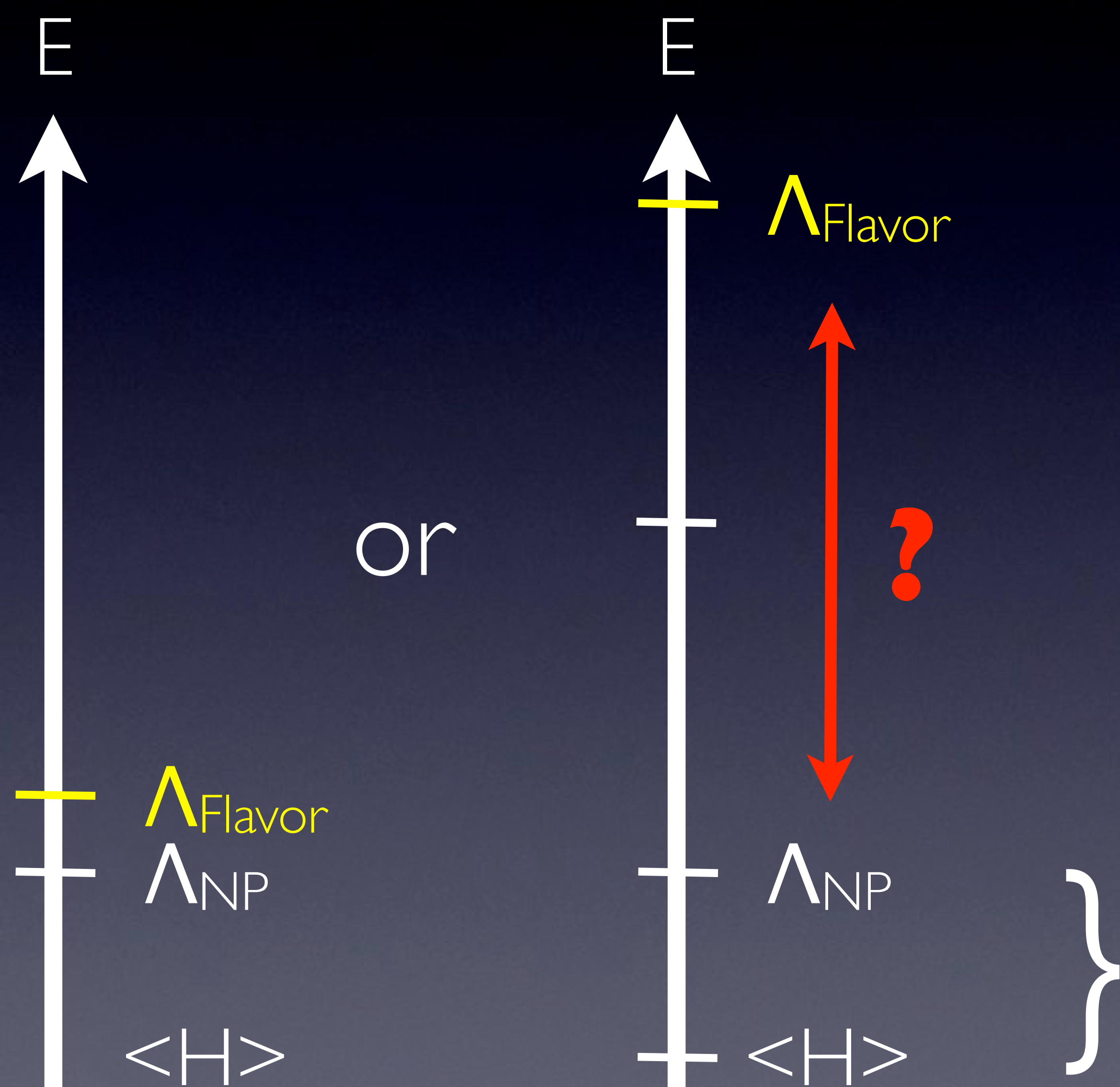

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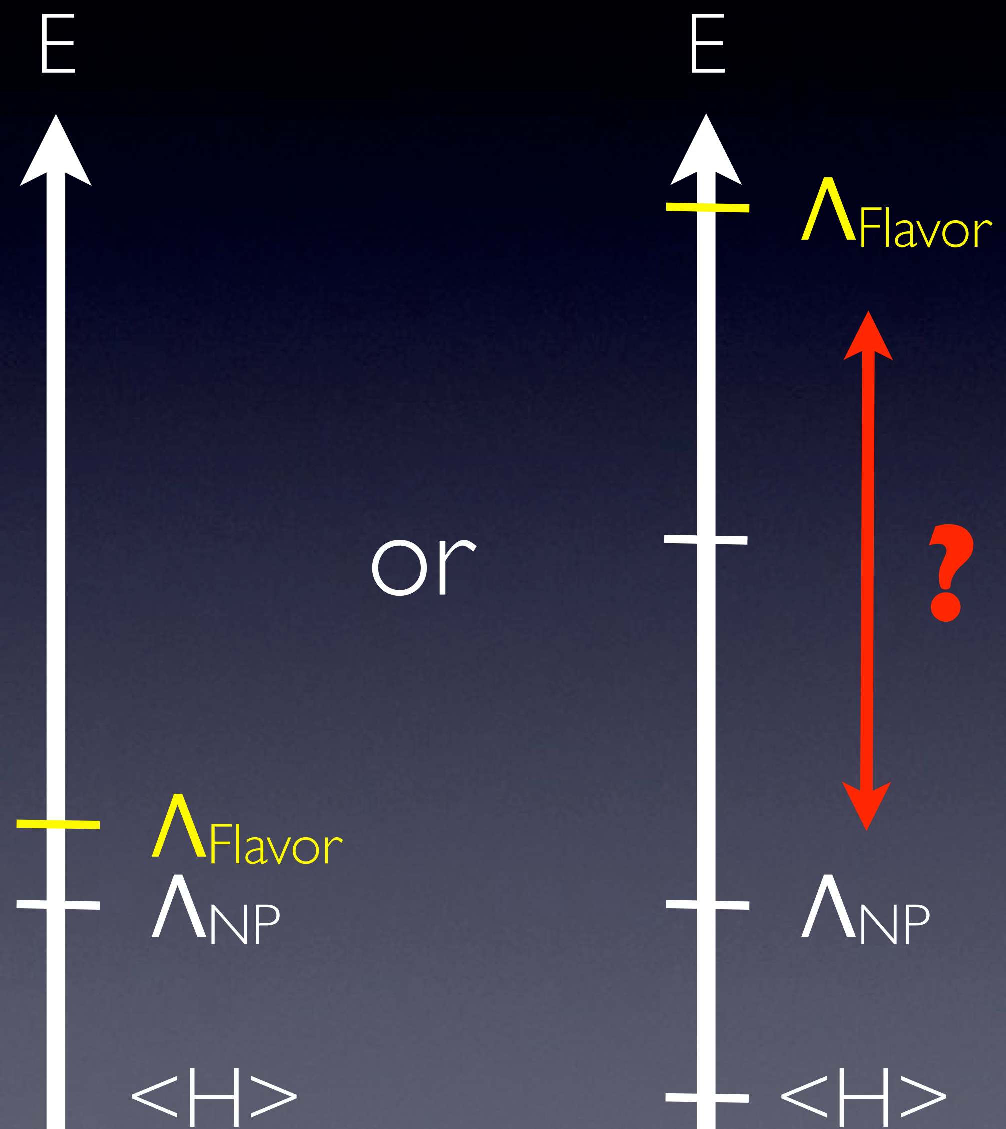


$$\frac{1}{\Lambda^2_{\mathrm{Flavor}}}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

only trace left: MFV

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

} naturalness

Model independent constraints

Minimal flavor violation

UTfit, Buras et. al, Hurth et al

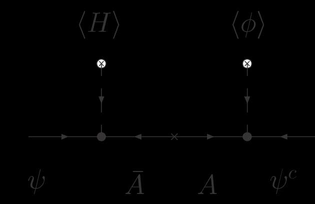
Tree

Operator	Bound on Λ	Observables
$H^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right)(e F_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma,\ B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L)^2$	5.9 TeV	$\epsilon_K,\ \Delta m_{B_d},\ \Delta m_{B_s}$
$H_D^\dagger\left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma,\ B \to X_s\ell^+\ell^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right)(\overline{E}_R\gamma_\mu E_R)$	2.7 TeV	$B \to X_s\ell^+\ell^-,\ B_s \to \mu^+\mu^-$
$i\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right) H_U^\dagger D_\mu H_U$	2.3 TeV	$B \to X_s\ell^+\ell^-,\ B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right)(\overline{L}_L\gamma_\mu L_L)$	1.7 TeV	$B \to X_s\ell^+\ell^-,\ B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger}\gamma_\mu Q_L\right)(e D_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s\ell^+\ell^-$

if 1-loop suppressed: $\Lambda_{\text{loop}} \approx \left(\frac{\alpha}{4\pi}\right)^{\frac{1}{2}}\Lambda_{\text{tree}} \approx \frac{1}{10}\Lambda_{\text{tree}}$

Alignment model bounds

Lalak et al



Flavour violating dimension six operator		Λ/Λ_{MFV} Ex. 1	Ex. 2	Ex. 3	$U(1)^2$	N-A	F
$\mathcal{O}_0 =$	$\frac{1}{2}(\bar{Q}_L X^Q_{LL} Q_L)^2$	ϵ^{-4}	ϵ^{-4}	1	1	ϵ^{-2}	1
$\mathcal{O}_{F1} =$	$H^\dagger \left(\bar{D}_R X^{D\dagger}_{LR} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$x\epsilon^{-2}$	$x\epsilon^{-3/2}$	$x\epsilon^{-2}$	$x\epsilon$	$x\epsilon^{-2}$	$x\epsilon^{-2}$
$\mathcal{O}_{G1} =$	$H^\dagger \left(\bar{D}_R X^{D\dagger}_{LR} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$x\epsilon^{-2}$	$x\epsilon^{-3/2}$	$x\epsilon^{-2}$	$x\epsilon$	$x\epsilon^{-2}$	$x\epsilon^{-2}$
$\mathcal{O}_{\ell 1} =$	$(\bar{Q}_L X^Q_{LL} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1
$\mathcal{O}_{\ell 2} =$	$(\bar{Q}_L X^Q_{LL} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1
$\mathcal{O}_{H1} =$	$(\bar{Q}_L X^Q_{LL} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1
$\mathcal{O}_{q5} =$	$(\bar{Q}_L X^Q_{LL} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	ϵ^{-2}	ϵ^{-2}	1	1	ϵ^{-1}	1

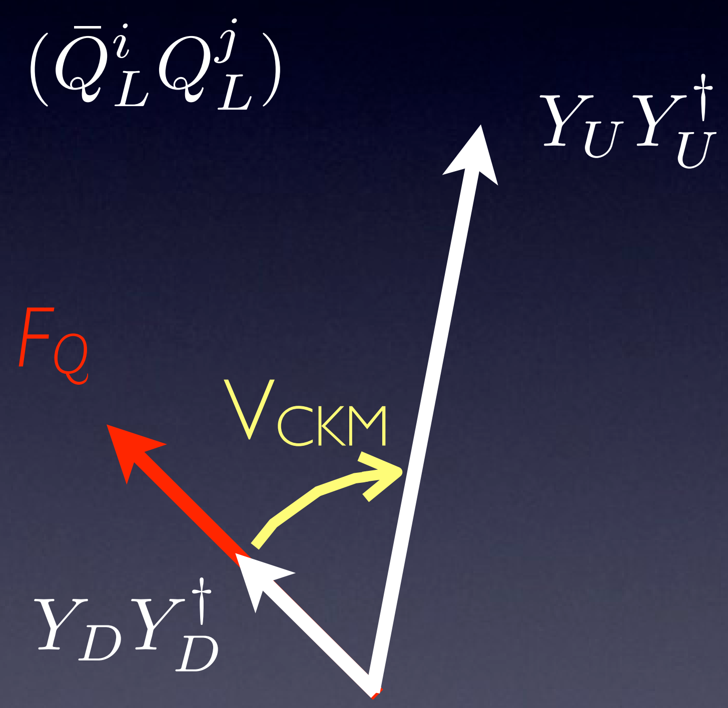
$$\epsilon = \frac{\text{flavon vev}}{\text{messenger mass}} \ll 1 \qquad x = (m_t/m_b)^{\frac{1}{2}}$$

=> more details in RS flavor

Combination of K-K and D-D

Nir 07; Blum et. al '09

Can not simultaneously evade constraints from DD & KK



contribution to D-D mixing

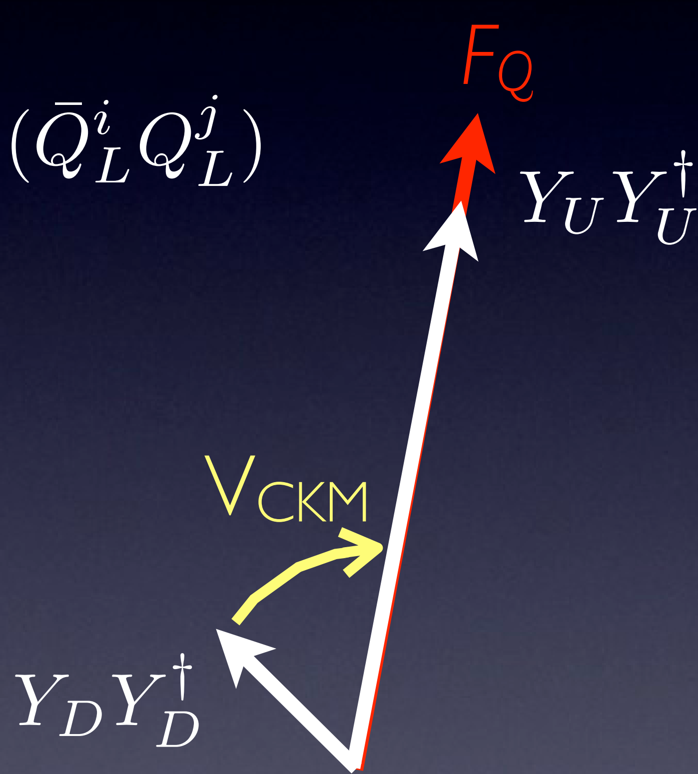
no effect in K-K mixing

Combination of K-<u>K</u> and D-<u>D</u>

Nir 07; Blum et. al '09

Can not simultaneously evade constraints from D<u>D</u> & K<u>K</u>

$(\bar{Q}^i_L Q^j_L)$



contribution to K-<u>K</u> mixing

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Combination of K-K and D-D

Nir 07; Blum et. al '09

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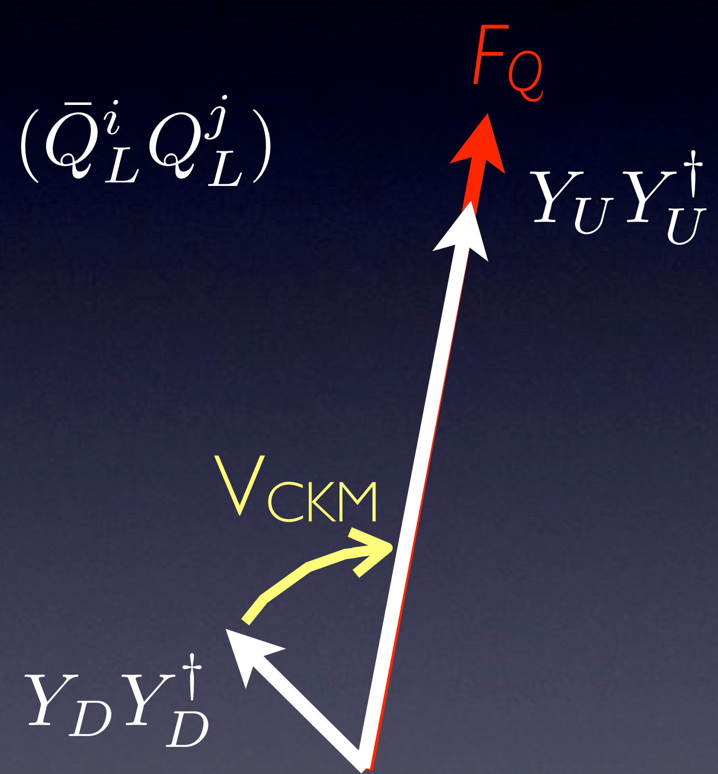


squarks$_{1,2}$ ~ degenerate

$$\frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}} \lesssim 0.05 - 0.14,$$
$$\frac{m_{\tilde{u}_2} - m_{\tilde{u}_1}}{m_{\tilde{u}_2} + m_{\tilde{u}_1}} \lesssim 0.02 - 0.04.$$

contribution to K-K mixing

no effect in D-D mixing

A particular class of models: compositeness (geometric alignment vs. MFV)

Weak scale is unstable

elementary scalar Higgs

$$\mathcal{L}_{Higgs} = \Lambda^2 H^2 + \dots$$ ✗

Compositeness

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

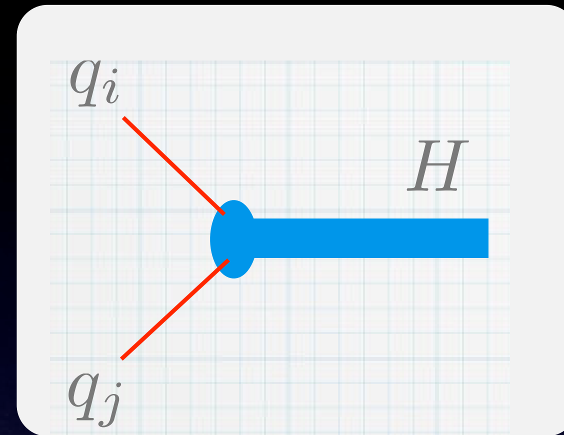
Higgs as a PGB (Randall-Sundrum, Little Higgses, SILH)

Idea: Higgs (if present) is a "pion" of some strongly coupled sector with $\Lambda \sim$ 1-10 TeV

Fermions get masses by coupling to this new sector

MFV or not MFV?

Two ways of giving mass to fermions…



Bi-linear (like SM):

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

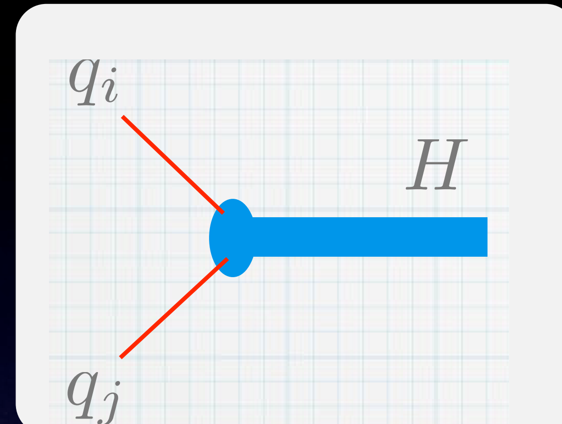
Linear:

D.B. Kaplan '91

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

$\propto$

Two ways of giving mass to fermions…



Bi-linear (like SM):

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

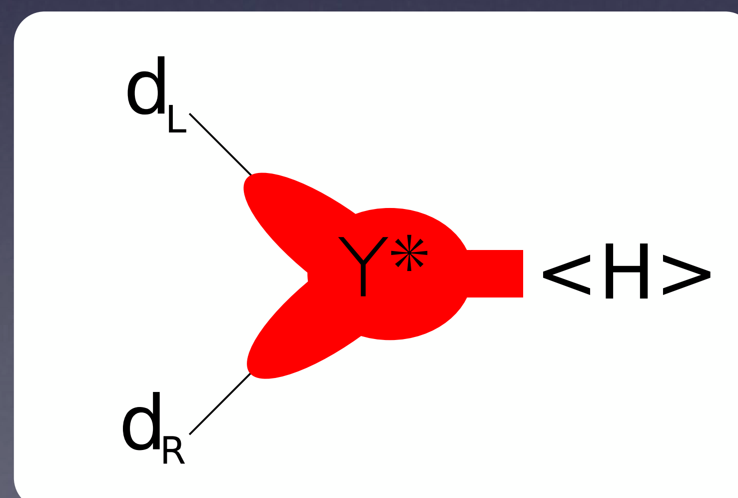
Linear:

D.B. Kaplan '91

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

Quarks & Leptons mix with strong sector

mass $\propto$ compositeness



strong sector

elementary fields

Higgs, top, resonances ρ_μ

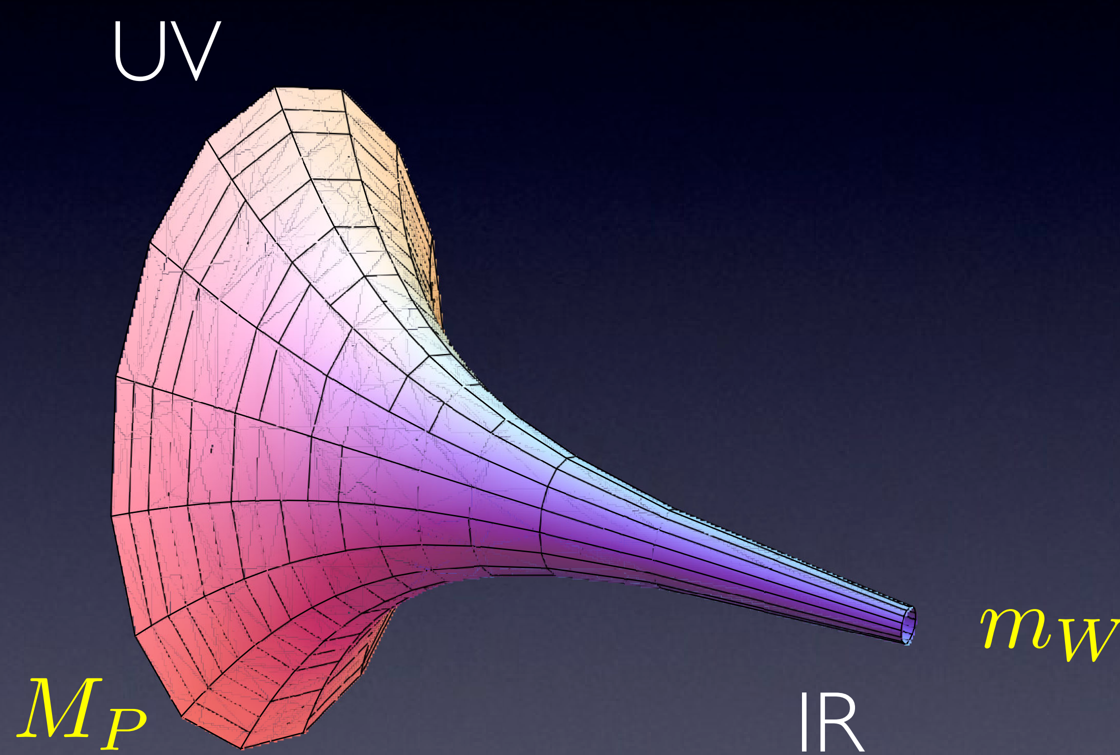
u, d, c, s, b, A_μ

$g_*, \ m_\rho$

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

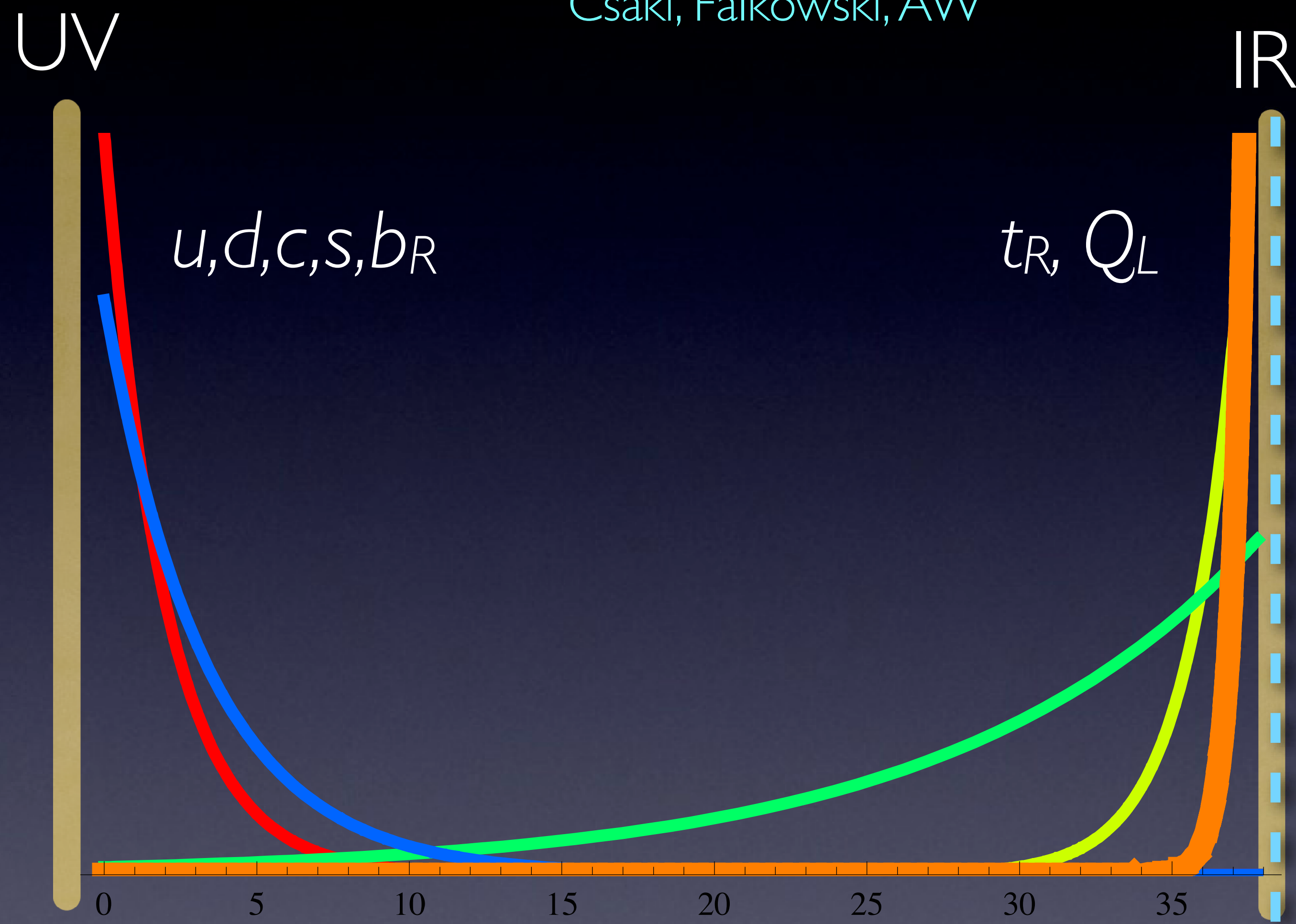
AdS/CFT => Randall Sundrum

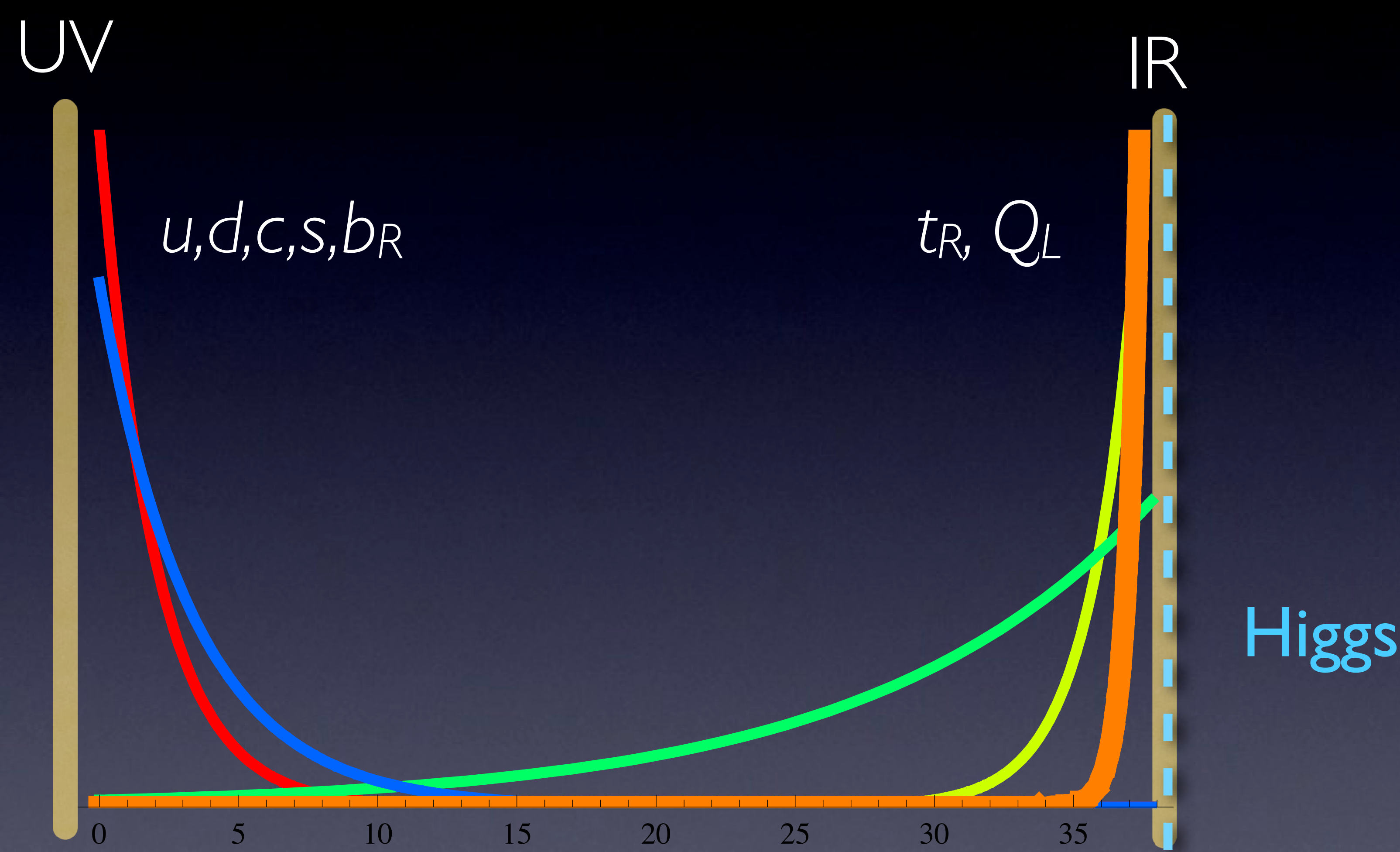
$$ds^2 = \left(\frac{R}{z}\right)^2 (dx_\mu dx_\nu - dz^2)$$



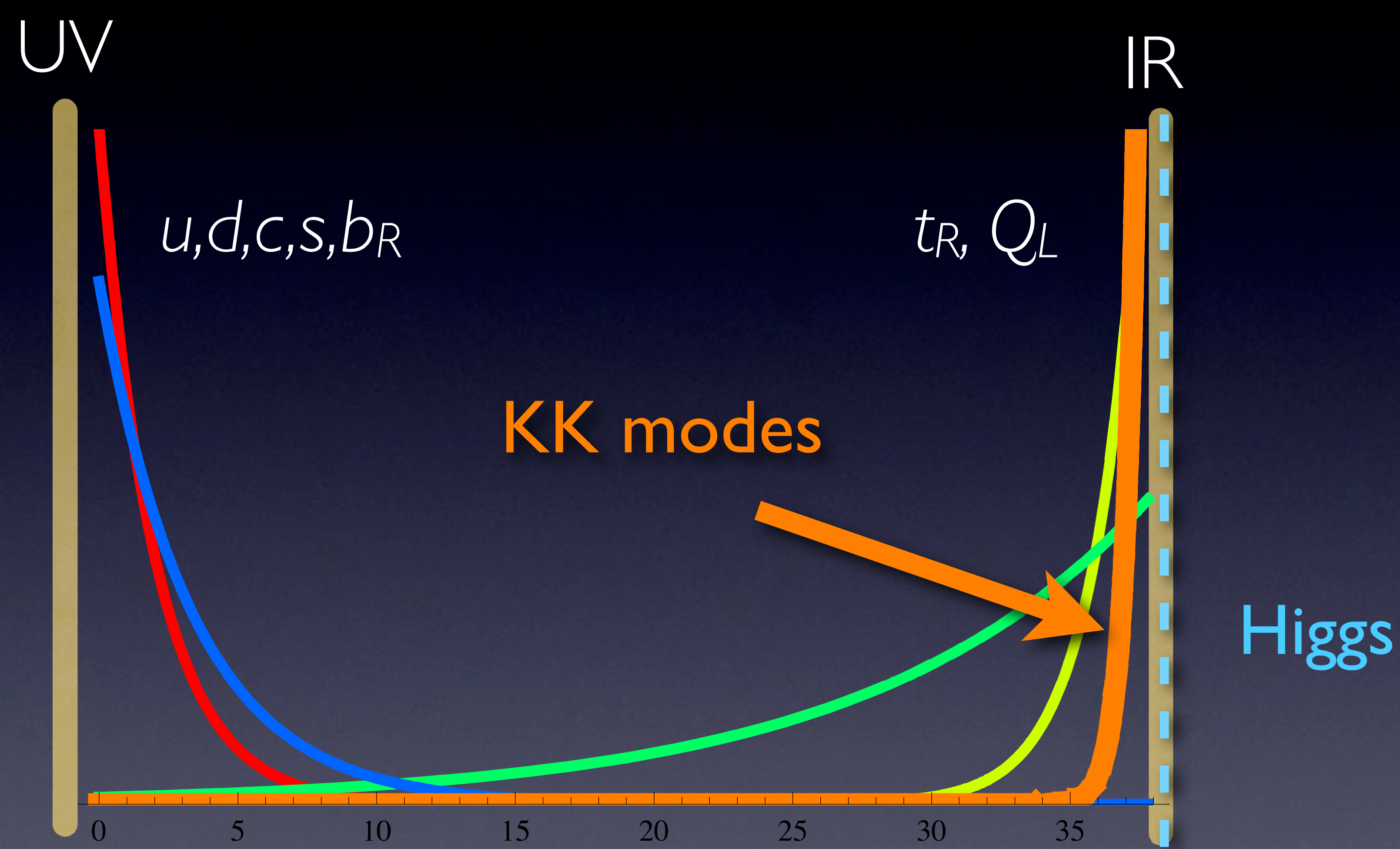
Geometrical sequestering in RS

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





RGE of the mixing UV → IR



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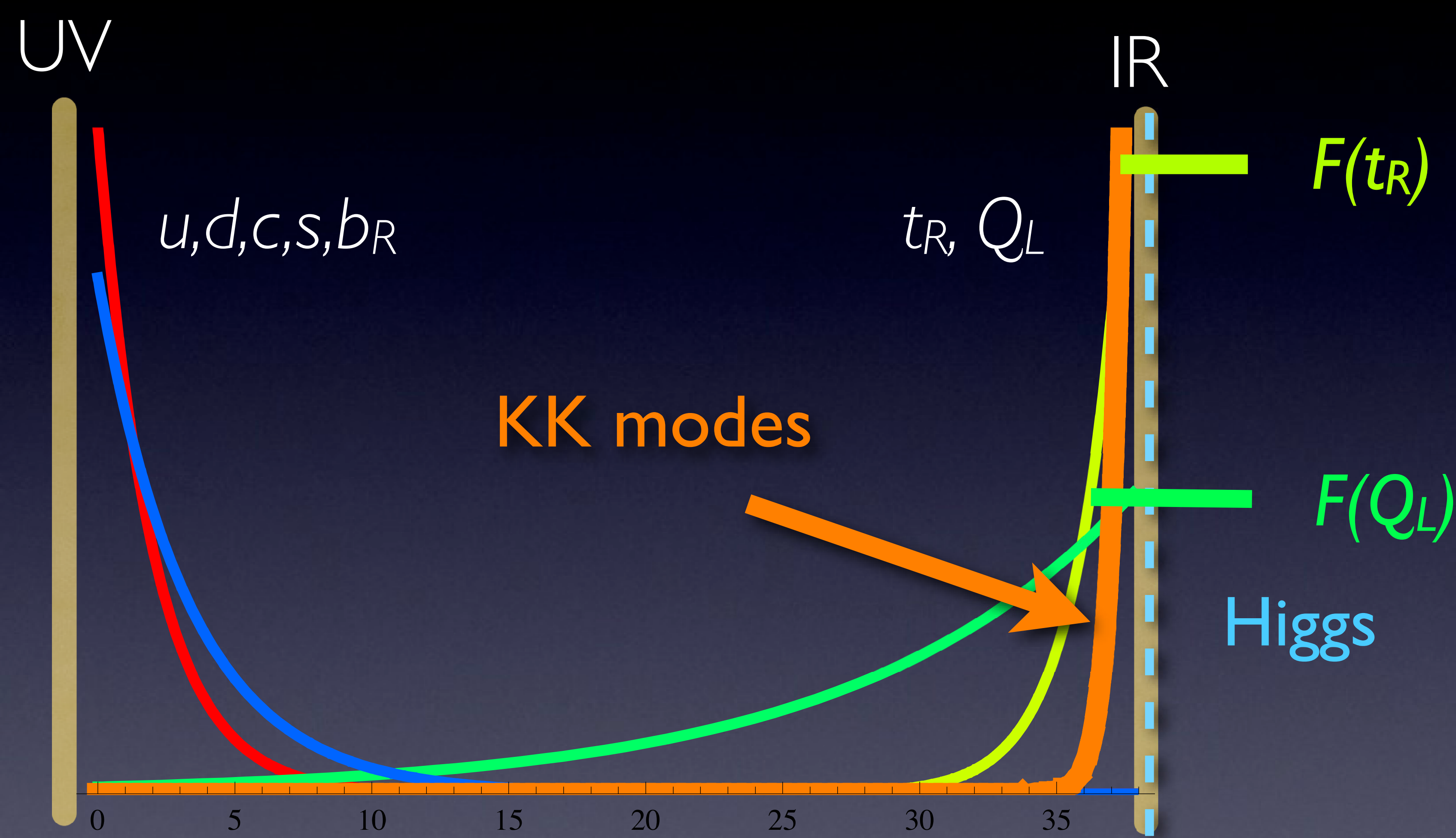
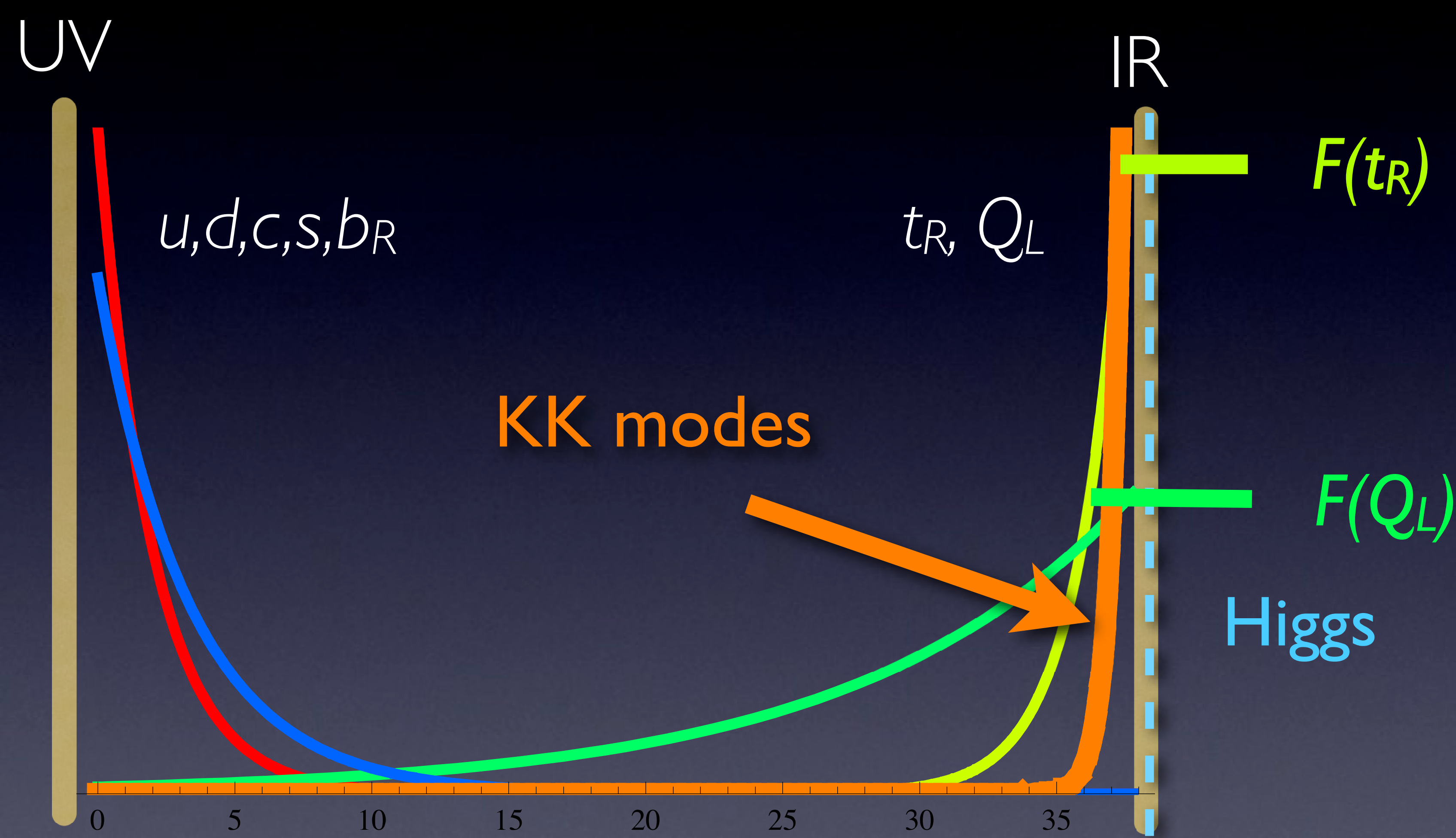


RGE of the mixing UV → IR

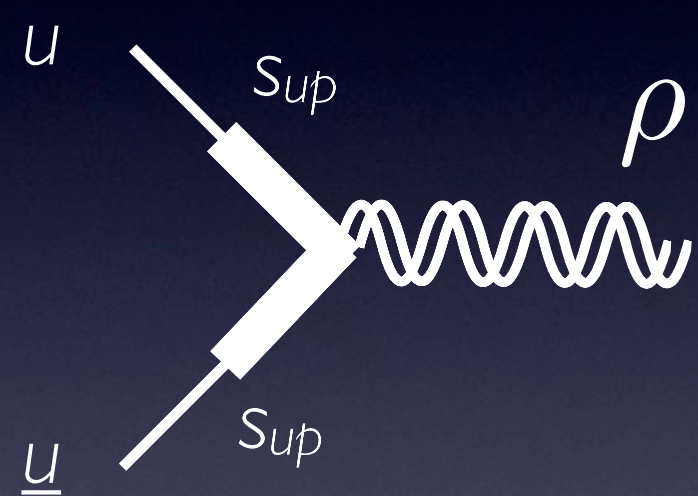
Degree of compositeness: $\sin\phi = F(c) \sim \left(\frac{\mathrm{TeV}}{\mathrm{M_{pl}}}\right)^{c-\frac{1}{2}}$



RGE of the mixing UV → IR

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)

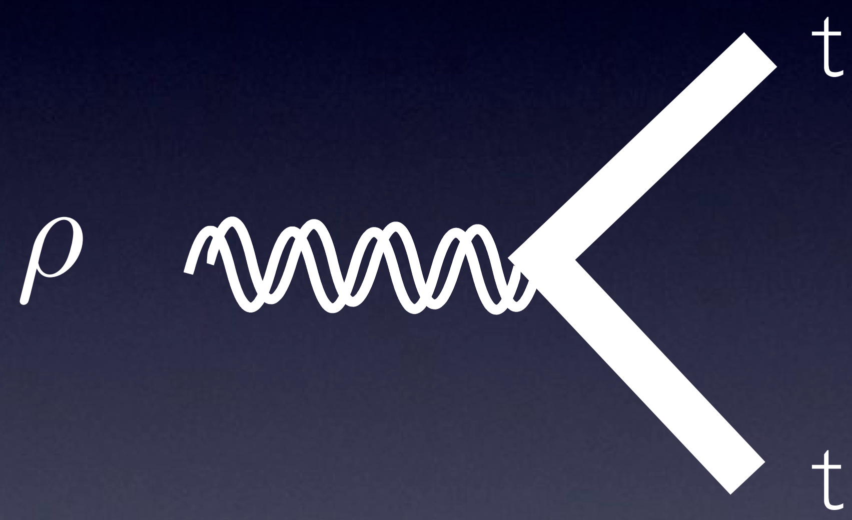
$$\sim \frac{g_s}{g*}$$

similar to $\gamma - \rho$ mixing

NB, gluon-rho-rho = 0

LHC implications

Resonance decay



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

Top FCNCs

SM $Br(t \to q(Z, \gamma, G)) \sim 10^{-12}$

partial compositeness/ warped flavor

$$Br(t \to c_R Z) \propto |U_R|_{23} \times \delta g_Z \sim 10^{-5}$$

LHC (100 1/fb)

$$Br(t \to (Z, \gamma)) \geq 10^{-5}$$

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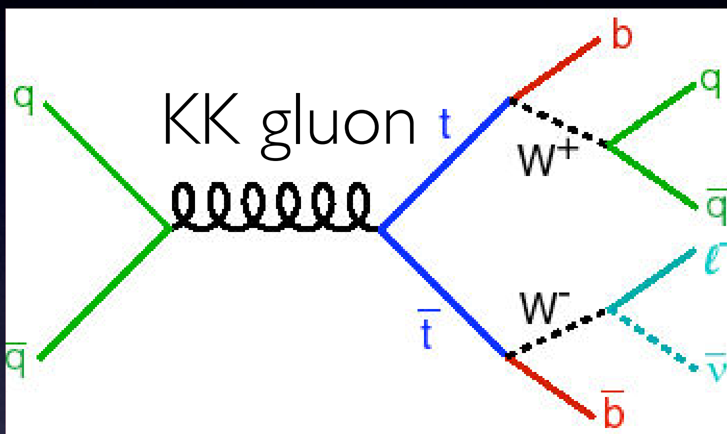
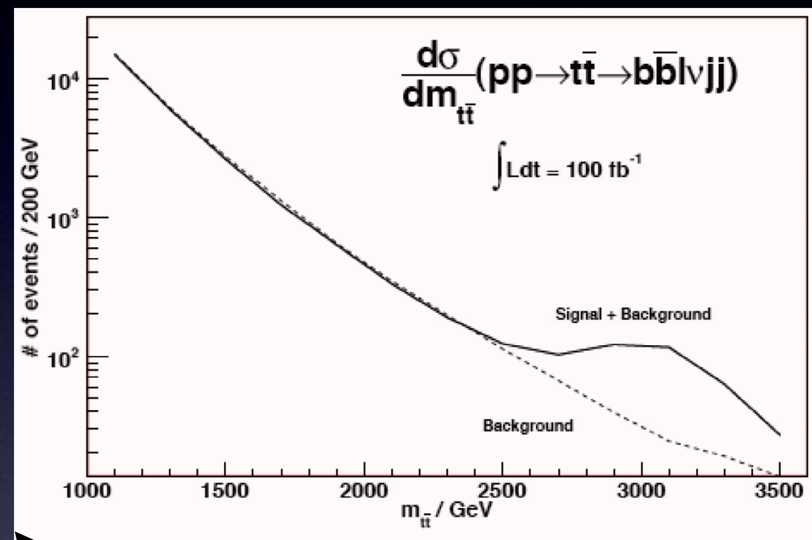
Resonances decay to Tops

Agashe et al, Lillie et al



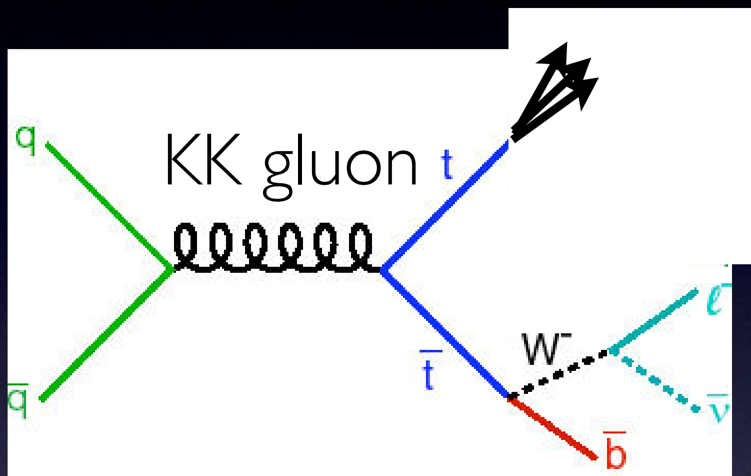


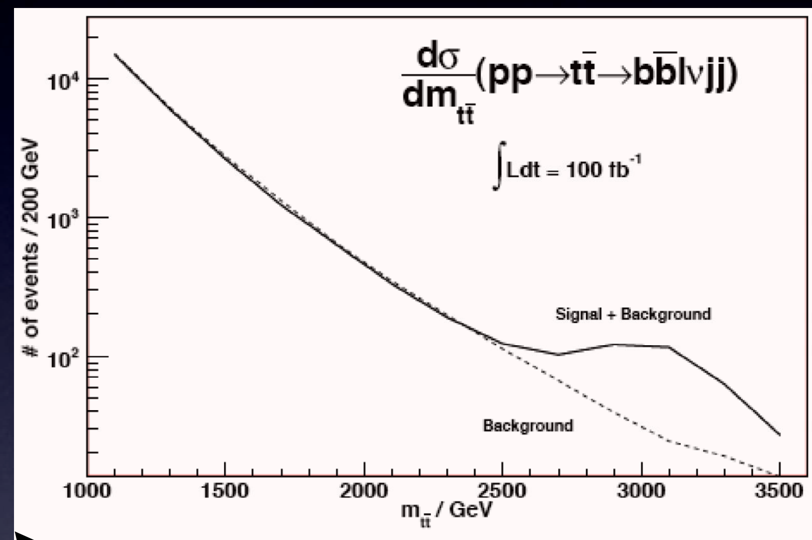
Collimation poses challenge
($m_{KK} \sim 3\ TeV$ vs. m_{top})

high p_T - flavor interplay!

Resonances decay to Tops

Agashe et al, Lillie et al





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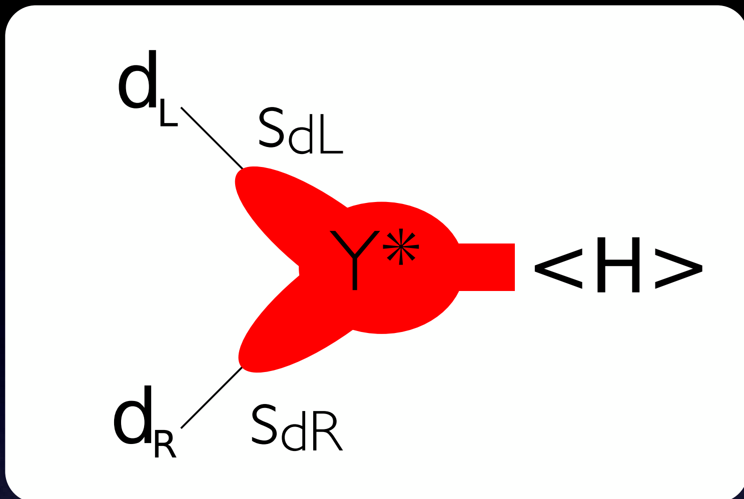
FCNCs

FCNC protection

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



masses from mixing in composites

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

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

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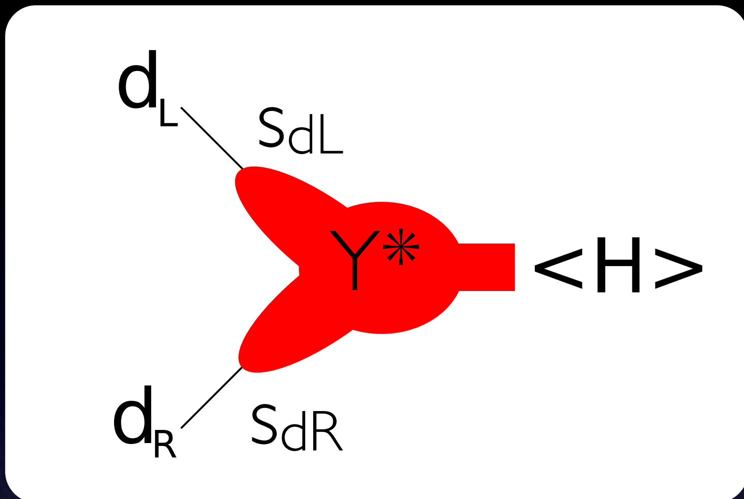

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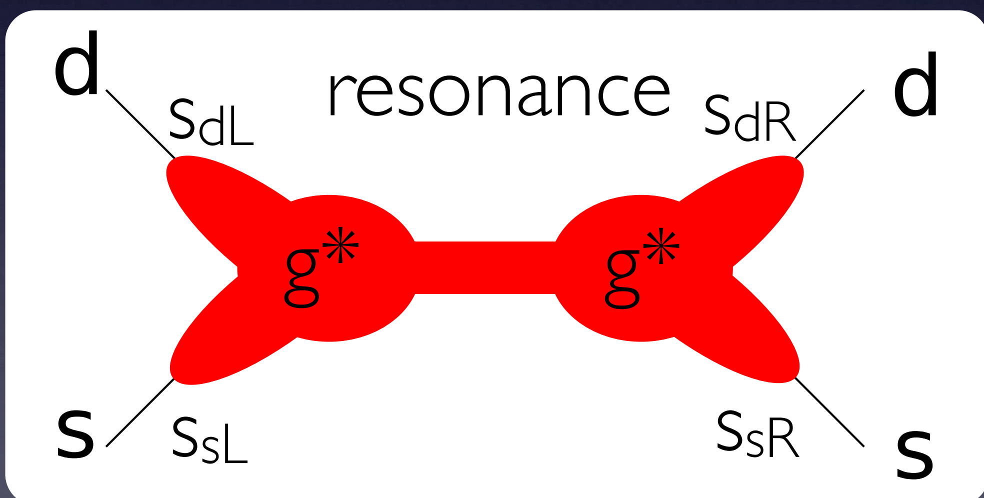
FCNCs suppressed by the same mixings



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

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

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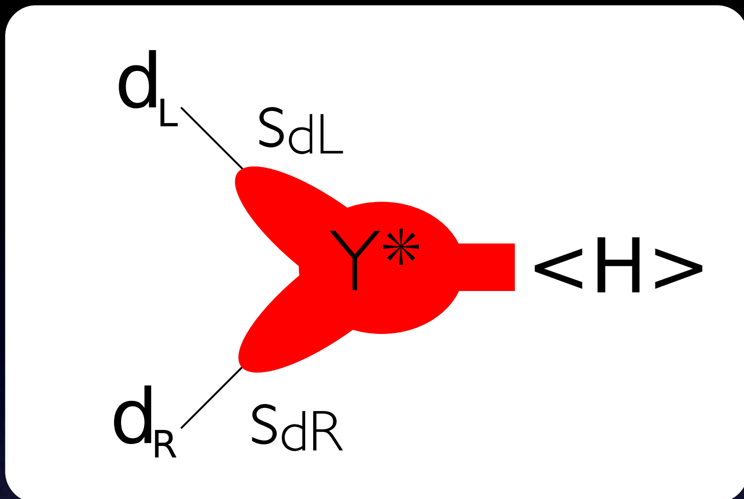

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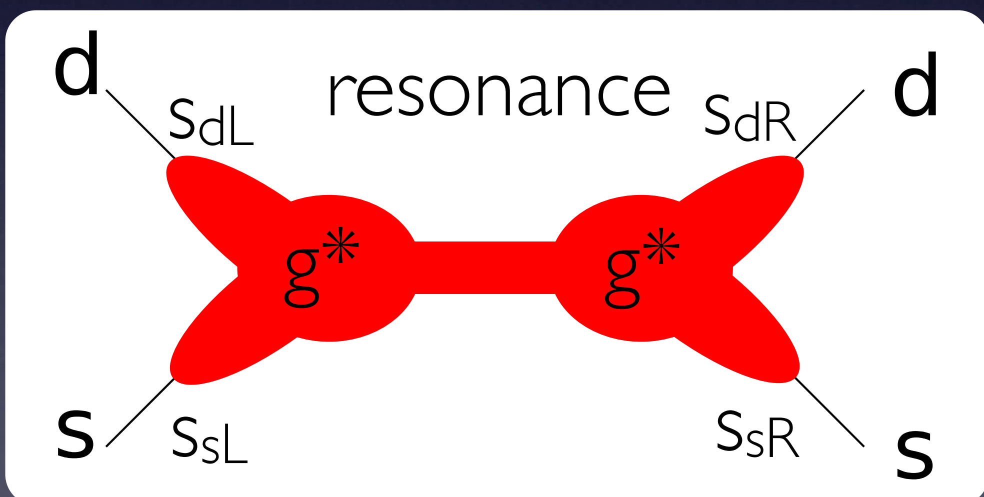


$K^0 - \bar{K}^0$

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

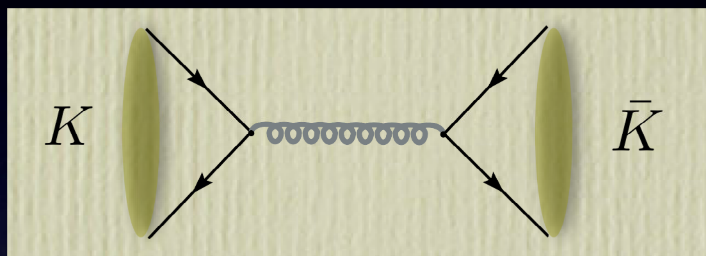
$$\sim \frac{g_*^2}{M_\rho^2} \frac{m_d m_s}{v Y_*^2}$$

RS-GIM

CP constraints on composite mass

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

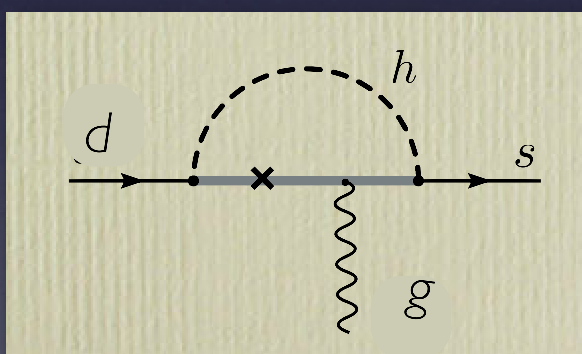
$\Delta F = 2$ (strongest constraint from ϵ_K)



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

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

Gedalia et. al



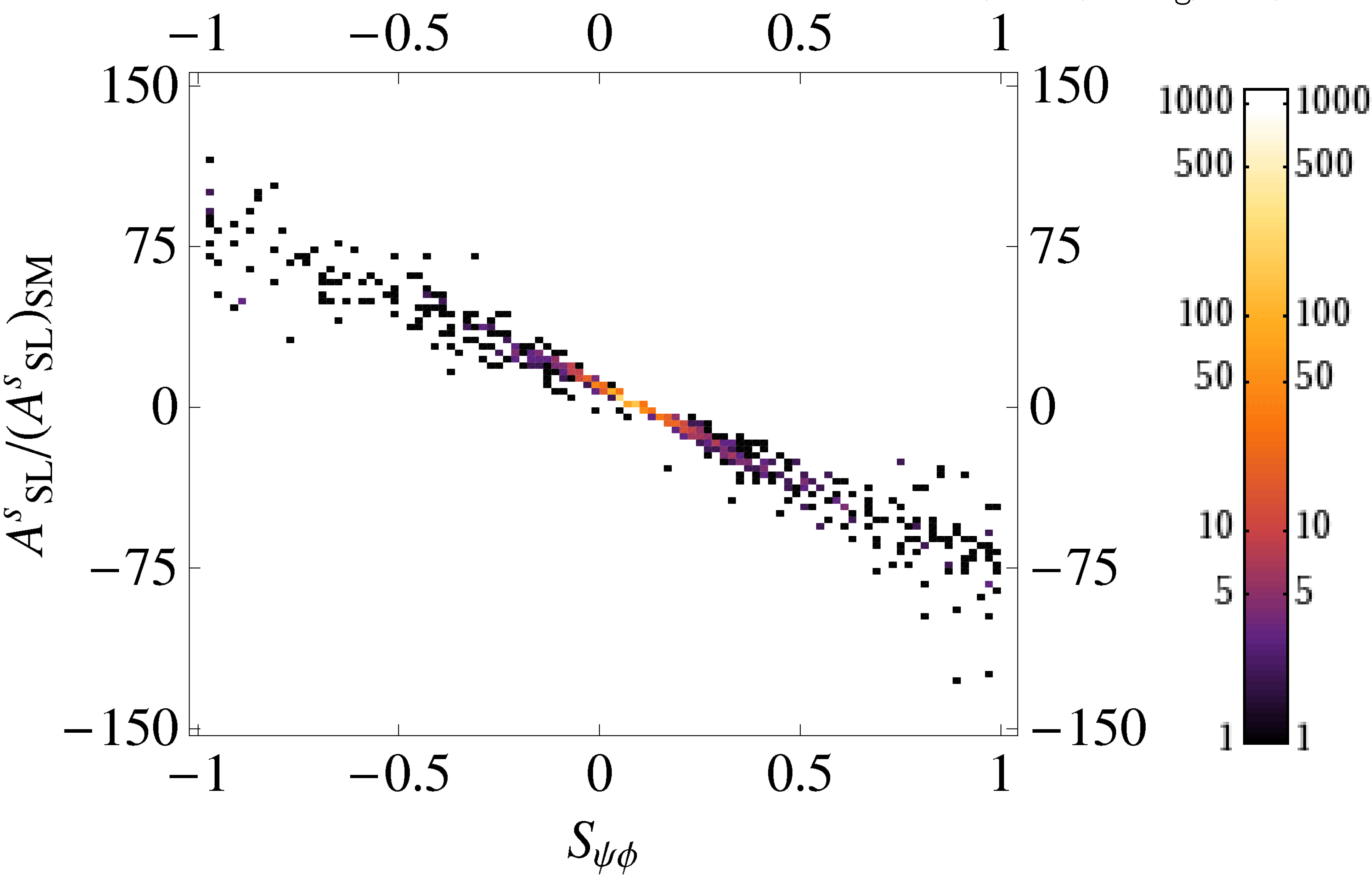
$$M_* \gtrsim 1.3\, Y_*\, \mathrm{TeV}$$

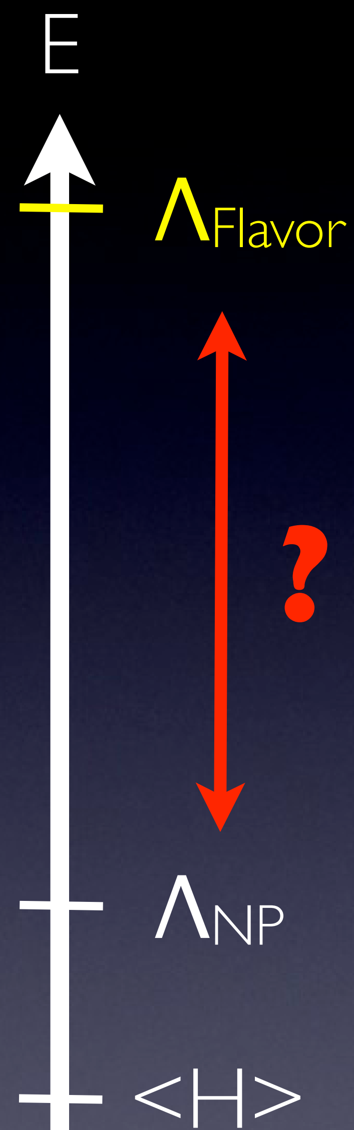
$\Delta F = 0$ neutron EDM

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

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

Blanke, Buras, Duling, Gori, AW





generate $Y_{U,D}$ at high scale

new physics dynamics can depend non-trivially on $Y_{U,D}$

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

$s_u, s_d \sim Y_u, Y_d$

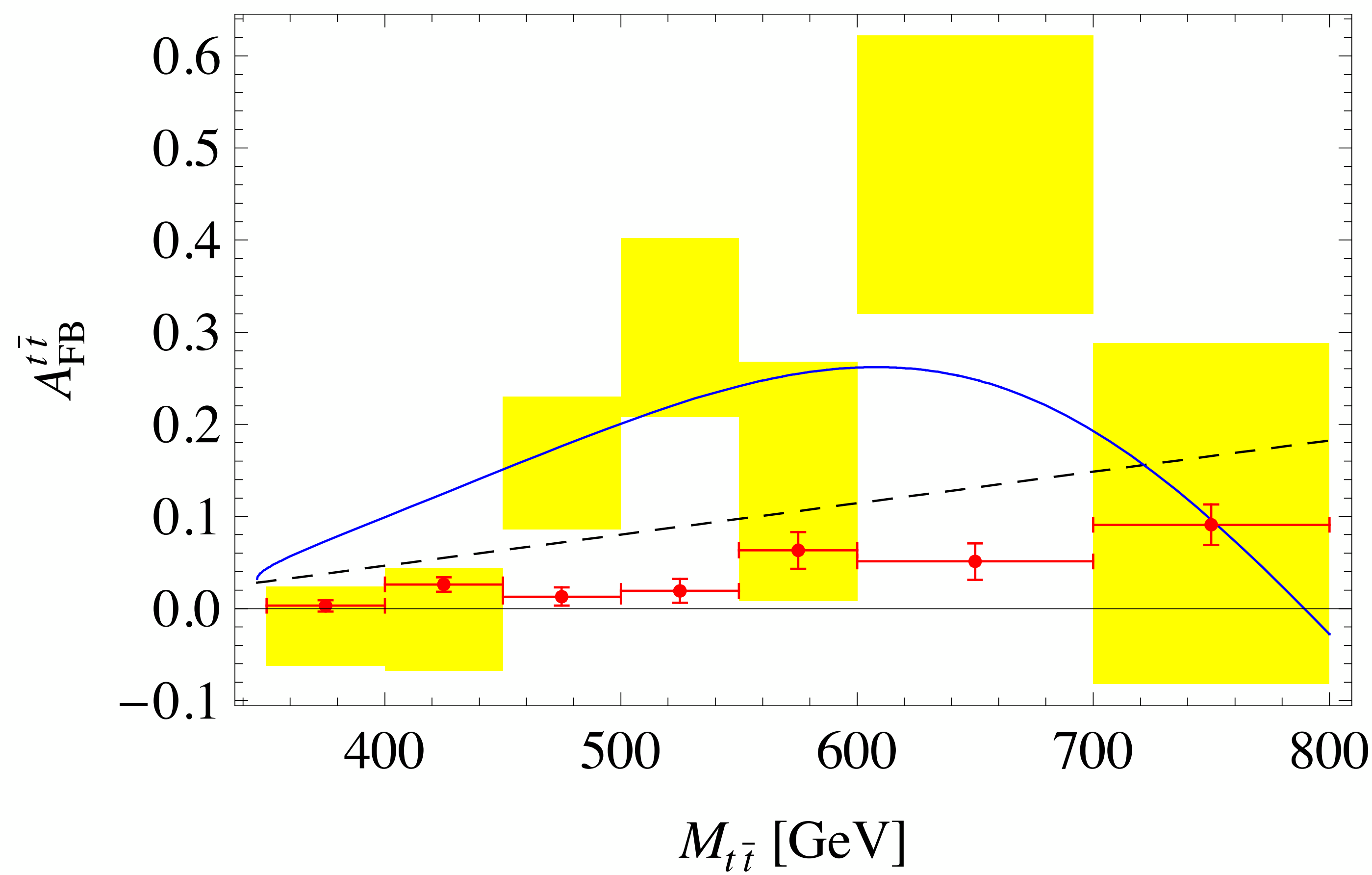
Delaunay et al

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

=> flavor gauge bosons predicted (in 2 slides)

mixing can be large (but universal)

MFV-RS allows for sizable *AFB* (new dijet bound?).
(No asymmetry in anarchic RS flavor. Bauer et al)



plot from Blum et al

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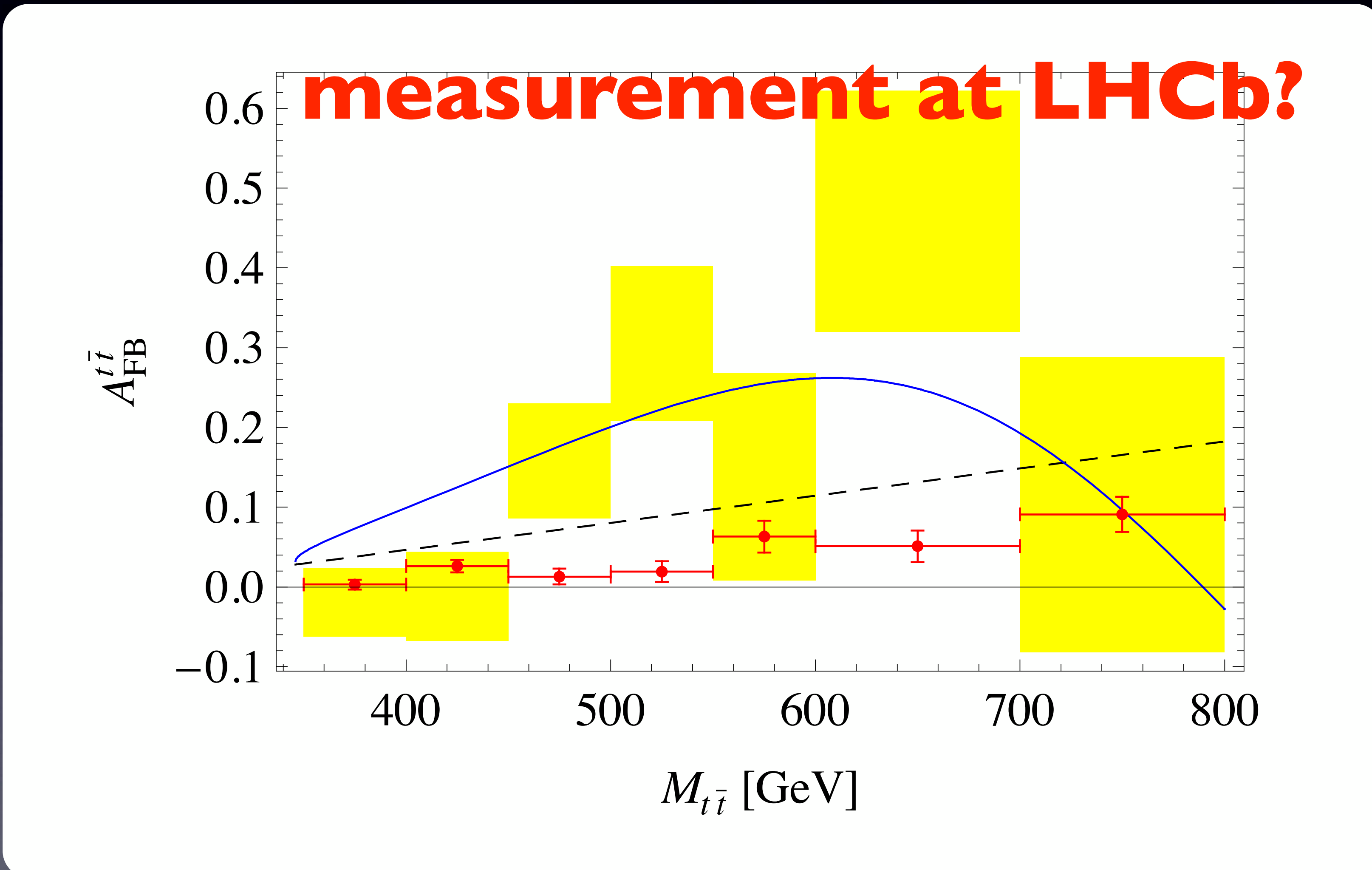
Kagan, Kamenik, Perez, Stone



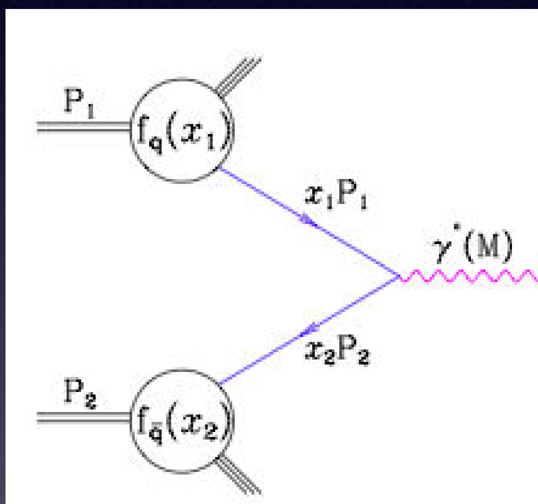
plot from Blum et al

Flavor gauge bosons at LHC

Csaki, Kagan, Lee, Perez, AW

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

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



no $\gamma - \rho$ mixing !

But quark composite mixing can be flavor universal & large

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

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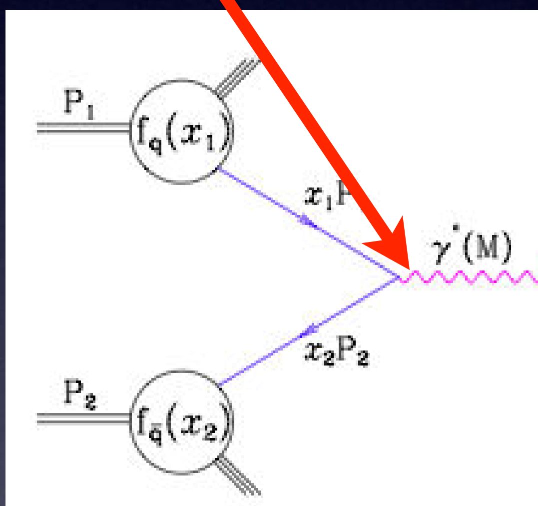

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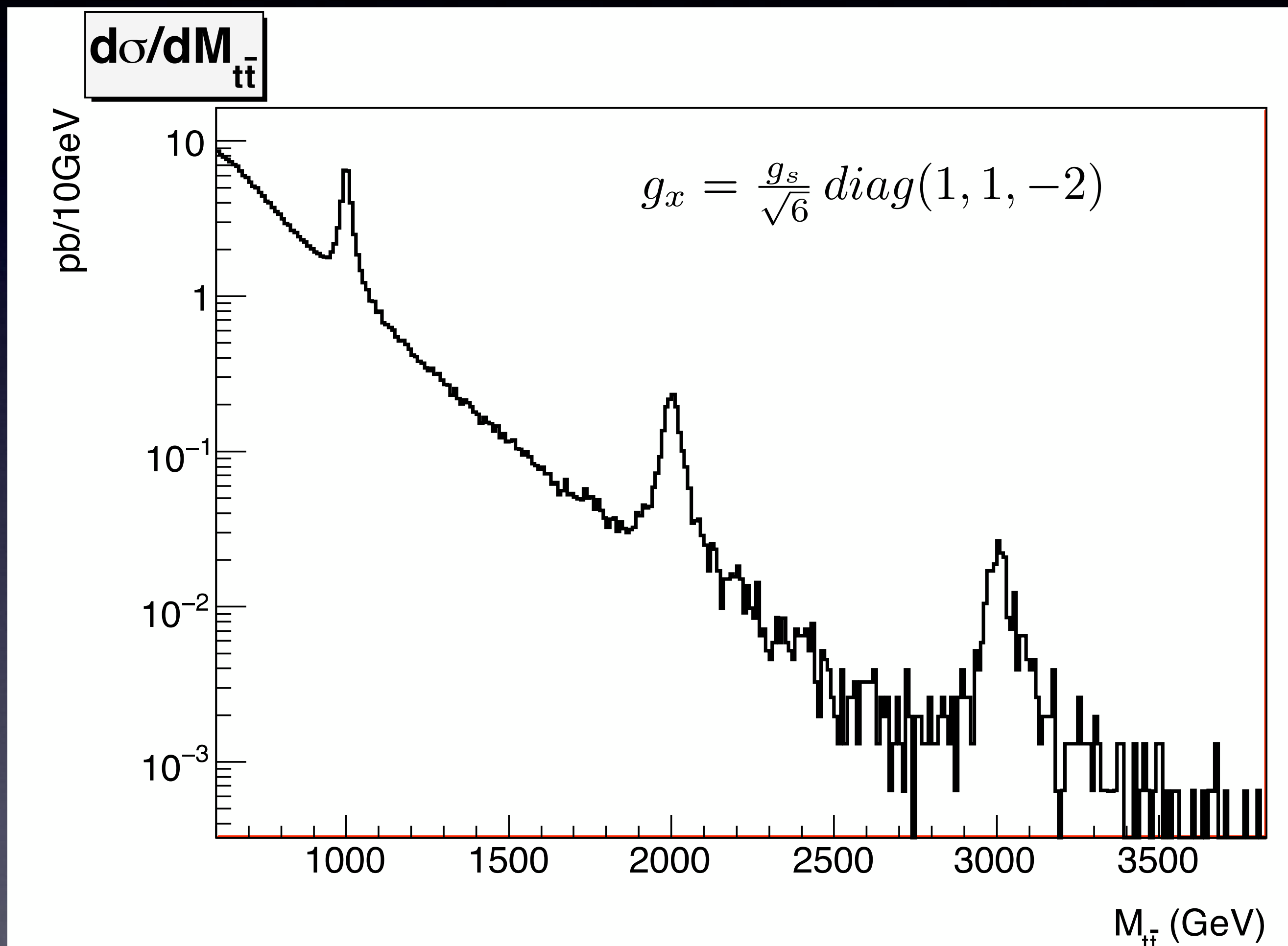
Flavor scalars & gauge bosons

Csaki, Kagan, Lee, Perez, AW



see also Grinstein et. al.

possible explanation of FB asymmetry at Tevatron


NP ?


NP !?
TERRA DE AVENTURA

Conclusions

The next year(s) will hopefully be a ‘bumpy’ ride

In many models high p_T and flavor are correlated (see also flavor violating Z’ to explain Tevatron anomalies)

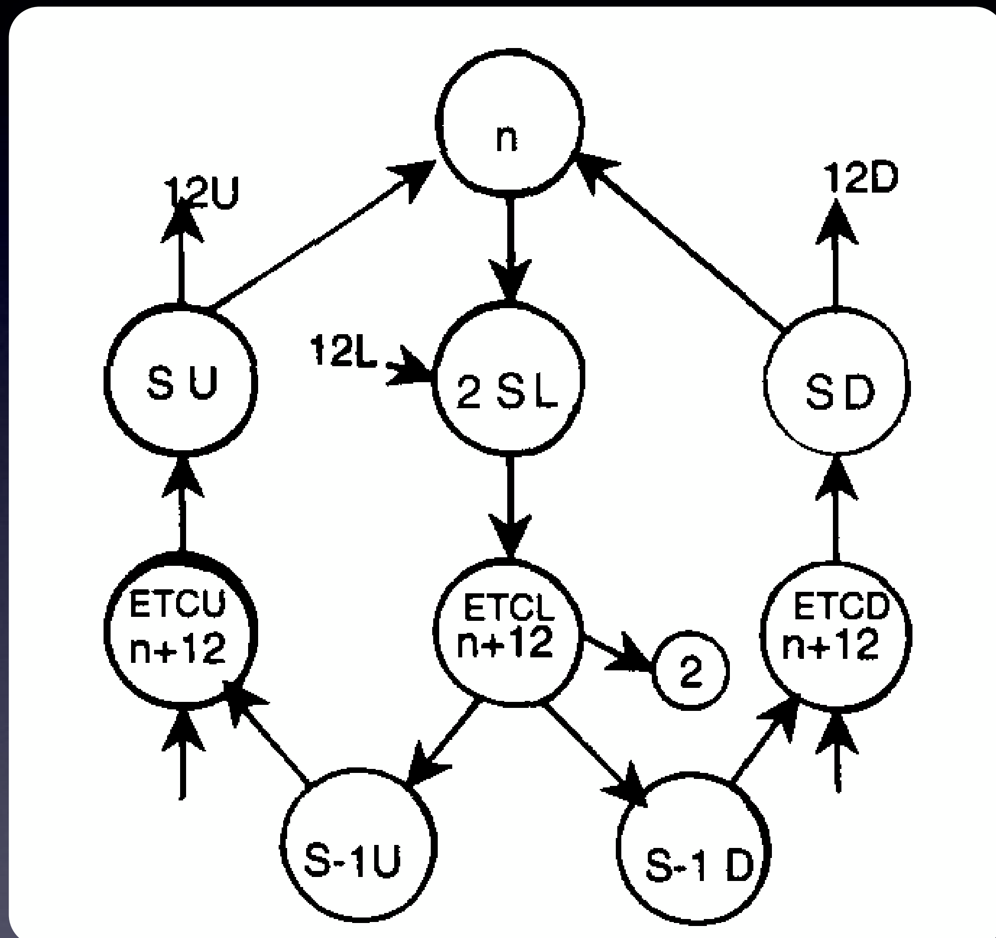
If there are non-MFV signals, might get insight in origin of Yukawas

Looking forward to LHC(b) results in summer/autumn!

THE END

MFV Technicolor?

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



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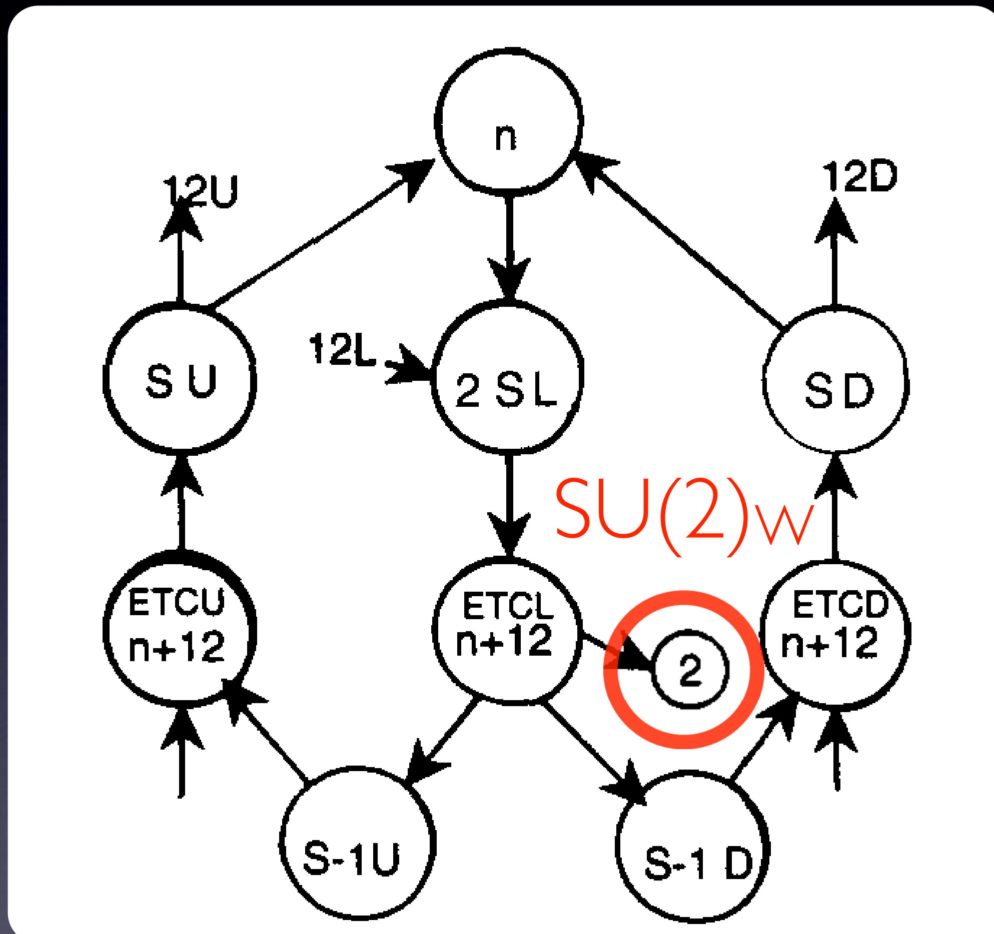

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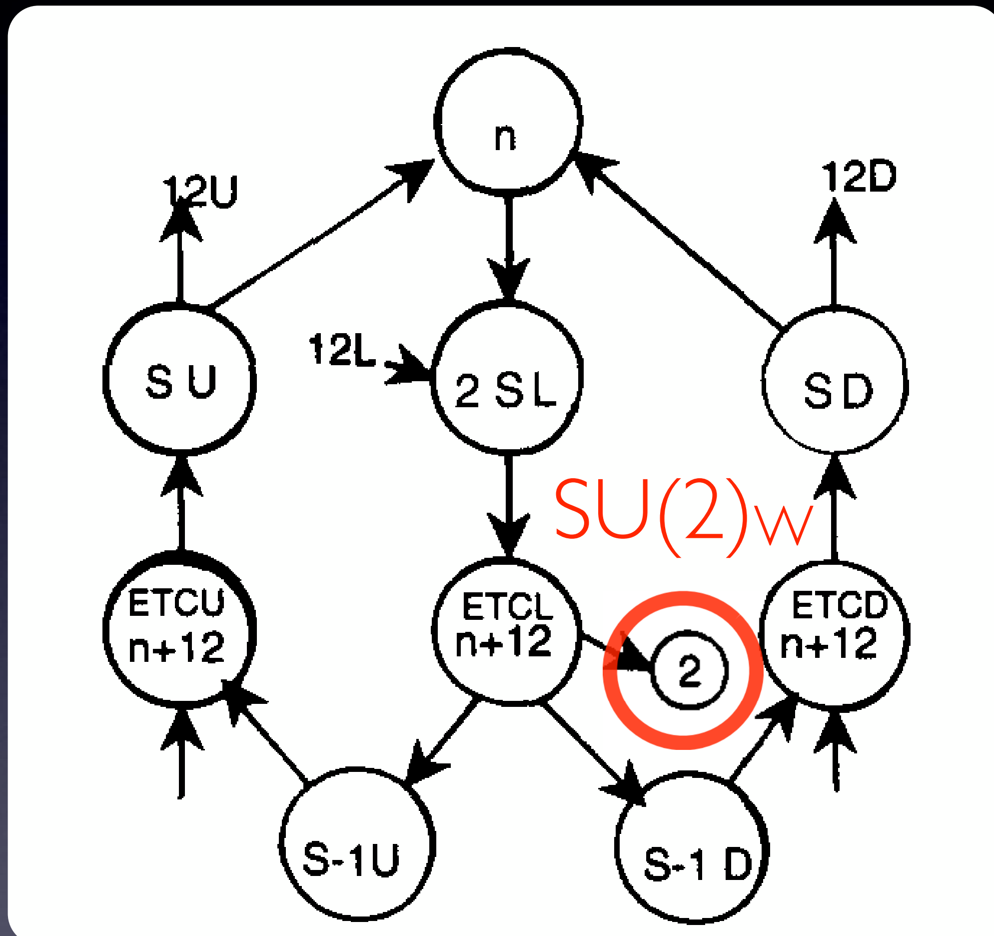


Simpler proposal:

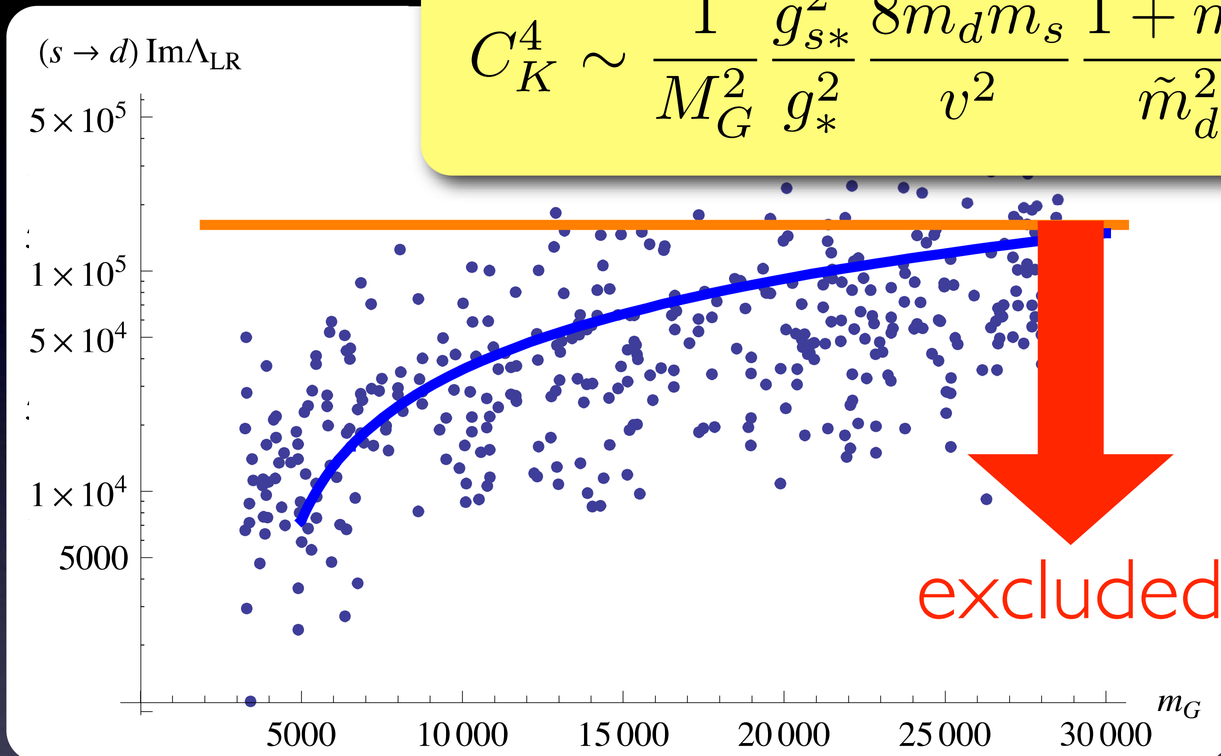
AdS/CFT construction : 5D GIM mechanism

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

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

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Csaki, Falkowski, A.W.;

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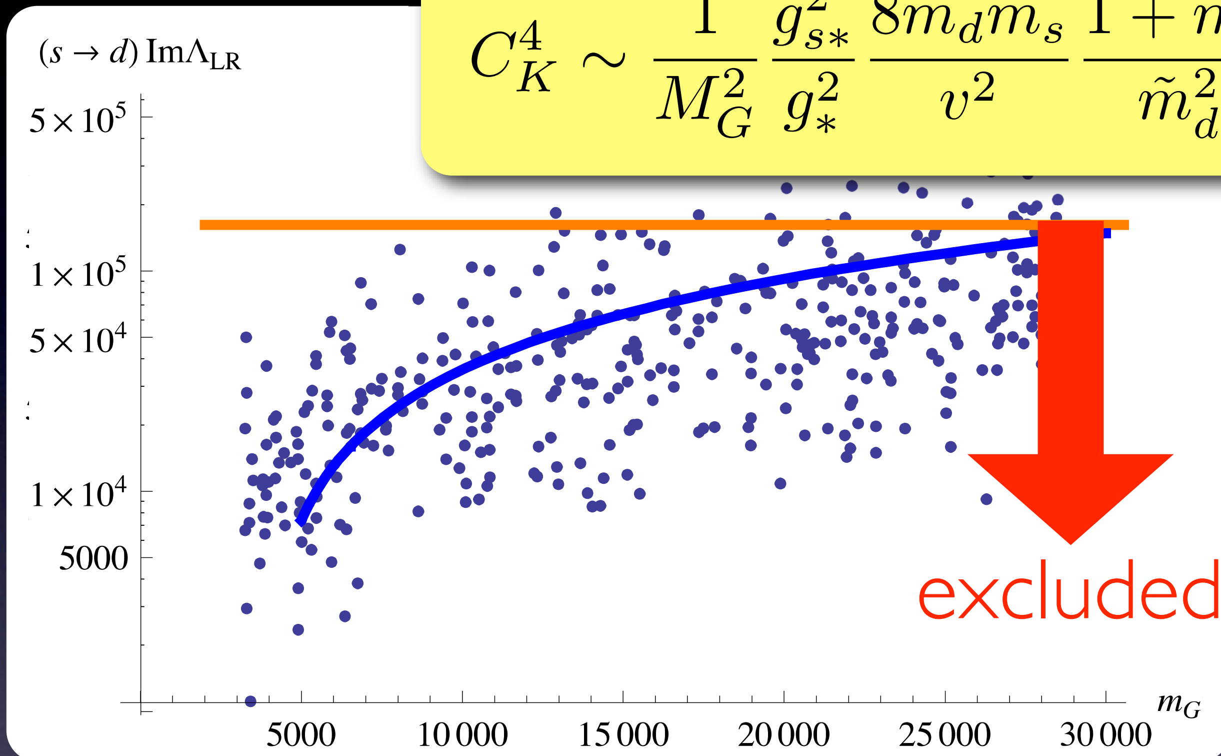

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