New physics and flavor

Andreas Weiler
CERN

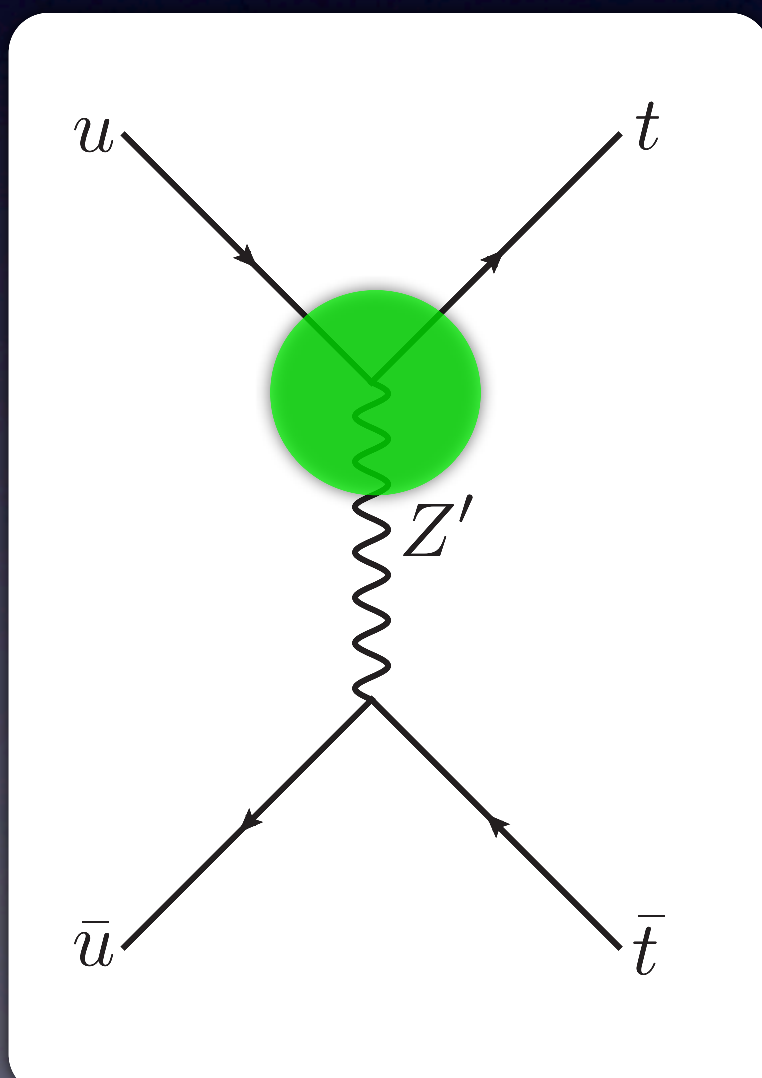
FPCP
Maale Hachamisha, Israel

24/5/2011

Flavor 2011: Z' & Tevatron $A_{FB}(m_{tt})$

e.g. 0907.4112, 1103.4835, 1103.6035

$$g_{ut}\, Z'_\mu\, \bar{u}\gamma^\mu P_R t + h.c.$$



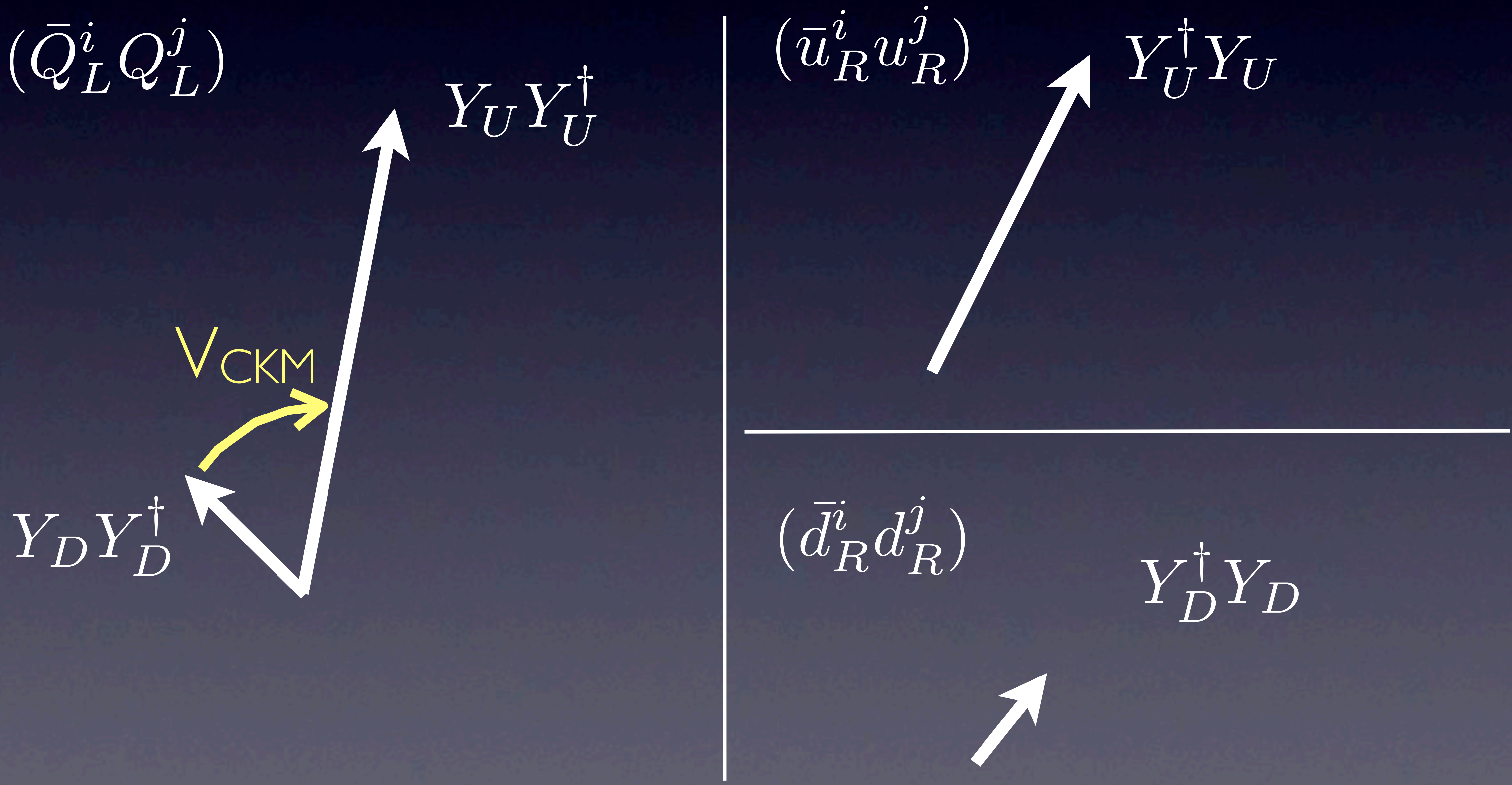
t-channel

FCNC coupling!

$\underline{D}$-D constraint?
Same sign di-leptons?

Flavor and CP in the SM

Yukawa matrices Y_U & Y_D encode flavor violation



+ LR, RL

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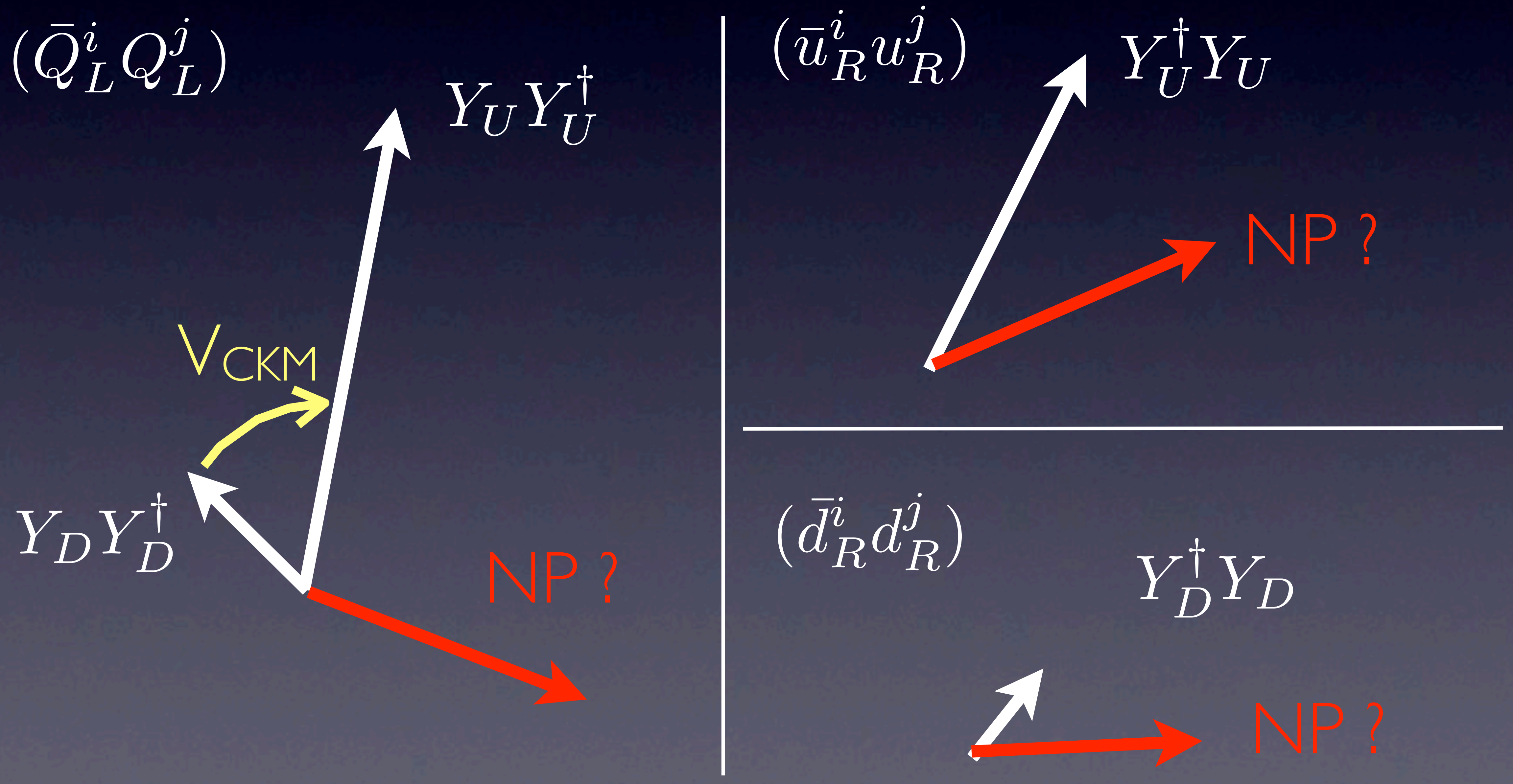
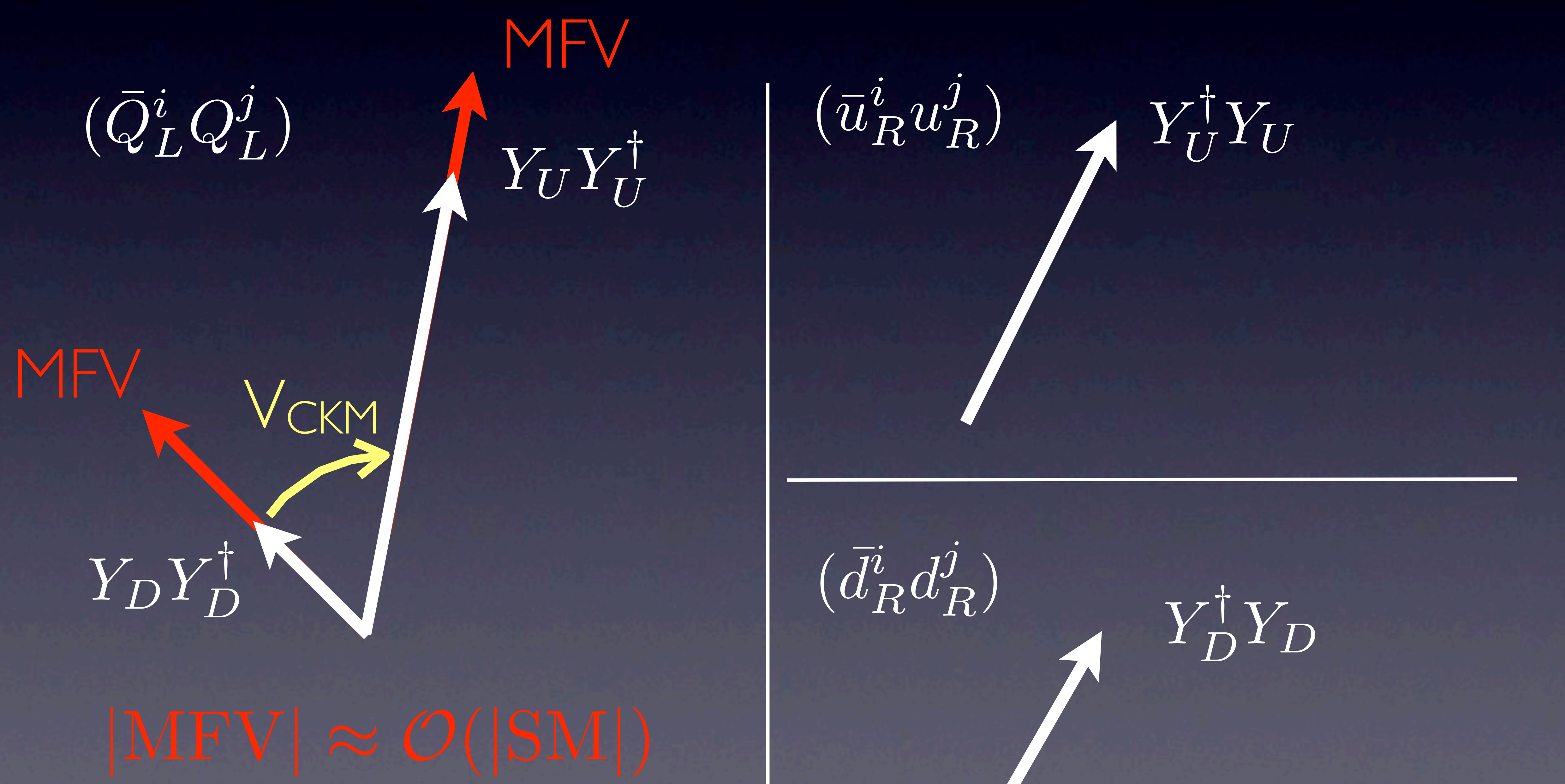


+ LR, RL

Minimal flavor violation

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

New particles/interactions, but flavor structure $\sim V_{CKM}$

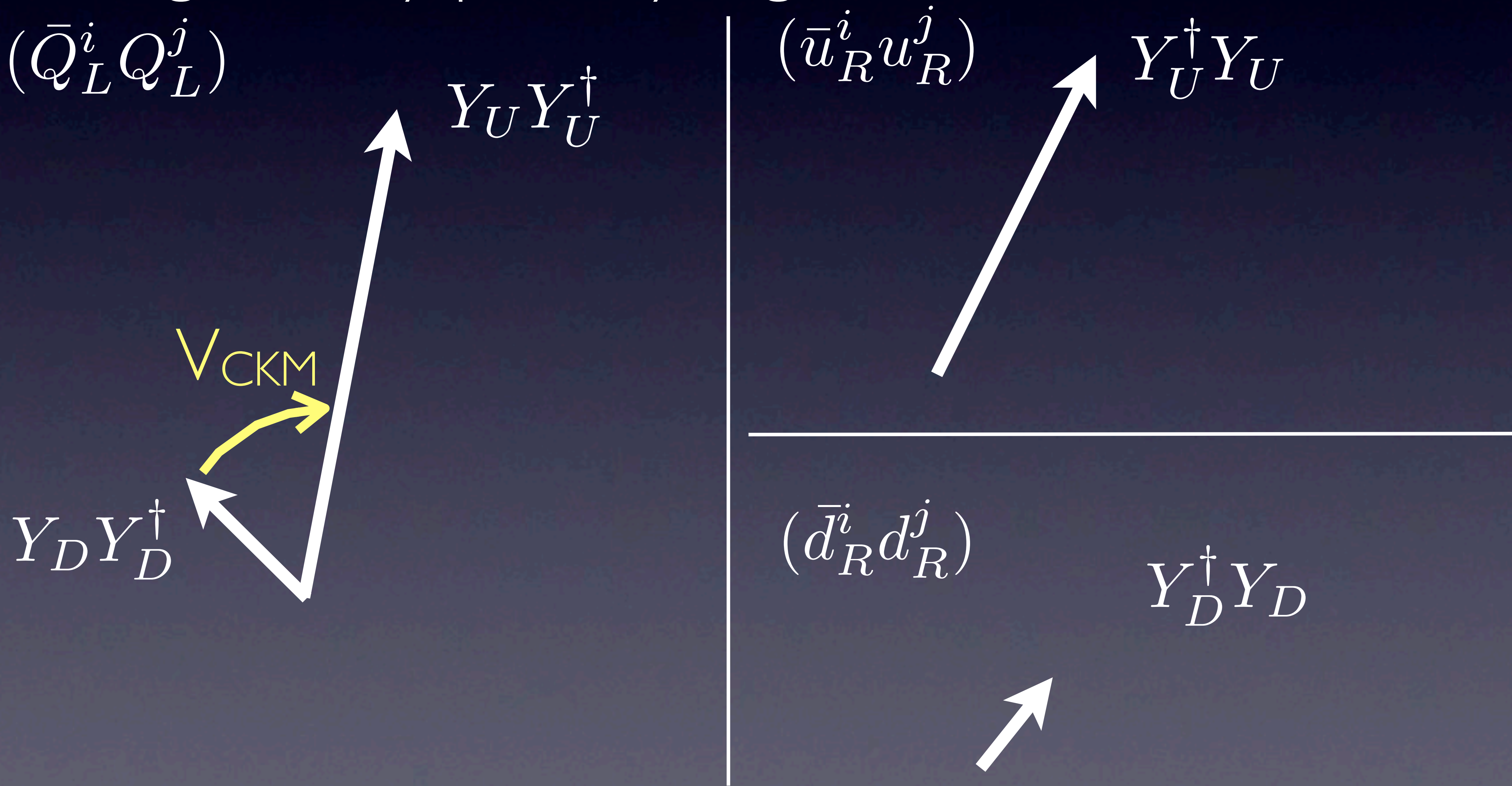


+ LR, RL

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

NP Flavor dynamics

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



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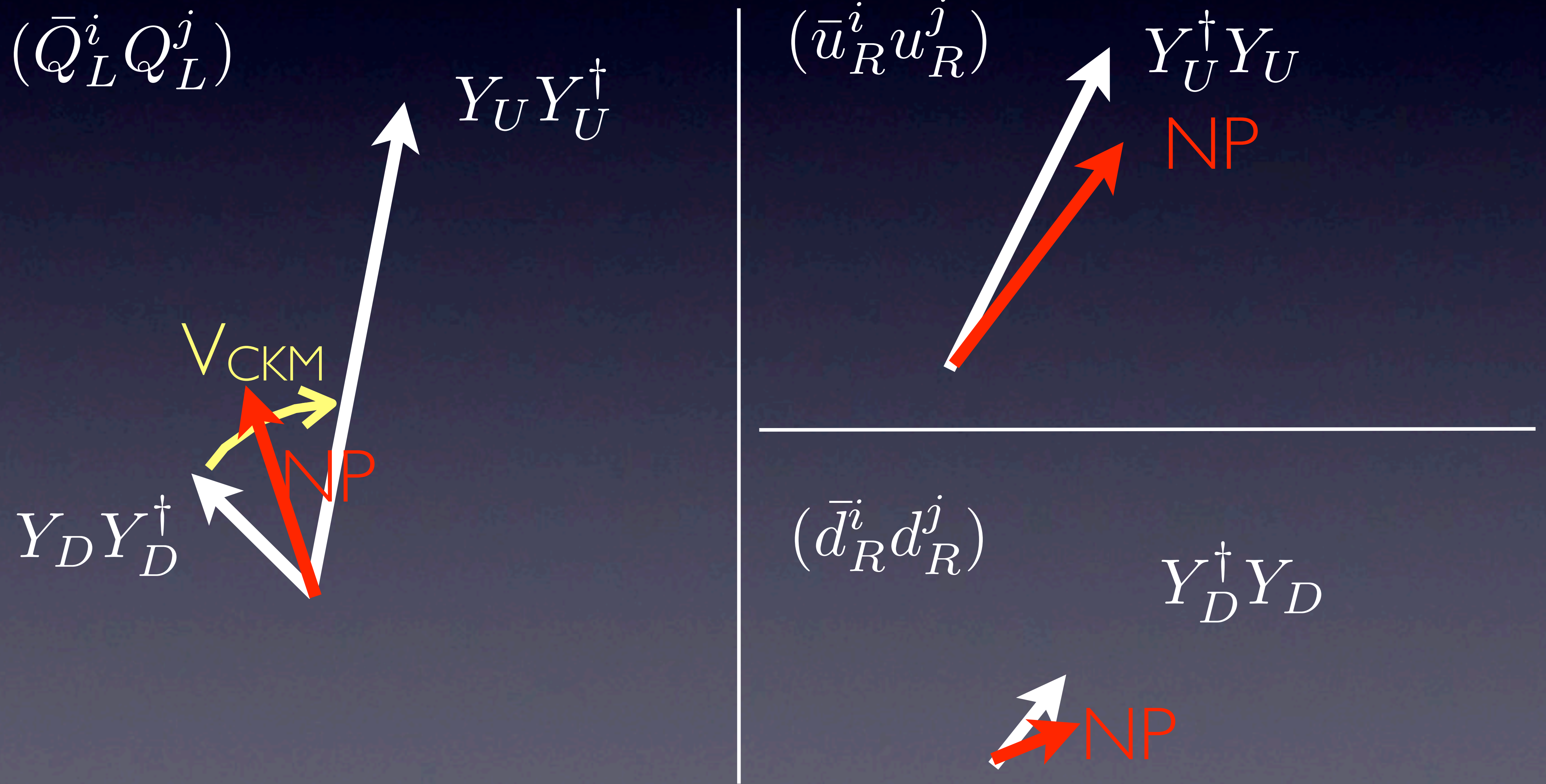

+ LR, RL

NP Flavor dynamics

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

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

$(\bar{u}^i_R u^j_R)$ $Y_U^\dagger Y_U$ 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

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

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

Origin of this structure?

Other dimensionless parameters of the SM:

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

UTfit 08, Isidori, Perez, Nir '10

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	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; $\|q/p\|, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\|q/p\|, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	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}
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Very strong suppression! New flavor violation must either approximately (exactly?) follow SM pattern…

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Very strong suppression! New flavor violation must either approximately (exactly?) follow SM pattern…

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

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

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

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”)

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

split fermions/RS

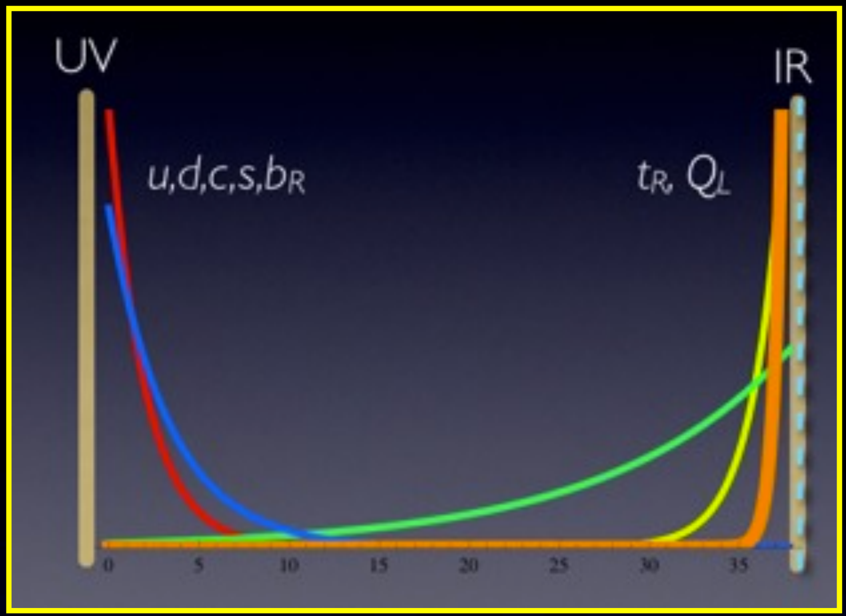
$$\propto \quad Y_{ij} \left(\frac{\mu_{\mathrm{low}}}{\mu_{\mathrm{high}}} \right)^{\gamma^i+\gamma^j}$$

strong dynamics

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

Froggatt-Nielsen

Hierarchy { => hierarchical masses & mixing angles anarchic ("structure-less")



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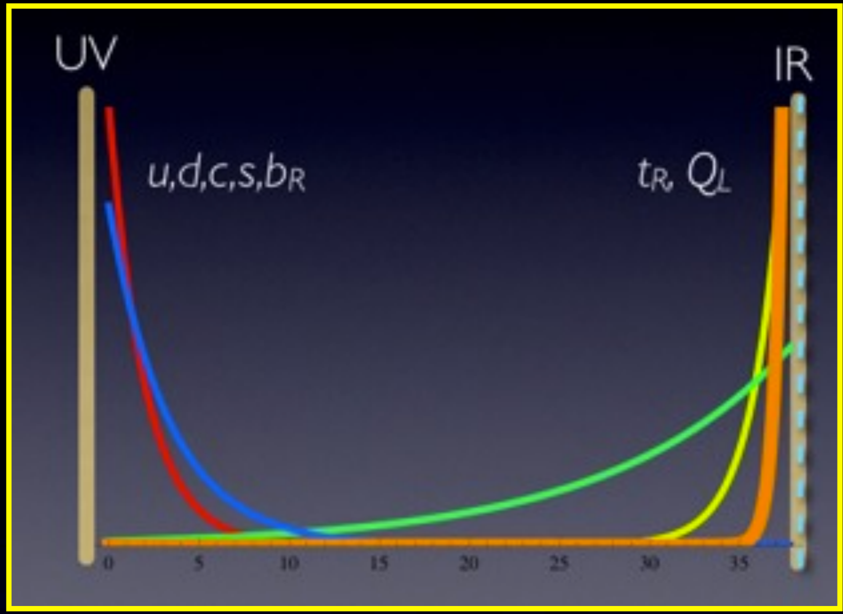

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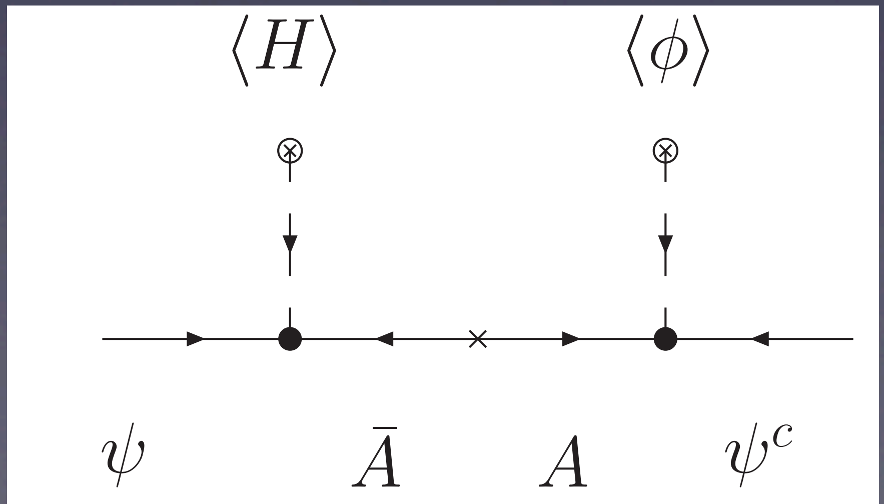
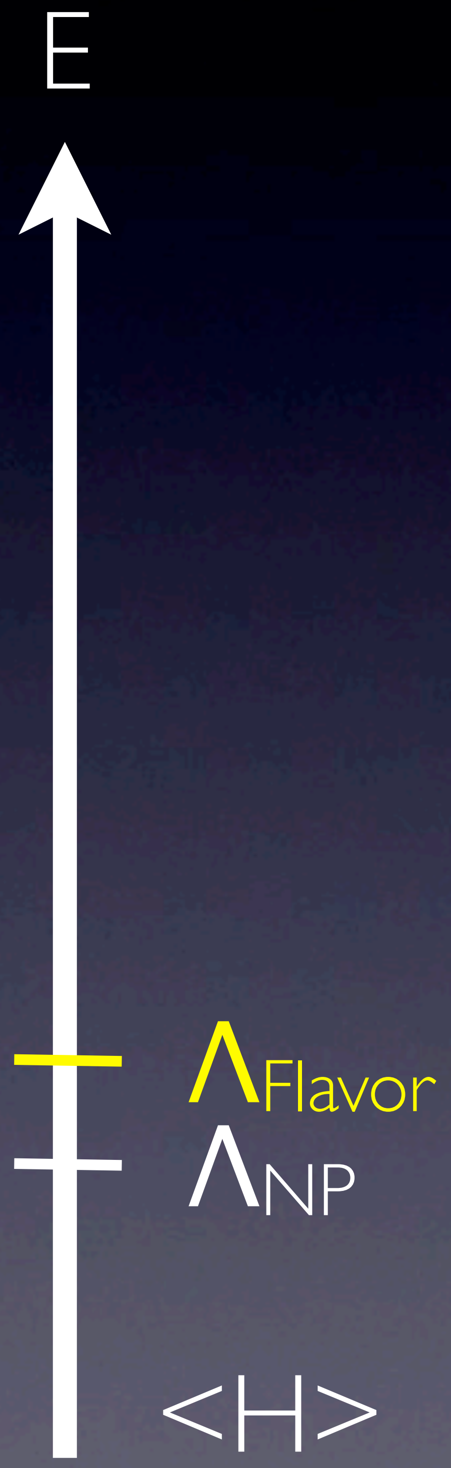


Hierarchy { => hierarchical masses & mixing angles

Flavorgenesis scale?

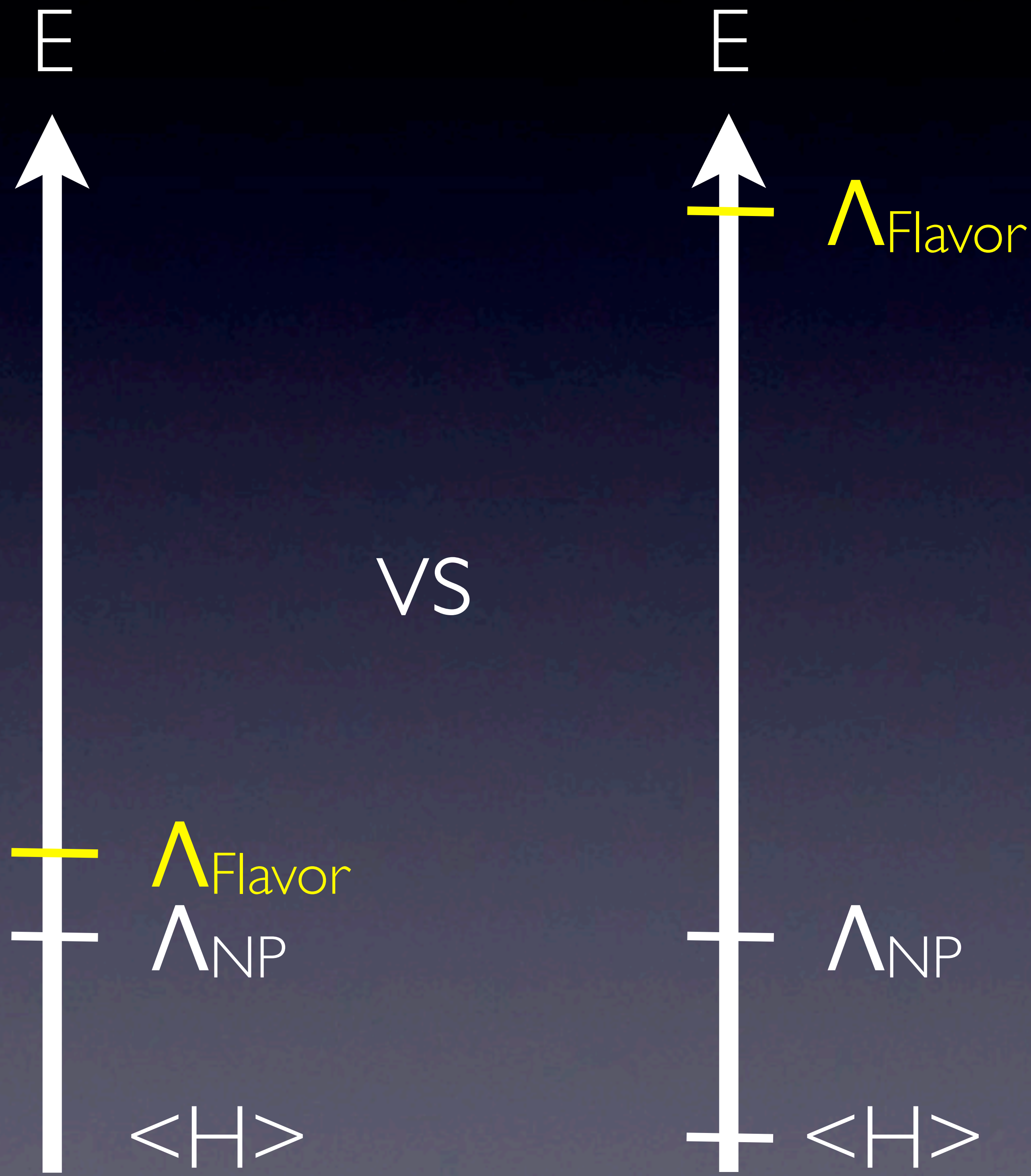


$$\frac{1}{\Lambda^2_{\text{Flavor}}}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

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

naturalness

Flavorgenesis scale?



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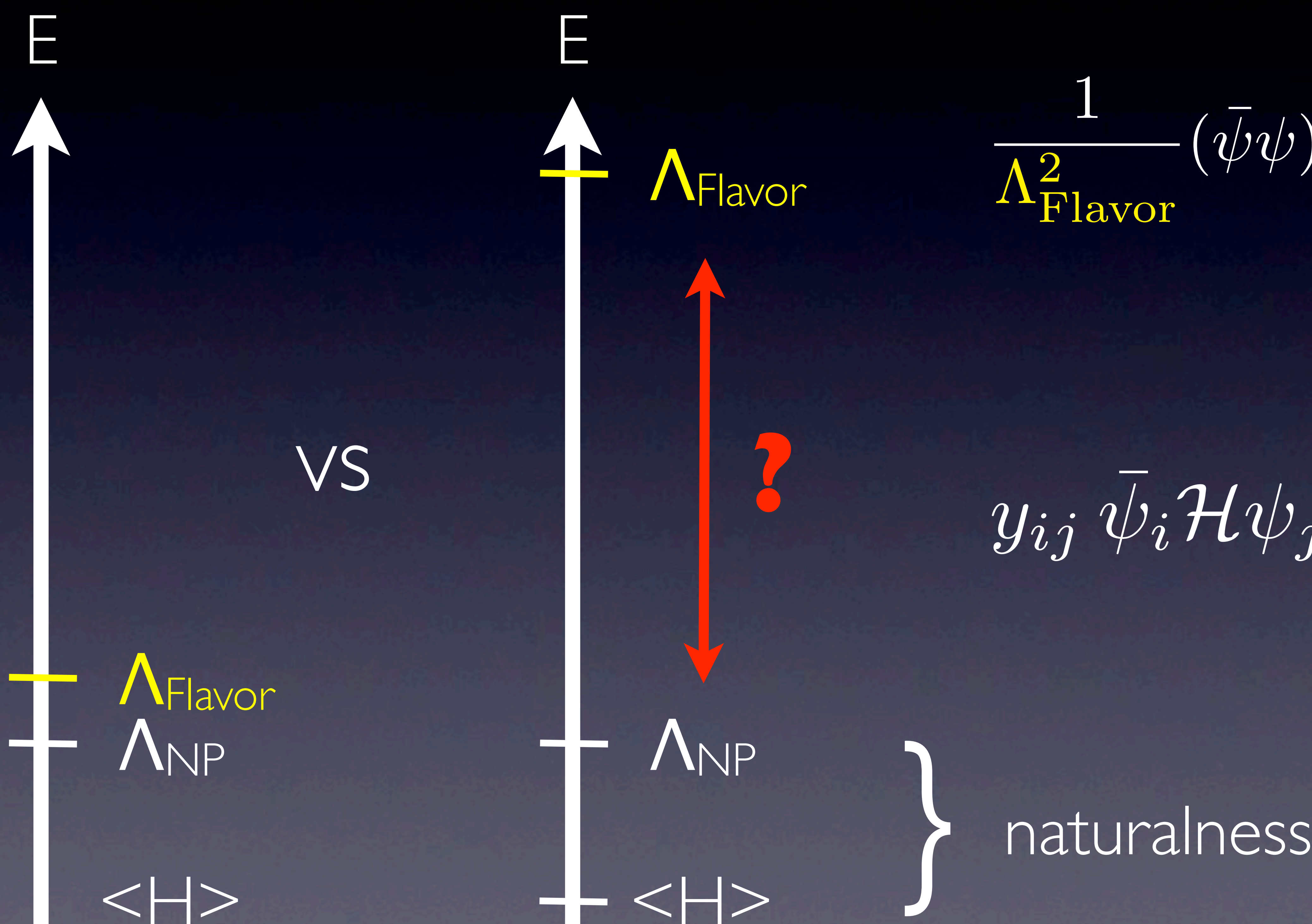

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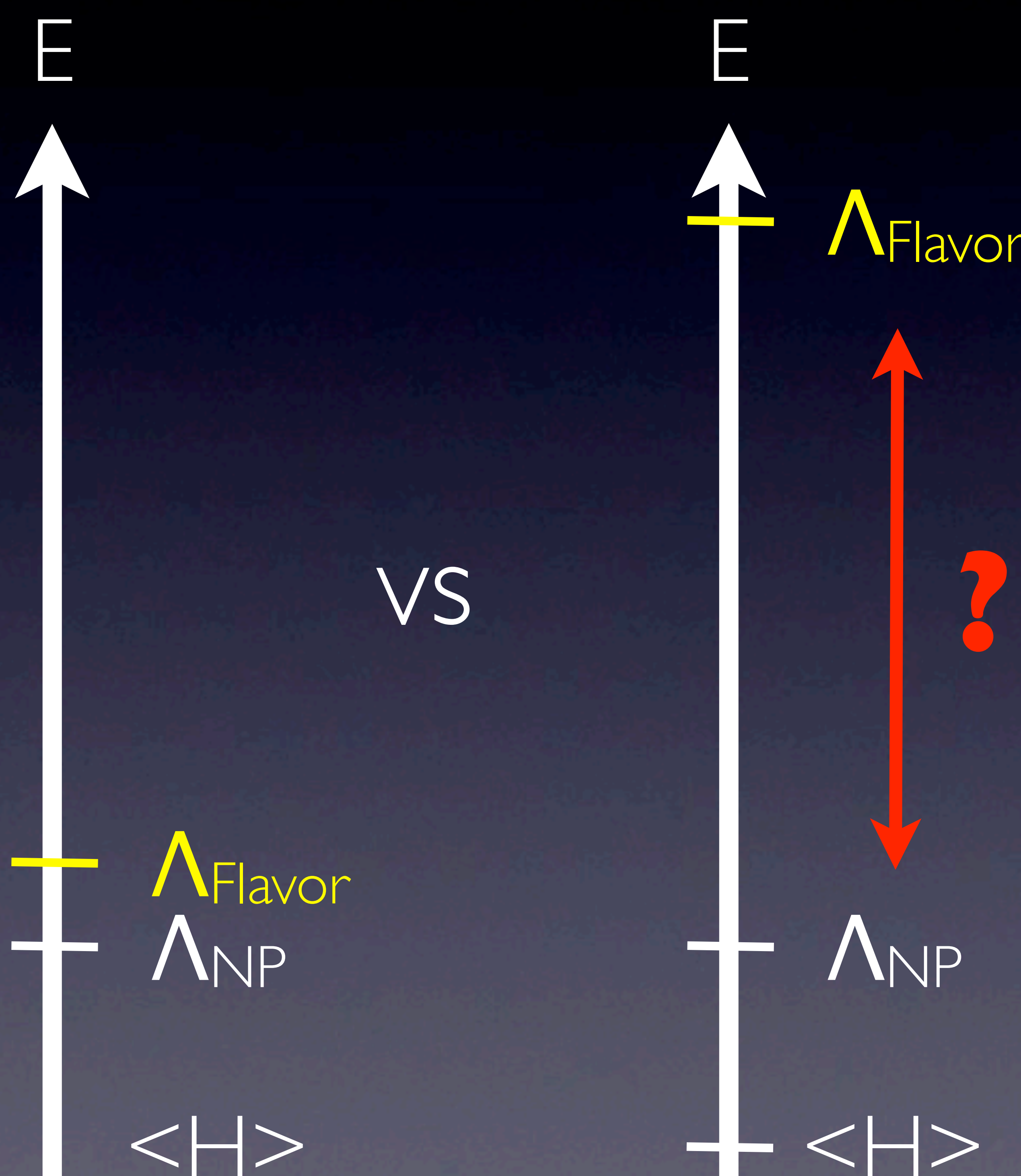

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naturalness

Flavorgenesis scale?

E

E

Λ_{Flavor}

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

Example: MSSM is MFV before susy breaking. If flavor is generated well above messenger scale, TeV theory flavor trivial (= *MFV*).

$$S=\int \mathrm{d}^4x\left(\mathrm{d}^2\theta\mathrm{d}^2\bar\theta\,\Phi_i^*\exp\left(2g_AT_A^aV_A^a\right)\Phi_i+\left\{\mathrm{d}^2\theta\left[\mathcal{W}(\{\Phi_i\})+\frac{1}{4}W_A^aW_A^a\right]+\text{h.c.}\right\}\right)$$

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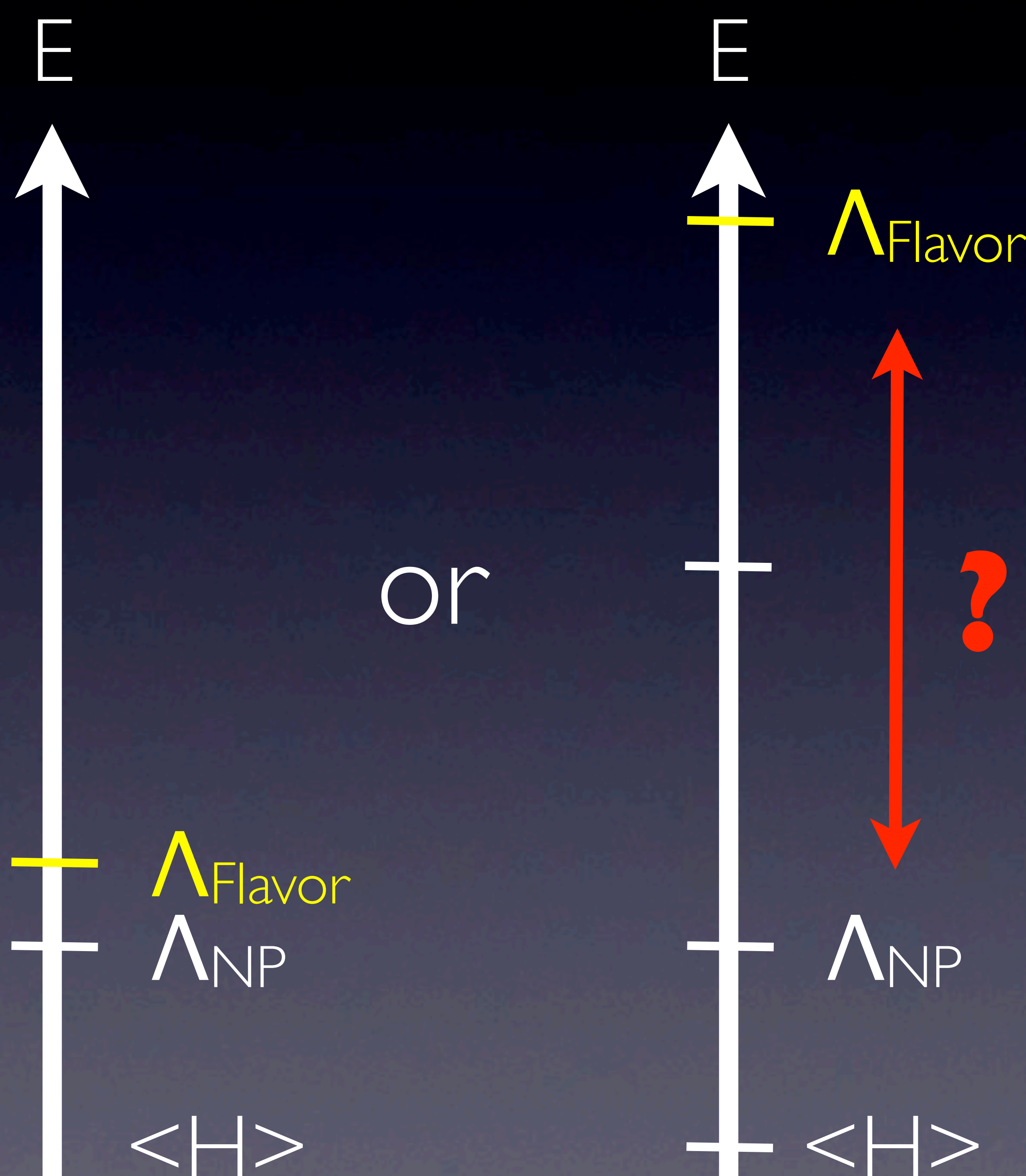
Flavorgenesis scale?



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

only trace left: MFV

$$\boxed{y_{ij}\,\bar\psi_i\mathcal{H}\psi_j}$$

} naturalness

Model independent constraints

Minimal flavor violation

UTfit, Buras et. al, Hurth et al

Tree

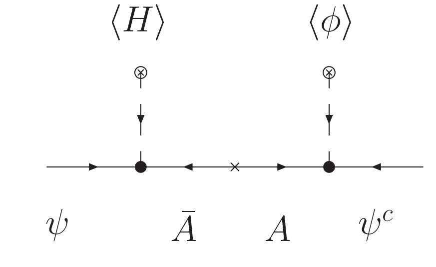
Operator	Bound on Λ	Observables
$H^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right) (eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$H_D^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right) (g_s G^a_{\mu\nu})$	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	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) (eD_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s\ell^+\ell^-$

If 1-loop suppressed like in MSSM < *TeV* !

$$\Lambda_{\rm loop} \approx \left(\frac{\alpha}{4\pi}\right)^{\frac{1}{2}} \Lambda_{\rm tree} \approx \frac{1}{10}\Lambda_{\rm tree}$$

Alignment vs. MFV

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

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

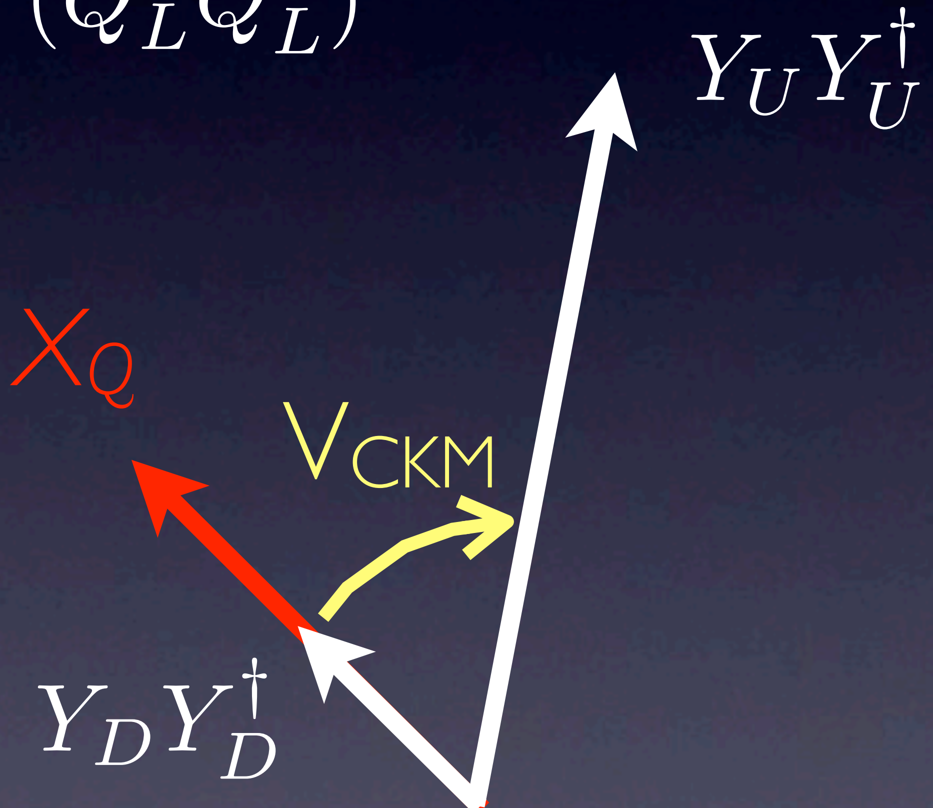
Here only MFV operators, flavorgenesis scale from first two generations

Combination of K-K and D-D

Nir 07; Blum et. al '09

Can not simultaneously evade constraints from DD & KK

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



D-D mixing !

no effect in K-K mixing

$$\frac{1}{\Lambda^2_{\rm NP}}(\overline{Q}_{Li}(X_Q)_{ij}\gamma_\mu Q_{Lj})(\overline{Q}_{Li}(X_Q)_{ij}\gamma^\mu Q_{Lj})$$

Combination of K-$\underline{K}$ and D-$\underline{D}$

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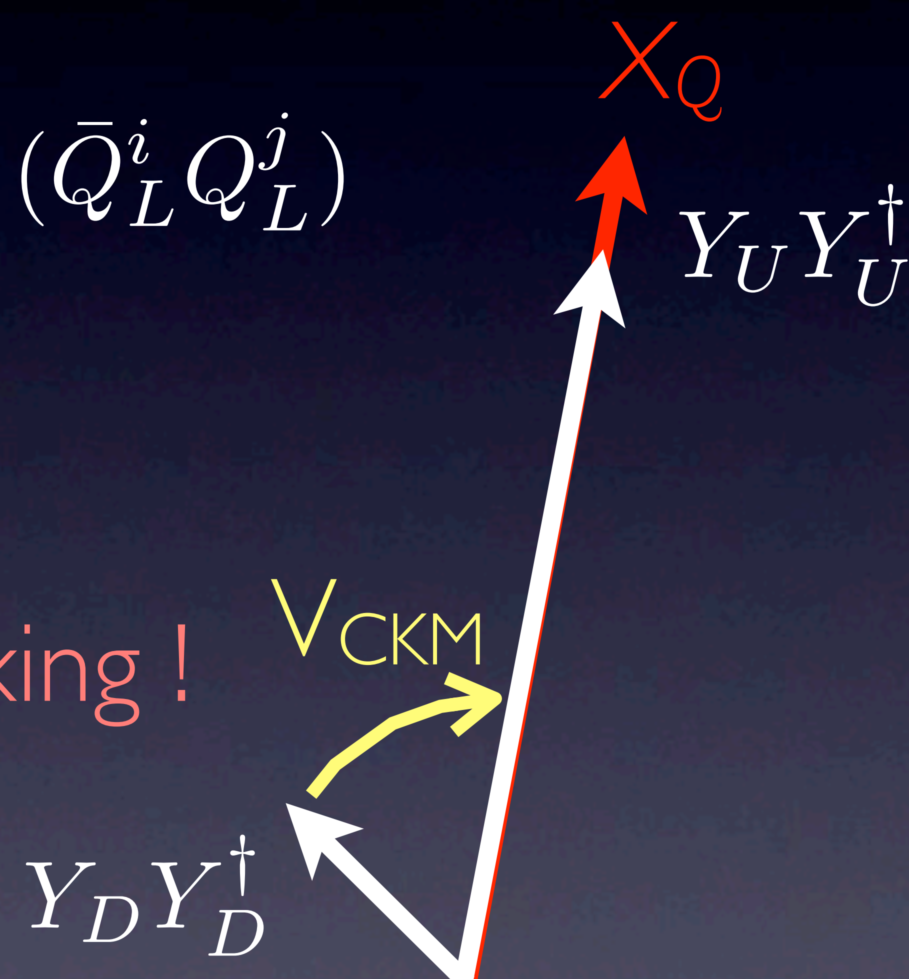
Can not simultaneously evade constraints from D$\underline{D}$ & K$\underline{K}$



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Combination of K-$\overline{K}$ and D-$\overline{D}$

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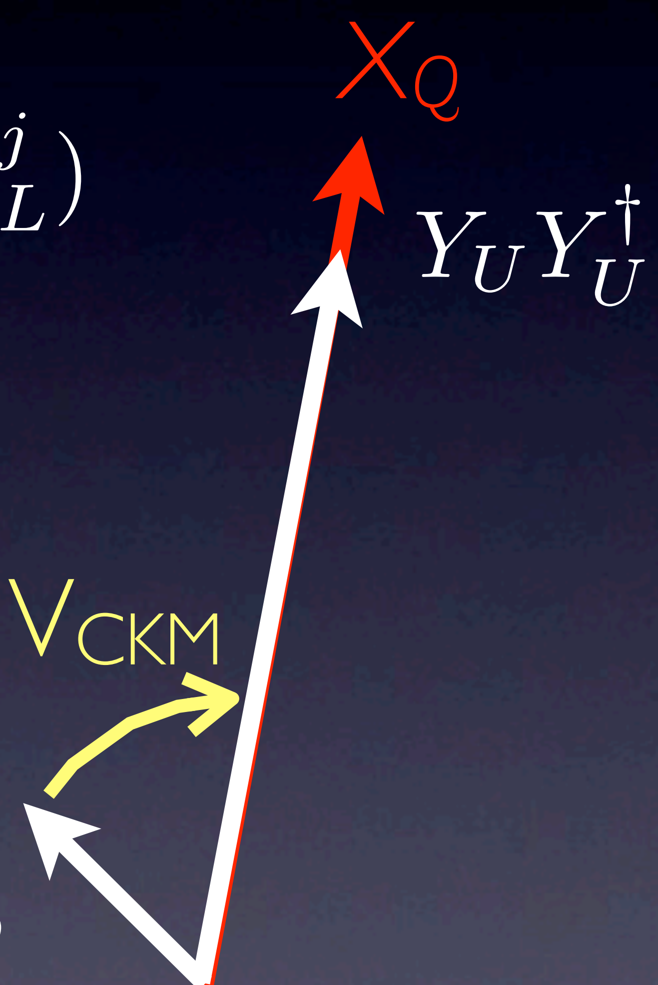
$(\bar{Q}_L^i Q_L^j)$



K-$\overline{K}$ mixing !

=> *squarks*$_{1,2}$ ≈ degenerate

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

no effect in D-$\overline{D}$ mixing

$$\frac{1}{\Lambda_{\rm NP}^2}(\overline{Q}_{Li}(X_Q)_{ij}\gamma_\mu Q_{Lj})(\overline{Q}_{Li}(X_Q)_{ij}\gamma^\mu Q_{Lj})$$

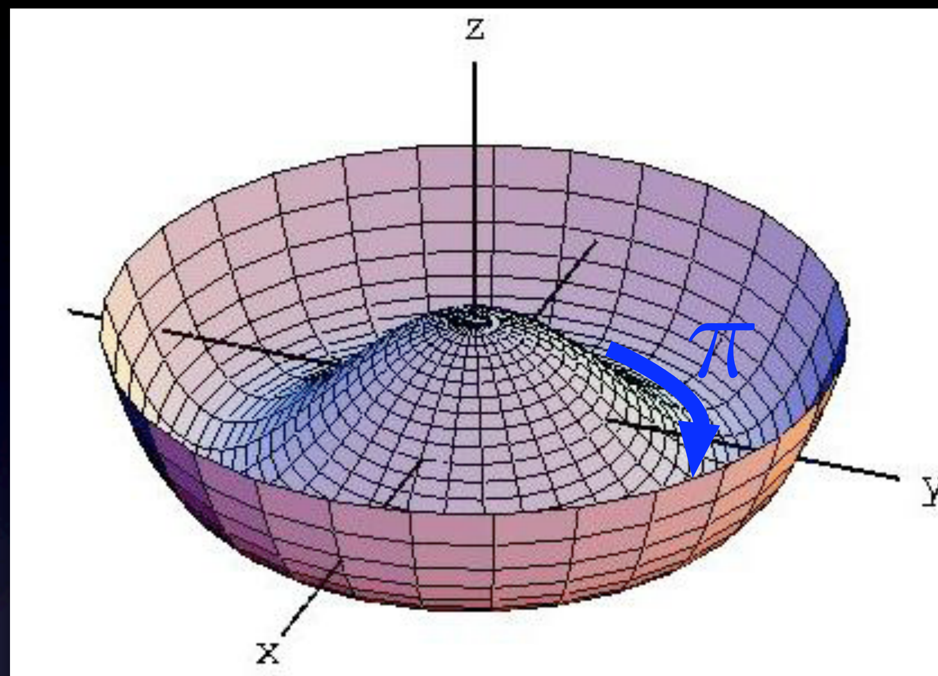
A particular class of models: partial compositeness (geometric alignment vs. MFV)

Weak scale is unstable

elementary scalar Higgs

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

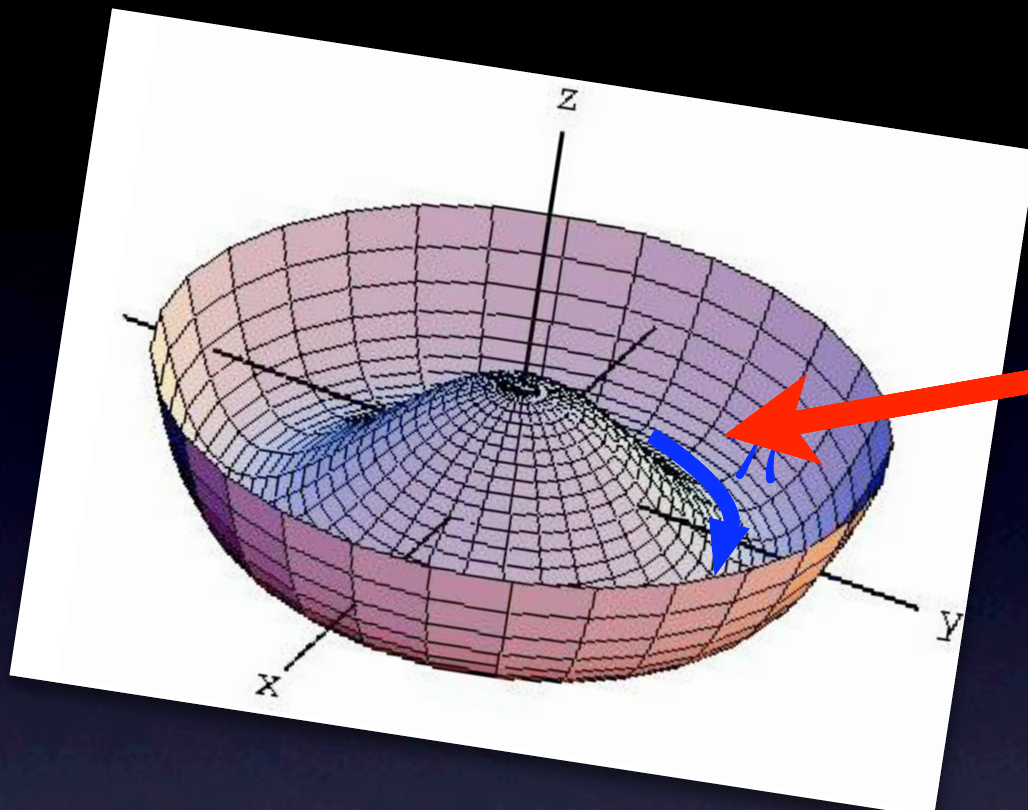
Inspiration by QCD



mass protected by global symmetry

$$\pi \rightarrow \pi + \alpha$$

Inspired by QCD



Potential tilted:
due to quark masses
and gauging of EM

GB → pGB

$$m_{\pi^\pm}^2 \approx \frac{\alpha_{em}}{4\pi}\Lambda_{QCD}^2$$

Fermions get masses by
coupling to this new sector

MFV or not MFV?

Old Flavor problem of composite Higgs

Higgs as bound state, naively $D_{\mathcal{H}=\langle\bar{\psi}\psi\rangle} \approx 3$

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

Λ can not be too large, because want top mass

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

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Λ can not be too large, because want top mass

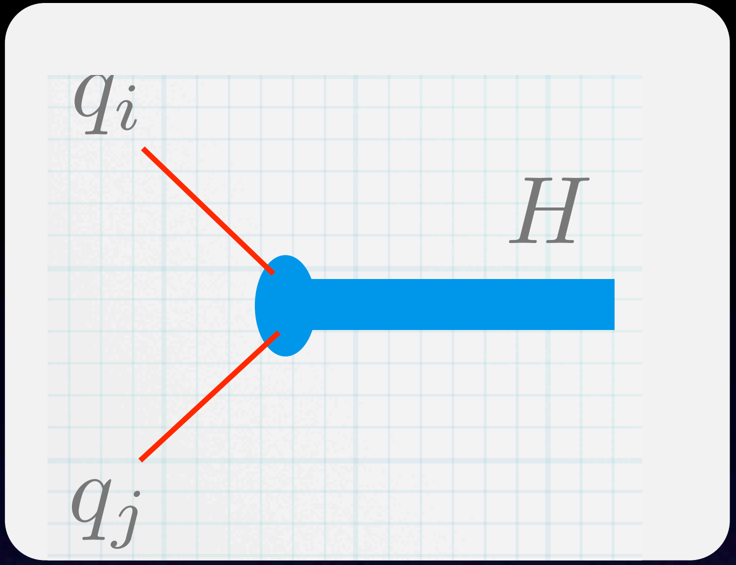
Λ must be very large because this leads to FCNCs

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

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

$$\Lambda > 10^5\,\mathrm{TeV}$$ ✗

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:

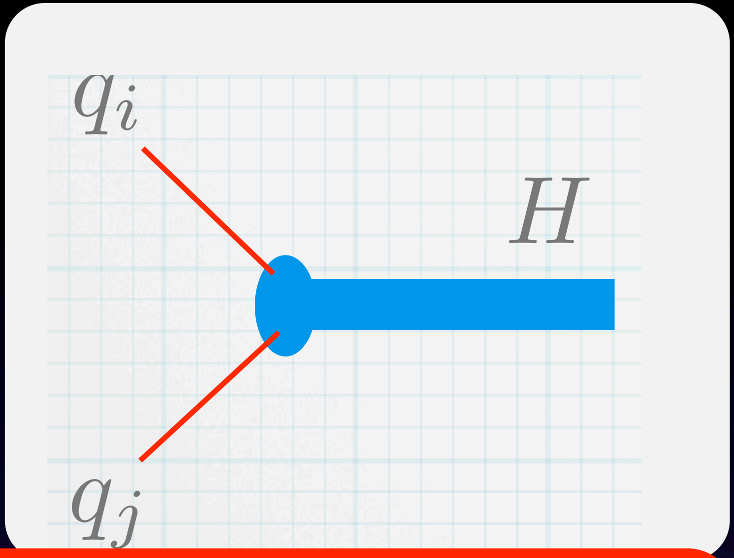
D.B. Kaplan '91

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

$\propto$

Two ways of giving mass to fermions…

Bi-linear (like SM):



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

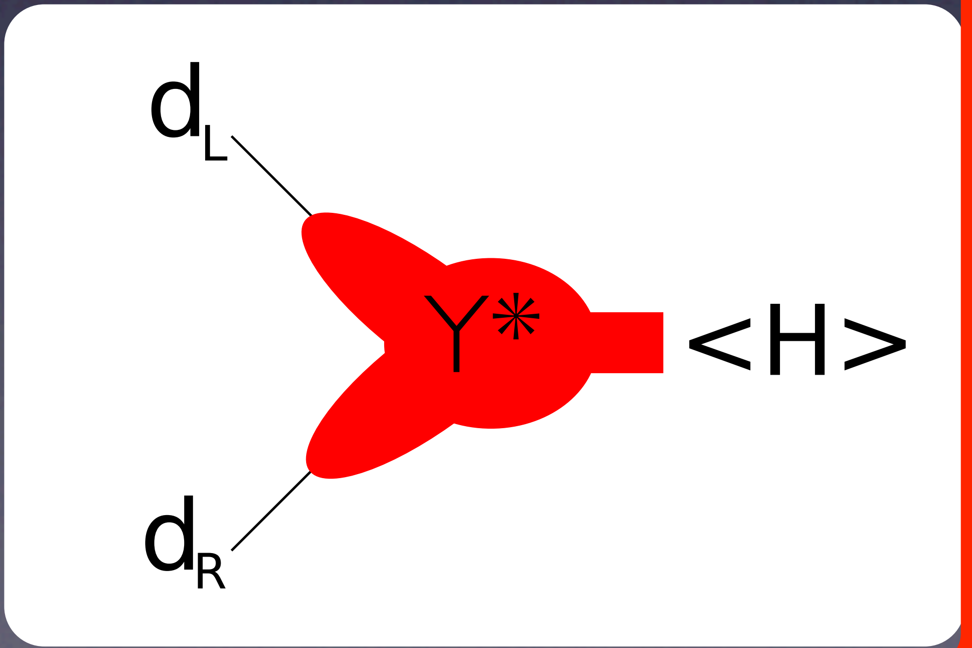
Linear:

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



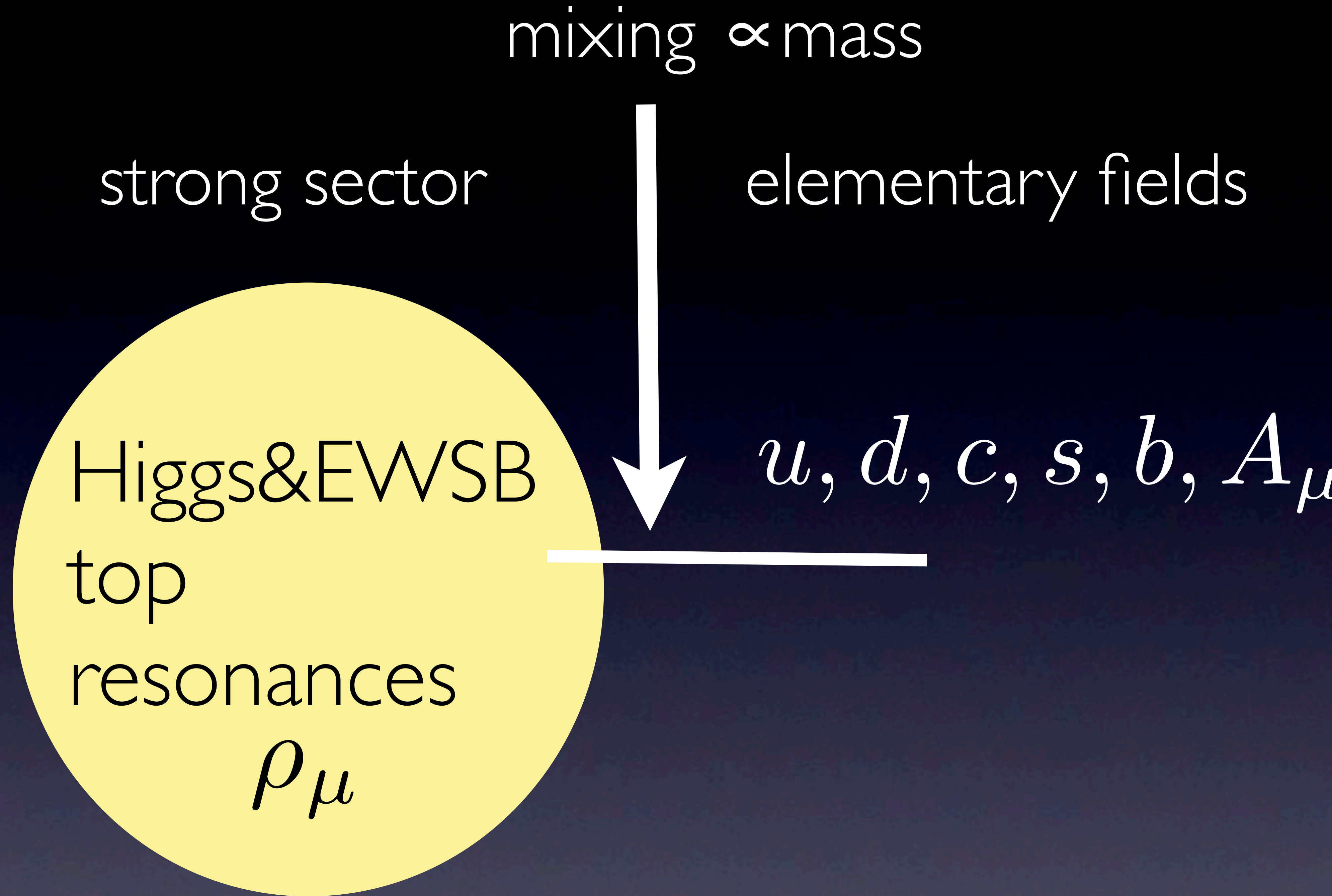
Partial compositeness

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

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

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

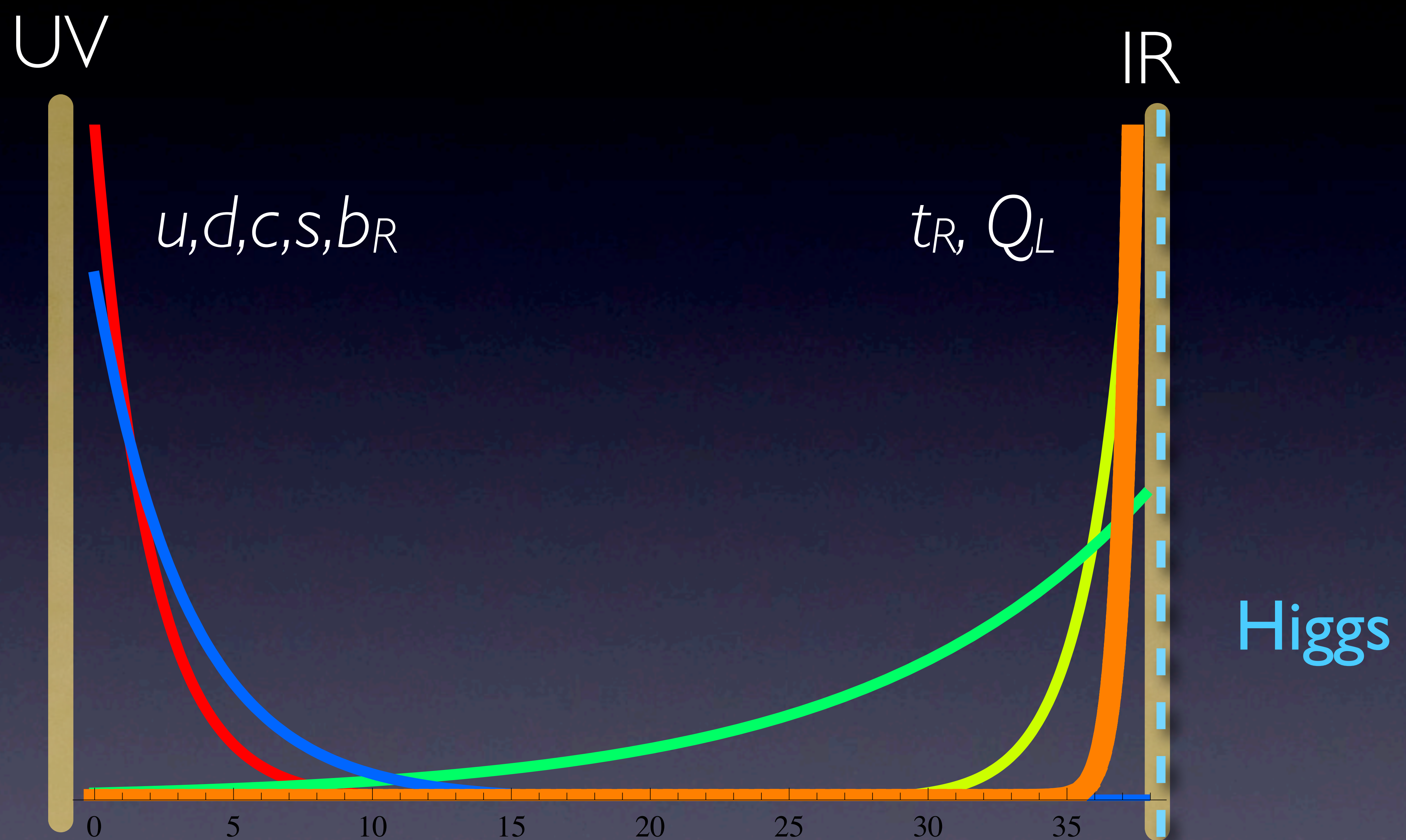
Light quarks have very little composite admixture.



$g_*, \; m_\rho$

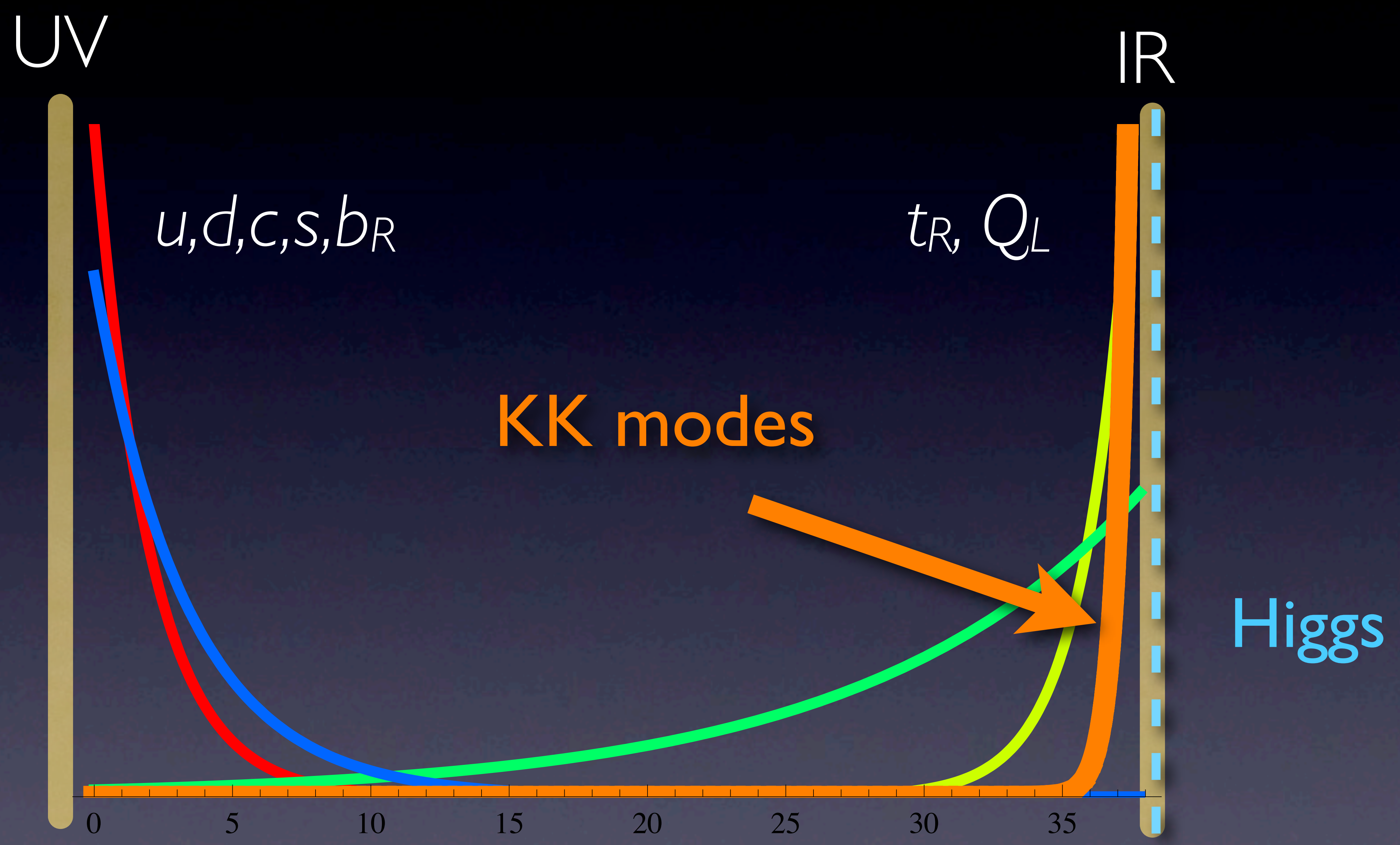
$1 \lesssim g_* \lesssim 4\pi$

Kaplan; Contino, Kramer, Son, Sundrum



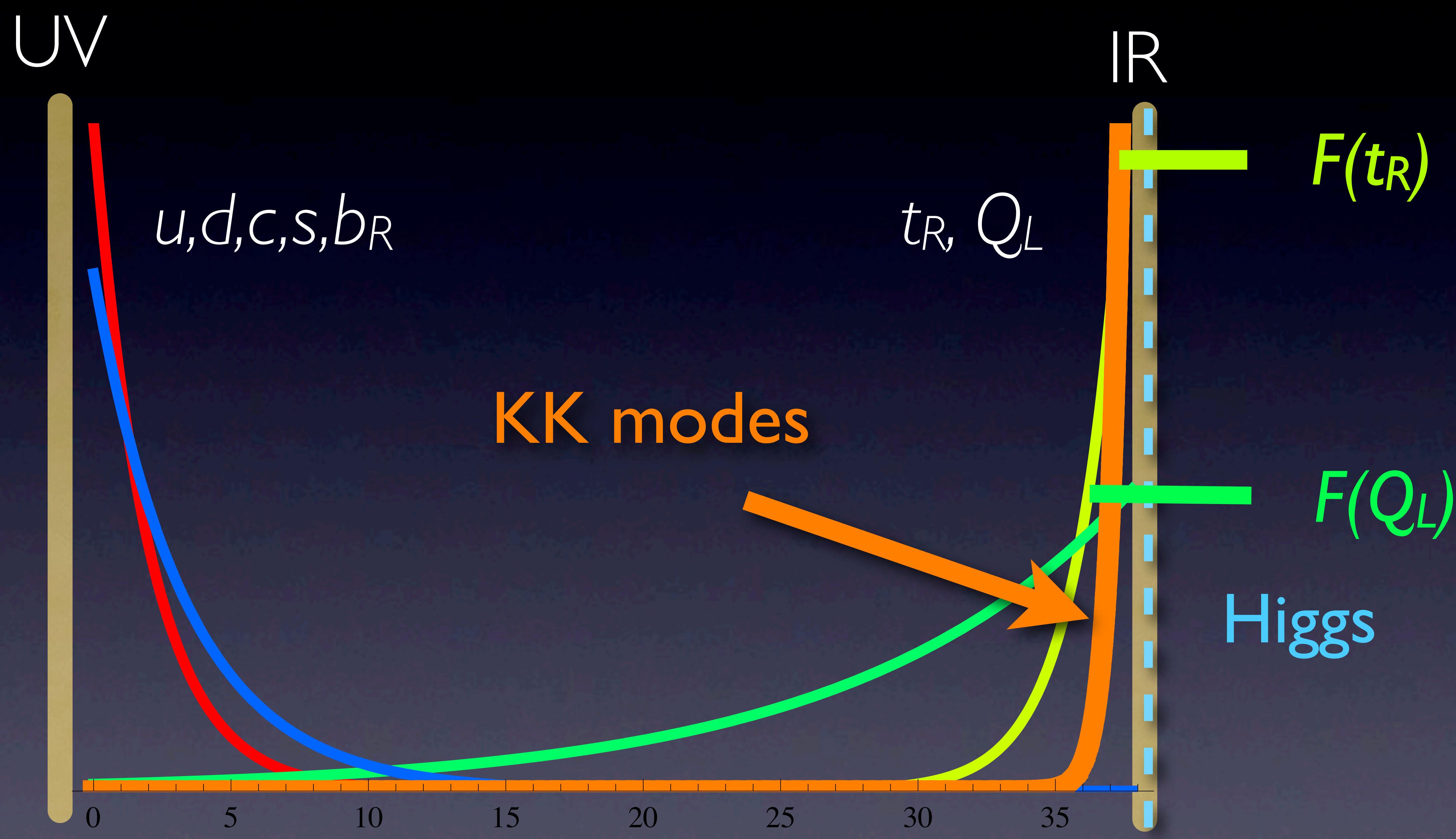
RGE of the mixing UV → IR

Contino, Pomarol;
Contino, et al



Contino, Pomarol;
Contino, et al

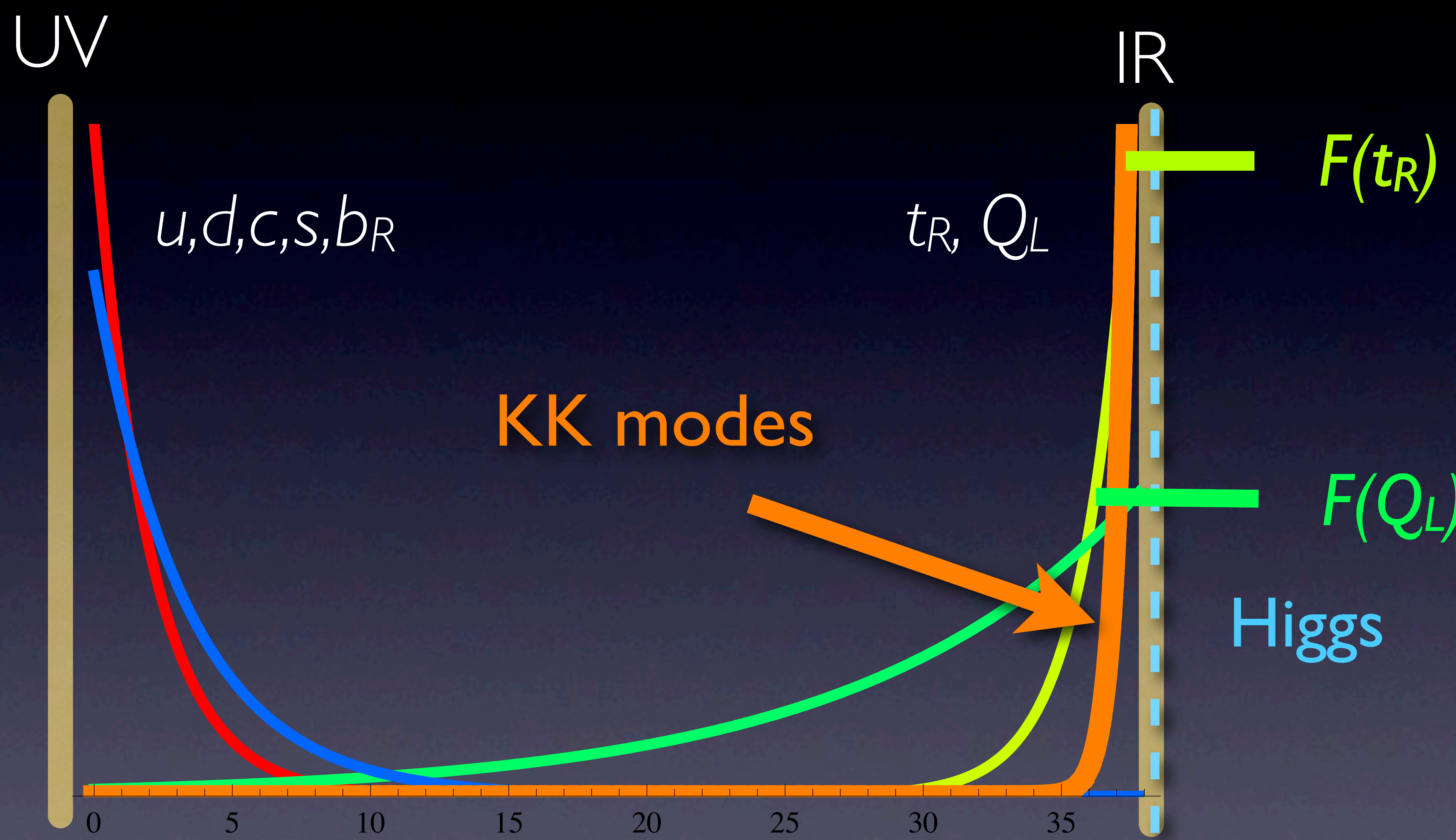
RGE of the mixing UV ⇒ IR



RGE of the mixing UV → IR

Contino, Pomarol;
Contino, et al

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



RGE of the mixing UV ➡ IR

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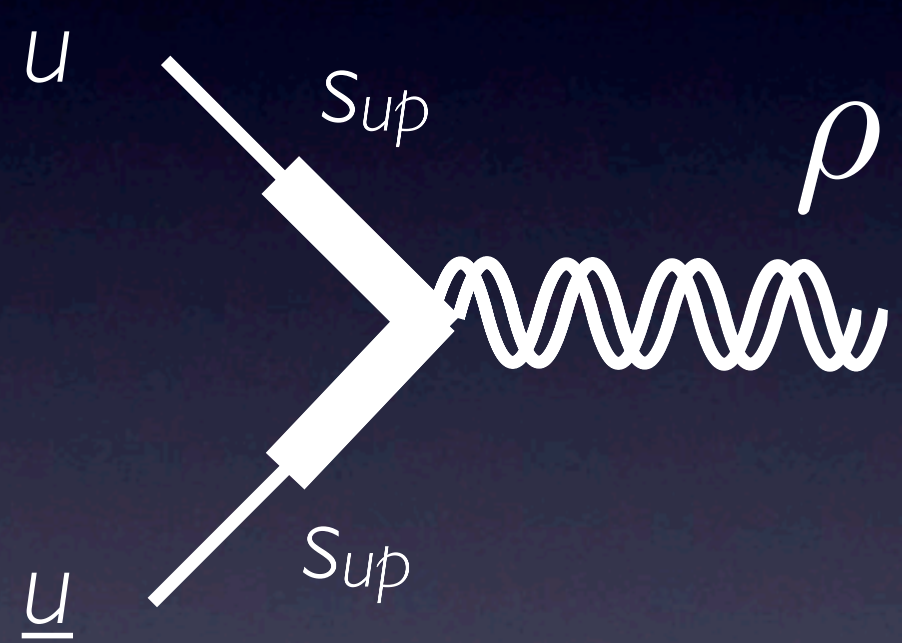
Contino, et al

high p_T

Resonance production (option 1)



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

strongly suppressed for light quarks!

high p_T

Resonance production (option 2)

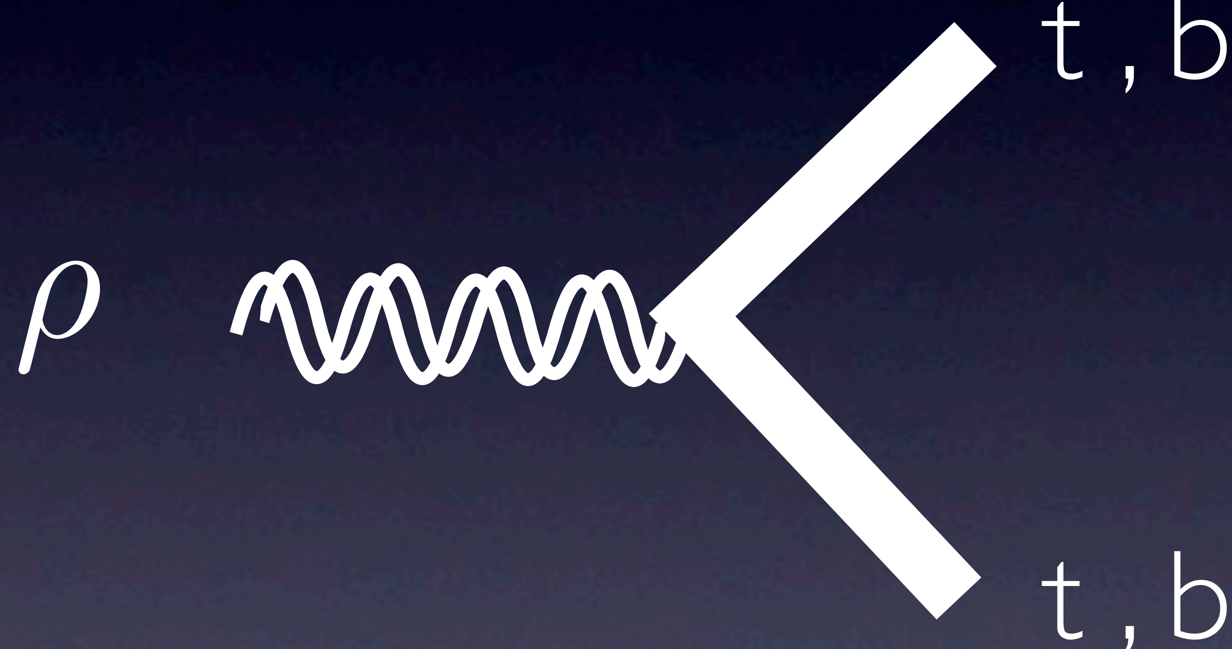
$$\sim \frac{g_s}{g*}$$

similar to $\gamma - \rho$ mixing

NB, gluon-rho-rho = 0

high p_T

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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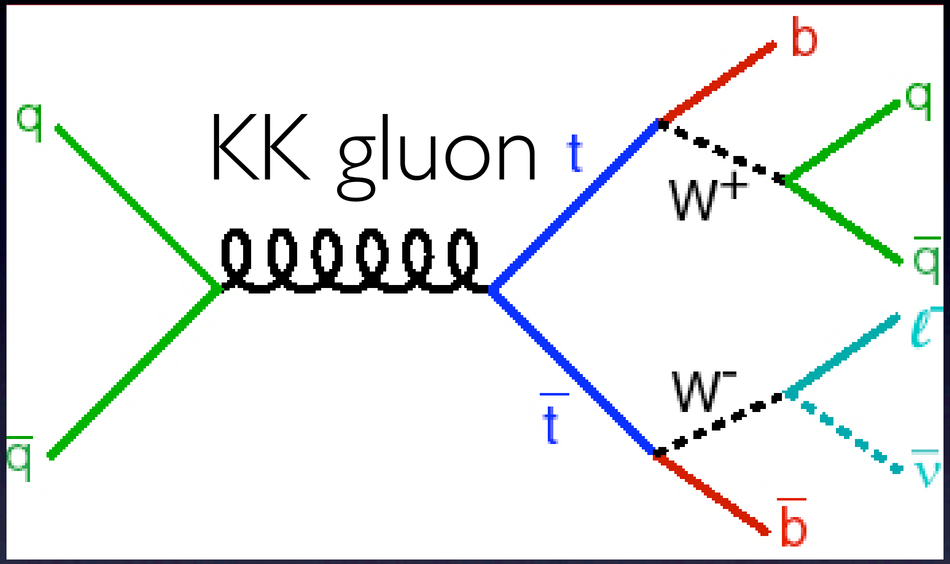
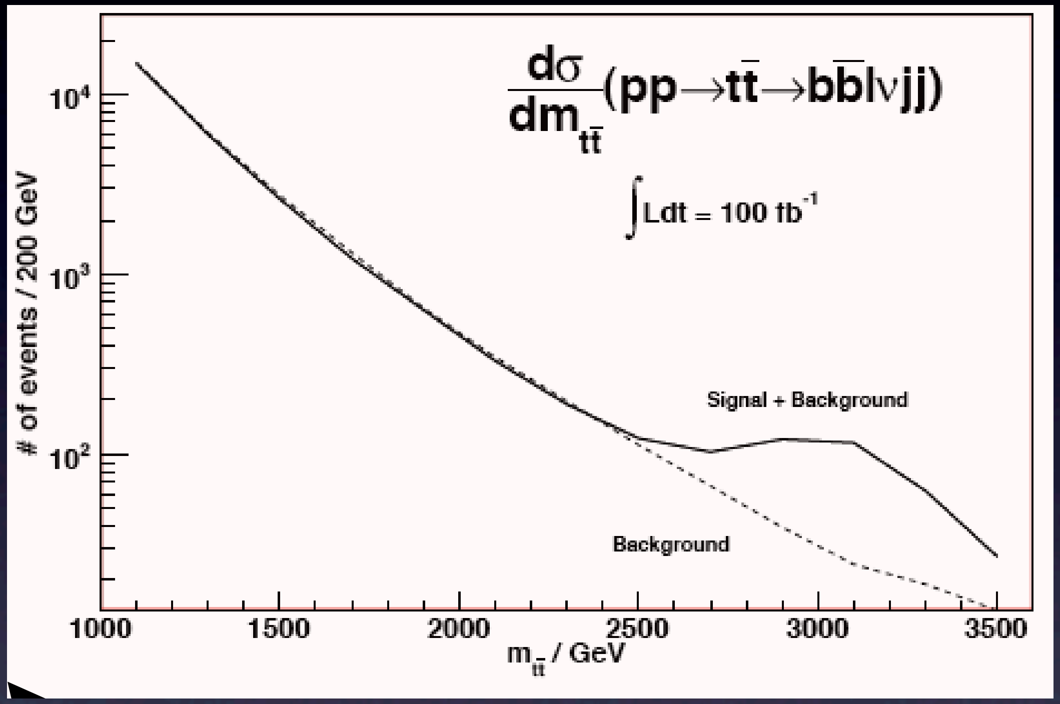
Resonances decay to Tops

Agashe et al, Lillie et al



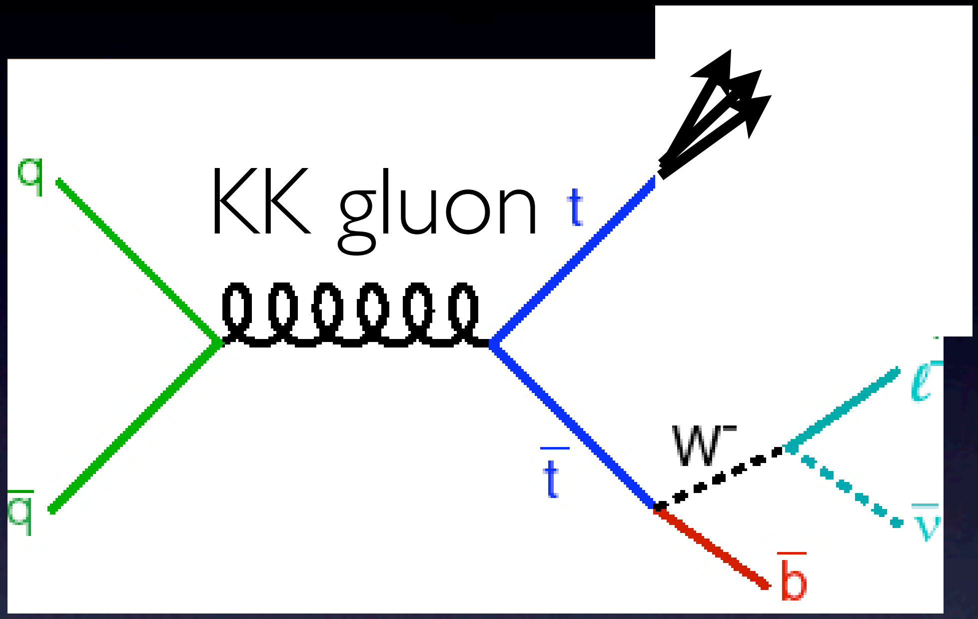


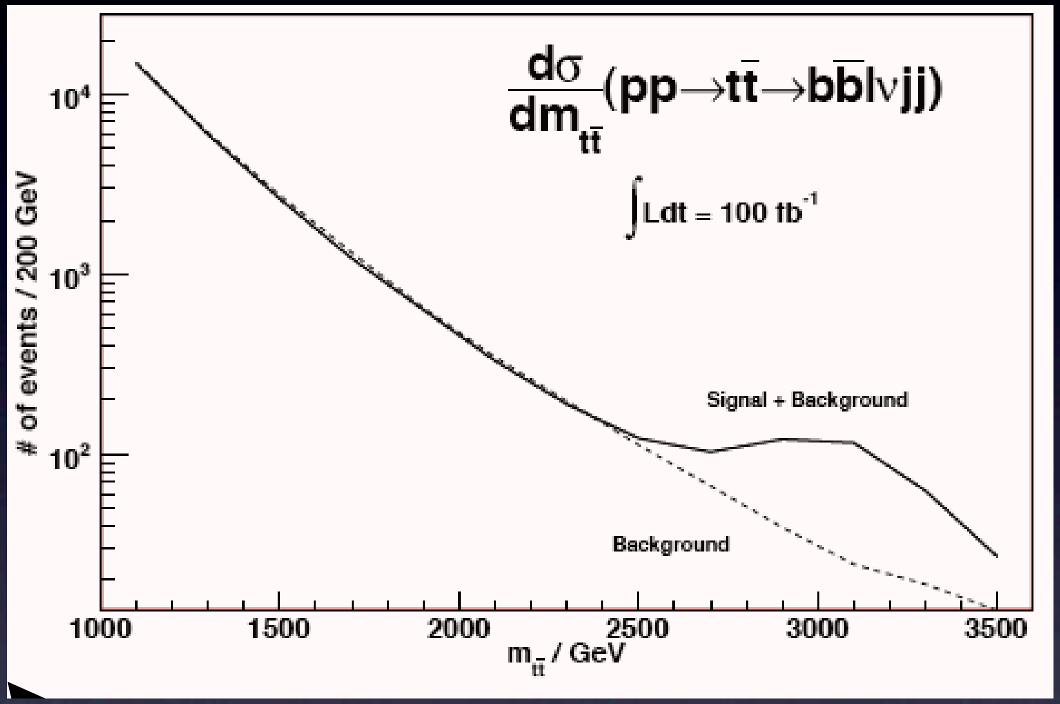
Collimation poses challenge
($m_{KK} \sim 3$ TeV vs. m_{top})

high p_T - flavor interplay!

Resonances decay to Tops

Agashe et al, Lillie et al





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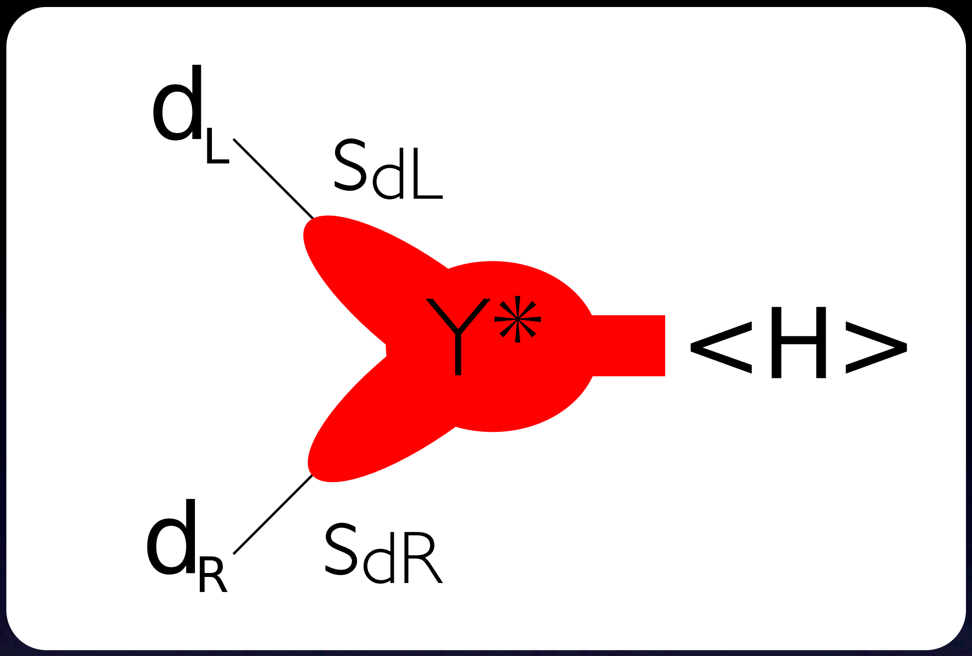
FCNCs

FCNC protection

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



masses from mixing in composites

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

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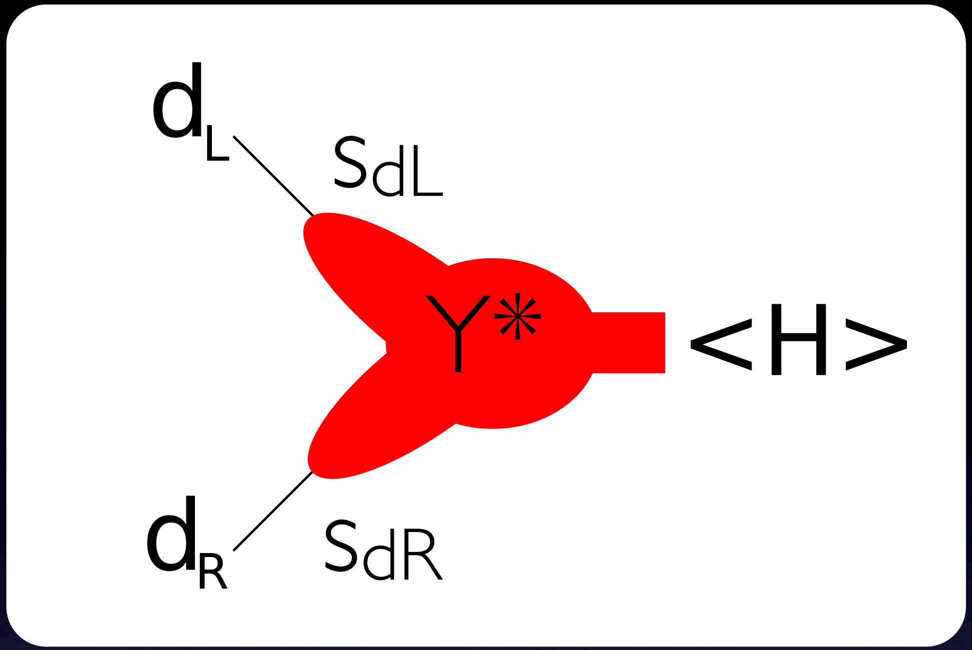

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RS-GIM

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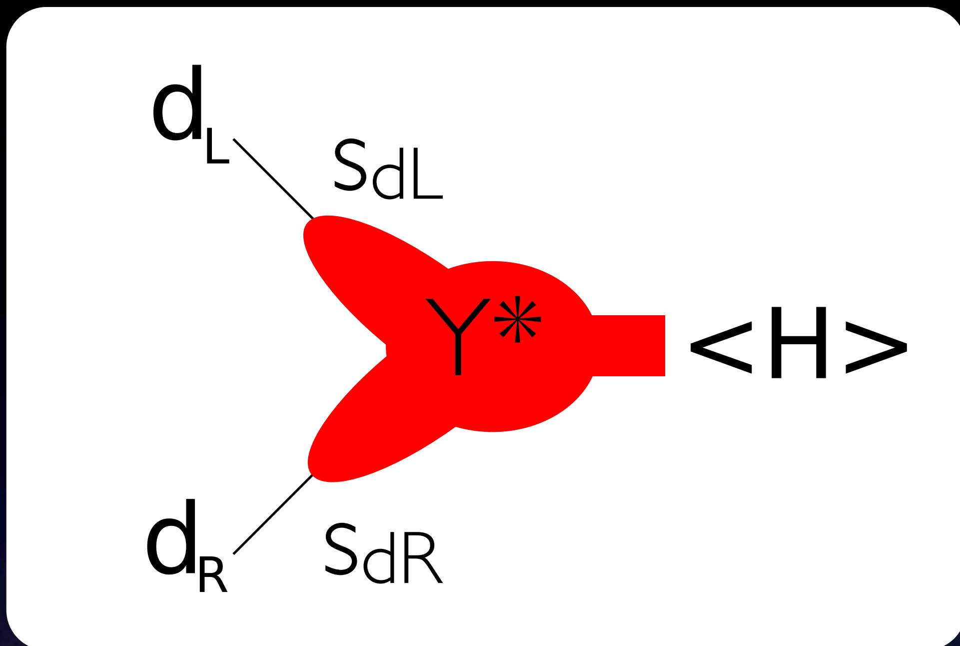

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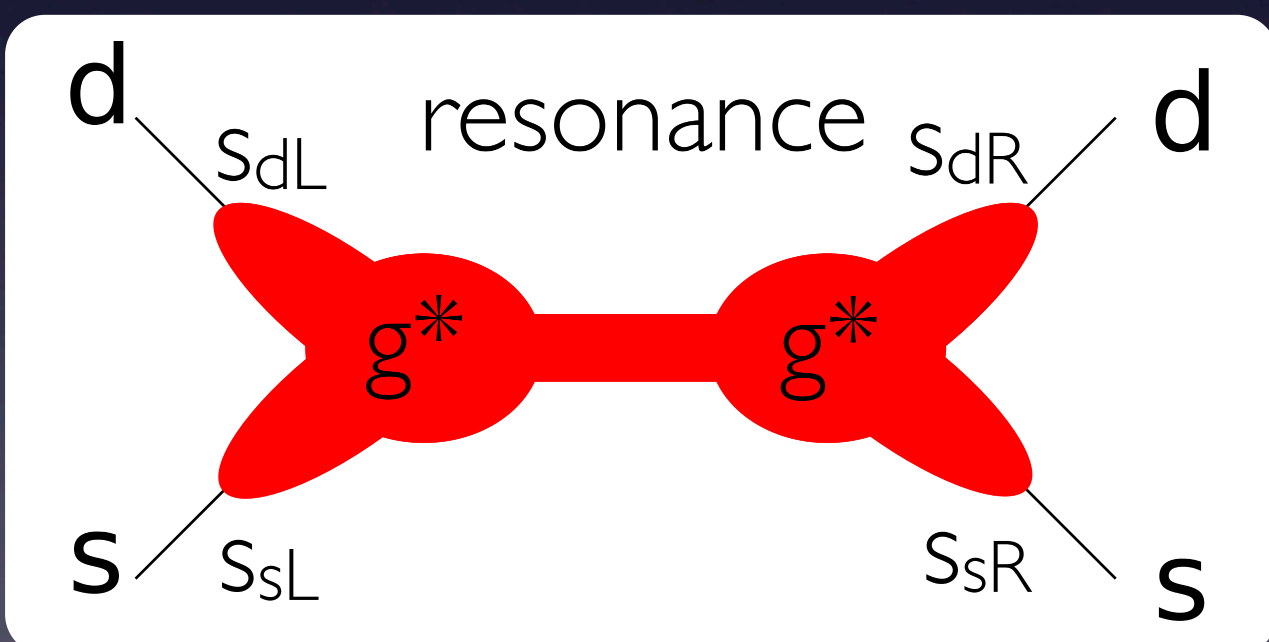


$$K^0 - \bar{K}^0$$

FCNCs suppressed by the same mixings

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

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

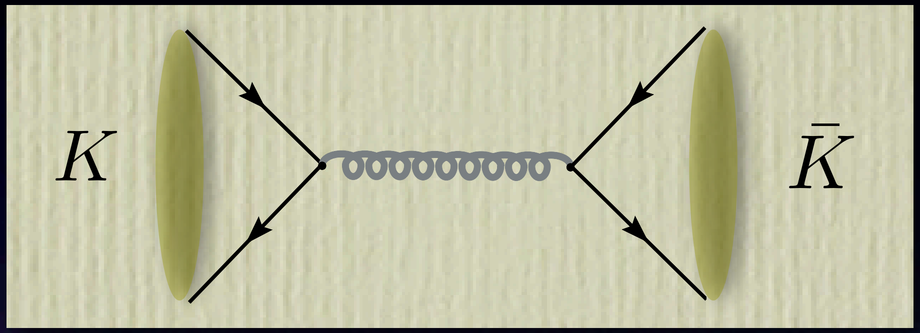
RS-GIM

Little CP problem

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

$\Delta F = 2$ (strongest from ϵ_K)

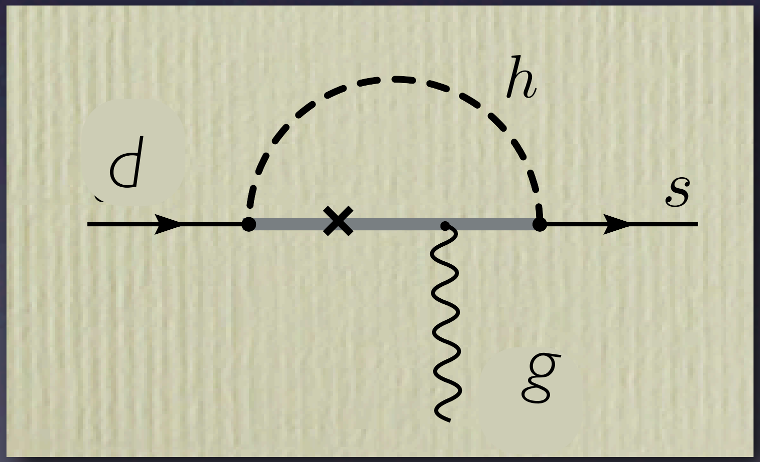
$$g_* \approx Y_* \approx 3 \ldots 6$$



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

$\Delta F = 1$ (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

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 *Y*'s "shine" into the bulk, $m_\rho \approx 2\,\mathrm{TeV}$

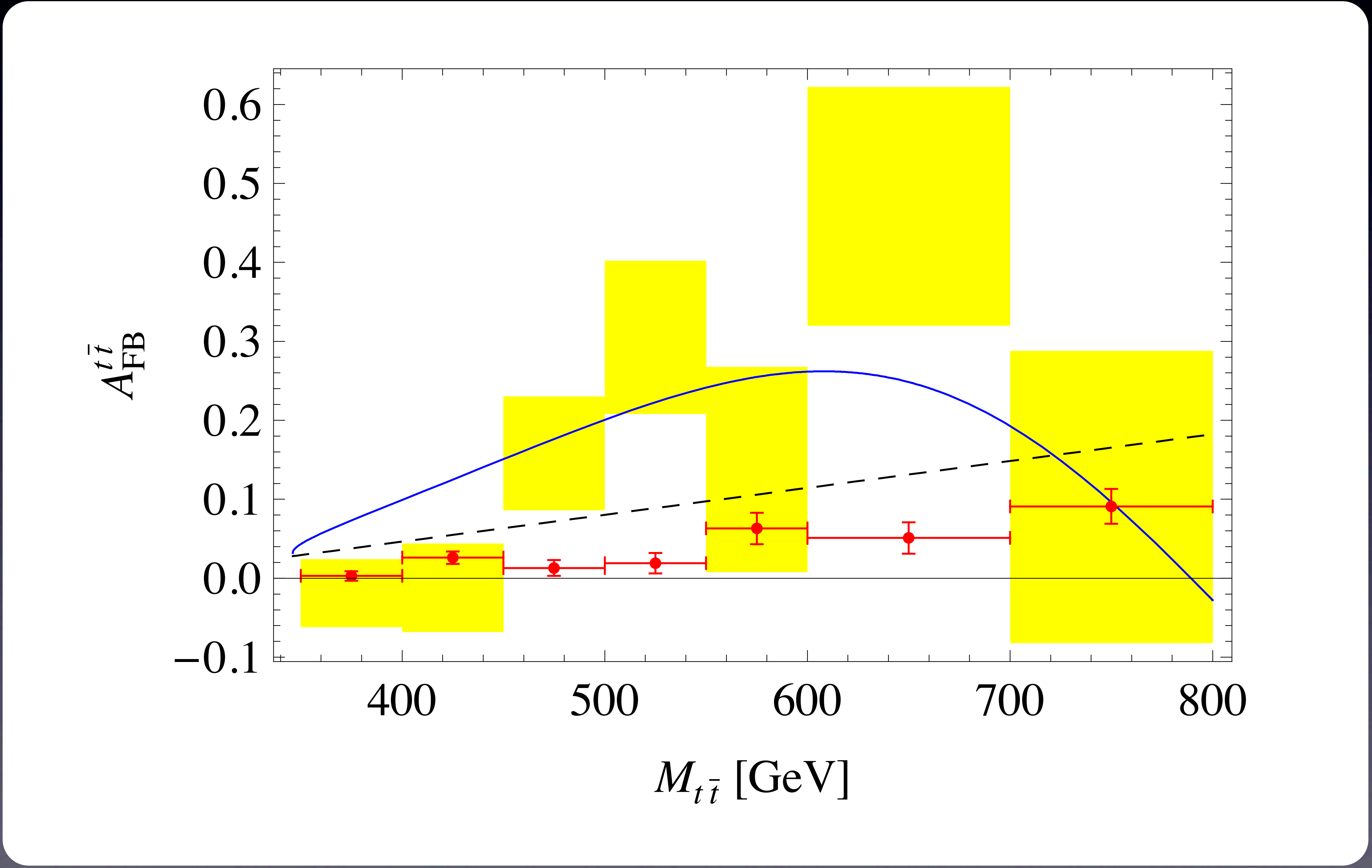
=> flavor gauge bosons predicted (in 2 slides)

mixing can be large & universal

MFV-RS allows for sizable A_{FB}

(Small asymmetry in anarchic warped flavor: Bauer et al)

plot from Blum et al



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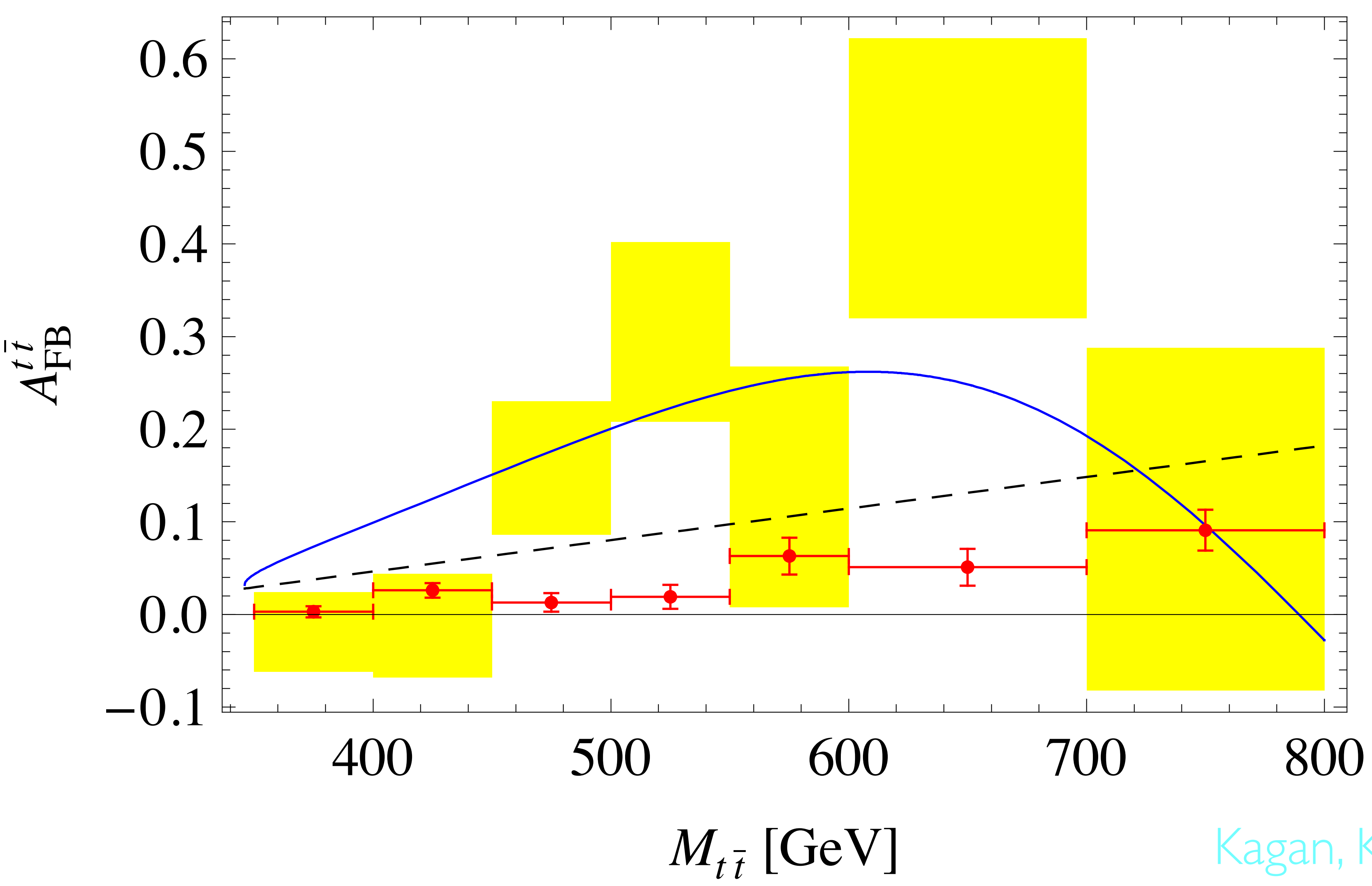


Kagan, Kamenik, Perez, Stone

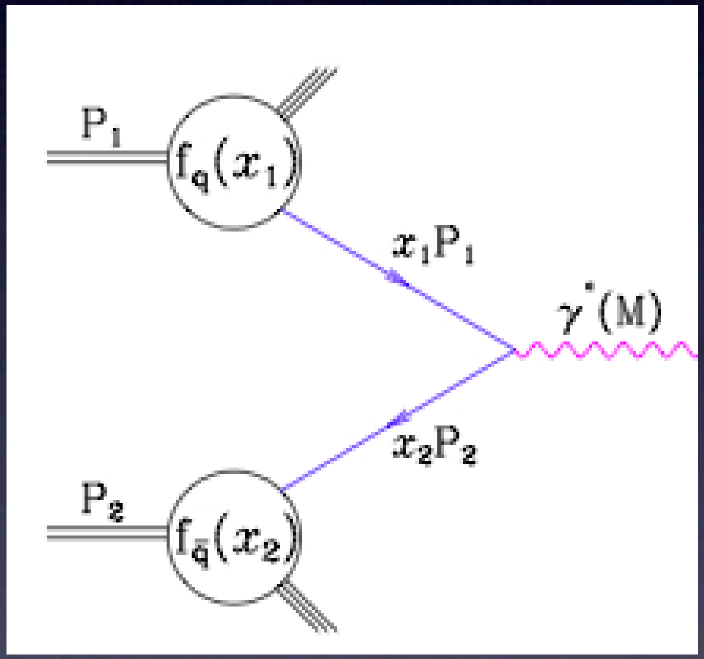
measurement at LHCb?

Flavor gauge bosons at LHC

Csaki, Kagan, Lee, Perez, AW

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

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



no $\gamma - \rho$ mixing !

But quark composite mixing can be flavor universal & large

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

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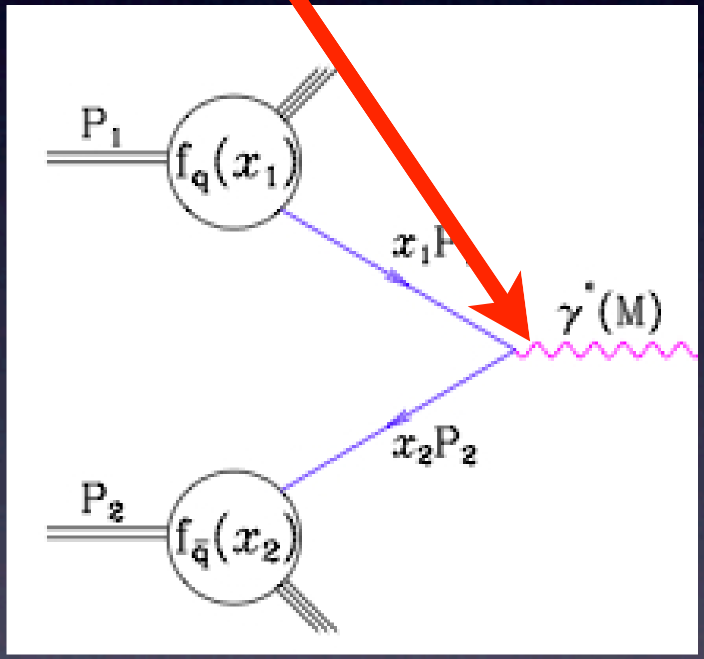

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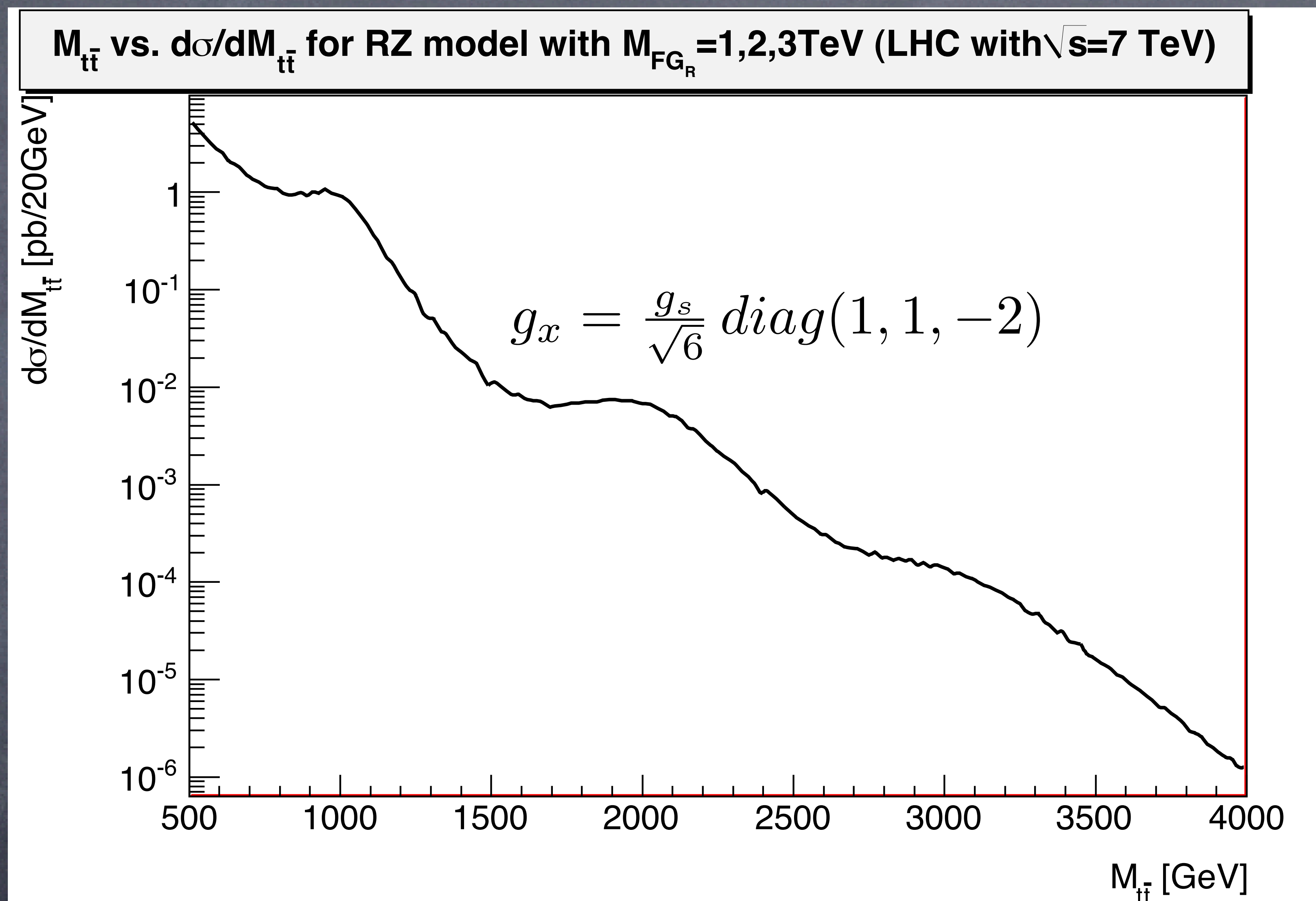
FGBs at the LHC (preliminary)

- The flavor gauge bosons & scalars might be observable.



$$
\begin{aligned}
\mathcal{L} \;&=\; \frac{\lambda}{2} V_\mu^8 \left(\frac{1}{\sqrt{3}} \bar{u}_R \gamma^\mu u_R + \frac{1}{\sqrt{3}} \bar{c}_R \gamma^\mu c_R - \frac{2}{\sqrt{3}} \bar{t}_R \gamma^\mu t_R \right) \\
&+\; \frac{\lambda}{2} \left((V_\mu^4 - i V_\mu^5) \bar{u}_R \gamma^\mu t_R + (V_\mu^6 - i V_\mu^7) \bar{c}_R \gamma^\mu t_R + h.c. \right)
\end{aligned}
$$

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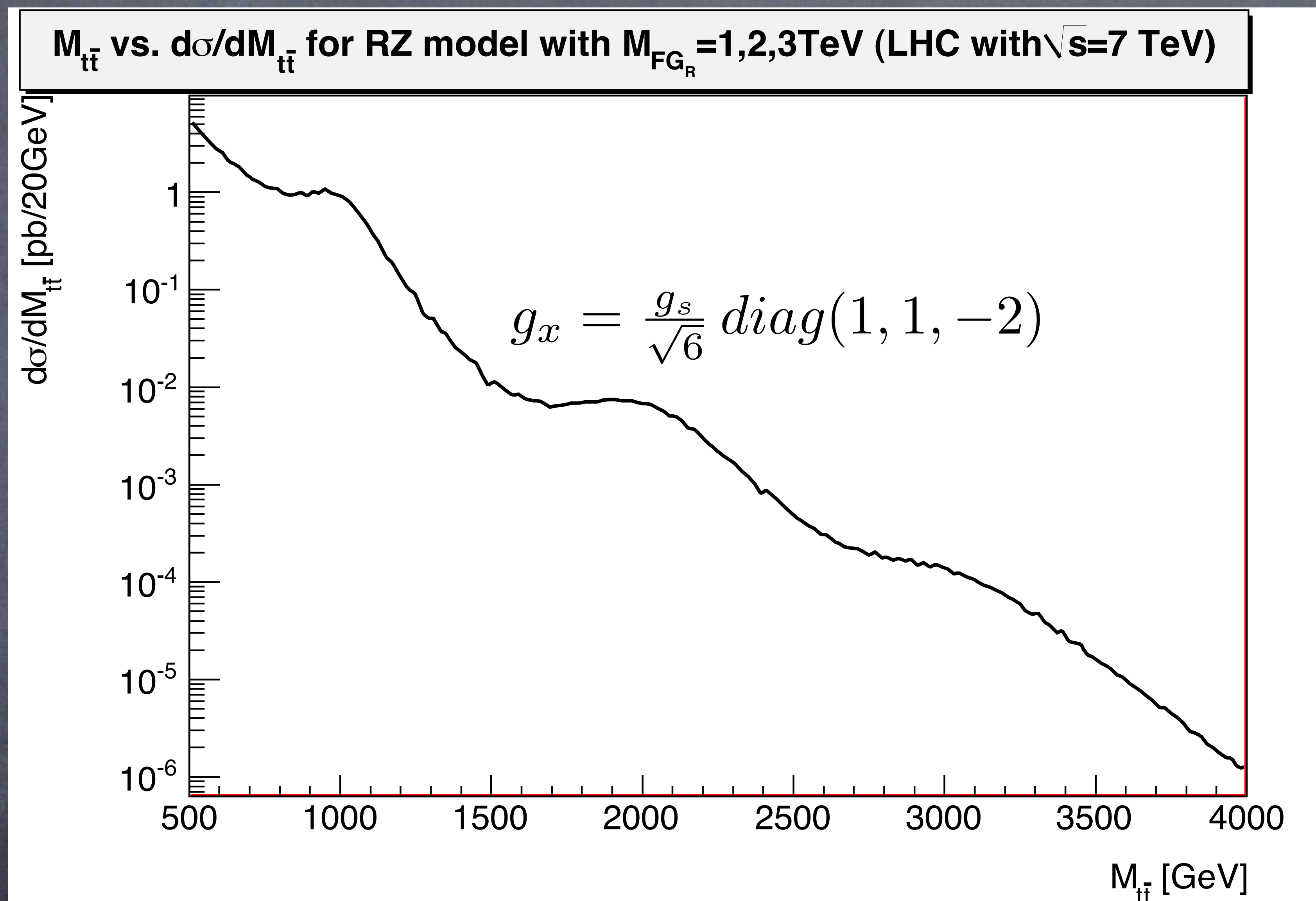

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\end{aligned}
$$

Flavor Gauge Boson @ Tevatron?

$$\mathcal{L} = g_{eff}\bar{u}_R V_\mu^A \frac{T^A}{2}\gamma_\mu u_R + h.c.$$

- Can partially explain A_{FB} with the usual constraints:

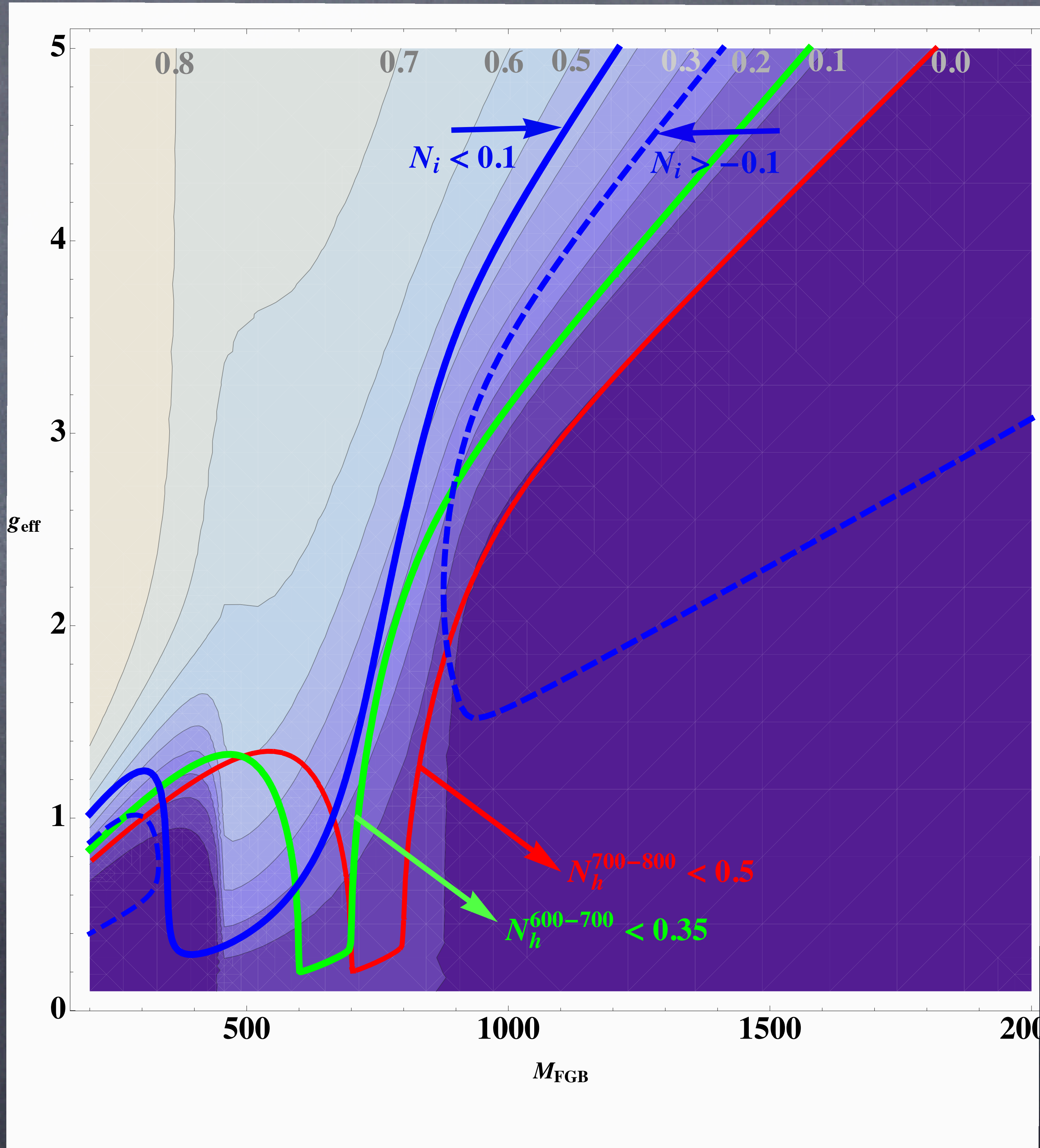
i) $\delta\sigma^{NP}_{700-800\,\mathrm{GeV}}/\sigma^{SM}_{700-800\,\mathrm{GeV}} \lesssim 47\%$

ii) $\delta\sigma^{NP}_{t\bar{t}}/\sigma^{SM}_{t\bar{t}} \lesssim 10\%$

- M_{FGB} <900 GeV, g_{eff} ~O(1)

$A^{t\bar{t}}_{FB}(M_{inv} > 450GeV) \lesssim 10\%$

- σ_{NP}/σ_{SM}(pT>400GeV): 2-3



Conclusions

Most well-motivated models of NP at the TeV predict experimentally resolvable deviations from the SM

Discovery of non-MFV new physics might give insight in origin of Yukawas

high p_T can also offer window into flavor (see explanations of the top FB anomaly)