Low Scale Flavor Gauge Symmetries

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in collaboration with
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Very strong bounds from flavor physics. Four fermions operators must be suppressed by high scale

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$$\frac{1}{\Lambda^2}(\bar{d}_R s_L \bar{d}_L s_R) \qquad\qquad \Lambda_{LR} > 10^4 - 10^5\ TeV$$

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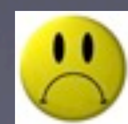
Flavor physics seems very far.

Major embarrassment for most BSM scenarios!



Without Yukawas SM (quark sector) has a flavor symmetry

$$SU(3)_{Q_L} \otimes U(3)_{U_R} \otimes U(3)_{D_R}$$

$$Q_L = (3,1,1)$$
$$U_R = (1,3,1)$$
$$D_R = (1,1,3)$$

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Minimal Flavor Violation: Yukawas are the only sources of flavor violation. Higher dimensional operators must be built with positive powers of Yukawas

$$\bar{q}_L y_u y_u^\dagger \gamma^\mu \bar{q}_L \qquad \bar{d}_R y_d^\dagger y_u y_u^\dagger d_L \qquad \bar{d}_R y_d^\dagger y_u y_u^\dagger y_d \gamma^\mu d_R$$

With MFV new physics can lie around the TeV scale.

But where is MFV coming from?

Can flavor be an exact symmetry of Nature?

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$$Y_u = (3, \bar{3}, 1)$$

$$Y_d = (3, 1, \bar{3})$$

$$y_{u,d} = \frac{< Y_{u,d} >}{M_{u,d}}$$

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$$f > 10^{12}\ GeV$$

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- Local

GBs are eaten and become longitudinal components of flavor gauge bosons.

$$\mathcal{L}_{mass} = \mathrm{Tr}|g_U A_U Y_u - g_Q Y_u A_Q|^2 + \mathrm{Tr}|g_D A_D Y_d - g_Q Y_d A_Q|^2$$
$$= \frac{1}{2} V_{Aa} (M_V^2)^{Aa,Bb} V_{Bb}\,,$$

$$M^2 \sim g^2 < Y^2 >$$

Flavor gauge bosons mediate FCNC

$$-\frac{1}{8}(M_V^2)^{-1}_{Aa,Bb}\, \lambda^a_{ij}\lambda^b_{hk}\, J^{ij,A}_\mu \;\; J^{\mu\, hk,B}$$

$$J^{\mu\, ij,A} = (g_Q \overline{Q}^i_L \gamma^\mu Q^j_L,\, g_U \overline{U}^i_R \gamma^\mu U^j_R,\, g_D \overline{D}^i_R \gamma^\mu D^j_R)$$

$$\sim \frac{1}{M^2}(\bar{q}\gamma^\mu q)^2 \sim \frac{1}{< Y^2_{u,d} >}(\bar{q}q)^2 \sim \frac{1}{M^2_{u,d} y^2_{u,d}}(\bar{q}q)^2$$

$$\mathcal{L}_{mass} = \mathrm{Tr}|g_U A_U Y_u - g_Q Y_u A_Q|^2 + \mathrm{Tr}|g_D A_D Y_d - g_Q Y_d A_Q|^2$$
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$$\sim \frac{1}{M^2}(\bar{q}\gamma^\mu q)^2 \sim \frac{1}{< Y^2_{u,d} >}(\bar{q}q)^2 \sim \frac{1}{M^2_{u,d} y^2_{u,d}}(\bar{q}q)^2$$

Maximal Flavor Violation!

Flavor must be broken at very high scale,

$$< Y > \geq 10^5\ TeV \qquad\qquad < M > \gg 10^5\ TeV$$

But is y=<Y>/M, really? In a renormalizable theory this could originate from,

$$\mathcal{L}_{yuk} = \bar{Q}\tilde{H}\Psi_R + \bar{\Psi}_L M_u \Psi_R + \bar{\Psi}_L Y_u U_R$$

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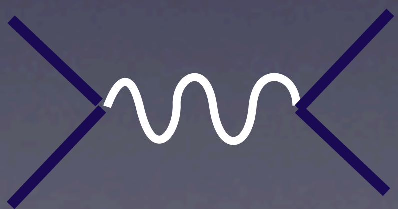
However functions of Y can transform as Y.

We could imagine an inverted hierarchy,

$$y \sim \frac{M}{Y^\dagger}$$

FCNC:



$$\sim \frac{1}{< Y^2_{u,d} >}(\bar{q}q)^2 \sim \frac{y^2_{u,d}}{M^2_{u,d}}(\bar{q}q)^2$$

Anomalies

Flavor symmetries are anomalous:

$SU(3)^3_{Q_L}$ $SU(3)^3_{U_R}$ $SU(3)^3_{D_R}$

$U(1)_Y \times SU(3)^2_{Q_L}$ $U(1)_Y \times SU(3)^2_{U_R}$ $U(1)_Y \times SU(3)^2_{D_R}$

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New fermions need to be added,

$$\Psi_{uR} = (3,1,1)$$

$$\Psi_{dR} = (3,1,1)$$

$$\Psi_{u} = (1,3,1)$$

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New fermions need to be added,

$$\Psi_{uR} = (3,1,1)_{\frac{2}{3}}$$

$$\Psi_{dR} = (3,1,1)_{-\frac{1}{3}}$$

$$\Psi_{u} = (1,3,1)_{\frac{2}{3}}$$

$$\Psi_{d} = (1,1,3)_{-\frac{1}{3}}$$

Flavor U(1) anomalies also cancel.

Model

	$SU(3)_{Q_L}$	$SU(3)_{U_R}$	$SU(3)_{D_R}$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q_L	3	1	1	3	2	1/6
U_R	1	3	1	3	1	2/3
D_R	1	1	3	3	1	-1/3
Ψ_{uR}	3	1	1	3	1	2/3
Ψ_{dR}	3	1	1	3	1	-1/3
Ψ_u	1	3	1	3	1	2/3
Ψ_d	1	1	3	3	1	-1/3
Y_u	$\overline{3}$	3	1	1	1	0
Y_d	$\overline{3}$	1	3	1	1	0
H	1	1	1	1	2	1/2

$$\begin{aligned}\mathcal{L} =&\mathcal{L}_{kin} - V(Y_u, Y_d, H)+\\ &\left(\lambda_u \overline{Q}_L \tilde{H} \Psi_{uR} + \lambda_u' \overline{\Psi}_u Y_u \Psi_{uR} + M_u \overline{\Psi}_u U_R + \right.\\ &\left.\lambda_d \overline{Q}_L H \Psi_{dR} + \lambda_d' \overline{\Psi}_d Y_d \Psi_{dR} + M_d \overline{\Psi}_d D_R + h.c.\right),\end{aligned}$$

Yukawas:

$$y_u = \frac{\lambda_u M_u}{\lambda'_u Y_u^\dagger}$$

$\langle Y \rangle \gg M$

$y_t \sim \lambda_u$

$\langle Y^\dagger \rangle \ll M$

$$y_d = \frac{\lambda_d M_d}{\lambda'_d Y_d^\dagger}$$

Yukawas:

$$y_u = \frac{\lambda_u M_u}{\lambda'_u Y_u^\dagger}$$

<Y> >> M

$$y_t \sim \lambda_u$$

<Y†> << M

$$y_d = \frac{\lambda_d M_d}{\lambda'_d Y_d^\dagger}$$

Inverted hierarchy!

Flavor physics can lie at the TeV scale.

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$$y_u = \frac{\lambda_u M_u}{\lambda'_u Y_u^\dagger}$$

$$y_d = \frac{\lambda_d M_d}{\lambda'_d Y_d^\dagger}$$

<Y> >> M

$y_t \sim \lambda_u$

<Yt> << M

Inverted hierarchy!

Flavor physics can lie at the TeV scale.

Exotic fermions:

$$m'_{u,d} \sim \lambda'_{u,d} < Y_{u,d} >$$

Flavon couplings highly suppressed

$$\sim \frac{M}{\hat{Y}^i + \delta Y^i} v\, \bar{q}_i q_i \approx \left(1 - y^i \frac{\delta Y^i}{M}\right) m_{q_i} \bar{q}_i q_i$$

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$$Y_d = \hat{Y}_d \qquad\qquad Y_u = \hat{Y}_d V$$

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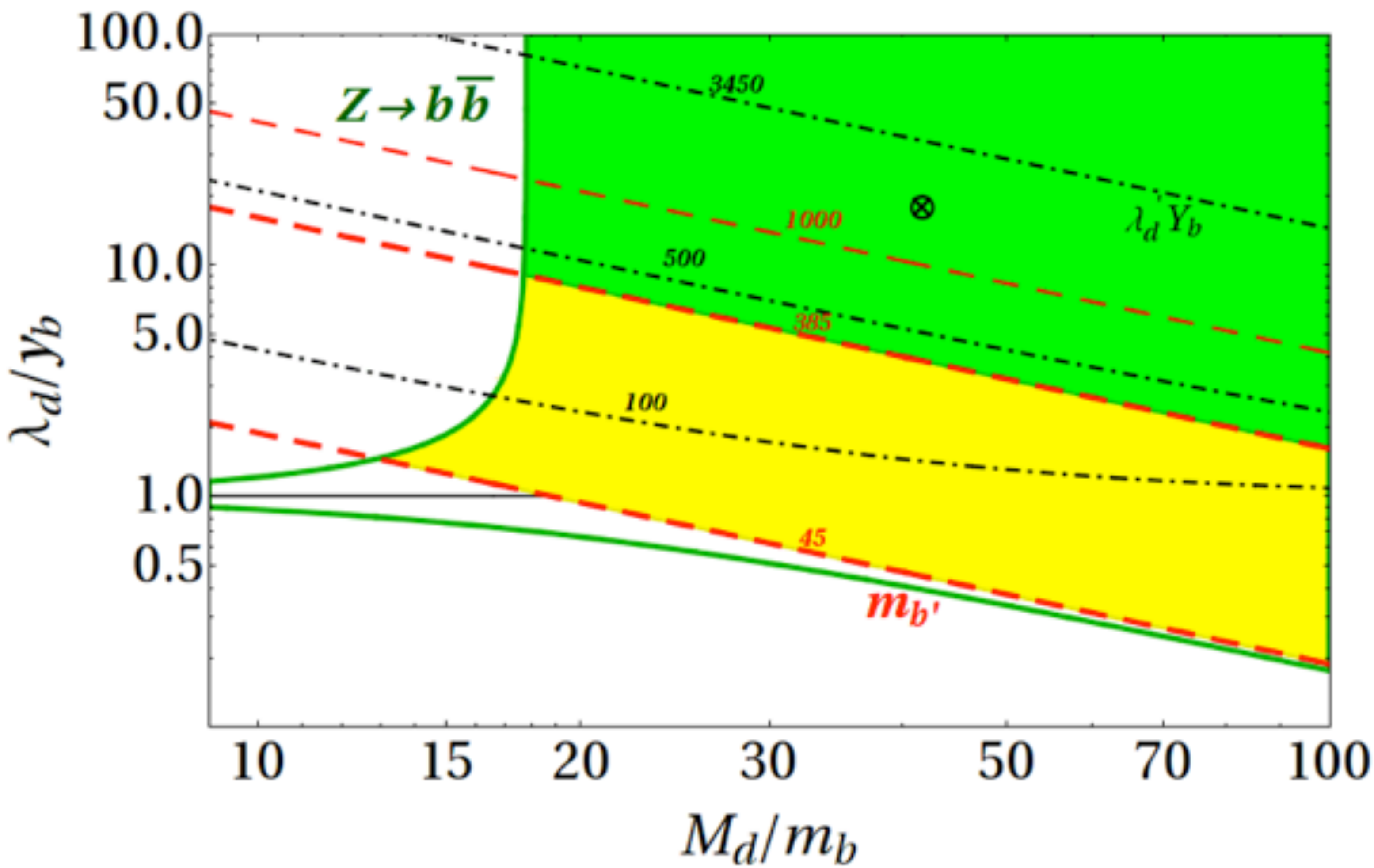
- Potential:

With two flavon fields no renormalizable potential.

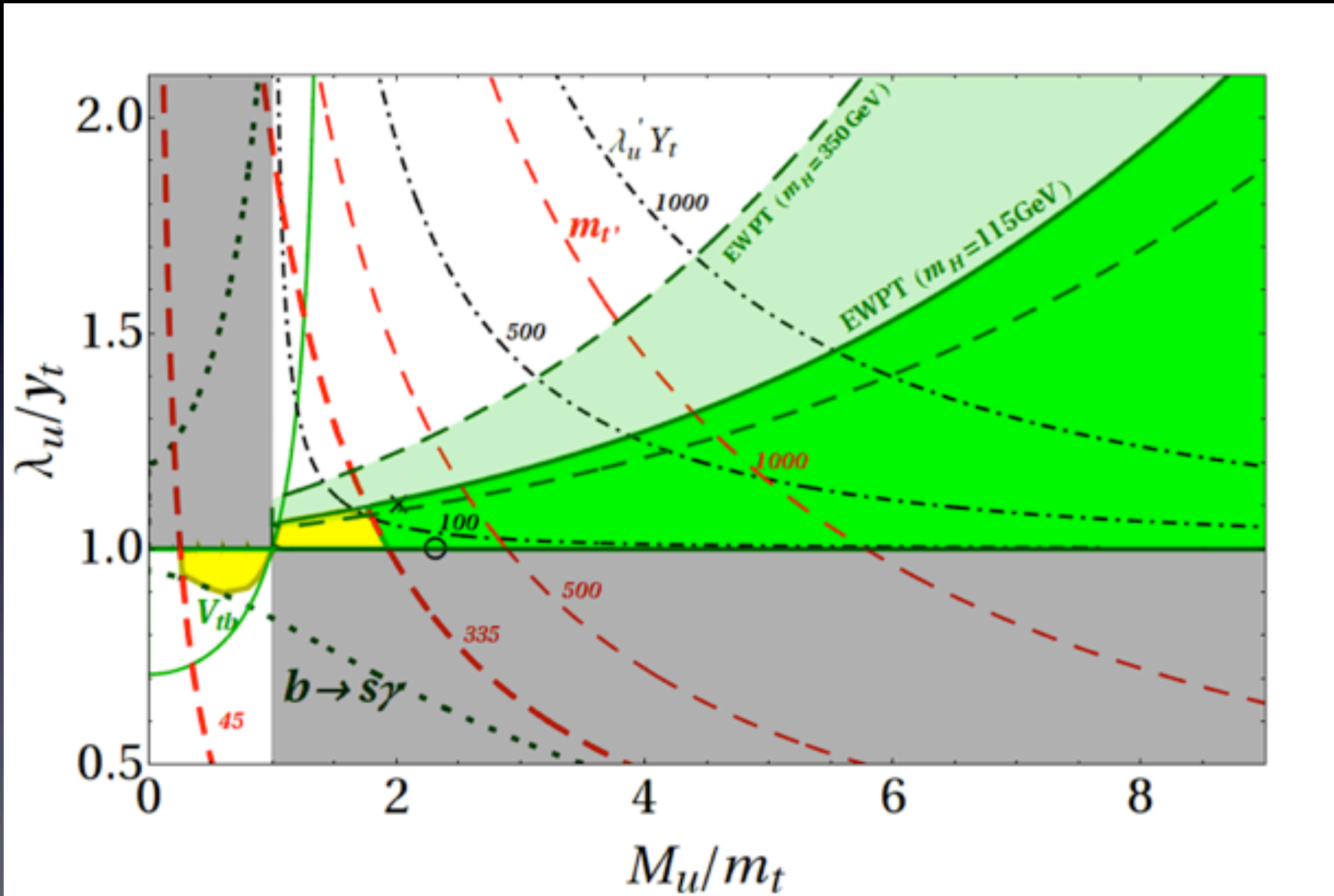
Possible to construct potential with high cut-off.

Adding several flavons: More flavor violating structures but still enough flavor suppression.

Bounds Down


$Z \to b\bar{b}$
3450
1000
500
385
100
45
$\lambda_d Y_b$
$m_{b'}$
100.0
50.0
10.0
5.0
1.0
0.5
λ_d/y_b
10
15
20
30
50
70
100
M_d/m_b

Bounds Up


λ_u/y_t
M_u/m_t
2.0
1.5
1.0
0.5
0
2
4
6
8
$\lambda_u' Y_t$
1000
500
100
$m_{t'}$
1000
500
335
45
EWPT (m_H=350GeV)
EWPT (m_H=115GeV)
V_{tb}
$b \to s\gamma$

Example

We choose models with $O(1)$ couplings. Always consistent with flavor bounds. Details of the spectrum model dependent but structure robust.

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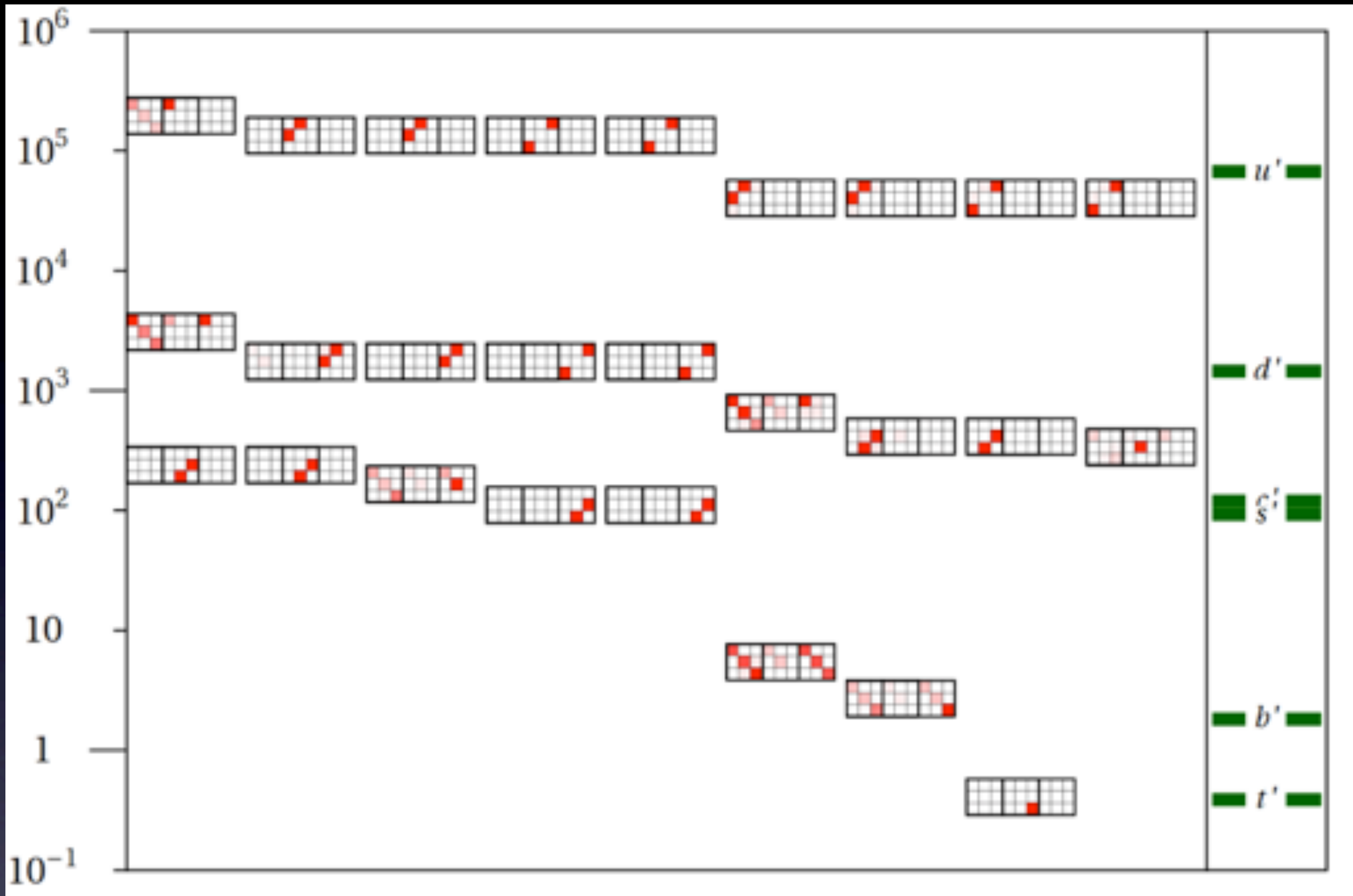
We choose models with $O(1)$ couplings. Always consistent with flavor bounds. Details of the spectrum model dependent but structure robust.

- $\mathbf{SU(3)_{Q_L} \otimes U(3)_{U_R} \otimes U(3)_{D_R}}$

M_u (GeV)	M_d (GeV)	λ_u	λ'_u	λ_d	λ'_d	g_Q	g_U	g_D
350	100	1.1	0.5	0.25	0.25	0.3	1	0.3

$$Y_u \approx \mathrm{Diag}\left(1\cdot 10^5\,,\ 2\cdot 10^2\,,\ 3\cdot 10^{-1}\right)\cdot V\ \mathrm{TeV}\,,$$
$$Y_d \approx \mathrm{Diag}\left(6\cdot 10^3\,,\ 4\cdot 10^2\,,\ 7\right)\ \mathrm{TeV}\,.$$



$$\frac{\delta R_b}{R_b} = -1.0 \cdot 10^{-3}\,,$$

$$S = 0.00\,,\ T = 0.15\,,\ U = 0.01\,,$$

$$V_{tb} = 0.97\,.$$

$$\mathrm{spin}_{\frac{1}{2}}\ :\ .4, 1.8, 90\ TeV$$

$$\mathrm{spin}_1\ :\ .29, 1.9, 3.9, 80\ TeV$$

Effective 4-Fermi operators from flavor gauge boson,

$$Q_1^{q_iq_j} = \overline{q}^{\alpha}_{jL}\gamma_\mu q^{\alpha}_{iL}\,\overline{q}^{\beta}_{jL}\gamma^\mu q^{\beta}_{iL}\,,$$
$$\tilde{Q}_1^{q_iq_j} = \overline{q}^{\alpha}_{jR}\gamma_\mu q^{\alpha}_{iR}\,\overline{q}^{\beta}_{jR}\gamma^\mu q^{\beta}_{iR}\,,$$
$$Q_5^{q_iq_j} = \overline{q}^{\alpha}_{jR} q^{\beta}_{iL}\,\overline{q}^{\beta}_{jL} q^{\alpha}_{iR}\,.$$

Model

	Re (in GeV^{-2})	Im (in GeV^{-2})
C_K^1	$-7\cdot 10^{-15}$	$-8\cdot 10^{-20}$
$\tilde{C}_K^1$	$-1\cdot 10^{-16}$	$-1\cdot 10^{-21}$
C_K^5	$-4\cdot 10^{-15}$	$-4\cdot 10^{-20}$
C_D^1	$-3\cdot 10^{-20}$	$-3\cdot 10^{-23}$
$\tilde{C}_D^1$	$-3\cdot 10^{-25}$	$-4\cdot 10^{-28}$
C_D^5	$-4\cdot 10^{-22}$	$-4\cdot 10^{-25}$
$C_{B_d}^1$	$2\cdot 10^{-16}$	$2\cdot 10^{-16}$
$\tilde{C}_{B_d}^1$	$1\cdot 10^{-21}$	$1\cdot 10^{-21}$
$C_{B_d}^5$	$2\cdot 10^{-18}$	$2\cdot 10^{-18}$
$C_{B_s}^1$	$3\cdot 10^{-13}$	$-4\cdot 10^{-13}$
$\tilde{C}_{B_s}^1$	$5\cdot 10^{-16}$	$-6\cdot 10^{-16}$
$C_{B_s}^5$	$5\cdot 10^{-14}$	$-6\cdot 10^{-14}$

Bounds

	Re (in GeV^{-2})	Im (in GeV^{-2})
C_K^1	$[-9.6, 9.6]\cdot 10^{-13}$	$[-4.4, 2.8]\cdot 10^{-15}$
$\tilde{C}_K^1$	$[-9.6, 9.6]\cdot 10^{-13}$	$[-4.4, 2.8]\cdot 10^{-15}$
C_K^5	$[-1.0, 1.0]\cdot 10^{-14}$	$[-5.2, 2.9]\cdot 10^{-17}$
$\lvert C_D^1\rvert$	$< 7.2\cdot 10^{-14}$	
$\lvert\tilde{C}_D^1\rvert$	$< 7.2\cdot 10^{-14}$	
$\lvert C_D^5\rvert$	$< 4.8\cdot 10^{-13}$	
$\lvert C_{B_d}^1\rvert$	$< 2.3\cdot 10^{-11}$	
$\lvert\tilde{C}_{B_d}^1\rvert$	$< 2.3\cdot 10^{-11}$	
$\lvert C_{B_d}^5\rvert$	$< 6.0\cdot 10^{-13}$	
$\lvert C_{B_s}^1\rvert$	$< 1.1\cdot 10^{-9}$	
$\lvert\tilde{C}_{B_s}^1\rvert$	$< 1.1\cdot 10^{-9}$	
$\lvert C_{B_s}^5\rvert$	$< 4.5\cdot 10^{-11}$	

Safer than MFV!

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b′ and t′ could be produced at LHC if allowed kinematically

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- Flavor gauge boson: Non-universal leptophobic Z′

Mostly coupled to third generation.

Drell-Yan production or gluon fusion.

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- Flavor physics might not be as far in energy as previously expected.
- Simplest construction of flavor gauge symmetries in the SM realizes the inverted hierarchical structure. This allows flavor physics to be around the electro-weak scale.
- Interesting phenomenology: new vector like fermions, flavor gauge bosons, flavons. Possibility of a heavy Higgs. Details model dependent but structure robust.
- So far the flavor scale is a free parameter. Possible to link it to the TeV scale in a theory that addresses the hierarchy problem?