Minimal Flavor Violation and New Physics at the Weak Scale.

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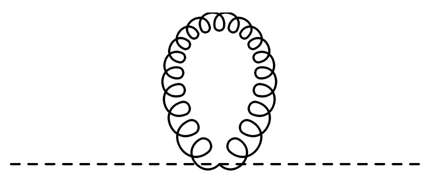
Outline

Field	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	Lorentz
$Q^i_L = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix}$	3	2	1/6	(1/2,0)
u^i_R	3	1	2/3	(0,1/2)
d^i_R	3	1	-1/3	(0, 1/2)
$L^i_L = \begin{pmatrix} \nu^i_L \\ e^i_L \end{pmatrix}$	1	2	-1/2	(1/2,0)
e^i_R	1	1	-1	(0,1/2)
$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$	1	2	1/2	(0,0)

Hierarchy Problem and Standard Model

- Motivation for new physics beyond weak scale, Hierarchy Problem. SM Higgs potential: $V(H) = \lambda(H^\dagger H - v^2/2)^2$ implies vacuum expectation value $H^0 = v/\sqrt{2}$ physical Higgs scalar mass $m_h \sim \sqrt{\lambda} v$. $v/M_{PL} \sim 10^{-17}$.

- One loop radiative corrections from coupling to W boson induce ; $\delta m_h^2 \sim g_2^2 \Lambda_c^2 / 16\pi^2$.



- If Λ_c is of order the Planck scale then $\delta m_h^2 \sim (10^{18}\text{GeV})^2$. To keep v small requires a delicate fine tuning between bare parameters and radiative corrections.

- Some of solutions proposed: Dynamical Symmetry Breaking (Technicolor), Low Energy Supersymmetry, Large Extra Dimensions, Warped Extra Dimensions, Anthropic Principle A...

- New ideas come with some new flavor physics at the weak scale. Usually give up some nice features of the standard model: no flavor changing neutral currents at tree level, baryon number and total lepton number conservation automatic by operators of dimension four and less (hence suppressed by some large mass scale M).

Minimal Flavor Violation

- Suppose operator, $\left(g^2/M^2\right)\bar{s}d\bar{s}d$. Contributes to $K-\bar{K}$ mixing $\Delta m \sim g^2 f_K^2 m_K/M^2$ which for $M = 1\text{TeV}$ implies a contribution $\Delta m = g^2 10^{-5}\text{MeV}$. Measured value $\Delta m \simeq 3.5\ 10^{-12}\text{MeV}$. Even worse if CP nonconservation from measured value of ϵ.

- Better if operator induced at one loop since then a loop suppression factor of $1/(16\pi^2) \sim 10^{-2}$ in addition to g^2. Furthermore we already know of small coupling constants, Yukawa coupling of the electron $g_e \sim 10^{-5}$.

- Minimal Flavor Violation (MFV) a way to suppress large flavor changing neutral currents from new physics at the weak scale in a model independent fashion. In minimal SM quarks get mass through Yukawa couplings,

$$L_Y = g_U^{ij}\bar{u}_R^i Q_L^j H + g_D^{ij}\bar{d}_R^i Q_L^j H^\dagger + \text{h.c.}$$

Has $SU(3)_U \times SU(3)_D \times SU(3)_Q$ flavor symmetry that is only broken by Yukawa coupling matrices g_U and g_D. Suppose true of new beyond the standard model physics. This is Minimal Flavor Violation (MFV). Restore symmetry by pretending that Yukawa matrices transform, $g_U \to V_U g_U V_Q^\dagger$ and $g_D \to V_D g_D V_Q^\dagger$.

Let us see how this helps with large flavor changing neutral currents from new physics. Firstly by far largest Yukawa is associated with the top quark. So lets only keep g_U to start. But note $\left(g_U^\dagger g_U\right) \to V_Q \left(g_U^\dagger g_U\right) V_Q^\dagger$. Bilinear $\bar{Q}_L \left(g_U^\dagger g_U\right) \gamma_\mu Q_L$ consistent with MFV. Now this contains the down type quark flavor changing neutral current $\bar{d}_L^i \left(g_U^\dagger g_U\right)^{ij} \gamma_\mu \bar{d}_L^j$. Redefining quarks to go from weak eigenstate to mass eigenstate basis this becomes (easy to see work in basis where down type quarks are mass eigenstates), then

$$g_U^\dagger g_U = V_{\text{CKM}}^\dagger \left(2m_t^2/v^2\right) I_t V_{\text{CKM}}$$

where $I_t = \text{diag}(0,0,1)$. So this bilinear contains,

$$\bar{s}_L \gamma_\mu d_L V_{32}^* (2m_t^2/v^2) V_{31}$$

Additional suppression by small angles, or small Yukawas.

Extensions of the Scalar Sector with MFV

Extend the scalar sector of the SM and lets focus on new scalars that can couple to quarks. Assume the new scalars do not transform under the flavor symmetries. One possibility is multiple scalar doublets, H_1, H_2, etc. In MFV at leading order in the Yukawa coupling matrices. Let us go to a basis where one of the doublets H gets a vev and the other S doesn't (H and S are linear combinations of H_1 and H_2)

$$L_Y = \bar{u}_R g_U Q_L H + \bar{d}_R g_D Q_L H^\dagger + \bar{u}_R Y_U Q_L S + \bar{d}_R Y_D Q_L S^\dagger + \text{h.c.}$$

Here

$$Y_D = \eta_D g_D + \eta'_D g_D \left(g_U^\dagger g_U \right) + \ldots \qquad Y_U = \eta_U g_U + \ldots$$

Can give new contribution through η' term to $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing that violates CP. The effective Hamiltonian takes the form, $H^{\text{NP}}_{q=d,s} \simeq (V^*_{tq}V_{tb})^2 C^{\text{NP}} (\bar{b}_R q_L)^2 + \text{h.c.}$ Writing for the meson mass matrix $M^q_{12} = (M^q_{12})^{\text{SM}}(1 - h_q e^{2i\sigma_q})$ in this approximation h and σ are independent of q. (**References**: Dobrescu, Fox and Martin, Phys Rev. Lett. **105** (2010) 041801, Buras, Carlucci, Gori and Isidori, ArXiv: 1007.529, Buras, Isidori and Paradisi ArXiv:1006.0470, Trott and Wise, Arxiv: 1009.2813)

MFV new type of scalar that is a singlet under the flavor group and couple to quarks is a color octet scalar S^A (**Reference**: Manohar and Wise, Phys. Rev. D. **74** (2006) 035009) with the same weak quantum numbers as the Higgs doublet.

$$L_{\text{octet}} = \bar{u}_R T^A Y_U Q_L S^A + \bar{d}_R T^A Y_D Q_L S^{A\dagger} + \text{h.c.}$$

If new scalars transform non trivially under the flavor group then new possibilities (**Reference**: Arnold, Pospelov, Trott, Wise, JHEP 1001:073,2010). For example, suppose the new scalar representation S transforms as a $\bar{6}$ under color (two color index symmetric), is a singlet under $SU(2)_L$ and has hypercharge $Y = -4/3$.

Under $SU(3)_U \times SU(3)_D \times SU(3)_Q$ new scalar S transforms as $(\bar{6}, 1, 1)$. Yukawa couplings to the quarks with no insertions of the Yukawa coupling matrices,

$$L_{\text{sextet}} = \eta \left(u^i_{R\alpha} u^j_{R\beta} \right) S^{\alpha\beta}_{ij} + \text{h.c}$$

Enhanced production at LHC and suppressed at Tevatron.

A Model Without MFV but new weak scale Physics.

Discuss simple extension of SM with new flavor physics at the weak scale but it only starts at one loop in a natural way. In SM baryon number can be violated by dimension 6 operators that schematically take form $qqql/\Lambda^2$. Operator conserves $B-L$ but violates B and L. But experimental limit on proton decay lifetime implies $\Lambda > 10^{15}\text{GeV}$. So unless desert have not explained proton stability. Example low energy supersymmetry where proton decay can occur through renormalizeable operators and is not explained by the model without imposing new symmetries by hand. Try explaining B (and L) conservation by gauging B (and L) and spontaneously breaking them at the weak scale. (**Reference**: Fileviez Perez and Wise Phys.Rev.D**82**:011901,2010, Erratum-ibid.D**82**:079901,2010.)

- B, L anomalous in SM. Cancel anomalies by adding fourth generation: Q'_L, u'_R, d'_R, L'_L, e'_R and ν'_R with usual standard model quantum numbers but minus three times the baryon and lepton number of standard model.

- Consistent with precision electroweak, $m_{t'} - m_{b'} = 50\text{GeV}$.

- Usual Higgs doublet H gives mass to ordinary quarks and to fourth generation. But no mass mixing because they have different B quantum numbers.

  $$L_Y = \bar{u}_R g_U Q_L H + \bar{d}_R g_D Q_L H^\dagger + g'_U \bar{u}'_R Q'_L H + g'_D \bar{d}'_R Q'_L H^\dagger + \text{h.c.}$$

- Stable fourth generation quark so add a new scalar doublet ϕ with same standard model quantum numbers as the Higgs doublet but, $B = -4/3$. Assume that it does not get a vev and the interactions

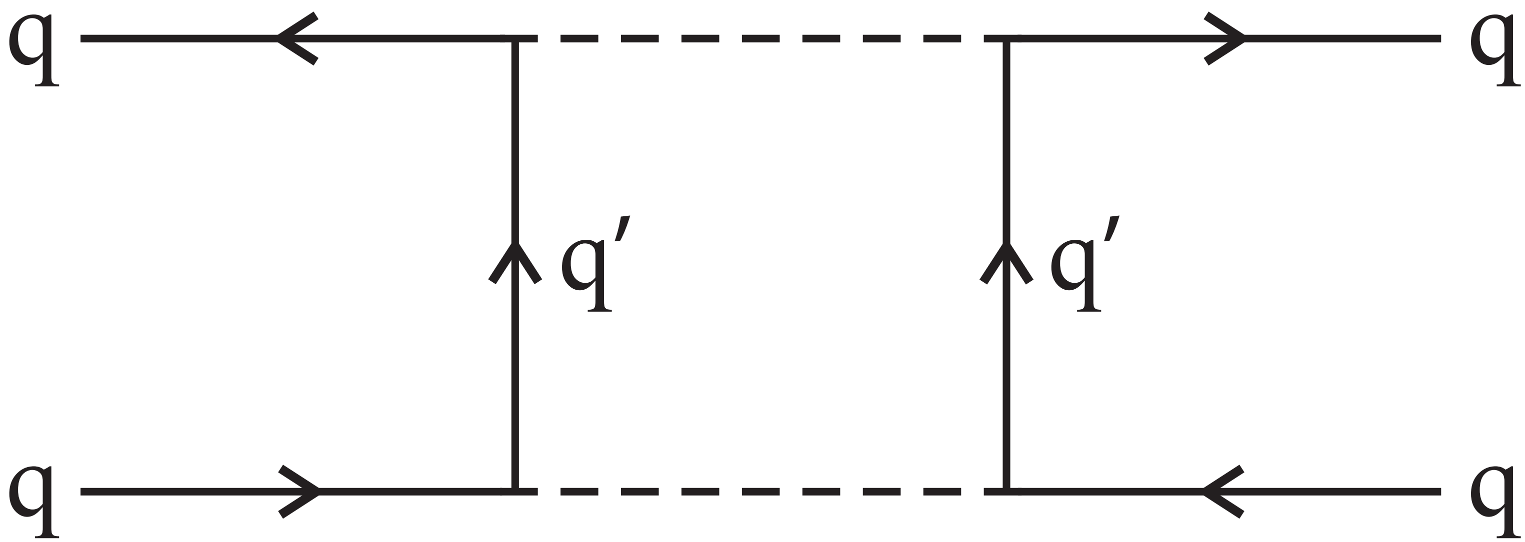
$$L_{\text{decay}} = h_U \bar{u}_R Q'_L \phi + h_U \bar{d}'_R Q_L \phi^\dagger + \text{h.c.}$$

Fourth generation decays. Dark matter candidate real part of ϕ^0 (**Reference**: Dulaney, Fileviez Perez, Wise, Arxiv:1005.0617) New scalar to spontaneously break baryon number.

- Flavor changing effects at one loop, eg.

$$\Delta m_K \sim \frac{f_K^2 m_K h^4}{16\pi^2 M^2}$$

For $M = 400$ GeV, $h = 0.1$ get $\Delta m_K \simeq 4 \times 10^{-11}$ MeV.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Conclusions

Looking Forward to the Physics Discoveries
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