Role of the Higgs Sector in the Generation & Flavor Problem

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The Higgs State Fare

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Outline of the Lectures

1. Part 1 (today)
   - Higgs and Flavor in the Standard Model

     (flavor symmetries, flavor violating Higgs decays, Standard Model flavor puzzle)

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   - Higgs and Flavor in the Standard Model

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2. Part 2 (tomorrow)
   - Higgs and Flavor beyond the Standard Model

     (extended Higgs sectors, “flavorful” Higgs bosons, flavor phenomenology, collider phenomenology)

Main Theme of Today's Lecture

Without the Higgs
there is no Flavor
in the Standard Model

The Standard Model Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\mathrm{SM}} \sim \quad & \Lambda^4 + \Lambda^2 H^2 + \lambda H^4 \\
& + \bar{\Psi} \not{D} \Psi + (D_\mu H)^2 + (F_{\mu\nu})^2 \\
& + Y H \bar{\Psi} \Psi + \frac{1}{\Lambda} (LH)^2 + \cdots
\end{aligned}
$$

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Higgs potential

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kinetic terms

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Yukawa couplings

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neutrino masses

The Fermion Gauge Quantum Numbers

				$SU(3)$	$SU(2)$	$U(1)_Y$
$Q_L^i =$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	3	2	$\frac{1}{6}$
$u_R^i =$	u_R	c_R	t_R	3	1	$\frac{2}{3}$
$d_R^i =$	d_R	s_R	b_R	3	1	$-\frac{1}{3}$
$L_L^i =$	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	1	2	$-\frac{1}{2}$
$e_R^i =$	e_R	μ_R	τ_R	1	1	-1

3 replica of the basic fermion family

Flavor Symmetry of the Gauge Interactions

$$\bar{\Psi}\not{D}\Psi = \sum_{i=1}^{3} \bar{Q}_i \not{D} Q_i + \sum_{i=1}^{3} \bar{u}_i \not{D} u_i + \sum_{i=1}^{3} \bar{d}_i \not{D} d_i$$

$$+ \sum_{i=1}^{3} \bar{L}_i \not{D} L_i + \sum_{i=1}^{3} \bar{e}_i \not{D} e_i$$

gauge interactions are flavor universal

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gauge interactions are flavor universal

this part of the SM Lagrangian has a large $U(3)^5$ flavor symmetry

$$Q \to V_Q Q \ , \quad u \to V_u u \ , \quad d \to V_d d \ , \quad L \to V_L L \ , \quad e \to V_e e$$

Flavor Symmetry of the Gauge Interactions

The $U(3)^5$ flavor symmetry can be decomposed in the following way

$$U(3)^5 =$$

$$U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_D \times U(1)_E$$
$$\times SU(3)_Q \times SU(3)_U \times SU(3)_D \times SU(3)_L \times SU(3)_E$$

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flavor mixing

Flavor Symmetry Breaking

the flavor symmetry is explicitly broken by the Yukawa couplings

$$Y\ H\bar{\Psi}\Psi = \sum_{i,j}(\hat{Y}_u)_{ij} H^c \bar{Q}_i u_j + \sum_{i,j}(\hat{Y}_d)_{ij} H \bar{Q}_i d_j + \sum_{i,j}(\hat{Y}_\ell)_{ij} H \bar{L}_i e_j \quad + \quad \text{h.c.}$$

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after electro-weak symmetry breaking we get fermion masses

$$\rightarrow \sum_{i,j}(\hat{m}_u)_{ij} \bar{u}_i^L u_j^R + \sum_{i,j}(\hat{m}_d)_{ij} \bar{d}_i^L d_j^R + \sum_{i,j}(\hat{m}_\ell)_{ij} \bar{e}_i^L e_j^R \quad + \quad \text{h.c.}$$

Going to Mass Eigenstates

Yukawa couplings and fermion masses are generic 3×3 matrices (not necessarily symmetric, hermitian, ...)

$$\bar{u}^L \hat{m}_u u^R + \bar{d}^L \hat{m}_d d^R + \bar{\ell}^L \hat{m}_\ell \ell^R \; + \; \text{h.c.}$$

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mass matrices for the fermions can be diagonalized by bi-unitary transformations

$$u^L \to V_u^L u^L \;\; , \quad u^R \to V_u^R u^R \;\; , \quad d^L \to V_d^L d^L \;\; , \quad d^R \to V_d^R d^R$$

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$$(V_u^L)^\dagger (\hat{m}_u)(V_u^R) = \text{diag}(m_u, m_c, m_t)$$
$$(V_d^L)^\dagger (\hat{m}_d)(V_d^R) = \text{diag}(m_d, m_s, m_b)$$
$$(V_\ell^L)^\dagger (\hat{m}_\ell)(V_\ell^R) = \text{diag}(m_e, m_\mu, m_\tau)$$

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[Exercise: show that any matrix can be diagonalized by a bi-unitary transformation]

The CKM Matrix

What happens to interactions in the mass eigenstate basis?

Lets start with the interactions of the W boson

$$\bar{\Psi} \not{D} \Psi \supset \frac{g_2}{\sqrt{2}} \left(\bar{u}_i^L \gamma^\mu d_i^L W_\mu^+ + \bar{d}_i^L \gamma^\mu u_i^L W_\mu^- \right)$$

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$$\rightarrow \frac{g_2}{\sqrt{2}} \left(V_{kj} (\bar{u}_k^L \gamma^\mu d_j^L W_\mu^+) + V_{kj}^* (\bar{d}_j^L \gamma^\mu u_k^L W_\mu^-) \right)$$

$V_{\text{CKM}} = (V_u^L)^\dagger (V_d^L)$ is the Cabibbo-Kobayashi-Maskawa matrix

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The CKM matrix is unitary (product of 2 unitary matrices)

Parameter Counting

How many flavor parameters are physical?

We started out with 3 Yukawa matrices: $\hat{Y}_u$, $\hat{Y}_d$, $\hat{Y}_\ell$

- Generic rule: Number of physical parameters =
  = Number of total free parameters
  - Number of *broken* symmetry generators

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- Number of total free parameters = $3 \times 3 \times 2 = 18$
  (9 magnitudes and 9 phases in the lepton Yukawa matrix)

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- Number of broken symmetry generators = $2 \times 9 - 3 = 15$
  (6 mixing angles and 12 phases in $U(3)_L \times U(3)_E$
  minus 3 phases in $U(1)_e \times U(1)_\mu \times U(1)_\tau$)

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$\Rightarrow$ we are left with 3 real physical parameters, which can be identified with the masses of the electron, muon, and tau

Parameter Counting (continued)

Now the quark sector:

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$\Rightarrow$ we are left with 10 physical parameters, one of which is a phase;
can be identified with the 6 masses of the quarks
+ 3 CKM mixing angles + 1 CKM phase

No Flavor Changing Neutral Currents at Tree Level

Lets look at the couplings of the Higgs

$$Y\ H\bar{\Psi}\Psi \supset \frac{1}{\sqrt{2}} h\Big((\hat{Y}_u)_{ij} \bar{u}_i^L u_j^R + (\hat{Y}_d)_{ij} \bar{d}_i^L d_j^R + (\hat{Y}_\ell)_{ij} \bar{\ell}_i^L \ell_j^R + \ h.c \Big)$$

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$$\rightarrow \quad \frac{1}{\sqrt{2}} h\Big((\hat{Y}_u)_{ij} (V_u^L)^*_{im} (V_u^R)_{jn} \bar{u}_m^L u_n^R + (\hat{Y}_d)_{ij} (V_d^L)^*_{im} (V_d^R)_{jn} \bar{d}_m^L d_n^R$$

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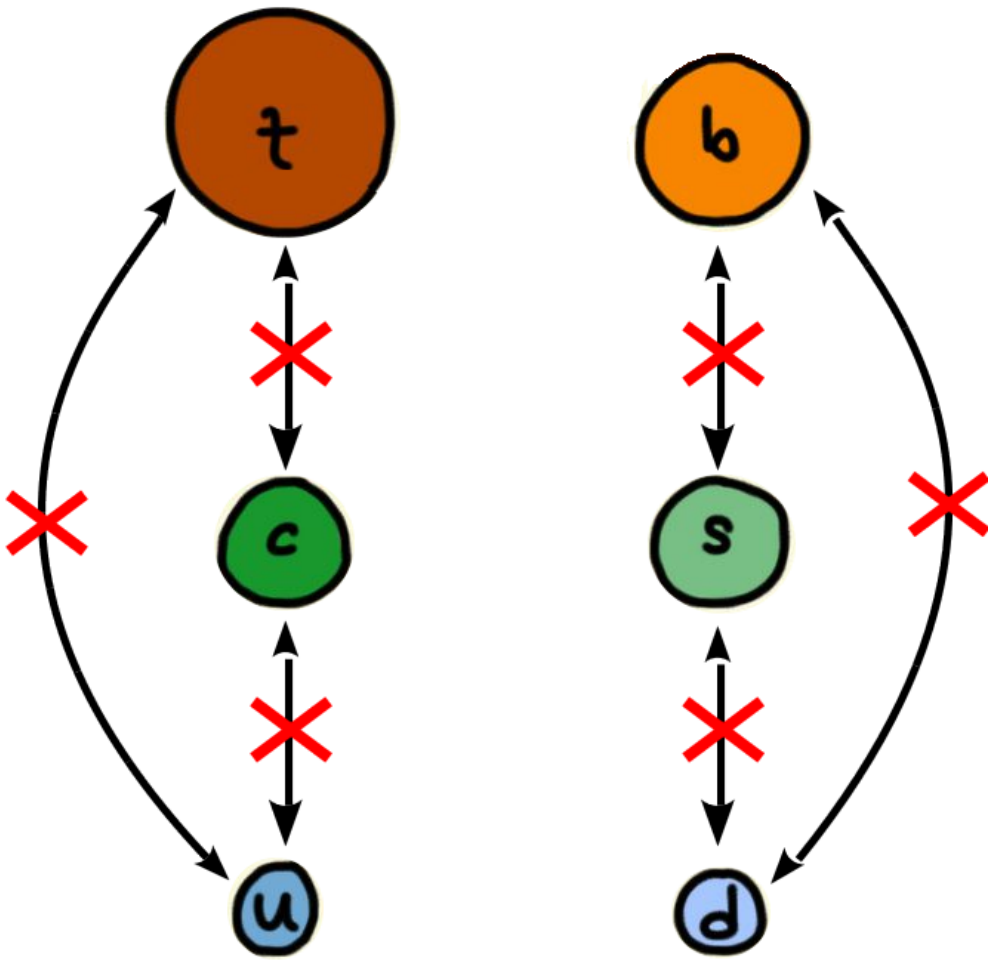
[Exercise: show that also the couplings of the photon, Z, and the gluons are flavor diagonal]

$\rightarrow$ There are no Flavor Changing Neutral Currents (FCNCs) in the Standard Model at tree level (GIM mechanism)

Flavor Transitions



no FCNCs at tree level

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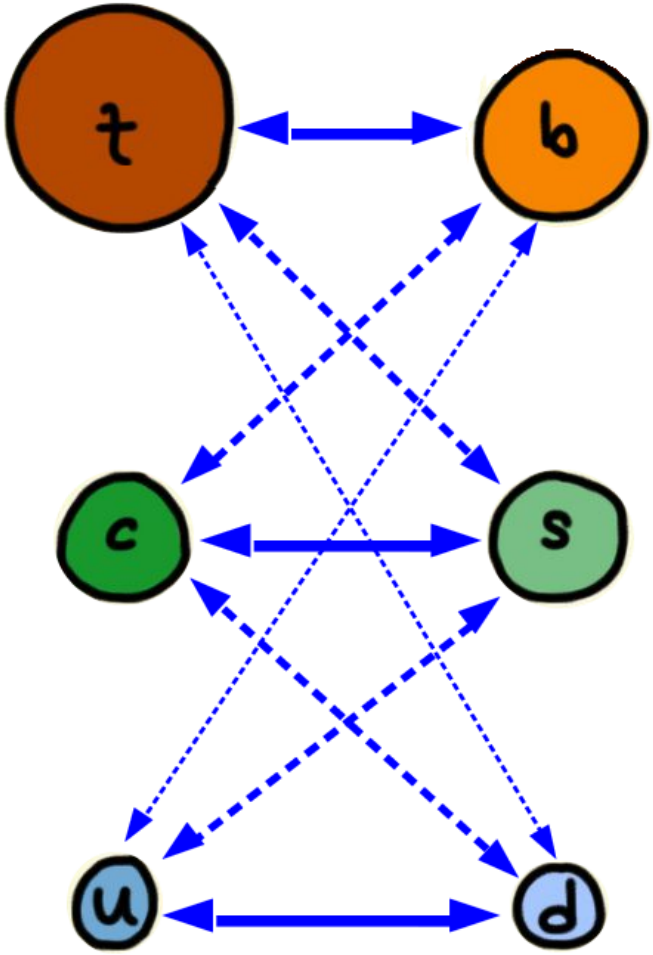

no FCNCs at tree level

transitions among the generations are mediated by the $W^{\pm}$ bosons and their relative strength is parametrized by the CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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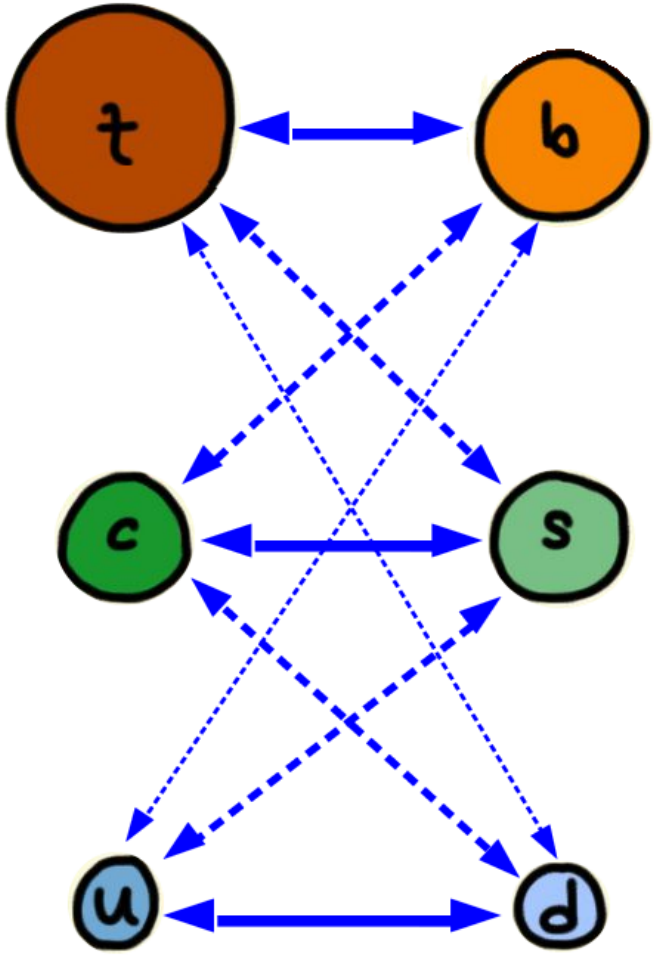

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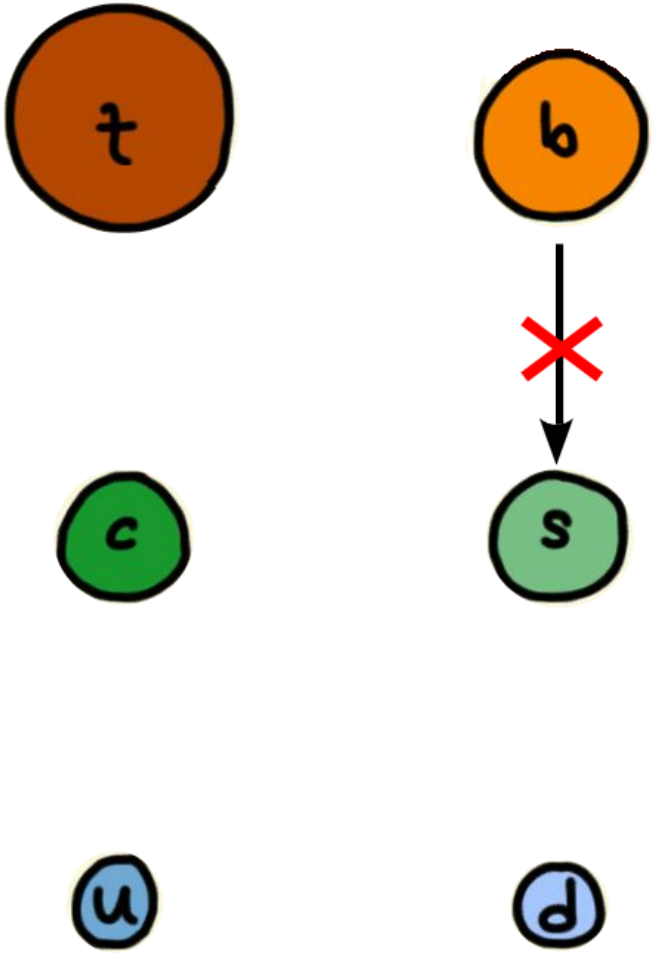
note that without the Higgs the concept of the CKM matrix does not exist

Flavor Changing Neutral Currents at Loop Level



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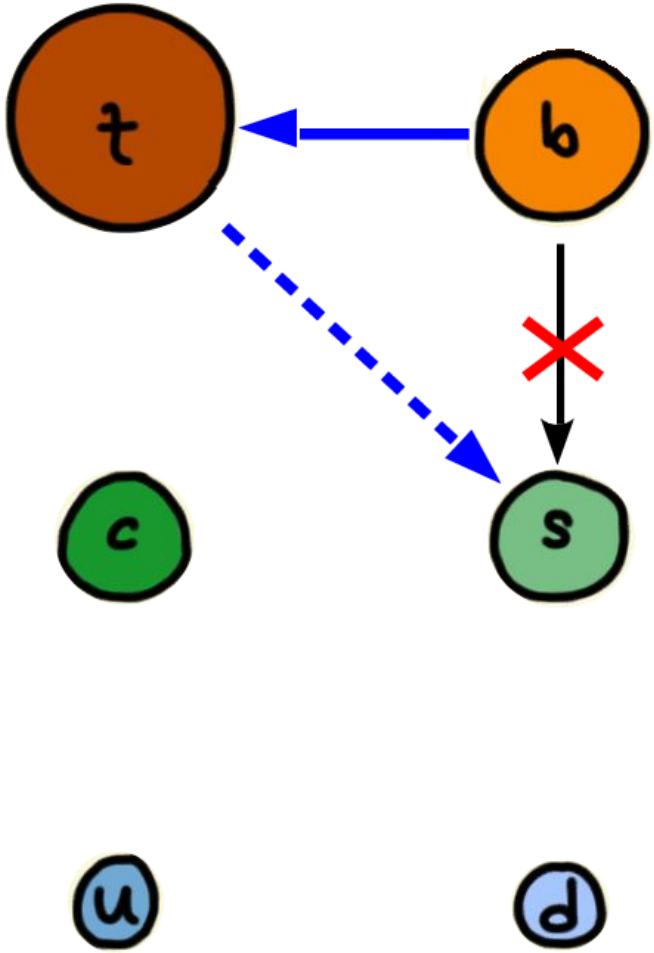

FCNCs can arise
at the loop level

they are suppressed
by loop factors

and small CKM elements

Recap: Flavor Properties of the Higgs in the SM

the tree level couplings of the Higgs to fermion mass eigenstates are
flavor diagonal and CP conserving

$$\frac{1}{v}\begin{pmatrix} m_{u,d,e} & 0 & 0 \\ 0 & m_{c,s,\mu} & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix}$$

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- How big are the flavor changing and CP violating couplings?

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- How big are the flavor changing and CP violating couplings?
- What are the SM predictions?
- What do we know experimentally?

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$$Q \to \mathbf{3}_Q\,, \qquad u \to \mathbf{3}_U\,, \qquad d \to \mathbf{3}_D\,, \qquad L \to \mathbf{3}_L\,, \qquad e \to \mathbf{3}_E$$

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- To restore invariance under the $SU(3)^5$ flavor symmetry, we declare

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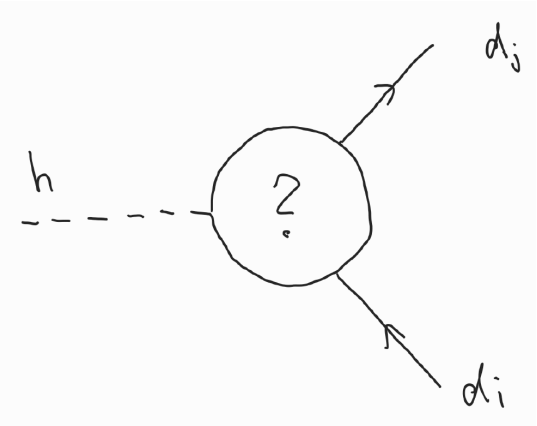
$$h \to \bar{d}_i^L d_j^R$$



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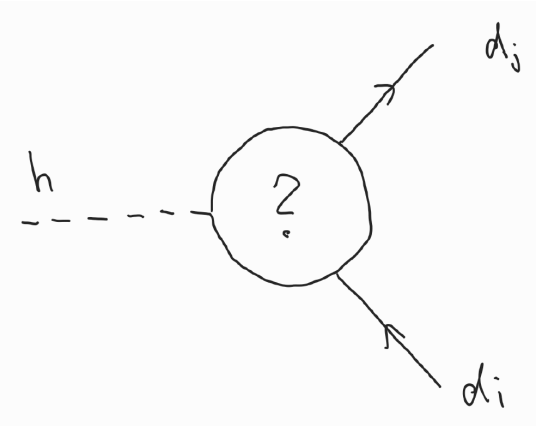

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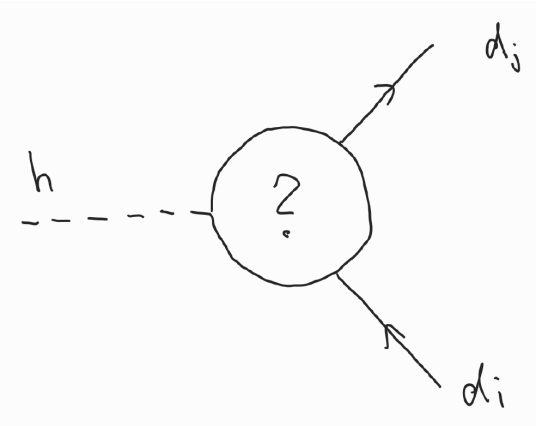

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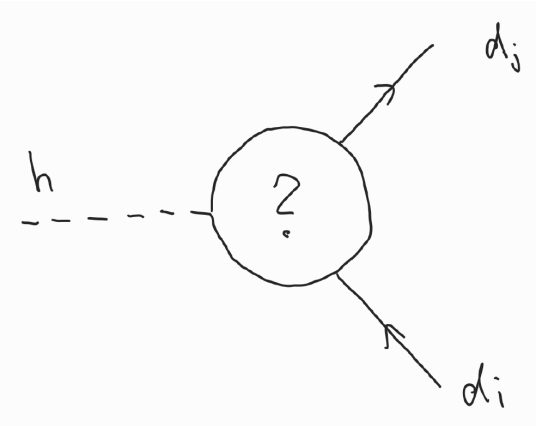

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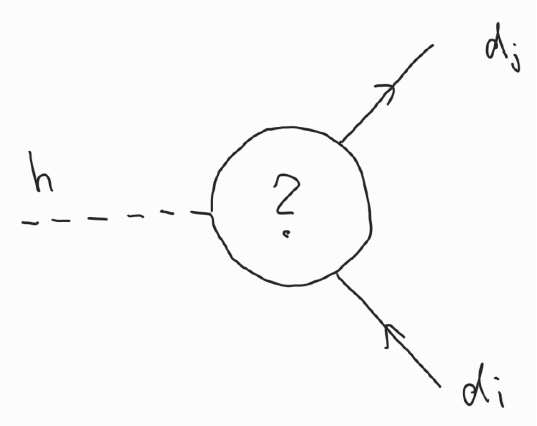

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Flavor Changing Decays: Spurion Analysis

Let's be more concrete and consider $h \to \bar{s}b$

In the mass eigenbasis, the amplitude has to be proportional to

$$\mathcal{A}(h \to \bar{s}b) \sim \frac{1}{16\pi^2}((V_d^L)^\dagger \hat{Y}_u \hat{Y}_u^\dagger \hat{Y}_d (V_d^R))_{23}$$

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[Exercise: Reproduce this result
using Feynman diagrams / Feynman rules]

Estimate of Flavor Changing Decay Rates

$$\frac{\mathrm{BR}(h \to \bar{s}b)}{\mathrm{BR}(h \to \bar{b}b)} \sim \frac{1}{(16\pi^2)^2} \frac{m_t^4}{v^4} |V_{ts}^* V_{tb}|^2 \sim 10^{-7}$$

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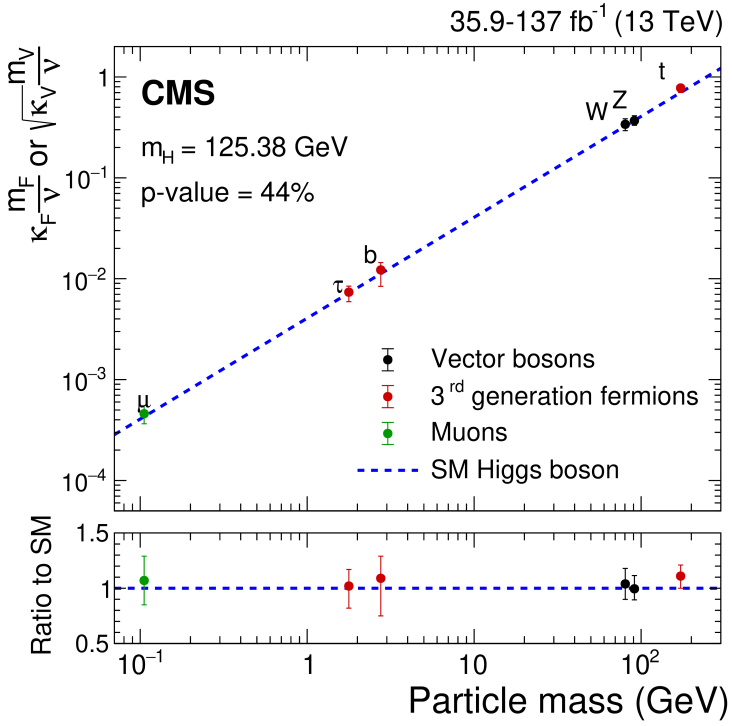
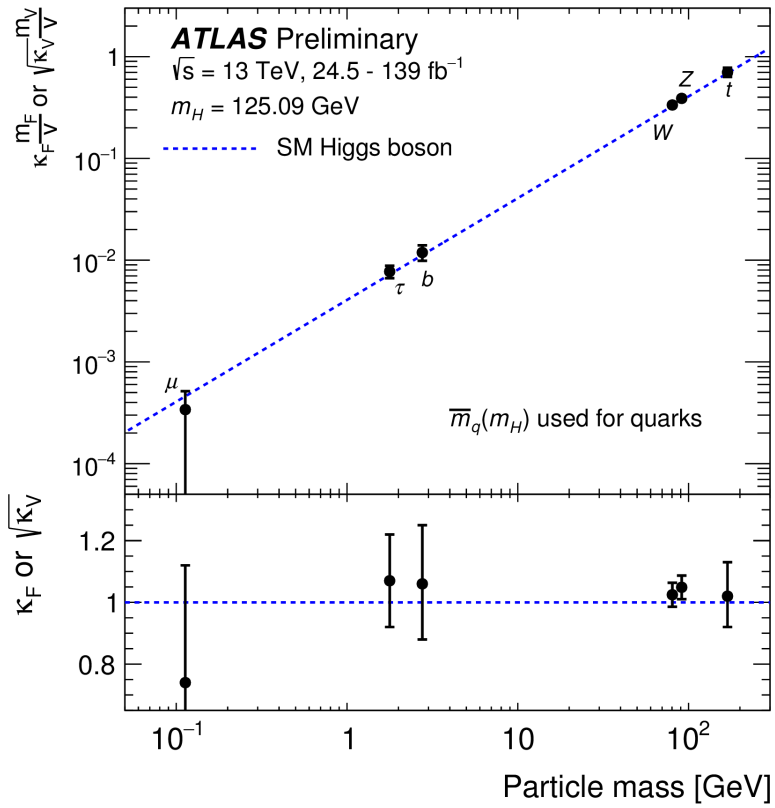
All those branching ratios are far below foreseeable sensitivities

Flavor changing Higgs decay are clear signatures of
physics beyond the Standard Model

Flavor Conserving Couplings: Experiment





good agreement with SM predictions!

Flavor Changing Couplings: Experiment

Let's assume the Higgs has flavor changing couplings
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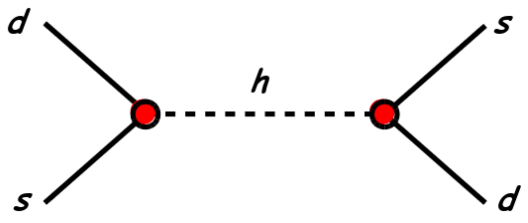
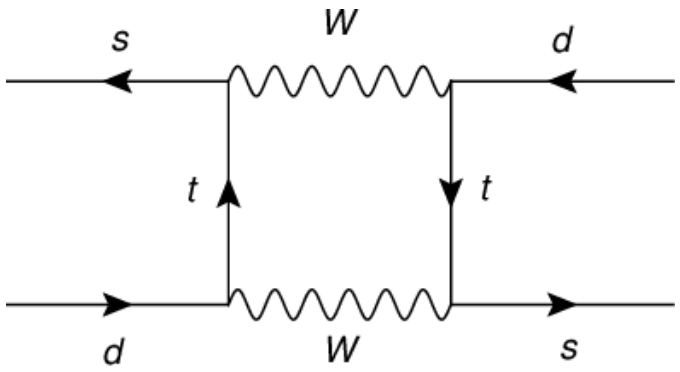
For example, flavor changing higgs-quark couplings are strongly constrained by neutral meson oscillations



Such a diagram gives tree-level contributions to Kaon mixing. Kaon mixing is known to have extreme sensitivity to "flavored" new physics.

Estimating Sensitivity of Meson Mixing

SM contribution



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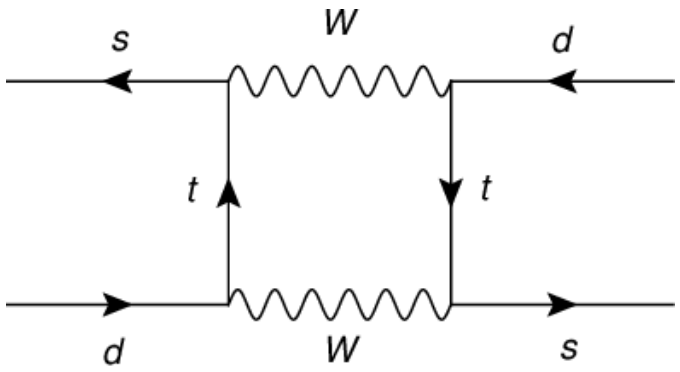

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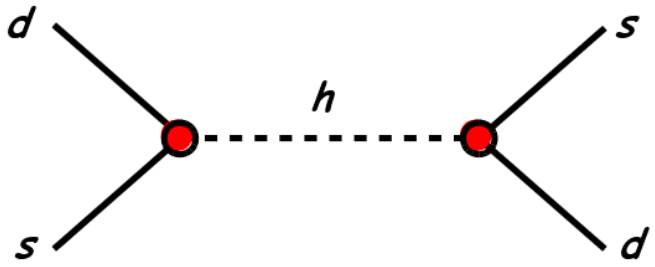

$$M_{12}^K \sim f_K^2 \frac{m_K^2}{m_s^2} \frac{Y_{sd}^2}{m_h^2}$$

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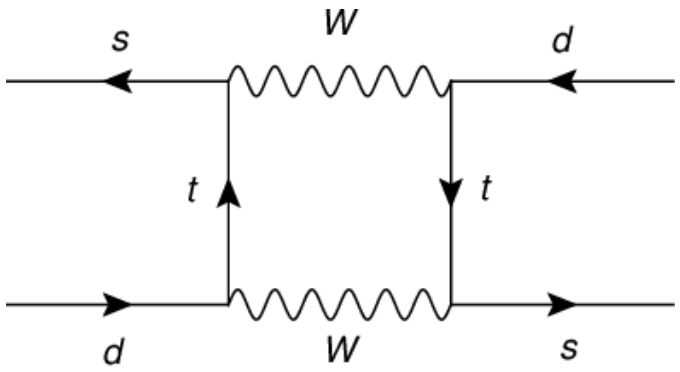

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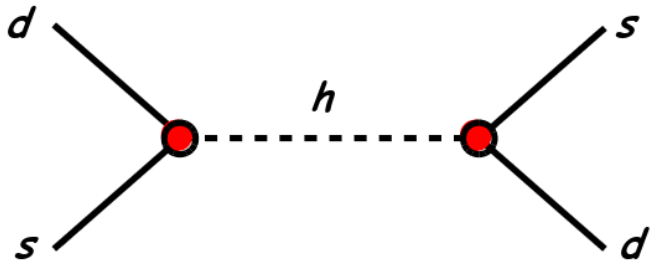

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Generously allowing an O(1) contribution from new physics we can estimate a bound on the flavor changing coupling

$$Y_{sd}^2 \lesssim \frac{m_s^2}{m_K^2} \frac{1}{16\pi^2} (V_{td}^* V_{ts})^2 \sim 10^{-10}$$

Summary of Constraints: Quarks

Technique	Coupling	Constraint
D^0 oscillations [48]	$\lvert Y_{uc}\rvert^2$, $\lvert Y_{cu}\rvert^2$	$< 5.0 \times 10^{-9}$
	$\lvert Y_{uc}Y_{cu}\rvert$	$< 7.5 \times 10^{-10}$
B_d^0 oscillations [48]	$\lvert Y_{db}\rvert^2$, $\lvert Y_{bd}\rvert^2$	$< 2.3 \times 10^{-8}$
	$\lvert Y_{db}Y_{bd}\rvert$	$< 3.3 \times 10^{-9}$
B_s^0 oscillations [48]	$\lvert Y_{sb}\rvert^2$, $\lvert Y_{bs}\rvert^2$	$< 1.8 \times 10^{-6}$
	$\lvert Y_{sb}Y_{bs}\rvert$	$< 2.5 \times 10^{-7}$
K^0 oscillations [48]	$\mathrm{Re}(Y_{ds}^2)$, $\mathrm{Re}(Y_{sd}^2)$	$[-5.9 \ldots 5.6] \times 10^{-10}$
	$\mathrm{Im}(Y_{ds}^2)$, $\mathrm{Im}(Y_{sd}^2)$	$[-2.9 \ldots 1.6] \times 10^{-12}$
	$\mathrm{Re}(Y_{ds}^* Y_{sd})$	$[-5.6 \ldots 5.6] \times 10^{-11}$
	$\mathrm{Im}(Y_{ds}^* Y_{sd})$	$[-1.4 \ldots 2.8] \times 10^{-13}$
single-top production [49]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 3.7
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 1.6
$t \to hj$ [50]	$\sqrt{\lvert Y_{tc}^2\rvert + \lvert Y_{ct}\rvert^2}$	< 0.34
	$\sqrt{\lvert Y_{tu}^2\rvert + \lvert Y_{ut}\rvert^2}$	< 0.34
D^0 oscillations [48]	$\lvert Y_{ut}Y_{ct}\rvert$, $\lvert Y_{tu}Y_{tc}\rvert$	$< 7.6 \times 10^{-3}$
	$\lvert Y_{tu}Y_{ct}\rvert$, $\lvert Y_{ut}Y_{tc}\rvert$	$< 2.2 \times 10^{-3}$
	$\lvert Y_{ut}Y_{tu}Y_{ct}Y_{tc}\rvert^{1/2}$	$< 0.9 \times 10^{-3}$
neutron EDM [37]	$\mathrm{Im}(Y_{ut}Y_{tu})$	$< 4.4 \times 10^{-8}$

Blankenburg, Ellis, Isidori 1202.5704; Harnik, Kopp, Zupan 1209.1397; ...

Lepton Flavor Violation

Lepton flavor violating Higgs couplings can be constrained by processes like $\mu \to e\gamma$, $\tau \to \mu\gamma$, ...

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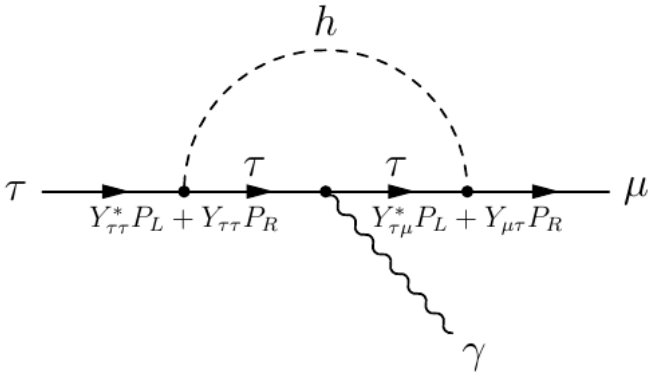

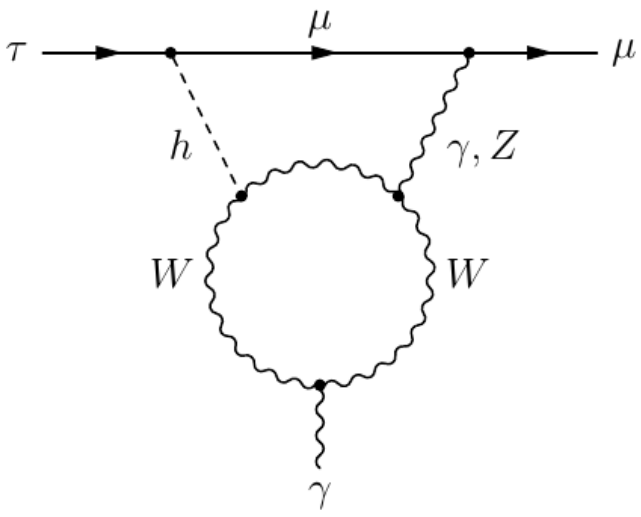

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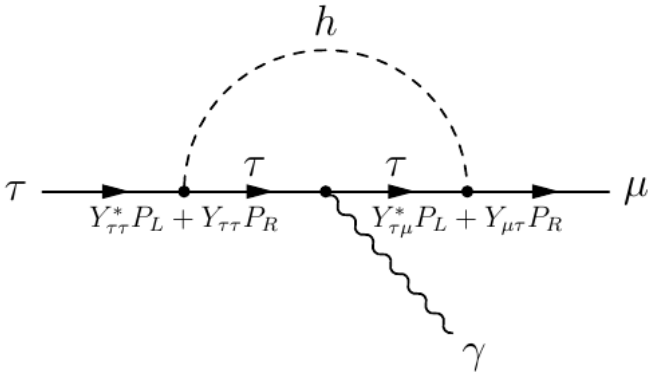
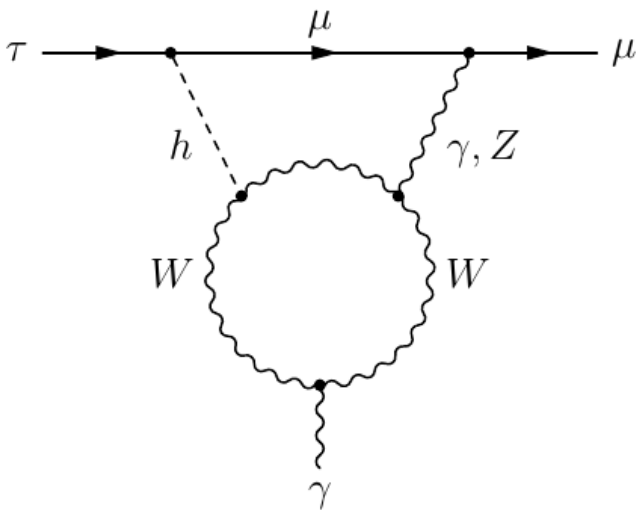




[Note: loop calculations with modified Higgs couplings that are introduced by hand might not lead to consistent results.]

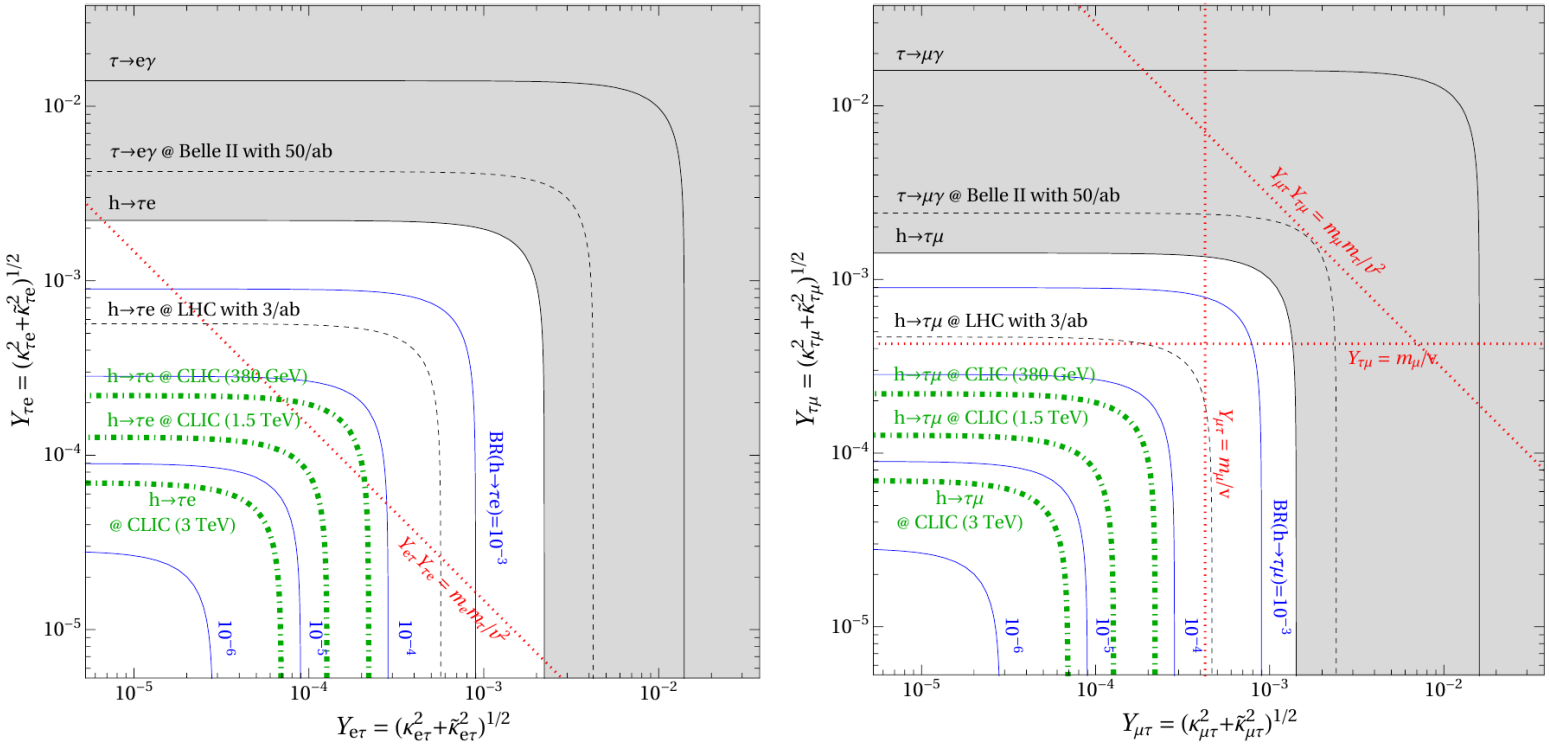
Summary of Constraints: Leptons

Channel	Coupling	Bound
$\mu \to e\gamma$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 3.6 \times 10^{-6}$
$\mu \to 3e$	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$\lesssim 3.1 \times 10^{-5}$
electron $g-2$	$\mathrm{Re}(Y_{e\mu} Y_{\mu e})$	$-0.019 \ldots 0.026$
electron EDM	$\lvert \mathrm{Im}(Y_{e\mu} Y_{\mu e})\rvert$	$< 9.8 \times 10^{-8}$
$\mu \to e$ conversion	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$< 1.2 \times 10^{-5}$
M-$\bar{M}$ oscillations	$\lvert Y_{\mu e} + Y^*_{e\mu}\rvert$	< 0.079
$\tau \to e\gamma$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	< 0.014
$\tau \to 3e$	$\sqrt{\lvert Y_{\tau e}\rvert^2 + \lvert Y_{e\tau}\rvert^2}$	$\lesssim 0.12$
electron $g-2$	$\mathrm{Re}(Y_{e\tau} Y_{\tau e})$	$[-2.1 \ldots 2.9] \times 10^{-3}$
electron EDM	$\lvert \mathrm{Im}(Y_{e\tau} Y_{\tau e})\rvert$	$< 1.1 \times 10^{-8}$
$\tau \to \mu\gamma$	$\sqrt{\lvert Y_{\tau\mu}\rvert^2 + \lvert Y_{\mu\tau}\rvert^2}$	0.016
$\tau \to 3\mu$	$\sqrt{\lvert Y^2_{\tau\mu} + \lvert Y_{\mu\tau}\rvert^2}$	$\lesssim 0.25$
muon $g-2$	$\mathrm{Re}(Y_{\mu\tau} Y_{\tau\mu})$	$(2.7 \pm 0.75) \times 10^{-3}$
muon EDM	$\mathrm{Im}(Y_{\mu\tau} Y_{\tau\mu})$	$-0.8 \ldots 1.0$
$\mu \to e\gamma$	$\left(\lvert Y_{\tau\mu} Y_{e\tau}\rvert^2 + \lvert Y_{\mu\tau} Y_{\tau e}\rvert^2\right)^{1/4}$	$< 3.4 \times 10^{-4}$

Blankenburg, Ellis, Isidori 1202.5704; Harnik, Kopp, Zupan 1209.1397 ; ...

LHC Searches for Lepton Flavor Violating Higgs

In the case of $h \to \tau\mu$ and $h \to \tau e$ couplings, direct searches at the LHC have the highest sensitivity.



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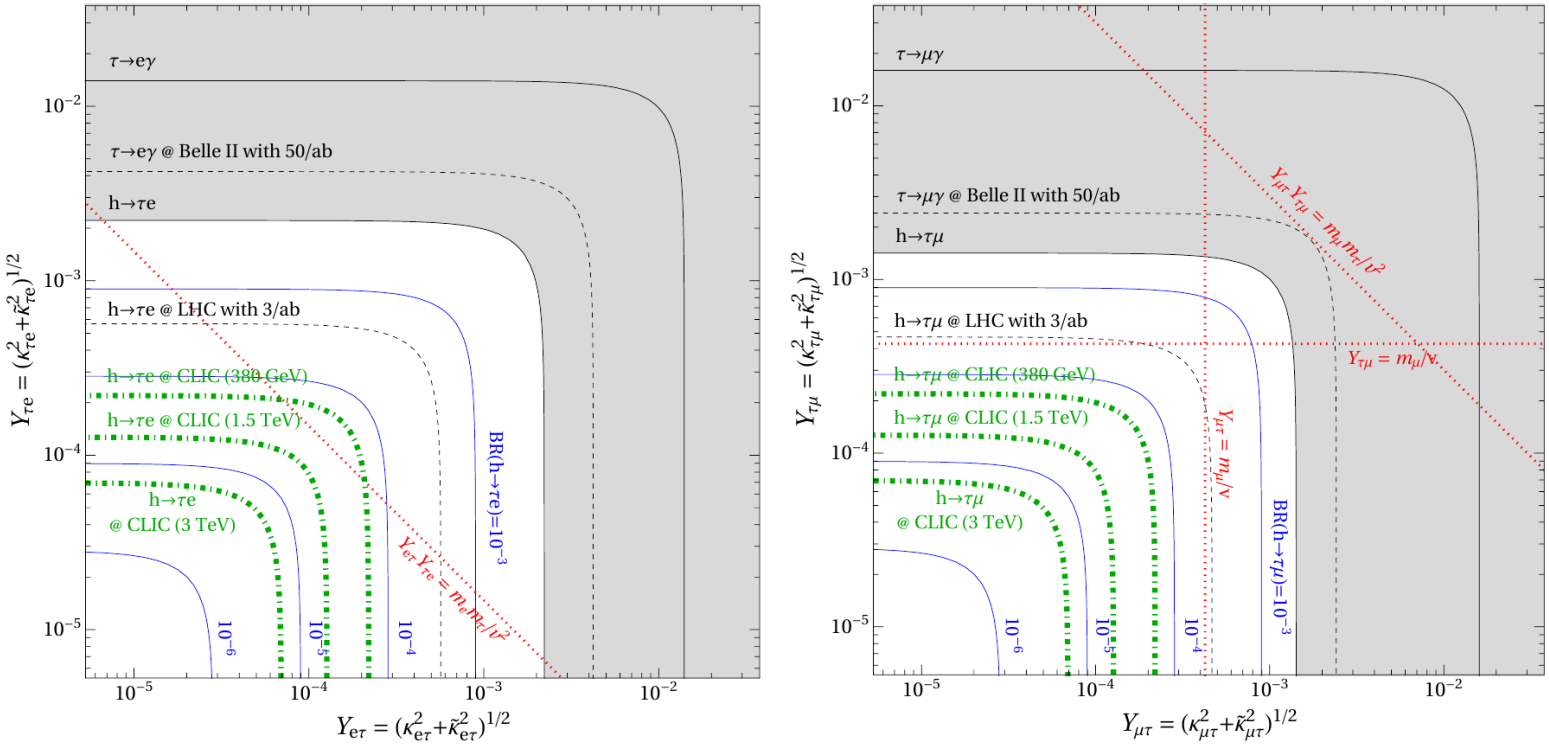
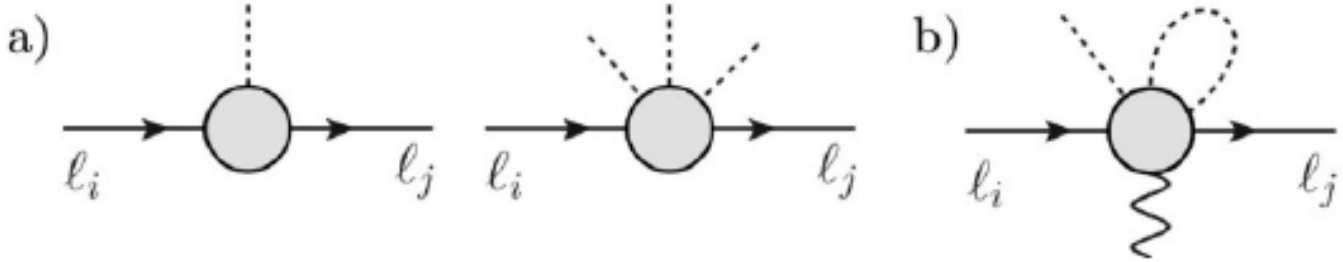


- But $\mu \to e\gamma$ strongly constrains BR($h \to \mu e$) and BR($h \to \tau\mu$)×BR($h \to \tau e$)

LFV Higgs Decays in Models of New Physics

New physics that generates the LFV Higgs coupling, will typically also give direct contributions to radiative decays (Dorsner et al. 1502.07784)



Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

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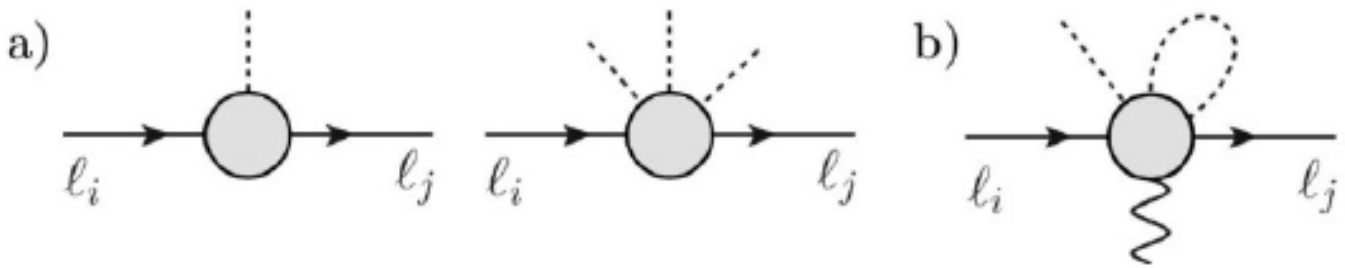


Contributions to lepton Yukawa couplings (a) , electromagnetic dipole (b)

generic upper bound in many models

$$\mathrm{BR}(h \to \tau\mu) \sim 26 \times \mathrm{BR}(\tau \to \mu\gamma) \lesssim 10^{-6}$$

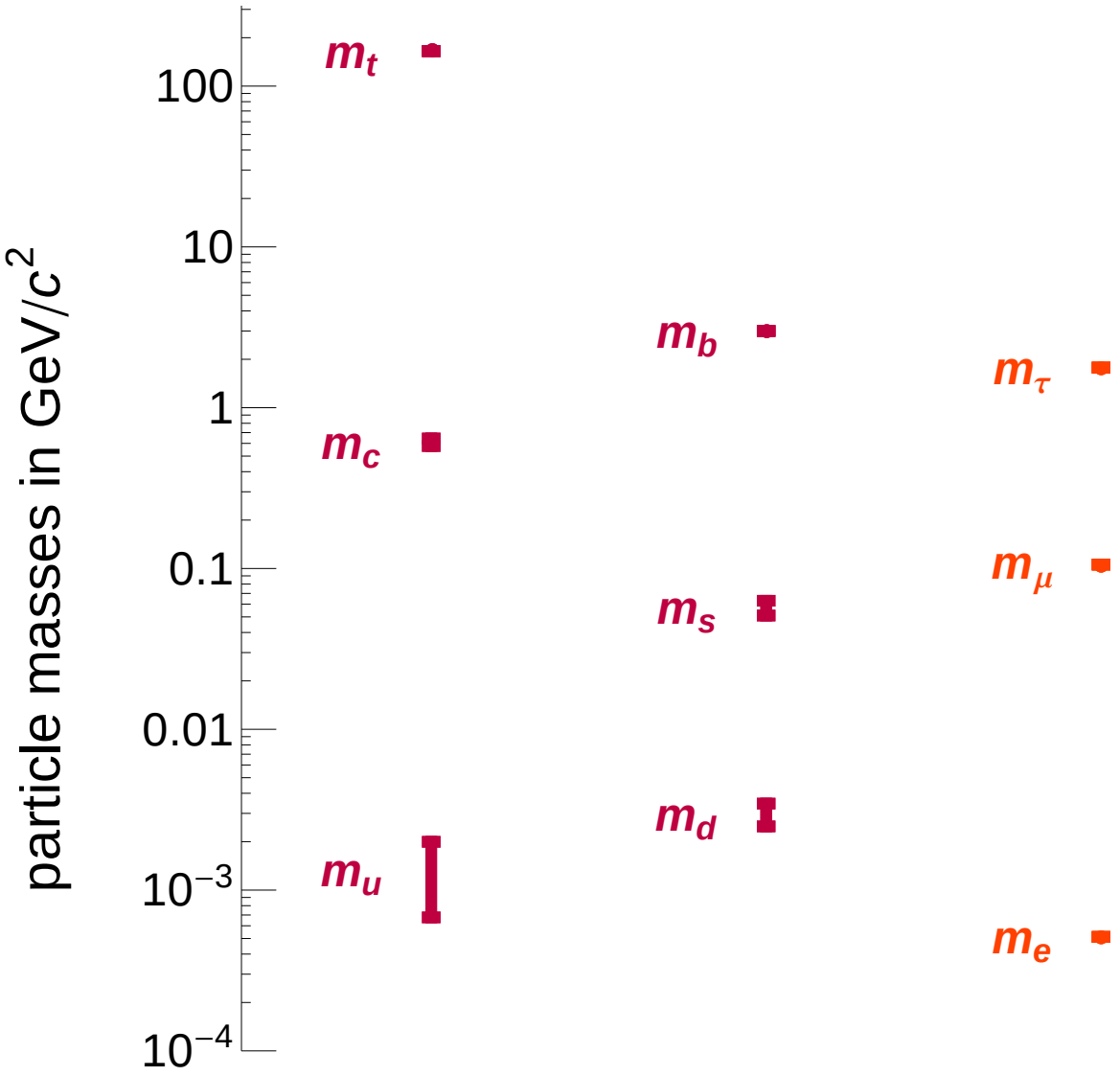
WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

Note: this is not a robust bound. It is based on theory bias.

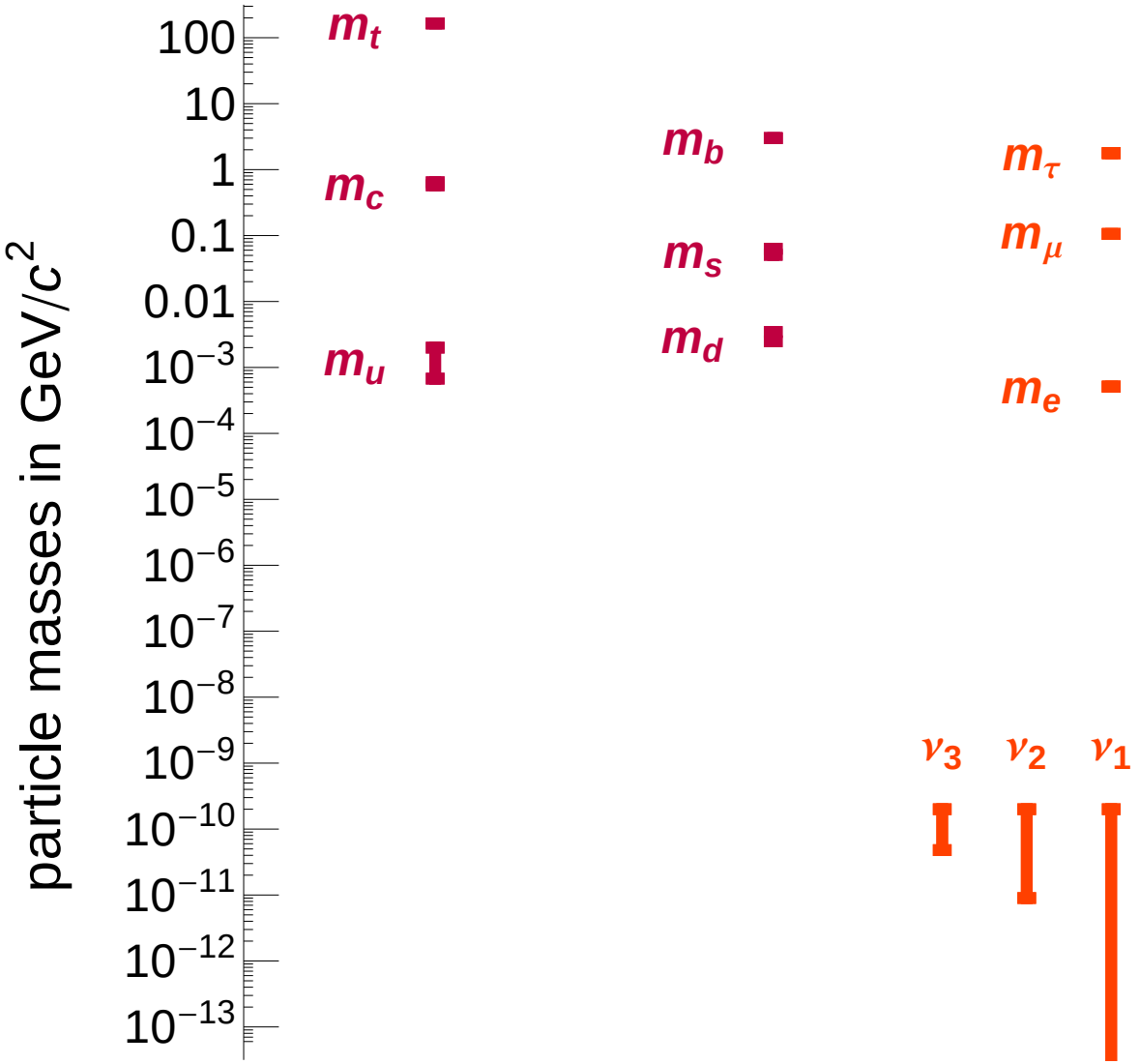
$\Rightarrow$ If LFV Higgs decays are observed above that bound, we learn something profound

So far, all measured Higgs properties agree with SM predictions. But in the SM, quark and lepton flavor is only accommodated, not explained.

Flavor Hierarchies



Flavor Hierarchies



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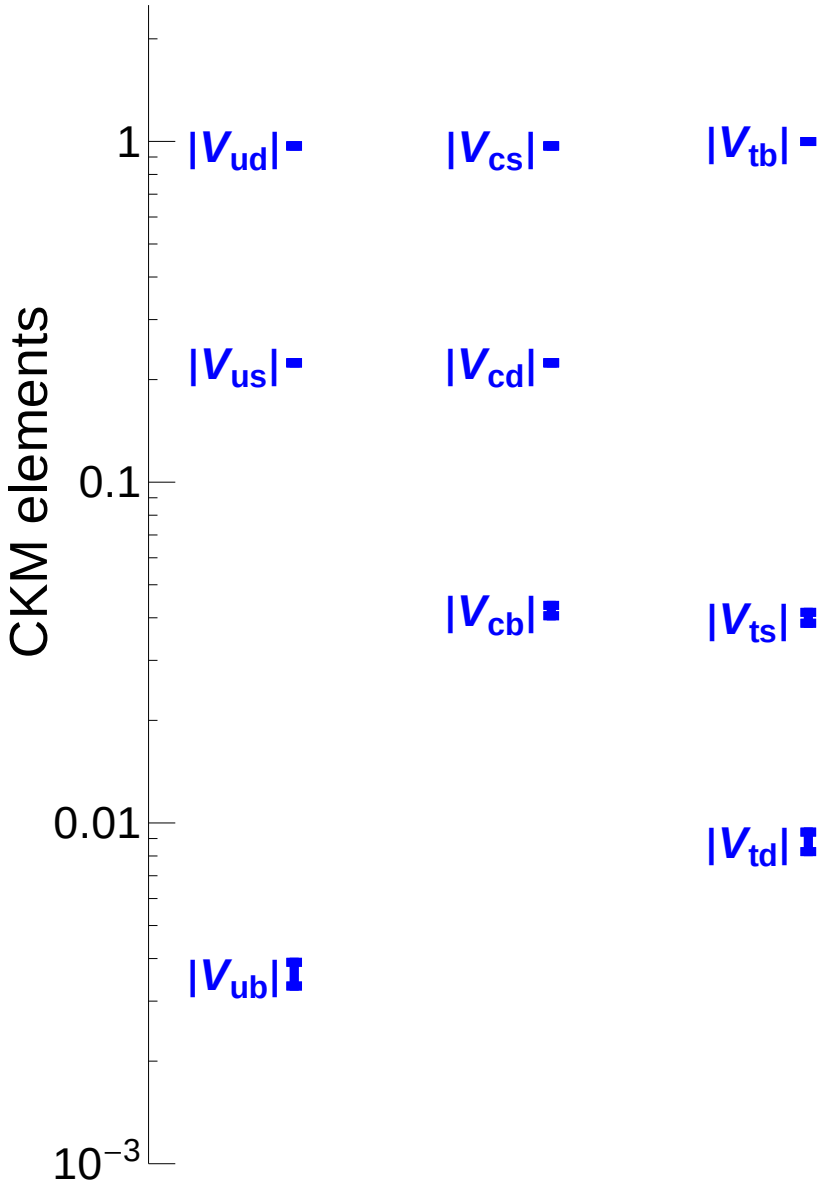

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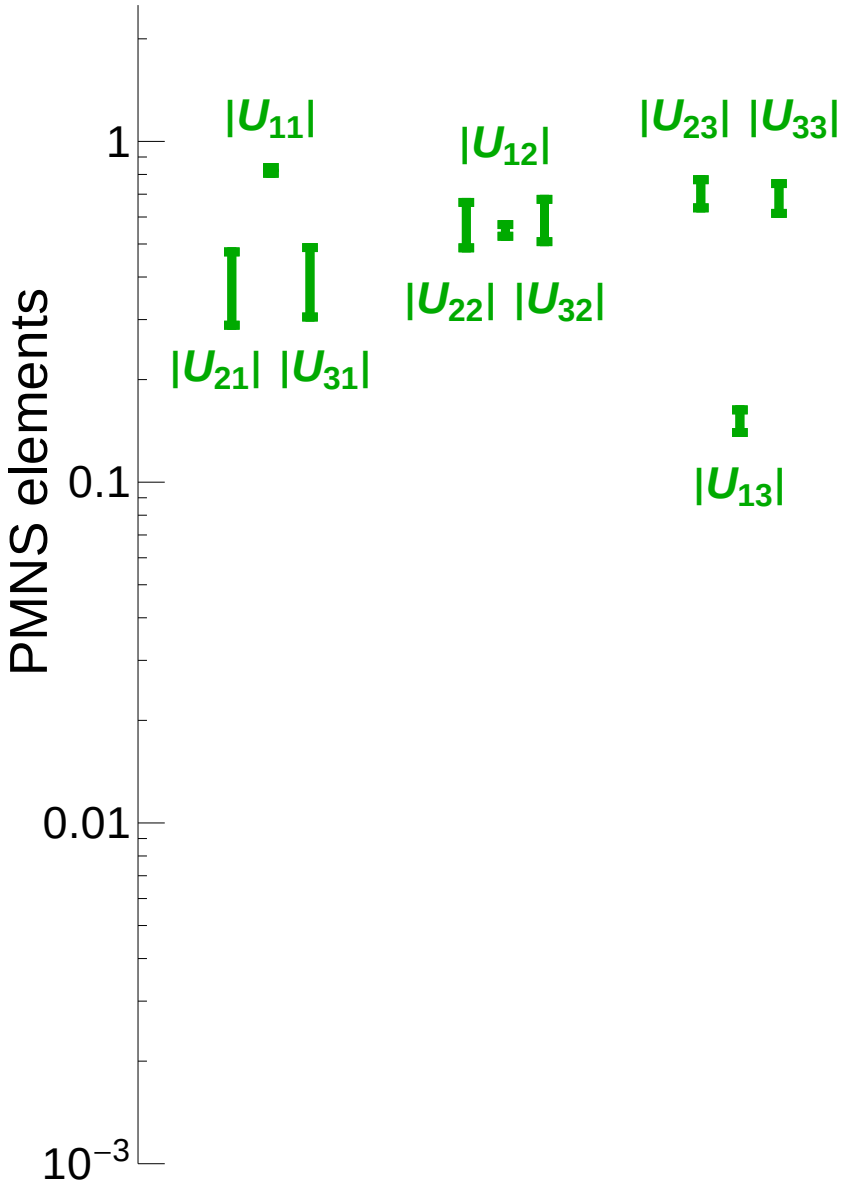


The Standard Model Flavor Puzzle

Why are there three flavors of quarks and leptons?

What is the origin of the hierarchies in the fermion spectrum?

What is the origin of the hierarchies in the quark mixing?

Is lepton mixing anarchic?

Addressing the SM Flavor Puzzle

- Option 1: Electroweak symmetry breaking is as in the SM

$\rightarrow$ Hierarchical structure of fermion masses and CKM matrix originates solely from the Yukawa couplings

$\rightarrow$ Introduce new physics that gives the Yukawa couplings a hierarchical structure

Addressing the SM Flavor Puzzle

- Option 1: Electroweak symmetry breaking is as in the SM

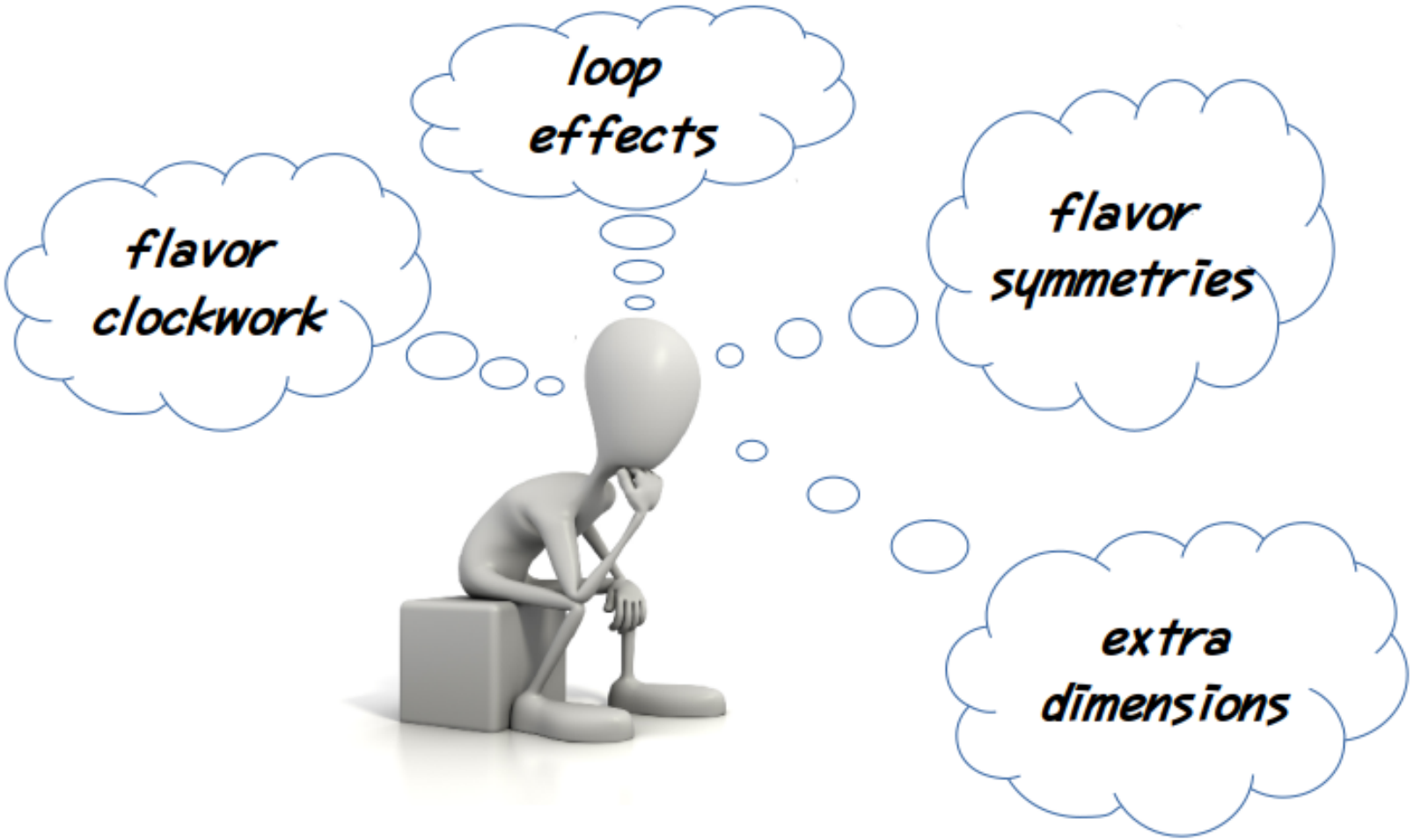
→ Hierarchical structure of fermion masses and CKM matrix originates solely from the Yukawa couplings

→ Introduce new physics that gives the Yukawa couplings a hierarchical structure

- Option 2: Extended electroweak symmetry breaking sector

→ Small quark and lepton masses from a subdominant source of electroweak symmetry breaking

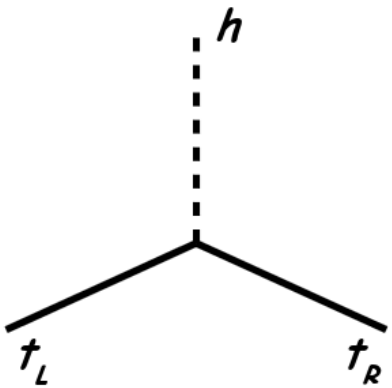
Origin of Hierarchical Yukawa Couplings



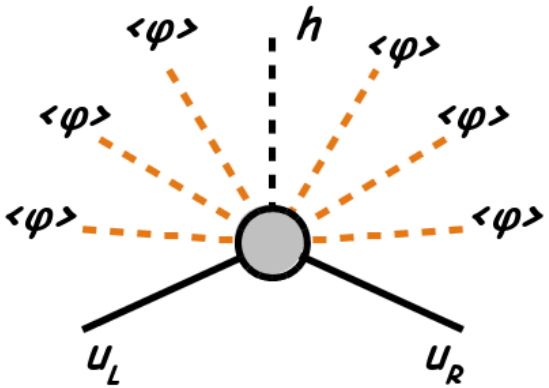
Hierarchy from Symmetry

(Froggatt, Nielsen '79; ...)

fermion masses are forbidden by flavor symmetries
and arise only after spontaneous breaking of the symmetry



$$h\bar{t}_R t_L$$



$$\frac{\varphi^6}{M^6} h\bar{u}_R u_L$$

Simple U(1) model:

$Q(t_L)=Q(t_R)=0$
$Q(u_L)=-Q(u_R)=3$
$Q(h)=0$
$Q(\varphi)=-1$

Hierarchy from Symmetry

mass and mixing hierarchies given by powers of the "spurion" $\langle\varphi\rangle/M$.
in the example from the previous slide we have

$$\frac{m_u}{m_t} \sim \left(\frac{\langle\varphi\rangle}{M}\right)^6 \sim \epsilon^6$$

Hierarchy from Symmetry

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in the example from the previous slide we have

$$\frac{m_u}{m_t} \sim \left(\frac{\langle\varphi\rangle}{M}\right)^6 \sim \epsilon^6$$

Exercise: Construct a U(1) model with the following hierarchies

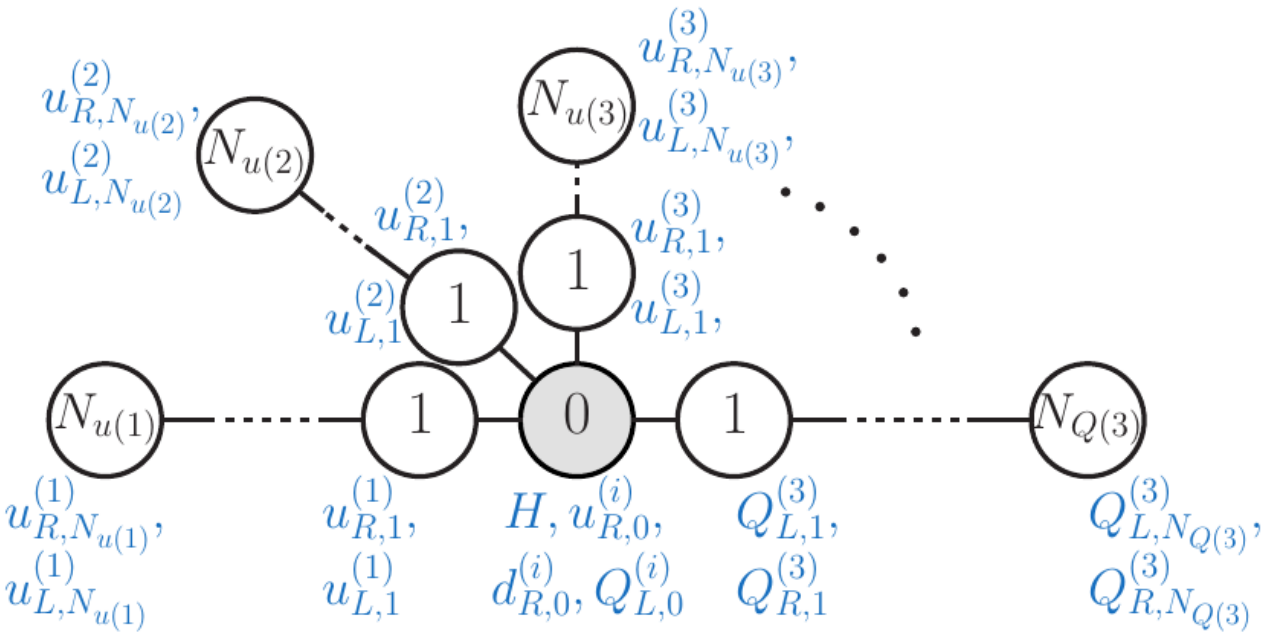
$$m_u \sim \epsilon^6 \quad , \quad m_c \sim \epsilon^3 \quad , \quad m_t \sim 1$$

$$m_d \sim \epsilon^5 \quad , \quad m_s \sim \epsilon^4 \quad , \quad m_b \sim \epsilon^2$$

Which predictions does your model make for the CKM hierarchies?

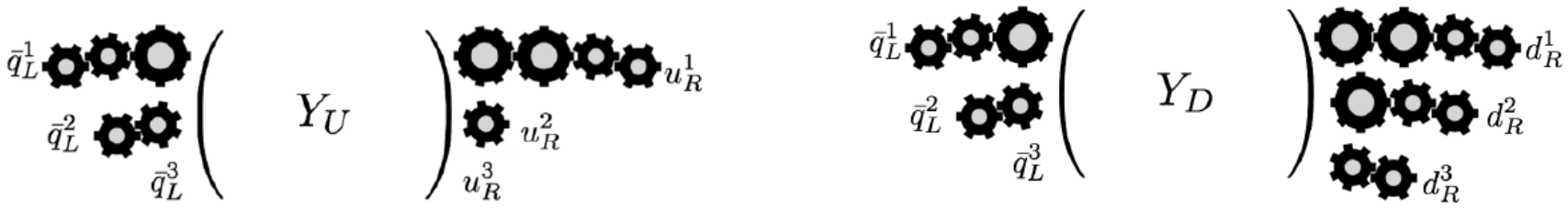
Hierarchy from Symmetry (clockwork variation)

The flavor clockwork mechanism (Giudice, McCullough 1610.07962), is similar to Froggatt-Nielsen with many individual $U(1)$ symmetries for each flavor



(Alonso et al. 1807.09792)

Hierarchy from Symmetry (clockwork variation)



(Alonso et al. 1807.09792)

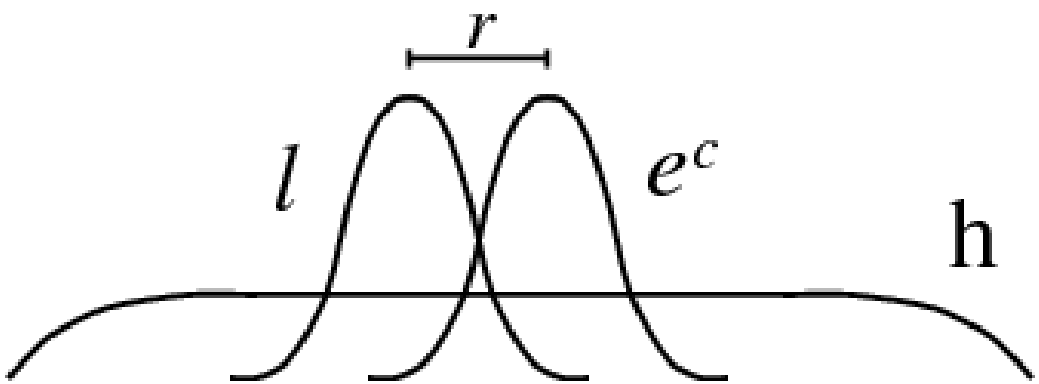
The numbers of clockwork sites play a similar role as the U(1) charges in the Froggatt-Nielsen setup

$$\frac{m_u}{m_t} \sim \epsilon^{N_{Q_1}+N_{u_1}-N_{Q_3}-N_{u_3}}$$

Hierarchy from Geometry

(Arkani-Hamed, Schmaltz '99; Grossman, Neubert '99; ...)

fermions are localized at different positions in an extra dimension



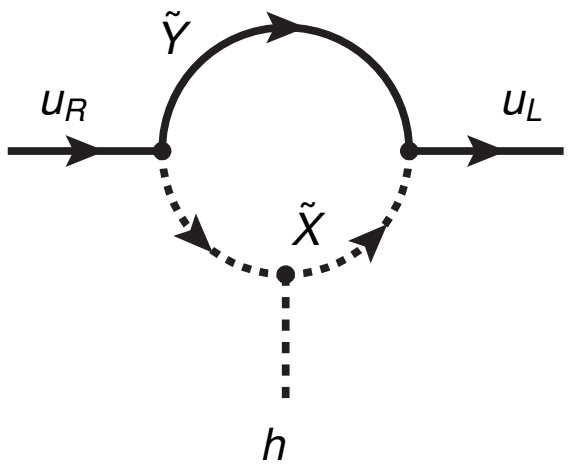
hierarchies from exponentially small wave-function overlap between left-handed and right-handed fermions and the Higgs

$$\frac{m_u}{m_t} \sim e^{-\Delta}$$

Hierarchy from Loops

(Weinberg '72; ...)

light fermion masses arise only from quantum effects



light fermions do not couple
to the higgs directly

couplings are loop-induced
by flavor violating new particles

mass and mixing hierarchies from loop factors

$$\frac{m_u}{m_t} \sim \left(\frac{1}{16\pi^2}\right)^n$$

Summary

1. Part 1 (today)
   - Higgs and Flavor in the Standard Model

     (flavor symmetries, flavor violating Higgs decays, Standard Model flavor puzzle)

2. Part 2 (tomorrow)
   - Higgs and Flavor beyond the Standard Model

     (extended Higgs sectors, “flavorful” Higgs bosons, flavor phenomenology, collider phenomenology)