Model Building Centered Around Flavor

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Largely based on 2412.04549 with Greljo
(invited review for Annual Review of Nuclear and Particle Science)

Beyond the Flavour Anomalies 2025
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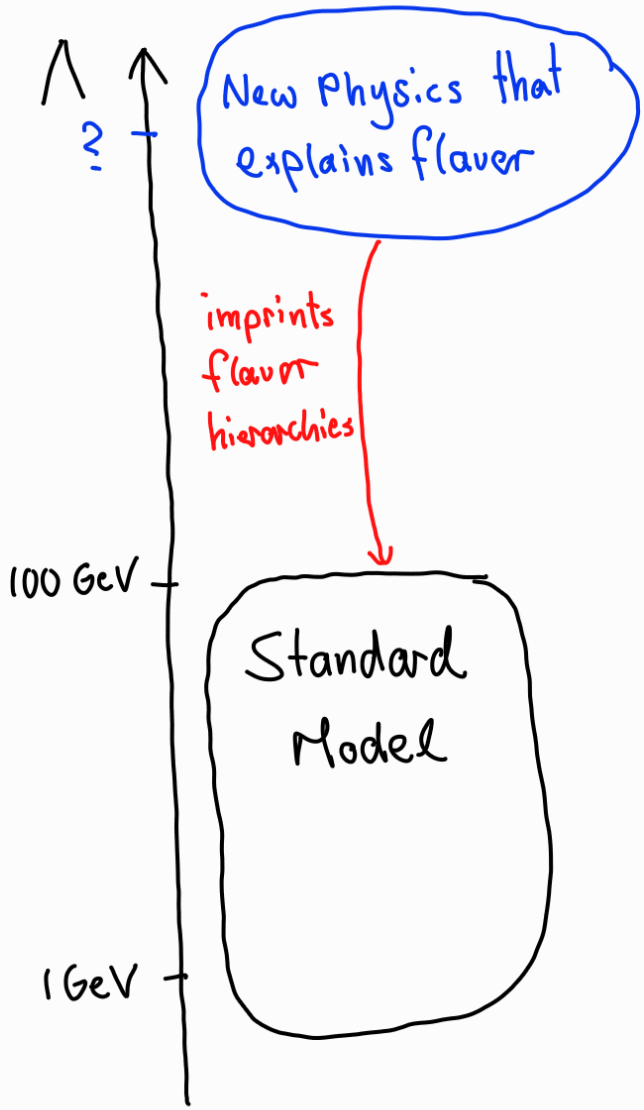
Advertisement

Basic Picture



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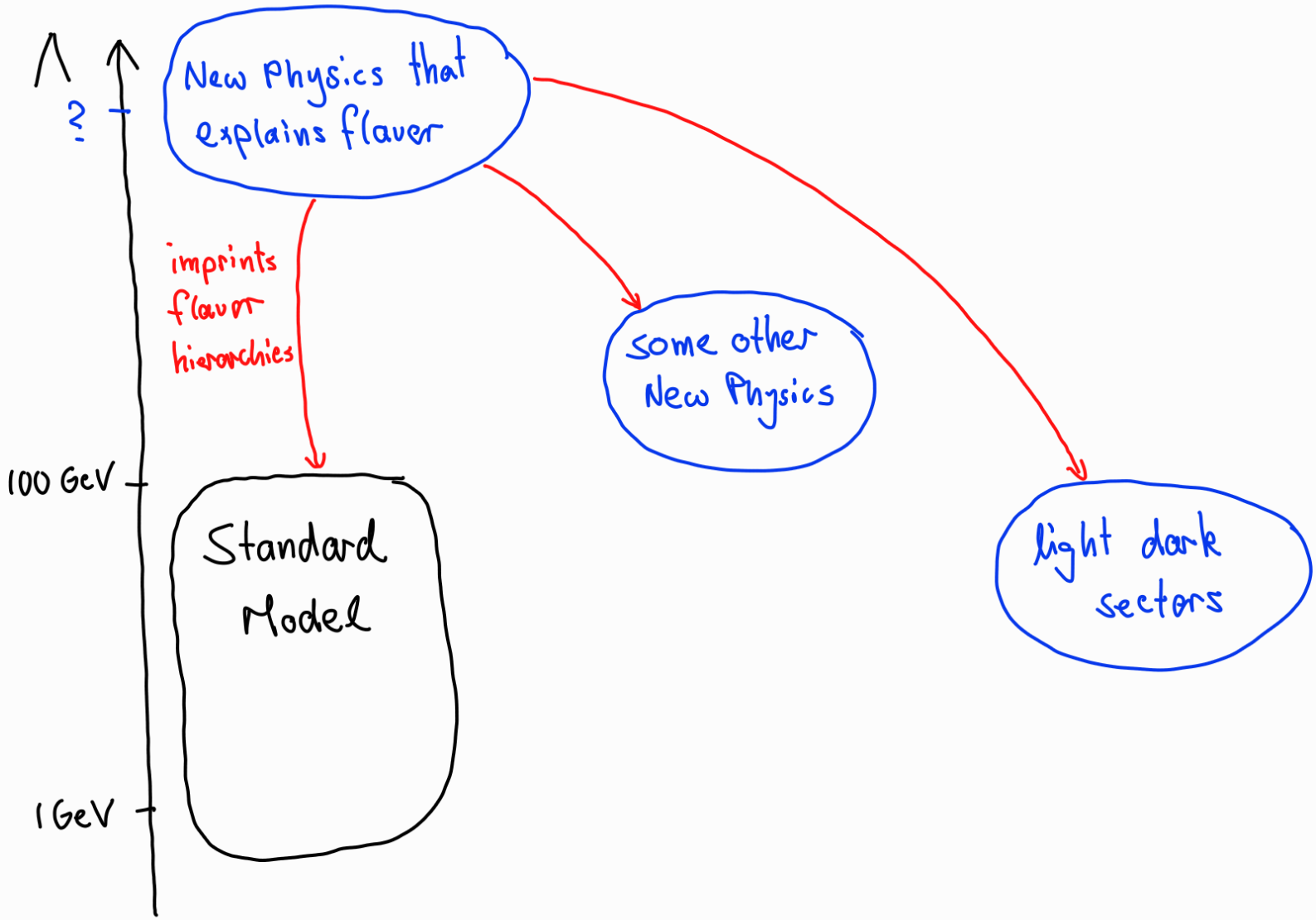

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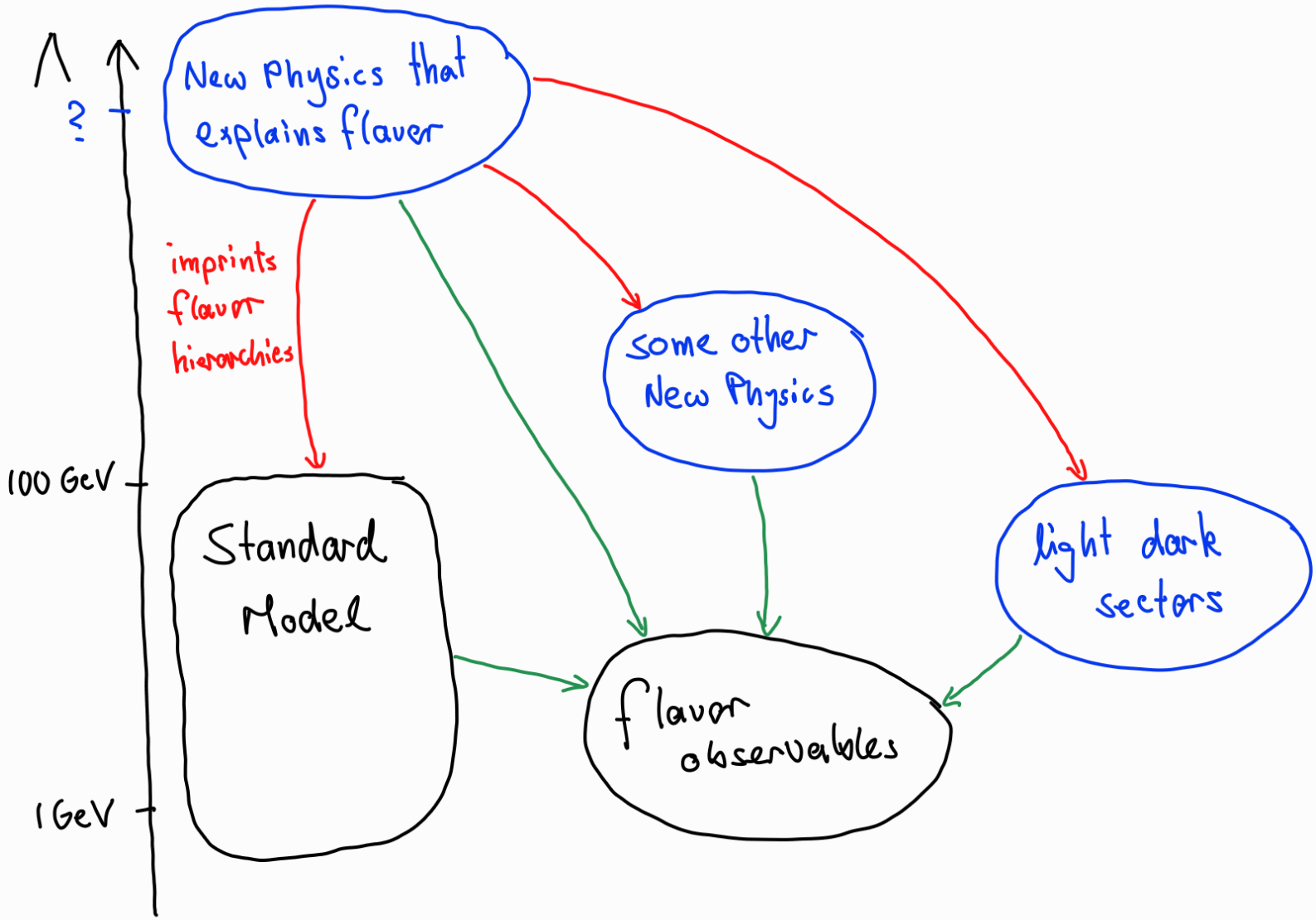


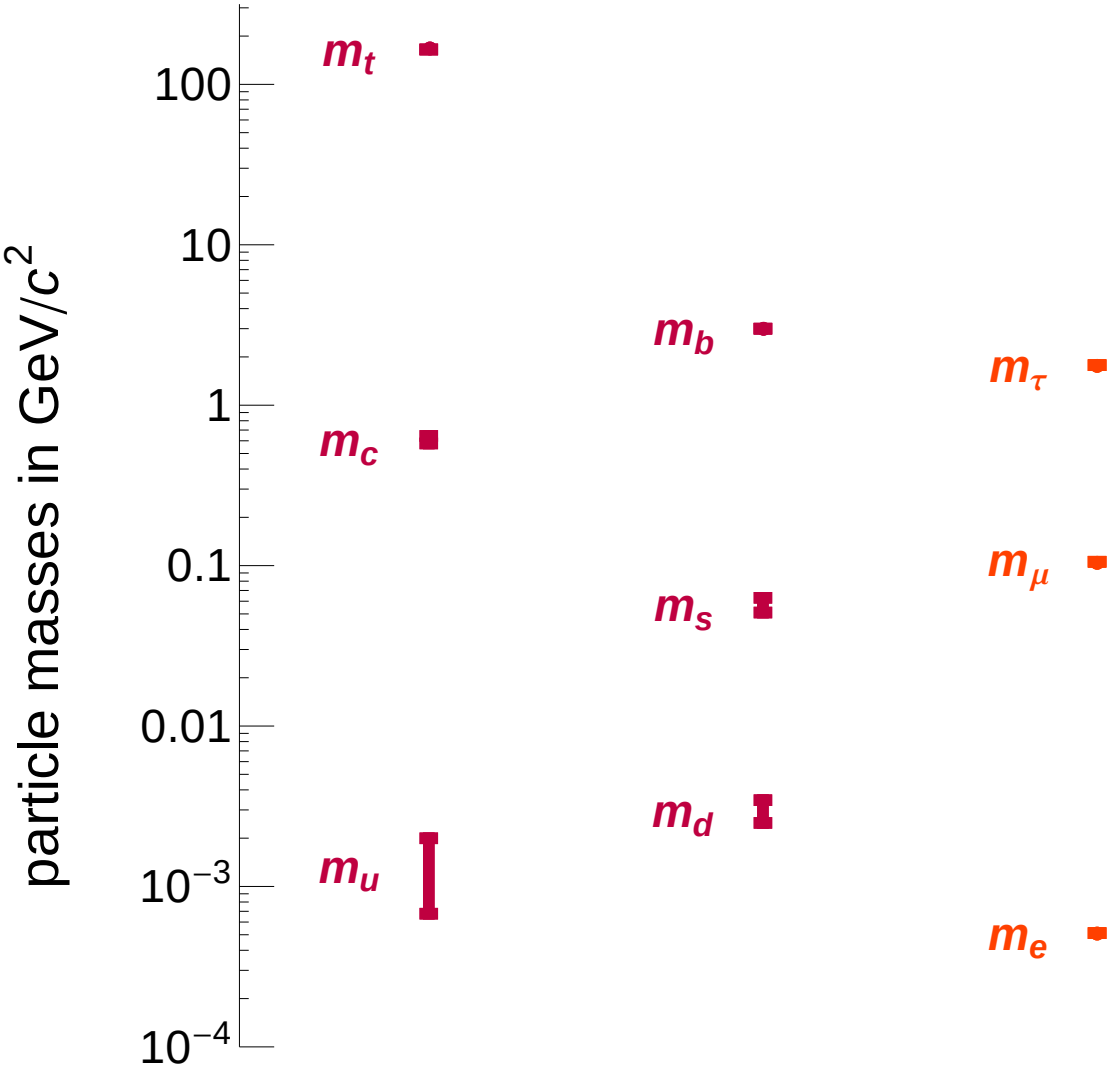
Flavor Model Building

1) Model building to address the Standard Model flavor puzzle

2) Model building to address the New Physics flavor puzzle

3) Model building to address flavor anomalies

Quark and Lepton Masses



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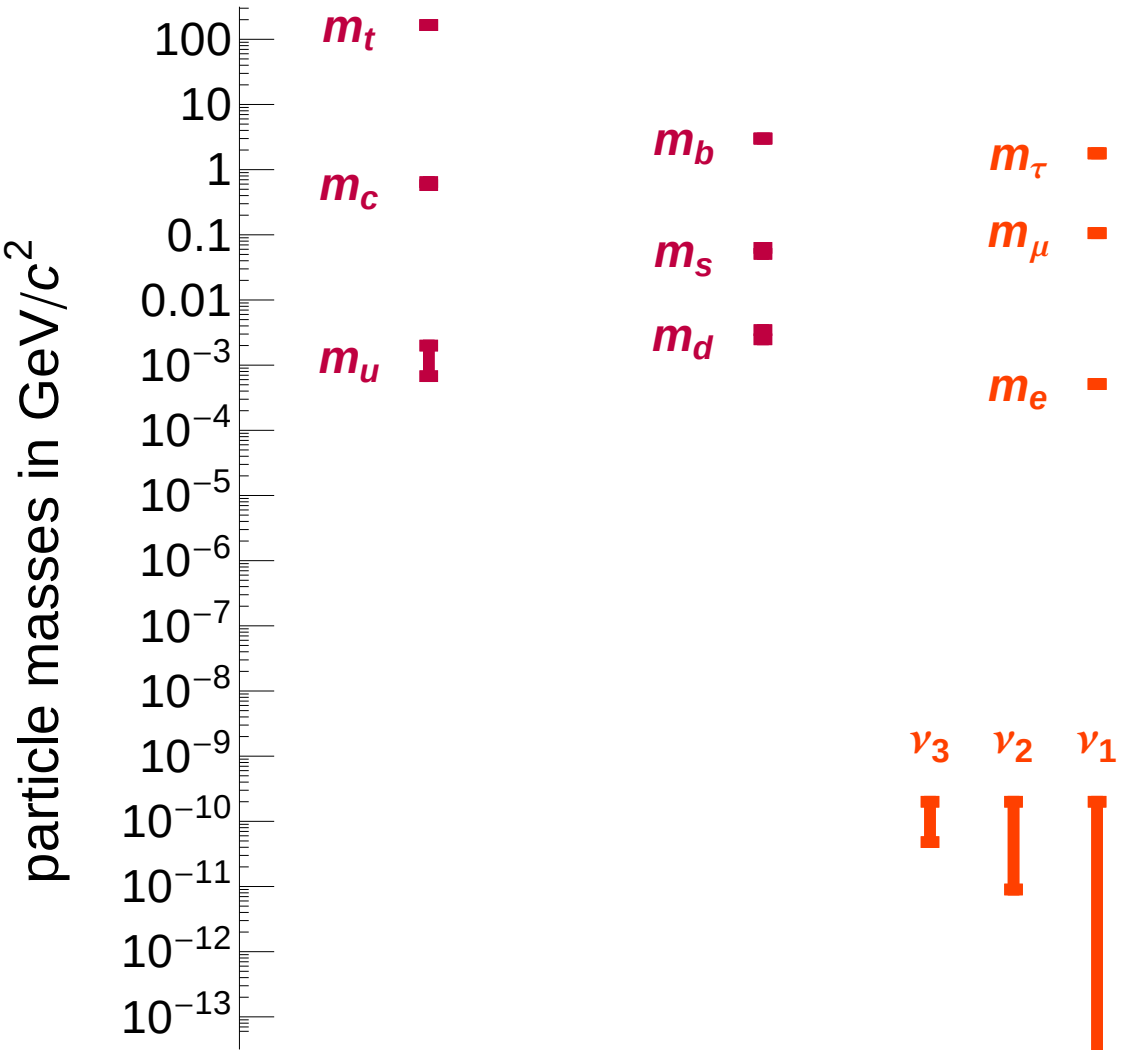
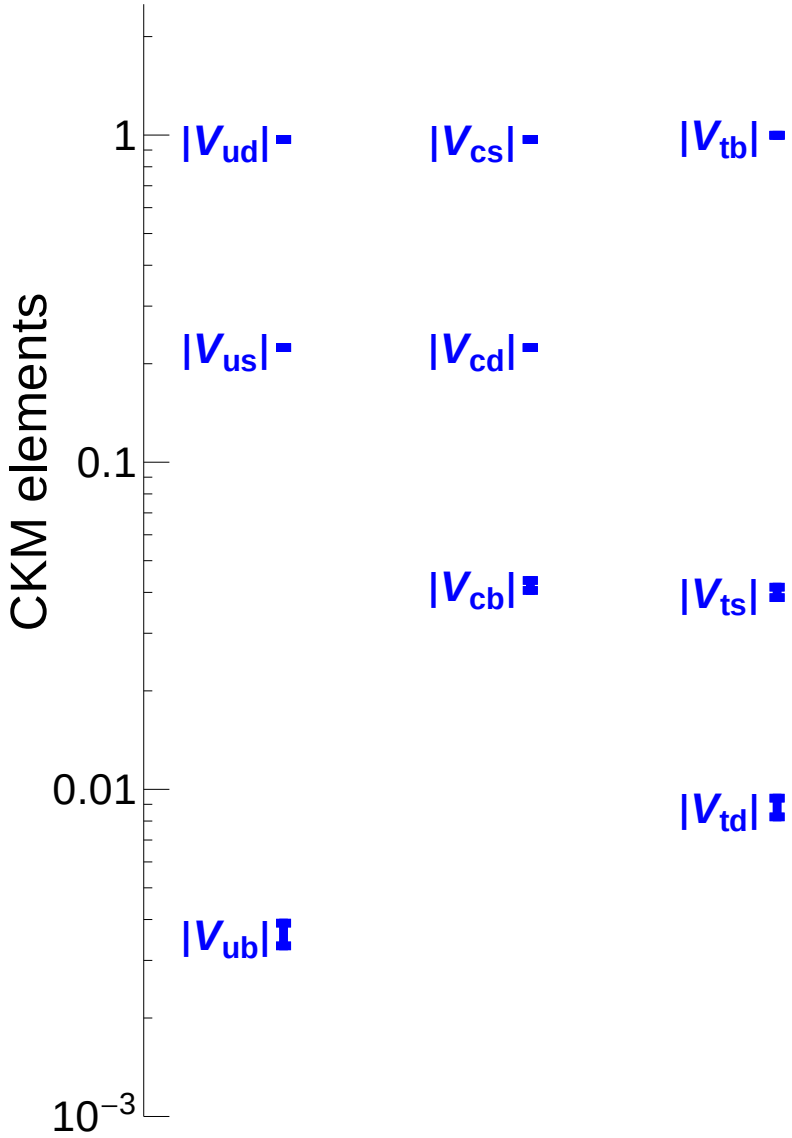
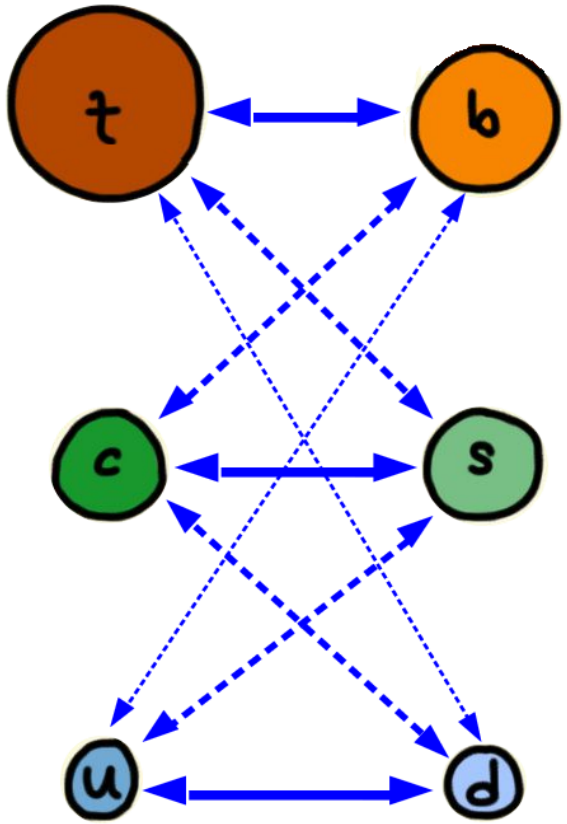
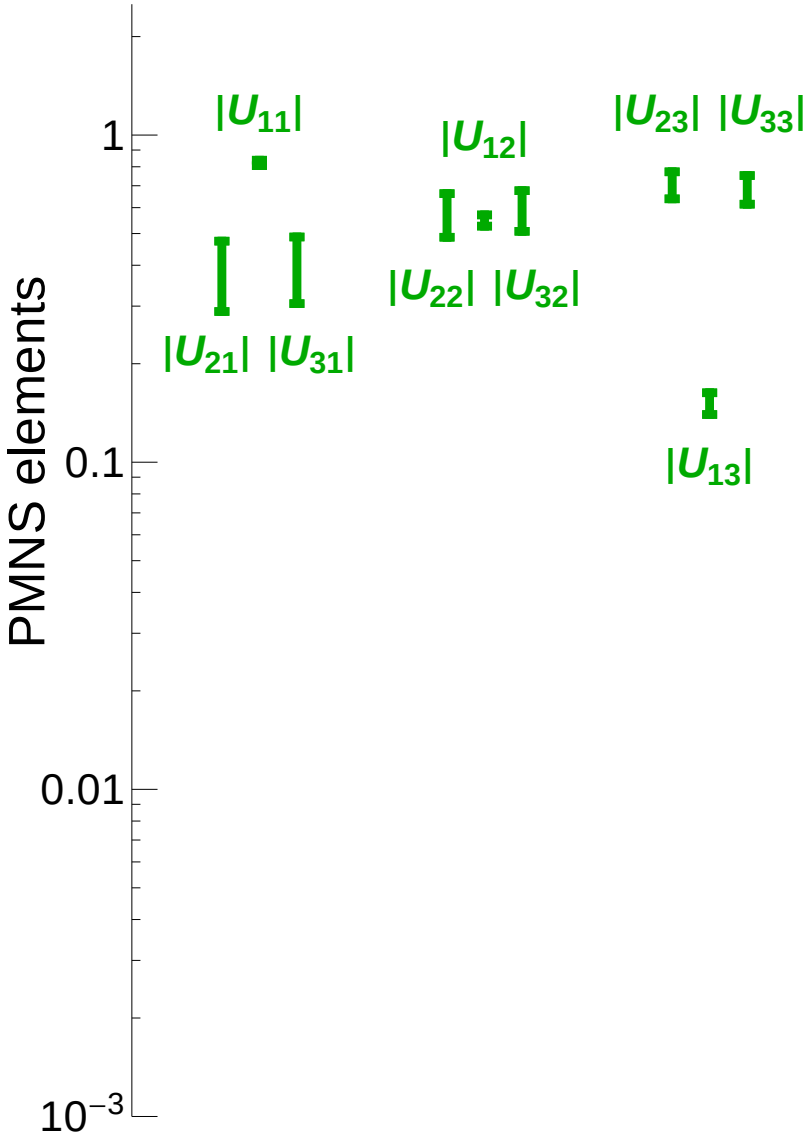


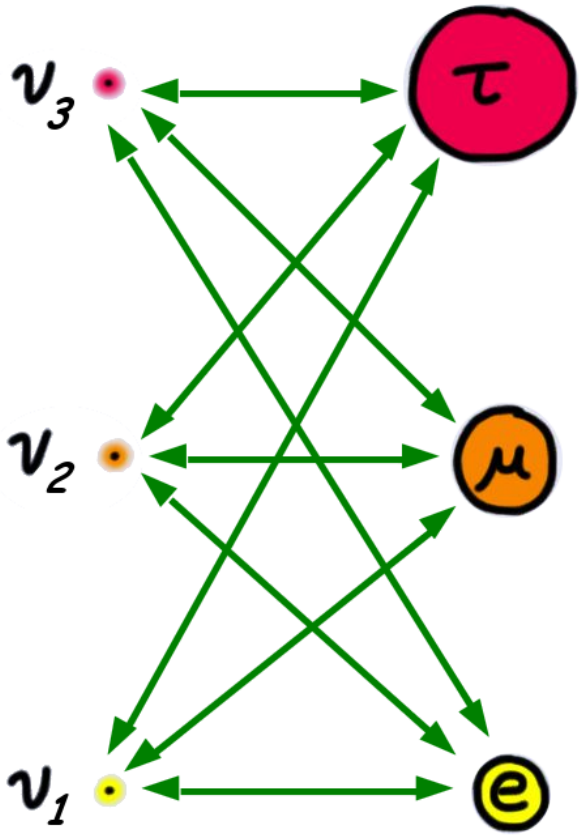
Hierarchical Quark Mixing





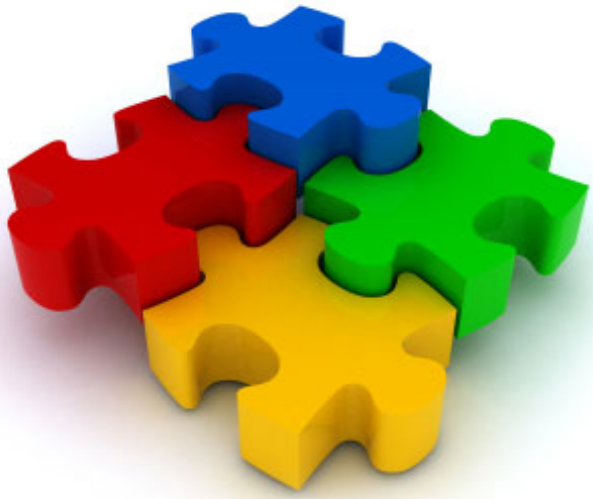
Anarchic Lepton Mixing?





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?

Naturalness

- Flavor in the Standard Model looks peculiar
  but it is not inconsistent.
- Flavor in the Standard Model is “technically natural”
  (the hierarchies are stable under quantum corrections)
- Flavor is not natural in Dirac’s sense:
  $\rightarrow$ dimensionless couplings should be of order 1.

Addressing the SM Flavor Puzzle

$$m = Y * v$$

- 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

- Option 2: Extended electroweak symmetry breaking sector

$\rightarrow$ Small quark and lepton masses from a subdominant source of electroweak symmetry breaking

Extra Higgses for the Flavor Puzzle

Maybe the first and second generation are light, because they get their mass from a subdominant source of electroweak symmetry breaking

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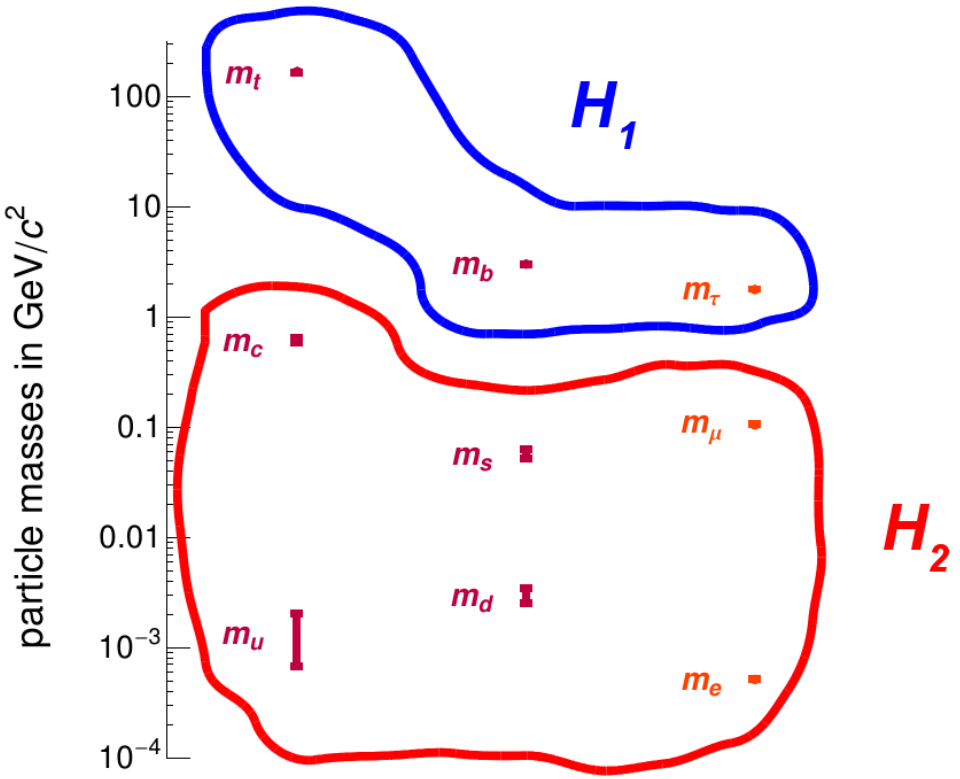
simple realization in the context of 2HDMs



one Higgs is responsible for the masses of the heaviest flavors

a second Higgs gives mass to the light flavors and is responsible for flavor mixing

WA, Gori, Kagan, Silvestrini, Zupan 1507.07927

A “Flavorful” 2HDM

Explains one part of the hierarchical fermion masses: $m_{2\text{nd}} \ll m_{3\text{rd}}$

Predicts interesting collider and flavor pheno

- Lepton flavor violating Higgs decays, $h \to \tau\mu$, $h \to \tau e$
- Rare top decays $t \to qh$
- Same sign di-top production $pp \to tH/A \to tt\bar{c}$

WA, Eby, Gori, Lotito, Martone, Tuckler 1610.02398

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- lepton flavor violating rare B meson decays

$$\text{BR}(B_s \to \tau\mu) \sim \text{few} \times 10^{-7}$$

$$\text{BR}(B \to K\tau\mu) \sim \text{few} \times 10^{-7}$$

$$\text{BR}(B \to K^*\tau\mu) \sim \text{few} \times 10^{-7}$$

WA, Maddock 1805.08659

A Generation Specific 3HDM

One Higgs for each generation?

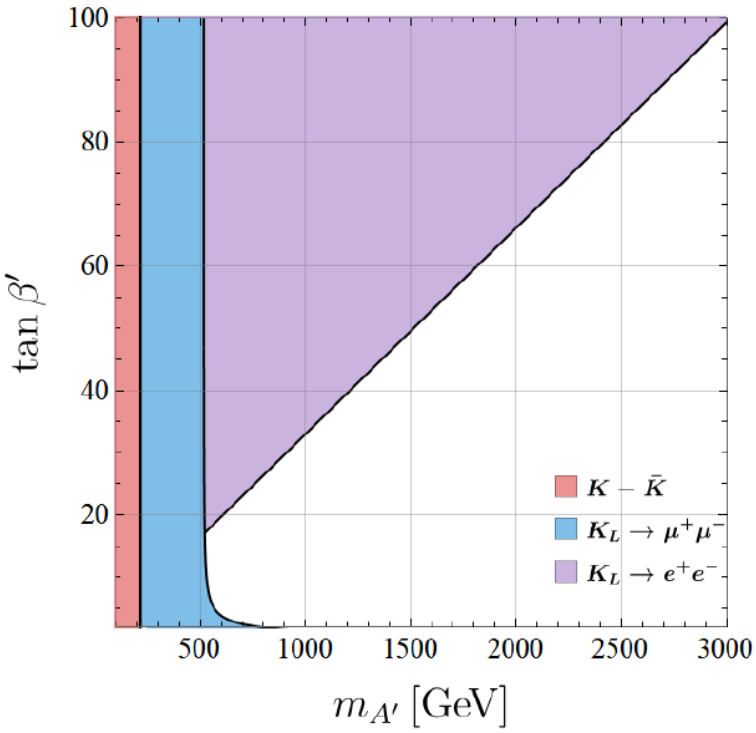
$$m_{1\text{st}} \ll m_{2\text{nd}} \ll m_{3\text{rd}} \text{ because } v_1 \ll v_2 \ll v_3 \text{ ?}$$

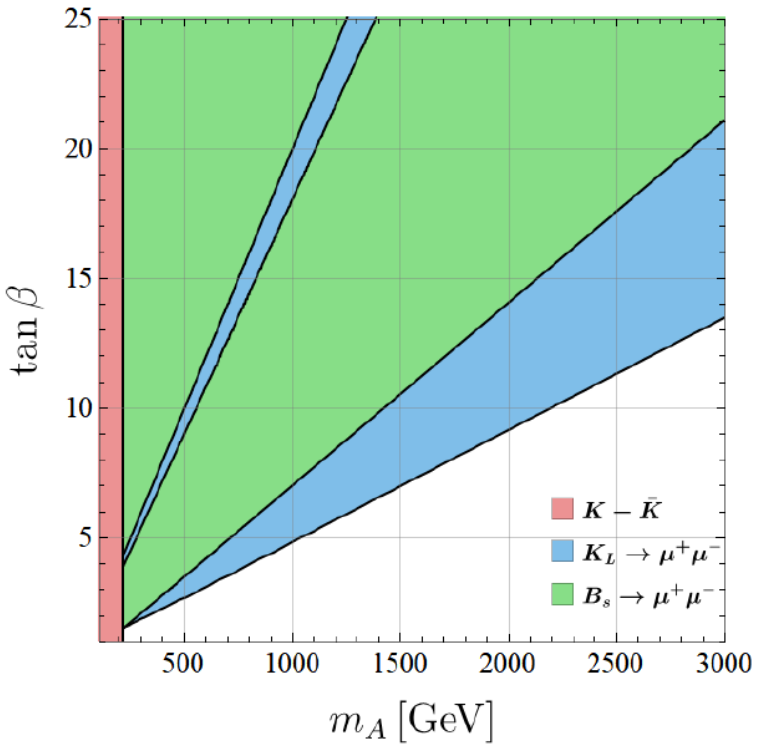
A Generation Specific 3HDM

One Higgs for each generation?

$m_{1\text{st}} \ll m_{2\text{nd}} \ll m_{3\text{rd}}$ because $v_1 \ll v_2 \ll v_3$?

badly breaks $SU(2)$ favor symmetry that acts on the first two generations
$\Rightarrow$ very strong constraints from kaon physics





WA, Toner 2502.04579

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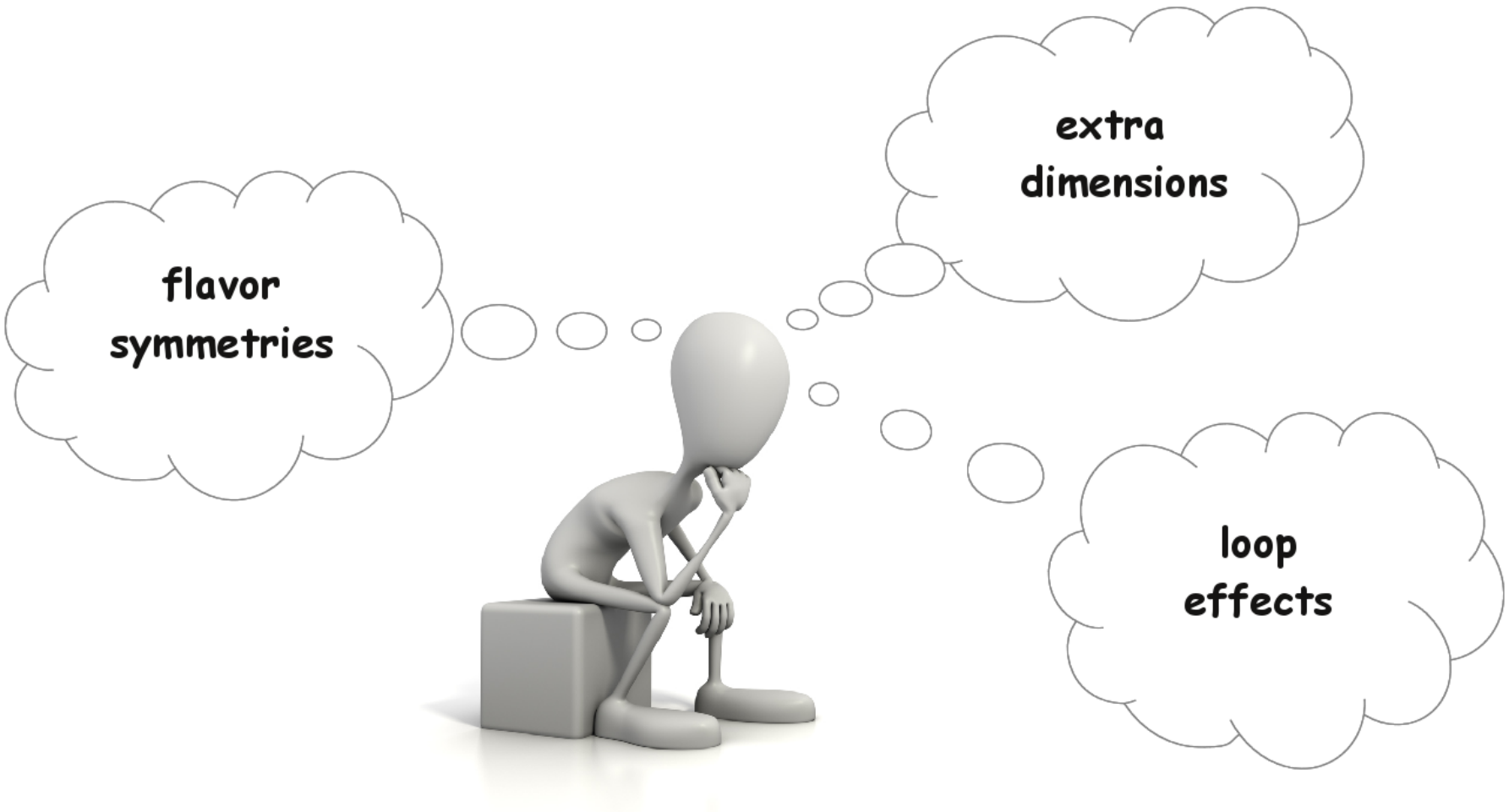
Model Building of Yukawa Hierachies

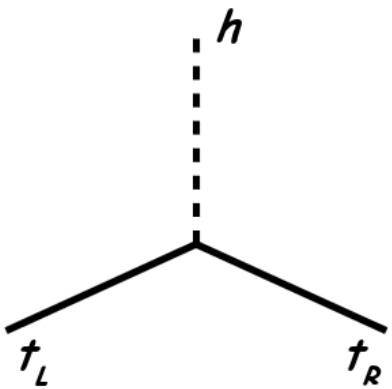


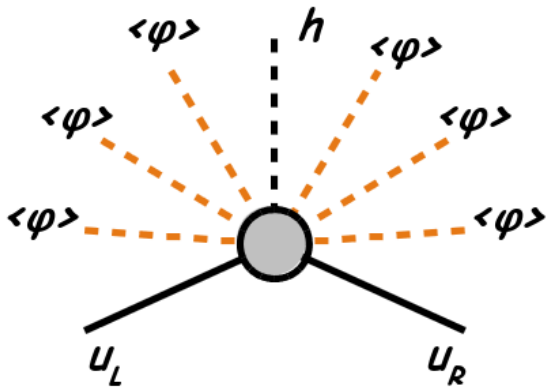
Common theme: “sequester” the light generations from the Higgs

Hierarchy from Symmetry

(Froggatt, Nielsen '79; ...)

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





Simple U(1) model:

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

$h\bar{t}_R t_L$

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

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

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

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"Master Model" that reproduces all masses, CKM, and PMNS mixing:

Leurer, Nir, Seiberg '93

$$Q_q = \begin{pmatrix} 3 \\ 2 \\ 0 \end{pmatrix}, \quad Q_u = \begin{pmatrix} -3 \\ -1 \\ 0 \end{pmatrix}, \quad Q_d = \begin{pmatrix} -3 \\ -2 \\ -2 \end{pmatrix}, \quad Q_\ell = \begin{pmatrix} 3 \\ 3 \\ 3 \end{pmatrix}, \quad Q_e = \begin{pmatrix} -5 \\ -2 \\ 0 \end{pmatrix}.$$

many other options are viable: see e.g. Fedele, Mastroddi, Valli 2009.05587

Implications of Froggatt-Nielsen

$U(1)$ is a gauge symmetry

- Z' gauge bosons with flavor changing couplings
- Z' mass of the order of the flavon vev $\langle\phi\rangle$
- generically very strong constraints from kaon mixing: $m_{Z'} \gtrsim 10^4$ TeV.

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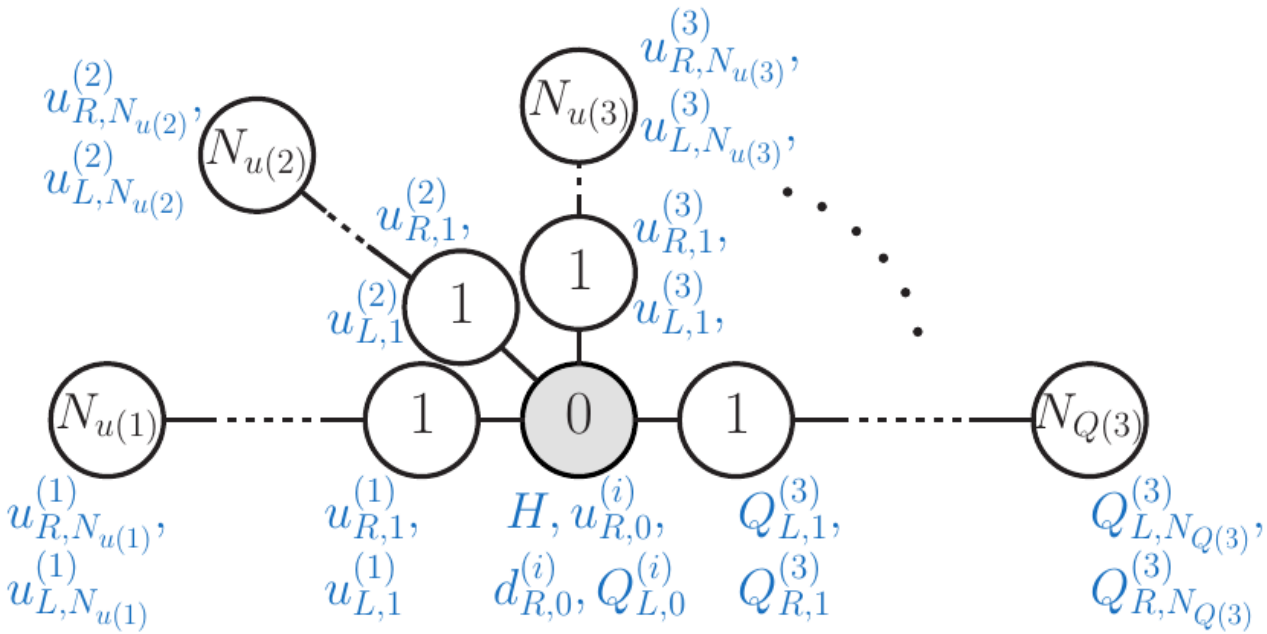
$U(1)$ is a global symmetry

- light pseudo-Nambu-Goldston boson from the spontaneous breaking of the flavor symmetry.
- has generically flavor changing couplings
- could be the axion that solves strong CP problem: "axi-flavon" or "flaxion"
- probed e.g. by $B \to K + \text{inv}$, $K \to \pi + \text{inv}$, $\mu \to e + \text{inv}$

Calibbi, Goertz, Redigolo, Ziegler, Zupan 1612.08040;
Ema, Hamaguchi, Moroi, Nakayam 1612.05492

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)

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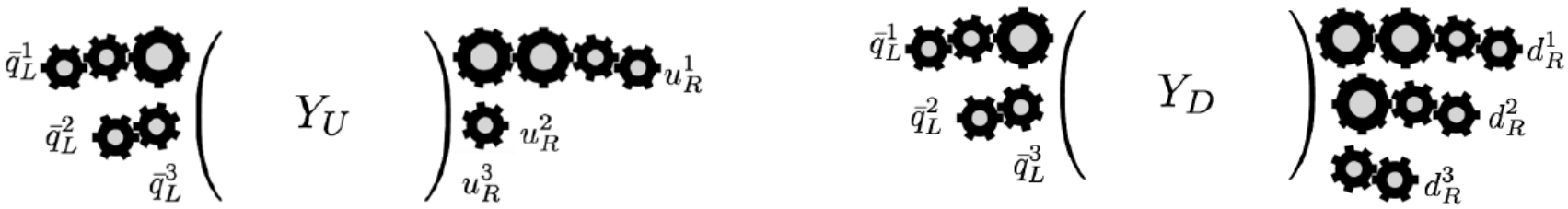

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The number of clockwork sites play a similar role as the $U(1)$ charges in the Froggatt-Nielsen setup

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

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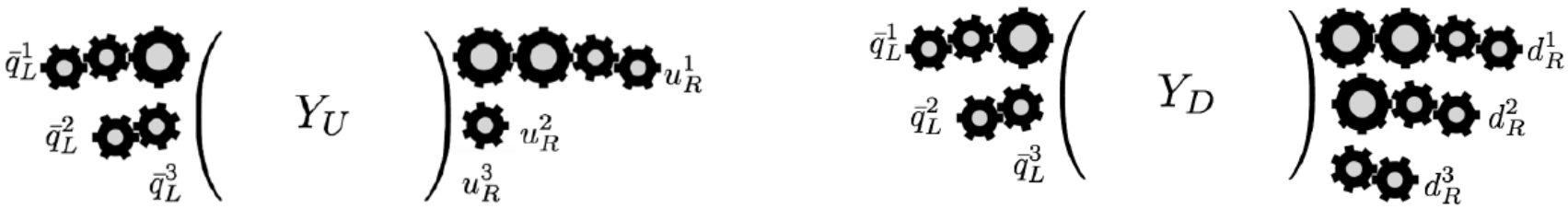

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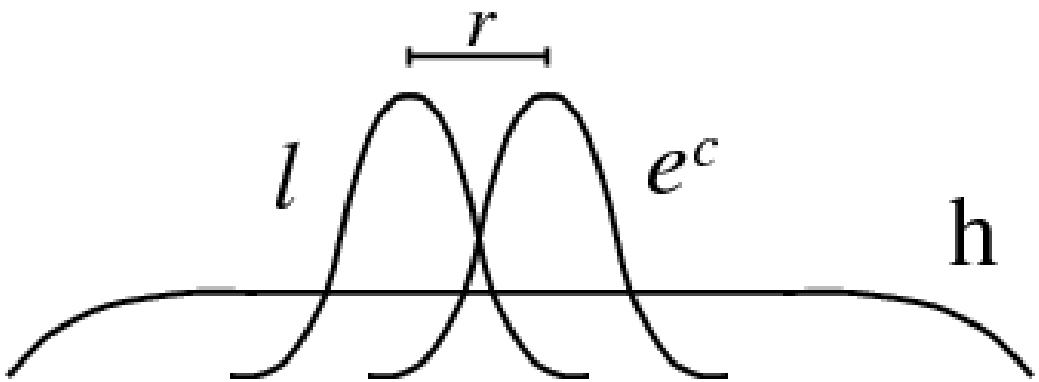
[minimal supersymmetric versions are strongly constrained by kaon mixing, $m_{\text{SUSY}} \gtrsim 1000$ TeV WA, Gadam 2106.09869]

Hierarchy from Geometry

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

fermions are localized at different positions in an extra dimension

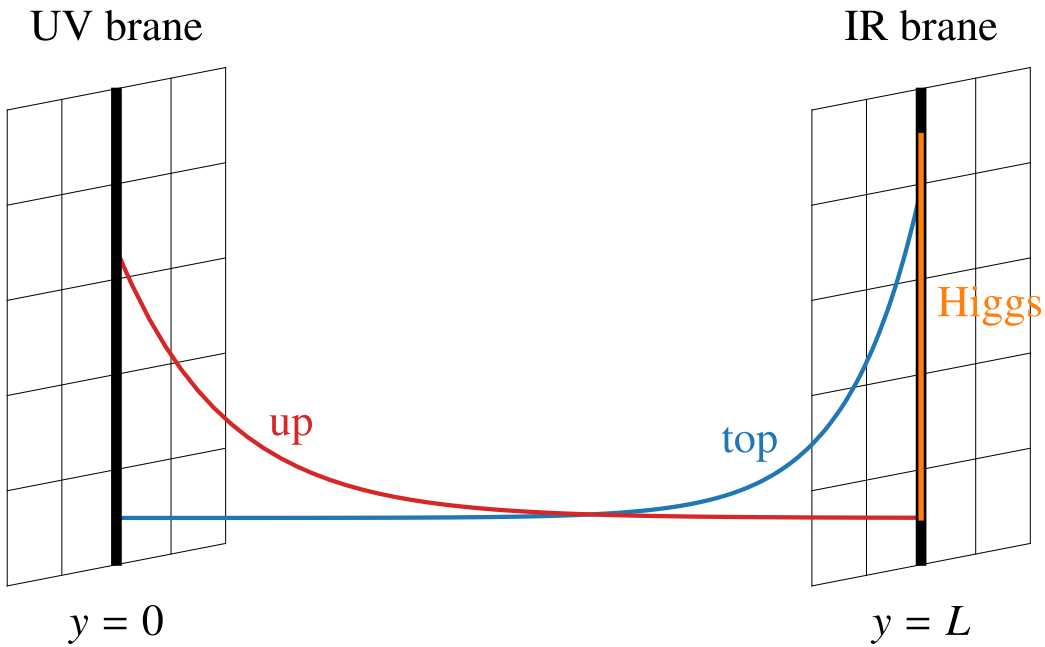


hierarchies from exponentially small wave-function overlap between left-handed and right-handed fermions and the Higgs

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

Warped Extra Dimensions

Most famous example of extradimensional flavor models:
Randall-Sundrum (hep-ph/9905221)



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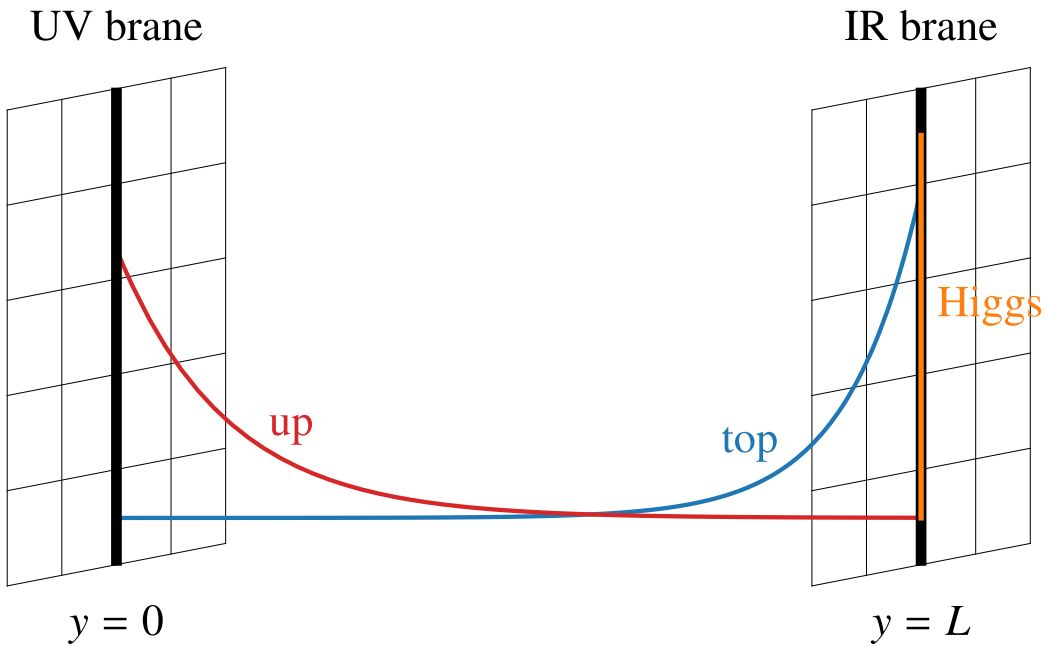


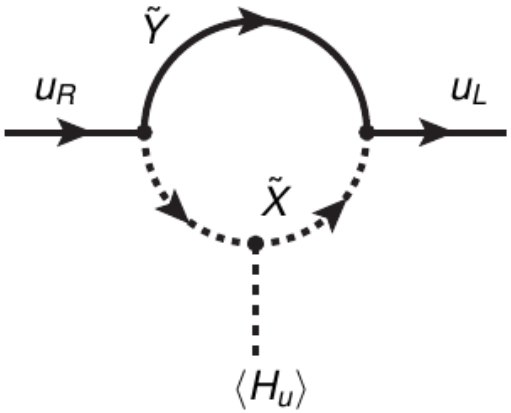
generically one gets Kaluza-Klein excitations of SM gauge bosons with flavor changing couplings

strong constraints from kaon mixing $\Lambda_{RS} \gtrsim 10$ TeV

Hierarchy from Loops

(Weinberg '72; ...)

light fermion masses arise only from quantum effects



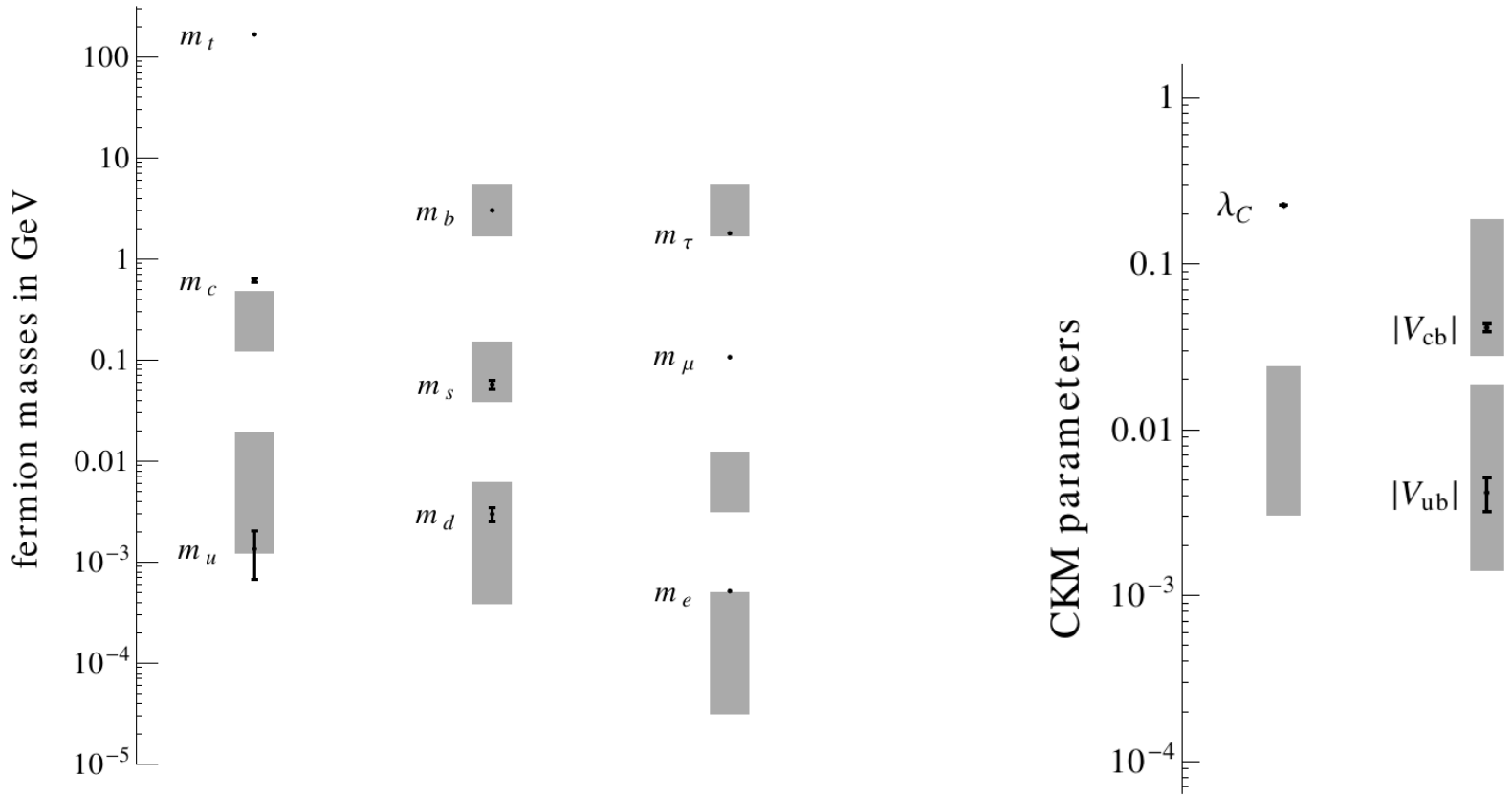
light fermions do not couple
to the higgs directly

couplings are loop-induced
by flavor violating new particles

mass and mixing hierarchies from loop factors

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

Supersymmetric Realization



Hierarchies from loops sort of works in minimal supersymmetric models (sfermions and gauginos run in the loops)

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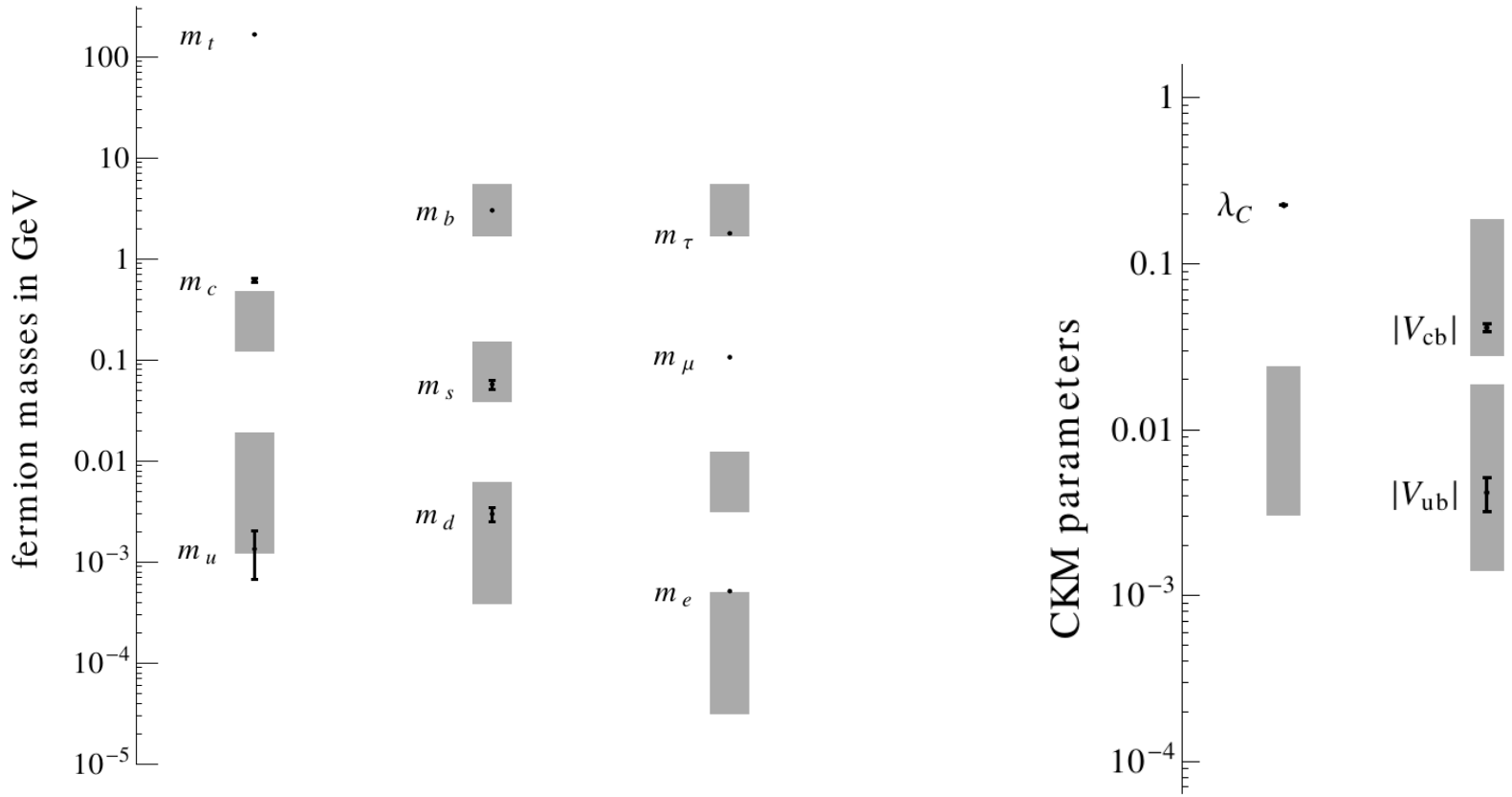

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strongest constraint from kaon mixing, $m_{\text{SUSY}} \gtrsim 1000$ TeV ...

Model Building to Control New Physics FCNCs

- Impose Minimal Flavor Violation:

  (D'Ambrosio, Giudice, Isidori, Strumia hep-ph/0207036; ...)

  SM Yukawas are the only source of flavor violation.

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- $U(2)$ flavor symmetries acting on the first two generations:

  (Barbieri, Dvali, Hall hep-ph/9512388; ...)

  $\rightarrow$ Controls FCNCs between first and second generation;

  Gives massless first and second generation;
  Good zeroth order starting point for flavor model building;
  Expect largest effect in FCNCs involving 3rd generation.

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- Flavor alignment: (Nir, Seiberg hep-ph/9304307; ...)

  New sources of flavor violation are (approximately) diagonal in the fermion mass eigenstate basis;

  Can align either in up sector or down sector.
  $\rightarrow$ main constraints either from kaons or D mesons.

Flavor Deconstruction

- Gauge group G is extended to $G_1 \times G_2 \times G_3$ in the UV, with one G factor assigned to each fermion generation.
- G could be the full SM gauge group, a subgroup, or an extension.
- Motivated by flavor non-universality.
- Symmetry breaking typically in two steps:
  at a high scale break $G_1 \times G_2 \to G_{12}$, then at a lower scale $G_{12} \times G_3 \to G$
- If SM Higgs only charged under G_3 can address the SM flavor puzzle.

Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368; Davighi, Tooby-Smith 2201.07245; Davighi, Isidori 2303.01520; Davighi, Stefanek 2305.16280; Davighi, Gosnay, Miller, Renner 2312.13346; Capdevila, Crivellin, Lizana, Pokorski 2401.00848; Fuentes-Martin, Lizana 2402.09507; Fernandez Navarro, King, Vicente 2404.12442; ...

Other Recent Developments

- Modular Flavor Symmetries: (Feruglio 1706.08749, ...)

  Mainly popular in neutrino mass model building;
  Combine discrete flavor symmetries with Froggatt-Nielsen like hierarchy patters.

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- Generalized Symmetries: (Gaiotto, Kapustin, Seiberg, Willett 1412.5148, ...)

  Extend that notion of what a symmetry is;
  Generators act on extended objects (lines, surfaces, ...);
  Symmetry group elements don't necessarily have an inverse; ...

  Give "selection rules" similar to ordinary symmetries.

  Not clear (to me) how useful they are for flavor model building.

Summary

- Flavor remains one of the key open questions in particle physics.
- SM flavor puzzle motivates new physics that generates hierarchies in the Yukawa couplings.
- NP flavor puzzle suggests that also new physics possess a non-generic flavor structure.
- Flavor model building seeks to address both puzzles by constructing mechanisms to generate hierarchical flavor couplings, integrating them into NP models, and deriving testable phenomenological predictions.