

# Lepton Flavor Violation

## I. The (Extended) Standard Model Flavor Puzzle

SSI<sub>2010</sub>: Neutrinos – Nature’s mysterious messengers  
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## Plan of Lectures

1. The (extended) Standard Model flavor puzzle
  - Introduction
  - The Standard Model
  - The extended Standard Model
2. The New Physics flavor puzzle
3. Leptogenesis

# Introduction

## What are flavors?

Copies of the same gauge representation:  $SU(3)_C \times U(1)_{\text{EM}}$

Up-type quarks       $(3)_{+2/3}$        $u, c, t$

Down-type quarks       $(3)_{-1/3}$        $d, s, b$

Charged leptons       $(1)_{-1}$        $e, \mu, \tau$

Neutrinos       $(1)_0$        $\nu_1, \nu_2, \nu_3$

## What are flavors?

In the interaction basis:

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Quark doublets	$(3, 2)_{+1/6}$	$Q_{Li}$
Up-type quark singlets	$(3, 1)_{+2/3}$	$U_{Ri}$
Down-type quark singlets	$(3, 1)_{-1/3}$	$D_{Ri}$
Lepton doublets	$(1, 2)_{-1/2}$	$L_{Li}$
Charged lepton singlets	$(1, 1)_{-1}$	$E_{Ri}$

In QCD:

$$SU(3)_C$$

Quarks (3)  $u, d, s, c, b, t$

# What is flavor physics?

- Interactions that distinguish among the generations:
  - Neither strong nor electromagnetic interactions
  - Within the SM: Only weak and Yukawa interactions
- In the interaction basis:
  - The weak interactions are also flavor-universal
  - The source of all SM flavor physics: Yukawa interactions among the gauge interaction eigenstates
- Flavor parameters:
  - Parameters with flavor index ( $m_i$ ,  $V_{ij}$ )

## More flavor dictionary

- Flavor universal:

- Coupling/parameters  $\propto \mathbf{1}_{ij}$  in flavor space
- Example: strong interactions

$$\overline{U_R} G^{\mu a} \lambda^a \gamma_\mu \mathbf{1} U_R$$

- Flavor diagonal:

- Coupling/parameters that are diagonal in flavor space
- Example: SM Yukawa interactions in mass basis

$$\overline{U_L} \lambda^u U_R H, \quad \lambda^u = \text{diag}(y_u, y_c, y_t)$$

## And more flavor dictionary

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- Flavor changing:
  - Initial flavor number  $\neq$  final flavor number
  - Flavor number = # particles – # antiparticles
  - $B \rightarrow \psi K$  ( $\bar{b} \rightarrow \bar{c}c\bar{s}$ );  $K^- \rightarrow \mu^-\bar{\nu}_2$  ( $s\bar{u} \rightarrow \mu^-\bar{\nu}_2$ )
- Flavor changing neutral current processes:
  - Flavor changing processes that involve either  $U$  or  $D$  but not both and/or either  $\ell^-$  or  $\nu$  but not both
  - $\mu \rightarrow e\gamma$ ;  $K \rightarrow \pi\nu\bar{\nu}$  ( $s \rightarrow d\nu\bar{\nu}$ );  $D^0 - \bar{D}^0$  mixing ( $c\bar{u} \rightarrow u\bar{c}$ )...
  - FCNC are highly suppressed in the SM

## Why is flavor physics interesting?

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- Flavor physics is sensitive to new physics at  $\Lambda_{\text{NP}} \gg E_{\text{experiment}}$
- The Standard Model flavor puzzle:  
Why are the flavor parameters small and hierarchical?
  - (Why) are the neutrino flavor parameters different?
- The New Physics flavor puzzle:  
If there is NP at the TeV scale, why are FCNC so small?
  - LFV provides theoretically clean null tests of the SM
  - LFV could be present even in MFV models
- $\delta_{\text{KM}}$  cannot explain the baryon asymmetry – a puzzle:  
There must exist new sources of CPV
  - Electroweak baryogenesis? (Testable at the LHC)
  - Leptogenesis? (Window to  $\Lambda_{\text{seesaw}}$ )

## A brief history of FV

- $\Gamma(K \rightarrow \mu\mu) \ll \Gamma(K \rightarrow \mu\nu) \implies$  Charm [GIM, 1970]
- $\Delta m_K \implies m_c \sim 1.5 \text{ GeV}$  [Gaillard-Lee, 1974]
- $\varepsilon_K \neq 0 \implies$  Third generation [KM, 1973]
- $\Delta m_B \implies m_t \gg m_W$  [Various, 1986]

## A brief history of FV

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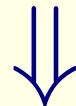
...and hopes for the future history:

- $\Gamma(\mu \rightarrow e\gamma) \neq 0 \implies ???$
- $d_e \neq 0 \implies ???$
- $\Delta m_{\tilde{\mu}\tilde{e}}^2 \neq 0 \implies ???$

# The Standard Model

## The Standard Model

- $G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$
- $\langle \phi(1, 2)_{+1/2} \rangle \neq 0$  breaks  $G_{\text{SM}} \rightarrow SU(3)_C \times U(1)_{EM}$
- Quarks:  $3 \times \{Q_L(3, 2)_{+1/6} + U_R(3, 1)_{+2/3} + D_R(3, 1)_{-1/3}\}$   
Leptons:  $3 \times \{L_L(1, 2)_{-1/2} + E_R(1, 1)_{-1}\}$



$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{kinetic+gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

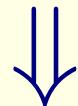
- $\mathcal{L}_{\text{SM}}$  depends on 18 parameters
- All but one ( $m_H$ ) have been measured

## Flavor Symmetry

- $\mathcal{L}_{\text{kinetic+gauge}} + \mathcal{L}_{\text{Higgs}}$  has a large global symmetry:  
 $G_{\text{global}} = U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$
- $Q_L \rightarrow V_Q Q_L, \quad U_R \rightarrow V_U U_R, \quad D_R \rightarrow V_D D_R,$   
 $L_L \rightarrow V_L L_L, \quad E_R \rightarrow V_E E_R$
- Take, for example  $\mathcal{L}_{\text{kinetic+gauge}}$  for  $Q_L(3, 2)_{+1/6}$ :  
 $i\overline{Q_L}_i(\partial_\mu + \frac{i}{2}g_s G_\mu^a \lambda^a + \frac{i}{2}g_s W_\mu^b \tau^b + \frac{i}{6}g' B_\mu)\gamma^\mu \delta_{ij} Q_{Lj}$   
 $\overline{Q_L} \mathbf{1} Q_L \rightarrow \overline{Q_L} V_Q^\dagger \mathbf{1} V_Q Q_L = \overline{Q_L} \mathbf{1} Q_L$
- Another example:  $\mathcal{L}_{\text{kinetic+gauge}}$  for  $L_L(1, 2)_{-1/2}$ :  
 $i\overline{L_L}_i(\partial_\mu + \frac{i}{2}g_s W_\mu^b \tau^b - \frac{i}{2}g' B_\mu)\gamma^\mu \delta_{ij} L_{Lj}$   
 $\overline{L_L} \mathbf{1} L_L \rightarrow \overline{L_L} V_L^\dagger \mathbf{1} V_L L_L = \overline{L_L} \mathbf{1} L_L$

## Flavor Violation

- $\mathcal{L}_{\text{Yukawa}} = \overline{Q_L}_i Y_{ij}^u \tilde{\phi} U_{Rj} + \overline{Q_L}_i Y_{ij}^d \phi D_{Rj} + \overline{L_L}_i Y_{ij}^e \phi E_{Rj}$   
breaks  $G_{\text{global}} \rightarrow U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$
- Flavor physics:  
interactions that break the  $[SU(3)]^5$  symmetry



- $Q_L \rightarrow V_Q Q_L, \quad U_R \rightarrow V_U U_R, \quad D_R \rightarrow V_D D_R$   
 $L_L \rightarrow V_L L_L, \quad E_R \rightarrow V_E E_R$   
= Change of interaction basis
- $Y^d \rightarrow V_Q Y^d V_D^\dagger, \quad Y^u \rightarrow V_Q Y^u V_U^\dagger, \quad Y^e \rightarrow V_L Y^e V_E^\dagger$
- Can be used to reduce the number of parameters in  $Y^u, Y^d, Y^e$

## The quark flavor parameters

- Convenient (but not unique) interaction basis:

$$Y^d \rightarrow V_Q Y^d V_D^\dagger = \lambda^d, \quad Y^u \rightarrow V_Q Y^u V_U^\dagger = V^\dagger \lambda^u$$

- $\lambda^d, \lambda^u$  diagonal and real:

$$\lambda^d = \begin{pmatrix} y_d & & & \\ & y_s & & \\ & & y_b & \\ & & & \end{pmatrix}; \quad \lambda^u = \begin{pmatrix} y_u & & & \\ & y_c & & \\ & & y_t & \\ & & & \end{pmatrix}$$

- $V$  unitary with 3 real ( $\lambda, A, \rho$ ) and 1 imaginary ( $\eta$ ) parameters:

$$V \simeq \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho + i\eta) \\ -\lambda & 1 & A\lambda^2 \\ A\lambda^3(1 - \rho + i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

- Another convenient basis:  $Y^d \rightarrow V \lambda^d, \quad Y^u \rightarrow \lambda^u$

# Kobayashi and Maskawa

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CP violation  $\leftrightarrow$  Complex couplings:

- Hermiticity:  $\mathcal{L} \sim g_{ijk}\phi_i\phi_j\phi_k + g_{ijk}^*\phi_i^\dagger\phi_j^\dagger\phi_k^\dagger$
- CP transformation:  $\phi_i\phi_j\phi_k \leftrightarrow \phi_i^\dagger\phi_j^\dagger\phi_k^\dagger$
- CP is a good symmetry if  $g_{ijk} = g_{ijk}^*$

The number of real and imaginary quark flavor parameters:

- With two generations:  

$$2 \times (4_R + 4_I) - 3 \times (1_R + 3_I) + 1_I = 5_R + 0_I$$
- With three generations:  

$$2 \times (9_R + 9_I) - 3 \times (3_R + 6_I) + 1_I = 9_R + 1_I$$
- The two generation SM is CP conserving  
 The three generation SM is CP violating

## The mass basis

- To transform to the mass basis:  $D_L \rightarrow D_L, U_L \rightarrow VU_L$
- $m_q = y_q \langle \phi \rangle$
- $V$  = The CKM matrix

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \overline{U_L} V \gamma^\mu D_L W_\mu^+ + \text{h.c.}$$

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

- $\eta$  - the only source of CP violation

## The lepton flavor parameters

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- Convenient interaction basis:  $Y^e \rightarrow V_L Y^e V_E^\dagger = \lambda^e$
- $\lambda^e$  diagonal and real

$[SU(3)_L \times SU(3)_E \rightarrow U(1)_e \times U(1)_\mu \times U(1)_\tau]$ :

$$\lambda^e = \begin{pmatrix} y_e \\ & y_\mu \\ & & y_\tau \end{pmatrix}$$

The number of real and imaginary lepton flavor parameters:

- With three generations:

$$1 \times (9_R + 9_I) - 2 \times (3_R + 6_I) + 3_I = 3_R + 0_I$$

- The mass basis:  $m_\ell = y_\ell \langle \phi \rangle$
- The lepton sector of the SM: neither mixing nor CP violation

# The SM Flavor Puzzle

## Smallness and Hierarchy

$$y_t \sim 1, \quad y_c \sim 10^{-2}, \quad y_u \sim 10^{-5}$$

$$y_b \sim 10^{-2}, \quad y_s \sim 10^{-3}, \quad y_d \sim 10^{-4}$$

$$y_\tau \sim 10^{-2}, \quad y_\mu \sim 10^{-3}, \quad y_e \sim 10^{-6}$$

$$|V_{us}| \sim 0.2, \quad |V_{cb}| \sim 0.04, \quad |V_{ub}| \sim 0.004, \quad \delta_{\text{KM}} \sim 1$$

- For comparison:  $g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 1$
- The SM flavor parameters have structure:  
smallness and hierarchy
- Why? = The SM flavor puzzle

## The Froggatt-Nielsen (FN) mechanism

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- Approximate “horizontal” symmetry (e.g.  $U(1)_H$ )
- Small breaking parameter  $\epsilon = \langle S_{-1} \rangle / \Lambda \ll 1$
- Each quark or lepton field carries an FN charge  $H(\psi)$
- Selection rules:
  - $Y_{ij}^d \sim \epsilon^{H(Q_i) + H(\bar{d}_j) + H(\phi_d)}$
  - $Y_{ij}^u \sim \epsilon^{H(Q_i) + H(\bar{u}_j) + H(\phi_u)}$
  - $Y_{ij}^e \sim \epsilon^{H(L_i) + H(\bar{\ell}_j) + H(\phi_d)}$

## The FN mechanism: An example

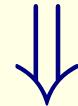
- $H(Q_i) = 2, 1, 0, \quad H(\bar{u}_j) = 2, 1, 0, \quad H(\phi_u) = 0$

$$Y^u \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

- $y_t : y_c : y_u \sim 1 : \epsilon^2 : \epsilon^4$
- $(V_L^u)_{12} \sim \epsilon, \quad (V_L^u)_{23} \sim \epsilon, \quad (V_L^u)_{13} \sim \epsilon^2$

## The FN mechanism: a viable model

- Approximate “horizontal” symmetry (e.g.  $U(1)_H$ )
- Small breaking parameter  $\epsilon = \langle S_{-1} \rangle / \Lambda \ll 1$
- $\mathbf{10}(2, 1, 0), \quad \bar{\mathbf{5}}(0, 0, 0)$



$$y_t : y_c : y_u \sim 1 : \epsilon^2 : \epsilon^4$$

$$y_b : y_s : y_d \sim 1 : \epsilon : \epsilon^2$$

$$y_\tau : y_\mu : y_e \sim 1 : \epsilon : \epsilon^2$$

$$|V_{us}| \sim |V_{cb}| \sim \epsilon, \quad |V_{ub}| \sim \epsilon^2, \quad \delta_{\text{KM}} \sim 1$$

## The FN mechanism: Predictions (quarks)

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- In the quark sector: 8 FN charges, 9 observables
- One prediction that is independent of charge assignments:

$$|V_{ub}| \sim |V_{us} V_{cb}|$$

Experimentally correct to within a factor of 2

- In addition, six inequalities:

$$|V_{us}| \gtrsim \frac{m_d}{m_s}, \frac{m_u}{m_c}; \quad |V_{ub}| \gtrsim \frac{m_d}{m_b}, \frac{m_u}{m_t}; \quad |V_{cb}| \gtrsim \frac{m_s}{m_b}, \frac{m_c}{m_t}$$

Experimentally fulfilled

- When ordering the quarks by mass:

$V_{CKM} \sim \mathbf{1}$  (diagonal terms not suppressed parameterically)

Experimentally fulfilled

# The Extended Standard Model

## Neutrino Masses – experimentally

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$$\Delta m_{21}^2 = (7.6 \pm 0.2) \times 10^{-5} \text{ eV}^2$$

$$|\Delta m_{32}^2| = (2.4 \pm 0.1) \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta_{12} = 0.87 \pm 0.03$$

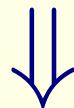
$$\sin^2 2\theta_{23} > 0.92$$

## Neutrino Masses – theoretically

- The only neutrino mass terms that can be written with the SM particle content:

$$-\mathcal{L}_{M_\nu} = \frac{1}{2} \sum_{k=1}^3 m_k (\bar{\nu}_k^c \nu_k + \text{h.c.})$$

- $\mathcal{L}_{M_\nu}$  violates  $B - L \implies$  Forbidden
- Within the SM, neutrino masses vanish to all orders in perturbation theory and even non-perturbatively



The SM must be extended

# The Extended Standard Model

The SM:

- $G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$
- $\langle \phi(1, 2)_{+1/2} \rangle \neq 0$  breaks  $G_{\text{SM}} \rightarrow SU(3)_C \times U(1)_{EM}$
- Quarks:  $3 \times \{Q_L(3, 2)_{+1/6} + U_R(3, 1)_{+2/3} + D_R(3, 1)_{-1/3}\}$   
Leptons:  $3 \times \{L_L(1, 2)_{-1/2} + E_R(1, 1)_{-1}\}$

The ESM:

- It is possible to extend the SM while maintaining the symmetry, the pattern of SSB, and the particle content, by giving up on renormalizability
- The SM = Low energy effective theory  
Not valid above a certain mass scale

## The ESM Lagrangian

$$\mathcal{L}_{\text{ESM}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{d=5}$$

$$\mathcal{L}_{d=5} = \frac{Z_{ij}^\nu}{\Lambda} L_i L_j \phi \phi + \text{h.c.}$$

$$\mathcal{L}_{M_\nu} = \frac{Z_{ij}^\nu}{2} \frac{v^2}{\Lambda} \bar{\nu}_i \nu_j^c + \text{h.c.}$$

$$(M_\nu)_{ij} = Z_{ij}^\nu \frac{v^2}{\Lambda}$$

## Flavor Violation

- $\mathcal{L}_{\text{kinetic+gauge}} + \mathcal{L}_{\text{Higgs}}$  has a large global symmetry:  
 $G_{\text{global}} = [U(3)]^5$
- $\mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{d=5}$  break  $G_{\text{global}} \rightarrow U(1)_B$



- $Q_L \rightarrow V_Q Q_L, \quad U_R \rightarrow V_U U_R, \quad D_R \rightarrow V_D D_R$   
 $L_L \rightarrow V_L L_L, \quad E_R \rightarrow V_E E_R$   
= Change of interaction basis
- $Y^d \rightarrow V_Q Y^d V_D^\dagger, \quad Y^u \rightarrow V_Q Y^u V_U^\dagger,$   
 $Y^e \rightarrow V_L Y^e V_E^\dagger, \quad Z^\nu \rightarrow V_L Z^\nu V_L^T$
- Can be used to reduce the number of parameters in  
 $Y^u, Y^d, Y^e, Z^\nu$

## The lepton flavor parameters

- $(9_R + 9_I) + (6_R + 6_I) - 2 \times (3_R + 6_I) = 9_R + 3_I$
- Convenient (but not unique) interaction basis:  
 $Y^e \rightarrow \lambda^e, \quad Z^\nu \rightarrow U^* \lambda^\nu U^\dagger$
- $v\lambda^e = \text{diag}(m_e, m_\mu, m_\tau)$   
 $(v^2/\Lambda)\lambda^\nu = \text{diag}(m_1, m_2, m_3)$
- $U$  = the leptonic mixing matrix:  
 $\mathcal{L}_{W^\pm}^\ell = \frac{g}{\sqrt{2}} \overline{E_L i} \gamma^\mu U_{ij} \nu_{Lj} W_\mu^\pm + \text{h.c.}$   
with 3 real and 3 imaginary parameters
- The lepton sector of the ESM: mixing and CP violation

# The ESM Flavor Puzzle

## The Froggatt-Nielsen (FN) mechanism

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- Approximate “horizontal” symmetry (e.g.  $U(1)_H$ )
- Small breaking parameter  $\epsilon = \langle S_{-1} \rangle / \Lambda \ll 1$
- Each quark and lepton field carries an FN charge  $H(\phi)$
- Selection rules:
  - $Y_{ij}^d \sim \epsilon^{H(Q_i) + H(\bar{d}_j) + H(\phi_d)}$
  - $Y_{ij}^u \sim \epsilon^{H(Q_i) + H(\bar{u}_j) + H(\phi_u)}$
  - $Y_{ij}^e \sim \epsilon^{H(L_i) + H(\bar{\ell}_j) + H(\phi_d)}$
  - $Z_{ij}^\nu \sim \epsilon^{H(L_i) + H(L_j) + 2H(\phi_u)}$

## The FN mechanism: Predictions (leptons)

---

- In the lepton sector: 5 FN charges, 9 observables
- Four predictions that are independent of charge assignments:

$$m_{\nu_i}/m_{\nu_j} \sim |U_{ij}|^2$$

$$|U_{e3}| \sim |U_{e2}U_{\mu 3}|$$

- In addition, three inequalities:

$$|U_{e2}| \gtrsim \frac{m_e}{m_\mu}; \quad |U_{e3}| \gtrsim \frac{m_e}{m_\tau}; \quad |U_{\mu 3}| \gtrsim \frac{m_\mu}{m_\tau}$$

- When ordering the leptons by mass:

$$U \sim 1$$

## Testing FN with Neutrinos

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- The data:

- $\Delta m_{21}^2 / |\Delta m_{32}^2| = 0.030 \pm 0.003$
- $\sin \theta_{12} = 0.57 \pm 0.02$ ,  $\sin \theta_{23} = 0.67^{+0.07}_{-0.04}$ ,  $\sin \theta_{13} = 0^{+0.07}_{-0.0}$

- The tests:

- $s_{23} \sim 1$ ,  $m_2/m_3 \sim \epsilon^x$ ?  
Inconsistent with FN
- $s_{23} \sim 1$ ,  $s_{12} \sim 1$ ,  $s_{13} \sim \epsilon^x$ ?  
Inconsistent with FN

- $\sin^2 2\theta_{23} = 1 - \epsilon^x$ ?  
Inconsistent with FN

## Neutrino Mass Anarchy

- Facts:

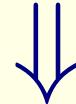
- $\sin \theta_{23} \sim 0.7 > \text{any } |V_{ij}|$
- $\sin \theta_{12} \sim 0.6 > \text{any } |V_{ij}|$
- $m_2/m_3 \gtrsim 1/6 > \text{any } m_i/m_j$  for charged fermions
- $\sin \theta_{13} \sim 0.1$  is still possible

- Possible interpretation:

- Neutrino parameters are all of  $O(1)$  (no structure):  
Neutrino mass anarchy
- Consistent with FN
- Close to SU(5)-GUT+FN predictions:  
 $s_{23} \sim \frac{m_s/m_b}{|V_{cb}|} \sim 1; \quad s_{12} \sim \frac{m_d/m_s}{|V_{us}|} \sim 0.2; \quad s_{13} \sim \frac{m_d/m_b}{|V_{ub}|} \sim 0.5$

## The FN mechanism: a viable model

- Approximate “horizontal” symmetry (e.g.  $U(1)_H$ )
- Small breaking parameter  $\epsilon = \langle S_{-1} \rangle / \Lambda \ll 1$
- $\mathbf{10}(2, 1, 0), \quad \bar{\mathbf{5}}(0, 0, 0)$



$$y_t : y_c : y_u \sim 1 : \epsilon^2 : \epsilon^4$$

$$y_b : y_s : y_d \sim 1 : \epsilon : \epsilon^2$$

$$y_\tau : y_\mu : y_e \sim 1 : \epsilon : \epsilon^2$$

$$|V_{us}| \sim |V_{cb}| \sim \epsilon, \quad |V_{ub}| \sim \epsilon^2, \quad \delta_{\text{KM}} \sim 1$$

+

$$m_3 : m_2 : m_1 \sim 1 : 1 : 1$$

$$|U_{e2}| \sim 1, \quad |U_{\mu 3}| \sim 1, \quad |U_{e3}| \sim 1$$

## Structure is in the eye of the beholder

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$$|U|_{3\sigma} = \begin{pmatrix} 0.79 - 0.86 & 0.50 - 0.61 & 0.0 - 0.2 \\ 0.25 - 0.53 & 0.47 - 0.73 & 0.56 - 0.79 \\ 0.21 - 0.51 & 0.42 - 0.69 & 0.61 - 0.83 \end{pmatrix}$$

- Tribimaximal-ists:

$$|U|_{TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \\ \sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

- Anarch-ists:

$$|U|_{\text{anarchy}} = \begin{pmatrix} \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \end{pmatrix}$$

## The (E)SM flavor confusion

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- The charged fermion flavor parameters: smallness and hierarchy
- Possibly a hint for NP: approximate symmetry, dynamics...
- Strong hierarchy, small mixing  $\implies$  Abelian symmetry?
- The three measured neutrino flavor parameters: neither small nor hierarchical
- Anarchy? Tribimaximal mixing? Neither?
- No symmetry? Non-Abelian symmetry?
- $U_{e3}$  likely to provide further guidance
- The difference between neutrinos and charged fermions is probably a hint to something deep...

Thanks to my low-energy-physics collaborators:

Gudrun Hiller, YN

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Yuval Grossman, YN, Gilad Perez

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