Lepton Flavor Violation

I. The (Extended) Standard Model Flavor Puzzle

SSI_{2010}: Neutrinos – Nature's mysterious messengers

SLAC, 9 August 2010

Yossi Nir (*Weizmann Institute of Science*)

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: $SU(3)_{\rm C}\times U(1)_{\rm EM}$

Up-type quarks	$(3)_{+2/3}$	u,c,t
Down-type quarks	$(3)_{-1/3}$	d,s,b
Charged leptons	$(1)_{-1}$	e,μ,τ
Neutrinos	$(1)_0$	ν_1,ν_2,ν_3

What are flavors?

In the interaction basis:

$SU(3)_{\rm C} \times SU(2)_{\rm L} \times U(1)_{\rm Y}$

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:

$SU(3)_{\rm C}$

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/paremeters $\propto \mathbf{1}_{ij}$ in flavor space
  - Example: strong interactions
    $\overline{U_R} G^{\mu a} \lambda^a \gamma_\mu \mathbf{1} U_R$
- Flavor diagonal:
  - Coupling/paremeters that are diagonal in flavor space
  - Example: SM Yukawa interactions in mass basis
    $\overline{U_L} \lambda^u U_R H, \quad \lambda^u = \mathrm{diag}(y_u, y_c, y_t)$

And more flavor dictionary

- Flavor changing:
  - Initial flavor number $\neq$ final flavor number
  - Flavor number = # particles – # antiparticles
  - $B \to \psi K \quad (\bar{b} \to \bar{c} c \bar{s})$; $K^- \to \mu^- \overline{\nu_2} \quad (s\bar{u} \to \mu^- \overline{\nu_2})$
- Flavor changing neutral current processes:
  - Flavor changing processes that involve either U or D but not both and/or either ℓ^- or ν but not both
  - $\mu \to e\gamma$; $K \to \pi\nu\bar{\nu}$ $(s \to d\nu\bar{\nu})$; $D^0 - \overline{D}^0$ mixing $(c\bar{u} \to u\bar{c})$...
  - FCNC are highly suppressed in the SM

Why is flavor physics interesting?

- Flavor physics is sensitive to new physics at $\Lambda_{\rm NP} \gg E_{\rm experiment}$
- 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
- $\delta_{\rm KM}$ cannot explain the baryon asymmetry – a puzzle:
  There must exist new sources of CPV
  - Electroweak baryogenesis? (Testable at the LHC)
  - Leptogenesis? (Window to $\Lambda_{\rm seesaw}$)

A brief history of FV

- $\Gamma(K \to \mu\mu) \ll \Gamma(K \to \mu\nu) \implies$ Charm [GIM, 1970]
- $\Delta m_K \implies m_c \sim 1.5\ GeV$ [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

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

...and hopes for the future history:

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

The Standard Model

The Standard Model

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

$$\Downarrow$$

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

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

Flavor Violation

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

$$\Downarrow$$

- $Q_L \to V_Q Q_L, \;\; U_R \to V_U U_R, \;\; D_R \to V_D D_R$
  $L_L \to V_L L_L, \;\; E_R \to V_E E_R$
  $=$ Change of interaction basis
- $Y^d \to V_Q Y^d V_D^\dagger, \quad Y^u \to V_Q Y^u V_U^\dagger, \quad Y^e \to V_L Y^e V_E^\dagger$
- 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:
  $Y^d \to V_Q Y^d V_D^\dagger = \lambda^d, \quad Y^u \to V_Q Y^u V_U^\dagger = V^\dagger \lambda^u$

- λ^d, λ^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 (λ, A, ρ) and 1 imaginary (η) 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: $Y^d \to V\lambda^d, \quad Y^u \to \lambda^u$

Kobayashi and Maskawa

CP violation $\leftrightarrow$ Complex couplings:

- Hermiticity: $\mathcal{L} \sim g_{ijk}\phi_i\phi_j\phi_k + g^*_{ijk}\phi^\dagger_i\phi^\dagger_j\phi^\dagger_k$
- CP transformation: $\phi_i\phi_j\phi_k \leftrightarrow \phi^\dagger_i\phi^\dagger_j\phi^\dagger_k$
- 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: $D_L \to D_L, \;\; U_L \to V U_L$
- $m_q = y_q \langle \phi \rangle$
- V = The CKM matrix

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

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

- η - the only source of CP violation

The lepton flavor parameters

- Convenient interaction basis: $Y^e \to V_L Y^e V_E^\dagger = \lambda^e$
- λ^e diagonal and real
  $[SU(3)_L \times SU(3)_E \to U(1)_e \times U(1)_\mu \times U(1)_\tau]$:
  $$\lambda^e = \begin{pmatrix} y_e & & \\ & y_\mu & \\ & & y_\tau \end{pmatrix}$$

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

$$y_t \sim 1, \quad y_c \sim 10^{-2}, \quad y_u \sim 10^{-5}$$
$$y_b \sim 10^{-2}, \quad y_s \sim 10^{-3}, \quad y_d \sim 10^{-4}$$
$$y_\tau \sim 10^{-2}, \quad y_\mu \sim 10^{-3}, \quad y_e \sim 10^{-6}$$
$$|V_{us}| \sim 0.2, \quad |V_{cb}| \sim 0.04, \quad |V_{ub}| \sim 0.004, \quad \delta_{\rm KM} \sim 1$$

- 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

- 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:
  - $Y^d_{ij} \sim \epsilon^{H(Q_i)+H(\bar{d}_j)+H(\phi_d)}$
  - $Y^u_{ij} \sim \epsilon^{H(Q_i)+H(\bar{u}_j)+H(\phi_u)}$
  - $Y^e_{ij} \sim \epsilon^{H(L_i)+H(\bar{\ell}_j)+H(\phi_d)}$

The FN mechanism: An example

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

$$\Downarrow$$

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

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

The FN mechanism: a viable model

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

$$\Downarrow$$

$$y_t : y_c : y_u \sim 1 : \epsilon^2 : \epsilon^4$$
$$y_b : y_s : y_d \sim 1 : \epsilon : \epsilon^2$$
$$y_\tau : y_\mu : y_e \sim 1 : \epsilon : \epsilon^2$$
$$|V_{us}| \sim |V_{cb}| \sim \epsilon, \quad |V_{ub}| \sim \epsilon^2, \quad \delta_{\rm KM} \sim 1$$

The FN mechanism: Predictions (quarks)

- In the quark sector: 8 FN charges, 9 observables
- One prediction that is independent of charge assignments:
  $\boxed{|V_{ub}| \sim |V_{us}V_{cb}|}$
  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

$$
\begin{aligned}
\Delta m^2_{21} &= (7.6 \pm 0.2) \times 10^{-5}\ \mathrm{eV}^2 \\
|\Delta m^2_{32}| &= (2.4 \pm 0.1) \times 10^{-3}\ \mathrm{eV}^2 \\
\sin^2 2\theta_{12} &= 0.87 \pm 0.03 \\
\sin^2 2\theta_{23} &> 0.92
\end{aligned}
$$

Neutrino Masses – theoretically

- The only neutrino mass terms that can be written with the SM particle content:
  $-\mathcal{L}_{M_\nu} = \frac{1}{2} \sum_{k=1}^{3} m_k (\overline{\nu}_k^c \nu_k + \text{h.c.})$
- $\mathcal{L}_{M_\nu}$ violates $B - L \Longrightarrow$ Forbidden
- Within the SM, neutrino masses vanish to all orders in perturbation theory and even non-perturbatively

$$\Downarrow$$

The SM must be extended

The Extended Standard Model

The SM:

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

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

$$
\begin{aligned}
\mathcal{L}_{\rm ESM} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{d=5} \\
\mathcal{L}_{d=5} &= \frac{Z^\nu_{ij}}{\Lambda} L_i L_j \phi\phi + {\rm h.c.} \\
\mathcal{L}_{M_\nu} &= \frac{Z^\nu_{ij}}{2}\frac{v^2}{\Lambda}\bar{\nu}_i \nu^c_j + {\rm h.c.} \\
(M_\nu)_{ij} &= Z^\nu_{ij}\frac{v^2}{\Lambda}
\end{aligned}
$$

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 $G_{\text{global}} \to U(1)_B$

$$\Downarrow$$

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

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:
  $Y^e \to \lambda^e, \quad Z^\nu \to U^* \lambda^\nu U^\dagger$
- $v\lambda^e = \mathrm{diag}(m_e, m_\mu, m_\tau)$
  $(v^2/\Lambda)\lambda^\nu = \mathrm{diag}(m_1, m_2, m_3)$
- U = the leptonic mixing matrix:
  $\mathcal{L}^\ell_{W^\pm} = \frac{g}{\sqrt{2}} \overline{E_{Li}} \gamma^\mu U_{ij} \nu_{Lj} W^-_\mu + \mathrm{h.c.}$
  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

- 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:
  - $Y^d_{ij} \sim \epsilon^{H(Q_i)+H(\bar{d}_j)+H(\phi_d)}$
  - $Y^u_{ij} \sim \epsilon^{H(Q_i)+H(\bar{u}_j)+H(\phi_u)}$
  - $Y^e_{ij} \sim \epsilon^{H(L_i)+H(\bar{\ell}_j)+H(\phi_d)}$
  - $Z^\nu_{ij} \sim \epsilon^{H(L_i)+H(L_j)+2H(\phi_u)}$

The FN mechanism: Predictions (leptons)

- In the lepton sector: 5 FN charges, 9 observables
- Four predictions that are independent of charge assignments:
  $\boxed{m_{\nu_i}/m_{\nu_j} \sim |U_{ij}|^2}$
  $|U_{e3}| \sim |U_{e2}U_{\mu 3}|$
- 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:
  $U \sim \mathbf{1}$

Testing FN with Neutrinos

- The data:
  - $\Delta m^2_{21}/|\Delta m^2_{32}| = 0.030 \pm 0.003$
  - $\sin\theta_{12} = 0.57 \pm 0.02, \quad \sin\theta_{23} = 0.67^{+0.07}_{-0.04}, \quad \sin\theta_{13} = 0^{+0.07}_{-0.0}$
- The tests:
  - $s_{23} \sim 1, \quad m_2/m_3 \sim \epsilon^x$?
    Inconsistent with FN
  - $s_{23} \sim 1, \quad s_{12} \sim 1, \quad s_{13} \sim \epsilon^x$?
    Inconsistent with FN
  - $\sin^2 2\theta_{23} = 1 - \epsilon^x$?
    Inconsistent with FN

Neutrino Mass Anarchy

- Facts:
  - $\sin\theta_{23} \sim 0.7 >$ any $|V_{ij}|$
  - $\sin\theta_{12} \sim 0.6 >$ any $|V_{ij}|$
  - $m_2/m_3 \gtrsim 1/6 >$ 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 $\epsilon = \langle S_{-1} \rangle / \Lambda \ll 1$
- $\mathbf{10}(2,1,0), \quad \bar{\mathbf{5}}(0,0,0)$

$$\Downarrow$$

$$y_t : y_c : y_u \sim 1 : \epsilon^2 : \epsilon^4$$
$$y_b : y_s : y_d \sim 1 : \epsilon : \epsilon^2$$
$$y_\tau : y_\mu : y_e \sim 1 : \epsilon : \epsilon^2$$
$$|V_{us}| \sim |V_{cb}| \sim \epsilon, \quad |V_{ub}| \sim \epsilon^2, \quad \delta_{\rm KM} \sim 1$$

$$+$$

$$m_3 : m_2 : m_1 \sim 1 : 1 : 1$$
$$|U_{e2}| \sim 1, \quad |U_{\mu 3}| \sim 1, \quad |U_{e3}| \sim 1$$

Structure is in the eye of the beholder

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

- 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

- The charged fermion flavor parameters: smallness and hierarchy
- Possibly a hint for NP: approximate symmetry, dynamics...
- Strong hierarchy, small mixing $\Longrightarrow$ Abelian symmetry?
- The three measured neutrino flavor parameters: neither small nor hierarchical
- Anarchy? Tribimaximal mixing? Neither?
- No symmetry? Non-Ablian 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

JHEP 0803 (2008) 046 [arXiv:0802.0916]

Gudrun Hiller, Yonit Hochberg, YN

JHEP 0903 (2009) 115 [arXiv:0812.0511]

JHEP 1003 (2010) 079 [arXiv:1001.1513]

Kfir Blum, Yuval Grossman, YN, Gilad Perez

Phys. Rev. Lett. 102 (2009) 211802 [arXiv:0903.2118]

Yuval Grossman, YN, Gilad Perez

Phys. Rev. Lett. 103 (2009) 071602 [arXiv:0904.0305]

Oram Gedalia, Yuval Grossman, YN, Gilad Perez

Phys. Rev. D80 (2009) 055024 [arXiv:0906.1879]

Kfir Blum, Yonit Hochberg, YN

arXiv:1007.1872

Helen Quinn + YN

'The Mystery of the Missing Antimatter' (PUP)