Flavor Physics and CP Violation: Past, Present, Future

CERN Academic Training Program
CERN, 6 April 2011

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Plan of Lectures

1. Lecture 1
   (a) What is flavor and why is it interesting?
   (b) Flavor in the Standard Model
2. Lecture 2
   (a) Lessons from the B-factories
   (b) The NP flavor puzzle
3. Lecture 3
   (a) Minimal Flavor Violation ($a^b_{\rm SL}$, $A^{t\bar t}_{\rm FB}$)
   (b) The SM flavor puzzle
   (c) Neutrino flavor surprises
4. Lecture 4
   (a) Flavor@LHC
   (b) Baryogenesis@LHC

Intermediate Summary II

- How does new physics at TeV suppress its flavor violation?
- Degeneracy? Alignment?
- Is the flavor structure of the NP related to the SM Yukawa structure?

The Supersymmetric Flavor Puzzle

- $\Delta m_K + \Delta m_D$: Alignment cannot solve the problem by itself
- $\widetilde{Q}_{L1}, \widetilde{Q}_{L2}$: if $m_{\tilde{Q}} <$ TeV, must be degenerate to within 10%
- RGE can give $\Delta\tilde{m}^2_{21}/\tilde{m}^2 \sim 0.1$
- Gauge mediation predicts $\Delta\tilde{m}^2_{21}/\tilde{m}^2 \sim 10^{-4}$

- Gauge mediation:
  - $\widetilde{M}^2_{\tilde{q}_L} = \tilde{m}^2 \mathbf{1} + D_{q_L} \mathbf{1} + v_q^2 Y_q Y_q^\dagger$
  - RGE: $\tilde{m}^2_{\tilde{Q}_L}(m_Z) = \tilde{m}^2 (r_3 \mathbf{1} + c_u Y_u Y_u^\dagger + c_d Y_d Y_d^\dagger)$
  - The only source of flavor violation = The SM Yukawa couplings
  - An example of minimal flavor violation (MFV)
  - MFV solves all SUSY flavor problems

Minimal Flavor Violation

Spurions

- $\mathcal{L}^{\rm SM}_{\rm gauge}$ has a global symmetry, $G^q_{\rm flavor} = SU(3)_Q \times SU(3)_U \times SU(3)_D$, under which $Q_L(3,1,1),\ U_R(1,3,1),\ D_R(1,1,3)$
- $\mathcal{L}^q_{\rm Yukawa} = \overline{Q_L}_i Y^u_{ij} \tilde{\phi} U_{Rj} + \overline{Q_L}_i Y^d_{ij} \phi D_{Rj}$ breaks $G^q_{\rm flavor}$
- $G^q_{\rm flavor}$ would be a good symmetry if Y^q were fields transforming as $Y^u(3,\bar{3},1),\ Y^d(3,1,\bar{3})$
- We say that Y^u, Y^d are spurions that break $G^q_{\rm flavor}$

MFV: Definition

A class of models that obey the following principle:

- The only breaking of flavor universality comes from Y_u, Y_d $(\lambda_d, \lambda_u, V)$
- The only spurions that break $SU(3)_Q \times SU(3)_U \times SU(3)_D$ are $Y_u(3, \bar{3}, 1)$ and $Y_d(3, 1, \bar{3})$

In MFV models, the NP flavor puzzle is solved

Operationally...

1. SM = Low energy effective theory:
   All higher dimensional operators, constructed from SM fields and the Y_q-spurions are formally invariant under $SU(3)^3$

2. A new high energy physics theory:
   All operators, constructed from SM and NP fields and the Y_q-spurions are formally invariant under $SU(3)^3$
   Example: Gauge mediated supersymmetry breaking (GMSB)

Example (1)

- Consider $\frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu d_L)^2$
- $\overline{s_L} \in (\bar{3},1,1), \quad d_L \in (3,1,1) \quad \Longrightarrow \quad (\overline{s_L}\gamma_\mu d_L) \in (8,1,1)$
- $Y_d Y_d^\dagger = (3,1,\bar{3}) \times (\bar{3},1,3) \supset (8,1,1)$
  $Y_u Y_u^\dagger = (3,\bar{3},1) \times (\bar{3},3,1) \supset (8,1,1)$
- But we are in the down mass basis: $Y_d = \lambda_d \Longrightarrow (Y_d Y_d^\dagger)_{12} = 0$
- Must be $(Y_u Y_u^\dagger)_{12} = (V^\dagger \lambda_u^2 V)_{12} \approx y_t^2 V_{td}^* V_{ts}$
- $z_{sd} \propto y_t^4 (V_{td}^* V_{ts})^2$
- $z_{cu} \propto y_b^4 (V_{ub} V_{cb}^*)^2$
  $z_{bd} \propto y_t^4 (V_{td}^* V_{tb})^2$
  $z_{bs} \propto y_t^4 (V_{ts}^* V_{tb})^2$
- With the help of a loop factor, phenomenologically OK!

Example (2)

- $\tilde{Q}_L^\dagger \tilde{Q}_L = (\bar{3},1,1) \times (3,1,1) = (1+8,1,1)$
- $\Longrightarrow \; m^2_{\tilde{Q}_L} = \mathbf{1} + a_u Y_u Y_u^\dagger + a_d Y_d Y_d^\dagger$
  $Y_d Y_d^\dagger$ – FC in u-basis; $Y_u Y_u^\dagger$ – FC in d-basis
- $\tilde{U}_R^\dagger \tilde{U}_R = (1,\bar{3},1) \times (1,3,1) = (1,1+8,1)$
- $\Longrightarrow \; m^2_{\tilde{U}_R} = \mathbf{1} + b_u Y_u^\dagger Y_u$ – no FC!
- $\tilde{D}_R^\dagger \tilde{D}_R = (1,1,\bar{3}) \times (1,1,3) = (1,1,1+8)$
- $\Longrightarrow \; m^2_{\tilde{D}_R} = \mathbf{1} + b_d Y_d^\dagger Y_d$ – no FC!

Example $(2 \to 1)$

GMSB, two generations:

- $\frac{\Delta m^2_{\tilde{d}_L}}{m^2_{\tilde{d}_L}} \sim y_c^2, \quad K^{d_L^*}_{21} K^{d_L}_{11} = V^*_{cd} V_{cs}$
  $\Longrightarrow \; z^{\rm GMSB}_{sd} \sim y_c^4 (V^*_{cd} V_{cs})^2$
- $\frac{\Delta m^2_{\tilde{u}_L}}{m^2_{\tilde{d}_L}} \sim y_c^2, \quad K^{u_L^*}_{21} K^{u_L}_{11} = \frac{y_s^2}{y_c^2} V_{us} V^*_{cs}$
  $\Longrightarrow \; z^{\rm GMSB}_{cu} \sim y_s^4 (V^*_{us} V_{cs})^2$

The dimuon CP asymmetry in $B_{s,d}$ decays

$a^b_{\rm SL} \equiv \frac{\Gamma(\bar B\to\mu^+X)-\Gamma(B\to\mu^-X)}{\Gamma(\bar B\to\mu^+X)+\Gamma(B\to\mu^-X)}$

- $(a^b_{\rm SL})^{D0} = (-9.6 \pm 2.5 \pm 1.5) \times 10^{-3}$
- $(a^b_{\rm SL})^{\rm SM} = (-0.23 \pm 0.05) \times 10^{-3}$
- $(a^b_{\rm SL})^{D0} = (0.51 \pm 0.04) a^d_{\rm SL} + (0.49 \pm 0.04) a^s_{\rm SL}$

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$$\Downarrow$$

- NP contribution to $B_s - \overline{B_s}$ and/or $B_d - \overline{B_d}$ mixing
- Comparable in size to SM, with a new phase of order one

EFT for B_s mixing

- EFT $\Longrightarrow \mathcal{H}_{\rm eff}^{\Delta B=\Delta S=2} = \frac{1}{\Lambda^2}\left(\sum_{i=1}^{5} z_i Q_i + \sum_{i=1}^{3} \tilde{z}_i \widetilde{Q}_i\right)$
- $Q_1^{sb} = \bar{b}_L^\alpha \gamma_\mu s_L^\alpha \bar{b}_L^\beta \gamma_\mu s_L^\beta, \quad Q_2^{sb} = \bar{b}_R^\alpha s_L^\alpha \bar{b}_R^\beta s_L^\beta, \quad Q_3^{sb} = \bar{b}_R^\alpha s_L^\beta \bar{b}_R^\beta s_L^\alpha,$
  $Q_4^{sb} = \bar{b}_R^\alpha s_L^\alpha \bar{b}_L^\beta s_R^\beta, \quad Q_5^{sb} = \bar{b}_R^\alpha s_L^\beta \bar{b}_L^\beta s_R^\alpha$

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  $Q_4^{sb} = \bar{b}_R^\alpha s_L^\alpha \bar{b}_L^\beta s_R^\beta, \quad Q_5^{sb} = \bar{b}_R^\alpha s_L^\beta \bar{b}_L^\beta s_R^\alpha$
- $Y_d = \lambda_d,\ Y_u = V^\dagger \lambda_u,\ A_d \equiv Y_d Y_d^\dagger,\ A_u \equiv Y_u Y_u^\dagger$
- MFV $\Longrightarrow$ $z_1 = r_1^+ (A_u)_{32}^2 + r_1^- (A_u)_{32}[A_u, A_d]_{32}$
  $z_{2,3} = r_{2,3}(v^2/\Lambda^2)(Y_d^\dagger A_u)_{32}^2$
  $z_{4,5} = r_{4,5}^+ (Y_d^\dagger A_u)_{32}(A_u Y_d)_{32} + r_{4,5}^- (Y_d^\dagger [A_u, A_d])_{32}(A_u Y_d)_{32}$
  $r_{1,4,5}^+$ real
- $z_1/[y_t^4 (V_{ts} V_{tb}^*)^2] = r_1^+ - r_1^- y_b^2,$
  $z_{2,3}/[y_t^4 (V_{ts} V_{tb}^*)^2] = r_{2,3}(v^2/\Lambda^2) y_b^2,$
  $z_{4,5}/[y_t^4 (V_{ts} V_{tb}^*)^2] = r_{4,5}^+ y_b y_s - r_{4,5}^- y_b^3 y_s$

CPV MFV contribution to B_s mixing

- For $y_b \ll 1$, the only contribution with a phase of $\mathcal{O}(1)$: Q_2
- The scale of NP must be low: $\Lambda_{Q_2} \lesssim 260$ GeV $\sqrt{\tan\beta}$
- Same contributions in B_d, B_s systems: $h_d = h_s,\ \sigma_d = \sigma_s$
  where $M_{12}^{d,s} = (M_{12}^{d,s})^{\rm SM}(1 + h_{d,s}e^{2i\sigma_{d,s}})$
- Further predictions:
  - $S_{\psi K} \approx 0.65 \pm 0.05, \quad S_{\psi\phi} \approx 0.25 \pm 0.06$
  - No effect on ϵ_K and on EDMs

MFV contributions to CPV

- Deviations from SM:

	$y_b \sim 1$			$y_b \ll 1$		
i	$S_{\psi\phi}$	$S_{\psi K}$	ϵ_K	$S_{\psi\phi}$	$S_{\psi K}$	ϵ_K
1	small	small	large	small	small	large
2,3	large	large	small	large	large	small
4,5	large	small	large	small	small	large

- MFV will be excluded if
  - $S_{\psi K}$-large and $S_{\psi\phi}$-small
  - $S_{\psi K}, S_{\psi\phi}, \epsilon_K$ all large

Forward-backward asymmetry in $t\bar{t}$ production

$A_{\rm FB}^{t\bar{t}} \equiv \frac{N(y_t - y_{\bar{t}} > 0) - N(y_t - y_{\bar{t}} < 0)}{N(y_t - y_{\bar{t}} > 0) + N(y_t - y_{\bar{t}} < 0)}$

- $[A_{\rm FB}^{t\bar{t}}(M_{t\bar{t}} > 450\ GeV)]^{\rm CDF} = +0.48 \pm 0.11$
- $[A_{\rm FB}^{t\bar{t}}(M_{t\bar{t}} > 450\ GeV)]^{\rm SM} = +0.09 \pm 0.01$

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$$\Downarrow$$

- NP contribution to $u\bar{u} \to t\bar{t}$
- Comparable to SM, but small effect on total cross section
  $\Longrightarrow$ Large contribution to $\frac{c_A^8}{\Lambda^2}(\bar{u}\gamma_\mu\gamma^5 T^a u)(\bar{t}\gamma^\mu\gamma^5 T^a t)$
- t-channel color-sextet scalar?
  s-channel color-octet vector-boson?

MFV Sextet Scalar

- Must have large Sut coupling
- S cannot be flavor-singlet
  $\Longrightarrow SU(3)_U$-sextet $S_{kl}^{\alpha\beta}$
- $\mathcal{L}_S = \eta_1 U_{R\alpha}^k U_{R\beta}^l S_{kl}^{\alpha\beta} + \eta_2 U_{R\alpha}^k (Y_U Y_U^\dagger)_m^l U_{R\beta}^m S_{kl}^{\alpha\beta} + \text{h.c.}$
  where $\alpha, \beta =$ color, $k, l, m =$ flavor
- Small effect on tt production and $D - \overline{D}$ mixing
- Enhancement of $t\bar{t}$ cross section at large $M_{t\bar{t}}$
- Unavoidable s-channel contribution – problematic

[Grinstein et al, 1002.3374] [Ligeti et al, 1003.2757]

MFV Octet Vector-Boson

- Must have opposite-sign $u\bar{u}$ and $t\bar{t}$ couplings
- V cannot be flavor-singlet
  $\Longrightarrow SU(3)_U$-octet $V \equiv V_{A,B}(T^A)_\alpha^\beta (T^B)_k^l$
  where $\alpha, \beta =$ color, $k, l =$ flavor
- $\mathcal{L}_V = \eta_1 \overline{U_R}\, \not{V} U_R + [\eta_2 \overline{U_R}\, \not{V}(Y_U Y_U^\dagger) U_R + \text{h.c.}]$
  $+\, \eta_3 \overline{U_R}(Y_U Y_U^\dagger)\, \not{V}(Y_U Y_U^\dagger) U_R$
- Small effect on tt production and $D - \overline{D}$ mixing
- Enhancement of $t\bar{t}$ cross section at large $M_{t\bar{t}}$

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$V_{\rm CKM}$, with apologies to BABAR and BELLE

- The CKM matrix a-la BABAR/BELLE:

$$V_{\rm CKM} =$$

$$\begin{pmatrix} 0.97383 \pm 0.00024 & 0.2272 \pm 0.0010 & (3.96 \pm 0.09) \times 10^{-3} \\ 0.2271 \pm 0.0010 & 0.97296 \pm 0.00024 & (4.221^{+0.010}_{-0.080}) \times 10^{-2} \\ (8.14^{+0.32}_{-0.64}) \times 10^{-3} & (4.161^{+0.012}_{-0.078}) \times 10^{-2} & 0.999100^{+0.000034}_{-0.000004} \end{pmatrix}$$

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- The CKM matrix a-la ATLAS/CMS:

$$V_{\text{CKM}} = \begin{pmatrix} 1 & 0.2 & 0 \\ -0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

MFV predictions: Mixing

- The only source of mixing – the CKM matrix:

$$V_{\rm CKM}^{\rm LHC} = \begin{pmatrix} 1 & 0.2 & 0 \\ -0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

New particles will decay to either 3rd generation or non-3rd generation quarks but not to both

- ATLAS/CMS can exclude MFV by observing $\mathrm{Br}(q_3) \sim \mathrm{Br}(q_{1,2})$
- Examples of new particles: Vector-like quarks; squarks...

MFV + SUSY

- Squarks:
  - Spectrum: $2+1$
  - Decays: $2 \to u, d, s, c, \quad 1 \to t, b$
- Sleptons, $\Lambda_{\text{seesaw}} > \Lambda_{\text{mediation}}$:
  - spectrum: 3
  - Decays: flavor diagonal
- Sleptons, $\Lambda_{\text{seesaw}} < \Lambda_{\text{mediation}}$:
  - $Y_N,\ M_R$ may leave a footprint on the slepton spectrum and flavor decomposition

Summary of MFV

A class of NP models where...

- The only violation of the global $[SU(3)]_q^3$ symmetry = The Yukawa-spurions: $Y_u(3,\bar{3},1), \quad Y_d(3,1,\bar{3})$
- 'Solution' to the NP flavor puzzle
- Examples: Gauge-, anomaly-, gaugino-mediated supersymmetry breaking
- Probably, only an approximation
- The NP is subject to an approximate $[SU(2)]^3$ symmetry
- All FC processes $\propto \; V_{\rm CKM}$
- Testable at flavor factories (LHCb) and (in principle) at ATLAS/CMS

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
  - Approximate symmetry? [Froggatt-Nielsen]
  - Strong dynamics? [Nelson-Strassler]
  - Location in extra dimension? [Arkani-Hamed-Schmaltz]
  - ?

The Froggatt-Nielsen (FN) mechanism

- Approximate "horizontal" symmetry (e.g. $U(1)_H$)
- Small breaking parameter $\epsilon = \langle S_{-1} \rangle / \Lambda \ll 1$
- $\epsilon(-1)$ is a spurion that breaks $U(1)_H$
- Selection rules:
  - $Y^d_{ij} \sim \epsilon^{H(Q_i)+H(\bar{d}_j)+H(\phi_d)}$
  - $Y^u_{ij} \sim \epsilon^{H(Q_i)+H(\bar{u}_j)+H(\phi_u)}$
  - $Y^\ell_{ij} \sim \epsilon^{H(L_i)+H(\bar{\ell}_j)+H(\phi_d)}$
  - $Y^\nu_{ij} \sim \epsilon^{H(L_i)+H(L_j)+2H(\phi_u)}$

The FN mechanism: An example

- $H(Q_i) = 3, 2, 0, \quad H(\bar{u}_j) = 4, 1, 0, \quad H(\phi_u) = 0$

$$\Downarrow$$

$$Y^u \sim \begin{pmatrix} \epsilon^7 & \epsilon^4 & \epsilon^3 \\ \epsilon^6 & \epsilon^3 & \epsilon^2 \\ \epsilon^4 & \epsilon & 1 \end{pmatrix}$$

- $Y_t : Y_c : Y_u \sim 1 : \epsilon^3 : \epsilon^7$
- $(V_L^u)_{12} \sim \epsilon, \quad (V_L^u)_{23} \sim \epsilon^2, \quad (V_L^u)_{13} \sim \epsilon^3$
- A good fit with $|\epsilon| \sim 0.2$

The FN mechanism: another example

- $U(1)_H$ broken by $\epsilon(-1) \sim 0.05$
- $\mathbf{10}(2,1,0), \quad \bar{\mathbf{5}}(0,0,0)$

$$\Downarrow$$

$$Y_t : Y_c : Y_u \sim 1 : \epsilon^2 : \epsilon^4$$
$$Y_b : Y_s : Y_d \sim 1 : \epsilon : \epsilon^2$$
$$Y_\tau : Y_\mu : Y_e \sim 1 : \epsilon : \epsilon^2$$
$$|V_{us}| \sim |V_{cb}| \sim \epsilon, \quad |V_{ub}| \sim \epsilon^2, \quad \delta_{\rm KM} \sim 1$$

$$+$$

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

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 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

- $\Delta m^2_{21} = (7.6 \pm 0.2) \times 10^{-5}\ \text{eV}^2, \quad |\Delta m^2_{32}| = (2.4 \pm 0.1) \times 10^{-3}\ \text{eV}^2$
- $|U_{e2}| = 0.56 \pm 0.02, \quad |U_{\mu 3}| = 0.68 \pm 0.06, \quad |U_{e3}| = 0.13^{+0.03}_{-0.06}$

[Gonzalez-Garcia, Maltoni, Salvado, JHEP04(2010)056]

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- Attempting a FN explanation:
  - $s_{23} \sim 1, \quad m_2/m_3 \sim \epsilon^x$?

    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 flavor parameters

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- Note:
  - $|U_{23}| >$ any $|V_{ij}|$; $|U_{12}| >$ any $|V_{ij}| \quad (i \neq j)$
  - $m_2/m_3 >$ any m_i/m_j for charged fermions
  - So far, neither smallness nor hierarchy
  - Is neutrino flavor different from charged fermion flavor?

Neutrino Mass Anarchy

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- $|U_{e2}| = 0.56 \pm 0.02, \quad |U_{\mu 3}| = 0.68 \pm 0.06, \quad |U_{e3}| = 0.13^{+0.03}_{-0.06}$

  [Gonzalez-Garcia, Maltoni, Salvado, JHEP04(2010)056]

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

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:

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

Intermediate Summary III

- Why is there smallness and hierarchy in the flavor parameters?

- Is there a relation Dirac/Majorana $\Leftrightarrow$ hierarchy/anarchy?
  Is there a relation Dirac/Majorana $\Leftrightarrow$ Abelian/non-Abelian?

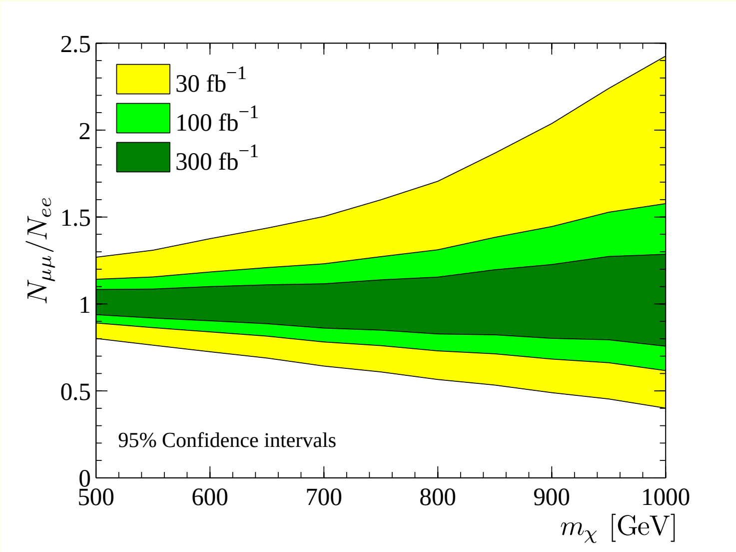
- How does new physics at TeV suppress its flavor violation?

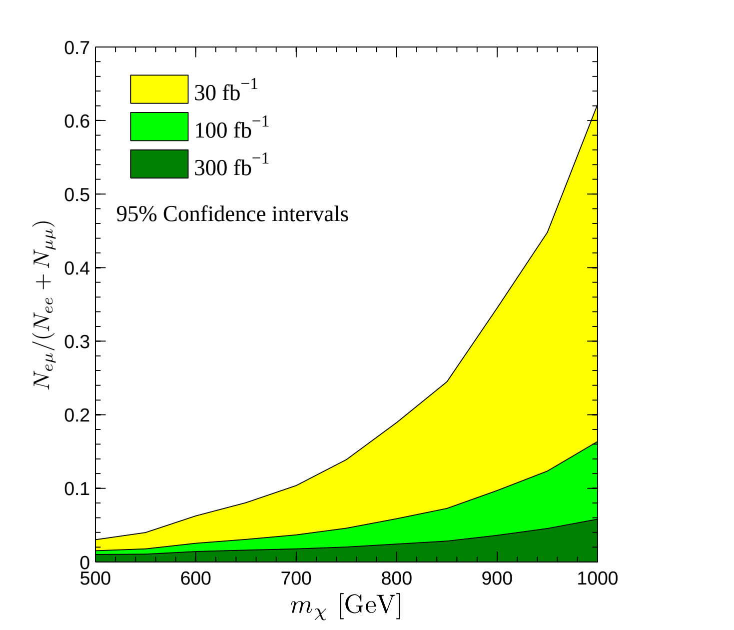
- Are the solutions to the NP and SM flavor puzzles related?

Vector-like leptons and MLFV

- Imagine: Vector-like lepton doublets with $m \lesssim TeV$
  - Avoid large FCNC by MLFV
  - The only LFV comes from $Y^E = \mathrm{diag}(y_e, y_\mu, y_\tau)$
    - The heavy mass spectrum:
      quasi-degeneracy or hierarchy $\propto Y^E$
    - The heavy-to-light couplings:
      universal or hierarchical (affects the lifetimes)
    - The heavy-to-light couplings:
      flavor-diagonal

Vector-like leptons and MLFV





- $N_{ee} \neq N_{\mu\mu}$ and/or $N_{e\mu} \neq 0$:
  Either MLFV with ν-related spurions or non-MLFV
- $N_{ee} = N_{\mu\mu}$ and $N_{e\mu} = 0$: Approximate $U(1)_e \times U(1)_\mu$
  Plus $m_{\chi_e} \approx m_{\chi_\mu}$: Approximate $U(2)_{e\mu}$

[Gross, Grossman, Nir, Vitells, PRD81 (2010) 055013 [1001.2883]]