Flavor Physics and CP Violation

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Plan of Lectures

1. Introduction
   - Definitions and Motivation
   - Flavor in the Standard Model
2. Past: What have we learned?
   - Lessons from the B-factories
3. Present: The open questions
   - The NP flavor puzzle
   - Minimal Flavor Violation
   - The SM flavor puzzle
   - The flavor of ν
4. Future: What will we learn?
   - Flavor@LHC
   - The flavor of h

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: 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

- 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 (FCNC) 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?

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]

What is CP violation?

- Interactions that distinguish between particles and antiparticles

($e.g.$ $e_L^- \leftrightarrow e_R^+$)

  - Neither strong nor electromagnetic interactions
    (Comment: $\theta_{\rm QCD}$ is irrelevant to our discussion)
  - Within the SM: Charged current weak interactions ($\delta_{\rm KM}$)
  - With NP: many new sources of CPV
  - Manifestations of CP violation:
    - $\Gamma(B^0 \to \psi K_S) \neq \Gamma(\overline{B^0} \to \psi K_S)$
    - $K_S, K_L \neq K_+, K_-$

Why is CPV interesting?

- Within the SM, a single CP violating parameter η:
  In addition, QCD = CP invariant ($\theta_{\rm QCD}$ irrelevant)
  Strong predictive power (correlations + zeros)
  Excellent tests of the flavor sector

- η 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 CPV

- $1964 - 2000$
  - $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$

A brief history of CPV

- 1964 – 2000
  - $|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$; $\mathcal{R}e(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$
- 2000 – 2012, 5σ
  - $S_{\psi K_S} = +0.68 \pm 0.02$
  - $S_{\phi K_S} = +0.74 \pm 0.12$, $S_{\eta' K_S} = +0.59 \pm 0.07$, $S_{f K_S} = +0.69 \pm 0.11$
  - $S_{K^+ K^- K_S} = +0.68 \pm 0.10$
  - $S_{\pi^+\pi^-} = -0.65 \pm 0.07$, $C_{\pi^+\pi^-} = -0.36 \pm 0.06$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{D^+D^-} = -0.98 \pm 0.17$, $S_{D^{*+}D^{*-}} = -0.77 \pm 0.10$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.087 \pm 0.008$
  - $\mathcal{A}_{D_+ K^\pm} = +0.19 \pm 0.03$

The Flavor Factories

- B-factories: Belle and BaBar
  Asymmetric $e^+ - e^-$ colliders producing $\Upsilon(4S) \to B\bar{B}$
- Tevatron: CDF and D0
  $p - \bar{p}$ colliders at 2 TeV (B_s...)
- LHC: LHCb, ATLAS, CMS
- Hypothetical future: Super-B, LHCb-upgrade...

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 have been measured

Flavor Symmetry

- $\mathcal{L}_{\text{kinetic+gauge}} + \mathcal{L}_{\text{Higgs}}$ has a large global symmetry: $G_{\text{global}} = [U(3)]^5$
- $Q_L \to V_Q Q_L, \quad U_R \to V_U U_R, \quad D_R \to V_D D_R,$ $L_L \to V_L L_L, \quad E_R \to V_E E_R$
- Take, for example $\mathcal{L}_{\text{kinetic+gauge}}$ for $Q_L(3,2)_{+1/6}$: $i\overline{Q_L}_i(\partial_\mu + \frac{i}{2}g_s G^a_\mu \lambda^a + \frac{i}{2}g_s W^b_\mu \tau^b + \frac{i}{6}g' B_\mu)\gamma^\mu \delta_{ij} Q_{Lj}$
- $\overline{Q_L}\mathbf{1}Q_L \ \to \ \overline{Q_L}V_Q^\dagger \mathbf{1} V_Q Q_L = \overline{Q_L}\mathbf{1}Q_L$

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

$$\Downarrow$$

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

Counting flavor parameters

- Quark sector:
  - $Y_u, Y_d \implies 2 \times [9_R + 9_I]$
  - $[SU(3)]_q^3 \to U(1)_B \implies -3 \times [3_R + 6_I] + 1_I$
  - Physical parameters: $9_R + 1_I$

- Lepton sector:
  - $Y_e \implies 9_R + 9_I$
  - $[SU(3)]_\ell^2 \to [U(1)]^3 \implies -2 \times [3_R + 6_I] + 3_I$
  - Physical parameters: 3_R

The quark flavor parameters

- Convenient (but not unique) interactions 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

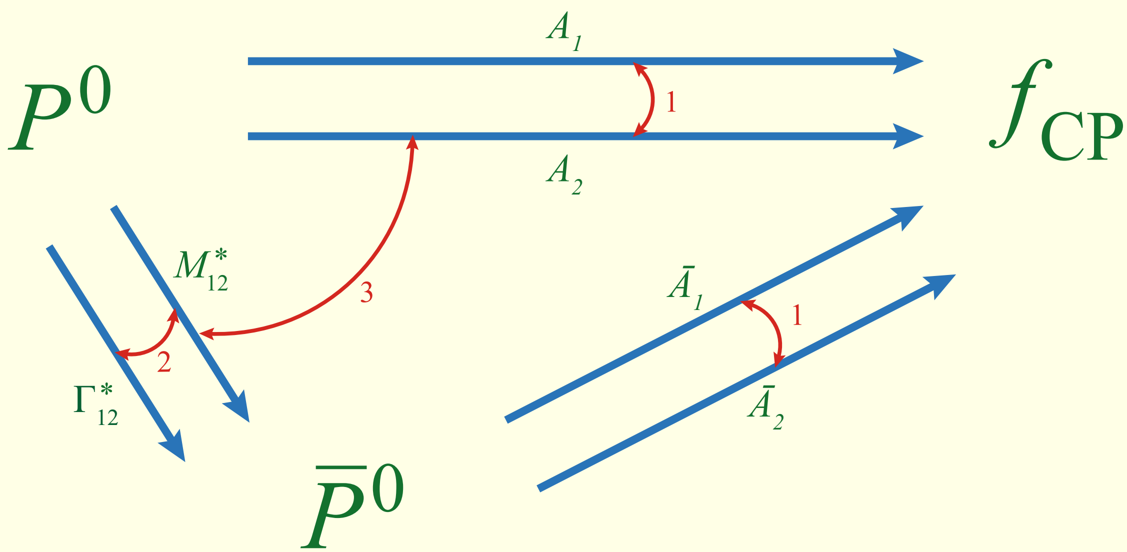
Intermediate summary I

- Flavor violation: m_q, $V_{\rm CKM}$
- Flavor changing processes: $V_{\rm CKM}$
- CP violation: η

- FFCC: tree level
- FCNC: loop- (α_2^2), CKM- (V_{ij}), GIM- $(\frac{m_2^2-m_1^2}{m_W^2})$ suppressed

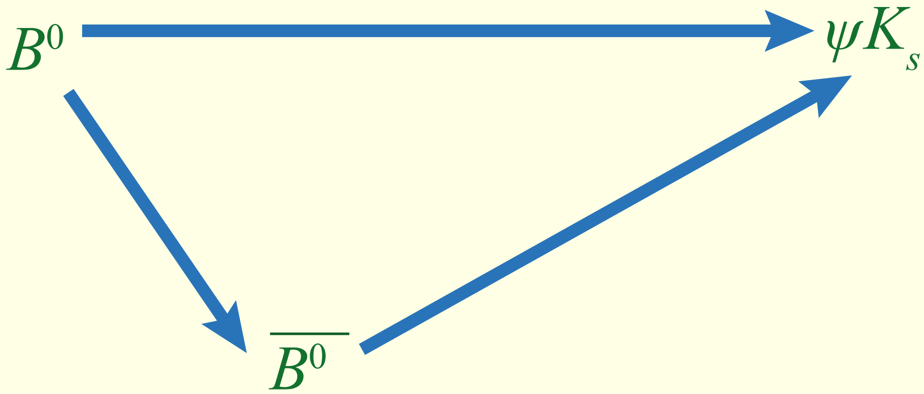
What have we learned?

The three types of CPV



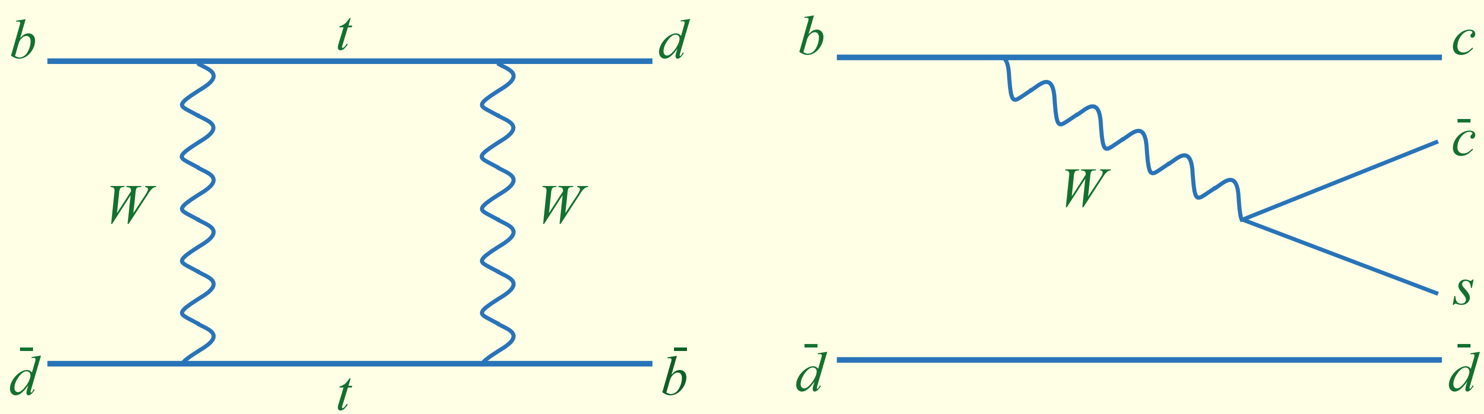
1	Decay	$\lvert\bar{A}/A\rvert \neq 1$	$\frac{\bar{A}}{A} = \frac{\bar{A}_1+\bar{A}_2}{A_1+A_2}$	$\mathcal{A}_{K^\mp\pi^\pm}$	$P^\pm \to f^\pm$
2	Mixing	$\lvert q/p\rvert \neq 1$	$\frac{q}{p} = \frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta M - i\Delta\Gamma}$	$\mathcal{R}e\ \varepsilon$	$P^0, \overline{P}^0 \to \ell^\pm X$
3	Interference	$\mathcal{I}m\lambda \neq 0$	$\lambda = \frac{M_{12}^*}{\lvert M_{12}\rvert}\frac{\bar{A}}{A}$	$S_{\psi K_S}$	$P^0, \overline{P}^0 \to f_{CP}$

$\underline{S_{\psi K_S}}$



- Babar/Belle: $A_{\psi K_S}(t) = \frac{\frac{d\Gamma}{dt}[\overline{B^0_{\rm phys}}(t)\to\psi K_S] - \frac{d\Gamma}{dt}[B^0_{\rm phys}(t)\to\psi K_S]}{\frac{d\Gamma}{dt}[\overline{B^0_{\rm phys}}(t)\to\psi K_S] + \frac{d\Gamma}{dt}[B^0_{\rm phys}(t)\to\psi K_S]}$
- Theory: $A_{\psi K_S}(t)$ dominated by interference between $A(B^0 \to \psi K_S)$ and $A(B^0 \to \overline{B^0} \to \psi K_S)$
- $\Longrightarrow A_{\psi K_S}(t) = S_{\psi K_S} \sin(\Delta m_B t)$
  $\Longrightarrow\ S_{\psi K_S} = \mathcal{I}m\left[\frac{A(B^0\to\overline{B^0})}{|A(B^0\to\overline{B^0})|}\frac{A(\overline{B^0}\to\psi K_S)}{A(B^0\to\psi K_S)}\right]$

$S_{\psi K_S}$ in the SM



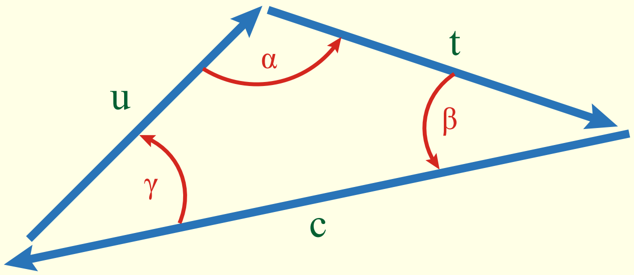
M_{12} $\bar{A}_{\psi K}$

- $$S_{\psi K_S} = \mathcal{I}m\left[\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}^*}{V_{cb}^* V_{cd}}\right] = \frac{2\eta(1-\rho)}{\eta^2+(1-\rho)^2}$$
- In the language of the unitarity triangle: $S_{\psi K_S} = \sin 2\beta$
- The approximations involved are better than one percent!
- Experiments: $S_{\psi K_S} = 0.68 \pm 0.02$

The Unitarity Triangle

- A geometrical presentation of $\boxed{V_{ub}^{*}V_{ud} + V_{tb}^{*}V_{td} + V_{cb}^{*}V_{cd} = 0}$

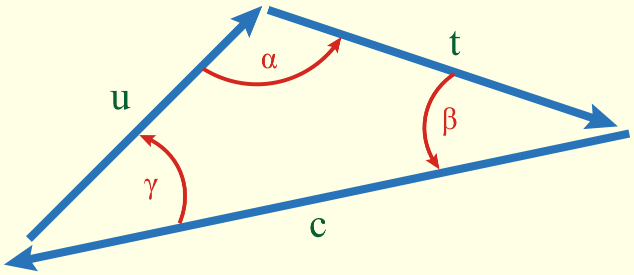
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



The Unitarity Triangle

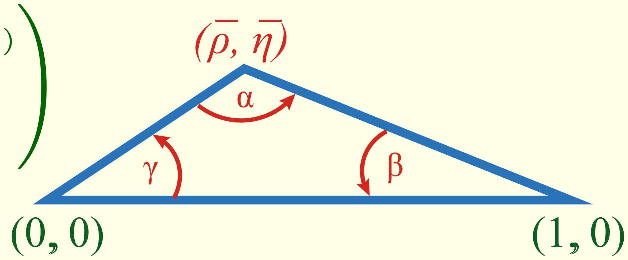
- A geometrical presentation of $V_{ub}^* V_{ud} + V_{tb}^* V_{td} + V_{cb}^* V_{cd} = 0$

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



- Rescale and rotate: $A\lambda^3 \left[(\rho + i\eta) + (1 - \rho - i\eta) + (-1)\right] = 0$

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



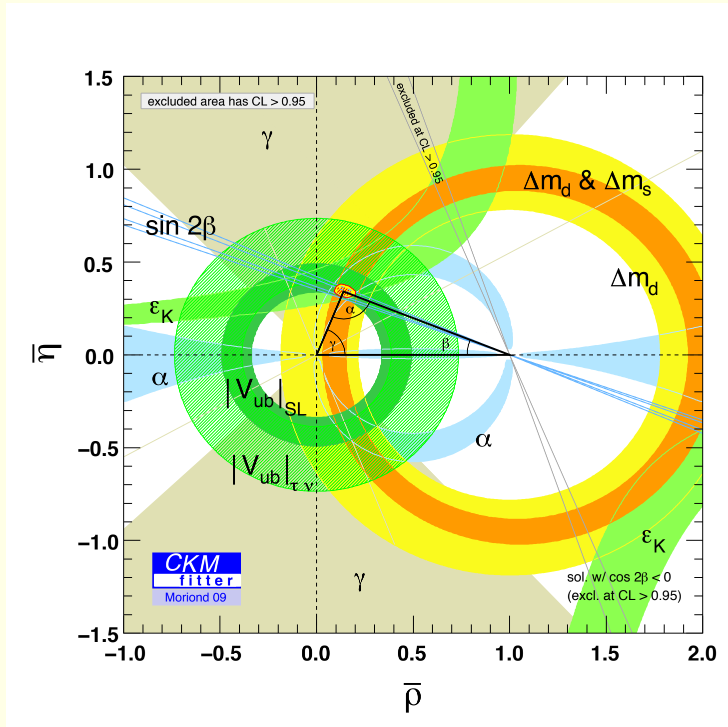
Wolfenstein (83); Buras *et al.* (94)

$\alpha \equiv \phi_2; \quad \beta \equiv \phi_1; \quad \gamma \equiv \phi_3$

Testing CKM – Take I

- Assume: CKM matrix is the only source of FV and CPV
- λ known from $K \to \pi \ell \nu$
  A known from $b \to c \ell \nu$
- Many observables are $f(\rho, \eta)$:
  - $b \to u \ell \nu \implies \propto |V_{ub}/V_{cb}|^2 \propto \rho^2 + \eta^2$
  - $\Delta m_{B_d}/\Delta m_{B_s} \implies \propto |V_{td}/V_{ts}|^2 \propto (1-\rho)^2 + \eta^2$
  - $S_{\psi K_S} \implies \frac{2\eta(1-\rho)}{(1-\rho)^2+\eta^2}$
  - $S_{\rho\rho}(\alpha)$
  - $\mathcal{A}_{DK}(\gamma)$
  - ϵ_K

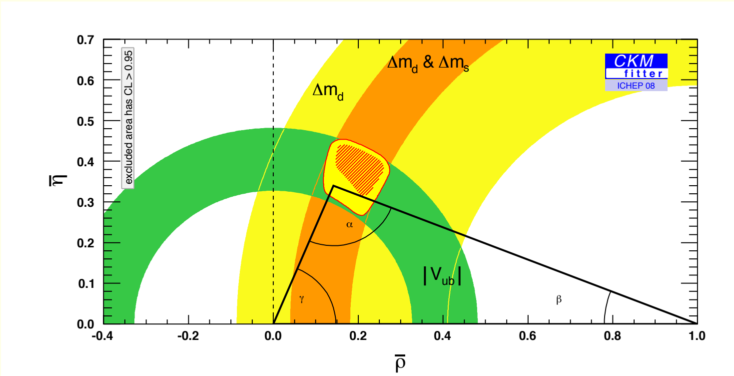
The B-factories Plot

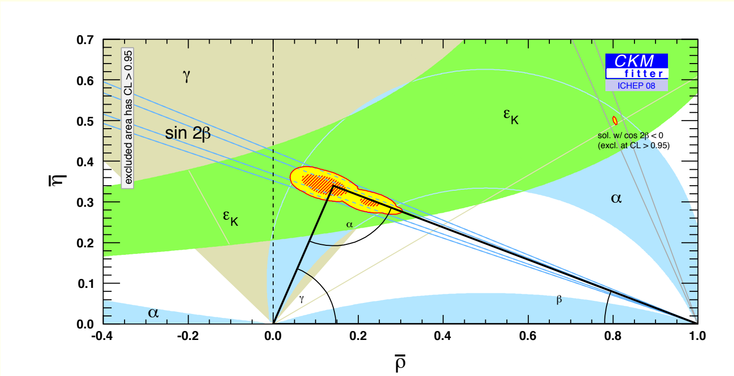


CKMFitter

Very likely, the CKM mechanism dominates FV and CPV

CPC vs. CPV

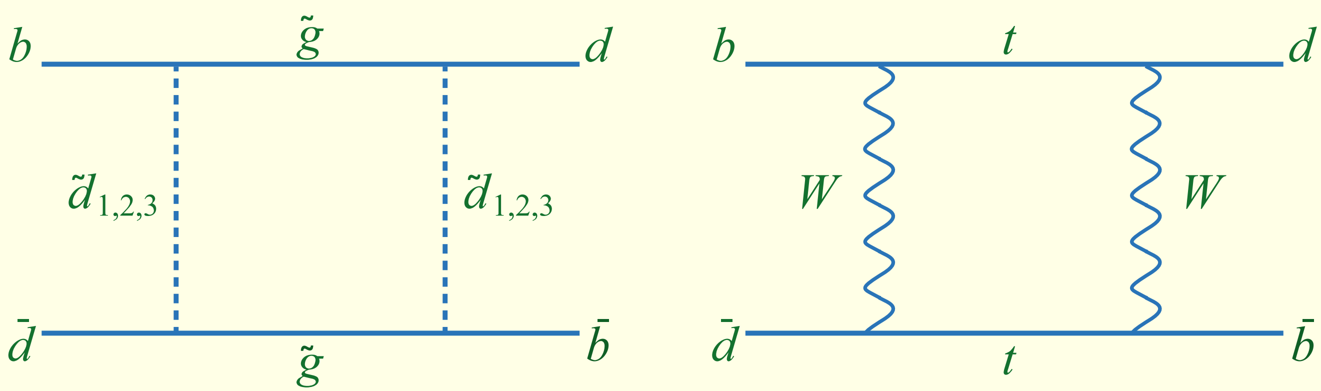




Very likely, the KM mechanism dominates CP violation

$S_{\psi K_S}$ with NP

- Reminder: $S_{\psi K_S} = \mathcal{I}m\left[\frac{A(B^0\to\overline{B^0})}{|A(B^0\to\overline{B^0})|}\frac{A(\overline{B^0}\to\psi K_S)}{A(B^0\to\psi K_S)}\right]$
- NP contributions to the tree level decay amplitude - negligible
- NP contributions to the loop + CKM suppressed mixing amplitude could be large
- Define $h_d e^{2i\sigma_d} = \frac{A^{\rm NP}(B^0\to\overline{B}^0)}{A^{\rm SM}(B^0\to\overline{B}^0)}$



$r_d e^{2i\theta_d} = 1 + h_d e^{2i\sigma_d} = \frac{A^{\rm full}(B^0\to\overline{B}^0)}{A^{\rm SM}(B^0\to\overline{B}^0)}$

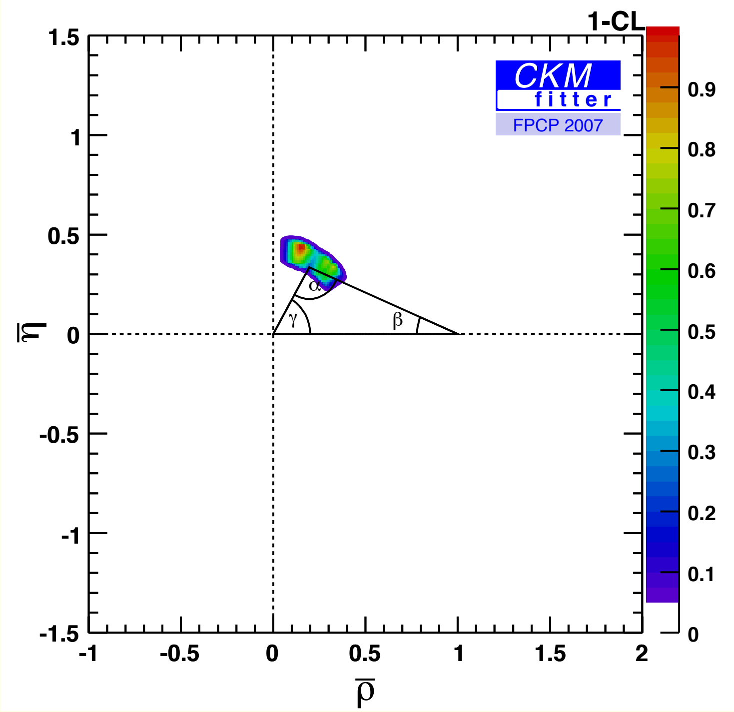
- $\boxed{S_{\psi K_S} = \sin[2(\beta+\theta_d)] = f(\rho,\eta,h_d,\sigma_d)}$

Testing CKM - take II

- Assume: NP in leading tree decays - negligible
- Allow arbitrary NP in loop processes
- Use only tree decays and $B^0 - \overline{B}^0$ mixing
- Use $|V_{ub}/V_{cb}|$, $\mathcal{A}_{DK}$, $S_{\psi K}$, $S_{\rho\rho}$, Δm_{B_d}, $\mathcal{A}_{\rm SL}^d$
- Fit to $\boxed{\eta}$, ρ, $\boxed{h_d}$, σ_d
- Find whether $\eta = 0$ is allowed
  If not $\Longrightarrow$ The KM mechanism is at work
- Find whether $h_d \gg 1$ is allowed
  If not $\Longrightarrow$ The KM mechanism is dominant

What have we learned?

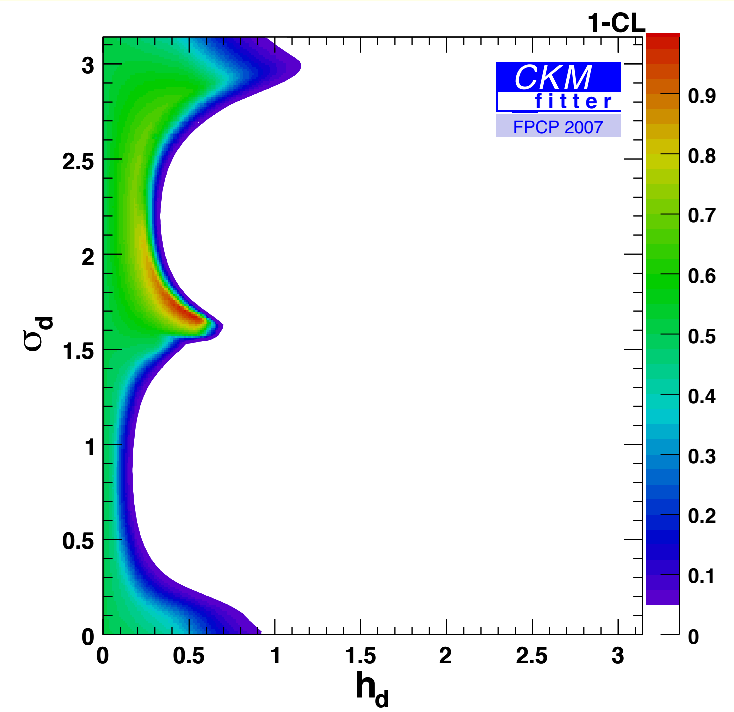
$\eta \neq 0$?



- The KM mechanism is at work

What have we learned?

$h_d \ll 1$?



- The KM mechanism dominates CP violation
- The CKM mechanism is a major player in flavor violation

Is CPV in $K \to \pi\pi$ small because of flavor?

SM:

- $\epsilon \sim 10^{-3}$, $\epsilon' \sim 10^{-5}$ because of flavor suppression
- Some CP violating phases are order one

Approximate CP:

- All CPV phases are small
- All CP asymmetries are small

Is CPV in $K \to \pi\pi$ small because of flavor?

SM:

- $\epsilon \sim 10^{-3}$, $\epsilon' \sim 10^{-5}$ because of flavor suppression
- Some CP violating phases are order one

Approximate CP:

- All CPV phases are small
- All CP asymmetries are small

B Physics: $S_{\psi K} \sim 0.7$

$\Longrightarrow$ Some CP violating phases are indeed $\mathcal{O}(1)$

Is CP violated in $\Delta B = 1$ processes?

SM:

- Indirect ($A(M^0 \to \overline{M}^0)$) and direct ($A(M \to f)$) CP violations are both large

Superweak:

- There is no direct ($A(M \to f)$) CP violation

K Physics: $\epsilon'/\epsilon = (1.67 \pm 0.26) \times 10^{-3}$

$\Longrightarrow$ CP is violated in $\Delta S = 1$ processes ($s \to u\bar{u}d$)

Is CP violated in $\Delta B = 1$ processes?

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- Indirect ($A(M^0 \to \overline{M}^0)$) and direct ($A(M \to f)$) CP violations are both large

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K Physics: $\epsilon'/\epsilon = (1.67 \pm 0.26) \times 10^{-3}$

$\Longrightarrow$ CP is violated in $\Delta S = 1$ processes ($s \to u\bar{u}d$)

B Physics: $\mathcal{A}_{K^\mp\pi^\pm} = -0.097 \pm 0.012$, $C_{\pi^+\pi^-} = -0.38 \pm 0.06$, $\mathcal{A}_{K^\mp\rho^0} = 0.37 \pm 0.10$

$\Longrightarrow$ CP is violated in $\Delta B = 1$ processes ($b \to u\bar{u}s$, $b \to u\bar{u}d$)

Intermediate summary II

- The KM phase is different from zero (SM violates CP)
- The KM mechanism is the dominant source of the CP violation observed in meson decays
- Complete alternatives to the KM mechanism are excluded (Superweak, Approximate CP)

- No evidence for corrections to CKM
- NP contributions to the observed FCNC are at most comparable to the CKM contributions
- NP contributions are very small in $s \to d$, $c \to u$, $b \to d$, $b \to s$

The NP Flavor Puzzle

The SM = Low energy effective theory

1. Gravity $\Longrightarrow \Lambda_{\rm Planck} \sim 10^{19}\ GeV$
2. $m_\nu \neq 0 \Longrightarrow \Lambda_{\rm Seesaw} \leq 10^{15}\ GeV$
3. m_H^2-fine tuning $\Longrightarrow \Lambda_{\rm top-partners} \sim\ TeV$
   Dark matter $\Longrightarrow \Lambda_{\rm wimp} \sim\ TeV$

$$\Downarrow$$

- The SM = Low energy effective theory
- Must write non-renormalizable terms suppressed by $\Lambda_{\rm NP}^{d-4}$
- $\mathcal{L}_{d=5} = \frac{y_{ij}^\nu}{\Lambda_{\rm seesaw}} L_i L_j \phi\phi$
- $\mathcal{L}_{d=6}$ contains many flavor changing operators

New Physics

- The effects of new physics at a high energy scale $\Lambda_{\rm NP}$ can be presented as higher dimension operators

- For example, we expect the following dimension-six operators:

$$\frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2+\frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2+\frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2+\frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2$$

- New contribution to neutral meson mixing, *e.g.*

$$\frac{\Delta m_B}{m_B}\sim\frac{f_B^2}{3}\times\frac{|z_{bd}|}{\Lambda_{\rm NP}^2}$$

- Generic flavor structure $\equiv z_{ij}\sim 1$ or, perhaps, $\text{loop}-\text{factor}$

Some data

$\Delta m_K/m_K$	7.0×10^{-15}
$\Delta m_D/m_D$	8.7×10^{-15}
$\Delta m_B/m_B$	6.3×10^{-14}
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}
ϵ_K	2.3×10^{-3}
$A_\Gamma/y_{\rm CP}$	≤ 0.2
$S_{\psi K_S}$	0.68 ± 0.02
$S_{\psi\phi}$	-0.04 ± 0.09

High Scale?

- For $z_{ij} \sim 1$ (and $\mathcal{I}m(z_{ij}) \sim 1$):

		$\Lambda_{\rm NP} \gtrsim$
$\Delta m_K/m_K$	7.0×10^{-15}	1000 TeV
$\Delta m_D/m_D$	8.7×10^{-15}	1000 TeV
$\Delta m_B/m_B$	6.3×10^{-14}	400 TeV
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}	70 TeV
ϵ_K	2.3×10^{-3}	20000 TeV
$A_\Gamma/y_{\rm CP}$	≤ 0.2	3000 TeV
$S_{\psi K_S}$	0.68 ± 0.02	800 TeV
$S_{\psi\phi}$	-0.04 ± 0.09	200 TeV

High Scale

- For $z_{ij} \sim 1$, $\Lambda_{\rm NP} \gg 1000\ TeV$
- For $z_{ij} \sim \alpha_2^2$, $\Lambda_{\rm NP} \gg 100\ TeV$

$$\Downarrow$$

Did we misinterpret the Higgs fine tuning problem?

Did we misinterpret the dark matter puzzle?

Small (hierachical?) flavor parameters?

- For $\Lambda_{\rm NP} \sim 1\ TeV$:

		$z_{ij} \lesssim$
$\Delta m_K/m_K$	7.0×10^{-15}	8×10^{-7}
$\Delta m_D/m_D$	8.7×10^{-15}	5×10^{-7}
$\Delta m_B/m_B$	6.3×10^{-14}	5×10^{-6}
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}	2×10^{-4}
		$\mathcal{I}m(z_{ij}) \lesssim$
ϵ_K	2.3×10^{-3}	6×10^{-9}
$A_\Gamma/y_{\rm CP}$	≤ 0.2	1×10^{-7}
$S_{\psi K_S}$	0.68 ± 0.02	1×10^{-6}
$S_{\psi\phi}$	-0.04 ± 0.09	2×10^{-5}

Small (hierachical?) flavor parameters

- For $\Lambda_{\rm NP} \sim$ TeV, $\mathcal{I}m(z_{sd}) < 6 \times 10^{-9}$
- For $\Lambda_{\rm NP} \sim$ TeV, $|z_{bs}| < 2 \times 10^{-4}$

$$\Downarrow$$

The flavor structure of NP@TeV must be highly non-generic

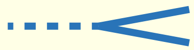
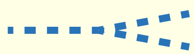
How? Why? = The NP flavor puzzle

How does the SM ($\Lambda_{\rm SM} \sim m_W$) do it?

		$z_{ij} \sim$	$z_{ij}^{\rm SM}$
$\Delta m_K/m_K$	7.0×10^{-15}	5×10^{-9}	$\alpha_2^2 y_c^2 \lvert V_{cd}V_{cs}\rvert^2$
$\Delta m_D/m_D$	8.7×10^{-15}	5×10^{-9}	Long Distance
$\Delta m_B/m_B$	6.3×10^{-14}	7×10^{-8}	$\alpha_2^2 y_t^2 \lvert V_{td}V_{tb}\rvert^2$
$\Delta m_{B_s}/m_{B_s}$	2.1×10^{-12}	2×10^{-6}	$\alpha_2^2 y_t^2 \lvert V_{ts}V_{tb}\rvert^2$
		$\frac{\mathcal{I}m(z_{ij})}{\lvert z_{ij}\rvert} \sim$	$\frac{\mathcal{I}m(z_{ij}^{\rm SM})}{\lvert z_{ij}^{\rm SM}\rvert}$
ϵ_K	2.3×10^{-3}	$\mathcal{O}(0.01)$	$\mathcal{I}m\frac{y_t^2(V_{td}^*V_{ts})^2}{y_c^2(V_{cd}^*V_{cs})^2} \sim 0.01$
A_Γ	≤ 0.004	≤ 0.2	0
$S_{\psi K_S}$	0.67 ± 0.02	$\mathcal{O}(1)$	$\mathcal{I}m\frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}}\frac{V_{cb}^*V_{cd}}{V_{cb}V_{cd}^*} \sim 0.7$
$S_{\psi\phi}$	≤ 1	≤ 1	$\mathcal{I}m\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}\frac{V_{cb}^*V_{cs}}{V_{cb}V_{cs}^*} \sim 0.02$

- Does the new physics know the SM Yukawa structure? (MFV)

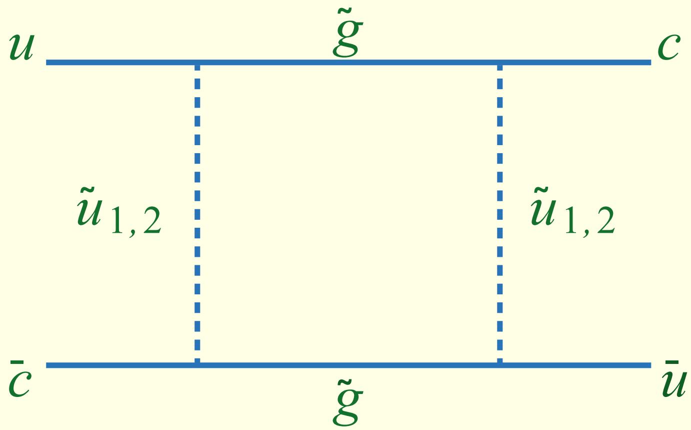
Supersymmetry for Phenomenologists

		FV	CPV
	Y	+	+
	μ	−	+
	A	+	+
	$m_{\tilde{g}}$	−	+
	$m^2_{\tilde{f}}$	+	+
	B	−	+

80 real + 44 imaginary parameters

The $D^0 - \overline{D^0}$ mixing challenge

Take, for example, the contribution from the first two generations of squark doublets to $D - \bar{D}$ mixing:



$\Lambda_{\rm NP} = m_{\tilde{Q}}$

$z_{cu} \sim 3.8 \times 10^{-5} \frac{(\Delta m^2_{\tilde{Q}})^2}{m^4_{\tilde{Q}}} (K^{u_L}_{21} K^{u_L *}_{11})^2$

$$\Longrightarrow \frac{TeV}{m_{\tilde{Q}}} \times \frac{\Delta m^2_{\tilde{Q}}}{m^2_{\tilde{Q}}} \times \sin 2\theta_u \leq 0.05 - 0.10$$

How can Supersymmetry do it?

$$\boxed{\frac{TeV}{\tilde{m}} \times \frac{\Delta\tilde{m}^2_{ij}}{\tilde{m}^2} \times K_{ij} \ll 1}$$

Why? = The SUSY flavor puzzle

How can Supersymmetry do it?

$$\boxed{\frac{TeV}{\tilde{m}} \times \frac{\Delta\tilde{m}^2_{ij}}{\tilde{m}^2} \times K_{ij} \ll 1}$$

Why? = The SUSY flavor puzzle

- Solutions:
  - Heaviness: $\tilde{m} \gg 1\ TeV$
  - Degeneracy: $\Delta\tilde{m}^2_{ij} \ll \tilde{m}^2$
  - Alignment: $K_{ij} \ll 1$
  - Split Supersymmetry
  - Gauge-mediation
  - Horizontal symmetries

Gauge Mediation vs. FN Symmetry

	Gauge mediation	FN symmetry
$\Delta\tilde{m}^2_{12}/\tilde{m}^2$	$(y_c^2/r_3) \sim 10^{-5}$	$1/r_3 \sim 0.2$
K^u_{12}	$y_b^2 V_{ub} V_{cb} \sim 10^{-7}$	$\lvert V_{us}\rvert \sim 0.2$
K^d_{12}	$y_t^2 V_{td} V_{ts} \sim 10^{-4}$	$\lesssim \lvert V_{us}\rvert \sim 10^{-4} - 10^{-2}$

- Can, in principle, distinguish in experiment

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

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 $\frac{z_{sd}}{\Lambda^2_{\rm NP}}(\overline{s_L}\gamma_\mu d_L)^2$
- $\overline{s_L} \in (\bar{3},1,1), \quad d_L \in (3,1,1) \quad \Longrightarrow \quad (\overline{s_L}\gamma_\mu d_L) \in (8,1,1)$
- $Y_d Y_d^\dagger = (\bar{3},1,3) \times (3,1,\bar{3}) \supset (8,1,1)$
  $Y_u Y_u^\dagger = (\bar{3},3,1) \times (3,\bar{3},1) \supset (8,1,1)$
- 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:

- $\frac{\Delta m^2_{\tilde{d}_L}}{m^2_{\tilde{d}_L}} \sim y_c^2, \quad K^{d_L^*}_{21} K^{d_L}_{11} = V^*_{cd} V_{cs}$
- $\frac{\Delta m^2_{\tilde{u}_L}}{m^2_{\tilde{d}_L}} \sim y_c^2, \quad K^{u_L^*}_{21} K^{u_L}_{11} = \frac{y_s^2}{y_c^2} V_{us} V^*_{cs}$

Intermediate summary III

- NP@TeV with generic flavor structure is excluded
- The most extreme solution: MFV
  MFV = A class of NP models where...
- The only violation of the global $[SU(3)]_q^3$ symmetry =
  The Yukawa-spurions: $Y_u(3,\bar{3},1), \quad Y_d = (3,1,\bar{3})$
- Examples: Gauge-, anomaly-, gaugino-mediated supersymmetry breaking
- The NP is subject to an approximate $[SU(2)]^3$ symmetry
- All FC processes $\propto\ V_{\rm CKM}$

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 $\epsilon = \langle S_{-1}\rangle/\Lambda \ll 1$
- 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

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

$$\Downarrow$$

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

- $Y_b : Y_s : Y_d \sim 1 : \epsilon^2 : \epsilon^4$
- $(V_L^d)_{12} \sim \epsilon, \quad (V_L^d)_{23} \sim \epsilon, \quad (V_L^d)_{13} \sim \epsilon^2$

The FN mechanism: a viable model

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

$$\Downarrow$$

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

$$+$$

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

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:
  $U \sim \mathbf{1}$

ν-flavor parameters for anarchists

- $\Delta m^2_{21} = (7.5 \pm 0.2) \times 10^{-5}$ eV^2, $|\Delta m^2_{32}| = (2.5 \pm 0.1) \times 10^{-3}$ eV^2
- $|U_{e2}| = 0.55 \pm 0.01$, $|U_{\mu 3}| = 0.64 \pm 0.02$, $\boxed{|U_{e3}| = 0.15 \pm 0.01}$

Gonzalez-Garcia et al., 1209.3023

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Gonzalez-Garcia et al., 1209.3023

- $|U_{\mu 3}| >$ any $|V_{ij}|$;
- $|U_{e2}| >$ any $|V_{ij}|$
- $|U_{e3}| \not\ll |U_{e2} U_{\mu 3}|$
- $m_2/m_3 \gtrsim 1/6 >$ any m_i/m_j for charged fermions

- So far, neither smallness nor hierarchy
- Anarchy? (Consistent with FN)

ν-flavor parameters for tribimaximalists

- $\Delta m^2_{21} = (7.5 \pm 0.2) \times 10^{-5}\ \text{eV}^2, \quad |\Delta m^2_{32}| = (2.5 \pm 0.1) \times 10^{-3}\ \text{eV}^2$
- $|U_{e2}| = 0.55 \pm 0.01, \quad |U_{\mu 3}| = 0.64 \pm 0.02, \quad \boxed{|U_{e3}| = 0.15 \pm 0.01}$

Gonzalez-Garcia et al., 1209.3023

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Gonzalez-Garcia et al., 1209.3023

- $\sqrt{1/3}$ = trimaximal mixing: $|U_{e2}| = \sqrt{1/3} - 0.03$;
- $\sqrt{1/2}$ = bimaximal mixing: $|U_{\mu 3}| = \sqrt{1/2} - 0.06$;
- 0 = bimaximal mixing: $\boxed{|U_{e3}| = 0 + 0.15}$

- Tribimaximal mixing?
- Non-Abelian flavor symmetry? A_4?

Structure is in the eye of the beholder

$$|U|_{3\sigma} = \begin{pmatrix} 0.79-0.85 & 0.51-0.59 & 0.13-0.18 \\ 0.20-0.54 & 0.42-0.73 & 0.58-0.81 \\ 0.21-0.55 & 0.41-0.73 & 0.57-0.80 \end{pmatrix}$$

- Tribimaximal-ists:

$$|U|_{\rm TBM} = \begin{pmatrix} 0.82 & 0.58 & 0 \\ 0.41 & 0.58 & 0.71 \\ 0.41 & 0.58 & 0.71 \end{pmatrix}$$

- Anarch-ists:

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

What will we learn?

Flavor Physics at the LHC era

- If ATLAS/CMS observe no NP...
- and flavor factories observe no NP...

Flavor Physics at the LHC era

- If ATLAS/CMS observe no NP...
- but flavor factories observe NP...
  - We may have misinterpreted the fine-tuning problem
  - We may have misinterpreted the dark matter puzzle
  - Flavor will provide the only clue for an accessible scale of NP

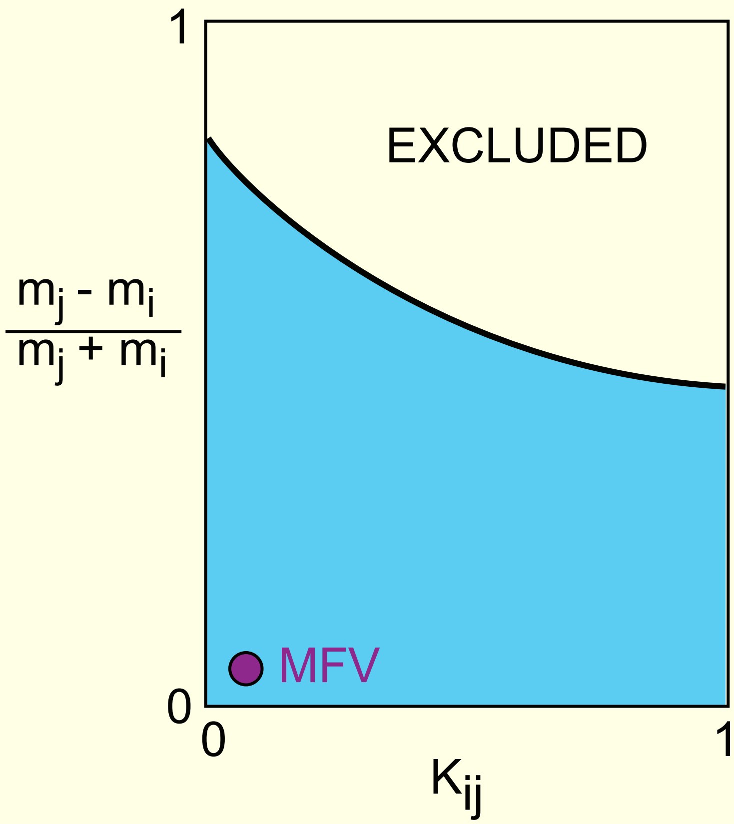
Flavor Physics at the LHC era

ATLAS/CMS will, hopefully, observe NP at $\Lambda_{\rm NP} \lesssim TeV$;

In combination with flavor factories, we may...

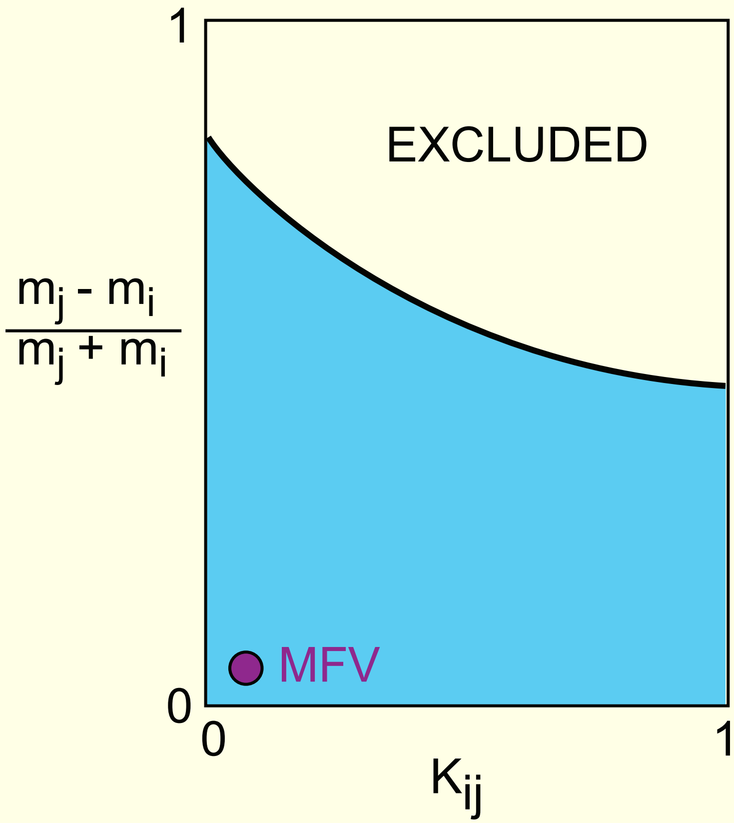
- Understand how the NP flavor puzzle is (not) solved
- Probe NP at $\Lambda_{\rm NP} \gg TeV$
- Get hints about the solution to the SM flavor puzzle

Intermediate summary IV

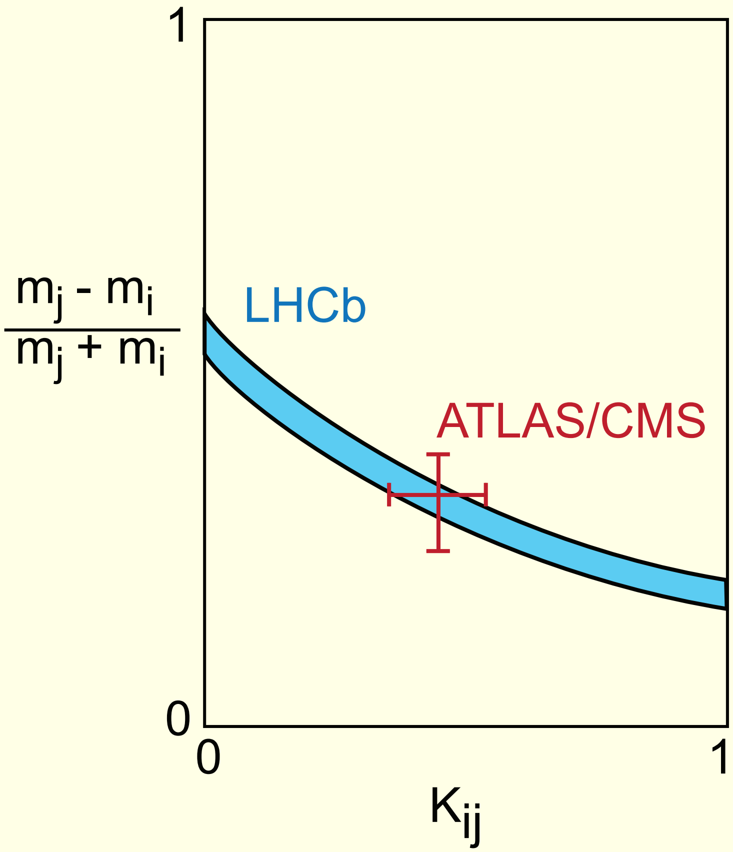


Flavor Factories

Intermediate summary IV



Flavor Factories



FF+ATLAS/CMS

Testing MFV at ATLAS/CMS

- Think of new quarks
  $Q_j \to (W, Z, h) q_i$
- Spectrum – degenerate (1) or hierarchical (Y_q)
- Decay modes – determined by $V_{\rm CKM}$
- How can we exclude MFV at ATLAS/CMS?

Apologies to BABAR and BELLE

- The CKM matrix a-la BABAR/BELLE:

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

Apologies to BABAR and BELLE

- The CKM matrix a-la BABAR/BELLE:

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- The CKM matrix a-la ATLAS/CMS:

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

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 (s)fermions will decay to either 3rd generation or non-3rd generation quarks but not to both

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

MFV + SUSY

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

The Flavor of Higgs

Avital Dery, Aielet Efrati, Yonit Hochberg, YN, arXiv:1302.3229

Present

Observable	Experiment
$R_{\gamma\gamma}$	1.6 ± 0.3
R_{ZZ^*}	1.0 ± 0.4

- $R_f = \frac{\sigma_{\rm prod}{\rm BR}(h\to f)}{[\sigma_{\rm prod}{\rm BR}(h\to f)]^{\rm SM}}$
- Indication that $Y_t = \mathcal{O}(1)$
- The beginning of Higgs flavor physics

Future

Observable	SM
$R_{\tau^+\tau^-}$	1
$X_{\mu\mu} = \frac{\mathrm{BR}(h\to\mu^+\mu^-)}{\mathrm{BR}(h\to\tau^+\tau^-)}$	$(m_\mu/m_\tau)^2$
$X_{\mu\tau} = \frac{\mathrm{BR}(h\to\mu^\pm\tau^\mp)}{\mathrm{BR}(h\to\tau^+\tau^-)}$	0

- What can we learn from $R_{\tau\tau},\ X_{\mu\mu},\ X_{\tau\mu}$?
- Interplay of flavor with electroweak symmetry breaking

Higgs with MFV

- $\lambda_{ij}\bar{L}_i\phi E_j + \frac{\lambda'_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{L}_i\phi E_j + \cdots$
- MFV: $\lambda' = a\lambda + b\lambda\lambda^\dagger\lambda + \cdots$

Higgs with MFV

- $\lambda_{ij}\bar{L}_i\phi E_j + \frac{\lambda'_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{L}_i\phi E_j + \cdots$
- MFV: $\lambda' = a\lambda + b\lambda\lambda^\dagger\lambda + \cdots$

$$\Downarrow$$

- $Y_\tau = \left(1 + \frac{av^2}{\Lambda^2}\right)\ \frac{\sqrt{2}m_\tau}{v}$
- $\frac{Y_\mu}{Y_\tau} = \left[1 - \frac{2b(m_\tau^2 - m_\mu^2)}{\Lambda^2}\right]\ \frac{m_\mu}{m_\tau}$
- $Y_{\mu\tau} = Y_{\tau\mu} = 0$

Higgs with FN

- $\lambda_{ij}\bar{L}_i\phi E_j + \frac{\lambda'_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{L}_i\phi E_j + \cdots$
- FN: $\lambda'_{ij} = \mathcal{O}(1) \times \lambda_{ij}$

Higgs with FN

- $\lambda_{ij}\bar{L}_i\phi E_j + \frac{\lambda'_{ij}}{\Lambda^2}(\phi^\dagger\phi)\bar{L}_i\phi E_j + \cdots$
- FN: $\lambda'_{ij} = \mathcal{O}(1)\times\lambda_{ij}$

$$\Downarrow$$

- $Y_\tau = \left[1+\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right]\ \frac{\sqrt{2}m_\tau}{v}$
- $\frac{Y_\mu}{Y_\tau} = \left[1+\mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right]\ \frac{m_\mu}{m_\tau}$
- $Y_{\mu\tau} = \mathcal{O}\left(\frac{|U_{23}|vm_\tau}{\Lambda^2}\right), \quad Y_{\tau\mu} = \mathcal{O}\left(\frac{vm_\tau}{|U_{23}|\Lambda^2}\right)$

Intermediate summary V

Model	$R_{\tau^+\tau^-}$	$X_{\mu^+\mu^-}/(m_\mu^2/m_\tau^2)$	$X_{\tau\mu}$
SM	1	1	0
MSSM	$(\sin\alpha/\cos\beta)^2$	1	0
MFV	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(v^4/\Lambda^4)$

Conclusions

ATLAS/CMS and flavor factories give complementary information

- In the absence of NP at ATLAS/CMS, flavor factories will be crucial to find $\Lambda_{\rm NP}$
- The NP flavor puzzle is likely to be understood
- Understanding the NP flavor puzzle $\Longrightarrow$
  Probe physics at $\Lambda_{\rm NP} \gg \Lambda_{\rm LHC}$
- With NP that is affected by the mechanism that determines the Yukawa structure:
  The SM flavor puzzle may be solved
- Example: higher-dimension Higgs couplings