Flavor Physics and CP Violation:
Past, Present, Future

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Plan of Lectures

1. Lecture1
    (a) What is flavor and why is it interesting?
    (b) Flavor in the Standard Model
2. Lecture2
    (a) Lessons from the B-factories
    (b) The NP flavor puzzle
3. Lecture3
    (a) Minimal Flavor Violation ($a^b_{\rm SL},\ A^{t\bar t}_{\rm FB}$)
    (b) The SM flavor puzzle
    (c) Neutrino flavor surprises
4. Lecture4
    (a) Flavor@LHC
    (b) Baryogenesis@LHC

What is Flavor Physics?

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
    $\overline{U_L} \lambda_u U_R H, \quad \lambda_u = \mathrm{diag}(y_u, y_c, y_t)$

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

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...)

- MEG: $\mu \to e\gamma$

- LHC: LHCb, ATLAS, CMS

- Future: NA62, Super-B, LHCb-upgrade...

Why is Flavor Physics Interesting?

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]

A recent example of flavor@GeV $\implies$ SUSY@TeV:

- $\Delta m_D + \Delta m_K \implies \Delta m_{\tilde{q}}/m_{\tilde{q}} \lesssim 0.04 - 0.1$

  [Ciuchini et al, PLB 655, 162 (2007); Nir, JHEP 0705, 102 (2007); Blum et al, PRL 102, 211802 (2009)]

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

- $1964 - 2000$
  - $|\varepsilon| = (2.232 \pm 0.007) \times 10^{-3}$; $\mathcal{R}e\ \varepsilon'/\varepsilon = (1.67 \pm 0.26) \times 10^{-3}$

A brief history of CPV

- 1964 – 2000
  - $|\varepsilon| = (2.232 \pm 0.007) \times 10^{-3}$; $\mathcal{R}e\ \varepsilon'/\varepsilon = (1.67 \pm 0.26) \times 10^{-3}$
- 2000 – 2011
  - $S_{\psi K_S} = +0.67 \pm 0.02$
  - $S_{\phi K_S} = +0.56 \pm 0.18$, $S_{\eta' K_S} = +0.59 \pm 0.07$,
    $S_{\pi^0 K_S} = +0.57 \pm 0.17$, $S_{f_0 K_S} = +0.62 \pm 0.12$
  - $S_{K^+K^-K_S} = -0.82 \pm 0.07$, $S_{K_S K_S K_S} = +0.74 \pm 0.17$
  - $S_{\pi^+\pi^-} = -0.65 \pm 0.07$, $C_{\pi^+\pi^-} = -0.38 \pm 0.06$
  - $S_{\psi\pi^0} = -0.93 \pm 0.15$, $S_{DD} = -0.89 \pm 0.26$, $S_{D^*D^*} = -0.77 \pm 0.14$
  - $\mathcal{A}_{K^\mp\rho^0} = +0.37 \pm 0.11$, $\mathcal{A}_{\eta K^\mp} = -0.37 \pm 0.09$, $\mathcal{A}_{f_2 K^\mp} = -0.68 \pm 0.20$
  - $\mathcal{A}_{K^\mp\pi^\pm} = -0.098 \pm 0.012$, $\mathcal{A}_{\eta K^{*0}} = +0.19 \pm 0.05$
  - $\ldots$

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

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

Quark Flavor Violation

- $\mathcal{L}^q_{\text{Yukawa}} = \overline{Q_L}_i Y^u_{ij} \tilde{\phi} U_{Rj} + \overline{Q_L}_i Y^d_{ij} \phi D_{Rj}$
  breaks $U(3)_Q \times U(3)_U \times U(3)_D \to U(1)_B$
- 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

Kobayashi and Maskawa (I)

CP violation ↔ 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 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: $Y^d \to V\lambda^d, \quad Y^u \to \lambda^u$

The mass basis

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

Kobayashi and Maskawa (II)

The achievements:

- Predicting the third generation
- Suggesting the correct mechanism of CP violation

Lepton Flavor Violation

- $\mathcal{L}^{\ell}_{\text{Yukawa}} = \overline{L_L}_i Y^e_{ij} \phi E_{Rj}$
  breaks $U(3)_L \times U(3)_E \to U(1)_e \times U(1)_\mu \times U(1)_\tau$
- Flavor physics:
  interactions that break the $[SU(3)]^5$ symmetry

$$\Downarrow$$

- $L_L \to V_L L_L, \quad E_R \to V_E E_R$
  $=$ Change of interaction basis
- $Y^e \to V_L Y^e V_E^\dagger$
- Can be used to make $Y^e \to \lambda_e = \text{diag}(Y_e, Y_\mu, Y_\tau)$
  No lepton flavor changing interactions within the SM

Intermediate Summary I

- Within the Standard Model
  - The W-mediated quark interactions – the only source of FC and CPV physics: $\mathcal{L}_W = \frac{g}{\sqrt{2}}\overline{U_L} V \gamma^\mu D_L W_\mu^+ + \text{h.c.}$
  - All flavor changing processes depend on 4 CKM parameters: λ, A, ρ, η
  - All CP violating processes depend on the single KM phase: η