(Hadronic) Flavor Physics

3 lectures

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Matter comes in generations

$$\psi \to \psi_i, i = 1, 2, 3$$

commonly labelled with increasing mass, distinguished by 'flavor'

Complex phenomenology: wide range in spectra, $m_u/m_t \sim 10^{-5}$, CP violation, mixing; Flavor physics intimately linked to the making of the Standard Model. New questions with new physics.

These lectures:

* Flavor in the Standard Model
* Flavor and New Physics/the EW scale
* Tools and directions

lecture 1: Flavor in the Standard Model

The Standard Model of Particle Physics

renormalizable quantum field theory + local symmetry

$$SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{em}$$

$$\mathcal{L}_{\mathcal{SM}} = -\frac{1}{4}F^2 + \bar{\psi} i \not{D} \psi + \frac{1}{2}(D\Phi)^2 - \underbrace{\bar{\psi} Y \Phi \psi}_{Yukawa\, interact.} + \mu^2 \Phi^2 - \lambda \Phi^4$$

ψ: fermions (quarks and leptons)

$F_{\mu\nu}$: gauge bosons g, γ, Z, W

Φ: Higgs boson (not observed to date)

Known fundamental matter comes in generations $\psi \rightarrow \psi_i$, $i = 1, 2, 3$.

Flavor physics$=$ investigations on generational structure of fermions (and partners)

The Standard Model of Particle Physics: Flavor

fields in representations under the SM group $SU(3)_C \times SU(2)_L \times U(1)_Y$

Higgs: $\Phi(1, 2, 1/2)$ hypercharge $Y = Q - T^3$

quarks: $Q_L(3, 2, 1/6)_i$, $D_R(3, 1, -1/3)_i$, $U_R(3, 1, 2/3)_i$

leptons: $L_L(1, 2, -1/2)_i$, $E_R(1, 1, -1)_i$ L: doublet, R:singlet under $SU(2)_L$

$$\mathcal{L}_{SM} = \sum_{\psi=Q,U,D,L,E} \bar{\psi}_i i \not{D} \psi_i$$

$$-\bar{Q}_{L_i}(Y_u)_{ij}\Phi^C U_{R_j} - \bar{Q}_{L_i}(Y_d)_{ij}\Phi D_{R_j} - \bar{L}_{L_i}(Y_e)_{ij}\Phi E_{R_j}$$

$$+\mathcal{L}_{higgs} + \mathcal{L}_{gauge}$$

Y_u, Y_d, Y_e: Yukawa matrices (3×3, complex), off diagonal entries mix generations. The Y_x are the sole sources of flavor in SM.

Gauge interactions are flavor universal.

The Standard Model of Particle Physics: Flavor

$$\mathcal{L}_{\mathcal{SM}} = \sum_{\psi=Q,U,D,L,E} \bar{\psi}_i i \not{D} \psi_i$$

$$-\bar{Q}_L Y_u \Phi^C U_R - \bar{Q}_L Y_d \Phi D_R - \bar{L}_L Y_e \Phi E_R \quad + \ldots (\text{no fermions})$$

Want mass eigenstates rather than the above gauge eigenstates:
perform unitary trafos on quark fields $Q_L = (U_L, D_L), U_R, D_R$
$q_A(gauge) \to \tilde{q}_A(mass) = V_{A,q} q_A$ with $V_{A,q} V_{A,q}^\dagger = 1$.

$$\mathcal{L}_{\mathcal{SM}}{}^{yukawa} = -\bar{U}_L \quad \underbrace{V_{L,u}^\dagger V_{L,u}}_{=1} \quad Y_u \Phi^C \quad \underbrace{V_{R,u}^\dagger V_{R,u}}_{=1} \quad U_R + \text{down quarks}$$

$$\mathrm{diag}(m_u, m_c, m_t) = \langle\Phi\rangle \cdot \mathrm{diag}(y_u, y_c, y_t) = \langle\Phi\rangle \cdot V_{L,u} Y_u V_{R,u}^\dagger$$

$$\mathrm{diag}(m_d, m_s, m_b) = \langle\Phi\rangle \cdot \mathrm{diag}(y_d, y_s, y_b) = \langle\Phi\rangle \cdot V_{L,d} Y_d V_{R,d}^\dagger$$

Higgs vev $\langle\Phi\rangle \simeq 174$ GeV

The Standard Model of Particle Physics: Flavor

unitary trafos: $\tilde{q}_A = V_{A,q} q_A$ with $V_{A,q} V_{A,q}^\dagger = 1$.

$$\mathcal{L}_{\mathcal{SM}}{}^{yukawa} = -\bar{U}_L \underbrace{V_{L,u}^\dagger V_{L,u}}_{=1} Y_u \Phi^C \underbrace{V_{R,u}^\dagger V_{R,u}}_{=1} U_R + \text{down quarks.}$$

$$\text{diag}(m_u, m_c, m_t) = \langle \Phi \rangle \cdot V_{L,u} Y_u V_{R,u}^\dagger$$

$$\text{diag}(m_d, m_s, m_b) = \langle \Phi \rangle \cdot V_{L,d} Y_d V_{R,d}^\dagger$$

$$\mathcal{L}_{\mathcal{SM}}{}^{yukawa} = -\underbrace{\bar{U}_L V_{L,u}^\dagger}_{\bar{\tilde{U}}_L} \Phi^C \underbrace{V_{L,u} Y_u V_{R,u}^\dagger}_{diagonal} \underbrace{V_{R,u} U_R}_{\equiv \tilde{U}_R} + \text{down quarks.}$$

The tilde basis are mass eigenstates.

What else has happened under the basis change in $\mathcal{L}_{\mathcal{SM}}$?

The Standard Model of Particle Physics: CKM

The SM higgs interactions are also diagonal.

Gauge interactions: neutral currents γ, Z, g stay being flavor universal, since they dont mix the chiralities, for instance:

$$\bar{U}_L \gamma^\mu A_\mu U_L = \bar{U}_L \ \ (V^\dagger_{L,u} V_{L,u}) \ \ \gamma^\mu A_\mu \ \ (V^\dagger_{L,u} V_{L,u}) \ \ U_L$$

$$= \bar{\tilde{U}}_L \gamma^\mu A_\mu V_{L,u} V^\dagger_{L,u} \tilde{U}_L = \bar{\tilde{U}}_L \gamma^\mu A_\mu \tilde{U}_L \qquad \text{nothing has happend!}$$

However, lets look at the charged currents $W^\pm$:

$$\bar{U}_L \gamma^\mu W^+_\mu D_L = \bar{U}_L \ \ (V^\dagger_{L,u} V_{L,u}) \ \ \gamma^\mu W^+_\mu \ \ (V^\dagger_{L,d} V_{L,d}) \ \ D_L$$

$$= \bar{\tilde{U}}_L \gamma^\mu W^+_\mu \ \ \underbrace{V_{L,u} V^\dagger_{L,d}}_{\equiv V_{CKM} = V \neq 1} \ \ \tilde{D}_L$$

Since Y_u and Y_d dont diagonalize (as observed!) under same unitary transformations, there is one important net effect related to flavor.

The Standard Model of Particle Physics: CKM

The charged current interaction gets a flavor structure, encoded in the Cabibbo Kobayashi Maskawa (CKM) matrix V.

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}} \left(\bar{\tilde{U}}_L \gamma^\mu W^+_\mu V \tilde{D}_L + \bar{\tilde{D}}_L \gamma^\mu W^-_\mu V^\dagger \tilde{U}_L \right) .$$

V_{ij} connects left-handed up-type quark of the ith gen. to left-handed down-type quark of jth gen. Intuitive labelling by flavor:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} , \qquad V_{13} = V_{ub} \;\; etc$$

Via W exchange is the only way to change flavor in the SM.

The Standard Model: CKM properties

V is unitary

V is in general complex, and induces CP violation

V has 4 physical parameters, 3 angles and 1 phase. Why?

unitary 3×3 matrix has 9 parameters. If V would be real, it would be orthogonal and contain 3 'Euler' angles $\Theta_{12}, \Theta_{13}, \Theta_{23}$. Then there should be 9-3=6 phases.

However, perform global, generation-dependent re-phasings of $(\tilde{q}_L)_k \to e^{i\alpha_{q_k}} (\tilde{q}_L)_k$, $q = U, D$, $k = 1, 2, 3$ in $\quad \mathcal{L}_{\rm CC} \sim \bar{\tilde{U}}_L \gamma^\mu W_\mu^+ V \tilde{D}_L$

(Rotate RH fields simultaneously $(\tilde{q}_R)_k \to e^{i\alpha_{q_k}} (\tilde{q}_R)_k$ to keep quark masses real.)

Removes 5 phases (6 fields have at most 5 indepednt rel. phases).

”PDG” parametrization (exact, fully general)

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$s_{ij} \equiv \sin\Theta_{ij}$, $c_{ij} \equiv \cos\Theta_{ij}$. δ is the CP violating phase.

In Nature, $\delta \sim \mathcal{O}(1)$.

The Standard Model: CKM properties

V in Nature is hierarchical $\Theta_{13} \ll \Theta_{23} \ll \Theta_{12} \ll 1$. Wolfenstein parametrization; expansion in $\lambda = \sin\Theta_C$, $A, \rho, \eta \sim \mathcal{O}(1)$

$$V = \begin{pmatrix} 1 - \lambda^2/2 & +\lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & +A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

fits: $\lambda = 0.225, \quad A = 0.81, \quad \bar{\rho} = 0.14, \quad \bar{\eta} = 0.34$

beyond lowest order $\bar{\rho} = \rho(1 - \lambda^2/2)$ and $\bar{\eta} = \eta(1 - \lambda^2/2)$

$\eta \neq 0$ signals CP violation; third gen. quarks decoupled at order λ^2.

There are in total 10 (known!) param. in quark flavor $\&$ CP sector:

6 masses, 3 angles and 1 phase in CKM-matrix

with accuracy: $|V_{us}| = 0.225$ (permille), $|V_{cb}| = 42 \cdot 10^{-3}$ (percent), $|V_{ub}| = 4 \cdot 10^{-3}$ (ten percent), $\sin 2\beta(\text{measured}) = 0.67$ (percent)

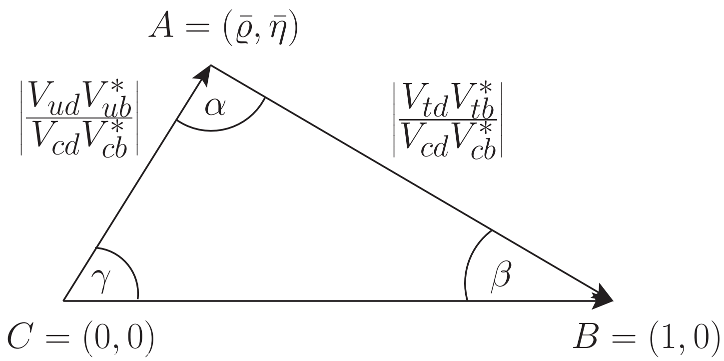
PS: enormous progress from B-factories over past decade. PPS: still improving precision.

All hadronic flavor violation, including decays, productions rates at colliders and meson mixing effects should be described by these 10 parameters alone, if SM is correct. Since all parameters are known, this statement is very predictive and subject to numerous tests.

V is unitary $VV^\dagger = 1$ or, $\sum_j V_{ij}V_{kj}^* = \delta_{ik}$.

the unitarity triangle

$V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0$, all terms order λ^3.

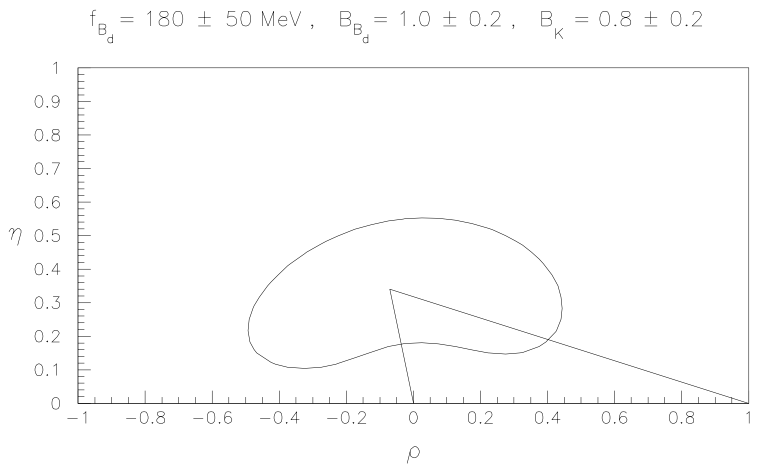


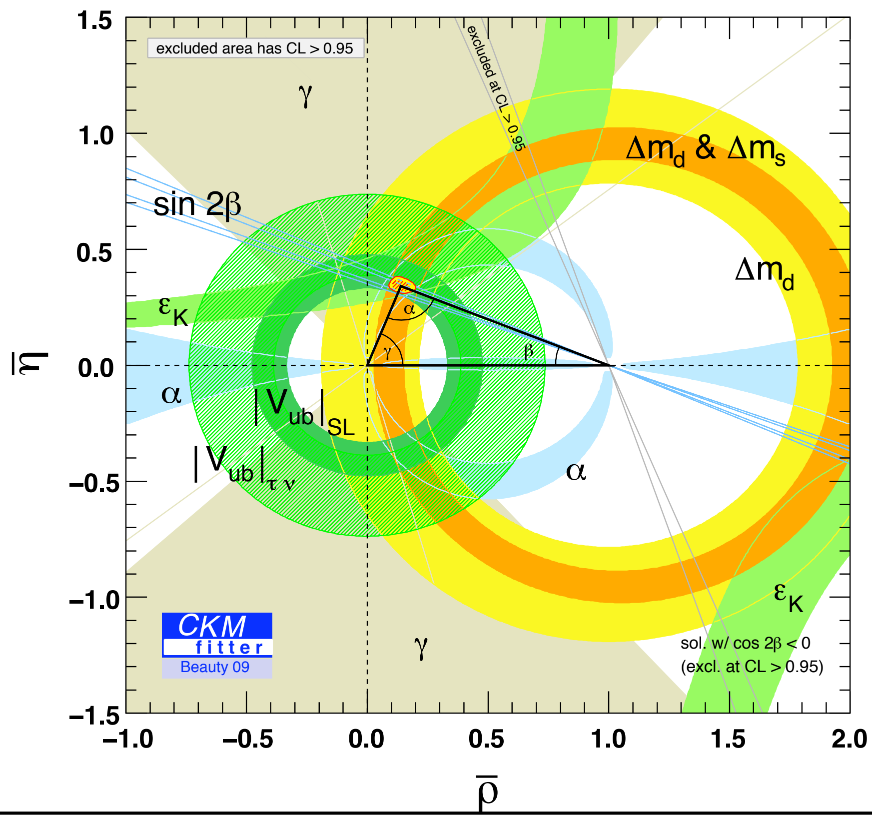
Its apex determines the Wolfenstein parameters $\bar\rho, \bar\eta$. In the absence of CP viol., the triangle would be squashed.

Information on the apex can come from various processes, measuring angles or sides.

SM tests with Quark flavor/CKM 1995 vs today

The CKM-picture of flavor and CP violation is currently consistent with all – and quite different – laboratory observations, although some tensions exist.





The quarks spectrum and mixings are hierarchical, and stem from the Yukawa matrices.

Numerically, we determined them as

$$
\begin{aligned}
Y_u &\sim \begin{pmatrix} 10^{-5} & -0.002 & 0.008 + i\,0.003 \\ 10^{-6} & 0.007 & -0.04 \\ 10^{-8} + i\,10^{-7} & 0.0003 & 0.94 \end{pmatrix} \\
Y_d &\sim \operatorname{diag}\left(10^{-5}, 5 \cdot 10^{-4}, 0.025\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle}) \\
Y_e &\sim \operatorname{diag}\left(10^{-6}, 6 \cdot 10^{-4}, 0.01\right) \quad (\cdot \frac{\langle H_u \rangle}{\langle H_d \rangle})
\end{aligned}
$$

Very peculiar pattern. We dont know why it is this way.