Flavour & EFT

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Main references:

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Plan of these lectures

- What is flavour?
- Flavour in SM
- Testing CKM
- CPV & neutral meson mixing
- Introduction to EFT
- Flavour probes of SM & NP

What is flavour?

- In SM: fermionic fields (spin 1/2)
- *matter flavours*: several copies of the same gauge representation

What is flavour?

- In SM: fermionic fields (spin $1/2$)
- *matter flavours*: several copies of the same gauge representation
- unbroken SM gauge group $\mathrm{SU}(3)_\mathrm{c} \times \mathrm{U}(1)_\mathrm{EM}$
  - up-type quarks: $(3)_{2/3} : u,\ c,\ t,$
  - down-type quarks: $(3)_{-1/3} : d,\ s,\ b,$
  - chrged leptons: $(1)_{-1} : e,\ \mu,\ \tau,$
  - neutrinos: $(1)_0 : \nu_1,\ \nu_2,\ \nu_3,$

$$\leftrightarrow$$

differ only in mass

What is flavour?

- Ordinary matter essentially first generation:
  - u and d quarks bound within protons & neutrons,
  - electrons form atoms;
  - "electron neutrinos", (admixture of $\nu_{1,2,3}$) are produced in reactions inside stars.
- 2nd and 3rd generation families decay via weak interactions into first generation particles.

Why there are thee almost identical replicas of quarks and leptons and which is the origin of their different masses?

What is flavour?

- *Flavour physics*
  - Within SM: weak and Yukawa interactions.
- *Flavour parameters*
  - Within SM: 9 masses of charged fermions
    & 4 mixing parameters (3 angles + 1 phase)
- *Flavour universal* (*flavour blind*)
  - Within SM: QCD & QED
- *Flavour diagonal*
  - Within SM: Yukawa interaction

What is flavour?

- *Flavour changing processes*
  - *Flavour changing charged currents:*

    $$\mu^- \to e^- \nu_i \bar{\nu}_j \qquad K^- \to \mu^- \bar{\nu}_i \;\; (s\bar{u} \to \mu^- \bar{\nu}_i)$$

    - Within SM: single W exchange at tree-level $(\mathcal{A} \propto G_F)$
  - *Flavour changing neutral currents:*

    $$\mu^- \to e^- \gamma \qquad K_L \to \mu^+ \mu^- \; (s\bar{d} \to \mu^+ \mu^-)$$

    - Within SM: higher orders in weak expansion(loops) - often highly suppressed

Why is flavour interesting?

- $\dfrac{\Gamma(K_L \to \mu^+\mu^-)}{\Gamma(K^- \to \mu^-\bar{\nu}_i)} \Rightarrow$ prediction of charm quark
- $\Delta m_K \equiv m_{K_L} - m_{K_S} \Rightarrow$ prediction of charm mass
- $K_L \to \pi^+\pi^-$ $(\varepsilon_K) \Rightarrow$ prediction of 3rd generation
- *CP Violation*
    - Within SM: single CP violating parameter

Why is flavour interesting?

- Electroweak (EW) hierarchy problem
  - requires NP $\lesssim$ 1 TeV
  - if generic flavour structure $\Rightarrow$ FCNCs
  - flavour probes NP scales $\lesssim 10^5$ TeV

NP flavour puzzle

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NP flavour puzzle

- SM flavour parameters
  - hierarchical: $m_u << m_c << m_t$
  - most are small: $m_{f\neq t} << m_{W,Z}$

SM flavour puzzle

Flavour in SM

Flavour in SM

$$\mathcal{L} = ?$$

i) Symmetries & their spontaneous breaking

ii) Representations of fermions & scalars

Flavour in SM

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i) Symmetries & their spontaneous breaking

ii) Representations of fermions & scalars

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i) $$\mathcal{G}^{\rm SM}_{\rm local} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\mathcal{G}^{\rm SM}_{\rm local} \to SU(3)_c \times U(1)_{\rm EM}$$

ii) $$Q^i_L \sim (3,2)_{1/6}\,,\ U^i_R \sim (3,1)_{2/3}\,,$$

$$D^i_R \sim (3,1)_{-1/3}\,,\ L^i_L \sim (1,2)_{-1/2}\,,$$

$$\phi \sim (1,2)_{1/2}\,,\ \langle\phi^0\rangle \equiv \frac{v}{\sqrt{2}} \simeq 174\text{GeV}\,,$$

Flavour in SM

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}^{\mathrm{SM}}_{\mathrm{kinetic}} + \mathcal{L}^{\mathrm{SM}}_{\mathrm{EWSB}} + \mathcal{L}^{\mathrm{SM}}_{\mathrm{Yukawa}}$$

- simple and symmetric (g, g', g_s)
- EWSB, 2 params
- SM flavour dynamics, flavour parameters

Interaction basis

$$\mathcal{L}_{\text{kinetic}}^{\text{SM}} = (D_\mu\phi)^\dagger(D^\mu\phi) + \sum_{i,j=1,2,3}\ \sum_{\psi=Q_L,\ldots,E_R} \bar{\psi}^i i\not{D}\delta^{ij}\psi^j$$
$$- \frac{1}{4}\sum_{a=1,\ldots,8} G^a_{\mu\nu}G^{a,\mu\nu} - \frac{1}{4}\sum_{a=1,2,3} W^a_{\mu\nu}W^{a,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

- $D_\mu = \partial_\mu + ig_s G^a_\mu L^a + igW^b_\mu T^b + ig' B_\mu Y$

$$\mathcal{L}_{\text{EWSB}}^{\text{SM}} = \mu^2\phi^\dagger\phi - \lambda(\phi^\dagger\phi)^2$$

Interaction basis

$$
\begin{aligned}
\mathcal{G}^{\rm SM}_{\rm flavour} &= U(3)^5 = SU(3)^3_q \times SU(3)^2_\ell \times U(1)^5 \,, \\
SU(3)^3_q &= SU(3)_Q \times SU(3)_U \times SU(3)_D \,, \\
SU(3)^2_\ell &= SU(3)_L \times SU(3)_E \,, \\
U(1)^5 &= U(1)_B \times U(1)_L \times U(1)_Y \times U(1)_{\rm PQ} \times U(1)_E \,.
\end{aligned}
$$

Interaction basis

$$-\mathcal{L}^{\mathrm{SM}}_{\mathrm{Yukawa}} = Y_d^{ij}\bar{Q}_L^i \phi D_R^j + Y_u^{ij}\bar{Q}_L^i \tilde{\phi} U_R^j + Y_e^{ij}\bar{L}^i \phi E_R^j + \mathrm{h.c.}\,,$$

$$\tilde{\phi} = i\sigma_2\phi,$$

- in general flavour dependent (unless $Y_F \propto I_{ij}$) & CPV

Interaction basis

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– $U(1)_E$ is broken by $Y_e \neq 0\,,$

– $U(1)_{\rm PQ}$ is broken by $Y_u \cdot Y_d \neq 0$ and $Y_u \cdot Y_e \neq 0\,,$

Interaction basis

$$-\mathcal{L}_{\text{Yukawa}}^{\text{SM}} = Y_d^{ij}\bar{Q}_L^i \phi D_R^j + Y_u^{ij}\bar{Q}_L^i \tilde{\phi} U_R^j + Y_e^{ij}\bar{L}^i \phi E_R^j + \text{h.c.}\,,$$

$$\tilde{\phi} = i\sigma_2\phi,$$

- in general flavour dependent (unless $Y_F \propto I_{ij}$) & CPV

– $U(1)_E$ is broken by $Y_e \neq 0$,

– $U(1)_{\text{PQ}}$ is broken by $Y_u \cdot Y_d \neq 0$ and $Y_u \cdot Y_e \neq 0$,

– $SU(3)_Q \times SU(3)_U \to U(1)_u \times U(1)_c \times U(1)_t$ is due to $Y_u \not\propto \mathrm{I}$,

– $SU(3)_Q \times SU(3)_D \to U(1)_d \times U(1)_s \times U(1)_b$ is due to $Y_d \not\propto \mathrm{I}$,

(Y_U & Y_D together break remaining $U(1)$ factors to $U(1)_B$)

Interaction basis

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y_d^{ij}\bar{Q}^i_L\phi D^j_R + Y_u^{ij}\bar{Q}^i_L\tilde{\phi}U^j_R + Y_e^{ij}\bar{L}^i\phi E^j_R + \text{h.c.}\,,$$

$$\tilde{\phi} = i\sigma_2\phi,$$

- in general flavour dependent (unless $Y_F \propto I_{ij}$) & CPV

– $U(1)_E$ is broken by $Y_e \neq 0\,$,

– $U(1)_{\rm PQ}$ is broken by $Y_u \cdot Y_d \neq 0$ and $Y_u \cdot Y_e \neq 0\,$,

– $SU(3)_Q \times SU(3)_U \to U(1)_u \times U(1)_c \times U(1)_t$ is due to $Y_u \not\propto \mathrm{I}\,$,

– $SU(3)_Q \times SU(3)_D \to U(1)_d \times U(1)_s \times U(1)_b$ is due to $Y_d \not\propto \mathrm{I}\,$,

(Y_U & Y_D together break remaining $U(1)$ factors to $U(1)_B$)

– finally, $SU(3)_L \times SU(3)_E \to U(1)_e \times U(1)_\mu \times U(1)_\tau$ due to $Y_e \not\propto \mathrm{I}$

$$\mathcal{G}^{\rm SM}_{\rm global}(Y_f \neq 0) = U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

Interaction basis

- *Flavour physics*: interactions which break $SU(3)_q^3 \times SU(3)_\ell^2$ are *flavour violating*
- Spurion analysis:

  $$Y_u \sim (3, \bar{3}, 1)_{SU(3)_q^3}\,,\ Y_d \sim (3, 1, \bar{3})_{SU(3)_q^3}\,,\ Y_e \sim (3, \bar{3})_{SU(3)_\ell^2}\,.$$

  - parameter counting
  - identification of suppression factors
  - idea of Minimal Flavour Violation

Counting SM quark flavour parameters

- global symmetry group G_f with N_{total} generators
- $G_f \rightarrow H_f$ with $N_{\text{total}} - N_{\text{broken}}$ generators
- $N_{\text{physical}} = N_{\text{general}} - N_{\text{broken}}$

Counting SM quark flavour parameters

- global symmetry group G_f with $N_{\rm total}$ generators
- $G_f \to H_f$ with $N_{\rm total} - N_{\rm broken}$ generators
- $N_{\rm physical} = N_{\rm general} - N_{\rm broken}$
- Within SM: $U(3)_Q \times U(3)_U \times U(3)_D \to U(1)_B$

$$N_{\rm total} = 3\times(3+6i), \quad N_{\rm broken} = N_{\rm total} - 1i = 9+17i,$$
$$N_{\rm general} = 2\times(9+9i) \; (Y_U,\; Y_D)$$
$$N_{\rm physical} = N_{\rm general} - N_{\rm broken} = 9 + 1i$$

Discrete SM symmetries

- Any local Lorentz invariant QFT conserves CPT $\Rightarrow$ CP violation $=$ T violation
- In SM: C & P violation maximally
  - C & P change chirality
  - Left- & right-handed fields in different gauge reps.

independent of SM parameters

Discrete SM symmetries

- Any local Lorentz invariant QFT conserves CPT $\Rightarrow$ CP violation = T violation

- In SM: CP violation depends on parameters

$$Y_{ij}\bar{\psi}^i_L\phi\psi^j_R + Y^*_{ij}\bar{\psi}^j_R\phi^\dagger\psi^i_L \stackrel{\mathrm{CP}}{\to} Y_{ij}\bar{\psi}^j_R\phi^\dagger\psi^i_L + Y^*_{ij}\bar{\psi}^i_L\phi\psi^j_R\,.$$

  - CP symmetric if $Y_{ij} = Y^*_{ij}$.

  - Jarlskog invariant

$$J \equiv \mathrm{Im}[\det(Y_dY_d^\dagger, Y_uY_u^\dagger)] = 0\,.$$

Discrete SM symmetries

- Any local Lorentz invariant QFT conserves CPT $\Rightarrow$ CP violation = T violation
- Experimental discovery of CPV in kaon decays

Cronin 1980 **Fitch**

Mass basis

- $\mathrm{Re}(\phi^0) \to (v+h)/\sqrt{2}$, ⇒ $M_q = \frac{v}{\sqrt{2}} Y_q$.
  - mass basis corresponds to diagonal M_q
- $Q_L \to V_Q Q_L\ ,\ U_R \to V_U U_R\ ,\ D_R \to V_D D_R$
  - $Y_u \to V_Q Y_u V_U^\dagger\ ,\ Y_d \to V_Q Y_d V_D^\dagger$
- $V_Q^u M_u V_U^\dagger = M_u^{\mathrm{diag}} = \frac{v}{\sqrt{2}} \lambda_u\ ; \quad \lambda_u = \mathrm{diag}(y_u, y_c, y_t)\ ,$

  $V_Q^d M_d V_D^\dagger = M_d^{\mathrm{diag}} = \frac{v}{\sqrt{2}} \lambda_d\ ; \quad \lambda_d = \mathrm{diag}(y_d, y_s, y_b)\ .$

Mass basis

- $V_{U,}\ V_D$ unphysical
- since $[M_u, M_d] \neq 0, \quad V_Q^u V_Q^{d\dagger} \equiv V_{\rm CKM} \neq 1$

Cabibbo, Kobayashi & Maskawa

2008

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Cabibbo, Kobayashi & Maskawa

- SM flavour Lagrangian

$$\mathcal{L}_m^F = \left(\bar{q}_i \not{D} q^j \delta_{ij}\right)_{\rm NC} + \frac{g}{\sqrt{2}} \bar{u}_L^i \not{W}^+ V_{\rm CKM}^{ij} d_L^j$$
$$+ \bar{u}_L^i \lambda_u^{ij} u_R^j \left(\frac{v+h}{\sqrt{2}}\right) + \bar{d}_L^i \lambda_d^{ij} d_R^j \left(\frac{v+h}{\sqrt{2}}\right) + \text{h.c.}\,,$$

NC $=$ neutral currents (g, γ, Z) $\qquad (u_L^i, d_L^i) \equiv Q_L^T$