Flavour physics and CP violation

Lecture 3: Flavour physics beyond the SM

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Outline

1. **Flavour physics in the Standard Model (SM)**
    - CKM matrix
    - flavour changing neutral currents
    - effective Hamiltonian
2. **Phenomenology of K and B meson decays**
    - neutral meson mixing
    - rare K decays
    - $b \to s$ transitions
3. **Flavour physics beyond the SM**
    - constraints on the scale of new physics
    - Minimal Flavour Violation
    - flavour hierarchies from partial compositeness

SM suppression of FCNCs

Flavour changing neutral currents in the SM strongly suppressed by

- loop suppression $\propto g^2/(16\pi^2)$
- CKM hierarchy

$$\underbrace{V_{ts}^* V_{td}}_{K \text{ system}} \sim 5 \cdot 10^{-4} \ll \underbrace{V_{tb}^* V_{td}}_{B_d \text{ system}} \sim 10^{-2} < \underbrace{V_{tb}^* V_{ts}}_{B_s \text{ system}} \sim 4 \cdot 10^{-2}$$

  ➢ K decays in general most sensitive to BSM physics

- GIM mechanism
- chirality of weak interactions: purely left-handed
  ➢ no strong RGE enhancements

Any of these could be absent in the presence of new physics!
➢ strong sensitivity!

New physics in the effective theory language

- SM is renormalisable
  ➢ all terms in the Lagrangian have mass dimension ≤ 4

- parametrise NP in a model-independent way by including higher dimensional effective operators consistent with SM symmetries

  ➢ SM as an effective theory

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda} \mathcal{O}_i^{\text{dim 5}} + \sum_i \frac{C_i}{\Lambda^2} \mathcal{O}_i^{\text{dim 6}} + \cdots$$

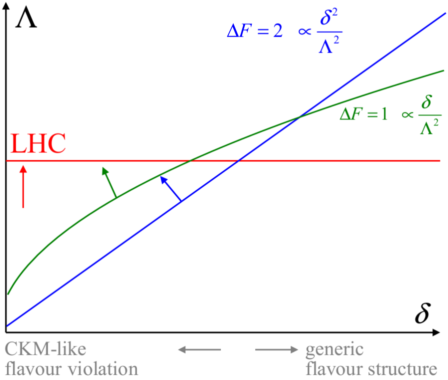
  - dimension 5: Weinberg operator ➢ neutrino masses
  - dimension 6: e. g. four fermion interactions mediating FCNCs

- NP flavour structure (δ: possible suppression of FCNC couplings)

$$C_i^{\Delta F=2} \propto \delta^2 \text{ while } C_i^{\Delta F=1} \propto \delta$$

Collider vs. flavour physics

New physics (NP) reach



- LHC bounds (mostly) independent of NP flavour structure
- for generic flavour structure $\delta \sim \mathcal{O}(1)$ meson mixing observables most sensitive
- if NP employs flavour hierarchies, $\Delta F = 1$ rare decays competitive

Effective Hamiltonian for $\Delta F = 2$ transitions

$$\mathcal{H}_{\text{eff}}^{\Delta F=2} = \frac{1}{\Lambda^2} \sum_{i=1}^{5} C_i \mathcal{O}_i + \sum_{i+1}^{3} \tilde{C}_i \tilde{\mathcal{O}}_i$$

with the four fermion operators for $B_{d,s} - \bar{B}_{d,s}$ mixing ($q = d, s$)

$$\mathcal{O}_1 = (\bar{q}^\alpha \gamma_\mu P_L b^\alpha)(\bar{q}^\beta \gamma^\mu P_L b^\beta) \qquad \text{(SM operator)}$$

$$\mathcal{O}_2 = (\bar{q}^\alpha P_L b^\alpha)(\bar{q}^\beta P_L b^\beta) \qquad \mathcal{O}_3 = (\bar{q}^\alpha P_L b^\beta)(\bar{q}^\beta P_L b^\alpha)$$

$$\mathcal{O}_4 = (\bar{q}^\alpha P_L b^\alpha)(\bar{q}^\beta P_R b^\beta) \qquad \mathcal{O}_5 = (\bar{q}^\alpha P_L b^\beta)(\bar{q}^\beta P_R b^\alpha)$$

$$\tilde{\mathcal{O}}_1 = (\bar{q}^\alpha \gamma_\mu P_R b^\alpha)(\bar{q}^\beta \gamma^\mu P_R b^\beta)$$

$$\tilde{\mathcal{O}}_2 = (\bar{q}^\alpha P_R b^\alpha)(\bar{q}^\beta P_R b^\beta) \qquad \tilde{\mathcal{O}}_3 = (\bar{q}^\alpha P_R b^\beta)(\bar{q}^\beta P_R b^\alpha)$$

and analogous expressions for $K^0 - \bar{K}^0$ mixing

α, β: colour indices

Constraints on the NP scale

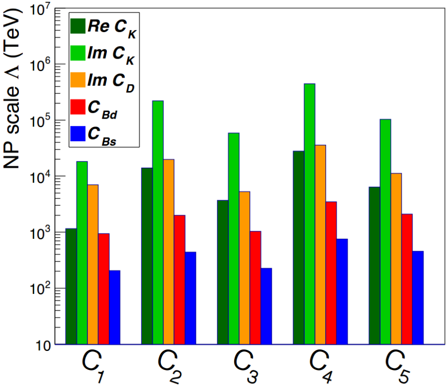
generic NP flavour structure:

$$|C_i| \sim \mathcal{O}(1) \quad \arg C \sim \mathcal{O}(1)$$

- strong constraints on $\Lambda > 100$ TeV
- CP violation in $K^0 - \bar{K}^0$ mixing most constraining

  ➢ scale of scalar LR operator C_4 restricted to $\Lambda \gtrsim 10^5$ TeV

UTFIT (2015)



The flavour of the TeV scale

- electroweak naturalness requires NP at the TeV scale
  - ➢ apparenyly incompatible with FCNC constraints

NP flavour problem

- Can NP conserve flavour?
  - ➢ no! - flavour already violated in the SM
- Can NP conserve flavour approximately?
  - ➢ yes!
  - invoke approximate flavour symmetry
  - . . . or a dynamical explanation of flavour hierarchies

Minimal Flavour Violation

Recall from Lecture 1: SM flavour symmetry

$$G_{\text{flavour}} = U(3)_Q \times U(3)_U \times U(3)_D$$

broken only by Yukawa couplings Y_U, Y_D

➢ hierarchical structure of Y_U, Y_D strongly suppresses FCNCs

Use the same mechanism in the NP sector:

Minimal Flavour Violation hypothesis

- all breaking of flavour symmetry G_{flavour} is driven by Yukawa couplings Y_U, Y_D
- also assume no new CP violating phases

➢ CKM suppression also effective in the NP sector

Yukawa couplings as spurions

We can restore the flavour symmetry G_{flavour} by treating the Yukawa couplings as dimensionless auxiliary fields ("spurions"). They transform as

$$Y_U \sim (3, \bar{3}, 1) \qquad Y_D \sim (3, 1, \bar{3})$$

Then the SM is (formally) invariant under G_{flavour}

$$\mathcal{L}_{\text{Yuk}} = \sum_{i,j=1}^{3} (-Y_{U,ij} \bar{Q}_{Li} \tilde{H} U_{Rj} - Y_{D,ij} \bar{Q}_{Li} H D_{Rj} + h.c.)$$

To render also higher-dimensional effective NP operators invariant, we add appropriate combinations of Y_U, Y_D.

How does this work?

We are interested in FCNCs in the down quark sector ➢ convenient to work in the down quark mass basis:

$$Y_D = \mathrm{diag}(y_d, y_s, y_b) \qquad Y_U = V_{\mathsf{CKM}}^\dagger \, \mathrm{diag}(y_u, y_c, y_t) \qquad \text{with} \quad y_i = m_i/v$$

Example: LL operator for $\Delta F = 2$

$$\mathcal{O}_1 : \quad \frac{C_1^{ij}}{\Lambda^2}(\bar{Q}_{Li}\gamma_\mu Q_{Lj})(\bar{Q}_{Li}\gamma^\mu Q_{Lj}) \qquad i \neq j$$

restoring the flavour symmetry, we find

$$\begin{aligned} C_1^{ij} &= (a \cdot \mathbb{1} + b \cdot Y_D Y_D^\dagger + c \cdot Y_U Y_U^\dagger)^2_{ij} \\ &= (c \cdot V_{\mathsf{CKM}}^\dagger \, \mathrm{diag}(y_u^2, y_c^2, y_t^2) V_{\mathsf{CKM}})^2_{ij} \\ &\simeq c^2 \cdot y_t^4 (V_{ti}^* V_{tj})^2 \end{aligned}$$

➢ same CKM and GIM suppression as in the SM

Scalar LR operator in MFV

Strongest constraint on generic NP scale from

$$\mathcal{O}_4^{ij}: \quad \frac{C_4^{ij}}{\Lambda^2}(\bar{D}_{Ri}Q_{Lj})(\bar{Q}_{Li}D_{Rj})$$

Again using the MFV hypothesis, we find

$$\begin{aligned} C_4^{ij} &= \left[Y_D^\dagger(a\cdot\mathbb{1} + b\cdot Y_D Y_D^\dagger + c\cdot Y_U Y_U^\dagger)\right]_{ij} \\ &\quad \times \left[(d\cdot\mathbb{1} + e\cdot Y_D Y_D^\dagger + f\cdot Y_U Y_U^\dagger)Y_D\right]_{ij} \\ &= c\cdot y_i y_t^2 (V_{ti}^* V_{tj}) \times f\cdot y_j y_t^2 (V_{ti}^* V_{tj}) \end{aligned}$$

➢ strong suppression by external quark masses $m_i m_j$!

Constrained MFV

- since $m_t \gg m_b$, in the SM $y_t \gg y_b$
- $y_t \gg y_b$ holds also in many NP models – can however be violated in the presence of an extended Higgs sector (e. g. MSSM at large $\tan\beta$
- then operators which involve Y_D become negligible
- only operators involving Q_L are relevant for K and B physics
- these are the ones already present in the SM effective Hamiltonian

Constrained Minimal Flavour Violation (CMFV)

- all breaking of flavour symmetry G_{flavour} is driven by Yukawa couplings Y_U, Y_D
- no new CP violating phases
- only SM effective operators

CMFV in $\Delta F = 2$ transitions

only one operator in $\Delta F = 2$ transitions

$$\mathcal{O}_1 : \quad \frac{C_1^{ij}}{\Lambda^2}(\bar{Q}_{Li}\gamma_\mu Q_{Lj})(\bar{Q}_{Li}\gamma^\mu Q_{Lj}) \qquad i \neq j$$

with the same CKM dependence as in the SM: $(V_{ti}^* V_{tj})^2$

➢ new CMFV contribution parametrised by a flavour-universal shift in the loop function

$$S_0(x_t) \to S(v)$$

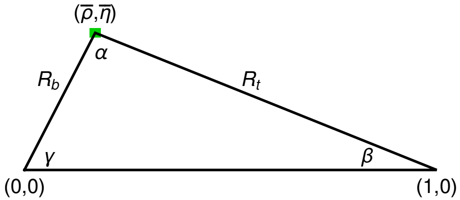
- $\Delta F = 2$ sector described by only one new parameter
- construct *universal* unitarity triangle

Universal unitarity triangle

Universal unitarity triangle holding within all CMFV models

- $|V_{us}|$ from tree-level decays
- angle β determined from time-dependent CP-asymmetry $S_{\psi K_S}$
- side R_t determined from $\Delta M_d/\Delta M_s$

➢ much more precise than tree level determination



$\bar{\rho}_{\text{UUT}} = 0.170 \pm 0.013$ $\bar{\eta}_{\text{UUT}} = 0.333 \pm 0.011$ $\gamma = (63.0 \pm 2.1)^\circ$

Must TeV scale NP be MFV?

MFV hypothesis is very powerful in avoiding problematic FCNCs

- ➢ Λ can be lowered to the TeV scale
- ➢ very predictive framework: correlations between FCNC observables

however it is not the only option

- different flavour symmetry and breaking pattern possible
  e. g. minimally broken $U(2)^3$
- or get flavour hierarchies from a dynamical origin
  ➢ **partial compositeness**

Quick and dirty intro to composite modelss

Basic idea:

- Higgs boson is a composite state, similar to the pion
  ➢ avoid naturalness problem
- EW symmetry broken by condensate of composite sector
- SM particles (mostly) elementary to avoid problems with precision tests
- composite resonances expected around the TeV scale (ρ, ω etc.)

Problem of original models: fermion masses

Partially composite fermions

elementary sector
known SM fermion fields

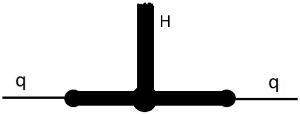
$\longleftrightarrow$

composite sector
operators describing composite states with identical quantum numbers

linear mixing

$$\mathcal{L}_{\text{mixing}} \sim \epsilon_Q \bar{Q}_L \mathcal{O}_Q + \epsilon_U \bar{U}_R \mathcal{O}_U + \epsilon_D \bar{D}_R \mathcal{O}_D$$

➢ observed Yukawa couplings are a combination of strong sector coupling $\lambda_{U,D}$ to the Higgs and elementary-composite mixings $\epsilon_{Q,U,D}$:



➢ $Y_{U,D} \sim \epsilon_Q \epsilon_{U,D} \lambda_{U,D}$

➢ elementary-composite mixing controls hierarchies of effective Yukawas

Flavour hierarchy from partial compositeness

- strong sector couplings are anarchic ("all hell breaks loose")

$$|\lambda_{U,D}^{ij}| \sim \mathcal{O}(1) \qquad \arg\lambda_{U,D}^{ij} \sim \mathcal{O}(1)$$

- we know experimentally (precision tests) that first two generations are mostly elementary

$$\epsilon_{U,D}^{1,2} \ll 1$$

- third generation less constrained
- large top quark mass requires

$$\epsilon_Q^3 \sim \epsilon_U^3 \sim \mathcal{O}(1)$$

quark masses require pattern:

$$\epsilon_Q^1 \ll \epsilon_Q^2 \ll \epsilon_Q^3 \sim \mathcal{O}(1) \qquad \epsilon_U^1 \ll \epsilon_U^2 \ll \epsilon_U^3 \sim \mathcal{O}(1) \qquad \epsilon_D^1 \ll \epsilon_D^2 \ll \epsilon_D^3 \ll 1$$

CKM hierarchy from partial compositeness

Hierachical structure of effective Yukawa couplings

$$Y_U \sim \begin{pmatrix} \epsilon_Q^1\epsilon_U^1 & \epsilon_Q^1\epsilon_U^2 & \epsilon_Q^1\epsilon_U^3 \\ \epsilon_Q^2\epsilon_U^1 & \epsilon_Q^2\epsilon_U^2 & \epsilon_Q^2\epsilon_U^3 \\ \epsilon_Q^3\epsilon_U^1 & \epsilon_Q^3\epsilon_U^2 & \epsilon_Q^3\epsilon_U^3 \end{pmatrix} \qquad Y_D \sim \begin{pmatrix} \epsilon_Q^1\epsilon_D^1 & \epsilon_Q^1\epsilon_D^2 & \epsilon_Q^1\epsilon_D^3 \\ \epsilon_Q^2\epsilon_D^1 & \epsilon_Q^2\epsilon_D^2 & \epsilon_Q^2\epsilon_D^3 \\ \epsilon_Q^3\epsilon_D^1 & \epsilon_Q^3\epsilon_D^2 & \epsilon_Q^3\epsilon_D^3 \end{pmatrix}$$

also generates small off-diagonal CKM elements:

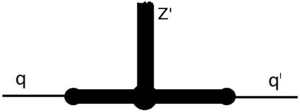
$$|V_{us}| \sim \frac{\epsilon_Q^1}{\epsilon_Q^2} \qquad |V_{ub}| \sim \frac{\epsilon_Q^1}{\epsilon_Q^3} \qquad |V_{cb}| \sim \frac{\epsilon_Q^2}{\epsilon_Q^3}$$

➢ prediction: $|V_{us}| \cdot |V_{cb}| \sim |V_{ub}|$

check: $|V_{us}| \sim 0.2,\ |V_{cb}| \sim 4 \cdot 10^{-2}$ ➢ $|V_{us}| \cdot |V_{cb}| \sim 8 \cdot 10^{-3} \sim 2|V_{ub}|$

Suppression of FCNCs

- composite sector introduces large tree level FCNCs (again "all hell breaks loose")
- mediated to the SM fermions by elementary-composite mixing



➢ suppressed by the same hierarchical pattern that generates the hierarchic quark masses and CKM mixing

Is this suppression sufficient?

- mostly yes
- however some tension with CP violation in the kaon system (ε, ε'/ε)
  - ➢ strong resonance masses $\gtrsim 10$ TeV required – or some extended model

But where does the hierarchy come from?

We have traced the SM flavour hierarchies back to exponentially small mixing of elementary fermions with the composite sector containing the Higgs.

But where does this exponential suppression come from?

From 4D to 5D: Holography

Holography:

- 2D holographic image contains information of a 3D image
  - ➢ 3D image and 2D hologram are dual descriptions of the same object
- can we get a better understanding of our 4D composite model by going to a 5D dual theory?

The AdS/CFT correspondence

AdS/CFT conjecture: Maldacena, hep-th/9711200

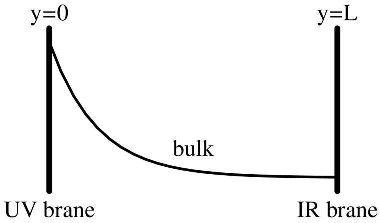
strongly coupled conformal (scale-invariant) 4D theory | is dual to | weakly coupled 5D theory in Randall-Sundrum background

- $SO(4,2)$ symmetry of 5D space-time corresponds to conformal symmetry of strongly coupled sector
- extradimensional coordinate y corresponds to energy scale Λ

Randall Sundrum model:

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2 \quad (0 \leq y \leq L)$$

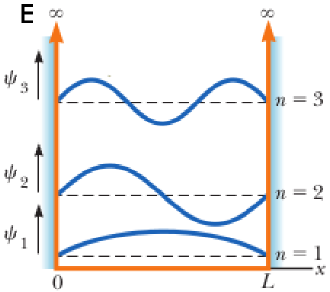
$\Lambda(y=0) \sim M_{\text{Planck}}$
$\Lambda(y=L) \sim 1\,\text{TeV}$



Kaluza-Klein decomposition

- fifth dimension too small for us to be seen
- but we can see its 4D remnants

- 5th dimension intervall acts like a potential well in quantum mechanics
- lowest mode remains massless: zero modes
  ➢ identified with SM fields
- excited modes with Kaluza-Klein masses $\sim$ TeV
  ➢ strongly coupled resonances

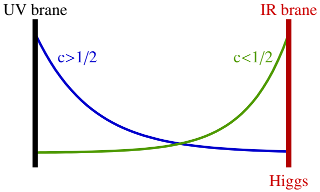


➢ In the warped background of the Randall-Sundrum metric this picture becomes a bit distorted...

Fermion localisation and Yukawa couplings

fermion zero mode profile depends strongly on bulk mass parameter c:

$$f^{(0)}(y,c) \propto e^{(\frac{1}{2}-c)ky}$$



$c > \frac{1}{2}$: localisation around UV brane
$c < \frac{1}{2}$: localisation around IR brane

effective 4D Yukawa couplings: $(Y_{U,D})_{ij} = (\lambda_{U,D})_{ij}\, f_i^Q\, f_j^{U,D}$

- observed hierarchical structure can be naturally generated by exponential suppression of $f^{Q,u,d}$ (fermion profile on IR brane)
- light fermions live close to the UV brane
  third generation localised closest to the IR brane

➢ **exponential hierarchies from $\mathcal{O}(1)$ parameters!**

Summary

- generic new flavour violating interactions are strongly constrained, with bound on the effective operator mass scale up to $\sim 10^5$ TeV
- Minimal Flavour Violation hypothesis provides a simple but effective solution based on symmetry principles
- dynamical origin of flavour hierarchies provided by models with partially composite fermions, or equivalently by fermions in a 5D Randall-Sundrum space-time