Flavour physics (1)

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Outline

- Why and how flavour is useful
  - Basics of flavour physics
  - CP-violation
  - Neutral-meson mixing
  - Effective approaches
- Flavour in the Standard Model
- Hints of NP in flavour data

Flavour physics

Particle physics

Central question of QFT-based particle physics

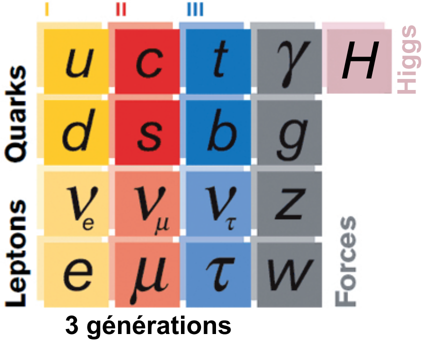
$$\mathcal{L} = ?$$

Particle physics

Central question of QFT-based particle physics

$$\mathcal{L} = ?$$

i.e. which degrees of freedom, symmetries, scales ?



SM best answer up to now, but

- neutrino masses
- dark matter
- dark energy
- baryon asymmetry of the universe
- hierarchy problem

$\Longrightarrow$3 generations playing a particular role in the SM

Flavour in the SM

$$\mathcal{L}_{SM} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j)$$

Gauge part $\mathcal{L}_{gauge}(A_a, \Psi_j)$

- Highly symmetric (gauge symmetry, flavour symmetry)
- Well-tested experimentally (electroweak precision tests)
- Stable with respect to quantum corrections

Higgs part $\mathcal{L}_{Higgs}(\phi, A_a, \Psi_j)$

- Ad hoc potential
- Dynamics not fully tested
- Not stable w.r.t quantum corrections
- Origin of flavour structure of the Standard Model

Fermions in SM

SM: $SU_C(3) \otimes SU_L(2) \otimes U_Y(1)$

- Colour (for quarks only)
- Weak isospin (for left-handed fermions only)
- Hypercharge (for everybody)

Standard Model is chiral: distinction between left- and right-chiralities

- Helicity: Projection of spin on momentum

  but notion which is frame dependent for massive particle
- Chirality: Lorentz-invariant equivalent, identical for $m = 0$

$$P_R = (1 + \gamma_5)/2 \qquad P_L = (1 - \gamma_5)/2$$

$\Longrightarrow$Left chirality with weak isospin, right chirality without

SM fermion assignments

Covariant derivative for fermions, involving $W^{1,2,3}$ and B gauge bosons

$$D_\mu\psi = (\partial_\mu - igW^a_\mu T^a - ig' YB_\mu)\psi$$

Using the physical W^+, W^-, Z^0 weak bosons and A_μ photon

$$D_\mu = \partial_\mu - \frac{ig}{\sqrt{2}}(W^+_\mu T^+ + W^-_\mu T^-) - i\frac{g^2 T^3 - g'^2 Y}{\sqrt{g^2+g'^2}} Z_\mu - i\frac{gg'}{\sqrt{g^2+g'^2}}(T^3+Y)A_\mu$$

where $Q = T_3 + Y$ and $e = \frac{gg'}{\sqrt{g^2+g'^2}}$

	Fields	T_3	Y	$Q = T_3 + Y$
E_L	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	1/2	-1/2	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
e_R	e_R	0	-1	-1
ν_R	ν_R	0	0	0
Q_L	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_L$	1/2	1/6	$\begin{pmatrix} 2/3 \\ -1/3 \end{pmatrix}$
u_R	u_R	0	2/3	2/3
d_R	d_R	0	-1/3	-1/3

- $W^\pm$ couples only to left-handed fermions in doublets
- ν_R no quantum numbers (needed only to provide masses to neutrinos)

Electroweak currents

Lagrangian for masless 1st generation $\psi \in \{E_L, e_R, Q_L, u_R, d_R\}$ in terms of mass-eigenstates for bosons

$$\mathcal{L}_{gauge,\psi} = \sum_\psi \bar\psi \not{D} \psi = \sum_\psi \bar\psi \not\partial \psi + g(W^+_\mu J^\mu_{W^+} + W^-_\mu J^\mu_{W^-} + Z_\mu J^\mu_Z) + eA_\mu J^\mu_{em}$$

$$J^\mu_{W^+} = \frac{1}{\sqrt{2}}(\bar\nu_L \gamma^\mu e_L + \bar u_L \gamma^\mu d_L) \qquad J^\mu_{W^-} = \frac{1}{\sqrt{2}}(\bar e_L \gamma^\mu \nu_L + \bar d_L \gamma^\mu u_L)$$

$$J^\mu_Z = \frac{1}{c_W}\left\{\frac{1}{2}\bar\nu_L\gamma_\mu\nu_L + \left(s^2_W - \frac{1}{2}\right)\bar e_L \gamma_\mu e_L + s^2_W \bar e_R \gamma_\mu e_R \right.$$

$$\left. + \left(\frac{1}{2} - \frac{2}{3}s^2_W\right)\bar u_L \gamma^\mu u_L - \frac{2}{3}s^2_W \bar u_R \gamma^\mu u_R + \left(\frac{1}{3}s^2_W - \frac{1}{2}\right)\bar d_L \gamma^\mu d_L + \frac{1}{3}s^2_W \bar d_R \gamma^\mu d_R\right\}$$

$$J^\mu_{em} = -\bar e \gamma^\mu e + \frac{2}{3}\bar u \gamma^\mu u - \frac{1}{3}\bar d \gamma^\mu d$$

- $c_W = g/\sqrt{g^2 + g'^2}, s_W = \sqrt{1 - c^2_W}$ weak mixing $(W^3_\mu, B_\mu) \leftrightarrow (Z^0_\mu, A_\mu)$
- charged-currents only left-handed $\psi_L = [(1 - \gamma_5)/2]\psi$
- neutral currents both left- and right-handed (and vector for photon)

From BEH to CKM

General Yukawa interaction between Higgs and (3 families of) quarks

$$\mathcal{L}_{Higgs,quarks} = \bar{Q}^i_L Y^{ik}_D d^k_R \phi + \bar{Q}^i_L Y^{ik}_U u^k_R \phi_c + h.c. + \dots$$

Vacuum expectation value for Higgs $\langle\phi\rangle \neq 0$ yields mass matrices

$$\mathcal{L}_{Higgs,quarks} = \bar{d}^i_L M^{ik}_D d^k_R + \bar{u}^i_L M^{ik}_U u^k_R + \dots$$

Diagonalise the mass matrices to get mass eigenstates ψ'

$$m_q = \frac{y_q \langle\phi\rangle}{\sqrt{2}} \quad M_D = \mathrm{diag}(m_d, m_s, m_b) \qquad M_U = \mathrm{diag}(m_u, m_c, m_t)$$

which are different from weak-interaction eigenstates ψ

$$U = \begin{pmatrix} u \\ c \\ t \end{pmatrix} = V_u \begin{pmatrix} u' \\ c' \\ t' \end{pmatrix} \qquad D = \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_d \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

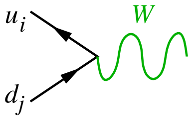
$\Longrightarrow$Potential misalignement between (unitary) rotations: $V_u \neq V_d$

CKM and flavour-changing charged currents

Charged currents in mass eigenstates involve matrix V

$$J_W^\mu = \bar{u}_L^i \gamma^\mu d_L^i \to \bar{u}_L' V_u^\dagger \gamma^\mu V_d d_L' = \bar{u}_L' V \gamma^\mu d_L'$$

Flavour-changing charged currents between generations at tree-level



$$\frac{g}{\sqrt{2}} [\bar{u}_{Li} V_{ij} \gamma^\mu d_{Lj} W_\mu^+ + \bar{d}_{Lj} V_{ij}^* \gamma^\mu u_{Li} W_\mu^-]$$

unitary Cabibbo-Kobayashi-Maskawa matrix
(linked to electroweak symmetry breaking)

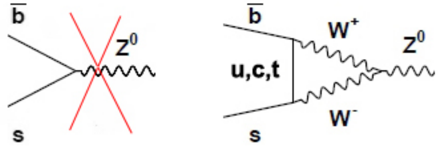
In $SM_{m_\nu \neq 0}$, there is an equivalent mixing matrix for leptons U_{PMNS}

FCNC or flavour-changing neutral currents

Neutral currents remain flavour-diagonal in mass eigenstates

$$\bar{u}^i_L \gamma^\mu u^i_L \to \bar{u}'_L V_u^\dagger \gamma^\mu V_u u'_L = \bar{u}'_L \gamma^\mu u'_L,$$
$$\bar{d}^i_L \gamma^\mu d^i_L \to \bar{d}'_L V_d^\dagger \gamma^\mu V_d d'_L = \bar{d}'_L \gamma^\mu d'_L,$$

No flavour-changing neutral currents within or between generations
. . . but only at tree level ! They can occur in loops



However, SM FCNC heavily suppressed by two mechanisms

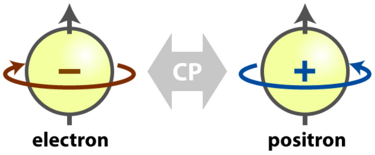
- Loop: Higher order in pert. theory (suppr. by powers of g, g')
- GIM: Vanish in degenerate case $m_u = m_c = m_t$
  (proportional to $V^*_{tb} V_{ts} + V^*_{cb} V_{cs} + V^*_{ub} V_{us} = 0$)

CP-violation

CP and CKM

C (Charge conjugation) and P (Parity) combined in *CP*

- $\bar\psi_1\gamma_\mu(1-\gamma_5)\psi_2 \to \bar\psi_2\gamma_\mu(1-\gamma_5)\psi_1$
  $\bar\psi_1\gamma_\mu(1+\gamma_5)\psi_2 \to \bar\psi_2\gamma_\mu(1+\gamma_5)\psi_1$
  (at $(\vec{x},t)$ and $(-\vec{x},t)$ respectively)
- symmetry of QCD/QED, but symmetry for weak interactions ?



$$\begin{aligned} & W_\mu^+ \bar{u}_i V_{ij} \gamma^\mu(1-\gamma_5) d_j + W_\mu^- \bar{d}_j V_{ij}^* \gamma^\mu(1-\gamma_5) u_i \\ \to \quad & W_\mu^- \bar{d}_i V_{ij} \gamma^\mu(1-\gamma_5) u_j + W_\mu^+ \bar{u}_j V_{ij}^* \gamma^\mu(1-\gamma_5) d_i \end{aligned}$$

Weak interactions are CP-invariant if V is real

For N_g generations, V contains

- $(N_g-1)(N_g-2)/2$ phases
- $N_g(N_g-1)/2$ moduli

Structure of CKM matrix

For two generations, 1 modulus, no phase, no CP violation (Cabbibo)

$$V = \begin{bmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

For three generations, 3 moduli and 1 phase, a unique source of CP violation in quark sector (Kobayashi-Maskawa)

$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq \begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

where we have exploited the observed hierarchy of matrix elements ($V = 1 + O(\lambda)$, close to unity)

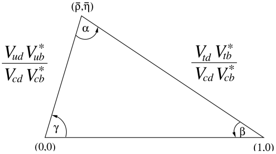
$\Longrightarrow$extremely predictive model for CP violation embedded in SM

Unitarity triangles

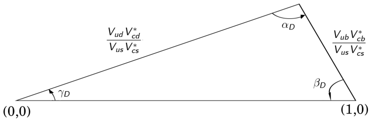
Many unitarity relations, e.g., related to 4 neutral mesons (no top)

- B_d meson (bd) : $V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$ $(\lambda^3, \lambda^3, \lambda^3)$
- B_s meson (bs) : $V_{us}V^*_{ub} + V_{cs}V^*_{cb} + V_{ts}V^*_{tb} = 0$ $(\lambda^4, \lambda^2, \lambda^2)$
- K meson (sd) : $V_{ud}V^*_{us} + V_{cd}V^*_{cs} + V_{td}V^*_{ts} = 0$ $(\lambda, \lambda, \lambda^5)$
- D meson (cu) : $V_{ud}V^*_{cd} + V_{us}V^*_{cs} + V_{ub}V^*_{cb} = 0$ $(\lambda, \lambda, \lambda^5)$

Representation of (ρ, η) through rescaled triangles



(small but non squashed)
B_D-meson triangle (bd)



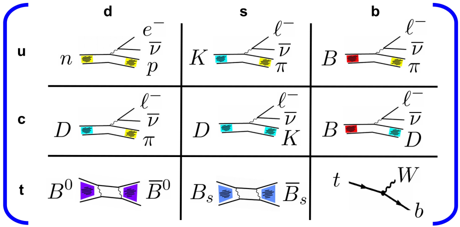
(large but squashed)
D-meson triangle (cu)

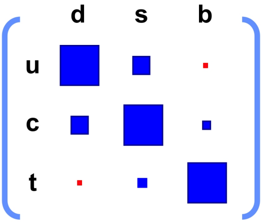
In practice, always B_d unitarity triangle (but only 2 parameters out of 4)

A handle on the CKM matrix

Measurements in terms of hadrons, not of quarks !

V =





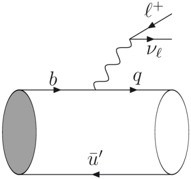
- $d \to u$: Nuclear physics (superallowed β decays)
- $s \to u$: Kaon physics (KLOE, KTeV, NA62)
- $c \to d, s$: Charm physics (CLEO-c, Babar, Belle, BESIII)
- $b \to u, c$ and $t \to d, s$: B physics (Babar, Belle, CDF, DØ, LHCb)
- $t \to b$: Top physics (CDF/DØ, ATLAS, CMS)

Determine structure of CKM matrix
from $|V_{ij}|$ (CP-allowed processes)
and/or $\arg(V_{ij})$ (CP-violating processes)

Long-distance QCD

Take processes conjugate under *CP*

$$b \to u \quad : \quad A(\bar{B}^0 \to \pi^+ \ell^- \bar{\nu}) \propto V_{ub} \times F_{B\to\pi}$$
$$\bar{b} \to \bar{u} \quad : \quad A(B^0 \to \pi^- \ell^+ \nu) \propto V_{ub}^* \times F_{B\to\pi}$$



where $F_{B\to\pi}$ form factor defined from $\langle \pi^+ | \bar{u}\gamma_\mu(1-\gamma_5) b | \bar{B}\rangle$
encoding hadronisation of quarks into hadrons

General feature : flavour processes with

- weak part : odd under CP (phase from CKM)
- strong part : even under CP (phase from strong interaction)

- $|V_{ij}|$ via CP-conserving quantity $(|A|^2)$
  from rates where hadronic quantities are crucial
- arg V_{ij} via CP-violating quantity $(\mathrm{Re}(A_1 A_2^*), \mathrm{Im}(A_1 A_2^*))$
  from asymmetries where hadronic quantities may cancel out
  CP-violation from relative phases between conjugate proc.

CP violation in decay

CP-conjugate processes $B \to f$ and $\bar{B} \to \bar{f}$ (*B* charged or neutral)

$$A_f = \sum_k A_k e^{i\delta_k} e^{i\phi_k} \qquad \bar{A}_{\bar{f}} = \sum_k A_k e^{i\delta_k} e^{-i\phi_k}$$

δ_k: *CP*-even strong phases ϕ_k: *CP*-odd weak phases

$$\left|\frac{A_f}{\bar{A}_{\bar{f}}}\right| \neq 1 \Longrightarrow CP \text{ violation in decay}$$

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Asymmetry of the form $\dfrac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} \propto \sin(\phi_i - \phi_j)\sin(\delta_i - \delta_j)$

- need two different contributions with different strong phases
- strong and weak phases from decay

Observed in K-decays (ϵ'), $B^0 \to K^+\pi^-, \pi^+\pi^-, \eta K^{*0} \ldots$
but weak phases do not only occur in decays

Neutral-meson mixing

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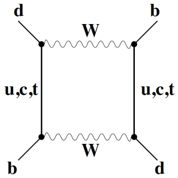


Loops allow $\Delta F = 2$ FCNC

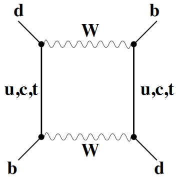
$\Longrightarrow$neutral-meson mixing possible

$$i\frac{d}{dt}\begin{pmatrix} |M(t)\rangle \\ |\bar{M}(t)\rangle \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} |M(t)\rangle \\ |\bar{M}(t)\rangle \end{pmatrix}$$

Quantum-Mech. for $M = K^0, D^0, B_d^0, B_s^0$, with M and Γ hermitian

- Γ from restriction to 2 states
- mixing due to non-diagonal terms $M_{12} - i\Gamma_{12}/2$

Neutral-meson mixing



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Diagonalisation: physical $|M_{H,L}\rangle$ of masses $M_{H,L}$, widths $\Gamma_{H,L}$

$$|M_L\rangle = p|M\rangle + q|\bar{M}\rangle, \qquad |M_H\rangle = p|M\rangle - q|\bar{M}\rangle \qquad |p|^2 + |q|^2 = 1$$

In terms of M_{12}, $|\Gamma_{12}|$ and $\phi = arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$

- Mass difference $\Delta M = M_H - M_L = 2|M_{12}|$
- Width difference $\Delta\Gamma_q = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos(\phi)$
- Mixing coefficients p and q

Time evolution

Evolution of mass eigenstates in terms of CP-eigenstates

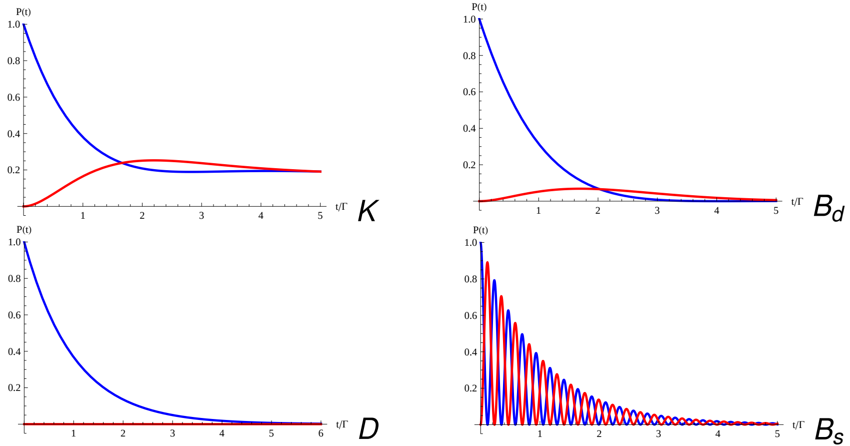
$$|M(t)\rangle = g_+(t)|M\rangle + \frac{q}{p}g_-(t)|\bar{M}\rangle\,, \quad |\bar{M}(t)\rangle = \frac{p}{q}g_-(t)|M\rangle + g_+(t)|\bar{M}\rangle$$

with time dependences $[g_+(0) = 1, g_-(0) = 1]$

$$\begin{aligned} g_+(t) &= e^{-iMt}e^{-\Gamma t/2}\left[\cosh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta M t}{2} - i\sinh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta M t}{2}\right] \\ g_-(t) &= e^{-iMt}e^{-\Gamma t/2}\left[-\sinh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta M t}{2} + i\cosh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta M t}{2}\right] \end{aligned}$$

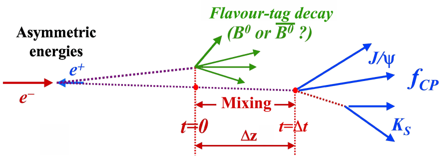
with average masses and widths M, Γ, as well as differences $\Delta\Gamma$, ΔM

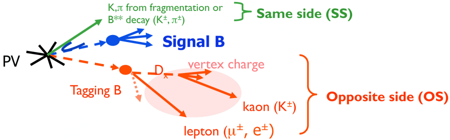
Four very different mesons



- K: $\Delta m \sim \Delta\Gamma \sim \Gamma$: K_L (long) and K_S (short) rather than heavy-light
- D: very little $\bar{D}$ before decay
- B: $\Delta\Gamma \simeq 0$
- B_s: $\Delta m \gg \Gamma$: very rapid oscillations

Oscillations





B-factories (Babar/Belle)

- Coherent production $\Upsilon(4S) \to B_d \bar{B}_d$ [idem with B_s at $\Upsilon(5S)$]
- Flavour tagged through one decay, which fixes the flavour of the other B and starts the clock for its evolution $t = 0$
- Low statistics, but very good control of kinematics

Hadronic machines (CDF/DØ/LHCb)

- Incoherent production of b-hadrons from pp collisions
- Possibility of oscillations for both tagging and signal b-hadrons (40% B_d, 10% B_s)
- High statistics, but less good control of kinematics

Time-dependent decay rates

$$\begin{aligned}\Gamma(M(t)\to f) &= N_f^2|A_f|^2 e^{-\Gamma t}\left\{\frac{1+|\lambda_f|^2}{2}\cosh\frac{\Delta\Gamma t}{2}+\frac{1-|\lambda_f|^2}{2}\cos(\Delta M t)\right.\\ &\qquad \left. -\mathrm{Re}\,\lambda_f\sinh\frac{\Delta\Gamma t}{2}-\mathrm{Im}\,\lambda_f\sin(\Delta M t)\right\}\\ \Gamma(\bar M(t)\to f) &= N_f^2|A_f|^2\left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left\{\frac{1+|\lambda_f|^2}{2}\cosh\frac{\Delta\Gamma t}{2}-\frac{1-|\lambda_f|^2}{2}\cos(\Delta M t)\right.\\ &\qquad \left. -\mathrm{Re}\,\lambda_f\sinh\frac{\Delta\Gamma t}{2}+\mathrm{Im}\,\lambda_f\sin(\Delta M t)\right\}\end{aligned}$$

- Decay amplitudes $A_f = A(M\to f)$, $\bar A_f = A(\bar M\to f)$
- Ratio of mixing and decay amplitude parameters

$$\lambda_f = \frac{q}{p}\frac{\bar A_f}{A_f}$$

- Similar possibilities with f replaced by CP-conjugate $\bar f$

CP violation in mixing

Neutral mass eigenstates not necessarily CP-eigenstates

$$|M_L\rangle = p|M\rangle + q|\bar{M}\rangle \qquad |M_H\rangle = p|M\rangle - q|\bar{M}\rangle$$

$$\left|\frac{q}{p}\right| \neq 1 \Longrightarrow CP \text{ violation in mixing}$$

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- flavour-specific decays ($\bar{A}_f = A_{\bar{f}} = 0$)
- with no CP-violation in decay ($|A_f| = |\bar{A}_{\bar{f}}|$)
- weak phase from mixing only

"Wrong-sign" semileptonic decays $\qquad (\ell^- \leftarrow \bar{B}(b\bar{d}) \leftrightarrow B(\bar{b}d) \rightarrow \ell^+)$

$$a_{SL} = \frac{\Gamma(\bar{B}^0(t) \to \ell^+\nu X) - \Gamma(B^0(t) \to \ell^-\bar{\nu}X)}{\Gamma(\bar{B}^0(t) \to \ell^+\nu X) + \Gamma(B^0(t) \to \ell^-\bar{\nu}X)} = \frac{|p|^4 - |q|^4}{|p|^4 + |q|^4}$$

Seen for K meson (ϵ_K),
but tiny asymmetry in SM for $B_{d,s}$ mesons, q/p almost a pure phase

CPV in interf. between decay with & w/o mixing

For decays into *CP*-eigenstate: $M \to f_{CP}$ and $M \to \bar{M} \to f_{CP}$ interfere

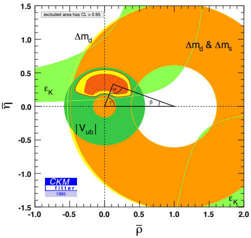
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \neq \pm 1 \Longrightarrow CP\text{-violation in interference}\ldots$$

$$\frac{\Gamma(\bar{M}(t)\to f) - \Gamma(M(t)\to f)}{\Gamma(\bar{M}(t)\to f) + \Gamma(M(t)\to f)} = -\frac{A_{CP}^{dir}\cos(\Delta M t) + A_{CP}^{mix}\sin(\Delta M t)}{\cosh(\Delta\Gamma t/2) + A_{CP}^{\Delta\Gamma}\sinh(\Delta\Gamma t/2)} + O\left(1-\left|\frac{q}{p}\right|^2\right)$$

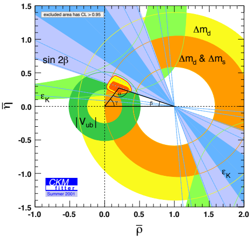
$$A_{CP}^{dir} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \quad A_{CP}^{mix} = -\frac{2\mathrm{Im}\ \lambda_f}{1+\lambda_f|^2} \quad A_{CP}^{\Delta\Gamma} = -\frac{2\mathrm{Re}\ \lambda_f}{1+\lambda_f|^2} \quad |A_{CP}^{dir}|^2 + |A_{CP}^{mix}|^2 + |A_{CP}^{\Delta\Gamma}|^2 = 1$$

- weak phase from both mixing and decay
- if one weak phase dominates decay amplitudes [“golden modes”]
  - $|A_f| = |\bar{A}_f|$ and $A_{CP}^{dir} = 0$
  - λ_f pure weak phase and $A_{CP}^{mix} = \mathrm{Im}\ \lambda_f$ $\quad B_d \to J/\psi K_S, B_s \to J/\psi\phi$
- if *A* has comparable amplitudes with different weak phases, interpretation more difficult $\quad B \to \pi K \ldots$

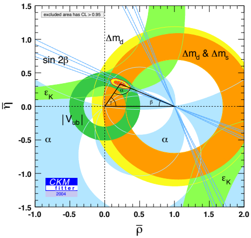
Two decades of CKM



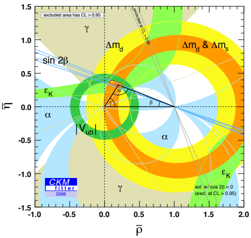
1995



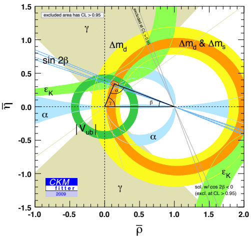
2001



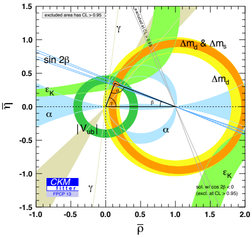
2004



2006

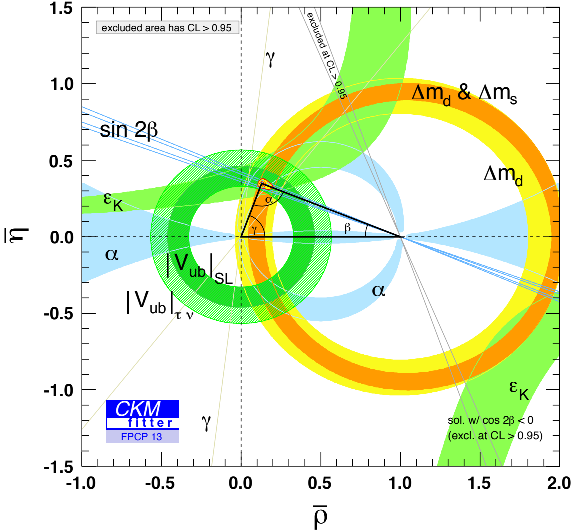


2009



2013

The current status of CKM



$|V_{ud}|, |V_{us}|, |V_{cb}|, |V_{ub}|_{SL}$

$B \to \tau\nu$

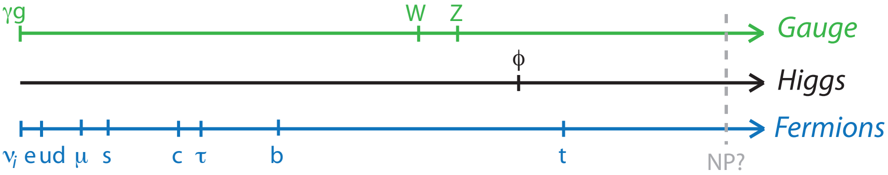
$\Delta m_d, \Delta m_s, \epsilon_K$

$\alpha, \sin 2\beta, \gamma$

$$A = 0.823^{+0.012}_{-0.033}$$
$$\lambda = 0.2246^{+0.0019}_{-0.0001}$$
$$\bar{\rho} = 0.129^{+0.018}_{-0.009}$$
$$\bar{\eta} = 0.348^{+0.012}_{-0.012}$$
(68% CL)

Effective approaches

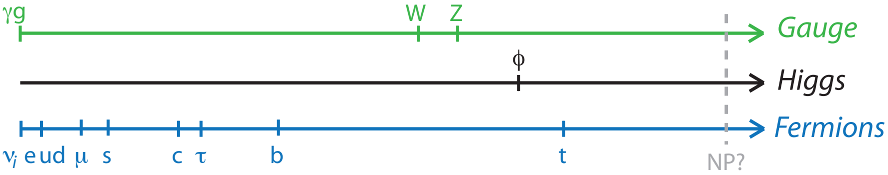
Quark flavour parameters and SM



Important, unexplained hierarchy among 10 of 19 params of $\mathrm{SM}_{m_\nu=0}$

- Mass (6 params, a lot of small ratios of scales)
- CP violation (4 params, strong hierarchy between generations)

Quark flavour parameters and SM



Important, unexplained hierarchy among 10 of 19 params of $\mathrm{SM}_{m_\nu=0}$

- Mass (6 params, a lot of small ratios of scales)
- CP violation (4 params, strong hierarchy between generations)

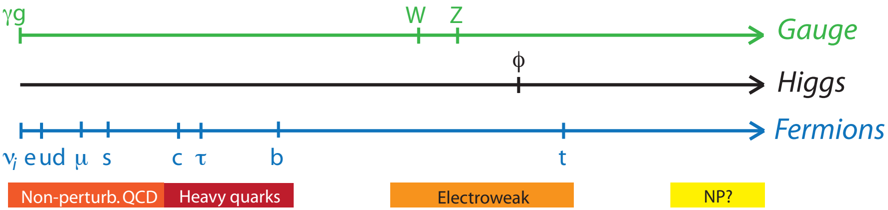
With interesting phenomenological consequences

- CP asymmetries from a single parameter
- Quantum sensitivity (via loops) to large range of scales
- Suppression of Flavour-Changing Neutral Currents

Very significant constraints on any NP extension

Good track record: charm (no $K_L \to \mu\mu$), 3rd family (ϵ_K), m_c (Δm_K), m_t (Δm_B)

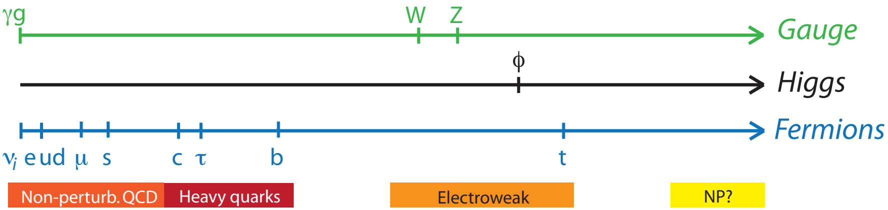
A multi-scale problem



- Tough multi-scale challenge with 3 interactions intertwined
- Several steps to separate/factorise scales

  BSM $\rightarrow$ SM+$1/\Lambda$ (Λ_{EW}/Λ) $\rightarrow \mathcal{H}_{eff}$ (m_b/Λ_{EW}) $\rightarrow$ *eff. th.* (Λ_{QCD}/m_b)

A multi-scale problem



- Tough multi-scale challenge with 3 interactions intertwined
- Several steps to separate/factorise scales

  BSM $\to$ SM+$1/\Lambda$ (Λ_{EW}/Λ) $\to$ $\mathcal{H}_{eff}$ (m_b/Λ_{EW}) $\to$ *eff. th.* (Λ_{QCD}/m_b)
- Th problem from hadronisation of quarks into hadrons:

  description/parametrisation in terms of QCD quantities

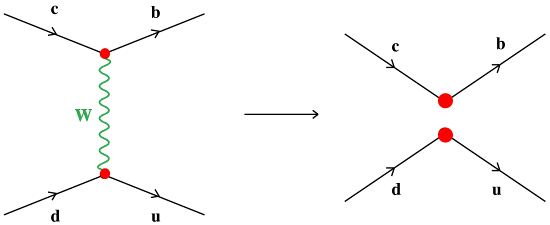
  decay constants, form factors, bag parameters. . .
- Long-distance non-perturbative QCD: source of uncertainties

  lattice QCD simulations, effective theories. . .

$\mathcal{H}_{eff}$: From Fermi to electroweak

Fermi-like approach : separation between different scales

- Short distances : numerical coefficients
- Long distances : local operator

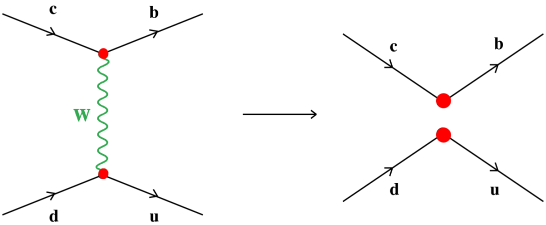


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \frac{m_W^2}{m_W^2 - p_W^2} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c$$

$\mathcal{H}_{eff}$: From Fermi to electroweak

Fermi-like approach : separation between different scales

- Short distances : numerical coefficients
- Long distances : local operator

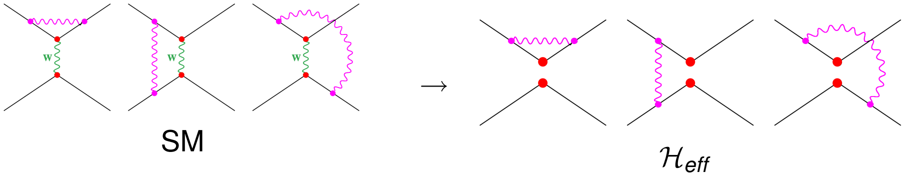


$$V_{ud} V_{cb}^* \frac{G_F}{\sqrt{2}} \bar{u}\gamma_\mu(1-\gamma_5)d\bar{b}\gamma^\mu(1-\gamma_5)c$$

Before/below SM, Fermi theory carried info on yesterday's NP (=EW)

- G_F: scale of "new physics"
- $\mathcal{O}_i$: interaction with left-handed fermions, through charged spin 1
- Obviously not all info (gauge structure, Z^0 ...), but a good start, especially if you cannot excite the NP degrees of freedom directly

$\mathcal{H}_{eff}$: From heavy quarks to SM (1)



Taking into account one (or more) gluons

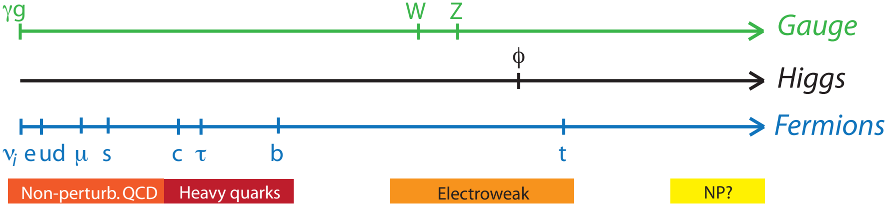
$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ud} [C_1(\mu) Q_1(\mu) + C_2(\mu) Q_2(\mu)]$$

$$Q_1 = (\bar{b}_\alpha c_\beta)_{V-A} (\bar{u}_\beta d_\alpha)_{V-A} \qquad (\bar{b}c)_{V-A} = \bar{b}\gamma_\mu(1-\gamma_5)c$$

$$Q_2 = (\bar{b}_\alpha c_\alpha)_{V-A} (\bar{u}_\beta d_\beta)_{V-A}$$

- new colour structures (flipped indices α, β)
- divergences absorbed by renormalisation
- C_1 and C_2 calculable fonctions of μ as perturbative series in α_s
- μ separation scale between short- and long-distance physics

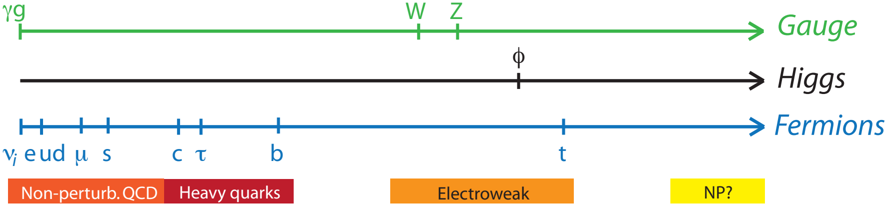
$\mathcal{H}_{eff}$: From heavy quarks to SM (2)



$A(B \to H) = \sum_i V_{CKM,i} C_i(\mu) \langle Q_i \rangle (\mu)$

- Simplification of the problem, keeping only relevant d.o.f.
- Matching to fundamental theory at a high scale $\mu_0 = O(M_W, m_t)$
- Evolution down to $\mu_b = O(m_b)$ done by renormalisation group $\Longrightarrow$resummation of large logs $\alpha_s(\mu_b)^n \log^k(\mu_b^2/\mu_0^2)$ in $C(\mu_b)$

$\mathcal{H}_{eff}$: From heavy quarks to SM (2)



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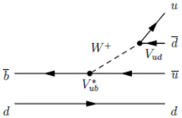
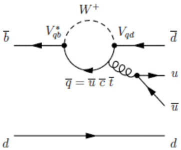
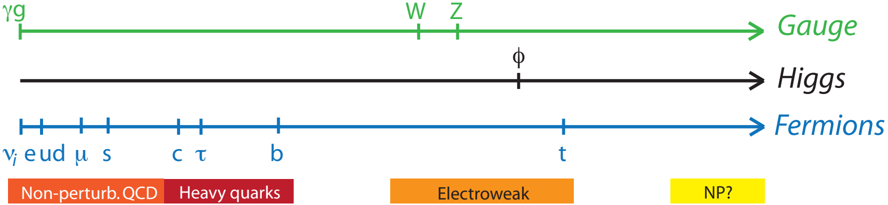


$V_{ud} V^*_{ub} (\bar{b}u)_{V-A} (\bar{u}d)_{V-A}$



$V_{qd} V^*_{qb} (\bar{b}d)_{V-A} \sum_q (\bar{q}q)_{V\pm A}$

$\mathcal{H}_{eff}$: From heavy quarks to SM (2)



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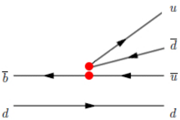
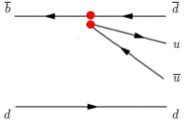
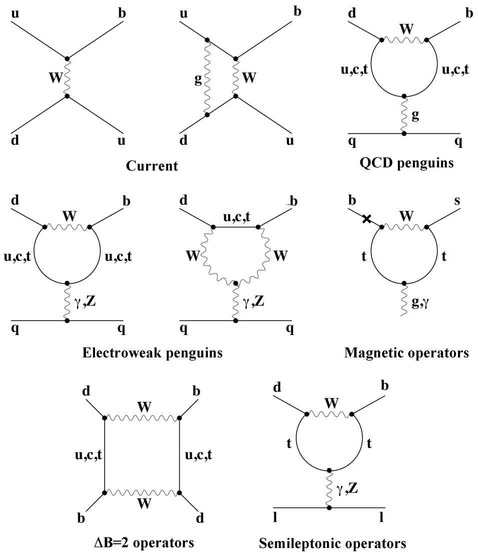




$V_{ud} V_{ub}^* (\bar{b}u)_{V-A} (\bar{u}d)_{V-A}$ $V_{qd} V_{qb}^* (\bar{b}d)_{V-A} \sum_q (\bar{q}q)_{V\pm A}$

$\mathcal{H}_{eff}$: From heavy quarks to SM (3)

- Current-curent
  - $(\bar{b}u)_{V-A}(\bar{u}d)_{V-A}$,
  - $(\bar{b}_i u_j)_{V-A}(\bar{u}_j d_i)_{V-A}$



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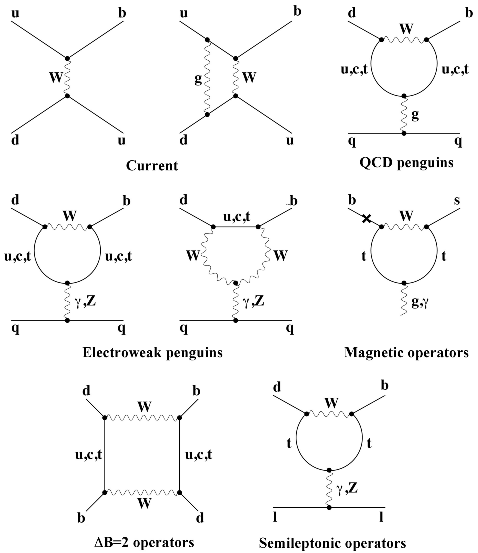
  - $(\bar{b}_i d_j)_{V-A}\sum_q(\bar{q}_j q_i)_{V\pm A}$



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- Electroweak penguins
  - $(\bar{b}d)_{V-A}\sum_q e_q(\bar{q}q)_{V\pm A}$,
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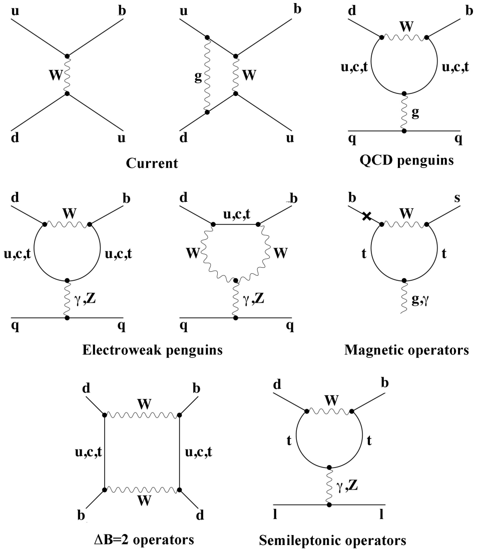

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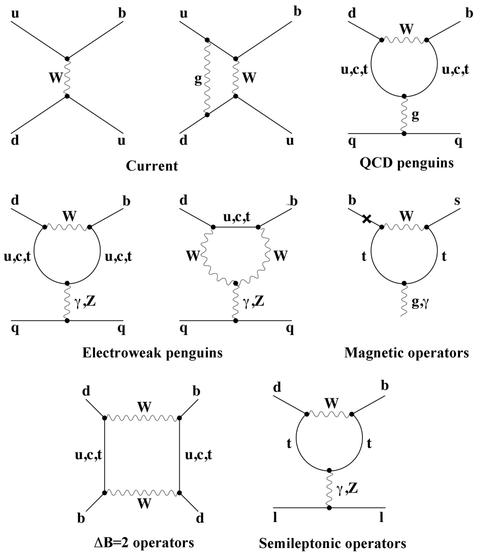
- Electroweak penguins
  - $(\bar{b}d)_{V-A}\sum_q e_q(\bar{q}q)_{V\pm A}$,
  - $(\bar{b}_i d_j)_{V-A}\sum_q e_q(\bar{q}_j q_i)_{V\pm A}$
- Magnetic operators
  - $\frac{e}{8\pi^2}m_b\bar{s}\sigma^{\mu\nu}(1+\gamma_5)bF_{\mu\nu}$,
  - $\frac{g}{8\pi^2}m_b\bar{s}\sigma^{\mu\nu}(1+\gamma_5)bG_{\mu\nu}$



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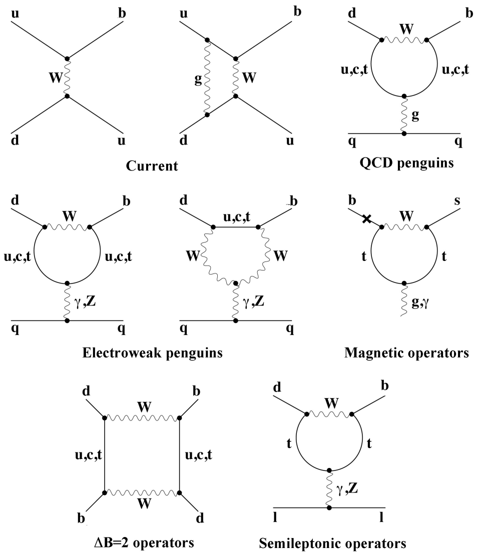
  - $\frac{g}{8\pi^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)bG_{\mu\nu}$
- $\Delta B = 2$ operators
  - $(\bar{b}d)_{V-A}(\bar{b}d)_{V-A}$



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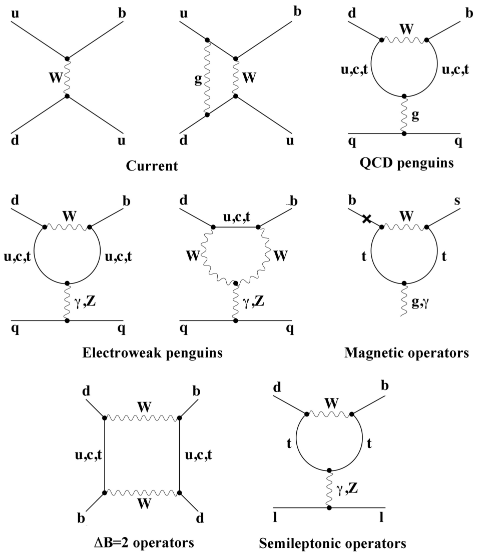
- Magnetic operators
  - $\frac{e}{8\pi^2}m_b\bar{s}\sigma^{\mu\nu}(1+\gamma_5)bF_{\mu\nu}$,
  - $\frac{g}{8\pi^2}m_b\bar{s}\sigma^{\mu\nu}(1+\gamma_5)bG_{\mu\nu}$
- $\Delta B = 2$ operators
  - $(\bar{b}d)_{V-A}(\bar{b}d)_{V-A}$
- Semileptonic operators
  - $(\bar{b}s)_{V-A}(\bar{e}e)_{V/A}$



$\mathcal{H}_{eff}$: From SM to NP

SM = effective low-energy theory from
an underlying, more fundamental and yet unknown, theory

At low energies, below the scale Λ of new particles

$$\mathcal{L}_{SM+1/\Lambda} = \mathcal{L}_{gauge}(A_a, \Psi_j) + \mathcal{L}_{Higgs}(\phi, A_a, \Psi_j) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\phi, A_a, \Psi_j)$$

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New operators O_n, suppressed by powers of Λ

- Describe impact of New Physics on "low-energy" physics
- Made of SM fields, compatible with its symmetries,
  e.g., dim. 5 effective neutrino mass term $(g^{ij}/\Lambda)\psi_L^i \psi_L^{Tj} \phi\phi^T$
- Split high energies c_n and low energies O_n, separated by scale Λ

$\mathcal{H}_{eff}$: From SM to NP

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- Split high energies c_n and low energies O_n, separated by scale Λ

- New d.o.f. and energy scale of NP ? — High-p_T expts
- Symmetries and structure ? — Flavour expts

Different processes for different goals

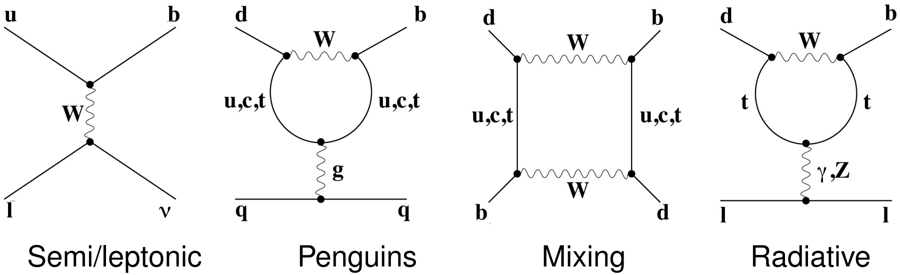
SM expected to be dominant (tree dominated) [semi/leptonic dec.]
Metrology of SM

SM and NP competing (loop dominated) [rare processes]
Constraints on NP

SM very small (“forbidden” by SM symmetry) [ultrarare processes]
Smoking guns of NP

Separation between the last two categories hinge on theorists’ beliefs concerning the size of NP, theoretical accuracy of SM prediction and experimental measurements. . .

Processes of interest



Process	Semi/leptonic	Penguins	Mixing	Radiative
	$\Delta F = 1$ FCCC	$\Delta F = 1$ FCCC	$\Delta F = 2$ FCNC	$\Delta F = 2$ FCNC
NP sensitiv.	Small	Large ?	Large	Large
B	$B \to D\ell\nu$, $B \to \tau\nu$	$B \to \pi\pi$	$\Delta m_d, \Delta m_s$	$B \to K^*\mu\mu, B_s \to \mu\mu$
D	$D \to K\ell\nu$, $D_s \to \mu\nu$	$D \to K\pi$	x, y, ϕ	$D \to X_u\ell\ell$
K	$K \to \pi\ell\nu$, $\tau \to K\nu$	$K \to \pi\pi$	ϵ_K	$K \to \pi\nu\nu, K \to \mu\mu$

Examples of these processes will be covered in the next two sessions, from SM and from NP points of view