Structure

1. FCNC $\longrightarrow$ no FCNC at tree level
2. How should an flavour experiment look like
3.

Theory that describes fundamental particles and their interactions is the Standard Model (SM)

$$\mathcal{G}_{SM} = \underbrace{SU(3)_c}_{\text{strong}} \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{electroweak}}$$

flavour conserved global symmetry

symmetry is broken

Focus of this lecture will be on the electroweak sector

Flavour physics: Study difference between the generations such as masses, flavour transitions and CP-violation

$$Q_{Li} = \begin{pmatrix} u_{Li} \\ d_{Li} \end{pmatrix} \quad \left(= \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix} \right)$$ Left handed $SU(2)$ doublets

i: generation index

$u_{Ri} = (u_R, c_R, t_R)$ Right handed $SU(2)$ singlets

$d_{Ri} = (d_R, s_R, b_R)$

Yukawa matrix complex, non-diagonal

$$\mathcal{L}_{Yukawa} = Y_{ij}^d \, \bar{Q}_{Li} \phi d_{Rj} + Y_{ij}^u \, Q_{Li} \tilde{\phi} u_{Rj} + h.c.$$

Higgs symmetry breaking

$$= \frac{v}{\sqrt{2}} \left(\bar{d}_{Li} Y_{ij}^d d_{Rj} + \bar{u}_{Li} Y_{ij}^u u_{Rj} \right) + h.c.$$

$$= \bar{d}_{Li} \overbrace{V_{Ld}^+ \underbrace{V_{Ld}}_{}}^{=\mathbb{1}} \underbrace{\frac{v}{\sqrt{2}} Y_{ij}^d V_{Rd}^+}_{\mathcal{M}_{ij}^d} \overbrace{}^{=\mathbb{1}} V_{Rd} d_{Rj} + \bar{u}_{Li} \overbrace{V_{Lu}^+ V_{Lu}}^{=\mathbb{1}} \underbrace{\frac{v}{\sqrt{2}} Y_{ij}^u V_{Ru}^+}_{\mathcal{M}_{ij}^u} V_{Ru} u_{Rj} + h.c$$

Skipped

V is defined such that $\frac{v}{\sqrt{2}} V_{Ld} Y_{ij}^d V_{Rd}^+ = diag(m_d, m_s, m_b) = \mathcal{M}^d$

and $\frac{v}{\sqrt{2}} V_{Lu} Y_{ij}^u V_{Ru}^+ = diag(m_u, m_c, m_t) = \mathcal{M}^u$

and $\tilde{u}_L = V_{Lu} u_L \quad \tilde{u}_R = V_{Ru} u_R \quad \Rightarrow \quad u_L = V_{Lu}^+ \tilde{u}_L \quad u_R = V_{Ru}^+ \tilde{u}_R$

$\tilde{d}_L = V_{Ld} d_L \quad \tilde{d}_R = V_{Rd} d_R \qquad d_L = V_{Ld}^+ d_L \quad d_R = V_{Rd} d_R$

insert

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \left(\bar{u}_{Li} \gamma^\mu W_\mu^+ d_{Li} + \bar{d}_{Li} \gamma^\mu W_\mu^- u_{Li} \right)$$

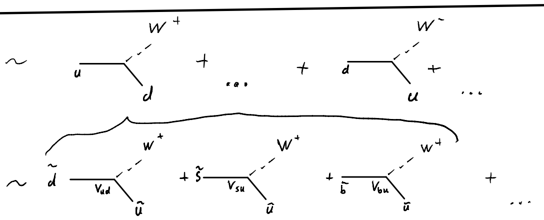
$$= -\frac{g}{\sqrt{2}} \left(\tilde{\bar{u}}_{Li} \gamma^\mu W_\mu^+ \underbrace{(V_{Lu} V_{Ld}^+)}_{V_{CKM}}{}_{ij} \tilde{d}_{Lj} + \tilde{\bar{d}}_{Li} \gamma^\mu W_\mu^- \underbrace{(V_{Ld} V_{Lu}^+)}_{V_{CKM}^+}{}_{ij} \tilde{u}_{Lj} \right.$$

$$\mathcal{L}_{NC} = \frac{g}{c_W} \left\{ \bar{u}_L \gamma^\mu \left(\tfrac{1}{2} - \tfrac{2}{3} s_W^2 \right) u_L + \bar{u}_R \gamma^\mu \left(-\tfrac{2}{3} s_W^2 \right) u_R + \bar{d}_L \gamma^\mu \left(-\tfrac{1}{2} + \tfrac{1}{3} s_W^2 \right) d_L + \bar{d}_R \gamma^\mu \left(\tfrac{1}{3} s_W^2 \right) d_R \right\} Z^{0\mu}$$

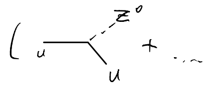
$\Rightarrow$ flavour diagonal $\Rightarrow$ no flavour mixing

$s_W = \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$

electroweak mixing angle



Transition between generations



flavour diagonal $\Rightarrow$ no flavour mixing

$V^+ V = \mathbb{1}$

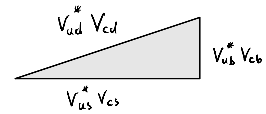
Properties of V_{CKM}:

- Unitary $(V^+ V = V V^+ = \mathbb{1})$
- 3 real parameters and 1 phase

$\downarrow$

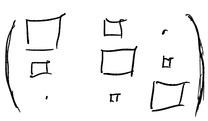
Reason for CPV

Remark
First: 18 parameters (9 real + 9 phases)
$\downarrow$
Unitary: 9 parameters (3 real + 6 phases)
$\downarrow$
5 phases are absolut quark phases: 4 parameters (3 real + 1 phase)



One goal is to overconstrain the unitarity triangle to search for new physics

$|V_{CKM}| =$

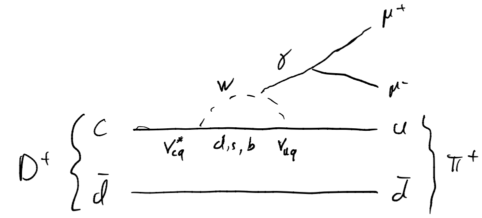


Magnitude of CKM elements is purely based on measurements

$$V_{CKM} \simeq \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

$\lambda = |V_{us}| \sim 0{,}22$

[PDG review]



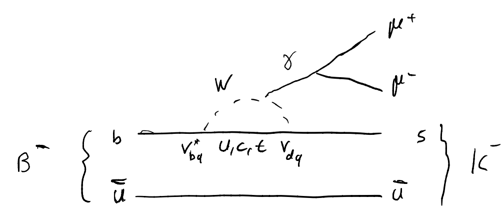
$$\mathcal{A}_{SM} \propto \underbrace{V_{cd}^* V_{ud} f\left(\tfrac{m_d^2}{m_W^2}\right)}_{} + V_{cs}^* V_{us} f\left(\tfrac{m_s^2}{m_W^2}\right) + V_{cb}^* V_{ub} f\left(\tfrac{m_b^2}{m_W^2}\right)$$

$\boxed{f\left(\frac{m_q^2}{m_W^2}\right) \sim \frac{1}{16\pi} \frac{m_q^2}{m_W^2}}$

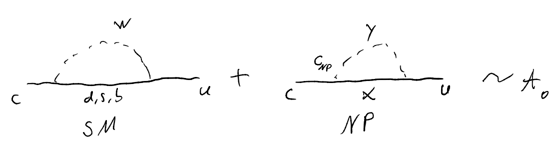
$$= -V_{cs}^* V_{us} f\left(\tfrac{m_d^2}{m_W^2}\right) - V_{cb}^* V_{ub} f\left(\tfrac{m_d^2}{m_W^2}\right)$$

$$= \underbrace{V_{cs}^* V_{us}}_{\sim\lambda} \Big[\underbrace{f\left(\tfrac{m_s^2}{m_W^2}\right) - f\left(\tfrac{m_d^2}{m_W^2}\right)}_{\text{"GIM suppressed"}} \Big] + \underbrace{V_{cb}^* V_{ub}}_{\sim\lambda^5} \left(f\left(\tfrac{m_b^2}{m_W^2}\right) - f\left(\tfrac{m_d^2}{m_W^2}\right) \right) \approx 10^{-8}$$

"CKM suppressed"



$$\mathcal{A}_{SM} \propto \underbrace{V_{bt}^* V_{st}}_{\lambda^2} \underbrace{f\left(\tfrac{m_t^2}{m_W^2}\right)}_{O(10^{-2})} \approx 10^{-3}$$



$\sim A_0 \left(\frac{m_q}{m_W^2} + \frac{c_{NP}}{\Lambda_{NP}} \right)$

The goal of flavour experiments is often to look at these loop processes to indirectly search for new physics. Even particles to heavy for direct production can contribute and change the final rate.