Yukawa alignment in type III two Higgs doublet models

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Two Higgs doublet Models (2HDM)

One of the easiest extensions of the SM: Just add another Higgs doublet.

$$\phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \qquad \phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

CP even neutral scalars

CP odd neutral scalar

Charged scalars

$\longrightarrow$ Yukawa sector of Lagrangian:

$$\mathcal{L}_{\text{Yukawa}} = \bar{q}'_L Y_u^{(1)} u'_R \tilde{\phi}_1 + \bar{q}'_L Y_d^{(1)} d'_R \phi_1 + \bar{l}'_L Y_e^{(1)} e'_R \phi_1 + \bar{q}'_L Y_u^{(2)} u'_R \tilde{\phi}_2 + \bar{q}'_L Y_d^{(2)} d'_R \phi_2 + \bar{l}'_L Y_e^{(2)} e'_R \phi_2 + \text{h.c.}$$

$$\left(\tilde{\phi}_a = i\tau_2 \phi_a^*\right)$$

FCNC in the Higgs sector

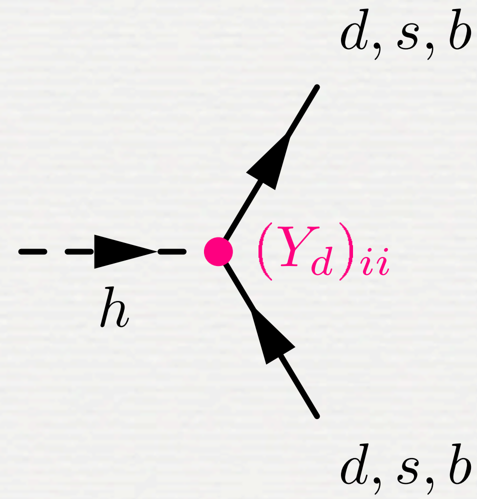
$$\mathcal{L}_{Yukawa} \supseteq \underbrace{\bar{u}'_L Y_d^{(1)} d'_R \phi_1^+ + \bar{d}'_L Y_d^{(1)} d'_R \phi_1^0}_{\text{SM}} + \bar{u}'_L Y_d^{(2)} d'_R \phi_2^+ + \bar{d}'_L Y_d^{(2)} d'_R \phi_2^0 + \text{h.c.}$$

In the SM there is only *one* Yukawa matrix for each fermion type, thus in the quark mass basis all higgs couplings are automatically diagonal

$$d_L = V_d^L d'_L$$

$$d_R = V_d^R d'_R$$

$$V_d^{L\dagger} Y_d V_d^R = \text{diag.}(y_d, y_s, y_b)$$

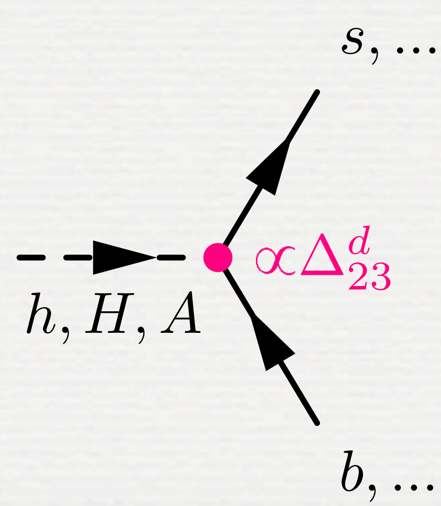


NO flavour changing couplings

In a general 2HDM, there are *two* Yukawa matrices for each fermion type. They cannot all be diagonalized at the same time.

$$V_d^{L\dagger} Y_d^{(1)} V_d^R = \text{diag.}(y_d^1, y_s^1, y_b^1)$$

$$V_d^{L\dagger} Y_d^{(2)} V_d^R \neq \text{diag.}(y_d^2, y_s^2, y_b^2)$$



Flavour changing couplings

Different „types“ of 2HDM

Usually one imposes a discrete symmetry such that all fermions of a given electric charge couple to no more than one Higgs boson and tree-level FCNC are absent.

Model	Symmetry	Couplings
type I	$\phi_1 \to -\phi_1 \quad \phi_2 \to \phi_2$ $d \to -d \quad u \to -u \quad e \to -e$	all fermions couple only to ϕ_1
type II	$\phi_1 \to -\phi_1 \quad \phi_2 \to \phi_2$ $d \to -d \quad u \to u \quad e \to -e$	d-type quarks and leptons couple to ϕ_1, u-type quarks to ϕ_2
„leptophilic“ or type X	$\phi_1 \to -\phi_1 \quad \phi_2 \to \phi_2$ $d \to -d \quad u \to -u \quad e \to e$	quarks couple to ϕ_1, leptons to ϕ_2
type Y	$\phi_1 \to -\phi_1 \quad \phi_2 \to \phi_2$ $d \to d \quad u \to -u \quad e \to -e$	u-type quarks and leptons couple to ϕ_1, d-type quarks to ϕ_2
type III	no discrete symmetry	all fermions couple to both Higgs doublets

Yukawa alignment

Type III 2HDM without any further protection lead to unacceptable high FCNC!
Ideas:

Hierarchical couplings (T. Cheng & M. Sher: Phys. Rev. D 35, 3484)

$$Y_{ij}^{u,d,l} = \lambda_{ij} \frac{\sqrt{m_i m_j}}{v}$$

Yukawa alignment (A. Pich & P. Tuzón: arXiv:0908.1554):

The Yukawa couplings of the two Higgs doublets are proportional to each other for each fermion of a given electric charge.

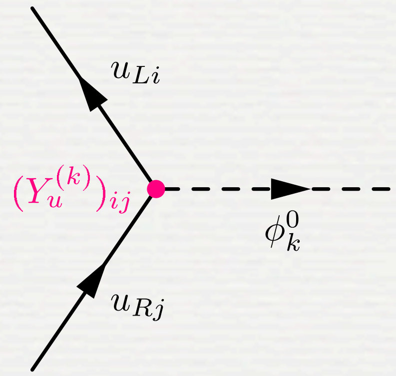
$$Y_u^{(1)} \propto Y_u^{(2)}$$
$$Y_d^{(1)} \propto Y_d^{(2)}$$
$$Y_e^{(1)} \propto Y_e^{(2)}$$

This condition must be imposed at the cut-off scale.

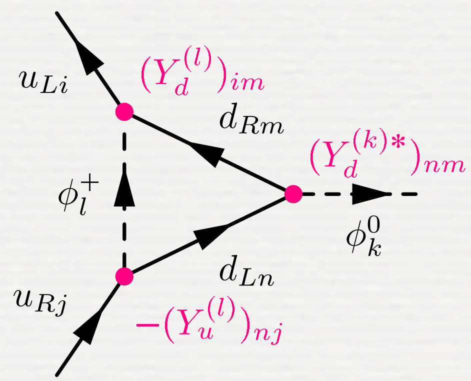
Radiative corrections to the couplings

Example: up-type Yukawa coupling

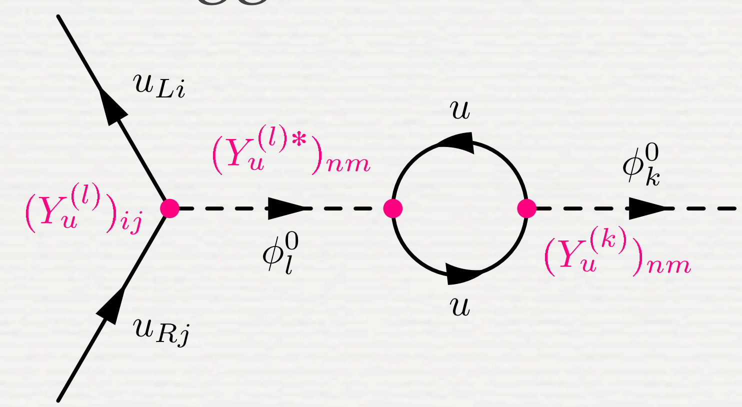
Tree-level:

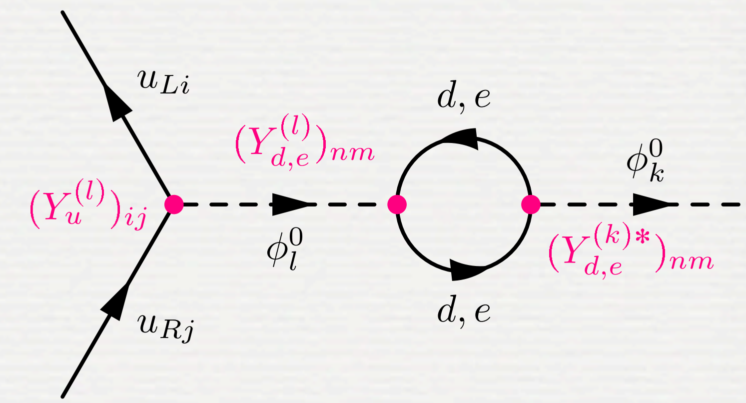


Vertex renormalization:

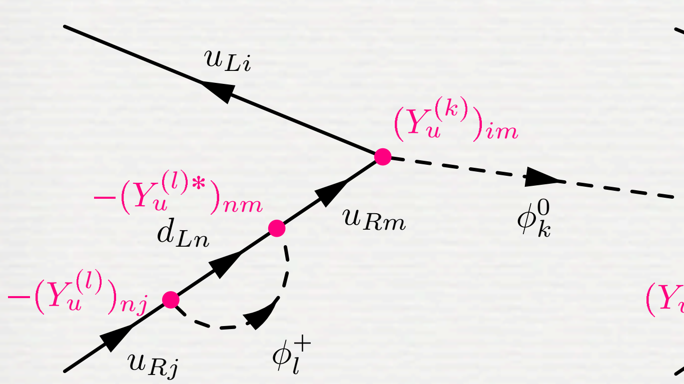


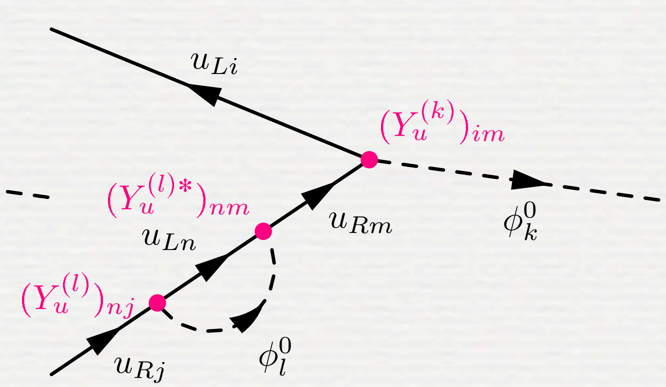
Higgs wave function renormalization:

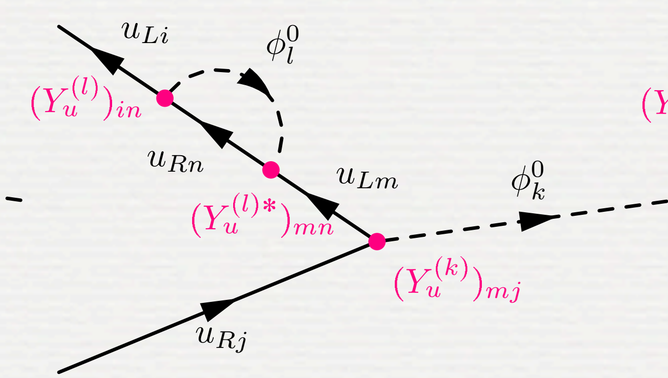


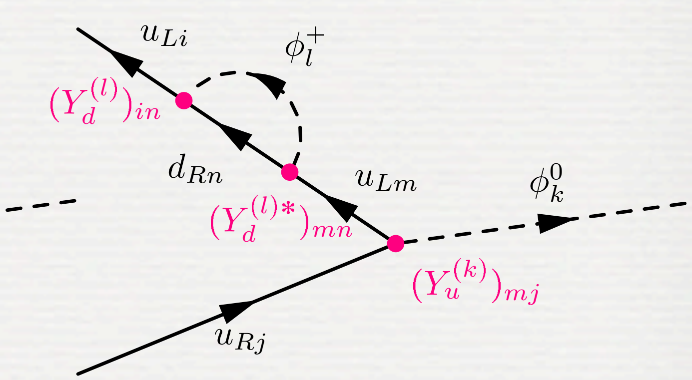


Fermion wave function renormalization:









Renormalization introduces FCNC

Due to the radiative corrections the couplings are energy-dependent. The methods of renormalization allow to remove ultraviolet divergences and to calculate this energy dependence, the beta function:

$$\beta_Y(E) = 16\pi^2 \frac{\partial}{\partial \ln E} Y$$

$$\beta_{Y_u^{(k)}} = a_u Y_u^{(k)} + \sum_{l=1,2} \left[3\mathrm{Tr}\left(\mathrm{Y_u^{(k)}} \mathrm{Y_u^{(l)\dagger}} \right) + \ldots \right] Y_u^{(l)} + \sum_{l=1,2} \left(-2 Y_d^{(l)} Y_d^{(k)\dagger} Y_u^{(l)} + \ldots \right)$$

Calculating the beta functions we see that they introduce a misalignment between the two Yukawa couplings.

The couplings at the electroweak scale can be calculated numerically or in the so-called „leading log“ approximation:

$$Y(M_Z) \approx Y(\Lambda) + \frac{1}{16\pi^2} \beta_Y(\Lambda) \log\left(\frac{M_Z}{\Lambda} \right)$$

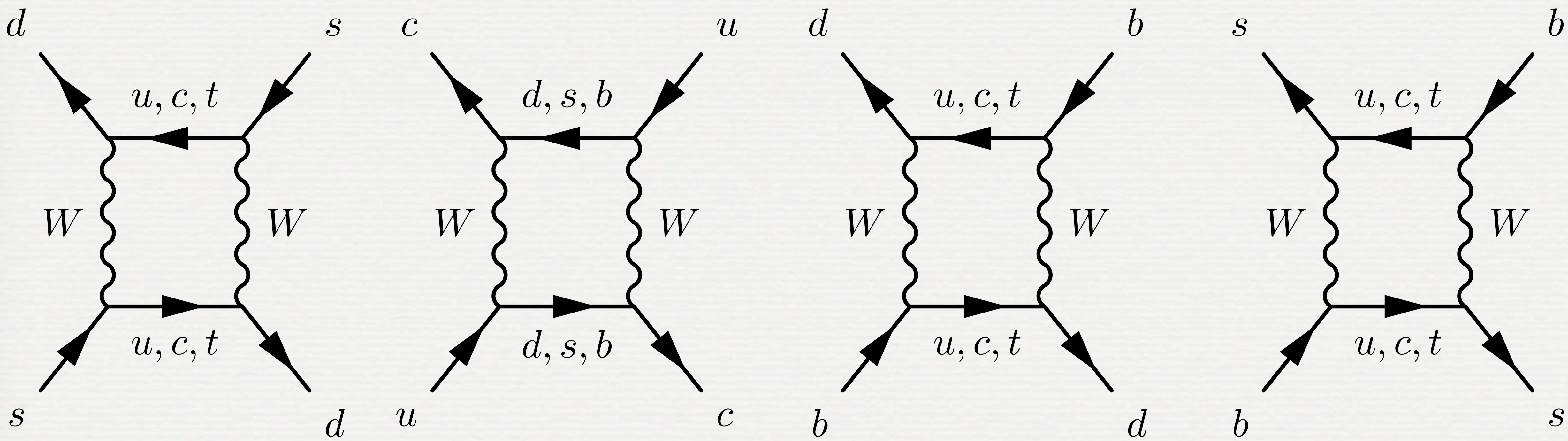
FCNC: meson-antimeson mass difference

Stringent experimental bounds on FCNC come from the mixing of neutral K, D, B_d and B_s mesons with their antiparticles.

$$K \propto \bar{s}d \qquad D \propto c\bar{u} \qquad B_d \propto \bar{b}d \qquad B_s \propto \bar{b}s$$

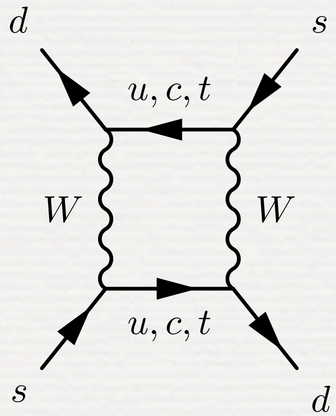
$$\bar{K} \propto s\bar{d} \qquad \bar{D} \propto \bar{c}u \qquad \bar{B}_d \propto b\bar{d} \qquad \bar{B}_s \propto b\bar{s}$$

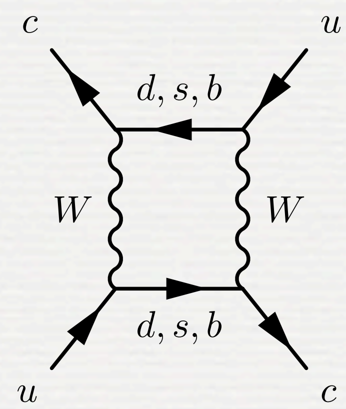
In the SM this mixing only occurs at loop-level:

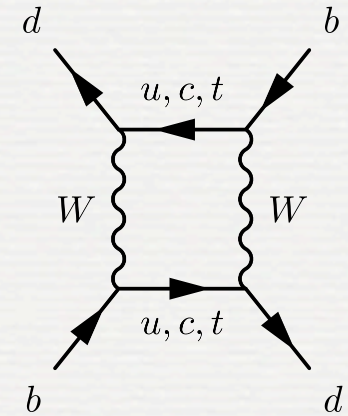


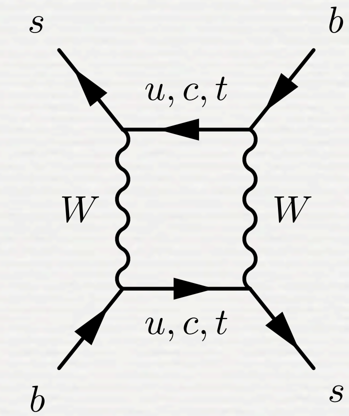
FCNC: meson-antimeson mass difference

Meson-antimeson mixing occurs at one-loop level in the SM:

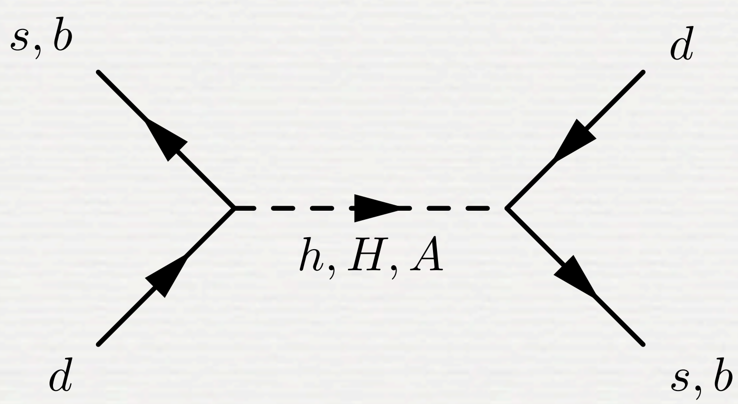


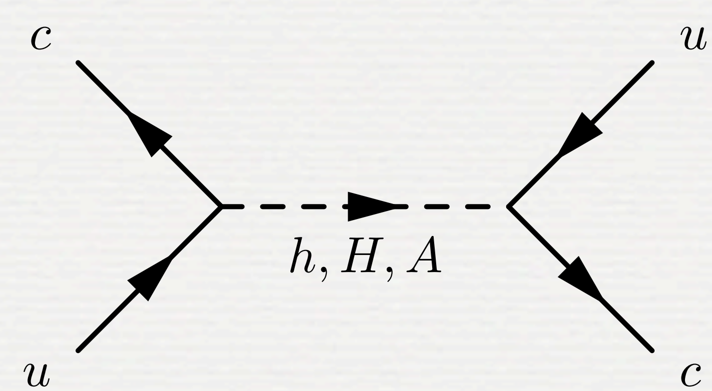






In 2HDM with FCNC mixing already occurs at the tree-level:





Because of the mixing, the flavour eigenstates $K, \bar{K}$, etc. are no longer mass eigenstates. Instead the mass eigenstates are a mixture of $K, \bar{K}$,etc.

$\longrightarrow$ The masses of mesons and antimesons are no longer degenerate.

FCNC: meson-antimeson mass difference

By calculating the meson-antimeson transition matrix element, the mass difference can be calculated, e.g. for Kaons:

$$M_K \Delta M_K \simeq \mathrm{Re}\, \langle K^0 |\, \mathcal{O}_{\Delta F=2}\, | \bar{K}^0 \rangle$$

The problem is however, that the operator $\mathcal{O}_{\Delta F=2}$ is written in terms of quarks, while the physical asymptotic states are hadrons. They must therefore be calculated using lattice methods. They can however be approximated by using the *vacuum-insertion approximation* (VIA):

The idea of the VIA is to separate the matrix element of a quartic operator into the product of two matrix elements of operators bilinear in the quark fields. The separation is performed not by inserting a complete set of states but by inserting only the vacuum.

$$\begin{aligned}\langle \overline{K^0} |\, (\bar{s}^+ d^+)(\bar{s}^- d^-)\, | K^0 \rangle &= \langle \overline{K^0} |\, (\bar{s}^+ d^+)\, | 0 \rangle \langle 0 |\, (\bar{s}^- d^-)\, | K^0 \rangle \\ &= \langle \overline{K^0} |\, (\bar{s} d)\, | 0 \rangle \langle 0 |\, (\bar{s} d)\, | K^0 \rangle\end{aligned}$$

These matrix elements can then easily be calculated.

FCNC: meson-antimeson mass difference

The matrix element of a meson-antimeson transition is usually written as:

$$\langle F^0 | \mathcal{O}_{\Delta F=2} | \overline{F^0} \rangle = B_F \, \langle F^0 | \mathcal{O}_{\Delta F=2} | \overline{F^0} \rangle_{VIA}$$

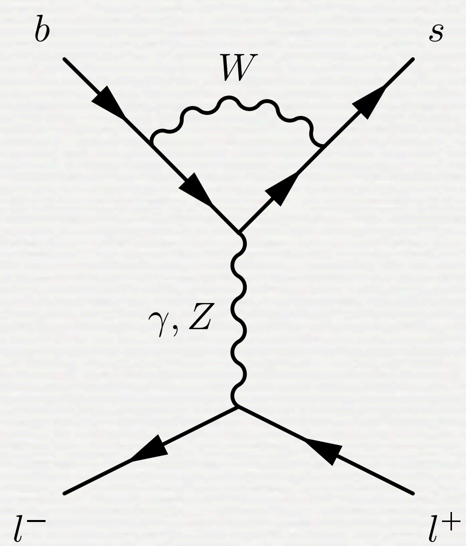
where the ratio of the matrix element itself to its value in the VIA is expressed by the B-parameter B_F, which can be calculated using lattice methods.

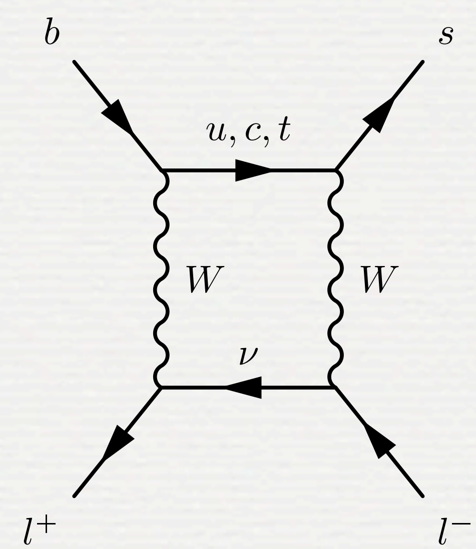
We calculated the matrix element for the $\Delta F = 2$ operator governing the tree-level meson-antimeson mixing in the 2HDM in the VIA and used the B-parameter of the SM calculation which can be found in the literature.

We find that - unless for extreme values of the input parameters - the sum of the SM mass differences plus the extra mass difference coming from the tree-level diagrams in the 2HDM are well within experimental bounds.
As the theoretical uncertainities on the SM values are bigger than the experimental uncertainities it is however not possible to make a clean prediction detectable by future experiments.

Rare B decays in the SM

The rare decays $B_d \to K l^+ l^-$ and $B_d \to l^+ l^-$ induced by $b \leftrightarrow s$ transitions.
In the SM these decay only occur at one loop level:





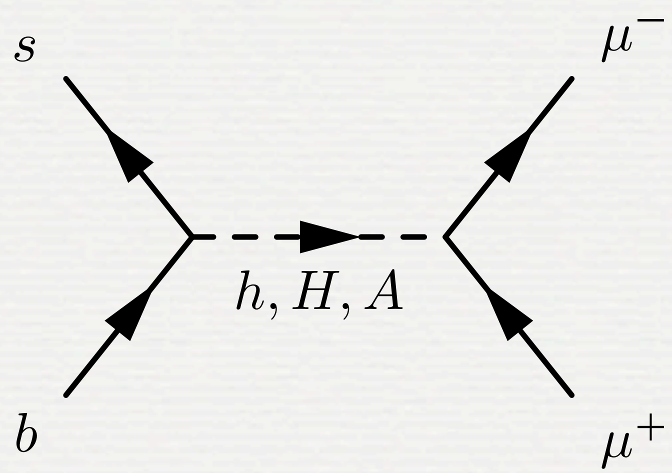
Since this decay is helicity suppressed, the $\tau^+\tau^-$ final state is most favoured. The taus decay however to jets or leptons whose observable invariant mass does not reconstruct back to a B meson. Therefore only the final state $\mu^+\mu^-$ has a clean signature.

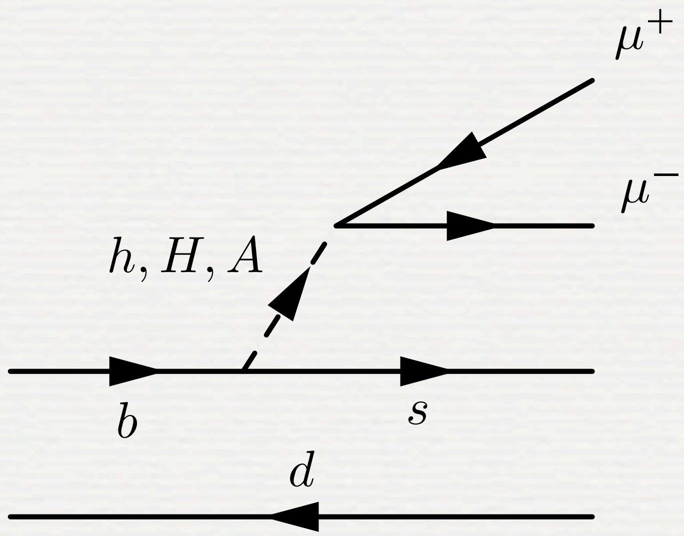
Branching ratio in the SM: $\mathrm{Br}(B_s \to \mu^+\mu^-) = (3.51 \pm 0.50) \times 10^{-9}$

Experimental limit: $\mathrm{Br}(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8} \quad (95\%\ \mathrm{CL})$

Rare B decays in the 2HDM

In a type III 2HDM rare B decays occur at tree level:





We have to calculate the branching ratios for these decays. As the SM values are much better know here than for the meson-antimeson mass differences, a prediction detectable by future experiments might be possible here.

Conclusions

- With the LHC finally running and searching for the Higgs(es) it is important to investigate different scenarios for the Higgs sector, in order to be able to interpret the data once they are coming.
- Yukawa alignment is a simple and effective way to prevent too large FCNC in 2HDM.
- It is sufficiently stable under renormalization running.

Flavour changing neutral currents (FCNC)

Recall that in the electroweak sector of the SM we have charged (coupling to W bosons) and neutral current (coupling to Z bosons and photons) interactions:

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{i=1,2,3} \left(\bar{u}_{Li}\gamma^\mu d_{Li} + \bar{\nu}_{Li}\gamma^\mu e_{Li}\right) W_\mu^+ + \text{h.c.} \qquad \mathcal{L}_{NC} = -eJ^\mu_{\text{em}}A_\mu - \frac{e}{\sin 2\theta_W} J^\mu_Z Z_\mu$$

with $J^\mu_{\text{em}} = \sum_{\substack{i=u,d,c,\\ s,t,b,e,\mu,\tau}} \bar{\psi}_i\gamma^\mu Q_i\psi_i \quad J^\mu_Z = \sum_{\substack{i=u,d,c,s,t,b,\\ e,\mu,\tau,\nu_e,\nu_\mu,\nu_\tau}} \bar{\psi}_i\gamma^\mu\left(v_i - a_i\gamma^5\right)\psi_i \qquad \psi_i = \psi_{Li} + \psi_{Ri}$

After EWSB the Yukawa couplings of the fermions to Higgs field look like:

$$\mathcal{L}_{Yukawa} = \underbrace{(y_u v)_{ij}}_{(m_u)_{ij}} \bar{u}_{Li}u_{Rj} + \underbrace{(y_d v)_{ij}}_{(m_d)_{ij}} \bar{d}_{Li}d_{Rj} + \underbrace{(y_e v)_{ij}}_{(m_e)_{ij}} \bar{e}_{Li}e_{Rj}$$

The mass matrices can be diagonalized by bi-unitary transformations:

$$V_u^{L\dagger} m_u V_u^R = \text{diag.}(m_u, m_c, m_t) \qquad V_u^{L\dagger}V_u^L = \mathbb{1} \quad V_u^{R\dagger}V_u^R = \mathbb{1}$$

The charged current couplings are no longer diagonal:

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}(V_{CKM})_{ij}\bar{u}_{Li}\gamma^\mu d_{Lj}W_\mu^+ \quad V_{CKM} \equiv V_u^{L\dagger}V_d^L$$

... but the neutral current ones are! => No FCNC at tree level in the SM gauge sector

Toward the basis of mass eigenstates

Before we can calculate the FCNC we must switch to the basis of the physical fields.

First, we switch to the so-called *Higgs basis*, where only one of the Higgs doublets gets a vacuum expectation value:

$$\begin{pmatrix} \Phi_1 \\ -\Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ \sin\beta & -\cos\beta \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$\mathcal{L}_{\text{Yukawa}} = \frac{\sqrt{2}}{v} \left\{ \bar{q}'_L \left(M_u \tilde{\Phi}_1 + \Gamma_u \tilde{\Phi}_2 \right) u'_R + \bar{q}'_L \left(M_d \Phi_1 + \Gamma_d \Phi_2 \right) d'_R + \text{h.c.} \right\}$$

Where the Higgs doublets are given as (in terms of the physical fields):

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \cos(\alpha-\beta)H - \sin(\alpha-\beta)h + iG^0) \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\sin(\alpha-\beta)H + \cos(\alpha-\beta)h + iA) \end{pmatrix}$$

Then we must switch to the basis of mass eigenstates by bi-unitary transformation. This diagonalizes $M_{u,d}$, but not $\Gamma_{u,d}$.