FLAVOR WINDOW TO PHYSICS BEYOND THE STANDARD MODEL

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THE IMPORTANCE OF THE FLAVOR WINDOW TO THE BSM PHYSICS IS STRONGLY LINKED TO THE STRUCTURE AND THE PRESENT STATE OF THE SM ITSELF.

AFTER THE DISCOVERY OF THE HIGGS BOSON, THE SM IS, MOST LIKELY, A RENORMALISABLE EFFECTIVE QFT OF ELEMENTARY INTERACTIONS AT THE ENERGY SCALES

$\mathcal{O}(100) GeV\,(10^{-18} m)$

(THE SM CANNOT BE THE THEORY OF EVERYTHING)

RENORMALISABLE BUT EFFECTIVE:

RENORMALISABILITY=PREDICTIVITY UP TO CORRECTIONS

$$\mathcal{O}(E/\Lambda)^2 \qquad \Lambda - \ Physical\ cut-off\ scale$$

MORE FORMALLY

$$\mathcal{L}_{SM}^{EFF} = \mathcal{L}_{SM} \ + \ HIGHER\ DIM\ OPERATORS$$
$$SUPPRESSED\ BY\ POWERS\ OF\ M$$

A NICE EXAMPLE WHICH IS NOW FULLY UNDER THEORETICAL CONTROL: QED AS AN EFFECTIVE RENORMALISABLE FIELD THEORY

(NOW DERIVABLE FROM THE STANDARD MODEL BY DECOUPLING HEAVY DEGREES OF FREEDOM)

RENORMALISABILITY OF AN EFFECTIVE QFT IS A BLESSING AND A CURSE AT THE SAME TIME

BLESSING:

ONE COULD FORMULATE QED (E~1 GeV) WITHOUT UNDERSTANDING THE SM (E~100 GeV)

CURSE:

TO FIND LAWS OF PHYSICS BEYOND THE EFFECTIVE THEORY VALID AT E ONE NEEDS ENERGY OF ORDER OF THE NEW MASS SCALE Λ OR PRECISION OF ORDER E^2/Λ^2

History will repeat itself?

QED → SM → Beyond?

How to find a deeper theory such that the SM will be its effective renormalisable approximation?

- SM IS RENORMALIZABLE, SO TO GO BEYOND IT ONE HAS THE TWO OPTIONS MENTIONED EARLIER

PRECISION VERSUS HIGH ENERGY FRONTIER

BUT WHERE IS THE NEW SCALE? CONTRARY TO THE PAST, WE ARE NOT (YET) DATA DRIVEN. WHY FLAVOR PHYSICS IS SO PROMISING?

IN SHORT, IT ALLOWS US TO LOOK DEEPER....

SM AND FLAVOR (= FERMION FAMILIES)

IN CERTAIN SENSE, FLAVOR IS A BEYOND THE SM CONCEPT!

3 FAMILIES OF QUARKS AND LEPTONS WITH IDENTICAL QUANTUM NUMBERS, AND IN CONSEQUENCE IDENTICAL GAUGE INTERACTIONS

GAUGE INTERACTIONS ARE FLAVOR BLIND!

FLAVOR DEPENDENT INTERACTIONS IN THE SM

ARE ONLY THE INTERACTIONS WITH THE

HIGGS FIELD, THAT IS THE YUKAWA COUPLINGS.

THEY ARE „TAKEN" FROM EXPERIMENT (ASSUMED TO BE SUCH THAT
ONE GETS CORRECT QUARK AND LEPTON MASSES AND QUARK MIXIN(

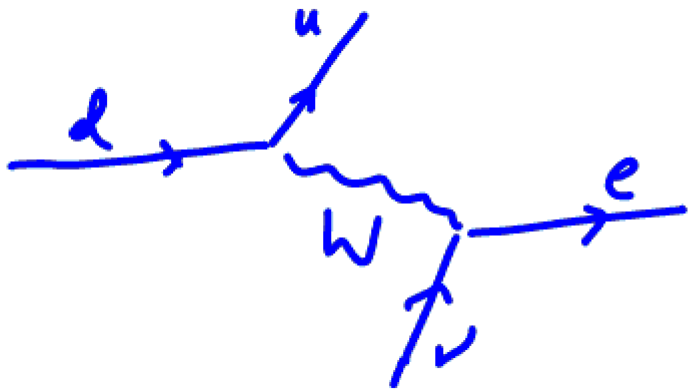
FLAVOR PHYSICS STUDIES TRANSITIONS
BETWEEN FERMIONS OF DIFFERENT FAMILIES
INDUCED (INDIRECTLY) BY THE INTERACTIONS
WITH THE HIGGS FIELD

THE FLAVOUR CHANGING TRANSITIONS ARE GENERATED BECAUSE FLAVOR GLOBAL SYMMETRY OF GAUGE INTERACTIONS

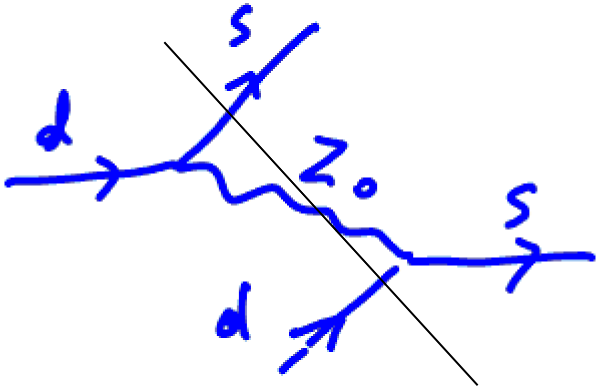
$$SU(3)^5 = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R} \otimes SU(3)_{L_L} \otimes SU(3)_{E_R}$$

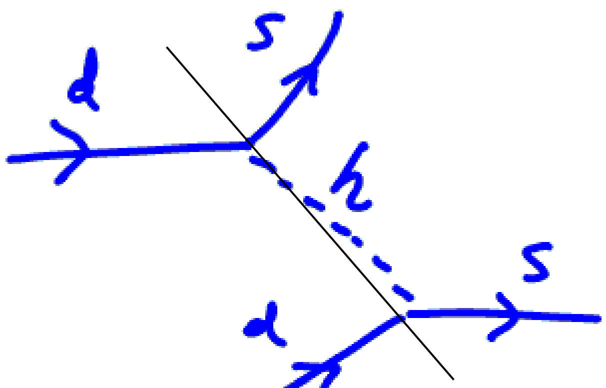
IS BROKEN ONLY BY YUKAWA MATRICES (GAUGE INTERACTIONS ARE FLAVOUR BLIND)

YUKAWA INTERACTIONS GENERATE FERMION MASSES AND THE TRANSFORMATION FROM THE INTERACTION BASIS TO THE MASS EIGENSTATE BASIS GENERATES FLAVOR CHANGING IN CHARGED W VERTICES, DESCRIBED BY THE CKM MATRIX neutron decay



$\bar{K}^0 - K^0$ mixing ?



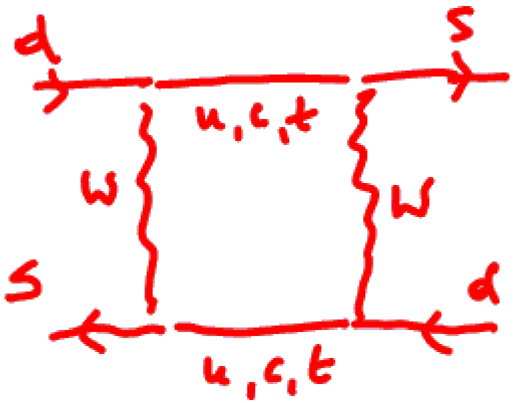


Flavour Changing Neutral Current (FCNC) processes

(ARE FORBIDEN AT THE TREE LEVEL)

Tree level diagrams are absent because of the structure of the theory (SU(2) quark and lepton doublets, only one Higgs doublet.)

But what about loops?



$$\mathcal{L}_{eff} = C\,(\bar{s}_L \gamma_\mu d_L)(\bar{s}_L \gamma_\mu d_L)$$

Generically

$$C \sim \frac{\alpha^2}{M_W^2} \sim \alpha G_F$$

Factor 10^4 too much

$$\mathcal{L}_{eff}^{\Delta S=2} \approx$$

GIM

$$\frac{1}{M_W^2}\frac{g^4}{(4\pi)^2}[(V_{ts}^* V_{td})^2 + (V_{cs}^* V_{cd})^2 \frac{m_c^2}{M_W^2} + \ldots](\bar{s}_L \gamma_\mu d_l)(\bar{s}\gamma^\mu d_L)$$

$$\approx \frac{1}{M_W^2}\frac{g^4}{(4\pi)^2} 10^{-5} (\bar{s}_L \gamma_\mu d_l)(\bar{s}\gamma^\mu d_L)$$

SUPPRESSION SCALE

ADDITIONAL SUPPRESSION

LOOP FACTOR

The success of the SM in the FCNC and CP violating sectors relies on:

- absence of tree-level effects
- GIM mechanism (unitarity of the quark mixing matrix)
- flavour global symmetry

  $$SU(3)^5 = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R} \otimes SU(3)_{L_L} \otimes SU(3)_{E_R}$$

  broken only by Yukawa matrices
- pattern of quark masses and mixing, taken from experiment

RESULT: STRONG SUPPRESSION OF FCNC AND CP VIOLATING PROCESSES

CP VIOLATION IS DESCRIBED BY THE PHASE IN THE CKM MATRIX

STRONG SUPPRESSION OF THE FCNC AND CP VIOLATING PROCESSES, SO FAR CONSISTENT WITH EXPERIMENTAL DATA, MAKES THEM PARTICULARLY SENSITIVE TO NEW PHYSICS EFFECTS (GIVEN THE HIGH PRECISION OF EXPERIMENTAL DATA)

VERY IMPORTANT CONCLUSION FOR CHARGED LEPTONS (IN THE APPROXIMATION OF ZERO NEUTRINO MASSES):

LEPTON FLAVOUR CONSERVATION

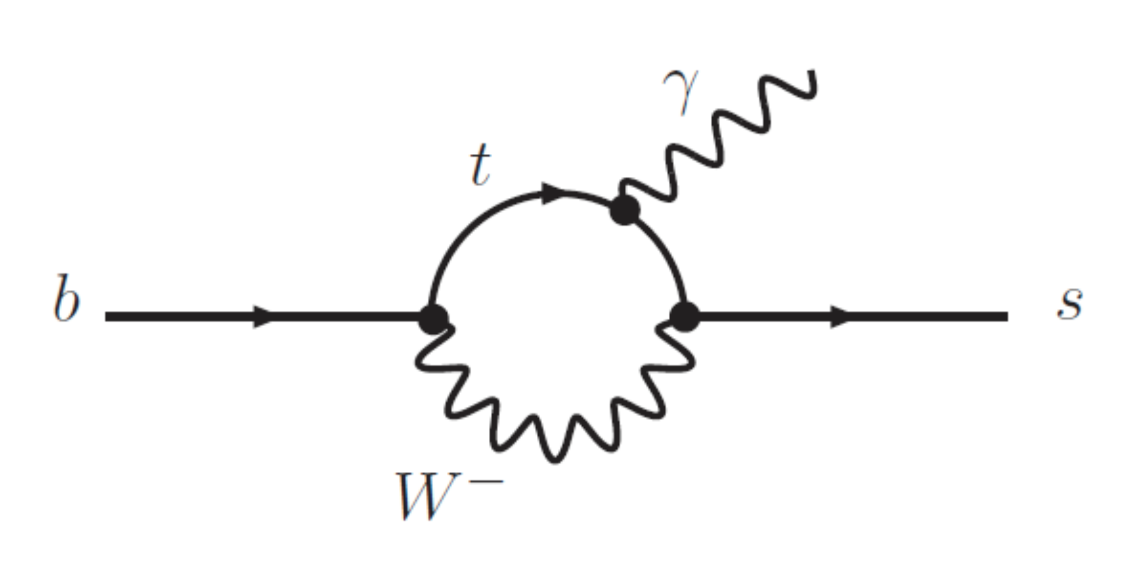
UNIVERSALITY OF LEPTON GAUGE INTERACTIONS, BOTH IN CHARGED AND NEUTRAL CURRENTS

$b \to s\gamma (B \to K\gamma)$ $\mu \to e\gamma$

allowed forbidden

$$Br_{SM}\left[B \to X_s\gamma\right] = \left(3.36 \pm 0.23\right) \times 10^{-4}$$

$$Br_{EXP}\left[B \to X_s\gamma\right] = \left(3.43 \pm 0.21 \pm 0.07\right) \times 10^{-4}$$



SM AS AN EFFECTIVE THEORY

L_{SM} + $SU(2)$ x U(1) invariant higher dim operators

e.g. dim 6 four fermion operators contributing to

$M - \bar{M}$ mixing

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{C_{ijkl}}{\Lambda^2}(\bar{Q}_i Q_j \bar{Q}_k Q_l) + \ldots .$$

$l_j \to l_i \gamma$ decays

$$\mathcal{L}_{eff} = \frac{C_{ij}}{\Lambda^2}(\bar{L}_j \sigma^{\mu\nu} E_i) H B^{\mu\nu}$$

PRESENT BOUNDS ON THE WILSON COEFFICIENTS (EXP ERROR)

$K - \bar{K}$ (0.1%) $\Lambda > 10^5 \sqrt{C}\ TeV$

$B_d - \bar{B}_d$ (1%) $\Lambda > 10^2 \sqrt{C}\ TeV$

$B_s - \bar{B}_s$ (10%) $\Lambda > 10 \sqrt{C}\ TeV$

$BR(\mu \to e\gamma) < 10^{-13} \quad \Lambda > 10^4 \sqrt{C}\ TeV$

A WINDOW TO VERY HIGH SCALES OF NEW PHYSICS (DEPENDENT ON THE MAGNITUDE OF THE FLAVOR DEPENDENT WILSON COEFFICIENTS)

LET'S CLASSIFY THE ULTIMATE BSM COMPLETIONS BY

1) $C \approx \mathcal{O}(1)$

2) THE ONLY FLAVOR DEPENDENT SECTOR REMAINS TO BE YUKAWA MATRICES (MINIMAL FLAVOR VIOLATION --> CONCRETE PREDICTIONS FOR C's

3) FLAVOR A MORE INHERENT PART OF BSM PHYSICS? NEW INTERACTIONS WHICH ARE ALSO (LIKE THE HIGGS FORCE) NOT FLAVOR BLIND? FLAVOR SYMMETRIES?

IN POINT (3), ANY LINK TO THE HIERARCHIES OF FERMION MASSES?

CP VIOLATION BEYOND THE SM?

THE SENSITIVITY OF THE EXPERIMENTAL DATA TO THE NEW PHYSICS SCALE DEPENDS ON THE CHOSEN SCENARIO BUT IT IS ALWAYS MUCH BETTER THAN IN THE LHC ETC

Hints for New Physics in the Flavor Sector

LEPTON NON-UNIVERSALITY IN B DECAYS

LHC, BELLE

$$R_K^{(*)} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

ANGULAR DISTRIBUTIONS IN

$$B \to K^{(*)}\mu\mu)$$

SEVERAL HINTS FOR SOME ANOMALIES IN PROCESSES INDUCED BY

$$b \to s\mu^+\mu^-$$

GLOBAL FITS WITH THE INCLUSION OF THE OPERATORS

$$\mathcal{O}_9 = \frac{\alpha_{EM}}{4\pi}[\bar{s}\gamma^\nu P_L b][\bar{\mu}\gamma_\nu \mu]$$

$$\mathcal{O}_{10} = \frac{\alpha_{EM}}{4\pi}[\bar{s}\gamma^\nu P_L b][\bar{\mu}\gamma_\nu \gamma_5 \mu]$$

Explanations of the Flavour Anomalies

$b \to s \mu^+ \mu^-$

$b \to c \tau \nu$

Additional neutral gauge bosons (Z')

Leptoquarks

Extended Higgs sector

SUMMARY

THE SUCCESS OF THE SM IN THE FLAVOR PHYSICS RELIES ON CERTAIN PATTERN OF ITS STRUCTURE AND ON (UNEXPLAINED) PHENOMENOLOGICAL PATTERN OF FERMION MASSES AND MIXING, AND THE NUMBER OF FAMILIES

FLAVOR WINDOW TO THE BSM PHYSICS IS IN PRINCIPLE SENTIVE TO VERY HIGH SCALES OF NEW PHYSICS

THERE ARE SOME EXPERIMENTAL HINTS FOR LEPTON FLAVOR UNIVERSALITY VIOLATION