OVERTURE

THE STANDARD MODEL OF PARTICLE PHYSICS

TELLS US WHAT ARE THE SMALLEST BUILDING

BLOCKS OF MATTER AND WHICH FORCES

ACT BETWEEN THEM UP TO THE MASS (LENGTH)

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

THE END OF A CERTAIN STORY…

THE STORY HAS BEGAN WITH THE DISCOVERY

OF RADIOACTIVITY (1896)

AFTER 120 YEARS OF RESEARCH THIS

CHAPTER IS KNOW CLOSED

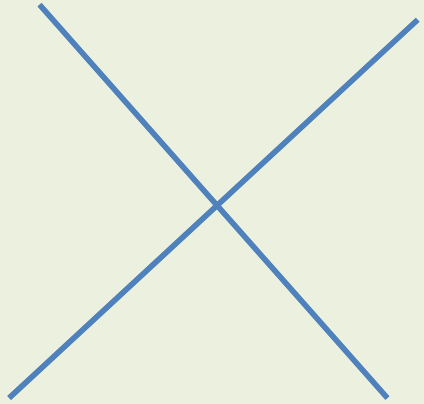
EVER SINCE 1896 THE PROGRESS WAS

DRIVEN BY EXPERIMENTAL DISCOVERIES

THE FERMI FOUR-FERMION THEORY FOR THE NEUTRON $\beta-$ DECAY HAS INTRODUCED A NEW MASS SCALE INTO PARTICLE PHYSICS AND A GUARANTEE OF NEW DISCOVERIEs

$$\mathcal{L}_F \approx G_F \bar{\Psi}^p_L \gamma_\mu \Psi^n_L \bar{\Psi}^e_L \gamma^\mu \Psi^\nu_L$$

$$G_F \approx 1/10^5 GeV^2$$



$$G_F E^2 \approx \frac{E^2}{(100\ GeV)^2}$$

2+2→2+2 SCATTERING AMPLITUDE

(e.g. N+positron→P+antyneutrino)

EVENTUALLY VIOLATES UNITARITY AND „SOMETHING NEW" MUST HAPPEN TO RESTORE IT!

MODERN PERSPECTIVE: FERMI 4-FERMION LAGRANGIAN IS AN ADDITION TO QED (RENORMALIZABLE THEORY) OF A NON-RENORMALIZABLE TERM WHICH IS INVARIANT UNDER U(1) BUT VIOLATES ONE OF THE QED CONSERVATION LAWS (BARYON CHARGE CONSERVATION):

$$\mathcal{L} = \mathcal{L}_{QED} + \mathcal{L}_F + \ldots$$

$$G_F m_l \bar{\Psi}^l_L \sigma_{\mu\nu} \Psi^l_R F^{\mu\nu}$$

RENORMALIZABLE + HIGHER DIM OPERATORS= EFFECTIVE THEORY STEMING FROM A DEEPER ONE:

We can organise particle physics in terms of hierarchical energy scales, thanks to the Appelquist-Carazzone decoupling theorem:

> If a gauge theory valid at energy scale M_1 is embedded into a larger theory with new particles of mass $M_2 \gg M_1$, the effects on observables probed at the scale M_1 are suppressed by powers of M_1/M_2.

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 M OR PRECISION OF ORDER E^2/M^2

THANKS TO THE HIGGS DISCOVERY

(BY THE WAY, THERE WAS AGAIN
THE GUARANTEE THAT „SOMETHING"
MUST HAVE HAPPENED TO UNITARIZE
THE WW SCATTERING AMPLITUDE)

WE HAVE NOW AT HAND A THEORY THAT
LOOKS LIKE A RENORMALIZABLE ONE
AND WE FIND OURSELVES AT A
TURNING POINT:

- THE SM CANNOT BE THE THEORY OF EVERYTHING.

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

BUT WHERE IS THE NEW SCALE? CONTRARY TO THE PAST, WE ARE NOT DATA DRIVEN

FLAVOR WINDOW TO PHYSICS BEYOND THE STANDARD MODEL

(FLAVOR PUZZLE)

WHO ORDERED THAT? (THE MUON)
I. RABI 1936

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 WHICH DIFFER ONLY BY THEIR INTERACTIONS WITH THE HIGGS FIELD **(FIFTH FORCE!)**

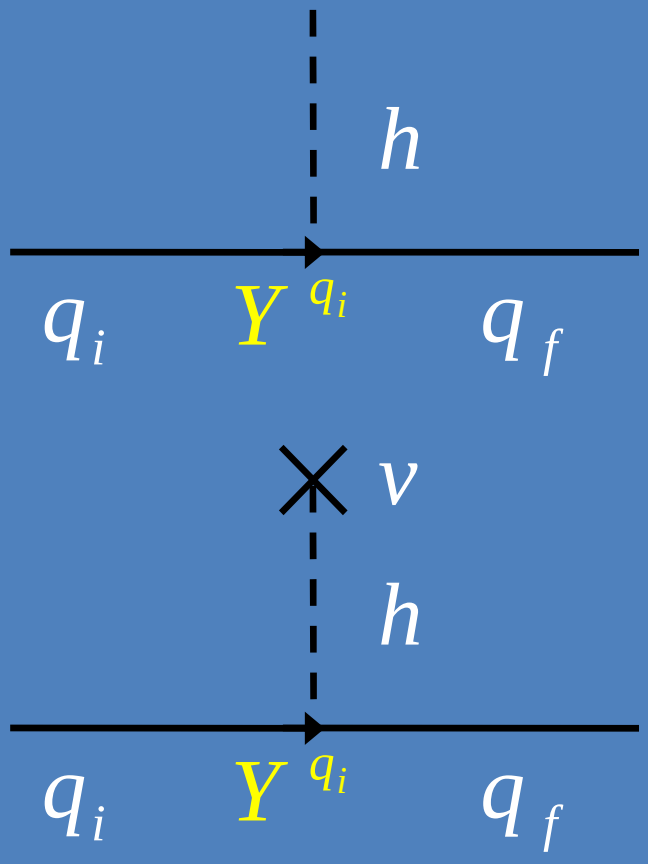
FLAVOR PHYSICS STUDIES TRANSITIONS BETWEEN FERMIONS OF DIFFERENT FAMILIES

Yukawa Interactions and fermion masses

- Interactions of the Higgs particle with fermions
- The quarks acquire masses after electroweak symmetry breaking

$$m_{q_i} = v Y^{q_i}$$

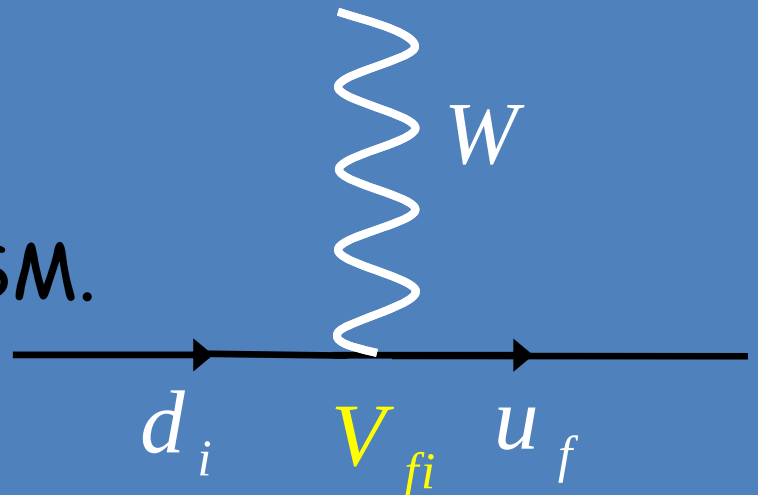
- Diagonalized by biunitray transformations
- Only the charged W vertex is flavor changing



13

The CKM matrix

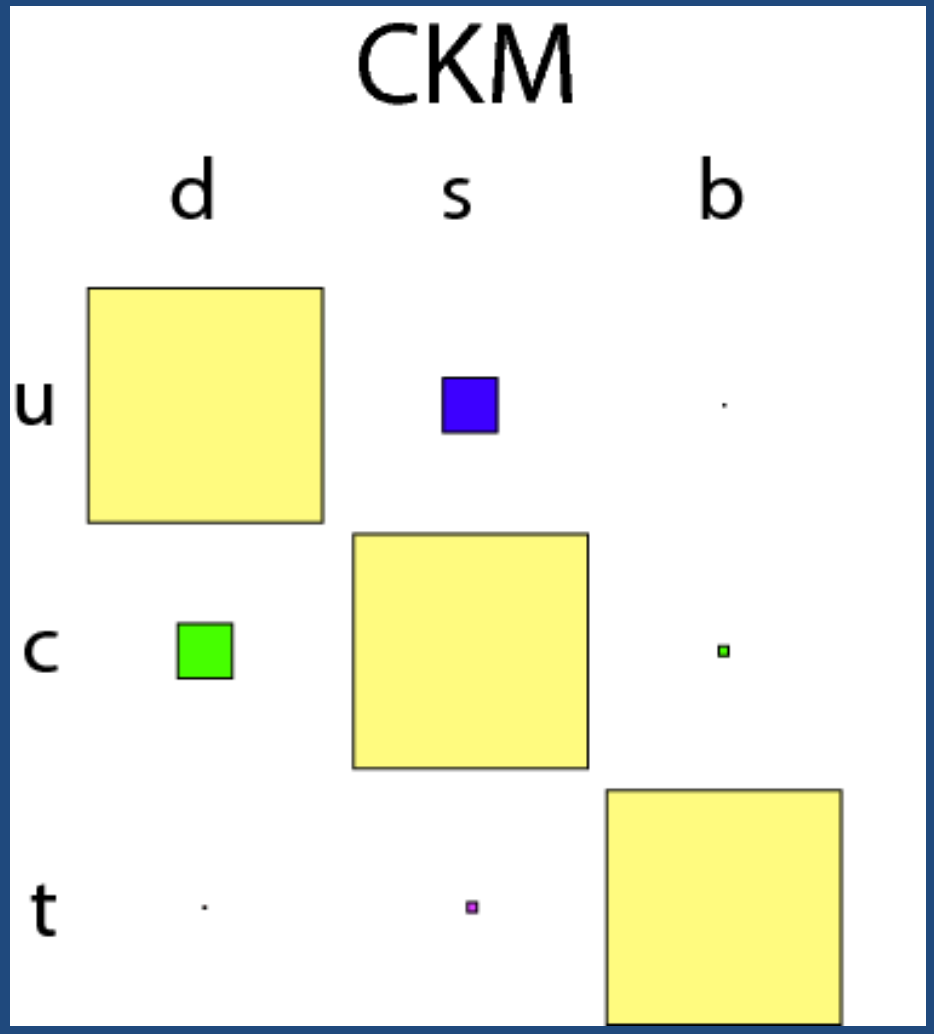
- The mass matrices are diagonalized by (bi) unitary transformations
  $U^{L\dagger}\mathbf{m}_u U^R = \mathbf{m}_u^D, \quad D^{L\dagger}\mathbf{m}_d D^R = \mathbf{m}_d^D$
- Neutral gauge interactions are proportional to the unit matrix
  ➡ $U^{L\dagger}U^L = \mathbf{1}$ etc.
- Only the W vertex is flavour changing in the SM.



CKM matrix $V = U^{L\dagger}D^L$

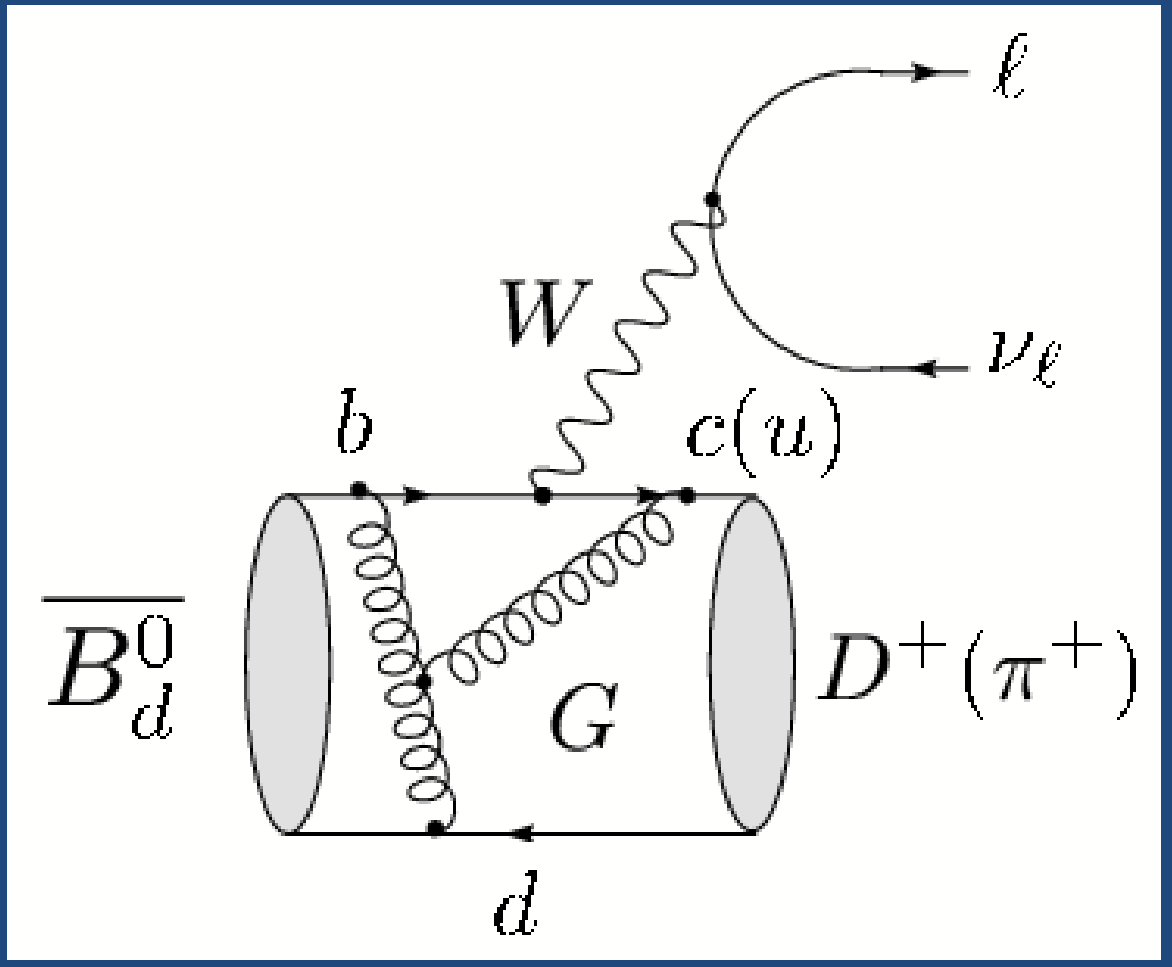
Magnitude of the CKM elements (tree-level)

- V_{ud} from beta decay
- V_{cd} and V_{cs} from D decays
- V_{tb}, V_{td} and V_{ts} determined by CKM unitarity
- V_{tb} also from $t \rightarrow Wb$ but not competititive



Tree-level determination of the CKM elements

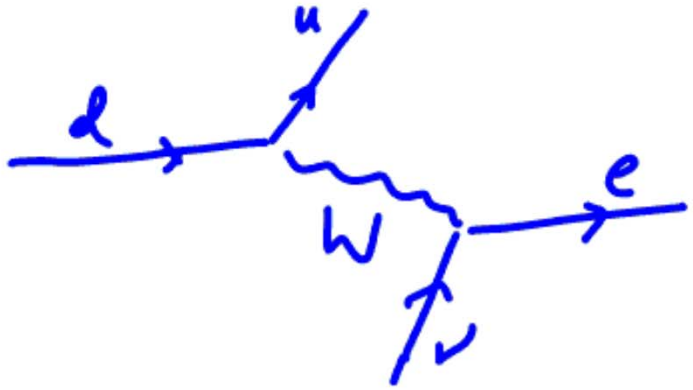
- V_{ub}
  - $B \to \pi \ell \nu$
  - $B \to X_u \ell \nu$
  - $B \to \rho \ell \nu$
  - $B \to \tau \nu$
- V_{cb}
  - $B \to D \ell \nu$
  - $B \to D^* \ell \nu$
  - $B \to X_c \ell \nu$
- V_{us}
  - Kaon decays



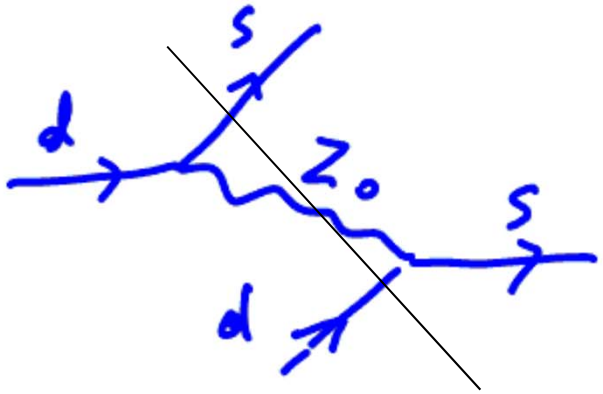
EFFECTIVE FERMI THEORY WITH FLAVOR INCLUDED IS A CONVENIENT BOOKEEPING FOR THE FULL SM CALCULATIONS

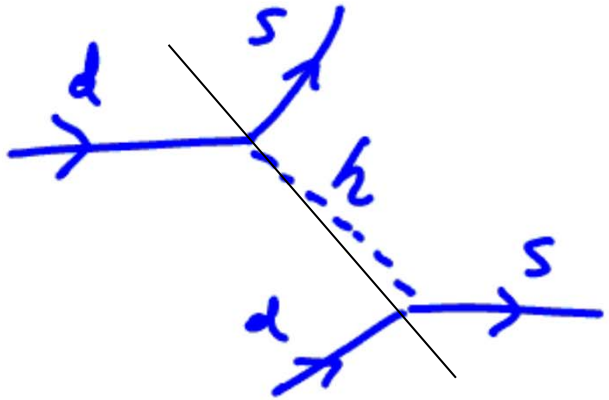
Flavour Changing Neutral Current (FCNC) processes

neutron decay



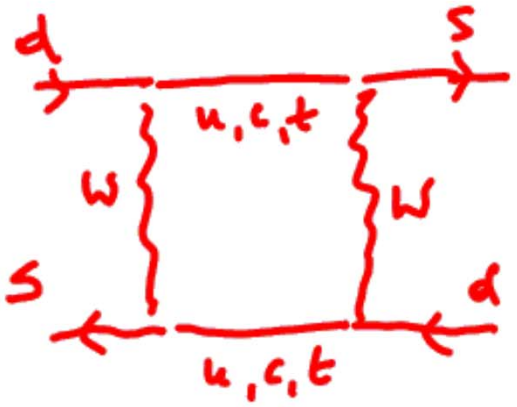
$\bar{K}^0 - K^0$ mixing ?





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

LOOP FACTOR

ADDITIONAL SUPPRESSION

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)
- pattern of quark masses and mixing,taken from experiment

RESULT: STRONG SUPPRESSION OF FCNC PROCESSES

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

LEPTON FLAVOUR CONSERVATION

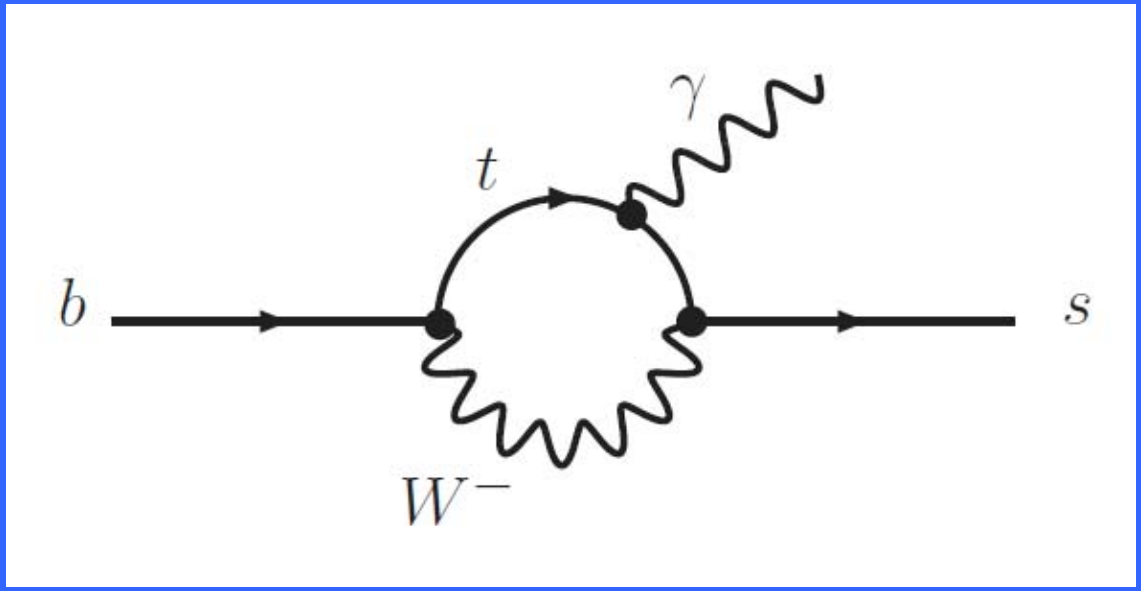
UNIVERSALITY OF LEPTON GAUGE INTERACTIONS, BOTH IN CHARGED AND NEUTRAL CURRENTS

$b \to s\gamma (B \to K\gamma)$ allowed

$\mu \to e\gamma$ forbidden

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

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



STRONG SUPPRESSION OF THE FCNC PROCESSES MAKES THEM PARTICULARLY SENSITIVE TO NEW PHYSICS EFFECTS (GIVEN THE HIGH PRECISION OF EXPERIMENTAL DATA)

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

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

$l_j \to l_i \gamma$ 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%) $\quad \Lambda > 10^5 \sqrt{C}\ TeV$

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

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

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

MUCH WEAKER BOUNDS FOR $\tau \to \mu(e)\gamma$

AND FOR MANY OTHER PROCESSES INVOLVING ONLY THE 2nd AND 3rd Family

WHAT CAN WE LEARN?

TWO „UNINTERESTING" CASES:

- WILSON COEFFICIENTS ARE FLAVOR UNIVERSAL
- WILSON COEFFICIENTS ARE FLAVOR DIAGONAL

→ LITTLE HOPE TO SEE NEW EFFECTS IN FLAVOR PHYSICS

BUT IF THEY HAVE SOME FLAVOR STRUCTURE (ANY LINK TO THE HIERARCHIES OF FERMION MASSES?) → REACH EXPERIMENTAL AND THEORETICAL POSSIBILITIES OPEN UP

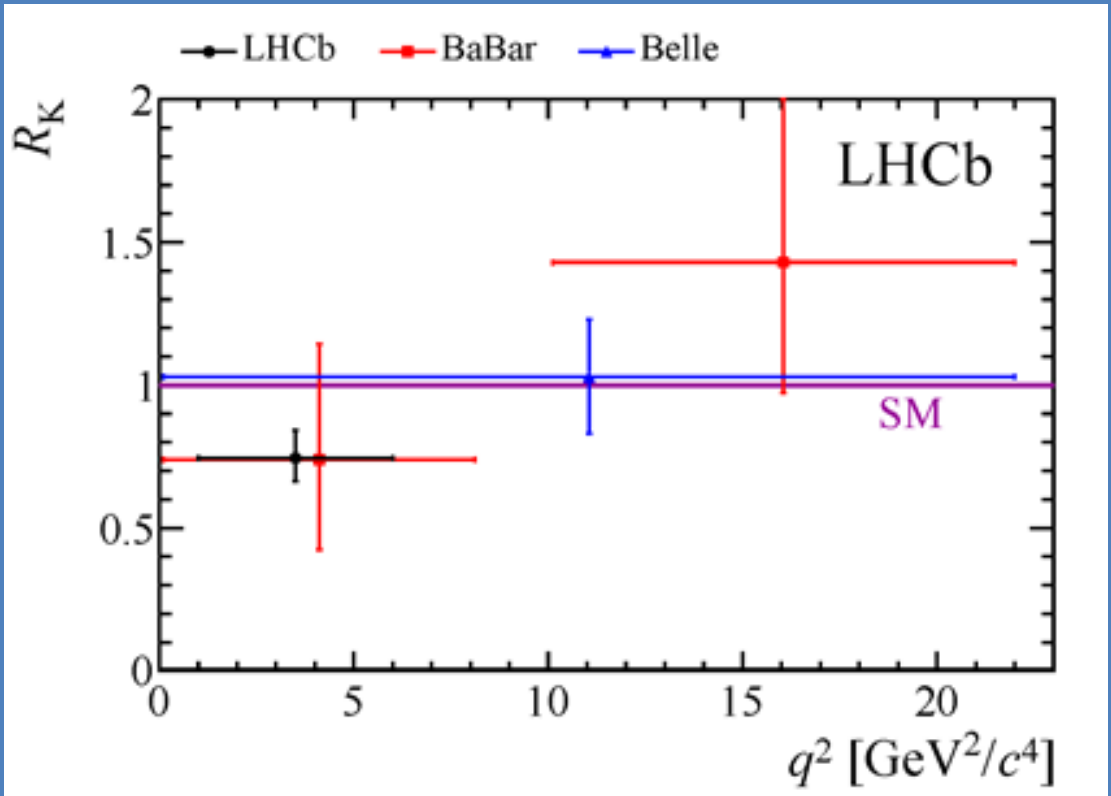
FLAVOR SENSITIVE NEW PHYSICS EVEN WITH LOW MASS SCALE IS STILL POSSIBLE AND CAN BE SEEN .

A VAST RANGE OF SCALES IS ACCESSIBLE

Hints for New Physics in the Flavor Sector

R(K) = B→Kμμ/B→Kee

- Lepton flavour universality violation
- 2.6 σ deviation from the theoretically clean SM expectation



$B \to K^* \mu\mu$

2-3 σ deviation from the SM in some angular distributions

LEPTON UNIVERSALITY VIOLATION IN

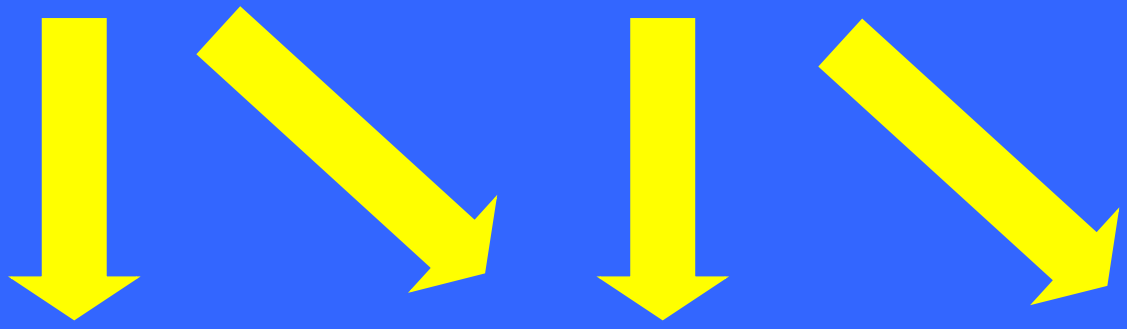
$$R(D^{(*)}) \equiv \frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}l\nu)}$$

$3 - 4\ \sigma$ EFFECT

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

FLAVOR IS AN ADDITION TO THE SM BUT CKM MECHANISM OF FLAVOR VIOLATION HAS BEEN CONFIRMED WITH HIGH PRECISION (FLAVOR SENSITIVE FIFTH FORCE)

STRONG SUPPRESSION OF FCNC PROCESSES FOLLOWS FROM EXPERIMENTALLY MEASURED FREE PARAMETRES (YUKAWAS) OF SM

STRONG SUPPRESSION OF FCNCs AND EXP PRECISION → SENSITIVITY TO HIGH MASS SCALES AND TO FLAVOR PATTERN OF NEW FORCES

HINTS FOR LEPTON FLAVOR UNIVERSALITY VIOLATION?

IS FLAVOR A MORE INHERENT PART OF BSM PHYSICS?