PART V

what do we learn from all that ?

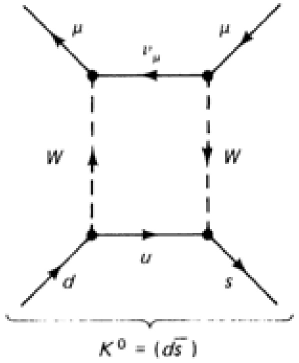
The quarks c b and t were discovered in an indirect way by using **rare decays**, and more precisely **FCNC**, such as

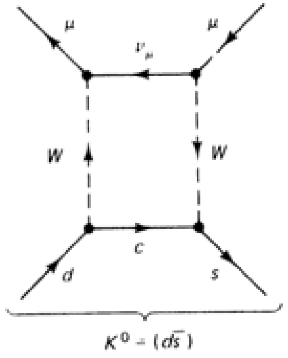
$K^0 \rightarrow \mu\mu$, $K_L \rightarrow \pi\pi$ and **B oscillations**

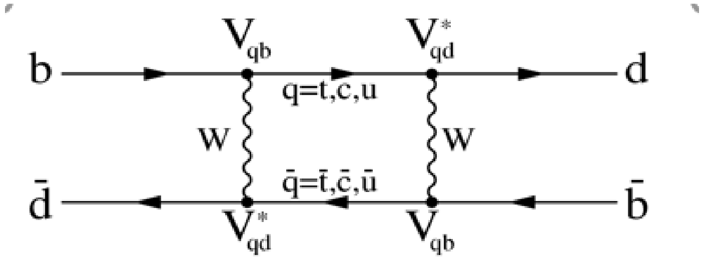
1. ~1970 charm quark from FCNC and GIM-mechanism $K^0 \rightarrow \mu\mu$
2. ~1973 3rd generation from CP violation in kaon (ε_K) KM-mechanism
3. ~1990 heavy top from B oscillations Δm_B

The Quantum path

The indirect searches
look for “New Physics”
through virtual effects from new particles in loop corrections

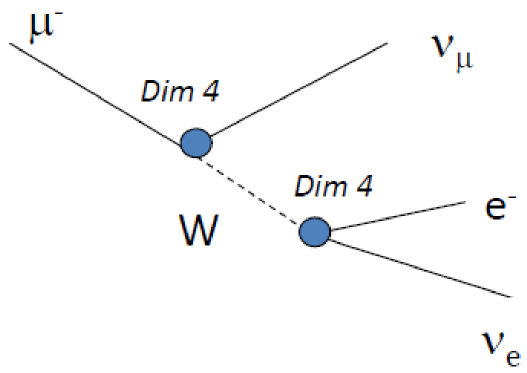






$$L_{CC} = \frac{g}{\sqrt{2}}\left(J_\mu^- W_-^\mu + J_\mu^+ W_+^\mu\right)$$

SM

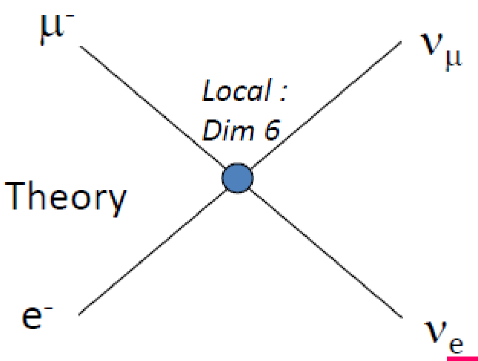


$$M = \left(\frac{g}{\sqrt{2}}\bar{u}_{\nu_\mu}\gamma^\mu \frac{1}{2}(1-\gamma_5)u_\mu\right)\frac{1}{M_W^2 - q^2}\left(\frac{g}{\sqrt{2}}\bar{u}_e\gamma_\mu \frac{1}{2}(1-\gamma_5)u_{\nu_e}\right)$$

if $q^2 \ll M_W^2$ (case of beta decay)

$$M = \frac{g^2}{8M_W^2}\left(\bar{u}_{\nu_\mu}\gamma^\mu(1-\gamma_5)u_\mu\right)\left(\bar{u}_e\gamma_\mu(1-\gamma_5)u_{\nu_e}\right)$$

Fermi
Effective Theory



$$M = \frac{G_F}{\sqrt{2}}\left(\bar{u}_{\nu_\mu}\gamma^\mu(1-\gamma_5)u_\mu\right)\left(\bar{u}_e\gamma_\mu(1-\gamma_5)u_{\nu_e}\right)$$

Experimentally from muon decay $G_F = 1.16 \times 10^{-5}\, GeV^{-2}$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

The effective coupling constant GF is expressed as the SM « fundamental » coupling constant g divided by the mass of the propagator M_W squared (consequence of Dim=6 operators [4legs])

In this specific case we know

→ from SM $e = g \sin(\theta_W)$

→ Experimentally $M_W \sim 80$ GeV

The weak interaction is not weak because of *g<<e* but because of the large value for the W mass

Effective Flavour Theory to New Flavour Physics :
A game of scale and coupling

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{k=1} \left(\sum_i C_i^k \, Q_i^{(k+4)}\right) / \Lambda^k$$

New operators which are of dimension >4, in principle the theory is not Renormalizable…as Fermi theory was not..!
[You can show that in B physics the new operators have dimension 6]

NP flavour effects are governed by two players

→ the value of the new phyiscs scale Λ

→ the effective flavour-violating coupling C's

In explicit models

Λ ~ mass of virtual particle (Fermi theory : M_W)

C ~loop coupling × flavour coupling (SM/MFV α_w × CKM)

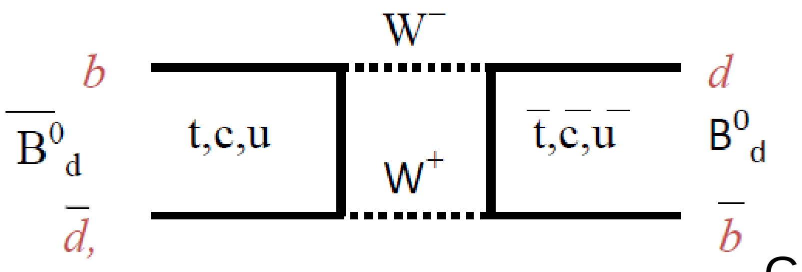
Example for B oscillations (FCNC-ΔB=2)

FCNC porcesses are ideal place to look for NP effects because they are suppressed in SM

Precise measurements are needed.

Effects goes $1/\Lambda^2$

SM

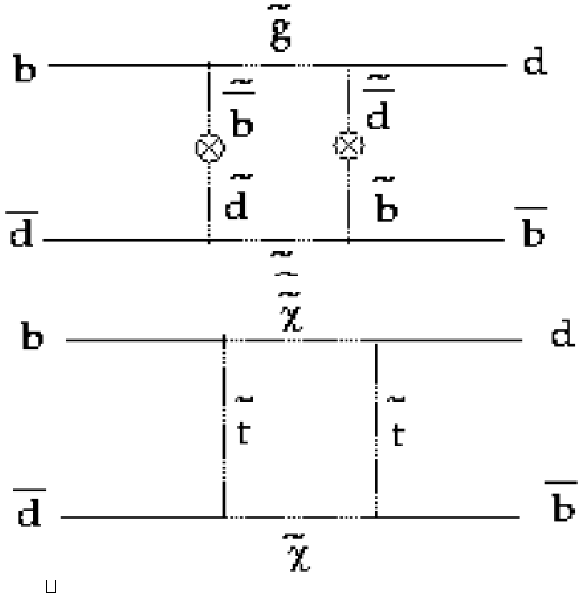


$$f(m) \times \frac{|V^*_{tb} V_{tq}|^2}{M_W^2}$$

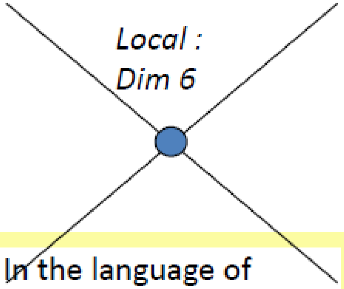
GIM mechanism

When I squared I have the m_t^2 at the numerator and M_W^4 at denominator. IMPORTANT at the end the dimension is $1/E^2$

BSM



$$\frac{|\delta_{bq}|^2}{\Lambda^2_{eff}}$$



In the language of
The EFT, the operators
have dimension 6
→ $1/\Lambda^2$

The measurements (in this case Δm_d)
are modified wrt the predictions of the SM by the presence of BSM particles.

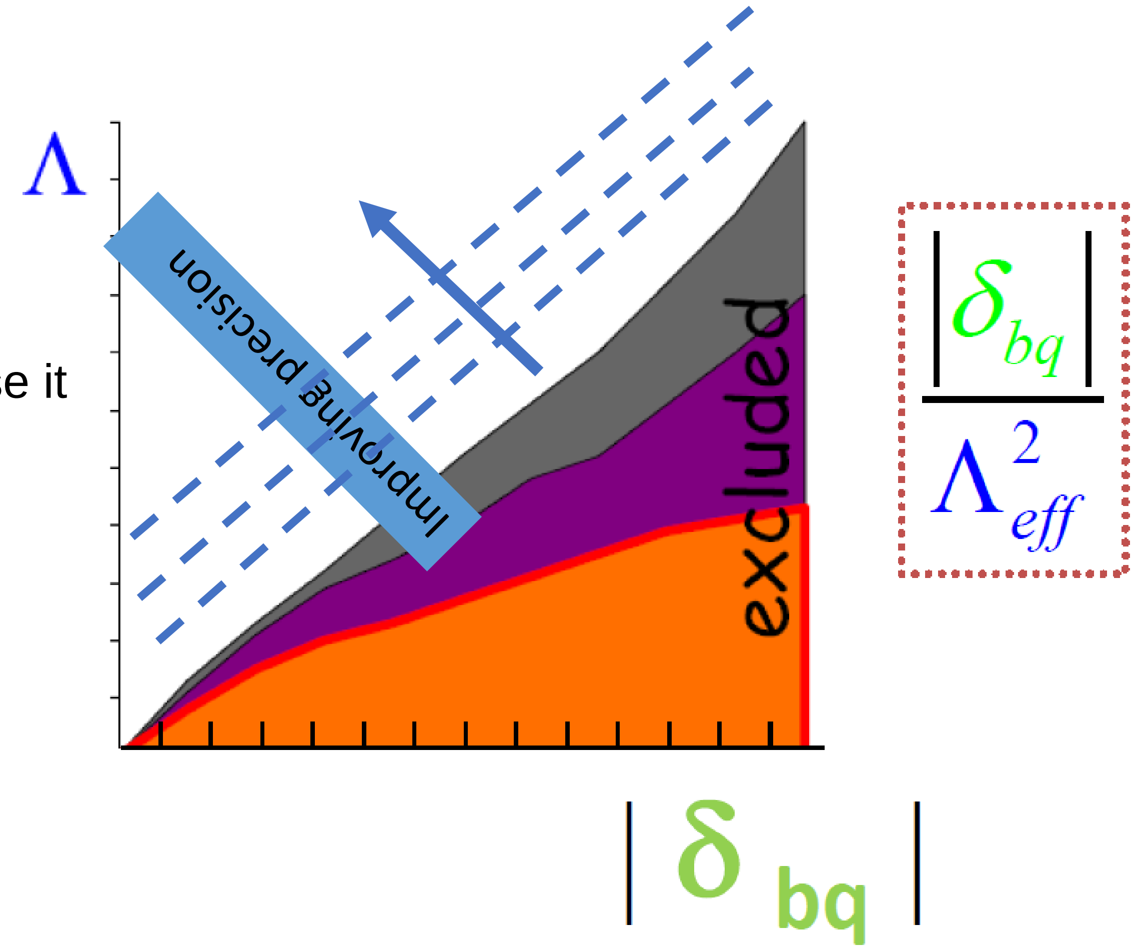
modifications are important if couplings are larger and/or NP masses are lighter

Pictorially

Flavour Physics

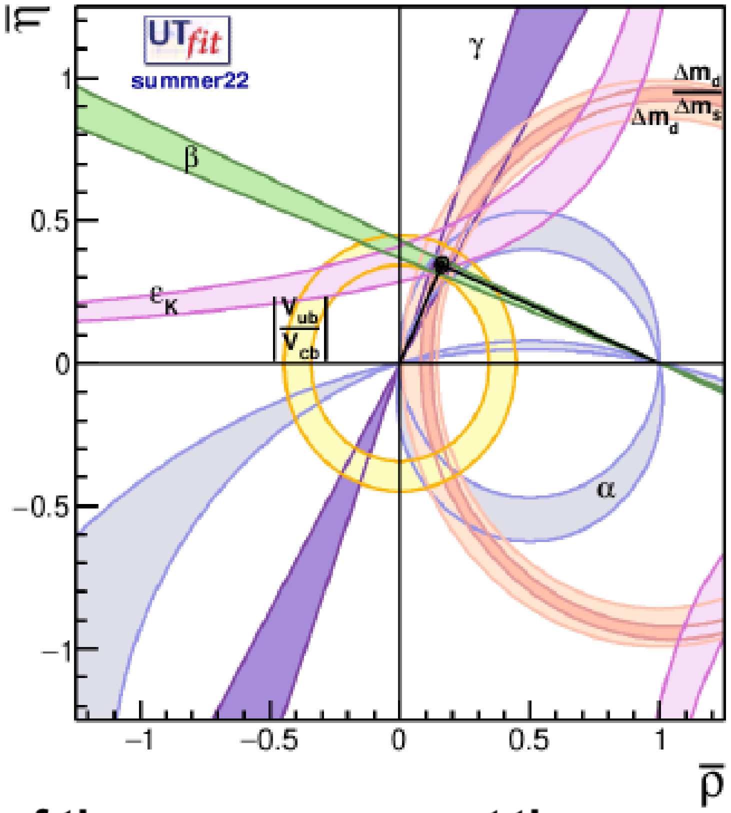
It is a game of couplings and scales

This is the basic region because it is important to have precise measurements



Global Fit within the SM

All the constraints
Look compatibles !



Coherent picture of FCNC and CPV processes in SM

CKM matrix is the dominant source of flavour mixing and CP violation

Out of these measurement there a general agreement that we have limited the contributions of New Physics amplitudes (A_{NP}) wrt to SM ones (A_{SM}) at the the level of

$$R = \frac{A_{NP}}{A_{SM}} < 20\%$$

What does it imply ?

UT analysis including new physics

fit simultaneously for the CKM and
the NP parameters (generalized UT fit)

- add most general loop NP to all sectors
- use all available experimental info
- find out NP contributions to ΔF=2 transitions

B_d and B_s mixing amplitudes
(2+2 real parameters):

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} \left(\Delta m_{q/K}\right)^{SM}$$
$$A_{CP}^{B_d \to J/\psi K_S} = \sin 2(\beta + \phi_{B_d})$$
$$A_{SL}^q = \mathrm{Im}\left(\Gamma_{12}^q / A_q\right)$$

$$\varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$
$$A_{CP}^{B_s \to J/\psi\phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$
$$\Delta\Gamma^q / \Delta m_q = \mathrm{Re}\left(\Gamma_{12}^q / A_q\right)$$

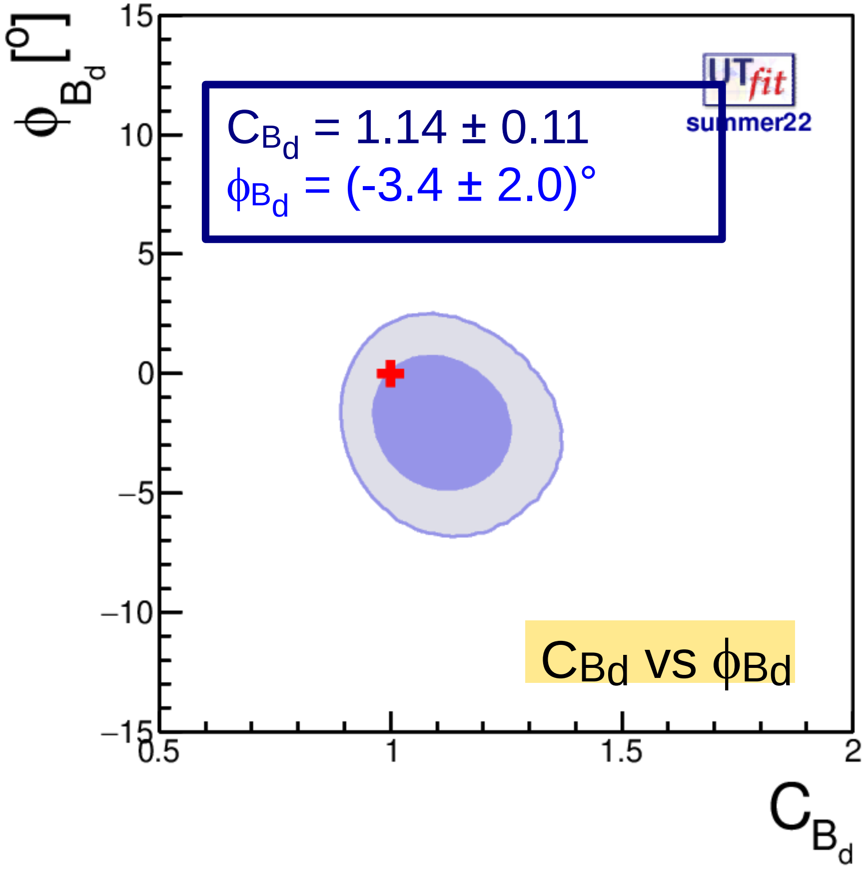
NP parameter results

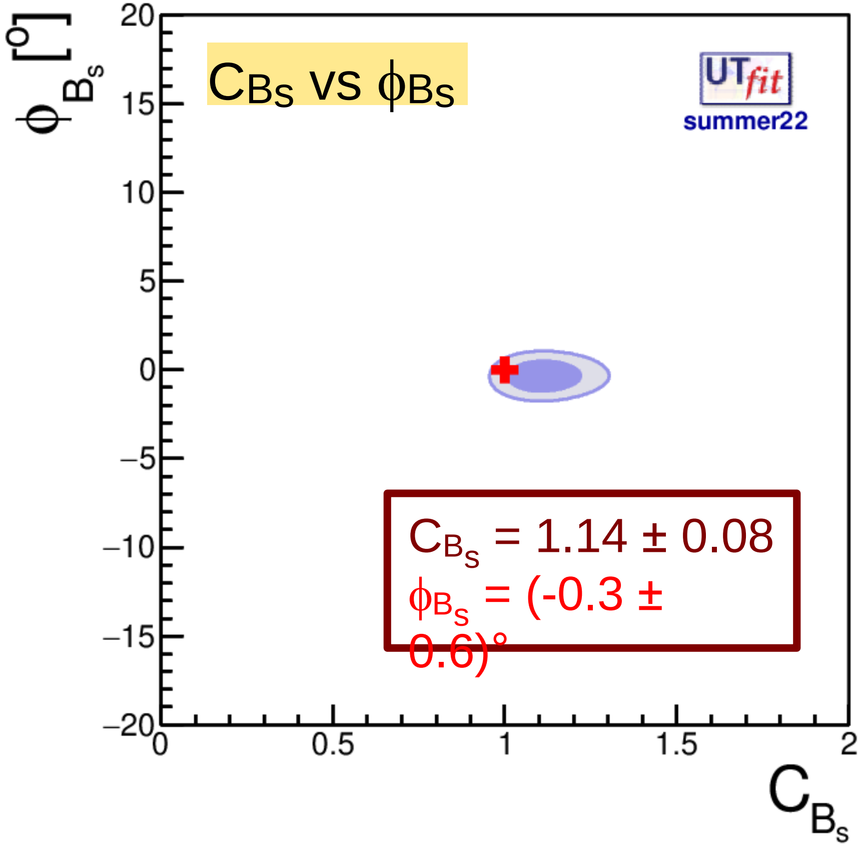
$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

dark: 68%
light: 95%
SM: red cross

K system

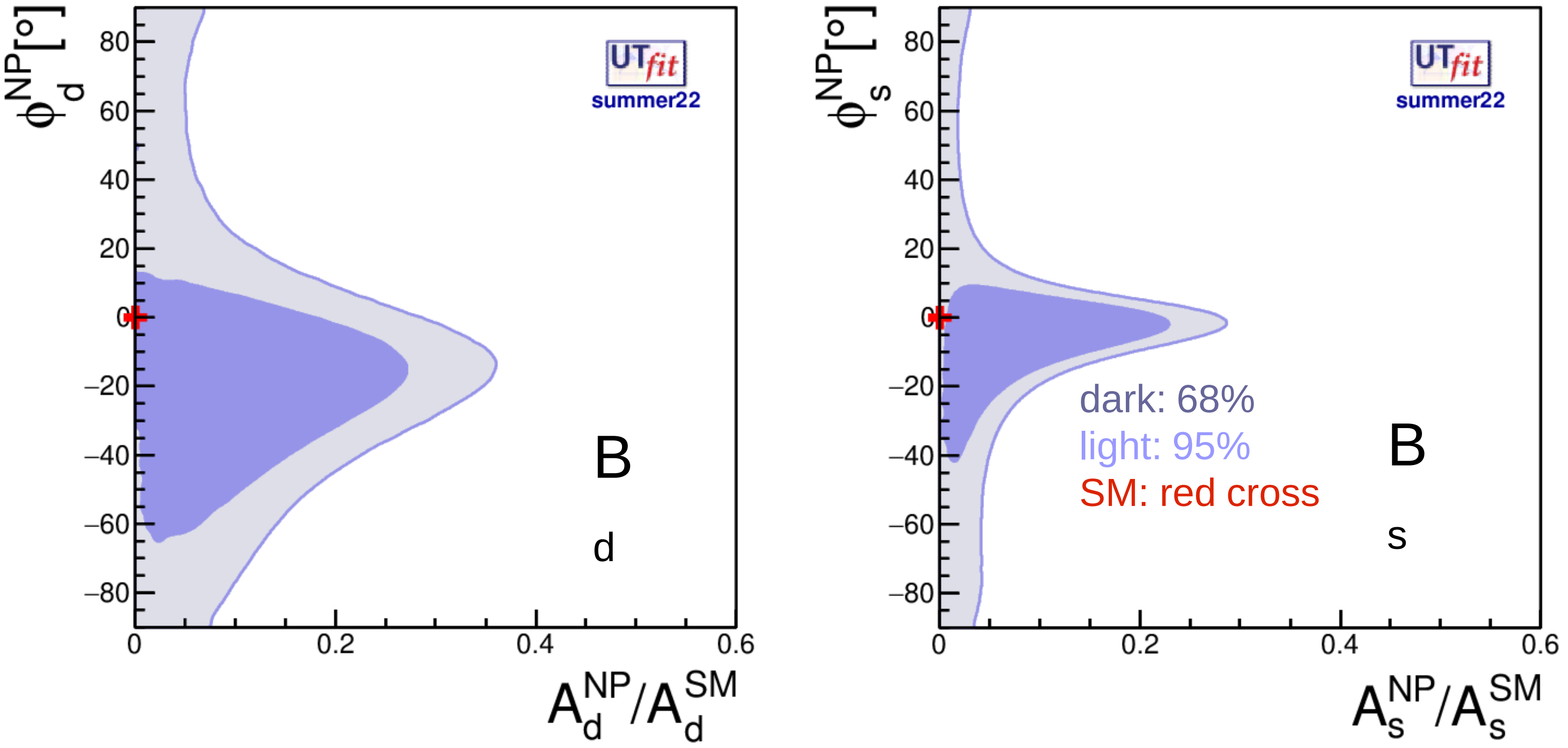
$C_{\epsilon_K} = 1.12 \pm 0.12$





NP parameter results

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP}-\phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

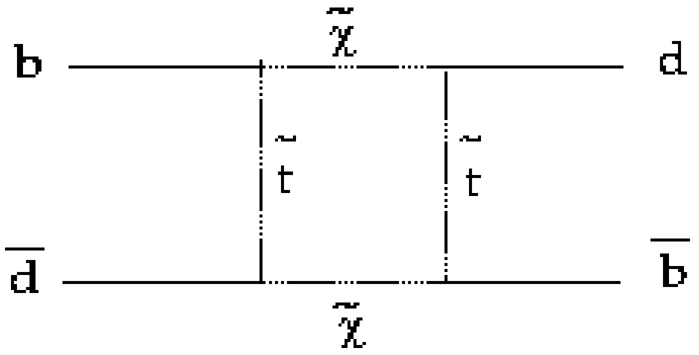


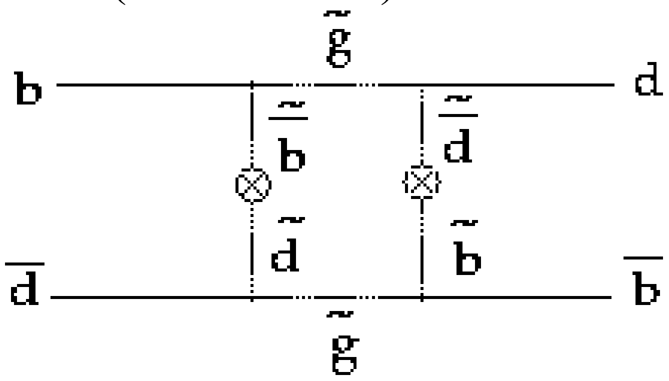
The ratio of NP/SM amplitudes is:

< 25% @68% prob. (35% @95%) in B_d mixing

< 25% @68% prob. (30% @95%) in B_s mixing

Simplify the discussion with one example : B oscillations (FCNC-$\Delta B=2$) :





$$\left|\frac{Q^{NP}_{\Delta B=2}}{Q^{SM}_{\Delta B=2}}\right| \leq r \rightarrow \frac{|\delta_{bq}|}{\Lambda_{eff}} \leq \sqrt{r}\,\frac{|V^*_{tb}V_{tq}|}{M_W}$$

r upper limit of the relative NP contribution

δ_{bd} NP physics coupling

Λ_{eff} NP scale (masses of new particles)

Minimal Flavour Violation

≡ no new sources of flavour and CP violation NP contributions governed by SM Yukawa couplings.

If couplings ~ 1

$\delta_{bq} \sim 1$ $\Lambda_{eff} \sim 10/\sqrt{r}$ TeV

$\delta_{bs} \sim 1$ $\Lambda_{eff} \sim 2/\sqrt{r}$ TeV

→

$$\delta_{q'd} \approx V^*_{tq'}V_{td}$$

(couplings small as CKM elements)

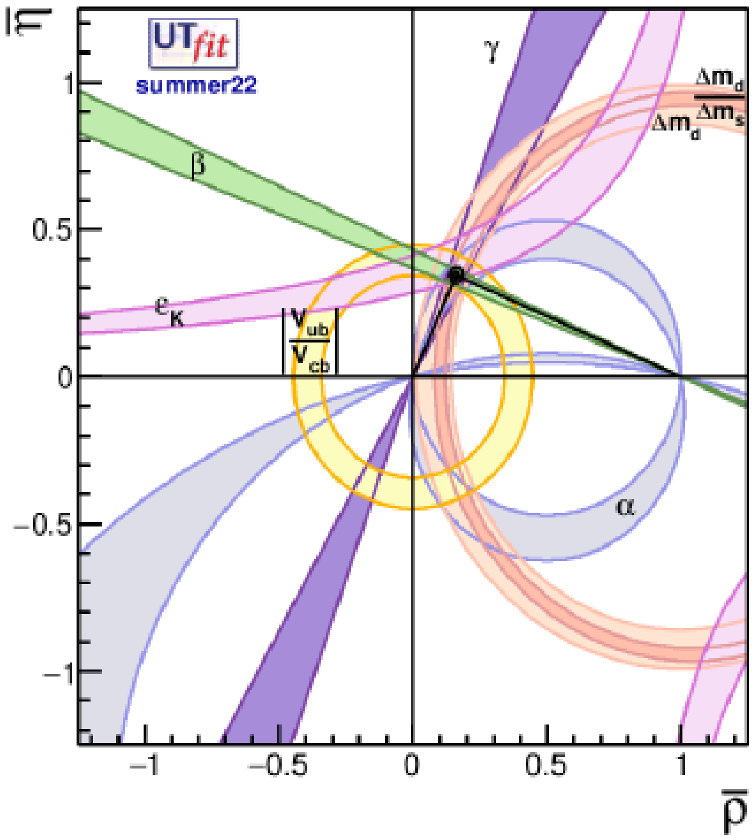
$\Lambda_{eff} \sim 0.08/\sqrt{r}$ TeV

Coupling δ	r=20% today
Order 1	$\Lambda_{eff} \sim 20$ TeV
MFV	$\Lambda_{eff} \sim 180$ GeV

r<0.2 → Λ_{eff} > 180 GeV . Particles below 180 GeV circulating in the loop would have given visible effects within the present level of precision

The test of the SM (in fermion sector)

1990-now → a huge number of precise measurements

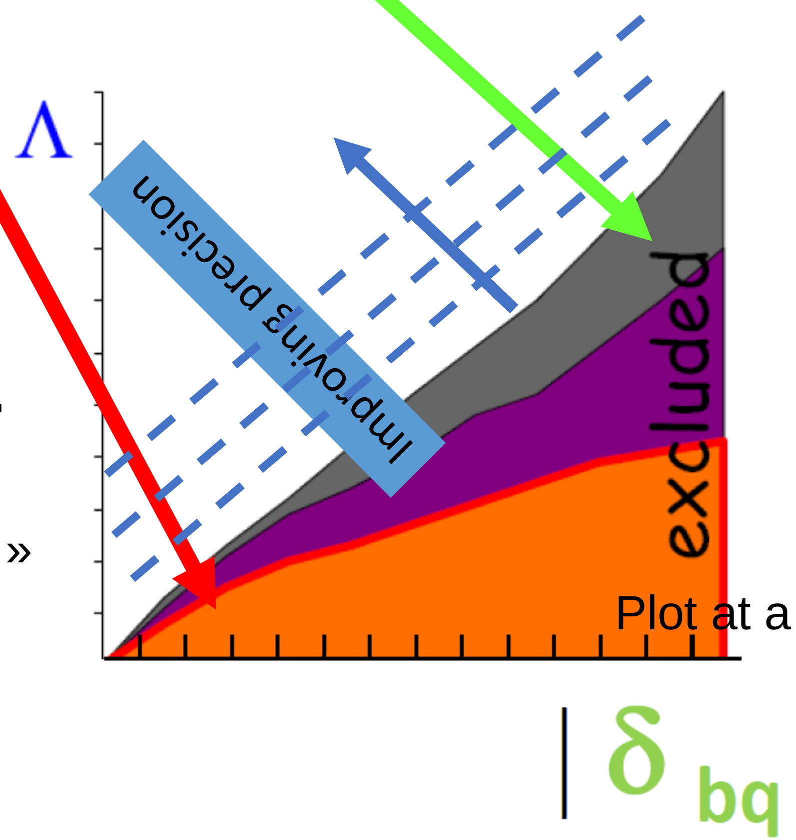


Discovery : absence of New Particles up to the ~2×Electroweak Scale !

….and at much larger scale (>TeV) for some New physics model

1. ~1970 charm quark from FCNC and GIM-mechanism $K^0 \to \mu\mu$
2. ~1973 3rd generation from CP violation in kaon (ε_K) KM-mechanism
3. ~1990 heavy top from B oscillations Δm_B
4. >2010 success of the description of FCNC and CPV in SM

Coupling δ	r=20% today	r=10% tomorrow	r=1% after tomorrow
Order 1	Λ_{eff} ~ 20 TeV	Λ_{eff} ~ 30 TeV	Λ_{eff} ~ 100 TeV
MFV	Λ_{eff} ~ 180 GeV	Λ_{eff} ~ 250 GeV	Λ_{eff} ~ 800 GeV



FLAVOUR PHYSICS IS CENTRAL IN THE NP SEARCH

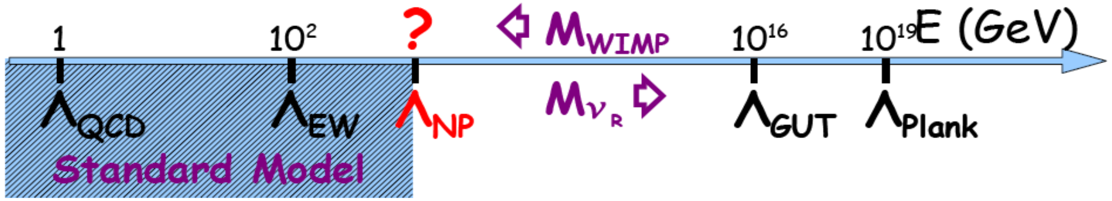
because ALLOW TO« DISCOVER » VERY HEAVY PARTICLE NOT ACCESSIBLE TO DIRECT SEARCH DEPENDING ON COUPLINGS

FLAVOUR PHYSICS IS AN EXPLORATORY PHYSICS !
IT ALLOWS TO EXPLORE SCALE FAR BEYOND THE REACH OF THE DIRECT SEARCH

SPAN FROM ELECTROWEAK SCALE TO SEVERAL TEV (up to 100TEV) !

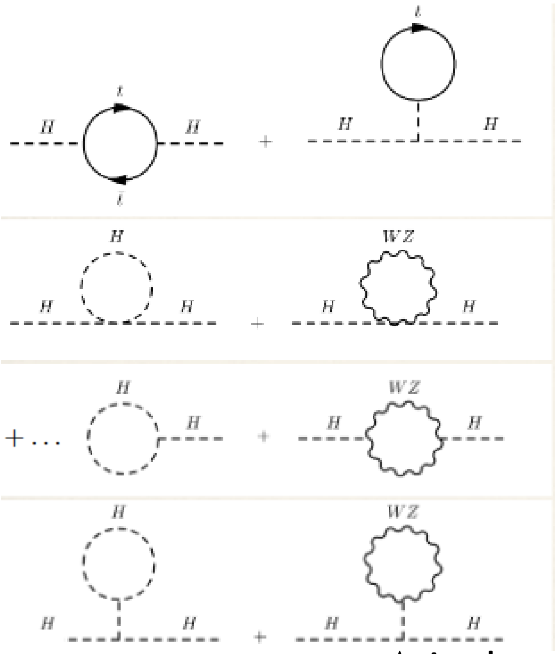
Where do we expect the scale of New Physics??
This IS THE QUESTION (for me) !

Rephrasing : The problem of particle physics today is : where is the NP scale $\Lambda \sim 0.5, 1\ldots10^{16}$ TeV



$$m_H^2 \rightarrow m_{bare}^2 + \delta m_H^2$$

$$M_H^2(p^2) = M_H^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2 + \ldots$$



$$\delta M_H^2 = \frac{G_F \Lambda^2}{4\pi^2\sqrt{2}}(6\,M_W^2 + 3\,M_Z^2 + M_H^2 - 12\,m_t^2) \approx -\frac{3G_F}{\pi^2\sqrt{2}} m_t^2 \Lambda^2 \approx -0.075\,\Lambda^2.$$

The corrections to the **Higgs mass are quadratically divergent*** and <u>Λ is the Energy cut-off to the divergent loop integrals.</u> (*ΔM_H increseas depending of the choosed cut off Λ.)

Λ is the energy scale where we decide to cut off..

Λ Set the scale of the « validity » of the theory

hierarcy problem

Stabilizing the mass $M_H = 125$ GeV requires DELICATE BALANCE of TWO NUMBERS

$\Lambda = 1$ TeV

$M_H^2(p^2) = (125\,\text{GeV})^2 = 1{,}56\,10^4\,\text{GeV}^2 = M_H^2(\Lambda^2) - 7.5\times10^4\,\text{GeV}^2$

$\Lambda = 10$ TeV . . . . $= M_H^2(\Lambda^2) - 7.5\,10^6\,\text{GeV}^2$

This delicate balance become more and more delicate as much as Λ increase ... up to the Planck scale

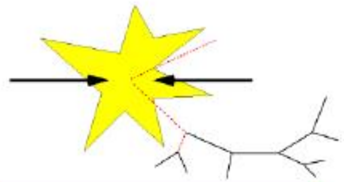
MH(bare) 300 GeV

MH(bare) 2,5 TeV

Another way of saying , **we need new particles in the loop to regularise this divergence**

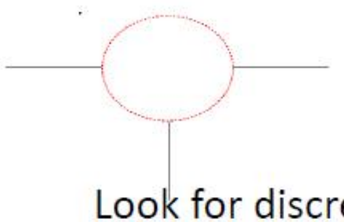
Explore New Energy scales

…Indeed historically we have always followed the two ways…



"Relativistic path"

Crucial : Center-of-mass energy



"Quantum path"

Crucial : Luminosity

Look for discrepancy wrt SM on many different measurements