SEARCHING FOR NEW PHYSICS THROUGH HEAVY FLAVOUR DECAYS

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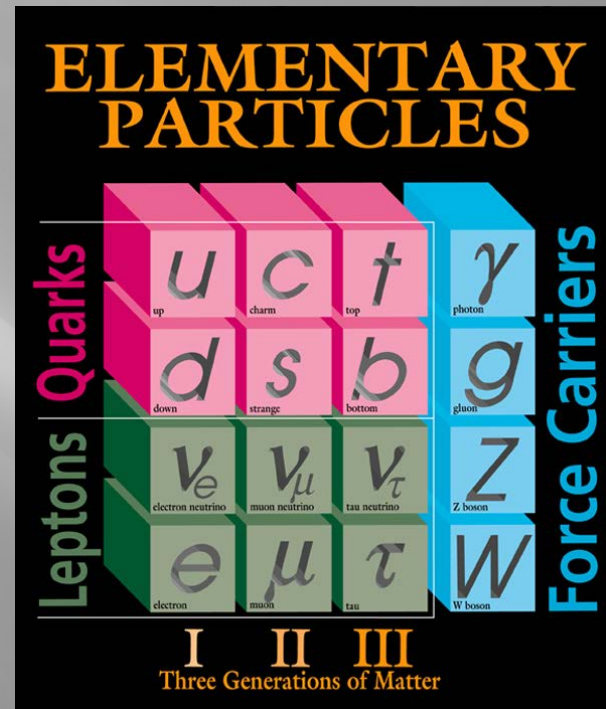Chennai

FLAVOUR

The term Flavour was coined in 1971 by Murray Gell-Mann and Harald Fritzsch

The Fundamental building blocks of matter are the elementary Fermions-quarks and leptons

Physics of Flavour deals with transitions between the 3 generations of the SM fermions.

Parameters of the Standard Model

❖ 3 gauge couplings
❖ 2 Higgs parameters
❖ 6 quark masses
❖ 3 quark mixing angles +1 phase
❖ 3 (+3 ?) lepton masses
❖ (3 lepton mixing angles +1 phase ?)

Flavour Parameters

Aim of the past, ongoing and future Flavour experiments
B factories, Tevatron, LHCb, BELLE II, Neutrino Physics and LFV
experiments is to precisely determine these flavour parameters,
including the CP violating phase(s) and to look for physics beyond the
Standard Model

CP Violation

Arises only when there is a change of flavour

❖ CP is the discrete symmetry which takes a particle to an antiparticle with reversed "charges".

❖ Universe was born with equal amounts of matter and antimatter.
  All evidence indicates that the universe is made up of matter alone.
  One necessary ingredient for this observed baryon asymmetry is CP Violation.

❖ Origin of CP violation not understood.

❖ CP violation is merely parameterized in the SM.

❖ CPV in SM not sufficient to explain the baryon asymmetry.
  ⇒New Physics

❖ CP violation has been observed in K meson and B meson decays. Significant effort in looking for CPV in the neutrino sector.

CPV in Standard Model

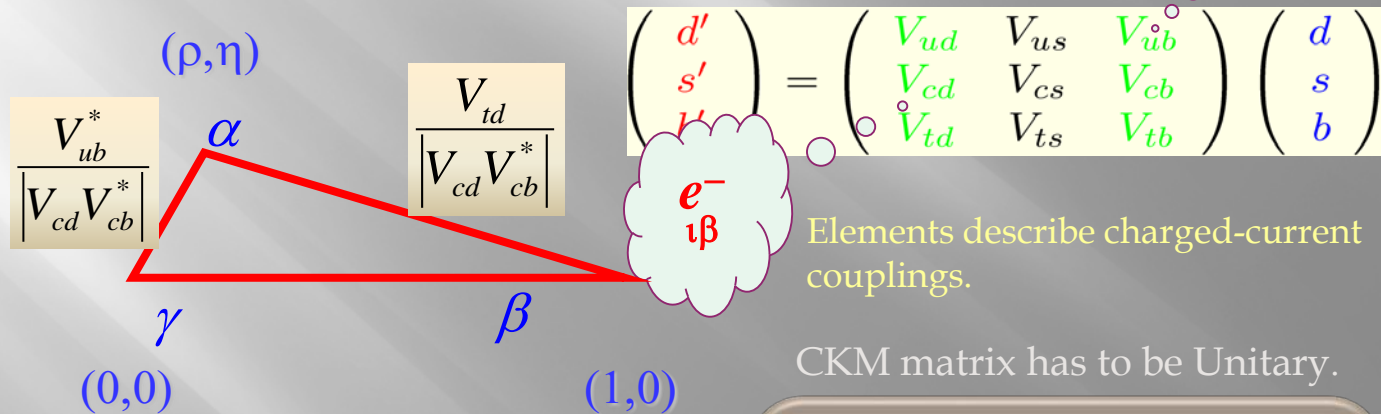$$\mathcal{L}_{SM} = \mathcal{L}_{kinetic} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa}$$

> CPV due to complex Yukawa couplings

CP conserving

CP violating

> Yukawa interactions ⇒ mass terms

> Product of Unitary matrix diagonalizing the mass matrices is the **CKM**

e^-

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

(ρ, η)

$$\dfrac{V_{ub}^*}{\left| V_{cd} V_{cb}^* \right|}$$

α

$$\dfrac{V_{td}}{\left| V_{cd} V_{cb}^* \right|}$$

e^-
ιβ

Elements describe charged-current couplings.

γ β

$(0,0)$ $(1,0)$

CKM matrix has to be Unitary.

$$V_{ud} V_{ub}{}^* + V_{cd} V_{cb}{}^* + V_{td} V_{tb}{}^* = 0$$

"The unitarity triangle (UT)":

"for the discovery of the violations of fundamental symmetry principles in the decay of neutral K-mesons"

1964

Discovered that there is CP violation at the 10^{-3} level in the decays of K_L mesons

1/2 of the prize	1/2 of the prize
USA	USA
University of Chicago Chicago, IL, USA	Prineton University Princeton, NJ, USA
b. 1931	b. 1940
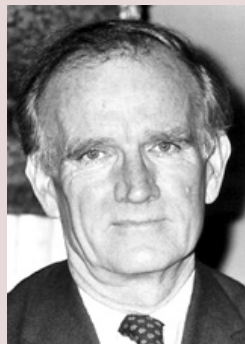
"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

1/4 of the prize

Japan

High Energy Accelerator Research Organization (KEK)
Tsukuba, Japan

b. 1944

1/4 of the prize

Japan

Kyoto Sangyo University; Yukawa Institute for Theoretical Physics (YITP), Kyoto University
Kyoto, Japan

b. 1940

Proposed a new scheme of weak interaction quark couplings.

This scheme requires three families of quarks and permits a CP violating phase in the quark mixing matrix.

At the time only three quarks (u,d and s) were known

Baryon Asymmetry

All evidence indicates that the universe is made up of matter
In the lab. possible to create antimatter-identical to matter, with opposite charges, matter+antimatter, annihilate.
Universe was born with equal amounts of both

Matter and antimatter do not behave identically

1967 Sakharov gave the famous three conditions for generating a baryon number asymmetry in the universe:
(1) Baryon number violation, so that the antibaryon disappears.
(2) CP Violation, since only antibaryon has to disappear.
(3) Departure from thermal equilibrium, otherwise the created asymmetry will disappear.

CKM has a hierarchical structure, in the Wolfenstein parametrization:

$$\mathbf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + A^2\lambda^5(\frac{1}{2} - \rho - i\eta) & 1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8}(1 + 4A^2) & A\lambda^2 \\ A\lambda^3(1 - \bar{\rho} - i\bar{\eta}) & -A\lambda^2 + A\lambda^4(\frac{1}{2} - \rho - i\eta) & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

NP may be of this order

Non zero values of the phases; $\eta \neq 0$ CPV

The B system is an excellent testing ground

B^+ $\bar{B}^0$ B^0 B_s B_c^+

$\bar{b}$ u b $\bar{d}$ $\bar{b}$ d b s $\bar{b}$ c
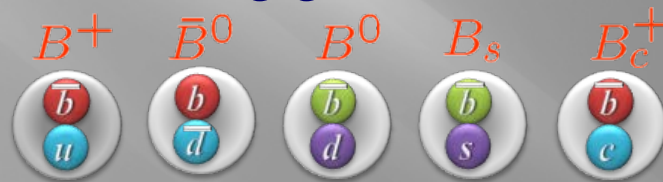
Hence, there was a huge worldwide effort to measure CPV in B mesons.

Decays rare-require large number of B mesons – B-factories

N≥ 3 Required for CPV

General N×N matrix $2N^2$ parameters

Unitarity N^2 conditions

Phases that may be absorbed
by rephasing the quark fields $2N-1$
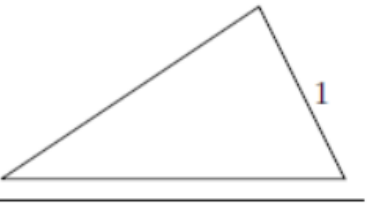
Free parameters $(N-1)^2$

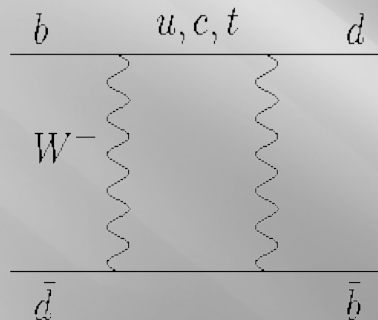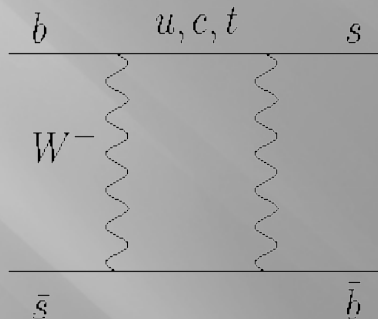| ij	$\sum V_{ik}V_{jk}^* = 0$	$\sim \epsilon^n$	shape (normalized to unit base)
12	$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$	$\epsilon + \epsilon + \epsilon^5 = 0$	ϵ^4
23	$V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0$	$\epsilon^4 + \epsilon^2 + \epsilon^2 = 0$	ϵ^2
13	$V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0$	$\epsilon^3 + \epsilon^3 + \epsilon^3 = 0$	1

Neutral Meson Mixing

$$K - \overline{K}$$
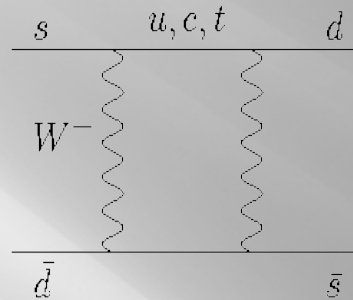
t: $(V_{ts}V^*_{td})^2 \sim \lambda^{10}, \quad m_t^2$
c: $(V_{cs}V^*_{cd})^2 \sim \lambda^2, \quad m_c^2$
u: $(V_{us}V^*_{ud})^2 \sim \lambda^2, \quad m_u^2$
c dominates

$$B - \overline{B}$$

t: $(V_{tb}V^*_{td})^2 \sim \lambda^6, \quad m_t^2$
c: $(V_{cb}V^*_{cd})^2 \sim \lambda^6, \quad m_c^2$
u: $(V_{usb}V^*_{ud})^2 \sim \lambda^6, \quad m_u^2$
top dominates

$$B_s - \overline{B_s}$$

t: $(V_{tb}V^*_{ts})^2 \sim \lambda^4, \quad m_t^2$
c: $(V_{cb}V^*_{cs})^2 \sim \lambda^4, \quad m_c^2$
u: $(V_{ub}V^*_{us})^2 \sim \lambda^8, \quad m_u^2$

Mixing in B Mesons

Within SM, $B_q - \overline{B}_q$ mixing induced through box diagrams.

Time evolution of any linear combination of the neutral meson flavor eigenstates $a|B^0\rangle + b|\overline{B^0}\rangle$ governed by the Schrodinger equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix} a \\ b \end{pmatrix} = (\mathbf{H})\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M_{22} - i\frac{\Gamma_{22}}{2} \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix}$$

where $M_{11}=M_{22}$, $\Gamma_{11}=\Gamma_{22}$ - CPT invariance.
M_{12}, $M_{21}=M_{12}^*$ -- due to 2nd order transitions via virtual states
Γ_{12}, $\Gamma_{21}=\Gamma_{12}^*$ -- on-shell intermediate states

The eigenstates of the Hamiltonian are given by:

$$|B_\pm\rangle = \frac{1}{\sqrt{|p|^2+|q|^2}}\left[p\,|B^0\rangle \pm q\,|\bar{B}^0\rangle \right]$$

where,

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - i\frac{\Gamma_{12}^*}{2}}{M_{12} - i\frac{\Gamma_{12}}{2}}}$$

The eigenvalues are, $\mu_\pm = H_{11} \pm \sqrt{H_{12}H_{21}} = M_\pm - i\dfrac{\Gamma_\pm}{2}$ with

$$M_\pm = M_{11} \pm \mathrm{Re}(H_{12}H_{21})^{1/2}, \quad \Gamma_\pm = \Gamma_{11} \mp \mathrm{Im}(H_{12}H_{21})^{1/2} .$$

Eigenstates of the Hamiltonian evolve as $B_\pm(t) = B_\pm e^{-i\mu_\pm t}$

the time evolution of the $|B^0\rangle$ and $|\bar{B}^0\rangle$ states can therefore be

$$\begin{aligned}
|B^0(t)\rangle &= g_+(t)|B^0\rangle + \frac{q}{p}\, g_-(t)|\bar{B}^0\rangle \\
|\bar{B}^0(t)\rangle &= \frac{p}{q}\, g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle ,
\end{aligned}$$

where,

with,

Measurements?

Side Measurements

Angle Measurements?

Phases are elusive, only relative phases are observable, through interference terms in modes to which two different amplitudes, with distinct phases contribute

The different ways in which interference terms appear, result in the following categories of CP violation.

$$\left|\frac{q}{p}\right| \neq 1 \qquad \text{CP violation in mixing}$$

$$\left|\frac{\overline{A}}{A}\right| \neq 1 \qquad \text{CP violation in decay (direct CPV)}$$

$$\Im\left(\frac{q}{p}\frac{\overline{A}}{A}\right) \neq 0 \qquad \text{CP violation in interference between mixing and decay}$$

For a decay amplitude with 2 or more weak contributions,

$$A = A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2}$$
$$\bar{A} = A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2}$$

$$A_{CP} = \frac{-2 A_1 A_2 \sin(\Delta\phi) \sin(\Delta\delta)}{A_1^2 + A_2^2 + 2 A_1 A_2 \cos(\Delta\phi) \cos(\Delta\delta)}$$

- The angle γ, phase of the V_{ub} element of the CKM matrix--was one of the most difficult to measure.
- γ cannot be measured using time dependent techniques
- Other methods developed:
---DK Methods, interference of b   c and b   u trees, CLEAN
---Kπ Methods, interference of b   u tree and b   s penguin

Tree is Cabibbo suppressed, Penguin contributions, including Electroweak Penguins cannot be neglected
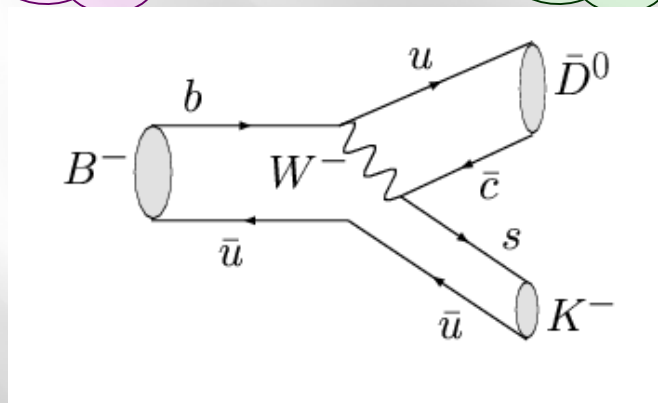Size of the tree and penguin unknown   hadronic uncertainties

Need to look for decay modes with two weak amplitude contributions:
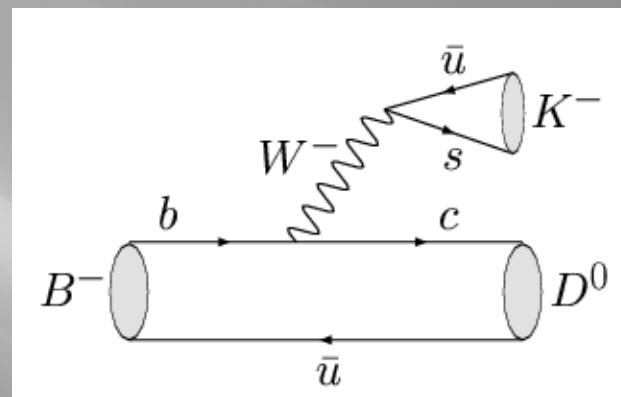
$$ae^{i\delta_a}e^{i\phi_3} + be^{i\delta_b},$$

b! u

b c

No final state with 2 such tree

contributions--BUT

color suppressed , $B^- \to \bar{D}^0 K^-$
$\sim V_{ub}V_{cs} \sim A\,\lambda^3(\rho + i\,\eta)$

color suppressed , $B^- \to D^0 K^-$
$\sim V_{cb}V_{us} \sim A\,\lambda^3$

Among the DK methods, there is GLW, ADS, SS
Attention has been paid to the GGSZ, using Daltz plot analysis
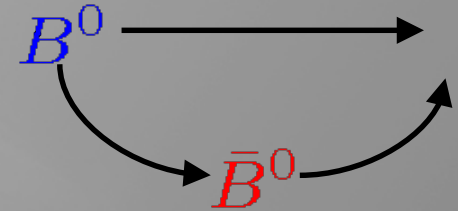
Final states f into which both B^0 and $\bar{B}^0$ can decay
have interfering amplitudes from:

B^0

$\bar{B}^0$

Similarly for other neutral mesons

The time dependent decay rate has the form,

$$\Gamma(B^0(t) \to f) =$$

$$e^{-\Gamma t}\left[\frac{|A|^2 + |\bar{A}|^2}{2} - \frac{|\bar{A}|^2 - |A|^2}{2}\cos(\Delta M t) - \mathrm{Im}\left(\frac{q}{p}\frac{\bar{A}}{A}\right)\sin(\Delta M t)\right]$$
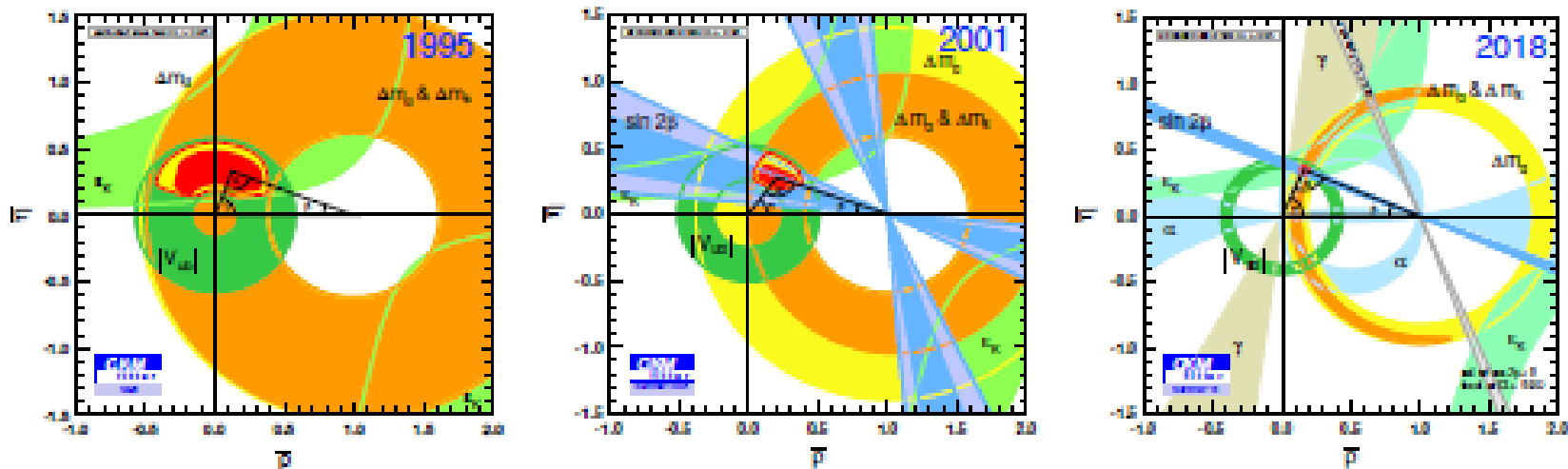
(for modes with

Fig. 5: The evolution of the constraints in the standard CKM unitarity triangle plane from 1995 (left), to just after the start of B factories (middle), to the present (right). Taken from the ckmfitter website [18].

All measurements result in a consistent picture indicating the KM mechanism as the dominant source of CPV.

SM has been extremely successful.

There are many unresolved questions

Why a problem?

➤ Why are there 3 generations ?

➤ What determines the patterns of the masses and mixings of quarks and leptons?

➤ CP Violation:Matter-Antimatter asymmetry of the Universe

➤ The Hierarchy Problem

➤ How to include Gravity?

➤ What is dark matter/dark energy?

⇒there must be Physics beyond the SM.

Most rare decay modes are Flavour changing neutral current Processes (FCNC). Not allowed at the tree level in SM appear at loop level.

Direct---Energy frontier
Indirect—Intensity frontier
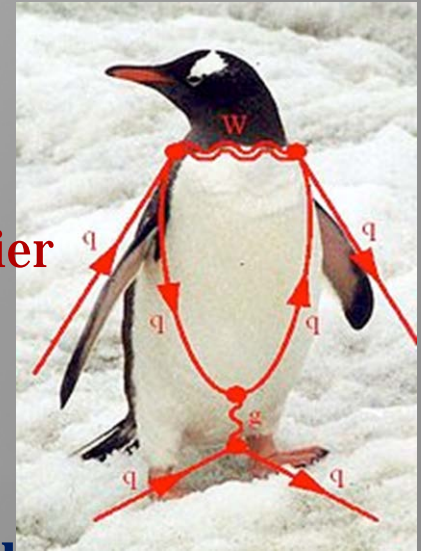
In presence of NP, new particles will appear in the virtual loops. Measurement of these rare decays could help constrain the NP

Flavour physics can have sensitivity to exchange of particles with masses in muti-TeV range *or* beyond
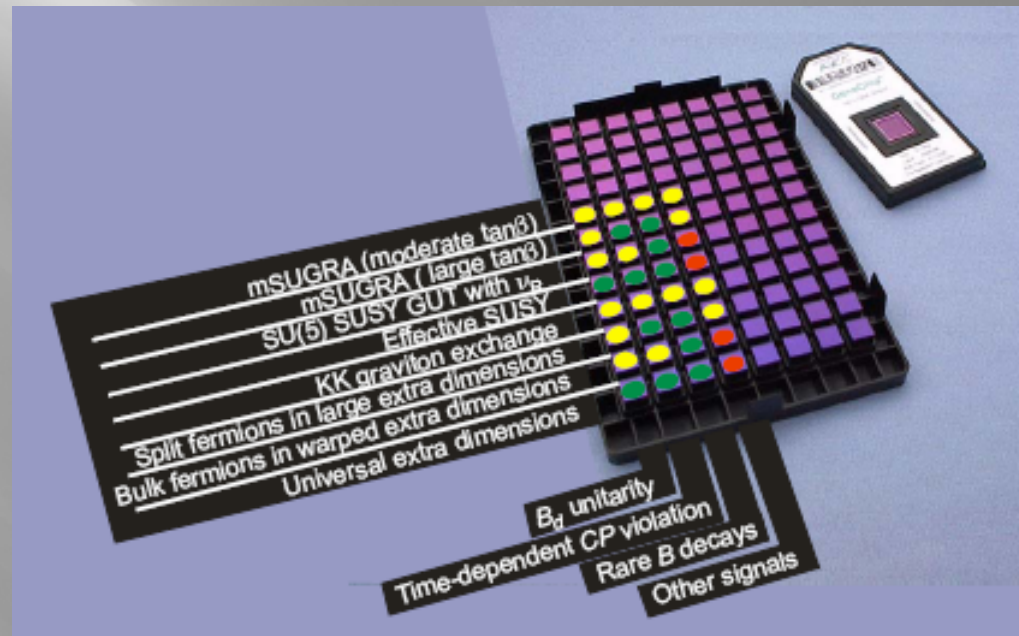**Can possibly put non-trivial constraints on NP Lagrangian**

B advantage is that many modes—allowing broad range of NP options. Current data –10% accuracy-----in this decade—1%---accessabile NP scale –multi-TeV
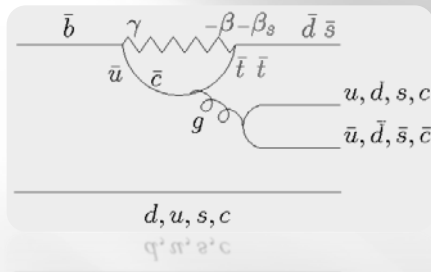
B, D and K mesons also decay though loop diagrams. If New Physics exists it can contribute to these rare decays through virtual contribution to the loops — very useful for probing new phenomena without directly producing the heavier particles at very high energies.
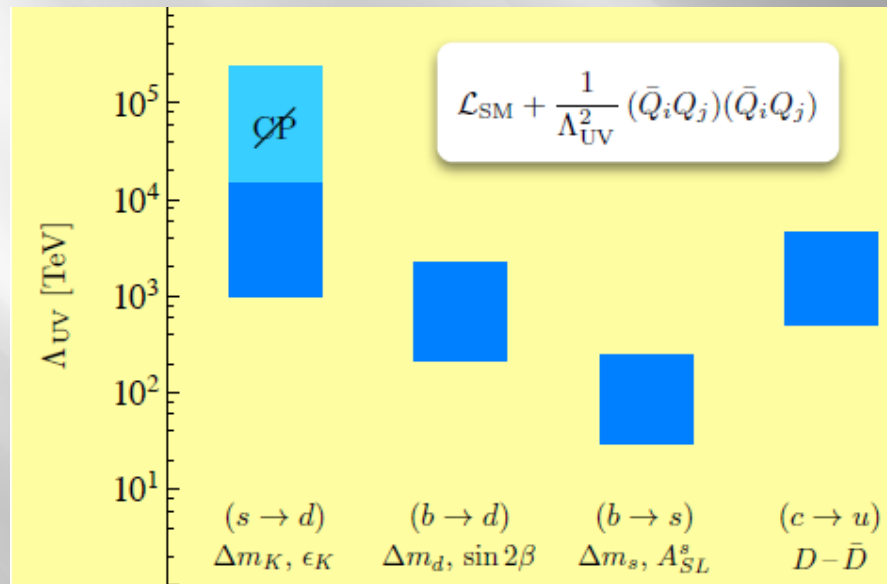
Such Precision measurements will be possible at the upcoming SuperBelle, Superflavour factory or at LHCb

Such decays have put strong constraints on various models of New Physics

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Sigma \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^d (\text{SM fields})$$

FCNC and CPV rates are generally smallest in the Kaon system.

In principle all of the suppression mechanisms Of the SM can be absent in BSM scenarios, so that large deviations can be predicted.

However such large deviations have not been observed ! ⇒

NP must also involve some kind of suppression of FCNC effects, or can arise only at very high scales

$$\mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{UV}}^2} (\bar{Q}_i Q_j)(\bar{Q}_i Q_j)$$

Thank you