Searching for new physics with heavy flavor decays

Dan Pirjol

Second Magurele School of Physics, 22-23.10.2009

Physical laws must be derived from few simple, general principles

Symmetries - gauge invariance

- discrete symmetries (P,C,T)
- supersymmetry, etc.

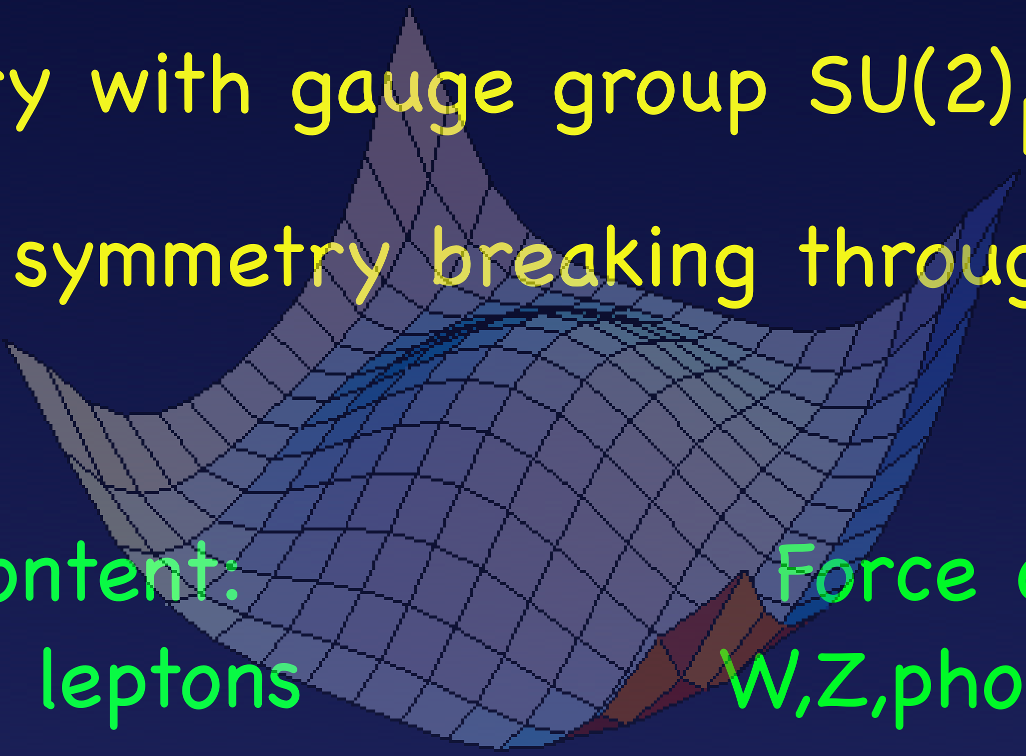
Simplicity, mathematical elegance

‘Physical laws must have mathematical beauty’
(Dirac)

Naturalness (no fine tuning)

The Standard Model

Weinberg, Glashow, Salam



Gauge theory with gauge group $SU(2)_L \times U(1)_Y \times SU(3)$

Electroweak symmetry breaking through the Higgs mechanism

Matter content:
quarks and leptons

Force carriers:
W,Z,photon,gluons

Extremely successful - confirmed over a very wide range of energies

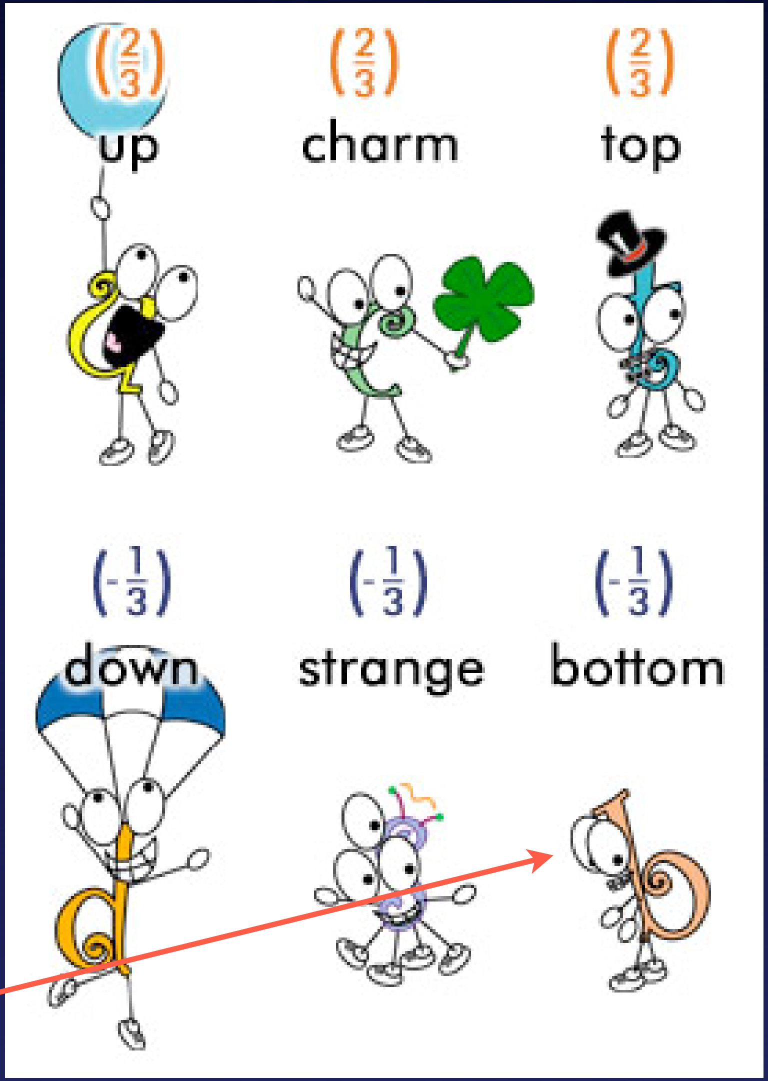
Quarks

3 generations of quarks and leptons

Only one generation encountered in ordinary matter: (u,d)

Two other generations of heavier, fast decaying quarks

b-quark: the main character



Outline

- The fundamental P,C,T symmetries
- Exploring the flavor structure of the Standard model
- Survey of new physics models
- Example: searching for NP in $\Delta S = 2$ decays

Browder,Gershon,DP,Soni,Zupan - Searching for New Physics at a Super-B Factory, arXiv:0802.3201

DP, Zupan - arXiv:0908.3150

Discrete symmetries

The ‘mirror’ transformations play a special role in the Standard Model

P = parity transformation $\vec{x} \rightarrow -\vec{x}$

C = charge conjugation exchange particles & antiparticles

T = time reversal $t \rightarrow -t$

Any symmetry has an associated unobservable quantity

P : no absolute right-handed coordinate system

C : no absolute sign of electric charge

T: no absolute direction of time

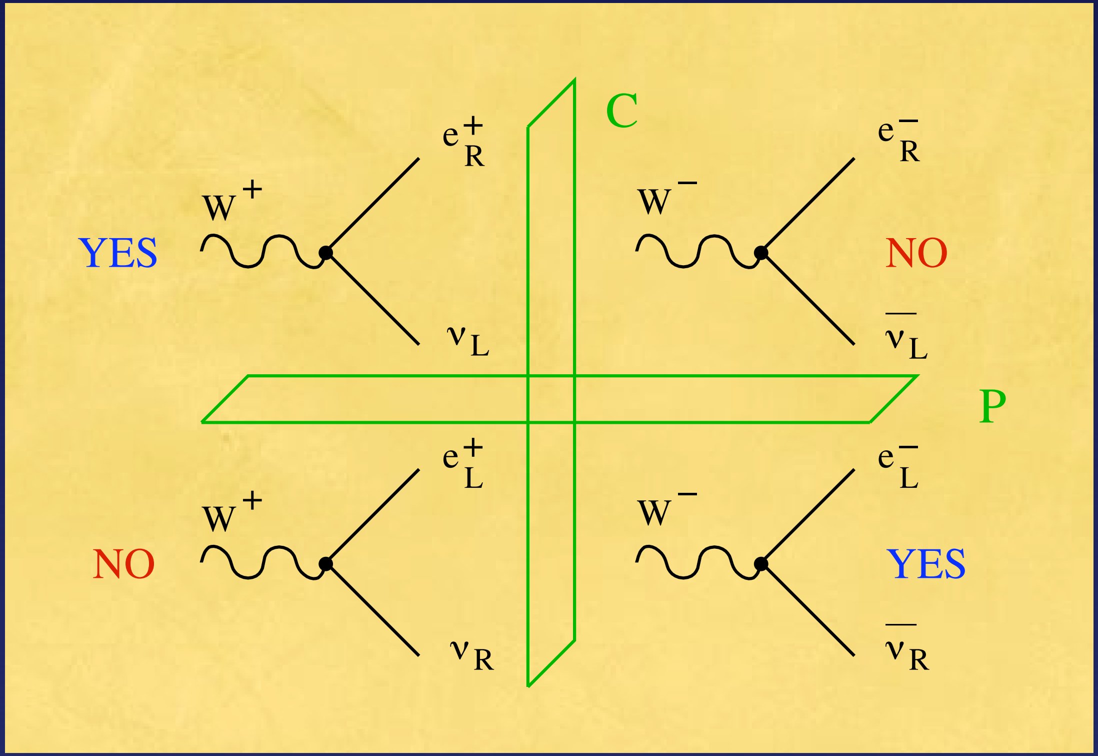
Parity violation

In 1956 Lee and Yang proposed, and in 1957 Wu and others showed experimentally, that Nature is not invariant under the parity transformation

Most interactions (electromagnetism and strong forces) are invariant, but weak interactions violate parity

In the SM, P and C are both violated...

...but CP appeared to be conserved



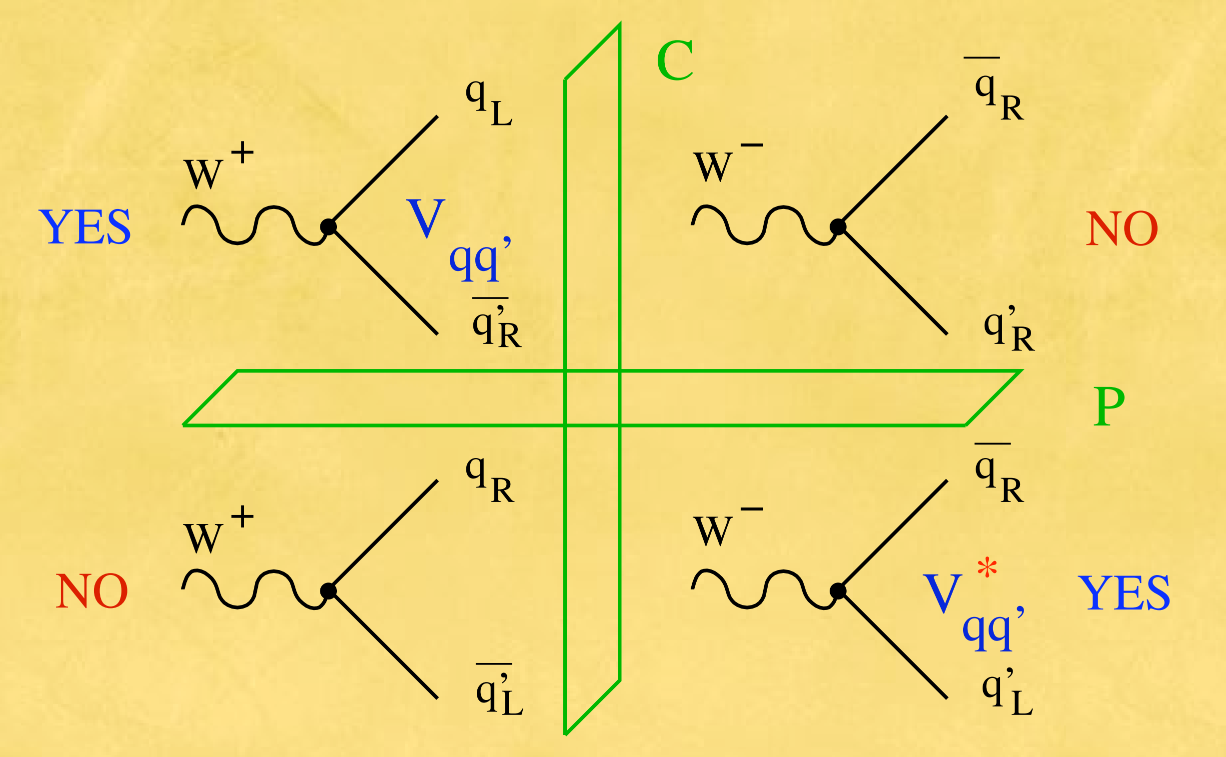
CP violation

In 1964 Cronin, Fitch and others found that also CP symmetry is violated in weak decays of neutral kaons

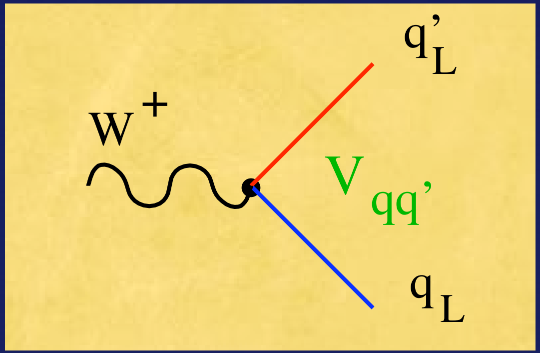
In the Standard Model, CP violation can be accomodated in the weak couplings of the quarks

Requires complex couplings

$$\boxed{V_{qq'} \neq V^*_{qq'}}$$



Weak couplings in the Standard Model



P, C, CP violating

The weak interactions connect u-type and d-type quarks: the Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \Rightarrow \begin{pmatrix} V_{ud} & V_{us} & \enclose{circle}{V_{ub}} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM matrix

- The CKM matrix has a hierarchical structure – interfamily couplings suppressed

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 0.975 & 0.221 & 0.003 \\ 0.221 & 0.975 & 0.040 \\ 0.005 & 0.040 & 1.000 \end{pmatrix}$$

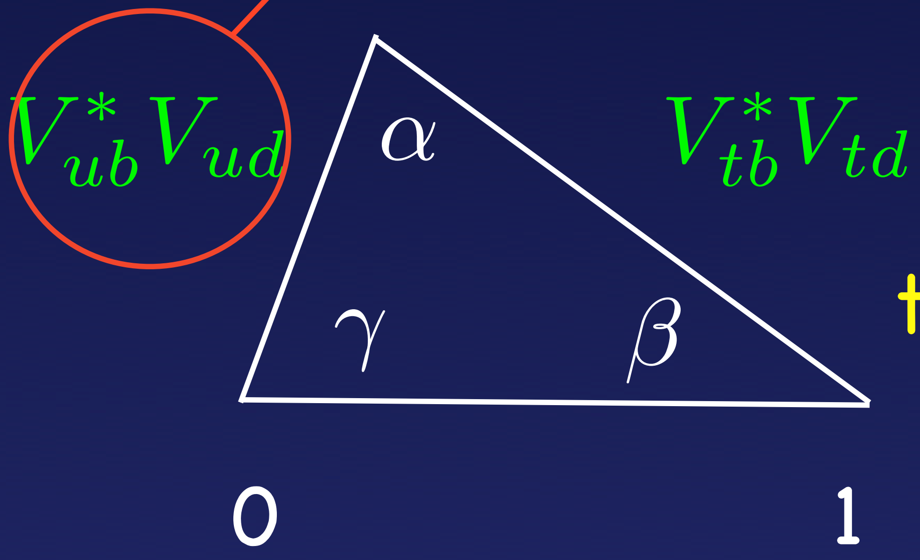
(absolute values)

- In 1973 Kobayashi and Maskawa showed that the Standard Model with 3 families naturally contains CP violation – complex couplings
- The complex couplings are V(td), V(ub) – smallest entries

Experimental information about the smallest entries can be summarized by representing the unitarity relation

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

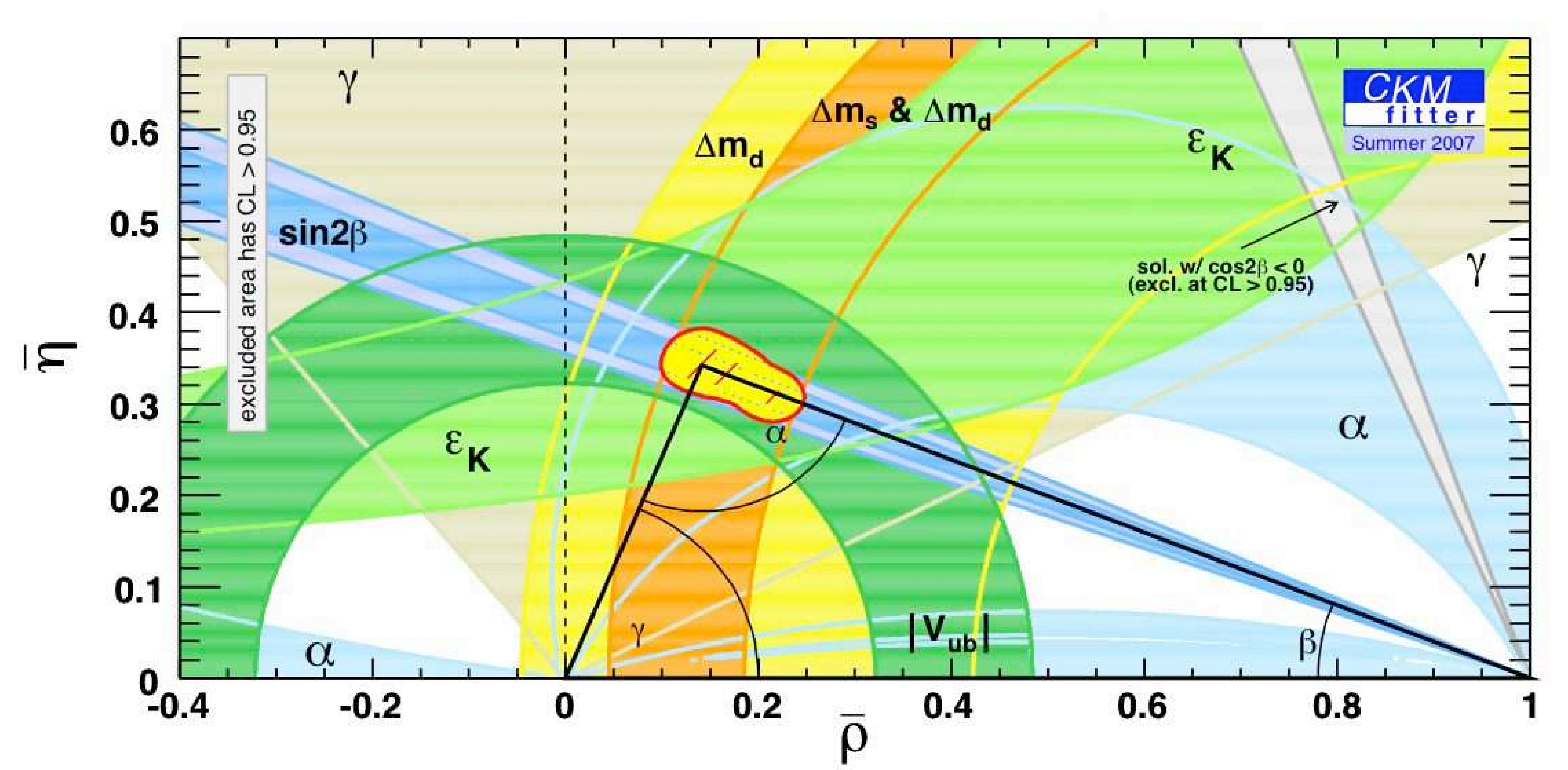
as a triangle in the complex plane (unitarity triangle)



Determining the unitarity triangle is one of the central goals of the current experimental program in flavor physics

Experimental constraints on the UT

CKMfitter



Why B physics?

What is a B?

Bound states of a b and a light antiquark - heaviest stable bound states

Best testing ground for CP violation

CP violation shows up also in kaon physics but the effect is small and fraught with theoretical uncertainties

CP violation in B decays is O(1) and has a clear interpretation in terms of fundamental parameters

Lots of data from the B factories

Asymmetric-energy e+e- storage rings, produced $\sim 1.7 \times 10^8 \Upsilon(4S)$

TM & © Nelvana

SLAC

450 fb^{-1}

KEK - Japan

800 fb^{-1}

Complement B programs at hadronic machines (CDF)

More to come: LHCb, super-B (?)

Significance of CP violation

CP-violating processes provide an absolute distinction between matter and antimatter

Example: CP-violating asymmetry in $K_L \rightarrow \pi^{\pm} e^{\mp} \nu$

The K_L decays slightly more often (0.33%) into final states containing an e^+ than into states containing e^-

CP violation is required for baryogenesis: the process which generated the observed matter-antimatter asymmetry in the Universe

Connection linking particle physics with cosmology

Sakharov criteria

1. CP violation
2. Baryon # violation
3. Nonequilibrium

The Standard Model
satisfies the conditions
for baryogenesis

-CP violation in the quark and lepton sector

Not enough CP violation in the SM to explain data!

New physics must be present!

Beyond the SM

- There are many other reasons to believe that the SM can't be the whole story
- It contains no explanation for the particular hierarchy of the weak couplings and quark masses observed in nature
- Why 3 generations?
- The hierarchy problem

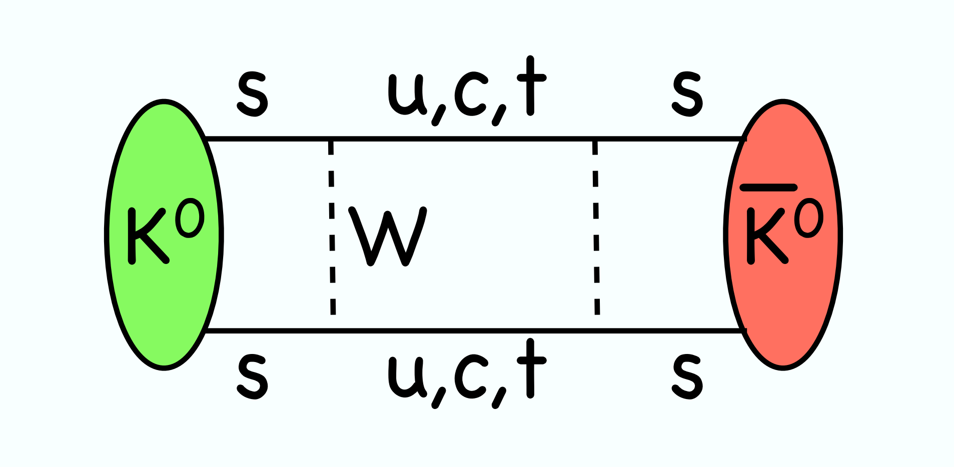
These questions are deeply connected to flavor physics

New physics and FCNC processes

In the SM, FCNC processes (flavor-changing neutral currents) are suppressed by the GIM mechanism

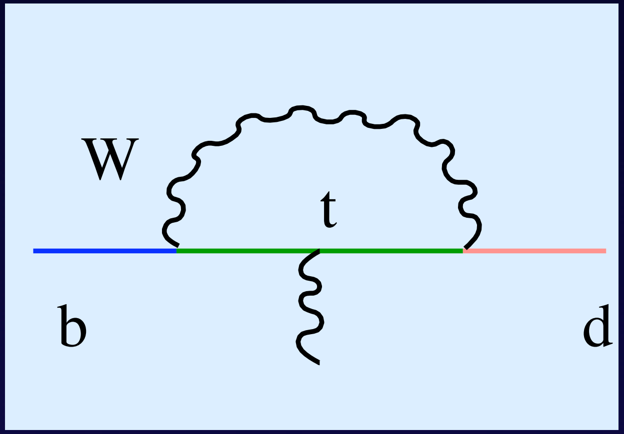
Forbidden at tree level; one-loop effects

Example: K-K mixing



Radiative $b \rightarrow s\gamma$ decays

In the Standard Model, they are mediated by electroweak penguin diagrams with internal top quarks



Sensitive to new physics particles running in the loop e.g. SUSY: charged higgs

One of the most important observables for testing the Standard Model

Any realistic model of NP must suppress FCNC (the flavor problem)

- Two-Higgs doublet models
- Minimal flavor violation (MFV)
- SUSY - the MSSM
- Extra dimensions

Two-Higgs doublet models

Extension of the SM containing two Higgs doublets

$$\mathcal{L} = \bar{Q}_i f_{ij}^{(D)} H_D D_j + \bar{Q}_i f_{ij}^{(U)} \tilde{H}_D U_j \\ +\bar{Q}_i g_{ij}^{(U)} H_U U_j + \bar{Q}_i g_{ij}^{(D)} \tilde{H}_U D_j + \mathrm{h.c.}$$

$$Q_i = (u_L, d_L)_i \qquad U_i = u_{R,i} \qquad D_i = d_{R,i}$$

FCNC absent if each Higgs doublet couples only to one quark doublet

Glashow, Weinberg

Type-I 2HDM $g_{ij}^{(U)} = g_{ij}^{(D)} = 0$ or $f_{ij}^{(U)} = f_{ij}^{(D)} = 0$

Type-II 2HDM $f_{ij}^{(U)} = g_{ij}^{(D)} = 0$

The electroweak symmetry is broken by Higgs vevs

$$\langle H_U \rangle = \left(\begin{array}{c} \frac{1}{\sqrt{2}} v_1 \\ 0 \end{array} \right) \qquad \langle H_D \rangle = \left(\begin{array}{c} 0 \\ \frac{1}{\sqrt{2}} v_2 \end{array} \right)$$

Quark masses are proportional to the vev's

$$m_{U,i} \propto v_1 \; , \qquad m_{D,i} \propto v_2$$

Natural explanation of the hierarchy of quark masses $m_t/m_b \sim 35$ in terms of a large ratio of the vevs $v_1/v_2 \equiv \tan\beta \gg 1$

Flavor violation: also present in charged Higgs couplings to quarks $V_{ij} H^+ U_i D_j$

Same CKM matrix as in the weak sector V_{ij}

Minimal Flavor Violation

The Standard Model has a large global symmetry group, broken only by the Yukawa couplings Y_U, Y_D

$$G_F = U(3)_Q \times U(3)_{U_R} \times U(3)_{D_R} \times U(3)_{L_L} \times U(3)_{E_R}$$

Under G_F, the quark fields transform as

$$Q_L \to U_L Q_L \,, \quad u_R \to U_U u_R \,, d_R \to U_D d_R$$

Promoting the Yukawas to fields (spurions) transforming as $Y_U \to U_L Y_U U_U^\dagger \,, \quad Y_D \to U_L Y_D U_D^\dagger$

the symmetry is restored

$$\mathcal{L}_Y = \bar{Q}_L \hat{Y}_D H D_R + \bar{Q}_L \hat{Y}_U \tilde{H} U_R + \text{ h.c.}$$ = invariant

Generalization of the GIM mechanism

Constructing NP operators invariant under G_F ensures that the FCNC effects are suppressed by $m_q/v \ll 1$ (except for top quark mass effects)

The only source of flavor violation in MFV is the CKM matrix of the SM

Building blocks: quark bilinears

$$\bar{Q}_L Y_U Y_U^\dagger Q_L\,, \quad \bar{d}_R Y_D^\dagger (Y_U Y_U^\dagger) Q_L\,, \quad \bar{d}_R Y_D^\dagger (Y_U Y_U^\dagger) Y_D d_R$$

Dim.-6 MFV operators

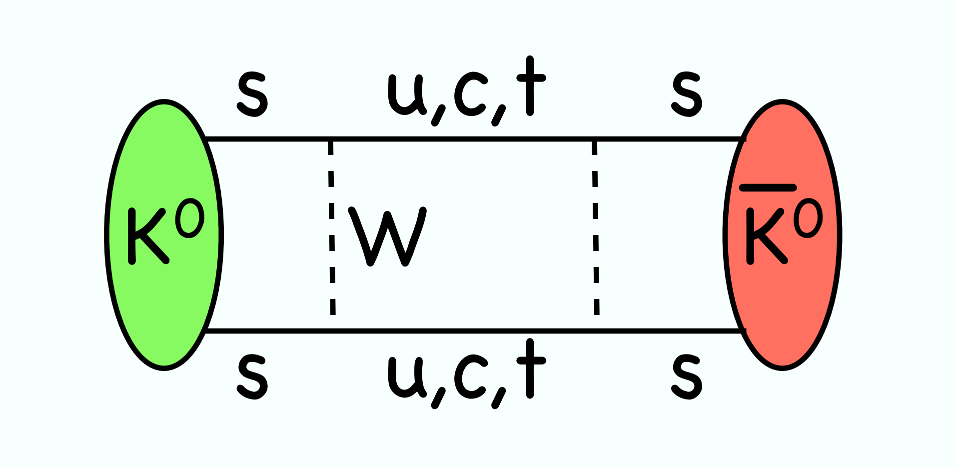
Complete list of dim-6 operators in MFV NP

d'Ambrosio, Giudice, Isidori, Strumia

Minimally flavour violating dimension six operator	main observables	Λ [TeV]		
		$-$	$+$	
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)^2$	$\epsilon_K, \quad \Delta m_{B_d}$	6.4	5.0	
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4	
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5	
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7	$*$
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0	$*$
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6	$*$
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi, \quad \epsilon'/\epsilon, \ldots$	~ 1		

Example: neutral meson mixing

NP can contribute to $K^0 - \bar{K}^0 \,, B_d - \bar{B}_d \,, B_s - \bar{B}_s$ mixing through new particles in the box graph



In MFV these contributions are very constrained: a single possible operator

$$\mathcal{L}_{\Delta F=2} = \frac{c}{\Lambda^2_{MFV}} (\bar{Q}_L Y_U Y_U^\dagger Q_L)^2$$

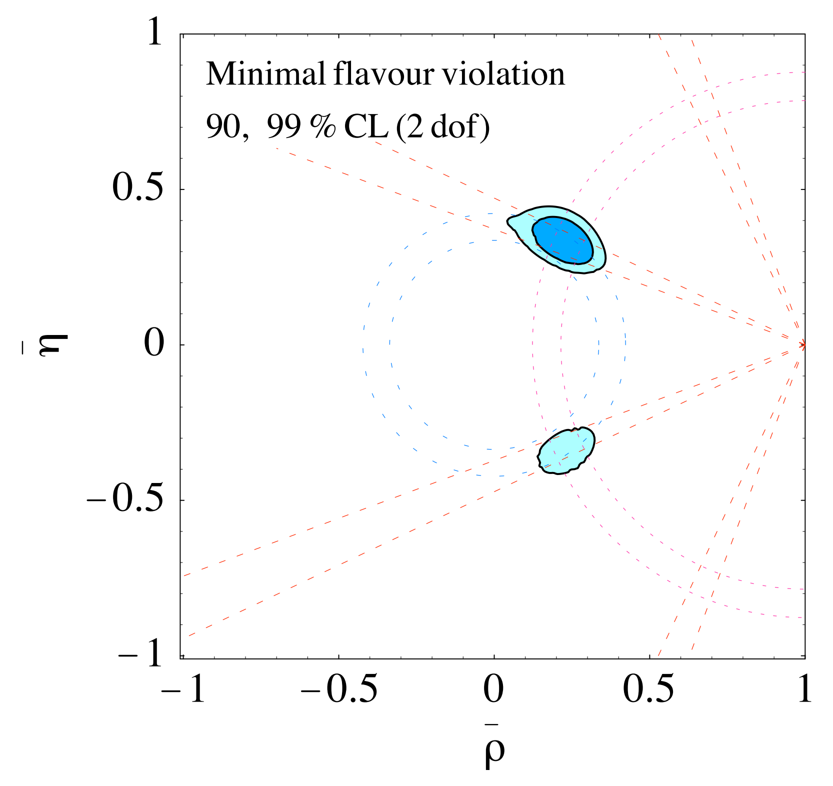
Correlations between NP effects in different $\Delta F = 2$ processes: very constraining

Global fit to $\Delta F = 2$ data UT Fit: arXiv:0707.0636

$$\Lambda_{MFV} > 5.5\ \mathrm{TeV}$$

MFV UT fit including $\Delta F = 2$ data

d'Ambrosio, Giudice, Isidori, Strumia

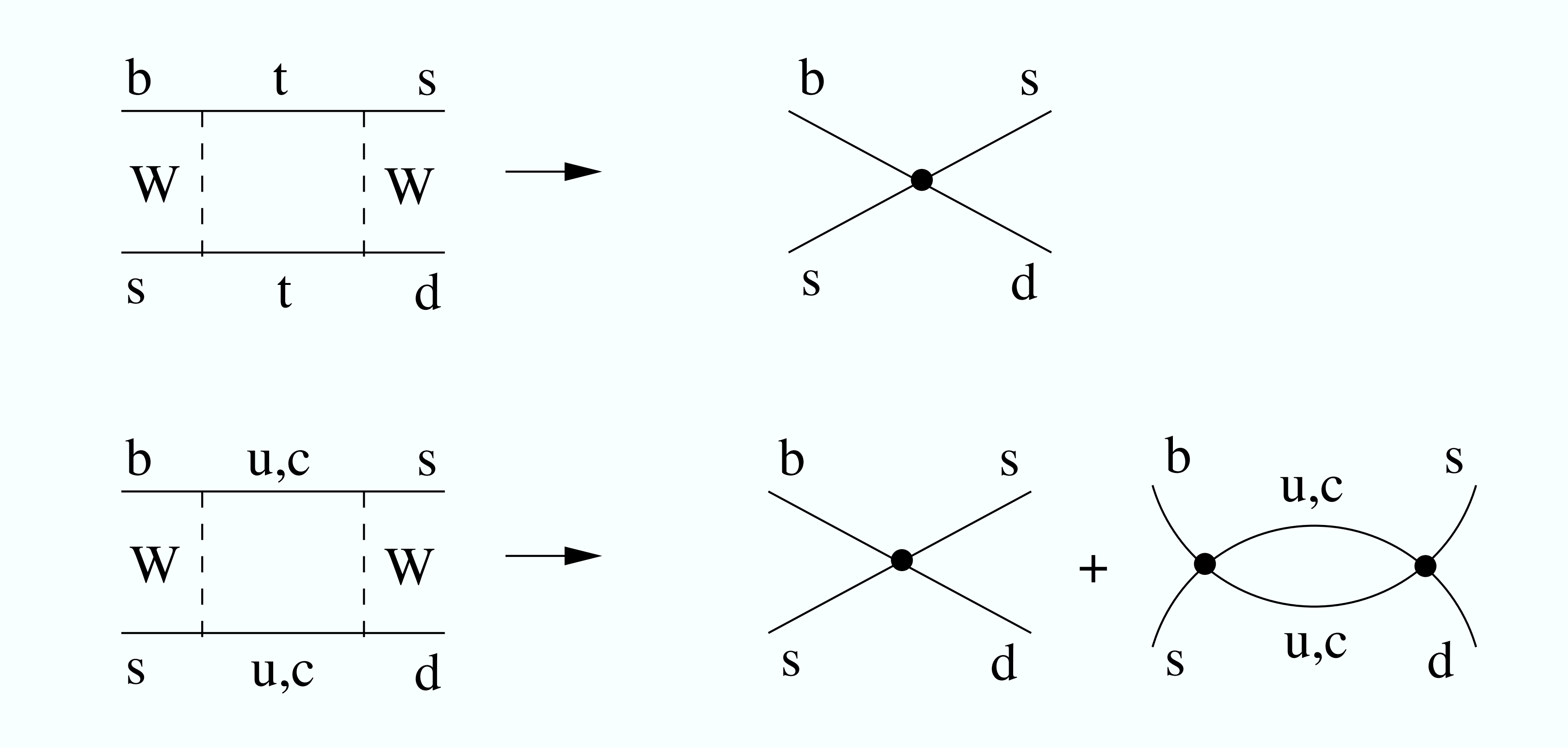


Example: b -> ssd decays

Searching for new physics with b -> ssd, dds decays

DP, Zupan

Similar to $\Delta F = 2$ processes



b->ssd decays in the SM

In the SM, the b->ssd decays are mediated by the effective Hamiltonian

$$H = \frac{G_F^2 m_W^2}{16\pi^2}(\lambda_t^d \lambda_t^b C_{tt} + \lambda_c^d \lambda_t^b C_{ct} + \lambda_t^d \lambda_c^b C_{tc})[(\bar{s}d)_{V-A}(\bar{s}b)_{V-A}]$$

$$C_{tt}(m_b) = 1.92, C_{tc}(m_b) = 3.75 x_c \sim 9.4 \cdot 10^{-4}$$

$$\lambda_q^{q'} = V_{qq} V_{qs}^*$$

The top box dominates, but the charm-top contributions are not negligible ~ 30%

SU(3) relations

The hadronic matrix elements of the (sd)(sb) operator can be related by SU(3) to observable decay amplitudes - precise predictions

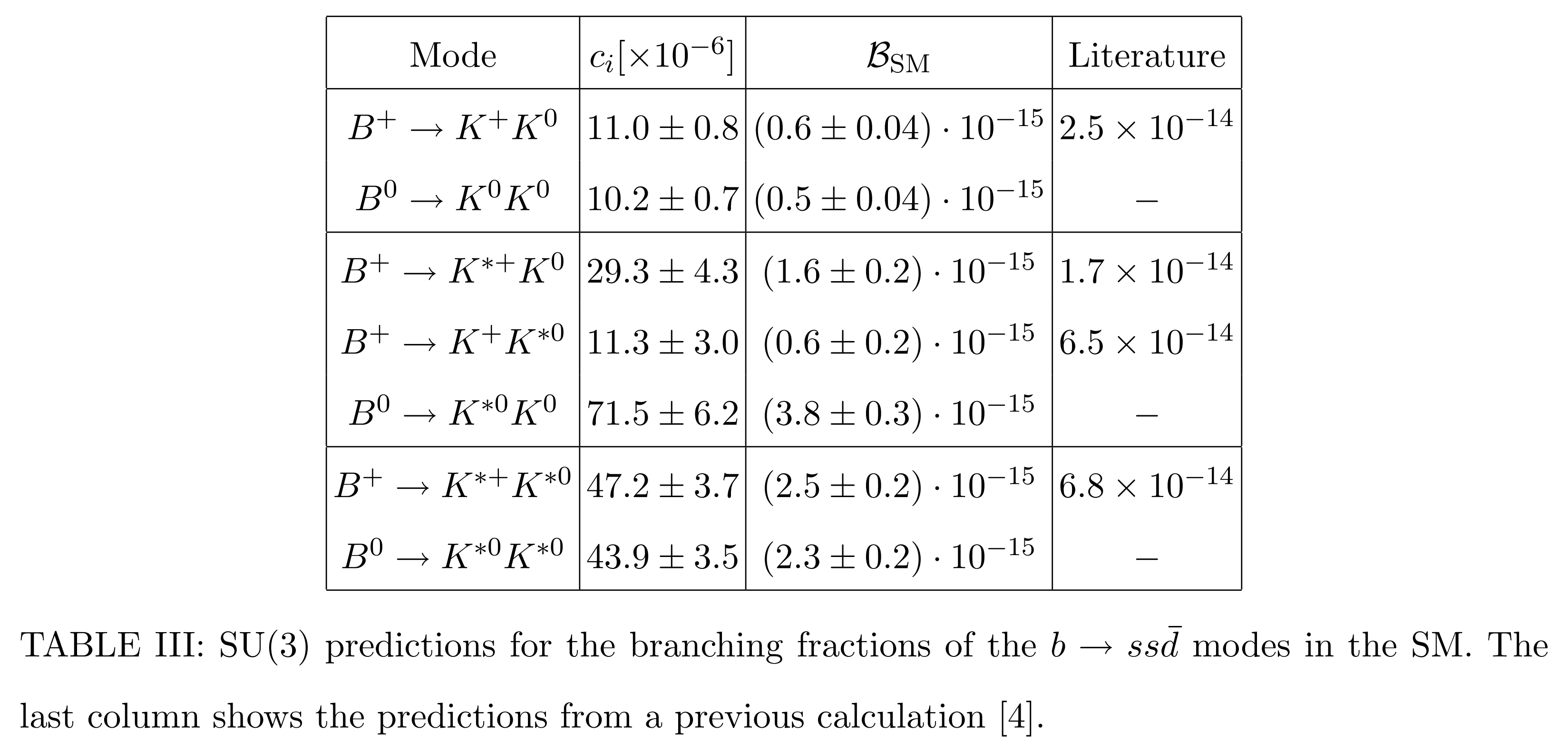
Example:

$$A(B^+ \to K^+ K^0) = \frac{\kappa_{ssd}}{C_1 + C_2} \sqrt{2} A(B^+ \to \pi^+ \pi^0)$$

$$\kappa_{ssd} = \frac{\sqrt{2} G_F m_W^2}{16\pi^2} \frac{V_{tb} V_{ts}^*}{V_{ub} V_{ud}^*} [V_{td} V_{ts}^* C_{tt} + V_{cd} V_{cs}^* C_{ct}] \sim (6.9 \cdot 10^{-6}) e^{i51^\circ}$$

Similar predictions can be made for all B-> PP, PV, VV decays

Numerical predictions from the SU(3) relations



Mode	$c_i[\times 10^{-6}]$	$\mathcal{B}_{\text{SM}}$	Literature
$B^+ \to K^+ K^0$	11.0 ± 0.8	$(0.6 \pm 0.04) \cdot 10^{-15}$	2.5×10^{-14}
$B^0 \to K^0 K^0$	10.2 ± 0.7	$(0.5 \pm 0.04) \cdot 10^{-15}$	–
$B^+ \to K^{*+} K^0$	29.3 ± 4.3	$(1.6 \pm 0.2) \cdot 10^{-15}$	1.7×10^{-14}
$B^+ \to K^+ K^{*0}$	11.3 ± 3.0	$(0.6 \pm 0.2) \cdot 10^{-15}$	6.5×10^{-14}
$B^0 \to K^{*0} K^0$	71.5 ± 6.2	$(3.8 \pm 0.3) \cdot 10^{-15}$	–
$B^+ \to K^{*+} K^{*0}$	47.2 ± 3.7	$(2.5 \pm 0.2) \cdot 10^{-15}$	6.8×10^{-14}
$B^0 \to K^{*0} K^{*0}$	43.9 ± 3.5	$(2.3 \pm 0.2) \cdot 10^{-15}$	–

TABLE III: SU(3) predictions for the branching fractions of the $b \to ss\bar{d}$ modes in the SM. The last column shows the predictions from a previous calculation [4].

Experimental limits:

$\mathcal{B}(B^+ \to K^{*0} K^+) < 24.0 \times 10^{-7}$ BELLE

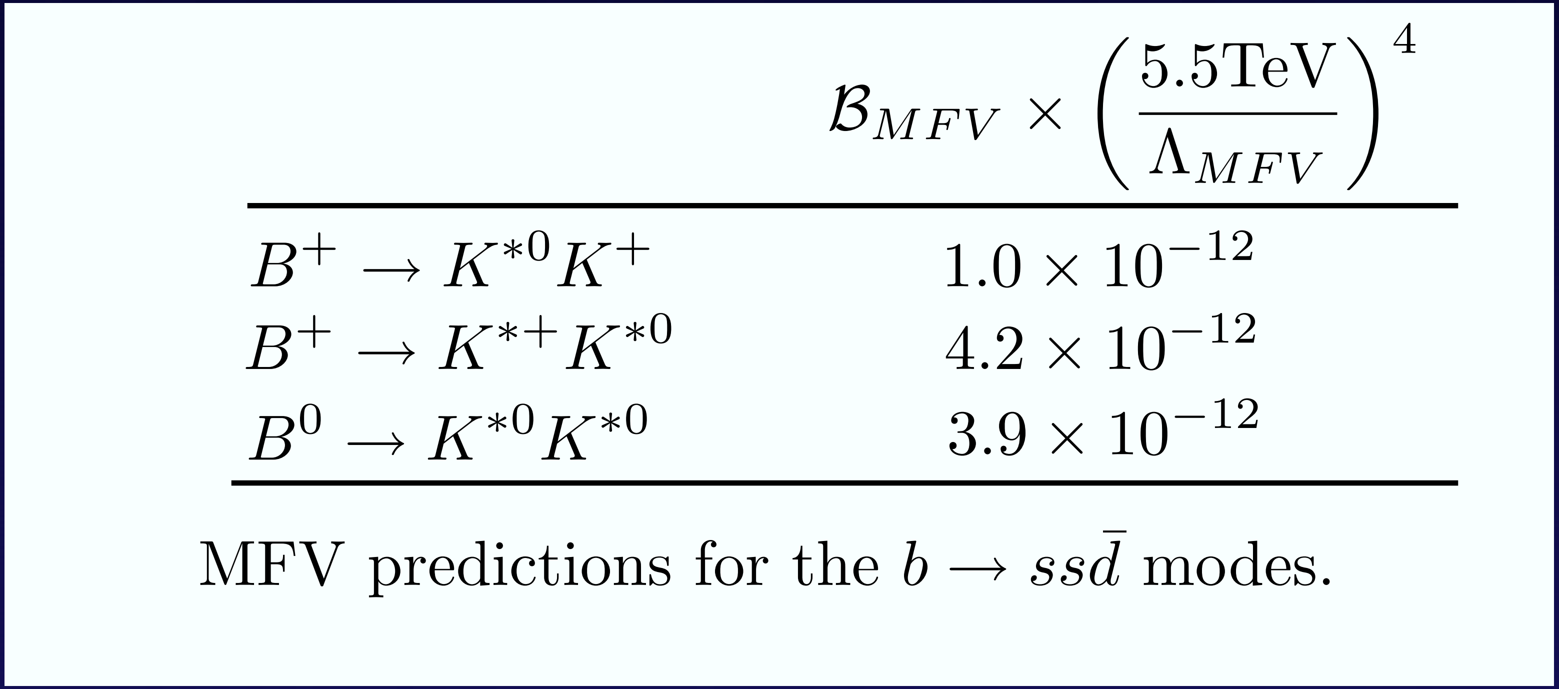
9.5×10^{-7} BABAR

$\mathcal{B}(B^+ \to K^{*0} K^0) < 180.0 \times 10^{-7}$ BELLE

b->ssd in MFV new physics

In MFV, the b->ssd decays get contributions from the same operator which mediates NP in mixing

$$\mathcal{L}_{\Delta F=2} = \frac{c}{\Lambda^2_{MFV}} (\bar{Q}_L Y_U Y_U^\dagger Q_L)^2$$



	$\mathcal{B}_{MFV} \times \left(\frac{5.5\mathrm{TeV}}{\Lambda_{MFV}}\right)^4$
$B^+ \to K^{*0} K^+$	1.0×10^{-12}
$B^+ \to K^{*+} K^{*0}$	4.2×10^{-12}
$B^0 \to K^{*0} K^{*0}$	3.9×10^{-12}

MFV predictions for the $b \to ss\bar{d}$ modes.

Enhancement mechanism

Is it possible to enhance b-> ssd decays without introducing large effects in K, B_s mixing?

Consider a NP field X carrying a conserved quantum number broken only by the flavor couplings

$$\mathcal{L}_{NP} = g_{bs}(\bar{s}b)X + g_{sb}(\bar{b}s)X + g_{ds}(\bar{s}d)X + g_{sd}(\bar{d}s)X + \text{ h.c.}$$

Integrating out X produces flavor-changing operators

$$\mathcal{L}_{eff} = \frac{1}{M_X^2}[g_{ds}g^*_{sd}(\bar{s}d)(\bar{s}d) + g_{bs}g^*_{sb}(\bar{s}b)(\bar{s}b)$$

K, B_s mixing

$$+(g_{bs}g^*_{sd} + g_{ds}g^*_{sb})(\bar{s}d)(\bar{s}b)]$$

b->ssd decays

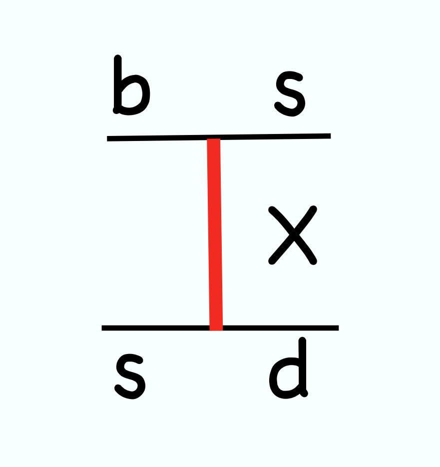
Yes, provided that the couplings satisfy hierarchies

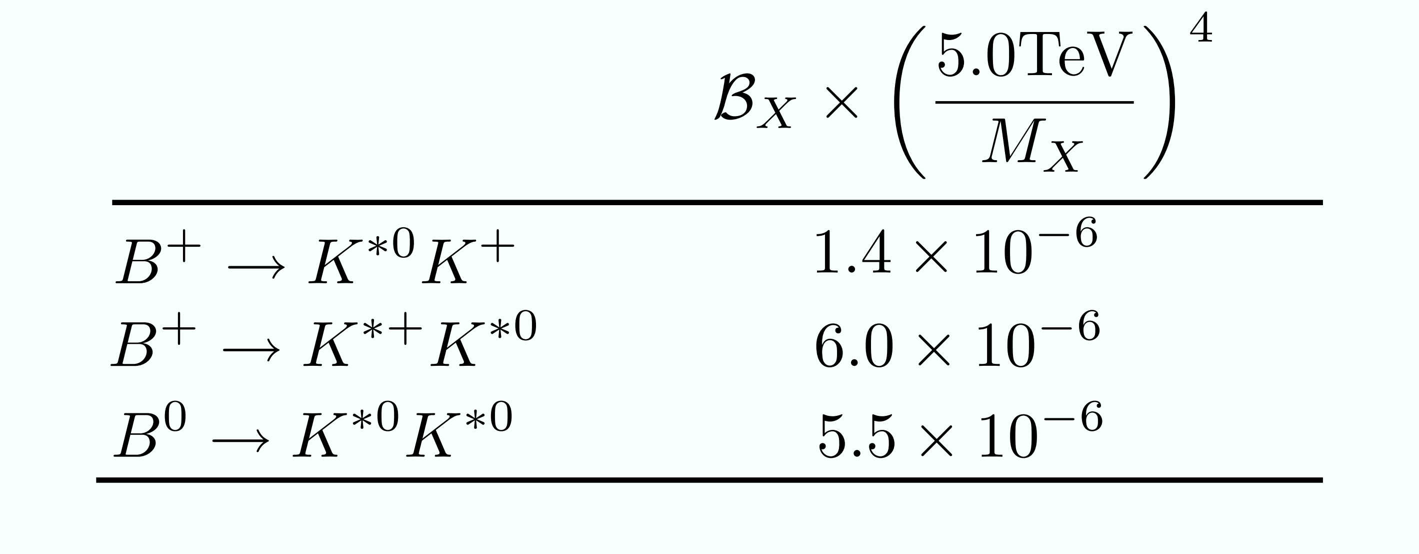
$g_{bs} \ll g_{sb}\,,\quad g_{sd} \ll g_{ds}$ or $g_{bs} \gg g_{sb}\,,\quad g_{sd} \gg g_{ds}$

This mechanism is realized specifically in R-parity violating SUSY (X = sneutrino)

The experimental bounds on B(b->ssd) give a lower bound on the mass of the NP field X

$$M_X \geq 5.0 \text{ TeV}$$





	$\mathcal{B}_X \times \left(\frac{5.0\text{TeV}}{M_X}\right)^4$
$B^+ \to K^{*0} K^+$	1.4×10^{-6}
$B^+ \to K^{*+} K^{*0}$	6.0×10^{-6}
$B^0 \to K^{*0} K^{*0}$	5.5×10^{-6}

Observability could be just beyond the corner!

Summary

- The b -> ssd modes can probe large NP scales with (almost) no SM background
- SU(3) symmetry: clean predictions without hadronic uncertainties
- Constraints/exclusion criteria on popular models of flavor violation (MFV)

Conclusions

- B physics is a fertile testing ground for the flavor physics of the Standard Model
- Strong experimental program - soon to be complemented by the LHCb and SuperB
- So far, data agrees with the CKM picture of flavor physics...
- ... but we know that this can not be the whole story

SUSY(MSSM?), extra dimensions?

Flavor physics could hold the key to NP