Plan of the lectures:

- An introduction to flavour physics
- Phenomenology of B and D decays

- Flavour physics beyond the SM
    - Minimal Flavour Violation
    - Flavour breaking in the MSSM
    - MSSM with MFV at large $\tan\beta$
    - SUSY beyond MFV
    - Flavour physics with partial compositeness
    - Conclusions

From the first lecture...

$$M(B_d-\overline{B}_d) \sim \frac{(y_t^2\, V_{tb}^{*} V_{td})^2}{16\pi^2 m_t^2} + c_{NP}\,\frac{1}{\Lambda^2}$$

c_{NP}:

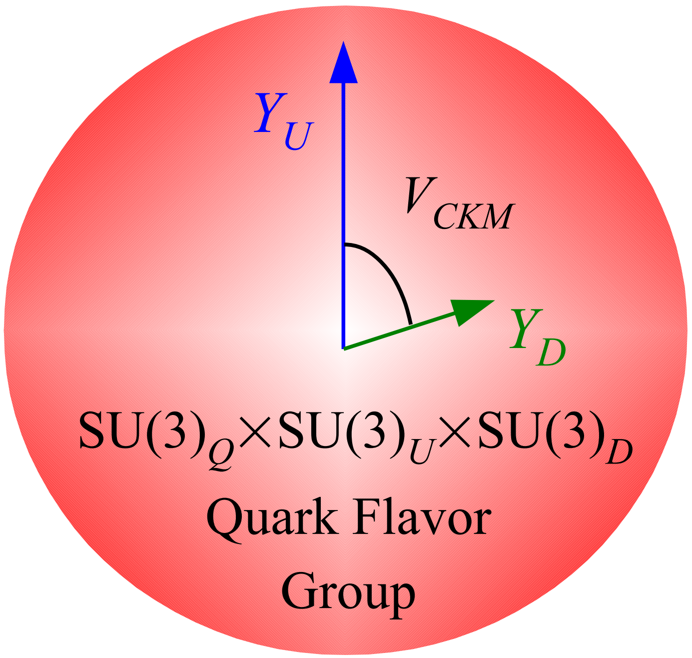
- $\sim 1 \xrightarrow{\text{tree/strong + generic flavor}} \Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\pi^2) \xrightarrow{\text{loop + generic flavor}} \Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t\, V_{ti}^{*} V_{tj})^2 \xrightarrow{\text{tree/strong + “alignment”}} \Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t\, V_{ti}^{*} V_{tj})^2/(16\pi^2) \xrightarrow{\text{loop + “alignment”}} \Lambda \gtrsim 0.5$ TeV [K & B]

- Can we build NP models where the alignment with the CKM is “natural”?

Minimal Flavour Violation

- Flavour symmetry:
  $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$
  [global symmetry of the SM gauge sector]

- Symmetry-breaking terms: Y_U & Y_D
  [quark Yukawa couplings]



$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge} + \mathscr{L}_{\rm Higgs}$$

$$\longrightarrow \bar{Q}_L^i \, Y_U^{ij} \, U_R^j \, \phi + \bar{Q}_L^i \, Y_D^{ij} \, D_R^j \, \phi_c$$

This specific symmetry + symmetry-breaking pattern is responsible for the GIM suppression of FCNCs, the suppression of CPV,...
all the successful SM predictions in the quark flavour sector

Minimal Flavour Violation

Since the global flavour symmetry is already broken within the SM, is not consistent to impose it as an exact symmetry beyond the SM (fine-tuning, not RGE invariant)

However, we can (formally) promote this symmetry to be an exact symmetry, assuming the Yukawa matrices are the vacuum expectation values of appropriate auxiliary fields:

E.g.: $Y_D \sim (3,1,\bar{3})$ & $Y_U \sim (3,\bar{3},1)$ under $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$

$$\mathscr{L}_{\text{Yukawa}} = \bar{Q}_L Y_D D_R \phi + \bar{Q}_L Y_U U_R \phi_c + \bar{L}_L Y_L e_R \phi + \text{h.c.}$$

$$(\bar{3},1,1) \qquad (3,1,\bar{3}) \qquad (1,1,3)$$

$$\Downarrow$$

$$(1,1,1)$$

Minimal Flavour Violation

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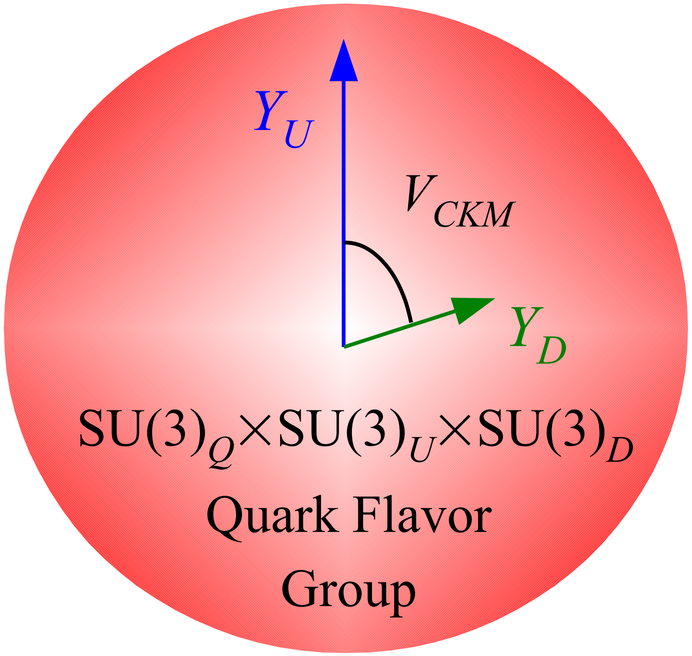
  [global symmetry of the SM gauge sector]

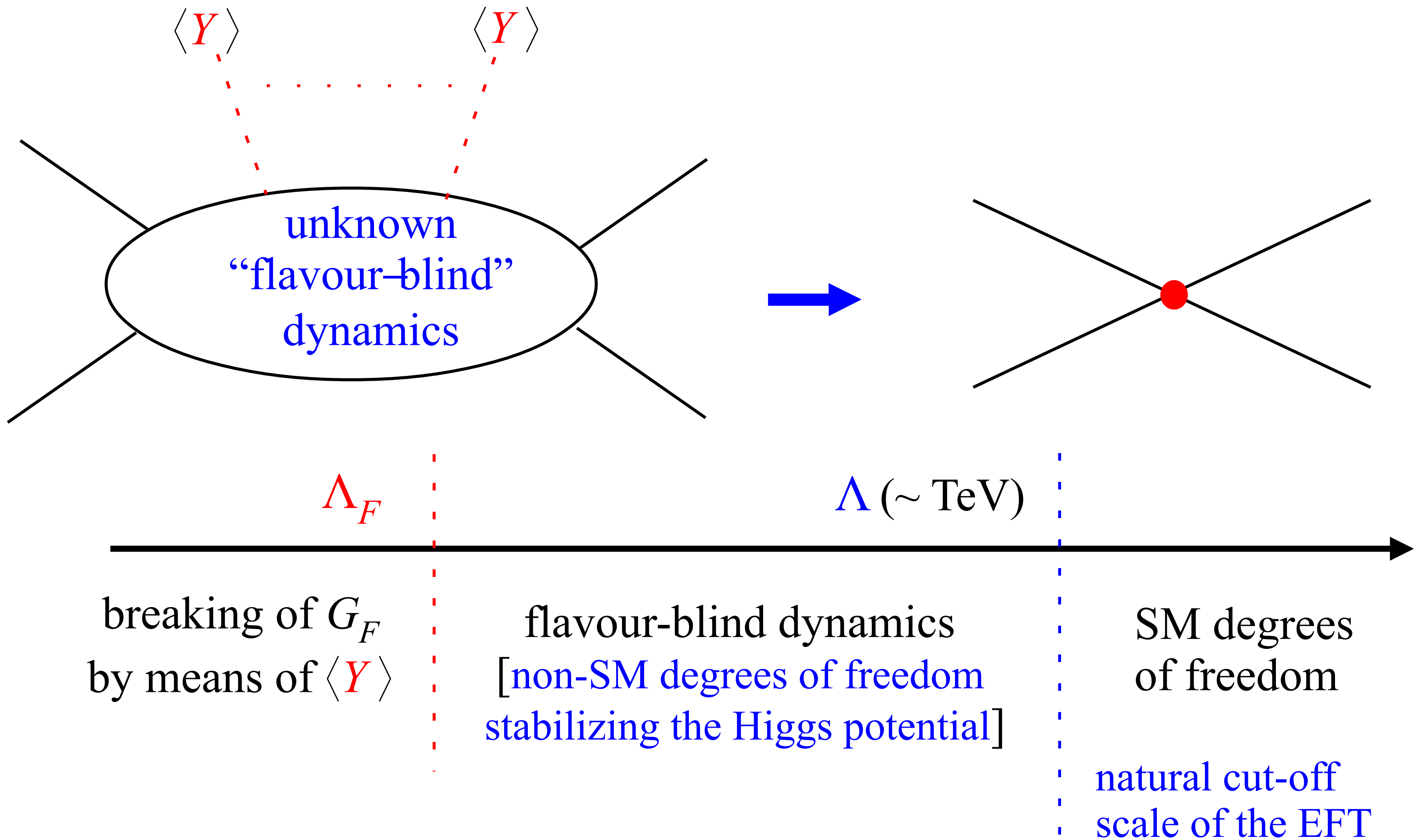
- Symmetry-breaking terms:
  $Y_D \sim 3_Q \times \bar{3}_D \qquad Y_U \sim 3_Q \times \bar{3}_U$
  [quark Yukawa couplings]



A natural mechanism to reproduce the SM successes in flavour physics -without fine tuning- is the MFV hypothesis:

Yukawa couplings = unique sources of flavour symmetry breaking also beyond SM

Minimal Flavour Violation



General principle (RGE invariant) which can be applied to any TeV-scale new-physics model

Minimal Flavour Violation

A low-energy EFT satisfies the criterion of MFV if all higher-dimensional operators, constructed from SM and Y fields, are (formally) invariant under the flavour group [$SU(3)_Q \times SU(3)_U \times SU(3)_D$]

We can always choose a quark basis where:

$$Y_D = \mathrm{diag}(y_d, y_s, y_b) \qquad Y_U = V^+ \times \mathrm{diag}(y_u, y_c, y_t) \qquad y_i = \frac{2^{1/2}\, m_{q_i}}{\langle \phi \rangle}$$

Typical FCNC dim.-6 operator: $\bar{Q}_L^{\,i}\, (Y_U Y_U^{+})_{ij}\, Q_L^{\,j} \times \bar{L}_L L_L$

$$\underbrace{\bar{Q}_L^{\,i}}_{(3,\bar{3},1)}\ \ \underbrace{Q_L^{\,j}}_{(\bar{3},3,1)} \ \Rightarrow\ (1,1,1)$$

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Typical FCNC dim.-6 operator: $\bar{Q}_L^{\,i}\, (Y_U Y_U^+)_{ij}\, Q_L^{\,j} \times \bar{L}_L L_L$

$$(Y_U Y_U^+)_{ij} \approx y_t^2\, V_{3i}^* V_{3j}$$

$$\downarrow$$

$$V^+ \times \mathrm{diag}(y_u^2, y_c^2, y_t^2) \times V$$

$$\approx V^+ \times \mathrm{diag}(0, 0, y_t^2) \times V$$

same CKM - Yukawa structure of the SM short-distance contribution !

Minimal Flavour Violation

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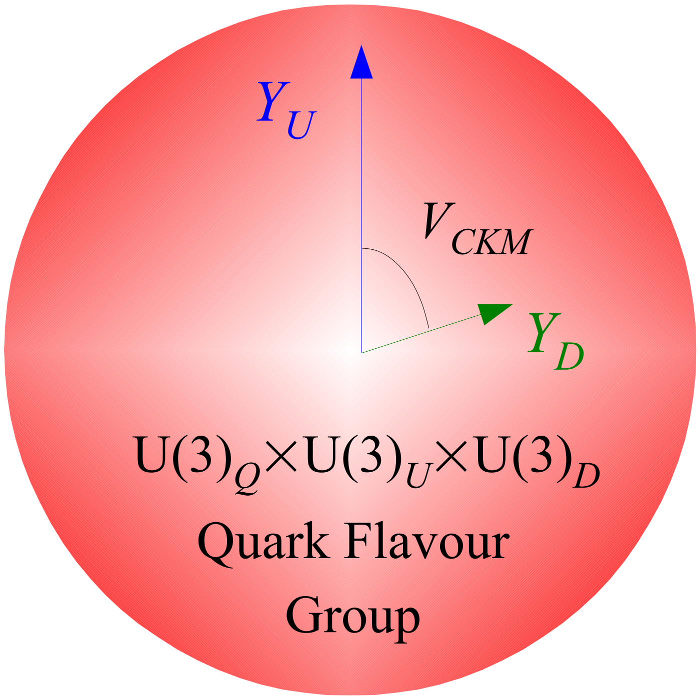
Typical FCNC dim.-6 operator: $\bar{Q}_L^{\,i}\, (Y_U Y_U^{+})_{ij}\, Q_L^{\,j} \times \bar{L}_L L_L$

In principle we can consider higher powers of the Y.
However, because of their hierarchical nature, this does not change the picture:

$$[\,(Y_U Y_U^{+})^n\,]_{ij} \approx (Y_U Y_U^{+})_{ij} \approx y_t^2\, V_{3i}^{*} V_{3j}$$

Basic assumptions:

- <u>Flavour symmetry:</u>
  $U(3)^5 = U(3)_Q \times U(3)_U \times U(3)_D \times \ldots$
- <u>Symmetry-breaking terms:</u>
  $Y_D \sim \bar{3}_Q \times 3_D \qquad Y_U \sim \bar{3}_Q \times 3_U$

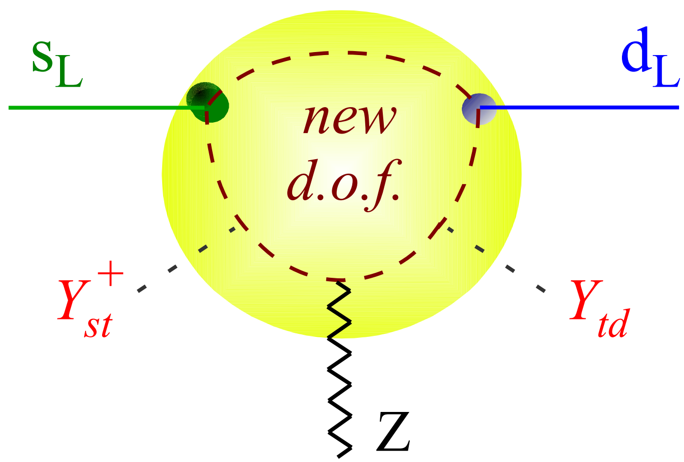


Main virtues:

- General principle that can be implemented independently of the specific UV completion of the theory
- Within the generic effective theory approach, the bounds on the scale of New Physics are reduced to few TeV (at most)
- It leads to a very predictive framework:

  All flavour-changing loop-induced amplitudes have the same CKM/Yukawa structure as in the SM. Only the flavour-independent magnitude of the transition amplitudes can be modified.

All flavour-changing loop-induced amplitudes have the same CKM/Yukawa structure as in the SM [e.g.: A($s \to dZ$) ~ $V_{ts}^* V_{td}$, A($b \to sZ$) ~ $V_{tb}^* V_{ts}$, …]. Only the flavour–independent magnitude can be modified



$$\left|\frac{A(s \to dZ)}{A(b \to sZ)}\right| = \left|\frac{V_{td}}{V_{tb}}\right|$$ as in the SM...

As a result, the most the tight experimental constraints on rare processes are naturally satisfied:

Operator	Bound on Λ	Observables
$H^\dagger\left(\bar{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right)(e F_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\bar{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV	ε_K, Δm_{B_d}, Δm_{B_s}
$H_D^\dagger\left(\bar{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$(\bar{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)(\bar{E}_R \gamma_\mu E_R)$	2.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$

A few important comments:

I) MFV is not a theory of flavour

It does not allow us to compute the Yukawa couplings in terms of some more fundamental parameters

It is a useful predictive (hence falsifiable) construction that allow us to identify which are the irreducible sources of flavour-symmetry breaking

A few important comments:

I) MFV is not a theory of flavour

II) Despite its phenomenological success, MFV is far from being "verified"

To prove MFV from data we would need to

- observe some deviation form the SM in rare processes
- observe the CKM pattern predicted by MFV [within same type of amplitudes]

$$A[b \to d(s)] \sim V_{td(s)} \left[c_{SM}^{(0)} \frac{1}{M_W^{\,2}} + c_{NP}^{(0)} \frac{1}{\Lambda^2} \right]$$

In most of the processes measured so far we cannot go beyond the 10%-20% level of precision (even if the exp. precision is much better) because of irreducible theoretical uncertainties on evaluating the overall strength of the SM amplitude (*non-perturbative effects of strong interactions*)

Some more rare decays not observed so far could provide more useful infos.
Very interesting candidates: $B_{d,s} \to l^+ l^-$ (*currently under investigation @ LHC*)

A few important comments:

I) MFV is not a theory of flavour

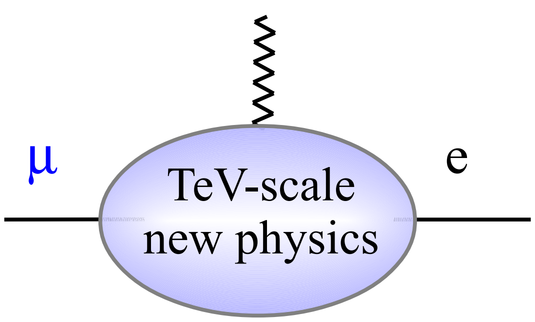
II) Despite its phenomenological success, MFV is far from being "verified"

III) Even within the "pessimistic" MFV hypothesis, we can still expect sizable deviations from the SM in various B physics observables...

Typical examples:

$B_{d,s} \to l^+ l^-$ Large enhancements possible in models with an extended Higgs sector

... and, hopefully, spectacular NP effects in the charged lepton sector:



B(μ→eγ) could reach values in the 10^{-12} - 10^{-13} range (*within the reach of MEG*)

A few important comments:

I) MFV is not a theory of flavour

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III) Even within the "pessimistic" MFV hypothesis, we can still expect sizable deviations from the SM in various B physics observables...

Three particularly interesting direction of research in flavour physics:

- Theoretical justification of MFV (or alternative "protective criteria") from explicit new-physics models (SUSY, SUSY-GUTS, Extra-dimensions...)
- Identifications of signals/observables which could proof of falsify the MFV scenario from data
- Connections with the lepton sector and with physics at the high-energy frontier

Flavour breaking in the MSSM

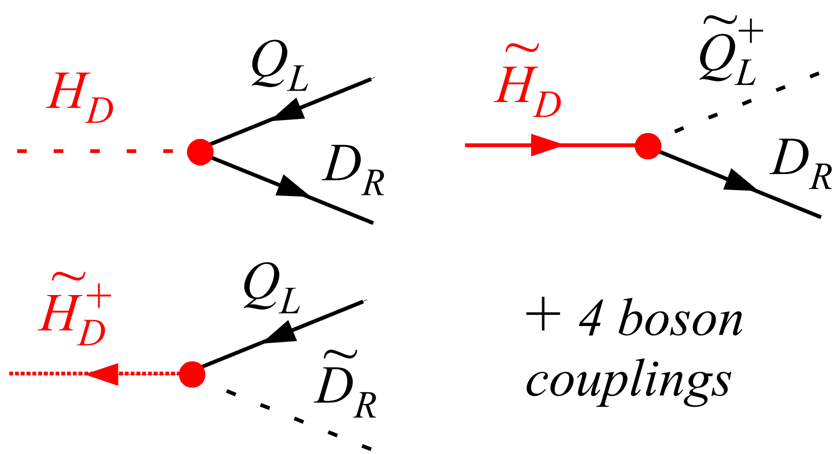
The Minimal Supersymmetric extension of the SM includes:

- scalar partners of the ordinary quarks and leptons $[\widetilde{Q}_L, \tilde{u}_R, \ldots]$
- spin-1/2 partners of the ordinary gauge bosons [*gauginos*]
- Two Higgs doublets $[H_U, H_D]$ with their corresponding spin-1/2 partners

The SUSY version of $\mathscr{L}_{\text{gauge}}$ is completely determ. by its symmetry properties

The SUSY version of $\mathscr{L}_{\text{Yukawa}}$ is also strongly constrained:

$$\mathscr{L}_Y^{\text{MSSM}} = \bar{Q}_L Y_D D_R H_D + \bar{Q}_L Y_U U_R H_U + \widetilde{Q}_L^+ Y_D D_R \widetilde{H}_D + \widetilde{Q}_L^+ Y_U U_R \widetilde{H}_U + \ldots$$



+ *4 boson couplings*

All the "difficulties" of the theory (e.g. a large number of free parameters) are hidden in the so-called soft-breaking sector:

$$\mathcal{L}_{soft} = (M_f)_{ij}\, \chi_i\, \chi_j + (M_s^2)_{ij}\, \phi_i\, \phi_j + A_{ijk}\, \phi_i\, \phi_i\, \phi_k$$

gaugino/higgsino masses

squark/slepton masses

trilinear scalar couplings

potential new sources of flavour-symmetry breaking

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$$\mathscr{L}_{soft} = \underbrace{(M_f)_{ij}\, \chi_i\, \chi_j}_{\text{gaugino/higgsino masses}} + \underbrace{\underbrace{(M_s^2)_{ij}\, \phi_i\, \phi_j}_{\text{squark/slepton masses}} + \underbrace{A_{ijk}\, \phi_i\, \phi_i\, \phi_k}_{\text{trilinear scalar couplings}}}_{\text{potential new sources of flavour-symmetry breaking}}$$

N.B.: while for the SM quarks [Dirac fermions] only LR mass terms are allowed, in the case of the s-quarks [scalars] all possibilities LL, LR and RR are allowed → 6×6 mass matrices.

$$\begin{bmatrix} M^2_{LL} & M^2_{LR} \\ (M^2_{LR})^+ & M^2_{RR} \end{bmatrix} \rightarrow$$

If the off-diagonal entries of this mass matrices are not sufficiently small, the model is ruled-out from flavour physics observables

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$$\mathscr{L}_{soft} = (M_f)_{ij}\, \chi_i\, \chi_j + (M_s^2)_{ij}\, \phi_i\, \phi_j + A_{ijk}\, \phi_i\, \phi_i\, \phi_k$$

gaugino/higgsino masses — squark/slepton masses — trilinear scalar couplings

The general MFV hypothesis provides a strong restriction to the possible structure of these terms

E.g.: $(M^2_{LL})\, \tilde{Q}_L^+\, \tilde{Q}_L$

General MFV prescription: $(M^2_{LL}) \propto \Sigma\, a_n (Y_U Y_U^+)^n \sim a_0 I + a_1 Y_U Y_U^+$

This is what we expect assuming, for instance, that at some heavy (GUT ?) scale $M^2_{LL} \propto I$ [universality] ➡ non-vanishing $a_{0,1}$ generated by RGE running

▸ *MSSM with MFV at large tanβ*

With two Higgs doublets we can change the relative normalization of Y_U & Y_D (controlled by $\tan\beta = \langle\phi_U\rangle/\langle\phi_D\rangle$)

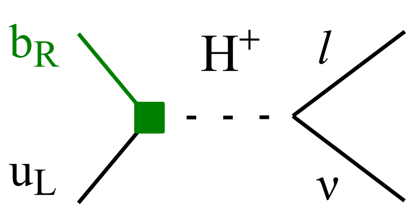
$$\mathscr{L}_{\text{q-Yukawa}} = \bar{Q}_L Y_D D_R \phi_D + \bar{Q}_L Y_U U_R \phi_U + \text{h.c.}$$

$$y_u = m_u / \langle\phi_U\rangle$$

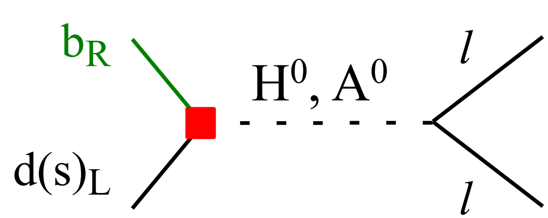
$$y_d = m_d / \langle\phi_D\rangle = \tan\beta \, m_d / \langle\phi_Y\rangle$$

$\Downarrow$

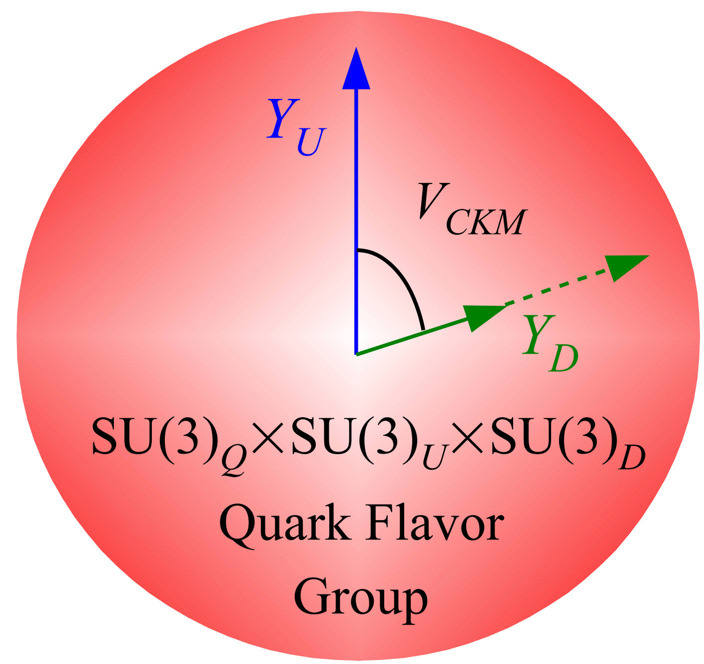
Interesting phenomenological signatures in *helicity-suppressed* observables:



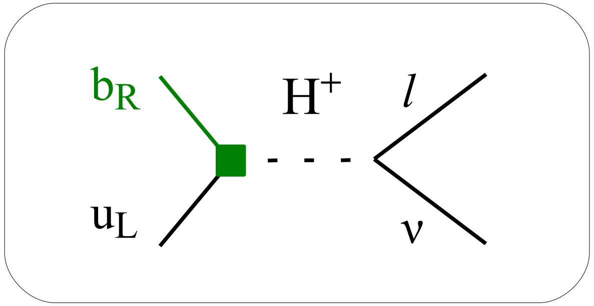
$B^+ \to l^+ \nu$



$B_{s,d} \to l^+ l^-$



MSSM with MFV at large tanβ



The H^+ exchange appears at the tree-level in charged-current amplitudes.

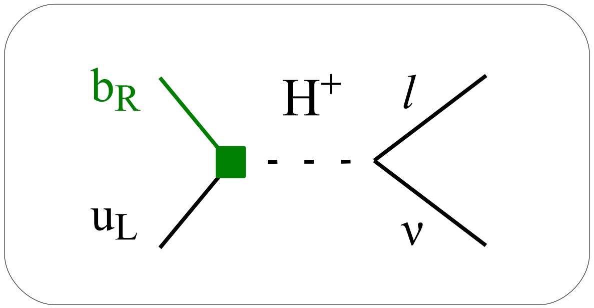
The effect is usually negligible (suppression of Yukawa couplings), except in helicity-suppressed observables (such as $B\to l\nu$) or τ leptons

Simple M_H & tanβ dependence
[mild dependence on other parameters]:

$$\mathcal{B}(B\to l\nu) = \mathcal{B}_{SM}\left(1 \quad \frac{m_B^2\ \tan\beta^2}{M_H^2\,(1+\epsilon_0\tan\beta)}\right)^2$$

- Natural to expect a O(10-30%) <u>suppression</u> in $B\to l\nu$
- And a O(0.1-0.3%) suppression in $K\to\ l\nu$

▸ *MSSM with MFV at large tanβ*



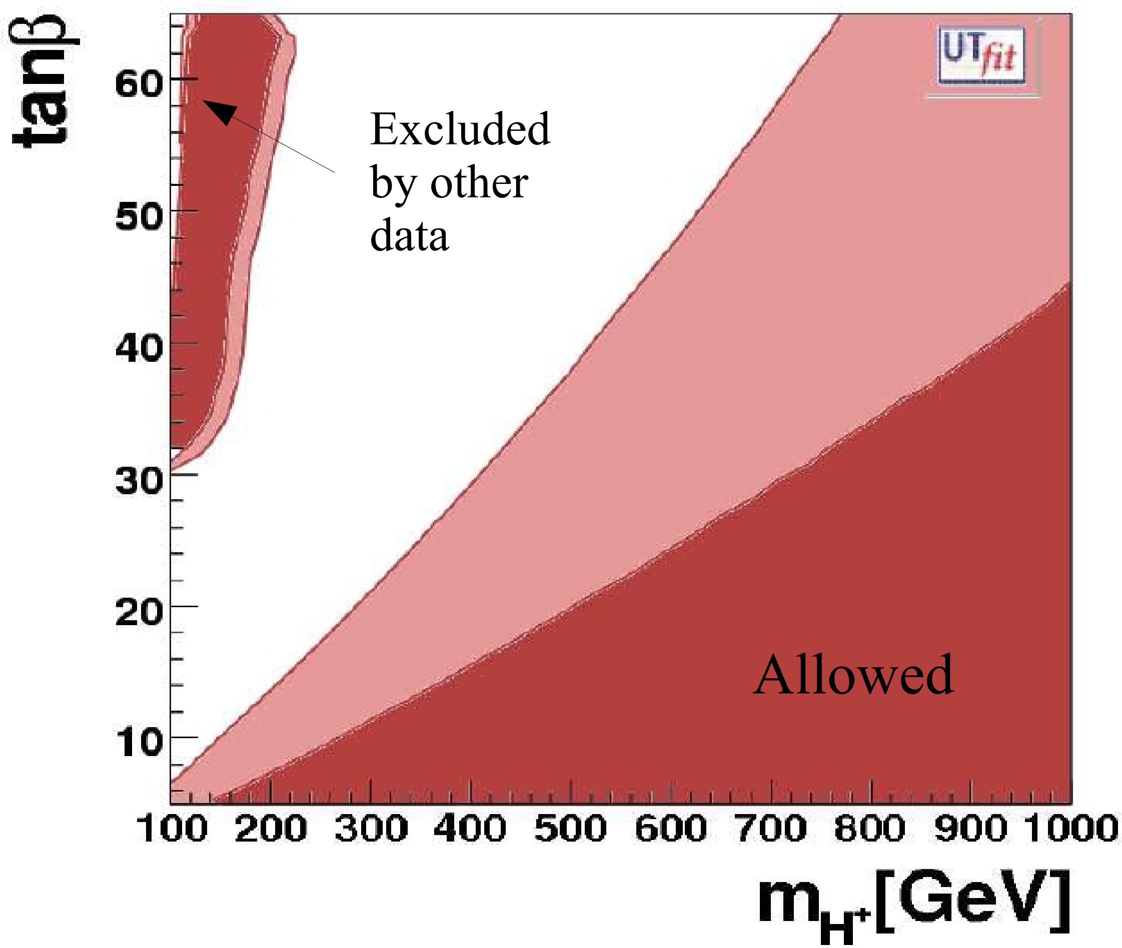
$$B(B\to l\nu) = B_{SM} \left(1 \quad \frac{m_B^{\,2}\ \tan\beta^2}{M_H^{\,2}\,(1 + \epsilon_0 \tan\beta)} \right)^2$$

$$B_{SM} = C_0\, f_B^{\,2}\, |V_{ub}|^2$$
$$= (0.79 \pm 0.07)\ 10^{-4}$$

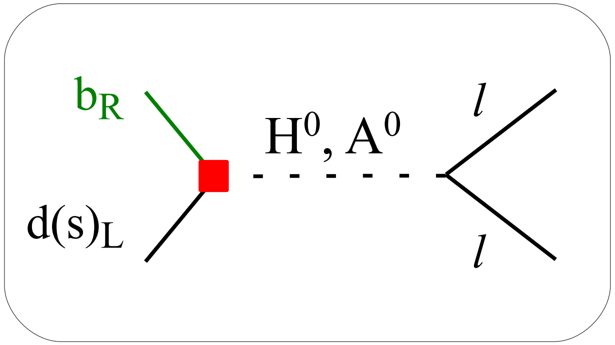
UTfit '10 [global fit]

$$B(B\to l\nu)_{exp} = (1.68 \pm 0.31)\ 10^{-4}$$

Given we don't see a suppression, the parameter space of the model is strongly constrained

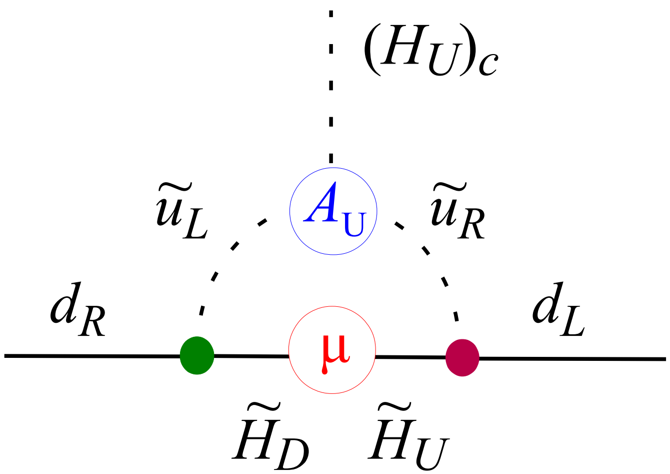


MSSM with MFV at large tanβ



There are no tree-level FCNC couplings of the neutral Higgses in MFV models.

However, effective couplings can appear at the one loop level and they are potentially quite large in the MSSM:



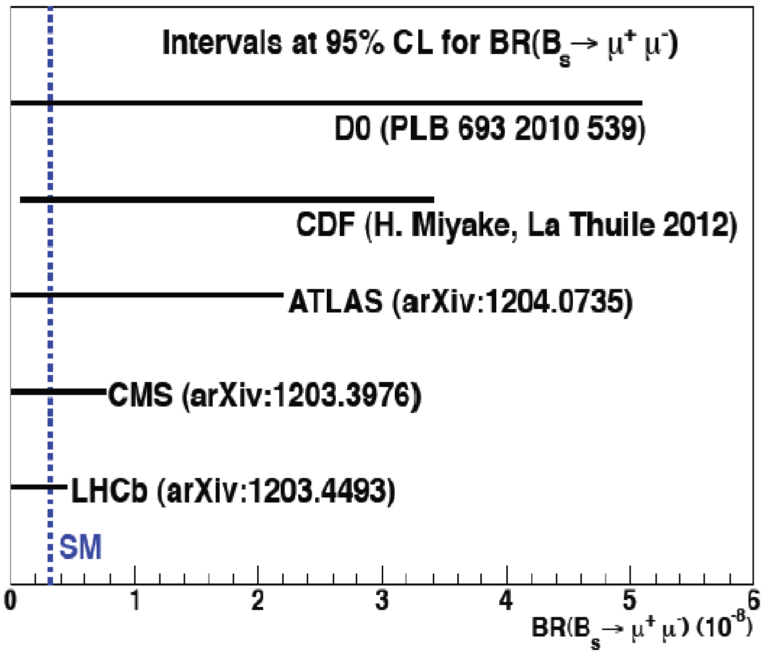
Crucial dependence on μ and A_U [+ M_H & tanβ]

$$A(B\to ll)_H \sim \frac{m_b\, m_l}{M_A^2}\, \frac{\mu\, A_U}{\tilde{M}_q^2}\, \tan^3\beta$$

Possible large enhancement over the SM, but the magnitude of the effect can vary a lot in different SUSY-breaking scenarios

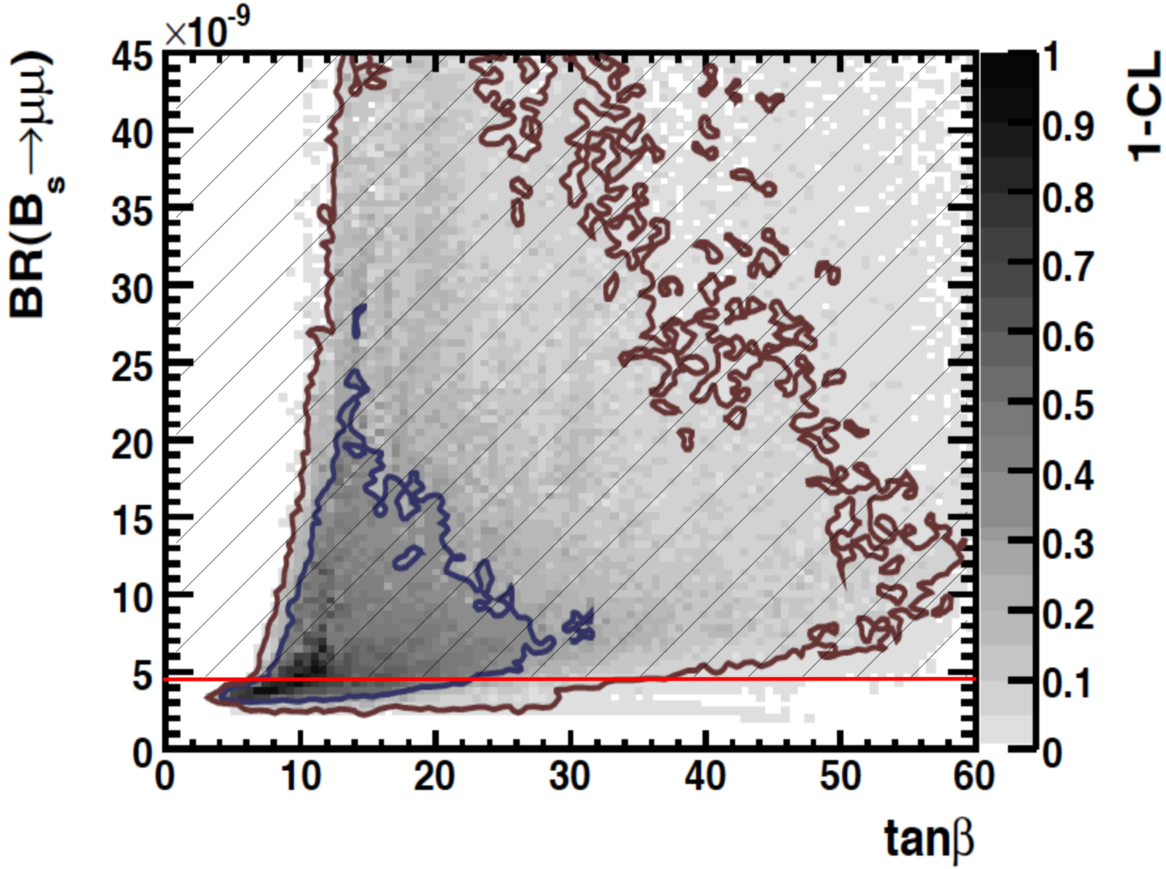
MSSM with MFV at large tanβ

The recent exp. bounds:



have strongly restricted the large tanβ scenario of minimal SUSY models

E.g.: MSSM with non-universal Higgs mass terms



SUSY beyond MFV

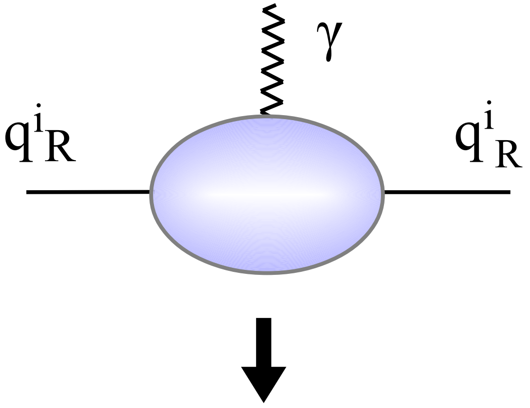
MFV virtue

Naturally small effects in FCNC observables

MFV main open problems

No explanation for small CPV flavor-conserving observables (EDMs)

No explanation for *Y* hierarchies (masses and mixing angles)



Electric Dipole Moment of the neutron

SUSY beyond MFV

MFV virtue

Naturally small effects in FCNC observables

MFV main open problems

No explanation for small CPV flavor-conserving observables (EDMs)

No explanation for *Y* hierarchies (masses and mixing angles)

Both issues can be improved with "split-family susy" + flavor symmetry acting only on 1st & 2nd generations

Natural suppression for 1st & 2nd generation EDMs of quarks and leptons

Partial explanation for *Y* hierarchies (3rd generation Yukawas allowed by the flavor symmetry)

MFV virtue

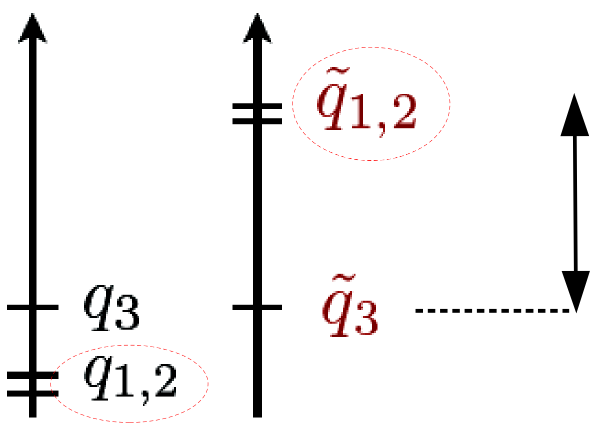
Naturally small effects in FCNC observables

Split-family SUSY

Natural suppression for 1^{st} & 2^{nd} gen. EDMs of quarks and leptons

Partial explanation for *Y* hierarchies (with help of flav. symm.)

Split-family SUSY with a U(2)^3 = $\mathrm{U(2)}_{Q_L}\times\mathrm{U(2)}_{U_R}\times\mathrm{U(2)}_{D_R}$ flavour symmetry



Large mass gap (several TeV) not controlled by flavor symmetries (as opposite to MFV) and fine-tuning considerations

On the breaking pattern of $U(2)^3$

The symmetry is a good approximation to the SM quark spectrum (exact symmetry for $m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$), hence we only need to introduce small breaking terms

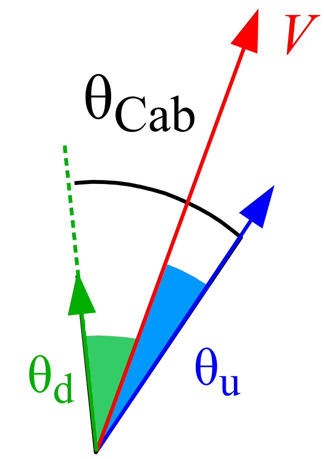
Unbroken

$$U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$$

$$\Downarrow$$

$$Y_u = y_t \left[\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right] \qquad Y_d = y_b \left[\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right] \qquad M_{\rm squarks} = \left[\begin{array}{c|c} m_{\rm heavy} & 0 \\ \hline 0 & m_3 \end{array}\right]$$

On the breaking pattern of U(2)^3



The symmetry is a good approximation to the SM quark spectrum (exact symmetry for $m_u = m_d = m_s = m_c = 0$, $V_{CKM} = 1$), hence we only need to introduce small breaking terms:

Minimal set of breaking terms necessary to reproduce the quark spectrum, while keeping small rare processes beyond SM:

$\boxed{V \sim (2,1,1) \quad O(\lambda^2 \sim 0.04)}$ Leading breaking [3rd gen. $\rightarrow$ 1,2 gen.]

$\Delta Y_u \sim (2,2,1)$ m_c, m_u, θ_u $O(y_c \sim 0.006)$

$\Delta Y_d \sim (2,1,2)$ m_s, m_d, θ_d $O(y_s < 0.001)$

$$U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$$

$$Y_u = y_t \left[\begin{array}{c|c} \Delta Y_u & c_u V \\ \hline 0 & 1 \end{array} \right] \qquad Y_d = y_b \left[\begin{array}{c|c} \Delta Y_d & c_d V \\ \hline 0 & 1 \end{array} \right] \qquad \rightarrow \qquad \begin{array}{l} |V_{us}| \approx |\theta_u - \theta_d| \\ |V_{td}/V_{ts}| = \theta_d \\ |V_{ub}/V_{cb}| = \theta_u \end{array}$$

MFV virtue

Naturally small effects in FCNC observables

Split-family SUSY

Natural suppression for 1^{st} & 2^{nd} gen. EDMs of quarks and leptons

Partial explanation for *Y* hierarchies (with help of flav. symm.)

Split-family SUSY with a $U(2)^3 = U(2)_{Q_L} \times U(2)_{U_R} \times U(2)_{D_R}$ flavour symmetry

$\boxed{\text{Split-family SUSY with “disoriented A terms”}}$

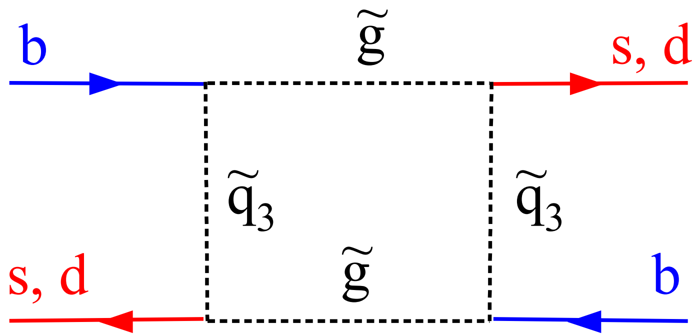
- The origin of flavor is all “confined” in the L-R mixing (Yukawas & A terms)

$$\mathscr{L}_{soft} = A_{ijk}\, \phi_i\, \phi_i\, \phi_k + O(\phi^+\phi)$$

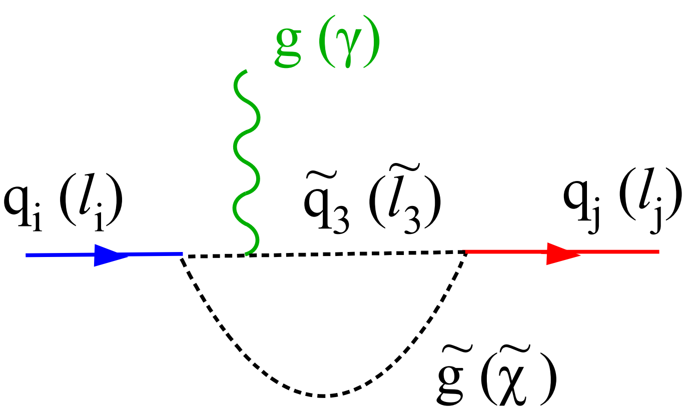
- Y & A are both proportional to quark & lepton masses, but are not perfectly aligned: potentially larger sources of flavour symmetry breaking, still compatible with existing bounds.

In both cases we expect interesting non-standard effects mediated by the exchange of the 3rd generation of squarks and leptons.

E.g.:



Possible solution of the "ε_K - sin(2β) tension"



Possible contribution to Δa_{CP} but also to LFV & edms

Split-family SUSY with $U(2)^3$

Two clean predictions for the LHC:

I. Small non standard CPV in B_s mixing

$$S_{\psi\phi}^{U(2)} = 0.07 - 0.20$$

$$\left[S_{\psi\phi}^{SM} = 0.041 \pm 0.01 \right]$$

Compatible with present LHCb data, possibly within their near-future reach

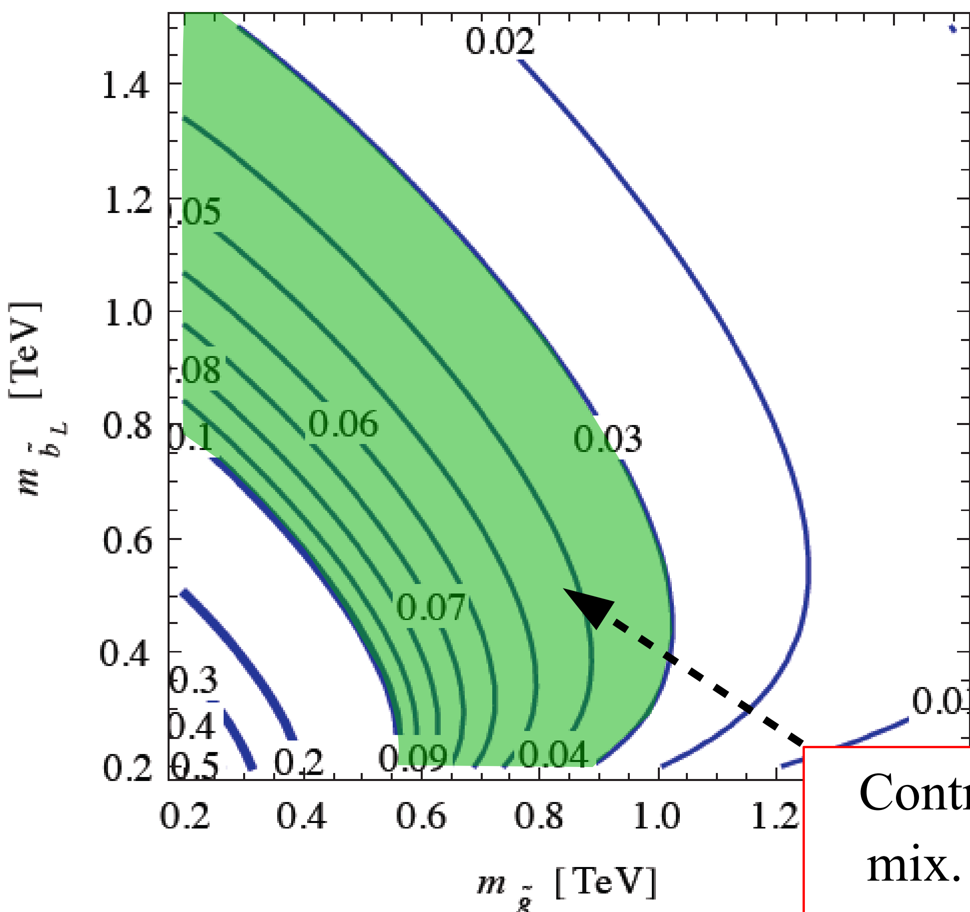
II. Relatively "light" gluinos and 3rd generation squarks

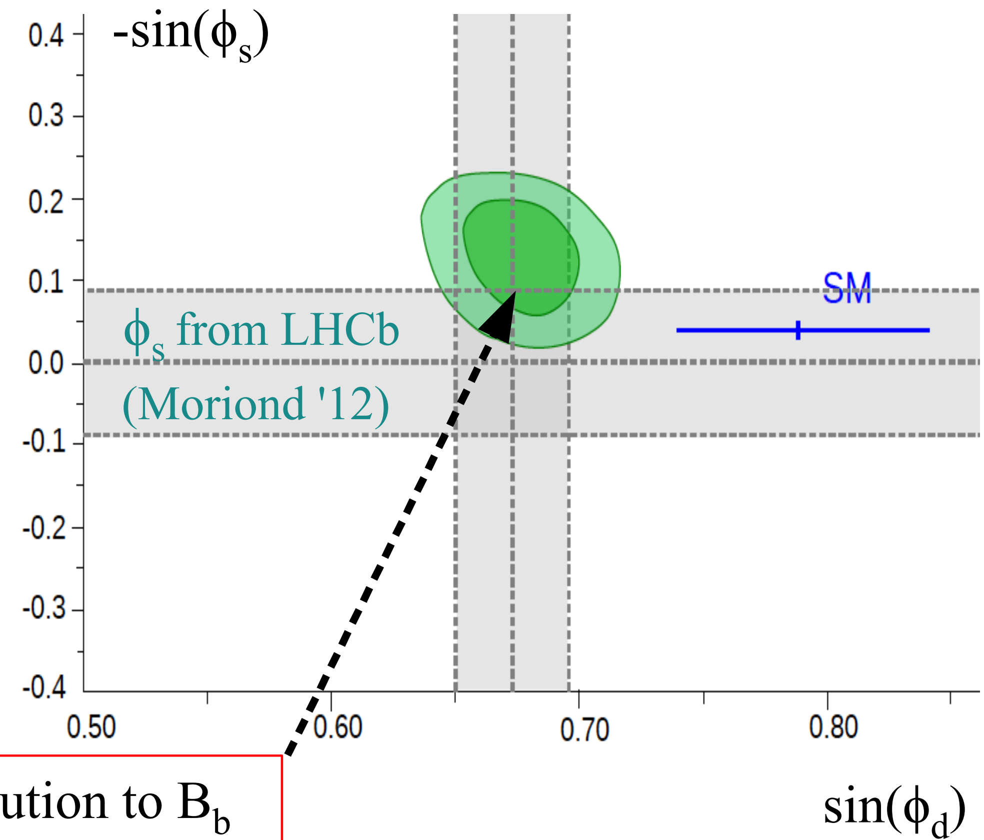
$$m_{\tilde{g}},\ m_{\tilde{q}_3} < 1.0,\ 1.5\ \text{TeV}$$

Compatible with present ATLAS & CMS data, within their near-future reach

Split-family SUSY with U(2)^3

The LHC experiments have just reached the level of precision necessary for testing this scenario (*possible surprises with more statistics...*):

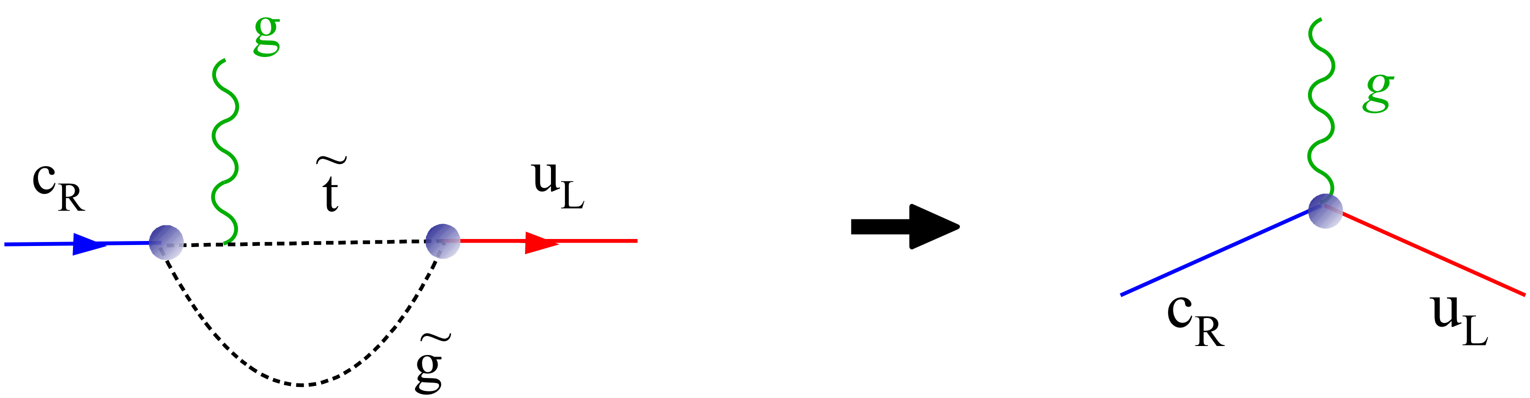




Contribution to B_b mix. reducing the present CKM tension

Split-family SUSY with "disoriented A terms"

In this less-minimal (but still natural) SUSY set-up we can generate a sizable contribution to Δa_{CP} (direct CP violation in the charm system) via an effective CP-violating *chromo-magnetic* operator:



Key question: how to distinguish NP vs. SM explanations?

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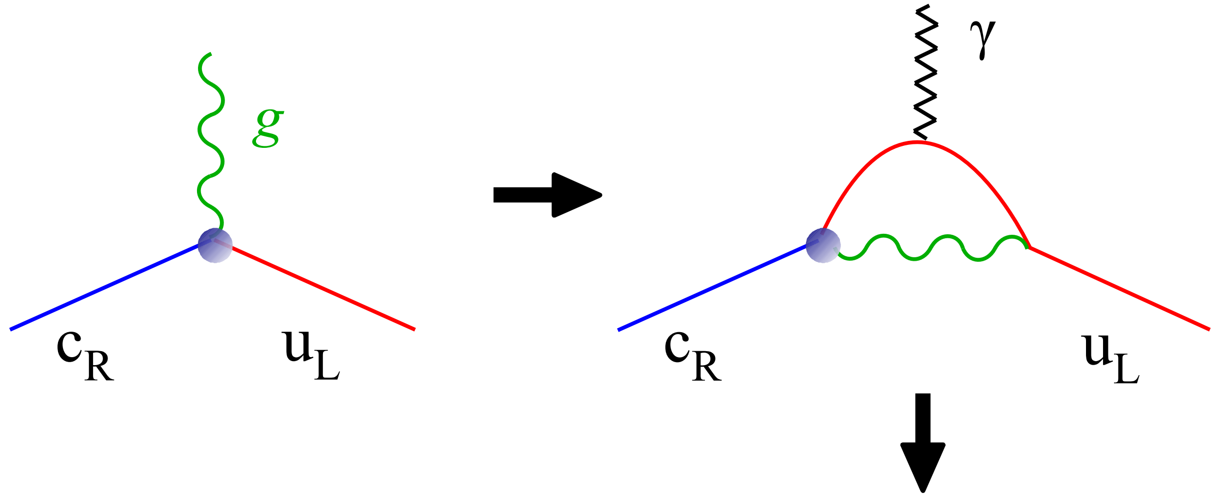
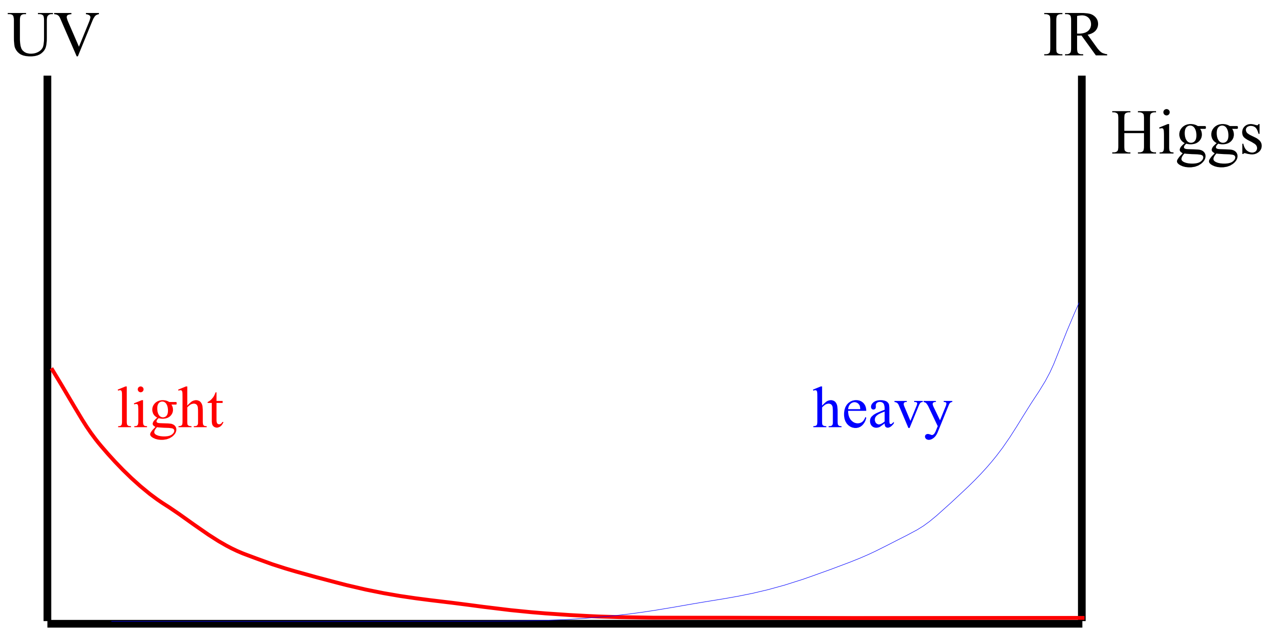


Unavoidable large CPV (*model-independent connection via QCD*) also in the *electric-dipole* operator.

- Radiative D decays, especially $D \to (P^+P^-)_V \gamma$, could help to shed light on the issue: *relative weight of NP substantially higher than in D→PP possible CPV asymmetries as large as 3-5%*.
- Natural correlation also with the neutron EDM, expected to be close to its experimental bound

Flavour physics with partial compositeness [or warped space time]

An interesting approach to explain the hierarchy of the Yukawa couplings, in the context of models with extra space-time dimensions, is to attribute this hierarchy to the different overlap of fermion wave-functions (spread along a 5D bulk) with the Higgs wave function (localized on the IR brane)



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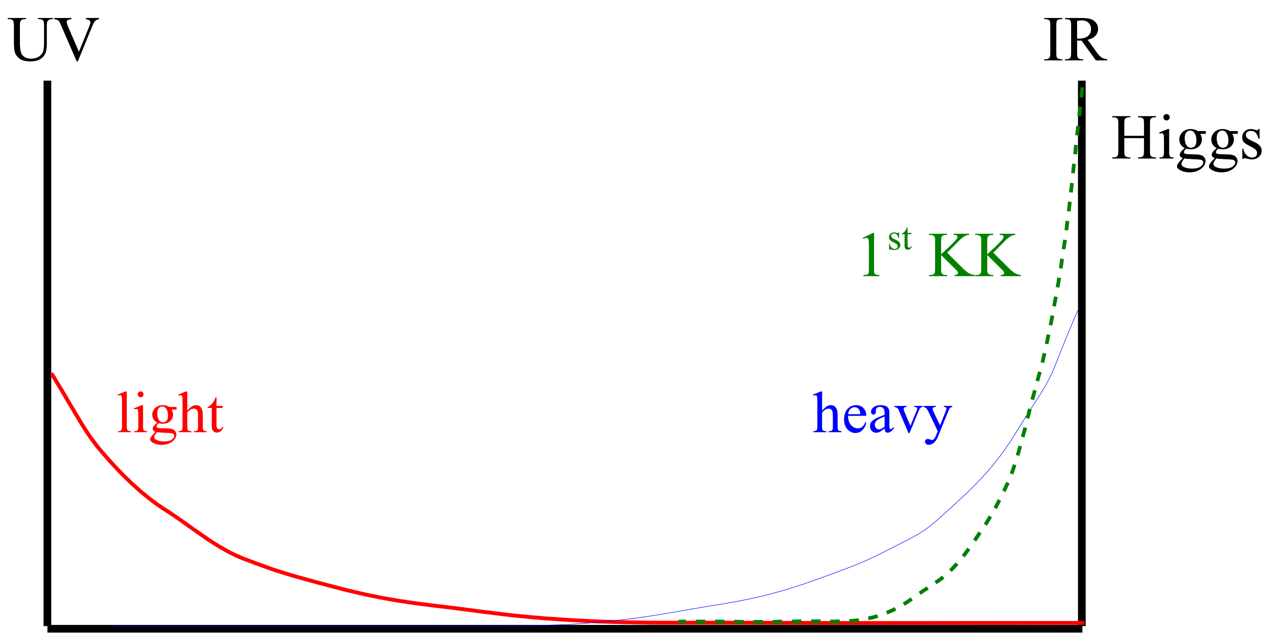


In 5D models with warped geometry, this construction provides a potentially interesting alternative to MFV to explain the suppression of FCNCs beyond the SM

Flavour physics with partial compositeness [or warped space time]

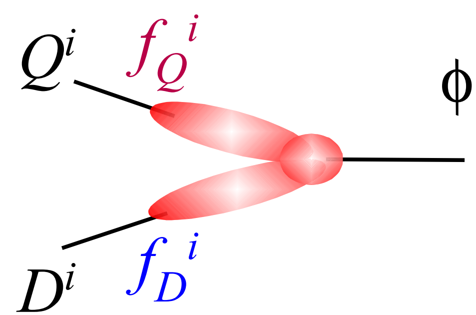
The model can be formulated in terms of the following 4D effective theory:

- SM fermions couples to the new-physics sector via some hierarchical wave funcions f_Q, f_D, f_U (in the quark sector), such that

$$Y_D^{ij} = f_Q^{\ i} \, (\boldsymbol{Y_D}^{\boldsymbol{5D}}) \, f_D^{\ j} \approx f_Q^{\ i} f_D^{\ j} \qquad\qquad Y_U^{ij} = f_Q^{\ i} \, (\boldsymbol{Y_U}^{\boldsymbol{5D}}) \, f_U^{\ j} \approx f_Q^{\ i} f_U^{\ j}$$

anarchic

hierarchical



$$f_Q^{\ 3} \gg f_Q^{\ 2} \gg f_Q^{\ 1}$$

$$f_D^{\ 3} \gg f_D^{\ 2} \gg f_D^{\ 1}$$

$$f_U^{\ 3} \gg f_U^{\ 2} \gg f_U^{\ 1}$$

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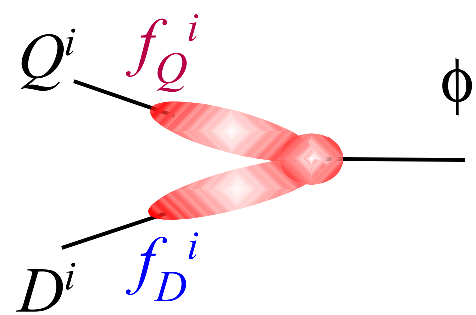
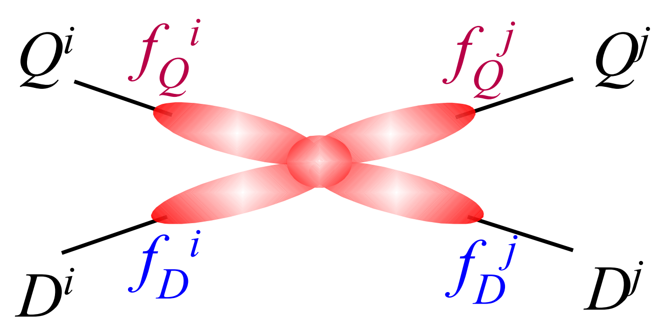


- There is no underlying flavour symmetry (complete anarchy) in the new strongly interacting sector:
  dim.-6 FCNC operators suppressed only by the light-fermion wave functions
  (= *mixing with the new heavy states*)



Flavour protection from warped space

This construction works remarkably well in various cases:

- The condition on the (4D) Yukawa couplings implies

$$f_Q^{\,1}/f_Q^{\,3} \sim |V_{31}| \quad \& \quad f_Q^{\,2}/f_Q^{\,3} \sim |V_{32}| \quad \xrightarrow{\text{predict}} \quad \boxed{f_Q^{\,1}/f_Q^{\,2} \sim |V_{21}| \sim |V_{31}/V_{32}|}$$

- All the left-handed FCNC operators (the leading ones in the SM) have the same suppression as in MFV:

$$f_Q^{\,i} f_Q^{\,j}\, \bar{Q}_L^{\,i}\, Q_L^{\,j} \quad \sim \quad V_{3i} V_{3j}\, \bar{Q}_L^{\,i}\, Q_L^{\,j}$$

to be compared with

$$\bar{Q}_L^{\,i}\, (Y_U Y_U^{\,+})_{ij}\, Q_L^{\,j} \;=\; y_t^{\,2}\, V_{3i}^{\,*} V_{3j}\, \bar{Q}_L^{\,i}\, Q_L^{\,j}$$

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- However, some differences arise with helicity-violating operators, in 2→1 transitions (kaon or charm physics):

$$f_D^{\,i} f_Q^{\,j}\ \bar{D}_R^{\,i} Q_L^{\,j} = f_D^{\,i} f_Q^{\,i} f_Q^{\,j} / f_Q^{\,i}\ \bar{D}_R^{\,i} Q_L^{\,j}$$

to be compared with

$$\bar{D}_R^{\,i}\,(Y_D Y_U Y_U^{\,+})_{ij}\ Q_L^{\,j} = y_{d_i}\, y_t^{\,2}\, V_{3i}^{\,*} V_{3j}\ \bar{Q}_R^{\,i}\, Q_L^{\,j}$$

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to be compared with

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important difference !

to be compared with

$$\bar{D}_R^{\,i}\, (Y_D Y_U Y_U^{\,+})_{ij}\, Q_L^{\,j} = y_{d_i}\, y_t^2\, V_{3i}^{\,*} V_{3j}\, \bar{Q}_R^{\,i}\, Q_L^{\,j} \quad \begin{cases} \sim y_b y_t^2\, V_{tb}^{\,*} V_{ts}\, (b_R s_L) \\ \boxed{\sim y_s y_t^2\, V_{ts}^{\,*} V_{td}\, (s_R d_L)} \end{cases}$$

Flavour protection from warped space

The constraints from ε and ε'/ε in the kaon system imply that this simple construction has to be improved with some sort of alignment, at least in the down sector. On the other hand, also in this model we can have a naturally sizable non-standard contribution to $\Delta a_{\rm CP}$

This discussion has allowed to illustrate once more two rather general points:

- MFV is not the only allowed solution to the flavour problem
- The most natural place to look for deviations from MFV are helicity-violating observables especially in the kaon & charm sector (because of their strong suppression in MFV)

Conclusions

The fact we have not discovered yet new physics in flavour-physics observables, and that the minimalistic scenario of MFV is consistent with data, should not discourage further searches.

We learned that new physics has a rather non-trivial flavour structure (MFV like), but *the origin of this structure has still to be discovered.*
Moreover, several key issues are still open: the MFV hypothesis has not been clearly established from data yet and could well be only an approximate property.

⬇

Important to continue high-statistics / high-precision flavour physics in the LHC era

In realistic models there is only a limited set of particularly interesting observables [*theoretically-clean leptonic/semileptonic/radiative final states*]

but these observables play a key role in determining the flavour symmetry structure of NP