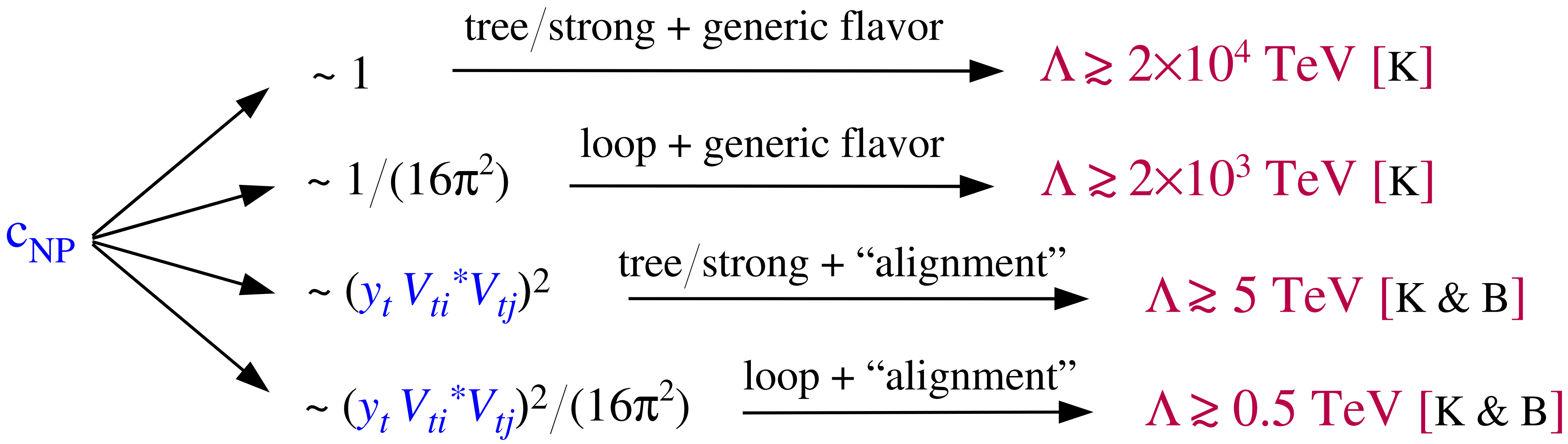
Plan of the lectures:

- Flavour physics in the LHC era
- B-physics phenomenology: mixing, CP violation, and rare decays

- Flavour physics beyond the SM: models and predictions
  - Minimal Flavour Violation
  - Flavour breaking in the MSSM
  - MSSM with MFV at large tanβ
  - Flavour protection in warped space
  - Conclusions

From the first lecture...



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 with such alignment ?

Do we need to impose it also in $\Delta F=1$ processes ?

Can we have $c_{NP} = 0$? or $\Lambda \gg 10$ TeV ?

Can we see deviations from the SM with more precise measurements ? Where ?

Minimal Flavour Violation

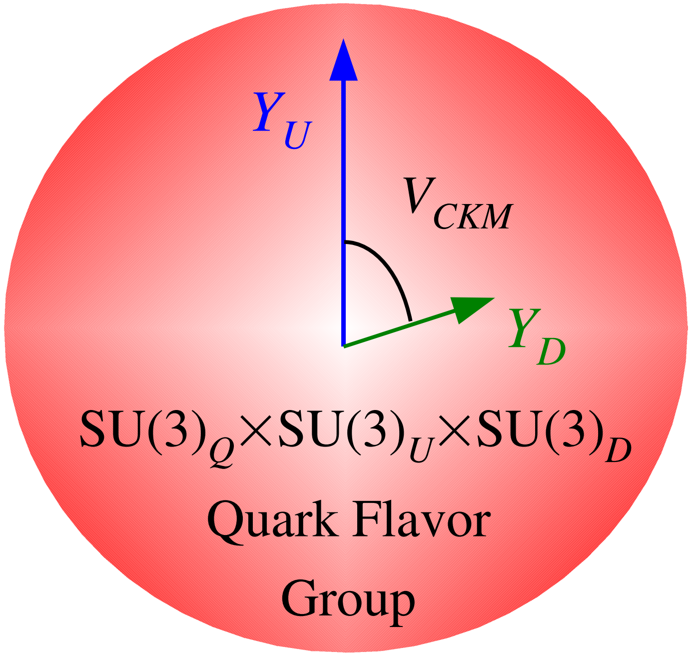
- Flavour symmetry:

  $\mathrm{U(3)}^5 = \mathrm{SU(3)}_Q \times \mathrm{SU(3)}_U \times \mathrm{SU(3)}_D \times \ldots$

  [global symmetry of the SM gauge sector]

- Symmetry-breaking terms: Y_U & Y_D

  [quark Yukawa couplings]



Y_U

V_{CKM}

Y_D

$\mathrm{SU(3)}_Q \times \mathrm{SU(3)}_U \times \mathrm{SU(3)}_D$

Quark Flavor Group

$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{gauge}} + \mathcal{L}_{\mathrm{Higgs}}$$

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

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

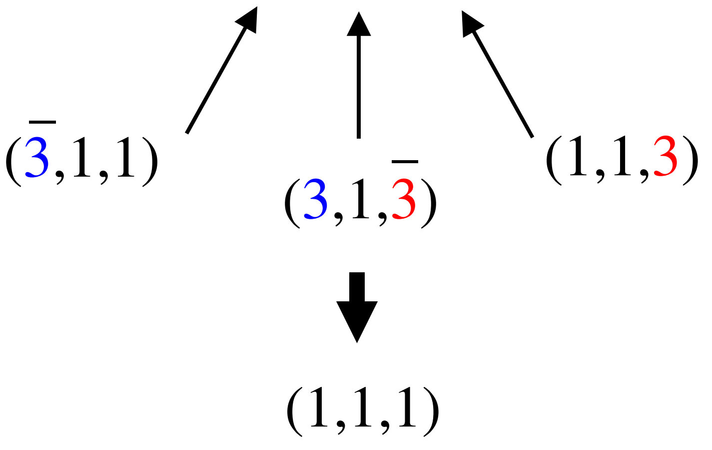
Minimal Flavour Violation

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 $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$

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



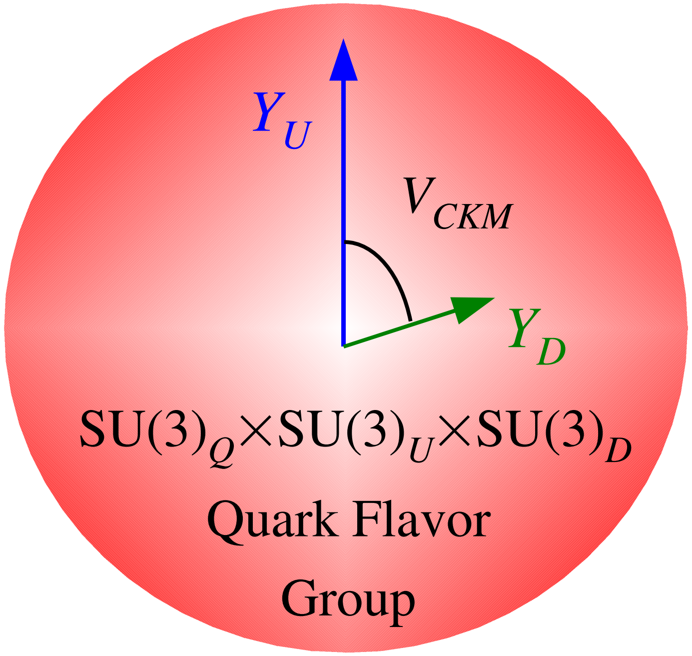
$(\bar{3},1,1)$

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

$(1,1,3)$

$(1,1,1)$

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:

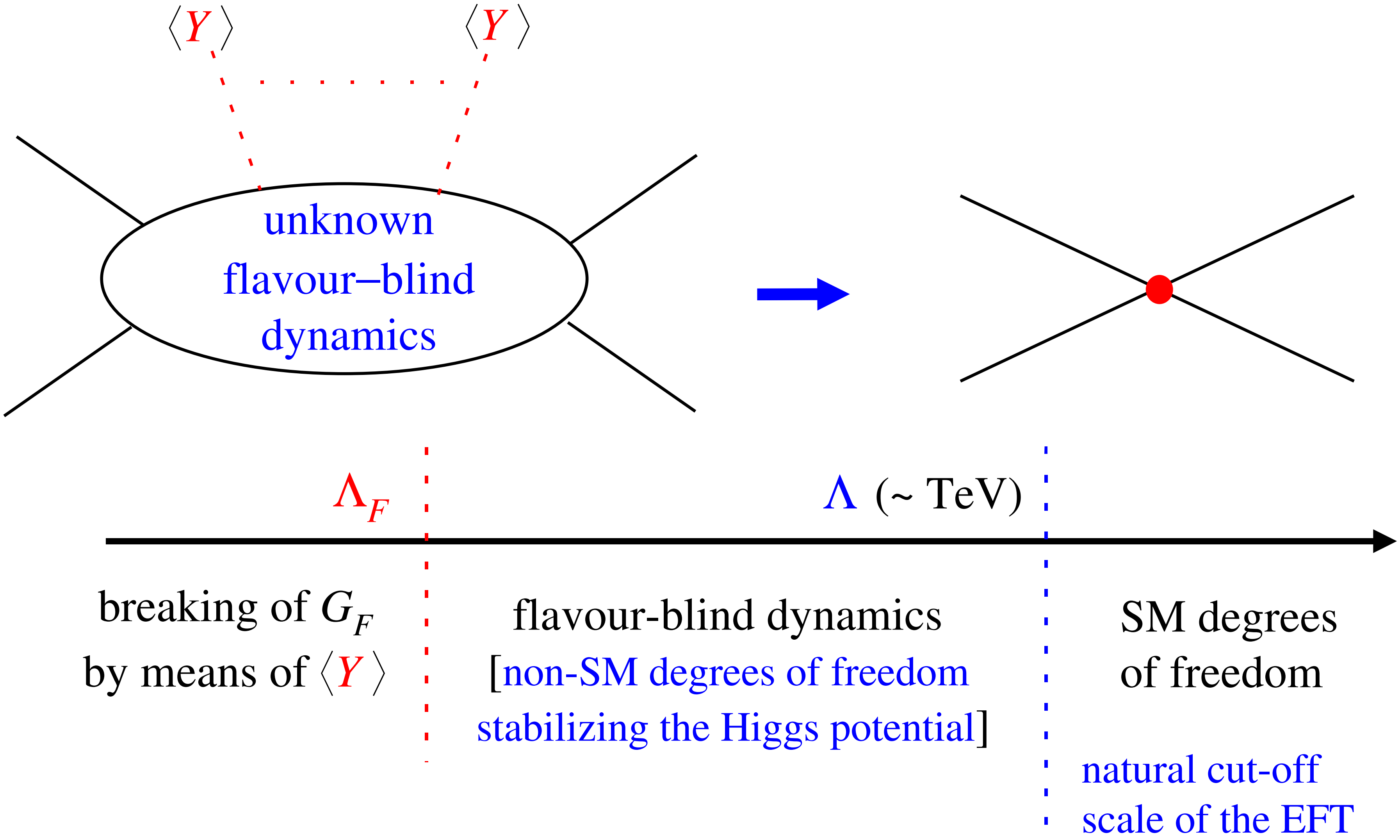
  $Y_D \sim 3_Q \times \bar{3}_D \qquad Y_U \sim 3_Q \times \bar{3}_U$

  [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



breaking of G_F
by means of $\langle Y \rangle$

flavour-blind dynamics
[non-SM degrees of freedom
stabilizing the Higgs potential]

SM degrees
of freedom

natural cut-off
scale of the EFT

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

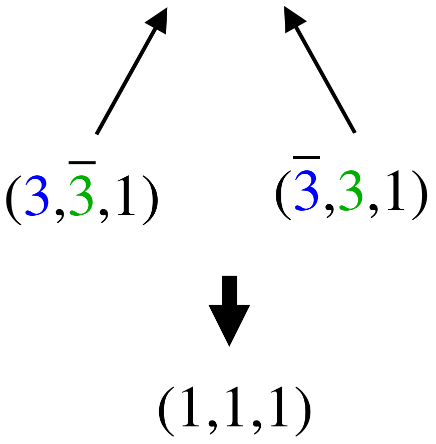
Minimal Flavour Violation

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:

$$Y_D = \mathrm{diag}(y_d, y_s, y_b) \qquad Y_U = V^+ \times \mathrm{diag}(y_u, y_c, y_t) \qquad y_q = m_q / \langle \phi \rangle$$

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



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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

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 [$SU(3)_Q \times SU(3)_U \times SU(3)_D$]

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

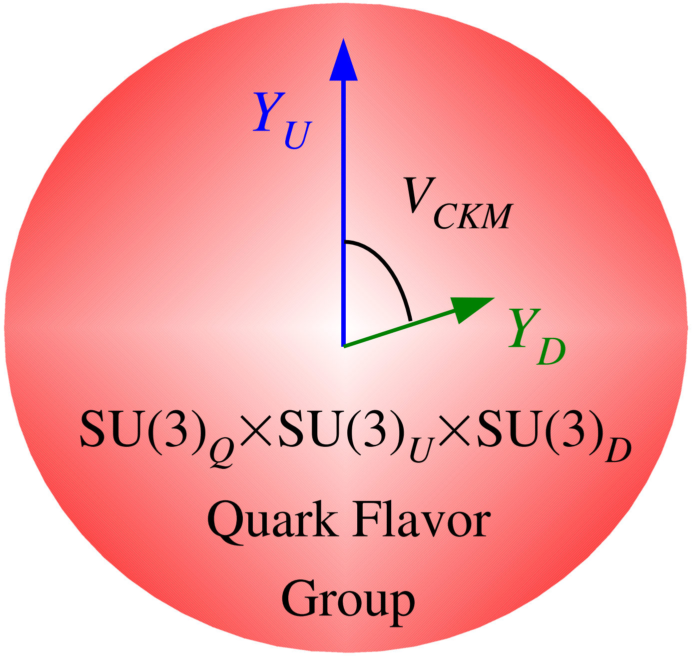
In principle we can consider higher powers of the Y.
However, because of their hierarchical nature this does not change the picture:

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

Basic MFV:

- Flavour symmetry:
  $\mathrm{U}(3)^5 = \mathrm{SU}(3)_Q \times \mathrm{SU}(3)_U \times \mathrm{SU}(3)_D \times \ldots$

- Symmetry-breaking terms:
  $Y_D \sim 3_Q \times \bar{3}_D \qquad Y_U \sim 3_Q \times \bar{3}_U$



Main virtues:

- Bounds on NP scales range from few×TeV (for strongly interacting theories) to few×100 GeV (for weakly interacting theories)

- Very predictive framework:
  - All FCNC amplitudes have the same CKM structure as in the SM [e.g.: $A(b\to s\gamma) \propto V_{bt}V_{ts}$, $A(s\to d\gamma) \propto V_{st}V_{td}$, ...] and only the flavour–independent magnitude can be modified
  - *Phase measurements* [e.g.: $A_{CP}(B\to\psi K_S)$, $A_{CP}(B\to\phi K_S)$, $\Delta M_{B_d}/\Delta M_{B_s}$] are completely unaffected by new physics

Basic MFV:

- Flavour symmetry:

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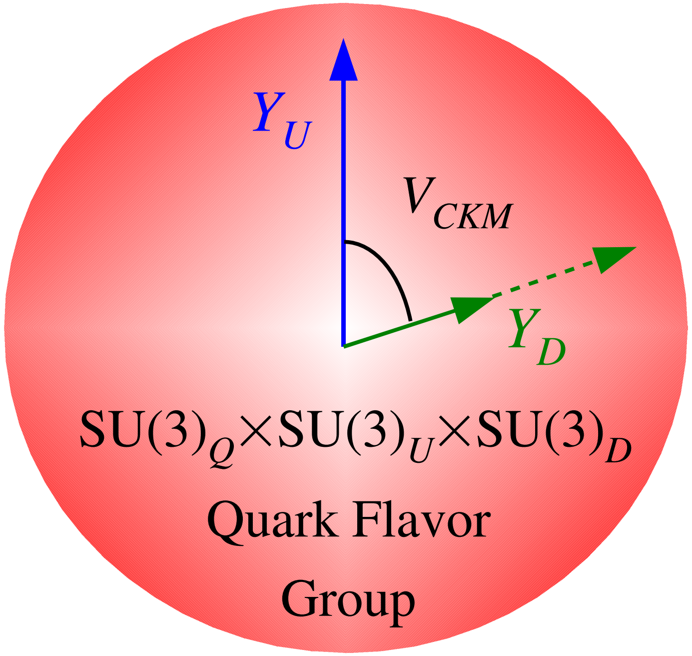


$SU(3)_Q \times SU(3)_U \times SU(3)_D$

Quark Flavor

Group

Interesting extension/variation in case of more than one Higgs doublet:

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

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

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

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

↓

Interesting phenomenological signatures in *helicity-suppressed* observables

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

But is a usueful predictive/falsifiable construction which allow us to identify which are the irreducible sources of flavour-symmetry breaking

A few important comments:

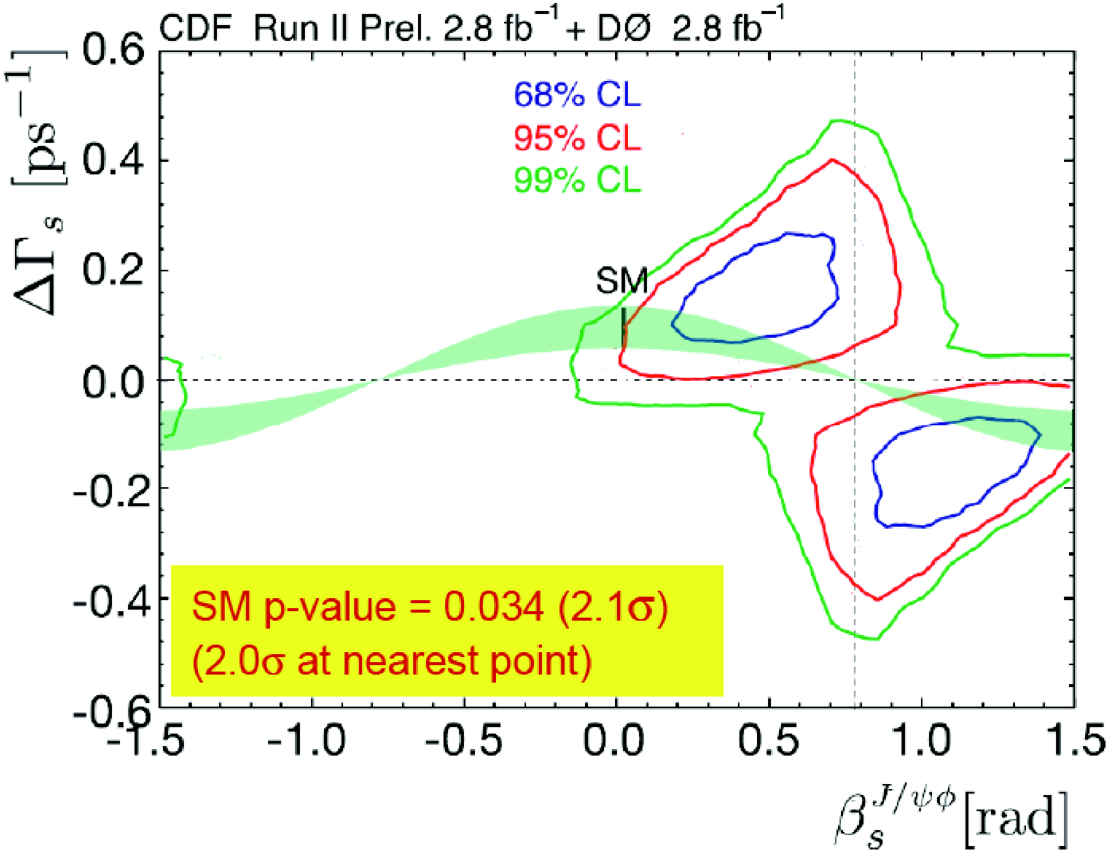
I) MFV is not a theory of flavour

II) There is still room for non-MFV effects

According to the recent CDF & D0 results on the time-dependent CP asymmetry in $B_s \to \psi\phi$, there is even a ~2σ deviation from MFV (and the SM) in the phase of B_s mixing.

If confirmed, this would rule out both SM and MFV hypothesis.

But we have to wait...



A few important comments:

I) MFV is not a theory of flavour

II) There is still room for non-MFV effects

III) Even if we forget about B_s mixing, MFV is far from being "verified"

To prove MFV from data we would need to

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

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

ΔF =2 processes are in principle good candidates to prove MFV, but so far we are limited by theoretical (Lattice) uncertainties

Some ΔF=1 rare decays could provide more useful infos to proof (or disproof) the MFV hypothesis from data (very interesting candidates: $B_{d,s} \to l^+ l^-$)

A few important comments:

I) MFV is not a theory of flavour

II) There is still room for non-MFV effects

III) Even if we forget about B_s mixing, MFV is far from being “verified”

IV) Even within the “pessimisic” MFV hypothesis, we can still expect sizable deviations from the SM in various B physics observables...

Typical examples:

$B_{d,s} \to l^+ l^-$ up to order of magnitude enhancements if tanβ is large

$A_{FB}(B \to K^* l^+ l^-)$ up to O(1) deviations from the SM

Flavour breaking in the MSSM

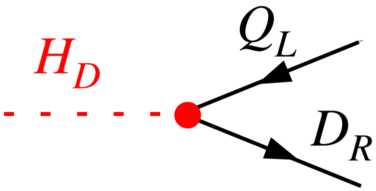
The Minimal Supersymmetric extension of the SM includes:

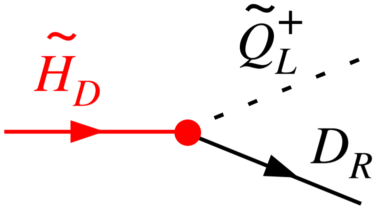
- scalar partners of the ordinary quarks and leptons [$\tilde{Q}_L$, $\tilde{u}_R$, ...]
- spin-1/2 partners of the ordinary gauge bosons [*gauginos*]
- Two Higgs doublets [H_U, H_D] with their corresponding spin-1/2 partners

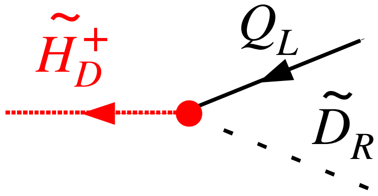
The SUSY version of $\mathscr{L}_{\text{gauge}}$ is completely determ. by its symmetry properties

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

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







+ 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:

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

potential new sources of
flavour-symmetry breaking

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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.

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

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

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

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

gaugino/higgsino masses squark/slepton masses trilinear scalar couplings

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

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

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

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 $\tan\beta = \langle\phi_U\rangle/\langle\phi_D\rangle$)

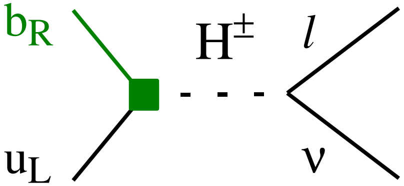
$$\mathcal{L}_{\text{q-Yukawa}} = \bar{Q}_L Y_D D_R \phi_D + \bar{Q}_L Y_U U_R \phi_U + \text{h.c.}$$

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

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

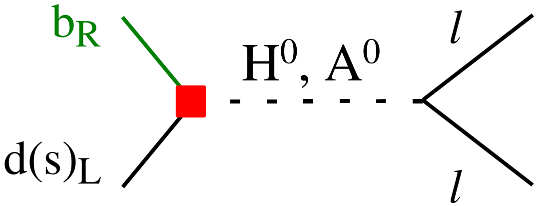
$$\Downarrow$$

Interesting phenomenological signatures in *helicity-suppressed* observables:

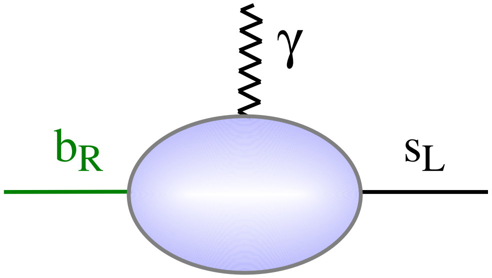


$B^{\pm} \to l^{\pm}\nu$

$(B \to D\tau\nu)$

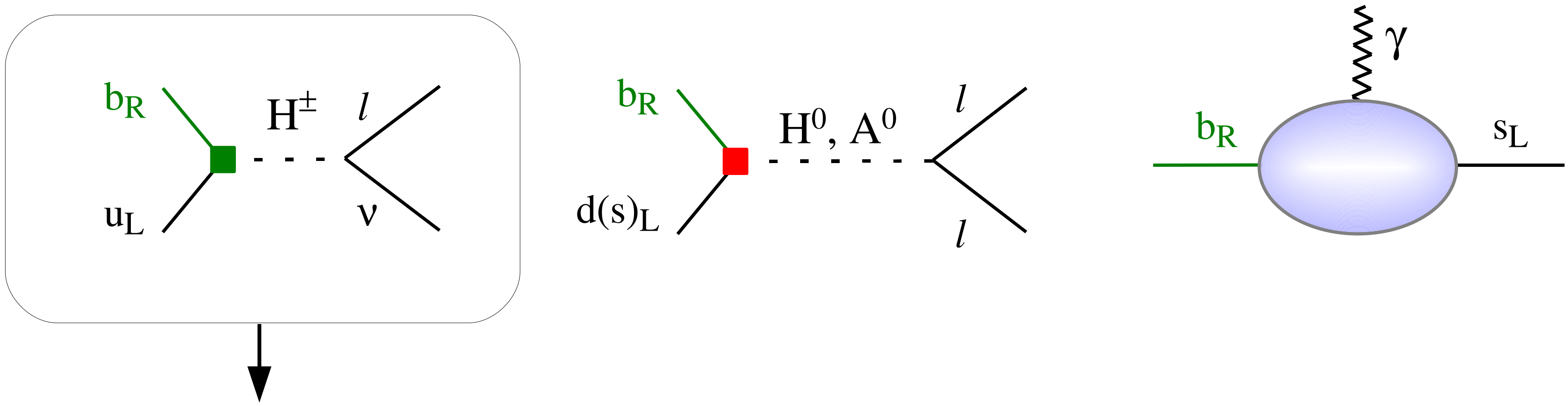


$B_{s,d} \to l^+ l^-$



$B \to X_s \gamma$

MSSM with MFV at large tanβ



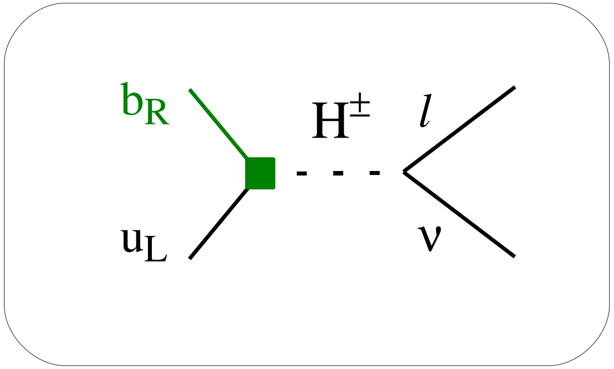
The $H^\pm$ exchange appear at the tree-level in charged-current amplitudes.
The effect is usually negligible (suppression of Yukawa couplings),
except for helicity suppressed observables ($B \to l\nu$) or τ final states ($B \to D\tau\nu$)

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

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

- O(10-30%) effect in $B \to l\nu$
- ~ 3 times smaller in $B \to D\tau\nu$
- ~ 100 times smaller in $K \to l\nu$

*MSSM with MFV at large tan*β



Present status:

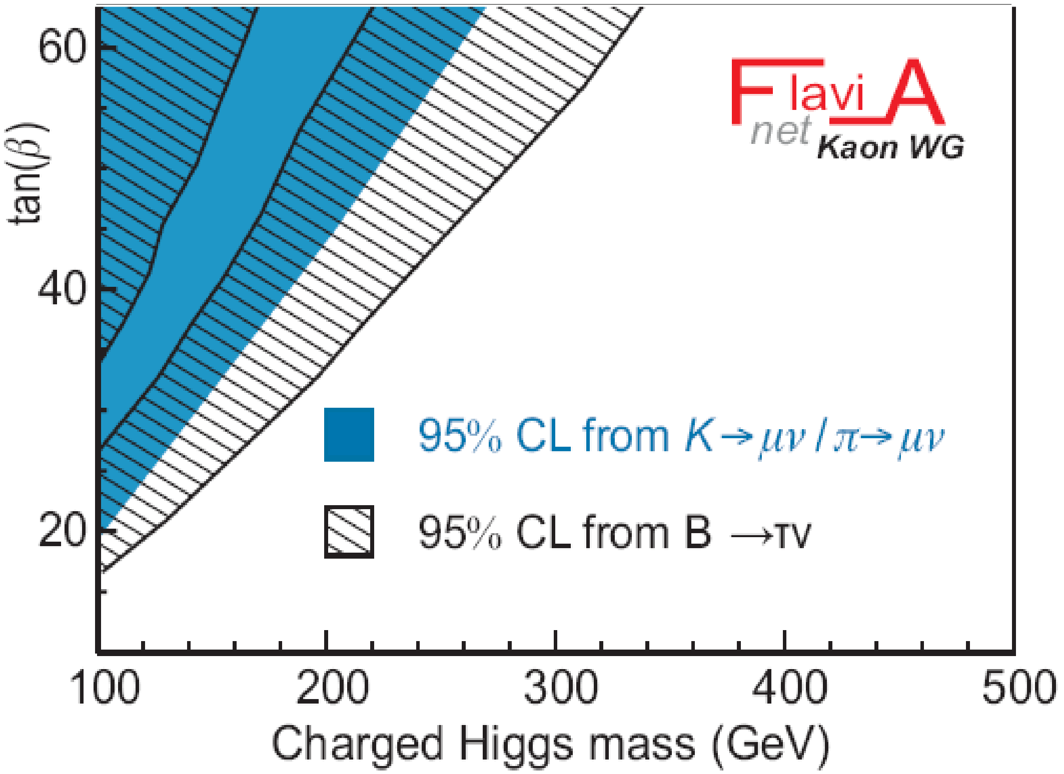
$$B(B \to \tau\nu) = (1.51 \pm 0.33)\times 10^{-4}$$

Babar+Belle '09

$$B(B \to \tau\nu)_{SM} = B_0 f_B^2\, V_{ub}^2 \approx 1.2\times 10^{-4}$$

sizable theoretical
(parametric) error

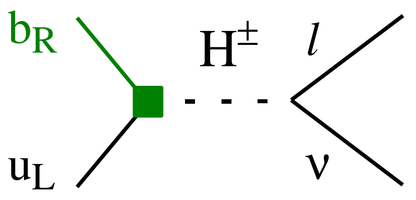
The B → *D* τ ν channel could be relevant for hadronic machines

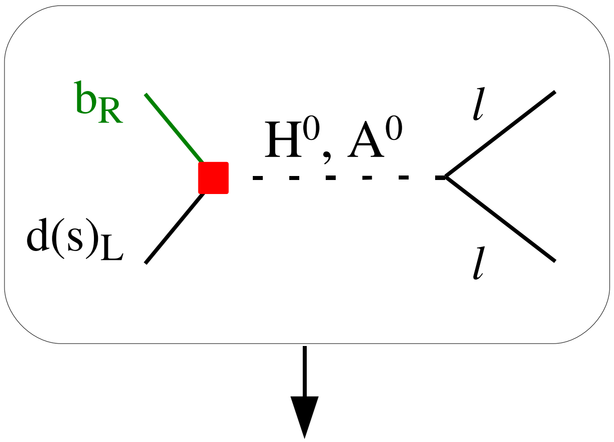


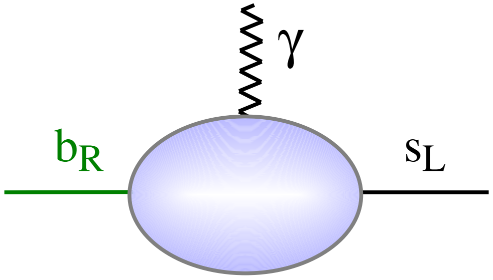
Improving th. and exps. on these channels can lead to very valuable infos on M_H & tanβ !

N.B.: key role played by lattice QCD

▸ *MSSM with MFV at large tan*β

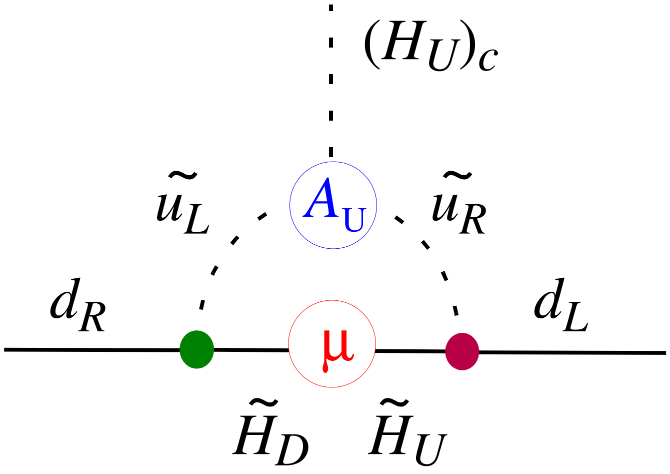






$B \to X_s \gamma$

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 & $\tan\beta$]

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

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 tan*β

Present status:

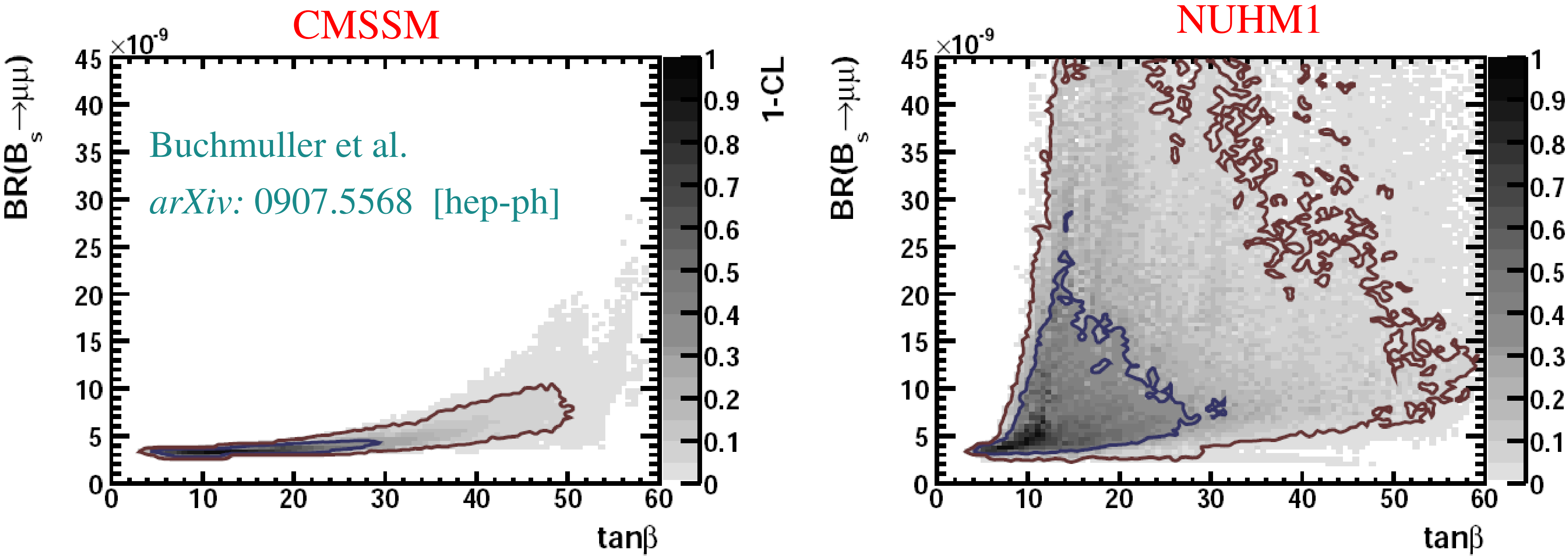
$\mathrm{B}(B_s \rightarrow \mu\mu) < 4.8 \times 10^{-8}$ (95%CL)

$\mathrm{B}(B_s \rightarrow \mu\mu) < 7.6 \times 10^{-9}$ (95%CL)

[CDF '09]

$\mathrm{B}(B_s \rightarrow \mu\mu)_{\mathrm{SM}} = 3.2(2) \times 10^{-9}$

$\mathrm{B}(B_d \rightarrow \mu\mu)_{\mathrm{SM}} \approx 1.0 \times 10^{-10}$



Buchmuller et al.

arXiv: 0907.5568 [hep-ph]

Reaching the SM level would lead to a very significant constraints in the (C)MSSM

*MSSM with MFV at large tan*β

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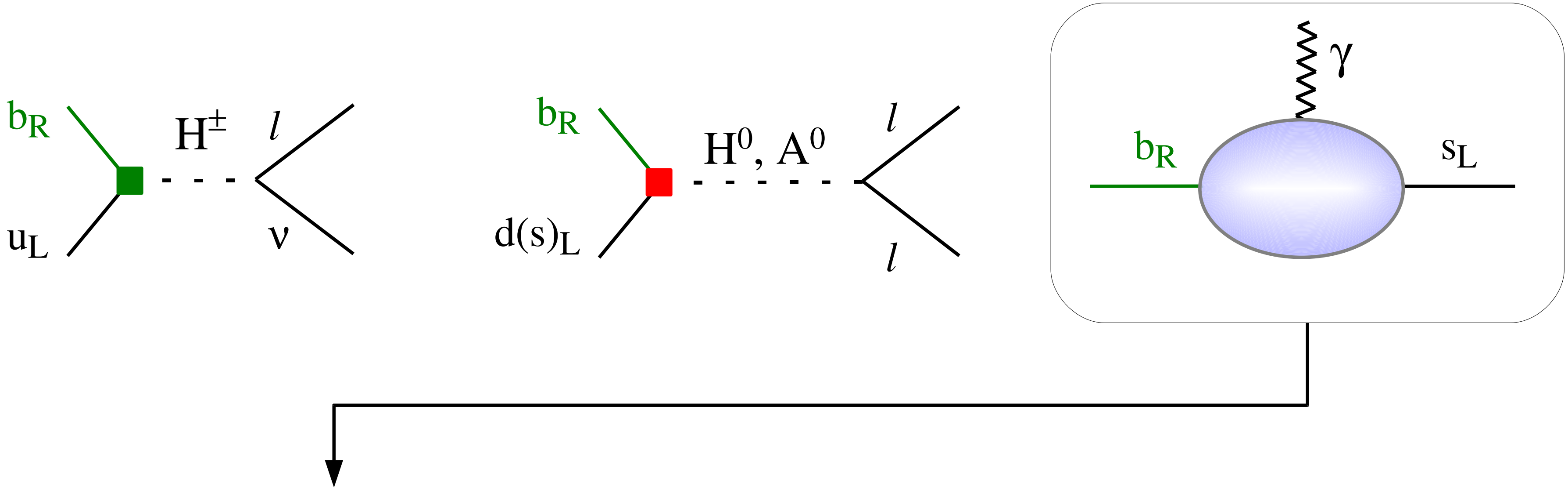
[CDF '09]

$\mathrm{B}(B_s \to \mu\mu)_{\mathrm{SM}} = 3.2(2) \times 10^{-9}$

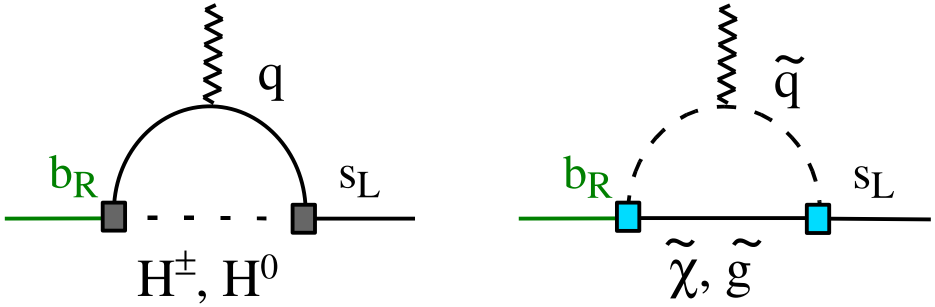
$\mathrm{B}(B_d \to \mu\mu)_{\mathrm{SM}} \approx 1.0 \times 10^{-10}$

- Th. error controlled by f_B (⇒lattice). Not a big issue if deviations from SM are large, but important to improve in view of future precise measurements
- The $\mathrm{B}(B_d \to \mu\mu)/\mathrm{B}(B_s \to \mu\mu)$ ratio is a key observable to proof or falsify MFV

MSSM with MFV at large tanβ



Most complicated observable with several, naturally competitive, contributions:



- positive
- decreasing with tanβ

- sign ~ sgn(μ,A)
- increasing with tanβ

One of the most significant constraint on the MSSM (even at small tanβ)

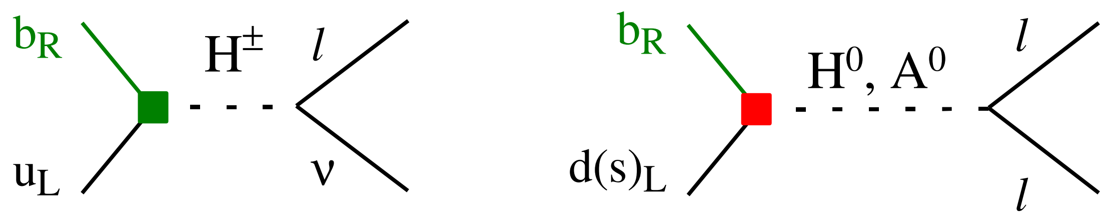
$$B(B \to X_s\gamma)^{\rm exp} = (3.57 \pm 0.24)\times 10^{-4}$$

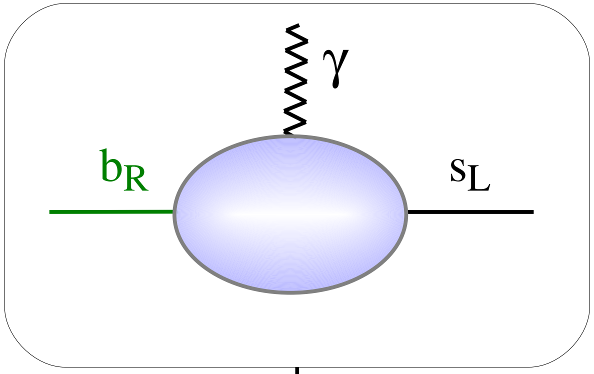
HFAG '09

$$B(B \to X_s\gamma)^{\rm SM} = (3.15 \pm 0.23)\times 10^{-4}$$

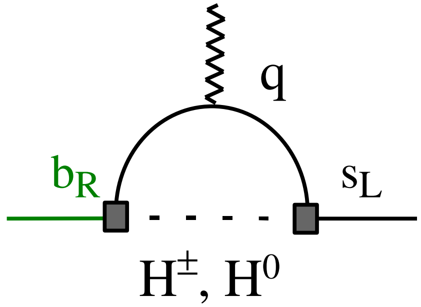
Misiak *et al.* '07

MSSM with MFV at large tanβ

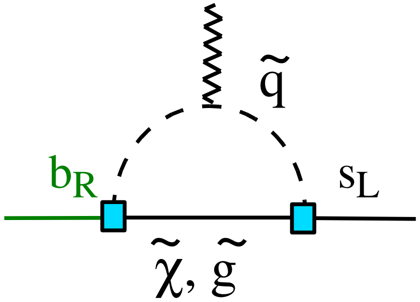




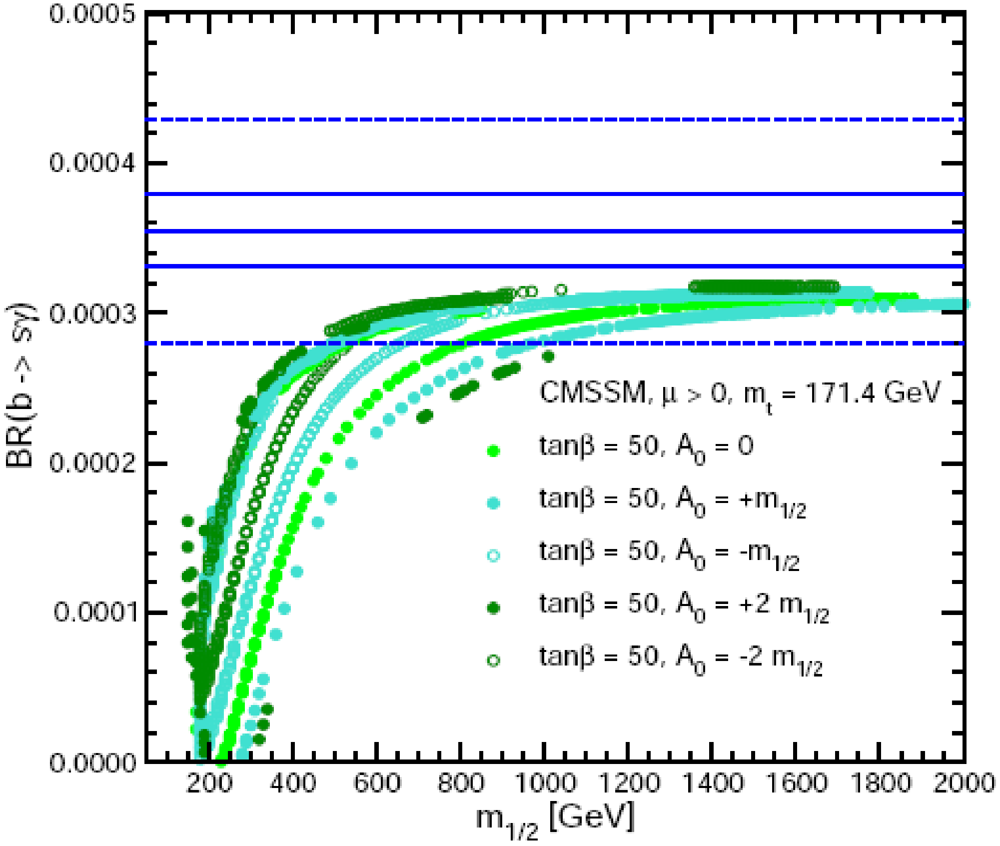
Most complicated observable with several, naturally competitive, contributions:



- positive
- decreasing with tanβ

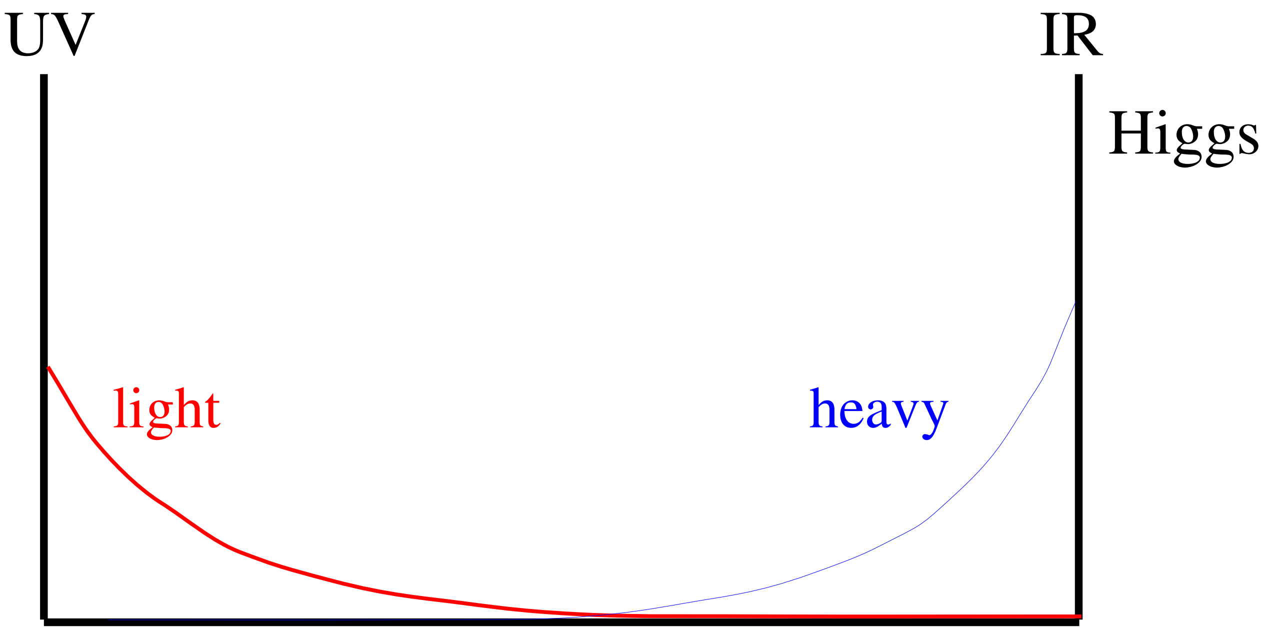


- sign ~ sgn(μ,A)
- increasing with tanβ



Flavour protection from warped space

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 (localised on the IR brane)



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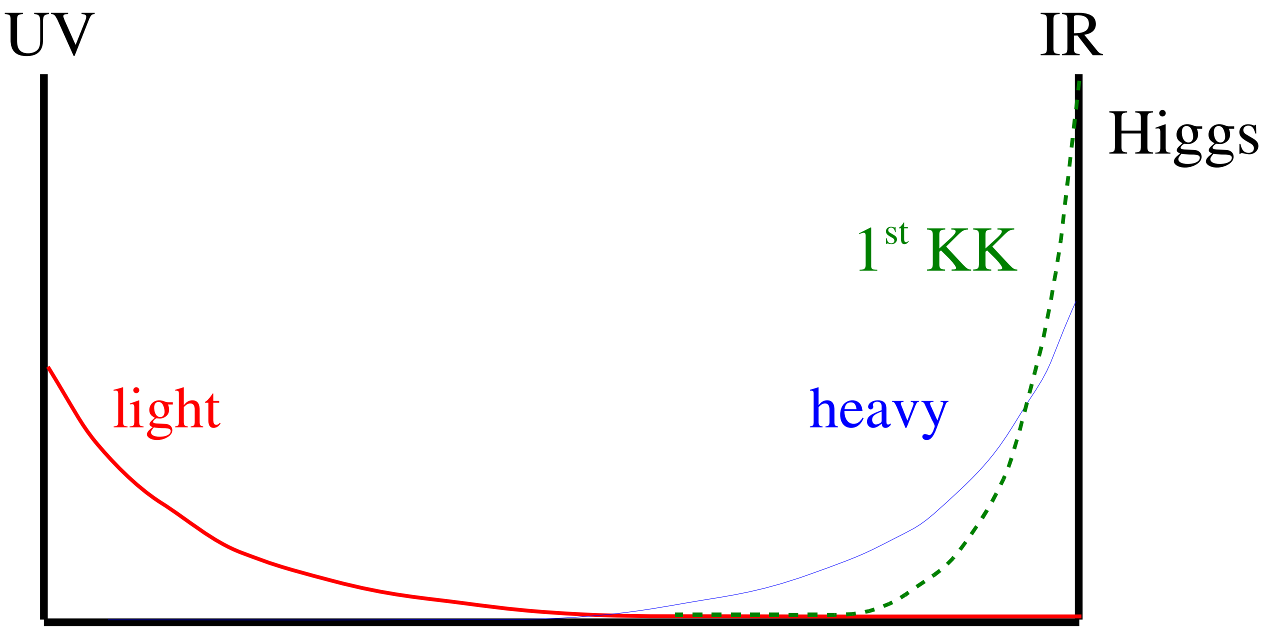


In 5D models with warped geometry, this construction provides a potentially interesting alternative to MFV to explain the suppression of FCNCs beyond the SM

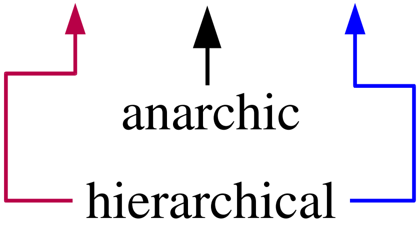
Flavour protection from warped space

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

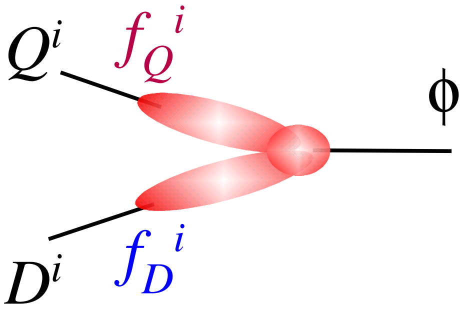
$$Y_D^{ij} = f_Q^{\,i}\,(\mathbf{Y}_D^{5D})\,f_D^{\,j} \approx f_Q^{\,i} f_D^{\,j}$$

$$Y_U^{ij} = f_Q^{\,i}\,(\mathbf{Y}_U^{5D})\,f_U^{\,j} \approx f_Q^{\,i} f_U^{\,j}$$



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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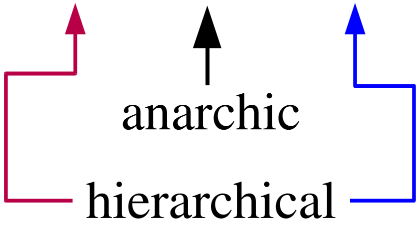
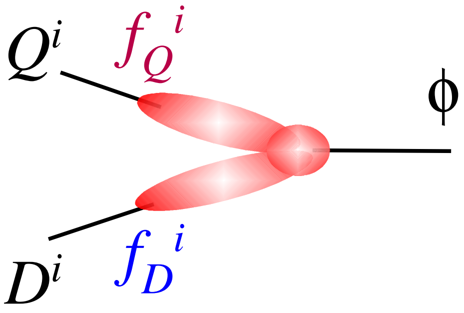
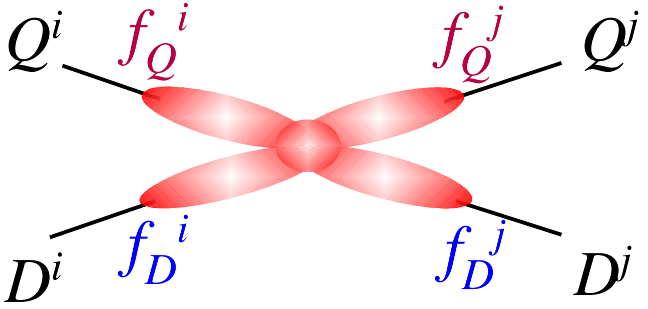


- There is no underlying flavour symmetry (complete anarchy) in the new strongly interacting sector: dim.-6 FCNC operators suppressed only by the light-fermion wave functions (= *mixing with the new heavy states*)





Flavour protection from warped space

This construction works remarkably well in various cases:

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

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

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

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

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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- All the left-handed FCNC operators (the leading ones in the SM) have the same suppression as in MFV:
- However, some problem arieses with helicity-suppressed operators, in 2 →1 transitions (kaon physics):

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

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

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to be compared with

$$\bar{D}_R^{\,i}\, (Y_D Y_U Y_U^{\,+})_{\rm ij}\ Q_L^{\,j} = y_{d_i}\, y_t^{\,2}\, V_{3\rm i}^{\,*} V_{3\rm j}\, \bar{Q}_R^{\,i}\ Q_L^{\,j} \nearrow \sim y_b\, y_t^{\,2}\, V_{\rm tb}^{\,*} V_{\rm ts}\, (b_R s_L)$$

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big difference !

to be compared with

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

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.

This discussion has allowed to illustrate 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-suppressed observables and/or clean kaon-physics observables (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 B physics in the LHC era

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

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