Plan of the lectures:

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

- Flavor physics beyond the SM
  - Minimal Flavor Violation
  - Flavor breaking in the MSSM
  - MSSM with MFV at large tanβ
  - SUSY beyond MFV
  - Flavor physics with partial compositeness
  - Conclusions

From the first lecture...

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

c_{NP}

$$\sim 1 \xrightarrow{\text{tree/strong + generic flavor}} \Lambda \gtrsim 2\times10^4\ \text{TeV [K]}$$

$$\sim 1/(16\pi^2) \xrightarrow{\text{loop + generic flavor}} \Lambda \gtrsim 2\times10^3\ \text{TeV [K]}$$

$$\sim (y_t\, V_{ti}^*V_{tj})^2 \xrightarrow{\text{tree/strong + “alignment”}} \Lambda \gtrsim 5\ \text{TeV [K \& B]}$$

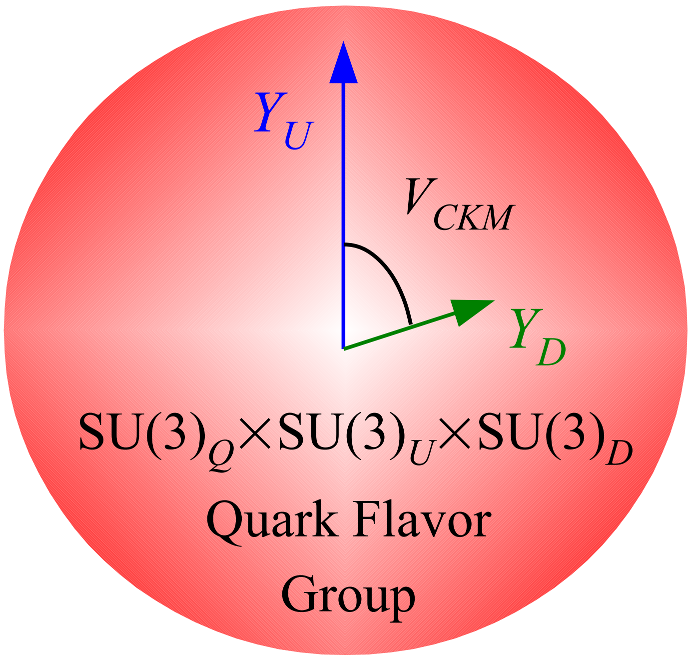
$$\sim (y_t\, V_{ti}^*V_{tj})^2/(16\pi^2) \xrightarrow{\text{loop + “alignment”}} \Lambda \gtrsim 0.5\ \text{TeV [K \& B]}$$

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

Within the SM...

- Flavor 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]



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

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

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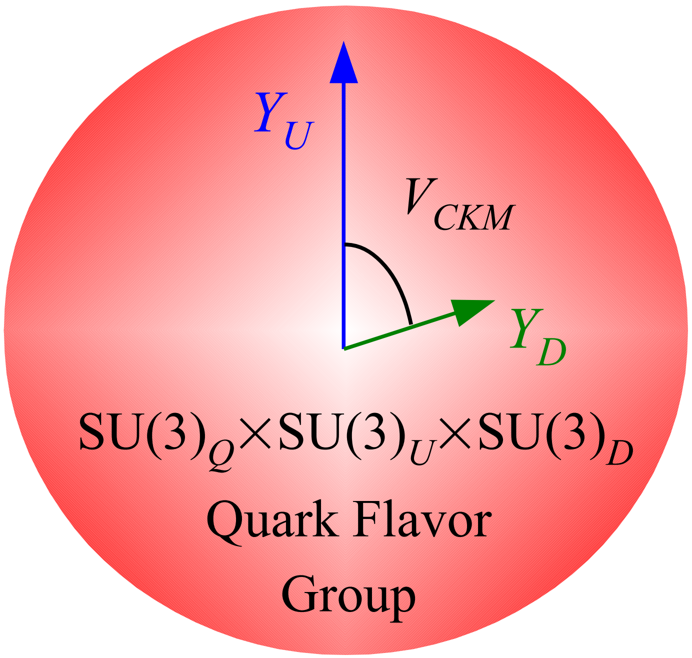

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This specific symmetry + symmetry-breaking pattern is responsible for the GIM suppression of Flavor Changing Neutral Currents, the suppression of CPV,...

all the successful SM predictions in the quark flavor sector

Minimal Flavor Violation

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

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

$$\mathscr{L}_{\text{Yukawa}} = \underbrace{\bar{Q}_L}_{(\bar{3},1,1)} \underbrace{Y_D}_{(3,1,\bar{3})} \underbrace{D_R}_{(1,1,3)} \phi + \bar{Q}_L Y_U U_R \phi_c + \bar{L}_L Y_L e_R \phi + \text{h.c.}$$

$\Downarrow$

$(1,1,1)$ = invariant

Minimal Flavor Violation

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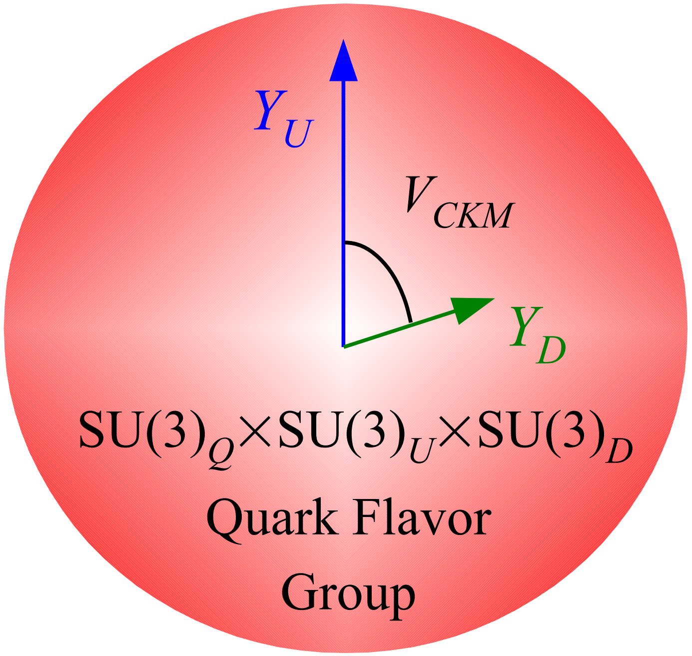
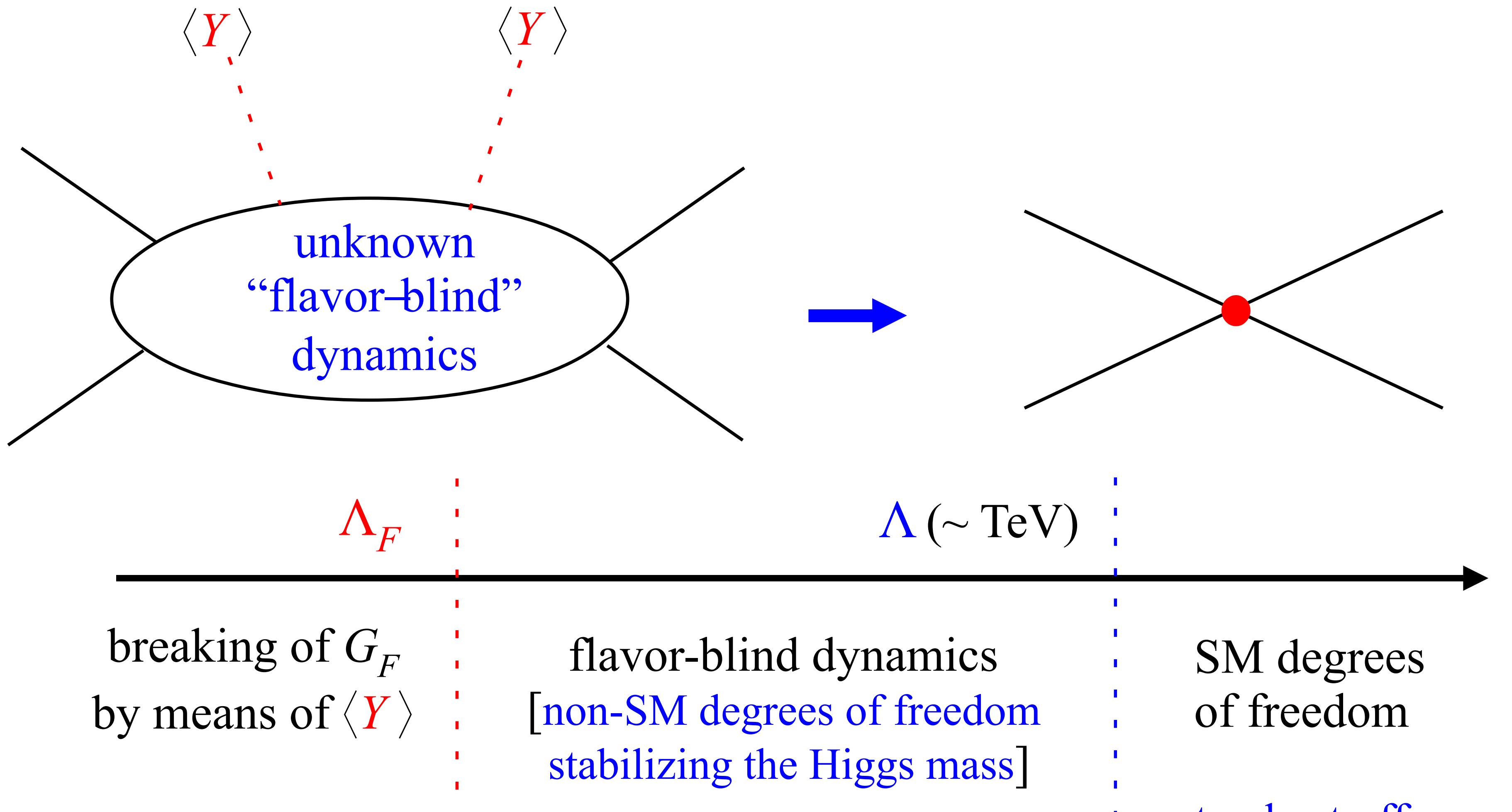


A natural mechanism to reproduce the SM successes in flavor physics -without fine tuning- is the MFV hypothesis:

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

Minimal Flavor Violation



natural cut-off
scale of the effective
theory

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

Minimal Flavor Violation

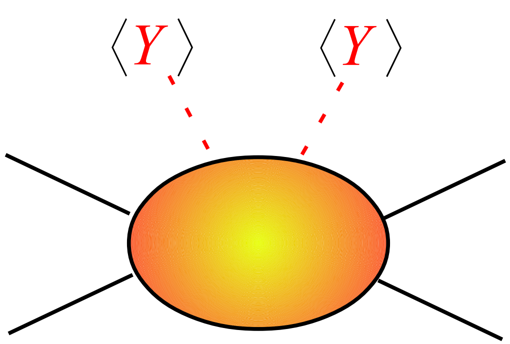
A low-energy EFT satisfies the criterion of MFV if all higher-dimensional operators, constructed from SM and Y fields, are (formally) invariant under the flavor group [$SU(3)_Q \times SU(3)_U \times SU(3)_D$]

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: $\bar{Q}_L^{\,i}\, (Y_U Y_U^{+})_{ij}\, Q_L^{\,j} \times \bar{L}_L L_L$

$$\underbrace{(3,\bar{3},1) \quad (\bar{3},3,1)}_{\displaystyle \Downarrow\ (1,1,1)}$$



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

$$\downarrow$$

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

same CKM structure
of the dominant
(top-induced or short-distance)
SM contribution !

Minimal Flavor Violation

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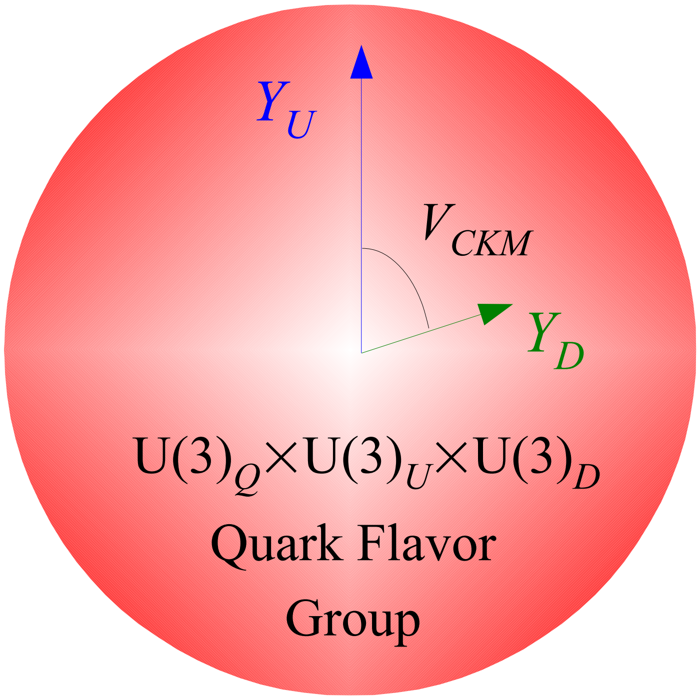
Typical FCNC dim.-6 operator: $\bar{Q}_L^{\,i}\, (Y_U Y_U^+)_{ij}\, Q_L^{\,j} \times \bar{L}_L L_L$

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:

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

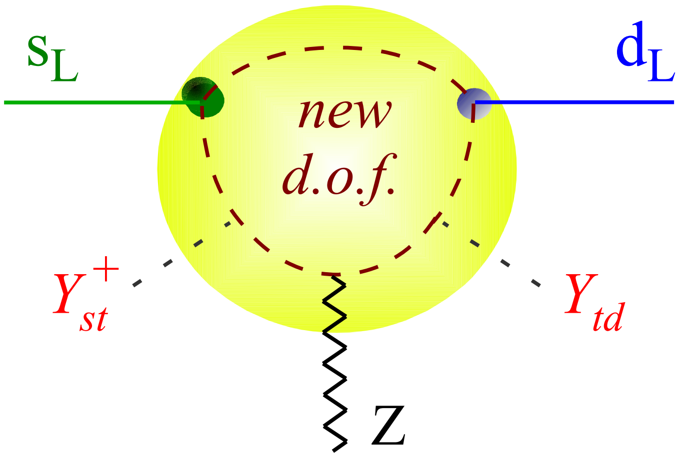


Main virtues:

- General principle that can be implemented independently of the specific high-energy 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 flavor-changing loop-induced amplitudes have the same CKM/Yukawa structure as in the SM. Only the flavor-independent magnitude of the transition amplitudes can be modified.

All flavor-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 flavor-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 flavor

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 flavor-symmetry breaking

A few important comments:

I) MFV is not a theory of flavor

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:

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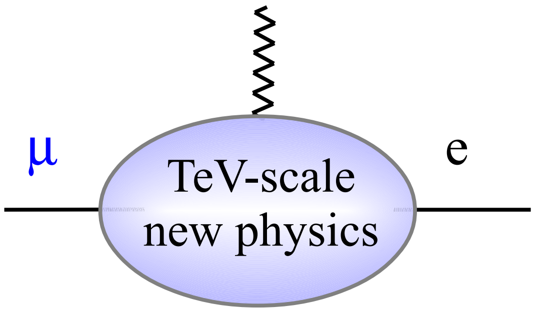
II) Despite its phenomenological success, MFV is far from being "verified"

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

Typical examples:

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

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



B($\mu \to e\gamma$) could reach values in the 10^{-12} - 10^{-13} range (*within the reach of MEG*)

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Three particularly interesting direction of research in flavor 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

Flavor breaking in the MSSM

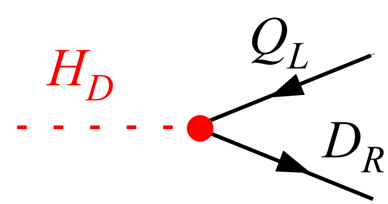
The Minimal Supersymmetric extension of the SM includes:

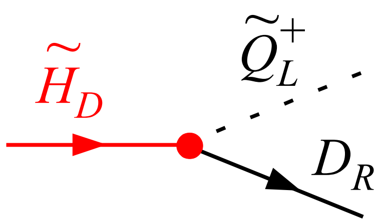
- scalar partners of the ordinary quarks and leptons [$\widetilde{Q}_L$, $\tilde{u}_R$, ...]
- spin-1/2 partners of the ordinary gauge bosons [*gauginos*]
- Two Higgs doublets [H_U, H_D] with their corresponding spin-1/2 partners

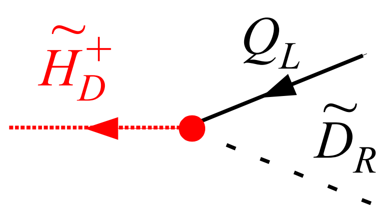
The SUSY version of $\mathscr{L}_{\text{gauge}}$ is completely determ. by its symmetry properties

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 (and a large number of new 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

potential new sources of flavor-symmetry breaking

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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 flavor physics observables

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

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

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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

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N.B.: The Constrained MSSM (CMSSM) is a particular choice (*dictated by minimality*) within the wider class of MSSM+MFV hypothesis

MSSM with MFV at large tanβ

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

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

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

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

The combination of vevs that determine W and Z masses is

$$v^2 = \langle\phi_U\rangle^2 + \langle\phi_D\rangle^2 = (246 \text{ GeV})^2$$

The two Higgs doublets contains 4 + 4 independent fields:

- 3 Goldstone bosons (as in the SM)
- 5 physical massive Higgs fields: $h^0 + H^0, A^0, H^\pm$

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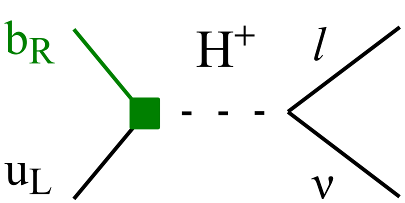
$$y_u = m_u / \langle\phi_U\rangle$$

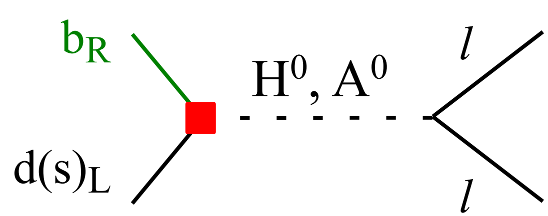
$$y_d = m_d / \langle\phi_D\rangle = \tan\beta\, m_d / \langle\phi_Y\rangle$$

$\Downarrow$

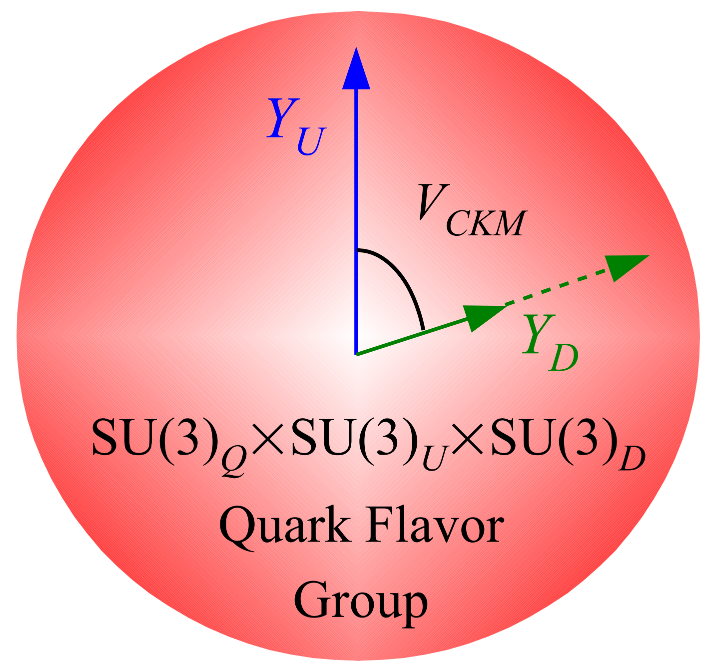
Interesting phenomenological signatures in *helicity-suppressed* observables:



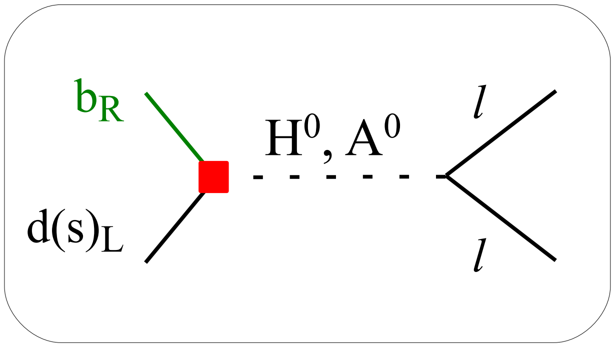
$B^+ \to l^+ \nu$



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

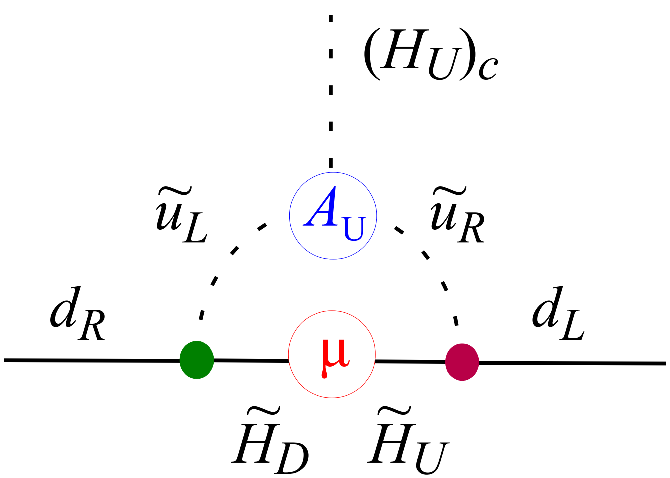


MSSM with MFV at large tanβ



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:



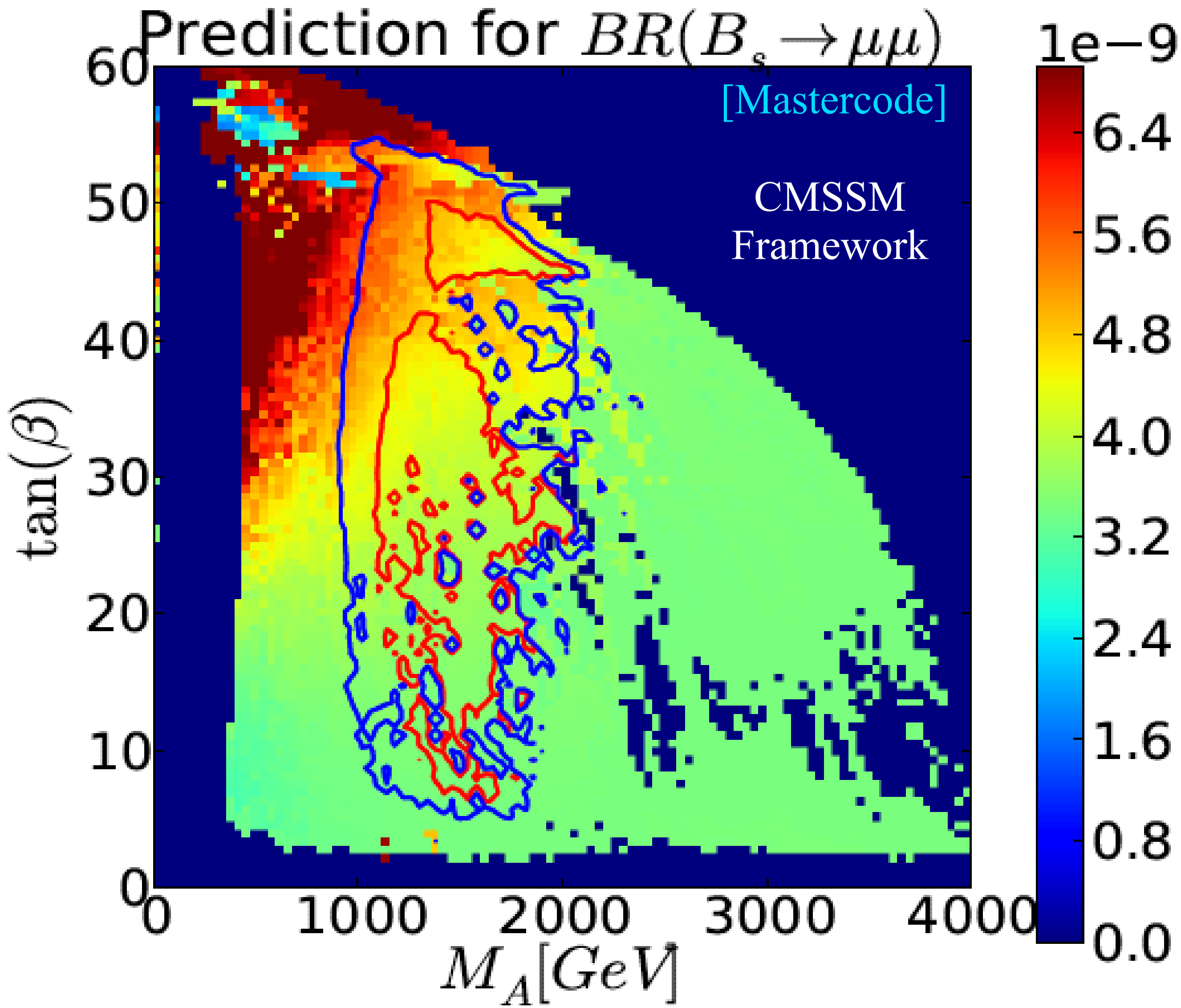
Crucial dependence on μ and A_U [+ M_H & tanβ]

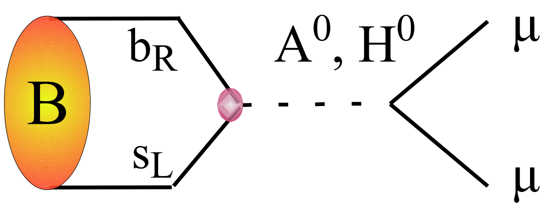
$$A(B\to ll)_H \sim \frac{m_b\, m_l}{M_A^{\,2}} \, \frac{\mu\, A_U}{\tilde{M}_q^{\,2}} \, \tan^3\beta$$

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

Impact of the present experimental bound on BR($B_s \to \mu^+\mu^-$) in constrained versions o the MSSM:





The possible large effects occurring in the large tanβ region are ruled out, but sizable modifications are still possible.

Buchmueller *et al*. [Mastercode]
Mahmoudi *et al.* [SuperIso]
Roszkowski *et al*
Haisch & Mahmoudi '12
…

MSSM with MFV at large tanβ

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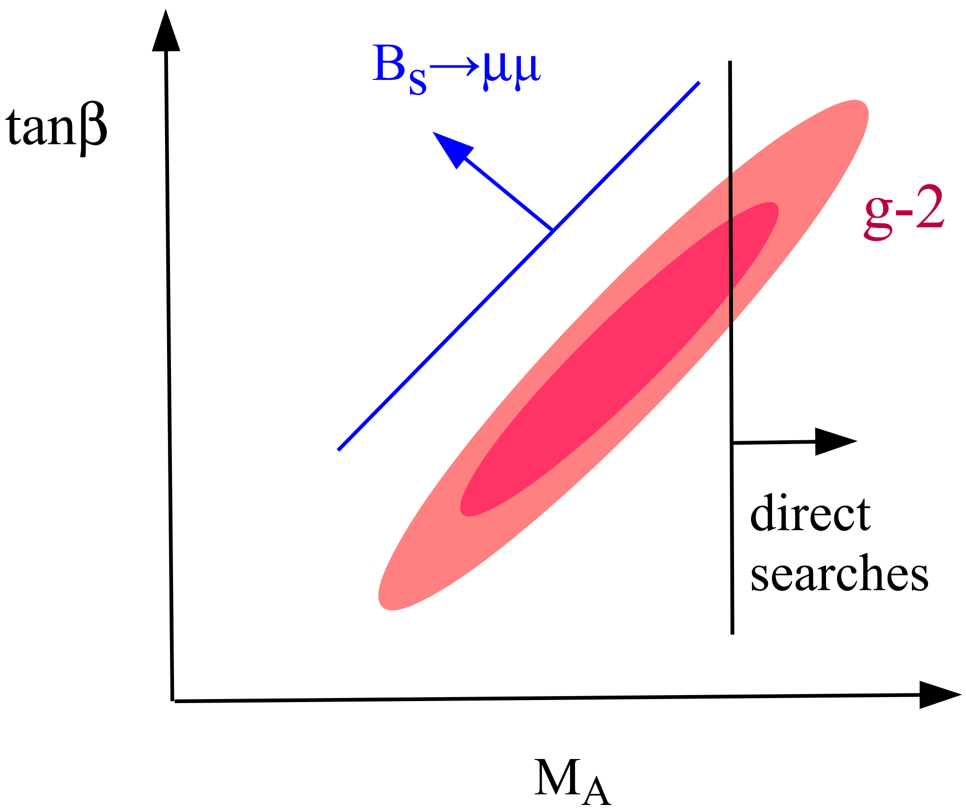
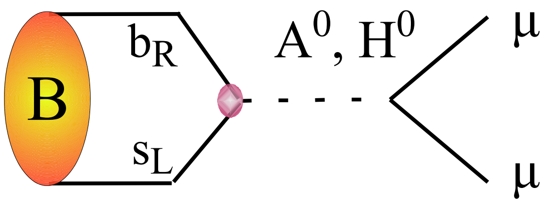




The possible large effects occurring in the large tanβ region are ruled out, but sizable modifications are still possible.

Nice complementarity with direct searches and other indirect observables...

SUSY beyond MFV

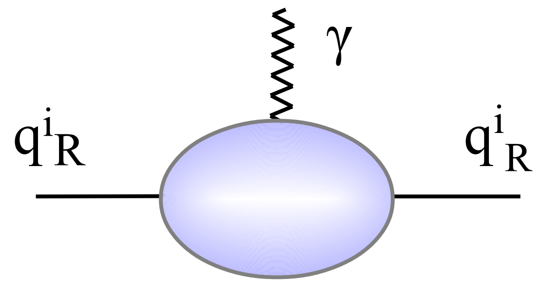
MFV virtue

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

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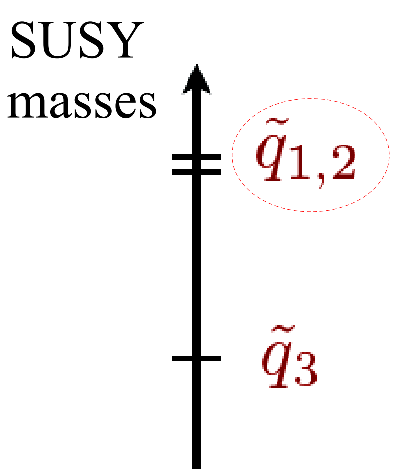


Both issues can be improved with "split-family susy" + flavor symmetry acting only on 1st & 2nd generations

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

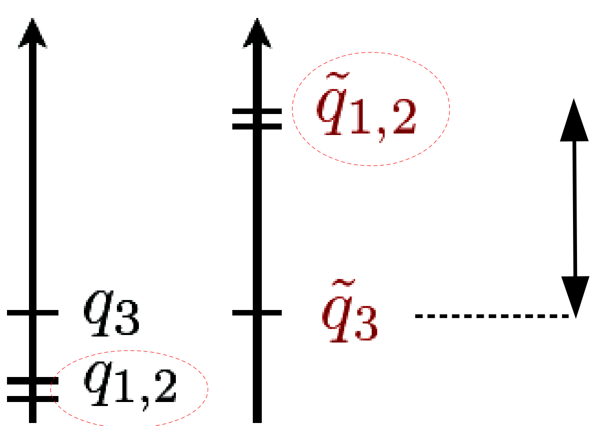
Split-family SUSY

Naturally small effects in FCNC observables

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

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

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

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

$$\downarrow$$

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

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

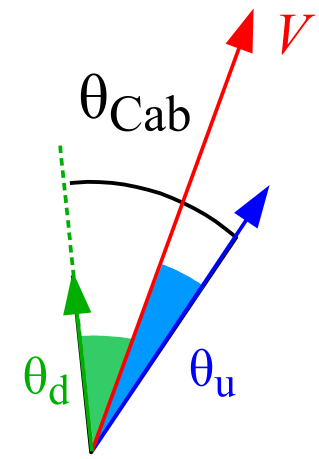
$$\boxed{V \sim (2,1,1) \quad O(\lambda^2 \sim 0.04)}$$

Leading breaking [3rd gen. → 1,2 gen.]

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

$$Y_u = y_t \left[\begin{array}{c|c} 0 & c_u V \\ \hline 0 & 1 \end{array}\right] \qquad Y_d = y_b \left[\begin{array}{c|c} 0 & c_d V \\ \hline 0 & 1 \end{array}\right] \quad \rightarrow \quad V_{CKM} \sim \left[\begin{array}{c|c} 1 & \lambda^2 \\ \hline 0 & 1 \end{array}\right]$$

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



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$\boxed{V \sim (2,1,1) \quad O(\lambda^2 \sim 0.04)}$ 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 $O(y_s < 0.001)$

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

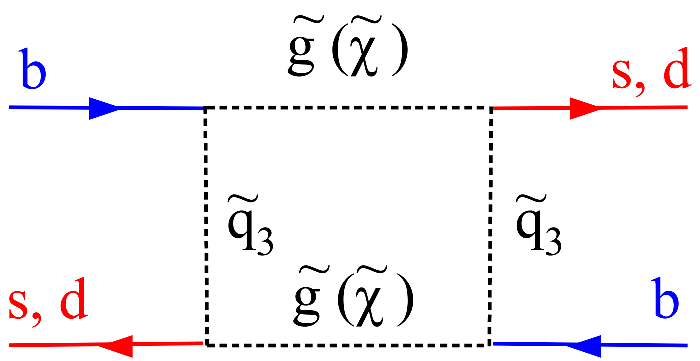
$$Y_u = y_t \begin{bmatrix} \Delta Y_u & c_u V \\ 0 & 1 \end{bmatrix} \qquad Y_d = y_b \begin{bmatrix} \Delta Y_d & c_d V \\ 0 & 1 \end{bmatrix} \quad \longrightarrow$$

$$|V_{us}| \approx |\theta_u - \theta_d|$$
$$|V_{td}/V_{ts}| = \theta_d$$
$$|V_{ub}/V_{cb}| = \theta_u$$

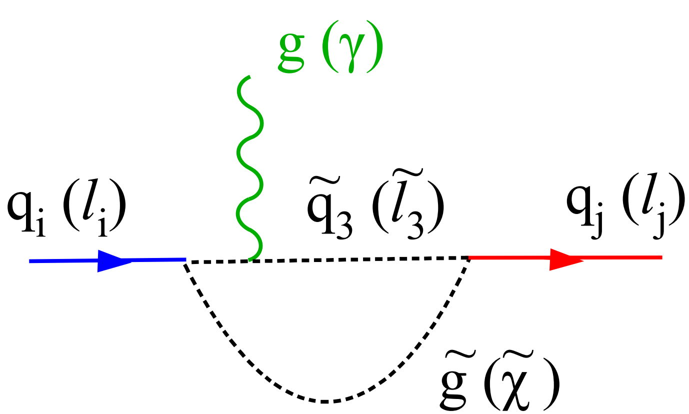
SUSY beyond MFV

In this framework 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"



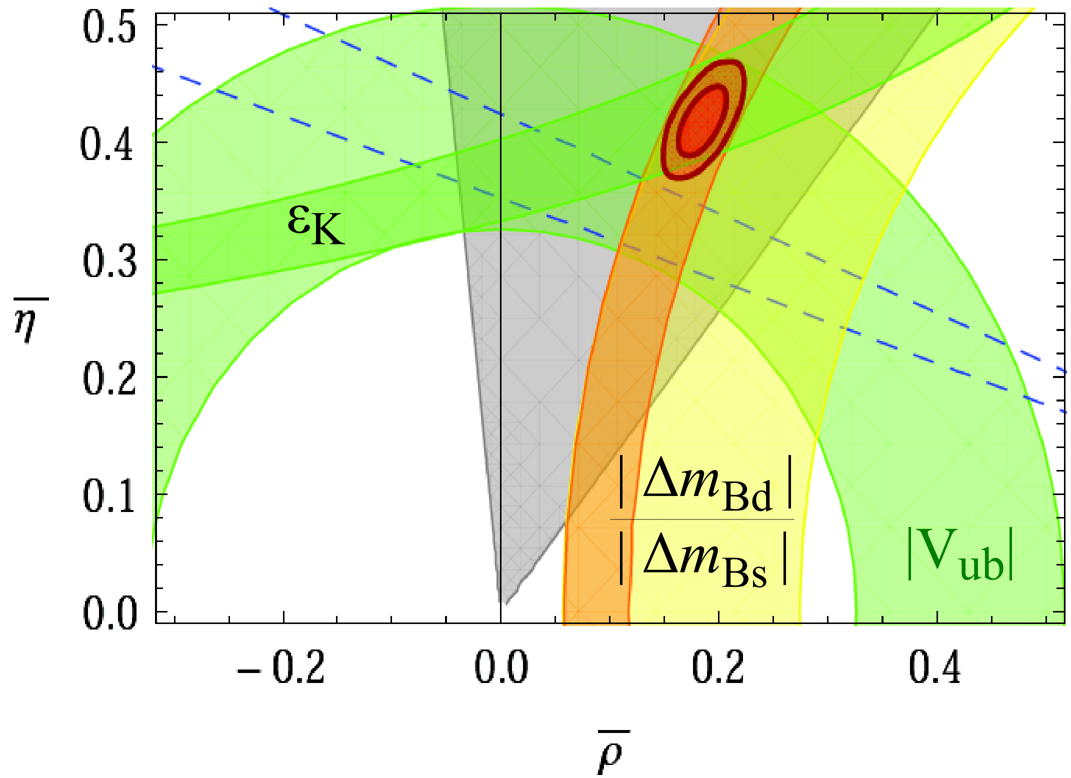
Possible non-standard contributions to LFV & EDMs + rare K, B and D decays

▸ *SUSY beyond MFV*

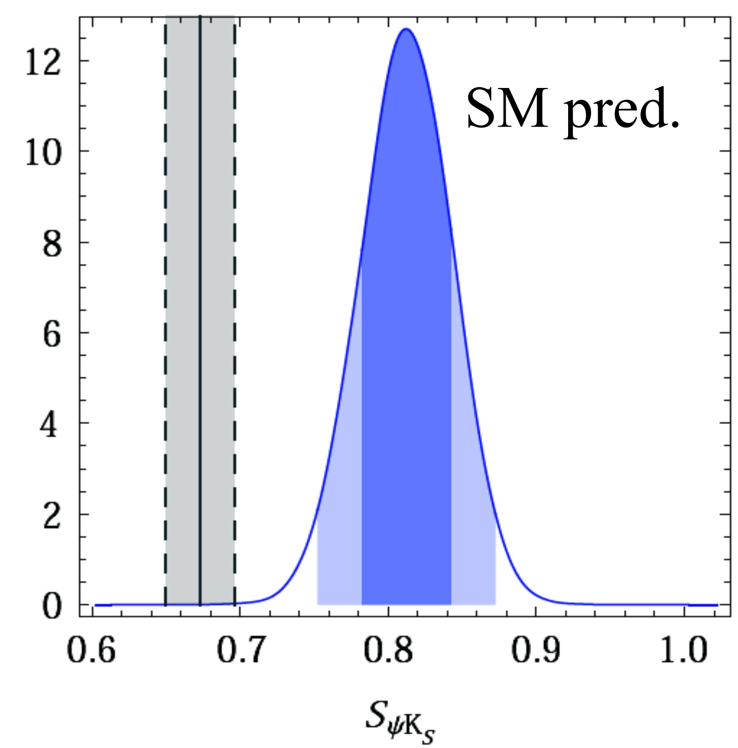
The “ε_K - sin(2β)” tension

Despite the overall consistency of the CKM picture, looking more closely the agreement of the various constraints is not perfect. At present there is a tension between ε_K (CPV in K^0 mixing) & $S_{\psi K}$= sin(2β) (CPV in B_d mixing)

SM fit, no $S_{\psi K}$ (no B_d mixing phase):



exp.

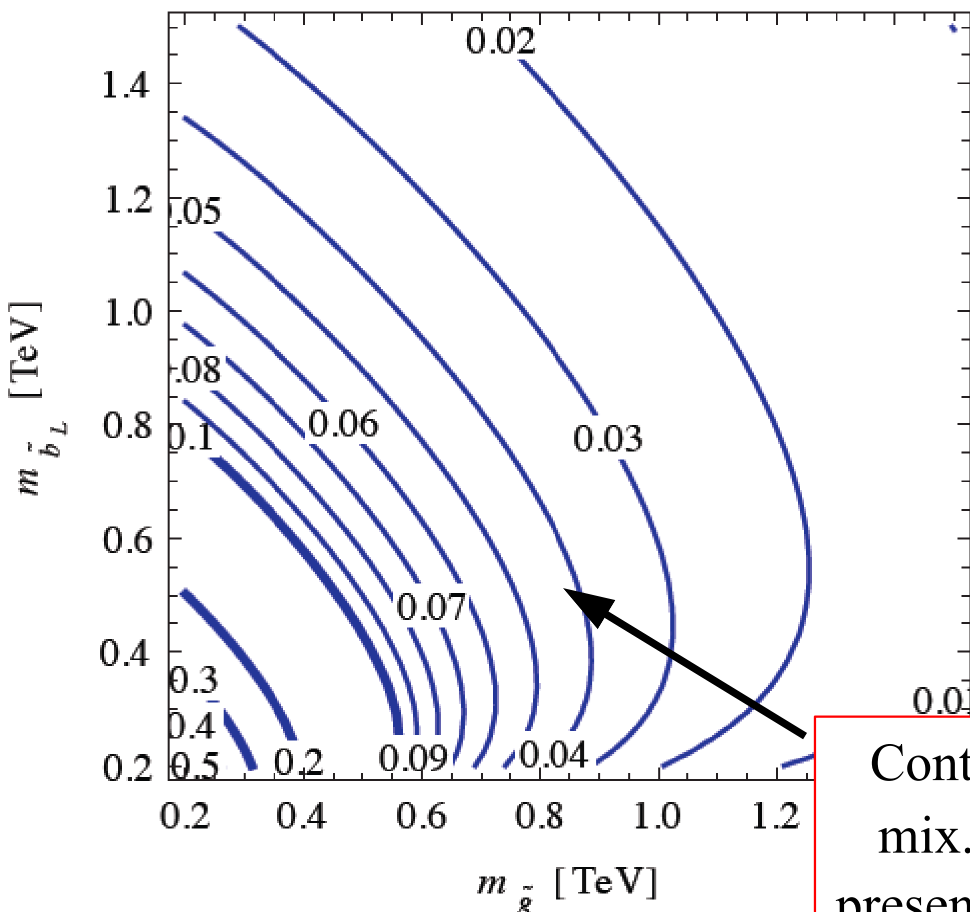


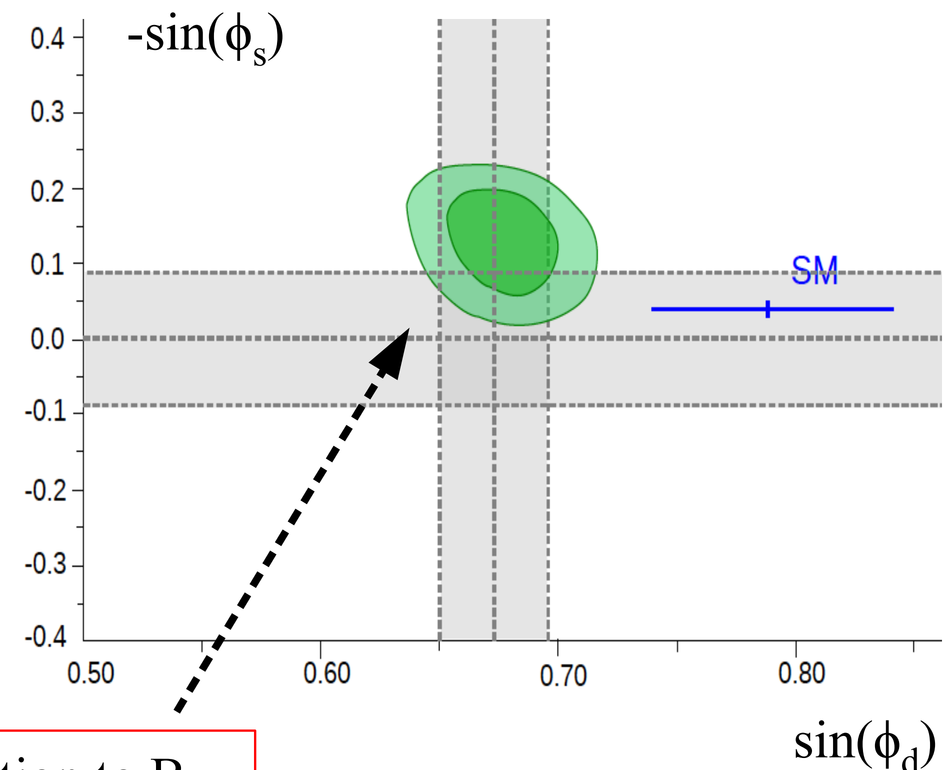
SUSY beyond MFV

The "ε_K - sin(2β)" tension

<u>Gluino-mediated contributions to the $B_{s,d}$ mixing amplitudes</u>

The LHC experiments are challenging this scenario, but we cannot rule it out yet completely





Contribution to B_b mix. reducing the present CKM tension

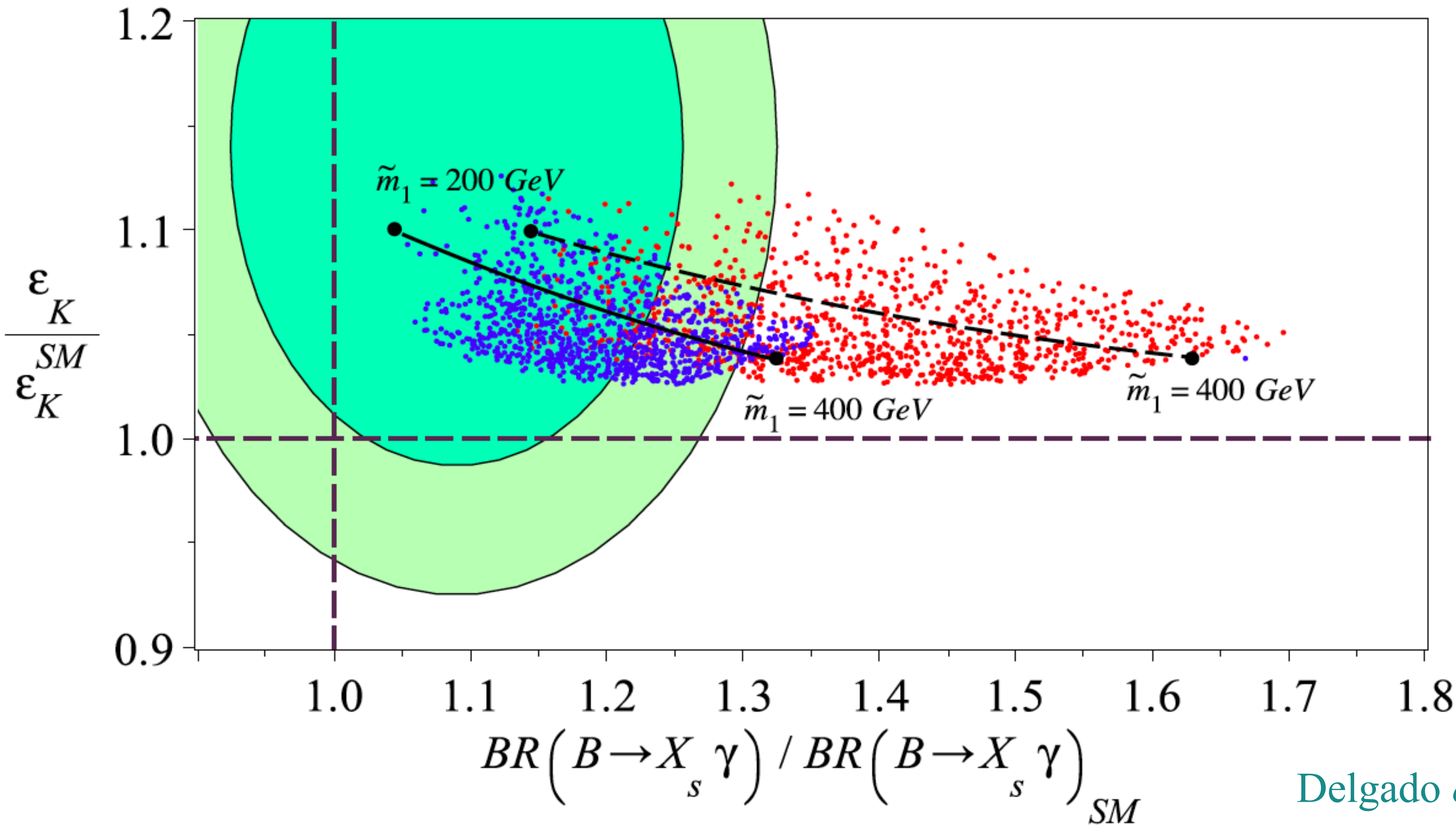
Barbieri *et al.*, '11

▸ *SUSY beyond MFV*

The "ε_K - sin(2β)" tension

Chargino-mediated contributions to the K-mixing amplitude

This scenario is in better shape, given the (relatively) weak bounds on the stop mass

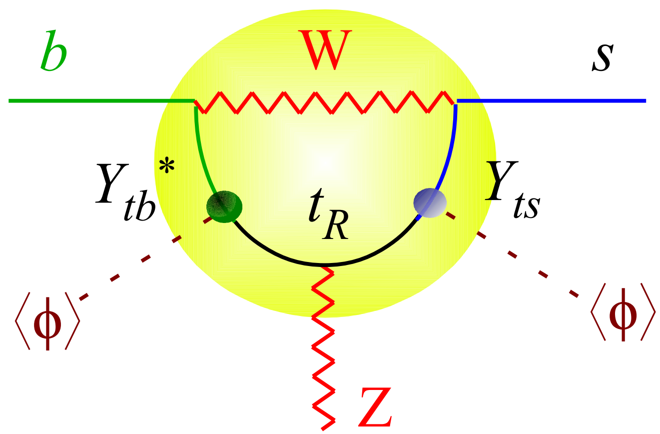


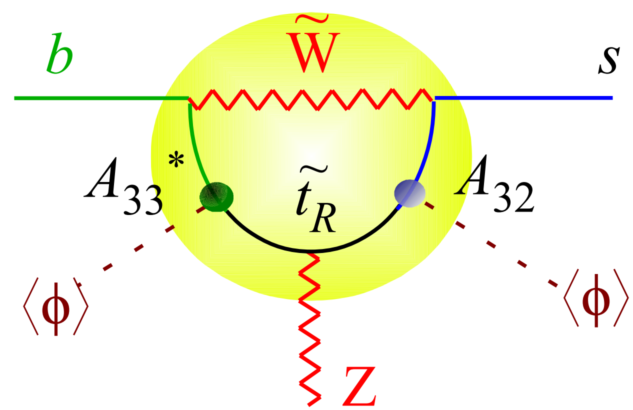
Delgado *et al.*, '13

▸ *SUSY beyond MFV*

Rare B and K decays

If the stops are light and the breaking of the $U(2)^3$ symmetry is non minimal ("*Disoriented A-terms*" framework) → possible visible effects in Z-mediated FCNCs





$$\frac{\mathcal{A}^{\rm SUSY}}{\mathcal{A}^{\rm SM}} = F\left(\frac{m^2_{\tilde t_R}}{M_2^2}, \frac{m^2_{\tilde t_R}}{m^2_{\tilde t_L}}\right) \times \frac{3m_t^2}{m^2_{\tilde t_L}} \times \boxed{\frac{(A^U_{33})^* A^U_{32}}{m^2_{\tilde t_L}}}$$

LR mixing term still largely unknown (m_h ~125 GeV → large A_{33})

O(1) loop function

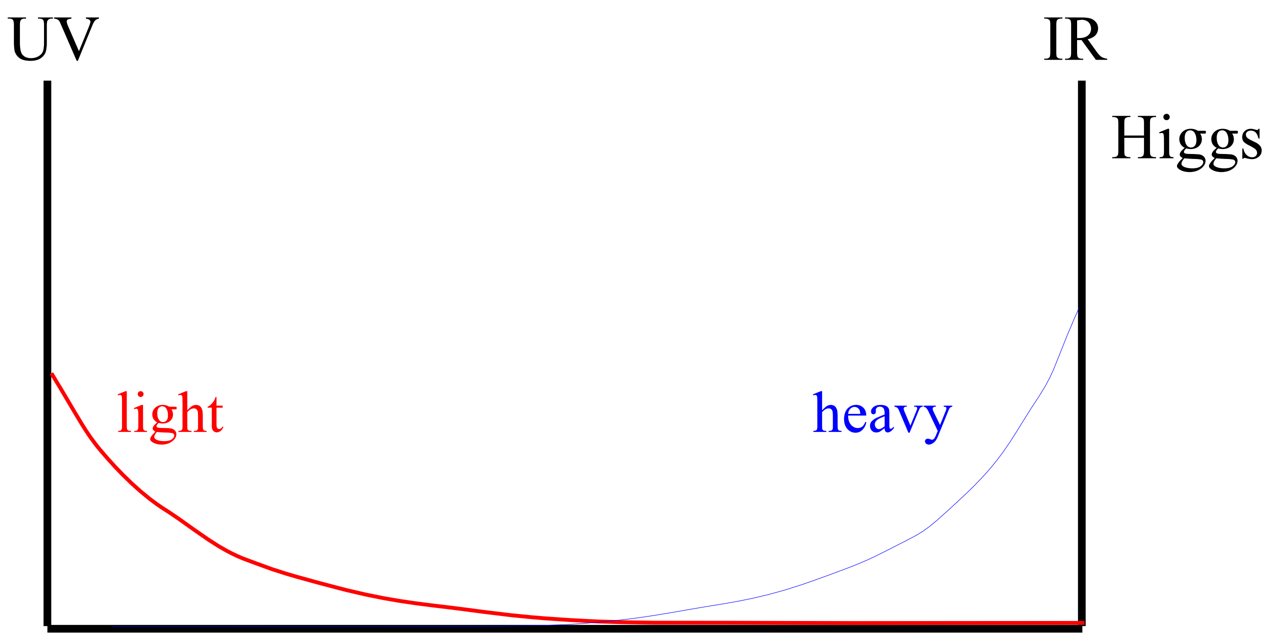
decoupling suppression factor

$\boxed{\ln(M_2^2/m^2_{\tilde t_L})}$ $\quad m^2_{\tilde t_L} \gg m^2_{\tilde t_R}, M_2^2$

$\boxed{\gtrsim 0.1}$ $\quad m^2_{\tilde t_L} \lesssim 1$ TeV

Flavor 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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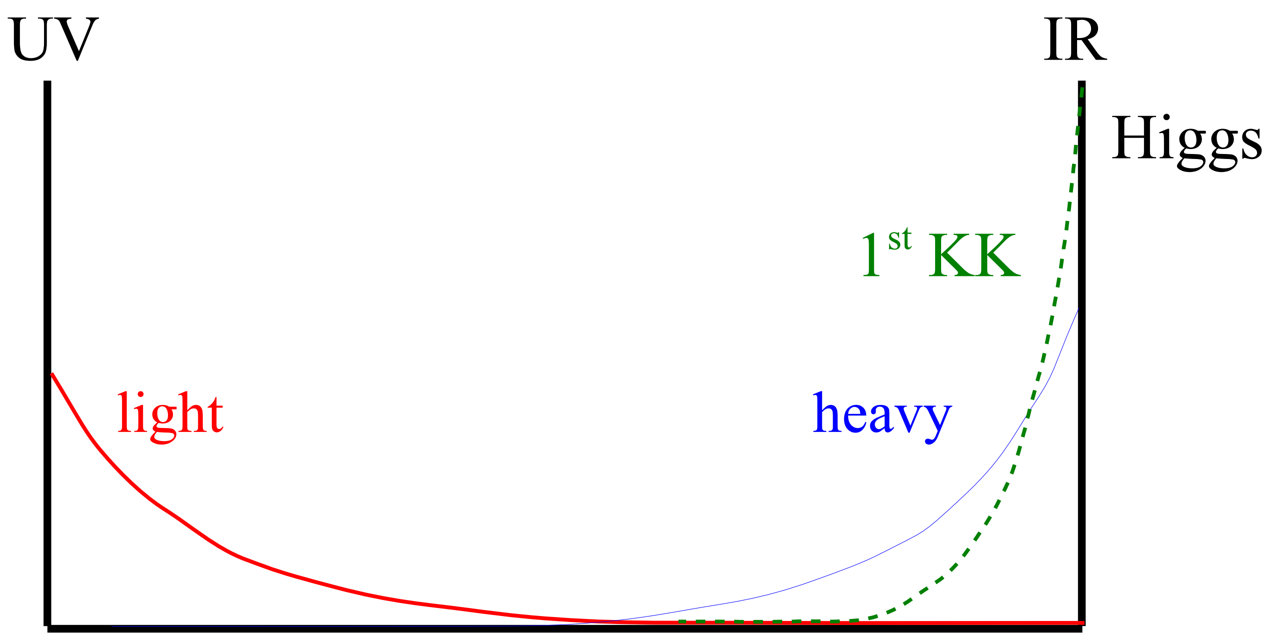


In 5D models with warped geometry, this construction provides a potentially interesting alternative to MFV to explain the suppression of FCNCs beyond the SM

Flavor physics with partial compositeness [or warped space time]

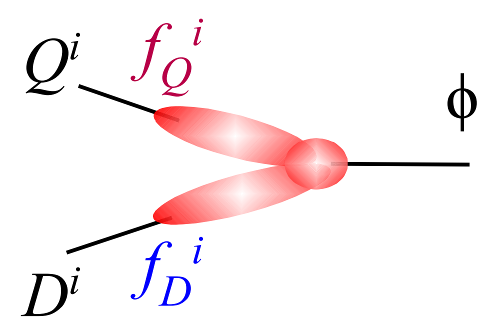
The model can be formulated in terms of the following 4D effective theory:

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

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

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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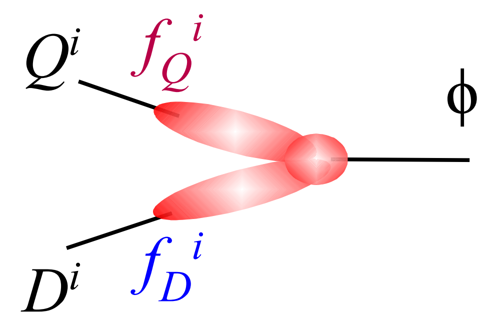
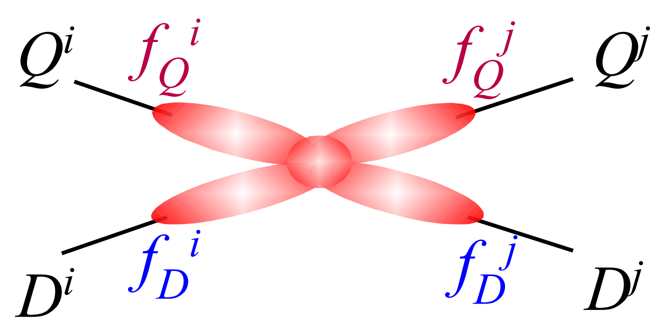


- There is no underlying flavor symmetry (complete anarchy) in the new strongly interacting sector:
dim.-6 FCNC operators suppressed only by the light-fermion wave functions
(= *mixing with the new heavy states*)



Flavor protection from warped space

This construction works remarkably well in various cases:

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

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

$$Y_D^{ij} \approx f_Q^{\,i} f_D^{\,j} \qquad\qquad Y_U^{ij} \approx f_Q^{\,i} f_U^{\,j}$$

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

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

$$f_D^{\,i} f_Q^{\,j}\ \bar{D}_R^{\,i} Q_L^{\,j} = f_D^{\,i} f_Q^{\,i} f_Q^{\,j} / f_Q^{\,i}\ \bar{D}_R^{\,i} Q_L^{\,j} \longrightarrow \sim y_b V_{ts}\,(b_R s_L)$$

to be compared with

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

Flavor protection from warped space

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$$\sim y_b V_{ts}\,(b_R s_L)$$

$$\boxed{\sim y_s V_{us}\,(s_R d_L)}$$

important difference !

to be compared with

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

$$\sim y_b y_t^2 V_{tb}^{*} V_{ts}\,(b_R s_L)$$

$$\boxed{\sim y_s y_t^2 V_{ts}^{*} V_{td}\,(s_R d_L)}$$

Flavor 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.

However, this discussion has allowed to illustrate once two rather general points:

- MFV is not the only allowed solution to the flavor problem
- The most natural place to look for deviations from MFV are helicity-suppressed 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 flavor-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 flavor 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 flavor 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 flavor symmetry structure of NP


Backup

What determines the observed pattern of quark & lepton masses?

Two main roads:

Anarchy
+
Anthropic selection

("*Chance & Necessity*" [J. Monod])

The symmetric way

("*The book of nature is written in terms of circles, triangles and other geometrical figures…*" [G. Galilei])

What determines the observed pattern of quark & lepton masses?

Two main roads:

Anarchy + Anthropic selection

("*Chance & Necessity*" [J. Monod])

- Many unanswered questions:

  It works well for $m_{u,d}$
  maybe also for m_t & ν mixing,
  but what about CKM and the other masses? Why 3 generations?

  ....

- No clear direction for future searches

The symmetric way

("*The book of nature is written in terms of circles, triangles and other geometrical figures...*" [G. Galilei])

- Main road of particle physics so far.
- It works well in the Yukawa sector (*several possible options*), less evident, but not excluded, in the neutrino case
- "large" flavor symm. + "small" breaking is the best way to explain the absence of NP signals so far [*and often implies visible NP signals with higher precision*].

The symmetric way [*a possible option*]

$$\boxed{\text{Minimally-broken } U(2)^3 = U(2)_{Q_L} \times U(2)_{U_R} \times U(2)_{D_R}}$$

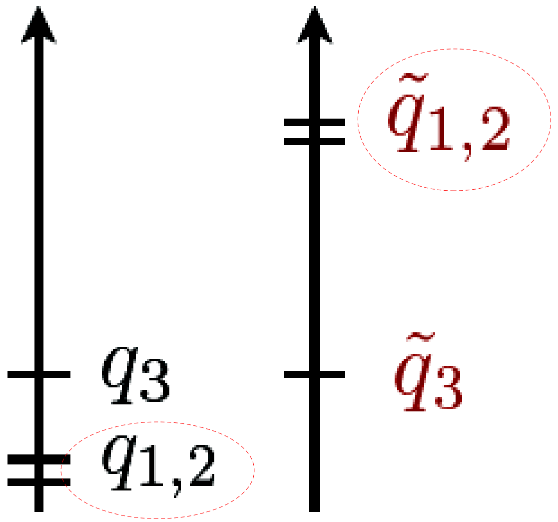
Barbieri *et al.* '11
Pomarol, Tommasini, '96
Barbieri, Dvali, Hall, '96

- The exact symmetry limit is good starting point for the SM quark spectrum ($m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$) $\rightarrow$ we only need to introduce small breaking terms

$$Y \propto (0,0,1)$$

This symmetry accommodates "naturally" heavy squarks for the first 2 generations (in the SUSY context)

The "small & minimal breaking" ensures small effects in rare processes (in agreement with present data)



The symmetric way [*a possible option*]

$U(3)^5$

LR LL

$Y \propto (0,0,1)$ [unbroken $U(2)_L x U(2)_R$]

$M_\nu \propto (1,1,1)$ [unbroken $O(3)_L$]

$\cancel{U(1)}_{\text{Lepton-Number}}$

Blankenburg, G.I., Jones-Perez, '12

Gavela *et al.*, work in prog.

The only possibility of extending this idea to the neutrino sector, is to assume a different initial symmetry for Dirac and Majorna sectors (*or a different initial breaking of some larger flavor symmetry*)

An interesting possibility is the assumption that the "starting point" for the two sectors correspond to two different breaking of some initial symmetry, preserving large unbroken subgroups.

Michel & Radicati, '69
Cabibbo & Maiani, '69

The symmetric way [*a possible option*]

$U(3)^5$

LR

LL

Blankenburg, G.I., Jones-Perez, '12

$Y \propto (0,0,1)$ [unbroken $U(2)_L x U(2)_R$]

$M_\nu \propto (1,1,1)$ [unbroken $O(3)_L$]

Small $U(2)_L$ breaking
leading to $3 \to 1,2$ mixing

Small angles: $|V_{cb}| = O(\varepsilon = 0.04)$

Large 2-3 mixing (because of degeneracy)
+ small mass-splitting

$$\frac{\Delta m_{atm}^2}{m_\nu^2} = O(\varepsilon = 0.04)$$

The symmetric way [*a possible option*]

$U(3)^5$

LR

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Blankenburg, G.I., Jones-Perez, '12

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Small angles: $|V_{cb}| = O(\varepsilon = 0.04)$

Large 2-3 mixing (because of degeneracy) + small mass-splitting

Sub-leading $U(2)_L \times U(2)_R$ breaking resolving 1-2 degeneracy

$$\frac{\Delta m_{atm}^{\ 2}}{m_\nu^{\ 2}} = O(\varepsilon)$$

$|V_{td} / V_{ts}| \sim O(\varepsilon'/\varepsilon \sim 0.2)$

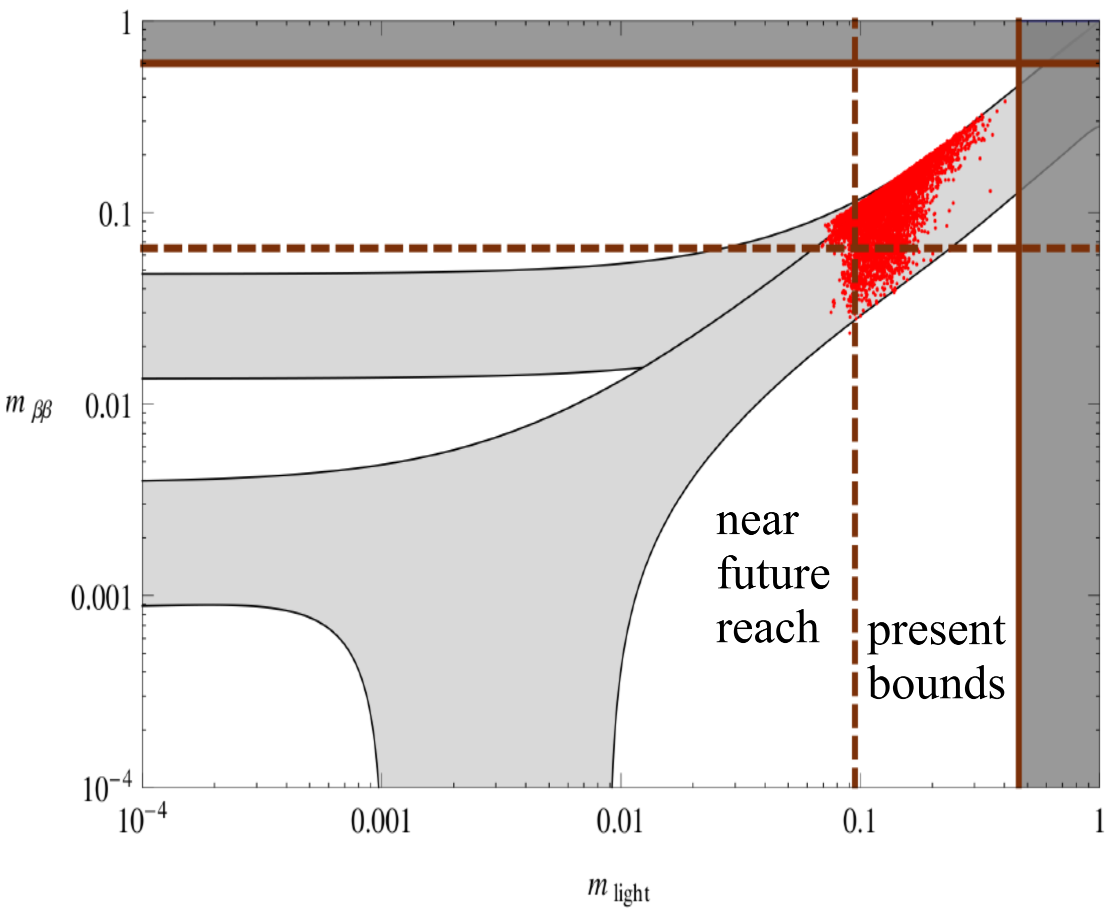
$|s_{13} / s_{23}| \sim O(\varepsilon'/\varepsilon \sim 0.2)$

In good agreement with recent s_{13} measurements...

The symmetric way [*a possible option*]

$U(3)^5$ → LL

Blankenburg, G.I., Jones-Perez, '12



$M_\nu \propto (1,1,1)$ [unbroken $O(3)_L$]

↓

Large 2-3 mixing
+ small mass-splitting

$$\frac{\Delta m_{atm}^2}{m_\nu^2} = O(\varepsilon)$$

If all this is correct... 0ν2β decay experiments (and maybe KATRIN) are very close to observe a positive signal...