Quark and Lepton Flavor connections

Gino Isidori
[*INFN, Frascati*]

- Introduction
- SUSY & Flavor
- Selected examples in the quark sector
- What determines the observed pattern of quark & lepton masses?
- Conclusions

Introduction
[*direct vs. indirect searches of New Physics*]

▶ *Introduction*

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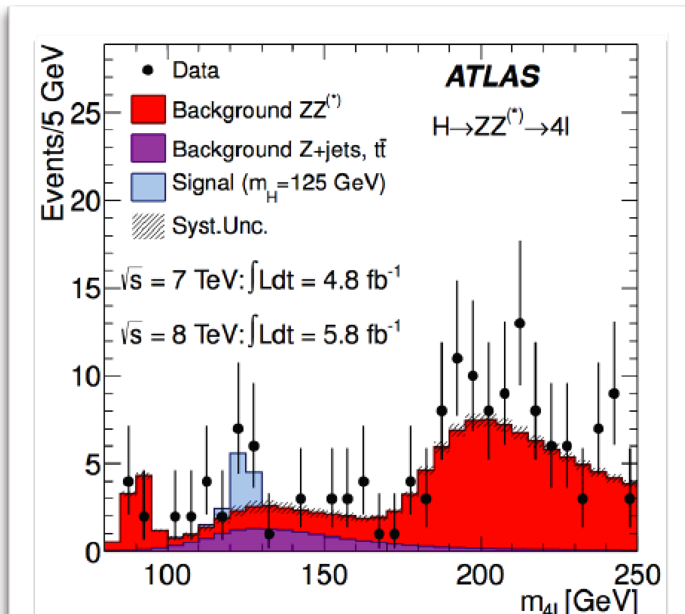
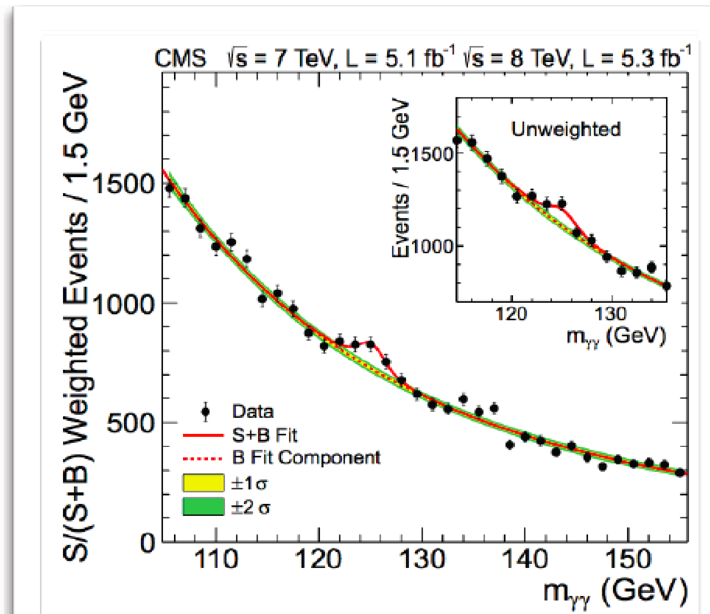


arXiv:1207.7214v1 [hep-ex]



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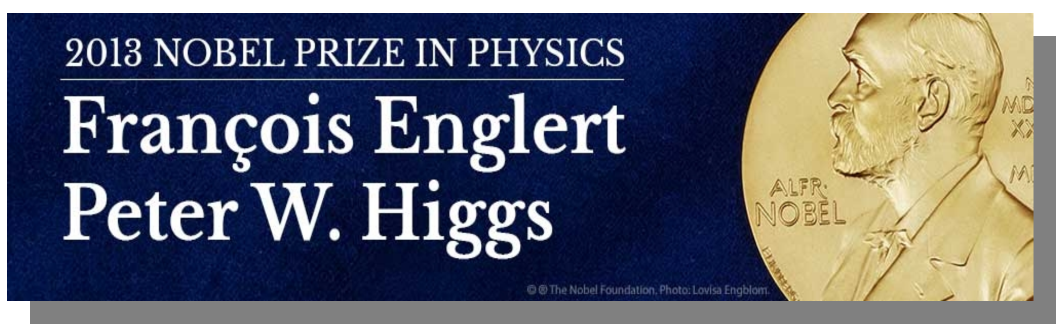

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Still, this theory suffers of a series of theoretical & cosmological problems:

- Fine-tuning/UV sensitivity of the Higgs-mass term ["*hierarchy problem*"]
- Unexplained hierarchical structure of the Yukawa couplings ["*flavor puzzle*"]
- No explanation for the quantization of the U(1) charges [*hint of unification*?]
- Non coherent inclusion of gravity at the quantum level
- No good candidate for dark matter

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$\Downarrow$

The SM is likely to be an *effective theory*, or the low-energy limit of a more fundamental theory, with new degrees of freedom around or above the electroweak scale (i.e. around or above 1 TeV).

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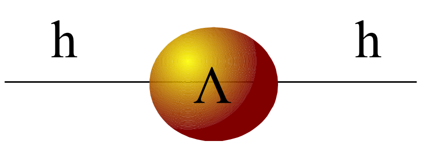
→ The only (qualitative) indication of NP around 1 TeV:

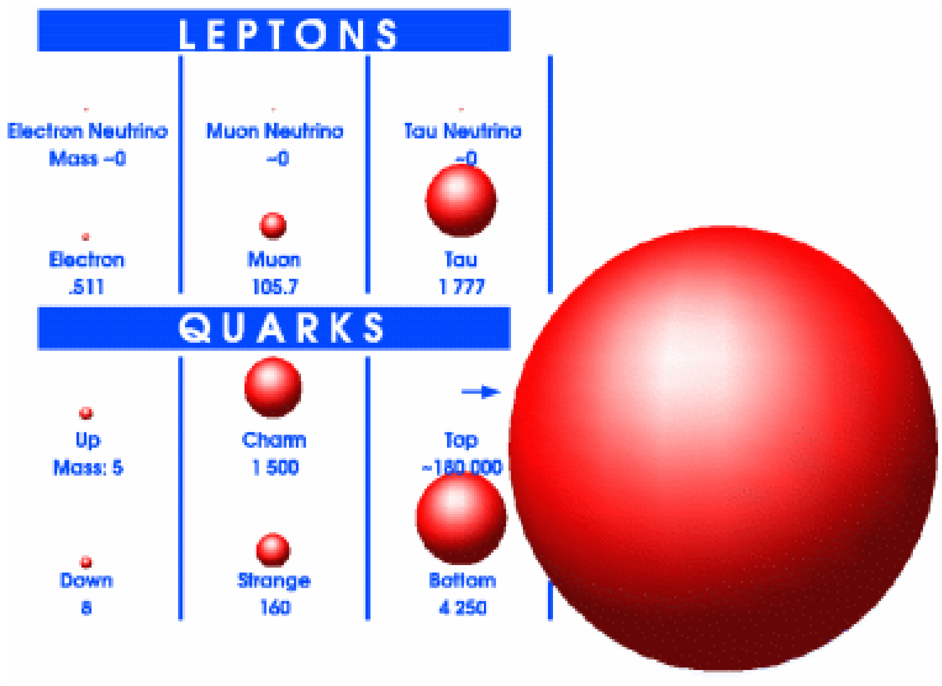


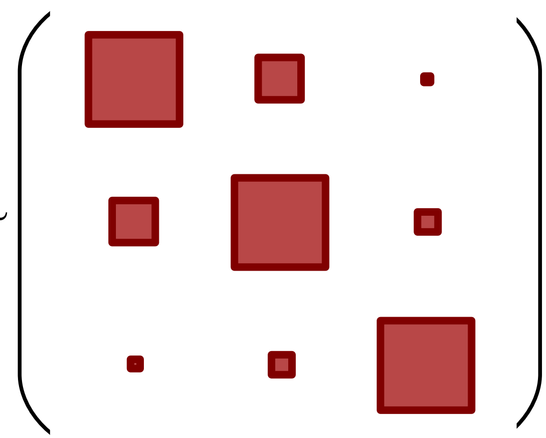
$$\Delta m_h^2 \sim \Lambda^2$$

Introduction

The SM is likely to be an *effective theory*, or the low-energy limit of a more fundamental theory, with new degrees of freedom around or above ~ 1 TeV

"Flavor physics" → *one of the arguments why we believe the SM is not a complete theory*



$V_{CKM} \sim$ 

These structures do not seem to be accidental...

Introduction

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"Flavor physics" → *one of the arguments why we believe the SM is not a complete theory*

"Flavor physics" → *key tool to investigate the nature of physics beyond the SM*

$$\mathscr{L}_{\mathrm{SM}+\nu} = \mathscr{L}_{\mathrm{gauge}}(A_a, \psi_i) + D\phi^+ D\phi - V_{\mathrm{eff.}}(\phi, A_a, \psi_i)$$

$$V_{\mathrm{eff.}} = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L{}^i \psi_R{}^j \phi + \frac{g^{ij}}{\Lambda} \psi_L{}^i \psi_L{}^{Tj} \phi \phi^T + \ldots$$

flavor-structure of the model

effective ν mass term

- From ν masses we already know the SM is an effective theory
- The vast majority (*and the less tested*) couplings of the Higgs boson are "flavor couplings"

$$V(\phi) = - \mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^{\,i} \psi_R^{\,j} \phi + \frac{g^{ij}}{\Lambda} \psi_L^{\,i}\psi_L^{\,Tj} \phi\, \phi^T + \ldots$$

Beside the direct searches of new degrees of freedom at high energies, the main goal now is to understand if, and how large, are the additional terms in this series (*natural to expect non-vanishing couplings in operators involving* ϕ)

→ Higgs physics & Flavor physics

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the (relatively) small value of m_h + compatibility of the h couplings with SM + absence of NP signals so far

↓

NP is likely to be *weakly coupled* with a *non-negligible mass gap* (*hopefully not too large..*) between NP and SM degrees of freedom

CAUTION *personal bias...*

↓

Indirect searches of NP require high precision, but are a fundamental ingredient in searching for physics beyond the SM

Under very general assumptions (gauge symmetry + absence of new light states) flavor and e.w. observables used for indirect NP searches can be decomposed as follows:

$$A = A_0 \left[c_{SM} \frac{1}{M_W^2} + c_{NP} \frac{1}{\Lambda^2} \right]$$

trivial kinematical factors

(adimensional) effective couplings

<u>This decomposition is very general:</u> it holds <u>both</u> for forbidden processes (e.g.: $\mu \to e\gamma$) and precision measurements (e.g.: $B_s \to \mu\mu$)

- The interest of a given obs. depends on the magnitude of c_{SM} vs. c_{NP} and on the theoretical error of c_{SM} → <u>concentrate on clean & rare processes</u>
- No way to disentangle Λ & c_{NP}, but <u>fully complementary</u> to direct searches at high-p_T → <u>symmetry-structure of NP & possible access to high scale dynamics</u>

The present lack of direct signals of NP at the high-energy frontier has reinforced the interest of indirect searches, given their potential sensitivity to high scales:

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM+}\nu} + \frac{c_{\text{NP}}}{\Lambda^2} O_{ij}^{(6)}$$

G.I., Perez, Nir '10 (2013 update)

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Bounds on Λ in TeV ($c_{\rm NP}=1$) Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Im	Observables
$(\bar s_L \gamma^\mu d_L)^2$	9.8×10^{2}	1.6×10^{4}	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar s_R\, d_L)(\bar s_L d_R)$	1.8×10^{4}	3.2×10^{5}	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar c_L \gamma^\mu u_L)^2$	1.2×10^{3}	2.9×10^{3}	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar c_R\, u_L)(\bar c_L u_R)$	6.2×10^{3}	1.5×10^{4}	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar b_L \gamma^\mu d_L)^2$	6.6×10^{2}	9.3×10^{2}	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_R\, d_L)(\bar b_L d_R)$	2.5×10^{3}	3.6×10^{3}	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar b_L \gamma^\mu s_L)^2$	1.4×10^{2}	2.5×10^{2}	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar b_R\, s_L)(\bar b_L s_R)$	4.8×10^{2}	8.3×10^{2}	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

If NP is not around the corner, flavor-changing processes <u>might</u> allow to probe high scales (*if the flavor structure of the theory is not trivial*)

N.B.: if NP contributes only at the loop level, then $\Lambda_{\text{NP}} \sim 4\pi\, m_{\text{NP}}$

The present lack of direct signals of NP at the high-energy frontier has reinforced the interest of indirect searches, given their potential sensitivity to high scales:

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM+\nu} + \frac{c_{\rm NP}}{\Lambda^2}\, O_{\rm ij}^{(6)}$$

This is of course true also in the lepton sector:

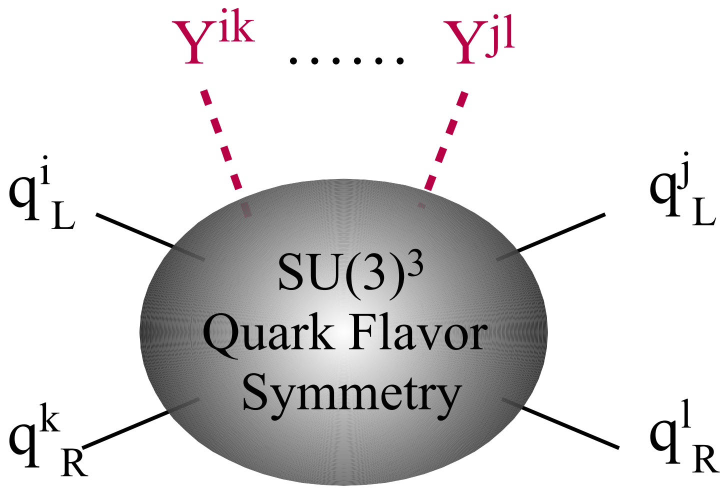
$$\frac{c_{\mu e}}{\Lambda^2}\, \bar{e}_L \sigma^{\mu\nu} \mu_R \phi F_{\mu\nu}$$

$$\Lambda > 4\times10^5 \text{ TeV} \times (c_{\mu e})^{1/2} \quad \text{from} \quad \text{BR}(\mu\to e\gamma)^{\rm exp} < 5.7\times10^{-13}$$

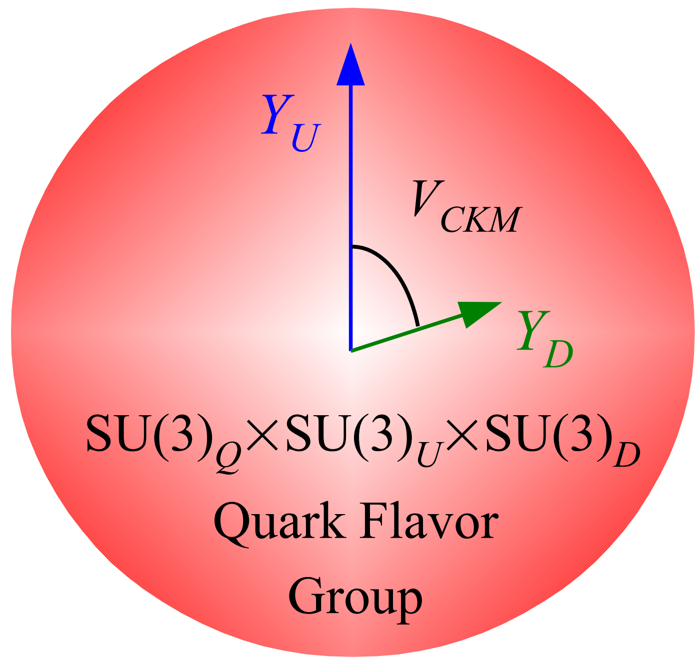
MEG '13

However, we should keep in mind that the constraints on the scale of NP become much less severe in realistic/motivated models where the mechanisms of *flavor-mixing* and *fermion masses* are linked together

E.g.: *Minimal Flavor Violation*



Yukawa couplings as unique sources of flavor symmetry breaking



Chivukula & Georgi, '89
D'Ambrosio, Giudice, G.I., Strumia, '02

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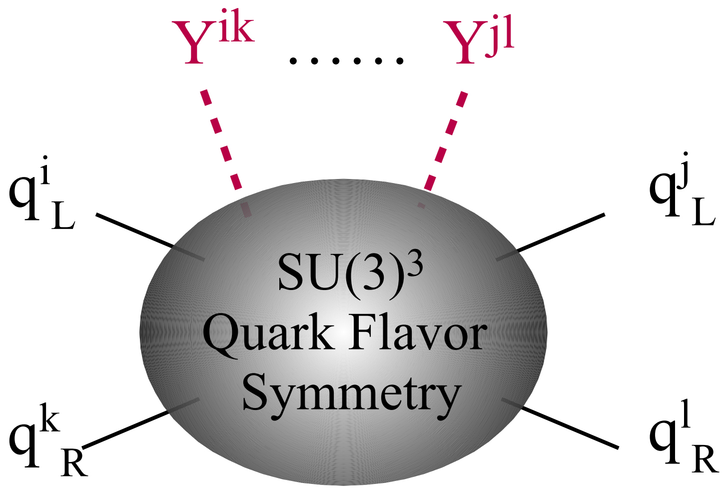
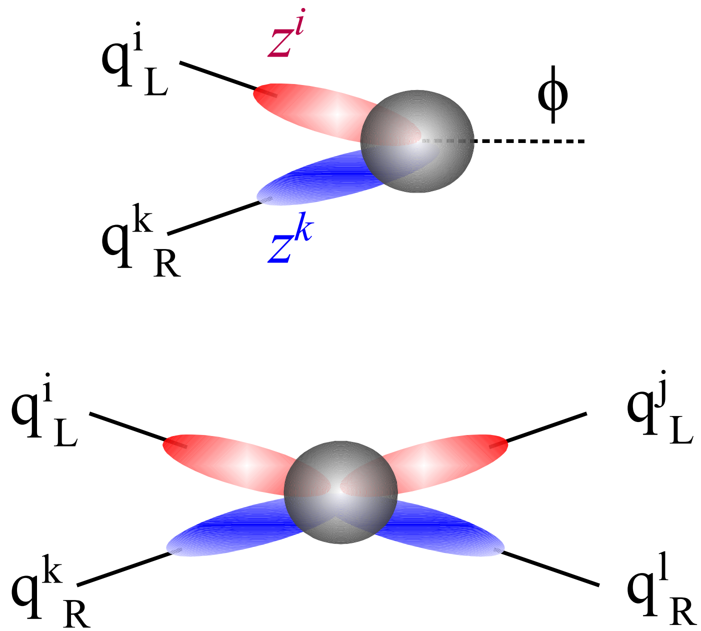
E.g.: *Minimal Flavor Violation* or *Partial Compositeness*



Yukawa couplings as unique sources of flavor symmetry breaking



“Elementary-composite mixing” as unique source of fermion mass hierarchies

Mass scale of New Physics (*new colored & flavored particles*)

Simplifying a complicated multi-dim. problem...	$<$ 1 TeV	few TeV	$>$ few TeV
	Direct New Physics searches @ high pT:		
	NP within direct reach @ 8 TeV	NP within reach @ 14 TeV	NP beyond direct searches @ LHC
	NP effects in Quark Flavor Physics:		
Flavor Structure			
Anarchic	huge [> O(1)]	sizable [O(1)]	sizable/small [< O(1)]
Small misalignment (*e.g. partial compositeness*)	sizable [O(1)]	small [O(10%)]	small/tiny [O(1-10%)]
Aligned to SM (*MFV*)	small [O(10%)]	tiny [O(1%)]	not visible [< 1%]

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There is still a wide range of "NP parameter space" that can and need to be explored (*without strong theoretical prejudices*) in quark & lepton flavor physics

SUSY & Flavor

A (very) concise summary about direct searches for New Physics

Despite several efforts, no non-standard state has been discovered so far at the LHC. Rough summary of the present status of high-energy searches:

- The Higgs boson is around 125 GeV
  - *within the "SUSY" region, despite a bit heavier than expected*
  - *technicolor and most composite-Higgs models somehow disfavored* *
- Bounds on generic "colored" new states typically above 1 TeV
- Colored new states coupled only to 3rd gen. quarks still allowed below 1 TeV
- Bounds on colorless new states still in the few 100 GeV domain

* but definitely not ruled out !

[wide literature...]

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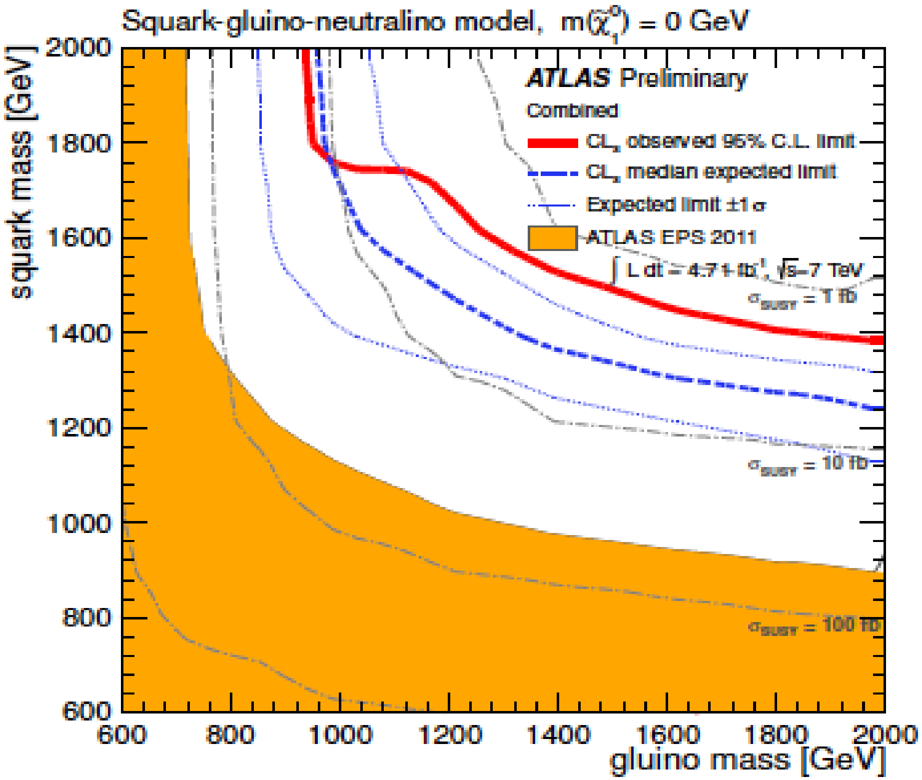
- Supersymmetry remains a good candidate : weakly coupled theory + light Higgs (+ dark-matter & unification)
- The SUSY spectrum is less trivial than expected: only a few new states below the TeV
- Some tuning in m_h is unavoidable: *do we really care if the fine-tuning is ~1% ?*

A (very) concise summary about direct searches for New Physics

The strongest bounds on the SUSY spectrum are on gluinos and 1st-2nd gen. squarks

They imply an overall heavy SUSY spectrum only in simplified models, with a MFV structure (such as the CMSSM)



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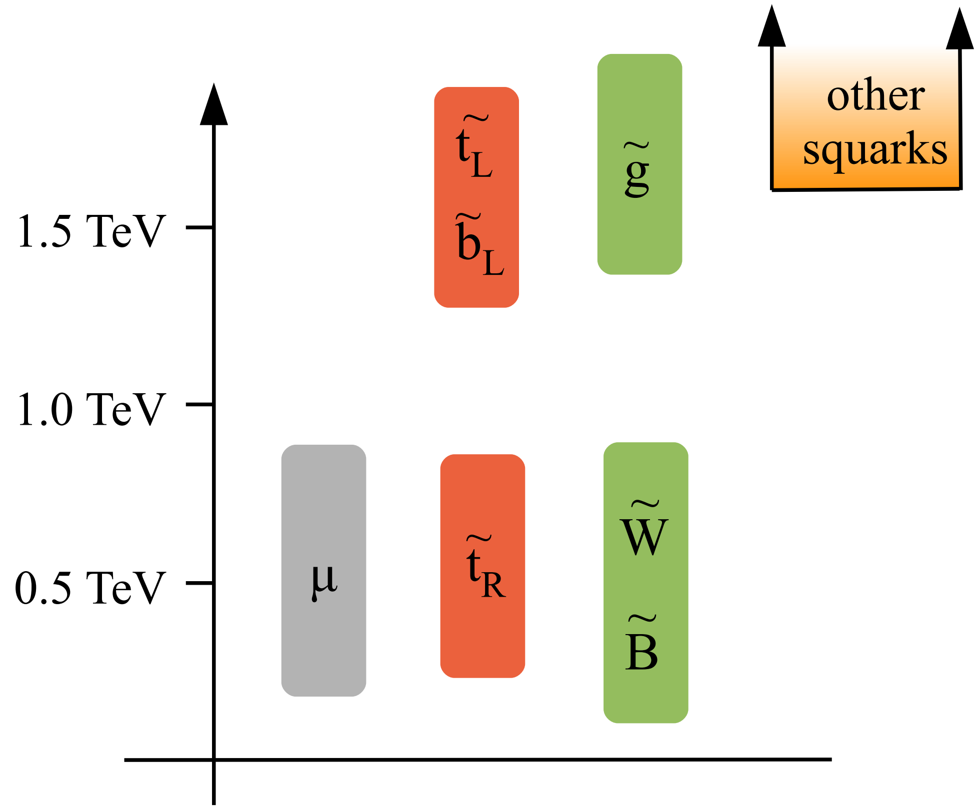
"Split-family" SUSY

Possible SUSY spectrum still compatible with present data that minimizes the fine-tuning problem in m_h

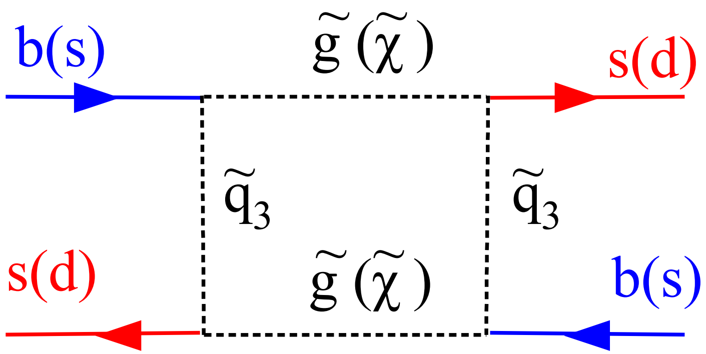


Dimopulos, Giudice, '95
Cohen, Kaplan, Nelson '96
+ many others...

- Only 3rd gen. squarks + Higgsinos need to be "light" to minimize the tuning in m_h
- A large stop-mixing term is needed to explain $m_h \sim 125$ GeV → large splitting among the stops → one of the two mass eigenstates (*an almost RH stop*) could well be in the few 100 GeV region, with all other colored states above 1 TeV
- The splitting of the 3rd family can be well motivated in flavor models (connection with large top mass)

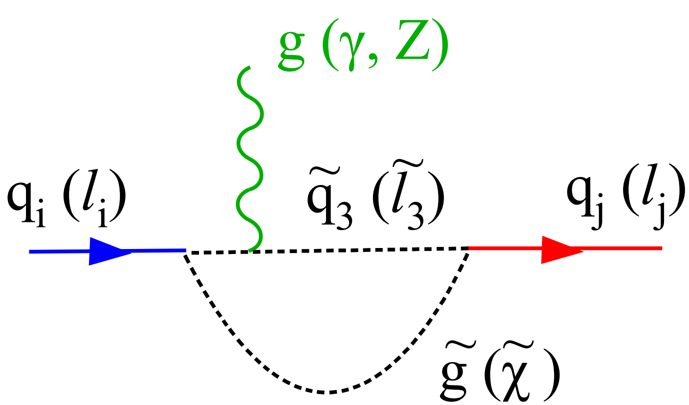
▶ *"Split-family" SUSY*

A scenario that LHC experiments have only started to explore, where flavor physics definitely plays a key role given the non-trivial flavor structure of the SUSY spectrum → interesting non-standard effects mediated by the exchange of the 3rd generation of squarks and leptons:



Possible "visible" effects in

- CPV in K mixing (ε_K)
- CPV in $B_{s,d}$ mixing ($\phi_{s,d}$)



Possible "visible" effects in

- Direct CPV in charm (Δa_{CP})
- Rare B decays ($B_s \to \mu\mu$)
- LFV ($\mu \to e\gamma$) & EDMs

▶ *"Mini-Split" SUSY*

If we give-up the goal of minimizing the fine-tuning in mh, retaining other appealing features of SUSY (such as unification), other options become possible. A particularly interesting one is the so-called "mini-split" scenario:

- "loop-splitting" between gauginos (~TeV) and sfermions (~10-100 TeV)

- Possible generic flavor structure (no "flavor-tuning" on squarks).

Giudice, Luty, Muraya, Rattazzi, '98
Arvanitaki et *al.* '12
+ many others...

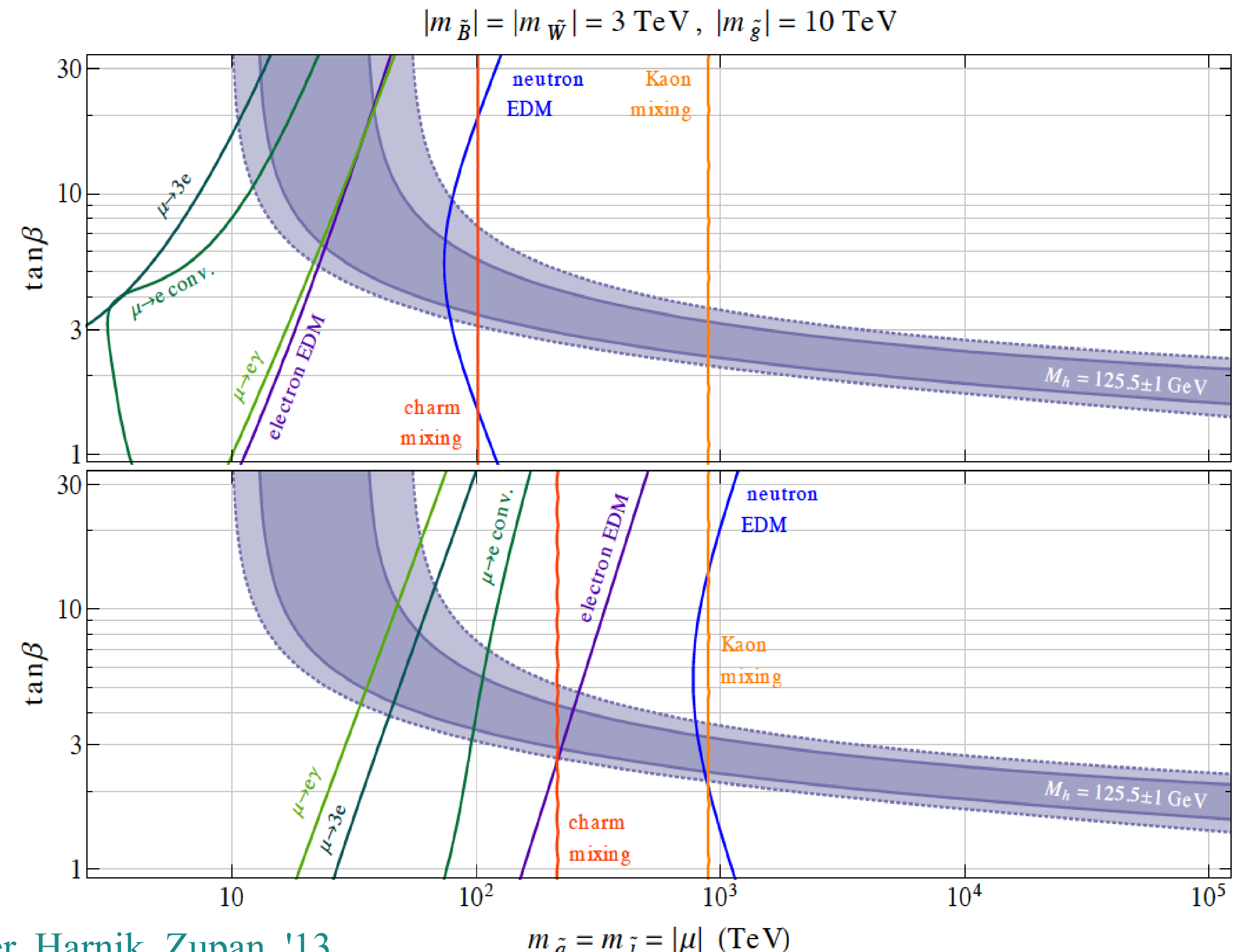
"Mini-Split" SUSY

Also in this case flavor observables may play a key role in finding-evidences or constraining the model:

Present bounds:

on specific sfermion masses by corresponding low-energy observables

Possible Future reach:



Althmanshofer, Harnik, Zupan, '13

Selected examples in the quark sector

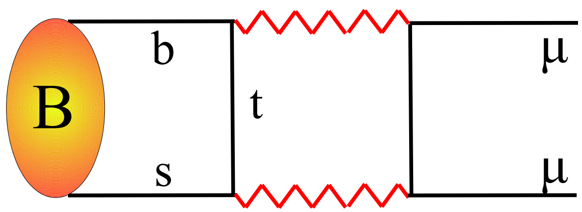
High-quality flavor physics requires a good selection...

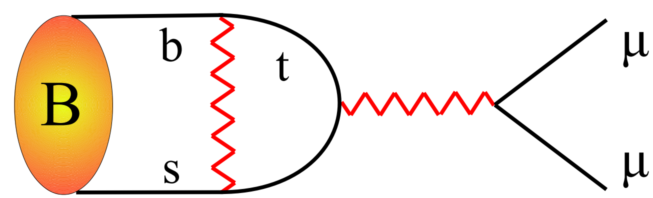
Example I: $B_{s,d} \to \mu\mu$

These modes are a unique source of information about flavor physics beyond the SM:

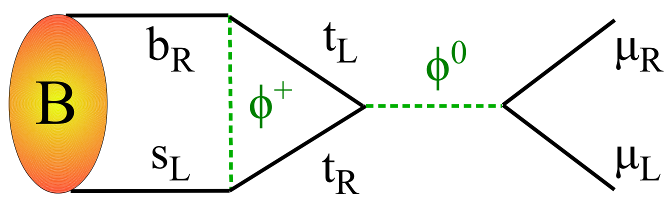
- theoretically very clean (virtually no long-distance contributions)
- particularly sensitive to FCNC *scalar currents* and FCNC *Z penguins*

Leading SM diagrams (unitary gauge):





gauge-less limit



good approx. to the full SM amplitude

Clean probe of the Yukawa interaction (→ Higgs sector) beyond the tree level

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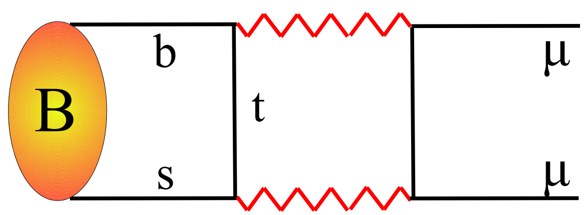
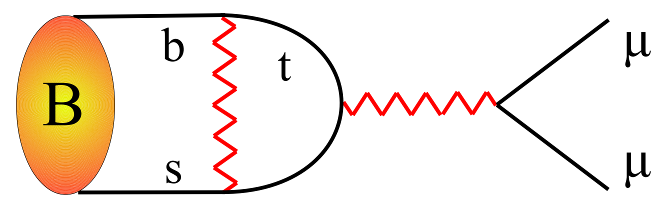
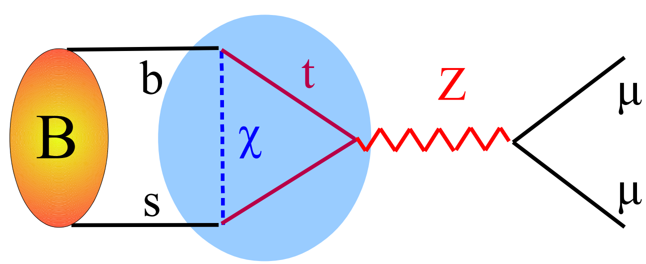
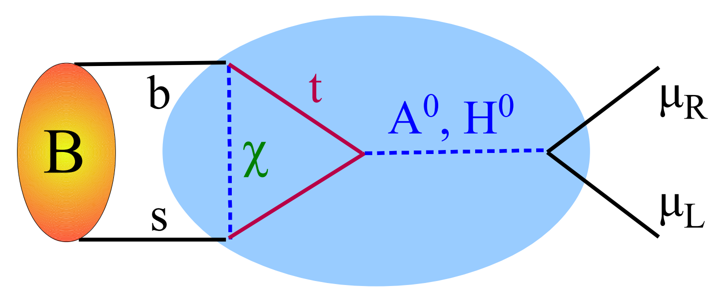




Possible non-SM contributions:





Relevant for BR = O(SM)

Possible large enhancement
(e.g. SUSY @ large tanβ)

Example I: $B_{s,d} \to \mu\mu$

Recent developments both on the theory and on the experimental side:

$$\overline{\mathrm{BR}}_{s,SM} = (3.65 \pm 0.23)\times 10^{-9}$$

(time-integrated average)

$$\overline{\mathrm{BR}}_{s}^{(\exp)} = (2.9 \pm 0.7)\times 10^{-9}$$

Bobeth, Gorbahn, Hermann, Misiak, Stamou, Steinhauser '13
+
progress from Lattice QCD

LHCb + CMS '13

$$\mathrm{BR}_{d,SM} = (1.06 \pm 0.09)\times 10^{-10}$$

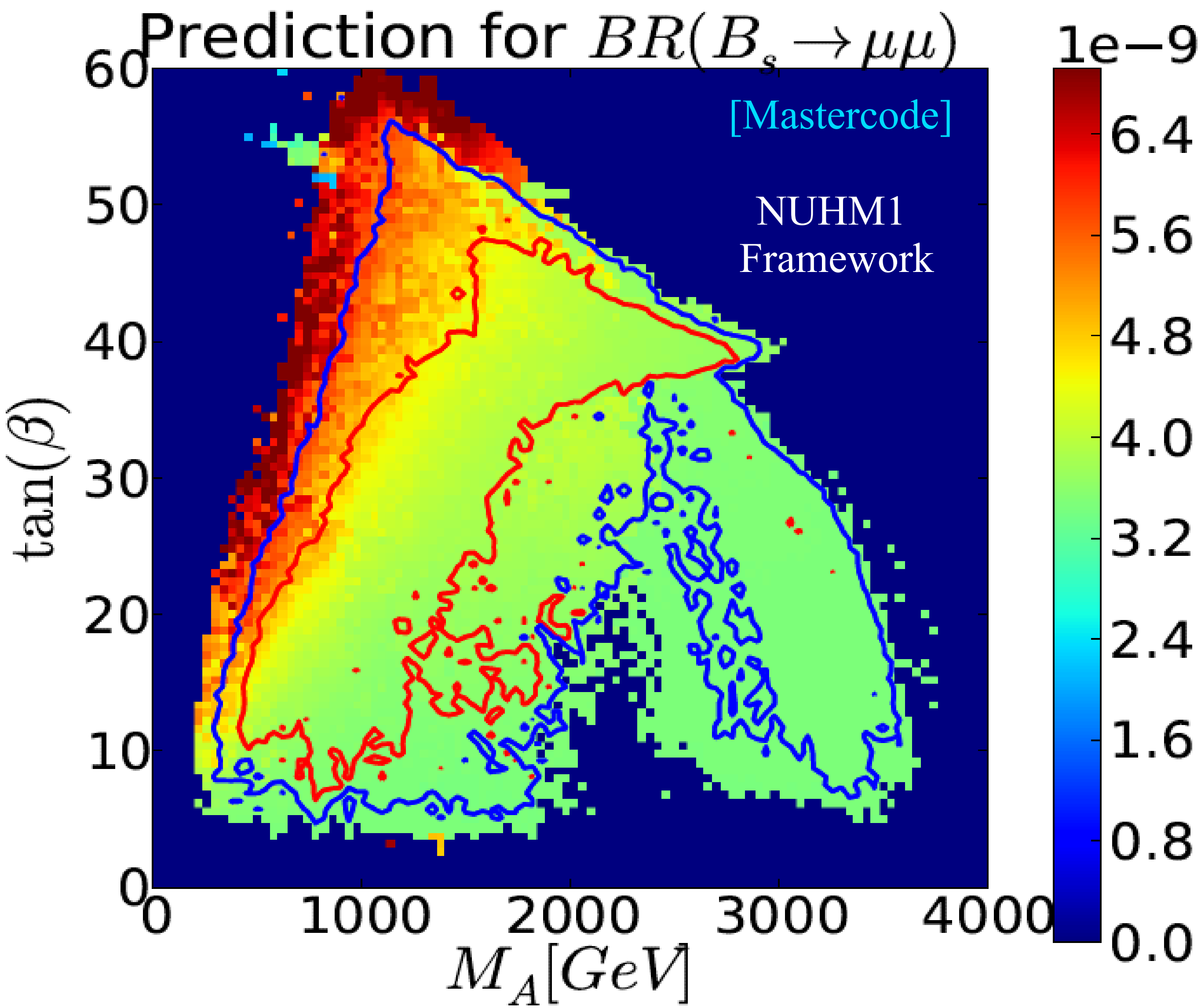
$$\mathrm{BR}_{d}^{(\exp)} = (3.6 \pm 1.5)\times 10^{-10}$$

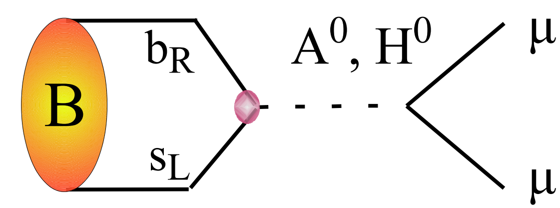
An overall th. error below 5% is definitely within the reach in the next few years

At this stage there is perfect compatibility, but we are only at the beginning...

...and the good agreement with SM has important implications:

E.g.: 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 MSSM at large tanβ are ruled out

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

The preferred regions (68% & 95% CL) do not take into account the new measurement

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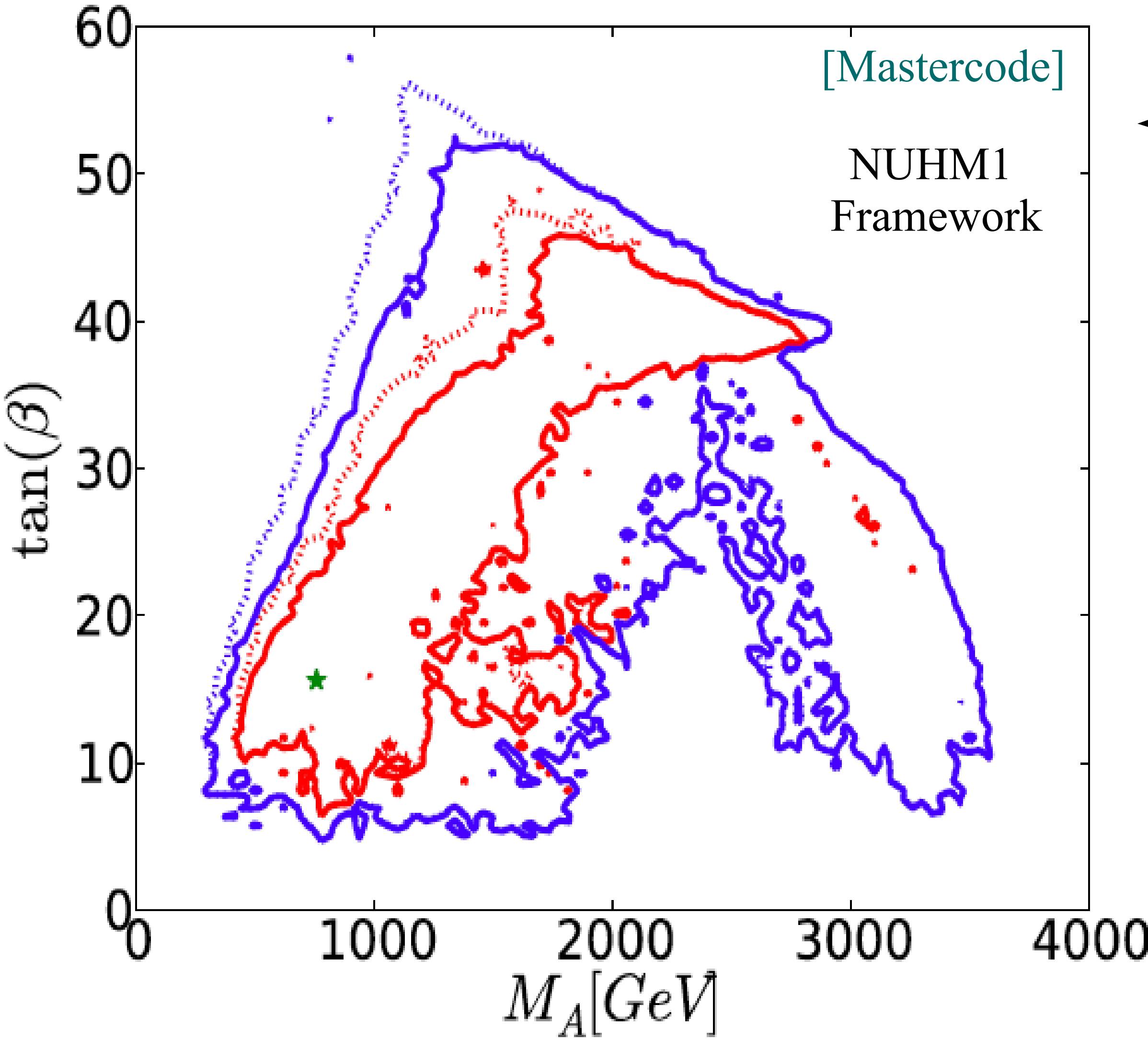


Shift in the preferred regions (68% & 95% CL) with an hypothetical measurement:

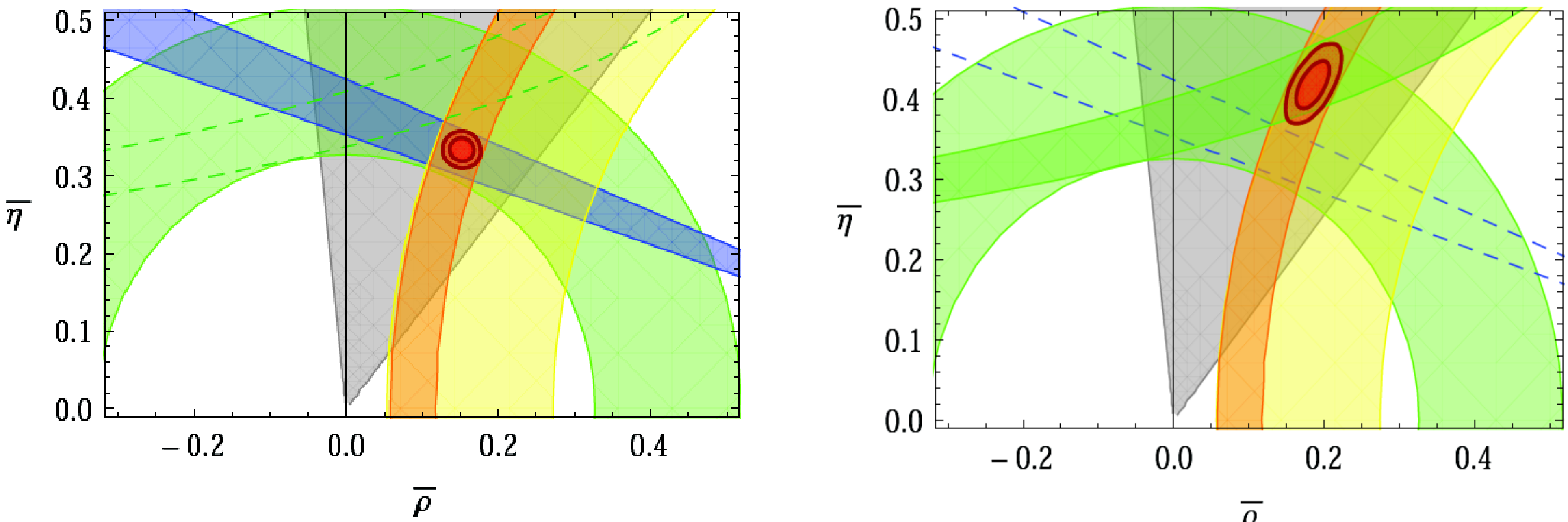
$$\overline{\mathrm{BR}}^{(\mathrm{exp})} = (3.5 \pm 1.0)\times 10^{-9}$$

The impact of $B_s \to \mu\mu$ is even more pronounced in scenarios such as "split-family" SUSY, if the stop is not too heavy.

Example II: $\Delta F=2$ amplitudes

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

SM fit, no ε_K (no K-meson mix. phase) SM fit, no ϕ_δ (no Bd mix. phase)



The discrepancy does not exceed the 2σ level, but is "intriguing", since it appears in two amplitudes particularly sensitive to NP.

Lunghi & Soni '08
Buras & Guadagnoli '08
Lenz *et al.* '12

Example II: $\Delta F=2$ amplitudes

Best way to clarify the situation: improve the precision on γ and $|V_{ub}|$ $\rightarrow$ CKM from pure tree-level observables (*not easy...*)

Alternative route: compare CKM constraints from $\Delta F=2$ with $K \rightarrow \pi\nu\nu$ (*not easy*

Two ways to disentangle NP in kaon mixing (*as expected in the "split-family" or "mini-split" SUSY models*)

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Two ways to disentangle NP in kaon mixing (*as expected in the "split-family" or "mini-split" SUSY models*)

Quite interesting to see also what happens in the $\Delta F=2$ $b \to s$ mixing amplitude (CPV in B_s mixing), where the SM prediction is more precise (*easier in the short term, but less conclusive...*):

$$\begin{tikzcd} B_s \arrow[rr] \arrow[dr] & & \psi\,\phi(f_0) \\ & \bar{B}_s \arrow[ur] & \end{tikzcd}$$

$$\sin(2\beta_s)^{SM} = 0.036 \pm 0.01$$
$$\sin(2\beta_s)^{exp} = -0.01 \pm 0.07 \pm 0.01$$

LHCb '13

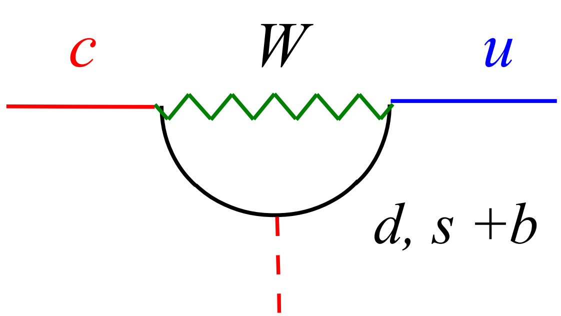
So far, no signs of deviations from the SM, but the precision is not conclusive yet

Example III: CP-violation in the charm system

The physics of charm mixing and charm decays ($c \to u$ transitions) is quite different with respect to the $B_{s,d}$ ($b \to s,d$) and K ($s \to d$) systems.

No top-enhancement of FCNC amplitudes (both $\Delta F=2$ & $\Delta F=1$):

$$V_{CKM} = \left[\begin{array}{cc|c} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ \hline V_{td} & V_{ts} & V_{tb} \end{array}\right]$$



- In all CP-conserving amplitudes we can safely approximate the CKM matrix to a *2x2 real mixing matrix*, and long-distance contributions are largely dominant
- CP-violating amplitudes are not calculable with high-accuracy within the SM, but are expected to be very small because of the CKM hierarchy ⇒ possible interesting null-tests of the SM

Example III: CP-violation in the charm system

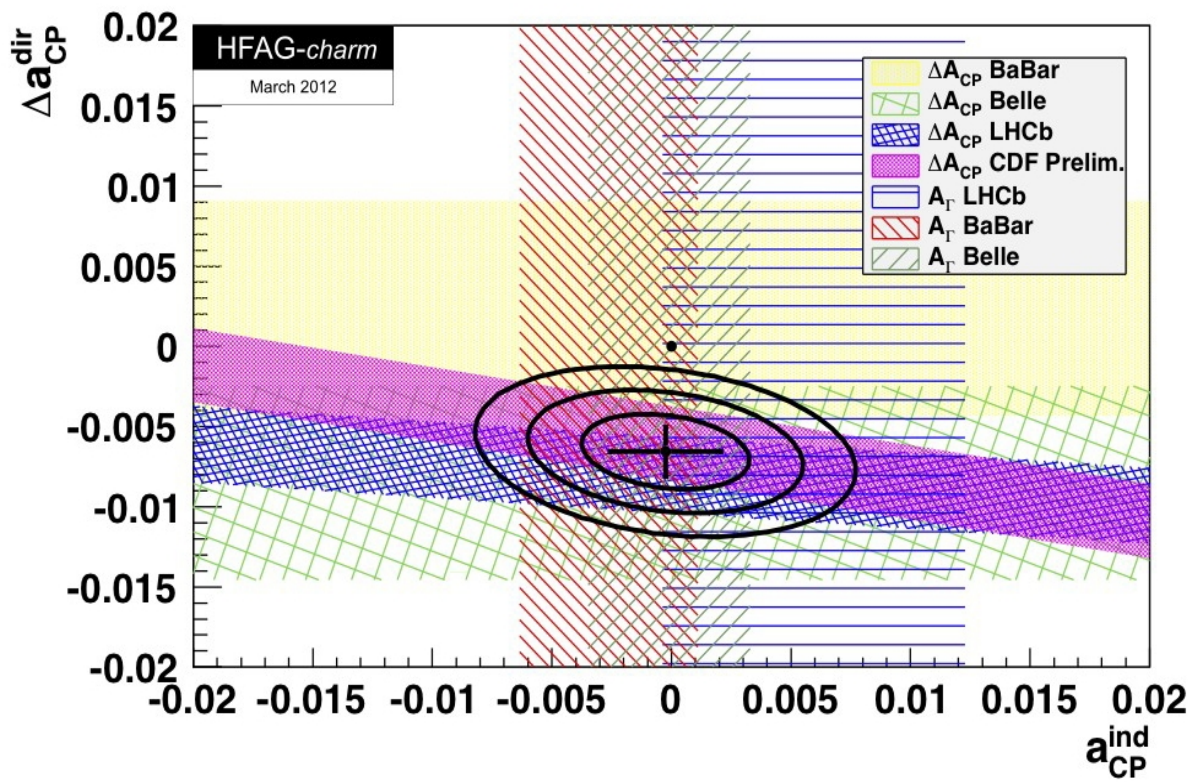
The "quasi-evidence" (4σ!) of CP violation in two-body Cabibbo-suppressed charm decays D→KK, ππ (c→u+ss,dd) reported by LHCb & other experiments in 2012 was a big surprise:

$$\Delta a_{CP} = a_{CP}(K^+K^-) - a_{CP}(\pi^+\pi^-) = (0.67 \pm 0.16)\%$$

- Unambiguous evidence of direct CP violation:

$$a_{CP}^{(dir)} = \frac{\Gamma(D\to PP) - \Gamma(\bar{D}\to PP)}{\Gamma(D\to PP) + \Gamma(\bar{D}\to PP)}$$

- Totally unexpected, at least according to (most of the) pre-LHCb predictions



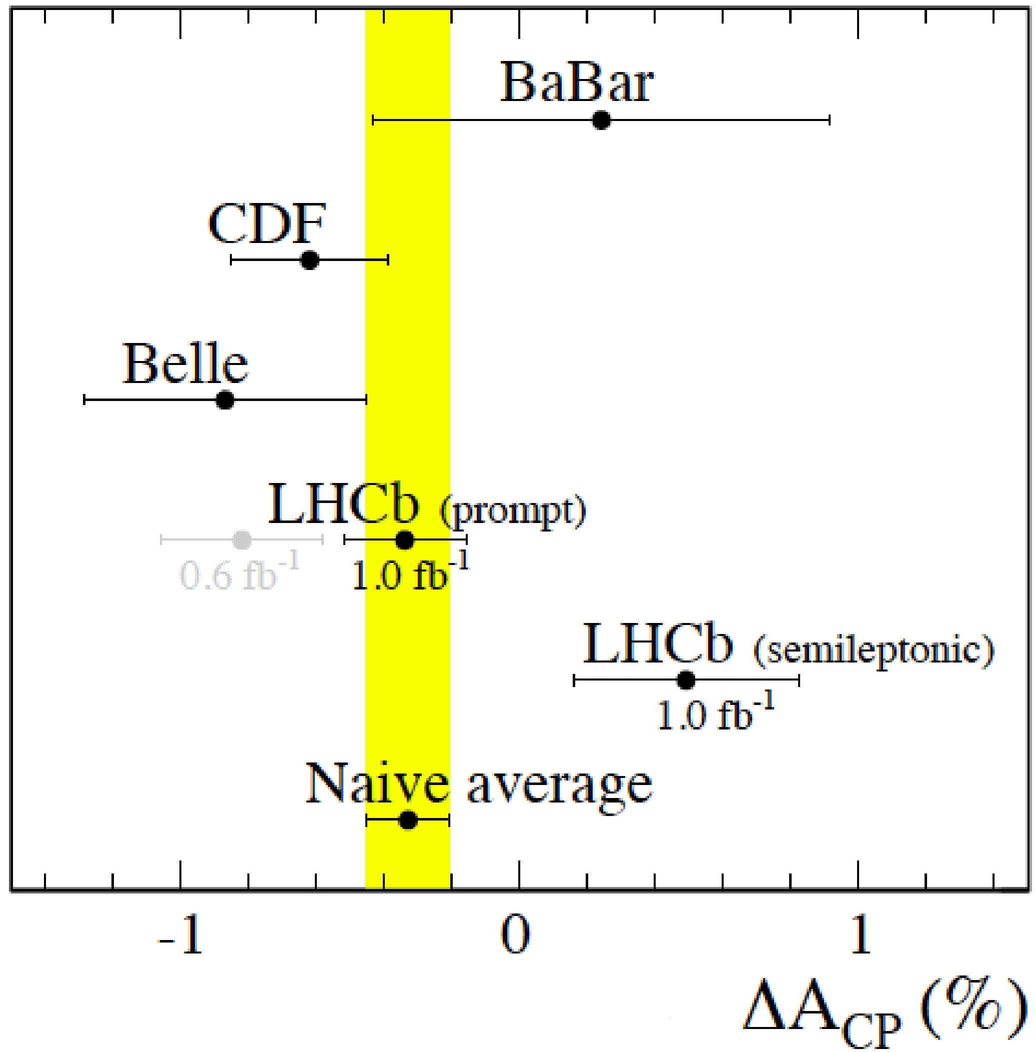
Example III: CP-violation in the charm system

The "quasi-evidence" (4σ!) of CP violation in two-body Cabibbo-suppressed charm decays $D \to KK, \pi\pi$ ($c \to u + ss, dd$) reported by LHCb & other experiments in 2012 was a big surprise.

After the 2013 LHCb results this evidence is much weaker...

- New HFAG average [March '13]

$$\Delta a_{CP}^{\rm dir} = (-0.33 \pm 0.12)\%$$



...but the basic question of what can we expect in the SM (*and what can we learn about BSM*) from direct CP-violation in Cabibbo-suppressed modes remains interesting.

Example III: CP-violation in the charm system

A value of $\Delta a_{CP} > 0.5\%$ is definitely too large compared to its "natural" SM expectation, but is not large enough, compared to SM uncertainties, to be considered a clear signal of NP:

$$\Delta a_{CP} \approx (0.13\%)\ \mathrm{Im}(\Delta R^{SM})$$

CKM suppression:

$$\arg\left(\frac{V_{cs}^* V_{us}}{V_{cd}^* V_{ud}}\right) = O(\lambda^4)$$

matrix-element ratio:

$$\frac{\text{"penguin"}}{\text{"tree"}}$$

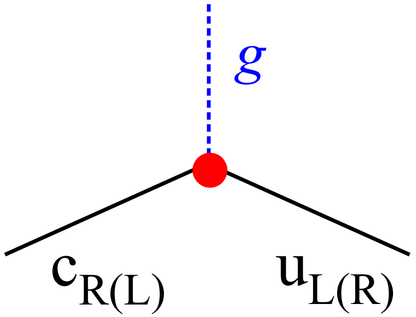
$\Delta R > 1$ is not what we expect for $m_c >> \Lambda_{QCD}$, but is not impossible treating the charm as a light quark (*possible connection with the $\Delta I=1/2$ rule in Kaons*)

More work (and especially more observables) needed in order to clarify the situation.

Example III: CP-violation in the charm system

A value of $\Delta a_{CP} > 0.5\%$ is definitely too large compared to its "natural" SM expectation, but is not large enough, compared to SM uncertainties, to be considered a clear signal of NP.

A value of $\Delta a_{CP} > 0.5\%$ fits well in a wide class of NP models predicting sizable CPV in *chromo-magnetic* operators (Q_8).



- Stringent bounds from D meson mixing naturally satisfied
- Easily generated in various well-motivated models (SUSY with partial compositness,....)
- Open window on flavor-mixing in the up sector (about which we know very little...)

Example III: CP-violation in the charm system

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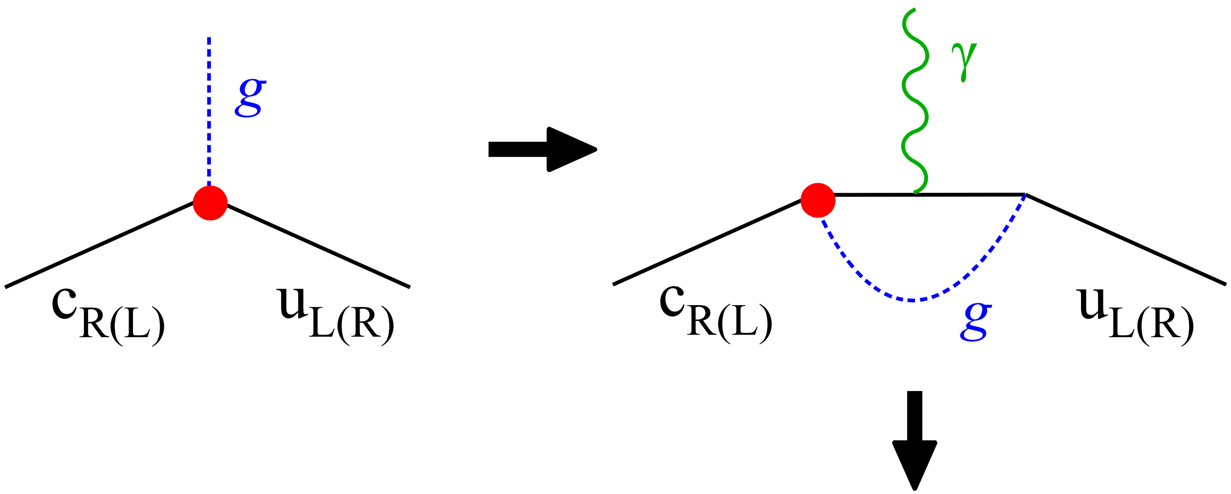
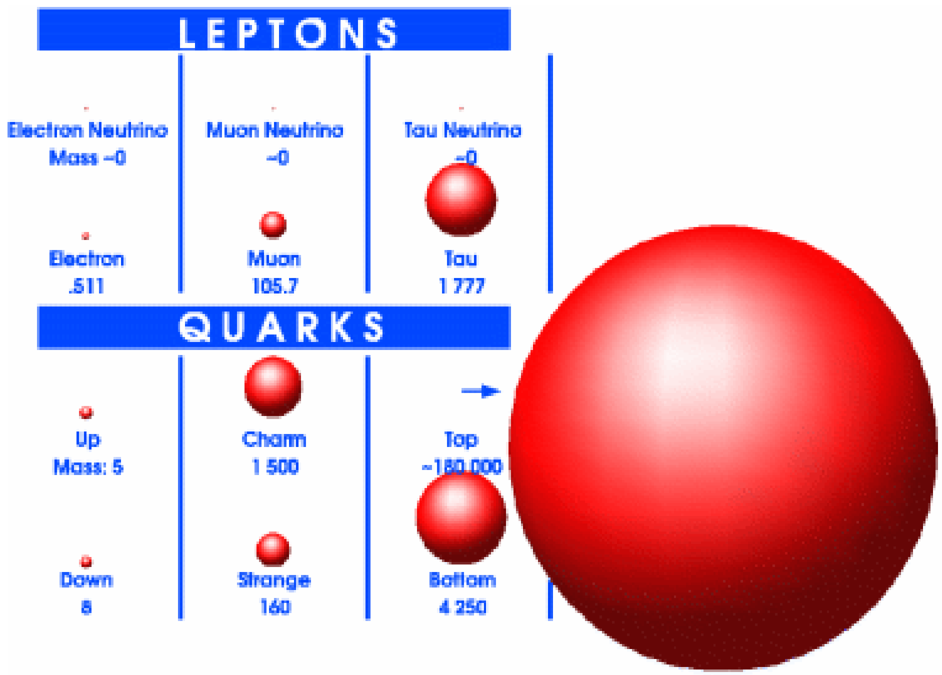


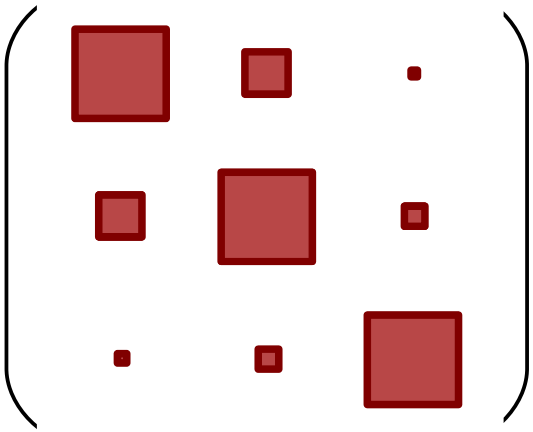
Unavoidable large CPV (*model-independent connection via QCD*) also in the *electric-dipole* operators (Q_7):

The best way to distinguish SM vs. NP is to look at radiative Cabibbo-suppressed decays, especially $D \to V\gamma$ or $D \to V\, l^+ l^-$ where the hadronic matrix element of Q_7 is enhanced [Δa_{CP}(radiative) $\sim 10\times\Delta a_{CP}$(non-leptonic)]

What determines the observed pattern of quark & lepton masses?



$V_{CKM} \sim$



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 symmetry + "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*]

Minimally-broken $U(2)^3 = U(2)_{Q_L} \times U(2)_{U_R} \times U(2)_{D_R}$
acting on the 1st & 2nd generations of quarks

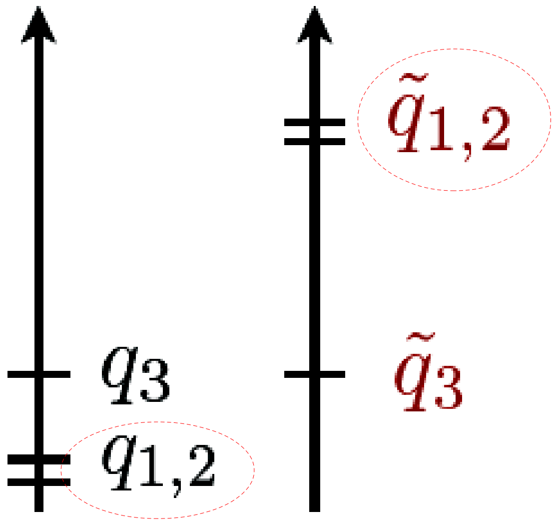
Barbieri *et al.* '11
Pomarol, Tommasini, '96
Barbieri, Dvali, Hall, '96

- The exact symmetry limit is good starting point for the SM quark spectrum ($m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$) → 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)



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A potential problem of this approach and, more generally, of any approach attributing a special role to the hierarchies in the Yukawa sector, is the problem of neutrino masses (*under the hypothesis we are interested to describe in a unified way quark and lepton sectors*):

- Why neutrino mixing angles are not as small as in the quark sector?
- Why the mass hierarchies in the neutrino sector are not as large as in the quark/charged-lepton sector?

The symmetric way [*a possible option*]

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*)

The only two small parameters in the neutrino (Majorana) mass matrix are

$$\zeta = \left| \frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}} \right|^{1/2} = 0.174 \pm 0.007 \,,$$

$$s_{13} = |(U_{\rm PMNS})_{13}| = 0.15 \pm 0.02 \,,$$

$$M_\nu^+ M_\nu \xrightarrow{\zeta,\, s_{13} \to 0} m_\nu^2\, I + \Delta m_{\rm atm}^2\, \Sigma \xrightarrow{\Delta m_{\rm atm}^2 << m_\nu^2} m_\nu^2\, I$$

$$\Sigma \approx \frac{1}{2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$$

The symmetric way [*a possible option*]

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

Alonso, Gavela, Isidori, Maiani, '13

$U(3)^5$

LR LL

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

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

Let's assume the Yukawa couplings and the neutrino mass matrix are *dynamical fields* of the the MFV flavor group, and that their values are determined by a *minimization principle* (e.g. the potential minimum)

"natural solutions" = configurations preserving maximally unbroken subgroups.

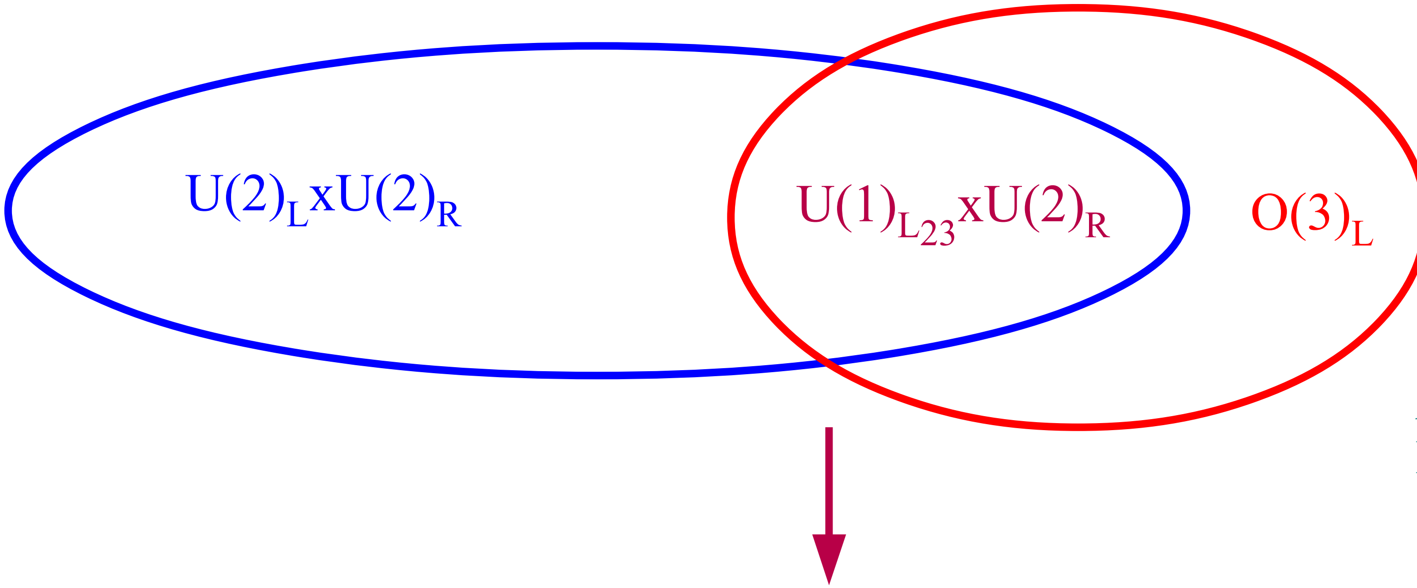
Michel & Radicati, '69
Cabibbo & Maiani, '69

The symmetric way [*a possible option*]

$U(3)^5$

LR: $Y \propto (0,0,1)$ [unbroken $U(2)_L \mathrm{x} U(2)_R$]

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



Alonso, Gavela, Isidori, Maiani, '13

A "natural orientation" of $O(3)_L$ vs. $U(2)_L$ preserving an unbroken U(1) symmetry implies a π/4 mixing angle in the PMNS matrix.

The symmetric way [*a possible option*]

$U(3)^5$

LR

LL

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

$$M_\nu \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \left(\begin{array}{c} \text{unbroken} \\ O(3)_L \end{array} \right)$$

same basis

The symmetric way [*a possible option*]

$U(3)^5$

LR $\swarrow$ $\searrow$ LL

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

$$M_\nu \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \left(\text{unbroken } O(3)_L \right)$$

same basis

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

$$\frac{m_\mu}{m_\tau} = O(\varepsilon)$$

$$|s_{13}| \sim O(\varepsilon), \quad |s_{12}| \sim O(1)$$

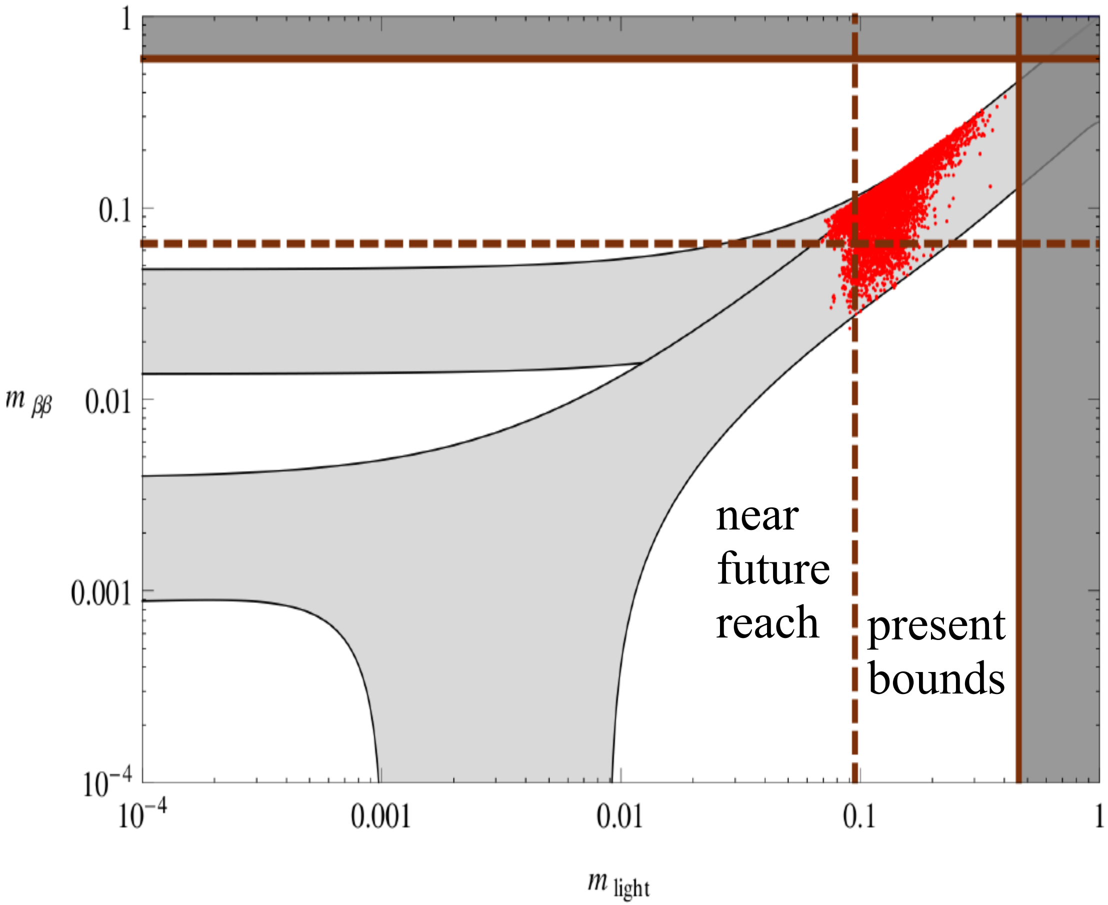
$$\frac{m_\mu}{m_\tau} \sim 0.06 < \frac{\Delta m_{atm}^{\ 2}}{m_\nu^{\ 2}} = O(\varepsilon) < |s_{13}| \sim 0.2$$

Alonso, Gavela, Isidori, Maiani, '13

The symmetric way [*a possible option*]

$U(3)^5$

LL



$$M_\nu \propto \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \qquad \left(\begin{array}{c}\text{unbroken} \\ O(3)_L\end{array}\right)$$

$+$

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

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

Conclusions

- Despite we have not seen any clear NP signal yet, it is still likely (and experimentally allowed) to expect some new degrees of freedom around the TeV scale.

- The absence of NP signal so far fits well with the idea of a *weakly interacting extension of the SM* + *little hierarchy around the e.w. scale* + *mildly broken flavor symmetry* (*coherent picture of precision tests* + *light Higgs* + *lack of deviations from SM at high-pT*) → Low-scale supersymmetry remains a good candidate.

- We have understood that the flavor structure of this weakly interacting extension of the SM is not trivial, but we have not clearly identified this structure yet → Improved experiments/searches in flavor physics play a key role in uncovering the nature of physics beyond the SM

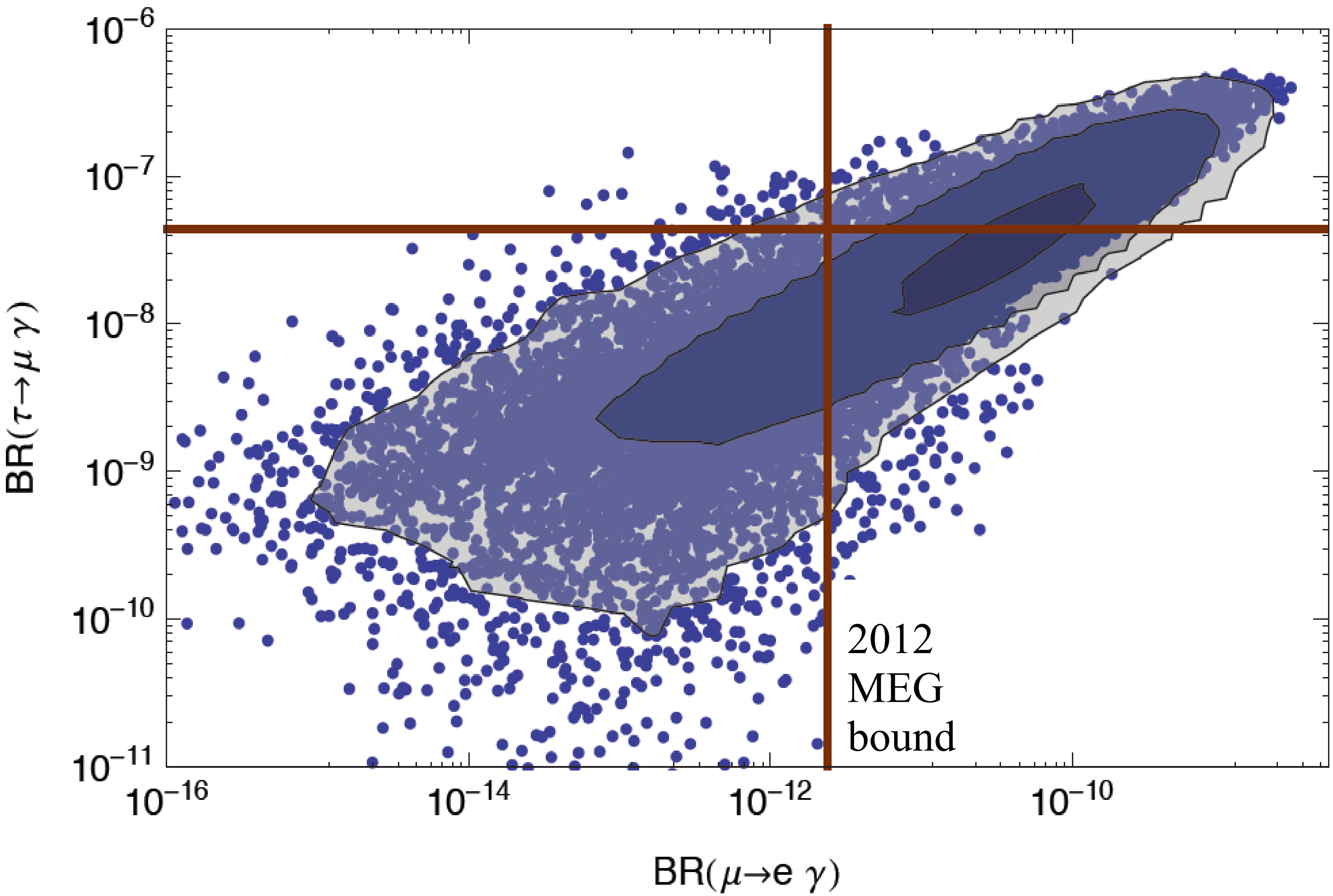

Backup

If all this is correct...

→ $0\nu2\beta$ decay experiments should be very close to observe a positive signal

… and if we add (low-energy) SUSY

→ LFV in charged leptons ($\mu \to e\gamma$) may also be close to present exp. bounds:



N.B.: LFV rates affected by a larger uncertainty

[$\mathrm{BR} \sim 1/\tilde{m}^4$]

▶ *Flavor-violating Higgs couplings*

If we consider the SM as a low-energy effective theory, it is natural to include possible flavor-violating couplings of the physical Higgs boson.

h-mediated FCNCs are unavoidable in models with more Higgs doublets and, more generally, can be viewed as the effect of higher-dimensional operators (in the EFT approach):

$$Y^{ij}\, \psi_L^{\,i}\, \psi_R^{\,j}\, \phi + \varepsilon^{ij}\, \psi_L^{\,i} \psi_R^{\,j}\, \phi^3 + \ldots \qquad\qquad \varepsilon^{ij} = \frac{c^{ij}}{\Lambda^2}$$

$$\Downarrow$$

$$\underbrace{(vY^{ij} + v^3\, \varepsilon^{ij})}_{vY_{\rm eff}}\, \psi_L^{\,i} \psi_R^{\,j} + (Y^{ij} + 3v^2\, \varepsilon^{ij})\, \psi_L^{\,i} \psi_R^{\,j}\, h + \ldots$$

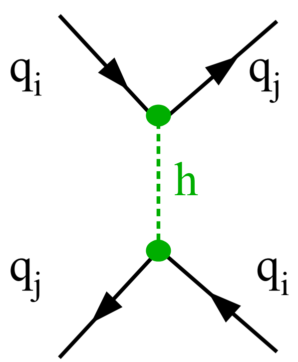
h FCNC couplings if $Y^{ij} \neq c\, \varepsilon^{ij}$

Flavor-violating Higgs couplings

$$\mathcal{L}_{\rm eff} = \sum_{i,j=d,s,b\ (i\neq j)} c_{ij}\ \bar{d}^i_L d^j_R h + \sum_{i,j=u,c,t\ (i\neq j)} c_{ij}\ \bar{u}^i_L u^j_R h + \sum_{i,j=e,\mu,\tau\ (i\neq j)} c_{ij}\ \bar{\ell}^i_L \ell^j_R h + \text{H.c.}$$

(fermion mass-eigenstate basis)

Strongly bounded by ΔF=2
(except for terms involving the top)



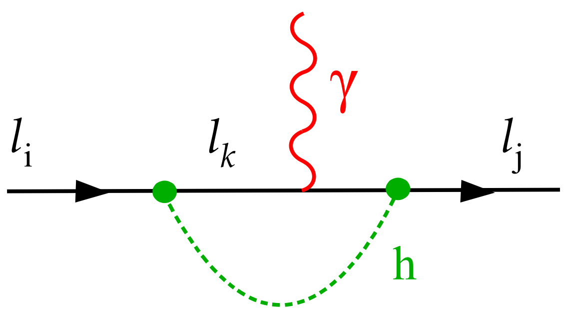
Operator	Eff. couplings	95% C.L. Bound $\lvert c_{\rm eff}\rvert$	95% C.L. Bound $\lvert{\rm Im}(c_{\rm eff})\rvert$	Observables
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	$c_{sd}\ c^*_{ds}$	1.1×10^{-10}	4.1×10^{-13}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R d_L)^2,\ (\bar{s}_L d_R)^2$	$c^2_{ds},\ c^2_{sd}$	2.2×10^{-10}	0.8×10^{-12}	
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	$c_{cu}\ c^*_{uc}$	0.9×10^{-9}	1.7×10^{-10}	$\Delta m_D;\ \lvert q/p\rvert, \phi_D$
$(\bar{c}_R u_L)^2,\ (\bar{c}_L u_R)^2$	$c^2_{uc},\ c^2_{cu}$	1.4×10^{-9}	2.5×10^{-10}	
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	$c_{bd}\ c^*_{db}$	0.9×10^{-8}	2.7×10^{-9}	$\Delta m_{B_d};\ S_{B_d\to\psi K}$
$(\bar{b}_R d_L)^2,\ (\bar{b}_L d_R)^2$	$c^2_{db},\ c^2_{bd}$	1.0×10^{-8}	3.0×10^{-9}	
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	$c_{bs}\ c^*_{sb}$	2.0×10^{-7}	2.0×10^{-7}	Δm_{B_s}
$(\bar{b}_R s_L)^2,\ (\bar{b}_L s_R)^2$	$c^2_{sb},\ c^2_{bs}$	2.2×10^{-7}	2.2×10^{-7}	

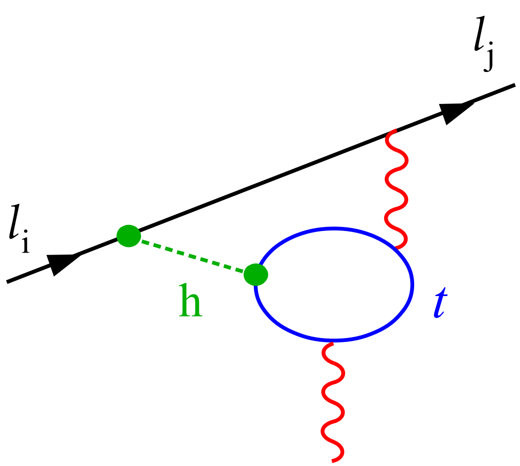
Blankenburg, Ellis, G.I. '12

Flavor-violating Higgs couplings

$$\mathcal{L}_{\rm eff} = \sum_{i,j=d,s,b\ (i\neq j)} c_{ij}\ \bar{d}^i_L d^j_R h + \sum_{i,j=u,c,t\ (i\neq j)} c_{ij}\ \bar{u}^i_L u^j_R h + \boxed{\sum_{i,j=e,\mu,\tau\ (i\neq j)} c_{ij}\ \bar{\ell}^i_L \ell^j_R h + \mathrm{H.c.}}$$

The bounds are significantly less severe in the lepton sector, especially for the τμ and τe effective couplings:





Eff. couplings	Bound	Constraint
$\lvert c_{e\tau}c_{\tau e}\rvert \quad (\lvert c_{e\mu}c_{\mu e}\rvert)$	$1.1\times10^{-2} \quad (1.8\times10^{-1})$	$\lvert\delta m_e\rvert < m_e$
$\lvert \mathrm{Re}(c_{e\tau}c_{\tau e})\rvert \quad (\lvert \mathrm{Re}(c_{e\mu}c_{\mu e})\rvert)$	$0.6\times10^{-3} \quad (0.6\times10^{-2})$	$\lvert\delta a_e\rvert < 6\times10^{-12}$
$\lvert \mathrm{Im}(c_{e\tau}c_{\tau e})\rvert \quad (\lvert \mathrm{Im}(c_{e\mu}c_{\mu e})\rvert)$	$0.8\times10^{-8} \quad (0.8\times10^{-7})$	$\lvert d_e\rvert < 1.6\times10^{-27}$ ecm
$\lvert c_{\mu\tau}c_{\tau\mu}\rvert$	2	$\lvert\delta m_\mu\rvert < m_\mu$
$\lvert \mathrm{Re}(c_{\mu\tau}c_{\tau\mu})\rvert$	2×10^{-3}	$\lvert\delta a_\mu\rvert < 4\times10^{-9}$
$\lvert \mathrm{Im}(c_{\mu\tau}c_{\tau\mu})\rvert$	0.6	$\lvert d_\mu\rvert < 1.2\times10^{-19}$ ecm
$\lvert c_{e\tau}c_{\tau\mu}\rvert,\ \lvert c_{\tau e}c_{\mu\tau}\rvert$	1.7×10^{-7}	$\mathcal{B}(\mu\to e\gamma) < 2.4\times10^{-12}$
$\lvert c_{\mu\tau}\rvert^2,\ \lvert c_{\tau\mu}\rvert^2$	0.9×10^{-2} [*]	$\mathcal{B}(\tau\to\mu\gamma) < 4.4\times10^{-8}$
$\lvert c_{e\tau}\rvert^2,\ \lvert c_{\tau e}\rvert^2$	0.6×10^{-2} [*]	$\mathcal{B}(\tau\to e\gamma) < 3.3\times10^{-8}$

Eff. couplings	Bound	Constraint
$\lvert c_{e\mu}\rvert^2,\ \lvert c_{\mu e}\rvert^2$	1×10^{-11} [*]	$\mathcal{B}(\mu\to e\gamma) < 2.4\times10^{-12}$
$\lvert c_{\mu\tau}\rvert^2,\ \lvert c_{\tau\mu}\rvert^2$	5×10^{-4} [*]	$\mathcal{B}(\tau\to\mu\gamma) < 4.4\times10^{-8}$
$\lvert c_{e\tau}\rvert^2,\ \lvert c_{\tau e}\rvert^2$	3×10^{-4} [*]	$\mathcal{B}(\tau\to e\gamma) < 3.3\times10^{-8}$

Flavor-violating Higgs couplings

$$\mathcal{L}_{\rm eff} = \sum_{i,j=d,s,b\ (i\neq j)} c_{ij}\ \bar{d}^i_L d^j_R h + \sum_{i,j=u,c,t\ (i\neq j)} c_{ij}\ \bar{u}^i_L u^j_R h + \boxed{\sum_{i,j=e,\mu,\tau\ (i\neq j)} c_{ij}\ \bar{\ell}^i_L \ell^j_R h + \text{H.c.}}$$

The bounds are significantly less severe in the lepton sector, especially for the $\tau\mu$ and τe effective couplings.

Taking into account also the smallness of the Higgs width for m ~ 125 GeV (dominant partial width controlled by $y_b \sim 0.02$)

$\Downarrow$

Flavor-changing decays into lepton pairs -with one tau- are not strongly constrained: $\text{BR}(h \to \tau\mu, \tau e) \lesssim 10\%$ $\to$ worth a direct search !!

Blankenburg, Ellis, G.I. '12

ATLAS & CMS already have the sensitivity to set bounds on $\text{BR}(h \to \tau\mu) \lesssim 1\%$

Harnik, Kopp, Zupan, '12
Davidson, Verdier, '12