Flavor physics: open problems, recent progress, and future prospects

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[*INFN, Frascati & CERN*]

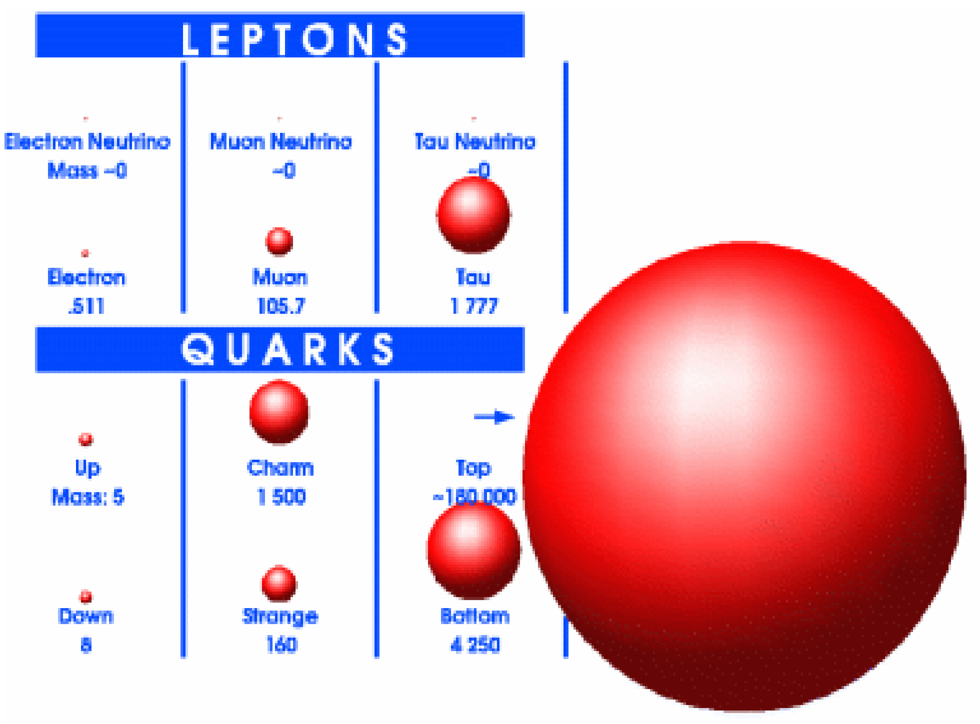
- Introduction
- Recent progress [*a personal selection*]
- Future prospects
- Conclusions

Introduction

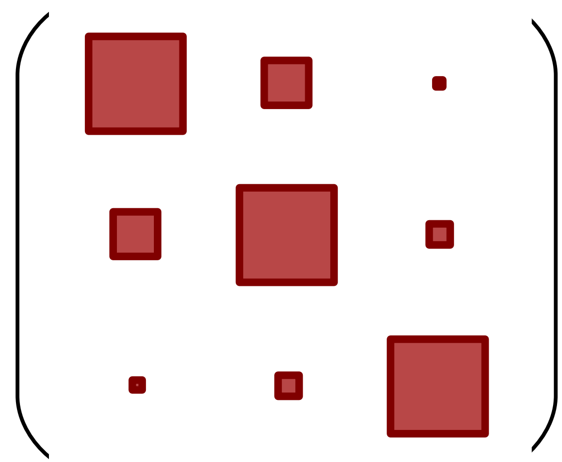
To a large extent, the origin of "flavor" is still a mystery...
Our "ignorance" can be summarized by the following two open questions:

- *What determines the observed pattern of masses and mixing angles of quarks and leptons?*

- *Which are the sources of flavor symmetry breaking accessible at low energies?*



$V_{CKM} \sim$



Introduction

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- *What determines the observed pattern of masses and mixing angles of quarks and leptons?*

- *Which are the sources of flavor symmetry breaking accessible at low energies?*

Answering the second question is more "easy":

- It can be formulated independently of the UV completion of the theory.
- It is mainly a question of precision (both on the theory and on the experimental side).

⬇

We learned a lot about the possible sources of flavor symmetry breaking from a series of high-precision measurements of flavor-changing processes performed in the recent past

Which are the sources of flavor symmetry breaking accessible at low energies?

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

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$)		Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar s_L \gamma^\mu d_L)^2$	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}; $S_{\psi\phi}$

New flavor-breaking sources at the TeV scale (if any) are highly tuned

Which are the sources of flavor symmetry breaking accessible at low energies?

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

The problem seems at least as severe in the charged-lepton sector (*although the lepton sector is definitely less explored*):

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

$\Lambda > 2\times 10^5$ TeV $\times (c_{\mu e})^{1/2}$ from $\mathrm{BR}(\mu\to e\gamma)^{\rm exp} < 2.4\times 10^{-12}$

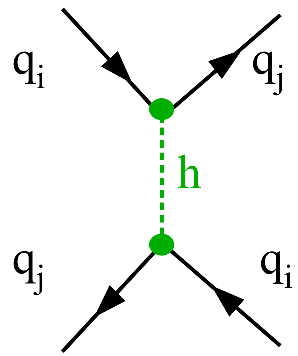
MEG '11

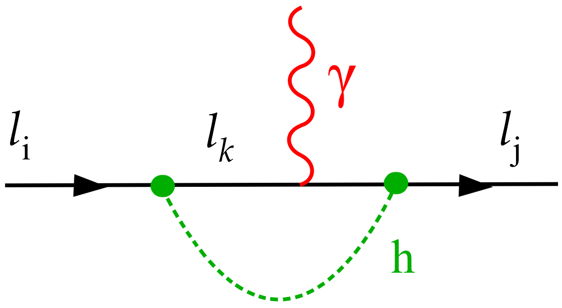
New flavor-breaking sources at the TeV scale (if any) are highly tuned

Which are the sources of flavor symmetry breaking accessible at low energies?

N.B.: If the ~ 126 GeV boson recently discovered is not (only) the SM Higgs, we can translate all these bounds into (model-independent) bounds on the possible couplings of the new particle:

$$\mathscr{L}_{\text{eff-h}} = \Sigma_{ij}\, c_{ij}\, \bar{\psi}_i\, \psi_j\, h + \ldots$$





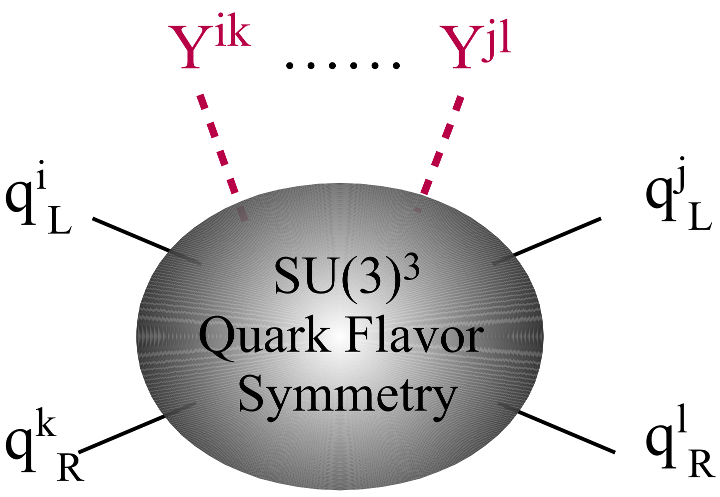
- Flavor-changing decays into quarks are beyond any realistic reach: $BR(h \to bs) < 4\times10^{-4}$
- While flavor-changing decays into lepton pairs -<u>with one tau</u>- are not strongly constrained: $BR(h \to \tau\mu, \tau e) \lesssim 10\%$ → <u>worth a direct search !!</u>

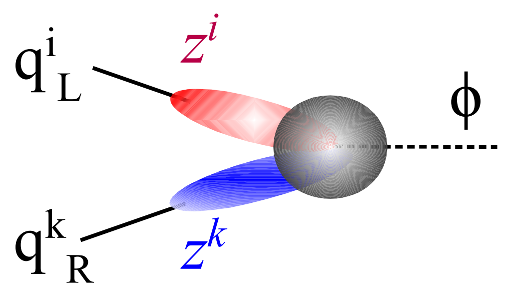
Blankenburg, Ellis, G.I. '12

Which are the sources of flavor symmetry breaking accessible at low energies?

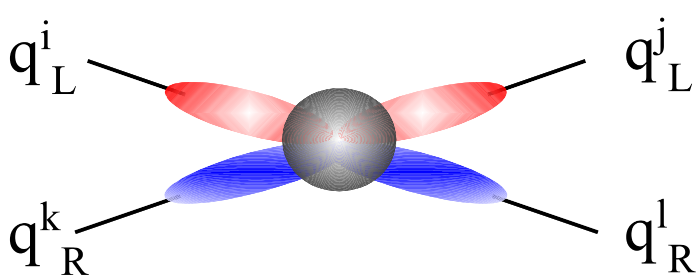
The good overall consistency of the SM predictions for flavor-changing processes indicates there is not much room for new sources of flavor symmetry breaking close to the TeV scale, or that the scale of New Physics (NP) is very high

However, the constraints on the scale of NP become much less severe in realistic models where the mechanisms of flavor-mixing and fermion masses are linked together [e.g.: *Minimal Flavor Violation*, or *Partial Compositeness*]





Gerghetta & Pomarol '00
Agashe *et al.* '05
Csaki, Falkowski, Weiler '08
Kerhen-Zur *et al.* '12
...



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In such models we can expect small but detectable deviations from the SM predictions in selected flavor-violating observables:

- Small/tiny corrections over leading SM amplitudes
- Rare/forbidden processes (such as LFV & EDMs)

We need more statistics on theoretically-clean observables to make progress

We have understood that the flavor structure of NP is highly non trivial, but we have not yet identified this structure yet.

What determines the observed pattern of masses and mixing angles of quarks and leptons?

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 masses and mixing angles of quarks and leptons?

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*]

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

$U(3)^N$

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

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

Small $U(2)_L$ breaking leading to $3\to1,2$ 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*]

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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*]

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

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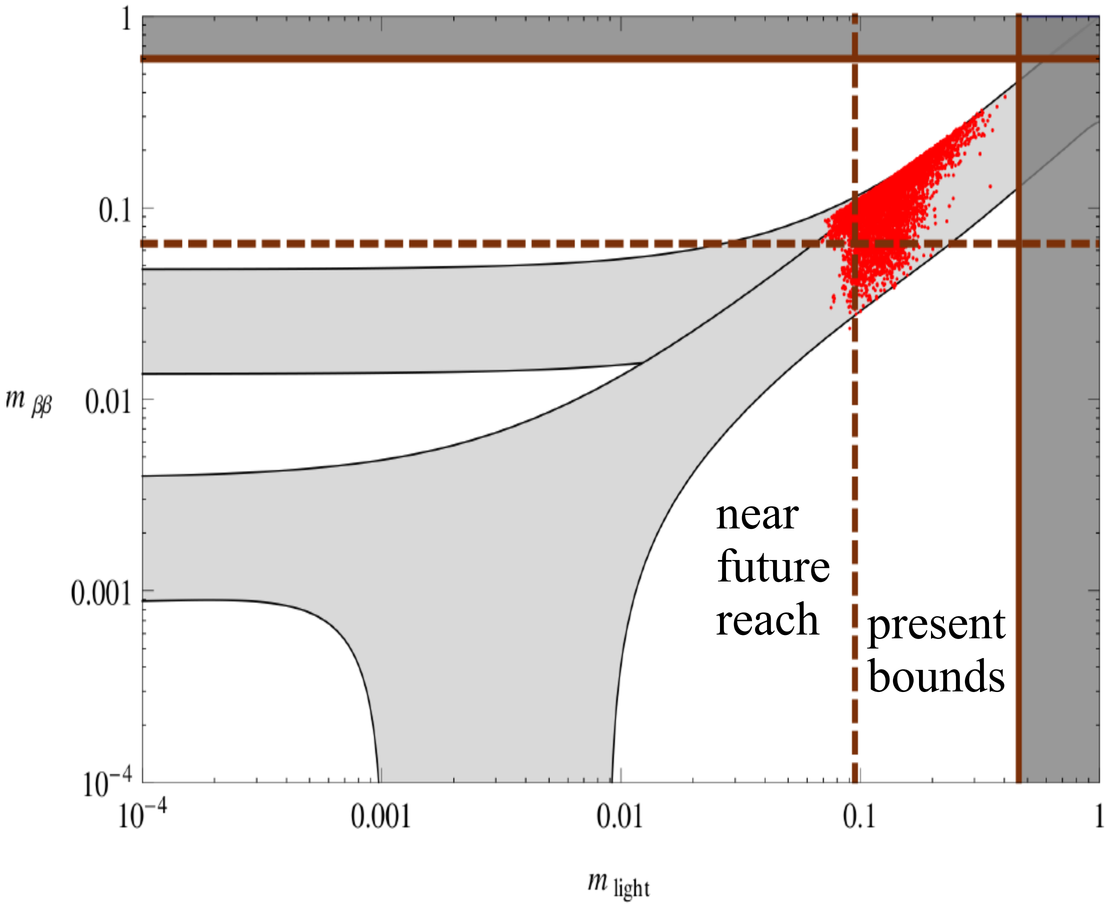
LL



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

Large 2-3 mixing
+ small mass-splitting

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

If all this is correct... 2β decay experiments (and maybe KATRIN) are very close to observe a positive signal...

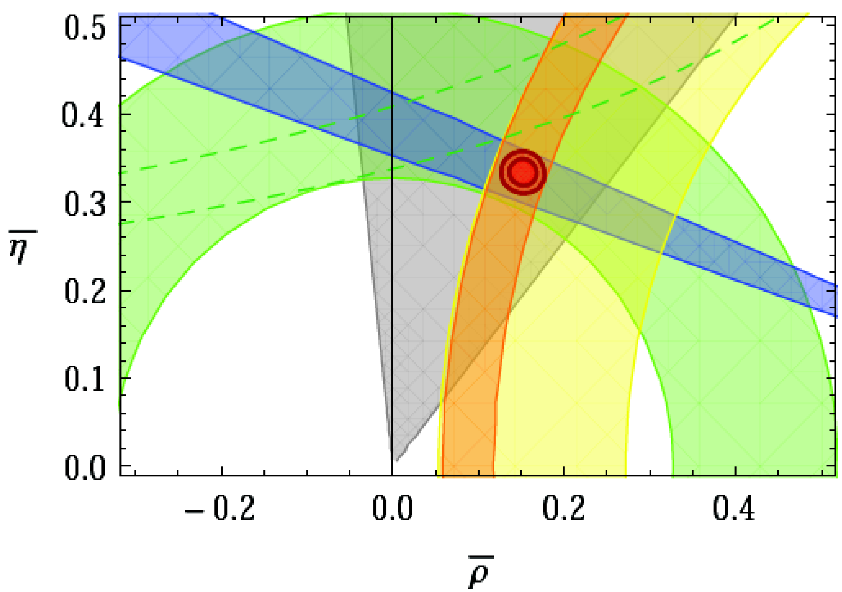
Recent Progress

I. CPV in B_S mixing

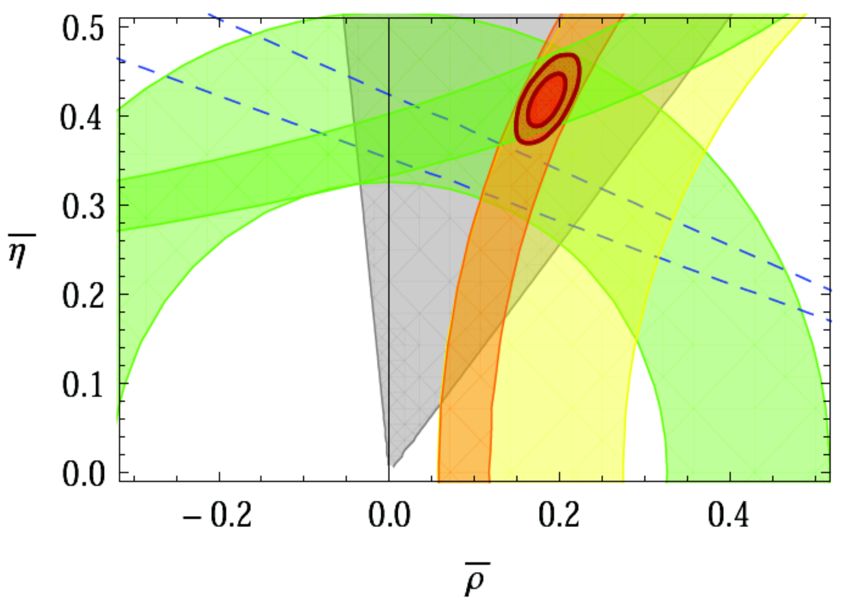
The B_s mixing phase is a key ingredient to clarify our understanding of down-type $\Delta F=2$ amplitudes ($s\to d$, $b\to d$, and $b\to s$).

The situation of $s\to d$ and $b\to d$ is not so clear given a tiny (~2σ) but long-standing discrepancy between ε_K ($s\to d$) and $\sin(2\beta)$ ($b\to d$):

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

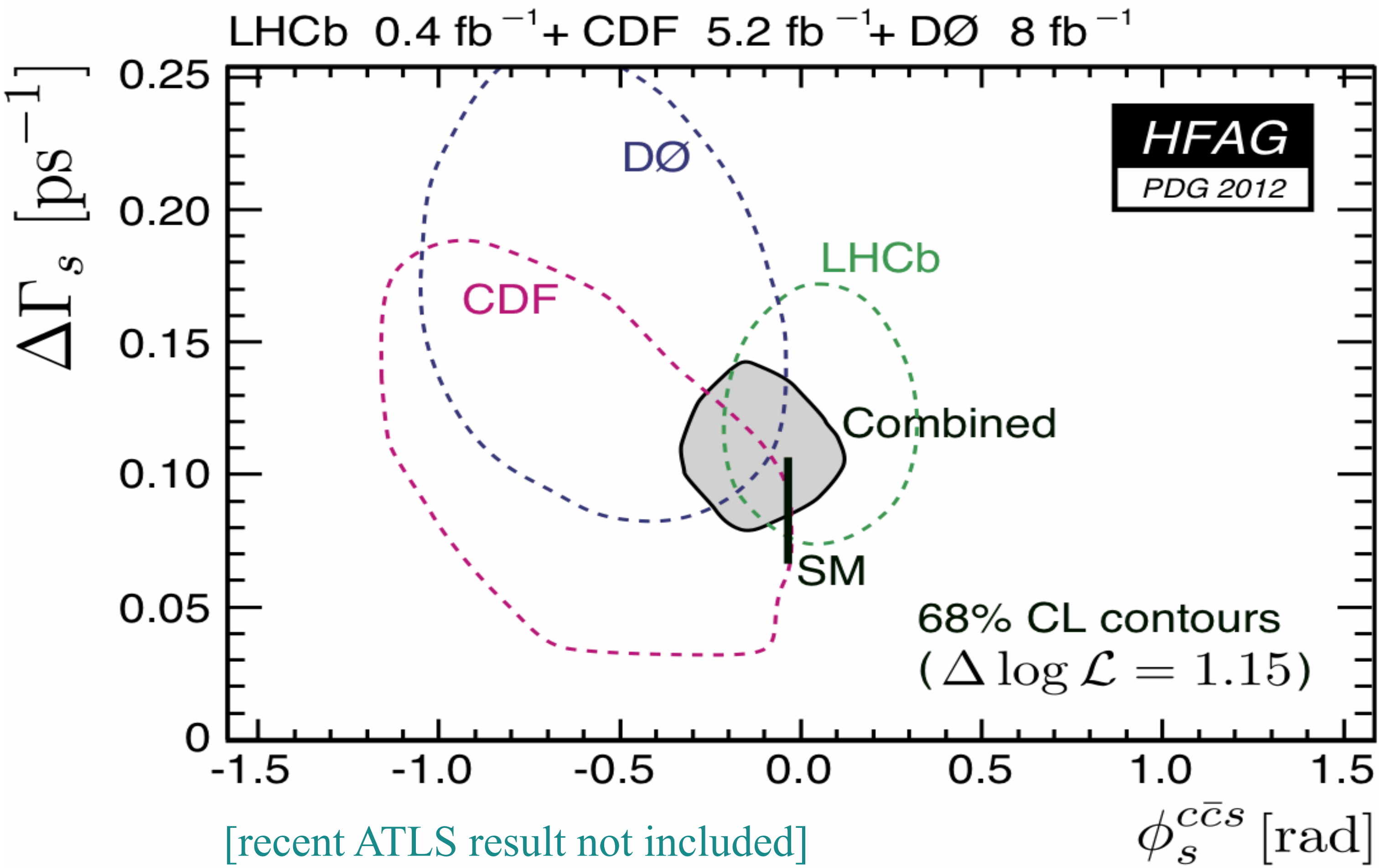


SM fit, no $S_{\psi K}$ (no Bd mix. phase)



I. CPV in B_s mixing

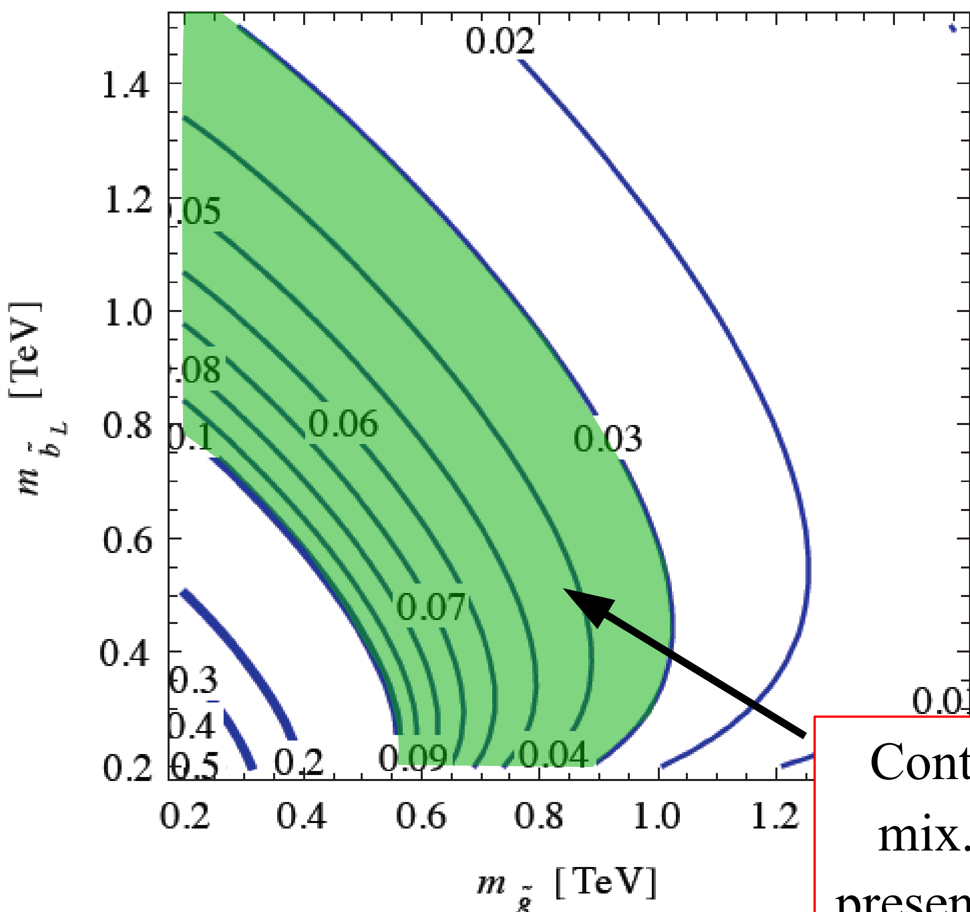
Thanks to the excellent measurement of LHCb, the phase of Bs mixing is now determined to a comparable level of precision, and shows no signs of deviations from the SM:

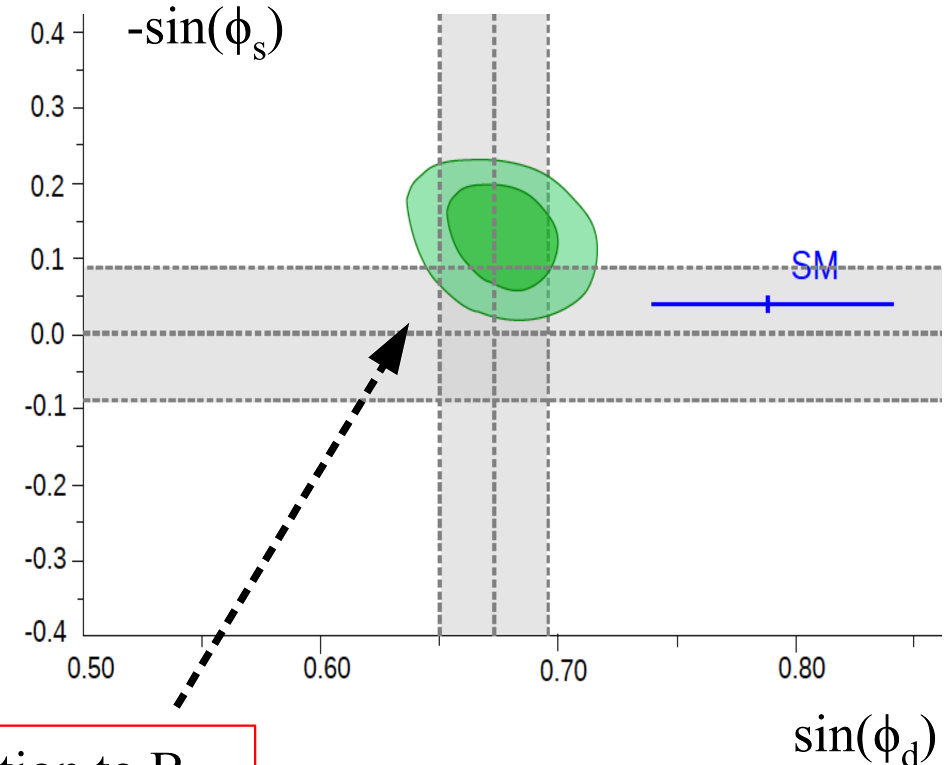


[recent ATLS result not included]

We have just reached the level of precision necessary for testing NP solutions of the ε_K-$\sin(2\beta)$ problem: *possible surprises with more statistics...*

E.g.: "Split-family" SUSY with minimal ~~$U(2)^3$~~





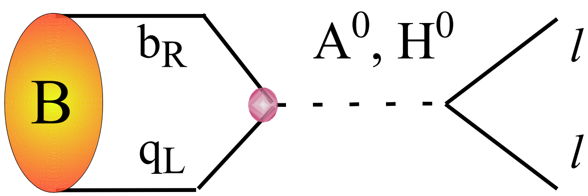
Contribution to B_b mix. reducing the present CKM tension

Barbieri *et al.*, '11

II. $B_s \to \mu\mu$

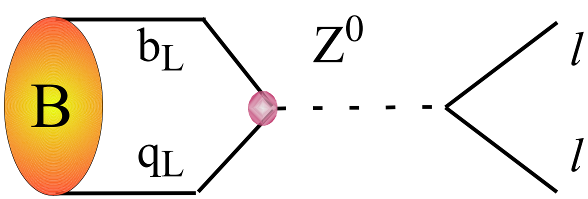
This mode is a unique source of information about flavor physics beyond the SM:

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



Possible large enhancements

$$BR^{SM} = (3.2 \pm 0.3)10^{-9}$$



Relevant for BR = O(SM)

Limits for B^0_s at 95% C.L.

- D0
  $BR(B^0_s \to \mu^+\mu^-) < 51\times10^{-9}$
- CDF
  $BR(B^0_s \to \mu^+\mu^-) < 31\times10^{-9}$
- ATLAS
  $BR(B^0_s \to \mu^+\mu^-) < 22\times10^{-9}$
- CMS
  $BR(B^0_s \to \mu^+\mu^-) < 7.7\times10^{-9}$
- LHCb
  $BR(B^0_s \to \mu^+\mu^-) < 4.5\times10^{-9}$

Preliminary upper limits (95% CL)
LHC combination: $BR(B_s \to \mu\mu) < 4.2\times10^{-9}$

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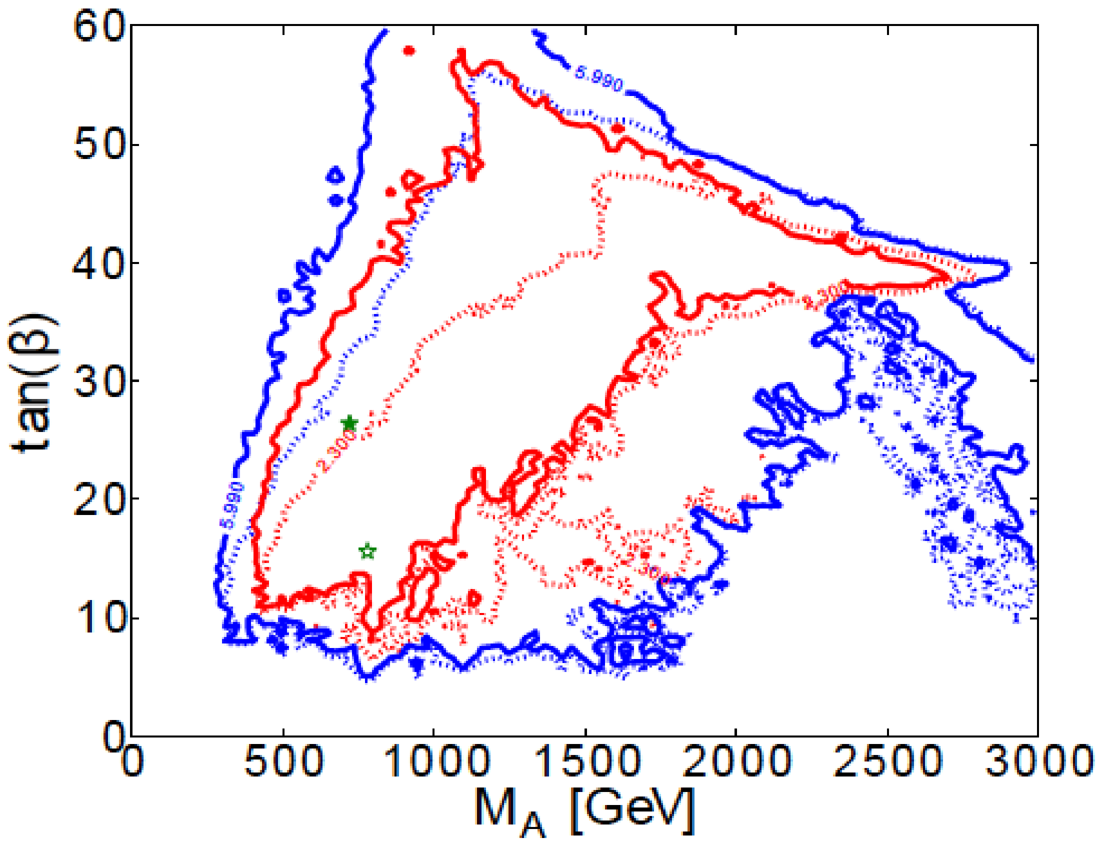
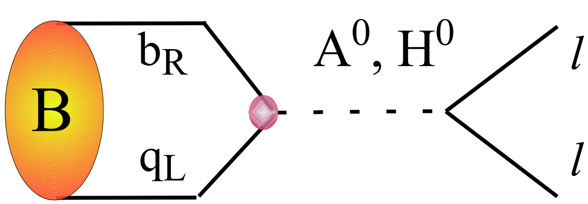


E.g.: Impact of the present exp. bound on $BR(B_s \to \mu^+\mu^-)$ in the NUHM-MSSM

Buchmueller *et al.* '12

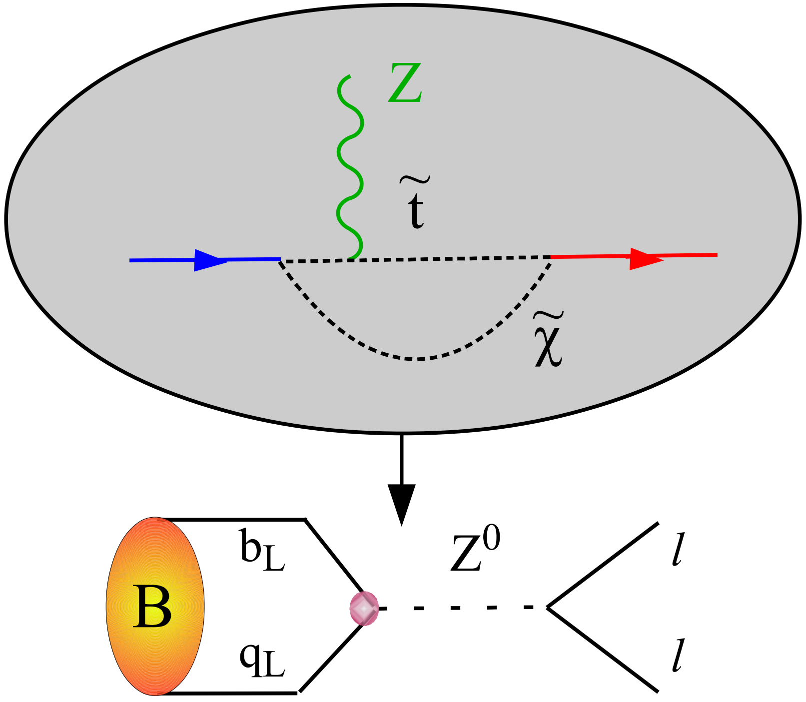


Possible large enhancements (*excluded by present data!*)

The fact we don't see large enhancements over the SM does not mean this decay mode is becoming less interesting.... !!

On the contrary, we are entering a regime where different type of amplitudes can affect the BR (not only scalar FCNC's)

E.g.: SUSY with light stops and "disoriented A terms"



Relevant for $B(B \to ll) = O(SM)$

Possible $O(\pm 50\%)$ corrections to the BR for $m_{stop} \lesssim 0.5$ TeV

Behring, Gross, Hiller, Schacht '12

(*effects of this size particularly welcome in models with NP in* Δa_{CP})

Recent developments concerning the SM prediction of BR($B_s \to \mu^+\mu^-$):

I) Updated prediction taking into account leading NLO EW (+ full NLO QCD) of the *photon-inclusive flavor-eigenstate* decay:

$$\mathrm{BR}^{(0)} = 3.2348 \times 10^{-9} \times \left(\frac{M_t}{173.2\ \mathrm{GeV}}\right)^{3.07} \left(\frac{f_{B_s}}{227\ \mathrm{MeV}}\right)^{2} \left(\frac{\tau_{B_s}}{1.466\ \mathrm{ps}}\right) \left|\frac{V_{tb}^{*}V_{ts}}{4.05\times 10^{-2}}\right|^{2}$$

~ 3% th. error, which could be further reduced with a full NLO EW calculation

$$= (3.23 \pm 0.15 \pm 0.23_{f_{B_s}}) \times 10^{-9}$$

SM prediction giving present best estimate of parametric inputs

Buras, Girrbach, Guadagnoli, G.I. '12

N.B: Full NLO EW available for the related mode $K\to\pi\nu\nu$

Brod, Gorbahn Stamou, '11

Preliminary upper limits (95% CL)
LHC combination: BR($B_s \to \mu\,\mu$)< $4.2\mathrm{x}10^{-9}$

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Buras, Girrbach, Guadagnoli, G.I. '12

II) Correction factors in relating $\mathrm{BR}^{(0)}$ to the experimentally accessible rate

- Photon-energy cut [Buras *et al.* '12] → ~ -10% (*already included in exp. efficiency*)
- $\Delta\Gamma_s \neq 0$ [Bruyn *et al.* '12] → ~ + 10% (*not included yet in exp. results*)

Preliminary upper limits (95% CL)
LHC combination: BR($B_s \to \mu\mu$)< 4.2×10^{-9}

Still a long way to go before being saturated by theoretical errors

III. CP violation in charm decays

The evidence of CPV in charm observed at LHCb, CDF & Belle is one of the *most interesting news in flavor physics* since a long time:

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

- Unambiguous evidence of <u>direct CP violation:</u>

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

- <u>Totally unexpected</u>, at least according to all the pre-LHCb predictions of the last 20 years: DCPV in charm above 0.1% quoted as "clear signal of physics beyond the SM"...

Post-measurement considerations:

The observed Δa_{CP} is large compared to its "natural" SM expectation:

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

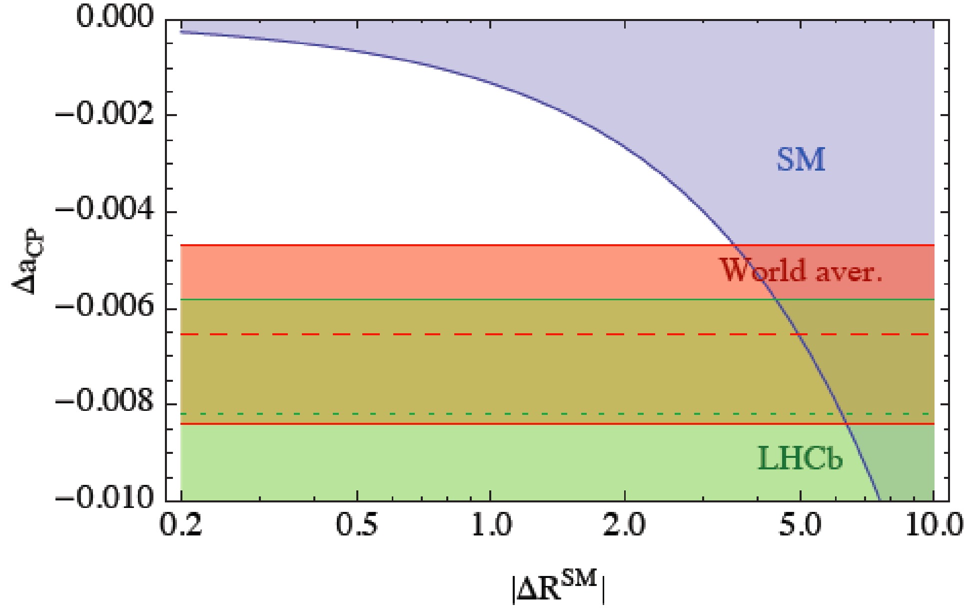
CKM suppression:

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

matrix-element ratio:

$$\frac{\text{"penguin" (disconnected)}}{\text{"tree" (connected)}}$$

naturally expected < 1



G.I., Kamenik, Ligeti, Perez '11

Post-measurement considerations:

The observed Δa_{CP} is large compared to its "natural" SM expectation, but is not large enough, compared to SM uncertainties, to be considered a clear signal of NP:

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

$$\mathcal{H}_{\rm eff} \approx V_{cd}^{*} V_{ud}\, \mathcal{H}^{(d)} + V_{cs}^{*} V_{us}\, \mathcal{H}^{(s)}$$

CKM suppression:

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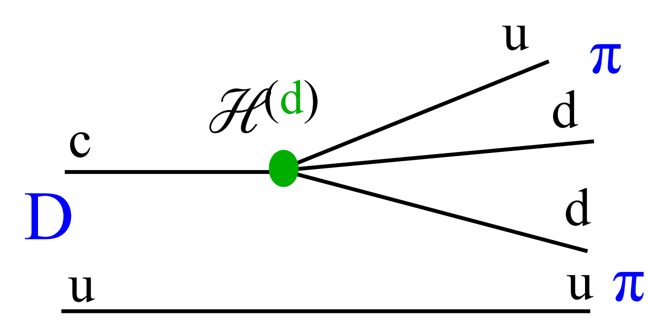
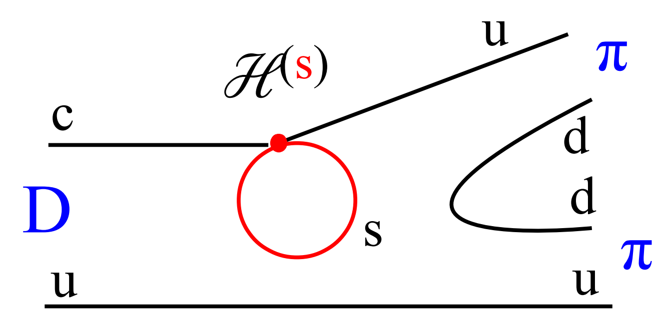


$\Delta R>1$ is not what we expect for $m_c >> \Lambda_{QCD}$, but is not impossible treating the charm as a light quark: possible connection with the $\Delta I=1/2$ rule in Kaons

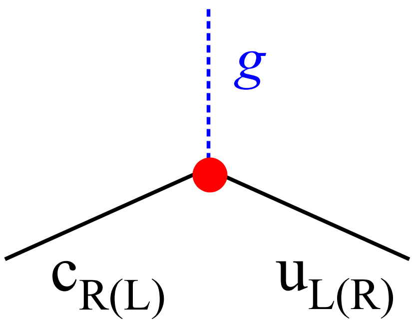
Golden, Grinstein '89

Brod *et al.* '11, '12
Feldmann *et al.* '12



Post-measurement considerations:

- The observed Δa_{CP} is large compared to its "natural" SM expectation, but is not large enough, compared to SM uncertainties, to be considered a clear signal of NP
- It fits well in a wide class of NP models predicting sizable CPV in *chromo-maganetic* operators (Q_8 & Q_8').



→ Strict bounds from D meson mixing naturally satisfied

→ Easily generated in various well-motivated models (SUSY, RS extra-dim.,....)

Giudice, GI, Paradisi, '12
Hiller, Hochberg, Nir, '12
Keren-Zur *et al.* '12
Delunay *et al.* '12
…

→ Open window on flavor-mixing in the up sector (about which we know very little...)

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

Post-measurement considerations:

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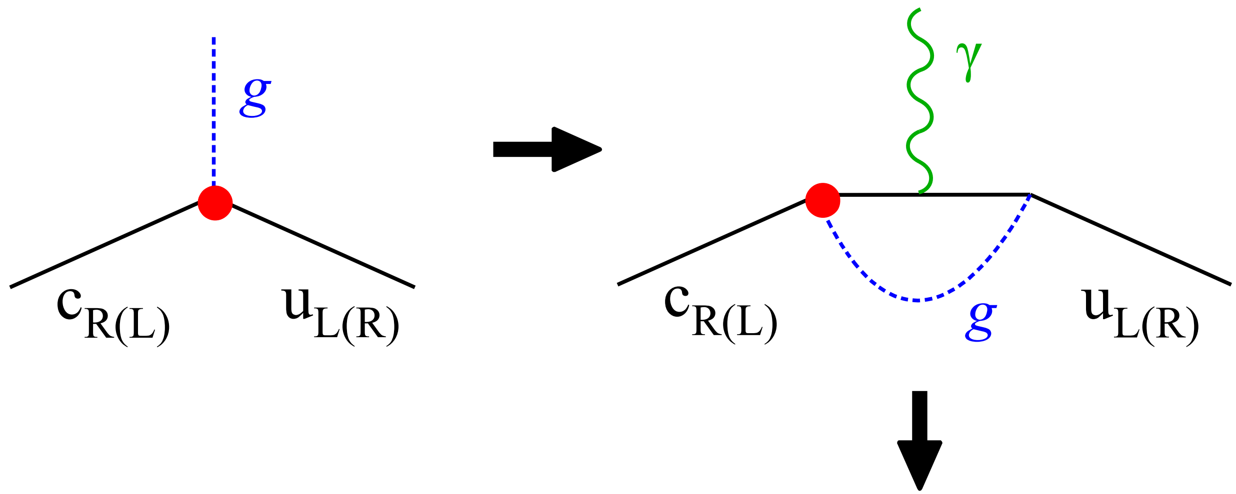
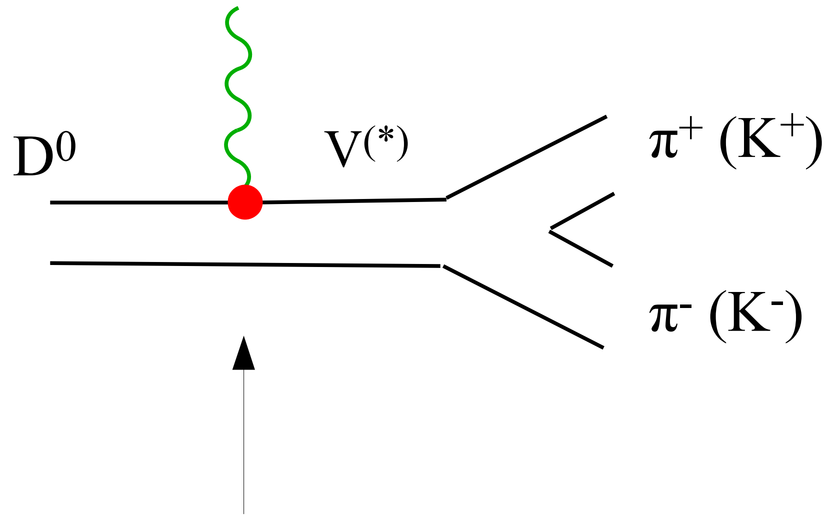


Unavoidable large CPV (*model-independent connection via QCD*) also in the *electric-dipole* operators (Q_7 & Q_7'):

- Radiative SCS D decays, especially $D \to (P^+P^-)_V\,\gamma$, could help to shed light on the issue.



Relative weight of NP substantially higher than in D→PP (*if NP appears mainly in* Q_7 *&* Q_8)

Relatively clean short-distance CPV amplitude due to $\langle Q_7 \rangle$:

sub-leading in the rates (10^{-7}-10^{-8}), but large enough to generate O(few%) CPV asymmetry when interfering with the (approximately CPC) SM amplitude

$\Delta a_{CP}(D\to\rho\gamma)^{max} \sim 10\%$

$\Delta a_{CP}(D\to\phi\gamma)^{max} \sim 6\%$

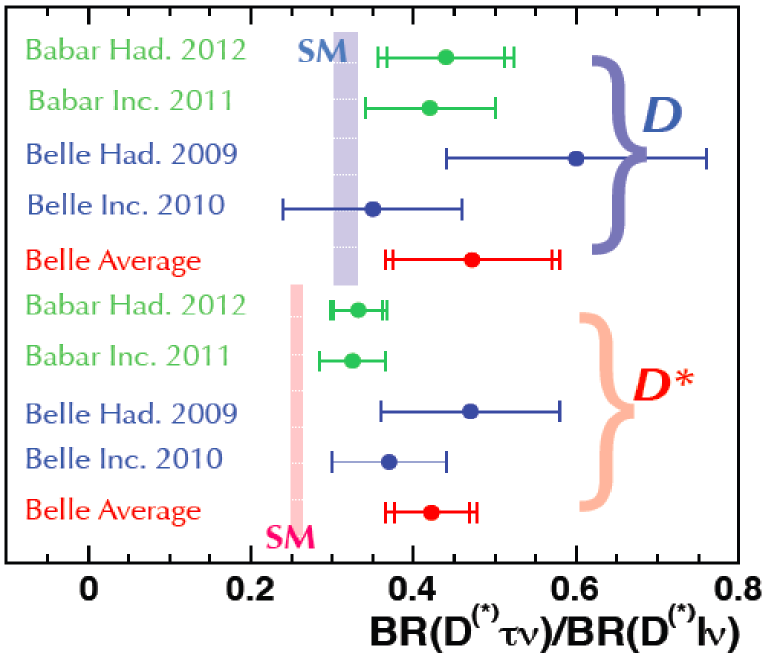
GI, Kamenik, '12

➡ CPV asymmetries above 3% would be a clear sign of NP in dipole operators

The neutron EDM and LFV in charged leptons are also expected to be close to their exp. bound, but in these cases the connections are more model-dependent.

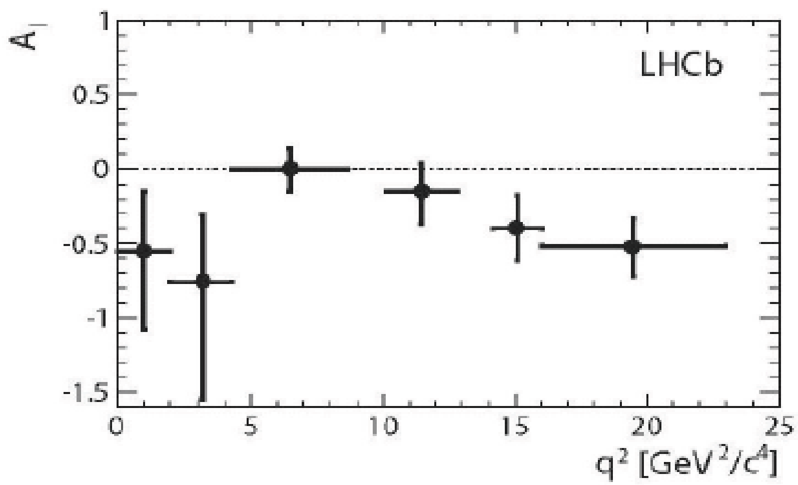
IV. Open issues in semi-leptonic B decays

Two potentially interesting deviations from the SM predictions have recently appeared in semi-leptonic B decays:



I) $\dfrac{BR(B \to D^{(*)} \tau\nu)}{BR(B \to D^{(*)} l\nu)}$ significantly higher than SM predictions

Babar (2012) claims > 3σ deviation combining D and D* modes

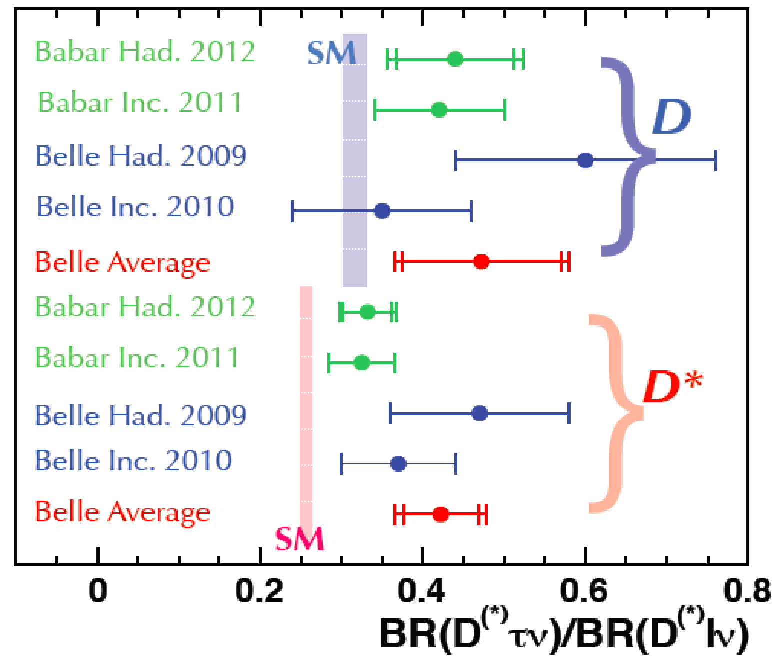


II) $\dfrac{\Gamma(B^0 \to K^0 \mu\mu)}{\Gamma(B^+ \to K^+ \mu\mu)} \neq 1$ (*isospin limit*)

LHCb (2012) claims ~ 4σ deviation from the isospin limit

IV. Open issues in semi-leptonic B decays

Two potentially interesting deviations from the SM predictions have recently appeared in semi-leptonic B decays:



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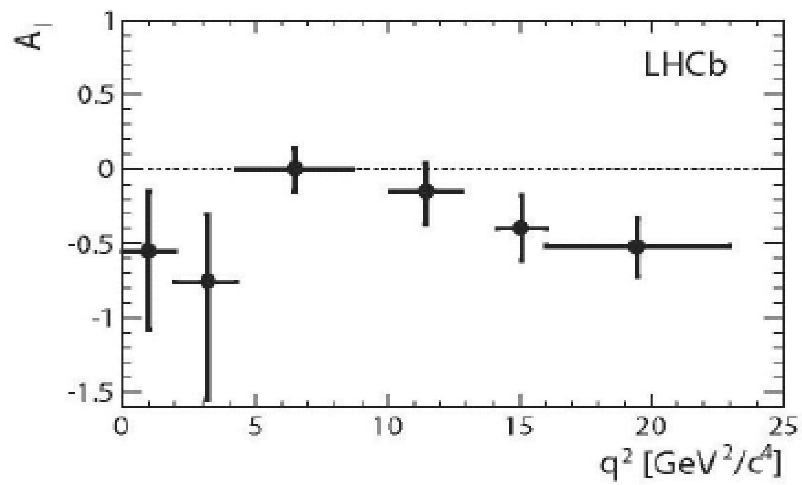

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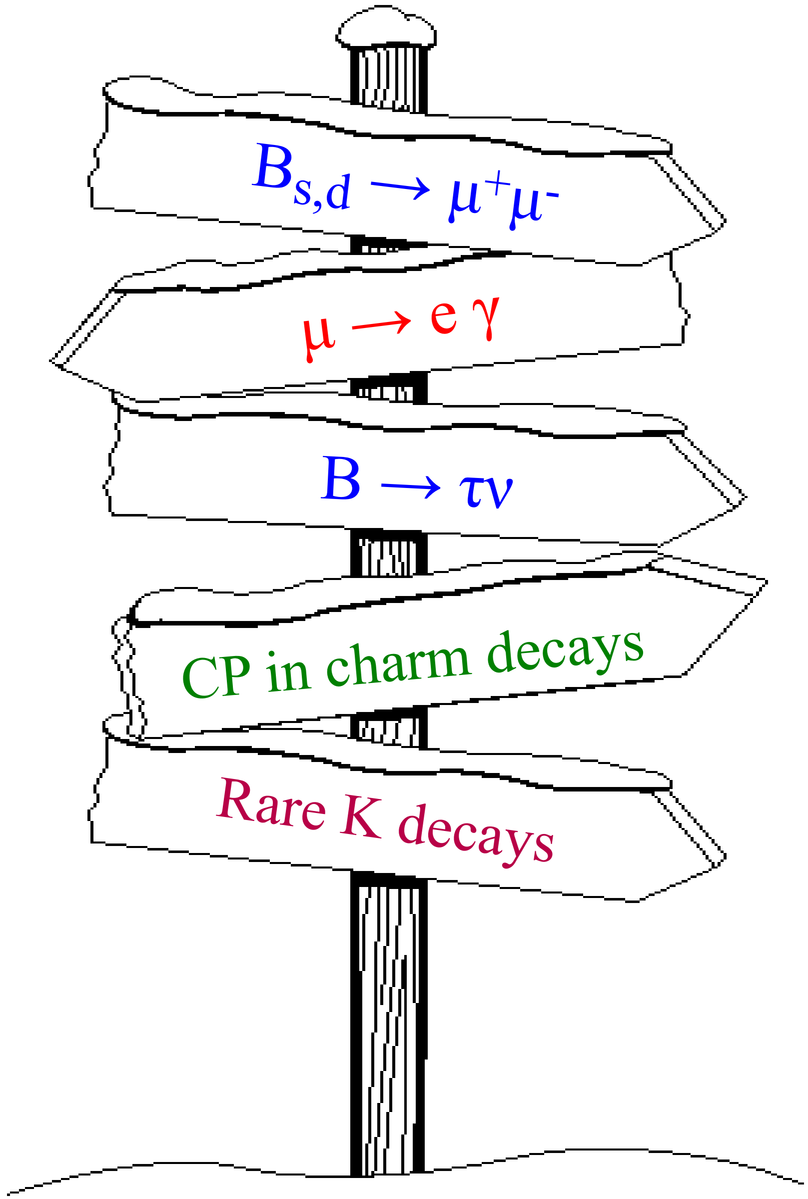
My interpretation: two difficult measurements, statistics still low, let's wait more data...

Future prospects



Future prospects

"Minimalistic" list of the key (low-energy) quark flavor-violating observables:

- γ from tree ($B \to DK$, ...)
- $|V_{ub}|$ from exclusive semi-leptonic B decays

→ Clean (tree-level) determination of the main SM inputs [key ingredient to improve the precision of $\Delta F=2$ tests]

- $B_{s,d} \to l^+l^-$ — Higgs-mediated FCNCs [$\sigma(f_B) < 5\%$ (from lattice)]
- CPV in B_s mix. [ϕ_s] — New CPV (SUSY, ...) [$\sigma(S_{\psi\varphi}) \sim 0.01$]
- $B \to K^{(*)} l^+l^-, \nu\nu$ — Non-standard FCNCs [$\sigma(A_{FB}) \lesssim 5\%$]
- $B \to \tau\nu, \mu\nu$ (+D) — Scalar charged currents [$\sigma(f_B) \to 5\%$ (from lattice)]
- $K \to \pi\nu\nu$ — Best probe of non-MFV [$\sigma(BR) \lesssim 5\%$]
- CPV in charm — Key window on up-type dynamics [more work on the th. side]

Future prospects

"Minimalistic" list of the key (low-energy) quark flavor-violating observables:

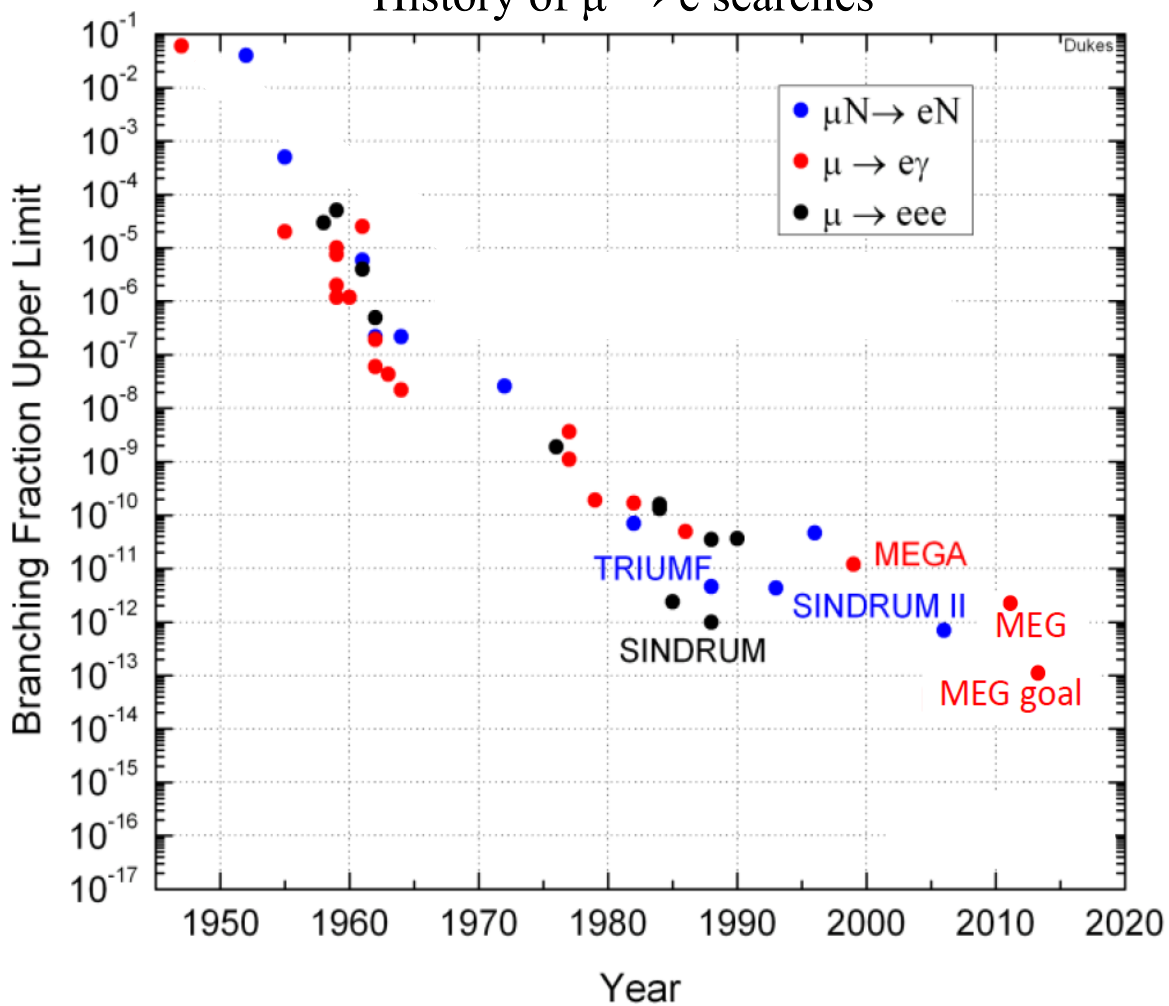
- γ from tree ($B \to DK$, ...) — S-LHCb
- $|V_{ub}|$ from exclusive semi-leptonic B decays — S-Bfactory
- $B_{s,d} \to l^+ l^-$ — S-LHCb + ATLAS & CMS
- CPV in B_s mix. [ϕ_s] — S-LHCb
- $B \to K^{(*)} l^+ l^-, \nu\nu$ — S-LHCb / S-Bfactory
- $B \to \tau\nu, \mu\nu$ (+D) — S-Bfactory
- $K \to \pi\nu\nu$ — Kaon beams
- CPV in charm — S-LHCb / S-Bfactory

The key role of LFV

After what we learned from neutrino physics, LFV in charged leptons is probably the most interesting (*and potentially rewarding*) search in the flavor sector.

- Neutrino oscillations => Lepton Flavor Violation
- No problems of SM (and SM + ν) backgrounds
- LFV in charged leptons at "visible rates" if there are new particles carrying lepton flavor not too far from the TeV scale (*as in most realistic NP models*)

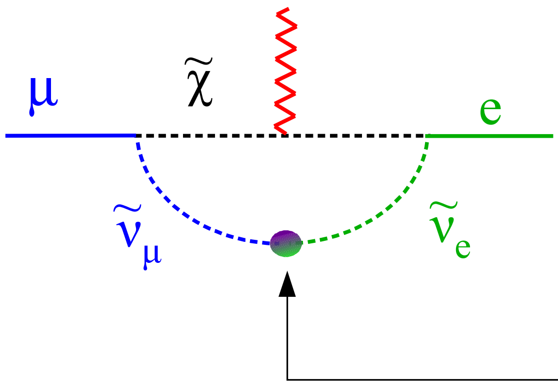
History of μ → e searches



✯ *The key role of LFV*

LFV in charged leptons at "visible rates" if there are new particles carrying lepton flavor not too far from the TeV scale:

E.g.: SUSY



$$(\delta_{LL})_{12} \sim \left[\begin{array}{ll} y_t^2 \;\; V_{13}V_{23}^* & [\textit{GUT}] \\ y_{\nu_3}^2 \; U_{13}U_{23}^* & [\textit{see-saw}] \end{array}\right.$$

$$BR(\mu \to e\gamma) \sim 10^{-13} \left[\frac{\tan\beta}{10}\right]^2 \left[\frac{0.5\ \mathrm{TeV}}{\tilde{m}}\right]^4 \left[\frac{(\delta_{LL})_{12}}{10^{-4}}\right]^2$$

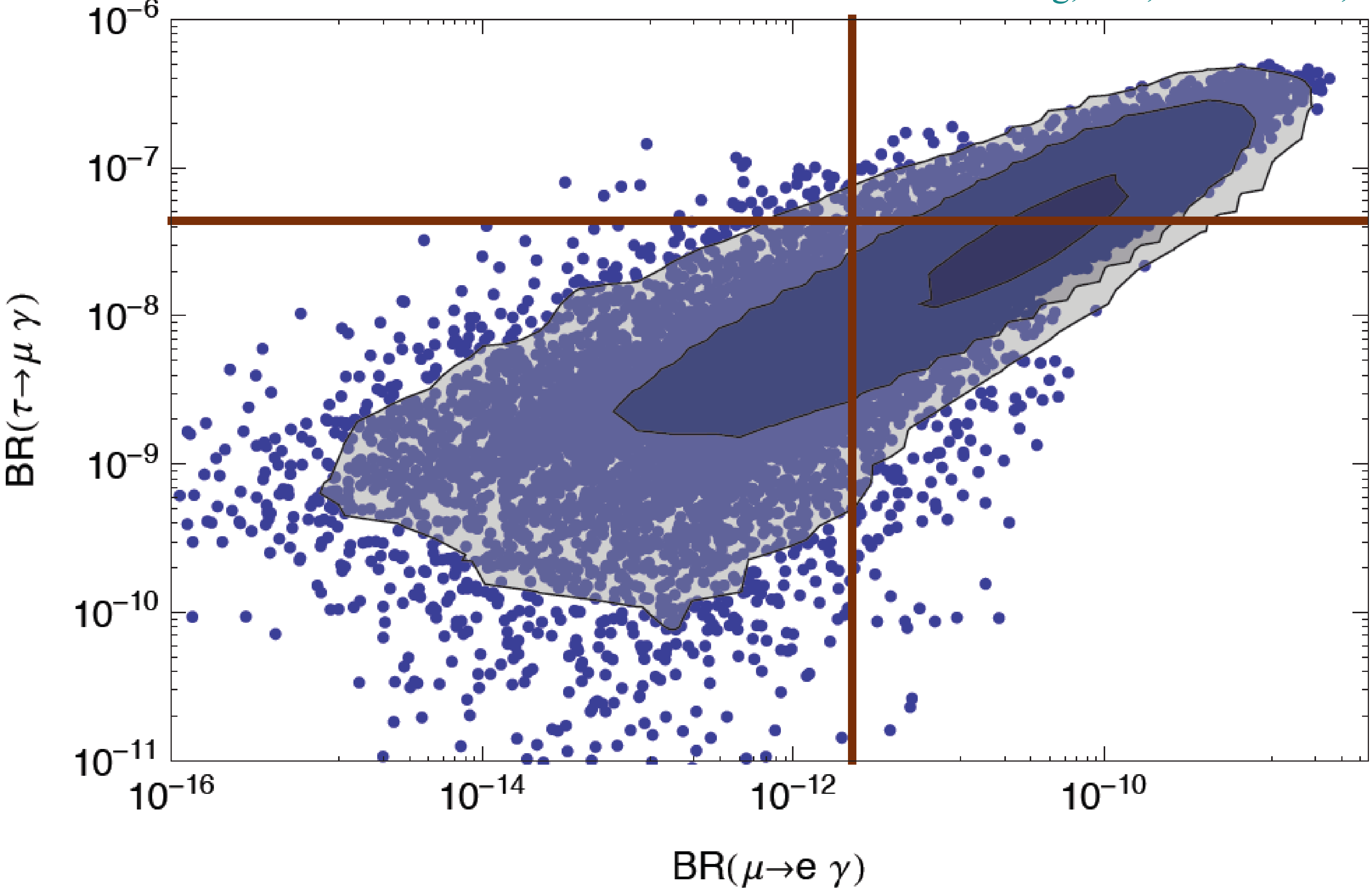
…and similar expressions holds in many other models:

=> MEG has realistic chances to see $\mu \to e\gamma$ (*but note that BR* $\sim \tilde{m}^{-4}$)

✯ *The key role of LFV*

E.g.: SUSY with minimally broken $U(3)^5$

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



Conclusions

- The success of the SM in describing flavor-changing processes of both quarks and charged leptons implies that large new sources of flavor symmetry breaking at the TeV scale are excluded. However, the two key questions about "the origin of flavor" are still open.

- The success of the SM in flavor physics fits well with the idea of a

  mildly broken flavor symmetry + weakly interacting NP
  + little hierarchy around the TeV scale

  (*coherent picture with e.w. precision tests + light Higgs + lack of deviations from SM at high-pT*). According to this picture, deviations from the SM could be within the reach of future experiments in flavor physics.

- The key tool to make progress in this field is to push forward the precision in the most clean observables (key role of LFV and EDMs):

  - full complementarity between low-energy and high-pT physics
  - full complementarity among the different low-energy facilities