Heavy flavour physics measurements and New Physics

Gino Isidori
[*INFN, Frascati & CERN*]

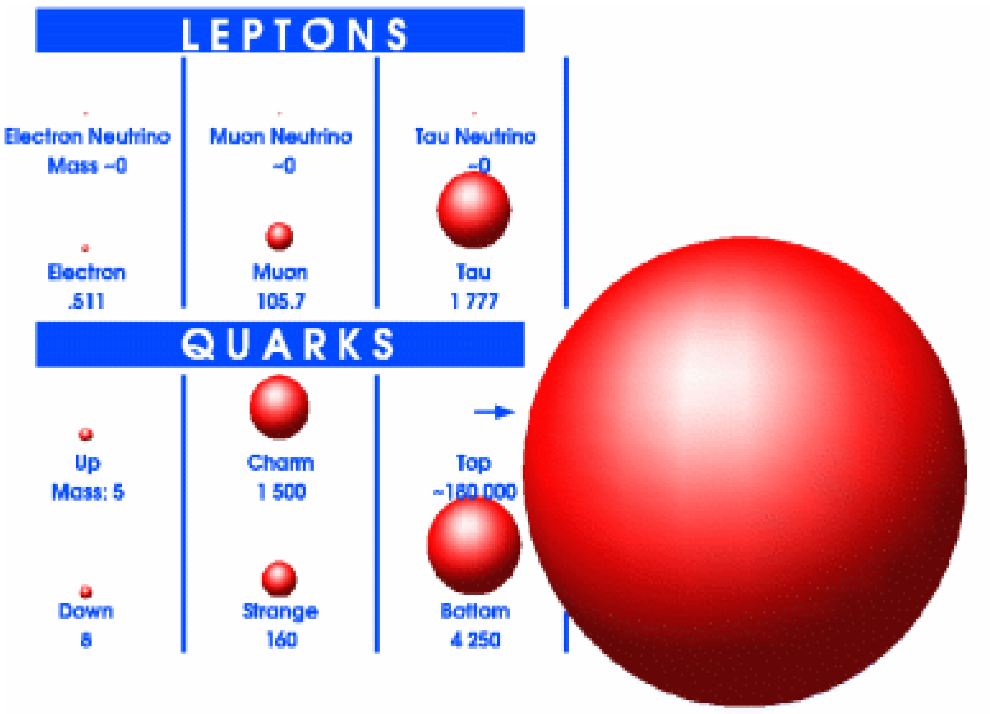
- Introduction
- News from the high-energy frontier
- Recent progress in B physics (ϕ_s & $B_s \to \mu\mu$)
- The *charming revolution* (Δa_{CP})
- Conclusions

Introduction

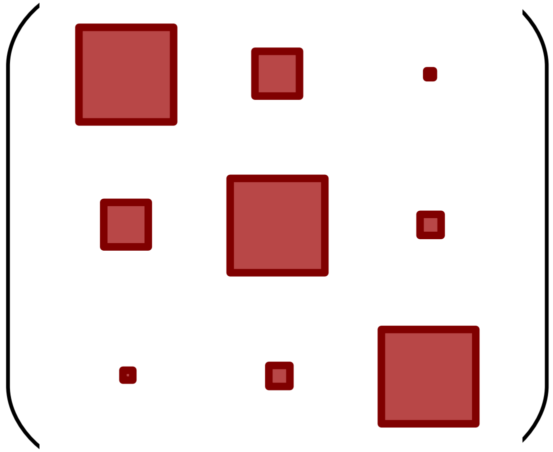
To a large extent, the origin of "flavour" is still a mystery...
Our "ignorance" can be summarized by the following two open questions:

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

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



$V_{CKM} \sim$



Introduction

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There are several options to address this question, but no clear answer:

- It is quite easy to reproduce the observed mass matrices in terms of a reduced number of free parameters, while it is difficult to avoid problems with FCNCs (without some amount of fine-tuning).
- Hard to make progress without knowing the ultraviolet completion of the SM.

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- *Which are the sources of flavour symmetry breaking accessible at low energies?*
  [Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

Answering this 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).

⬇

Main goal of Flavour Physics in the near future

Introduction

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  [Is there anything else beside SM Yukawa couplings & neutrino mass matrix?]

High-Intensity Frontier

↕

- *What determines the Fermi scale?*

- *Is there anything else beyond the SM Higgs at the TeV scale?*

High-Energy Frontier

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

Beside a few "anomalies" (*on which I'll come back...*) the measurements of quark flavor-violating observables show a remarkable success of the CKM picture:

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

G.I, Nir, Perez '10

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} ($\Lambda = 1$ 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}	$\Delta m_K;\ \varepsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \varepsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ \lvert q/p \rvert,\ \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ \lvert q/p \rvert,\ \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};\ S_{B_d \to \psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};\ S_{B_d \to \psi K}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
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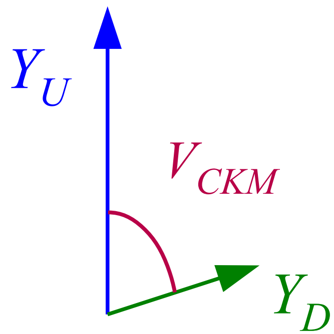
New flavor-breaking sources at the TeV scale (if any) are highly tuned

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

The measurements of quark flavor-violating observables show a remarkable overall success of the CKM picture:

- A popular way to take into account this observation, saving the "natural" expectation of NP at the TeV scale, is the so-called Minimal Flavor Violation hypothesis:

  - Large quark-flavor symmetry: $U(3)^3 = U(3)_Q \times U(3)_U \times U(3)_D$ (SM gauge sector)
  - Minimal breaking by the two Yukawa couplings, Yu & Yd,
    to account for quark masses



- The CKM matrix controls all flavor-changing phenomena in the quark sector
- Small effects in quark flavor-changing processes even for TeV new-physics

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

The measurements of quark flavor-violating observables show a remarkable overall success of the CKM picture:

- A popular way to take into account this observation, saving the "natural" expectation of NP at the TeV scale, is the so-called MFV hypothesis.

- However, MFV is not the only possibility. The key point is to link flavour-mixing and fermion masses $\rightarrow$ natural protection of flavour-breaking effects involving the light families, where the exp. bounds are stronger (*MFV is the minimal or most-strong link of this type*):

  - Hirarchical kinetic terms/partial compositeness ($Y_{ij} \sim Z_{Li} \times Z_{Rj}$)
  - SUSY with "disoriented A terms" (*Y & A both proportional to fermion masses, but not aligned in flavour space*)
  - Underlying $U(2)^3$, rather than $U(3)^3$, flavour symmetry

  ...

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Contrary to MFV, these alternatives also help to address the 1st flavor question

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↓

In most of these cases we do expect <u>tiny deviations from the SM in selected low-energy observables</u> that would allow to proof or disproof the hypotheses.

It is not easy to detect these effects, but is not impossible with <u>improved precision</u> both on the theory and on the exp. side (*some of the present "anomalies", may turn into real "NP signals"…*).

News from the high-energy frontier

The recent searches for new physics at the high-energy frontier can be (*roughly*...) summarized by two main messages:

- The Higgs boson is likely to be around 125 GeV (*in the "SUSY" region*...)
- No large signal of physics beyond the SM in pp collisions at 7 TeV.

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Supersymmetry remains a very good candidate (*shares of supersymmetry are definitely rising with respect to those of composite-Higgs models or extra-dimensions*): weakly coupled theory + light Higgs

But the SUSY spectrum cannot be (almost) degenerate, as in the most popular versions of the MSSM, and in MFV (otherwise too-large fine-tuning in m_h).

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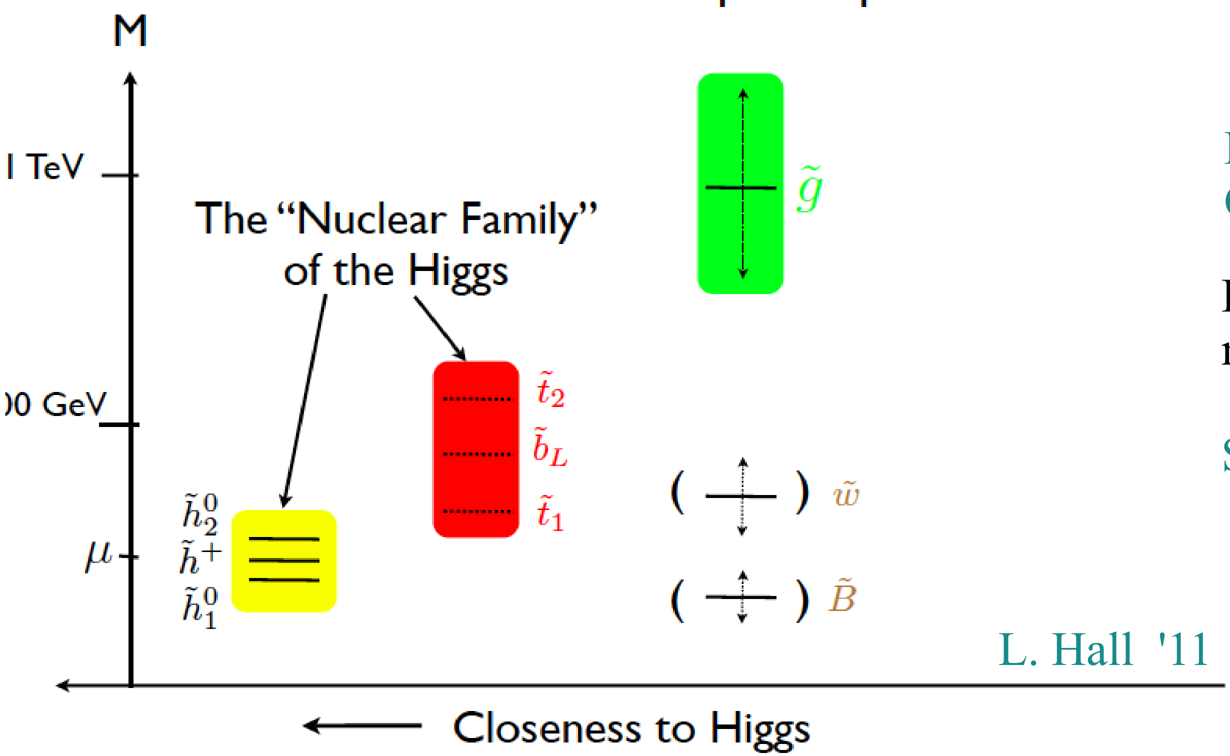
Supersymmetry with "split families" (3^{rd} gen. light, 1^{st} & 2^{nd} well above 1 TeV) is emerging as a very appealing possibility

A Natural Spectrum

General "bottom-up" viewpoint



L. Hall '11

Dimopulos, Giudice, '95
Cohen, Kaplan, Nelson '96

Renewed recent interest by many theorists:

See talks by Csaki & Weiler

- Only 3rd gen. squarks and Higgsinos need to be light to avoid tuning in m_h (naturalness)
- With heavy 1st & 2nd gen. squarks less "flavour problem" + easy to escape susy searches at LHC

News from the high-energy frontier (the "natural" SUSY spectrum)

SUSY with split families does not fit well with the idea of MFV, at least in its minimal version, that would predict an almost degenerate squark spectrum.

More natural to consider non-minimal link between masses and flavor mixing. These could offer interesting prospects for

- solving some of the open problems of MFV
- addressing the existing anomalies in the quark sector (most notably, ε_K vs. $\sin(2\beta)$ tension & Δa_{CP} in the charm system)
- observing clear non-standard signals in other observables, such as $B\to\mu\mu$, radiative D decays, LFV in charged leptons, quark & lepton EDMs

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Low-energy flavor physics is definitely non trivial

Recent progress in B physics

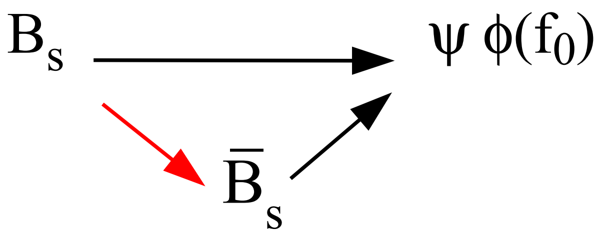
Several new results during the last few months, mainly thanks to LHCb, but the two highlights in terms of NP searches are definitely

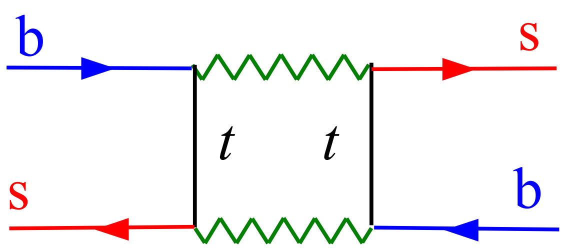
- The improved bounds on CPV in B_s mixing
- The improved bounds on $B(B_s \to \mu\mu)$

I. CPV in B_s mixing

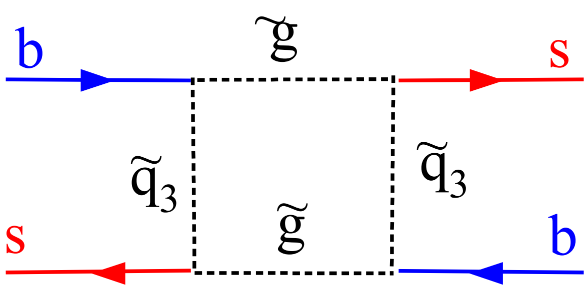
The B_s mixing phase is a key ingredient to clarify our understanding of down-type $\Delta F=2$ amplitudes ($s\to d$, $b\to d$, and $b\to s$).

Theoretically clean determination:





Tiny CPV asymmetry if the mixing phase is determined only by the Yukawa couplings (SM & MFV)



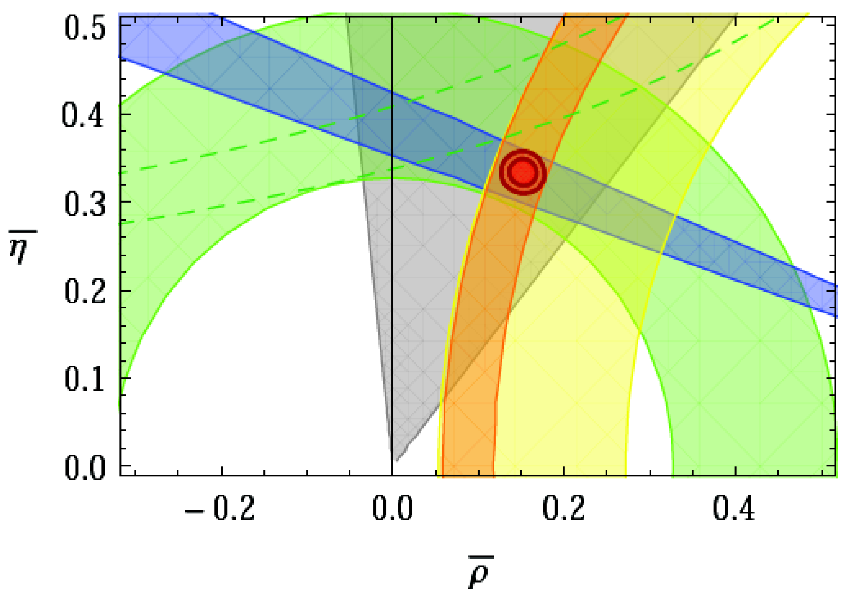
Possible sizable corrections from NP (*e.g. relatively light stops in "split-family" SUSY*)

I. CPV in B_s mixing

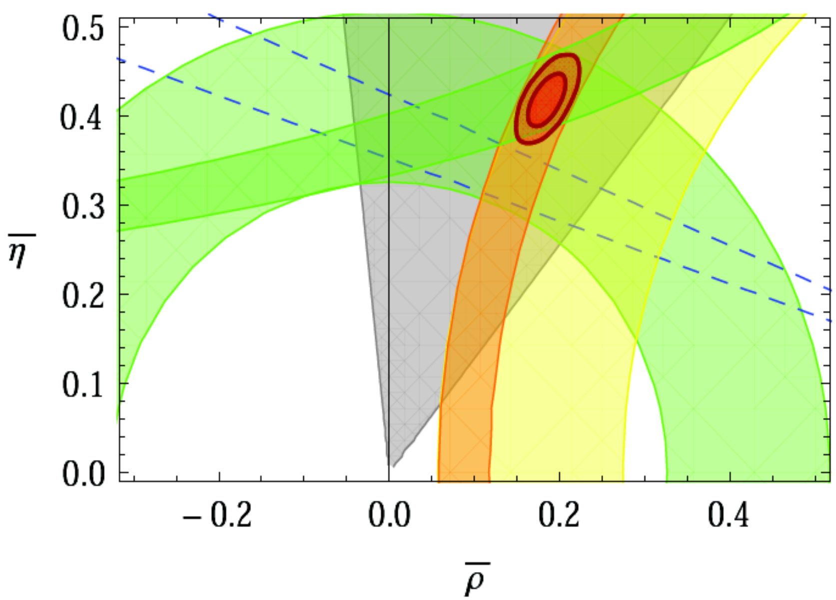
The B_s mixing phase is a key ingredient to clarify our understanding of down-type $\Delta F=2$ amplitudes ($s\to d$, $b\to d$, and $b\to s$).

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)

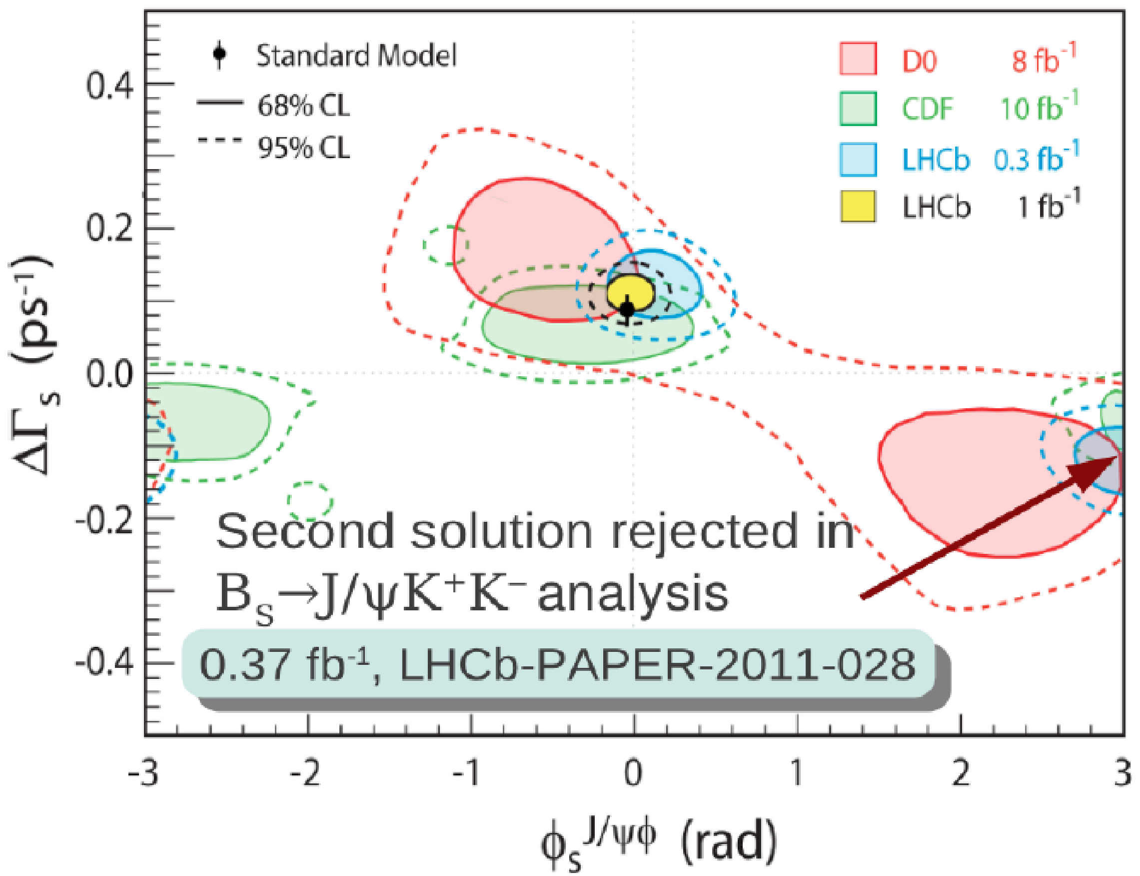


SM fit, no $S_{\psi K}$ (no Bd mix. phase)



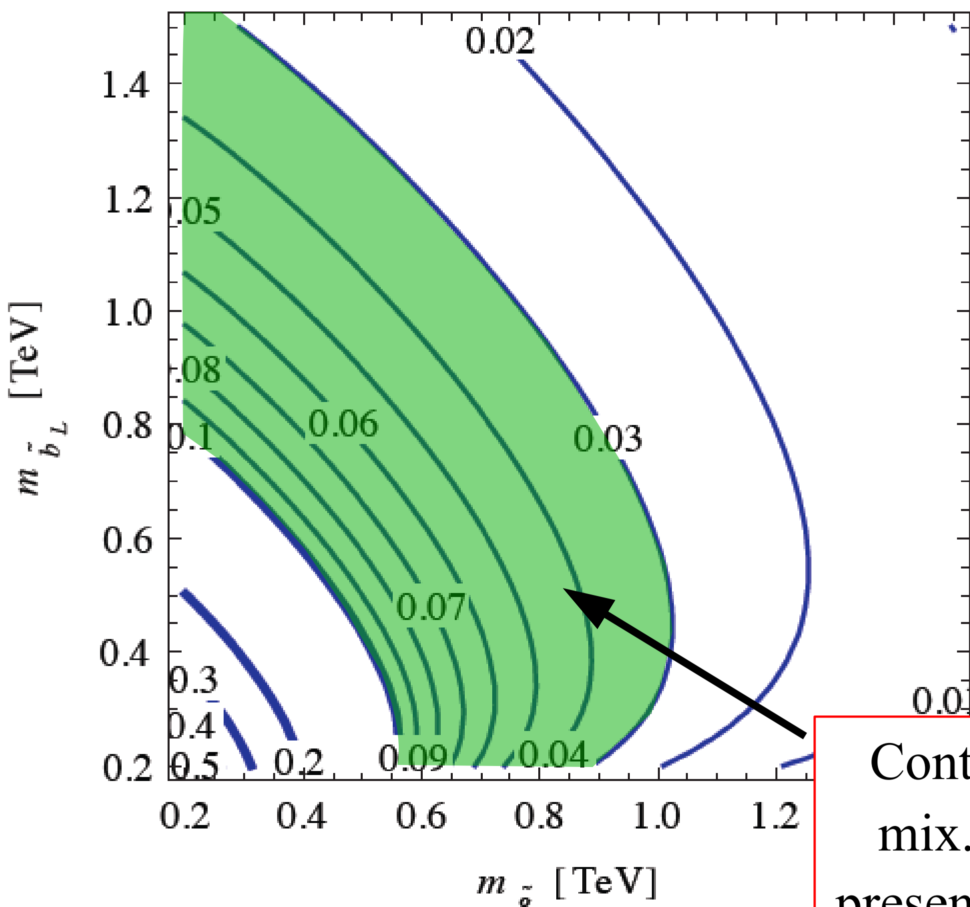
I. CPV in B_S mixing

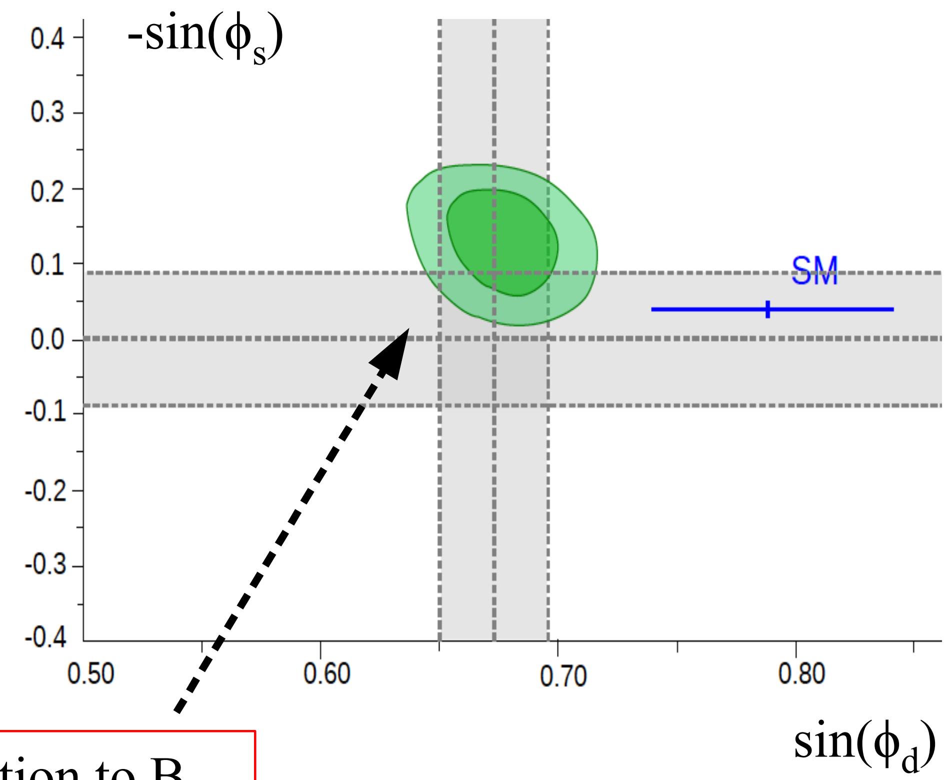
Thanks to the excellent measurement of LHCb, the phase of Bs mixing is now determined to a comparable level of precision, and shows no signs of deviations from the SM:



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

E.g.: “Split-family” SUSY with $U(2)^3$





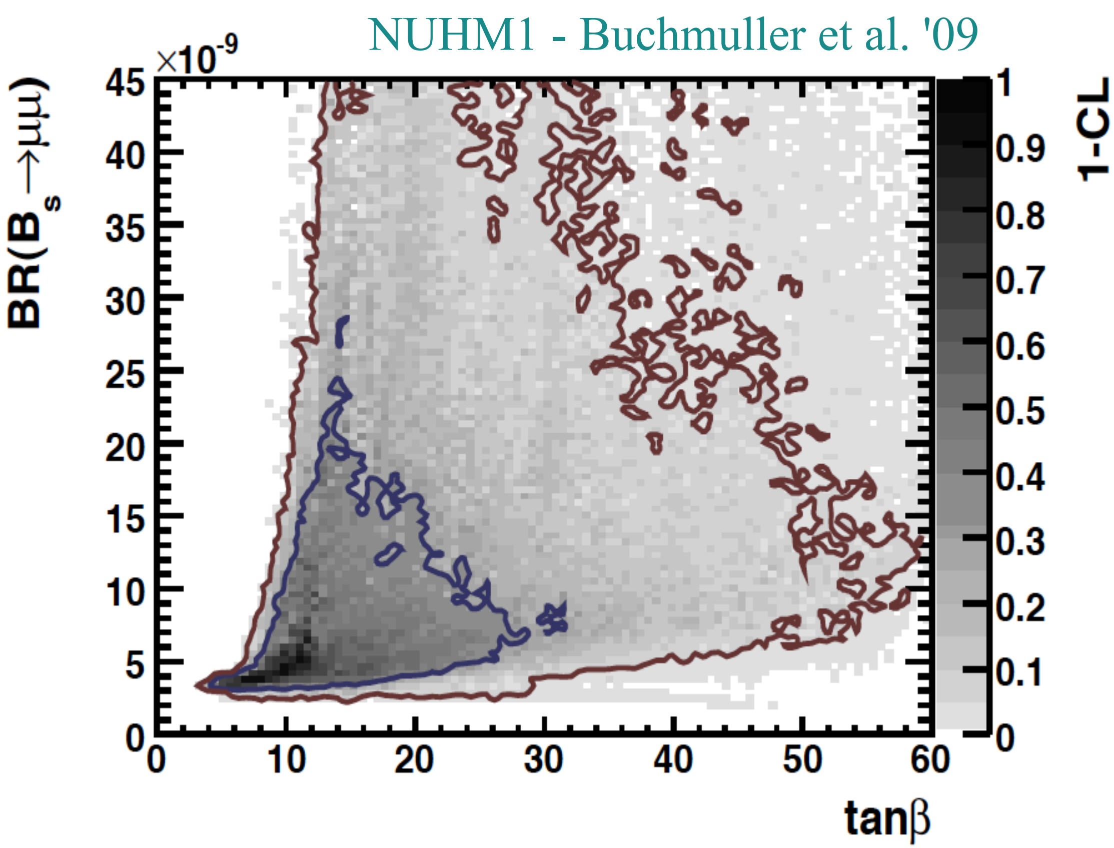
Contribution to B_b mix. reducing the present CKM tension

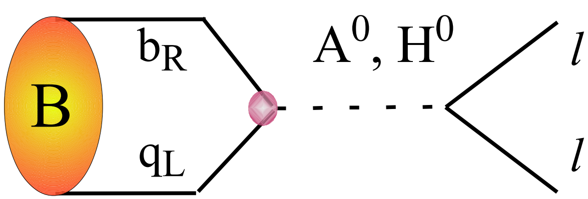
Barbieri *et al.*, '11

II. $B_S \to \mu\mu$

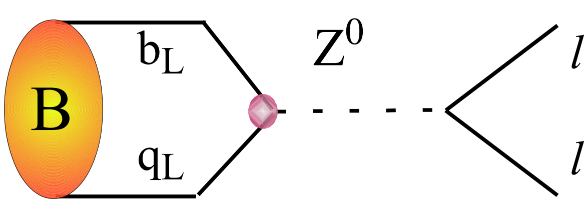
This mode is a <u>unique</u> source of information about flavor physics beyond the SM:

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





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



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

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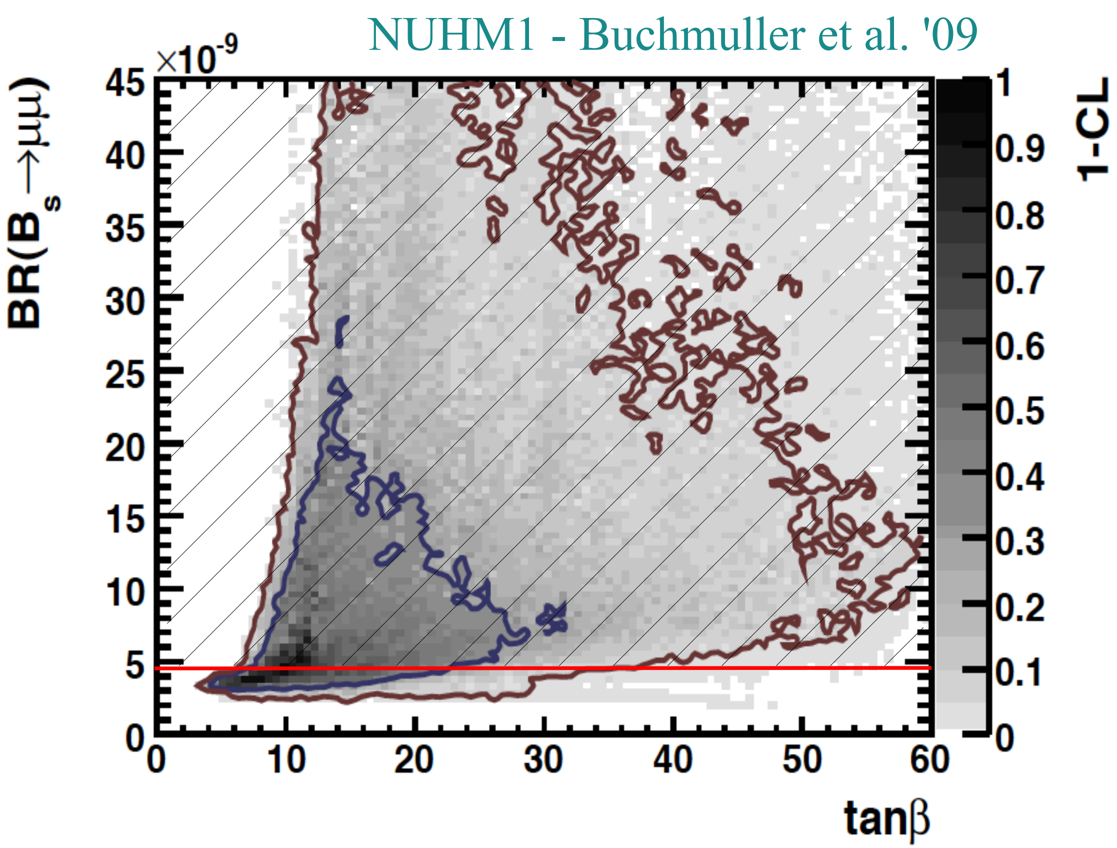
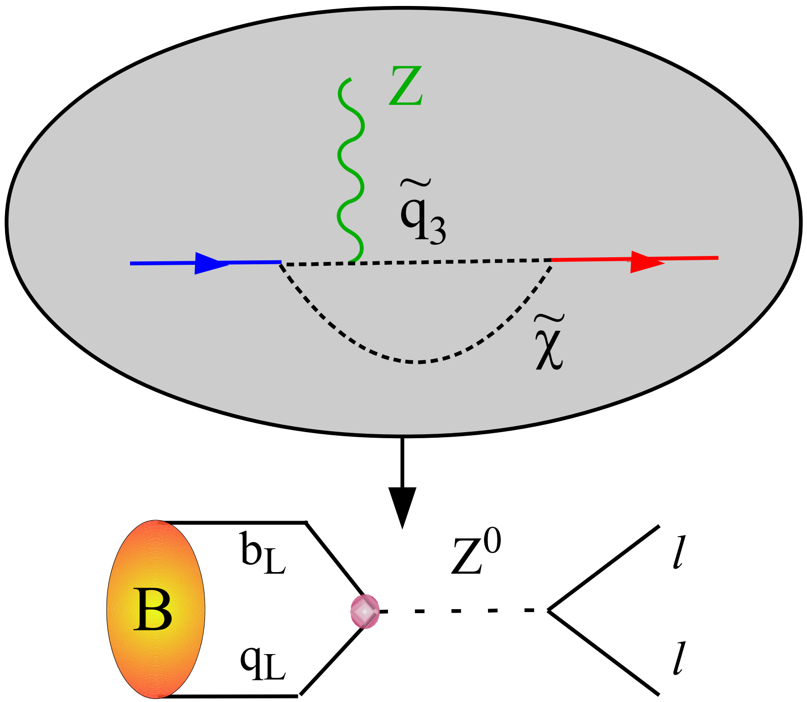


The possibility of large FCNC scalar currents (occurring in SUSY for low M_A and large $\tan\beta$) is essentially ruled out thank to the improved exp. limits on $B_S \to \mu\mu$

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.: "Split-SUSY" with "disoriented A terms"



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

Easy to generate O(±30%) corrections to the BR for $m_{stop} \lesssim 0.5$ TeV

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

Still a long way to go
(and a lot to learn...)
before being saturated
by the theory error (~5%)

▶ *The charming revolution:*

The charming revolution:

The evidence of CPV in charm observed at LHCb & CDF is definitely the *most interesting news in flavour physics* since a long time:

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

- Unambiguos evidence of direct CP violation:

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

- Totally unexpected, 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:

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

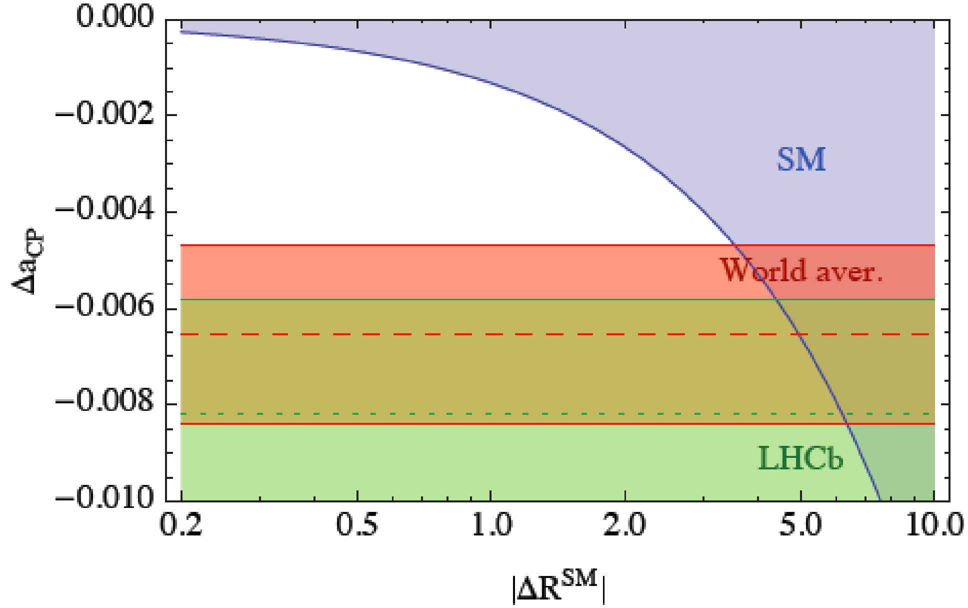
CKM suppression:

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

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:

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

CKM suppression:

matrix-element ratio:

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

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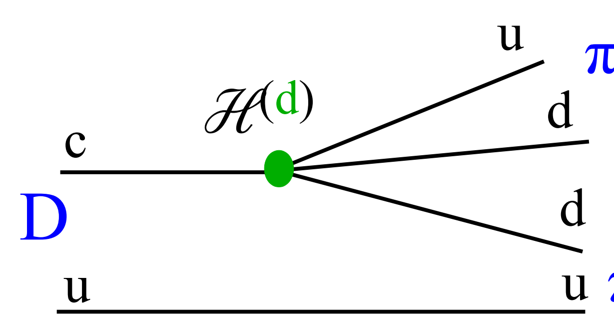
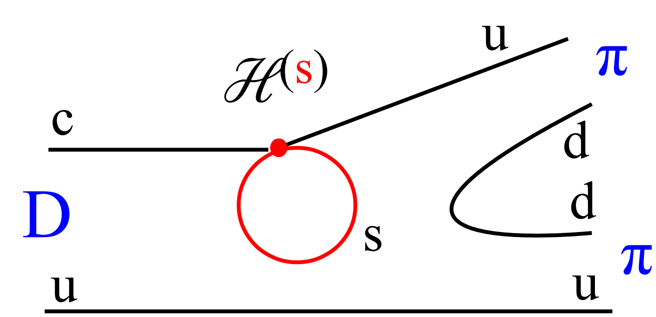
$$\mathcal{H}_{\rm eff} \approx V_{cd}^{\ *}V_{ud}\ \mathcal{H}^{(d)} + V_{cs}^{\ *}V_{us}\ \mathcal{H}^{(s)}$$



$\Delta R>1$ 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

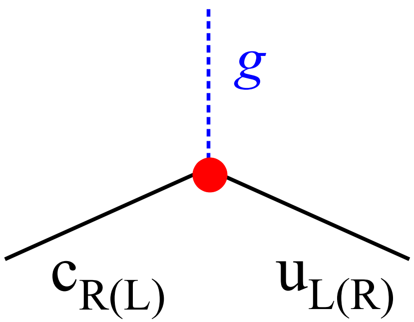
Brod et al. '11, '12
Feldmann et al. '12



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
Rattazzi *et al.* (to appear)
Perez *et al.* (to appear)
…

- Fist interesting window on flavour-mixing in the up sector (on which we know very little...)

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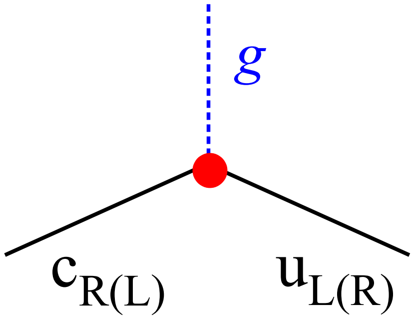

Key question: how to distinguish NP vs. SM explanations?

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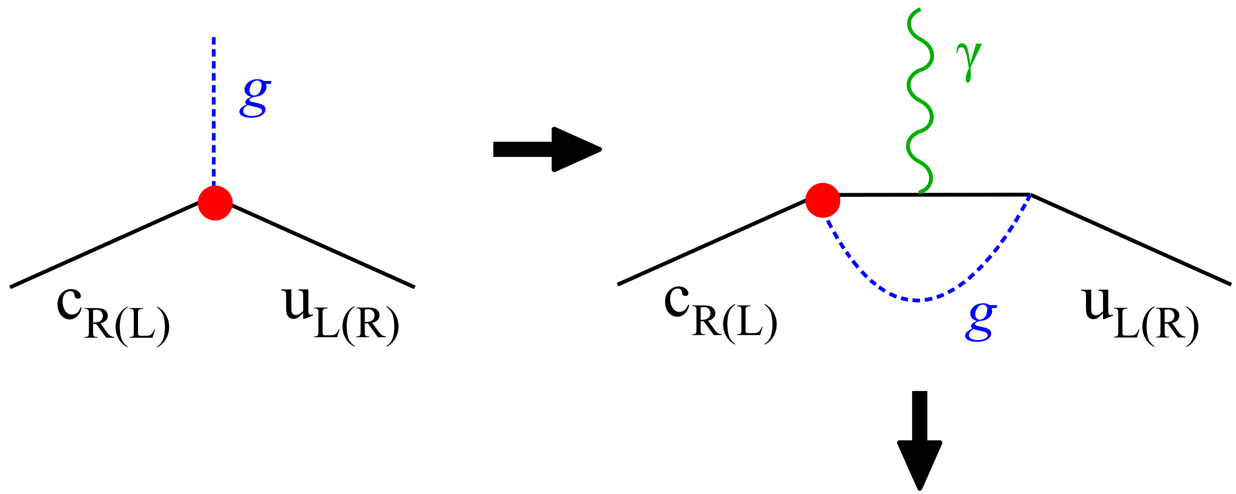
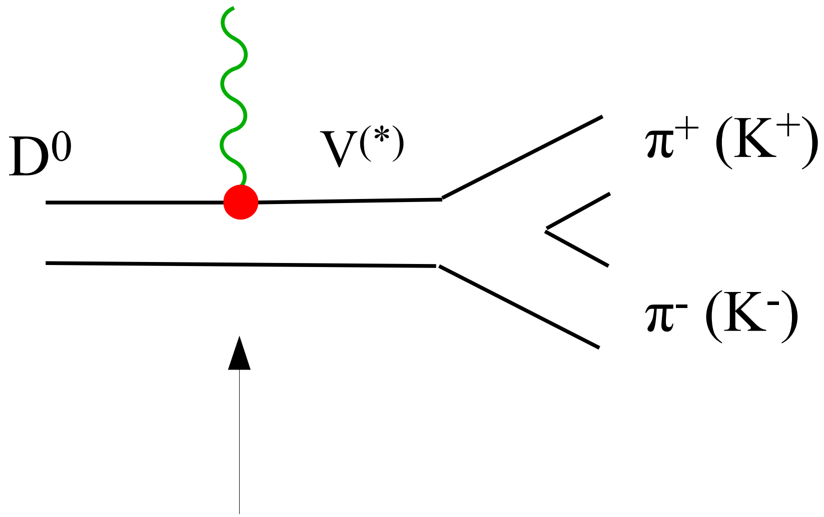


Unavoidable large CPV

(*model-independent connection via QCD*)

also in the *electric-dipole* 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.

Conclusions

To a large extent, the origin of "flavour" is still a mystery...

...but we are making some progress:

- Large new sources of flavour symmetry breaking at the TeV scale are excluded
- The lack of large deviations from SM, even in suppressed observables, points toward protective mechanisms for 1st-2nd generations + weakly interacting NP at the TeV (coherent picture with e.w. precision tests + lack of large deviations at high-pT) => split-family SUSY emerging as a natural candidate
- MFV is less likely than in pre-LHC era and some deviations from the SM in low-energy precisions observables are expected (flavour is not trivial!): we need to improve the precision in the most clean observables
- Some of the present "anomalies" (ε_K vs. $\sin(2\beta)$ or Δa_{CP}) may turn into real "NP signals"...