Flavor Physics and CP violation

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I. Introduction

II. The CKM matrix and neutral meson mixing

III. Rare B and K decays

IV. Flavor Physics beyond the SM

IV. Flavor Physics beyond the SM

- From yesterday's lecture
- Tests of Lepton Flavor Universality
  - *Generalities*
  - *Tests of LFU in* $b \to s\, ll$
  - *Tests of LFU in* $b \to c\, \tau\nu$
  - *Summary*
- Flavor Symmetries
  - *Generalities*
  - *The MFV hypothesis*
- Beyond MFV
- Conclusions

From yesterday's lecture

No clear indications of New Physics effects

- in meson-antimeson mixing amplitudes (*detailed exploration*)
- in clean rare B and K decays such as $B_s \to \mu\mu$ (*although here the exploration has only started, and the errors are still large...*)

⬇

Stringent bounds on couplings and masses of possible new particles

As we have seen by means of the Effective Theory approach to New Physics:

Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...

From yesterday's lecture

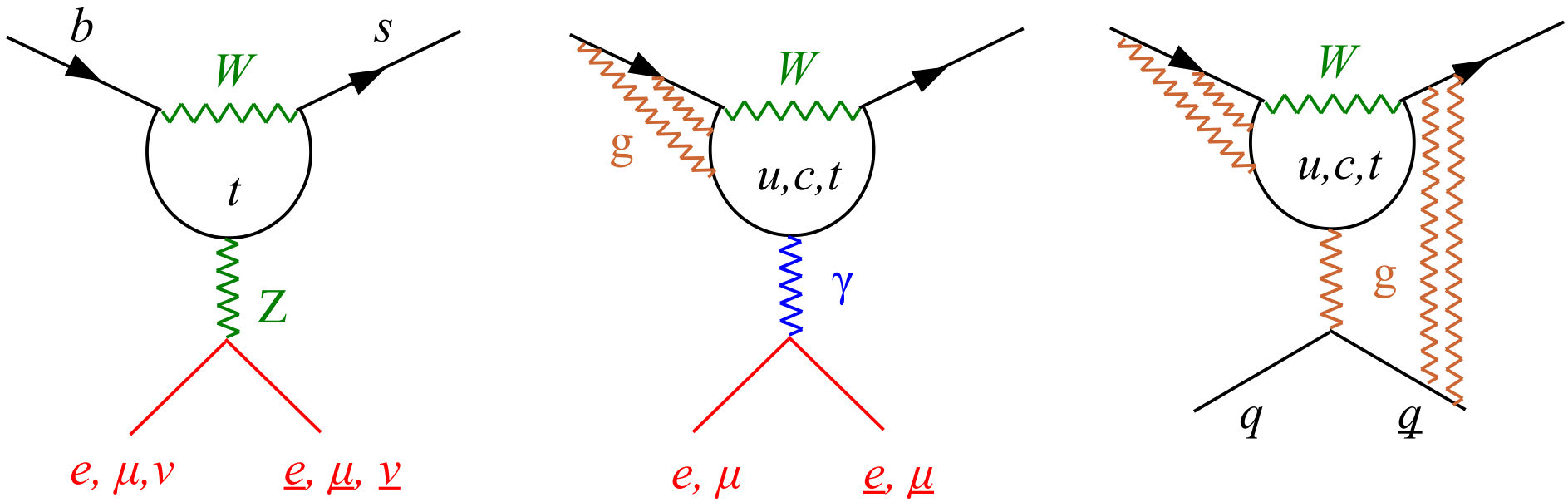
Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...

- Can we build NP models where the alignment with the CKM occurs "naturally?
- Does this shed light on the origin of fermion masses and CKM hierarchies?
- Can we see deviations from the SM with more precise measurements? If yes, where?

Rare K and B decays are potentially interesting candidates

From yesterday's lecture

Not all "penguin diagrams" are the same... *and correspondingly not all rare decays are equally interesting...*



- Very "clean" [*top quark*]
- Less "clean" [*charm quark*]
- "dirty"

$B_{s,d} \to \mu\mu$

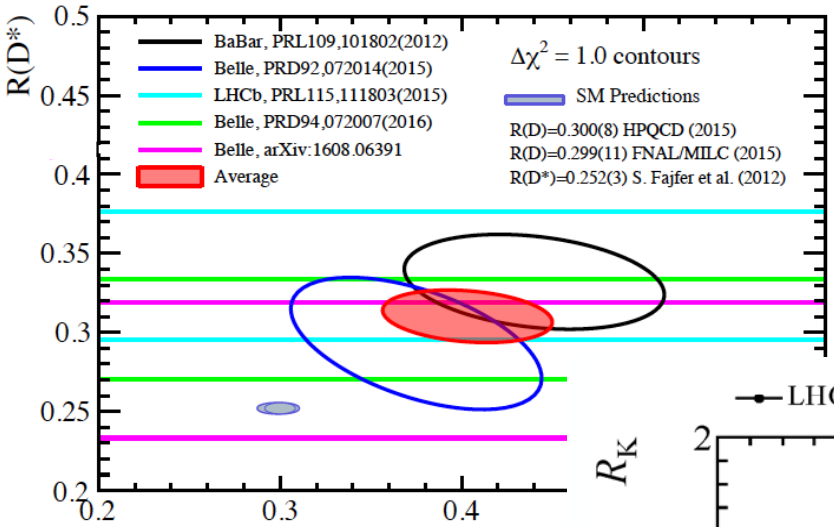
$B \to K\nu\nu$, $K \to \pi\nu\nu$

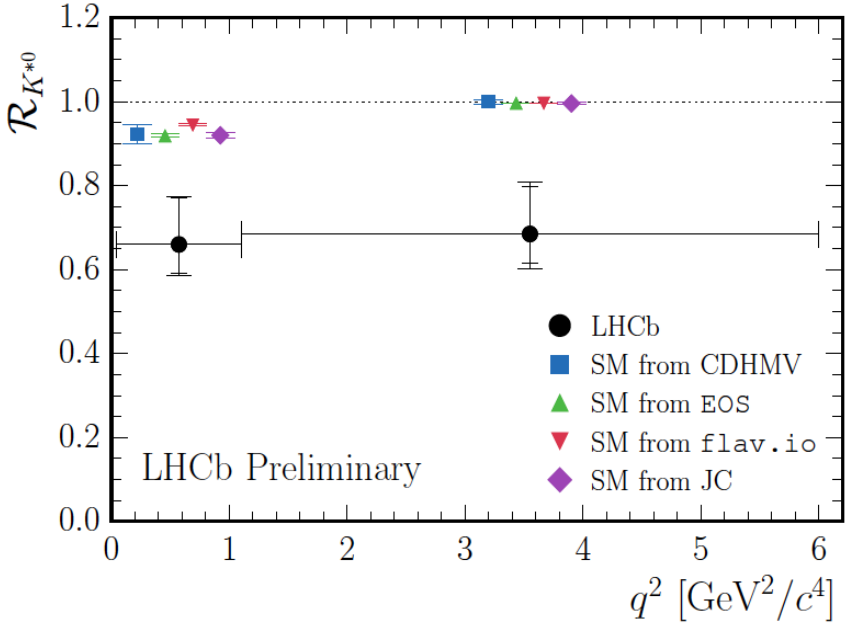
$B \to K\mu\mu$, $B \to Kee$

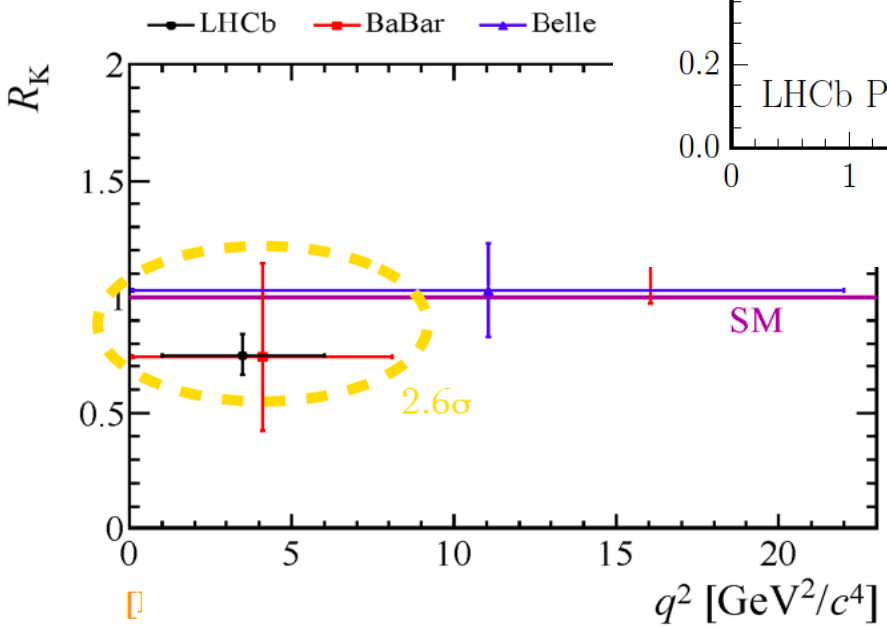
$B \to K^*\mu\mu$, $B \to K^*ee$

These channels are not hopeless, but we cannot extract the interesting info directly from the BR...

Lepton Flavor Universality Tests







Generalities

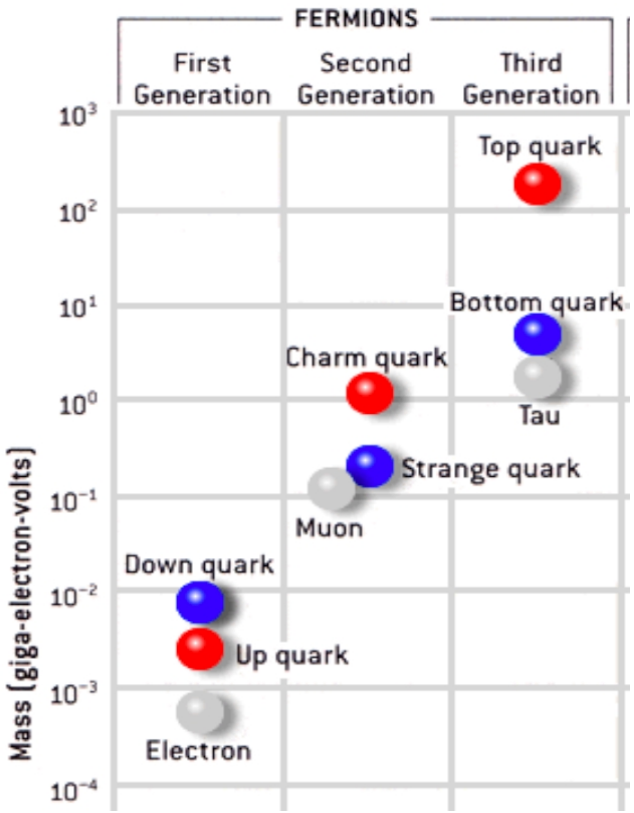
We denote Lepton Flavor Universality the property that the three charged leptons (e, μ, τ) couple in a universal way to the SM gauge bosons.

Within the SM lepton flavor physics is somehow "boring":
the only flavor non-universal terms are the three lepton masses
(N.B.: *by construction, neutrinos are massless within the SM*)

⬇

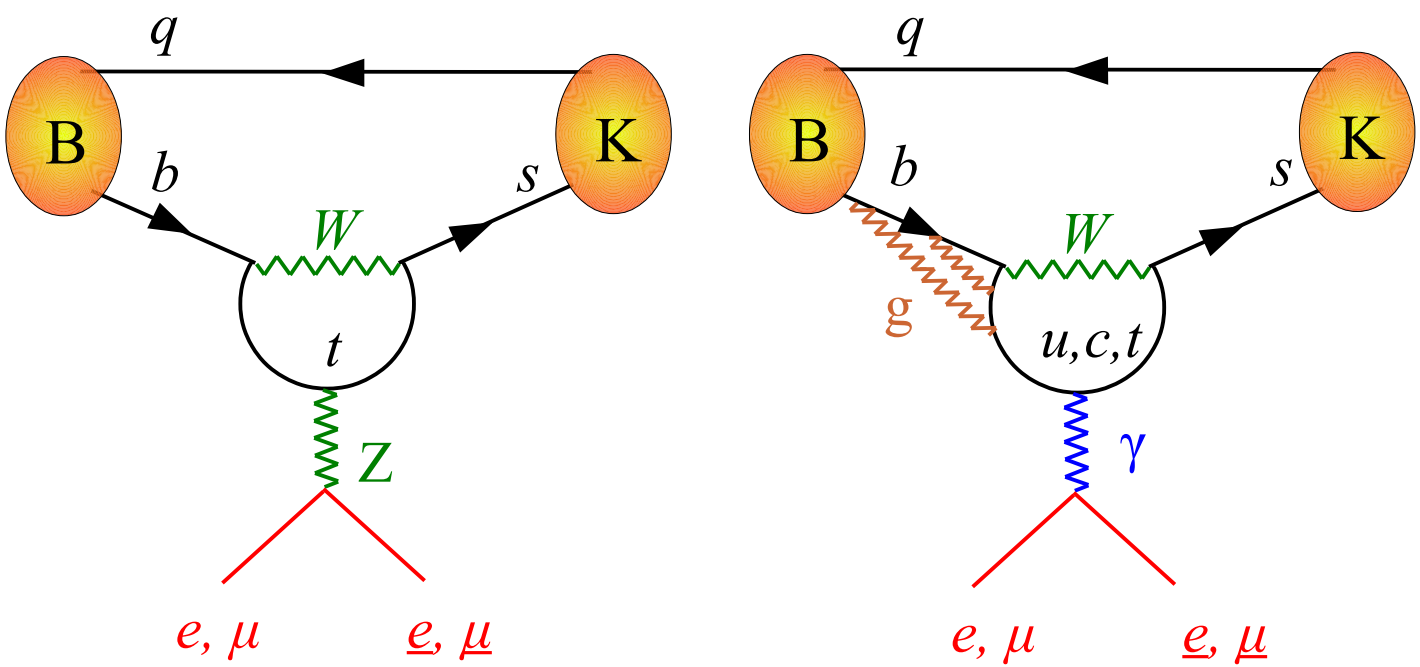
We can turn this "boring" property into a powerful tool to discover physics beyond the SM

If physics beyond the SM couples into a non-universal way to the different families of leptons (*and there is no reason why this should not happen...*) then we can discover it comparing similar rare decays with different paris of leptons
[LFU tests]



LFU tests in $b \to s\, ll$

The process $B \to K\,(K^*) + ll$ are mediated by the "clean" Z-penguin diagrams and also by the "less clean" photon-penguin diagrams. The latter are more difficult to estimate precisely; however, in both cases one predicts the e/μ ratio to be 1 (*mass effects are negligible* $m_B >> m_\mu$)

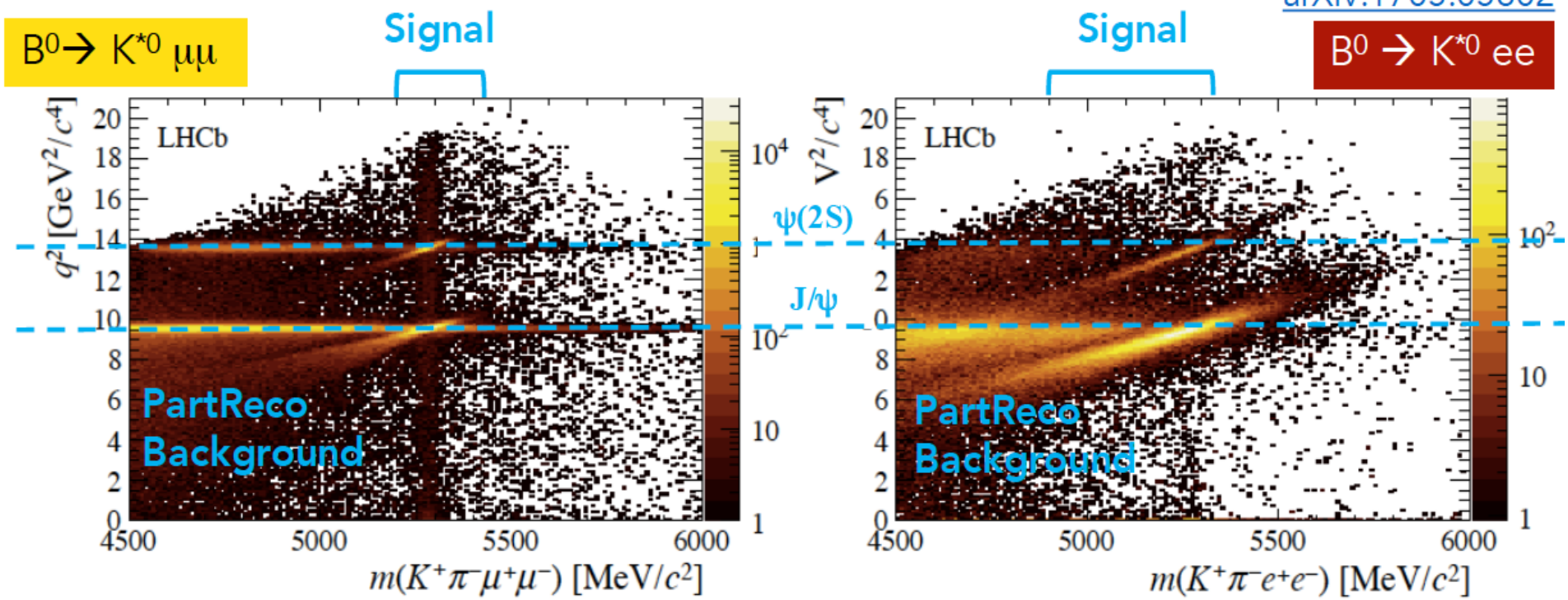


$$\rightarrow \quad \left.\frac{\int d\Gamma(B \to K\,\mu\mu)}{\int d\Gamma(B \to K\,ee)}\right|_{SM} = \left.\frac{\int d\Gamma(B \to K^*\,\mu\mu)}{\int d\Gamma(B \to K^*\,ee)}\right|_{SM} = 1 \qquad (\text{ th. error} < 1\%\ )$$

LFU tests in $b \to s\, ll$

As it often happens, what is nice theoretically is a real exp. challenge...

arXiv:1705.05802



Electrons emit a large amount of bremsstrahlung → degraded momentum and mass resolutions → recovery procedure is in place but incomplete (calorimeter acceptance, E_T of the photon > 75 MeV ....)

⟹ the reconstructed B mass shifts towards lower values and events migrate in and out of the q2 bins

[Marie-Helene Schune [LHCb], CERN talk March '17

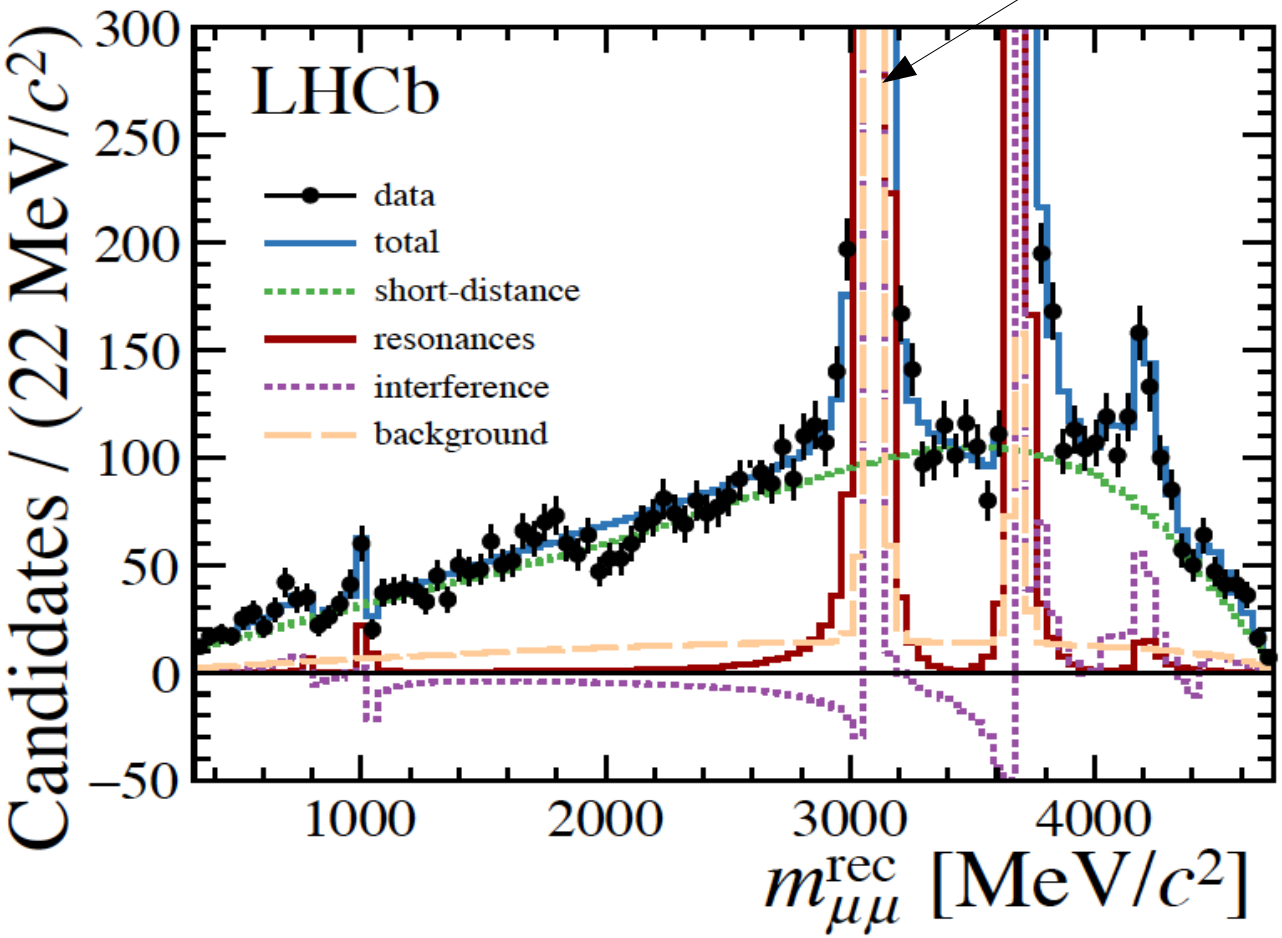
LFU tests in b → s ll

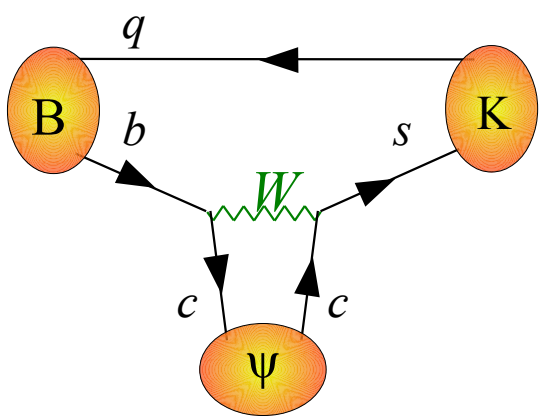
As it often happens, what is nice theoretically is a real exp. challenge...

... but there are ways to handle the problem

$B \to K + \psi\ (\to \mu\mu)$

($\underline{c}c$ resonance)





LFU tests in $b \to s\, ll$

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... but there are ways to handle the problem

- $$R_{K^{(*0)}} = \frac{\mathcal{B}(B \to K^{(*0)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*0)} J/\psi\,(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B \to K^{(*0)} e^+e^-)}{\mathcal{B}(B \to K^{(*0)} J/\psi\,(\to e^+e^-))}$$

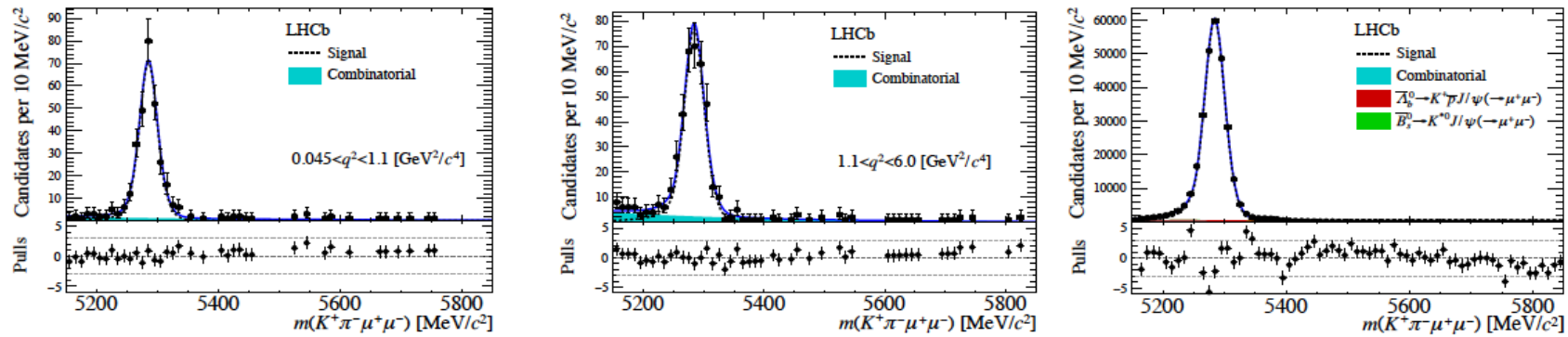
- Selection as similar as possible between μμ and ee for physics-related variables

Mitigating electron/muon differences

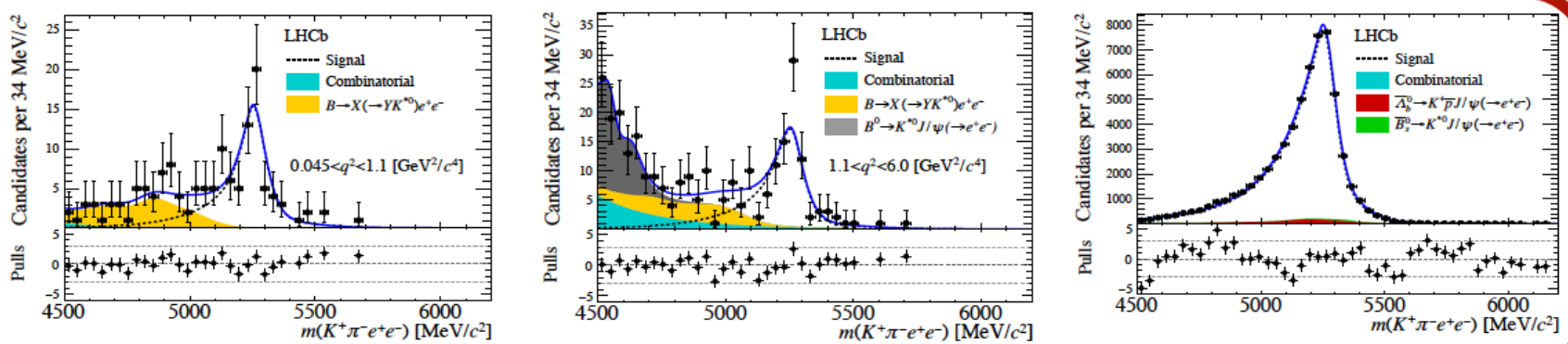
LFU tests in $b \to s\, ll$

Low-q^2 Central-q^2 J/ψ

$B^0 \to K^{*0}\, \mu\mu$



$B^0 \to K^{*0}\, ee$



Yields : Low-q^2 Central-q^2 J/ψ arXiv:1705.05802

$q^2 = m_{ll}^2$

μμ	285 ± 18	353 ± 21	274k
ee	89 ± 11	111 ± 14	58k

LFU tests in $b \to s\, ll$

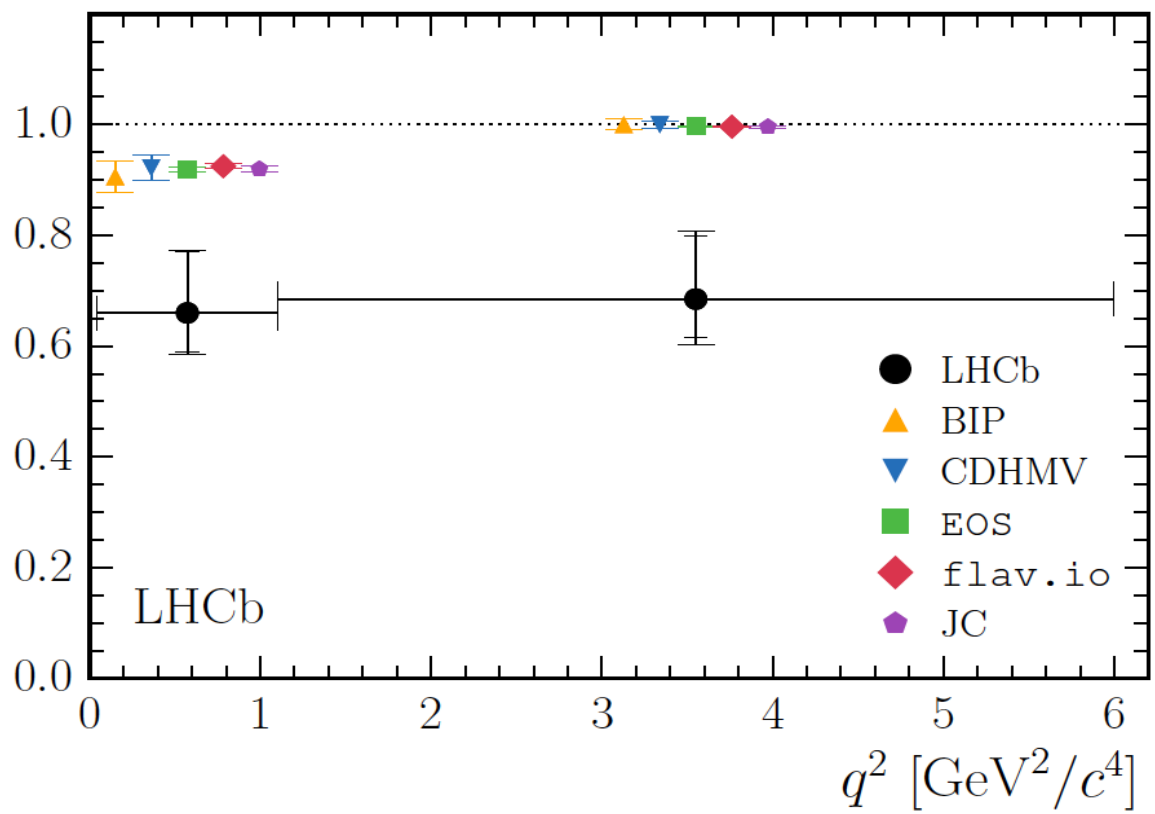
Finally the interesting results:

1) $$R_K = \frac{\int d\Gamma(B^+ \to K^+\mu\mu)}{\int d\Gamma(B^+ \to K^+ee)}\Bigg|^{(exp)} = 0.75 \pm 0.09 \quad \text{vs.} \quad R_K^{(SM)} = 1.00 \pm 0.01$$

[1-6] GeV^2

2) $$R_{K^*} = \frac{\int d\Gamma(B^0 \to K^*\mu\mu)}{\int d\Gamma(B^0 \to K^*ee)}$$

Overall significance of the deviations from the SM ~ 3.8σ (*LFU ratios only*)



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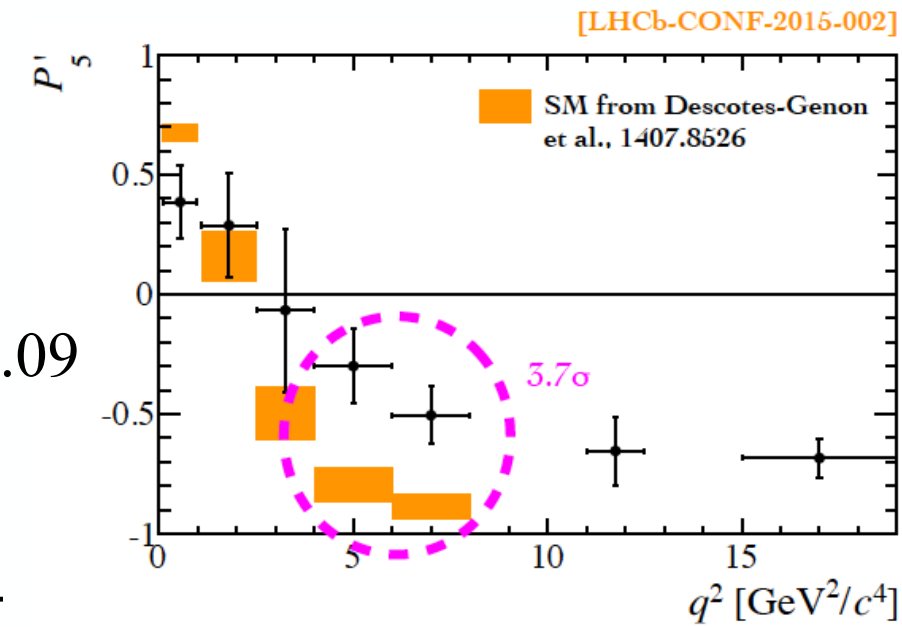

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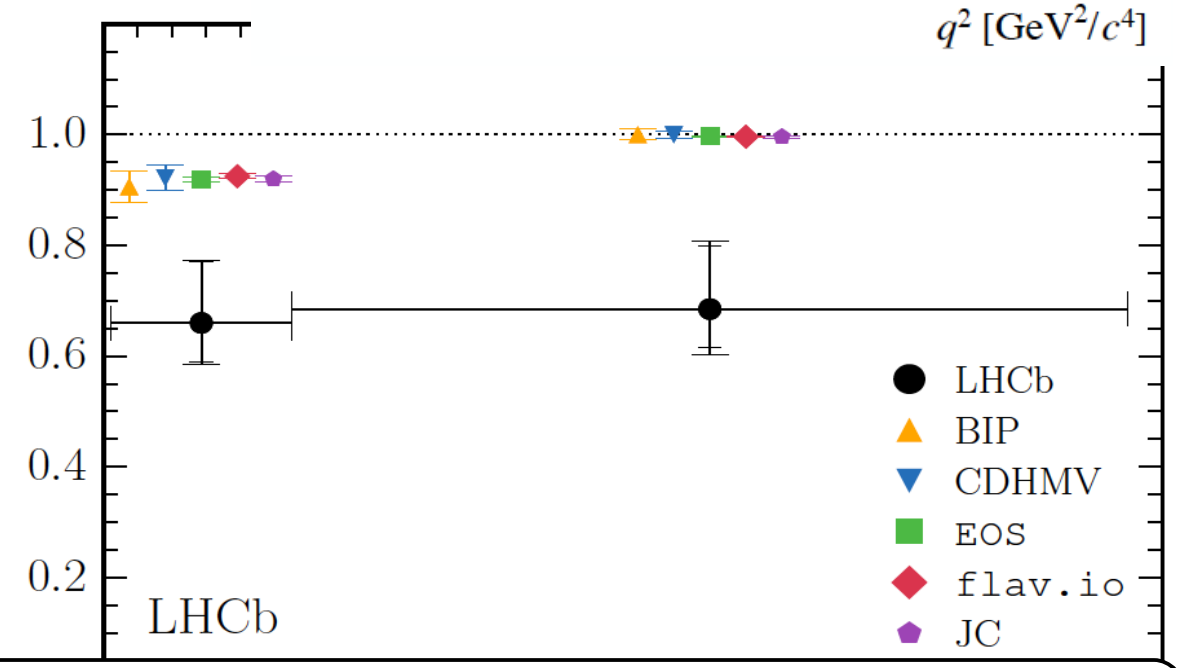


Overall significance of the deviations from the SM ~ 3.8σ (*LFU ratios only*)

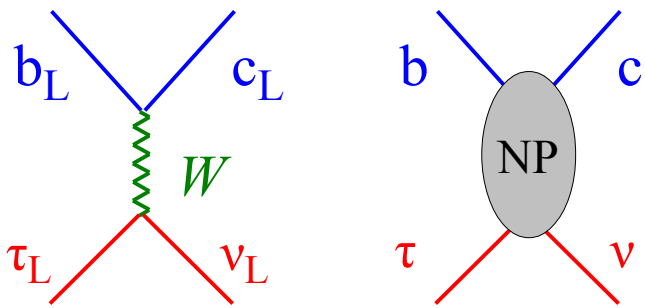
Actually the tension with the SM increases taking into account also a series of angular distributions that points to NP in the muon modes only

LFU tests in $b \to c\,\tau\nu$

Interestingly enough, a deviation from LFU seems to emerge also in a different class of decays: the charged-current decays of B mesons into tau's

Test of LFU in charged currents
[τ vs. light leptons (μ, e)]:

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$



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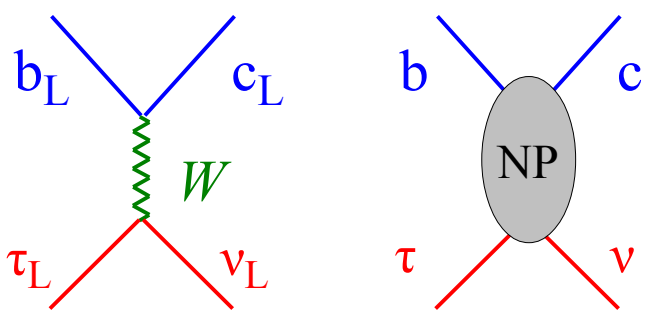

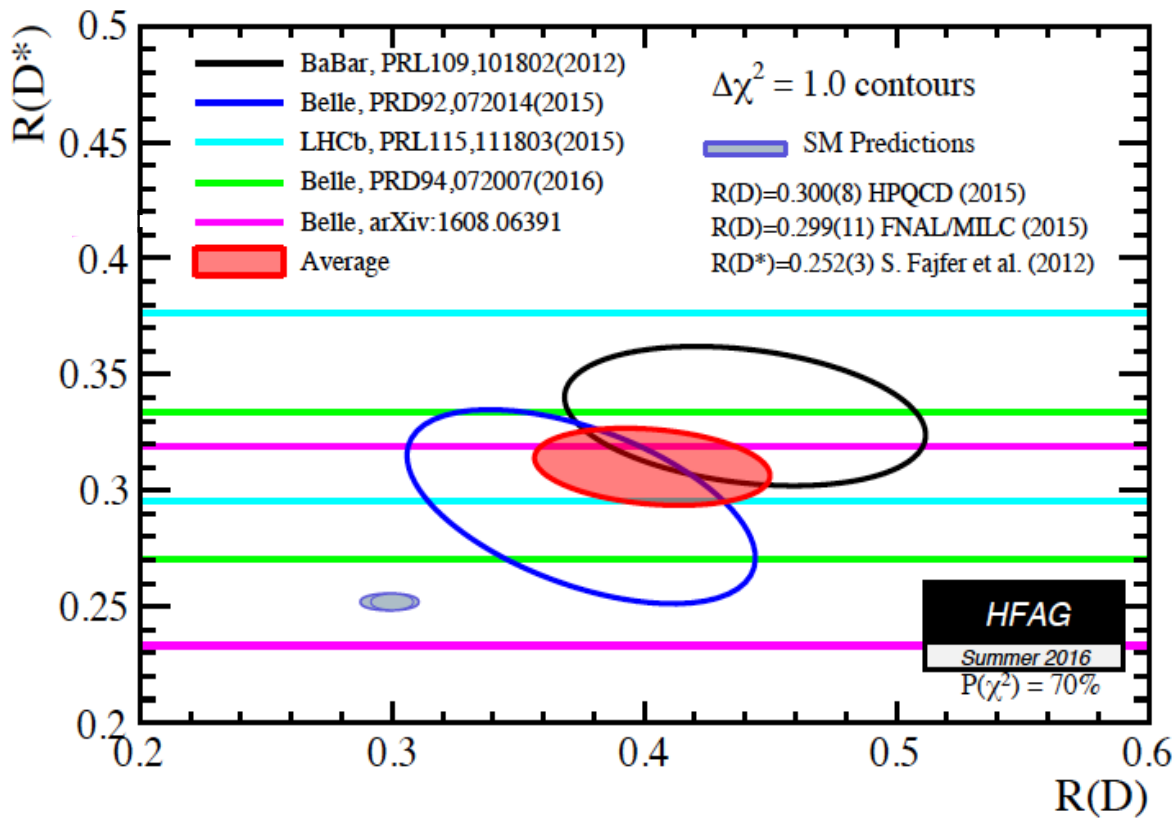

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  - 3.9σ excess over SM (if D and D* combined)

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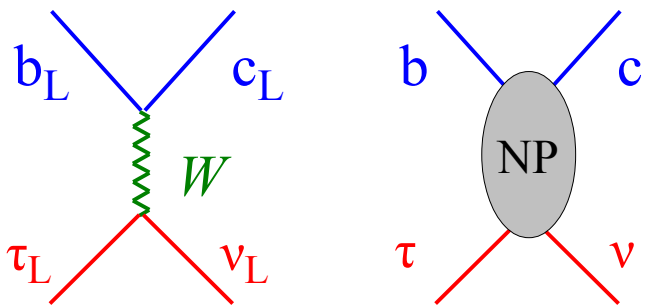

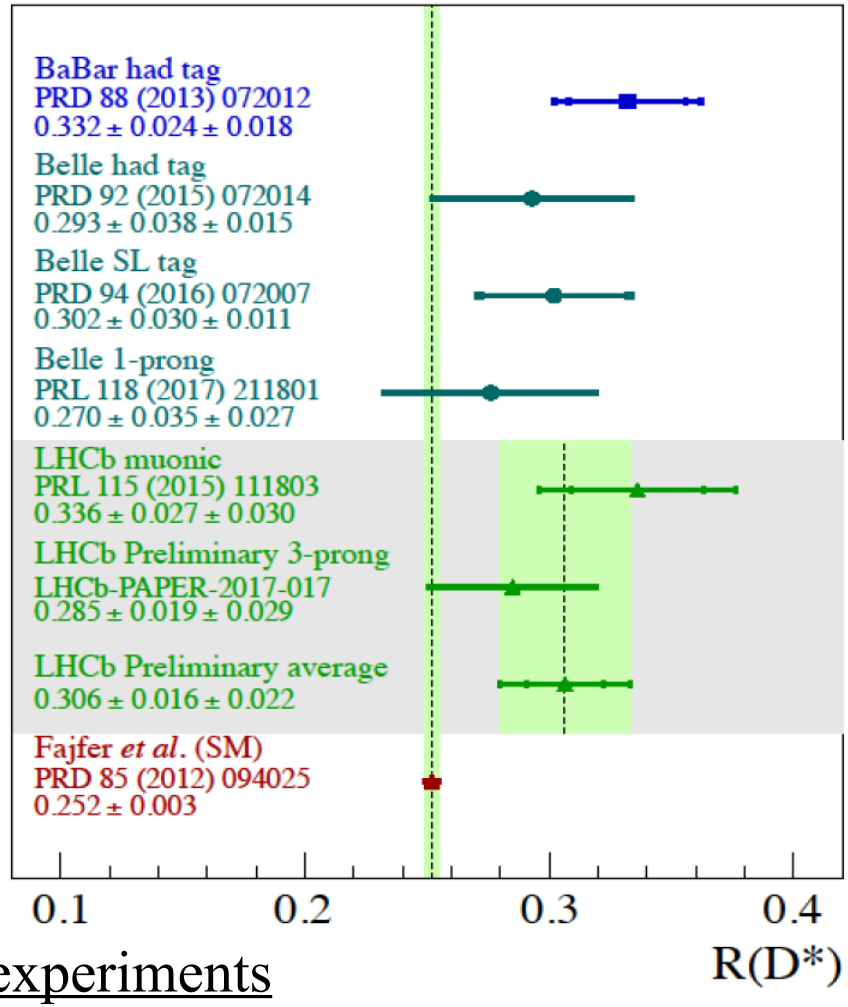

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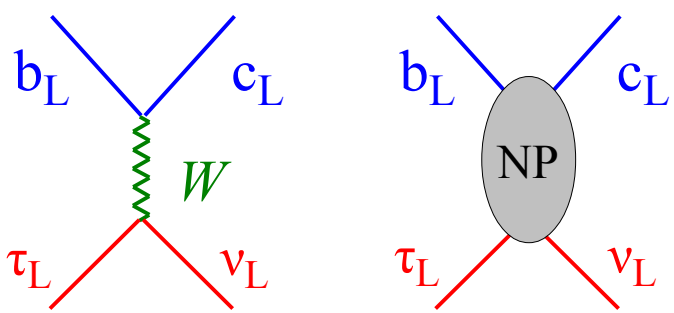

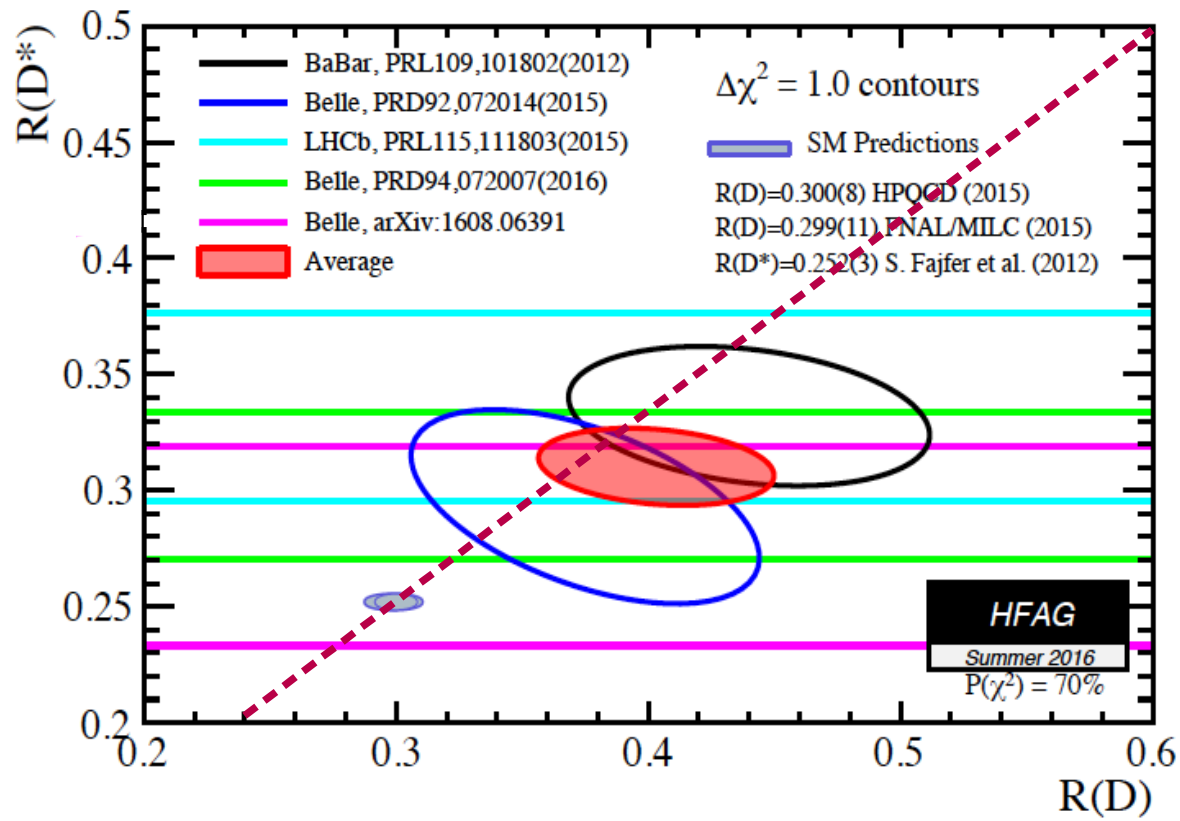

- SM prediction quite solid
- Consistent exp. results by 3 (very) different experiments
- The two channels are well consistent with a universal enhancement (~30%) of the SM $b_L \to c_L\,\tau_L\,\nu_L$ amplitude (*RH or scalar amplitudes disfavored*)

Summary

This pattern of deviations from LFU is very interesting... !

However, please wait before getting super-excited... the statistical significance is high, but not high enough to claim a discovery (*with many searches some anomalies are expected...*)

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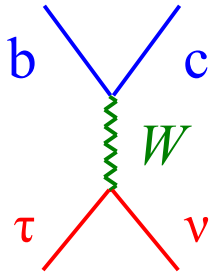
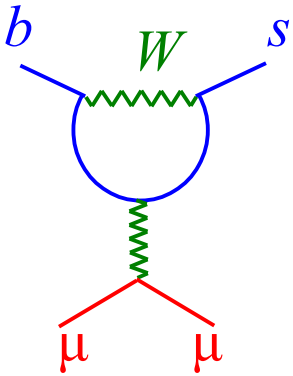
Still, while waiting for more precision studies, it is interesting to speculate a bit on what we seem to observe → two rather different classes of phenomena:

- b → c charged currents: τ vs. light leptons (μ, e)
  Large effect (*competing with SM tree-level*)



- b → s neutral currents: μ vs. e
  Small effect (*competing with a SM rare amplitude*)



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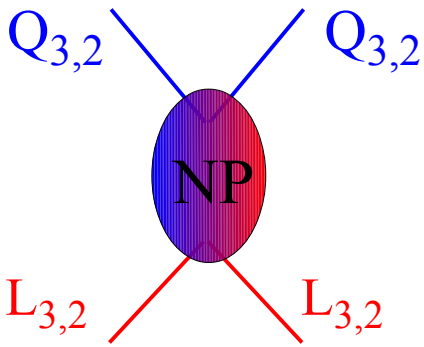


This pattern is not un-natural in extensions of the SM where NP coupled predominantly to the 3rd generation → possible link to a dynamical explanation of the observed hierarchies in the Yukawa couplings

Flavor Symmetries

Generalities

Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...

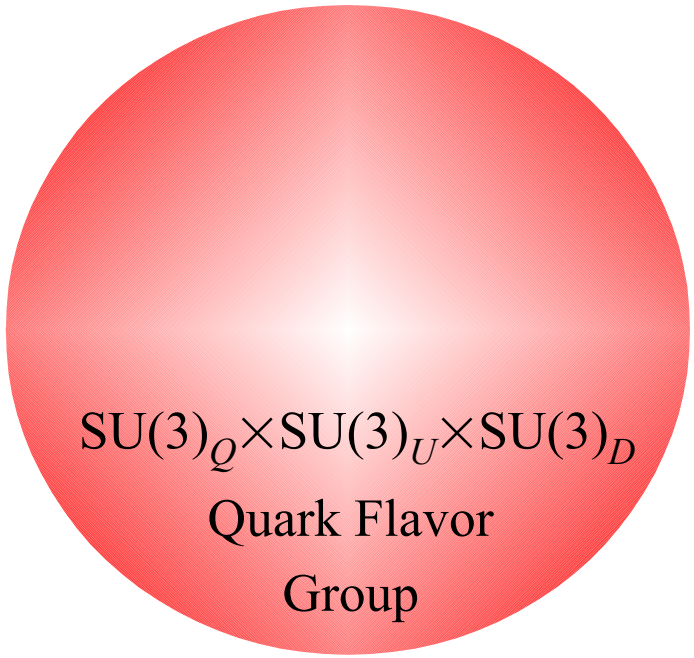
- Can we build NP models where the alignment with the CKM occurs "naturally?
- Does this shed light on the origin of fermion masses and CKM hierarchies?
- Can we see deviations from the SM with more precise measurements? If yes, where?

Maybe we are starting to see some deviations from the SM in LFU ratios... and the (flavor) pattern is clearly non-trivial

Generalities

The flavor structure of the SM is characterized by:

- 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]



$$\mathscr{L}_{\text{gauge}} = \Sigma_a - \frac{1}{4g_a^2}(F_{\mu\nu}^a)^2 + \Sigma_\psi \Sigma_i \bar{\psi}_i i\not{D}\psi_i$$

The gauge Lagrangian is invariant under
5 independent U(3) global rotations for
each of the 5 independent fermion fields

E.g.: $Q_L^i \to U^{ij} Q_L^j$

SU(3) flavor-dependent mixing matrix

$$Q_L = \begin{bmatrix} u_L \\ d_L \end{bmatrix}, \quad u_R, \quad d_R, \quad L_L = \begin{bmatrix} \nu_L \\ e_L \end{bmatrix}, \quad e_R$$

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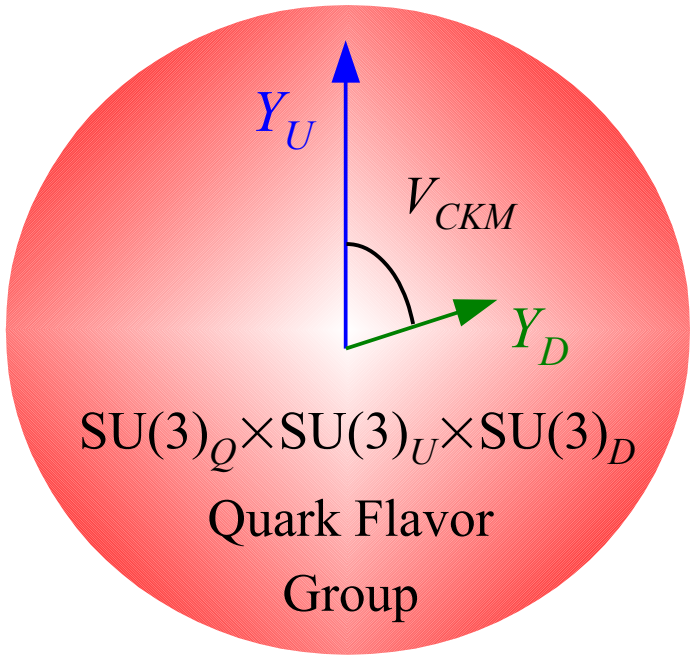
  [quark Yukawa couplings]



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

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

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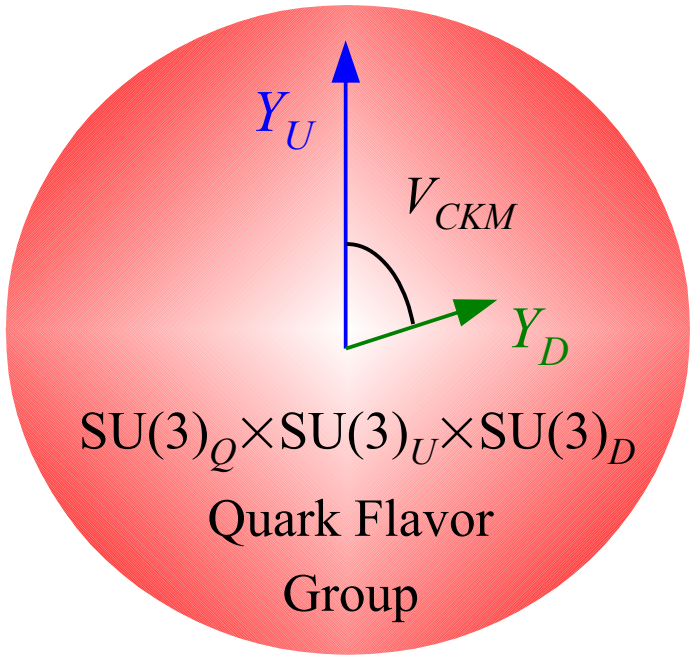

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This specific symmetry + symmetry-breaking pattern is responsible for the suppression of Flavor Changing Neutral Currents, the meson-antimeson mixing amplitudes,...

all the successful SM predictions in the quark flavor sector

The MFV hypothesis

Since the global flavor symmetry is already broken within the SM, is not consistent to impose it as an exact symmetry beyond the SM

However, if we want to "protect" flavor mixing beyond the SM, we can do it in a consistent way "promoting" the Yukawa matrices to be the vacuum expectation values of appropriate auxiliary fields, and assume that that these vacuum expectation values are the only sources of flavor symmetry breaking

E.g.: $Y_D \sim (3,1,\bar{3})$ & $Y_U \sim (3,\bar{3},1)$ under $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$

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

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

$\Downarrow$

$(1,1,1)$ = invariant

The MFV hypothesis

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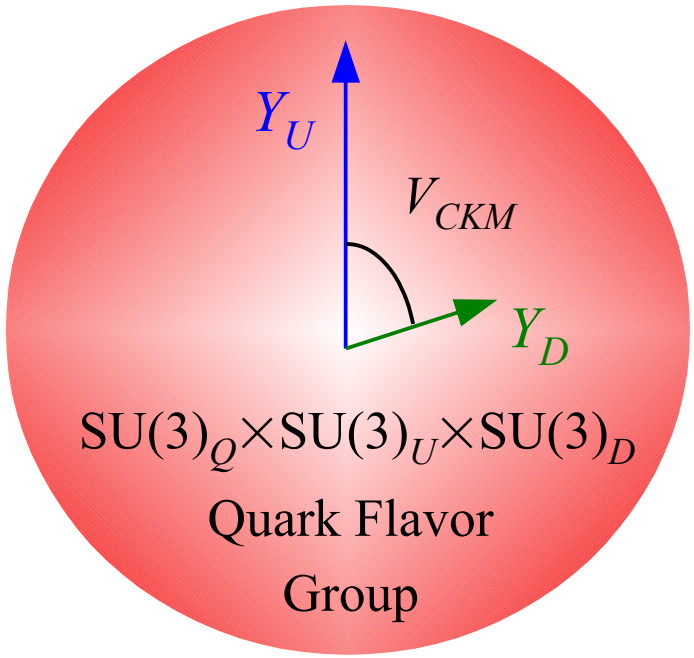
  $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \ldots$
  [global symmetry of the SM gauge sector]

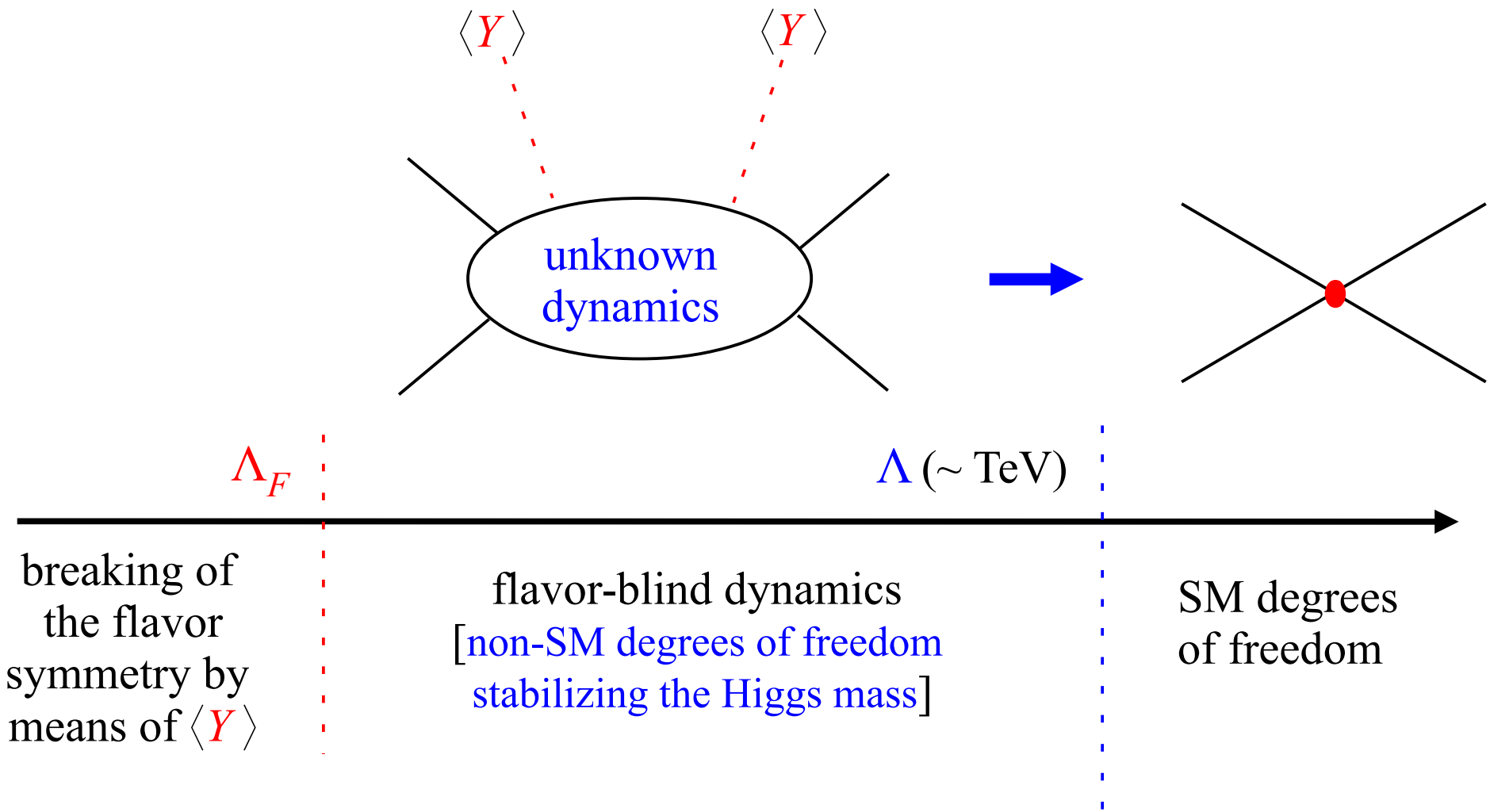
- Symmetry-breaking terms:
  $Y_D \sim 3_Q \times \bar{3}_D \qquad Y_U \sim 3_Q \times \bar{3}_U$
  [quark Yukawa couplings]



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

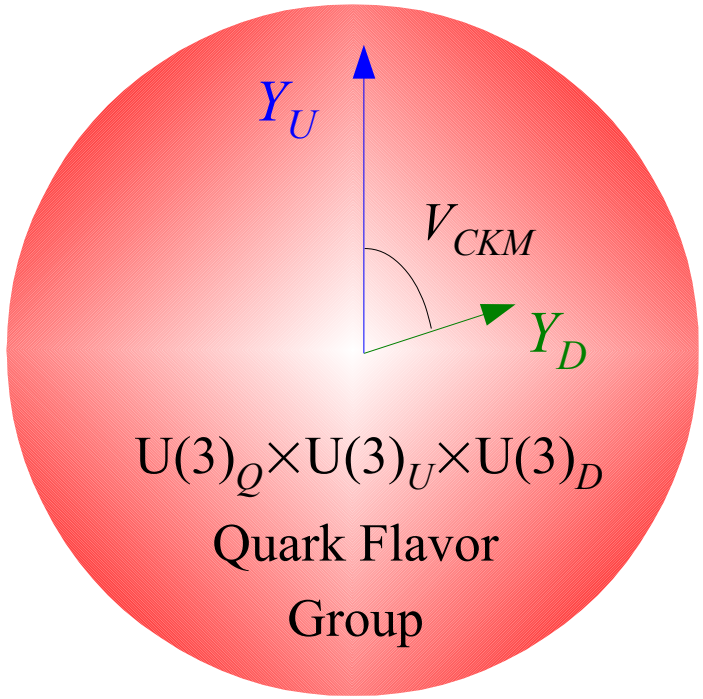
Yukawa couplings = unique sources of flavor symmetry breaking also beyond SM

The MFV hypothesis



General principle which can be applied to any extension of the SM

The MFV hypothesis



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- 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 → *natural stabilization of the Higgs sector*
- It leads to a rather predictive framework:

  All flavor-changing amplitudes must have the same CKM/Yukawa structure as in the SM. Only the flavor-independent magnitude of the transition amplitudes can be modified.

If we apply the MFV hypothesis to the meson-antimeson mixing amplitudes, we get exactly the "alignment" we were hoping for in order to keep a low scale of NP:

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

c_{NP}

- ~ 1 —tree/strong + generic flavor→ $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\pi^2)$ —loop + generic flavor→ $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (V_{ti}^* V_{tj})^2$ —tree/strong + "alignment"→ $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (V_{ti}^* V_{tj})^2/(16\pi^2)$ —loop + "alignment"→ $\Lambda \gtrsim 0.5$ TeV [K & B]

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$$c_{NP} \longrightarrow (Y_U^+ Y_U)_{bd}^2 \sim (V_{tb}^* V_{td})^2$$

c_{NP} →

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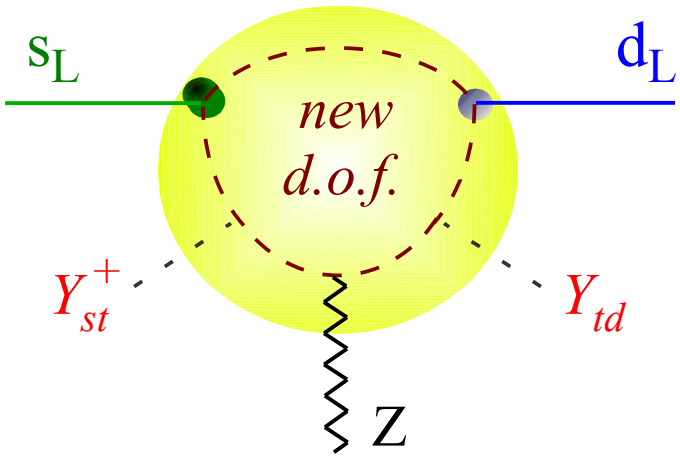
All flavor-changing loop-induced amplitudes have the same CKM/Yukawa structure as in the SM [e.g.: A($s\to dZ$) ~ $V_{ts}^* V_{td}$, A($b\to sZ$) ~ $V_{tb}^* V_{ts}$, …].
Only the flavor-independent magnitude can be modified



$$\left|\frac{A(s\to dZ)}{A(b\to sZ)}\right| = \left|\frac{V_{td}}{V_{tb}}\right|$$ as in the SM...

As a result, the tight experimental constraints on rare processes are naturally satisfied:

Operator	Bound on Λ	Observables
$H^\dagger(\bar{D}_R Y^{d\dagger} Y^u Y^{u\dagger}\sigma_{\mu\nu} Q_L)(eF_{\mu\nu})$	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}
$H_D^\dagger(\bar{D}_R Y^{d\dagger} Y^u Y^{u\dagger}\sigma_{\mu\nu} T^a Q_L)(g_s G^a_{\mu\nu})$	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]

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

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

Some more rare decays not precisely measured yet could provide more useful infos → Very interesting candidates: $B_{d,s} \to \mu\mu$ & $K \to \pi\nu\nu$

Beyond MFV [from $U(3)^3$ to $U(2)^3$]

Beyond MFV

MFV virtue

↓

Naturally small effects in FCNC observables

MFV main open problem

↓

No explanation for Y hierarchies (masses and mixing angles)

Beyond MFV

MFV virtue

↓

Naturally small effects in FCNC observables

MFV main open problem

↓

No explanation for Y hierarchies (masses and mixing angles)

If the deviations from the SM in the LFU tests were confirmed, this would also be a problem (*they cannot be explained in MFV since the lepton Yukawa couplings are too small*)

Beyond MFV

MFV virtue

↓

Naturally small effects in FCNC observables

MFV main open problem

↓

No explanation for Y hierarchies (masses and mixing angles)

To solve this issue
+ other issues on the Higgs stability
+ hints of LFU violations

⬇

NP coupled mainly to 3rd gen.
+
flavor symmetry acting
only on 1st & 2nd generations

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To solve this issue
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NP coupled mainly to 3rd gen.
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$U(2)^n = U(2)_Q \times U(2)_U \times U(2)_D \times \ldots$ flavor symmetry

Not the only option, but one of the most interesting ones..

The $U(2)^n$ flavor symmetry

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

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

2×2 block of the first two generations

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

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

$V \sim (2,1,1) \quad O(|V_{ts}| \sim 0.04)$ Leading breaking [3rd gen. → 1,2 gen.]

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

$$Y_u = y_t \begin{bmatrix} 0 & c_u V \\ 0 & 1 \end{bmatrix} \qquad Y_d = y_b \begin{bmatrix} 0 & c_d V \\ 0 & 1 \end{bmatrix} \quad \rightarrow \quad V_{CKM} \sim \begin{bmatrix} 1 & O(|V_{ts}|) \\ 0 & 1 \end{bmatrix}$$

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$V \sim (2,1,1)$ $\quad O(|V_{ts}| \sim 0.04)$ Leading breaking [3rd gen. → 1,2 gen.]

$\Delta Y_u \sim (2,2,1)$ $\quad m_c, m_u, \theta_u$ $\quad O(0.005)$

$\Delta Y_d \sim (2,1,2)$ $\quad m_s, m_d, \theta_d$ $\quad O(0.001)$

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

$$Y_u = y_t \left[\begin{array}{c|c} \Delta Y_u & c_u V \\ \hline 0 & 1 \end{array}\right] \qquad Y_d = y_b \left[\begin{array}{c|c} \Delta Y_d & c_d V \\ \hline 0 & 1 \end{array}\right]$$

→ *full* V_{CKM}

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

$V \sim (2,1,1)$ $\quad O(|V_{ts}| \sim 0.04)$ Leading breaking [3rd gen. → 1,2 gen.]

The main idea is that the flavor symmetry is broken in two (or more) steps

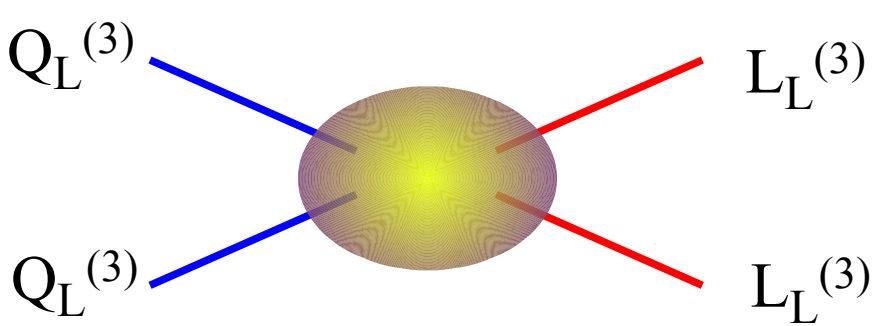
The "virtue" (from the NP point of view) is more freedom for non-standard effects → possibility to have a relatively light NP sector coupled mainly to the 3rd generation

Possible links to the recent B-physics anomalies

- Models of NP based on U(2)-type flavor symmetries (*acting on both quarks and leptons*) can provide a rational for the pattern of observed hints of LFU non-universality (*taking into account the tight bounds from other low-energy processes*)

Main idea:

- NP coupled mainly to 3rd generation (competing with SM tree-level) in $q_3\, q_3 \to l_3\, l_3$ => $V_{cb}\, bc \to \tau\, \nu_\tau$



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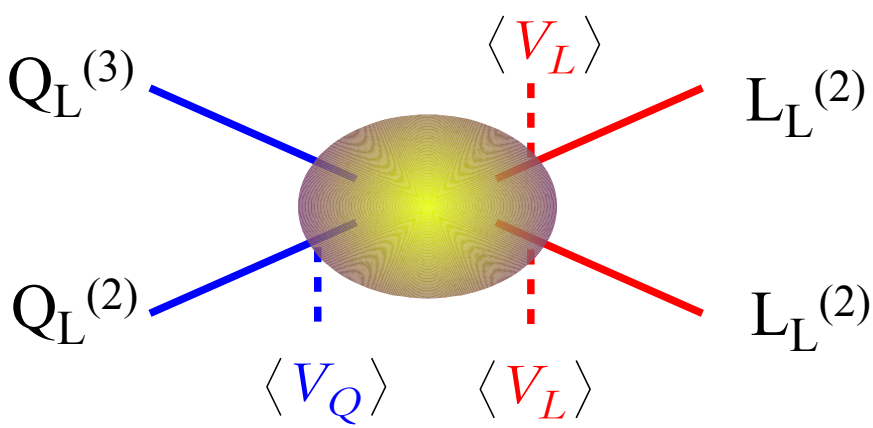
Main idea:

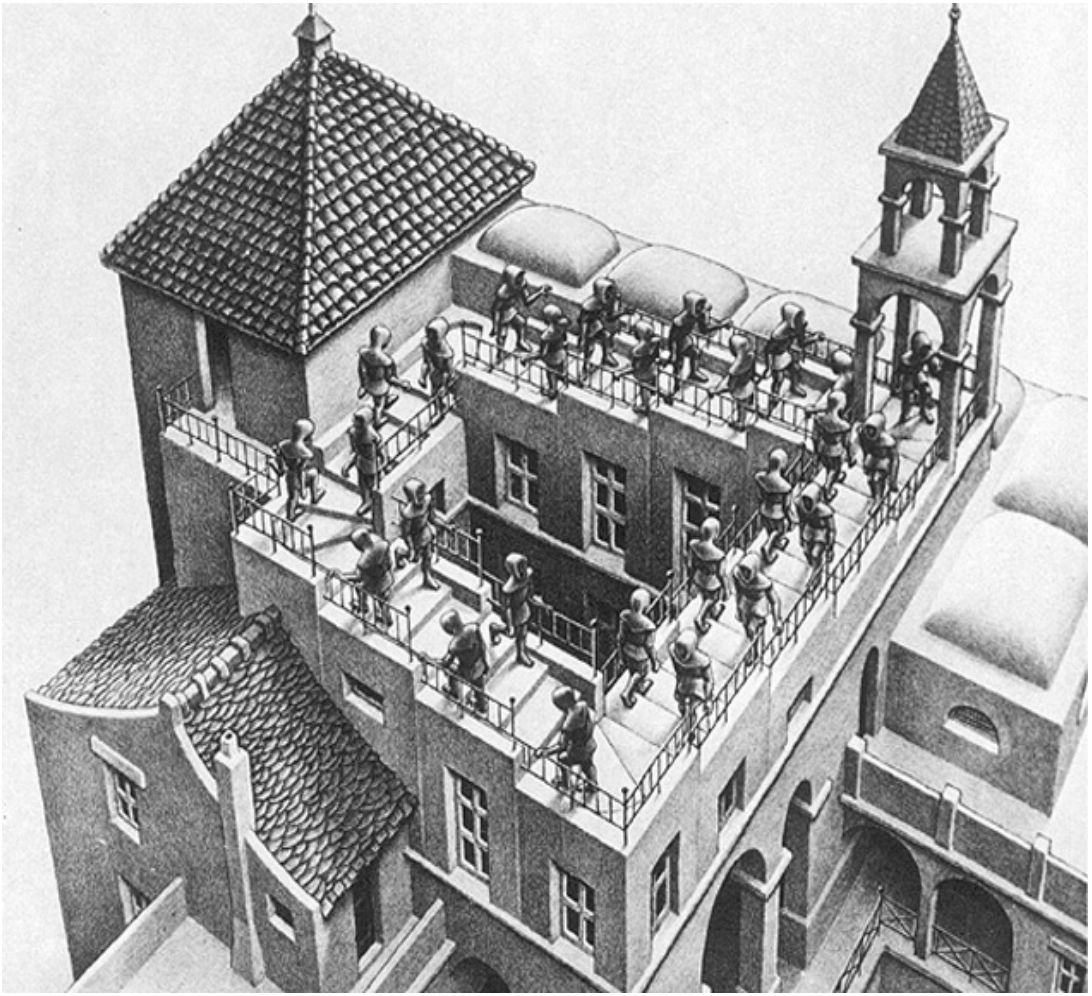
- NP coupled mainly to 3rd generation (competing with SM tree-level) in $q_3\, q_3 \to l_3\, l_3$ => $V_{cb}\, bc \to \tau\, \nu_\tau$

- Small non-vanishing coupling (competing with SM FCNC) in $bs \to \mu\mu$



Glashow, Guadagnoli, Lane '14
Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
Barbieri, GI, Pattori, Senia '15
...

Conclusions



Conclusions

The filed of flavor physics is some how old... but is also in rapid evolution.
The fact we have not discovered yet new physics in flavor-physics observables, should not discourage further investigations.

- We learned that new physics has a rather non-trivial flavor structure, but *the origin of this structure is still to be discovered.*
- There are several key issues that are still open (the origin of the Yukawa couplings, etc....) and maybe we are starting to see NP effects (→ *interesting hints of LFU violations in B decays*).

⬇

We need to continue high-precision flavor-physics experiments and, at the same time, we need to further improve theory tools to describe (quark) flavor-changing transitions with higher precision

I hope I convinced you that this field is quite interesting...