Old and recent puzzles in Flavor Physics

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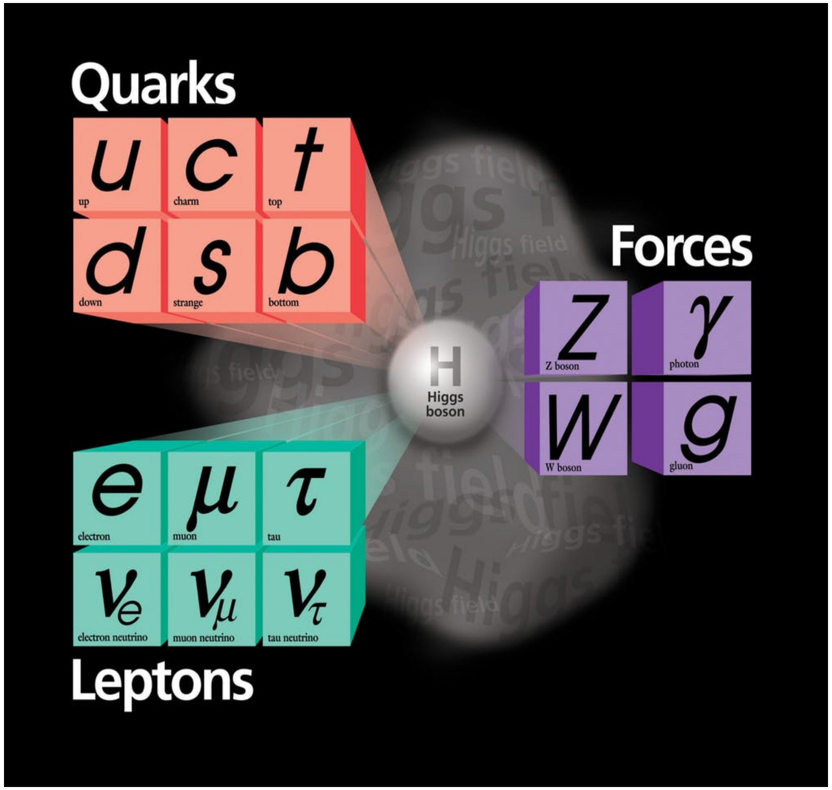
- Introduction [*Open problems, common lore, recent hopes*]
- On the recent "anomalies" in B-physics
- Bottom-up approaches to describe the anomalies
- Speculations on UV completions
- Possible future implications
- Conclusions

Introduction

All microscopic phenomena seems to be well described by a remarkably simple Theory (*that we continue to call "model" only for historical reasons...*):

$$\mathscr{L}_{\text{Standard Model}} = \mathscr{L}_{\text{gauge}}(\psi_i, A_a) + \mathscr{L}_{\text{Higgs}}(H, A_a, \psi_i)$$



Introduction

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However, this Theory has some deep unsolved problems:

Electroweak hierarchy problem

Flavor puzzle

Neutrino masses

U(1) charges

Dark-matter

Dark-energy

Inflation

Quantum gravity

→

The Standard Model (SM) should be regarded as an *effective theory*

i.e. the limit (*in the range of energies and effective couplings so far probed*) of a more fundamental theory with new degrees of freedom

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	problem due to...	*...indicating*
Electroweak hierarchy problem	→ *Instability of the Higgs mass term*	→ *New dynamics close to the Fermi scale* (~ 1 TeV)
Flavor puzzle Neutrino masses U(1) charges	→ *Ad hoc tuning in the model parameters*	*No well-defined energy scale*
Dark-matter Dark-energy Inflation	→ *Cosmological implementation of the SM*	
Quantum gravity	→ *General problem of any QFT*	

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"Common lore" (I) :

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge}(A_a, \psi_i) + \mathscr{L}_{\rm Higgs}(H, A_a, \psi_i)$$

Understanding what stabilizes the Higgs sector (*EW hierarchy problem*) is the natural "main avenue" to discover New Physics

Introduction

This "main avenue" has led to very appealing BMS constructions that, however, so far do not find experimental confirmation (*making these theories less and less appealing...*) → worth to explore new directions.

Electroweak hierarchy problem

Flavor puzzle

Neutrino masses

U(1) charges

→ A direction which seems to be suggested by recent low-energy data ("flavor anomalies" …)

If correct... → very important implications for addressing also the other problems

Dark-matter

Dark-energy

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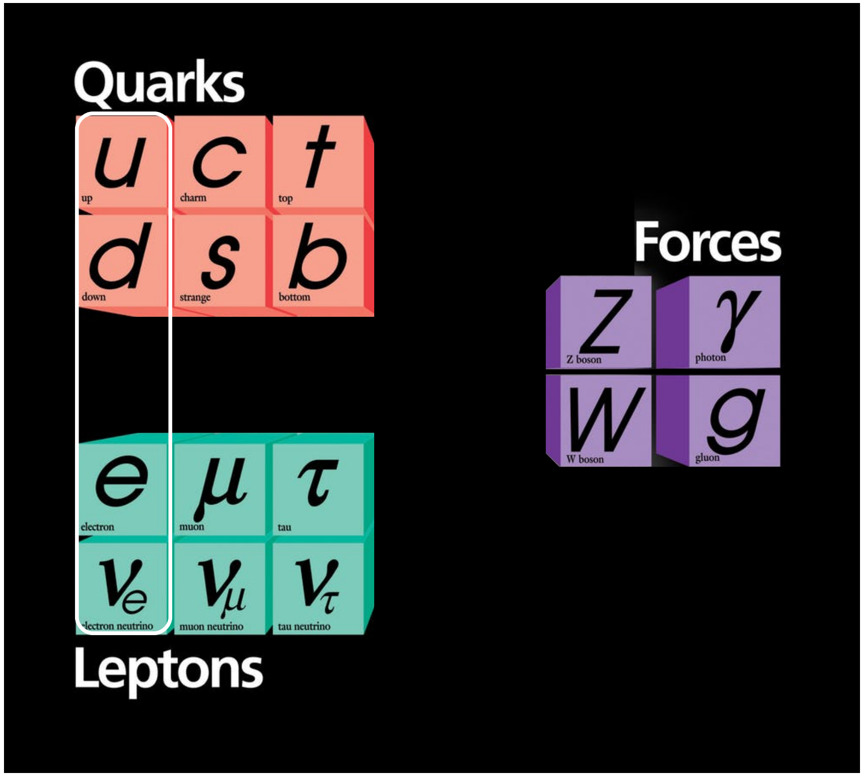
Introduction [*the flavor structure of the SM*]

$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm gauge}(A_{\rm a}, \psi_{\rm i}) + \mathscr{L}_{\rm Higgs}(\mathrm{H}, A_{\rm a}, \psi_{\rm i})$$

3 identical replica of the basic fermion family
$[\psi = Q_L, u_R, d_R, L_L, e_R] \Rightarrow$ huge flavor-degeneracy [$U(3)^5$ *symmetry*]

$$Q_L = \begin{bmatrix} u_{\rm L} \\ d_{\rm L} \end{bmatrix} \quad u_{\rm R} \quad d_{\rm R} \quad L_L = \begin{bmatrix} \nu_{\rm L} \\ e_{\rm L} \end{bmatrix} \quad e_{\rm R}$$

$$\mathscr{L}_{\rm gauge} = \Sigma_{\rm a} - \frac{1}{4g_{\rm a}^{\,2}} (F_{\mu\nu}^{\ \ a})^2 + \Sigma_\psi \Sigma_{\rm i} \bar{\psi}_{\rm i}\, i \not{D}\, \psi_{\rm i}$$



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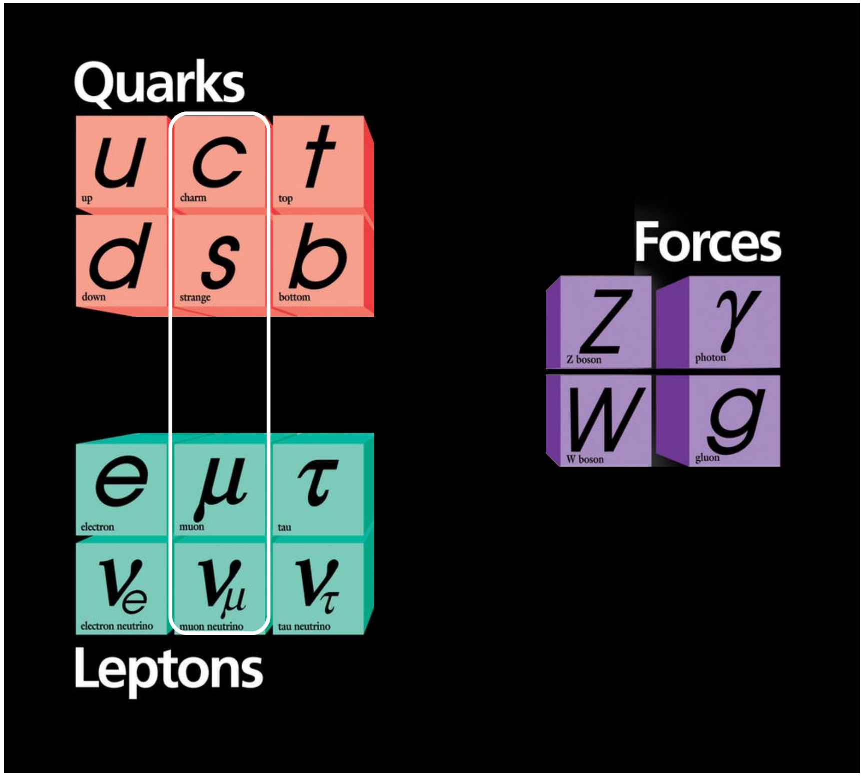

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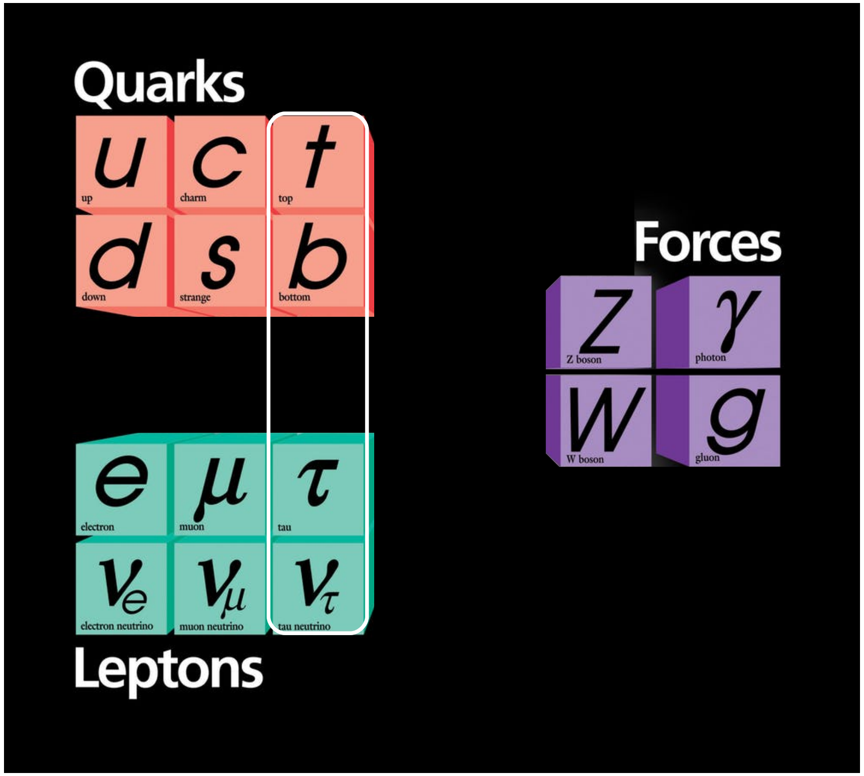

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Within the SM the flavor-degeneracy is broken only by the Yukawa interaction:

$$\bar{L}_L^{\,i}\, Y_L^{ik}\, e_R^{\,k}\, \mathrm{H} \quad + \; h.c.$$

$$\bar{Q}_L^{\,i}\, Y_D^{ik}\, d_R^{\,k}\, \mathrm{H} \quad + \; h.c.$$

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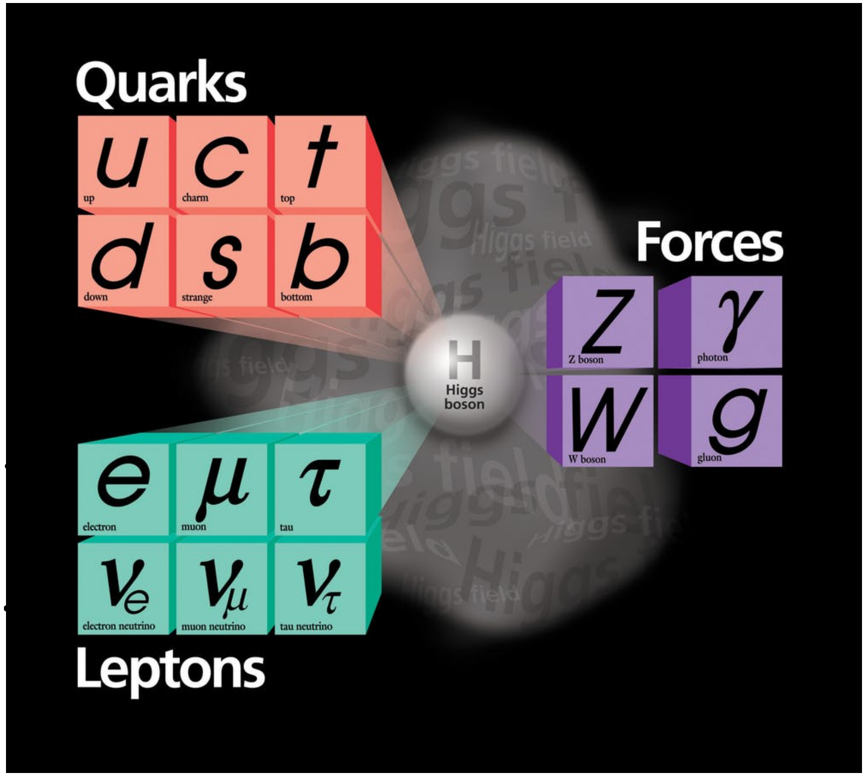

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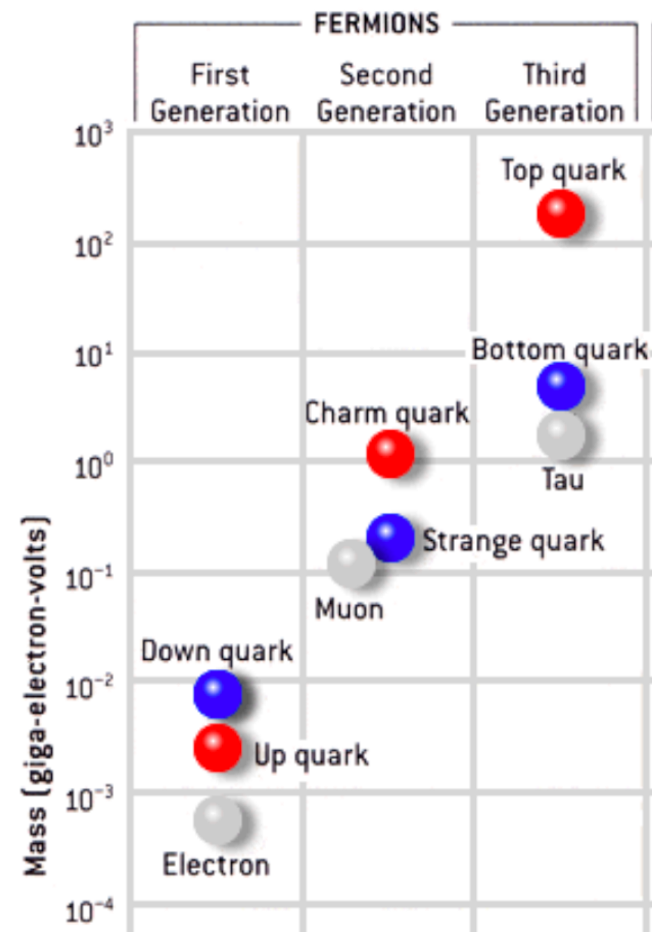
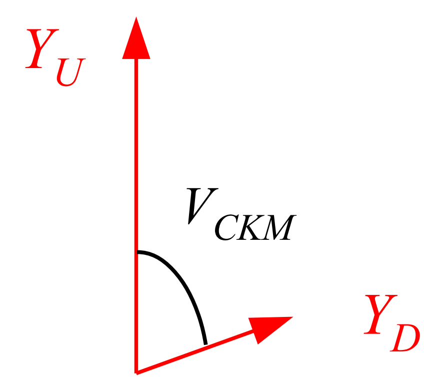
$$\bar{Q}_L^{\,i}\, Y_D^{ik}\, d_R^{\,k}\, {\rm H} \;\rightarrow\; d_L^{\,i}\, M_D^{ik}\, \bar{d}_R^{\,k} + \ldots$$

$$\bar{Q}_L^{\,i}\, Y_U^{ik}\, u_R^{\,k}\, {\rm H_c} \;\rightarrow\; u_L^{\,i}\, M_U^{ik}\, \bar{u}_R^{\,k} + \ldots$$

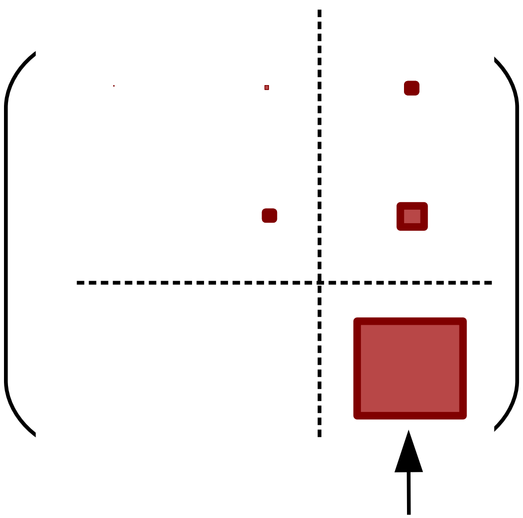




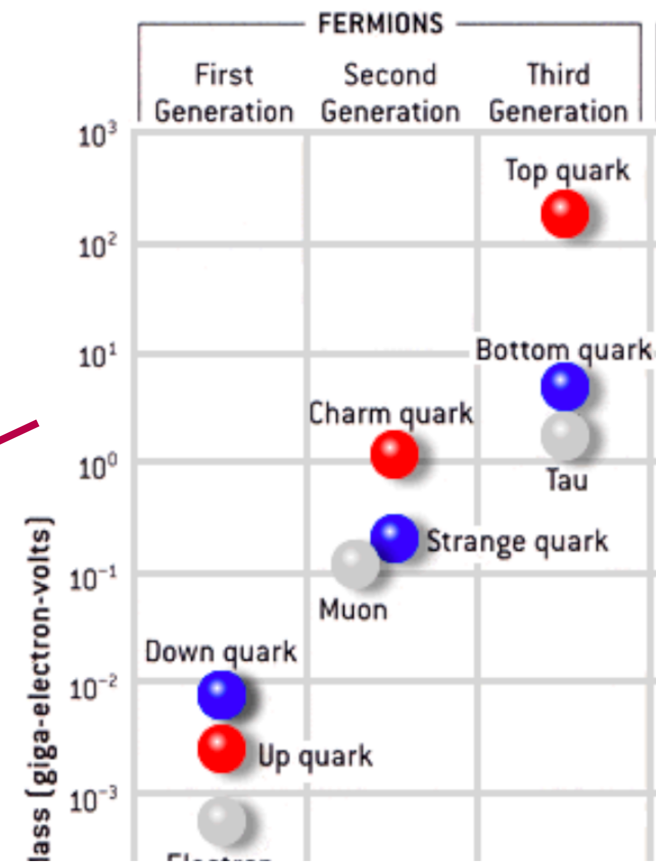
<u>*Introduction*</u> [*the flavor structure of the SM*]

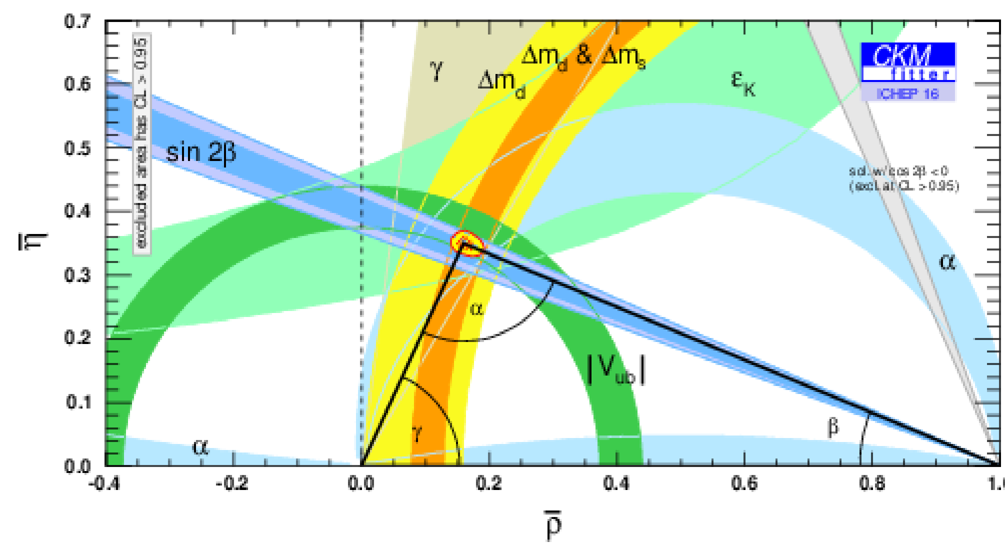
The SM flavor sector (= *the Yukawa sector*) contains a large number of free parameters (<u>fermion masses</u> & <u>mixing angles</u>), which *do not look at all accidental...*

E.g.:

$Y_U \sim$ 

$$y_t = \frac{\sqrt{2}\, m_t}{\langle H \rangle} \approx 1$$





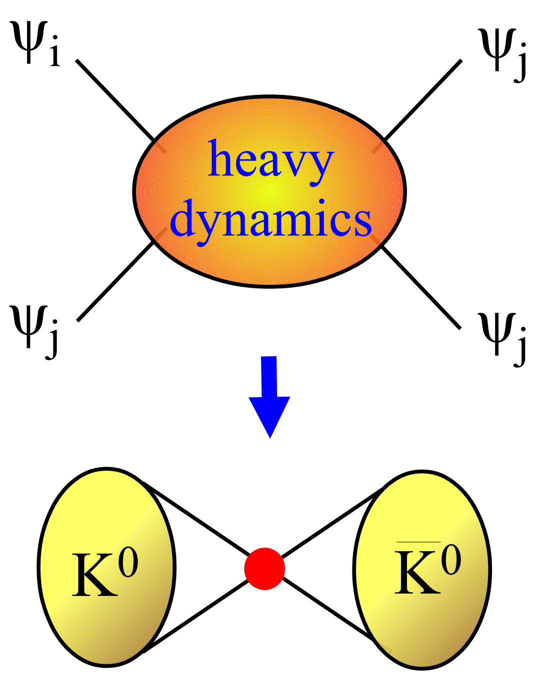
The "old" flavor puzzle...

Introduction [*the flavor structure of the SM & beyond...*]

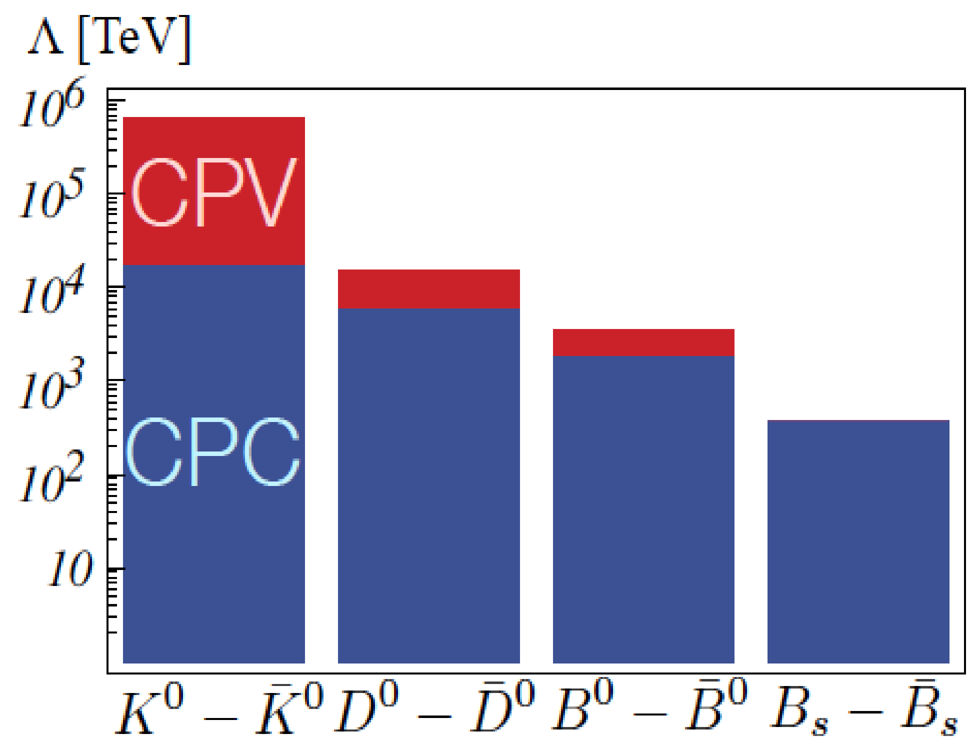
"Common lore" (II) :

The flavor structures are generated at some very heavy energy scale → *No chance to probe their dynamical origin*

This idea is supported by a series of precision measurement of rare flavor-violating processes which show no deviations from the SM:



$$\frac{1}{\Lambda^2}(\bar{\psi}_i\,\psi_j)^2$$



Since so far (*almost*) everything fits well with the SM→ Strong limits on NP

Introduction [*the flavor structure of the SM & beyond...*]

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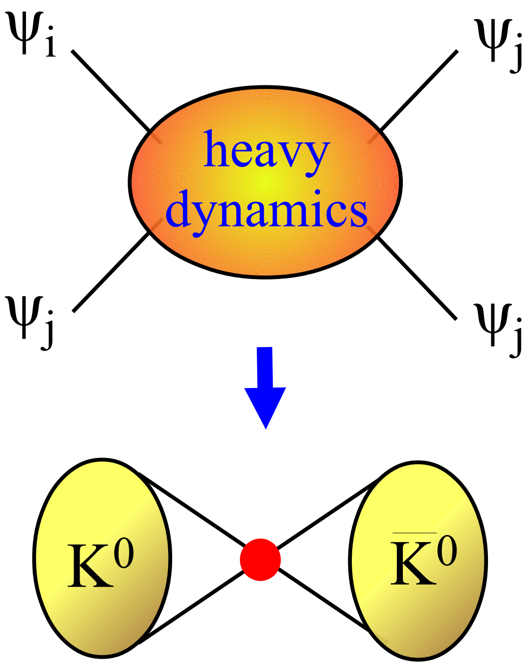

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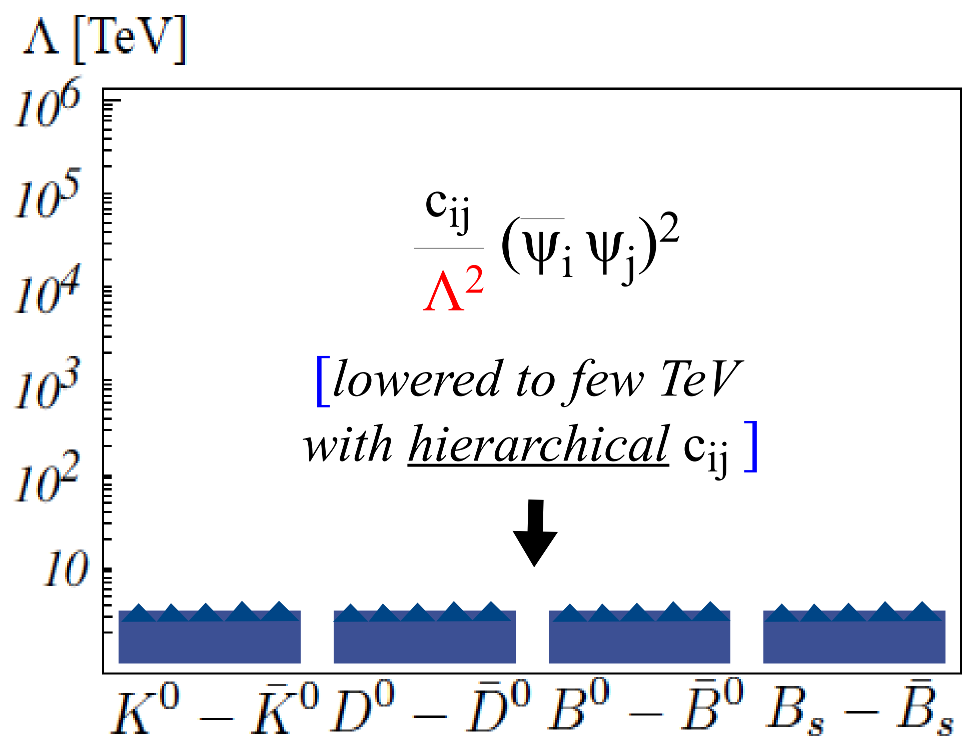

There is a flaw in the argument.... *bounds above few TeV are misleading* !

Introduction [*the flavor structure of the SM & beyond...*]

The point of view that non-trivial flavor dynamics cannot be probed at low energies is challenged by a series of recent "anomalies" in B physics: the observation of a different (*non-universal*) behavior of different lepton species in specific in b (3rd gen.) $\to$ c,s (2nd) semi-leptonic processes:

- $b \to c$ charged currents: τ vs. light leptons (μ, e)
- $b \to s$ neutral currents: μ vs. e

IF taken together... this is probably the largest "coherent" set of NP effects in present data...

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The "new" flavor puzzle...

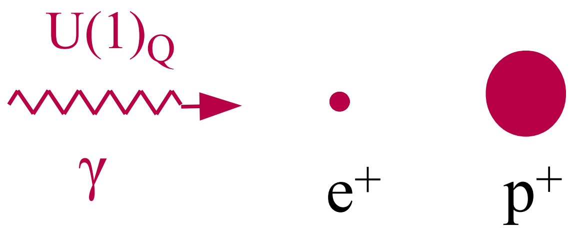
What is particularly interesting, is that these anomalies are challenging an assumption (Lepton Flavor Universality), that we gave for granted for many years (*without many good theoretical reasons...*)

⬇

Interesting shift of paradigm
(*in flavor physics, but possibly also beyond*)

Introduction [*General considerations on LFU*]

Suppose we could test matter only with long wave-length photons...



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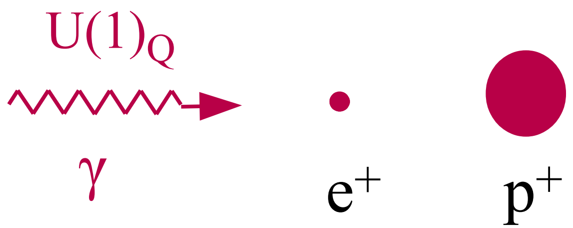

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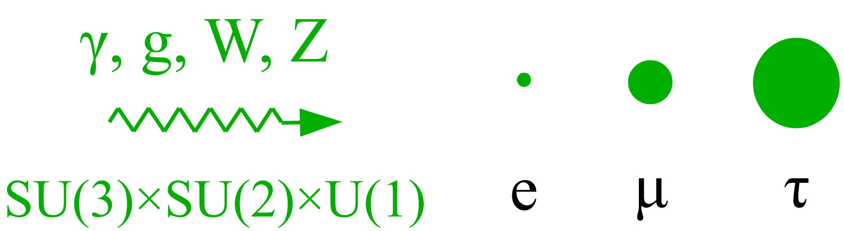
This is exactly the same (*potentially misleading*) argument we use to infer LFU in the SM...

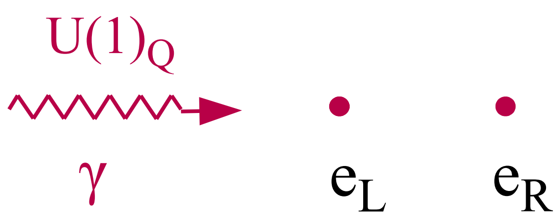


These three (families) of particles seems to be "identical copies" but for their mass ...

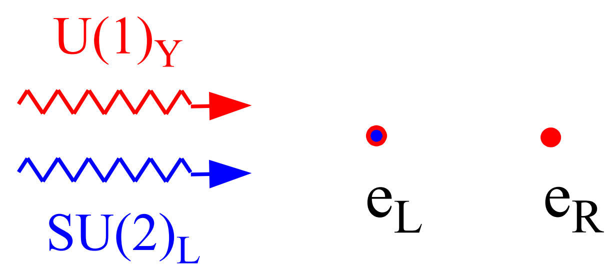
The SM quantum numbers of the three families could be an "accidental" low-energy property: the different families may well have a very different behavior at high energies, as signaled by their different mass

Introduction [*General considerations on LFU*]

Along the same line...



Low energies



High energies

▶ Introduction [*General considerations on LFU*]

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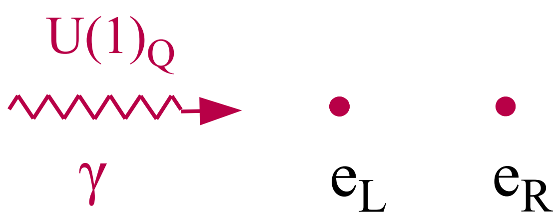

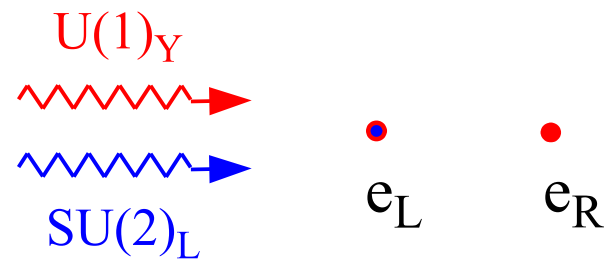

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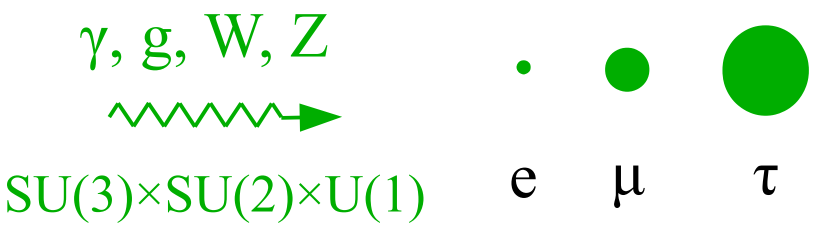

???

The apparent flavor symmetry of the SM could well be only an accidental low-energy property, such as isospin or SU(3) in QCD...

▶ *Introduction* [*General considerations on LFU*]

So far, the vast majority of BSM model-building attempts

- Concentrate only on the Higgs hierarchy problem

"Common lore" (I)

- Postpone (ignore) the flavor problem, implicitly assuming the 3 families are "identical" copies (but for Yukawa-type interactions)

"Common lore" (II)

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The recent flavor anomalies seem to suggest a shift of paradigm:

- We should not ignore the flavor problem [→ *new (non-Yukawa) interactions at the TeV scale distinguishing the different families*]
- A (very) different behavior of the 3 families (with special role for 3^{rd} gen.) *may be the key to solve/understand also the gauge hierarchy problem*

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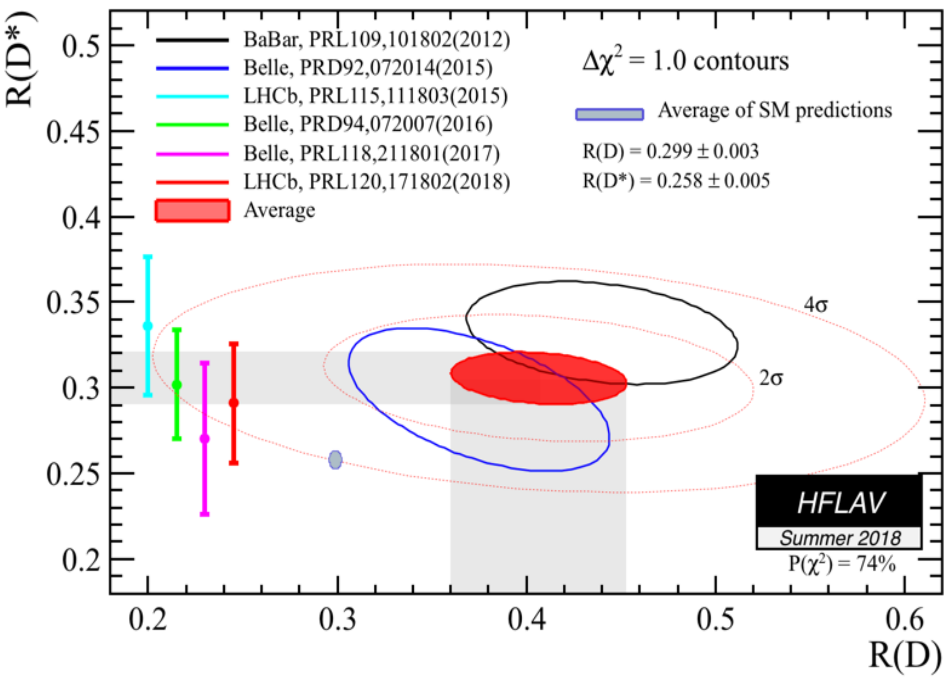
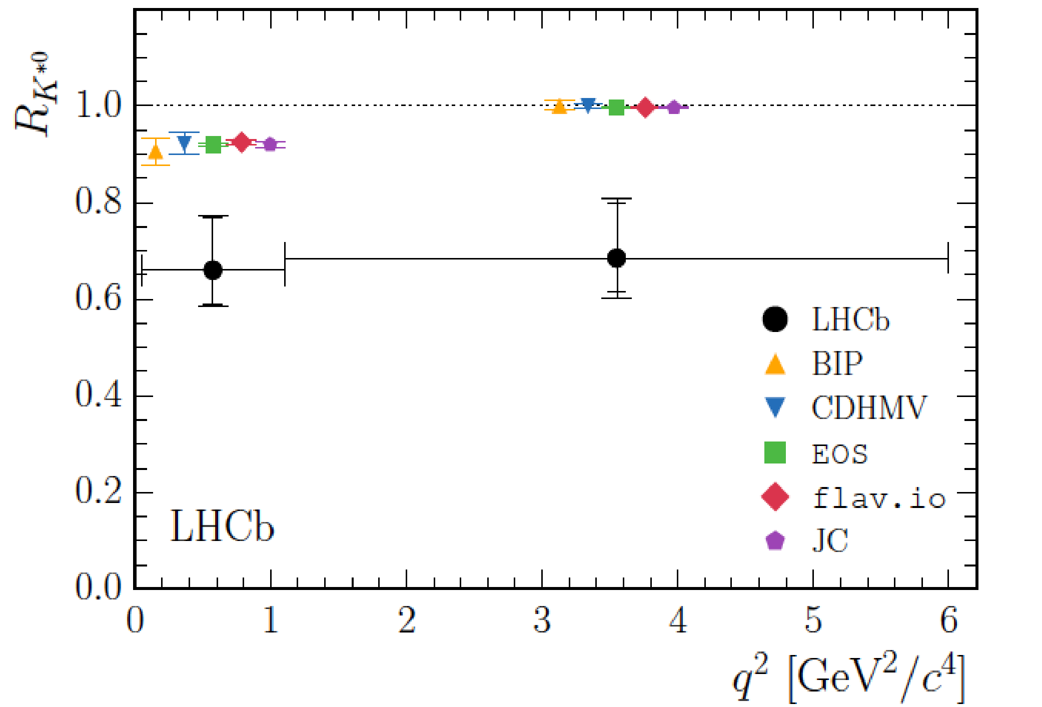
And, if we are lucky... these anomalies may help us to find new ways to achieve quark-lepton unification (→ solve the problem of the quantization of the U(1) charges)

On the recent B-physics anomalies



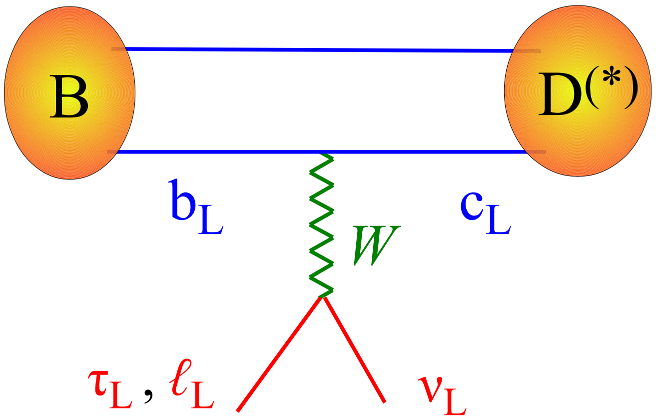


▸ $B \to D^{(*)} \tau\nu$ [Babar, Belle, LHCb]

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

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

$$X = \mathrm{D\ or\ D^*}$$



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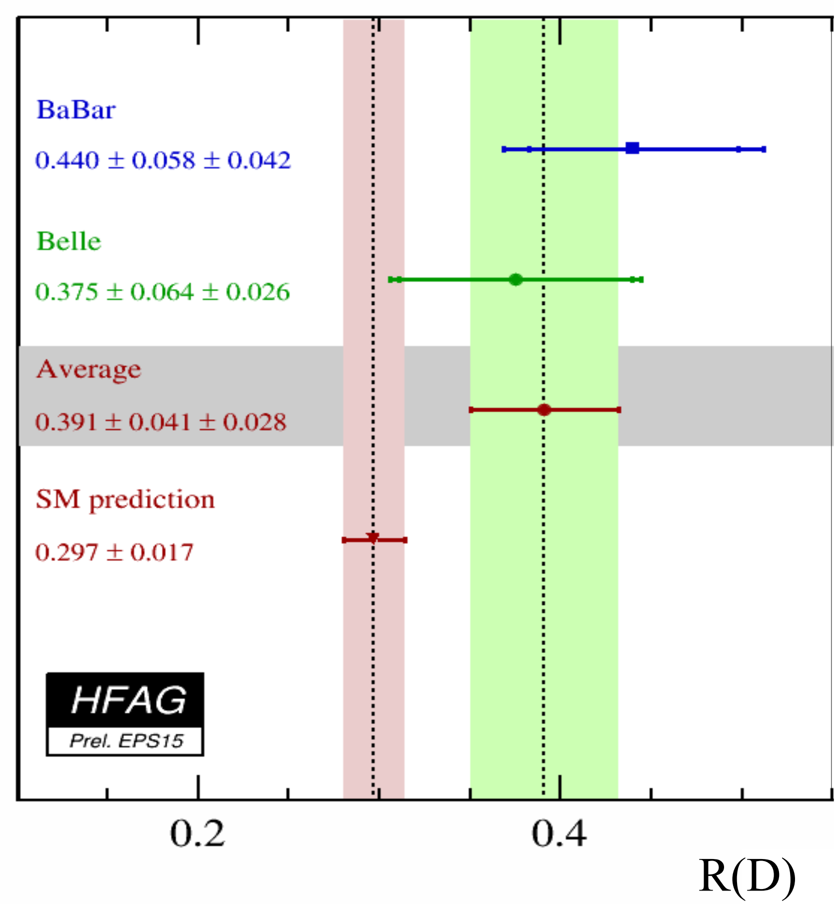
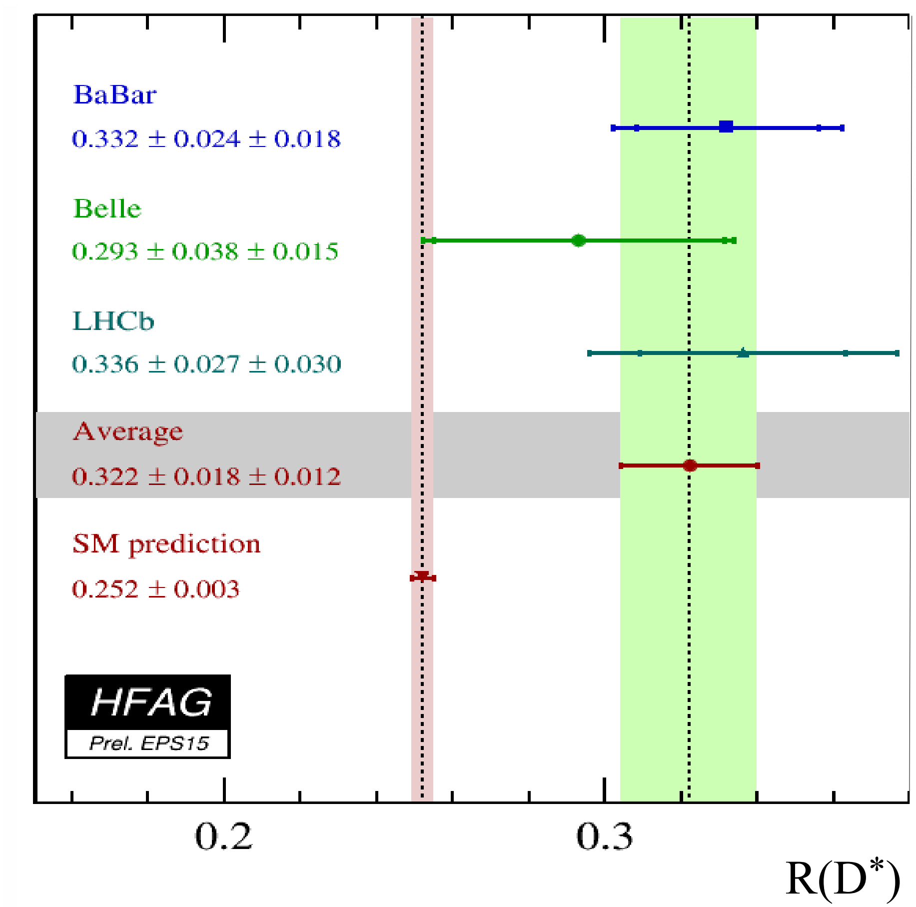
2015





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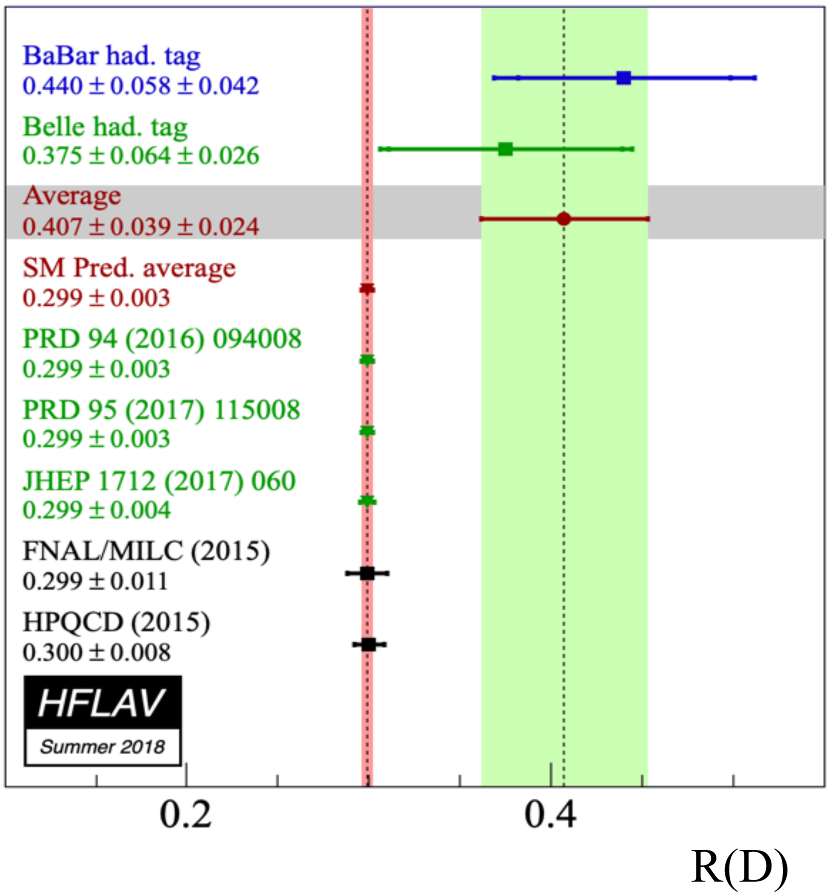
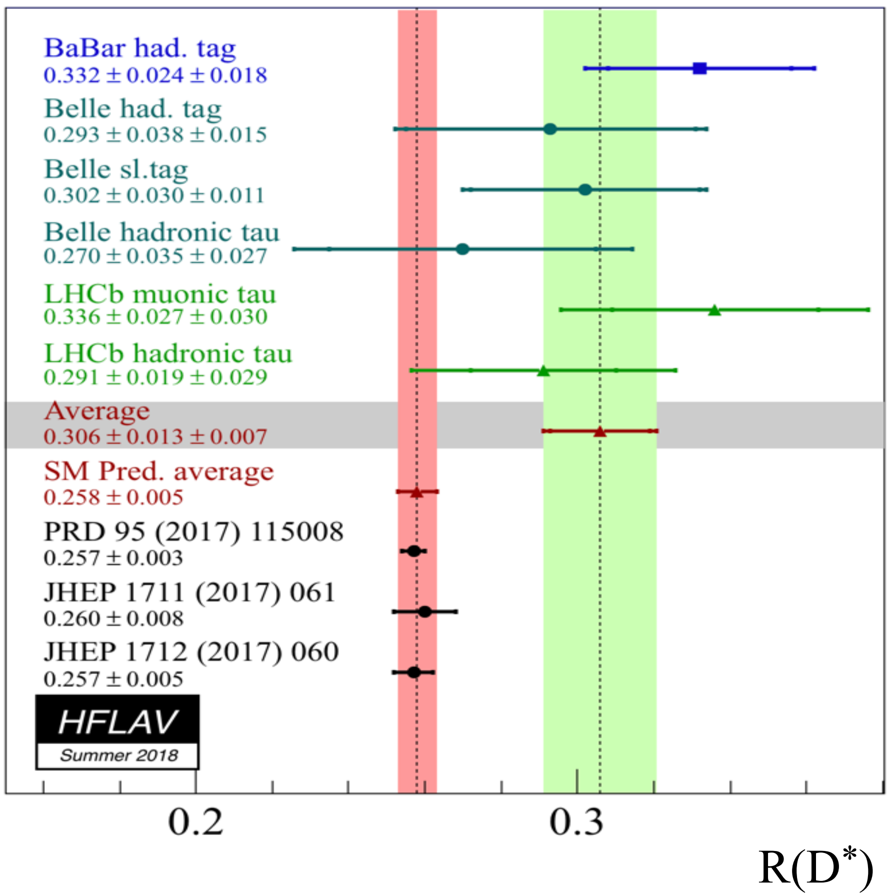
2018





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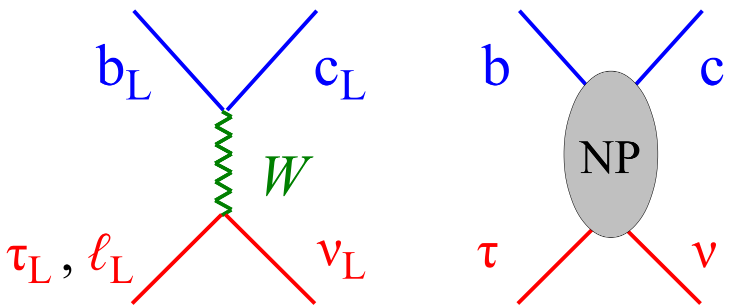

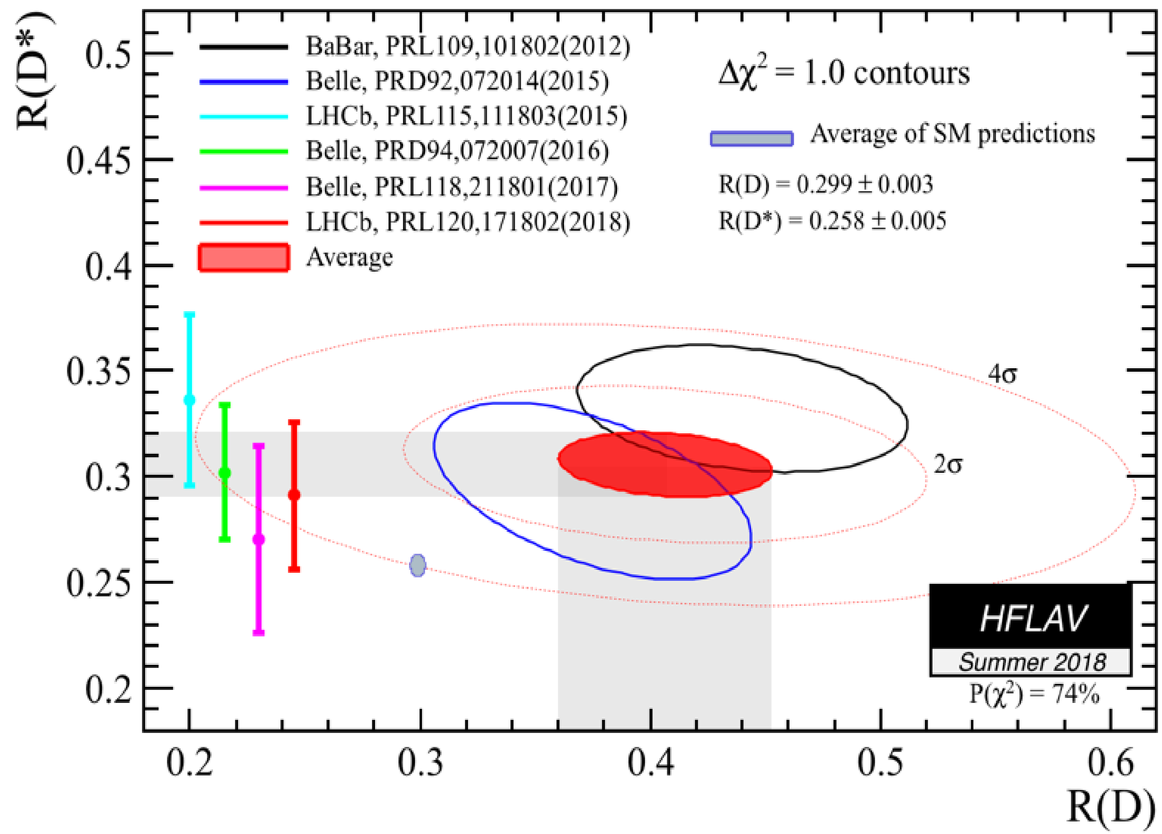

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- Consistent results by 3 different exps. → 3.6–3.9σ excess over SM (D + D^*)

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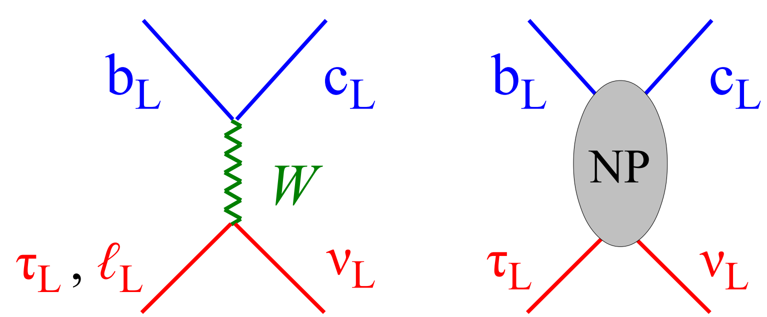
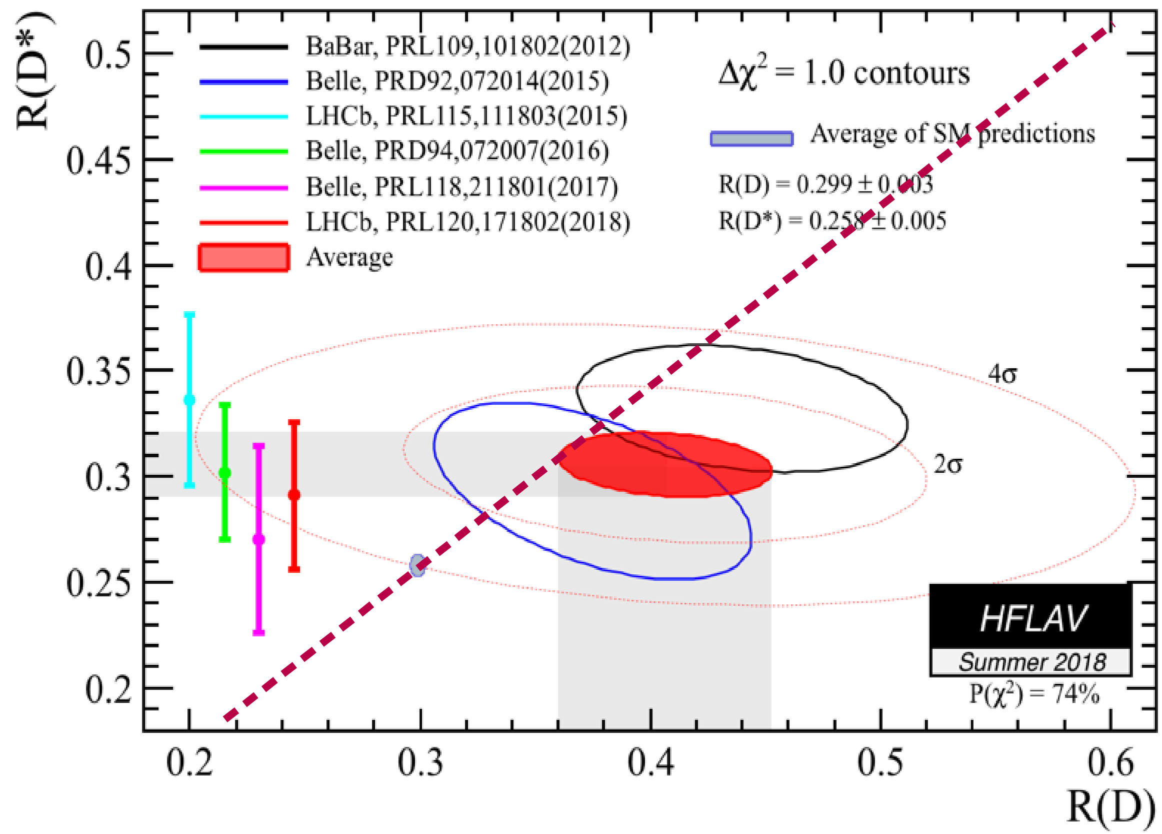




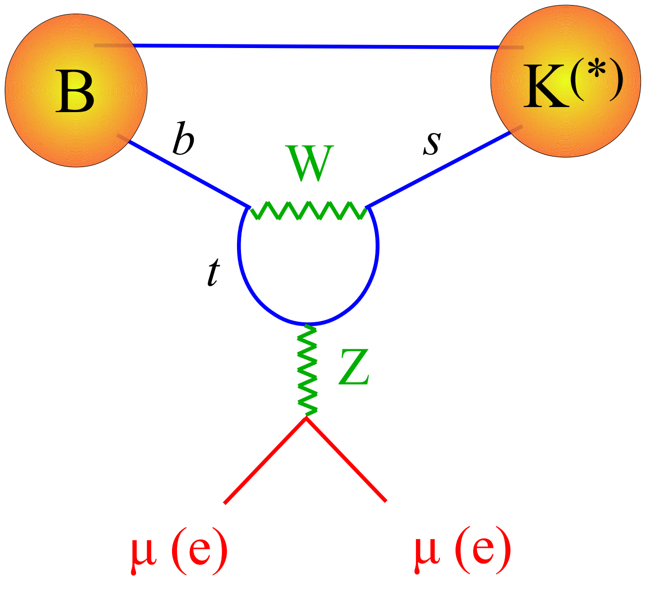
- **SM** prediction quite solid: hadronic uncertainties cancel (*to large extent*) in the ratio and deviations from 1 in R(X) expected only from phase-space differences
- Consistent results by 3 different exps. → 3.6–3.9σ excess over SM ($D + D^*$)
- The two channels are well consistent with a universal enhancement (~30%) of the SM $b_L \to c_L\ \tau_L\ \nu_L$ amplitude

Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

- The largest anomaly is the one [*observed in 2013 and confirmed with higher statistics in 2015*] in the $B \to K^{*}\mu\mu$ angular distribution.
- Less significant correlated anomalies present also in other $B \to K^{*}\mu\mu$ observables and also in other $b \to s\,\mu\mu$ channels [overall smallness of all BR's]

N.B.: $b \to s\, ll$ transitions are Flavor Channing Neutral Current amplitudes

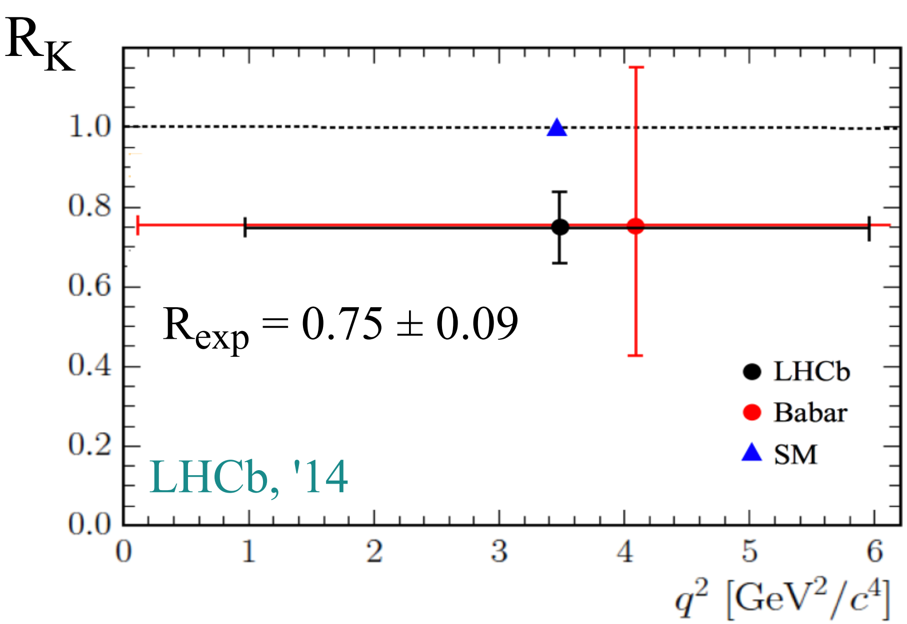
- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Sizable hadronic uncertainties in the rates

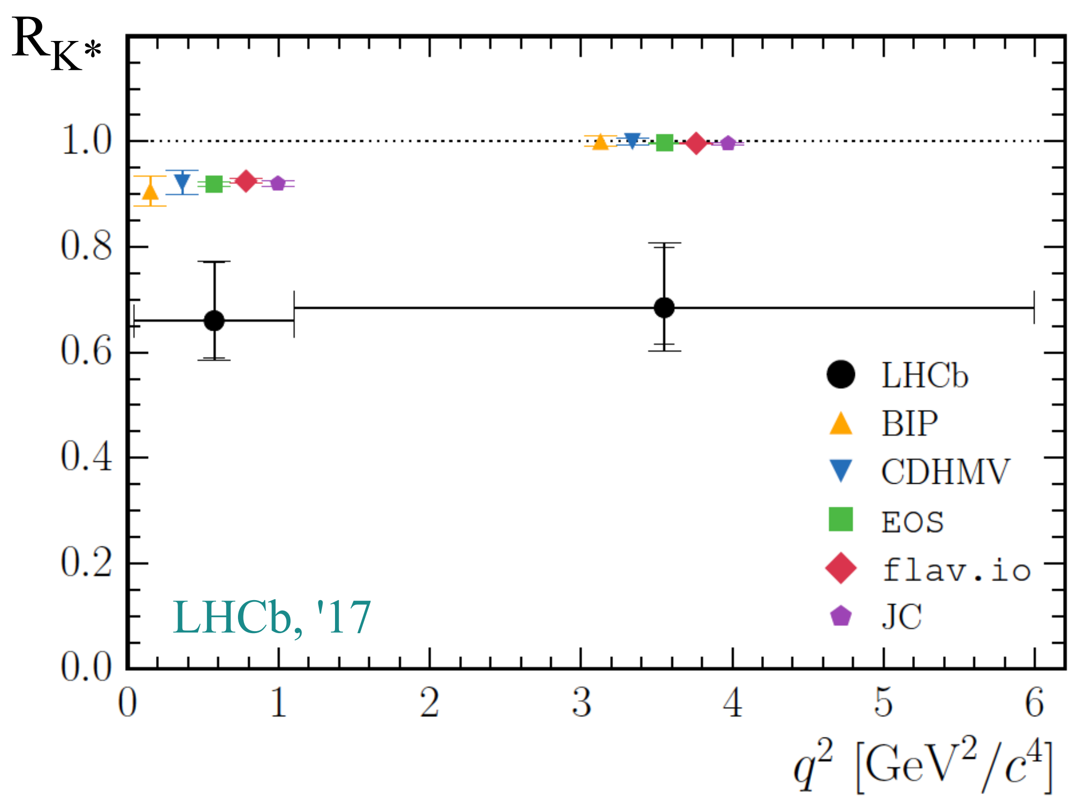


Anomalies in $B \to K^{(*)}\ \mu\mu$ / ee [LHCb]

- But also in this case the most interesting effects are the deviations from the SM in appropriate μ/e "clean" LFU ratios:

$$R_H = \frac{\int d\Gamma(B \to H\,\mu\mu)}{\int d\Gamma(B \to H\,ee)}$$



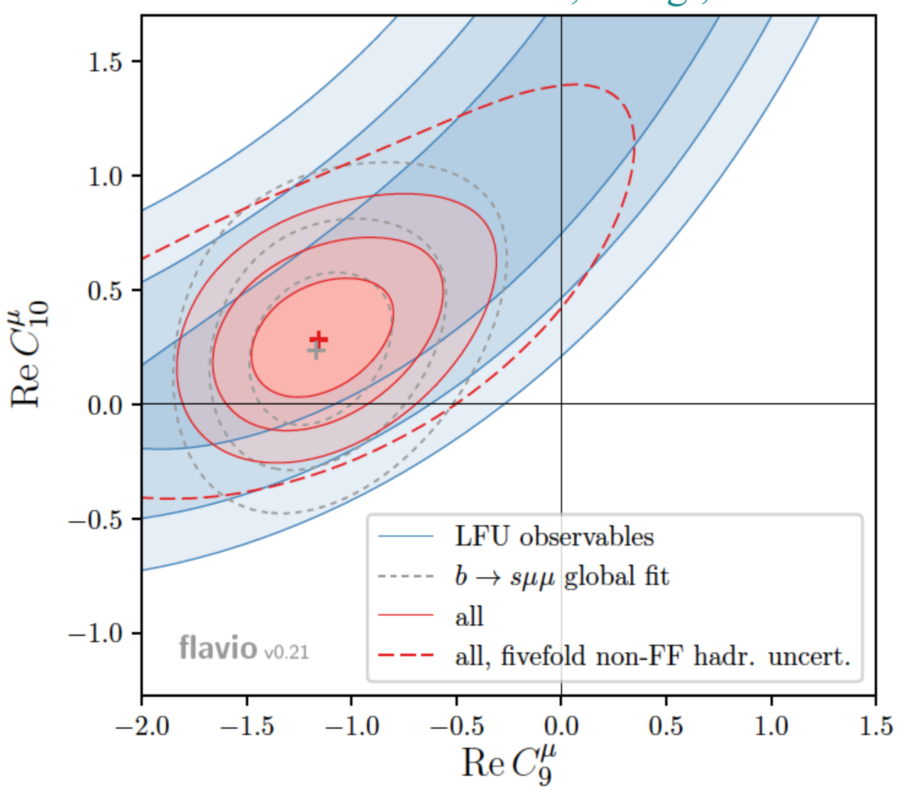


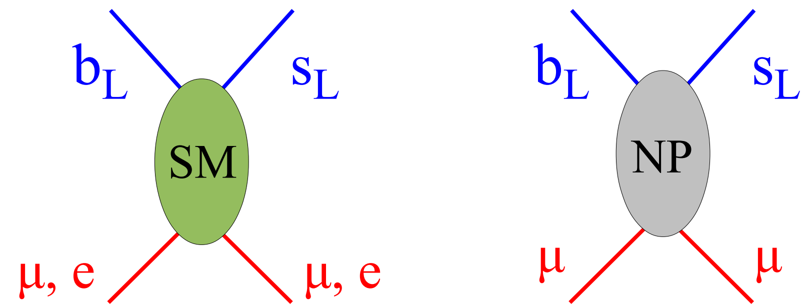
Overall significance ~ 3.8σ
(*LFU ratios only*)

Anomalies in B → $K^{(*)}$ μμ / ee [LHCb]

Reduced tension in all the observables (LFU violation + BR's + angular distribut.] with a unique (and simple) set of non-standard short-distance contributions:

Altmannshofer, Stangl, Straub '17





$$\mathcal{O}_9 = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

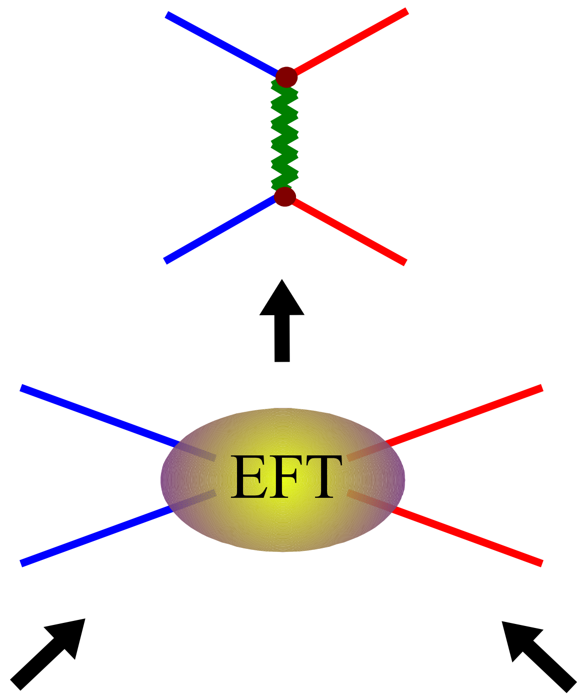
$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

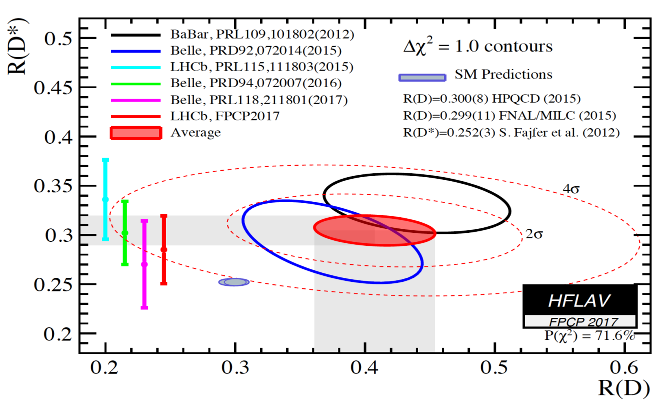
Also consistent with:

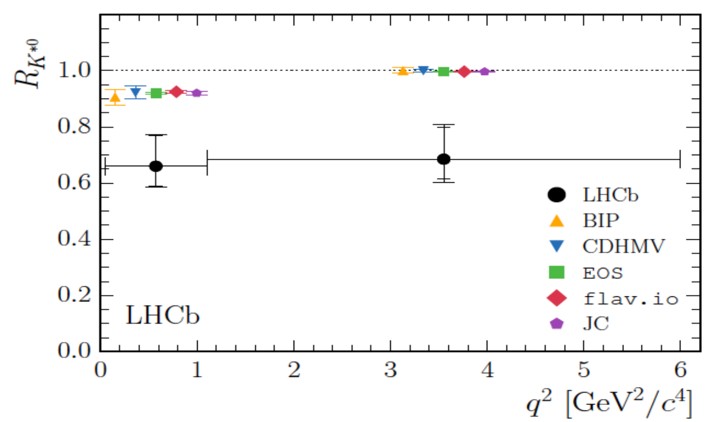
$$\mathrm{BR}(B_s \to \mu\mu)_{SM} = (\,3.57 \pm 0.17\,) \times 10^{-9}$$
$$\mathrm{BR}(B_s \to \mu\mu)_{exp} = (\,2.65 \pm 0.43\,) \times 10^{-9}$$

- All effects well described by NP of short-distance origin only in b→sμμ and (& not in ee)
- LH structure on the quark side largely favored

Bottom-up approaches to describe the anomalies

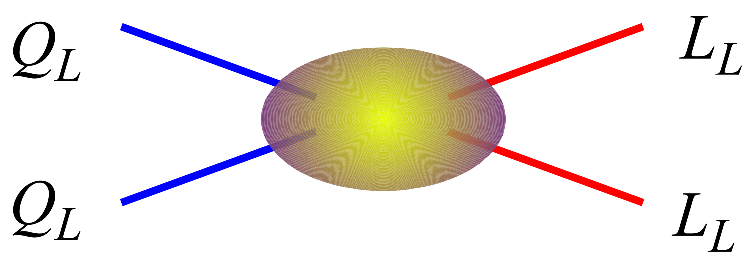






Effective Field Theory considerations

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- Data largely favor non-vanishing left-handed current-current operators [*Fermi-like effective theory*], although other contributions are also possible



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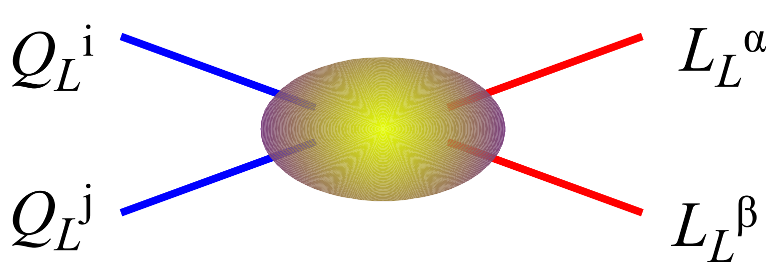

- Large coupling (competing with SM tree-level) in bc → $l_3\, \nu_3$
- Small non-vanishing coupling (competing with SM FCNC) in bs → $l_2\, l_2$

$C_{ij\alpha\beta} \propto (\delta_{i3}\times\delta_{3j})\times(\delta_{\alpha3}\times\delta_{3\beta})$ + small terms for 2nd (& 1st) generations

Link to pattern of the Yukawa couplings !

Effective Field Theory considerations

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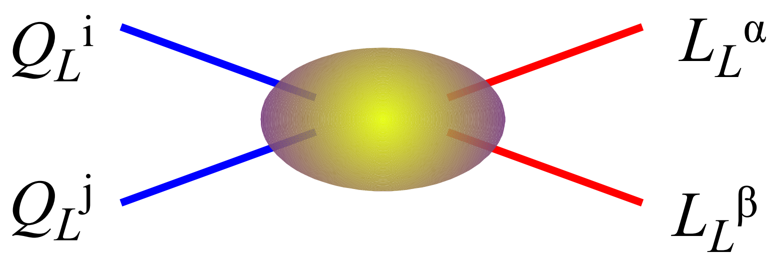
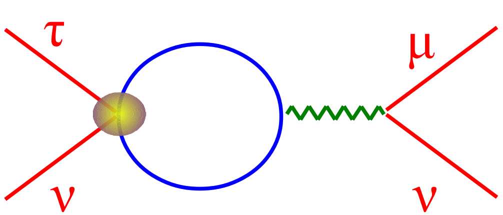
- Data largely favor non-vanishing left-handed current-current operators [*Fermi-like effective theory*], although other contributions are also possible

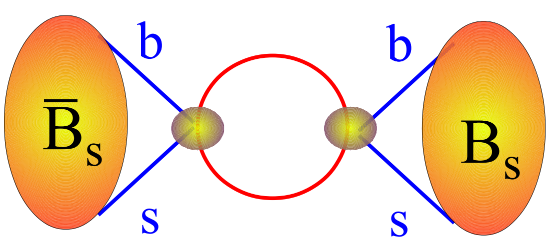


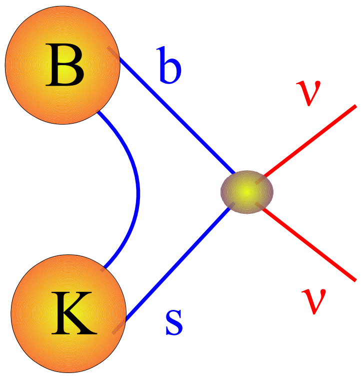
→ *Long list of constraints* from other low-energy processes

E.g:



Feruglio, Paradisi, Pattori '16





Calibbi, Crivellin, Ota, '15
(+many others...)

+ *many more...*

Effective Field Theory considerations

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
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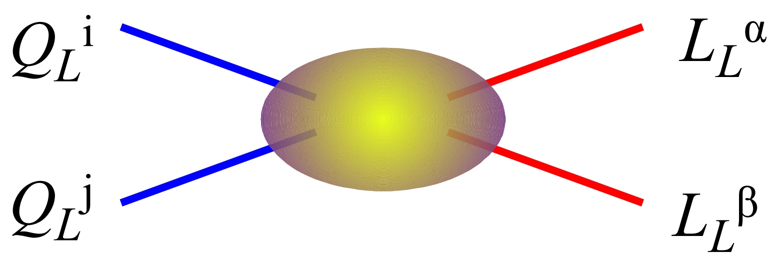


→ *Long list of constraints* from other low-energy processes

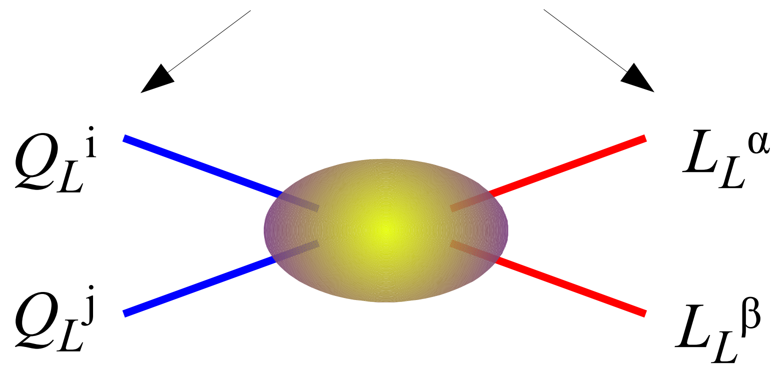
⬇

Essential role of *flavor symmetries*, not only to explain the pattern of the anomalies, but also to "protect" against too large effects in other low-energy observables

▶ *EFT-type considerations* [*The* U(2)^{n} *flavor symmetry*]

A very good candidate to address both these issues (link with the origin of the Yukawa couplings + compatibility with other low-energy data) is a flavor symmetry of the type

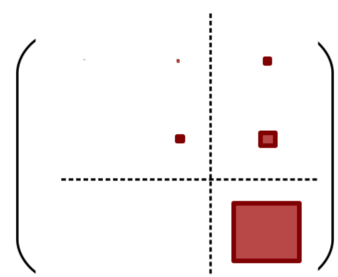
$$G_{\text{flav}} \supset U(2)_q \times U(2)_l$$



i.e. a (chiral flavor) symmetry acting only on the two "light" generations inspired by the structure observed in the Yukawa couplings:

$$\mathscr{L}_Y = Q_L{}^i \, Y_U{}^{ij} U_R{}^j \, \phi$$

$$Y_U = y_t \begin{array}{c} \scriptstyle U(2)_u \\ \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \end{array} \xleftarrow{} U(2)_q \quad \longrightarrow \quad \begin{bmatrix} \Delta & V \\ 0 & 1 \end{bmatrix} \equiv$$

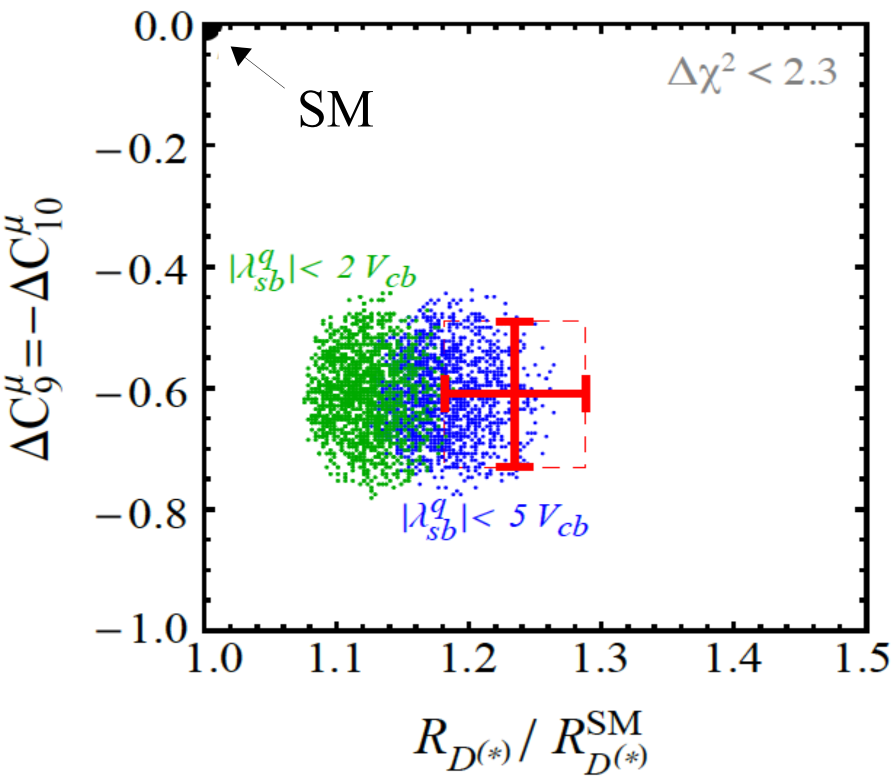


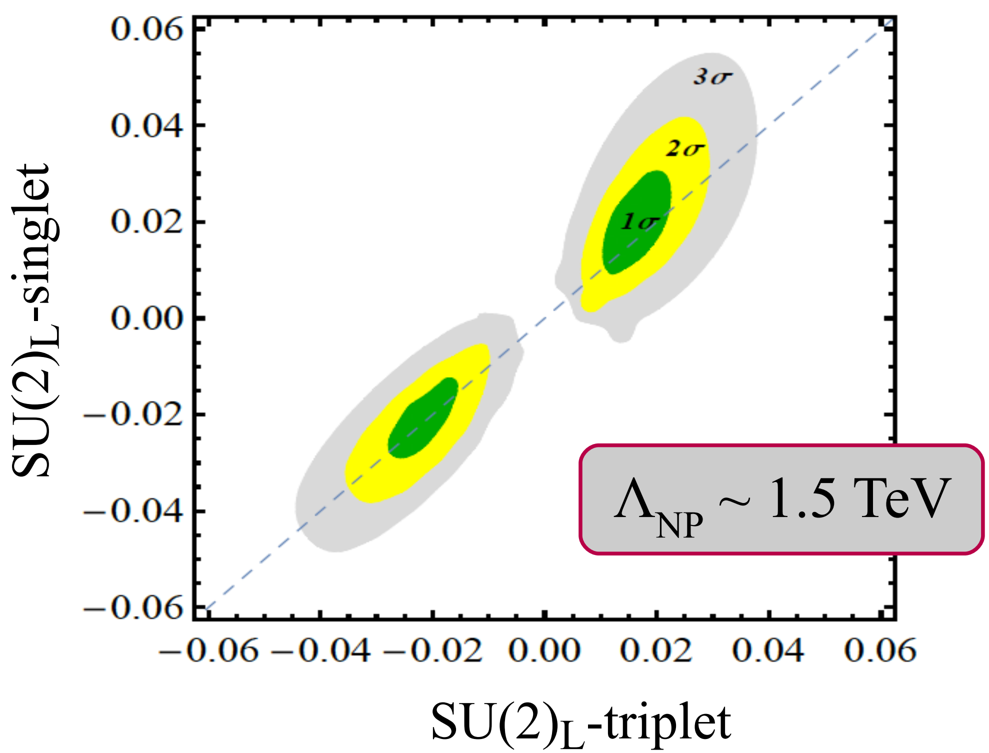
unbroken symmetry *breaking terms*

▸ EFT-type considerations [*"The Zurich's guide"*]

Adopting the $U(2)_q \times U(2)_l$ symmetry, with Yukawa-type breaking pattern, as guiding principle for the EFT describing the anomalies, leads to a good fit to all available data:

Buttazzo Greljo, GI, Marzocca '17





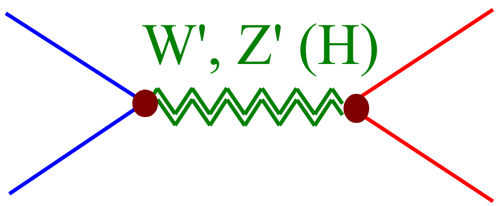
The virtue of this EFT analysis is the demonstration that is possible to find a "combined" (*motivated*) explanation of the two set of anomalies.

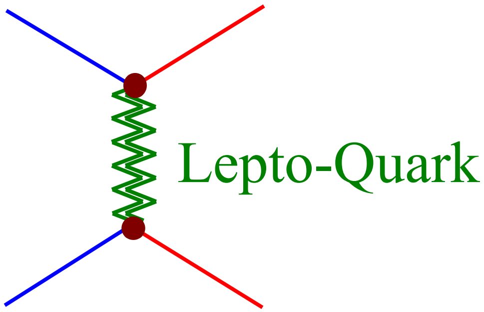
- ***Simplified dynamical models*** [*"The Return of the LeptoQuark"...*]

If we ask which tree-level mediators can generate the effective operators required by the EFT fit, we have not many possibilities...

Three main options
(*for the combined explanation*):

	$SU(2)_L$ singlet	$SU(2)_L$ triplet
Vector LQ:	U_1	U_3
Scalar LQ:	S_1	S_3
Colorless vector:	B'	W'





Simplified dynamical models [*"The Return of the LeptoQuark"*...]

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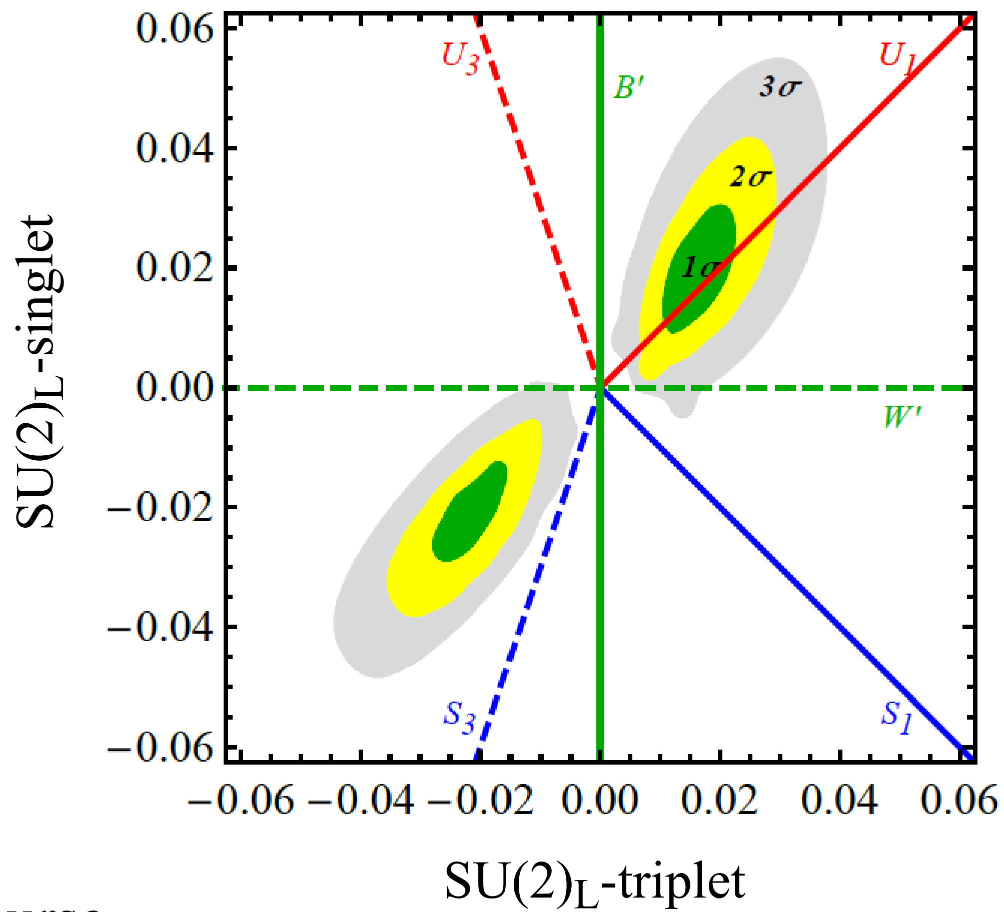


The U_1 option fits quite nicely... but of course models with more than one mediators are possible

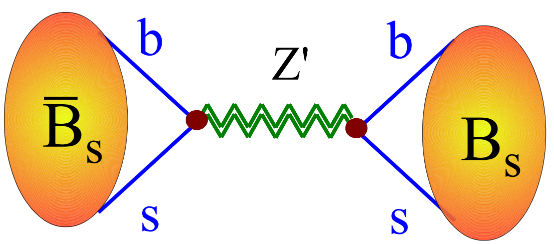
Simplified dynamical models [*"The Return of the LeptoQuark"...*]

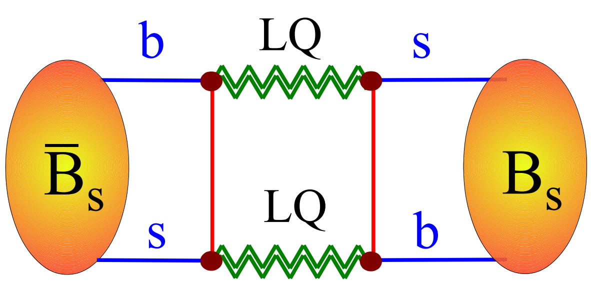
If we ask which tree-level mediators can generate the effective operators required by the EFT fit, we have not many possibilities...

Three main options
(*for the combined explanation*):

	$SU(2)_L$ singlet	$SU(2)_L$ triplet
Vector LQ:	U_1	U_3
Scalar LQ:	S_1	S_3
Colorless vector:	B'	W'

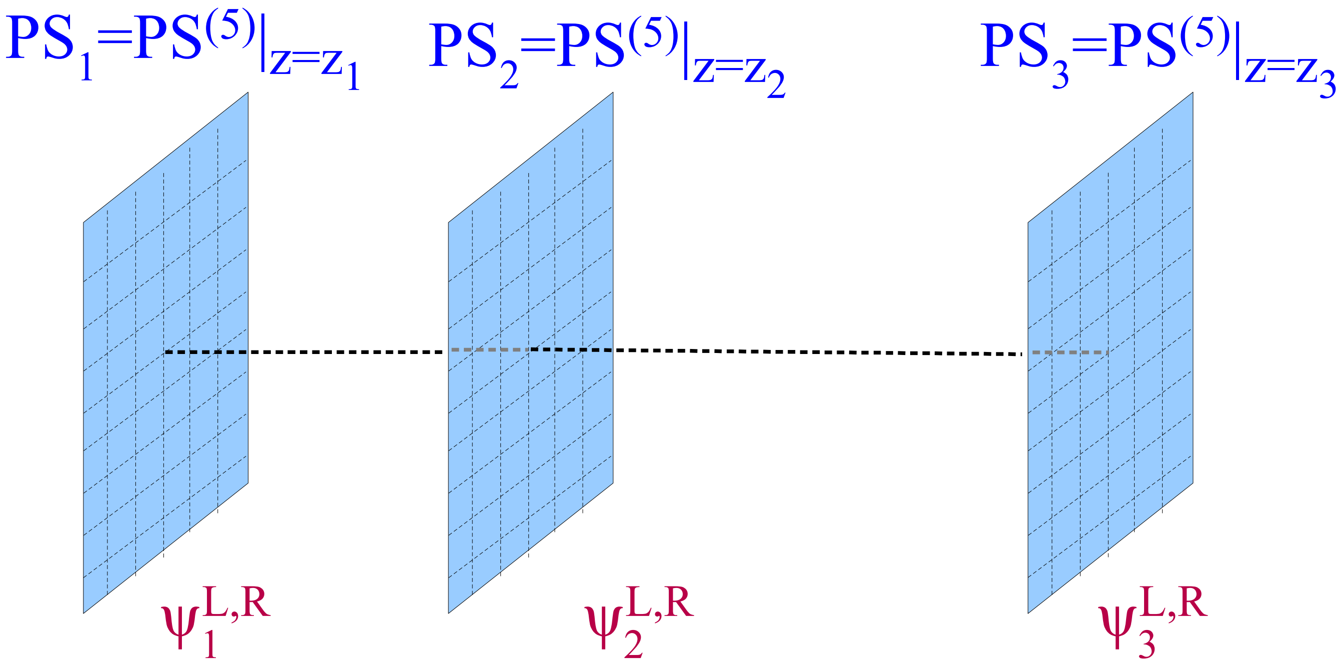
Most important: LQ (both scalar and vectors) have an <u>additional</u> clear advantage concerning constraints from non-semileptonic processes:





Similarly, 3rd gen. LQ are in very good shape also as far as direct searches are concerned (*contrary to Z'...*):

Speculations on UV completions



Speculations on UV completions

Two main approaches

Non-perturbative
TeV-scale dynamics
[*non-renormalizable models*]

Perturbative
TeV-scale dynamics
[*renormalizable models*]

Long list of interesting attempts in the recent literature, not worth (*and practically impossible*) to cover them all.

In the following I will now concentrate on one (class of) option(s) that I find particularly interesting.

Speculations on UV completions

Starting observation: a gauge theory proposed in the 70's to unify quarks and leptons by Pati & Salam predicts a massive vector LQ with the correct quantum numbers to fit the anomalies (*best single mediator*):

Pati-Salam group: $SU(4)\times SU(2)_L\times SU(2)_R$

Fermions in SU(4): $\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix} \quad \begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$

Main Pati-Salam idea:
Lepton number as "the 4th color"

The massive LQ [U_1] arise from the breaking $SU(4) \to SU(3)_C\times U(1)_{B-L}$

$$SU(4) \sim \left[\begin{array}{c|c} SU(3)_C & 0 \\ \hline 0 & 0 \end{array}\right] \quad \left[\begin{array}{c|c} 0 & LQ \\ \hline LQ & \end{array}\right] \quad \left[\begin{array}{c|c} \frac{1}{3} & 0 \\ \hline 0 & -1 \end{array}\right]$$

Speculations on UV completions

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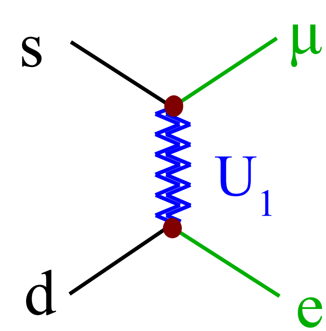
The massive LQ [U_1] arise from the breaking $SU(4) \rightarrow SU(3)_C\times U(1)_{B-L}$

The problem of the "original PS model" are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 200$ TeV from $K_L \rightarrow \mu e$]

→ we must go beyond the original model



The PS^3 *model*

$$[\ \mathrm{PS}\ ]^3 = [\ \mathrm{SU(4)}\times \mathrm{SU(2)_L}\times \mathrm{SU(2)_R}\ ]^3$$

Bordone, Cornella, Fuentes-Martin, GI, '17

Main idea: at high energies the 3 families are charged under 3 independent gauge groups (*gauge bosons carry a flavor index !*)

UV

PS_1 $\psi_1^{L,R}$ PS_2 $\psi_2^{L,R}$ PS_3 $\psi_3^{L,R}$

Unification of quarks and leptons
[natural explanation for $\mathrm{U(1)_Y}$ charges]

"De-unification" (= *flavor deconstruction*)
of the gauge symmetry

SM

IR

$Q_i,\ u_i,\ d_i,\ L_i,\ e_i$

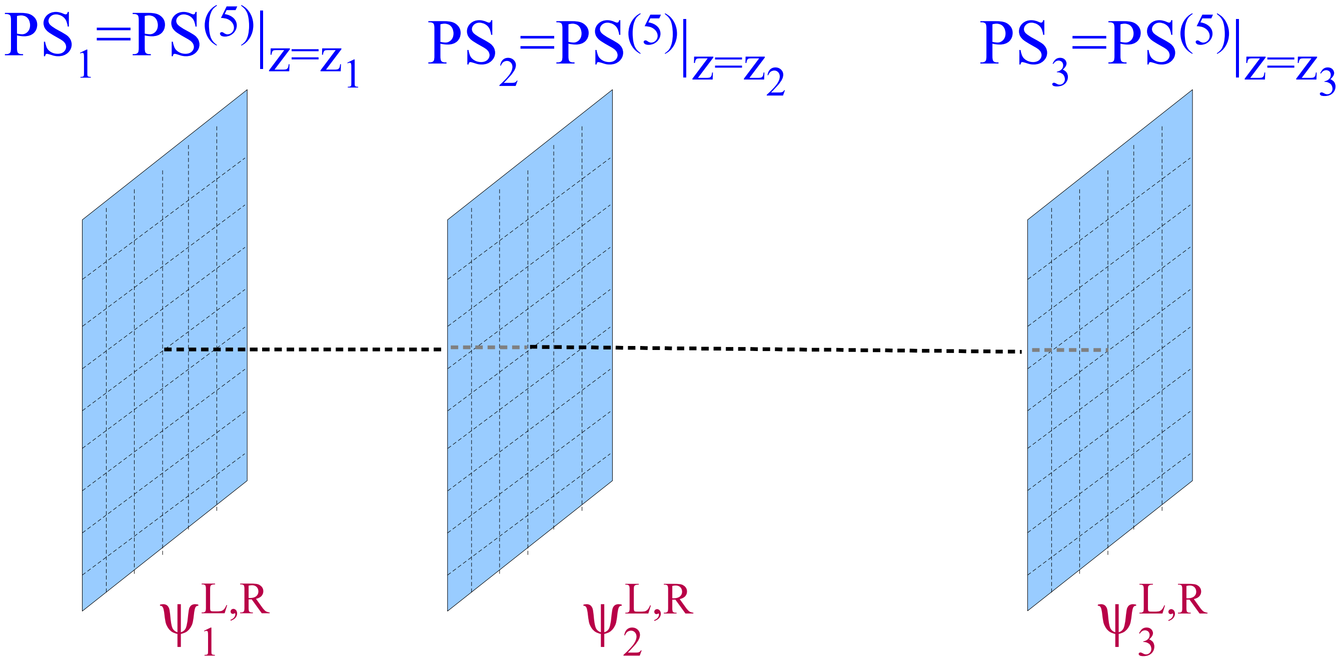
Key advantages:

- Light LQ coupled mainly to 3rd gen.
- Accidental $\mathrm{U(2)}^5$ flavor symmetry
- Natural structure of SM Yukawa couplings

The PS^3 *model*

$$[\ \mathrm{PS}\ ]^3 = [\ SU(4)\times SU(2)_L \times SU(2)_R\ ]^3$$

Bordone, Cornella, Fuentes-Martin, GI, '17



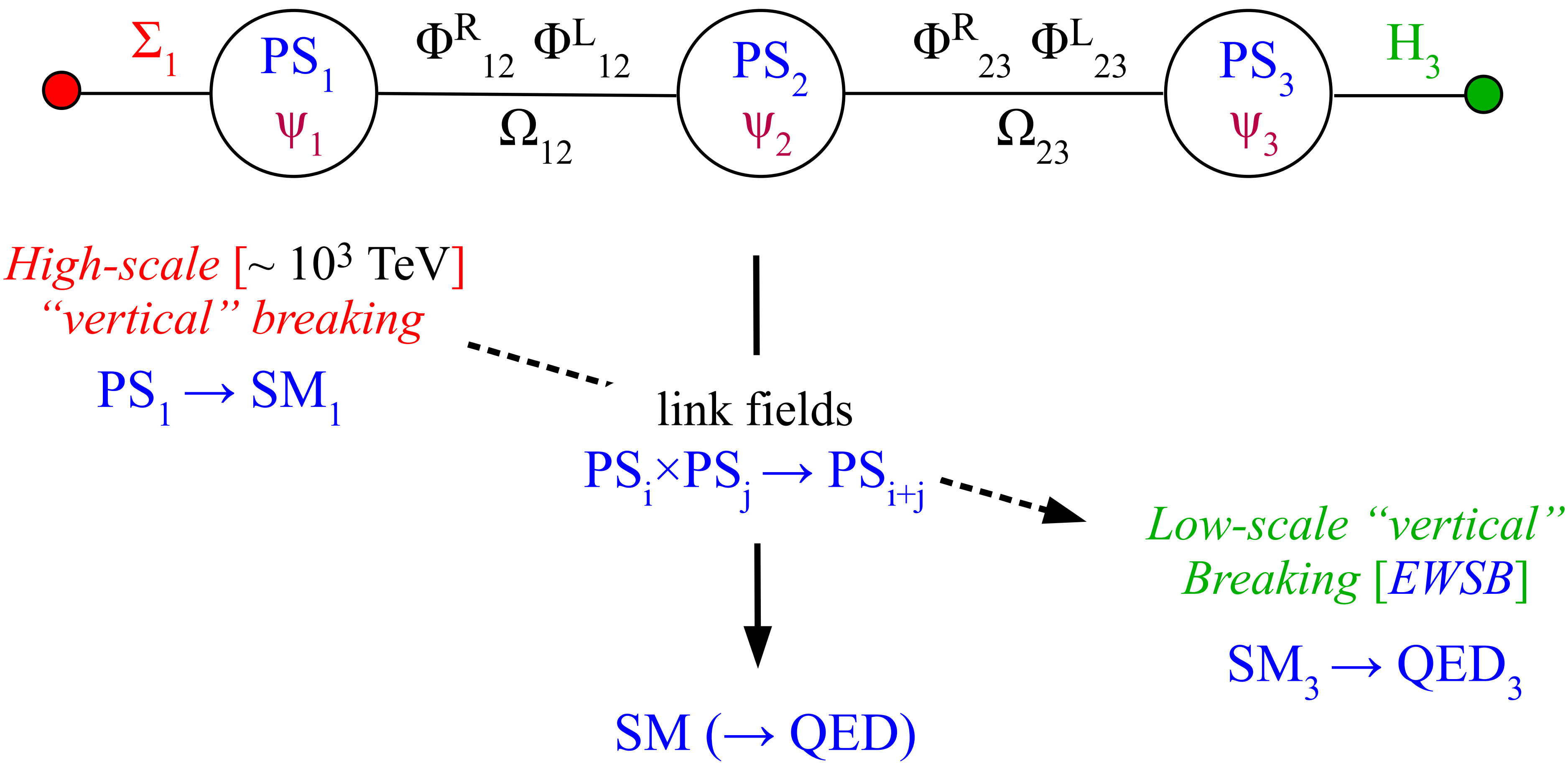
Unification
of quarks and leptons

"De-unification"
(= *flavor deconstruction*)
of the gauge symmetry

This construction can find a "natural" justification in the context of models with extra space-time dimensions

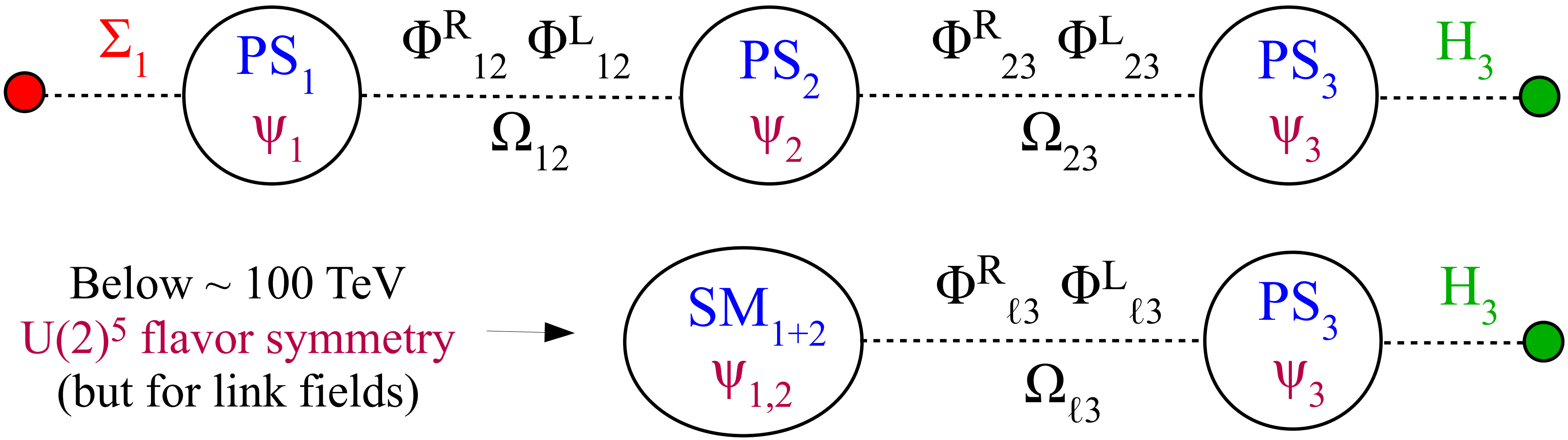
The 4D description is apparently more complex, but it allow us to derive precise low-energy phenomenological signatures (*4D renormalizable gauge model*)

The PS^3 *model*



- The breaking to the diagonal SM group occurs via appropriate "link" fields, responsible also for the generation of the hierarchy in the Yukawa couplings.
- The 2-3 breaking gives a TeV-scale LQ [+ Z' & G'] coupled mainly to 3rd gen.

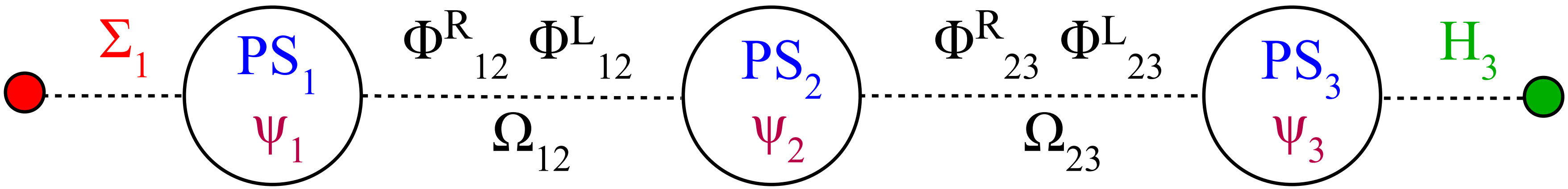
The PS^3 *model*



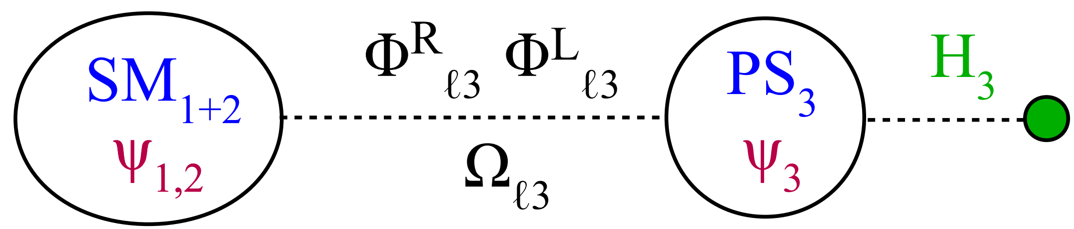
Leading flavor structure:

- Yukawa coupling for 3rd gen. only
- "Light" LQ field (from PS$_3$) coupled only to 3rd gen.
- U(2)^5 symmetry protects flavor-violating effects on light gen.

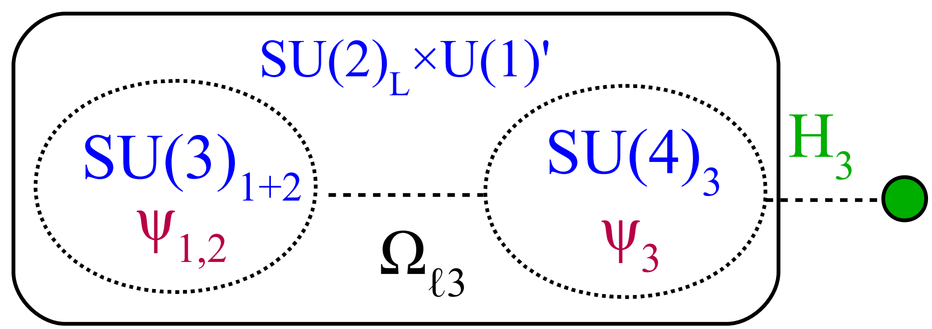
The PS^3 *model*



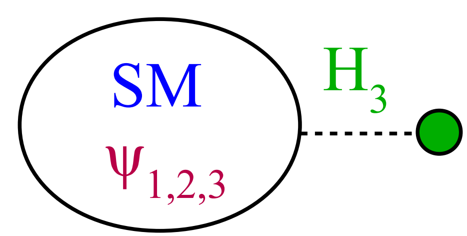
Below ~ 100 TeV
U(2)^5 flavor symmetry
(but for link fields)



$\rightarrow$ $W_L' + W_R'$ [~ 5-10 TeV]



$\rightarrow$ LQ [U_1] + Z' + G' [~ 1-2 TeV]



Sub-leading Yukawa terms from higher dim ops:

$$Y_U = \begin{bmatrix} \Delta & V \\ & y_t \end{bmatrix}$$

$$\frac{\langle \Phi^R_{\ell 3} \Phi^L_{\ell 3} \rangle}{(\Lambda_{23})^2} \qquad \frac{\langle \Omega_{\ell 3} \rangle}{\Lambda_{23}}$$

The PS^3 *model*

Collider phenomenology and flavor anomalies are controlled by the last-but one step in the breaking chain.

Despite the apparent complexity, the construction is highly constrained:

$$SU(4)_3 \times SU(3)_{1+2} \times [\, SU(2)_L \times U(1)' \,]$$
$$\psi_3 \qquad \psi_{1,2}$$

$$\Big\downarrow \langle \Omega_{\ell 3} \rangle \quad \rightarrow \text{LQ } [U_1] + Z' + G' \quad [\sim 1\text{-}3 \text{ TeV}]$$

$$\text{SM}$$
$$\psi_{1,2,3}$$

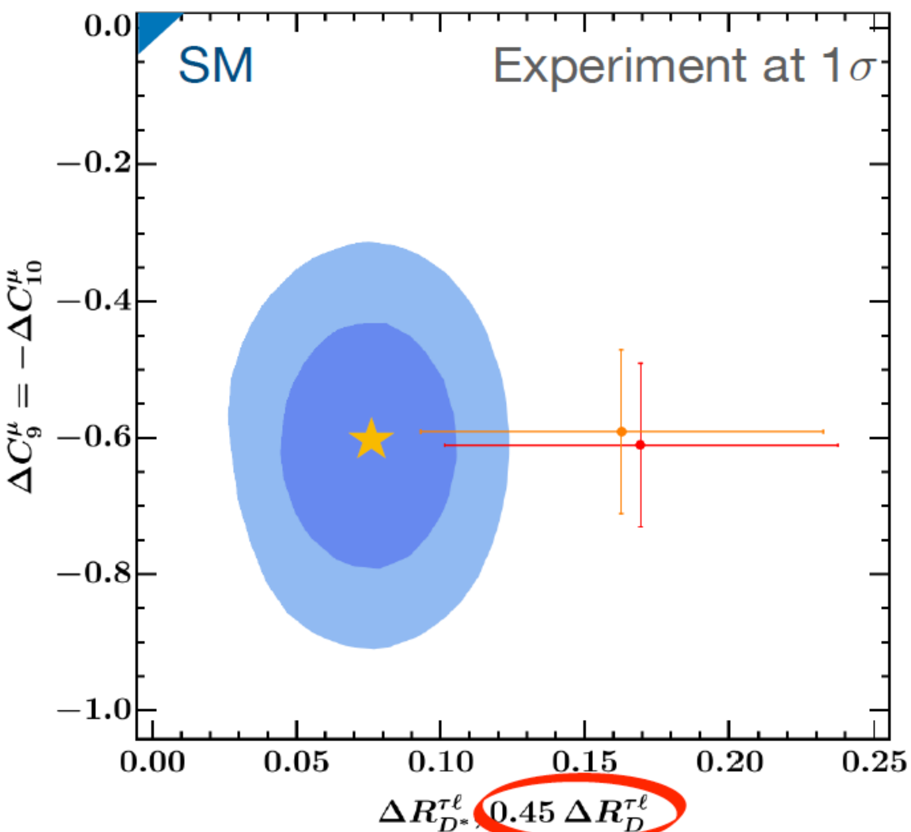
Quark flavor structure determined up to an angle (→ *degree of alignment to d-quark mass basis*)

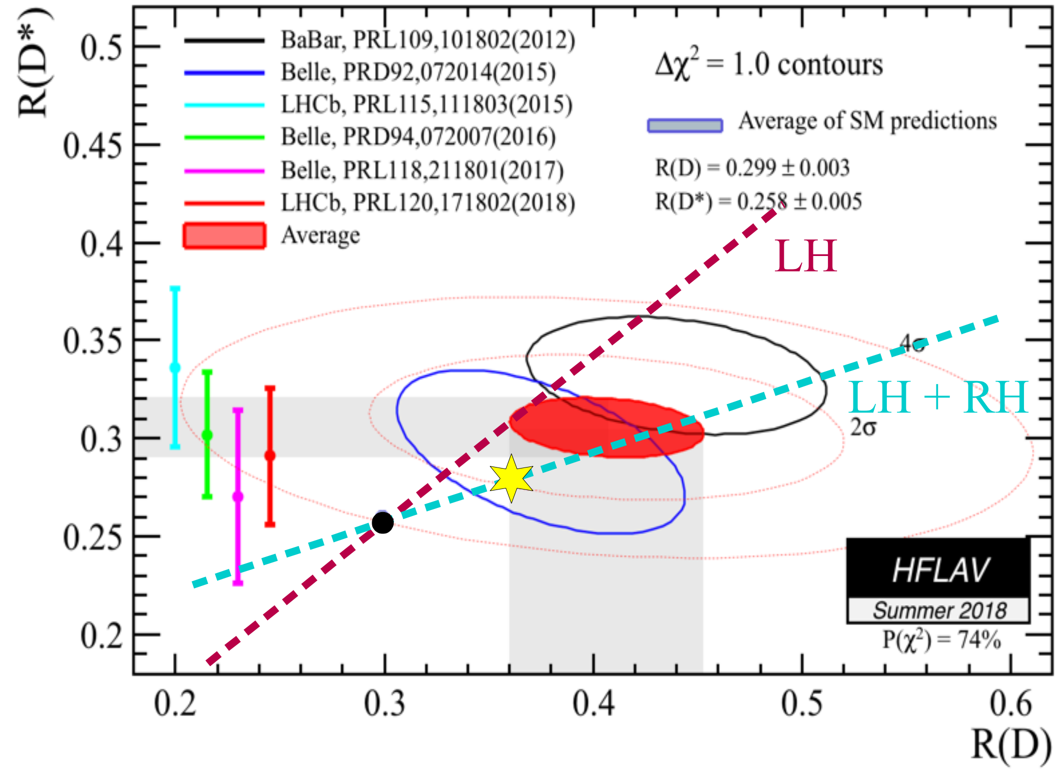
Key difference to all existing pheno models: unsupressed b_R-τ_R coupling of the LQ

The PS³ *model*

Collider phenomenology and flavor anomalies are controlled by the last-but one step in the breaking chain.

Despite the apparent complexity, the construction is highly constrained

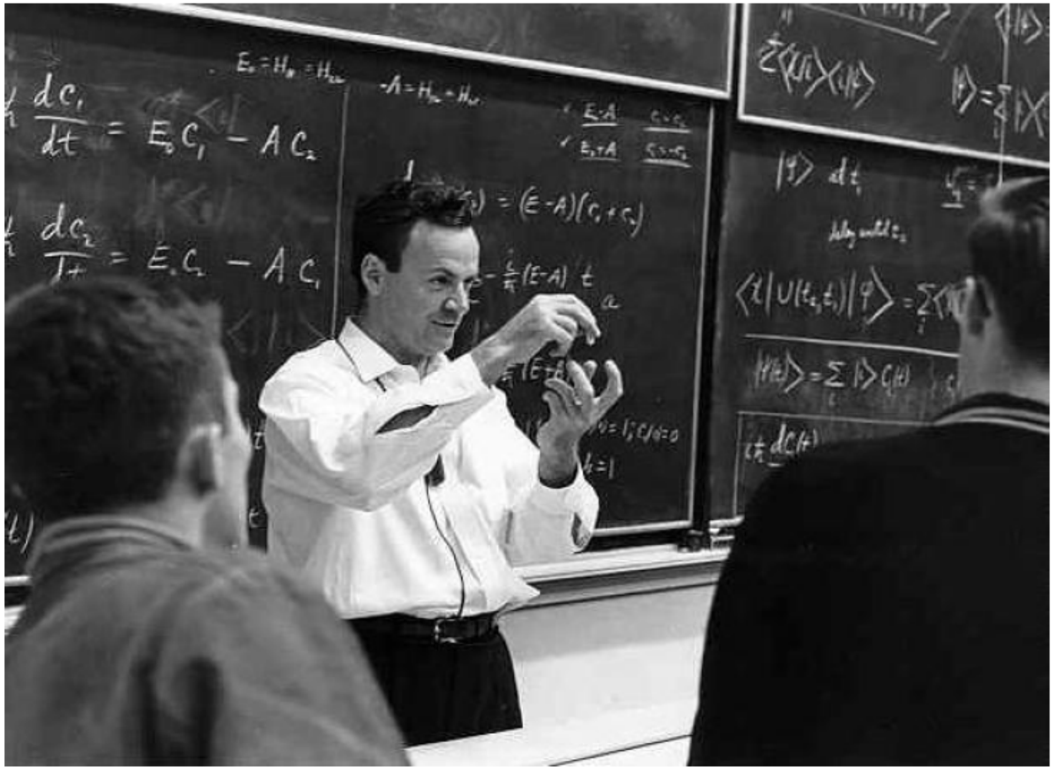




The fit to low-energy data is very good

(*although slightly smaller NP effects in R_D, mainly because of radiative constraints*)

Possible future implications



"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." [Feynman]

Implications for low-energy flavor physics

If the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables

Main message: "super-reach" flavor program for LHCb, but also other flavor physics facilities (Belle-II, Kaons, CLFV)

- This program is essential to determine the flavor structure of the new sector
- Correlations among low-energy obs. can be studied by means of EFT

  and already with low-energy data we could rule-out many models...

Implications for low-energy flavor physics

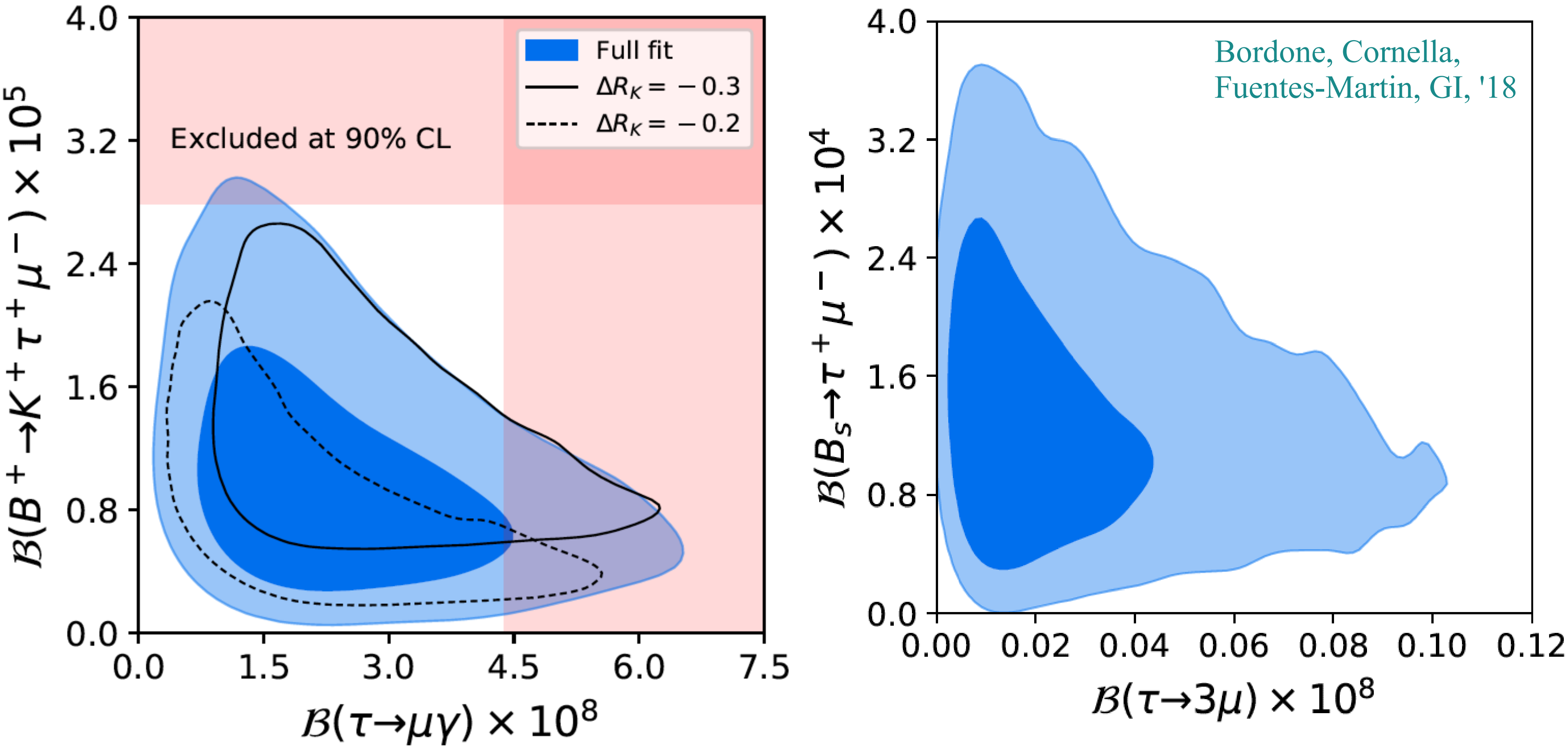
If the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables

E.g.: correlations among down-type FCNCs [*using the results of* U(2)-*based EFT*]:

	$\mu\mu$ (ee)	$\tau\tau$	$\nu\nu$	$\tau\mu$	μe
$b \to s$	R_K, R_{K^*} O(20%)	$B \to K^{(*)} \tau\tau$ $\to$ 100×SM	$B \to K^{(*)} \nu\nu$ O(1)	$B \to K \tau\mu$ $\to \sim 10^{-5}$	$B \to K \mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi \mu\mu$ $B_s \to K^{(*)} \mu\mu$ O(20%) [$R_K = R_\pi$]	$B \to \pi \tau\tau$ $\to$ 100×SM	$B \to \pi \nu\nu$ O(1)	$B \to \pi \tau\mu$ $\to \sim 10^{-7}$	$B \to \pi \mu e$???
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi \nu\nu$ O(1)	*NA*	$K \to \mu e$???

Implications for low-energy flavor physics

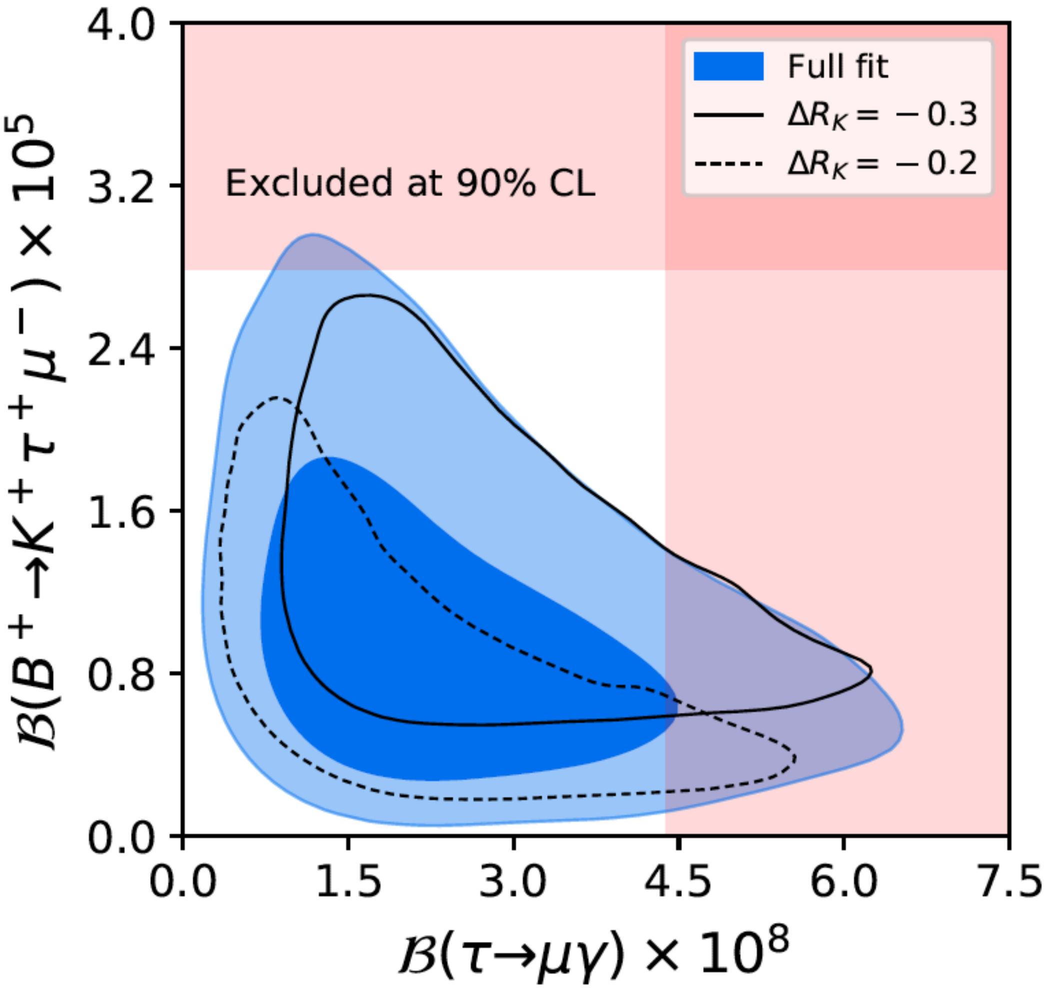
E.g: expectation of LFV processes in the PS^3 model:



$$\left(\frac{\Delta R_D}{0.2}\right)^2 \left(\frac{\Delta R_K}{0.3}\right)^2 \approx 3 \left[\frac{\mathcal{B}(B \to K\tau^+\mu^-)}{3 \times 10^{-5}}\right] \left[\frac{\mathcal{B}(\tau \to \mu\gamma)}{5 \times 10^{-8}}\right] \approx \left[\frac{\mathcal{B}(B_s \to \tau^\pm\mu^\mp)}{2 \times 10^{-4}}\right] \left[\frac{\mathcal{B}(\tau \to \mu\gamma)}{5 \times 10^{-8}}\right]$$

Implications for low-energy flavor physics

E.g: expectation of LFV processes in the PS^3 model:



More difficult to make precise predictions for $\mu \to$ e transitions.

But both $\mu \to 3e$ and $K_L \to \mu e$ could be quite close to their present exp. bounds:

BR($\mu \to 3e$) $\to$ few 10^{-14}

BR($K_L \to \mu e$) $\to$ few 10^{-12}

$$\left(\frac{\Delta R_D}{0.2}\right)^2 \left(\frac{\Delta R_K}{0.3}\right)^2 \approx 3\left[\frac{\mathcal{B}(B \to K\tau^+\mu^-)}{3\times 10^{-5}}\right]\left[\frac{\mathcal{B}(\tau \to \mu\gamma)}{5\times 10^{-8}}\right] \approx \left[\frac{\mathcal{B}(B_s \to \tau^\pm\mu^\mp)}{2\times 10^{-4}}\right]\left[\frac{\mathcal{B}(\tau \to \mu\gamma)}{5\times 10^{-8}}\right]$$

Implications for high-p_T physics

Some general considerations:

Independently of the details of the UV models, the anomalies (and particularly the $b \to c$ one) point to NP in the ball-park of direct searches @ LHC

This NP could have escaped detection so far only under specific circumstances (*that are fulfilled by the proposed UV completions...*):

- Coupled mainly to 3rd generation (→ *no large coupl. to proton valence quarks*)
- No narrow peaks in dilepton pairs (*including tau pairs*)

⬇

Significant room for improvement for the corresponding searches @ HL-LHC
But only HE-LHC would be able to rule out all reasonable models

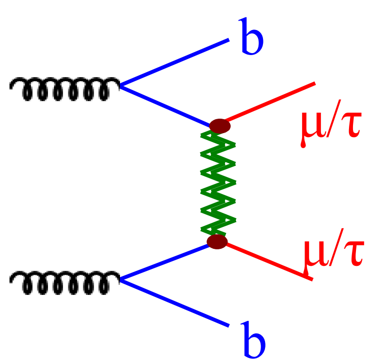
Implications for high-p_T physics

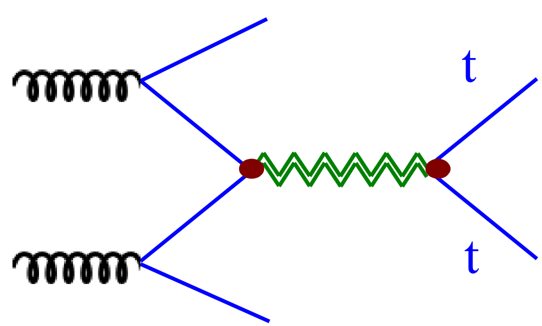
Some general considerations:

Independently of the details of the UV models, the anomalies (and particularly the $b \to c$ one) point to NP in the ball-park of direct searches @ LHC

Most interesting signatures:

- unambiguous (model-independent) prediction of large $pp \to \tau\tau$ & $pp \to \tau\nu$, which is quite close to present sensitivity
- models predicting companions of the LQ coupled to 3rd gen. quark currents (such as Z' or "heavy gluons") lead to large $pp \to tt$, which starts to be in tension with present data

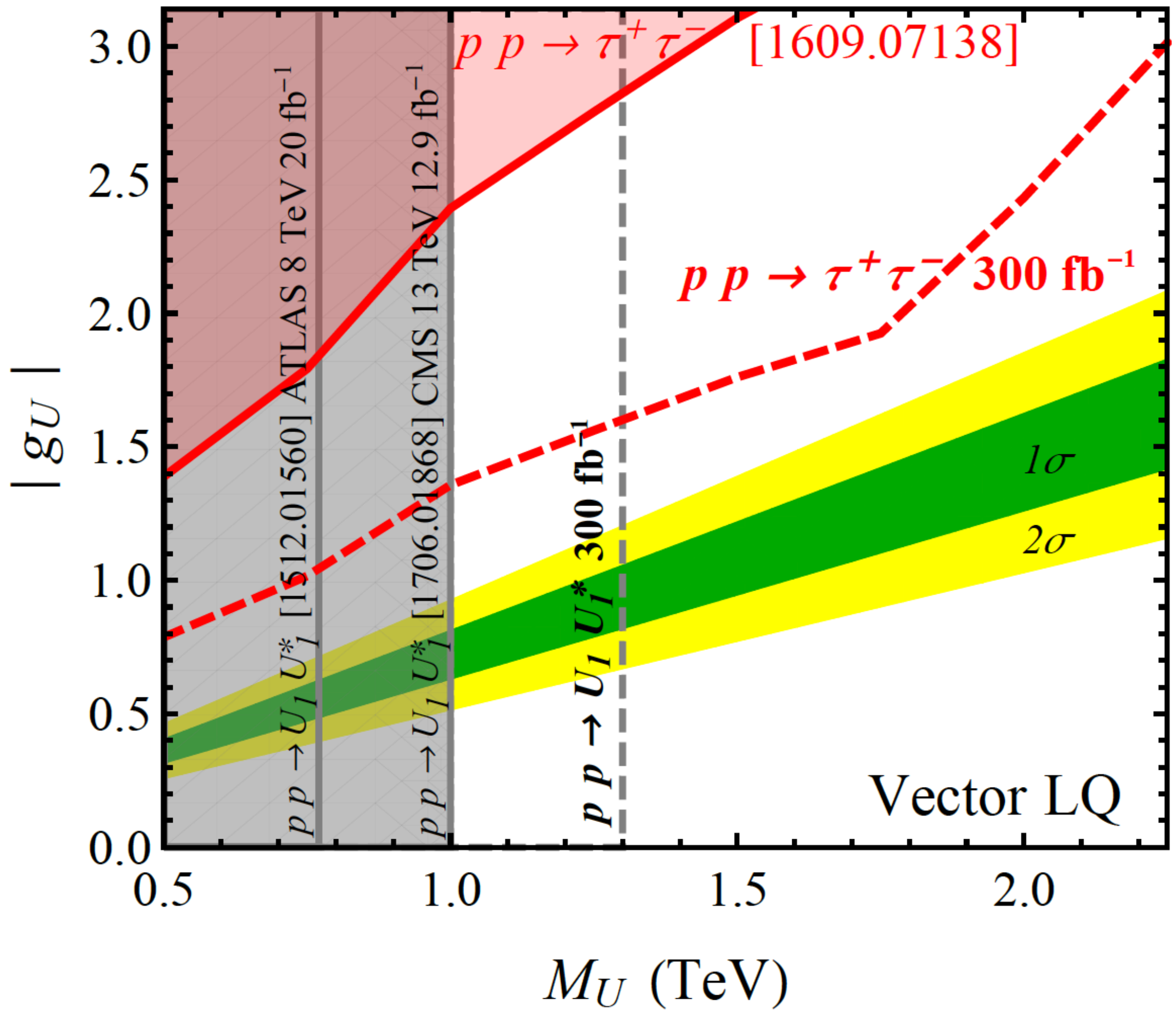


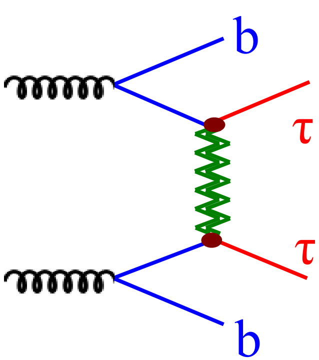


▶ Implications for high-p_T physics

E.g.: pp → ττ from t-channel exchange LQ production
(re-interpretation of ATLAS & CMS ττ resonance search)

Buttazzo *et al.* '17

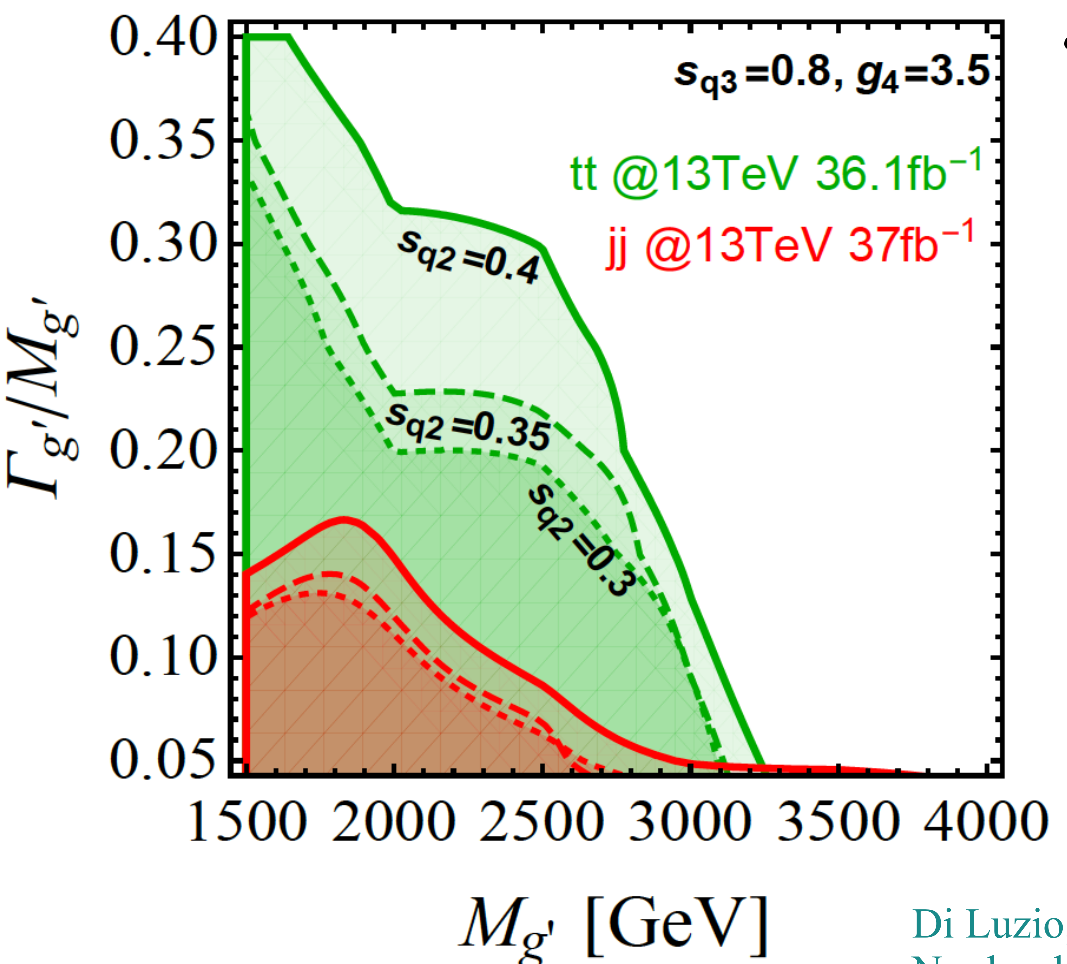




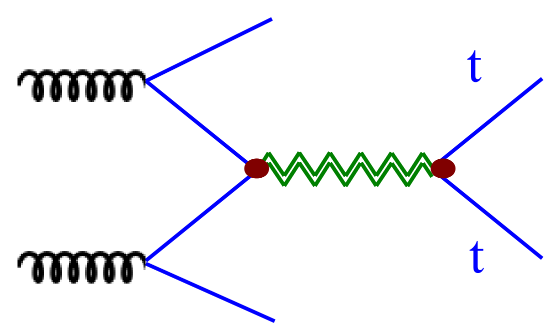
► *Implications for high-p_T physics & neutrino physics*

In specific models, such at the PS[3], the TeV-scale phenomenology involve (several) additional states not directly involved in the anomalies

E.g.: I. The "Coloron" in pp → tt



"Coloron" = "heavy gluon" coupled preferably to 3rd generation

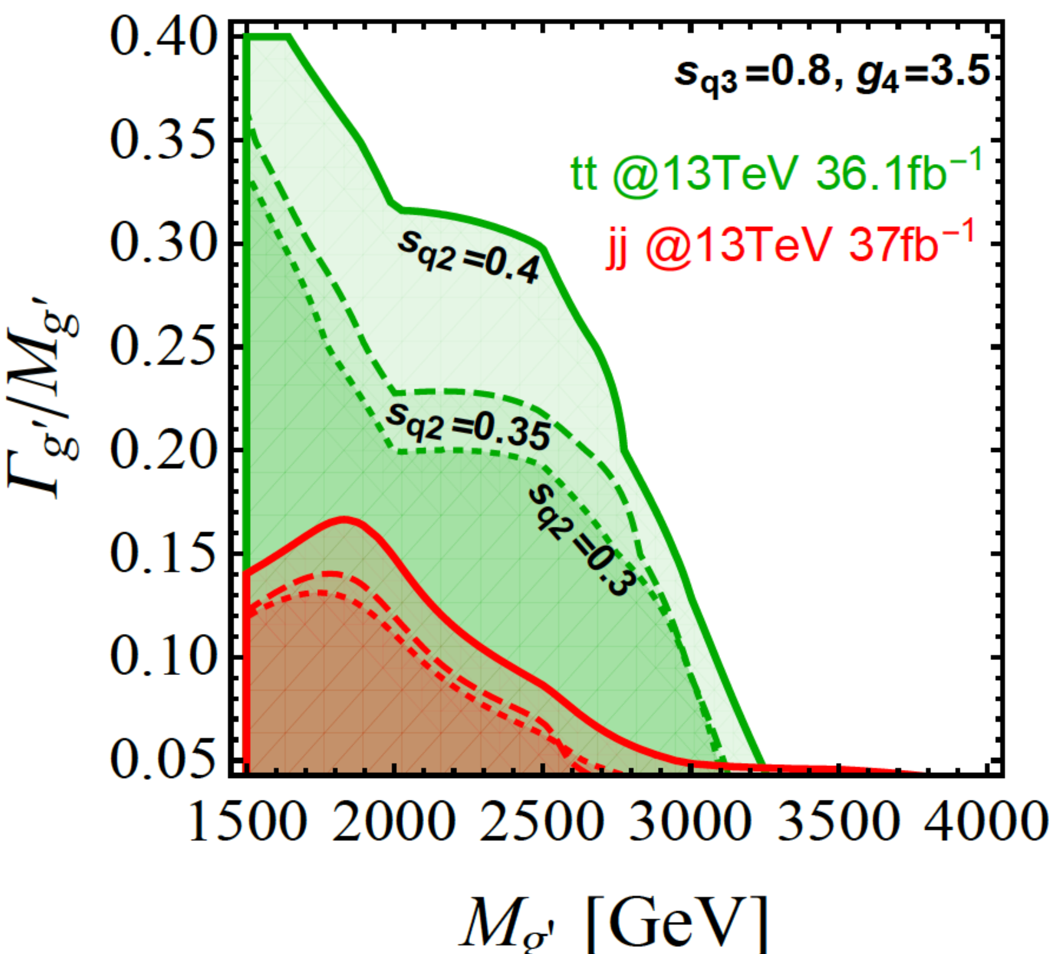


Di Luzio, Fuentes-Martin, Greljo, Nardecchia, Renner '18

▸ Implications for high-p_T physics & neutrino physics

In specific models, such at the PS^3, the TeV-scale phenomenology involve (several) additional states not directly involved in the anomalies

E.g.: I. The "Coloron" in pp → tt



E.g.: II. TeV-scale RH neutrinos

General prediction of TeV-scale PS-like models, where small neutrino masses occurs via the *inverse see-saw*

⬇

Deviations from PMNS unitarity correlated to the B-physics anomalies in the 10^{-6}-10^{-5} range [Greljo, Stefanek '18]

Consistent with (*but not far from…*) present bounds

Conclusions

- If these ~~LFU~~ anomalies are confirmed, it would be a fantastic discovery, with far-reaching implications
- If interpreted as NP signals, both set of anomalies are <u>not in contradiction</u> among themselves & with existing low- & high-energy data. <u>Taken together,</u> they point out to NP coupled mainly to 3rd generation, with a flavor structure connected to that appearing in the SM Yukawa couplings
- Simplified models with LQ states seem to be favored. However, realistic UV completions for these models naturally imply a much richer spectrum of states at the TeV scale (*and possibly above...*) → nearby signatures at high-pT
- The PS^3 model I have presented is an interesting as example of the change of paradigm in model building that these anomalies could imply. But many points/possible-variations remains to be clarified/explored...

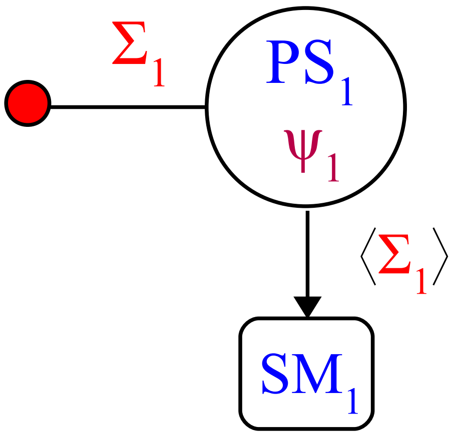
⬇

<u>A lot of fun ahead of us...</u>

(both on the exp., the pheno, and model-building point of view)


Backup

▶ *Symmetry breaking pattern in* PS^3

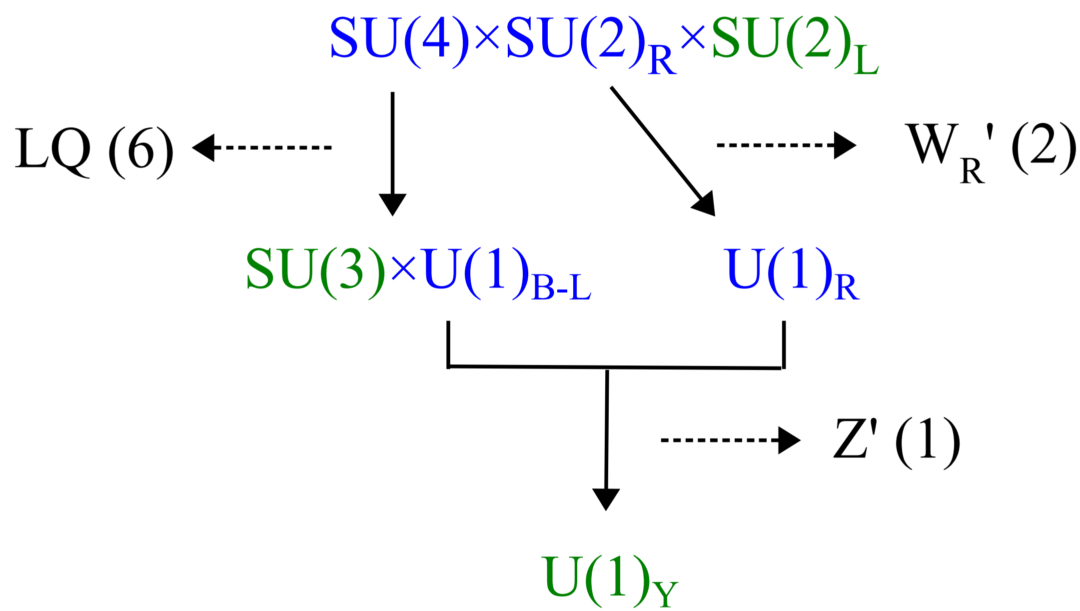


High-scale [$\sim 10^3$ TeV]
"vertical" breaking [PS $\rightarrow$ SM]

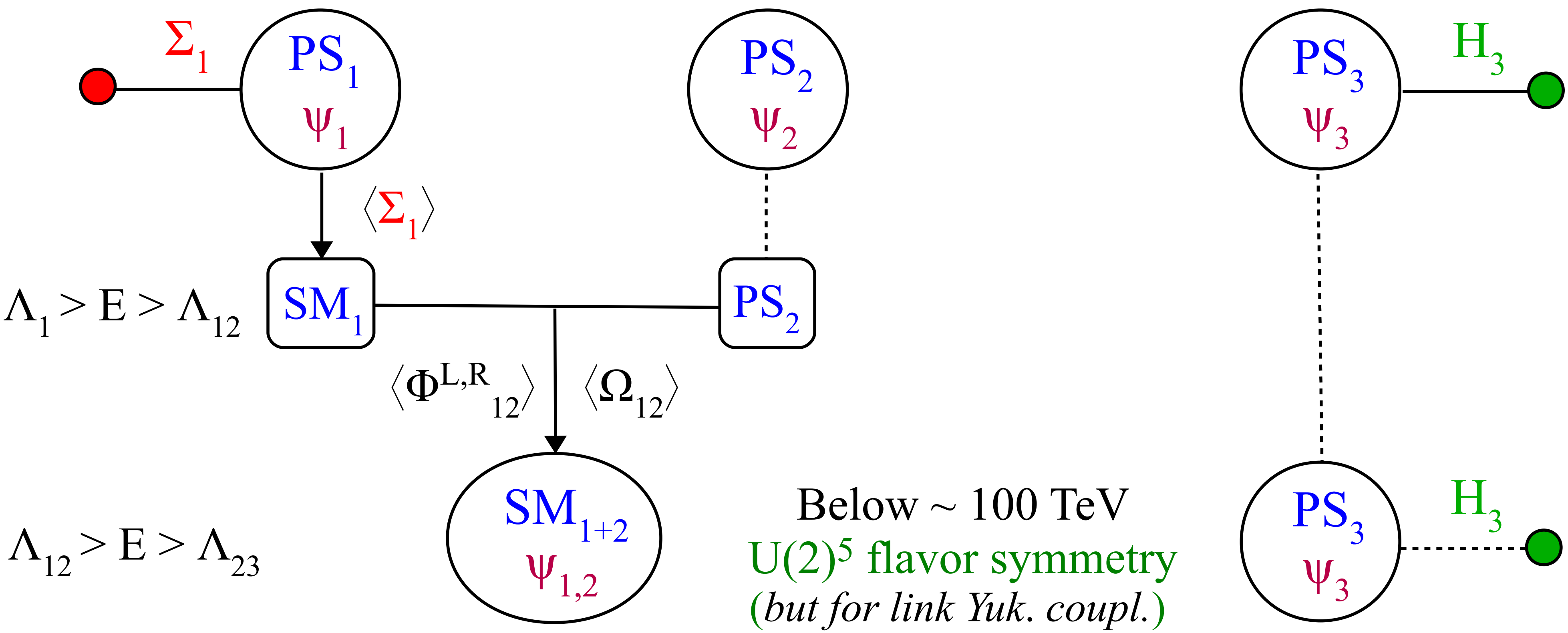
PS_1 [$SU(4)_1 \times SU(2)^R_1$]

$\downarrow$

SM_1 [$SU(3)_1 \times U(1)^Y_1$]



Symmetry breaking pattern in PS^3



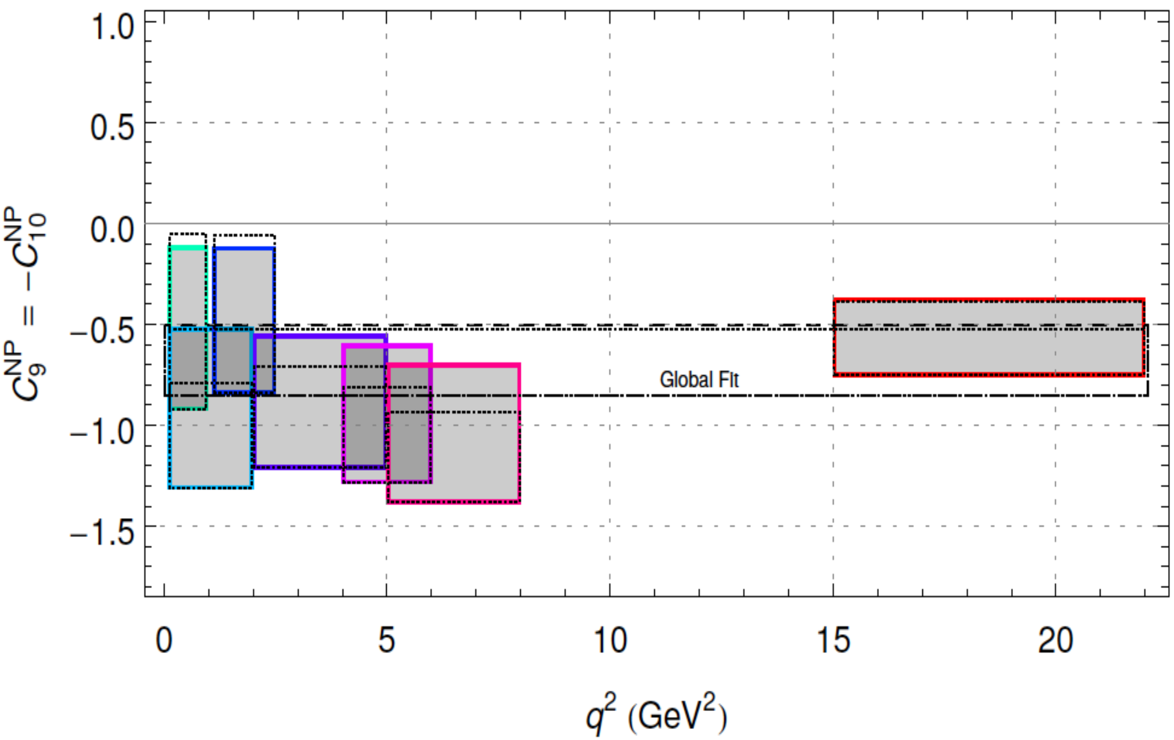
$\Phi^L{}_{12} \sim (1,2,1)_1 \times (1,2,1)_2$ VEV $\to SU(2)^L{}_{1+2}$

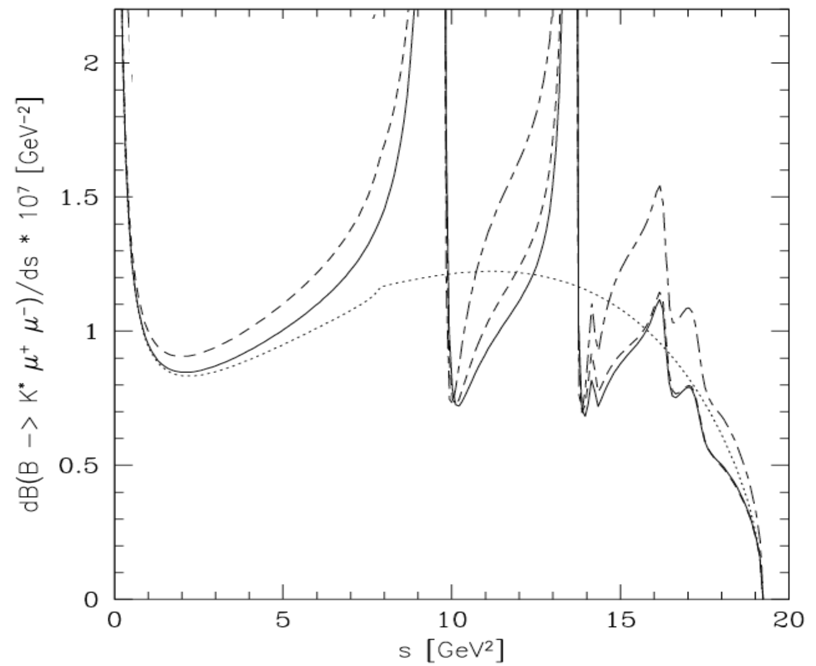
$\Phi^R{}_{12} \sim (1,1,2)_1 \times (1,1,\underline{2})_2$ VEV $\to SU(2)^R{}_{1+2}$

$\Omega_{12} \sim (4,2,1)_1 \times (\underline{4},\underline{2},1)$ VEV $\to SU(4)_{1+2}$ & $SU(2)^L{}_{1+2}$

Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

- Reduced tension in all the observables with a unique fit of non-standard short-distance Wilson coefficients





More precise data on the $q^2=m_{\mu\mu}$ distribution can help to distinguish NP vs. SM

Descotes-Genon, Matias, Virto '15

Anomalies in B → $K^{(*)}$ μμ / ee [LHCb]

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

"dangerous" choice of the bin starting from the di-muon threshold