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Hints of New Physics from flavor-changing processes

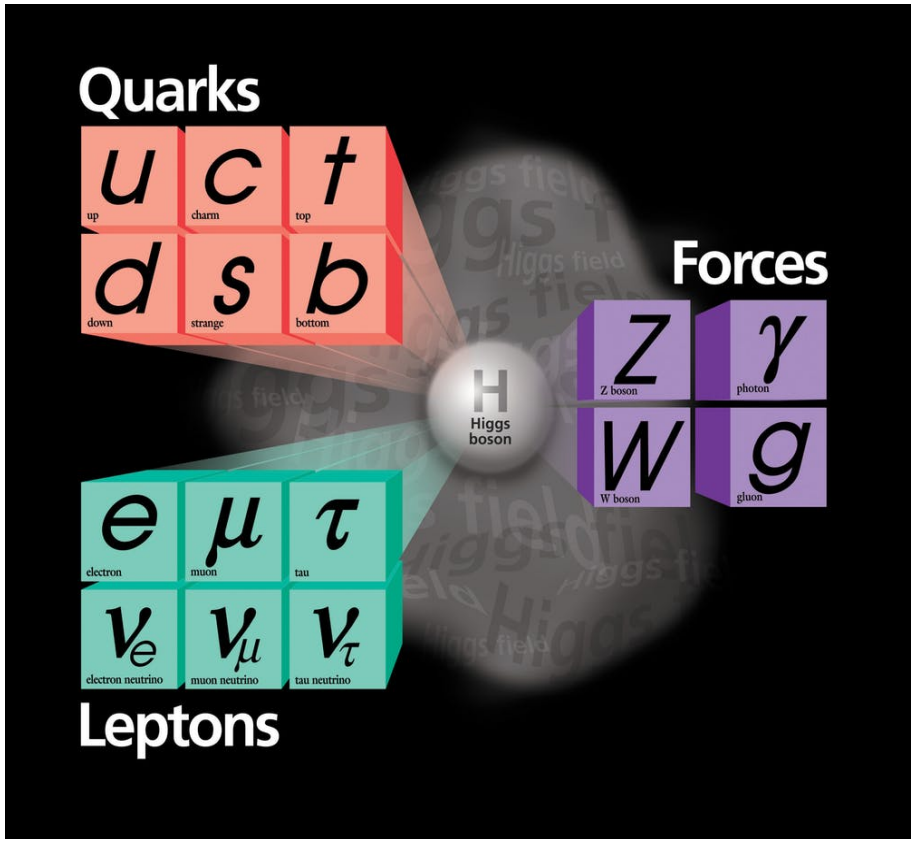
Gino Isidori
[*University of Zürich*]

- Introduction [*Open problems, common lore, recent hopes*]
- 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...*):

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



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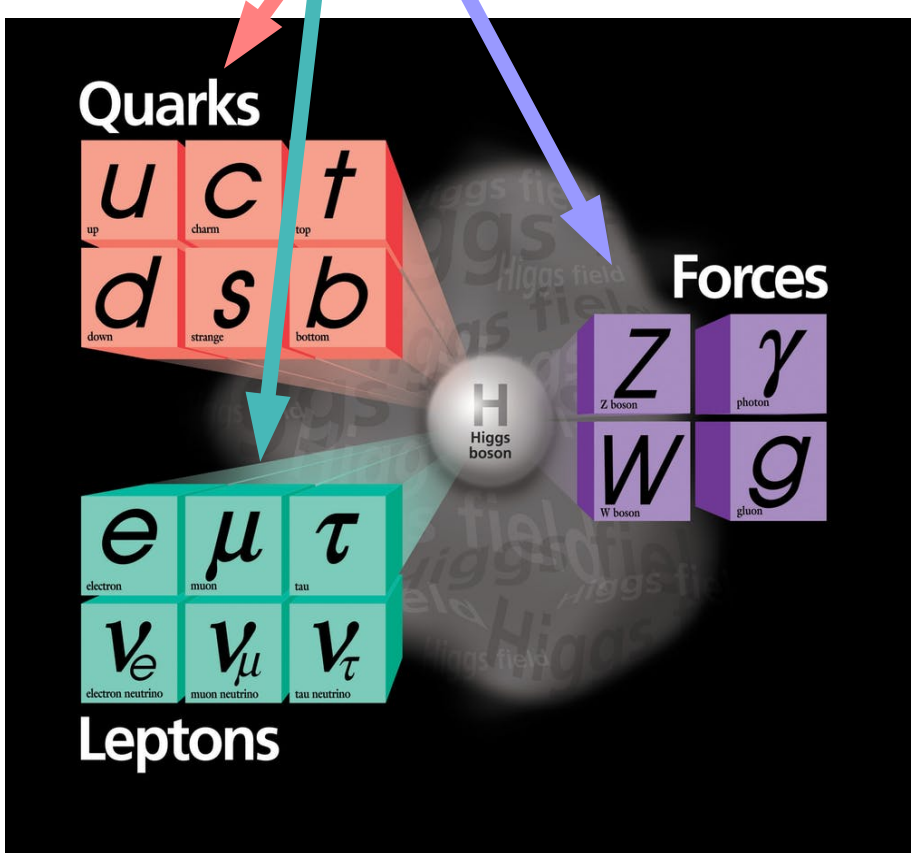

Strong
Weak
Electromagnetic
(*gauge interactions*)

Introduction

However, despite all its phenomenological successes, this Theory has some deep unsolved problems:

	due to...
Electroweak hierarchy problem	→ *Instability of the Higgs mass term*
Flavor puzzle Neutrino masses U(1) charges	→ *Ad hoc tuning in the model parameters*
Dark-matter Dark-energy Inflation	→ *Cosmological implementation of the SM*
Quantum gravity	→ *General problem of any QFTs*

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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 accessible range of energies and effective couplings*– of a more fundamental theory, with new degrees of freedom

Introduction

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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*	
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Quantum gravity		

"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" …)

Dark-matter

Dark-energy

Inflation

Matter-antim. Asym.

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

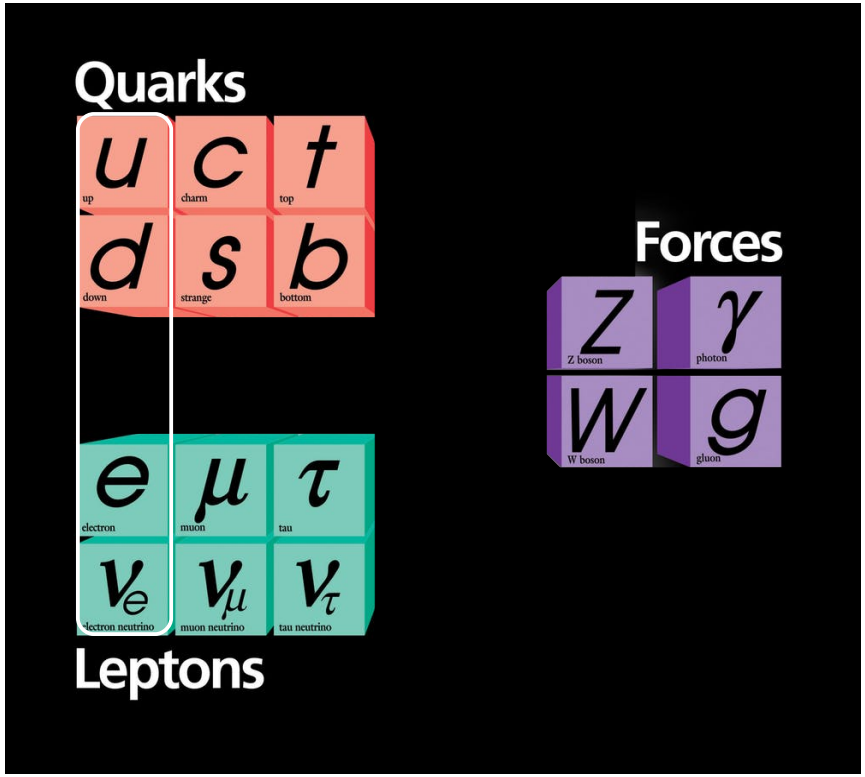
Quantum gravity

Introduction [*the flavor structure of the SM*]

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

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

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



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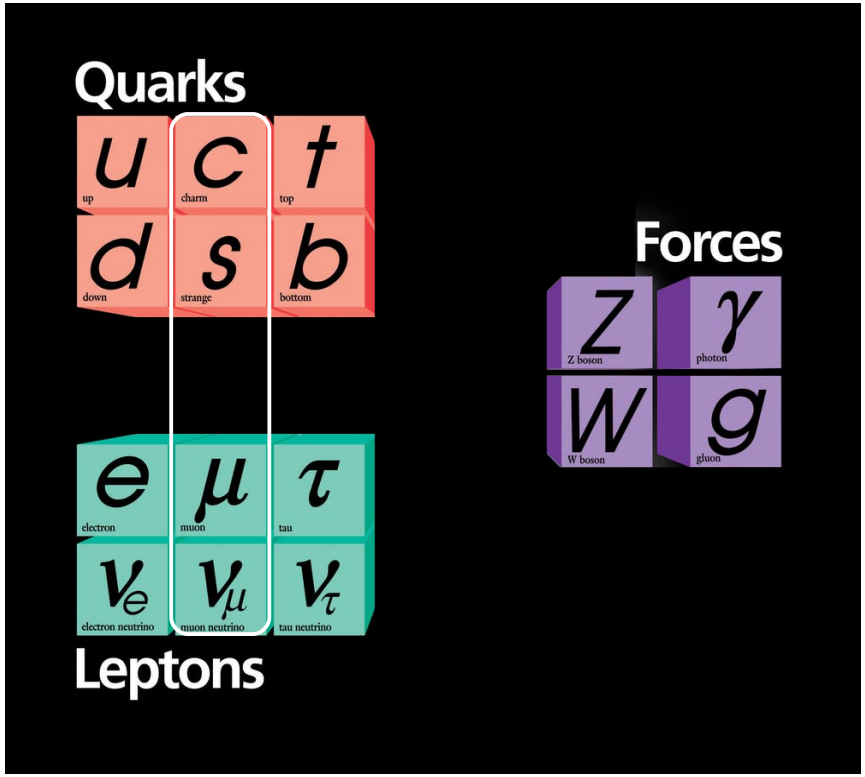

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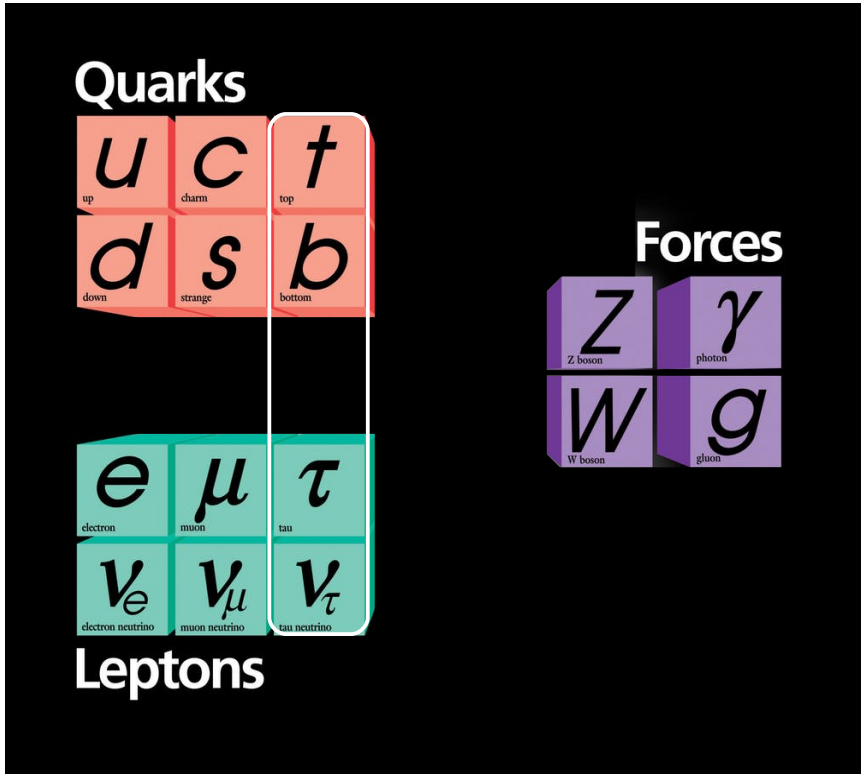

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Within the SM the flavor-degeneracy is broken only by the Yukawa interaction:

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

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

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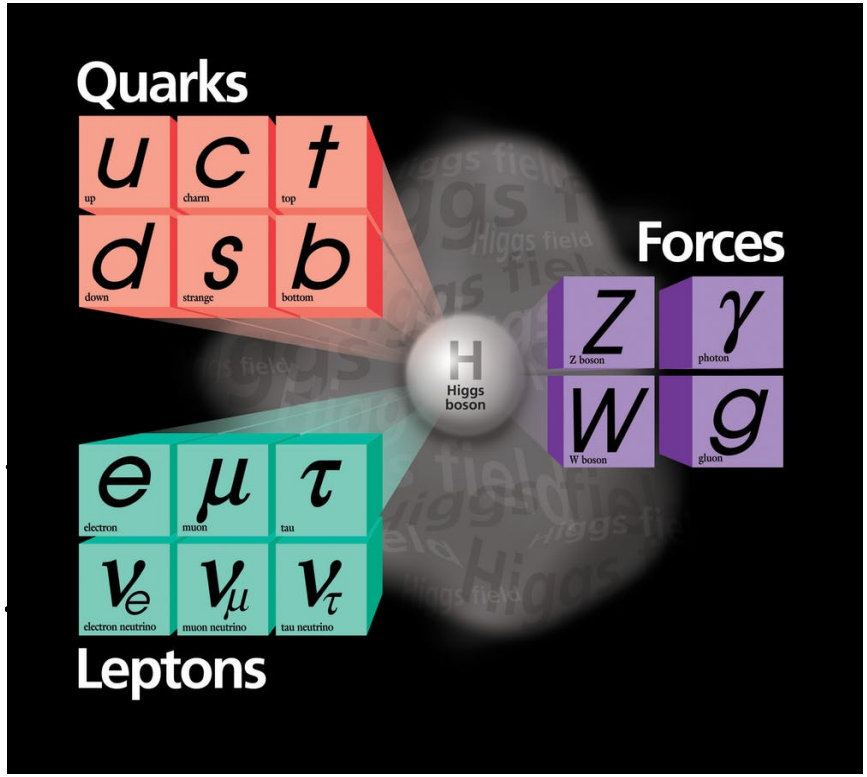

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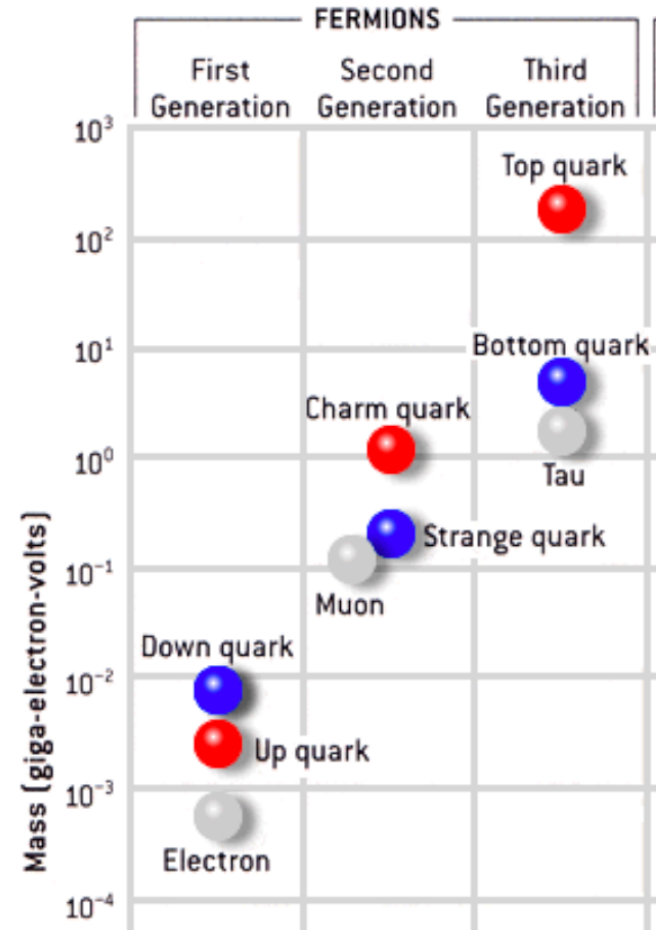
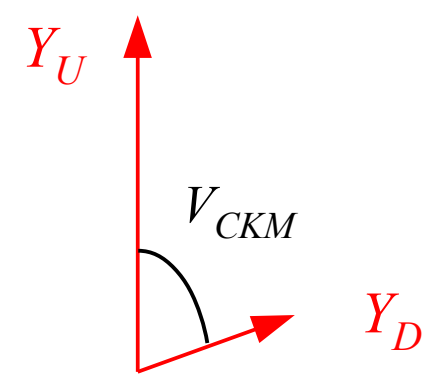


$$\bar{L}_L^i\, Y_L^{ik}\, e_R^k\, H \;\rightarrow\; l_L^i\, M_L^{ii}\, \bar{l}_R^i + \ldots$$

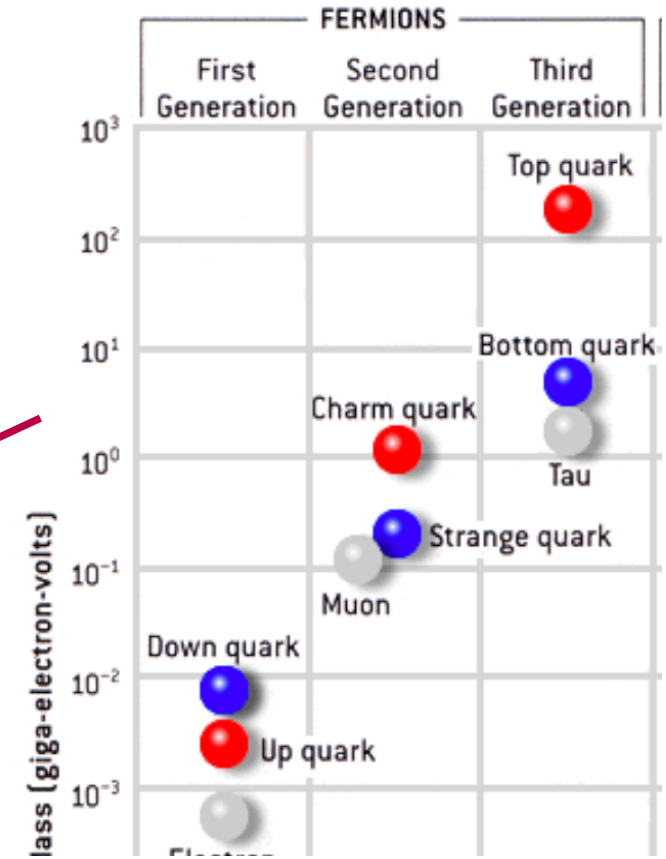
$$\bar{Q}_L^i\, Y_D^{ik}\, d_R^k\, H \;\rightarrow\; d_L^i\, M_D^{ik}\, \bar{d}_R^k + \ldots$$

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



Introduction [*the flavor structure of the SM*]

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

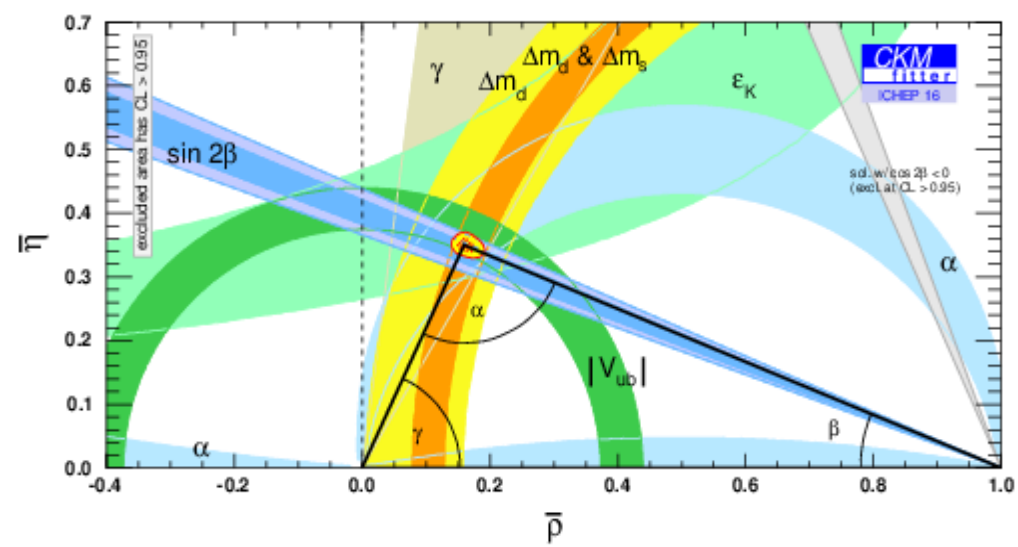


E.g.:

$$Y_U \sim \begin{pmatrix} \cdot & \cdot \\ \cdot & \cdot \end{pmatrix}$$

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

The "old" flavor puzzle...

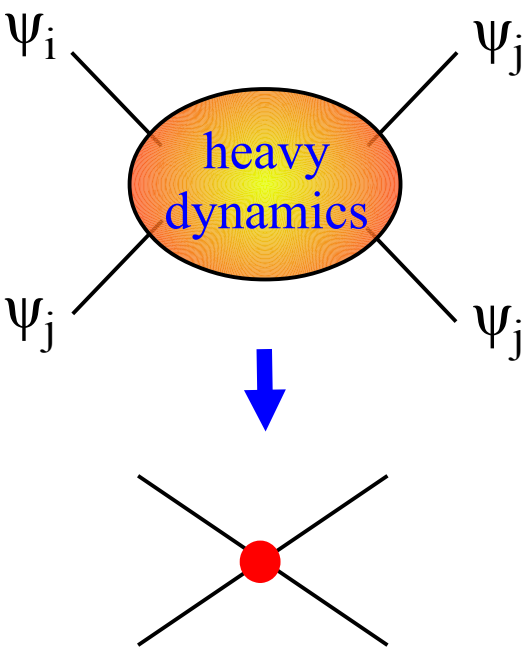


Introduction [*the flavor structure of the SM & beyond...*]

"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:



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

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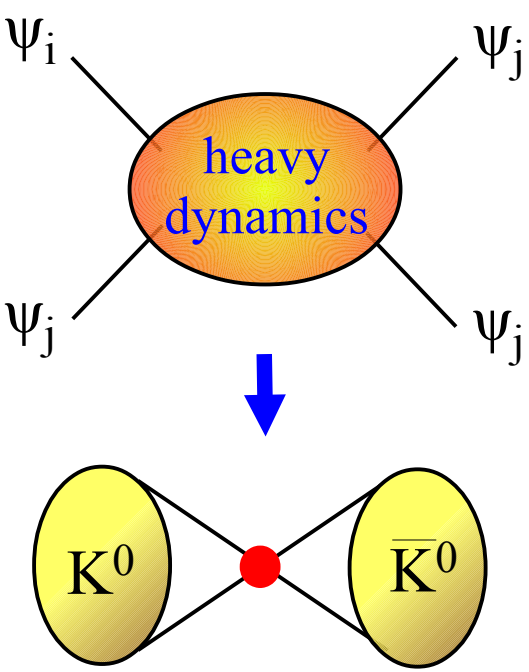

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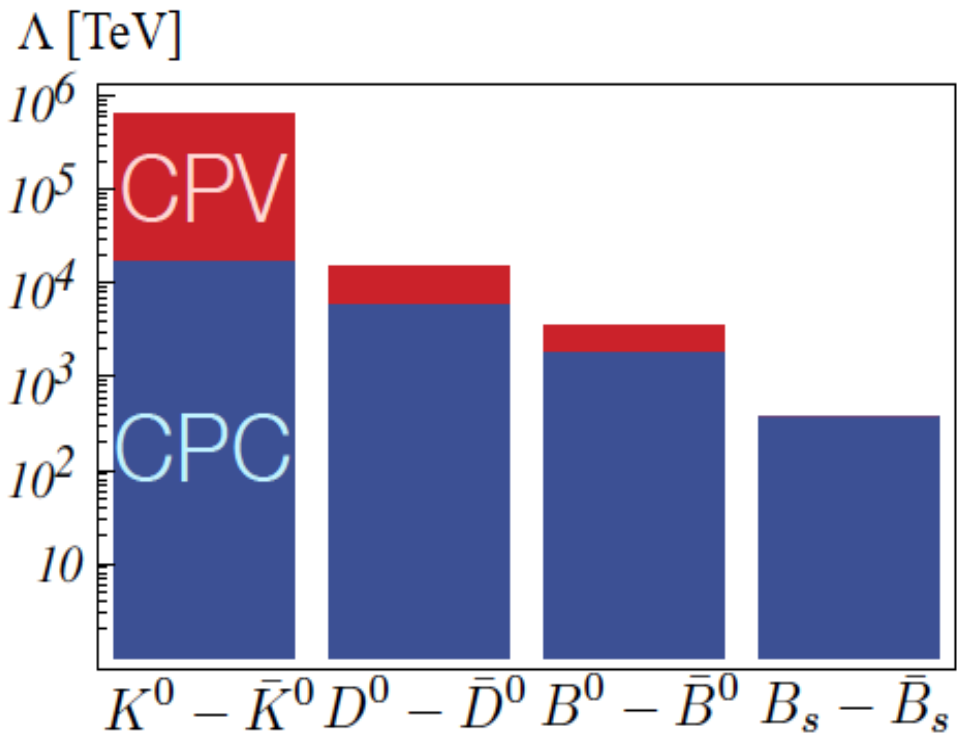


Since so far (*almost*) everything fits well with the SM→ Strong limits on NP

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

This point of view is challenged by the recent "anomalies" in B physics, i.e. the observation of a different (*non-universal*) behavior of different lepton species in specific 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...

The "new" flavor puzzle...

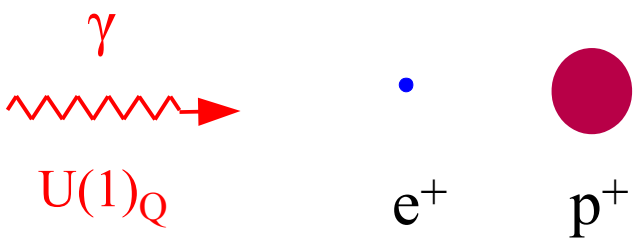
What is particularly interesting, is that these anomalies are challenging an assumption (Lepton Flavor Universality), that we gave for granted for many years (*without many good theoretical reasons...*)

⬇

Interesting new avenue in beyond-the-SM constructions

Introduction [a digression on LFU]

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



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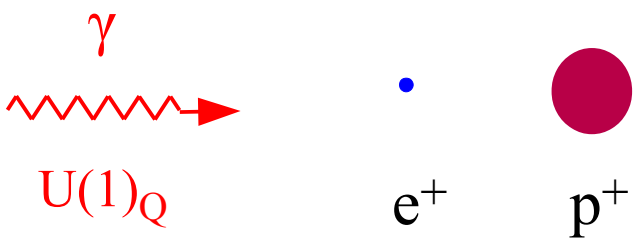

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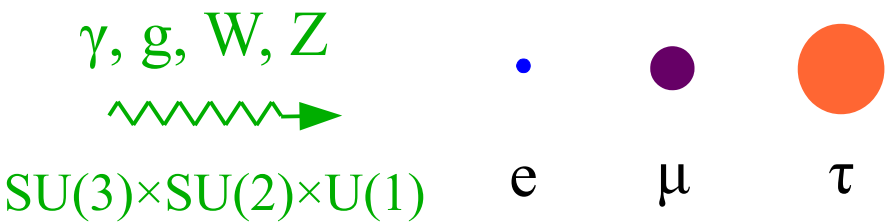
That's exactly the same (misleading) argument we use to infer LFU...



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 [*a digression on LFU*]

So far, the vast majority of beyond-the-SM model-building attempts

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

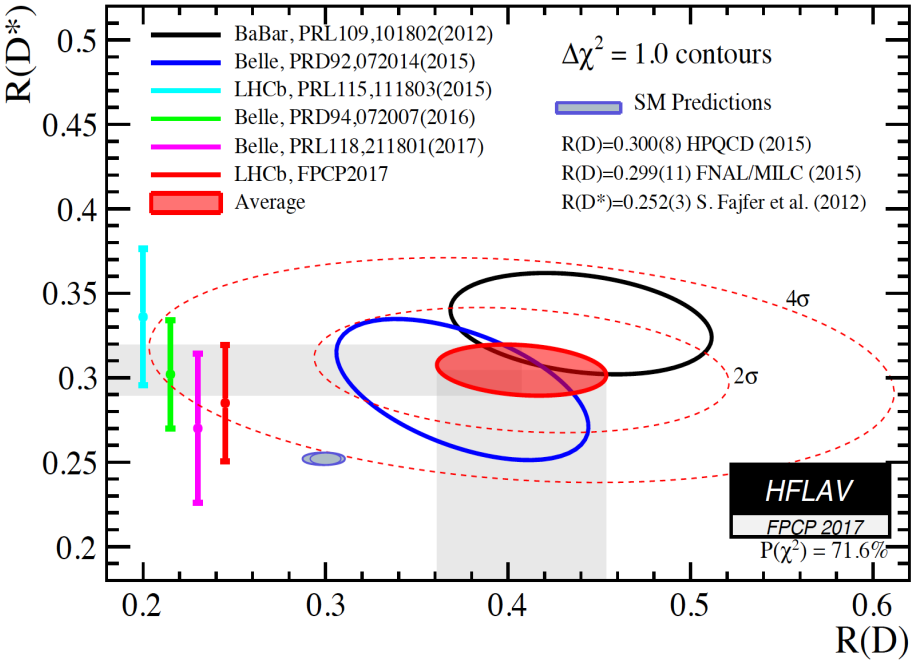
~~*"Common lore"* (I)~~

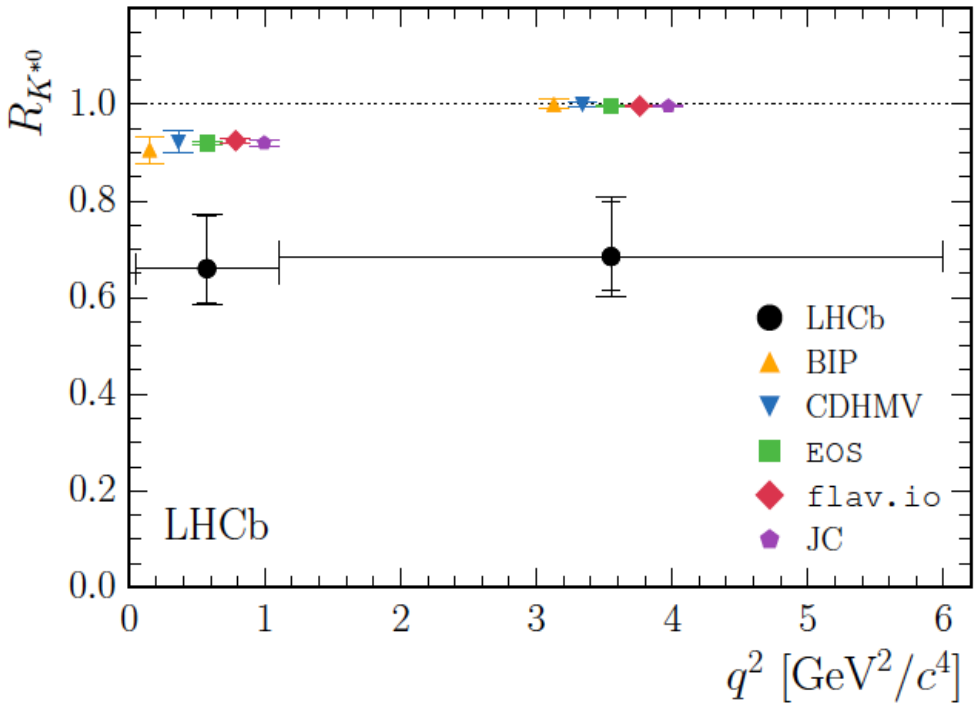
~~*"Common lore"* (II)~~

The recent flavor anomalies seem to suggest a new avenue:

- We should not ignore the flavor problem [→ *new "forces" at the TeV scale distinguishing the different families*]
- *A (very) different behavior of the 3 families* (with special role for 3rd gen.) may be the key to solve/understand also the electroweak hierarchy problem and *explain why we have not seen yet NP directly at colliders*

On the recent B-physics anomalies



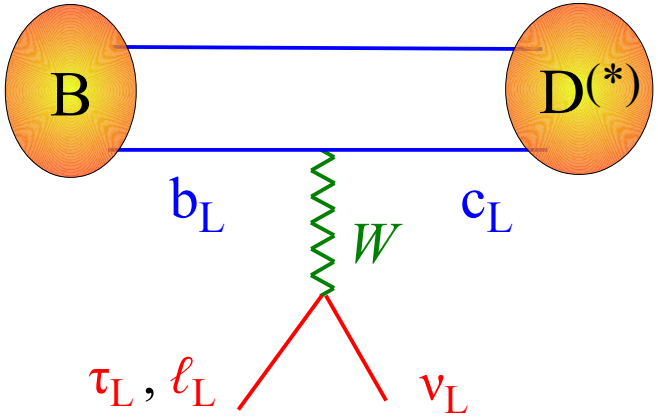


$B \to D^{(*)} \tau\nu$ [Babar, Belle, LHCb]

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 = D or D*



- 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 and radiative corrections

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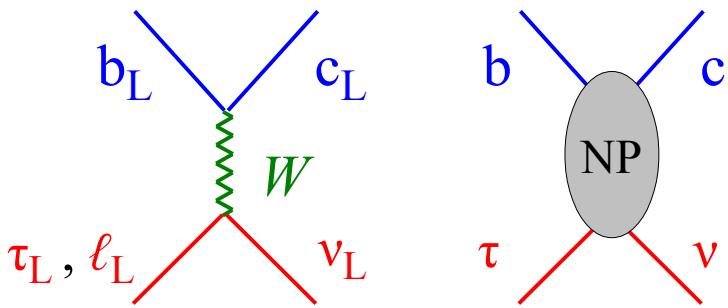

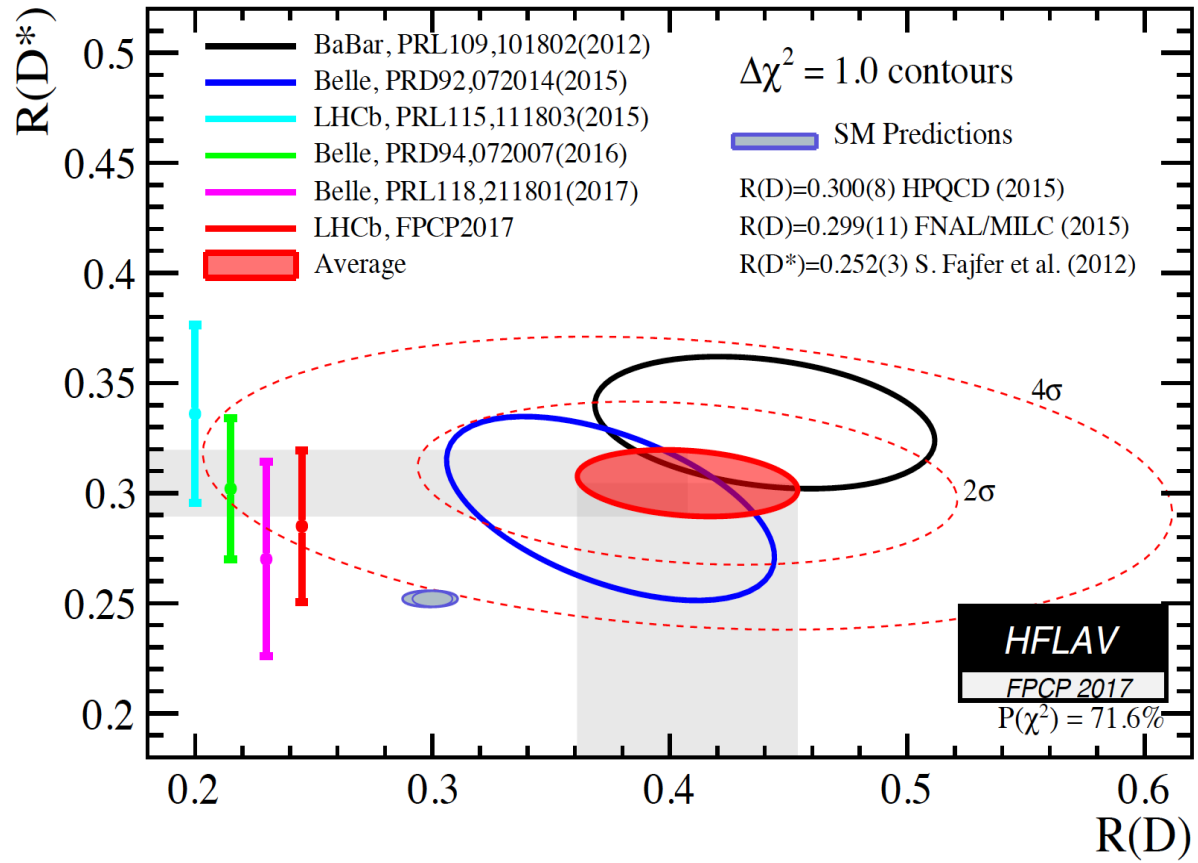

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- Consistent results by 3 different exps. → 3.6–3.9σ excess over SM ($D + D^*$)

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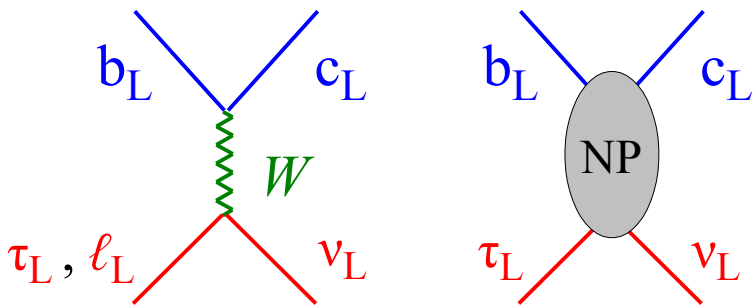
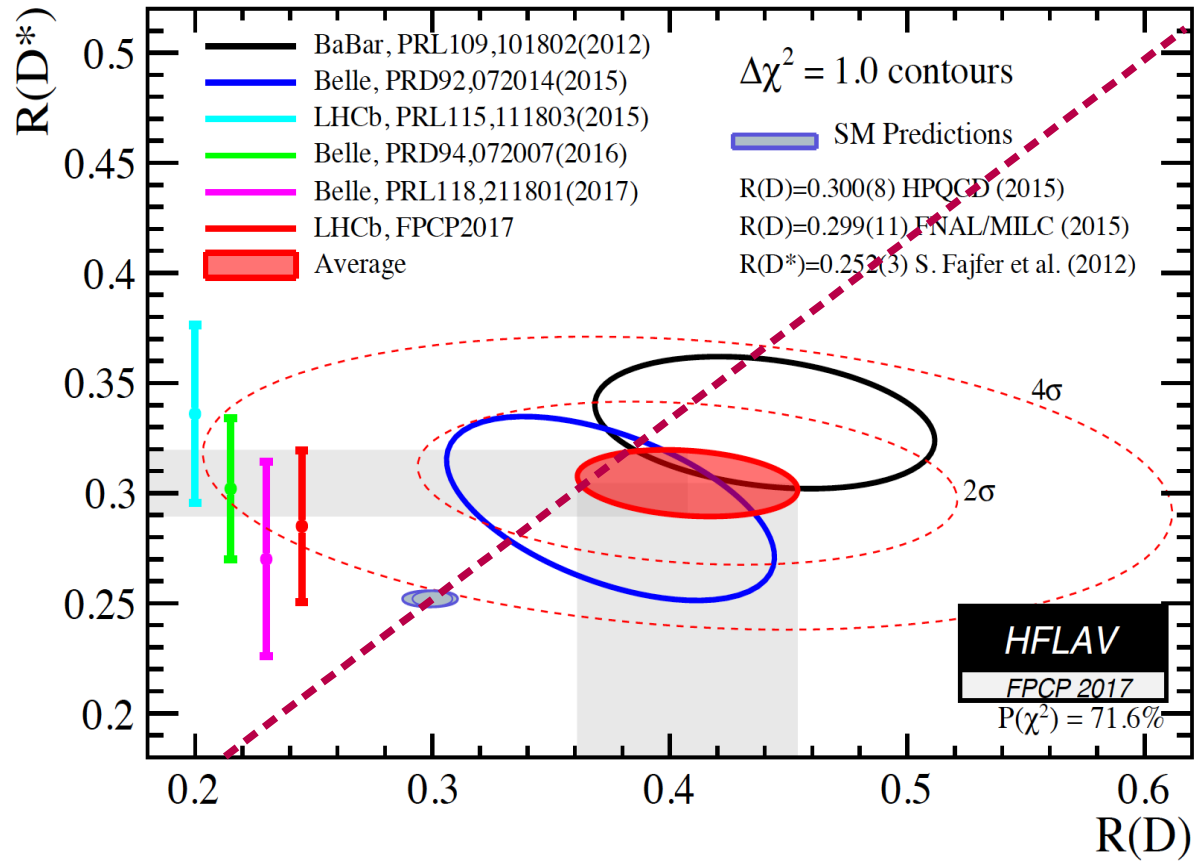




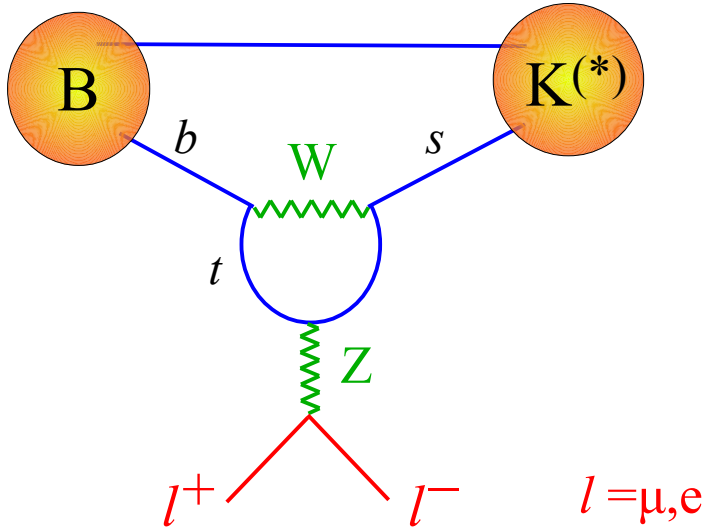
- SM prediction quite solid: hadronic uncertainties cancel (*to large extent*) in the ratio and deviations from 1 in R(X) expected only from phase-space differences
- Consistent results by 3 different exps. → 3.6–3.9σ excess over SM ($D + D^*$)
- The two channels are well consistent with a universal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

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

Precise SM tests in neutral-current processes of the type $b \to s\, l^+ l^-$

These 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



- The largest anomaly is the one in the $B \to K^* \mu\mu$ angular distribution.
- Less significant correlated anomalies present also in other $b \to s\, \mu\mu$ channels: overall smallness of all $\Gamma(B \to \text{Hadron} + \mu\mu)$
- But also in this case the most interesting effects are the deviations from the SM in appropriate μ/e "clean" LFU ratios:

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

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

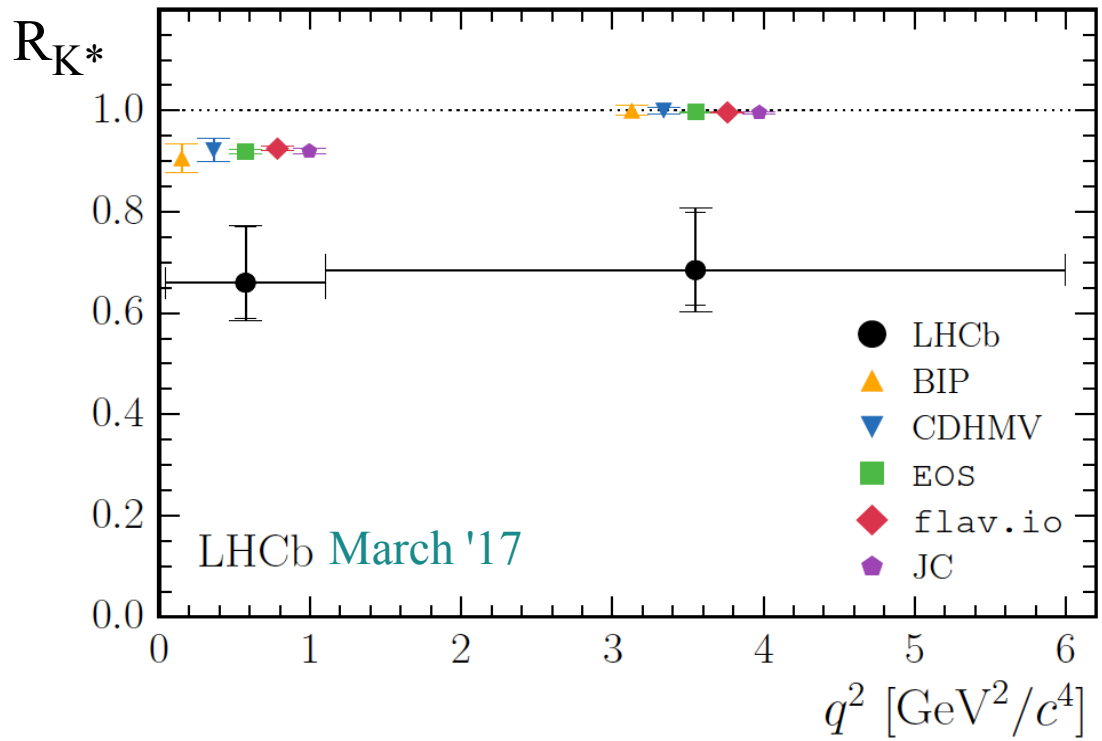
$$R_H = \frac{\int d\Gamma(B \to H\,\mu\mu)}{\int d\Gamma(B \to H\,ee)}$$

R_K [1-6 GeV^2] = 0.75 ± 0.09

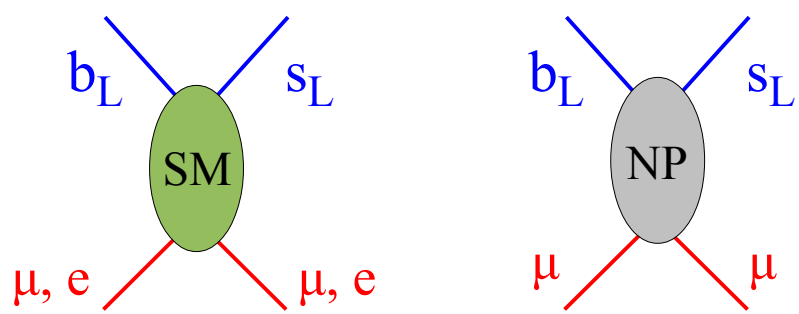
LHCb, '14

(vs. 1.00±0.01 SM)

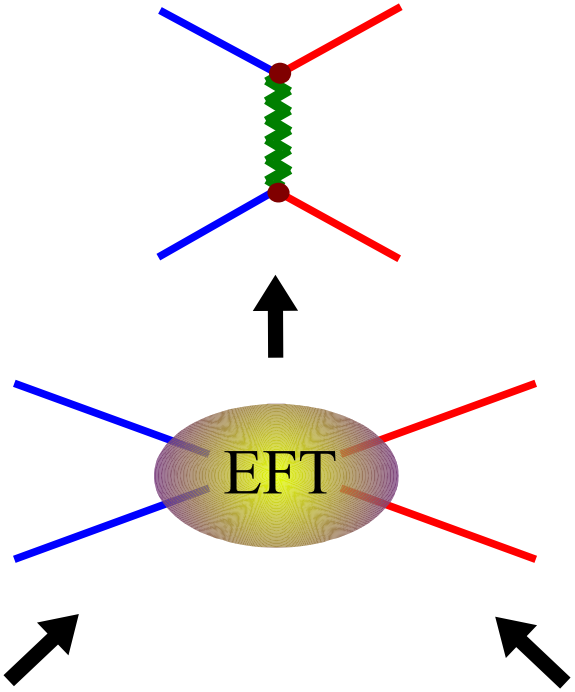
Overall significance ~ 3.8σ
(*LFU ratios only*)

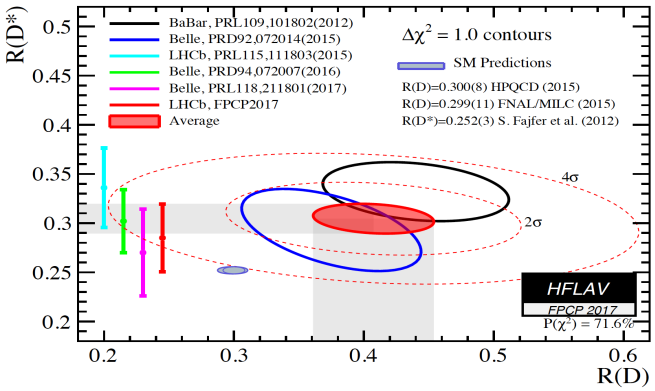


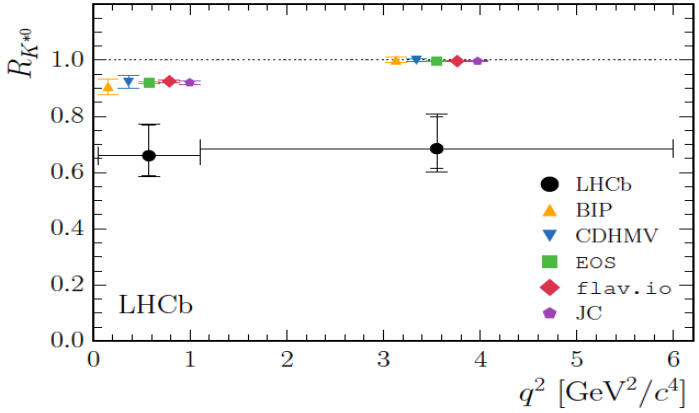
→ very coherent picture: all effects well described by NP of short-distance origin only in b→sμμ and (& not in ee)



Bottom-up approaches to describe the anomalies

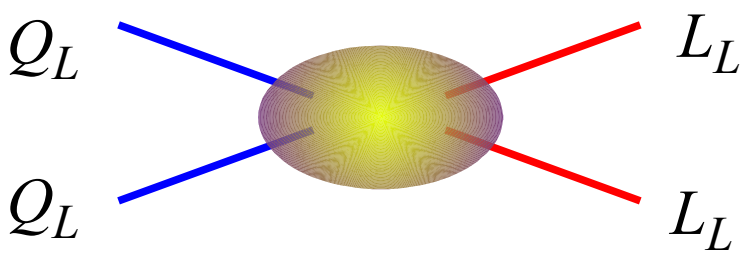






Effective Field Theory considerations

- 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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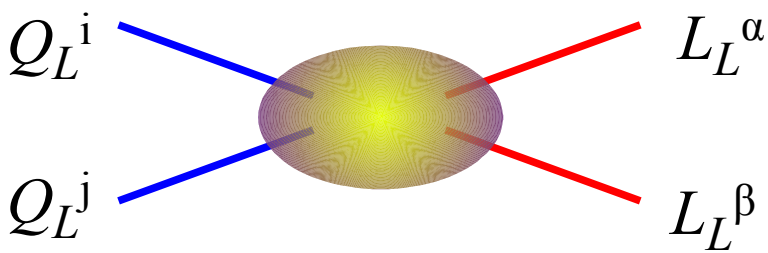

- Large coupling (competing with SM tree-level) in bc → $l_3\, \nu_3$
- Small non-vanishing coupling (competing with SM FCNC) in bs → $l_2\, l_2$

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

→ *Link to pattern of the Yukawa couplings !*

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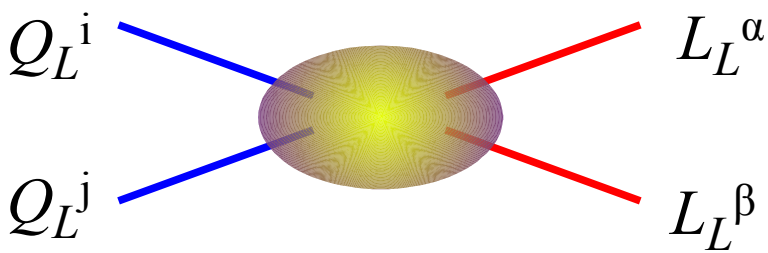
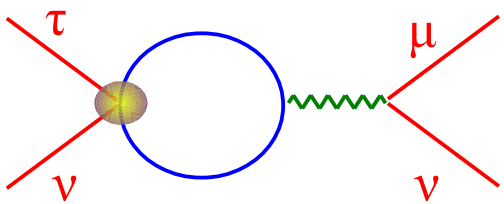
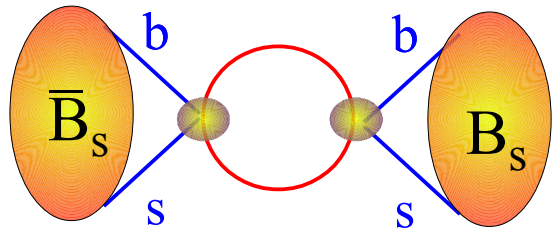
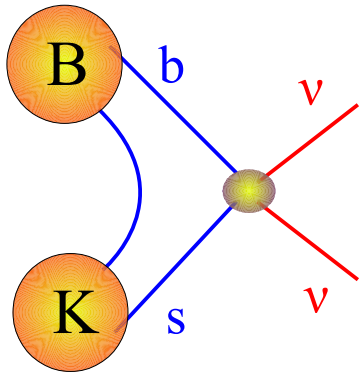
- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- Data largely favor non-vanishing left-handed current-current operators [*Fermi-like effective theory*], although other contributions are also possible



Highly non-trivial to build a consistent EFT, given the *long list of constraints* from other rare processes, where we do not see large deviations from the SM, e.g:





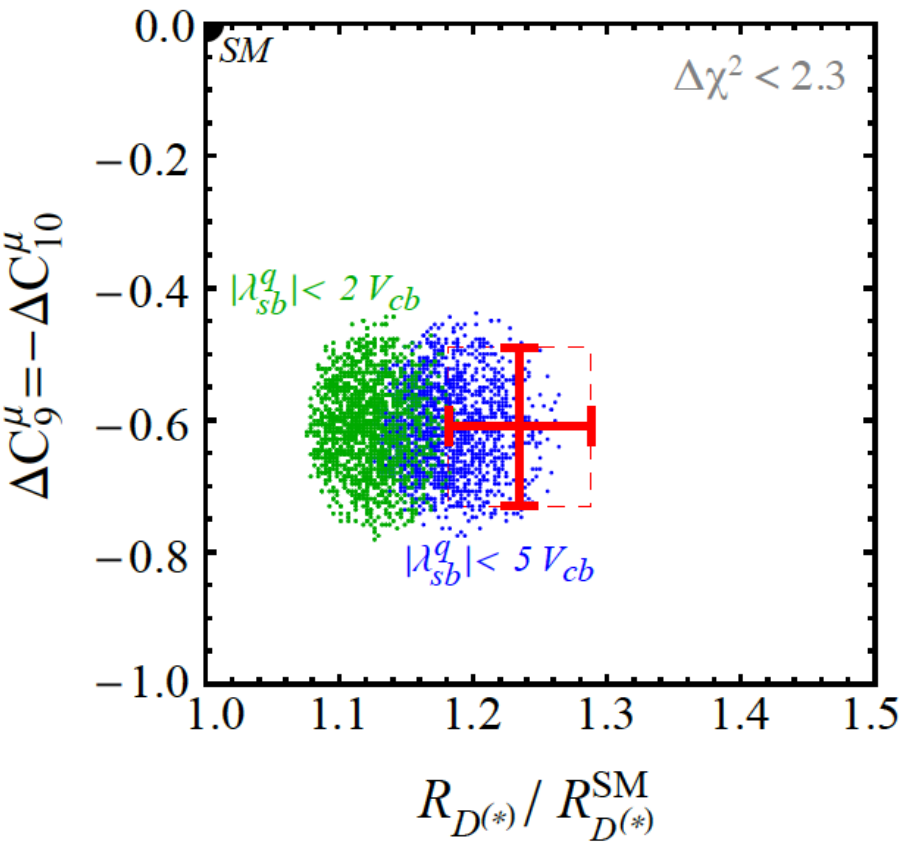


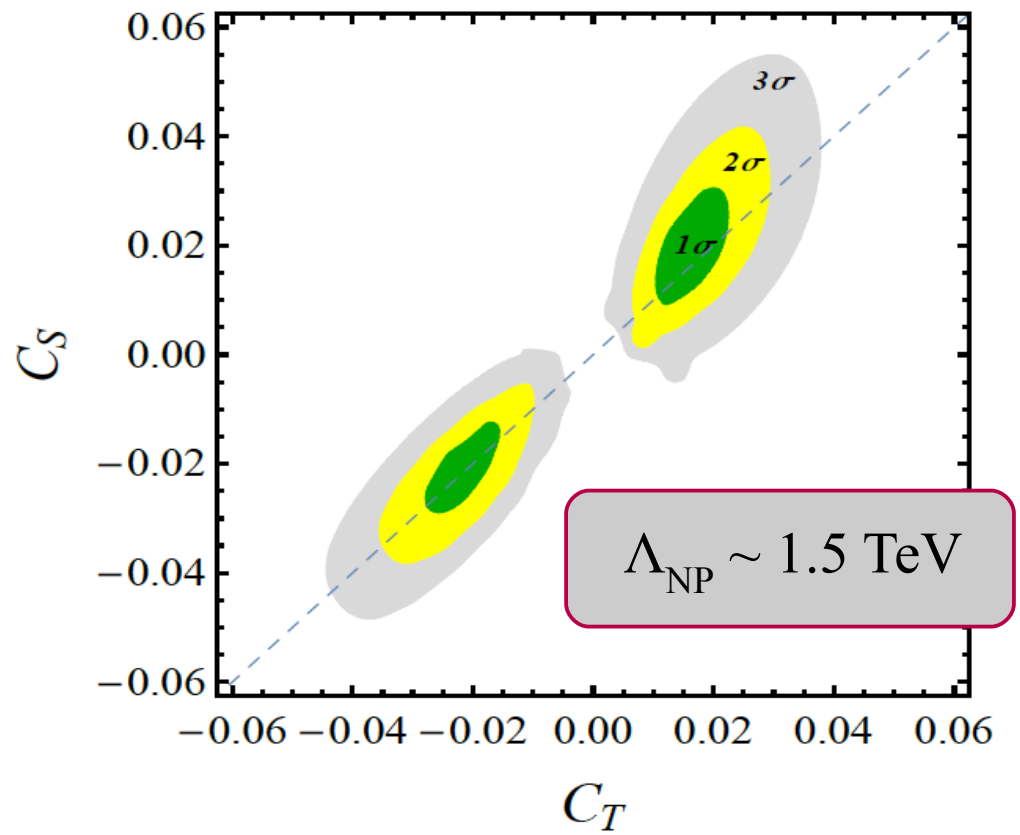
+ *many more...*

Effective Field Theory considerations

… but if we "mimic" the flavor structure of the Yukawa couplings, is possible to pass all bounds without fine-tuning and have an excellent description of data

four main free parameters: $C_{S,T} = O\left(\frac{\langle H \rangle}{\Lambda_{NP}^2}\right)$, $\lambda_{bs} = O(V_{cb})$, $\lambda_{\mu\mu} = O(|V_{\tau\mu}|^2)$



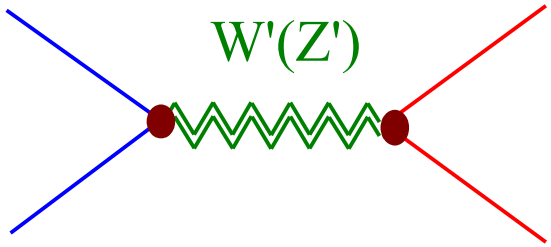


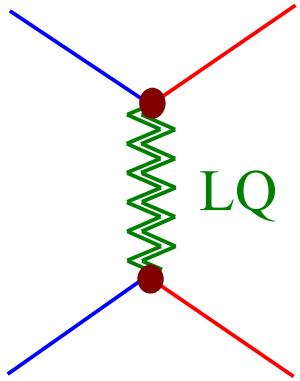
- *Simplified dynamical models* [*"The Return of the LeptoQuark"...*]

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:	Z'	W'





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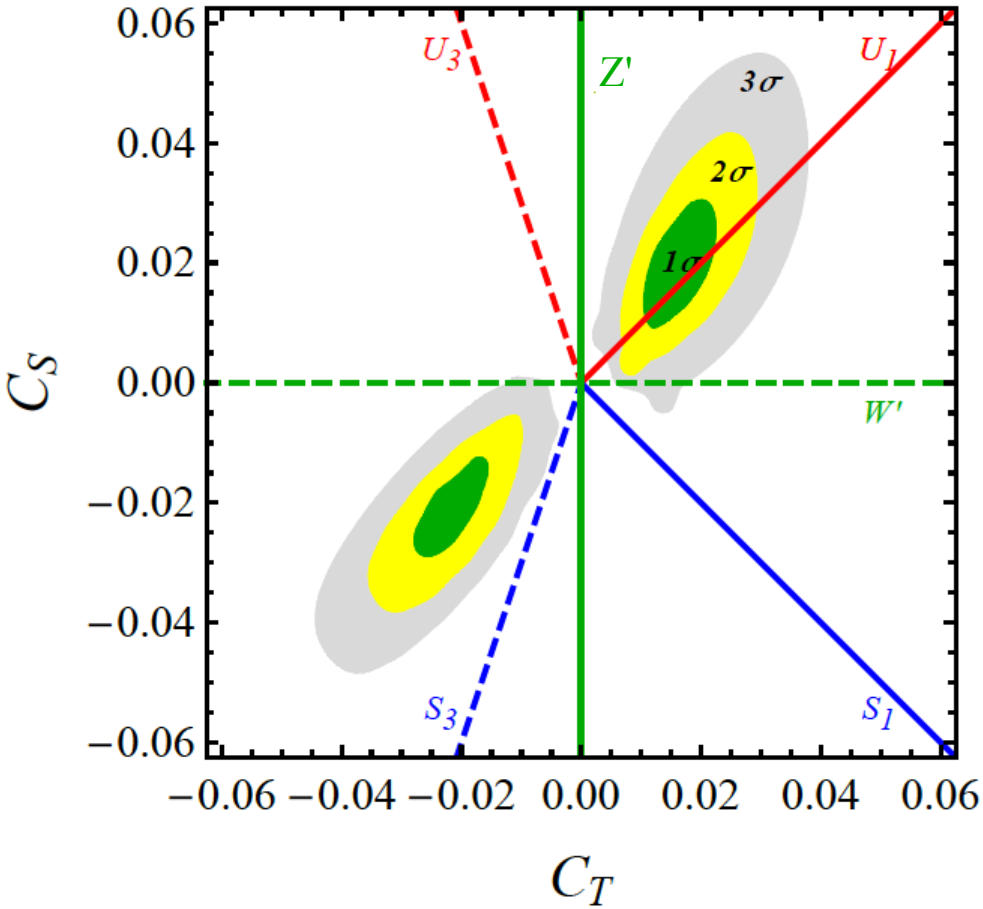
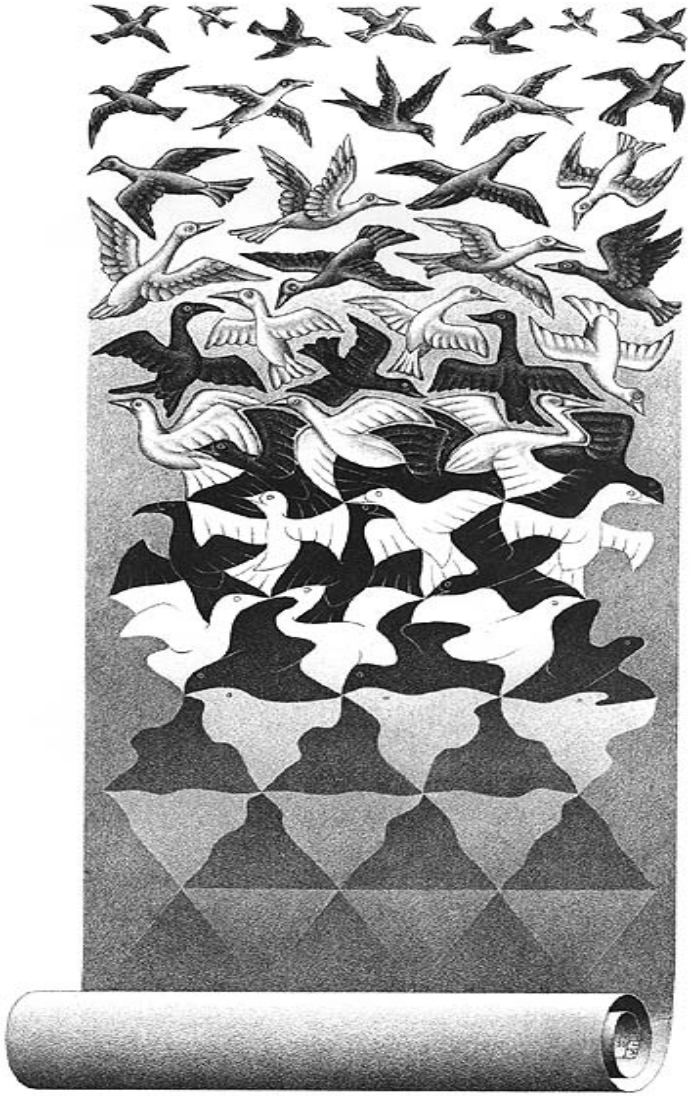


The U_1 option fits quite nicely... but of course models with more than one mediators are also possible

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 $SU(4) \to SU(3)_c$

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 $K_L \to \mu e$] → we must go beyond the original model

The PS^3 *model*

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

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

New 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 $U(1)_Y$ 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 flavor symmetry "protecting" light-fermions
- Natural structure of SM Yukawa couplings

The PS^3 *model*

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

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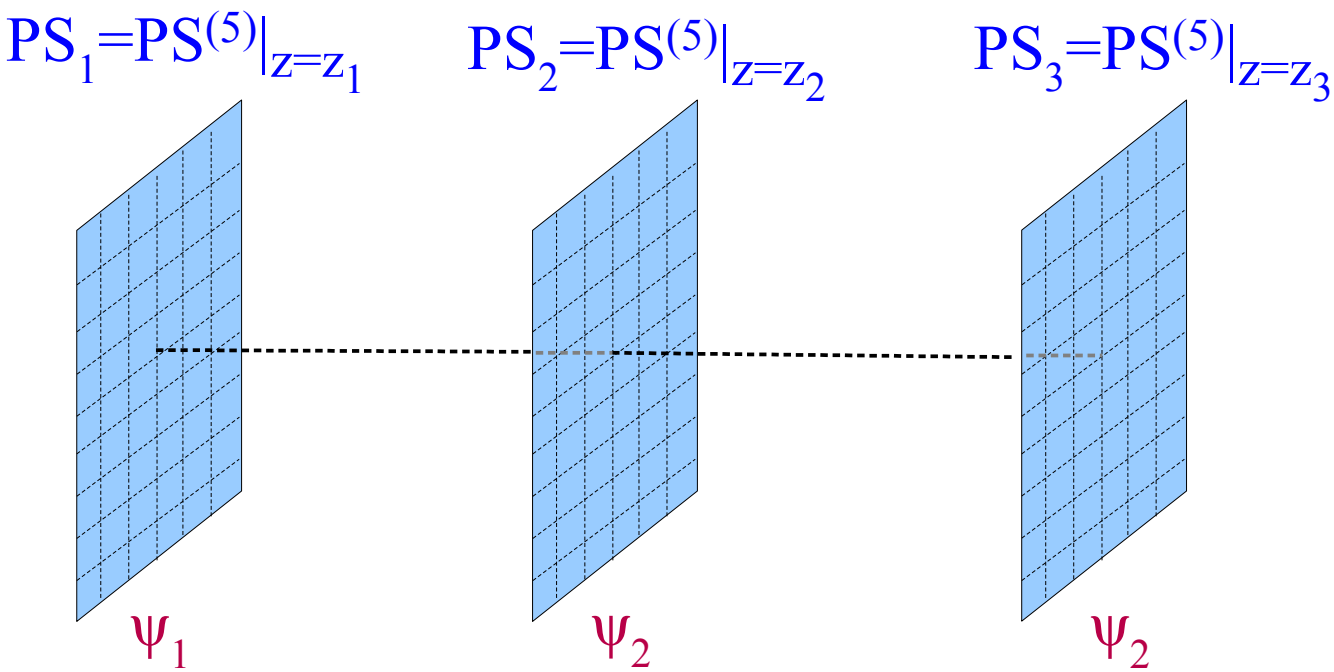


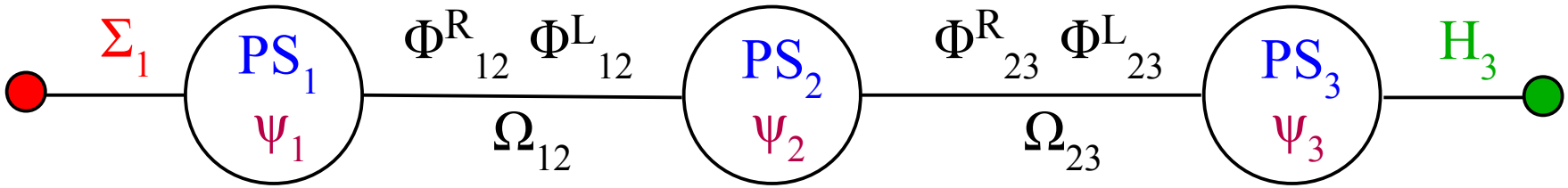
Unification
of quarks and leptons

"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*



High-scale [~ 10^3 TeV]
"vertical" breaking

$PS_1 \to SM_1$

link fields

$PS_i \times PS_j \to PS_{i+j}$

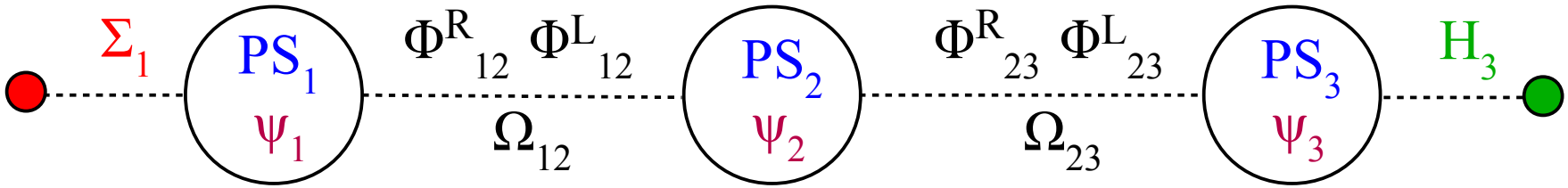
Low-scale "vertical" Breaking [*EWSB*]

$SM_3 \to QED_3$

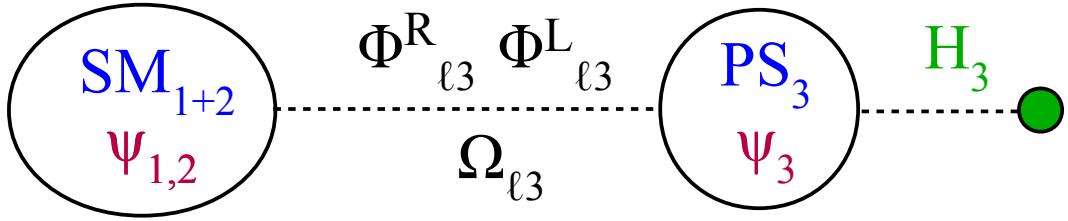
SM ($\to$ QED)

- 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*



Below ~ 100 TeV
Flavor-degeneracy
of light quarks

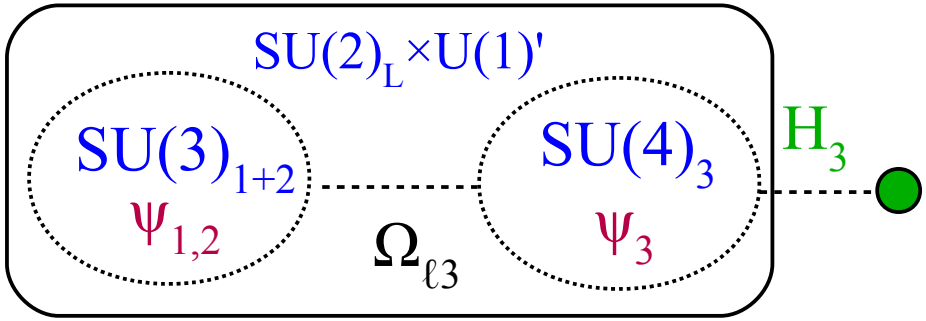


$\rightarrow W_L' + W_R'$ [~ 5-10 TeV]

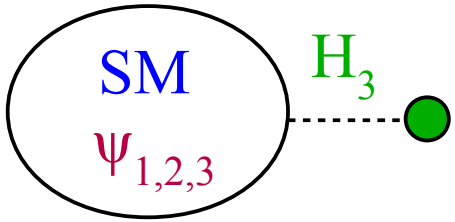
Sub-leading Yukawa terms from higher dim ops:

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

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



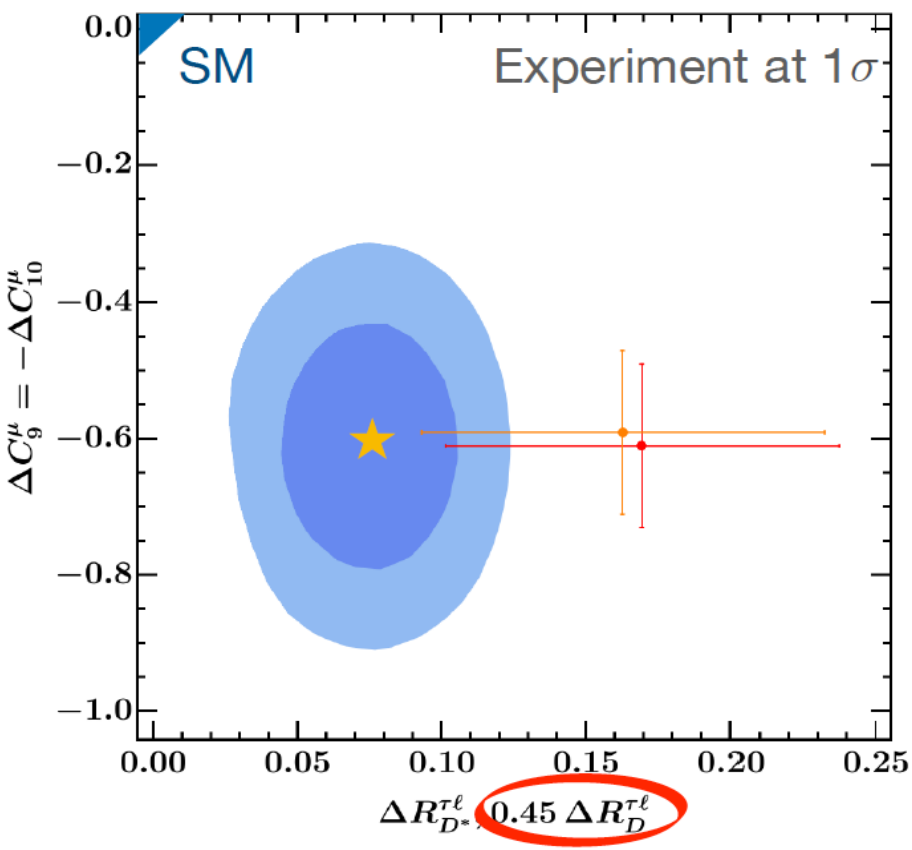
$\rightarrow$ LQ [U_1] + Z' + G' [~ 2-3 TeV]

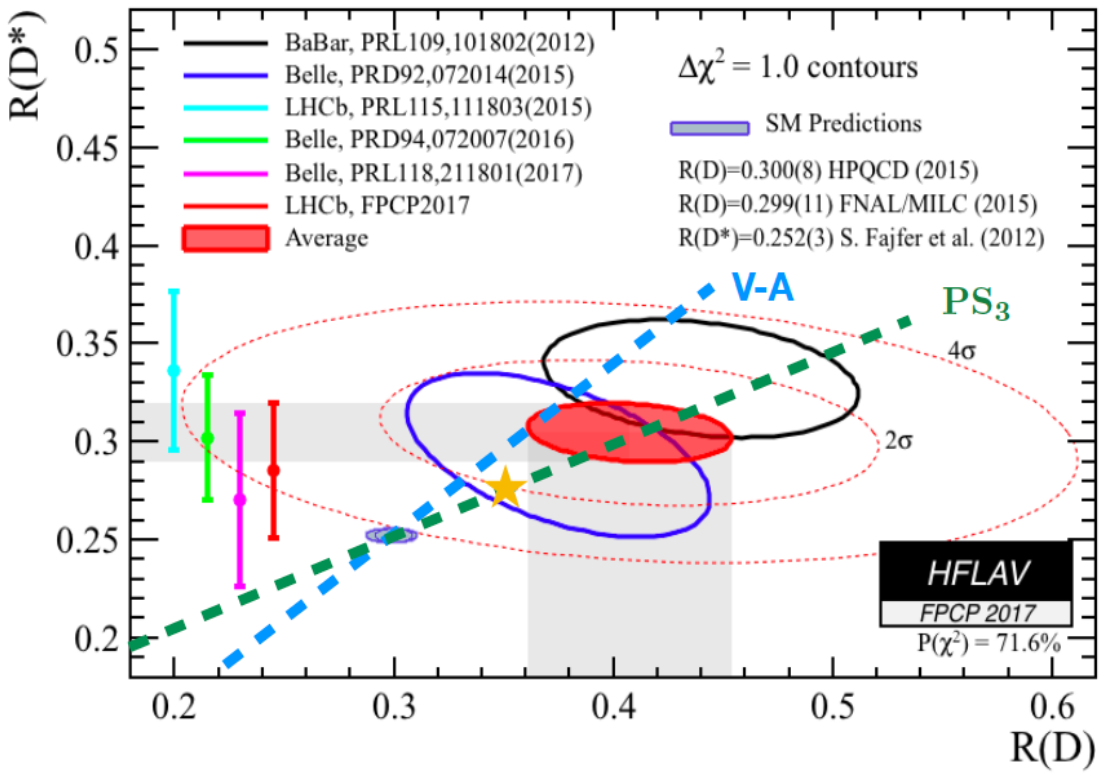


The PS^3 *model*

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





The fit to low-energy data is rather good

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

Important difference with respect to all other models:
right-handed couplings of the LQ

Possible future implications

"It is very difficult to make predictions, especially about the future"

[attributed to Niels Bohr]

- *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, LFV in charged leptons)

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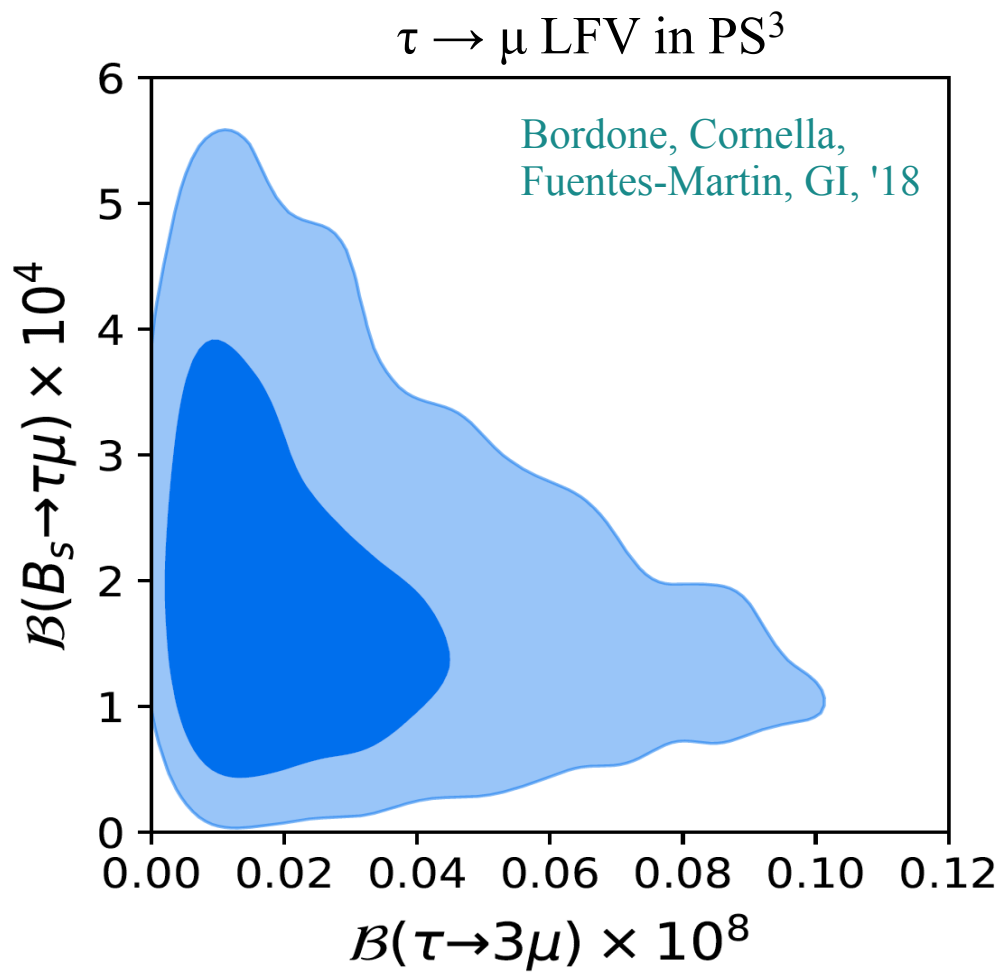
E.g: Possible large $\tau \to \mu$ LFV transitions

Glashow, Guadagnoli, Lane '15



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E.g: Possible large $\tau \to \mu$ LFV transitions

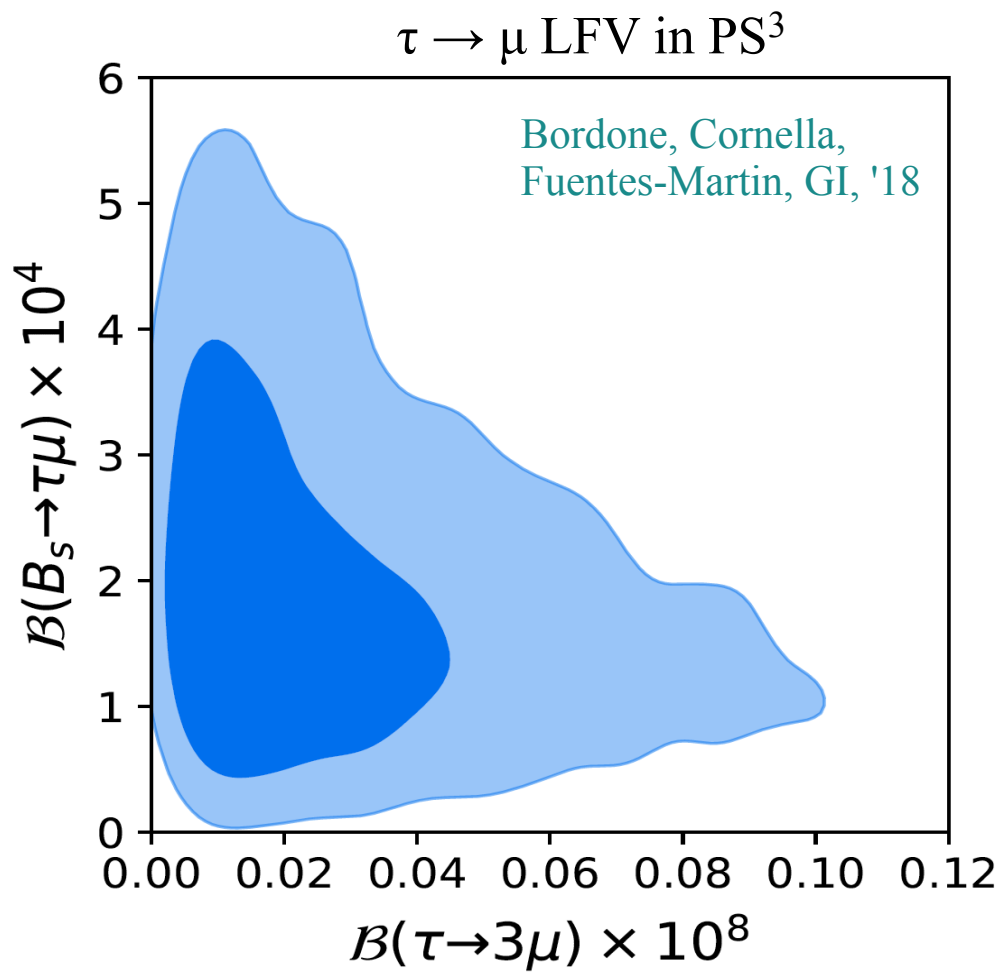
Glashow, Guadagnoli, Lane '15

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}



Implications for high-p_T physics

Some general considerations:

Independently of the details of the UV models, the anomalies point to NP in the ball-park of direct searches @ LHC

- $R_{D(*)}$ necessarily points to a low NP scale: $M \sim g \times (1.0\ \text{TeV})$
- $R_{K(*)}$ also points to a low NP scale, except for (unnaturally) large flavor-violating couplings

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 di-lepton pairs (*including tau-lepton pairs*)

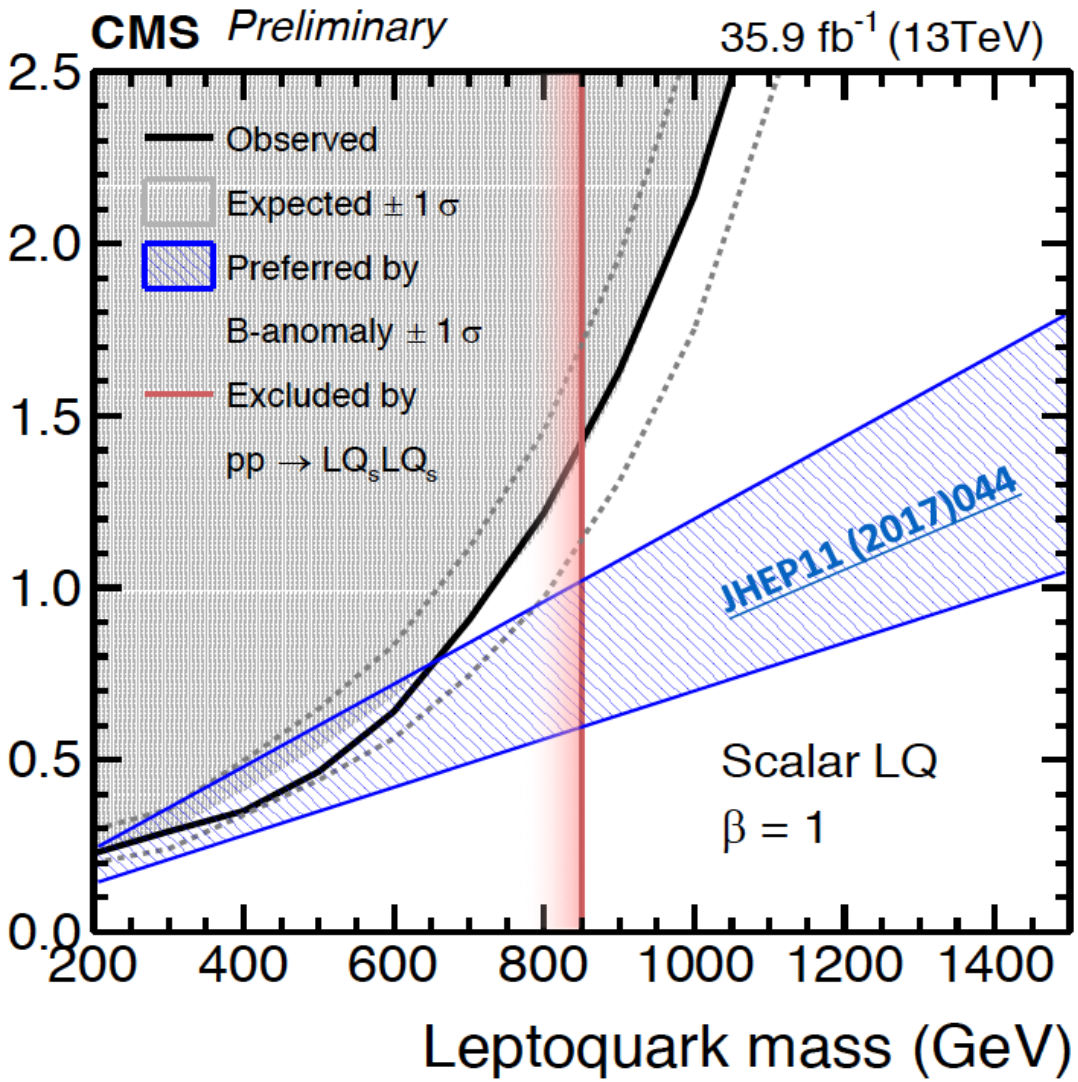
⬇

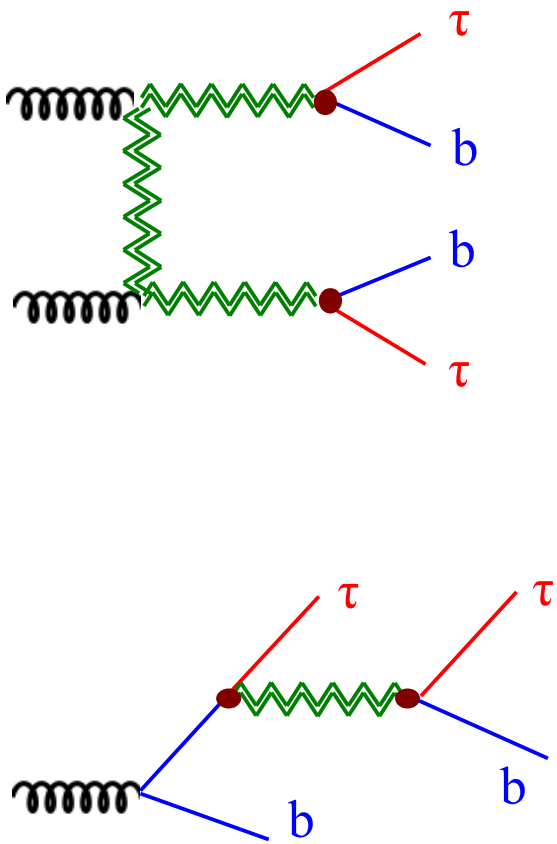
Significant room for improvement for the corresponding searches @ HL-LHC

But only a collider with (slightly) larger energy (such as HE-LHC) would be able to rule out all reasonable models

Implications for high-p_T physics

Also as far as direct searches are concerned, 3rd gen. LQ are in good shape:

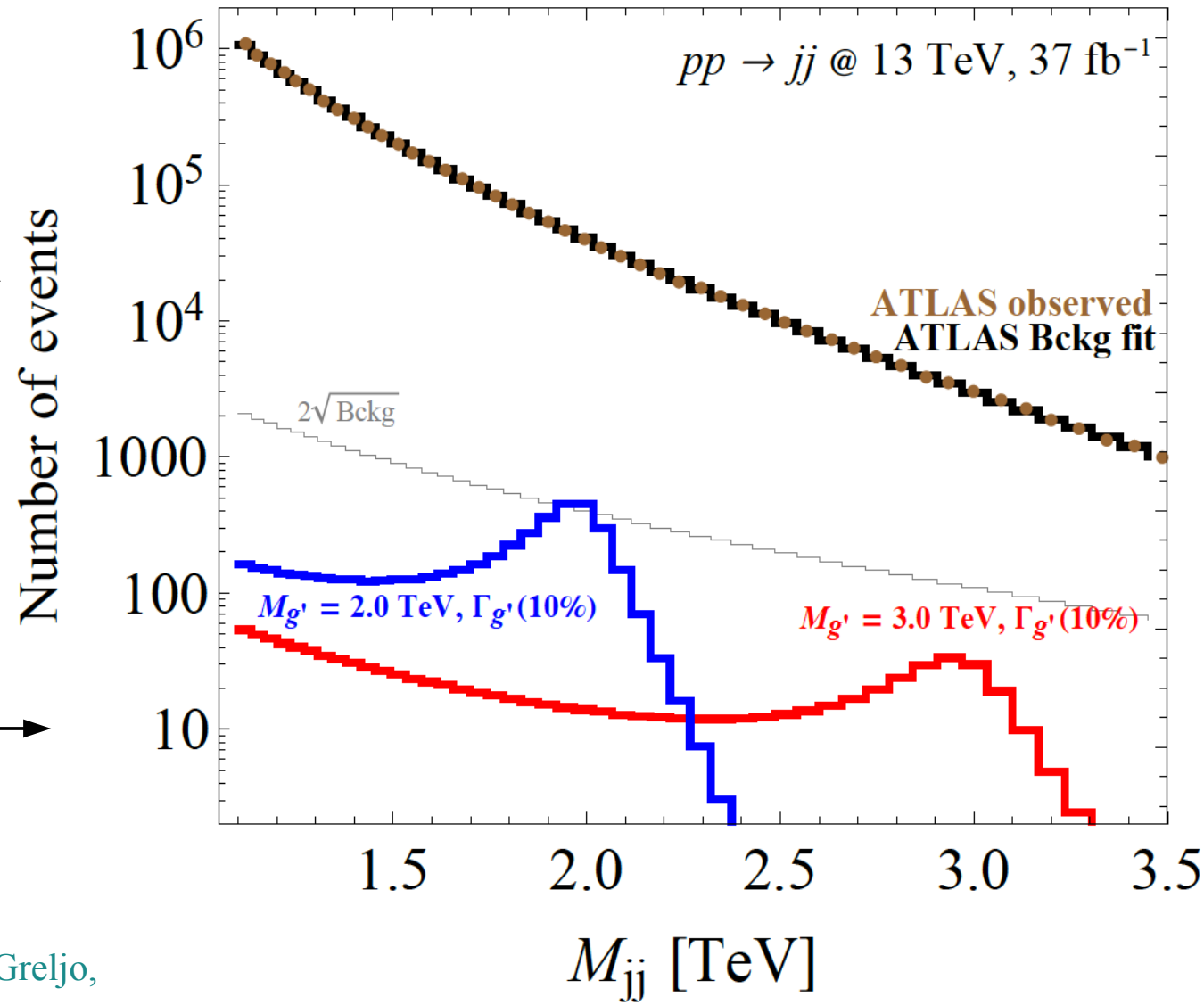




Implications for high-p_T physics

In many appealing UV models the LQ is accompanied by other TeV-scale particles, with dominant coupling to 3rd generation quarks

E.g.: the "coloron" = non-universal heavy gluon, coupled mainly to 3rd gen.



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

Conclusions

- If these ~~LFU~~ anomalies were 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 for these models naturally imply a much richer spectrum of states at the TeV scale (*and possibly above...*).
- The PS^3 model I have presented is particularly interesting as example of the change of approach 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)