New Prospects for BSM Physics

Gino Isidori
[*University of Zürich*]

- Introduction [*Flavor vs. Hierarchy problems in the SM-EFT*]
- LFU anomalies & Flavor symmetries [*The* $U(2)^n$ *case*]
- Simplified models: The Return of the Leptoquark
- Non-universal gauge interactions [*The* PS^3 *hypothesis*]
- Conclusions

University of Zurich UZH

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Introduction

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

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

▶ *Introduction*

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However, this Theory has some deep unsolved problems:

	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*	

Introduction

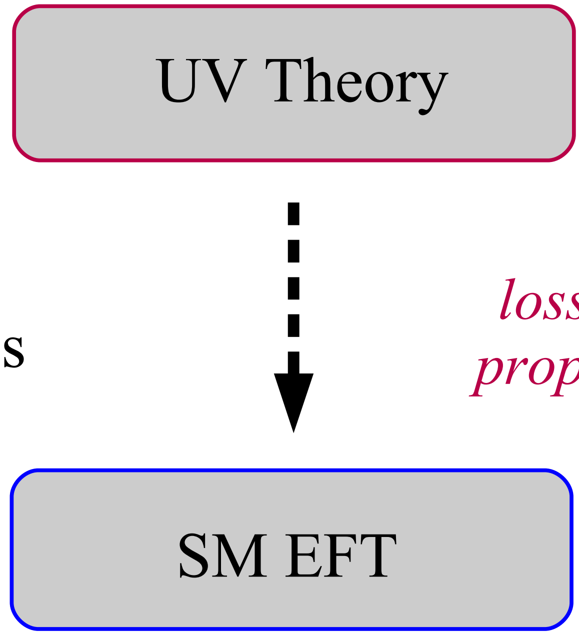
All microscopic phenomena seems to be well described by a remarkably simple Theory (*that we continue to call "model" only for historical reasons...*).

However, this Theory has some deep unsolved problems:

	problem due to...	*...indicating*
Electroweak hierarchy problem	→ *Instability of the Higgs mass term*	*Non-trivial properties of the SM Lagrangian if interpreted as EFT*
Flavor puzzle Neutrino masses U(1) charges	→ *Ad hoc tuning in the model parameters*	↓
Dark-matter Dark-energy Inflation		Useful hints for its UV completion
Quantum gravity		

Hierarchy vs. Flavor problem in the SM EFT

Integrate out the
high-energy modes

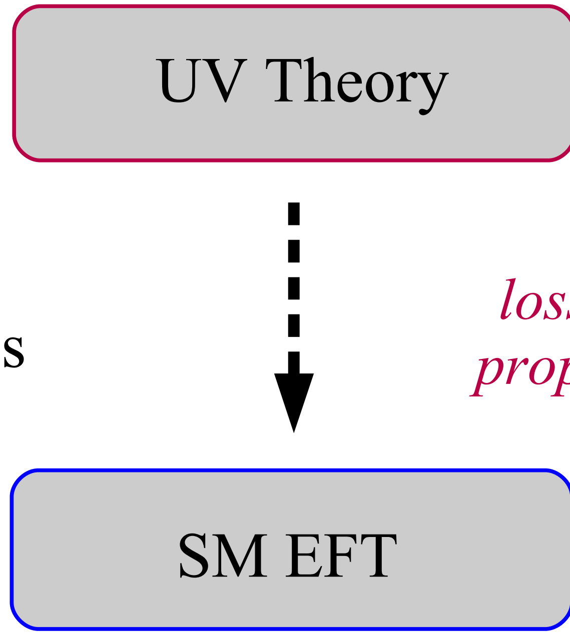


low-energy "projection"

loss of information about nature & properties of the high-energy modes

Reconstructing the UV theory from its low-energy limit is a very difficult problem with no unique solution [*~ 35 years from the Fermi Theory to the GSW model...*]

Hierarchy vs. Flavor problem in the SM EFT



Integrate out the high-energy modes

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loss of information about nature & properties of the high-energy modes

Reconstructing the UV theory from its low-energy limit is a very difficult problem with no unique solution [*~ 35 years from the Fermi Theory to the GSW model...*]

- The light fields appearing in the EFT are often superposition of the fundamental fields [*N.B.: true also for weak theories & gauge fields:* $A_\mu = c_\theta B_\mu + s_\theta W_\mu$]
- Many global symmetries of the EFT could by accidental low-energy properties
- The most interesting hints on UV dynamics comes from *un-natural features* of the EFT...

Hierarchy vs. Flavor problem in the SM EFT

"trivial" low-energy projection

↓

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yuk}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

Structure fully dictated by

- Number of light fields
- Their charges under long-range interactions

Contains only "natural" O(1) couplings

Hierarchy vs. Flavor problem in the SM EFT

Non-trivial UV imprints

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yuk}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

I $m_\phi^2 H^2$ (→ $\mathscr{L}_{\text{Higgs}}$)

III $y_{ij}\, \psi_i \psi_j H$ (→ $\mathscr{L}_{\text{Yuk}}$)

- $\Lambda_{t,W,H} >$ (few) TeV — II
- $\Lambda_{CP,\,F} > 10^{2\text{-}4}$ TeV — IV
- $\Lambda_L \sim 10^{14}$ TeV
- $\Lambda_B > 10^{15}$ TeV

- Hierarchy problem (II vs. I): $m_\phi \ll \Lambda_{t,W,H}$
- SM Flavor problem (III): $y_e \ll y_t$ [N.B.: 5 orders of magnitude !]
- NP Flavor problem (IV vs. I): $m_\phi \ll \Lambda_{CP,\,F}$

Hierarchy vs. Flavor problem in the SM EFT

Non-trivial UV imprints

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$\Lambda_{t,W,H} >$ (few) TeV (II)

$\Lambda_{CP,\,F} > 10^{2\text{-}4}$ TeV (IV)

(I) $m_\phi^2 H^2$ → $\mathscr{L}_{\text{Higgs}}$

(III) $y_{ij}\, \psi_i \psi_j H$ → $\mathscr{L}_{\text{Yuk}}$

The MFV "solution" (popular in the *pre-LHC era*):

- The genuine hierarchy problem is not too severe → expect NP at TeV scale
- Postpone the solution of III to very high scale, and assume no other sources of flavor-breaking at low-energies → TeV scale NP is flavor-blind

Try to separate the two problems & postpone the Flavor one

Hierarchy vs. Flavor problem in the SM EFT

Non-trivial UV imprints

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$\Lambda_{CP,\,F} > 10^{2\text{-}4}$ TeV (IV)

(I) $m_\phi^2 H^2$ (III) $y_{ij}\, \psi_i \psi_j H$

The anthropic/landscape idea (popular in the *post LHC run-I era*):

- The genuine hierarchy problem is already too severe → give up on it... (at least at the EFT level)
- Push the scale of NP to very high scale, so there is no NP flavor problem

Ignore both the Hierarchy & the SM Flavor problems

Hierarchy vs. Flavor problem in the SM EFT

Non-trivial UV imprints

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yuk}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

$\Lambda_{t,W,H} >$ (few) TeV II

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I $m_\phi^2 H^2$

III $y_{ij}\, \psi_i \psi_j H$

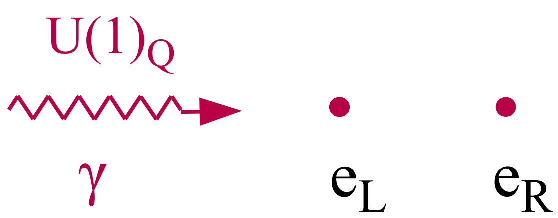
The path of flavor non-universal interactions (not so popular *yet*...):

- The hierarchical structure of the SM Yukawa coupl. is a clear indication that all the new degrees of freedom are coupled in a non-universal way to SM fermion families → expect TeV scale NP coupled mainly to 3rd gen.
- Genuine hierarchy problem less severe for NP coupled mainly to 3rd gen.

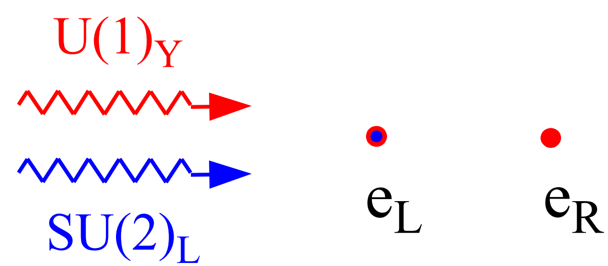
We should not give up & should not try to separate the two problems

▶ *Hierarchy vs. Flavor problem in the SM EFT*

In the low-energy limit of the SM (= QED×QCD) we observe perfect universality of LH and RH gauge couplings. However, we know this is a low-energy artifact:

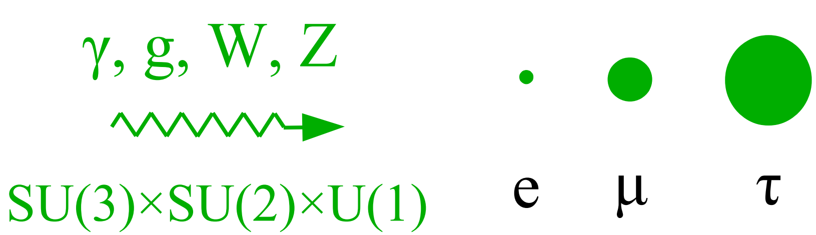


Low energies



High energies

Similarly, the apparent flavor symmetry of the SM could well be only an accidental low-energy property...



???

Hierarchy vs. Flavor problem in the SM EFT

Non-trivial UV imprints

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{yuk}} + \sum_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

I $m_\phi^2 H^2$ III $y_{ij}\, \psi_i \psi_j H$

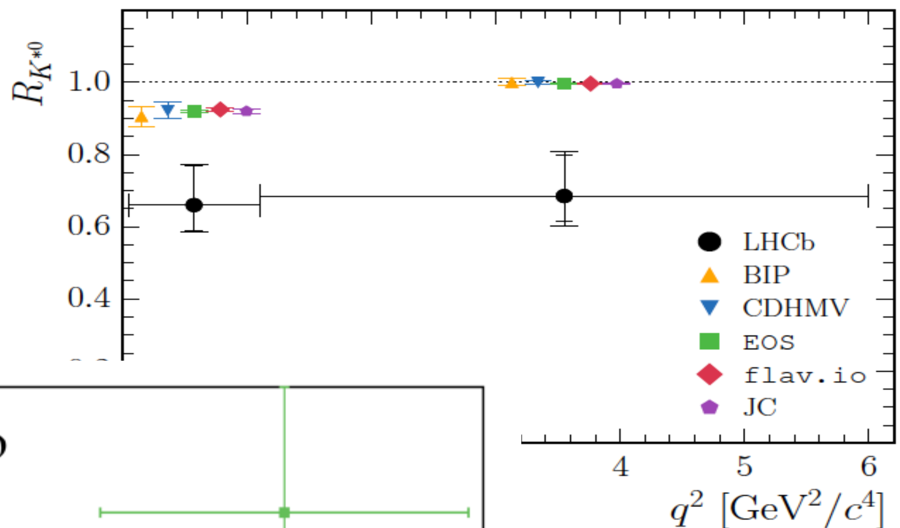
- $\Lambda_{t,W,H} >$ (few) TeV
- $\Lambda_{LFU} \sim$ few TeV
- $\Lambda_{CP,\,F} > 10^{2\text{-}4}$ TeV

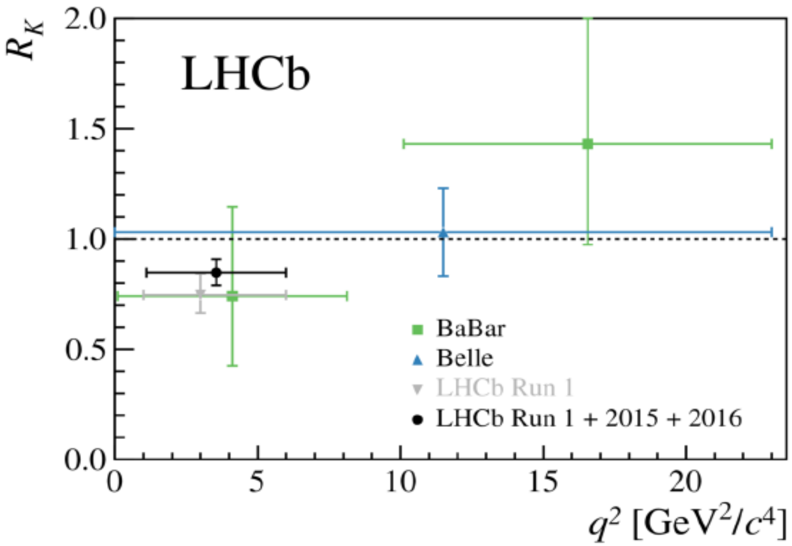
The path of flavor non-universal interactions (not so popular *yet*...):

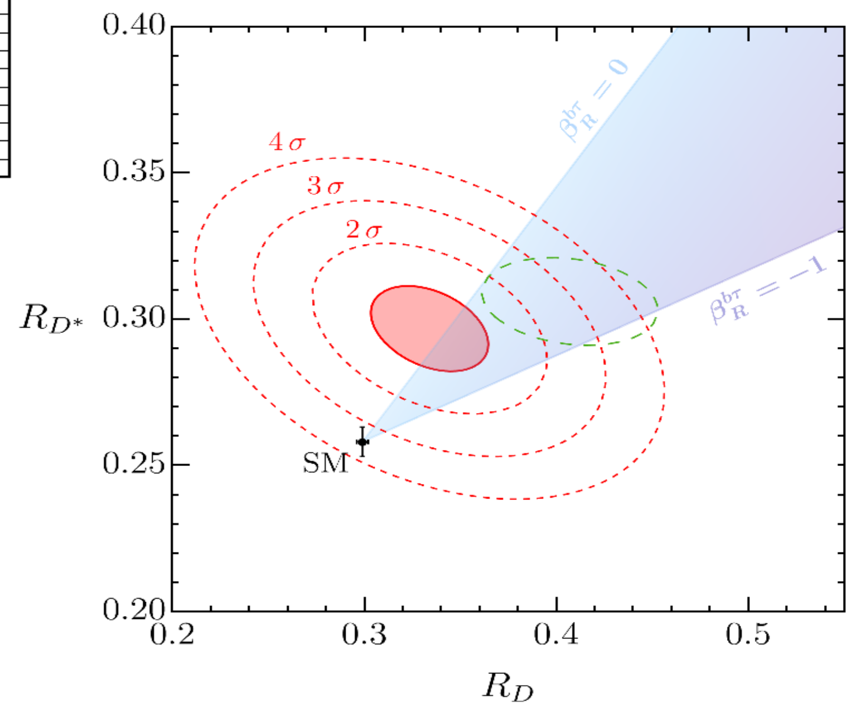
- The hierarchical structure of the SM Yukawa coupl. is a clear indication that all the new degrees of freedom are coupled in a non-universal way to SM fermion families → expect TeV scale NP coupled mainly to 3rd gen.

This is the path that seems to be indicated by the recent hints of Lepton Flavor non Universality in semi-leptonic B decays

LFU anomalies & Flavor symmetries







On the LFU anomalies

Recent data show some convincing evidences of Lepton Flavor Universality violations

- $b \to c$ charged currents: τ vs. light leptons (μ, e) [R_D, R_{D*}]
- $b \to s$ neutral currents: μ vs. e [R_K, R_{K*} (+ P_5 *et al.*)]

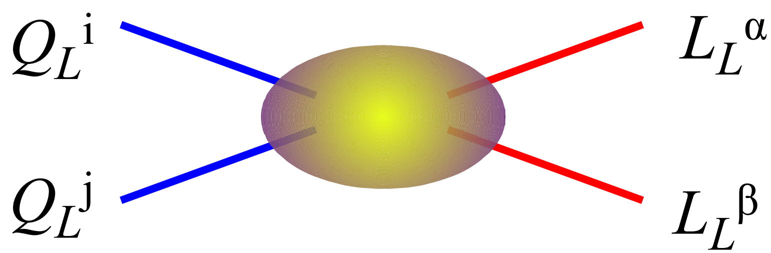
IF taken together... this is probably the largest "coherent" set of deviations from the SM we have ever seen...

I made statements of this type back in 2015... Since then the evidence for the anomalies has significantly increased.

This winter we have seen a first small decrease of the significance of some the anomalies; however, the overall picture has not changed. Actually, I dare to say it has become even more consistent...

On the LFU anomalies

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- We definitely need non-vanishing left-handed current-current operators although other contributions are also possible



Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)

- Large coupling [*competing with SM tree-level*] in $bc \to l_3 \nu_3$ [R_D, R_{D*}]
- Small coupling [*competing with SM loop-level*] in $bs \to l_2 \, l_2$ [R_K, R_{K*}, ...]

$$\Lambda_{ij\alpha\beta} = (\delta_{i3}\times\delta_{3j})\times(\delta_{\alpha3}\times\delta_{3\beta}) \quad + \quad \text{small terms for } 2^{nd} \text{ (\& } 1^{st}\text{) generations}$$

→ *Link to pattern of the Yukawa couplings !*

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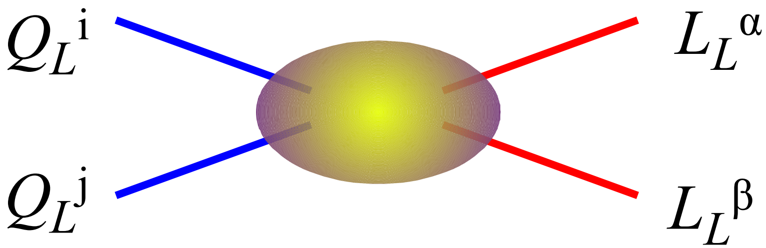

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(+many others...)

Long list of constraints [FCNCs + semi-leptonic b decays + π, K, τ decays + EWPO]

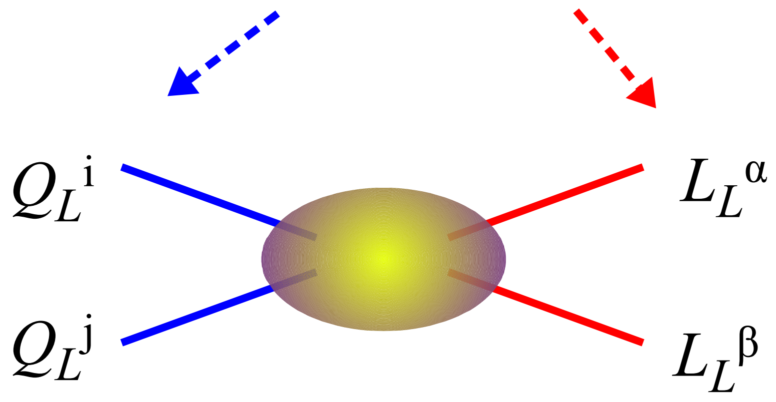
↓

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

▶ *LFU anomalies & 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 chiral flavor symmetry of the type U(2)^n

$$U(2)^n \supset U(2)_q \times U(2)_l$$



….with suitable (small) symmetry-breaking terms, related to the structures observed in the SM Yukawa couplings

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

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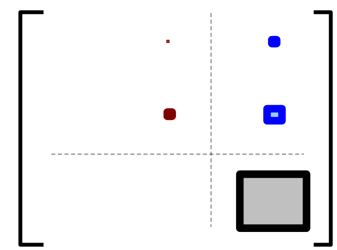
E.g. up-sector: $U(2)_q \times U(2)_u$

$$Y_U = y_t \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \leftarrow U(2)_q \quad \longrightarrow \quad \begin{bmatrix} \Delta & V \\ & 1 \end{bmatrix} \equiv$$



$\uparrow$ $U(2)_u$

unbroken symmetry

after symmetry symmetry

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

Main idea: the same symmetry-breaking pattern control the mixing $3^{rd} \to 1^{st}, 2^{nd}$ gen. for the NP responsible for the anomalies

$|V| \approx |V_{ts}| = 0.04$

$|\Delta| \approx y_c = 0.006$

N.B.: this symmetry & symmetry-breaking pattern was proposed well-before the anomalies appeared [*it is not ambulance chasing...!*]

LFU anomalies & the U(2)^n *flavor symmetry*

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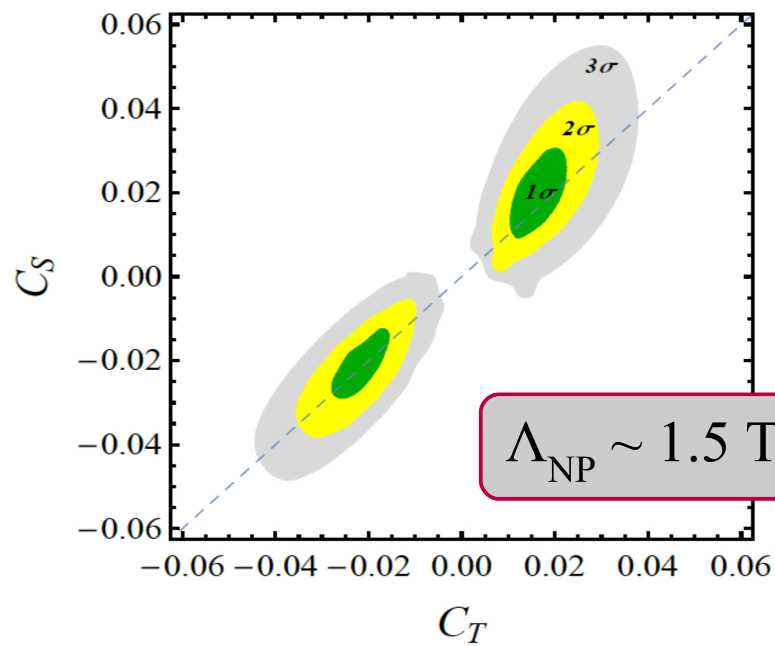
An EFT based on the following two hypothesis:

- $U(2)_q \times U(2)_l$ chiral flavor symmetry
- NP in left-handed semi-leptonic operators only [*at the high-scale*]

provides an excellent fit to the data

Buttazzo, Greljo, GI, Marzocca, '17



$\Lambda_{NP} \sim 1.5$ TeV

LFU anomalies & the U(2)^n *flavor symmetry*

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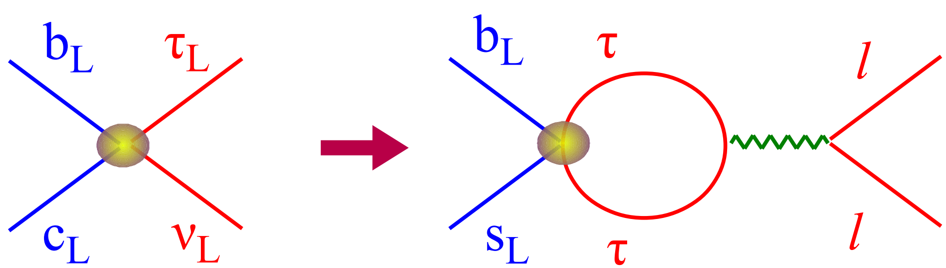
New data make this picture even more consistent:

I. Higher NP scale given smaller central value of $b \to c$ anomaly

II. Rising "evidence" of LFU contribution to C_9, naturally expected in this framework:

Alguero *et al.* '19
Aebischer *et al.* '19



Crivellin, Greub, Muller, Saturnino '19

▶ LFU anomalies & the $U(2)^n$ flavor symmetry

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⬇

An EFT based on the following two hypothesis:

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provides an excellent fit to the data

New data make this picture even more consistent:

I. Higher NP scale given smaller central value of $b \to c$ anomaly

II. Rising "evidence" of LFU contribution to C_9.

III. Rising "evidence" of a suppression of BR($B_s \to \mu\mu$), naturally expected by $\Delta C_9 = -\Delta C_{10}$

Greljo, GI, Marzocca, '15

$$BR(B_s \to \mu\mu)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$ Beneke et al. '19

$$BR(B_s \to \mu\mu)_{exp} = (2.72 \pm 0.34) \times 10^{-9}$$

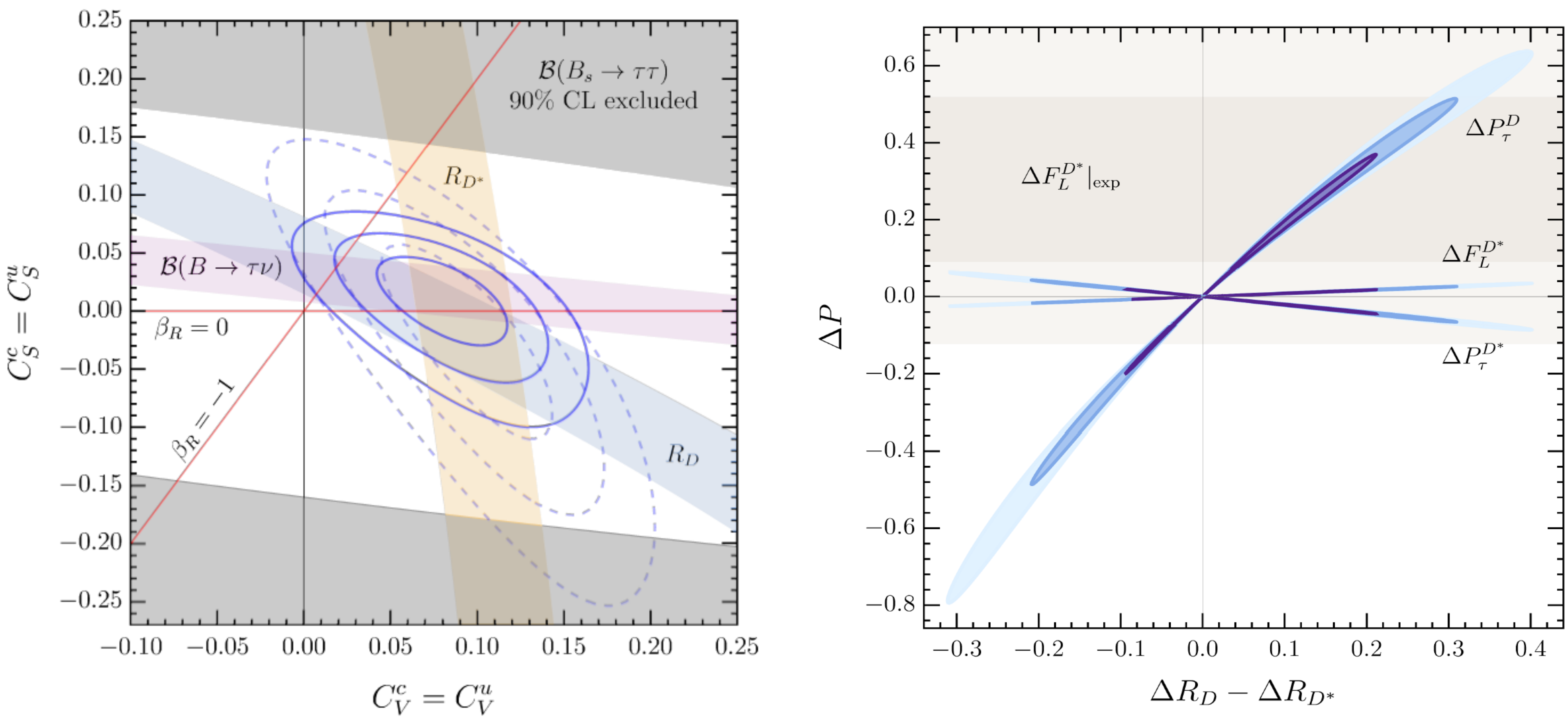
ATLAS+CMS+LHCb '19

2.6σ

▶ *LFU anomalies & the* U(2)^n *flavor symmetry*

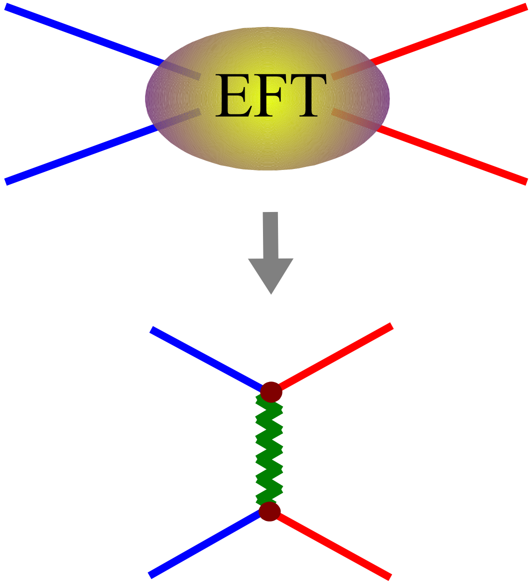
A nice virtue of the EFT approach with flavor symmetries is the predictive power.

Clear example in semileptonic charged-currents (*only 2 effective parameters, even dropping the assumption of pure LH couplings*):



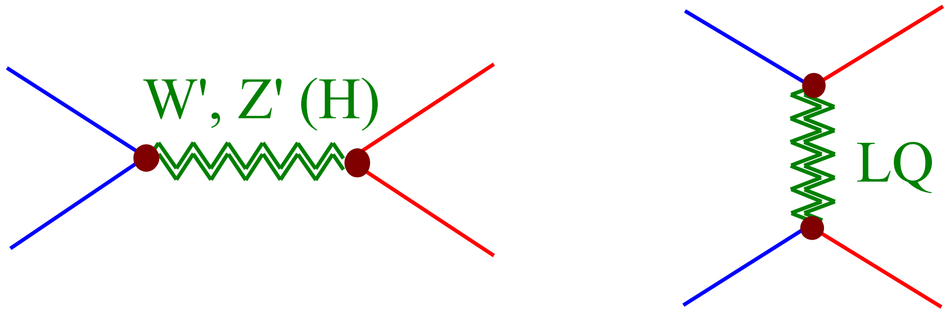
Fuentes-Martin, GI, Pages, Yamamoto, '19

Simplified models: the return of the Leptoquark



General considerations

Which tree-level mediators can generate the effective operators required for a successful EFT fit? Not many possibilities...



N.B.: Given the effective low-scale of NP, we are naturally lead to simplified models with tree-level leading mediators

These simplified models are not meant to be complete UV models, but rather a "tool" to connect

- low- vs. high-energy phenomenology,
- disconnected sectors of the EFT (e.g. semi-leptonic vs. $\Delta F=2$ ops.)

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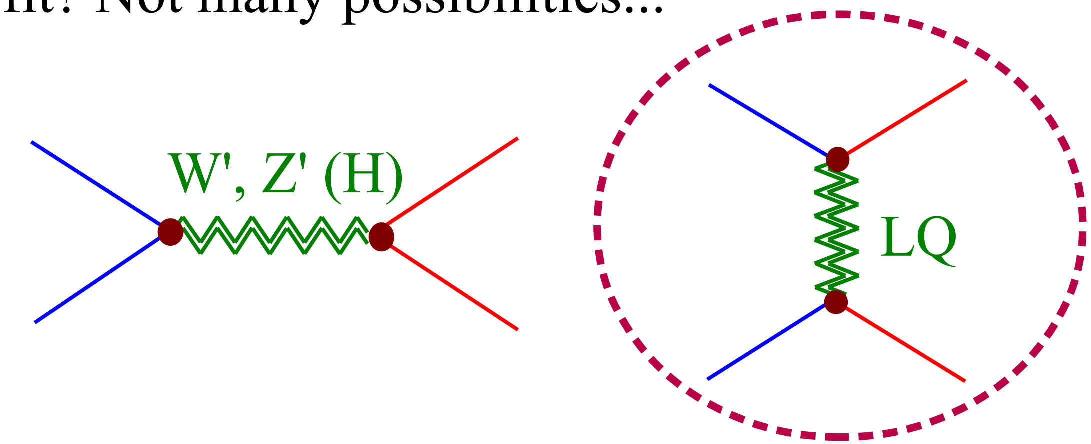
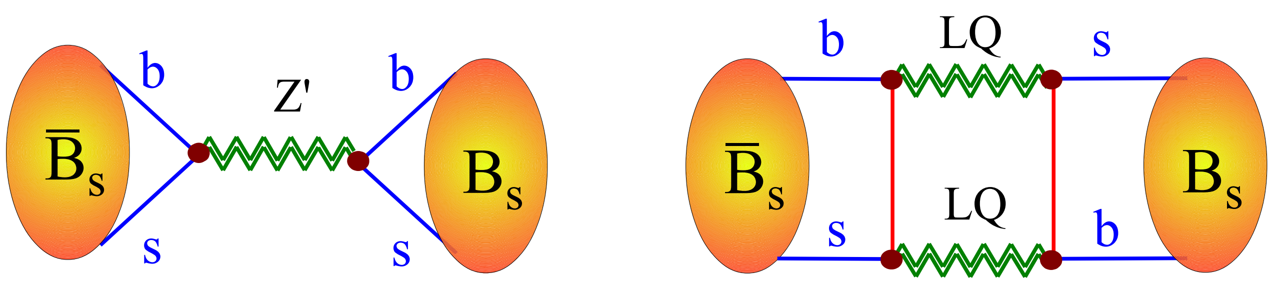


LQ (both scalar and vectors) have two general strong advantages with respect to the other mediators:

I. $\Delta F=2$ & $\tau \rightarrow l\nu\nu$



II. Direct searches: 3rd gen. LQ are also in better shape as far as direct searches are concerned (*contrary to Z'...*).

▶ *General considerations*

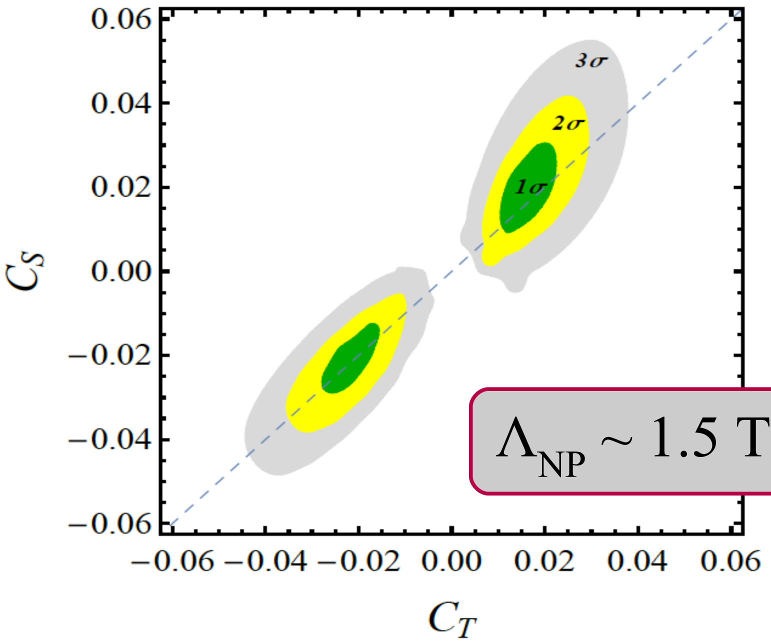
Which LQ explain which anomaly?

	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
Scalars	$S_1 = (\mathbf{3}, \mathbf{1})_{-1/3}$	✗	✓	✗
	$R_2 = (\mathbf{3}, \mathbf{2})_{7/6}$	✗	✓	✗
	$\widetilde{R}_2 = (\mathbf{3}, \mathbf{2})_{1/6}$	✗	✗	✗
	$S_3 = (\mathbf{3}, \mathbf{3})_{-1/3}$	✓	✗	✗
Vectors	$U_1 = (\mathbf{3}, \mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3}, \mathbf{3})_{2/3}$	✓	✗	✗

Angelescu, Becirevic, DAF, Sumensari [1808.08179]

There is one clear winner [U_1]...

Buttazzo, Greljo, GI, Marzocca, '17



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General considerations

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Vectors	$U_1 = (\mathbf{3},\mathbf{1})_{2/3}$	✓	✓	✓
	$U_3 = (\mathbf{3},\mathbf{3})_{2/3}$	✓	✗	✗

There is one clear winner [U_1]...

...but the single-mediator case is definitely an over simplification [*as we learned in the last ~ 2 years...*]

3 interesting options:

- U_1 + colorless-vectors

  Being a massive vector, U_1 requires an appropriate UV compl. → always accompanied by (at least) a Z'

  Alonso, Grinstein, Camalich '15
  Barbieri, GI , Pattori, Senia '15
  + wide literature

- S_1 & S_3

  Good option for the EFT "pure-LH" solution

  Crivellin, Muller, Ota '17
  Buttazzo *et al.* '17
  Marzocca '18

- R_2 & S_3

  GUT-inspired option for EFT solution including also RH currents

  Becirevic *et al.* '18

▶ *A "consistent" simplified model for the* U_1

- Initial attempts focused on LQ with few, purely LH couplings.
  However, the quantum numbers of the U_1 allow both RH and LH currents.
- A consistent reduction in the number if free parameters is achieved with the help of the flavor symmetry:

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_{i\alpha}^L (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) - \beta_{i\alpha}^R (\bar{d}_R^i \gamma_\mu e_R^\alpha)\right] + \text{h.c.}$$

U(2)^n flavor symm. with
Yukawa-like breaking

to a good approximation...

$$\beta_{ql}^L \sim \begin{bmatrix} 0 & 0 & 10^{-2} \\ 0 & 10^{-2} & 10^{-1} \\ 10^{-2} & 10^{-1} & 1 \end{bmatrix} + O(10^{-3})$$

$O(|V_{ts}|)$

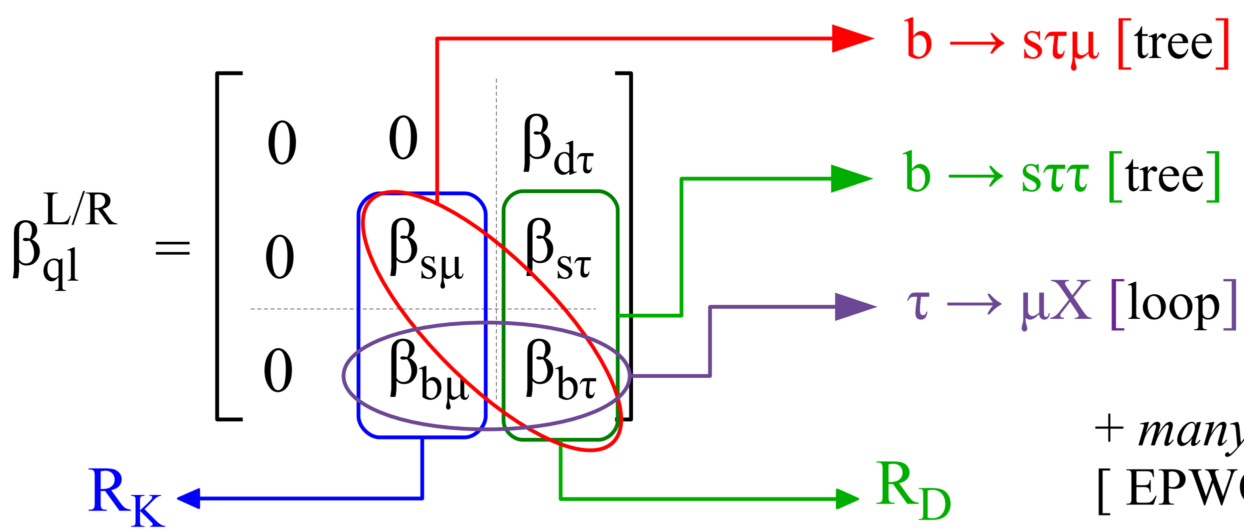
$$\beta_{ql}^R \sim \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 10^{-2} \\ 0 & 10^{-2} & 1 \end{bmatrix} + O(10^{-3})$$

$O(\,|V_{ts}|\, m_s/m_b\,)$

A "consistent" simplified model for the U_1

- Initial attempts focused on LQ with few, purely LH couplings. However, the quantum numbers of the U_1 allow both RH and LH currents.
- A consistent reduction in the number if free parameters is achieved with the help of the flavor symmetry:

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta^L_{i\alpha}(\bar{q}^i_L \gamma_\mu \ell^\alpha_L) - \beta^R_{i\alpha}(\bar{d}^i_R \gamma_\mu e^\alpha_R)\right] + \mathrm{h.c.}$$



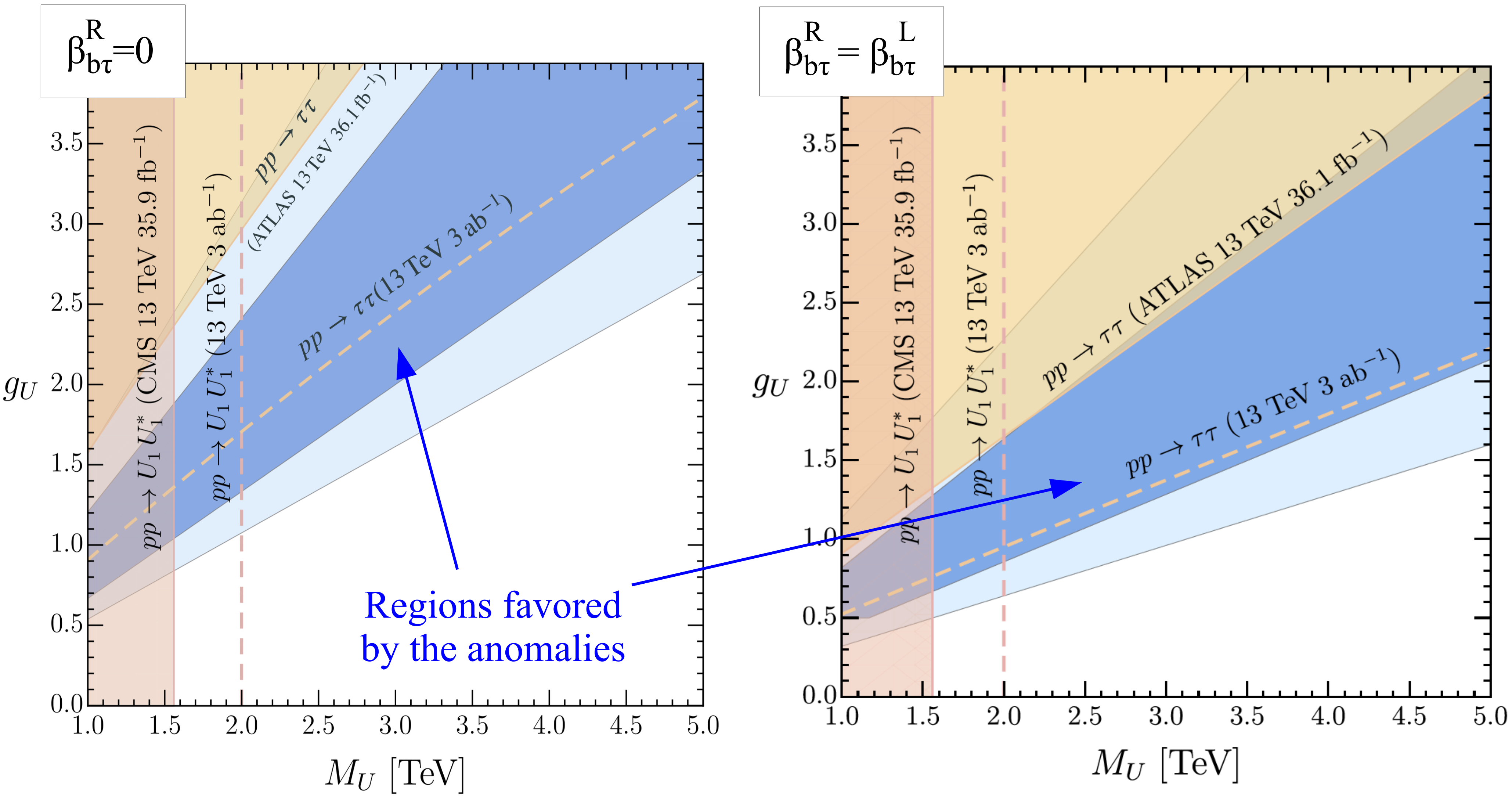
+ *many other effects*
[EPWO, LFU in τ's...]

The presence of the (motivated) extra coupling leads to a series of interesting effects at both low- and high-energies

Bordone, Cornella, Fuentes-Martin, GI, '18
Cornella, Fuentes-Martin, GI, '19

▶ A "consistent" simplified model for the U_1

The presence of RH couplings leads to significant differences at high-p_T:

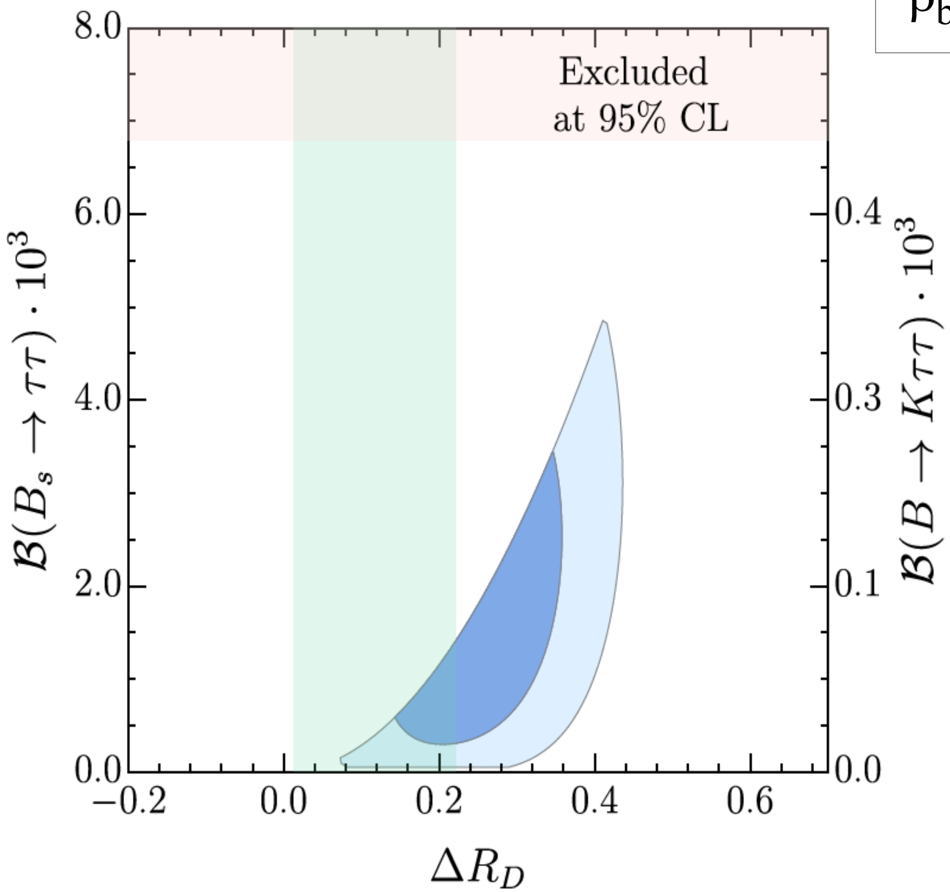


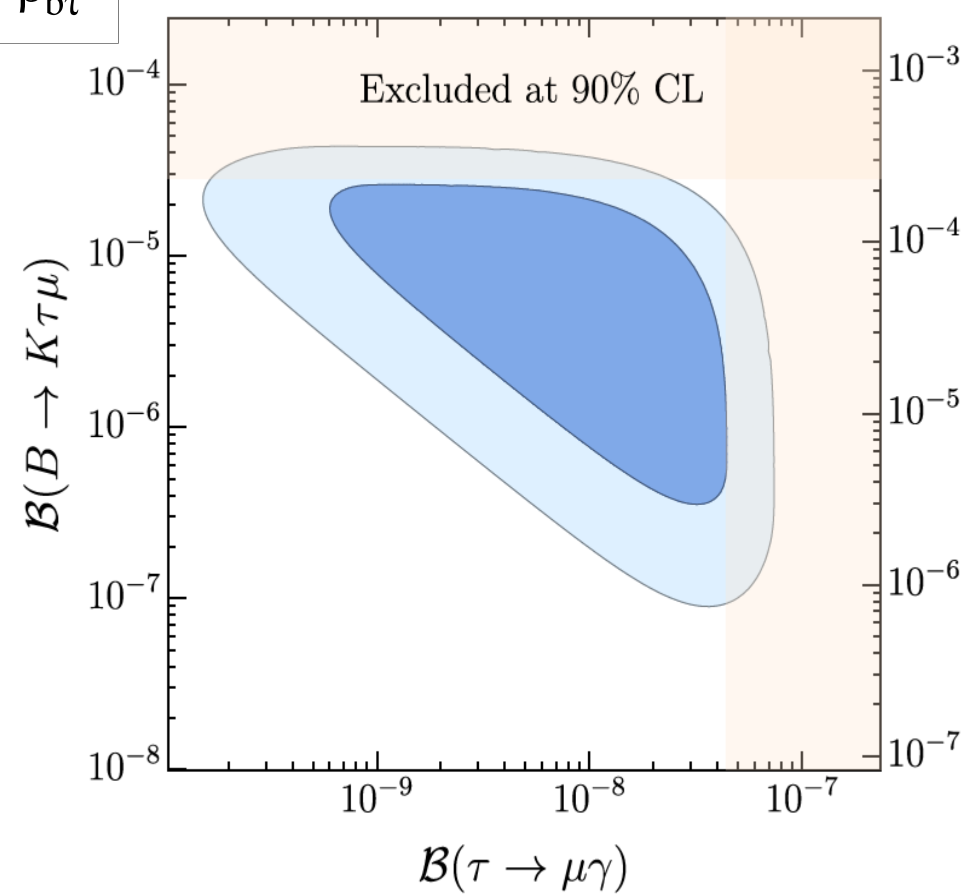
Baker, Fuentes-Martin, GI, König, '19

▶ *A "consistent" simplified model for the* U_1

Probably the most striking signature of large RH couplings is the (unavoidable) large enhancement of B(B→ ττ) & B(B→ τμ):

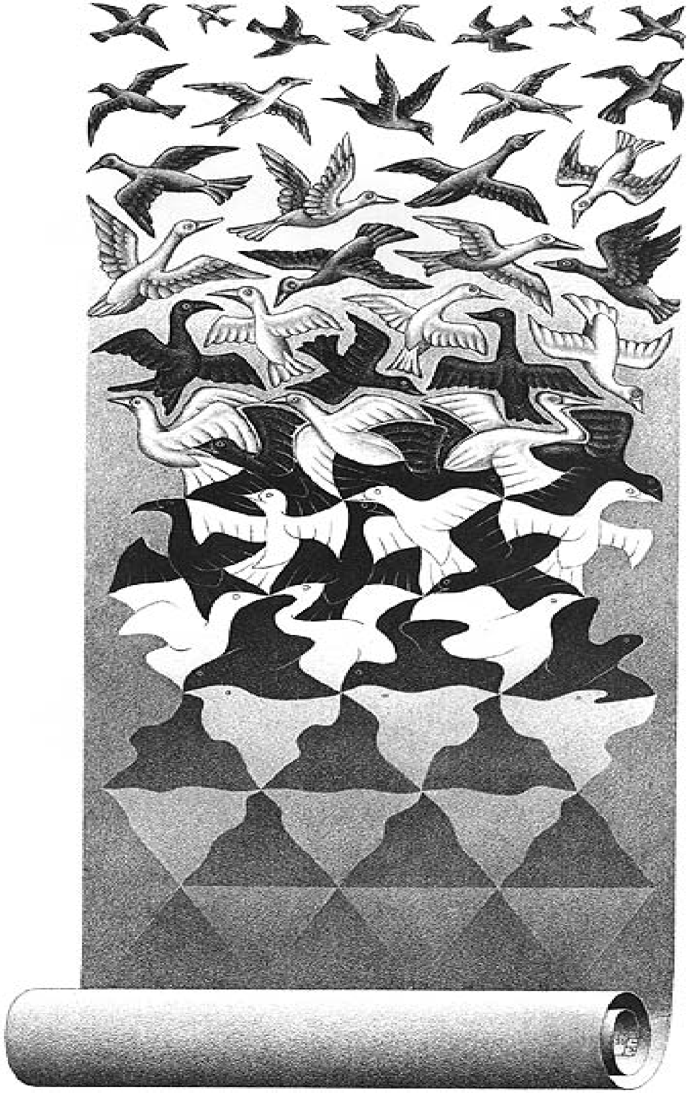
$$\beta^R_{b\tau} = \beta^L_{b\tau}$$





Cornella, Fuentes-Martin, GI, '19

Non-universal gauge interactions & the PS^3 hypothesis



▶ *Toward a UV completion: the* PS³ *hypothesis*

Starting observation: the 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:

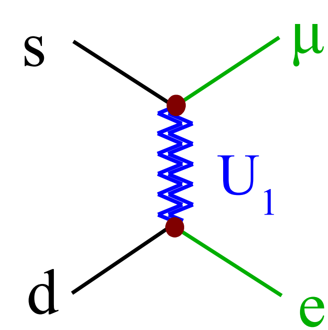
Pati-Salam group: $SU(4) \times SU(2)_L \times SU(2)_R$

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 $SU(4) \to SU(3)_C \times U(1)_{B-L}$

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 $K_L \to \mu e$]



Interesting recent attempts to solve this problem adding extra fermions and/or modifying the gauge group [Calibbi, Crivellin, Li, '17; Di Luzio, Greljo, Nardecchia, '17]

The PS^3 *model*

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

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 $U(1)_Y$ charges]

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

SM

IR

Q_i, u_i, d_i, L_i, e_i

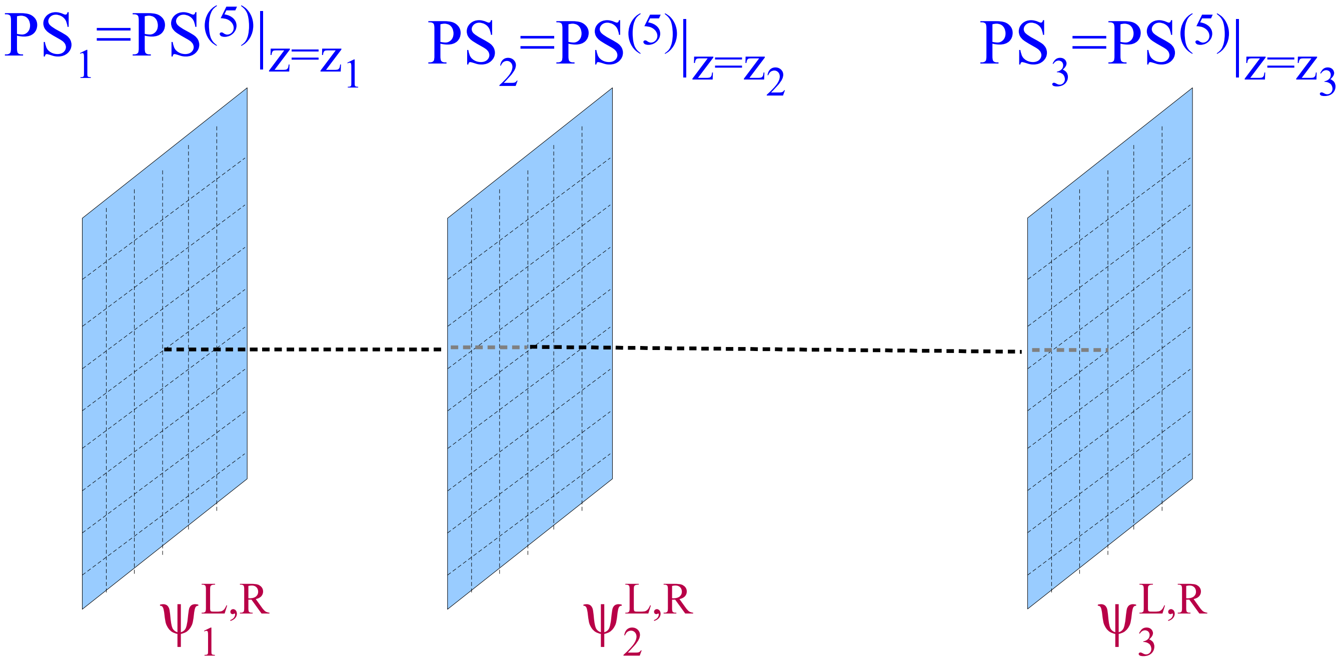
Key advantages:

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

▶ *The* PS^3 *model*

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

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



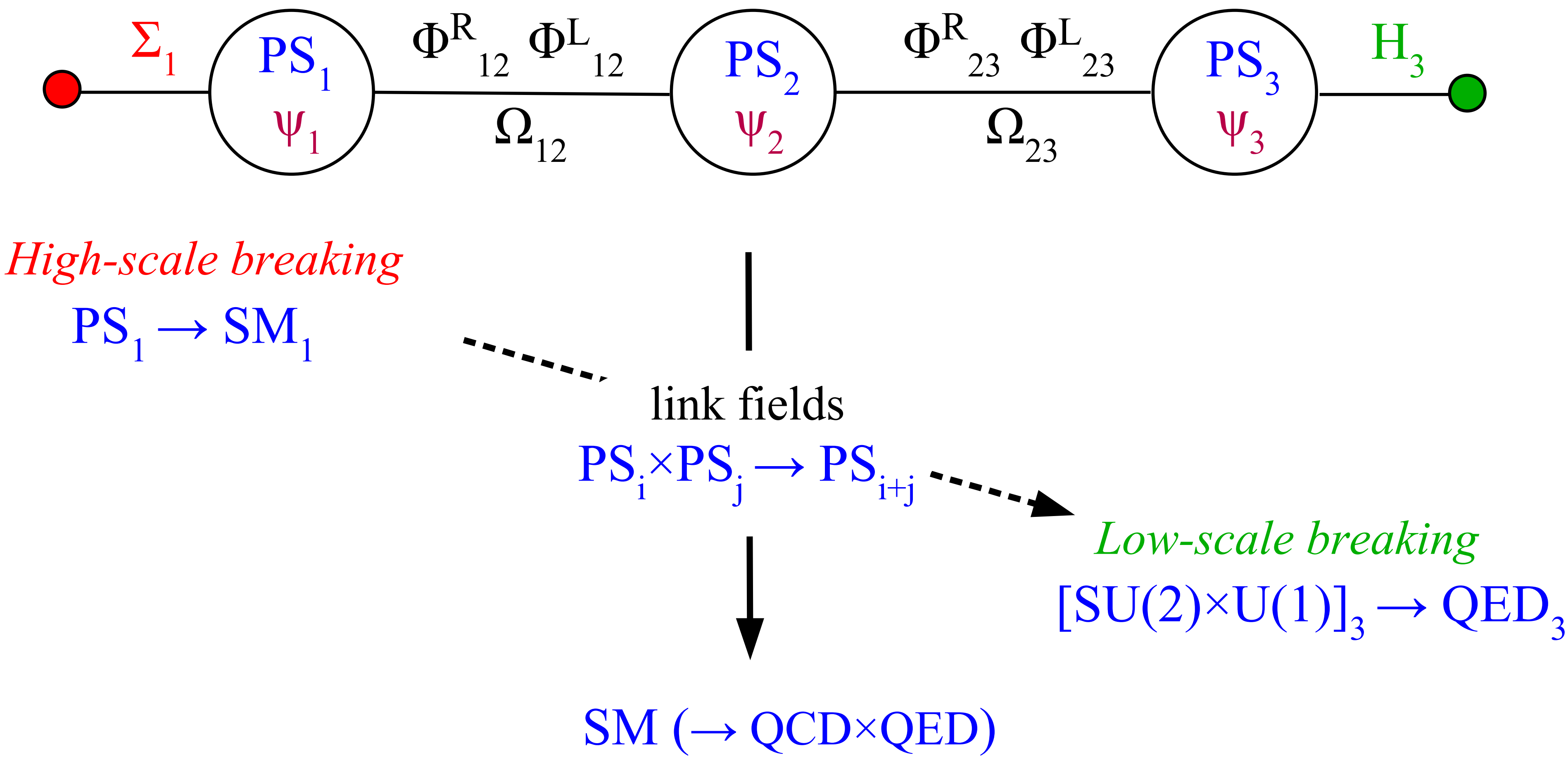
Unification
of quarks and leptons

"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*)

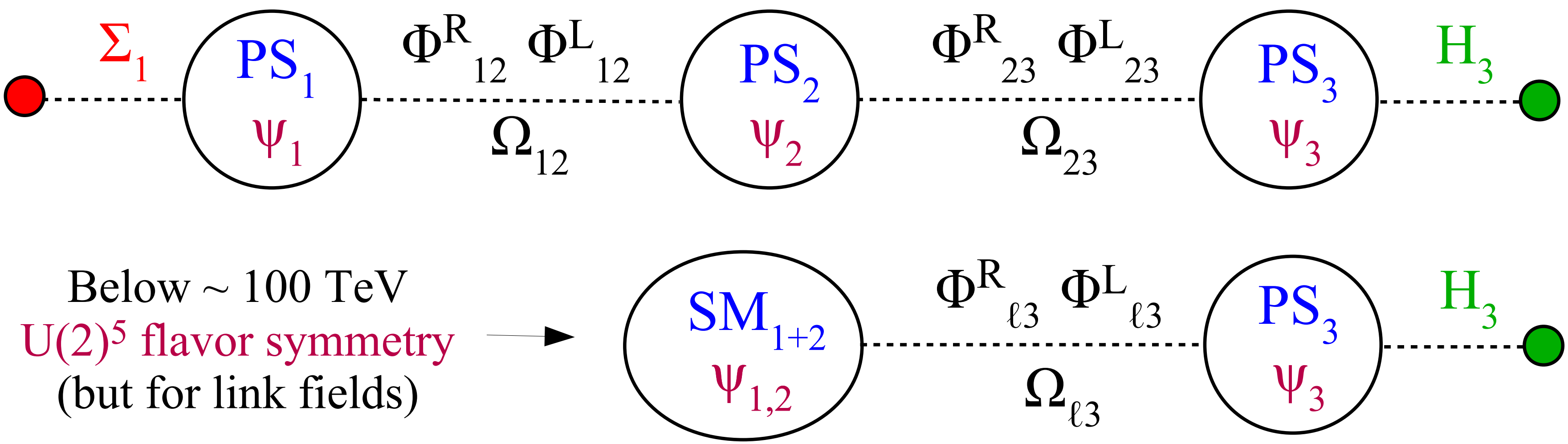
▸ *The* PS^3 *model*



- 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., as in the "4321" model [Di Luzio, Greljo, Nardecchia, '17]

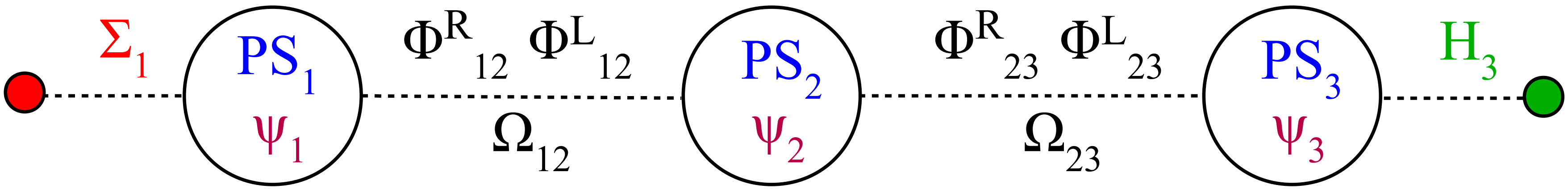
The PS^3 *model*



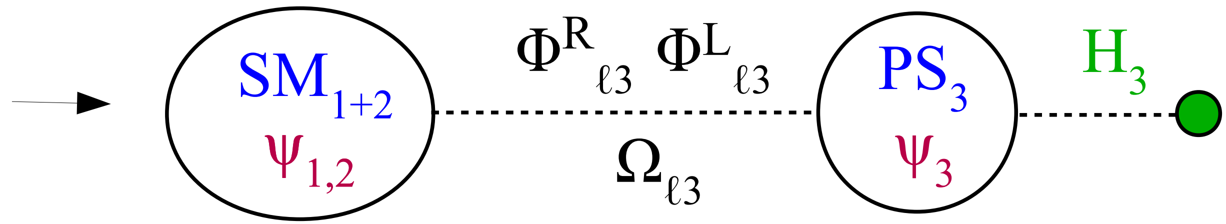
Leading flavor structure:

- 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*

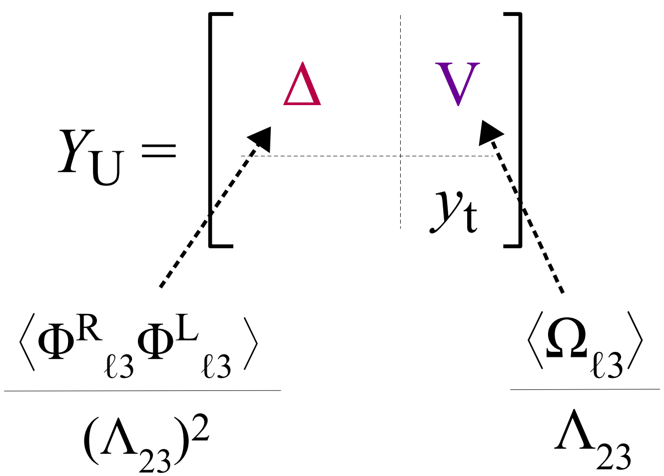


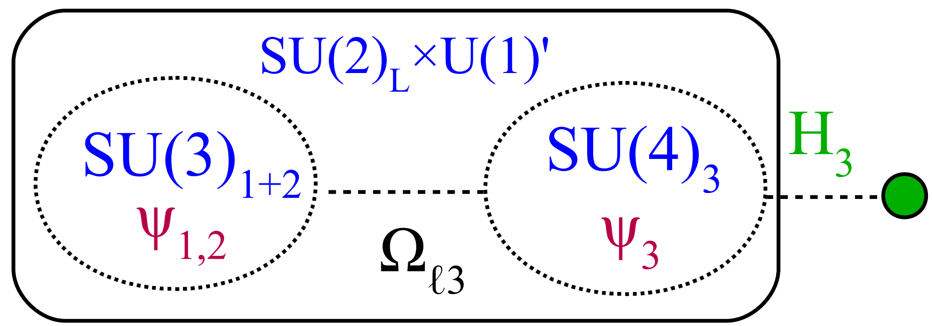
Below ~ 100 TeV
U(2)^5 flavor symmetry
(but for link fields)



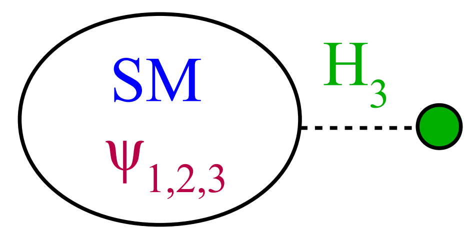
→ $W_L' + W_R'$ [~ 5-10 TeV]

Sub-leading Yukawa terms from higher dim ops:





→ LQ [U_1] + Z' + G' [~ 1-5 TeV]



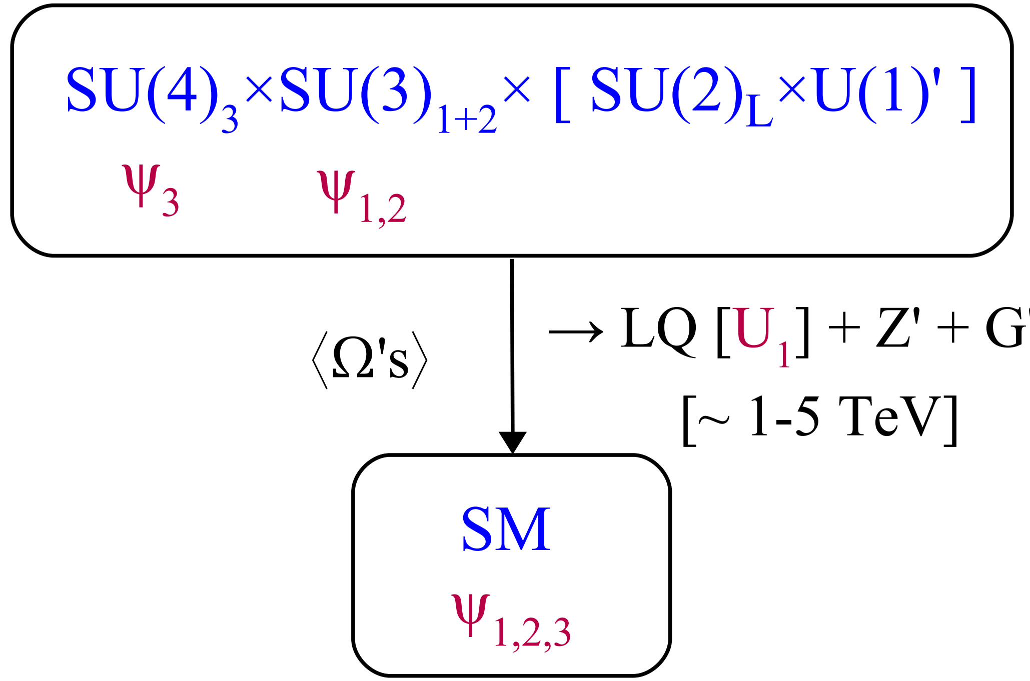
The PS^3 *model*

Present collider and low-energy pheno are controlled by the last-step in the breaking chain [4321 → SM]

Despite the apparent complexity, the construction is highly constrained

Renormalizable structure (no d>5 ops) achieved with vector-like fermions

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)'$
$q_L'^i$	**1**	**3**	**2**	$1/6$
$u_R'^i$	**1**	**3**	**1**	$2/3$
$d_R'^i$	**1**	**3**	**1**	$-1/3$
$\ell_L'^i$	**1**	**1**	**2**	$-1/2$
$e_R'^i$	**1**	**1**	**1**	-1
ψ_L'	**4**	**1**	**2**	0
ψ_u'	**4**	**1**	**1**	$1/2$
ψ_d'	**4**	**1**	**1**	$-1/2$
χ_L^i	**4**	**1**	**2**	0
χ_R^i	**4**	**1**	**2**	0
H_1	**1**	**1**	**2**	$1/2$
H_{15}	**15**	**1**	**2**	$1/2$
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	$-1/2$
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	$1/6$
Ω_{15}	**15**	**1**	**1**	0



We can reproduce all the positive features the simplified model

+

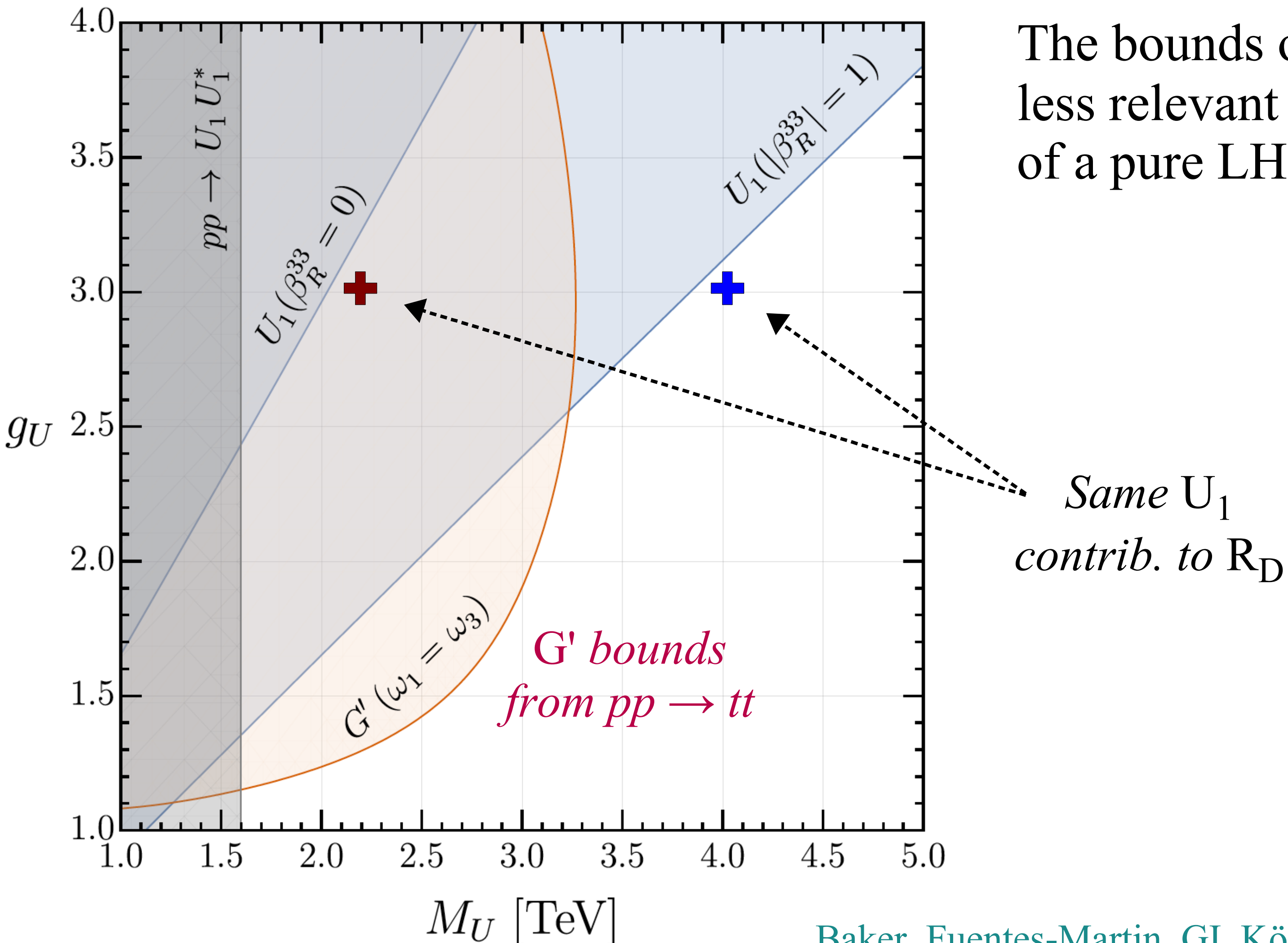
Calculability of ΔF=2 processes

[*in agreement with present data in large area of param. space*]

Greljo, Stefanek, '18; Di Luzio *et al.* '18; Cornella, Fuentes-Martin, GI, '19

The PS^3 *model*

A key difference between the simplified model and this complete UV model is the high-pT phenomenology, which now involves more states



The bounds on the coloron are less relevant in PS^3 vs. the case of a pure LH coupled U_1

Baker, Fuentes-Martin, GI, König, '19

Conclusions

- The recent LFU anomalies provide a concrete demonstration of the high discovery potential of indirect NP searches. Even if they will go away, they have been very beneficial in shaking some prejudices in model building and in (re-)opening new interesting directions.

- If interpreted as NP signals, both set of anomalies are not in contradiction among themselves & with existing low- & high-energy data.
Taken together, they point to NP coupled mainly to 3^{rd} generation, with a flavor structure connected to that appearing in the SM Yukawa couplings

- Simplified models with LQ states seem to be favored. Among them, the U_1 case stands for simplicity & phenomenological success.
The PS^3 model is an interesting example of (class of) UV framework(s) which could host it, and could help to shed light on Flavor & Hierarchy problems.

↓

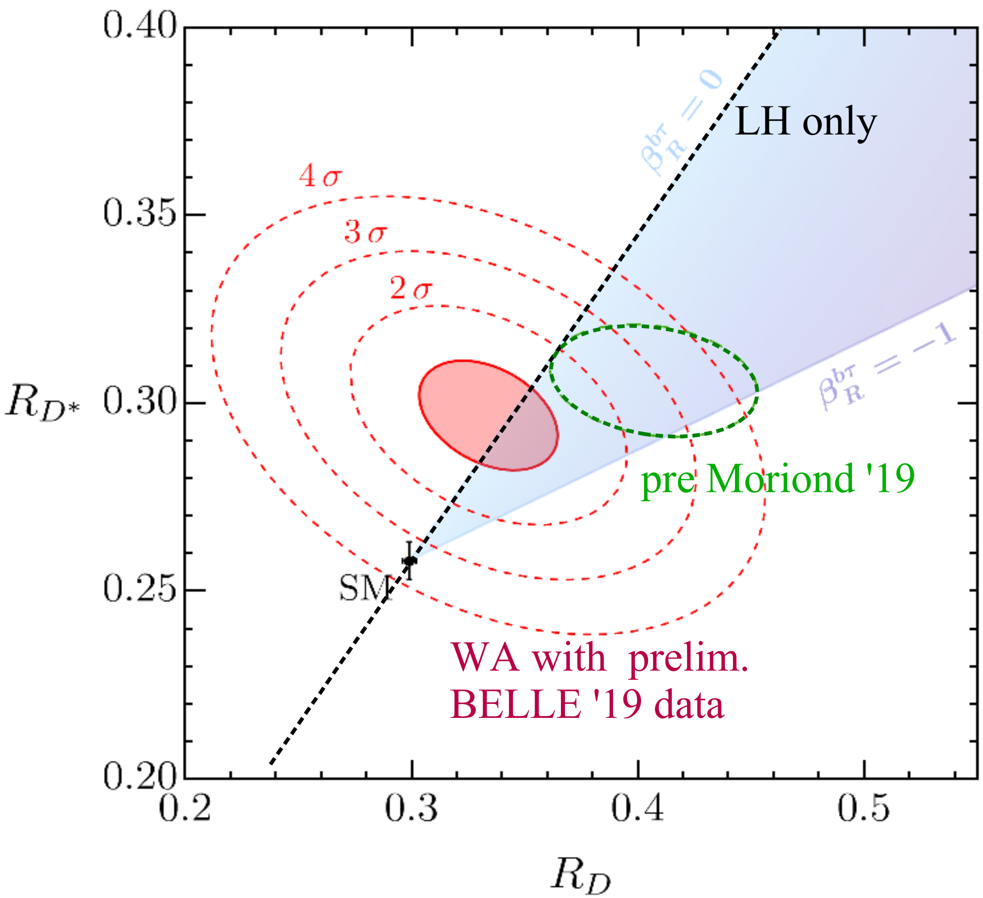
... a lot of fun ahead of us !
[both on the exp. / pheno / model-building point of view]

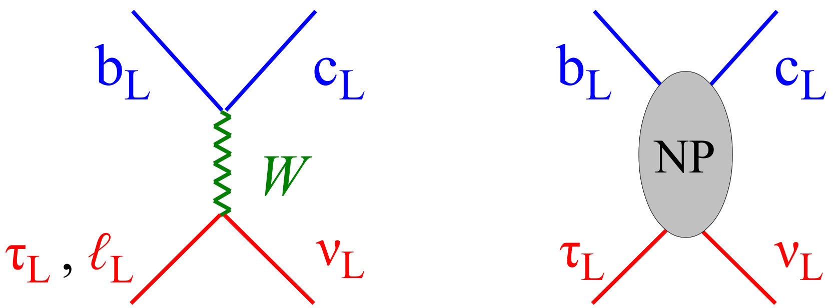

Backup

On the LFU anomalies

Recent data show some convincing evidences of Lepton Flavor Universality violations

- $b \to c$ charged currents: τ vs. light leptons (μ, e) [R_D, R_{D*}]
- $b \to s$ neutral currents: μ vs. e [R_K, R_{K*} (+ P_5 *et al.*)]





Several results by different exps.
all central values above the SM
→ combined deviation > 3σ

- Data can be explained by NP contributing only to $b_L \to c_L \, \tau_L \, \nu_L$ (*but other amplitudes possible...*)

On the LFU anomalies

Recent data show some convincing evidences of Lepton Flavor Universality violations

- $b \to c$ charged currents: τ vs. light leptons (μ, e) [R_D, R_{D*}]
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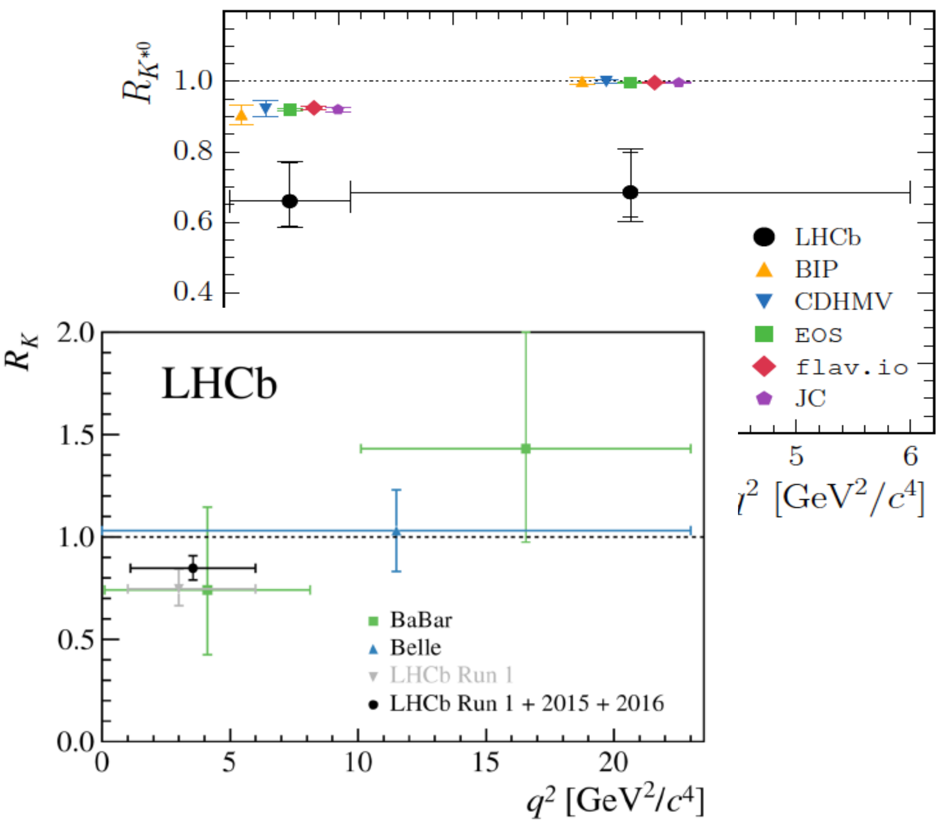
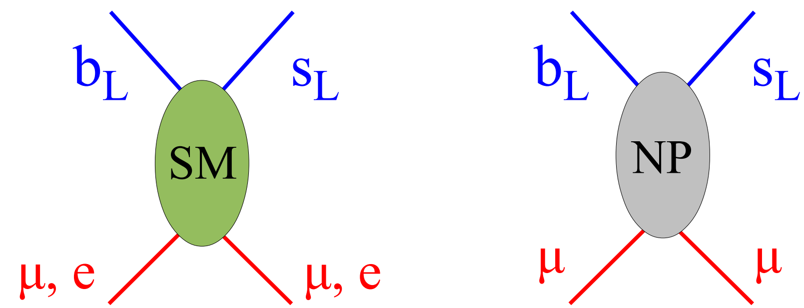
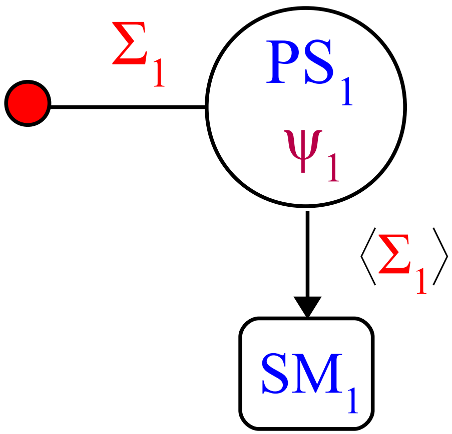


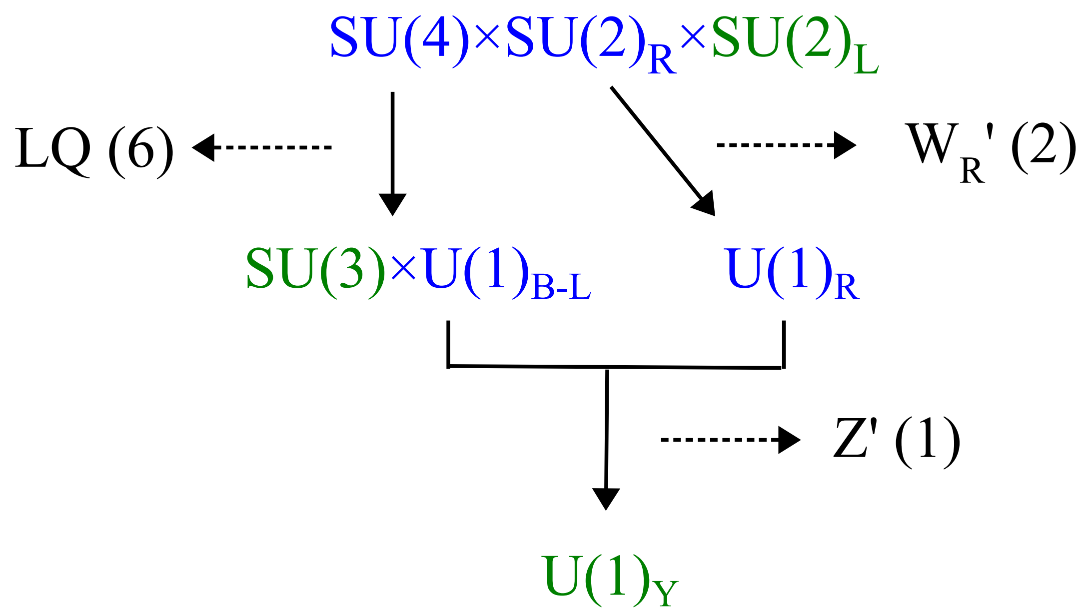


Non-trivial fit of several observables indicating NP of short-distance origin [3.8σ significance from LFU ratios only]

- Data can be explained by NP contributing only to $b_L \to s_L\, \mu_L \mu_L$ (*but other amplitudes possible.... & in this case definitely welcome*)

Symmetry breaking pattern in PS^3





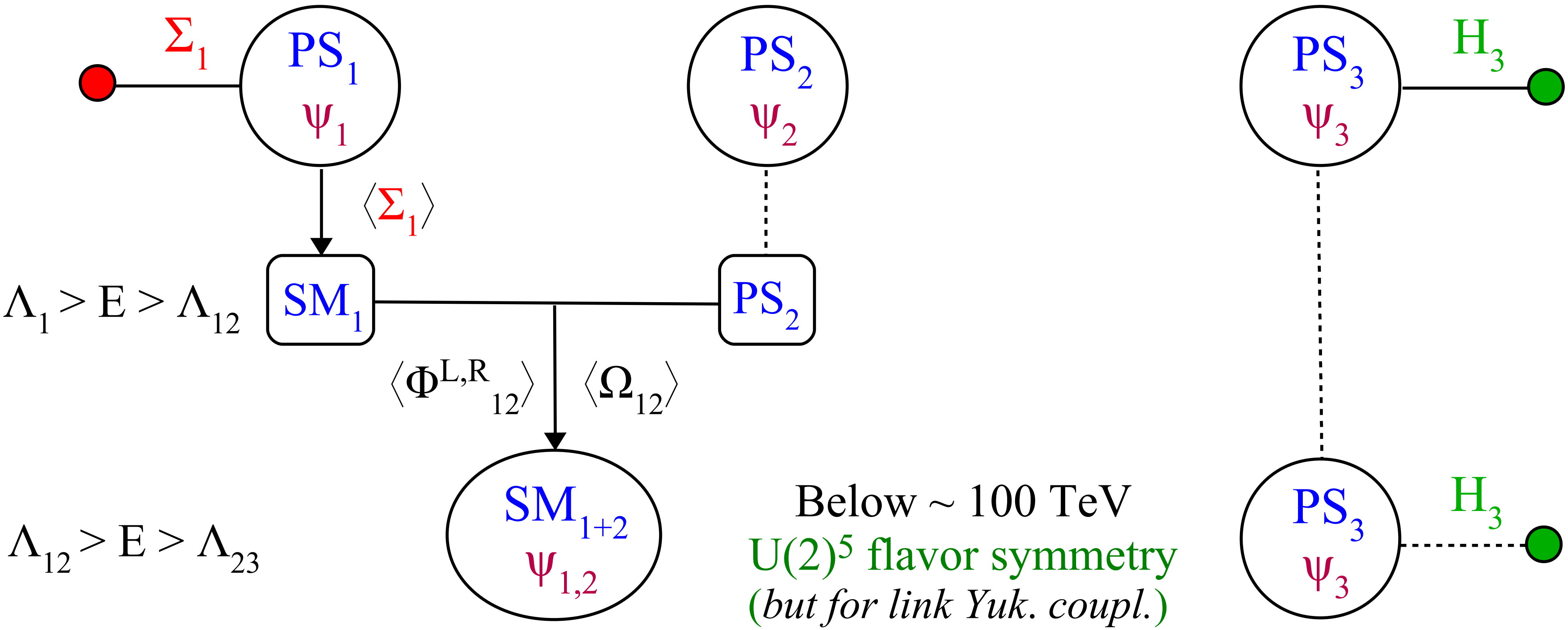
High-scale [~ 10^3 TeV]
"vertical" breaking [PS → SM]

PS_1 [$SU(4)_1 \times SU(2)^R{}_1$]

↓

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 $\rightarrow SU(2)^L{}_{1+2}$

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

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

The $b \to s\ell\ell$ anomalies

The largest (and statistically more significant) set of anomalies is the one extracted from rare decays mediated by $b \to s\, \ell^+\ell^-$ amplitudes [$\ell = \mu, e$]:

I. P'_5 anomaly [$B \to K^*\mu\mu$ angular distribution]

II. Smallness of all $B \to H_s\, \mu\mu$ rates [H_s=K, K^*, ϕ (from B_s)]

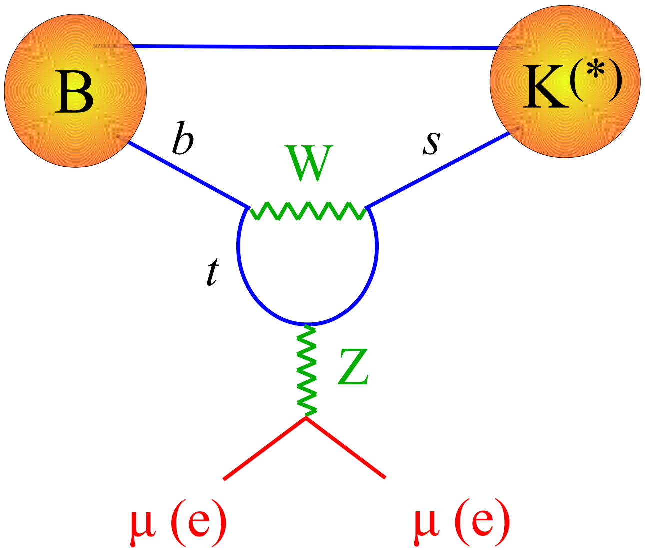
III. LFU ratios (μ vs. e) in $B \to K^*\ell\ell$ & $B \to K\,\ell\ell$

IV. Smallness of BR($B_s \to \mu\mu$)

chronological order

$b \to s\, \ell\ell$ transitions are Flavor Channing Neutral Current amplitudes

- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- *Sizable theory uncertainties* (*in some observables*)



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- LFU ratios (μ vs. e) in $B \to K^*\ell\ell$ & $B \to K\,\ell\ell$
- Smallness of BR($B_s \to \mu\mu$)

(bright green smiley) = th. error very small ($\lesssim$1%)

(olive green smiley) = th. error few %

Charm contributions (pert. +non-pert.) can induce only <u>lepton-universal</u> corrections <u>to C_9</u> (not to C_{10})

Generally they lead to <u>non-local effects</u> ($\leftrightarrow$ non-trivial q^2 dependence)

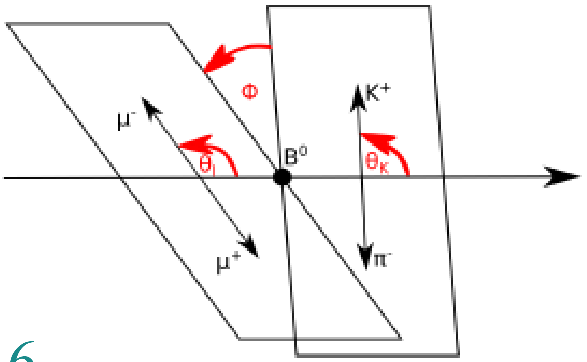
$$Q_9 = (\bar{b}_L \gamma_\mu s_L)\, \bar{l}\, \gamma^\mu l$$

$$Q_{10} = (\bar{b}_L \gamma_\mu s_L)\, \bar{l}\, \gamma^\mu \gamma_5 l$$

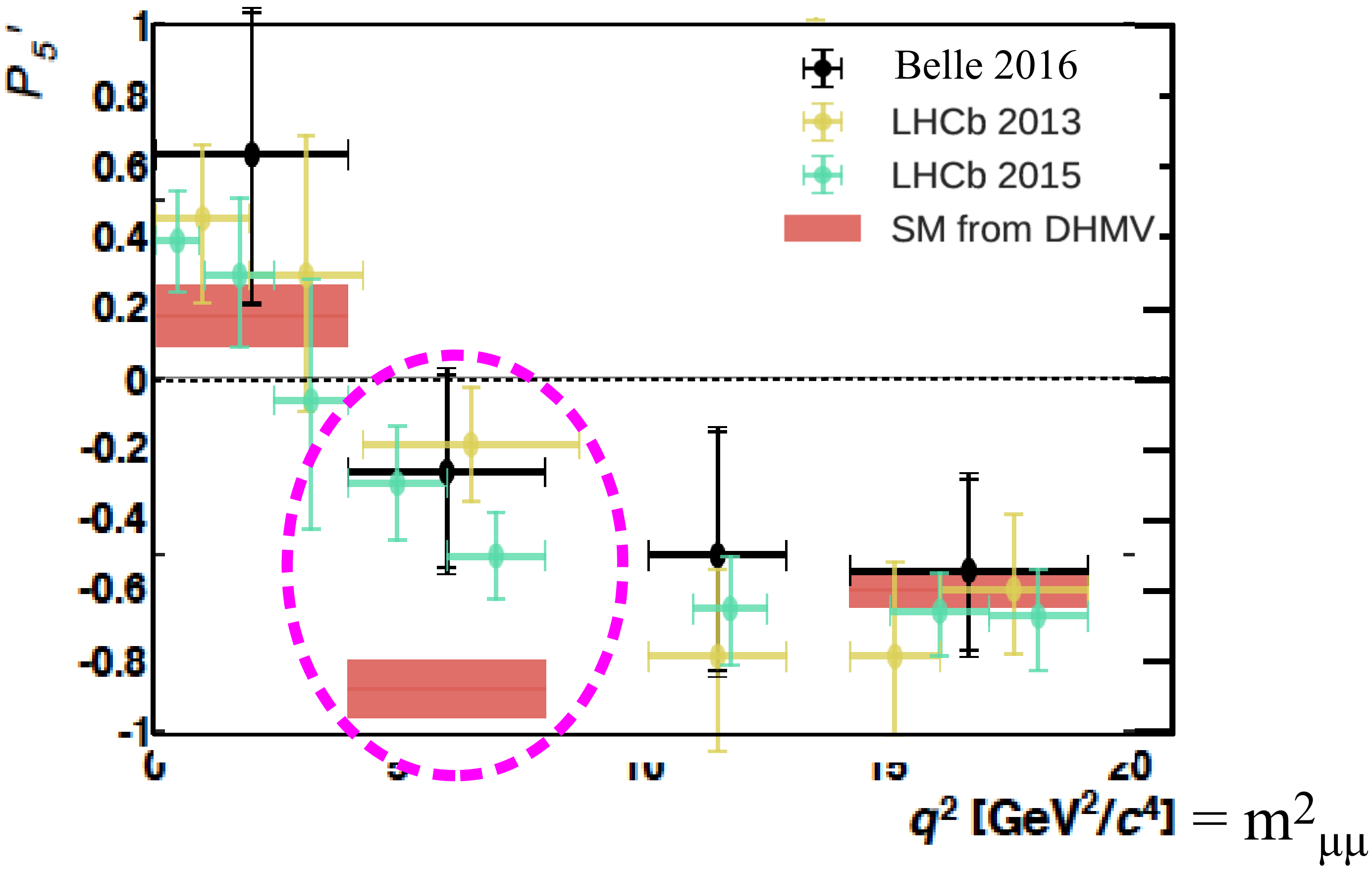
▶ *The $b \to s\ell\ell$ anomalies*

I. The P'_5 anomaly

The $B \to K^{*}\mu\mu$ differential distribution:



2016



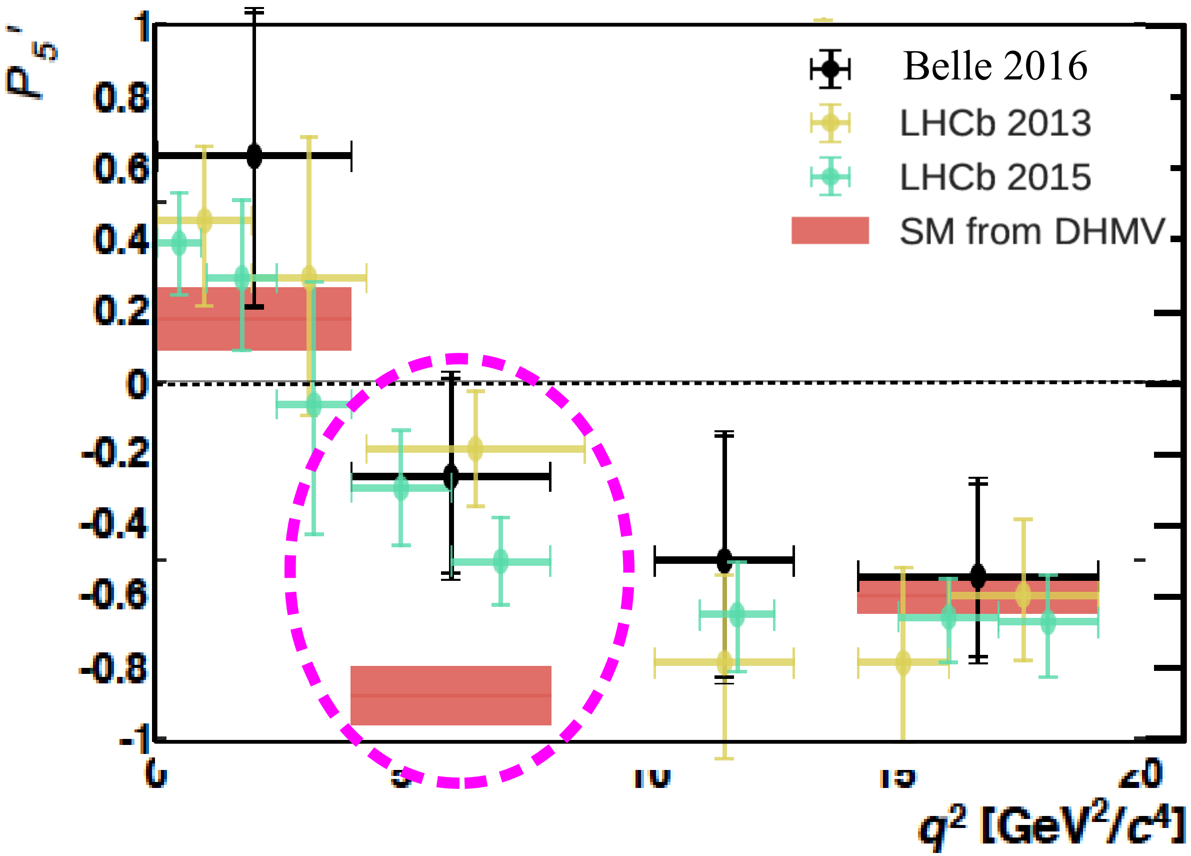
The $b \to s\ell\ell$ anomalies

I. The P'_5 anomaly [$B \to K^* \mu\mu$ differential distribution]

+

II. The smallness of $d\Gamma(B \to H_s\, \mu\mu)$ in several modes [$H_s = K$, K^*, ϕ (from Bs)]

2016



Pro NP:

Reduced tension in all the observable -*in all bins*- with a unique fit of non-standard $C_i(M_W) \to$ compatible with effect of short-distance origin

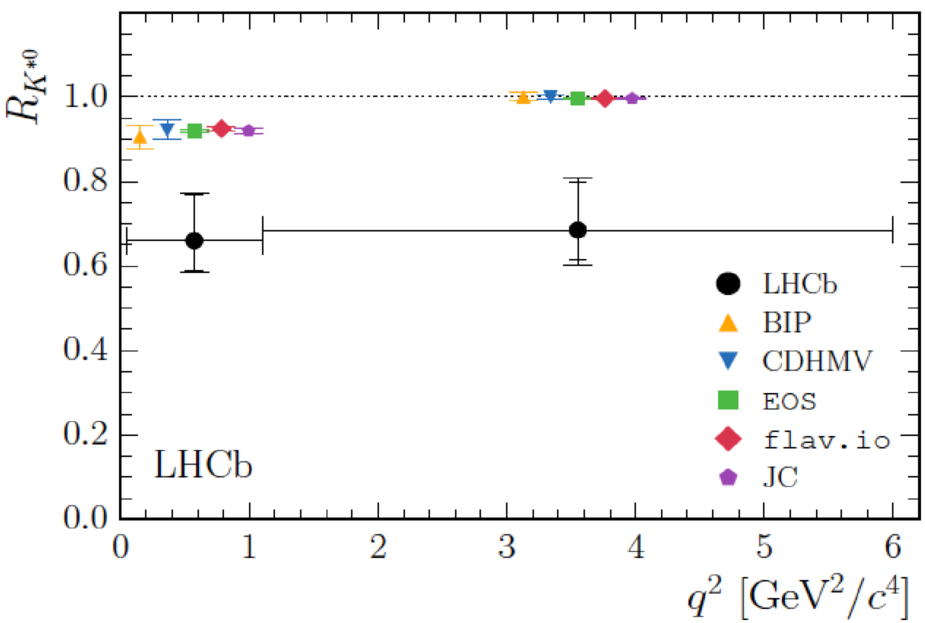
[*non-trivial:* O(100) *observ. few Wilson coeff.*]

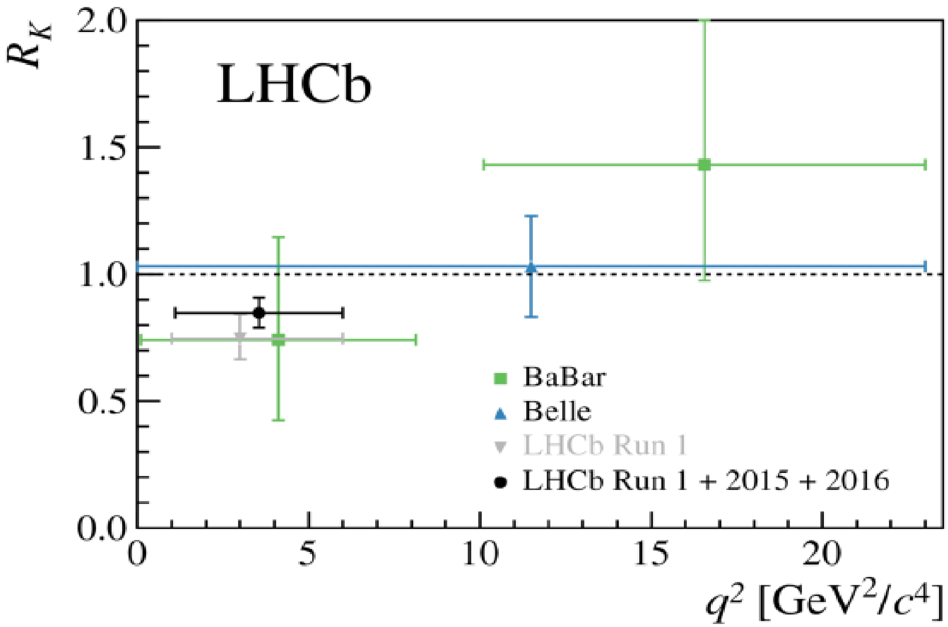
Against NP:

Non-standard effect mainly driven by C_9 ($\leftrightarrow$ *charm loops*) $\to$ significance reduced with conservative estimates of long-distance corrections

▶ The $b \to s\ell\ell$ anomalies

III. The "clean" LFU ratios: $$R_H = \frac{\int d\Gamma(B \to H\,\mu\mu)}{\int d\Gamma(B \to H\,ee)}$$





Deviations from the (*precise & reliable*) SM predictions ranging from 2.2σ to 2.5σ in each of the 3 bins measured by LHCb

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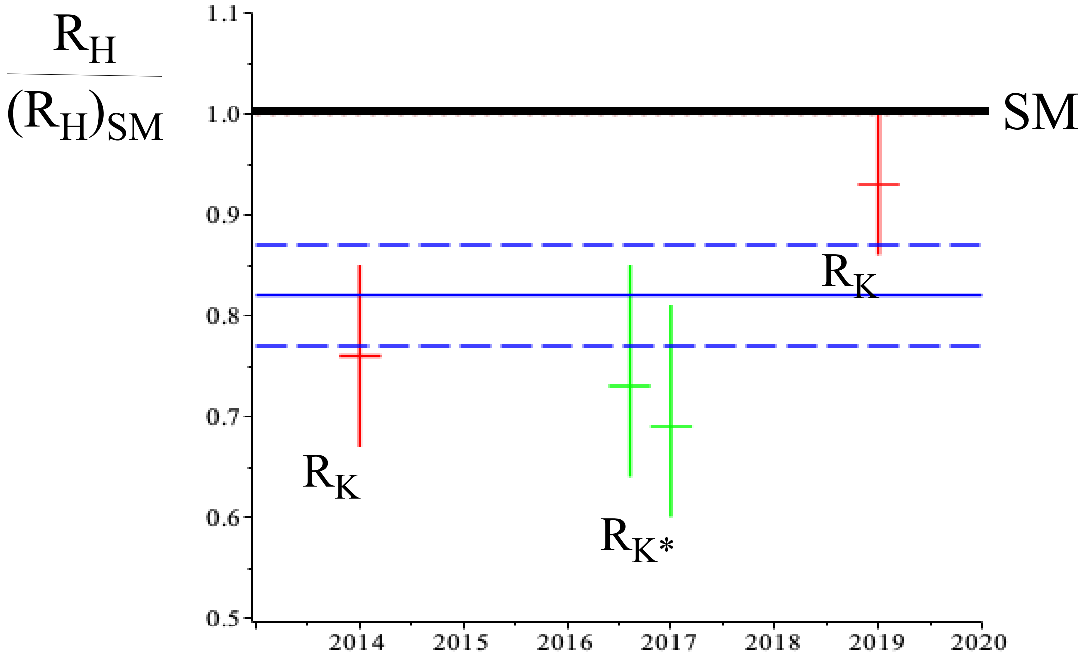

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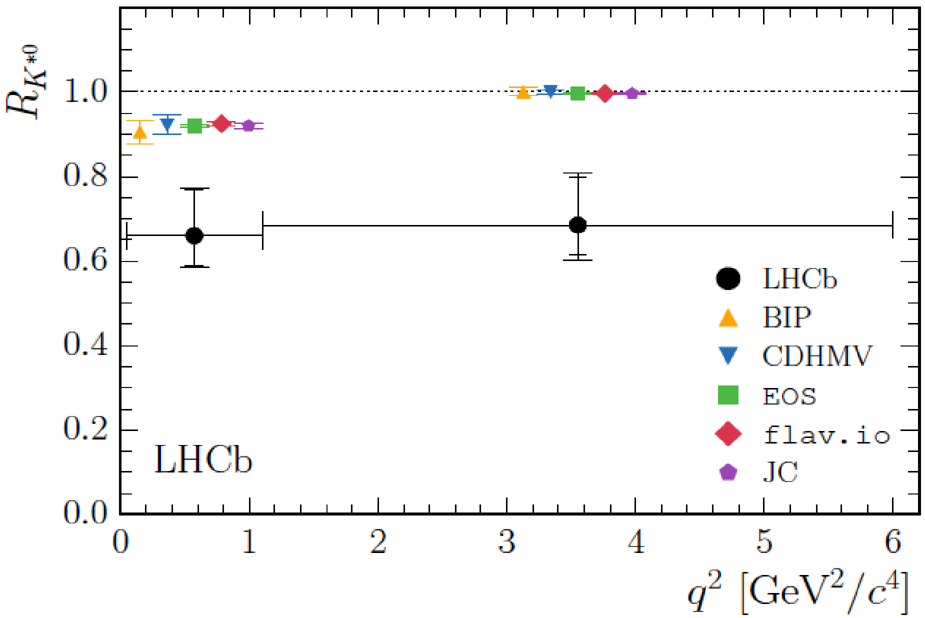
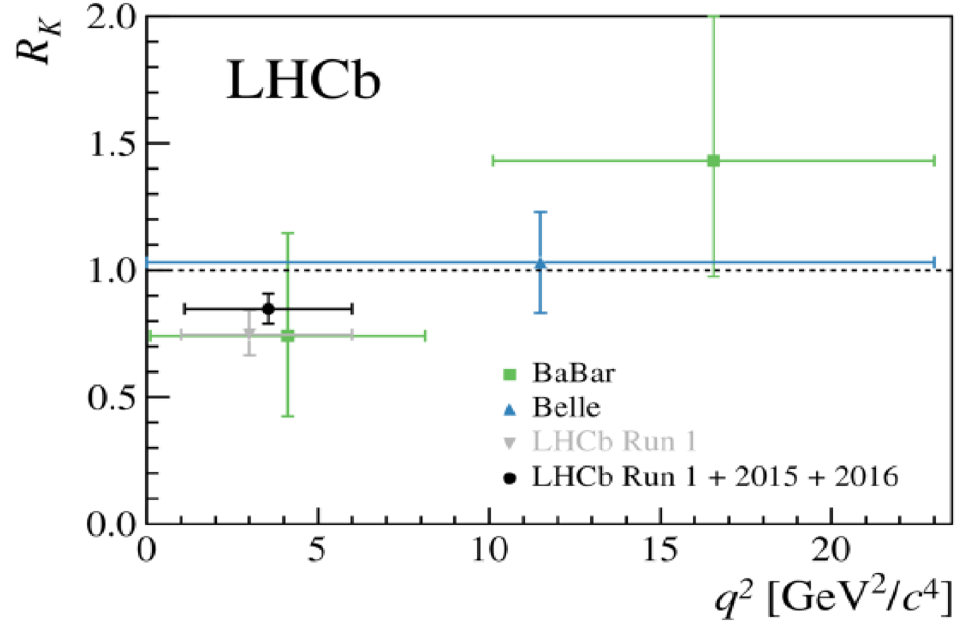
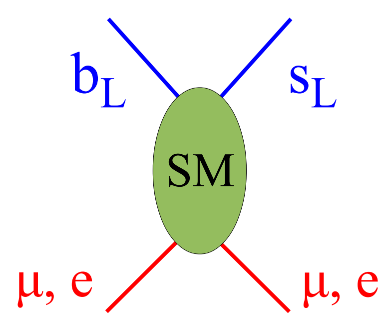
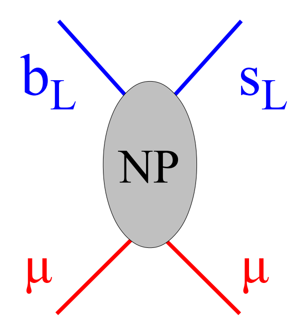




Deviations from the (*precise & reliable*) SM predictions ranging from 2.2σ to 2.5σ in each of the 3 bins measured by LHCb

What is particularly remarkable is that both these LFU breaking effects & the anomalies (I.+II.) are well described by the same set of Wilson coeff. assuming NP only in b→sμμ and (& not in ee)





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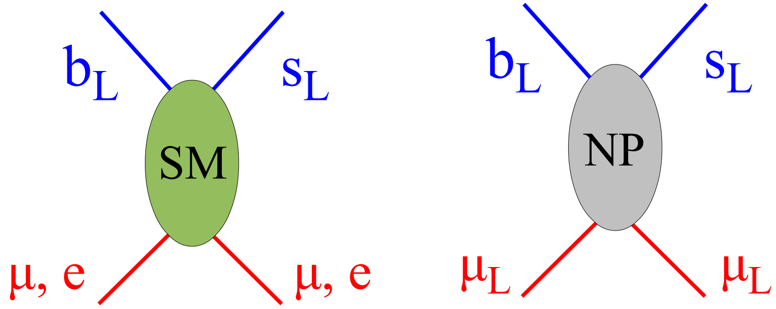


Despite the significance has not increased with the release of new data in 2019, the overall consistency has further increased, as well as the evidence that the putative NP effects come from a pure left-handed operator → expected suppression of $BR(B_s \to\mu\mu)$ by ~ 20% compared to its SM expectation:

$$Q_L = (\bar{b}_L \gamma_\mu s_L)(\bar{l}_L \gamma^\mu l_L)$$

IV. $$BR(B_s \to\mu\mu)_{SM} = (3.66 \pm 0.14) \times 10^{-9}$$
$$BR(B_s \to\mu\mu)_{exp} = (2.72 \pm 0.34) \times 10^{-9}$$

[LHCb+CMS+ATLAS '19]

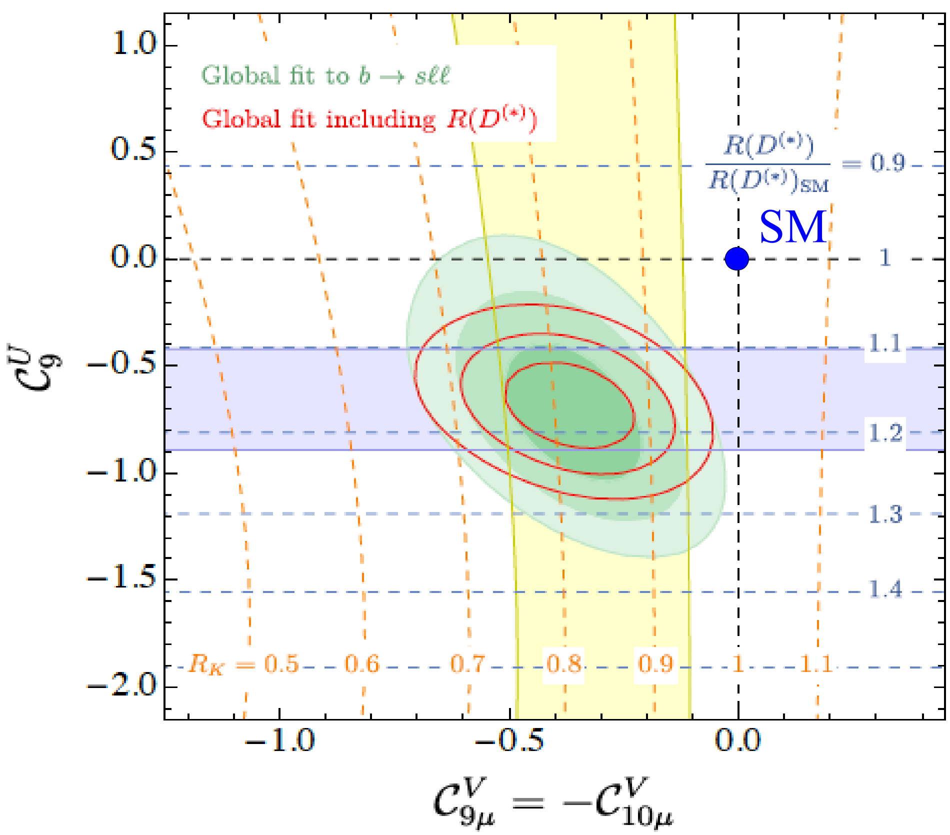
A conservative analysis, taking into account only the observables III. & IV, with a single NP operator, leads to a pull of 4.2σ compared to the SM.

▶ *The $b \to s\ell\ell$ anomalies*

A conservative analysis, taking into account only the observables III. & IV, with a single NP operator, leads to a pull of 4.2σ compared to the SM.

More sophisticated analyses, taking into account all observables, with state-of-the-art estimates of hadronic form factors + realistic (*but somehow model-dependent*) estimates of long-distance effects → pull exceeding 5σ:

Alguero *et al.* '19



Aebischer *et al.* '19