University of Zurich[UZH]

Flavor physics: present status & next steps

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[*University of Zürich*]

- Part I: Some general considerations
  [*from the discussion in Granada*]

- Part II: Status of the LFU anomalies
  [*attempt of "unbiased" discussion...*]

- Concluding remarks

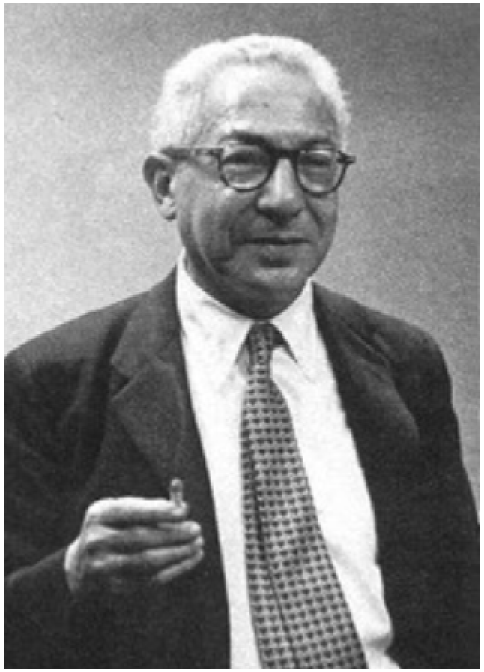
Part I:

Some general considerations

[*from the discussion in Granada*]

- *Why* are we interested in flavor physics?
- *How* can we make progress in this area in the short, mid, and long term?

▶ Why?



Isidor Issac Rabi

(1898—1988)

Why?

- *Why 3 fermion generations ?*
- *Are fermion masses calculable from new basic principles?*
- *Is there a connection between quarks, charged-leptons, and neutrino masses?*

- *Beside the Higgs, are there other interactions distinguishing the 3 families?*
- *If so, which is their energy scale?*

- *Is there CP violation in flavor-blind processes?*
- *What is the explanation of the strong CP problem?*

….

We need to address these fundamental questions !

(*which are not less crucial or fundamental than Higgs hierarchy problem*)

Many theoretical ideas, but no clear answers yet...

To make progress we need experimental clues, which can only come from dedicated experiments

Why?

Flavor and CP violating processes are also particularly interesting since they allow us to (indirectly) *probe very high energy scales*

$$A(\psi_i \to \psi_j + X) = A_0 \left(\frac{c_{\mathrm{SM}}}{v^2} + \frac{c_{\mathrm{NP}}}{\Lambda_{\mathrm{NP}}^2} \right)$$

This is particularly important, in view of the present lack of clear indications about NP scale [*synergy with high-energy*]

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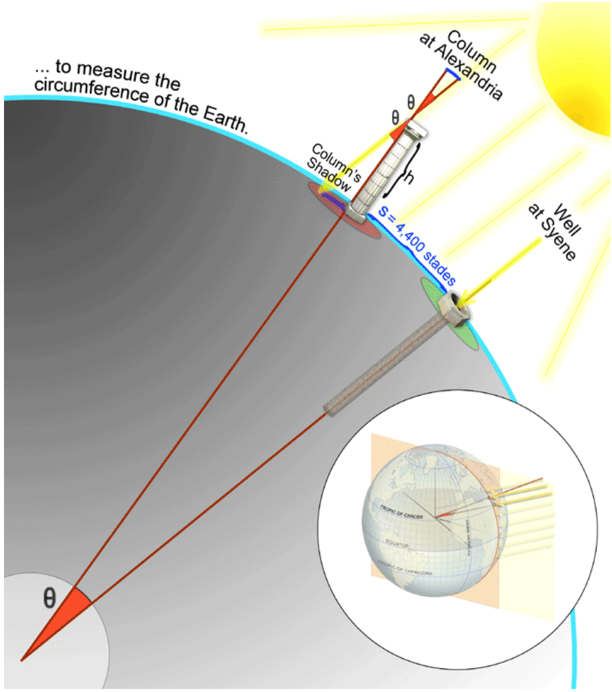

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Λ_{NP}, c_{NP} | N → $3\times\Lambda_{NP}$, $0.1\times c_{NP}$ | $100\times$N

(for th. clean observables)

Why?

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- SM success in flavor physics @ B factories + EWPO @ LEP → strong indication of light Higgs + energy gap @ LHC (*that is what we se now...*)
- All "recent" discoveries at the HE frontier in particle physics [c, b, t, H] were anticipated by indirect indications from flavor, CPV, and EWPO
- Hard to expect a discovery at HE without indirect clues at low energies...

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Indirect NP searches must be a key ingredient of our future strategy!

How?

I. The light sector [u, d, s + e, μ]

Three "clear" cases calling for **diversity** in the **short/mid-term**:

	addresses:	*requires*:
• EDMs [d_e, d_n, d_N,...]	Strong CP light Y's	**Rings/Magnetic traps** [*Long list...*]
• Å→e processes	$1^{st}\leftrightarrow 2^{nd}$ lepton mix.	**Intense Å beams** [MEG, Mu3e,Mu2e, COMET]
• Rare K decays	$1^{st}\leftrightarrow 2^{nd}$ quark mix.	**Intense K beams** [NA62, KEVLER, KOTO]

- ✓ Outstanding physics goals (fundamental & unique)
- ✓ Difficult experiments, but on a smaller scale

Two or more experiments for each of these dedicated "low-energy" research lines would be extremely welcome !

▸ How?

II. The heavy sector [b, c + τ]

Bright near-term future [~ 10 yrs] with **LHCb (I+II)** & **Belle-II**

This is likely to be the most exciting frontier of particle physics in the next ~ 10 years:

- Large discovery potential
  (*wide parameter range still to be explored*)
- Further "enriched" by
  - → *present anomalies* [→ Part II]
  - → expected progress from lattice QCD

▸ How?

II. The heavy sector [b, c + τ]

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Clear mid-term future [~ 10-20 yrs] with an outstanding case:

- **LHCb-II** [@ HL-LHC]: ultimate precision on "all-visible" B and D decay modes [$B_{s,d} \to \mu\mu$, R_{K,K^*}, CKM, charm CPV, ...]

possibly complemented by specific initiatives, especially on tau decays:

- **TauFV** [@ SHIP beam line]
- **STC** @ Novosibirsk

In both cases the competitiveness after Belle-II still to be carefully evaluated...

▶ How?

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possibly complemented by specific initiatives, such as **TauFV** & **STC**

A strong case for the long-term future [> 20 yrs]:

- **Flavor physics @ FCC-ee** [running at the Z-pole , with 5×10^{12} Z's !]

  Unique potential on b and τ decays with missing energy, from $Z \to bb$, $\tau\tau$
  Just one example: $B \to K^*\tau\tau$ [*holy grail of present anomalies...*]:
  ~1000 SM events @ FCC-ee vs. ~10 @ Belle-II

  And of course FCC-ee would allow major improvements on EWPO & Higgs
  → **ideal set-up to optimize indirect NP searches**

Part II:

Status of the LFU anomalies

- General considerations on LFU
- The $b \rightarrow c\, l\nu$ anomalies
- The $b \rightarrow s\, ll$ anomalies
- EFT considerations on the anomalies

General considerations on LFU

In the last few years LHCb, Babar and (to some extent) also Belle reported some "anomalies" (= *deviations from SM predictions*) in B-meson decays.

Data seem to indicate a different (*non-universal*) behavior of different lepton species in specific b (3rd gen.) → 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

This challenges an assumption (Lepton Flavor Universality), that we gave for granted for many years (*without many good theoretical reasons…*).

Before discussing the precise structure (and the reliability) of these anomalies, it is worth clarifying what we mean by LFU and why it is interesting to test it.

General considerations on LFU

LFU [= *identical behavior of the 3 charged leptons in the limit where we neglect their masses*] is a consequence of the accidental flavor symmetry of the SM Lagrangian in the limit where we neglect the (small) lepton Yukawa couplings:

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

3 identical replica of the basic fermion family [$\psi = Q_L, u_R, d_R, L_L, e_R$]
in the gauge sector ⇒ huge flavor-degeneracy [$U(3)_L \times U(3)_E \times \ldots$]

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No reason to assume it holds beyond the SM...
[*it is not even an exact symmetry of the SM* !]

SM ↓ Yukawa

$U(1)_e \times U(1)_\mu \times U(1)_\tau$

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No reason to assume it holds beyond the SM...

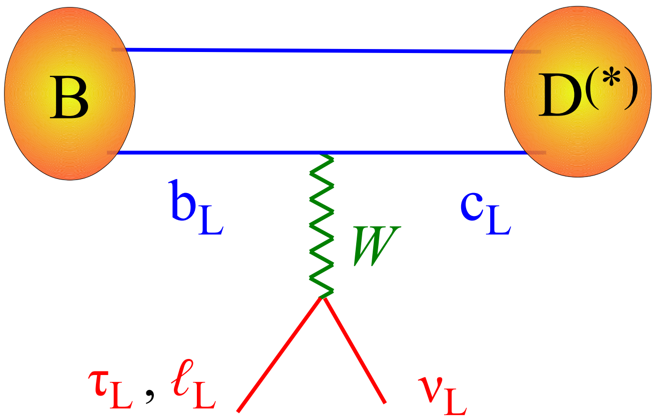
However, it has been verified with extremely high accuracy in several systems:

- $Z \to ll$ decays [~ 0.1%]
- $\tau \to l\nu\nu$ decays [~ 0.1%]
- $K \to (\pi) l\nu$ decays [~ 0.1%] & $\pi \to l\nu$ decays [~ 0.01%]

This is why is often assumed as a "sacred principle"....

Still, no deep reason, and no strong experimental tests in semileptonic processes involving 3rd generation quarks, before these recent measurements

LFU tests in $b \to c$ transitions

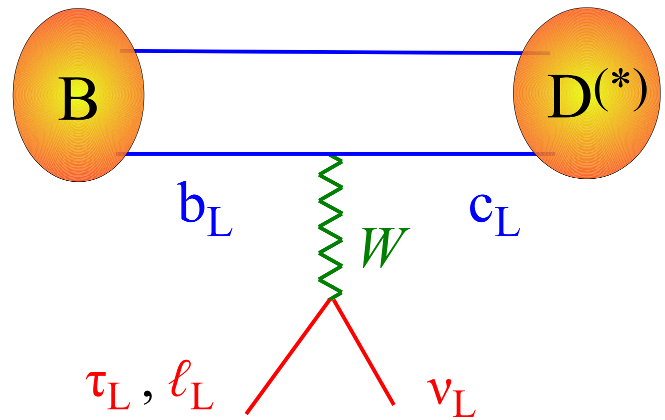


LFU tests in $b \to c$ transitions

The way we test LFU in charged-current $b \to c$ transitions is via the ratios

$$R(H_c) = \frac{\Gamma(B \to H_c\, \tau\nu)}{\Gamma(B \to H_c\, \ell\nu)}$$

$$H_c = D \text{ or } D^*$$



We are not able to compute very precisely, separately, numerators and denominators in these ratios because of hadronic uncertainties...

E.g.: $A(B \to D\ell\nu)_{SM} = G_{eff}\, V_{cb} \langle D \,|\, \bar{b}_L \gamma_\mu c_L \,|\, B \rangle\, \bar{\ell}\gamma^\mu\nu$

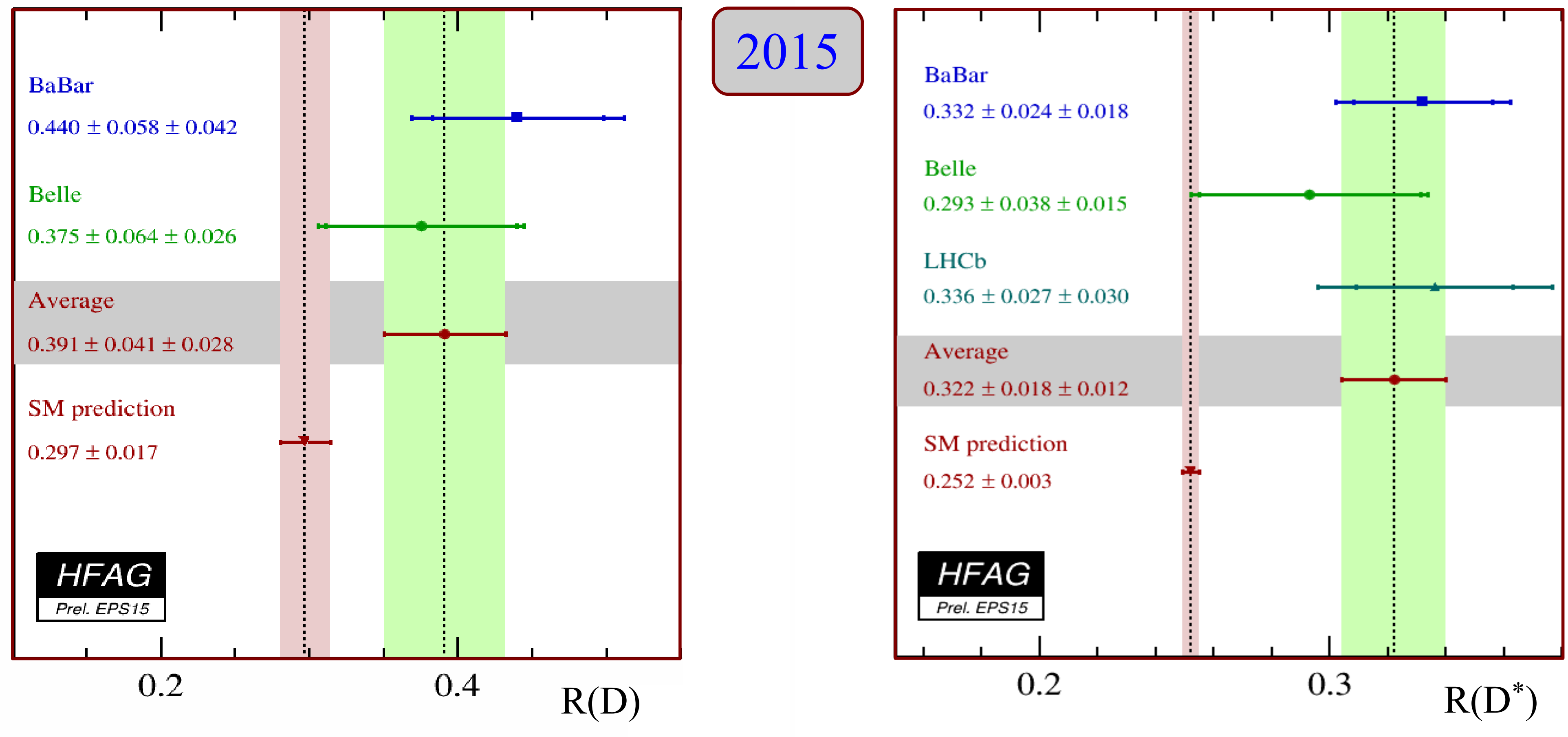
$\to f_+(q^2)\,(p_B+p_D)_\mu + f_-(q^2)\,(p_B-p_D)_\mu$

But these uncertainties cancels (to a large extent) in the ratios

Anomalies appeared when comparing τ vs. light leptons (μ, e)

LFU tests in $b \to c$ transitions

Test of Lepton Flavor Universality in (charged current) $b \to c$ transitions [τ vs. light leptons (μ, e)]:



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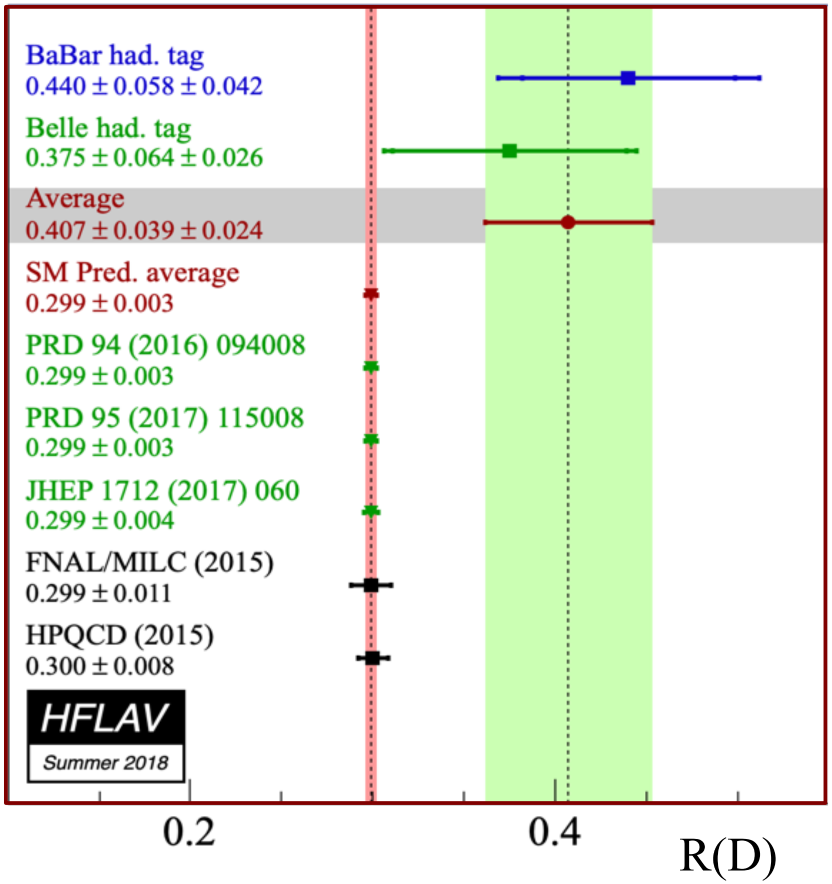
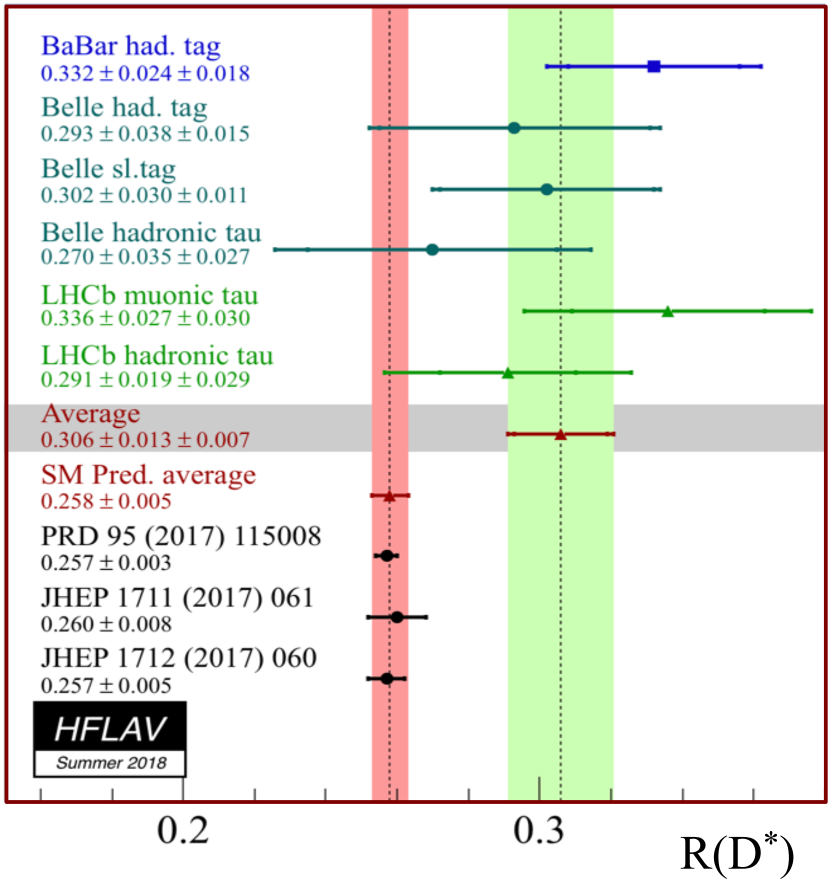


2018



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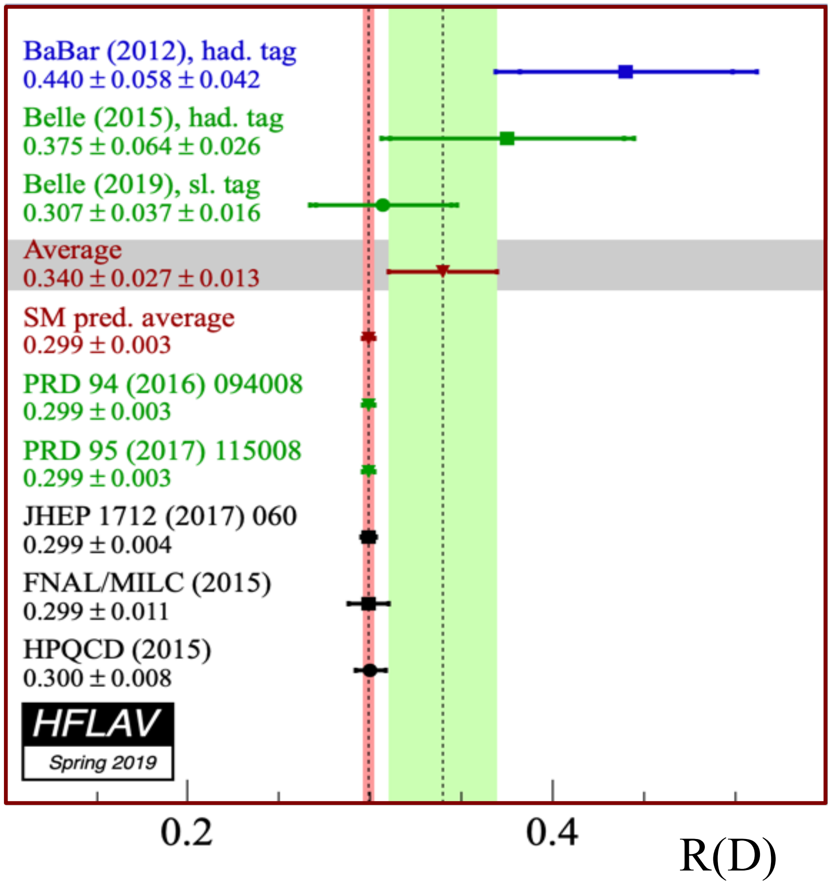
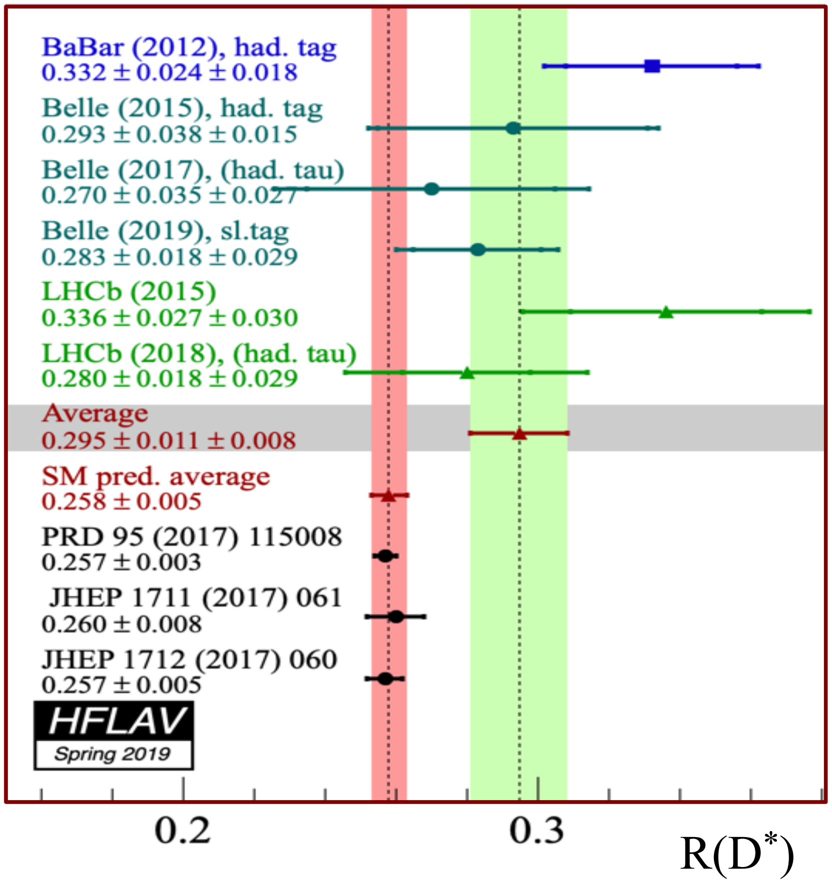


2019



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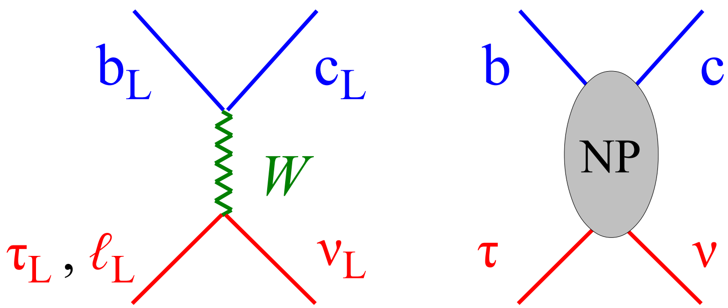

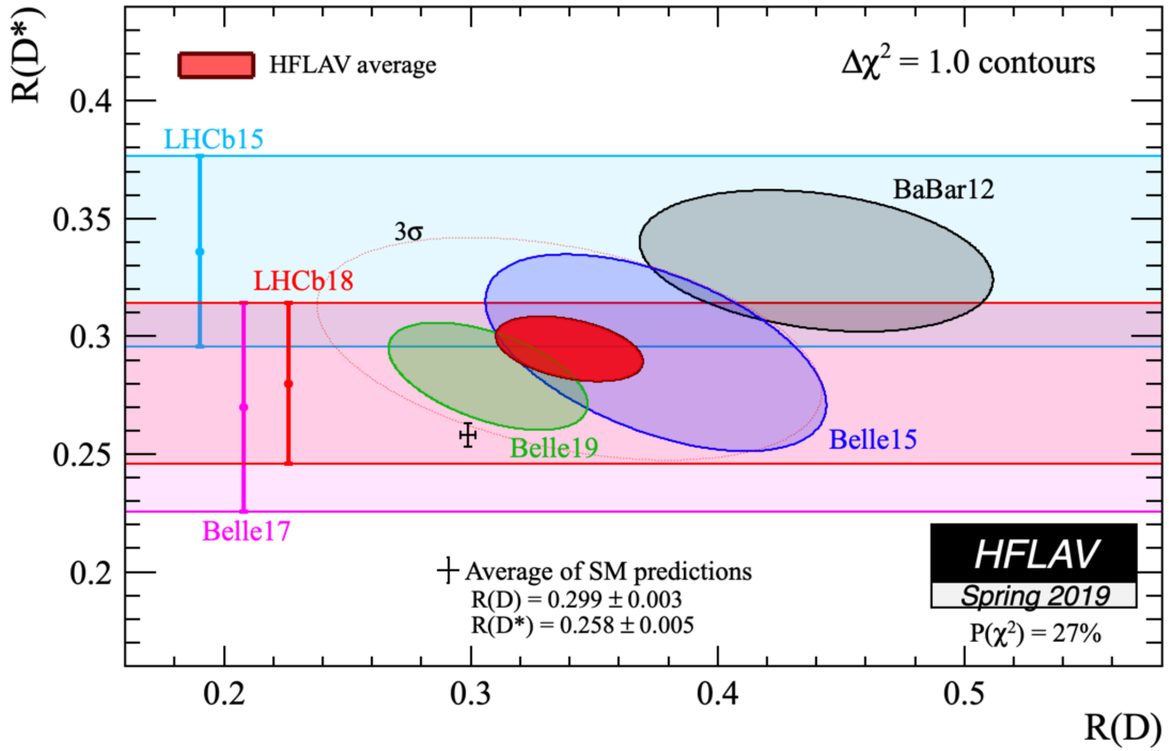

- SM prediction quite solid: hadronic uncertainties cancel (*to large extent*) in the ratio and deviations from 1 in R(X) expected only from phase-space differences
- Consistent results by 3 different exps. → 3.1σ excess over SM ($D + D^*$)

LFU tests in b → c transitions

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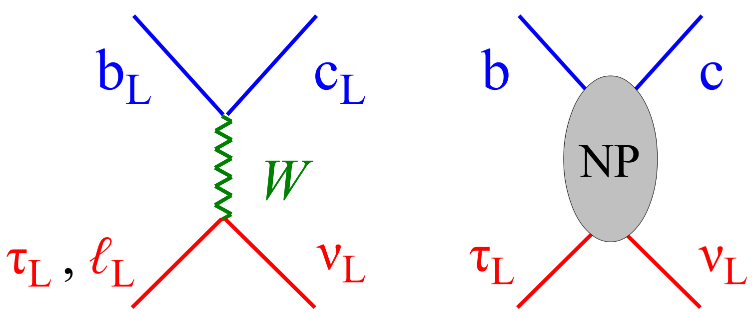
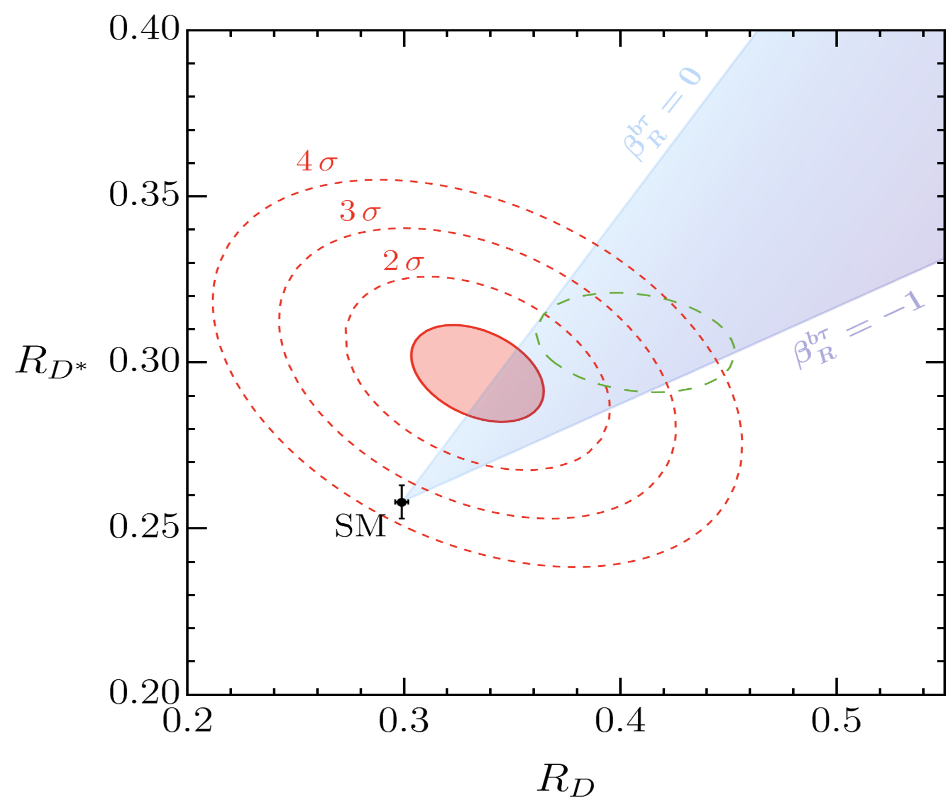
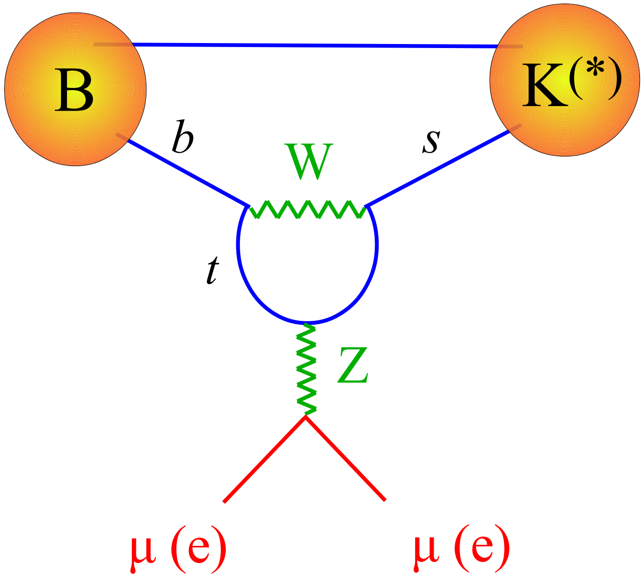




- SM prediction quite solid: hadronic uncertainties cancel (*to large extent*) in the ratio and deviations from 1 in *R*(X) expected only from phase-space differences
- Consistent results by 3 different exps. → 3.1σ excess over SM (*D* + *D**)
- The two channels are well consistent with a universal enhancement (~30%) of the SM $b_L \to c_L\, \tau_L\, \nu_L$ amplitude, but other options are possible

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



▶ *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)]

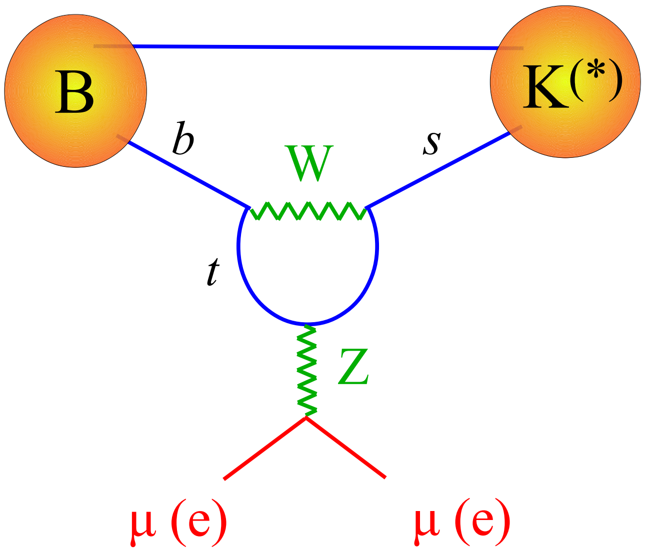
III. LFU ratios (μ vs. e) in $B \to K^*\ell\ell$ & $B \to K\,\ell\ell$

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* (*at least in some observables*)



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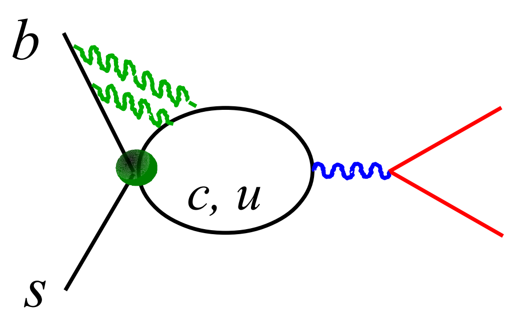
Sizable theory uncertainties:



$$Q_1 = (\bar{b}_L \gamma_\mu s_L)(\bar{c}_L \gamma^\mu c_L)$$
$$Q_2 = (\bar{b}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu s_L)$$
$$\downarrow$$
$$Q_9 = (\bar{b}_L \gamma_\mu s_L)\bar{l}\gamma^\mu l$$
$$Q_{10} = (\bar{b}_L \gamma_\mu s_L)\bar{l}\gamma^\mu \gamma_5 l$$

Mixing of the four-q. Q_i into the FCNC Q_i
[perturbative long-distance contribution]

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

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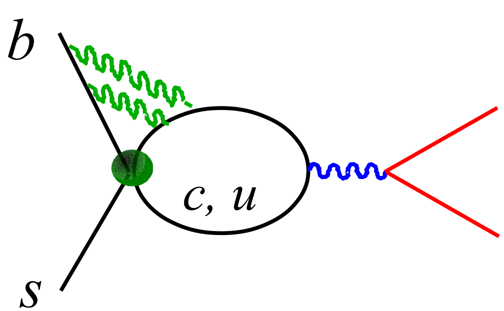
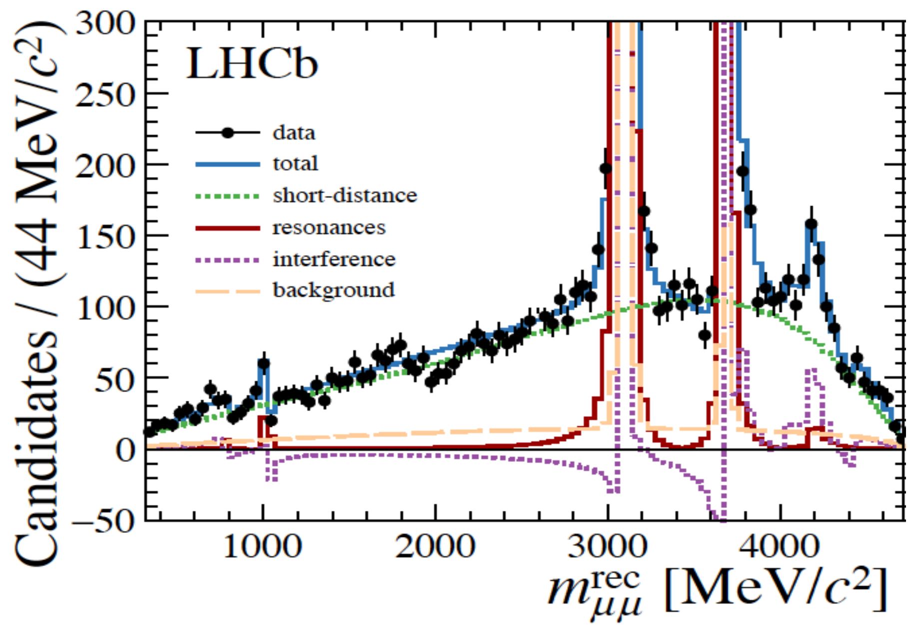


Mixing of the four-q. Q_i into the FCNC Q_i [perturbative long-distance contribution]



Non-perturbative long-distance effects (particularly large close to $c\bar{c}$ resonances)

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

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

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

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

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

= 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)

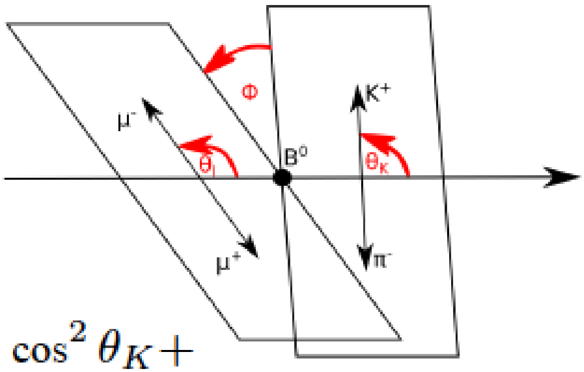
$$Q_9 = (\bar{b}_L \gamma_\mu s_L)\, \bar{l}\, \gamma^\mu l$$

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

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

I. The P'_5 anomaly

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



$$\frac{d^4(\Gamma+\bar\Gamma)}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K +$$

$$\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell +$$

$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$

$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell +$$

$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$

$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$P'_{4,5} = \frac{S_{4,5}}{\sqrt{F_L(1-F_L)}}$$

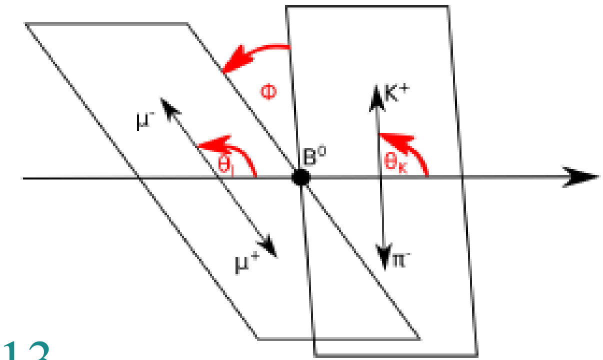
observables designed to cancel f.f. dependence in the heavy-quark limit

Descotes-Genon, Matias, Ramon, Virto '12

▸ The $b \to s\ell\ell$ anomalies

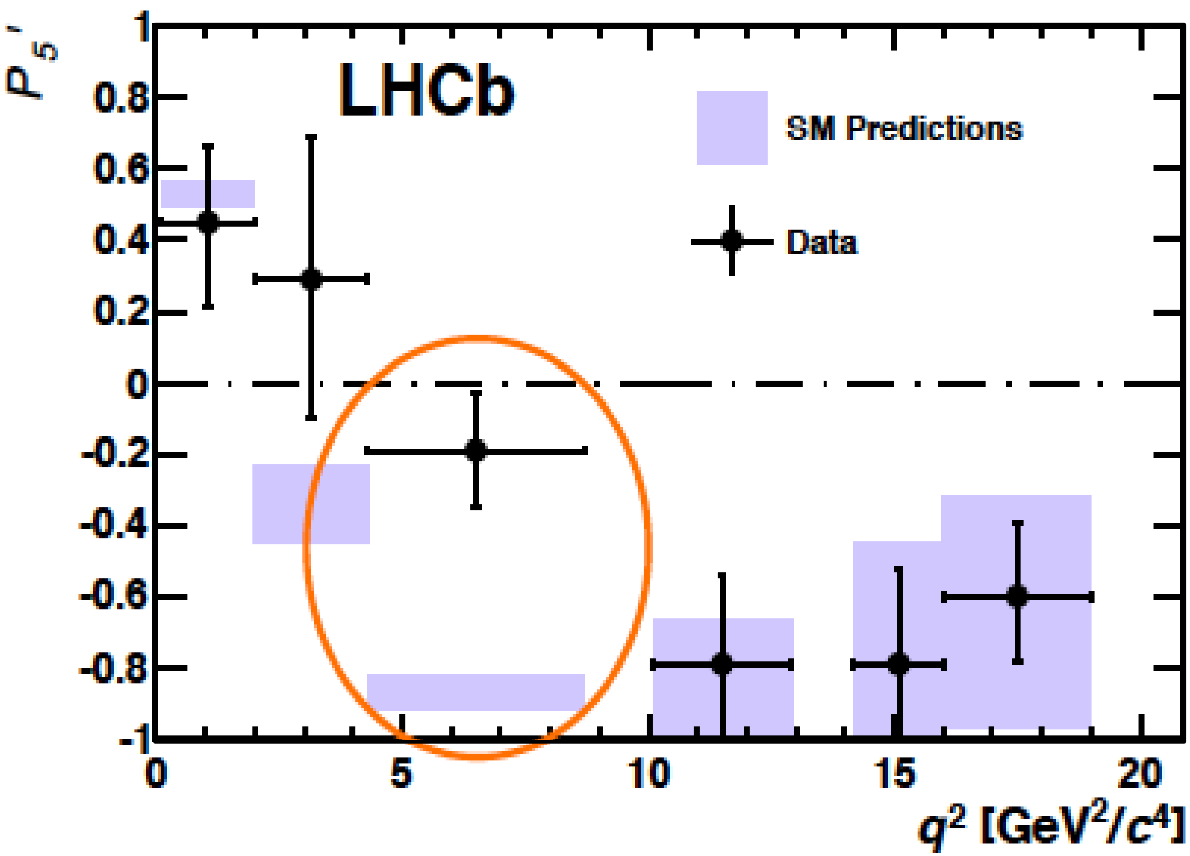
I. The P'_5 anomaly

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



↓

2013



$= m^2_{\mu\mu}$

▸ *The $b \to s\ell\ell$ anomalies*

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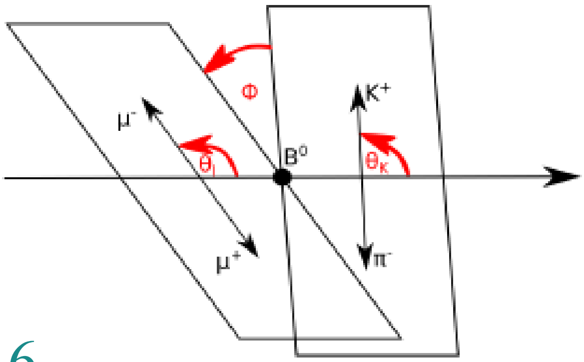
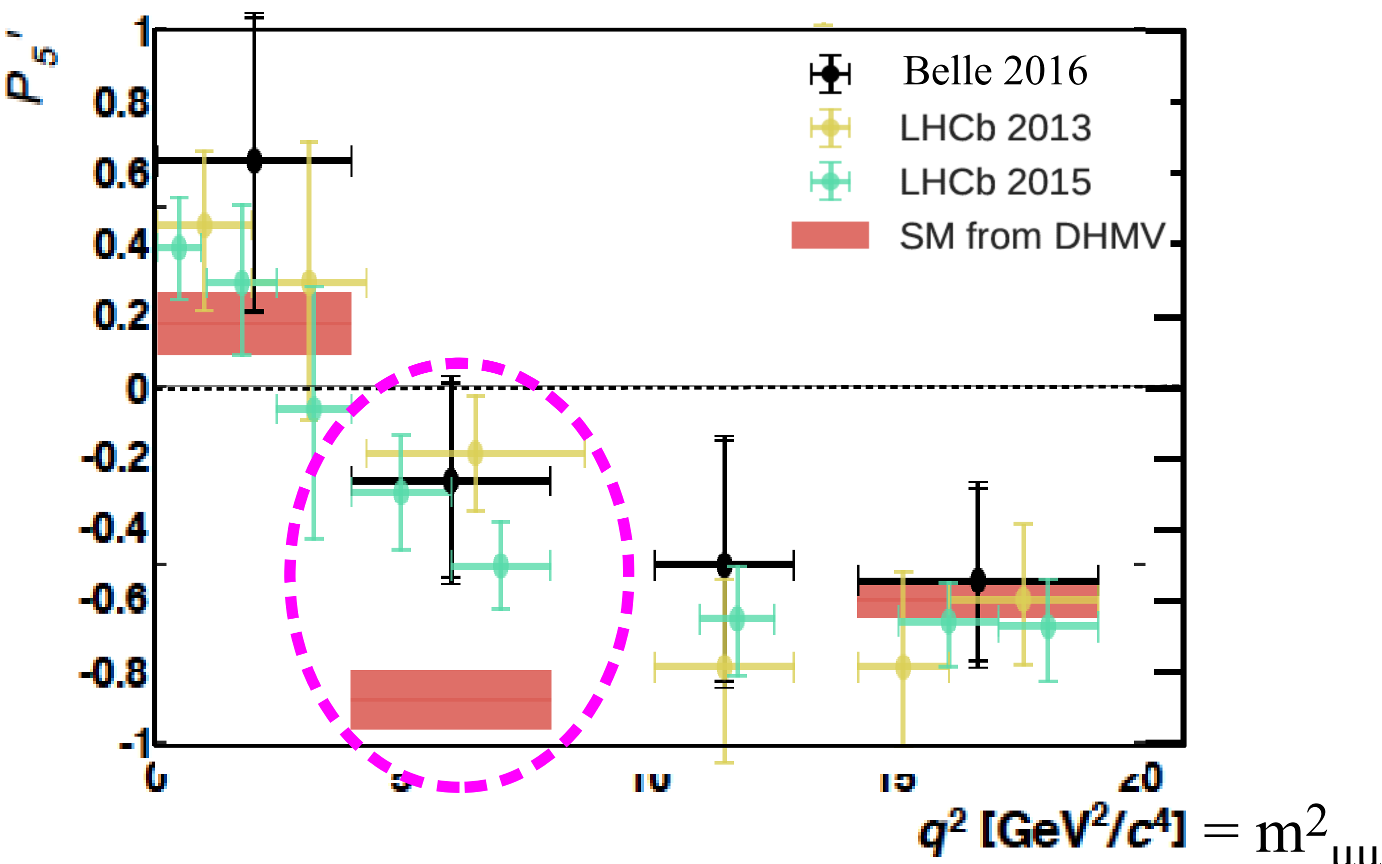


2016



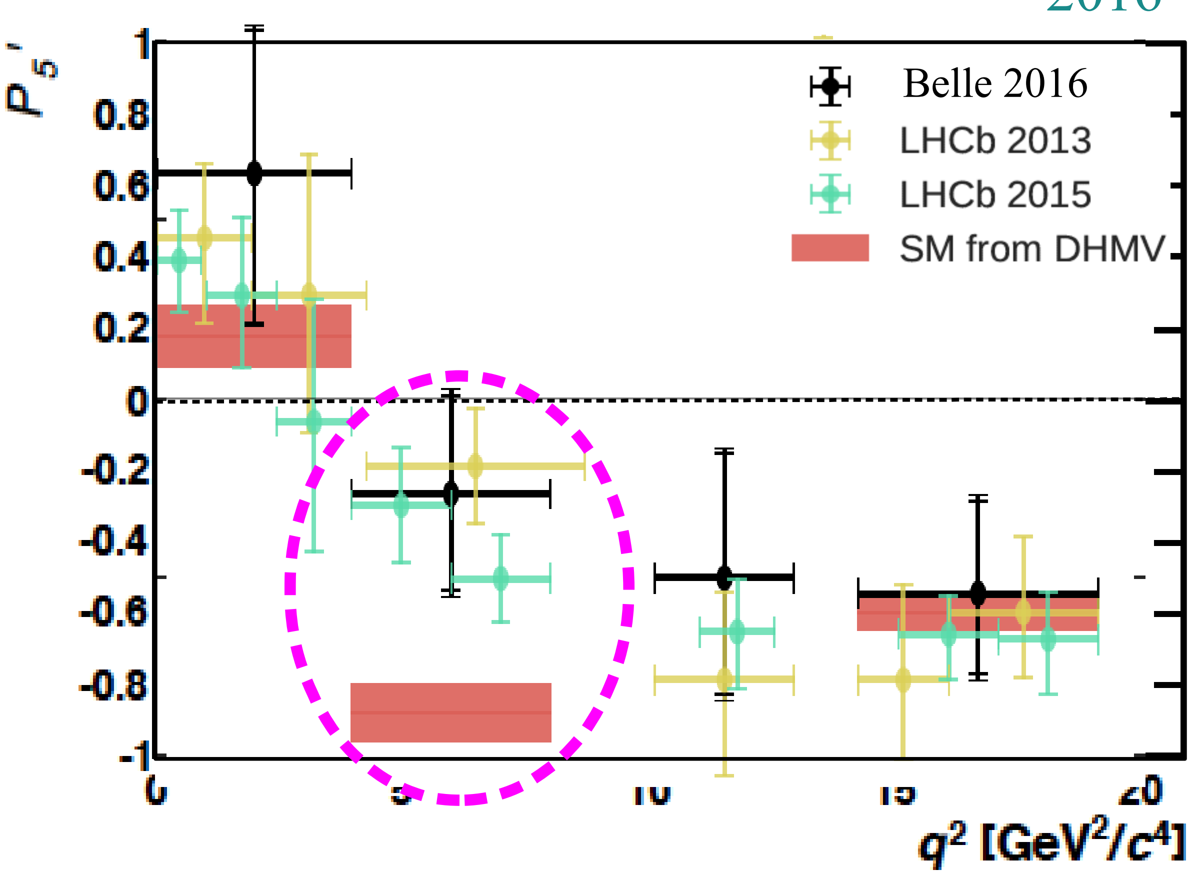
The $b \to s\ell\ell$ anomalies

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.*]

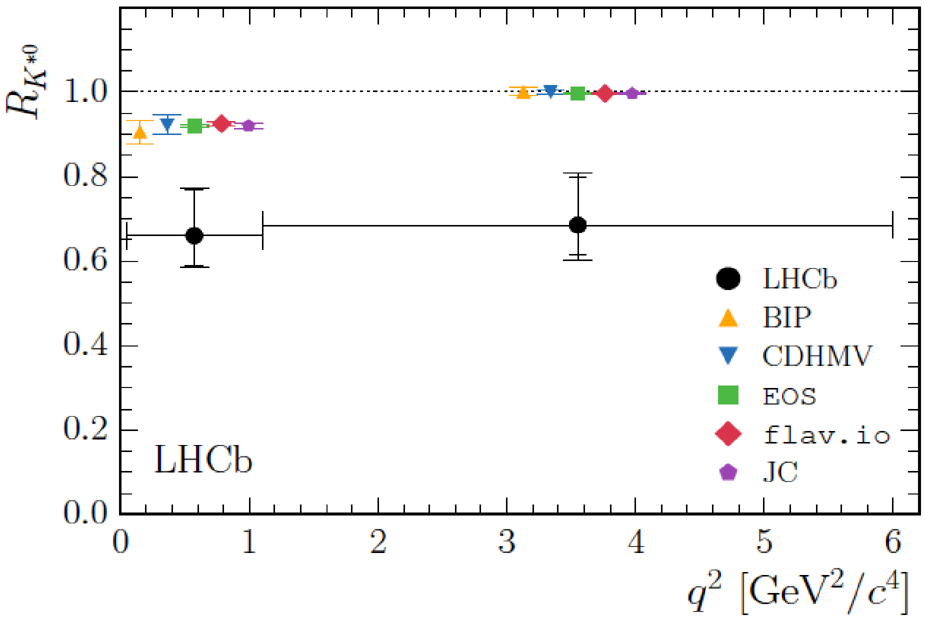
Against NP:

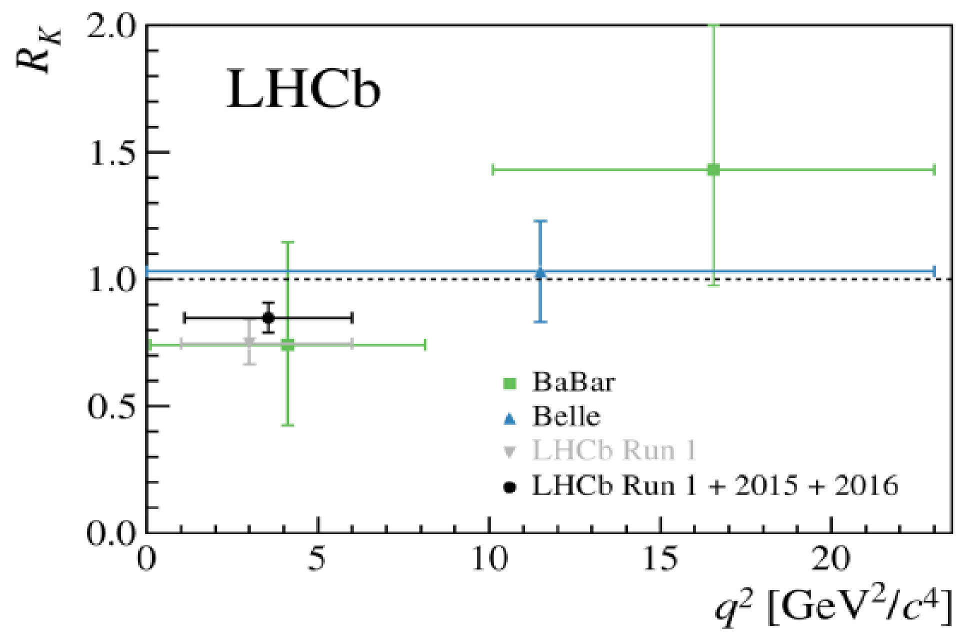
Non-standard effect mainly driven by C_9 ($\leftrightarrow$ *charm loops*) $\to$ significance reduced with conservative estimates of long-distance corrections

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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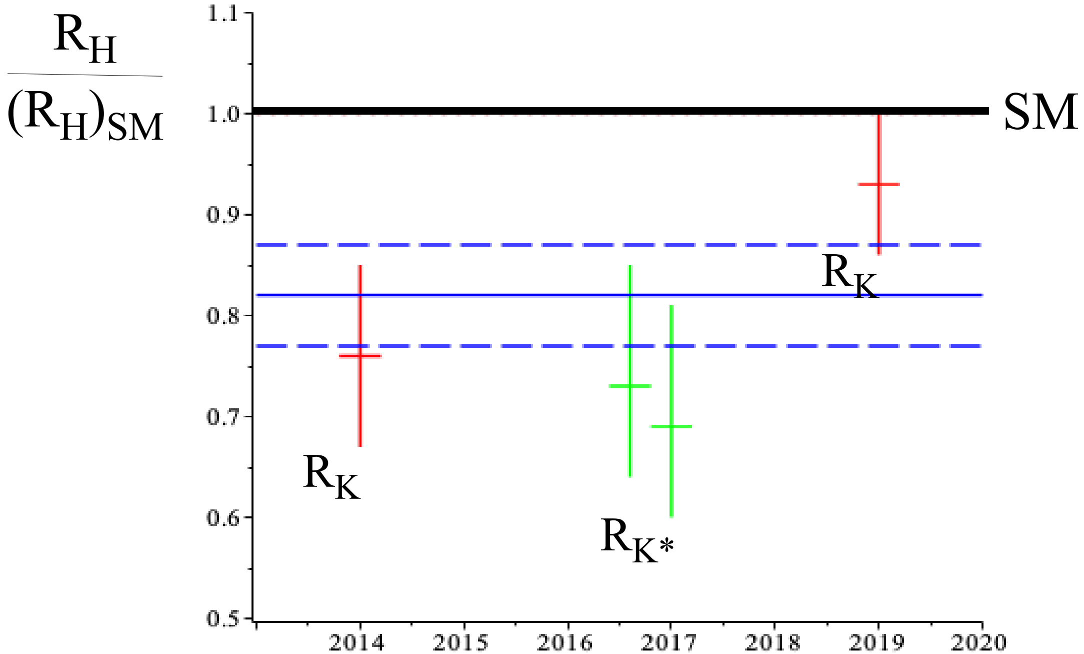

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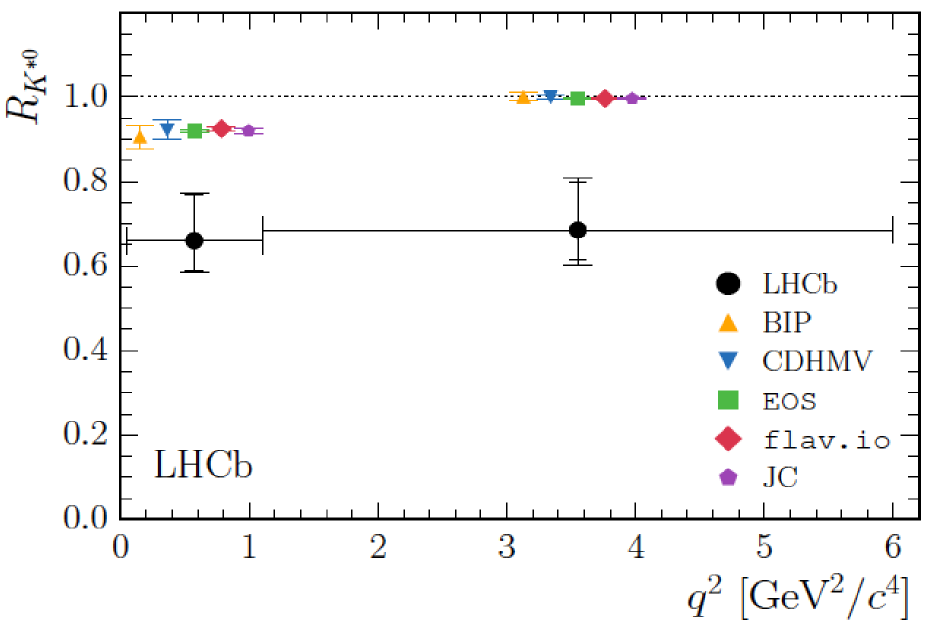

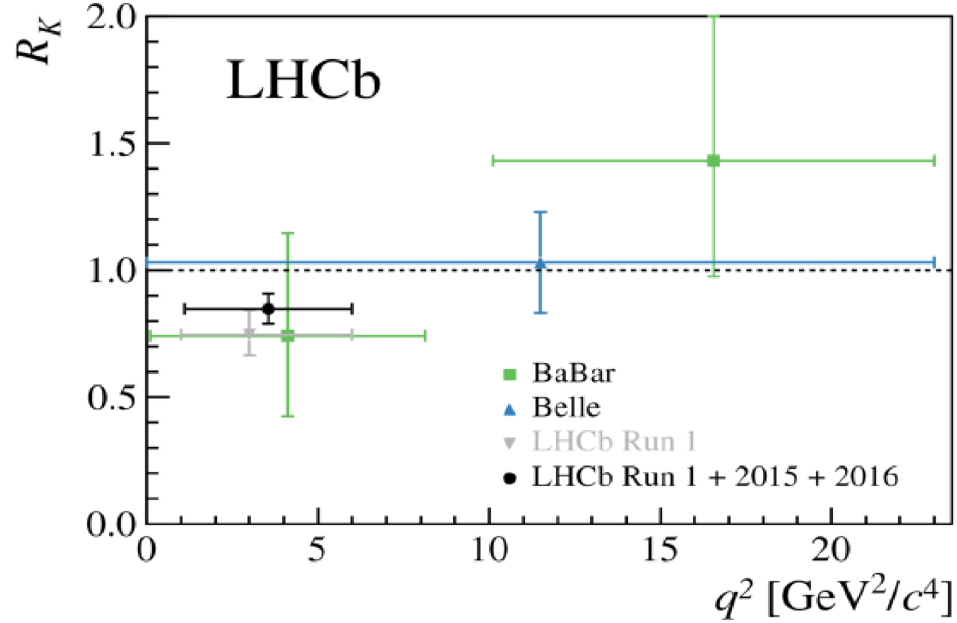

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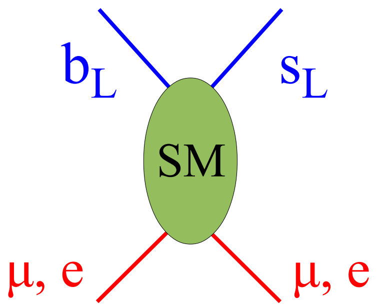

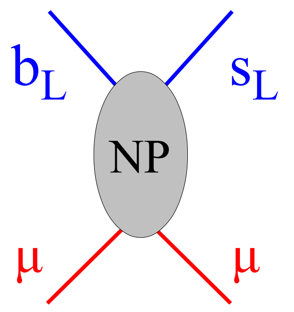

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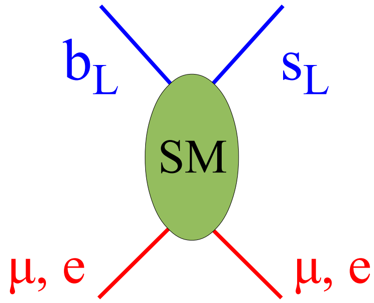

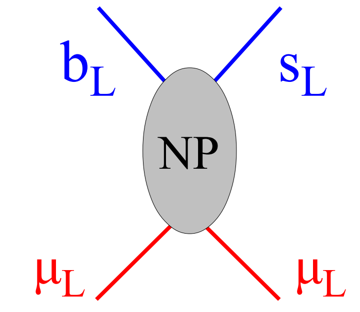

Despite the significance has not increased with the release of new data in 2019, the overall consistency has further increased, as well as the evidence that the putative NP effects come from a pure left-handed operator → expected suppression of $BR(B_s \to \mu\mu)$ by ~ 20% compared to its SM expectation:

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

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

[LHCb+CMS+ATLAS '19]

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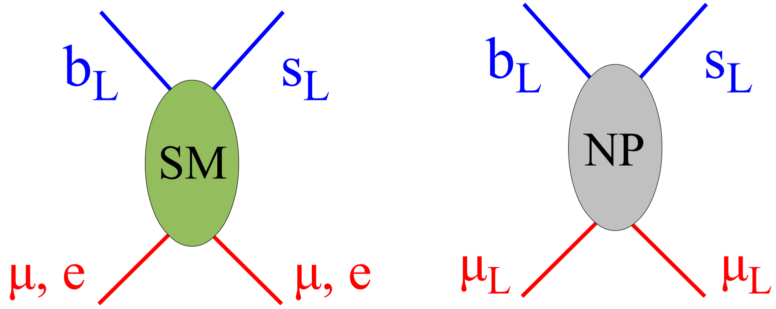

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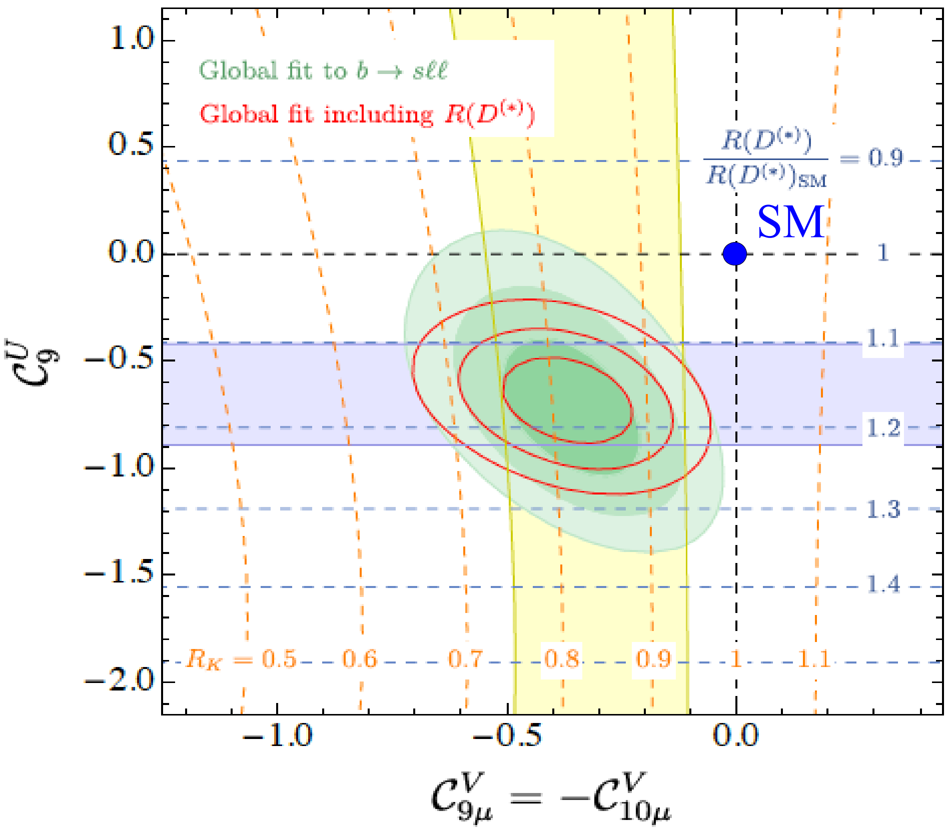
A very conservative analysis, taking into account only the observables III. & IV, with a single NP operator, leads to a pull of 3.2σ compared to the SM.

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

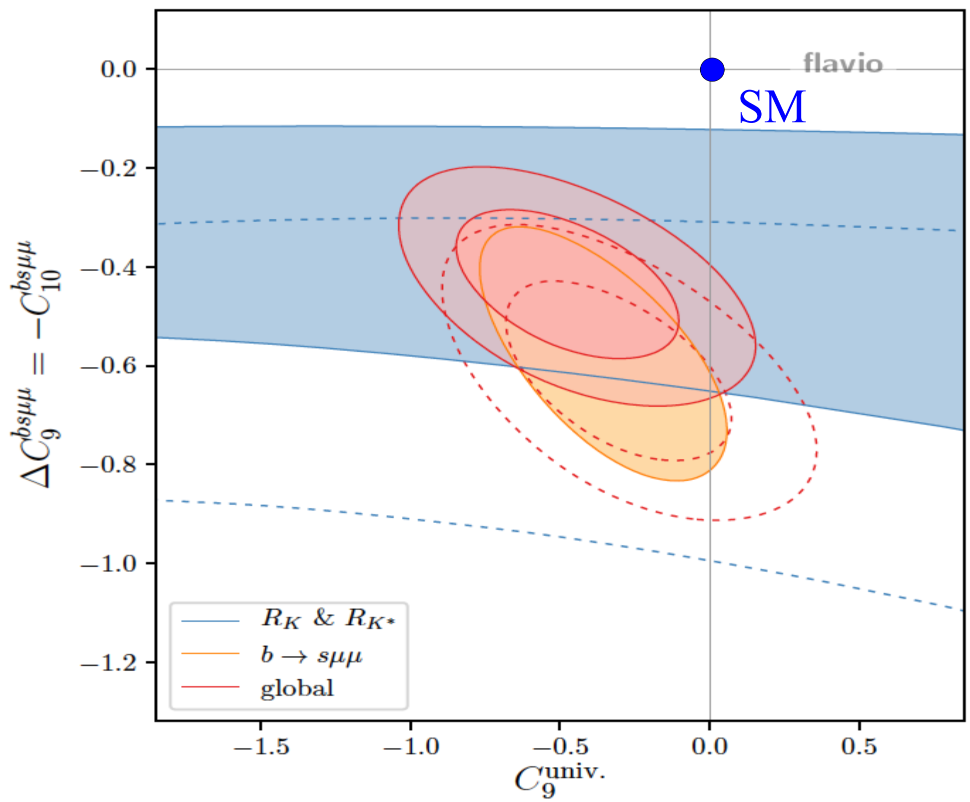
A very conservative analysis, taking into account only the observables III. & IV, with a single NP operator, leads to a pull of 3.2σ compared to the SM.

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:

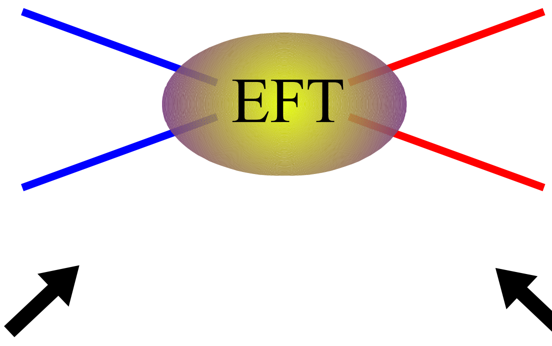
Alguero *et al.* '19

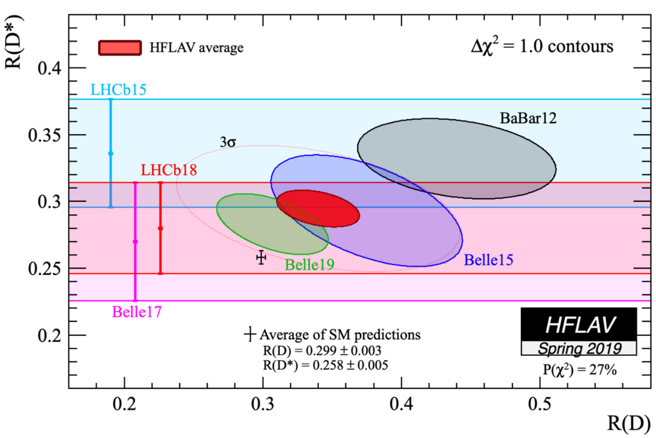


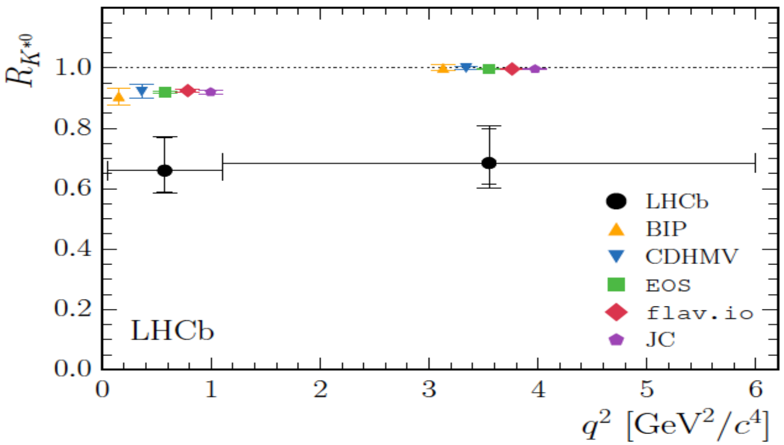
Aebischer *et al.* '19



EFT considerations







EFT approaches to the anomalies

Beside analyzing the significance of the two anomalies, two natural questions to address are:

- Are these “anomalies” compatible with other observations?
  [*is it plausible/consistent that NP shows there and not in high-pT and/or other low-energy observables?*]

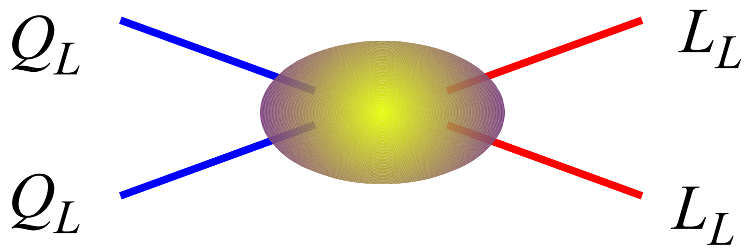
- If consistent and confirmed, can they have a common origin?

↓

We can address both questions by means of
a suitable EFT approach

EFT approaches to the anomalies

- Anomalies are seen (*so far...*) only in semi-leptonic (quark×lepton) operators
- Data largely favor 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...)

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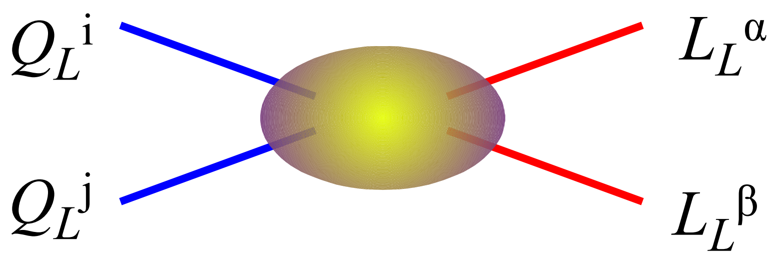

$$\frac{F_{ij\alpha\beta}}{\Lambda^2}\ \bar{Q}_L^{\,i}\,\Gamma\, Q_L^{\,j}\ \bar{L}_L^{\,\alpha}\,\Gamma\, L_L^{\,\beta}$$

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

↓

$$F_{ij\alpha\beta} = (\delta_{i3}\times\delta_{3j})\times(\delta_{\alpha 3}\times\delta_{3\beta}) \ +$$ small terms for 2nd (& 1st) generations → *Link to pattern of the Yukawa couplings !*

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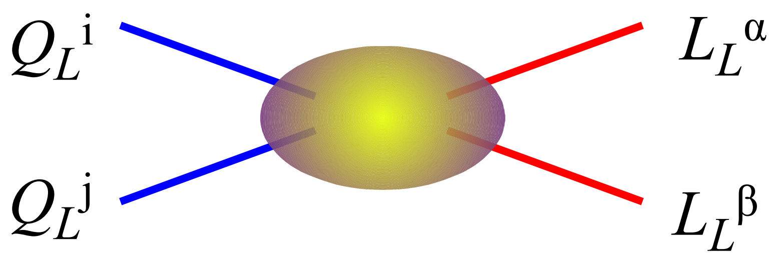
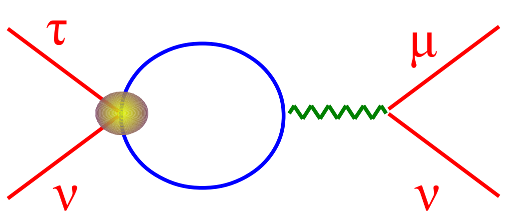


$$\frac{F_{ij\alpha\beta}}{\Lambda^2}\;\bar{Q}_L^{\,i}\,\Gamma\,Q_L^{\,j}\;\bar{L}_L^{\,\alpha}\,\Gamma\,L_L^{\,\beta}$$

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

E.g.:



Feruglio, Paradisi, Pattori '16

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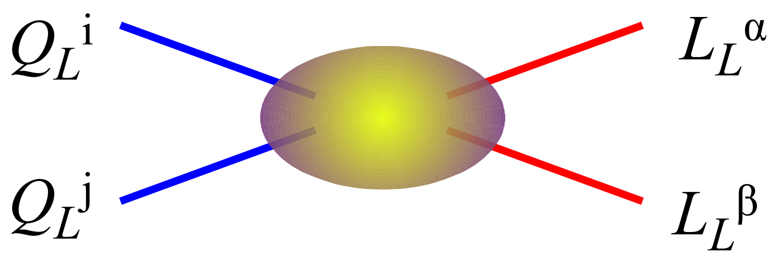

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Long list of constraints [FCNCs + semi-leptonic b decays + π, K, τ decays + EWPO]

⬇

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

We need to go *beyond MFV*, but we must somehow retain many of its good phenomenological features...

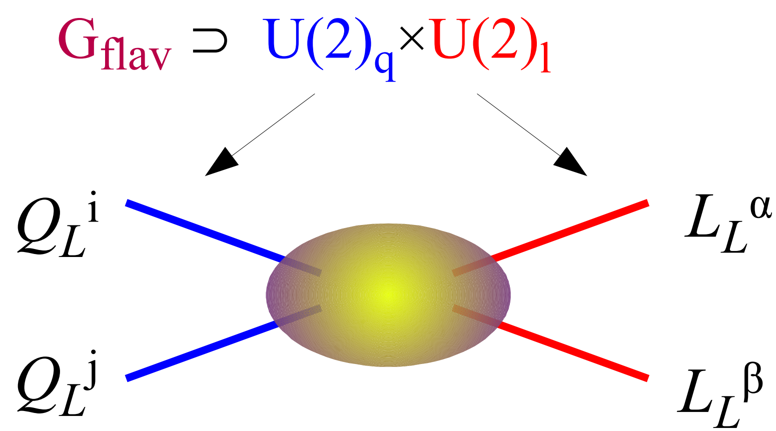
A combined EFT solution for the anomalies

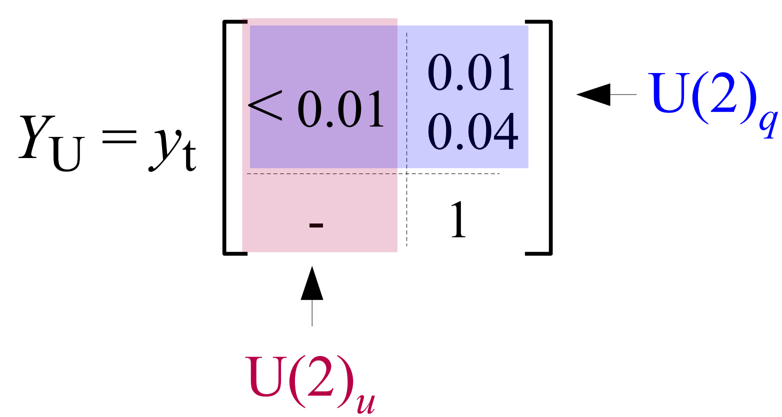
It turns out that a

- *U(2) flavor symmetry acting on the light generations of left-handed fields*
- *with small breaking terms as in the quark Yukawa couplings*

allows us to build a consistent EFT able to reach the twofold goal of

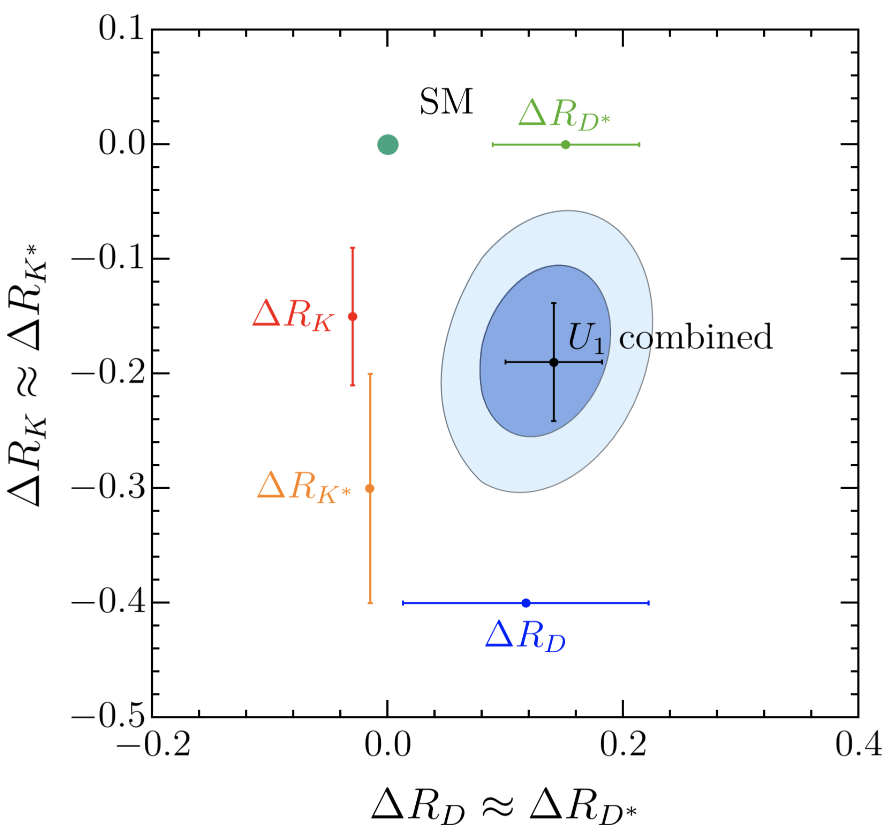
- *Link the recent LFU anomalies to the SM Yukawa couplings*
- *Address the compatibility with other low-energy data*





A combined EFT solution for the anomalies

The implementation of all the constraints -*beyond the tree-level*- is a non-trivial exercise where the power of the EFT in connecting processes at different energies becomes very relevant



Some comments:

- The virtue of this analysis is to show that a (*motivated*) combined explanation of the two sets of anomalies is possible
- The effective scale of NP is quite low (1.5-2.0 TeV) → important to address also high-pT bounds

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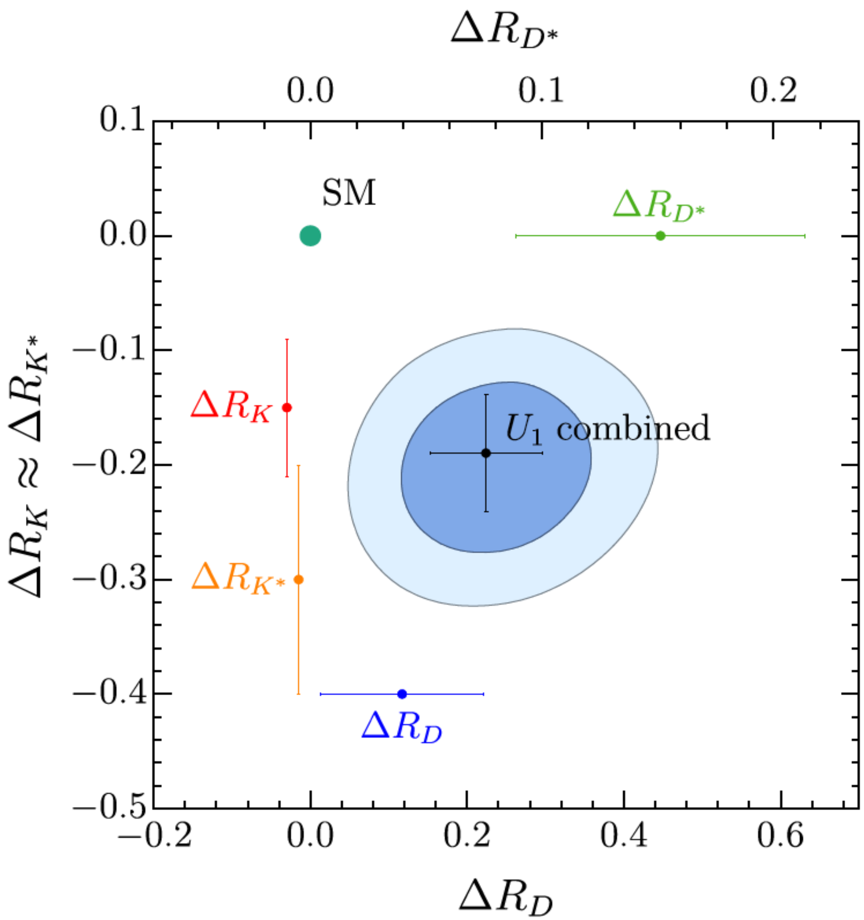


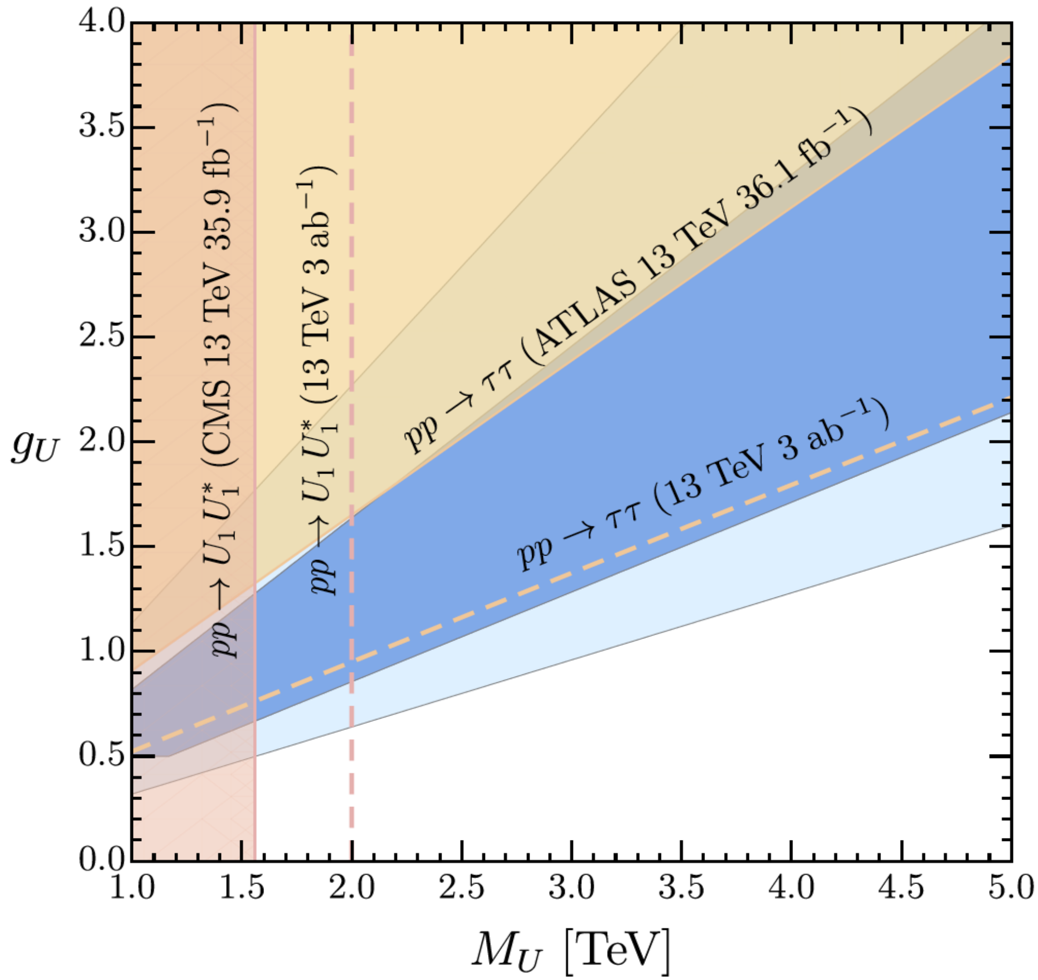
U(2)-*allowed operators with* b_R *fields included*

Some comments:

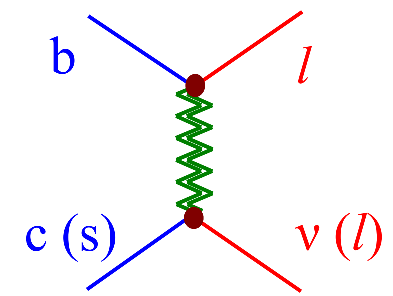
- The virtue of this analysis is to show that a (*motivated*) combined explanation of the two sets of anomalies is possible
- The effective scale of NP is quite low (1.5-2.0 TeV) → important to address also high-pT bounds
- Other options (e.g. with specific RH contributions) are also possible, but the overall picture does not change
- Significant changes occur only if we drop one the two anomalies, or if we invoke non-combined explanations

A combined EFT solution for the anomalies

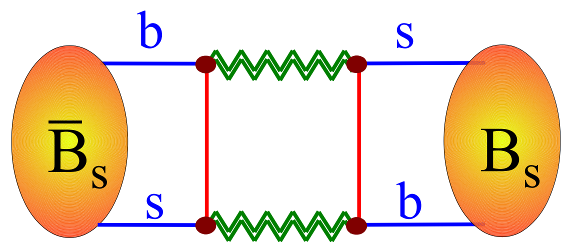
Consistent UV completions for this EFT exists and point to leptoquark meditators (naturally reduced impact in ΔF=2 and direct searches)



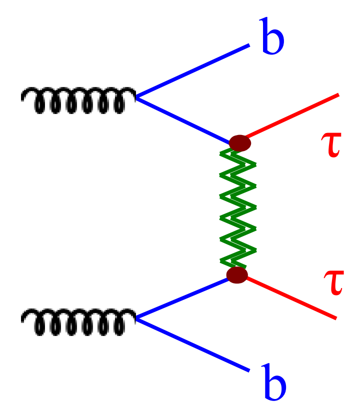
Tree-level
(un-suppress)
in b → c(s)+ν(*l*)



One-loop
(suppressed)
in ΔF=2



No di-lepton
mass peak in
high-pT



What we learned so far?

Even if the anomalies turned out to be a mere statistical fluctuation, this (EFT+simplified-model) "exercise" has been quite useful:

- Explicit example of new physics at the TeV scale that
  - shows up first in flavor observables
  - is within (*but not yet in*...) in the reach of direct searches at high energies

- Key role of flavor observables & interplay with high-pT in the *bottom → up reconstruction of a NP model*

- Critical re-thinking of theoretical hypothesis about physics beyond SM [*LFU does not need to hold...*] → Widening/re-thinking about possible NP search strategies

How to proceed?

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...

How to proceed?

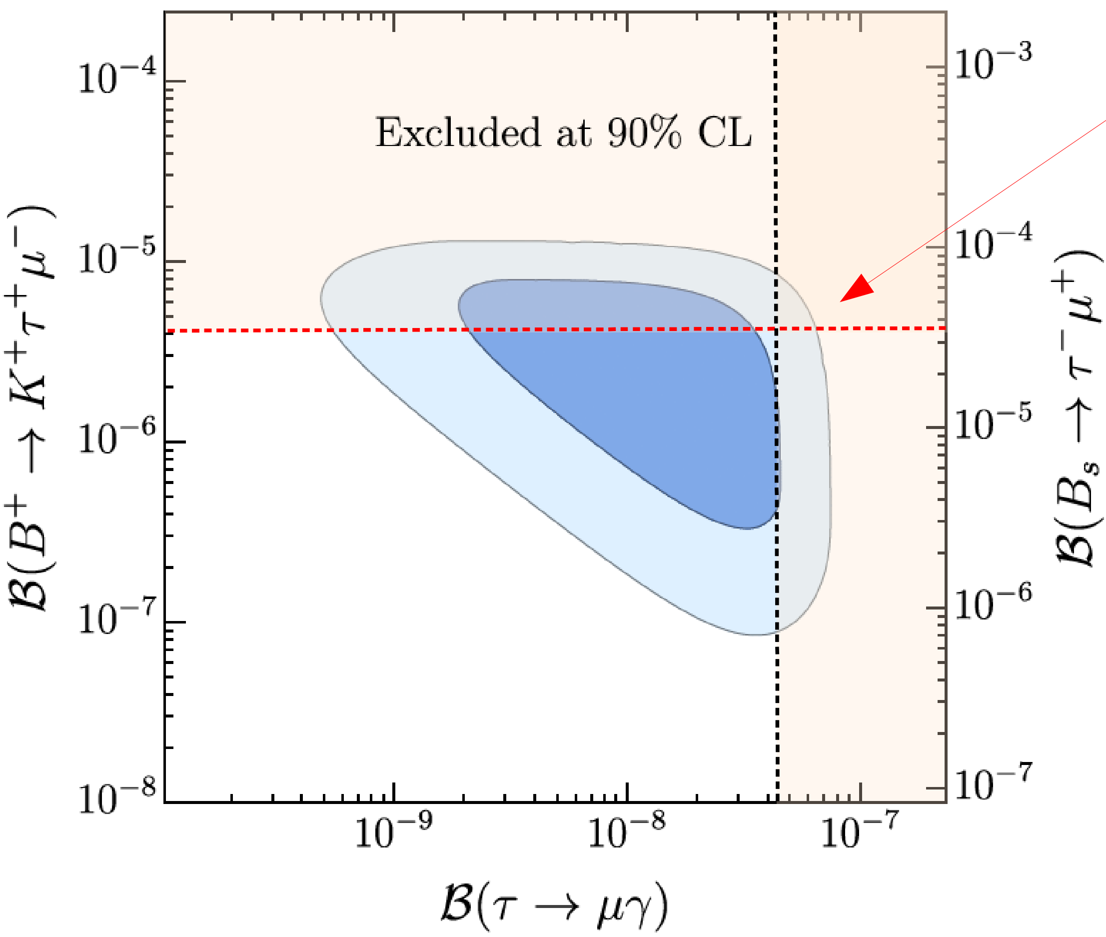
If the anomalies are due to NP, we should expect to see several other BSM effects in low-energy observables

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)	$B \to K\,\tau\mu$ $\to 10^{-6}$	$B \to K\,\mu e$???
$b \to d$	$B_d \to \mu\mu$ $B \to \pi\,\mu\mu$ $B_s \to K^{(*)}\,\mu\mu$ O(20%) [$R_K = R_\pi$]	$B \to \pi\,\tau\tau$ $\to$ 100×SM	$B \to \pi\,\nu\nu$ O(1)	$B \to \pi\,\tau\mu$ $\to 10^{-7}$	$B \to \pi\,\mu e$???
$s \to d$	*long-distance pollution*	*NA*	$K \to \pi\,\nu\nu$ O(1)	*NA*	$K \to \mu e$???

How to proceed?

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



Very recent bound by LHCb entering the interesting region of parameter space

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}

Concluding remarks

- Flavor physics remains somehow a mystery [*who ordered the muon?*]: we do not have yet clear answers for the two (*SM* & *NP*) *flavor puzzles.*
- But flavor physics is also a great opportunity → *great potential to explore physics beyond the SM*, in a way that is complementary to that of direct searches, it is very effective, and it is particularly interesting in the next 10-15 years.

Concluding remarks

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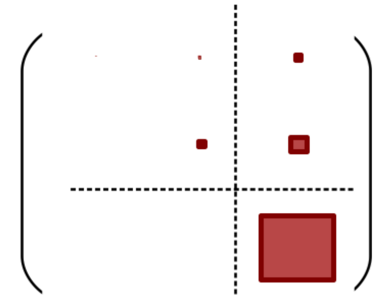
- But flavor physics is also a great opportunity → *great potential to explore physics beyond the SM*, in a way that is complementary to that of direct searches, it is very effective, and it is particularly interesting in the next 10-15 years.
- The recent LFU anomalies provides a concrete demonstration of the above statement [*nice internal consistency of present data, but significance still low*].
- If interpreted as NP signals, these anomalies are not in contradiction with existing low- & high-energy data. Taken together, they point out to a well-defined structure of NP coupled mainly to 3rd generation, with a flavor structure connected to that appearing in the SM Yukawa couplings.


Backup

The U(2)^n *flavor symmetry*

$$\mathscr{L}_{\rm Yukawa} = Q_L^{\,i}\, Y_U^{\,ij}\, U_R^{\,j}\, \phi + \ldots \qquad Y_U\,|_{\rm exp} = V_{\rm CKM}^{\,+}\, {\rm diag}(y_u, y_c, y_t) =$$



The symmetry in the quark sector:

$$U(2)^3 = U(2)_q \times U(2)_u \times U(2)_d$$

$$Y_U\,|_{\rm th} = y_t \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \rightarrow \begin{bmatrix} 0 & V \\ 0 & 1 \end{bmatrix} \rightarrow \begin{bmatrix} \Delta & V \\ 0 & 1 \end{bmatrix}$$

leading breaking *final breaking*

Minimal breaking necessary to reproduce SM Yukawa couplings:

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

$$|\Delta| \approx y_c = 0.006$$

- The assumption of a single leading breaking ensures an protection of FCNCs as in MFV:

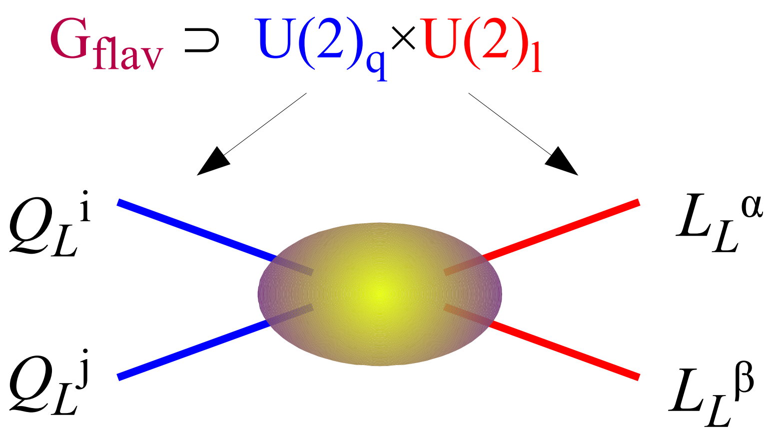
$$\mathcal{M}(B_d - B_d) \to \sim (y_t\, V_{tb}^{\,*} V_{td})^2 \quad [\text{MFV}]$$

$$\mathcal{M}(B_d - B_d) \to \sim (V_{tb}^{\,*} V_{td})^2 \quad [\text{U(2)}^n]$$

A combined EFT solution for the anomalies

A chiral U(2) symmetry acting on the light generations of left-haded quarks and leptons turns out to be the ideal "tool" to reach the twofold goal of

- *Link the recent LFU anomalies to the SM Yukawa couplings*
- *Address the compatibility with other low-energy data*



Assumptions:

- NP in left-handed operators only [at the high-scale]
- Flavor structure controlled by $U(2)_q \times U(2)_l$ minimally broken as in the SM

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{v^2} \lambda^q_{ij} \lambda^\ell_{\alpha\beta} \left[C_T \, (\bar Q^i_L \gamma_\mu \sigma^a Q^j_L)(\bar L^\alpha_L \gamma^\mu \sigma^a L^\beta_L) + C_S \, (\bar Q^i_L \gamma_\mu Q^j_L)(\bar L^\alpha_L \gamma^\mu L^\beta_L) \right]$$

four free parameters...

C_T, C_S
$\lambda_{bs} = O(V_{cb})$
$\lambda_{\mu\mu} = O(|V_{\tau\mu}|^2)$

...and a long list of constraints

[FCNCs + semi-leptonic b decays
π, K, τ decays + EWPO]

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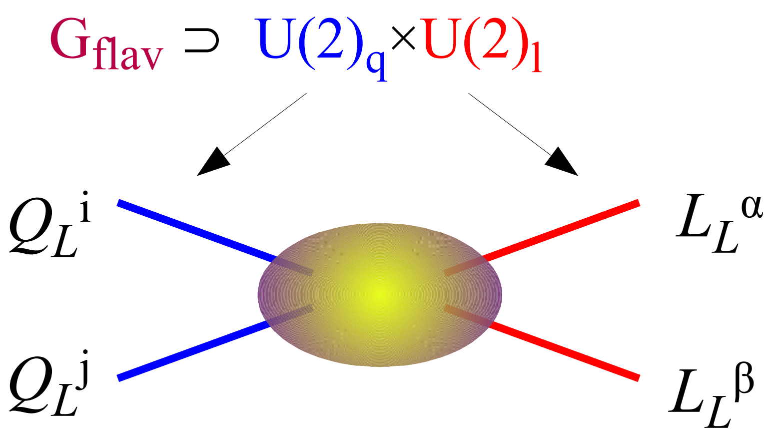
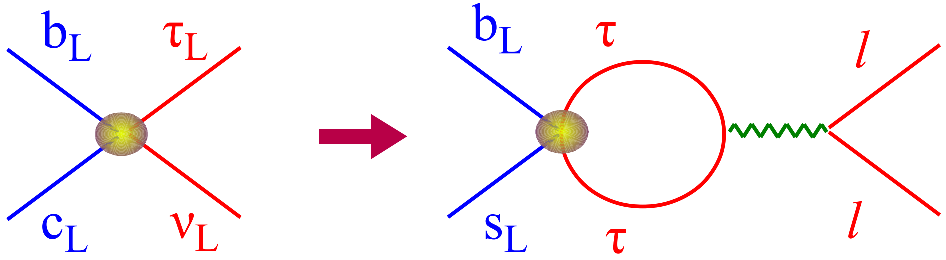


New data make this picture even <u>more consistent</u>:

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:



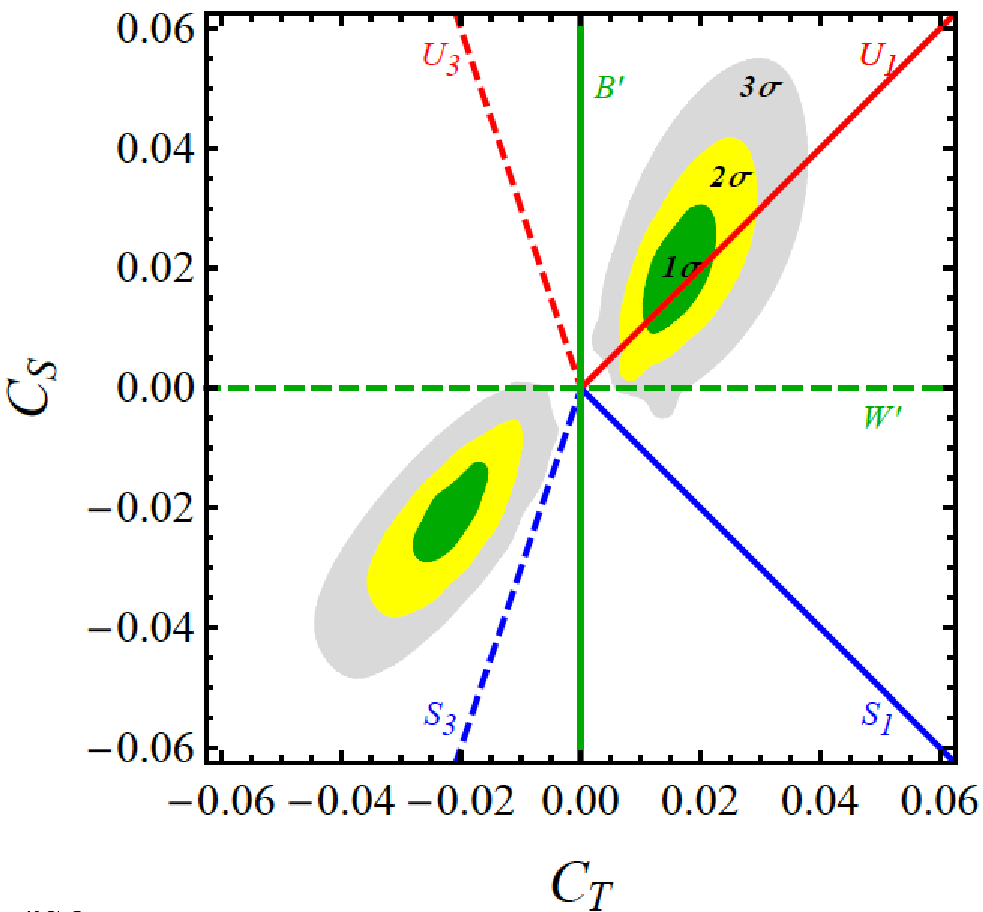
Crivellin, Greub, Muller, Saturnino '19

Simplified models and high-pT constraints

The effective scale of the EFT is quite low → the four-fermion operators must be generated by tree-level exchange of some new massive mediator in order to have a realistic chance to be consistent with bounds from direct searches
→ *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'



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

▶ General EFT & simplified-model considerations

Which LQ explain which anomaly?

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

There is one 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'

Barbieri, GI, Pattori, Senia, '15
Di Luzio, Greljo, Nardecchia, '17
+ many others...

- 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

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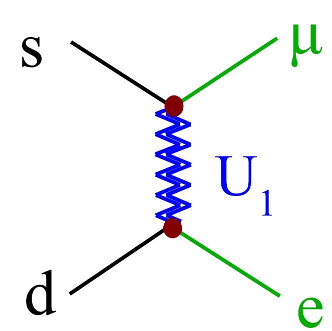
The problem of the "original PS model" are the strong bounds on the LQ couplings to 1st & 2nd generations [e.g. $M > 200$ TeV from $K_L \to \mu e$]

→ we must go beyond the original model



Speculations on UV completions

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

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 $U(1)_Y$ charges]

↑

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

IR: SM

Q_i, u_i, d_i, L_i, e_i

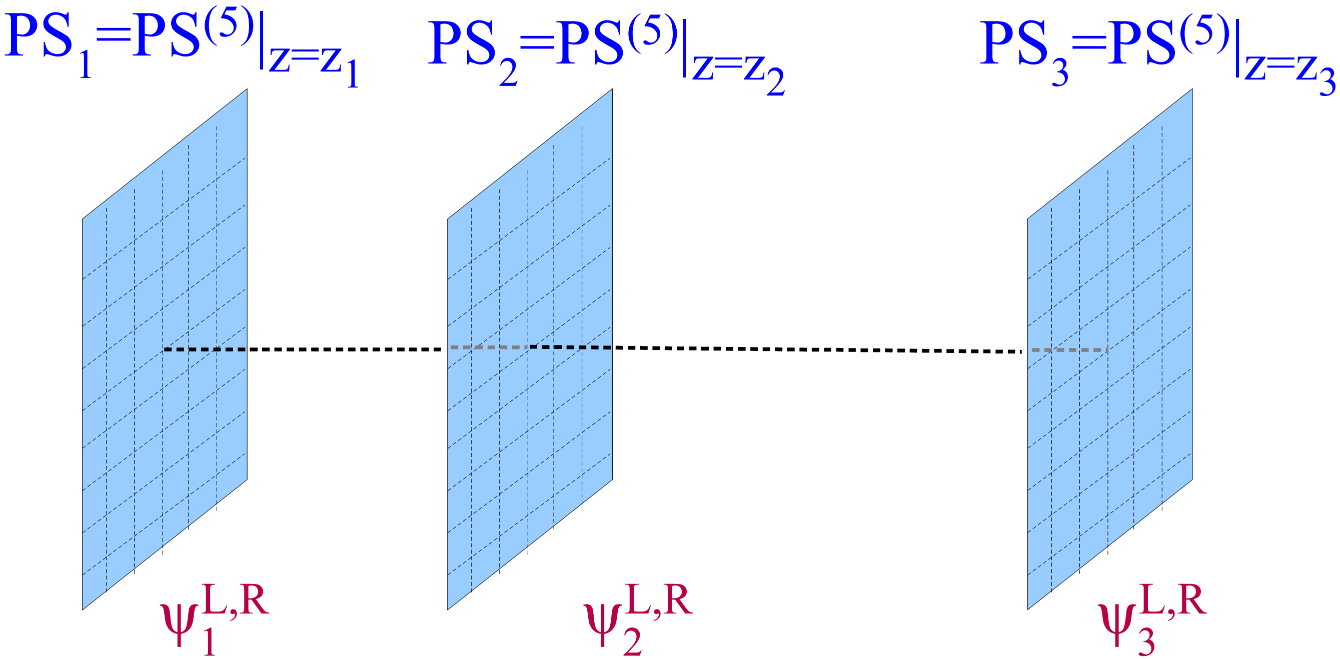
Key advantages:

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

Speculations on UV completions

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

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



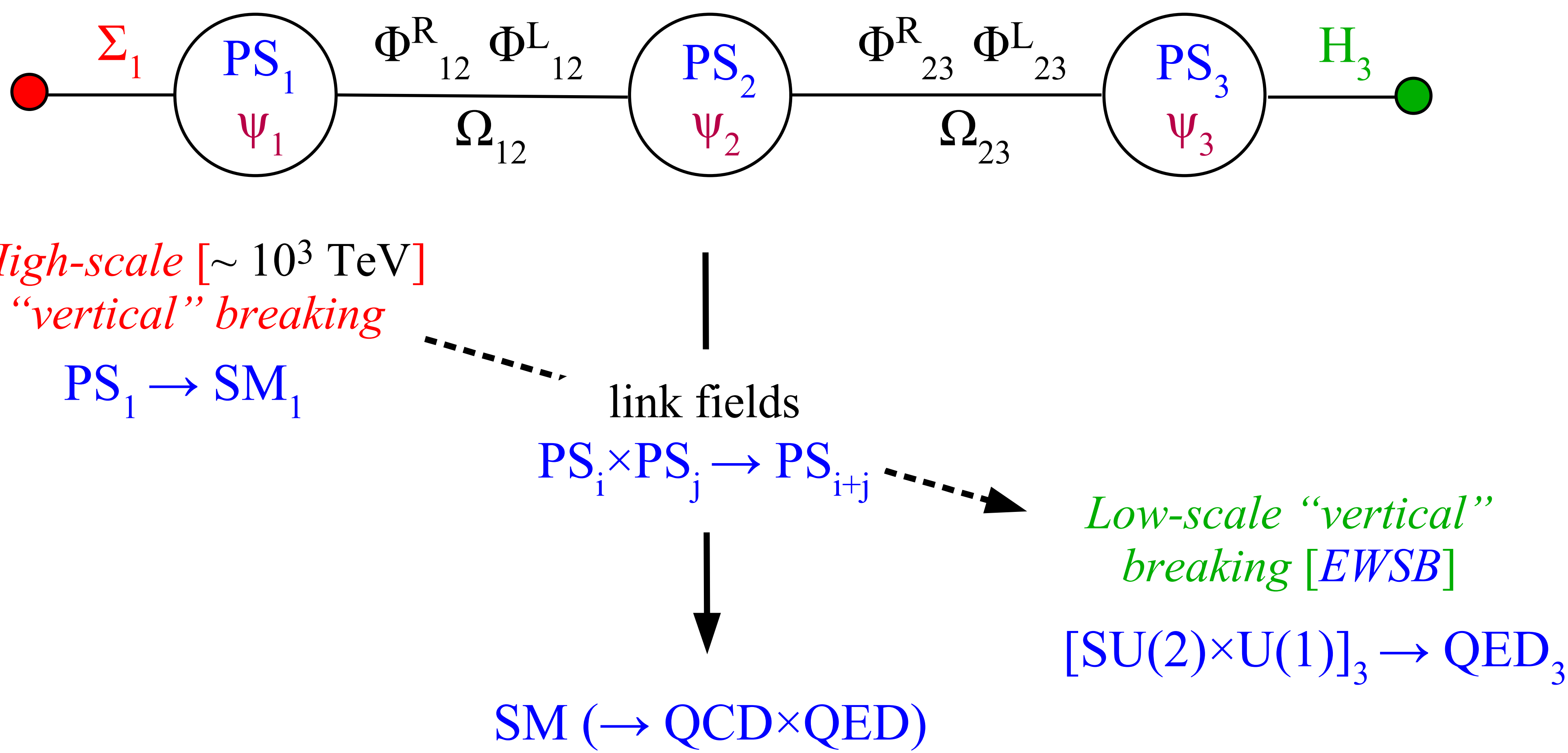
Unification
of quarks and leptons

"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

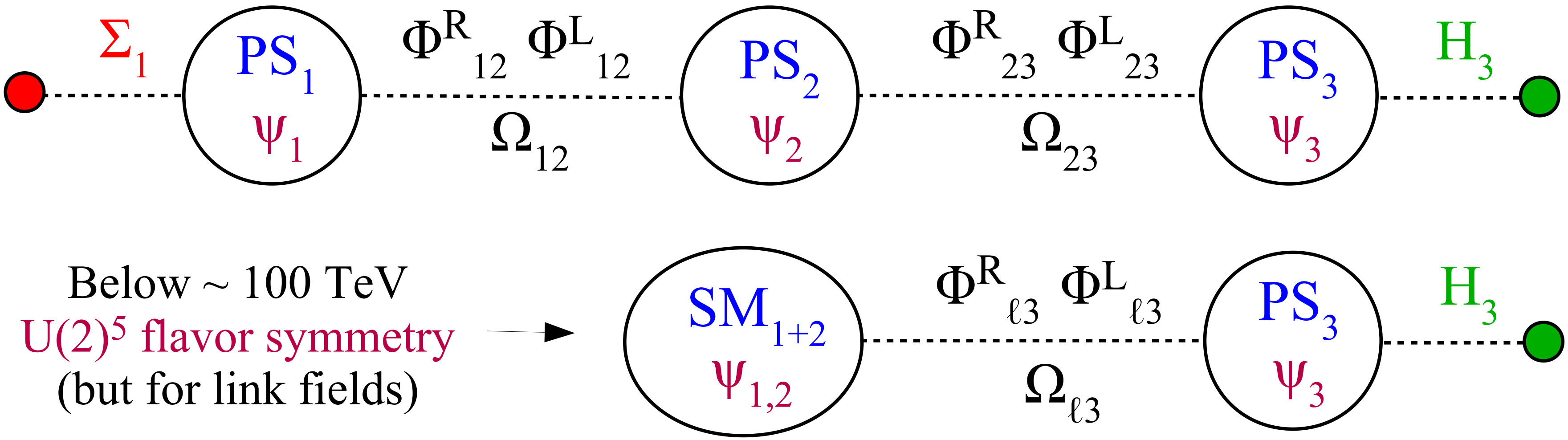
The 4D description is apparently more complex, but it allow us to derive precise low-energy phenomenological signatures (*4D renormalizable gauge model*)

Speculations on UV completions



- The breaking to the diagonal SM group occurs via appropriate "link" fields, responsible also for the generation of the hierarchy in the Yukawa couplings.
- LQ (and other exotic) fields coupled mainly to light families acquire very heavy masses, while the lightest exotic states are coupled mainly to the 3rd generation

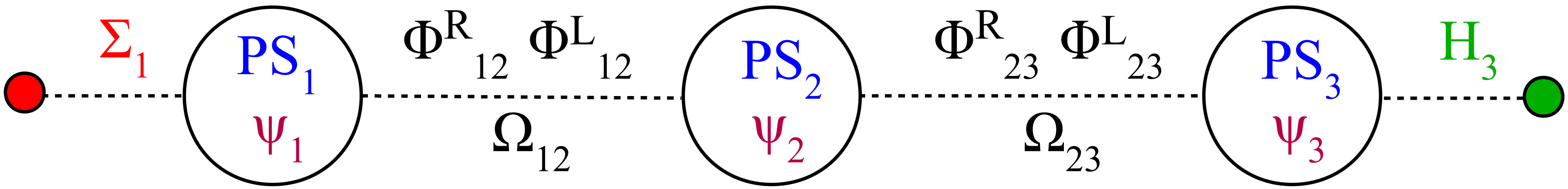
Speculations on UV completions



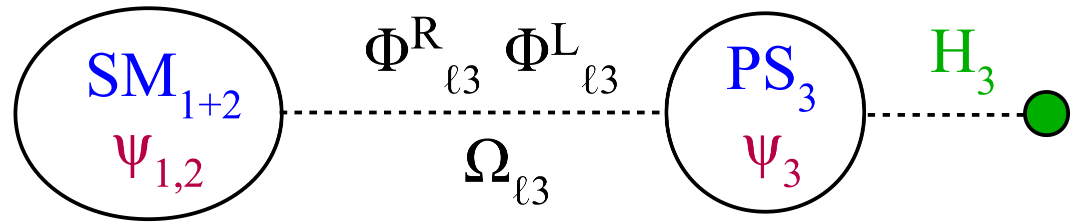
Leading flavor structure:

- 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.

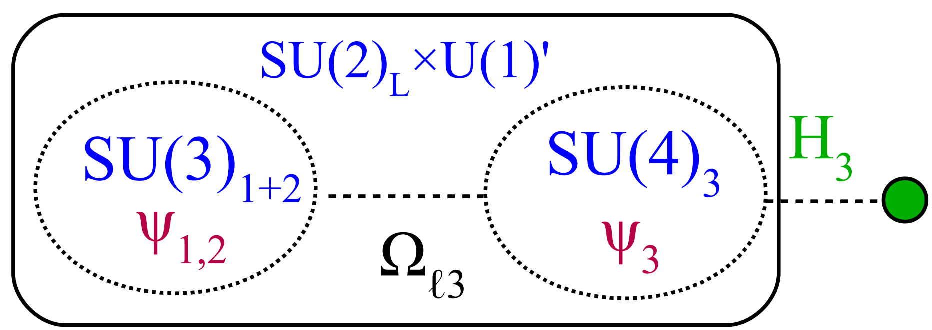
Speculations on UV completions



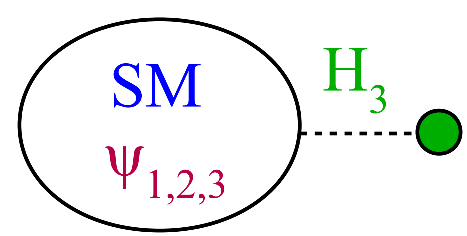
Below ~ 100 TeV
$U(2)^5$ flavor symmetry
(but for link fields) →



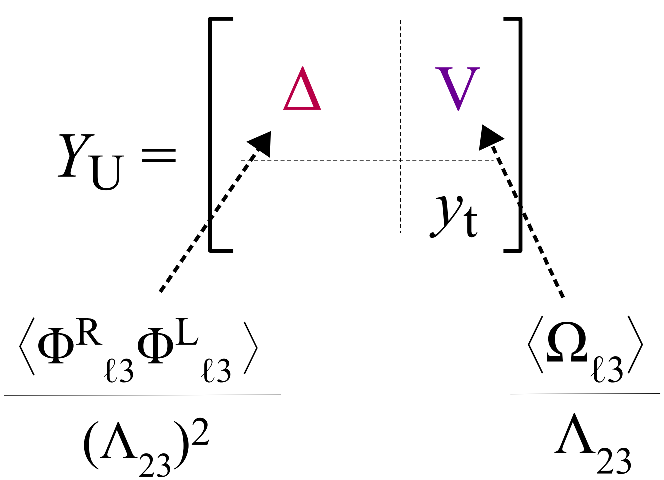
→ $W_L' + W_R'$ [~ 5-10 TeV]



→ LQ [U_1] + Z' + G' [~ 1-5 TeV]

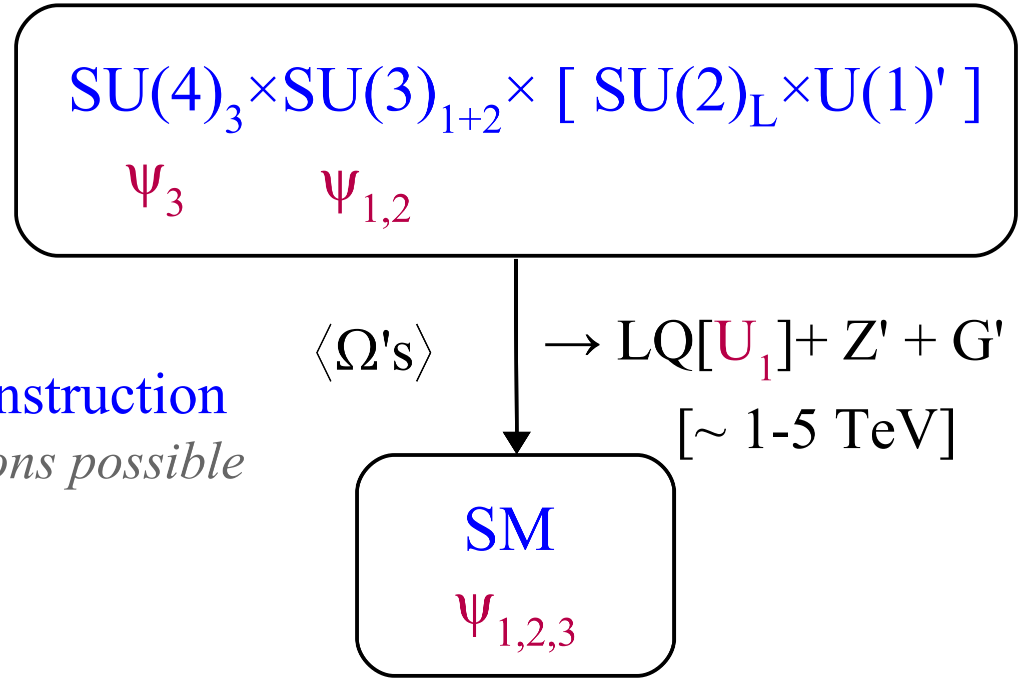


Sub-leading Yukawa terms from higher dim ops:



Speculations on UV completions

Collider phenomenology and flavor anomalies are controlled by the last-but one step in the breaking chain: 4321 → SM [Di Luzio, Greljo, Nardecchia, '17]



Despite the apparent complexity, the construction is quite constrained [*still, several variations possible according to detailed field content*]

⬇

Possible to reproduce all the positive features the EFT + simplified model

+

Calculability of $\Delta F=2$ processes

[*in good agreement with present data*]

+

New exotic high-pT signatures [Z' & G']
[*compatible with present bounds*]

G' = massive copy of the gluon, coupled mainly to 3rd gen. quarks

Speculations on UV completions

Collider phenomenology and flavor anomalies are controlled by the last-but one step in the breaking chain: 4321 → SM [Di Luzio, Greljo, Nardecchia, '17]

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

ψ_3 $\psi_{1,2}$

$\langle \Omega\text{'s} \rangle$ → LQ[U_1]+ Z' + G' [~ 1-5 TeV]

SM

$\psi_{1,2,3}$

Despite the apparent complexity, the construction is quite constrained [*still, several variations possible according to detailed field content*]

Possible to reproduce all the positive features the EFT + simplified model

+

Calculability of ΔF=2 processes

[*in good agreement with present data*]

+

New exotic high-pT signatures [Z' & G']
[*compatible with present bounds*]

General comments:

Not easy to build consistent UV models, but not impossible...

The attempt leads to interesting, somehow unexplored, directions in model-space...

Speculations on UV completions

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

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

Ψ_3 $\Psi_{1,2}$

$\langle \Omega\text{'s} \rangle$ → LQ [U_1] + Z' + G' [~ 1-5 TeV]

SM

$\Psi_{1,2,3}$

We can reproduce all the positive features the simplified model

+

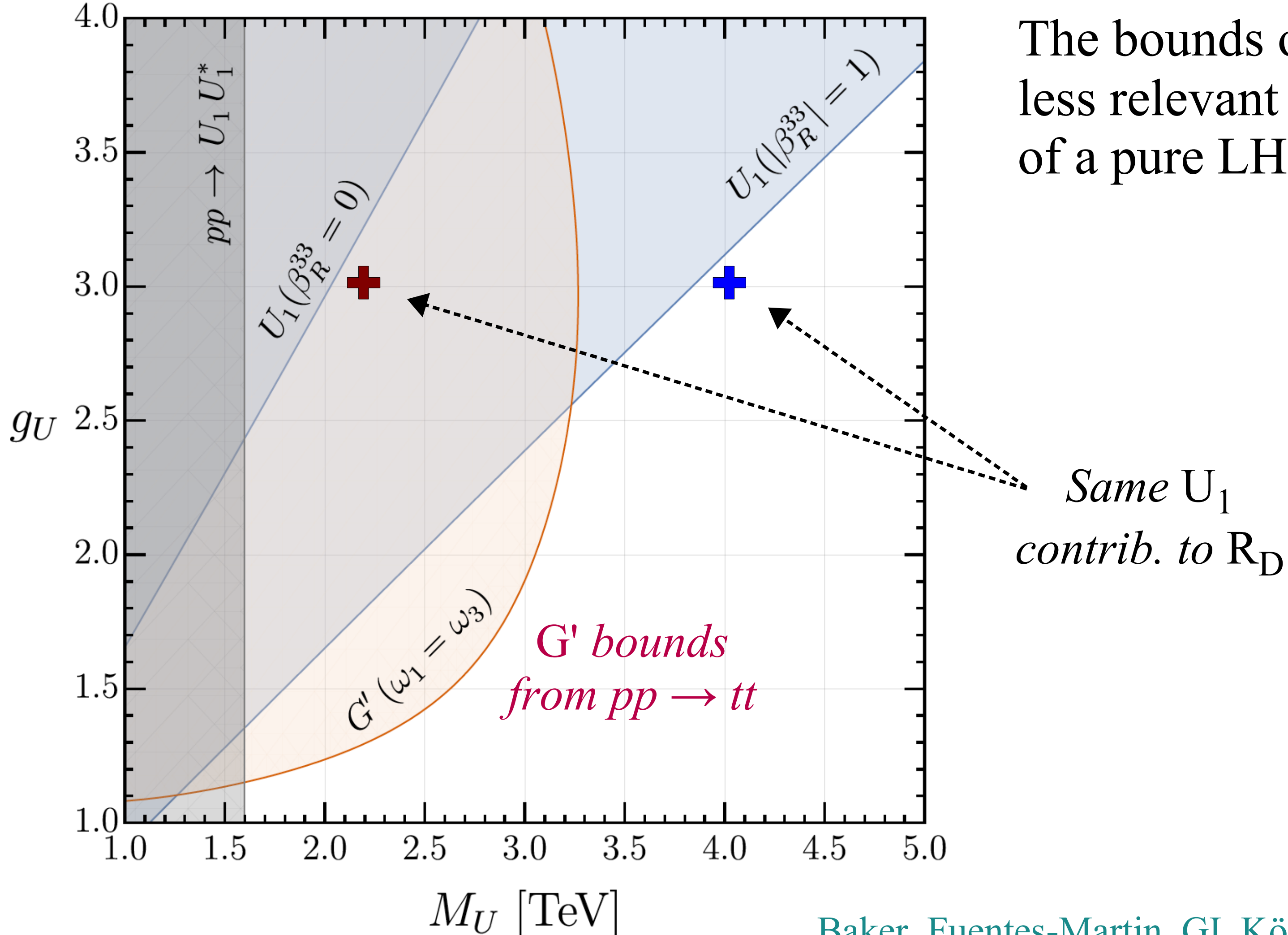
Calculability of ΔF=2 processes

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

Cornella, Fuentes-Martin, GI, '19

The PS^3 *model*

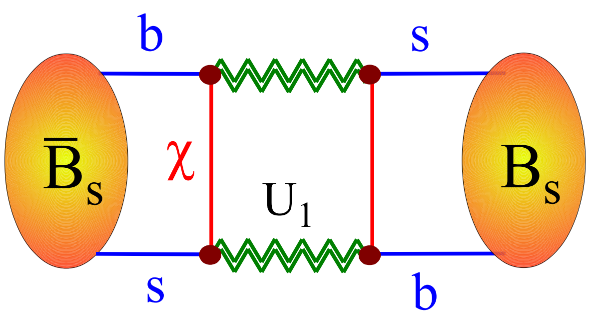
A key difference between the simplified model and this complete UV model is the high-pT phenomenology, which now involves more states

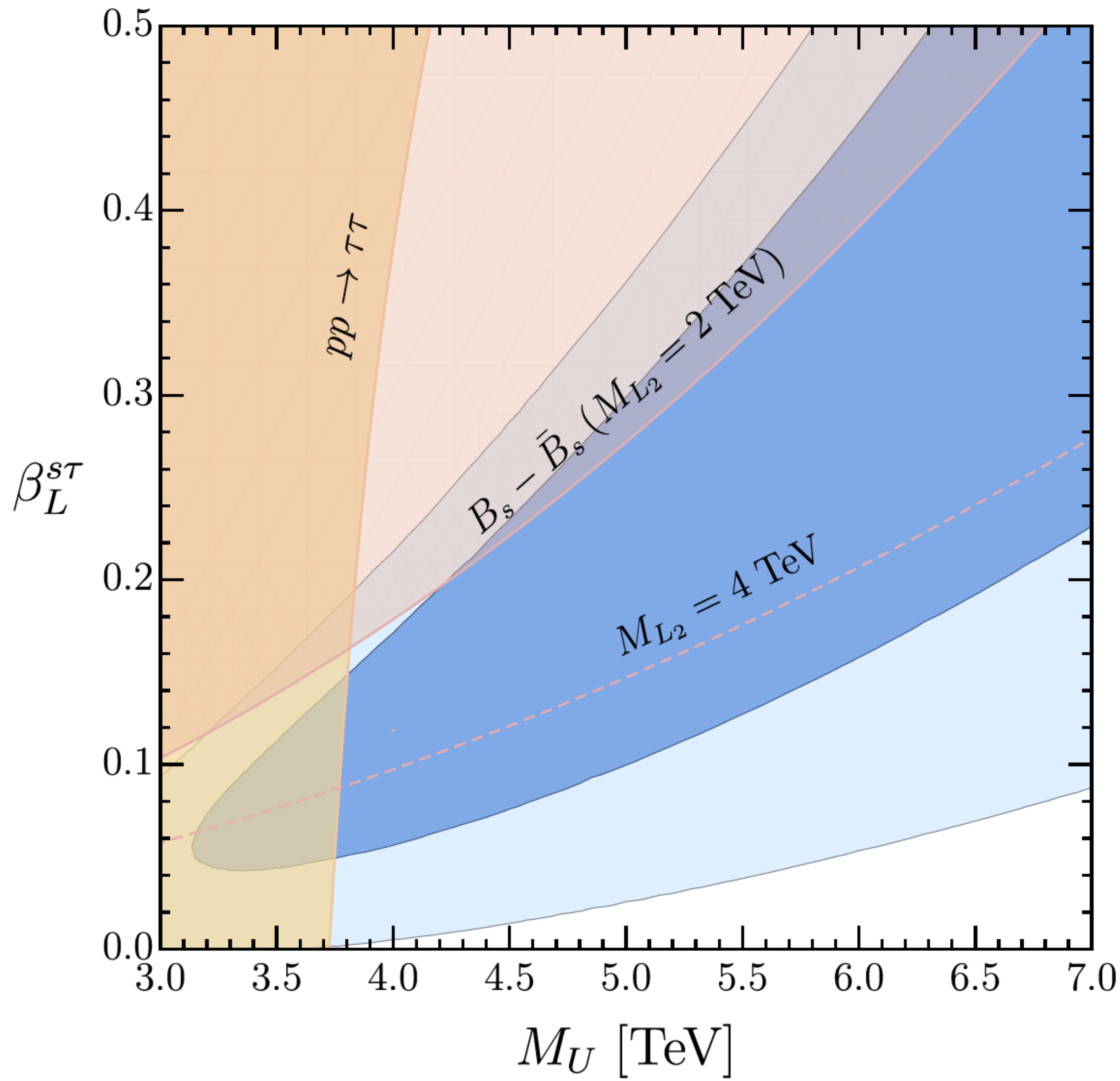


The bounds on the coloron are less relevant in PS^3 vs. the case of a pure LH coupled U_1

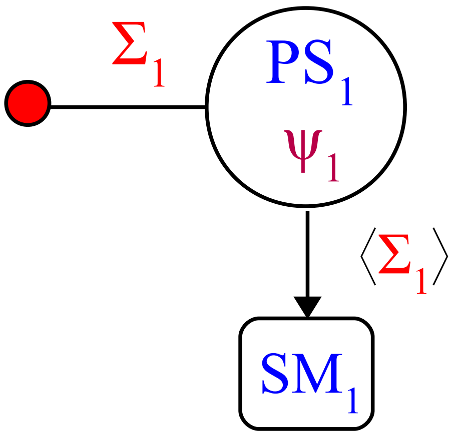
Baker, Fuentes-Martin, GI, König, '19

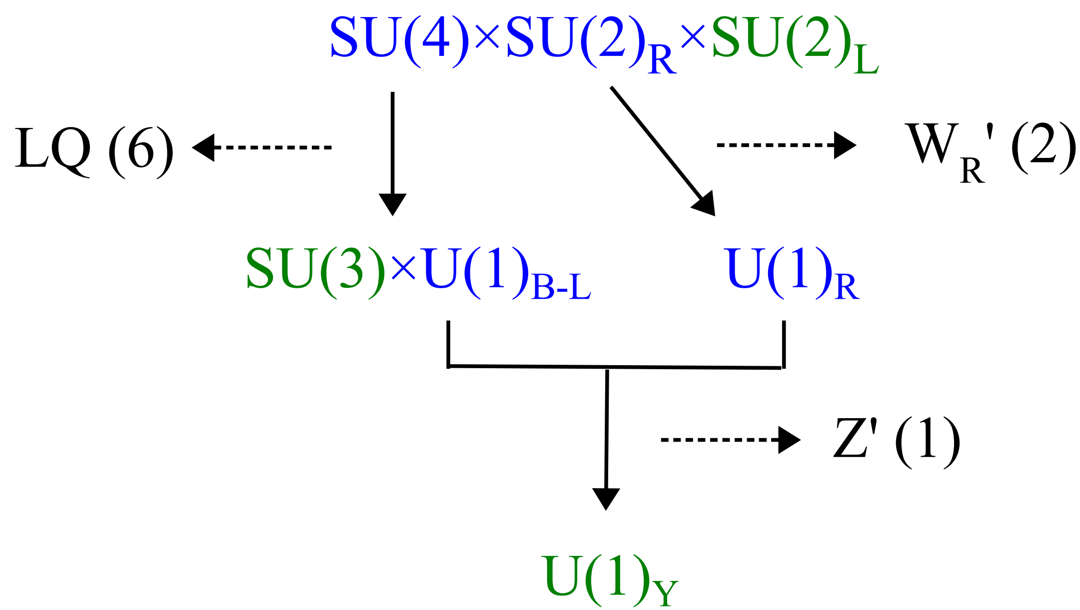
Bounds on vector-like fermion masses from ΔF=2





Symmetry breaking pattern in PS^3





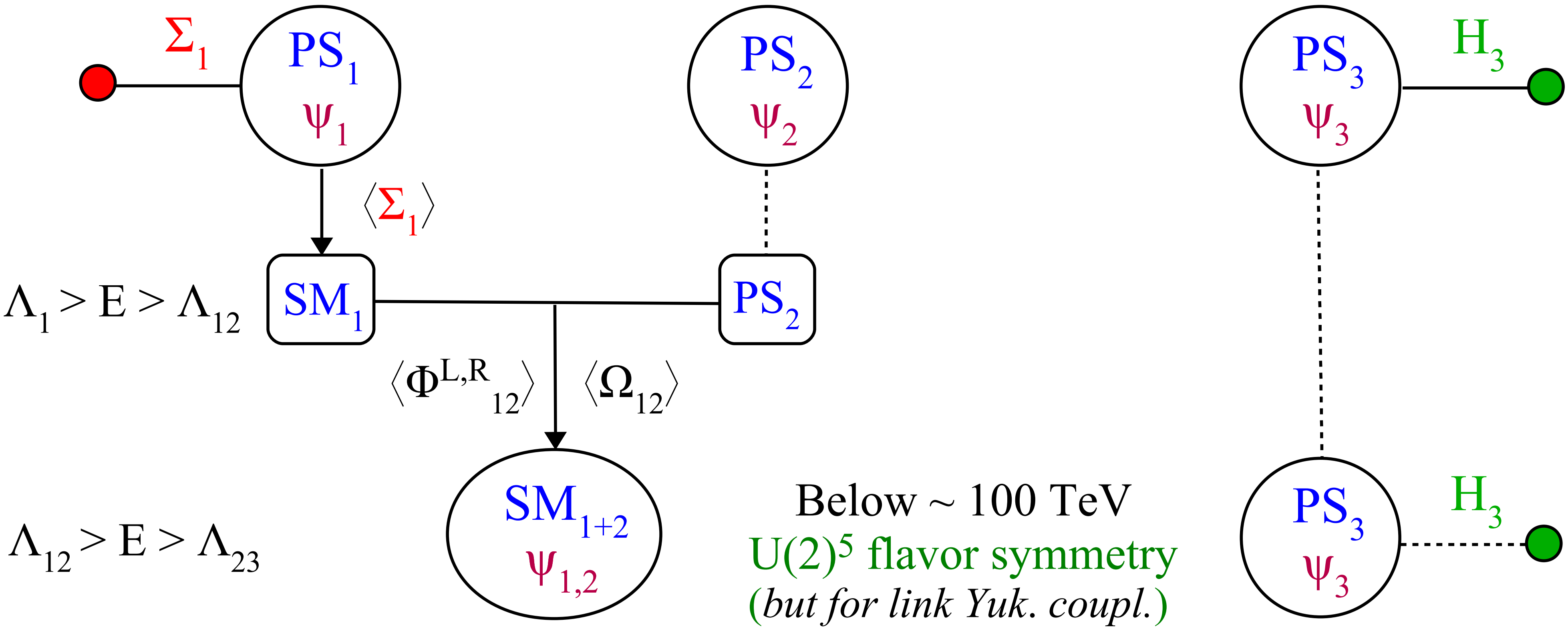
High-scale [~ 10^3 TeV]
"vertical" breaking [PS → SM]

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 $\rightarrow SU(4)_{1+2}$ & $SU(2)^L{}_{1+2}$

Implications for future low-energy measurements

A similar table can be made also for charged currents, and in this case the predictions of the EFT are more simple/robust:

I) LH operators [universality of all $R^{\tau/\mu}(b\to c)$ ratios]:

$$\frac{R_D}{(R_D)_{SM}} = \frac{\Gamma(B\to D^*\tau\nu)/\Gamma_{SM}}{\Gamma(B\to D^*\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(B_c\to\psi\tau\nu)/\Gamma_{SM}}{\Gamma(B_c\to\psi\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(\Lambda_b\to\Lambda_c\tau\nu)/\Gamma_{SM}}{\Gamma(\Lambda_b\to\Lambda_c\mu\nu)/\Gamma_{SM}} = \ldots$$

II) U(2) symmetry [$R^{\tau/\mu}(b\to c)=R^{\tau/\mu}(b\to u)$ universality]:

$$\frac{\Gamma(B\to\pi\,\tau\nu)/\Gamma_{SM}}{\Gamma(B\to\pi\,\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(\Lambda_b\to p\,\tau\nu)/\Gamma_{SM}}{\Gamma(\Lambda_b\to p\,\mu\nu)/\Gamma_{SM}} = \frac{\Gamma(B_s\to K^*\tau\nu)/\Gamma_{SM}}{\Gamma(B_s\to K^*\mu\nu)/\Gamma_{SM}} = \ldots = \frac{R_D}{(R_D)_{SM}}$$

Any mode for which we can predict well the LFU ratio is good for such tests...

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N.B.: The only info on $b \to u\tau\nu$ we have is $BR(B_u\to\tau\nu)^{exp}/BR_{SM} = 1.31 \pm 0.27$
→ perfectly consistent with I+II
UTfit. '16

N.B.: The predictions for $R^{\mu/e}(b\to c)$ are more uncertain, but up to O(2%) possible
→ worth to improve

Implications for future low-energy measurements

The low-energy observables with large uncertainties are those mediated by four-quark or four-leptons effective operators (*larger model-dependence in connecting them to the semi-leptonic operators, hence to the anomalies*)

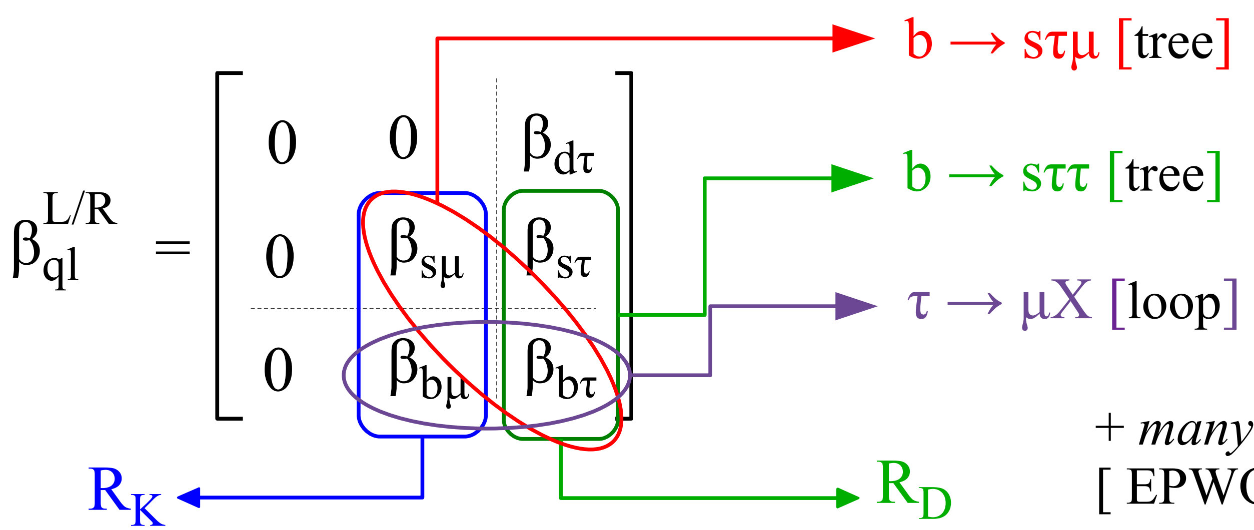
However, in many explicit constructions, the effects are close to present bounds:

- Meson mixing
  - O(1-30%) deviations from SM in ΔM_{Bs} & ΔM_{Bd}
  - O(0.1-1%) CPV violation D-D mixing
- τ decays
  - $\tau \to 3\mu$ can be close to exp. bound (BR ~ 10^{-9})
  - O(0.1%) deviations in $BR(\tau\to\mu\nu\nu)/BR(\tau\to e\nu\nu)$ and $G_F^{(\tau)}$ vs. $G_F^{(\mu)}$

Role of RH currents

- Despite no clear evidence of RH current in present data, the quantum numbers of the U_1 allow both RH and LH currents
- A U_1 with both RH and LH currents is particularly welcome from the UV point of view (→ *more later*)

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



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

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

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