On the breaking of Lepton Flavor Universality in B decays

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- Introduction
- On the recent B-physics anomalies
- EFT-type considerations
- Simplified dynamical models
- Conclusions

Disclaimer:
- this is not a review
- apologies for missing citations

Introduction

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 NP effects in present data...

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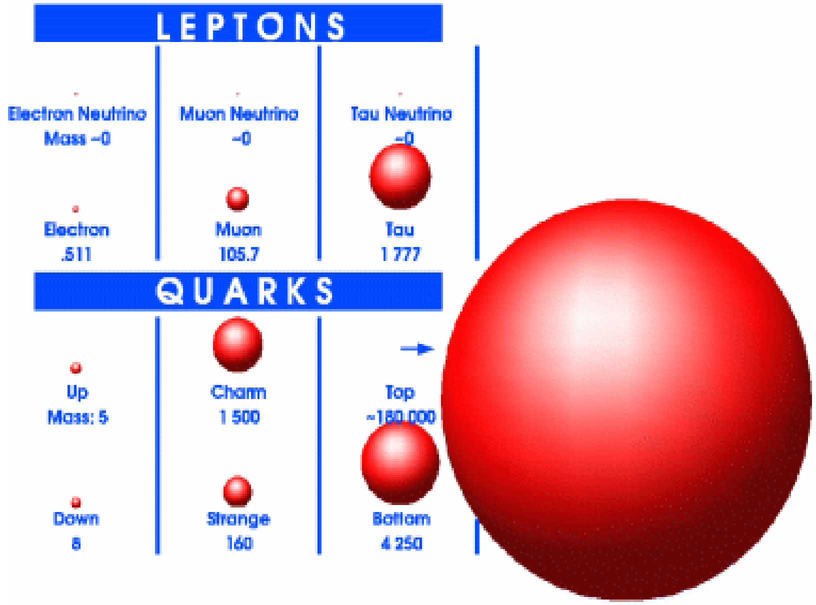
A few general messages:

- LFU is not a fundamental symmetry of the SM Lagrangian (*global symmetry of the gauge sector only, badly broken by Yukawas*)
- LFU tests at the Z peak are not as stringent as they may appear ($\to$ gauge sector)
- Most stringent tests of LFU involve only 1st-2nd gen. quarks & leptons



Natural to conceive NP models where LFU is violated more in processes involving 3rd gen. quarks & leptons (↔ *hierarchy in Yukawa coupl.*)

Introduction

These recent results have stimulated a lot of theoretical activity
(*not particularly instructive to discuss all NP proposals...*)

What I will discuss next is a bottom-up approach made of three main steps:

Generic EFT approach – with flavor symmetries

↓

Simplified Dynamical Models

↓

High-energy behavior and UV completion

The main guide will be the attempt to describe both LFU effects within the same framework [*possibly linking them to the observed pattern of Yukawa couplings*] and, while "going up" in energies (and assumptions), check the consistency with

- other low-energy data
- high-pT physics

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Generic EFT approach – with flavor symmetries — Bordone, GI, Trifinopoulos '17

↓

Simplified Dynamical Models — Greljo, GI, Marzocca '15; Barbieri, GI, Pattori, Senia '15

↓

High-energy behavior and UV completion — Buttazzo, Greljo, GI, Marzocca '15; Faroughy, Greljo, Kamenik '16

The main guide will be the attempt to describe both LFU effects within the same framework [*possibly linking them to the observed pattern of Yukawa couplings*] and, while "going up" in energies (and assumptions), check the consistency with

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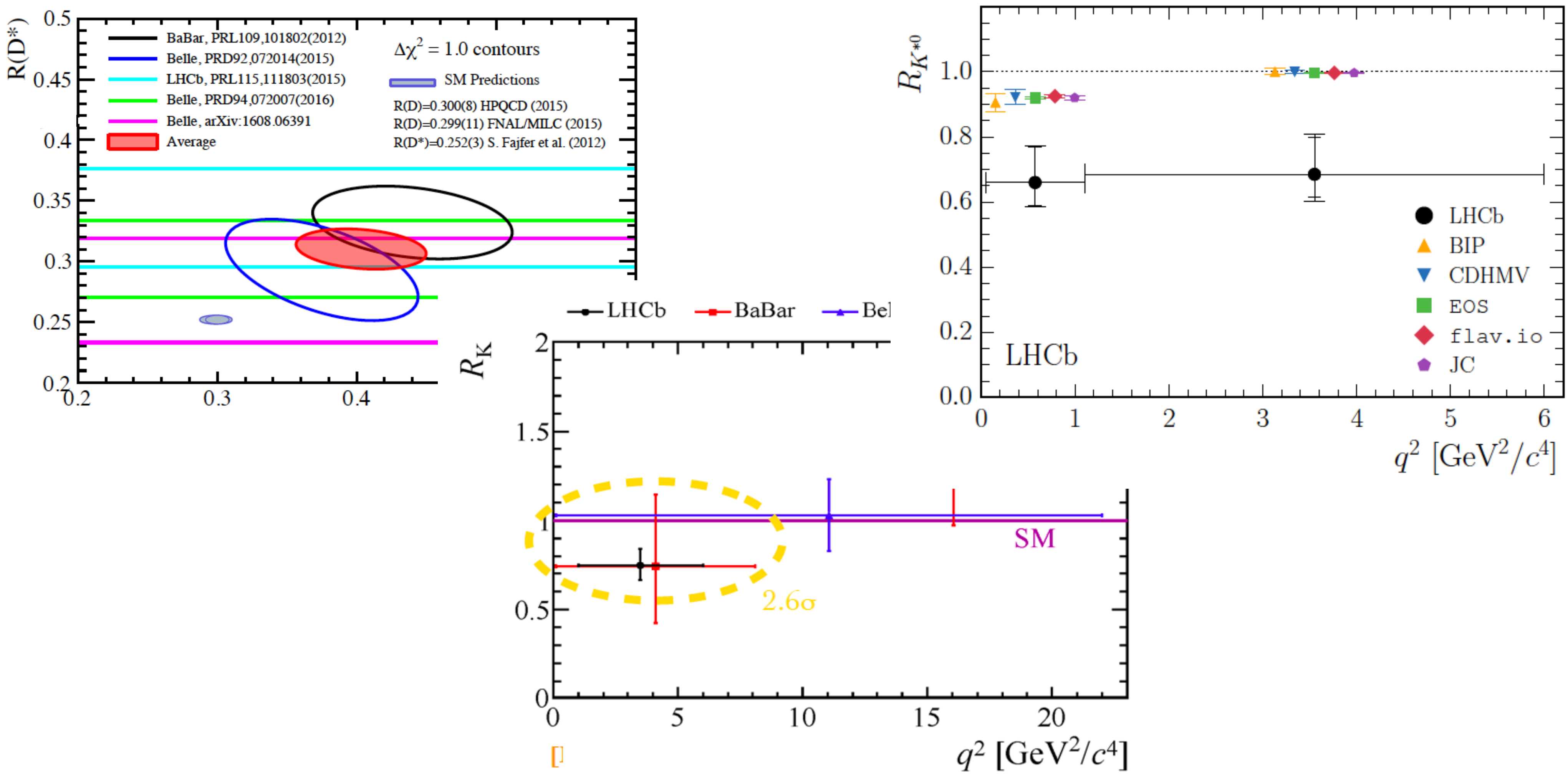
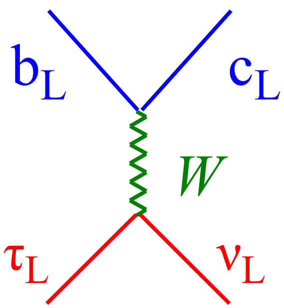
On the recent B-physics anomalies

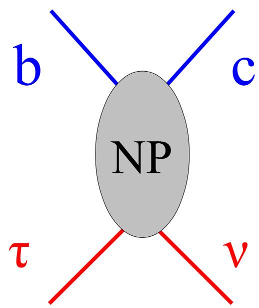


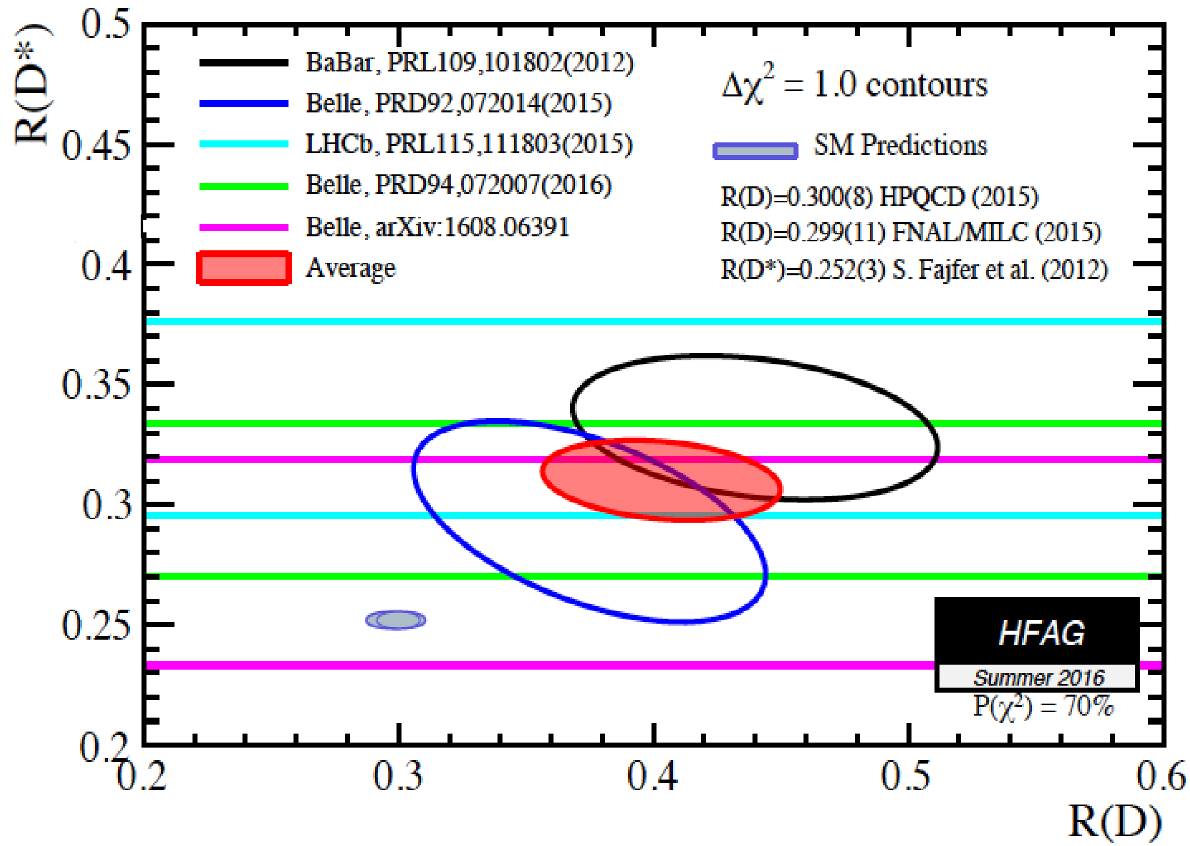
I. $B \to D^{(*)} \tau\nu$ [Babar, Belle, LHCb]

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

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







- SM prediction quite solid: f.f. uncertainty cancel (*to a good extent...*) in the ratio
- Consistent exp. results by 3 (very) different experiments
  - 3.9σ excess over SM (if D and D* combined)

I. B → $D^{(*)}$ τν [Babar, Belle, LHCb]

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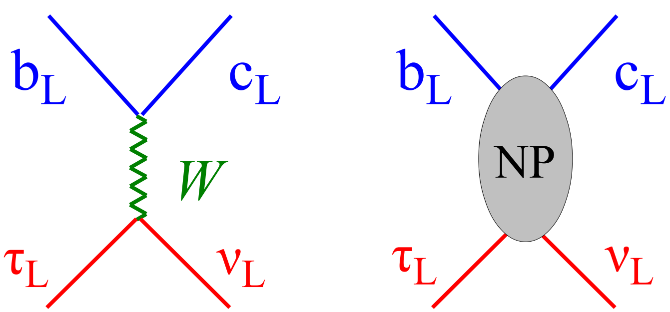

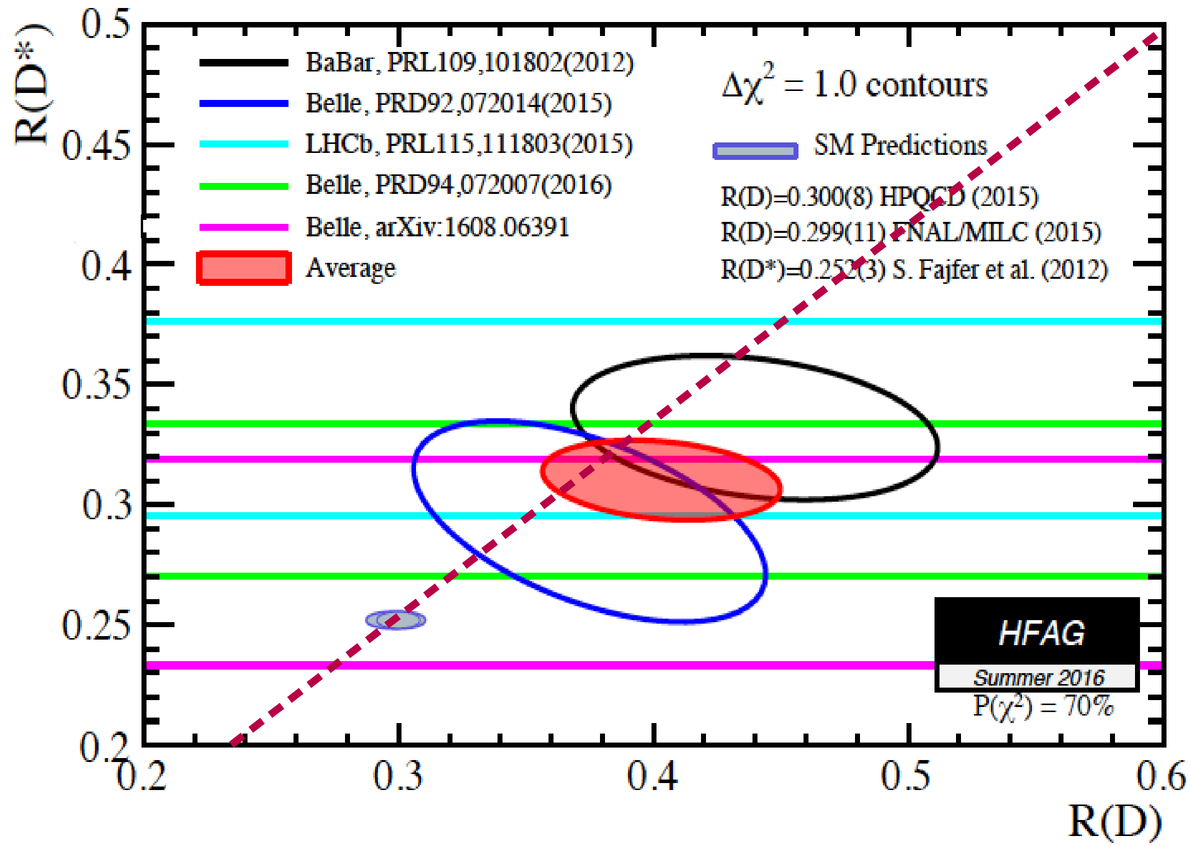

- SM prediction quite solid: f.f. uncertainty cancel (*to a good extent…*) in the ratio
- Consistent exp. results by 3 (very) different experiments
  - 3.9σ excess over SM (if D and D* combined)
  - The two channels are well consistent with a universal enhancement (~30%) of the SM $b_L \to c_L\ \tau_L\ \nu_L$ amplitude (*RH or scalar amplitudes disfavored*)

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

The largest anomaly is the one [*obs. in 2013 and confirmed with higher stat. in 2015*] in the P_5' [$B \to K^* \mu\mu$] angular distribution.

Less significant correlated anomalies present also in other $B \to K^* \mu\mu$ observables and also in other $b \to s\mu\mu$ channels [overall smallness of all BR($B \to$ Hadron + $\mu\mu$)]

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But the most interesting effects in $b \to s ll$ transitions are deviations from μ/e universality in appropriate "clean" ratios:

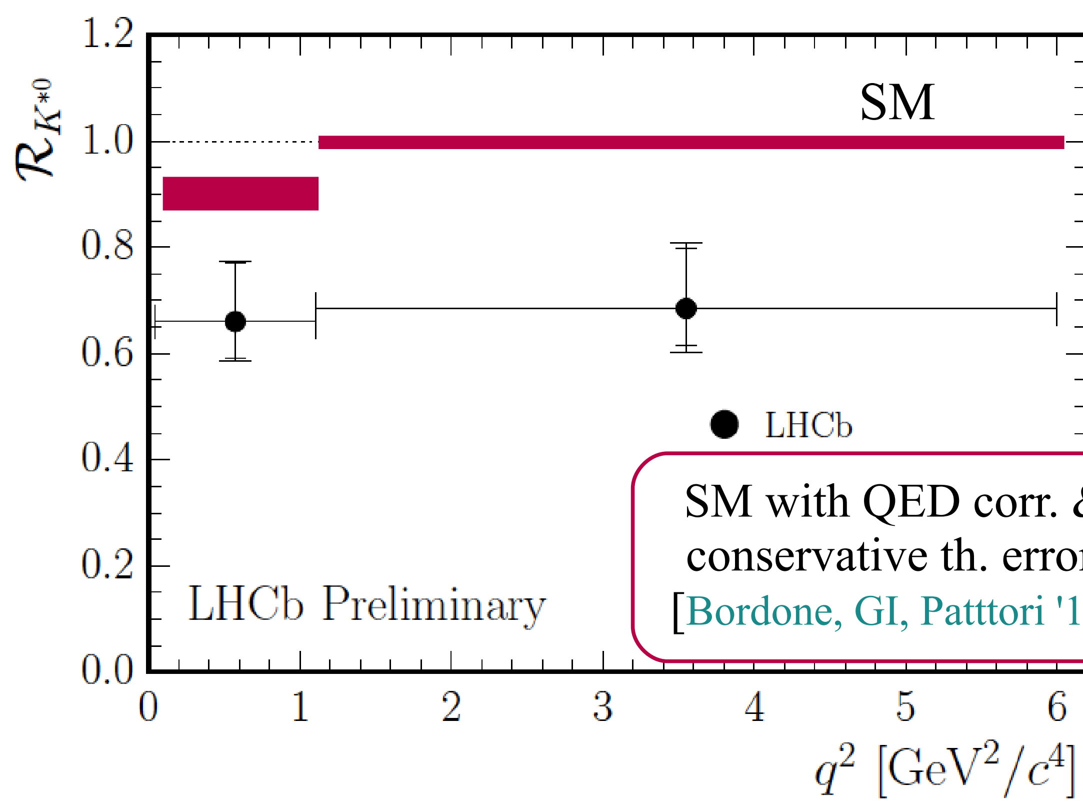
$$R_H = \frac{\int d\Gamma(B \to H\, \mu\mu)}{\int d\Gamma(B \to H\, ee)}$$

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*)



SM with QED corr. & conservative th. error [Bordone, GI, Patttori '16]

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

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Less significant correlated anomalies present also in other B → K^*μμ observables and also in other b→sμμ channels [overall smallness of all BR(B → Hadron + μμ)]

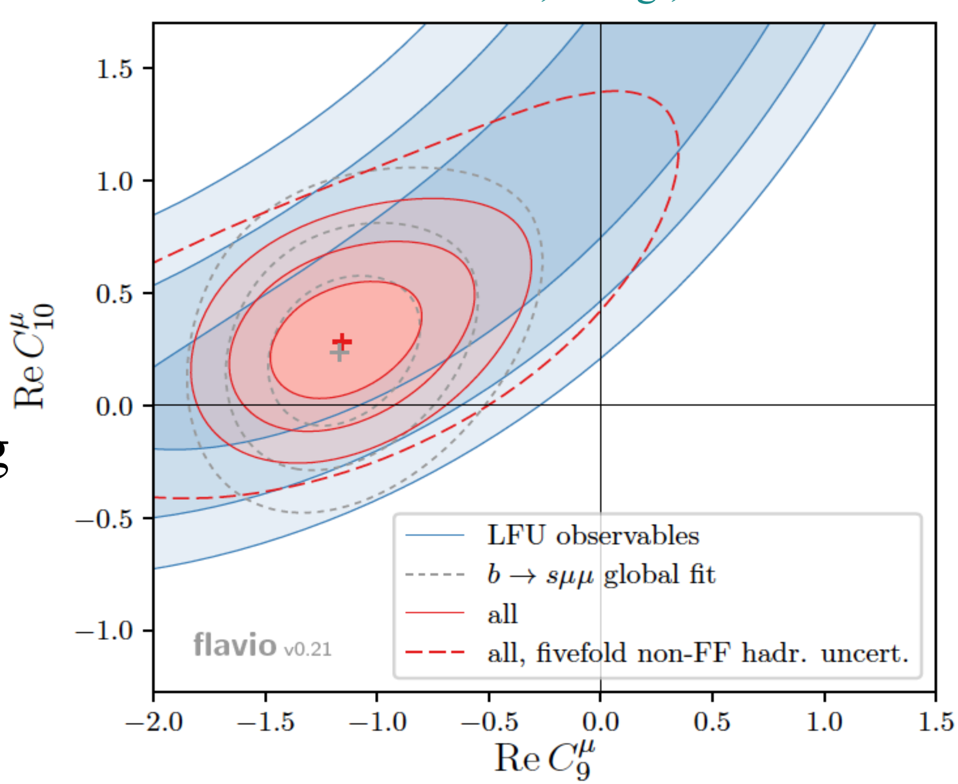
But the most interesting effects in b → s*ll* transitions are deviations from μ/e universality in appropriate "clean" ratios:

After the new results on R_{K*} various "*instant papers*" appeared with updated the fit to b → s*ll* Wilson coeff.

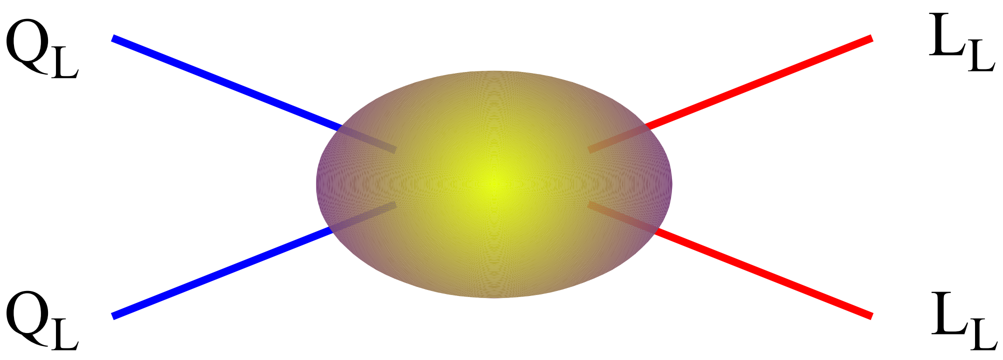
Main message: new results perfectly consistent with what we already knew:

- All anomalies are well described assuming NP only in b→sμμ and not in b → see [*non-trivial:* O(100) *observ. few Wilson coeff.*]
- Stronger indication in favor of V-A interaction

Altmannshofer, Stangl, Straub '17



EFT-type considerations



EFT-type considerations

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- RR and scalar currents disfavored → LL current-current operators
- Necessity of at least one $SU(2)_L$-triplet effective operator (*as in the Fermi theory*):

$$\frac{g_q g_\ell}{\Lambda^2} \lambda^q_{ij} \lambda^\ell_{kl} (\bar{Q}^i_L T^a \gamma_\mu Q^j_L)(\bar{L}^k_L T^a \gamma^\mu L^l_L)$$

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

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

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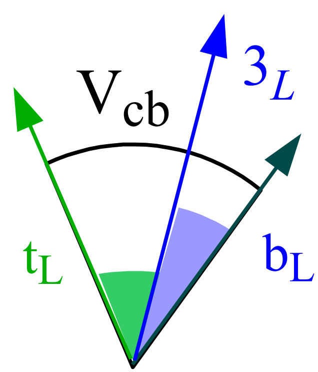
- Large coupling (competing with SM tree-level) in bc ($=33_{CKM}$) → $l_3\, \nu_3$
- Small non-vanishing coupling (competing with SM FCNC) in bs → $l_2\, l_2$

$$Q_L^{(3)} \sim q_L^{(b)} = \begin{bmatrix} V_{ib}^* u^i_L \\ b_L \end{bmatrix}$$

up to CKM rotations of $O(V_{cb})$



↓

$$\lambda^{q,\ell}_{ij} = \delta_{i3}\delta_{3j}$$ + small corrections for 2nd (& 1st) generations

Glashow, Guadagnoli, Lane '14

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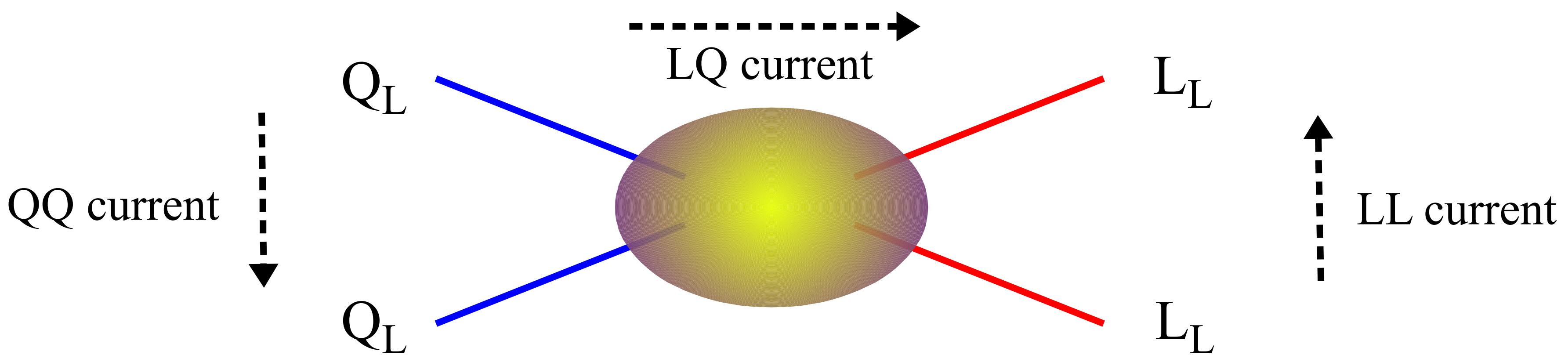

- Two natural classes of mediators, giving rise to different correlations among quark×lepton (evidence) and quark×quark + lepton×lepton (bounds)

- *EFT-type considerations* [general consequences in charged currents]

$$\frac{\mathcal{A}(b \to c\,\ell^i \bar{\nu}^i)_{\rm SM+NP}}{\mathcal{A}(b \to c\,\ell^i \bar{\nu}^i)_{\rm SM}} = 1 + R_0 \lambda^\ell_{ii} \qquad R_0 \equiv \frac{g_\ell g_q}{g^2} \frac{m_W^2}{\Lambda^2}$$

↳ 1 *for 3rd gen.*

I. From R(D*) & R(D) data [Γ(b → cτν)/Γ(b → cμν)] → $R_0 = 0.14 \pm 0.04$

NP Scale: 200 GeV (weak coupl.) ⟷ 2 TeV (strong coup.)

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λ^ℓ_{ii} → 1 *for 3rd gen.*

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NP Scale: 200 GeV (weak coupl.) ⟷ 2 TeV (strong coup.)

The only possibility to get a larger NP scale is to remove the CKM suppression in the NP amplitude ($\Lambda \to \sim 5\times\Lambda$), alining it to the b-c direction (*strong MFV*). However...

Crivellin, Muller, Ota '17

- This is not nice form the model-building side
- It creates a serious fine-tuning problem in $b_L \to s_L\, \nu_3 \nu_3$ (and other FCNCs)

↓

not discussed further...

▸ *EFT-type considerations* [general consequences in charged currents]

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II. In principle, it should be possible to get a strong bound on the sub-leading leptonic coupling ($\lambda_{\mu\mu}$) from Γ(b → cμν)/Γ(b → ceν), but surprisingly it is not so stringent ($|\lambda_{\mu\mu}| \lesssim 0.1$) → *no dedicated studies @ B-facotries !*

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III. This breaking of LFU in c.c. is expected to be universal on the quark side for b → c and b→ u

$$\mathrm{BR}(B\to D^*\tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(B\to D\tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(\Lambda_b \to \Lambda_c\tau\nu)/\mathrm{BR}_{SM} = \ldots$$
$$= \mathrm{BR}(B \to \pi\, \tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(\Lambda_b \to p\, \tau\nu)/\mathrm{BR}_{SM} = \mathrm{BR}(B_u \to \tau\nu)/\mathrm{BR}_{SM}$$
$$= \ldots$$

N.B.: $\mathrm{BR}(B_u \to \tau\nu)^{\rm exp}/\mathrm{BR}_{SM} = 1.31 \pm 0.27$ UTfit. '16

EFT-type considerations [U(2)^n flavor symmetry]

To go beyond charged currents, and discuss possible connections between quark×lepton (evidence) and quark×quark + lepton×lepton (bounds) we need extra theoretical assumptions → *flavor symmetries*

Given....

- Small deviations from SM in $\Delta F=2$
  [up to 20% vs. SM amplitude that is CKM and loop suppressed]
  with particularly tight constraints from MFV-type tests
  [$\Delta M_s/\Delta M_d$, sin(2β) → up to few% vs. SM]
- Per-mill constraints on LFU violations in purely leptonic tau decays and in semi-leptonic processes involving only light quarks
- Very stringent constraints on LFV in charged leptons

- Possible link to the observed pattern of Yukawa couplings

↓

U(2)^n (chiral) flavor symmetry

- 3rd generations fermions are singlets
- 1st and 2nd generation fermions are doublets

EFT-type considerations [U(2)^n flavor symmetry]

A brief detour: U(2)^n flavor symmetries (acting on light generations)

- The exact symmetry limit is good starting point for the SM spectrum ($m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$) → small breaking terms needed
- Efficient protection of FCNCs (~MFV like)

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

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

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

unbroken symmetry

Natural stable subgroup of models with "dynamical Yukawas"

Alonso, Gavela, G.I., Maiani '13

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$$Y_u = y_t \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \rightarrow \begin{bmatrix} \Delta & V \\ 0 & 1 \end{bmatrix}$$

unbroken symmetry

Minimal breaking to reproduce SM Yukawa couplings while keeping small FCNCs:

$|V| \sim 0.04 \quad \sim 2_q$

$|\Delta| \sim 0.006 \quad \sim 2_q \times 2_u$

- The assumption of a single (2,1,1) breaking term [*= a single spurion connecting the light generations to the third one*] ensures a MFV-like protection of FCNCs
- More "efficient" than MFV for having large effects for 3rd generation

EFT-type considerations [$U(2)^n$ flavor symmetry]

General EFT analysis of (LH) four-fermion operators based on the flavor symmetry $U(2)_q \times U(2)_l$ broken only by two spurions $V_Q = (V_{td}, V_{ts})$ and $V_l = (V_e, V_\mu) \approx (0, V_\mu)$

Bordone, GI, Trifinopoulos '17

$$\bar{q}^{(3)} \Gamma q^{(3)} \times \bar{l}^{(3)} \Gamma l^{(3)}$$

$$\bar{q}_{light} V_Q \Gamma q^{(3)} \times \bar{l}^{(3)} \Gamma l^{(3)}$$

$$\bar{q}^{(3)} \Gamma q^{(3)} \times \bar{l}_{light} V_l \Gamma l^{(3)}$$

$$\vdots$$

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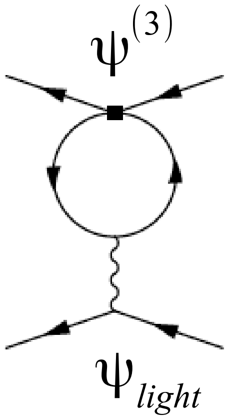
Bordone, GI, Trifinopoulos '17

Strategy/goal:

- Overall scale fixed by R_{D*} → check the consistency with all the other low-energy processes → determine additional dynamical conditions (+ size of $|V_l|$) to ensure a "natural" EFT

Approximations/assumptions:

- Include leading radiatively generated terms in the running $\Lambda \to m_W$ (sizable impact in $\tau \to l\nu\nu$ decays)
- Neglect constraints from observables sensitive at the tree level to non four-quark operators



Feruglio, Paradisi, Pattori '16, '17

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

Process	Combination	Constraint
$R_{D^{(*)}}$	$\mathrm{Re}\left(C^q_{02} + V_{Q_s} C^q_{12} \frac{V_{cs}}{V_{cb}}\right)$	$(0.7 \pm 0.2) \times 10^{-1}$
$B \to D\mu\nu_\mu$	$\mathrm{Re}\left(C^q_{04} + V_{Q_s} C^q_{14} \frac{V_{cs}}{V_{cb}}\right)$	$-(0.8 \pm 2.5) \times 10^{-2}$
$\tau \to \mu\nu\bar{\nu}$	$\mathrm{Re}\left(C^\ell_{04}\right)$	$-(1.2 \pm 0.5) \times 10^{-2}$
$\lvert V_{us}\rvert_\tau / \lvert V_{us}\rvert_\mu$	$\mathrm{Re}\big[C^q_{08} - C^q_{06} + (C^q_{14} - C^q_{12}) \lvert V_{Q_s} V_{ub}/V_{us}\rvert\big]$	$(0.7 \pm 0.4) \times 10^{-2}$
$\tau \to \mu ee$, $\tau \to 3\mu$	$\lvert V_l\rvert \times \left(\lvert C^\ell_{13} + C^\ell_{14}\rvert^2 + \lvert C^\ell_{R2}\rvert^2 + \lvert C^\ell_{T2}\rvert^2\right)^{1/2}$	$\leq 3.2 \times 10^{-4}$
$\tau \to \rho\mu$	$\lvert C^q_{24}\rvert \lvert V_l\rvert$	$\leq 1.4 \times 10^{-4}$
$\tau \to \omega\mu$	$\lvert C^q_{23}\rvert \lvert V_l\rvert$	$\leq 3.2 \times 10^{-4}$
$B \to K\nu\bar{\nu}$	$\lvert \mathrm{Re}(C^q_{11} - C^q_{12})\rvert$	$\leq 8.0 \times 10^{-2}$
$B^0 - \overline{B}^0$	$\lvert C^{qq}_{01} + C^{qq}_{02}\rvert$	$\leq 0.42 \times 10^{-3}$
$B_d \to \tau\mu$	$\lvert C^q_{31} + C^q_{32}\rvert \lvert V_l\rvert$	$\leq 4.5 \times 10^{-2}$
$R_K^{(*)}$	$\mathrm{Re}\left(C^{q-2}_{13} + C^{q-2}_{14}\right) \lvert V_l\rvert^2$	$-(0.8 \pm 0.2) \times 10^{-3}$

- Two main anomalies we want to fit
- Terms that depends on $\lvert V_l\rvert$

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$\lvert V_{us}\rvert_\tau / \lvert V_{us}\rvert_\mu$	$\mathrm{Re}[C^q_{08} - C^q_{06} + (C^q_{14} - C^q_{12})\lvert V_{Q_s} V_{ub}/V_{us}\rvert]$	$(0.7 \pm 0.4) \times 10^{-2}$
$\tau \to \mu ee$, $\tau \to 3\mu$	$\lvert V_l\rvert \times (\lvert C^\ell_{13} + C^\ell_{14}\rvert^2 + \lvert C^\ell_{R2}\rvert^2 + \lvert C^\ell_{T2}\rvert^2)^{1/2}$	$\leq 3.2 \times 10^{-4}$
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- Two main anomalies we want to fit
- Terms that depends on $|V_l|$
- Strong (residual) bounds from ΔF=2 (after CKM suppression)

without quark spurion:

→ 6×10^{-7}

→ 3×10^{-5}

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$B \to D\mu\nu_\mu$	$\text{Re}\left(C^q_{04} + V_{Q_s} C^q_{14} \frac{V_{cs}}{V_{cb}}\right)$	$-(0.8 \pm 2.5) \times 10^{-2}$
$\tau \to \mu\nu\bar{\nu}$	$\text{Re}\left(C^\ell_{04}\right)$	$-(1.2 \pm 0.5) \times 10^{-2}$
$\|V_{us}\|_\tau / \|V_{us}\|_\mu$	$\text{Re}[C^q_{08} - C^q_{06} + (C^q_{14} - C^q_{12})\|V_{Q_s} V_{ub}/V_{us}\|]$	$(0.7 \pm 0.4) \times 10^{-2}$
$\tau \to \mu ee$ $\tau \to 3\mu$	$\|V_l\| \times \left(\|C^\ell_{13} + C^\ell_{14}\|^2 + \|C^\ell_{R2}\|^2 + \|C^\ell_{T2}\|^2\right)^{1/2}$	$\leq 3.2 \times 10^{-4}$
$\tau \to \rho\mu$	$\|C^q_{24}\|\|V_l\|$	$\leq 1.4 \times 10^{-4}$
$\tau \to \omega\mu$	$\|C^q_{23}\|\|V_l\|$	$\leq 3.2 \times 10^{-4}$
$B \to K\nu\bar{\nu}$	$\|\text{Re}(C^q_{11} - C^q_{12})\|$	$\leq 8.0 \times 10^{-2}$
$B^0 - \overline{B}^0$	$\|C^{qq}_{01} + C^{qq}_{02}\|$	$\leq 0.42 \times 10^{-3}$
$B_d \to \tau\mu$	$\|C^q_{31} + C^q_{32}\|\|V_l\|$	$\leq 4.5 \times 10^{-2}$
$R^{(*)}_K$	$\text{Re}\left(C^{q-2}_{13} + C^{q-2}_{14}\right)\|V_l\|^2$	$-(0.8 \pm 0.2) \times 10^{-3}$

- Two main anomalies we want to fit
- Terms that depends on $|V_l|$
- Strong (residual) bounds from ΔF=2 (after CKM suppression)
- Non-vanishing term needed to compensate RGE effect in $\tau \to l\nu\nu$

↓

Extra dynamical assumptions necessary to obtain a consistent picture

EFT-type considerations [U(2)^n flavor symmetry]

General EFT analysis of (LH) four-fermion operators based on the flavor symmetry $U(2)_q \times U(2)_l$ broken only by two spurions $V_Q = (V_{td}, V_{ts})$ and $V_l = (V_e, V_\mu) \approx (0, V_\mu)$

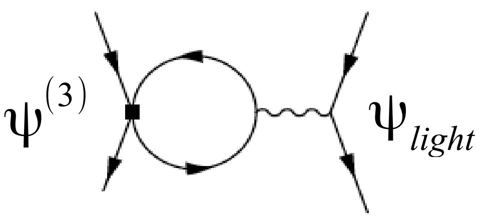
Bordone, GI, Trifinopoulos '17

⬇ *coherent picture if*

- weaker coupling of the light-quark flavor-singlet combinations to NP (*easy to implement in explicit NP constructions, e.g. partial compositeness*)

$$\overline{\psi}_{light}\gamma^\mu\psi_{light} \longrightarrow \varepsilon_{light}\,\overline{\psi}_{light}\gamma^\mu\psi_{light}$$

$|\varepsilon_{light}| \sim 0.1$ (radiatively stable)



- $|V_l| \sim 0.3 - 0.1$

But residual O(10%) tuning needed in order to satisfy the bounds from

- Bs mixing (↔ alignment to down-quark mass basis)
- LFU in $\tau \to l\nu\nu$

As already found in explicit model constructions [Greljo *et al.* '15, Barbieri *et al.* '16]

▸ *EFT-type considerations* [U(2)^n flavor symmetry]

This coherent picture leads to several testable predictions in other low-energy observables:

- $b \to c(u)\, l\nu$ — $BR(B\to D^*\tau\nu)/BR_{SM} = BR(B\to D\tau\nu)/BR_{SM} = BR(\Lambda_b \to \Lambda_c\tau\nu)/BR_{SM}$ $= BR(B \to \pi\, \tau\nu)/BR_{SM} = BR(\Lambda_b \to p\, \tau\nu)/BR_{SM} = BR(B_u \to \tau\nu)/BR_{SM}$

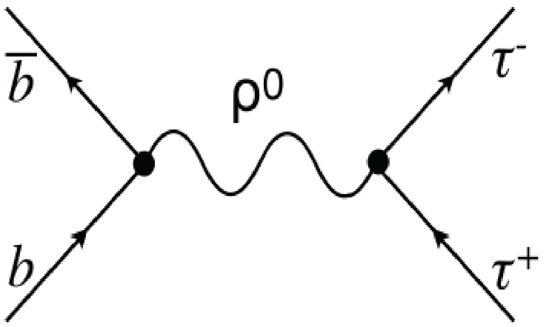
- $b \to s\, \mu\mu$ — $\Delta C_9^\mu = -\Delta C_{10}^\mu$ (→ to be checked in several other modes...)
- $b \to s\, \tau\tau$ — $|NP| \sim |SM|$ → large enhancement (easily 10×SM)
- $b \to s\, \nu\nu$ — ~ O(1) deviation from SM in the rate

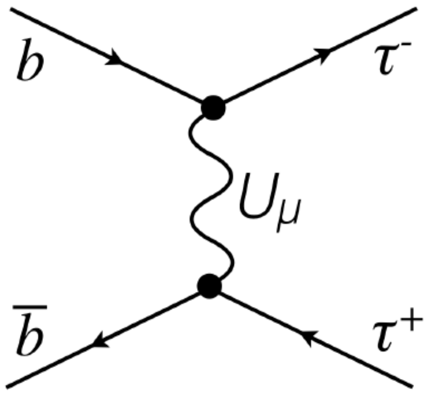
- $K \to \pi\, \nu\nu$ — ~ O(1) deviation from SM in the rate

---

- Meson mixing — ~ 10% deviations from SM both in ΔM_{Bs} & ΔM_{Bd}
- τ decays — $\tau \to 3\mu$ not far from present exp. Bound ($BR \sim 10^{-9}$)

Simplified dynamical models





Simplified dynamical models

While the EFT is useful to derive relation among low-energy observables, simplified dynamical models with explicit mediators are particularly useful to

- reduce the number of free parameters
- check the consistency with high-energy data (*that is very relevant...*)
- identify possible UV completions

Simplified dynamical models

While the EFT is useful to derive relation among low-energy observables, simplified dynamical models with explicit mediators are particularly useful to

- reduce the number of free parameters
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- identify possible UV completions

I. The triplet-vector model

Greljo, GI, Marzocca '15
Boucenna *et al.* '16

First concrete dynamical model addressing all anomalies...

- The leading effective triplet operator is the result of integrating-out a heavy $SU(2)_L$-triplet of vector bosons (W', Z') coupled to a single current:

$$J^a_\mu = g_q \lambda^q_{ij} \left(\bar{Q}^i_L \gamma_\mu T^a Q^j_L \right) + g_\ell \lambda^\ell_{ij} \left(\bar{L}^i_L \gamma_\mu T^a L^j_L \right) \longrightarrow \frac{1}{2m_V^2} J^a_\mu J^a_\mu$$

- Flavor on-Universal flavor structure of the currents:
  - → Coupling to 3rd generations not suppressed
  - → Coupling to light generations controlled by small $U(2)_q \times U(2)_l$ breaking

Overall good fit of the data (*that improves if the anomaly on R_D would decrease*)

Simplified dynamical models

II. LQ models

- The leading effective triplet operator is the result of integrating-out Lepto-Quark (LQ) fields

Long list of literature.....

- Flavor non-Universal flavor structure of the currents:
  → Coupling to 3rd generations not suppressed
  → Coupling to light generations controlled by small $U(2)_q \times U(2)_l$ breaking

Barbieri, GI, Pattori, Senia '15

The Vector LQ produce a very good fit of both R_{K*} and R_D (*without extra tuning*), with a significant non-trivial advantage compared to the vector triplet:

- *Problem in Bs mixing less severe* (loop level)

Calibbi, Crivellin, Muller, Ota '15

Minor tension remains with tau decays & EWPO

Simplified dynamical models

In both cases (heavy vector triplets & vector LQ) we should address two basic questions:

- *Are these models compatible with high-energy (direct) searches?*
- *Can we find meaningful UV completions?*

Simplified dynamical models

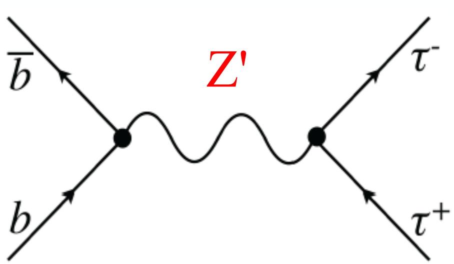
In both cases (heavy vector triplets & vector LQ) we should address two basic questions:

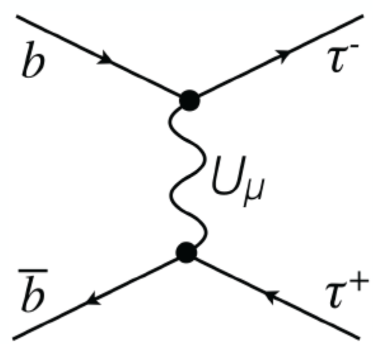
- *Are these models compatible with high-energy (direct) searches?* Yes, but...

  In both cases no real problem provided we are in a regime of strong-coupling [large couplings → heavy masses & large widths].

  E.g.: the heavy vectors could have a mass ~ 1-2 TeV (*not easily detectable due to small coupling to light quarks & large width*)

In both cases there is a model-independent expectation of sizable (broad) excess in $pp \to \tau\tau$ & $pp \to bb$, tt that should be accessible in Run-II

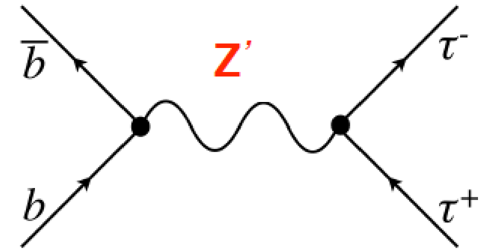


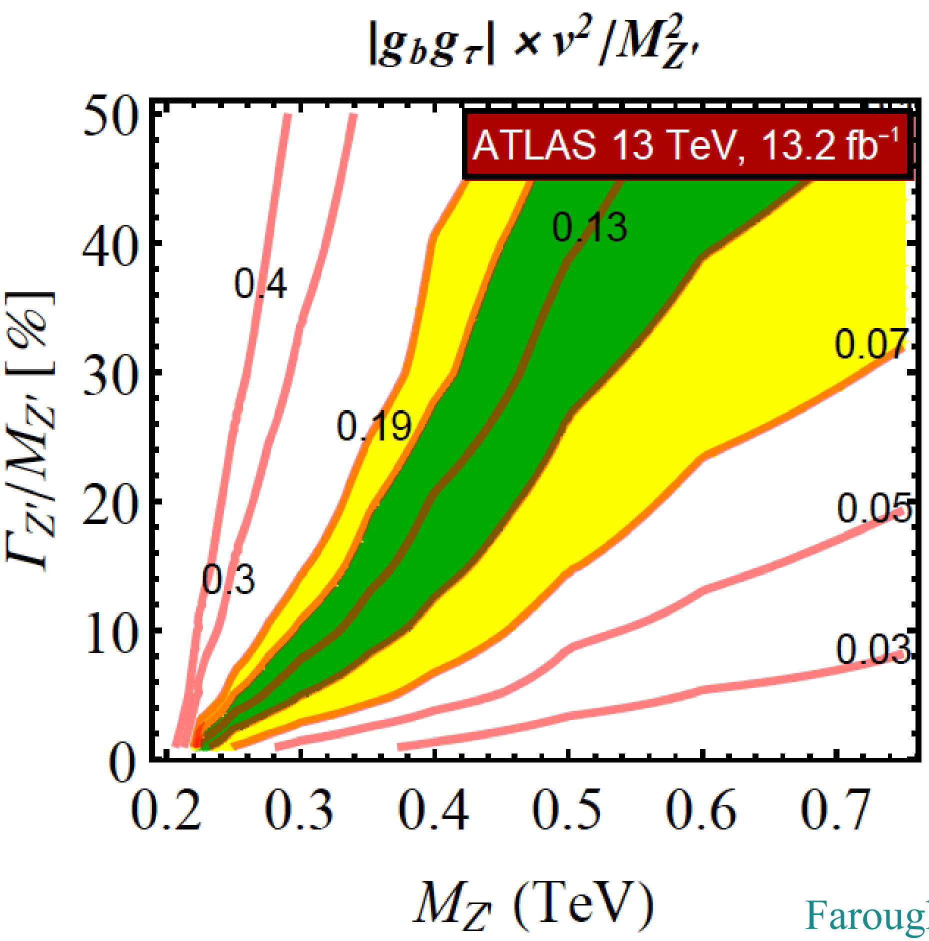


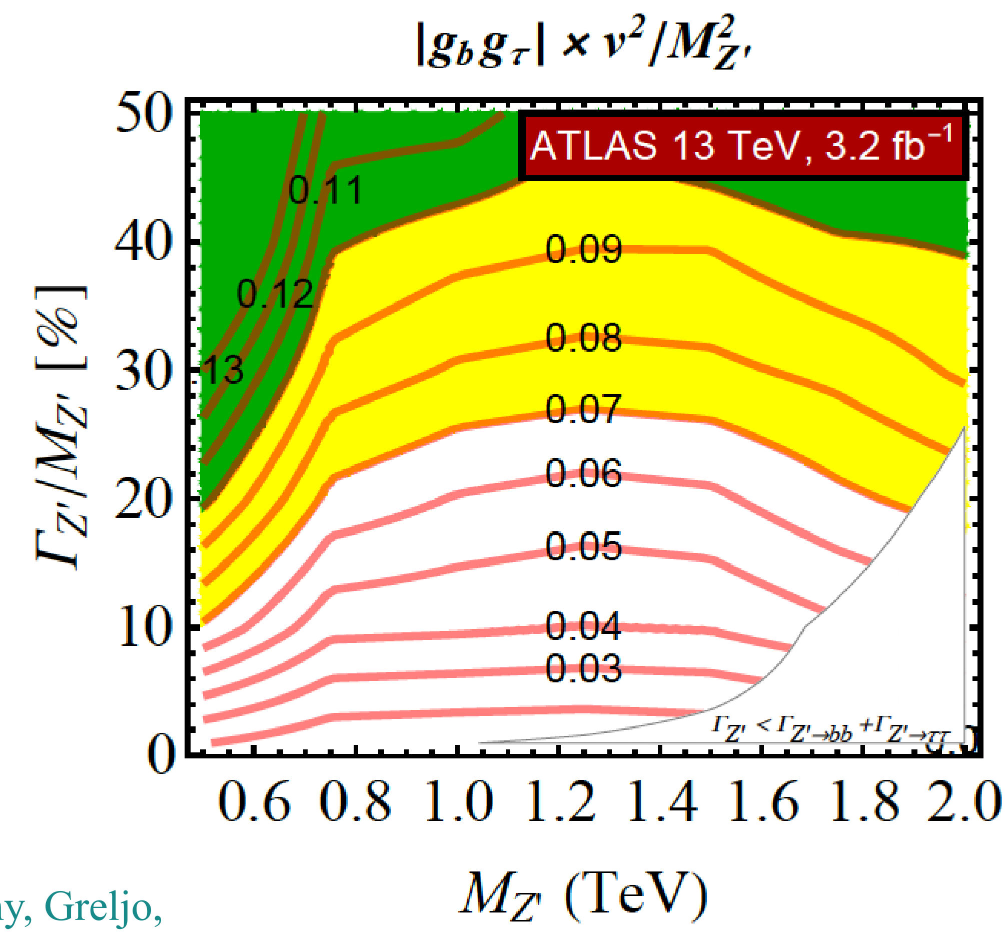
- *Already some tension with ATLAS & CMS.*
- *Deviations from SM should be seen soon...*

Simplified dynamical models

Recast of recent ATLAS searches of Z' → ττ



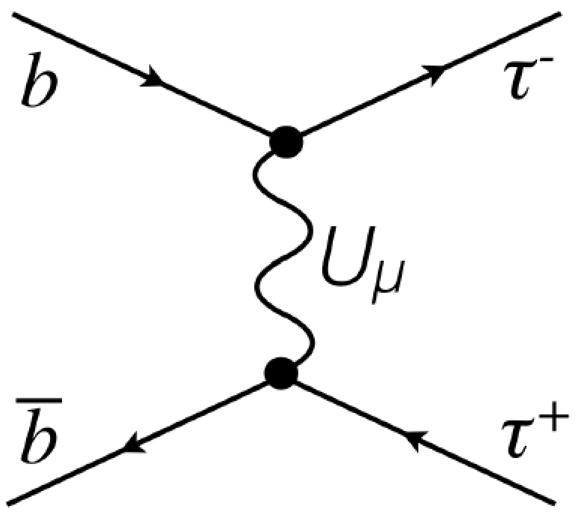


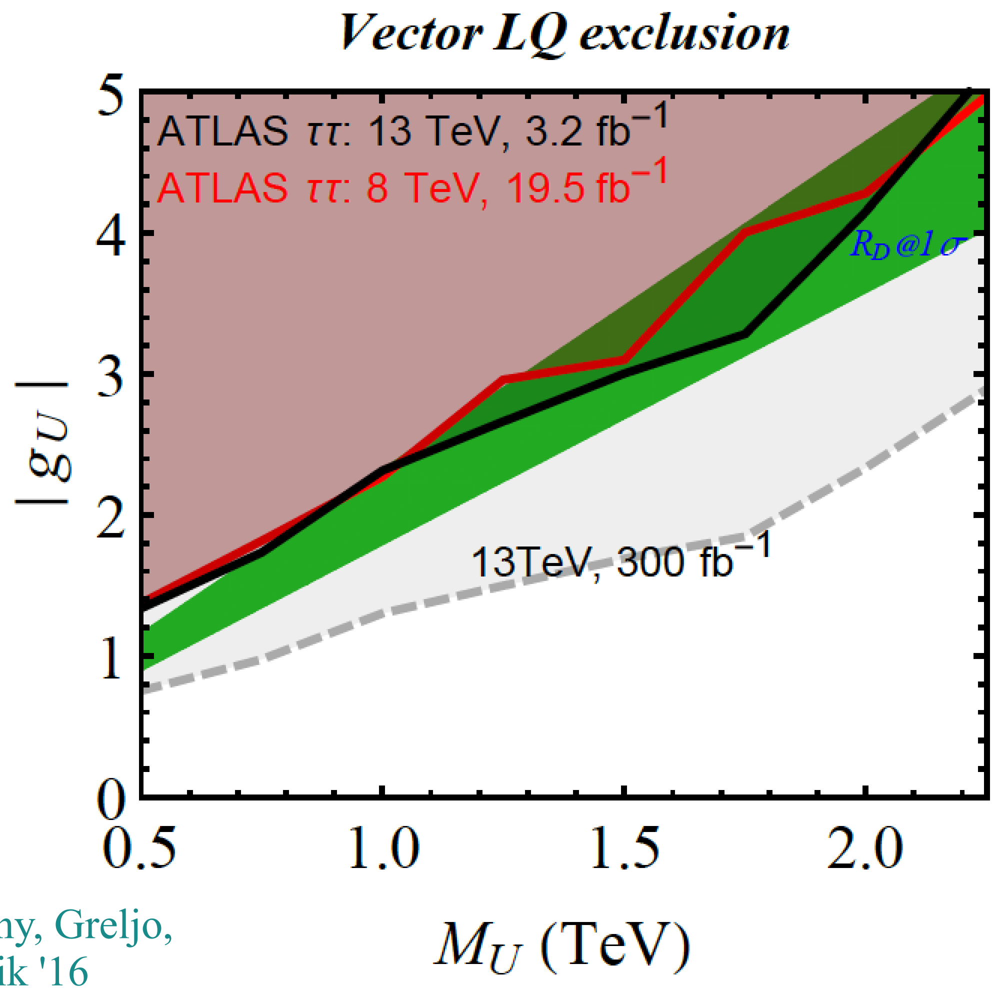


Faroughy, Greljo, Kamenik '16

Simplified dynamical models

Recast of recent ATLAS searches of $Z' \to \tau\tau$ interpreted in the vector LQ model





Faroughy, Greljo, Kamenik '16

Simplified dynamical models

In both cases (heavy vector triplets & vector LQ) we should address two basic questions:

- *Are these models compatible with high-energy (direct) searches?* Yes, but...
- *Can we find meaningful UV completions?* Maybe...

An attractive possibility is to consider these heavy (spin-1) mediators as composite state of some new strong dynamics

- RS [→ talk by Quiros]
- SU(N)×SU(N) vector-like confinement
  [Buttazo, Greljo, GI, Marzocca, '16 → *backup slides*]
- SU(4)×SO(5) ×U(1) CHM
  [Barbieri, Murphy, Senia '16]
- ...

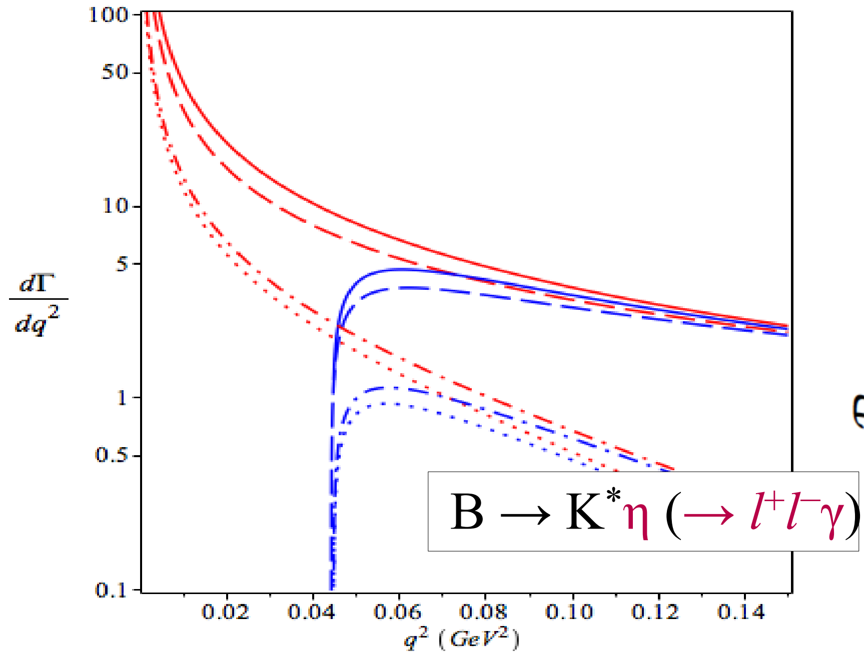
Conclusions

- Very interesting hints of LF non Universality in recent semi-leptonic B-physics data
- The overall picture is still far form being clear, but the patter of anomalies is apparently coherent → more data can help to clarify the situation
- EFT based on $U(2)^n$ + NP coupled mainly to 3rd gen. quite successful
- Main messages in view of future data:
  - Plenty of interesting LFU tests in B physics still to be performed
  - The search for LFV in charged leptons is extremely well motivated
  - The interplay of low- and high-energy searches is essential [*tau physics at high* p_T]

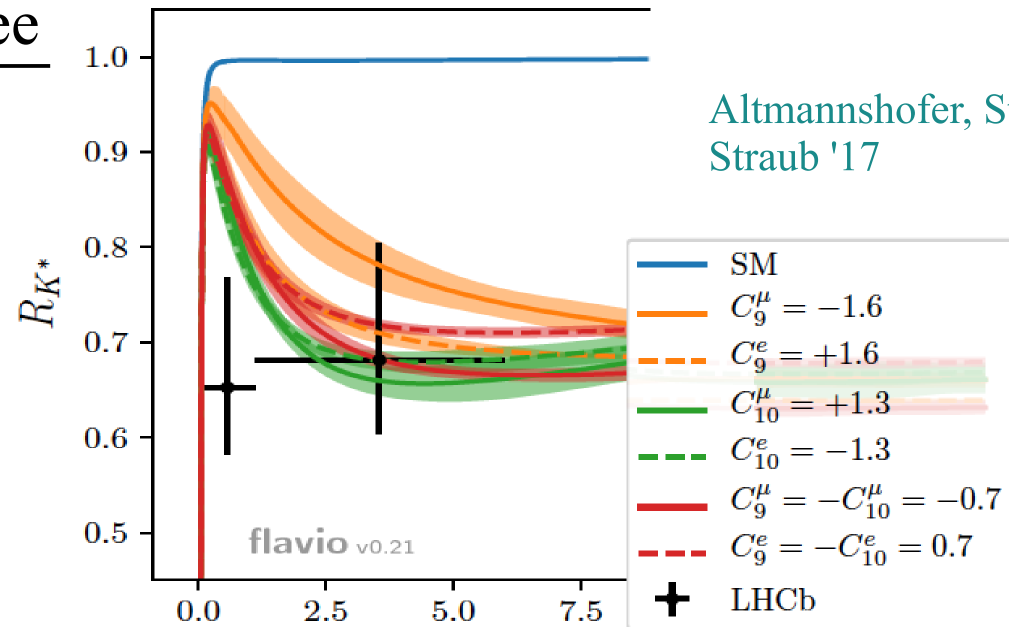

Backup

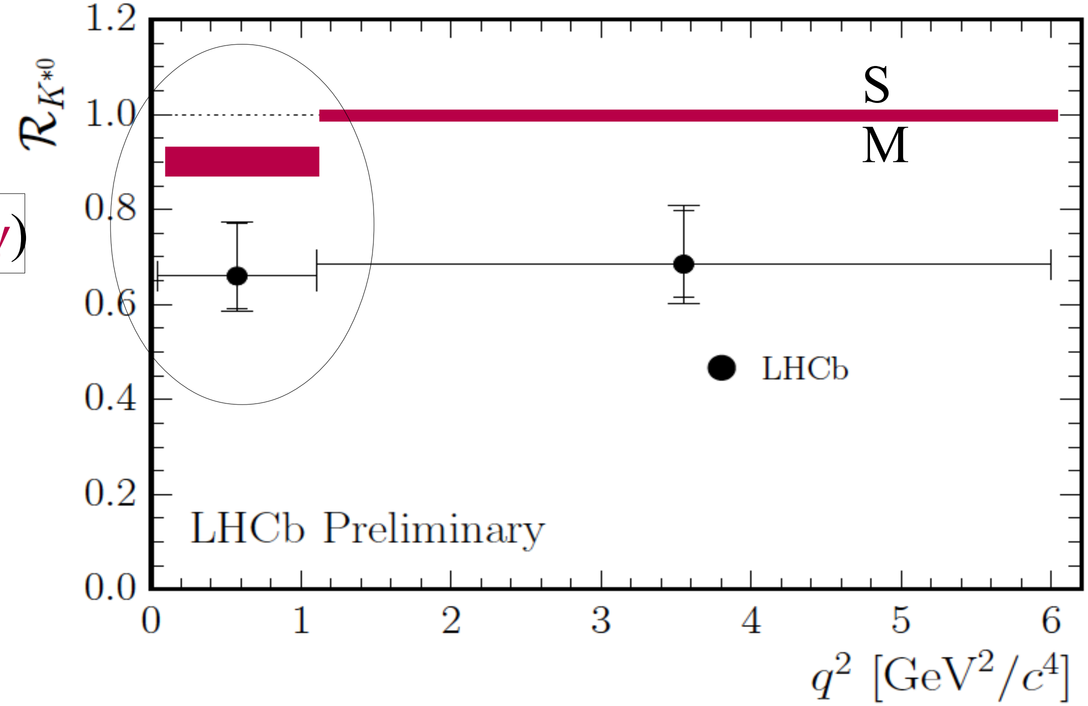
II. Anomalies in $B \to K^{(*)}\, \mu\mu$ / ee

Bordone et al. '16 [→ *addendum*]



Altmannshofer, Stangl, Straub '17





▸ *Simplified dynamical models* [(I) Vector Triplet]

Five free parameters:

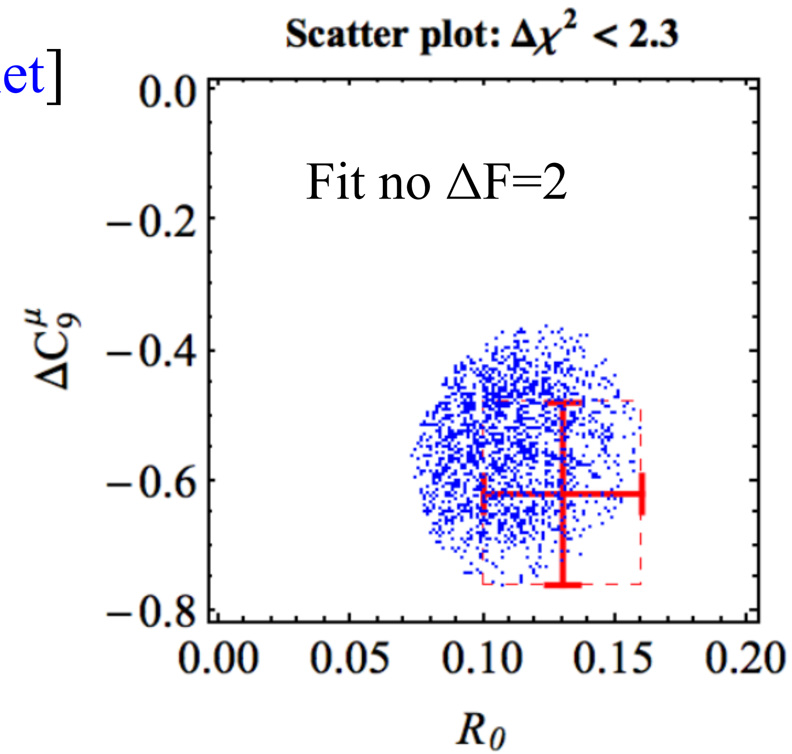
$$\epsilon_{\ell,q} \equiv \frac{g_{\ell,q}\, m_W}{g\, m_V} \quad + \lambda^q_{bs},\ \lambda^\ell_{\mu\mu},\ \lambda^\ell_{\tau\mu}$$

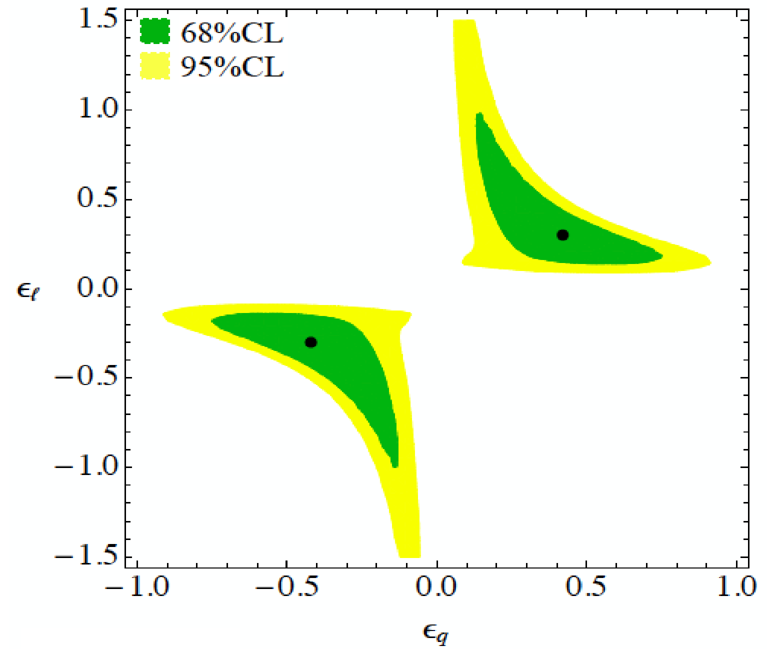
Several low-energy constraints

↓

Overall good fit of low-energy data

Some residual tension
[ΔF=2 vs. LFU tests in tau decays]
which can be ameliorated including extra contributions
(e.g. $SU(2)_L$ singlets Z' or color-octet)





UV completions and high-energy bounds

SM

$SU(3)\times SU(2)\times U(1)_Y$

$f_i^{\mathrm{SM,chiral}}$

New sector

$SU(N_{TC})_{TC}$

$\Psi_{L,R}$ [different SM charges]

$SU(N_F)_L\times SU(N_F)_R\times U(1)_V$

↓

$SU(N_F)_{L+R}\times U(1)_V$

Global "flavor symmetry"
Spontaneously broken as in QCD
at a scale $\Lambda_{TC}\sim$ TeV

Basic construction is based on the idea of "*Vector-like confinement*"

- Very similar to the old idea of technicolor
- Key difference is that the SSB of the new sector preserves the SM gauge symmetry, that is broken in a 2nd step by an appropriate Higgs field

UV completions and high-energy bounds

SM

$SU(3)\times SU(2)\times U(1)_Y$

$f_i^{\rm SM,chiral}$

New sector

$SU(N_{TC})_{TC}$

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$SU(N_F)_{L+R}\times U(1)_V$

Global "flavor symmetry"
Spontaneously broken as in QCD
at a scale $\Lambda_{TC} \sim$ TeV

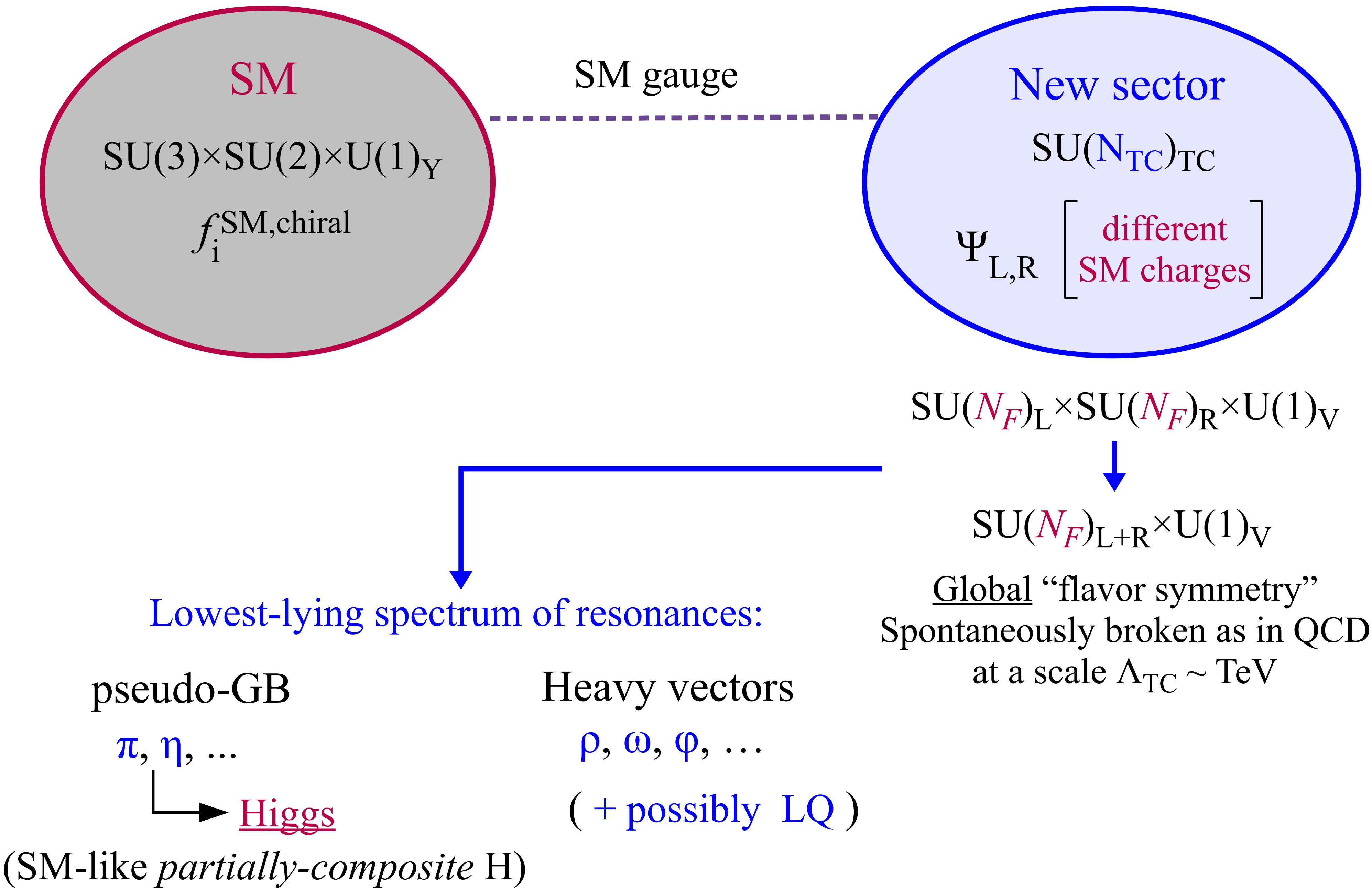
Lowest-lying spectrum of resonances:

pseudo-GB
π, η, ...

Heavy vectors
ρ, ω, φ, ...

(+ possibly LQ)

UV completions and high-energy bounds



▶ *UV completions and high-energy bounds*

SM

$SU(3)\times SU(2)\times U(1)_Y$

$f_i^{\rm SM,chiral}$

SM gauge

$f_3^{\rm SM} - B(\Psi_{L,R})$

New sector

$SU(N_{TC})_{TC}$

$Q = (N_{TC}, 3, 2, Y_Q)$

$L = (N_{TC}, 1, 2, Y_L)$

Buttazo, Greljo, GI, Marzocca, '16

$SU(N_F)_L\times SU(N_F)_R\times U(1)_V$

↓

$SU(N_F)_{L+R}\times U(1)_V$

Lowest-lying spectrum of resonances:

pseudo-GB

π, η, ...

→ Higgs

(SM-like *partially-composite* H)

Heavy vectors

ρ, ω, φ, ...

4f operators that can "solve" flavor anomalies