# *Lepton Flavor Universality violations and Flavor Symmetries*

Gino Isidori
[ *University of Zürich* ]

▶ Introduction

▶ EFT-type considerations

▶ Simplified dynamical models

▶ Conclusions

*Disclaimer:*
 ✦ this is not review
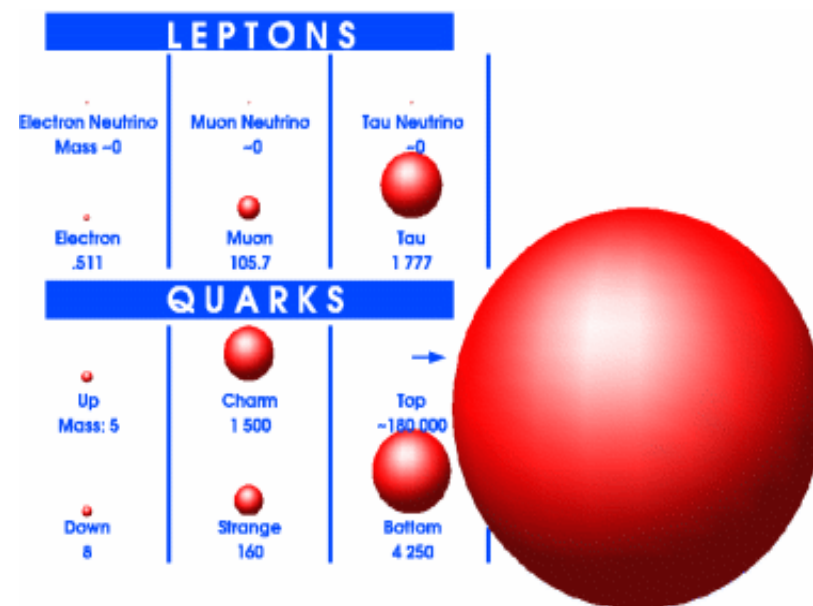 ✦ apologies for missing citations

▶ *Introduction*

Recent data show some <u>convincing</u> evidences of Lepton Flavor Universality violations

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

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 (→ gauge sector)

- Most stringent tests of LFU involve only 1st-2nd gen. quarks & leptons



**LEPTONS**

| Electron Neutrino Mass ~0 | Muon Neutrino ~0 | Tau Neutrino ~0 |
| Electron .511 | Muon 105.7 | Tau 1 777 |

**QUARKS**

| Up Mass: 5 | Charm 1 500 | Top ~180 000 |
| Down 8 | Strange 160 | Bottom 4 250 |

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 <u>flavor symmetries</u>

⬇

Simplified Dynamical Models

⬇

High-energy behavior and UV completion

The main guide will be the attempt to describe <u>both LFU effects</u> 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

- → <u>other low-energy data</u>
- → <u>high-pT physics</u>

## ▶ *Introduction*

These recent results have stimulated a lot of theoretical activity
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What I will discuss next is a bottom-up approach made of three main steps:

Generic EFT approach – with <u>flavor symmetries</u>    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 <u>both LFU effects</u> 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

- → <u>other low-energy data</u>

- → <u>high-pT physics</u>

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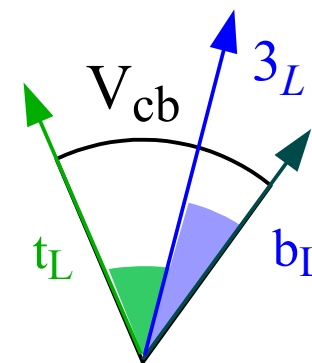
Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)

- 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$_{cb}$)



$$\downarrow$$

$$\lambda^{q,\ell}_{ij} = \delta_{i3}\delta_{3j} \; + \; \text{small corrections}$$
for 2$^{nd}$ (& 1$^{st}$) generations
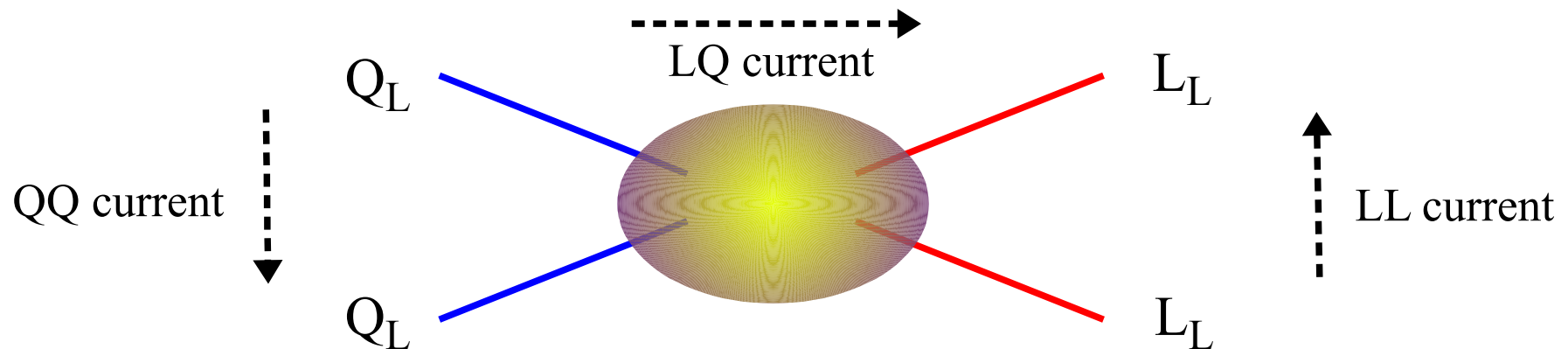
Glashow, Guadagnoli,
Lane '14

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  (*as in the Fermi theory*):

$$\frac{g_q g_\ell}{\Lambda^2} \lambda_{ij}^q \lambda_{kl}^\ell (\bar{Q}_L^i T^a \gamma_\mu Q_L^j)(\bar{L}_L^k T^a \gamma^\mu L_L^l)$$



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

▶ <u>*EFT-type considerations*</u> [general consequences in charged currents]

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

I.  From R(D$^*$) & R(D) data [$\Gamma(b \to c\tau\nu)/\Gamma(b \to c\mu\nu)$] $\to$ $\boxed{R_0 = 0.14 \pm 0.04}$

NP Scale:      200 GeV $\longleftrightarrow$ 2 TeV
(weak coupl.)         (strong coup.)

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NP Scale:     200 GeV  $\longleftrightarrow$  2 TeV
            (weak coupl.)        (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 <u>serious fine-tuning problem</u> in $b_L \to s_L\, \nu_3 \nu_3$ (and other FCNCs)

$\downarrow$

*not discussed further...*

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

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

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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 $\Gamma(b \to c\mu\nu)/\Gamma(b \to ce\nu)$, but surprisingly it is not so stringent $(|\lambda_{\mu\mu}| \lesssim 0.1) \to$ *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

   BR(B→D*τν)/BR$_{\text{SM}}$ = BR(B→Dτν)/BR$_{\text{SM}}$ = BR($\Lambda_b \to \Lambda_c\tau\nu$)/BR$_{\text{SM}}$ = …
   = BR(B → π τν)/BR$_{\text{SM}}$ = BR($\Lambda_b \to p\,\tau\nu$)/BR$_{\text{SM}}$ = BR(B$_u \to \tau\nu$)/BR$_{\text{SM}}$
   = …

   N.B.:    BR(B$_u \to \tau\nu$)$^{\text{exp}}$/BR$_{\text{SM}}$ = 1.31 ± 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 ΔF=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

- 3$^{rd}$ generations fermions are singlets
- 1$^{st}$ and 2$^{nd}$ 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 <u>good starting point for the SM spectrum</u> ($m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$) → <u>small breaking terms</u> needed

- Efficient protection of FCNCs (~MFV like)          Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

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

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

*unbroken symmetry*

▶ *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 <u>good starting point for the SM spectrum</u> ($m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$) → <u>small breaking terms</u> needed

- Efficient protection of FCNCs (~MFV like)     Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

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

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

*unbroken symmetry*

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

$$|V| \sim 0.04 \quad \sim 2_q$$
$$|\Delta| \sim 0.006 \sim 2_q \times 2_u$$

- 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) <u>four-fermion operators</u> based on the flavor symmetry U(2)$_q$ × U(2)$_l$ broken only by two spurions $V_Q$ =($V_{td}$, $V_{ts}$) and $V_l$ = ($V_e$ , $V_\mu$) ≈ (0, $V_\mu$)

Bordone, GI,
Trifinopoulos '17

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

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

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

⋮

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

General EFT analysis of (LH) <u>four-fermion operators</u> based on the flavor symmetry $U(2)_q \times U(2)_l$ broken only by two spurions $V_Q = (V_{td}, V_{ts})$ and $V_l = (V_e, V_\mu) \approx (0, V_\mu)$
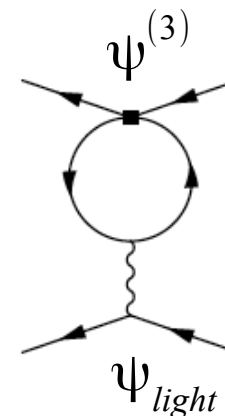
Bordone, GI,
Trifinopoulos '17

Strategy/goal:

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

Approximations/assumptions:

- Include leading radiatively generated terms in the running $\Lambda \rightarrow m_W$ (sizable impact in $\tau \rightarrow l\nu\nu$ decays)

$\psi^{(3)}$

$\psi_{light}$

Feruglio, Paradisi,
Pattori '16, '17

- Neglect constraints from observables sensitive at the tree level to non four-quark operators

▶ **_EFT-type considerations_** [U(2)$^n$ flavor symmetry]

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

- Two main anomalies we want to fit

- Terms that depends on $\|V_l\|$

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

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

- Two main anomalies we want to fit

- Terms that depends on $\|V_l\|$

- Strong (residual) bounds from ΔF=2 (after CKM suppression)

*without quark spurion:*

⟶  $6 \times 10^{-7}$

⟶  $3 \times 10^{-5}$

▶ **_EFT-type considerations_** [U(2)$^n$ flavor symmetry]

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|---------|-------------|------------|
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| $B \to D\mu\nu_\mu$ | $\mathrm{Re}\left(C_{04}^q + V_{Q_s} C_{14}^q \frac{V_{cs}}{V_{cb}}\right)$ | $-(0.8 \pm 2.5) \times 10^{-2}$ |
| $\tau \to \mu\nu\bar{\nu}$ | $\mathrm{Re}\left(C_{04}^\ell\right)$ | $-(1.2 \pm 0.5) \times 10^{-2}$ |
| $|V_{us}|_\tau / |V_{us}|_\mu$ | $\mathrm{Re}\left[C_{08}^q - C_{06}^q + (C_{14}^q - C_{12}^q)|V_{Q_s} V_{ub}/V_{us}|\right]$ | $(0.7 \pm 0.4) \times 10^{-2}$ |
| $\tau \to \mu ee$ $\tau \to 3\mu$ | $|V_l| \times \left(|C_{13}^\ell + C_{14}^\ell|^2 + |C_{R2}^\ell|^2 + |C_{T2}^\ell|^2\right)^{1/2}$ | $\leq 3.2 \times 10^{-4}$ |
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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)

- Non-vanishing term needed to compensate RGE effect in $\tau \to l\nu\nu$

↓

Extra dynamical assumpt. necessary to obtain a consistent picture

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

General EFT analysis of (LH) <u>four-fermion operators</u> based on the flavor symmetry U(2)$_q$ × U(2)$_l$ broken only by two spurions V$_Q$ =(V$_{td}$, V$_{ts}$) and
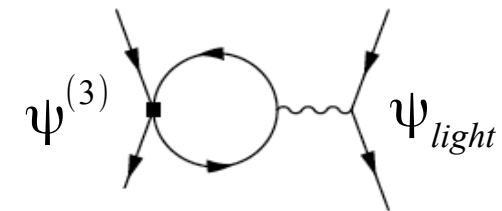V$_l$ = (V$_e$ , V$_μ$) ≈ (0, V$_μ$)

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*)

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

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

$\psi^{(3)}$          $\psi_{light}$

• $|V_l| \sim 0.3 - 0.1$

But residual O(10%) tuning needed in order to satisfy the bounds from
  ➤ Bs mixing (↔ <u>alignment to down-quark mass basis</u>)
  ➤ LFU in τ → *lνν*
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 → c(u) *lv*

$$\text{BR}(B \rightarrow D^* \tau\nu)/\text{BR}_{SM} = \text{BR}(B \rightarrow D\tau\nu)/\text{BR}_{SM} = \text{BR}(\Lambda_b \rightarrow \Lambda_c \tau\nu)/\text{BR}_{SM}$$
$$= \text{BR}(B \rightarrow \pi \tau\nu)/\text{BR}_{SM} = \text{BR}(\Lambda_b \rightarrow p \tau\nu)/\text{BR}_{SM} = \text{BR}(B_u \rightarrow \tau\nu)/\text{BR}_{SM}$$

- b → s μμ          $\Delta C_9^\mu = -\Delta C_{10}^\mu$

- b → s ττ          |NP| ~ |SM| → large enhancement (easily 10×SM)

- b → s νν          ~ O(1) deviation from SM in the rate

- K → π νν          ~ O(1) deviation from SM in the rate

- Meson mixing      ~ 10% deviations from SM both in $\Delta M_{Bs}$ & $\Delta M_{Bd}$

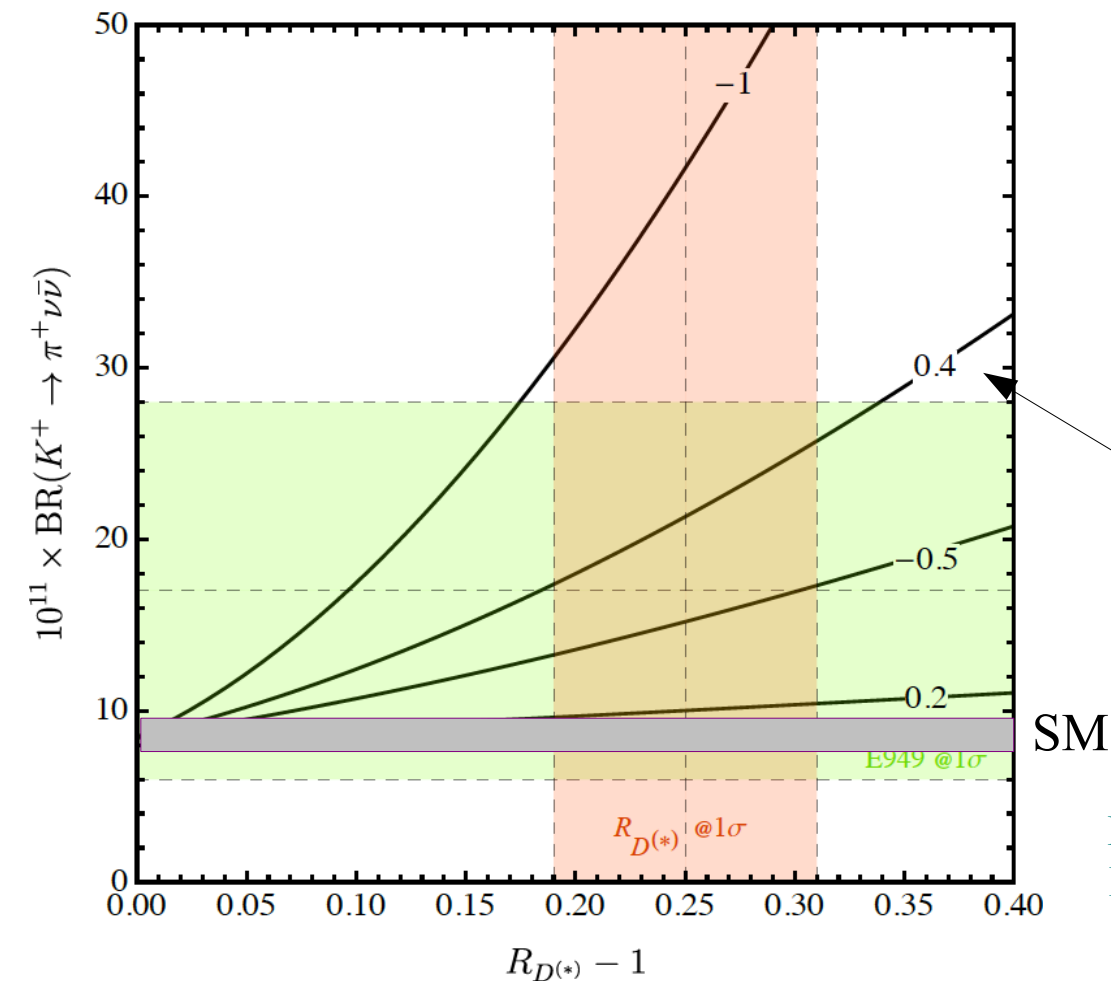- τ decays          τ → 3μ not far from present exp. Bound (BR ~ 10$^{-9}$)

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

$$\Gamma(K \rightarrow \pi\nu\nu) = \Gamma(K \rightarrow \pi\nu_e\overline{\nu}_e) + \Gamma(K \rightarrow \pi\nu_\mu\overline{\nu}_\mu) + \Gamma(K \rightarrow \pi\nu_\tau\overline{\nu}_\tau)$$

SM like          few % deviation          possible large deviation
                 as in b→sµµ               from SM as in b→sττ



Very interesting in view of NA62

O(1) parameter
of the EFT

SM

Barbieri *et al.* '16
Bordone, Buttazzo, GI, Monard (*to appear...*)

▶ *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

I. The triplet-vector model

<div align="right">
Greljo, GI, Marzocca '15<br>
Boucenna *et al.* '16
</div>

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:

$$J_\mu^a = g_q \boxed{\lambda_{ij}^q} \left( \bar{Q}_L^i \gamma_\mu T^a Q_L^j \right) + g_\ell \boxed{\lambda_{ij}^\ell} \left( \bar{L}_L^i \gamma_\mu T^a L_L^j \right) \longrightarrow \frac{1}{2m_V^2} J_\mu^a J_\mu^a$$

- 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 goof 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

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

Only Vector LQ produce a very good fit of both R$_{K*}$ and R$_D$ (*without extra tuning*)

- *Problem in Bs mixing less severe than in the vector triplet* (loop level)
- *Problem in (radiatively induced) $\tau \to l\nu\nu$ more severe*

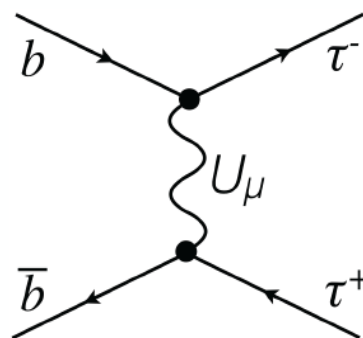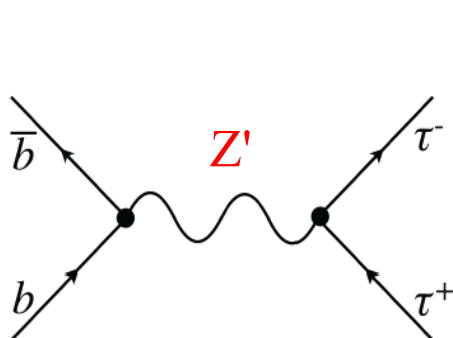▶ *<u>Simplified dynamical models</u>*

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
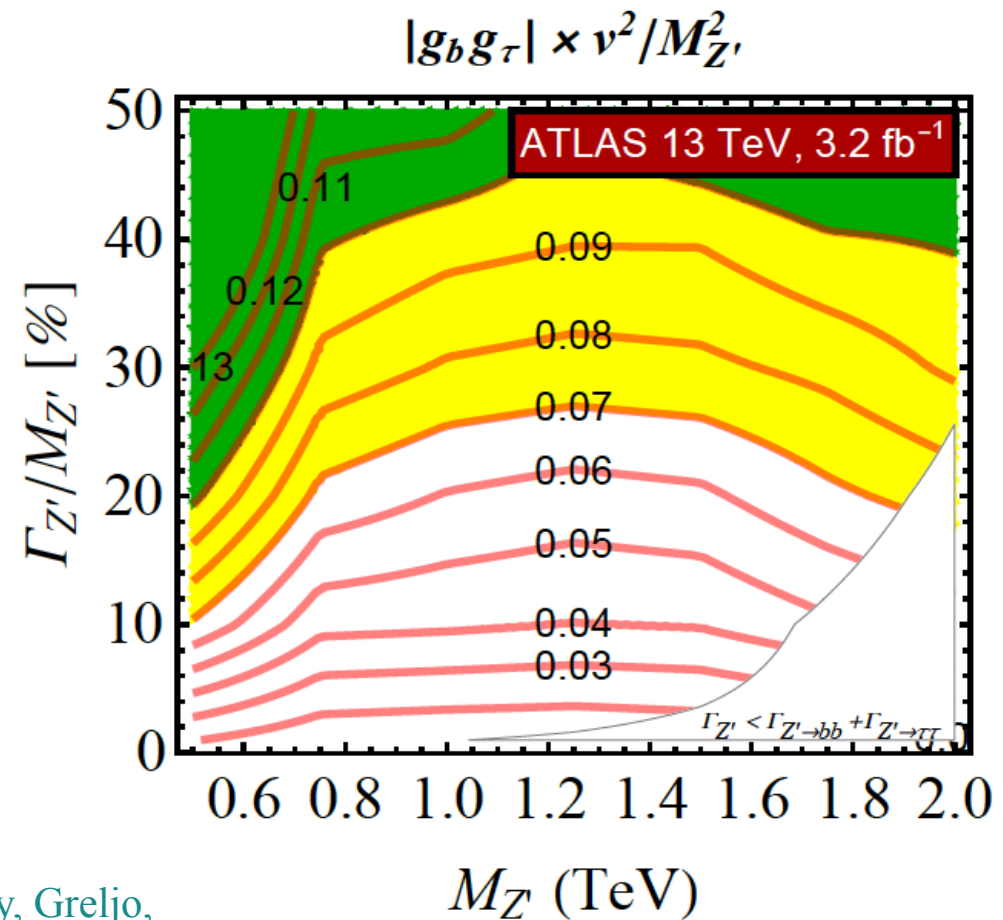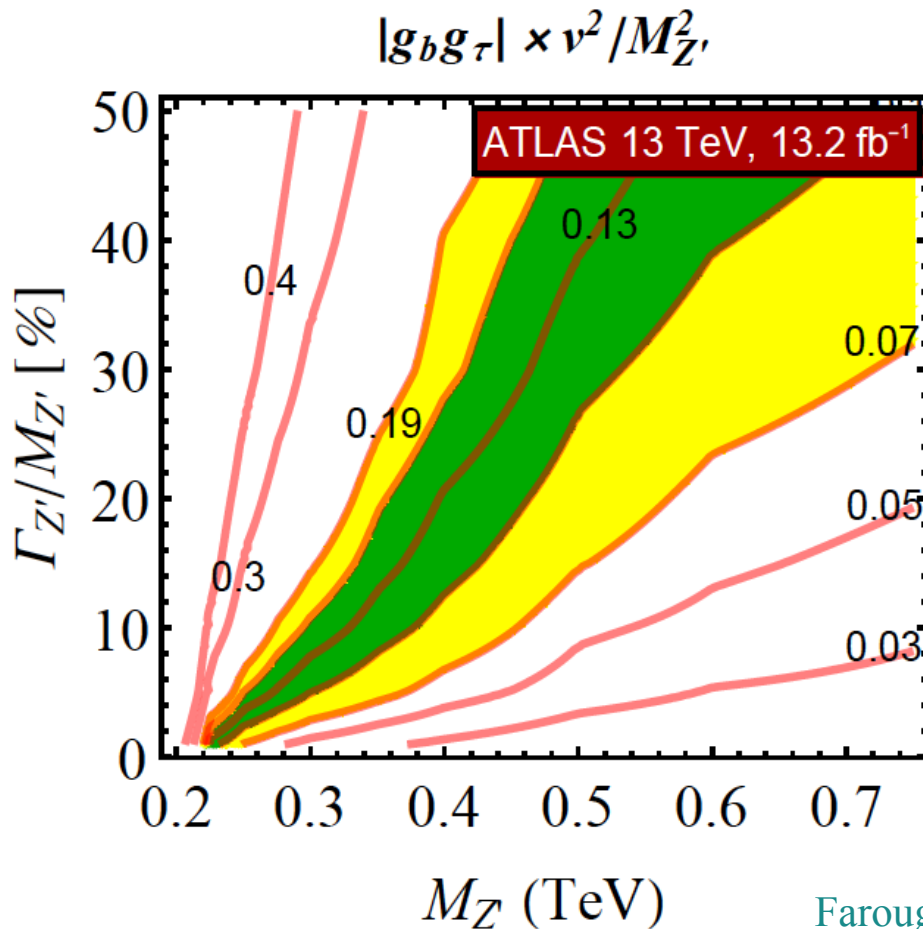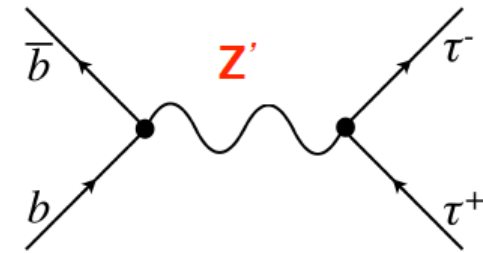  (*not easily detectable due to small coupling to light quarks & large width*)

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



- *Already some tension with ATLAS & CMS.*
- *Deviations from SM around the corner...*
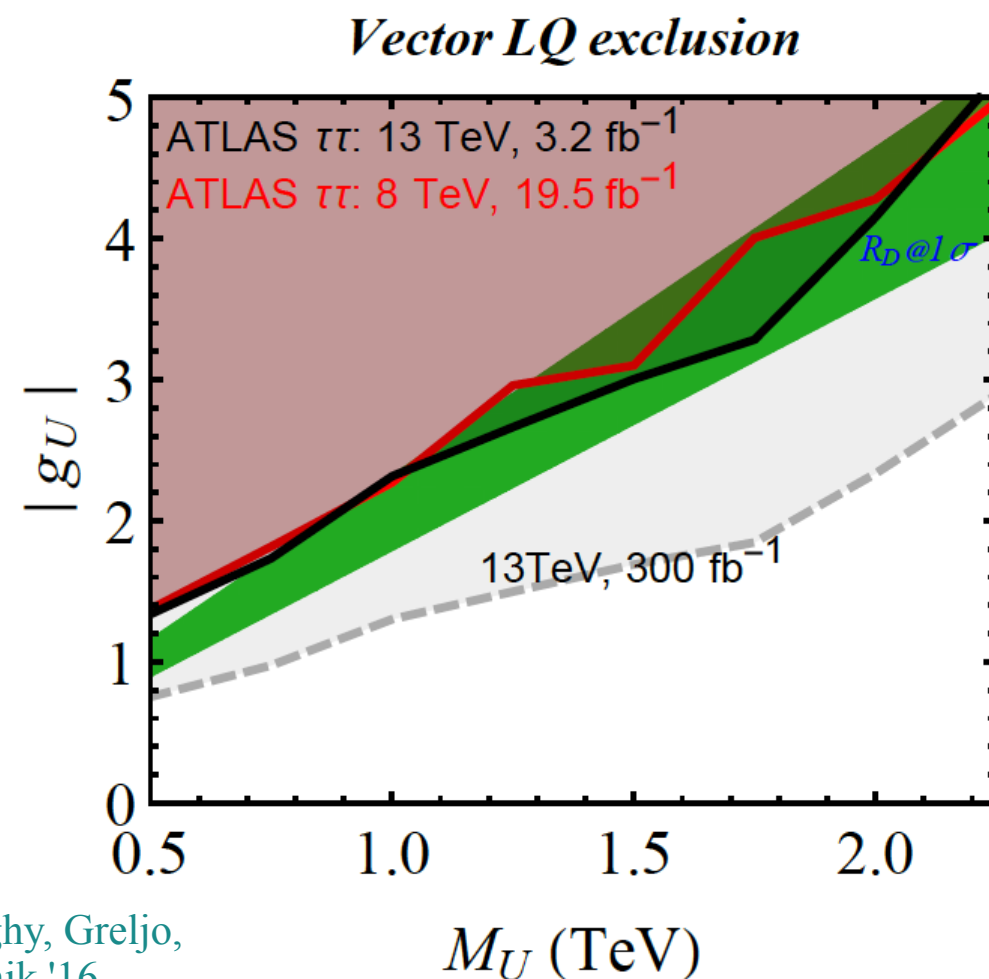
▶ *Simplified dynamical models*

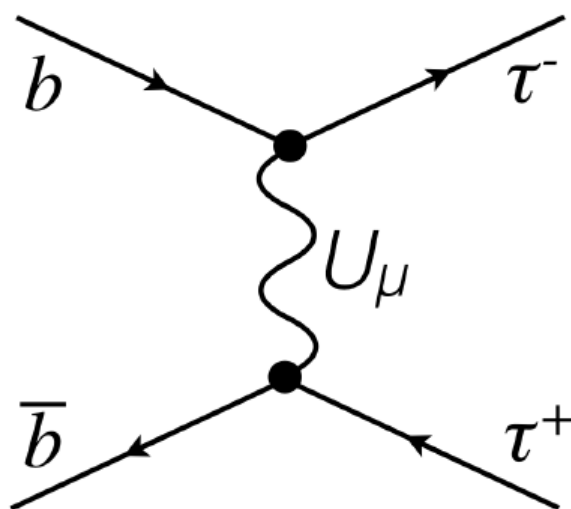Recast of recent ATLAS searches of Z' → ττ





Faroughy, Greljo,
Kamenik '16

▶ *Simplified dynamical models*

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



**Vector LQ exclusion**

ATLAS $\tau\tau$: 13 TeV, 3.2 fb$^{-1}$
ATLAS $\tau\tau$: 8 TeV, 19.5 fb$^{-1}$

$R_D @ 1\sigma$

13TeV, 300 fb$^{-1}$

$|g_U|$

$M_U$ (TeV)

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

→ Gripajos, Panico & Quiros talks

Buttazo, Greljo, GI, Marzocca, '16 (*backup slides*)

Conclusions

- <u>Very interesting hints of LF non Universality</u> in recent semi-leptonic B-physics data

- The overall picture is still far form being clear, <u>but the patter of anomalies is apparently coherent</u>→ more data can help to clarify the situation

- EFT based on $U(2)^n$ + NP coupled mainly to $3^{rd}$ 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 $p_T$*]

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

Five free parameters:

$$\epsilon_{\ell,q} \equiv \frac{g_{\ell,q}\, m_W}{g\, m_V} \;+\; \lambda^q_{bs},\; \lambda^\ell_{\mu\mu},\; \lambda^\ell_{\tau\mu}$$
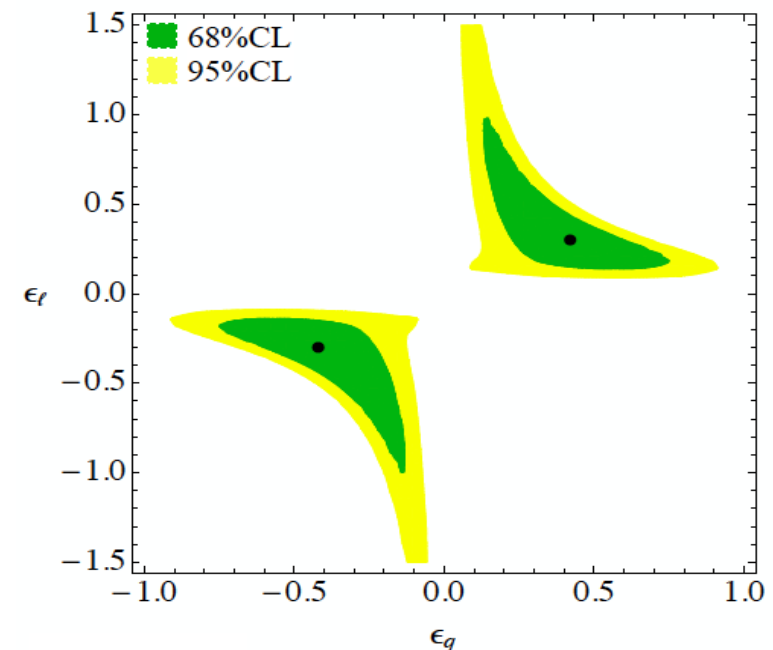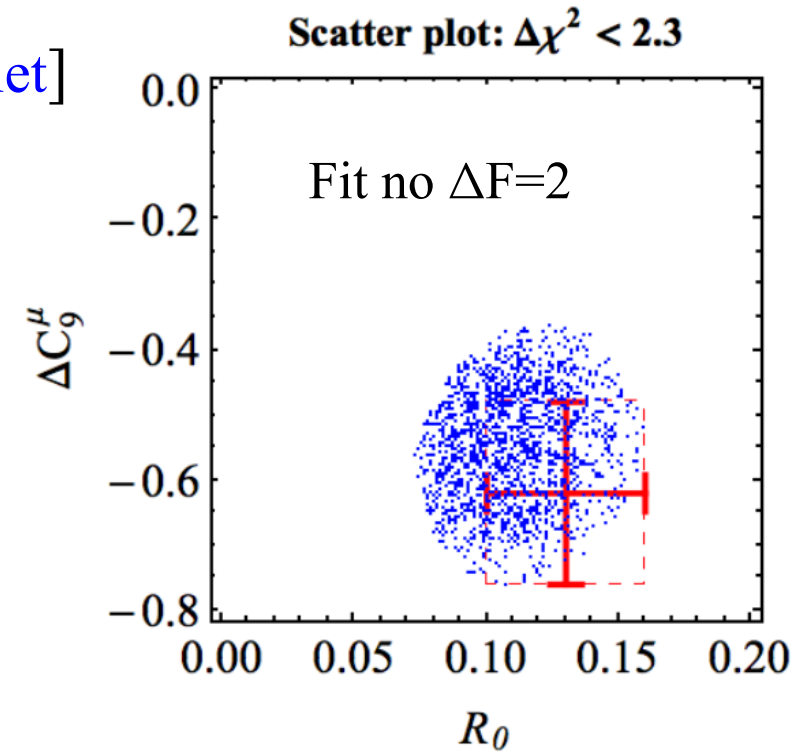
Several low-energy constraints

⬇

Overall good fit of low-energy data

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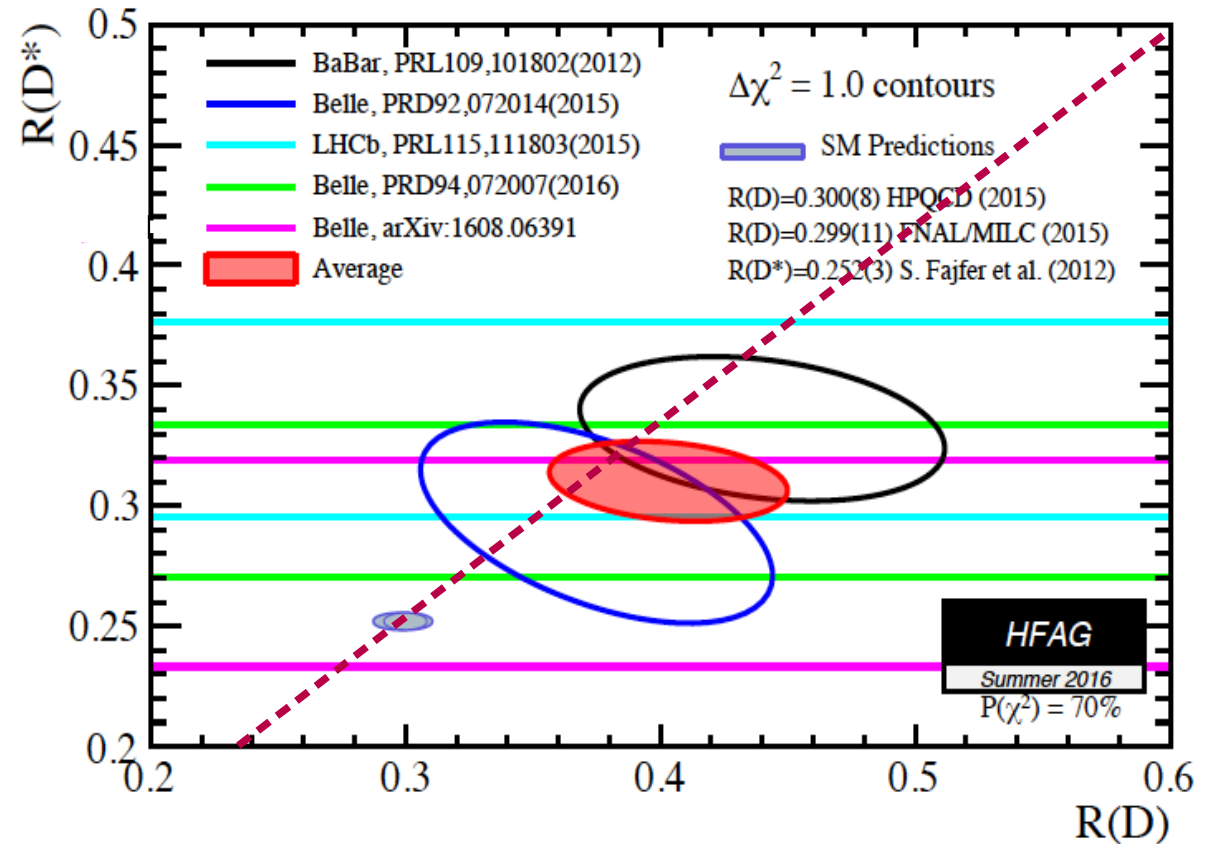[ $\Delta F=2$ vs. LFU tests in tau decays ]
which can be ameliorated including
extra contributions
(e.g. $SU(2)_L$ singlets Z' or color-octet)



Scatter plot: $\Delta\chi^2 < 2.3$

Fit no $\Delta F=2$

$\Delta C_9^\mu$ vs $R_0$



68%CL
95%CL

$\epsilon_\ell$ vs $\epsilon_q$

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

Test of LFU in charged currents
[$\tau$ vs. light leptons ($\mu$, e) ]:

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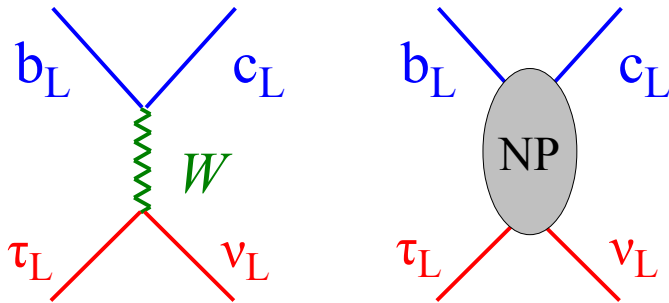


- SM prediction quite solid: f.f. uncertainty cancel (*to a good extent...*) in the ratio
- Consistent exp. results by 3 (very) different experiments
  - 4σ excess over SM (if D and D* combined)
  - The two channels are well consistent with a <u>universal enhancement</u> (~30%) of the SM $b_L \to c_L \tau_L \nu_L$ amplitude (*RH or scalar amplitudes disfavored*)

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

But the most interesting effects in b → s*ll* transitions are deviations from µ/e universality in the "clean" ratios R$_K$ & R$_{K*}$ (combined effect exceeding 3σ) :

Various "*instant papers*" have updated the fit to  b → s*ll*  Wilson coeff.

*Main messages*:

- Low-q$^2$ bin a bit too low (*the central value cannot be explained by NP – but there the theory error is larger...*)

- <u>All the rest perfectly consistent with what we already knew</u>:

- All anomalies are well described assuming NP only in b→sµµ
- Stronger indication in favor of V-A interaction
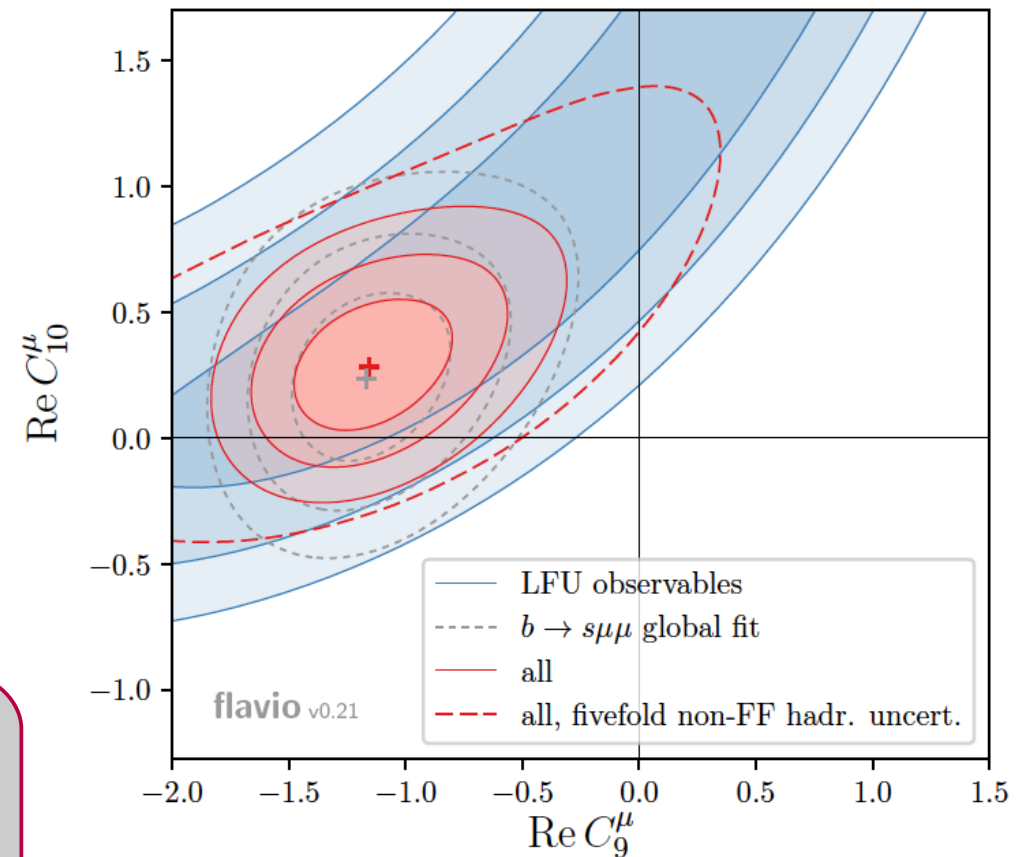


Altmannshofer, Stangl, Straub '17

▶ *UV completions and high-energy bounds*

**SM**

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

$f_i^{SM,chiral}$

**New sector**

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

$\Psi_{L,R}$ $\begin{bmatrix} \text{different} \\ \text{SM charges} \end{bmatrix}$

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

↓
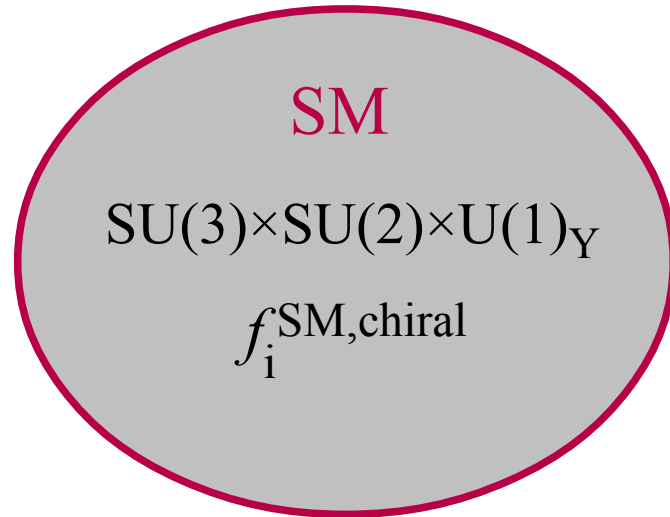
$SU(N_F)_{L+R} \times U(1)_V$

The basic construction is based on the idea of "*Vector-like confinement*"
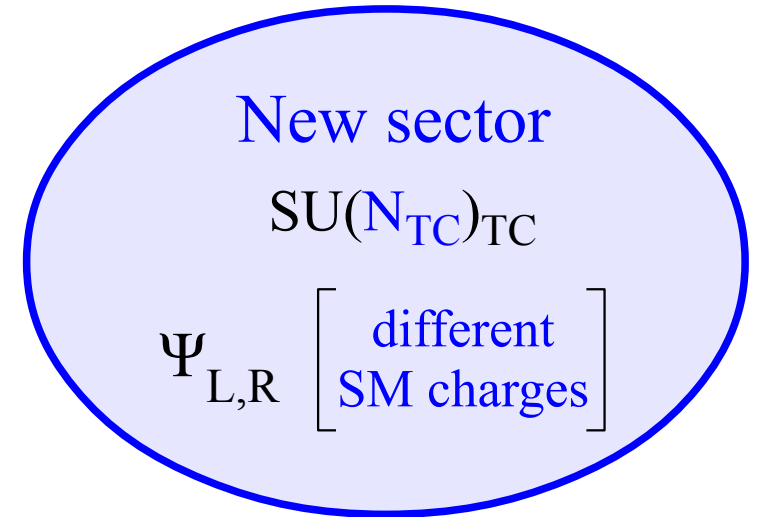
<u>Global</u> "flavor symmetry"
Spontaneously broken as in QCD
at a scale $\Lambda_{TC} \sim$ TeV

- ➤ 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**

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

$f_i^{SM,chiral}$

**New sector**

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

$\Psi_{L,R} \left[ \begin{array}{c} \text{different} \\ \text{SM charges} \end{array} \right]$

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

$\downarrow$

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

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

Lowest-lying spectrum of resonances:

pseudo-GB

$\pi, \eta, ...$

Heavy vectors

$\rho, \omega, \varphi, \ldots$

( + possibly  LQ )

▶ *UV completions and high-energy bounds*

**SM**

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

$f_i^{SM,chiral}$

SM gauge

**New sector**

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

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

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

↓
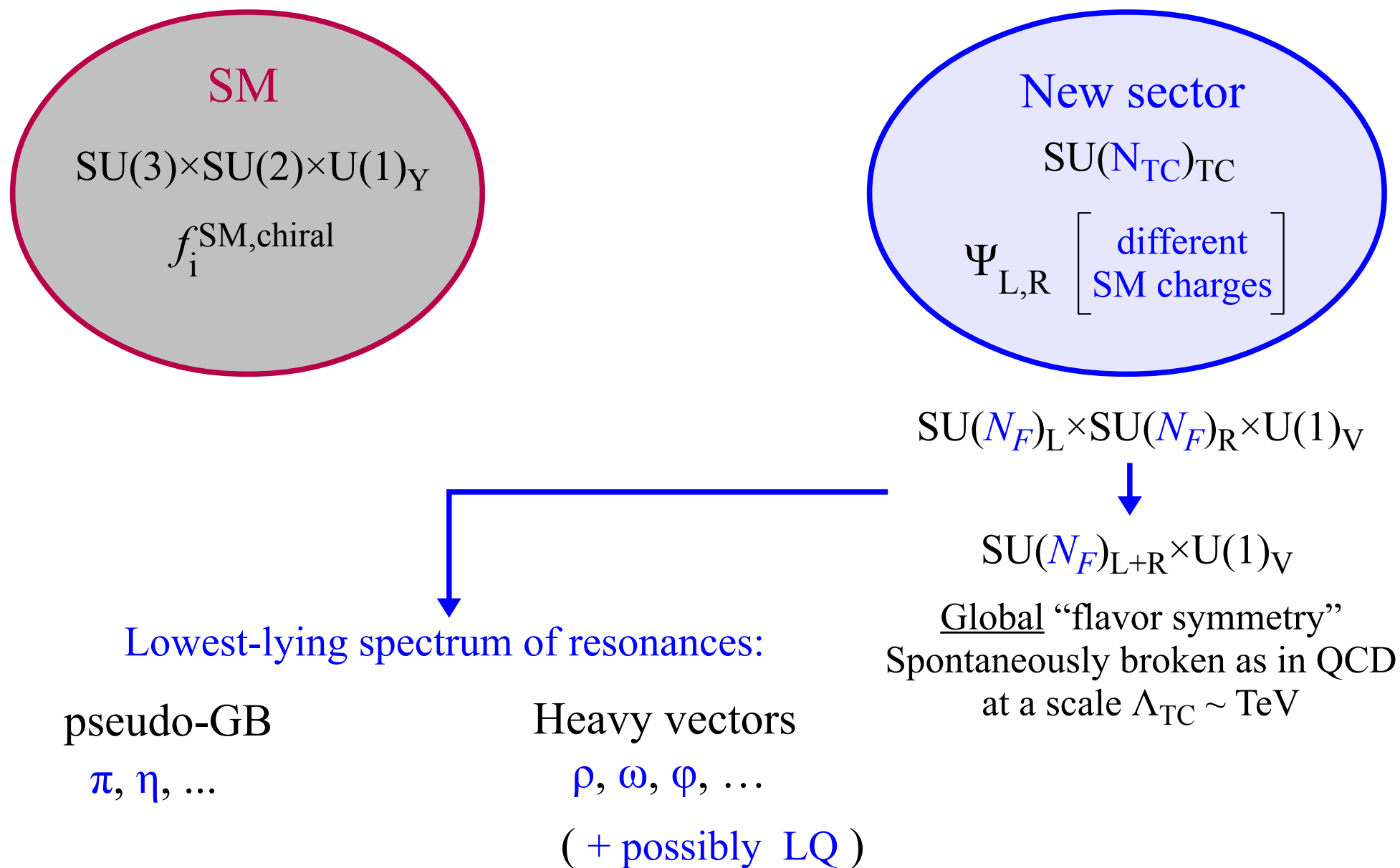
$SU(N_F)_{L+R} \times U(1)_V$

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

Lowest-lying spectrum of resonances:

pseudo-GB

$\pi$, $\eta$, ...

→ Higgs

(SM-like *partially-composite* H)

Heavy vectors

$\rho$, $\omega$, $\varphi$, …

( + possibly  LQ )

▶ *UV completions and high-energy bounds*

$$\text{SM}$$

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

$$f_i^{SM,chiral}$$

SM gauge

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

New sector

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

$$\Psi_{L,R} \begin{bmatrix} \text{different} \\ \text{SM charges} \end{bmatrix}$$

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

$$\downarrow$$

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

Lowest-lying spectrum of resonances:

pseudo-GB

$$\pi, \eta, ...$$

$$\longrightarrow \underline{\text{Higgs}}$$

(SM-like *partially-composite* H)

Heavy vectors

$$\rho, \omega, \varphi, ...$$

4f operators that can "solve" flavor anomalies