# B-physics anomalies & flavor non-universal gauge interactions

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- Introduction
- Bottom-up considerations
- Speculations on UV completions
- Conclusions

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

- b  $\rightarrow$  c charged currents:  $\tau$  vs. light leptons ( $\mu$ , e) [R<sub>D</sub>, R<sub>D\*</sub>]
- → b → s neutral currents:  $\mu$  vs. e [R<sub>K</sub>, R<sub>K\*</sub> (+ P<sub>5</sub> *et al.*)]

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

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• R(D) and R(D\*) consistent with a <u>universal enhancement</u> (~30%) of the SM  $b_L \rightarrow c_L \tau_L v_L$  amplitude

Consistent results by 3 different exps.  $\rightarrow 3.6-3.9\sigma$  excess over SM  $(D + D^*)$ 

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 All effects well described by NP only in b→sµµ and (& not in ee)

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

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- All effects well described by NP only in b→sµµ and (& not in ee)
- <u>LH structure on the quark side</u> largely favored
- Helicity structure on the lepton side less clear → Talk by Matias

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

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

Interesting <u>shift of paradigm</u> (in flavor physics, but possibly also beyond)

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



These two particles seems to be "<u>identical copies</u>" <u>but for their mass</u> ...

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



These two particles seems to be "identical copies" but for their mass ...

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



These three (families) of particles seems to be "<u>identical copies</u>" <u>but for their mass</u> ...

The SM quantum numbers of the three families could be an "accidental" <u>low-</u> <u>energy property</u>: the different families may well have a very different behavior at high energies, as <u>signaled by their different mass</u>

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# Introduction

So far, the vast majority of BSM model-building attempts

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

*"Common lore"* (I)

"Common lore" (II)



large (more interesting...)



small (less interesting...)

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The recent flavor anomalies seem to suggest a shift of paradigm:

- <u>We should not ignore the flavor problem</u> [→ *new (non-Yukawa) interactions at the TeV scale distinguishing the different families*]
- A (very) different behavior of the 3 families (with special role for 3<sup>rd</sup> gen.) *may be the key to solve/understand also the gauge hierarchy problem*





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# Bottom-up approaches to describe the anomalies [*from EFT to simplified models*]



- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- Data largely favor non-vanishing <u>left-handed</u> current-current operators [*the Fermi-like* SU(2)<sub>L</sub> *triplet contributes to both charged & neutral curr.*], although other contributions are also possible



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

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- Large coupling (competing with SM tree-level ) in  $bc \rightarrow l_3 v_3$
- Small non-vanishing coupling (competing with SM FCNC) in  $bs \rightarrow l_2 l_2$

$$\Lambda_{ij\alpha\beta} = (\delta_{i3} \times \delta_{3j}) \times (\delta_{\alpha3} \times \delta_{3\beta}) +$$

small terms for 2<sup>nd</sup> (& 1<sup>st</sup>) generations Link to pattern of the Yukawa couplings !

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Two classes of (tree-level) mediators, giving rise to different correlations among the anomalies, other lowenergy observables, and high- $p_T$  physics

Three main problems identified in the recent literature (*driven mainly by*  $R_D$ ...):

I. <u>high-p<sub>T</sub> constraints</u>



[low naïve EFT scale:  $\Lambda \sim 700 \text{ GeV}$ ]

Faroughy, Greljo, Kamenik '16

II. radiative constraints



Feruglio, Paradisi, Pattori '16

# III. flavor bounds



Greljo, GI, Marzocca '15 Calibbi, Crivellin, Ota, '15 (+many others...)

# EFT-type considerations [The U(2)<sup>n</sup> flavor symmetry]

A solution to all these "*combination*" problems + natural link with the origin of the Yukawa couplings, is provided by a suitable EFT based on the hypothesis of an approximate  $U(2)_q \times U(2)_l$  flavor symmetry

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A brief detour: U(2)<sup>n</sup> flavor symmetries (acting on light generations)

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

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

The exact symmetry limit is good starting point for the SM spectrum  $(m_u=m_d=m_s=m_c=0, V_{CKM}=1)$ 

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A brief detour: U(2)<sup>n</sup> flavor symmetries (acting on light generations)

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





Minimal breaking to reproduce SM Yukawa couplings:

$$|\mathbf{V}| \approx |\mathbf{V}_{\rm ts}| = 0.04$$
  
 $|\Delta| \approx y_{\rm c} = 0.006$ 

- The assumption of a single leading breaking ensures an effective protection of FCNCs
   → consistency with CKM fits
- Large NP effects possible for 3<sup>rd</sup> generation

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Assumption of NP in left-handed semi-leptonic operators only [*high-scale matching*]

Buttazzo, Greljo, GI, Marzocca, '17 "The Zürich's Guide"

 $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2} \lambda_{ij}^q \lambda_{\alpha\beta}^\ell \left[ \underline{C_T} \left( \bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j \right) (\bar{L}_L^\alpha \gamma^\mu \sigma^a L_L^\beta) + \underline{C_S} \left( \bar{Q}_L^i \gamma_\mu Q_L^j \right) (\bar{L}_L^\alpha \gamma^\mu L_L^\beta) \right]$ 

four free parameters...

$$C_{T}, C_{S}$$
$$\lambda_{bs} = O(V_{cb})$$
$$\lambda_{\mu\mu} = O(|V_{\tau\mu}|^{2})$$

...*and a <u>long list of constraints</u>* [ FCNC and CC semi-leptonic processes, tau decays, EWPO ]

#### EFT-type considerations ["The Zurich's guide"]

Excellent fit to both anomalies, passing all existing constraints with no fine tuning



→ Possible to find a "combined" *motivated* explanation of the 2 set of anomalies.

The EFT solution is not unique [e.g. sub-leading RH currents can be added], but large variations are possible only if the R<sub>D</sub> anom. goes away completely

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

If we ask which tree-level mediators can generate the effective operators required by the EFT fit, we have not many possibilities...



The U<sub>1</sub> option [Alonso, Grinstein, Camalich '15; Barbieri, GI, Pattori, Senia '15] fits quite nicely... but of course models with more than one mediators are also possible

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

If we ask which tree-level mediators can generate the effective operators required by the EFT fit, we have not many possibilities...

Three main options (*for combined tree-level explanations*):



Similarly,  $3^{rd}$  gen. LQ are in very good shape also as far as direct searches are concerned (*contrary to Z'*...):

LQ (both scalar and vectors) have an <u>additional</u> clear advantage concerning constraints from non-semilpetonic processes:







# Speculations on UV completions

There are several possibilities to find UV completions for the simplified models addressing the anomalies (*gauge models vs. composite models*) [*wide literature*]

Non-perturbative TeV-scale dynamics [non-renormalizable models]

• Scalar LQ as PNG

Gripaios, '10 Gripaios, Nardecchia, Renner, '14 Marzocca '18

• Vector LQ (or W',Z') as technifermion resonances

> Barbieri *et al.* '15, Buttazzo *et al.* '16 Barbieri, Murphy, Senia, '17 Blanke, Crivellin, '17

• W', Z' as Kaluza-Klein excitations [*e.g. from warped extra dim.*]

Megias, Quiros, Salas '17 Megias, Panico, Pujolas, Quiros '17 *Perturbative TeV-scale dynamics* [renormalizable models]

• Renormalizable models with scalar mediators [*LQ*, *but also RPV-SUSY*]

Hiller & Schmaltz, '14 Becirevic *et al.* '16, Fajfer *et al.* '15-'17 Dorsner *et al.* '17 Crivellin, Muller, Ota '17 Altmannshofer, Dev, Soni, '17 + ...

Gauge models

Cline, Camalich '17 Calibbi, Crivellin, Li, '17 Assad, Fornal, Grinstein, '17 Di Luzio, Greljo, Nardecchia, '17 Bordone, Cornella, Fuentes-Martin, GI, '17 + ...

# Speculations on UV completions

In the following I will now concentrate on one (class of) option(s) that I find particularly interesting.

Starting observation: the <u>Pati-Salam</u> model <u>predicts</u> a massive vector LQ with the correct quantum numbers to fit the anomalies (*best single mediator*):

<u>Pati-Salam</u> group:  $SU(4) \times SU(2)_L \times SU(2)_R$ 

Fermions in SU(4):

$$\begin{bmatrix} Q_{L}^{\alpha} \\ Q_{L}^{\beta} \\ Q_{L}^{\gamma} \\ L_{L} \end{bmatrix} \begin{bmatrix} Q_{R}^{\alpha} \\ Q_{R}^{\beta} \\ Q_{R}^{\gamma} \\ L_{R} \end{bmatrix}$$

LQ  $[U_1]$  from SU(4)  $\rightarrow$  SU(3)<sub>c</sub>

The problem of the "original PS model" are the strong bounds on the LQ couplings to 1<sup>st</sup> & 2<sup>nd</sup> generations [e.g. M > 100 TeV from  $K_L \rightarrow \mu e$ ].

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

▶ <u>The PS<sup>3</sup> model</u>

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

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

Main idea: at high energies the 3 families are charged under 3 <u>independent gauge</u> groups (gauge bosons carry a flavor index !)



→ Light LQ coupled mainly to 3<sup>rd</sup> gen.

Key advantages:

- Accidental U(2)<sup>5</sup> flavor symmetry
- Natural structure of SM Yukawa couplings

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Unification of quarks and leptons

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

This construction can find a "natural" justification in the context of models with extra space-time dimensions

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

▶ <u>The PS<sup>3</sup> model</u>



- \* The breaking to the diagonal SM group occurs via appropriate "link" fields, responsible also for the generation of the hierarchy in the Yukawa couplings.
- \* The 2-3 breaking gives a TeV-scale LQ [+ Z' & G'] coupled mainly to 3<sup>rd</sup> gen. [similar to "4321" (Di Luzio et al. '17) but "natural" flavor structure: no ad-hoc mixings]

### ▶ <u>The PS<sup>3</sup> model</u>



#### *Leading flavor structure:*

- Yukawa coupling for 3<sup>rd</sup> gen. only
- "Light" LQ field (from PS<sub>3</sub>) coupled only to 3<sup>rd</sup> gen.
- U(2)<sup>5</sup> symmetry protects flavorviolating effects on light gen.

<u>The PS<sup>3</sup> model</u>



# ▶ <u>The PS<sup>3</sup> model</u>

Collider phenomenology and flavor anomalies are controlled by the lastbut one step in the breaking chain.

Despite the apparent complexity, the construction is highly constrained:

Quark flavor structure determined up to an angle  $(\rightarrow degree \ of \ alignment \ to \ d-quark \ mass \ basis)$ 

Key difference to all existing pheno models: unsupressed  $b_R$ - $\tau_R$  coupling of the LQ



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# ▶ <u>The PS<sup>3</sup> model</u>

Collider phenomenology and flavor anomalies are controlled by the lastbut one step in the breaking chain.

Despite the apparent complexity, the construction is highly constrained





The fit to low-energy data is very good (although slightly smaller NP effects in  $R_D$ , mainly because of radiative constraints)

 ΔF=2 constraints imply 5-10% alignment to d-quark mass basis

## Low-energy implications

All models addressing the anomalies predict a rich low-energy phenomenology to be tested in the near future  $[B_s \rightarrow \tau\tau, B \rightarrow K\tau\tau, B \rightarrow \tau\nu, B \rightarrow K\nu\nu, \Delta M_{B_s}, ...]$ 

A particularly striking signature of the PS<sup>3</sup> model are large  $\tau \rightarrow \mu$  LFV effects:



# High-energy implications

Also the high-energy phenomenology is rich (exotic states in the few TeV range), but still consistent with the present exclusion bounds given the new states couple mainly to 3<sup>rd</sup> gen. quarks.



# Conclusions

- If these LFU anomalies were confirmed, it would be a fantastic discovery, with far-reaching implications
- If interpreted as NP signals, both set of anomalies are <u>not in contradiction</u> among themselves & with existing low- & high-energy data. <u>Taken together</u>, they point out to NP coupled mainly to 3<sup>rd</sup> generation, with a flavor structure connected to that appearing in the SM Yukawa couplings
- Simplified models with LQ states seem to be favored. However, realistic UV completions for these models naturally imply a much richer spectrum of states at the TeV scale (*and possibly above...*).
- The PS<sup>3</sup> model I have presented is particularly interesting as example of the shift of paradigm that these anomalies could imply. But of many points (and possible variations) remains to be clarified/explored...

### A lot of fun ahead of us...

(both on the exp., the pheno, and model-building point of view)



Symmetry breaking pattern in PS<sup>3</sup>



Symmetry breaking pattern in PS<sup>3</sup>



 $\Phi^{L}_{12} \sim (1,2,1)_{1} \times (1,2,1)_{2}$  $\Phi^{R}_{12} \sim (1,1,2)_{1} \times (1,1,\underline{2})_{2}$  $\Omega_{12} \sim (4,2,1)_{1} \times (\underline{4},\underline{2},1)$ 

```
VEV \rightarrow SU(2)_{1+2}^{L}VEV \rightarrow SU(2)_{1+2}^{R}VEV \rightarrow SU(4)_{1+2} \& SU(2)_{1+2}^{L}
```

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

 Reduced tension in all the observables with a unique fit of non-standard shortdistance Wilson coefficients



More precise data on the  $q^2=m_{\mu\mu}$  distribution can help to distinguish NP vs. SM

Descotes-Genon, Matias, Virto '15

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

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



#### Implications for low-energy measurements

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

<u>Main message</u>: "super-reach" flavor program for LHCb, but also other flavor physics facilities (Belle-II, Kaons, CLFV)

- This program is <u>essential</u> to determine the flavor structure of the new sector
- Correlations among low-energy obs. can be studied by means of EFT

#### Implications for low-energy measurements

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E.g.: <u>correlations among down-type FCNCs</u> [using the results of U(2)-based EFT]:

	μμ (ee)	ττ	VV	τμ	μe
$b \rightarrow s$	R <sub>K</sub> , R <sub>K*</sub> O(20%)	$B \rightarrow K^{(*)} \tau \tau$ $\rightarrow 100 \times SM$	$B \rightarrow K^{(*)} vv$ $O(1)$	$B \rightarrow K \tau \mu$ $\rightarrow \sim 10^{-6}$	$ \begin{array}{c} \mathbf{B} \to \mathbf{K} \ \mu \mathbf{e} \\ \hline ??? \end{array} $
$b \rightarrow d$	$B_{d} \rightarrow \mu\mu$ $B \rightarrow \pi \mu\mu$ $B_{s} \rightarrow K^{(*)} \mu\mu$ $O(20\%) [R_{K}=R_{\pi}]$	$B \rightarrow \pi \tau \tau$ $\rightarrow 100 \times SM$	$B \rightarrow \pi \nu \nu$	$B \rightarrow \pi \tau \mu$ $\rightarrow \sim 10^{-7}$	$B \rightarrow \pi \mu e$ ???
$s \rightarrow d$	long-distance pollution	NA	$\begin{array}{c} \mathbf{K} \rightarrow \pi \ \mathbf{vv} \\ \hline \mathbf{O}(1) \end{array}$	NA	$\frac{\mathbf{K} \rightarrow \mu \mathbf{e}}{???}$

#### Implications for 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(1-10%) deviations from SM in  $\Delta M_{Bs} \& \Delta M_{Bd}$ 
  - O(0.1%) CPV violation D-D mixing
- LFV decays  $\tau \to 3\mu \& \tau \to \mu\gamma$  can be close to their exp. bounds
  - LFV B decays,  $B_s \rightarrow \tau \mu$  or  $B \rightarrow K \tau \mu$  could also be within the reach

In the PS<sup>3</sup> model:

$$\left(\frac{\Delta R_D}{0.2}\right)^2 \left(\frac{\Delta R_K}{0.3}\right)^2 \approx 3 \left[\frac{\mathcal{B}(B \to K\tau^+\mu^-)}{3 \times 10^{-5}}\right] \left[\frac{\mathcal{B}(\tau \to \mu\gamma)}{5 \times 10^{-8}}\right] \approx \left[\frac{\mathcal{B}(B_s \to \tau^\pm\mu^\mp)}{2 \times 10^{-4}}\right] \left[\frac{\mathcal{B}(\tau \to \mu\gamma)}{5 \times 10^{-8}}\right]$$



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



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