B-physics anomalies: model building & future implications

Gino Isidori
[ University of Zürich ]

Introduction

Part (I): Model-building
- EFT-type considerations
- Simplified models
- UV completions

Part (II): Implications
- Low-energy measurements
- High-pT physics

Conclusions

Disclaimer:
This is not a review talk...
→ no attempts to cite/discuss all models (sorry!)
Introduction

Recent data show some convincing evidences of Lepton Flavor Universality violations

- $b \rightarrow c$ charged currents: $\tau$ vs. light leptons ($\mu$, $e$) [$R_D$, $R_{D^*}$]
- $b \rightarrow s$ neutral currents: $\mu$ vs. $e$ [$R_K$, $R_{K^*}$ (+ P5 et al.)]

If taken together... this is probably the largest “coherent” set of NP effects in present data...
**Introduction**

Recent data show some convincing evidences of Lepton Flavor Universality violations

- $b \to c$ charged currents: $\tau$ vs. light leptons ($\mu$, $e$) [$R_D$, $R_D^*$]
- $b \to s$ neutral currents: $\mu$ vs. $e$ [$R_K$, $R_K^*$ (+ P5 et al. )]

IF taken together... this is probably the largest “coherent” set of NP effects in present data...

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

---

**Interesting shift of paradigm**
*(in flavor physics, but possibly also beyond)*
Introduction [a digression on LFU]

Let's go back ~ 100 years, and suppose we can test matter only with long wavelength photons...

\[ \gamma \]
\[ U(1)_Q \]
\[ e^+ \quad p^+ \]

These two particles seem to be "identical copies" but for their mass...
Introduction [a digression on LFU]

Let's go back ~ 100 years, and suppose we can test matter only with long wavelength photons...

\[ \gamma, \ p^+ \]

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

\[ U(1)_Q \]
\[ e^+, \ p^+ \]

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

\[ \gamma, \ g, \ W, \ Z \]
\[ SU(3) \times SU(2) \times U(1) \]
\[ e, \ \mu, \ \tau \]

These three (families) of particles seems to be “identical copies” but for their mass...

The SM quantum numbers of the three families could be an “accidental” low-energy property: the different families may well have a very different behavior at high energies, as signaled by their different mass.
**Introduction** *a possible shift of parading in model-building*

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

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

\[ W, Z + H \]

large (*more interesting...*)

small (*less interesting...*)
Introduction [a possible shift of parading in model-building]

So far, the vast majority of BSM model-building attempts
- Concentrate only on the (SM gauge) hierarchy problem
- Postpone (ignore) the flavor problem, implicitly assuming the 3 families are “identical” copies (but for Yukawa-type interactions)

The recent flavor anomalies seem to suggest a shift of paradigm:
- We should not ignore the flavor problem [→ 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\textsuperscript{rd} gen.) may be the key to solve/understand also the gauge hierarchy problem

\[ W, Z + H \]

small (less interesting...)

large (more interesting...)

\[ 3^\text{rd} \]

\[ 3^\text{rd} \]

\[ 3^\text{rd} \]

\[ 3^\text{rd} \]

small (less interesting...)

large (more interesting...)
Part (I): **Model-building**

- EFT-type considerations
- Simplified models
- UV completions
**EFT-type considerations**

Recent data show some **convincing** 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.)]

- R(D) and R(D*) consistent with a **universal enhancement** (~30%) of the SM \( b_L \rightarrow c_L \tau_L \nu_L \) amplitude

\( RH \) or scalar amplitudes disfavored
**EFT-type considerations**

Recent data show some **convincing** evidences of **Lepton Flavor Universality** violations

- \( b \rightarrow c \) charged currents: \( \tau \) vs. light leptons (\( \mu \), \( e \)) \([R_D, R_{D^*}]\)
- \( b \rightarrow s \) neutral currents: \( \mu \) vs. \( e \) \([R_K, R_{K^*} (+P_5 \text{ et al.})]\)

→ **talks Wednesday morning**

All effects well described by NP only in \( b \rightarrow s \mu \mu \) and (\& not in \( ee \))

- **LH structure on the quark side** largely favored
- Helicity structure on the lepton side less clear
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 is we aim to a combined explanation (as in the Fermi theory):

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

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

Bhattacharya et al. '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15
(+many others...)
**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 is we aim to a combined explanation (*as in the Fermi theory*):

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

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

\[Q_L^{(3)} \sim q_L^{(b)} = \begin{bmatrix} V_{ib}^* u^i_L \\ b_L \end{bmatrix} \text{ up to CKM rotations of } O(V_{cb})\]
**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 is we aim to a combined explanation (*as in the Fermi theory*):

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

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

\[Q_L^{(3)} \sim q_L^{(b)} = \begin{bmatrix} V_{ib}^* u_L^i \\ b_L \end{bmatrix} \text{ up to CKM rotations of } O(V_{cb})\]

\[\lambda_{i,j}^{q,\ell} = \delta_{i3} \delta_{3j} + \text{ small corrections for } 2^{\text{nd}} (\& 1^{\text{st}}) \text{ generations}\]
**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 is we aim to a combined explanation (*as in the Fermi theory*):

\[
\frac{g_q g_{\ell}}{\Lambda^2} \lambda_{ij}^q \lambda_{kl}^\ell (\bar{Q}^i_L T^a \gamma_\mu Q^j_L)(\bar{L}^k_L T^a \gamma_\mu L^l_L)
\]

- Two classes of (tree-level) mediators, giving rise to different correlations among the anomalies, other low-energy observables, and high-$p_T$ physics
EFT-type considerations [The main problems]

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

I. high-$p_T$ constraints

Naïve EFT scale

[from $R_D$ - setting $g, \lambda \to 1$]: $\Lambda \sim 700$ GeV

Vector LQ exclusion

$|g_U|$

$M_U$ (TeV)

$Z'$ exclusion

$g_1$

$M_{\gamma\gamma}$ (GeV)

Faroughy, Greljo, Kamenik '16
**EFT-type considerations** [The main problems]

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

**I. high-$p_T$ constraints**

[Diagram showing $b\tau$ and $Z'(W')$ processes]

**II. radiative constraints**

[Diagram showing $\tau\nu$ and $b\tau$ processes]

---

Feruglio, Paradisi, Pattori '16

---

G. Isidori – B-physics anomalies: model building & future implications

LHCb implications, CERN, 10th Nov 2017
**EFT-type considerations** [The main problems]

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

I. *high-\( p_T \) constraints*

\[
\begin{align*}
&\text{\( b \rightarrow \tau \)} \\
&\text{\( Z'(W') \)}
\end{align*}
\]

II. *radiative constraints*

\[
\begin{align*}
&\text{\( b \rightarrow \tau \)} \\
&\text{\( \text{LQ} \)}
\end{align*}
\]

III. *flavor bounds*

\[
\begin{align*}
&\text{\( \overline{B_s} \rightarrow \tau \)} \\
&\text{\( \text{B} \)} \\
&\text{\( \text{K} \)}
\end{align*}
\]

Greljo, GI, Marzocca '15
Calibbi, Crivellin, Ota, '15
(+many others...)
**EFT-type considerations** [The $U(2)^n$ flavor symmetry]

A solution to all these “combination” problems is provided by a suitable EFT based on a few simple assumptions:

- NP in left-handed operators only
- Leading NP effects in $3^{rd}$ generation only
- Light generation couplings controlled by $U(2)_q \times U(2)_l$ flavor symmetry minimally broken (→ link to SM Yuk. coupl.)

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

→ talk by Admir Greljo

four free parameters...

\[
\begin{bmatrix}
C_T, C_S \\
\lambda_{bs} = O(V_{cb}) \\
\lambda_{\mu\mu} = O(|V_{\tau\mu}|^2)
\end{bmatrix}
\]

...and a long list of constraints
**EFT-type considerations** [The global fit]

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

- SU(2)$_L$ singlet & triplet operators
- Flavor symmetry
- Deviation from “pure-mixing”
- O(V$_{cb}$) misalignment to $b$-quark mass basis

Key features compared to previous analyses:

\[ |\lambda_{sb}^g| < 2V_{cb} \]

\[ |\lambda_{sb}^g| < 5V_{cb} \]

\[ \Delta \chi^2 < 2.3 \]

\[ \Lambda_{\text{NP}} \text{ raised to } \sim 1.5 \text{ TeV} \]
**EFT-type considerations** [The global fit]

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

- This EFT approach shows that it is possible to find a “combined” (motivated) explanation of the two set of anomalies. Very useful in identifying implications in other low-energy measurements [→ more later...]

- The EFT solution is not unique [e.g. sub-leading RH currents can be added], but large variations are possible only if the $R_D$ anom. goes away completely [→ higher effective NP scale, no need of charged curr. → an heavy Z' can do the job...]
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 (*not always...*)
- check the consistency with high-energy data (*that is quite relevant...*)
- identify possible UV completions

Three main options
*for the combined explanation*:

<table>
<thead>
<tr>
<th>SU(2)$_L$</th>
<th>singlet</th>
<th>triplet</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vector LQ:</strong></td>
<td>$U_1$</td>
<td>$U_3$</td>
</tr>
<tr>
<td><strong>Scalar LQ:</strong></td>
<td>$S_1$</td>
<td>$S_3$</td>
</tr>
<tr>
<td><strong>Colorless vector:</strong></td>
<td>$B'$</td>
<td>$W'$</td>
</tr>
</tbody>
</table>
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 (not always...)
- check the consistency with high-energy data (that is quite relevant...)
- identify possible UV completions

Three main options (for the combined explanation):

SU(2)$_L$

- singlet
- 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
Simplified dynamical models [main features of the 3 options]

I. Vector LQ \([U_1]\)

- Minimal number of free parameters (3) \(\rightarrow\) very good fit of both \(R_{K^*}\) and \(R_D\) + all radiative constraints, without any tuning
- Not renormalizable at the level of simplified model (\(\rightarrow\) quadratically divergent contribution to Bs mixing not fully under control)
- UV completion not in main stream BSM...
**Simplified dynamical models** [main features of the 3 options]

I. **Vector LQ** $[\mathbf{U}_1]$

- Minimal number of free parameters (3) $\rightarrow$ very good fit of both $R_{K^*}$ and $R_D$ + all radiative constraints, without any tuning
- Not renormalizable at the level of simplified model ($\rightarrow$ quadratically divergent contribution to $B_s$ mixing not fully under control)
- UV completion not in main stream BSM...

II. **Scalar LQ model** $[S_1, S_3]$

- Renormalizable (small contrib. to $B_s$ mixing), easy to explain why these are the lightest NP states (possible NG bosons)
- Good fit of both $R_{K^*}$ and $R_D$ + all radiative constraints require some adjustment among the coupling of the two mediators

III. **Colorless vectors** $[W', Z']$

- Very natural NP states in many NP models (↔ hierarchy problem)
- Significant (but not unnatural) tuning of the various couplings to evade bounds + light masses $\rightarrow$ tension with direct searches & $B_s$ mixing
Speculations on UV completions
Speculations on UV completions

Two main approaches

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

- Possible connections to EW hierarchy prob.
- Light mediators as PNGB
- Rather ugly cosets...
- Limited calculability

Perturbative
TeV-scale dynamics
[renormalizable models]

- Good predictive powers beyond lowest-order
- No simple connections to EW hierarchy prob. *(at least so far..)*
- Flavor structure put by hand *(at least so far..)*
Speculations on UV completions

Two main approaches

Non-perturbative TeV-scale dynamics
[non-renormalizable models]
- Scalar LQ as PNG
  Gripaios, '10
  Gripaios, Nardecchia, Renner, '14
- Vector LQ (or W',Z') as technifermion resonances
  Barbieri et al. '15, Buttazzo et al. '16
  Barbieri, Murphy, Senia, '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
  + ...
Speculations on UV completions

Two main approaches

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

Scalar LQ as PNG
Gripaios, '10
Gripaios, Nardecchia, Renner, '14

SU(4) × SU(3) × SU(2)_L × U(1) → SM
SU(3)_C

TeV-scale LQ [U_1] + Z' + G'

Ad-hoc flavor mixing with vector-like fermions

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

\[[ PS ]^3 = [ SU(4) \times SU(2)_L \times SU(2)_R ]^3\]
A more ambitious attempt...

High-scale [\(\sim 10^3 \text{ TeV}\)]
“vertical” breaking [PS \(\rightarrow\) SM]

\[
\begin{align*}
\text{PS}_1 [ & \quad \text{SU}(4)_1 \times \text{SU}(2)^R_1 ] \\
\downarrow \\
\text{SM}_1 [ & \quad \text{SU}(3)_1 \times \text{U}(1)^Y_1 ]
\end{align*}
\]

Low-scale “vertical” Breaking [EWSB]

\[
\begin{align*}
\text{SM}_3 [ & \quad \text{SU}(2)_1^L \times \text{U}(1)^Y_1 ] \\
\downarrow \\
\text{QED}_3 [ & \quad \text{U}(1)_Q^1 ]
\end{align*}
\]

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

- 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\(^{rd}\) gen. [very similar to “DGN-4321” but “natural” flavor structure & no vector-like quarks]
A more ambitious attempt...

Below ~ 100 TeV
U(2)⁵ flavor symmetry
(but for link fields)
**A more ambitious attempt...**

\[ Y_U = \begin{bmatrix} \Delta & V \\ \overline{y}_t & \overline{\Omega}_{2'3} \end{bmatrix} \]

\[ \frac{<\Phi^R_{2'3}, \Phi^L_{2'3}>}{\Lambda_{23}} \]

\[ (\Lambda_{23})^2 \]

Below \(\sim 100\) TeV

\[ \text{U}(2)^5 \text{ flavor symmetry} \]

(but for link fields)

\[ \to W_L' + W_R' [\sim 5-10\text{ TeV}] \]

\[ \to \text{LQ} [U_1] + Z' + G' [\sim 1-2\text{ TeV}] \]
A more ambitious attempt...

Collider pheno and flavor anomalies are controlled by the last-but one step in the breaking chain.

In its minimal version, the model works better for $R_D$ than for $R_K$ (LQ fully aligned to 3rd generation)

But a good fit to $R_K$ can be achieved with a (slightly) more involved structure of the link fields.
Part (II): Implications

- Low-energy measurements
- High-pT physics
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

Main message: “super-reach” flavor program for LHCb upgrades (I, II and beyond...) and 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
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

E.g.: **correlations among down-type FCNCs** [using the results of $U(2)$-based EFT]:

- $\mu\mu$ (ee)
- $b \rightarrow s$, $R_K$, $R_{K^*}$

More statistics on the various $B \rightarrow K^{(*)}ll$ modes would allow to better determine the helicity structure of the amplitudes...

→ talks on Wednesday morning
**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

E.g.: **correlations among down-type FCNCs** [using the results of $\text{U}(2)$-based EFT]:

<table>
<thead>
<tr>
<th></th>
<th>$\mu\mu$ (ee)</th>
<th>$\tau\tau$</th>
<th>$\nu\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \to s$</td>
<td>$R_K, R_{K^*}$ \textit{present anomalies}</td>
<td>$B \to K(*) \tau\tau$</td>
<td>$B \to K(*) \nu\nu$</td>
</tr>
<tr>
<td>$b \to d$</td>
<td>$B_d \to \mu\mu$</td>
<td>$B \to \pi \tau\tau$</td>
<td>$B \to \pi \nu\nu$</td>
</tr>
<tr>
<td>$s \to d$</td>
<td>\textit{long-distance pollution}</td>
<td>$NA$</td>
<td>$K \to \pi \nu\nu$</td>
</tr>
</tbody>
</table>
### 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.

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

<table>
<thead>
<tr>
<th></th>
<th>$\mu\mu$ (ee)</th>
<th>$\tau\tau$</th>
<th>$\nu\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \rightarrow s$</td>
<td>$R_K, R_{K^*}$</td>
<td>$B \rightarrow K^{(*)}\tau\tau$</td>
<td>$B \rightarrow K^{(*)}\nu\nu$</td>
</tr>
<tr>
<td></td>
<td>$O(20%)$</td>
<td>$\rightarrow 100 \times \text{SM}$</td>
<td>$O(1)$</td>
</tr>
<tr>
<td>$b \rightarrow d$</td>
<td>$B_d \rightarrow \mu\mu$</td>
<td>$B \rightarrow \pi\tau\tau$</td>
<td>$B \rightarrow \pi\nu\nu$</td>
</tr>
<tr>
<td></td>
<td>$B \rightarrow \pi\mu\mu$</td>
<td>$\rightarrow 100 \times \text{SM}$</td>
<td>$O(1)$</td>
</tr>
<tr>
<td></td>
<td>$B_s \rightarrow K^{(*)}\mu\mu$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$O(20%)$ [$R_K = R_{\pi}$]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$s \rightarrow d$</td>
<td><em>long-distance pollution</em></td>
<td><em>NA</em></td>
<td>$K \rightarrow \pi\nu\nu$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$O(1)$</td>
</tr>
</tbody>
</table>
### 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.

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

<table>
<thead>
<tr>
<th></th>
<th>$\mu\mu$ (ee)</th>
<th>$\tau\tau$</th>
<th>$\nu\nu$</th>
<th>$\tau\mu$</th>
<th>$\mu\epsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \to s$</td>
<td>$R_K, R_{K^*}$</td>
<td>$B \to K^* \tau\tau$</td>
<td>$B \to K^* \nu\nu$</td>
<td>$B \to K \tau\mu$</td>
<td>$B \to K \mu\epsilon$</td>
</tr>
<tr>
<td></td>
<td>$O(20%)$</td>
<td>$\to 100 \times SM$</td>
<td>$O(1)$</td>
<td>$\to \sim 10^{-6}$</td>
<td>$??$</td>
</tr>
<tr>
<td>$b \to d$</td>
<td>$B_d \to \mu\mu$</td>
<td>$B \to \pi \tau\tau$</td>
<td>$B \to \pi \nu\nu$</td>
<td>$B \to \pi \tau\mu$</td>
<td>$B \to \pi \mu\epsilon$</td>
</tr>
<tr>
<td></td>
<td>$B \to \pi \mu\mu$</td>
<td>$\to 100 \times SM$</td>
<td>$O(1)$</td>
<td>$\to \sim 10^{-7}$</td>
<td>$??$</td>
</tr>
<tr>
<td></td>
<td>$O(20%) \ [R_K=R_\pi]$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$s \to d$</td>
<td>long-distance pollution</td>
<td>NA</td>
<td>$K \to \pi \nu\nu$</td>
<td>NA</td>
<td>$K \to \mu\epsilon$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$O(1)$</td>
<td></td>
<td>$??$</td>
</tr>
</tbody>
</table>
**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.

E.g.: **correlations among down-type FCNCs** [using the results of $U(2)$-based EFT]:

\[ \Delta \chi^2 < 2.3 \]

\[ |\lambda_{sb}^q| < 5 \, V_{cb} \]

\[ |\lambda_{sb}^q| < 2 \, V_{cb} \]
Implications for 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...
Implications for 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 $R^{\tau/\mu}(b\rightarrow c)$ ratios]:

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

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

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

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

UTfit '16

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

- **$\tau$ decays**
  - $\tau \rightarrow 3\mu$ can be close to exp. bound ($BR \sim 10^{-9}$)
  - O(0.1%) deviations in $BR(\tau \rightarrow \mu \nu \nu)/BR(\tau \rightarrow e \nu \nu)$ and $G_F(\tau)$ vs. $G_F(\mu)$
Implications for high-pT physics
**Implications for high-$p_T$ physics**

Some general considerations:

Independently of the details of the UV models, the anomalies point to **NP in the ball-park of direct searches @ LHC**

- $R_D(*)$ necessarily points to a low NP scale: $M \sim g \times (1.0 \div 1.5) \text{ TeV}$

- $R_K(*)$ also points to a low NP scale, but for (unnaturally) large flavor-violating coupl.: $M \sim g \times (8.0 \text{ TeV}) \left[ \frac{\lambda_{bs} \lambda_{\mu\mu}}{V_{ts}} \right]^{1/2}$

This NP could have escaped detection so far only under specific circumstances (that are fulfilled by the proposed UV completions):

- Coupled mainly to 3$^{\text{rd}}$ generation ($\rightarrow$ no large coupl. to proton valence quarks)
- No narrow peaks in dilepton pairs (including tau pairs)

Significant room for improvement for the corresponding searches @ HL-LHC
But only HE-LHC would be able to rule out all reasonable models
Implications for high-$p_T$ physics

This NP could have escaped detection so far only under specific circumstances:
- Coupled mainly to 3$^\text{rd}$ generation (→ no large coupl. to proton valence quarks)
- No narrow peaks in dilepton pairs (including tau pairs)

![Graph showing 95% CL limits on MFV Z' from $p p \rightarrow \mu^+ \mu^-$](image)

Faroughy, Greljo, Kamenik '16

![Graph showing $|g_b g_\tau| \times v^2/M_Z^2, \Gamma_Z/M_Z, \%$](image)

Greljo, Marzocca '17
Implications for high-$p_T$ physics

Also as far as direct searches are concerned, 3rd gen. LQ are in good shape:
**Implications for high-\(p_T\) physics**

Also as far as direct searches are concerned, 3\(^{\text{rd}}\) gen. LQ are in good shape:

N.B.: The single production (*for which so far there are no dedicated searches*) might be the dominant prod. channel.
**Implications for high-\(p_T\) physics**

Also as far as direct searches are concerned, 3\textsuperscript{rd} gen. LQ are in good shape:

**N.B.:** The **single production** *(for which so far there are no dedicated searches)* might be the dominant prod. channel

**N.B.:** More generally, \(pp \rightarrow b\,\tau \rightarrow b\,l + E_T\) is a key (model-independent) search relevant to any model addressing the RD anomaly

![Graphs showing event distributions for SM, Vector, and Scalar models](chart.png)

Altmannshofer, Dev, Soni, '17
Implications for high-$p_T$ physics

More specific considerations for direct searches:

I. The production of all type of mediators occurs predominantly in conjunction with $b$ quarks $\rightarrow$ b-tag helps!

II. The $R_D$ anomaly unambiguously points out to large BRs into $\tau$ pairs in the final state [$\text{but narrow peaks in } \tau\tau \text{ disfavored}$].
Implications for high-$p_T$ physics

More specific considerations for direct searches:

I. The production of all type of mediators occurs predominantly in conjunction with $b$ quarks → b-tag helps!

II. The $R_D$ anomaly unambiguously points out to large BRs into $\tau$ pairs in the final state [but narrow peaks in $\tau\tau$ disfavored]

III. Large BRs into top pairs naturally expected in most models [but S/B worse due to SM top production]
Implications for high-\(p_T\)-physics

More specific considerations for direct searches:

I. The production of all type of mediators occurs predominantly in conjunction with \(b\) quarks → \(b\)-tag helps!

II. The \(R_D\) anomaly unambiguously points out to large BRs into \(\tau\) pairs in the final state [\textit{but narrow peaks in} \(\tau\tau\) \textit{disfavored}]

III. Large BRs into \textit{top pairs} naturally expected in most models

IV. BR into \(\mu\) pairs (or \(\mu\tau\)) always expected but \textit{naturally suppressed} vs. taus [\(O(0.1)\) @ amplitude level for each muon – larger model dependence] except in models addressing only \(R_K\)
IV. BR into $\mu$ pairs (or $\mu\tau$) always expected but naturally suppressed vs. taus [O(0.1) @ amplitude level for each muon – larger model dependence] except in models addressing only $R_K$
Conclusions

Maybe it's all a castle in the air...
Or maybe it is not...

- 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 not in contradiction among themselves & with existing low- & high-energy data. Taken together, they point out to NP coupled mainly to 3rd generation, with a flavor structure connected to that appearing in the SM Yukawa couplings.

- UV completions with LQ states seem to be favored, but to early to draw definite conclusions [still a lot of work on the model-building side... ]
Or maybe it is not...

- 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 not in contradiction among themselves & with existing low- & high-energy data. Taken together, they point out to NP coupled mainly to 3rd generation, with a flavor structure connected to that appearing in the SM Yukawa couplings.

- UV completions with LQ states seem to be favored, but to early to draw definite conclusions [still a lot of work on the model-building side...]

- These anomalies cannot “remain isolated”... Many additional signals expected both at low- and at high-energy (although many are not easy...)

- Clear model-independent implication of RD → large deviations from SM in ττ final states both at high-energy (pp → ττ) and in rare decays (B → Xττ)

A lot of fun ahead of us...
If you wish to discuss more about flavor anomalies (and more generally about flavor physics BSM), you are all cordially invited to:

**ZPW2018**

Flavours: light, heavy and dark

[Link](https://www.zpw.ethz.ch/2018/)

Zürich, Jan. 15-17 2018