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LEPTON NONUNIVERSALITY ANOMALIES & IMPLICATIONS

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We discuss avenues for diagnosing new physics hinted from lepton nonuniversality in rare $b$-decays, and physics implications.

1 The situation

We are presently seeing $\sim 2.6\sigma$ hints of new physics (NP) in rare semileptonic $b\rightarrow sll$ transitions, indicating lepton nonuniversality (LNU) between electrons and muons in each observable $R_K$ and $R_{K^*}$.\footnote{1,2,3,4} \footnote{For the dilepton mass cuts $q^2_{\text{min}} = 1.1\text{GeV}^2$ for $R_{K^*}$ and 1 GeV$^2$ for $R_K$, and $q^2_{\text{max}} = 6\text{GeV}^2$. In lepton-universal models including the SM holds $R_H = 1$ up to tiny corrections of $O(m^2_\mu/m^2_b)$ despite of the sizable hadronic uncertainties in the individual rates\cite{1}. Electromagnetic corrections $^5,^6$ are found to not exceed percent level\cite{7}. $R_H - 1$ are clean null tests of the standard model (SM). Previous measurements of $R_{K,K^*}$ by Belle and BaBar are consistent with one.} \footnote{In section 2 which operators can be responsible for the deviation (2) from universality $^8,^9$. In section 3 lepton-specific measurements are emphasized as a means to understand whether the present LNU anomalies are due to physics beyond the standard model (BSM) in electrons, in muons, or in both $^{10,11}$, and CP violation is commented on. We discuss side effects from flavor $^{12,13}$ in section 4, which addresses correlations with other sectors, such as charm, or Kaon physics $^{14,15}$, as well as lepton flavor violation (LFV), and decays with $\tau$’s, or $\nu$’s. Collider implications and leptoquark signatures related to the $b$-decay anomalies are discussed in section 5 $^{16,17,18}$. We comment on the status of $R_{D,D^*}$ in section 6.}

$$R_H = \frac{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 d\mathcal{B}(\bar{B}\rightarrow H\mu\mu)}{\int_{q^2_{\text{min}}}^{q^2_{\text{max}}} dq^2 d\mathcal{B}(\bar{B}\rightarrow H\mu\mu)}, \quad H = K, K^*, X_s, ...$$

$$R_{K,LHC} = 0.745^{+0.090}_{-0.07} \pm 0.036, \quad R_{K^*,LHC} = 0.69^{+0.11}_{-0.07} \pm 0.05 \quad (2)$$

for the dilepton mass cuts $q^2_{\text{min}} = 1.1\text{GeV}^2$ for $R_{K^*}$ and 1 GeV$^2$ for $R_K$, and $q^2_{\text{max}} = 6\text{GeV}^2$. In lepton-universal models including the SM holds $R_H = 1$ up to tiny corrections of $O(m^2_\mu/m^2_b)$ despite of the sizable hadronic uncertainties in the individual rates\cite{1}. Electromagnetic corrections $^5,^6$ are found to not exceed percent level\cite{7}. $R_H - 1$ are clean null tests of the standard model (SM). Previous measurements of $R_{K,K^*}$ by Belle and BaBar are consistent with one. We discuss in section 2 which operators can be responsible for the deviation (2) from universality $^8,^9$. In section 3 lepton-specific measurements are emphasized as a means to understand whether the present LNU anomalies are due to physics beyond the standard model (BSM) in electrons, in muons, or in both $^{10,11}$, and CP violation is commented on. We discuss side effects from flavor $^{12,13}$ in section 4, which addresses correlations with other sectors, such as charm, or Kaon physics $^{14,15}$, as well as lepton flavor violation (LFV), and decays with $\tau$’s, or $\nu$’s. Collider implications and leptoquark signatures related to the $b$-decay anomalies are discussed in section 5 $^{16,17,18}$. We comment on the status of $R_{D,D^*}$ in section 6.

2 Model-independent analysis

One employs an effective low energy theory $\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_i C_i(\mu) O_i(\mu)$ at dimension six

$$V,A \text{ operators } \mathcal{O}_9 = [\bar{s}\gamma_{\mu} P_L b] [\bar{\ell}\gamma^\mu \ell], \quad \mathcal{O}_9' = [\bar{s}\gamma_{\mu} P_R b] [\bar{\ell}\gamma^\mu \ell], \quad (3)$$

$$\mathcal{O}_{10} = [\bar{s}\gamma_{\mu} P_L b] [\bar{\ell}\gamma^\mu \gamma_5 \ell], \quad \mathcal{O}_{10}' = [\bar{s}\gamma_{\mu} P_R b] [\bar{\ell}\gamma^\mu \gamma_5 \ell], \quad (4)$$

$$S,P \text{ operators } \mathcal{O}_S = [s P_L b] [\bar{\ell}\ell], \quad \mathcal{O}_S' = [s P_L b] [\bar{\ell}\ell], \quad (5)$$
\[ \mathcal{O}_F = [s \bar{P}_R b] [\bar{\ell} \gamma_5 \ell], \quad \mathcal{O}_F' = [s \bar{P}_L b] [\bar{\ell} \gamma_5 \ell], \quad \mathcal{O}_T = [s \bar{\sigma}_{\mu \nu} b] [\bar{\sigma}^{\mu \nu} \ell], \quad \mathcal{O}_{T5} = [s \bar{\sigma}_{\mu \nu} b] [\bar{\sigma}^{\mu \nu} \gamma_5 \ell]. \] (6)

This set of semileptonic operators is complete. To discuss LNU one needs to add lepton specific indices \( C_i O_i \rightarrow C'_i O'_i, \ell = e, \mu, \tau \). In the SM, only \( O_9, O_{10} \) receive non-negligible and universal contributions, \( C_9^0 \simeq -C_{10}^0 \simeq 4.1 \), all other operators are BSM-induced.

To interpret LNU data (2) it is useful to employ the approximation where BSM physics enters the branching ratios linearly, schematically, with amplitude \( A = A^{SM} + A^{NP} \),

\[ B = |A|^2 = |A^{SM}|^2 + 2 \text{Re}(A^{SM} A^{NP^*}) + |A^{NP}|^2, \] (8)

that is, assuming \( |C^{NP}| \ll |C^{SM}| \). The complementarity between \( R_K \) and \( R_{K^*} \) becomes manifest. In fact, it suffices to measure two different (by spin parity of the final hadron) \( R_H \) ratios. Then, all others serve as consistency checks, because the Wilson coefficients \( C \) and \( C' \) enter decay amplitudes in specific combinations dictated by parity and Lorentz invariance

\[ C + C' : \quad K, K^*_\perp, \ldots \]
\[ C - C' : \quad K_0(1430), K_0, \ldots \] (9)

In addition, the \( K^*_\perp \) amplitude is subleading at both high and low \( q^2 \) windows. Here, \( C \) and \( C' \) refer to V-A and V+A quark currents, respectively, and \( 0, \|, \perp \) refers to longitudinal and transverse parallel and perpendicular transversity, respectively. It follows that

\[ R_K \simeq R_\eta \simeq R_{K(1270,1400)}, \quad R_{K^*} \simeq R_\Phi \simeq R_{K_0(1430)}, \] (10)

and all \( R_H \) are equal if all \( C' \) vanish.

Which operators are responsible for the deviation (2) from universality in \( R_K, R_{K^*} \)?

\[ \text{Re}[C_{10}^{NP\mu} - C_{10}^{NP\mu} - (\mu \rightarrow e)] \sim -1.1 \pm 0.3, \quad \text{Re}[C_{10}^{\mu\mu} - C_{10}^{\mu\mu} - (\mu \rightarrow e)] \sim 0.1 \pm 0.4. \] (11)

The constraint from the \( B_s \rightarrow \mu \mu \) branching ratio \( 0 \lesssim \text{Re}[C_{10}^{NP\mu} - C_{10}^{\mu\mu}] \lesssim 0.9 \) can be simultaneously satisfied. The measurement of \( R_K \) and \( R_{K^*} \) identifies the V-A-type operators as the dominant source behind the anomalies. Within leptoquark explanations, this singles out three kinds that can account for (2) at tree level: the scalar triplet leptoquark \( S_3 \), the vector triplet \( V_3 \) and the vector singlet \( V_1 \), whereas the scalar doublet \( S_2 \) is disfavored as it induces V+A Wilson coefficients. Furthermore, LHCb data allows one to predict \( R_{X_s} \simeq 0.73 \pm 0.07 \), the LNU ratio for inclusive \( B \rightarrow X_s \ell \ell \) decays, which can be probed at Belle II.

3 Which BSM in electrons, in muons, or in both?

The observation of \( R_H < 1 \) suggests too few muons, or too many electrons, or a combination thereof. To disentangle this lepton specific measurements are required. Presently much more data is available on \( b \)-decays to muons than on decays to electrons. Global \( b \rightarrow s \) fits to Wilson coefficients from \( B \rightarrow (K, K^*) \mu \mu, B_s \rightarrow \mu \mu \) precision studies are presently hinting at NP, too, and can point into the same direction as \( R_{K, K^*} \). Therefore, BSM effects in electrons are presently not necessary to account for the data. Analogous studies in \( B \rightarrow H ee \) are, however, are required for consolidation of this possibility. Early data are already available from Belle.

Two main types of explicit BSM models can naturally address LNU at the required level of \( \sim 15\% \) on the SM amplitude: \( U(1) \) extensions with gauged lepton flavor (\( Z' \)-models) and leptoquarks, that can be charged under a flavor symmetry and couple non-universally. Inspection of (8) shows that close to maximal BSM-CP violation switches off SM-NP interference. Together with \( R_H < 1 \) this requires large NP couplings to electrons as muons would enhance \( R_H \). Such large CP phases in the \( b \rightarrow see \) transition can be searched for with the angular distribution in \( B \rightarrow K^{*}ee, \ e.g. \ J_{7,8,9}^{0} \). An explanation of \( R_K \) is also possible at 2\( \sigma \) with (pseudo)-scalar operators, a scenario that can be cross checked with the \( B \rightarrow K ee \) angular distribution.
4 Side effects from flavor

From a flavor perspective, LNU generically implies LFV\textsuperscript{12}. This is obvious for leptoquarks (LQs), which couple with matrix structure $\lambda_{q\ell}$ to quarks $q$ and leptons $\ell$ of three generations each

$$
\lambda_{q\ell} = \begin{pmatrix}
\lambda_{q_1e} & \lambda_{q_1\mu} & \lambda_{q_1\tau} \\
\lambda_{q_2e} & \lambda_{q_2\mu} & \lambda_{q_2\tau} \\
\lambda_{q_3e} & \lambda_{q_3\mu} & \lambda_{q_3\tau}
\end{pmatrix},
$$

(12)

and rows=quarks, columns=leptons. Mixing of quark and lepton flavor in one coupling is very different from the SM-Yukawas. The upper left sub-matrix in red indicates the couplings relevant for Kaon and charm physics. Explaining $R_{K,L^*}$ requires\textsuperscript{19}

$$
\frac{\lambda_{b\mu}^*\lambda_{e\mu}^* - \lambda_{b\ell}^*\lambda_{e\ell}^*}{M^2} \simeq \frac{1.1}{(35 \text{ TeV})^2},
$$

(13)

where $M$ denotes the LQ mass. In matrix form, where entries with an 's' do not matter,

$$
\begin{pmatrix}
\lambda_{q_2e} & \lambda_{q_2\mu} & \lambda_{q_2\tau} \\
\lambda_{q_3e} & \lambda_{q_3\mu} & \lambda_{q_3\tau}
\end{pmatrix} + \text{Occam’s razor} (b \to s \text{ fit}):
\begin{pmatrix}
\lambda_{q_2e} & \lambda_{q_2\mu} & \lambda_{q_2\tau} \\
\lambda_{q_3e} & \lambda_{q_3\mu} & \lambda_{q_3\tau}
\end{pmatrix}.
$$

(14)

The latter pattern assumes muon couplings only which is consistent with the global $b \to s$ fit. Viable patterns from flavor models simultaneously explain quark and lepton masses, and CKM and PMNS mixing\textsuperscript{13,22}. For instance, models based on $U(1)_{FN} \times A_4$, with $\epsilon, \delta, c_\ell, c_\nu \lesssim 0.2$, give

\begin{pmatrix}
\rho_d \kappa_e & \rho_d \kappa_\tau & \rho_d \kappa_\tau \\
\rho_e \kappa_e & \rho_e \kappa_\tau & \rho_e \kappa_\tau \\
\kappa_e & 1 & \kappa_\tau
\end{pmatrix},

\begin{pmatrix}
0 & c_\ell \epsilon & 0 \\
0 & c_\ell \epsilon & 0 \\
0 & c_\ell & 0
\end{pmatrix},

\begin{pmatrix}
c_\nu \kappa e^2 & c_\ell \epsilon e^2 + c_\nu \kappa e^2 & c_\nu \kappa e^2 \\
c_\nu \kappa e^2 & c_\ell \epsilon e^2 + c_\nu \kappa e^2 & c_\nu \kappa e^2 \\
c_\ell \delta + c_\nu \kappa e^2 & c_\ell \delta + c_\nu \kappa e^2 & c_\ell \delta + c_\nu \kappa e^2
\end{pmatrix}.

(15)

LFV and off-diagonal couplings appear generically, as well as electron couplings, or taus. Phenomenological constraints apply\textsuperscript{13,22}. LQs which are $SU(2)_L$ triplets couple doublets to doublets, implying BSM effects in $b \to s\nu\nu$\textsuperscript{8} and $b \to c\ell\nu$, see section 6. Predictions for charm decays are given in Table 1\textsuperscript{23}. They depend on the flavor pattern. Here, i) hierarchy, ii) muons only iii) skewed, 1) no kaon bounds 2) kaon bounds apply for $SU(2)_L$-doublet quarks $q_2 = (c, s)$.

| pattern | $B(D^+ \to \pi^+ \mu\mu)$ | $B(D^0 \to \mu\mu)$ | $B(D^+ \to \pi^+ e\mu)$ | $B(D^0 \to e\mu)$ | $B(D^+ \to \pi^+ \nu\bar{\nu})$ |
|---------|--------------------------|----------------------|--------------------------|--------------------|-----------------------------|
| i)      | SM-like                  | SM-like              | $\lesssim 2 \cdot 10^{-13}$ | $\lesssim 7 \cdot 10^{-15}$ | $\lesssim 3 \cdot 10^{-14}$ |
| ii.1)   | $\lesssim 7 \cdot 10^{-8}$ ($2 \cdot 10^{-8}$) | $\lesssim 3 \cdot 10^{-9}$ | 0                      | 0                  | $\lesssim 8 \cdot 10^{-8}$ |
| ii.2)   | SM-like                  | $\lesssim 4 \cdot 10^{-13}$ | 0                      | 0                  | $\lesssim 4 \cdot 10^{-12}$ |
| iii.1)  | SM-like                  | SM-like              | $\lesssim 2 \cdot 10^{-6}$ | $\lesssim 4 \cdot 10^{-8}$ | $\lesssim 2 \cdot 10^{-6}$ |
| iii.2)  | SM-like                  | SM-like              | $\lesssim 8 \cdot 10^{-15}$ | $\lesssim 2 \cdot 10^{-16}$ | $\lesssim 9 \cdot 10^{-15}$ |

5 Collider implications – leptoquarks!

Producing LQs at the LHC happens through pair production with cross section $\sigma(p p \to \phi^+ \phi^-) \propto \alpha_s^2$, recently, e.g.\textsuperscript{24,25,26}. Single LQ production in association with a lepton $\sigma(p p \to \phi \ell)$ $\propto |\lambda_{q\ell}|^2 \alpha_s$ depends on flavor, and is lesser phase space limited than pair production. Links with $b$-anomalies and flavor are manifest via (13)-(15). While $b$-studies are in principle able to determine the columns, the lepton flavor structure of $\lambda_{q\ell}$, theory input is presently required to go on and break
Figure 1 – Red bands: $R_{K,K^*}$ with flavor (16). Plot to the left shows $\lambda_{bl}$ vs $M$. Green vertical band gives flavor model prediction $\lambda_{bl} \sim c_t$ which points to $M \lesssim 7–8$ TeV. Other plots: Single LQ production cross section for $\sqrt{s} = 13$ TeV and 33 TeV. Magenta, yellow, blue line corresponds to $\lambda_{du} = 1, \lambda_{mu} = 1, \lambda_{ub} = 1$, respectively. Black dashed line: no-loss reach with 3 ab$^{-1}$. Green curve: pair production (LO Madgraph). Figures from 26.

the ambiguity in the product $\lambda_{bl}\lambda_{sl}^*$. Quark hierarchies $m_b \gg m_s \gg m_d$, when addressed with a flavor symmetry, imply hierarchies for LQs $\lambda_{sl} \sim (m_s/m_b)\lambda_{bl}$. It follows that third generation quark couplings dominate. Together with (13) one obtains the range from $R_{K,K^*}$ data for $\lambda_{bl}$, $M/11.6$ TeV $\lesssim \lambda_{bl} \lesssim M/3.9$ TeV. (16)

In figure 1 the single and pair production cross section for the scalar triplet $S_3$ is shown for $\sqrt{s} = 13$ TeV and 33 TeV. One finds that beauty production wins – $bg$-fusion over $dg$- and $sg$-fusion– also at hadronic level despite its PDF suppression if $\lambda_{ql} \ell$ follow quark mass hierarchies. Inverted hierarchies $\lambda_{sl} > \lambda_{bl}$ would be surprising from a symmetry-based flavor perspective and suggest means beyond. Looking for $pp \to \ell\ell(q)q$ is therefore very important, yet the vanilla theory channel is $b\ell\ell(q)$, or in pair production, $b\ell\ell(q)$, $\ell,\ell' = e,\mu$, also LFV $\ell \neq \ell'$, and $t\ell\nu_{\ell(q)}$.

6 LNU in charged currents

We briefly comment on the status of LNU in $b \to c\ell\nu$ decays. Input is compiled in table 222.

$$R_{D(\ast)} = \frac{B(B \to D(\ast)\tau\nu_\tau)}{B(B \to D(\ast)\ell\nu_\ell)}, \quad \hat{R}_{D(\ast)} = \frac{R_{D(\ast)}}{R_{D(\ast)}^{SM}},$$

(17)

where in the denominator of $R_{D(\ast)}$ $\ell = \mu$ at LHCb and $\ell = e,\mu$ at Belle and BaBar.

$$\hat{R}_D^{exp} = 1.35 \pm 0.17, \quad \hat{R}_{D^+}^{exp} = 1.23 \pm 0.07; \quad (18)$$

$$\hat{R}_D = (1.35 \pm 0.17)/(1 + x), \quad \hat{R}_{D^+} = 1.18 \pm 0.07; \quad (NEW)$$

(19)

and $x = 3.6\% (D^0)$ and $x = 5.5\% (D^+)$ from QED corrections35, hence $\hat{R}_D^{exp} = 1.30 \pm 0.16$ and $1.28 \pm 0.16$, respectively $^a$. See, e.g.,37 38 for other recent SM predictions of $R_{D^+}$.

In some scenarios, such as LQs $S_3, V_3$ and $V_1$ BSM effects in $R_{K,K^*}$ imply BSM effects in $R_{D,D^+}$, however, due to the large SM contribution in the tree level decays, at a reduced level. Flavor models predict effects up to few percent and around 10 percent in $R_{D^+}$ and $R_D$. 22, respectively, below the present 1 $\sigma$ ranges, (18)-(19).

7 Summary

Current data on $R_K, R_{K^*}, R_D, R_{D^+}$ in semileptonic $B$-meson decays hint at violation of lepton-universality, and therefore the breakdown of the SM. The April 2017 release of $R_{K^*}$ by LHCb has

$^a$There are two caveats on the QED effects: The dependence on experimental cuts and that the radiative corrections are not for electrons.
Table 2: Experimental results and SM predictions for $R_D^{(*)}$, 'NEW' labels updates since 2016. See text. *Error weighted average; we added statistical and systematical uncertainties in quadrature.

|         | $R_D$                | $R_D^{(*)}$          |
|---------|----------------------|----------------------|
| BaBar   | 0.440 ± 0.058 ± 0.042| 0.332 ± 0.024 ± 0.018|
| Belle   | 0.375 ± 0.064 ± 0.026| 0.293 ± 0.038 ± 0.015|
| Belle   | 0.302 ± 0.030 ± 0.011| 0.270 ± 0.035 ± 0.028 ± 0.025|
| LHCb    | 0.336 ± 0.027 ± 0.030| 0.286 ± 0.019 ± 0.025 ± 0.021|
| LHCb NEW| 0.406 ± 0.050        | 0.307 ± 0.015         |
| average NEW | 0.300 ± 0.008 ± 0.033| 0.252 ± 0.003 ± 0.032 |
| SM      | 0.300 ± 0.008(1 + %) | 0.260 ± 0.008         |

strengthened the previous hints and allowed to pin down the Dirac structure of the underlying physics to be predominantly of V-A-type. Future data – LNU updates and other observables $R_D, R_{Xs}...$ from LHCb and in the nearer future from Belle II are eagerly awaited.

What makes these LNU-anomalies – iff true – so important? They are theoretically clean and intimately linked to flavor: they can give new insights towards the origin of flavor and structure by probing models of flavor. Correspondingly, one should look for imprints in other sectors: $D, K$ physics, LFV, including $\mu - e$ conversion and lepton decays.

In addition, new BSM model building has been triggered that deserves attention in direct searches at ATLAS and CMS and future colliders. Leptoquarks are flavorful and can be in reach of the LHC, where they can provide complementary information to rare decays, on the couplings $\lambda_{ef}, \lambda_{eb}$ and masses $M$ separately vs their product (13). Model-independent upper limits on $M$ are at the few $O(10)$ TeV level, 40, 45 and 20 TeV for $S_d, V_1$ and $V_3$, respectively (19). The bulk of the parameter space lies outside of the LHC (25, 26).

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