Diagnosing New Physics with LUV and LFV B Decays

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CIPANP
In recent times there have been some anomalies in $B$ decays that indicate lepton non-universal new physics.

These are in semileptonic $b \to c\tau\bar{\nu}_\tau$ transitions: $R_{D(*)}$ puzzle.

These are in semileptonic $b \to s\ell^+\ell^-(l = \mu, e)$ transitions: $R_K$, $R_{K(*)}$ puzzles. BR of $b \to s\mu^+\mu^-$ modes are lower and also deviation in $P_5'$ angular observable.

These all indicate LUV New Physics.
If NP is present how to probe this NP in distributions and related decays.

LUV can often lead to lepton flavor violation.

Will consider simultaneous explanation of $R_{D(\ast)}$ and $R_K$ puzzles (1412.7164, 1609.09078) and LFV tests.
$R_{D(*)}$ puzzle

$$A_{SM} = \frac{G_F}{\sqrt{2}} V_{cb} \left[ \langle D^{(*)}(p') | \bar{c} \gamma^\mu (1 - \gamma_5) b | \bar{B}(p) \rangle \right] \bar{\tau} \gamma_\mu (1 - \gamma_5) \nu_\tau$$

$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^+ \ell^- \bar{\nu}_\ell)} \quad R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+} \ell^- \bar{\nu}_\ell)}.$$
$R_D$, $R_{D^*}$, HFAG

BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average

$\Delta \chi^2 = 1.0$ contours

- $R(D)=0.300(8)$ HPQCD (2015)
- $R(D)=0.299(11)$ FNAL/MILC (2015)
- $R(D^*)=0.252(3)$ S. Fajfer et al. (2012)

HFLAV FPCP 2017

$P(\chi^2) = 71.6\%$
Experiments: $R_{D(*)}$ puzzle

The average of $R(D)$ and $R(D^*)$ measurements evaluated by the Heavy-Flavor Averaging Group are

$$R(D)_{\exp} = 0.407 \pm 0.039 \pm 0.024, \quad (1)$$
$$R(D^*)_{\exp} = 0.304 \pm 0.013 \pm 0.007. \quad (2)$$

The combined analysis of $R(D)$ and $R(D^*)$, taking into account measurement correlations, finds that the deviation is at the level of $4.1\sigma$ from the SM prediction.

$$R(D)_{SM} = 0.298 \pm 0.003, \quad (3)$$
$$R(D^*)_{SM} = 0.255 \pm 0.004.$$  

There are lattice QCD predictions for the ratio $R(D)_{SM}$ in the Standard Model that are in good agreement with one another,

$$R(D)_{SM} = 0.299 \pm 0.011 \quad [\text{FNAL/MILC}],$$
$$R(D)_{SM} = 0.300 \pm 0.008 \quad [\text{HPQCD}].$$
Model independent NP analysis (See for example: Datta, Duraisamy, Ghosh)

At the $m_b$ scale: $SU(3)_c \times U(1)_{em}$.

- Effective Hamiltonian for $b \rightarrow c l^- \bar{\nu}_l$ with Non-SM couplings. The NP has to be LUV.

$$\mathcal{H}_{eff} = \frac{4G_F V_{cb}}{\sqrt{2}} \left[ (1 + V_L) \left[ \bar{c} \gamma_\mu P_L b \right] \left[ \bar{l} \gamma^\mu P_L \nu_l \right] + V_R \left[ \bar{c} \gamma_\mu P_R b \right] \left[ \bar{l} \gamma^\mu P_L \nu_l \right] + S_L \left[ \bar{c} P_L b \right] \left[ \bar{l} P_L \nu_l \right] + S_R \left[ \bar{c} P_R b \right] \left[ \bar{l} P_L \nu_l \right] + T_L \left[ \bar{c} \sigma^{\mu\nu} P_L b \right] \left[ \bar{l} \sigma_{\mu\nu} P_L \nu_l \right] \right]$$

The NP can be probed via distributions and other related decays.
$B \rightarrow D^{(*)}\tau\nu_\tau$ in SM

The helicity amplitudes and consequently the NP couplings can be extracted from an angular distribution and compared with models.

Distributions have been measured very well by Belle for $B \rightarrow D^{(*)}\ell\nu_\ell$. We can then extract the Form Factors assuming no NP in these modes. If we observe $\tau$ decay then we can measure $\tau$ polarization and CPV.
Decay Distribution described by Helicity Amplitudes

\[ H_0 = \frac{4GF V_{cb}}{\sqrt{2}} \frac{1}{2m_{D^*} \sqrt{q^2}} \left[ (m_B^2 - m_{D^*}^2 - q^2)(m_B + m_{D^*})A_1(q^2) \right. \\
\left. - \frac{4m_B^2 |p_{D^*}|^2}{m_B + m_{D^*}} A_2(q^2) \right](1 + V_L - V_R), \]

\[ H_{||} = \frac{4GF V_{cb}}{\sqrt{2}} \sqrt{2}(m_B + m_{D^*})A_1(q^2)(1 + V_L - V_R), \]

\[ H_{\perp} = -\frac{4GF V_{cb}}{\sqrt{2}} \sqrt{2} \frac{2m_B V(q^2)}{(m_B + m_{D^*})} |p_{D^*}|(1 + V_L + V_R), \]

\[ H_t = \frac{4GF V_{cb}}{\sqrt{2}} \frac{2m_B |p_{D^*}| A_0(q^2)}{\sqrt{q^2}} (1 + V_L - V_R), \]

\[ H_P = -\frac{4GF V_{cb}}{\sqrt{2}} \frac{2m_B |p_{D^*}| A_0(q^2)}{(m_b(\mu) + m_c(\mu))} (S_R - S_L). \]
Distributions

- $F_L$ ($D^*$) polarization. Distribution in $\theta^*$. 

- $A_{FB}$ for both $D$ and $D^*$. Distribution in $\theta_I$. 

- If we make the $\tau$ decay then we can measure the longitudinal tau polarization $P_{\tau}(D^{(*)})$. 

- Finally we can look at CP violating terms in the angular distribution.
CPV Triple products

There are triple products that appear in the angular distributions proportional to $\sin \chi$ (Datta and Duraisamy.)

The triple product in the $B$ rest frame: $\sim (\vec{n}_D \times \vec{n}_l).\vec{p}_D^* \sim \sin \chi$ with $\vec{n}_D \sim \vec{p}_D \times \vec{p}_\pi$ and $\vec{n}_l \sim \vec{p}_l \times \vec{p}_\nu$.

These T.P. are proportional to $\mathcal{I}(H_iH^*_\perp)$. There are CPV. In the SM these terms are absent because all SM amplitudes have the same weak phase - $V_{cb}$.

Since the $p_\tau$ momentum is not known we make the $\tau$ decay: $\tau \rightarrow V\nu_\tau$ and use the $V$ momentum to construct the T.P. (Hagiwara, Nojiri, Sakaki).
Other Decays

NP can be constrained from other decays have the same quark transition as $R_D(\ast)$

- $B_c \to \tau^- \bar{\nu}_\tau$ (Alonso, Grinstein, Camalich). $\Gamma[B_c] > \Gamma[B_c \to \tau^- \bar{\nu}_\tau]$. $g_P$ coupling is very constrained.
- $B_c \to J/\psi \tau^- \bar{\nu}_\tau$ LHCb measurement finds about a $2\sigma$ deviation from the SM.
- $b \to \tau \nu X$(LEP) (Saeed Kamali, AD).

- Measurements in $\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau$ can further constrain the NP parameter space. (Datta:2017aue, Shivashankara:2015cta).
- $\Lambda_b \to \Lambda_c$ form factors are calculated from lattice QCD (Datta:2017aue, Detmold:2015aaa)
\[ R_{\Lambda_c}^{\text{Ratio}} = 1.3 \pm 3 \times 0.05 \]
Interesting Facts

\[
R(D)^{\text{Ratio}} = \frac{R(D)_{\text{exp}}}{R(D)_{\text{SM}}} = 1.36 \pm 0.15(1.30 \pm 0.17),
\]
\[
R(D^*)^{\text{Ratio}} = \frac{R(D^*)_{\text{exp}}}{R(D^*)_{\text{SM}}} = 1.19 \pm 0.06(1.25 \pm 0.08). \quad (7)
\]

If NP is just V − A then
\[
R_D^{\text{ratio}} \equiv \frac{R_D^{\text{expt}}}{R_D^{\text{SM}}} = |1 + V_L|^2 = R_D^{\text{ratio}} \equiv \frac{R_D^{\text{expt}}}{R_D^{\text{SM}}}.
\]

If NP couples to RH particles only
\[
R_D^{\text{ratio}} \equiv \frac{R_D^{\text{expt}}}{R_D^{\text{SM}}} = (1 + |V_L|^2) = R_D^{\text{ratio}} \equiv \frac{R_D^{\text{expt}}}{R_D^{\text{SM}}}.
\]

\[ W' \text{ models from } SU(2)_L \times SU(2)_V \times U(1)_X \rightarrow SU(2)_L \times U(1)_Y \]
\[ (1804.04135, 1804.04642) \]
$b \to s \mu^+ \mu^-$ Anomaly

\[
H_{\text{eff}}(b \to s \ell \bar{\ell}) = -\frac{\alpha G_F}{\sqrt{2\pi}} V_{tb} V_{ts}^* \left[ C_9 \left( \bar{s} L \gamma^\mu b_L \right) \left( \bar{\ell} \gamma_\mu \ell \right) + C_{10} \left( \bar{s} L \gamma^\mu b_L \right) \left( \bar{\ell} \gamma_\mu \gamma^5 \ell \right) \right],
\]

\[
H_{\text{eff}}(b \to s \nu \bar{\nu}) = -\frac{\alpha G_F}{\sqrt{2\pi}} V_{tb} V_{ts}^* C_L \left( \bar{s} L \gamma^\mu b_L \right) \left( \bar{\nu} \gamma_\mu (1 - \gamma^5) \nu \right),
\]

\[
H_{\text{eff}}(b \to s \gamma^*) = C_7 \frac{e}{16\pi^2} \left[ \bar{s} \sigma_{\mu\nu} \left( m_s P_L + m_b P_R \right) b \right] F^{\mu\nu}.
\]
$R_K$ puzzle, Ratios of $b \rightarrow s\mu^+\mu^-$ and $b \rightarrow se^+e^-$. Part II(Clean), 1708.02515

$$R_K \equiv \mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)/\mathcal{B}(B^+ \rightarrow K^+e^+e^-)$$

$$R_{K}^{\text{expt}} = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)}$$

$$1 \leq q^2 \leq 6.0 \text{ GeV}^2$$

Figure: Comparison of the measurements of $R_K$ from LHCb (black dots), BaBar (red squares) and Belle (blue triangles) with the SM expectation (purple line).
Figure: Comparison of the measurements of $R_{K^*}$ from LHCb with (left) SM predictions and (right) BaBar and Belle.

\[
\begin{align*}
R_{K^*}^{\text{expt}} &= \begin{cases} 
0.660^{+0.110}_{-0.070} \text{ (stat)} \pm 0.024 \text{ (syst)} & 0.045 \leq q^2 \leq 1.1 \text{ GeV}^2, \\
0.685^{+0.113}_{-0.069} \text{ (stat)} \pm 0.047 \text{ (syst)} & 1.1 \leq q^2 \leq 6.0 \text{ GeV}^2.
\end{cases}
\end{align*}
\]

$R_K$ and $R_{K^*}$ in the SM very close to 1 in the central bin and $R_{K^*} \sim 0.92$ in the low bin.
\( R_{K(\ast)} \) puzzle: Other Experiment

- Measurements from Belle finds difference in same \( q^2 \) bin as LHCb

\[
Q_5 = P'_5(\mu\mu) - P'_5(ee)
\]

(1612.05014). Large errors.

- Low \( q^2 \) dominated by photon pole which is not LUV. Hence measurement difficult to understand with heavy NP.
Deviations in $b \to s\mu^+\mu^-$ Part I- Hadronic Uncertainty

- Anomalies appear in $B \to K^{(*)}\mu^+\mu^-$ (LHCb, Belle, Atlas, CMS): Deviations in branching ratios and in the angular observable like $P'_5$.

- BR are lower than the SM predictions.

- (LHCb) $B^0_s \to \phi\mu^+\mu^-$ which are lower than SM predictions based on lattice QCD and QCD sum rules.

- Note all these are in $b \to s\mu^+\mu^-$ and the SM predictions are not free of hadronic uncertainties.
$P_5'$ in $B \rightarrow K^*(K\pi)\mu^+\mu^-$
\[ P'_5 \text{ in } B_d^0 \rightarrow K^* \mu^+ \mu^- \]

\[
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_k + F_L \cos^2 \theta_k \right. \\
+ \frac{1}{4} (1 - F_L) \sin^2 \theta_k \cos 2\theta_l \\
- F_L \cos^2 \theta_k \cos 2\theta_l + S_3 \sin^2 \theta_k \sin^2 \theta_l \cos 2\phi \\
+ S_4 \sin 2\theta_k \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_k \sin \theta_l \cos \phi \\
+ \frac{4}{3} A_{FB} \sin^2 \theta_k \cos \theta_l + S_7 \sin 2\theta_k \sin \theta_l \sin \phi \\
+ S_8 \sin 2\theta_k \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_k \sin^2 \theta_l \sin 2\phi \right].
\]

(8)
Optimal observables. When $E_K$ is large, small $q^2$, in leading order in SCET these observables are free from form factors. Corrections are $\sim O\left(\frac{1}{E_K}\right)$ and $\alpha_s$.

\begin{align*}
P_1 &= \frac{2 S_3}{(1 - F_L)} = A_T^{(2)} , \\
P_2 &= 2 \frac{A_{FB}}{3 (1 - F_L)} , \\
P_3 &= -S_9 \frac{}{(1 - F_L)} , \\
P'_{4,5,8} &= S_{4,5,8} \sqrt{F_L (1 - F_L)} , \\
P'_6 &= \frac{S_7}{\sqrt{F_L (1 - F_L)}} .
\end{align*}

Just like $B \rightarrow D^{(*)} \tau \nu_{\tau}$ one can look at other observables like $F_L$, $A_{FB}$ and CP violating co-efficients.
Figure: The optimized angular observables in bins of $q^2$, determined from a maximum likelihood fit to the data. The shaded boxes show the SM prediction taken from Ref. [?].

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B Decays

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Recent Fits after $R_K(\ast)$

Fits by many authors (1704.05435, 1704.05438, 1704.05444, 1705.05446, 1704.05447....) to all $b \rightarrow s \ell\ell$ observables: arXiv:1704.07397 : Alok et.al.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>WC</th>
<th>pull</th>
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<tbody>
<tr>
<td>(I) $\Delta C^\mu\mu_9 (NP)$</td>
<td>$-1.25 \pm 0.19$</td>
<td>5.9</td>
</tr>
<tr>
<td>(II) $\Delta C^\mu\mu_9 (NP) = -\Delta C^\mu\mu_{10} (NP)$</td>
<td>$-0.68 \pm 0.12$</td>
<td>5.9</td>
</tr>
<tr>
<td>(III) $\Delta C^\mu\mu_9 (NP) = -\Delta C^\mu\mu_{9} (NP)$</td>
<td>$-1.11 \pm 0.17$</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Here NP effects only the muons.

Remember in the $R_D(\ast)$ puzzle also indicated LH NP interactions. This gives a hint to connect the two anomalies.
Glashow, Guadagnoli and Lane (GGL), 1411.0565 pointed out in general
LUV ⇒ LFV.

\[ \frac{G}{\Lambda_{NP}^2} (b'_L \gamma_\mu b'_L)(\bar{\tau}'_L \gamma_\mu \tau'_L) \]

where \( G = O(1), \frac{G}{\Lambda_{NP}^2} \ll G_F \)

When one transforms to the mass basis, this generates the operator
\( (b_L \gamma_\mu s_L)(\bar{\mu}_L \gamma_\mu \mu_L) \) that contributes to \( \bar{b} \rightarrow \bar{s}\mu^+\mu^- \).

The contribution to \( \bar{b} \rightarrow \bar{s}e^+e^- \) is much smaller, leading to a violation of lepton flavor universality.

GGL’s point was that LFV decays, such as \( B \rightarrow K\mu e, K\mu \tau \) and \( B^0_s \rightarrow \mu e, \mu \tau \), are also generated.
Assuming the scale of NP is much larger than the weak scale, the semileptonic operators should be made invariant under the full \( SU(3)_C \times SU(2)_L \times U(1)_Y \) gauge group. (Bhattacharya, Datta, London, Shivshankara, 1412.7164) considered two possibilities for LH interactions:

\[
O^{NP}_1 = \frac{G_1}{\Lambda_{NP}^2} (\bar{Q}'_L \gamma_{\mu} Q'_L)(\bar{L}'_L \gamma^\mu L'_L),
\]

\[
O^{NP}_2 = \frac{G_2}{\Lambda_{NP}^2} (\bar{Q}'_L \gamma_{\mu} \sigma^I Q'_L)(\bar{L}'_L \gamma^\mu \sigma^I L'_L)
\]

\[
= \frac{G_2}{\Lambda_{NP}^2} \left[ 2(\bar{Q}'_L \gamma_{\mu} Q'_L)(\bar{L}'_L \gamma^\mu L'_L) - (\bar{Q}'_L \gamma_{\mu} Q'_L)(\bar{L}'_L \gamma^\mu L'_L) \right].
\]

Here \( Q' \equiv (t', b')^T \) and \( L' \equiv (\nu'_\tau, \tau')^T \). The key point is that \( O^{NP}_2 \) contains both neutral-current (NC) and charged-current (CC) interactions. The NC and CC pieces can be used to respectively explain the \( R_K \) and \( R_{D(*)} \) puzzles.
UV completion

- UV completions considered by many authors e.g. L. Calibbi, A. Crivellin and T. Ota, 1506.02661 considered possible UV completions that can give rise to $O_{1,2}^{NP}$.

- (i) a vector boson ($VB$) that transforms as $(1,3,0)$ under $SU(3)_C \times SU(2)_L \times U(1)_Y$, as in the SM.

- (ii) an $SU(2)_L$-triplet scalar leptoquark ($S_3$) $[(3,3,-2/3)$.

- (iii) an $SU(2)_L$-singlet vector leptoquark ($U_1$) $[(3,1,4/3)$.

- $SU(2)_L$-triplet vector leptoquark ($U_3$) $[(3,3,4/3)$.

- The vector boson generates only $O_{2}^{NP}$, but the leptoquarks generate particular combinations of $O_{1}^{NP}$ and $O_{2}^{NP}$. 
Models

- Note to simply explain $b \rightarrow s\ell^+\ell^-$ we can have $Z'$ $(1, 1, 0)$ from $U(1)$. One can consider both $(1, 3, 0)$ and $(1, 1, 0)$.

- Models with $U(2)_q \times U_l(2)$ flavor symmetry and breaking: See for example: Dario Buttazzo, Admir Greljo, Gino Isidori David Marzocca (Zurich U.) 1706.07808.

- Many of the general features can be understood in a simple analysis.

- In models other processes get affected and so specific models are more constrained.
Models: Bhattacharya, Datta, Guevin, London, Watanabe, 1609.09078

Models: Vector Bosons and Leptoquarks.

Transform to the mass basis:

\[ u'_L = U u_L, \quad d'_L = D d_L, \quad \ell'_L = L \ell_L, \quad \nu'_L = L \nu_L, \]

The CKM matrix is given by \( V_{CKM} = U^\dagger D \). The assumption is that the transformations \( D \) and \( L \) involve only the second and third generations:

\[ D = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_D & \sin \theta_D \\ 0 & -\sin \theta_D & \cos \theta_D \end{pmatrix} \]

\[ L = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_L & \sin \theta_L \\ 0 & -\sin \theta_L & \cos \theta_L \end{pmatrix} \]
SM-like vector bosons

This model contains vector bosons (VBs) that transform as \((1,3,0)\) under \(SU(3)_C \times SU(2)_L \times U(1)_Y\), as in the SM. The coupling is to only third generation. In the gauge basis, the Lagrangian describing the couplings of the VBs to left-handed third-generation fermions is

\[
\mathcal{L}_V = g_{qV}^{33} \left( \bar{Q}'_{L3} \gamma^\mu \sigma^I Q'_{L3} \right) V^I_\mu + g_{\ell V}^{33} \left( \bar{L}'_{L3} \gamma^\mu \sigma^I L'_{L3} \right) V^I_\mu .
\]

\[
\mathcal{L}^{\text{eff}}_V = - \frac{g_{qV}^{33} g_{\ell V}^{33}}{m^2_V} \left( \bar{Q}'_{L3} \gamma^\mu \sigma^I Q'_{L3} \right) \left( \bar{L}'_{L3} \gamma^\mu \sigma^I L'_{L3} \right) .
\]

\[
g_1 = 0 , \quad g_2 = -g_{qV}^{33} g_{\ell V}^{33} .
\]

The VB model also generates 4 quark and 4 lepton operators that contribute to \(B_s\) mixing, \(\tau \to \mu \mu \mu\) e.t.c. Variation of this model with more parameters.
Models: allowed parameter space:
\[ R_K \sim \sin \theta_D \cos \theta_D \sin^2 \theta_L \]

- **VB model:** \[ g_{qV}^{33} = g_{1V}^{33} = \sqrt{0.5} \]
- **U_1 model:** \[ |h_{U_1}^{33}|^2 = 1 \]
This decay is particularly interesting because only the VB model contributes to it. The present experimental bound is $B(\tau^- \rightarrow \mu^- \mu^+ \mu^-) < 2.1 \times 10^{-8}$ at 90% C.L. Belle II expects to reduce this limit to $< 10^{-10}$. The reach of LHCb is somewhat weaker, $< 10^{-9}$. Now, the amplitude for $\tau \rightarrow 3\mu$ depends only on $\theta_L$. The allowed value of $\theta_L$ corresponds to the present experimental bound. That is, VB predicts

$$B(\tau^- \rightarrow \mu^- \mu^+ \mu^-) \approx 2.1 \times 10^{-8}.$$

Thus, the VB model predicts that $\tau \rightarrow 3\mu$ should be observed at both LHCb and Belle II. This is a smoking-gun signal for the model.
\( \Upsilon \) Modes (Leptoquarks)

- \( \Upsilon(3S) \rightarrow \mu\tau \):

  \[ V_B \quad \mathcal{B}(\Upsilon(3S) \rightarrow \mu\tau) \simeq 3.0 \times 10^{-9}, \]

  \[ U_1 \quad \mathcal{B}(\Upsilon(3S) \rightarrow \mu\tau) |_{\text{max}} = 8.0 \times 10^{-7}. \]

  Belle II should be able to measure \( \mathcal{B}(\Upsilon(3S) \rightarrow \mu\tau) \) down to \( \sim 10^{-7} \).

- Even though we do not find observable effects in \( b \rightarrow s\tau\tau \) or \( b \rightarrow s\tau\mu \) others have found larger effects (See for e.g. 1703.09226).
High-$p_T$ searches are concerned, particularly stringent bounds are set by $pp \rightarrow \tau \bar{\tau} + X$

$$
\Delta \mathcal{L}_{bb\tau\tau} = -\frac{1}{\Lambda_0^2} (\bar{b}_L \gamma_{\mu} b_L) (\bar{\tau}_L \gamma_{\mu} \tau_L), \quad \Lambda_0^2 = \frac{v^2}{G_1 + G_2} .
$$

(10)

The present bounds on the EFT scale $\Lambda_0$ were derived recasting different ATLAS searches for $\tau \bar{\tau}$ resonances, and read $\Lambda_0 > 0.62$ TeV. Newer fits: $\Lambda_0 \approx 1.2$ TeV, which is well within the experimental limit.

Lepton flavor violating decays: $gg \rightarrow \tau \mu$ (1802.06082, 1802.09822) or $gg \rightarrow \bar{t}t\tau\mu$ (1412.7164).

$$
\Delta \mathcal{L}_{tt\tau\mu} = -\frac{1}{\Lambda_0^2} (\bar{t}_L \gamma_{\mu} t_L) (\bar{\tau}_L \gamma_{\mu} \mu_L)
$$

(11)
Collider Search: 1706.07808

$Z'$ ($1, 3, 0$) is strongly constrained (ruled out) unless width is large. $Z'$ ($1, 1, 0$) explaining only $R_K$ is fine: $M_{Z'} \sim 30$ TeV.
Conclusions

- Several anomalies in $B$ decays indicating lepton non-universal interactions.
- These anomalies may arise from the same New Physics.
- Anomalies indicate LUV. In general we should also observe LFV processes.
- Interesting modes are $\tau \rightarrow 3\mu$ and $\Upsilon(3S) \rightarrow \mu\tau$. Observation of these modes can point to specific models of new physics.
- Other analysis find $b \rightarrow s\tau\tau (B_s \rightarrow \tau^+\tau^-, B \rightarrow M\tau^+\tau^-)$ or $b \rightarrow s\tau\mu (B \rightarrow M\tau\mu, B_s \rightarrow \tau\mu)$ also promising.