Lepton flavour non-universality: Couplings between the gauge bosons and the leptons are independent of the lepton generation

LFU is an accidental symmetry of SM that is only broken by the Yukawa term in the SM Lagrangian
=> BR can only differ due to the masses of leptons

Some Beyond-SM theories predict a non-universal coupling between the three quark and lepton families, e.g. Z', leptoquark
Testing the LFU hypothesis is fundamental
=> A violation of LFU would be a clear sign of New Physics (NP)
LFNU - B decays

The focus of this talk

**Tree**

\[ R(D^{(*)}) = \frac{B \rightarrow D^* \tau \nu}{B \rightarrow D^* \mu \nu} \]

\[ R(D^*) = 0.258 \pm 0.005 \]

**Loop**

\[ R(K^{(*)}) = \frac{B \rightarrow K \mu \mu}{B \rightarrow K \text{ee}} \]

\[ R(K) \sim 1 \sigma(10^{-2}) \text{ in SM} \]

R(K)/R(K*)


\[ R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)} \]

JHEP 08 (2017) 055

<table>
<thead>
<tr>
<th>( R_{K^{*0}} )</th>
<th>low-( q^2 )</th>
<th>central-( q^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>95.4% CL</td>
<td>0.66 ± 0.11/0.07 ± 0.03</td>
<td>0.69 ± 0.11/0.07 ± 0.05</td>
</tr>
<tr>
<td>99.7% CL</td>
<td>[0.52, 0.89]</td>
<td>[0.53, 0.94]</td>
</tr>
</tbody>
</table>

See also the talk of Maarten van Veghel on LFV
LFNU - Semi-leptonic B decays

Tension with SM in $R(D)$ vs $R(D^*) \sim 4\sigma \rightarrow$ new physics at tree-level?

S. Benson - LFNU - TAU
S. Benson - LFNU - TAU

LFNU - Semi-leptonic B decays at LHCb

\[ \gamma^B \beta^B \approx \gamma^{vis} \beta^{vis} \]

\[ B^0 \rightarrow D^{*+} \rightarrow D^0 \rightarrow \tau^- \rightarrow \mu^+ \]

\[ m_{vis}, p_T \]

\[ m^2_{miss} \]

\[ q^2 \]

hadronic channel

\[ z \]

\[ \bar{B}^0 \rightarrow D^{*+} \rightarrow D^0 \rightarrow \tau^- \rightarrow \nu \]

\[ K^- \]

\[ \pi^+ \]

\[ \pi^- \]

\[ \pi^0 \]

\[ \nu \]

\[ \bar{\nu} \]

\[ \mu \]

\[ \tau \]

\[ s \]

\[ t \]

\[ u \]
Muonic R(D*) method

3D fit using templates
- \( \mu \) mis-ID and combinatorial taken from data
- simulation used for other contributions

Largest backgrounds:
- \( B \to D^{**}\mu\nu \)
- \( B \to D^{**}X_cX_c \to X\mu\nu \)
  - Reduced with charged isolation variable

\[ (p_B)_z = \frac{m_B}{m_{\text{reco}}} (p_{\text{reco}})_z \]

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Muonic R(D*) results

Run 1, 3 fb⁻¹:

\[ R(D^*) = 0.336 \pm 0.027\text{(stat)} \pm 0.030\text{(syst)} \]

2.1 \(\sigma\) deviation from SM prediction
The results of the fit to the signal sample are shown in Fig. 1. Values of the $B^0 \to D^*\pi \mu \nu$ form factor parameters determined by the fit agree with the current world average values. The fit finds $363000 \pm 1600$ $B^0 \to D^*\pi \mu \nu$ decays in the signal sample and an uncorrected ratio of yields $N(B^0 \to D^*\pi \mu \nu)/N(B^0 \to D^*\pi \tau \mu \nu) = (4.54 \pm 0.46) \times 10^{-2}$. Accounting for the $\tau \to \mu \nu$ branching fraction [25] and the ratio of efficiencies results in $R(D^*) = 0.336 \pm 0.034$, where the uncertainty includes the statistical uncertainty, the uncertainty due to form factors, and the statistical uncertainty in the kinematic distributions used in the fit. As the signal yield is large, this uncertainty is dominated by the determination of various background yields in the fit and their correlations, which are as large as $0.68$ in the case of $B \to D^*\pi \mu \nu$. Form factor parameters are included in the likelihood as nuisance parameters, and represent a source of systematic uncertainty. The total uncertainty on $R(D^*)$ is summarized in Table 1. The uncertainty in extracting $R(D^*)$ from the fit (model uncertainty) is dominated by the statistical uncertainty of the simulated samples; this contribution is estimated via the reduction in the fit uncertainty when the sample statistical uncertainty is not considered in the likelihood.

**Table 1: Systematic uncertainties in the extraction of $R(D^*)$.**

<table>
<thead>
<tr>
<th>Model uncertainties</th>
<th>Absolute size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>2.0</td>
</tr>
<tr>
<td>Misidentified $\mu$ template shape</td>
<td>1.6</td>
</tr>
<tr>
<td>$B^0 \to D^{**}(\tau^-/\mu^-)\bar{\nu}$ form factors</td>
<td>0.6</td>
</tr>
<tr>
<td>$B \to D^{**}H_c(\to \mu \nu X')X$ shape corrections</td>
<td>0.5</td>
</tr>
<tr>
<td>$\mathcal{B}(B \to D^{<strong>}\tau^-\bar{\nu})/\mathcal{B}(B \to D^{</strong>}\mu^-\bar{\nu}_\mu)$</td>
<td>0.5</td>
</tr>
<tr>
<td>$B \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections</td>
<td>0.4</td>
</tr>
<tr>
<td>Corrections to simulation</td>
<td>0.4</td>
</tr>
<tr>
<td>Combinatorial background shape</td>
<td>0.3</td>
</tr>
<tr>
<td>$B \to D^{**}(\to D^*\pi\pi)\mu^-\bar{\nu}_\mu$ form factors</td>
<td>0.3</td>
</tr>
<tr>
<td>$B \to D^{**}(D_s \to \tau\nu)X$ fraction</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total model uncertainty</strong></td>
<td><strong>2.8</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normalization uncertainties</th>
<th>Absolute size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>0.6</td>
</tr>
<tr>
<td>Hardware trigger efficiency</td>
<td>0.6</td>
</tr>
<tr>
<td>Particle identification efficiencies</td>
<td>0.3</td>
</tr>
<tr>
<td>Form-factors</td>
<td>0.2</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}<em>\mu\nu</em>\tau)$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td><strong>Total normalization uncertainty</strong></td>
<td><strong>0.9</strong></td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td><strong>3.0</strong></td>
</tr>
</tbody>
</table>
Major backgrounds:
$B \rightarrow D^*\pi\pi\pi X$.
- removed with a flight distance requirement on the $\tau$
$B \rightarrow D^*X_c(\rightarrow\pi\pi\pi X)$
- distinguished with multivariate discriminator

---

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Hadronic R(D*) results

Run 1, 3 fb$^{-1}$. Fit $q^2$, $t_\tau$, BDT classifier:

B-$D^*D_0(X)$ control sample used to determine necessary fit fractions

$N_{\text{sig}} = 1296 \pm 86 \ B^0 \rightarrow D^{-}\tau^+\nu_\tau$ decays

17808 candidates found in the control sample
Hadronic $R(D^*)$ results

B$\to$D$^*3\pi$ & B$\to$D$^*\mu\nu$ BR taken from PDG & HFLAV respectively

$K(D^{*-}) = 1.97 \pm 0.13 \text{ (stat)} \pm 0.18 \text{ (syst)}$

$B(B^0 \to D^{*-}\tau^+\nu_\tau) = (1.42 \pm 0.094 \text{ (stat)} \pm 0.129 \text{ (syst)} \pm 0.054 \text{ (ext)}) \times 10^{-2}$

$R(D^{*-}) = 0.291 \pm 0.019 \text{ (stat)} \pm 0.026 \text{ (syst)} \pm 0.013 \text{ (ext)}$
Contributions above 2%:

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Value in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B \to D^{**+}\tau^+\nu_\tau$</td>
<td>2.3</td>
</tr>
<tr>
<td>$D^+_s \to 3\pi X$ decay model</td>
<td>2.5</td>
</tr>
<tr>
<td>$D^+_s$, $D^0$ and $D^+$ template shape</td>
<td>2.9</td>
</tr>
<tr>
<td>$B \to D^{<em>-}D^+_s(X)$ and $B \to D^{</em>-}D^0(X)$ decay model</td>
<td>2.6</td>
</tr>
<tr>
<td>$D^{*-}3\pi X$ from $B$ decays</td>
<td>2.8</td>
</tr>
<tr>
<td>Size of simulation samples</td>
<td>4.1</td>
</tr>
<tr>
<td>Online selection</td>
<td>2.0</td>
</tr>
<tr>
<td>Offline selection</td>
<td>2.0</td>
</tr>
<tr>
<td>Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Total uncertainty</strong></td>
<td><strong>9.1</strong></td>
</tr>
</tbody>
</table>

Main message (apart from R(D*)) is a hard measurement to make:
While it is systematics limited, the systematics will be improved
On the todo list...

high stats

- \( b \rightarrow u \)
  - Flavour structure probes
  - \( \Lambda b \rightarrow \rho \tau \nu \)
  - \( B \rightarrow \rho \rho \tau \nu \)
  - \( B \rightarrow \rho \tau \nu \)

- \( b \rightarrow c \)
  - \( B_s \rightarrow D \tau \nu \)
  - \( B_c \rightarrow J/\psi \tau \nu \)
  - \( B \rightarrow D^{**} \tau \nu \)

theoretically studied

- \( \Lambda b \rightarrow \Lambda c \tau \nu \)

Lower statistics

Theoretically studied

Baryons:

- \( \Lambda b \rightarrow \Lambda c \tau \nu \)

Decent statistics

Theoretically challenged

\( b \rightarrow u \) transitions:

- Probe flavour structure

Statistically challenged

Theoretically challenged

BEACH 2018
Lepton universality
19 June 2018
R(J/ψ)

\[ R(J/ψ) = \frac{\mathcal{B}(B_+^c \rightarrow J/ψ \tau^+ ν_τ)}{\mathcal{B}(B_+^c \rightarrow J/ψ μ^+ ν_μ)} \quad τ^+ \rightarrow μ^+ \bar{ν}_τ ν_μ \]

SM expectation 0.25 – 0.28 (probes same physics as R(D*))

Only measurement is from LHCb

Difference wrt R(D*): use of the decay time in the fit to determine the signal

Complication wrt R(D*): unknown form factors so estimated from fit to enriched sample of the normalisation mode.
R(J/ψ) - results

3D template fit:

\[ R(J/ψ) = 0.71 \pm 0.17 \pm 0.18 \]

Compatible with SM at 2 \( \sigma \).

First evidence of decay \( B_C^+ \rightarrow J/ψ \tau^+\nu_\tau \)

Largest systematics from \( B_C \rightarrow J/ψ \) form-factor and limited simulation sample size - both can be improved.

Lattice form-factor calculation is on the way

**Phys. Rev. Lett. 120, 121801 (2018)**
Prospects for the future

Upgrade I:  
CERN-LHCC-2012-007

Upgrade II:  
CERN-LHCC-2017-003

Improvement in the plot assumes:
- More simulated events
- theory input
- experimental input

arXiv:1808.08865
Summary

Presented IMO some of the most interesting results in the field.

Tensions are present (all above SM predictions) that need to be resolved or understood.

Systematics are a continual challenge but we haven’t reached the end yet so as always...

Stay Tuned!
Backup
Backup: hadronic $R(D^*)$ control samples

Table 4: Relative fractions of the various components obtained from the fit to the $B \rightarrow D^* D_s^\star$ control sample. The values used in the simulation and the ratio of the two are also shown.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation</th>
<th>Fit</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{c/b}$</td>
<td>—0.014</td>
<td>—0.54</td>
<td>0.594 ± 0.041</td>
</tr>
<tr>
<td>$f_{D_s^0}$</td>
<td>0.08</td>
<td>0.08</td>
<td>0.000 ± 0.040</td>
</tr>
<tr>
<td>$f_{D_s^+}$</td>
<td>0.39</td>
<td>0.365</td>
<td>0.94 ± 0.14</td>
</tr>
<tr>
<td>$f_{D_s^0}$</td>
<td>0.22</td>
<td>0.416</td>
<td>0.89 ± 0.31</td>
</tr>
<tr>
<td>$f_{D_s^0}$</td>
<td>0.23</td>
<td>0.093</td>
<td>0.40 ± 0.12</td>
</tr>
</tbody>
</table>

Figure 14: Results from the fit to data for candidates containing a $D^* D_s^\star$ pair, where $D_s^\star \rightarrow 3\pi$. The fit components are described in the legend. The figures correspond to the fit projection on (a) $m(D^* - 3\pi)$, (b) $q^2$, (c) $3\pi$ decay time $t_\tau$ and (d) BDT output distributions.