TESTS OF LEPTON FLAVOUR UNIVERSALITY IN $b \rightarrow c\ell\nu$ DECAYS AT THE LHCb EXPERIMENT

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On behalf of the LHCb collaboration

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Lepton flavour universality

- Lepton flavour universality is an accidental symmetry of the Standard Model

- Equality of the couplings of gauge bosons to leptons \((g_e = g_\mu = g_\tau)\)

- Discrepancies between decays with the different lepton species in the SM originate only from their different masses (Phase Space)
  - Any deviation could be a clear signature of New Physics effects

- Some discrepancies between SM predictions and measurements have been reported in \(B\) meson decays
  - Neutral current decays \(b \rightarrow s\ell\ell\) (See talk from Jozef)
  - Charged current decays \(b \rightarrow c\ell\nu\) (This talk)
Semileptonic transitions can benefit:
- **Experimentally** from high transition rates
- **Theoretically** from a simple description, through tree level diagrams

Test variables are ratios of branching fractions
- Hadronic uncertainties partially cancel in the ratio
- Theoretical uncertainty well under control, $O(\%)$

Two decays are exploited at the LHCb experiment for lepton universality tests in charged current decays

The $B$ momentum is not constrained in $pp$ collisions
- The momentum of the $B$ meson is reconstructed using approximated methods in semileptonic decays that exploit information from its flight direction

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$</td>
<td>$17.39 \pm 0.04$</td>
</tr>
<tr>
<td>$\tau^- \to \pi^+ \pi^- \pi^- \nu_\tau$</td>
<td>$9.00 \pm 0.06$</td>
</tr>
</tbody>
</table>
The experimental status as of today

- All the $\mathcal{R}(D^{(*)})$ measurements exceed the Standard Model prediction $(0.258 \pm 0.005)$
- Combining 6 measurements of $\mathcal{R}(D)$ and $\mathcal{R}(D^{*})$ from 3 experiments (LHCb, Belle and Babar)
  - tension with the SM predictions of $\approx 3\sigma$ (very likely to change, see talk at beauty)
  - Theory uncertainty reduced to a level of $\%$ after updating SM calculations \[\text{arXiv:1908.09398}\]
- LHCb contributes with two measurements of $\mathcal{R}(D^{*})$ using semileptonic and hadronic decays of the $\tau$ lepton, and a measurement of $\mathcal{R}(J/\Psi)$ (Run I dataset, $2 \text{fb}^{-1}$)
$\mathcal{R}(D^*)$ with $\tau \to \mu \nu \nu$

- $B^0 \to (D^* \to D^+\pi^-)\ell\nu$
- $B \to D^*\tau\nu$ separated from $B^0 \to D^*\mu\nu$ exploiting differences in kinematic variables computed in the $B$ rest frame

**Event reconstruction strategy**

- The $B$ flight direction is measured from the position of the primary and decay vertex
- The longitudinal momentum from collinear approximation

$$ (\gamma\beta_z)_B \approx (\gamma\beta_z)_{Hc\mu} \Rightarrow (p_z)_B = \frac{m_B}{m_{Hc\mu}} (p_z)_{Hc\mu} $$

- Thanks to the excellent vertexing system of LHCb, the resolution that can be achieved on these variables ($\approx 20\%$) is sufficient for a good separation between the signal and normalization channels

$p_B^2 = (p_B - p_{D^*})^2$
$m_{miss}^2$

$q^2 = (p_B - p_{D^*})^2$

$B^0 \to D^*\mu\nu$
$B^0 \to D^*\tau\nu$
\[ \mathcal{R}(D^*) \text{ with } \tau \rightarrow \mu\nu\nu \]

Main backgrounds

- Semileptonic decays with excited \( D^{**} \), \( \approx 12\% \)
- Decays into double charm final states \( B \rightarrow D^*H_cX, H_c \rightarrow \mu\nu X'; \approx 6 - 8\% \)
- Combinatorial and MisID \( (h \rightarrow \mu); \approx 1\% \)

- 3D binned fits with templates that represent signal, normalization and backgrounds

- The shape of the physical backgrounds is calibrated in control regions enriched in the presence of specific hadron tracks that have not been associated to the decay vertex (anti-isolation)
$\mathcal{R}(D^*)$ with $\tau \to \mu \nu \nu$

\begin{align*}
\mathcal{R}(D^*) &= 0.336 \pm 0.027\text{(stat.)} \pm 0.030\text{(syst.)} \\
&= 2.1 \sigma \text{ higher than the Standard Model}
\end{align*}

- **Main Systematic uncertainties**
  - MC Statistics
  - Shape of the MisID background

- The shape of the physical backgrounds is calibrated in control regions enriched in the presence of specific hadron tracks that have not been associated to the decay vertex (anti-isolation)

**Main backgrounds**

- **Semileptonic decays with excited $D^{**}$**, $\approx 12\%$
- **Decays into double charm final states $B \to D^{*}H_{c}X$, $H_{c} \to \mu \nu X'$**, $\approx 6 - 8\%$
- **Combinatorial and MisID ($h \to \mu$)**, $\approx 1\%$

- $\mathcal{R}(D^*)$ with $\tau \to \mu \nu \nu$

(PRL 115, 11804)
**\( \mathcal{R}(D^*) \) with \( \tau \to \pi\pi\pi\nu \)**

- Very different background contributions with respect to \( \tau \to \mu\nu\nu \) analyses

\[ \mathcal{K}(D^*) = \frac{B(B^0 \to D^* - \tau^+ \nu_\mu)}{B(B^0 \to D^* - 3\pi^\pm)} \]

- Measurement converted to \( \mathcal{R}(D^*) \) through external measurements

\[ \mathcal{R}(D^*) = \mathcal{K}(D^*) \frac{B(B^0 \to D^* - 3\pi^\pm)}{B(B^0 \to D^* - \mu^+\nu_\mu)} \]

- The decay is normalized to a similar fully hadronic decay \( B \to D^* 3\pi \), whose normalization is measured through a fit to the mass of the \( D^* 3\pi \) system

- Fit performed on \( \tau \) lifetime, \( q^2 \) and output of a BDT trained to reject double charm decays

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(Università degli studi di Milano Bicocca)  
**LFU in \( b \to c\ell\nu \) decays at LHCb**  
9 January 2020  
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\( \mathcal{R}(D^*) \) with \( \tau \rightarrow \pi\pi\pi\nu \)

- No background from semileptonic decays

\[
\mathcal{K}(D^*) = \frac{B(B^0 \rightarrow D^*3\pi^{\pm})}{B(B^0 \rightarrow D^{*-}\mu^+\nu_\mu)}
\]

\[
\mathcal{R}(D^*) = 0.283 \pm 0.019\text{(stat.)} \pm 0.025\text{(syst.)} \pm 0.013\text{(ext.)}
\]

1 \( \sigma \) higher than the Standard Model

- Measurement converted through external measurements

\[
\mathcal{R}(D^*) = 0.283 \pm 0.019\text{(stat.)} \pm 0.025\text{(syst.)} \pm 0.013\text{(ext.)}
\]

- Main Systematic uncertainties
  - MC Statistics
  - External measurements (PDG averages)
  - Background shapes and models

- The decay is normalized to a similar fully hadronic decay

- Main background is coming from prompt \( D^*3\pi \) combinations, reduced to \( O(10^{-3}) \) cutting on \( \tau \) lifetime significance

- Remaining dominant background from \( B \rightarrow D^*D^{(*)}S \) decays

- Fit performed on \( \tau \) lifetime, \( q^2 \) and output of a BDT trained to reject double charm decays
\( \mathcal{R}(J/\Psi) \) with \( \tau \to \mu \nu \nu \\

\[ \mathcal{R}(J/\Psi) = \frac{B(B_c \to J/\Psi \tau \nu)}{B(B_c \to J/\Psi \mu \nu)} \times \frac{J/\Psi \to \mu^+ \mu^-}{} \]

- First observation \( B_c \to J/\Psi \tau \nu \) (3 \( \sigma \)) decay
- \( B_c \) channel not accessible at \( \Upsilon(4S) \)
- Number of signal events extracted with a fit to
  - \( m_{\text{miss}}^2 \)
  - \( B_c \) decay time
  - combination of \( q^2 \) e \( E_\mu \)

Main backgrounds
- Mis-Identification (\( h \to \mu \))
- Combinatorial
The ratio \( \mathcal{R}(J/\psi) \) with \( \tau \to \mu\nu\nu \) was measured:

\[
\mathcal{R}(J/\psi) = \frac{B(B_c \to J/\psi \tau\nu)}{\mathcal{B}(\tau \to \mu\nu\nu)} \text{, } J/\psi \to \mu^+\mu^-
\]

First observation \( B_c \to J/\psi \tau\nu \) decay

- \( B_c \) channel not accessible at \( \Upsilon(4S) \)
- Number of signal events extracted with a fit to

- \( m^2_{\text{miss}} \)
- \( B_c \) decay time
- Combination of \( q^2_eE_\mu \)

The production rate partially compensated with the higher \( \mu \) trigger

- \( B_c \) lifetime much lower than the \( B_0,\pm \)
- Bc flight distance fully rejects \( B_0,\pm \) backgrounds

Main Systematic uncertainties

- MC Statistics
- MisID and Combinatorial background shape
- Hadronic Form Factors

\( \mathcal{R}(J/\psi) = 0.71 \pm 0.17(\text{stat.}) \pm 0.18(\text{syst.}) \)

2 \( \sigma \) higher than the Standard Model

- New theoretical form factor calculations are available Talk at Beauty 2019
Next steps: New analyses

- Many other analyses are ongoing at the LHCb experiment to test Lepton Flavour Universality in $b \rightarrow c \ell \nu$ transitions
  - $\mathcal{R}(D^+), \mathcal{R}(D^0), \mathcal{R}(D^*_s), \mathcal{R}(J/\Psi)$
  - in both $\tau$ decay channels [arXiv:1808.08865]

**Experimental advantages**

- $\Lambda_b$ production cross section is $\approx 40\%$ the one of $B$ mesons
- $\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c \mu \nu) \approx 3 \times \mathcal{B}(B \rightarrow D \mu \nu)$
- Smaller Feed Down contribution due to isospin conservation
  - $\Lambda_c^{**}$ decays with at least two $\pi$
  - Simpler background to reject

- Especially interesting are baryonic decays, exclusive to hadron colliders
  $$\mathcal{R}(\Lambda_c^{(*)}) = \frac{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^{(*)} \tau \nu)}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^{(*)} \mu \nu)}$$

**Theoretical interest**

- Different NP Lorentz structure tested
  - Higher sensitivity to tensorial structure
- Very useful cross check for present discrepancies
  - Model independent relation [arXiv:1811.09603]

$$\frac{\mathcal{R}(\Lambda_c)}{\mathcal{R}(\Lambda_c)_{SM}} \approx 0.262 \frac{\mathcal{R}(D)}{\mathcal{R}(D)_{SM}} + 0.738 \frac{\mathcal{R}(D^*)}{\mathcal{R}(D^*)_{SM}}$$
Next steps: larger data samples, larger MC samples

• In the coming years of data taking the integrated luminosity will greatly increase
  ▶ Expected integrated luminosity after the UpgradeII is \( \approx 300 \text{ fb}^{-1} \)

• Evaluation of systematic uncertainties assumes uncertainties due to background modelling to scale with luminosity
  ▶ The higher statistics in the control regions will help constraining the background models

• Very large MC samples will be needed to keep under control the systematics due to MC statistics that affects all these analyses
  ▶ Fast simulations are already being used [arXiv:1810.10362]

[arXiv:1809.06229]
Next steps: Further improvements in the analyses

- Up to now only the ratios of branching fractions have been used to test LFU
- Very rich angular structure can be exploited and can give higher sensitivity to NP Wilson coefficients [arXiv:1602.03030v2]

- $B \to D^* \tau \nu$, $\tau \to \mu \nu \nu$
- $B \to D^* \mu \nu$

- With the high statistics collected it will be possible to perform angular analyses even with a quite poor resolution on angular observables [arXiv:1808.08865]
Conclusions

• $b \rightarrow c\ell\nu$ can be a very interesting laboratory to observe indirect effect of NP

• Some discrepancies have been reported with respect to the Standard Model predictions

• Very rich program in this area from the LHCb experiment
  ▶ Update of analyses with new data collected
  ▶ Both hadronic and leptonic decays of the $\tau$ lepton are being exploited
  ▶ New decays are now under consideration

• Very high statistics will be a challenge from the experimental side...
• ... it will enable to reduce the uncertainties to the measured parameters...
• ... it will enable us to explore new interesting ideas!

• **STAY TUNED!**
$\mathcal{R}(D^*)$ with $\tau \to \mu\nu\nu$

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

2.1 $\sigma$ higher than the Standard Model

<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>$\bar{B} \to D^{**}H_c(\to \mu\nu X')X$ shape corrections</td>
<td>0.5</td>
</tr>
<tr>
<td>$B(\bar{B} \to D^{<strong>}\tau^-\bar{\nu}_\tau)/B(\bar{B} \to D^{</strong>}\mu^-\bar{\nu}_\mu)$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ 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>$\bar{B} \to D^{<strong>}(\to D^{</strong>}\pi)\mu^-\bar{\nu}_\mu$ form factors</td>
<td>0.3</td>
</tr>
<tr>
<td>$\bar{B} \to D^{**}(D_s \to \tau\nu)X$ fraction</td>
<td>0.1</td>
</tr>
<tr>
<td>Total model uncertainty</td>
<td>2.8</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>$B(\tau^- \to \mu^-\bar{\nu}<em>\mu\nu</em>\tau)$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>Total normalization uncertainty</td>
<td>0.9</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**systematic uncertainties**

- **MC statistics**
- **Shape of the Mis-ID background**
  - Depend on the statistics in the control regions
  - They will be reduced in the measurements performed with the RunII data
- **Hadronic form factors**
R(D*) with $\tau \rightarrow \pi\pi\nu$

$R(D^*) = 0.283 \pm 0.019\text{ (stat.)} \pm 0.025\text{ (syst.)} \pm 0.013\text{ (ext.)}$

1 $\sigma$ higher than the Standard Model

Systematic uncertainties

- External measurements (PDG averages)
- Background shapes and models
  - Extensive studies performed in dedicated control regions to keep it under control
- MC statistics
- Hadronic form factors

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Value in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(\tau^+ \rightarrow 3\pi\bar{\nu}<em>\tau)/B(\tau^+ \rightarrow 3\pi^0\bar{\nu}</em>\tau)$</td>
<td>0.7</td>
</tr>
<tr>
<td>Form factors (template shapes)</td>
<td>0.7</td>
</tr>
<tr>
<td>Form factors (efficiency)</td>
<td>1.0</td>
</tr>
<tr>
<td>$\tau$ polarization effects</td>
<td>0.4</td>
</tr>
<tr>
<td>Other $\tau$ decays</td>
<td>1.0</td>
</tr>
<tr>
<td>$B \rightarrow D^{*+}\tau^+\nu_\tau$</td>
<td>2.3</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D^{*+}\tau^+\nu_\tau$ feed-down</td>
<td>1.5</td>
</tr>
<tr>
<td>$D^{+} \rightarrow 3\pi X$ decay model</td>
<td>2.5</td>
</tr>
<tr>
<td>$D^{*,0}$ and $D^+$ template shape</td>
<td>2.9</td>
</tr>
<tr>
<td>$B \rightarrow D^{<em>-}D^{</em>+}(X)$ and $B \rightarrow D^{*-}D^0(X)$ 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>Combinatorial background (shape + normalization)</td>
<td>0.7</td>
</tr>
<tr>
<td>Bias due to empty bins in templates</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Size of simulation samples</strong></td>
<td><strong>4.1</strong></td>
</tr>
<tr>
<td>Trigger acceptance</td>
<td>1.2</td>
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<tr>
<td>Trigger efficiency</td>
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<tr>
<td>Online selection</td>
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<tr>
<td>Offline selection</td>
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<tr>
<td>Charged-isolation algorithm</td>
<td>1.0</td>
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<tr>
<td>Particle identification</td>
<td>1.3</td>
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<tr>
<td>Normalization channel</td>
<td>1.0</td>
</tr>
<tr>
<td>Signal efficiencies (size of simulation samples)</td>
<td>1.7</td>
</tr>
<tr>
<td>Normalization channel efficiency (size of simulation samples)</td>
<td>1.6</td>
</tr>
<tr>
<td>Normalization channel efficiency (modeling of $B^0 \rightarrow D^{*-}3\pi$)</td>
<td>2.0</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>9.1</td>
</tr>
</tbody>
</table>
$\mathcal{R}(J/\Psi)$ with $\tau \rightarrow \mu \nu \nu$

$\mathcal{R}(J/\Psi) = 0.71 \pm 0.17(\text{stat.}) \pm 0.18(\text{syst.})$

$2 \sigma$ higher than the Standard Model

### Systematic Uncertainties

- **MC Statistics**
  - High theoretical uncertainties
  - New theoretical form factor calculations are available
  - Talk at Beauty 2019

- **Form Factors**
  - Given the final state ($\mu^+ \mu^- \mu^\mp$) no reliable Wrong Sign control sample available
  - Had to rely on MC simulation for estimating the shape of this background

- **MisID and Combinatorial background shape**
  - Represents a complementary measurement for testing New Physics operators with a different Lorentz structure from the one tested with $B$ meson decays
• PHOTOS is used to simulate QED corrections
• It does include interference effects between the emitted photons
• It does not include Coulomb interactions

The Coulomb corrections depend on the kinematics of the particles, therefore selections
They can be included with dedicated, analysis dependent studies