Lepton-flavour universality tests with semitauonic b-hadron decays at LHCb

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The Standard Model predicts **Lepton Flavour Universality (LFU)**: equal couplings between gauge bosons and the three lepton families.

\[
\mathcal{R}(H_c) = \frac{\mathcal{B}(H_b \rightarrow H_c \tau \nu)}{\mathcal{B}(H_b \rightarrow H_c \mu \nu)} \quad \text{should only account for phase space effects}
\]

Yet, tensions between SM expectations and experimental results are found in:

- semitauonic B decays → this talk
- \(b \rightarrow sl\) transitions → Violaine’s presentation

Several models (charged Higgs, leptoquarks, \(W'\)) add new interactions with a stronger coupling with the \(\tau\)

Some models (leptoquarks & \(W'/Z'\) models) try to explain both discrepancies.

\[\text{NP ?} \quad l \quad \nu_l \quad b \quad c\]

Why using semitauonic B decays?

As tree level decays, they combine some nice features:

- **Precise prediction from SM** using ratios with shared systematics cancelling
- **Abundant channel**: BR(B→D*τν) ~ 1.2% (in SM)
- **Sensitivity to NP** contributions

\[ \mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*-} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*-} \mu^- \bar{\nu}_\mu)} \]

Different hadron species:

- D*, D^0, D^+, D_s, Λ_c (s), J/Ψ
- Not only spectator quarks differ but also the spin:
  - 0: D^0, D^+, D_s
  - 1: D^*, J/Ψ
  - ½: Λ_c (s)

Two reconstruction channels for τ at LHCb:

τ→μνν

- longitudinal component of B momentum missing:
  - Assuming βγ_z,tot = βγ_z,visible
- Can then calculate rest frame quantities:
  - \( m^2_{\text{missing}}, E_\mu, q^2 \)

τ→ππ+π−(π^0)ν → later in the talk
R(D*) with τ→μνν

- 3D MC-template based binned fit to $m^2_{\text{missing}}$ vs $E_\mu$ in coarse $q^2$ bins

- Fit to isolated data, used to determine ratio of $B \rightarrow D^* \tau \nu$ and $B \rightarrow D^* \mu \nu$

- Templates are a good description of the data

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030 \rightarrow \text{consistent with SM at } 2.1\sigma \text{ level}$$
\[ R(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} \]

LFU probed with a new hadronisation:

- SM expectation: 0.25 – 0.28
- Lower statistics due to \( B_c^+ \) production fraction

Same strategy as \( R(D^*) \) analysis:

- Use of \( m_{\text{miss}}^2, q^2, E_\mu \)
  - \( q^2 \) and \( E_\mu \) combined into \( Z \)

\( B_c^+ \) specificities:

- \( B_c^+ \) decay-time shorter than other \( B \to \) helps reducing background
- \( B_c^+ \to J/\psi \) form-factors unknown
  - estimated from fit to enriched sample of the normalisation mode.
R(J/\psi)

- 3D template fit using $\tau(B_c^+), m_{miss}^2, Z$
- Largest systematics
  - $B_c^+ \rightarrow J/\psi$ form-factor
  - Simulation sample size
- First evidence of $B_c^+ \rightarrow J/\psi \tau \nu$

$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18 \rightarrow \text{compatible with SM at 2}\sigma.$$
Semileptonic decay without charged lepton in the final state
- → Zero background from normal semileptonic decays!
- No signal mass peak due to neutrinos
- but several hadronic ones ($D^0 \rightarrow K3\pi$, $D^+ \rightarrow K\pi\pi$, ...)
  - It provides control on the various background channels
- Only one $\nu$ at the $\tau$ vertex
  - Partial reconstruction can be applied with good precision
- $B^0 \rightarrow D^* \pi^+ \pi^- \pi^+$ is used as normalisation

\[
R_{\text{had}}(D^*) = \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\pi^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\pi^+\pi^-\pi^+)}
\]

\[
R(D^*) = R_{\text{had}} \times \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\pi^+\pi^-\pi^+)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)}
\]

Same final state: shared systematics uncertainties cancel

External inputs
Most abundant background: hadronic B decays into $D^*3\pi X$:

- yield is 100x bigger than SM expectation for signal yield!

Good precision on $\tau$ decay vertex position

**Detachment cut:** $\tau$ vertex is downstream with respect to the $B^0$ vertex with a significance of at least 4$\sigma$

$D^*3\pi$ background reduced by 3 orders of magnitude

Double charm background

○ The remaining background consists of $B^0$ decays where the $3\pi$ vertex is transported away from the $B^0$ vertex by a charm carrier: $D_s$, $D^+$ or $D^0$, e.g. $B \rightarrow D^*DX$, $D \rightarrow 3\pi X$

○ Total yield is $\sim10x$ higher than SM expectation for signal

○ LHCb has three very good tools to limit this background:
  □ 3π dynamics
  □ Isolation criteria against charged tracks and neutral energy deposits
  □ Partial reconstruction in both signal and background hypotheses

○ A Boosted Decision Tree (BDT) is trained using these tools to discriminate double charm decays from signal
Signal extraction and fit

Signal reconstruction:
- Assume 2 neutrinos in the event → can be used to access full kinematics
  - Reconstruction of $\tau$ and $B^0$ momentum and $\tau$ decay time
  - Kinematics solution found ~95% of the time

Fit strategy:
- A high BDT cut is applied
- A 3D template fit is performed in $q^2$ (squared-momentum transferred to the $\tau$-$\nu$ system)
- $\tau$ lifetime
- The output of the BDT

The 3D template binned likelihood fit results are presented for the lifetime and $q^2$ in four BDT bins.

The increase in signal purity as function of BDT is very clearly seen, as well as the decrease of the $D_s$ component.

The dominant background at high BDT becomes the $D^+$ component, with its distinctive long lifetime.

The overall $\chi^2$ per dof is 1.15
### Main systematics

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Value %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>4.7</td>
</tr>
<tr>
<td>Signal modeling</td>
<td>1.8</td>
</tr>
<tr>
<td>$D^\ast \tau \nu$ and $D_s^\ast \tau \nu$ feed-downs</td>
<td>2.7</td>
</tr>
<tr>
<td>$D_{s} \rightarrow 3\pi X$ decay model</td>
<td>2.5</td>
</tr>
<tr>
<td>$B \rightarrow D^* D_s^* X, B \rightarrow D^* D^0 X, B \rightarrow D^* D^0 X$ backgrounds</td>
<td>3.9</td>
</tr>
<tr>
<td>Combinatorial background</td>
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<tr>
<td>$B \rightarrow D^* 3\pi X$ background</td>
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<tr>
<td>Empty bins in templates</td>
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<tr>
<td>Efficiency ratio</td>
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<td>Normalisation channel efficiency</td>
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<td><strong>Total internal uncertainty</strong></td>
<td><strong>9.1</strong></td>
</tr>
<tr>
<td>$B(B^0 \rightarrow D^* 3\pi)$ and $B(B^0 \rightarrow D^* \mu \nu \mu)$</td>
<td><strong>4.8</strong></td>
</tr>
</tbody>
</table>

Room for progress exists on a longer timescale on both internal and external sources!

In red: can be reduced with help from other experiments (BELLE, BES, ...)

In green: can be reduced internally by LHCb
The fit results give a branching fraction which is:

\[ \text{BR}(B^0 \to D^{*+}\tau\nu) = (1.40 \pm 0.09\text{(stat)} \pm 0.13\text{(syst)} \pm 0.18\text{(ext)}) \% \]

To be compared to PDG 2017: \[ \text{BR}(B^0 \to D^{*+}\tau\nu) = (1.67 \pm 0.13) \% \]

Using the HFLAV \[ \text{BR}(B^0 \to D^{*}\mu\nu) = (4.88 \pm 0.1) \% \], we get:

\[ R(D^*) = 0.286 \pm 0.019\text{(stat)} \pm 0.025\text{(syst)} \pm 0.021\text{(ext)} \]

Impact on World Average:

- \[ R(D^*): 3.3\sigma \to 3.4\sigma \] from SM prediction
- Adding \( R(D) \): \[ 4.0\sigma \to 4.1\sigma \]

It is also possible to compute an LHCb average of \( R(D^*) \):

\[ R_{\text{LHCb}}(D^*) = 0.309 \pm 0.016\text{(stat)} \pm 0.024\text{(syst)} \]

○ Latests results of Run1 dataset:
  □ $R(J/\psi)$ using muonic $\tau$
  □ $R(D^*)$ using hadronic $\tau$

○ both statistical and systematic uncertainties will be reduced using large statistics collected during Run2

○ LFU can be tested using
  □ Precise measurements of $R(D^{(*)})$
  □ several hadrons ($J/\psi$ but also $D^{0,+}$, $D_s$, $\Lambda_c^{(*)}$) → probing different dynamics and spin structures

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**Conclusion**

WA combination of $R(D)$ and $R(D^*)$ is in tension with SM at the $4.1\sigma^*$ level!

*: this is reduced with latest theory input

arXiv:1707.0950
Thank you for your attention!

Any question?
Backup
The LHCb detector

- **Single arm spectrometer** at LHC in the pseudorapidity range $2<\eta<5$
- Optimized to study hadron decays containing $b$ and $c$ quarks:
  - CP violation, rare decays, heavy flavor production;
- **Excellent vertex resolution** and separation of B vertices
- Good **momentum and mass resolution**
- Excellent **PID** capabilities (good separation $K-\pi$ and muon identification)
The world average of the combination of $R(D)$ and $R(D^*)$ is in tension with the SM expectation at the $4\sigma$ level!
To determine the $D_s$ decay model:

- The BDT output is used to select an enriched sample of $D_s$ events directly from data.
- Several variables related to the $3\pi$ dynamics are simultaneously fitted.

The weights obtained are used to construct the $D_s$ templates.
Normalisation channel

- The normalisation channel has to be as similar as possible to the signal channel to cancel all systematics linked to trigger, particle ID, selection cuts.
- They differ by:
  - softer pions and $D^*$ due to the presence of two $\nu$.
  - kinematics of the $3\pi$ system is not exactly the same:
    - This gives a small residual effect on the efficiency ratio.

Absolute BR recently measured by BABAR with a precision of 4.3%

Run 1, 3 fb$^{-1}$

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Control channels

3π mass after vertex topology cut

$D^0 \rightarrow K3\pi$ peak: anti-isolation cut

$D^+ \rightarrow K\pi\pi$ peak: anti-PID cut

“Standard candles” used to check Data and MC agreement