Lepton Flavour Universality in $b \to c \ell \nu$ decays at LHCb

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Lepton Flavour Universality

The Standard Model (SM) predicts equal couplings between gauge bosons and the lepton families. This is called Lepton Flavour Universality (LFU).

Lepton Flavour Universality Violation

Some discrepancies between SM predictions and measurements have been reported in b-hadron decays.

Neutral current: $b \to s \ell \ell$ (see talk from Samuel)
Charged current: $b \to c \ell \nu \ell$ (this talk)

Many SM extensions foresee new processes involving mostly the third generation of quarks and leptons.
Semileptonic decays:

- Tree level diagrams with $\mathcal{B} \sim 10^{-2}$
- Sensitive to New Physics processes in couplings with different generations

$$\frac{d\Gamma}{dq^2}(H_b \rightarrow H_c \tau^- \bar{\nu}_\tau) \propto G_F^2 |V_{cb}|^2 f(q^2)^2$$

$$R(H_c) = \frac{\mathcal{B}(H_b \rightarrow H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \rightarrow H_c \mu^- \bar{\nu}_\mu)} = \frac{N_{sig}}{N_{norm}} \times \frac{\varepsilon_{norm}}{\varepsilon_{sig}}$$

Features:
- Partial cancellation of form factor uncertainties and dependence from $|V_{cb}|$
- Reduce experimental uncertainties $R(H_c) \neq 1$ due to different lepton masses

$$m_\tau \sim \begin{cases} 17 \times m_\mu \\ 3500 \times m_e \end{cases}$$

Needed approximations to reconstruct the $b$-hadron momentum
\( R(D^*) \) with \( \tau \to \mu \nu \nu 

Signal and normalization channel separated by 3-D fit

\[
m_{\text{miss}}^2 = (p_B - p_{D^*} - p_{\mu})^2 \quad E_\mu^* \quad q^2 = (p_B - p_{D^*})^2
\]

To obtain \( p_B \):

\[
(\gamma \beta_z)_B = (\gamma \beta_z)_{D^* \mu}
\]

\[ B \to D^* \tau \nu_\tau \]

\[ B \to D^* \mu \nu_\mu \]

\[
m_{miss}^2 > 0 \quad \text{if} \quad E_\mu \text{ spectrum is soft}
\]

\[
m_{miss}^2 = 0 \quad \text{and} \quad m_{miss}^2 \leq q^2 \leq 10.6
\]

\[
0 \leq q^2 \leq 10.6
\]

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**$R(D^*)$ with $\tau \rightarrow \mu\nu\nu$**

- Data
  - $B \rightarrow D^*\tau\nu$
  - $B \rightarrow D^*H_c(\rightarrow \nu X')X$
  - $B \rightarrow D^{**}\nu$
  - $B \rightarrow D^*\mu\nu$
  - Combinatorial
  - Misidentified $\mu$

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

- Good agreement with the previous measurements
- Compatible in 2.1σ with the SM: $R(D^*) = 0.258 \pm 0.005$
- Systematic uncertainty dominated by MC statistics and MisID background

Run 1

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\( R(D^*) \) with \( \tau \to \pi \pi \pi \nu \)

\[ B(\tau^+ \to \pi^+ \pi^- \pi^+(\pi^0)\bar{\nu}_\tau) \sim 14\% \text{, similar to } B(\tau^+ \to \bar{\nu}_\tau \mu^+ \nu_\mu) \]

\[
R(D^*) \equiv \frac{B(B^0 \to D^{*-} \tau^+ \nu_\tau)}{B(B^0 \to D^{*-} \pi^+ \pi^- \pi^+)} \times \frac{B(B^0 \to D^{*-} \pi^+ \pi^- \pi^+)}{B(B^0 \to D^{*-} \mu^+ \nu_\mu)} \]

\( K(D^*) \)

\(~ 4\% \text{ precision, BaBar, Belle, LHCb} \)

\(~ 2\% \text{ precision, HFLAV2016} \)

Approximations needed to determine \( p_B \) e \( p_\tau \)

- **Normalization** yield from a fit to \( M(B^0 \to D^{*-} \pi^+ \pi^- \pi^+) \)
- **Backgrounds**: suppressed with kinematics properties and with a multivariate analysis (BDT)
- **Signal** yield from a 3D fit to: \( t_\tau , q^2 \), BDT result

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\( R(D^*) \) with \( \tau \to \pi\pi\pi\nu \)

\[
K(D^*) = 1.93 \pm 0.12 \text{(stat.)} \pm 0.17 \text{(syst.)}
\]

\[
R(D^*) = 0.291 \pm 0.019 \text{(stat.)} \pm 0.026 \text{(syst.)} \pm 0.013 \text{(B)}
\]

Updated by HFLAV

\[
R(D^*) = 0.280 \pm 0.018 \text{(stat.)} \pm 0.029 \text{(syst.)}
\]

- first measurement obtained exploiting \( \tau \to 3\pi\nu \);
- compatible into \( \sim 1\sigma \) with the SM prediction: \( R(D^*) = 0.258 \pm 0.005 \);
- systematic uncertainty dominated by MC statistics, external measurements and background shapes and models
**$R(J/\psi)$ with $\tau \rightarrow \mu \nu \nu$**

Same visible final state for **Signal** and **Normalization** channel

Similar to $R(D^*)$ with $\tau \rightarrow \mu \nu \nu$

The ratio is obtained from a 3-D fit to:

- $m_{miss}^2$;
- $Z(q^2,E^*_\mu)$;
- $B^+_c$ decay time

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

- compatible into $2\sigma$ with the SM: $R(J/\psi) \in [0.25; 0.28]$
- systematic uncertainty dominated by MC statistics and uncertainty on Form Factors

*New theoretical form factor calculations are available Talk at Beauty 2019*
Current State of art:

LHCb R(J/ψ)
PRL 120, 121801 (2018)
0.71 ± 0.17 ± 0.18

SM predictions
PLB 452 (1999) 129
PRD 73 (2006) 054024
PRD 74 (2006) 074008
Range 0.25 - 0.28

BaBar (2012), had. tag
0.332 ± 0.024 ± 0.018
Belle (2015), had. tag
0.293 ± 0.038 ± 0.015
Belle (2017), (had. tau)
0.270 ± 0.035 ± 0.027
Belle (2019), sl.tag
0.283 ± 0.018 ± 0.014
LHCb (2015), (muonic tau)
0.336 ± 0.027 ± 0.030
LHCb (2018), (had. tau)
0.280 ± 0.018 ± 0.029
Average
0.295 ± 0.011 ± 0.008

SM pred. average
0.258 ± 0.005
PRD 95 (2017) 115008
0.257 ± 0.003
JHEP 1711 (2017) 061
0.260 ± 0.008
JHEP 1712 (2017) 060
0.257 ± 0.005

Δχ² = 1.0 contours

3.08σ above the SM prediction

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Next steps:

- New results are expected from:
  - Data collected by LHCb during Run2 (statisticsx4);
  - Total uncertainties reduction
  - Ongoing analyses:
    - $R(D^0): B^+ \rightarrow D^0 \tau \nu_\tau$
    - $R(D^+): \bar{B}^0 \rightarrow D^+ \tau \nu_\tau$
    - $R(D_s^{(*)}): B_s \rightarrow D_s^{(*)} \tau \nu_\tau$
    - $R(\Lambda_c^{(*)}): \Lambda_b \rightarrow \Lambda_c^{(*)} \tau \nu_\tau$
    - $R(J/\psi): B_c^+ \rightarrow J/\psi \tau \nu_\tau$
    - $R(p): \Lambda_b \rightarrow p \tau \nu_\tau$
  - Form factors measurements:
    - $\Lambda_b \rightarrow \Lambda_c \ell \nu_\ell$
    - $\Lambda_b \rightarrow \Lambda_c^{*} \ell \nu_\ell$
    - $B_s \rightarrow D_s^{(*)} \ell \nu_\ell$
  - Increased Luminosity
  - Angular analysis
To Conclude:

- Presented three measurements using the $b \rightarrow c \ell \nu_\ell$ b-hadron decays
- Discrepancies have been reported with respect to the SM predictions
- Many other analyses are ongoing at LHCb and there is an updating with Run2 data the previous measurements
- The LHCb upgrade in the near future will allow to increase the luminosity
  
  big chance for more precise measurements!

  ... stay tuned!
Thank you for the attention!