Lepton Flavour Universality tests at LHCb

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Outline:
• Introduction
• LHCb detector & data taking
• $b \rightarrow c \ell \nu$
• $b \rightarrow s \ell^+ \ell^-$
• Summary

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Lepton Flavour Universality

In the Standard Model (SM) quarks and leptons exist in 3 generations of 2 members each. SM assumes Lepton Flavour Universality (LFU):

- the equal gauge couplings for all 3 generations
- difference is only due to mass

LFU is established in the decay of light mesons, e.g. $\pi \to \ell\nu$, $K \to \pi\ell\ell$, $J/\psi \to \ell\ell$

LEP measurements of decays $W \to \ell\nu$ and $Z \to \ell\ell$ confirm LU, however there is some tension in $W \to \tau\nu$

Some SM extensions include particles that can cause LUV and/or LFV (e.g. LQ, $Z'$)

Processes with 3rd generation of quarks and leptons ($B$ and $\tau$) are prominent for LFU violation search:

- Lower experimental constraints
- Stronger couplings to 3rd generation predicted by BSM theories foreseeing LFU violation
LFU in b decays

Tree-level decays $b \to c\ell\nu$:

- abundant
- very well known in the SM
- BSM theories predict enhanced coupling with 3rd generation → interested in testing $\tau$ against $\mu$ / $e$

Loop-level decays $b \to s\ell^+\ell^-$:

- forbidden at tree-level in SM
- sensitive to NP contributions in loops
LHCb experiment
LHCb performance

- Momentum resolution: 0.4 – 0.6% at 5 – 100 GeV
- Muon ID efficiency: 97 % with 1-3 % π → μ mis-ID probability
- Electron ID efficiency: 90% with 4% h → e mis-ID probability
- Kaon ID efficiency: 95% with 5 % π → K mis-ID probability

Acceptance: 2 < η < 5

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2018

- 2018 (6.5 TeV): 1.80 /fb
- 2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
- 2016 (6.5 TeV): 1.67 /fb
- 2015 (6.5 TeV): 0.33 /fb
- 2012 (4.0 TeV): 2.08 /fb
- 2011 (3.5 TeV): 1.11 /fb
- 2010 (3.5 TeV): 0.04 /fb

1) Commun. 208 35 -42
LFU in semileptonic b decays

Measurement of ratios of branching fractions allows to

- cancel $|V_{cb}|$ dependence
- partially cancel out model uncertainties
- reduce experimental systematic uncertainties
SM prediction of $R_{D^*}$

\[ R_{D^*} \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu)} \overset{\text{SM}}{=} 0.258 \pm 0.005 \]

HFLAV average

→ Hadronic uncertainties cancel to large extent in the ratio

→ Difference from unity due to different lepton masses

• First deviation from SM was observed by BaBar and Belle

• LHCb performed two independent measurements using
  – $\tau^- \to \mu^- \bar{\nu}_\tau \bar{\nu}_\mu$ [PRL 115 (2015) 111803]
  – $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ [PRD 97 (2018) 072013]
\( R_{D^*} \) in muonic \( \tau \) decays

- \( \tau \) reconstructed by \( \tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu \)
- Both channels have the same final state (\( K\pi\pi\mu \))

- Separation using three kinematic parameters:
  - \( E^*_\mu = E_\mu \) in \( \bar{B}^0 \) rest frame
  - \( m^2_{\text{miss}} = (p_{B0} - p_{D^*} - p_{\mu})^2 \)
  - \( q^2 = (p_{B0} - p_{D^*})^2 \)

- Approximate \( p_{B0} \) using
  - \( \bar{B}^0 \) flight direction
  - \( (p_{B0})_z = m_B / m_{\text{reco}} (p_{\text{reco}})_z \)
$R_{D^*}$ in muonic $\tau$ decays

- Yields are extracted with a 3D binned ML fit in $E_\mu^*$, $m_{miss}^2$, $q^2$
- Templates for the signal, normalization and backgrounds are obtained on MC and checked against control samples

$R_{D^*} = 0.336 \pm 0.027 \text{ (stat)} \pm 0.030 \text{ (syst)}$ 2$\sigma$ above SM

- Main background: Partially reconstructed and mis-ID decays
- Main systematic: Size of the simulated sample

$R_{D^*}$ in hadronic $\tau$ decays

$\tau$ reconstructed by $\tau^- \rightarrow \pi^-\pi^-\pi^+ \nu_\tau$ independent from $R_{D^*}$ muonic

$$R_{D^*} = \frac{\mathcal{B}(B^0 \rightarrow D^{*-\tau^+\nu_\tau})}{\mathcal{B}(B^0 \rightarrow D^{*-3\pi})} \cdot \frac{\mathcal{B}(B^0 \rightarrow D^{*-\mu^+\nu_\mu})}{\mathcal{B}(B^0 \rightarrow D^{*-\mu^+\nu_\mu})}$$

measured ratio $\mathcal{K}(D^{*-})$

external inputs

~4% precision (BABAR, Belle, LHCb)

~2% precision, HFLAV

- Partial cancellation of experimental systematic uncertainties
- Main background:
  - $B^0 \rightarrow D^*\pi\pi\pi X$, suppressed with $\tau$ decay time, $t_\tau$
  - $B \rightarrow DD_{(s)}X$, suppressed with BDT
R_{D^*} in hadronic $\tau$ decays

- Yields are extracted by a binned ML fit on $q^2$, BDT and $t_\tau$

- $R_{D^*} = 0.291 \pm 0.019 \text{ (stat)} \pm 0.026 \text{ (syst)} \pm 0.013 \text{ (ext)}$

  1$\sigma$ above SM

- Main systematic: Size of the simulated sample

- LHCb average: $R_{D^*} = 0.310 \pm 0.016 \text{ (stat)} \pm 0.022 \text{ (syst)}$

  2.2$\sigma$ above SM

Measurements of $R_D$ and $R_{D^*}$ are consistent with each other.
Combined result is $3.8\sigma$ above SM prediction.
SM prediction of $R_{J/\psi}$

Test of LFU in $b \to c \ell \nu$ decays with a different spectator quark using large $B^+_c$ sample available at LHCb

$R_{J/\psi} \equiv \frac{\mathcal{B}(B^+_c \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B^+_c \to J/\psi \mu^+ \nu_\mu)} \overset{\text{SM}}{\in} [0.25, 0.28]


Lattice calculation is in progress
$R_{J/\psi}$ results

$\tau$ reconstructed by $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$

Analysis strategy as in $R_{D^*} + t_\tau$ as 4$^{th}$ discriminating variable

Main backgrounds: $B \rightarrow J/\psi + \text{mis-ID hadron}$

Systematic: MC sample, $B_c^+ \rightarrow J/\psi$ form factors

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


First evidence ($3\sigma$) of $B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau$
LFU tests in $b \to s \ell^+ \ell^-$

$b \to s \ell^+ \ell^-$ are FCNC processes that can only occur at loop-level in SM.

$$R_H \equiv \frac{\mathcal{B}(B \to H \mu^+ \mu^-)}{\mathcal{B}(B \to H e^+ e^-)} \overset{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-3}) \pm \mathcal{O}(10^{-2}) \quad \text{[EPJC76(2016)8,440]}
$$

- Neglect $m_\ell$
- QED effects

Use double ratio to reduce systematic effects:

$$R_H \equiv \frac{\mathcal{B}(B \to K \mu^+ \mu^-)}{\mathcal{B}(B \to K (J/\psi \to \mu^+ \mu^-))} \cdot \frac{\mathcal{B}(B \to K (J/\psi \to e^+ e^-))}{\mathcal{B}(B \to K e^+ e^-)}$$
Measurement of $R_{K^*}$

$LHCb$

$m(K^+\pi^-\mu^+\mu^-)$ [MeV/c$^2$]

$q^2$ [GeV$^2$/c$^4$]

$LHCb$

$m(K^+\pi^-e^+e^-)$ [MeV/c$^2$]

$q^2$ [GeV$^2$/c$^4$]

$LHCb$

$B^0\rightarrow K^{*0}\mu^+\mu^-$

Combinatorial

$1.1 < q^2 < 6.0$ [GeV$^2$/c$^4$]

$LHCb$

$B^0\rightarrow K^{*0}e^+e^-$

$B\rightarrow Xe^+e^-$

$B^0\rightarrow K^{*0}J/\psi$

$1.1 < q^2 < 6.0$ [GeV$^2$/c$^4$]

Pulls Candidates per 34 MeV/c$^2$

Pulls Candidates per 10 MeV/c$^2$
$R_{K^*}$ results

\[
R_{K^*} = \begin{cases} 
0.66^{+0.11}_{-0.07}\text{(stat)} \pm 0.03\text{(syst)}, & \text{at low } q^2 (\sim 2.2\sigma \text{ below SM}) \\
0.69^{+0.11}_{-0.07}\text{(stat)} \pm 0.05\text{(syst)}, & \text{at central } q^2 (\sim 2.4\sigma \text{ below SM})
\end{cases}
\]

- Most precise measurement to date
- Compatible with BaBar and Belle
- Statistically limited by the electron sample
$R_K$ results

$LHCb$ [PRL 113 (2014) 151601]

$Babbar$ [PRD 86 (2012) 032012]

$Belle$ [PRL 103 (2009) 171801]

$LHCb$ graph shows $R_K$ results with data points from LHCb, Babar, and Belle collaborations.

$R_K \equiv \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$ in central $q^2$ region [1,6]GeV$^2/c^4$

$R_K = 0.745^{+0.090}_{-0.074} \text{(stat)} \pm 0.036 \text{(syst)} \sim 2.6\sigma$ below SM
Combination of $R_{K^{(*)}}$, $R_{K}$ and [PRL 118 (2017) 111801] is $\sim4\sigma$ from SM

- $b \to s\mu^+\mu^-$ BR and angular obs. are in agreement with LFU tests
- Considered together the tension with SM further increases
Prospects for LFU tests at LHCb

LHCb aims to perform complementary LFU tests:

• $b \to c\ell\nu$ transitions:
  - $R_{\Lambda^*}$, $R_{D_s}$, $R_{D_s^*}$ and others

• $b \to u\ell\nu$ transitions:
  - $R_{p\bar{p}} = \frac{B(B^+ \to p\bar{p}\tau\nu)}{B(B^+ \to p\bar{p}\mu\nu)}$ and others

• $b \to s\ell\ell$ transitions:
  - $R_{K_s}$, $R_{K^{*+}}$, $R_{K^{*0}}$, $R_{pK^*}$, $R_\varphi$, $R_\Lambda$, direct fit to $\Delta C_9^{\mu,e}$ and others

⇒ Update of $R_K$, $R_{K^*}$, $R_{D^*}$ and $R_{J/\psi}$ with Run 2 data is currently on-going. 4 times more statistics: expected improvement on both statistical and systematic uncertainties
Tests of LFU in heavy flavour physics present a tension with the SM predictions:

- **3.4 σ** from angular distributions of $B^0 \rightarrow K^{*0} \mu^+\mu^-$
- Measurements of ratios of branching fractions in both $b \rightarrow c\ell\nu$ and $b \rightarrow s\ell^+\ell^-$
  - **3.8σ** tension in $R_D$ and $R_{D^*}$ when combining BaBar, Belle and LHCb
  - **2.5σ** below SM prediction in $R_{K(*)}$ at central $q^2$

Anomalies in both $b \rightarrow c\ell\nu$ and $b \rightarrow s\ell^+\ell^-$ decays could be described with same New Physics models

LHCb continue testing the LFU hypothesis. Please stay tuned!
Backup
Angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

NP models which explain the observed discrepancies in the measurement of $R(K(*))$ w.r.t SM predictions, foresee anomalous behaviors also in the angular distribution of the decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$.

Decay amplitude can be described using $q^2$ and three angles: $\theta_\ell$, $\theta_K$, $\phi$: 
Decay amplitude of $B^0 \to K^{*0} \mu^+ \mu^-$

$$
\frac{d^4 (\Gamma + \bar{\Gamma})}{d \Omega \, dq^2} = \frac{9}{32 \pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_k + F_L \cos^2 \theta_k 
+ \frac{1}{4} (1 - F_L) \sin^2 \theta_k \cos 2\theta_\ell - F_L \cos^2 \theta_k \cos 2\theta_\ell 
+ S_3 \sin^2 \theta_k \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_k \sin 2\theta_\ell \cos \phi 
+ S_5 \sin 2\theta_k \sin \theta_\ell \cos \phi + \frac{4}{3} A_{FB} \sin^2 \theta_k \cos \theta_\ell 
+ S_7 \sin 2\theta_k \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_k \sin 2\theta_\ell \sin \phi 
+ S_9 \sin^2 \theta_k \sin^2 \theta_\ell \sin 2\phi \right],
$$
The $P'_5$ anomaly

- Angular observable:
  \[ P'_5 \equiv \frac{S_5}{\sqrt{F_L(1 - F_L)}} \]

- LHCb measurement differs by $3.4\sigma$ from the SM prediction

- Can be explained by
  - SM charm-loop effects (cannot explain tension in $R_{K^*}$)
  - New Physics

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ATLAS measurement differs by $2.7\sigma$ from the SM prediction.

CMS results are consistent with SM prediction and other measurements.
Measurement of $R_{D^*}$

**B factories**

\[ e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-(B^0\bar{B}^0) \]

- Reconstruction of other B
- Clean signal but low efficiency

**LHCb**

- Large boost, flight direction determined by PV & SV
- Huge B production
Main systematic uncertainties due to:

- Size of simulated sample
- Shape of the background \( B \to D^* D_s^+ X \)
- \( D_{(s)}^+ \to \pi^+ \pi^- \pi^+ X \) decay mode. BESII future measurement will reduce it. Improvement as well of the upgraded ECAL
- Branching fraction of normalisation mode \( B^0 \to D^* \pi^+ \pi^- \pi^+ \) known with \( \sim 4\% \) precision. Belle II can measure it precisely
$R_{D^*}$ in muonic channels

MC truth

$B \to D^* \mu \nu$

$B \to D^* \tau \nu$

Reconstructed