Tests of Lepton Universality at LHCb

Kristof De Bruyn
On behalf of the LHCb Collaboration

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Puzzling Tensions in $b \to s \ell \ell$ Transitions

$B^0 \to K^0 \mu^+ \mu^-$

- Angular Observable “$P'_5$”

$B^+(s) \to \mu^+ \mu^-$

- Ratio of $B^0$ to $B^0(s)$ branching fraction

$B^0 \to K^+ \mu^+ \mu^-$

- Differential branching fraction

$B^0 \to K^0 \mu^+ \mu^-$

- Differential branching fraction

LHCb, JHEP 02 (2016) 104, arxiv:1512.04442

CMS+LHCb, Nature 522 (2015), arxiv:1411.4413

LHCb, JHEP 06 (2014) 133, arxiv:1403.8044

LHCb, JHEP 06 (2014) 133, arxiv:1403.8044
Hints for Lepton Universality Violation?

- Model-independent approach: Effective Hamiltonian
- Best fit model has Wilson coefficient $C_{9}^{NP} \approx -1$ (4 to 5σ)
- What can explain this?
  1. Statistical fluctuations
  2. Not-yet-understood SM effects
  3. New Physics
- Strong case for violation of lepton universality

This Talk
1. $R_K$
2. $R(D^*)$
3. $\mathcal{B}(B_s^0 \to \tau^+\tau^-)$ ← New!

S.Descotes-Genon et al., JHEP 06 (2016) 092
arxiv:1510.04239

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The LHCb Detector

Forward arm spectrometer to study b- and c-hadron decays

- Pseudo-rapidity coverage: $2 < \eta < 5$

- Good impact parameter resolution to identify secondary vertices:
  $(15 + 29/p_T) \mu m$

- Invariant mass resolution:
  - $8 \text{ MeV}/c^2$ ($B \rightarrow J/\psi X$)
  - $22 \text{ MeV}/c^2$ ($B \rightarrow hh$)

- Excellent particle identification:
  - 95% K ID efficiency
  - 5% $\pi \rightarrow K$ mis-ID

- Versatile & efficient trigger for b- and c-hadrons and forward EW signals
\[ R_K \quad R(D^*) \quad \mathcal{B}(B_s^0 \rightarrow \tau^+\tau^-) \]
Test of Lepton Universality: $R_K$

LHCb, PRL 113 (2014) 151601, arxiv:1406.6482

- **Definition**

$$R_K \equiv \frac{\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)} \xrightarrow{SM} 1 \pm \mathcal{O}(10^{-4})$$

- Measured relative to their $B^+ \rightarrow J/\psi (\rightarrow \ell^+ \ell^-)K^+$ counterparts
- Determined for the range $1 < q^2 < 6\text{GeV}^2/c^4$ in momentum transfer $q^2$ to lepton system
- Using the full Run 1 data

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

- 2.6$\sigma$ deviation from the SM
$R_K$

\[ R(D^*) \]

$B(S^0 \rightarrow \tau^+ \tau^-)$
Test of Lepton Universality: $R(D^*)$

► Definition

$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu)}$$

► In the SM, only difference between $\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau$ and $\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu$ is due to dependence on the lepton mass

► Theoretically clean quantity $\rightarrow$ accurate SM prediction

$$R(D^*)^{SM} = 0.252 \pm 0.003$$

S. Fajfer et al., PRD85 (2012) 094025, arxiv:1203.2654

LHCb Analysis for $\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau$

► Reconstructed in $D^{*+} \to D^0 (\to K^- \pi^+) \pi^+$ mode

► Reconstructed in leptonic $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ mode

$\rightarrow$ Similar to the normalisation mode $\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu$
Experimental Signature

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

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

Challenges

1. 3 missing neutrinos
   - No narrow (mass) peak to fit

2. Feeddown from higher \( D^* \) resonances
   - Need large MC samples to control the background distributions

3. Large combinatorial background
   - Use isolation variables to suppress or enrich background
Fit Strategy

- Exploit the kinematic differences between the signal and background.
- Perform a 3-dimensional histogram fit to
  1. Missing mass $m_{\text{miss}}^2 = (p_B^\mu - p_{D^*}^\mu - p_\mu^\mu)^2$
  2. Muon energy $E_\mu^\mu$
  3. Four-momentum transfer $q^2 = (p_B^\mu - p_{D^*}^\mu)^2$
- Rest-frame quantities calculated using the $B$’s flight direction to estimate the transverse component of missing momentum.

Legend: $\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$  $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$
Background Sources

Templates

- $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$ Signal [MC]
- $\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu$ Normalisation [MC]
- Combinatorial Background [Data]
- Misidentified $\mu$ background [Data]
- Double charm hadrons [MC]
- $B \rightarrow D^{**} \ell \nu$ [MC]

Form factor dependence included in the fit

Data-driven systematic uncertainties on template shapes
Results

- We measure

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

- 2.1\(\sigma\) deviation from SM

- Good agreement with other measurements

Still to come . . .

- Update including \(R(D)\)

- Measurement of \(R(D^*)\) using hadronic \(\tau^- \to \pi^- \pi^+ \pi^- \nu_{\tau}\) decay
**Experimental Average:**

- $R(D^*) = 0.316 \pm 0.016 \text{ (stat)} \pm 0.010 \text{ (syst)}$
- $R(D) = 0.397 \pm 0.040 \text{ (stat)} \pm 0.028 \text{ (syst)}$

$\Delta \chi^2 = 1.0$

**SM Expectation:**

- $R(D^*) = 0.252 \pm 0.003$
- $R(D) = 0.300 \pm 0.008$

$\gg 4\sigma$ deviation from SM

*Does not yet include latest result from Belle*

Belle, (2016), arxiv:1608.06391
$\mathcal{B}(B_s^0 \rightarrow \tau^+ \tau^-)$
Test of Lepton Universality: $B(B_s^0 \to \tau^+ \tau^-)$

- In the SM, only difference between $B_s^0 \to \tau^+ \tau^-$ and $B_s^0 \to \mu^+ \mu^-$ is due to helicity suppression (lepton mass)
- Theoretically clean quantity $\rightarrow$ accurate SM prediction

\[
B(B^0 \to \tau^+ \tau^-) \overset{\text{SM}}{=} (2.22 \pm 0.19) \times 10^{-8} \quad (1)
\]
\[
B(B_s^0 \to \tau^+ \tau^-) \overset{\text{SM}}{=} (7.73 \pm 0.49) \times 10^{-7} \quad (2)
\]

Bobeth et al., PRL 96 (2006) 241802, arxiv:hep-ex/0511015

- Branching ratio enhanced in many new physics models (leptoquarks, $Z'$, ...)
- Current best limit:

\[
B(B^0 \to \tau^+ \tau^-) < 4.1 \times 10^{-3} \quad \text{at 90\% C.L.}
\]

BaBar, PLB 687 (2010) 139, arxiv:1001.3221

LHCb Analysis for $B_s^0 \to \tau^+ \tau^-$

- Reconstructed in hadronic $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ mode (both $\tau$s)
- Normalisation mode: $B^0 \to D^+ (\to \pi^+ K^- \pi^+) D_s^- (\to K^- K^+ \pi^-)$
Experimental Signature

\[ B^0_s \rightarrow \tau^+ \tau^- \]

\[ B^0 \rightarrow D^+ D^- \]

Challenges

1. 2 missing neutrinos
   - No narrow (mass) peak to fit
   - Cannot differentiate \( B^0_s \) from \( B^0 \)

2. 6 pions = large combinatorial background
   - Use isolation variables to suppress background
   - Use decay geometry to approximately reconstruct the \( B \) and \( \tau \) properties
Intermediate Resonances

- Predominantly proceeds through

\[ \tau^- \rightarrow a_1^-(1260)\nu_\tau \rightarrow \rho^0(770)\pi^-\nu_\tau. \]

- Exploit this in analysis

Subsamples:

- Signal Region [SR]: \((\tau^+ \in 5) \& (\tau^- \in 5)\)

- Background Region [BR]: \((\tau^+ \in 1, 3, 7, 9) \& (\tau^- \in 1, 3, 7, 9)\)

- Control Region [CR]: \((\tau^{\pm} \in 4, 5, 8) \& (\tau^{\mp} \in 4, 8)\)

Selection:

- Cut-based loose selection
- Two-stage neural network
Fit Strategy

- Perform a 1-dimensional histogram fit to the output of a neural network
- Output is remapped such that signal is flat
- The Signal templates are taken from simulation
- The Background template is taken from data control region
Fit Model

Events:

- **Signal**: 17% $B_s^0 \rightarrow \tau^+ \tau^-$ Simulation versus 4.8% data
- **Background**: 11% $B_s^0 \rightarrow \tau^+ \tau^-$ Simulation versus 44% data
- **Control**: 55% $B_s^0 \rightarrow \tau^+ \tau^-$ Simulation versus 41% data

▶ ...so the data control region might also contain signal.

Model:

$$\text{NN}_{\text{data}}^{\text{SR}} = s \times \hat{\text{NN}}_{\text{sim}}^{\text{SR}} + f_b \times \left( \text{NN}_{\text{data}}^{\text{CR}} - s \cdot \frac{\epsilon_{\text{CR}}}{\epsilon_{\text{SR}}} \times \hat{\text{NN}}_{\text{sim}}^{\text{CR}} \right)$$

▶ $s$: signal yield (free parameter)
▶ $f_b$: scale factor for background template (free parameter)
▶ $\epsilon_i$: efficiencies, taken from simulation
▶ $\hat{\cdot}$: indicates normalised distributions
Fit to Data

Background-Only Model

Nominal Fit Model

$N_{\tau^+\tau^-}^{\text{obs}} = s = -46 \pm 51$

- Compatible with the background-only hypothesis
- Set an upper limit
\[ \mathcal{B}(B_s^0 \to \tau^+\tau^-) = \alpha_s \cdot N_{\tau^+\tau^-}^{\text{obs}}, \]

- Assume all signal comes from \( B_s^0 \to \tau^+\tau^- \), i.e. ignore \( B^0 \to \tau^+\tau^- \) completely
- Determine \( \alpha_s \) using \( B^0 \to D^- D_s^+ \) normalisation mode

\[
\alpha_s = \frac{\epsilon^{D^- D_s^+} \cdot \mathcal{B}(B^0 \to D^- D_s^+) \cdot \mathcal{B}(D^+ \to \pi^- K^- \pi^+) \cdot \mathcal{B}(D_s^+ \to K^+ K^- \pi^+)}{N_{D^- D_s^+}^{\text{obs}} \cdot \epsilon^{\tau^+\tau^-} \cdot [\mathcal{B}(\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau)]^2} \cdot \frac{f_d}{f_s}
\]

- Fit to data, Efficiencies from simulation, External Input

\[
\alpha_s = (3.16 \pm 0.43) \times 10^{-5} \quad \rightarrow \quad N_{\tau^+\tau^-}^{\text{SM}} = 0.0245 \pm 0.0037 \quad (3)
\]

\[
\alpha_d = (0.94 \pm 0.16) \times 10^{-5} \quad \rightarrow \quad N_{\tau^+\tau^-}^{\text{SM}} = 0.0024 \pm 0.0004 \quad (4)
\]

- Model-dependent result based on EvtGen simulation of \( \tau^- \to \pi^- \pi^+ \pi^- \nu_\tau \)
Branching Fraction Limit

$LHCb$, $LHCb$-CONF-2016-011

$B_s^0 \rightarrow \tau^+ \tau^-$

$B^0 \rightarrow \tau^+ \tau^-$

- Observed limit

$$B(B_s^0 \rightarrow \tau^+ \tau^-) < 3.0 \times 10^{-3} \quad @ \text{95\% C.L.}$$

$$B(B^0 \rightarrow \tau^+ \tau^-) < 1.3 \times 10^{-3} \quad @ \text{95\% C.L.}$$

- Model-dependent result based on EvtGen simulation of $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$
Conclusion

- Ratio of branching fraction involving $B^+ \rightarrow K^+ \ell^+ \ell^-$
  \[ R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)} \]
  \( \rightarrow \) 2.6\( \sigma \) deviation from the SM

- Ratio of branching fraction involving $\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau$
  \[ R(D^*) = 0.336 \pm 0.027 \text{ (stat)} \pm 0.030 \text{ (syst)} \]
  \( \rightarrow \) 2.1\( \sigma \) deviation from the SM

- First limit on the $B^0_s \rightarrow \tau^+ \tau^-$ branching ratio
  \[ \mathcal{B}(B^0_s \rightarrow \tau^+ \tau^-) < 3.0 \times 10^{-3} \quad @ \text{95\% C.L.} \]
  \[ \mathcal{B}(B^0 \rightarrow \tau^+ \tau^-) < 1.3 \times 10^{-4} \quad @ \text{95\% C.L.} \]

- Decays involving $\tau$’s play an important role in tests of lepton universality