Status of LFU tests in B-meson decays from LHCb

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On behalf of the LHCb Collaboration
Universidade de Santiago de Compostela
Today's outline

INTRODUCTION
- Lepton Flavour Universality
- LHCb experiment

CHARGED CURRENTS
- Muonic $R(D^*)$
- Hadronic $R(D^*)$
- $R(J/\psi)$

NEUTRAL CURRENTS
- $R(K^*)$
- $R(K)$

PROSPECTS
- Future analysis
- Future strategies

CONCLUSIONS
- Global picture
- Conclusions
Introduction
SM predicts **Lepton Flavour Universality (LFU)**: equal couplings between gauge bosons and the three lepton families.

Observation of violation of LFU would be sign of **new physics**.

A large class of BSM models contain new interactions that involve third generations of quarks and leptons:

- Charged Higgs
- Leptoquarks
- $Z'$
- $W'$
- ...

Tensions between SM expectation and experimental results:

- **Charged currents**: $b \rightarrow cl\nu$
- **Neutral currents**: $b \rightarrow sll$
\[ R \left( D^{(*)} \right) = \frac{\mathcal{B}(B \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^-\bar{\nu}_\mu)} \]

- **Tree Level**
- Potential NP that couples different between generations

\[ R \left( K^{(*)} \right) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} \]

- **FCNC process.** Forbidden tree level in SM
- Sensitive to either tree or loop NP contributions

[\( b \to c l \nu \)]

[\( b \to s l l \)]
The LHCb detector

- Excellent vertex and momentum resolution

[IP* resolution 20 µm
δp/p=[0.5-1]% (low p-200GeV/c)]

*Impact Parameter: Transverse distance of closest approach between a particle trajectory and a vertex
The LHCb detector

- Excellent **vertex and momentum resolution**
- Excellent **charged particle identification**

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*Impact Parameter: Transverse distance of closest approach between a particle trajectory and a vertex*
The LHCb detector

- Excellent **vertex and momentum resolution**
- Excellent **charged particle identification**
- Capability for **neutral particle identification**

*Impact Parameter: Transverse distance of closest approach between a particle trajectory and a vertex*

**IP** resolution 20 μm

\[ \delta p/p = [0.5-1] \% \text{ (low p-200GeV/c)} \]
Charged currents
**Why semitauonic decays?**

**Tree level decays** in the SM, mediated by a $W$ boson

\[
R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \tau \nu_\tau)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \mu \nu_\mu)}
\]

\[\mathcal{H}_b = B^0, B^{+}_c, \Lambda^0_b, B^0_s, \ldots\]

\[\mathcal{H}_c = D^*, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi, \ldots\]

- **Clean prediction from SM**
  - Partial cancellation of form factor uncertainties in the ratio
  - **Large rate** of charged current decays: $\mathcal{B}(B \to D^* \tau \nu) \sim 1.2\%$ in SM
  - Deviation from unity due to different lepton masses ($\tau, \mu$)

- **Sensitivity to NP** contributions at tree level
Why semitauonic decays?

Tree level decays in the SM, mediated by a $W$ boson

$$R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \tau \nu_\tau)}{\mathcal{B}(\mathcal{H}_b \to \mathcal{H}_c \mu \nu_\mu)}$$

- $\mathcal{H}_b = B^0, B^+_c, \Lambda_b^0, B^0_s ...$
- $\mathcal{H}_c = D^*, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi ...$

- **Clean prediction from SM**
  - Partial cancellation of form factor uncertainties in the ratio
  - **Large rate** of charged current decays: $\mathcal{B}(B \to D^* \tau \nu) \sim 1.2 \%$ in SM
  - Deviation from unity due to different lepton masses ($\tau, \mu$)

- **Sensitivity to NP** contributions at tree level

At LHCb...

- Missing momentum of neutrinos: Missing kinematic constraints
- $B$ momentum unknown: approximations
- **Two reconstruction channels for $\tau$**
  - Muonic mode: $\tau \to \mu \nu_\mu \nu_\tau$
  - Hadronic mode: $\tau \to \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau$
Before LHCb...

Belle and BaBar studied semitauonic B decays at the B-factories

- $e^+e^-$ collisions producing $\Upsilon(4S) \rightarrow B\bar{B}$
- Measurement of the B-signal using fully reconstructed B-tag and a constraint to the $\Upsilon(4S)$ mass
- Complementary measurement of $R(D)$ and $R(D^*)$ yielded $3.7\sigma$ from SM
In hadron collisions things are not as clean as in B factories...

- Unknown CM frame for $gg \rightarrow b\bar{b}$
- Need to deal with missing kinematic constraints
- A lot of additional particles in the event: large backgrounds from combinatorial and partially-reconstructed B decays
First measurement of $R(D^*)$ in a hadron collider, using the muonic decay of $\tau$

$$R\left(D^*\right) = \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^* + \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^* + \mu^- \bar{\nu}_\mu)}$$

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

**Features of the analysis...**

- Missing kinematic constraints. **Rest frame approximation**
- $B$ boost along $z$ axis $>>$ boost of decay products in $B$ rest frame

$$ (\gamma \beta_z)_B = (\gamma \beta)_{D^* \mu} \Rightarrow (p_z)_B = \frac{m_B}{m(D^* \mu)} (p_z)_{D^* \mu} $$

18% **resolution on** $p_B$, good enough to preserve signal and background discrimination
18\% resolution on $p_B$, good enough to preserve signal and background discrimination.
**Result:** separate $\tau$ and $\mu$ components via a **3D binned template fit** to the $q^2$, $m_{miss}^2$ and $E^*_\mu$ distributions

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

$\sim 2.1 \sigma$ from SM

$$\frac{q^2}{(p_B - p_{D^*})^2} = m_{W^*}^2$$

$$m_{miss}^2 = (p_B - p_{D^*} - p_\mu)^2 = m_{3\ell}^2$$
R(D*) muonic at LHCb

### Systematics:

<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>$B^0 \rightarrow D^{*+}(\tau^-/\mu^-)\bar{\nu}^\nu$ form factors</td>
<td>0.6</td>
</tr>
<tr>
<td>$\bar{B} \rightarrow D^{*+}H_c(\rightarrow \mu\nuX')X$ shape corrections</td>
<td>0.5</td>
</tr>
<tr>
<td>$B(\bar{B} \rightarrow D^{**}\tau^-\bar{\nu}<em>\tau)/B(\bar{B} \rightarrow D^{*+}\mu^-\bar{\nu}</em>\mu)$</td>
<td>0.5</td>
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<tr>
<td>$\bar{B} \rightarrow D^{**}(\rightarrow D^*\pi\pi)\mu\nu$ shape corrections</td>
<td>0.4</td>
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<tr>
<td>Corrections to simulation</td>
<td>0.4</td>
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<tr>
<td>Combinatorial background shape</td>
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<tr>
<td>$\bar{B} \rightarrow D^{**}(\rightarrow D^{*+}\pi)^\mu^-\bar{\nu}_\mu$ form factors</td>
<td>0.3</td>
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<tr>
<td>$\bar{B} \rightarrow D^{*+}(D_s \rightarrow \tau\nu)X$ fraction</td>
<td>0.1</td>
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<tr>
<td>Total model uncertainty</td>
<td><strong>2.8</strong></td>
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</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>
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<tr>
<td>Hardware trigger efficiency</td>
<td>0.6</td>
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<tr>
<td>Particle identification efficiencies</td>
<td>0.3</td>
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<tr>
<td>Form factors</td>
<td>0.2</td>
</tr>
<tr>
<td>$B(\tau^- \rightarrow \mu^-\bar{\nu}<em>\mu\nu</em>\tau)$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>Total normalization uncertainty</td>
<td><strong>0.9</strong></td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td><strong>3.0</strong></td>
</tr>
</tbody>
</table>
**R(D*) hadronic at LHCb**

- First measurement of R(D*) using the hadronic $\tau$ decay with $\tau \rightarrow \pi^+ \pi^- \pi^0 \nu_\tau$
- What is measured:

\[
R_{\text{had}}(D^{*-}) = \frac{B(B^0 \rightarrow D^{*-} \tau^+ \nu_\mu)}{B(B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}} \times \frac{1}{B(\tau^+ \rightarrow \pi^+ \pi^- \pi^+ \pi^0 \bar{\nu}_\tau)}
\]

- Approximations are done to reconstruct the $B$ and $\tau$ momentum. Good precision obtained
- Signal and normalization same visible state: $D^{*-} \pi^+ \pi^- \pi^+$
- Most of the theoretical and experimental uncertainties on cancel out in the ratio
- $R(D^{*-})$ obtained from:

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

<table>
<thead>
<tr>
<th>$\tau$ decay mode</th>
<th>BR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu \nu_\mu \nu_\tau$</td>
<td>17.39 ± 0.04</td>
</tr>
<tr>
<td>$\tau \rightarrow e \nu_\mu \nu_\tau$</td>
<td>17.82 ± 0.04</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$</td>
<td>9.31 ± 0.05</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$</td>
<td>4.62 ± 0.05</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^- \nu_\tau$</td>
<td>10.82 ± 0.05</td>
</tr>
<tr>
<td>$\tau \rightarrow \rho^- \nu_\tau$</td>
<td>25.49 ± 0.09</td>
</tr>
</tbody>
</table>

[PRD 97, 072013 (2018)] [PRL 120, 171802 (2018)]
\textbf{R(D\*) hadronic at LHCb}

- Largest background due to $B \rightarrow D^* \pi^+ \pi^- \pi^+ X$ (neutrals), where 3 pions come from the $B$ vertex (100 higher than the signal)
  - Requirement: decay topology with minimum distance between $B$ and $\tau$ vertices: $\Delta z > 4 \sigma_{\Delta z}$
  - Suppressed by 3 orders of magnitude
- 2nd largest background is the double charm $B \rightarrow D^* D_s^+ X$: Multivariate Analysis

\begin{itemize}
  \item \textbf{Measurements of $R(D^*)$ using 3-prong hadronic $\tau^+ \rightarrow \pi^- \pi^+ \pi^+$ decays.}
  \item Most abundant background $B \rightarrow D^* \pi^+ \pi^- \pi^+$ suppressed by requiring a significant displacement between the $\tau$ and $B$ vertices.
  \item $B^0 \rightarrow D^* \pi^+ \pi^- \pi^+$ used as normalisation.
  \item Main remaining background due to $B \rightarrow D^* \pi^+ \pi^- \pi^+ X$ decays, with $D \rightarrow \pi^+ \pi^- \pi^+ X$.
  \item Signal yield extracted from a 3D fit to $q^2$, $\tau$ decay time a BDT (includes kinematic and isolation variables).
\end{itemize}

\begin{align*}
R(D^*) &= 0.285 \pm 0.019 \text{(stat)} \pm 0.025 \text{(syst)} \pm 0.014 \text{(ext)}
\end{align*}

[arXiv:1711.02505]
R(D*) hadronic at LHCb

- Most important background after the vertex cut comes from $B \rightarrow D^* - D_s^+ X$
- Multivariate Analysis: 18 variables combined in a BDT:
  - 3 $\pi$ variables
  - $D^* - 3\pi$ dynamics
  - Neutral isolation variables

BDT used as variable in the fit to extract signal yield
**R(D*) hadronic at LHCb**

**Result Run 1 data:**
- \(N(B^0 \rightarrow D^* \pi^+ \pi^- \pi^+ \pi^-)\) unbinned likelihood fit to \(M(D^* \pi^+ \pi^- \pi^-)\)
- \(N(B^0 \rightarrow D^* \tau^+ \nu_{\tau})\) three dimensional binned fit to data

**Variables:** \(\tau\) decay time, \(q^2\), BDT output

\[
R(D^*) = 0.291 \pm 0.019\,(stat) \pm 0.026\,(syst) \pm 0.013\,(ext)
\]
R(D*) hadronic at LHCb

Systematics:

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Value in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(\tau^+ \to 3\pi \nu_\tau)/B(\tau^+ \to 3\pi(\pi^0)\nu_\tau)$</td>
<td>0.7</td>
</tr>
<tr>
<td>Form factors (template shapes)</td>
<td>0.7</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>$B \to D^{**}\tau^+\nu_\tau$</td>
<td>2.3</td>
</tr>
<tr>
<td>$B^0 \to D^{*+}\tau^+\nu_\tau$ feed-down</td>
<td>1.5</td>
</tr>
<tr>
<td>$D_s^+ \to 3\pi X$ decay model</td>
<td>2.5</td>
</tr>
<tr>
<td>$D_s^+, D^0$ and $D^+$ template shape</td>
<td>2.9</td>
</tr>
<tr>
<td>$B \to D*-D_s^+(X)$ and $B \to D*-D^0(X)$ decay model</td>
<td>2.6</td>
</tr>
<tr>
<td>$D*-3\pi X$ from $B$ decays</td>
<td>2.8</td>
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<tr>
<td>Combinatorial background (shape + normalization)</td>
<td>0.7</td>
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<tr>
<td>Bias due to empty bins in templates</td>
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<tr>
<td>Size of simulation samples</td>
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<td>Trigger acceptance</td>
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<td>Trigger efficiency</td>
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<td>Online selection</td>
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<td>Offline selection</td>
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<td>Charged-isolation algorithm</td>
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<td>Normalization channel</td>
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<td>Particle identification</td>
<td>1.3</td>
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<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 $B^0 \to D*-3\pi$)</td>
<td>2.0</td>
</tr>
<tr>
<td>Form factors (efficiency)</td>
<td>1.0</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>9.1</td>
</tr>
</tbody>
</table>
R(D^*) hadronic at LHCb

Main systematic uncertainties due to:

- Size of simulated simple
- Shape of the background $B \to D^*-D_s^+X$
- $D_{(s)}^+ \to \pi^+\pi^-\pi^+X$ decay mode. BESIII future measurement will reduce this uncertainty. Improvement as well of the upgraded ECAL
- Branching fraction of normalisation mode $B^0 \to D^*-\pi^+\pi^-\pi^+$ known with ~4% precision. Belle II can measure it precisely
**R(D(∗)) global picture**

- **R(D(∗)) world average** is in tension with the SM at the level of 3.0 σ

*Graphical data and conclusions:*

- WA combination of R(D) and R(D(∗)) is in tension with SM at the 3.8 σ level

*Statistical summaries:*

- **BaBar had. tag**
  - 0.322 ± 0.024 ± 0.018

- **Belle had. tag**
  - 0.293 ± 0.038 ± 0.015

- **Belle sl.tag**
  - 0.302 ± 0.030 ± 0.011

- **Belle hadronic tau**
  - 0.270 ± 0.035 ± 0.027

- **LHCb muonic tau**
  - 0.336 ± 0.027 ± 0.030

- **LHCb hadronic tau**
  - 0.291 ± 0.019 ± 0.029

- **Average**
  - 0.306 ± 0.013 ± 0.007

- **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

- **Average of SM predictions**

- **Δχ² = 1.0 contours**
  - R(D) = 0.299 ± 0.003
  - R(D(∗)) = 0.258 ± 0.005

*Statistical significance:*

- HFLAV Summer 2018
  - P(χ²) = 74%

*Comparative analysis:*

- **R(D) = 0.299 ± 0.003**
- **R(D(∗)) = 0.258 ± 0.005**

- BaBar, PRL109,101802(2012)
- Belle, PRD92,072014(2015)
- LHCb, PRL115,111803(2015)
- Belle, PRD94,072007(2016)
- Belle, PRD94,072007(2016)
- Belle, PRL118,211801(2017)
- LHCb, PRL120,171802(2018)
The $R(J/\psi)$ global picture

Generalization of $R(D^*)$ in the $B_c$ sector

$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)}$$

with $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$

- Form factors unconstrained experimentally
  Poorly calculated from theory

**Result:** 3D binned maximum likelihood fit to data

Variables: decay time, $m_{miss}^2$, $Z(E^*, q^2)$

$$R(J/\psi) = 0.71 \pm 0.17(stat) \pm 0.18(syst)$$

$$R_{SM}(J/\psi) \in [0.25, 0.28]$$

~2σ from SM
### Systematics:

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>Size ($\times 10^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite simulation size</td>
<td>8.0</td>
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<tr>
<td>$B_c^+ \rightarrow J/\psi$ form factors</td>
<td>12.1</td>
</tr>
<tr>
<td>$B_c^+ \rightarrow \psi(2S)$ form factors</td>
<td>3.2</td>
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<tr>
<td>Fit bias correction</td>
<td>5.4</td>
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<tr>
<td>$Z$ binning strategy</td>
<td>5.6</td>
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<tr>
<td>Mis-ID background strategy</td>
<td>5.6</td>
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<tr>
<td>combinatorial background cocktail</td>
<td>4.5</td>
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<tr>
<td>combinatorial $J/\psi$ background scaling</td>
<td>0.9</td>
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<tr>
<td>$B_c^+ \rightarrow J/\psi H_c X$ contribution</td>
<td>3.6</td>
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<tr>
<td>$\psi(2S)$ and $\chi_c$ feed-down</td>
<td>0.9</td>
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<tr>
<td>Weighting of simulation samples</td>
<td>1.6</td>
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<tr>
<td>Efficiency ratio</td>
<td>0.6</td>
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<tr>
<td>$\mathcal{B}(\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau)$</td>
<td>0.2</td>
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<tr>
<td>Systematic uncertainty</td>
<td>17.7</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>17.3</td>
</tr>
</tbody>
</table>
Neutral currents
Rare $b \rightarrow s l l$ decays

**Flavour Changing Neutral Current transitions.** Proceed via loop diagrams. Within a given range of the dilepton mass squared, $q^2$:

$$R_X[q_{min}^2, q_{max}^2] = \frac{\int_{q_{min}^2}^{q_{max}^2} dq^2 \frac{d\Gamma(B \rightarrow X \mu^+ \mu^-)}{dq^2}}{\int_{q_{min}^2}^{q_{max}^2} dq^2 \frac{d\Gamma(B \rightarrow X e^+ e^-)}{dq^2}}$$

with $X = K, K^*, \phi$...

- **SM expectation** $R_X = 1$, neglecting lepton masses
  - Partial cancellation of hadronic uncertainties in theoretical predictions
- **Suppressed in SM**: more sensitive to NP

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**At LHCb...**

- Extremely challenging due to significant differences in the way $\mu$ and $e$ interact with the detector: Bremsstrahlung, trigger
- **LHCb published measurements**:
  - $R_K$
  - $R_K^*$

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Beatriz García Plana (IGFAE-USC)  
Mainz Model Builders 2019
LHCb measured $R(K^*)$ for $q^2 \in [0.045, 1.1]$ and $[1.1, 6.0]$ GeV$^2$/c$^4$, with $K^{*0} \to K^* \pi^-$ Double ratio to reduce systematics:

\[
R(K^*) = \frac{\mathcal{B}(B^0 \to K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi \to (\mu^+ \mu^-))} \bigg/ \frac{\mathcal{B}(B^0 \to K^{*0} e^+ e^-)}{\mathcal{B}(B^0 \to K^{*0} J/\psi \to (e^+ e^-))}
\]

**Bremsstrahlung effects:**
**two reconstruction strategies**

- **Upstream of the magnet:** Photon energy is likely to be in different calorimeter cell than electron (E1)
- **Downstream of the magnet:** Photon energy is likely to be in the same calorimeter cell as the electron (E2)
**Bremsstrahlung effects**

- Worse separation of partially reconstructed backgrounds
- Recovery procedure → improvement of momentum resolution, B mass resolution
- Background from the $J/\psi$ and $\psi(2S)$ contaminate the signal region

○ Electron sample is separated in **3 Bremsstrahlung categories** (0γ, 1γ, ≥2γ)

○ **3 types of trigger**: electrons (L0E), hadrons (L0H) and signal independence (L0I)

**Maximize the electron sample size**
Result: Fit to $B$ mass distribution in lower and central $q^2$ bin

Simultaneous fit $M(K^+\pi^-l^+l^-)$ to the $J/\psi$ and non-resonant channels

**Low $q^2$ bin**

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

$0.045 < q^2 < 1.1 \text{ [GeV}^2/c^4]\text{]}

**Central $q^2$ bin**

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

$1.1 < q^2 < 6.0 \text{ [GeV}^2/c^4]\text{]}

**Normalization channel**

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

$-5 \leq \text{Pulls Candidates per 10 MeV}/c^2 \leq 5$

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

$B^0 \rightarrow \pi^0\pi^0\pi^0$

$-5 \leq \text{Pulls Candidates per 10 MeV}/c^2 \leq 5$

$m(K^+\pi^-\pi^0\pi^0) \text{ [MeV}/c^2]\text{]}

$B^0 \rightarrow K^0\pi^+\pi^-$

$-5 \leq \text{Pulls Candidates per 10 MeV}/c^2 \leq 5$

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

$B^0 \rightarrow K^0\pi^+\pi^-$

$-5 \leq \text{Pulls Candidates per 34 MeV}/c^2 \leq 5$

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

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

$B^0 \rightarrow K^0\pi^+\pi^-$

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

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

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Mainz Model Builders 2019
### LHCb:

<table>
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<tr>
<th>$q^2$ bin</th>
<th>$\mathcal{R}(K^*)$</th>
<th>$\sigma$ from SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>$0.66^{+0.11}_{-0.07} \pm 0.03$</td>
<td>$\sim 2.2$</td>
</tr>
<tr>
<td>Central</td>
<td>$0.69^{+0.11}_{-0.07} \pm 0.05$</td>
<td>$\sim 2.4$</td>
</tr>
</tbody>
</table>

- **LHCb result most precise measurement up to date**
- **Statistically limited by the electron sample size**
# Systematics:

<table>
<thead>
<tr>
<th>Trigger category</th>
<th>( \Delta R_{K^{*0}} / R_{K^{*0}} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low-(q^2)</td>
</tr>
<tr>
<td></td>
<td>L0E</td>
</tr>
<tr>
<td>Corrections to simulation</td>
<td>2.5</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.1</td>
</tr>
<tr>
<td>PID</td>
<td>0.2</td>
</tr>
<tr>
<td>Kinematic selection</td>
<td>2.1</td>
</tr>
<tr>
<td>Residual background</td>
<td>–</td>
</tr>
<tr>
<td>Mass fits</td>
<td>1.4</td>
</tr>
<tr>
<td>Bin migration</td>
<td>1.0</td>
</tr>
<tr>
<td>( r_{J/\psi} ) ratio</td>
<td>1.6</td>
</tr>
<tr>
<td>Total</td>
<td>4.0</td>
</tr>
</tbody>
</table>
In 2014, LHCb measured $R(K)$ for $q^2 \in [1, 6]$ GeV$^2$/c$^4$

- Double ratio of rare/$J/\psi$ channel used to reduce the systematic uncertainties
- Low efficiency for electrons: Bremsstrahlung effects
- Signal extracted via **invariant mass fits**
- Dominant source of systematic uncertainty are due to the parametrization $B^+ \rightarrow J/\psi (\rightarrow e^+e^-)K^+$ mass distribution and trigger efficiencies. Both contribute $\sim 3\%$ to the value of $R(K)$

\[
R(K) = 0.755^{+0.090}_{-0.074} (\text{stat}) \pm 0.036 (\text{syst})
\]

\[
R_{SM}(K) = 1 \pm \mathcal{O}(10^{-2})
\]

2.6 $\sigma$ from SM

**Global fit. NP preferred over SM by $\sim 4\sigma$**

Beatriz García Plana (IGFAE-USC)

Mainz Model Builders 2019
Future prospects
R(H_c) future analysis

- **R(Λ_c):** Hadronic mode \( \tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0)\nu_\tau \)
  - Reconstruction mode \( \Lambda_c^+ \rightarrow pK^-\pi^+ \)
  - Measurement stategy: \( R(\Lambda_c) = \mathcal{K}(\Lambda_c) \times N_1 \times N_2 \times N_3 \)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Method to obtain it</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{K}<em>c = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \tau^- \bar{\nu}</em>\tau)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-)} )</td>
<td>( \frac{N_{\text{sig}}}{N_{\text{norm}}} \times \frac{\epsilon_{\text{norm}}}{\epsilon_{\text{sig}}} \times \frac{1}{\mathcal{B}(\tau^- \rightarrow \pi^- \pi^+ \pi^- (\pi^0)\nu_\tau)} )</td>
</tr>
<tr>
<td>( N_1 = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^- \pi^+ \pi^-)}{\mathcal{B}(B^0 \rightarrow D^*^- \pi^+ \pi^- \pi^+)} )</td>
<td>Estimated directly within LHCb with a good statistical and systematic uncertainty</td>
</tr>
<tr>
<td>( N_2 = \frac{\mathcal{B}(B^0 \rightarrow D^- \mu^+ \nu_\mu)}{\mathcal{B}(B^0 \rightarrow D^*^- \pi^+ \pi^- \pi^+)} )</td>
<td>Measured branching fractions (PDG), uncertainty ( \sim 5% )</td>
</tr>
<tr>
<td>( N_3 = \frac{\tau_{B^0}}{\tau_{\Lambda_b^0}} \times \frac{\Gamma(B^0 \rightarrow D^- \mu^+ \nu_\mu)}{\Gamma(\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu)} )</td>
<td>Partial widths computed using Lattice QCD, uncertainty 9%</td>
</tr>
</tbody>
</table>

- Total uncertainty coming from normalization \( \sim 10-12\% \)

- **R(Λ_c): Muonic ongoing**
R(H_c) future analysis

- **R(D), R(D\(*\)):** Hadronic and muonic mode
  - Selection \( B \rightarrow D^{\{+,0\}} 3\pi \)
  - Analized modes:
    - \( D^- \rightarrow K^+ \pi^- \pi^- \)
    - \( D^0 \rightarrow K^- \pi^+ \)
    - \( D^*^- \rightarrow D^0 \pi^- \)
    - \( D^*^- \rightarrow D^- \pi^0 \)
    - \( D^*0 \rightarrow D^0 \pi^0 \)

- Measurement strategy:
  - Hadronic mode: Choice of normalization channel. Possible strategy simultaneous fit to different categories
  - Muonic mode: Alternative strategies for \( D^0 \) and \( D^- \) samples

### Possible Norm. Channels

<table>
<thead>
<tr>
<th>Decay</th>
<th>BR (PDG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^0 \rightarrow D^- 3\pi )</td>
<td>((6.0 \pm 0.7) \times 10^{-3})</td>
</tr>
<tr>
<td>( B^0 \rightarrow D^- D_s^+ )</td>
<td>((7.2 \pm 0.8) \times 10^{-3})</td>
</tr>
<tr>
<td>( B^0 \rightarrow D^*^- 3\pi )</td>
<td>((7.21 \pm 0.29) \times 10^{-3})</td>
</tr>
<tr>
<td>( B^0 \rightarrow D^*^- D_s^+ )</td>
<td>((8.0 \pm 1.1) \times 10^{-3})</td>
</tr>
<tr>
<td>( B^- \rightarrow D^0 3\pi )</td>
<td>((5.6 \pm 2.1) \times 10^{-3})</td>
</tr>
<tr>
<td>( B^- \rightarrow D^0 D_s^- )</td>
<td>((9.0 \pm 0.9) \times 10^{-3})</td>
</tr>
<tr>
<td>( B^- \rightarrow D^*0 3\pi )</td>
<td>((1.03 \pm 0.12) \times 10^{-2})</td>
</tr>
<tr>
<td>( B^- \rightarrow D^*0 D_s^+ )</td>
<td>((8.2 \pm 1.7) \times 10^{-3})</td>
</tr>
<tr>
<td>( D_s^- \rightarrow 3\pi )</td>
<td>((1.09 \pm 0.05) \times 10^{-2})</td>
</tr>
</tbody>
</table>

We need precise measurements! (BelleII, BESIII...)
Future prospects

LHCb phase 1 upgrade:
- Run 3 (2021-2023): 22 fb$^{-1}$
- Run 4 (2026-2029): 50 fb$^{-1}$

Belle II:
- 2024: 50 ab$^{-1}$

**R(D*) future prospects**

![R(D*) plot]

**R(H_c) future prospects**

![R(H_c) plot]

[arXiv:1709.10308]

Conclusions
Conclusions

**LFUV road to new physics!**

Semileptonic B decays hint anomalies with respect to the SM at both tree and loop levels
Conclusions

**LFUV road to new physics!**

Semileptonic B decays hint anomalies with respect to the SM at both tree and loop levels

• LHCb results using Run 1 data. Dominated by statistical uncertainties
• Systematic uncertainties:
  • Many are assumed to scale with the accumulated statistics at LHCb
  • Others will be improved with external measurements

Belle II
BESIII
Conclusions

**LFUV road to new physics!**

Semileptonic B decays hint anomalies with respect to the SM at both tree and loop levels

- LHCb results using Run 1 data. Dominated by statistical uncertainties
- Systematic uncertainties:
  - Many are assumed to scale with the accumulated statistics at LHCb
  - Others will be improved with external measurements
- 9.2 fb⁻¹ recorded at the end of Run 2. Exciting program ahead!

*Ongoing and planned*

\[ R(D^{(*)0}), R(D^{(*)+}), R(\Lambda_c^{(*)}), R(D_s^{(*)+}), R(J/\psi), \ldots \]

\[ R(\Phi), R(K_s), R(\Lambda), \ldots \]
Thank for your attention

Any question?
Backup slides
Angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ exhibits rich angular structure
- Optimized angular observable $P'_5$
  - The differential decay width can be parametrised in terms of this observable
  - Aim to reduce dependence on hadronic form factors

- LHCb measurement is in tension at the 3.4 $\sigma$
- Global picture at $q^2$ bins [4,6] and [6,8] GeV$^2$/c$^4$ is in tension with the SM at the level of 2.8 $\sigma$ and 3 $\sigma$

LHCb: JHEP02 (2016) 104
Belle: PRL 118 (2017) 111801
ATLAS: arXiv:1805.04000
CMS: CMS-PAS-BPH-15-008
$|\vec{p}_\tau| = \frac{(m_{3\pi}^2 + m_\tau^2)|\vec{p}_{3\pi}| \cos \theta \pm E_{3\pi} \sqrt{(m_{\tau}^2 - m_{3\pi}^2)^2 - 4m_\tau^2|\vec{p}_{3\pi}|^2 \sin^2 \theta}}{2(E_{3\pi}^2 - |\vec{p}_{3\pi}|^2 \cos^2 \theta)}$,

$|\vec{p}_{B^0}| = \frac{(m_{D^*\tau}^2 + m_{B^0}^2)|\vec{p}_{D^*\tau}| \cos \theta' \pm E_{D^*\tau} \sqrt{(m_{B^0}^2 - m_{D^*\tau}^2)^2 - 4m_{B^0}^2|\vec{p}_{D^*\tau}|^2 \sin^2 \theta'}}{2(E_{D^*\tau}^2 - |\vec{p}_{D^*\tau}|^2 \cos^2 \theta')}$

$\theta_{\text{max}} = \arcsin \left( \frac{m_\tau^2 - m_{3\pi}^2}{2m_\tau |\vec{p}_{3\pi}|} \right)$

$\theta'_{\text{max}} = \arcsin \left( \frac{m_{B^0}^2 - m_{D^*\tau}^2}{2m_{B^0} |\vec{p}_{D^*\tau}|} \right)$

LHCb simulation

$\frac{q_{\text{reco}}^2 - q_{\text{true}}^2}{q_{\text{true}}^2}$

arbitrary units