Lepton Flavour Universality tests using semitauonic decays at LHCb

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Introduction

Standard Model (CKM)
Lepton universality (LFU)
R(D(\ast)) and BSM physics

Status

Previous R(D(\ast)) measurements
World average

Method

The LHCb experiment
Analysis method
Control samples

Results

Fit results
R(D(\ast)) results
Cross-checks
Systematic uncertainties

Conclusions

Prospects

Conclusions
• In the SM, quarks and leptons are divided in 3 families (or generations).

• Transitions between quarks (i.e. $b \rightarrow c$) of different flavour mediated by a W boson.

• Transitions between quarks of different families suppressed ($|V_{tb}| \sim 1$, $|V_{cb}| \sim 0.04$, $|V_{ub}| \sim 0.004$).
Lepton Flavour Universality

• In the SM, charged lepton flavours are identical copies of one another:
  • Amplitudes for processes involving $e, \mu, \tau$ must be identical up to effects depending on lepton mass.
  • Lepton universality in the SM might be broken by mass-dependent couplings.

• Observation of violations of lepton universality would be a clear sign for new physics.

• Searches have been underway for violations in a number of different systems. For instance $R_K$ and $R_{K^*}$:

$$R_K^{(*)} = \frac{BR(B \rightarrow K^{(*)}\mu\mu)}{BR(B \rightarrow K^{(*)}ee)}$$

• A lot of interest in this area generated by $b \rightarrow sll$ LHCb measurements. [PRL 113, 151601 (2014)] [arXiv:1705.05802]

[S. Bifani LHC seminar, 18/04/2017]
The $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$ decay

- **Tree level transition** mediated by a W in the SM:

  $$B_q \left\{ \begin{array}{c} b \\ q \end{array} \right\} \rightarrow D^{(*)} + B_q \left\{ \begin{array}{c} b \\ q \end{array} \right\} \rightarrow D^{(*)}$$

- New physics (NP) could couple only to the 3\textsuperscript{rd} generation ($\tau$).

- Comparison between semitauonic ($\tau$) and semimuonic ($\mu$) decays sensitive to NP.

- If NP present → Modified BR and angular distributions.
Predictions on $R(D^*)$

- What we want to measure:
  - $R(D^*) = \frac{BR(B^0 \rightarrow D^{*-}\tau^+\nu)}{BR(B^0 \rightarrow D^{*-}\mu^+\nu)}$

- Very clean SM prediction due to cancellation of $B \rightarrow D^*$ form-factor uncertainties.
  - $R_{SM}(D^*) = 0.252 \pm 0.003$

- Deviation from unity due to different $\mu/\tau$ masses (available phase space).


[PRD 85 094025 (2012)]

R($D^*$) in SM and 2 NP scenarios.
Experimental status
R(D(*)) measurements at the B-factories

- $e^+/e^-$ collisions producing $\Upsilon(4S) \rightarrow B\bar{B}$.

- Using fully reconstructed B-tag and a constraint to the $\Upsilon(4S)$ mass, possible to measure the momentum of the B-signal.

- Then, the missing mass (neutrinos) can be measured with high precision.

- At B-factories, semitauonic B decays studied using:
  - **Leptonic**: $\tau \rightarrow \mu \nu \nu$ and $\tau \rightarrow e \nu \nu$. $R(D^{(*)})$ measured with respect to $[BR(B \rightarrow D^{(*)}\mu \nu) + BR(B \rightarrow D^{(*)}e \nu)]/2$.
  - **Hadronic**: $\tau \rightarrow \pi \nu$ and $\tau \rightarrow \rho \nu$.
  - **Hadronic and semileptonic B-tag**.
• Use of $\tau \rightarrow \mu \nu \nu$ and $\tau \rightarrow e \nu \nu$ to reconstruct the $\tau$ lepton.

• Simultaneous analysis $R(D^*)$ vs $R(D)$ using $B^0 \rightarrow D^* \tau \nu$, $B^+ \rightarrow D^{*0} \tau \nu$, $B^0 \rightarrow D^+ \tau \nu$, $B^+ \rightarrow D^0 \tau \nu$.

• Unbinned maximum likelihood fit to $m^2_{\text{miss}}$ and $|p_{\ell^*}|$:
  • $R(D) = 0.440 \pm 0.058 \pm 0.042 \ (2.0\sigma \text{ from SM})$.
  • $R(D^*) = 0.332 \pm 0.024 \pm 0.018 \ (2.7\sigma \text{ from SM})$.
  • Combination at 3.4$\sigma$ above SM.

$\chi^2$: 6.6/12, $p = 88.4\%$

$D^* \ell$

Fit projections on $m^2_{\text{miss}}$ and $|p_{\ell^*}|$:

$\chi^2$ vs $q^2 (\text{GeV}^2)$

$m^2_{\text{miss}} = (p_{B} - p_{D^*} - p_{\ell})^2 = m^2_{3\nu}$

$|p_{\ell^*}|$: Lepton (e/μ) momentum in B rest frame.

$q^2 = (p_B - p_{D^*})^2 = m^2_{W^*}$
Belle measurements

- **\( \tau \to \mu \nu \nu \) and \( \tau \to e \nu \nu \), hadronic B-tag** [Phys. Rev. D 92, 072014 (2015)]:
  - \( R(D^*) = 0.293 \pm 0.038 \text{ (stat)} \pm 0.015 \text{ (syst)} \)
  - \( R(D) = 0.375 \pm 0.064 \text{ (stat)} \pm 0.026 \text{ (syst)} \)

- **\( \tau \to \mu \nu \nu \) and \( \tau \to e \nu \nu \), semileptonic B-tag** [Phys. Rev. D 94, 072007 (2016)]:
  - \( R(D^*) = 0.302 \pm 0.030 \text{ (stat)} \pm 0.011 \text{ (syst)} \)

- **\( \tau \to \pi \nu \) and \( \tau \to \rho \nu \)**, [Phys. Rev. Lett. 118, 211801 (2017)]:
  - \( R(D^*) = 0.270 \pm 0.035 \text{ (stat)}^{+0.028}_{-0.025} \text{ (syst)} \)
  - \( P_\tau(D^*) = -0.38 \pm 0.51 \text{ (stat)}^{+0.21}_{-0.16} \text{ (syst)} \)

- All \( R(D^*) \) measurements consistent but above SM.

06/06/17

A. Romero Vidal
BaBar measurement disfavours Type-II 2HDM.

Compatible with Type-II 2HDM in the region around \( \tan\beta/m_{H^+} = 0.5 \text{ c}^2/\text{GeV} \)

Studied 2 types of leptoquark models. Results allow additional contributions from scalar and vector operators.
LHCb muonic $R(D^*)$

- First measurement of $R(D^*)$ in a hadron collider.

- $\tau$ reconstructed with $\tau \rightarrow \mu \nu \nu$.

- Difficult, due to missing kinematic constraints ($\Upsilon(4S)$).

- $B$ boost along $z \gg$ boost of decay products in $B$ rest frame.

- The $B$ momentum approximated by:

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

- 18% resolution on $p_B$ good enough to preserve signal and background discrimination in $m_{\text{miss}}^2$, $E_\mu^*$ and $q^2$.
**LHCb muonic R(D*)**


- **R(D*)**: fit parameter obtained from a 3-dimensional template fit to $m^2_{miss}$, $E_\mu^*$ and $q^2$:
  - $R(D^*) = 0.336 \pm 0.027 \pm 0.030$

- **Result is 2.1$\sigma$ above SM.**

\[ m^2_{miss} = (p_B - p_{D^*} - p_\mu)^2 = m^2_{3v} \]

\[ E_\mu^*: \text{muon energy in B rest frame.} \]

\[ q^2 = (p_B - p_{D^*})^2 = m^2_{W^*} \]
R(D(\*)) status

- **R(D(\*)) in tension with SM at 3.4\(\sigma\) level.**

- **R(D) and R(D(\*)) combination in tension with SM at the level of 3.9\(\sigma\).**
Measuring $R(D^*)$ using 3-prong $\tau^- \rightarrow \pi^- \pi^+ \pi^-(\pi^0) \nu$ decays

LHCb-PAPER-2017-017, in preparation
• \( \tau \) lepton reconstructed using the \( \tau^− \rightarrow \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau \) decay mode.

• A semileptonic decay without charged leptons in final state (pions and kaons).

• **Zero background** from normal semileptonic decays
  \((B^0 \rightarrow D^*^- \mu^+ \nu_\mu X)\).

• In this analysis, it is the background \((B \rightarrow D^*^- DX)\) that leads to nice mass peaks and not the signal. This provides key handle to control the various backgrounds.

• **Only 1 neutrino** emitted at the \( \tau \) vertex \((\tau^− \rightarrow \pi^- \pi^+ \pi^- (\pi^0) \nu_\tau \) vs \( \tau^\rightarrow \mu \nu_\mu \nu_\tau \)). Fit variables can be reconstructed with reasonable precision.

### \( \tau \) decay mode | BR (%) [PDG-2017]
---|---
\( \tau^\rightarrow \mu \nu_\mu \nu_\tau \) | 17.39 ± 0.04
\( \tau^\rightarrow e \nu_\mu \nu_\tau \) | 17.82 ± 0.04
\( \tau^\rightarrow \pi^\pi^\pi^\nu_\tau \) | 9.31 ± 0.05
\( \tau^\rightarrow \pi^\pi^\pi^0 \nu_\tau \) | 4.62 ± 0.05
\( \tau^\rightarrow \pi^\nu_\tau \) | 10.82 ± 0.05
\( \tau^\rightarrow \rho^\nu_\tau \) | 25.49 ± 0.09

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LHCb Preliminary
Method for measuring $R(D^*)$

- What we measure:

$$K_{\text{had}}(D^*) = \frac{BR(B^0 \to D^* \tau^+\nu_\tau)}{BR(B^0 \to D^* \pi^+\pi^-\pi^+)}$$

$$= \frac{N(B^0 \to D^* \tau^+\nu_\tau)}{N(B^0 \to D^* \pi^+\pi^-\pi^-)} \times \frac{1}{BR(\tau^+ \to \pi^+\pi^-\pi^+(\pi^0)\bar{\nu}_\tau)} \times \frac{\epsilon(B^0 \to D^* \pi^-\pi^+\pi^-)}{\epsilon(B^0 \to D^* \tau^+\nu_\tau)}$$

- Signal and normalization share same visible final state ($D^*\pi^+\pi^-\pi^+$).

- Most of the systematic uncertainties cancel in the ratio (PID, trigger …).

- $R(D^*)$ obtained from:

$$R(D^*) = K_{\text{had}}(D^*) \times \frac{BR(B^0 \to D^* \pi^+\pi^-\pi^+)}{BR(B^0 \to D^* \mu^+\nu_\mu)}$$

[~4% precision] [~2% precision] [PDG 2016]

- $N(B^0 \to D^* \pi^+\pi^-\pi^+)$ from an un-binned likelihood fit to $m(D^*\pi^+\pi^-\pi^+)$.  
- $N(B^0 \to D^* \tau^+\nu_\tau)$ from a 3-dimensional template fit.
Displaced vertex

- The most abundant background is due to ("prompt") $X_b \to D^* \pi^+ \pi^- \pi^+ + N$ (neutrals) where the 3 pions come from the $X_b$ vertex ($\text{BR} \approx 100$ times higher than signal).

- Suppressed by requiring minimum distance between $X_b$ and $\tau$ vertices ($>4\sigma_{\Delta z}$).

- This background suppressed by 3 orders of magnitude. 35% efficient on signal.

- Possible due to the excellent LHCb vertex resolution.
• **Excellent vertex resolution**: 20μm resolution on impact parameter.

• **Excellent particle identification.**

• **Calorimeter systems**: in this analysis used to suppress events with missing neutral energy: $\pi^0$, $K^0$, $\gamma$. 
• >90% data taking efficiency with >99% of collected data good for analysis.

• Luminosity collected:
  • 1 fb$^{-1}$ at 7 TeV
  • 2 fb$^{-1}$ at 8 TeV
The normalization mode

- Normalization channel as similar as possible to the signal (same visible final state) $\mathcal{B}^0 \rightarrow D^{*} \pi^+ \pi^- \pi^+$. 
- This cancels production yield and systematics linked to trigger, PID and selection.
- In PDG 2014, $\text{BR}(\mathcal{B}^0 \rightarrow D^{*} \pi^+ \pi^- \pi^+)$ known with 11% precision.
- New BaBar measurement 4.3% precision.
  
- In this analysis ~17000 events (1% precision).
Selection: displaced vertex

- The $4\sigma_{\Delta z}$ vertex cut suppresses $X_b \rightarrow D^*\pi^+\pi^-\pi^+X$ events by 3 orders of magnitude.

- Remaining background due to doubly charmed decays $X_b \rightarrow D^*D_s^+X$, $X_b \rightarrow D^*D^+X$, $X_b \rightarrow D^*D^0X$, i.e. mediated by particles with non-negligible lifetime.
  - $X_b \rightarrow D^*D_s^+X$: $\sim 10 \times$ signal
  - $X_b \rightarrow D^*D^+X$: $\sim 1 \times$ signal
  - $X_b \rightarrow D^*D^0X$: $\sim 0.2 \times$ signal
• Signal candidates are required to be well isolated.

• Events with extra charged particles pointing to the B and/or $\tau$ vertices are vetoed.

• Events with neutral energy (signal in calorimeters) suppressed by a BDT.
• 4-fold ambiguity:

\[
|\vec{p}_\tau| = \frac{(m^2_{3\pi} + m^2_\tau)|\vec{p}_{3\pi}| \cos \theta \pm E_{3\pi} \sqrt{(m^2_\tau - m^2_{3\pi})^2 - 4m^2_\tau|\vec{p}_{3\pi}|^2 \sin^2 \theta}}{2(E^2_{3\pi} - |\vec{p}_{3\pi}|^2 \cos^2 \theta)}
\]

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

• Can be approximated by doing:

\[
\theta_{max} = \arcsin \left( \frac{m^2_\tau - m^2_{3\pi}}{2m_\tau|\vec{p}_{3\pi}|} \right) \quad \theta'_{max} = \arcsin \left( \frac{m^2_{B^0} - m^2_{D*\tau}}{2m_{B^0}|\vec{p}_{D*\tau}|} \right)
\]

• Possible to reconstruct rest frame variables such as tau decay time and \( q^2 \).

• These variables have negligible biases, and sufficient resolution to preserve good discrimination between signal and background.
Rejecting $X_b \rightarrow D^* - D_s^+ X$ events using a BDT

- BDT trained to suppress main background: $X_b \rightarrow D^* - D_s^+ X$ events.
- Training: background MC vs signal MC.
  Input variables:
  - $3\pi$ dynamics.
  - $D^*3\pi$ dynamics.
  - Neutrals isolation variables.
- BDT is used as a variable in the fit to extract signal yield.
- Tightening BDT cut, \(\sim50\%\) purity can be achieved. Important for (future) angular analysis.
The $D_s \rightarrow 3\pi X$ decay model: low-BDT fit

- $D_s$ decay modes with 3 pions + neutrals not very well measured.
- Exclusive $D_s \rightarrow 3\pi$ is only 1/15 of the inclusive $D_s \rightarrow 3\pi X$.
- $D_s \rightarrow 3\pi X$ decay model obtained from data.
- Low BDT region (not used for signal extraction) is used to measure the $D_s \rightarrow 3\pi X$ composition.

- Simultaneous fit to:
  \[
  \min[m(\pi^+\pi^-)] \\
  \max[m(\pi^+\pi^-)] \\
  m(\pi^+\pi^+) \\
  m(3\pi)
  \]
The $D_s \to 3\pi X$ decay model: low-BDT fit

Fit components:

- $D_s$ decays with at least 1 pion from $\eta$ or $\eta'$: $\eta^{(*)}\pi^+$, $\eta^{(*)}\rho^+$.
- $D_s$ decays with at least 1 pion from an intermediate state (IS) other than $\eta$ or $\eta'$: $\omega$ or $\phi$.
- $D_s$ decays where none of the 3 pions come from a IS: $K^0\pi3\pi$, $\eta3\pi$, $\eta'^*3\pi$, $\omega3\pi$, $\phi3\pi$, non-resonant.

Fit results used to describe the $D_s \to 3\pi X$ model at high BDT.
• Different control samples are used to study background components:
  • $D_s^+ \to \pi^+\pi^+\pi^+$: control sample for $X_b \to D^*D_sX$.
  • $D^0 \to K^-\pi^+\pi^+$ (kaon recovered by isolation tools): control sample for $X_b \to D^*D^0X$.
  • $D^+ \to K^-\pi^+\pi^+$ (mis-ID kaon/pion): control sample for $X_b \to D^*D^+X$.

• Simulation corrected to match these data.
**X_b → D*D_sX control sample**

- A pure $X_b \rightarrow D^* D_s X$ control sample obtained by selecting exclusive $D_s \rightarrow 3\pi$ decays.

- Allows to know the different $X_b \rightarrow D^* D_s X$ contributions from a fit to $m(D^* D_s)$:
  
  - $B^0 \rightarrow D^* D_s$, $B^0 \rightarrow D^* D_s^*$, $B^0 \rightarrow D^* D_{s0}^*$, $B^0 \rightarrow D^* D_{s1}^*$, $B_s^0 \rightarrow D^* D_s X$, $B \rightarrow D^{**} D_s X$

- Uncertainties in the fit parameters propagated to final analysis.

LHCb Preliminary

![Graphs showing data and model fits](LHCb-PAPER-2017-017)
$X_b \rightarrow D^*D^0X$ control sample

- $X_b \rightarrow D^*D^0X$ decays can be isolated by selecting exclusive $D^0 \rightarrow K^-3\pi$ decays (kaon recovered using isolation tools).

- A correction to the $q^2$ distribution is applied to the simulation to match the data.
Signal extraction: fit model

- 3D extended maximum likelihood fit to data.
- Fit components described by templates obtained from simulation (and corrected from control samples):
  - $q^2$ (8 bins).
  - $3\pi$ decay time (8 bins): important to separate $D^+$ component (large lifetime).
  - BDT (4 bins).

### Model components

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \nu_\tau$</td>
<td>Ratio constrained using known BR and efficiencies.</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- \pi^+ \pi^0 \nu_\tau$</td>
<td></td>
</tr>
<tr>
<td>$X_b \rightarrow D^{**} \tau \nu$</td>
<td>Ratio to signal fixed to $0.11 \pm 0.04$ from theory.</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^- D_s^+$</td>
<td>Relative yields constrained from $X_b \rightarrow D^* D_s^+ X$ control sample.</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^* D_s^{*-}$</td>
<td></td>
</tr>
<tr>
<td>$B^0 \rightarrow D^* D_{s0}^{*-}$</td>
<td></td>
</tr>
<tr>
<td>$B^0 \rightarrow D^* D_{s1}'$</td>
<td></td>
</tr>
<tr>
<td>$B_s^0 \rightarrow D^* D_s^+ X$</td>
<td></td>
</tr>
<tr>
<td>$B \rightarrow D^{**} D_s^+ X$</td>
<td></td>
</tr>
<tr>
<td>$X_b \rightarrow D^* D^+ X$</td>
<td></td>
</tr>
<tr>
<td>$X_b \rightarrow D^* D^0 X$</td>
<td>Yields constrained from control samples.</td>
</tr>
<tr>
<td>$X_b \rightarrow D^* \pi^+ \pi^- \pi^+ X$</td>
<td></td>
</tr>
<tr>
<td>Comb. Bkg.</td>
<td></td>
</tr>
</tbody>
</table>
• Signal yield: 1300 events.

• Leads to $K_{\text{had}}(D^*) = 1.93 \pm 0.13(\text{stat}) \pm 0.17(\text{syst})$

• Using measured $\text{BR}(B^0 \to D^*3\pi) = (7.26 \pm 0.11 \pm 0.31) \times 10^{-3}$:
  
  $\text{BR}(B^0 \to D^*\tau\nu) = (1.40 \pm 0.09(\text{stat}) \pm 0.12(\text{syst}) \pm 0.06(\text{ext}))\%$

• Important to check the quality of the model as a function of the BDT output.

• Good agreement in BDT bins.

• High signal purity at high BDT.
Fit projections on $m(D^{*+}\pi\pi\pi)$ and $\min[m(\pi^+\pi^-)]$

- Important variables in BDT training.

- Good agreement with data.
Fit projections in BDT bins

• Important check: $m(D^*3\pi)$ vs BDT bin.

• Good agreement.
Systematic uncertainties and cross-checks
We have split the data in:

1. **Different trigger configurations:**
   - Event triggered by our candidate (trigger on signal, TOS).
   - Event triggered by other tracks in the event (not-TOS).

2. **Different year (beam energy).**

Both decompositions correspond to 2/3-1/3 of both data samples. Bias corrections are needed to take into account the lack of MC statistics in the 1/3 samples.

Found consistent results in all sub-samples.
Additional cross-checks: $X_b \rightarrow D^{**}\tau\nu$

- $B^0 \rightarrow D^{**}\tau\nu$ and $B^+ \rightarrow D^{**0}\tau\nu$ constitute potential feed-down to the signal.

- $D^{**}(2420)^0$ is reconstructed using its decay to $D^{**}\pi^-$ as a cross-check.

- The observation of the $D^{**}(2420)^0$ peak allows to compute the $D^{**}$ BDT distribution and to deduce a $D^{**}\tau\nu$ upper limit. This upper limit is consistent with the theory.

- Ratio of $D^{**}\tau\nu$ yield with respect to signal yield of $0.11 \pm 0.04$ from theory leads to a systematic uncertainty of 2.3%.
Summary of systematic uncertainties

- Effect of MC statistics studied by performing toys studies.
- Templates fluctuated according to Poisson statistics.
- Small bias of 3% used to correct the signal yield.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta R(D^{<em>-})/R(D^{</em>-})$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>4.7</td>
</tr>
<tr>
<td>Signal decay model</td>
<td>1.8</td>
</tr>
<tr>
<td>$D^{<strong>}\tau\nu$ and $D_s^{</strong>}\tau\nu$ feeddowns</td>
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<tr>
<td>$D^+_s \rightarrow 3\pi X$ decay model</td>
<td>2.5</td>
</tr>
<tr>
<td>$B \rightarrow D^{<em>-}D^+_s X$, $B \rightarrow D^{</em>-}D^+X$, $B \rightarrow D^{*-}D^0X$ backgrounds</td>
<td>3.9</td>
</tr>
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<td>0.7</td>
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<td>$B \rightarrow D^*3\pi X$ background</td>
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</tr>
<tr>
<td>Empty bins in templates</td>
<td>1.3</td>
</tr>
<tr>
<td>Efficiency ratio</td>
<td>3.9</td>
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<td>Total internal uncertainty</td>
<td>8.9</td>
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<tr>
<td>$B(B^0 \rightarrow D^<em>3\pi)$ and $B(B^0 \rightarrow D^</em>\mu\nu\mu)$</td>
<td>4.8</td>
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Summary of systematic uncertainties

- $D_s \rightarrow 3\pi X$ decay model, obtained from a fit to low-BDT events, is varied using toys.
- Future BESIII measurements on inclusive $D_{(s)} \rightarrow 3\pi X$ decays can help to reduce this error.
### Summary of systematic uncertainties

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- Templates shape allowed to vary using “histogram interpolation” technique.
- Allows to change templates shape depending on external variables.
- Same method applied for the combinatorial background.
Summary of systematic uncertainties

- Total systematic uncertainty 8.9%.
- Additional external uncertainty due to precision in $\text{BR}(B^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+)$ and $\text{BR}(B^0 \rightarrow D^{*} \mu \nu$).
Using $BR(B^0 \to D^{*} \mu \nu) = (4.93 \pm 0.11)\%$ [PDG-2016] we measure:

$$R(D^*) = 0.285 \pm 0.019\text{(stat)} \pm 0.025\text{(syst)} \pm 0.014\text{(ext)}$$

In combination with the muonic LHCb measurement:

$$R(D^*) = 0.336 \pm 0.027 \pm 0.030,$$

the LHCb average is:

- $R_{LHCb}(D^*) = 0.306 \pm 0.016 \pm 0.022$
- $2.1\sigma$ above the SM.

Naïve new WA:
- $R(D^*) = 0.305 \pm 0.015$
- $3.4\sigma$ above the SM.

Naïve $R(D)/R(D^*)$ combination at $4.1\sigma$ from SM.
For $R(D^*)$, Run-2 will ~quadruple the dataset, the statistical uncertainty can decrease by a factor of $\approx 2$.

The internal systematic uncertainty can also decrease by a factor of $\approx 2$.

Other measurements on going (including run-2 data) using:

<table>
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<th>Observable</th>
</tr>
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<tbody>
<tr>
<td>$B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$</td>
<td>$R(D^{*-})$</td>
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<tr>
<td>$B^0 \rightarrow D^- \tau^+ \nu_\tau$</td>
<td>$R(D^-)$</td>
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<tr>
<td>$B^+ \rightarrow D^0 \tau^+ \nu_\tau$</td>
<td>$R(D^0)$</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow D_s^{(*)} \tau^+ \nu_\tau$</td>
<td>$R(D_s^{(*)})$</td>
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<td>$B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau$</td>
<td>$R(J/\psi)$</td>
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<tr>
<td>$\Lambda_b \rightarrow \Lambda_c^{(*)} \tau^+ \nu_\tau$</td>
<td>$R(\Lambda_c^{(*)})$</td>
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</tbody>
</table>
Conclusions

• We have measured the ratio $K_{\text{had}}(D^*) = \frac{\text{BR}(B^0 \rightarrow D^*\tau\nu)}{\text{BR}(B^0 \rightarrow D^*3\pi)}$ using the $3\pi(\pi^0)$ hadronic decay of the $\tau$ lepton.

• The result regarding $R(D^*)$ is compatible with all other measurements and with the SM, having the smallest statistical error.

• This analysis was made possible due to the unique LHCb capabilities for separating secondary and tertiary vertices with excellent resolution.
BACKUP
LHCb muonic $R(D^*)$ [Phys. Rev. Lett. 115, 111803 (2015)]

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<td>PRL 115 (2015) 11108</td>
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</tbody>
</table>

Standard Model

Fajfer et al, PRD 85 (2012) 094025

Fajfer et al, PRD 85 (2012) 094025

$D^*\tau\nu$

$D^*H_L \rightarrow l\nu X$X

$|\mu|$

Combination

Misidentified $\mu$

Data

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

$B \rightarrow D^*H_L \rightarrow l\nu X$X

$B \rightarrow D^*\nu\nu$

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

Combinatorial

Misidentified $\mu$
LHCb Preliminary

\[ \mathcal{B}^0 \rightarrow D^{*-} \pi^+ \pi^- \pi^+ \]

\[ X_b \rightarrow D^{*-} \pi^+ \pi^- \pi^+ X \]

Events / (11 MeV/c^2) vs. \( m(D^{*-} \pi^+ \pi^- \pi^+) \) [MeV/c^2]