Review of R measurements in LHCb in the hadronic channel

A R’s review

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Second LHCb open semitauonic workshop
**LFU: a hot topic**

- The Standard Model predicts *Lepton Flavour Universality* (LFU): equal couplings between gauge bosons and the three lepton families.

- But, there are tensions between SM expectations and experimental results in:
  - **Semitauonic B decays**
  - $b \to sll$ transitions with for instance a $2.4\sigma$ deviation for the recent LHCb result on $R(K^{*0})$.

- Several SM extensions add new interactions with a stronger coupling with the third generation of leptons (charged Higgs, leptoquarks, ...).
Why using semitauonic B decays?

○ As tree level decays, they combine some nice features:
  □ Precise prediction from SM using ratios with shared systematics cancelling
  □ Abundant channel: BR(B → D*τν) ~ 1.2%
  □ Sensitivity to NP contributions

\[
R(D^*) = \frac{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^– \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^– \bar{\nu}_\mu)}
\]

○ Different hadronisation schemes are possible:
  □ D^*, D^0, D^+, D_s, Λ_c, J/Ψ
  □ Not only spectators quarks differ but also the spin:
    ○ 0: D^0, D^+, D_s
    ○ 1: D^*, J/Ψ
    ○ \(\frac{1}{2}\): Λ_c
Beyond $R(D^*)$

- Ongoing analyses using the hadronic $\tau$ decay:
  - $R(\Lambda_c^*): \Lambda_b \rightarrow \Lambda_c^* l \nu$
  - $R(J/\psi): B_c \rightarrow J/\psi l \nu$

- Other possible modes:
  - $R(D^+): B^0 \rightarrow D^+ l \nu$
  - $R(D^0): B^+ \rightarrow D^0 l \nu$
  - $R(D^{**}): B \rightarrow D^{**} l \nu$
  - $R(\Lambda_c^*): \Lambda_b \rightarrow \Lambda_c^* l \nu$ with $\Lambda_c^* \rightarrow \Lambda_c \pi \pi$
  - $R(D_s): B_s \rightarrow D_s l \nu$

- In a far future:
  - $B^0 \rightarrow p \tau \nu$
R\( (X_c) \) recipe

- **Semileptonic decay without charged lepton** in the final state
  - \( \rightarrow \textbf{Zero} \) background from normal semileptonic decays!

- **No signal mass peak but several hadronic ones**
  - for instance, \( D^0 \rightarrow K3\pi, D^+ \rightarrow K\pi\pi, \ldots \)
  - It provides control on the various background channels

- Only one \( \nu \) at the \( \tau \) vertex
  - **Partial reconstruction can be applied** with good precision

- **Prompt 3\( \pi \) background is dominant**:
  - Specificities for each \( X_c \) but same tool to suppress it: \textit{vertex displacement}

- Double charm background is rejected using a BDT

- Extraction of the measurement using a **3D template fit in \( q^2 \), BDT output and \( t_{\tau} \)**
Double charm background

- The remaining background consists of $X_b$ decays where the $3\pi$ vertex is transported away from the $X_b$ vertex by a charm carrier: $D_s$, $D^+$ or $D^0$ (in that order of importance)
  - Total yield is $\sim 10x$ higher than SM expectation for signal
  - This background does not depend on the nature of $X_c$

- LHCb has three very good tools to limit this background:
  - 3π dynamics
  - Isolation criteria against charged tracks and neutral energy deposits
  - Partial reconstruction in both signal and background hypotheses

- A Boosted Decision Tree (BDT) discriminates double charm decays from signal
- The $D_s$ decay model from the $R(D^*)$ analysis can be reused for every $R(X_c)$
$R(\Lambda_c)$

- Same strategy as $R(D^*)$, the goal is to measure:

$$R(\Lambda_c) = \frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu)}$$

- Precise prediction from LQCD: $R_{SM}(\Lambda_c) = 0.3328 \pm 0.0074^{\text{stat}} \pm 0.0070^{\text{syst}}$ \[1\]

- Probing LFU with a baryon with a different spin structure

- Use of $\Lambda_b \to \Lambda_c 3\pi$ as normalization channel

- Measurement of $R(\Lambda_c)$ on both Run1 and Run2 datasets with an error estimation of:
  - 4% for $\epsilon_{\text{stat}}$
  - 6-10% for $\epsilon_{\text{syst}}$
  - 7% of uncertainty due to normalization

\[1\]: [W. Detmold, C. Lehner, S. Meinel, PRD 92, 034503 (2015)]
\( R(\Lambda_c) \)

Comparison between \( \Lambda_c \tau \nu \) and \( D^* \tau \nu \) analyses:

- \( \Lambda_c 3\pi, \Lambda_c D_s \) peaks on MC and data:
  - data rates are comparable with \( D^* 3\pi \) and \( D^* D_s \)
    (lower \( \Lambda_b \) production but higher \( \Lambda_c \) visibility)

\[ \Lambda_c \tau \nu, \mathcal{L} = 0.87 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>( \Lambda_c^+ 3\pi )</th>
<th>normal</th>
<th>inverted</th>
<th>6630 ± 93</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda_c^+ D_s^{(*)} )</td>
<td>inverted</td>
<td>495 ± 35</td>
<td></td>
</tr>
<tr>
<td>( \Lambda_c^+ D_s )</td>
<td>inverted</td>
<td>77 ± 10</td>
<td></td>
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</tbody>
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\[ D^* \tau \nu, \mathcal{L} = 1.0 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>( D^* 3\pi )</th>
<th>normal</th>
<th>inverted</th>
<th>6702 ± 89</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D^* D_s^{(*)} )</td>
<td>inverted</td>
<td>404 ± 14</td>
<td></td>
</tr>
<tr>
<td>( D^* D_s )</td>
<td>inverted</td>
<td>67 ± 10</td>
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→ Same sensitivity expected
\( R(\Lambda_c) \)

Yields for each year of data taking per fb\(^{-1}\)

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<tbody>
<tr>
<td>( \Lambda_c )</td>
<td>5709 ± 92</td>
<td>6749 ± 80</td>
<td>27509 ± 41</td>
<td>29182 ± 336</td>
<td>4.32 ± 0.07</td>
</tr>
<tr>
<td>( \Lambda_c D_s X )</td>
<td>202 ± 18</td>
<td>237 ± 11</td>
<td>962 ± 52</td>
<td>1056 ± 48</td>
<td>4.46 ± 0.29</td>
</tr>
<tr>
<td>( \Lambda_c D_s )</td>
<td>37 ± 7</td>
<td>40 ± 4</td>
<td>92 ± 12</td>
<td>110 ± 17</td>
<td>2.75 ± 0.51</td>
</tr>
<tr>
<td>( \Lambda_c 3\pi )</td>
<td>129 ± 18</td>
<td>154 ± 10</td>
<td>645 ± 49</td>
<td>627 ± 38</td>
<td>4.07 ± 0.36</td>
</tr>
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</table>

All plots are using Splot technique to select \( \Lambda_c \).
The goal is to measure:

\[
R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \tau^-)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}
\]

This analysis is using:
- $J/\psi \to \mu \mu$
- As there is no input from $B$ factories, normalisation channel will be $B_c^+ \to J/\psi \mu X$

In LHCb-PAPER-2012-010 [1], the decay $B_c \to J/\psi D_s$ is observed with $D_s \to KK\pi$ with 3 fb$^{-1}$ of data (BR ~5 times larger than $D_s \to 3\pi$)

[1]: [Phys.Rev. D87 (2013) no.11, 112012]
In the $R(D^*)$ analysis:

- Background contribution from $D^{**}$ states such as $D_1(2420)^0 \to D^+\pi^-$
- Upper limit in Run I, a measurement of $R(D_1(2420)^0)$ can be performed with Run II data.
- To illustrate, the up plot shows $m(D^*-\pi^+)-m(D^*)$ without a BDT cut (enriched in $D^{**}D_s$ events) and the bottom one shows the same distribution with a BDT cut (should contain a large fraction of $D^{**}\tau\nu$ events).
Normalisation

How to normalise hadronic analyses?

- **R(D*)**: Use of two external BR from PDG
  - $B^0 \rightarrow D^*3\pi$, 4% uncertainty
  - $B^0 \rightarrow D^*\mu\nu$, 2% uncertainty

What can we do with other modes?

- Direct normalisation using same strategy:
  - $\Lambda_b \rightarrow \Lambda_c 3\pi$, 14% uncertainty

- Use of inputs from LQCD to reuse $R(D^*)$ normalisation:
  - for instance: $K = \frac{\Gamma(\Lambda_b^0 \rightarrow \Lambda_c^+\mu\nu)}{\Gamma(B^0 \rightarrow D^+\mu\nu)}$ \[1\]

- Investigate other modes:
  - $\Lambda_b \rightarrow \Lambda_c D_s$
  - $B_c \rightarrow J/\psi D_s$
  - $\Lambda_b \rightarrow \Lambda_c \mu\nu$

With $D_s \rightarrow 3\pi$, closer topology to signal but low Branching fraction

[1]: Meinel's talk during first LHCb semitauonic workshop
Conclusion

After $R(D^*)$, more modes are coming

- Probing LFU with different spin structure
- $R(\Lambda_c)$ and $R(J/\psi)$ are ongoing
- Run1 and Run2 combinations will allow great statistical improvement

$R(D^*)$ tools and strategy can be applied for other modes:

- Yields of control channels in the $R(\Lambda_c)$ analysis are very similar
- Normalisation strategies for each mode have to be studied
Thank you for your attention!

Any question?
Backup
The LHCb detector

- **Single arm spectrometer** at LHC in the pseudorapidity range $2<\eta<5$
- Optimized to study hadron decays containing $b$ and $c$ quarks:
  - CP violation, rare decays, heavy flavor production;
- **Excellent vertex resolution** and separation of B vertices
- Good **momentum and mass resolution**
- Excellent **PID** capabilities (good separation $K-\pi$ and muon identification)