Recent results using semileptonic decays with LHCb

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on behalf of the LHCb collaboration

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Semileptonic $B$ decays at the LHC

- B mesons copiously produced at LHCb: **large $B$ production cross-section.**
- Also, large number of $\Lambda_b^0$, $B_s^0$ and $B_c^+$ hadrons produced.
- High branching fractions, $\mathcal{B}(B \rightarrow X\ell\nu_\ell) \approx 10\%$: **tree level transition** mediated by a $W^\pm$ boson in the SM.
- Theoretically clean: only **one hadronic current**, parameterised in terms of scalar functions (**form-factors**).

- Partially reconstructed signal: difficult to reconstruct due to **missing neutrino(s).**
- No beam energy **constraint** (as in B-factories).

Semileptonic (SL) B decays provide powerful probes for:

- **Testing the SM.** SL B decays involving **electrons** and **muons** expected to be free of BSM contributions: Used to measure CKM parameters $|V_{ub}|$ and $|V_{cb}|$.

- **Searching for physics BSM:** decays involving $\tau$ (semitauonic) sensitive to contributions BSM.
Outline


- Determination of $|V_{ub}|/|V_{cb}|$ and search for the decay $B^- \rightarrow \mu^+\mu^-\mu^-\nu_\mu$. [Nature Physics 11 743-747 (2015), arXiv:1812.06004]

Charmed baryons lifetimes

- Lifetime of charmed baryons are known with **less precision** than charmed mesons.
- They can be used to test Heavy Quark Expansion (HQE).
- A lifetime **hierarchy** is expected: $\tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0)$.
- Previous measurements **consistent** with this hierarchy.

- $\Omega_c^0$ reconstructed using SL $\Omega_b^- \rightarrow \Omega_c^0\mu^-\nu_\muX$ decays with $\Omega_c^0 \rightarrow pK^-K^+\pi^+$.
- Measured ratio $\tau(\Omega_c^0)/\tau(D^+)$ with $D^+ \rightarrow K^-\pi^+\pi^+$ to reduce systematic uncertainties.
- Analysis using LHC run-1 data: 1 fb$^{-1}$ at 7 TeV and 2 fb$^{-1}$ at 8 TeV.
- Much larger signal wrt previous experiments: $978 \pm 60 \Omega_c^0$ candidates.
Charmed baryons lifetimes

- Measured lifetime:
  \[ \tau (\Omega_c^0) = 268 \pm 21 \text{(stat)} \pm 10 \text{ (syst)} \pm 2 \text{ (D^+) fs.} \]

- Four times larger than, and **inconsistent** with world average: \( \tau_{\text{PDG}} (\Omega_c^0) = 69 \pm 12 \text{ fs.} \)

- Same method can be used to measure the lifetime of other charmed baryons:
  - \( \Lambda_c^+ \rightarrow pK^-\pi^+ \) from \( \Lambda_b^0 \rightarrow \Lambda_c^+\mu^-\nu_\mu X \) decays.
  - \( \Xi_c^+ \rightarrow pK^-\pi^+ \) from \( \Xi_b^0 \rightarrow \Xi_c^+\mu^-\nu_\mu X \) decays.
  - \( \Xi_c^0 \rightarrow pK^-K^-\pi^+ \) from \( \Xi_b^- \rightarrow \Xi_c^0\mu^-\nu_\mu X \) decays.
Charmed baryons lifetimes

\[ \tau (\Lambda_c^+) = 203.5 \pm 1.0 \, \text{(stat)} \pm 1.3 \, \text{(syst)} \pm 1.4 \, \text{(D)} \, \text{fs} \]

\[ \tau (\Xi_c^+) = 456.8 \pm 3.5 \, \text{(stat)} \pm 2.9 \, \text{(syst)} \pm 3.1 \, \text{(D)} \, \text{fs} \]

\[ \tau (\Xi_c^0) = 154.5 \pm 1.7 \, \text{(stat)} \pm 1.6 \, \text{(syst)} \pm 1.0 \, \text{(D)} \, \text{fs} \]

- \( \Xi_c^0 \) lifetime 3.3\( \sigma \) above WA.
- \( \Omega_c^0 \) lifetime incompatible with WA.
- Need to understand better hierarchy of charmed baryons lifetime.
Determination of $|V_{ub}|/|V_{cb}|$

- $|V_{ub}|/|V_{cb}|$ accessible by measuring the ratio of branching fractions:
  \[
  \frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)} R_{FF} \quad (R_{FF} \text{ from Lattice})
  \]

- Measurement from a 1D fit to the corrected mass:
  \[
  M_{corr} = \sqrt{M_{p\mu}^2 + p_{\perp}^2 + p_{\perp}^2}
  \]
Search for $B^- \to \mu^+ \mu^- \mu^- \nu_\mu$ decay

- Similar method used for $B^- \to \mu^+ \mu^- \mu^- \nu_\mu$ decays:
  $\Rightarrow$ fit to $M_{\text{corr}}$.

- Very suppressed decay with $\text{BF} \propto |V_{ub}|^2$.

- Theoretical prediction (vector-meson dominance):
  $\mathcal{B}(B^- \to \mu^+ \mu^- \mu^- \nu_\mu) \sim 1.3 \times 10^{-7}$ (PAN (2018) 81, 347).

- Signal normalised to $B^+ \to J/\psi K^+$.

- Selected $M_{\mu\mu}^{\text{min}} < 980$ MeV/$c^2$.

- 4.7 fb$^{-1}$ of 2011-2016 data.

- No signal found:
  $\Rightarrow \mathcal{B}(B^- \to \mu^+ \mu^- \mu^- \nu_\mu) < 1.6 \times 10^{-8}$.

[arXiv:1812.06004]
Prospects on $|V_{ub}|$ and $|V_{cb}|$

- $|V_{ub}|/|V_{cb}|$ from the ratio $B_s^0 \rightarrow K^+ \mu \nu$ to $B_s^0 \rightarrow D_s^+ \mu \nu$.
  - Precise form-factors calculation possible due to relatively large $s$ quark mass.
  - Large $B_s^0 \rightarrow D_s^+ \mu \nu$ yield, but ...
  - Large feed-down from excited $D_s$ meson decays with neutrals: $D_s^* \rightarrow D_s \gamma$.
  - $B_s^0 \rightarrow K^+ \mu \nu$ signal rate $\sim 1$ order of magnitude smaller than $\Lambda_b^0 \rightarrow \rho \mu^- \nu_{\mu}$.

- Good prospects to perform a differential measurement in many $q^2$ bins with $\Lambda_b^0 \rightarrow \rho \mu^- \nu_{\mu}$ decays. Requires larger data samples.

- Measurements in $B_c^+ \rightarrow D^0 \mu \nu$ decays can provide a competitive measurement of $|V_{ub}|$: 30,000 events expected at the end of LHCb Upgrade II (300 fb$^{-1}$).

- Expected $\sim 1\%$ precision in $|V_{ub}|/|V_{cb}|$ with LHCb Upgrade II dataset.
Tests of LFU using SL B decays

- In the SM, amplitudes for processes involving e, μ, τ must be identical up to effects depending on lepton mass: Lepton Flavor Universality (LFU).
- Observation of violations of LFU would be a sign for new physics (NP).

\[ R(D^{(*)}) = \frac{B(B^0 \to D^{(*)}\tau\nu)}{B(B^0 \to D^{(*)}\mu\nu)} \]

- Comparison between semitauonic (τ) and semimuonic (μ) decays is sensitive to NP, which could modify branching ratios and angular distributions.

- \( R(D^{(*)}) \) very clean SM prediction due to partial cancellation of form factors uncertainties in the ratio.

<table>
<thead>
<tr>
<th></th>
<th>( R_{SM}(D) )</th>
<th>( R_{SM}(D^*) )</th>
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<tbody>
<tr>
<td>PRD94 (2016)</td>
<td>0.299 ± 0.003</td>
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<tr>
<td>PRD95 (2017)</td>
<td>0.299 ± 0.003</td>
<td>0.257 ± 0.003</td>
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<tr>
<td>JHEP 1711 (2017) 061</td>
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<td>0.260 ± 0.008</td>
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<tr>
<td>JHEP 1712 (2017) 060</td>
<td>0.299 ± 0.004</td>
<td>0.257 ± 0.005</td>
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</table>
R(D*) with $\tau^- \rightarrow \mu^- \nu_\mu \nu_\tau$ decays

- R(D*) measured using $B^0 \rightarrow D^* \tau^+ \nu_\tau$ decays with $\tau \rightarrow \mu \nu_\mu \nu_\tau$ and $D^*^- \rightarrow D^0(\rightarrow K\pi)\pi^-$.  

  **Approximation** needed to estimate the B momentum $p_B$.

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

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

- ~8% resolution on $p_B$ enough to preserve signal and background discrimination.

- R(D*) obtained from 3D template fit to $m^2_{\text{miss}}$, $E_\mu^*$ and $q^2$:

  \[ R(D*) = 0.336 \pm 0.027 \text{ (stat, 8.0\%)} \pm 0.030 \text{ (syst, 8.9\%)} \]

  (2.1\sigma above SM)

- Largest systematic uncertainties are the size of simulated samples and $\mu \leftrightarrow \pi$ misID.
R(D*) with $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ decays

- R(D*) measured using $B^0 \rightarrow D^*^- \tau^+ \nu_\tau$ decays with $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ and $D^*^- \rightarrow D^0(\rightarrow K\pi)\pi^-.$
- $B^0 \rightarrow D^*^- \pi^+ \pi^- \pi^+$ used as normalisation mode.

$$R(D^*) = \frac{N_{sig}}{N_{norm}} \times \frac{\varepsilon_{norm}}{\varepsilon_{sig}} \times \frac{1}{B(\tau \rightarrow \pi^+ \pi^+ \pi^- (\pi^0)\nu_\tau)} \times \left( \frac{B(B^0 \rightarrow D^*^- \pi^+ \pi^+ \pi^-)}{B(B^0 \rightarrow D^*^- \mu^+ \nu_\mu)} \right)_{ext}$$

- **Most abundant background** $B \rightarrow D^* \pi^+ \pi^- X$ suppressed by requiring a significant displacement between the $\tau$ and $B$ vertices.
- Main **remaining background** due to $B \rightarrow D^*^- DX$ decays, with $D \rightarrow \pi^+ \pi^- \pi^+ X$ (D lifetime).
- This doubly-charmed background can be controlled using **control samples:**
  - $D_s^- \rightarrow \pi^- \pi^+ \pi^-,$ $D^- \rightarrow K^+ \pi^- \pi^-,$ and $D^0 \rightarrow K^+ \pi^- \pi^- \pi^-.$
- $B \rightarrow D^*^- DX$ decays further suppressed using a **BDT** (includes kinematic+isolation variables).
R(D*) with $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$ decays

- Signal yield extracted from a 3D fit to $q^2$, $\tau$ decay time and BDT: $N_{\text{sig}} = 1296 \pm 86$.
- Normalisation yield from a fit to $M(D^*-\pi^+\pi^-\pi^+)$ invariant mass: $N_{\text{norm}} = 17080 \pm 143$.

Using 2017 WA:

$$B(B^0 \rightarrow D^{*-} \pi^+\pi^+\pi^-) = (7.21 \pm 0.28) \times 10^{-3}$$

$$B(B^0 \rightarrow D^{*-} \mu^+\nu_\mu) = (4.88 \pm 0.10) \times 10^{-2}$$

$$\Rightarrow R(D^*) = 0.291 \pm 0.019 \pm 0.026 \pm 0.013$$

Recently, HFLAV provided separated averages for $B^0$ and $B^+$ semileptonic decays:

$$B(B^0 \rightarrow D^{*-} \ell^+\nu_\ell) = (5.05 \pm 0.02 \pm 0.14) \times 10^{-2}$$

$$B(B^+ \rightarrow D^{*0} \ell^+\nu_\ell) = (5.66 \pm 0.07 \pm 0.21) \times 10^{-2}$$

$$\Rightarrow R(D^*) \text{ changes to } \Rightarrow R(D^*) = 0.280 \pm 0.018 \pm 0.029$$

New updated result closer to SM prediction (<1σ)
R(J/ψ) with τ⁻→μ⁻ν_μν_τ decays

- Goal: measurement of \( R(J/ψ) = \frac{B(B_c^+ → J/ψτν)}{B(B_c^+ → J/ψμν)} \) using τ⁻→μ⁻ν_μν_τ decays.
- Only possible at LHCb (B_c^+ only at LHC).
- Same reconstruction (p_B) method as in muonic R(D*) measurement.
- R(J/ψ) obtained from a 3D template fit to B_c^+ decay time, m_{miss}^2 and Z(E_μ^*,q^2). Form-factors obtained from a sample enriched in normalisation decays.

Main backgrounds:
- B_c^+→J/ψμν (normalisation), B_c^+→ψ(2S)μν, B_c^+→J/ψD(→μνX)X.
- Hadron misidentified as a muon.
- Combinatorial background (J/ψ and μ not from same B).

Systematic uncertainties dominated by knowledge of form-factors and the size of the simulation samples.

R(J/ψ) = 0.71 ± 0.17 ± 0.18 (R_{SM}(J/ψ) ~ 0.25–0.28) (2σ from SM)

First evidence of the B_c^+→J/ψτν decay (3σ)
Summary on $R(X_c)$

New $R(D)/R(D^*)$ combined measurement by Belle using SL tagging available in arXiv:1904.08794

- New $R(D)/R(D^*)$ combination BaBar/Belle/LHCb at $3.1\sigma$ from the SM.
- Previous combination at $3.8\sigma$.
- Tension with SM reduced.
LHCb prospects on $R(X_c)$

- LHCb can perform measurements of LFU not accessible at Belle II:
  - $R(\Lambda_c^{(*)})$, $R(J/\psi)$, $R(D_s^{(*)})$
- Production fractions and efficiencies used to extrapolate the uncertainties.
- Precision in $R(X_c)$ about 2-3% at the end of the Upgrade II.
- Sensitivity to angular observables need to be studied.

[arXiv:1808.08865]
Conclusions

• Study of semileptonic B decays at LHCb very challenging due to the missing neutrinos and no beam-energy constraint.

• Semileptonic b-hadron decays used to determine charmed baryons lifetimes.

• $|V_{ub}|/|V_{cb}|$ can be measured using channels and techniques complementary to those of B-factories.

• LHCb is able to perform measurements on semitauonic B decays using $\tau \rightarrow \mu \nu \nu$ and $\tau^+ \rightarrow \pi^+ \pi^+ \pi^- (\pi^0) \nu_\tau$ decays. Different systematics.

• $R(J/\psi)$ measured for the first time (first evidence of $B_c^+ \rightarrow J/\psi \tau \nu$).

• Measurements of $R(\Lambda_c^{(*)})$, $R(J/\psi)$ and $R(D_s^{(*)})$ only possible at LHCb.

• LHCb aim to measure $R(D)$ and $R(D^*)$ with 2-3% precision.
BACKUP
# Systematics muonic $R(D^*)$

<table>
<thead>
<tr>
<th>Model uncertainties</th>
<th>Absolute size ($\times 10^{-2}$)</th>
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<tbody>
<tr>
<td>Simulated sample size</td>
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<tr>
<td>Misidentified $\mu$ template shape</td>
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<tr>
<td>$\bar{B}^0 \to D^{**}(\tau^-/\mu^-)\bar{\nu}$ form factors</td>
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<td>$\bar{B} \to D^{**}H_c(\to \mu\nu X')X$ shape corrections</td>
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<td>$\mathcal{B}(\bar{B} \to D^{<strong>}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{</strong>}\mu^-\bar{\nu}_\mu)$</td>
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<tr>
<td>Corrections to simulation</td>
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<tr>
<td>Combinatorial background shape</td>
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<tr>
<td>$\bar{B} \to D^{**}(\to D^*\pi)\mu^-\bar{\nu}_\mu$ form factors</td>
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<td>$\bar{B} \to D^{**+}(D_s \to \tau\nu)X$ fraction</td>
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<td>Total model uncertainty</td>
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<table>
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<th>Normalization uncertainties</th>
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<tr>
<td>Hardware trigger efficiency</td>
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<tr>
<td>Particle identification efficiencies</td>
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<tr>
<td>Form factors</td>
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<tr>
<td>$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}<em>\mu\nu</em>\tau)$</td>
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<td>Total normalization uncertainty</td>
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<td>Total systematic uncertainty</td>
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Systematics hadronic $R(D^*)$

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Value in %</th>
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<tr>
<td>$B(\tau^+ \to 3\pi \bar{\nu}<em>\tau)/B(\tau^+ \to 3\pi(\pi^0)\bar{\nu}</em>\tau)$</td>
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<td>Other $\tau$ decays</td>
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<td>$B \to D^{**}\tau^+\nu_\tau$</td>
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<td>$B_s^0 \to D^{**}\tau^+\nu_\tau$ feed-down</td>
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<tr>
<td>$D_s^+ \to 3\pi X$ decay model</td>
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<td>$D_s^+, D^0$ and $D^+$ template shape</td>
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<td>$B \to D^{<em>-}D_s^+(X)$ and $B \to D^{</em>-}D^0(X)$ decay model</td>
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<td>$D^{*-}3\pi X$ from $B$ decays</td>
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<td>Combinatorial background (shape + normalization)</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>Signal efficiencies (size of simulation samples)</td>
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<td>Normalization channel efficiency (size of simulation samples)</td>
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<tr>
<td>Normalization channel efficiency (modeling of $B^0 \to D^{*-}3\pi$)</td>
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<tr>
<td>Form factors (efficiency)</td>
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<tr>
<td>Total uncertainty</td>
<td>9.1</td>
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</tbody>
</table>
Using the $\Lambda_b^0$ mass and direction of flight, $q^2 = (p_{\Lambda_b} - p_p)^2$ can be estimated up to a two-fold ambiguity.

Events selected with $q^2 > 7 \text{ GeV}^2 (p\mu\nu_\mu)$ and $q^2 > 15 \text{ GeV}^2 (\Lambda_c^+\mu\nu_\mu)$ (both $q^2$ solutions above cut). Highest rate, best resolution ($\sim 1\text{ GeV}^2$) and most precise Lattice calculations.

Result: $\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\text{exp}) \pm 0.004(\text{lattice})$
LHCb prospects on $R(X_c)$

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