New predictions for $\Lambda_b \rightarrow \Lambda_c^+ \ell^- \bar{\nu}_\ell$ decays

Motivation

\[ R \left(D^{(*)}\right) = \frac{\mathcal{B}(B \to D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)} \ell^- \bar{\nu}_\ell)} \]

- New physics will influence several modes.
- Large LHCb dataset of \( \Lambda_b \) baryons.

Still a \( \sim 3\sigma \) deviation from SM.

- Available LQCD prediction and LHCb shape measurement.

LQCD [S. Meinel et al. 1503.01421] LHCb [1709.01920]
Motivation

$$R \left( \Lambda_c^{(*)} \right) = \frac{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^{(*)} + \tau - \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^{(*)} + \ell - \bar{\nu}_\ell)}$$

- Still a $\sim 3\sigma$ deviation from SM.

- New physics will influence several modes.

- Large LHCb dataset of $\Lambda_b$ baryons.

LQCD [S. Meinel et al. 1503.01421] LHCb [1709.01920]

- Available LQCD prediction and LHCb shape measurement.
\[ \Lambda_b \rightarrow \Lambda_c \ell^- \bar{\nu}_\ell \] SM vs NP theory

In the SM can parametrise hadronic matrix elements in terms of 6 form factors.

Form factors are functions of \( w = v \cdot v' = (m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2)/(2m_{\Lambda_b}m_{\Lambda_c}) \).

New physics introduces the possibility of scalar, pseudoscalar and tensor terms with 6 new form factors.

\[
\begin{align*}
\langle \Lambda_c(p', s')| \bar{c} \gamma_\nu b |\Lambda_b(p, s) \rangle &= h_S \bar{u}(p', s') u(p, s), \\
\langle \Lambda_c(p', s')| \bar{c} \gamma_\nu \gamma_5 b |\Lambda_b(p, s) \rangle &= h_P \bar{u}(p', s') \gamma_5 u(p, s), \\
\langle \Lambda_c(p', s')| \bar{c} \sigma_{\mu\nu} b |\Lambda_b(p, s) \rangle &= \bar{u}(p', s') [h_1 \sigma_{\mu\nu} + i h_2 (v_\mu \gamma_\nu - v_\nu \gamma_\mu) + i h_3 (v'_\mu \gamma_\nu - v'_\nu \gamma_\mu) + i h_4 (v_\mu v'_\nu - v_\nu v'_\mu) ] u(p, s).
\end{align*}
\]
In the $m_Q \gg \Lambda_{QCD}$ limit, the heavy quark acts a fixed color source with fixed velocity $v^\mu$ Isgur & Wise

$\Rightarrow$ for $Q\bar{q}$ wave function of light quarks insensitive to spin and flavour of $Q$.

Analogous situation in atomic physics:

- Different isotopes have same chemistry as they feel the same electric field $\sim$ flavour symmetry.
- Hyperfine levels of atoms almost degenerate $\sim$ Spin symmetry.
When $b \to c$ only velocity change $\nu \to \nu'$ felt and potentially a $\bar{s}_Q$ flip.

All form factors are related to a single function of $w = v \cdot v'$, $\zeta(w)$ (Isgur Wise function)

In particular at leading order in HQET one finds:

$$f_1(w) = g_1(w) = h_5(w) = h_P(w) = h_1(w) = \zeta(w),$$
$$f_2(w) = f_3(w) = g_2(w) = g_3(w) = h_2(w) = h_3(w) = h_4(w) = 0.$$

At 0 recoil, $w = 1$, no change in color field $\zeta(1) = 1$.
Now we consider higher order corrections at orders $\alpha_s$, $\Lambda_{QCD}/m_{b,c}$, $\alpha_s\Lambda_{QCD}/m_{b,c}$ and $\Lambda_{QCD}^2/m_c^2$

$$\bar{\Lambda}_\Lambda = \text{energy of light degrees of freedom in } m_Q \to \infty \implies m_{\Lambda_Q} = m_Q + \bar{\Lambda}_\Lambda + \cdots$$

$$f_1 = \zeta(w) \left\{ 1 + \hat{\alpha}_s C_{V_1} + \varepsilon_c + \varepsilon_b + \hat{\alpha}_s \left[ C_{V_1} + 2(w - 1)C'_{V_1} \right] (\varepsilon_c + \varepsilon_b) + \frac{\hat{b}_1 - \hat{b}_2}{4m_c^2} \right\} + \cdots,$$

where $\varepsilon_{c,b} = \bar{\Lambda}_\Lambda/(2 m_{c,b})$ [prior work: Falk & Neubert, hep-ph/9209269]

- Remarkable simplification at $O(\Lambda_{QCD}/m_{b,c})$ compared to $B$ mesons. No sub-leading Isgur Wise functions (SIW).
- Only 2 sub-leading IW functions, $\hat{b}_1(w), \hat{b}_2(w)$ at $O(\Lambda_{QCD}^2/m_c^2)$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$N_{IW}$ at $O(1)$</th>
<th>$N_{SIW}$ at $O(\Lambda_{QCD}/m_{b,c})$</th>
<th>$N_{SIW}$ at $O(\Lambda_{QCD}^2/m_c^2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b \to \Lambda_c \ell^- \bar{\nu}_\ell$</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>$B \to D^* \ell \nu$</td>
<td>1</td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

- Decay $\Lambda_b \to \Lambda_c \ell^- \bar{\nu}_\ell$ is simpler as light quarks ($ud$) in a spin 0 state, $J = 0$. 

William Sutcliffe
New predictions for $\Lambda_b \to \Lambda_c^+ \ell^- \bar{\nu}_\ell$ decays
12 July 2019
Perform fits to LQCD Predictions and to LHCb differential shape measurement.

\[ \zeta(w) = 1 + (w - 1) \zeta' + \frac{1}{2}(w - 1)^2 \zeta'' \]

\[ \hat{b}_{1,2} \text{ assumed constants.} \]

---

<table>
<thead>
<tr>
<th>( \zeta' )</th>
<th>( \zeta'' )</th>
<th>( \hat{b}_1/\text{GeV}^2 )</th>
<th>( \hat{b}_2/\text{GeV}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 3.16 \pm 0.38 )</td>
<td>( 3.28 \pm 0.36 )</td>
<td>( 0.46 \pm 0.15 )</td>
<td>( 0^* )</td>
</tr>
<tr>
<td>( 3.40 \pm 0.02 )</td>
<td>( 0 )</td>
<td>( 0 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>( 4.72 \pm 0.05 )</td>
<td>( 4.69 \pm 0.04 )</td>
<td>( 0.46 \pm 0.15 )</td>
<td>( 0.39 \pm 0.39 )</td>
</tr>
<tr>
<td>( 3.3237 \pm 0.0036 )</td>
<td>( 3.3252 \pm 0.0035 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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1% uncertainty on \( R(\Lambda_c) \) compared to 3% from LQCD \( \Rightarrow \) most precise \( R(\Lambda_c) \) to date.

First estimate from data of \( \mathcal{O}(\Lambda_{QCD}^2/m_c^2) \) HQET corrections for an exclusive decay.

\[ \hat{b}_1 = -0.46 \text{ GeV}^2 \] smaller than model dependent estimate \( \hat{b}_1 = -3\Lambda_{\Lambda}^2 = -2 \text{ GeV}^2 \)

SM Form factors

- Predict SM form factors under HQET from fitted parameters.
- Compare these with LQCD predictions.
- $O(\Lambda_{QCD}^2/m_c^2)$ corrections necessary to match LQCD.
We now construct several form factor ratios $f_1/g_1$, $f_{i=2,3}/f_1$ and $g_{i=2,3}/g_1$.

- $f_{i=2,3}/f_1$ and $g_{i=2,3}/g_1$ are $O(\alpha_s, \varepsilon_{c,b})$.
- $f_1/g_1 \sim O(1)$ as expected.
Fitted values for $\zeta(w)$, $\hat{b}_{1,2}$ allow us to predict form factors associated with possible NP interactions.

Can compare with LQCD predictions in [Datta, Kamali, Meinel, Rashed, 1702.02243]

4 tensor form factors: $h_1$, $h_2$, $h_3$, $h_4$

In chosen HQET basis: $h_1 = \mathcal{O}(1)$, $h_{2,3,4} = \mathcal{O}(\alpha_s, \varepsilon_{c,b})$

While in LQCD basis all 4 $\mathcal{O}(1)$

Tension in $h_1$ to be understood.
Switch on several possible new physics operators, \(O(V - A), O(V + A), O(T)\) and \(O(S)\) and compute allowed regions in \(R(\Lambda_c) vs R(D)\) and \(R(\Lambda_c) vs R(D^*)\).

NP coefficients real at boundaries.

Inner region requires phase between NP and SM.

Can look at \(R(X)_{NP}/R(X)_{SM}\) as a function of potential NP couplings (real) for \(X = D, D^*\) and \(\Lambda_c\).
Conclusion

- Computed SM and NP form factors of $\Lambda_b \to \Lambda_c \ell^- \bar{\nu}_\ell$ decays up to $\mathcal{O}(\Lambda_{\text{QCD}}^2/m_c^2)$ using HQET.
- HQET based fit made to LHCb measurements and LQCD predictions for $\zeta(w)$ and $\hat{b}_{1,2}$.
- First determination of the magnitude of $\mathcal{O}(\Lambda_{\text{QCD}}^2/m_c^2)$ corrections in HQET for an exclusive decay.
- Most precise value of $R(\Lambda_c) = 0.3237 \pm 0.0036$ to date. A factor of three times more precise than LQCD prediction alone.
- NP form factors are computed using parameters from HQET fit and were used to assess the sensitivity of $R(\Lambda_c)$ to NP.