Semileptonic $\Lambda_b \rightarrow \Lambda_c^{(*)}\mu\nu$ Decays

Marcello Rotondo
Laboratori Nazionali di Frascati
On behalf of the LHCb collaboration
Why $\Lambda_b \rightarrow \Lambda_c \mu \nu$?

- $B \rightarrow D \mu \nu$ and $B \rightarrow D^* \mu \nu$ decays well studied at B-Factories
  - A lot of information about $B \rightarrow D^{**} \mu \nu$ and $B \rightarrow D \pi(\pi) \mu \nu$ also available
- $\Lambda_b$ (bdu) have different spin structure and because the (ud) di-quark has $j=0$, HQET makes clean predictions
- Only few measurements (Delphi, CDFII) available for semileptonic $\Lambda_b$
  - $\Lambda_c^+ \ell^- \bar{\nu}_\ell$ anything (10.3 ± 2.1)%
  - $\Lambda_c^+ \ell^- \bar{\nu}_\ell$ (6.2$^{+1.4}_{-1.3}$)%
  - $\Lambda_c^+ \pi^+ \pi^- \ell^- \bar{\nu}_\ell$ (5.6 ± 3.1)%
  - $\Lambda_c(2595)^+ \ell^- \bar{\nu}_\ell$ (7.9$^{+4.0}_{-3.5}$)$\times 10^{-3}$
  - $\Lambda_c(2625)^+ \ell^- \bar{\nu}_\ell$ (1.3$^{+0.6}_{-0.5}$)%
  - $\Sigma_c(2455)^0 \pi^+ \ell^- \bar{\nu}_\ell$
  - $\Sigma_c(2455)^{++} \pi^- \ell^- \bar{\nu}_\ell$
- LHCb has the unique capability to study in detail the semileptonic $\Lambda_b$ decays
**$\Lambda_b \rightarrow \Lambda_c \mu \nu$**

- Measure differential spectrum

\[ \frac{d\Gamma}{dw} = GK(w)\xi_B^2(w) \]

\[ w = v_{\Lambda_b} \cdot v_{\Lambda_c} = \frac{m_{\Lambda_b}^2 + m_{\Lambda_c}^2 - q^2}{2m_{\Lambda_b}m_{\Lambda_c}} \]

- Extract information on function \( \xi_B(w) \) assuming parameterizations based on phenomenological models or simple expansion around \( w=1 \)

\[ \xi_B(w) = 1 - \rho^2(w - 1) + \frac{1}{2}\sigma^2(w - 1)^2 + \cdots \]

- Check precise lattice results
- Test HQET predictions in baryons
- First step toward a precise \( |V_{cb}| \) from baryon decays

$$\Lambda_b \rightarrow \Lambda_c \mu \nu: \text{ yields and backgrounds}$$

- Run1 data: $3\text{fb}^{-1}$  
  \[ N(\Lambda_c^+ \mu^-) = (2.74 \pm 0.02) \times 10^6 \]

Very large and clean sample of $\Lambda_b \rightarrow \Lambda_c \mu \nu X$

Main peaking backgrounds:

- $\Lambda_b \rightarrow \Lambda_c^* \mu \nu$ with $\Lambda_c^* \rightarrow \Lambda_c \pi^+ \pi^-$ and $\Lambda_c \pi^0 \pi^0$
  Fit on data using $\Lambda_c \pi^+ \pi^-$ decay which covers 2/3 of the $\Lambda_c^*$ decays

- $\Lambda_b \rightarrow \Sigma_c^{++} \mu \nu$ and $\Sigma_c^{0} \mu \nu$ with $\Sigma_c \rightarrow \Lambda_c \pi$
  From data reconstructing $\Sigma_c \rightarrow \Lambda_c \pi$

Measured raw yields

\[
\begin{align*}
\Lambda_c(2595)^+ & \mu^- \bar{\nu}_\mu & 8569 \pm 144 \\
\Lambda_c(2625)^+ & \mu^- \bar{\nu}_\mu & 22965 \pm 266 \\
\Lambda_c(2765)^+ & \mu^- \bar{\nu}_\mu & 2975 \pm 225 \\
\Lambda_c(2880)^+ & \mu^- \bar{\nu}_\mu & 1602 \pm 95 \\
\end{align*}
\]

Significant yields with excited states: opportunity to study them
Reconstruction of the $q^2$

- The knowledge of the $\Lambda_b$ momentum $P_b$ is needed to measure $q^2 = (P_b - P_c)^2$

- No constraints from beam energy as at B-Factories
  - Hypothesis of just 1-neutrino missing and the well-measured $\Lambda_b$ flight direction gives the momentum with a 2-fold ambiguity, $P_+$ and $P_-$
  - Without selection both solutions have same chances to be the correct
  - After all selections the solution with smaller $P_b$ momentum is more often the correct one

- Ciezarek et al JHEP02(2017)021
  - The $q^2$ resolution can be improved exploiting other information as decay length and angle with respect to the beam line
  - Important when angular variables will be considered
Extraction of the $q^2$ spectrum

- Sample of $\Lambda_b \rightarrow \Lambda_c \mu \nu X$ extracted in 14 bins of $q^2$ (take lower $p_{\Lambda_b}$ solution)
- Correct for feed-down from peaking backgrounds in each bin
- Correct for selection efficiency
- Distribution unfolded with SVD technique (regularization parameter chosen from simulation)

Background subtracted $\Lambda_b \rightarrow \Lambda_c \mu \nu$ candidates

Unfolded distribution (7 $q^2$ bins)
\( \Lambda_b \rightarrow \Lambda_c \nu \nu: \) results

\[
\frac{dN_{\text{corr}}}{d\varpi} K(\varpi) = 8000
\]

Taylor expansion fit
\[
\rho^2 = 1.63 \pm 0.07 \pm 0.08
\]

<table>
<thead>
<tr>
<th>Shape</th>
<th>( \rho^2 )</th>
<th>( \sigma^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exponential*</td>
<td>1.65 ( \pm 0.03 )</td>
<td>2.72 ( \pm 0.10 )</td>
</tr>
<tr>
<td>Dipole*</td>
<td>1.82 ( \pm 0.03 )</td>
<td>4.22 ( \pm 0.12 )</td>
</tr>
<tr>
<td>Taylor series</td>
<td>1.63 ( \pm 0.07 )</td>
<td>2.16 ( \pm 0.34 )</td>
</tr>
</tbody>
</table>

- Different parameterizations have good fit quality: data/HQET predictions agree
- Knowledge of \( \Lambda_b \rightarrow \Lambda_c \) form-factors crucial for \( R(\Lambda_c) \)
- A suitable normalization would allow \( |V_{cb}| \) extraction
- Open the route to measurements of FF in other B-hadrons

- Comparison with recent lattice calculation shows good agreement
  - Support the lattice calculation used in the \( |V_{ub}|/|V_{cb}| \) measurement
  - In future further L-QCD calculations would be really desirable!
Excited states $\Lambda_c^{1/2}$ and $\Lambda_c^{3/2}$

- Interesting opportunities to study $\Lambda_b \rightarrow \Lambda_c^* \mu \nu$ in particular the copious $\Lambda_b \rightarrow \Lambda_c(2595) \mu \nu$ and $\Lambda_b \rightarrow \Lambda_c(2625) \mu \nu$ channels

- Interesting in near future for LFU test with $\Lambda_b$ semi-tauonic decays
  - Reduced feed-down from higher order excited states
  - $\Lambda_c^* \rightarrow \Lambda_c \pi^+ \pi^-$, di-pion allows a clean experimental signature

- Theoretical papers on these decays
  - Leibovich, Stewart PRD57(1998)5620
  - Pervin et al. PRC72(2005)035291
  - Gutsche et al. arXiv:1807.11300

- Sensitivity in LHCb to the form factors in these decays has been investigated in Böer et al. JHEP06(2018)155
\( \Lambda_b \rightarrow \Lambda_c^{*} \mu \nu: \text{LHCb sensitivity} \)

- Decomposing the \( \Lambda_b \rightarrow \Lambda_c^J \mu \nu \) decay rate in helicity basis
  - 6 form factors for 1/2 state
  - 8 form factors for 3/2 state
- Up to 1/m corrections can be reduced to two independent Isgur-Wise functions
  - Interestingly the same functions describe both states
- For unpolarized \( \Lambda_b \) the differential decay rate is
  \[
  \frac{1}{\Gamma_0^{(\ell)}} \frac{d^2 \Gamma_0^{(\ell)}}{dq^2 d \cos \theta_\ell} = \left( a_\ell^{(J)} + b_\ell^{(J)} \cos \theta_\ell + c_\ell^{(J)} \cos^2 \theta_\ell \right)
  \]
  \(\text{Coefficients } a,b,c \text{ depend on } J \text{ and Lepton kind}\)

- Strategy for the sensitivity study in LHCb
  - Parametrize the relevant form-factors with a phenomenological model
  - Generate and fit toys at different luminosity scaling properly the yields extracted in LHCb
    - Considering the resolution on \( q^2 \) and \( \cos \theta_\ell \) as in \textit{JHEP02(2017)021}
FF parameters sensitivity

- Form-factors parameterized with exponential functions

\[
\zeta(q^2) \bigg|_{\text{exp}} \equiv \zeta(q_{\text{max}}^2) \exp \left[ \rho \left( \frac{q^2}{q_{\text{max}}^2} - 1 \right) \right]
\]

\[
\zeta_{\text{SL}}(q^2) \bigg|_{\text{exp}} \equiv \zeta(q_{\text{max}}^2) \delta_{\text{SL}} \exp \left[ \rho_{\text{SL}} \left( \frac{q^2}{q_{\text{max}}^2} - 1 \right) \right]
\]

- Fits with different configurations:
  - Separately for $\Lambda_c^{1/2}$ and $\Lambda_c^{3/2}$
  - 1-Dimensional $q^2$
  - 2-Dimensional combined $q^2$ and $\cos \theta_\ell$

Sensitivity corresponding to the data available at the end of Run2 ~20K $\Lambda_c^{1/2}$ and ~50K $\Lambda_c^{3/2}$

- Best sensitivity with simultaneous 2D fit on both resonances: analysis ongoing in LHCb

Böer et al. JHEP06(2018)155
Expectations for $R(\Lambda_c^{(*)})$

- From recent calculations from Gutsche et al. arXiv:1807.11300

<table>
<thead>
<tr>
<th></th>
<th>$\Lambda_c^+\left(\frac{1}{2}^+\right)$</th>
<th>$\Lambda_c^{(*)+}\left(\frac{1}{2}^-\right)$</th>
<th>$\Lambda_c^{(*)+}\left(\frac{3}{2}^-\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>6.80 ± 1.36</td>
<td>0.86 ± 0.17</td>
<td>0.17 ± 0.03</td>
</tr>
<tr>
<td>$\mu$</td>
<td>6.78 ± 1.36</td>
<td>0.85 ± 0.17</td>
<td>0.17 ± 0.03</td>
</tr>
<tr>
<td>$\tau$</td>
<td>2.00 ± 0.40</td>
<td>0.11 ± 0.02</td>
<td>0.018 ± 0.004</td>
</tr>
<tr>
<td>$R(\Lambda_c^{(*)})$</td>
<td>0.30 ± 0.06</td>
<td>0.13 ± 0.03</td>
<td>0.11 ± 0.02</td>
</tr>
</tbody>
</table>

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

- The decay into ground state is more favourable because of the large BF, higher efficiency
- With higher statistics the excited states would allow better control of the systematics due to the peaking backgrounds
Properties of semileptonic decays of b-baryons can be studied in LHCb with high precision

Great opportunities

- Measurements of CKM parameters, LFU tests
- hope to get soon similar/better level of knowledge as in B meson decays

Crucial interplay with theorists

- L-QCD is an essential ingredient but it usually requires time
- Predictions using other approaches are of course very welcome

News from baryons in the next months!
BACKUP
\(|V_{ub}| \) at LHCb

- B-baryons provide complementary informations to B-mesons
- Copious production of \( \Lambda_b \)

- Kinematic constraints allow the determination of the \( p_{\Lambda_b} \) (modulo 2-fold ambiguity)
- Large background from \( \Lambda_b \to \Lambda_c \mu \nu \)
- LHCb determines (in the high \( q^2 \) region) the ratio

\[
R_{exp} = \frac{B(\Lambda_b \to p \mu \nu)}{B(\Lambda_b \to \Lambda_c \mu \nu)}
\]

- Precise F.F. calculation on L-QCD

\[
\Lambda_b \to p \mu \nu \\
q^2 > 15 \text{ GeV}^2
\]

\[
\Lambda_b \to \Lambda_c \mu \nu \\
q^2 > 7 \text{ GeV}^2
\]

- Detmold et al PRD92(2015)034503
\( \Lambda_b \rightarrow p\mu\nu \) signal & \(|V_{ub}|\)

\[ M_{corr} = \sqrt{p_{\perp}^2 + M_{p\mu}^2} + p_{\perp} \]

\[ N_{\text{sig}} = 17687 \pm 733 \]

\[ \frac{|V_{ub}|}{|V_{cb}|} = 0.080 \pm 0.004_{\text{Exp.}} \pm 0.004_{\text{F.F.}} \]

\( \sigma_{\text{tot}} = 7\% \)

Inclusive \(|V_{cb}|\), global fit in KS
\(|V_{ub}|\), GGOU

\[ R = \frac{\mathcal{B}(\Lambda_b \rightarrow p\mu\nu)_{q^2>15 \text{ GeV}^2}}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c\mu\nu)_{q^2>7 \text{ GeV}^2}} = (0.95 \pm 0.04 \pm 0.07) \times 10^{-2} \]

Systematics dominated by
\[ \text{BF}(\Lambda_c \rightarrow pK\pi) = (6.46 \pm 0.24)\% \]

HFLAV using BESIII-Belle measurements
New global picture?

Inclusive $|V_{cb}|$, global fit in KS

$|V_{ub}|$, HFLAV GGOU

$B \to D\ell\nu$

$B \to D^*\ell\nu$

$B \to \pi^+\ell\nu$

$\Lambda_b \to p\mu\nu$

$|V_{ub}| [10^{-3}]$

$|V_{cb}| [10^{-3}]$