LHCb prospects for $V_{ub}$ and $V_{cb}$

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University of Warwick
1st October 2018

XIII Meeting on B Physics:
Synergy between LHC and SUPERKEKB
in the Quest for New Physics
Outline

• Semileptonic decays at LHCb.
• Current results and analysis activities.
• Future prospects.
LHCb

Excellent reconstruction of charged final states, while neutrals and missing energy are more challenging.

Well suited to measurements of exclusive semileptonic decays, to charged final states, of a range of b hadrons.
Suitable observables

• The $b$ cross section isn’t known.
• We can measure ratios of BF
  s.
• And normalised differential decay rates.
Operations

LHCb Integrated Recorded Luminosity in pp, 2010-2018

- 2018 (6.5 TeV): 1.88/fb
- 2017 (6.5+2.51 TeV): 1.71/fb + 0.10/fb
- 2016 (6.5 TeV): 1.67/fb
- 2015 (6.5 TeV): 0.33/fb
- 2012 (4.0 TeV): 2.08/fb
- 2011 (3.5 TeV): 1.11/fb
- 2010 (3.5 TeV): 0.04/fb

Month of year

Integrated Recorded Luminosity (1/fb)
The typical signature(s)
The typical signature(s)
The typical signature(s)

Discrimination between decays

- Isolation
- Vertex topology
- Kinematics
The typical signature

LHCb simulation

- $p\mu\nu$ low $\sigma_{\text{mcorr}}$
- $p\mu\nu$ high $\sigma_{\text{mcorr}}$
- $\Lambda_c\mu\nu$ low $\sigma_{\text{mcorr}}$
- $\Lambda_c\mu\nu$ high $\sigma_{\text{mcorr}}$

Kinematics

Well known formula for missing 3-momentum using topological information, but subject to quadratic ambiguity.

Dambach, Langenegger, Starodumov, NIM A569 (2006) 824
Well known formula for missing 3-momentum using topological information, but subject to quadratic ambiguity.

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Don’t need to choose randomly though.

JHEP (2017) 2017: 21

Closest to unbiased momentum estimator

Random
Kinematic “tag” approach

We can further impose $m(\Lambda_b \pi) = m(\Sigma_b)$.

Other possibilities, e.g. $B_s^{**} \rightarrow BK$.

Let’s see some measurements!
Ratio of $V_{ub}$ and $V_{cb}$ decays of the $\Lambda_b$
Ratio of $V_{ub}$ and $V_{cb}$ decays of the $\Lambda_b$

$LHCb$ simulation

- both solutions
- one solution

$q^2$ selection efficiency [%]

$q^2$ [$GeV^2/c^4$]
Ratio of $V_{ub}$ and $V_{cb}$ decays of the $\Lambda_b$
Ratio of $V_{ub}$ and $V_{cb}$ decays of the $\Lambda_b$

\[
\frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu)_{q^2>15\text{ GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-\bar{\nu}_\mu)_{q^2>7\text{ GeV}/c^2}} = \frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004
\]

(1.00 ± 0.04 ± 0.08) × 10^{-2}

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(\Lambda_c^+ \rightarrow pK^+\pi^-)$</td>
<td>4.7% ± 5.3%</td>
</tr>
<tr>
<td>Trigger</td>
<td>3.2%</td>
</tr>
<tr>
<td>Tracking</td>
<td>3.0%</td>
</tr>
<tr>
<td>$\Lambda_c^+$ selection efficiency</td>
<td>3.0%</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow N^*\mu^-\bar{\nu}_\mu$ shapes</td>
<td>2.3%</td>
</tr>
<tr>
<td>$\Lambda_b^0$ lifetime</td>
<td>1.5%</td>
</tr>
<tr>
<td>Isolation</td>
<td>1.4%</td>
</tr>
<tr>
<td>Form factor</td>
<td>1.0%</td>
</tr>
<tr>
<td>$\Lambda_b^0$ kinematics</td>
<td>0.5%</td>
</tr>
<tr>
<td>$q^2$ migration</td>
<td>0.4%</td>
</tr>
<tr>
<td>PID</td>
<td>0.2%</td>
</tr>
<tr>
<td>Total</td>
<td>7.8% ± 8.2%</td>
</tr>
</tbody>
</table>
Form factors of $\Lambda_b \rightarrow \Lambda_c \mu \nu$

Very interesting from an HQET point of view, but only one experimental study from Delphi. 

$$\frac{d\Gamma}{dw} = G K(w) \xi^2_B(w) \quad w \equiv \mathcal{U}_{\Lambda_b}^0 \cdot \mathcal{U}_{\Lambda_c}^+$$

Predictions of the form factor slope at zero recoil.

<table>
<thead>
<tr>
<th>$\rho^2$</th>
<th>Approach</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.35\pm0.13$</td>
<td>QCD sum rules</td>
<td>22</td>
</tr>
<tr>
<td>$1.2^{+0.8}_{-1.1}$</td>
<td>Lattice QCD (static approximation)</td>
<td>23</td>
</tr>
<tr>
<td>$1.51$</td>
<td>HQET + Relativistic wave function</td>
<td>21</td>
</tr>
</tbody>
</table>
Form factors of $\Lambda_b \to \Lambda_c \mu \nu$

First challenge is to subtract $\Lambda_b \to \Lambda_c \pi \pi \mu \nu$
Form factors of $\Lambda_b \to \Lambda_c \mu \nu$

$$1 - \rho^2 (w - 1) + \frac{1}{2} \sigma^2 (w - 1)^2 + \ldots$$

<table>
<thead>
<tr>
<th>Shape</th>
<th>$\rho^2$</th>
<th>$\sigma^2$</th>
<th>correlation coefficient</th>
<th>$\chi^2$/DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exponential*</td>
<td>1.65 ± 0.03</td>
<td>2.72 ± 0.10</td>
<td>100%</td>
<td>5.3/5</td>
</tr>
<tr>
<td>Dipole*</td>
<td>1.82 ± 0.03</td>
<td>4.22 ± 0.12</td>
<td>100%</td>
<td>5.3/5</td>
</tr>
<tr>
<td>Taylor series</td>
<td>1.63 ± 0.07</td>
<td>2.16 ± 0.34</td>
<td>97%</td>
<td>4.5/4</td>
</tr>
</tbody>
</table>
Semileptonic width ratios among beauty hadrons

I.I. Bigi,\textsuperscript{a} Th. Mannel,\textsuperscript{b} N. Ural'tsev\textsuperscript{a,b,c}

Abstract

We present predictions based on the heavy quark expansion in QCD. We find $SU(3)$ breaking in $B$ mesons suppressed in the framework of the HQE. $B_s$ is expected to have the semileptonic width about 1\% lower and $\Lambda_b$ about 3\% higher when compared to $\Gamma_{\text{s}l}(B_d)$. The largest partial-rate preasymptotic effect is Pauli interference in the $b \rightarrow u \ell \nu$ channel in $\Lambda_b$, about $+10\%$. We point out that the $\Omega_b$ semileptonic width is expected not to exceed that of $B_d$ and may turn out to be the smallest among stable $b$ hadrons despite the large mass. The underlying differences with phase-space models are briefly addressed through the heavy mass expansion.
Semileptonic width ratios among beauty hadrons

I.I. Bigi, Th. Mannel, N. Uraltsev

\[ \Gamma(\Lambda_b^0 \to X_c \mu \nu X) = \tau_B \times \mathcal{B} \mathcal{F}(B \to X_c \mu \nu X)(1 + \delta) \]

\[ \delta = (3 \pm 1.5) \times 10^{-2} \]

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$\Omega_c$ lifetime study, with $\Omega_b \to \Omega_c \mu \nu$
$\Omega_c$ lifetime study, with $\Omega_b \rightarrow \Omega_c \mu \nu$

$\Xi_c^+$ (PDG)

$\Lambda_c^+$ (PDG)

$\Xi_c^0$ (PDG)

$\Omega_c^0$ (PDG)

E687 [1995]

WA89 [1995]

FOCUS [2003]

PDG Average

PRL 121, 092003 (2018)
$\Omega_c$ lifetime study, with $\Omega_b \to \Omega_c\mu\nu$

$268 \pm 24 \pm 10 \pm 2$ fs
Future synergy with Belle and BES

Huge potential for LHCb to measure form-factors and $|V_{ub}|/|V_{cb}|$ ratios with a range of b hadrons.

The full exploitation requires knowledge of the charm hadron branching ratios.

E.g. $\text{BF}(\Lambda_c \rightarrow pK\pi)$ was the dominant experimental source of uncertainty in Nature Phys 10 (2015) 1038

Rumours of BEPC plans to reach $\Xi_c\Xi_c$ threshold.

Hai-Ping Peng slides @ICHEP2018.
$B$ decays with $B_s^{**}$ tag

PRL 110, 151803 (2013)
Application to $B \rightarrow D^{(*)}\mu\nu$

Aim for contribution to understanding of inclusive-exclusive gap puzzle...
Kinematic resolution

\[ \text{Fraction} / (0.05 \text{ GeV}^2) \]

![Graph showing kinematic resolution with various decay modes labeled: $D^0 \mu^- \bar{\nu}_\mu$, $D^{*0} \mu^- \bar{\nu}_\mu$, $D^{**0} \mu^- \bar{\nu}_\mu$. The graph plots $m_{\text{miss}}^2$ against the fraction.]

LHCb simulation
The $D$ fractions fit

$$f_{D^0} = 0.25 \pm 0.06$$

$$f_{D^{*0}} = 0.21 \pm 0.07$$
Purely leptonic: $B \rightarrow \mu \mu \mu \nu$

(+\(\rho, \omega\) interference)

Naive expected BF \(\sim 10^{-8}\)

Vector dominance prediction of \(1.3 \times 10^{-7}\)

Purely leptonic: $B \rightarrow \mu \mu \mu \nu$

$\min(m_{\mu+\mu-}) < 980 \text{ MeV}$

95% C.L. U.L. of $1.4 \times 10^{-8}$
Plans for $B \rightarrow p\bar{p}\mu\nu$

Evidence from Belle

$\mathcal{B}(B^- \rightarrow p\bar{p}\mu\bar{\nu}) = (3.1^{+3.1}_{-2.4} \pm 0.7) \times 10^{-6}$

PRD 89, 011101 (2014)
$B_s$ decays

Strong motivation from LQCD to measure

Recent dedicated study on the ratio.

Monahan et al., 1808.09285
Progress towards $B_s \rightarrow K\mu\nu/B_s \rightarrow D_s\mu\nu$

Analysis in progress with 3/fb of Run-I data

Similar idea to $p\mu\nu/\Lambda_c\mu\nu$, but backgrounds larger.

Target two $q^2$ bins across the full range.

See Marta Calvi’s talk at Challenges in Semileptonic B Decays
Longer term aspirations for differential measurement

Toy measurement of $d\Gamma/dq^2$ of $B_s \rightarrow K\mu\nu$
Towards $B_s \rightarrow D_s^{(*)}$ form factors

Measurement of $B_s$ - $B_d$ lifetime difference, and $\tau_{D_s}$.

$R(B_s^0/B^0) = 0.0115 \pm 0.0053 \pm 0.0041 \text{ ps}^{-1}$
The long term future prospects
Physics Case for an LHCb Upgrade II

opportunities in flavour physics, and beyond, in the HL-LHC era
The Upgrade II detector

- Fast timing to suppress pileup.
- Higher granularity and radiation hardness.
The VELO and the RF foil
The VELO and the RF foil
Effect of improved corrected mass resolution?

Toy study with simulated $B_s \rightarrow K\mu\nu$ signal
Low momentum particle ID

Smaller LQCD uncertainties at low $q^2$

Hadron often below the RICH PID threshold…
Low momentum particle ID

Smaller LQCD uncertainties at low $q^2$

Hadron often below the RICH PID threshold…

TORCH
Low momentum tracking

The $[B_s^{**} \rightarrow BK, \Sigma_b \rightarrow \Lambda_b \pi \text{ etc...}]$ approach is statistically challenging, which isn’t helped by losing many tagging kaons in the magnet.

Magnet stations boost the useable acceptance by 60%.
Outlook

Exclusive $b \to \{c, u\} \mu \nu$ decays are an area with really interesting synergies between LHCb with Belle(-II).

Exciting to think about all of the measurements with unexplored decays and observables that can go into future figures like this:
Backup slides follow from here...
$\Omega_b^- \rightarrow \Omega_c^0 \mu^- \bar{\nu} X$

- Data
- Fit

$\tau = 69 \text{ fs}$
Figure 5: Missing-mass distribution for data and estimated background contributions in the (left) same-sign kaon sample and (right) opposite-sign sample. The other background decays include contributions from misreconstructed backgrounds, and semileptonic decays of $B_s^0$ and $\Lambda_b^0$ mesons. The remainder of the SSK sample not from $B^0$ or other background decays is used to define the background contribution from $B^-$ semileptonic decays. This is then extrapolated to the OSK sample, where the remainder is composed of signal. The background distributions are stacked.
Candidates/ (8 MeV)

\[ m(pK^{-}\pi^{+}\pi^{+}\pi^{-}) - m(pK^{-}\pi^{+}) + m_{\text{PDG}}(\Lambda_c^+) \text{ [MeV]} \]
The graph shows the unfolded $dN_{\text{corr}} / dq^2$ distribution as a function of $q^2_{\text{unfolded}}$ (GeV$^2$) with error bars for each point. The data points are marked with black circles and triangles, and the shaded regions represent the uncertainty ranges. The curve is a fit to the data. The LHCb experiment is credited at the top right of the graph.