Studies of the CKM matrix with semileptonic b-hadron decays at LHCb

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Outline

- Status of CKM matrix
- $B_s^0$ and $\Lambda_b^0$ decays
  - Production at LHCb
  - Form factor measurements
- $\frac{|V_{ub}|}{|V_{cb}|}$ with $\Lambda_b^0 \to p\mu^+\bar{\nu}$ at LHCb
- Future prospects at LHCb
  - $B_s^0 \to K^-\mu^+\nu$
  - Fully leptonic $B^+ \to \mu^+\mu^-\mu^+\nu$
Status of CKM matrix

Precision measurements of CKM elements $|V_{ub}|$ and $|V_{cb}|$:

- improve precision: $|V_{ub}|$ ($\approx 12\%$ rel. error), $|V_{cb}|$ ($\approx 3\%$) (PDG 2014)
- resolve tension between inclusive and exclusive measurements
- test the unitarity of the CKM matrix complementary to measurement of $\sin(2\beta)$

$|V_{ub}|_{SL}$: standard modes for exclusive semileptonic decays

$\bar{B} \rightarrow \pi l\bar{\nu}_l \propto |V_{ub}|$ and $\bar{B} \rightarrow D(\ast) l\bar{\nu} \propto |V_{cb}|$

$|V_{ub}|_{\Lambda_b}$: $|V_{ub}|/|V_{cb}|$ from $\Lambda_b$ decay - latest LHCb result

Updated results and plots (2015)
LHCb’s unique $\Lambda_b$ and $B_s$ production

- Standard modes are hard to reconstruct at LHCb!
- Alternative: decays of $\Lambda_b$ and $B_s$
- At $s = \sqrt{7}$ TeV $\approx 100,000$ $b\bar{b}$ produced per second

Production fraction of $B_s$ mesons $\approx 14\%$

Production fraction of $\Lambda_b$ dependent on charmed hadron-muon pair’s transverse momentum and $b$-hadron pseudorapidity, $\eta$, $\approx 20\%$

Lattice QCD calculations for $\Lambda_b$ and $B_s$

To be able to extract $|V_{ub}|$ or $|V_{cb}|$ from exclusive decays, measurement of form factors (FF) is necessary!

- Differential decay rate
  \[
  \frac{d\Gamma[B_s \rightarrow Pl\nu]}{dq^2} \propto |V_{ub}|^2 \times (A(q^2)|f_+(q^2)|^2 + B(q^2)|f_0(q^2)|^2)
  \]

- Calculated non-pertubatively with lattice QCD

- $f_+(q^2)$ and $f_0(q^2)$ parametrize the hadronic contributions

- Recent calculation of $B_s \rightarrow K\mu\nu$ FF improved compared to the standard mode by factor of 2
Why $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}$ at LHCb?

- Baryonic version of standard mode but with proton and muon $\rightarrow$ higher identification rates at LHCb
- **Displaced vertex** ($\Lambda_b^0$ flies on average 1 cm before decaying) $\rightarrow$ LHCb’s excellent vertexing and tracking ability.
- **Challenges**: big backgrounds from $\Lambda_b^0 \rightarrow \Lambda_c^+(\rightarrow pX)\mu^-\bar{\nu}$ decays, missing neutrino in a final state, high precision
- **Method**: fit to corrected mass, $M_{(\Lambda_b^0)\text{corr}} = \sqrt{M_{p\mu^-}^2 + |p_T'|^2} + |p_T'|$
  - $M_{p\mu^-}$: invariant visible mass
  - $p_T'$: missing momentum transverse to the direction of flight of $\Lambda_b^0$
\[ \Lambda_b^0 \rightarrow p\mu^-\bar{\nu} \text{ - Results} \]

\[ \begin{align*}
\text{Combinatorial} & \quad \text{Mis-identified} \\
D^0p\mu^-\bar{\nu} & \quad \Lambda_c^+\mu^-\bar{\nu} \\
\Lambda_c^0\mu^-\bar{\nu} & \quad \Lambda_c^+\mu^-\bar{\nu} \\
N\mu^-\bar{\nu} & \quad p\mu^-\bar{\nu}
\end{align*} \]

\[ \text{Candidates} / (50 \text{ MeV}/c^2) \]


- Measurement of ratio
  \[ \frac{\mathcal{B}(\Lambda_b^0\rightarrow p\mu^-\bar{\nu})_{q^2>15\text{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0\rightarrow \Lambda_c^0\mu^-\bar{\nu})_{q^2>7\text{GeV}/c^2}} \times R_{\text{FF}} = \frac{|V_{ub}|^2}{|V_{cb}|^2} \rightarrow \]
  \[ |V_{ub}| = (3.27 \pm 0.15(\text{exp}) \pm 0.16(\text{LQCD}) \pm 0.06(\text{LQCD})) \times 10^{-3} \]

- 17687 ± 733 events were observed in Run 1 with 2fb^{-1}

- Consistent with other exclusive \(|V_{ub}|\) measurements

- Right-handed coupling not supported by this measurement
New HFAG world average for $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$

- In measurement of $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}$, $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$ used published by Belle, with $6.84 \pm 0.24 ^{+0.21}_{-0.27}$%.
- Another measurement was published later using BESIII data.
- HFAG performed global fit to all branching fractions of the Cabibbo-favoured $\Lambda_c^+$ decays yielding $6.46 \pm 0.24$%.
Future prospects at LHCb

$B_s^0 \to K^- \mu^+ \nu$ → natural candidate for the next measurement!

Most dangerous background
$B_s^0 \to K^{*-} (\to K^- \pi^0) \mu^+ \nu$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\Lambda_b^0 \to p \mu^- \nu$</th>
<th>$B_s^0 \to K^- \mu^+ \nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production fraction</td>
<td>20%</td>
<td>14%</td>
</tr>
<tr>
<td>Branching fraction</td>
<td>$4 \times 10^{-4}$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>Source of backgrounds</td>
<td>$\Lambda_c^+$</td>
<td>$\Lambda_c^+$, $D^0$, $D^+$, $D_s$</td>
</tr>
<tr>
<td>$B(X_c)$ error (PDG 2014)</td>
<td>$+5.3%$ $-4.7%$ (biggest systematic!)*</td>
<td>$\pm 3.9%$</td>
</tr>
<tr>
<td>Theory error FF (slide 5)</td>
<td>5%</td>
<td>$&lt; 5%$</td>
</tr>
<tr>
<td>Normalization channel</td>
<td>$\Lambda_b^0 \to \Lambda_c^+ \mu^- \nu$</td>
<td>$B_s^0 \to D_s^- \mu^+ \nu$</td>
</tr>
</tbody>
</table>

* will be soon improved (slide 8)
Other future prospects at LHCb

Semileptonic decays

- E.g. $B \rightarrow \rho \mu \nu$, $B \rightarrow p \bar{p} \mu \nu$, but additional final states $\rightarrow$ more complicated for FF calculation

Fully leptonic decays

- Measurement of $B^+ \rightarrow \tau^+ \nu$ at LHCb not feasible $\rightarrow$ $B^+ \rightarrow \mu^+ \nu$ $\rightarrow$ helicity suppressed ($\sim 1/250$)
- Addition of virtual photon decaying into a pair of muons lifts the helicity suppression
- Final state with 3 muons $\rightarrow$ good experimental signature
- Decay not observed yet $\rightarrow$ rare $\approx 10^{-8}$
- Need computation of FF, arXiv:1606.03080v1
Conclusion

- Probing CKM structure with exclusive semileptonic decays is becoming more precise → both theoretically and experimentally
- LHCb’s production of $\Lambda_b^0$ and $B_s^0$ provide interesting alternative to standard modes → already published $\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}$ analysis
- Tension between inclusive and exclusive measurements persists
- New ideas with semileptonic or fully leptonic B-decays are under way
Backup
Facing challenges of search for $\Lambda^0_b \rightarrow p \mu^- \bar{\nu}$

To reduce $V_{cb}$ backgrounds:

- charm has a big lifetime → vertex quality cut
- charm backgrounds have presence of additional tracks → train MVA technique to distinguish them
- reject candidates if: $\sigma_{Mcorr} > 100$ MeV/c$^2$