Semileptonic decays of $b$-baryons at LHCb $|V_{ub}|$

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HQL 2016, Blacksburg  
May 22-27, 2016
Why is $|V_{ub}|$ important?

- Quarks change their flavour in the SM by the emission of a $W$-Boson
- The rate is proportional to the coupling strength $|V_{ub}|^2$

- These 9 different couplings form the CKM matrix:

\[
V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}, \quad \sigma(\frac{V_{CKM}}{|V_{CKM}|}) = \begin{pmatrix}
0.02\% & 0.3\% & 12\%
4\% & 2\% & 2\%
7\% & 7\% & 3\%
\end{pmatrix}
\]  

[PDG 2014]

→ $|V_{ub}|$ is least well known element of the CKM matrix
In the SM the CKM matrix is unitary

Leads to several unitarity equations, e.g.:

\[
\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{cd}V_{cb}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0
\]

Precision limited by magnitude and phase of \(|V_{ub}|\)

→ If it is no triangle → New Physics

\[
|V_{ub}| < 0.04 \quad \sin 2\beta \quad \text{sol. w/ cos} 2\alpha = 0
\]
• $|V_{ub}|$ measured using (semi-)leptonic decays

• 3 different strategies:
  • **exclusive**: semileptonic decays such as $\bar{B}^0 \rightarrow \pi^+ l^- \bar{\nu}$
  • **inclusive**: all semileptonic $B \rightarrow X_u l^- \bar{\nu}$ transitions
  • measure pure leptonic decay $B^+ \rightarrow \tau \nu$

• Semileptonic decays rely on non-perturbative FF calculations from LQCD or QCD sum rules
  \[
  \frac{d\Gamma}{dq^2} \propto G_F^2 |V_{ub}| |f^+(q^2)|
  \]
The $|V_{ub}|$ puzzle

- **Discrepancy between exclusive vs. inclusive measurement:**
  
  excl.: \((3.28 \pm 0.29) \times 10^{-3}\) [PDG 2014]
  
  incl.: \((4.14 \pm 0.15^{+0.15}_{-0.19}) \times 10^{-3}\)
  
  $\rightarrow$ ~3$\sigma$ deviation

- **Leptonic measurements not precise enough, favours inclusive results**
  
  $\rightarrow$ More precise measurements needed
First LHCb $|V_{ub}|$ measurement: $\Lambda_b \to p\mu^-\nu_\mu$
Nature Physics 10 (2015) 1038
**$V_{ub}$ in $\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu$**

- Baryonic version of $\bar{B}^0 \rightarrow \pi^+ l^- \bar{\nu}_\mu$
- Excellent $\mu$ and $p$ PID at LHCb from RICH/Muon systems
- High production fraction of $\Lambda_b$: ~20% of $b$-hadrons
- Improved FF calculations from theory for $\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu$ and $\Lambda_b \rightarrow \Lambda_c^+ \mu^-\bar{\nu}_\mu$ in high $q^2$ region

\[ \Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu \]

\[ \Lambda_b \rightarrow \Lambda_c^+ \mu^-\bar{\nu}_\mu \]
How to extract $|V_{ub}|$?

\[
\frac{\mathcal{B}(\Lambda_b \rightarrow p\mu^-\nu_{\mu})}{ \mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+\mu^-\nu_{\mu})} = R_{FF} \times \frac{|V_{ub}|^2}{|V_{cb}|^2}
\]

- Reduce systematic uncertainties by restricting measurement to $q^2 > 15(7)\text{ GeV}^2$
  → LQCD here most precise

- $R_{FF} = \frac{(\Lambda_b \rightarrow p\mu^-\nu_{\mu})_{q^2 > 15\text{ GeV}^2}}{(\Lambda_b \rightarrow \Lambda_c^+\mu^-\nu_{\mu})_{q^2 > 7\text{ GeV}^2}} = 0.68 \pm 0.07$ [Phys. Rev. D 92, 034503 (2015)]
  → 5% uncertainty on $|V_{ub}|$ from theory

- Experimental challenges:
  $|V_{ub}|$ much smaller compared to $|V_{cb}|$ background, missing neutrino $\rightarrow \Lambda_b$ not fully reconstructed
Analysis strategy

• 2012 Dataset (~2 fb⁻¹)
• Normalise signal yield to cancel systematic uncertainties:

\[
\frac{B(\Lambda_b \rightarrow p\mu^-\nu_\mu)_{q^2>15 \text{ GeV}^2}}{B(\Lambda_b \rightarrow (\Lambda_c^+ \mu^-\nu_\mu)_{q^2>7 \text{ GeV}^2}} = \frac{N(\Lambda_b \rightarrow p\mu^-\nu_\mu)}{N(\Lambda_b \rightarrow (\Lambda_c^+ \rightarrow pK^-\pi^+)\mu^-\nu_\mu)} \times \frac{\epsilon(\Lambda_b \rightarrow p\mu^-\nu_\mu)}{\epsilon(\Lambda_b \rightarrow (\Lambda_c^+ \rightarrow pK^-\pi^+)\mu^-\nu_\mu)} \times B(\Lambda_c^+ \rightarrow pK^-\pi^+)
\]

• Determine yields of \(\Lambda_b \rightarrow p\mu^-\nu_\mu\) and \(\Lambda_b \rightarrow (\Lambda_c^+ \rightarrow pK^-\pi^+)\mu^-\nu_\mu\)
• Estimate relative experimental efficiency with high precision
• Use \(B(\Lambda_c^+ \rightarrow pK^-\pi^+)\) from Belle [PRL 113,042002(2014)]
Selection

- Reconstruct $q^2$ up to 2-fold ambiguity
- Require both solutions to fulfill $q^2 > q^2_{cut}$

- Significant background from $\Lambda_b \rightarrow X_c \mu^- \nu_\mu$ decays (partially reconstructed backgrounds)
- Dedicated MVA classifier used to remove backgrounds with additional charged tracks that vertex with $p_\mu$ candidate → track isolation
Extracting Yields

- Fit to corrected mass
  \[ m_{corr} = \sqrt{m_{h\mu}^2 + p_{\perp}^2 + p_{\perp}} \]
  performed for signal and normalisation separately

- Determine its uncertainty and reject candidates if
  \[ \sigma_{m_{corr}} > 100 \text{ MeV}/c^2 \] for signal fits

\[ N(\Lambda_b \rightarrow p\mu^-\nu_\mu) = 17687 \pm 733 \]

\[ N(\Lambda_b \rightarrow \Lambda_c^+\mu^-\nu_\mu) = 34255 \pm 571 \]
Relative efficiencies

- Different decay topologies between $\Lambda_b \rightarrow p\mu^-\nu_\mu$ and $\Lambda_b \rightarrow (\Lambda_c^+ \rightarrow pK^-\pi^+)\mu^-\nu_\mu$ leads to different experimental efficiencies.

- Relative efficiency determined from simulation.

- Difference between data and simulation calculated from control sample with data-driven corrections.

\[
\frac{\epsilon(\Lambda_b \rightarrow p\mu^-\nu_\mu)}{\epsilon(\Lambda_b \rightarrow (\Lambda_c^+ \rightarrow pK^-\pi^+)\mu^-\nu_\mu)} = 3.52 \pm 0.20
\]

- Uncertainty of ratio is dominated by systematic uncertainties.
Systematic uncertainties

- Dominated by $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+) \text{ from Belle}$ [PRL 113,042002(2014)]
- Trigger uncertainties can be further reduced $\rightarrow$ size of control sample in data
- Tracking uncertainties dominated by material interaction of kaon and $\pi$
- $\Lambda_c^+ \rightarrow pK^-\pi^+$ selection efficiency from knowledge on its Dalitz structure
- Fit systematic dominated by form factors of $\Lambda_b \rightarrow N^*\mu^-\nu_\mu$ decays

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(A_c^+ \rightarrow pK^+\pi^-)$</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>$A_b^0 \rightarrow N^*\mu^-\overline{\nu}_\mu$ shapes</td>
<td>2.3</td>
</tr>
<tr>
<td>$A_b^0$ 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>$A_b^0$ 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>
Results I

• Measure the relative branching fraction:

\[
\frac{\mathcal{B}(\Lambda_b \rightarrow p \mu^- \nu_\mu)_{q^2 > 15 \text{ GeV}^2}}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \mu^- \nu_\mu)_{q^2 > 7 \text{ GeV}^2}} = (1.00 \pm 0.04(\text{stat}) \pm 0.08(\text{syst})) \times 10^{-2}
\]

• Including \( \frac{\mathcal{B}(\Lambda_b \rightarrow p \mu^- \nu_\mu)}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+ \mu^- \nu_\mu)} = R_{FF} \times \frac{|V_{ub}|^2}{|V_{cb}|^2} \) with \( R_{FF} = 0.68 \pm 0.07 \) [Phys. Rev. D 92, 034503 (2015)] gives

\[
\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\text{exp.}) \pm 0.004(\text{theo.})
\]

• Use world average for exclusive \( |V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \) measurements [PDG 2014]

\[
|V_{ub}| = (3.27 \pm 0.15(\text{exp.}) \pm 0.16(\text{theo.}) \pm 0.06(|V_{cb}|)) \times 10^{-3}
\]
Results II

- LHCb is 3.5σ away from inclusive measurement of $|V_{ub}|$
- Consistent with other exclusive measurements
• $|V_{ub}|$ measurement depends on possible right-handed current in SM [Phys. Rev. D 81, 031301 (2010)]

• Previously exclusive/inclusive discrepancy suggested significant right-handed coupling fraction ($\epsilon_R$) → solution to $|V_{ub}|$ puzzle?

→ LHCb results does not support that

![Graph showing $|V_{ub}|$ vs $\epsilon_R$](image-url)
Future plans

- We are working currently on extraction $|V_{ub}|$ exclusively from $B_s^0 \rightarrow K^- \mu^+ \nu_\mu$, using normalisation channel of $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu$
- Smaller FF uncertainty $\sim 3\%$ [Phys. Rev. D 91, 074510 (2015)]
- Production fraction $\sim 10\%$, smaller compared to $\Lambda_b$ ($\sim 20\%$)
- More difficult to handle background ($\Lambda_c, D_s, D^+, D^0$) w.r.t. $\Lambda_b$

[Phys. Rev. D 91, 074510 (2015)]
Conclusions

• LHCb performed a precise measurement of $|V_{ub}|$ using the decay $\Lambda_b \rightarrow p\mu^-\nu_\mu$.

• First determination of $|V_{ub}|$ in a hadron collider and in a baryonic decay

$$|V_{ub}| = (3.27 \pm 0.15(\text{exp.}) \pm 0.16(\text{theo.}) \pm 0.06(|V_{cb}|)) \times 10^{-3}$$

• Consistent with other exclusive $|V_{ub}|$ measurements in $\bar{B}^0 \rightarrow \pi^+ l^- \nu_\mu$.

• Measurement is $3.5\sigma$ below inclusive measurement of $|V_{ub}|$.

• Right-handed currents can no longer explain the $|V_{ub}|$ puzzle.

• LHCb is starting to determine $|V_{ub}|$ in $B^0_s \rightarrow K^- \mu^+ \nu_\mu$ decays.
Thanks for your attention!
Backup Slides
Corrected mass error

- Cutting on the uncertainty of $m_{corr}$ to increase separation to background
- Uncertainty dominated by resolution of PV and $\Lambda_b$ vertex
- Reject candidates if $\sigma_{m_{corr}} > 100$ MeV/$c^2$ for signal fits (~23% survive)
- Compare simulated signal and background shapes for low and high $\sigma_{m_{corr}}$
• Calculate 6 form factors (3 vector, 3 axial) for each decay. Lattice QCD with 2 + 1 dynamical domain-wall fermions.
• Calculation performed with six pion masses and two different lattice spacings.
• b and c quarks implemented with relativistic heavy-quark actions.
• Uses gauge-field configurations generated by the RBV and UKQCD collaborations.
• $b \rightarrow u$ and $b \rightarrow c$ currents renormalised with a mostly non-perturbative method.
• Parametrises the form factor $q^2$ dependence with a $z$ expansion.
• Systematics include: the continuum extrapolation uncertainty, the kinematic ($q^2$) extrapolation uncertainty, the perturbative matching uncertainty, the uncertainty due to the finite lattice volume and the uncertainty from the missing isospin breaking effects.

• Use the latest Lattice QCD results for these decays to calculate:

\[ R_{\text{FF}} = \frac{\int_{q_{\text{max}}^{15 \text{ GeV}/c^2}} \frac{d\Gamma(\Lambda_b \rightarrow p \mu^- \nu\mu)}{dq^2}}{\int_{q_{\text{max}}^{7 \text{ GeV}/c^2}} \frac{d\Gamma(\Lambda_b \rightarrow \Lambda_c^+ \mu^- \nu\mu)}{dq^2}} / |V_{ub}|^2 dq^2 \]
• convert measured ratio into bf using:

\[
\mathcal{B}(\Lambda_b \rightarrow p\mu^-\nu_\mu) = \tau_{\Lambda_b} \frac{\mathcal{B}(\Lambda_b \rightarrow p\mu^-\nu_\mu)q^2 > 15 \text{ GeV}/c^2}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c^+\mu^-\nu_\mu)q^2 > 7 \text{ GeV}/c^2} |V_{cb}|^2 R_{FF} \\
= \tau_{\Lambda_b} \mathcal{B}_{\text{ratio}} \int_{7 \text{ GeV}/c^2}^{q_{\text{max}}'} \frac{d\Gamma(\Lambda_b \rightarrow \Lambda_c^+\mu^-\nu_\mu)}{dq^2} / |V_{cb}|^2 dq^2 \\
\times \int_{0 \text{ GeV}^2/c^4}^{q_{\text{max}}} \frac{d\Gamma(\Lambda_b \rightarrow p\mu^-\nu_\mu)}{dq^2} / |V_{ub}|^2 dq^2 \\
\times \int_{15 \text{ GeV}/c^2}^{q_{\text{max}}'} \frac{d\Gamma(\Lambda_b \rightarrow p\mu^-\nu_\mu)}{dq^2} / |V_{ub}|^2 dq^2
\]

• results in:

\[
\mathcal{B}(\Lambda_b \rightarrow p\mu^-\nu_\mu) = (4.1 \pm 1.0) \times 10^{-4}
\]
Possible Right-handed currents

\[ \mathcal{L}_{\text{eff}} = \frac{-4G_F}{\sqrt{2}} V_{ub} L (\bar{u} \gamma_\mu P_L b + \epsilon_R \bar{u} \gamma_\mu P_R b)(\bar{\nu} \gamma_\mu P_L l) + h.c. \]

- \( B \rightarrow \pi \ell \nu \) is purely a vector current whereas \( B \rightarrow X_\ell \ell \nu \) is a V-A
- Adding right-handed current (V+A), increases vector current \( V \rightarrow (1 + \epsilon_R) V \) but decreases axial-vector current \( A \rightarrow (1 - \epsilon_R) A \)
- negative right-handed current was able to reduce the tension between inclusive and exclusive result

[Phys. Rev. D 90, 094003 (2014)]