V_{ub} using \Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu decays at LHCb

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IOP
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Why is $|V_{ub}|$ important?

- $|V_{ub}|$ is one of the least known of the CKM parameters.
- $|V_{ub}|$ constrains the unitarity triangle opposite the angle $\beta$. 

![Diagram](image-url)
1. Introduction

The $|V_{ub}|$ puzzle

\[ \Lambda_b^0 \rightarrow \bar{d} \pi^+ \]
\[ B^0 \rightarrow d \bar{\nu}_l \]
\[ W^- \rightarrow u \bar{\nu}_l \]

\[ |V_{ub}| \]

\[ 0.0025 \quad 0.003 \quad 0.0035 \quad 0.004 \quad 0.0045 \quad 0.005 \]

Inclusive

Exclusive

LHCb

made using PDG (2014)

see arxiv:1503.07839 for $B \rightarrow \pi l \nu$ LQCD update
What makes $|V_{ub}|$ possible at LHCb?

- Long thought that measuring $|V_{ub}|$ is impossible at hadron colliders.
- Lack the beam energy constraints of $e^+e^-$ colliders.

It is particularly important to stress that many of the measurements that constitute the primary physics motivation for SuperB cannot be performed in the hadronic environment. For example, modes with missing energy, such as $B^+ \rightarrow \ell^+\nu_\ell$ and $B^+ \rightarrow K^+\nu\bar{\nu}$, measurements of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$, and inclusive analyses of processes such as $b \rightarrow s\gamma$ are unique to SuperB.

CDR, SuperB factory, arXiv 0709.0451

- $26 \times 10^{10}$ $b\bar{b}$ pairs.
- Choose $\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu$
  - Excellent $\mu$ and $p$ PID.
- Precision vertexing and tracking.
2. Strategy

**Analysis strategy**

- Normalise $\Lambda_b \rightarrow p\mu\bar{\nu}$ to $\Lambda_b \rightarrow \Lambda_c(\rightarrow pK\pi)\mu\bar{\nu}$ in the high $q^2 (= m_{\mu\bar{\nu}}^2)$ region where theory uncertainty is lowest:

$$\frac{\mathcal{B}(\Lambda_b \rightarrow p\mu\bar{\nu})_{q^2 > 15 \text{ GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c\mu\nu)_{q^2 > 7 \text{ GeV}^2/c^4}} = \frac{N(\Lambda_b \rightarrow p\mu\bar{\nu})}{N(\Lambda_b \rightarrow (\Lambda_c \rightarrow pK\pi)\mu\bar{\nu})} \times \frac{\epsilon(\Lambda_b \rightarrow (\Lambda_c \rightarrow pK\pi)\mu\bar{\nu})}{\epsilon(\Lambda_b \rightarrow p\mu\bar{\nu})} \times \mathcal{B}(\Lambda_c \rightarrow pK\pi)$$

- 2012 Dataset ($\sim 2\text{ fb}^{-1}$)
- Recent measurement of $\mathcal{B}(\Lambda_c \rightarrow pK\pi)$ from Belle [arXiv:1312.7826]

$$R_{\text{exp}} = R_{\text{theory}} (|V_{ub}|^2 / |V_{cb}|^2)$$

$$R_{\text{theory}} = 1.470 \pm 0.115(\text{stat}) \pm 0.104(\text{syst})$$

Reconstruct $q^2$ up to a 2-fold ambiguity.

Require both solutions $> q_{cut}^2$.

Boosted decision tree removes backgrounds with additional charged tracks that could vertex with $p\mu$ candidate.
The corrected mass

- Fit the corrected mass:
  \[ M_{\text{corr}} = \sqrt{p_{\perp}^2 + M_{p\mu}^2} + p_{\perp} \]

- Determine its uncertainty.
- Reject candidates if:
  \[ \sigma_{M_{\text{corr}}} > 100 \text{ MeV}/c^2 \]

- Compare simulated \textit{signal} and \textit{background} shapes for low and high \( \sigma_{M_{\text{corr}}} \)
- Truncation at \( m_{\Lambda_b} \) due to \( q^2 \) cut.

![Diagram of \( \Lambda_b \rightarrow p\mu^-\nu \)]
4. Signal fit

- Fit $p\mu$ corrected mass, $N(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu) = 17687 \pm 733$.

- First observation of the decay $\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu$.

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Normalisation fit

- Fit $pK\pi\mu$ corrected mass.
- $N(\Lambda_b \rightarrow (\Lambda_c \rightarrow pK\pi)\mu^-\bar{\nu}_\mu) = 34255 \pm 571.$
6. Efficiencies and systematics

Relative efficiency and systematic uncertainties

- Efficiency from simulation with many data-driven corrections.

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

- Systematics:

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{B}(\Lambda_c \to 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>( N^* ) shapes</td>
<td>2.3</td>
</tr>
<tr>
<td>( \Lambda_b ) 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 ) production</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><strong>Total</strong></td>
<td>+7.8 (-8.2 )</td>
</tr>
</tbody>
</table>

LHCb-preliminary

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7. Results

Ratio of branching fractions and $\mathcal{B}(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu)$

- Measure the ratio of branching fractions to be:

$$\frac{\mathcal{B}(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu)_{q^2>15\text{ GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \rightarrow \Lambda_c\mu\nu)_{q^2>7\text{ GeV}^2/c^4}} = (1.00 \pm 0.04(\text{stat}) \pm 0.08(\text{syst})) \times 10^{-2}$$

LHCb-preliminary

- Can use theory to extrapolate to a full branching fraction for $\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu$ decays:

$$\mathcal{B}(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu) = (3.92 \pm 0.83) \times 10^{-4}$$

LHCb-preliminary

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The $|V_{ub}|$ puzzle revisited

$$|V_{ub}|^2 = |V_{cb}|^2 \left( \frac{R_{\text{exp}}}{R_{\text{theory}}} \right)$$

Inclusive

Exclusive

LHCb

$V_{ub}$ from $\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu$
What can LHCb say?

\[ |V_{ub}| = (3.27 \pm 0.15(\text{exp}) \pm 0.17(\text{theory}) \pm 0.06(|V_{cb}|)) \times 10^{-3} \]
8. Implications

- Total uncertainty on $|V_{ub}|$ is 7.2% (8.8% for exclusive average).
- $|V_{ub}|$ from $\Lambda_b \to p\mu^-\bar{\nu}_\mu$ is $3.5\sigma$ below the inclusive average.
- Can check the consistency of $|V_{ub}|/|V_{cb}|$ with $\beta$ and $\gamma$. 

\[ \bar{\eta} \]

\[ (0,0) \]

\[ (1,0) \]

\[ \beta \]

\[ \gamma \]

\[ \bar{\rho} \]

LHCb $|V_{ub}|/|V_{cb}|$

$\gamma$ (CKM 2014)

Inclusive $|V_{ub}|$

$\beta$ (HFAG 2014)
Can new physics explain the puzzle?

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

- \( \chi^2/n_{dof} = 2.8/1 \), p-value = 0.1
- Fit favours a right handed current over SM (\( \epsilon_R = 0 \)).

Bernlochner et al. [arXiv:1408.2516]

Also see Crivellin [arXiv:0907.2461]
8. Implications

Can new physics explain the puzzle?

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

- \( \chi^2/n_{dof} = 16.4/2 \), p-value = \( 3 \times 10^{-4} \)
- No longer possible to get a good global fit.
Conclusion

- $\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu$ decays are observed for the first time:
  - $\mathcal{B}(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu) = (3.92 \pm 0.83) \times 10^{-4}$

- The first determination of $|V_{ub}|$ at a hadron collider and in a baryon decay is:
  - $|V_{ub}| = (3.27 \pm 0.23) \times 10^{-3}$.

- This measurement is $3.5\sigma$ below the inclusive measurement but agrees well with current exclusive average using $B \rightarrow \pi l\nu$ decays.

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

Many thanks to Stefan Meinel for pioneering the LQCD predictions for $\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu$ and $\Lambda_b \rightarrow \Lambda_c\mu^-\bar{\nu}_\mu$. Additional thanks to Florian Bernlochner.
Use the latest Lattice QCD results for these decays to calculate:

\[
R_{\text{theory}} = \frac{\int_{q^2_{\text{max}} = 15 \text{ GeV}^2/c^4} d\Gamma(\Lambda_b \to p\mu^-\bar{\nu}_\mu) / |V_{ub}|^2 dq^2}{\int_{q^2_{\text{max}}' = 7 \text{ GeV}^2/c^4} d\Gamma(\Lambda_b \to \Lambda_c \mu^-\bar{\nu}_\mu) / |V_{cb}|^2 dq^2}
\]

\[
R_{\text{theory}} = 1.470 \pm 0.115(\text{stat}) \pm 0.104(\text{syst})
\]

Lattice Calculation

- 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 nonperturbative 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.

Branching Fraction Extrapolation Factor

\[ B(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu) = \tau_{\Lambda_b} \frac{B(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu)_{q^2>15 \text{ GeV}^2/c^4}}{B(\Lambda_b \rightarrow \Lambda_c\mu^-\bar{\nu}_\mu)_{q^2>7 \text{ GeV}^2/c^4}} |V_{cb}|^2 F_{\text{theory}} \]

\[ = \tau_{Lb} R_{\text{exp}} |V_{cb}|^2 \int_{\frac{7 \text{ GeV}^2}{c^4}} q_{\text{max}}' \frac{d\Gamma(\Lambda_b \rightarrow \Lambda_c\mu^-\bar{\nu}_\mu)}{dq^2} / |V_{cb}|^2 dq^2 \]

\[ \times \int_{\frac{0 \text{ GeV}^2}{c^4}} q_{\text{max}} \frac{d\Gamma(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu)}{dq^2} / |V_{ub}|^2 dq^2 \]

\[ \int_{\frac{15 \text{ GeV}^2}{c^4}} q_{\text{max}} \frac{d\Gamma(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu)}{dq^2} / |V_{ub}|^2 dq^2 \]

(1)

(2)
Efficiency correction vs $\epsilon_R$

LHCb simulation