Measuring $|V_{ub}|$ at LHCb

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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:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \quad \frac{\sigma(V_{CKM})}{|V_{CKM}|} = \begin{pmatrix} 0.02\% & 0.3\% & 12\% \\ 4\% & 2\% & 2\% \\ 7\% & 7\% & 3\% \end{pmatrix} \quad [PDG \, 2014]$$

$\rightarrow |V_{ub}|$ is least well known element of the CKM matrix
CKM unitarity

- In the SM the CKM matrix is unitary
- Leads to several unitarity equations, e.g.:
  \[
  \frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} + \frac{V_{cd} V_{cb}^*}{V_{cd} V_{cb}^*} + \frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*} = 0
  \]
- Commonly represented as a unitarity triangle (UT)
- Precision limited by magnitude and phase of \(|V_{ub}|\)

→ If it is no triangle → New Physics
• $|V_{ub}|$ measured using (semi-)leptonic decays

• 3 different strategies:
  • **exclusive**: semileptonic decays such as $B^0 \rightarrow \pi^+ l^- \bar{\nu}$
  • **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.:** $(4.14 \pm 0.15^{+0.15}_{-0.19}) \times 10^{-3}$
  - $\rightarrow \sim 3\sigma$ deviation
  - $\rightarrow$ More precise measurements needed
Is it possible to measure $|V_{ub}|$ 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 $B^+ \to \ell^+\nu_\ell$ and $B^+ \to K^+\nu\bar{\nu}$, measurements of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$, and inclusive analyses of processes such as $b \to s\gamma$ are unique to SuperB."

CDR, SuperB factory, arXiv 0709.0451

LHCb

- forward spectrometer covering pseudorapidity $2<\eta<5$
- $26 \times 10^{10}$ $b\bar{b}$ pairs

S. Braun (Heidelberg University)
Experimental Challenge at LHCb

- Missing neutrino momentum → B no fully reconstructed
- Affects momentum transferred to the $\mu\nu$ pair ($q^2$) → two-fold ambiguity (momentum transferred to the $\mu\nu$ pair)
- Generally affected by much higher (x10) $X_b \rightarrow X_c\mu\nu$ backgrounds
- "Golden channel" $\bar{B}^0 \rightarrow \pi^+ l^- \bar{\nu}$ suffers from high pion background at LHC

BUT: use $\Lambda_b \rightarrow p\mu^-\nu_\mu$

- Excellent $\mu$ and $p$ PID at LHCb from RICH/Muon systems
- precision vertexing and tracking used → displaced $p\mu$ vertex
- MVA classifier used to remove backgrounds with additional charged tracks
How to extract $|V_{ub}|$?

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

**Experimental measurement**

- \[
\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)} \begin{align*}
&= \frac{N(\Lambda_b \to p\mu^-\nu_\mu)}{N(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)} \\
&\times \frac{\epsilon(\Lambda_b \to p\mu^-\nu_\mu)}{\epsilon(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)
\end{align*}
\]

- Use $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ from Belle [PRL 113, 042002(2014)]

**Theory:**

- Restricting measurement to $q^2 > 15(7)$ GeV$^2$ → LQCD here most precise
- $R_{FF} = 0.68 \pm 0.07$ [Phys. Rev. D 92, 034503 (2015)]

→ 5% uncertainty on $|V_{ub}|$ from theory
Extracting Yields

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

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

\[ N(\Lambda_b \to \Lambda_c^+ \mu^- \nu_{\mu}) = 34255 \pm 571 \]
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 \( R_{\text{FF}} = 0.68 \pm 0.07 \) [Phys. Rev. D 92, 034503 (2015)] gives

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

(1)

- Use world average for exclusive \(|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}\) measurements [PDG 2014]
• LHCb is $3.5\sigma$ 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?
• \(|V_{ub}|\) 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?

\[|V_{ub}| \times 10^3\]

\[\epsilon_R\]

\[\begin{array}{c}
\text{B} \to X_{ib}l_{\nu} & \text{HFAG BLNP} \\
\text{B} \to \tau l_{\nu} & \text{HFAG} \\
\text{B} \to \pi l_{\nu} & \text{HFAG avg. w/ Lattice}
\end{array}\]

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

→ LHCb results does not support that
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
Selection

- $\Lambda_b$ produced at the primary vertex (PV)
- Displaced $p\mu$ vertex
- 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
  $\rightarrow$ track isolation

Signal

```
X_b
\rightarrow
PV
```

```
A_b^0
\rightarrow
PV
```

```
\rightarrow
\nu_\mu
\rightarrow
\mu^-
```

```
\rightarrow
\nu_\mu
```

Background

```
X_b
\rightarrow
PV
```

```
A_b^0
\rightarrow
PV
```

```
\rightarrow
\nu_\mu
\rightarrow
\mu^-
```

```
\rightarrow
\nu_\mu
```

Analysis strategy

- 2012 Dataset (~2 fb$^{-1}$)
- Normalise signal yield to cancel systematic uncertainties:

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

- 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)]
Relative efficiencies

- Different decay topologies between $\Lambda_b \rightarrow p\mu^-\nu_\mu$ and $\Lambda_b \rightarrow (\Lambda_c^+ \rightarrow pK^-\pi^+)\mu^-\nu_\mu$ lead 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 $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ 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 $\pi$
- $\Lambda_c^+ \to pK^-\pi^+$ selection efficiency from knowledge on its Dalitz structure
- Fit systematic dominated by form factors of $\Lambda_b \to N^*\mu^-\nu_\mu$ decays

<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>
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</tr>
<tr>
<td>$\Lambda_b^0 \to N^*\mu^-\nu_\mu$ shapes</td>
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<tr>
<td>$\Lambda_b^0$ lifetime</td>
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</tr>
<tr>
<td>Isolation</td>
<td>1.4</td>
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<tr>
<td>Form factor</td>
<td>1.0</td>
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<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>
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 $\sigma_{m_{corr}}$
Lattice Calculations

- 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.

Theory ratio

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

\[ R_{FF} = \frac{\int_{q_{max}^{15 \text{ GeV}/c^2}} \frac{d\Gamma(\Lambda_b \rightarrow p\mu^-\nu_\mu)}{dq^2}}{\left| V_{ub} \right|^2 dq^2} \]

\[ \hat{R}_{FF} \equiv \frac{\int_{q_{max}^{q'_{max}} \text{ GeV}/c^2} \frac{d\Gamma(\Lambda_b \rightarrow \Lambda_c^+\mu^-\nu_\mu)}{dq^2}}{\left| V_{cb} \right|^2 dq^2} \]
Branching fraction extrapolation factor

- convert measured ratio into bf using:
  \[ B(\Lambda_b \rightarrow p\mu^-\nu_\mu) = \tau_{\Lambda_b} \frac{B(\Lambda_b \rightarrow p\mu^-\nu_\mu)q^2 > 15 \text{GeV}/c^2}{|V_{cb}|^2 R_{FF}} \]
  \[ = \tau_{\Lambda_b} B_{ratio} \int_{7 \text{ GeV}/c^2}^{q_{\text{max}}'} \frac{d\Gamma(\Lambda_b \rightarrow \pi^-\mu^-\nu_\mu)}{dq^2} \left/ |V_{cb}|^2 \right. \right. \] 
  \[ \times \int_{0 \text{ GeV}^2/c^4}^{q_{\text{max}}} \frac{d\Gamma(\Lambda_b \rightarrow p\mu^-\nu_\mu)}{dq^2} \left/ |V_{ub}|^2 \right. \] 
  \[ \times \int_{15 \text{ GeV}/c^2}^{q_{\text{max}}} \frac{d\Gamma(\Lambda_b \rightarrow p\mu^-\nu_\mu)}{dq^2} \left/ |V_{ub}|^2 \right. \] 

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

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

- \( B \rightarrow \pi l\nu \) is purely a vector current whereas \( B \rightarrow X_u l\nu \) 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)]

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