Measurement of $V_{ub}$ at LHCb

Current status and future perspectives

Marina Artuso

On behalf of the LHCb collaboration
$V_{ub}$ and semileptonic $b$ decays

The vertex is proportional to $V_{ub}$.

$q^2 = m^2(\mu \nu)$

“exclusive” study a specific final state

“inclusive” study an inclusive property of the decay ($E_\mu$, $M_{had}, q^2$)

Experimental observables

What we want to know

$(\Gamma, d\Gamma/dq^2) = |V_{ub}|^2 \times$ (Hadronic matrix element) x (known factors)

$\Gamma = m_B^2 \frac{G_F^2 M^2}{8\pi} \frac{1}{2} |V_{ub}|^2 \times$ (Hadronic matrix element) x (known factors)

Lattice QCD, LC sum rules, HQE...

M. Artuso, EPS 2015
3 σ discrepancy between inclusive and exclusive determinations of $V_{ub}$.

Fermilab/MILC 2015+BaBar+Belle $B \rightarrow \pi/\nu$

Fermilab/MILC 2008 + HFAG 2014, $B \rightarrow \pi/\nu$

RBC/UKQCD 2015 + BaBar + Belle, $B \rightarrow \pi/\nu$

Imsong et al. 2014 + BaBar12 + Belle13, $B \rightarrow \pi/\nu$

HPQCD 2006 + HFAG 2014, $B \rightarrow \pi/\nu$

BLNP 2004 + HFAG 2014, $B \rightarrow X_{\mu/\nu}$

UTFit 2014, CKM unitarity

M. Artuso, EPS 2015
Possible explanations

☐ Failure of LQCD & Sum rules to predicted exclusive form-factors?
☐ Failure of the HQE to evaluate correctly the hadronic matrix element?
  ☐ General framework: non-quantified uncertainties such as assumption of quark-hadron duality
  ☐ Analysis specific: effects of phase space cuts introduced to suppress Cabibbo favored semileptonic decay background
☐ Problems in Monte Carlo modeling the inclusive charmless semileptonic decays?
☐ New physics?
⇒ More measurements are needed!
Why $\Lambda_b$ semileptonic decays?

- Use of $b$-baryon decays provides complementary information to $B$ mesons.
- At LHCb $\Lambda_b$ are produced copiously.
1) Kinematic constraints allow determination of magnitude of $\Lambda_b$ momentum (modulo 2-fold ambiguity)

2) LHCb determines the ratio $\Lambda_b \rightarrow p \mu \nu / \Lambda_b \rightarrow \Lambda_c \mu \nu$ in high $q^2$ region
   ⇒ Minimize background from Cabibbo favored decays in $\Lambda_b \rightarrow p \mu \nu$
   ⇒ Use region where lattice predictions are expected to be more reliable

3) Use normalization factor derived from Lattice QCD calculation to extract $|V_{ub}/V_{cb}|^2$
Cabibbo favored decays typically have additional tracks forming a good secondary vertex with the proton emitted in the semileptonic decay \( \Lambda_b^{0} \rightarrow p \mu \nu \). Train multivariate classifier to distinguish between these two configurations, get 90% rejection & 80% efficiency.
Displaced vertex information allow to define the corrected mass
\[ M_{\text{corr}} = \sqrt{M_{\mu\nu}^2 + p_{\perp}^2 + p_{\perp}^2} \]

- \( M_{\text{corr}} \) is used to disentangle different fit components
- Uncertainty in \( M_{\text{corr}} \) is used to discriminate between signal and background

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 \( \sigma_{\text{mcorr}} \)

\( M_{\text{corr}} \) peaks at \( \Lambda_b \) mass also when \( \nu \) is there
The signal fits

\[ N(\Lambda_b \rightarrow p\mu\nu) = 17687 \pm 733 \]

\[ N(\Lambda_b \rightarrow \Lambda_c\mu\nu) = 34255 \pm 571 \]

Candidates / (50 MeV/c^2)

Corrected \( p\mu^- \) mass [MeV/c^2]

Candidates / (40 MeV/c^2)

Corrected \( pK^-\pi^+\mu^- \) mass [MeV/c^2]

\( \mathcal{L} = 2 \text{fb}^{-1} \)

M. Artuso, EPS 2015
Experimental result

\[ R_{\text{exp}} \equiv \frac{B(\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu)_{q^2 > 15 \text{GeV}^2}}{B(\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-\bar{\nu}_\mu)_{q^2 > 7 \text{GeV}^2}} = \left(1.0 \pm 0.04(\text{stat}) \pm 0.08(\text{syst})\right) \times 10^{-2} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B(\Lambda_c^+ \rightarrow pK^+\pi^-))</td>
<td>+4.7</td>
</tr>
<tr>
<td>Trigger</td>
<td>-5.3</td>
</tr>
<tr>
<td>Tracking</td>
<td>3.2</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>1.0</td>
</tr>
<tr>
<td>Form factors</td>
<td>0.5</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>Particle Identification Efficiency</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>+7.8</td>
</tr>
<tr>
<td></td>
<td>-8.2</td>
</tr>
</tbody>
</table>

arXiv:1504:01568
Most recent calculation uses 2+1 flavors of dynamical domain-wall fermions, RBC & UKQCD configurations & $q^2$ dependence parameterized with $z$-expansion

- LHCb uses $q^2 > 15$ GeV$^2$ for $\Lambda_b \rightarrow p\mu\nu$ and $q^2 > 7$ GeV$^2$ for $\Lambda_b \rightarrow \Lambda_c\mu\nu$

$\Rightarrow$ Most reliable theory prediction
Theory input II

□ Theory normalization

\[ R_{TH} \equiv \frac{1}{\left| V_{ub} \right|^2} \int_{q_{\text{max}}^2}^{15 GeV^2} \frac{d\Gamma(\Lambda_b^0 \rightarrow p\mu\bar{\nu}_\mu)}{dq^2} dq^2 \frac{1}{\left| V_{cb} \right|^2} \int_{q_{\text{max}}^2}^{7 GeV^2} \frac{d\Gamma(\Lambda_b^0 \rightarrow \Lambda_c^0\mu\bar{\nu}_\mu)}{dq^2} dq^2 = \frac{(12.31 \pm 0.76 \pm 0.77) ps^{-1}}{(8.37 \pm 0.16 \pm 0.34) ps^{-1}} = 1.471 \pm 0.094 \pm 0.109 \]

4.9% theoretical error on \( |V_{ub}/V_{cb}| \)

\[ \frac{\Gamma(\Lambda_b^0 \rightarrow p\mu\bar{\nu}_\mu)}{\left| V_{ub} \right|^2} = (25.7 \pm 2.6 \pm 4.6) ps^{-1} \]

\[ \frac{\Gamma(\Lambda_b^0 \rightarrow \Lambda_c^0\mu\bar{\nu}_\mu)}{\left| V_{cb} \right|^2} = (21.5 \pm 0.8 \pm 1.1) ps^{-1} \]

Using the full \( \Gamma_c \) width, theoretical error on \( |V_{cb}| \) 3.2%, using \( \Gamma_c \) in \( q^2 \geq 7 GeV^2 \) region, theoretical error 2.2%
Using:

\[ V_{ub} = V_{cb}^{\text{excl}} \sqrt{\frac{R_{\text{exp}}}{R_{TH}}} = V_{cb}^{\text{excl}} \sqrt{\frac{(1.0 \pm 0.04 \pm 0.08) \times 10^{-2}}{1.471 \pm 0.095 \pm 0.110}} \]

and

\[ |V_{cb}^{\text{excl}}| = (39.5 \pm 0.8) \times 10^{-3} \]

PDG2014

LHCb gets: \[ |V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3} \]

exp \quad lattice \quad V_{cb} \text{ norm.}
Exclusive data consistent with each other and with indirect determination of $|V_{ub}|$

- Fermilab/MILC 2008 + HFAG 2014, $B \to \pi l \nu$
- RBC/UKQCD 2015 + BaBar + Belle, $B \to \pi l \nu$
- Imsong et al. 2014 + BaBar12 + Belle13, $B \to \pi l \nu$
- HPQCD 2006 + HFAG 2014, $B \to \pi l \nu$
- Detmold et al. 2015 + LHCb 2015, $\Lambda_b \to pl \nu$
- BLNP 2004 + HFAG 2014, $B \to X_u l \nu$

New physics in $|V_{ub}|$ from inclusive measurement?
Conjecture that discrepancy between $|V_{ub}|$ from inclusive and exclusive determinations could be attributed to right-handed currents.

Constraint from this measurement disfavors this solution of the puzzle
Conclusions and outlook

- LHCb has performed its first high precision determination of $|V_{ub}|$ and is poised to continue studies on $V_{xb}$ from exclusive semileptonic decays:
  - Form factors and $V_{cb}$ determination from $\Lambda_b \rightarrow \Lambda_c \mu \nu$
  - New $b \rightarrow u$ decays (e.g. $B_s \rightarrow K \mu \nu$)
  - ...

- Inclusive measurements with less restrictive phase space cuts may reduce tension on $V_{ub}$ + refinement of previous exclusive studies (Belle II)

- New lattice QCD calculations on the way

- The pursuit of the ultimate precision on $V_{xb}$ will keep us busy for a while!

M. Artuso, EPS 2015
THE END
In the forward region at LHC the $b\bar{b}$ production $\sigma$ is large.
The hadrons containing the $b$ & $\bar{b}$ quarks are both likely to be in the acceptance. Essential for “flavor tagging”.
LHCb uses the forward direction where the $B$’s are moving with considerable momentum $\sim 100$ GeV, thus minimizing multiple scattering.
At $\mathcal{L}=4 \times 10^{32}/\text{cm}^2/\text{s}$, we get $\sim 10^{12}$ $B$ hadrons in $10^7$ sec in the LHCb acceptance.

Measured cross section at 7 TeV in LHCb acceptance is $\sim 90 \, \mu b$.

Production $\theta$ of $B$ vs $\bar{B}$

M. Artuso, EPS 2015
The two-fold ambiguity

LHCb simulation

- both solutions
- one solution

$q^2$ selection efficiency [%]

$q^2$ [GeV$^2$/c$^4$]

M. Artuso, EPS 2015
Experimental background studies

- After selection reconstruct additional tracks to determine background yields

M. Artuso, EPS 2015