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

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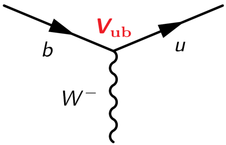
HQL 2016, Blacksburg
May 22-27, 2016

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:

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

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

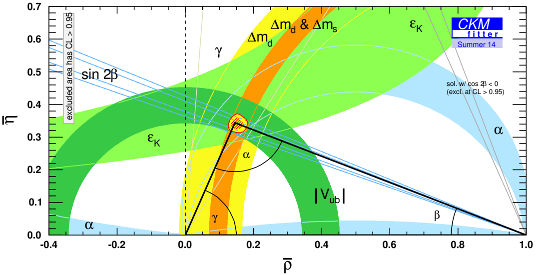
CKM unitarity

- In the SM the CKM matrix is unitary
- Leads to several unitarity equations, e.g.:

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

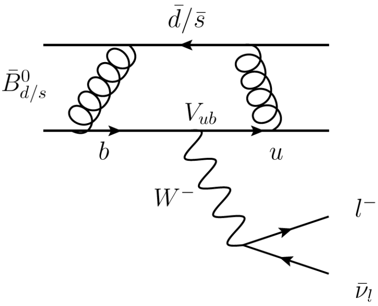
- Precision limited by magnitude and phase of $|V_{ub}|$

$\rightarrow$ If it is no triangle $\rightarrow$ New Physics



Measuring $|V_{ub}|$

- $|V_{ub}|$ measured using (semi-)leptonic decays
- 3 different strategies:
  - **exclusive**: semileptonic decays such as $\bar{B}^0 \to \pi^+ l^- \bar{\nu}$
  - **inclusive**: all semileptonic $B \to X_u l^- \bar{\nu}$ transitions
  - measure pure leptonic decay $B^+ \to \tau\nu$
- 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

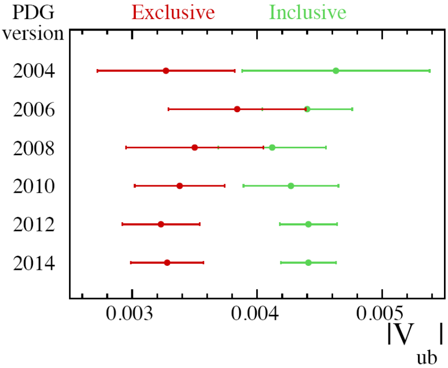
- **Discrepancy between exclusive vs. inclusive measurement**:

  excl.: $(3.28 \pm 0.29) \times 10^{-3}$ [PDG 2014]

  incl.: $(4.14 \pm 0.15^{+0.15}_{-0.19}) \times 10^{-3}$

  $\rightarrow$ **~3σ** deviation
- Leptonic measurements not precise enough, favours inclusive results

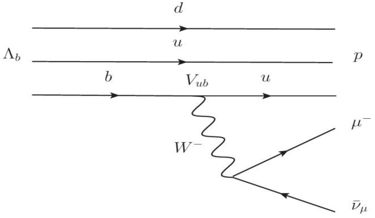
  $\rightarrow$ More precise measurements needed

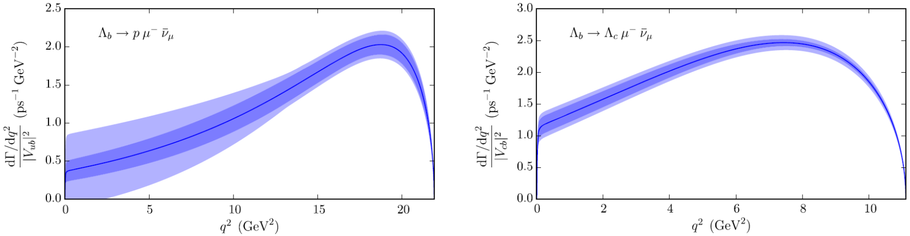


First LHCb $|V_{ub}|$ measurement: $\Lambda_b \to p\mu^-\nu_\mu$
Nature Physics 10 (2015) 1038

$|V_{ub}|$ in $\Lambda_b \to p\mu^-\nu_\mu$

- Baryonic version of $\bar{B}^0 \to \pi^+ l^- \bar{\nu}_\mu$
- Excellent μ and p PID at LHCb from RICH/Muon systems
- High production fraction of Λ_b: ~20% of b-hadrons [Phys. Rev. D85 (2012) 032008]
- Improved FF calculations from theory for $\Lambda_b \to p\mu^-\nu_\mu$ and $\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu$ in high q^2 region





[Phys. Rev. D 92, 034503 (2015)]

How to extract $|V_{ub}|$?

$$\underbrace{\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)}}_{\textbf{experimental measurement}} = \underbrace{R_{\rm FF}}_{\textbf{theoretical calculations}} \times \frac{|V_{ub}|^2}{|V_{cb}|^2}$$

- Reduce systematic uncertainties by restricting measurement to $q^2 > 15(7)\,\mathrm{GeV}^2$
  $\rightarrow$ LQCD here most precise
- $R_{\rm FF} = \frac{(\Lambda_b \to p\mu^-\nu_\mu)_{q^2>15\,\mathrm{GeV}^2}}{(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)_{q^2>7\,\mathrm{GeV}^2}} = 0.68 \pm 0.07$ [Phys. Rev. D 92, 034503 (2015)]

  $\rightarrow$ 5% uncertainty on $|V_{ub}|$ from theory
- Experimental challenges:
  $|V_{ub}|$ much smaller compared to $|V_{cb}|$ background, missing neutrino $\rightarrow$ Λ_b not fully reconstructed

Analysis strategy

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

$$\frac{\mathcal{B}(\Lambda_b\to p\mu^-\nu_\mu)_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b\to(\Lambda_c^+\mu^-\nu_\mu)_{q^2>7\,\mathrm{GeV}^2}} = \frac{N(\Lambda_b\to p\mu^-\nu_\mu)}{N(\Lambda_b\to(\Lambda_c^+\to pK^-\pi^+)\mu^-\nu_\mu)} \times \frac{\epsilon(\Lambda_b\to p\mu^-\nu_\mu)}{\epsilon(\Lambda_b\to(\Lambda_c^+\to pK^-\pi^+)\mu^-\nu_\mu)} \times \mathcal{B}(\Lambda_c^+\to pK^-\pi^+)$$

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

Selection

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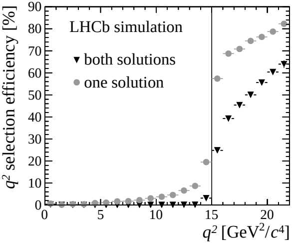
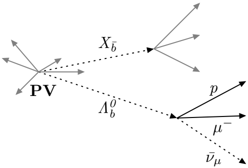
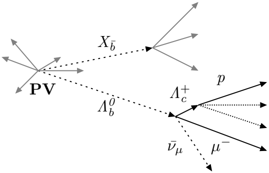
- Reconstruct q^2 up to 2-fold ambiguity
- Require both solutions to full fill $> q^2_{cut}$



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



signal



background

Extracting Yields

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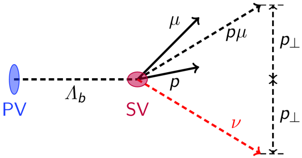
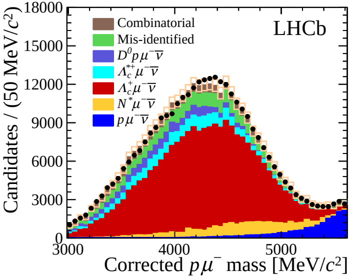
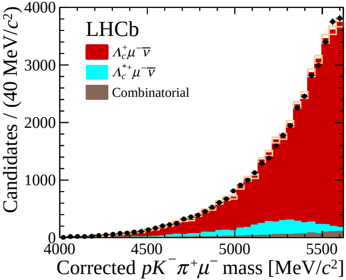
- Fit to corrected mass
  $m_{corr} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$, $h = p, \Lambda_c$
  performed for signal and normalisation separately



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





$N(\Lambda_b \to p\mu^-\nu_\mu) = 17687 \pm 733$ $\qquad$ $N(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu) = 34255 \pm 571$

Relative efficiencies

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

- Relative efficiency determined from simulation

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

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

- Uncertainty of ratio is dominated by systematic uncertainties

Systematic uncertainties

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

Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c^+ selection efficiency	3.0
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

Results I

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- Measure the relative branching fraction:

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

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

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(exp.) \pm 0.004(theo.) \qquad (1)$$

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

exclusive $|V_{ub}|$ LHCb result

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

Results II

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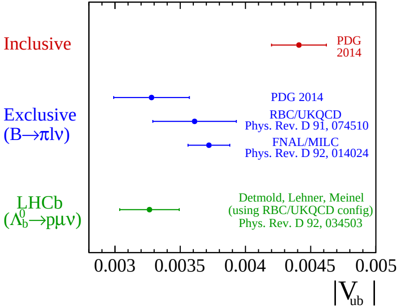
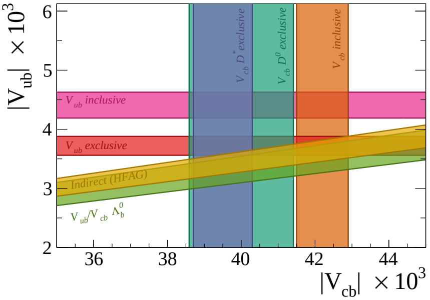
- LHCb is 3.5σ away from inclusive measurement of $|V_{ub}|$
- Consistent with other exclusive measurements





Results III

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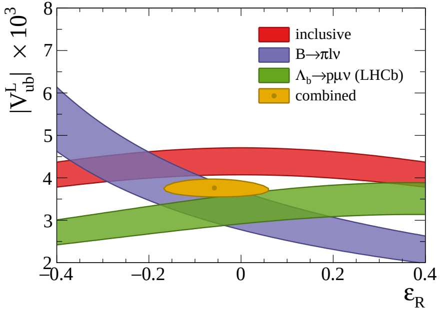
- $|V_{ub}|$ measurement depends on possible right-handed current in SM [Phys. Rev. D 81, 031301 (2010)]
- Previously exclusive/inclusive discrepancy suggested significant right-handed coupling fraction (ϵ_R) $\rightarrow$ solution to $|V_{ub}|$ puzzle?

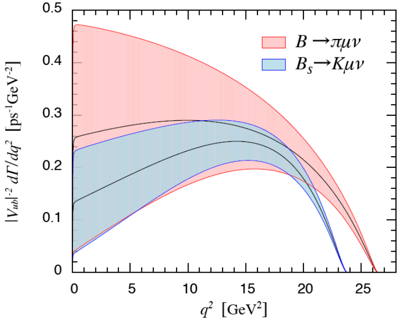
$\rightarrow$ LHCb results does not support that



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

Future plans

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



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

Conclusions

- LHCb performed a precise measurement of $|V_{ub}|$ using the decay $\Lambda_b \to p\mu^-\nu_\mu$
- First determination of $|V_{ub}|$ in a hadron collider and in a baryonic decay

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

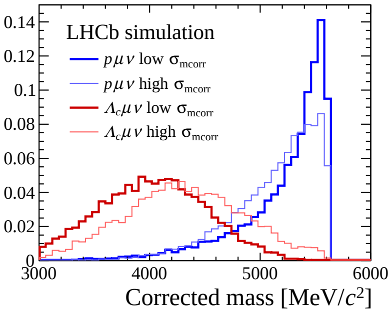
- Consistent with other exclusive $|V_{ub}|$ measurements in $\bar{B}^0 \to \pi^+ l^- \nu_\mu$
- Measurement is 3.5σ below inclusive measurement of $|V_{ub}|$
- Right-handed currents can no longer explain the $|V_{ub}|$ puzzle
- LHCb is starting to the determine $|V_{ub}|$ in $B_s^0 \to K^- \mu^+ \nu_\mu$ 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 Λ_b vertex
- reject candidates if $\sigma_{m_{corr}} > 100\,\mathrm{MeV}/c^2$ for signal fits (~23% survive)
- Compare simulated signal and background shapes for low and high $\sigma_{m_{corr}}$



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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 (q2) extrapolation uncertainty, the perturbative matching uncertainty, the uncertainty due to the finite lattice volume and the uncertainty from the missing isospin breaking effects.

W. Detmold, C. Lehner and S. Meinel [Phys. Rev. D 92, 034503 (2015)]

Theory ratio

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

$$R_{\text{FF}} = \frac{\int_{15\,\mathrm{GeV}/c^2}^{q_{max}} \frac{d\Gamma(\Lambda_b \to p\mu^- \nu_\mu)}{dq^2} / |V_{ub}|^2 dq^2}{\int_{7\,\mathrm{GeV}/c^2}^{q'_{max}} \frac{d\Gamma(\Lambda_b \to \Lambda_c^+ \mu^- \nu_\mu)}{dq^2} / |V_{cb}|^2 dq^2}$$

Branching fraction extrapolation factor

- convert measured ratio into bf using:

$$\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu) = \tau_{\Lambda_b} \frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)_{q^2 > 15\,\mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)_{q^2 > 7\,\mathrm{GeV}/c^2}} |V_{cb}|^2 R_{FF}$$

$$= \tau_{\Lambda_b} \mathcal{B}_{ratio} \int_{7\,\mathrm{GeV}/c^2}^{q'_{max}} \frac{d\Gamma(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)}{dq^2} / |V_{cb}|^2 dq^2$$

$$\times \frac{\int_{0\,\mathrm{GeV}^2/c^4}^{q_{max}} \frac{d\Gamma(\Lambda_b \to p\mu^-\nu_\mu)}{dq^2} / |V_{ub}|^2 dq^2}{\int_{15\,\mathrm{GeV}/c^2}^{q_{max}} \frac{d\Gamma(\Lambda_b \to p\mu^-\nu_\mu)}{dq^2} / |V_{ub}|^2 dq^2}$$

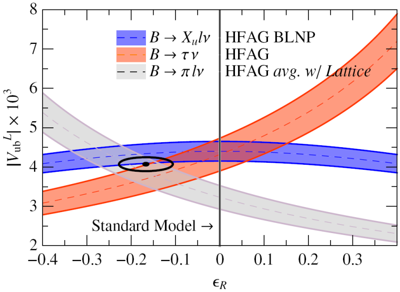
- results in:

$$\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu) = (4.1 \pm 1.0) \times 10^{-4}$$

Possible Right-handed currents

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

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



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