$|V_{ub}|$ using $\Lambda_b \to p\mu^-\overline{\nu}_\mu$ decays at LHCb

William Sutcliffe

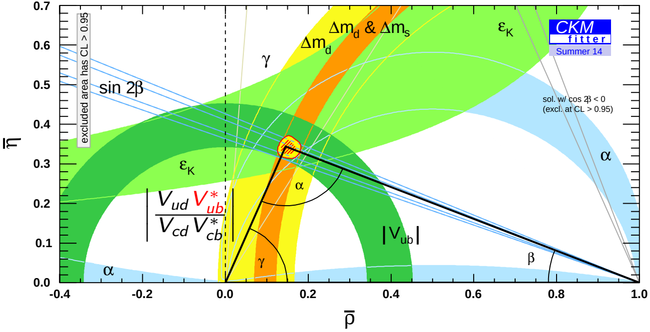
On behalf of the LHCb Collaboration

Imperial College London

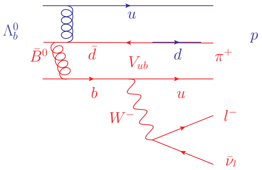
Moriond Electroweak
March 20, 2015

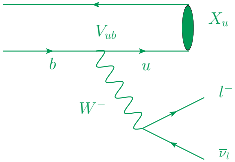
Why is $|V_{ub}|$ important?

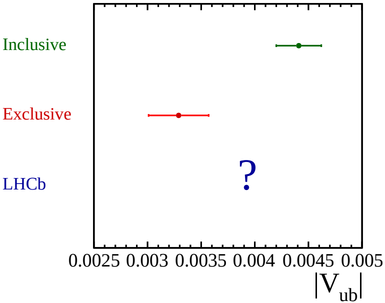
- $|V_{ub}|$ is one of the least known of the CKM parameters.
- $|V_{ub}|$ constrains the unitarity triangle opposite the angle β.



The $|V_{ub}|$ puzzle







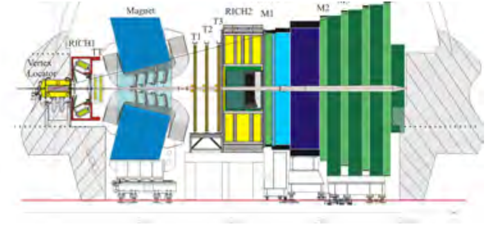
PDG (2014)

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.

Observable/mode	Current now	LHCb (2017)	Super$B$ (2021)	Belle II (2021)	LHCb upgrade (10 years of running)	theory now
		$5\,\text{fb}^{-1}$	$75\,\text{ab}^{-1}$	$50\,\text{ab}^{-1}$	$50\,\text{fb}^{-1}$	
$\|V_{cb}\|$ (inclusive) %	1.7		0.5%	0.6 (est.)		dominant
$\|V_{cb}\|$ (exclusive) %	2.2		1.0%	1.2 (est.)		dominant
$\|V_{ub}\|$ (inclusive) %	4.4		2.0%	3.0		dominant
$\|V_{ub}\|$ (exclusive) %	7.0		3.0%	5.0		dominant

Expected experimental sensistivities for $|V_{ub}|$ as quoted in arXiv:1109.5028 (2011).



- 26×10^{10} $b\bar{b}$ pairs.
- Choose $\Lambda_b \to p\mu^-\overline{\nu}_\mu$
  - Excellent μ and p PID.
- Precision vertexing and tracking.

Analysis strategy

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

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = \frac{N(\Lambda_b \to p\mu^-\overline{\nu}_\mu)}{N(\Lambda_b \to (\Lambda_c \to pK\pi)\mu^-\overline{\nu}_\mu)} \times \frac{\epsilon(\Lambda_b \to (\Lambda_c \to pK\pi)\mu^-\overline{\nu}_\mu)}{\epsilon(\Lambda_b \to p\mu^-\overline{\nu}_\mu)} \times \mathcal{B}(\Lambda_c \to pK\pi)$$

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

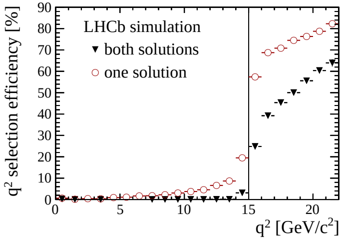
$$R_{exp} = R_{theory}(|\mathrm{V_{ub}}|^2/|\mathrm{V_{cb}}|^2)$$

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

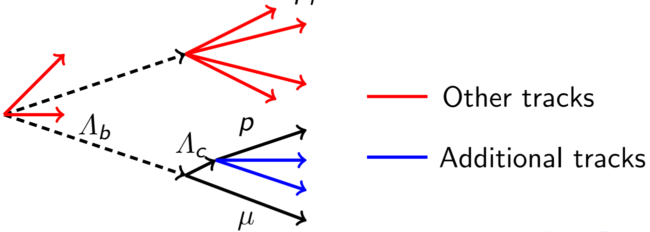
W. Detmold, C. Lehner and S. Meinel [arXiv:1503.01421]

Selection

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



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

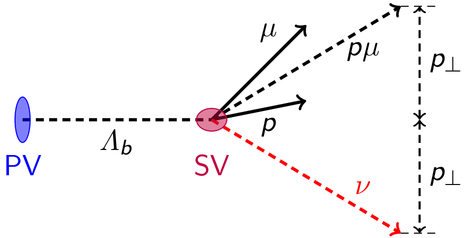


The corrected mass

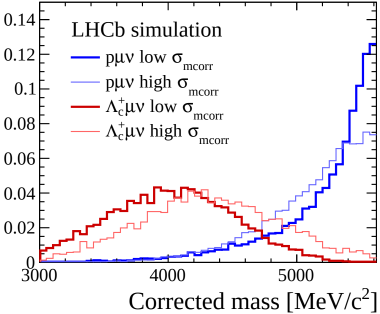
- Fit the corrected mass:

$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$

- Determine its uncertainty.
- Reject candidates if: $\sigma_{M_{corr}} > 100\,\mathrm{MeV}/c^2$

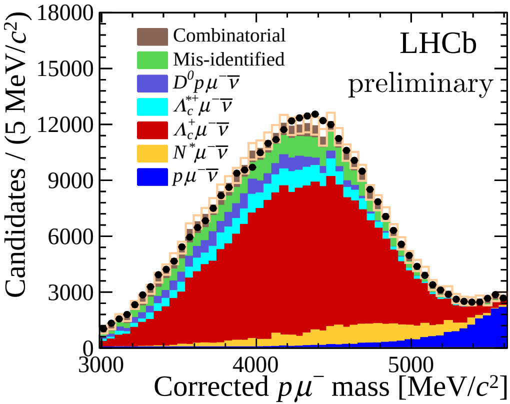


- Compare simulated signal and background shapes for low and high $\sigma_{M_{corr}}$
- Truncation at m_{Λ_b} due to q^2 cut.
- All curves normalised to unit area.



Signal fit

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

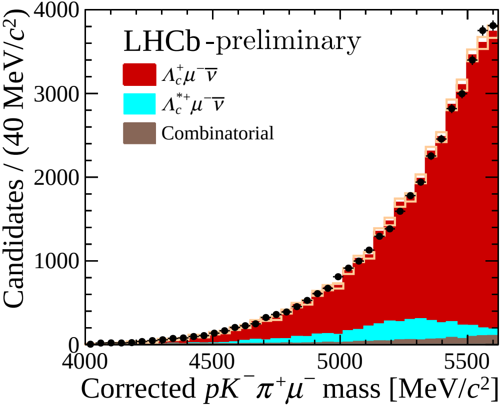


- First observation of the decay $\Lambda_b \to p\mu^- \overline{\nu}_\mu$.

LHCB-PAPER-2015-013

Normalisation fit

- Fit $pK\pi\mu$ corrected mass, $N(\Lambda_b \to (pK\pi)\mu^-\overline{\nu}_\mu) = 34255 \pm 571$.



LHCB-PAPER-2015-013

Relative efficiency and systematic uncertainties

- Efficiency from simulation with many data-driven corrections.

$$\epsilon(\Lambda_b \to p\mu^-\overline{\nu}_\mu)/\epsilon(\Lambda_b \to (\Lambda_c \to pK\pi)\mu^-\overline{\nu}_\mu) = 3.52 \pm 0.20$$

- Systematics:

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
N^* shapes	2.3
Λ_b lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b production	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

LHCb-preliminary

LHCB-PAPER-2015-013

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

- Measure the ratio of branching fractions to be:

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

LHCb-preliminary

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

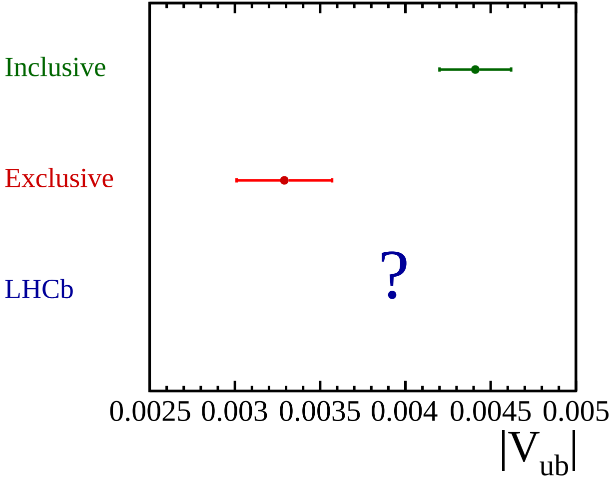
$$\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu) = (3.92 \pm 0.83) \times 10^{-4}$$

LHCb-preliminary

LHCB-PAPER-2015-013

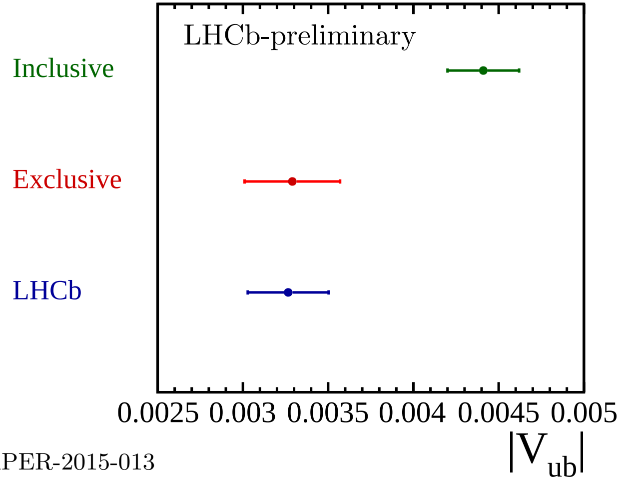
The $|V_{ub}|$ puzzle revisited

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



What can LHCb say?

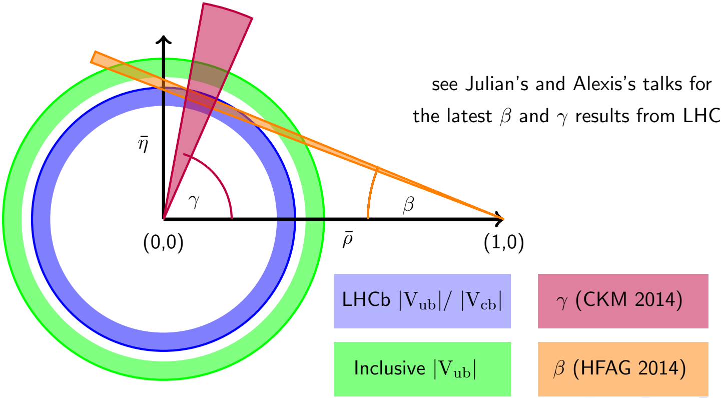
$$|V_{ub}| = (3.27 \pm 0.15(exp) \pm 0.17(theory) \pm 0.06(|V_{cb}|)) \times 10^{-3}$$



LHCB-PAPER-2015-013

Implications

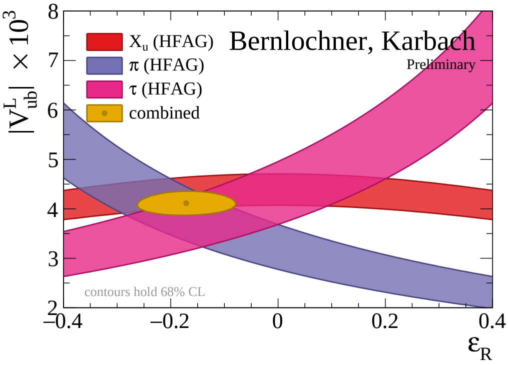
- Total uncertainty on $|V_{ub}|$ is 7.2% (8.8% for exclusive average).
- Experimental uncertainty is 4.6%.
- $|V_{ub}|$ from $\Lambda_b \to p\mu^-\overline{\nu}_\mu$ is 3.5σ below the inclusive average.
- Can check the consistency of $|V_{ub}|/|V_{cb}|$ with β and γ.



see Julian's and Alexis's talks for the latest β and γ results from LHCb

Can new physics explain the puzzle?

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



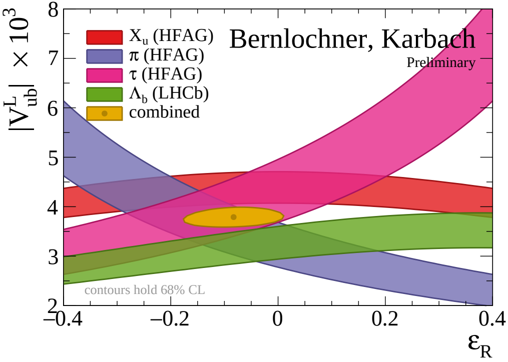
Bernlochner et al. [arXiv:1408.2516]

Also see Crivellin [arXiv:0907.2461]

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

Can new physics explain the puzzle?

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



Bernlochner et al. [arXiv:1408.2516]

Also see Crivellin [arXiv:0907.2461]

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

Conclusion

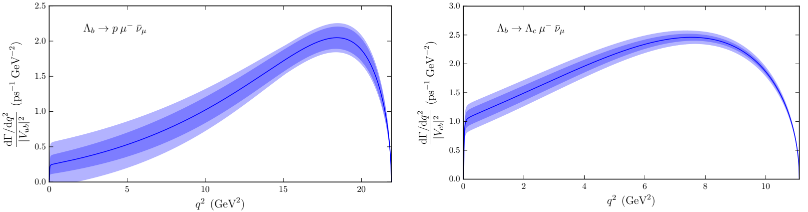
- $\Lambda_b \to p\mu^-\overline{\nu}_\mu$ decays are observed for the first time:
  - $\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu) = (3.92 \pm 0.83) \times 10^{-4}$
- The first determination of of $|\mathrm{V_{ub}}|$ at a hadron collider and in a baryon decay is:
  - $|V_{ub}| = (3.27 \pm 0.23) \times 10^{-3}$.
- This measurement is 3.5σ below the inclusive measurement but agrees well with current exclusive average using $B \to \pi l \nu$ decays.
- Right-handed currents no longer can explain the $|\mathrm{V_{ub}}|$ puzzle.

Many thanks to Stefan Meinel for pioneering the LQCD predictions for $\Lambda_b \to p\mu^-\overline{\nu}_\mu$ and $\Lambda_b \to \Lambda_c\mu^-\overline{\nu}_\mu$. Additional thanks to Florian Bernlochner.

Theory ratio

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

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



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

W. Detmold, C. Lehner and S. Meinel [arXiv:1503.01421]

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.
- $b \to u$ and $b \to c$ 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.

W. Detmold, C. Lehner and S. Meinel [arXiv:1503.01421]

Branching Fraction Extrapolation Factor

$$\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu) = \tau_{\Lambda_b} \frac{\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}} |V_{cb}|^2 F_{theory}$$

$$= \tau_{Lb} R_{exp} |V_{cb}|^2 \int_{7\,\mathrm{GeV}^2/c^4}^{q'_{max}} \frac{d\Gamma(\Lambda_b \to \Lambda_c\mu^-\overline{\nu}_\mu)}{dq^2} / |V_{cb}|^2 dq^2 \quad (1)$$

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

Efficiency correction vs ϵ_R