DETERMINATION OF THE QUARK COUPLING STRENGTH $|\mathbf{V_{ub}}|$ USING BARYONIC DECAYS

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A measurement of the ratio of branching fractions between $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ and $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ decays is performed using data corresponding to 2 fb^{-1} of integrated luminosity, collected by the LHCb detector in 2012. This combined with the latest form factor predictions obtained from lattice QCD calculations leads to the first determination of $|V_{ub}|$ at a hadron collider and in a baryon decay, $|V_{ub}| = (3.27 \pm 0.23) \times 10^{-3}$. The measurement is consistent with existing exclusive measurements made using $\bar{B}^0 \to \pi^+\mu^-\bar{\nu}_\mu$, but disagrees with those made inclusively.

1 Context and motivation

In the Standard Model (SM) of particle physics, quark mixing occurs through the weak force according to the 3×3 unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix [1,2]. The unitarity of the CKM matrix results in nine constraints, six of which may be represented as triangles in the complex plane. Constraints from a variety of measurements on the most commonly used triangle are shown in Fig. 1. The uncertainty on the length of this unitarity triangle opposite the angle β is dominated by the uncertainty on $|V_{ub}|$. An inconsistency between this length and the angle β could signify new physics as β is measured in loop level processes which may be affected by new particles in extensions of the Standard Model.

The magnitude of $|V_{ub}|$ is the least known of the CKM matrix elements. The best existing measurements for $|V_{ub}|$ have been made by the e^+e^- collider beauty factory experiments BaBar [3,4] and Belle [5,6] using semi-leptonic exclusive $\bar{B}^0 \to \pi^+\mu^-\bar{\nu}_\mu$ and inclusive $B \to X_u\mu^-\bar{\nu}_\mu$ decays. The world averages for these approaches are respectively $|V_{ub}| = (3.28 \pm 0.29) \times 10^{-3}$ (exclusive) and $|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.17}) \times 10^{-3}$ (inclusive) [7]. In the exclusive scenario, the dominant uncertainty arises in predicting the influence of QCD on the decay. The nature of these interactions can be encompassed within a form factor which is computed using non-perturbative techniques such as lattice QCD (LQCD) or QCD sum rules. In the inclusive case the differential rate for all possible B meson decays containing a $b \to ul^-\bar{\nu}$ quark level transition is measured. In order to suppress the background from $b \to cl^-\bar{\nu}$ decays, the differential rate is measured in a small region of phase space. This is then extrapolated to the full region using theory, which results in the dominant uncertainty. The discrepency between inclusive and exclusive measurements is approximately three standard deviations and has been a long standing puzzle in flavour physics. A proposed explanation for the discrepency is to introduce a right-handed coupling as an extension to the left-handed W coupling of the SM [8,9,10].

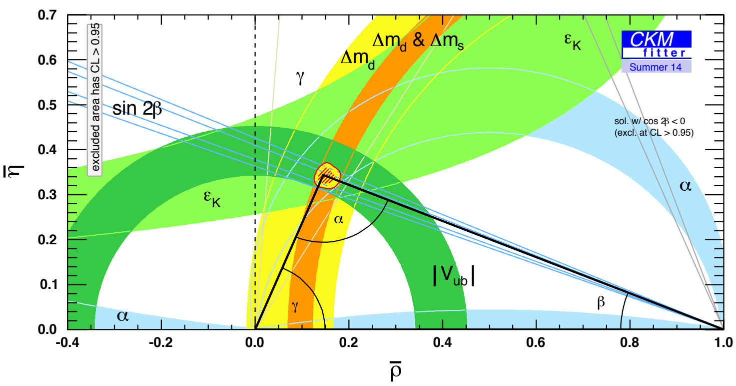

Figure 1 – Global fit for the apex of the unitarity triangle produced by the CKMfitter group [16]. The green circular band shows a constraint on the length of the side opposite the angle β. The uncertainty on this length is dominated by that on the world average of $|V_{ub}|$ made using semi-leptonic exclusive $\bar{B}^0 \to \pi^+\mu^-\bar{\nu}_\mu$ and inclusive $B \to X_u\mu^-\bar{\nu}_\mu$ decays.

The LHCb detector [11,12] is a single-arm forward spectrometer covering the range $2 < \eta < 5$, in which the majority of forward going $b\bar{b}$ pairs are produced. Around 20% of the B hadrons produced in the hadronisation process of b quarks from pp collisions at the LHC are Λ_b^0 (bud) baryons [13]. This allows for the possiblity of an exclusive measurement of $|V_{ub}|$ using the decay $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ [14], which has not been considered previously as Λ_b^0 baryons are not produced at an e^+e^- B-factory. The proton in the final state makes for a distinctive signature given that there are far fewer final state protons than kaons and pions produced from B-hadron decays within the detector. At a hadron collider it is not possible to use the beam energy constraints as employed by e^+e^- colliders. However, the LHCb detector's precision vertexing and excellent particle identification, in conjunction with the large number of Λ_b^0 baryons produced, make this measurement possible.

2 Analysis strategy

A measurement of the ratio of branching fractions of the Λ_b^0 baryon into $p\mu^-\bar{\nu}_\mu$ and $\Lambda_c^+\mu^-\bar{\nu}_\mu$ final states is made at high $\mu\nu$ invariant mass squared, q^2. This is performed using proton-proton collison data from the LHCb detector, corresponding to 2.0 fb^{-1} of integrated luminosity collected at a centre-of-mass energy 8 TeV. This measurement together with recent LQCD calculations [15] allow for the determination of $|V_{ub}|^2/|V_{cb}|^2$ according to

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}} R_{FF} \tag{1}$$

where $\mathcal{B}$ denotes the branching fractions and R_{FF} is a ratio of the relevant form factors, calculated using LQCD. This is then converted into a measurement of $|V_{ub}|$ using the world average for $|V_{cb}|$ from exclusive decays. The choice to measure the branching fractions at high q^2 reflects the fact that lattice QCD predictions for the form factors are most precise in the high q^2 region.

The normalisation to the decay $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ is necessary to cancel a number of experimental uncertainties, including the uncertainty on the total production rate of Λ_b^0 baryons. In order to select this decay, the Λ_c^+ baryon is reconstructed decaying to the final state $pK^-\pi^+$. The required ratio of branching fractions is determined experimentally from

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = \frac{N(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}}{N(\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}} \cdot \frac{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}{\epsilon_{rel}} \tag{2}$$

where $N(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}$ and $N(\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}$ are respectively the yields for the decays $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ and $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\mu$. Meanwhile ϵ_{rel} is the relative efficiency for selecting the two modes and $B(\Lambda_c^+ \to pK^-\pi^+)$ is the branching fraction of $\Lambda_c^+ \to pK^-\pi^+$ for which the most recent Belle measurement is used $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.84 \pm 0.24^{+0.21}_{-0.27})\%$ [17]. At the LHC the, number of $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ candidates is large, therefore the event selection is designed to mimimise systematic effects.

3 Selection

In order to select candidates for the decay $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$, proton and muon candidates are combined. The proton is distinguished from kaons and pions by information from the detector's two ring-imaging Cherenkov (RICH) detectors, meanwhile, the muon in the decay can be identified by its penetration of the calorimeters to the muon tracking system. A requirement is made that the $p\mu^-$ vertex is displaced from primary proton-proton interaction vertex due to the lifetime of the Λ_b^0 baryon. The associated vertex fit is required to be of good quality which reduces most of the background resulting from $b \to c\mu^-\bar{\nu}_\mu$ decays as the resulting ground state charmed hadrons have a significant lifetime. A tight momentum cut of $P > 15$ GeV/c is placed on the proton as the particle identification performance is most effective for high-momentum protons.

In order to select the decay $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\mu$ an additional two tracks, positively identified as a pion and kaon, are combined with the proton to form a $\Lambda_c^+ \to pK^-\pi^+$ candidate.

There is a large background from b-hadron decays with additional charged tracks in the decay products. To reduce this background, a multivariate classifier (a boosted decision tree, BDT), is used to determine the compatibility of each track in the event to orginate from the same vertex as the signal candidate.

The Λ_b^0 mass is reconstructed using the so-called *corrected mass*

$$m_{corr} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp \tag{3}$$

where $m_{h\mu}$ is the visible mass of the combined $h\mu$ pair, $p_\perp$ is the momentum of the combined $h\mu$ system perpendicular to the Λ_b^0 flight direction and h is either the p or Λ_c^+ candidate. The flight direction of the Λ_b^0 baryon is determined using the PV and $h\mu$ vertices. An event-by-event uncertainty on the corrected mass associated with the uncertainty on the PV and $h\mu$ vertex positions is determined. Candidates for the $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decay with an uncertainty of greater than 100 MeV/c^2 are rejected. This significantly increases the seperation in m_{corr} between signal and background as shown in Fig. 2(a).

It is possible to reconstruct the neutrino in the decay and hence q^2 up to a two-fold ambiguity. In order to minimise the influence of the large form factor uncertainty at low q^2 on the $|V_{ub}|$ measurement both solutions are required to exceed 15 GeV$^2/c^4$ for $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays and 7 GeV$^2/c^4$ for $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\mu$ decays (see Fig. 2(b)).

4 Signal and normalisation fits

The signal and normalisation yields respectively, $N(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)$ and $N(\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\mu)$, are determined by binned χ^2 fits to the m_{corr} distributions of $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ and $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\mu$ candidates as shown in Fig. 3.

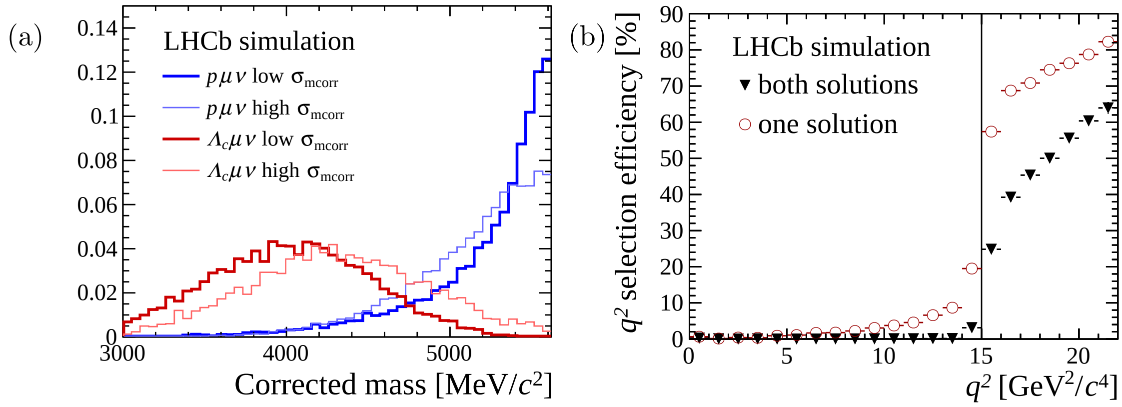

Figure 2 – (a) A comparison of the m_{corr} distributions for simulated signal ($\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$) and background ($\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$) decays with low and high corrected mass uncertainty. (b) Efficiency of the q^2 selection as a function of q^2 for $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays. The choice of requiring both q^2 solutions to be above $15\,\mathrm{GeV}^2/c^4$ as opposed to just one solution minimises the efficiency of selecting events with q^2 below $15\,\mathrm{GeV}^2/c^4$.

The fit to the m_{corr} distribution for $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ candidates includes a variety of backgrounds. The largest background source is from $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ decays in which the decay of the Λ_c^+ contains a proton and additional particles. The majority of the backgrounds are controlled using data-driven techniques except for the background from $\Lambda_b^0 \to N^{*+}\mu^-\bar{\nu}_\mu$ decays, which is given a large freedom in the fit.

For the fit to the $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\mu$ corrected mass, background from combinatorial and $\Lambda_b^0 \to (\Lambda_c^{*+} \to \Lambda_c^+\pi\pi)\mu^-\bar{\nu}_\mu$ decays are considered. The level of combinatorial background is estimated using a fit to the $pK^-\pi^+$ mass.

The observed yields for $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ and $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\mu$ decays are respectively $17,687 \pm 733$ and $34,255 \pm 571$, with this being the first observation of the decay $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$.

The relative efficiency, ϵ_{rel}, for reconstruction, trigger and event selection is determined from simulation. A number of corrections are applied to this efficiency to account for differences between data and simulation in the detector response and differences in the kinematic properties of the Λ_b^0 baryon for selected $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ and $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\mu$ candidates. The relative efficiency is determined to be $\epsilon_{rel} = 3.52 \pm 0.20$, where a number of sources of systematic uncertainty are considered.

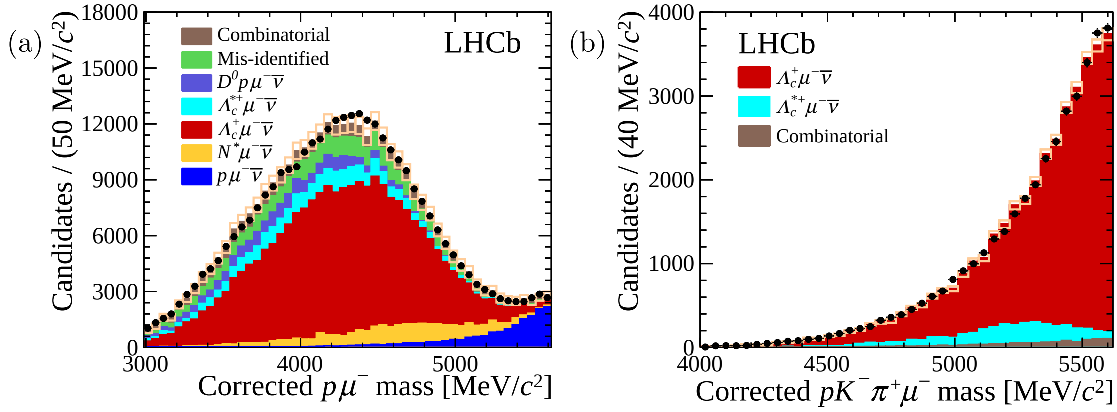

Figure 3 – Fits to the m_{corr} distribution for selected (a) $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ and (b) $\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\bar{\nu}_\mu$ candidates.

5 Results

Substituting the relevant yields, relative efficiency and $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ into equation 2, the ratio of branching fractions between $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ and $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ decays in the selected q^2 regions is

$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu)_{q^2>15\,\mathrm{GeV}^2/c^4}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu)_{q^2>7\,\mathrm{GeV}^2/c^4}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2} \tag{4}$$

where, the first uncertainty is statistical and the second systematic. An overview of the systematic uncertainties considered for the measurement of the ratio of branching ratios of $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ to $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ decays is given in the journal article corresponding to the result [14]. The dominant source of systematic uncertainty is due to the uncertainty on $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$.

From the determination of the branching fraction ratio a measurement of $|V_{ub}|/|V_{cb}| = 0.083 \pm 0.004 \pm 0.004$ is made using equation 1 with $R_{FF} = 0.68 \pm 0.07$, as computed using the latest LQCD predictions [15]. The first uncertainty arises from the experimental measurement and the second is due from the LQCD prediction. Finally, using the world average of $|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$ measured from exclusive decays, $|V_{ub}|$ is measured as

$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.17 \pm 0.06) \times 10^{-3} \tag{5}$$

where, the first uncertainty is due the experimental measurement, the second uncertainty is associated with LQCD prediction and the final uncertainty results from the uncertainty on $|V_{cb}|$.

In addition a measurement of $\mathcal{B}(\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu) = (3.9 \pm 0.8) \times 10^{-4}$ is made by extrapolating the measured ratio of branching fractions to the full q^2 region. Here the dominant theory uncertainty arises in the $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ form factor predictions at low q^2.

Fig. 4(a) shows a comparison of the measured value $|V_{ub}|$ from $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays with existing exclusive and inclusive measurements of $|V_{ub}|$. The measurement is 3.5σ below the inclusive measurement, but agrees with the exclusive measurement from $\bar{B}^0 \to \pi^+\mu^-\bar{\nu}_\mu$ decays.

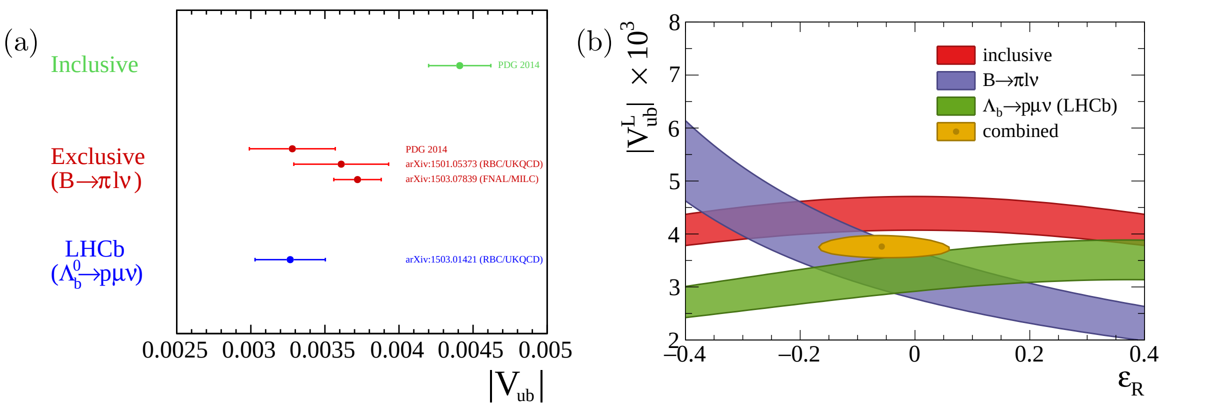

Figure 4 – (a) A comparison of the measurement of $|V_{ub}|$ from $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays with existing measurements using exclusive $\bar{B}^0 \to \pi^+\mu^-\bar{\nu}_\mu$ and inclusive $B \to X_u\mu^-\bar{\nu}_\mu$ decays. (b) Experimental constraints on the left-handed coupling, $|V_{ub}^L|$ and a fractional right-handed coupling, ϵ_R.

The value of of $|V_{ub}|$ determined from the measured ratio of branching fractions can be influenced by a right-handed coupling. This is shown in Fig. 4(b), which shows experimental constraints on the left-handing coupling, $|V_{ub}^L|$, against a fractional right-handed coupling ϵ_R. The constraint associated with $|V_{ub}|$ from $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays is compared with that from exclusive $\bar{B}^0 \to \pi^+\mu^-\bar{\nu}_\mu$ and inclusive $B \to X_u\mu^-\bar{\nu}_\mu$ decays. The measurement from $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays gives a different sensistivity to ϵ_R than that from $\bar{B}^0 \to \pi^+\mu^-\bar{\nu}_\mu$ decays given that the spin of the proton allows for an axial-vector current. The overlap of the bands associated with previous exclusive and inclusive measurements suggests a significant right-handed coupling, however, the inclusion of the $|V_{ub}|$ measurement from $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays does not support this.

6 Conclusion

The CKM matrix element $|V_{ub}|$ is an important parameter in constraining global fits to the unitarity of the CKM matrix. The discrepency between exclusive and inclusive measurements of $|V_{ub}|$ has been a long standing puzzle in flavour physics. Whether this is a systematic issue with the lattice QCD predictions used in the determination of exclusive measurements or an issue with the theoretical issues facing the inclusive measurement is unknown. The puzzle has resulted in a number of proposals which attempt to explain the discrepency with an addition of a right-handed coupling to the SM.

The first determination of $|V_{ub}|$ at a hadron collider and in a baryon decay has been performed using $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decays, which are observed for the first time. This provides a new avenue for constraining the CKM sector of the SM at the LHC. The measurement is in agreement with the existing exclusive $\bar{B}^0 \to \pi^+\mu^-\bar{\nu}_\mu$ measurement thereby increasing the tension between inclusive and exclusive measurements while at the same time disfavouring a right-handed coupling as an explanation for the discrepency.

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