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Beauty 2020 Workshop Summary

Phillip Urquijo[a,*]

[a] *The University of Melbourne,*
Parkville, Victoria, Australia

E-mail: `purquijo@unimelb.edu.au`

A summary of selected key results shown at Beauty 2020 are presented, including measurements from NA62, BESIII, BaBar, Belle and Belle II, LHCb, ALICE, ATLAS and CMS. Future flavour programmes at the major experimental flavour research facilities are also discussed.

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[*] Speaker

1. Introduction

The purpose of this proceedings is to summarise selected key results presented at Beauty 2020 and to provide insight into the future flavour programmes at the major experimental facilities. Research programme outputs from KOTO, NA62, BESIII, Belle and Belle II, BaBar, LHCb, ALICE, ATLAS and CMS are presented. The extended flavour programmes at these facilities are designed to address many of the prominent questions in particle physics, including, but not limited to, the following.

- Are there new CP-violating phases in the quark sector, hence an explanation for the observed matter-antimatter asymmetry in the Universe? This is being addressed through measurements probing for new sources of CP-violation in hadronic decays, as well as precision CKM metrology. A key driver of recent efforts has been to better understand strong interaction effects to improve the precision of theoretical interpretations.
- Is there more than one Higgs boson in nature and can there be an explanation for the mass hierarchy of fermions? Recent efforts have been driven by observed anomalies in semileptonic and leptonic B decays, including evidence for lepton flavour universality violation. Experimentally leptons of different flavour have different detector responses, thus any observed anomalies demand confirmation from multiple experiments.
- Does nature have a left-right symmetry at higher energies? Recent efforts include searches for new right handed interactions in a variety of semileptonic and radiative decay processes.
- Is there a dark sector of particle physics at the same mass scale as ordinary matter? A growing experimental programme of searches is underway at the kaon, charm and beauty flavour experiments. The models probed predict dark photons, axion-like particles, dark matter, as well as dark Higgs and Z bosons.
- Can we improve our understanding of strong interaction dynamics? Recent fruitful efforts are presented on conventional and exotic hadron spectroscopy.

A wide variety of results on these topics were presented at Beauty 2020, on B physics and in related programmes at flavour machines. At the time of Beauty 2020 the newest B experiment, Belle II at SuperKEKB, had collected 74 fb^{-1} of data near $\sqrt{s}$ = 10.58 GeV. While SuperKEKB reached a record for instantaneous luminosity already, it is expected to continue to ramp up to a factor 40 times that of KEKB. At Beauty 2020 LHCb had collected about 10 fb^{-1} of data before the long shutdown across all runs at varying $\sqrt{s}$. ATLAS and CMS had collected about 140 fb^{-1} at $\sqrt{s}$ = 13 TeV. BESIII had collected 16 fb $^{-1}$ of data at varying $\sqrt{s}$ near the open charm production threshold.

2. CP violation and Hadronic B decays

2.1 CKM metrology

At the core of the B-physics flavour programme is the measurement of the CKM matrix element magnitudes and CP violation phase(s). The single Standard Model (SM) CP violation phase is constrained through a series of independent measurements of the angles and side-lengths "B_d" Unitarity Triangle (UT). On the hadronic decay side the most significant improvements are on the UT angle $\phi_3(\gamma)$.

LHCb presented a new measurement of ϕ_3 based on a Dalitz plot analysis of $B \to Dh$ ($h = K$, π), $D \to K^0_S\pi^+\pi^-$. This is the single most precise measurement of ϕ_3, with large local CP violation observed in specific Dalitz bins [1]. The value of ϕ_3 was found to be $(69 \pm 5)^\circ$ [2], in agreement with global UT fits. Improving precision on ϕ_3 to near 1° may ultimately rely on inputs of strong phase parameters measured directly in quantum correlated D production. BESIII provides new measurements of phase inputs from $D \to K^0_{S,L}\pi^+\pi^-$ [3] and D^0 and $\bar{D}^0 \to K^0_{S,L}\pi^+\pi^-$ [4]. An intriguing orthogonal method for measuring ϕ_3 comes from time dependent measurements of B^0_s decays at LHCb in the channel $B^0_s \to K^0_S\pi^+\pi^-$ [5]. Specifically the measurement is used to extract ϕ_3-$2\beta_s$, for which the value is $(42^{+20}_{-13})^\circ$ and in agreement with the world average value owing to its large relative uncertainty.

Early Belle II data has been used to demonstrate the experiment's capacity for precision measurements of time dependent CP violation for both CKM metrology and new sources of CP violation. The flavour tagging efficiency for Belle II is around $(33.8 \pm 3.9)\%$ in a dataset of 8.7 fb^{-1}, a relative increase in efficiency of at least 10% with respect to Belle [6]. The first preliminary measurements of $\phi_1 = 0.55 \pm 0.21 \pm 0.04$ and $\Delta m_d = 0.531 \pm 0.046 \pm 0.013$ were also performed on a dataset of 34.6 fb^{-1}.

2.2 New sources of CP violation

Beauty 2020 saw two new results on the "B_s" UT angle ϕ_s from ATLAS [7] and CMS [8] with 13 TeV data. Angular analyses are utilised to disentangle two CP eigenstates from the decay $B^0_s \to J/\psi\phi$. The ATLAS combined run 1 and run 2 result is $(-8.7 \pm 3.7 \pm 1.9)$ mrad with 99.7 fb^{-1} while the CMS result is $(-21 \pm 44 \pm 10)$ mrad. Both are compatible with results from LHCb, as well as the SM prediction, implying strong constraints on new sources of CP violation beyond the SM.

Measurements from the Belle dataset continue to be produced, with new searches for CP violation in s-penguin modes [9]. Belle measures ϕ_1 from time dependent CP violation in $B^0 \to K^0_SK^0_SK^0_S$ decays and finds it to be $0.71 \pm 0.23 \pm 0.05$, consistent with SM expectation. LHCb has simultaneously measured the time-dependent and time-integrated CP asymmetries in $B_{(s)} \to hh'$ decays, leading to the first observation of time-dependent CP violation in $B^0_s \to hh$ decays with 6.7σ significance, $S_{B^0_s\to K^+K^-} = 0.123 \pm 0.034 \pm 0.015$ [10].

In the past two years LHCb found several significant sources of direct CP violation in 3-body charmless hadronic B decays, attributable to large local strong phase effects [11]. Since then a effort has focused on understanding the origin of the observed CP violation, by way of amplitude analyses and the measurement of $B \to h^+h^{+\prime}h^{-\prime}$ branching ratios [12]. Interpreting CP violation in charmless hadronic B decays also relies on precise measurements of neutral modes, which is a notable strength of Belle II. With 34.6 fb^{-1} of data Belle II performed its first measurements of branching fractions, CP asymmetries and polarisation (where applicable) in $B \to hh$, $B \to Khh$ ($h = K, \pi$), and $B \to \phi K^*$ including modes with neutrals [13]. Highlights include the measurement $\mathcal{B}(B^0 \to K^0\pi^0) = (10.9 \pm 2.9 \pm 1.6) \times 10^{-6}$.

2.3 Charm CP violation

The most significant study shown at Beauty in the charm sector was on the search for mixing-induced indirect CP violation. LHCb's 2020 result is based on measurements of charm from B decays with data from runs at $\sqrt{s} = 13$ TeV. Two channels are studied, with asymmetries found to be $A_\Gamma(D^0 \to K^+K^-) = (-4.3 \pm 3.6 \pm 0.5) \times 10^{-4}$ and $A_\Gamma(D^0 \to \pi^+\pi^-) = (2.2 \pm 7.0 \pm 0.8) \times 10^{-4}$. Both are consistent with with zero mixing-induced CP violation in charm [14]. Looking towards the future for Belle II, preliminary studies of proper time resolution in collision data show that Belle II has a factor 2 better resolution than Belle, with excellent implications for mixing parameter measurements [15].

3. CKM matrix elements and Tree level Semileptonic Decays

The research programme on tree-level semileptonic and leptonic decays has had two major directions in recent times: (i) CKM element metrology, and (ii) lepton flavour universality. In these areas there there has been continued tension either between orthogonal measurements of $|V_{ub}|$ and $|V_{cb}|$, or between measurements and the SM expectation in the case of $B \to D^{(*)}\tau\bar{\nu}$. It is a remark of the author that the latter tension is not observed by Belle, for which there is good agreement with SM expectations [16].

On $|V_{cb}|$ LHCb has provided new insights from B_s^0 decays in an area typically dominated by B^0 and B^+ results. For B_s^0 decays LQCD predictions can in principle reach higher precision than in B decays, owing to the lack of a light u or d quark in the decay process. LHCb initially reported a combined measurement of $B_s^0 \to D_s^-\mu^+\bar{\nu}$ and $B_s^0 \to D_s^{*-}\mu^+\bar{\nu}$ to extract a value of $|V_{cb}| = (42.3 \pm 0.8 \pm 0.9 \pm 1.2) \times 10^{-3}$ [17]. The latter uncertainties relate largely to normalisation parameters and theoretical inputs. LHCb since reported on measurements of form factors in $B_s^0 \to D_s^{*-}\mu^+\bar{\nu}$ in CLN and BGL parameterisations, and found them to be compatible with results from $B^0 \to D^{*-}\mu^+\bar{\nu}$ [18]. Preliminary LQCD non-zero recoil data from the JLQCD group has been used to re-fit the Belle untagged $B^0 \to D^{*-}\ell^+\bar{\nu}$ measurement in the BGL scheme, with $|V_{cb}| = (38.40 \pm 0.32 \pm 0.96) \times 10^{-3}$ [19].

A major update to $|V_{ub}|$ with inclusive charmless semileptonic B decays was presented by Belle [20]. The analyses uses a sample where one B is fully reconstructed in a hadronic channel, and the other B is reconstructed inclusively in a semileptonic channel followed by a fit to the hadronic invariant mass and q^2 distributions. The final value of $|V_{ub}|$ is found to be $(4.10 \pm 0.09 \pm 0.22 \pm 0.15) \times 10^{-3}$ based on a lepton momentum threshold of > 1 GeV$/c$. This result is lower than the Belle result that it supersedes, and is in much less tension with the exclusive determinations.

Belle II has invested significant effort to prepare for for tagged semileptonic B decay measurements, most notably towards $B \to D^{(*)}\tau\bar{\nu}$. Preliminary results were shown at Beauty on exclusive semileptonic B decays in a tagged sample [21], and in an untagged sample [22]. A complementary programme on improvements to lepton identification and reconstruction is also underway with first lepton flavour universality violation (LFUV) test results expected within the next year.

It is worth noting that LFUV tests of charged weak interactions are also possible via a more direct approach at the LHC. A long standing LEP hint for LFUV in the $R = W \to \tau\bar{\nu}/W \to \mu\bar{\nu}$ ratio motivated a more precise ATLAS measurement of $R = 0.992 \pm 0.013 \pm 0.007 \pm 0.011$, consistent with 1 and with the SM expectation [23].

4. Flavour changing neutral current B decays

Flavour changing neutral current (FCNC) decays provide an excellent probe for new phenomena, and are considered in three categories: (i) purely leptonic helicity suppressed decays, and (ii) angular analyses in semileptonic decays, and (iii) LFUV studies in leptonic and semileptonic decays.

On $B_{s,d} \to \mu^+\mu^-$ the most recent results are from CMS, which succeeded in reaching 5 σ significance for $B_s^0 \to \mu^+\mu^-$ with branching fraction of $(2.9^{+0.7}_{-0.6} \pm 0.2) \times 10^{-9}$. They also measure the B_s^0 lifetime in the decay with 20-30% precision, which was found to be consistent with the SM [24]. These and the results from ATLAS and LHCb with data from 2011-2016 have been combined in the $\mathcal{B}(B_d \to \mu^+\mu^-) - \mathcal{B}(B_s^0 \to \mu^+\mu^-)$ plane. They find $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$ and $\mathcal{B}(B_d \to \mu^+\mu^-) < 1.9 \times 10^{-10}$, which is 2.1 σ from SM expectations [25]. The $B_{s,d} \to e^+e^-$ channel is helicity suppressed by a factor 10^{-4} below the $\mu\mu$ channel, thus it provides a test of LFUV. LHCb has significantly improved over the previous best limit from CDF with $\mathcal{B}(B_s^0 \to e^+e^-) < 9.4 \times 10^{-10}$ and $\mathcal{B}(B_d \to e^+e^-) < 2.5 \times 10^{-10}$ at 90% CL [26].

Angular analyses of exclusive semileptonic $b \to s\ell^+\ell^-$ decays see a persistent tension between measurement and SM predictions, most notably in the ratio p_5'. This has prompted extensive efforts to understand the observed discrepancy from theory and experiment, and to provide orthogonal tests. LHCb recently performed a full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$ with 4.7 fb^{-1} of data [27], confirming the previously observed tension in p_5' in two q^2 bins at the level of 2.5 to 2.9 σ. CMS is providing more data to this picture through analysis of the relatively challenging mode for the LHC $B^+ \to K^{*+}\mu^+\mu^-$ [28], with new measurements of the forward-backward asymmetry and longitudinal polarisation fraction.

Belle has performed both LFUV and lepton flavour violation (LFV) tests in $B \to K\ell^+\ell^-$ and $B \to K\ell^+\ell'^-$ decays. LFUV is measured in bins of q^2 and found to be consistent with the SM with precision of around 25% per bin. The differential branching fractions are found to be lower than the SM expectation at q^2 values below the the charmonium resonances, but this is consistent with that seen from LHCb [29] and should ultimately be addressed. LHCb has performed the first branching fraction measurement of $\Lambda_b \to pK^-\mu^+\mu^-$ and the first observation of $\Lambda_b \to pK^-e^+e^-$ [30].

5. Rare and forbidden charm, kaon and Upsilon decays

Complementary to the B programme, many searches for FCNC and LFV channels have been performed in charm hadrons with limits in the range of 10^{-4} to 10^{-8}. Many new limits on rare and forbidden D decays have been performed by BaBar. In searches for $D^0 \to h^{-\prime}h^+\ell'^{\pm}\ell^{\mp}$ and $D^0 \to h^{-\prime}h^-\ell'^+\ell^+$ 12 new upper limits were set in the range $(1-30) \times 10^{-7}$. In $D^0 \to X^0e^{\pm}\mu^{\mp}$ 7 new upper limits were set in the range $(5-30) \times 10^{-7}$ [31]. These represent of order 100 times better upper limits than previous results. Similarly, new upper limits have been set by LHCb in searches for 25 rare and forbidden decays of D^+ and D_s^+ mesons to $h^{\pm}\ell\ell$ and $h^{\pm}\ell\ell'$ at levels of a factor 500 lower than previous experiments [32].

The NA62 experiment presented new results on $K^+ \to \pi^+\nu\bar{\nu}$ [33], with a branching fraction measurement of $(11.0^{+4.0}_{-3.5} \pm 0.3) \times 10^{-11}$ at 3.5 σ significance. This is in agreement with the SM expectation. The NA62 experiment also searched for heavy neutral leptons in $K^+ \to e^+N$ [34], with tight constraints on masses in the 50 to 450 MeV/c^2 range, and for new phenomena in other lepton number violating modes [35].

Using a 26.9 fb^{-1} sample collected at the $\Upsilon(3S)$ Babar peformed a high precision test of LFUV in the ratio $R = \mathcal{B}(\Upsilon(3S) \to \tau^+\tau^-)/\mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 0.9662 \pm 0.0016$ [36]. This is in agreement with the SM expectation of 0.9948.

6. Dark sector searches at flavour factories

In 2020 Belle II published its first physics analysis paper on searches for a dark Z' coupled to leptons with a dataset of 0.276 fb^{-1} [37]. This sets new constraints on possible Z' models predicted to affect $(g-2)_\mu$. BaBar performed the first search for leptophilic dark scalars produced in τ pair events, also with implications for $(g-2)_\mu$ [38].

Belle II's second paper was on the search for axion like particles (ALPs) through photon couplings in electron-positron annihilation, [39]. New limits are set on ALPs with masses from 150 MeV/c^2 to 10 GeV/c^2 and couplings ($g_{a\gamma\gamma}$) down to around 10^{-3}. Complementary searches for ALPs in B decays have been performed by BaBar in $B^+ \to K^+ a$, $a \to \gamma\gamma$, setting new limits on g_{aW} at levels near 10^{-5} (preliminary results were shown).

7. Spectroscopy and exotica

Significant progress towards a better understanding of exotic hadrons were presented at Beauty 2020, on both charm and beauty hadrons. LHCb has performed an amplitude analysis of $B^+ \to D^+D^-K^+$ to study the $X(2900)$ [40]. They find reasonable agreement with data when including two D^-K^+ Breit-Wigners. If interpreted as resonances this would be the first observation of exotic hadrons with open flavour, and without a heavy quark-antiquark pair. LHCb has significantly improved the characterisation of the mass and width of $X(3872)$, otherwise known as $\chi_{c1}(3872)$ [41, 42]. This is the first width measurement, and found to be $\Gamma^{BW}_{\chi_{c1}(3872)} = 1.19 \pm 0.19$ MeV. On XYZ state studies at BESIII: they have observed the production of $Y(4220)$ and $Y(4360)$ in the process $e^+e^- \to \eta J/\psi$ [43], and studied the process $e^+e^- \to \pi^0\pi^0 J/\psi$ to characterise the neutral charmonium-like state $Z_c(3900)^0$ [44].

In the beauty hadron sector, LHCb has observed a state that could be interpreted as the $X(6900)$ decaying to J/ψ pairs [45]. If confirmed it is the first observation of an exotic hadron made of 4 heavy quarks of the same flavour. CMS has similarly searched for a $bbbb$ state via $\Upsilon(1S)\mu\mu$. No significant excess of events compatible with a narrow resonance was observed in the window between 16.5 and 27 GeV/c^2 [46]. Finally, on b hadron spectroscopy at LHCb: isospin amplitudes have been measured in $\Lambda^0_b \to J/\psi\Lambda(\Sigma^0)$ and $\Xi^0_b \to J/\psi\Xi^0(\Lambda)$ decays [47], and the first observations of excited Ω^-_b states have been claimed [48].

8. Outlook

Over the coming decade significant upgrades and high luminosity operation campaigns are foreseen at Belle II [49], LHCb [50] (and other LHC experiments), and BESIII [51]. Each of these collaborations have put forward detailed future physics analysis programmes, focusing on flavour.

Despite the triumphant effort on CKM metrology and new searches phenomena to date, many if not most key channels will still in some way remain statistics limited for many years to come, and not limited by theory or irreducible systematic uncertainties. The B experiments, Belle II and LHCb will see a decade of healthy competition and complementary efforts to better understand flavour transitions. Belle II has strengths in modes with photons and neutrinos, e.g. $B \to K\nu\bar{\nu}$ and $B \to \mu\bar{\nu}$, inclusive transitions and time dependent CP violation in B_d. LHCb benefits from higher production rates to study ultra rare B, D and K decays and has access to all b-hadron flavours, with high boost to see fast B_s^0 oscillations.

The B-factories (and LHCb) were built to be very capable for flavour physics studies, but have weaknesses. Continued upgrades and technique developments are well justified. On LFUV anomalies, for example, event signatures often contain electrons, muons and neutrinos: their reconstruction or inferred presence demands efforts for (i) improved calorimetry techniques, reduced material to minimise bremmstrahlung, and improved detector mapping, (ii) better particle identification at low momentum and (iii) robust tracking with maximal phase space coverage. Theory errors are often substantial in SM precision measurements, for which we need sufficient emphasis on measurements of theory error control modes, QCD effects in precision SM analyses and FCNC decays, and tests of predictions from LQCD and LCSR. Collaborative work between flavour machines to address outstanding problems are also an important area of future research efforts, e.g. LHC-wide efforts on $B \to \mu^+\mu^-/e^+e^-$, cross experiment efforts from BESIII, BelleII, and LHCb on ϕ_3, HFLAV activities on a variety of topics, and measurements of charm and b-hadron absolute branching fractions for normalisation. The physics plans for the coming decade (from Belle II, BESIII, LHCb etc.) were written to benchmark the experiment prospects and develop research programme ideas. The field is encouraged to not just read and follow these physics plans but to build on them with exciting new ideas.

9. Acknowledgements

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