CP Violation with B-Mesons: Probing Physics Beyond the Standard Model with the Unitary Triangle

Keri Heuer

1 Introduction

The Standard Model of particle physics is the theory that classifies all known elementary particles and describes three of the four known fundamental forces: the electromagnetic, weak, and strong interactions. In addition to classical conservation laws (*i.e.* energy, charge), conservation laws related to baryon and lepton number as well as parity, isospin, and strangeness have been developed to describe particle interactions. The combination of charge-conjugation (C), parity (P), and time-reversal (T) symmetry is considered to be a fundamental symmetry operation. Known as CPT invariance, this combination is crucial to our understanding of transformations under which the laws of physics hold. In the Standard Model, CP violation arises from the complex phase angle of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix that describes weak couplings in the quark sector. The CKM matrix describes the unitary rotation between the mass eigenstates and weak eigenstates of the quark sector and has an imaginary phase δ_{KM} Aubert et al. (2007). δ_{KM} is known as the the Kobayashi-Maskawa (KM) phase, which is the result of complex coefficients in the Lagrangian due to Yukawa couplings between fermions and the Higgs boson. This is referred to as the KM mechanism for CP violating effects in the Standard Model and not only gives an irreducible phase but is the single source of CP violation predicted by the Standard Model.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \tag{1}$$

1: CKM matrix with standard parameterization

As such, high-precision measurements of CP violating observables are required to better constrain the Standard Model and test models of new physics. Not only does the Standard Model have a large number of parameters that are unfixed and determined experimentally, but it does not fully explain fundamental interactions and all observed phenomena. For example, the Standard Model does not account for the accelerating expansion of the Universe (possibly due to dark energy), incorporate the full theory of gravitation, contain any viable dark matter particle with the properties required of observational cosmology, include neutrino oscillations and their non-zero masses, or account for the observed baryon asymmetry. The Standard Model predicts an amount of CP violation that is orders of magnitudes too small to produce the asymmetrical ratio of baryons to photons in the Universe. Moreover, inflationary models have argued that an early period of exponential expansion would have diluted the prior abundance of any unseen, heavy (meta-)stable particles, potentially explaining the theorized existence of particles that have yet to be observed (Particle Data Group et al., 2020). Observations of new sources of CP violation could thus indicate physics beyond the Standard Model and determine the nature of dynamics underlying CP violation, which currently only arise from weak interactions in the quark sector.

1.1 CP Violation in the Standard Model

While CP violation is predicted in the Standard Model, the Standard Model only allows for the existence of CP violation under certain assumptions, some of which are still being tested. The Standard Model implies that there is no mixing in the lepton sector because the CKM mixing matrix becomes a unit matrix if neutrinos are mass-less; it also posits that neutral current interactions are universal in the mass basis, so there are no additional flavor parameters in the descriptions of such interactions (Nir, 2000). This understanding is what points to the single source of CP violation in the Standard Model: mixing in charged interactions of quarks that is related to flavor-changing interactions. CP violation is allowed in three different quark interactions:

- Neutral meson state mixing (indirect CP violation)
- Neutral or charged meson decay (direct CP violation)
- Interference of mixing and decay amplitudes

Mixing-induced CP violation results from physical eigenstates differing from the CP eigenstates; this effect is experimentally observed as asymmetries in mass eigenstates Nir (2000). Mixing in observed oscillations of a particle between two flavors has a mixing frequency $\omega = \Delta$m (*i.e* the mixing frequency is equal to the mass difference between the two flavor states in natural units) due to CP violation, giving unequal probabilities of an particle turning into its antiparticle and an antiparticle transitioning into a particle (Britsch, 2014). Decay-induced CP violation arises from interference in decay amplitudes leading to the same final state and can have tree-level contributions to the decay amplitudes as well as penguin (loop) diagram contributions. Observables that are measured to quantify CP asymmetries in decays are the total number of decays from $B \to f$ and $\overline{B} \to \overline{f}$ (where the bar and f indicate the CP transformed state and the final state) and the partial decay width of those transitions (Britsch, 2014).

1.2 B physics

Before discussing the CKM matrix and the Unitary Triangle, it is important to highlight aspects of B physics relevant to CP violation now that the different types of CP violation have been introduced. The potential contributions of B physics to probing the Standard Model and understanding the origin of CP violation are crucial to keep in mind when discussing the Unitary Triangle measurements and future prospects.

Parameters of interest in the B sector include those governing $B^0 - \overline{B}^0$ and $B_s^0 - \overline{B}_s^0$ mixing, branching fractions from inclusive/exclusive semileptonic B decays to determine CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$, branching fractions for B decays to final states involving open charm/charmonium mesons, and branching fractions and CP asymmetries for charmless, radiative, leptonic, and baryonic B-meson decays (rare decays) (Amhis et al., 2017).

CP violation can be characterized in the particle-antiparticle mixing that occurs in both the neutral $B^0 - \overline{B}^0$ and $B_s^0 - \overline{B}_s^0$ systems by measuring $|\frac{q_q}{p_q}|^2 \neq 1$ (where the subscript $q = d$ for a $B_d^0 = B^0$ meson and $q = s$ for the B_s^0 meson); the semileptonic asymmetry involving the quantities $(\frac{q_q}{p_q})^2$ and $|\frac{p_q}{q_q}|^2$ is also used to characterize CP violation in neutral B meson mixing and mixing-induced CP violation in B_s^0 decays (Amhis et al., 2017). For CP violation induced by $B_s^0 - \overline{B}_s^0$ mixing, such as in the decay $B_s^0 \to J/\psi\phi$, the main CP violating observable is the phase $\phi_s^{c\bar{c}s}$, which is the the weak phase difference between the $B_s^0 - \overline{B}_s^0$ mixing amplitude and the $b \to c\bar{c}s$ decay

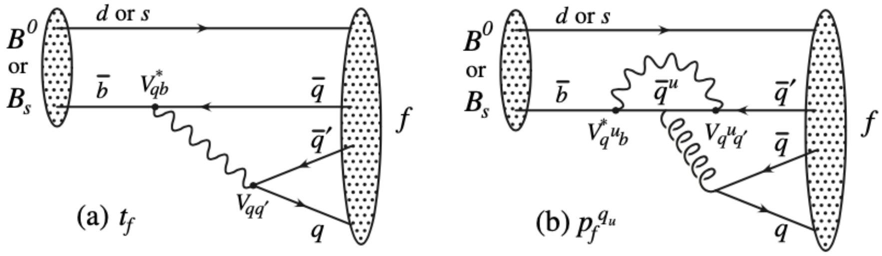

Figure 1: Feynman diagrams for (a) tree and (b) penguin amplitudes that contribute to $\mathrm{B}^0 \to f$ or $B_s^0 \to f$ via a $b \to qqq$ transition from PDG.

amplitude. The weak phase difference ϕ_s causes CP violation in B_s^0 mixing (which is predicted to be very small in the Standard Model: $\phi_{12}^s = 0.0046 \pm 0.0012$) and is one area where contributions from new physics could be observed (see Section 1.3.4) (Amhis et al., 2017).

One important class of quark transitions with B-mesons are transitions of the mode $\overline{b} \to \overline{q}q\overline{q}'$ with $\overline{q}' = s$ or d (PDG review 2020). Decays mediated by this mode with $q = s$ or d only have penguin contributions to the final state amplitude and not tree contributions, while decays with $q = c$ or u have contributions from both tree and penguin (loop) diagrams, each carrying a different phase (Particle Data Group et al., 2020). Not only are penguin contributions small in the Standard Model, but the additional phase from a penguin contribution complicates determination of Unitary Triangle angles from decay modes that are not purely tree-dominated (see Figure 1). The contribution from tree-level and penguin processes due to interference in amplitudes can cause large CP asymmetries to occur, so determining Unitary Triangle measurements from such decays requires isospin analysis to detangle the CP-odd and CP-even components of the final state. Decays such as $B^0 \to J/\psi K_s$ that are mediated by the $\overline{b} \to \overline{c}c\overline{s}$ transition only consist of tree-contributions, making them suitable for clean determination of the Unitary Triangle γ and for probing new physics (since tree-level processes are expected to be insensitive to new physics) (Particle Data Group et al., 2020).

CP violation effects in mixing-decay interference are often studied with final states common to B^0 and $\overline{B^0}$. For example, CP violation is often observed in the decays $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$ since the final state is accessible to both B_s^0 and $\overline{B_s^0}$. Being accessible to both B_s^0 and $\overline{B_s^0}$ means that a CP violating phase can arise from interference between the decay amplitudes and the B_s^0 - $\overline{B_s^0}$ mixing amplitude. This CP violating phase $\phi_s = \phi_M - 2\phi_D$ (with ϕ_M and ϕ_D being the mixing phase and the weak decay phase respectively) can be precisely predicted in the Standard Model because of the weak decay phase being very small (Krüger & Romão, 2000). Moreover, ϕ_s is one of the several measurements that are sensitive to possible contributions from new physics regarding B_s^0 - $\overline{B_s^0}$ mixing (oscillations) as flavor physics becomes better understood.

While decays with penguin contributions can be used to determine $\sin(2\beta)$ through isospin analysis, the importance of penguin-dominated decays mainly lies in their potential to discover new physics: CP violation measurements between tree-dominated and penguin-dominated modes in B_s^0 decays and similar decay modes can reveal contributions to new physics because of the suppression of penguin amplitudes in the Standard Model (see Figure 2 (Particle Data Group et al., 2020). One such decay is $B_s^0 \to \mu^+\mu^-$, which occurs via $\overline{b} \to \mu^+\mu-$ loops. Loop-dominated decays are rare because 1) they often involve heavier particles and the Standard Model suppresses decay more for heavier particles and 2) the probability of a transition rapidly decreases with the number of electroweak vertices (and a loop has three or four vertices opposed to two vertices of a tree decay) (Koppenburg et al., 2016). These rare decays make for good searches for new physics since suppressed decay amplitudes as predicted by the Standard Model may potentially be the

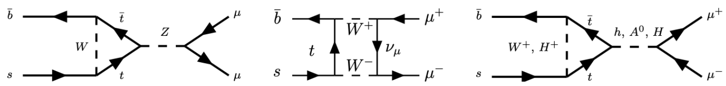

Figure 2: Feynman diagram of dominating Standard Model contributions to the decay $B_s^0 \rightarrow \mu^+\mu^-$ (left and middle) and a potential contribution in the supersymmetric picture (right) (Koppenburg et al., 2016)

$$V_{CKM} = \begin{pmatrix} 1{-}1_{\overline{2\lambda^2}} & \lambda & A\lambda^3(\rho - i\eta) \\ \text{-}\lambda & 1{-}1_{\overline{2\lambda^2}} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \tag{2}$$

2: Wolfenstein paramaterization of the CKM matrix to $\mathcal{O}\lambda^4$, unitary to all orders of λ.

same size as new physics amplitudes; however, disentangling the contribution from Standard Model processes and new physics will require a significant increase in experimental precision (Koppenburg et al., 2016).

Forbidden decays, such as those that violate lepton flavor, are also of great interest and being searched for. These include $B_s^0 \rightarrow e^\pm\mu^\mp$ and the charged counterparts of these decays, such as $B^+ \rightarrow l + \mu$ (where l is a lepton of e, μ, τ) (Koppenburg et al., 2016).

1.3 CKM Matrix and The Unitary Triangle

In the mass basis, CP violation is related to the CKM matrix, namely the complex phase that arises from the CKM unitarity condition. For the matrix to be unitary, orthogonality conditions between pairs of rows and columns of the matrix require the sum of three complex numbers to vanish. These conditions can be geometrically represented in the complex plane as a triangle and are thus known as unitary triangles. Upon Wolfenstein parameterization, where the area of all unitary triangles are half the Jarkslog invariant J that measures CP violation, only four of eighteen angles from six unitary triangles arising from the orthogonality conditions remain (Particle Data Group et al., 2020).

This means that all CP asymmetries can be completely expressed in terms of these four independent angles: three rotation angles and one complex phase. This CP-violating phase η is one of the four Wolfenstein parameters: the complex phase η, λ (the sine of the Cabbibo angle which represents the expansion parameter in the Standard Model), A, ρ Nir (2000). Wolfenstein parameterization is convenient because J $\equiv \rho + i\eta = \frac{-(V_{ud}V_{ub}^*)}{V_{cd}V_{cb}^*}$ is independent of phase-convention and thus measures CP violation in any parameterization: CP violation in the Standard Model occurs when J $\neq 0$, with the sign of J indicating the direction of complex vectors around the triangles (Particle Data Group et al., 2020). Additionally, a non-zero value of η indicating the CKM matrix is not purely real in any parametrization means that the complex coefficients and phase of the CKM matrix is the origin of CP violation in the Standard Model. Currently, the world average of $\eta = 0.3540^{+0.00042}_{-0.0076}$ (Amhis et al., 2017).

A major goal of flavor physics is to overconstrain CKM elements, so rescaling the unitary triangles in the (ρ, η) plane allows for convenient display and comparison of measurements (Particle Data Group et al., 2020). The most commonly measured triangle of the untary triangles is referred to as *the* Unitary Triangle. It is made up of the three rotation angles α, β, and γ and has its vertex at (ρ, η). The Unitary Triangle arises from the unitary condition of the CKM matrix within the Standard Model requiring that:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \tag{3}$$

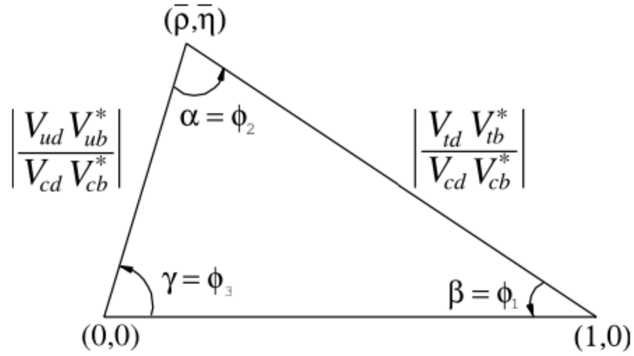

Figure 3: Normalized Unitary Triangle in (ρ, η) parameter space (Britsch, 2014).

This is just a triangle in complex space, so checking whether the sum of α, β, and γ equals 180° is a way to test CKM unitary and therefore probe the Standard Model. Moreover, this triangle relation is of particular importance to the B system as it is specifically related to the flavor-changing neutral current $b \to d$ transitions (Amhis et al., 2017).

It is important to note that the measurements of three angles of the Unitary Triangle are closely related to CP violating observables, while the lengths of the Unitary Triangle's sides can be determined from CP conserving observables (Krüger & Romão, 2000). For brevity, only determination of Unitary Triangle angles and not its side lengths will be discussed. The three angles of the Unitary Triangle can be extracted from the following types of B decays: neutral B decays to CP eigenstates, neutral B decays to non-CP eigenstates, charged B decays. Using the experimental observables of ratios and CP asymmetries of time integrated and time dependent decay rates, one can calculate and constrain Unitary Triangle elements. Because the Unitary Triangle is constructed with experimental values of the various CKM matrix elements, precise measurements of CKM elements are crucial to testing Standard Model predictions and better understanding the origin of CP violation. Predictions for future measurements of CP violating observables will entail determining the allowed ranges for the CKM phases and parameters, the latter of which are determined by Nir (2000):

- Direct measurements via Standard Model tree level processes (*i.e.* CKM matrix elements $|V_{ud}|, |V_{us}|, |V_{ub}|, |V_{cd}|, |V_{cs}|, |V_{cb}| and |V_{tb}|$).
- Indirect measurements related to loop processes in the Standard Model (*i.e.* δ_{KM} or equivalently η)
- CKM matrix unitary condition (V$^{\dagger}_{CKM}V_{CKM} = 1$) that relates and constrains various matrix elements

Using isospin (SU(2)) symmetry, one can relate the amplitude of B decays to final states and use measurements of branching fractions and charge asymmetries to determine an angle in the Unitary Triangle (see Figure 4) (Aubert et al., 2007). Oftentimes, δa (where a represents an angle in the Unitary Triangle) is measured along with a and indicates a phase difference in decay amplitudes from penguin contributions. When $\delta a = 0$, there is only tree-level decays and the angle a can be cleanly determined in the absence of penguin contributions (*i.e.* isospin analysis is not required to disentangle the CP components of the final eigenstate). This phase difference due to penguin contributions is often a significant contribution to the error in Unitary Triangle angle measurements. CKM and Unitary Triangle elements can also be determined using flavor analysis (SU(3) symmetry).

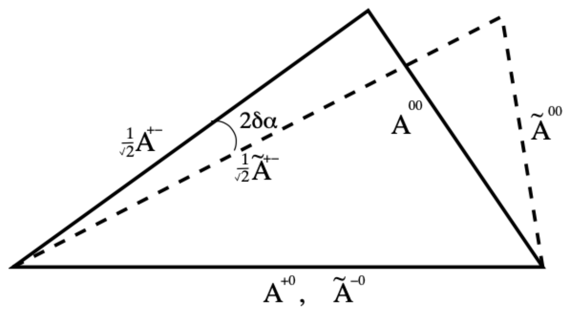

Figure 4: The isospin triangle for $B \to \rho\rho$ decays that relates decay amplitudes to determine α (Aubert et al., 2007).

1.3.1 $\alpha \equiv arg(\frac{-V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}) \sim arg(\frac{-1-\rho-i\eta}{1-\rho+i\eta})$

α is often determined by decays mediated by the $b \to u\overline{u}d$ transition, such as the decay $B_d^0 \to \pi^+\pi_-$ (Krüger & Romão, 2000) or $B^0 \to \rho^\pm\pi^\mp$ (Amhis et al., 2017). Various methods have been used to obtain constraints on this angle from measurements of time-dependent asymmetries in decay rates sensitive to α, including isospin and U-spin analysis. In the decay $B^0 \to \rho^+\rho^-$, there is no evidence for CP violation in decay or mixing, so in addition to the lack of evidence for penguin contributions to this mode, this decay is one that provides strong constraints on α. In the absence of penguin decays, the indirect CP component of time-dependence = 0 and the direct CP component S = sin(2α); when gluonic penguin diagrams are considered, however, C $\propto$ sin(δ) and S = 1 - Csin($2\alpha_{eff}$) where δ is the difference between the tree and penguin strong phases and α_{eff} is the effective value of α (Hutchcroft, 2007).

The power of $\Delta\alpha = (\alpha - \alpha_{eff})$ is that it can constrain the possible penguin contribution to measurements of CP violation and probe of physics beyond the Standard Model. A small value of $\Delta\alpha$ implies measuring a small branching ratio and thus small penguin contribution to the decay, whereas a large value would imply a large branching ratio and significant penguin contribution. For example, BaBar measurements of the $B \to \rho\rho$ system where tree decays dominate have yielded a constraint of $\alpha_{eff} \leq 11^\circ$ (babar/belle alpha measurements) and $\alpha = 73.1^\circ$ at a 68% confidence level using isospin analysis (Aubert et al., 2007).

1.3.2 $\beta \equiv arg(\frac{-V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}) \sim arg(\frac{1}{1-\rho-i\eta})$

β is a CP violating weak phase determined by time-dependent CP violation measurements of $\overline{b} \to \overline{c}c\overline{s}$ transitions (BaBar et al., 2018). β is a particularly important Unitary Triangle measurement to constrain because it is determined trigonometrically from measurements of sin(2β) and cos(2β). This means that there is a twofold trigonometric ambiguity in inferring β and thus an ambiguity in determining the apex of the Unitary Triangle, namely whether η is positive or negative (BaBar et al., 2018).

The Heavy Flavor Averaging Group has determined $\beta = (68.1 \pm 0.7)^\circ$ with measurements from BaBar, Belle, and LHCb of decays mediated by the $b \to c\overline{c}s$ transitions such as $B^0 \to J/\psi K_s^0$ giving sin($2\beta = 0.691 \pm 0.017$) with a precision less than 2.5% (Amhis et al., 2017). The current world average is sin(2β) = $0.699^\circ \pm 0.017$ (Particle Data Group et al., 2020). Measurements of β with $b \to c\overline{c}s$ decays to a 1° precision are consistent with current Standard Model predictions (Aubert et al., 2007).

1.3.3 $\gamma \equiv arg(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}) \sim arg(\rho + i\eta)$

The decay of $B^+ \to f$ and its charge conjugate process $B^- \to f$, where f is the final eigenstate, are especially informative when the D and $\overline{D}^0$ decay into a common final state. This results in interference effects between the two decay amplitudes with a sensitivity to $\delta \pm \gamma$, where δ is the difference in the relevant CP-conserving strong phase (PDG review 2020). By measuring branching ratios and CP asymmetries, γ (and δ) can be determined from amplitude triangle relations with negligible theoretical uncertainty.

1.3.4 $\beta_s \equiv arg(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*})$

While not a Unitary Triangle angle, β_s is a relevant angle to measurements of CP violation in B decays and probing physics beyond the Standard Model. β_s is an angle in one of the (non-standard unitary triangles) determined from a mixing phase ϕ_s from interference of amplitudes in B_s^0 mixing (equivalent to $\phi_{c\bar{c}s}^s$ from Section 1.2). Φ_s, a physical observable, is approximately equal to the angle -2β in the Standard Model. CP asymmetry in the decay of $B_s^0 \to J/\psi\phi$ via the $\bar{b} \to \bar{c}c\bar{s}$ mode can determine $\sin(2\beta_s)$ but requires angular analysis to disentangle CP-even and CP-odd components of the final state. The decay $B_s^0 \to J/\psi\pi^+\pi^-$ is another commonly studied decay for determining $\sin(2\beta_s)$ as it does not require angular analysis. Constraining the mixing phase ϕ_s well (as has been done by LHCb in the multi-body decay $B_s^0 \to D_s^{\mp}K^{\pm}\pi^{\pm}\pi^{\mp}$) is important for constraining the Unitary Triangle as β_s is often taken as an external input for calculating β (Aaij et al., 2016).

The combination of current world averages from these types of decays give -2β_s = -0.021±0.031 rad, which is consistent with the Standard Model prediction β_s = -0.0184±0.0004. However, many new physics models predict larger values for β_s if non-Standard Model particles contribute to B_s^0-$\overline{B}_s^0$ oscillations (Aaij et al., 2019). If penguin contributions to decays are not neglible, then the CP violating phase ϕ_s will no longer equal -2β_s. While the current world average of $\phi_s = 0.030 \pm 0.033$ (versus the Standard Model prediction of $\phi_s = 0.0046 \pm 0.0012$) changes, new physics in B_s^0 mixing could change the observable phase such that $\phi_s = \phi_s^{SM} + \phi_s^{NP}$ (where SM and NP indicate Standard Model and New Physics and ϕ_s^{SM} is the current predicted value) (Amhis et al., 2017).

2 Experiments studying CP violation with b hadrons

Experiments measuring CP violation in B decays are of two types: those performed at e^+e^- colliders like the B-factories and those performed at hadron colliders such as LHC. BaBar and Belle are B-experiments at the respective SLAC and KEK facilities, while LHCb is specifically a B-physics experiment at LHC.

Regardless of the type of CP violation being measured (*i.e.* due to mixing, decay, or mixing-decay interference), all CP violation measurements seek to quantify the difference in total or differential decay rates of b hadrons to a particular final state. As such, flavor tagging (information on whether the decaying meson was in a B or $\overline{B}$ state when tagged) is required (Gershon & Gligorov, 2017). The method of flavor tagging is one notable difference between e^+e^- and hadron colliders (although for the purpose of this discussion the specifics will not be reviewed). The primary difference between these types of experiments is that e^+e^- colliders are better able to study final states involving several neutral particles or missing energy due to more powerful flavor tagging capabilities, while hardon colliders have marge larger production rates (especially for final states involving only charged particles) and provide access to all flavors of b hadrons (Gershon &

Gligorov, 2017).

2.1 LHC-b

LHCb is the leading experimental facility studying b hadrons with a single-arm forward detector that is designed to exploit the relatively large $\bar{b}b$ production in LHC pp collisions (Koppenburg et al., 2016). It produces $10^{11} B$ and $\overline{B}$ mesons per year via gluon fusion and has a dipole spectrometer that measures CP violating asymmetries in B decays to a precision on the order of 10^{-2} and has uniquely good π/K separation as required for B physics (Gershon & Gligorov, 2017).

2.2 BaBar/Belle (B-factories)

BaBar and Belle are equipped with e^+e- colliders PEP-II and KEK-B respectively that have asymmetric beam energies running at Υ(4S) which boost produced B mesons to separate their decay vertices; more specifically, they produce B meson/anti-meson pairs via the decay of $b\bar{b}$ resonance that e^+e- collisions produce (Gershon & Gligorov, 2017). BaBar and Belle played a crucial role in validating the Kobayashi-Maska (KM) mechanisms by measuring $\sin(2\beta)$, making the first observations of CP violation outside the kaon sector (Gershon & Gligorov, 2017).

2.3 Current measurements of Unitary Triangle angles

The following subsections provide an overview on the current status of Unitary Triangle measurements from several different B decays. Multiple measurements are listed to show difference in measurements from various analysis methods and the range of values that have been measured by experiments, *i.e.* that there is still better precision that future experiments need to obtain in order to accurately constrain the CKM paradigm and probe the Standard Model.

2.3.1 α

Both BaBar and Belle have conducted isospin analysis in the $\rho\rho$ system, with BaBar giving a value of $\alpha = 92.4^{+6}_{-5}{}^{\circ}$ from $B^0 \to \rho^+\rho^0$ decay and Belle finding $\alpha = (93.7 \pm 10.6)^{\circ}$ from $B^0 \to \rho^+\rho^-$ decays; results from the $\rho\rho$ system have yieleded the most precise constraints on α of $\sim 6^{\circ}$ (Amhis et al., 2017). BaBar in particular has measured α in the $\rho\rho$ system to be 73.1° using isospin symmetry and $\alpha = 83.3^{\circ}$ with flavor symmetry, both at a 68% confidence level (Aubert et al., 2007).

BaBar and Belle have also studied $B^0 \to \pi^+\pi^-$ decays to obtain a value of $\Delta\alpha \leq 35\%$ at a 90% confidence level (babar/belle alpha measurements). BaBar and Belle have combined their results on $B \to \pi\pi, \pi\pi\pi^0$, and $\rho\rho$ decays to provide the constraint $\alpha = (88 \pm 5)^{\circ}$ (Amhis et al., 2017).

Both BaBar and Belle have studied $B^0 \to \rho\pi$ decays. For $B^0 \to (\rho\pi)^0$ BaBar has determined a likely value of $\alpha = (89)^{\circ}$ using time-independent Dalitz plot amplitude analysis (Miyashita & BaBar Collaboration, 2011).

Belle II, the next-generation of the Belle experiment, expects to be able to measure $\sin(2\alpha)$ with a precision of $\sim$1% due to its increased sample size (Oberhof & Belle Collaboration, 2018).

2.3.2 β

BaBar and Belle have directly measured $\sin(2\beta) = 0.75 \pm 0.10$ (BaBar); 0.99 ± 0.15 (Belle) with the decay $B^0_d(\overline{B^0_d}) \to J/\Phi/K_s$ (Nath et al., 2010). From decays with $b \to \bar{c}c\bar{s}$ transitions, the world average of $\sin(2\beta) = 0.691 \pm 0.017$ only has an uncertainty of $0.7°$(BaBar et al., 2018). While $\sin(2\beta)$ has been precisely measured, measurements of $\cos(2\beta)$ usually have larger uncertainties.

Using Dalitz plot amplitude analysis, BaBar obtains $\sin(2\beta) = 0.91 \pm 0.20$, $\cos(2\beta) = 0.97 \pm 31$ and $\beta = (25.6 \pm 6.4)°$ while Belle measures $\sin(2\beta) = 0.70 \pm 0.20$, $\cos(2\beta) = 0.96 \pm 30$ and $\beta = (19.6 \pm 6.1)°$ (BaBar et al., 2018). $\sin(2\beta)$ agrees with the world average within 0.7 standard deviations, and the measured value of β is in very good agreement for the preferred solution of the Unitary Triangle using the world average of $(21.9 \pm 0.7)\dot{°}$Moreover, this is the most precise measurement of $\cos(2\beta)$ and the first evidence for $\cos(2\beta) > 0$ (excluding the trigonometric second solution of $pi/2 - \beta = (68.1 \pm 0.7)°)$ allowing resolution of the ambiguity in the determination of the Unitary Triangle apex (BaBar et al., 2018).

2.3.3 γ

LHCb, BaBar, and Belle have observed various $B_{(s)} \rightarrow D_{(s)}K^{(*)}$ decays that allow a determination of γ by measuring the ratio of interference amplitudes. A combination of their measurements with the ADS method (which considers final states where the Cabbibo-allowed $\overline{D}^0$ and doubly-Cabbibo-suppressed D^0 decays interfere) gives $\gamma = (72^{+12}_{-14})°$ while the BPGGSZ method with analysis of Dalitz plot dependence of interferences gives $\gamma = (73.8^{+6.8}_{-7.0}{}^{\circ}$ (Particle Data Group et al., 2020). The latter is the current best determination of γ.

Using the decays $B^+ \rightarrow DK^+$, $B^+ \rightarrow DK^{*+}$, and $B^+ \rightarrow D * K^+$, BaBar has obtained a value of $\gamma = (68^{+15}_{-14}{}^{\circ}$ (Amhis et al., 2017). Belle has obtained $\gamma = 78^{+11}_{-12}{}^{\circ}$ from the modes DK^+ and D^*K^+ and LHCb has obtained $\gamma = 84^{+49}_{-42}{}^{\circ}$ from the DK^+ mode (Amhis et al., 2017).

LHCb has also measured $\gamma = (63.5^{+7.2}_{6.7})°$ using U-spin symmetry of the tree-level decay $B^0_s \rightarrow K^+K^-$ (Oberhof & Belle Collaboration, 2018).

The current world average of $\gamma = (74.0^{+5.8}_{-6.4})°$ is expected to increase in precision with more data from the future Belle II and LHCb (Amhis et al., 2017). Belle II in particular anticipates measuring γ with a precision of $1.6°$ (Aaij et al., 2016).

2.3.4 β_s and ϕ_s

LHCb has measured $-2\beta_s = 0.12^{+0.14}_{-0.16}$ rad with U-spin symmetry of the tree-level decay $B^0_s \rightarrow K^+K^-$ (Aaij et al., 2015). LHCb has also measured $\psi_s =$ from $B^0_s \rightarrow J/\psi K^+K^-$, $B^0_s \rightarrow J/\phi\pi^+\pi^-$, and $B^0_s \rightarrow D^+_s D^-_s$ decays (Aaij et al., 2019).

3 Implications of CP Violation and the Unitary Triangle for Physics Beyond the Standard Model

While the Standard Model allows for CP violation and most of the existing measurements of CKM elements and Unitary Triangle angles are consistent with Standard Model predictions, there is still much room for new physics to emerge through CP violation studies. With the current world averages of Unitary Triangle angles being $sum(\alpha + \beta + \gamma) = (179^{+7}_{-6})°$ there is still potential for more precise measurements in the future and over-constraining of CKM elements. Furthermore, the origin of CP violation is still being debated as the amount of CP violation allowed by the Standard Model is not nearly as large as the amount needed to observe baryon asymmetry and explain inflation. The Unitary Triangle is a promising way to test different models of physics because as its angles, apex, and side-lengths are more precisely measured and over-constrained, any inconsistencies between such measurements would indicate physics beyond the Standard Model (Gershon & Gligorov, 2017). Future experimental measurements measurements that would point to physics beyond the Standard Model include:

- Branching ratios and CP asymmetries that disagree with Standard Model predictions
- Modified mixing amplitudes and new CP violating phases
- Changes in observable phases that determine and would thus change Unitary Triangle measurements (such as ϕ_s)
- Values of ρ and η (the vertex coordinates of the Wolfenstein-parameterized Unitary Triangle) determined from B decay that disagree with those from K decay
- Values of ρ and η deduced from penguin loop-induced decays that disagree with CP asymmetries
- High, unexpected levels of forbidden and rare decays
- Decays to final states involving photons or leptons
- Large CP asymmetries in charged B decays
- Flavor-diagonal CP violation

Further CP violation measurements or the discovery of new sources of CP violation could support new models or extensions to the Standard Model, such as supergravity, grand-unified theories like supersymmetry, or the minimal supersymmetric extension to the Standard Model (MSSM). If future experimental measurements are inconsistent with those predicted by the Standard Model (e.g. a strong correlation between CP violation in $B \to \psi K_s$ and in $K_L \to \pi\nu\nu^-$, equal asymmetries in $B \to \psi K_s$ and $B \to \phi K_s$, small CP asymmetries in $B_s \to \psi\phi$), there may be several independent phases rather than just one independent phase as suggested by the CKM matrix Nir (2000). This would support models with a larger number of independent phases, such as the supersymmetric standard model that has forty-four independent phases. Even if no new phases are discovered, modifications to mixing and decay amplitudes that significantly change Unitary Triangle would violate unitarity as required by the Standard Model (Aaij et al., 2019). As such, experimental measurements of existing physical observables such as ϕ_s that deviate from values predicted by the Standard Model would be clear evidence for new physics .

Future B-physics experiments will be essential to discovering not only potential new phases but supersymmetric particles and new heavy particles through observing forbidden or rare decays. Rare decays such as $B^0 \to \phi K_s$ mediated by the $\bar{b} \to \bar{s}s\bar{s}$ may carry new weak phases in the presence of new physics; they could also show modified amplitudes and mass differences with contributions comparable to the size of the Standard Model (Particle Data Group et al., 2020). Rare decays of the most commonly produced b hadrons ($B^0(\bar{b}d)$, $B^+(\bar{b}u)$, and $B_s^0(\bar{b}s)$ mesons and their antiparticles) are an active field of flavor physics, the study of transitions of quarks or leptons of one species/flavor to another. These decays are very promising for identifying contributions from new hypothetical particles that are too heavy to be produced at colliders as previous observations of these dominant hadronic decays revealed a variety of exotic particles that do not fit conventional meson spectroscopy, such as the $\chi(3872)$ state from $B^+ \to J/\phi\pi^+\pi^-K^+$ (Koppenburg et al., 2016). Observations of rare decays may indeed reveal new particles that have only been theorized to exist.

New physics would also have significant implications for decays dominated by penguin contributions (*i.e.* decays mediated by the $\overline{b} \to \overline{q}q\overline{s}$ transition with $q = u, d, s$) as the contribution from penguin-mediated decays may be much larger than currently observed and/or anticipated by the Standard Model. Penguin-dominated decays, among other processes where the Standard Model predicts small levels of asymmetry, are thus an excellent area to search for indicators of new physics with high-sensitivity instrumentation (Krüger & Romão, 2000). All current measurements of penguin-dominated decays are consistent with the Standard Model prediction of the penguin contribution term being negligible. Combining methods based on flavor symmetries that allow limits to be obtained with next-generation instrumentation will thus be crucial to experimental verification of the level of suppression of penguin contributions observed in nature. Future experiments will have even larger data samples than that of current generations of LHCb and BaBar/Belle and will be more primed to study rare decays in which Standard Model amplitudes are suppressed, *i.e.* contributions from new physics could manifest as observable deviations from Standard Model predictions (Koppenburg et al., 2016).

With the precision of particle physics experiments continuing to improve significantly across various sectors, it is not unreasonable to expect discoveries of new CP violation sources. While B-physics is an extremely rich area to search for non-Standard Model physics because of the number of experimental observables, new CP violation may also be observed in other processes such as top-quark production and decay, neutrino oscillations, and Higgs boson decays (Particle Data Group et al., 2020). For example, observation of CP violation in the lepton sector would have significant implications for physics beyond the Standard Model. A CP-violating phase due to mixing in the lepton sector would indicate that neutrinos have mass as opposed to the mass-less neutrinos of the Standard Model and confirm predictions of a CP-violating phase in the lepton sector analogous to that in the quark sector as predicted by theories that consider non-vanishing neutrino masses. Future experiments DUNE and Hyper-Kamiokande will play an important role in the next decade of CP violation as they have the potential to confirm the predicted presence of CP violation in the lepton sector (Particle Data Group et al., 2020).

While the Standard Model anticipates certain processes such as CP violation in B-baryon decays or mixing-decay interference in the B_s^0 system, it is still to be determined whether Standard Model dynamics alone can explain more puzzling CP violating phenomena, such as the large asymmetries observed in regions of phase space for charmless three-body B decays (Gershon & Gligorov, 2017). Next-generation experiments such as the upgraded LHCb and Belle II bring the vast improvements to sensitivity and experimental precision required to decrease systematic uncertainties that, even without any new sources of CP violation, will lead to increasingly strong constraints on new physics. In addition to advances in instrumentation, strict control of theoretical uncertainties relevant to interpreting experimental CKM observables will be key to resolving discrepancies, however small, between theory and experiment. For example, global fits to the parameters of the CKM matrix by groups such as CKMFitter or UTFit Collaborations have established that Standard Model predictions of CP violation currently hold at the 5-10% level. More precise experimental measurements and tighter theoretical constraints in the near future aim to test the CKM paradigm in the Standard Model and flavor physics at the percent level (Gershon & Gligorov, 2017).

With future experiments that are poised to produce more precise measurements or new measurements of CKM observables that constrain the Unitary Triangle and test the Standard Model (*i.e.* whether the sum of Unitary Triangle angles equal 180°), the Unitary Triangle is a powerful tool with which to probe physics beyond the Standard Model and transform our understanding of CP-violating phenomena.

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