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CKM and CPV measurements in the beauty and charm sector

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Measurements of CKM elements and *CP*-violating observables are sensitive to revealing effects beyond the SM. These proceedings discuss four recent LHCb results. The first one presents *CP* violation measurements in B_s^0 decays. Tree-level measurements of the CKM angle γ are one of the most important tests of *CP* violation in the SM. Additionally, the second one presents the results of a recent analysis of $B^\pm \to [h'^+ h'^- \pi^+ \pi^-]_D h^\pm$ $(h = K, \pi)$. The third one discusses the combination of previous LHCb γ measurements except for the presented results. Achieved precision of the LHCb result: $(67 \pm 4)^\circ$ dominates the world average. Charm physics serves as a unique probe to test the flavor sector in the SM. The fourth one shows the search for *CP* violation in the multi-body D decays.

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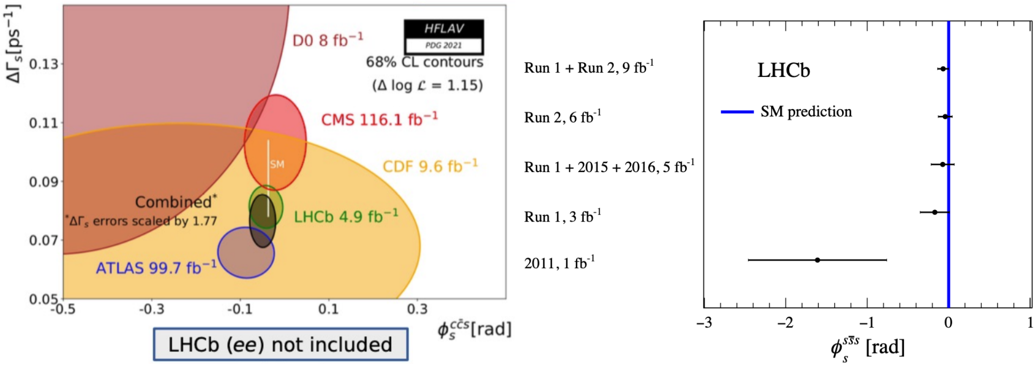

Figure 1: Confidence level contours [11] (left) of ATLAS, CMS, CDF, D0 and LHCb measurements [7–10], combined contour in a black solid line and shaded area, as well as the SM predictions in a very thin white rectangle. Comparison [12] (right) of $\phi_s^{s\bar{s}s}$ measurements from various analyses [13–15] by the LHCb collaboration. The vertical band indicates the SM prediction [16–18].

1. Introduction

The CKM matrix elements (denoted as V_{ij}) represent the strength of flavour-changing weak interactions [1]. Charge parity (*CP*) symmetry violation (*CP* violation) involves the phases of CKM elements [2, 3]. Many measurements of *CP*-violating observables serve to improve the determination of the CKM elements or to reveal effects beyond the Standard Model (SM). The unitarity of the CKM matrix can be checked. Deviation from the CKM unitarity can be a signal of new physics (NP) beyond the SM.

2. *CP* violation in B_s^0 decays

CP violation can originate from the interference of the decay amplitude and $\phi_s = -2\arg[-(V_{ts}V_{tb}^*)(V_{cs}V_{cb}^*)]$ can be predicted very precisely within the SM [4, 5] assuming no NP contributions, so any deviation would be a strong hint of some effects beyond the SM (BSM). Another physical quantity is the width difference. The width difference is predicted less precisely [6]. NP contribution also influences the width difference.

There are many measurements of ϕ_s from LHCb, ATLAS and CMS [7–10]. In LHCb, both same-side and opposite-side taggers are used, while in CMS and ATLAS, only the opposite-side tagger is utilized. The helicity basis for the angular definition is employed in LHCb, whereas the transversity basis for the angular definition is used for ATLAS and CMS. The flavor-tagged time-dependent angular analysis is performed for the signal extracted from the data by all three collaborations. The measurements from ATLAS [7], CMS [8], and LHCb [9, 10] are consistent with each other. The combined result is consistent with SM predictions, as shown in the left plot of Fig. 1.

Flavor-changing neutral current decays of B mesons are highly sensitive to NP. The $B_s^0 \to \phi\phi$ decay, which proceeds via a $b \to s\bar{s}s$ transition, is a benchmark channel. Time-dependent *CP* violation arises from the interference between the direct decay and the decay after B_s^0 and $\bar{B}_s^0$ mixing, which can be characterized by the phase $\phi_s^{s\bar{s}s}$ and the parameter $|\lambda|$, which is related to

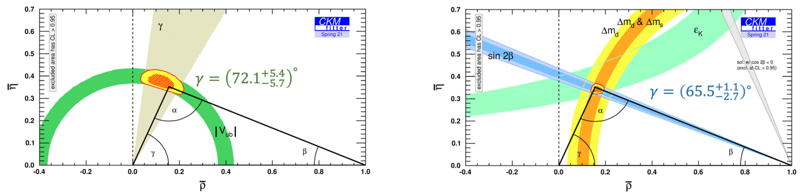

Figure 2: Comparison between direct measurements (left) of the CKM angle γ [19] and indirect measurements (right) of the CKM angle γ [4].

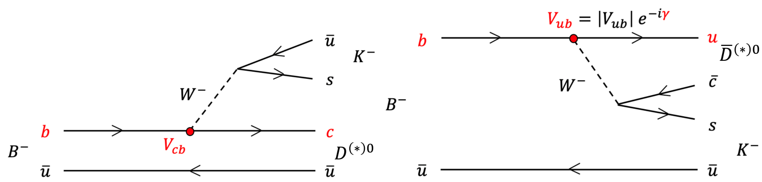

Figure 3: Description of the Feynman diagrams for the processes (left) $B^- \to D^{(*)0}K^-$ and (right) $B^- \to \bar{D}^{(*)0}K^-$.

direct *CP* violation [12]. NP contributions could significantly alter the values predicted by the SM. In addition, the final state has three polarization states, and NP may depend on the B_s^0 polarisation. The flavor-tagged time-dependent angular analysis is performed to measure $\phi_s^{s\bar{s}s} = -0.042 \pm 0.075$ and $|\lambda| = 1.004 \pm 0.030$, which is consistent with and supersedes the previous measurement [15], and agrees with the SM expectation, as shown in the right plot of Fig. 1.

3. Direct measurement of the CKM angle γ

Direct measurements of the angle $\gamma \equiv \arg[-V_{ud}V_{ub}^* V_{cd}V_{cb}^*]$ can be accessible at tree level and serve as benchmarks of the SM. Assuming no NP at tree level processes, the theoretical uncertainties are negligible in such direct measurements [19]. In indirect measurements, there are some inputs including loop processes, and the angle γ is obtained from the global fit to the unitary triangle, assuming a closed triangle. The comparison between direct measurements and indirect measurements is shown in the left and right plots in Fig. 2 [4]. Loop processes are expected to be sensitive to a possible BSM signature. A discrepancy between direct and indirect measurements would be a clear sign of NP.

The most powerful method for determining the angle γ in decays dominated by tree-level contributions utilizes the $B^\pm \to D^{(*)}K^\pm$ decays, where $D^{(*)}$ represents an admixture of the $D^{(*)0}$ and $\bar{D}^{(*)0}$ states. Fig. 3 shows the interference between $b \to c$ and $b \to u$ can give sensitivity to the angle γ [20]. Several methods are available to measure the angle γ using decays such as $B^\pm \to D^{(*)}K^\pm$. The GLW method considers decays of the D meson to *CP* eigenstates. The ADS approach requires Cabibbo-favored and doubly Cabibbo-suppressed (DCS) D decays. BPGGSZ utilizes D decays to self-conjugate final states, measuring the *CP* asymmetries over the phase space.

The first measurement of *CP* violation in the $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$ mode, where h is K or π, is presented [21]. It is the first measurements of the global *CP* asymmetries for this decay, and global measurements have been updated for the mode $B^\pm \to [\pi^+\pi^-\pi^+\pi^-]_D h^\pm$. The *CP* observables obtained from the phase space (PS) integrated measurements can be interpreted in terms of the angle

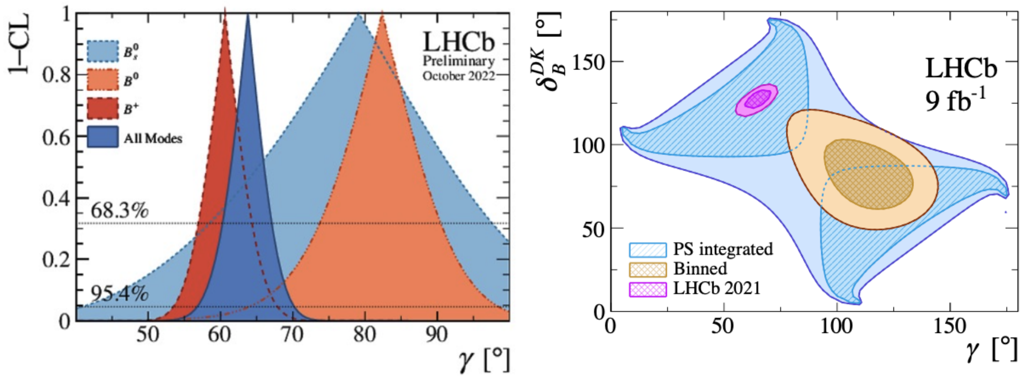

Figure 4: Combination (left) of the CKM angle γ determined in LHCb and the confidence level (right) of γ and δ_B^{DK} are shown, PS integrated results in the blue region and binned results in the brown region as well as LHCb 2021 results in the pink region.

γ and strong phase differences. The results are compatible with measurements using other decay channels and supersede the previous $B^\pm \to [\pi^+\pi^-\pi^+\pi^-]_D h^\pm$ measurement [22], as shown on the right in Fig. 4 with blue region.

The analysis is also performed in bins of PS, which are optimized for sensitivity to local *CP* asymmetries. The analysis requires external information on charm-decay parameters [23], which are currently taken from an amplitude analysis of LHCb data but can be updated in the future when direct measurements become available. That will allow the *CP*-violating observables to be determined in a model-independent fashion. A model-dependent value of $(116 \pm 12)^\circ$ is obtained. This result will be updated when the observables are re-evaluated using model-independent inputs. The precision is limited by the sample size and is expected to improve with future data from LHCb, as shown on the right in Fig. 4 with brown region.

The combination of measurements of the angle γ is updated, including two new measurements related to B decays published by the LHCb in 2022 such as $B^\pm \to [K^\mp\pi^\pm\pi^\pm\pi^\mp]_D h^\pm$ [24], $B^\pm \to [h^\pm h'^\mp\pi^0]_D h^\pm$ [25] modes, as well as updates in the charm sector [26]. The determined value $(63.8^{+3.5}_{-3.7})^\circ$, as shown in Fig. 4 (left), is compatible with the previous LHCb combination [23], $(65.4^{+3.8}_{-4.2})^\circ$, and in excellent agreement with the global CKM fit predictions [4]. This is the most precise determination of the angle γ from a single experiment [26].

4. *CP* violation in charm sector

The charm sector offers a unique probe to the up-type sector which is important on its own as well as complementary to searches in the strange and beauty sector. The asymmetries from the CKM matrix elements responsible for *CP* violation in charm decays are typically of the order of $10^{-4} - 10^{-3}$ in the SM [27–31]. In the charm quark sector, the recent observation of *CP* violation has stimulated a wide discussion. The discovery used the difference of *CP* asymmetries in $D \to K^-K^+$ and $D \to \pi^-\pi^+$ decays [32]. Further precise measurements are necessary and may resolve the theoretical debate on whether the observed value is consistent with the SM. For DCS decays, *CP* violation is highly suppressed within the SM [30, 33, 34], thus its observation would indicate a manifestation of physics beyond the SM. Direct *CP* violation occurs when a given final state is produced through amplitudes with different weak phases, while the presence of different strong phases is also required. Final states are mainly reached via resonances in multi-body charm decays, providing an important source of strong-phase differences that vary across the two-dimensional Dalitz plot. This feature can enhance the sensitivity to *CP* asymmetries. The model-independent method is used for two multi-body D decay measurements. Comparing the Dalitz distributions of D^0 and $\bar{D}^0$ meson decays provides a sensitive search for *CP* violation within the phase space of these decays.

For the $D^0 \to \pi^-\pi^+\pi^0$ decay, the unbinned model-independent method is used [35]. The test quantifies localized sample differences, which can be converted into a p-value by comparing the nominal result to the distribution expected under the null hypothesis. The p-value is given, providing no indication of any *CP* violation in localized regions of the phase space. This measurement confirms that potential nuisance asymmetries can be neglected for data corresponding to Run I and II statistics.

A search for direct *CP* violation in the Cabibbo-suppressed decay $D_s^+ \to K^-K^+K^+$ and in the doubly Cabibbo-suppressed decay $D^+ \to K^-K^+K^+$ is reported [36]. The binned model-independent method is used. A variation of the origin *Miranda* technique [37, 38] is applied, dividing the PS in two-dimensional bins and computing the significance of the difference in the number of $D^+_{(s)}$ and $D^-_{(s)}$ candidates. A two-sample χ^2 test is performed on the $D^+_{(s)}$ and $D^-_{(s)}$ samples. The resulting p-value from this test is defined as the probability of obtaining a test variable that is at least as high as the value observed, under the assumption of *CP* conservation. The results are given as p-values with respect to the null hypothesis of *CP* conservation. They are found to be 13.3% for the $D_s^+ \to K^-K^+K^+$ channel and 31.6% for the $D^+ \to K^-K^+K^+$ channel. The results are consistent with the hypothesis of no localized *CP* violation in either channel. No evidence of *CP* violation is found. This is the first search for *CP* violation in the Cabibbo-suppressed channel $D_s^+ \to K^-K^+K^+$ and in the doubly Cabibbo-suppressed channel $D^+ \to K^-K^+K^+$.

5. summary

The measurements of ϕ_s by ATLAS, CMS and LHCb are in agreement with the SM. Results based on decays with electrons in the final state are an important crosscheck.

The $\phi_s^{s\bar{s}s}$ measurement is consistent with and supersedes the previous measurement, and agrees with the SM expectation of a tiny *CP* violation.

The direct measurement of the angle γ in B decays improves precision, with an uncertainty smaller than 4°. The precision will be further improved with other decay modes and more knowledge of charm hadronic parameters.

The first search for *CP* violation in the Cabibbo-suppressed channel $D_s^+ \to K^-K^+K^+$ and in the doubly Cabibbo-suppressed channel $D^+ \to K^-K^+K^+$ has been presented. The results are consistent with the hypothesis of no localized *CP* violation in either channel. There is also a new search of *CP* violation in the charm sector such as $D \to \pi\pi\pi^0$ channel with results being consistent with no *CP* violation hypothesis.

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