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Search for new physics in CP violation with beauty and charm decays at LHCb

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The LHCb detector is one of the four large experiments collecting data at the LHC and is optimally designed to study Charge-Parity (CP) violation in beauty and charm hadrons. The LHCb collaboration has recently reported results from $B_s^0 \to K^+K^-$ decays which show 4.0σ evidence for time-dependent CP violation in the B_s^0 sector and measurements of the unitarity triangle angle γ from $B_s^0 \to D_s^{\mp}K^{\pm}$ decays, which are consistent with global fits from LHCb at 7 and 8 TeV. Measurements of CP violation in both $B^- \to D_{(s)}^- D^0$ and $D^0 \to K^-\pi^+$ decays at 7 and 8 TeV show no evidence of CP violation while a combined measurement of ΔA_{CP}^{wgt} from $\Lambda_c^+ \to ph^+h^-$ at 7, 8 and 13 TeV is also consistent with the hypothesis of CP conservation.

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1. Introduction

When we look around it is apparent that there is a difference between matter and antimatter; we live in a matter dominated universe even though the Big Bang predicts equal quantities of matter and antimatter to be produced. In the 1960's Sakharov proposed three rules that must be fulfilled to explain this asymmetry, known as the Sakharov conditions. They are [1]:

1. Baryon Number Violation
2. Charge-Parity (CP) Violation
3. For these above conditions to occur outside thermal equilibrium

The Large Hadron Collider beauty (LHCb) experiment is a forward arm spectrometer located at the Large Hadron Collider (LHC). It is optimised to study particles containing b and c quarks by covering a pseudorapidity of $2 < \eta < 5$ [2]. While LHCb covers approximately 2 % of the solid angle, this area contains approximately 27 % of the b-quarks produced around LHCb. Achieving the aim of the LHCb physics program requires both precise vertex knowledge and excellent particle identification. The former is achieved through the vertex locator (VELO) that surrounds the interaction region with it's closest active region at only 8.2 mm from the beam. This allows for excellent vertex resolution, with a mean resolution down to approximately 12 μm [3]. The latter is achieved via two ring imaging Cherenkov detectors while are capable of particle identification; specifically identification of pions, kaons, proton, electrons and muons [4].

2. Neutral Meson Oscillations and CP Violation in the Standard Model

Neutral mesons are allowed to oscillate between particles and antiparticles so long as there is a difference between their mass eigenstates, where the mass difference will dictate the oscillation period. The heavy and light mass eigenstates ($|P_H\rangle$ and $|P_L\rangle$ respectively) exist as linear superposition's of the weak eigenstates ($|P^0\rangle$ and $|\bar{P}^0\rangle$)

$$|P_H\rangle = p|P^0\rangle + q|\bar{P}^0\rangle \tag{2.1}$$
$$|P_L\rangle = p|P^0\rangle - q|\bar{P}^0\rangle \tag{2.2}$$

where p and q are complex amplitudes. The oscillation period has been measured to be 661^{+285}_{-306} ps for D^0 mesons [5], 12.41 ± 0.05 (syst.) $\pm$ 0.02 (stat.) ps for B^0 mesons [6] and 353.6 ± 0.5 (syst.) $\pm$ 0.1 (stat.) fs for B^0_s mesons [7].

There are three types of CP violation allowed. The first is when the ratio of the complex amplitudes, p and q is not equal to one. This would describe CP violation present in the oscillation (also known as *CP violation in the mixing*). The second type of CP violation occurs in the decay of particles, when the decay rate of a particle to a final state, f, is not the same as its CP conjugate decay. The decay amplitudes are given by

$$A_f = \langle f|\hat{H}|P^0\rangle \tag{2.3}$$
$$\bar{A}_{\bar{f}} = \langle \bar{f}|\hat{H}|\bar{P}^0\rangle. \tag{2.4}$$

Thus if the ratio of A_f and $\bar{A}_{\bar{f}}$ was not one then this indicates CP violation is occurring in the decay of particles. The third type of CP violation arises from the quantum interference between the mixing and the decay.

The CP asymmetry, A_{CP}, can be measured from the difference between the decay rates for a particle and its charge conjugate [8]

$$A_{\text{CP}} = \frac{\Gamma[\bar{P} \to \bar{f},t] - \Gamma[P \to f,t]}{\Gamma[\bar{P} \to \bar{f},t] + \Gamma[P \to f,t]} = \frac{S_f \sin(\Delta mt) - C_f \cos(\Delta mt)}{\cosh\left(\frac{\Delta\Gamma}{2}t\right) - A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma}{2}t\right)} \tag{2.5}$$

where C_f describes CP violation in the decay while S_f and $A_f^{\Delta\Gamma}$ describe CP violation in the interference.

The Cabibbo-Kobayashi-Maskawa (CKM) matrix describes the connection between the mass and weak eigenstates for the down-type quarks and also indicates the coupling probabilities between different generations of up-type and down-type quarks. The CKM matrix is given in its Wolfenstein parametrisation as [9]

$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4). \tag{2.6}$$

The CKM matrix contains a complex phase which allows CP violation in the Standard Model, however the amount allowed differs from the measured baryon density by ten orders of magnitude [10, 11]. The matrix can be represented as a set of Argand diagrams known as the unitarity triangles. As the angles of these triangles should be theoretically well known, precision measurements of different decays will place tight constraints on them and could reveal the presence of new physics. The least well known unitarity triangle angle is γ which is parametrised as

$$\bar{\rho} + i\bar{\eta} = \frac{|V_{ud}V_{ub}^*|}{|V_{cd}V_{cb}^*|} e^{i\gamma} \tag{2.7}$$

where $[\bar{\rho}/\bar{\eta}] = [\rho/\eta](1-\lambda^2/2)$.The current LHCb measurement on γ is $(76.8^{+5.1}_{-5.7})^\circ$ [12]. The LHCb determination of γ from different b-meson decays that contribute to the current measurements can be seen in Figure 1.

3. CP Violation in the Beauty Sector

In the beauty sector, there are two neutral mesons; the B^0 $(\bar{b}d)$ and the B_s^0 $(\bar{b}s)$. Both of these mesons undergo mixing and CP violation has been established for both of them [13, 14, 15]. LHCb has recently released measurements of CP violation in the decay of neutral b-mesons in 5 channels; $B_s^0 \to K^+K^-$, $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, $B_s^0 \to \pi^+K^-$[16] and $B_s^0 \to D_s^{\mp}K^{\pm}$[17] at a centre of mass energy 7 and 8 TeV recorded in 2011 and 2012 respectively.

The $B_s^0 \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ decay spectra can suffer from large contaminations from $B^0 \to K^+\pi^-$ decays, thus tight particle identification (PID) requirements are imposed using information from the RICH detectors to reduce this. $B_s^0 \to D_s^{\mp}K^{\pm}$ decays can also have large contribution from $B_s^0 \to D_s^{\mp}\pi^{\pm}$ and $B_s^0 \to D_s^{(*)\mp}K^{(*)\pm}$ decays which are reduced by imposing tight

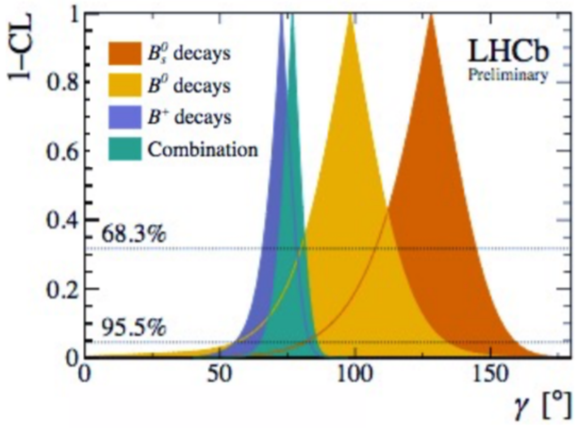

Figure 1: Confidence limits on the LHCb determination of the unitarity triangle angle γ from different b-meson decays with 1 and 2 σ limits. Orange is the determination from B_s^0 decay, mustard is the determination from B^0 decays, blue is the determination from $B^{\pm}$ decays and cyan is the combined determination [12].

Channel	S_f	C_f	$A_f^{\Delta\Gamma}$
$B^0 \to \pi^+\pi^-$	-0.63 ± 0.05 (stat.) ± 0.01 (syst.)	-0.34 ± 0.06 (stat.) ± 0.01 (syst.)	-
$B_s^0 \to K^+K^-$	0.18 ± 0.06 (stat.) ± 0.02 (syst.)	0.20 ± 0.06 (stat.) ± 0.2 (syst.)	-0.79 ± 0.07 (stat.) ± 0.10 (syst.)
$B_s^0 \to D_s^- K^+$	-0.52 ± 0.20 (stat.) ± 0.07 (syst.)	0.73 ± 0.14 (stat.) ± 0.05 (syst.)	0.39 ± 0.28 (stat.) ± 0.15 (syst.)
$B_s^0 \to D_s^+ K^-$	-0.49 ± 0.20 (stat.) ± 0.07 (syst.)	-0.73 ± 0.14 (stat.) ± 0.05 (syst.)	0.31 ± 0.28 (stat.) ± 0.15 (syst.)

Table 1: Measured asymmetry parameters from $B^0 \to \pi^+\pi^-$, $B_s^0 \to K^+K^-$, $B_s^0 \to D_s^+K^-$ and $B_s^0 \to D_s^-K^+$ decays.

PID and invariant mass requirements respectively. The combinatorial background contribution is affected by decays that do not contain a true $D_s^{\mp}$ decay so the invariant mass distribution is performed via a multivariate fit to the $D_s^{\mp}K^{\pm}$ invariant mass, $D_s^{\mp}$ mass and log-likelihood separation of the pion and kaon hypothesis for the companion kaon. The measured asymmetries for $B^0 \to \pi^+\pi^-$, $B_s^0 \to K^+K^-$, $B_s^0 \to D_s^+K^-$and $B_s^0 \to D_s^-K^+$ are given in Figure 2 and Table 1. The resultant fit to $B_s^0 \to K^+K^-$ gives 4.0σ evidence for time-dependent CP violation in the B_s^0 sector while γ from $B_s^0 \to D_s^{\mp}K^{\pm}$ decays was measured to be $\gamma = (128^{+17}_{-22})^{\circ}$ is compatible at 2.8σ with the combined LHCb measurement [12].

A measurement of direct CP violation in charged b-mesons ($b\bar{u}$) was recently released for the decay channel $B^- \to D^-_{(s)}D^0$ [18]. The raw asymmetry is given from the difference in yields, i.e.

$$A_{\text{raw}} = \frac{\mathrm{N}(f) - \mathrm{N}(\bar{f})}{\mathrm{N}(f) + \mathrm{N}(\bar{f})} = A_{\text{CP}} + A_{\text{P}} + A_{\text{D}} \tag{3.1}$$

where $A_{\text{P/D}}$ is the production/detection asymmetry. There is a different production cross section for B^+ and B^- at hadron colliders while the main contribution to the detection asymmetry comes from the different interaction cross sections for $K^{\pm}$ though there are extra contributions from the track reconstruction, trigger and PID efficiencies. A_{P} + A_{D} was measured to be $(-1.4 \pm 0.05)\%$ and $(-0.3 \pm 0.04)\%$ for $B^- \to D_s^- D^0$ and $B^- \to D^- D^0$ decays respectively. The measured yields in the final states are given in Table 2 with a resulting CP asymmetry of (-0.4 ± 0.5 (stat.) ± 0.5 (syst.))%

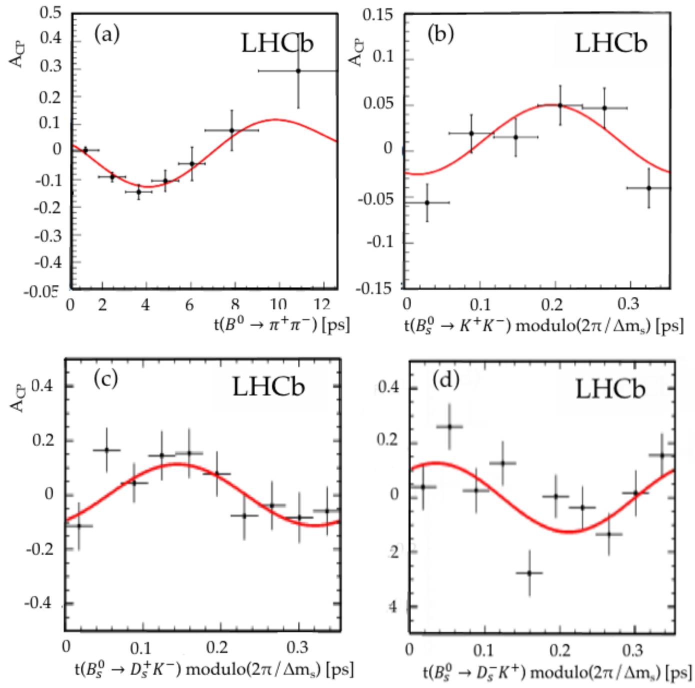

Figure 2: Asymmetry distributions for (a) $B^0 \to \pi^+\pi^-$, (b) $B_s^0 \to K^+K^-$, (c) $B_s^0 \to D_s^+K^-$ and (d) $B_s^0 \to D_s^-K^+$.

Channel	$N(B^-)$	$N(B^+)$
$B^- \to D_s^- D^0$	21375 ± 165	22153 ± 168
$B^- \to D^- D^0$	1046 ± 40	1005 ± 39

Table 2: Measured yields for the four final states; $B^- \to D_s^- D^0$, $B^+ \to D_s^+ \bar{D}^0$, $B^- \to D^- D^0$ and $B^+ \to D^+ \bar{D}^0$ [18].

and $(2.3 \pm 2.7\ (\text{stat.}) \pm 0.4\ (\text{syst.}))\%$ for $B^- \to D_s^- D^0$ and $B^- \to D^- D^0$ decays respectively. This is consistent with the hypothesis of CP conservation in these channels.

4. CP Violation in the Charm Sector

LHCb has also reported on measurements of CP violation searches in the decay $D^0 \to K^\mp\pi^\pm$ using data collected at 7, 8 & 13 TeV [19]. It is possible for a D^0 to decay to a Cabibbo-favoured $K^-\pi^+$ (*right-sign*) or a doubly-Cabibbo-suppressed $K^+\pi^-$ (*wrong-sign*) final state. It has been well established that D^0 mesons can undergo mixing [20, 21, 22] so the time-dependent ratio of right-sign to wrong-sign decays, $R_D^\pm(t)$, can increase as particles tagged as $\overset{(-)}{D}{}^0$ at production can oscillate and decay to their Cabibbo favoured modes. $R_D^\pm(t)$ can be expanded, giving terms to describe CP violation in the decay, mixing and interference [23]

$$R_D^\pm(t) \approx R_D^\pm + \sqrt{R_D^\pm y'^\pm}\,\frac{t}{\tau} + \frac{(x'^\pm)^2 + y'^\pm)^2}{4}\left(\frac{t}{\tau}\right)^2 \tag{4.1}$$

where

$$x'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1}\left(\left[\frac{\Delta m}{\Gamma}\cos\delta + \frac{\Delta\Gamma}{2\Gamma}\sin\delta\right]\cos\phi \pm \left[\frac{\Delta\Gamma}{2\Gamma}\cos\delta - \frac{\Delta m}{\Gamma}\sin\delta\right]\sin\phi\right) \tag{4.2}$$

$$y'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1}\left(\left[\frac{\Delta m}{\Gamma}\cos\delta + \frac{\Delta\Gamma}{2\Gamma}\sin\delta\right]\sin\phi \mp \left[\frac{\Delta\Gamma}{2\Gamma}\cos\delta - \frac{\Delta m}{\Gamma}\sin\delta\right]\cos\phi\right) \tag{4.3}$$

δ is the strong phase difference and ϕ is the phase difference between the mixing and decay amplitudes. The CP asymmetry is taken from the difference in the right-to-wrong side ratios between $\bar{D}^0$ and D^0 decays, thus the first term in equation 4.1 will describe direct CP violation, the second term will describe CP violation in the interference and the third will describe CP violation in the mixing. The measured yield was 1.77×10^8 right-sign and 7.22×10^5 wrong-sign decays. The time dependent results can be seen in Figure 3 while A_{CP} was measured to be $(-0.1 \pm 9.1) \times 10^{-3}$ which is consistent with no CP violation in D^0.

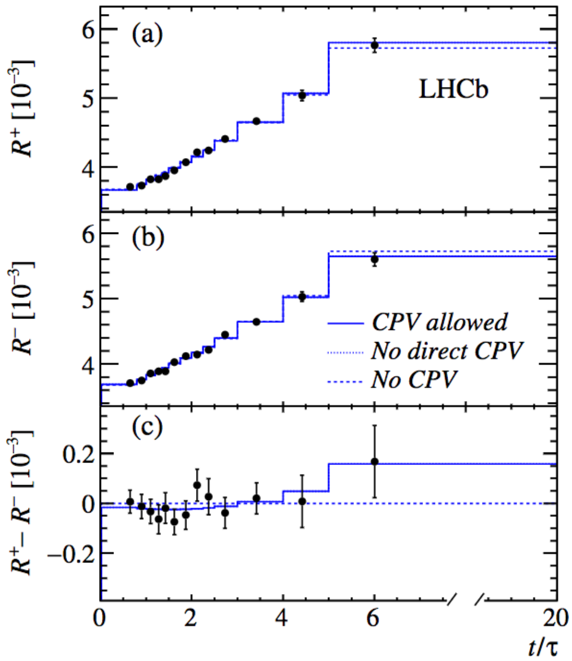

Figure 3: Results of the fit to the time dependant right-to-wrong side ratio of $D^0 \to K^-\pi^+$ decays. (a) The time-dependent wrong-to-right sign ratio for decays from a D^0 at production, (b) The time-dependent wrong-to-right sign ratio for decays from a $\bar{D}^0$ at production and (c) the asymmetry between the two ratios. The error bars include the statistical uncertainty only[19].

Finally, LHCb has released results on the search for CP violation in charm baryons [24] at 7 and 8 TeV. If CP violation is allowed here, it is believed to be measurable in the difference between two final states. Thus, a non-zero difference in the CP asymmetries, ΔA_{CP} would indicate the presence of CP violation. This method also helps in reducing systematic errors. ΔA_{CP} was measured as the difference between $\Lambda_c^+ \to pK^-K^+$ and $\Lambda_c^+ \to p\pi^-\pi^+$ decay channels. A kinematic reweighting of pseudorapidity and transverse momentum was performed on the $p\pi^-\pi^+$ sample and, as there is no mixing in Λ_c^+, the proton charge was used to tag the flavour of the mother. This results in a final measurement of the parameter ΔA_{CP}^{wgt}. The data sample was split into subsamples by their centre-of-mass energy and magnet polarity with the results presented in Figure 4. ΔA_{CP}^{wgt} was measured to be $(0.30 \pm 0.91\ (\text{stat.}) \pm 0.61\ (\text{syst.}))\%$ which is consistent with the hypothesis of CP conservation in charm baryons.

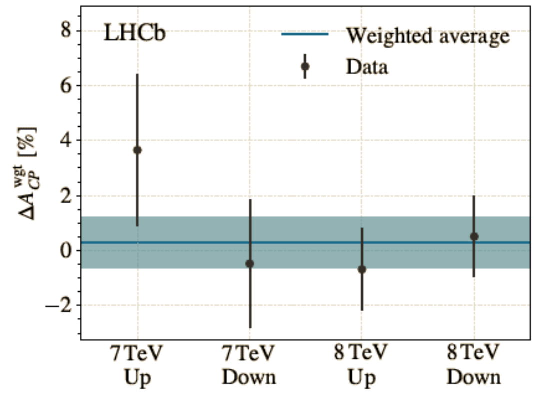

Figure 4: Measurements of ΔA_{CP}^{wgt} from $\Lambda_c^+ \to p[K/\pi]^-[K/\pi]^+$ decays in subsamples split by their centre-of-mass energy and magnet polarity[24].

5. Conclusion

The LHCb collaboration has recently reported studies of $D^0 \to K^-\pi^+$, $B^- \to D_{(s)}^- D^0$ and Λ_c^+ decays, none of which show any evidence for CP violation. Measurements of γ from $B_s^0 \to D_s^- K^+$ show it to be consistent with the combined LHCb measurement at the level of 2.8σ while there is 4.0σ evidence for time-dependent CP violation from $B_s^0 \to K^+K^-$ decays. Many of the reported channels were studied using Run I data collected at the LHC with updates under study using Run II data where many statistically limited analyses will benefit from the increased data samples available.

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