CP violation in the *B* system at LHCb

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A selection of recent LHCb results on *CP* violation in the *B* system is presented. These include direct *CP* violation measurements in $B^0 \to \phi K^*(892)^0$, $B^0_{(s)} \to K^\pm\pi^\pm$, $B^\pm \to K^\pm\pi^+\pi^-$, $B^\pm \to K^\pm K^+K^-$ and $B^\pm \to \phi K^\pm$ decays; time-dependent *CP* violation measurements in $B^0_s \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ decays; determination of the flavour-specific *CP*-violating asymmetry a^s_{sl} in B^0_s decays; and study of the mixing-induced *CP* violation in $B^0_s \to J/\psi K^+K^-$ and $B^0_s \to J/\psi\pi^+\pi^-$ decays.

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1 Introduction.

A selection of recent LHCb[1] measurements on *CP* violation and related results in the *B* system is presented. Unless otherwise explicitly stated, all measurements reported here are based on the analysis of a data sample corresponding to 1.0 fb^{-1} of integrated luminosity from *pp* collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. The inclusion of charge-conjugate decay modes is implied throughout.

2 Direct *CP* violation.

Direct *CP* violation occurs when the decay rate of a B meson to a final state f differs from the decay rate of the $\overline{B}$ antimeson to the *CP*-conjugate final state $\bar{f}$. We start this section reporting recent measurements in the $B^0 \to \phi K^*(892)^0$ decay, and continue with a summary of results on *CP*-violating asymmetries in several two-body and three-body charmless B decays.

2.1 Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$.

The measurement of observables related to *CP* violation in the decay $B^0 \to \phi K^*(892)^0$, which proceeds in the Standard Model (SM) mainly through a gluonic penguin, is a sensitive probe for contributions from new physics in the loop. Since this decay involves two spin-1 vector mesons ($B \to VV$), an angular analysis is needed to distinguish the three independent configurations of the final-state spin vectors: a longitudinal component where in the B^0 rest frame both resonances are polarized in their direction of motion, and two transverse components with collinear and orthogonal polarizations.

The angular analysis reported in Ref.[2] is performed in terms of three helicity angles $(\theta_1, \theta_2, \Phi)$, where θ_1 (θ_2) is defined as the angle between the K^+ direction and the reverse of the B^0 direction in the K^{*0} (ϕ) rest frame, and Φ is the angle between the decay planes of the ϕ and K^{*0} mesons in the B^0 rest frame. To determine the polarization amplitudes, the B^0 and $\bar{B}^0$ decays are combined. In addition to the three dominant vector-vector (P-wave) amplitudes, contributions

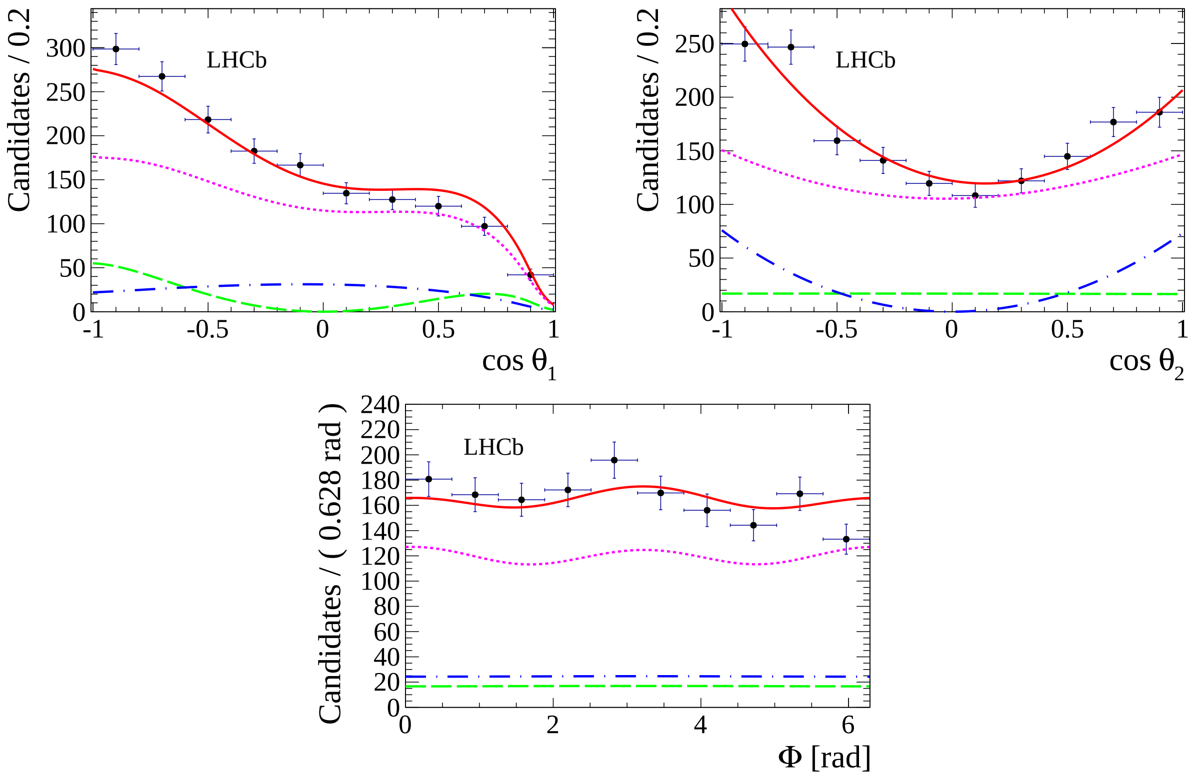

Figure 1 – Background-subtracted data distributions for the helicity angles in $B^0 \to \phi K^*(892)^0$ decays with the different fit components superimposed. The dashed-dotted blue line is the $K\pi$ S-wave, the dashed-green line is the KK S-Wave, the dotted purple line is the P-wave and solid red line is the overall fit.

where either the K^+K^- or the $K^+\pi^-$ pair is produced in a spin-0 (S-wave) state are also taken into account. Fig. 1 shows the background-subtracted data distributions for the helicity angles.

The measured polarization fractions are[a] $f_{\rm L} = 0.497 \pm 0.019 \pm 0.015$, $f_\perp = 0.221 \pm 0.016 \pm 0.013$, $f_{\rm S}(K\pi) = 0.143 \pm 0.013 \pm 0.012$, and $f_{\rm S}(KK) = 0.122 \pm 0.013 \pm 0.008$. The results for the P-wave polarization fractions are consistent with the presence of a large transverse component. A significant S-wave contribution is also observed. For the CP asymmetries (A_{CP}) the flavour of the decaying B^0 meson is determined by the charge of the kaon from the K^{*0} decay. Instrumental and production asymmetries are corrected for using as a control channel the $B^0 \to J/\psi K^{*0}$ decay, where A_{CP} is assumed to be zero, therefore $A_{CP}(\phi K^{*0}) - A_{CP}(J/\psi K^{*0}) \approx A_{CP}(\phi K^{*0})$. The final result is $A_{CP}(\phi K^{*0}) = (+1.5 \pm 3.2 \pm 0.5)\%$, which is consistent with zero asymmetry, in agreement with Babar[3] and Belle[4] results, but a factor two more precise.

2.2 CP violation in $B \to K\pi$ decays.

LHCb has performed the first measurement of CP violation in the B_s^0 meson system[5]. Direct CP violation in $B_s^0 \to K^-\pi^+$ decays is measured to be $A_{CP}(B_s^0 \to K^-\pi^+) = 0.27 \pm 0.04 \pm 0.01$, with a significance exceeding five standard deviations. An improved determination of direct CP violation in $B^0 \to K^+\pi^-$ decays is also performed, giving a value of $A_{CP}(B^0 \to K^+\pi^-) = 0.080 \pm 0.007 \pm 0.003$, which is the most precise measurement of this quantity to date. These results allow a stringent test of the validity of the relation between $A_{CP}(B^0 \to K^+\pi^-)$ and $A_{CP}(B_s^0 \to K^-\pi^+)$ in the SM based on arguments of approximate flavour symmetry[6]

$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} \frac{\tau_d}{\tau_s} = 0. \qquad (1)$$

[a] Unless otherwise stated, all results reported in this paper are quoted with the statistical uncertainty followed by the systematic uncertainty.

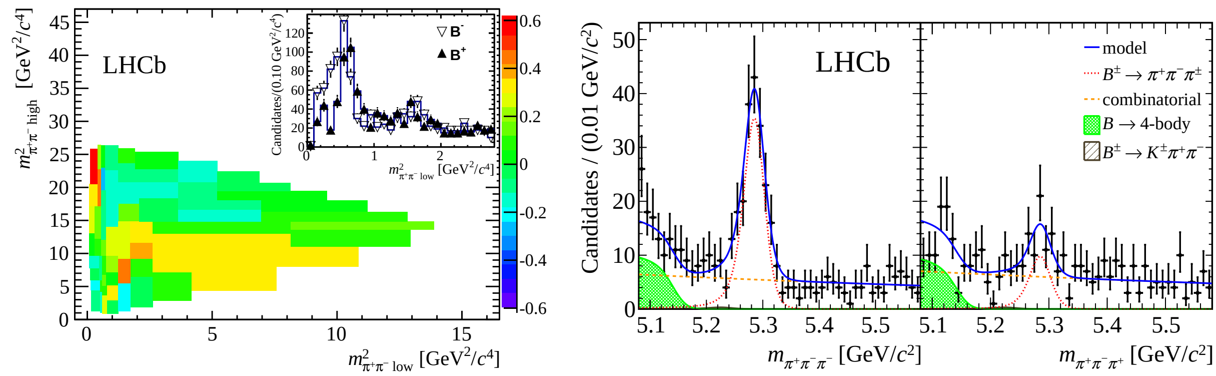

Figure 2 – Asymmetries of the number of events in bins of the Dalitz plot for $B^\pm \to \pi^+\pi^-\pi^\pm$ decays (left), and invariant mass spectra in selected regions of large asymmetries. The inset figure shows the projection of the number of events in bins of the $m^2_{\pi^+\pi^-\mathrm{low}}$ variable for $m^2_{\pi^+\pi^-\mathrm{high}} > 15$ GeV$^2/c^4$.

Using *CP*-averaged branching fractions[7] and the world averages for the B^0 and B^0_s mean lifetimes, the result obtained is $\Delta = -0.02 \pm 0.05 \pm 0.04$, where the first uncertainty is from the measurements of the *CP* asymmetries and the second is from the input values of the branching fractions and the lifetimes. No evidence for a deviation from zero of Δ is observed with the present precision.

2.3 CP violation in the phase space of three-body charmless B decays.

Inclusive charge asymmetries were measured in the three-body charmless decays $B^\pm \to K^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+ K^-$. The results are[8] $A_{CP}(B^\pm \to K^\pm\pi^+\pi^-) = 0.032 \pm 0.008 \pm 0.004 \pm 0.007\,(J/\psi K^\pm)$ and $A_{CP}(B^\pm \to K^\pm K^+ K^-) = -0.043 \pm 0.009 \pm 0.003 \pm 0.007\,(J/\psi K^\pm)$, where the third uncertainty is due to the *CP* asymmetry of the $B^\pm \to J/\psi K^\pm$ reference mode[9]. The significance of $A_{CP}(B^\pm \to K^\pm K^+ K^-)$ exceeds three standard deviations, yielding the first evidence of an inclusive *CP* asymmetry in charmless three-body decays. Large *CP* asymmetries are also observed in localized regions of the phase space outside resonances.

The analysis of the charmless decays $B^\pm \to K^+K^-\pi^\pm$ and $B^\pm \to \pi^+\pi^-\pi^\pm$ reported in Ref.[10] determines the inclusive *CP* asymmetries to be $A_{CP}(B^\pm \to K^+K^-\pi^\pm) = -0.141 \pm 0.040 \pm 0.018 \pm 0.007\,(J/\psi K^\pm)$ and $A_{CP}(B^\pm \to \pi^+\pi^-\pi^\pm) = 0.117 \pm 0.021 \pm 0.009 \pm 0.007\,(J/\psi K^\pm)$. The left plot of Fig. 2 shows asymmetries in the number of events in bins of the Dalitz plot for $B^\pm \to \pi^+\pi^-\pi^\pm$ decays. Large asymmetries are clearly visible in the localized region of phase space defined by $m^2_{\pi^+\pi^-\mathrm{high}} > 15$ GeV$^2/c^4$ and $m^2_{\pi^+\pi^-\mathrm{low}} < 0.4$ GeV$^2/c^4$. The regional asymmetry is measured to be $A^{\mathrm{reg}}_{CP}(B^\pm \to \pi^+\pi^-\pi^\pm) = 0.584 \pm 0.082 \pm 0.027 \pm 0.007\,(J/\psi K^\pm)$.

2.4 Charge asymmetry in $B^\pm \to \phi K^\pm$ and search for $B^\pm \to \phi\pi^\pm$ decays.

The $B^\pm \to \phi K^\pm$ decay can only occur through loop diagrams in the SM, leading to a branching fraction of the order of 10^{-5}. Because the dominant amplitudes have similar weak phases, the *CP*-violating charge asymmetry $A_{CP}(B^\pm \to \phi K^\pm)$ is predicted to be very small in the SM, around 1-2%. The measurement of a significantly larger value would signal interference with an amplitude not described in the SM. We have just seen that large *CP* violation effects are reported in some regions of the $B^\pm \to K^+K^-K^\pm$ phase space, but not around the ϕ resonance. LHCb has measured[11] the *CP*-violating charge asymmetry in $B^\pm \to \phi K^\pm$ decays to be $A_{CP}(B^\pm \to \phi K^\pm) = 0.022 \pm 0.021 \pm 0.009$. In addition, a search for the highly suppressed $B^\pm \to \phi\pi^\pm$ decay mode has been performed, using the $B^\pm \to \phi K^\pm$ decay rate for normalization. An upper limit on the branching fraction $\mathcal{B}(B^\pm \to \phi\pi^\pm) < 1.5 \times 10^{-7}$ is set at a 90% confidence level.

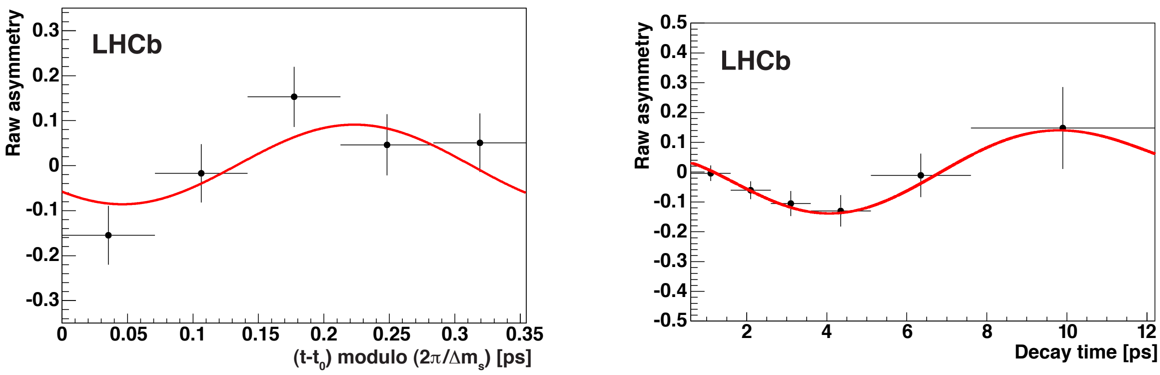

Figure 3 – Time-dependent raw asymmetry for candidates in the signal mass window for $B_s^0 \to K^+K^-$ decays (left) and $B^0 \to \pi^+\pi^-$ decays (right).

2.5 Time-dependent CP violation in $B_s^0 \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ decays.

Assuming *CPT* invariance, the time-dependent *CP* asymmetry for neutral *B* mesons decaying to a *CP* eigenstate *f* is given by

$$\mathcal{A}(t) = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) - A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}, \tag{2}$$

where $\Delta m_{d(s)} = m_{d(s),\mathrm{H}} - m_{d(s),\mathrm{L}}$ and $\Delta\Gamma_{d(s)} = \Gamma_{d(s),\mathrm{H}} - \Gamma_{d(s),\mathrm{L}}$ are the mass and width differences of the $B^0_{(s)} - \bar{B}^0_{(s)}$ system mass eigenstates. The subscripts H and L denote the heaviest and lightest of these eigenstates, respectively. The terms C_f and S_f parameterize direct and mixing-induced *CP* violation, respectively.

In Ref.[12] LHCb reported the first measurement of time-dependent *CP* violation in $B_s^0 \to K^+K^-$ decays. The results are $C_{KK} = 0.14 \pm 0.11 \pm 0.03$ and $S_{KK} = 0.30 \pm 0.12 \pm 0.04$. The corresponding quantities are also determined for $B^0 \to \pi^+\pi^-$ decays to be $C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$ and $S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$, in good agreement with existing measurements. The significances for (C_{KK}, S_{KK}) and $(C_{\pi\pi}, S_{\pi\pi})$ to differ from $(0,0)$ are determined to be 2.7σ and 5.6σ, respectively. The time-dependent raw asymmetries are shown in Fig. 3.

3 Mixing and mixing-induced *CP* violation.

3.1 Flavour-specific CP-violating asymmetry a_{sl}^s in B_s^0 decays.

The *CP*-violating asymmetry in semileptonic B_s^0 decays to a flavour-specific final state *f* is given by $a_{sl}^s = \frac{\Delta\Gamma}{\Delta M} \tan\phi_{12}$, where the phase $\phi_{12} \equiv \arg(-M_{12}/\Gamma_{12})$ is related to the off-diagonal elements of the effective hamiltonian which describes the B_s^0-mixing, while ΔM and $\Delta\Gamma$ are the mass and width differences of the mass eigenstates, respectively. The term "flavour-specific" means that the final state is only reachable by the decay of a *B* meson, and consequently reachable by a meson originally produced as a $\bar{B}$ only through mixing.

LHCb has reported in Ref.[13] the measurement of the asymmetry between $D_s^+ X \mu^- \bar{\nu}$ and $D_s^- X \mu^+ \nu$ decays, with *X* representing possible associated hadrons. The reconstructed final states are $D_s^\pm \mu^\pm$, with the $D_s^\pm$ particle decaying in the $\phi\pi^\pm$ mode. The $D_s^\pm \mu^\pm$ yields are summed over B_s^0 and $\bar{B}_s^0$ initial states, and integrated with respect to decay time. Data-driven methods are used to measure efficiency ratios. The result obtained for the *CP*-violating asymmetry is $a_{sl}^s = (-0.06 \pm 0.50 \pm 0.36)\%$, consistent with previous measurements and with the SM prediction[14].

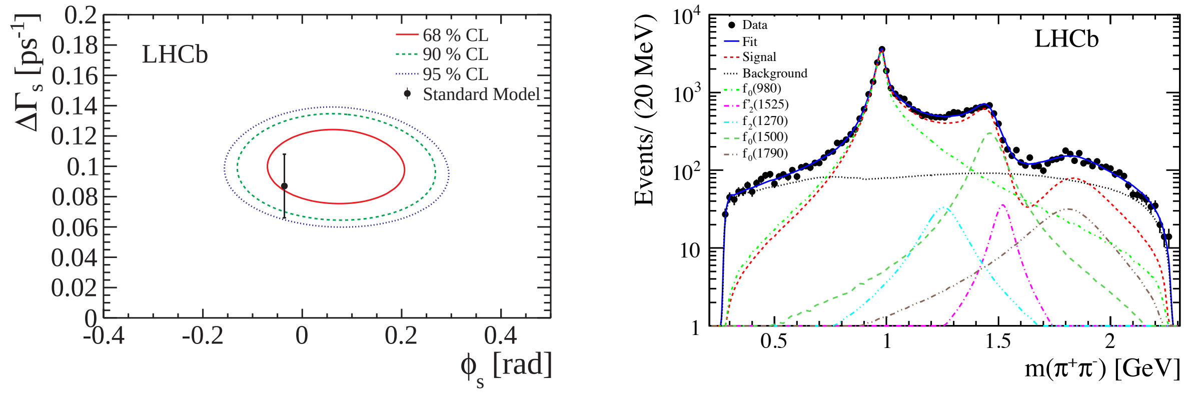

Figure 4 – Left plot: two-dimensional profile likelihood in the $(\Delta\Gamma_s, \phi_s)$ plane for the LHCb $B_s^0 \to J/\psi K^+K^-$ dataset (left); the SM expectation of $\Delta\Gamma_s = 0.087 \pm 0.021$ ps^{-1} and $\phi_s = -0.036 \pm 0.002$ rad is shown in as a black point with error bar. Right plot: distribution of $m(\pi^+\pi^-)$ for $B_s^0 \to J/\psi\pi^+\pi^-$ candidates, with the fit contributing components superimposed.

3.2 CP violation and $\Delta\Gamma_s$ with $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays.

The interference between B_s^0 meson decay amplitudes to *CP* eigenstates $J/\psi X$, directly or via mixing, gives rise to a measurable *CP*-violating phase ϕ_s. Ignoring subleading contributions, for $b \to c\bar{c}s$ transitions this phase is predicted to be $-2\beta_s$ in the SM, where $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ and the V_{ij} are elements of the CKM matrix. There is a precise indirect determination of this phase via global fits within the SM, which gives[15] $2\beta_s = 0.0364 \pm 0.0016$ rad. Direct measurements of ϕ_s are therefore of very high interest, since new particles could contribute to the $B_s^0 - \bar{B}_s^0$ mixing box diagrams modifying the SM prediction.

LHCb has measured the time-dependent *CP* asymmetry in $B_s^0 \to J/\psi K^+K^-$ decays[16]. The decay time distribution is characterized by the decay widths $\Gamma_{\rm L}$ and $\Gamma_{\rm H}$ of the light and heavy mass eigenstates of the $B_s^0 - \bar{B}_s^0$ system and by the *CP*-violating phase ϕ_s. The final state is dominated by the contribution from $B_s^0 \to J/\psi\phi$ decays. These parameters are measured to be $\phi_s = 0.07 \pm 0.09 \pm 0.01$ rad, $\Gamma_s = 0.663 \pm 0.005 \pm 0.006$ ps^{-1} and $\Delta\Gamma_s = \Gamma_{\rm L} - \Gamma_{\rm H} = 0.100 \pm 0.016 \pm 0.003$ ps^{-1}. These are the single most precise measurements to date. The left plot of Fig. 4 shows the two-dimensional profile likelihood in the $(\Delta\Gamma_s, \phi_s)$ plane. Furthermore, a combined analysis with $B_s^0 \to J/\psi\pi^+\pi^-$ decays gives $\phi_s = 0.01 \pm 0.07 \pm 0.01$ rad, $\Gamma_s = 0.661 \pm 0.004 \pm 0.006$ ps^{-1} and $\Delta\Gamma_s = \Gamma_{\rm L} - \Gamma_{\rm H} = 0.106 \pm 0.011 \pm 0.007$ ps^{-1}. All measurements are in agreement with SM predictions.

3.3 Measurement of resonant and CP components in $B_s^0 \to J/\psi\pi^+\pi^-$ decays.

The last result we are reporting in these proceedings is based on the analysis of the full LHCb data sample collected in 2011 and 2012, which corresponds to 3 fb^{-1} of integrated luminosity. These data are used in Ref.[17] to study the resonant structure of the decay $B_s^0 \to J/\psi\pi^+\pi^-$. Five interfering $\pi^+\pi^-$ states are required to describe the decay: $f_0(980)$, $f_0(1500)$, $f_0(1790)$, $f_2(1270)$ and $f_2'(1525)$. The right plot on Fig. 4 shows the contribution of each resonance as a function of $m(\pi^+\pi^-)$. An alternative model including these states and a non-resonant $J/\psi\pi^+\pi^-$ component also provides a good description of the data. Based on the different transversity components measured for the spin-2 intermediate states, the final state is found to be compatible with being entirely *CP*-odd. The *CP*-even part is found to be $< 2.3\%$ at 95% confidence level.

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