PROCEEDINGS OF SCIENCE

f_L measurements with $B \to VV$ decays at LHCb

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Some of the latest results on longitudinal polarisation measurements at LHCb are summarised here. The experimental observables are introduced as well as the main frameworks within QCD that are used to study them from a theoretical point of view. Seven analyses are discussed, containing both charmed and charmless B-decays. While charmed B-decays proceed through tree diagrams at leading order, charmless B-decays can proceed through tree, tree and penguin, or pure penguin diagrams.

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1. Introduction

Angular analyses of 4-body B-decays that aim to measure polarisation fractions may operate in the angular basis given by the angles θ_1, θ_2 and ϕ, that are shown in Figure 1. For all these types of analyses, the angular differential decay rate can be written as

$$\frac{d\Gamma}{d\Omega} = \sum_i A_i f_i(\theta_1, \theta_2, \phi), \tag{1}$$

where the amplitudes A_i are usually given in the helicity formalism (A_0, A_+, A_-) or in the transversity basis ($A_0, A_\parallel, A_\perp$). Critically, the longitudinal amplitude A_0, is common to both. Within this

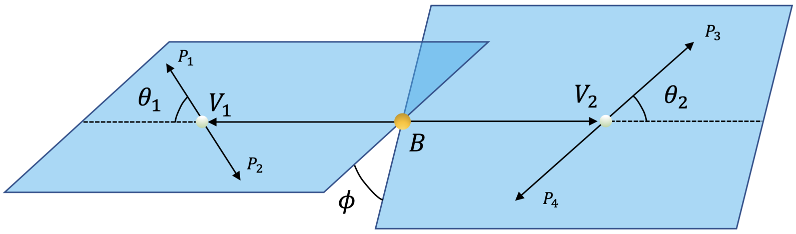


Figure 1: Definition of the helicity angles. The variable θ_1 (θ_2) is the angle between the directions of motion of P_1 (P_3) in the V_1 (V_2) rest frame, and V_1 (V_2) in the B rest frame, while ϕ is the angle between both decay planes.

framework, f_L is therefore defined by

$$f_L = \frac{|A_0|^2}{\sum_i |A_i|^2}, \tag{2}$$

and determines the fractional contribution of A_0 to the total decay rate.

The Standard Model (SM) of particle physics is capable of predicting these observables by naively applying the counting rules given by $V - A$ theory, obtaining the fractional contributions that follow,

$$f_L \sim 1 - O(m_V^2/m_B^2), \; f_\parallel \sim f_\perp \sim O(m_V^2/m_B^2). \tag{3}$$

While the naive SM predicts a high longitudinal polarisation fractions for light vector mesons, BaBar [1] and Belle [2] measured in the early 2000s a value of $f_L \sim 0.6$ for $B \to \phi K^{*0}$ decays. This polarisation inconsistency was later confirmed by LHCb in $B_s^0 \to \phi\phi$ [3] and $B_s^0 \to K^{*0}\overline{K}^{*0}$ [4] decays, both of which will be discussed here.

These and other deviations from naive expectations have motivated theoretical studies investigating Quantum Chromodynamics (QCD) effects and possible New Physics (NP) scenarios. Three major QCD approaches have been proposed to calculate non-leptonic charmless B-decays [5]: QCD factorisation (QCDF), perturbative QCD (PQCD) and soft-collinear effective theory (SCET). These approaches differ in the power counting at different mass scales. In SCET, a possible important contribution from intermediate charm loops (charming penguins), that might break the naive helicity relations, is discussed.

Also, the extremely different polarisation fractions between B_s^0 and B^0 meson decays in $B_{(s)}^0 \to K^{*0}\overline{K}^{*0}$ has been interpreted by some authors as a deficit of $b \to s$ versus $b \to d$ transitions, in a NP scenario [6]. They also analyse the main sources of hadronic uncertainty, defining and calculating a new observable whereby these sources are significantly reduced,

$$L_{K^{*0}\overline{K}^{*0}} = \frac{\mathcal{B}(B_s^0 \to K^{*0}\overline{K}^{*0})}{\mathcal{B}(B^0 \to K^{*0}\overline{K}^{*0})} \frac{g_{b\to d}}{g_{b\to s}} \frac{f_L^{B_s^0}}{f_L^{B^0}} = \frac{|A_0^s|^2 + |\bar{A}_0^s|^2}{|A_0^d|^2 + |\bar{A}_0^d|^2} = 19.5^{+9.3}_{-6.8}, \tag{4}$$

that deviates from data, as will be seen.

The analyses presented in this article are performed analysing different subsamples of data of proton-proton collisions collected with the LHCb experiment during Run 1, at a centre-of-mass energies of 7 and 8 TeV, and Run 2, at a centre-of-mass energy of 13 TeV.

2. $B_s^0 \to J/\psi(\to \mu^+\mu^-)K^+K^-$

An amplitude analysis is performed using a sample collected during LHCb Run 2 and corresponding to an integrated luminosity of 1.9 fb^{-1}. The main purpose of this analysis is to give a very precise measurement of the weak phase $\phi_s^{c\bar{c}}$ [7]. The decay is dominated by tree diagrams and favoured by CKM matrix elements, leading to a very large data sample. The invariant mass of the muon pairs, $m(\mu^+\mu^-)$, is required to fall in the region [3020, 3170] MeV/c^2, while $m(K^+K^-)$ must be within [990, 1050] MeV/c^2. A 4-body invariant mass fit is performed in 6 isopopulated bins of $m(K^+K^-)$. After a time-dependent angular analysis (Figure 2), the longitudinal polarisation fraction is measured with high precision to be

$$f_L = 0.5186 \pm 0.0029 \pm 0.0023 \tag{5}$$

from this analysis, and

$$f_L = 0.5195 \pm 0.0034 \tag{6}$$

when combined with the Run 1 measurement. The result is well understood in the SM, the J/ψ being a heavy meson.

3. $B_s^0 \to J/\psi(\to e^+e^-)\phi(\to K^+K^-)$

A similar analysis is very recently performed where the J/ψ meson is reconstructed through dielectrons, using the full LHCb Run 1 dataset corresponding to 3 fb^{-1} of integrated luminosity [8]. The e^+e^- pairs are required to have an invariant mass within [2500, 3300] MeV/c^2 to account for the energy loss due to bremsstrahlung radiation of electrons and positrons, whilst the kaon pairs are required to be in a window of 30 MeV/c^2 around the known $\phi(1020)$ mass. The longitudinal polarisation fraction is measured to be

$$f_L = 0.530 \pm 0.029 \pm 0.013, \tag{7}$$

which is compatible with SM predictions as well as with the dimuon result. The angular fit is shown in Figure 3. This result also shows no e/μ lepton anomaly observed in f_L at a very good precision level.

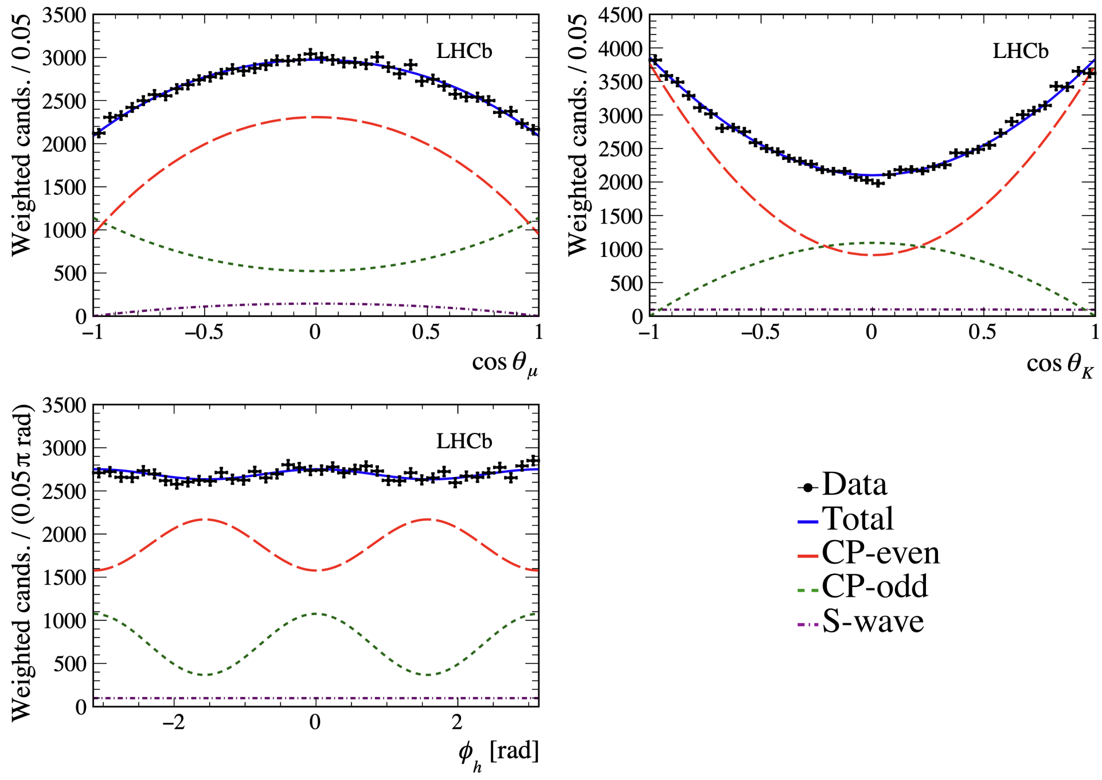


Figure 2: Helicity-angle fit results for background subtracted $B_s^0 \to J/\psi(\to \mu^+\mu^-)K^+K^-$ decays.

4. $B^0 \to D^{*-}D_s^{*+}(\to D_s^+\gamma)$

Another tree-dominated decay is studied using the full LHCb Run 2 dataset of 6 fb^{-1} [9]. For the f_L measurement, the strong correlation between $\cos\theta_X$, the cosine of the angle between the D_s^+ meson and the direction opposite the B^0 momentum vector in the D_s^{*+} rest frame, and $m(D^{*-}D_s^+)$, the invariant mass of all the bodies excluding the photon, is exploited (Figure 4 right). Using this correlation, a fit to $m(D^{*-}D_s^+)$ is performed in order to separate the contributions from the different polarisations and, hence, measure f_L with world-best precision (Figure 4 left). The value obtained is

$$f_L = 0.578 \pm 0.010 \pm 0.011, \tag{8}$$

which is compatible with previous measurements and well understood in QCD as $f_L \sim 0.52$ from naive factorisation [10].

5. $B^0 \to \rho^0(\to \pi^+\pi^-)\rho^0(\to \pi^+\pi^-)$

LHCb has performed an amplitude analysis of $B^0 \to (\pi^+\pi^-)(\pi^+\pi^-)$ decays, where the $\rho^0\rho^0$ intermediate state is expected to dominate, using the 3 fb^{-1} of the Run 1 dataset [11], also constituting its first observation of this decay with a 7σ significance. For the signal selection, $m(\pi^+\pi^-)$ is required to be less than 1100 MeV$/c^2$. To reduce contamination from charm backgrounds and from $B^0 \to a_1^+(\to \rho^0\pi^+)\pi^-$, the invariant mass of any 3-body combination in the event is required to

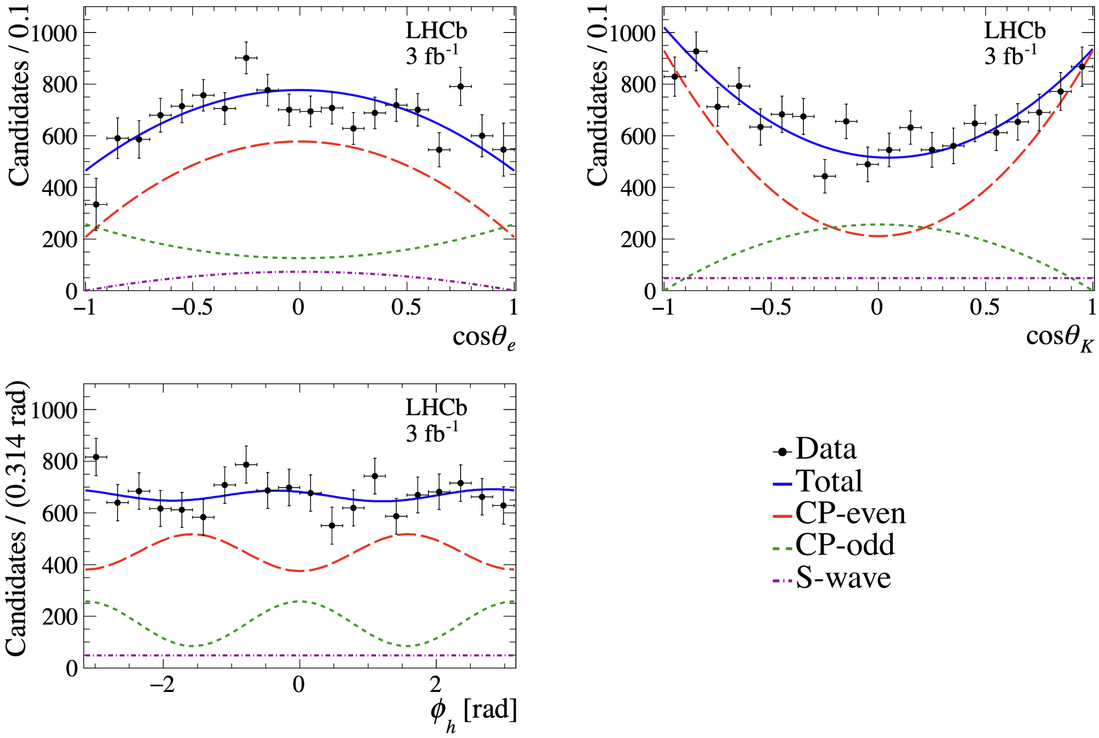


Figure 3: Helicity-angle fit results for background subtracted $B_s^0 \to J/\psi(\to e^+e^-)\phi$ decays.

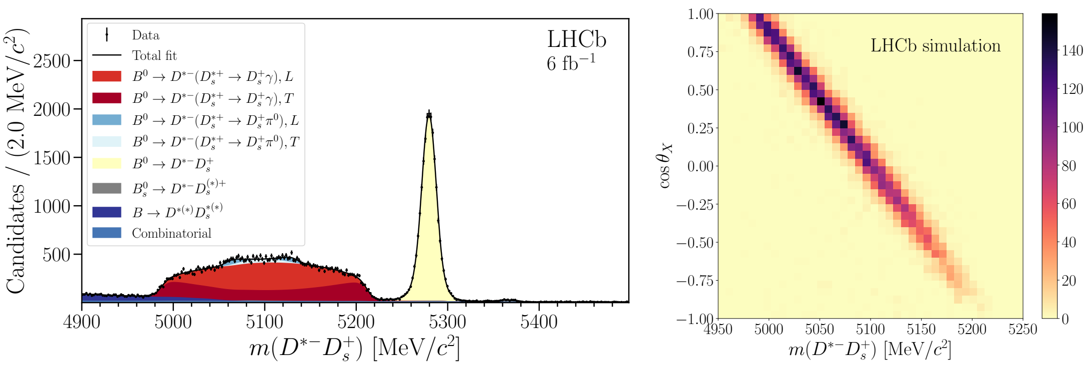


Figure 4: Mass fit (left) and angle-mass correlation (right) for $B^0 \to D^{*-}D_s^{*+}(\to D_s^+\gamma)$.

be larger than 2100 MeV$/c^2$. A high polarisation fraction is measured through an angular analysis (Figure 5), yielding

$$f_L = 0.745^{+0.048}_{-0.058} \pm 0.034. \tag{9}$$

This result marks an improved approach over the BaBar [12] and Belle [13] results through the introduction of amplitude analysis.

6. $B_s^0 \to \phi(\to K^+K^-)\phi(\to K^+K^-)$

This decay proceeds through a gluonic penguin diagram at leading order, so the branching ratio is relatively small. The analysis uses the full LHCb Run 1 data and a part of Run 2, accounting for

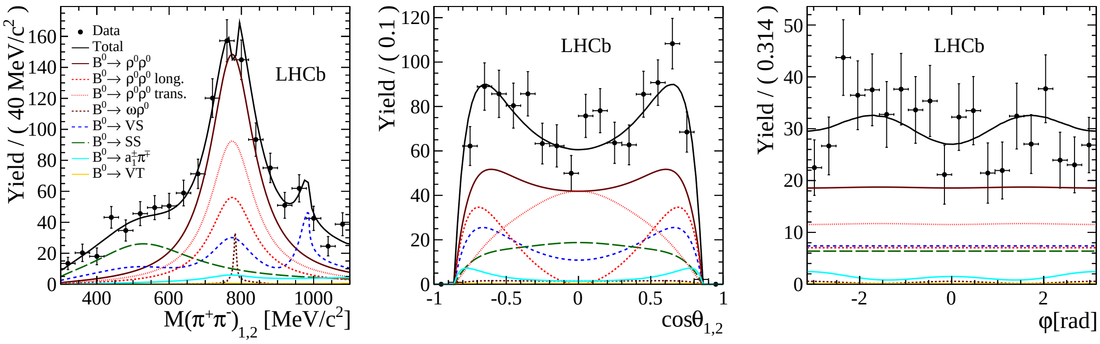


Figure 5: 2-body mass and helicity-angle fit results for $B^0 \to \rho^0\rho^0$.

5 fb^{-1} in total [3]. After the angular fit shown in Figure 6, a low polarisation fraction is measured,

$$f_L = 0.381 \pm 0.007 \pm 0.012, \tag{10}$$

which is nevertheless compatible with QCDF predictions [14].

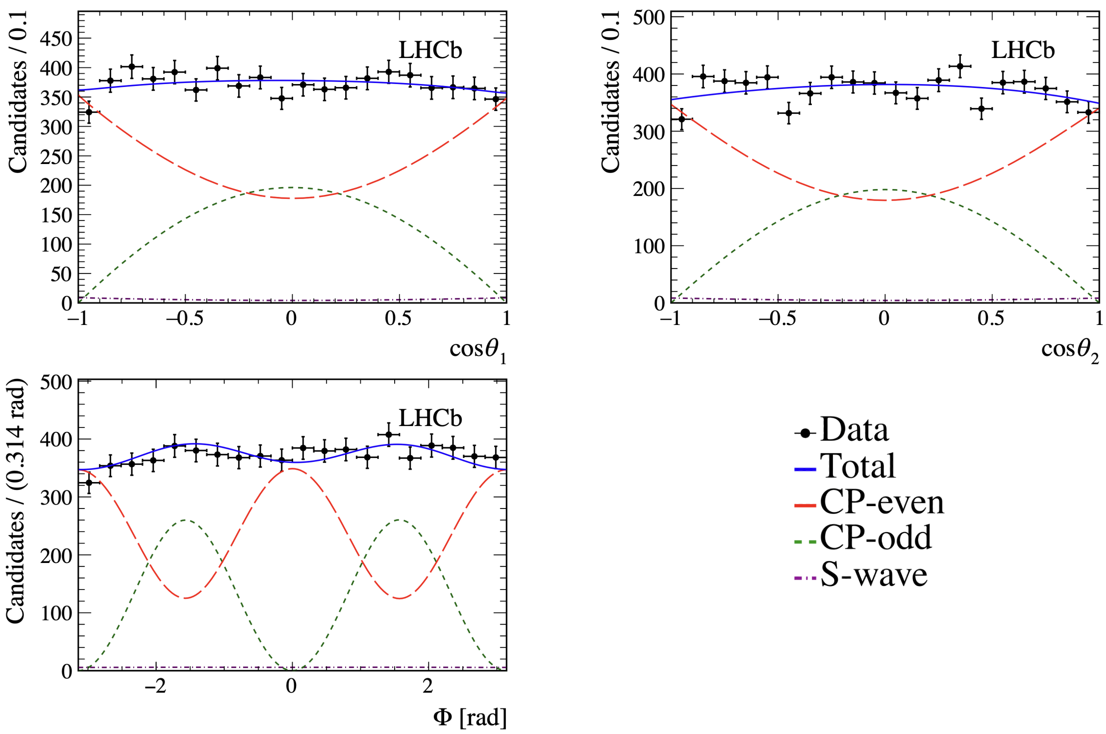
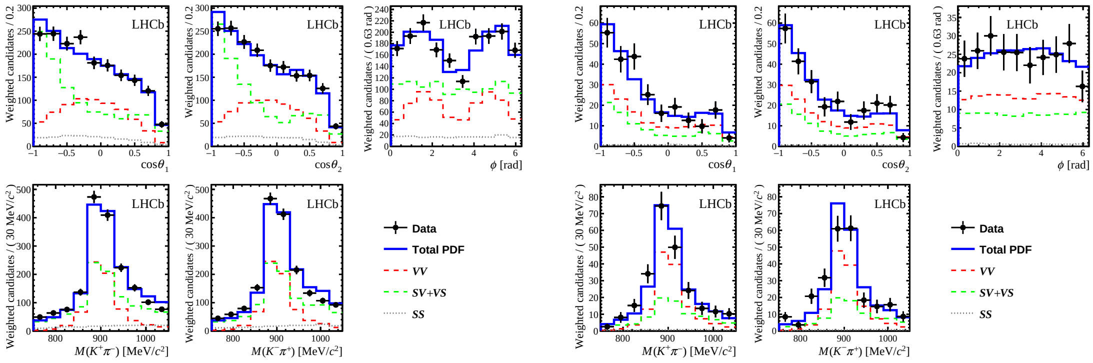


Figure 6: Helicity-angle fit results for background subtracted $B_s^0 \to \phi(\to K^+K^-)\phi(\to K^+K^-)$ decays.

7. $B^0_{(s)} \to K^{*0}(\to K^+\pi^-)\overline{K}^{*0}(\to K^-\pi^+)$

This analysis covers two decays into $K^{*0}\overline{K}^{*0}$ from the B_s^0 and B^0 initial states. Both decays also proceed through gluonic penguin diagrams at leading order. The measurements are performed



(a) $B_s^0 \to K^{*0}\overline{K}^{*0}$ **(b)** $B^0 \to K^{*0}\overline{K}^{*0}$

Figure 7: 2-body mass and helicity-angle fit results for $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ decays.

with 3 fb^{-1} of the LHCb Run 1 dataset [4]. The $K^{*0}/\overline{K}^{*0}$ candidates are formed through $K\pi$ pairs in a mass window of 150 MeV$/c^2$ around the known pole. The polarisation fractions are obtained through the angular fits shown in Figure 7, appearing to be high for the B^0 decay, while being fairly low for the B_s^0,

$$\begin{aligned} f_L^{B^0} &= 0.724 \pm 0.051 \pm 0.016, \\ f_L^{B_s^0} &= 0.240 \pm 0.031 \pm 0.025. \end{aligned} \tag{11}$$

Finally, the experimental value of the L-observable seems to be quite low, $L_{K^{*0}\overline{K}^{*0}} = 4.43 \pm 0.92$ [6], giving rise to a 2.6σ tension with QCDF predictions (equation 4).

8. $B^0 \to \rho^0(\to \pi^+\pi^-)K^{*0}(\to K^+\pi^-)$

The final study to be discussed is an amplitude analysis of $B^0 \to (\pi^+\pi^-)(K^+\pi^-)$ decays, where the $\rho^0 K^{*0}$ is expected to dominate, using the full Run 1 dataset [15]. This decay proceeds through tree, electroweak penguin and gluonic penguin diagrams. Pion pairs are required to have $m(\pi^+\pi^-) \in [300, 1100]$ MeV$/c^2$, while $K\pi$ pairs must satisfy $m(K^+\pi^-) \in [750, 1200]$ MeV$/c^2$. Accompanying these, the constraint $|\cos\theta_{\pi\pi}| < 0.8$ is also required to strongly supress other backgrounds coming from 3-body resonances. A very low polarisation fraction is measured, as well as a significant CP asymmetry, deviating from 0 by 4.9 standard deviations,

$$\begin{aligned} \tilde{f}_L &= \frac{f_L^B + f_L^{\bar{B}}}{2} = 0.164 \pm 0.015 \pm 0.022, \\ \mathcal{A}_L &= \frac{f_L^B - f_L^{\bar{B}}}{f_L^B + f_L^{\bar{B}}} = -0.62 \pm 0.09 \pm 0.09. \end{aligned} \tag{12}$$

The following theoretical values were computed within the QCDF framework [14] and PQCD [16]:

$$\begin{aligned} \text{QCDF}: \; f_L &= 0.22^{+0.03+0.53}_{-0.03-0.14}, \; \mathcal{A}_L = -0.30^{+0.11+0.61}_{-0.11-0.49}, \\ \text{PQCD}: \; f_L &= 0.65^{+0.03+0.03}_{-0.03-0.04}, \; \mathcal{A}_L = -0.0364^{+0.0120}_{-0.0107}. \end{aligned} \tag{13}$$

Both observables are in agreement with QCDF but not with PQCD, though it should be noted that the uncertainties in the QCDF calculations are relatively large.

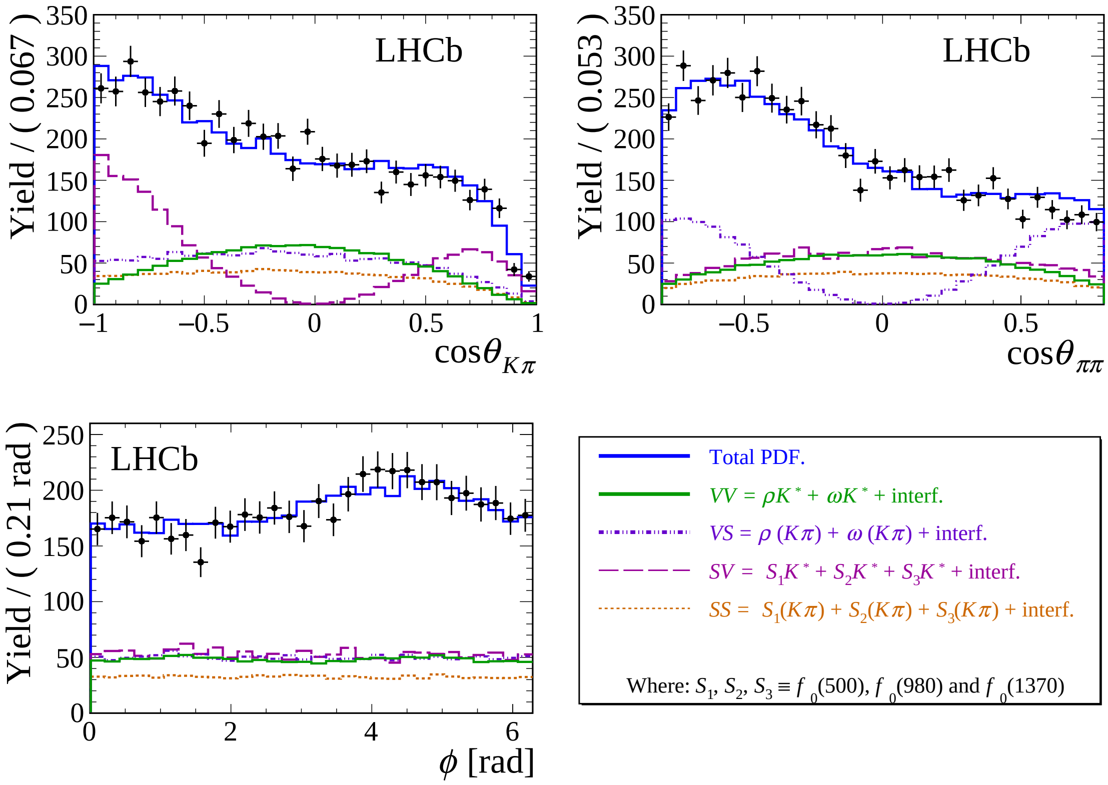


Figure 8: Helicity-angle fit results for $B^0 \to \rho^0 K^{*0}$ decays.

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