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Abstract

We present the first measurement of the time-integrated mixing probability χ_d using Belle II data collected at a center-of-mass (CM) energy of 10.58 GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance, with an integrated luminosity of 34.6 fb^{-1} at the SuperKEKB e^+e^- collider. We reconstruct pairs of B mesons both of which decay to semileptonic final states. Using a novel methodology, we measure $\chi_d = 0.187 \pm 0.010$ (stat.) ± 0.019 (syst.), which is compatible with existing indirect and direct determinations.

1. INTRODUCTION

The time evolution of the neutral $B^0 - \overline{B}^0$ meson system has been studied by a number of experiments. The first signal for $B^0 - \overline{B}^0$ mixing was reported by the ARGUS experiment in Ref. [1] and the observed level of mixing provided first indications for the mass scale of the top quark. The two B^0 mesons produced in an $\Upsilon(4S)$ decay evolve in a coherent P-wave state. For this reason the neutral B mesons' flavor in the coherent quantum state are always opposite. Due to the quantum entanglement of the B meson states in the coherent quantum state, they cannot change flavor until one of them has decayed. Therefore, the B mesons' flavor can only be determined relative to each other after one of the mesons decays. The mixing properties of the $B^0 - \overline{B}^0$ system can be described by four parameters (x_d, y_d, q, and p) and its time evolution is described by the Schrödinger equation, which depends on the relative time difference between the two neutral B meson decays. The heavy (H) and light (L) mass eigenstates of the system are related to the B^0 and $\overline{B}^0$ flavor eigenstates by:

$$|B_{L/H}\rangle = p|B_d^0\rangle \pm q|\overline{B}_d^0\rangle \,. \tag{1}$$

In the absence of CP violation in mixing $|q/p| = 1$, and we can express x_p and y_p as a function of the mass difference, $\Delta m_d = m_H - m_L$, and the lifetime difference, $\Delta\Gamma_d = \Gamma_L - \Gamma_H$ of the two mass eigenstates:

$$x_d = \Delta m_d/\Gamma_d \,, \qquad y_d = \Delta\Gamma_d/\Gamma_d \,, \tag{2}$$

where $\Gamma_d = (\Gamma_L + \Gamma_H)/2$ is the average decay width. Experimentally, both parameters can be constrained by measuring the time-integrated mixing probability,

$$\chi_d = \frac{\Gamma(B^0 \to \overline{B}^0)}{\Gamma(B^0 \to B^0) + \Gamma(B^0 \to \overline{B}^0)} = \frac{x_d^2 + y_d^2}{2(x_d^2 + 1)} \,, \tag{3}$$

and the value of y_d can be determined in combination with direct measurements of Δm_d and the B meson lifetime. The current most precise value of χ_d is obtained by combining the information from time-independent and time-dependent measurements: $\chi_d^{\text{WA}} = 0.186 \pm 0.001$ [2]. The world average obtained using only time-independent measurements has a much larger uncertainty and results in $\chi_d^{\text{WA}\,t-\text{in.}} = 0.182 \pm 0.015$.

Here we provide the first direct determination of χ_d using a time-independent approach and semileptonic $B \to X\,e^+\,\nu_e$ decays using data recorded by the Belle II experiment at the SuperKEKB e^+e^- collider in 2019 and 2020. We analyze an integrated luminosity of 34.6 fb^{-1} of recorded collision data, corresponding to $(37.7 \pm 0.6) \times 10^6$ of B meson pairs. We identify events in which both B mesons decayed via a semileptonic $B \to X\,e^+\,\nu_e$ transition. The value of χ_d is obtained by determining the number of $e^\pm e^\pm$ same-sign (N_{SS}) and $e^\pm e^\mp$ opposite-sign (N_{OS}) electron pair candidates from $B \to X\,e^+\,\nu_e$ decays, as the charge of the lepton in a semileptonic B decay directly encodes the flavor of the B meson. Contributions from charged B mesons are subtracted using a correction factor r_B and then the number of opposite- and same-sign events are corrected for selection and acceptance effects to determine the time-integrated mixing probability

$$\chi_d = \frac{N_{\text{SS}}}{N_{\text{SS}} + N_{\text{OS}} \cdot (\epsilon_{\text{OS}}/\epsilon_{\text{SS}})^{-1}} \cdot (1 + r_B) \,. \tag{4}$$

Here ϵ_{OS} and ϵ_{SS} denote the efficiencies for opposite-sign and same-sign signal, respectively, which are obtained from studies on simulated samples and corrected using data-driven methods to account for differences in particle identification and reconstruction efficiencies, with $(\epsilon_{\mathrm{OS}}/\epsilon_{\mathrm{SS}}) = 0.92 \pm 0.01$ (stat.). Further, $r_B = f_{+0} \cdot \tau_{+0}^2 = 1.2 \pm 0.1$ with $\tau_{+0} = 1.078 \pm 0.004$ denoting the charged and neutral B meson lifetime ratio and $f_{+0} = \mathcal{B}(\Upsilon(4S) \to B^+ B^-)/\mathcal{B}(\Upsilon(4S) \to B^0 \overline{B}^0) = 1.058 \pm 0.024$ [2].

2. THE BELLE II DETECTOR AND DATA SAMPLE

The Belle II detector [3, 4] operates at the SuperKEKB asymmetric-energy electron-positron collider [5], located at the KEK laboratory in Tsukuba, Japan. The detector consists of several nested detector subsystems arranged around the beam pipe in a cylindrical geometry. The innermost subsystem is the vertex detector, which includes two layers of silicon pixels and four outer layers of silicon strip detectors. Currently, the second pixel layer is installed in only a small part of the solid angle, while the remaining vertex detector layers are fully installed. Most of the tracking volume consists of a small-cell drift chamber filled with a helium and ethane mixture gas. Outside the drift chamber, a Cherenkov-light imaging and time-of-propagation detector provides charged-particle identification in the barrel region. In the forward endcap, this function is provided by a proximity-focusing, ring-imaging Cherenkov detector with an aerogel radiator. At higher radius is an electromagnetic calorimeter, consisting of a barrel and two endcap sections made of CsI(Tl) crystals. A uniform 1.5 T magnetic field is provided by a superconducting solenoid situated outside the calorimeter. The K_L^0 and muon identification system consists of multiple layers of scintillators in the endcaps, and two layers of scintillators and multiple layers of resistive plate chambers in the barrel region, located between the magnetic flux-return iron plates.

The data used in this analysis were collected at a center-of-mass (CM) energy of 10.58 GeV, corresponding to the mass of the $\Upsilon(4S)$ resonance. The energies of the electron and positron beams are 7 GeV and 4 GeV, respectively, resulting in a boost of $\beta\gamma = 0.28$ of the CM frame relative to the laboratory frame. In addition, 3.2 fb^{-1} of off-resonance collision data, collected 60 MeV below the $\Upsilon(4S)$ resonance, is used to model background from $e^+ e^-$ continuum processes, i.e. $e^+ e^- \to u\bar{u}, d\bar{d}, s\bar{s}$ and $c\bar{c}$.

Simulated Monte Carlo (MC) samples of $B \to X \ell^+ \nu_\ell$ signal and background processes are used to obtain the reconstruction efficiencies and study the key kinematic distributions. These events are generated with EvtGen [6] and the branching fractions used are summarized in Table I. Inclusive semileptonic $B \to X \ell^+ \nu_\ell$ decays are dominated by $B \to D \ell^+ \nu_\ell$ and $B \to D^* \ell^+ \nu_\ell$ transitions. We model the $B \to D \ell^+ \nu_\ell$ decays using the BGL parametrization [7] with form factor central values and uncertainties taken from the fit in Ref. [8]. For $B \to D^* \ell^+ \nu_\ell$ we use the BGL implementation proposed in Refs. [9, 10] with form factor central values and uncertainties from the fit to the measurement of Ref. [11]. Both semileptonic modes are normalized to the average branching fraction of Ref. [12] assuming isospin symmetry. Semileptonic $B \to D^{**} \ell^+ \nu_\ell$ decays with $D^{**} = \{D_0^*, D_1^*, D_1, D_2^*\}$ denoting the four orbitally excited charmed mesons are modeled using the heavy-quark-symmetry-based form factors proposed in Refs. [13, 14]. To fill the remaining 'gap' between the sum of all measured exclusive modes and the inclusive $B \to X_c \ell^+ \nu_\ell$ branching fraction, we simulate $B \to D^{(*)} \pi \pi \ell^+ \nu_\ell$ and $B \to D^{(*)} \eta \ell^+ \nu_\ell$ decays using a model based on a uniform distri-

TABLE I. Branching fractions for $B \to X_c \ell^+ \nu_\ell$ and $B \to X_u \ell^+ \nu_\ell$ processes that were used to generate simulated samples are listed.

$\mathcal{B}$	B^+	B^0
$B \to X_c \ell^+ \nu_\ell$		
$\quad B \to D \ell^+ \nu_\ell$	$(2.41 \pm 0.07) \times 10^{-2}$	$(2.24 \pm 0.07) \times 10^{-2}$
$\quad B \to D^* \ell^+ \nu_\ell$	$(5.50 \pm 0.11) \times 10^{-2}$	$(5.11 \pm 0.11) \times 10^{-2}$
$\quad B \to D_0^* \ell^+ \nu_\ell$	$(0.42 \pm 0.08) \times 10^{-2}$	$(0.39 \pm 0.07) \times 10^{-2}$
$\quad B \to D_1^* \ell^+ \nu_\ell$	$(0.42 \pm 0.09) \times 10^{-2}$	$(0.39 \pm 0.08) \times 10^{-2}$
$\quad B \to D_1 \ell^+ \nu_\ell$	$(0.66 \pm 0.11) \times 10^{-2}$	$(0.62 \pm 0.10) \times 10^{-2}$
$\quad B \to D_2^* \ell^+ \nu_\ell$	$(0.29 \pm 0.03) \times 10^{-2}$	$(0.27 \pm 0.03) \times 10^{-2}$
$\quad B \to D\pi\pi \ell^+ \nu_\ell$	$(0.06 \pm 0.09) \times 10^{-2}$	$(0.06 \pm 0.09) \times 10^{-2}$
$\quad B \to D^*\pi\pi \ell^+ \nu_\ell$	$(0.22 \pm 0.10) \times 10^{-2}$	$(0.20 \pm 0.10) \times 10^{-2}$
$\quad B \to D_s K \ell^+ \nu_\ell$	$(0.03 \pm 0.01) \times 10^{-2}$	-
$\quad B \to D_s^* K \ell^+ \nu_\ell$	$(0.03 \pm 0.01) \times 10^{-2}$	-
$\quad B \to D\eta \ell^+ \nu_\ell$	$(0.41 \pm 0.41) \times 10^{-2}$	$(0.41 \pm 0.41) \times 10^{-2}$
$\quad B \to D^*\eta \ell^+ \nu_\ell$	$(0.41 \pm 0.41) \times 10^{-2}$	$(0.41 \pm 0.41) \times 10^{-2}$
$B \to X_u \ell^+ \nu_\ell$	$(0.22 \pm 0.03) \times 10^{-2}$	$(0.21 \pm 0.03) \times 10^{-2}$
$B \to X \ell^+ \nu_\ell$	$(10.99 \pm 0.28) \times 10^{-2}$	$(10.33 \pm 0.28) \times 10^{-2}$

bution of all final-state particles in phase-space and add them to the simulated samples. Semileptonic $B \to X_u \ell^+ \nu_\ell$ decays are modeled as a mixture of specific exclusive modes and non-resonant contributions adapted from the approach described in Ref. [15].

3. ANALYSIS STRATEGY

Our general analysis strategy is as follows: we first identify samples of same-sign and opposite-sign di-electron candidates. We then apply a selection based on tracks and global event properties to enrich the samples with double-semileptonic $B^0 - \overline{B^0}$ ("signal") decays. For events passing the selection, we construct a variable that can distinguish between signal and misreconstructed events, which we then fit to extract N_{SS} and N_{OS}. We describe these steps in more detail below.

3.1. Di-electron candidate selection

We form electron pairs from single electron candidates that satisfy the following criteria. We demand the single electron candidate having a center-of-mass momentum of $|p_e^*| > 1$ GeV. In addition, we demand that the impact parameter is consistent with the interaction point by requiring the track to pass the interaction point within 4 cm along the beam axis in the laboratory frame and within 2 cm transverse to the beam axis. Furthermore, we require the single electron candidates to have an electron ID likelihood above 0.9. The efficiency of

this selection for single electron candidates is 93.7% while the pion-electron misidentification rate is 2.2%.

Each electron candidate energy is corrected for loss due to bremsstrahlung radiation and final state radiation using a dedicated search algorithm that matches electromagnetic clusters in the calorimeter to electron candidates. We then separate the electron pair candidates according to their reconstructed charges into SS and OS categories.

3.2. Signal enrichment

Using the correspondence between the generated particles and the reconstructed tracks, we classify the pair as "Signal" if both electrons are daughters of different B mesons, and label the rest "Other". We use the off-resonance dataset to describe the continuum background distributions.

We use the following selections to suppress the major backgrounds. First, we reject lepton pairs coming from photon conversion or resonant decay by checking whether either of the signal electron candidates can match to an opposite-sign track in the event under the electron mass hypothesis and give an invariant mass near zero ($m_{ee} < 0.2$ GeV) or near the J/ψ resonance (2.92 GeV $< m_{ee} < 3.14$ GeV). We discard di-electron candidates if either criterion is satisfied ($\epsilon_{SS} = 0.958$, $\epsilon_{OS} = 0.896$). Next, if multiple di-electron pair candidates are present in an event, we randomly choose one as the best candidate in the event ($\epsilon_{SS} = 0.999$, $\epsilon_{OS} = 0.990$). We discard events in which there are less than five total tracks that pass the same impact parameter selections as the signal leptons ($\epsilon_{SS} = 0.923$, $\epsilon_{OS} = 0.917$). In order to suppress continuum backgrounds, we then retain only events with a normalized Fox-Wolfram moment [16] value $R_2 < 0.3$ ($\epsilon_{SS} = 0.889$, $\epsilon_{OS} = 0.895$). Finally, we discard events for which electron ID corrections are not available for both electron candidates ($\epsilon_{SS} = 0.890$, $\epsilon_{OS} = 0.894$).

After these selections, the remaining backgrounds are largely from mis-identified electrons, electron pairs in which both electrons have the same common B-meson ancestor, $B \to (X_c \to X_s e^- \overline{\nu_e}) e^+ \nu_e$ (OS only), and continuum events.

3.3. The extraction variable

Our signal consists of two electrons from semileptonic B decays, each of which has a mean energy above that of the primary background sources. Therefore, the sum of the magnitude of the momenta in the center-of-mass frame of the two electrons:

$$p_{ee} = |p_{e1}^*| + |p_{e2}^*| \tag{5}$$

provides discrimination between signal and background. This variable has not been exploited thus far in time-integrated χ_d measurements. In Fig. 1 we show this spectrum in OS and SS for MC and data.
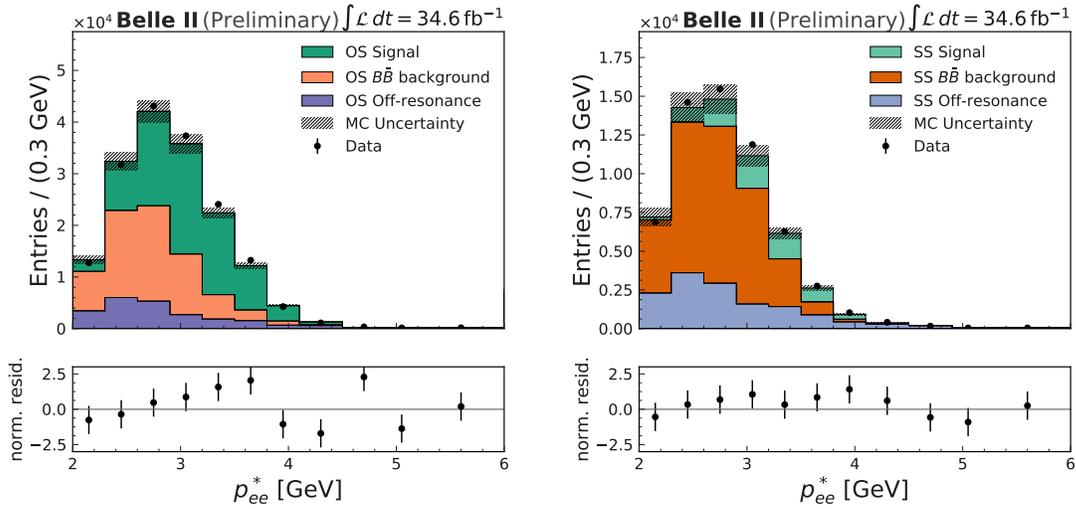
FIG. 1. The p_{ee} spectrum for opposite-sign (left) and same-sign (right) di-electron samples after all selections and before fitting. The shaded, stacked histograms show the expected spectra from the sum of "Signal" MC (green), "Other" $B\overline{B}$ MC (orange), and scaled off-resonance data (purple). The black points with error bars indicate the spectrum as measured in data. The shaded area shows the size of the systematic uncertainty from lepton identification efficiencies, signal and background shapes, and the statistical uncertainty of the off-resonance data. The panels below the histograms show the normalized residuals between data and MC calculated as $(N_{\text{data}} - N_{\text{MC}})/\sqrt{\sigma_{\text{data}}^2 + \sigma_{\text{MC}}^2}$, where N is the number of entries, σ_{data} denotes the statistical uncertainty of the data and σ_{MC} is the total uncertainty of MC in each bin.

4. FITTING PROCEDURE

The number of same-sign and opposite-sign $B \to X\,e^+\,\nu_e$ candidates is determined by a simultaneous binned likelihood fit to the p_{ee} distribution of both samples and in 11 p_{ee} bins ranging from 2 - 6 GeV. For each of the 11 p_{ee} bins, the free parameters of the fit are the number of same-sign and opposite-sign $B \to X\,e^+\,\nu_e$ candidates N_{SS}, N_{OS}, the number of background events in each sample from B meson decays N_{BSS}, N_{BOS} as well as he number of background events in each sample from continuum processes N_{CSS}, N_{COS}

These parameters correspond to the yields of the three event categories considered. The total likelihood function is

$$\mathcal{L} = \prod_{i}^{\text{bins}} \mathcal{P}\left(n_i; \nu_i\right) \times \prod_{k} \mathcal{G}_k \,, \tag{6}$$

with n_i denoting the number of observed data events and ν_i the total number of expected events in a given bin i. Here, $\mathcal{G}_k$ are nuisance-parameter (NP) constraints for a given template k, whose role is to incorporate systematic uncertainties and the number of expected continuum events, as determined from the off-resonance data, directly into the fit. The number of expected events in a given bin, ν_i, is estimated using MC and off-resonance data

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and is given by

$$\nu_i = N_{\text{SS}} \cdot f_{i,\text{SS}} + N_{\text{BSS}} \cdot f_{i,\text{BSS}} + N_{\text{CSS}} \cdot f_{i,\text{CSS}}\,, \tag{7}$$

or

$$\nu_i = N_{\text{OS}} \cdot f_{i,\text{OS}} + N_{\text{BOS}} \cdot f_{i,\text{BOS}} + N_{\text{COS}} \cdot f_{i,\text{COS}}\,, \tag{8}$$

for same-sign or opposite-sign events, respectively. Here the f_i correspond to the fraction of events of each category being reconstructed in bin i as determined by the MC simulation or the off-resonance data. The NP constraints are constructed such that they take into account uncertainties due to the electron identification efficiency, signal and background template compositions, and the statistical uncertainty of the template in question. They are incorporated using multivariate Gaussian distributions, $\mathcal{G}_k = \mathcal{G}_k(\mathbf{0}; \boldsymbol{\theta}_k, \Sigma_k)$. Here Σ_k denotes the systematic covariance matrix for a given template k and $\boldsymbol{\theta}_k$ is a vector of NPs. The covariance matrix Σ_k is the sum over all possible uncertainty sources for a given template. The fractions in Eqs. 7 and 8 are allowed to change within these systematic uncertainties according to:

$$f_i = \frac{N_i^{\text{MC}}\left(1 + \theta_i\right)}{\sum_j N_j^{\text{MC}}\left(1 + \theta_j\right)}\,, \tag{9}$$

with N_i^{MC} denoting the number of expected events of a given category in bin i as estimated by MC, and θ_j the jth element of the NP vector $\boldsymbol{\theta}_k$. The likelihood function is maximized numerically to determine all components and NP constraints. Confidence intervals for the N_{SS} and N_{OS} components are constructed using the profile likelihood ratio method.

5.   RESULTS

Figure 2 shows the post-fit p_{ee} distribution for same-sign and opposite-sign candidates. The goodness-of-fit cannot be judged based on the residuals alone, but also depends on the NP pulls, which we show in Appendix A. From this fit, we measure:

$$\chi_d = 0.187 \pm 0.010\,(\text{stat.}) \pm 0.019\,(\text{syst.}) \tag{10}$$

where the first uncertainty is statistical and the second is systematic. The overall uncertainty is dominated by the statistical uncertainty of the same-sign sample, the limited size of the off-resonance data sample, and the systematic uncertainty of the electron identification corrections. The size of these systematic uncertainties is expected to decrease with larger control samples. The obtained value of χ_d is compatible with the world average from time-independent and time-dependent determinations [2] and already has a precision comparable to the time-independent world average.
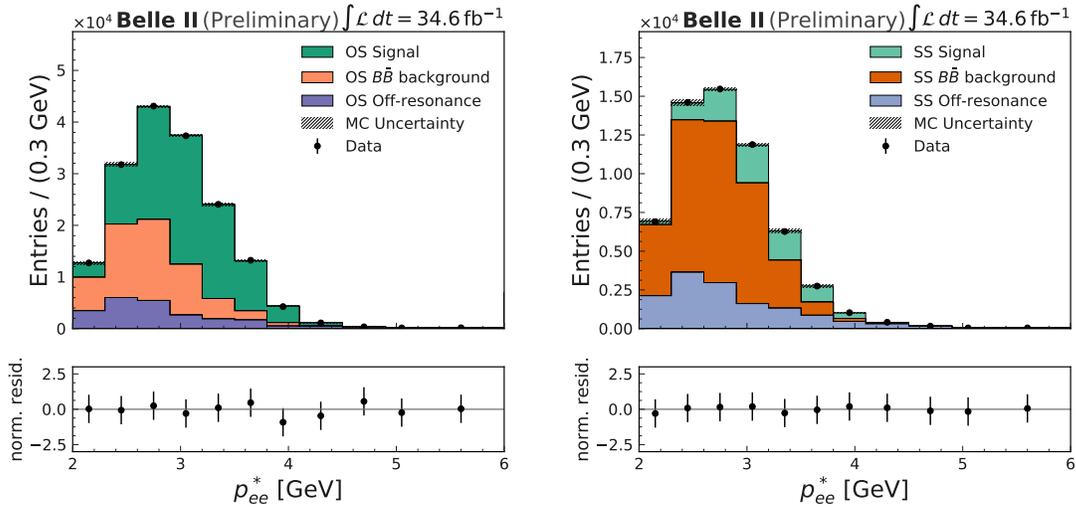
FIG. 2. The p_{ee} spectrum for opposite-sign (left) and same-sign (right) di-electron samples after fitting. The shaded, stacked histograms show the fitted spectra from the sum of "Signal" MC (green), "Other" $B\overline{B}$ MC (orange), and scaled off-resonance data (purple). The black points with error bars indicate the spectrum as measured in data. The shaded area around the MC expectation correspond to the post-fit uncertainty. The panels below the histograms show the normalized residuals between data and MC calculated as $(N_{\text{data}}-N_{\text{MC}})/\sqrt{\sigma^2_{\text{data}}+\sigma^2_{\text{MC}}}$, where N is the number of entries, σ_{data} denotes the statistical uncertainty of the data and σ_{MC} is the total uncertainty of MC in each bin..

6. ACKNOWLEDGEMENTS

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Appendix A: Nuisance parameter pulls

We include distributions of the NP pulls from the fit shown in Fig. 2, for the signal (Fig. 3), other $B\overline{B}$ (Fig. 4), and off-resonance (Fig. 5) templates. The modest deviation that can be seen in the pulls of the OS signal template corresponds to higher values in p_{ee}, which is mostly occupied by $B \to X_u \ell^+ \nu_\ell$ decays.
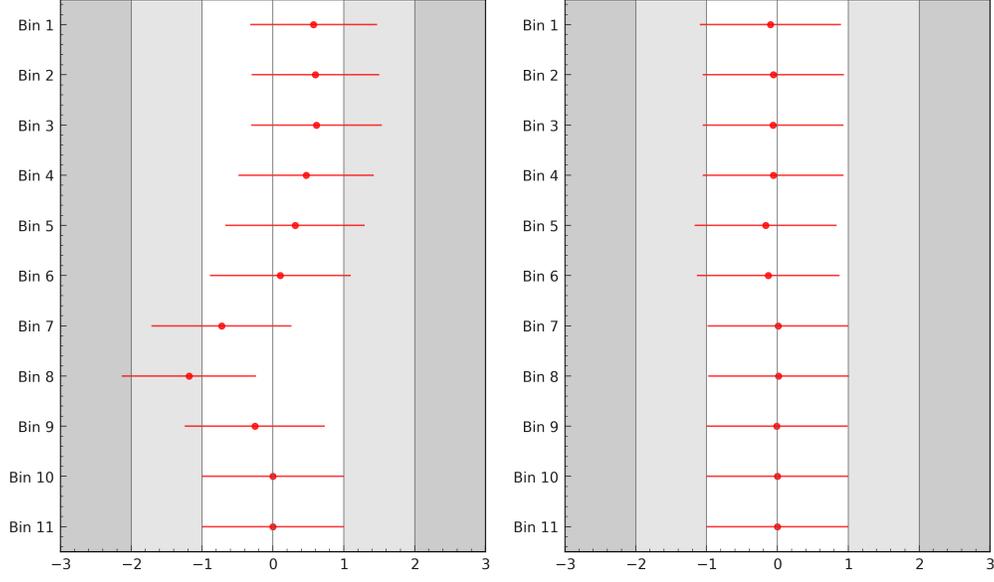

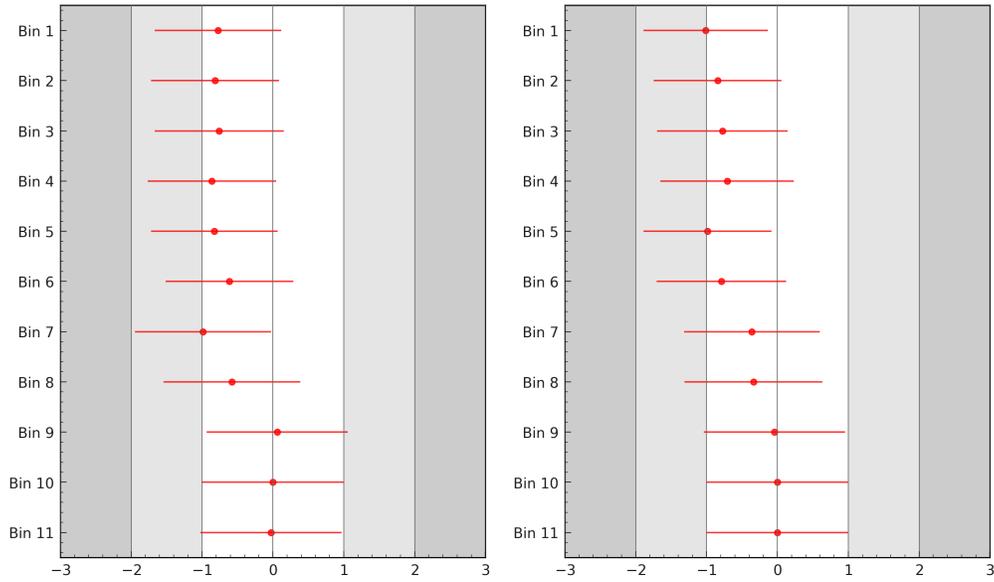FIG. 3. Pulls on the nuisance parameters for the OS (left) and SS (right) signal templates.

FIG. 4. Pulls on the nuisance parameters for the OS (left) and SS (right) $B\overline{B}$ background templates.
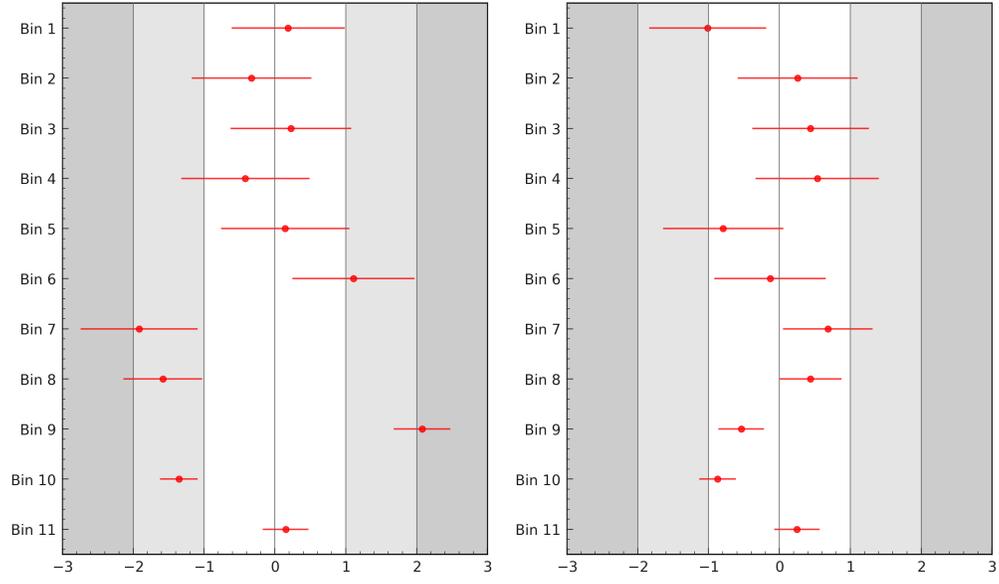
FIG. 5. Pulls on the nuisance parameters for the OS (left) and SS (right) off-resonance templates.