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Phys. Rev. D 93, 032008 - Published 22 February 2016
DOI: 10.1103/PhysRevD.93.032008

## Measurement of the Lepton Forward-Backward Asymmetry in $B \rightarrow X_{s} \ell^{+} \ell^{-}$Decays with a Sum of Exclusive Modes

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We report the first measurement of the lepton forward-backward asymmetry $\mathcal{A}_{\mathrm{FB}}$ as a function of the squared four-momentum of the dilepton system, $q^{2}$, for the electroweak penguin process $B \rightarrow X_{s} \ell^{+} \ell^{-}$with a sum of exclusive final states, where $\ell$ is an electron or a muon and $X_{s}$ is a hadronic recoil system with an $s$ quark. The results are based on a data sample containing $772 \times 10^{6}$ $B \bar{B}$ pairs recorded at the $\Upsilon(4 S)$ resonance with the Belle detector at the KEKB $e^{+} e^{-}$collider. $\mathcal{A}_{\mathrm{FB}}$ for the inclusive $B \rightarrow X_{s} \ell^{+} \ell^{-}$is extrapolated from the sum of 10 exclusive $X_{s}$ states whose invariant mass is less than $2 \mathrm{GeV} / c^{2}$. For $q^{2}>10.2 \mathrm{GeV}^{2} / c^{2}, \mathcal{A}_{\mathrm{FB}}<0$ is excluded at the $2.3 \sigma$ level, where $\sigma$ is the standard deviation. For $q^{2}<4.3 \mathrm{GeV}^{2} / c^{2}$, the result is within $1.8 \sigma$ of the Standard Model theoretical expectation.

PACS numbers: 11.30.Er, 11.30.Hv, 12.15.Ji, 13.20.He

## I. INTRODUCTION

In the Standard Model (SM), quark-level flavorchanging neutral current $b \rightarrow s \ell^{+} \ell^{-}$decays [1] are allowed at higher order via the electroweak loop (penguin) and $W^{+} W^{-}$box diagrams. The corresponding decay amplitude can be expressed via the Operator Product Expansion [2] in terms of the effective Wilson coefficients for the electromagnetic penguin, $C_{7}^{\mathrm{eff}}$, and the vector and axial-vector electroweak contributions, $C_{9}^{\mathrm{eff}}$ and $C_{10}^{\mathrm{eff}}$, respectively [3]. If physics beyond the SM contributes to $b \rightarrow s \ell^{+} \ell^{-}$decays, then the effective Wilson coeffi-
cients are expected to differ from the SM expectations. Therefore the decay rate and angular distributions of $b \rightarrow s \ell^{+} \ell^{-}$decays constitute good probes to search for new physics [4].

Inclusive measurements of the $b \rightarrow s \ell^{+} \ell^{-}$process are preferable to exclusive measurements because of lower theoretical uncertainties, although they are experimentally more challenging. The branching fraction for inclusive $B \rightarrow X_{s} \ell^{+} \ell^{-}$, where $B$ is either $\bar{B}^{0}$ or $B^{-}, \ell$ is either an electron or a muon, and $X_{s}$ is a hadronic recoil system with an $s$ quark, has been measured by Belle [5] and BABAR [6]. Both results are consistent with the

SM prediction. The lepton forward-backward asymmetry, defined as

$$
\begin{align*}
& \mathcal{A}_{\mathrm{FB}}\left(q_{\min }^{2}, q_{\max }^{2}\right) \\
& \quad=\frac{\int_{q_{\min }^{2}}^{q_{\max }^{2}} d q^{2} \int_{-1}^{1} d \cos \theta \operatorname{sgn}(\cos \theta) \frac{d^{2} \Gamma}{d q^{2} d \cos \theta}}{\int_{q_{\min }^{2}}^{q_{\max }^{2}} d q^{2} \int_{-1}^{1} d \cos \theta \frac{d^{2} \Gamma}{d q^{2} d \cos \theta}} \tag{1}
\end{align*}
$$

is considered to have different and greater sensitivity to physics beyond the SM than the branching fraction $[7,8]$. Here, $q^{2}$ is the squared four-momentum of the dilepton system and $\theta$ is the angle between the $\ell^{+}\left(\ell^{-}\right)$and the $B$ meson momentum in the $\ell^{+} \ell^{-}$center-of-mass frame in $\bar{B}^{0}$ or $B^{-}\left(B^{0}\right.$ or $\left.B^{+}\right)$decays. Although $\mathcal{A}_{\mathrm{FB}}$ in exclusive $B \rightarrow K^{(*)} \ell^{+} \ell^{-}$has been measured by Belle [9], BABAR [10], CDF [11], LHCb [12] and CMS [13], $\mathcal{A}_{\mathrm{FB}}$ in inclusive $B \rightarrow X_{s} \ell^{+} \ell^{-}$is yet to be measured. At lowest order, the numerator in Eq. 1 for inclusive $B \rightarrow X_{s} \ell^{+} \ell^{-}$can be written [14] as a function of $q^{2}$

$$
\begin{align*}
& \int_{-1}^{1} \operatorname{sgn}(\cos \theta) \frac{d^{2} \Gamma}{d q^{2} d \cos \theta} d \cos \theta \\
& \quad=-3 \Gamma_{0} m_{b}^{3} c^{8}(1-s)^{2} s C_{10} \operatorname{Re}\left(C_{9}+\frac{2}{s} C_{7}\right) \tag{2}
\end{align*}
$$

where $m_{b}$ is the $b$-quark mass, $s=q^{2} /\left(m_{b}^{2} c^{2}\right)$, and $\Gamma_{0}=$ $\frac{G_{F}^{2}}{48 \hbar^{6} c^{6} \pi^{3}} \frac{\alpha_{\mathrm{em}}}{16 \pi^{2}}\left|V_{t b} V_{t s}^{*}\right|^{2}$. Here, $G_{F}$ is the Fermi coupling constant, $V_{t b}$ and $V_{t s}$ are Cabibbo-Kobayashi-Maskawa matrix elements [15], and $\alpha_{\mathrm{em}}$ is the fine-structure constant.

We report the first measurement of the lepton forwardbackward asymmetry for inclusive $B \rightarrow X_{s} \ell^{+} \ell^{-}$, which is extrapolated from the sum of 10 exclusive $X_{s}$ states with an invariant mass $M_{X_{s}}<2.0 \mathrm{GeV} / c^{2}$, corresponding to $50 \%$ of the inclusive rate. We also report this asymmetry for the subsamples of $B \rightarrow K^{(*)} \ell^{+} \ell^{-}$with the $X_{s}$ invariant mass $M_{X_{s}}<1.1 \mathrm{GeV} / c^{2}$ and $B \rightarrow X_{s} \ell^{+} \ell^{-}$ with $M_{X_{s}}>1.1 \mathrm{GeV} / c^{2}$, where this asymmetry for $B \rightarrow K \ell^{+} \ell^{-}$is expected to be zero in the SM. We assume that $\mathcal{A}_{\mathrm{FB}}$ is independent of lepton flavor. When the final state $X_{s}$ is not a $K^{(*)}$, we also assume $\mathcal{A}_{\text {FB }}$ depends neither on $X_{s}$ nor on the $X_{s}$ mass. The results are based on the full $\Upsilon(4 S)$ data sample containing $772 \times 10^{6} B \bar{B}$ pairs recorded with the Belle detector [16] at the KEKB $e^{+} e^{-}$collider [17].

## II. DETECTOR

The Belle detector is a general-purpose magnetic spectrometer which consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), time-offlight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of $\mathrm{CsI}(\mathrm{Tl})$ crystals. The devices are located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron fluxreturn located outside the coil is instrumented to detect
$K_{L}^{0}$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [16].

## III. SIGNAL MODEL

We study the acceptance for $B \rightarrow X_{s} \ell^{+} \ell^{-}$via Monte Carlo (MC) simulation. For this simulation, we use a sum of exclusive $B \rightarrow K^{(*)} \ell^{+} \ell^{-}$events and non-resonant $B \rightarrow X_{s} \ell^{+} \ell^{-}$events with $M_{X_{s}}>1.1 \mathrm{GeV} / c^{2}$. The former are generated according to Refs. [4, 18], while the latter are generated using a model based on Refs. $[4,19]$ and the Fermi motion model of Ref. [20]. The two MC samples are mixed assuming the measured branching fractions [21].

## IV. EVENT SELECTION

Charged tracks are reconstructed with the SVD and CDC, and the tracks other than $K_{S}^{0} \rightarrow \pi^{+} \pi^{-}$daughters are required to originate from the interaction region. Electrons are identified by a combination of the specific ionization $(d E / d x)$ in the CDC , the ratio of the cluster energy in the ECL to the track momentum measured with the SVD and CDC, the response of the ACC, the shower shape in the ECL, and position matching between the shower and the track. Muons are identified by the track penetration depth and hit scatter in the KLM. Electrons and muons are required to have momenta greater than $0.4 \mathrm{GeV} / c$ and $0.8 \mathrm{GeV} / c$, respectively. To recover bremsstrahlung photons from leptons, we add the fourmomentum of each photon detected within 0.05 rad of the original track direction. Charged kaons are identified by combining information from the $d E / d x$ in the CDC, the flight time measured with the TOF, and the response of the ACC [22]. We select electron, muon, and kaon candidate tracks in turn, while the remaining tracks are assumed to be charged pions.
$K_{S}^{0}$ candidates are formed by combining two oppositely charged tracks, assuming both are pions with requirements on their invariant mass, flight length, and consistency between the $K_{S}^{0}$ momentum direction and vertex position. Neutral pion candidates are formed from pairs of photons that have an invariant mass within $10 \mathrm{MeV} / c^{2}$ of the nominal $\pi^{0}$ mass, where photons are measured as an energy cluster in the ECL with no associated charged tracks. Neutral pions and their photon daughters are required to have an energy greater than 400 MeV and 50 MeV , respectively. A mass-constrained fit is then performed to obtain the $\pi^{0}$ momentum.

We reconstruct $X_{s}$ from 18 hadronic final states (see Table I), that consist of one $K^{ \pm}$or $K_{S}^{0}$ and up to four pions, of which at most one can be neutral. To reject a large part of the combinatorial background, we require $M_{X_{s}}<2 \mathrm{GeV} / c^{2}$, which preserves $91 \%$ of signal.

We combine the $X_{s}$ with two oppositely charged leptons to form a $B$ meson candidate. To identify the

TABLE I. The 18 hadronic final states used to reconstruct $X_{s}$. The 8 final states enclosed in parentheses are not used for the measurement of $\mathcal{A}_{\text {FB }}$.

| $B^{0}$ decays |  | $B^{-}$decays |  |
| :--- | :--- | :--- | :--- |
| $\left(K_{S}^{0}\right)$ | $K^{-}$ |  |  |
| $K^{-} \pi^{+}$ | $\left(K_{S}^{0} \pi^{0}\right)$ | $K^{-} \pi^{0}$ | $K_{0}^{0} \pi^{-}$ |
| $K^{-} \pi^{+} \pi^{0}$ | $\left(K_{0}^{0} \pi^{-} \pi^{+}\right)$ | $K^{-} \pi^{+} \pi^{-}$ | $K_{0}^{0} \pi^{-} \pi^{0}$ |
| $K^{-} \pi^{+} \pi^{-} \pi^{+} \quad\left(K_{S}^{0} \pi^{-} \pi^{+} \pi^{0}\right)$ | $K^{-} \pi^{+} \pi^{-} \pi^{0}$ | $K_{0}^{0} \pi^{-} \pi^{+} \pi^{-}$ |  |
| $\left(K^{-} \pi^{+} \pi^{-} \pi^{+} \pi^{0}\right)\left(K_{S}^{0} \pi^{-} \pi^{+} \pi^{-} \pi^{+}\right)\left(K^{-} \pi^{+} \pi^{-} \pi^{+} \pi^{-}\right)\left(K_{S}^{0} \pi^{-} \pi^{+} \pi^{-} \pi^{0}\right)$ |  |  |  |

signal, we use two kinematic variables defined in the $\Upsilon(4 S)$ rest frame: the beam-energy constrained mass $M_{\mathrm{bc}}=\sqrt{E_{\mathrm{beam}}^{* 2}-\left|\vec{p}_{B}\right|^{2}}$, and the energy difference $\Delta E=$ $E_{B}-E_{\text {beam }}^{*}$, where $E_{\text {beam }}^{*}$ is the beam energy and $\left(\vec{p}_{B}, E_{B}\right)$ is the reconstructed momentum and energy of the $B$ candidate. We require $M_{\mathrm{bc}}>5.22 \mathrm{GeV} / c^{2}$ and $-100 \mathrm{MeV}<\Delta E<50 \mathrm{MeV}(-50 \mathrm{MeV}<\Delta E<50$ MeV ) for the electron (muon) channel.

To reject large contamination from charmonium backgrounds $B \rightarrow J / \psi(\psi(2 S)) X_{s}$ followed by $J / \psi(\psi(2 S)) \rightarrow$ $\ell^{+} \ell^{-}$, we reject events having dilepton invariant mass in the following veto regions: -400 to $150 \mathrm{MeV} / c^{2}(-250$ to $100 \mathrm{MeV} / c^{2}$ ) around the $J / \psi$ mass and -250 to 100 $\mathrm{MeV} / c^{2}\left(-150\right.$ to $\left.100 \mathrm{MeV} / c^{2}\right)$ around the $\psi(2 S)$ mass for the electron (muon) channel. In the electron channel, there is non-negligible peaking background from events in which the bremsstrahlung photon recovery fails and instead the radiated photon together with another random photon forms a misreconstructed $\pi^{0}$ as $X_{s}$ 's daughter. To veto such events, the $\pi^{0}$ 's photon daughter with the highest energy is added in the calculation of the dilepton invariant mass, and events with invariant mass from $150 \mathrm{MeV} / c^{2}$ below to $50 \mathrm{MeV} / c^{2}$ above the nominal $J / \psi$ mass are rejected for the modes involving $\pi^{0}$. We also require the dilepton mass to be greater than $0.2 \mathrm{GeV} / c^{2}$ to remove the photon conversion and $\pi^{0}$ Dalitz decays.

## V. BACKGROUND SUPPRESSION

The main background comes from random combinations of two semileptonic $B$ or $D$ decays, which have both large missing energy due to neutrinos, and displaced origin of leptons from $B$ or $D$ mesons. The displacement between the two leptons is measured by the distance $\Delta z_{\ell^{+} \ell^{-}}$ between the points of closest approach to the beam axis along the beam direction. We also use the confidence level of the $B$ vertex $\left(\mathcal{C}_{\mathrm{vtx}}\right)$, constructed from all charged daughter particles except for $K_{S}^{0}$ daughters. We set requirements on $\Delta z_{\ell^{+} \ell^{-}}$and $\mathcal{C}_{\mathrm{vtx}}$ to preserve about $79 \%$ of the signal while rejecting $66 \%$ of the background. Other background originates from $e^{+} e^{-} \rightarrow q \bar{q}(q=u, d, s, c)$ continuum events, which can be efficiently suppressed using event shape variables.

To suppress the continuum background and further reduce the semileptonic background, we employ a neural network based on the software package "NeuroBayes"
[23]. The inputs to the network are (i) a likelihood ratio based on $\Delta E$, (ii) the cosine of the angle between the $B$ candidate and the beam axis in the $\Upsilon(4 S)$ rest frame, (iii) $\Delta z_{\ell^{+} \ell^{-}}$, (iv) $\mathcal{C}_{\mathrm{vtx}}$, (v) the total visible energy, (vi) the missing mass [24], and (vii) 17 event shape variables based on modified Fox-Wolfram moments [25]. For the different types of backgrounds (semileptonic and continuum), the neural network is trained separately and requirements on two output values are chosen to maximize the statistical significance. This optimization is performed separately for electron and muon channels and for the regions $M_{X_{s}}<1.1 \mathrm{GeV} / c^{2}$ and $M_{X_{s}}>1.1 \mathrm{GeV} / c^{2}$, and the obtained selection preserves $51 \%$ (63\%) of the signal while rejecting $98 \%$ ( $96 \%$ ) of the background for electron (muon) channels. According to the MC simulation, $83 \%$ of the remaining background consists of semileptonic events.

The probability of multiple $B$ candidates in a signal event is $8 \%$ with the average number of $B$ candidates per signal event being 1.1. When multiple $B$ candidates are found in an event, we select the most signal-like $B$ candidate based on the neural network output. For the measurement of $\mathcal{A}_{\mathrm{FB}}$, information on the flavor of the $B$ candidate is necessary. For $\bar{B}^{0}$ mesons, only the selftagging modes with a $K^{-}$are kept, after selecting one $B$ candidate per event. We also remove candidates with $X_{s}$ reconstructed from one kaon plus four pions because expected signal yields are less than one event. Therefore, we use 10 final states as listed in Table I for the $X_{s}$ to measure $\mathcal{A}_{\mathrm{FB}}$.

## VI. MAXIMUM LIKELIHOOD FIT

To examine the $q^{2}$ dependence of $\mathcal{A}_{\mathrm{FB}}$, we divide the data into 4 bins of measured $q^{2}:[0.2,4.3],[4.3,7.3(8.1)]$, [10.5(10.2), 11.8(12.5)], $[14.3,25.0] \mathrm{GeV}^{2} / c^{2}$ for the electron (muon) channel, where the gap regions correspond to the veto regions for charmonium background events. The bins are numbered in the order of increasing $q^{2}$; the lowest $q^{2}$ for bin number 1 , and the highest for bin number 4 . In order to extract $\mathcal{A}_{\mathrm{FB}}$, an extended unbinned maximum likelihood fit to four $M_{\mathrm{bc}}$ distributions (positive/negative $\cos \theta$ for electron/muon channel) is simultaneously performed for each $q^{2}$ bin. We also measure $\mathcal{A}_{\mathrm{FB}}$ in the low- $q^{2}$ region, $1<q^{2}<6 \mathrm{GeV}^{2} / c^{2}$, where it is theoretically clean.

The raw asymmetry $\mathcal{A}_{\mathrm{FB}}^{\mathrm{raw}}=\frac{N(\cos \theta>0)-N(\cos \theta<0)}{N(\cos \theta>0)+N(\cos \theta<0)}$, where $N$ is the observed signal yields, differs from $\mathcal{A}_{\mathrm{FB}}$ due to the dependence of the signal reconstruction efficiency on $q^{2}$ and $\cos \theta$. Figure 1 show the reconstruction efficiencies on a plane of $q^{2}$ and $\cos \theta$. This pronounced dependence arises from events with low $q^{2}$ and high $\cos \theta$ having lepton momenta below the event selection requirements. We define $\alpha$ as a scaling factor that relates $\mathcal{A}_{\mathrm{FB}}^{\text {raw }}$ to $\mathcal{A}_{\mathrm{FB}}$. We assume that $\mathcal{A}_{\mathrm{FB}}$ does not depend on the lepton flavor. However, $\mathcal{A}_{\mathrm{FB}}$ in the second and third $q^{2}$ bins do differ between electron and muon channels due to


FIG. 1. Reconstruction efficiency on a plane of $q^{2}$ and $\cos \theta$ for (a) the electron and (b) the muon channels. The $J / \psi$ and $\psi(2 S)$ veto regions are shown as hatched regions.
the distinct charmonium-veto regions. We identify $\mathcal{A}_{\text {FB }}$ as the fit parameter for the $q^{2}$ regions of the muon channel and then introduce the scaling factor $\beta$ between the values in the electron and muon channels. With these factors, the fit parameter $\mathcal{A}_{\mathrm{FB}}$ is

$$
\begin{align*}
\mathcal{A}_{\mathrm{FB}} & \equiv \mathcal{A}_{\mathrm{FB}}^{\mu \mu} \\
& =\beta \cdot \mathcal{A}_{\mathrm{FB}}^{e e}, \text { where } \\
\mathcal{A}_{\mathrm{FB}}^{\ell \ell} & =\alpha^{\ell \ell} \cdot \mathcal{A}_{\mathrm{FB}}^{\text {raw }, \ell \ell} \quad(\ell=e, \mu) . \tag{3}
\end{align*}
$$

To derive $\alpha^{\ell \ell}(\ell=e, \mu)$, we generate several sets of signal MC samples with various Wilson coefficients $\left(C_{7}\right.$, $C_{9}, C_{10}$ ), and calculate $\mathcal{A}_{\mathrm{FB}}^{\ell \ell}$ for each set. We evaluate $\mathcal{A}_{\mathrm{FB}}^{\text {raw }, \ell \ell}$ using the reconstruction efficiency as a function of $q^{2}$ and $\cos \theta$. We derive $\alpha^{\ell \ell}$ by fitting the relation between $\mathcal{A}_{\mathrm{FB}}^{\ell \ell}$ and $\mathcal{A}_{\mathrm{FB}}^{\mathrm{raw}, \ell \ell}$ to a straight line. In the first $q^{2}$ bin, the quite distinct values of $\alpha$ between electron and muon channels reflect the different lepton momentum selection criteria. To derive $\beta$, we fit the relation between $\mathcal{A}_{\mathrm{FB}}^{e e}$ and $\mathcal{A}_{\mathrm{FB}}^{\mu \mu}$ in the same way. The values of $\alpha$ and $\beta$ are summarized in Table II.

The likelihood function consists of four components: signal, self cross-feed, combinatorial background, and peaking background. The signal is modeled with a Gaussian function with parameters obtained from the $B \rightarrow J / \psi X_{s}$ data. The self cross-feed is described by a MC histogram, where the yield ratio to the signal is fixed according to the MC expectation. The combinato-
rial background is modeled by an ARGUS function [26], where the endpoint is fixed to the nominal beam energy in the $\Upsilon(4 S)$ rest frame, $E_{\text {beam }}^{*}=5.289 \mathrm{GeV}$. We have three peaking background sources. First is charmonium peaking background, $B \rightarrow J / \psi(\psi(2 S)) X_{s}$ decays with The yields and shape of these charmonium peaking backgrounds is modeled by histogram shape of charmonium MC samples. The yields of charmonium peaking background are estimated to be $0.9 \pm 0.2$ and $2.1 \pm 0.2$ events in the electron and muon channels, respectively. We treat contributions from charmonium resonances higher than $\psi(2 S)$ as signal. Second is $B \rightarrow D^{(*)} n \pi(n>0)$ decay with misidentification of two charged pions as two leptons. The yields and shape of this peaking background is determined directly from the data by performing the analysis without the lepton identification requirements. Taking the $\pi \rightarrow \ell$ misidentification rates into account, We estimate this peaking background to be $0.07 \pm 0.01$ and $5.0 \pm 0.2$ events in the electron and muon channels, respectively. Third is $B \rightarrow J / \psi(\psi(2 S)) X_{s}$ with swapped misidentification between a lepton and a pion. The yields and shape of this peaking background is determined directly from the data by performing the analysis selecting dilepton invariant mass around $J / \psi$ and $\psi(2 S)$. Taking the $\pi \rightarrow \ell$ misidentification rates and particle identification efficiencies into account, we estimate this peaking background to be $0.06 \pm 0.02$ and $4.3 \pm 0.2$ events in the electron and muon channels, respectively.

## VII. SYSTEMATIC UNCERTAINTIES

To estimate systematic uncertainties, we repeat the $\mathcal{A}_{\mathrm{FB}}$ fit with varied input parameters and the resulting change in $\mathcal{A}_{\mathrm{FB}}$ is taken as the systematic uncertainty for the varied parameter. Systematic uncertainties for $\mathcal{A}_{\text {FB }}$ are summarized in Table III. In the 1st $q^{2}$ bin, the dominant systematic uncertainty arises from the translation of $\mathcal{A}_{\mathrm{FB}}^{\text {raw }}$ to $\mathcal{A}_{\mathrm{FB}}$ with $\alpha$ and $\beta$. Even if a MC sample with a different set of Wilson coefficients produces the same values of $\mathcal{A}_{\mathrm{FB}}$, the $\mathcal{A}_{\mathrm{FB}}^{\text {raw }}$ values and hence the $\alpha$ coefficient may differ. It gives rise to an uncertainty of the offset in the linear fit. To estimate this uncertainty, the relation between $\mathcal{A}_{\mathrm{FB}}^{\text {raw }}$ and $\mathcal{A}_{\mathrm{FB}}$ are projected onto the axis perpendicular to the fitted linear line and fitted by a Gaussian function. To estimate systematic uncertainties from the peaking background, the yield of each such background is varied by its uncertainty. For the charmonium peaking background, the yield is varied by $\pm 100 \%$, conservatively, because it is determined from MC events. A possible peaking background from $B \rightarrow K n \pi \ell \nu(n>0)$, where one pion is misidentified as a lepton and the missing neutrino is compensated by a pion of the other $B$ decay, is examined. The number of events in the whole $q^{2}$ region is estimated from MC to be $0.2 \pm 0.6(1.1 \pm 0.7)$ for electron (muon) channel, and the resulting systematic error is $\mathcal{O}(0.001)$. In the 2nd $q^{2}$ bin, the systematic uncertainty from charmonium

TABLE II. Fit results for the five $q^{2}$ bins. For $\mathcal{A}_{\mathrm{FB}}$, the first uncertainty is statistical and the second uncertainty is systematic. $\mathcal{A}_{\mathrm{FB}}$ values predicted by the $\mathrm{SM}[4,7]$ are also shown with systematic uncertainties. For the signal yields, only statistical uncertainties are shown. The uncertainties of $\alpha$ and $\beta$ are due to the statistical uncertainties of the MC.

|  | 1st $q^{2}$ bin | $2 \mathrm{nd} q^{2}$ bin | $3 \mathrm{rd} q^{2}$ bin | 4th $q^{2}$ bin |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $q^{2}$ range $\left[\mathrm{GeV}^{2} / c^{2}\right]$ | $[0.2,4.3]$ | $[4.3,7.3]_{X_{s} e^{+} e^{-}}$ | $[10.5,11.8]_{X_{s} e^{+} e^{-}}$ | $[14.3,25.0]$ | $[1.0,6.0]$ |
| $\mathcal{A}_{\mathrm{FB}}$ | $0.34 \pm 0.24 \pm 0.03$ | $[4.3,8.1]_{X_{s} \mu^{+} \mu^{-}}$ | $[10.2,12.5]_{X_{s} \mu^{+} \mu^{-}}$ |  |  |
| $\mathcal{A}_{\mathrm{FB}}$ (theory) | $-0.11 \pm 0.03$ | $0.13 \pm 0.31 \pm 0.05$ | $0.28 \pm 0.21 \pm 0.02$ | $0.28 \pm 0.15 \pm 0.02$ | $0.30 \pm 0.24 \pm 0.04$ |
| $N_{\text {sig }}^{e e}$ | $45.6 \pm 10.9$ | $30.0 \pm 9.2$ | $0.32 \pm 0.04$ | $0.40 \pm 0.04$ | $-0.07 \pm 0.04$ |
| $N_{\text {sig }}^{\mu \mu}$ | $43.4 \pm 9.2$ | $23.9 \pm 10.4$ | $25.0 \pm 7.0$ | $39.2 \pm 9.6$ | $50.3 \pm 11.4$ |
| $\alpha_{\text {ee }}^{e e}$ | $1.289 \pm 0.004$ | $1.139 \pm 0.003$ | $30.7 \pm 9.9$ | $62.8 \pm 10.4$ | $35.3 \pm 9.2$ |
| $\alpha^{\mu \mu}$ | $2.082 \pm 0.010$ | $1.375 \pm 0.003$ | $1.063 \pm 0.003$ | $1.121 \pm 0.003$ | $1.255 \pm 0.003$ |
| $\beta$ | 1.000 | $1.019 \pm 0.003$ | $1.003 \pm 0.003$ | $1.082 \pm 0.003$ | $1.863 \pm 0.006$ |
|  |  |  |  | 1.000 | 1.000 |

peaking background is dominant. To estimate the systematic uncertainties from signal modeling, the related parameters are varied. The fraction of $B \rightarrow K^{(*)} \ell^{+} \ell^{-}$ and non-resonant $B \rightarrow X_{s} \ell^{+} \ell^{-}$are varied within experimental uncertainties. $B \rightarrow K^{(*)} \ell^{+} \ell^{-}$MC samples are generated with different form factors [27, 28]. The Fermi motion parameter is varied in accordance with measurements of hadronic moments in semileptonic $B$ decays [29] and the photon spectrum in inclusive $B \rightarrow X_{s} \gamma$ decays [30]. The $b$-quark pole mass is varied by $\pm 0.15$ $\mathrm{GeV} / c^{2}$ around $4.80 \mathrm{GeV} / c^{2}$. The threshold point of non-resonant $B \rightarrow X_{s} \ell^{+} \ell^{-}$events is varied by $\pm 100$ $\mathrm{MeV} / c^{2}$ around $M_{X_{s}}=1.1 \mathrm{GeV} / c^{2}$. In the region $M_{X_{s}}<1.1 \mathrm{GeV} / c^{2}$, there is possible contamination from the non-resonant $S$-wave component of the $K \pi$ system. Nevertheless, we find negligible systematic uncertainty from this effect by adding $5 \%$ contributions of $S$-wave components to the dominant $K^{*}$ in this $M_{X_{s}}$ region [31]. We check the hadronization process in the non-resonant $B \rightarrow X_{s} \ell^{+} \ell^{-}$events by comparing the $B \rightarrow J / \psi X_{s}$ events in data and MC simulations. To estimate the systematic uncertainties related to $X_{s}$ spin components, we generate non-resonant $B \rightarrow X_{s} \ell^{+} \ell^{-}$MC samples with spin 0 and 1 using the form factor for $B \rightarrow K^{(*)} \ell^{+} \ell^{-}$. In these MC samples, $X_{s}$ always decays to the two-body $K \pi$ final states to enhance the effect of the $X_{s}$ spin. We replace the nominal non-resonant $B \rightarrow X_{s} \ell^{+} \ell^{-}$MC samples with these MC samples, and estimate the systematic uncertainty from the difference between MC samples with spin 0 and 1 . The signal shape parameters are fixed using the $J / \psi X_{s}$ data. The mean and width of the signal Gaussian function are varied within their uncertainties. The histogram shape of the self cross-feed background is estimated from signal MC events. The entries in the bins are varied according to a Gaussian distribution whose standard deviation is the statistical uncertainty of the MC sample. The total systematic uncertainty is estimated by summing the above uncertainties in quadrature.

## VIII. FORWARD-BACKWARD ASYMMETRY

Figure $2,3,4,5$, and 6 show the $M_{\mathrm{bc}}$ distributions for $B \rightarrow X_{s} e^{+} e^{-}$and $B \rightarrow X_{s} \mu^{+} \mu^{-}$candidates with positive and negative $\cos \theta$ in each $q^{2}$ bin. The total signal yields for $B \rightarrow X_{s} e^{+} e^{-}$and $B \rightarrow X_{s} \mu^{+} \mu^{-}$are $140 \pm$ 19 (stat) and $161 \pm 20$ (stat), respectively. The fit results obtained in each $q^{2}$ bins are summarized in Table II. Figure 7 shows the $\mathcal{A}_{\mathrm{FB}}$ distribution as a function of $q^{2}$. The $\mathcal{A}_{\mathrm{FB}}$ results are found to be consistent with the SM prediction in the 2 nd to 4 th $q^{2}$ bins, while it deviates from the SM in the 1 st $q^{2}$ bin by $1.8 \sigma$; here, the systematic uncertainty is taken into account. The results in the 3rd and 4 th bin also excludes $\mathcal{A}_{\mathrm{FB}}<0$ at the $2.3 \sigma$ level.

To distinguish the contributions from $B \rightarrow K \ell^{+} \ell^{-}$, $B \rightarrow K^{*} \ell^{+} \ell^{-}$, and non- $K^{(*)} \ell^{+} \ell^{-}$candidates, we divide the samples into distinct $M_{X_{s}}$ ranges and extract $\mathcal{A}_{\mathrm{FB}}$ by the same fitting method. Table IV shows the $\mathcal{A}_{\text {FB }}$ values in each subsample. $\mathcal{A}_{\mathrm{FB}}$ in $B \rightarrow K \ell^{+} \ell^{-}$is consistent with null, as expected in the SM, while $\mathcal{A}_{\mathrm{FB}}$ in $B \rightarrow$ $K^{*} \ell^{+} \ell^{-}$is consistent with previous measurements [9-13].

## IX. CONCLUSION

In conclusion, we report the first measurement of the lepton forward-backward asymmetry for the electroweak penguin process $B \rightarrow X_{s} \ell^{+} \ell^{-}$using a data sample containing $772 \times 10^{6} B \bar{B}$ pairs collected with the Belle detector. $\mathcal{A}_{\mathrm{FB}}$ for the inclusive $B \rightarrow X_{s} \ell^{+} \ell^{-}$is extrapolated from the sum of 10 exclusive $X_{s}$ states, assuming $\mathcal{A}_{\text {FB }}$ depends neither on the lepton flavor nor on the $X_{s}$ mass. For $q^{2}>10.2 \mathrm{GeV}^{2} / c^{2}, \mathcal{A}_{\mathrm{FB}}<0$ is excluded at the $2.3 \sigma$ level. For $q^{2}<4.3 \mathrm{GeV}^{2} / c^{2}$, the result is within $1.8 \sigma$ of the SM expectation. The results can be used to constrain various extensions of the SM.

## X. ACKNOWLEDGEMENT

We thank T. Morozumi and T. Goto for their invaluable suggestions. We thank the KEKB group for the

TABLE III. Summary of systematic uncertainties in the five $q^{2}$ bins.

| Sources of uncertainties | 1 st $q^{2}$ bin | 2nd $q^{2}$ bin | 3rd $q^{2}$ bin | 4th $q^{2}$ bin | $1<q^{2}<6 \mathrm{GeV}^{2} / \mathrm{c}^{2}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| Translation from $\mathcal{A}_{\mathrm{FB}}^{\text {raw }}$ to $\mathcal{A}_{\mathrm{FB}}$ | 0.019 | 0.013 | 0.007 | 0.003 | 0.020 |
| Peaking background | 0.004 | 0.050 | 0.007 | 0.002 | 0.021 |
| Signal modeling | 0.018 | 0.003 | 0.021 | 0.017 | 0.019 |
| Signal shape and self cross-feed | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 |
| Total | 0.027 | 0.052 | 0.023 | 0.017 | 0.035 |

TABLE IV. Fit results for subsamples of (i) $B \rightarrow K \ell^{+} \ell^{-}$, (ii) $B \rightarrow K^{-} \pi^{+} \ell^{+} \ell^{-}, K^{-} \pi^{0} \ell^{+} \ell^{-}$, or $K_{S}^{0} \pi^{-} \ell^{+} \ell^{-}$with $M_{X_{s}}<1.1$ $\mathrm{GeV} / c^{2}$, and (iii) $B \rightarrow X_{s} \ell^{+} \ell^{-}$with $M_{X_{s}}>1.1 \mathrm{GeV} / c^{2}$ for the five $q^{2}$ bins. The uncertainty includes only statistical uncertainty. Unfortunately, $\mathcal{A}_{\mathrm{FB}}$ for $B \rightarrow K \ell^{+} \ell^{-}$can not be obtained in 3rd $q^{2}$ bin, due to too low statistics.

| State | 1st $q^{2}$ bin | 2nd $q^{2}$ bin | 3rd $q^{2}$ bin | 4th $q^{2}$ bin | $1<q^{2}<6 \mathrm{GeV}^{2} / c^{2}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $K$ | $-0.05 \pm 0.24$ | $-0.11 \pm 0.29$ | n.a. | $0.12 \pm 0.18$ | $0.00 \pm 0.13$ |
| $K^{*}$ with $M_{X_{s}}<1.1 \mathrm{GeV} / c^{2}$ | $0.62 \pm 0.42$ | $0.20 \pm 0.33$ | $0.01 \pm 0.34$ | $0.21 \pm 0.22$ | $0.55 \pm 0.43$ |
| $X_{s}$ with $M_{X_{s}}>1.1 \mathrm{GeV} / c^{2}$ | $0.25 \pm 0.45$ | $0.97 \pm 0.60$ | $0.92 \pm 0.32$ | $0.65 \pm 0.54$ | $0.74 \pm 0.54$ |

excellent operation of the accelerator; the KEK cryogenics group for the efficient operation of the solenoid; and the KEK computer group, the National Institute of Informatics, and the PNNL/EMSL computing group for valuable computing and SINET4 network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan, the Japan Society for the Promotion of Science (JSPS), and the Tau-Lepton Physics Research Center of Nagoya University; the Australian Research Council; Austrian Science Fund under Grant No. P 22742N16 and P 26794-N20; the National Natural Science Foundation of China under Contracts No. 10575109, No. 10775142 , No. 10875115 , No. 11175187, No. 11475187 and No. 11575017; the Chinese Academy of Science Center for Excellence in Particle Physics; the Ministry of Education, Youth and Sports of the Czech Republic under Contract No. LG14034; the Carl Zeiss Foundation, the Deutsche Forschungsgemeinschaft, the Excellence Cluster Universe, and the VolkswagenStiftung; the Department of Science and Technology of India; the Istituto Nazionale di Fisica Nucleare of Italy; the WCU program of the Ministry of Education, National Research Foundation (NRF) of Korea Grants No. 20110029457, No. 2012-0008143, No. 2012R1A1A2008330, No. 2013R1A1A3007772, No. 2014R1A2A2A01005286, No. 2014R1A2A2A01002734, No. 2015R1A2A2A01003280, No. 2015H1A2A1033649; the Basic Research Lab program under NRF Grant No. KRF-2011-0020333, Center for Korean J-PARC Users, No. NRF-2013K1A3A7A06056592; the Brain Korea 21-Plus program and Radiation Science Research Institute; the Polish Ministry of Science and Higher Education and the National Science Center; the Ministry of Education and Science of the Russian Federation and the Russian Foundation for Basic Research; the Slovenian Research Agency; Ikerbasque, Basque Foundation for Science and the Euskal Herriko Unibertsitatea (UPV/EHU) under program UFI 11/55
(Spain); the Swiss National Science Foundation; the Ministry of Education and the Ministry of Science and Technology of Taiwan; and the U.S. Department of Energy and the National Science Foundation. This work is supported by a Grant-in-Aid from MEXT for Science Research in a Priority Area ("New Development of Flavor Physics") and from JSPS for Creative Scientific Research ("Evolution of Tau-lepton Physics").


FIG. 2. $M_{\mathrm{bc}}$ distributions in 1st $q^{2}$ bin for (a) $B \rightarrow X_{s} e^{+} e^{-}$candidates with $\cos \theta>0$, (b) $B \rightarrow X_{s} e^{+} e^{-}$candidates with $\cos \theta<0$, (c) $B \rightarrow X_{s} \mu^{+} \mu^{-}$candidates with $\cos \theta>0$, and (d) $B \rightarrow X_{s} \mu^{+} \mu^{-}$candidates with $\cos \theta<0$. The thicker dashed curve (red) shows the sum of the signal and the self cross-feed components. The thinner dashed curve (green) shows the combinatorial background component. The filled histogram (gray) shows the peaking background component. The sums of all components are shown by the solid curve (blue).


FIG. 3. $M_{\mathrm{bc}}$ distributions in $2 \mathrm{nd} q^{2}$ bin for (a) $B \rightarrow X_{s} e^{+} e^{-}$candidates with $\cos \theta>0$, (b) $B \rightarrow X_{s} e^{+} e^{-}$candidates with $\cos \theta<0$, (c) $B \rightarrow X_{s} \mu^{+} \mu^{-}$candidates with $\cos \theta>0$, and (d) $B \rightarrow X_{s} \mu^{+} \mu^{-}$candidates with $\cos \theta<0$. The thicker dashed curve (red) shows the sum of the signal and the self cross-feed components. The thinner dashed curve (green) shows the combinatorial background component. The filled histogram (gray) shows the peaking background component. The sums of all components are shown by the solid curve (blue).


FIG. 4. $M_{\mathrm{bc}}$ distributions in $3 \mathrm{rd} q^{2}$ bin for (a) $B \rightarrow X_{s} e^{+} e^{-}$candidates with $\cos \theta>0$, (b) $B \rightarrow X_{s} e^{+} e^{-}$candidates with $\cos \theta<0$, (c) $B \rightarrow X_{s} \mu^{+} \mu^{-}$candidates with $\cos \theta>0$, and (d) $B \rightarrow X_{s} \mu^{+} \mu^{-}$candidates with $\cos \theta<0$. The thicker dashed curve (red) shows the sum of the signal and the self cross-feed components. The thinner dashed curve (green) shows the combinatorial background component. The filled histogram (gray) shows the peaking background component. The sums of all components are shown by the solid curve (blue).


FIG. 5. $M_{\mathrm{bc}}$ distributions in 4 th $q^{2}$ bin for (a) $B \rightarrow X_{s} e^{+} e^{-}$candidates with $\cos \theta>0,(\mathrm{~b}) B \rightarrow X_{s} e^{+} e^{-}$candidates with $\cos \theta<0$, (c) $B \rightarrow X_{s} \mu^{+} \mu^{-}$candidates with $\cos \theta>0$, and (d) $B \rightarrow X_{s} \mu^{+} \mu^{-}$candidates with $\cos \theta<0$. The thicker dashed curve (red) shows the sum of the signal and the self cross-feed components. The thinner dashed curve (green) shows the combinatorial background component. The filled histogram (gray) shows the peaking background component. The sums of all components are shown by the solid curve (blue).


FIG. 6. $M_{\mathrm{bc}}$ distributions in the low- $q^{2}$ region, $1<q^{2}<6 \mathrm{GeV}^{2}$ for (a) $B \rightarrow X_{s} e^{+} e^{-}$candidates with $\cos \theta>0$, (b) $B \rightarrow X_{s} e^{+} e^{-}$candidates with $\cos \theta<0$, (c) $B \rightarrow X_{s} \mu^{+} \mu^{-}$candidates with $\cos \theta>0$, and (d) $B \rightarrow X_{s} \mu^{+} \mu^{-}$candidates with $\cos \theta<0$. The thicker dashed curve (red) shows the sum of the signal and the self cross-feed components. The thinner dashed curve (green) shows the combinatorial background component. The filled histogram (gray) shows the peaking background component. The sums of all components are shown by the solid curve (blue).


FIG. 7. Measured $\mathcal{A}_{\text {FB }}$ as a function of $q^{2}$. The curve (black) with the band (red) and dashed boxes (black) represent the SM prediction while filled circles with error bars show the fit results. The $J / \psi$ and $\psi(2 \mathrm{~S})$ veto regions are shown as teal hatched regions. For the electron channel, the pink shaded regions are added to the veto regions due to the large bremsstrahlung effect. The uncertainty on the SM prediction is estimated by varying the $b$-quark mass ( $4.80 \pm 0.15$ $\left.\mathrm{GeV} / c^{2}\right)$, the $s$-quark mass $\left(0.20 \pm 0.10 \mathrm{GeV} / c^{2}\right)$, and the renormalization scale ( $\mu=2.5$ and 5 GeV ) [4, 7]. The lower edge of the uncertainty is set to zero in the $q^{2}$ region larger than maximum possible value, which is determined by the masses of the bottom and strange quarks.
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