## Angular Analysis of $B^{0} \rightarrow K^{*}(892)^{0} \ell^{+} \ell^{-}$

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We present a measurement of angular observables, $P_{4}^{\prime}, P_{5}^{\prime}, P_{6}^{\prime}, P_{8}^{\prime}$, in the decay $B^{0} \rightarrow$ $K^{*}(892)^{0} \ell^{+} \ell^{-}$, where $\ell^{+} \ell^{-}$is either $e^{+} e^{-}$or $\mu^{+} \mu^{-}$. The analysis is performed on a data sample corresponding to an integrated luminosity of $711 \mathrm{fb}^{-1}$ containing $772 \times 10^{6} B \bar{B}$ pairs, collected at the $\Upsilon(4 S)$ resonance with the Belle detector at the asymmetric-energy $e^{+} e^{-}$collider KEKB. Four angular observables, $P_{4,5,6,8}^{\prime}$ are extracted in five bins of the invariant mass squared of the lepton system, $q^{2}$. We compare our results for $P_{4,5,6,8}^{\prime}$ with Standard Model predictions including the $q^{2}$ region in which the LHCb collaboration reported the so-called $P_{5}^{\prime}$ anomaly.

## I. INTRODUCTION

Rare decays of $B$ mesons are an ideal probe to search beyond the Standard Model (SM) of particle physics, since contributions from new particles lead to effects that are of similar size as the SM predictions. The rare decay $B^{0} \rightarrow K^{*}(892)^{0} \ell^{+} \ell^{-}$involves the quark transition $b \rightarrow s \ell^{+} \ell^{-}$, a flavor changing neutral current that is forbidden at tree level in the SM. Higher order SM processes such as penguin or $W^{+} W^{-}$box diagrams allow for such transitions, leading to branching fractions of less than one in a million. Various extensions to the SM predict contributions from new physics, which can interfere with the SM amplitudes and lead to enhanced or suppressed branching fractions or modified angular distributions of the decay products.

We present an angular analysis, using the decay modes $B^{0} \rightarrow K^{*}(892)^{0} \mu^{+} \mu^{-}$and $B^{0} \rightarrow K^{*}(892)^{0} e^{+} e^{-}$, in a data sample recorded with the Belle detector. The LHCb collaboration reported a discrepancy in the angular distribution of the decay $B^{0} \rightarrow K^{*}(892)^{0} \mu^{+} \mu^{-}$, corresponding to a $3.4 \sigma$ deviation from the SM prediction [1]. In contrast to the LHCb measurement here the di-electron channel is also used in this analysis.

## II. DETECTOR AND DATASETS

We use the full $\Upsilon(4 S)$ data sample containing $772 \times$ $10^{6} B \bar{B}$ pairs recorded with the Belle detector [2] at the asymmetric-energy $e^{+} e^{-}$collider KEKB [3].

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of $\mathrm{CsI}(\mathrm{Tl})$ crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron fluxreturn located outside of the coil is instrumented to detect $K_{L}^{0}$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [2].

This analysis is validated and optimized on simulated Monte Carlo (MC) data. The software packages EvtGen [4] and PYTHIA [5] are used to simulate the particle decays. The decay chain is generated, meaning that all intermediate and final state particles are determined. Final state radiation is calculated by the PHOTOS package [6]. The detector response is simulated with the GEANT3 software package [7.

## III. RECONSTRUCTION

For all charged tracks loose impact parameter constraints are applied with respect to the nominal interaction point in the radial direction $(|d r|<1.0 \mathrm{~cm})$ and along the beam direction $(|d z|<5.0 \mathrm{~cm})$. Belle
provides a particle identification (PID) likelihood calculated from the energy loss in the $\operatorname{CDC}(\mathrm{d} E / \mathrm{d} x)$, time-offlight, response of ACC, shape and size of the showers in the ECL and information about hits in the KLM. Electrons are identified using the likelihood ratio $\mathcal{P}_{\text {eid }}(e)=$ $L(e) /(L(e)+L$ (hadron) $)$. All charged tracks satisfying $\mathcal{P}_{\text {eid }}(e)>0.1$ are accepted as electrons. To recover the original momentum of the electrons, a search for photons in a cone of 0.05 radians around the initial momentum direction of the track is performed. If photons are found in this region, their momenta are added to the electron. Charged tracks are accepted as muons if they satisfy the muon likelihood ratio requirement $\mathcal{P}_{\text {muid }}(\mu)>0.1$. Charged kaons are selected with the requirement on the likelihood $\mathcal{P}(K / \pi)=L(K) /(L(K)+L(\pi))>0.1$. For $\pi^{ \pm}$candidates no PID selection is applied.
$K^{*}$ candidates are formed in the channel $K^{* 0} \rightarrow$ $K^{+} \pi^{-}$. For these candidates, an invariant mass requirement of $0.6 \mathrm{GeV} / c^{2}<M_{K^{*}}<1.4 \mathrm{GeV} / c^{2}$ is applied and a vertex fit is performed, which is used for background suppression later on.

In the final stage of the reconstruction $K^{*}$ candidates are combined with oppositely charged lepton pairs to form $B$ meson candidates. The large combinatoric background is suppressed by applying requirements on kinematic variables. Two independent variables can be constructed using constraints that in $\Upsilon(4 S)$ decays $B$ mesons are produced pairwise and each carries half the center-ofmass (CM) frame beam energy, $E_{\text {Beam }}$. These variables are the beam constrained mass, $M_{\mathrm{bc}}$, and the energy difference, $\Delta E$, in which signal features a distinct distribution that can discriminate against background. The variables are defined in the $\Upsilon(4 S)$ rest frame as

$$
\begin{align*}
M_{\mathrm{bc}} & \equiv \sqrt{E_{\mathrm{Beam}}^{2} / c^{4}-\left|\vec{p}_{B}\right|^{2} / c^{2}} \text { and }  \tag{1}\\
\Delta E & \equiv E_{B}-E_{\mathrm{Beam}} \tag{2}
\end{align*}
$$

where $E_{B}$ and $\left|\vec{p}_{B}\right|$ are the energy and momentum of the reconstructed candidate, respectively. Correctly reconstructed candidates are located around the nominal $B$ mass in $M_{\mathrm{bc}}$ and feature $\Delta E$ of around zero. Candidates are selected satisfying $5.22<M_{\mathrm{bc}}<5.3 \mathrm{GeV} / c^{2}$ and $-0.10(-0.05)<\Delta E<0.05 \mathrm{GeV}$ for $\ell=e(\ell=\mu)$.

Large irreducible background contributions arise from charmonium decays $B \rightarrow K^{(*)} J / \psi$ and $B \rightarrow K^{(*)} \psi(2 S)$, in which the $c \bar{c}$ state decays into two leptons. These decays have the same signature as the desired signal and are vetoed with the following requirements on $q^{2}=M_{\ell^{+} \ell^{-}}$, the invariant mass of the lepton pair:

$$
\begin{aligned}
& -0.25 \mathrm{GeV} / c^{2}<M_{e e(\gamma)}-m_{J / \psi}<0.08 \mathrm{GeV} / c^{2} \\
& -0.15 \mathrm{GeV} / c^{2}<M_{\mu \mu}-m_{J / \psi}<0.08 \mathrm{GeV} / c^{2} \\
& -0.20 \mathrm{GeV} / c^{2}<M_{e e(\gamma)}-m_{\psi(2 S)}<0.08 \mathrm{GeV} / c^{2} \text { and } \\
& -0.10 \mathrm{GeV} / c^{2}<M_{\mu \mu}-m_{\psi(2 S)}<0.08 \mathrm{GeV} / c^{2}
\end{aligned}
$$

In the electron case, the 4-momentum of detected photons from the bremsstrahlung recovery process is added
before these requirements are applied. Di-electron background can also arise from photon conversions $(\gamma \rightarrow$ $e^{+} e^{-}$) and $\pi^{0}$ Dalitz decays ( $\pi^{0} \rightarrow e^{+} e^{-} \gamma$ ). We require $M_{e(\gamma) e(\gamma)}>0.14 \mathrm{GeV} / c^{2}$. For the $B$ meson candidates, a vertex fit is performed, which is used for background suppression. From this fit the distance between the two leptons along the beam direction $\Delta z_{\ell \ell}$ is also derived.

## IV. BACKGROUND SUPPRESSION

In the selection of $B$ candidates we face different sources of possible backgrounds. In continuum background events, $e^{+} e^{-}$annihilates into light quark pairs $u \bar{u}, d \bar{d}, s \bar{s}$ as well as events containing charm quarks $c \bar{c}$. These initial quark pairs however exhibit a large energy release, forming back to back jet-like structures. Combinatorial background arises from incorrect combinations of tracks in $B \bar{B}$ decays, which is the dominant source of background. Finally, a process is referred to as "peaking background" when it mimics the signal shape in $M_{\mathrm{bc}}$. For the peaking background several sources have to be taken into account: (1) irreducible background from $B \rightarrow K^{*} J / \psi$ and $B \rightarrow K^{*} \psi(2 S)$ events, which passes the $q^{2}$ vetoes; (2) doubly misidentified events from $B \rightarrow K^{*} \pi \pi$ can occur when both pions are misidentified as muons.

To maximize signal efficiency and purity, neural networks are developed sequentially from the bottom to the top of the decay chain, transferring each time the output probability to the subsequent step so that the most effective selection requirements are applied in the last stage based on all information combined. All particle candidates are analyzed with a neural network (NeuroBayes [8]) and an output, $N B_{\text {out }}$, is assigned. This output is chosen to correspond to a Bayesian probability in the range $[0,1]$ where the value of one corresponds to signal. To transfer quality information about the primary particles in the detector to higher stage composite particles $\left(K^{*}\right.$ and $\left.B\right)$ the network output of the secondary particles of each candidate is included as neural network input. In this manner the classifiers for the $B$ mesons have $N B_{\text {out }}$ for both leptons and the $K^{*}$ included as input. The classifiers for $e^{ \pm}, \mu^{ \pm}, K^{ \pm}$and $\pi^{ \pm}$are taken from the neural network based full reconstruction, widely used at Belle 9 . They use kinematic variables as inputs as well as variables derived from the particle identification system, for instance TOF and KLM information and energy loss in the CDC. For $K^{*}$ selection a classifier is trained on simulated data using kinematic variables and vertex fit information. The final classification is performed with a requirement on the neural network output $N B_{\text {out }}$ for the $B$ mesons. Separate classifiers are trained for $B^{0} \rightarrow K^{*}(892)^{0} \mu^{+} \mu^{-}$and $B^{0} \rightarrow K^{*}(892)^{0} e^{+} e^{-}$ using event shape variables (i.e. Fox Wolfram Moments [10]), vertex fit information and kinematic variables. The most important variables for the neural networks are $\Delta E$, the reconstructed mass of the $K^{*}$, the product of the net-
work outputs of all secondary particles and the distance between the two leptons along the beam direction $\Delta z_{\ell \ell}$. In case of multiple candidates per event the most probable candidate is chosen, based on the neural network output $N B_{\text {out }}$. The final neural network output for signal and background events is displayed in Figure 1.

The selection requirement for the neural networks are optimized for the sensitivity of the angular analysis using pseudo experiments with simulated data, described in Section VI.

## V. SIGNAL YIELDS

Signal and background yields are extracted by an unbinned extended maximum likelihood fit to the $M_{\mathrm{bc}}$ distribution of $B^{0} \rightarrow K^{*}(892)^{0} \ell^{+} \ell^{-}$candidates. The signal distribution is parametrized by an empirically determined function introduced by the Crystal Ball Collaboration [11]. This so-called Crystal Ball function accounts for radiative tails in the distribution and for the calorimeter resolution. All shape parameters are determined by a fit to data in the control channel $B \rightarrow K^{*} J / \psi$ in the corresponding $q^{2}$ veto region and fixed in the extraction of the $B^{0} \rightarrow K^{*}(892)^{0} \ell^{+} \ell^{-}$yield. The background distribution is parametrized by an empirically determined shape introduced by the ARGUS Collaboration [12] and its shape parameters are floated in the fit. The result of the fits are shown in Figure 2 In the total $q^{2}$ range there are $118 \pm 12$ signal candidates for $B^{0} \rightarrow K^{*}(892)^{0} \mu^{+} \mu^{-}$ and $69 \pm 12$ for $B^{0} \rightarrow K^{*}(892)^{0} e^{+} e^{-}$. For the angular analysis the number of signal events $n_{\text {sig }}$ and background events $n_{\mathrm{bkg}}$ in the signal region $M_{\mathrm{bc}}>5.27 \mathrm{GeV} / c^{2}$ are obtained by a fit to $M_{\mathrm{bc}}$ in bins of $q^{2}$. The extracted yields and the definition of the bin ranges are presented in Table I. As a cross-check, the branching fractions for both modes are calculated and found to be consistent with PDG values within statistical errors.

TABLE I. Fitted yields and statistical error for signal ( $n_{\text {sig }}$ ) and background ( $n_{\mathrm{bkg}}$ ) events in the binning of $q^{2}$ for both the combined electron and muon channel.

| Bin | $q^{2}$ range in $\mathrm{GeV}^{2} / c^{4}$ | $n_{\text {sig }}$ | $n_{\text {bkg }}$ |
| :---: | :---: | :---: | :---: |
| 0 | $1.00-6.00$ | $49.5 \pm 8.4$ | $30.3 \pm 5.5$ |
| 1 | $0.10-4.00$ | $30.9 \pm 7.4$ | $26.4 \pm 5.1$ |
| 2 | $4.00-8.00$ | $49.8 \pm 9.3$ | $35.6 \pm 6.0$ |
| 3 | $10.09-12.90$ | $39.6 \pm 8.0$ | $19.3 \pm 4.4$ |
| 4 | $14.18-19.00$ | $56.5 \pm 8.7$ | $16.0 \pm 4.0$ |

## VI. ANGULAR ANALYSIS

We perform an angular analysis of $B^{0} \rightarrow$ $K^{*}(892)^{0} \ell^{+} \ell^{-}$including the electron and muon modes. The decay is kinematically described by three angles $\theta_{\ell}, \theta_{K}$ and $\phi$ and the invariant mass squared


FIG. 1. Performance of the neural networks for the classification of $B^{0} \rightarrow K^{*}(892)^{0} \ell^{+} \ell^{-}$. Signal MC (red line) and simulated background processes from $e^{+} e^{-} \rightarrow q \bar{q}(q=u, d, s, c, b)$ decays (blue filled) corresponding to two times the expected size in the Belle dataset are shown.


FIG. 2. Signal extraction for $B \rightarrow K^{(*)} \ell^{+} \ell^{-}$on the total range of $q^{2}$. Combinatorial (dashed blue), signal (red filled) and total (solid) fit distributions are superimposed on the data points.
of the lepton pair $q^{2}$. The angle $\theta_{\ell}$ is defined as the angle between the direction of $\ell^{+}\left(\ell^{-}\right)$and the opposite direction of $B(\bar{B})$ in the rest frame of the dilepton system. The angle $\theta_{K}$ is defined between the direction of the kaon and the opposite direction of $B(\bar{B})$ in the $K^{*}$ rest frame. Finally, the angle $\phi$ is determined as the angle between the decay plane formed by the $\ell^{+} \ell^{-}$system and the $K^{*}$ decay plane. Definitions of the angles follow Ref. [13]. The analysis is performed
in four bins of $q^{2}$ with an additional zeroth bin in the range $1.0<q^{2}<6.0 \mathrm{GeV}^{2} / c^{4}$, which is considered to be the cleanest regarding form-factor uncertainties [14]. The binning in $q^{2}$ is detailed in Table I together with the measured signal and background yields. Uncovered regions in the $q^{2}$ spectrum arise from vetoes against backgrounds of the charmonium resonances $J / \psi \rightarrow \ell^{+} \ell^{-}$ and $\psi(2 S) \rightarrow \ell^{+} \ell^{-}$and vetos against $\pi^{0}$ Dalitz decays and photon conversion.

The full angular distribution of $B \rightarrow K^{* 0}\left(\rightarrow K^{ \pm} \pi^{\mp}\right) \ell^{+} \ell^{-}$can be parametrized using definitions presented in Ref. [14] by

$$
\begin{align*}
\frac{1}{\mathrm{~d} \Gamma / \mathrm{d} q^{2}} \frac{\mathrm{~d}^{4} \Gamma}{\mathrm{~d} \cos \theta_{\ell} \mathrm{d} \cos \theta_{K} \mathrm{~d} \phi \mathrm{~d} q^{2}}= & \frac{9}{32 \pi}\left[\frac{3}{4}\left(1-F_{L}\right) \sin ^{2} \theta_{K}+F_{L} \cos ^{2} \theta_{K}\right. \\
& +\frac{1}{4}\left(1-F_{L}\right) \sin ^{2} \theta_{K} \cos 2 \theta_{\ell} \\
& -F_{L} \cos ^{2} \theta_{K} \cos 2 \theta_{\ell}+S_{3} \sin ^{2} \theta_{K} \sin ^{2} \theta_{\ell} \cos 2 \phi \\
& +S_{4} \sin 2 \theta_{K} \sin 2 \theta_{\ell} \cos \phi+S_{5} \sin 2 \theta_{K} \sin \theta_{\ell} \cos \phi \\
& +S_{6} \sin ^{2} \theta_{K} \cos \theta_{\ell}+S_{7} \sin 2 \theta_{K} \sin \theta_{\ell} \sin \phi \\
& \left.+S_{8} \sin 2 \theta_{K} \sin 2 \theta_{\ell} \sin \phi+S_{9} \sin ^{2} \theta_{K} \sin ^{2} \theta_{\ell} \sin 2 \phi\right] \tag{3}
\end{align*}
$$

where the observables $F_{L}$ and $S_{i}$ are functions of $q^{2}$ only. The observables are functions of Wilson coefficients, containing information about the short-distance effects and can be affected by new physics. The observables $P_{i}^{\prime}$, introduced in Ref. [15], defined as

$$
\begin{equation*}
P_{i=4,5,6,8}^{\prime}=\frac{S_{j=4,5,7,8}}{\sqrt{F_{L}\left(1-F_{L}\right)}} \tag{4}
\end{equation*}
$$

are considered to be largely free from form-factor uncertainties [16]. In total, there are eight free parameters, which can be obtained from a fit to the data. The statistics in this analysis are not sufficient to perform an eight-dimensional fit. In the following a folding technique is described, which reduces the number of fitting parameters and hence improves the convergence of the fit. The folding is applied to specific regions in the threedimensional angular space, exploiting the symmetries of the cosine and sine functions to cancel terms in Eq. (3). As a consequence the number of free parameters in the fit is reduced without losing experimental sensitivity. This procedure is explained in more detail in Refs. 17] and [18]. With the following transformations to the dataset one can be sensitive to the observable of interest:

$$
\begin{gather*}
P_{4}^{\prime}, S_{4}: \begin{cases}\phi \rightarrow-\phi & \text { for } \phi<0 \\
\phi \rightarrow \pi-\phi & \text { for } \theta_{\ell}>\pi / 2 \\
\theta_{\ell} \rightarrow \pi-\theta_{\ell} & \text { for } \theta_{\ell}>\pi / 2\end{cases}  \tag{5}\\
P_{5}^{\prime}, S_{5}: \begin{cases}\phi \rightarrow-\phi & \text { for } \phi<0 \\
\theta_{\ell} \rightarrow \pi-\theta_{\ell} & \text { for } \theta_{\ell}>\pi / 2\end{cases}  \tag{6}\\
P_{6}^{\prime}, S_{7}: \begin{cases}\phi \rightarrow \pi-\phi & \text { for } \phi>\pi / 2 \\
\phi \rightarrow-\pi-\phi & \text { for } \phi<-\pi / 2 \\
\theta_{\ell} \rightarrow \pi-\theta_{\ell} & \text { for } \theta_{\ell}>\pi / 2\end{cases} \tag{7}
\end{gather*}
$$

$$
P_{8}^{\prime}, S_{8}: \begin{cases}\phi \rightarrow \pi-\phi & \text { for } \phi>\pi / 2  \tag{8}\\ \phi \rightarrow-\pi-\phi & \text { for } \phi<-\pi / 2 \\ \theta_{K} \rightarrow \pi-\theta_{K} & \text { for } \theta_{\ell}>\pi / 2 \\ \theta_{\ell} \rightarrow \pi-\theta_{\ell} & \text { for } \theta_{\ell}>\pi / 2\end{cases}
$$

Each of the transformations causes all $S_{i}$ terms of Eq. (3), except for $S_{3}$ and the corresponding $S_{i}$ term, to vanish. The number of free parameters of each transformed decay rate is consequently reduced to three: $F_{L}, S_{3}$ and one of the observables $S_{4,5,7,8}$ or $P_{4,5,6,8}^{\prime}$.

One can extract the transverse polarization asymmetry $A_{T}^{(2)}$ with the transformation: $A_{T}^{(2)}=2 S_{3} /\left(1-F_{L}\right)$. To parameterize the background we use smoothed template histograms. A three-dimensional PDF is constructed by multiplying the histograms of each projection of the angular variables:

$$
\begin{array}{r}
f_{\mathrm{bkg}}^{\mathrm{hist}}\left(q^{2}, \cos \theta_{\ell}, \cos \theta_{K}, \phi\right)= \\
h_{1}\left(q^{2}, \cos \theta_{\ell}\right) \cdot h_{2}\left(q^{2}, \cos \theta_{K}\right) \cdot h_{3}\left(q^{2}, \phi\right)
\end{array}
$$

This method is fast and robust even if the background shape is complex. The correlation in the background sample between the observables is negligible allowing for this procedure. However, it introduces systematic deviations from the true PDF due to statistical fluctuations. To compensate for this, the histograms are smoothed with an algorithm introduced in Ref. [19, which takes into account Poisson errors for bins with a small number of entries. This method aims to optimize the pull distribution from smoothed histograms to the original histogram with statistical fluctuations by a least square minimization.

All methods are tested in toy MC studies using simulated events where each measurement is performed 10,000 times. The most important optimization is that of the neural network requirement for both $B^{0} \rightarrow$ $K^{*}(892)^{0} e^{+} e^{-}$and $B^{0} \rightarrow K^{*}(892)^{0} \mu^{+} \mu^{-}$, which determines the signal to background ratio in the fit. The sensitivity is optimized by minimizing the total error of
$P_{5}^{\prime}$ in $q^{2}$ bin 2. In the toy studies this is calculated as the linear sum of the mean statistical error from the toy study $e_{\text {stat }}$, the systematic error from a fit bias $e_{\text {bias }}$ and the estimated error from peaking background $\hat{e}_{\text {peaking }}$. From this procedure, the estimated sensitivity for each pair of requirements is obtained.

## VII. ACCEPTANCE AND EFFICIENCY

We account for acceptance and efficiency effects in the fit by assigning weights to the data. We weight each event by the inverse of its combined efficiency, which is derived from the direct product of the efficiencies of the angular observables and $q^{2}$. The individual reconstruction efficiency for each observable $x$ is obtained by extracting the differences between the reconstructed and generated distributions. In order to minimize statistical fluctuations in this process, the generated distribution is transformed to a flat distribution. For $x_{\text {gen }}$ from generated events in the signal MC the corresponding cumulative density distribution is derived by a spline interpolation $s_{\text {gen }}$ from a histogram of the cumulative density distribution of $x_{\mathrm{gen}}$. In the next step we transform the $x_{\text {rec }}$ value from reconstructed signal MC events, which include reconstruction and acceptance effects, with $s_{\text {gen }}$ and derive the distribution of the reconstruction efficiency. The distribution of the reconstruction efficiency follows

$$
\begin{equation*}
x_{\mathrm{eff}}=s_{\mathrm{gen}}\left(x_{\mathrm{rec}}\right) \tag{9}
\end{equation*}
$$

The final efficiency for each observable is then fitted with a spline fit $s_{\text {eff }}$ to the distribution of $x_{\text {eff }}$, which fits orthogonal splines to the data so that the pull between the fit and the data-points becomes a Gaussian with width one and mean zero. Finally, the efficiency $\epsilon(x)$ for observable $x$ is calculated from

$$
\begin{equation*}
\epsilon(x)=s_{\mathrm{eff}}\left(s_{\mathrm{gen}}(x)\right) \tag{10}
\end{equation*}
$$

The combined efficiency $f_{\text {eff }}^{\text {bin }}$ is determined in each bin of $q^{2}$ and is calculated by

$$
\begin{align*}
f_{\mathrm{eff}}^{\mathrm{bin}}\left(\cos \theta_{\ell}, \cos \theta_{K}, \phi, q^{2}\right)= & \epsilon\left(\cos \theta_{\ell}\right) \otimes \epsilon\left(\cos \theta_{K}\right) \otimes \epsilon(\phi) \otimes \\
& \epsilon\left(q^{2}\right) \tag{11}
\end{align*}
$$

assuming that the efficiency is uncorrelated in the threedimensional angular space, which is validated for the systematic uncertainties. The fits for the efficiencies in the $q^{2}$ range $4<q^{2}<8 \mathrm{GeV}^{2} / c^{4}$ are shown in Figure 3. In the final fit the weights are normalized, so that the sum of all weights equals the total number of events in the fit.

## VIII. FIT PROCEDURE

The signal and background fractions are derived from a fit to $M_{\mathrm{bc}}$ beforehand, where the yields are listed in Table The $M_{\mathrm{bc}}$ variable is split into a signal (upper) and
sideband (lower) region at $5.27 \mathrm{GeV} / c^{2}$. In the second step the shape of the background for the angular observables is estimated on the $M_{\mathrm{bc}}$ sideband. This is possible as the angular observables have shown to be uncorrelated to $M_{\mathrm{bc}}$ in the background sample.

All observables $P_{4,5,6,8}^{\prime}$ are extracted from the data in the signal region using three-dimensional unbinned maximum likelihood fits in four bins of $q^{2}$ and the additional zeroth bin using the folded signal PDF, fixed background shapes and a fixed number of signal events. Each $P_{4,5,6,8}^{\prime}$ is fitted with $F_{L}$ and $A_{T}^{(2)}$. Counting also the zeroth bin, which exhibits overlap with the range of the first and second bin, 20 measurements are performed.

## IX. SYSTEMATIC STUDIES

For the angular analysis sources of systematic uncertainty are considered, if they introduce an angular or $q^{2}$ dependent bias to the distributions of signal or background candidates. Systematic uncertainties are examined using pseudo-experiments with large signal yields in order to minimize statistical fluctuations and compare the nominal with a varied model. The variation between the average of two models is taken as systematic uncertainty. Observed differences between data and MC are modeled within the fit for the efficiency correction as a bias. A systematic error is derived from the difference between the results from a fit with the nominal efficiency correction and the modified correction including differences observed on data. Due to the limited number of candidates in some measurements, a fit bias is observed in some bins of the angular analysis. In 10,000 pseudo experiments on simulated data the fit for each measurement is performed and the results are compared to the simulated values. The mean of the pull distribution from the toy study is used for each measurement to determine a systematic bias on the measurement. The central values of the measurements are not corrected for the bias but the absolute value of the deviation is assigned as a systematic error. For the fit of the reconstruction efficiency function a factorization of the efficiencies in the angular observables and $q^{2}$ is assumed, which is not the case for $\cos \theta_{\ell}$ in the low $q^{2}$ region. The deviation in a simulated dataset with efficiency correction weights and a dataset based on generator truth is evaluated. The difference between the two fits is taken into account as a systematic uncertainty for the efficiency correction in the fit.

Peaking backgrounds are estimated for each $q^{2}$ bin using MC. In total less than six such background events are expected in the muon channel, and less than one in the electron channel. The impact of the peaking component is simulated by repeating the toy study and replacing six randomly selected events from the signal with events from the peaking background in each bin. The mean deviation of the procedure is $\pm 0.027$ for the value of $P_{4,5,6,8}^{\prime}$, which corresponds to approximately $2-5 \%$


FIG. 3. Example for the fits of the efficiencies in $q^{2}$ bin 2. Both the efficiency fits (solid lines) for the electron (black) and muon (red) channel are superimposed over the ratio of generated and reconstructed events (data points).
of the statistical error. The signal cross-feed is calculated for the $B^{0}$ decay channels ( $B^{0} \rightarrow K^{*}(892)^{0} \mu^{+} \mu^{-}$, $\left.B^{0} \rightarrow K^{*}(892)^{0} e^{+} e^{-}, B^{0} \rightarrow K^{0} \mu^{+} \mu^{-}, B^{0} \rightarrow K^{0} e^{+} e^{-}\right)$ and found to be insignificant. The parametrization in Eq. (3) does not include a potential $S$-wave contribution from $K^{*}(892)$ decays. The fraction $F_{S}$ is searched for in our data by fitting the invariant mass of the $K \pi$ pair resulting in $F_{S}$ being consistent with zero with a small uncertainty. If there is a production, detection or direct $\mathcal{C P}$ asymmetry observed, the measured $\mathcal{C P}$-symmetric parameters, must be corrected. Since the yields of $B^{0}$ and $\bar{B}^{0}$ events are statistically equal in the signal region of our measurement with 153 and 150 events, respectively, and the theoretical values are small for the $\mathcal{C P}$ asymmetric parameters $A_{i}^{(s)}\left(\lesssim \mathcal{O}\left(10^{-3}\right)[14]\right)$ influences of this kind are neglected. All sources of included systematics are summarized separately for $P_{4}^{\prime}, P_{5}^{\prime}, P_{6}^{\prime}$ and $P_{8}^{\prime}$ in Tables III III, IV and V. The total systematic uncertainty is calculated as the square root of the quadratic sum of all systematic uncertainties.

TABLE II. Summary of all systematic uncertainties for $P_{4}^{\prime}$.

| Bin | 0 | 1 | 2 | 3 | 4 |
| :--- | :--- | :--- | :--- | :--- | :--- |

Peaking Background 0.08550 .06460 .03660 .04570 .0358 Data/MC Difference 0.01090 .00880 .00200 .00030 .0047 Efficiency Correction 0.14750 .02410 .05990 .08770 .0650 | Fit Bias | 0.0316 | 0.0114 | 0.0007 | 0.0558 | 0.0027 |
| :--- | :--- | :--- | :--- | :--- | :--- | :--- | :--- |
| Total | 0.1738 | 0.0704 | 0.0702 | 0.1135 | 0.0744 |

TABLE III. Summary of all systematic uncertainties for $P_{5}^{\prime}$.

| Bin | 0 | 1 | 2 | 3 | 4 |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Peaking Background | 0.0901 | 0.0636 | 0.0078 | 0.0498 | 0.0131 |
| Data/MC Difference | 0.0112 | 0.0067 | 0.0208 | 0.0142 | 0.0029 |
| Efficiency Correction | 0.0397 | 0.0205 | 0.0098 | 0.0215 | 0.0327 |
| Fit Bias | 0.0031 | 0.0061 | 0.0430 | 0.0127 | 0.0460 |
| Total | 0.0992 | 0.0675 | 0.0494 | 0.0575 | 0.0580 |

TABLE IV. Summary of all systematic uncertainties for $P_{6}^{\prime}$.

| Bin | 0 | 1 | 2 | 3 | 4 |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Peaking Background | 0.0170 | 0.0513 | 0.0229 | 0.0215 | 0.0026 |
| Data/MC Difference | 0.1298 | 0.1378 | 0.1655 | 0.2201 | 0.2341 |
| Efficiency Correction | 0.0835 | 0.0432 | 0.0683 | 0.0218 | 0.0192 |
| Fit Bias | 0.0735 | 0.1189 | 0.0562 | 0.0027 | 0.0268 |
| Total | 0.1718 | 0.1939 | 0.1890 | 0.2222 | 0.2364 |

TABLE V. Summary of all systematic uncertainties for $P_{8}^{\prime}$.

| Bin | 0 | 1 | 2 | 3 | 4 |
| :--- | :---: | :---: | :---: | :---: | :---: |
| Peaking Background | 0.1242 | 0.0161 | 0.0395 | 0.0518 | 0.0255 |
| Data/MC Difference | 0.1433 | 0.1630 | 0.1531 | 0.1955 | 0.2316 |
| Efficiency Correction | 0.0319 | 0.0824 | 0.0359 | 0.0418 | 0.0099 |
| Fit Bias | 0.0337 | 0.1033 | 0.0579 | 0.0048 | 0.0047 |
| Total | 0.1952 | 0.2105 | 0.1722 | 0.2065 | 0.2332 |

## X. RESULTS

The measurements are compared with SM predictions based upon different theoretical calculations. Values from DHMV refer to the soft-form-factor method of Ref. [20], which is also used in the LHCb measurement. BSZ corresponds to using QCD form factors computed from LCSRs with $K^{*}$ distribution amplitudes described in [21]. The third set of theoretical predictions is provided by the methods and authors of Refs. [22, 23] whose framework is specially tailored to the low $q^{2}$ region. It is referred to as JC. The results are listed in Table VI and are shown in Figure 5 together with available SM prediction from DHMV and LHCb measurements.

For $P_{5}^{\prime}$ a deviation with respect to the DHMV SM prediction is observed with a significance of $2.1 \sigma$ in the $q^{2}$ range $4.0<q^{2}<8.0 \mathrm{GeV}^{2} / c^{4}$. The fit result is displayed in Figure 4 with the corresponding projections. The distance to the SM prediction from BSZ and JC corresponds to $1.72 \sigma$ and $1.68 \sigma$, respectively.

The discrepancy in $P_{5}^{\prime}$ supports measurements by LHCb [17, where a $3.7 \sigma$ deviation was observed in the region $4.30<q^{2}<8.68 \mathrm{GeV}^{2} / c^{4}$. To avoid unknown theory errors originating from the $J / \psi$ resonance the low $q^{2}$ region is limited to $q^{2}<8.0 \mathrm{GeV}^{2} / c^{4}$ in the present measurement. LHCb performed an update on the analysis 1 with three times the integrated luminosity. In the update the overall discrepancy of the differential distributions with the DHMV SM prediction was $3.4 \sigma$ [1].

## XI. CONCLUSION

We present results of the first angular analysis of $B^{0} \rightarrow K^{*}(892)^{0} \ell^{+} \ell^{-}$in three dimensions at $B$ factories, including both the muon and electron modes. In total $117.6 \pm 12.4$ signal candidates for $B^{0} \rightarrow K^{*}(892)^{0} \mu^{+} \mu^{-}$ and $69.4 \pm 12.0$ signal events for $B^{0} \rightarrow K^{*}(892)^{0} e^{+} e^{-}$are
observed. The signal yields are consistent with those expected from previous measurements. With the combined data of both channels a full angular analysis in three dimensions in five bins of $q^{2}$, the di-lepton invariant mass squared, is performed. A data transformation technique is applied to reduce the dimension of the differential decay rate from eight to three. By this means the fit is independently sensitive to observables $P_{4}^{\prime}, P_{5}^{\prime}, P_{6}^{\prime}$ and $P_{8}^{\prime}$, which are optimized regarding theoretical uncertainties from form-factors. Altogether 20 measurements are performed extracting $P_{4,5,6}^{\prime}$ or $P_{8}^{\prime}$, the $K^{*}$ longitudinal polarization $F_{L}$ and the transverse polarization asymmetry $A_{T}^{(2)}$. The results are compared with SM predictions and overall agreement is observed. One measurement is found to deviate by $2.1 \sigma$ from the predicted value into the same direction and in the same $q^{2}$ region where the LHCb collaboration reported the so-called $P_{5}^{\prime}$ anomaly [1, 17.

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FIG. 4. Projections for the fit result of $P_{5}^{\prime}$ in bin 2. Fit to the $M_{\mathrm{bc}}$ sideband for the determination of the background shape (top) and signal region (bottom) are displayed. Combinatorial (dashed blue), signal (red filled) and total (solid) fit distributions are superimposed on the data points.

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FIG. 5. Result for the $P^{\prime}$ observables compared to SM predictions from various sources described in Section X Results from LHCb [1. 17] are shown for comparison.

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TABLE VI. Results of the angular analysis. The first errors of the measurement are the statistical and the second the systematic error. Observables are compared to SM predictions provided by the authors of Refs. [20, 22, 23].

| $q^{2}$ in $\mathrm{GeV}^{2} / c^{4}$ | Observable | Measurement | DHMV | BSZ | JC |
| :---: | :---: | :---: | :---: | :---: | :---: |
| [1.00, 6.00] | $P_{4}^{\prime}$ | $-0.095_{-0.309}^{+0.302} \pm 0.174$ | - | - | $-0.300_{-0.080}^{+0.090}$ |
|  | $P_{5}^{\prime}$ | $0.385_{-0.285}^{+0.276} \pm 0.099$ | - | - | $-0.360_{-0.170}^{+0.190}$ |
|  | $P_{6}^{\prime}$ | $-0.202_{-0.270}^{+0.278} \pm 0.172$ | - | - | $0.040_{-0.100}^{+0.100}$ |
|  | $P_{8}^{\prime}$ | $0.440_{-0.320}^{+0.311} \pm 0.195$ | - | - | $0.010_{-0.019}^{+0.020}$ |
| [0.10, 4.00] | $P_{4}^{\prime}$ | $0.208_{-0.434}^{+0.400} \pm 0.070$ | $-0.026 \pm 0.098$ | $-0.029 \pm 0.103$ | $-0.010_{-0.060}^{+0.060}$ |
|  | $P_{5}^{\prime}$ | $0.631_{-0.419}^{+0.403} \pm 0.067$ | $0.175 \pm 0.086$ | $0.199 \pm 0.077$ | $0.200_{-0.110}^{+0.110}$ |
|  | $P_{6}^{\prime}$ | $-0.670_{-0.387}^{+0.419} \pm 0.194$ | $-0.055 \pm 0.018$ | $-0.056 \pm 0.018$ | $0.040_{-0.060}^{+0.060}$ |
|  | $P_{8}^{\prime}$ | $-0.309_{-0.472}^{+0.519} \pm 0.210$ | $-0.030 \pm 0.017$ | $-0.031 \pm 0.016$ | $0.006_{-0.033}^{+0.033}$ |
| [4.00, 8.00] | $P_{4}^{\prime}$ | $-0.477_{-0.252}^{+0.266} \pm 0.070$ | $-0.441 \pm 0.106$ | $-0.521 \pm 0.087$ | $-0.490_{-0.060}^{+0.070}$ |
|  | $P_{5}^{\prime}$ | $-0.267_{-0.269}^{+0.275} \pm 0.049$ | $-0.881 \pm 0.082$ | $-0.770 \pm 0.100$ | $-0.810_{-0.140}^{+0.170}$ |
|  | $P_{6}^{\prime}$ | $-0.057_{-0.262}^{+0.264} \pm 0.189$ | $-0.003 \pm 0.011$ | $-0.002 \pm 0.008$ | $0.020_{-0.110}^{+0.110}$ |
|  | $P_{8}^{\prime}$ | $0.130_{-0.259}^{+0.257} \pm 0.172$ | $-0.022 \pm 0.010$ | $-0.020 \pm 0.007$ | $0.007_{-0.021}^{+0.020}$ |
| [10.09, 12.90] | $P_{4}^{\prime}$ | $-0.088_{-0.402}^{+0.414} \pm 0.114$ | - - | - | - |
|  | $P_{5}^{\prime}$ | $-0.504_{-0.327}^{+0.351} \pm 0.057$ | - | - | - |
|  | $P_{6}^{\prime}$ | $-0.341_{-0.326}^{+0.347} \pm 0.222$ | - | - | - |
|  | $P_{8}^{\prime}$ | $-1.017_{-0.374}^{+0.415} \pm 0.207$ | - | - | - |
| [14.18, 19.00] | $P_{4}^{\prime}$ | $-0.371_{-0.252}^{+0.272} \pm 0.074$ | $-0.632 \pm 0.026$ | $-0.632 \pm 0.026$ | - |
|  | $P_{5}^{\prime}$ | $-0.547_{-0.225}^{+0.257} \pm 0.058$ | $-0.601 \pm 0.051$ | $-0.601 \pm 0.051$ | - |
|  | $P_{6}^{\prime}$ | $0.384_{-0.306}^{+0.292} \pm 0.236$ | $-0.004 \pm 0.069$ | $-0.004 \pm 0.069$ | - |
|  | $P_{8}^{\prime}$ | $0.242_{-0.309}^{+0.301} \pm 0.233$ | $-0.001 \pm 0.028$ | $-0.001 \pm 0.028$ | - |

