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# Angular analysis and branching fraction measurement of the decay $B^0 \to K^{*0}\mu^+\mu^-$ ☆

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ABSTRACT

The angular distributions and the differential branching fraction of the decay $B^0 \to K^*(892)^0\mu^+\mu^-$ are studied using a data sample corresponding to an integrated luminosity of 5.2 $fb^{-1}$ collected with the CMS detector at the LHC in pp collisions at $\sqrt{s} = 7$ TeV. From more than 400 signal decays, the forward–backward asymmetry of the muons, the $K^*(892)^0$ longitudinal polarization fraction, and the differential branching fraction are determined as a function of the square of the dimuon invariant mass. The measurements are in good agreement with standard model predictions.



## 1. Introduction

It is possible for new phenomena (NP) beyond the standard model (SM) of particle physics to be observed either directly or indirectly, i.e., through their influence on other physics processes. Indirect searches for NP generally proceed by comparing experimental results with theoretical predictions in the production or decay of known particles. The study of flavor-changing neutral-current decays of b hadrons such as $B^0 \to K^{*0}\mu^+\mu^-$ ($K^{*0}$ indicates the $K^*(892)^0$ and charge conjugate states are implied in what follows, unless explicitly stated otherwise) is particularly fertile for new phenomena searches, given the modest theoretical uncertainties in the predictions and the low rate as the decay is forbidden at tree level in the SM. On the theoretical side, great progress has been made since the first calculations of the branching fraction [1–4], the forward–backward asymmetry of the muons, $A_{FB}$ [5], and the longitudinal polarization fraction of the $K^{*0}$, $F_L$ [6–11]. Robust calculations of these variables [12–19] are now available for much of the phase space of this decay, and it is clear that new physics could give rise to readily observable effects [8,16,20–34]. Finally, this decay mode is relatively easy to select and reconstruct at hadron colliders.

The quantities $A_{FB}$ and $F_L$ can be measured as a function of the dimuon invariant mass squared ($q^2$) and compared to SM predictions [14]. Deviations from the SM predictions can indicate new physics. For example, in the minimal supersymmetric standard model (MSSM) modified with minimal flavor violation, called flavor blind MSSM (FBMSSM), effects can arise through NP contributions to the Wilson coefficient $C_7$ [16]. Another NP example is the MSSM with generic flavor-violating and CP-violating soft SUSY-breaking terms (GMSSM), in which the Wilson coefficients $C_7$, $C_7'$, and $C_{10}$ can receive contributions [16]. As shown there, these NP contributions can dramatically affect the $A_{FB}$ distribution (note that the variable $S_6^s$ defined in Ref. [16] is related to $A_{FB}$ measured in this Letter by $S_6^s = -\frac{4}{3}A_{FB}$), indicating that precision measurements of $A_{FB}$ can be used to identify or constrain new physics.

While previous measurements by BaBar, Belle, CDF, and LHCb are consistent with the SM [35–38], these measurements are still statistically limited, and more precise measurements offer the possibility to uncover physics beyond the SM.

In this Letter, we present measurements of $A_{FB}$, $F_L$, and the differential branching fraction $d\mathcal{B}/dq^2$ from $B^0 \to K^{*0}\mu^+\mu^-$ decays, using data collected from pp collisions at the Large Hadron Collider (LHC) with the Compact Muon Solenoid (CMS) experiment in 2011 at a center-of-mass energy of 7 TeV. The analyzed data correspond to an integrated luminosity of $5.2 \pm 0.1$ $fb^{-1}$ [39]. The $K^{*0}$ is reconstructed through its decay to $K^+\pi^-$ and the $B^0$ is reconstructed by fitting the two identified muon tracks and the two hadron tracks to a common vertex. The values of $A_{FB}$ and $F_L$ are measured by fitting the distribution of events as a function of two angular variables: the angle between the positively charged muon and the $B^0$ in the dimuon rest frame, and the angle between the kaon and the

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$B^0$ in the $K^{*0}$ rest frame. All measurements are performed in $q^2$ bins from 1 to 19 GeV$^2$. The $q^2$ bins $8.68 < q^2 < 10.09$ GeV$^2$ and $12.90 < q^2 < 14.18$ GeV$^2$, corresponding to the $B^0 \to K^{*0} J/\psi$ and $B^0 \to K^{*0}\psi'$ decays ($\psi'$ indicates the $\psi(2S)$ in what follows), respectively, are both used to validate the analysis, and the former is used to normalize the branching fraction measurement.

## 2. CMS detector

A detailed description of the CMS detector can be found elsewhere [40]. The main detector components used in this analysis are the silicon tracker and the muon detection systems. The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.4$, where $\eta = -\ln[\tan(\theta/2)]$ and $\theta$ is the polar angle of the track relative to the beam direction. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules and is located in the 3.8 T field of the superconducting solenoid. The reconstructed tracks have a transverse impact parameter resolution ranging from ≈100 μm to ≈20 μm as the transverse momentum of the track ($p_T$) increases from 1 GeV to 10 GeV. In the same $p_T$ regime, the momentum resolution is better than 1% in the central region, increasing to 2% at $\eta \approx 2$, while the track reconstruction efficiency is nearly 100% for muons with $|\eta| < 2.4$ and varies from ≈95% at $\eta = 0$ to ≈85% at $|\eta| = 2.4$ for hadrons. Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers, all of which are sandwiched between the solenoid flux return steel plates. Events are selected with a two-level trigger system. The first level is composed of custom hardware processors and uses information from the calorimeters and muon systems to select the most interesting events. The high-level trigger processor farm further decreases the event rate from nearly 100 kHz to around 350 Hz before data storage.

## 3. Reconstruction, event selection, and efficiency

The signal ($B^0 \to K^{*0}\mu^+\mu^-$) and normalization/control samples ($B^0 \to K^{*0} J/\psi$ and $B^0 \to K^{*0}\psi'$) were recorded with the same trigger, requiring two identified muons of opposite charge to form a vertex that is displaced from the pp collision region (beamspot). The beamspot position and size were continuously measured from Gaussian fits to reconstructed vertices as part of the online data quality monitoring. Five dimuon trigger configurations were used during 2011 data taking with increasingly stringent requirements to maintain an acceptable trigger rate as the instantaneous luminosity increased. For all triggers, the separation between the beamspot and the dimuon vertex in the transverse plane was required to be larger than three times the sum in quadrature of the distance uncertainty and the beamspot size. In addition, the cosine of the angle between the dimuon momentum vector and the vector from the beamspot to the dimuon vertex in the transverse plane was required to be greater than 0.9. More than 95% of the data were collected with triggers that required single-muon pseudorapidity of $|\eta(\mu)| < 2.2$ for both muons, dimuon transverse momentum of $p_T(\mu\mu) > 6.9$ GeV, single-muon transverse momentum for both muons of $p_T(\mu) > 3.0, 4.0, 4.5, 5.0$ GeV (depending on the trigger), and the corresponding vertex fit probability of $\chi^2_{\text{prob}} > 5\%, 15\%, 15\%, 15\%$. The remaining data were obtained from a trigger with requirements of $|\eta(\mu)| < 2.5$, $\chi^2_{\text{prob}} > 0.16\%$, and $p_T(\mu\mu) > 6.5$ GeV. The events used in this analysis passed at least one of the five triggers.

The decay modes used in this analysis require two reconstructed muons and two charged hadrons, obtained from offline reconstruction. The reconstructed muons are required to match the muons that triggered the event readout and to pass several muon identification requirements, namely a track matched with at least one muon segment, a track fit $\chi^2$ per degree of freedom less than 1.8, at least 11 hits in the tracker with at least 2 from the pixel detector, and a transverse (longitudinal) impact parameter less than 3 cm (30 cm). The reconstructed dimuon system is further required to satisfy the same requirements as were used in the trigger. In events where multiple trigger configurations are satisfied, the requirements associated with the loosest trigger are used.

While the muon requirements are based on the trigger and a CMS standard selection, most of the remaining selection criteria are optimized by maximizing $S/\sqrt{S+B}$, where $S$ is the expected signal yield from Monte Carlo (MC) simulations and $B$ is the background estimated from invariant-mass sidebands in data, defined as $>3\sigma_{m(B^0)}$ and $<5.5\sigma_{m(B^0)}$ from the $B^0$ mass [41], where $\sigma_{m(B^0)}$ is the average $B^0$ mass resolution of 44 MeV. The optimization is performed on one trigger sample, corresponding to an integrated luminosity of 2.7 fb$^{-1}$, requiring $1.0 < q^2 < 7.3$ GeV$^2$ or $16 < q^2 < 19$ GeV$^2$ to avoid $J/\psi$ and $\psi'$ contributions. The hadron tracks are required to fail the muon identification criteria, and have $p_T(h) > 0.75$ GeV and an extrapolated distance of closest approach to the beamspot in the transverse plane greater than 1.3 times the sum in quadrature of the distance uncertainty and the beamspot transverse size. The two hadrons must have an invariant mass within 80 MeV of the nominal $K^{*0}$ mass for either the $K^+\pi^-$ or $K^-\pi^+$ hypothesis. To remove contamination from $\phi$ decays, the hadron-pair invariant mass must be greater than 1.035 GeV when the charged K mass is assigned to both hadron tracks. The $B^0$ candidates are obtained by fitting the four charged tracks to a common vertex and applying a vertex constraint to improve the resolution of the track parameters. The $B^0$ candidates must have $p_T(B^0) > 8$ GeV, $|\eta(B^0)| < 2.2$, vertex fit probability $\chi^2_{\text{prob}} > 9\%$, vertex transverse separation from the beamspot greater than 12 times the sum in quadrature of the separation uncertainty and the beamspot transverse size, and $\cos\alpha_{xy} > 0.9994$, where $\alpha_{xy}$ is the angle, in the transverse plane, between the $B^0$ momentum vector and the line-of-flight between the beamspot and the $B^0$ vertex. The invariant mass of the four-track vertex must also be within 280 MeV of the world-average $B^0$ mass for either the $K^-\pi^+\mu^+\mu^-$ or $K^+\pi^-\mu^+\mu^-$ hypothesis. This selection results in an average of 1.06 candidates per event in which at least one candidate is found. A single candidate is chosen from each event based on the best $B^0$ vertex fit $\chi^2$.

The four-track vertex candidate is identified as a $B^0(\bar{B}^0)$ if the $K^+\pi^-(K^-\pi^+)$ invariant mass is closest to the nominal $K^{*0}$ mass. In cases where both $K\pi$ combinations are within 50 MeV of the nominal $K^{*0}$ mass, the event is rejected since no clear identification is possible owing to the 50 MeV natural width of the $K^{*0}$. The fraction of candidates assigned the incorrect state is estimated from simulations to be 8%.

From the retained events, the dimuon invariant mass $q$ and its corresponding calculated uncertainty $\sigma_q$ are used to distinguish between the signal and normalization/control samples. The $B^0 \to K^{*0} J/\psi$ and $B^0 \to K^{*0}\psi'$ samples are defined as $m_{J/\psi} - 5\sigma_q < q < m_{J/\psi} + 3\sigma_q$ and $|q - m_{\psi'}| < 3\sigma_q$, respectively, where $m_{J/\psi}$ and $m_{\psi'}$ are the world-average mass values. The asymmetric selection of the $J/\psi$ sample is due to the radiative tail in the dimuon spectrum, while the smaller signal in the $\psi'$ mode made an asymmetric selection unnecessary. The signal sample is the complement of the $J/\psi$ and $\psi'$ samples.

The global efficiency, $\epsilon$, is the product of the acceptance and the trigger, reconstruction, and selection efficiencies, all of which are obtained from MC simulations. The pp collisions are simulated using PYTHIA [42] version 6.424, the unstable particles are decayed by EVTGEN [43] version 9.1 (using the default matrix element for the signal), and the particles are traced through a detailed model

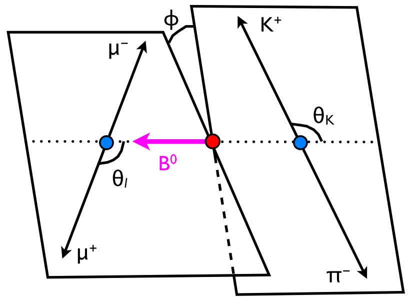


**Fig. 1.** Sketch showing the definition of the angular observables for the decay $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$.

of the detector with GEANT4 [44]. The reconstruction and event selection for the generated samples proceed as for the data events. Three simulation samples were created in which the $B^0$ was forced to decay to $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$, $B^0 \to K^{*0}(K^+\pi^-)J/\psi(\mu^+\mu^-)$, or $B^0 \to K^{*0}(K^+\pi^-)\psi'(\mu^+\mu^-)$. The acceptance is calculated as the fraction of events passing the single-muon cuts of $p_T(\mu) > 2.8$ GeV and $|\eta(\mu)| < 2.3$ relative to all events with a $B^0$ in the event with $p_T(B^0) > 8$ GeV and $|\eta(B^0)| < 2.2$. The acceptance is obtained from the generated events before the particle tracing with GEANT4. To obtain the reconstruction and selection efficiency, the MC simulation events are divided into five samples, appropriately sized to match the amount of data taken with each of the five triggers. In each of the five samples, the appropriate trigger and matching offline event selection is applied. Furthermore, each of the five samples is reweighted to obtain the correct distribution of pileup events (additional pp collisions in the same bunch crossing as the collision that produced the $B^0$ candidate), corresponding to the data period during which the trigger was active. The reconstruction and selection efficiency is the ratio of the number events that pass all the selections and have a reconstructed $B^0$ compatible with the generated $B^0$ in the event relative to the number of events that pass the acceptance criteria. The compatibility of generated and reconstructed particles is enforced by requiring the reconstructed $K^+$, $\pi^-$, $\mu^+$, and $\mu^-$ to have $\sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} < 0.3$ for hadrons and 0.004 for muons, where $\Delta\eta$ and $\Delta\varphi$ are the differences in $\eta$ and $\varphi$ between the reconstructed and generated particles, and $\varphi$ is the azimuthal angle in the plane perpendicular to the beam direction. The efficiency and purity of this compatibility requirement are greater than 99%.

## 4. Analysis method

The analysis measures $A_{FB}$, $F_L$, and $d\mathcal{B}/dq^2$ of the decay $B^0 \to K^{*0}\mu^+\mu^-$ as a function of $q^2$. Fig. 1 shows the relevant angular observables needed to define the decay: $\theta_K$ is the angle between the kaon momentum and the direction opposite to the $B^0$ ($\bar{B}^0$) in the $K^{*0}$ ($\bar{K}^{*0}$) rest frame, $\theta_l$ is the angle between the positive (negative) muon momentum and the direction opposite to the $B^0$ ($\bar{B}^0$) in the dimuon rest frame, and $\phi$ is the angle between the plane containing the two muons and the plane containing the kaon and pion. Since the extracted angular parameters $A_{FB}$ and $F_L$ and the acceptance times efficiency do not depend on $\phi$, $\phi$ is integrated out. Although the $K^+\pi^-$ invariant mass must be consistent with a $K^{*0}$, there can be contributions from a spinless (S-wave) $K^+\pi^-$ combination [45–47]. This is parametrized with two terms related to the S-wave fraction, $F_S$, and the interference amplitude between the S-wave and P-wave decays, $A_S$. Including this component, the angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$ can be written as [47]:

$$\begin{aligned}
&\frac{1}{\Gamma}\frac{d^3\Gamma}{d\cos\theta_K\, d\cos\theta_l\, dq^2} \\
&= \frac{9}{16}\Biggl\{\left[\frac{2}{3}F_S + \frac{4}{3}A_S\cos\theta_K\right]\left(1-\cos^2\theta_l\right) \\
&\quad + (1-F_S)\Bigl[2F_L\cos^2\theta_K\left(1-\cos^2\theta_l\right) \\
&\quad + \frac{1}{2}(1-F_L)\left(1-\cos^2\theta_K\right)\left(1+\cos^2\theta_l\right) \\
&\quad + \frac{4}{3}A_{FB}\left(1-\cos^2\theta_K\right)\cos\theta_l\Bigr]\Biggr\}. \qquad (1)
\end{aligned}$$

The main results of the analysis are extracted from unbinned extended maximum-likelihood fits in bins of $q^2$ to three variables: the $K^+\pi^-\mu^+\mu^-$ invariant mass and the two angular variables $\theta_K$ and $\theta_l$. For each $q^2$ bin, the probability density function (PDF) has the following expression:

$$\begin{aligned}
&\mathrm{PDF}(m, \cos\theta_K, \cos\theta_l) \\
&= Y_S \cdot S(m)\cdot S(\cos\theta_K, \cos\theta_l)\cdot \epsilon(\cos\theta_K, \cos\theta_l) \\
&\quad + Y_{Bc}\cdot B_c(m)\cdot B_c(\cos\theta_K)\cdot B_c(\cos\theta_l) \\
&\quad + Y_{Bp}\cdot B_p(m)\cdot B_p(\cos\theta_K)\cdot B_p(\cos\theta_l). \qquad (2)
\end{aligned}$$

The signal yield is given by the free parameter $Y_S$. The signal shape is described by the product of a function $S(m)$ of the invariant mass variable, the theoretical signal shape as a function of two angular variables, $S(\cos\theta_K, \cos\theta_l)$, and the efficiency as a function of the same two variables, $\epsilon(\cos\theta_K, \cos\theta_l)$. The signal mass shape $S(m)$ is the sum of two Gaussian functions with a common mean. While the mean is free to float, the two resolution parameters and the relative fraction are fixed to the result from a fit to the simulated events. The signal angular function $S(\cos\theta_K, \cos\theta_l)$ is given by Eq. (1). The efficiency function $\epsilon(\cos\theta_K, \cos\theta_l)$, which also accounts for mistagging of a $B^0$ as a $\bar{B}^0$ (and vice versa), is obtained by fitting the two-dimensional efficiency histograms (6 $\cos\theta_K$ bins and 5 $\cos\theta_l$ bins) to polynomials in $\cos\theta_K$ and $\cos\theta_l$. The $\cos\theta_K$ polynomial is degree 3, while the $\cos\theta_l$ polynomial is degree 6, with the 1st and 5th orders removed, as these were the simplest polynomials that adequately described the efficiency in all bins. For some $q^2$ bins, simpler polynomials are used as they are sufficient to describe the data. There are two contributions to the background, with yields given by $Y_{Bp}$ for the "peaking" background and $Y_{Bc}$ for the "combinatorial" background. The peaking background is due to the remaining $B^0 \to K^{*0}J/\psi$ and $B^0 \to K^{*0}\psi'$ decays, not removed by the dimuon mass or $q^2$ requirements. For these events, the dimuon mass is reconstructed far from the true $J/\psi$ or $\psi'$ mass, which results in a reconstructed $B^0$ mass similarly displaced from the true $B^0$ mass. The shapes of this background in the mass, $B_p(m)$, and angular variables, $B_p(\cos\theta_K)$ and $B_p(\cos\theta_l)$, are obtained from simulation of $B^0 \to K^{*0}J/\psi$ and $B^0 \to K^{*0}\psi'$ events, fit to the sum of two Gaussian functions in mass and polynomials in $\cos\theta_K$ and $\cos\theta_l$. The background yield is also obtained from simulation, properly normalized by comparing the reconstructed $B^0 \to K^{*0}J/\psi$ and $B^0 \to K^{*0}\psi'$ yields in data and MC simulation. The remaining background, combinatorial in nature, is described by a single exponential in mass, $B_c(m)$, and a polynomial in each angular variable, $B_c(\cos\theta_K)$ and $B_c(\cos\theta_l)$, varying between degree 0 and 4, as needed to describe the data.

The results of the fit in each $q^2$ bin (including the $J/\psi$ and $\psi'$ bins) are $A_{FB}$ and $F_L$. In the fits to the data, the yield $Y_{Bp}$ and all but one of the parameters that define the shapes of $S(m)$, $B_p(m)$, $B_p(\cos\theta_K)$, and $B_p(\cos\theta_l)$ are initially set to the values obtained from simulation, with a Gaussian constraint defined by the uncertainty found in the fit to the simulated events. The $S(m)$ mass parameter is not constrained. The first fit to the data is to the control samples: $B^0 \to K^{*0}J/\psi$ and $B^0 \to K^{*0}\psi'$. The values for $F_S$ and $A_S$ from the $B^0 \to K^{*0}J/\psi$ fit are used in the signal $q^2$ bins, with Gaussian constraints defined by the uncertainties from the fit. The longitudinal polarization fraction $F_L$ and the scalar fraction $F_S$ are constrained to lie in the physical region of 0 to 1. In addition, penalty terms are added to ensure that $|A_{FB}| < \frac{3}{4}(1 - F_L)$ and $|A_S| < \frac{1}{2}[F_S + 3F_L(1 - F_S)]$, which are necessary to avoid a negative decay rate.

The differential branching fraction, $d\mathcal{B}/dq^2$, is measured relative to the normalization channel $B^0 \to K^{*0}J/\psi$ using

$$\frac{d\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{dq^2} = \frac{Y_S}{Y_N}\frac{\epsilon_N}{\epsilon_S}\frac{d\mathcal{B}(B^0 \to K^{*0}J/\psi)}{dq^2}, \qquad (3)$$

where $Y_S$ and $Y_N$ are the yields of the signal and normalization channels, respectively, $\epsilon_S$ and $\epsilon_N$ are the efficiencies of the signal and normalization channels, respectively, and $\mathcal{B}(B^0 \to K^{*0}J/\psi)$ is the world-average branching fraction for the normalization channel [41]. The yields are obtained with fits to the invariant-mass distributions and the efficiencies are obtained by integrating over the angular variables using the values obtained from the previously described fits.

Three methods are used to validate the fit formalism and results. First, 1000 pseudo-experiment samples are generated in each $q^2$ bin using the PDF in Eq. (2). The log-likelihood values obtained from the fits to the data are consistent with the distributions from the pseudo-experiments, indicating an acceptable goodness of fit. The pull distributions obtained from the pseudo-experiments indicate the uncertainties returned by the fit are generally overestimated by 0–10%. No attempt is made to correct the experimental uncertainties for this effect. Second, a fit is performed to a sample of MC simulation events that approximated the data sample in size and composition. The MC simulation sample contains a data-like mixture of four types of events. Three types of events are generated and simulated events from $B^0 \to K^{*0}\mu^+\mu^-$, $B^0 \to K^{*0}J/\psi$, and $B^0 \to K^{*0}\psi'$ decays. The last event type is the combinatorial background, which is generated based on the PDF in Eq. (2). Third, the fit is performed on the normalization/control samples and the results compared to the known values. Biases observed from these three checks are treated as systematic uncertainties, as described in Section 5.

## 5. Systematic uncertainties

A variety of systematic effects are investigated and the impacts on the measurements of $F_L$, $A_{FB}$, and $d\mathcal{B}/dq^2$ are evaluated.

The finite sizes of the MC simulation samples used to measure the efficiency introduce a systematic uncertainty of a statistical nature. Alternative efficiency functions are created by randomly varying the parameters of the efficiency polynomials within the fitted uncertainties for the MC samples. The alternative efficiency functions are applied to the data and the root-mean-squares of the returned values taken as the systematic uncertainty.

The fit algorithm is validated by performing 1000 pseudo-experiments, generated and fit with the PDF of Eq. (2). The average deviation of the 1000 pseudo-experiments from the expected mean is taken as the systematic uncertainty associated with possible bias from the fit algorithm. This bias is less than half of the statistical uncertainty for all measurements. Discrepancies between the functions used in the PDF and the true distribution can also give rise to biases. To evaluate this effect, a MC simulation sample similar in size and composition to the analyzed data set is fit using the PDF of Eq. (2). The differences between the fitted values and the true values are taken as the systematic uncertainties associated with the fit ingredients.

Mistagging a $B^0$ as a $\bar{B}^0$ (and vice versa) worsens the measured $B^0$ mass resolution. A comparison of resolutions for data and MC simulations (varying the mistag rates in the simulation) indicates the mistag rate may be as high as 12%, compared to the value of 8% determined from simulation. The systematic uncertainty in the mistag rate is obtained from the difference in the final measurements when these two values are used.

The systematic uncertainty related to the contribution from the $K\pi$ S-wave (and interference with the P-wave) is evaluated by taking the difference between the default results, obtained by fitting with a function accounting for the S-wave (Eq. (1)), with the results from a fit performed with no S-wave or interference terms ($F_S = A_S = 0$ in Eq. (1)).

Variations of the background PDF shapes, versus mass and angles, are used to estimate the effect from the choice of PDF shapes. The mass-shape parameters of the peaking background, normally taken from a fit to the simulation, are left free in the data fit and the difference adopted as a systematic uncertainty. The degree of the polynomials used to fit the angular shapes of the combinatorial background are increased by one and the difference taken as a systematic uncertainty. In addition, the difference in results obtained by fitting the mass-shape parameters using the data, rather than using the result from simulations, is taken as the signal mass-shape systematic uncertainty.

The effect of the experimental resolution of $\cos\theta_K$ and $\cos\theta_l$ is estimated as the difference, when significant, of the returned values for $A_{FB}$ and $F_L$ when the reconstructed or generated values of $\cos\theta_K$ and $\cos\theta_l$ are used. The effect of the dimuon mass resolution is found to be negligible.

A possible difference between the efficiency computed with the simulation and the true efficiency in data is tested by comparing the measurements of known observables between data and simulation using the control channels. The differences in the measurements of $F_L$ and $A_{FB}$ are computed using the $B^0 \to K^{*0}J/\psi$ decay. For the differential branching fraction measurement, the systematic uncertainty is estimated using the ratio of branching fractions $\mathcal{B}(B^0 \to K^{*0}J/\psi(\mu^+\mu^-))/\mathcal{B}(B^0 \to K^{*0}\psi'(\mu^+\mu^-))$, where our measured value of $15.5 \pm 0.4$ (statistical uncertainty only) is in agreement with the most-precise previously published value of $16.2 \pm 0.5 \pm 0.3$ [48]. We use the difference of 4.3% between these two measurements as an estimate of the systematic uncertainty from possible $q^2$-dependent efficiency mismodeling.

For the branching fraction measurement, a common normalization systematic uncertainty of 4.6% arises from the branching fractions of the normalization mode ($B^0 \to K^{*0}J/\psi$ and $J/\psi \to \mu^+\mu^-$) [41]. Finally, variation of the number of pileup collisions is found to have no effect on the results.

The systematic uncertainties are measured and applied in each $q^2$ bin, with the total systematic uncertainty obtained by adding in quadrature the individual contributions. A summary of the systematic uncertainties is given in Table 1; the ranges give the variation over the $q^2$ bins.

## 6. Results

The $K^+\pi^-\mu^+\mu^-$ invariant-mass, $\cos\theta_K$, and $\cos\theta_l$ distributions for the $q^2$ bin corresponding to the $B^0 \to K^{*0}J/\psi$ decay are shown in Fig. 2, along with the projection of the maximum-likelihood fit described in Section 4. The results are used to validate the fitting procedure and obtain the values for $F_S$ and $A_S$ used in the fits to the signal $q^2$ bins. From 47 000 signal events, the fitted values are $F_L = 0.554 \pm 0.004$, $A_{FB} = -0.004 \pm 0.004$, $F_S = 0.01 \pm 0.01$, and $A_S = -0.10 \pm 0.01$, where the uncertainties are statistical. Considering also the typical systematic uncertainties (Table 1), the result for $F_L$ is compatible with the world-average value of

**Table 1**
Systematic uncertainty contributions for the measurements of $F_L$, $A_{FB}$, and $d\mathcal{B}/dq^2$. The $F_L$ and $A_{FB}$ uncertainties are absolute values, while the $d\mathcal{B}/dq^2$ uncertainties are relative to the measured value. The ranges given refer to the variations over the $q^2$ bins.

| Systematic uncertainty | $F_L(10^{-3})$ | $A_{FB}(10^{-3})$ | $d\mathcal{B}/dq^2$ (%) |
|---|---|---|---|
| Efficiency statistical uncertainty | 5–7 | 3–5 | 1 |
| Potential bias from fit algorithm | 3–40 | 12–77 | 0–2.7 |
| Potential bias from fit ingredients | 0 | 0–17 | 0–7.1 |
| Incorrect CP assignment of decay | 2–6 | 2–6 | 0 |
| Effect of $K\pi$ S-wave contribution | 5–23 | 6–14 | 5 |
| Peaking background mass shape | 0–26 | 0–8 | 0–15 |
| Background shapes vs. $\cos\theta_{L,K}$ | 3–180 | 4–160 | 0–3.3 |
| Signal mass shape | 0 | 0 | 0.9 |
| Angular resolution | 0–19 | 0 | 0 |
| Efficiency shape | 16 | 4 | 4.3 |
| Normalization to $B^0 \to K^{*0}J/\psi$ | – | – | 4.6 |
| Total systematic uncertainty | 31–190 | 18–180 | 8.6–17 |

$0.570 \pm 0.008$ [41], while the value for $A_{FB}$ is consistent with the expected result of no asymmetry. The same fit is performed for the $B^0 \to K^{*0}\psi' q^2$ bin, where 3200 signal events yield results of $F_L = 0.509 \pm 0.016$ (stat.), which is consistent with the world-average value of $0.46 \pm 0.04$ [41], and $A_{FB} = 0.013 \pm 0.014$ (stat.), compatible with no asymmetry, as expected in the SM.

The $K^+\pi^-\mu^+\mu^-$ invariant mass distributions for each $q^2$ bin of the signal sample $B^0 \to K^{*0}\mu^+\mu^-$ are shown in Fig. 3, along with the projection of the unbinned maximum-likelihood fit described in Section 4. Clear signals are seen in each bin, with yields ranging from $23 \pm 6$ to $103 \pm 12$ events. The fitted results for $F_L$ and $A_{FB}$ are shown in Fig. 4, along with the SM predictions. The values of $A_{FB}$ and $F_L$ obtained for the first $q^2$ bin are at the physical boundary, which is enforced by a penalty term. This leads to statistical uncertainties, obtained from MINOS [49], of zero for the positive (negative) uncertainty for $F_L$ ($A_{FB}$).

The SM predictions are taken from Ref. [14] and combines two calculational techniques. In the low-$q^2$ region, a QCD factorization approach [10] is used, which is applicable for $q^2 < 4m_c^4$, where $m_c$ is the charm quark mass. In the high-$q^2$ region, an operator product expansion in the inverse b-quark mass and $1/\sqrt{q^2}$ [50,51] is combined with heavy quark form factor relations [52]. This is valid above the open-charm threshold. In both regions, the form factor calculations are taken from Ref. [53], and a dimensional estimate is made of the uncertainty from the expansion corrections [27]. Other recent SM calculations [15,17–19] give similar results, with the largest variations found in the uncertainty estimates and the differential branching fraction value. Between the $J/\psi$ and $\psi'$ resonances, reliable theoretical predictions are not available.

Using the efficiency corrected yields for the signal and normalization modes ($B^0 \to K^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}J/\psi$) and the world-average branching fraction for the normalization mode [41], the branching fraction for $B^0 \to K^{*0}\mu^+\mu^-$ is obtained as a function of $q^2$, as shown in Fig. 5, together with the SM predictions. The results for $A_{FB}$, $F_L$, and $d\mathcal{B}/dq^2$ are also reported in Table 2.

The angular observables can be theoretically predicted with good control of the relevant form-factor uncertainties in the low dimuon invariant-mass region. It is therefore interesting to perform the measurements of the relevant observables in the $1 < q^2 < 6\ \text{GeV}^2$ region. The experimental results in this region, along with the fit projections, are shown in Fig. 6. The values obtained from this fit for $F_L$, $A_{FB}$, and $d\mathcal{B}/dq^2$ are shown in the bottom row of Table 2. These results are consistent with the SM predictions of $F_L = 0.74^{+0.06}_{-0.07}$, $A_{FB} = -0.05 \pm 0.03$, and $d\mathcal{B}/dq^2 = (4.9^{+1.0}_{-1.1}) \times 10^{-8}\ \text{GeV}^{-2}$ [54].

The results of $A_{FB}$, $F_L$, and the branching fraction versus $q^2$ are compared to previous measurements that use the same $q^2$ binning [36–38,55,56] in Fig. 7. The CMS measurements are more precise than all but the LHCb values, and in the highest-$q^2$ bin, the CMS measurements have the smallest uncertainty in $A_{FB}$ and $F_L$. Table 3 provides a comparison of the same quantities in the low dimuon invariant-mass region: $1 < q^2 < 6\ \text{GeV}^2$.

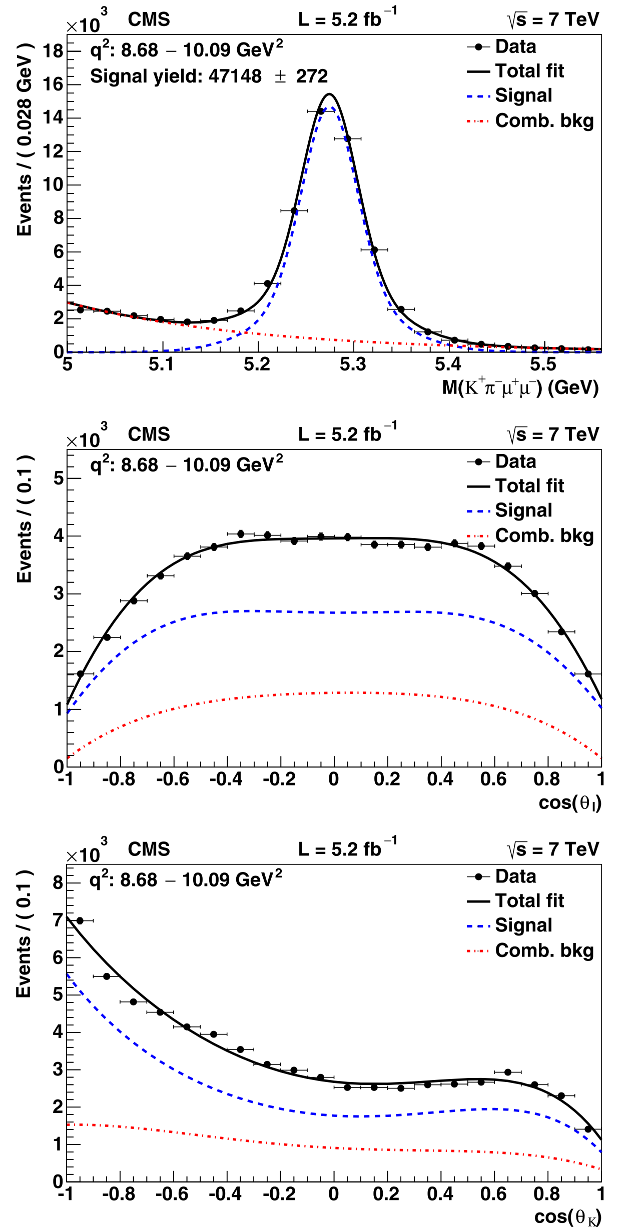


**Fig. 2.** The $K^+\pi^-\mu^+\mu^-$ invariant-mass (top), $\cos\theta_l$ (middle), and $\cos\theta_K$ (bottom) distributions for the $q^2$ bin associated with the $B^0 \to K^{*0}J/\psi$ decay, along with results from the projections of the overall unbinned maximum-likelihood fit (solid line), the signal contribution (dashed line), and the background contribution (dot-dashed line).

## 7. Summary

Using a data sample recorded with the CMS detector during 2011 and corresponding to an integrated luminosity of 5.2 $\text{fb}^{-1}$, an angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$ has been carried out. The data used for this analysis include more than 400 signal decays and 50 000 normalization/control mode decays ($B^0 \to K^{*0}J/\psi$ and $B^0 \to K^{*0}\psi'$). Unbinned maximum-likelihood fits have been performed in bins of the square of the dimuon invariant mass ($q^2$)

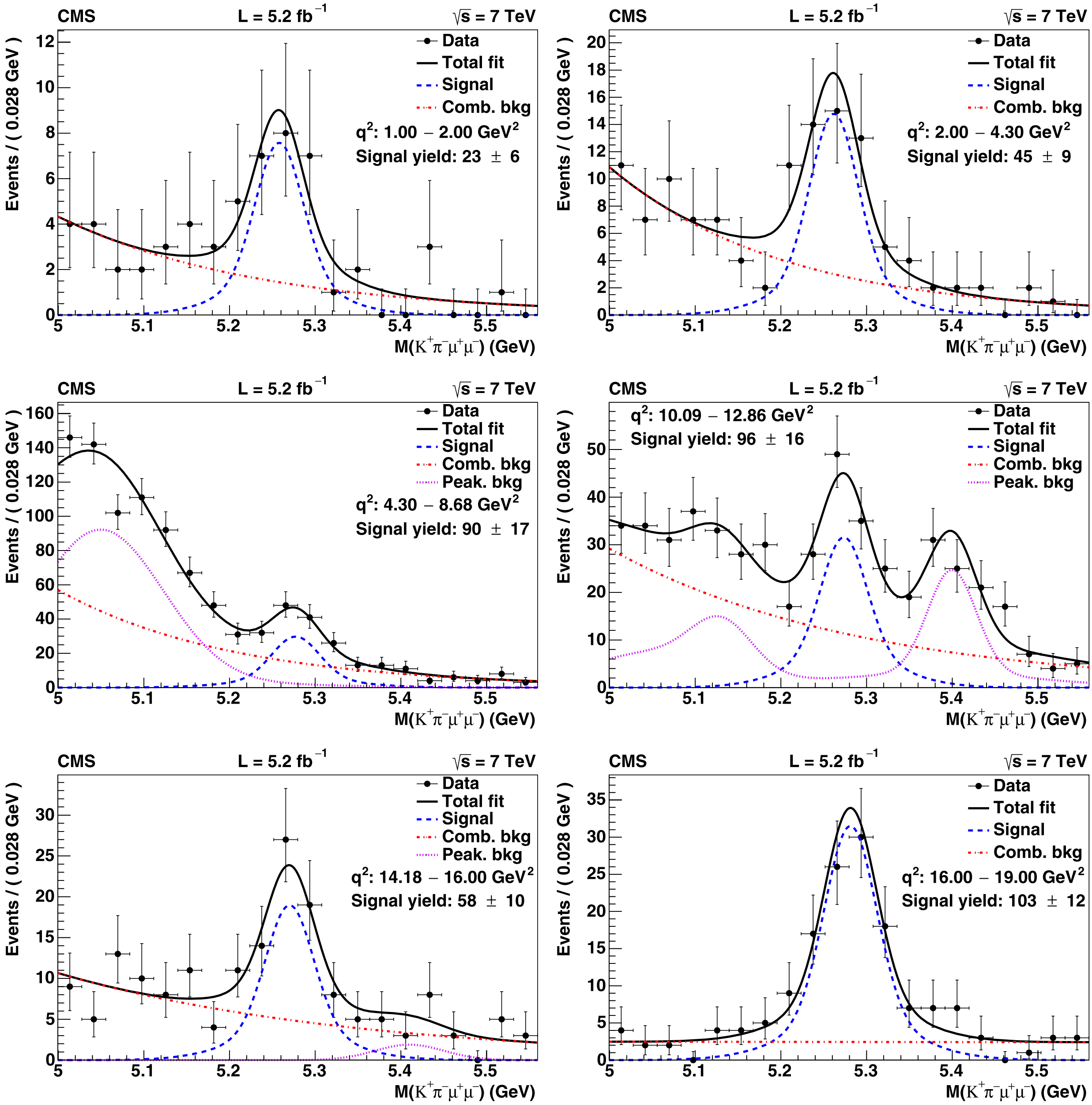


**Fig. 3.** The $K^+\pi^-\mu^+\mu^-$ invariant-mass distributions for each of the signal $q^2$ bins. Overlaid on each mass distribution is the projection of the unbinned maximum-likelihood fit results for the overall fit (solid line), the signal contribution (dashed line), the combinatorial background contribution (dot-dashed line), and the peaking background contribution (dotted line).

**Table 2**
The yields and the measurements of $F_L$, $A_{FB}$, and the branching fraction for the decay $B^0 \to K^{*0}\mu^+\mu^-$ in bins of $q^2$. The first uncertainty is statistical and the second is systematic.

| $q^2$ ($GeV^2$) | Yield | $F_L$ | $A_{FB}$ | $d\mathcal{B}/dq^2$ ($10^{-8}$ $GeV^{-2}$) |
|---|---|---|---|---|
| 1–2 | $23.0 \pm 6.3$ | $0.60^{+0.00}_{-0.28} \pm 0.19$ | $-0.29^{+0.37}_{-0.00} \pm 0.18$ | $4.8^{+1.4}_{-1.2} \pm 0.4$ |
| 2–4.3 | $45.0 \pm 8.8$ | $0.65 \pm 0.17 \pm 0.03$ | $-0.07 \pm 0.20 \pm 0.02$ | $3.8 \pm 0.7 \pm 0.3$ |
| 4.3–8.68 | $90 \pm 17$ | $0.81^{+0.13}_{-0.12} \pm 0.05$ | $-0.01 \pm 0.11 \pm 0.03$ | $3.7 \pm 0.7 \pm 0.4$ |
| 10.09–12.86 | $96 \pm 16$ | $0.45^{+0.10}_{-0.11} \pm 0.04$ | $0.40 \pm 0.08 \pm 0.05$ | $5.4 \pm 0.9 \pm 0.9$ |
| 14.18–16 | $58 \pm 10$ | $0.53 \pm 0.12 \pm 0.03$ | $0.29 \pm 0.09 \pm 0.05$ | $4.6^{+0.9}_{-0.8} \pm 0.5$ |
| 16–19 | $103 \pm 12$ | $0.44 \pm 0.07 \pm 0.03$ | $0.41 \pm 0.05 \pm 0.03$ | $5.2 \pm 0.6 \pm 0.5$ |
| 1–6 | $107 \pm 14$ | $0.68 \pm 0.10 \pm 0.02$ | $-0.07 \pm 0.12 \pm 0.01$ | $4.4 \pm 0.6 \pm 0.4$ |

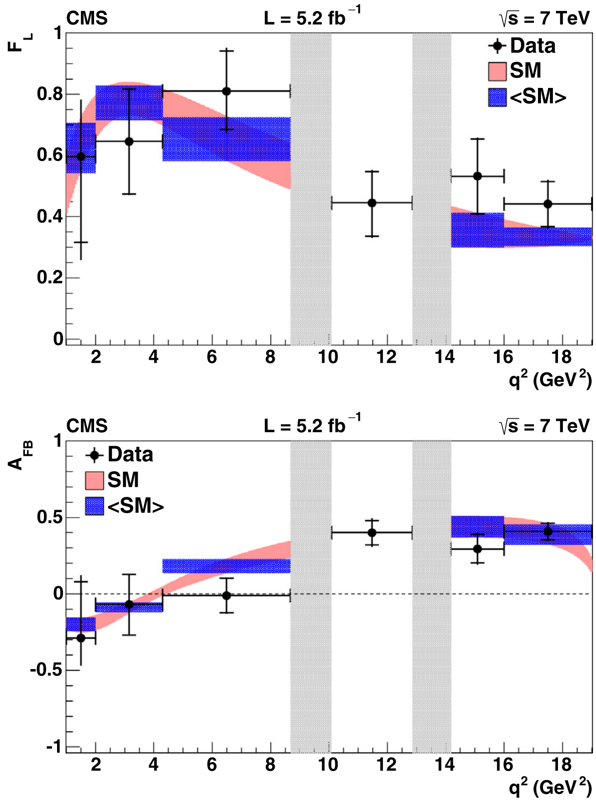


**Fig. 4.** Results of the measurement of $F_L$ (top) and $A_{\text{FB}}$ (bottom) versus $q^2$. The statistical uncertainty is shown by inner error bars, while the outer error bars give the total uncertainty. The vertical shaded regions correspond to the J/$\psi$ and $\psi'$ resonances. The other shaded regions show the SM prediction as a continuous distribution and after rate-averaging across the $q^2$ bins ($\langle$SM$\rangle$) to allow direct comparison to the data points. Reliable theoretical predictions between the J/$\psi$ and $\psi'$ resonances ($10.09 < q^2 < 12.86$ GeV$^2$) are not available.

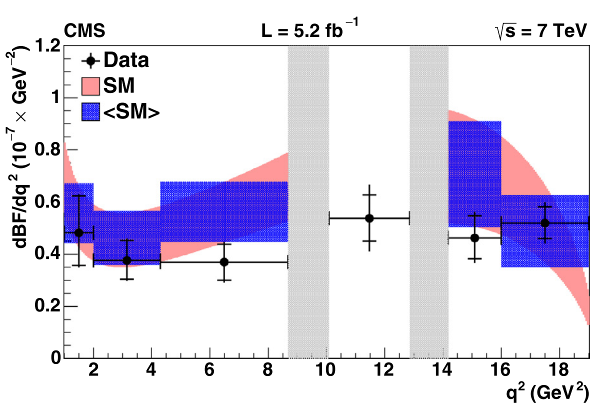


**Fig. 5.** Results of the measurement of $d\mathcal{B}/dq^2$ versus $q^2$. The statistical uncertainty is shown by inner error bars, while the outer error bars give the total uncertainty. The vertical shaded regions correspond to the J/$\psi$ and $\psi'$ resonances. The other shaded regions show the SM prediction as a continuous distribution and after rate-averaging across the $q^2$ bins ($\langle$SM$\rangle$) to allow direct comparison to the data points. Reliable theoretical predictions between the J/$\psi$ and $\psi'$ resonances ($10.09 < q^2 < 12.86$ GeV$^2$) are not available.

with three independent variables, the $K^+\pi^-\mu^+\mu^-$ invariant mass and two decay angles, to obtain values of the forward–backward asymmetry of the muons, $A_{\text{FB}}$, and the fraction of longitudinal polarization of the $K^{*0}$, $F_L$. Using these results, unbinned maximum-likelihood fits to the $K^+\pi^-\mu^+\mu^-$ invariant mass in $q^2$ bins have been used to extract the differential branching fraction $d\mathcal{B}/dq^2$. The results are consistent with the SM predictions and previous

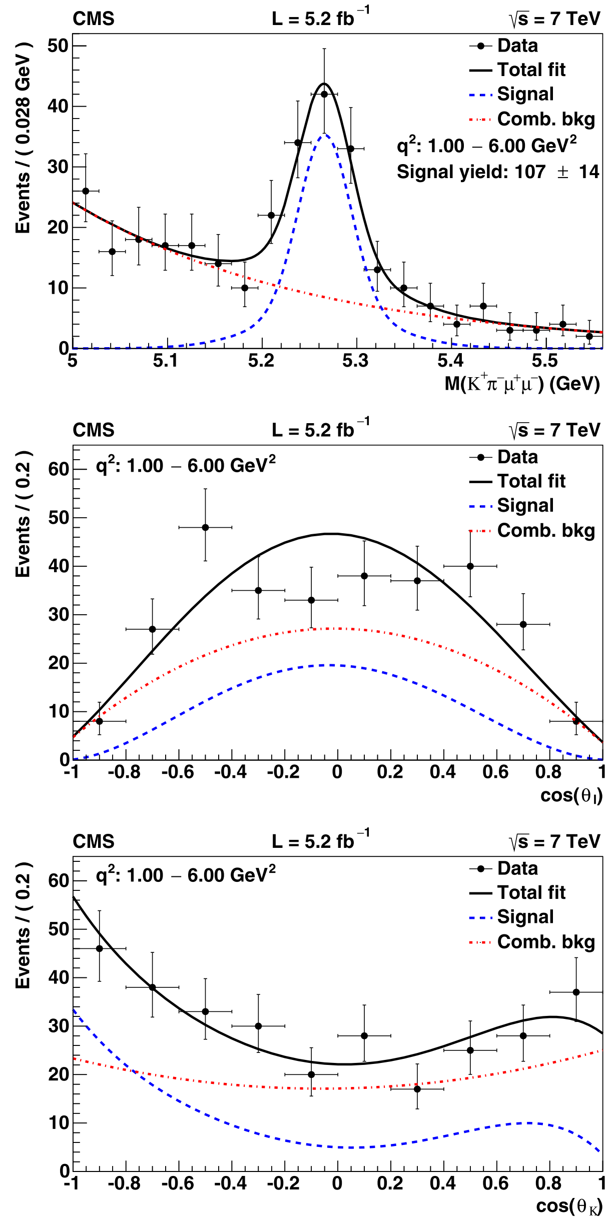


**Fig. 6.** The $K^+\pi^-\mu^+\mu^-$ invariant-mass (top), $\cos\theta_l$ (middle), and $\cos\theta_K$ (bottom) distributions for $1 < q^2 < 6$ GeV$^2$, along with results from the projections of the overall unbinned maximum-likelihood fit (solid line), the signal contribution (dashed line), and the background contribution (dot-dashed line).

measurements. Combined with other measurements, these results can be used to rule out or constrain new physics.

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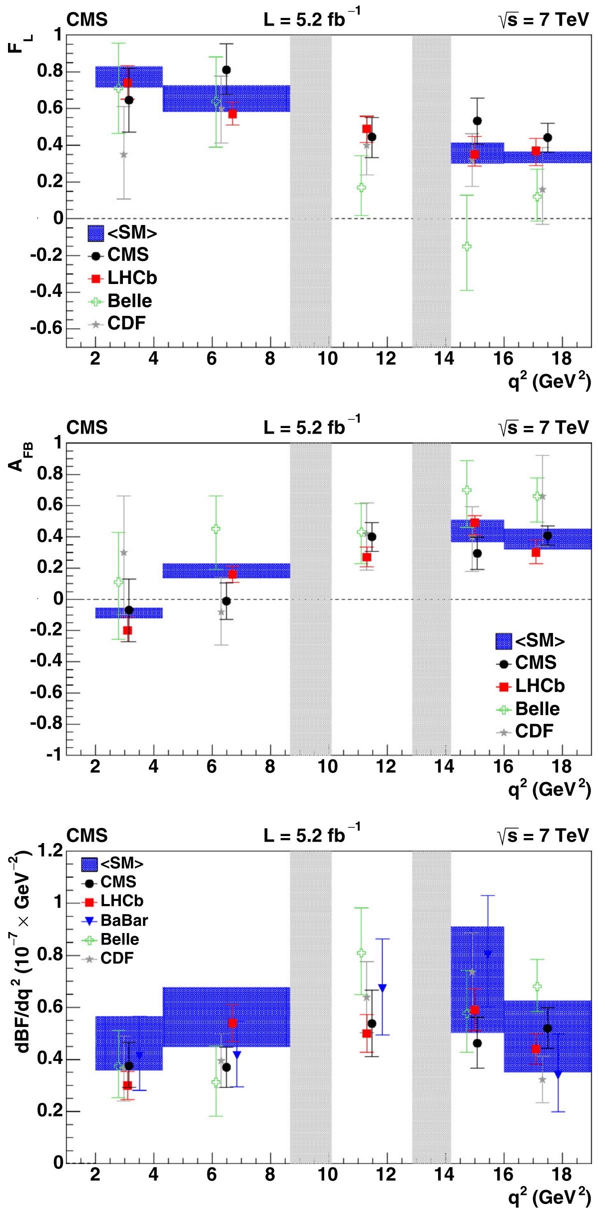


**Fig. 7.** Measurements versus $q^2$ of $F_L$ (top), $A_{FB}$ (middle), and the branching fraction (bottom) for $B \to K^*\ell^+\ell^-$ from CMS (this Letter), Belle [36], CDF [37,55], BaBar [56], and LHCb [38]. The error bars give the total uncertainty. The vertical shaded regions correspond to the J/$\psi$ and $\psi'$ resonances. The other shaded regions are the result of rate-averaging the SM prediction across the $q^2$ bins to allow direct comparison to the data points. Reliable theoretical predictions between the J/$\psi$ and $\psi'$ resonances ($10.09 < q^2 < 12.86$ GeV$^2$) are not available.

**Table 3**
Measurements from CMS (this Letter), LHCb [38], BaBar [56], CDF [37,55], and Belle [36] of $F_L$, $A_{FB}$, and $d\mathcal{B}/dq^2$ in the region $1 < q^2 < 6$ GeV$^2$ for the decay $B \to K^*\ell^+\ell^-$. The first uncertainty is statistical and the second is systematic. The SM predictions are also given [14].

| Experiment | $F_L$ | $A_{FB}$ | $d\mathcal{B}/dq^2$ ($10^{-8}$ GeV$^{-2}$) |
|---|---|---|---|
| CMS | $0.68 \pm 0.10 \pm 0.02$ | $-0.07 \pm 0.12 \pm 0.01$ | $4.4 \pm 0.6 \pm 0.4$ |
| LHCb | $0.65^{+0.08}_{-0.07} \pm 0.03$ | $-0.17 \pm 0.06 \pm 0.01$ | $3.4 \pm 0.3^{+0.4}_{-0.5}$ |
| BaBar | – | – | $4.1^{+1.1}_{-1.0} \pm 0.1$ |
| CDF | $0.69^{+0.19}_{-0.21} \pm 0.08$ | $0.29^{+0.20}_{-0.23} \pm 0.07$ | $3.2 \pm 1.1 \pm 0.3$ |
| Belle | $0.67 \pm 0.23 \pm 0.05$ | $0.26^{+0.27}_{-0.32} \pm 0.07$ | $3.0^{+0.9}_{-0.8} \pm 0.2$ |
| SM | $0.74^{+0.06}_{-0.07}$ | $-0.05 \pm 0.03$ | $4.9^{+1.0}_{-1.1}$ |

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