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Angular analysis of the decay $B^0 \to K^{*0}\mu^+\mu^-$ from pp collisions at $\sqrt{s} = 8$ TeV

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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 data corresponding to an integrated luminosity of 20.5 fb^{-1} collected with the CMS detector at the LHC in pp collisions at $\sqrt{s} = 8$ TeV. From 1430 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 dimuon invariant mass squared. The measurements are among the most precise to date and are in good agreement with standard model predictions.

1. Introduction

Phenomena beyond the standard model (SM) of particle physics can manifest themselves directly, via the production of new particles, or indirectly, by affecting the production and decay of SM particles. Analyses of flavor-changing neutral current (FCNC) decays are particularly sensitive to the effect of new physics, since such decays are highly suppressed in the SM. The FCNC decay, $B^0 \to K^{*0}\mu^+\mu^-$ (K^{*0} indicates the $K^*(892)^0$, and charge-conjugate states are implied for all particles unless stated otherwise), provides many opportunities to search for new phenomena. In addition to the branching fraction, other properties of the decay can be measured, including the forward–backward asymmetry of the muons, A_{FB}, and the longitudinal polarization fraction of the K^{*0}, F_L. To better understand this decay, these quantities can be measured as a function of the dimuon invariant mass squared (q^2). New physics may modify any of these quantities [1–17] relative to their SM values [1,18–24]. While previous measurements by BaBar, Belle, CDF, LHCb, and CMS are consistent with the SM [25–29], they 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 CERN LHC by the CMS experiment at a center-of-mass energy of 8 TeV. The data correspond to an integrated luminosity of 20.5 ± 0.5 fb^{-1} [30]. 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 K^+ and the 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 $B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi' K^{*0}$ decays (ψ' refers to the $\psi(2S)$), respectively, are used to validate the analysis. The former is also used to normalize the differential branching fraction.

2. CMS detector

A detailed description of the CMS detector, together with a definition of the coordinate system used and the standard kinematic variables, can be found in Ref. [31]. The main detector components used in this analysis are the silicon tracker and the muon detection systems. The silicon tracker, located in the 3.8 T field of a superconducting solenoid, consists of three pixel layers and ten strip layers (four of which have a stereo view) in the barrel region accompanied by similar endcap pixel and strip detectors on each side that extend coverage out to $|\eta| < 2.5$. For tracks with transverse momenta $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [32]. Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate

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chambers [33]. In addition to the tracker and muon detectors, CMS is equipped with electromagnetic and hadronic calorimeters that cover $|\eta| < 5$.

Events are selected using a two-level trigger system. The first level has specialized hardware processors that use information from the calorimeters and muon systems to select the most interesting events. A high-level trigger processor farm further decreases the event rate from around 90 kHz to around 400 Hz, before data storage.

3. Reconstruction, event selection, and efficiency

The criteria used to select the candidate events during data taking (trigger) and after full event reconstruction take advantage of the fact that B^0 mesons have relatively long lifetimes and therefore decay on average about 1 mm from their production point. The trigger only uses muons to select events, while the offline selection includes the full reconstruction of all decay products.

All events used in this analysis 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 (most probable collision point) and size (the extent of the luminous region covering 68% of the collisions in each dimension) were continuously measured through Gaussian fits to reconstructed vertices as part of the online data quality monitoring. The trigger required each muon to have $p_T > 3.5$ GeV, $|\eta| < 2.2$, and to pass within 2 cm of the beam axis. The dimuon system was required to have $p_T > 6.9$ GeV, a vertex fit χ^2 probability larger than 10%, and a separation of the vertex relative to the beamspot in the transverse plane of at least 3σ, where σ includes the calculated uncertainty in the vertex position and the measured size of the beamspot. In addition, the cosine of the angle, in the transverse plane, between the dimuon momentum vector and the vector from the beamspot to the dimuon vertex was required to be greater than 0.9.

The offline reconstruction requires two muons of opposite charge and two oppositely charged hadrons. The muons are required to match those that triggered the event readout, and also to pass general muon identification requirements. These include a track matched to at least one muon segment (collection of hits in a muon chamber consistent with the passage of a charged particle), a track fit χ^2 per degree of freedom less than 1.8, hits in at least six tracker layers with at least two from the pixel detector, and a transverse (longitudinal) impact parameter with respect to the beamspot less than 3 cm (30 cm). The reconstructed dimuon system must also satisfy the same requirements that were applied in the trigger.

The hadron tracks are required to fail the muon identification criteria, have $p_T > 0.8$ GeV, and have an extrapolated distance of closest approach to the beamspot in the transverse plane greater than twice the sum in quadrature of the distance uncertainty and the beamspot transverse size. The two hadrons must have an invariant mass within 90 MeV of the accepted K^{*0} mass [34] for either the $K^+\pi^-$ or $K^-\pi^+$ hypothesis. To remove contamination from $\phi(1020) \to K^+K^-$ decays, the invariant mass of the hadron pair must be greater than 1.035 GeV when the charged kaon mass is assigned to both hadrons. 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 $p_T > 8$ GeV, $|\eta| < 2.2$, vertex fit χ^2 probability larger than 10%, 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 α_{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 m of the B^0 candidate must also be within 280 MeV of the accepted B^0 mass m_{B^0} [34] for either the $K^-\pi^+\mu^+\mu^-$ or $K^+\pi^-\mu^+\mu^-$ hypothesis. The selection criteria are optimized using simulated signal samples (described below) and background from data using sidebands of the B^0 mass. After applying the selection criteria, events in which at least one candidate is found contain on average 1.05 candidates. A single candidate is chosen from each event based on the best B^0 vertex fit χ^2.

From the selected events, the dimuon invariant mass q and its calculated uncertainty σ_q are used to distinguish the signal from the control samples. The control samples $B^0 \to J/\psi K^{*0}$ and $B^0 \to \psi' K^{*0}$ are defined by $|q - m_{J/\psi}| < 3\sigma_q$ and $|q - m_{\psi'}| < 3\sigma_q$, respectively, where $m_{J/\psi}$ and $m_{\psi'}$ are the accepted masses [34]. The average value for σ_q is about 26 MeV. The signal sample is composed of the events that are not assigned to the J/ψ and ψ' samples.

The signal sample still contains contributions from the control samples, mainly due to unreconstructed soft photons in the charmonium decay. These events will have a low q value and fall outside the selection described above. These events will also have a low m value and therefore they can be selectively removed using a combined selection on q and m. For $q < m_{J/\psi}$ ($q > m_{J/\psi}$), we require $|(m - m_{B^0}) - (q - m_{J/\psi})| > 160$ (60) MeV. For $q < m_{\psi'}$ ($q > m_{\psi'}$), we require $|(m - m_{B^0}) - (q - m_{\psi'})| > 60$ (30) MeV. The requirements are set such that less than 10% of the background events originate from the control channels.

The four-track vertex candidate is identified as a B^0 or $\bar{B}^0$ depending on whether the $K^+\pi^-$ or $K^-\pi^+$ invariant mass is closest to the accepted K^{*0} mass. The fraction of candidates assigned to the incorrect state is estimated from simulations to be 12–14%, depending on q^2.

The global efficiency, ϵ, is the product of the acceptance and the combined trigger, reconstruction, and selection efficiency, both of which are obtained from Monte Carlo (MC) simulations. The pp collisions are simulated using PYTHIA [35] version 6.424, the unstable particles are decayed by EVTGEN [36] version 9.1 (using the default matrix element for the signal), and the particles are propagated through a detailed model of the detector with GEANT4 [37]. The reconstruction and selection of the generated events proceed as for data. Three simulated samples were created in which the B^0 was forced to decay to $K^{*0}(K^+\pi^-)\mu^+\mu^-$, $J/\psi(\mu^+\mu^-)K^{*0}(K^+\pi^-)$, or $\psi'(\mu^+\mu^-)K^{*0}(K^+\pi^-)$. The samples were constructed to ensure that the number and spatial distribution of pp collision vertices in each event match the distributions found in data. The acceptance is obtained from generated events, before the particle propagation with GEANT4, and is calculated as the fraction of events passing the single-muon requirement of $p_T(\mu) > 3.3$ GeV and $|\eta(\mu)| < 2.3$ relative to all events with $p_T(B^0) > 8$ GeV and $|\eta(B^0)| < 2.2$. As the acceptance requirements are placed on the generated quantities, they are less restrictive than the final selection requirements, which are based on the reconstructed quantities, to allow for the effect of finite resolution. Only events passing the acceptance criteria are processed through the GEANT simulation, the trigger simulation, and the reconstruction software. The combined trigger, reconstruction, and selection efficiency is the ratio of the number of events that pass the trigger and selection requirements 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^+, π^-, μ^+, and μ^- to have $\sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$ less than 0.3 (0.004) for hadrons (muons), where $\Delta\eta$ and $\Delta\varphi$ are the differences in η and φ between the reconstructed and generated particles. Requiring all four particles in the B^0 decay to be matched results in an efficiency of 99.6%

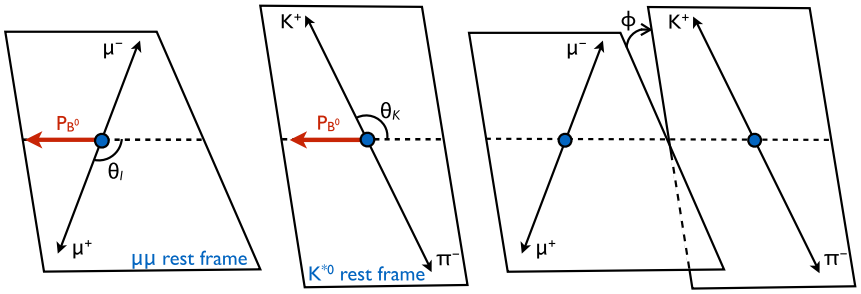

Fig. 1. Sketch showing the definition of the angular observables θ_l (left), θ_K (middle), and ϕ (right) for the decay $B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$.

(0.4% of the events have a correctly reconstructed B^0 that is not matched to a generated B^0) and a purity of 99.5% (0.5% of the matched candidates are not a correctly reconstructed B^0). Efficiencies are determined for both correctly tagged (the K and π have the correct charge) and mistagged (the K and π charges are reversed) candidates.

4. Analysis method

This 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 angular observables needed to define the decay: θ_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, θ_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 ϕ is the angle between the plane containing the two muons and the plane containing the kaon and pion. As the extracted angular parameters A_{FB} and F_L do not depend on ϕ and the product of the acceptance and efficiency is nearly constant as a function of ϕ, the angle ϕ is integrated out. Although the $K^+\pi^-$ invariant mass must be consistent with that of a K^{*0}, there can be a contribution from spinless (S-wave) $K^+\pi^-$ combinations [24,38–40]. This is parametrized with two terms: F_S, which is related to the S-wave fraction, and A_S, which is the interference amplitude between the S-wave and P-wave decays. Including this component, the angular distribution of $B^0 \to K^{*0}\mu^+\mu^-$ can be written as [24]:

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

For each q^2 bin, the observables of interest are extracted from an unbinned extended maximum-likelihood fit to three variables: the $K^+\pi^-\mu^+\mu^-$ invariant mass m and the two angular variables θ_K and θ_l. For each q^2 bin, the unnormalized probability density function (PDF) has the following expression:

$$\begin{aligned}\mathrm{PDF}(m,\theta_K,\theta_l) = Y_S^C\Big[&S^C(m)\,S^a(\theta_K,\theta_l)\,\epsilon^C(\theta_K,\theta_l)\\ &+ \frac{f^M}{1-f^M}\,S^M(m)\,S^a(-\theta_K,-\theta_l)\,\epsilon^M(\theta_K,\theta_l)\Big]\\ &+ Y_B\,B^m(m)\,B^{\theta_K}(\theta_K)\,B^{\theta_l}(\theta_l), \end{aligned} \quad (2)$$

where the contributions correspond to correctly tagged signal events, mistagged signal events, and background events. The parameters Y_S^C and Y_B are the yields of correctly tagged signal events and background events, respectively, and are free parameters in the fit. The parameter f^M is the fraction of signal events that are mistagged and is determined from MC simulation. The signal mass probability functions $S^C(m)$ and $S^M(m)$ are each the sum of two Gaussian functions and describe the mass distribution for correctly tagged and mistagged signal events, respectively. In the fit, there is one free parameter for the mass value in both signal functions, while the other parameters (four Gaussian σ parameters and two fractions relating the contribution of each Gaussian) are obtained from MC simulation, which has been found to accurately reproduce the data. The function $S^a(\theta_K,\theta_l)$ describes the signal in the two-dimensional (2D) space of the angular observables and corresponds to Eq. (1). The combination $B^m(m)\,B^{\theta_K}(\theta_K)\,B^{\theta_l}(\theta_l)$ is obtained from B^0 sideband data and describes the background in the space of (m,θ_K,θ_l), where the mass distribution is an exponential function and the angular distributions are polynomials ranging from second to fourth degree, depending on the q^2 bin and the angular variable. The functions $\epsilon^C(\theta_K,\theta_l)$ and $\epsilon^M(\theta_K,\theta_l)$ are the efficiencies in the 2D space of $-1 \le \cos\theta_K \le 1, -1 \le \cos\theta_l \le 1$ for correctly tagged and mistagged signal events, respectively. The efficiency function for correctly tagged events is obtained from a fit to the 2D-binned efficiency from simulation and is constrained to be positive. There are 30 bins (5 in $\cos\theta_K$ and 6 in $\cos\theta_l$), and the efficiency fit function is a polynomial of third degree in $\cos\theta_K$ and fifth degree in $\cos\theta_l$ (and all cross terms), for a total of 24 free parameters. This procedure does not work for the mistagged events because of the much smaller number of events (resulting in empty bins) and a more complicated efficiency. For mistagged events, the 2D efficiency is calculated in 5×5 bins of $\cos\theta_K$ and $\cos\theta_l$, and an interpolation is performed. This interpolation function is used to generate a new binned efficiency (in 120 × 120 bins), with all bin contents constrained to be nonnegative. The efficiency function uses this finely binned efficiency, with linear interpolation between bins. The efficiencies for both correctly tagged and mistagged events peak at $\cos\theta_l$ near 0 for $q^2 < 10$ GeV^2, becoming flat for larger values of q^2. The efficiency for correctly tagged events tends to decrease with increasing $\cos\theta_K$, and for $q^2 > 14$ GeV^2 a small decrease is seen for $\cos\theta_K$ near -1. The efficiency for mistagged events is maximal near $\cos\theta_K = 0$, with an increase as $\cos\theta_K$ approaches $+1$ that becomes more pronounced as q^2 increases.

The fit is performed in two steps. The initial fit uses the data from the sidebands of the B^0 mass to obtain the $B^{\theta_K}(\theta_K)$ and $B^{\theta_l}(\theta_l)$ distributions (the signal component is absent from this fit). The sideband regions are $3\sigma_m < |m - m_{B^0}| < 5.5\sigma_m$, where σ_m is the average mass resolution (≈45 MeV), obtained from fitting the MC simulation signal to a sum of two Gaussians with a common mean. The distributions obtained in this step are then fixed for the second step, which is a fit to the data over the full mass range. The free parameters in this fit are A_{FB}, F_L, F_S, A_S, the parameters in

$B^m(m)$, the mass parameter in $S^C(m)$ and $S^M(m)$, and the yields Y_S^C and Y_B. In addition, the remaining parameters in $S^C(m)$ and $S^M(m)$ are free parameters with Gaussian constraints from previous fits to simulated signal events.

The PDF in Eq. (2) is only guaranteed to be nonnegative for particular ranges of A_{FB}, F_L, A_S, and F_S. While the definition of the precise physical region is a more complicated expression, the approximate ranges of validity are: $0 < F_L < 1$, $|A_{FB}| < \frac{3}{4}(1 - F_L)$, $0 < F_S < \min\left[\frac{3(1-F_L)}{1+3F_L}, 1\right]$, and $|A_S| < F_S + 3F_L(1 - F_S)$. In addition, the interference term A_S must vanish if either of the two interfering components vanish. From Ref. [24], this constraint is implemented as $|A_S| < \sqrt{12F_S(1-F_S)F_L}R$, where R is a ratio related to the S-wave and P-wave line shapes, estimated to be 0.89 near the K^{*0} mass. During the MINUIT [41] minimization, penalty terms are introduced to ensure that parameters remain in the physical region. When assessing the statistical uncertainties with MINOS [41], the penalty terms are removed. However, a negative value for Eq. (2) results in the minimizing algorithm generating a large positive jump in the negative log-likelihood, tending to remove the unphysical region. The results of the fit in each signal q^2 bin are A_{FB}, F_L, A_S, F_S, and the correctly tagged signal yield Y_S^C.

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

$$\frac{d\mathcal{B}\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{dq^2} = \left(\frac{Y_S^C}{\epsilon^C} + \frac{Y_S^C f^M}{(1-f^M)\epsilon^M}\right)\left(\frac{Y_N^C}{\epsilon_N^C} + \frac{Y_N^C f_N^M}{(1-f_N^M)\epsilon_N^M}\right)^{-1} \times \frac{\mathcal{B}\left(B^0 \to J/\psi K^{*0}\right)}{\Delta q^2}, \quad (3)$$

where Y_S^C and Y_N^C are the yields of the correctly tagged signal and normalization channels, respectively; ϵ_S^C and ϵ_N^C are the efficiencies for the correctly tagged signal and normalization channels, respectively; f^M and f_N^M are the mistag rates for the signal and normalization channels, respectively; ϵ_S^M and ϵ_N^M are the efficiencies for the mistagged signal and normalization channels, respectively; and $\mathcal{B}\left(B^0 \to J/\psi(\mu^+\mu^-)K^{*0}\right) = 0.132\% \times 5.96\%$ is the accepted branching fraction for the normalization channel [34], corresponding to the q^2 bin $\Delta q^2 = 8.68$–10.09 GeV^2. The efficiencies are obtained by integrating the efficiency functions over the angular variables, weighted by the decay rate in Eq. (1), using the values obtained from the fit of Eq. (2) to the data.

The fit formalism and results are validated through fits to pseudo-experimental samples, MC simulation samples, and control channels. Additional details, including the sizes of the systematic uncertainties assigned from these fits, are described in Section 5.

5. Systematic uncertainties

Since the efficiency is computed with simulated events, it is essential that the MC simulation program correctly reproduces the data, and extensive checks have been performed to verify the accuracy of the simulation. The systematic uncertainties associated with the efficiencies, and other sources of systematic uncertainty are described below and summarized in Table 1.

The correctness of the fit function and the procedure for measuring the variables of interest are verified in three ways. First, a high-statistics MC sample (approximately 400 times that of the data) is used to verify that the fitting procedure produces results consistent with the input values to the simulation. This MC sample includes the full simulation of signal and control channel events plus background events obtained from the PDF in Eq. (2). The discrepancy between the input and output values in this check is assigned as a simulation mismodeling systematic uncertainty. It was also verified that fitting a sample with only mistagged events gives the correct results. Second, 1000 pseudo-experiments, each with the same number of events as the data sample, are generated in each q^2 bin using the PDF in Eq. (2), with parameters obtained from the fit to the data. These are used to estimate the fit bias. Much of the observed bias is a consequence of the fitted parameters lying close to the boundaries of the physical region. In addition, the distributions of results are used to check the returned statistical uncertainty from the fit and are found to be consistent. Third, the high-statistics MC signal sample is divided into 400 subsamples and combined with background events to mimic 400 independent data sets of similar size to the data. Fits to these 400 samples do not reveal any additional systematic uncertainty.

Table 1
Systematic uncertainty contributions for the measurements of F_L, A_{FB}, and the branching fraction for the decay $B^0 \to K^{*0}\mu^+\mu^-$. The values for F_L and A_{FB} are absolute, while the values for the branching fraction are relative. The total uncertainty in each q^2 bin is obtained by adding each contribution in quadrature. For each item, the range indicates the variation of the uncertainty in the signal q^2 bins.

Systematic uncertainty	$F_L(10^{-3})$	$A_{FB}(10^{-3})$	$d\mathcal{B}/dq^2$ (%)
Simulation mismodeling	1–17	0–37	1.0–5.5
Fit bias	0–34	2–42	–
MC statistical uncertainty	3–10	5–18	0.5–2.0
Efficiency	34	5	–
$K\pi$ mistagging	1–4	0–7	0.1–4.1
Background distribution	20–36	12–31	0.0–1.2
Mass distribution	3	1	3.2
Feed-through background	0–27	0–5	0.0–4.0
Angular resolution	6–24	0–5	0.2–2.1
Normalization to $B^0 \to J/\psi K^{*0}$	–	–	4.6
Total systematic uncertainty	41–65	18–74	6.4–8.6

Because the efficiency functions are estimated from a finite number of simulated events, there is a corresponding statistical uncertainty in the efficiency. The efficiency functions are obtained from fits to simulated data. Alternatives to the default efficiency function are generated by randomly varying the fitted parameters within their uncertainties (including all correlations). The effect of these different efficiency functions on the final result is used to estimate the systematic uncertainty.

The main check of the correctness of the efficiency is obtained by comparing the efficiency-corrected results for the control channels with the corresponding world-average values. The efficiency as a function of the angular variables is checked by comparing the F_L and A_{FB} measurements from the $B^0 \to J/\psi K^{*0}$ sample, composed of 165 000 signal events. The value of F_L obtained in this analysis is 0.537 ± 0.002 (stat), compared with the world-average value of 0.571 ± 0.007 (stat + syst) [34], indicating a discrepancy of 0.034, which is taken as the systematic uncertainty for the signal measurements of F_L. For A_{FB}, the measured value is 0.008 ± 0.003 (stat), compared to a SM expectation of ≈ 0. Adding an S-wave contribution in the fit changes the measured value of A_{FB} by less than 0.001. From this, we conclude that the S-wave effects are minimal, and assign a systematic uncertainty of 0.005 for A_{FB}. To validate that the simulation accurately reproduces the efficiency as a function of q^2, we measure the branching ratio between two different q^2 bins, namely the two control channels. The branching ratio result, $\mathcal{B}\left(B^0 \to \psi' K^{*0}\right)/\mathcal{B}\left(B^0 \to J/\psi K^{*0}\right) = 0.479 \pm 0.005$, is in excellent agreement with the most precise reported measurement: 0.476 ± 0.014 (stat) ± 0.010 (syst) [42].

The PDF used in the analysis accommodates cases in which the kaon and pion charges are correctly and incorrectly assigned. Both of these contributions are treated as signal. The mistag frac-

tion is fixed to the value obtained from MC simulation. In the high-statistics control channel $B^0 \to J/\psi K^{*0}$, the mistag fraction is allowed to float in the fit and a value of $f^M = (14.5 \pm 0.5)\%$ is found, to be compared to the simulated value of $(13.7 \pm 0.1)\%$. The effect of this 5.8% difference in the mistag fraction on the measured values is taken as a systematic uncertainty.

The systematic uncertainty associated with the functions used to model the angular distribution of the background is obtained from the sum in quadrature of two uncertainties. The first uncertainty is evaluated by fitting the background with polynomials of one degree greater than used in the default analysis and taking the difference in the observables of interest between these two fits as the systematic uncertainty. The second uncertainty is owing to the statistical uncertainty in the background shape, as these shapes are fixed in the final fit. This uncertainty is obtained by taking the difference in quadrature between the returned statistical uncertainties on the parameters of interest when the background shapes are fixed and allowed to vary. In q^2 bins where the unconstrained fit does not converge, the associated uncertainty is obtained from extrapolation of nearby bins.

The mass distributions for the correctly tagged and mistagged events are each described by the sum of two Gaussian functions, with a common mean for all four Gaussian functions. The mean value is obtained from the fit to the data, while the other parameters (four σ and two ratios) are obtained from fits to MC-simulated events, with the uncertainty from those fits used as Gaussian constraints in the fits to the data. For the high-statistics control channels, it is possible to fit the data, while allowing some of the parameters to vary. The maximum changes in the measured values in the two control channel q^2 bins when the parameters are varied are taken as the systematic uncertainty for all q^2 bins.

The q^2 bins just below and above the J/ψ region may be contaminated with $B^0 \to J/\psi K^{*0}$ feed-through events that are not removed by the selection criteria. A special fit in these two bins is made, in which an additional background term is added to the PDF. This background distribution is obtained from the MC simulation and the background yield is a free parameter. The resulting changes in the fit parameters are used as estimates of the systematic uncertainty associated with this contribution.

The effects from angular resolution in the reconstructed values for the angular variables θ_K and θ_l are estimated by performing two fits on the same MC-simulated events. One fit uses the true values of the angular variables and the other fit their reconstructed values. The difference in the fitted parameters between the two fits is taken as an estimate of the systematic uncertainty.

The differential branching fraction has an additional systematic uncertainty of 4.6% coming from the uncertainty in the branching fraction of the normalization mode $B^0 \to J/\psi K^{*0}$.

The systematic uncertainties are measured and applied in each q^2 bin, with the total systematic uncertainty obtained by adding the individual contributions in quadrature.

6. Results

The signal data, corresponding to 1430 signal events, are fit in seven disjoint q^2 bins from 1 to 19 GeV^2. Results are also obtained for a wide, low-q^2 bin ($1 < q^2 < 6$ GeV^2), where the theoretical uncertainties are best understood. The $K^+\pi^-\mu^+\mu^-$ invariant mass distributions for all of the q^2 signal bins, as well as the fit projections, are shown in Fig. 2. Fig. 3 plots the projections of the fit and the data on the $\cos\theta_K$ (top) and $\cos\theta_l$ (bottom) axes for the combined low-q^2 bin (left, $1 < q^2 < 6$ GeV^2) and the highest q^2 bin (right, $16 < q^2 < 19$ GeV^2). The fitted values of signal yield, F_L, A_{FB}, and $d\mathcal{B}/dq^2$, along with their associated uncertainties, are given for each of the disjoint q^2 regions in Table 2. These results are also shown in Fig. 4, along with two SM predictions. The fitted values for F_S are all less than 0.03, while the values for A_S vary from -0.3 to $+0.3$.

The SM predictions, derived from Refs. [18,20], combine two calculational techniques. In the low-q^2 region, a quantum chromodynamic factorization approach [43] is used, which is applicable for $q^2 < 4m_c^2$, 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 $1/\sqrt{q^2}$ [44,45] is combined with heavy-quark form-factor relations [46]. This is valid above the open-charm threshold ($q^2 \gtrsim 13.9$ GeV^2). The two SM predictions shown in Fig. 4 differ in the calculation of the form factors. The light-cone sum rules (LCSR) calculation is made at low q^2 [47] and is extrapolated to high q^2 [48]. The lattice gauge (Lattice) calculation of the form factors is from Ref. [49]. Controlled theoretical predictions are not available near the J/ψ and ψ' resonances. The SM predictions are in good agreement with the CMS experimental results, indicating no strong contribution from physics beyond the standard model.

The results described are combined with previous CMS measurements, obtained from an independent data sample collected at $\sqrt{s} = 7$ TeV [29]. The systematic uncertainties associated with the efficiency, $K\pi$ mistagging, mass distribution, angular resolution, and the $B^0 \to J/\psi K^{*0}$ branching fraction are assumed to be fully correlated between the two samples, with the remaining uncertainties assumed to be uncorrelated. To combine the results from the 7 TeV and 8 TeV data, the uncorrelated systematic uncertainties are combined in quadrature with the statistical uncertainties. To account for the asymmetric uncertainties, the linear variance method from Ref. [50] is used to average the 7 TeV and 8 TeV measurements, as well as to average the two q^2 bins covering 4.30 to 8.68 GeV^2, which was a single bin in the 7 TeV analysis. After the combination, the correlated systematic uncertainties are added in quadrature. The combined CMS measurements of A_{FB}, F_L, and the differential branching fraction versus q^2 are compared to previous measurements [26–29,51,52] in Fig. 5. The CMS measurements are consistent with the other results, with comparable or higher precision. Table 3 provides a comparison of the measured quantities in the low dimuon invariant mass region: $1 < q^2 < 6$ GeV^2, as well as the corresponding theoretical calculations.

7. Summary

Using pp collision data recorded at $\sqrt{s} = 8$ TeV with the CMS detector at the LHC, corresponding to an integrated luminosity of 20.5 fb^{-1}, an angular analysis has been carried out on the decay $B^0 \to K^{*0}\mu^+\mu^-$. The data used for this analysis include 1430 signal decays. For each bin of the dimuon invariant mass squared (q^2), unbinned maximum-likelihood fits were performed to the distributions of the $K^+\pi^-\mu^+\mu^-$ invariant mass and two decay angles, to obtain values of the forward–backward asymmetry of the muons, A_{FB}, the fraction of longitudinal polarization of the K^{*0}, F_L, and the differential branching fraction, $d\mathcal{B}/dq^2$. The results are among the most precise to date and are consistent with standard model predictions and previous measurements.

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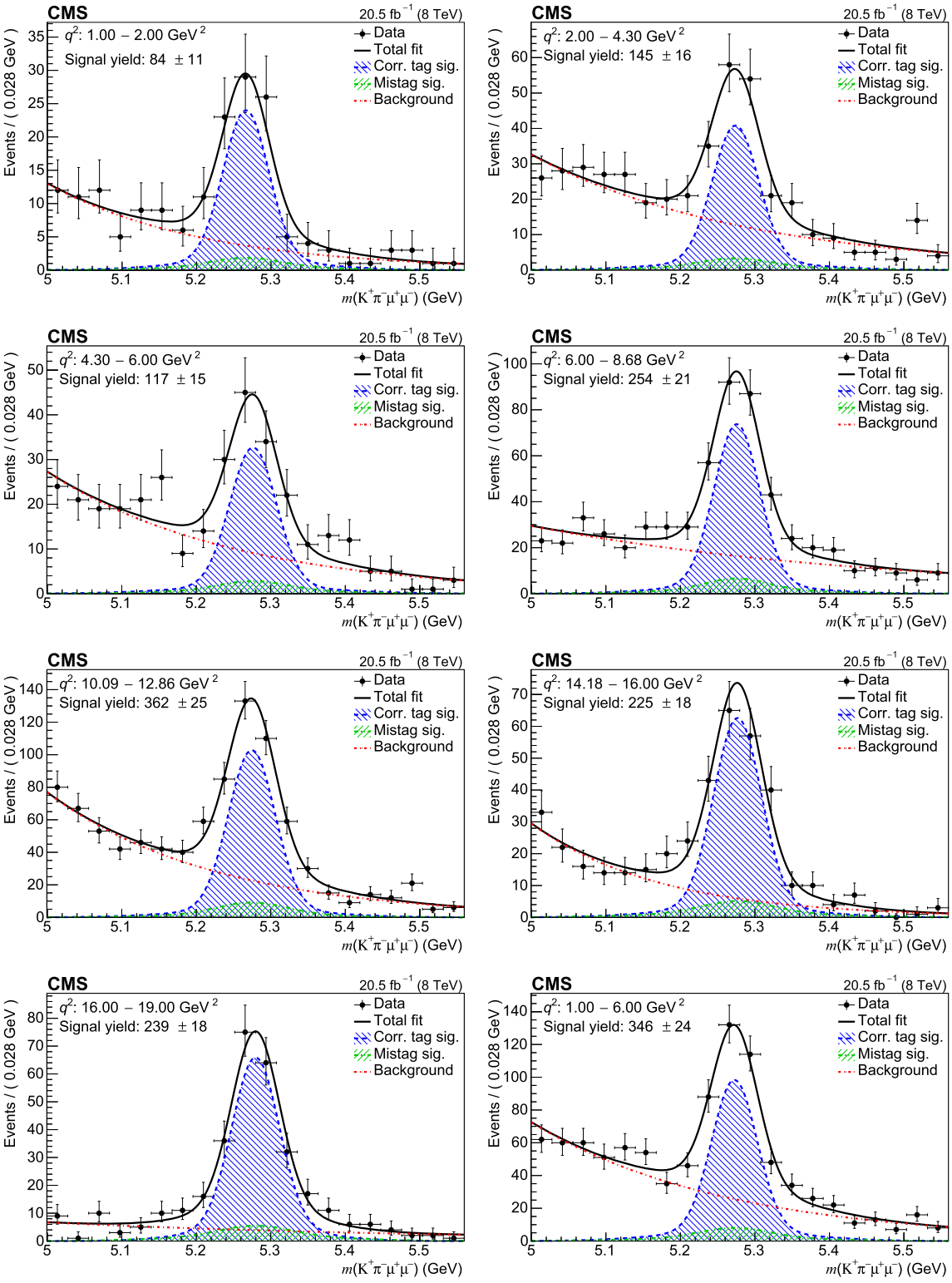

Fig. 2. The $K^+\pi^-\mu^+\mu^-$ invariant mass distributions for the seven signal q^2 bins and the combined $1 < q^2 < 6$ GeV^2 bin. Overlaid on each is the projection of the results for the total fit, as well as the three components: correctly tagged signal, mistagged signal, and background. The vertical bars give the statistical uncertainties, the horizontal bars the bin widths.

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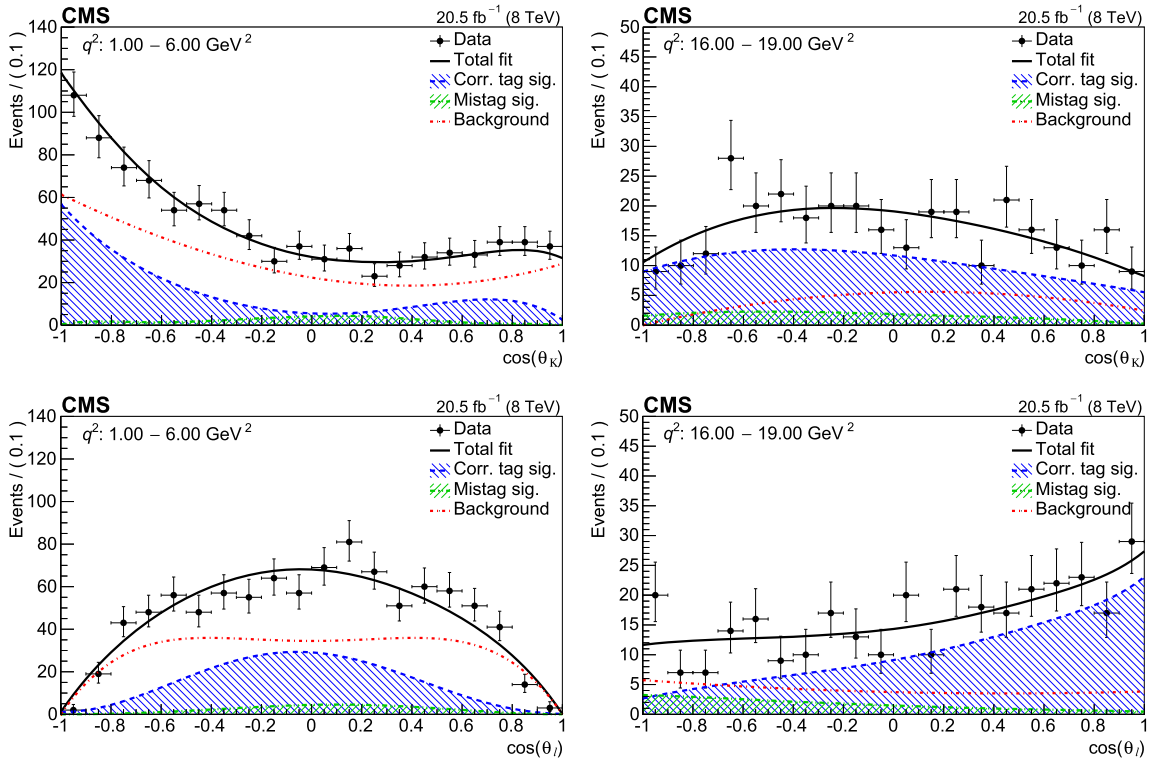

Fig. 3. Data and fit results for $1 < q^2 < 6$ GeV^2 (left) and $16 < q^2 < 19$ GeV^2 (right), projected onto the $\cos\theta_K$ axis (top), and $\cos\theta_l$ axis (bottom). The fit results show the total fit, as well as the three components: correctly tagged signal, mistagged signal, and background. The vertical bars give the statistical uncertainties, the horizontal bars the bin widths.

Table 2
The measured values of signal yield (including both correctly tagged and mistagged events), F_L, A_{FB}, and differential 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 (when present) is systematic. The bin ranges are selected to allow comparisons to previous measurements.

q^2 (GeV^2)	Signal yield	F_L	A_{FB}	$d\mathcal{B}/dq^2$ (10^{-8} GeV^{-2})
1.00–2.00	84 ± 11	$0.64 \pm^{0.10}_{0.09} \pm 0.07$	$-0.27 \pm^{0.17}_{0.40} \pm 0.07$	$4.6 \pm 0.7 \pm 0.3$
2.00–4.30	145 ± 16	$0.80 \pm 0.08 \pm 0.06$	$-0.12 \pm^{0.15}_{0.17} \pm 0.05$	$3.3 \pm 0.5 \pm 0.2$
4.30–6.00	117 ± 15	$0.62 \pm^{0.10}_{0.09} \pm 0.07$	$0.01 \pm 0.15 \pm 0.03$	$3.4 \pm 0.5 \pm 0.3$
6.00–8.68	254 ± 21	$0.50 \pm 0.06 \pm 0.06$	$0.03 \pm 0.10 \pm 0.02$	$4.7 \pm 0.4 \pm 0.3$
10.09–12.86	362 ± 25	$0.39 \pm 0.05 \pm 0.04$	$0.16 \pm 0.06 \pm 0.01$	$6.2 \pm 0.4 \pm 0.5$
14.18–16.00	225 ± 18	$0.48 \pm^{0.05}_{0.06} \pm 0.04$	$0.39 \pm^{0.04}_{0.06} \pm 0.01$	$6.7 \pm 0.6 \pm 0.5$
16.00–19.00	239 ± 18	$0.38 \pm^{0.05}_{0.06} \pm 0.04$	$0.35 \pm 0.07 \pm 0.01$	$4.2 \pm 0.3 \pm 0.3$

Table 3
Measurements from CMS (the 7 TeV results [29], this work for 8 TeV, and the combination), LHCb [28], BaBar [52], CDF [27,51], and Belle [26] of F_L, A_{FB}, and $d\mathcal{B}/dq^2$ in the region $1 < q^2 < 6$ GeV^2 for the decay $B^0 \to K^{*0}\mu^+\mu^-$. The CMS and LHCb results are from $B^0 \to K^{*0}\mu^+\mu^-$ decays. The remaining experiments add the corresponding B^+ decay, and the BaBar and Belle experiments also include the dielectron mode. The first uncertainty is statistical and the second is systematic. For the combined CMS results, only the total uncertainty is reported. The two SM predictions are also given.

Experiment	F_L	A_{FB}	$d\mathcal{B}/dq^2$ (10^{-8} GeV^{-2})
CMS (7 TeV)	$0.68 \pm 0.10 \pm 0.02$	$-0.07 \pm 0.12 \pm 0.01$	$4.4 \pm 0.6 \pm 0.4$
CMS (8 TeV, this analysis)	$0.73 \pm 0.05 \pm 0.04$	$-0.16 \pm^{0.10}_{0.09} \pm 0.05$	$3.6 \pm 0.3 \pm 0.2$
CMS (7 TeV + 8 TeV)	0.72 ± 0.06	-0.12 ± 0.08	3.8 ± 0.4
LHCb	$0.65 \pm^{0.08}_{0.07} \pm 0.03$	$-0.17 \pm 0.06 \pm 0.01$	$3.4 \pm 0.3 \pm^{0.4}_{0.5}$
BaBar	–	–	$4.1 \pm^{1.1}_{1.0} \pm 0.1$
CDF	$0.69 \pm^{0.19}_{0.21} \pm 0.08$	$0.29 \pm^{0.20}_{0.23} \pm 0.07$	$3.2 \pm 1.1 \pm 0.3$
Belle	$0.67 \pm 0.23 \pm 0.05$	$0.26 \pm^{0.27}_{0.32} \pm 0.07$	$3.0 \pm^{0.9}_{0.8} \pm 0.2$
SM (LCSR)	$0.79 \pm^{0.09}_{0.12}$	$-0.02 \pm^{0.03}_{0.02}$	$4.6 \pm^{2.3}_{1.7}$
SM (Lattice)	$0.73 \pm^{0.08}_{0.10}$	$-0.03 \pm^{0.04}_{0.03}$	$3.8 \pm^{1.2}_{1.0}$

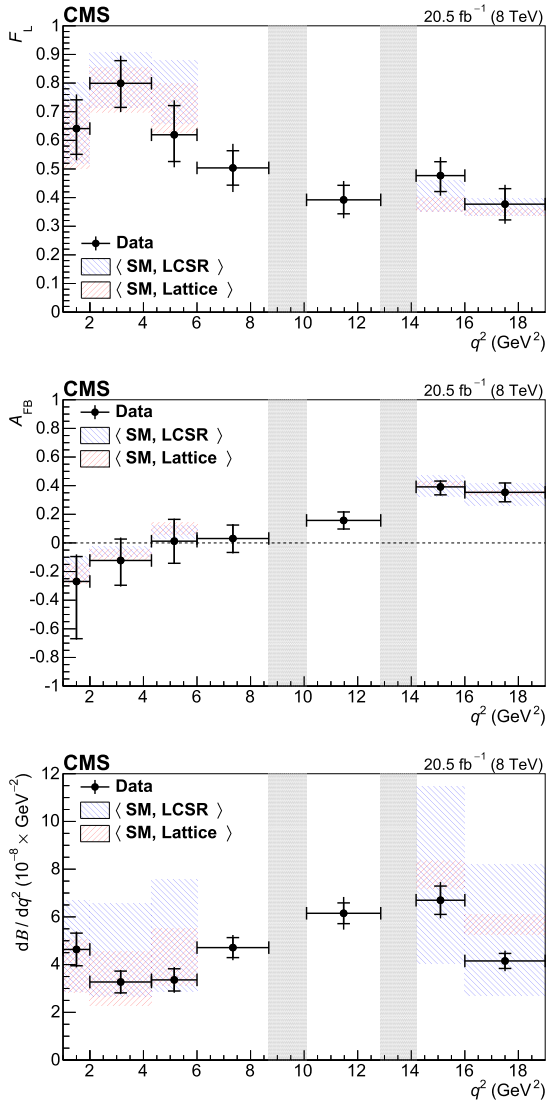

Fig. 4. Measured values of F_L, A_{FB}, and $d\mathcal{B}/dq^2$ versus q^2 for $B^0 \to K^{*0}\mu^+\mu^-$. The statistical uncertainty is shown by the inner vertical bars, while the outer vertical bars give the total uncertainty. The horizontal bars show the bin widths. The vertical shaded regions correspond to the J/ψ and ψ' resonances. The other shaded regions show the two SM predictions after rate averaging across the q^2 bins to provide a direct comparison to the data. Controlled theoretical predictions are not available near the J/ψ and ψ' resonances.

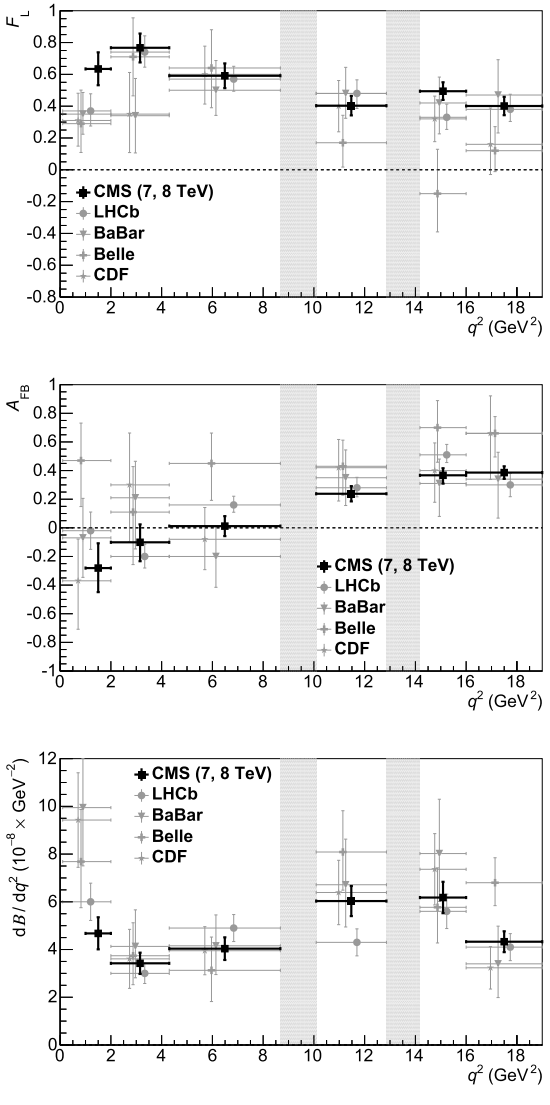

Fig. 5. Measured values of F_L, A_{FB}, and $d\mathcal{B}/dq^2$ versus q^2 for $B^0 \to K^{*0}\mu^+\mu^-$ from CMS (combination of the 7 TeV [29] results and this analysis), Belle [26], CDF [27, 51], BaBar [52], and LHCb [28]. The CMS and LHCb results are from $B^0 \to K^{*0}\mu^+\mu^-$ decays. The remaining experiments add the corresponding B^+ decay, and the BaBar and Belle experiments also include the dielectron mode. The vertical bars give the total uncertainty. The horizontal bars show the bin widths. The horizontal positions of the data points are staggered to improve legibility. The vertical shaded regions correspond to the J/ψ and ψ' resonances.

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