Angular analysis of the decay $B^+ \to K^+\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV

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The angular distribution of the flavor-changing neutral current decay $B^+ \to K^+\mu^+\mu^-$ is studied in proton-proton collisions at a center-of-mass energy of 8 TeV. The analysis is based on data collected with the CMS detector at the LHC, corresponding to an integrated luminosity of 20.5 fb^{-1}. The forward-backward asymmetry A_{FB} of the dimuon system and the contribution F_H from the pseudoscalar, scalar, and tensor amplitudes to the decay width are measured as a function of the dimuon mass squared. The measurements are consistent with the standard model expectations.

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I. INTRODUCTION

The decay $B^+ \to K^+\mu^+\mu^-$ is a manifestation of a flavor-changing neutral current process of the type $b \to s\ell^+\ell^-$, with ℓ denoting a charged lepton. In the standard model (SM), this decay is forbidden at tree level and occurs through higher-order processes. This makes the measurement of this process more sensitive to possible physics phenomena beyond the SM (BSM).

In the SM, three amplitudes contribute to $B^+ \to K^+\mu^+\mu^-$ via either electroweak Z/γ penguin diagrams or a W^+W^- box diagram, as shown in Fig. 1. Two independent parameters describe the decay rate for the $B^+ \to K^+\mu^+\mu^-$ process: the forward-backward asymmetry A_{FB} of the dimuon system and the contribution F_H from the pseudoscalar, scalar, and tensor amplitudes to the decay width. Theoretical predictions are available for both parameters [1–3]. In the SM, A_{FB} is zero up to small corrections, and F_H is also small. Because SM amplitudes may interfere with the contributions from BSM particles in loop diagrams, the decay can probe the presence of yet-unobserved particles and processes [4–9]. For example, a nonzero A_{FB} or large F_H would point to a BSM contribution [1,10], which can be probed [11,12] by comparing the experimental measurements with the theoretical predictions [6,10,13].

In this paper, we report the measurement of A_{FB} and F_H as a function of the dimuon mass squared (q^2) based on an angular fit of the decay $B^+ \to K^+\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV. Charge-conjugate decay modes are implied throughout this paper. The data, corresponding to an integrated luminosity of 20.5 fb^{-1} [14], were collected by the CMS experiment at the LHC in 2012. The angular distribution of this decay has previously been studied by the *BABAR* [15], Belle [16], CDF [17], and LHCb [18,19] experiments, but no hints of BSM have been seen.

II. THE CMS DETECTOR

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and a strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end-cap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and end-cap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found elsewhere [20].

The events are selected online using a two-stage trigger system [21]. The first level is composed of custom hardware processors and uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

III. EVENT SELECTION

The data for this analysis was recorded using a low-mass dimuon HLT with a displaced vertex. The trigger requires a

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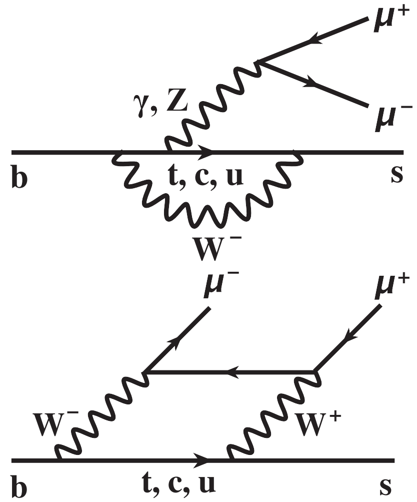

FIG. 1. The SM electroweak Z/γ penguin (left) and W^+W^- box (right) diagrams for the decay process $B^+ \to K^+\mu^+\mu^-$.

pair of opposite-sign muons with a dimuon vertex displaced from the interaction point by more than three times the calculated uncertainty. The trigger also requires the dimuon candidate to have invariant mass in the range 1.0–4.8 GeV and $p_T > 6.9$ GeV, and for each muon to have $p_T > 3.5$ GeV and $|\eta| < 2.2$.

Monte Carlo (MC) simulated event samples are widely used in the analysis. The number of simulated events for the signal sample $B^+ \to K^+\mu^+\mu^-$ corresponds to more than 160 times that of the data. Other simulated samples used in this analysis are $B^+ \to K^+J/\psi(\mu^+\mu^-)$, $B^+ \to K^+\psi(2S)(\mu^+\mu^-)$, and $B^+ \to \mu^+\mu^-X$. In the last decay mode, the muon pairs come from J/ψ or $\psi(2S)$ decay, and X denotes all other final-state particles. The MC samples are produced using the PYTHIA generator [22] version 6.424. Decays of B^+ and J/ψ or $\psi(2S)$ mesons are processed by the EVTGEN [23] version 9.1 program (with the default matrix element for the signal), in which final-state radiation is generated using PHOTOS [24]. Particles are traced through a detailed model of the detector with GEANT4 [25], producing signals similar to the actual detector responses. Particles coming from other proton-proton collisions in the same or nearby beam crossings (pileup) are simulated according to the data-taking conditions, but their effects on this analysis are small.

The selected events are reconstructed through the decay into the fully charged final state of one charged hadron and a pair of oppositely charged muons. Events from the control channels $B^+ \to K^+J/\psi(\mu^+\mu^-)$ and $B^+ \to K^+\psi(2S)(\mu^+\mu^-)$ have the same final state as the signal process $B^+ \to K^+\mu^+\mu^-$, and are extensively used to validate the analysis and to evaluate the systematic uncertainties. The muons are reconstructed using information from the silicon tracker and muon detector systems [26]. They must satisfy the off-line muon identification criteria that are optimized for low-p_T muons [27]. Dimuon candidates are formed from two oppositely charged muons matching the HLT criteria that triggered the event readout. To discriminate signal events from background, additional selection criteria on kinematic variables are used. The following selection criteria are determined through a maximization of the expected signal significance using MC signal events and the surviving data events in the final B^+ meson invariant mass fitting region, 5.1–5.6 GeV. The charged hadron track must have $p_T > 1.3$ GeV and the distance of closest approach in the transverse plane of the charged hadron trajectory to the interaction point, divided by its uncertainty, must be greater than 3.3. The B^+ meson candidate is formed by combining a dimuon candidate with the charged hadron track assumed to be a kaon. The event kinematic information is updated by fitting these three tracks to a common vertex. The chi-squared probability of the vertex fit for the B^+ candidate is required to be greater than 12%. To further reduce the background, the distance in the transverse plane between the B^+ vertex and the interaction point must be larger than 10.6 times its uncertainty. The cosine of the angle in the transverse plane between the B^+ momentum and a vector from the interaction point to the B^+ meson vertex must be greater than 0.9997. After applying the selection criteria, less than 1% of the selected events contain multiple B^+ candidates. In these events, only the candidate with the highest B^+ decay vertex fit probability is retained.

Events with a dimuon invariant mass (q) close to the J/ψ or $\psi(2S)$ resonance region are rejected to remove this contamination from the control channels, as in Ref. [28]. The J/ψ and $\psi(2S)$ resonance regions are defined as $m^{\mathrm{PDG}}_{J/\psi} - 5\sigma_q < q < m_{J/\psi} + 3\sigma_q$ and $|q - m^{\mathrm{PDG}}_{\psi(2S)}| < 5\sigma_q$, respectively, where σ_q is the calculated uncertainty in q, and the PDG superscript indicates the world-average mass value [29] for each particle. We further suppress such events by requiring, $|(m - m^{\mathrm{PDG}}_{B^+}) - (q - m^{\mathrm{PDG}}_{J/\psi})| > 0.13$ GeV and $|(m - m^{\mathrm{PDG}}_{B^+}) - (q - m^{\mathrm{PDG}}_{\psi(2S)})| > 0.06$ GeV in the B^+ meson invariant mass region of 5.1–5.6 GeV, where m is the B^+ candidate invariant mass. With these requirements, the maximum contribution of events containing a J/ψ or $\psi(2S)$ is less than 7% in any q^2, and the kinematic distributions of these events can be described together with those of the combinatorial background.

IV. ANGULAR ANALYSIS

The measurement of A_{FB} and F_{H} is performed through angular analysis in seven q^2 ranges from 1 to 22 GeV^2. The q^2 ranges used in this analysis are the same as in previous measurements [16–18], facilitating the comparison. The J/ψ and $\psi(2S)$ regions, corresponding to q^2 ranges of 8.68–10.09 and 12.86–14.18 GeV^2, respectively, are used as control regions [28,30]. Additionally, we define an inclusive low-q^2 range of 1.00–6.00 GeV^2 in order to compare the results to SM calculations with the best-controlled theoretical uncertainty, and a full inclusive q^2 range of 1.00–22.00 GeV^2, excluding the control regions. The analysis for these two ranges is performed with the same procedure as for the other ranges.

The decay rate for the process $B^+ \to K^+\mu^+\mu^-$ depends on $\cos\theta_\ell$, where θ_ℓ is the angle between the directions of the μ^- and K^+ in the dilepton rest frame. The differential decay width Γ_ℓ with respected to $\cos\theta_\ell$ can be parametrized [1,8,9] in terms of the observables of interest A_{FB} and F_{H} as:

$$\frac{1}{\Gamma_\ell}\frac{\mathrm{d}\Gamma_\ell}{\mathrm{d}\cos\theta_\ell} = \frac{3}{4}(1-F_{\mathrm{H}})(1-\cos^2\theta_\ell) + \frac{1}{2}F_{\mathrm{H}} + A_{\mathrm{FB}}\cos\theta_\ell. \tag{1}$$

The requirement for the decay rate to remain positive over all possible lepton angles constrains the parameter space to the region $0 \le F_{\mathrm{H}} \le 3$ and $|A_{\mathrm{FB}}| \le \min(1, F_{\mathrm{H}}/2)$. The angular observables A_{FB} and F_{H} are extracted from a two-dimensional extended unbinned maximum-likelihood fit to the angular distribution of the selected B^+ meson candidates in each q^2 range. The unnormalized probability density function (pdf) used in the two-dimensional fit is

$$\mathrm{pdf}(m,\cos\theta_\ell) = Y_{\mathrm{S}}S_{\mathrm{m}}(m)S_{\mathrm{a}}(\cos\theta_\ell)\epsilon(\cos\theta_\ell) + Y_{\mathrm{B}}B_{\mathrm{m}}(m)B_{\mathrm{a}}(\cos\theta_\ell), \tag{2}$$

where the two contributions on the right-hand side correspond to the parametrization of the signal and background. The parameters Y_{S} and Y_{B} are the yields of signal and background events, respectively. The functions $S_{\mathrm{m}}(m)$ and $S_{\mathrm{a}}(\cos\theta_\ell)$ describe the signal invariant mass and angular distributions, while $B_{\mathrm{m}}(m)$ and $B_{\mathrm{a}}(\cos\theta_\ell)$ are similar functions describing the background. The function $\epsilon(\cos\theta_\ell)$ is the signal efficiency as a function of $\cos\theta_\ell$.

The signal distribution $S_{\mathrm{m}}(m)$ is modeled as the sum of two Gaussian functions with a common mean, and $S_{\mathrm{a}}(\cos\theta_\ell)$ is given in Eq. (1). The background distribution $B_{\mathrm{m}}(m)$ is modeled as a single exponential function, while $B_{\mathrm{a}}(\cos\theta_\ell)$ is parametrized as the sum of a Gaussian function and a third- or fourth-degree polynomial, depending on the particular q^2 range.

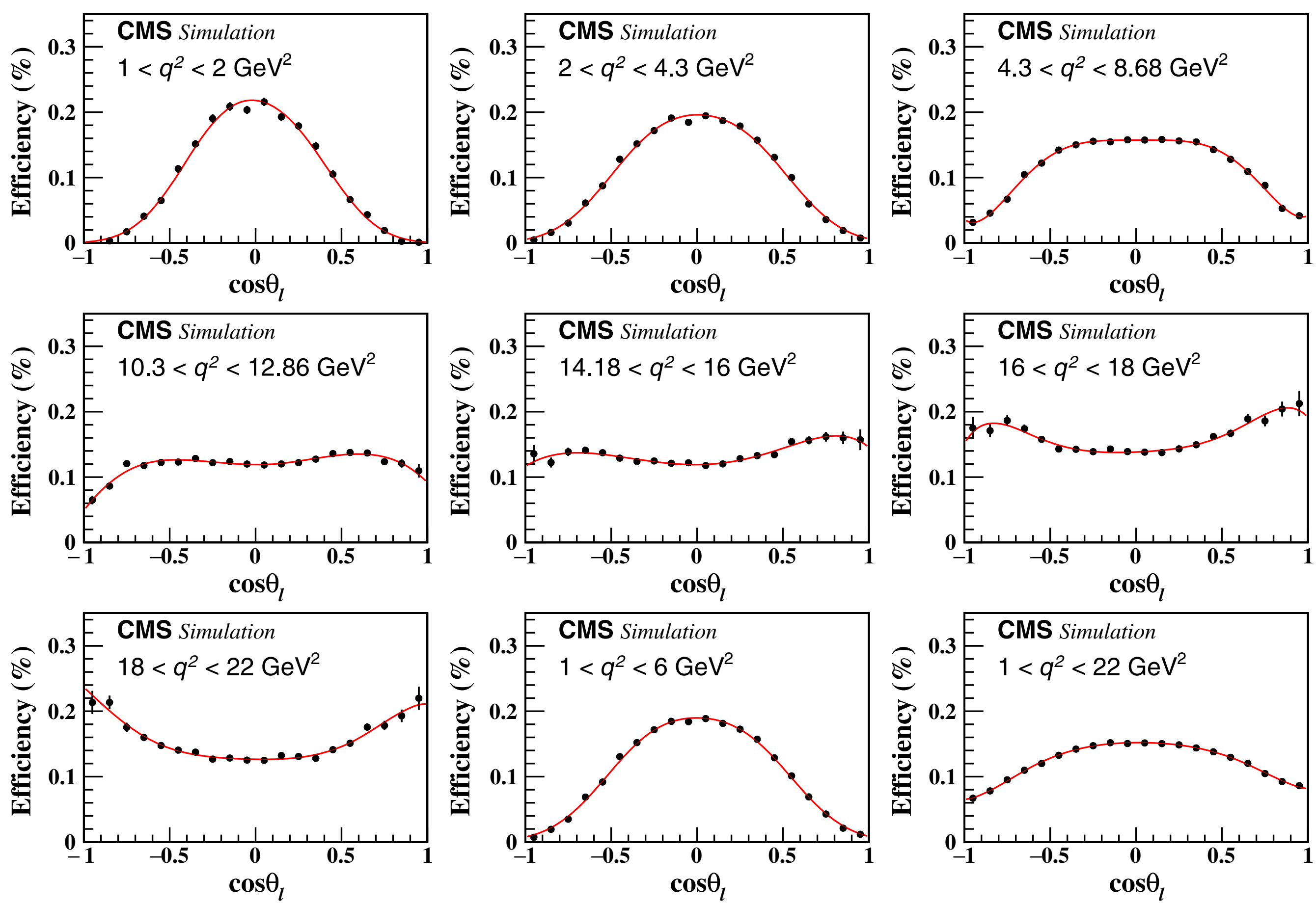

FIG. 2. The signal efficiency determined from simulated events as a function of $\cos\theta_\ell$ for the different q^2 ranges (points). The vertical bars indicate the statistical uncertainty. The curves show the sixth-order polynomial fits to the points.

Many of the parameters in the final fit are set to a given value with a Gaussian constraint that reflects the input uncertainty of the value. For the $S_{\rm m}(m)$ function, the mean is constrained to the world-average B^+ mass [29] and the widths and relative fraction of the two Gaussians are constrained to the values found from fitting simulated events. The parameters of the $B_{\rm a}(\cos\theta_\ell)$ function are obtained by fitting the events in the B^+ meson invariant mass sideband regions of 5.10–5.21 and 5.35–5.46 GeV. The free parameters of the fit are $Y_{\rm S}$, $Y_{\rm B}$, $A_{\rm FB}$, and $F_{\rm H}$, as well as the exponential decay parameter of $B_{\rm m}(m)$.

The signal efficiency $\epsilon(\cos\theta_\ell)$ is factorized into an acceptance $\epsilon_{\rm acc}$ times a reconstruction efficiency $\epsilon_{\rm reco}$, which are both functions of $\cos\theta_\ell$. The acceptance is obtained from generated events, before the particle propagation with GEANT4, and is calculated as the fraction of MC simulated signal events passing the muon requirement of $p_{\rm T} > 3.5$ GeV and $|\eta| < 2.2$ relative to all generated events. It varies from 2 to 4% depending on q^2. The reconstruction efficiency is obtained from the ratio of the number of reconstructed MC events passing the final event selection to the number of events passing the single-muon selection at the generator level. It varies from 4 to 7% depending on q^2. The signal efficiency $\epsilon(\cos\theta_\ell)$ is parametrized and fit with a sixth-order polynomial, as shown in Fig. 2 for the nine different signal q^2 ranges used in this analysis.

The angular distributions of data and simulation from the two control channels are compared and the good agreement between them provides a validation of the efficiency description. We also check that the ratio of the branching fractions of the two control channels is consistent with the world-average value [29] within their uncertainties. The MC simulation samples are used to validate the fitting procedure in each q^2 range. The results of fitting the signal MC sample at the generator level and the standard signal simulation are consistent with each other. The large MC signal sample is divided into 20 subsamples and fits of

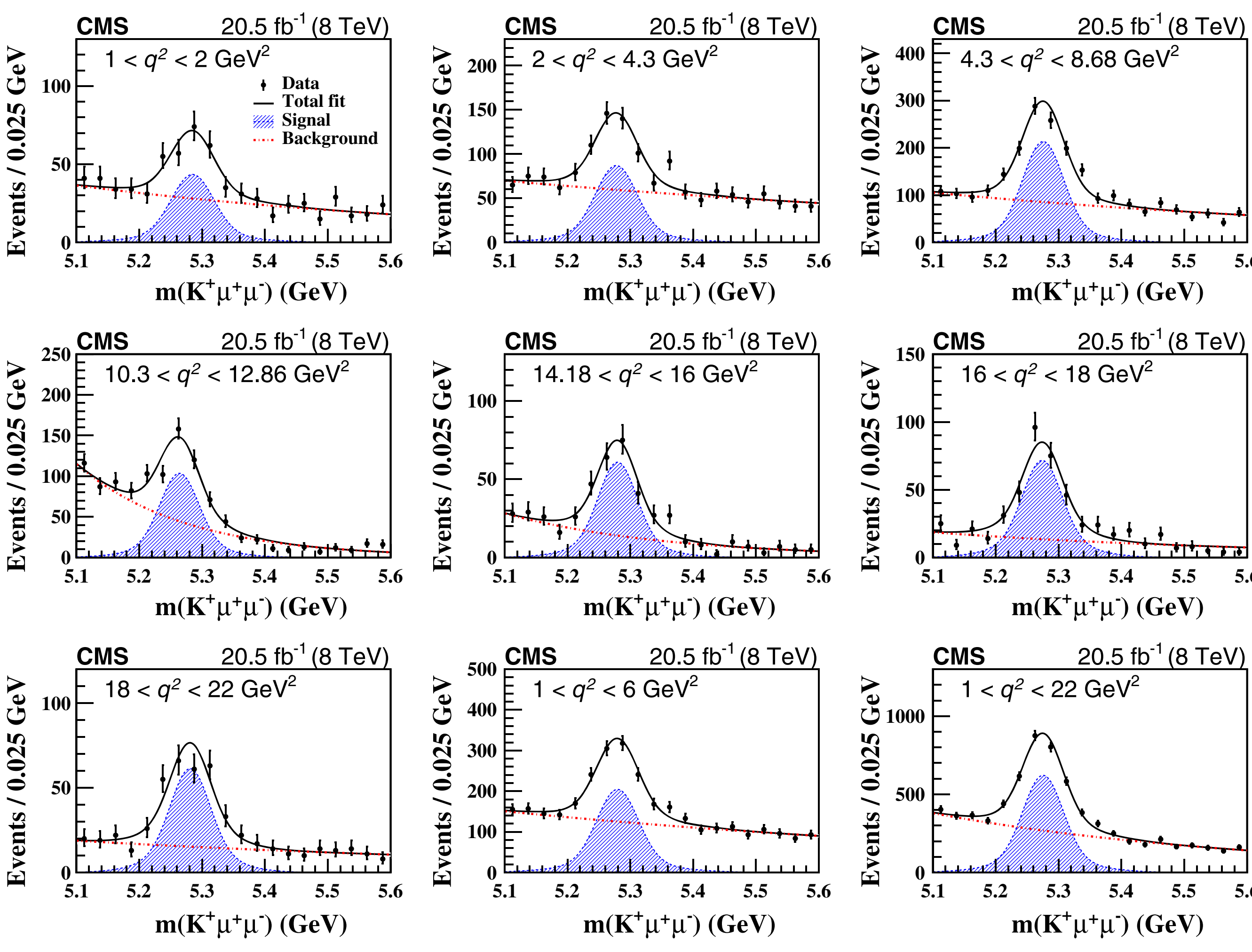

FIG. 3. Projections of the $K^+\mu^+\mu^-$ invariant mass distributions for each q^2 range from the two-dimensional fit of data. The solid lines show the total fit, the shaded area the signal contribution, and the dashed-dotted lines the background. The vertical bars on the points represent the statistical uncertainty in the data.

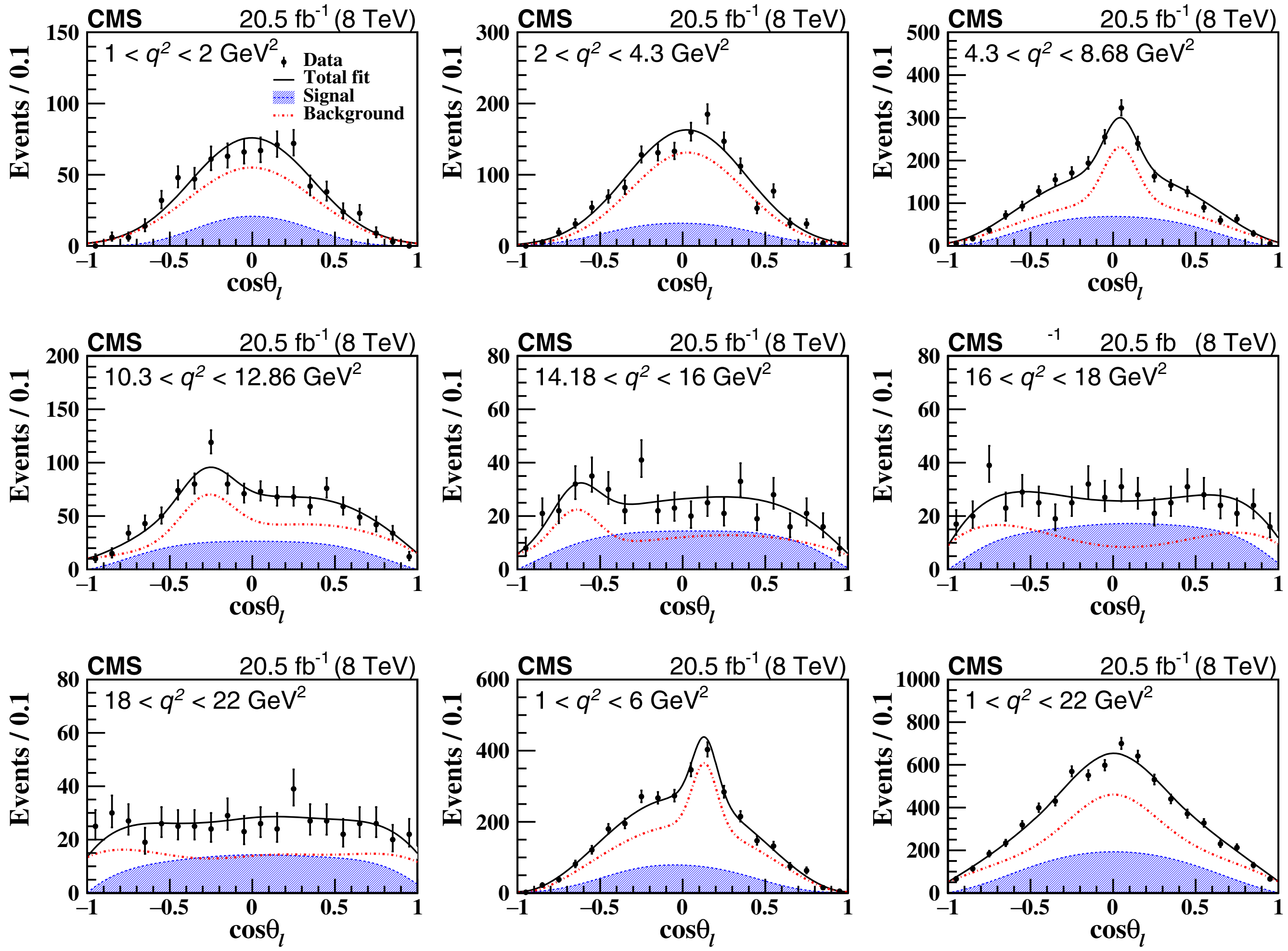

FIG. 4. Projections of the $\cos\theta_\ell$ distributions for each q^2 range from the two-dimensional fit of data. The solid lines show the total fit, the shaded area the signal contribution, and the dashed-dotted lines the background. The vertical bars on the points represent the statistical uncertainty in the data.

these subsamples reveal no additional bias. In addition, we generate 200 pseudoexperiments of 100 times the size of data, using the pdf in Eq. (2), with parameters from fitting the data. The differences between the fitted values from these samples and the input parameters from data follow Gaussian distributions with the means consistent with zero and the widths smaller than the variations among the signal MC subsample fits in the same q^2 range.

The final fit is performed over the full B^+ meson invariant mass range and results in 2286 ± 73 signal events with q^2 from 1 to 22 GeV^2. Figures 3 and 4 show the $K^+\mu^+\mu^-$ invariant mass and the $\cos\theta_\ell$ projections, respectively, for each q^2 range from the two-dimensional fit to the data.

V. SYSTEMATIC UNCERTAINTIES

Several sources of systematic uncertainty in the measured values of A_{FB} and F_{H} are considered, as summarized in Table I. Varying the parameter values of $S_{\mathrm{m}}(m)$ used to fit the signal invariant mass distribution within their uncertainties results in a negligible change in the measured values of A_{FB} and F_{H}.

The finite size of the simulated event samples can affect the accuracy of the efficiency determination. To estimate the uncertainty, 200 alternative efficiency functions are created by varying the parameters of the signal efficiency function $\epsilon(\cos\theta_\ell)$ within their uncertainties. These alternative efficiencies are independently used to fit the data. The standard deviations of the resulting A_{FB} and F_{H} fit values are taken as their systematic uncertainties from this source. The systematic uncertainty due to the efficiency description is estimated by changing the modeling of $\epsilon(\cos\theta_\ell)$. The fit to $\epsilon(\cos\theta_\ell)$ is modified from a sixth-order polynomial to the product of a Gaussian function and a sixth-order polynomial, where the Gaussian function parameters are the fit results from ϵ_{acc}, and the sixth-order polynomial parameters are the fit results from ϵ_{reco}. The differences in the results of A_{FB} and F_{H} are used as the systematic uncertainties.

TABLE I. Absolute values of the uncertainty contributions in the measurements of A_{FB} and F_H. For each item, the range indicates the variation of the uncertainty in the signal q^2 ranges.

Systematic uncertainty	$A_{FB}(\times 10^{-2})$	$F_H(\times 10^{-2})$
Finite size of MC samples	0.4–1.8	0.9–5.0
Efficiency description	0.1–1.5	0.1–7.8
Simulation mismodeling	0.1–2.8	0.1–1.4
Background parametrization model	0.1–1.0	0.1–5.1
Angular resolution	0.1–1.7	0.1–3.3
Dimuon mass resolution	0.1–1.0	0.1–1.5
Fitting procedure	0.1–3.2	0.4–25
Background distribution	0.1–7.2	0.1–29
Total systematic uncertainty	1.6–7.5	4.4–39

The simulated signal sample is used to evaluate the effects of any simulation mismodeling. The difference in the fitted values of A_{FB} and F_H between a simulated sample at the generator level without the detector simulation and reconstruction steps, and the standard signal simulation sample is assigned as the systematic uncertainty. The specific parametrization of the function used to fit the backgrounds can cause the results to change. To evaluate the effect of fitting the background $\cos\theta_\ell$ distribution, the degrees of the polynomials used to describe the angular shapes of the combinatorial background are decreased by one. After fitting with the alternative background parametrization, the differences in the A_{FB} and F_H results are taken as the systematic uncertainties from the background parametrization model. The systematic uncertainties coming from the experimental resolution in $\cos\theta_\ell$ and q^2 are estimated by comparing the values of A_{FB} and F_H obtained from the reconstructed MC events with those found using the generated values of $\cos\theta_\ell$ and q^2 in the fit.

An estimate of the systematic uncertainty from the fitting procedure is calculated using two different methods. In the first method, we divide the large simulated signal sample into multiple subsamples, each with a size similar to that of the data. The difference between the average of the fitted values of A_{FB} and F_H from the subsamples and the fitted value from the full sample is taken as an estimate of the systematic uncertainty from the modeling of the signal. In the second method, we generate many pseudoexperiments in which each of the mass and $\cos\theta_\ell$ distributions are obtained from combining a signal and background distribution. The signal distribution is obtained by selecting signal events from the simulated sample, with the number of events determined by the fit to the data. The background distribution is obtained from sampling a parent distribution that comes from subtracting the fitted signal distributions from the data. The mean value of the differences from these pseudoexperiments and the measurements from the reconstruction-level simulated signal sample is taken as an estimate of the fitting uncertainty due to the presence of background. The estimates from the two methods are then added in quadrature to obtain the overall systematic uncertainty from the fitting procedure.

In some q^2 ranges there are visible structures in the background $\cos\theta_\ell$ distributions, as seen in Fig. 4. We have investigated many possible contributions to these structures, and none of them has been identified. This uncertainty is estimated using the "second" method from the fitting procedure systematic uncertainty calculation, with the $\cos\theta_\ell$ distribution for the background obtained separately from the lower- and higher-mass sideband regions, 5.10–5.21 and 5.35–5.60 GeV. The larger of the two differences between these alternative fits and the nominal fit is taken as the systematic uncertainty from fitting the background $\cos\theta_\ell$ distribution.

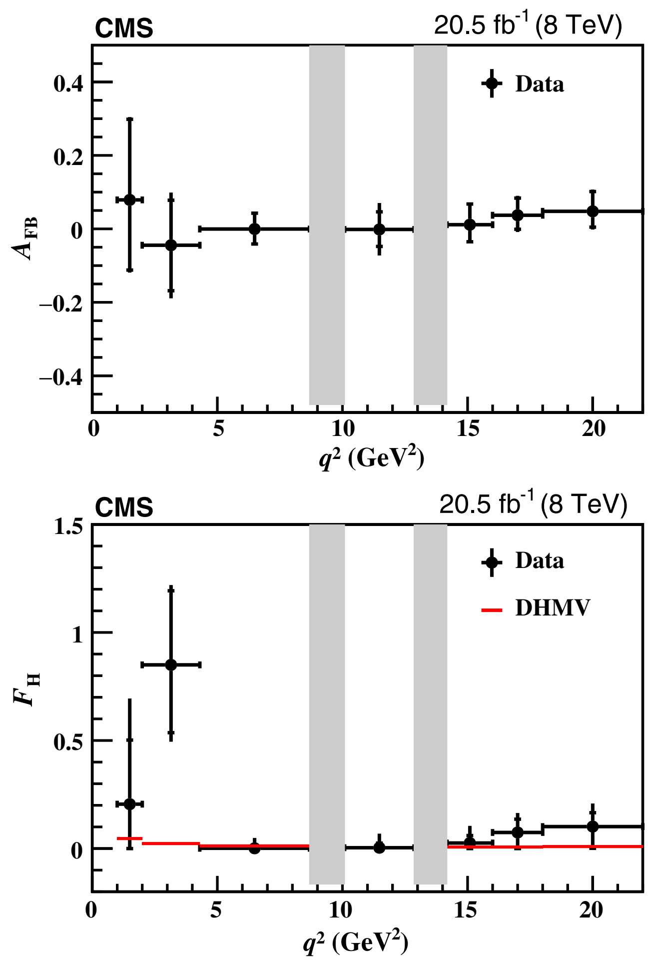

FIG. 5. Results of the A_{FB} (left) and F_H (right) measurements in ranges of q^2. The statistical uncertainties are shown by the inner vertical bars, while the outer vertical bars give the total uncertainties. The horizontal bars show the q^2 range widths. The vertical shaded regions are 8.68–10.09 and $12.86 - 14.18$ GeV^2, corresponding to the J/ψ- and $\psi(2S)$-dominated control regions, respectively. The horizontal lines in the right plot show the DHMV SM theoretical predictions [32,33], whose uncertainties are smaller than the line width.

TABLE II. Results of the fit for each q^2 range, together with several SM predictions. The inclusive $q^2 = 1.00$–$22.00\ \mathrm{GeV}^2$ range in the bottom line does not include events from the J/ψ and $\psi(2S)$ resonance regions. The signal yield Y_S is given, along with its statistical uncertainty. The measured values of A_{FB} and F_H are presented, where the first uncertainties are statistical and the second are systematic. The fifth column is a theoretical prediction by C. Bobeth *et al.* [1,3] using the EOS package [34] with the form factors from Refs. [2,35,36]. The sixth column is the calculation from S. Descotes-Genon *et al.* (DHMV) based on Refs. [32,33]. The last column is the prediction using the FLAVIO package [37] with the form factors from Ref. [38]. Only the central values of the theoretical predictions are shown, since their uncertainties are insignificant compared to those in the measurements.

q^2 (GeV^2)	Y_S	A_{FB}	F_H	F_H (EOS)	F_H (DHMV)	F_H (FLAVIO)
1.00–2.00	169 ± 22	$0.08\,^{+0.22}_{-0.19} \pm 0.05$	$0.21\,^{+0.29}_{-0.21} \pm 0.39$	0.047	0.046	0.045
2.00–4.30	331 ± 32	$-0.04\,^{+0.12}_{-0.12} \pm 0.07$	$0.85\,^{+0.34}_{-0.31} \pm 0.14$	0.024	0.023	0.022
4.30–8.68	785 ± 42	$0.00\,^{+0.04}_{-0.04} \pm 0.02$	$0.01\,^{+0.02}_{-0.01} \pm 0.04$	…	0.012	0.011
10.09–12.86	365 ± 29	$0.00\,^{+0.05}_{-0.05} \pm 0.05$	$0.01\,^{+0.02}_{-0.01} \pm 0.06$	…	…	…
14.18–16.00	215 ± 19	$0.01\,^{+0.06}_{-0.05} \pm 0.02$	$0.03\,^{+0.03}_{-0.03} \pm 0.07$	0.007	0.007	0.006
16.00–18.00	262 ± 21	$0.04\,^{+0.05}_{-0.04} \pm 0.03$	$0.07\,^{+0.06}_{-0.07} \pm 0.07$	0.007	0.007	0.006
18.00–22.00	226 ± 20	$0.05\,^{+0.05}_{-0.04} \pm 0.02$	$0.10\,^{+0.06}_{-0.10} \pm 0.09$	0.008	0.009	0.008
1.00–6.00	778 ± 47	$-0.14\,^{+0.07}_{-0.06} \pm 0.03$	$0.38\,^{+0.17}_{-0.21} \pm 0.09$	0.025	0.025	0.020
1.00–22.00	2286 ± 73	$0.00\,^{+0.02}_{-0.02} \pm 0.03$	$0.01\,^{+0.01}_{-0.01} \pm 0.06$	…	…	…

The systematic uncertainties are estimated for each q^2 range independently. As the systematic uncertainty sources are considered to be independent, they are added in quadrature to obtain the total systematic uncertainties, as shown in the last row of Table I.

VI. RESULTS

To evaluate the statistical uncertainties, the 68.3% confidence level intervals on A_{FB} and F_H are estimated using the profiled Feldman-Cousins technique [31]. When estimating the uncertainty in A_{FB} and F_H, the other variable is treated as a nuisance parameter and profiled. A large number of pseudoexperiments are generated with the maximum-likelihood estimate of the nuisance parameter. The correlation between the two variables is ignored by setting the confidence interval after using this profiling method. The systematic and statistical uncertainties are added in quadrature to obtain the total uncertainty.

The measured values of A_{FB} and F_H for each q^2 range are shown in Fig. 5. The numerical results are summarized in Table II, including the two special q^2 ranges. The measured values of A_{FB} are consistent with the SM expectation of no asymmetry. Table II also includes three SM predictions for F_H with different input parameters and different handling of higher-order corrections, one of which is also shown in Fig. 5. There is generally good agreement between the predictions and our results, as well as between our results and previous measurements [15–19].

VII. SUMMARY

An angular analysis of the decay $B^+ \to K^+\mu^+\mu^-$ has been performed using a data sample of proton-proton collisions corresponding to an integrated luminosity of $20.5\ \mathrm{fb}^{-1}$ recorded with the CMS detector at $\sqrt{s} = 8$ TeV. The forward-backward asymmetry A_{FB} of the muon system and the contribution F_H of the pseudoscalar, scalar, and tensor amplitudes to the decay width are measured as a function of the dimuon mass squared. The results are consistent with previous measurements, and are also compatible with three different standard model predictions.

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