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Angular analysis of the decay $B^+ \rightarrow K^*(892)^+ \mu^+ \mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV

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Abstract

Angular distributions of the decay $B^+ \rightarrow K^*(892)^+ \mu^+ \mu^-$ are studied using events collected with the CMS detector in $\sqrt{s} = 8$ TeV proton-proton collisions at the LHC, corresponding to an integrated luminosity of 20.0 fb^{-1} . The forward-backward asymmetry of the muons and the longitudinal polarization of the $K^*(892)^+$ meson are determined as a function of the square of the dimuon invariant mass. These are the first results from this exclusive decay mode and are in agreement with a standard model prediction.

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1 Introduction

The decays of heavy-flavor hadrons can be used to probe high mass scales by searching for effects caused by unknown heavy particles that modify the standard model (SM) description of the decay. Flavor changing neutral current decays, such as those involving $b \rightarrow s\mu^+\mu^-$ transitions, are particularly promising as they are forbidden at tree level, and only occur via loop diagrams. The lack of a dominating tree-level process allows for a greater sensitivity to the effects of new particles inside these loops. These effects can appear as differences in the overall decay rate or as modifications to the angular distributions of the decay products.

In this paper, an analysis of the $B^+ \rightarrow K^{*+}\mu^+\mu^-$ decay is performed, where K^{*+} indicates the $K^*(892)^+$ meson. Charge-conjugate states are implied throughout the paper. The theoretical description of this decay requires four independent kinematic variables, which are chosen by convention to be three angles plus the square of the dimuon invariant mass (q^2). Two angular distributions are used to measure two decay observables, the muon forward-backward asymmetry, A_{FB} , and the K^{*+} longitudinal polarization fraction, F_L , in bins of q^2 . The data for this analysis were collected in proton-proton (pp) collisions at a center-of-mass energy of 8 TeV by the CMS detector at the CERN LHC, and correspond to an integrated luminosity of 20.0 fb^{-1} [1]. Previous measurements of A_{FB} and F_L have been made in the exclusive mode $B^0 \rightarrow K^*(892)^0\mu^+\mu^-$ [2–5] and in a combination of decays of the form $B \rightarrow K^*(892)\ell^+\ell^-$ [6, 7], where ℓ refers to an electron or a muon. The results are generally consistent with the SM predictions [8–18]. This paper reports the first measurement of A_{FB} and F_L in the exclusive decay $B^+ \rightarrow K^{*+}\mu^+\mu^-$, with the K^{*+} meson reconstructed in the $K_S^0\pi^+$ decay mode and the K_S^0 meson identified from its decay to a pair of charged pions.

2 The CMS detector

The central feature of the CMS apparatus 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 strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. During the LHC running period when the data used in this paper were recorded, the silicon tracker consisted of 1440 silicon pixel and 15 148 silicon strip detector modules. For nonisolated particles of $1 < p_T < 10 \text{ GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [19]. Muons with $|\eta| < 2.4$ are measured with gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [20].

Events of interest are selected using a two-tiered trigger system [21]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing.

3 Event selection

The events used in this analysis are selected by a trigger designed specifically for finding b hadron decays that include two muons. The trigger required two oppositely charged muons, each with transverse momentum $p_T > 3.5 \text{ GeV}$ and $|\eta| < 2.2$. The two muons are fitted to

a common vertex and retained if the fit χ^2 probability is greater than 10% and the vertex is displaced from the beamline (in the transverse plane) by at least three times the uncertainty in the distance. The dimuon system is further required to have $p_T > 6.9 \text{ GeV}$, invariant mass between 1 and 4.8 GeV, and a momentum vector whose angle α with respect to the vector between the beamline and the dimuon vertex (in the transverse plane) satisfies $\cos \alpha > 0.9$.

The offline reconstruction of the signal decay $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ requires two oppositely charged muons and a K^{*+} meson, where the K^{*+} meson is reconstructed in the $K_S^0 \pi^+$ decay mode, and the K_S^0 meson is identified through its decay to $\pi^+ \pi^-$. The trigger requirements are reapplied to the corresponding offline quantities and the offline muon candidates must that pass the soft muon criteria [22] and correspond to the muons that satisfied the trigger requirements. The K_S^0 meson candidates are reconstructed by fitting pairs of oppositely charged tracks to a common vertex and selected using standard selection criteria. In particular, the tracks must have at least 6 hits in the silicon tracker, a χ^2 per degree of freedom (dof) less than 5, pass at a distance from the beamline at least 2 times its uncertainty, and have the closest distance between their trajectories be less than 1 cm. In addition, the fitted vertex must have a $\chi^2/\text{dof} < 7$ and be located at a distance from the beamline that is at least 15 times the calculated uncertainty in the distance. The two-track invariant mass must be within 17.3 MeV (three times the average resolution) of the K_S^0 meson mass [23] when the tracks are assigned the charged pion mass. To remove $\Lambda \rightarrow p \pi^-$ decays, the two-track combination is rejected if the invariant mass is in the range 1.11–1.125 GeV when the high and low momentum tracks are assigned the proton and charged pion mass, respectively. Each K_S^0 candidate is combined with two oppositely charged muons and a non-muon track, assumed to be a pion, in a fit to a common vertex to form a B^+ meson candidate. The $K_S^0 \pi^+$ invariant mass is required to be within 100 MeV of the world-average K^{*+} mass [23], and the invariant mass of the $K_S^0 \pi^+ \mu^+ \mu^-$ system, m , must be in the range $4.76 < m < 5.8 \text{ GeV}$.

The remaining selection criteria are obtained by maximizing $S/\sqrt{S+B}$ for different event shape variables. The number of signal events, S , is obtained from the simulation (normalized to the data) and the number of background events, B , is obtained from the $K_S^0 \pi^+ \mu^+ \mu^-$ data side-band invariant mass regions 4.76–5.18 and 5.38–5.8 GeV. The K_S^0 meson p_T must be greater than 1 GeV. The pion track from the K^{*+} decay must have $p_T > 0.4 \text{ GeV}$ and a transverse impact parameter with respect to the beamline of at least 0.4 times the uncertainty in this parameter found from the vertex fit. The B^+ candidate vertex must have a fit χ^2 probability larger than 10% and a separation from the beamline of at least 12 times the calculated uncertainty in the separation. The angle α between the vector from the beamline to the vertex location and the B^+ candidate momentum vector (in the transverse plane) must satisfy $\cos \alpha > 0.9994$. In 0.3% of the events in which a candidate passes the selection criteria, a second candidate also passes the same criteria. In these cases, the candidate with the smaller vertex fit χ^2 value is chosen.

The decay modes $B^+ \rightarrow K^{*+} J/\psi$ and $B^+ \rightarrow K^{*+} \psi(2S)$, followed by the dimuon decays of charmonium states J/ψ and $\psi(2S)$, have the same final-state particles as the signal mode. As described in Section 4, the analysis is performed in bins of q^2 that exclude candidates in the $B^+ \rightarrow K^{*+} J/\psi$ and $B^+ \rightarrow K^{*+} \psi(2S)$ regions, namely $8.68 < q^2 < 10.09 \text{ GeV}^2$ and $12.86 < q^2 < 14.18 \text{ GeV}^2$. However, since events from charmonium decay are produced quite copiously, a significant contribution can still appear in the signal q^2 regions. This primarily occurs through two effects: finite detector resolution resulting in a reconstructed dimuon mass different than the true value, and decays of the two charmonium states in which a low-energy photon is emitted in addition to the two muons. Two additional requirements are used to remove these contributions. First, candidates that satisfy either $m_{J/\psi} - 5\sigma_q < q < m_{J/\psi} + 3\sigma_q$ or $|q - m_{\psi(2S)}| < 3\sigma_q$ are removed, where $m_{J/\psi}$ and $m_{\psi(2S)}$ are the world-average J/ψ and

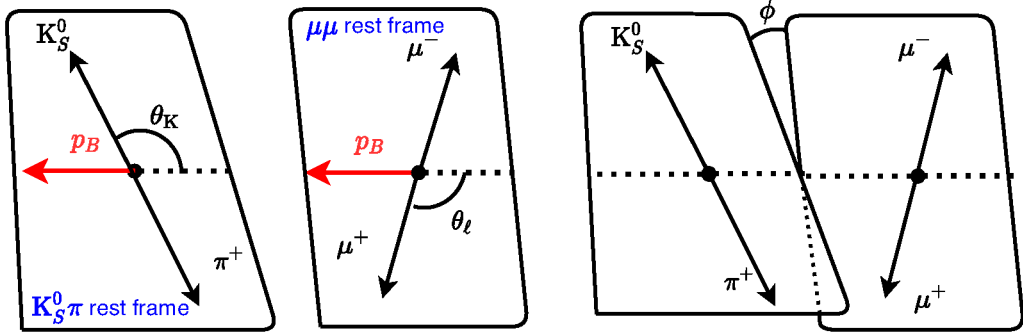


Figure 1: Definition of the angular observables θ_K (left), θ_ℓ (middle), and ϕ (right) for the decay $B^+ \rightarrow K^{*+} \mu^+ \mu^-$.

$\psi(2S)$ masses [23], respectively, and σ_q is the calculated uncertainty in q for each candidate. The second requirement specifically targets the radiative background by using the fact that the missing low-energy photon will shift q and m from their nominal values by a similar amount. Thus, these events are suppressed by requiring $|(m - m_{B^+}) - (q - m_{J/\psi})| > 0.09 \text{ GeV}$ and $|(m - m_{B^+}) - (q - m_{\psi(2S)})| > 0.03 \text{ GeV}$. When the $B^+ \rightarrow K^{*+} J/\psi$ decay mode is used as a control sample, the requirements in this paragraph are not applied.

The Monte Carlo (MC) samples corresponding to the signal and control channels are simulated using PYTHIA 6.426 [24], with the unstable particle decays modeled by EVTGEN version 9.1 [25]. The particles are then propagated through a detailed model of the CMS detector with GEANT4 [26]. The reconstruction and selection of the MC generated events follow the same algorithms as for the collision data. The number and spatial distribution of additional pp collision vertices in the same or nearby beam crossings in the data are simulated by weighting the MC samples to match the distributions found in data. The signal MC samples are used to estimate the efficiency, which includes the detector acceptance, the trigger efficiency, and the efficiency for reconstructing and selecting the signal candidates.

4 Angular analysis

The measurement of A_{FB} and F_L is performed in three q^2 regions: $1 < q^2 < 8.68 \text{ GeV}^2$, $10.09 < q^2 < 12.86 \text{ GeV}^2$, and $14.18 < q^2 < 19 \text{ GeV}^2$. The angular distribution of the signal process, $B^+ \rightarrow K^{*+} \mu^+ \mu^-$, depends on three variables as shown in Fig. 1: θ_K (the angle in the K^{*+} meson rest frame between the momentum of the K_S^0 meson and the negative of the B^+ meson momentum), θ_ℓ (the angle in the dimuon rest frame between the momentum of the positively charged muon and the negative of the B^+ meson momentum), and ϕ (the angle in the B^+ meson rest frame between the plane containing the two muons and the plane containing the K_S^0 and π^+ mesons). Since the extracted angular observables A_{FB} and F_L do not depend on ϕ , this angle is integrated out. While the $K_S^0 \pi^+$ invariant mass is required to be consistent with coming from a K^{*+} resonance decay, there can still be S -wave $K_S^0 \pi^+$ contributions [15, 27–29]. This is parameterized by two terms: the S -wave fraction, F_S , and the interference amplitude, A_S , between S - and P -wave decays. The parameters A_{FB} , F_L , F_S , and A_S are functions of q^2 . The differential decay rate of the signal decay $B^+ \rightarrow K^{*+} \mu^+ \mu^-$, as a function of the angular variables and q^2 , can be written [15, 29] as:

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

For each q^2 bin, the observables A_{FB} and F_L are extracted by performing an unbinned extended maximum likelihood fit with three independent variables: m , $\cos\theta_K$, and $\cos\theta_\ell$. The unnormalized probability density function (pdf) used to fit the data is:

$$\begin{aligned}
\text{pdf}(m, \cos\theta_K, \cos\theta_\ell) = & Y_S S^m(m) S^a(\cos\theta_K, \cos\theta_\ell) \epsilon(\cos\theta_K, \cos\theta_\ell) \\
& + Y_B B^m(m) B^{\theta_K}(\cos\theta_K) B^{\theta_\ell}(\cos\theta_\ell). \tag{2}
\end{aligned}$$

The parameters Y_S and Y_B are the signal and background yields, respectively, and are free parameters in the fit. The signal mass shape, $S^m(m)$, is modeled by the sum of two Gaussian functions with a common mean, and all parameters (other than the amplitude) are fixed to the values obtained from fitting simulated signal events. The mass shape of the background, $B^m(m)$, is an exponential function with the exponent as a free parameter. The function $S^a(\cos\theta_K, \cos\theta_\ell)$ is obtained from Eq. (1) to describe the signal event distribution in the $(\cos\theta_K, \cos\theta_\ell)$ angular space. Since the S -wave contribution is found to be small, F_S and A_S are fixed to zero in the nominal fit. The functions $B^{\theta_K}(\cos\theta_K)$ and $B^{\theta_\ell}(\cos\theta_\ell)$ are the background shapes in the angular space. They are obtained by fitting the data events in the B^+ invariant mass sideband regions and fixed in the final fit. The $B^{\theta_K}(\cos\theta_K)$ distributions are fitted to a sum of two exponential functions, a fourth-degree polynomial, and a third-degree polynomial for the low, middle, and high q^2 ranges, respectively. The $B^{\theta_\ell}(\cos\theta_\ell)$ distributions are fitted to a sum of two Gaussian functions, a fourth-degree polynomial, and a linear function for the low, middle, and high q^2 ranges, respectively.

The signal efficiency function in the two-dimensional angular spaces $\epsilon(\cos\theta_K, \cos\theta_\ell)$ is obtained from the simulated samples in a two-step process. In the first step, the efficiency in each q^2 bin is fitted to a product of two one-dimensional functions, one for each angular variable, assuming there is no correlation between the variables. The one-dimensional functions are polynomials of degree six, except for the $\cos\theta_\ell$ distribution of the first q^2 bin, which is a sum of three Gaussian functions. In the second step, a two-dimensional fit is performed on both angular variables, where the results from the first step are fixed, and an additional cross-term function is added to account for correlations. The correlation function is the product of a third-degree Legendre polynomial (with $\cos\theta_K$ as the argument) and a fourth-order ordinary polynomial (with $\cos\theta_\ell$ as the argument), with each cross term controlled by a free parameter in the fit. The signal efficiencies and the corresponding fits for each q^2 bin are shown as projections on $\cos\theta_K$ (upper plots) and $\cos\theta_\ell$ (lower plots) in Fig. 2.

To test the fit, the reconstructed signal MC data set is split into 2000 random, disjoint samples, each with a similar number of signal events as the data sample. These are combined with background events generated using the appropriate pdf in Eq. (2), with parameters taken from the fit to the data. Each sample is fitted in the same manner as the data and the resulting values for A_{FB} and F_L are found to have approximately Gaussian distributions with mean values

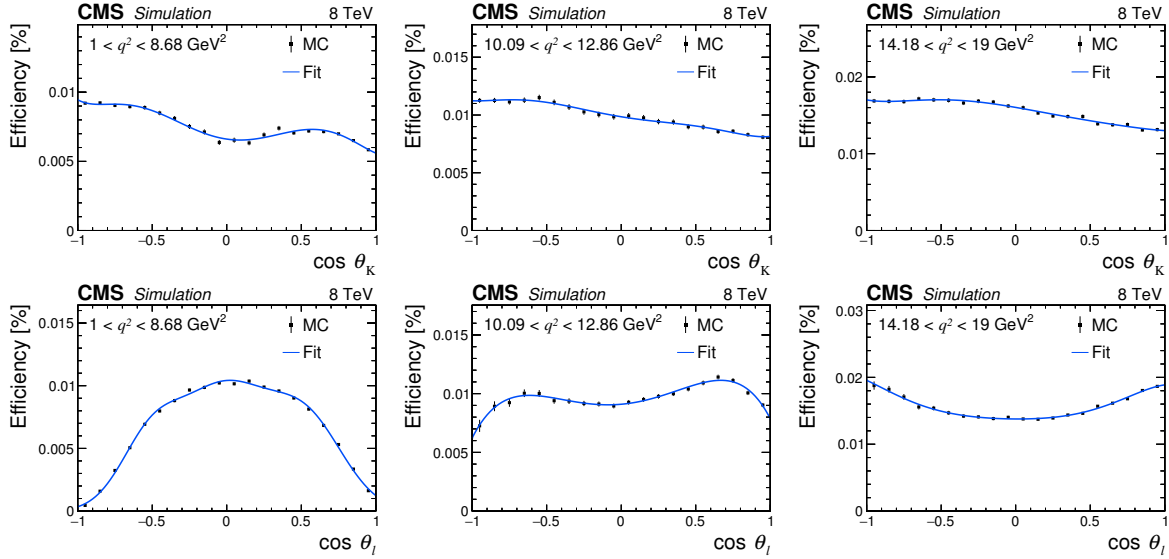


Figure 2: The signal efficiency as a function of $\cos \theta_K$ (upper row) and $\cos \theta_\ell$ (lower row) from simulation for the q^2 ranges indicated. The vertical bars indicate the statistical uncertainty. The curves show the projection of the fitted result obtained from the two-dimensional fit, as described in the text.

close to the MC values. This indicates the fit is unbiased and accurate, even in the presence of background.

The degree to which the simulation describes the data is examined by using the $B^+ \rightarrow K^{*+}J/\psi$ MC sample to determine the efficiency, correcting the $B^+ \rightarrow K^{*+}J/\psi$ data by this efficiency, and comparing the $\cos \theta_K$ and $\cos \theta_\ell$ distributions with the SM expectations. The residual discrepancies are found to have a negligible effect on the measured values of A_{FB} and F_L .

5 Systematic uncertainties

Several sources of systematic uncertainties are considered in this analysis. First, the statistical uncertainty associated with the finite number of signal MC events is evaluated by generating 200 alternative efficiency functions, varying the function parameters according to their uncertainties. Each of these efficiency functions is used to fit the data, and the standard deviations of the distributions of the fitted values for A_{FB} and F_L are taken as the systematic uncertainty in each quantity. The second source of systematic uncertainty is from the shape used to parameterize the efficiency. The difference between the values of A_{FB} and F_L obtained from fitting the generator-level MC signal events (with no efficiency function) and the reconstructed MC signal events (with the efficiency function) is taken as the estimate for this systematic uncertainty.

The third systematic uncertainty arises from modeling the angular distribution of the background events and is composed of three components. The first component is intended to check the functional form. Instead of fitting the sideband data with the functional forms described in Section 4, the lower and upper sidebands are individually fit to a smooth function and the two pdfs are combined according to their relative yields. The difference between the results obtained with this alternative background pdf and the default function is taken as a systematic uncertainty. The second component is intended to account for the uncertainty regarding how well the background in the sideband regions represents the background in the signal region. In the nominal fit, large B^+ invariant mass sideband regions are used to determine the

background shape in order to reduce the statistical uncertainty. As an alternate method, the background shape is determined from narrower sideband regions ($4.96 < m < 5.18$ GeV and $5.38 < m < 5.6$ GeV), which are expected to be more representative of the signal region. Once the new background shape is determined, the fit is redone using all events (including the original sideband region), and the change in A_{FB} and F_{L} with respect to the nominal fit is used as the systematic uncertainty. Since the background shape parameters are fixed in the determination of A_{FB} and F_{L} , the third component accounts for the statistical uncertainty in the background shape. The data are fitted with 200 different background shapes obtained by varying the shape parameters by their uncertainties. The standard deviation of the distributions of the angular observables A_{FB} and F_{L} obtained from these 200 fits is included as a systematic uncertainty.

The fourth source of systematic uncertainty is the effect from S -wave contamination. The nominal fit does not include any S -wave contribution. We perform an alternative fit in which the S -wave fraction F_S is set to 5% and the S - P interference term A_S is a free parameter. The change in A_{FB} and F_{L} from the default fit is taken as the systematic uncertainty from S -wave contamination. Since the analysis of the similar decay mode $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ did not find F_S above 3% in any q^2 bin with many more signal events [5], an upper limit of 5% is a conservative choice.

The total systematic uncertainty is obtained by adding the individual contributions in quadrature for each q^2 bin. The systematic uncertainties are summarized in Table 1.

Table 1: Sources of systematic uncertainties and the effect on A_{FB} and F_{L} . The values given are absolute and the ranges indicate the variation over the q^2 bins.

Source	$A_{\text{FB}} (10^{-3})$	$F_{\text{L}} (10^{-3})$
MC statistical uncertainty	12 – 29	18 – 38
Efficiency model	3 – 25	4 – 12
Background shape functional form	0 – 9	0 – 33
Background shape statistical uncertainty	16 – 73	20 – 87
Background shape sideband region	28 – 153	38 – 78
S -wave contamination	4 – 22	5 – 12
Total systematic uncertainty	42 – 174	55 – 127

6 Results

Fits to the data are performed in three independent q^2 bins between 1 and 19 GeV². As described in Section 4, the measured values for A_{FB} and F_{L} are obtained from an unbinned maximum likelihood fit in which both parameters are allowed to vary freely. The necessity of a non-negative decay rate results in physical limits on A_{FB} and F_{L} that make it difficult to determine the statistical uncertainties from the likelihood function. Therefore, the statistical uncertainties in A_{FB} and F_{L} (including their correlations) are evaluated using the profiled version of the Feldman-Cousins technique [30]. During this procedure, the other variables (signal yield, background yield, and background mass shape parameter) are considered as nuisance parameters and profiled. A large number of pseudo-experiments are generated with the maximum likelihood estimate of the nuisance parameter. The correlation between the two angular observables is ignored when calculating the confidence interval after the profiling method.

The results of the unbinned maximum likelihood fit are overlaid on the data in projections of m (upper plots), $\cos \theta_K$ (middle plots), and $\cos \theta_\ell$ (lower plots) for each q^2 region in Fig. 3. The fitted values of Y_S , A_{FB} , and F_{L} , along with their associated uncertainties, are given in Table 2 for each of the q^2 bins. In order to more clearly observe the signal features, the data

and fit results are shown versus the two angular variables in the invariant mass signal region $5.18 < m < 5.38 \text{ GeV}$ in Fig. 4. The fitted values of A_{FB} and F_L are shown as a function of q^2 in Fig. 5, along with a SM prediction. This prediction combines quantum chromodynamic factorization and soft collinear effective theory at large recoil with heavy-quark effective theory and lattice gauge theory at small recoil to separate hard physics (around the b quark mass) from soft physics (around Λ_{QCD}) [16]. While theoretical predictions are unavailable for the region between the J/ψ and $\psi(2S)$ meson masses ($10.09 < q^2 < 12.86 \text{ GeV}^2$), the SM prediction agrees with the experimental results for the other q^2 bins, indicating no evidence of contributions from physics beyond the SM.

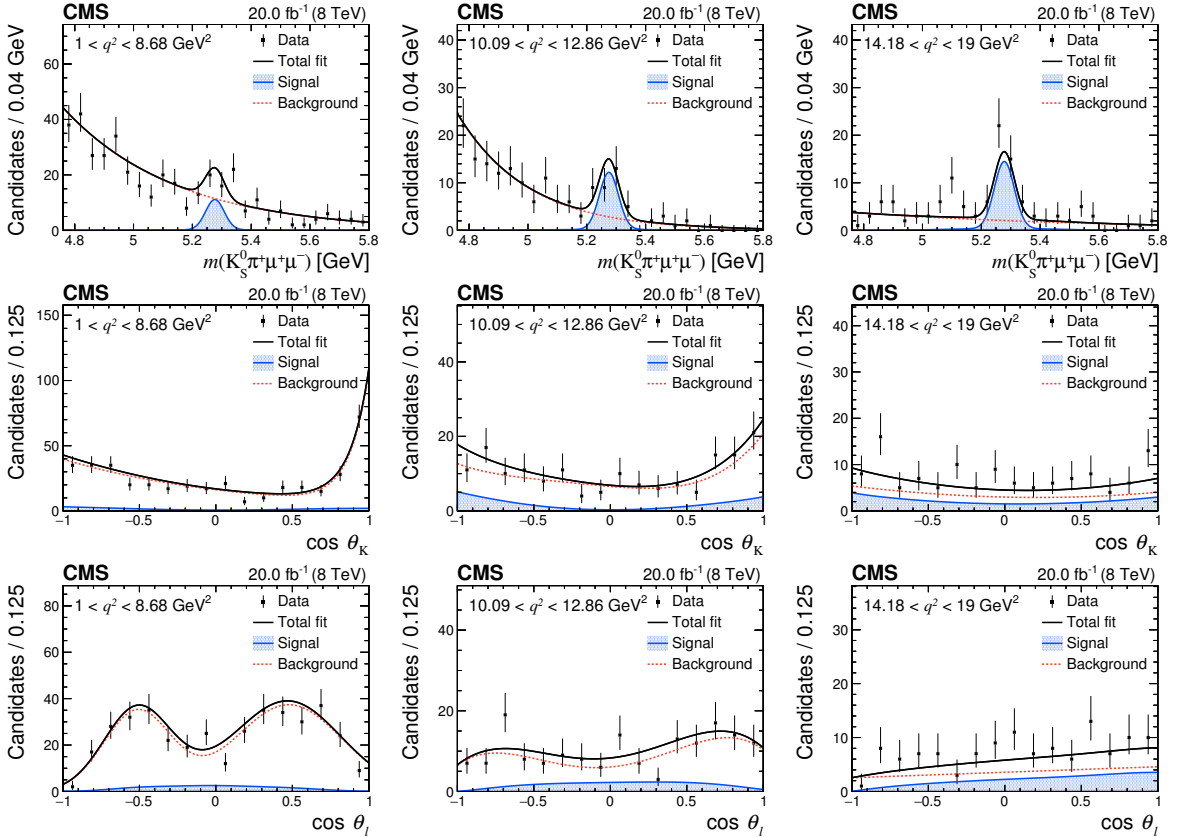


Figure 3: The $K_S^0 \pi^+ \mu^+ \mu^-$ invariant mass (upper row), $\cos \theta_K$ (middle row), and $\cos \theta_\ell$ (lower row) distributions for each q^2 range is shown for data, along with the fit projections. The vertical bars on the data points indicate the statistical uncertainty. The filled areas, dashed lines, and solid lines represent the signal, background, and total contributions, respectively.

Table 2: The Y_S , A_{FB} , and F_L values from the fit for each q^2 range. The first uncertainty is statistical and the second is systematic.

q^2 (GeV^2)	Y_S	A_{FB}	F_L
1 – 8.68	22.1 ± 8.1	$-0.14^{+0.32}_{-0.35} \pm 0.17$	$0.60^{+0.31}_{-0.25} \pm 0.13$
10.09 – 12.86	25.9 ± 6.3	$0.09^{+0.16}_{-0.11} \pm 0.04$	$0.88^{+0.10}_{-0.13} \pm 0.05$
14.18 – 19	45.1 ± 8.0	$0.33^{+0.11}_{-0.07} \pm 0.05$	$0.55^{+0.13}_{-0.10} \pm 0.06$

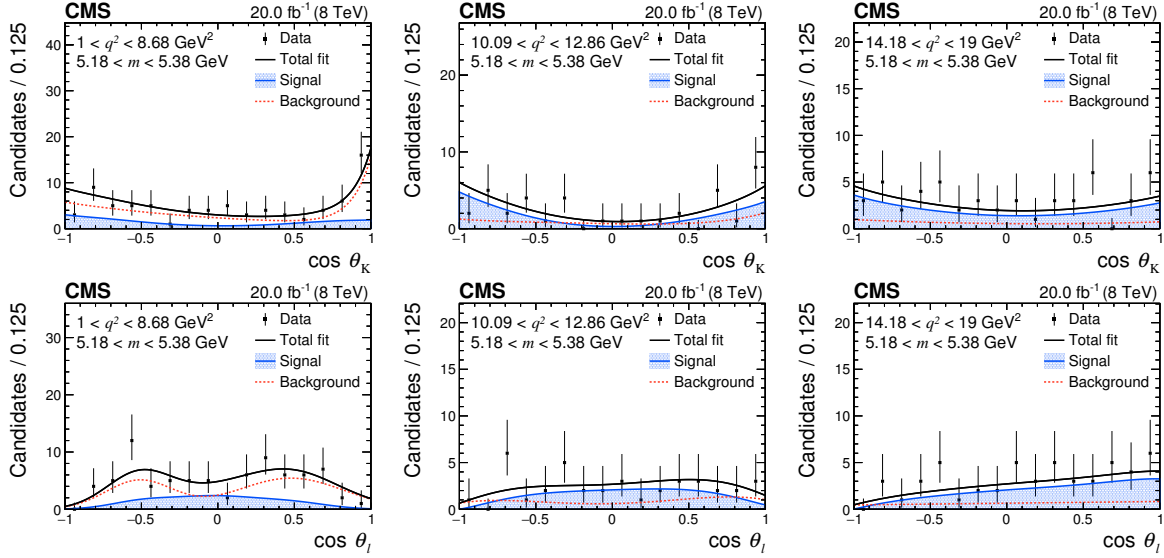


Figure 4: The $\cos \theta_K$ (upper row) and $\cos \theta_\ell$ (lower row) distributions for each q^2 range is shown for data in the invariant mass region $5.18 < m < 5.38$ GeV, along with the fit projections for the same region. The vertical bars on the data points indicate the statistical uncertainty. The filled areas, dashed lines, and solid lines represent the signal, background, and total contributions, respectively.

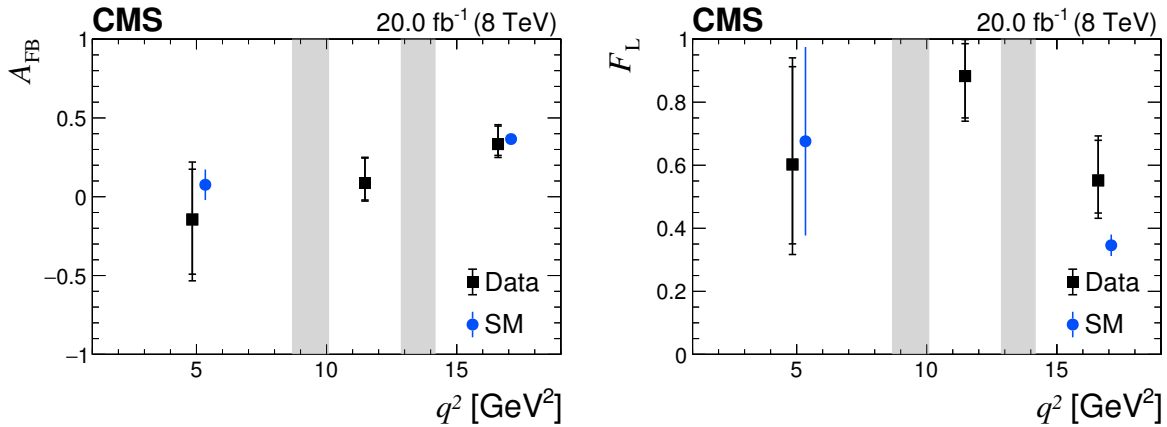


Figure 5: The measured values of A_{FB} (left) and F_L (right) versus q^2 for $B^+ \rightarrow K^{*+} \mu^+ \mu^-$ decays are shown with filled squares, centered on the q^2 bin. The statistical (total) uncertainty is shown by inner (outer) vertical bars. The vertical shaded regions correspond to the regions dominated by $B^+ \rightarrow K^{*+} J/\psi$ and $B^+ \rightarrow K^{*+} \psi(2S)$ decays. The SM predictions and associated uncertainties are shown by the filled circles and vertical bars, with the points slightly offset from the center of the q^2 bin for clarity.

7 Summary

The first angular analysis of the exclusive decay $B^+ \rightarrow K^*(892)^+ \mu^+ \mu^-$, including the charge-conjugate state, has been performed using a sample of proton-proton collisions at a center-of-mass energy of 8 TeV. The data were collected with the CMS detector in 2012 at the LHC, and correspond to an integrated luminosity of 20.0 fb^{-1} . For each bin of the dimuon invariant mass squared (q^2), a three-dimensional unbinned maximum likelihood fit is performed on the distributions of the $K^*(892)^+ \mu^+ \mu^-$ invariant mass and two decay angles. The muon forward-backward asymmetry, A_{FB} , and the $K^*(892)^+$ longitudinal polarization fraction, F_L , are extracted from the fit in bins of q^2 and found to be consistent with a standard model prediction.

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