Angular analyses of $b \to sll$ transitions at CMS

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Abstract. The flavour changing neutral current decays are interesting probes for searching for new physics. Angular distributions of $b \to s\ell^+\ell^-$ transition processes of both $B_0 \to K^*\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^-$ are studied using a sample of proton-proton collisions at $\sqrt{s} = 8$ TeV collected with the CMS detector at the LHC, corresponding to an integrated luminosity of 20.5 fb$^{-1}$. Angular analyses are performed to determine $P_1$ and $P_5'$ angular parameters for $B_0 \to K^{*0}\mu^+\mu^-$ and $A_{FB}$ and $F_H$ parameters for $B^+ \to K^+\mu^+\mu^-$, all as functions of the dimuon invariant mass squared. All of the measurements are consistent with the standard model predictions.

1. Introduction
Phenomena beyond the standard model (BSM) can become manifest directly, via the production of new particles, or indirectly, by affecting the production and decay of SM particles. The transitions of the type $b \to s\ell^+\ell^-$ is a flavor-changing neutral current (FCNC) process, with $\ell$ denoting a charged lepton. In the SM, the transition is forbidden at tree level but occurs via either electroweak $Z/\gamma$ penguin diagrams or a $W^+W^-$ box diagram. This makes the measurement of these rare FCNC decays more sensitive to BSM.

CMS has recently analysed two such FCNC decays: $B_0 \to K^{*0}\mu^+\mu^-$, where $K^{*0}$ indicates the $K^{*0}(892)$ meson, and $B^+ \to K^+\mu^+\mu^-$. Both analyses use a sample of events collected in proton-proton (pp) collisions at a center-of-mass energy of 8 TeV. The data correspond to an integrated luminosity of 20.5 fb$^{-1}$[1].

2. Angular analysis of $B_0 \to K^{*0}\mu^+\mu^-$[2]

The differential decay rate for $B_0 \to K^{*0}\mu^+\mu^-$ can be written in terms of the dimuon mass squared ($q^2$) and three angular variables as a combination of spherical harmonics. $\theta_\ell$ 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, $\theta_K$ is the angle between the kaon momentum and the direction opposite to the $B_0$ ($\bar{B}_0$) in the $K^{*0}$ ($\bar{K}^{*0}$) rest frame, and $\phi$ is the angle between the plane containing the two muons and the plane containing the kaon and pion in the $B_0$ rest frame.

New physics may modify any of the angular variables[3] relative to their SM values[4, 5]. Previous measurements of some of these quantities by the BaBar, Belle, CDF, LHCb, and CMS experiments are consistent with the SM[6]. The $P_5$ parameter in the decay $B^0 \to K^{*0}\mu^+\mu^-$ is of particular interest due to recent LHCb and Belle measurements[7, 8, 9] that indicate a potential discrepancy with the standard model. CMS performed a new measurement of the $P_1$ and $P_5'$ angular parameters [2], trying to elucidate the situation. In the measurement, the values of $P_1$ and $P_5'$ angular parameters are determined by fitting the distribution of events as a function of
the three angular variables. 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 $B^0 \rightarrow K^{*0} J/\psi$ and $B^0 \rightarrow K^{*0} \psi'$ decays, respectively, are used to validate the analysis.

There can be a contribution from spinless (S-wave) $K^-\pi^+$ combinations[5]. This is parametrized with three terms: $f^S$, which is related to the S-wave fraction, and $A_S$ and $A_S^\pm$, which are the interference amplitudes between the S-wave and P-wave decays. Including these components, the angular distribution of $B^0 \rightarrow K^{*0} \mu^+\mu^-$ can be written as[5]:

$$
\frac{1}{d\Gamma/dq^2 dq^2 d\cos\theta_{\ell} d\cos\theta_K d\phi} = \frac{9}{8\pi} \left\{ \frac{2}{3} \left[ (F_S + A_S \cos \theta_K) (1 - \cos^2 \theta_\ell) + A_S^\pm \sqrt{1 - \cos^2 \theta_K} \right] \right.
\begin{align*}
\sqrt{1 - \cos^2 \theta_\ell} \cos \varphi &+ (1 - F_S) \left[ 2F_L \cos^2 \theta_K (1 - \cos^2 \theta_\ell) \\
+ \frac{1}{2} (1 - F_L) (1 - \cos^2 \theta_K) (1 + \cos^2 \theta_\ell) &+ \frac{1}{2} P_1 (1 - F_L) \\
(1 - \cos^2 \theta_K)(1 - \cos^2 \theta_\ell) &\cos 2\varphi + 2P_5' \cos \theta_K \sqrt{F_L (1 - F_L)} \\
\sqrt{1 - \cos^2 \theta_K} &\sqrt{1 - \cos^2 \theta_\ell} \cos \varphi \right].
\end{align*}
\right\}
$$

where $F_L$ denotes the longitudinal polarization fraction of the $K^{*0}$. This expression is an exact simplification of the full angular distribution, obtained by folding the $\varphi$ and $\theta_\ell$ angles about zero and $\pi/2$, respectively.

For each $q^2$ bin, the observables of interest are extracted from an 4D unbinned extended maximum-likelihood fit. For each $q^2$ bin, the unnormalized probability density function has the following expression:

$$
pdf(m, \theta_K, \theta_\ell, \varphi) = Y^C_S \left[ S^C(m) S^a(\theta_K, \theta_\ell, \varphi) e^C(\theta_K, \theta_\ell, \varphi) \right. \\
+ \left. \frac{f^M}{1 - f^M} S^M(m) S^a(-\theta_K, -\theta_\ell, \varphi) e^M(\theta_K, \theta_\ell, \varphi) \right] \\
+ Y_B B^m(m) B^{2K}(\theta_K) B^{\theta_\ell}(\theta_\ell) B^{\varphi}(\varphi),
$$

where the contributions correspond to correctly tagged and mistagged signal events, and background events. The parameters $Y^C_S$ and $Y_B$ are the yields of correctly tagged signal events and background events. The parameter $f^M$ is the mistagged fraction. The signal mass probability functions $S^C(m)$ and $S^M(m)$ describe the mass distribution for correctly tagged and mistagged signal events. $S^a(\theta_K, \theta_\ell, \varphi)$ describes the signal in 3D space of the angular variables and corresponds to Eq.(1). The combination $B^m(m) B^{2K}(\theta_K) B^{\theta_\ell}(\theta_\ell) B^{\varphi}(\varphi)$ is obtained from $B^0$ sideband data and describes the background.

The fit formalism and results are validated through fits to pseudo-experimental samples, MC simulation samples, and control channels. To ensure correct coverage for the uncertainties of the angular parameters, the Feldman-Cousins(FC) method[10] is used with nuisance parameters.

The signal data, corresponding to 1397 events, are fit in seven $q^2$ bins from 1 to 19 GeV$^2$. As an example, distributions for the second $q^2$ bin, along with the fit projections, are shown in Fig.1.

The fitted values of $P_1$, and $P_5'$, along with their associated uncertainties, for each of the $q^2$ regions are shown in Fig.2, along with the SM predictions. The results are among the most precise to date for these parameters and are consistent with the predictions of SM.
Figure 1. $K^+\pi^-\mu^+\mu^-$ invariant mass and angular distributions for the second $q^2$ bin $2.00 < q^2 < 4.30$ GeV$^2$. Overlaid on each plot is the projection of the results for the total fit, as well as for the three components: correctly tagged signal, mistagged signal, and background. The vertical bars indicate the statistical uncertainties in the data[11].

Figure 2. CMS measurements of the (left) $P_1$ and (right) $P'_5$ angular parameters versus $q^2$ for $B^0 \rightarrow K^*\mu^+\mu^-$ decays[2], in comparison to results from the LHCb[8] and Belle[9] Collaborations. The statistical uncertainties are shown by the inner vertical bars, while the outer vertical bars give the total uncertainties. The horizontal bars show the bin widths. The vertical shaded regions correspond to the $J/\psi$ and $\psi'$ resonances. The hatched region shows the prediction from SM calculations from Refs.[3, 5], averaged over each $q^2$ bin.

3. Angular analysis of $B^+ \rightarrow K^+\mu^+\mu^-$ [11]

The decay rate for the process $B^+ \rightarrow K^+\mu^+\mu^-$ depends on $\cos \theta_\ell$, where $\theta_\ell$ is the angle between the directions of the $\mu^-$ and $K^+$ in the dilepton rest frame. The $\cos \theta_\ell$ dependence of the decay width $\Gamma_\ell$ can be parametrized[12, 13, 14] in terms of the observables of interest $A_{FB}$ and $F_H$ as:
\[ \frac{1}{\Gamma_{\ell}} \Gamma_{\ell} \cos \theta_{\ell} = \frac{3}{4}(1 - F_{\text{H}})(1 - \cos^2 \theta_{\ell}) + \frac{1}{2} F_{\text{H}} + A_{\text{FB}} \cos \theta_{\ell}. \]  

(3)

The requirement for the decay rate to remain positive over all possible lepton angles constrains the parameter space to the region \( 0 \leq F_{\text{H}} \leq 3 \) and \( |A_{\text{FB}}| \leq \min(1, F_{\text{H}}/2) \).

The angular observables \( A_{\text{FB}} \) and \( F_{\text{H}} \) are extracted from a 2D 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 used in the 2D fit is:

\[
\text{pdf}(m, \cos \theta_{\ell}) = Y_S \times S_m(m) \times S_a(\cos \theta_{\ell}) + Y_B \times B_m(m) \times B_a(\cos \theta_{\ell}),
\]

where the two contributions on the righthand side correspond to the parametrization of the signal and background events. The parameters \( Y_S \) and \( Y_B \) are the yields of signal and background events. The functions \( S_m(m) \) and \( S_a(\cos \theta_{\ell}) \) describe the signal invariant mass and angular distributions, while \( B_m(m) \) and \( B_a(\cos \theta_{\ell}) \) are similar functions describing the background. The function \( \epsilon(\cos \theta_{\ell}) \) is the signal efficiency as a function of \( \cos \theta_{\ell} \).

The final fit is performed over the full \( B^+ \) meson invariant mass range and results in \( 2286 \pm 73 \) signal events with \( q^2 \) from 1 to 22 GeV$^2$. Projections of the fit results from data for the \( K^+ \mu^+ \mu^- \) invariant mass and \( \cos(\theta_{\ell}) \) distributions for the inclusive \( q^2 \) bin of 1–22 GeV$^2$ (excluding the resonance regions) are shown in Fig.3. To evaluate the statistical uncertainties, the 68.3% confidence level intervals on \( A_{\text{FB}} \) and \( F_{\text{H}} \) are estimated using the profiled Feldman–Cousins technique[10]. The systematic and statistical uncertainties are added in quadrature to obtain the total uncertainty.

\[ A_{\text{FB}} \]

\[ F_{\text{H}} \]

\[ \epsilon(\cos \theta_{\ell}) \]

(4)

Figure 3. Projections of the fit results from data for the \( K^+ \mu^+ \mu^- \) invariant mass and \( \cos(\theta_{\ell}) \) distributions for the inclusive \( q^2 \) bin of 1–22 GeV$^2$ (excluding the resonance regions). The vertical bars represent the statistical uncertainties in the data[11].

The measured values of \( A_{\text{FB}} \) and \( F_{\text{H}} \) for each \( q^2 \) range are shown in Fig.4. The measured values of \( A_{\text{FB}} \) are consistent with the SM expectation of no asymmetry. We also compare the measured results with three SM predictions for \( F_{\text{H}} \) with different input parameters and different handling of higher-order corrections, one of which is also shown in Fig.4. There is generally good agreement between the predictions and our results, as well as between our results and previous measurements[17, 18, 19, 20, 21].

4. Summary and outlook

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$^{-1}$, angular analyses have been performed.
Figure 4. Results of the measurement of $A_{FB}$ and $F_H$ in bins of $q^2[11]$. The statistical uncertainties are shown by the inner vertical bars, while the outer vertical bars give the total uncertainties. The horizontal bars show the bin widths. The vertical shaded regions are 8.68–10.09 and 12.86–14.18 GeV$^2$, and correspond to the $J/\psi$ and $\psi'$-dominated control regions, respectively. The red line in the right plot shows the DHMV SM theoretical prediction[15, 16],

for the decays of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ and $B^+ \rightarrow K^+ \mu^+ \mu^-$. For each bin of the dimuon invariant mass squared ($q^2$), unbinned maximum-likelihood fits were performed to the distributions of the $B$ meson invariant mass and the three decay angles, to obtain values of angular parameters. The results are among the most precise to date and are consistent with previous measurements and with standard model predictions. The CMS experiment will continue to use flavour changing neutral current decays to test the standard model with higher precision in future.

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