

Electroweak penguins at LHCb

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Abstract

Electroweak penguin decays are flavour-changing neutral current processes, and are highly suppressed in the Standard Model. They can only proceed via loop diagrams. Such decays may receive contributions from New Physics and change their decay behaviours like decay rate and angular distribution. Studying the properties of these decays thus provides a powerful method to probe for New Physics. In this contribution the most recent LHCb results on electroweak penguin decays are reported.

Keywords: Flavour physics, B physics, Rare decay, Electroweak penguin, LHCb

1. Introduction

In the Standard Model (SM), electroweak penguin decays, such as the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay¹, are flavour-changing neutral current (FCNC) processes. They are highly suppressed, and can proceed only through loop diagrams. However, such decays may receive contributions from New Physics and change their decay behaviours like decay rate and angular distribution. Studying the properties of these decays thus provides a powerful method to probe for New Physics.

The LHCb experiment [1] is designed to search for physics beyond the SM through precision study of the beauty and charm hadrons. The LHCb detector has excellent tracking, particle identification performance, and a flexible trigger system. In the run-I phase, the LHCb experiment has collected a dataset corresponding to 1 fb^{-1} of integrated luminosity at $\sqrt{s} = 7 \text{ TeV}$ in 2011, and 2 fb^{-1} of integrated luminosity at $\sqrt{s} = 8 \text{ TeV}$ in 2012. The results reported in this contribution are based on these datasets.

¹The inclusion of charge conjugate modes is implied throughout this contribution.

2. $B^0 \rightarrow K^{*0} \mu^+ \mu^-$, angular analysis

The differential decay rate of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay can be defined by $q^2 = M^2(\mu^+ \mu^-)$, and three angles θ_ℓ , θ_K and ϕ , and can be written as (see for example Ref. [2])

$$\begin{aligned} & \frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d \cos \theta_\ell d \cos \theta_K d\phi dq^2} \\ &= \frac{9}{32\pi} \left[\frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \right. \\ &+ \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell - F_L \cos^2 \theta_K \cos 2\theta_\ell \\ &+ S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi \\ &+ S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + S_6 \sin^2 \theta_K \cos \theta_\ell \\ &+ S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi \\ &\left. + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right], \end{aligned} \quad (1)$$

where θ_ℓ is the angle between the flight direction of the μ^+ and the B^0 meson in the dimuon rest frame; θ_K is the angle between the flight direction of the charged kaon and the B^0 meson in the K^{*0} rest frame; ϕ is the angle between the decay planes of the K^{*0} and the dimuon

system in the B^0 meson rest frame; and the q^2 dependent observables F_L and S_i are bilinear combinations of the K^{*0} decay amplitudes.

Using data collected in 2011, the LHCb experiment has measured differential branching fraction, and several angular observables of the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay [3]. The zero crossing point of the forward-backward asymmetry \mathcal{A}_{FB} , q_0^2 , has been measured to be, $q_0^2 = 4.9 \pm 0.9 \text{ GeV}^2/c^4$. Figure 1 shows the differential branching fraction and forward-backward asymmetry \mathcal{A}_{FB} , of the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay as a function of q^2 . All these measurements are consistent with SM expectations.

Recently, new angular observables denoted as P'_4 , P'_5 , P'_6 and P'_8 ,

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}, \quad (2)$$

that are free from form-factor uncertainties at leading order [6] have been proposed. The LHCb experiment has performed the first measurement [5] of these new angular observables using data collected in 2011. The measured values of P'_4 and P'_5 are shown in Fig. 2. For P'_5 a local discrepancy of 3.7σ is observed in one q^2 bin ($4.30 - 8.68 \text{ GeV}^2/c^4$) between the measurement and the SM prediction given by Ref. [6]. However, the SM prediction is affected by non-perturbative power corrections, which may shift the central value or change the theoretical uncertainties of the prediction, therefore change the significance of the discrepancy, see for example Refs. [7, 8] for more discussions. The measurement is being updated using all the Run-I data, which may help to shed light on the situation.

3. $B \rightarrow K^{(*)}\mu^+\mu^-$, differential branching fraction and isospin asymmetry

The branching fractions of the $B \rightarrow K^{(*)}\mu^+\mu^-$ decays are highly sensitive to contributions from vector or axial-vector like particles from physics beyond the SM. The LHCb experiment has measured the differential branching fraction of the $B^+ \rightarrow K^+\mu^+\mu^-$, $B^0 \rightarrow K^0\mu^+\mu^-$, and $B^+ \rightarrow K^{*+}\mu^+\mu^-$ decays [9], using all the Run-I data. The results are shown in Figure 3. The data seem to lie below the theory predictions, especially in the low q^2 region. However, there are large uncertainties on the theory coming from the form-factors. The $B^+ \rightarrow K^+\mu^+\mu^-$ sample is big enough to see new structure around $q^2 = 17 \text{ GeV}^2/c^4$, which corresponds to the $\psi(4160)$ resonance, as observed by the LHCb experiment [10].

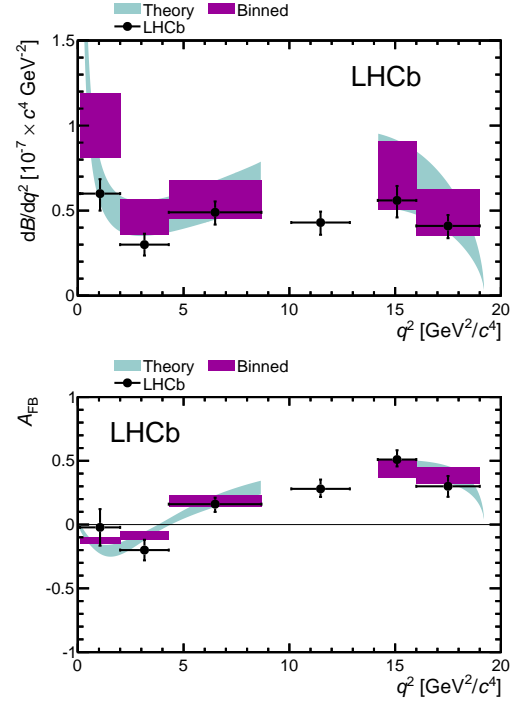


Figure 1: Differential branching fraction and forward-backward asymmetry \mathcal{A}_{FB} of the $B^0 \rightarrow K^{*0}\mu^+\mu^-$ decay [3]. The data are overlaid with the SM prediction based on Ref. [4] and references therein.

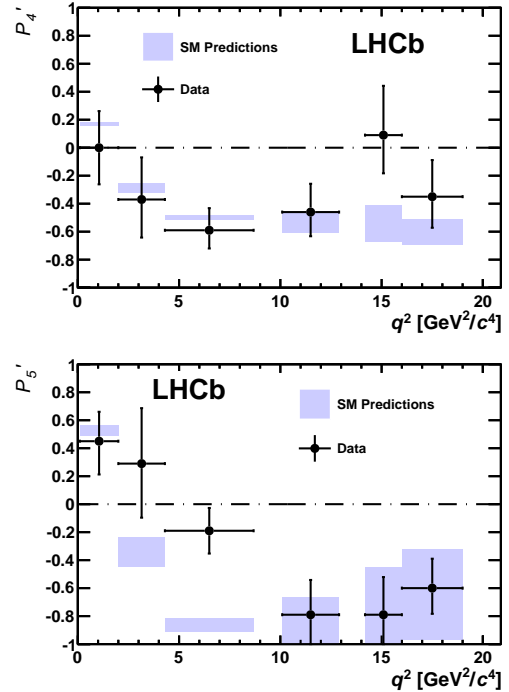


Figure 2: Measured values of P'_4 and P'_5 [5]. The data are overlaid with the SM prediction described in Ref. [6].

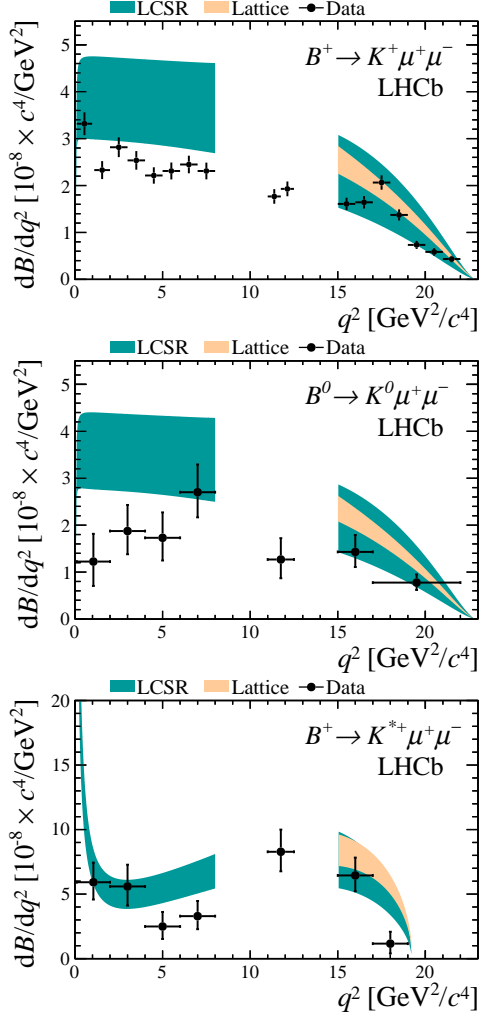


Figure 3: Differential branching fraction results for the $B^+ \rightarrow K^+\mu^+\mu^-$, $B^0 \rightarrow K^0\mu^+\mu^-$, and $B^+ \rightarrow K^{*+}\mu^+\mu^-$ decays [9]. The theoretical predictions from light cone sum rule calculations [4, 11] and lattice QCD calculations [12] are overlaid.

To maximise sensitivity, the CP -averaged isospin asymmetry \mathcal{A}_I ,

$$\mathcal{A}_I = \frac{\Gamma(B^0 \rightarrow K^{(*)0}\mu^+\mu^-) - \Gamma(B^+ \rightarrow K^{(*)+}\mu^+\mu^-)}{\Gamma(B^0 \rightarrow K^{(*)0}\mu^+\mu^-) + \Gamma(B^+ \rightarrow K^{(*)+}\mu^+\mu^-)}, \quad (3)$$

has also been measured by the LHCb experiment [9], as shown in Figure 4. Some of the theoretical uncertainties on things like form factor cancel in the asymmetry. The isospin asymmetry \mathcal{A}_I is expected to be very close to zero in the SM, see for example Ref. [13]. Some sign of deviation from zero has been observed in 2011 data [14] for the $B \rightarrow K\mu^+\mu^-$ decays. However, such tension has been much reduced after adding the 2012 data. Now the results are consistent with the SM.

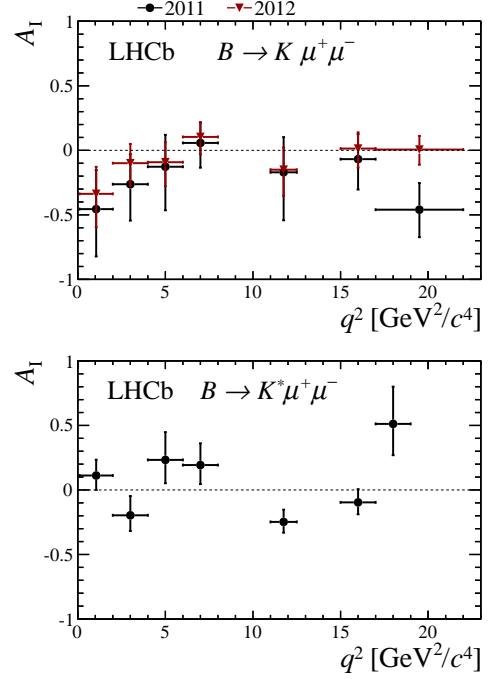


Figure 4: Isospin asymmetries of the $B \rightarrow K\mu^+\mu^-$ and $B \rightarrow K^*\mu^+\mu^-$ decays [9].

4. $B \rightarrow K\mu^+\mu^-$, angular analysis

The differential decay rate of the $B^+ \rightarrow K^+\mu^+\mu^-$ and $B^0 \rightarrow K_S^0\mu^+\mu^-$ decays can be defined by a single angle θ_ℓ , which is the angle between the direction of the μ^- lepton and the K^+ meson in the dimuon rest frame for the B^+ decay, and is always defined with respect to the μ^+ for decays to the $K_S^0\mu^+\mu^-$ final-state without tagging the flavour of the neutral B at production. Such decay rates can be written as

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_\ell} = \frac{3}{4}(1 - \mathcal{F}_H)(1 - \cos^2 \theta_\ell) + \frac{1}{2}\mathcal{F}_H + \mathcal{A}_{FB} \cos \theta_\ell \quad (4)$$

and

$$\frac{1}{\Gamma} \frac{d\Gamma}{d |\cos \theta_\ell|} = \frac{3}{2}(1 - \mathcal{F}_H)(1 - |\cos \theta_\ell|^2) + \mathcal{F}_H, \quad (5)$$

respectively, where \mathcal{A}_{FB} is the forward-backward asymmetry, and \mathcal{F}_H corresponds to the fractional contribution of (pseudo)scalar and tensor amplitudes to the decay width in the approximation that muons are massless. The forward-backward asymmetry \mathcal{A}_{FB} is almost zero in the SM, and the flat term \mathcal{F}_H is non-zero but should be small in the SM, due to the finite muon mass.

The LHCb experiment has performed angular analysis for these decays using the Run-I data [15]. The

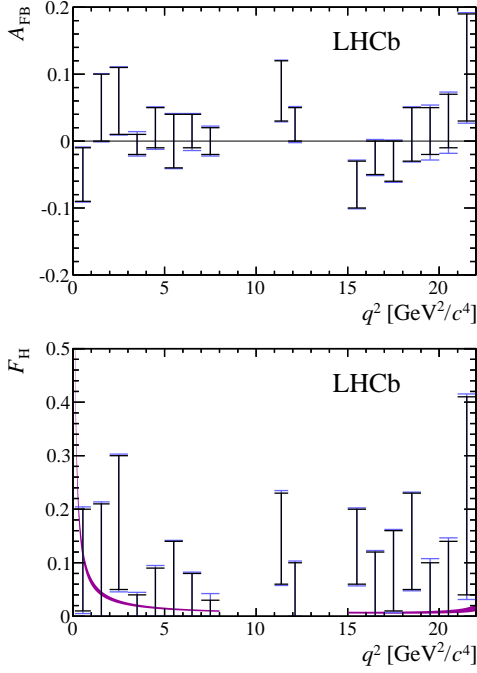


Figure 5: Dimuon forward-backward asymmetry, \mathcal{A}_{FB} , and the parameter \mathcal{F}_H of the $B^+ \rightarrow K^+ \mu^+ \mu^-$ decay [15]. The theoretical prediction of SM in Ref. [11] is overlaid.

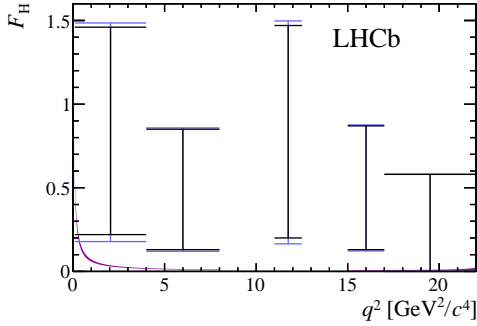


Figure 6: The parameter \mathcal{F}_H of the $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ decay [15]. The theoretical prediction of SM in Ref. [11] is overlaid.

results for the $B^+ \rightarrow K^+ \mu^+ \mu^-$ decay are shown in Fig. 5, and that for the $B^0 \rightarrow K_S^0 \mu^+ \mu^-$ decay is shown in Fig. 6. The measurements are compatible with predictions from the SM.

5. Lepton universality

In the SM, the three lepton families have identical couplings to the gauge bosons, this is known as lepton universality. As a result, the ratio of the branching frac-

tions of $B^+ \rightarrow K^+ \mu^+ \mu^-$ to $B^+ \rightarrow K^+ e^+ e^-$ decays,

$$R_K = \frac{\int_1^{6 \text{ GeV}^2/c^4} \frac{d\Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{dq^2} dq^2}{\int_1^{6 \text{ GeV}^2/c^4} \frac{d\Gamma(B^+ \rightarrow K^+ e^+ e^-)}{dq^2} dq^2}, \quad (6)$$

is predicted to be very close to unity with small uncertainty $R_K = 1.0003 \pm 0.0001$ [16].

The LHCb experiment has measured R_K with all the Run-I data [17]. The analysis has been done in the range $1 < q^2 < 6 \text{ GeV}^2/c^4$, which is both experimentally and theoretically favoured as it excludes the $B^+ \rightarrow K^+ J/\psi (\ell^+ \ell^-)$ resonant region, and precise theoretical predictions are possible. The R_K is determined using the double ratio, i.e., the ratio of the relative branching fractions of the $B^+ \rightarrow K^+ \ell^+ \ell^-$ and $B^+ \rightarrow K^+ J/\psi (\ell^+ \ell^-)$ decays. The data have been split into three categories according to the way how the signal candidates are triggered, then the results have been combined. The R_K is measured to be

$$R_K = 0.745_{-0.074}^{+0.090} (\text{stat.}) \pm 0.036 (\text{syst.}), \quad (7)$$

which is compatible with the SM at the level of 2.6σ . Figure 7 shows the likelihood scans of the three trigger categories and the combined one, and the R_K measured by the BaBar [18], Belle [19] and LHCb [17] experiments.

6. $B^+ \rightarrow K^+ \pi^+ \pi^- \{\phi K^+\} \mu^+ \mu^-$

Using all the Run-I data, the LHCb experiment has observed the $B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-$ and $B^+ \rightarrow \phi K^+ \mu^+ \mu^-$ decays [20]. Figure 8 shows the invariant mass distribution of the $B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-$ decay, and that of the $B^+ \rightarrow \phi K^+ \mu^+ \mu^-$ decay is shown in Fig. 9. The branching fractions of these decays are measured to be,

$$\begin{aligned} \mathcal{B}(B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-) \\ = (4.36_{-0.27}^{+0.29} \pm 0.20 \pm 0.18) \times 10^{-7}, \end{aligned} \quad (8)$$

and

$$\begin{aligned} \mathcal{B}(B^+ \rightarrow \phi K^+ \mu^+ \mu^-) \\ = (8.22_{-1.67}^{+1.88} \pm 0.35 \pm 2.74) \times 10^{-8}, \end{aligned} \quad (9)$$

respectively, where the uncertainties are statistical, systematic, and due to the uncertainty on the branching fractions of the normalisation modes. The signal yield of the $B^+ \rightarrow K^+ \pi^+ \pi^- \mu^+ \mu^-$ decay is big enough and the differential branching fraction as function of $q^2 = M^2(\mu^+ \mu^-)$ has also been measured, as shown in Fig. 8.

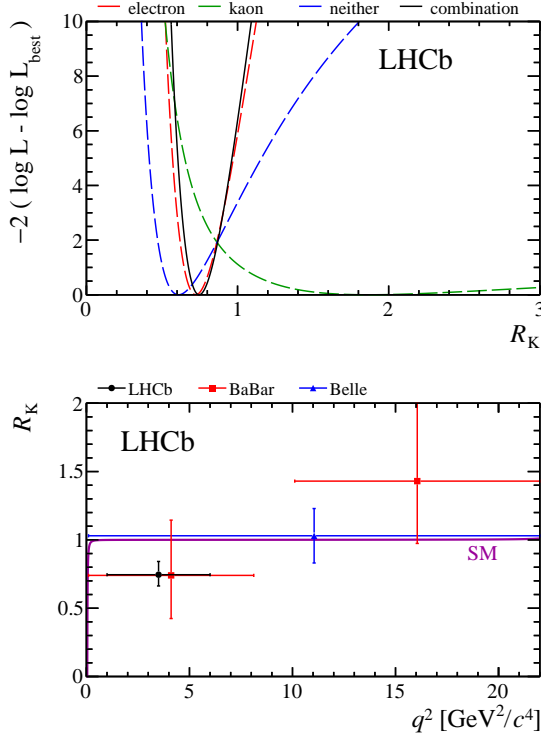


Figure 7: Likelihood scans of the three trigger categories and the combined one, and the R_K measured by the BaBar [18], Belle [19] and LHCb [17] experiments.

7. Photon polarisation

The photon in the $b \rightarrow s\gamma$ transition is predominantly left-handed in the SM since the recoiling s -quark that couples to a W boson is left-handed. One way of test the photon polarisation is to measure the up-down asymmetry in the $B^+ \rightarrow K^+\pi^+\pi^-\gamma$ decay, which is proportional to the photon polarisation [21, 22]. Thus a measured value different from zero means that the photon is polarized. The up-down asymmetry \mathcal{A}_{ud} is defined as,

$$\mathcal{A}_{ud} \equiv \frac{\int_0^1 d\cos\theta \frac{d\Gamma}{d\cos\theta} - \int_{-1}^0 d\cos\theta \frac{d\Gamma}{d\cos\theta}}{\int_{-1}^1 d\cos\theta \frac{d\Gamma}{d\cos\theta}}, \quad (10)$$

where θ is defined in the rest frame of the final state hadrons as the angle between the direction opposite to the photon momentum \vec{p}_γ and the normal $\vec{p}_{\pi,slow} \times \vec{p}_{\pi,fast}$ to the $K^+\pi^+\pi^-$ plane, where $\vec{p}_{\pi,slow}$ and $\vec{p}_{\pi,fast}$ correspond to the momenta of the lower and higher momentum pions, respectively.

Using all the Run-I data, the LHCb experiment has performed the first measurement of the photon polarisation with the $B^+ \rightarrow K^+\pi^+\pi^-\gamma$ decay [23]. To relate \mathcal{A}_{ud}

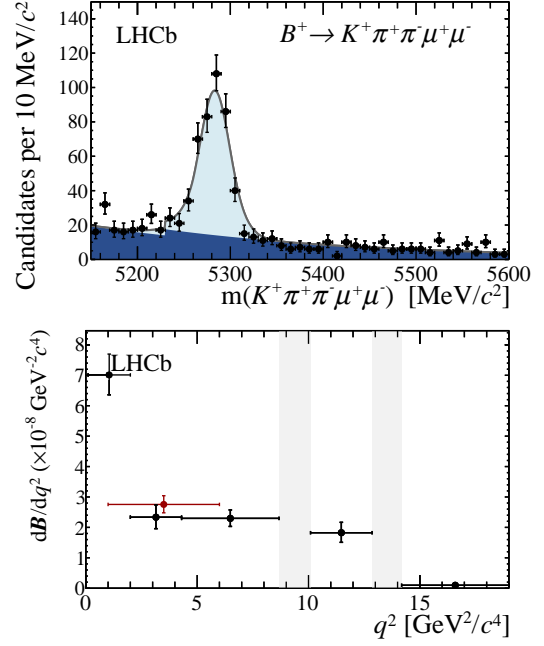


Figure 8: Invariant mass distribution and differential branching fraction of the $B^+ \rightarrow K^+\pi^+\pi^-\mu^+\mu^-$ decay [20].

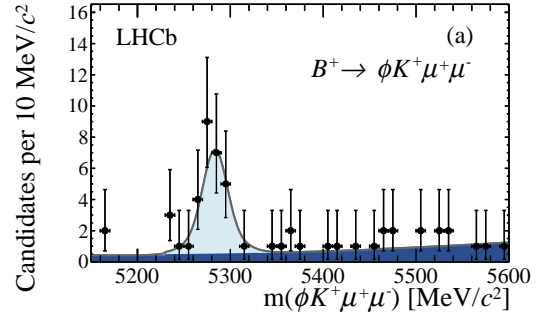


Figure 9: Invariant mass distribution of the $B^+ \rightarrow \phi K^+\mu^+\mu^-$ decay [20].

to the photon polarisation it is important to understand how the structure of the $K^+\pi^+\pi^-$ system impacts θ . The $K^+\pi^+\pi^-$ mass spectrum is complicated therefore the up-down asymmetry has been measured inclusively in four intervals of $K^+\pi^+\pi^-$ mass, as shown in Fig. 10. Combining measurements in the four bins, the significance of the non-zero up-down asymmetry is determined to be 5.2σ . This is the first observation of the photon polarisation in the $b \rightarrow s\gamma$ transition. More work from both the experimental and theoretical sides is needed to determine if the measured \mathcal{A}_{ud} is consistent with the almost pure left-handed polarisation expected in the SM.

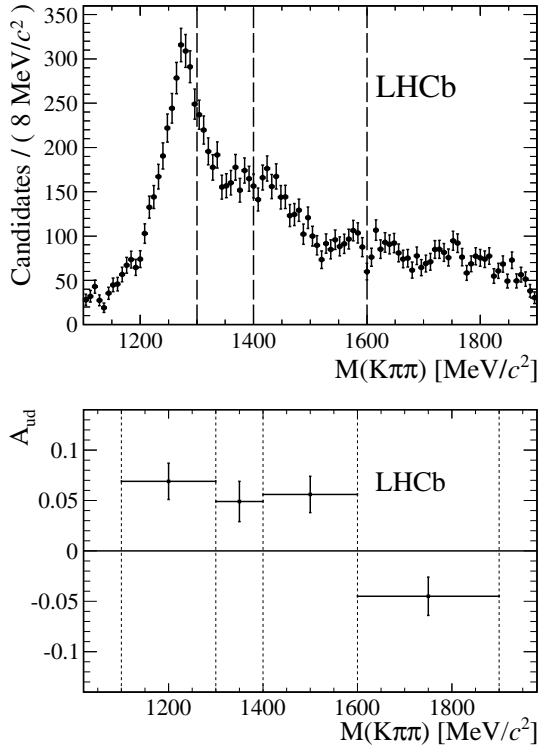


Figure 10: Background-subtracted $M(K^+\pi^+\pi^+)$ distribution of the $B^+ \rightarrow K^+\pi^+\pi^-\gamma$ signal and the up-down asymmetry in four bins of $M(K^+\pi^-\pi^+)$ [23].

8. Conclusion

Thanks to the large production cross-section of b -hadrons, and the excellent performance of the LHC, the LHCb experiment has become new flavour factory, and has produced many important results on the electroweak penguin decays. The decay rates, angular distributions of decays like $B^0 \rightarrow K^{*0}\mu^+\mu^-$ have been studied extensively. The Standard Model seems to work extremely well. However, some tension from the SM, e.g., the P'_5 puzzle, has been observed and need confirmation with more data. The photon in the $b \rightarrow s\gamma$ transition has been observed to be polarized for the first time.

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