

$B_d \rightarrow K^{*0} \mu^+ \mu^-$ as a lab for discovering new physics at LHCb

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Abstract. The analysis of the penguin decay $B_d \rightarrow K^{*0} \mu^+ \mu^-$ at LHCb can act as a laboratory for the discovery and understanding of new physics. Through the Operator Product Expansion, the decay kinematics are well understood in both the Standard Model and in a large range of new physics scenarios. The theoretical errors from QCD effects can be characterized and a set of observables have been derived which minimise their influence in measurements. We will describe how these measurements can be made in LHCb with special emphasis on what can be done with a first run of the LHC with a few hundred pb^{-1} of integrated luminosity.

1. Introduction

As a flavour changing neutral current process, $B_d \rightarrow K^{*0} \mu^+ \mu^-$ is suppressed in the Standard Model. The decay occurs through a $\bar{b} \rightarrow \bar{s}$ quark transition, via a loop or box diagram, as shown in figure 1.

The measured branching ratio is $(9.8 \pm 2.1) \times 10^{-7}$ [1]. The kinematics of the decay can be fully described in terms of three angles, θ_L , θ_K and ϕ , in addition to the di-muon invariant mass squared, q^2 . Many properties of the decay can be used as powerful indirect searches for new physics.

The forward-backward asymmetry (A_{FB}) of the muon pair in this decay is one such interesting observable. Formed from the lepton helicity angle θ_L , and varying as a function of q^2 , the hadronic uncertainties in the prediction of this observable cancel when $A_{FB} = 0$, and are smallest in the range $1 < q^2 < 6 \text{ GeV}^2/c^4$.

2. Status of measurements of $B_d \rightarrow K^{*0} \mu^+ \mu^-$

The decay $B_d \rightarrow K^{*0} \mu^+ \mu^-$ has been observed at three independent experiments: the B-factories Belle and BaBar, and the CDF experiment at the Tevatron [2]. Each of these has recorded $\mathcal{O}(100)$ events, and measured the branching ratio and $A_{FB}(q^2)$.

3. The LHCb experiment

LHCb is a dedicated b-physics experiment at CERN's Large Hadron Collider (LHC). The detector, shown in figure 2 and described in detail in reference [3], has a forward geometry, with an angular acceptance from 10 to 250/300 mrad. There are several detector components, including a precise vertex locator, with silicon detector modules only 5 mm from the

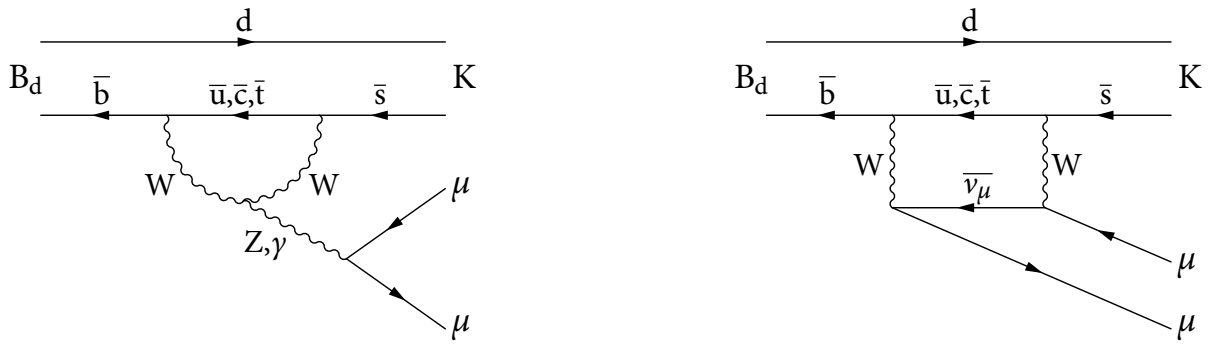


Figure 1. Example Feynman diagrams for the decay $B_d \rightarrow K^{*0} \mu^+ \mu^-$ in the Standard Model.

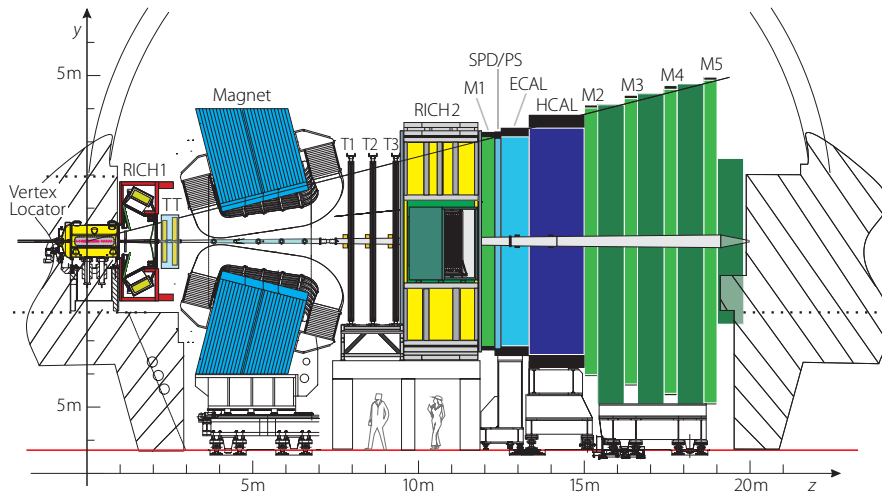


Figure 2. LHCb, a forward spectrometer designed for b-physics measurements at the LHC.

proton beams. In addition, two ring imaging Cherenkov detectors provide accurate particle identification, particularly for distinguishing between kaons and pions. One of LHCb's priorities for the first LHC run, during 2010-2011, is to measure A_{FB} in $B_d \rightarrow K^{*0} \mu^+ \mu^-$, where the K^{*0} decays to $K^+ \pi^-$. The planned analysis is described in the following sections, and in further detail in reference [4].

4. Event trigger and selection

The LHCb trigger is a two-level system. First, a hardware-based 'Level 0' trigger is used to reduce the 40 MHz bunch crossing rate to 1 MHz, using information from the muon and calorimetry detectors. For the decay $B_d \rightarrow K^{*0} \mu^+ \mu^-$, the event rate is reduced by applying a minimum value cut to the transverse momentum of a single muon, or to the sum of the transverse momentum of two muons

When an event is accepted by the Level 0 trigger, the full detector is read out and the data passed to the software-based 'High Level' trigger. In the case of $B_d \rightarrow K^{*0} \mu^+ \mu^-$, this trigger applies cuts to the impact parameter and transverse momentum of a single muon, or to the impact parameter and vertex displacement of a muon and another charged track.

Once the triggered data is stored, it can then be analysed offline. For the offline event selection, LHCb intends to use a Fisher discriminant, applying a cut to separate signal from background. Specific vetos are also used to remove particle mis-identification backgrounds from

$B_s \rightarrow \phi(\rightarrow KK)\mu^+\mu^-$ and $B_d \rightarrow X(\rightarrow Y\pi)J/\psi(\rightarrow \mu^+\mu^-)$, with generic X, Y . Yields of 6200_{-1500}^{+1700} signal and 1550 ± 310 background events per 2 fb^{-1} are expected [5].

5. Correcting the detector acceptance

Before measuring observables such as A_{FB} , the acceptance must be corrected. The acceptance of events can vary as a function of the lepton helicity angle, θ_L , and therefore shift the observed value of A_{FB} , which measures the asymmetry of the θ_L distribution. A non-flat acceptance in θ_L can be caused by the detector and by the event trigger and selection processes. Cuts on the p_T of both muons can greatly reduce the acceptance at low (~ 0) and high ($\sim \pi$) values of θ_L , while reducing the acceptance much less at intermediate θ_L values [4]. The LHCb detector has a similar, but less pronounced, effect, because of the forward geometry which only allows muons with $p > 3 \text{ GeV}/c$ to reach the muon detectors. This results in a non-flat acceptance because decays with high or low values of θ_L have one muon with high p_T and one with low p_T , whereas intermediate values of θ_L are associated with muon pairs with similar p_T .

The acceptance will be corrected by unfolding the acceptance that is measured on simulated data samples of the signal decay. Also under investigation is the use of a control channel, $B_d \rightarrow K^{*0}J/\psi$, to measure the acceptance.

6. Measuring the forward-backward asymmetry

Two methods have been considered by LHCb for measuring the forward-backward asymmetry. Firstly, accepted events can be binned in q^2 and in θ_L . A value of A_{FB} can then be calculated for each bin of q^2 from the numbers of forward and backward events in that q^2 bin.

Secondly, events can again be divided into two bins of θ_L , i.e. into forward and backward categories. For each of these two categories, the q^2 distribution of the events is fitted with a third-order polynomial to find the functions $N_{\text{forward}}(q^2)$ and $N_{\text{backward}}(q^2)$. First-order polynomials, fitted to forward and backward simulated backgrounds, are then subtracted. The two fitted and subtracted polynomials, representing forward and backward signal contributions separately, can then be algebraically manipulated to find a functional form of $A_{\text{FB}}(q^2)$.

Both methods, the counting method using bins in both θ_L and q^2 , and the fitting of forward and backward events separately, achieve approximately the same precision on a measurement of the zero crossing point, s_0 , (at which $A_{\text{FB}}=0$) in simulated data using the Standard Model prediction, with a forecast sensitivity of $\sigma(s_0) = 0.5 \text{ GeV}^2/c^4$ with 2 fb^{-1} of integrated luminosity.

7. What can LHCb do with early data from the LHC?

With data from the first LHC run, at $\sqrt{s} = 7 \text{ TeV}$ during 2010-2011, LHCb intends to measure the forward-backward asymmetry A_{FB} , which has previously been measured at BaBar, Belle and CDF.

Figure 3 shows predicted LHCb statistical precision for a measurement of A_{FB} in a single bin, $1 < q^2 < 6 \text{ GeV}^2/c^4$, for two different integrated luminosities, 0.1 fb^{-1} and 1 fb^{-1} . LHCb expects to select $1400 B_d \rightarrow K^{*0}\mu^+\mu^-$ events per fb^{-1} for offline analysis. The current LHC plan allows for 1 fb^{-1} of integrated proton-proton luminosity to be delivered to the experiments during the 2010-2011 run. As shown in the figure, LHCb will start to compete with the B-factories BaBar and Belle with just 0.1 fb^{-1} , and will have significantly improved precision with 1 fb^{-1} .

8. What can LHCb do with more data?

After the 2010-2011 run, an LHC shutdown is planned, followed by further running, up to the design energy, $\sqrt{s} = 14 \text{ TeV}$. Integrated luminosity will rapidly increase beyond the 1 fb^{-1} that is expected during 2010-2011. With the larger dataset, LHCb will continue to improve the precision on its measurement of A_{FB} . In addition, the increased data will allow several further

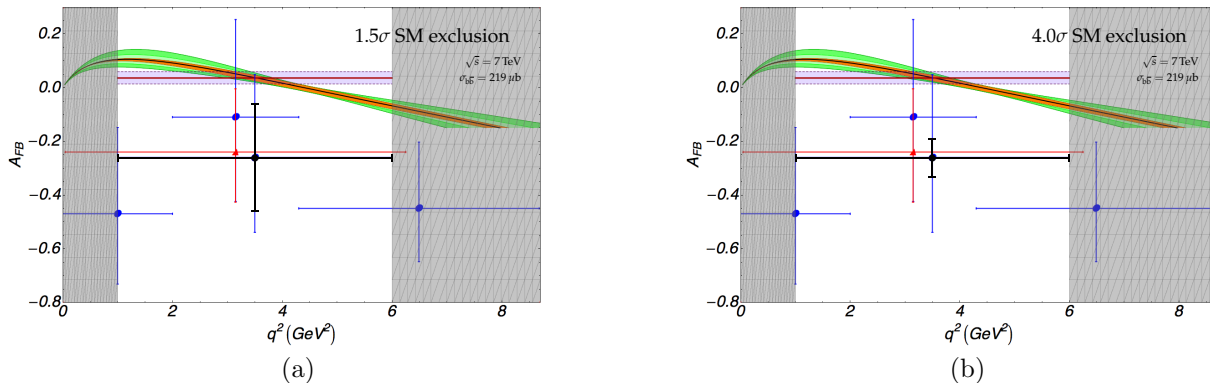


Figure 3. Forecast sensitivity of LHCb with (a) 0.1 fb^{-1} (b) 1 fb^{-1} , compared with published results from BaBar (red) and Belle (blue). The Standard model prediction is shown as a curve in orange and green, and as an average over $1 < q^2 < 6 \text{ GeV}^2/c^4$ in pink [6]. Forecast error bars for LHCb are shown in black on a data point that assumes the same central value as the Belle measurement. For this central value in an LHCb measurement, the Standard Model prediction would be excluded by 1.5σ after 0.1 fb^{-1} , and 4.0σ after 1 fb^{-1} .

measurements of the decay. Firstly, projections of the three angles θ_L , θ_K and ϕ will become possible. This will allow the measurement of the longitudinal polarization, F_L , for which very precise theoretical predictions can be made.

With more data, it will become possible to perform a full angular fit. Fitting the three angles θ_L , θ_K and ϕ , simultaneously with q^2 , will enable the measurement of a wide range of further observables with sensitivity to new physics. For example, the $A_T^{(2)}$ observable is very sensitive to the right-handed C_7' Wilson coefficient [7], and the S_5 observable is sensitive to a range of supersymmetric models [8].

9. Conclusions

The decay $B_d \rightarrow K^{*0} \mu^+ \mu^-$ has properties that are precisely predicted both in the Standard Model, and in various new physics models. LHCb, a dedicated b-physics experiment at the LHC, is ideally suited to studying this decay, using it as an indirect probe of new physics.

LHCb will quickly collect large numbers of $B_d \rightarrow K^{*0} \mu^+ \mu^-$ events. Signal (background) yields of 6200^{+1700}_{-1500} (1550 ± 310) events are expected per nominal year of 2 fb^{-1} with $\sqrt{s} = 14 \text{ TeV}$, assuming a $b\bar{b}$ production cross-section of $\sigma_{b\bar{b}} = 500 \mu\text{b}$. At the currently planned energy of $\sqrt{s} = 7 \text{ TeV}$, yields of approximately 1400 signal events are expected during a 2010-11 run of $\sim 1 \text{ fb}^{-1}$. This number of events is sufficient for LHCb's precision to compete with previous results during this first data run. LHCb will then go on to make first measurements of further observables that are powerful probes of new physics.

References

- [1] C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667** (2008) 1, and 2009 update (<http://pdg.lbl.gov/>)
- [2] BaBar collaboration, Phys. Rev. D **79** (2009) 031102, arXiv:0804.4412; Belle collaboration, Phys. Rev. Lett. **103** (2009) 171801, arXiv:0904.0770; CDF collaboration, CDF note 10047
- [3] LHCb collaboration, The LHCb Detector at the LHC, JINST **3** (2008) S08005
- [4] LHCb collaboration, arXiv:0912.4179, Chapter 6
- [5] M. Patel and H. Skottowe, A Fisher discriminant selection for $B_d \rightarrow K^{*0} \mu^+ \mu^-$ at LHCb, LHCb-2009-009
- [6] U. Egede, T. Hurth, J. Matias, M. Ramon, W. Reece, JHEP **11** (2008) 032, arXiv:0807.2589
- [7] F. Krüger and J. Matias, Phys. Rev. D **71** (2005) 094009, arXiv:hep-ph/0502060
- [8] W. Altmannshofer *et al.*, JHEP **01** (2009) 019, arXiv:0811.1214