Decays of Hadrons as Probes of the Standard Model and Beyond

A thesis submitted in partial fulfilment of
the requirements for the degree of

Doctor of Philosophy

by

Girish Kumar

(Roll No. 11330021)

Under the guidance of

Dr. Namit Mahajan

Associate Professor

Theoretical Physics Division

Physical Research Laboratory, Ahmedabad, India.

DEPARTMENT OF PHYSICS

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to

my mother

Declaration

I declare that this written submission represents my ideas in my own words and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

(Signature)

(Name: Girish Kumar)

(Roll No: 11330021)

Date: September 2, 2016

CERTIFICATE

It is certified that the work contained in this thesis titled **"Decays of Hadrons as Probes of the Standard Model and Beyond"** by **Mr. Girish Kumar** (Roll No. 11330021), has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

Dr. Namit Mahajan
(Thesis Supervisor)
Associate Professor,
Theoretical Physics Division,
Physical Research Laboratory,
Ahmedabad, India.

Date: September 2, 2016

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Abstract

Flavor physics is the study of quark "flavors" and their interactions involving change of one type of flavor to another type of flavor. It is known that, historically, the study of flavor physics has played a key role in the development of the Standard Model (SM) of particle physics. The recent discovery of the last missing piece, the Higgs boson, in the first run of the Large Hadron Collider (LHC) marks the completion of the SM. The SM has been exceptionally successful in explaining the experimental data collected so far. However, there are many experimental measurements which point towards the existence of physics beyond the SM. Therefore, it is natural to consider SM as the low-energy limit of a more general theory above the electroweak scale. The next important task is then to look for hints of the physics beyond the SM. In this endeavour, the study of flavor physics continues to be an integral part of the searches at the intensity frontier. The study of flavor physics offers unique possibilities to study the weak interactions operating at the fundamental level governing the decays in conjunction with the strong forces responsible for keeping the constituents bound in various colorless hadronic states. In recent years, due to dedicated efforts by the Belle, BaBar, CDF, and LHCb experiments, a great theoretical understanding of the flavor dynamics of the SM has been achieved, and severe constraints on the new physics parameters have been imposed. The rare and flavor changing neutral current processes of b quark have been quite instrumental and valuable probes of new physics, thanks to their suppressed nature in the SM and high sensitivity to the new physics effects.

In this context, the exclusive semileptonic decay $B \to K^* \ell^+ \ell^-$ governed by the quark-level transition $b \to s\ell^+\ell^-$ is one of the most interesting candidates, which has received great attention, experimentally as well as theoretically. The analysis of the angular distribution of its four-body final state gives access to a large number of experimentally accessible observables as a function of invariant mass squared of the dilepton system (q^2). Interestingly, the LHCb collaboration has found deviations from the SM predictions in the measurement of angular observables of $B \to K^* \mu^+ \mu^-$. These measurements are reported in bins of q^2.

Particularly, the discrepancy in one of the angular observables, P_5', in two of low q^2 bins is quite intriguing. However, in order to be certain that the reported deviations are hints of new physics or artifacts of underestimated theoretical uncertainties, it is necessary to measure the observables which are as insensitive to hadronic effects as possible with more precision. In this thesis, we study some of these "theoretically cleaner" observables which are independent of hadronic form factors within the heavy quark effective framework. We show that zero crossing points of observables P_5', P_4', and of a new observable, $O_T^{\mathrm{L,R}}$, are independent of form factors, and are functions of short-distance Wilson coefficients in the considered limit. The zero crossing of $O_T^{\mathrm{L,R}}$ in the standard model coincides with the zero crossing of the forward-backward asymmetry (A_{FB}) of the lepton pair. But in the presence of new physics contributions they show different behaviors. Moreover, we show that there exist relations between the zeros of P_5', P_4', $O_T^{\mathrm{L,R}}$, and the zero of A_{FB}, which are also independent of hadronic uncertainties. We point out that precise measurements of these zeros in the near future would provide a crucial test of the standard model and would be useful in distinguishing between different possible new physics contributions to the Wilson coefficients. If the experimental observations are in fact due to NP in $b \to s\ell\ell$, then similar effects must also be seen in other $b \to s\ell\ell$ transitions involving different hadronic states. This fact sets the tone for our next work in which we study the semileptonic baryonic $b \to s$ decay, $\Lambda_b \to \Lambda\ell^+\ell^-$. We construct new angular observables and asymmetries; all of which have zero crossing points in the large q^2 region. The zeros of proposed observables in the heavy quark and large q^2 limit are again functions of Wilson coefficients only, and therefore have less sensitivity to hadronic effects. We discuss the potential of the decay $\Lambda_b \to \Lambda\ell^+\ell^-$ in probing the new physics effects in $b \to s\ell^+\ell^-$ along with the decays $B \to K^{(*)}\ell^+\ell^-$.

In the second part of the thesis, we present the explanation of some of the experimentally observed anomalies in the flavor sector within the framework of left-right symmetric gauge theories motivated by one of the low-energy subgroups of E_6 naturally accommodating leptoquarks. First, we explain the enhanced decay rates of $B \to D^{(*)}\tau\nu$ in E_6 motivated Alternative Left-Right Symmetric

Model. We discuss the constraints from the flavor sector on the couplings involved in explaining the experimental data. We further consider the framework of E_6 motivated Neutral Left-Right Symmetric Model, and give simultaneous explanation for B decay anomalies in $B \to D^{(*)}\tau\nu$ and $\bar{B} \to \bar{K}\ell^+\ell^-$ together with the anomalous magnetic moment of the muon, consistent with the constraints from other flavor data.

In the last part of the thesis, we carry out a detailed study of the effects of new physics originating from a scalar leptoquark model on the kaon sector. It is known that kaon decays provide some of the most stringent constraints on various extensions of the SM. We consider a simple extension of the SM by a scalar leptoquark of charge $-1/3$ with $(\mathrm{SU(3)_C}, \mathrm{SU(2)_L})$ quantum numbers $(3, 1)$, which is able to account for the deviations observed in B decays. The leptoquark we consider is a TeV-scale particle and within the reach of the LHC. We use the existing experimental data on the several kaon processes including $K^0 - \bar{K}^0$ mixing, rare decays $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi\nu\bar{\nu}$, the short-distance part of $K_L \to \mu^+\mu^-$, and lepton-flavor-violating decay $K_L \to \mu^\pm e^\mp$ to obtain useful constraints on the model.

Keywords: flavor physics, rare decays, semileptonic B decays, Kaon decays, baryonic b decay, effective field theory, Wilson coefficients, beyond the Standard Model, leptoquarks.

Acronyms and Abbreviations

GWS	Glashow-Weinberg-Salam
SM	Standard Model
BSM	Beyond Standard Model
QCD	Quantum Chromodynamics
SSB	Spontaneous Symmetry Breaking
VEV	Vacuum Expectation Value
CKM	Cabibbo-Kobayashi-Maskawa
CP	Charge-Parity
CPV	CP Violation
LFV	Lepton Flavor Violation
PDG	Particle Data Group
UT	Unitarity Triangle
EFT	Effective Field Theory
OPE	Operator Product Expansion
RG	Renormalization Group
LLA	Leading-Logarithmic Approximation
NLO	Next-to-Leading Order
NNLO	Next-to-Next-Leading Order
HQET	Heavy Quark Effective Theory
GIM	Glashow-Iliopoulos-Maiani
FCNC	Flavor Changing Neutral Current
NP	New Physics
LHC	Large Hadron Collider
QCDF	QCD Factorization
FFs	Form Factors
C.L.	Confidence Level
2HDM	two-Higgs Doublet Model
MSSM	Minimal Supersymmetric Standard Model
RPV	R-Parity Violating
ALRSM	Alternative Left-Right Symmetric Model
NLRSM	Neutral Left-Right Symmetric Model
HFAG	Heavy Flavor Averaging Group
GUT	Grand Unified Theory

Contents

List of Figures

List of Tables

ing observables which are more or less free from such hadronic effects. We have shown that similar to the celebrated zero crossing of the forward-backward asymmetry of the lepton pair, $A_{\rm FB}$, the zero crossings of the observables P_4' and P_5' are also free from form factors in the large recoil region and heavy quark limit. We also proposed a new observable, $O_T^{\rm L,R}$, which has a unique property that its zero crossing, in the SM-like operator basis, coincides with the zero of $A_{\rm FB}$. But, in the presence of NP (for example, finite contribution of right-handed operators), the zero crossings of $O_T^{\rm L,R}$ and $A_{\rm FB}$ shift differently. This feature can be useful to probe NP once the precise measurements on the value of zero crossings are available. All the zero crossings of the considered observables depend on the Wilson coefficients and the mass of the B meson, and therefore are sensitive to NP and theoretically cleaner observables to measure experimentally. We have pointed out that in the heavy quark and large recoil limit, the zero crossings of $A_{\rm FB}$, P_5', P_4', and $O_T^{\rm L,R}$ are correlated in the SM. The relations, in the considered approximation, are also independent of form factors. Since the zeros and the relation among them are functions of the Wilson coefficients only, their measurement can be used to constrain the NP contribution present in the Wilson coefficients. We have discussed the constraints on the $C_7^{\rm NP} - C_9^{\rm NP}$ plane, stemming from the zeros of these observables. We considered multiple BSM scenarios, which are favoured over the SM by the present global fits to present data on $b \to s\ell^+\ell^-$, and showed that precise measurements of the zero crossings have the potential of differentiating between different BSM cases. Interestingly, the LHCb collaboration has started measuring the zero crossing of these observables. Current measurements still have large uncertainties to have any conclusive result on the presence of NP. But, high precision data on these zeros in the future can certainly provide crucial information in this regard.

In Chapter 3, we have studied the semileptonic $b \to s$ baryonic decay $\Lambda_b \to \Lambda\ell^+\ell^-$. The angular distribution of the final state, similar to mesonic counterpart $B \to K^*\ell^+\ell^-$, gives access to many observables. The analysis of these observables can offer information which can complement the current search of NP in $b \to s$ transition. We have listed the angular observables and asymmetries which can be

used to extract all the angular coefficients independently. In order to probe the short-distance NP, it is necessary to focus on observables which do not depend on hadronic form factors or are largely insensitive to them. With this in mind, we have presented three new observables [$\mathcal{T}_1(q^2)$, $\mathcal{T}_2(q^2)$, and $\mathcal{T}_3(q^2)$], which can be experimentally probed. The new observables are constructed such that the zero crossings of these observables lie in the large q^2 region. In the HQET and large q^2 approximation, these zeros turn out to be less sensitive to the form factors (especially the zero of $\mathcal{T}_1(q^2)$), and therefore their measurement holds a better chance of probing the NP effects in $b \to s$ transitions.

In Chapter 4 and 5, we have presented an NP explanation of the flavor anomalies seen in B decays in the framework of E_6 motivated left-right symmetric gauge theories. E_6 provides one of the natural, anomaly free choices for grand unified theories which have a unique virtue of unifying matter–leptons and quarks. Due to the presence of new particles in the theory, the phenomenology of low energy subgroups is quite rich and interesting. We have considered the maximal subgroup, $\mathrm{SU(3)_C} \times \mathrm{SU(3)_L} \times \mathrm{SU(3)_R}$, of E_6. The $SU(3)_{(L,R)}$ in the maximal subgroup can further break into $SU(2)_{(L,R)} \times U(1)_{(L,R)}$. Among the three possible options for choosing $SU(2)_R$, in Chapter 4, we have considered the choice where (h^c, u^c) is assigned to the $SU(2)_R$ doublet. This subgroup is referred to as the Alternative Left-Right Symmetric Model (ALRSM). We have studied ALRSM in the context of charged decay modes $B \to D^{(*)}\tau\nu$, and have shown that the enhanced decay rates reported by the Belle, BaBar and LHCb collaborations can be explained with new contributions involving the tree level exchange of scalar leptoquark. We have discussed the constraints on the NP couplings coming from $B \to \tau\nu$, $D_{(s)} \to \tau\nu$ and $D^0 - \bar{D}^0$ in detail. The constraints are compatible with the size of the couplings required to explain the data. In Chapter 5, we have studied E_6 motivated Neutral Left-Right Symmetric Model (NLRSM), which corresponds to the choice where $(h^c, d^c)_L$ is chosen as the $SU(2)_R$ doublet. Working in this framework, we have shown that anomalies observed in R_K and $R_{D^{(*)}}$ can be simultaneously explained. In this model, $R_{D^{(*)}}$ can be explained via new contribution from tree level Feynman diagrams involving exchange of scalar

leptoquarks, while R_K can be explained by the one loop diagrams involving leptoquarks. We have also shown that the anomalous magnetic moment of the muon can also be explained simultaneously. The analysis is compatible with present measurements of other flavor observables like $B^0 - \bar{B}^0$ and $D^0 - \bar{D}^0$ mixings, and (semi) leptonic decays of B and D.

In Chapter 6, noticing that NP models having a scalar leptoquark ϕ of charge $-1/3$ with $(\mathrm{SU}(3)_\mathrm{C}, \mathrm{SU}(2)_\mathrm{L})$ quantum numbers $(3, 1)$ are capable of explaining the flavor anomalies in semileptonic B decays, we have investigated the constraints from the kaon sector. This study provides the information on the allowed size of the couplings of the scalar leptoquark, and helps in shedding light on the kaon observables where promising signals of the considered leptoquark can be expected. We have analysed the effects of the leptoquark on the neutral kaon mixing, rare decays $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$, $K_L \to \mu^+\mu^-$, and lepton flavor violating decay $K_L \to \mu^\mp e^\pm$. The scalar leptoquark ϕ contributes to $K^0 - \bar{K}^0$ via new box diagrams involving internal exchange of leptoquark and neutrinos. We noticed that constraints from $K^0 - \bar{K}^0$ on the left-handed coupling ξ_{ds} are $\sim O(10^{-2})$. On the other hand, scalar leptoquark ϕ contributes to rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ via tree level exchange. We found that the constraints from $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$ turn out be about 2 orders of magnitude tighter. We then discussed the effects of leptoquark ϕ on the decay $K_L \to \mu^+\mu^-$. The leptoquark ϕ contributes to $K_L \to \mu^+\mu^-$ via box diagrams. We have found that present measurement of $\mathrm{BR}(K_L \to \mu^+\mu^-)$ allows generation-diagonal coupling of the leptoquark to be $\sim O(1)$, which is compatible with the required size of the relevant couplings needed to explain the B decay anomalies. We also studied the leptoquark effects on the LFV decay $K_L \to \mu^\mp e^\pm$, which allows to constrain the off-diagonal couplings as well. We found that the present experimental data on $K_L \to \mu^\mp e^\pm$ allows the involved coupling to be $\sim O(1)$. Therefore, at present, the tightest bounds on the leptoquark couplings in kaon-related observables are from the decay $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$, and therefore appears to be the most interesting observable to test the NP effects of scalar leptoquark in the kaon sector.

In the end, we would like to conclude with the following remarks. At present,

in the face of non-observation of new particles at direct collider searches, and with the lack of any unambiguous signal of NP in flavor precision data, the task of uncovering NP seems to be challenging. However, there are some tantalizing hints of NP in the flavor sector, as discussed in this thesis, which demand for a more careful scrutiny of these signals in order to probe NP. The advancement of flavor physics has always banked on close interplay and cooperation between experiment and theory. On the theory side, there has been immense progress in calculating the low-energy observables with high precision. The theoretical uncertainties in the estimation of several observables have reduced significantly, and the current values are sufficiently accurate to be compared with the high-precision experimental data to detect any discrepancy between the SM and experiment. On the other hand, very high-luminosity particle physics experiments are now able to measure the flavor-precision observables with great accuracy and large statistics. With the upgraded LHC, and the possible future experimental facilities such as super B-factories, capable of providing higher luminosity, the level of precision in the measurements of low-energy observables is certainly going to improve. Hopefully, with these improvements, flavor physics will be able to either provide unambiguous signs of NP or give us a clear direction towards this goal.

Appendix

A A compendium of effective operators

Here, we present a partial list of the effective operators relevant for weak decays of hadrons given in Refs. [264] (for a recent review, see [296]).

A.1 The effective $\Delta F = 1$ nonleptonic operators

Current-Current operators

$$O_1(\Delta S = 1) = (\bar{s}_i \gamma^\mu \mathrm{L} u_j)\,(\bar{u}_j \gamma_\mu \mathrm{L} d_i), \tag{A.1}$$

$$O_2(\Delta S = 1) = (\bar{s}_i \gamma^\mu \mathrm{L} u_i)\,(\bar{u}_j \gamma_\mu \mathrm{L} d_j), \tag{A.2}$$

$$O_1(\Delta C = 1) = (\bar{s}_i \gamma^\mu \mathrm{L} c_j)\,(\bar{u}_j \gamma_\mu \mathrm{L} d_i), \tag{A.3}$$

$$O_2(\Delta C = 1) = (\bar{s}_i \gamma^\mu \mathrm{L} c_i)\,(\bar{u}_j \gamma_\mu \mathrm{L} d_j), \tag{A.4}$$

$$O_1(\Delta B = 1) = (\bar{b}_i \gamma^\mu \mathrm{L} c_j)\,(\bar{u}_j \gamma_\mu \mathrm{L} d_i), \tag{A.5}$$

$$O_2(\Delta B = 1) = (\bar{b}_i \gamma^\mu \mathrm{L} c_i)\,(\bar{u}_j \gamma_\mu \mathrm{L} d_j). \tag{A.6}$$

QCD-Penguin operators

$$O_3 = (\bar{s}_i \gamma^\mu \mathrm{L} b_i) \sum_q (\bar{q}_j \gamma_\mu \mathrm{L} q_j), \tag{A.7}$$

$$O_4 = (\bar{s}_i \gamma^\mu \mathrm{L} b_j) \sum_q (\bar{q}_j \gamma_\mu \mathrm{L} q_i), \tag{A.8}$$

$$O_5 = (\bar{s}_i\gamma^\mu \mathrm{L} b_i)\sum_q(\bar{q}_j\gamma_\mu \mathrm{R} q_j), \tag{A.9}$$

$$O_6 = (\bar{s}_i\gamma^\mu \mathrm{L} b_j)\sum_q(\bar{q}_j\gamma_\mu \mathrm{R} q_i). \tag{A.10}$$

Electroweak-Penguin operators

$$O_7^{\mathrm{EW}} = \frac{3}{2}(\bar{s}_i\gamma^\mu \mathrm{L} b_i)\sum_q e_q(\bar{q}_j\gamma_\mu \mathrm{R} q_j), \tag{A.11}$$

$$O_8^{\mathrm{EW}} = \frac{3}{2}(\bar{s}_i\gamma^\mu \mathrm{L} b_j)\sum_q e_q(\bar{q}_j\gamma_\mu \mathrm{R} q_i), \tag{A.12}$$

$$O_9^{\mathrm{EW}} = \frac{3}{2}(\bar{s}_i\gamma^\mu \mathrm{L} b_i)\sum_q e_q(\bar{q}_j\gamma_\mu \mathrm{L} q_j), \tag{A.13}$$

$$O_{10}^{\mathrm{EW}} = \frac{3}{2}(\bar{s}_i\gamma^\mu \mathrm{L} b_j)\sum_q e_q(\bar{q}_j\gamma_\mu \mathrm{L} q_i). \tag{A.14}$$

Magnetic-Penguin operators

$$O_7 = \frac{e}{16\pi^2} m_b(\bar{s}_i\sigma^{\mu\nu}\mathrm{R} b_i)F_{\mu\nu}, \tag{A.15}$$

$$O_8 = \frac{g_s}{16\pi^2} m_b(\bar{s}_i T^a_{ij}\sigma^{\mu\nu}\mathrm{R} b_j)G^a_{\mu\nu}. \tag{A.16}$$

A.2 $\Delta S = 2$ and $\Delta B = 2$ operators

$$O(\Delta S = 2) = (\bar{s}_i\gamma^\mu \mathrm{L} d_i)(\bar{s}_j\gamma_\mu \mathrm{L} d_j), \tag{A.17}$$

$$O(\Delta B = 2) = (\bar{b}_i\gamma^\mu \mathrm{L} d_i)(\bar{b}_j\gamma_\mu \mathrm{L} d_j). \tag{A.18}$$

A.3 Semileptonic operators

$$O^\ell_{9V} = (\bar{s}_i\gamma^\mu \mathrm{L} b_i)(\bar{\ell}\gamma_\mu \ell), \tag{A.19}$$

$$O^\ell_{10A} = (\bar{s}_i\gamma^\mu \mathrm{L} b_i)(\bar{\ell}\gamma_\mu\gamma_5 \ell), \tag{A.20}$$

$$O(\bar{\nu}\nu) = (\bar{s}_i\gamma^\mu \mathrm{L} b_i)\,(\bar{\nu}\gamma_\mu \mathrm{L}\nu). \tag{A.21}$$

where i, j are the color indices and $\mathrm{L/R} = (1 \mp \gamma_5)/2$.

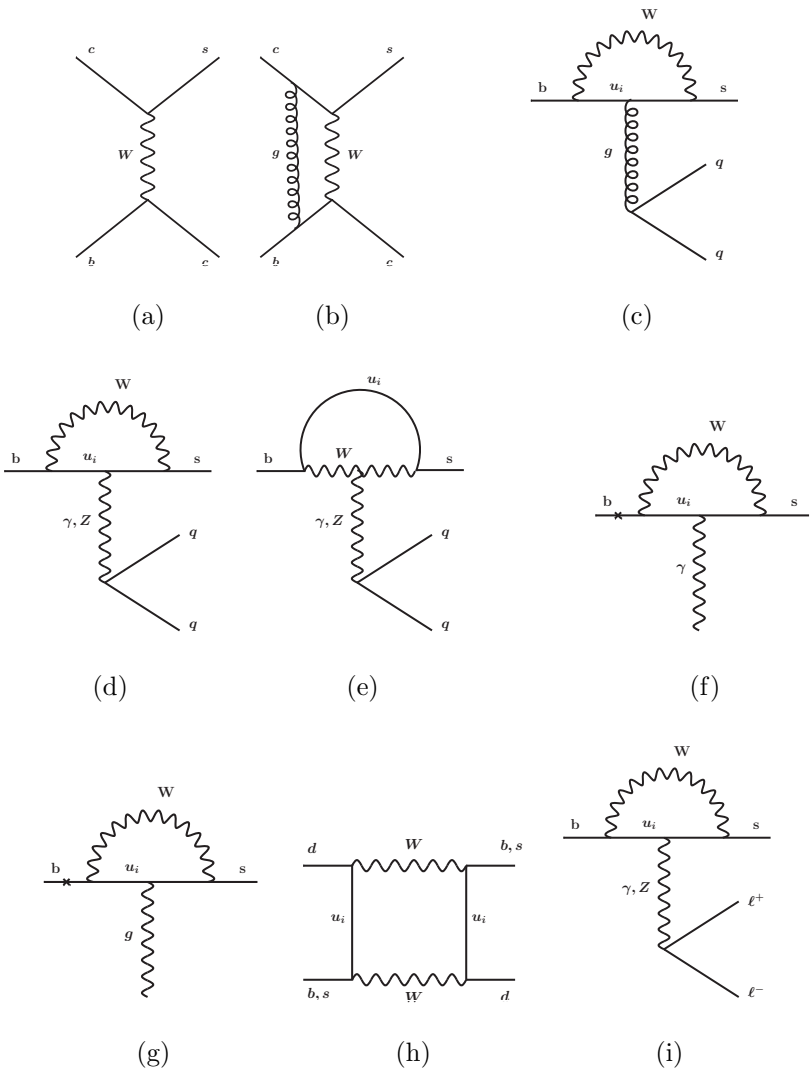

Figure A: Representative Feynman diagrams in the full theory. (a), (b) the current-current diagrams, (c) QCD-penguin diagram, (d), (e) electroweak penguin diagram, (f) QED magnetic penguin diagram, (g) QCD magnetic penguin diagram, (h) $\Delta F = 2$ box diagram, and (i) semileptonic penguin diagram.

B Form Factors for $B \to K^*$

Here, we give q^2 dependence of the form factors for the process $B \to K^*$. We have employed two sets of form factors (V, $A_{0,1,2}$, $T_{1,2,3}$) [75] and ($\xi_\perp$, $\xi_\parallel$) [79] for numerical evaluation of the zeroes of the angular observables in chapter 2. The form factors (V, $A_{0,1,2}$, $T_{1,2,3}$) are valid in full kinematical range of q^2, while the form factors ($\xi_\perp$, $\xi_\parallel$) are applicable in the large recoil (low-q^2) region. The

parametrization of q^2 dependence of V, $A_{0,1,2}$, $T_{1,2,3}$ is given by [75]

$$V(q^2) = \frac{r_1}{1-q^2/m_R^2} + \frac{r_2}{1-q^2/m_{\rm fit}^2}, \tag{B.1}$$

$$A_0(q^2) = \frac{r_1}{1-q^2/m_R^2} + \frac{r_2}{1-q^2/m_{\rm fit}^2}, \tag{B.2}$$

$$A_1(q^2) = \frac{r_2}{1-q^2/m_{\rm fit}^2}, \tag{B.3}$$

$$A_2(q^2) = \frac{r_1}{1-q^2/m_{\rm fit}^2} + \frac{r_2}{(1-q^2/m_{\rm fit}^2)^2}, \tag{B.4}$$

$$T_1(q^2) = \frac{r_1}{1-q^2/m_R^2} + \frac{r_2}{1-q^2/m_{\rm fit}^2}, \tag{B.5}$$

$$T_2(q^2) = \frac{r_2}{1-q^2/m_{\rm fit}^2}, \tag{B.6}$$

$$\tilde{T}_3(q^2) = \frac{r_1}{1-q^2/m_{\rm fit}^2} + \frac{r_2}{(1-q^2/m_{\rm fit}^2)^2}, \tag{B.7}$$

where form factor T_3 is related to $\tilde{T}_3$ through the following relation

$$T_3(q^2) = \frac{m_B^2 - m_{K^*}^2}{q^2}[\tilde{T}_3(q^2) - T_2(q^2)]. \tag{B.8}$$

The values of the parameters r_1, r_2, m_R^2, and $m_{\rm fit}^2$ are given in Ref. [75], and are listed in the Table below.

	r_1	m_R^2	r_2	$m_{\rm fit}^2$
$V(q^2)$	0.923	28.30	-0.511	49.40
$A_0(q^2)$	1.364	27.88	-0.990	36.78
$A_1(q^2)$			0.290	40.38
$A_2(q^2)$	-0.084		0.342	52.00
$T_1(q^2)$	0.823	28.30	-0.491	46.31
$T_2(q^2)$			0.333	41.41
$\tilde{T}_3(q^2)$	-0.036		0.368	48.10

Table A: Values of the fit parameters for $B \to K^*$ form factors.

On the other hand, for the form factors $\xi_\perp$, $\xi_\parallel$, we use the following parametriza-

tion [78]

$$\xi_\perp(q^2) = \xi_\perp(0)\left(\frac{1}{1-q^2/m_B^2}\right)^2, \tag{B.9}$$

$$\xi_\parallel(q^2) = \xi_\parallel(0)\left(\frac{1}{1-q^2/m_B^2}\right)^3, \tag{B.10}$$

where $\xi_\perp(0) = 0.266 \pm 0.032$ and $\xi_\parallel(0) = 0.118 \pm 0.008$ [74].

C $\Lambda_b \to \Lambda$ Helicity Form Factors

Here we provide the relations of helicity amplitudes and $\Lambda_b \to \Lambda$ form factors for a particular Dirac spinor $[u\left(p(k), s_{\Lambda_b(\Lambda)}\right)]$ representation as obtained in Ref. [124]. The helicity amplitudes $H_\lambda^{V,A,T,T5}$ are defined by

$$H_\lambda^\kappa(s_{\Lambda_b}, s_\Lambda) \equiv \epsilon^*(\lambda) \cdot \langle \Lambda(k, s_\Lambda|\bar{s}\Gamma^\kappa b|\Lambda_b(p, s_{\Lambda_b}\rangle, \tag{C.1}$$

where $s_{\Lambda_{(b)}}$ are the spin vectors associated with the baryons; $\epsilon^*(\lambda = t, +, -, 0)$ are virtual polarization vectors with $q.\epsilon(\pm) = 0 = q.\epsilon(0)$; and $\Gamma^\kappa = \gamma^\mu$, $\gamma^\mu\gamma_5$, $i\sigma^{\mu\nu}q_\nu$, and $i\sigma^{\mu\nu}q_\nu\gamma_5$ correspond to helicity amplitudes H_λ^V, $H_\lambda^{A,}$, H_λ^T, and H_λ^{T5}, respectively.

For the vector current, the corresponding helicity amplitudes $H_i^V(s_{\Lambda_b}, s_\Lambda)$ in terms of helicity form factors f_t^V, f_0^V, $f_\perp^V$ are given by

$$H_t^V(1/2,1/2) = H_t^V(-1/2,-1/2) = f_t^V(q^2)\frac{m_{\Lambda_b}-m_\Lambda}{\sqrt{q^2}}\sqrt{s_+}, \tag{C.2}$$

$$H_0^V(1/2,1/2) = H_0^V(-1/2,-1/2) = f_0^V(q^2)\frac{m_{\Lambda_b}+m_\Lambda}{\sqrt{q^2}}\sqrt{s_-}, \tag{C.3}$$

$$H_+^V(-1/2,1/2) = H_-^V(1/2,-1/2) = -f_\perp^V(q^2)\sqrt{2s_-}. \tag{C.4}$$

For the axial-vector current, the analogous expressions for the corresponding helicity amplitudes $H_\lambda^A(s_{\Lambda_b}, s_\Lambda)$ are given by

$$H_t^A(1/2,1/2) = -H_t^A(-1/2,-1/2) = f_t^A(q^2)\frac{m_{\Lambda_b}+m_\Lambda}{\sqrt{q^2}}\sqrt{s_-}, \tag{C.5}$$

$$H_0^A(1/2,1/2) = -H_0^A(-1/2,-1/2) = f_0^A(q^2)\frac{m_{\Lambda_b}-m_\Lambda}{\sqrt{q^2}}\sqrt{s_+}, \tag{C.6}$$

$$H_+^A(-1/2,1/2) = -H_-^A(1/2,-1/2) = -f_\perp^A(q^2)\sqrt{2s_+}. \tag{C.7}$$

For the tensor current, the corresponding nonzero helicity amplitudes $H_\lambda^T(s_{\Lambda_b}, s_\Lambda)$ involve two form factors f_0^T and $f_\perp^T$ only

$$H_0^T(1/2,1/2) = H_0^T(-1/2,-1/2) = -f_0^T(q^2)\sqrt{q^2}\sqrt{s_-}\,, \tag{C.8}$$

$$H_+^T(-1/2,1/2) = H_-^T(1/2,-1/2) = f_\perp^T(q^2)(m_{\Lambda_b}+m_\Lambda)\sqrt{2s_-}\,. \tag{C.9}$$

The expressions for nonzero $H_\lambda^{T_5}(s_{\Lambda_b}, s_\Lambda)$ corresponding to pseudo-tensor current involve two more form factors $f_0^{T_5}$ and $f_\perp^{T_5}$

$$H_0^{T_5}(1/2,1/2) = -H_0^{T_5}(-1/2,-1/2) = f_0^{T_5}(q^2)\sqrt{q^2}\sqrt{s_+}\,, \tag{C.10}$$

$$H_+^{T_5}(-1/2,1/2) = -H_-^{T_5}(1/2,-1/2) = -f_\perp^{T_5}(q^2)(m_{\Lambda_b}-m_\Lambda)\sqrt{2s_+}\,. \tag{C.11}$$

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List of Publications

Publications in Journals

1. **Girish Kumar**, Namit Mahajan, $B \to K^* l^+ l^-$: *Zeros of angular observables as test of standard model*, Phys. Rev. D **93**, (2016) no.5, 054041, doi: 10.1103/PhysRevD.93.054041.

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3. **Girish Kumar**, *Constraints on a scalar leptoquark from the kaon sector*, Phys. Rev. D **94**, (2016) no.1, 014022, doi: 10.1103/PhysRevD.94.014022.

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Preprints

1. **Girish Kumar**, Namit Mahajan, *Asymmetries and observables for* $\Lambda_b \to \Lambda \ell^+ \ell^-$, arXiv:1511.00935.