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B meson decays in leptons: powerful probes of new physics

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Abstract. We review some recent measurements of B meson decays that involve leptons in the final states and that are sensitive to physics beyond the Standard Model, such as the electroweak penguin decays $B \to X_s \ell^+ \ell^-$, the Lepton Number Violating process $B \to X \ell^\pm \ell'^\pm$ and the tree-level dominated decay with τ leptons: $B \to \tau \nu_\tau$ and $B \to D^{(*)} \tau \nu_\tau$.

1 Introduction

The BaBar experiment has collected about $470 \cdot 10^6$ couple of $B\overline{B}$ events from the $\Upsilon(4S)$ decays. This huge sample allowed to perform stringent studies on B meson properties and successfully confirmed the Standard Model (SM) predictions in the flavour sector. Although no relevant deviations from the SM have yet been found with the current statistics by BaBar and Belle, it is of paramount importance to continue to search for New Physics (NP) sign through indirect virtual contributions in the B decays. Here we present some recent result from BaBar on B meson decays in channels with leptons in the final state. All the results presented are based on the full available dataset.

2 Inclusive $B \to X_s \ell^+ \ell^-$ decays

The process $b \to s \ell^+ \ell^-$, where b is a bottom quark, s is a strange quark, and $\ell^+ \ell^-$ is a $e^+ e^-$ or $\mu^+ \mu-$ pair, is a FCNC process forbidden at lowest order in the Standard Model but is allowed via EW penguin and W-box diagrams. The amplitude for this decays is expressed in terms of perturbatively calculable effective Wilson coefficients. The non-SM contributions can modify the Wilson coefficients from the SM expectations. The exclusive channels $B \to K \ell^+ \ell^-$ and $B \to K^* \ell^+ \ell^-$ are currently extensively studied at B-Factories and LHCb. The study of the inclusive channel, where one does not look in a specific final state, is complementary to the exclusive studies.

Here we report a recent BaBar measurement [2] of the $B \to X_s \ell^+ \ell^-$ decay, using a sum over exclusive final states, which provides a basis for an extrapolation to the fully inclusive rate. We measure the total Branching Fraction (BF) as well as partial BF in five bins of $q^2 \equiv m^2_{\ell^+\ell^-}$. The X_s states are reconstructed in 10 separate X_s hadronic final states (K^+,$K^+\pi^0$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+$, K^0_s, $K^0_s\pi^0$, $K^0_s\pi^+$, $K^0_s\pi^+\pi^0$ and $K^0_s\pi^+\pi^-$), combining these with e^+e^- and $\mu^+\mu^-$ pairs. We limit the number of pions in the final state to two and require $m_{X_s} < 1.8$ GeV$/c^2$ since the expected S/N ratio decrease very rapidly with the mass and the X_s pion multiplicity. The reconstructed states, taking into account

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the presence of the K_L and the $K_s \to \pi^0\pi^0$, represent about 70% of the total inclusive rate. We suppress the $e^+e^- \to q\bar{q}$ events (where $q = u, d, s,$ or c quark) and $B\bar{B}$ combinatoric background using Boosted Decision Trees (BDTs) exploiting many kinematical and topological quantities. In each q^2 bin, we extract the signal yield with a 2-D maximum likelihood fit using the mass of the B meson candidate and a likelihood ratio based on the BDTs used to suppress the $B\bar{B}$ backgrounds. From the extracted signal yields and the efficiencies, we compute the partial BFs in each q^2 bin. The measured partial BFs in the various q^2 bins analysed is reported in Fig. 1. The lepton-flavour averaged result for the

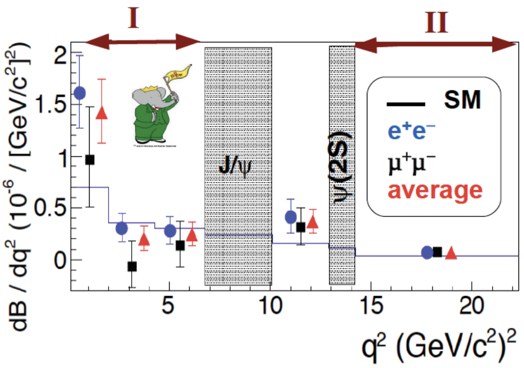

Figure 1. Differential BF as a function of q^2 for e^+e^-, $\mu^+\mu^-$ and lepton-flavour averaged final states. The histogram shows the SM expectation which is affected by an uncertainty of 10% – 30% depending on the q^2 regions. The shaded boxes denote the vetoed regions to remove the copious production of $B \to X_s J/\psi$ and $B \to X_s\psi'$, where $J/\psi(\psi') \to \ell^+\ell^-$. The region **I** and **II** are defined respectively as $1 < q^2 < 6$ GeV$^2/c^4$ and $q^2 > 14.4$ GeV$^2/c^4$.

range $1 < q^2 < 6$ GeV$^2/c^4$ (**I**) is $BF = (1.60^{+0.44}_{-0.39}\,^{+0.17}_{-0.13} \pm 0.18) \cdot 10^{-6}$ and for $q^2 > 14.4$ GeV$^2/c^4$ (**II**) is $BF = (0.57^{+0.16}_{-0.15}\,^{+0.03}_{-0.02} \pm 0.00) \cdot 10^{-6}$, where the uncertainties are statistical, systematics and due to the model-dependent extrapolation to the full rates. The measured rate is in very in good agreement with the SM predictions in region **I** ($BF(B \to X_s\mu^+\mu^-) = (1.59 \pm 0.11) \cdot 10^{-6}$ [3]), and it is within 2σ with the prediction in the region **II** ($BF(B \to X_s\mu^+\mu^-) = (0.24 \pm 0.07) \cdot 10^{-6}$ [3]). It is interesting to note that the e^+e^- results are systematically higher than the $\mu^+\mu^-$ case, but they are compatible within the experimental uncertainties. It should be noted here that the explanation of the LHCb observation of the anomaly in one of the observables [4], as suggested in [5] would result in a decrease of the inclusive BF of up to about 25% in both the region **I** and **II** and this is not compatible with our result.

3 Search for $B \to X\ell^\pm\ell'^\pm$

The neutrino oscillation suggests that lepton number may not be conserved, moreover the lepton-number violation (LNV) is a necessary condition for leptogenesis as an explanation of the baryon asymmetry of the Universe [7]. Many models beyond the SM predict the LNV in B meson decays with a rate that could be accessible with the present data available [6]. CLEO performed [8] for the first time searches of LNV processes in the B meson decays like $B^+ \to X\ell^+\ell'^+$, where X is a charged particle or resonance and $\ell/\ell' = e$ or μ. Recently LHCb [11], BaBar [10] and Belle [9] reported search for these processes using much higher statistics.

Here we report the recent BaBar search [12] for $B^+ \to X\ell^+\ell'^+$ with $X = K^-, \pi^-\rho^-, K^{*-}$ or D^-. The huge background is suppressed with a BDT that uses many event-shape and signal kinematic discriminant variables. The signal is extracted from a 3-D unbinned maximum likelihood fit to the BDT output, the B candidate mass, and $\Delta E = E^*_B - E_{c.m.}$, where E^*_B is the energy of the B candidate in the $c.m.$ frame. We find no significant signal yields and place upper limits on the BF in the range $(1.5 - 26) \cdot 10^{-7}$. These limits are in many cases more stringent than previous best measurements. In Fig. 2 we report a summary of the existing upper limits on a large set of studies B-meson LNV processes.

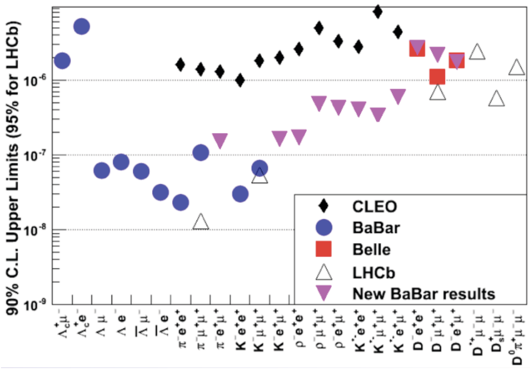

Figure 2. The upper limits on various B meson LNV processes obtained by CLEO, Belle, BaBar and LHCb. The most recent upper limits (90% C.L.) on the BF of various $B^+ \to X\ell^+\ell'^+$ processes obtained by BaBar [12] are in the range $1.2 \cdot 10^{-7} - 26 \cdot 20^{-7}$ and they are indicated with the filled triangles. For modes with ρ, π and K the limits are an order of magnitues more stringent than previous best results [8]. The upper limit for the $B \to D\ell^+\ell'^+$ are compatible wih those reported by Belle in Ref. [9].

4 $B \to \tau\nu_\tau$ and $B \to D^*\tau\nu_\tau$

The FCNC processes are powerful tools to search for physics beyond the SM, but tree level dominated processes are good as well to constraint important kind of NP. Many extended versions of the SM require changes in the Higgs sector, with the prediction of many Higgs bosons, both neutral and charged. A prototype of these models is the widely studies 2 Higgs-Doublet-Model of type-II, that predicts the existence of a charged Higgs H^+. A virtual H^+ can replace the W^+ in the leptonic $B \to \tau\nu$ and semileptonic $B \to D^*\tau\nu_\tau$ decays, which results in a significant enhancement and suppression of the predicted SM rates. These decays with τ in the final states are challenging to identify experimentally, since they include multiple neutrinos in the final state: one ν_τ from the W and one or two more from the τ decay. At the B-Factories these decays can be reconstructed exploiting the fact that only a B meson pair is produced from the $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ process. It is possible to reconstruct one of the B mesons (B_{tag}) in a large number of decays and identify the signal decays (B_{sig}) from the rest of the event.

The BaBar measurement [13] uses the hadronic tag where one of the B meson of the $\Upsilon(4S)$ decay is reconstructed in a large set of hadronic $B^+ \to D^{(*)0}X^+$ decays or $B^+ \to J/\psi X^+$ decays (where X^+ denotes a system of hadrons with charge +1 composed of combinations of π^+, π^0, $K^\pm$ and K^0_s, and the $D^{(*)0}$ is reconstructed in many different decay channels to maximize the efficiency). Once the B_{tag} is reconstructed, the rest of the event is due to the decay products of the τ that comes from the B_{sig} decays. We reconstruct the τ in both leptonic and hadronic modes. The most significant discriminating variable is E_{extra} defined as the sum of the energies of the neutral clusters not associated with the B_{tag} or with the products of the signal τ. Signal events tend to peak at low E_{extra}, instead background event, which contain additional neutral clusters, tend to be distribute at higher values. We fit $N_{sig} = 62.1 \pm 17.3$ signal events corresponding to $BF(B \to \tau\nu) = (1.83^{+0.53}_{-0.49}(stat) \pm 0.24(syst)) \cdot 10^{-4}$, excluding the null hypothesis by 3.8σ. Our measurement is compatible with other measurements [14] and exceeds the prediction of the SM determination by 2.4σ and 1.6σ according to the used value of $|V_{ub}|$, exclusive or inclusive respectively. The BaBar result is marginally compatible with the most recent one obtained by Belle [15] obtained with an improved hadronic B tag technique. The Belle result is perfectly compatible with the SM expectation. Despite the not clear situation on the $B \to \tau\nu$ decays, the measured BF put not trivial constraints on $\tan\beta/m_{H^+}$ for the 2HDM as shown in Fig. 3 (right).

BaBar published an interesting result [16] on the semileptonic $B \to D^{(*)}\tau\nu$ decays using the hadronic tag. The signal signature of the $B \to D^{(*)}\tau\nu$ decays are represented by a large value of missing mass, determined from the kinematic of the reconstructed B_{tag}, the signal $D^{(*)}$ and the lepton (e or μ that comes from the τ decay), and a soft lepton momentum. The fit is performed simultaneously on D^0, D^+, D^{*0} and D^{*+} and the results are $R(D) = BF(B \to D\tau\nu)/BF(B \to D\ell(e \text{ or } \mu)\nu) = 0.440 \pm 0.058(stat) \pm 0.042(syst)$ and $R(D^*) = BF(B \to D^*\tau\nu)/BF(B \to D^*\ell(e \text{ or } \mu)\nu) = 0.332 \pm 0.024(stat) \pm 0.018(syst)$ (B^0 and B^+ isospin constrained results). The measurement of the ratios $R(D)$ and $R(D^*)$ has the advantage that they are experimentally very clean because many systematics cancel in the ratio. Moreover the theoretical predictions in the SM are reliable and affected by a small uncertainties: $R(D) = 0.297 \pm 017$ and $R(D) = 0.252 \pm 0.003$ [17]. The BaBar result is compatible with the Belle results obtained with a similar technique [18] and exceed the SM prediction by 3.4σ, if we consider the excess in both the R^D and R^{D^*} ratios. In the 2HDM of type II, there is a substantial impact on the ratios $R(D)$ and $R(D^*)$ due to the H^+ contribution. Because the preferred $\tan\beta/m_{H^+}$ regions for $R(D)$ and $R(D^*)$ are not compatible, we are able to put a severe constraint in the $\tan\beta/m_{H^+}$ plane for the 2HDM of type II (Fig. 3), that is so disfavoured at more than 3σ.

The hadronic B tagging technique allows to measure the $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$ decays with good precision despite the weak experimental signature. These channels put constraints on $\tan\beta/m_{H^+}$ ratio for the 2HDM that are complementary or stronger than the constraints set by CMS and ATLAS.

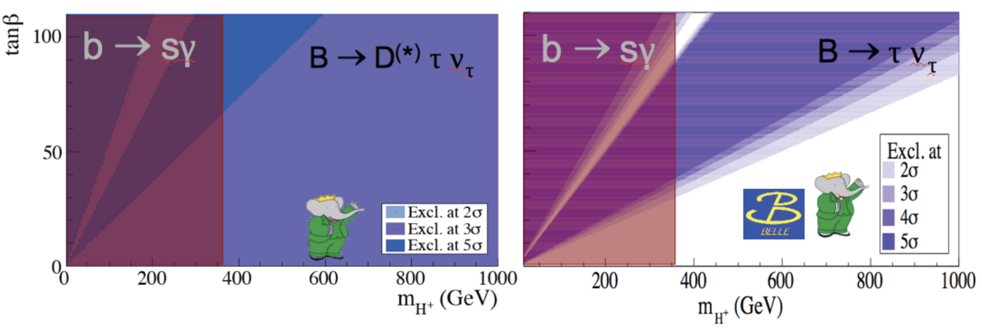

Figure 3. Constraints in the $\tan\beta - m_{H^+}$ plane in the 2HDM of type II obtained from the BaBar measurement of $R(D^{(*)})$ (left) and from the BaBar and Belle results on $B \to \tau\nu_\tau$ branching fraction (right). The vertical red band is the excluded region of m_{H^+} that comes from $B \to X_s\gamma$ [19]. The BaBar $R(D^{(*)})$ allows to exclude the entire plane at more than 3σ level.

5 Conclusions

The decays of B mesons with leptons in the final states are a very powerful probe to search for NP effects due to virtual heavy particles in the tree and loop diagrams. Here we presented some recent BaBar results. NP has not been observed yet, but some interesting tensions are present and these require more studies from both the experimental and theoretical side.

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