IL NUOVO CIMENTO Vol. 32 C, N. 3-4 Maggio-Agosto 2009
DOI 10.1393/ncc/i2009-10452-2

Colloquia: IFAE 2009

Search for $B \to \ell\nu$, $B \to K^{(*)}\nu\bar{\nu}$, and $B \to K^{(*)}\ell\ell$ at B factories

E. Manoni
Università di Perugia and INFN, Sezione di Perugia - Perugia, Italy

(ricevuto il 19 Settembre 2009; pubblicato online il 13 Novembre 2009)

Summary. — A review of the searches for the $B \to \ell\nu$, $B \to K^{(*)}\nu\bar{\nu}$, and $B \to K^{(*)}\ell\ell$ rare decays performed with data samples collected by the BaBar and Belle detectors will be presented.

PACS 14.40.Nd – Bottom mesons.

1. – Rare decays and New Physics

The Standard Model (SM) predictions in the flavour sector have been experimentally confirmed in many ways and with good precision. Anyway, it is known that this is not the ultimate theory and many New Physics (NP) models have been built to answer the SM open questions. To detect NP effects two approaches are feasible: direct search for NP states at the Large Hadron Collider (TeV scale) or indirect search at machines running at lower energy but with a very clean environment. In the second scenario, decays which are predicted to be rare in the SM (with branching fraction $\mathcal{B}$ as low as 10^{-11} or even rarer) but can receive NP contributions offer an optimal ground where to search for deviation from the SM. These transitions happen through second-order diagrams and NP states can enter boxes or penguins giving contributions of the same order of the SM terms. From the experimental measurements, constraints on parameters defining NP models can be imposed and evidence for NP can be claimed if the results are far away from the SM predictions. Such experimental searches are challenging since invisible energy can be involved and the low expected branching fraction makes a high and clean sample necessary. The PeP-II and KEK-B B factory provide a unique environment for the high number of produced $B\bar{B}$ pairs and the very clean sample due the closed kinematics of the initial state. In fact, the e^+-e^- beams collide at a center-of-mass (CM) energy corresponding to the $\Upsilon(4S)$ mass and this resonance decays in a $B\bar{B}$ pair (and nothing else) almost 100% of times. In this work a review of the most recent results of the searches for $B \to \ell\nu$, $B \to K^{(*)}\nu\bar{\nu}$, and $B \to K^{(*)}\ell\ell$ channels are reported. All the Upper Limits (ULs) reported in the following are at 90% of confidence level and charge conjugation is implied.

2. – Analysis overview

Depending on the searched final state, different analysis strategies are exploited. In some cases the *recoil method* is used: one B in the event (B_{tag}) is reconstructed in semileptonic ($B \to D^{(*)}\ell\nu$) or hadronic ($B \to DY$, where Y is a collection of charged and neutral pions and kaons) modes; the signal B (B_{sig}) signature is then searched for in the other hemisphere of the event. This method is used when one or more neutrinos are expected in the signal side and the lack of information due to their undetectability is compensated by requiring the four-vector conservation of the reconstructed $B\bar{B}$ pair. The recoil method is used in the $B \to K^{(*)}\nu\bar{\nu}$ and $B \to \ell\nu$ analyses. For the latter, also a total inclusive approach is adopted: a high-momentum track identifies the signal side lepton and all the remaining reconstructed objects are asked to come from the B_{tag}. This technique ensures a higher statistic sample with respect to the recoil approach, the price to be paid is a higher background contamination. Finally, in the search for the $B \to K^{(*)}\ell\ell$ decay the signal side is completely reconstructed and the final state kinematics is constrained to the B hypothesis, no requirements on the B_{tag} are imposed.

3. – Searches for $B \to \ell\nu$

The $B \to \ell\nu$ is mediated by an annihilation diagram in which a W-boson decays to an $\ell\nu$ pair. The SM branching fraction depends on the CKM matrix element V_{ub}, on the B-meson decay constant f_B and on the second power of the final-state lepton mass m_ℓ. Using for f_B and V_{ub} the numerical values of refs. [1] and [2], respectively, the SM predictions are: $\mathcal{B}(B \to e\nu)_{\text{SM}} = (1.1 \pm 0.2) \times 10^{-11}$, $\mathcal{B}(B \to \mu\nu)_{\text{SM}} = (4.7 \pm 0.7) \times 10^{-7}$, $\mathcal{B}(B \to \tau\nu)_{\text{SM}} = (1.3 \pm 0.4) \times 10^{-4}$. In some NP models [3], a charged Higgs boson can replace the W and the branching fraction turn out to be sensitive to physics beyond the SM.

From the experimental point of view, two approaches have been used: a recoil analysis and an inclusive technique. The first is performed searching for the signal signature in the recoil of a semileptonic B decay, from both BaBar [4] ($418\,\text{fb}^{-1}$) and Belle [5] ($605\,\text{fb}^{-1}$). In the BaBar analysis, all the three leptonic channels are examined while Belle studies only the final state with the heaviest lepton. Signal events are selected exploiting event shape properties, kinematic variables and the extra energy deposited in the calorimeter neither associated to the B_{sig} nor to the B_{tag} (E_{extra}). BaBar estimates the expected background yield from a region of the E_{extra} range where signal events are not expected to lie (E_{extra} sideband). Belle extracts the signal yield by a maximum likelihood fit to the E_{extra} distributions. Both experiments have found evidence for signal in the $B \to \tau\nu$ search, while BaBar has set UL on $\mathcal{B}$ for the electron and muon channels: $\mathcal{B}(B \to \tau\nu) = 1.8 \pm 0.8 \pm 0.1$ (BaBar), $\mathcal{B}(B \to \tau\nu) = 1.65^{+0.38}_{-0.37}$ (Belle), $\mathcal{B}(B \to \mu\nu) < 11 \times 10^{-6}$, $\mathcal{B}(B \to e\nu) < 7.7 \times 10^{-6}$.

The inclusive analysis of the $B \to e\nu, \mu\nu$ modes has been published from both BaBar [6] ($426\,\text{fb}^{-1}$) and Belle [7] ($253\,\text{fb}^{-1}$). The B_{tag} kinematics and the signal side lepton momentum are used at the selection stage. In Belle, the yield extraction is made by fitting the distribution of the B_{tag} energy-substituted mass ($m_{\text{ES}} = \sqrt{E^{\text{CM}\,2}_{\text{beam}} - p^{\text{CM}\,2}_{B_{\text{tag}}}}$, $E^{\text{CM}}_{\text{beam}}$ and $p^{\text{CM}}_{B_{\text{tag}}}$ being the beam energy and the B_{tag} momentum in the CM frame, respectively). BaBar applies a two-dimensional fit to the distributions of m_{ES} and of a variable which is a linear combination of the lepton momentum in the CM frame and in the B_{sig} rest frame. The most stringent constraints (also considering the semileptonic recoil analysis) come from the BaBar inclusive search: $\mathcal{B}(B \to \mu\nu) < 1.0 \times 10^{-6}$ and $\mathcal{B}(B \to e\nu) < 1.9 \times 10^{-6}$.

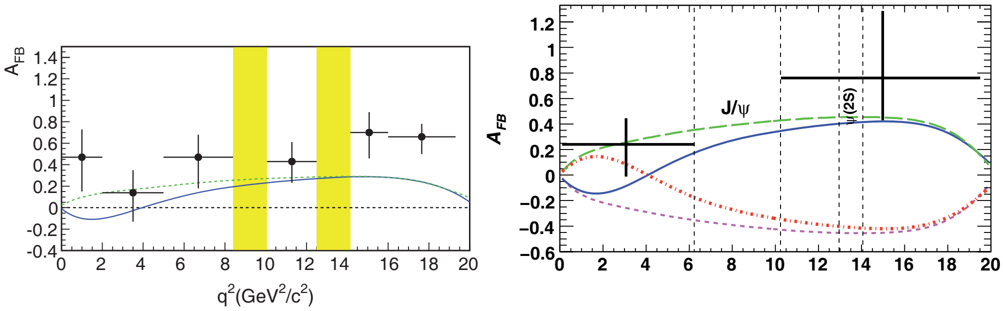

Fig. 1. – (Colour on-line) Forward-backward asymmetry from the Belle (left) and BaBar (right) analysis: bars represent the experimental data, SM prediction in blue, $C_9C_{10} = -C_9^{\mathrm{SM}}C_{10}^{\mathrm{SM}}$ hypothesis in pink, $C_7 = -C_7^{\mathrm{SM}}$ and $C_9C_{10} = -C_9^{\mathrm{SM}}C_{10}^{\mathrm{SM}}$ hypothesis in red.

4. – Searches for $B \to K^{(*)}\ell\ell$

The $b \to s\ell\ell$ transition is mediated by Flavour-Changing Neutral Current (FCNC) and is therefore forbidden at tree level in the SM. It occurs via an electroweak penguin or a W box. In the Operator Product Expansion framework, three Wilson coefficients (C_7, C_9, and C_{10}) in the effective Hamiltonian account for the SM couplings. The transition has been studied in many NP scenarios which predict changes in magnitude and relative sign of the three coefficients [8]. In samples of $350\,\mathrm{fb}^{-1}$ for BaBar [9] and of $597\,\mathrm{fb}^{-1}$ for Belle [10], events with e^+e^- or $\mu^+\mu^-$ pairs associated to a $K^{(*)}$ (reconstructed as K^+, K^0_S, $K^{*0} \to K^+\pi^-$, $K^{*+} \to K^+\pi^0$, $K^{*+} \to K^0_S\pi^+$) are selected. After having applied a selection on event shape, kinematics, and vertexing information, the signal yield is estimated from a fit to the m_{ES} distribution (in the Belle analysis, for the K^* modes, the $K - \pi$ invariant mass is also fitted). A veto in the two-lepton invariant mass ($q^2 = m_{\ell\ell}$) is imposed in order to exclude resonant decays in which J/Ψ or $\Psi(2S)$ mesons, decaying to e^+e^- or $\mu^+\mu^-$, are produced with a K or a K^*. As a consequence, in Belle (BaBar) the results are extracted in 6 (2) q^2 bins, half the bins in the low-q^2 region and the other half in the high-q^2 region. As detailed in refs. [9] and [10], several quantities are measured in order to find discrepancies with respect to the SM predictions such as the branching fraction, the CP and the isospin asymmetries. Moreover, an angular analysis is performed to determine the forward-backward asymmetry (A_{FB}) and the fraction of longitudinally polarized K^* (F_{L}). The distributions of such quantities strongly depend on the relative signs of the Wilson Coefficients. The distributions of the fitted forward-backward asymmetries are shown in fig. 1. As can be noticed, the experimental data seems to agree with the $C_7 = -C_7^{\mathrm{SM}}$ hypothesis but a higher statistic sample with more q^2 bins and precise theoretical calculations would be needed to make tighter constraints; also the other measurements (branching fraction, isospin asymmetry, F_{L}) performed with the same sample can be considered in agreement with the SM prediction.

5. – Searches for $B \to K^{(*)}\nu\bar{\nu}$

The $b \to s\nu\nu$ decay represents another process mediated by FCNC. The SM predicts a branching fraction of the order of 10^{-6} for both $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$ [11]. Several mechanisms predicted in NP scenarios can enhance the SM $\mathcal{B}$ such as non-standard Z^0 couplings [12] or new sources of missing energy [13, 14]. Belle has performed an analysis using a statistics of $492\,\mathrm{fb}^{-1}$ and selecting events with one $K^{(*)}$ accompanied by missing energy, in the recoil of hadronic B decays. A selection based on particle identification requirements, tracks and neutral multiplicity and kinematics variables is exploited, the number of expected background events is extracted by properly normalizing the number of simulated events in the E_{extra} sideband surviving the selection. For all the investigated final states no evidence for signal is found and ULs on $\mathcal{B}$ are set.

BaBar separately analyzes events with a K or a K^* in the final state. The $B \to K\nu\bar{\nu}$ is searched for in the recoil of a semileptonic B decay. Twenty-two selection variables are combined in a multivariate algorithm, the Random Forest [15]; a signal region is defined according to the Random Forest output and the expected background is estimated from simulated samples and data sideband.

A sample of $413\,\mathrm{fb}^{-1}$ is used to select semileptonic and hadronic B decays and the $B \to K^*\nu\bar{\nu}$ signature is searched for in the recoil of such events. In the semileptonic analysis the Punzi figure of merit [16] is used to optimize the signal selection. The signal yield is extracted by a maximum likelihood fit to the E_{extra} distribution. In the hadronic analysis, the selection variables are used as inputs for a Neural Network, its output allows to define a signal region and its distribution is there fitted in order to extract the signal yield.

No evidence for signal is found in the searched channels and the following represent the most stringent constraints reported to date on exclusive $b \to s\nu\bar{\nu}$ searches: $\mathcal{B}(B \to K^+\nu\bar{\nu}) < 1.4 \times 10^{-5}$ (Belle), $\mathcal{B}(B \to K^0\nu\bar{\nu}) < 1.6 \times 10^{-4}$ (Belle), $\mathcal{B}(B \to K^{*+}\nu\bar{\nu}) < 8.0 \times 10^{-5}$ (BaBar), $\mathcal{B}(B \to K^{*0}\nu\bar{\nu}) < 12.0 \times 10^{-5}$ (BaBar), $\mathcal{B}(B \to K^*\nu\bar{\nu}) < 8.0 \times 10^{-5}$ (BaBar). Both BaBar and Belle results are in agreement with the SM predictions and the experimental sensitivities are one order of magnitude far from the theoretical SM expectations.

REFERENCES

[1] Gray A. *et al.* (HPQCD Collaboration), *Phys. Rev. Lett.*, **95** (2005) 212001.

[2] Barberio E. *et al.* (Heavy Flavor Averaging Group (HFAG)), hep-ex/0603003 (2006).

[3] Hou. W. S., *Phys. Rev. D*, **48** (1993) 2342.

[4] Aubert B. *et al.* (BaBaR Collaboration), hep-ex/08094027 (2008).

[5] Adachi I. *et al.* (Belle Collaboration), hep-ex/08093834 (2008).

[6] Aubert B. *et al.* (BaBaR Collaboration), *Phys. Rev. D*, **79** (2009) 091101.

[7] Adachi I. *et al.* (Belle Collaboration), *Phys. Lett. B*, **647** (2007) 67.

[8] Ali A. *et al.*, *Phys. Rev. D*, **61** (2000) 074024; Buchalla G. *et al.*, *Phys. Rev. D*, **63** (2002) 014015; Ali A. *et al.*, *Phys. Rev. D*, **66** (2002) 034002; Krüger F. *et al.*, *Phys. Rev. D*, **61** (2000) 114028; *Phys. Rev. D*, **71** (2005) 094009.

[9] Aubert B. *et al.* (BaBaR Collaboration), *Phys. Rev. Lett.*, **79** (2009) 031102.

[10] Adachi I. *et al.* (Belle Collaboration), hep-ex/0810335 (2008).

[11] Altmannshofer W. *et al.*, *JHEP*, **0904** (2009) 22.

[12] Buchalla G. *et al.*, *Phys. Rev. D*, **63** (2001) 014015.

[13] Georgi H., *Phys. Rev. Lett.*, **98** (2007) 221601; Aliev M. T. *et al.*, *JHEP*, **0707** (2007) 072.

[14] Bird C. *et al.*, *Phys. Rev. Lett.*, **93** (2004) 201803.

[15] Breiman L., *Mach. Learn.*, **45** (2001) 5.

[16] Punzi G., physics/0308063 (2003).